Potential for Exoplanet Science Measurements from Solar System Probes

& Report on May Exoplanet/Solar System Workshop

David Bennett

Exoplanet Program Analysis Group

- Formed in 2010 as lowest level of NASA advisory structure
  - Does “analysis” instead of “advice”
  - Reports to the Astrophysics Subcommittee of the NASA Advisory Council
- Based on success of PAGs in Solar System Division
- 5 Science Analysis Groups Selected:
  1. Debris Disks and Exozodiacal Dust
  2. Potential for Exoplanet Science Measurements from Solar System Probes
  3. Planetary Architecture and Dynamical Stability
  4. Planetary Measurements Needed for Exoplanet Characterization
  5. State of External Occulter Concepts and Technology

Goals for ExoPAG SAG 2:

- Determine the Exoplanet science that is possible with solar system missions using existing instruments
- Are there (low risk) instruments that can be added to missions in development?
  - e.g. GRB detectors for timing localization
- Look at practical implementation issues
  - Late and extended mission observations don’t risk prime science
  - Sources of funding
- Get NASA to Reward such efforts in competed missions
- Parallel efforts
  - Mario Perez (HQ) - astrophysics w/ solar system missions
  - Cosmology at 5 AU

SAG 2 Report Outline

- Introduction
  - Past and present successes, e.g. EPOXI, and difficulties
- Science Opportunities
  - Exoplanet mass measurements through microlensing parallax observations at 0.1-100 AU distances from Earth
  - Precise, continuous observations of known transiting planets
    - Transit timing variations
    - Reflected light phase variations and secondary eclipses
    - Search for moons and additional (small) planets
  - Methane fluorescence at 3.3μm (Cassini/VIMMS Sotin)
    - (in between HST & Spitzer)
    - Observed for HD189733b with IRTF
  - Remote observations of Earth or other planets (Earth as an Exoplanet)
  - In situ Zodi observations
  - Stellar parallax observations from 9 AU or more

SAG 2 Report Outline (cont.)

- Solar System Mission Capabilities and Constraints
  - EPOXI
  - Cassini
  - New Horizons
  - Rosetta
  - Juno
  - Heliophysics missions
- Added Capabilities to New Missions
  - Focus mechanism for transit observations
  - Calibration mechanisms
  - Cheap instruments (?)
- Programmatic and Political Issues
  - Multi-division missions
  - Bias against non-prime science and need for incentives
  - New Science Extended missions
- Conclusions

Historical Background: Microlensing 1993 : 1st Microlensing Events

- Could mean that Milky Way's dark halo was made of brown dwarf or old white dwarfs
- But we don't know if the lens objects are in the Milky Way halo, disk, or Large Magellanic Cloud
- A 30cm telescope in a heliocentric orbit would answer this question
  - Dark Object Microlens Explorer (1995 Midex proposal)
    - PI: Alcock
    - Lost to WMAP
  - But the 30cm telescopes are launched into heliocentric orbit regularly by NASA's Solar System Exploration Division

Late 1990’s

- Attempted Cassini Cruise Phase Observations of Microlensing events
- Convinced Cassini/ISS PI Carolyn Porco to attempt test observations
  - But after reaction wheel anomaly, test observations and many other cruise phase ISS observations are canceled.

2003-2004

- Lobbied NASA HQ for the opportunity to propose astrophysics observations with Solar System Missions
  - NASA adds “New Science Extended Mission” to SMEX Mission of Opportunity Proposals
- Worked with Mike A’Hearn on Deep Impact Extended Mission after HQ allows “new science” extended mission proposal: Deep Impact Microlens Explorer (DIME)
- Support from JPL
- Extended mission proposed prior to launch due to
- But, at the last minute, DI launch pushed back from 2004 to 2005 - and JPL proposal team recalled for prime mission work
- Proposed with pseudo-budget estimated by GSFC
  - Rejected due to dubious budget
  - Strong science review - told to re-propose in 2005
- 2005 AO canceled

2005-2010

- Deep Impact completes prime mission: Nov. 2005
- EPOCh and DIXI proposals submitted to Discovery 2006 competition
- Selected in combined EPOXI mission in July, 2007
- EPOCH exoplanet mission ran from Jan.-Aug., 2008
- Comet Boethin goes AWOL - so Nov. 2010 flyby of Comet 103P/Hartley instead of Dec., 2008 flyby of Boethin
- Microlensing Deep Impact opportunity missed due to proposal schedule - not science
  - Science case faded a bit
- EPOCh used only 8 months out of 5 yr extended mission

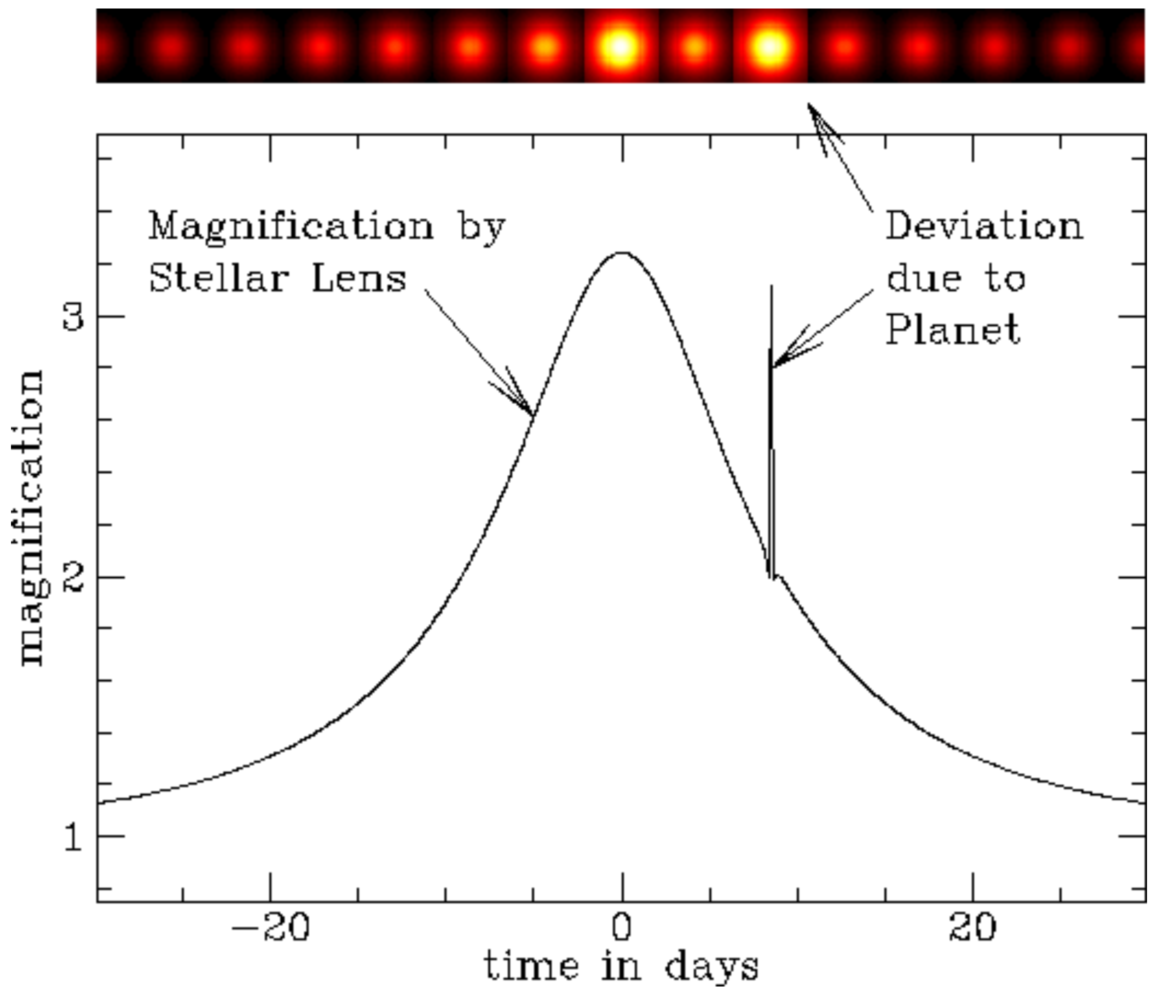
Science Opportunities and Results

Microlensing Parallax

PLANET
Probing Lensing Anomalies NETwork

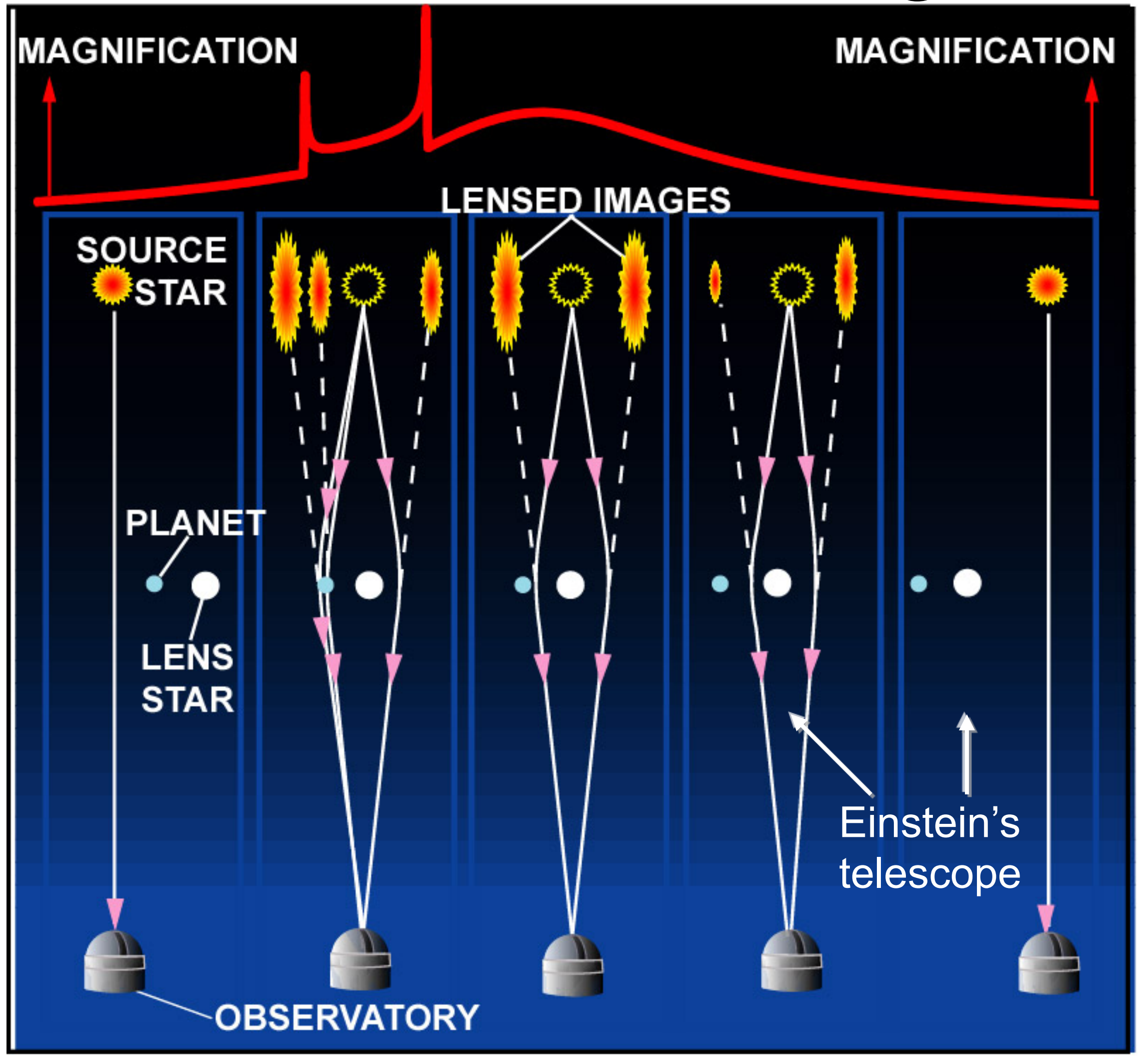
MicroFUN
Microlensing Follow-Up Network

OGLE



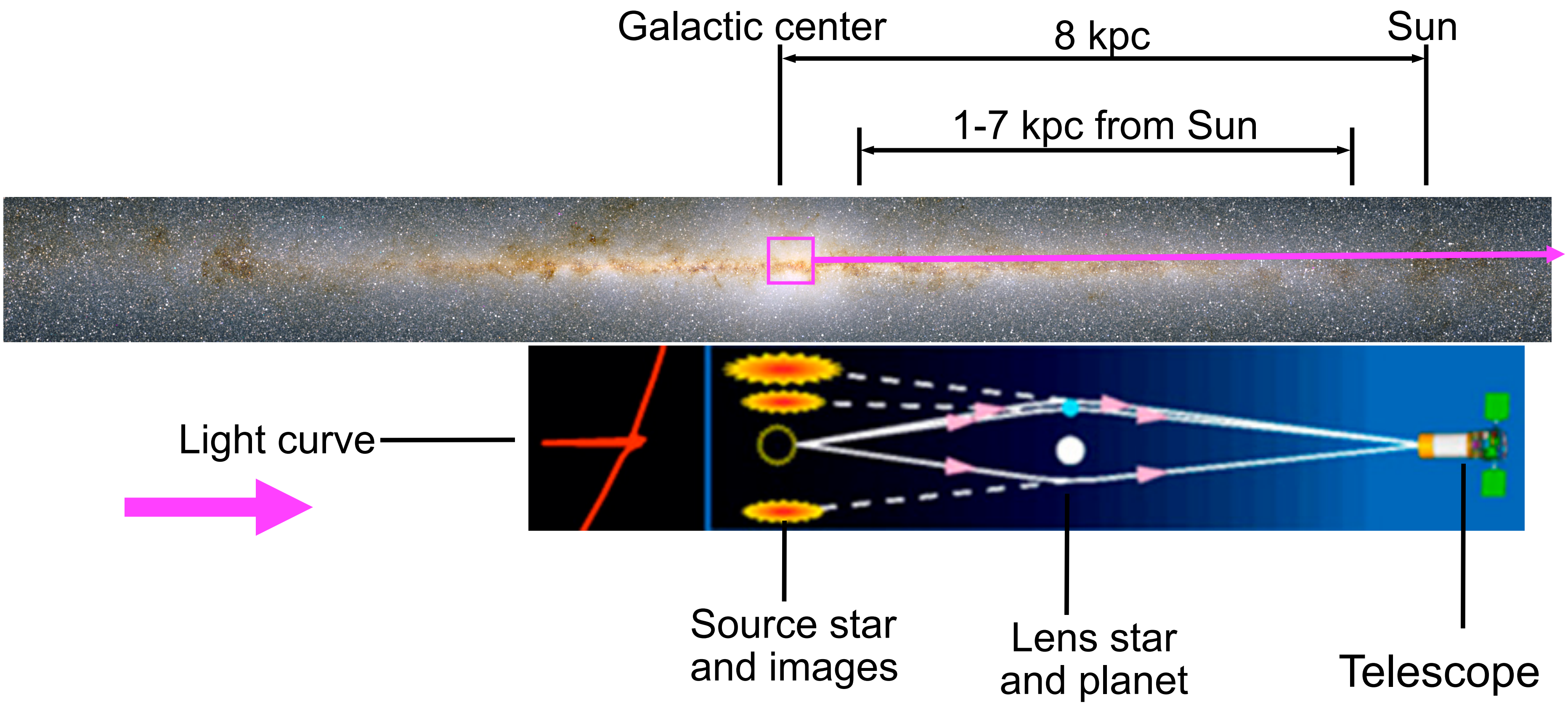
The Physics of Microlensing

- Foreground "lens" star + planet bend light of "source" star
- Multiple distorted images
  - Only total brightness change is observable
- Sensitive to planetary mass
- Low mass planet signals are rare – not weak
- Stellar lensing probability ~a few $\times 10^{-6}$
  - Planetary lensing probability ~0.001-1 depending on event details
- Peak sensitivity is at 2-3 AU: the Einstein ring radius, R_E



Key Fact: $1\ \mathrm{AU} \approx \sqrt{R_{Sch} R_{GC}} = \sqrt{\frac{2GM}{c^2} R_{GC}}$

Microlensing Target Fields are in the Galactic Bulge

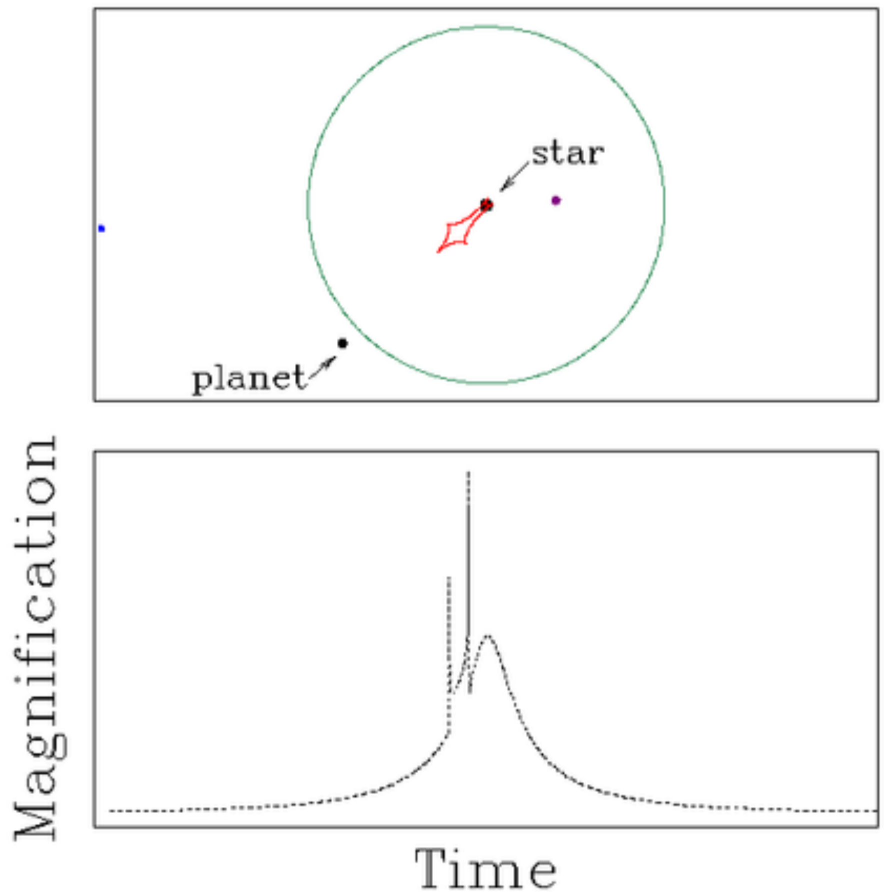


10s of millions of stars in the Galactic bulge in order to detect planetary companions to stars in the Galactic disk and bulge.

