An Update on the Extreme Precision Radial Velocity Initiative for the Exoplanet Program Analysis Group Meeting 22

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on behalf of NASA's Exoplanet Exploration Program

and

the EPRV Working Group

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Outline

- Motivation for EPRV - *Scott Gaudi*
- Current State of the Art – *Jenn Burt*
- Methodology – *Jenn Burt*
- Architecture Simulations - *Jenn Burt*
- Proposed Research Program – *Jenn Burt*

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 $\gtrsim$\$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.

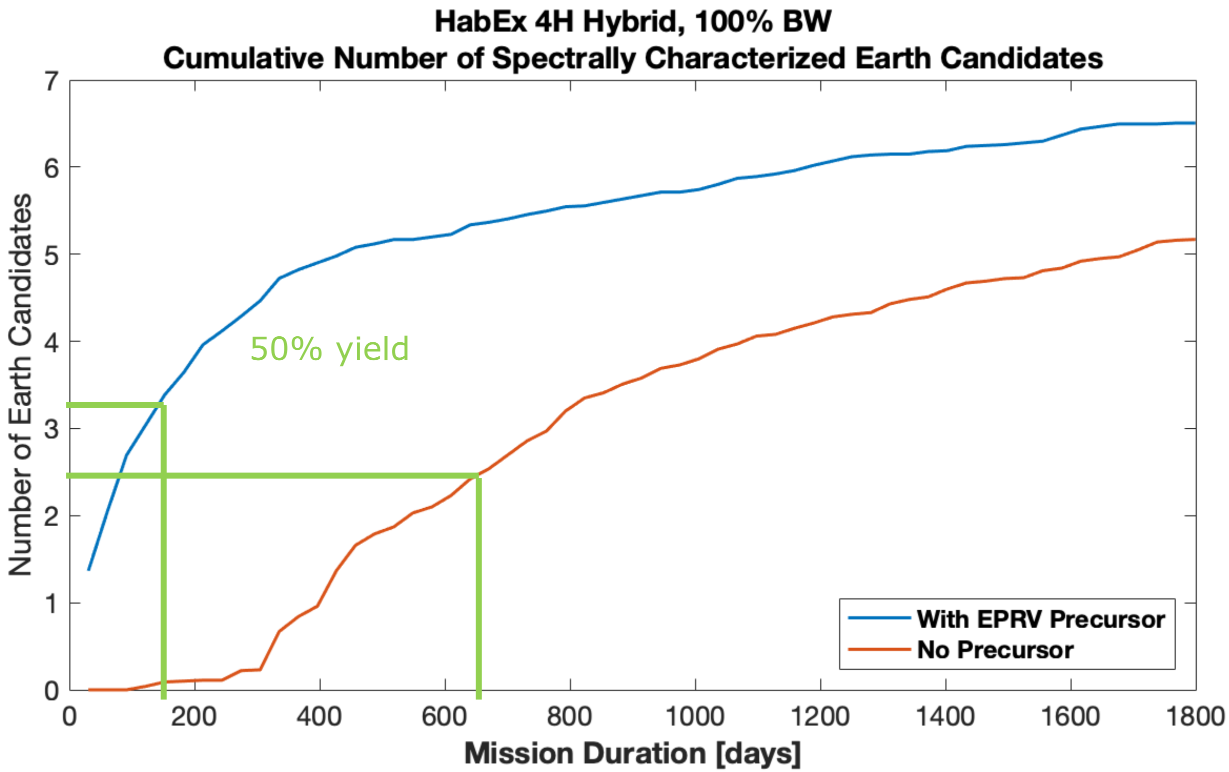
[1]As well as the masses of rocky terrestrial transiting planets.

[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, can also improve the yield of characterized planets.

EPRV Accelerates the Yield

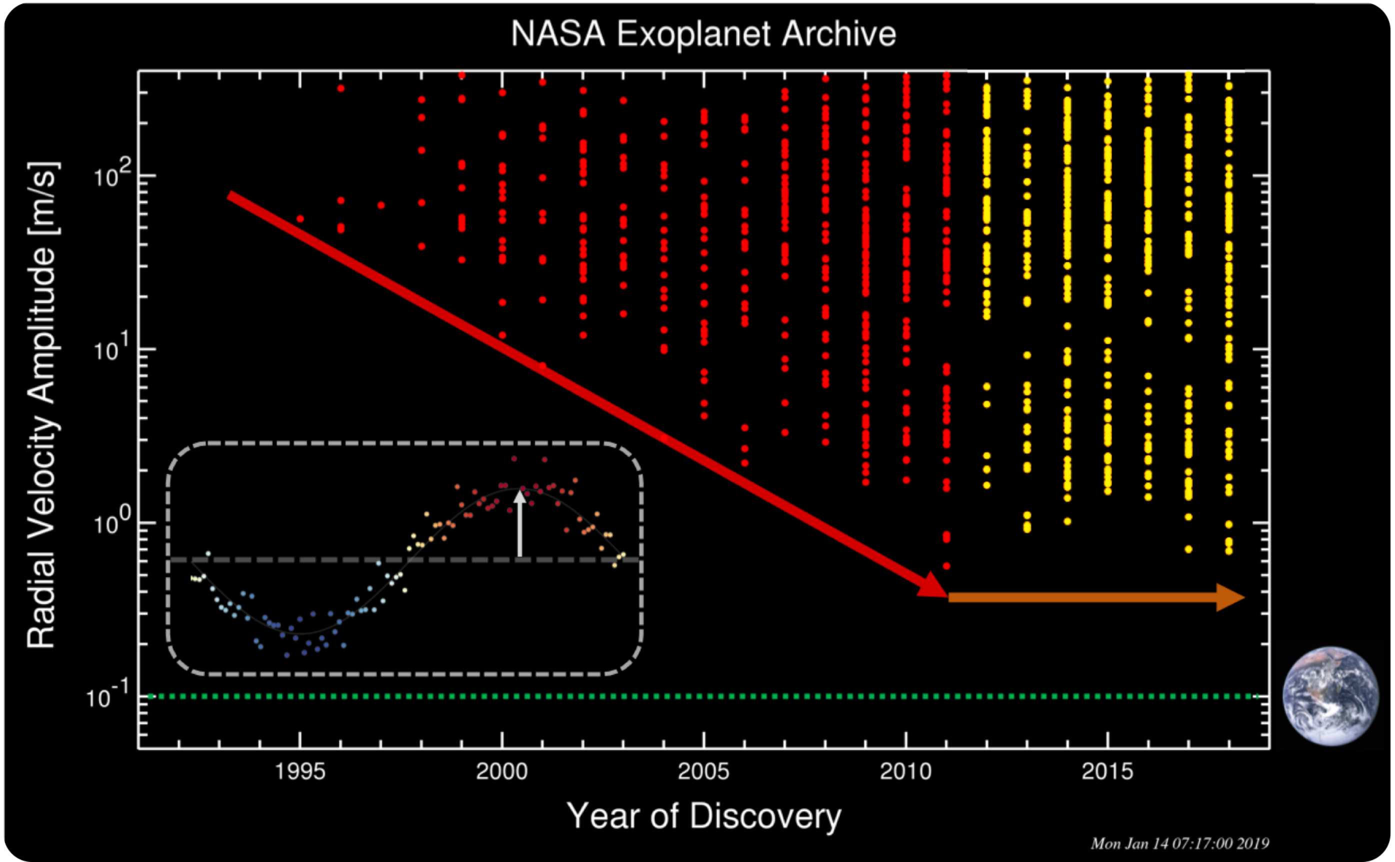


Preliminary Results from ExoSIMs: R. Morgan

- 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.



