Extreme Precision Radial Velocity Initiative Plan

Presentation to NASA and NSF

NASA's Exoplanet Exploration Program
and
the EPRV Working Group

Document Clearance Number CL#20-1588

2020 March 24

Outline

- Motivation for EPRV - *Scott Gaudi*
- Current State of the Art - *John Callas*
- Methodology - *John Callas*
- Proposed Architectures - *Jenn Burt*
- Proposed Research Program - *John Callas*
- Implementation - *John Callas*
  - Plan
  - Schedule
  - Budget
  - Top Risks
- ExoTAC Report - *Alan Boss*
- Chairs' Summary

Motivation for EPRV

(e.g., Why Do We Need to Measure the Masses of Earthlike Planets Orbiting Nearby Sun-like Stars?)

The Need to Measure Exoplanet Masses

> “Mass is the most fundamental property of a planet, and knowledge of a planet’s mass (along with a knowledge of its radius) is essential to understand its bulk composition and to interpret spectroscopic features in its atmosphere. If scientists seek to study Earth-like planets orbiting Sun-like stars, they need to push mass measurements to the sensitivity required for such worlds.”
>
> -National Academy of Sciences Exoplanet Survey Strategy Report.

A (nearly) Airtight Argument for Beginning an EPRV Initiative Now.

Extreme Precision Radial Velocity (EPRV): Learn it, Love it, Use it!

- We need to measure the masses of directly-imaged habitable planets[1].
- We have two choices:
  - Astrometry with a systematic floor of **few tens of nanoarcseconds**, or
  - RV with a systematic floor of a **few cm/s**.
- Astrometry must be done from space, so is likely ≳$1B for a dedicated mission.
  - A specially-designed instrument on another large aperture space mission (e.g., LUVOIR) is plausible, but would still be expensive (hundreds of $M) and would require significant technology development (and a mission!).
- On the other hand, EPRV at a few cm/s may be doable from the ground[2], and if so, would likely be cheaper than any other options.
- Thus, given that we should first try what is likely to be the cheapest option, we should perform the R&A needed to determine if it we can achieve a few cm/s.
- Furthermore, if we can achieve a few cm/s accuracy from the ground, we can dramatically improve the efficiency of direct imaging missions, as well as increase the yield.

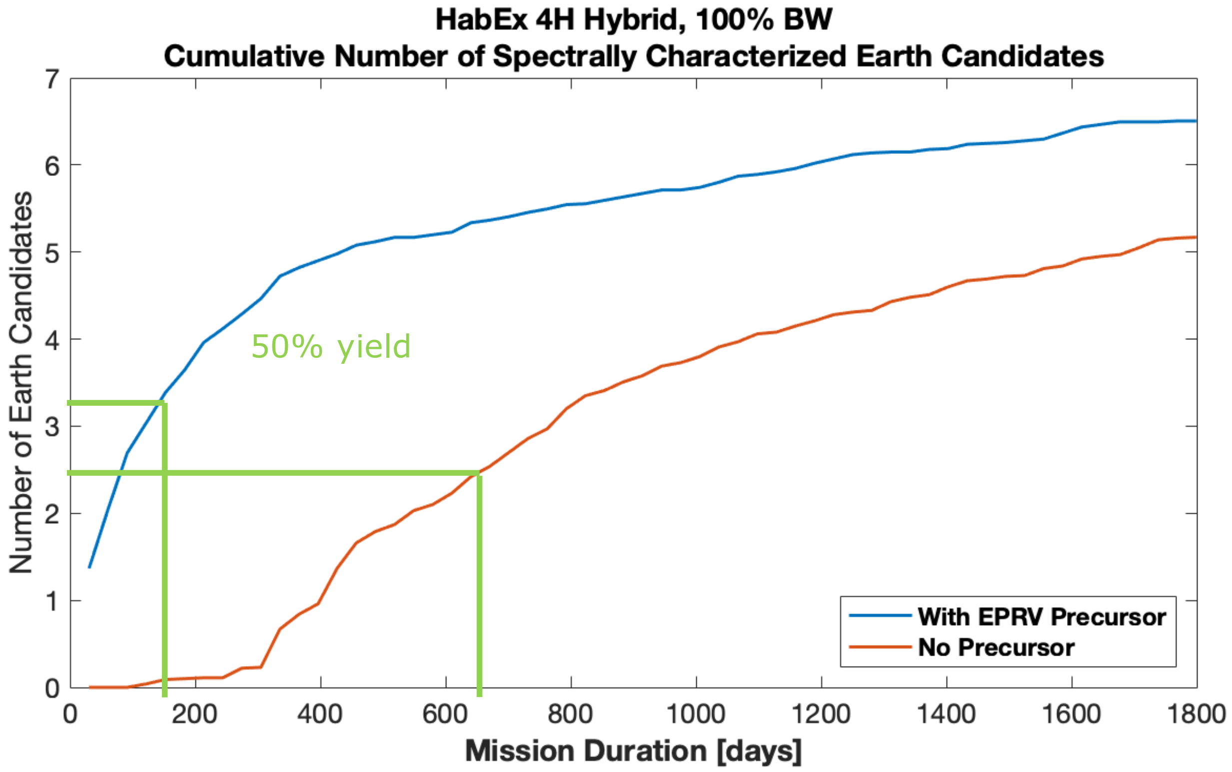
[1] As well as the masses of rocky terrestrial transiting planets.

[2] People will tell you it is impossible. This may be true, but we do not know this yet. It is an opinion, not a demonstrated fact. See recent RV stellar activity work by Lanza et al. 2018, Dumusque et al. 2018, Wise et al. 2018, Rajpaul et al. 2019 for promising progress on mitigating stellar activity.

The Value of Precursor Observations

- Precursor observations generally help if $T_{detect} \gg T_{characterize}$, for example:
  - Low completeness per visit:
    - Small dark hole
    - Large IWA
    - Small η_{Earth}
- If the yield is resource limited, e.g.,
  - A limited number of slews for a starshade.
  - Long integration times for characterization.
- Then precursor observations:
  - Can dramatically improve the efficiency of direct imaging missions, allowing time for other science.
  - In certain circumstances, improve the yield of characterized planets.

EPRV Accelerates the Yield

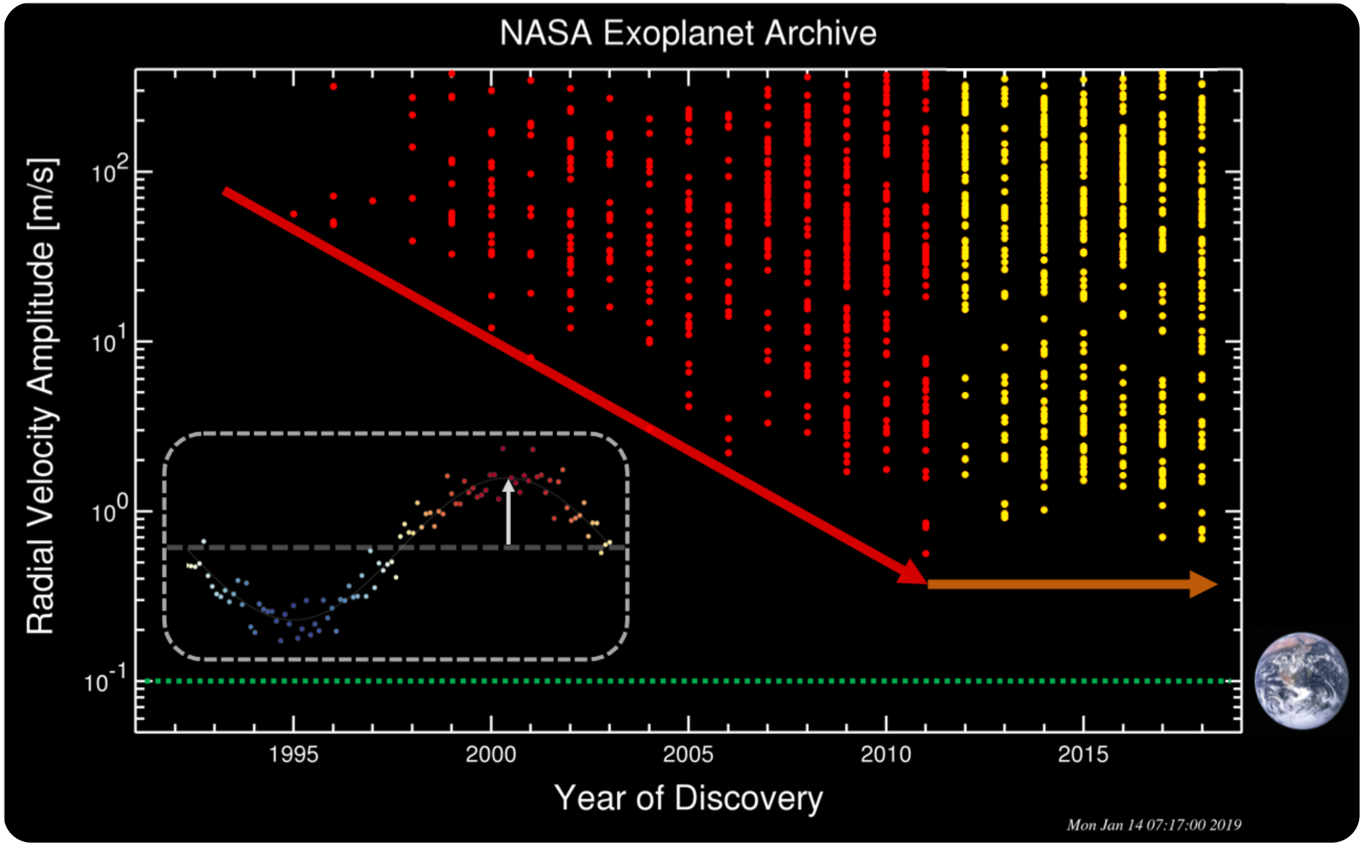


Preliminary Results from ExoSIMs: R. Morgan

- EPRV precursor observations reduce the mission time to achieve 50% of the yield or characterized planets by a factor of 3!
  - High impact science occurs earlier in the mission, allowing time for follow up characterization
  - More immediate science results excite the public and science community
  - Mitigates risk of early mission failure
- EPRV makes missions more nimble and powerful
  - Precursor spectral targets on Mission Day 1 ensure robust scheduling opportunities for starshade arrival at optimal viewing epochs

We are stuck at roughly 1m/s

- As documented in Fischer et al. 2016 and Dumusque 2016, a community-wide data challenge was conducted. Many of the best EPRV modelers and statisticians in the world participated.
- The primary conclusion was: **"Even with the best models of stellar signals, planetary signals with amplitudes less than 1 m s^{-1} are *rarely extracted correctly with current precision and current techniques*."**
- In other words, we must do something *fundamentally different* than we have been doing to achieve 10 cm s^{-1} precision and 1 cm s^{-1} accuracy.



National Academy of Sciences
Exoplanet Science Strategy

Improving the Precision of Radial Velocity Measurements Will Support Exoplanet Missions

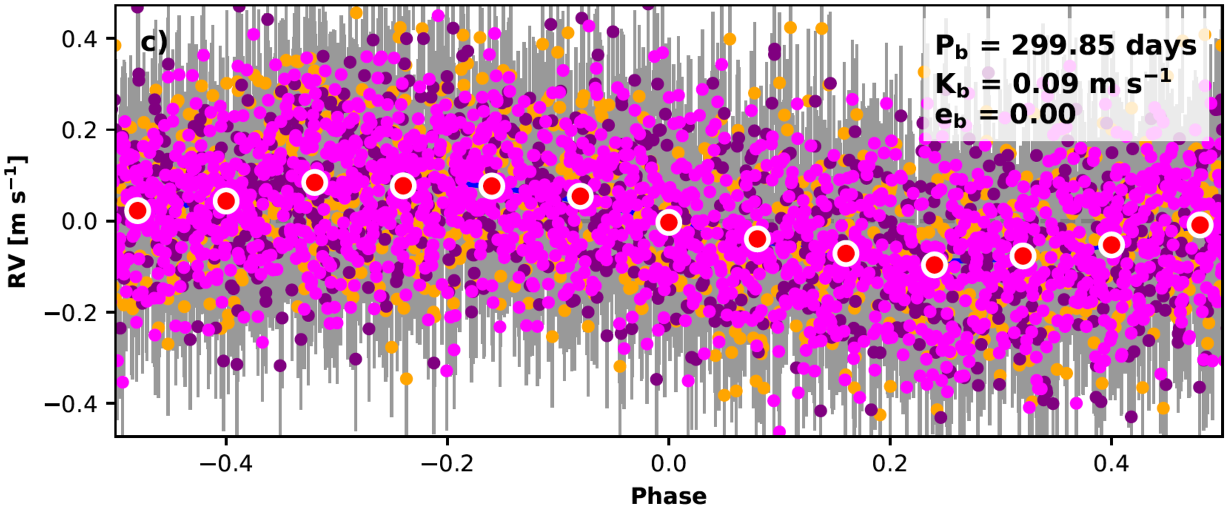
FINDING: The radial velocity method will continue to provide essential mass, orbit, and census information to support both transiting and directly imaged exoplanet science for the foreseeable future.

FINDING: Radial velocity measurements are currently limited by variations in the stellar photosphere, instrumental stability and calibration, and spectral contamination from telluric lines. *Progress will require new instruments installed on large telescopes, substantial allocations of observing time, advanced statistical methods for data analysis informed by theoretical modeling, and collaboration between observers, instrument builders, stellar astrophysicists, heliophysicists, and statisticians.*

RECOMMENDATION: NASA and NSF should establish a strategic initiative in extremely precise radial velocities (EPRVs) to develop methods and facilities for measuring the masses of temperate terrestrial planets orbiting Sun-like stars.

What Accuracy (e.g., Systematic Floor) Do We Need?

- The RV amplitude of an Earth-mass planet orbiting sun-like star is roughly ~ 10 cm/s.
- To detect an Earth analogue at signal-to-noise ratio of ~ 10 (thus satisfying the required precision of ~10% on the planet mass), and assuming a single-measurement precision of ~10 cm/s, this requires *at least* N~250 measurements
- This therefore requires systematic accuracy of **few cm/s**.

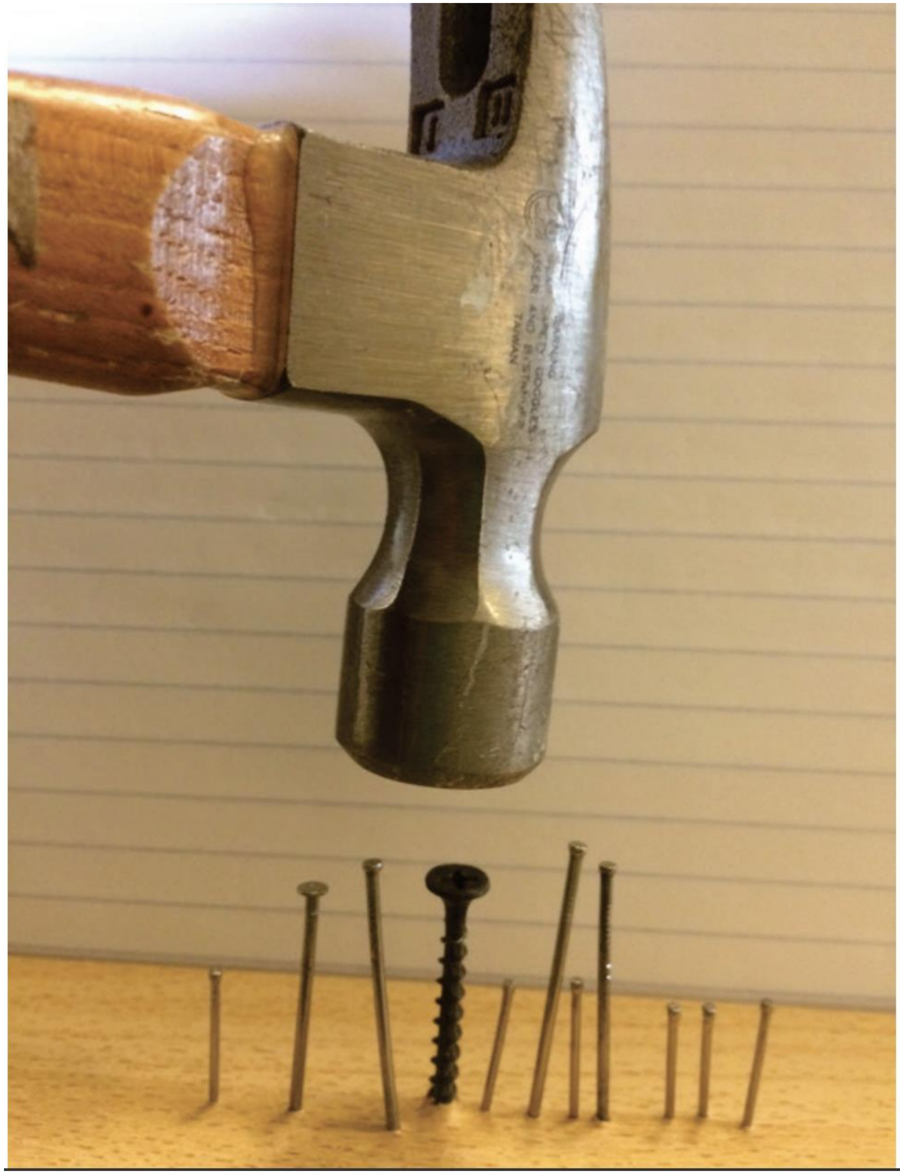


Courtesy of Patrick Newman and Peter Plavchan (GMU)

Simulated observations of a 300d planet with a 9 cm/s RV signal observed over 10 years from telescopes in Australia, South Africa, and Chile. 3748 measurements with precisions of 14 cm/s.

Issues that must be overcome…
(e.g., the Known Unknowns and the Unknown Unknowns)

Debra Fischer, NAS ESS presentation



The problem going from 10 m/s to 1 m/s were the number of unanticipated, unidentified errors.

The problem going from 1 m/s to 10 cm/s is the number of unanticipated and uncharacterized errors.

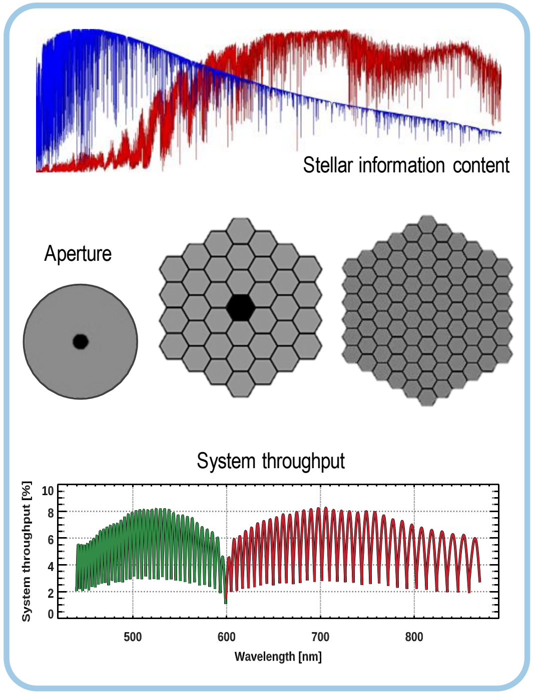
It is probably true that the challenge in going below 10 cm/s (which we have not yet reached) will be the number of unanticipated terms in the error budget and we will need new tools to address them.

Current State of the Art

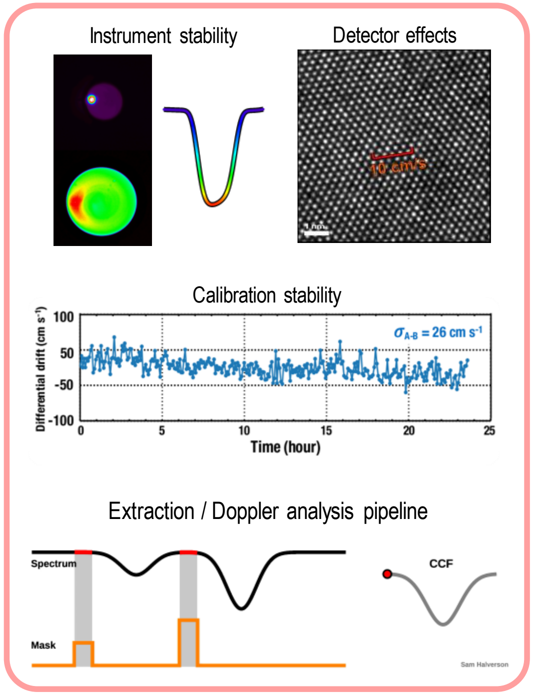
Deconstructing RV Measurement Precision

σ_{RV}

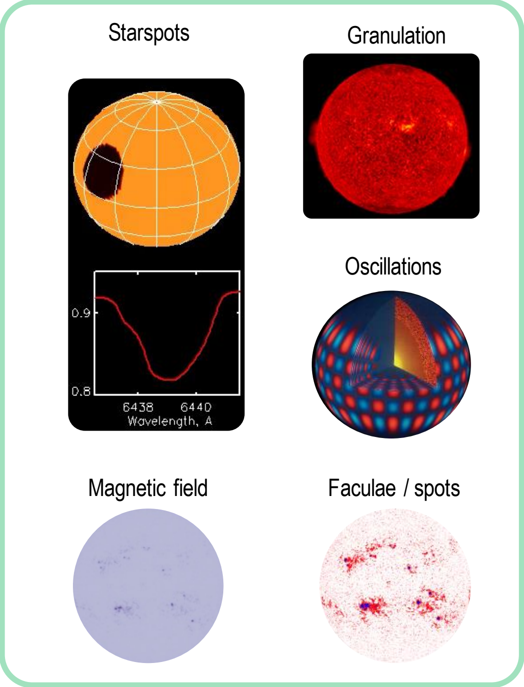
σ_{photon}



σ_{facility}



σ_{star}



Telescope Aperture and Cadence

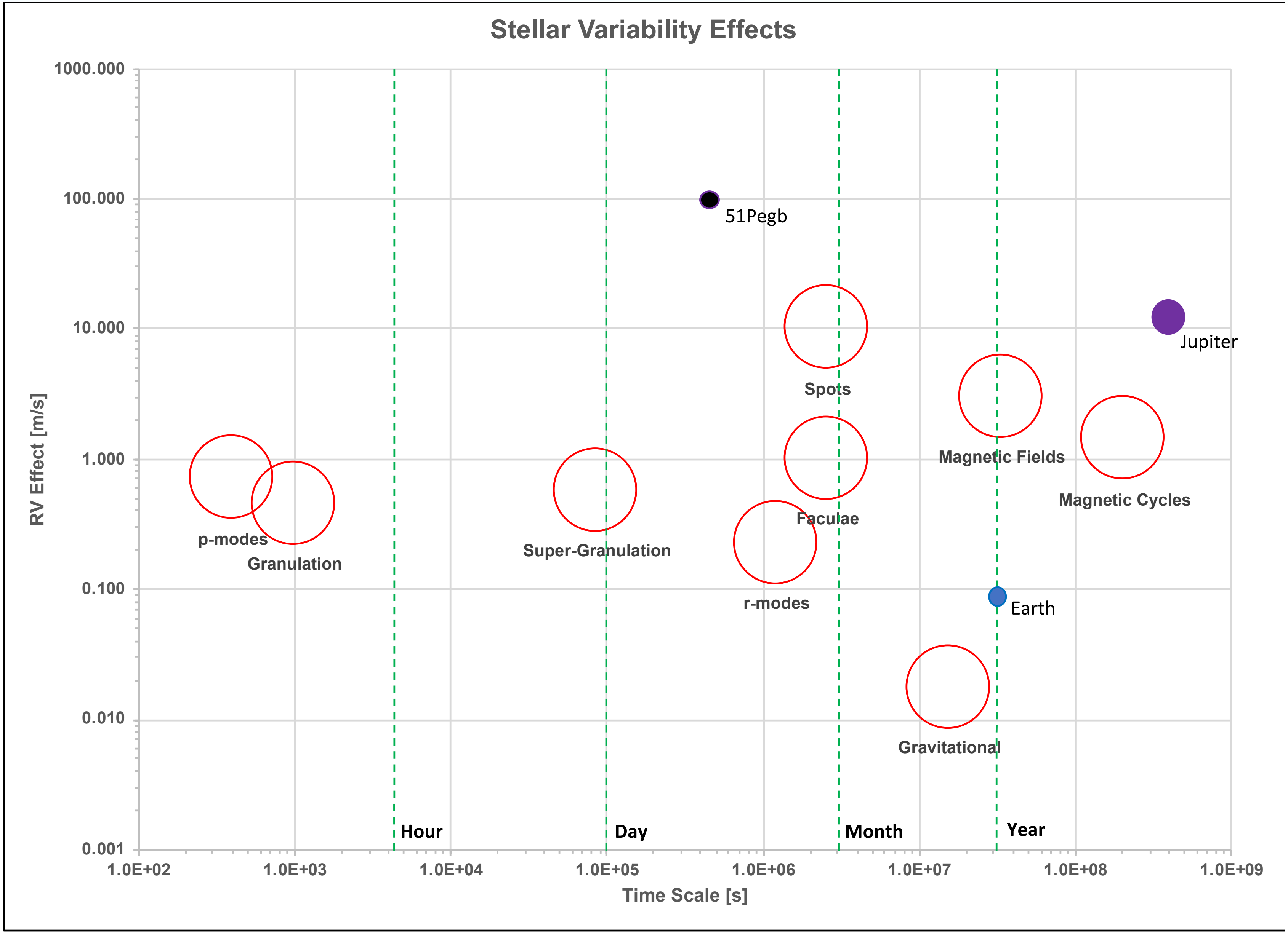
Technology/Instrumentation and Tellurics Research

Stellar Variability and Data Analytics Research

Proposed Architectures

Proposed Research

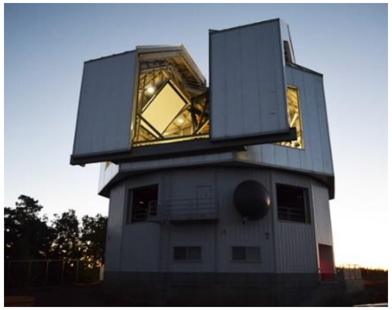
Stellar Variability



Planned (Visible) EPRV Facilities

Sub 50 cm/s RV

Northern Hemisphere



4.3-m LDT/EXPRES
15% time, solar calibrator

3.5-m WIYN/NEID
40% time, solar calibrator

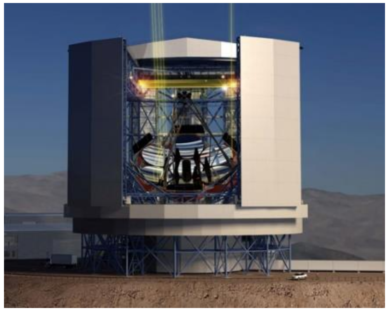
2.5-m INT/HARPS3*
50% time, solar calibrator (TBD)

10-m Keck/KPF (2023)
25% time, solar calibrator

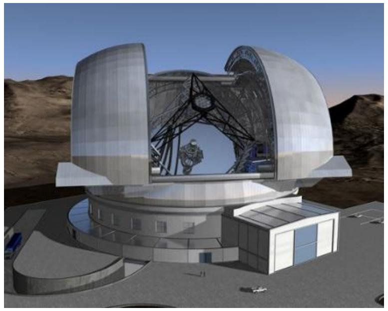
30-m TMT/MOHDIS
(mid to late-2020s)

Southern Hemisphere

8-m VLT/ESPRESSO
10% time, solar calibrator (TBD)



6x8-m GMT/G-CLEF
(late-2020s)



39-m E-ELT/HIRES
(mid to late-2020s)

*HARPS Heritage

Methodology

Methodology

- Established Terms of Reference: membership, ground rules
  - World experts (>50)
  - Open, [accessible via google drive folder]