Lensed images at μarcsec resolution

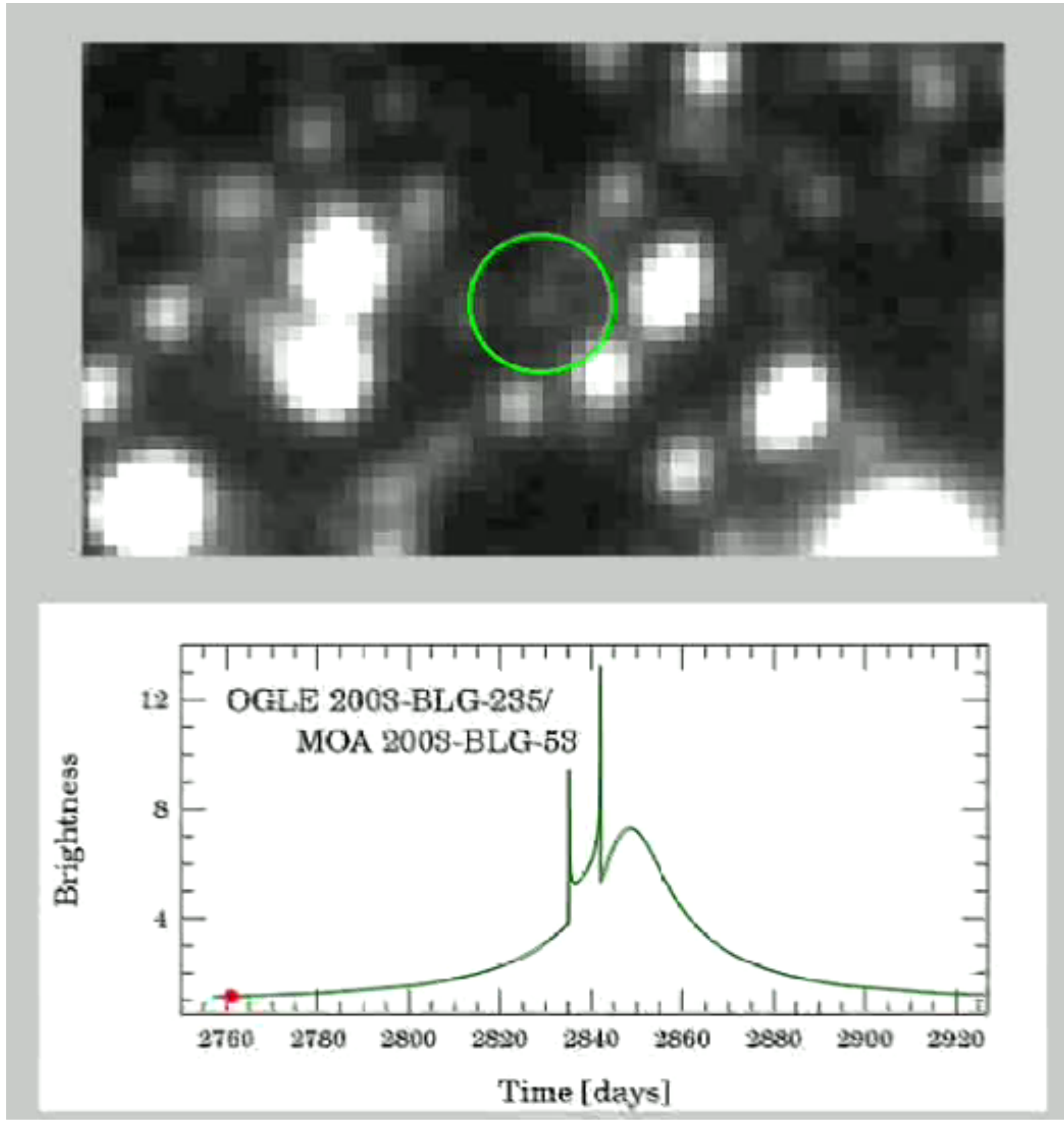
View from telescope

A planet can be discovered when one of the lensed images approaches its projected position.



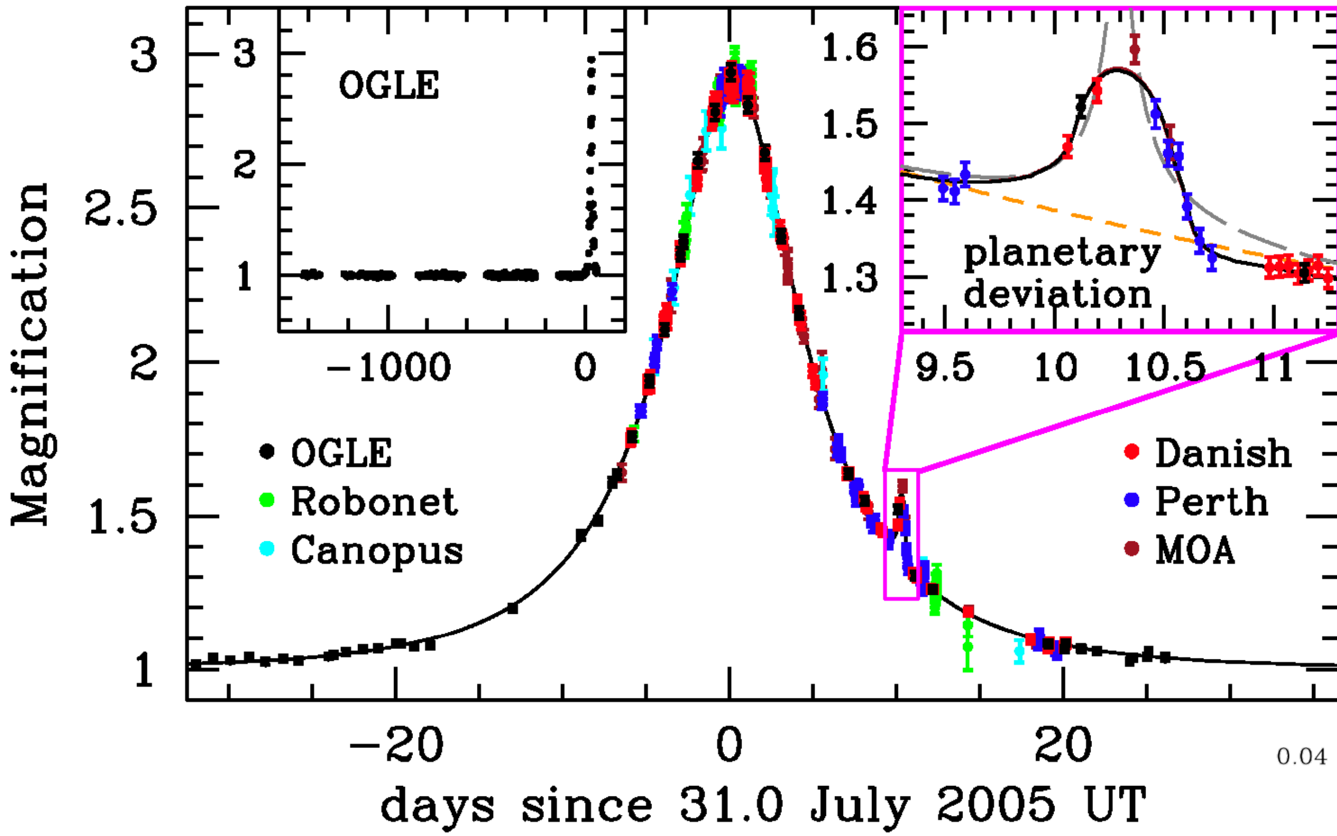
Simulated Lightcurve of 1st Planetary Event

Simulated version of actual data



Best fit light curve simulated on an OGLE image

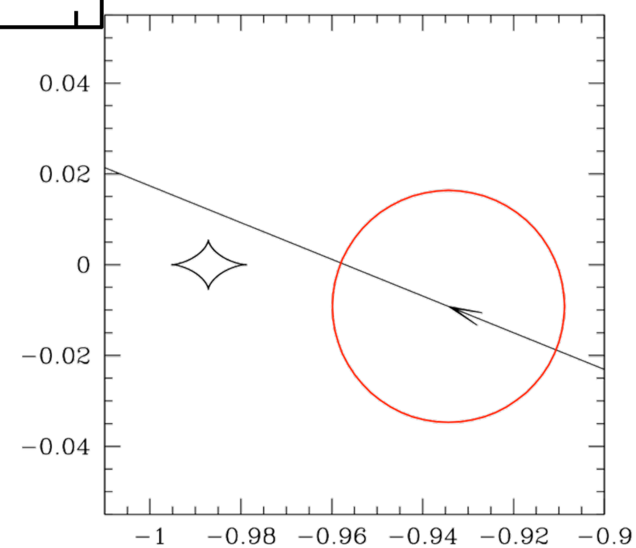
OGLE-2005-BLG-390Lb - “lowest” mass exoplanet



A 5.5 $M_\oplus$ planet discovered by microlensing: OGLE-2005-BLG-390Lb. The lowest mass planet discovered when announced in 2006.

Source passes over caustic => significant finite source effect and clear measurement of t_*

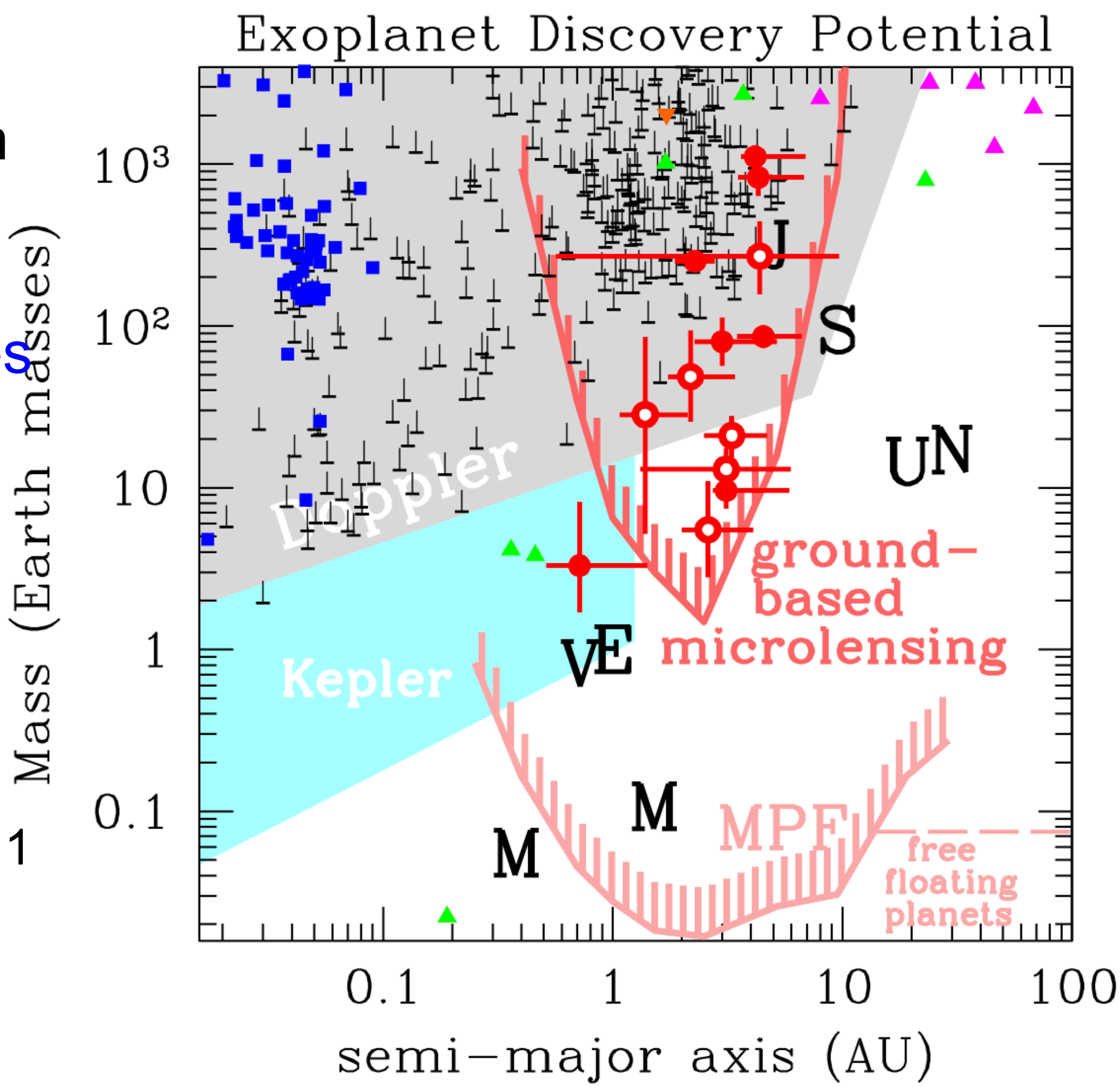
Giant source star means lens star detection will be difficult