Improving the Precision of Radial Velocity Measurements Will Support Exoplanet Missions

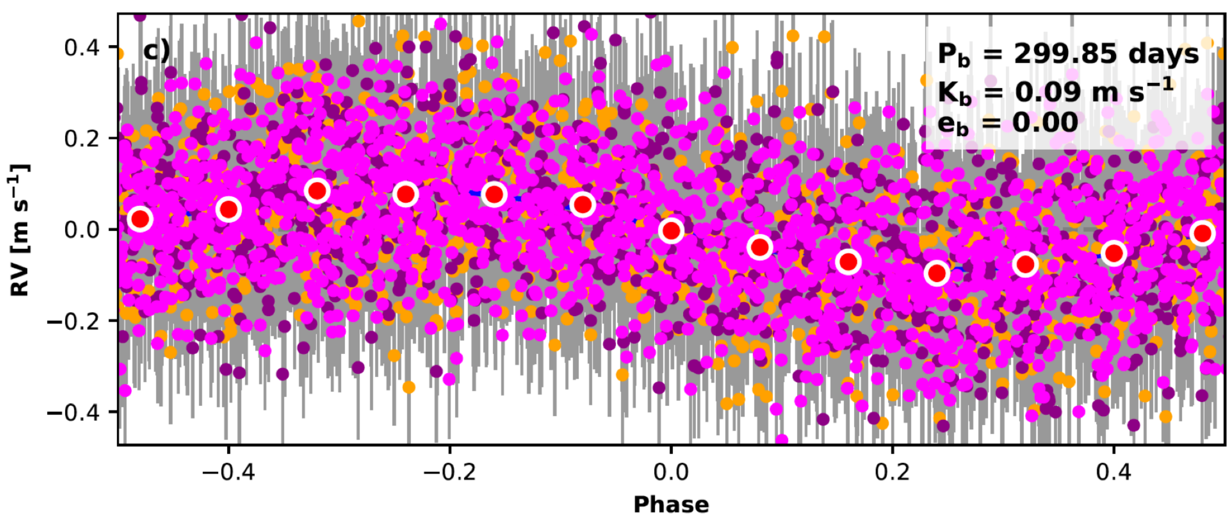
FINDING: The radial velocity method will continue to provide essential mass, orbit, and census information to support both transiting and directly imaged exoplanet science for the foreseeable future.

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**.

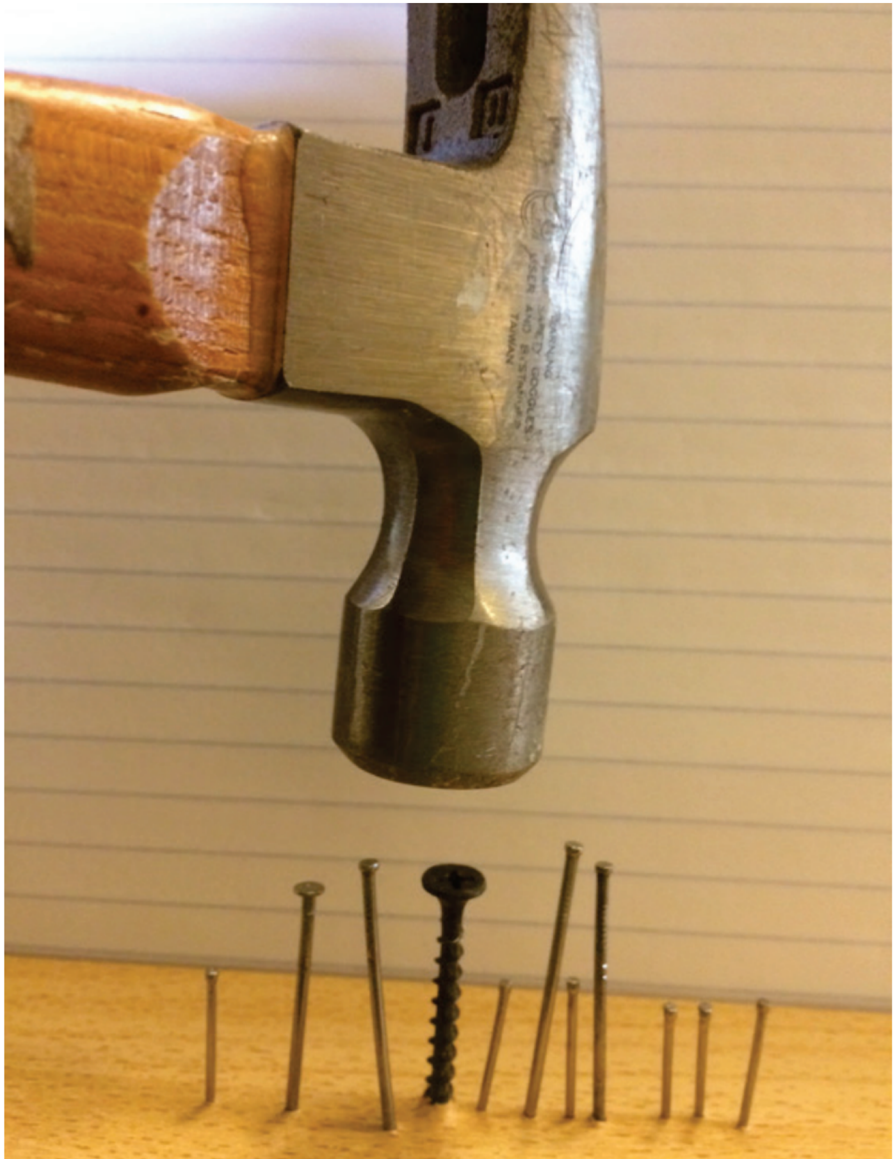


Courtesy of
Patrick Newman and
Peter Plavchan (GMU)

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.

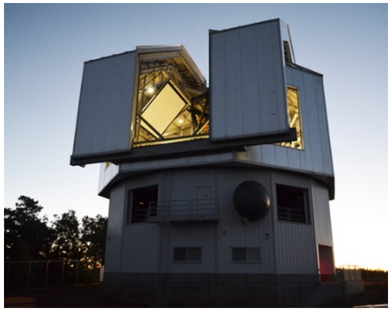
It is probably true that the challenge in going below 10 cm/s (which we have not yet reached) will be the number of unanticipated terms in the error budget and we will need new tools to address them.