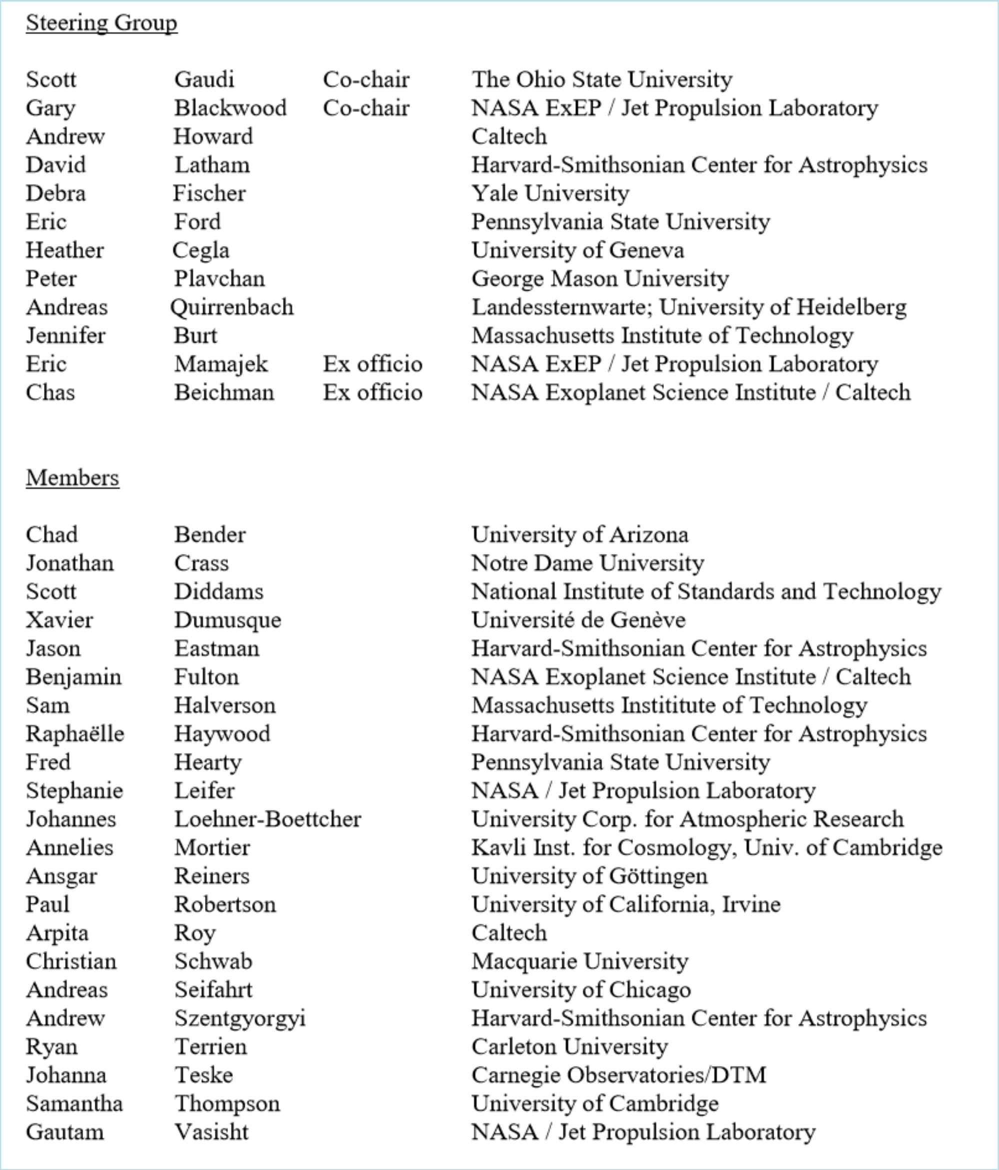
- Formed an EPRV working group (~36)

- Established eight sub-groups
  - (bi-)weekly teleconferences
  - each formulating research recommendations

- Held 3 face-to-face, multi-day workshops (St. Louis, New York, Washington)
  - Used Kepner-Trego methods to develop solution
    - formulated decision statement
    - Formulated success criteria
    - formulated candidate architectures
    - conducted weighted trade studies and accounted for risks
  - and established an "existence proof" that the EPRV objective can be achieved
  - reached full consensus on above

- Conducted Red Team review (02/06/2020)
- Held ExoTAC briefing (03/10/2020)

Named in the Terms of Reference

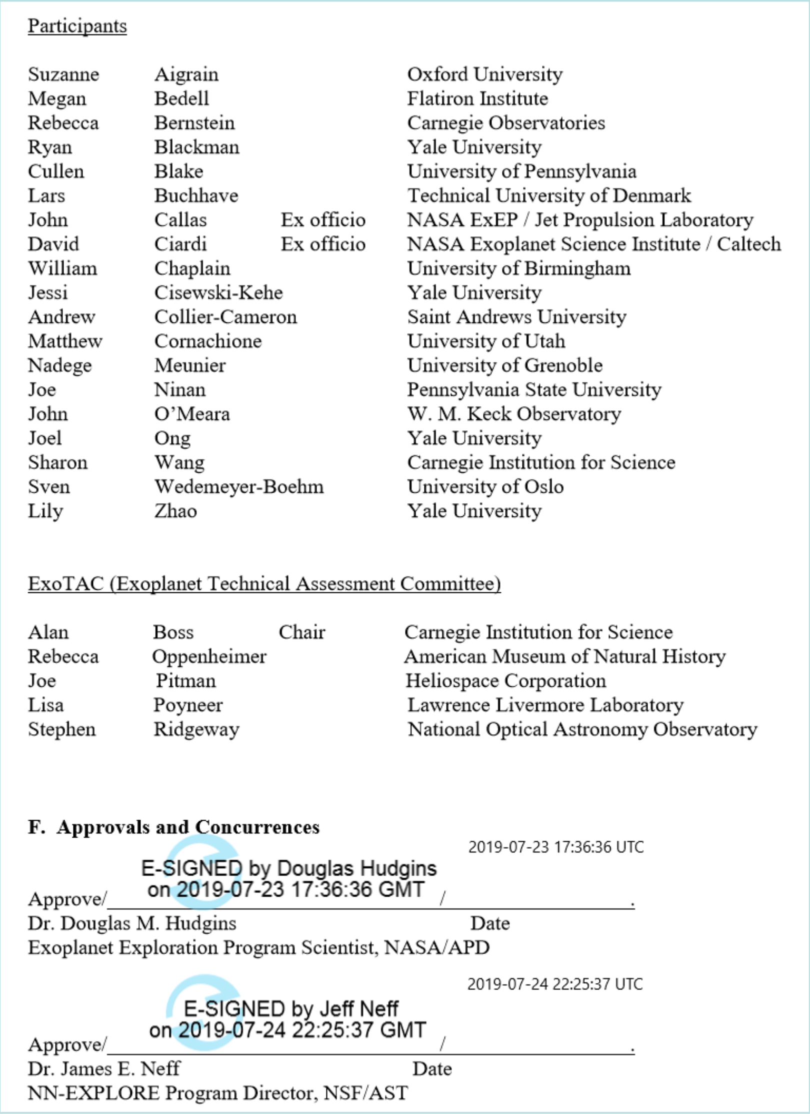


Steering Group

Scott	Gaudi	Co-chair	The Ohio State University
Gary	Blackwood	Co-chair	NASA ExEP / Jet Propulsion Laboratory
Andrew	Howard		Caltech
David	Latham		Harvard-Smithsonian Center for Astrophysics
Debra	Fischer		Yale University
Eric	Ford		Pennsylvania State University
Heather	Cegla		University of Geneva
Peter	Plavchan		George Mason University
Andreas	Quirrenbach		Landessternwarte; University of Heidelberg
Jennifer	Burt		Massachusetts Institute of Technology
Eric	Mamajek	Ex officio	NASA ExEP / Jet Propulsion Laboratory
Chas	Beichman	Ex officio	NASA Exoplanet Science Institute / Caltech

Members

Chad	Bender	University of Arizona
Jonathan	Crass	Notre Dame University
Scott	Diddams	National Institute of Standards and Technology
Xavier	Dumusque	Université de Genève
Jason	Eastman	Harvard-Smithsonian Center for Astrophysics
Benjamin	Fulton	NASA Exoplanet Science Institute / Caltech
Sam	Halverson	Massachusetts Institute of Technology
Raphaëlle	Haywood	Harvard-Smithsonian Center for Astrophysics
Fred	Hearty	Pennsylvania State University
Stephanie	Leifer	NASA / Jet Propulsion Laboratory
Johannes	Loehner-Boettcher	University Corp. for Atmospheric Research
Annelies	Mortier	Kavli Inst. for Cosmology, Univ. of Cambridge
Ansgar	Reiners	University of Göttingen
Paul	Robertson	University of California, Irvine
Arpita	Roy	Caltech
Christian	Schwab	Macquarie University
Andreas	Seifahrt	University of Chicago
Andrew	Szentgyorgyi	Harvard-Smithsonian Center for Astrophysics
Ryan	Terrien	Carleton University
Johanna	Teske	Carnegie Observatories/DTM
Samantha	Thompson	University of Cambridge
Gautam	Vasisht	NASA / Jet Propulsion Laboratory



Participants

Suzanne	Aigrain		Oxford University
Megan	Bedell		Flatiron Institute
Rebecca	Bernstein		Carnegie Observatories
Ryan	Blackman		Yale University
Cullen	Blake		University of Pennsylvania
Lars	Buchhave		Technical University of Denmark
John	Callas	Ex officio	NASA ExEP / Jet Propulsion Laboratory
David	Ciardi	Ex officio	NASA Exoplanet Science Institute / Caltech
William	Chaplain		University of Birmingham
Jessi	Cisewski-Kehe		Yale University
Andrew	Collier-Cameron		Saint Andrews University
Matthew	Cornachione		University of Utah
Nadege	Meunier		University of Grenoble
Joe	Ninan		Pennsylvania State University
John	O'Meara		W. M. Keck Observatory
Joel	Ong		Yale University
Sharon	Wang		Carnegie Institution for Science
Sven	Wedemeyer-Boehm		University of Oslo
Lily	Zhao		Yale University

ExoTAC (Exoplanet Technical Assessment Committee)

Alan	Boss	Chair	Carnegie Institution for Science
Rebecca	Oppenheimer		American Museum of Natural History
Joe	Pitman		Heliospace Corporation
Lisa	Poyneer		Lawrence Livermore Laboratory
Stephen	Ridgeway		National Optical Astronomy Observatory

F. Approvals and Concurrences

2019-07-23 17:36:36 UTC

E-SIGNED by Douglas Hudgins
on 2019-07-23 17:36:36 GMT

Approve/____________________________/________________.
Dr. Douglas M. Hudgins Date
Exoplanet Exploration Program Scientist, NASA/APD

2019-07-24 22:25:37 UTC

E-SIGNED by Jeff Neff
on 2019-07-24 22:25:37 GMT

Approve/____________________________/________________.
Dr. James E. Neff Date
NN-EXPLORE Program Director, NSF/AST

EPRV Sub-Groups

Science Mission Drivers
Leads: Howard & Bender

Identify science goals for the initiative and determine target star list to guide EPRV survey considerations

Instrument Performance Evaluation
Lead: Halverson

Assess top level system error budgets in the context of community derived science goals and requirements

Instrumentation & Calibration
Leads: Leifer & Szentgyorgyi

Identify new EPRV and supporting instrumentation and technology needed before the 2030 survey begins

Intrinsic Stellar Variability
Leads: Cegla & Haywood

Identify observational and analytical techniques needed to characterize & correct various types of stellar variability

Survey Strategy
Leads: Burt & Teske

Evaluate ability of architectures to observe prime target list. Design 2020s PRV survey to characterize stellar variability & multiplicity

Pipelines, Analysis & Statistical Inference
Leads: Roy & Ford

Identify research efforts necessary to improve spectral analysis, RV determination & noise modeling

Realistic Resource Evaluation
Leads: Quirrenbach & Diddams

Evaluate expected costs, risks, and realism of EPRV architectures and supporting research efforts

Telluric Mitigation Strategies
Lead: Bender

Identify observational and analytical techniques needed to quantify the impacts of telluric lines and mitigate their effects

Decision Statement

- Arrived at by consensus, following the Exoplanet Science Strategy Recommendation and the Charter of the Working Group:

Recommend the best ground-based program architecture and implementation (aka Roadmap) to achieve the goal of measuring the masses of temperate terrestrial planets orbiting Sun-like stars

Success Criteria

- Six Musts (requirements) were documented:
  1. Determine by 2025 **feasibility to detect earth-mass planets** in HZ of solar-type stars
  2. **Demonstrate (validate)** feasibility to detect at this threshold
  3. Conduct **precursor surveys** to characterize stellar variability
  4. Demonstrate feasibility to **survey (~100) stars on "green" list**
  5. Demonstrate by 2025 **on-sky precision to 30 cm/sec**
  6. **Capture knowledge** from current and near-term instruments

- Options were developed to meet these Musts.

- Detailed Description of Musts, and their Evaluation, listed in Backup

Success Criteria

(Key and Driving Wants)

- Sixteen weighted Wants (desires, or goals) were documented
- Options were proposed (and iteratively improved) to best meet the Wants

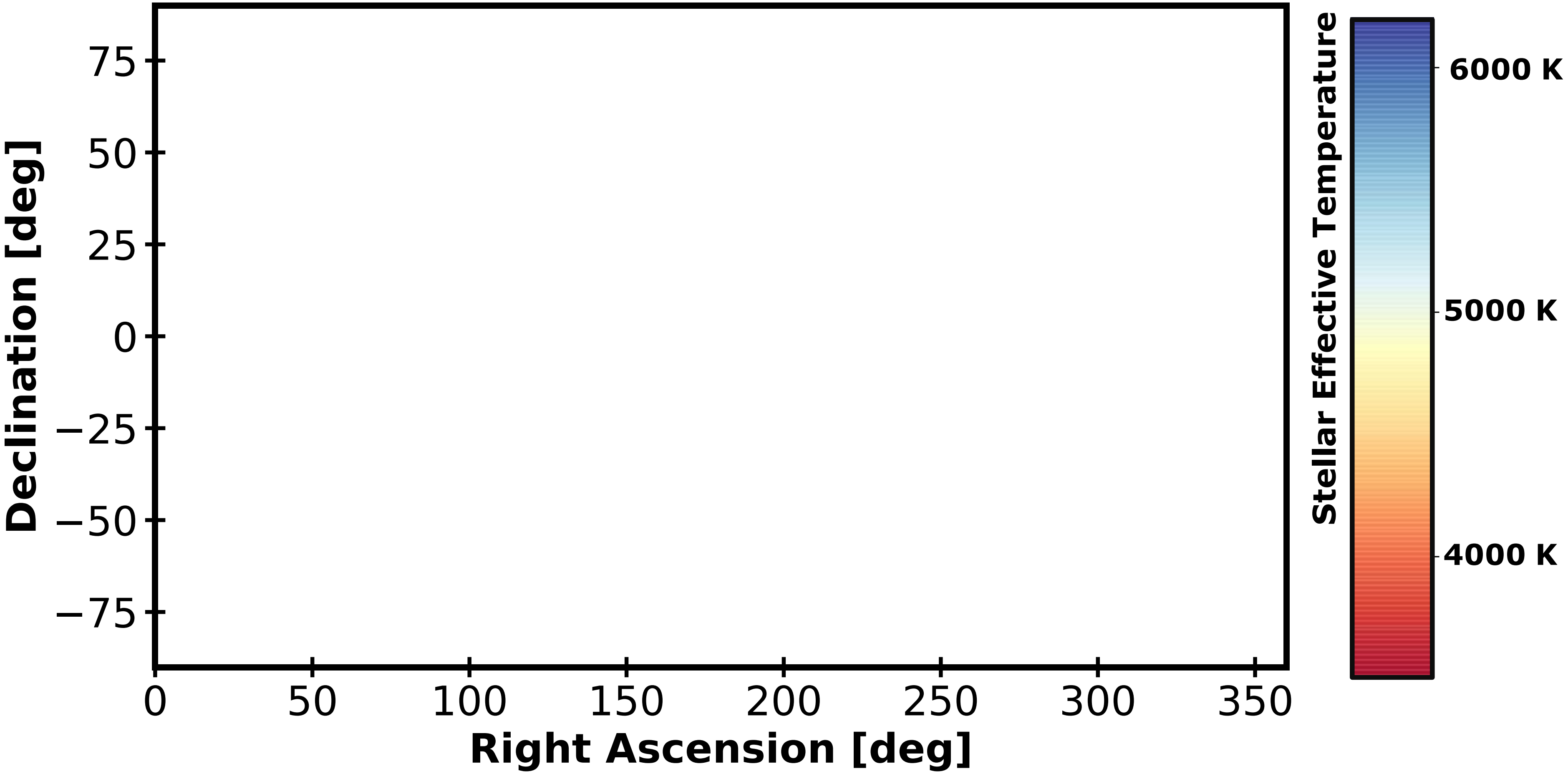
- Four Wants emerged as Key and Driving:
  1. Survey as many stars as possible on the “Yellow” list (~100)
  2. Follow up transit discoveries to inform mass-radius relation
  3. Greatest relative probability of success to meet stellar variability requirement
  4. Least estimated cost

- Detailed Description of Wants, and their Evaluation, listed in Backup

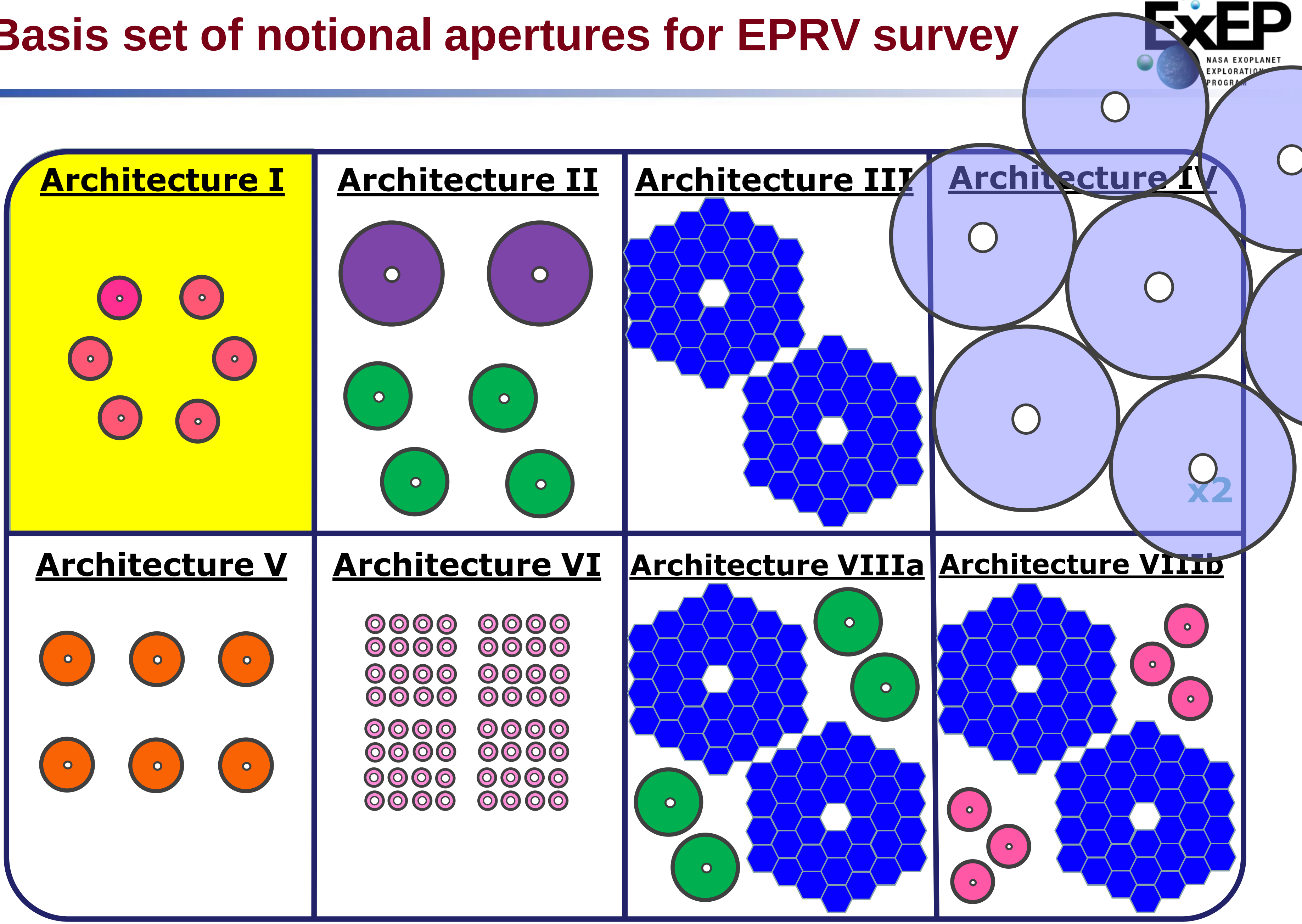
Proposed Architectures

Future Direct Imaging Mission Target Stars

- Have compiled two EPRV target lists based upon LUVOIR/HabEx/Starshade lists
  - "**Green stars**": Sun-like (F7-K9), vsini<5km/s and on at least 2 mission study lists
  - "**Yellow stars**": Sun-like (F7-K9), vsini 5-10km/s or only on one mission study list



Basis set of notional apertures for EPRV survey



Architecture I

Architecture II

Architecture III

Architecture IV

x2

Architecture V

Architecture VI

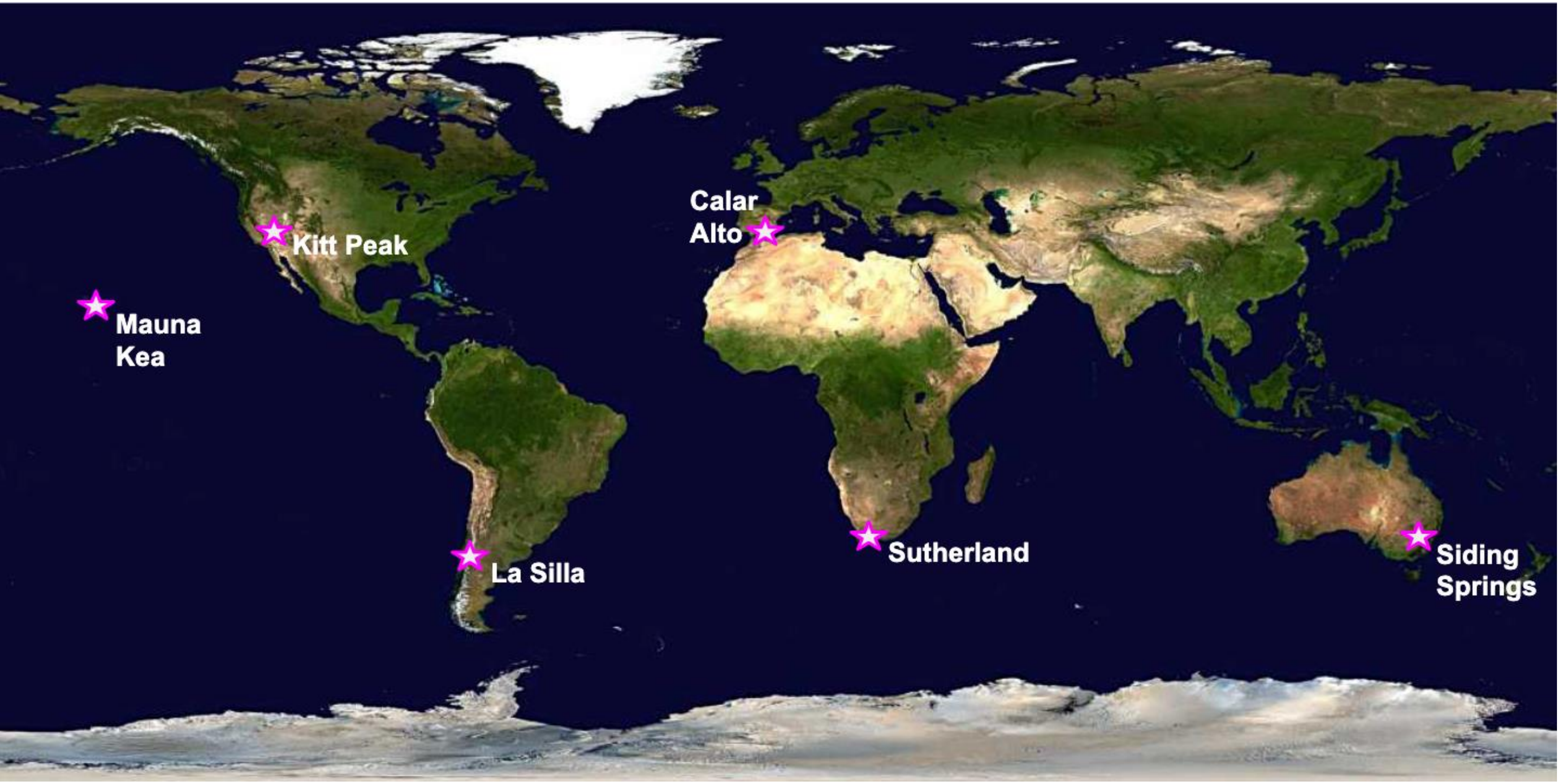
Architecture VIIIa

Architecture VIIIb

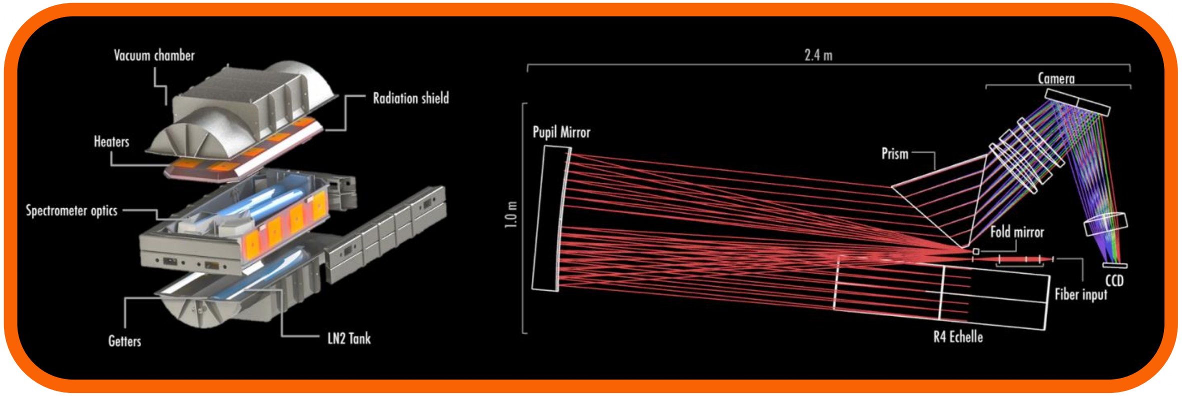
● 1m ● 2.4m ● 3m ● 4m ● 6m ⬢ 10m ● 24.5m

Architecture I: Six Identical Facilities

spread across longitude and latitude



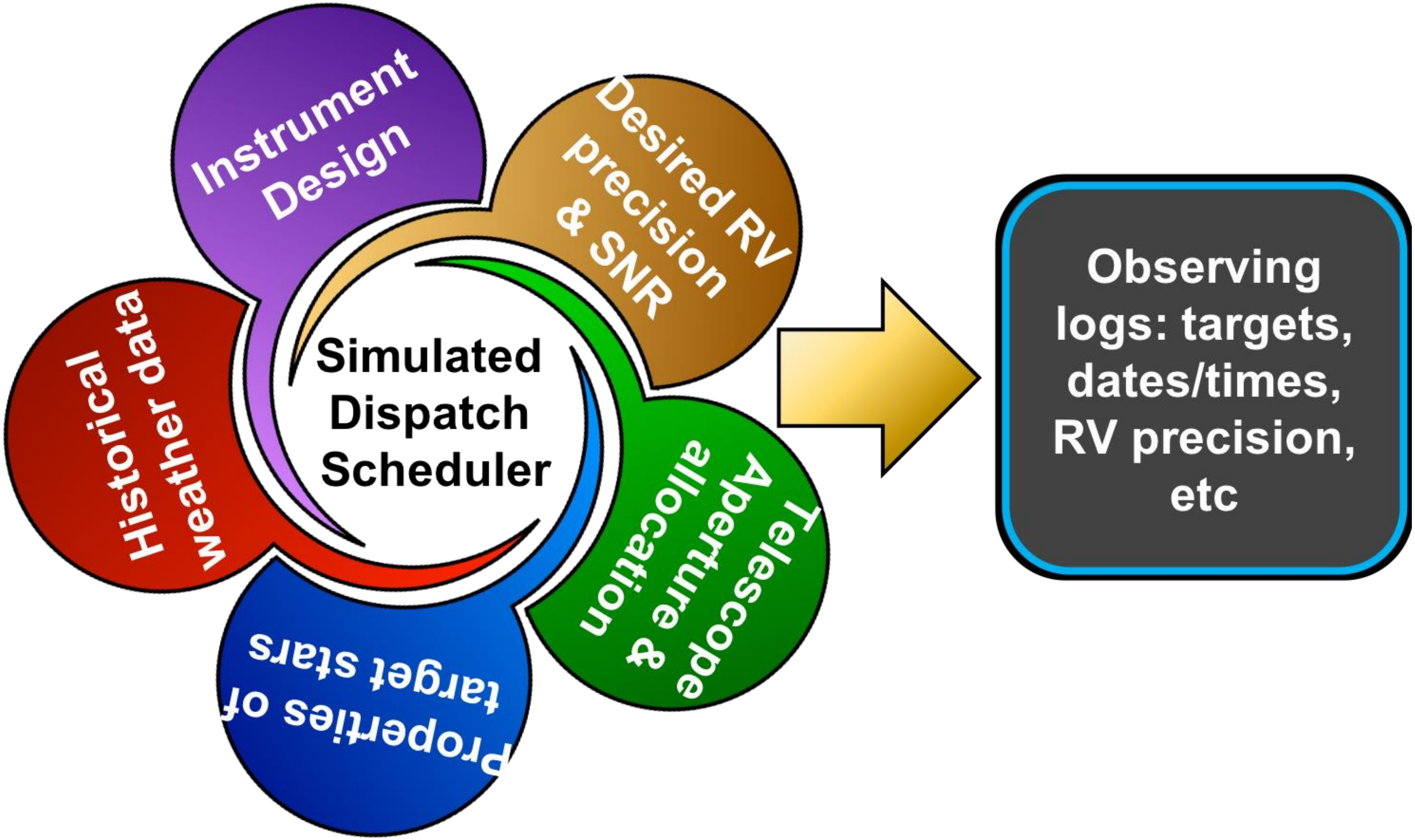
Each facility contains: 2.4m telescope, next generation EPRV spectrograph, and solar telescope



Instrument/Observing Details

Wavelength coverage : 380-930nm
Spectral resolution : 150,000
Total system efficiency : 7%
Instrumental noise floor : 10 cm/s
Telescope allocation : 100%

Details are then fed into a dispatch scheduler that simulates a decade long observing campaign