PLANET, OGLE & MOA Collaborations

Microlensing Discoveries vs. Other Techniques

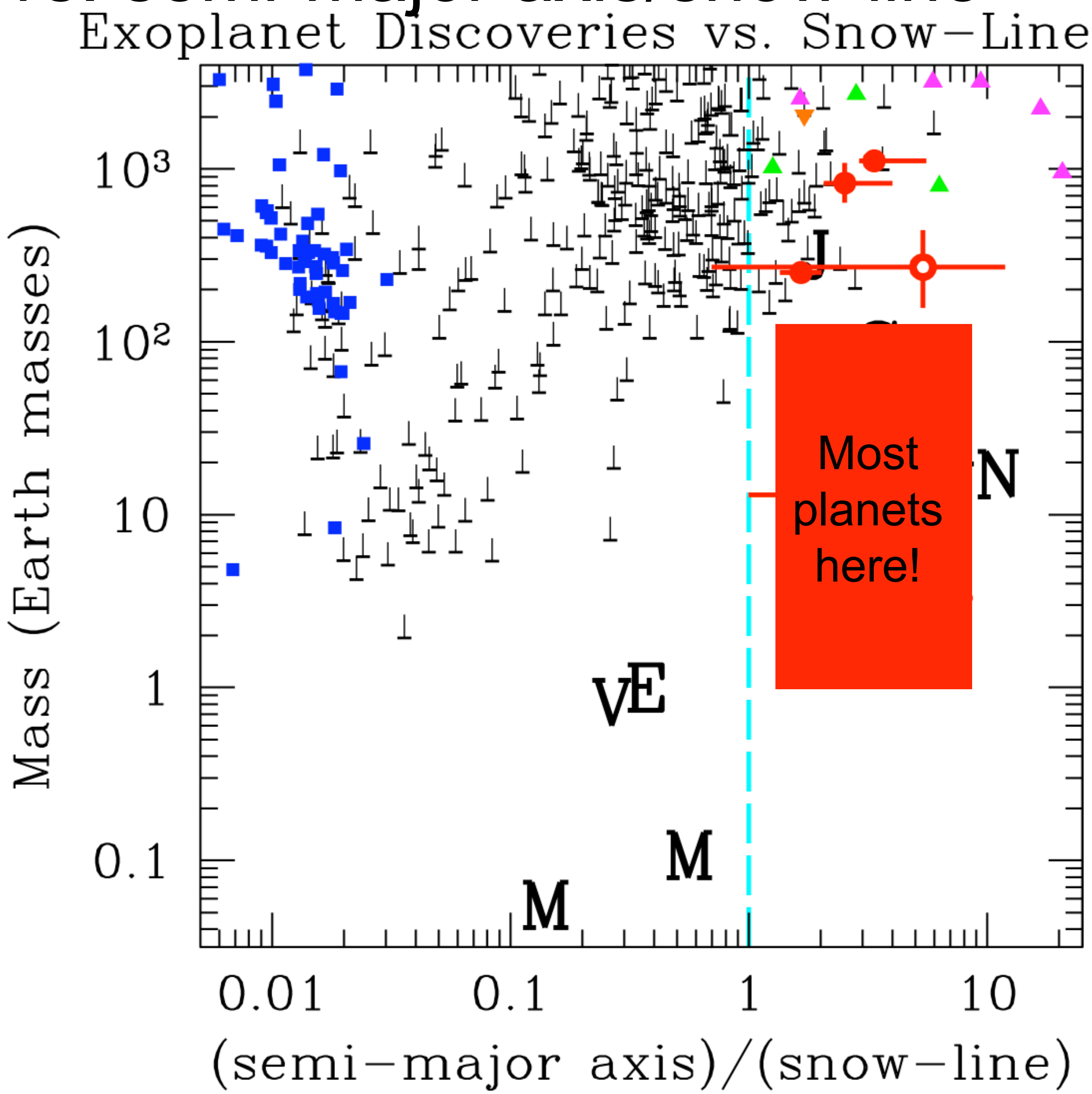
- Microlensing discoveries in red
- Doppler discoveries in black
- Transit discoveries shown as blue squares
- Direct detection, and timing are magenta and green triangles
- Microlensing opens a new window on exoplanets at 1-5 AU
  - Sensitivity approaching 1 Earth-mass



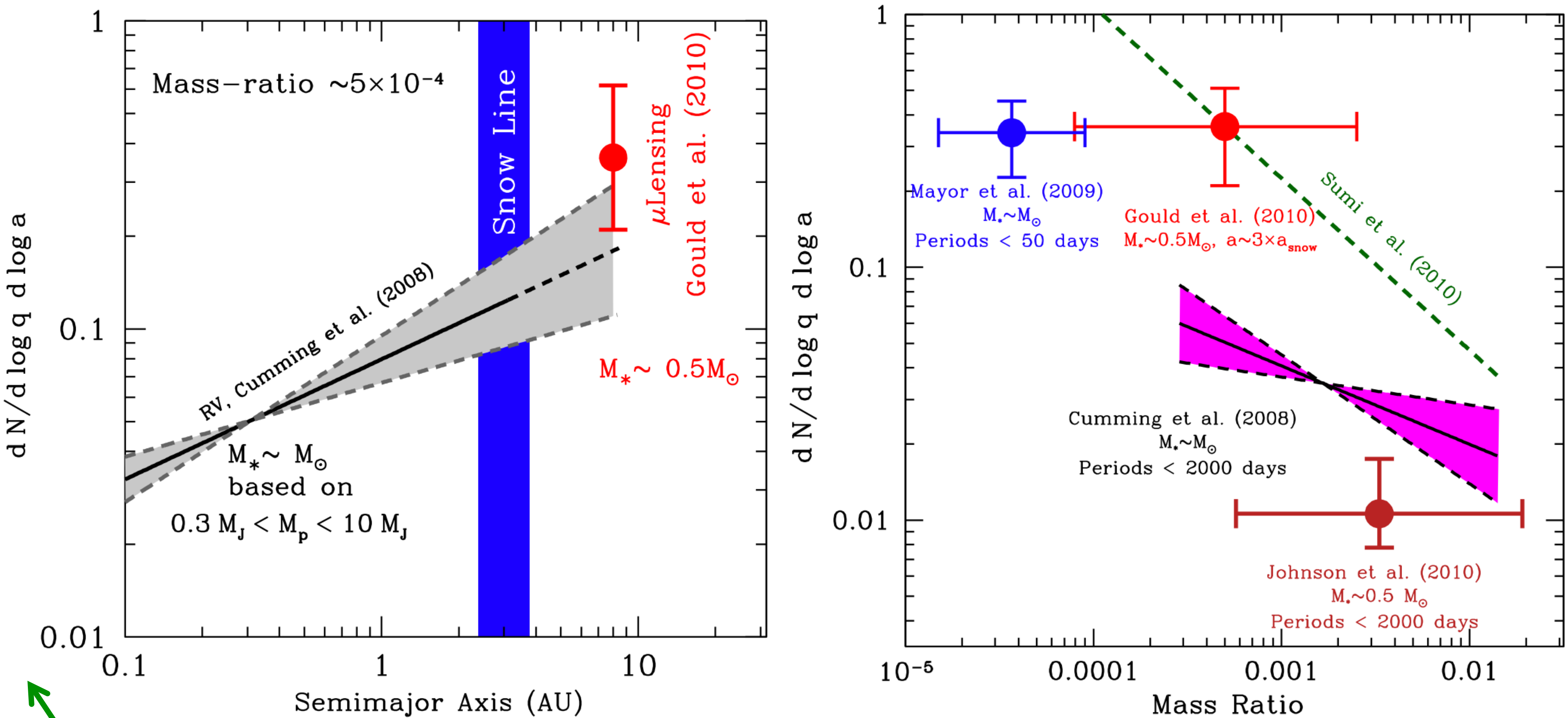
Planet mass vs. semi-major axis/snow-line

- “snow-line” defined to be 2.7 AU ($M/M_{\odot}$)
  - since L$\propto$ M^2 during planet formation
- Microlensing discoveries in **red.**
- Doppler discoveries in black
- Transit discoveries shown as blue circles

- Super-Earth planets beyond the snow-line appear to be the most common type yet discovered



Comparison of Statistical Results



Kepler 2010

Sumi et al. (2010) : $dN_p/d(\log q) \sim q^{-0.7}$

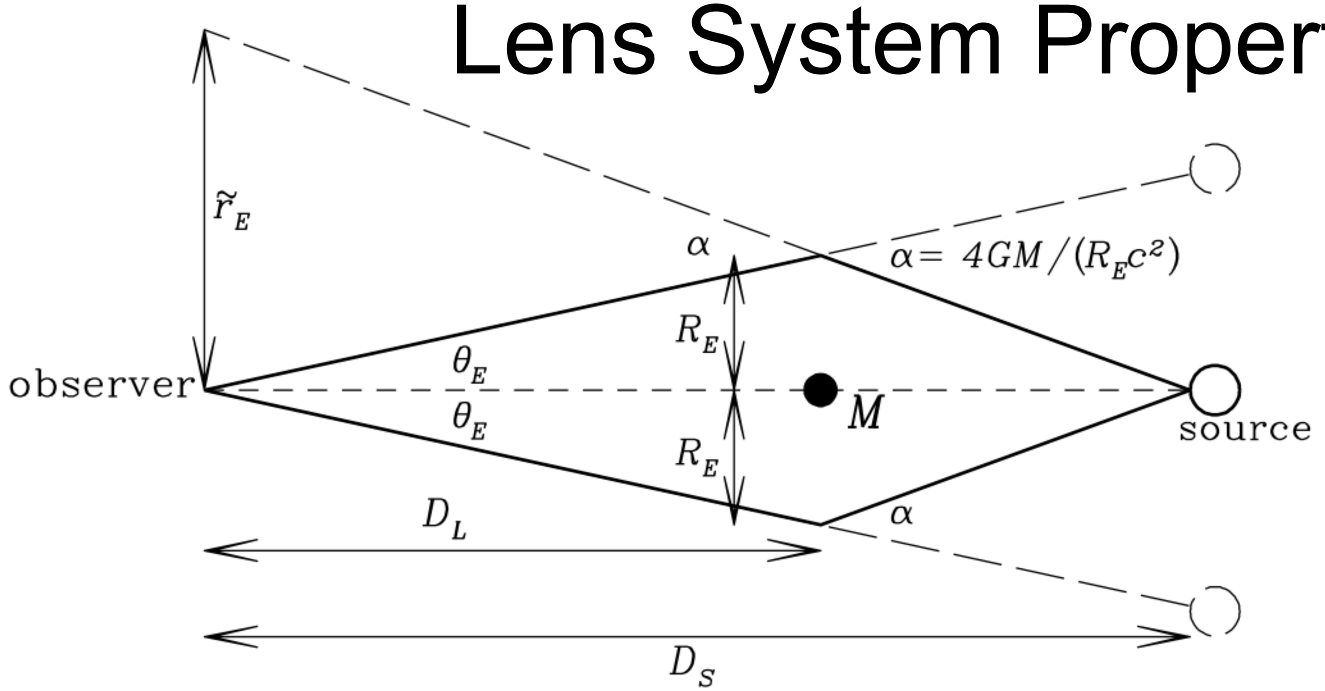
Gould et al. (2010) : $d^2N/d(\log q)\, d(\log a) = 0.36 \pm 0.15$

for $M \approx 0.5\, M_\odot$ and $q \approx 5 \times 10^{-4}$

Lens System Properties

- For a single lens event, 3 parameters (lens mass, distance, and velocity) are constrained by the Einstein radius crossing time, t_E
- There are two ways to improve upon this with light curve data:
  - Determine the angular Einstein radius : $\theta_E = \theta_* t_E / t_* = t_E \mu_{rel}$ where θ_* is the angular radius of the star and μ_{rel} is the relative lens-source proper motion
  - Measure the projected Einstein radius, $\tilde{r}_E$, with the microlensing parallax effect (due to Earth's orbital motion).

Lens System Properties



- Einstein radius : $P_E = \theta_* t_E / t_*$ and projected Einstein radius, $\tilde{r}_E$
  - t_* = the angular radius of the star
  - $\tilde{r}_E$ from the microlensing parallax effect (due to Earth's orbital motion).

$$R_E = \theta_E D_L, \text{ so } \alpha = \frac{\tilde{r}_E}{D_L} = \frac{4GM}{c^2 \theta_E D_L}. \text{ Hence } M = \frac{c^2}{4G}\theta_E \tilde{r}_E$$

Finite Source Effects & Microlensing Parallax Yield Lens System Mass

- If only θ_E or $\tilde{r}_E$ is measured, then we have a mass-distance relation.
- Such a relation can be solved if we detect the lens star and use a mass-luminosity relation
  - This requires HST or ground-based adaptive optics
- With θ_E, $\tilde{r}_E$, and lens star brightness, we have more constraints than parameters

mass-distance relations:

$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

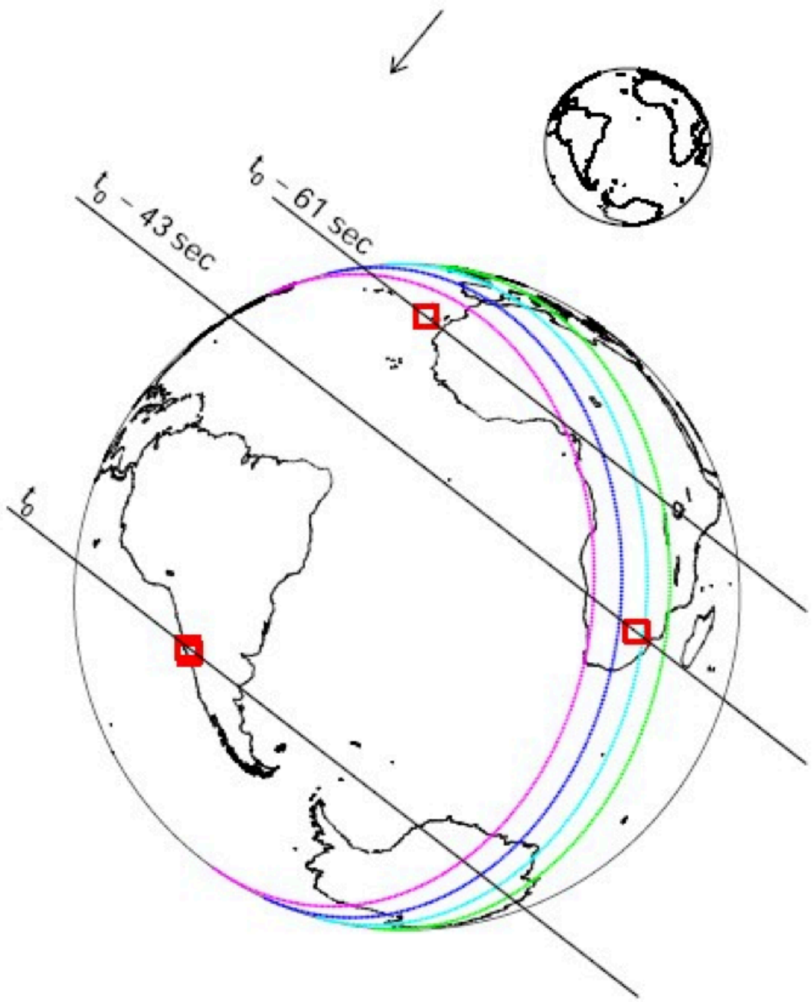
$$M_L = \frac{c^2}{4G}\tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E \theta_E$$

3 Ways to Measure Microlensing Parallax

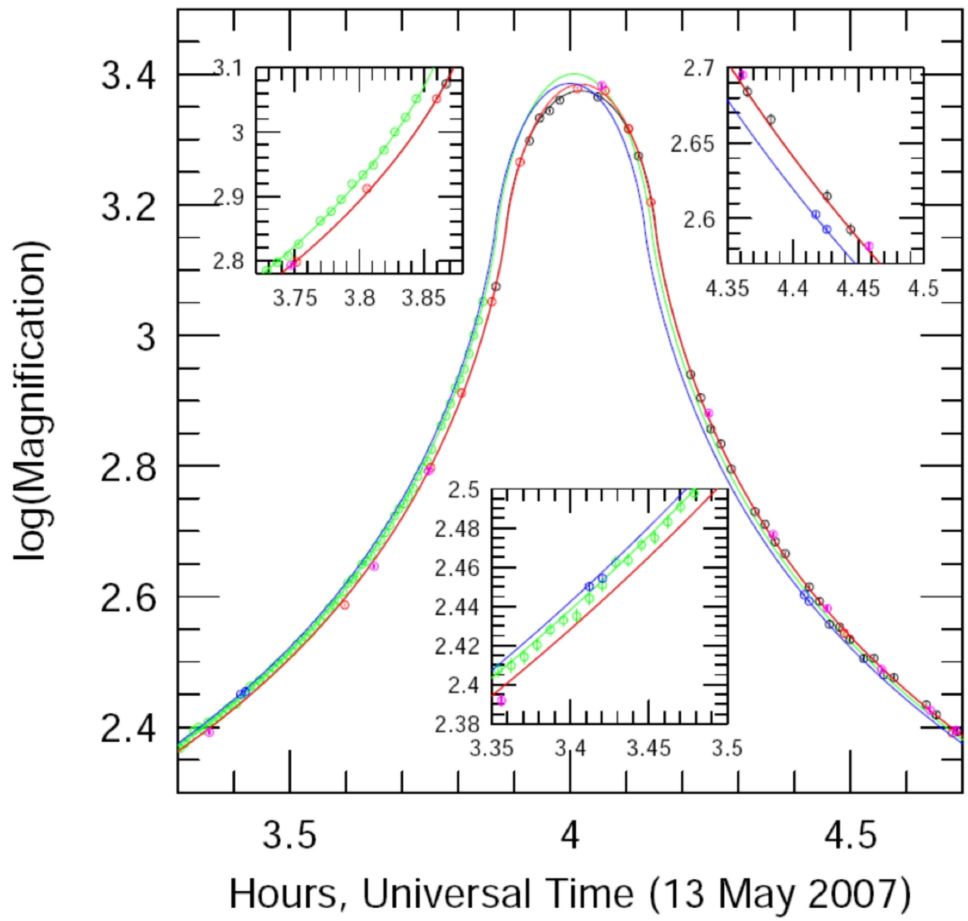
- Terrestrial - from different locations on the Earth
  - Requires very high magnification - rapid change in brightness
  - Measured for OGLE-2007-BLG-224 - disk brown dwarf
- Orbital motion of the Earth
  - Requires a long Einstein radius crossing time, $t_E \geq 100$ days
  - Measurable for some lenses in the Galactic disk, but not in the Galactic bulge
- From a Satellite far from Earth
  - Solar System missions provide “opportunities”
    - Cassini (late 1990’s)
    - Deep Impact 2004 (proposal)
  - OGLE-2005-SMC-1 measured by Spitzer
  - MOA-2009-BLG-266 - first planetary microlensing event with extra-terrestrial observations - by EPOXI (formerly Deep Impact) in Oct., 2009.