Current State of the Art

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

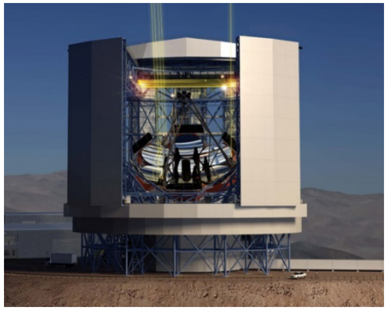
2.5-m INT/HARPS3*
50% time, solar calibrator (TBD)

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

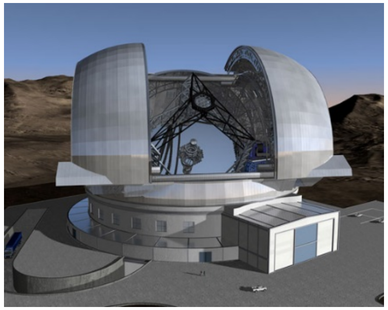
30-m TMT/MOHDIS
(mid to late-2020s)

Southern Hemisphere

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



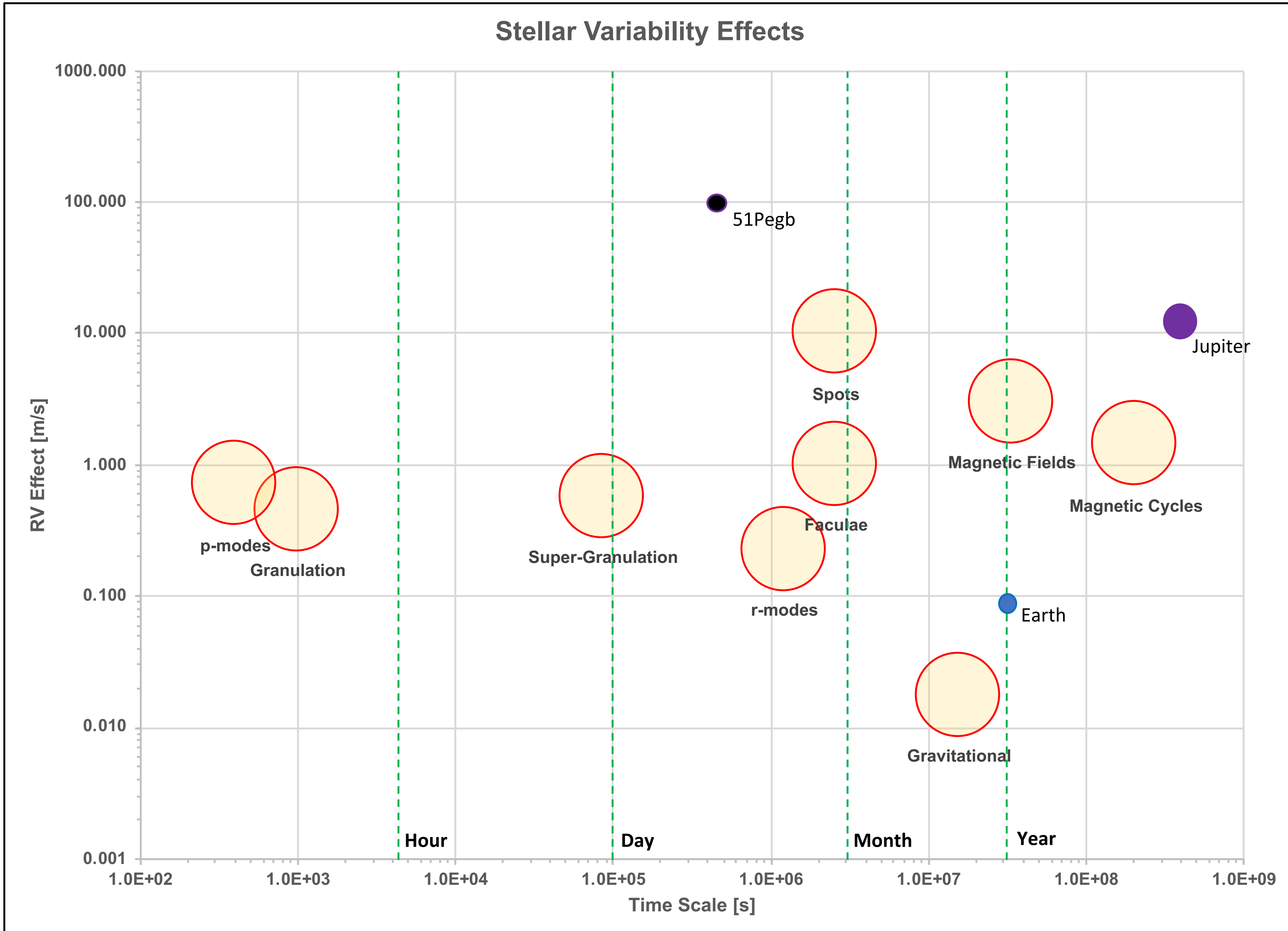
6x8-m GMT/G-CLEF
(late-2020s)



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

*HARPS Heritage

Stellar Variability



EPRV Working Group Methodology

Methodology

- Established Terms of Reference: membership, ground rules
  – 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)

EPRV Sub-Groups

<u>Science Mission Drivers</u>
Leads: Howard & Bender

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

<u>Survey Strategy</u>
Leads: Burt & Teske

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

<u>Instrument Performance Evaluation</u>
Lead: Halverson

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

<u>Pipelines, Analysis & Statistical Inference</u>
Leads: Roy & Ford

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

<u>Instrumentation & Calibration</u>
Leads: Leifer & Szentgyorgyi

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

<u>Realistic Resource Evaluation</u>
Leads: Quirrenbach & Diddams

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

<u>Intrinsic Stellar Variability</u>
Leads: Cegla & Haywood

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

<u>Telluric Mitigation Strategies</u>
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 accompanying R&D focus areas 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

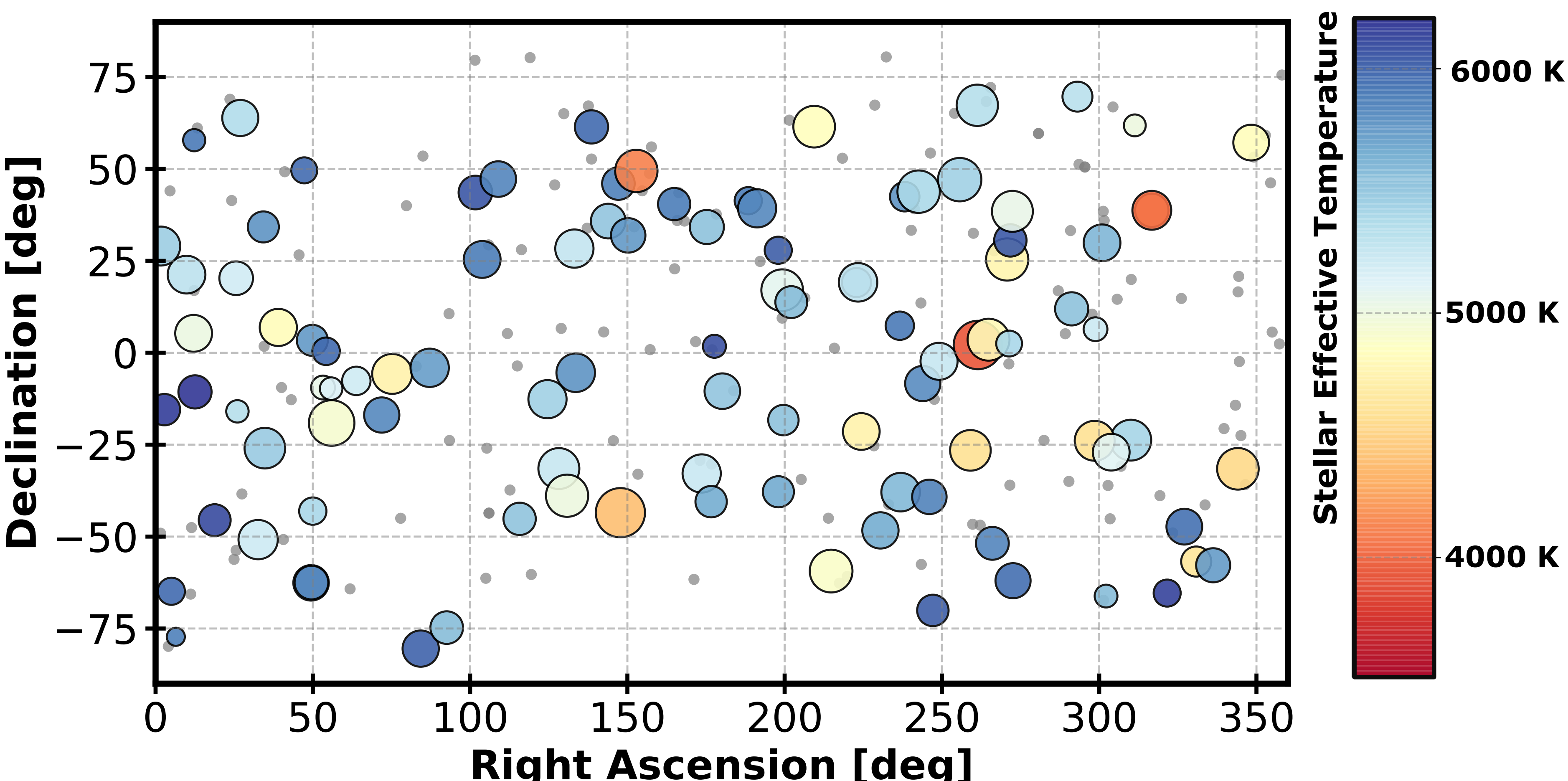
- Observing architectures were developed to meet these Musts.