Instrument Design

Desired RV precision & SNR

Telescope Aperture & allocation

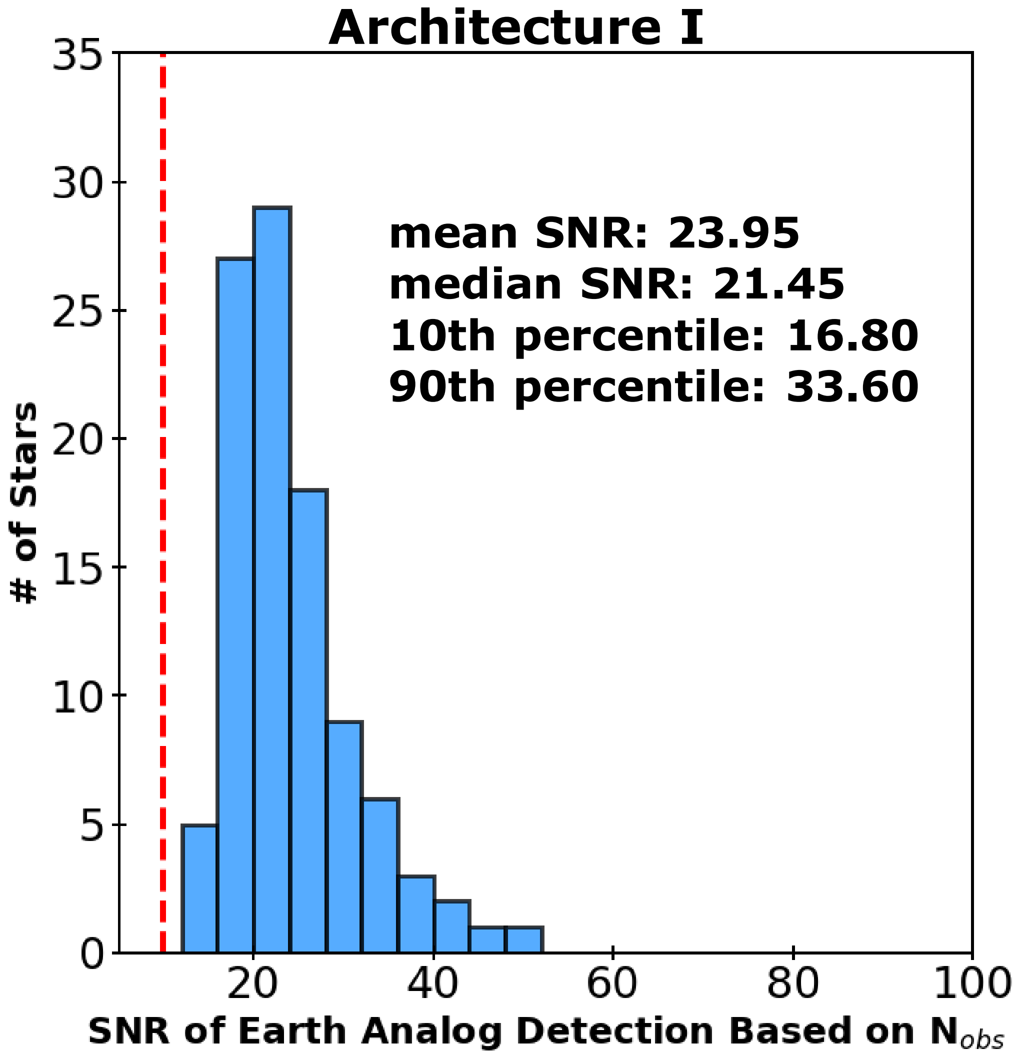
Properties of target stars

Historical weather data

Simulated Dispatch Scheduler

Observing logs: targets, dates/times, RV precision, etc

Success metric : Earth analog detection significance



If there were an Earth analog around each star

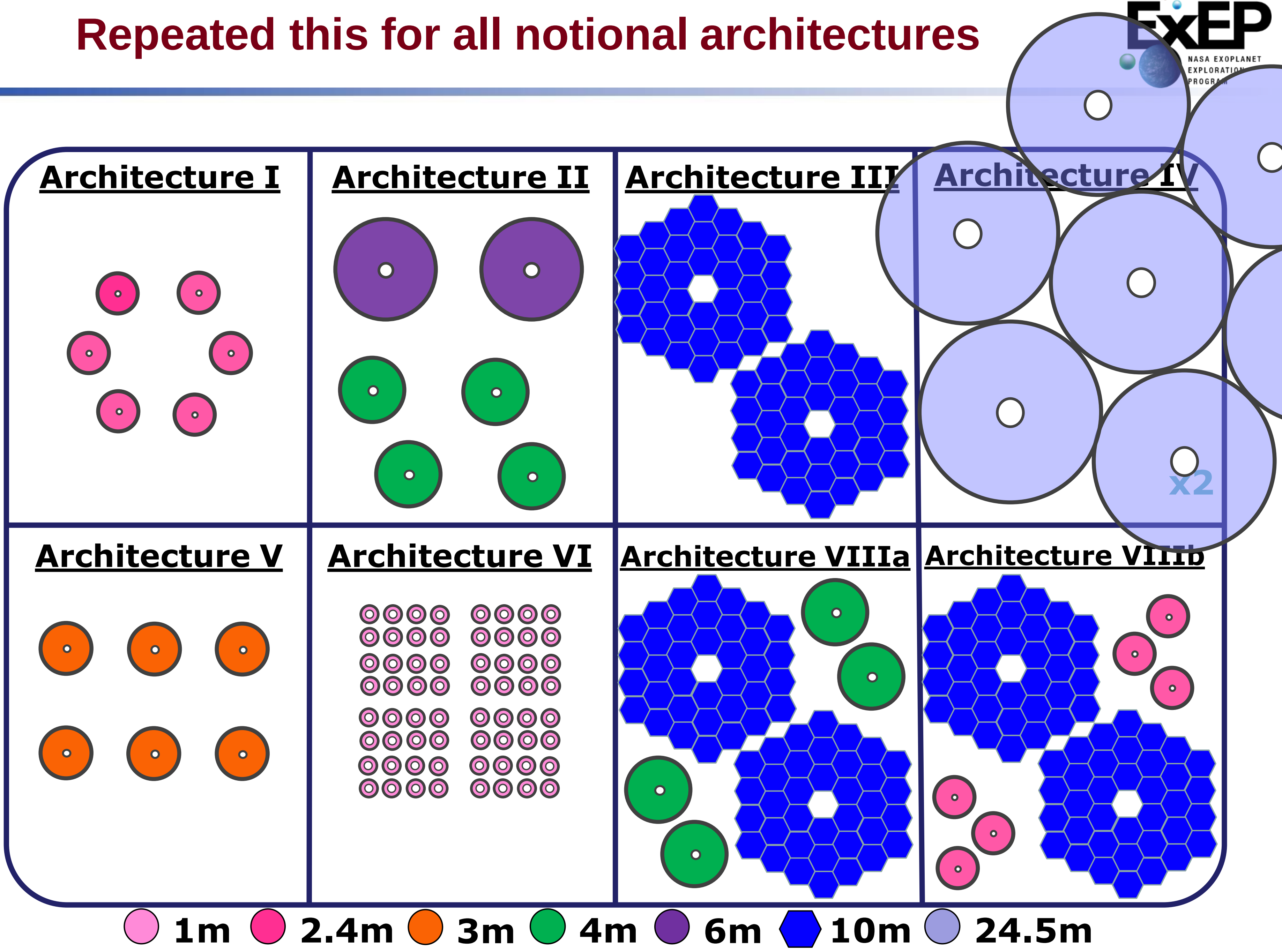
and

If we were able to completely remove the star's variability from our RV data

then

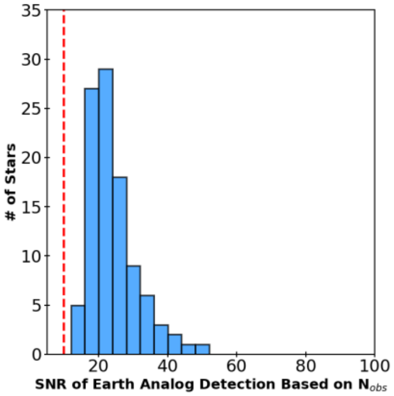
How significant would our detection of that Earth analog be, based on the simulated RV data?

Repeated this for all notional architectures

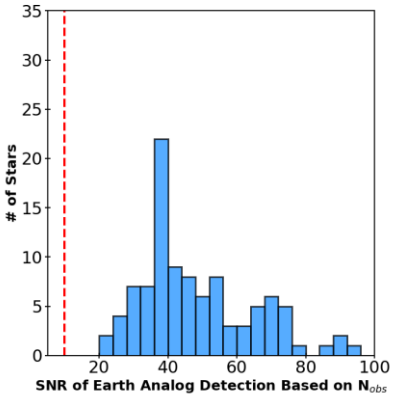


Earth analog detection significance by architecture

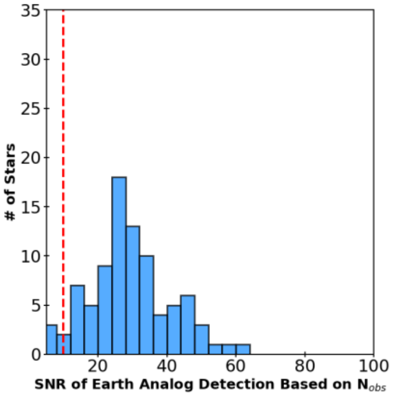
Architecture I



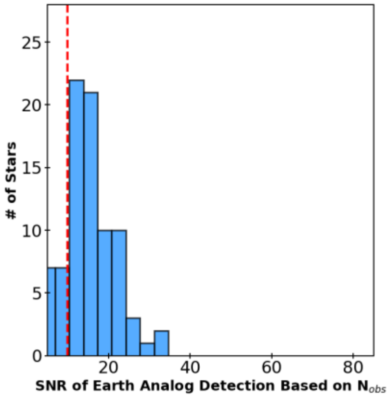
Architecture II



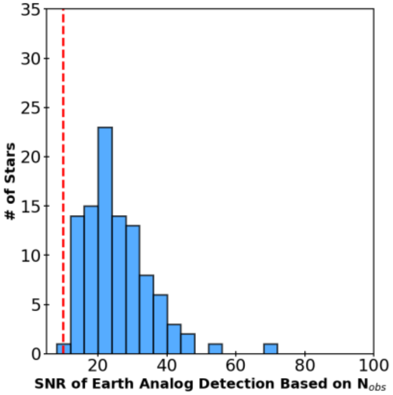
Architecture III



Architecture IV



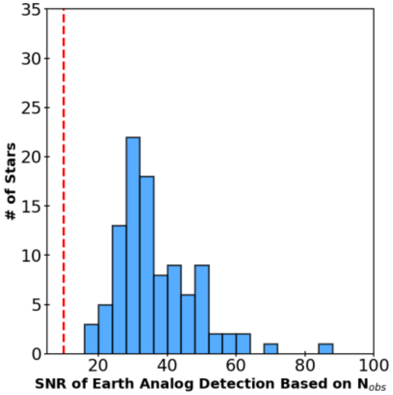
Architecture V



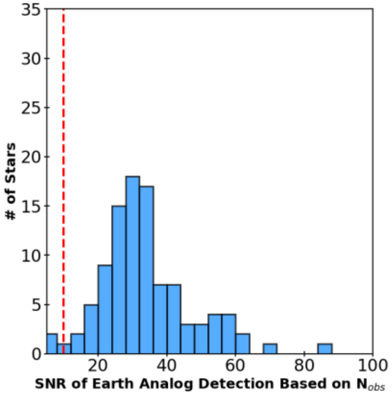
Architecture VI

Scalable to other architectures based on number of 1m telescopes

Architecture VIIIa



Architecture VIIIb



Architecture simulation key points

- Many of these basis set architecture options meet all of our “musts” (and many of our “wants”) and close the KT matrix
- Multiple telescopes per N/S hemisphere are required for high cadence observing to mitigate stellar variability and for Earth analog verification
- Further study shows that this could also be accomplished with <100% allocations on a variety of existing facilities, enabling partnership options

Now that our early results show the aperture/facility aspect is likely solvable, we need to progress towards a more detailed understanding of exactly what cadence, RV precision, and spectral SNR are needed to mitigate stellar variability and enable Earth analog detections via a sustained R&A program

MUSTS	Success Criteria
M0a	Determine the feasibility by 2025 to detect (with a well characterized and sufficiently small false discovery rate) and measure the mass (msini with <=10% fractional precision) of <=1earth mass planets that orbit a 1 M_Sun main sequence star and receive insolation within 10% Insolation_Earth
M0b	**Demonstrate the feasibility** to detect (with a well characterized and sufficiently small false discovery rate) and measure the mass (msini with <=10% fractional precision) of <=1earth mass planets that orbit a 1 M_Sun main sequence star and receive insolation within 10% Insolation_Earth prior to 2030 Decadal Survey.
M1a	Design and execute a set of **precursor surveys and analysis activities** on the 'green' and 'yellow' stars on Eric's evolving target star list and on the Sun
M1b	**Demonstrate the feasibility to survey each of the 'green' stars on Eric's evolving target list at the level of M0b.**
M2	**Meet Intermediate Milestone:** By 2025, demonstrate on-sky feasibility with capabilities in-hand to detect K down to 30 cm/s for periods out to few hundred days using a statistical method that has been validated using simulated and/or observed spectra time-series
M4	**Capture Knowledge** from current and near-future generation of instruments, surveys, analysis, and coordination activities to help inform development of future EPRV instruments.

Proposed Research Program

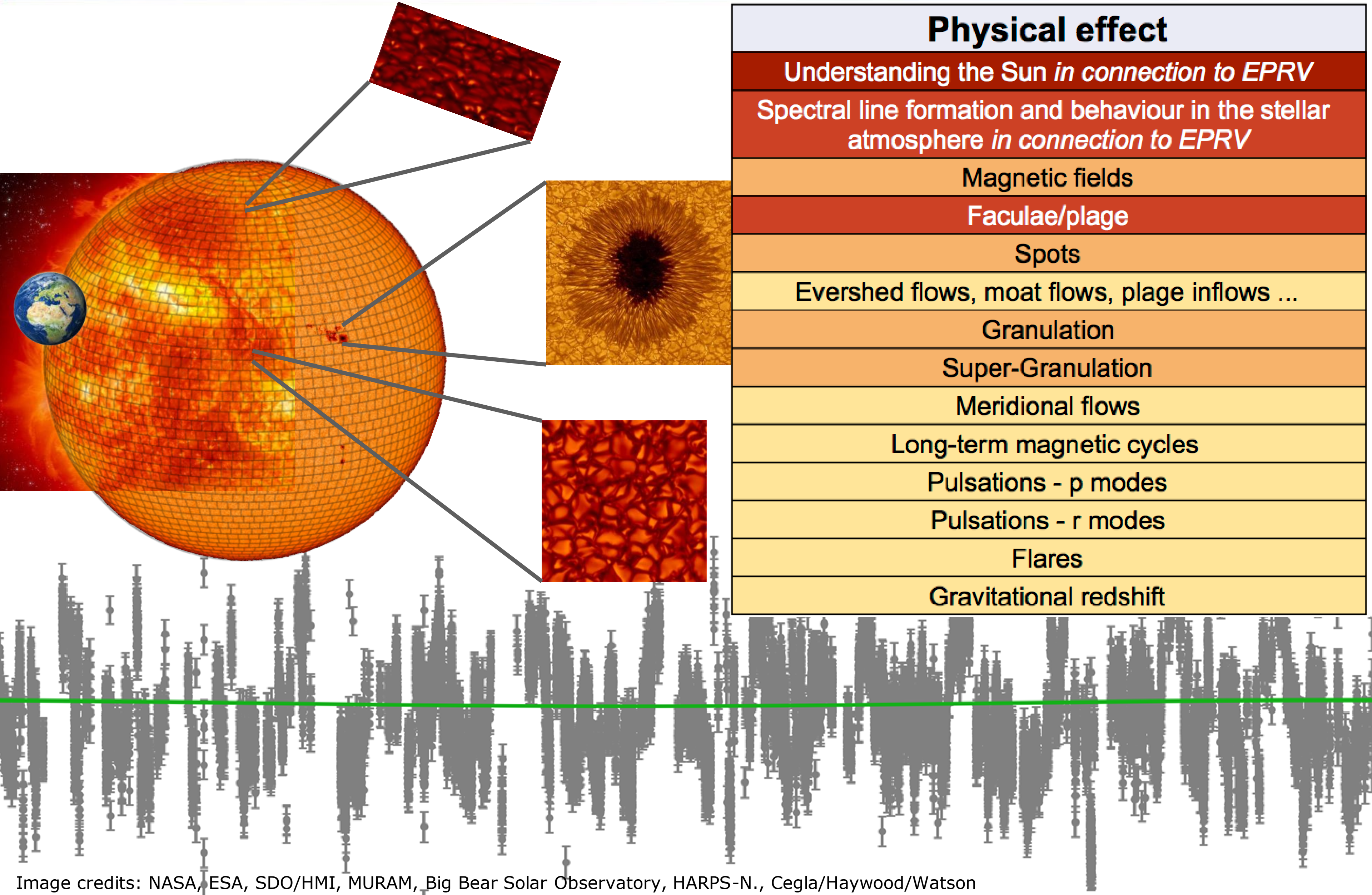
Research Program

- Establish an EPRV-dedicated, sustained research and analysis program with multiple proposal calls to address stellar variability, technology development, tellurics and data analytics.
  - A **dedicated** program so that EPRV issues are addressed.
  - A **sustained** (>3-5 year awards) program allows researchers to commit to graduate students and post-docs, and educational departments to make offers to early career hires.
- Mechanisms should be developed to enable **international** involvement.
  - e.g., Dual-hosting, international contributions in kind, etc.
- Selected PIs become part of a new EPRV Research Coordination Network (RCN) to foster interdisciplinary cross-fertilization and collaboration.
- Engage other disciplines (e.g., Heliophysics, Earth Sciences, etc.).

EPRV Research Coordination Network (RCN)

- Establish a Research Coordination Network (RCN) for EPRV
  - RCN co-leads
    - Appointed by NASA/NSF
    - Weekly teleconferences
  - Steering Council
    - Perhaps, initially appointed by NASA/NSF, but likely some from the EPRV working group. Then, **interdisciplinary PIs included as selected under EPRV SR&T**. Plus, affiliates.
    - Monthly videoconferences (e.g., formulate activities, workshops, etc.)
  - Activities to spawn interaction
    - Workshops (state-of-the-field papers)
    - Face-to-face meetings
    - Webinars
    - Community working groups
    - Public outreach
    - Newsletter

Stellar Variability Research



Physical effect
Understanding the Sun *in connection to EPRV*
Spectral line formation and behaviour in the stellar atmosphere *in connection to EPRV*
Magnetic fields
Faculae/plage
Spots
Evershed flows, moat flows, plage inflows ...
Granulation
Super-Granulation
Meridional flows
Long-term magnetic cycles
Pulsations - p modes
Pulsations - r modes
Flares
Gravitational redshift

Image credits: NASA, ESA, SDO/HMI, MURAM, Big Bear Solar Observatory, HARPS-N., Cegla/Haywood/Watson

Data Analytics Research

- Areas of activity
  - Collect PRV observations of sun (**solar data**).
  - Collect PRV observations of RV **benchmark stars.**
  - Perform **cross-comparisons** of data from different instruments to evaluate effectiveness of mitigation strategies and to inform future spectrograph/survey designs.
  - Conduct a series of EPRV **data challenges.**
  - Develop modular, **open-source pipeline** for EPRV science.
  - Research and develop **statistical methodology** for detecting planets and measuring masses given time series of apparent velocities and stellar variability indicators.

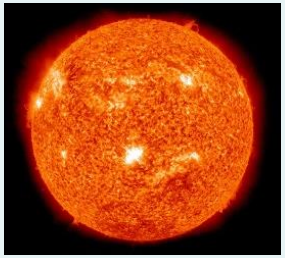
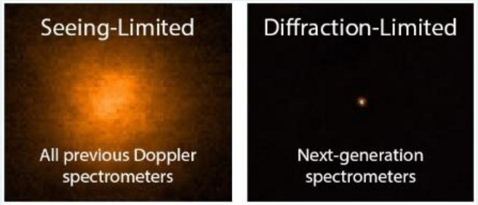
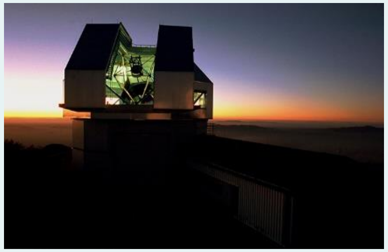
Technology Research

Technology	Need	Risk/Concern	Mitigation/Technology Path
Calibration	Exquisitely-stable, long-life calibration standards in the visible band	Not quite there yet.	Multiple technology development efforts can be leveraged (e.g., LFC, etalons, novel electro-optical). Calibration systems at facilities can be upgraded over time.
Detectors	Large-format, well-characterized detectors	Large-format CCDs may not be available.	Explore large-format CMOS development effort.
Gratings	Large, precise-ruled gratings	May not be available or achievable for large (MMF), high-R EPRV instruments	Explore alternate fabrication techniques with multiple vendors.
Fiber Front End	High-injection efficiency, stability	Challenging error source	Explore coupling efficiency and Strehl improvements
Adaptive Optics	Visible-light AO systems to enable diffraction-limited spectrographs	Visible-light AO currently not proven for EPRV	Advance visible AO development and maturity to viability for diffraction-limited, single-mode fiber EPRV spectrographs.

Tellurics Research

- Areas of Investigation
  - Can the correction of telluric absorption be achieved at a level sufficient for EPRV using **existing software modeling** tools from the atmospheric science community?
    - Can improvements to the software tools make them more applicable to the broadband ground-based visible spectroscopy problem?
  - Are the **existing line lists** of sufficient quality for the correction EPRV requires, or is more theoretical or laboratory work necessary?
  - Can telluric correction from the **solar datasets** sufficiently inform on the corrections for target EPRV stars?
  - Can the data driven models be **applied across target stars** of varying temperature and for data collected **across different sites** and conditions?

Major Decision Points at 3-5 Years

Key Questions	Can **stellar variability** be understood well enough to correct for its contribution to the RV signal?	Are **AO-fed, diffraction limited SMF fed spectrographs** a viable architecture? **Revolutionary** vs. **Evolutionary** instrument?	Are there **existing telescopes** credibly identified as candidates for dedicated, robotic telescopes for EPRV?
			
Key Actions	• Establish a Research Coordination Network (RCN) • Fund ambitious research programs	• Fund R&D for visible AO, calibration standards, detector characterization and other technologies	• Engage telescope custodians, agencies and user communities. • Workshop(s) on telescope repurposing/re-furbishing and robotic operations

Implementation

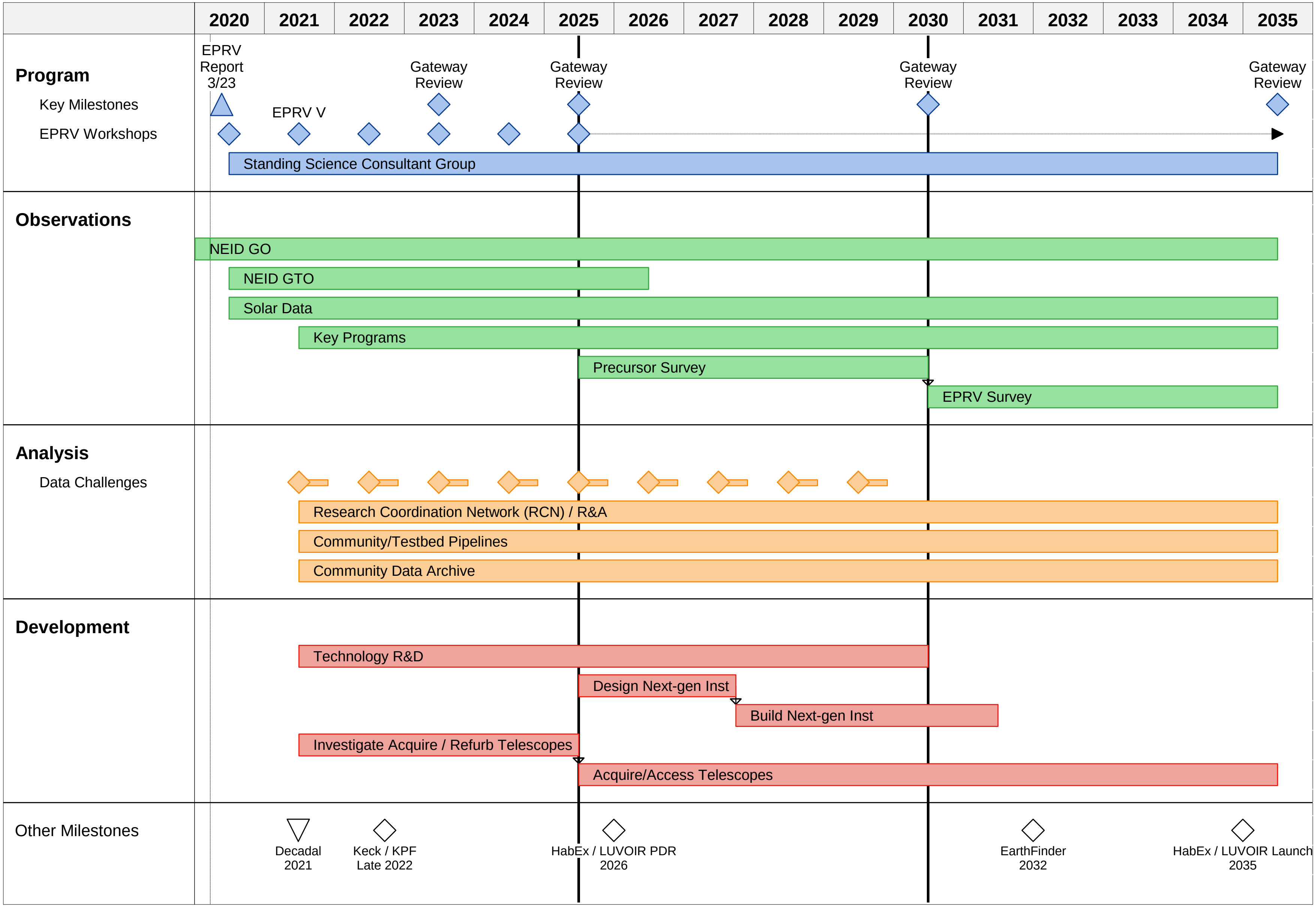
Plan

- Right Now (1-2 years)
  - NEID, EXPRES, HARPS **solar data** archive into NExScI community archive
  - NEID and other telescopes/instruments observe **standard stars**
  - Key Programs (**simultaneous observations**, etc.)
- Near-Term (2-5 years)
  - Establish Research Coordination Network (**RCN**) with separate, dedicated EPRV SR&T funding program for Stellar Variability, Analytics, Technology (next generation of instruments) and Tellurics.
  - Establish pipeline testbed, instrument **testbeds**, system **simulators**.
  - Conduct **telescope workshops**; begin **telescope candidate survey**.
  - Evaluate success in addressing stellar variability and tellurics.
- Medium-Term (5-10 years)
  - Continue Research Coordination Network (RCN) and SR&T funding.
  - Conduct **Precursor Survey** using existing RV instruments to characterize stellar variability.
  - Conduct **Auxiliary Surveys** for photometric monitoring, stellar rotation and check for multiplicity.
  - Decide instrument path and **build next generation instruments**.
  - **Acquire/refurbish portfolio of telescopes** based on available candidates versus new builds.
  - **Operate** as new instrument/apertures come online.
- Longer Term (10-15 years)
  - **Conduct/complete EPRV Survey** with next generation of instruments

Schedule

NASA EXOPLANET EXPLORATION PROGRAM

3/23/2020



2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035

Program

Key Milestones

EPRV Report 3/23

Gateway Review (2023)

Gateway Review (2025)

Gateway Review (2030)

Gateway Review (2035)

EPRV Workshops

EPRV V

Standing Science Consultant Group

Observations

NEID GO

NEID GTO

Solar Data

Key Programs

Precursor Survey

EPRV Survey

Analysis

Data Challenges

Research Coordination Network (RCN) / R&A

Community/Testbed Pipelines

Community Data Archive

Development

Technology R&D

Design Next-gen Inst

Build Next-gen Inst

Investigate Acquire / Refurb Telescopes

Acquire/Access Telescopes

Other Milestones

Decadal 2021

Keck / KPF Late 2022

HabEx / LUVOIR PDR 2026

EarthFinder 2032

HabEx / LUVOIR Launch 2035

"This document has been reviewed and determined not to contain export controlled technical data. Clearance #20-1588"

EPRV Budget Model

		Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Program	EPRV Mgt.	FTE	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	EPRV Adm.	FTE	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3
	Project Scientist	FTE	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	R&A/RCN Adm.	FTE	0.25	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.25	0.25	0.25	0.25
	Technology Mgt.	FTE		0.5	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0				
	Telescope Eng.	FTE		0.5	0.5	0.5	1.0	2.0	2.0	2.0	2.0	2.0	2.0				
Observations	Solar Data	K$	160	165	170	278	286	295	304	313	322	332					
	Special Programs	K$	250	258	265	273	281	290	299	307							
	Precursor Survey	K$						400	412	424	437	450					
SR&T	Data Challeneges		400	412	424	437	450	464	478	492	507	522					
	Stellar Variability	K$	1851	2168	4128	4128	4128	2191	1150	1150	1150	1150					
	Ph.D. student	*FTE*	*9.0*	*10.0*	*20.6*	*20.6*	*20.6*	*11.2*	*5.7*	*5.7*	*5.7*	*5.7*					
	Post-Doc	*FTE*	*6.0*	*7.0*	*13.4*	*13.4*	*13.4*	*7.1*	*3.7*	*3.7*	*3.7*	*3.7*					
	Scientist/Faculty	*FTE*	*3.0*	*4.0*	*6.3*	*6.3*	*6.3*	*3.1*	*1.8*	*1.8*	*1.8*	*1.8*					
	Tellurics	K$	250	750	1250	1288	1326	1366									
	Researcher	*FTE*	*1.0*	*3.0*	*5.0*	*5.0*	*5.0*	5.0									
	Pipeline/Analytics	K$	450	2700	2781	2864	2950	3039	3130	3224	3321	3420					
	Engineer/Post-Doc	*FTE*	2.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0					
	Detectors	K$	100	400	515	530	546	563									
	Gratings	K$		200	206	212	219	225									
	Calibration Sources	K$	100	500	515	530	546	563									
	AO/SMF	K$	210	2025	3100	2150	1000	1030									
	Other Technology	K$	100	400	515	530	546	563									
	Inst Prototype/Testbed	K$				1300	3900	3900	3900								
	Instrument 1, 2	K$						6753	11255	4502							
	Instrument 3, 4	K$							6753	11255	4502					***Notional***	
	Instrument 5, 6	K$								6753	11255	4502					
	Telescope 1, 2	K$						7505	10007	7505							
	Telescope 3, 4	K$							7505	10007	7505						
	Telescope 5, 6	K$								7505	10007	7505					
EPRV Survey	Telescope Operations	K$								760	1543	2303	2372	2443	2517	2592	2670
	Instrument Operations	K$								507	1029	1535	1581	1629	1678	1728	1780
	Network Operations	K$								380	391	403	415	428	441	454	467
	Processing/Archive	K$								380	771	1151	1186	1222	1258	1296	1335
	Science Analysis/R&A	K$								2280	4629	6909	7116	7330	7550	7776	8009
	Totals [K$]:		4,634	11,377	15,306	16,171	18,048	31,410	47,525	60,148	49,844	32,732	15,217	14,291	14,719	15,161	15,616
														Grand Total [K$]:		**$362,198**

Top Risks

Risk	Mitigation
Insufficient expertise available. Unable to attract talent. Unable to ramp up sufficiently.	Provide long-term (3-5+ year), stable funding that can support grad students and post-docs and that enables early career hires. Establish and support fellowships.
Unable to engage international expertise	Explore funding mechanisms to international partners including dual-host appointments. Explore in-kind contributions from international organizations. NASA/ApD engage with ESA; NSF engage with ESO.
Unable to refurbish/access existing apertures.	Explore a range of aperture architectures and options.
Stellar variability intractable, unable to advance toward few cm/s.	Conduct ambitious research program.