Terrestrial Microlensing Parallax



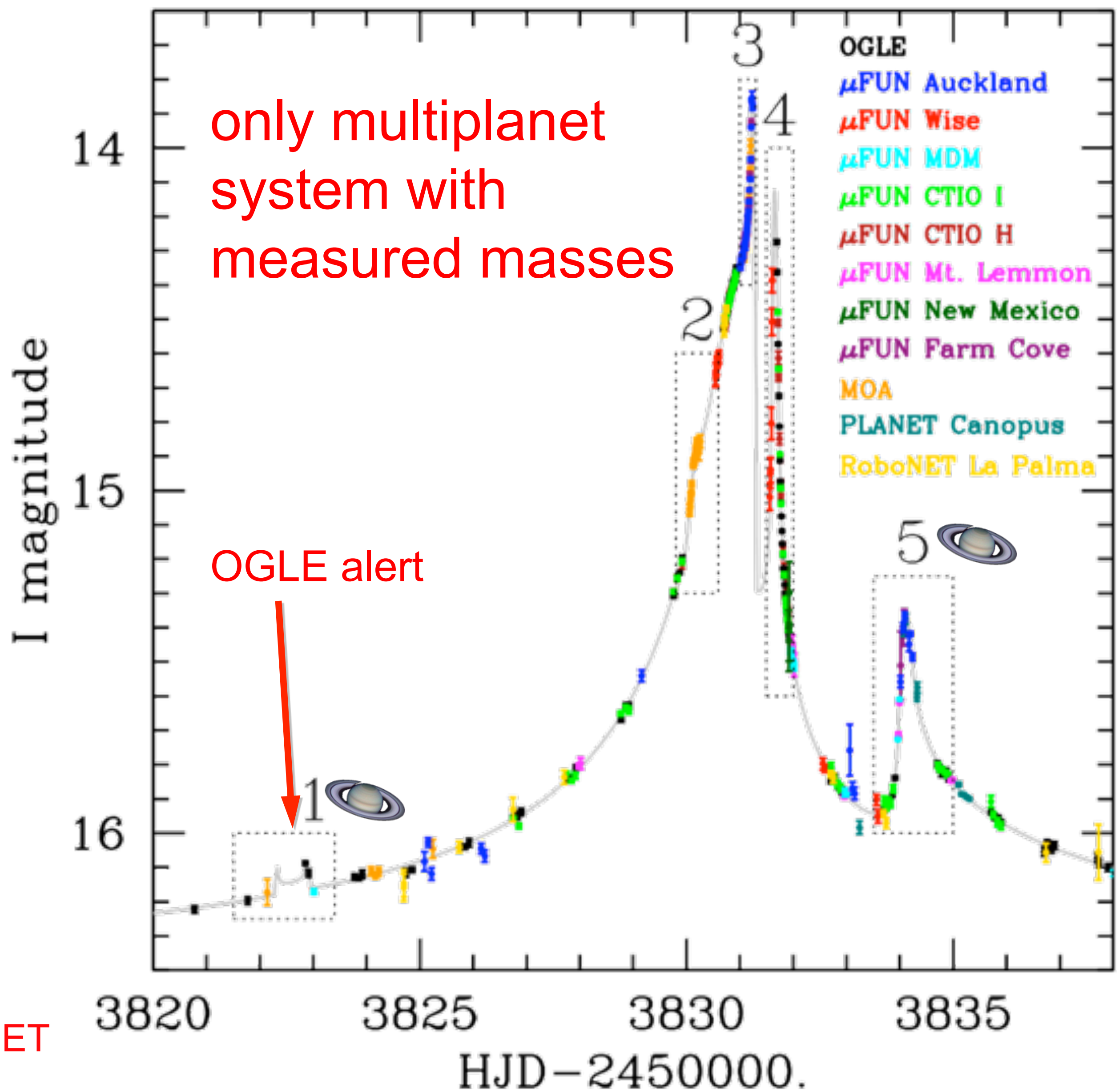
OGLE-2007-BLG-224

Canaries South Africa Chile



Double-Planet Event: OGLE-2006-BLG-109

- 5 distinct planetary light curve features
- OGLE alerted 1st feature as potential planetary signal
- High magnification
- Feature #4 requires an additional planet
- Planetary signals visible for 11 days
- Features #1 & #5 require the orbital motion of the Saturn-mass planet

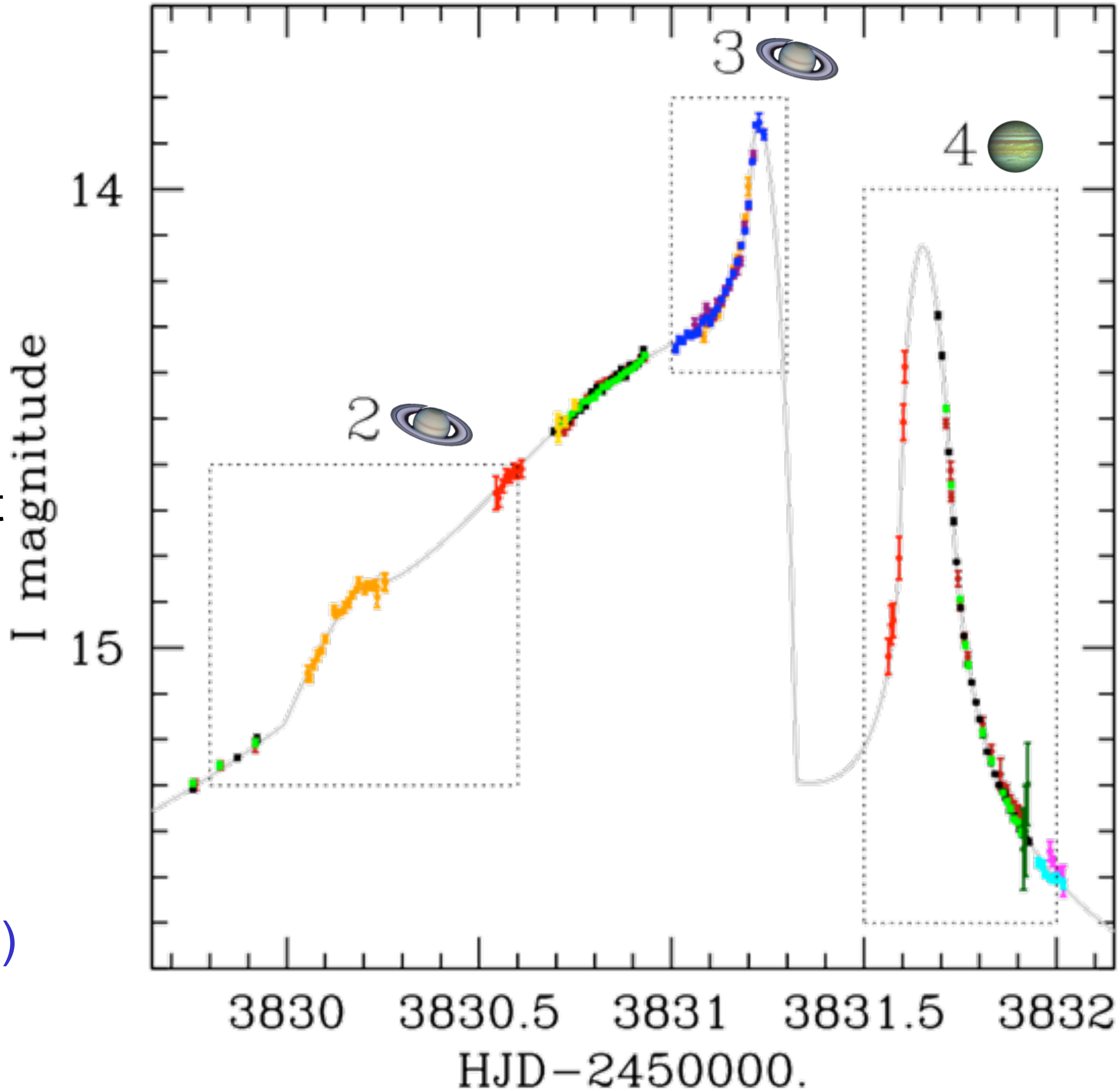


μFUN, OGLE, MOA & PLANET

OGLE-2006-BLG-109 Light Curve Detail

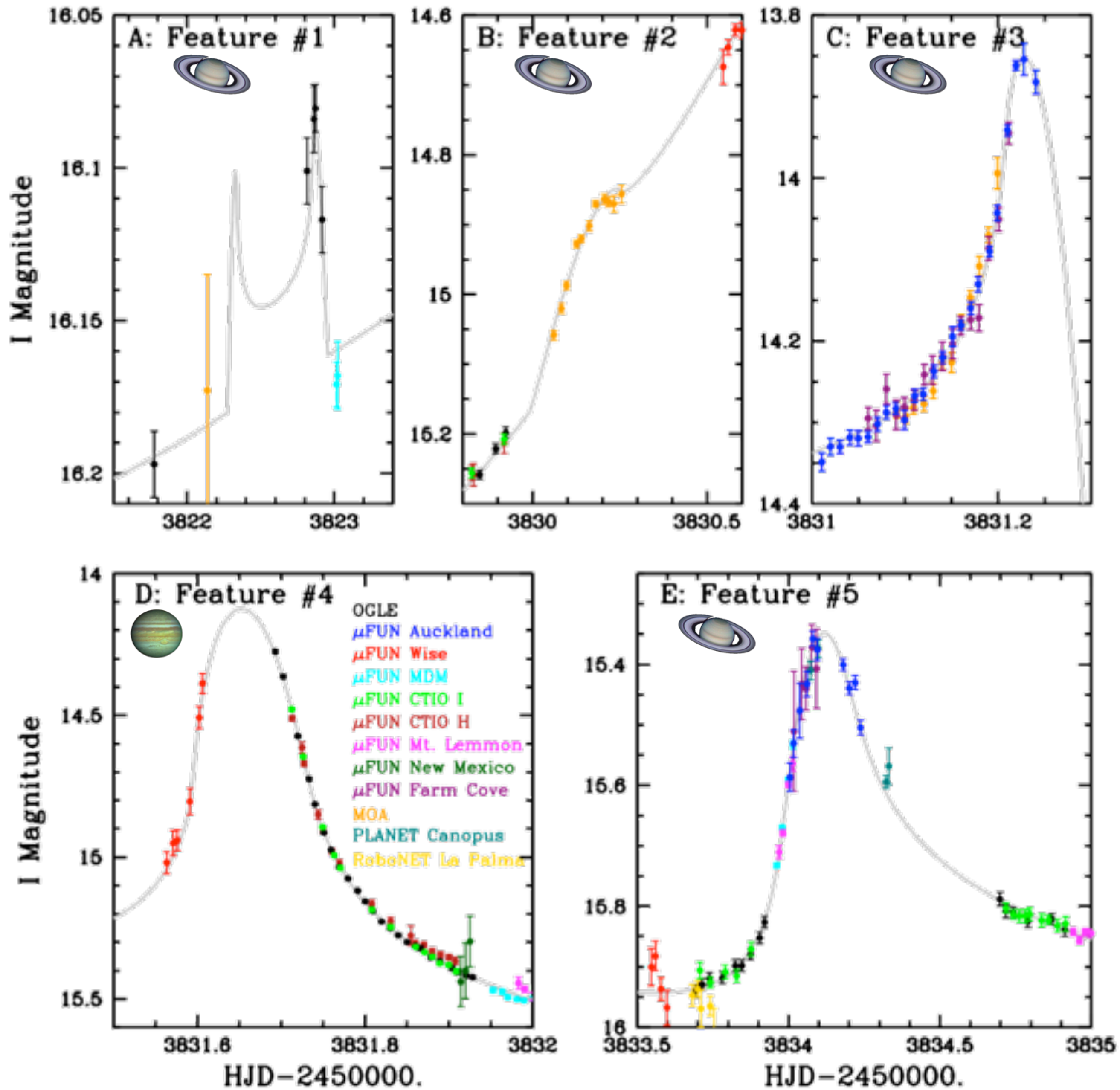
- OGLE alert on feature #1 as a potential planetary feature
- μFUN (Gaudi) obtained a model approximately predicting features #3 & #5 prior to the peak
- But feature #4 was not predicted - because it is due to the Jupiter - not the Saturn

Gaudi et al (2008)
Bennett et al (2010)