- 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

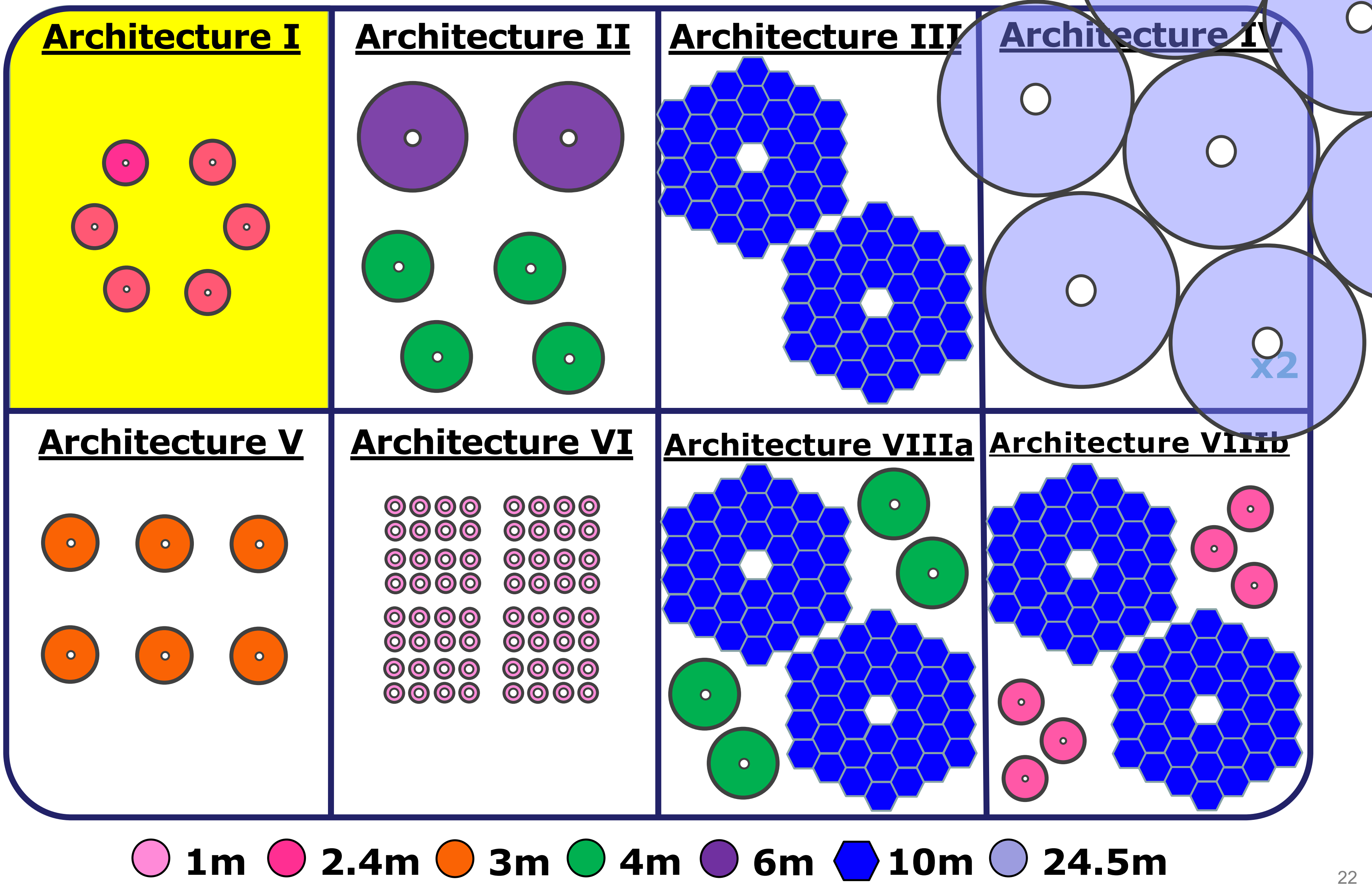
Proposed Architectures

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

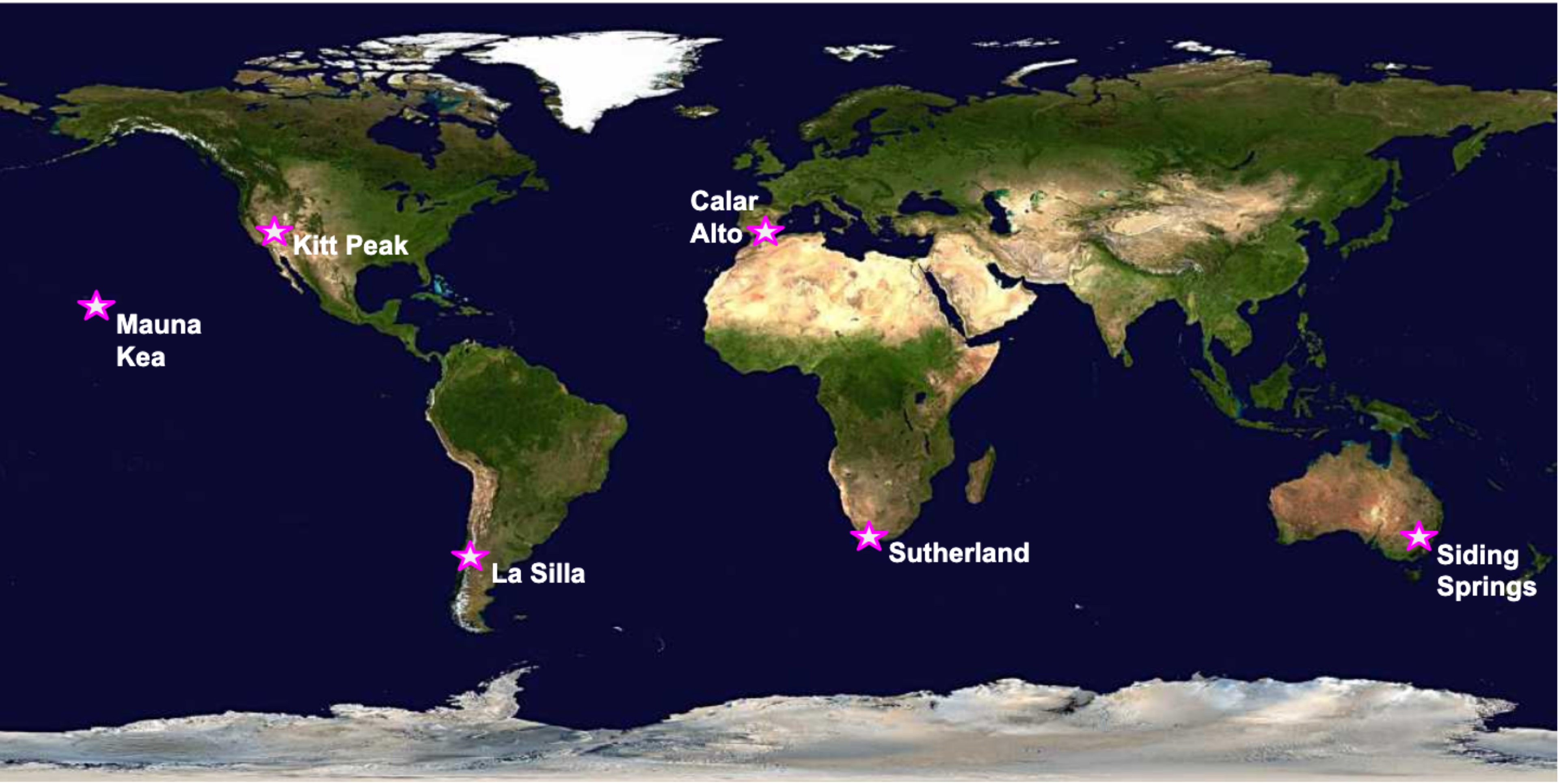


Basis set of notional apertures for EPRV survey