Summary

- Precise mass measurements of earth-mass planets around sun-like stars is essential for characterization of directly imaged exoplanets.
- With sustained research investments in stellar variability, technology, tellurics and analytics progress can be made toward cm/s RV precision in the 5 to 10 year time frame.
- Telescope architectures leveraging existing apertures (with refurbishments) and new state-of-the-art spectrographs are identified to accomplish a survey of the direct-imaging stellar candidates ahead of the direct imaging missions.
  - Telescope options and technology choices add architecture flexibility.
- This proposed plan provides the investment roadmap to establish that capability with flexible options and responsive option paths.

ExoTAC Report on NASA/NSF EPRV

Alan Boss, Chair
Exoplanet Exploration Program
Technology Assessment Committee

ExoTAC Report on EPRV Initiative –March 18, 2020

ExoTAC Members

Alan Boss (Chair), Carnegie Institution

Rebecca Oppenheimer, American Museum of Natural History

Joe Pitman, Heliospace Corporation

Lisa Poyneer, Lawrence Livermore National Laboratory

Stephen Ridgway, NSF's National Optical-Infrared Astronomy Research Laboratory

ExoTAC Report on EPRV Initiative –March 18, 2020

- An hour-long telecon review of the NASA-NSF Extreme Precision Radial Velocity (EPRV) initiative was held on March 10, 2020.
- Rebecca Oppenheimer was unable to join the telecon, but has studied the slides and participated in subsequent discussions.
- The Chair was able to observe essentially all of the weekly telecons and the three F2F meetings of the EPRV initiative, and can attest to the transparency and thoroughness of the entire process.
- The ExoTAC agrees that the objective of 1 cm/sec Doppler accuracy, needed to determine the minimum masses of Earth-like exoplanets, would be of great value, especially if it can be achieved from ground-based telescopes.

ExoTAC Report on EPRV Initiative –March 18, 2020

- However, because of the limited amount of detailed material presented to the ExoTAC (37 charts, plus backup), *the ExoTAC is unable to provide an endorsement of the EPRV initiative as presented*.
- The presentation raised many more questions for the ExoTAC than it answered.
- Instead, we look forward to working in the future with the EPRV Working Group on performing a detailed technical evaluation of their science and technology advancement plan and Milestones.
- Such an approach would more closely follow that used for standard ExoTAC evaluations, where White Papers with proposed Milestones are scrutinized and revised prior to acceptance.
- This approach would also avoid having the ExoTAC make a snap judgment, with either acceptance or rejection, about the material presented during the March 10 telecon.

ExoTAC Report on EPRV Initiative – March 18, 2020

- The ExoTAC agrees that the EPRV initiative should start small, and suggests starting by issuing a call in ROSES for a competed opportunity to advance the most critical science questions and technology enablers that need to be addressed before proceeding with plans for attaining the ground-based resources needed for the EPRV survey itself.
- The annual SAT call could serve as a template for the EPRV ROSES program element, where the highest priority topics requested for the proposals may change from year to year as progress is made or new problems are identified.
- Targeted areas could include stellar variability and exoplanet demographics as science questions, and enabling technologies such as AO for EPRV spectrographs, optical fiber feeds, and miniaturization and stabilization of EPRV spectrographs.
- The ExoTAC would welcome working with the EPRV Working Group, NASA, and NSF to help develop the language, rationale, and selection criteria for such a ROSES program element.

Chairs' Response to ExoTAC

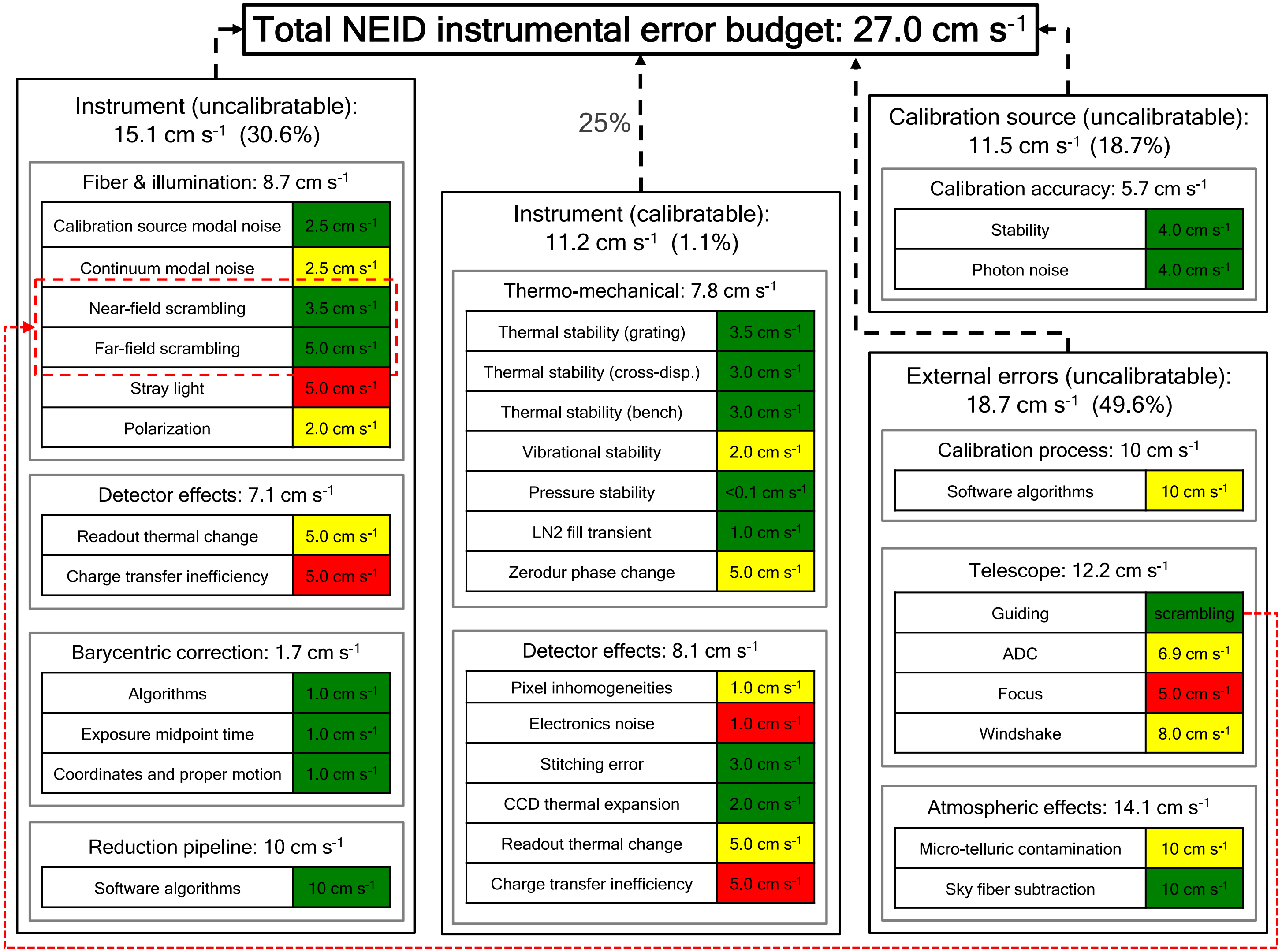
- Acknowledge that full ExoTAC review requires more time and depth than was available
- The Chairs and WG offer to provide and thoroughly review with the ExoTAC:
  - A written report of criteria, evaluation, and technical approach (May 24)
  - Implementation plan (Preliminary: June 24, Final: Aug 24)
- Accept their help in crafting the SR&T R&A call

Summary

- Precise mass measurements of earth-mass planets around sun-like stars is essential for characterization of directly imaged exoplanets.
- With sustained research investments in stellar variability, technology, tellurics and analytics progress can be made toward cm/s RV precision in the 5 to 10 year time frame.
- Telescope architectures leveraging existing apertures (with refurbishments) and new state-of-the-art spectrographs are identified to accomplish a survey of the direct-imaging stellar candidates ahead of the direct imaging missions.
  - Telescope options and technology choices add architecture flexibility.
- This proposed plan provides the investment roadmap to establish that capability with flexible options and responsive option paths.

Backup

Facility (Instrumentation) Limitations



Total NEID instrumental error budget: 27.0 cm s^{-1}

25%

Instrument (uncalibratable): 15.1 cm s^{-1} (30.6%)

Fiber & illumination: 8.7 cm s^{-1}

Calibration source modal noise	2.5 cm s^{-1}
Continuum modal noise	2.5 cm s^{-1}
Near-field scrambling	3.5 cm s^{-1}
Far-field scrambling	5.0 cm s^{-1}
Stray light	5.0 cm s^{-1}
Polarization	2.0 cm s^{-1}

Detector effects: 7.1 cm s^{-1}

Readout thermal change	5.0 cm s^{-1}
Charge transfer inefficiency	5.0 cm s^{-1}

Barycentric correction: 1.7 cm s^{-1}

Algorithms	1.0 cm s^{-1}
Exposure midpoint time	1.0 cm s^{-1}
Coordinates and proper motion	1.0 cm s^{-1}

Reduction pipeline: 10 cm s^{-1}

Software algorithms	10 cm s^{-1}

Instrument (calibratable): 11.2 cm s^{-1} (1.1%)

Thermo-mechanical: 7.8 cm s^{-1}

Thermal stability (grating)	3.5 cm s^{-1}
Thermal stability (cross-disp.)	3.0 cm s^{-1}
Thermal stability (bench)	3.0 cm s^{-1}
Vibrational stability	2.0 cm s^{-1}
Pressure stability	<0.1 cm s^{-1}
LN2 fill transient	1.0 cm s^{-1}
Zerodur phase change	5.0 cm s^{-1}

Detector effects: 8.1 cm s^{-1}

Pixel inhomogeneities	1.0 cm s^{-1}
Electronics noise	1.0 cm s^{-1}
Stitching error	3.0 cm s^{-1}
CCD thermal expansion	2.0 cm s^{-1}
Readout thermal change	5.0 cm s^{-1}
Charge transfer inefficiency	5.0 cm s^{-1}

Calibration source (uncalibratable): 11.5 cm s^{-1} (18.7%)

Calibration accuracy: 5.7 cm s^{-1}

Stability	4.0 cm s^{-1}
Photon noise	4.0 cm s^{-1}

External errors (uncalibratable): 18.7 cm s^{-1} (49.6%)

Calibration process: 10 cm s^{-1}

Software algorithms	10 cm s^{-1}

Telescope: 12.2 cm s^{-1}

Guiding	scrambling
ADC	6.9 cm s^{-1}
Focus	5.0 cm s^{-1}
Windshake	8.0 cm s^{-1}

Atmospheric effects: 14.1 cm s^{-1}

Micro-telluric contamination	10 cm s^{-1}
Sky fiber subtraction	10 cm s^{-1}

Observing Requirements

	Minimum requirement	Best
Cadence	Nightly	3x a night
R	100k	130-180k
SNR	>300	800-1000
Activity Indicator	Ca HK (390 nm)	Ca HK + more
Supplementary obs.	Solar telescope	
Call to action:		
	Increase Research Effort	
	Plan for global coordination	
	Precursor survey	
	Standardised data products	

Minimum Aperture Requirements

Apertures per Hemisphere

	Green Stars Only	**Green Stars Only**	**Green and Yellow Stars**
Target Observation	**1 observation/night**	**3 observations/night**	**1 observation/night**
SNR = 300	one 2.4-m (V<7.3) one 3.5-m (50%)	three 2.4-m (V<7.3) two 3.5-m one 6.5-m one 2.4-m + 4.3-m (50%)	two 2.4-m (V<7.3) one 2.4-m + 3.5-m (50%) one 4.3-m
SNR = 500	one 3.5-m (V<7.3) one 6.5-m (50%)	one 2.4-m + 6.5-m (90%) two 2.4-m + 6.5-m (75%) two 2.4-m + 8.1-m (50%) two 2.4-m + 10-m (35%) one 10-m one 2.4-m + 3.5-m (50%) + 8.1m (50%)	two 2.4-m + one 4.3-m one 6.5-m

(5 minute minimum observation and 2 minute slew)

Green Stars	**F7-K9 (Sun-like), vsini<5 km/s (slow rotator) and appears on more than one study list**
Yellow Stars	**F7-K9 (Sun-like), vsini ~5 - 10 km/s (medium rotator) or appears on only 1 study list**

Example Candidate Set:	*Northern Hemisphere*	*Southern Hemisphere*
	APF, SINGLE or Hiltner *50% WIYN, DCT or Mayall* *50% Gemini or 35% Keck*	*TBD 2.4-m* *50% Blanco, AAT or SOAR* *50% Gemini or 75% MGN*

Stellar Variability

	Near Term (2020-2025)	Medium Term (2025-2030)	Long Term (2030+)
High importance	How does convection interact with magnetic fields? How do stellar surface phenomena (ranked by importance: **granulation/faculae/plage, supergranulation, spots/Evershed flows/other velocity flows, meridional flows, r-modes**) drive Sun-as-a-star RV variations? Understand line formation and behaviour to a level of detail necessary to create the next generation of physically motivated solar/stellar models and instrumentation. How are magnetic fields generated? How does the solar/stellar photosphere connect to the chromosphere?	How does solar knowledge (observations/theory/simulations) connect to stellar knowledge? What instrumentation/simulations/precursor surveys are needed to answer the unknowns from above? Continue efforts from near term (B2)	Develop and apply stellar models and mitigation frameworks (RV and others such as photometry, spectropolarimetry, etc.) as a function of surface gravity and surface temperature. Incorporate models and frameworks into RV observation and analysis toolkits/strategies for use by the exoplanet community.
Medium importance	How do stellar surface phenomena and their RV impact change over the magnetic cycle? Identify new, robust observable stellar variability indicators for RV variations to inform future instrumentation, observational surveys/strategies. Explore data-driven techniques for solar and stellar variability mitigation in EPRV.	How do these processes change as a function of surface gravity and surface temperature? Continue efforts from near term (C2)	Improve and optimise RV observation and analysis toolkits/strategies.
Low importance	How do flares and gravitational redshift impact solar/stellar RV variations? Can improve p-mode mitigation?	Design physically motivated RV models for M dwarfs. Develop and apply RV observation and analysis toolkits/strategies to M-dwarfs hosts and key transiting systems.	How does stellar activity impact observations of exoplanet atmospheres and exoplanetary habitability?

Data Analysis

Requirement	Strongly Recommended
PRV observations of sun	Collect solar data as many days as practical from three or more high priority instruments* as long as instruments are in operation and place in public archive. (Data collection + ~1 FTE/year/instrument, GS or PD-level for associated analysis)
PRV observations of RV benchmark stars	Collect data on 4-10 benchmark stars from three or more high priority instruments* and place in in public archive. For cadence see Group D requirement. (Data collection + ~1 FTEs/year/instrumnt, GS or PD-level for associated analysis)
R&A in Stellar Variability Mitigation	Develop and apply at least three stellar variability mitigation strategies for both wavelength and temporal domains. Verify, validate and assess utility of each mitigation strategy using solar and RV benchmark star observations. (~8 FTEs/year, GS or PD level)
Cross-comparisons of data from different instruments to evaluate effectiveness of mitigation strategies and to inform future spectrograph/survey designs	Compare precision of RV amplitudes as a function of instrument specifications (e.g., R, SNR, sampling, etc.), temporal instrument characteristics (e.g., absolute and relative drift), and observing strategies, orbital period, for all data, including both bare minimum and additional data collected to meet "strongly recommend" for requirements 1 & 2. (~1 FTE/year/instrument + additional 2FTE/year not associated with an instrument team)
Developing modular, open-source pipeline for EPRV science	Fund development of community pipeline, based on heritage of best existing codes. Include modular design with multiple algorithms for key modules. Support multiple teams making targeted contributions to improve code. (~6FTE/year, 3 Engineer-level, 3 PD-level)
Series of EPRV Data Challenges	Fund a series of planned data challenges to address specific aspects of problem, using both simulated and real data, so as to compare effectiveness of strategies, learn from each exercise and improve the state-of-the-art. This would be limited by human capacity at ~1 data challenge per year. (~6-8 FTEs/year until EPRV goals are met)
EPRV Center for comprehensive approach to problem	Fund EPRV Center and/or other mechanism for providing coordination of research, stable funding for long-term projects, and ability to nimbly fund small targeted efforts (e.g., contributions to data challenges).
R&A in Statistical Methodology for detecting planets and measuring masses given time series fo apparent veloccities and stellar variability indiators.	Formalize statistical methodology, test and validate method using both simulated data (as for bare minimum) and observed solar spectra time-series. (~6 FTEs)

Risks

Risk Number	Risk Description	0 : New funds requested using existing assets and organizations			I : 2.4m telescopes combined with NEID-like instruments			II : 4-6m class telescopes			IV : 25m class telescopes			V : Terra-hunting-experiment-like - 3m class + SMF Instruments			VI : Minerva-LikeTelescope Tech			VIII : Hybrid Exclusive		
		C	L		C	L		C	L		C	L		C	L		C	L		C	L	
Key and Driving Risks																						
R1	Can't get enough/desired observing time/cadence/schedule	5	5	25	5	1	5	5	1	5	5	5	25	5	1	5	5	1	5	5	1	5
R2	Photon limited				5	3	15	3	1	3	3	1	3	5	3	15	5	3	15	3	1	3
R3	Luvoir/HabEx not selected	2	2	4	4	2	8	4	2	8	2	2	4	2	2	4	4	2	8	4	2	8
R4	Cannot meet schedule				3	2	6	3	3	9	3	5	15	3	3	9	3	3	9	3	3	9
R5	Upgrading/repurposing of existing facilities results in more work time, challenges to implementation	2	3	6	3	4	12	3	4	12	3	4	12	3	4	12	1	1	1	3	4	12
R6	GMT cost risk and TMT location uncertainty for large aperture options	1	1	1	1	1	1	1	1	1	5	3	15	1	1	1	1	1	1	1	1	1
R7	Non-robotic operations of telescopes impacts cost, staffing, uniformity	1	5	5	3	3	9	4	3	12	4	3	12	4	3	12	5	1	5	4	3	12
R8	AO performance in visible getting below 600 nm, below 500 nm increasingly difficult; need coverage at shorter wavelengths	1	1	1	1	1	1	1	1	1	1	1	1	5	3	15	1	1	1	1	1	1
R9	Slicing on high resolution, large aperture options, equivalent to many small telescopes (e.g. Minerva but then higher read noise)	1	1	1	1	1	1	3	2	6	5	2	10	1	1	1	5	3	15	5	2	10
R10	Long integration times and imperfect characterization of system throughput --> barycentric correction challenge				1	1	1	1	1	1	1	1	1	3	2	6	1	1	1	1	1	1
R11	Requires new technology not demonstrated in allocated time frame	1	1	1	1	1	1	1	1	1	4	2	8	4	3	12	1	1	1	1	1	1
R12	Extrapolation of technologies from Architecture "0" to other architectures may not be valid	1	1	1	1	1	1	2	2	4	3	3	9	4	4	16	2	2	4	2	2	4
R13	Unlikely to obtain high enough SNR or high enough resolution spectra for science goals				5	4	20	5	2	10	5	3	15	5	2	10	5	4	20	5	3	15
R14	Unrealistic system efficiency estimation compared to what was submitted				4	2	8	4	3	12	4	3	12	4	3	12	4	3	12	4	3	12
R15	Telluric correction in NIR is much worse (> ~900 nm)				1	1	1	1	1	1	2	3	6	3	3	9	1	1	1	1	1	1
R16	Lack of broad spectral coverage impacts stellar variability mitigation				3	1	3	4	1	4	3	1	3	4	2	8	3	1	3	4	1	4
R17	Lessons learned have to be applied to architecture for success				2	1	2	2	1	2	3	2	6	4	3	12	4	3	12	3	3	9
R18	Availability of components from at, risk, sole-source supplier				5	3	15	5	3	15	5	3	15	5	2	10	5	3	15	5	3	15
R19	Requirement to build new telescopes				5	3	15	5	4	20	5	4	20	5	3	15	5	2	10	5	4	20
R20	Coordination between different telescope facilities problemmatic				3	1	3	3	4	12	3	4	12	3	2	6	3	1	3	3	4	12
Project Risks Common to All Architectures																						
R21	Sun's variability is not representative of target stars in list/stellar variability cannot be adequately subtracted	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15
R22	Telluric line contamination cannot be adequately mitigated	4	2	8	4	2	8	4	2	8	4	2	8	4	3	12	4	2	8	4	2	8
R23	Not enough staffing to execute program	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15
R24	Difficulty in funding non-US participants				5	5	25	5	5	25	5	5	25	5	5	25	5	5	25	5	5	25
R25	Knowledge retention in the field				5	5	25	5	5	25	5	5	25	5	5	25	5	5	25	5	5	25
Sum							216			227			292			282			230			243
Rank by points					3		831	3		816	3		840	2		879	4		785	1		932
Rank accounting for Risk					2			2			5			3			4			1		

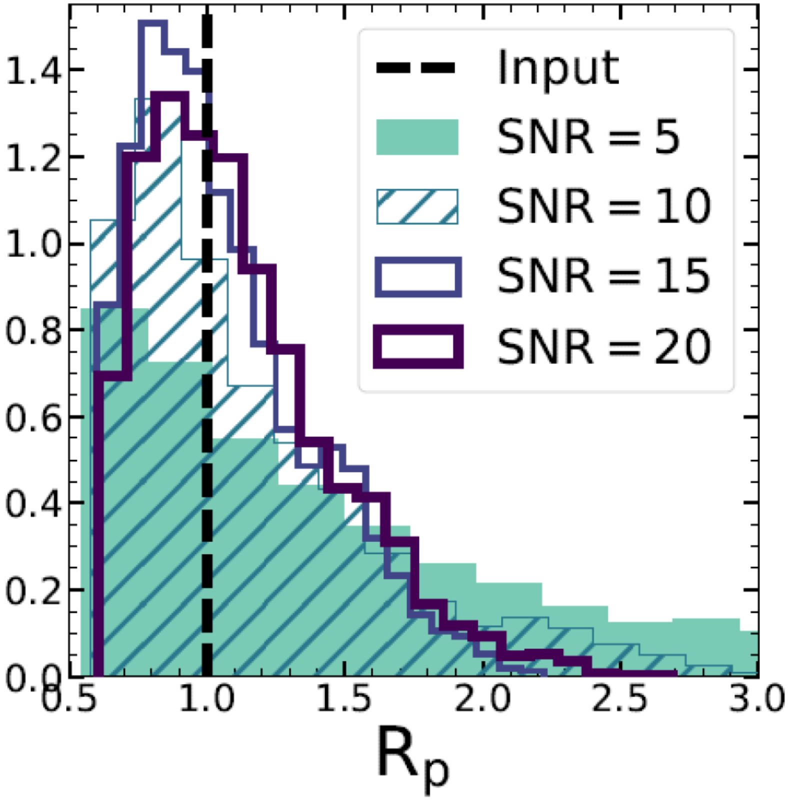
Inferring and Measuring Exoplanet Radii

Both mass and radii are ultimately needed to properly interpret the spectra of potentially habitable planets.

As planetary radius is concerned,

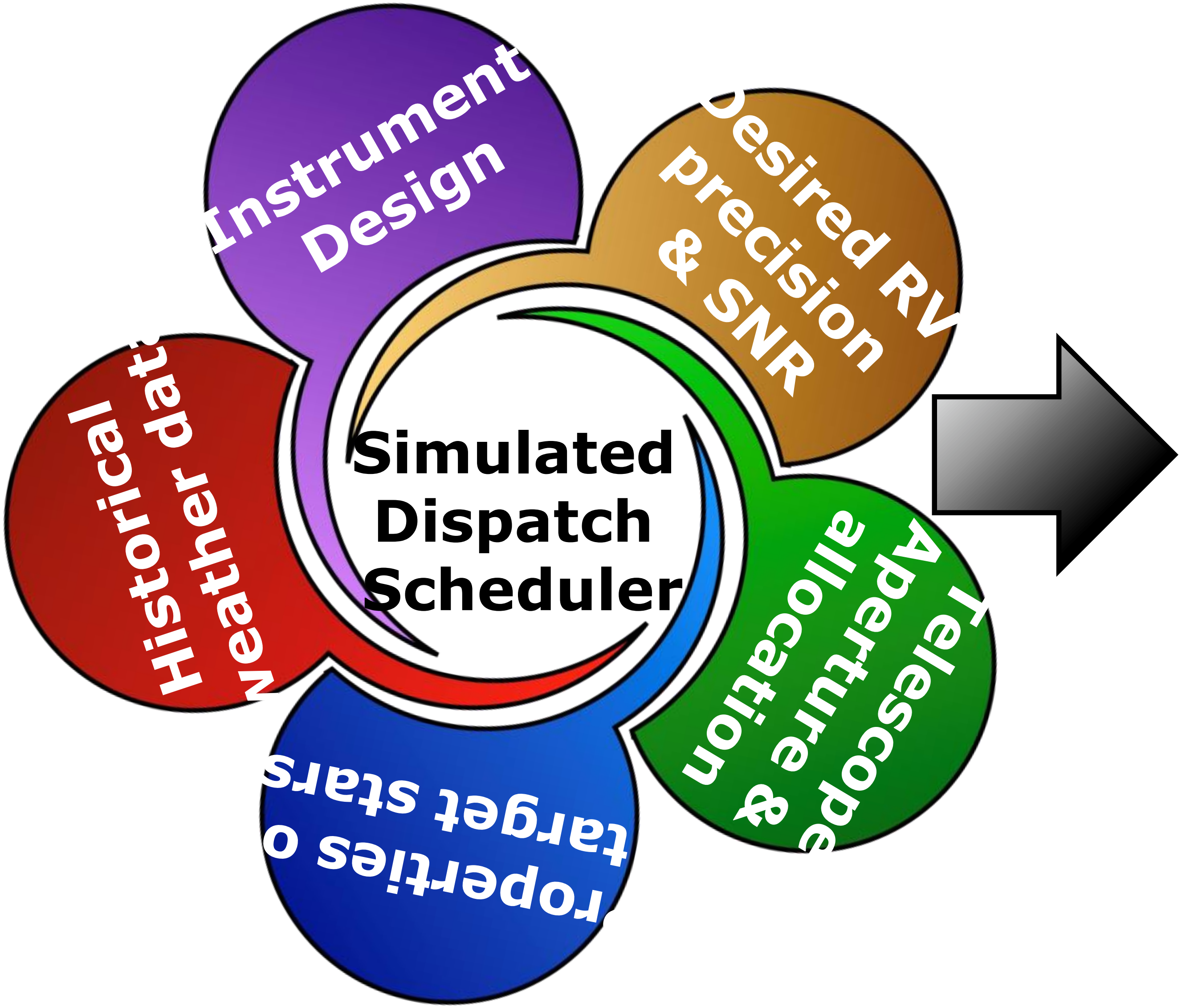
- Broad-band direct imaging alone at multiple epochs can only estimate it within a factor of ~2 due to the albedo size degeneracy (Section 3.1).
- Better accuracy can potentially be achieved through spectral observations over a broad wavelength range and subsequent spectral retrieval of planet parameters (e.g., Feng et al. 2018). But for visible spectra, accuracies will remain limited to >30–60% depending on exact planet type and spectral information available.
- …accurate radii measurements of HabEx detected exoplanets would have to wait for follow-up mid-infrared detections, [which] would break the degeneracy between albedo and radius … which in turn will likely require a midinfrared space interferometer.”