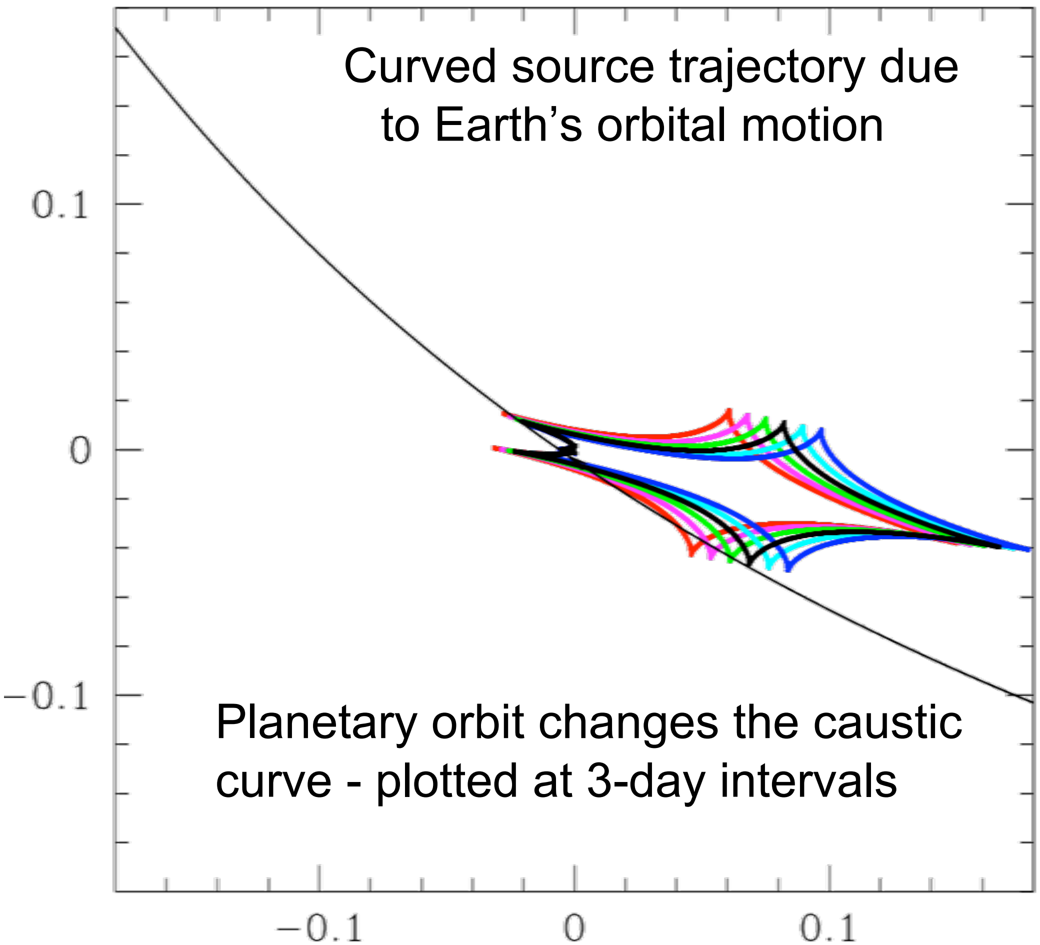


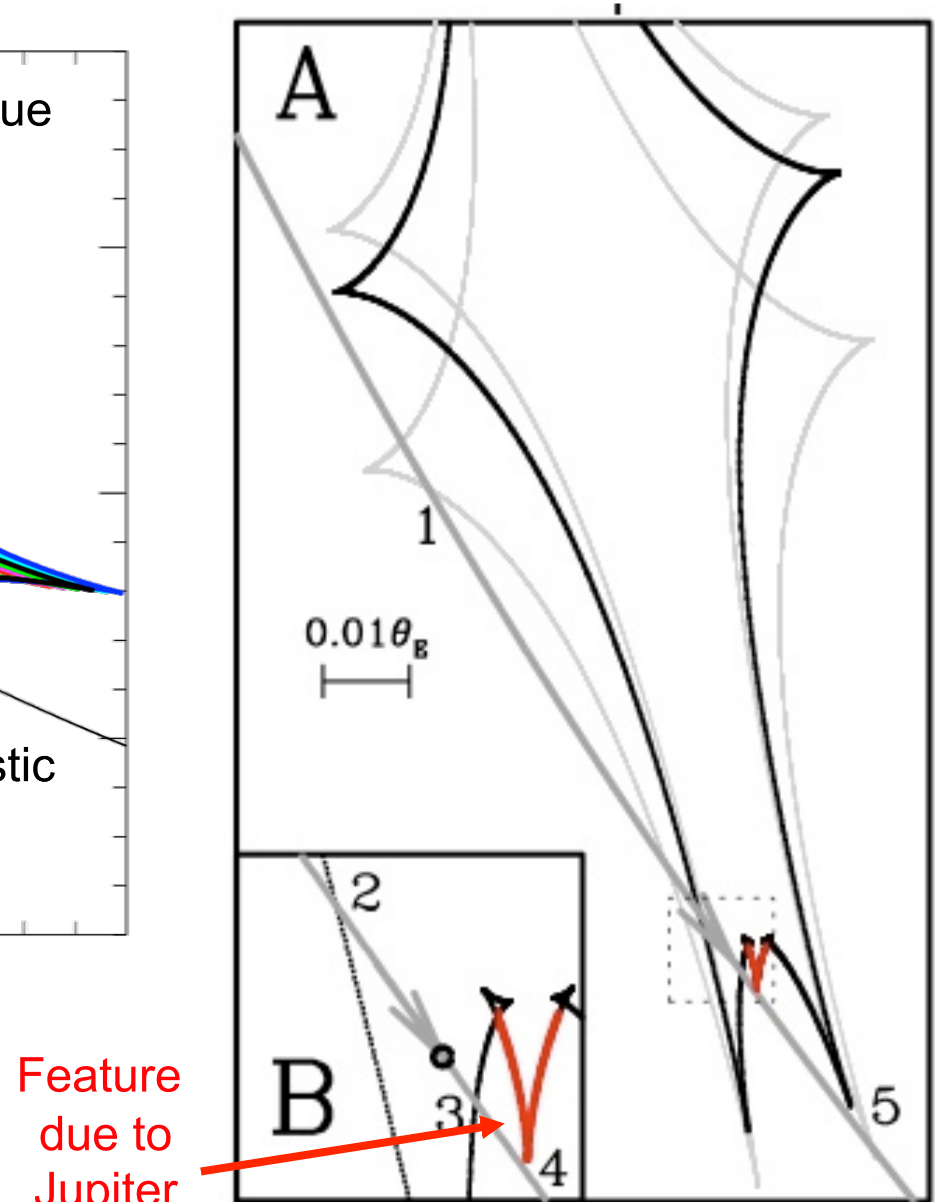
OGLE-2006-BLG-109 Light Curve Features

- The basic 2-planet nature of the event was identified during the event,
- But the final model required inclusion of orbital motion, microlensing parallax and computational improvements (by Bennett).



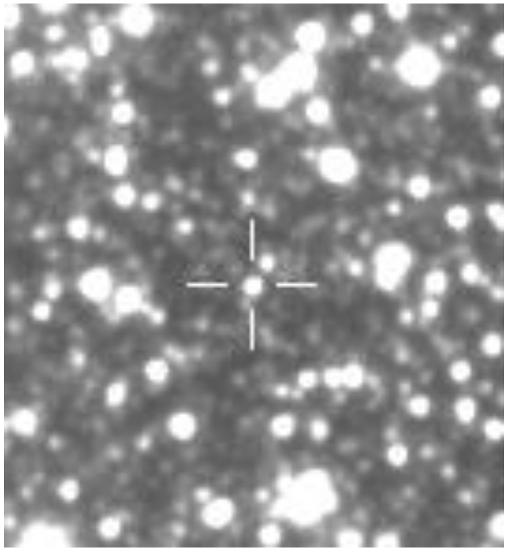
OGLE-2006-BLG-109Lb,c Caustics



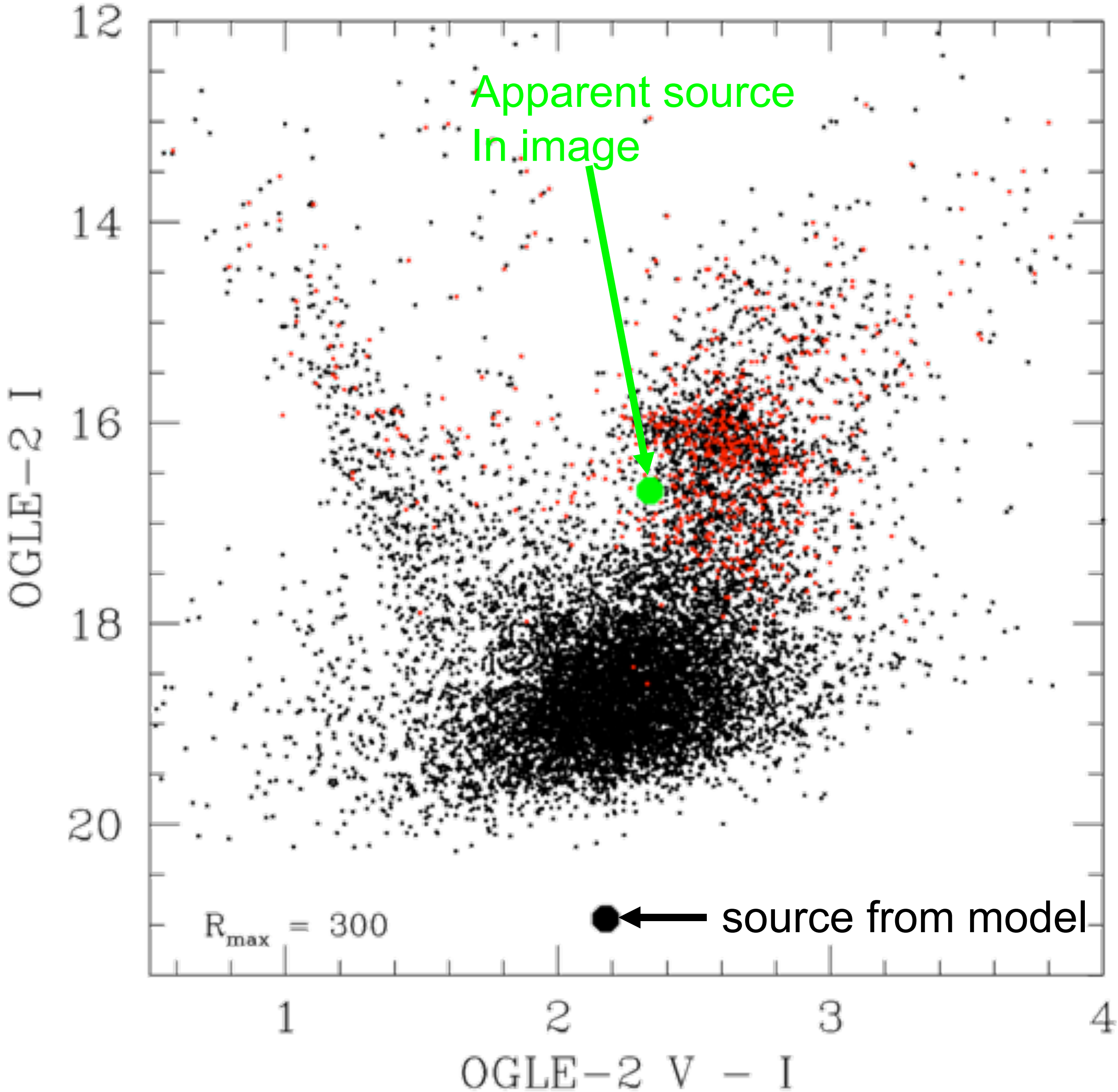


more analysis details later

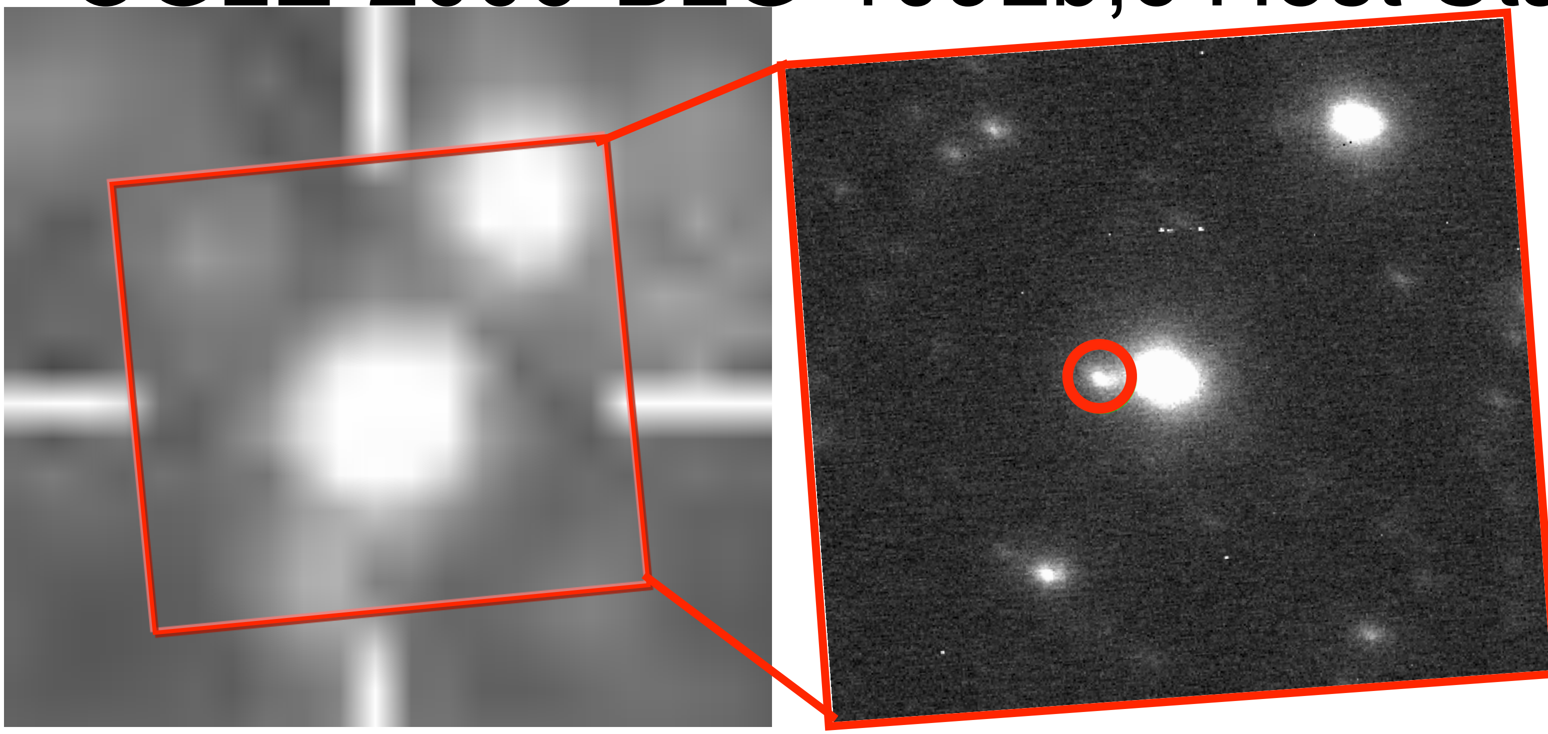
OGLE-2006-BLG-109 Source Star



The model indicates that the source is much fainter than the apparent star at the position of the source. Could the brighter star be the lens star?



OGLE-2006-BLG-109Lb,c Host Star



- OGLE images show that the source is offset from the bright star by 350 mas
- B. Macintosh: Keck AO images resolve lens+source stars from the brighter star.
- But, source+lens blend is 6× brighter than the source (from CTIO H-band light curve), so the lens star is 5× brighter than source.
  - H-band observations of the light curve are critical because the lens and source and not resolved
- Planet host (lens) star magnitude H ≈ 17.17
  - JHK observations will help to constrain the extinction toward the lens star

Only Multiplanet System with Measured Masses

Host star mass: $M_L = 0.52^{+0.18}_{-0.07} M_\odot$ from light curve model.

- Apply lens brightness constraint: $H_L \approx 17.17$.
- Correcting for extinction: $H_{L0} = 16.93 \pm 0.25$
  - Extinction correction is based on H_L-K_L color
  - Error bar includes both extinction and photometric uncertainties
- Lens system distance: $D_L = 1.54 \pm 0.13$ kpc

Host star mass: $M_L = 0.51 \pm 0.05 M_\odot$ from light curve and lens H-magnitude.

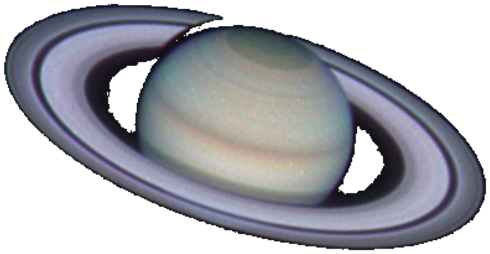
Other parameter values:

- "Jupiter" mass: $m_b = 0.73 \pm 0.06\ M_{Jup}$
  semi-major axis: $a_b = 2.3 \pm 0.5\,\mathrm{AU}$
- "Saturn" mass: $m_c = 0.27 \pm 0.03\ M_{Jup} = 0.90\ M_{Sat}$
  semi-major axis: $a_c = 4.5^{+2.2}_{-1.0}\,\mathrm{AU}$
- "Saturn" orbital velocity $v_t = 9.5 \pm 0.5$ km/sec
  eccentricity $\varepsilon = 0.15^{+0.17}_{-0.10}$
  inclination $i = 63 \pm 6°$

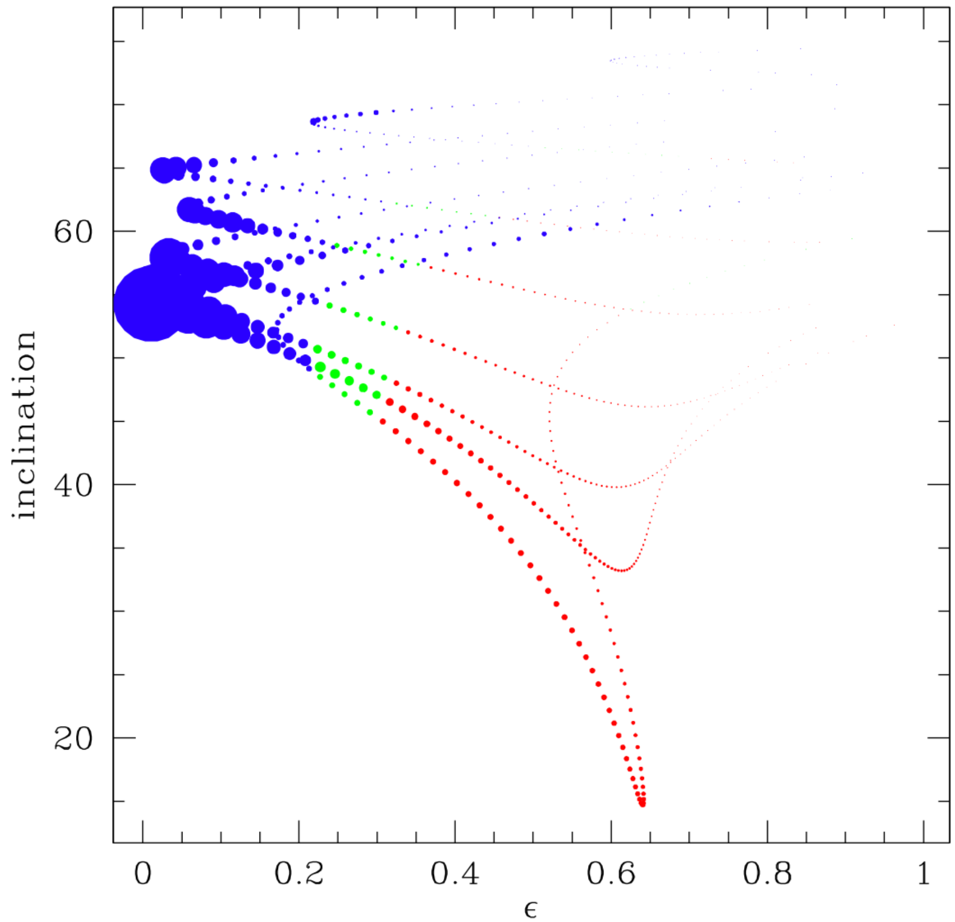
Orbital Motion Modeling

- 4 orbital parameters are well determined from the light curve
  - 2-d positions and velocities
  - Slight dependence on distance to the source star when converting to physical from Einstein Radii units
- Masses of the host star and planets are determined directly from the light curve
  - So a full orbit is described by 6 parameters (3 relative positions & 3 relative velocities)
  - A circular orbit is described by 5 parameters
- Models assume planetary circular motion
  - 2-d positions and velocities are well determined
  - Orbital period is constrained, but not fixed by the light curve
  - The orbital period parameter can be interpreted as acceleration or 3-d Star-Saturn distance (via $a = GM/r^2$)
- Details in Bennett et al (2010)

Full Orbit Determination for OGLE-2006-BLG-109Lc



- Series of fits with fixed orbital acceleration (weight with fit χ^2)
- Each fit corresponds to a 1-parameter family of orbits parameterized by v_z
  - unless $\frac{1}{2}\left(v_x^2 + v_y^2\right) - \frac{GM}{r} > 0$
- Assume the Jupiter orbits in the same plane and reject solutions crossing the Jupiter orbit or that are Hill-unstable
- Weight by prior probability of orbital parameters
  - planet is unlikely to be near periastron if ε >> 0



Families of solutions corresponding to best models at various values of a.