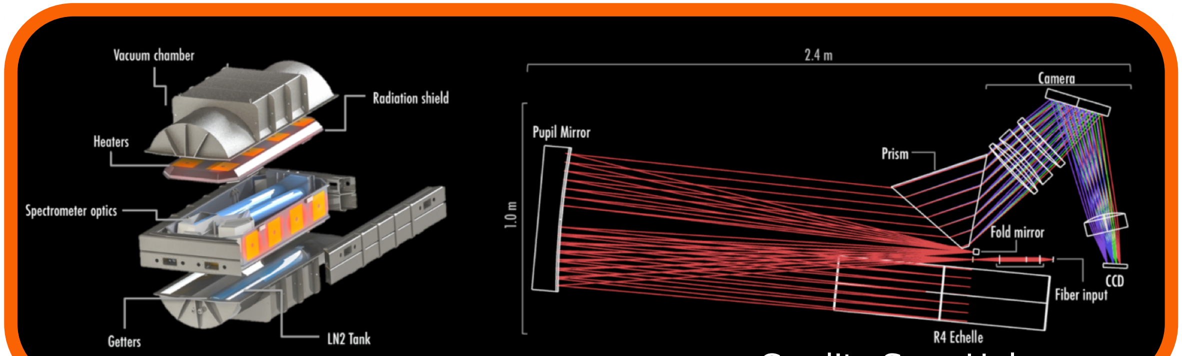


Architecture I: Six Identical Facilities

spread across longitude and latitude



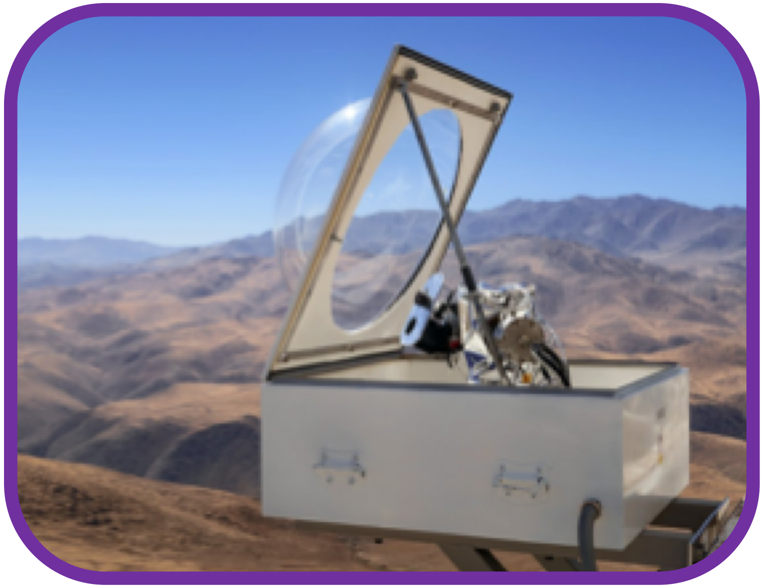
Each facility contains: 2.4m telescope, next generation EPRV spectrograph, and solar telescope