-HabEx Final Report, Chapter 12



(Feng et al. 2018)

Those details feed into our observing simulations



Instrument
Design

Desired RV
precision
& SNR

Telescope
Aperture &
allocation

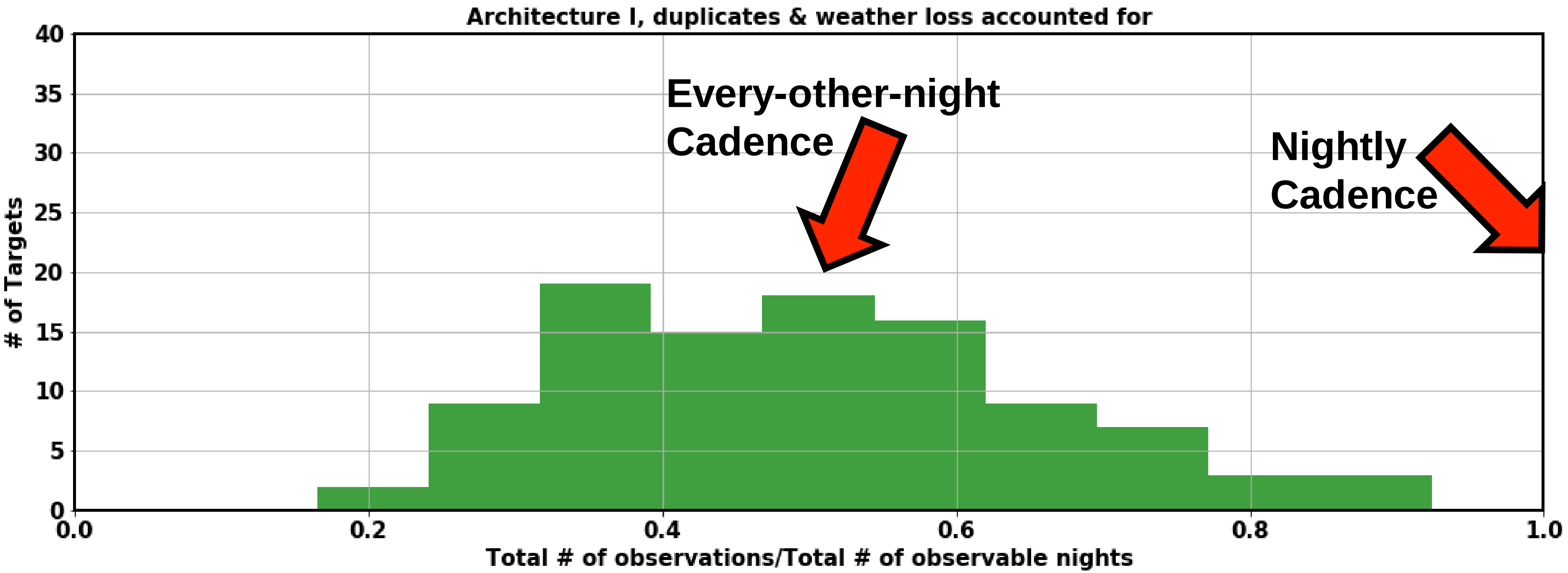
roperties o
target stars

Historical
weather dat

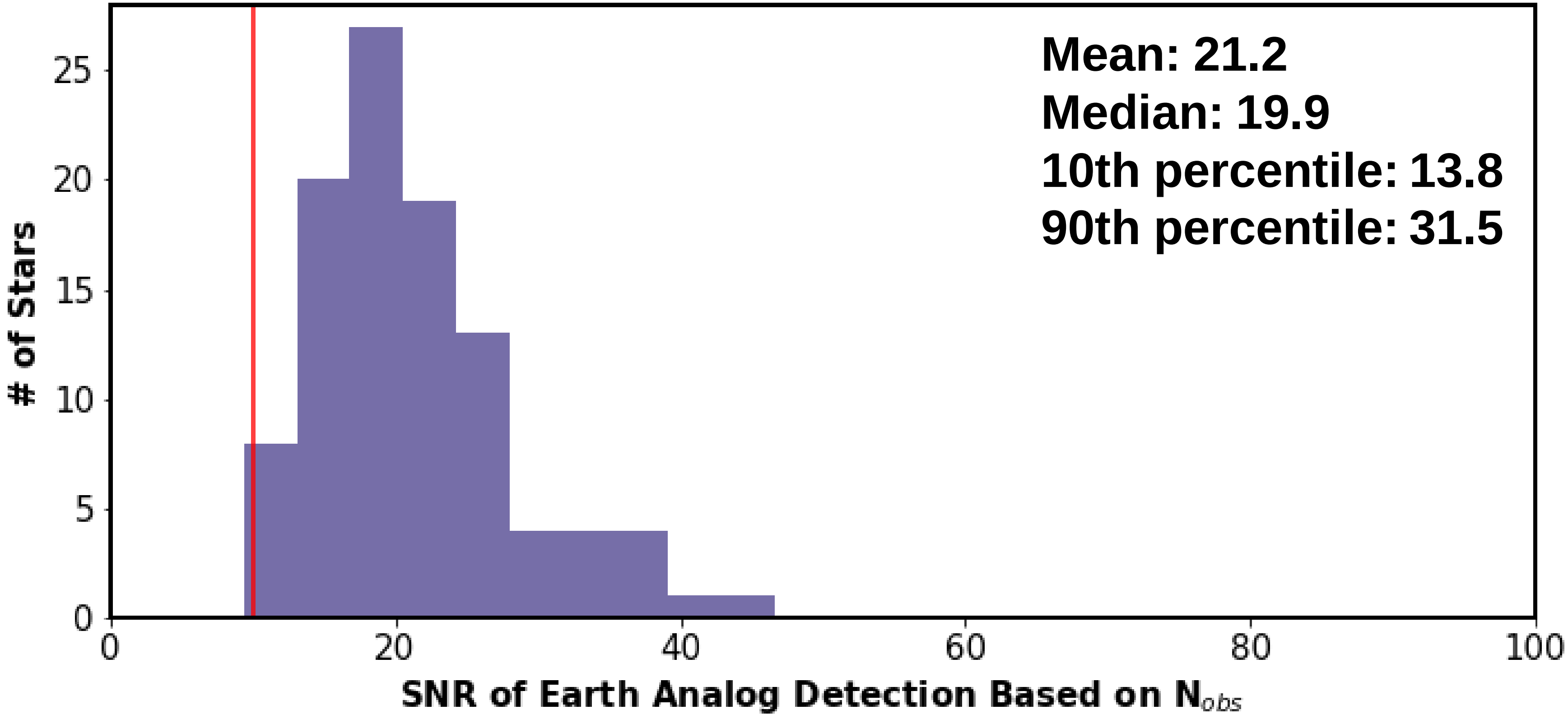
Simulated
Dispatch
Scheduler

Observing
logs: targets,
dates/times,
RV precision,
etc

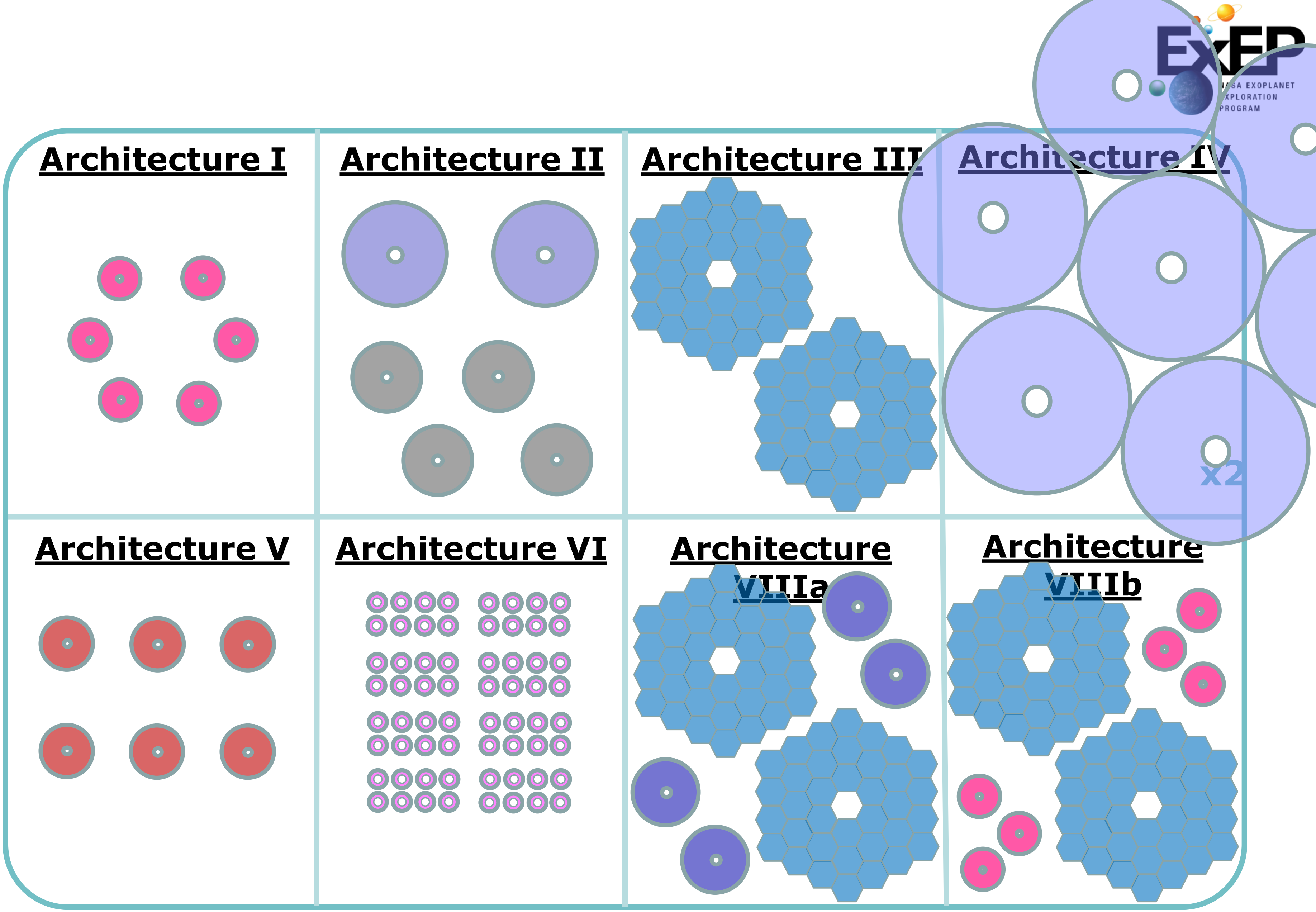
And then we use the logs to assess the architecture's performance in terms of cadence



And its ability to detect an Earth analog's RV signal if there were no stellar activity present



Mean: 21.2
Median: 19.9
10th percentile: 13.8
90th percentile: 31.5



Architecture I

Architecture II

Architecture III

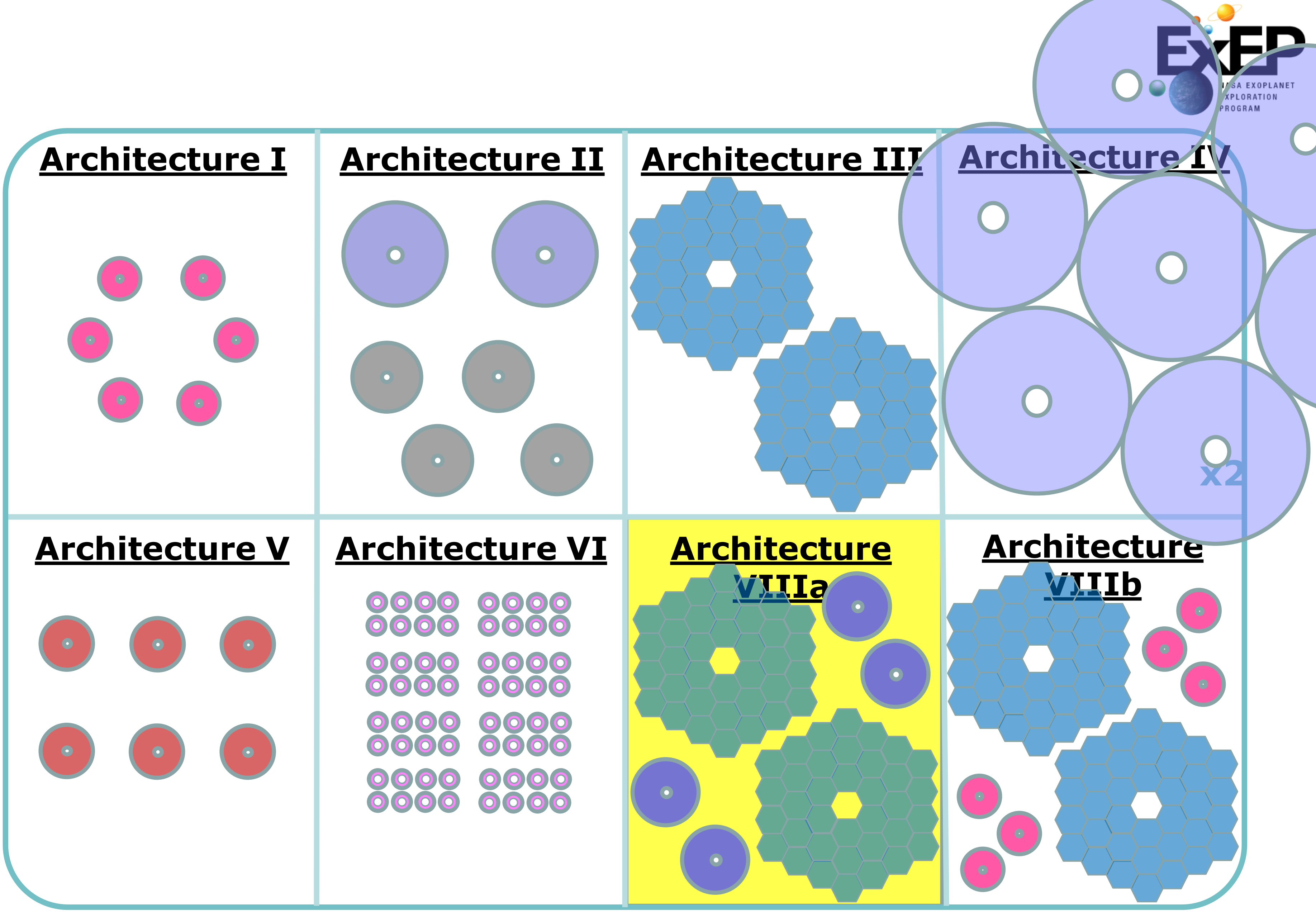
Architecture IV

Architecture V

Architecture VI

Architecture VIIIa

Architecture VIIIb



Architecture I

Architecture II

Architecture III

Architecture IV

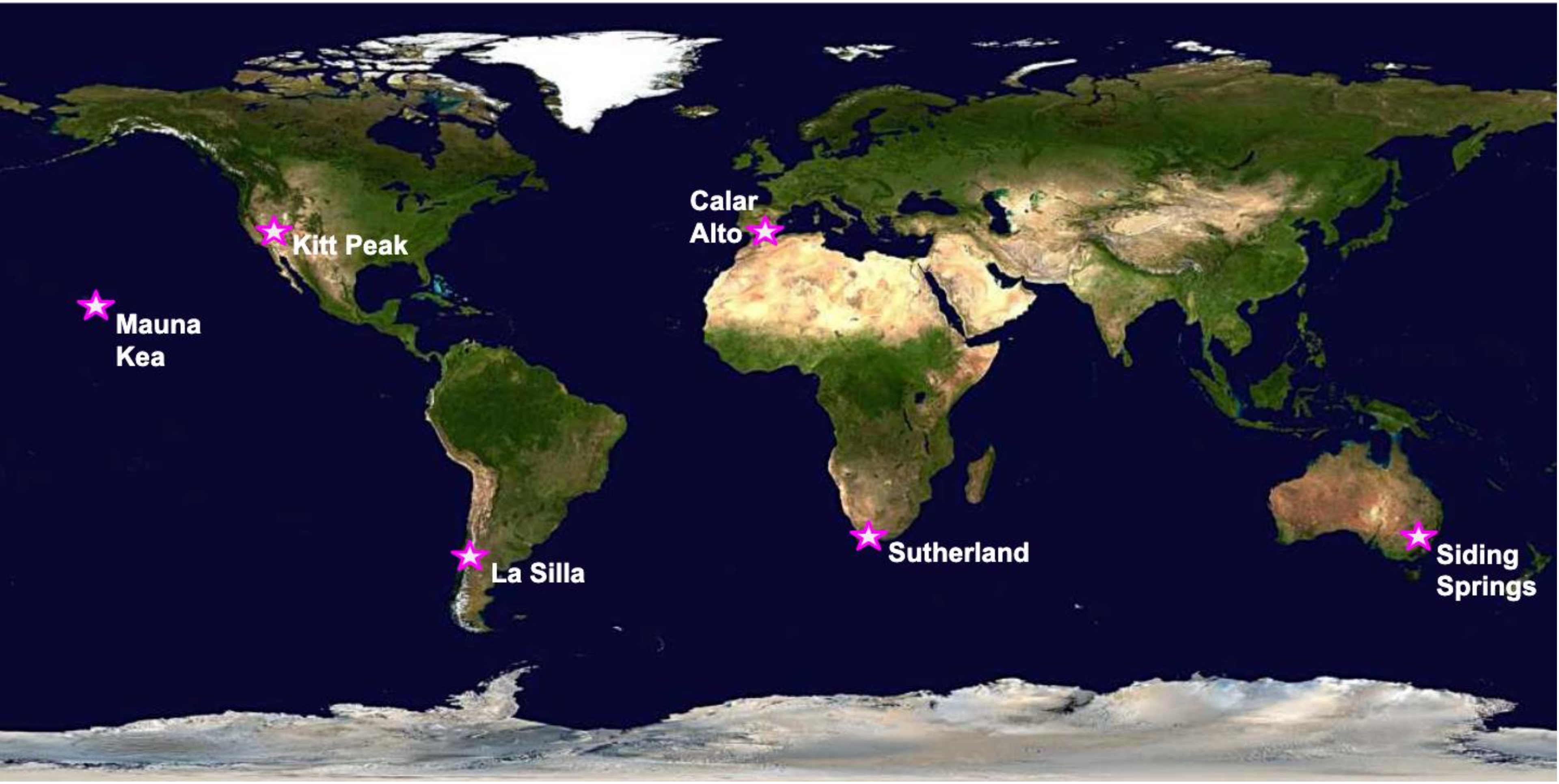
Architecture V

Architecture VI

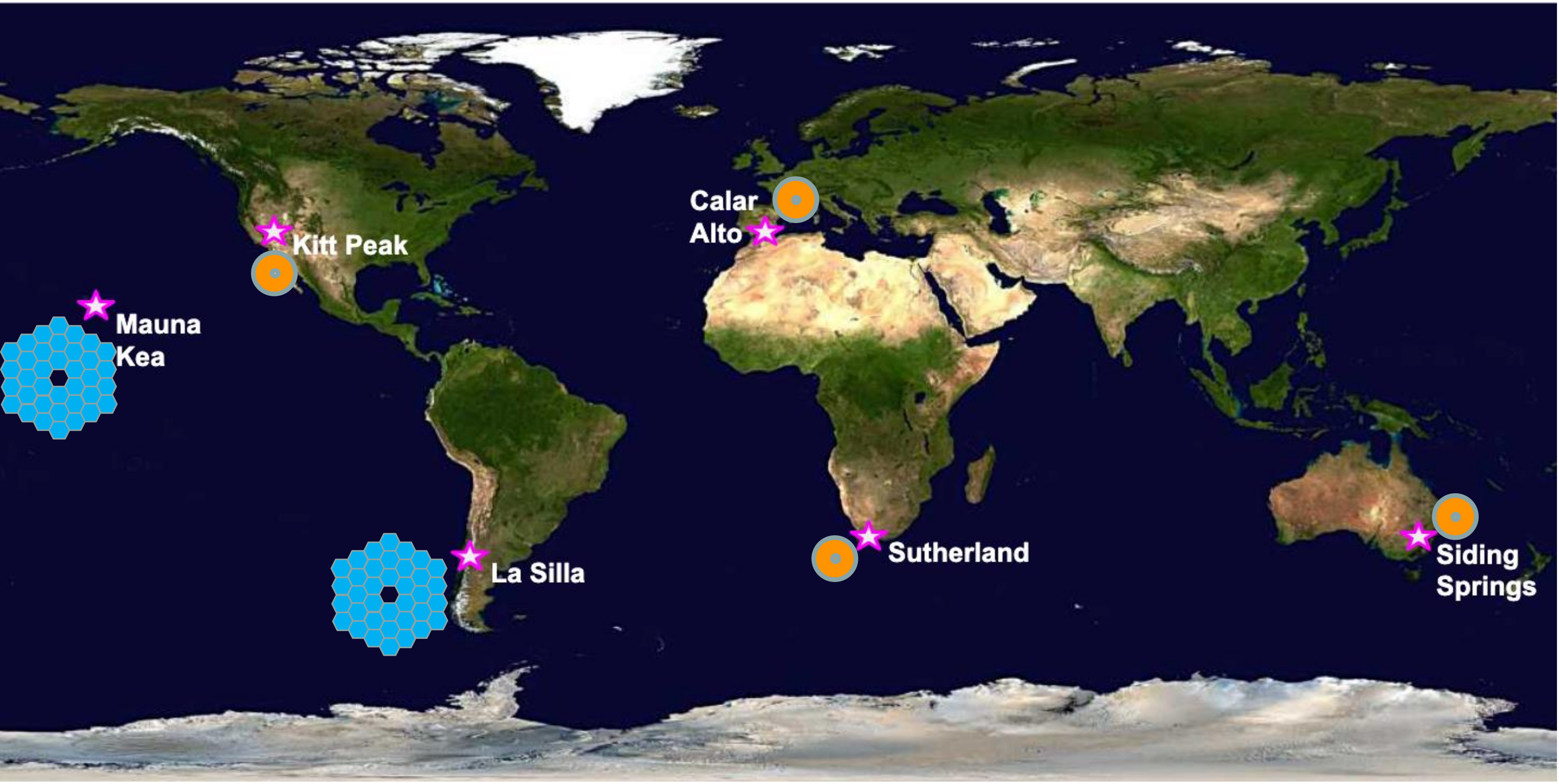
Architecture VIIIa

Architecture VIIIb

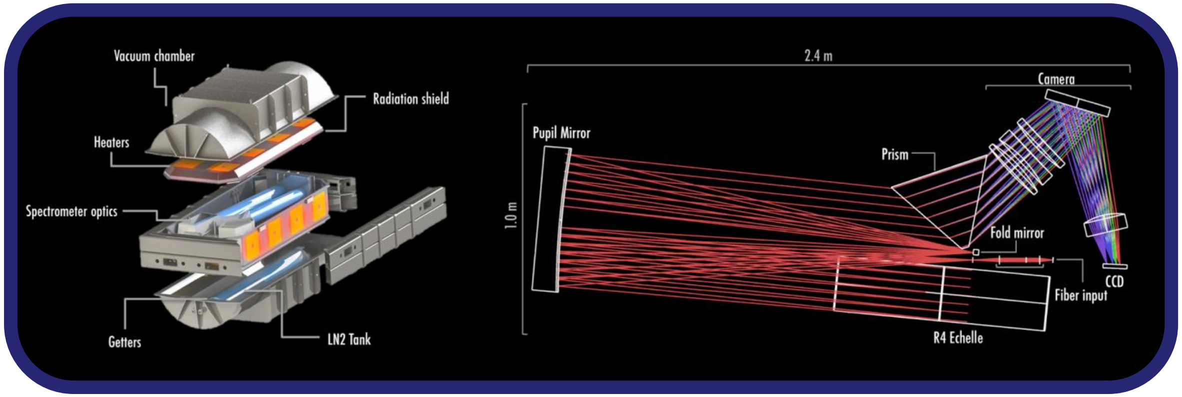
Same locations, but different distribution of facilities



Same locations, but different distribution of facilities



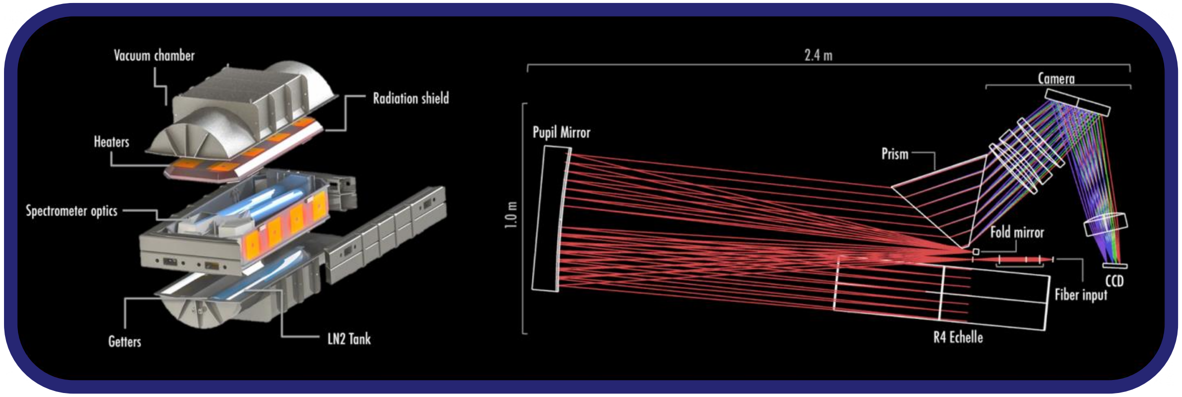
Mauna Kea and La Silla facilities contain 10m telescopes, each with an “ultra-NEID” and a 10cm solar telescope



Instrument/Observing Details

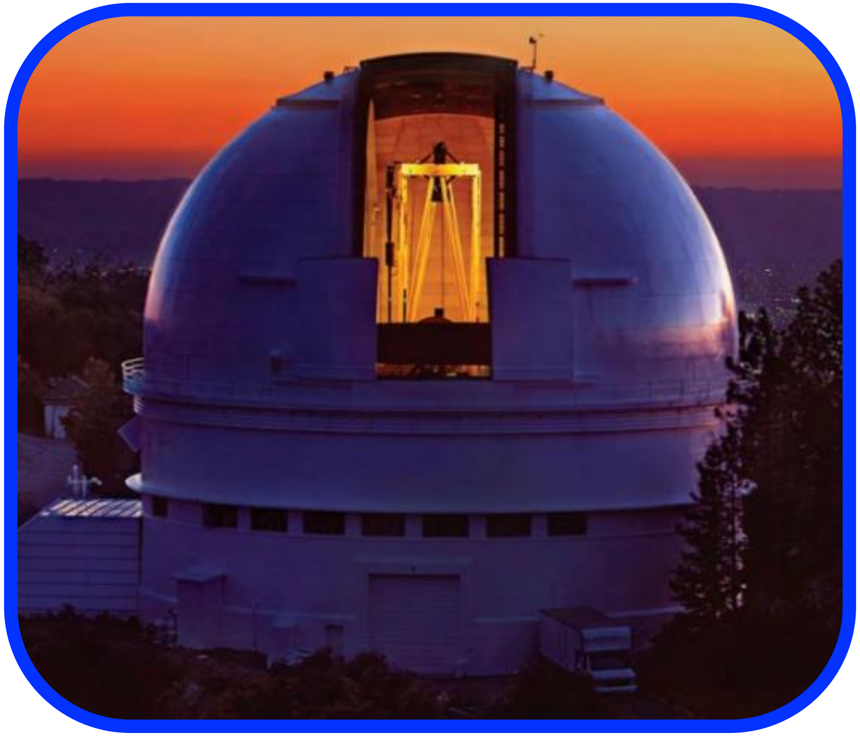
Wavelength coverage : 380-930nm
Spectral resolution : 180,000
Total system efficiency : 7%
Instrumental noise floor : 5 cm/s
Telescope allocation : 100%
Cadence: weekly

Other facilities contain 3m telescope, each with same "super-NEID" as architecture #1, and a 10cm solar telescope