Full Orbit Determination for OGLE-2006-BLG-109Lc

- Full calculation using Markov chains run at fixed acceleration.
- Include only Hill-stable orbits
- results:

$$M_{LA} = 0.51 \pm 0.05 M_{\odot}$$

$$M_{Lc} = 0.27 \pm 0.03 M_J$$

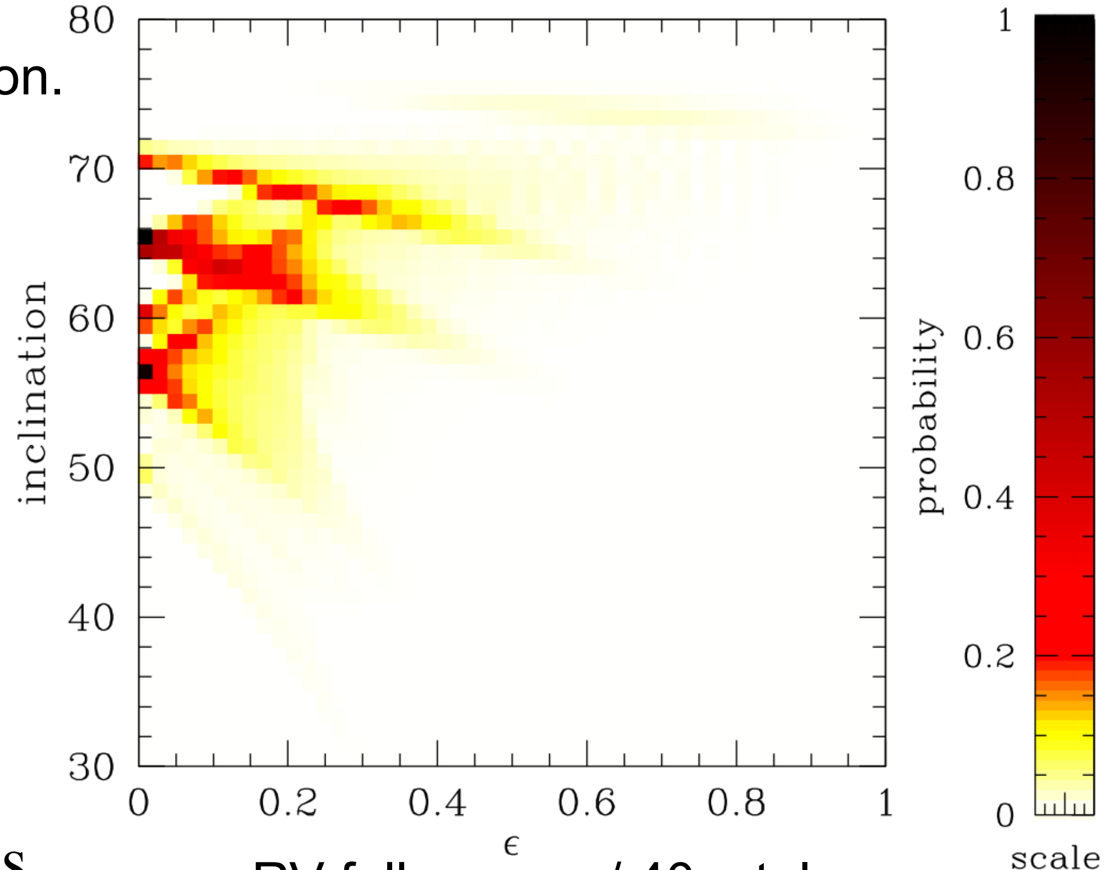
$$M_{Lb} = 0.73 \pm 0.07 M_J$$

$$a_{Lc} = 4.5^{+2.2}_{-1.0}\,\mathrm{AU}$$

$$a_{Lb} = 2.3 \pm 0.5\,\mathrm{AU}$$

$$\text{inclination} = 64^{+4}_{-7}\ \text{degrees}$$

$$\varepsilon = 0.15^{+0.17}_{-0.10}$$



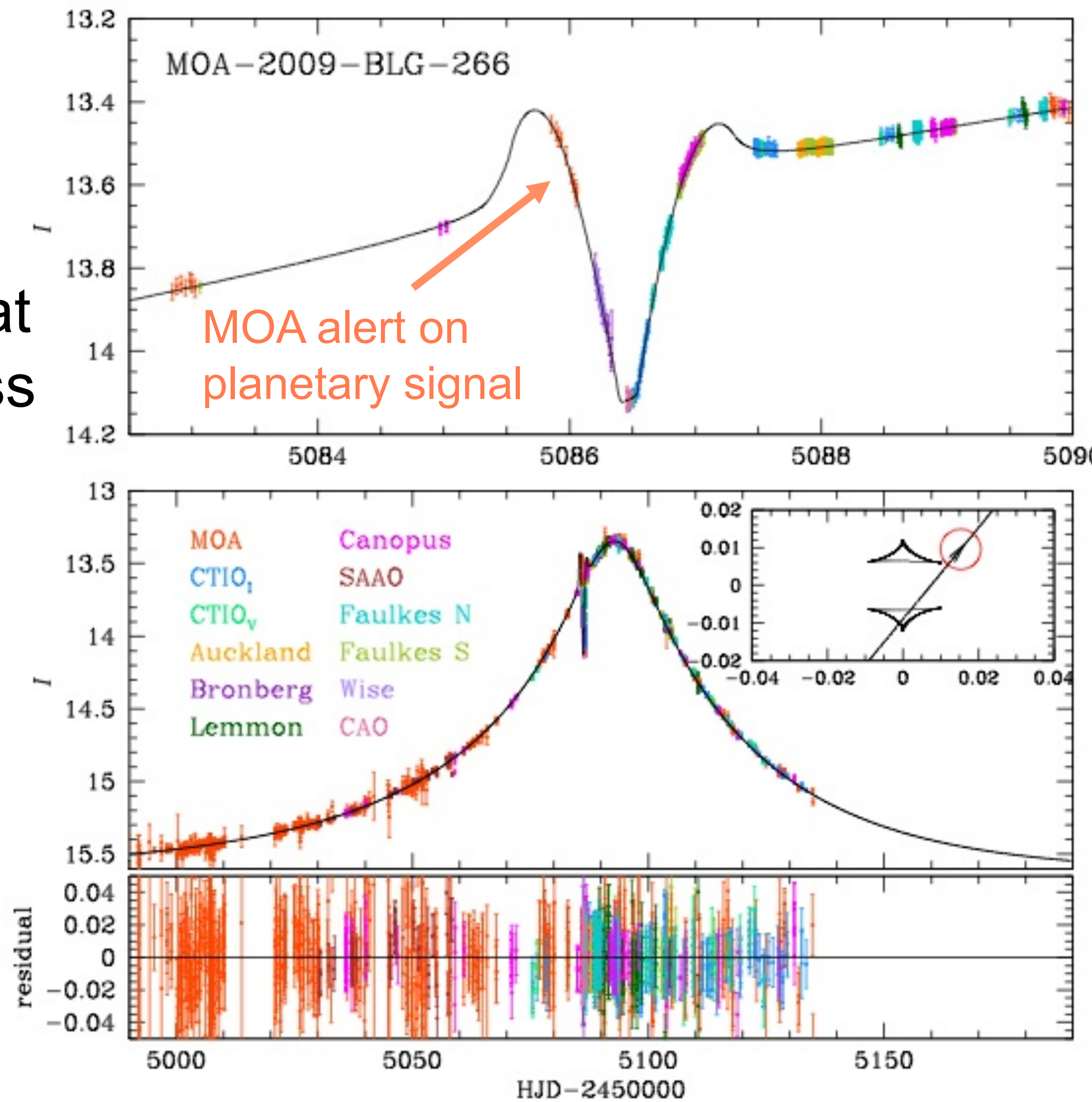
- RV follow-up w/ 40m telescope
  –K = 19 m/sec (H = 17.2)

OGLE-2006-BLG-Lb,c Discovery Implications

- OGLE-2006-BLG-109L is the first lens system with a Jovian Planet which has very high sensitivity to additional Saturn-mass planets
  - OGLE-2003-BLG-235 and OGLE-2005-BLG-71 had much lower magnification
  - OGLE-2005-BLG-169 had only a Neptune (or Super-earth)
- Jupiter + Saturn systems may be common among systems with gas-giant planets
  - Radial velocity planets 47 UMa & 14 Her are similar systems with more massive planets.

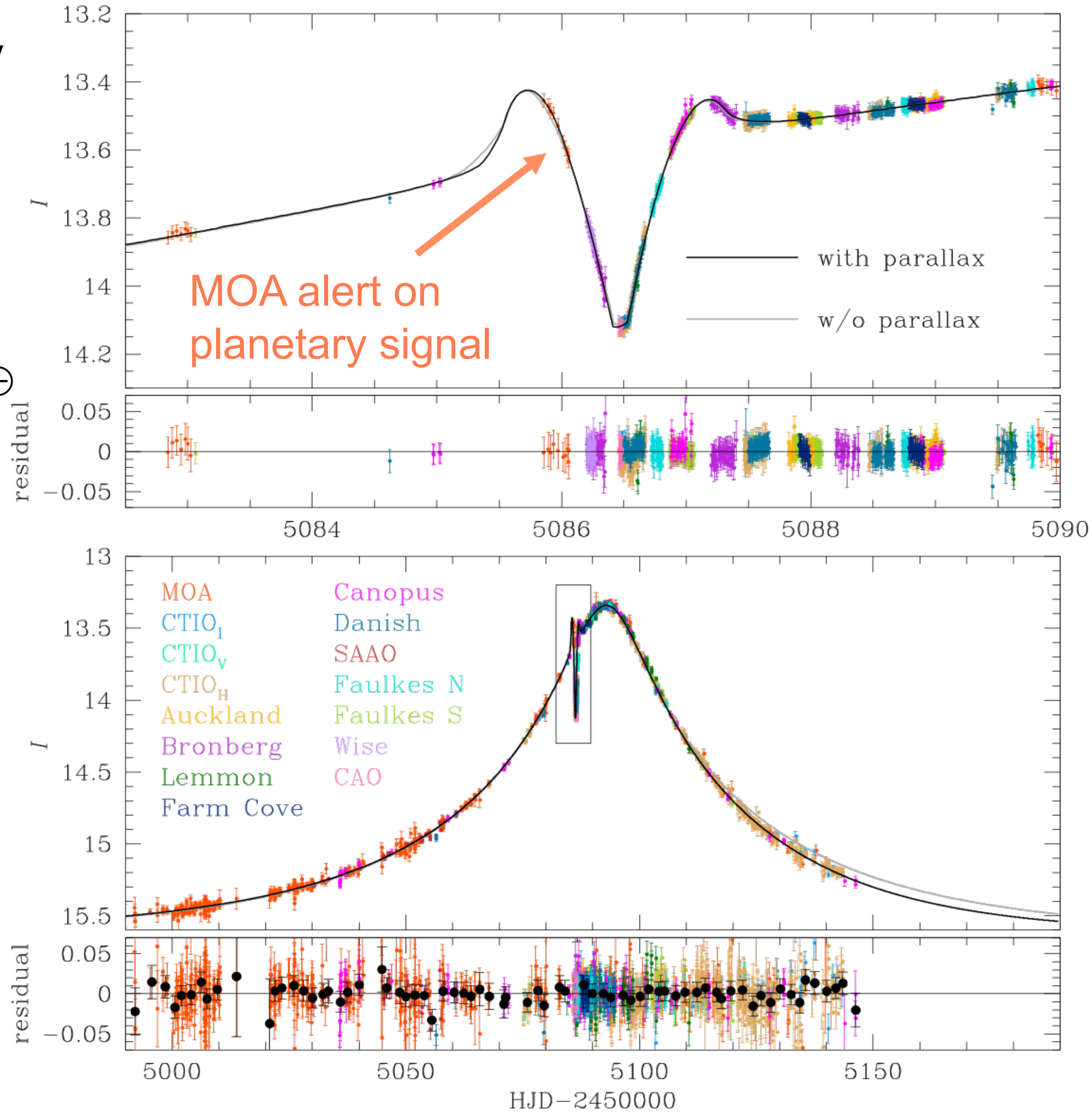
Survey Discovery: MOA-2009-BLG-266

- Planet discovered by MOA on Sept. 11, 2009
- Lowest mass planet at > 0.05 AU with a mass measurement
  $\sim 10 M_{\oplus}$ at $\sim 3\text{AU}$
- Mass measurement from Deep Impact (now EPOXI) Spacecraft



Survey Discovery: MOA-2009-BLG-266

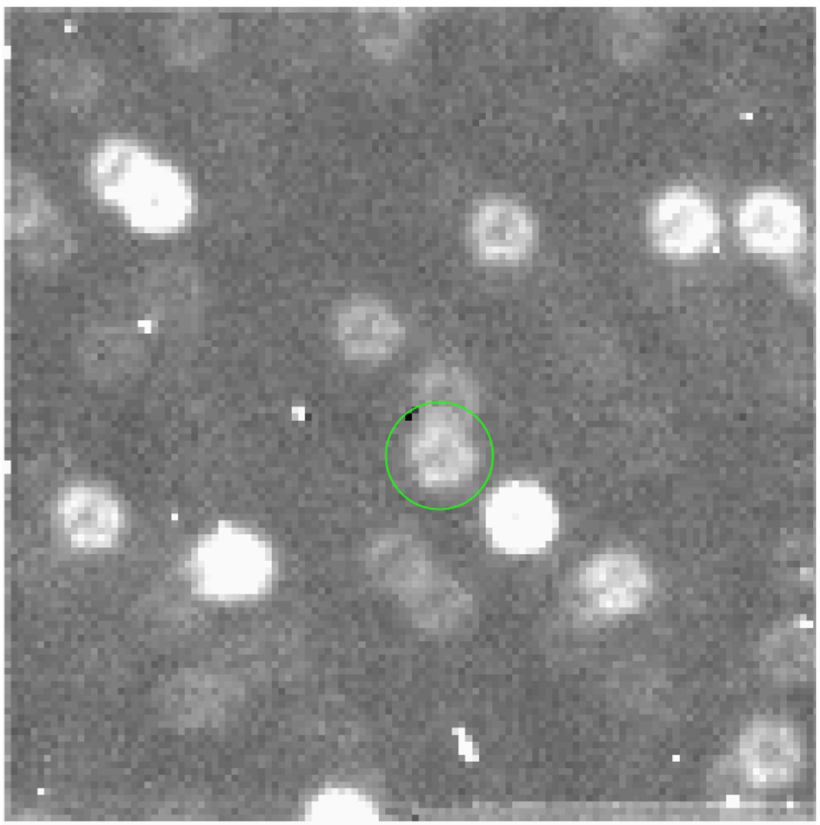
- Planet discovered by MOA on Sept. 11, 2009
- Low-mass planet
  - Probably $\sim 10 M_{\oplus}$
- Mass measurement from Deep Impact (now EPOXI) Spacecraft