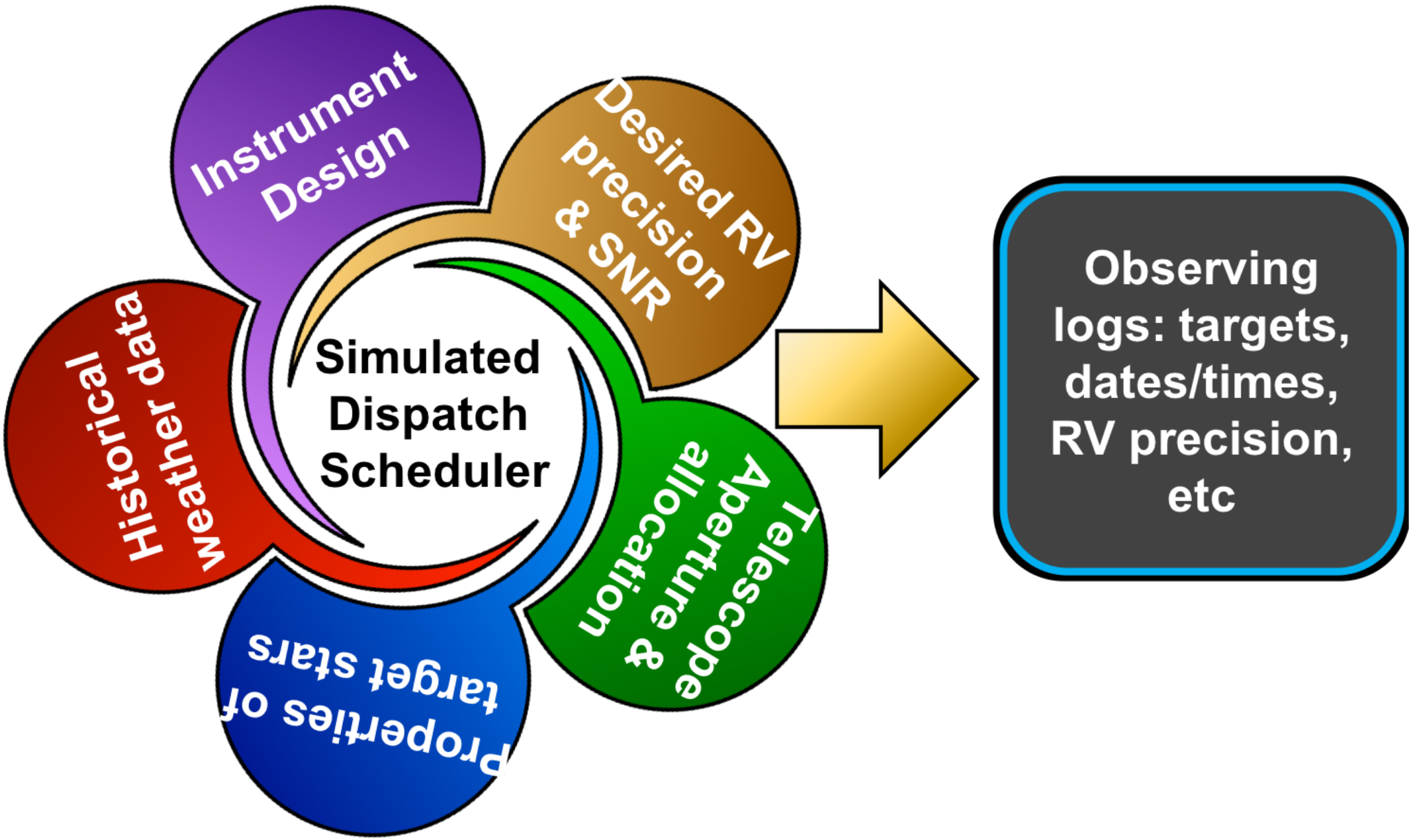
Credit: Sam Halverson

Instrument/Observing Details

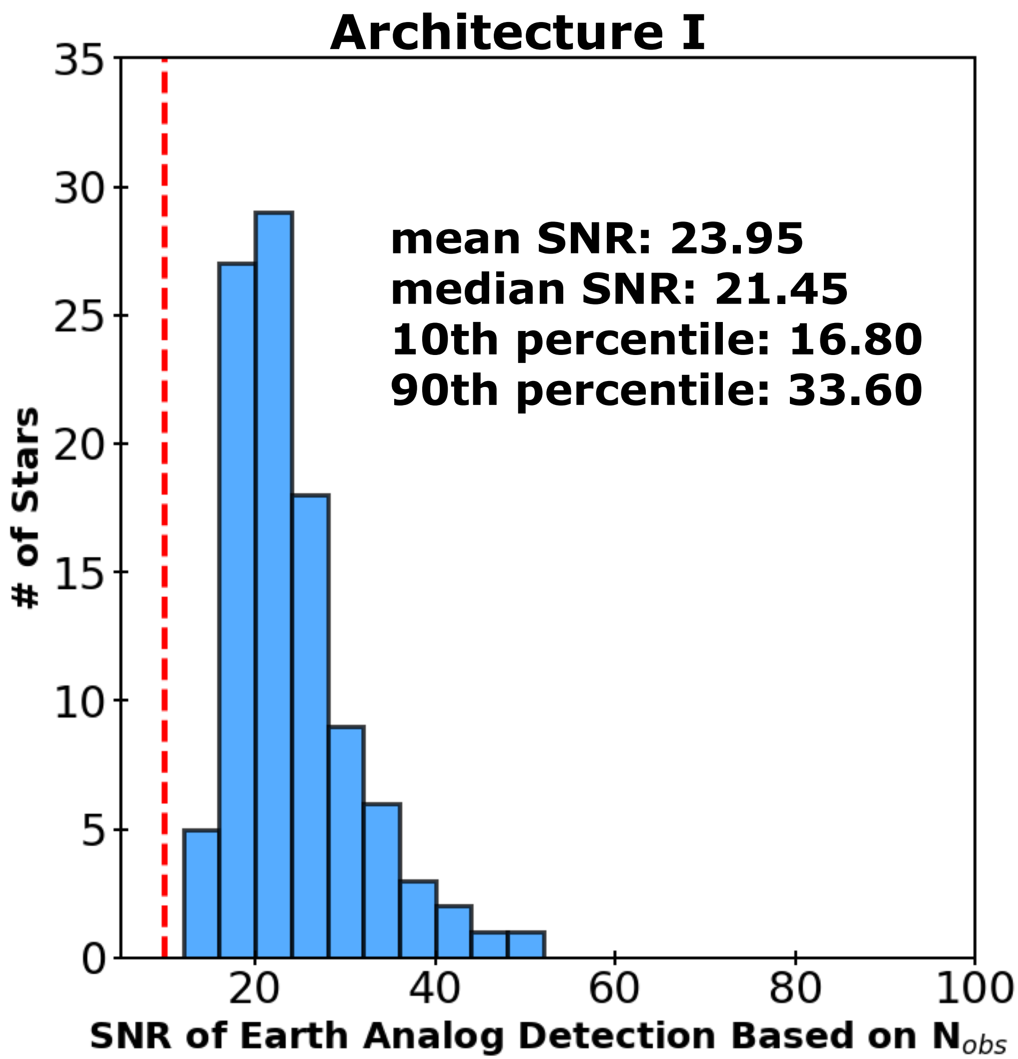
Wavelength coverage : 380-930nm
Spectral resolution : 150,000
Total system efficiency : 7%
Instrumental noise floor : 10 cm/s
Telescope allocation : 100%