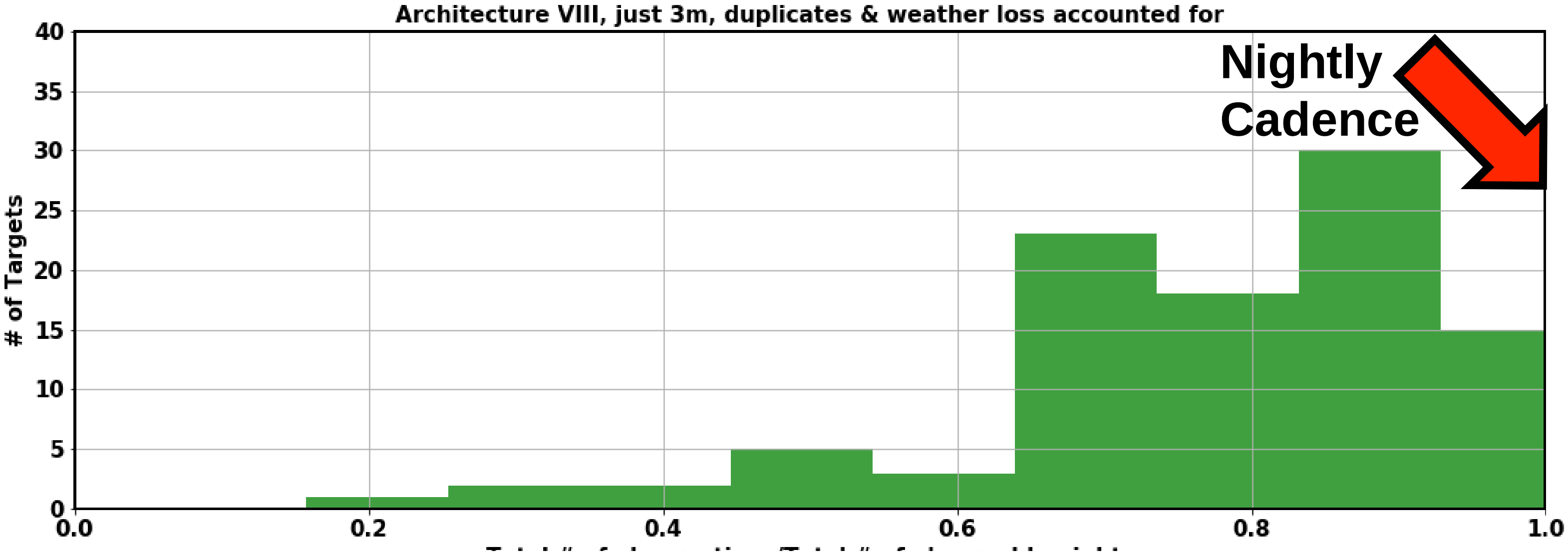


Instrument/Observing Details

Wavelength coverage : 380-930nm
Spectral resolution : 150,000
Total system efficiency : 7%
Instrumental noise floor : 10 cm/s
Telescope allocation : 100%
Cadence: nightly

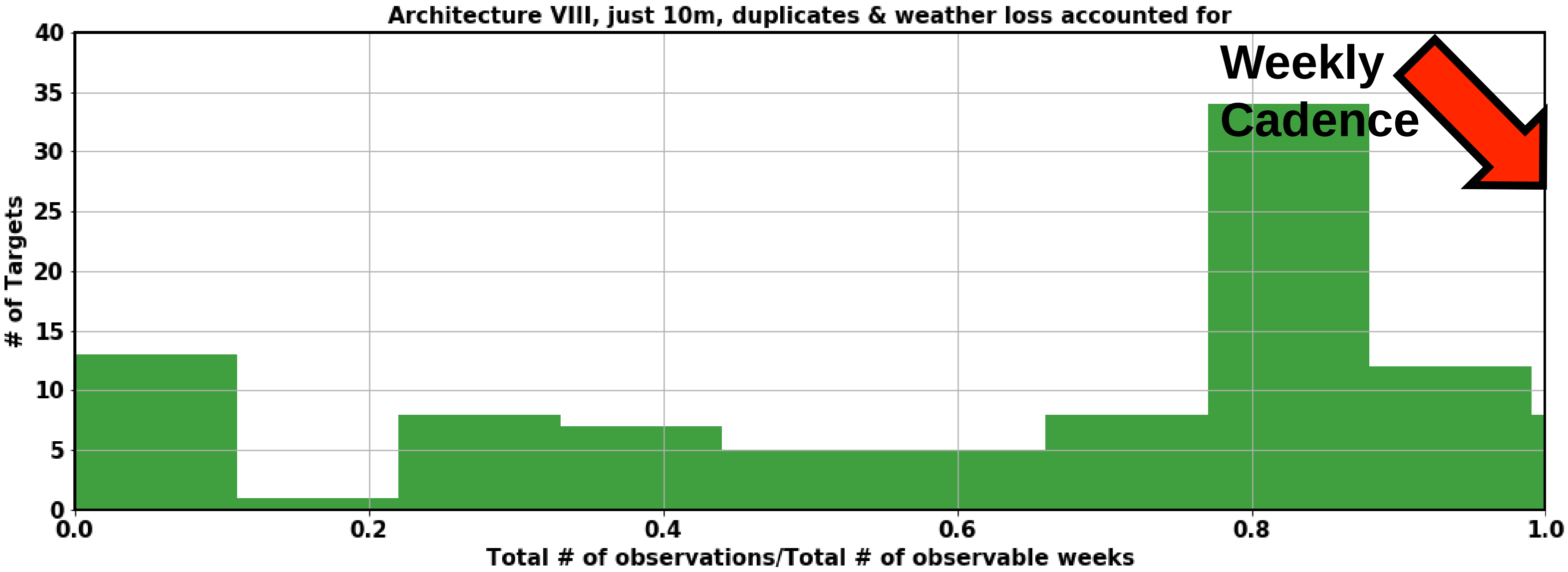


Architecture #8a : Cadence



Architecture VIII, just 3m, duplicates & weather loss accounted for

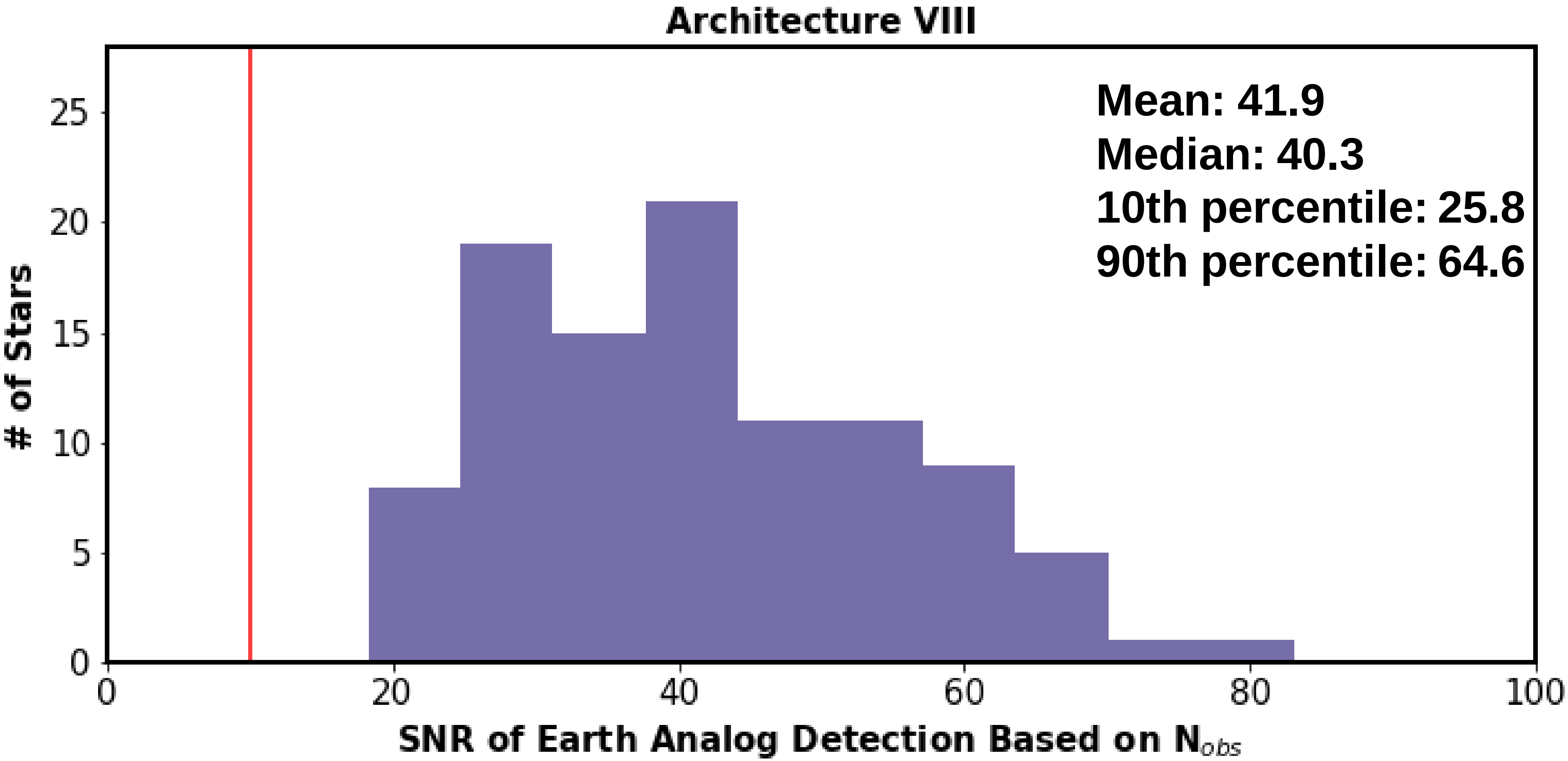
Nightly Cadence



Architecture VIII, just 10m, duplicates & weather loss accounted for

Weekly Cadence

Architecture #8a: S/N of an Earth analog detection if there were no stellar activity

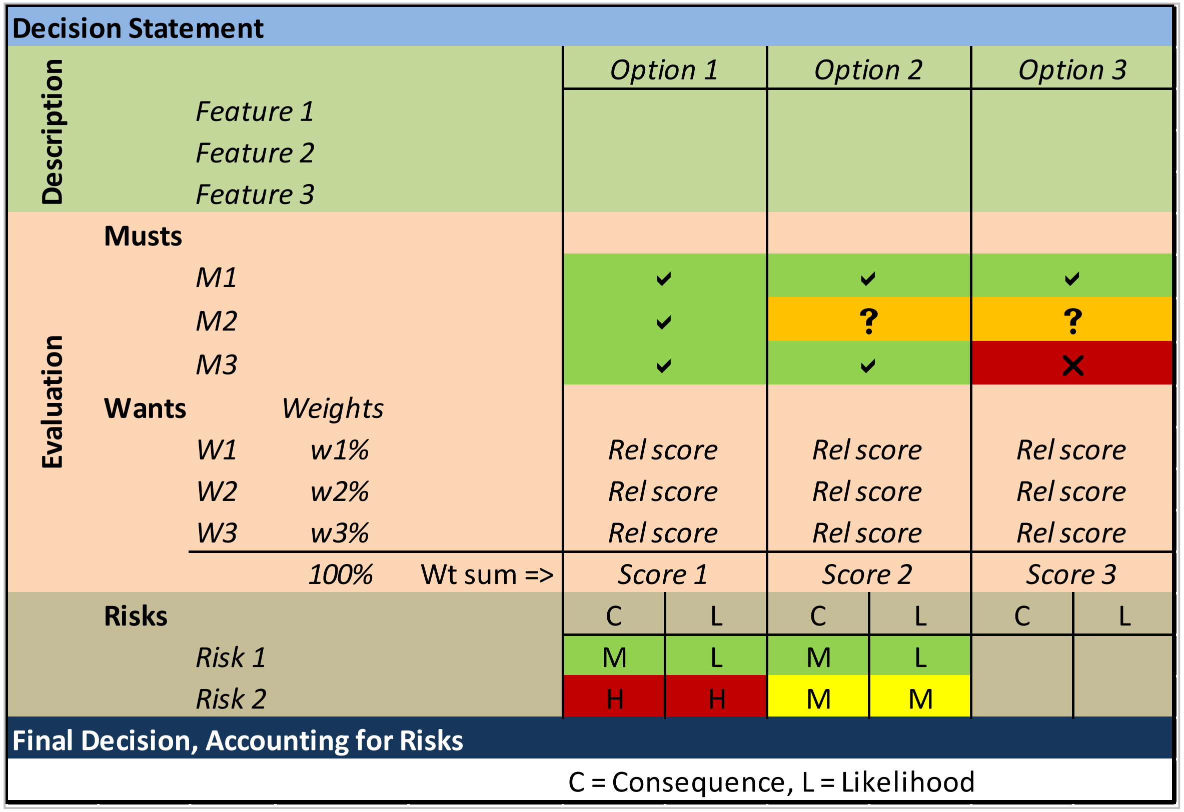


TRADE PROCESS

Trade Process

Used for *Design* and *Choice* of Strongest Options

- Adapted from Kepner-Tregoe methods. The Rational Manager, Kepner and Trego, 1965
- A systematic approach for decision making



Decision Statement

				Option 1		Option 2		Option 3	
Description	*Feature 1*								
	Feature 2								
	Feature 3								
Evaluation	**Musts**								
	M1			✓		✓		✓	
	M2			✓		?		?	
	M3			✓		✓		✗	
	Wants	*Weights*							
	W1	*w1%*		*Rel score*		*Rel score*		*Rel score*	
	W2	*w2%*		*Rel score*		*Rel score*		*Rel score*	
	W3	*w3%*		*Rel score*		*Rel score*		*Rel score*	
		100%	Wt sum =>	*Score 1*		*Score 2*		*Score 3*	
Risks				C	L	C	L	C	L
	Risk 1			M	L	M	L		
	Risk 2			H	H	M	M		

Final Decision, Accounting for Risks

C = Consequence, L = Likelihood

A little consensus at a time

Process Overview

- Agree on **Evaluation Criteria** and **Weights**
- Document **Options** and **Description**
- **Evaluate** Options vs Criteria
- Reach **Consensus** on Evaluation
- Document **Risks, Opportunities**
- **Recommendation** accounting for Risks, Opportunities

Consensus

Drawn from NASA Policies

- Consensus decisions
  - May produce more durable decisions than those by votes or decree.
  - However, convergence time can be a factor.
- We adopt a Constrained Consensus method defined as: *Strive for consensus in the reasonable time available, else, the leaders make a decision. Dissent (if any) is captured and the group moves on with full support of the decision.*
- Follow 7120.5E, Chapter 3.4, “Process for Handling Dissenting Opinion”
  - Three options:
    - (1) Agree,
    - (2) Disagree but fully support the decision,
    - (3) Disagree and raise a dissenting opinion
  - Treat (1) and (2) as consensus for LMAT Working Group
  - Dissents (3) if any will be documented and delivered to Chairs and to NASA APD management

How the EPRV WG Reached Consensus

- Reached consensus, a little at a time
- Row-by-row evaluation invited consideration of risks (and opportunities) and balancing of the evaluation by all LMAT consensus members
- Adjective scoring first, then numerical
- How we used risks and opportunities:
  - Treated differently than weighted Wants. Instead we stood back from the weighted scoring and asked:
    - When we fully factor in risks and opportunities do we instead consider the second-highest scoring option for the recommendation?
    - This is the traditional Kepner-Tregoe method
- “Use the Matrix – Don’t let the Matrix Use Us”

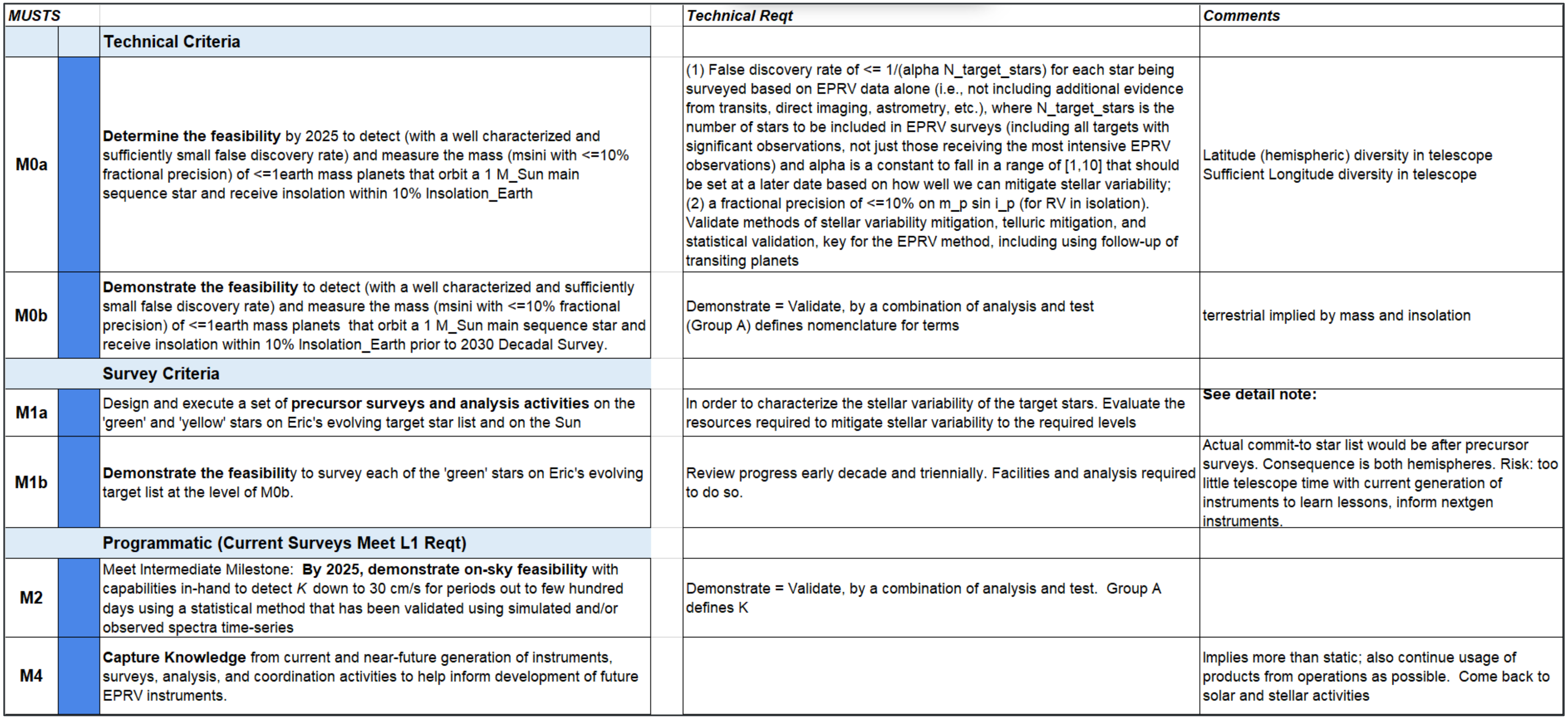
Decision Statement

- Arrived at by consensus, following the ESS Recommendation and the Charter of the Working Group:

Recommend the best ground-based program architecture and implementation (aka Roadmap) to achieve the goal of measuring the masses of temperate terrestrial planets orbiting Sun-like stars

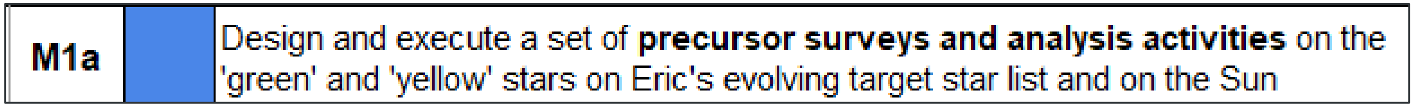
Evaluation Criteria

Trade: Musts



MUSTS			*Technical Reqt*	*Comments*
		Technical Criteria		
M0a		**Determine the feasibility** by 2025 to detect (with a well characterized and sufficiently small false discovery rate) and measure the mass (msini with <=10% fractional precision) of <=1earth mass planets that orbit a 1 M_Sun main sequence star and receive insolation within 10% Insolation_Earth	(1) False discovery rate of <= 1/(alpha N_target_stars) for each star being surveyed based on EPRV data alone (i.e., not including additional evidence from transits, direct imaging, astrometry, etc.), where N_target_stars is the number of stars to be included in EPRV surveys (including all targets with significant observations, not just those receiving the most intensive EPRV observations) and alpha is a constant to fall in a range of [1,10] that should be set at a later date based on how well we can mitigate stellar variability; (2) a fractional precision of <=10% on m_p sin i_p (for RV in isolation). Validate methods of stellar variability mitigation, telluric mitigation, and statistical validation, key for the EPRV method, including using follow-up of transiting planets	Latitude (hemispheric) diversity in telescope Sufficient Longitude diversity in telescope
M0b		**Demonstrate the feasibility** to detect (with a well characterized and sufficiently small false discovery rate) and measure the mass (msini with <=10% fractional precision) of <=1earth mass planets that orbit a 1 M_Sun main sequence star and receive insolation within 10% Insolation_Earth prior to 2030 Decadal Survey.	Demonstrate = Validate, by a combination of analysis and test (Group A) defines nomenclature for terms	terrestrial implied by mass and insolation
		Survey Criteria		
M1a		Design and execute a set of **precursor surveys and analysis activities** on the 'green' and 'yellow' stars on Eric's evolving target star list and on the Sun	In order to characterize the stellar variability of the target stars. Evaluate the resources required to mitigate stellar variability to the required levels	**See detail note:**
M1b		**Demonstrate the feasibilit**y to survey each of the 'green' stars on Eric's evolving target list at the level of M0b.	Review progress early decade and triennially. Facilities and analysis required to do so.	Actual commit-to star list would be after precursor surveys. Consequence is both hemispheres. Risk: too little telescope time with current generation of instruments to learn lessons, inform nextgen instruments.
		Programmatic (Current Surveys Meet L1 Reqt)		
M2		Meet Intermediate Milestone: **By 2025, demonstrate on-sky feasibility** with capabilities in-hand to detect *K* down to 30 cm/s for periods out to few hundred days using a statistical method that has been validated using simulated and/or observed spectra time-series	Demonstrate = Validate, by a combination of analysis and test. Group A defines K	
M4		**Capture Knowledge** from current and near-future generation of instruments, surveys, analysis, and coordination activities to help inform development of future EPRV instruments.		Implies more than static; also continue usage of products from operations as possible. Come back to solar and stellar activities

M1a: Detail Comment

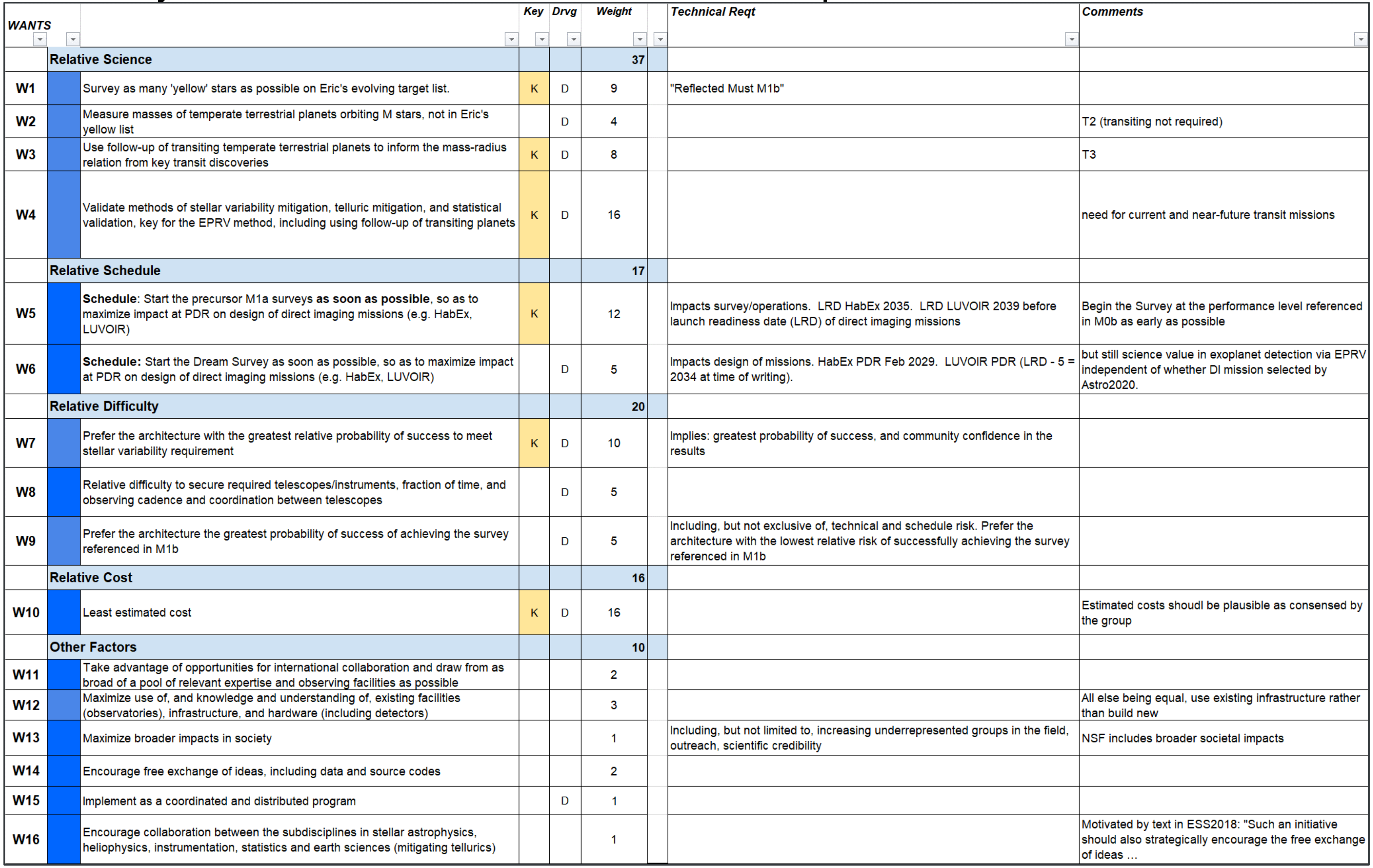


M1a	🟦	Design and execute a set of **precursor surveys and analysis activities** on the 'green' and 'yellow' stars on Eric's evolving target star list and on the Sun

- The target list is those objects for which a HZ Earth analog has predicted spectroscopic exposure times < 60 days as calculated by a NASA mission concept study.
- The target list is provided by the ExEP Science Office and is informed by the NASA Astrophysics Decadal Mission Concept Studies for LUVOIR-A, LUVOIR-B, HabEx, and Starshade Rendezvous, with additional criteria relevant for measuring precise radial velocities.
- Targets are classified as required (must=green) or desired (want=yellow).
- Required targets appear on the HabEx deep list, or two or more of the above noted study target lists, are restricted to spectral types F7-K9, and have literature rotation velocities of vsini < 5 km/s.
- Desired targets are not included in the required target sample, appear on at least one study list, expand the allowed spectral type range to include M-dwarfs, and have vsini < 10 km/s.
- The required list currently has ~100 targets; the desired list currently has ~125 targets.