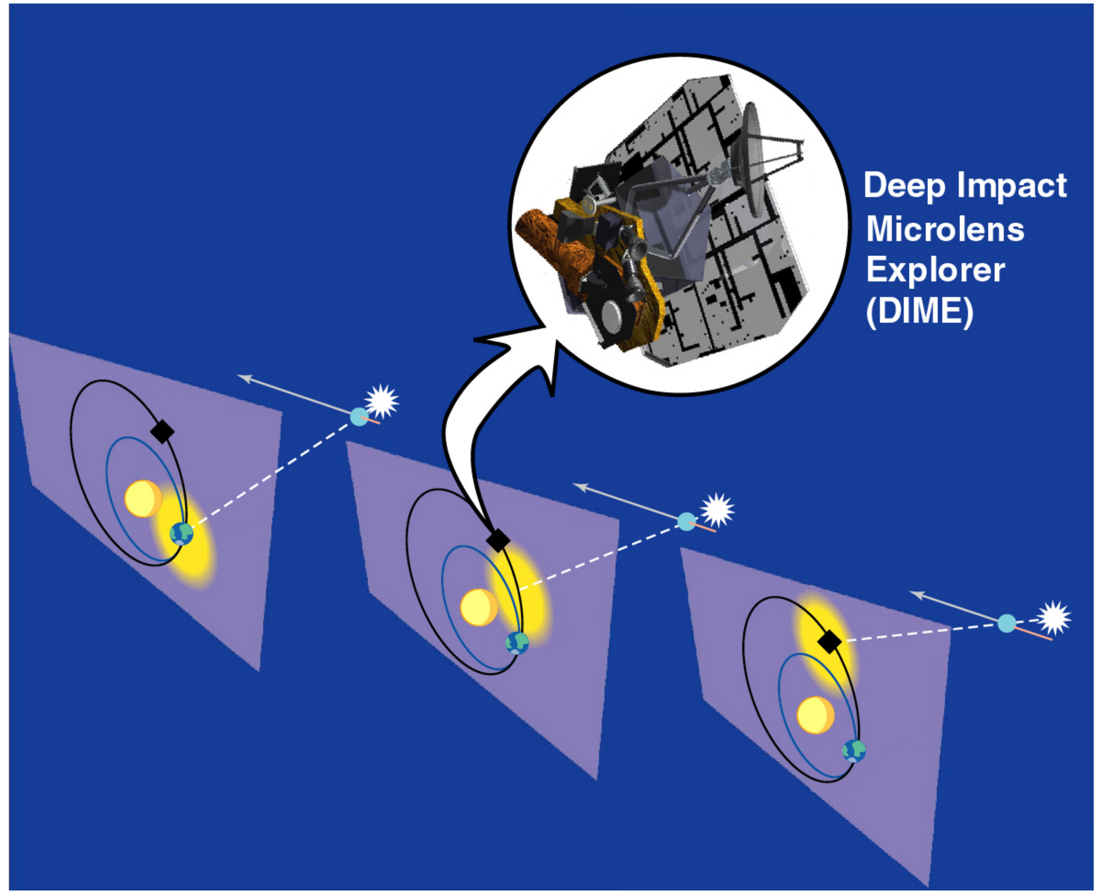


Space-Based Microlensing Parallax

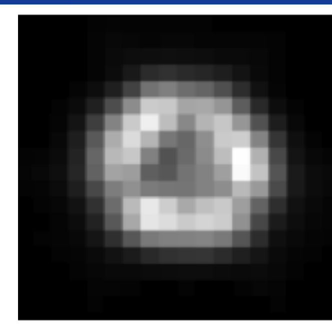
2004: study LMC microlensing w/ DI imaging (proposed)

2009: Geometric exoplanet and host star mass measurements with DI

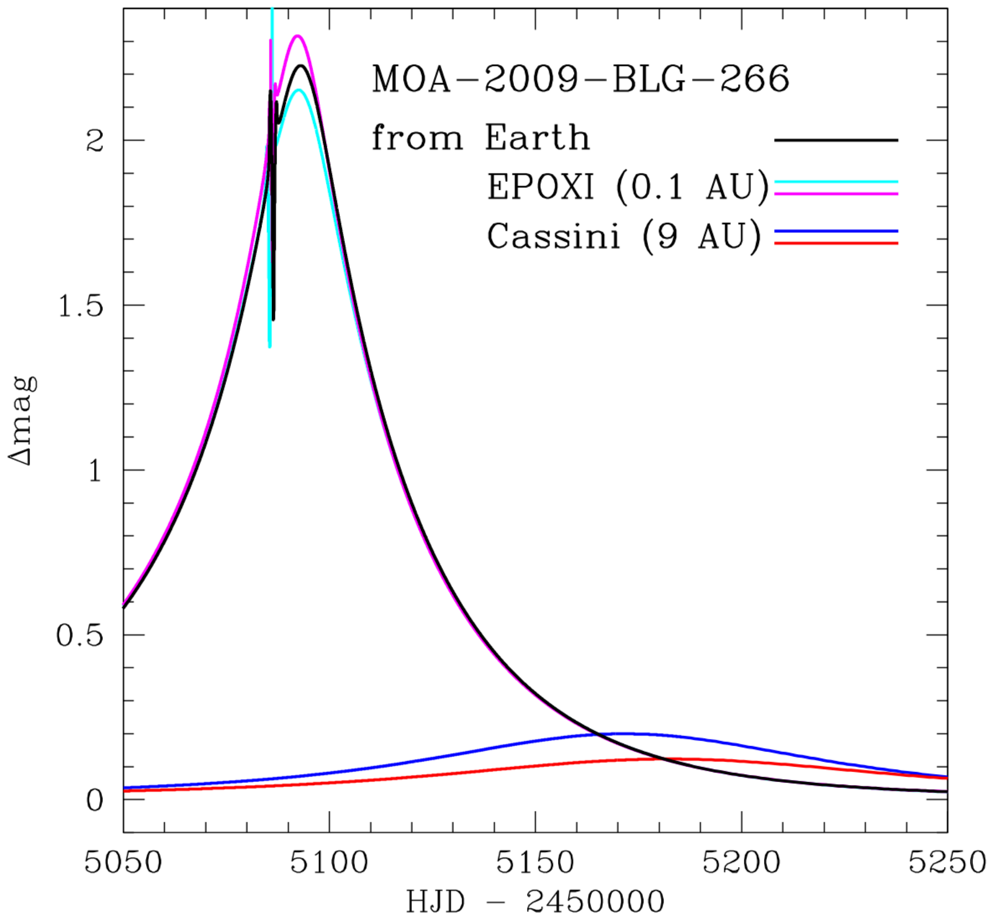




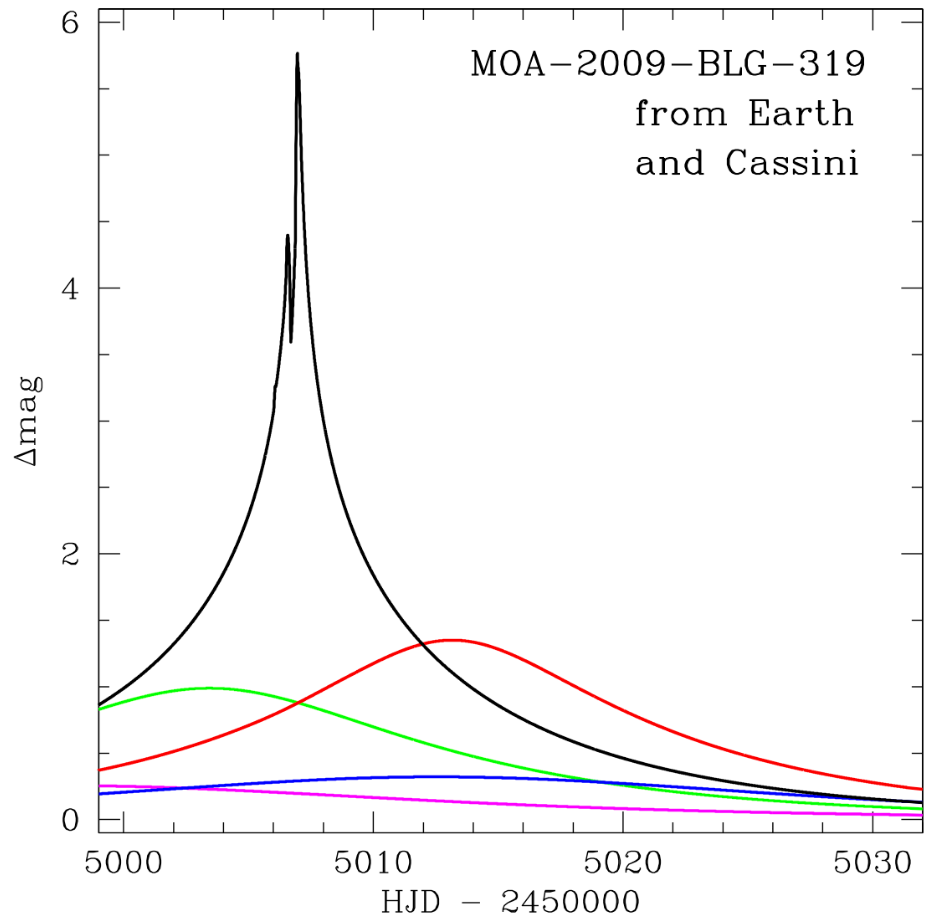
EPOXI PSF!



Satellite Observations of Exoplanet Microlensing events



Galactic disk lens system
(long)



Galactic bulge lens system
(short)

Satellite Observations of Exoplanet Microlensing events

- Observe during host star lensing event
  - Targets are known only weeks to months before event is over
  - But most targets are within 5-10 degrees of the central Galactic bulge
  - Plan observations of a central bulge field, and update the coordinates just before the observations?
- Optimum Earth-satellite separation ~a few times smaller than Einstein Radius, R_E
  - But depends on detailed characteristics of the event
- Different event classes
  - Long events - months
  - Short events - 1-2 weeks
- Targets are usually “faint” I ~ 13-20
  - Long exposures, good pointing stability
  - Low precision photometry compared to transits

Long Exoplanet Microlensing events

- Long events - months
  - Planetary host stars in the Galactic disk and/or have high mass
    - High mass means M > 0.3 solar masses
  - Many have partial of full microlensing parallax measurements
  - Projected Einstein radius ~ 4 AU
  - Satellite observations to remove degeneracies in modeling
  - MOA-2009-BLG-266 is an example
    - 3 kpc away
    - Host mass = 0.5 or 0.7 solar masses
  - Best observed by a satellite 0.5-2 AU from the Earth in projected separation
    - e.g. Cassini in 2016 or 2017
    - Mars missions

Short Exoplanet Microlensing events

- Short events - 1-2 weeks
  - Host stars in the bulge and/or low mass (< 0.3 solar masses)
  - No microlensing parallax data from the ground
  - Projected Einstein radius 10-30 AU
  - Best observed by a satellite at 2-15 AU in projected separation
    - e.g. Cassini in 2011-2015
  - Usually no signal from the ground
  - A few observations from a 2nd satellite are sometimes helpful

The NASA *EPOXI* Mission

Michael A'Hearn - EPOXI PI, Tilak Hewagama, Jessica Sunshine, Dennis Wellnitz (U. Maryland)

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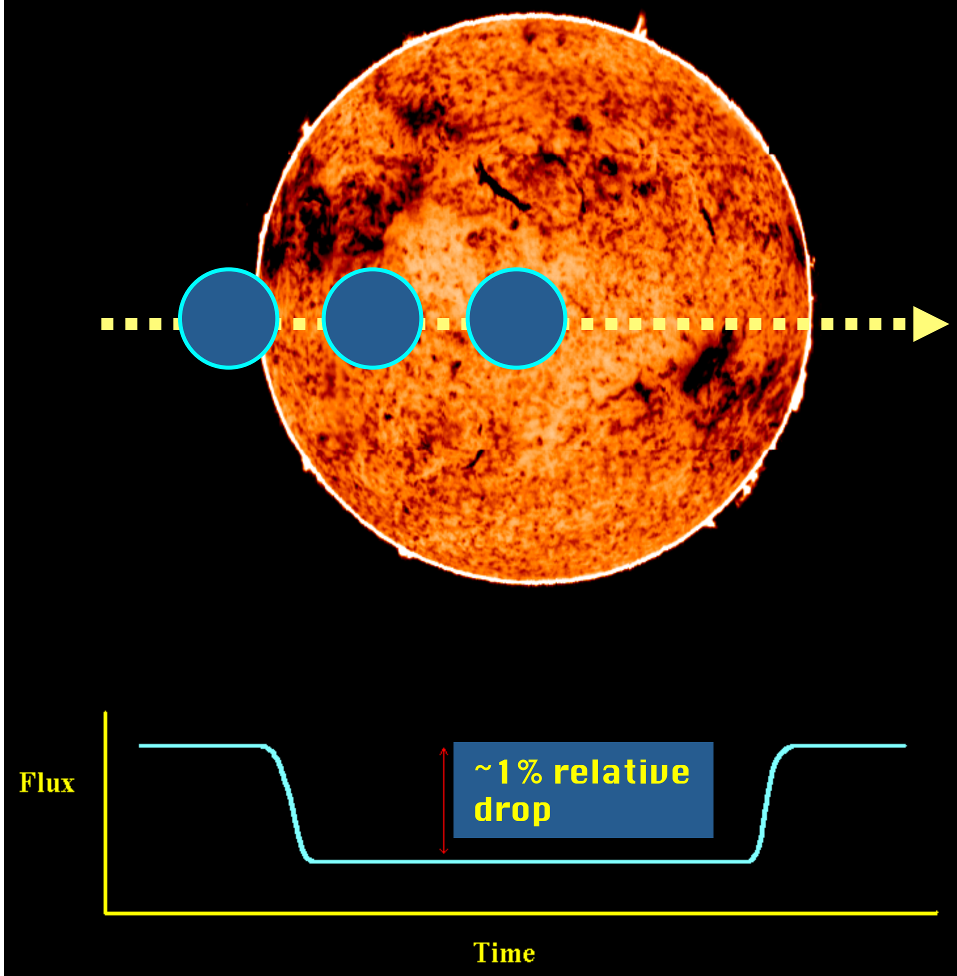
David Charbonneau, Matt Holman, **Jessie Christiansen**, David Weldrake, Sarah Ballard (CfA)

Don Hampton (U. Alaska), Carey Lisse (JHU), Sara Seager (MIT), Joseph Veverka (Cornell)

Transiting Planets



Bulk properties
- radius
- density

Atmospheric properties
- transmission
- emission

Informative but elusive…
- high precision
- high phase coverage
- high cadence

= space…!

Spacecraft Requirements*

TRANSIT DISCOVERY

- At least 1% photometric precision
- Stable over timescales of days/weeks
- Either wide field of view (> 1 degree square) to survey lots of stars (Kepler/CoRoT) or…
- Narrow field of view to target a specific set of stars (Mearth) although wide enough for nearby stars of comparable brightness
- Significant dedicated instrument time and…
- High data downlink capacity

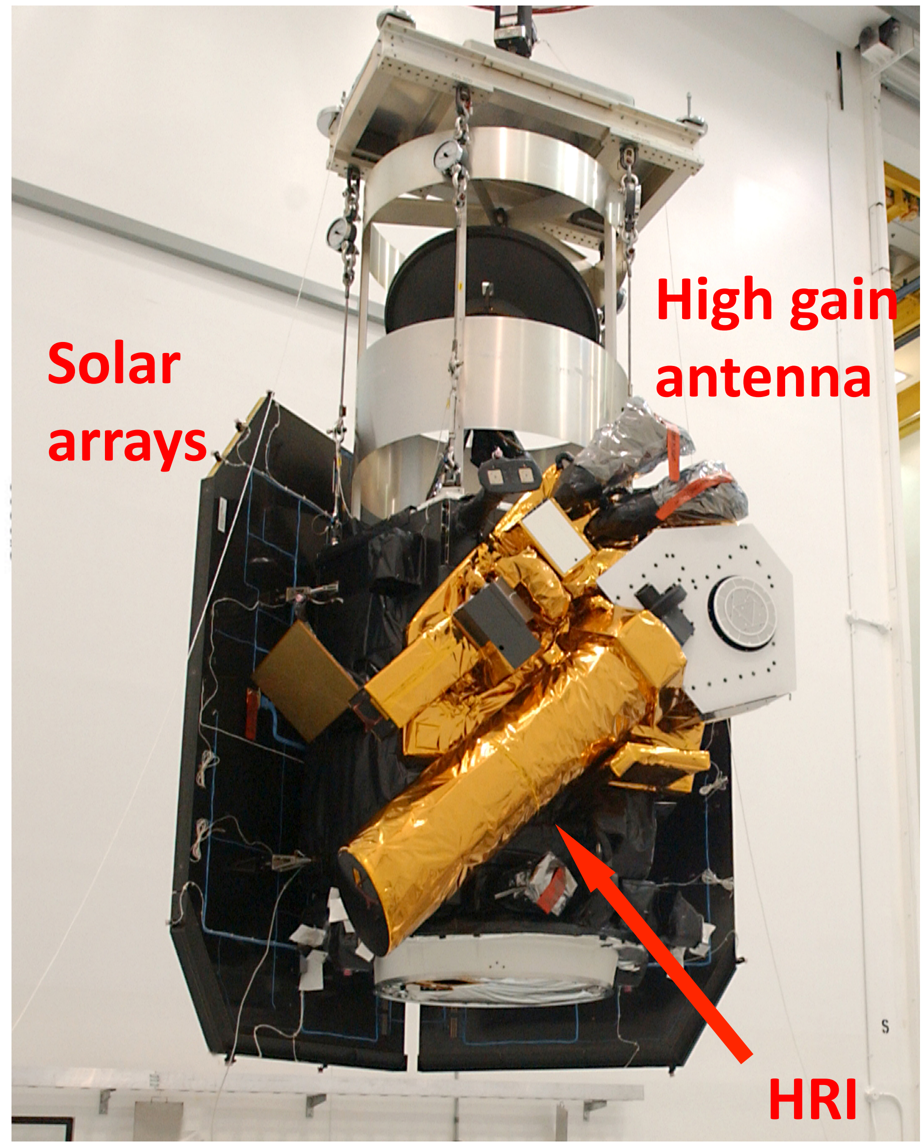
TRANSIT CHARACTERIZATION

- ~0.1% photometric precision
- Stable over timescales of hours
- Multiple filters an advantage
- Narrow field of view sufficient, although wide enough for nearby stars of comparable brightness
- Less dedicated instrument time but…
- Strict time constraints