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



Success metric : Earth analog detection significance



If there were an Earth analog around each star

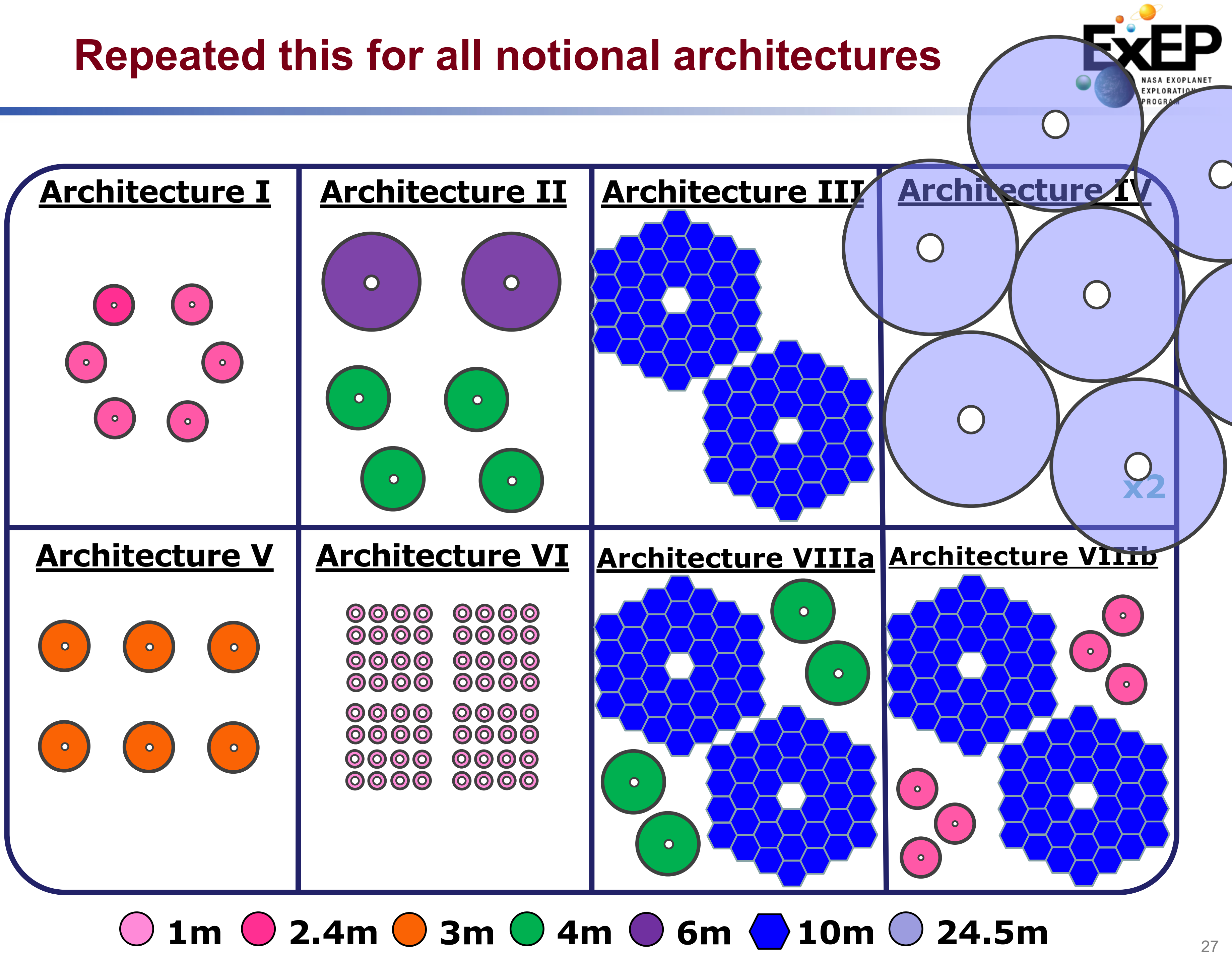
and

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?

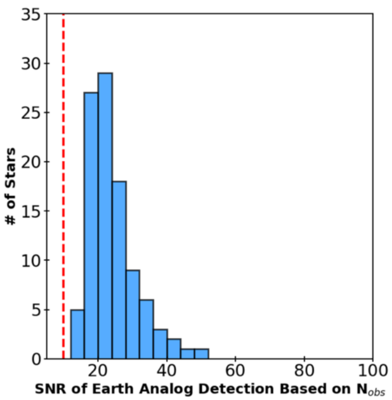
Repeated this for all notional architectures



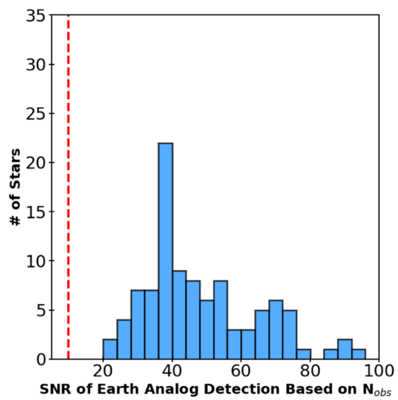
Earth analog detection significance by architecture

ExEP NASA EXOPLANET EXPLORATION PROGRAM

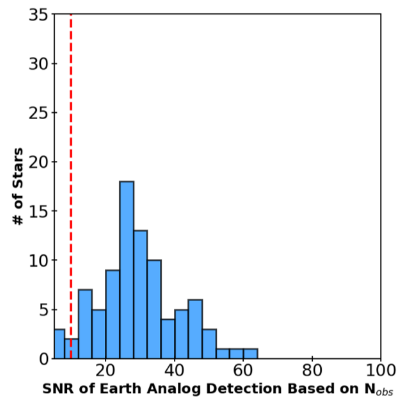
Architecture I



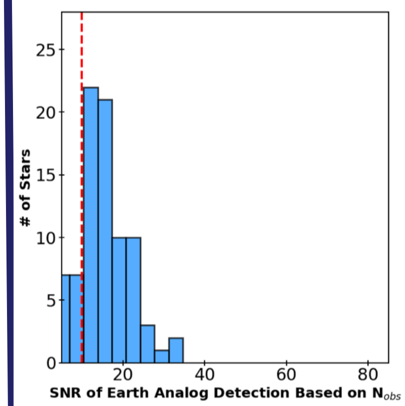
Architecture II



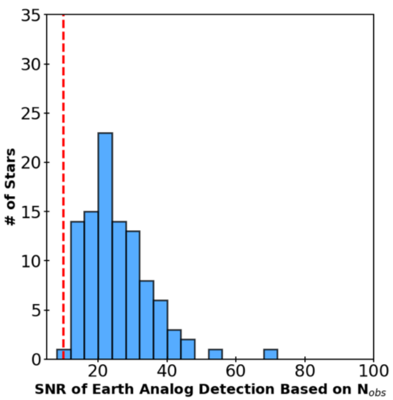
Architecture III



Architecture IV



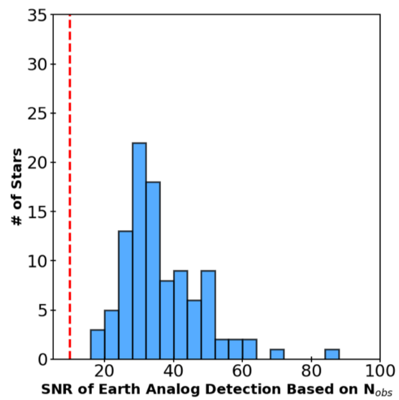
Architecture V



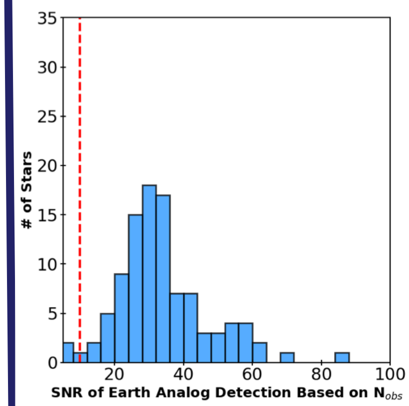
Architecture VI

Scalable to other architectures based on number of 1m telescopes

Architecture VIIIa



Architecture VIIIb



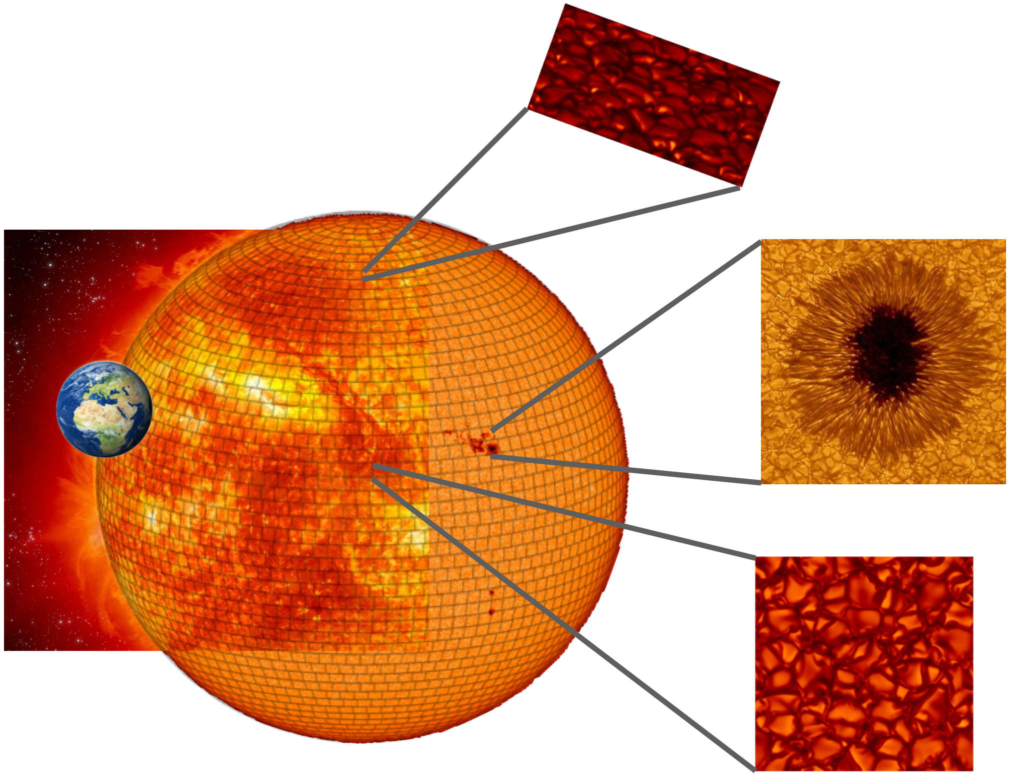
Architecture simulation key points

- 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.