Trade: Wants

6 “Key” Wants account for 71 of 100 total points



WANTS		Key	Drvg	Weight	Technical Reqt	Comments
	Relative Science			**37**		
W1	Survey as many 'yellow' stars as possible on Eric's evolving target list.	K	D	9	"Reflected Must M1b"	
W2	Measure masses of temperate terrestrial planets orbiting M stars, not in Eric's yellow list		D	4		T2 (transiting not required)
W3	Use follow-up of transiting temperate terrestrial planets to inform the mass-radius relation from key transit discoveries	K	D	8		T3
W4	Validate methods of stellar variability mitigation, telluric mitigation, and statistical validation, key for the EPRV method, including using follow-up of transiting planets	K	D	16		need for current and near-future transit missions
	Relative Schedule			**17**		
W5	**Schedule**: Start the precursor M1a surveys **as soon as possible**, so as to maximize impact at PDR on design of direct imaging missions (e.g. HabEx, LUVOIR)	K		12	Impacts survey/operations. LRD HabEx 2035. LRD LUVOIR 2039 before launch readiness date (LRD) of direct imaging missions	Begin the Survey at the performance level referenced in M0b as early as possible
W6	**Schedule:** Start the Dream Survey as soon as possible, so as to maximize impact at PDR on design of direct imaging missions (e.g. HabEx, LUVOIR)		D	5	Impacts design of missions. HabEx PDR Feb 2029. LUVOIR PDR (LRD - 5 = 2034 at time of writing).	but still science value in exoplanet detection via EPRV independent of whether DI mission selected by Astro2020.
	Relative Difficulty			**20**		
W7	Prefer the architecture with the greatest relative probability of success to meet stellar variability requirement	K	D	10	Implies: greatest probability of success, and community confidence in the results	
W8	Relative difficulty to secure required telescopes/instruments, fraction of time, and observing cadence and coordination between telescopes		D	5		
W9	Prefer the architecture the greatest probability of success of achieving the survey referenced in M1b		D	5	Including, but not exclusive of, technical and schedule risk. Prefer the architecture with the lowest relative risk of successfully achieving the survey referenced in M1b	
	Relative Cost			**16**		
W10	Least estimated cost	K	D	16		Estimated costs shoudl be plausible as consensed by the group
	Other Factors			**10**		
W11	Take advantage of opportunities for international collaboration and draw from as broad of a pool of relevant expertise and observing facilities as possible			2		
W12	Maximize use of, and knowledge and understanding of, existing facilities (observatories), infrastructure, and hardware (including detectors)			3		All else being equal, use existing infrastructure rather than build new
W13	Maximize broader impacts in society			1	Including, but not limited to, increasing underrepresented groups in the field, outreach, scientific credibility	NSF includes broader societal impacts
W14	Encourage free exchange of ideas, including data and source codes			2		
W15	Implement as a coordinated and distributed program		D	1		
W16	Encourage collaboration between the subdisciplines in stellar astrophysics, heliophysics, instrumentation, statistics and earth sciences (mitigating tellurics)			1		Motivated by text in ESS2018: "Such an initiative should also strategically encourage the free exchange of ideas …

Definition of Option

(for Purposes of Trade)

Roadmap + Survey (Architecture)

- R&A
- Precursor Surveys
- ~2020’s

- “Architecture” of Survey: telescopes, cadence, instruments, etc
- ~2030’s

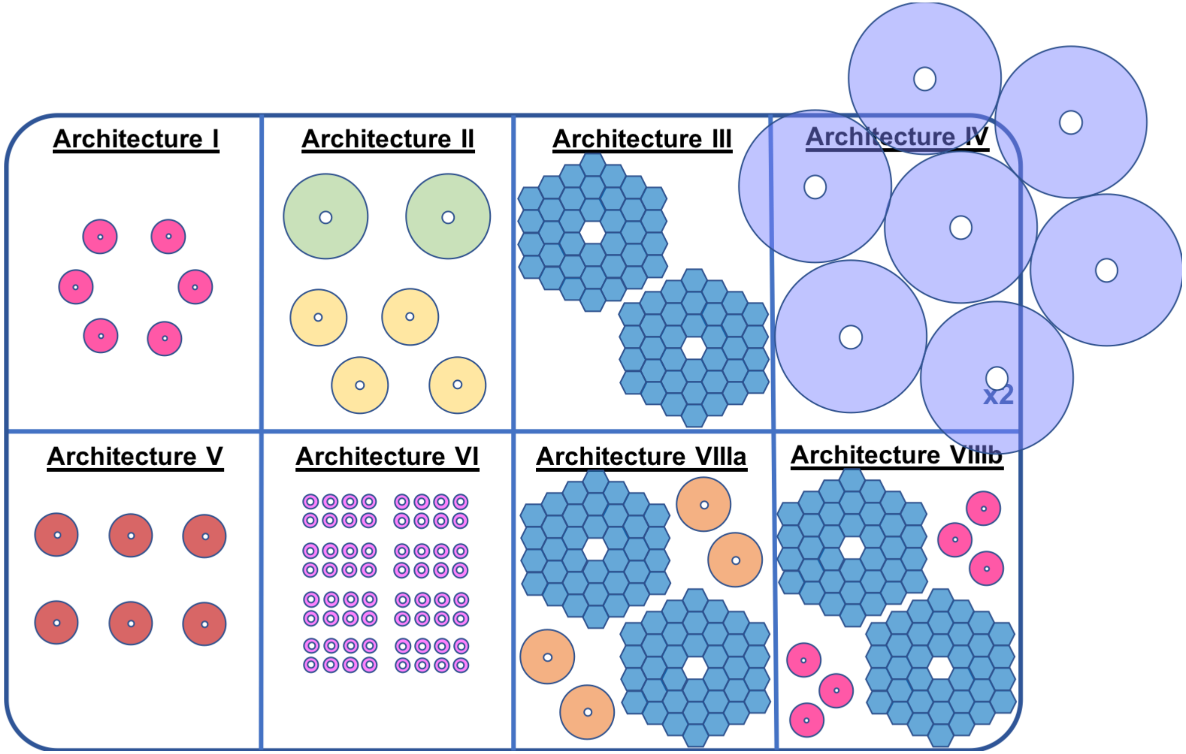
- Premise that Survey Architecture may expand or contract the scope of Roadmap investments
- NSF cares about facilities needed for Survey Architecture
- Survey Architecture evolves per Roadmap progress
- Trade: evaluate full “Option” vs Criteria

Roadmap ✚ Survey (Architecture)

Option Terminology

Option = Roadmap + Survey Architecture

0a Scott	0b Fred	I Jenn	II Andrew	III John	IV (VIII + 25m) Andy	V Chas	VI Peter	VII Peter	VIII BJ
Existing Plans	Existing -Plus New Funds	2.4m	4-6m	10m	25m + VIIIa	3m + SMF	Novel Tel. Tech	Novel InstrTech	Hybrid
		2.4m x 6	4m x 2	10m x 2	25m x 1	3m x 6			10m x 2
			6m x 2		10m x 2				4m x 4
					4m x 4				



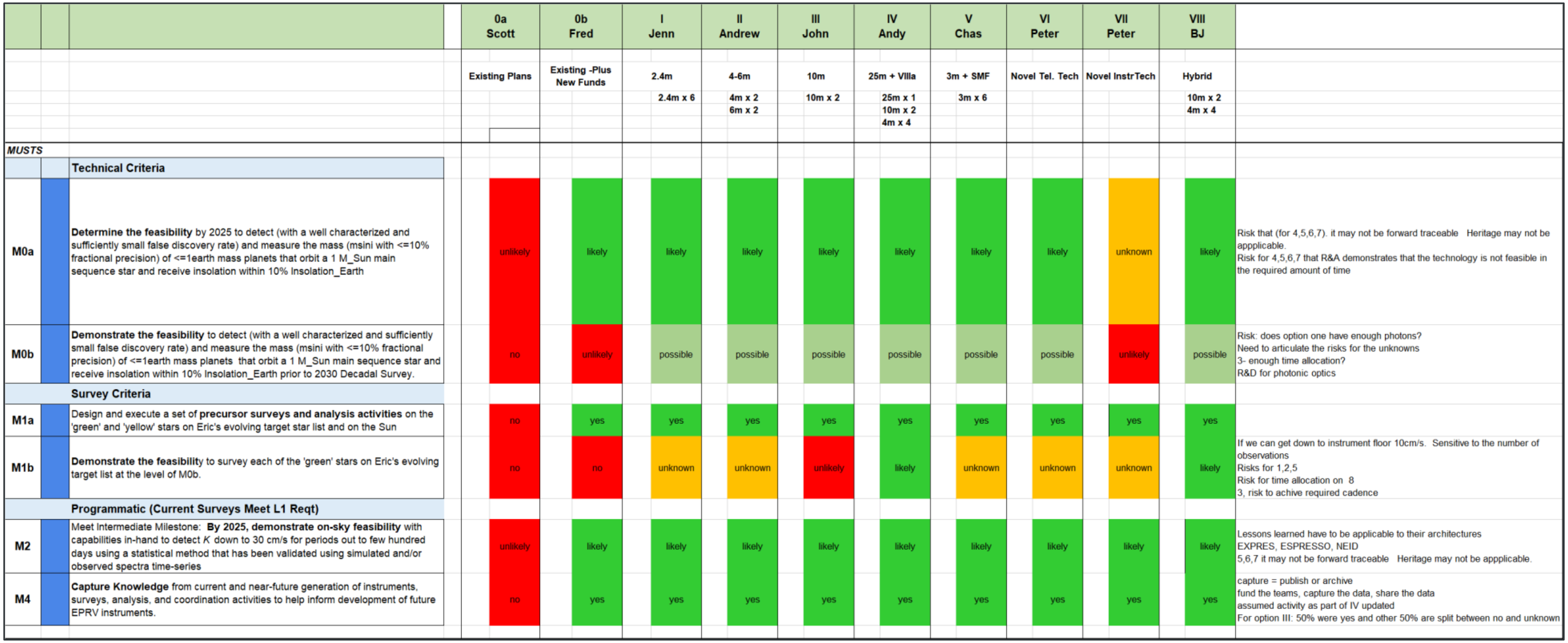
Evaluation of Musts

- Each Must is a Pass/Fail
- Choices
  - Yes
  - Likely
  - Possible
  - Unknown
  - Unlikely
  - No

Treated as a “Pass” for this Trade

Evaluation of Musts

Only these Options Pass: I, II, IV, V, VI, VII, VIII



		0a Scott	0b Fred	I Jenn	II Andrew	III John	IV Andy	V Chas	VI Peter	VII Peter	VIII BJ	
		Existing Plans	Existing -Plus New Funds	2.4m 2.4m x 6	4-6m 4m x 2 6m x 2	10m 10m x 2	25m + VIIa 25m x 1 10m x 2 4m x 4	3m + SMF 3m x 6	Novel Tel. Tech	Novel InstrTech	Hybrid 10m x 2 4m x 4	
MUSTS												
	Technical Criteria											
M0a	**Determine the feasibility** by 2025 to detect (with a well characterized and sufficiently small false discovery rate) and measure the mass (msini with <=10% fractional precision) of <=1earth mass planets that orbit a 1 M_Sun main sequence star and receive insolation within 10% Insolation_Earth	unlikely	likely	likely	likely	likely	likely	likely	likely	unknown	likely	Risk that (for 4,5,6,7). it may not be forward traceable Heritage may not be appplicable. Risk for 4,5,6,7 that R&A demonstrates that the technology is not feasible in the required amount of time
M0b	**Demonstrate the feasibility** to detect (with a well characterized and sufficiently small false discovery rate) and measure the mass (msini with <=10% fractional precision) of <=1earth mass planets that orbit a 1 M_Sun main sequence star and receive insolation within 10% Insolation_Earth prior to 2030 Decadal Survey.	no	unlikely	possible	possible	possible	possible	possible	possible	unlikely	possible	Risk: does option one have enough photons? Need to articulate the risks for the unknowns 3- enough time allocation? R&D for photonic optics
	Survey Criteria											
M1a	Design and execute a set of **precursor surveys and analysis activities** on the 'green' and 'yellow' stars on Eric's evolving target star list and on the Sun	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	
M1b	**Demonstrate the feasibility** to survey each of the 'green' stars on Eric's evolving target list at the level of M0b.	no	no	unknown	unknown	unlikely	likely	unknown	unknown	unknown	likely	If we can get down to instrument floor 10cm/s. Sensitive to the number of observations Risks for 1,2,5 Risk for time allocation on 8 3, risk to achive required cadence
	Programmatic (Current Surveys Meet L1 Reqt)											
M2	Meet Intermediate Milestone: **By 2025, demonstrate on-sky feasibility** with capabilities in-hand to detect K down to 30 cm/s for periods out to few hundred days using a statistical method that has been validated using simulated and/or observed spectra time-series	unlikely	likely	likely	likely	likely	likely	likely	likely	likely	likely	Lessons learned have to be applicable to their architectures EXPRES, ESPRESSO, NEID 5,6,7 it may not be forward traceable Heritage may not be appplicable.
M4	**Capture Knowledge** from current and near-future generation of instruments, surveys, analysis, and coordination activities to help inform development of future EPRV instruments.	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	capture = publish or archive fund the teams, capture the data, share the data assumed activity as part of IV updated For option III: 50% were yes and other 50% are split between no and unknown

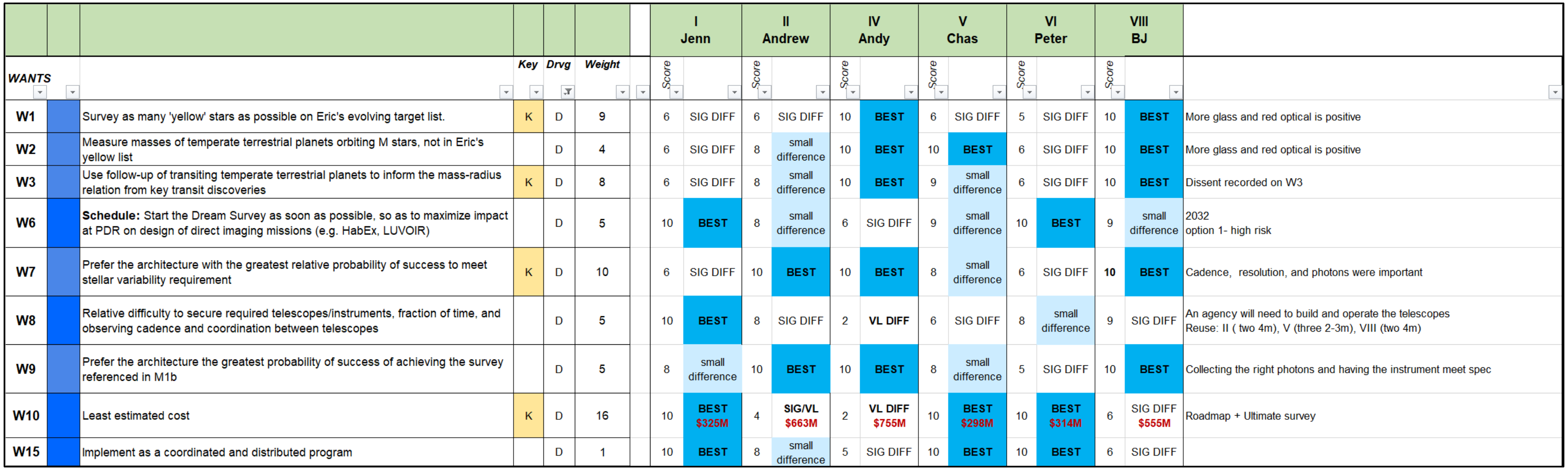
- Many risks captured for the Passing Options
- Options 0a, 0b, II, VII do not Pass, and not Evaluated for Wants or Risks

Evaluation of Wants (All)

WANTS		Key	Drvg	Weight	I Jenn		II Andrew		IV Andy		V Chas		VI Peter		VIII BJ		
					Score		Score		Score		Score		Score		Score		
	Relative Science			**37**	**254**		**294**		**370**		**310**		**245**		**370**		
W1	Survey as many 'yellow' stars as possible on Eric's evolving target list.	K	D	9	6	SIG DIFF	6	SIG DIFF	10	**BEST**	6	SIG DIFF	5	SIG DIFF	10	**BEST**	More glass and red optical is positive
W2	Measure masses of temperate terrestrial planets orbiting M stars, not in Eric's yellow list		D	4	6	SIG DIFF	8	small difference	10	**BEST**	10	**BEST**	6	SIG DIFF	10	**BEST**	More glass and red optical is positive
W3	Use follow-up of transiting temperate terrestrial planets to inform the mass-radius relation from key transit discoveries	K	D	8	6	SIG DIFF	8	small difference	10	**BEST**	9	small difference	6	SIG DIFF	10	**BEST**	Dissent recorded on W3
W4	Validate methods of stellar variability mitigation, telluric mitigation, and statistical validation, key for the EPRV method, including using follow-up of transiting planets	K	D	16	8	small difference	9	small difference	10	**BEST**	9	small difference	8	small difference	10	**BEST**	8 had sig diff on account of the testbed 7 adopted all of the bonuses 6 was strong because of roadmap activity 4,8 were strong because of the glass Talk to PLATO work package involved w/ ground based follow up to ask about their forward plan on steller variability, tellurics etc
	Relative Schedule			**17**	**170**		**160**		**150**		**165**		**170**		**165**		
W5	**Schedule**: Start the precursor M1a surveys **as soon as possible**, so as to maximize impact at PDR on design of direct imaging missions (e.g. HabEx, LUVOIR)	K		12	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	Auxillary and precourser ASAP After precourser surveys (ESPRESSO, NEID) we will assess whether we are ready to go ahead with architecture or if we need more R&A Etc
W6	**Schedule:** Start the Dream Survey as soon as possible, so as to maximize impact at PDR on design of direct imaging missions (e.g. HabEx, LUVOIR)		D	5	10	**BEST**	8	small difference	6	SIG DIFF	9	small difference	10	**BEST**	9	small difference	2032 option 1- high risk
	Relative Difficulty			**20**	**150**		**190**		**160**		**150**		**125**		**195**		Revisit for final report
W7	Prefer the architecture with the greatest relative probability of success to meet stellar variability requirement	K	D	10	6	SIG DIFF	10	**BEST**	10	**BEST**	8	small difference	6	SIG DIFF	**10**	**BEST**	Cadence, resolution, and photons were important
W8	Relative difficulty to secure required telescopes/instruments, fraction of time, and observing cadence and coordination between telescopes		D	5	10	**BEST**	8	SIG DIFF	2	**VL DIFF**	6	SIG DIFF	8	small difference	9	SIG DIFF	An agency will need to build and operate the telescopes Reuse: II (two 4m), V (three 2-3m), VIII (two 4m)
W9	Prefer the architecture the greatest probability of success of achieving the survey referenced in M1b		D	5	8	small difference	10	**BEST**	10	**BEST**	8	small difference	5	SIG DIFF	10	**BEST**	Collecting the right photons and having the instrument meet spec
	Relative Cost			**16**	**160**		**64**		**32**		**160**		**160**		**96**		Estimates for roadmap are equally included but not yet the full amount
W10	Least estimated cost	K	D	16	10	**BEST $325M**	4	**SIG/VL $663M**	2	**VL DIFF $755M**	10	**BEST $298M**	10	**BEST $314M**	6	SIG DIFF **$555M**	Roadmap + Ultimate survey
	Other Factors			**10**	**97**		**92**		**80**		**94**		**85**		**90**		
W11	Take advantage of opportunities for international collaboration and draw from as broad of a pool of relevant expertise and observing facilities as possible			2	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	
W12	Maximize use of, and knowledge and understanding of, existing facilities (observatories), infrastructure, and hardware (including detectors)			3	9	small difference	8	small difference	5	SIG DIFF	8	small difference	5	SIG DIFF	8	small difference	
W13	Maximize broader impacts in society			1	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	
W14	Encourage free exchange of ideas, including data and source codes			2	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	
W15	Implement as a coordinated and distributed program		D	1	10	**BEST**	8	small difference	5	SIG DIFF	10	**BEST**	10	**BEST**	6	SIG DIFF	
W16	Encourage collaboration between the subdisciplines in stellar astrophysics, heliophysics, instrumentation, statistics and earth sciences (mitigating tellurics)			1	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	
	Subtotal			100													
	Total				**831**		**800**		**792**		**879**		**785**		**916**		
	Ranking by Points				**3**		**4**		**4**		**2**		**4**		**1**		

Analysis: Driving Wants

Driving = more than a small difference between options

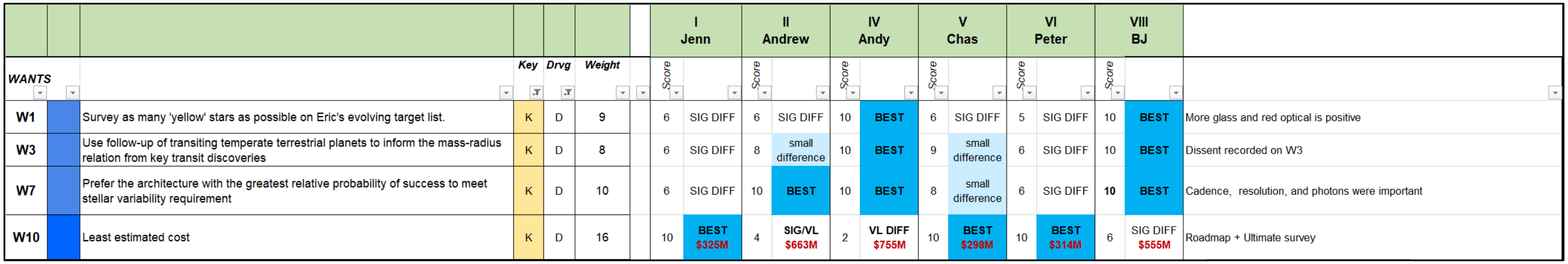


							I Jenn		II Andrew		IV Andy		V Chas		VI Peter		VIII BJ		
WANTS			***Key***	***Drvg***	***Weight***		*Score*		*Score*		*Score*		*Score*		*Score*		*Score*		
W1		Survey as many 'yellow' stars as possible on Eric's evolving target list.	K	D	9		6	SIG DIFF	6	SIG DIFF	10	**BEST**	6	SIG DIFF	5	SIG DIFF	10	**BEST**	More glass and red optical is positive
W2		Measure masses of temperate terrestrial planets orbiting M stars, not in Eric's yellow list		D	4		6	SIG DIFF	8	small difference	10	**BEST**	10	**BEST**	6	SIG DIFF	10	**BEST**	More glass and red optical is positive
W3		Use follow-up of transiting temperate terrestrial planets to inform the mass-radius relation from key transit discoveries	K	D	8		6	SIG DIFF	8	small difference	10	**BEST**	9	small difference	6	SIG DIFF	10	**BEST**	Dissent recorded on W3
W6		**Schedule:** Start the Dream Survey as soon as possible, so as to maximize impact at PDR on design of direct imaging missions (e.g. HabEx, LUVOIR)		D	5		10	**BEST**	8	small difference	6	SIG DIFF	9	small difference	10	**BEST**	9	small difference	2032 option 1- high risk
W7		Prefer the architecture with the greatest relative probability of success to meet stellar variability requirement	K	D	10		6	SIG DIFF	10	**BEST**	10	**BEST**	8	small difference	6	SIG DIFF	**10**	**BEST**	Cadence, resolution, and photons were important
W8		Relative difficulty to secure required telescopes/instruments, fraction of time, and observing cadence and coordination between telescopes		D	5		10	**BEST**	8	SIG DIFF	2	**VL DIFF**	6	SIG DIFF	8	small difference	9	SIG DIFF	An agency will need to build and operate the telescopes Reuse: II (two 4m), V (three 2-3m), VIII (two 4m)
W9		Prefer the architecture the greatest probability of success of achieving the survey referenced in M1b		D	5		8	small difference	10	**BEST**	10	**BEST**	8	small difference	5	SIG DIFF	10	**BEST**	Collecting the right photons and having the instrument meet spec
W10		Least estimated cost	K	D	16		10	**BEST** **$325M**	4	**SIG/VL** **$663M**	2	**VL DIFF** **$755M**	10	**BEST** **$298M**	10	**BEST** **$314M**	6	SIG DIFF **$555M**	Roadmap + Ultimate survey
W15		Implement as a coordinated and distributed program		D	1		10	**BEST**	8	small difference	5	SIG DIFF	10	**BEST**	10	**BEST**	6	SIG DIFF	

Analysis: Key & Driving Wants

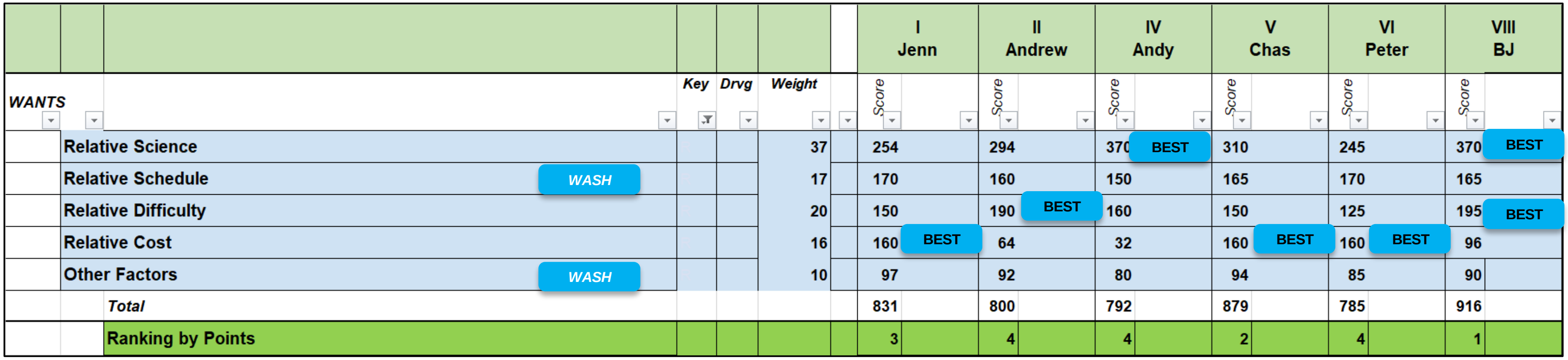
Key = 8 or more points in Weights

Target stars, transit science, stellar variability, cost



							I Jenn		**II Andrew**		**IV Andy**		**V Chas**		**VI Peter**		**VIII BJ**		
WANTS			***Key***	***Drvg***	***Weight***		*Score*		*Score*		*Score*		*Score*		*Score*		*Score*		
W1		Survey as many 'yellow' stars as possible on Eric's evolving target list.	K	D	9		6	SIG DIFF	6	SIG DIFF	10	**BEST**	6	SIG DIFF	5	SIG DIFF	10	**BEST**	More glass and red optical is positive
W3		Use follow-up of transiting temperate terrestrial planets to inform the mass-radius relation from key transit discoveries	K	D	8		6	SIG DIFF	8	small difference	10	**BEST**	9	small difference	6	SIG DIFF	10	**BEST**	Dissent recorded on W3
W7		Prefer the architecture with the greatest relative probability of success to meet stellar variability requirement	K	D	10		6	SIG DIFF	10	**BEST**	10	**BEST**	8	small difference	6	SIG DIFF	**10**	**BEST**	Cadence, resolution, and photons were important
W10		Least estimated cost	K	D	16		10	**BEST** **$325M**	4	**SIG/VL** **$663M**	2	**VL DIFF** **$755M**	10	**BEST** **$298M**	10	**BEST** **$314M**	6	SIG DIFF **$555M**	Roadmap + Ultimate survey

Analysis of Weighted Score

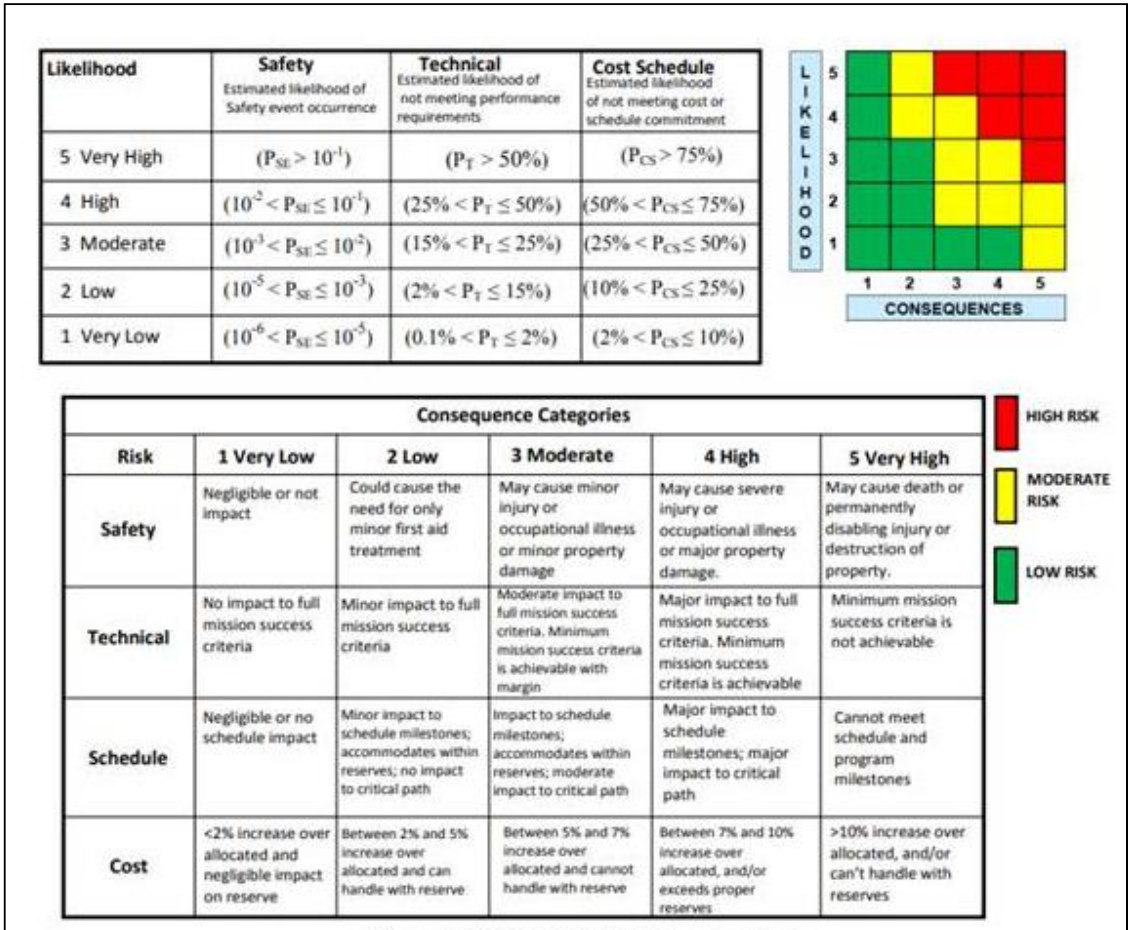


WANTS	Key	Drvg	Weight	I Jenn	II Andrew	IV Andy	V Chas	VI Peter	VIII BJ
				Score	Score	Score	Score	Score	Score
Relative Science			37	254	294	370 BEST	310	245	370 BEST
Relative Schedule WASH			17	170	160	150	165	170	165
Relative Difficulty			20	150	190 BEST	160	150	125	195 BEST
Relative Cost			16	160 BEST	64	32	160 BEST	160 BEST	96
Other Factors WASH			10	97	92	80	94	85	90
Total				831	800	792	879	785	916
Ranking by Points				3	4	4	2	4	1

Risk Analysis – Kepner Tregoe

Risks identified during the Working Group evaluation of Musts and Wants.

Risks are not weighted, rather, they are looked at holistically to see if the preferred option priorities change



Likelihood	**Safety** Estimated likelihood of Safety event occurrence	**Technical** Estimated likelihood of not meeting performance requirements	**Cost Schedule** Estimated likelihood of not meeting cost or schedule commitment
5 Very High	$(P_{SE} > 10^{-1})$	$(P_T > 50\%)$	$(P_{CS} > 75\%)$
4 High	$(10^{-2} < P_{SE} \leq 10^{-1})$	$(25\% < P_T \leq 50\%)$	$(50\% < P_{CS} \leq 75\%)$
3 Moderate	$(10^{-3} < P_{SE} \leq 10^{-2})$	$(15\% < P_T \leq 25\%)$	$(25\% < P_{CS} \leq 50\%)$
2 Low	$(10^{-5} < P_{SE} \leq 10^{-3})$	$(2\% < P_T \leq 15\%)$	$(10\% < P_{CS} \leq 25\%)$
1 Very Low	$(10^{-6} < P_{SE} \leq 10^{-5})$	$(0.1\% < P_T \leq 2\%)$	$(2\% < P_{CS} \leq 10\%)$

LIKELIHOOD	1	2	3	4	5
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩	🟨	🟨	🟥
2	🟩	🟩	🟨	🟨	🟨
1	🟩	🟩	🟩	🟩	🟨

CONSEQUENCES

Consequence Categories

Risk	1 Very Low	2 Low	3 Moderate	4 High	5 Very High
Safety	Negligible or not impact	Could cause the need for only minor first aid treatment	May cause minor injury or occupational illness or minor property damage	May cause severe injury or occupational illness or major property damage.	May cause death or permanently disabling injury or destruction of property.
Technical	No impact to full mission success criteria	Minor impact to full mission success criteria	Moderate impact to full mission success criteria. Minimum mission success criteria is achievable with margin	Major impact to full mission success criteria. Minimum mission success criteria is achievable	Minimum mission success criteria is not achievable
Schedule	Negligible or no schedule impact	Minor impact to schedule milestones; accommodates within reserves; no impact to critical path	Impact to schedule milestones; accommodates within reserves; moderate impact to critical path	Major impact to schedule milestones; major impact to critical path	Cannot meet schedule and program milestones
Cost	<2% increase over allocated and negligible impact on reserve	Between 2% and 5% increase over allocated and can handle with reserve	Between 5% and 7% increase over allocated and cannot handle with reserve	Between 7% and 10% increase over allocated, and/or exceeds proper reserves	>10% increase over allocated, and/or can't handle with reserves

🟥 HIGH RISK

🟨 MODERATE RISK

🟩 LOW RISK

Figure 3, GSFC Risk Matrix Standard Scale

Risk Analysis

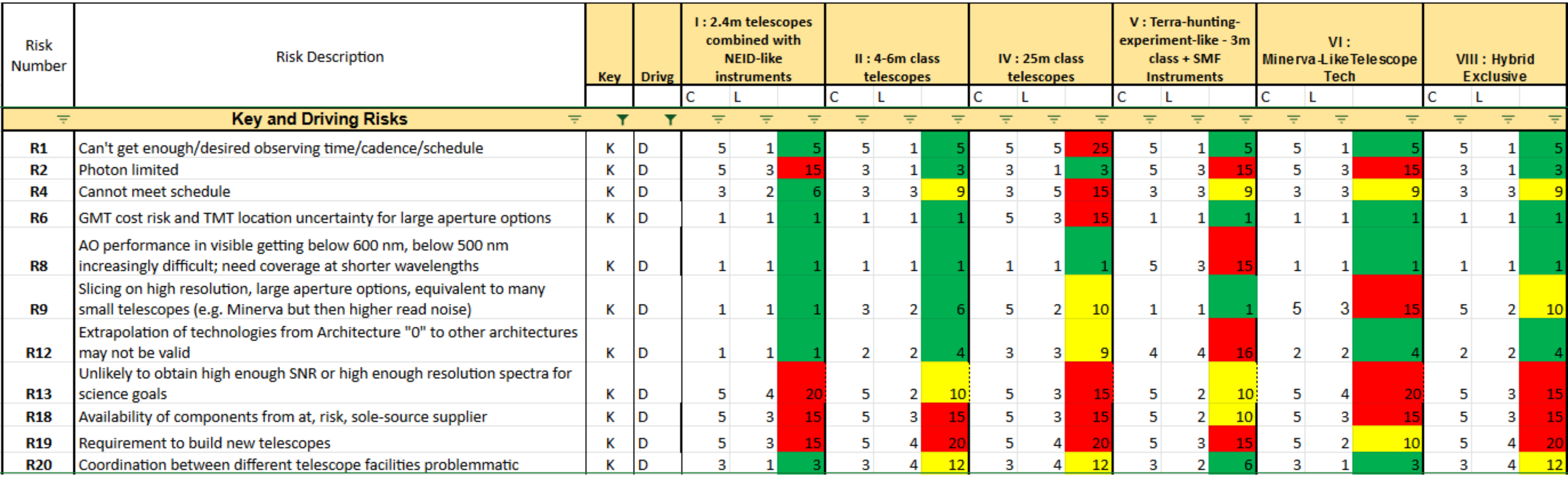
Risks can reorder priority of options. Risks prioritize future work.

Risk Number	Risk Description	0 : New funds requested using existing assets and organizations			I : 2.4m telescopes combined with NEID-like instruments			II : 4-6m class telescopes			IV : 25m class telescopes			V : Terra-hunting-experiment-like - 3m class + SMF Instruments			VI : Minerva-LikeTelescope Tech			VIII : Hybrid Exclusive		
		C	L		C	L		C	L		C	L		C	L		C	L		C	L	
	Key and Driving Risks																					
R1	Can't get enough/desired observing time/cadence/schedule	5	5	25	5	1	5	5	1	5	5	5	25	5	1	5	5	1	5	5	1	5
R2	Photon limited				5	3	15	3	1	3	3	1	3	5	3	15	5	3	15	3	1	3
R3	Luvoir/HabEx not selected	2	2	4	4	2	8	4	2	8	2	2	4	2	2	4	4	2	8	4	2	8
R4	Cannot meet schedule				3	2	6	3	3	9	3	5	15	3	3	9	3	3	9	3	3	9
R5	Upgrading/repurposing of existing facilities results in more work time, challenges to implementation	2	3	6	3	4	12	3	4	12	3	4	12	3	4	12	1	1	1	3	4	12
R6	GMT cost risk and TMT location uncertainty for large aperture options	1	1	1	1	1	1	1	1	1	5	3	15	1	1	1	1	1	1	1	1	1
R7	Non-robotic operations of telescopes impacts cost, staffing, uniformity	1	5	5	3	3	9	4	3	12	4	3	12	4	3	12	5	1	5	4	3	12
R8	AO performance in visible getting below 600 nm, below 500 nm increasingly difficult; need coverage at shorter wavelengths	1	1	1	1	1	1	1	1	1	1	1	1	5	3	15	1	1	1	1	1	1
R9	Slicing on high resolution, large aperture options, equivalent to many small telescopes (e.g. Minerva but then higher read noise)	1	1	1	1	1	1	3	2	6	5	2	10	1	1	1	5	3	15	5	2	10
R10	Long integration times and imperfect characterization of system throughput --> barycentric correction challenge				1	**1**	1	1	1	1	1	1	1	3	2	6	1	1	1	1	1	1
R11	Requires new technology not demonstrated in allocated time frame	1	1	1	1	1	1	1	1	1	4	2	8	4	3	12	1	1	1	1	1	1
R12	Extrapolation of technologies from Architecture "0" to other architectures may not be valid	1	1	1	1	1	1	2	2	4	3	3	9	4	4	16	2	2	4	2	2	4
R13	Unlikely to obtain high enough SNR or high enough resolution spectra for science goals				5	4	20	5	2	10	5	3	15	5	2	10	5	4	20	5	3	15
R14	Unrealistic system efficiency estimation compared to what was submitted				4	2	8	4	3	12	4	3	12	4	3	12	4	3	12	4	3	12
R15	Telluric correction in NIR is much worse (> ~900 nm)				1	1	1	1	1	1	2	3	6	3	3	9	1	1	1	1	1	1
R16	Lack of broad spectral coverage impacts stellar variability mitigation				3	1	3	4	1	4	3	1	3	4	2	8	3	1	3	4	1	4
R17	Lessons learned have to be applied to architecture for success				2	1	2	2	1	2	3	2	6	4	3	12	4	3	12	3	3	9
R18	Availability of components from at, risk, sole-source supplier				5	3	15	5	3	15	5	3	15	5	2	10	5	3	15	5	3	15
R19	Requirement to build new telescopes				5	3	15	5	4	20	5	4	20	5	3	15	5	2	10	5	4	20
R20	Coordination between different telescope facilities problemmatic				3	1	3	3	4	12	3	4	12	3	2	6	3	1	3	3	4	12
	Project Risks Common to All Architectures																					
R21	Sun's variability is not representative of target stars in list/stellar variability cannot be adequately subtracted	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15
R22	Telluric line contamination cannot be adequately mitigated	4	2	8	4	2	8	4	2	8	4	2	8	4	3	12	4	2	8	4	2	8
R23	Not enough staffing to execute program	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15	5	3	15
R24	DIfficulty in funding non-US participants				5	5	25	5	5	25	5	5	25	5	5	25	5	5	25	5	5	25
R25	Knowledge retention in the field				5	5	25	5	5	25	5	5	25	5	5	25	5	5	25	5	5	25
Sum							216			227			292			282			230			243

Key and Driving Risks

Key: at least one Red.

Driving: Differences in ratings across the row (not a wash)



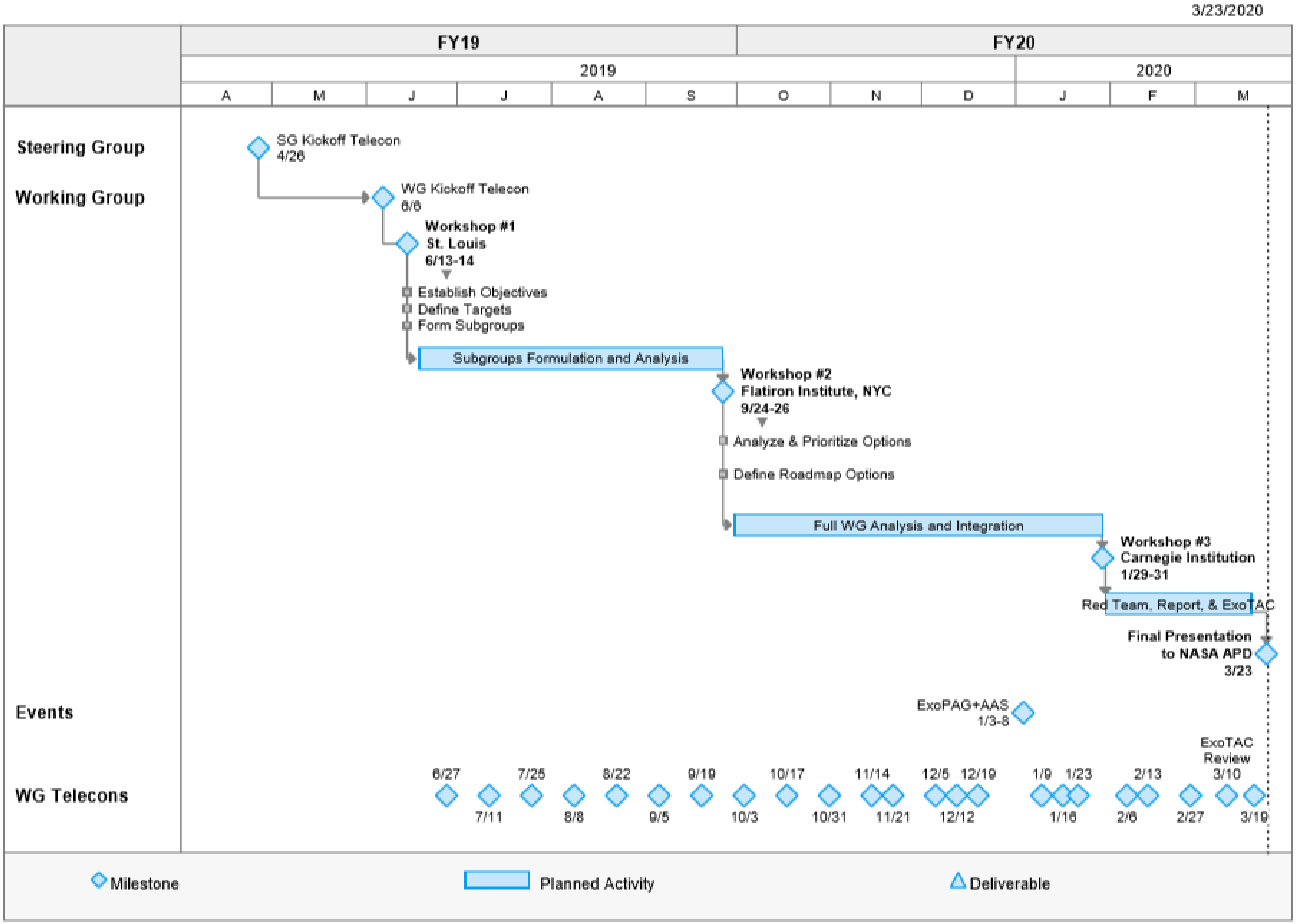
Risk Number	Risk Description	Key	Drivg	I : 2.4m telescopes combined with NEID-like instruments			II : 4-6m class telescopes			IV : 25m class telescopes			V : Terra-hunting-experiment-like - 3m class + SMF Instruments			VI : Minerva-Like Telescope Tech			VIII : Hybrid Exclusive		
				C	L		C	L		C	L		C	L		C	L		C	L	
	Key and Driving Risks																				
R1	Can't get enough/desired observing time/cadence/schedule	K	D	5	1	5	5	1	5	5	5	25	5	1	5	5	1	5	5	1	5
R2	Photon limited	K	D	5	3	15	3	1	3	3	1	3	5	3	15	5	3	15	3	1	3
R4	Cannot meet schedule	K	D	3	2	6	3	3	9	3	5	15	3	3	9	3	3	9	3	3	9
R6	GMT cost risk and TMT location uncertainty for large aperture options	K	D	1	1	1	1	1	1	5	3	15	1	1	1	1	1	1	1	1	1
R8	AO performance in visible getting below 600 nm, below 500 nm increasingly difficult; need coverage at shorter wavelengths	K	D	1	1	1	1	1	1	1	1	1	5	3	15	1	1	1	1	1	1
R9	Slicing on high resolution, large aperture options, equivalent to many small telescopes (e.g. Minerva but then higher read noise)	K	D	1	1	1	3	2	6	5	2	10	1	1	1	5	3	15	5	2	10
R12	Extrapolation of technologies from Architecture "0" to other architectures may not be valid	K	D	1	1	1	2	2	4	3	3	9	4	4	16	2	2	4	2	2	4
R13	Unlikely to obtain high enough SNR or high enough resolution spectra for science goals	K	D	5	4	20	5	2	10	5	3	15	5	2	10	5	4	20	5	3	15
R18	Availability of components from at, risk, sole-source supplier	K	D	5	3	15	5	3	15	5	3	15	5	2	10	5	3	15	5	3	15
R19	Requirement to build new telescopes	K	D	5	3	15	5	4	20	5	4	20	5	3	15	5	2	10	5	4	20
R20	Coordination between different telescope facilities problemmatic	K	D	3	1	3	3	4	12	3	4	12	3	2	6	3	1	3	3	4	12

Final Ranking, Accounting for Risks

		Key	Drvg	Weight	I Jenn		II Andrew		IV Andy		V Chas		VI Peter		VIII BJ		
WANTS					*Score*		*Score*		*Score*		*Score*		*Score*		*Score*		
	Relative Science			**37**	**254**		**294**		**370**		**310**		**245**		**370**		
W1	Survey as many 'yellow' stars as possible on Eric's evolving target list.	K	D	9	6	SIG DIFF	6	SIG DIFF	10	**BEST**	6	SIG DIFF	5	SIG DIFF	10	**BEST**	More glass and red optical is positive
W2	Measure masses of temperate terrestrial planets orbiting M stars, not in Eric's yellow list		D	4	6	SIG DIFF	8	small difference	10	**BEST**	10	**BEST**	6	SIG DIFF	10	**BEST**	More glass and red optical is positive
W3	Use follow-up of transiting temperate terrestrial planets to inform the mass-radius relation from key transit discoveries	K	D	8	6	SIG DIFF	8	small difference	10	**BEST**	9	small difference	6	SIG DIFF	10	**BEST**	Dissent recorded on W3
W4	Validate methods of stellar variability mitigation, telluric mitigation, and statistical validation, key for the EPRV method, including using follow-up of transiting planets	K	D	16	*8*	small difference	9	small difference	10	**BEST**	9	small difference	8	small difference	10	**BEST**	8 had sig diff on account of the testbed 7 adopted all of the bonuses 6 was strong because of roadmap activity 4,8 were strong because of the glass Talk to PLATO work package involved w/ ground based follow up to ask about their forward plan on steller variability, tellurics etc
	Relative Schedule			**17**	**170**		**160**		**150**		**165**		**170**		**165**		
W5	**Schedule**: Start the precursor M1a surveys **as soon as possible**, so as to maximize impact at PDR on design of direct imaging missions (e.g. HabEx, LUVOIR)	K		12	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	Auxillary and precourser ASAP After precourser surveys (ESPRESSO, NEID) we will assess whether we are ready to go ahead with architecture or if we need more R&A Etc
W6	**Schedule:** Start the Dream Survey as soon as possible, so as to maximize impact at PDR on design of direct imaging missions (e.g. HabEx, LUVOIR)		D	5	10	**BEST**	8	small difference	6	SIG DIFF	9	small difference	10	**BEST**	9	small difference	2032 option 1- high risk
	Relative Difficulty			**20**	**150**		**190**		**160**		**150**		**125**		**195**		Revisit for final report
W7	Prefer the architecture with the greatest relative probability of success to meet stellar variability requirement	K	D	10	6	SIG DIFF	10	**BEST**	10	**BEST**	8	small difference	6	SIG DIFF	**10**	**BEST**	Cadence, resolution, and photons were important
W8	Relative difficulty to secure required telescopes/instruments, fraction of time, and observing cadence and coordination between telescopes		D	5	10	**BEST**	8	SIG DIFF	2	**VL DIFF**	6	SIG DIFF	8	small difference	9	SIG DIFF	An agency will need to build and operate the telescopes Reuse: II (two 4m), V (three 2-3m), VIII (two 4m)
W9	Prefer the architecture the greatest probability of success of achieving the survey referenced in M1b		D	5	8	small difference	10	**BEST**	10	**BEST**	8	small difference	5	SIG DIFF	10	**BEST**	Collecting the right photons and having the instrument meet spec
	Relative Cost			**16**	**160**		**64**		**32**		**160**		**160**		**96**		Estimates for roadmap are equally included but not yet the full amount
W10	Least estimated cost	K	D	16	10	**BEST** **$325M**	4	**SIG/VL** **$663M**	2	**VL DIFF** **$755M**	10	**BEST** **$298M**	10	**BEST** **$314M**	6	SIG DIFF **$555M**	Roadmap + Ultimate survey
	Other Factors			**10**	**97**		**92**		**80**		**94**		**85**		**90**		
W11	Take advantage of opportunities for international collaboration and draw from as broad of a pool of relevant expertise and observing facilities as possible			2	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	
W12	Maximize use of, and knowledge and understanding of, existing facilities (observatories), infrastructure, and hardware (including detectors)			3	9	small difference	8	small difference	5	SIG DIFF	8	small difference	5	SIG DIFF	8	small difference	
W13	Maximize broader impacts in society			1	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	
W14	Encourage free exchange of ideas, including data and source codes			2	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	
W15	Implement as a coordinated and distributed program		D	1	10	**BEST**	8	small difference	5	SIG DIFF	10	**BEST**	10	**BEST**	6	SIG DIFF	
W16	Encourage collaboration between the subdisciplines in stellar astrophysics, heliophysics, instrumentation, statistics and earth sciences (mitigating tellurics)			1	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	10	***WASH***	
	Subtotal			100													
	Total				**831**		**800**		**792**		**879**		**785**		**916**		
	Ranking by Points				**3**		**4**		**4**		**2**		**4**		**1**		
	Rank Accounting for Risks				2		2		5		3		4		1		

WORKING GROUP CHARTS

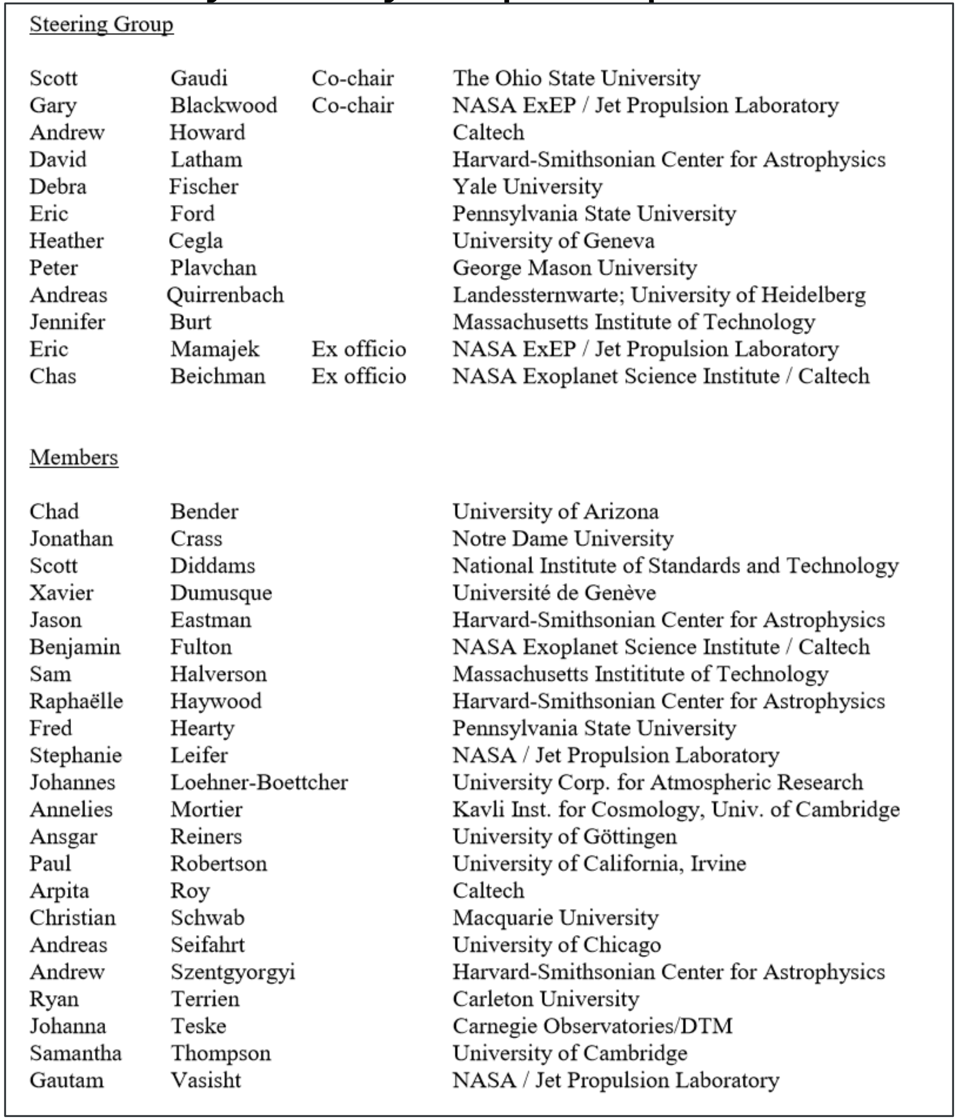
Working Group Schedule



"This document has been reviewed and determined not to contain export controlled technical data. Clearance #20-1588"

Named in ToR

Thank you for your participation!

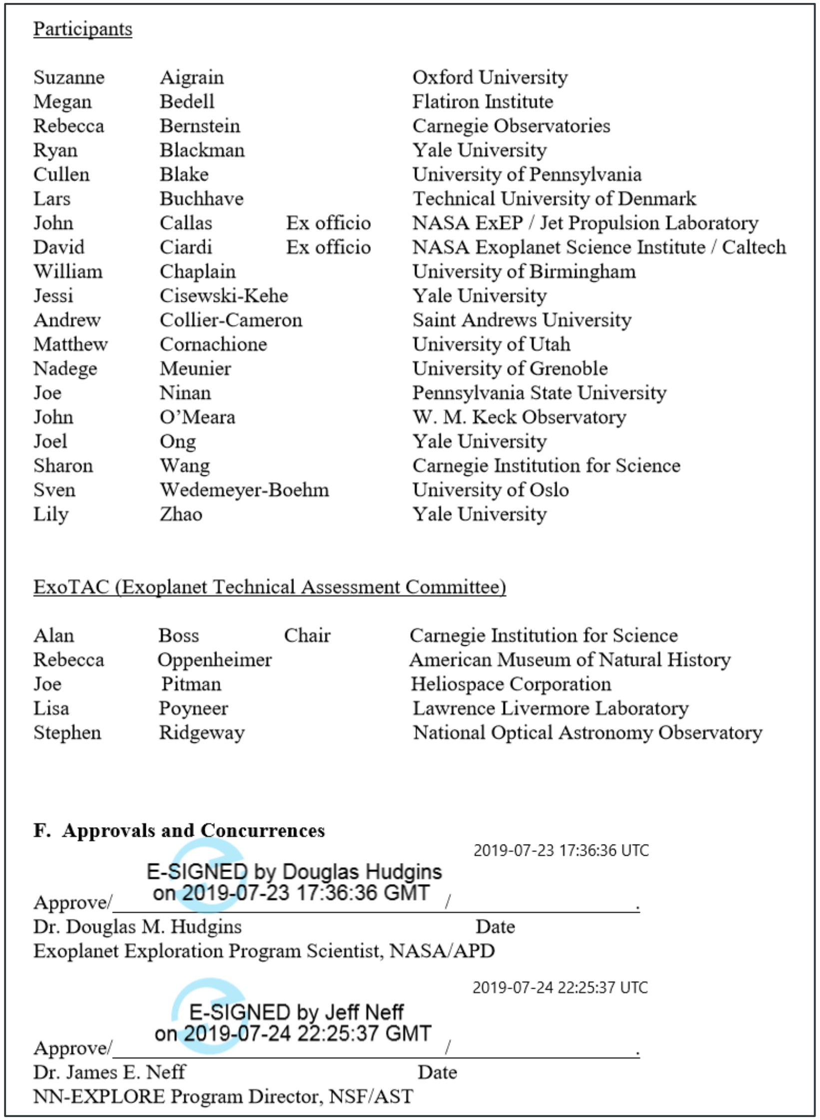


Steering Group

Scott	Gaudi	Co-chair	The Ohio State University
Gary	Blackwood	Co-chair	NASA ExEP / Jet Propulsion Laboratory
Andrew	Howard		Caltech
David	Latham		Harvard-Smithsonian Center for Astrophysics
Debra	Fischer		Yale University
Eric	Ford		Pennsylvania State University
Heather	Cegla		University of Geneva
Peter	Plavchan		George Mason University
Andreas	Quirrenbach		Landessternwarte; University of Heidelberg
Jennifer	Burt		Massachusetts Institute of Technology
Eric	Mamajek	Ex officio	NASA ExEP / Jet Propulsion Laboratory
Chas	Beichman	Ex officio	NASA Exoplanet Science Institute / Caltech

Members

Chad	Bender	University of Arizona
Jonathan	Crass	Notre Dame University
Scott	Diddams	National Institute of Standards and Technology
Xavier	Dumusque	Université de Genève
Jason	Eastman	Harvard-Smithsonian Center for Astrophysics
Benjamin	Fulton	NASA Exoplanet Science Institute / Caltech
Sam	Halverson	Massachusetts Instititute of Technology
Raphaëlle	Haywood	Harvard-Smithsonian Center for Astrophysics
Fred	Hearty	Pennsylvania State University
Stephanie	Leifer	NASA / Jet Propulsion Laboratory
Johannes	Loehner-Boettcher	University Corp. for Atmospheric Research
Annelies	Mortier	Kavli Inst. for Cosmology, Univ. of Cambridge
Ansgar	Reiners	University of Göttingen
Paul	Robertson	University of California, Irvine
Arpita	Roy	Caltech
Christian	Schwab	Macquarie University
Andreas	Seifahrt	University of Chicago
Andrew	Szentgyorgyi	Harvard-Smithsonian Center for Astrophysics
Ryan	Terrien	Carleton University
Johanna	Teske	Carnegie Observatories/DTM
Samantha	Thompson	University of Cambridge
Gautam	Vasisht	NASA / Jet Propulsion Laboratory



Participants

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Megan	Bedell		Flatiron Institute
Rebecca	Bernstein		Carnegie Observatories
Ryan	Blackman		Yale University
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Joel	Ong		Yale University
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Sven	Wedemeyer-Boehm		University of Oslo
Lily	Zhao		Yale University

ExoTAC (Exoplanet Technical Assessment Committee)

Alan	Boss	Chair	Carnegie Institution for Science
Rebecca	Oppenheimer		American Museum of Natural History
Joe	Pitman		Heliospace Corporation
Lisa	Poyneer		Lawrence Livermore Laboratory
Stephen	Ridgeway		National Optical Astronomy Observatory

F. Approvals and Concurrences

2019-07-23 17:36:36 UTC

Approve/ E-SIGNED by Douglas Hudgins on 2019-07-23 17:36:36 GMT /.
Dr. Douglas M. Hudgins Date
Exoplanet Exploration Program Scientist, NASA/APD

2019-07-24 22:25:37 UTC

Approve/ E-SIGNED by Jeff Neff on 2019-07-24 22:25:37 GMT /.
Dr. James E. Neff Date
NN-EXPLORE Program Director, NSF/AST

Recognize: Additional Involvement

Red Team				
	Jacob	Bean	U. Chicago	
	Steve	Howell	NASA/Ames	
	Michael	McElwain	NASA/GSFC	
	Josh	Winn	Princeton	**unavailable**
Stakeholders				
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	Douglas	Hudgins	NASA HQ	
	James	Neff	NSF	
	Richard	Green	NSF	
ExoTAC				
	Alan	Boss	Carnegie Institution of Science	
	Rebecca	Oppenheimer	AMNH	
Mailing List				
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	Mercedes	Lopez-Morales	Harvard-Smithsonian CfA	
	H. Philip	Stahl	NASA/MSFC	
ex officio	Karl	Stapelfeldt	NASA ExEP / JPL	
ex officio	Martin	Still	NASA HQ	**NSF**
	Mathias	Zechmeister	University of Göttingen	

Jet Propulsion Laboratory
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