Focus areas : Stellar variability



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

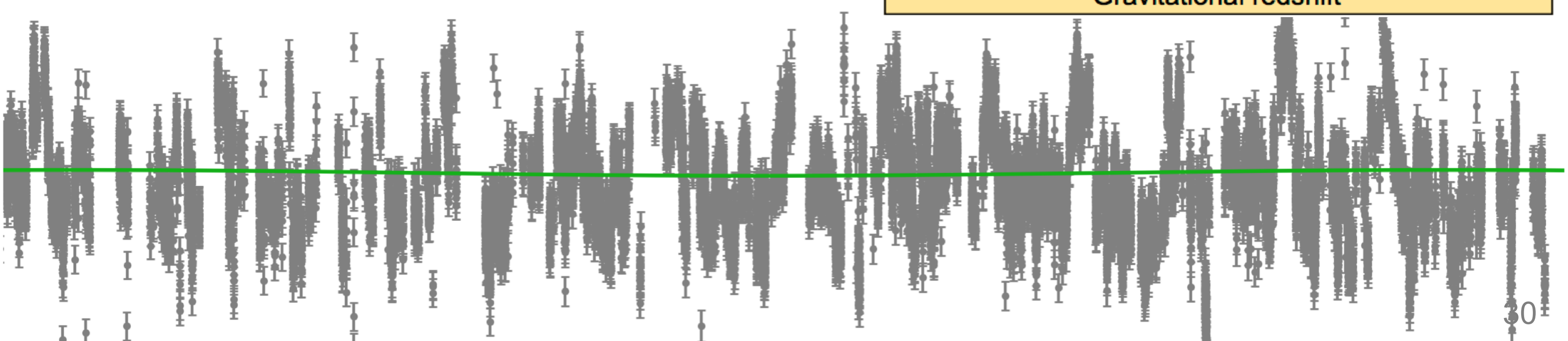


Image credits: NASA, ESA, SDO/HMI, MURAM, Big Bear Solar Observatory, HARPS-N., **Slide credit: Cegla/Haywood/Watson**

Focus areas : Data reduction pipelines

#	Requirement	Bare Minimum	Strongly Recommended	Bonus
2)	PRV observations of sun	Collect solar data for at least of half days each year for one solar cycle from a least 2 high priority instruments* and place in public archive. (Data collection + ~2 FTEs/year, GS or PD-level for associated analysis)	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)	Fund solar telescopes for additional high-priority instruments.
1)	PRV observations of RV benchmark stars	Collect data on 4 RV benchmark stars from at least 2 high priority instruments* and place in in public archive. For cadence see Group D requirement. (Data collection + ~2 FTEs/year, GS or PD-level for associated analysis)	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)	Standardize data products and data format in archive.
3)	R&A in Stellar Variability Mitigation	Develop and apply stellar variability for at least one wavelength-domain mitigation strategy and one temporal domain mitigation strategy. Verify, validate and assess utility of mitigation strategies using solar and RV benchmark star observations. (~4 FTEs/year, GS or PD level)	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)	
4)	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), observing strategies, and orbital period, for data meeting bare minimum requirements 1 & 2. (~2 FTE/year = 0.5 FTE for each instrument + additional 1 FTE independent of any instrument team)	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)	Fund teams closely associated with each instrument and at least one team quite distant from each high-priority instrument being compared to gain benefit of each team's experience and independent perspectives
5)	Developing modular, open-source pipeline for EPRV science	Adapt existing proven RV pipeline (eg. ESPRESSO, future KPF public code) to be usable across instruments and open-source. Validate and verify result code on data from at least 2 high priority instruments. (~2FTE/year, 1 Engineer-level, 1 PD-level)	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)	Gather instrument/testbed data on sub-pixel detector properties, calibration stability etc. for pipeline ingestion.
6)	Series of EPRV Data Challenges	Fund data challenges to compare effectiveness of strategies for: (1) mitigation of rotationally-modulated signals for sun, (2) mitigation of granulation, super-granulation and pulations for sun, (3) mitigation of combined stellar variability for other sun-like stars. (~15-24 FTEs, spread over ~6 years)	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	Strategy for integrating expertse/contributions from international colleagues.

Focus areas : Technology development

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.

Questions?

https://exoplanets.nasa.gov/exep/NNExplore/EPRV

(And look for ROSES solicitation this August!!)

Jennifer Burt (JPL) and Scott Gaudi (OSU/JPL)

on behalf of NASA's Exoplanet Exploration Program

and

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Some of the research presented here was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

Questions?

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(And look for ROSES solicitation this August!!)

BREAKING NEWS:

NEW ROSES 2020 SOLICITATION COMING

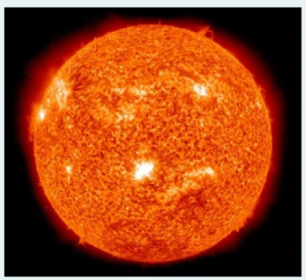
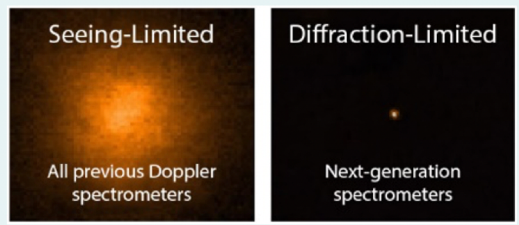
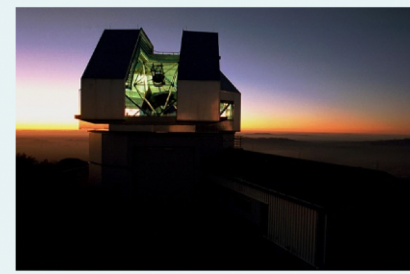
Extreme Precision Radial Velocity Supporting Research and Technology Development

- Expected Timeline:
  - *Solicitation issued in August;*
  - *Proposals due in Nov.-Dec. time frame;*
  - *Selections announced in Spring 2021;*
  - *2-year awards fully funded in FY21. Total ~$1.5M available.*
- Represents an initial response to the recommendations of EPRV WG report.
- Initial solicitation will probably be focused on “tall tent pole” items; continuation/expansion of the scope of the program contingent on Astro2020.

on … m

Some of the research presented he … f Technology under a contract
with the National Aeronautics and … ment sponsorship acknowledged.

The path forward

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