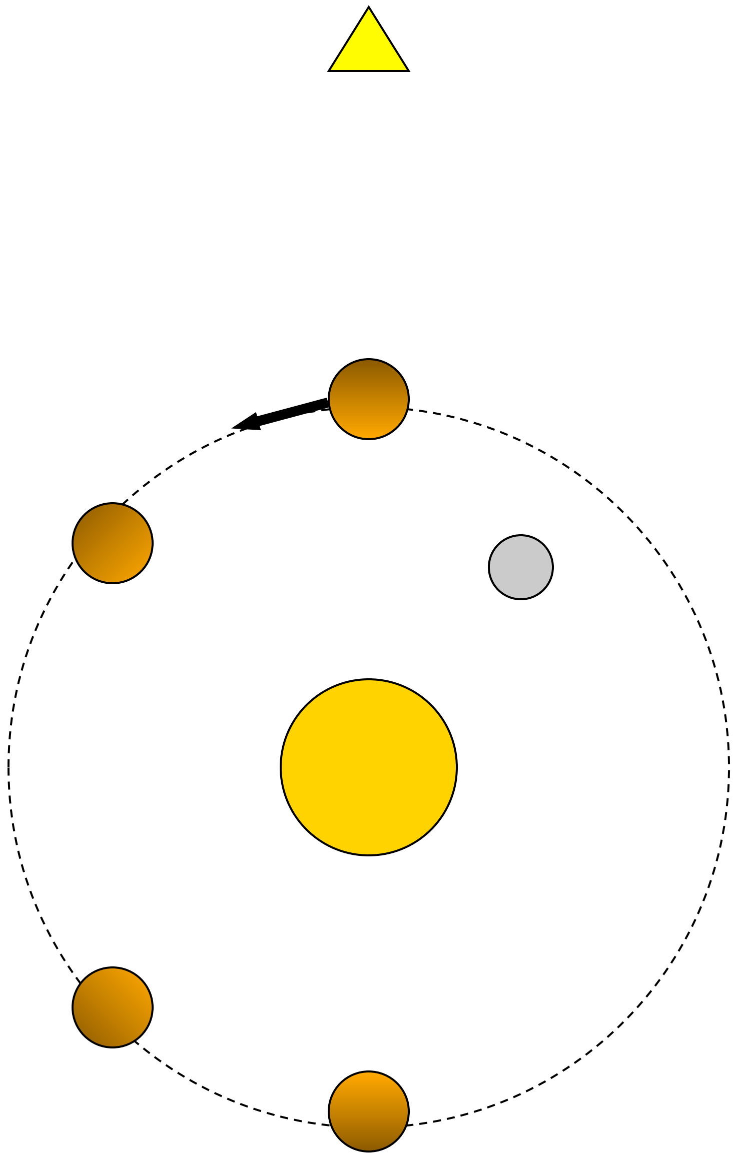
*Gas Giants

High-res vis instrument

- 30-cm aperture, clear filter (350-950nm)
- 1k x 1k CCD, 0.4”/pixel, FOV 51” in 128x128 sub-array
- 230MB of onboard memory ~ 7000 images
- Defocus (FWHM~10 pixels) an advantage for high precision photometry!

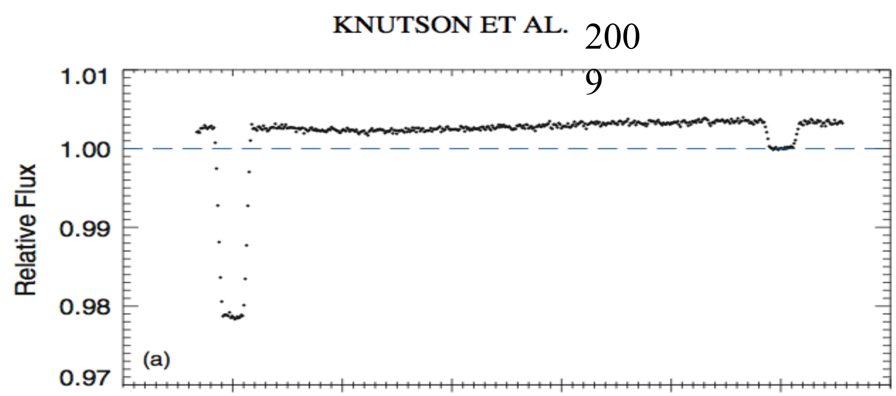


EPOCh Science goals



Obtaining ultraprecise, high phase coverage time series photometry for characterization of a small set of known transiting planets

- Additional transiting planets
- Transit timing variations
- Reflected light at secondary eclipse

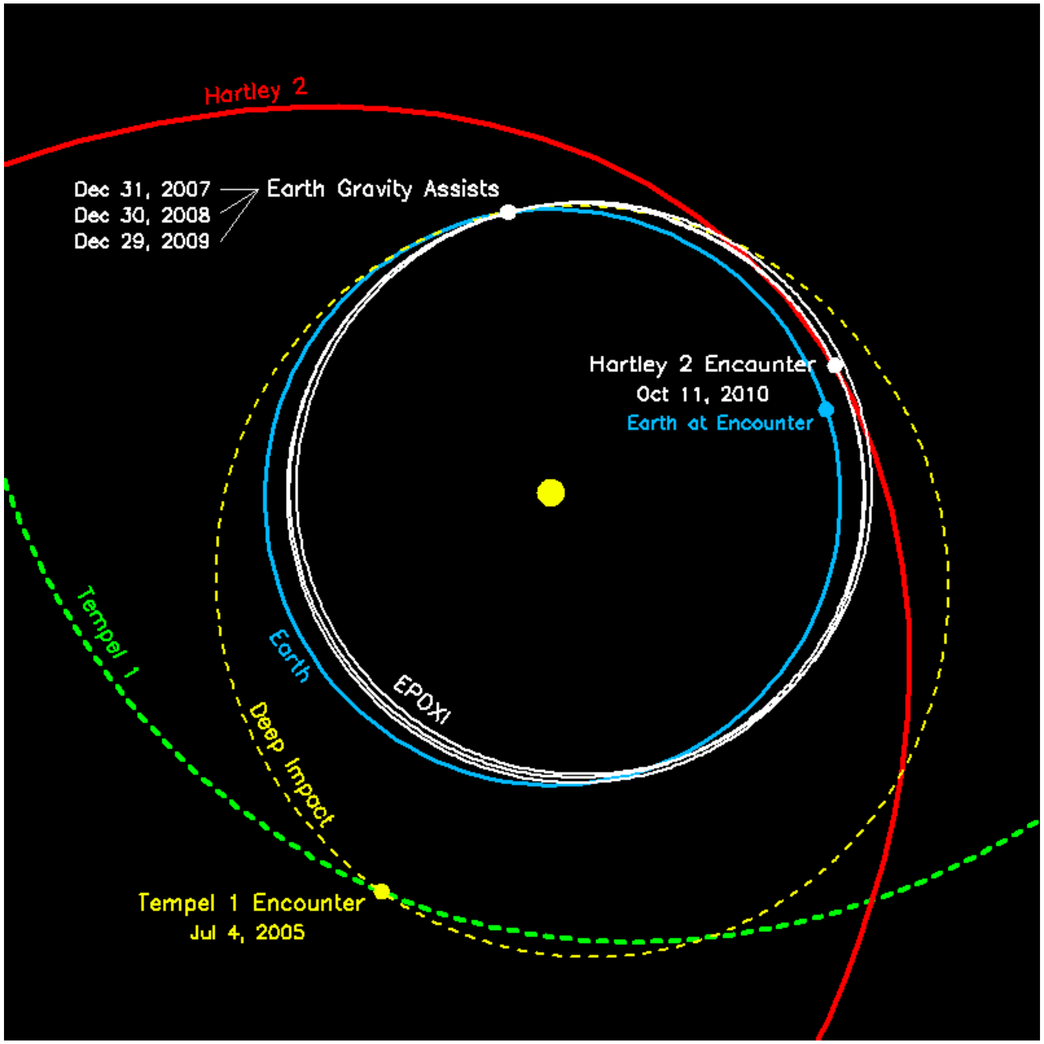


Mission overview

Jul 2005: Deep Impact Comet Tempel I encounter

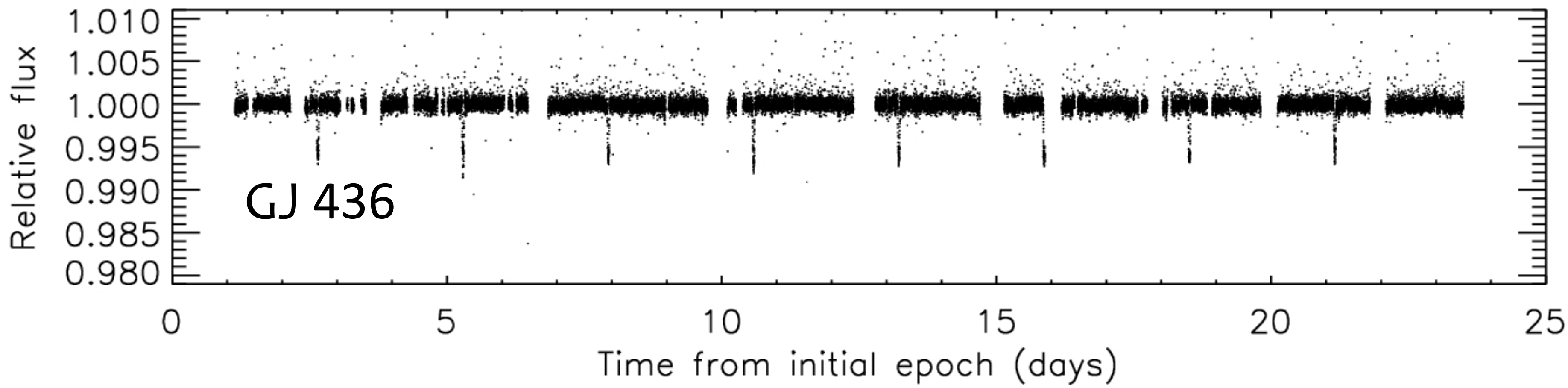
Jan - Aug 2008: EPOCh observations

Dec 2010: DIXI Comet Hartley 2 encounter

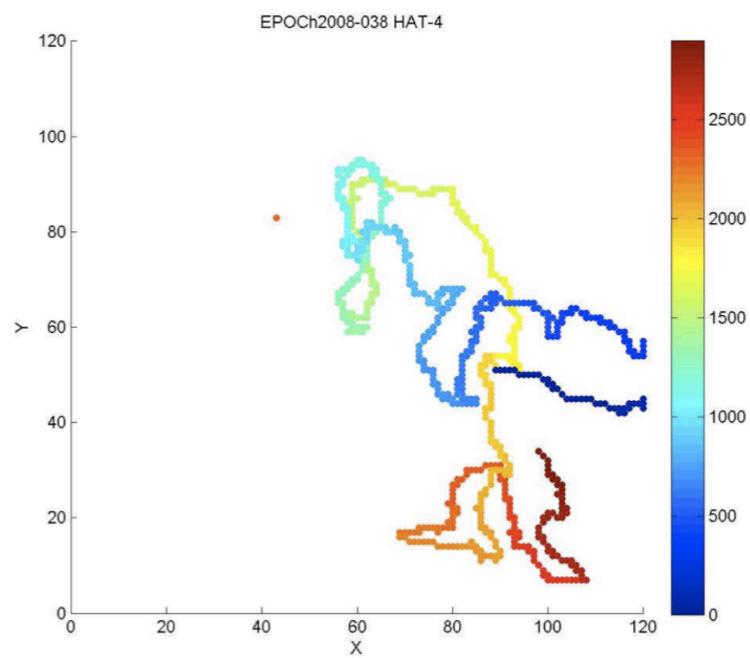


(stable heliocentric orbit)

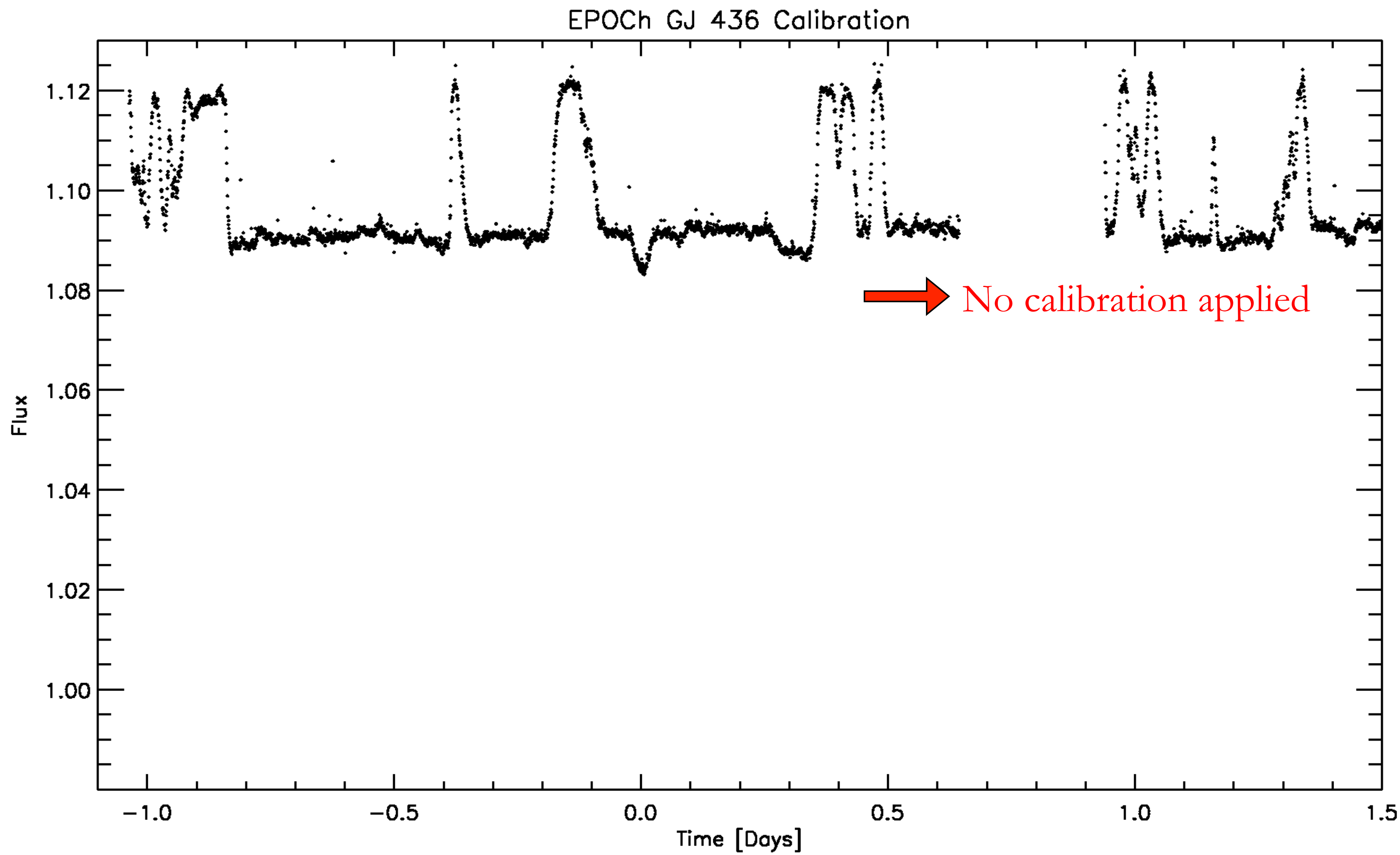
Photometry



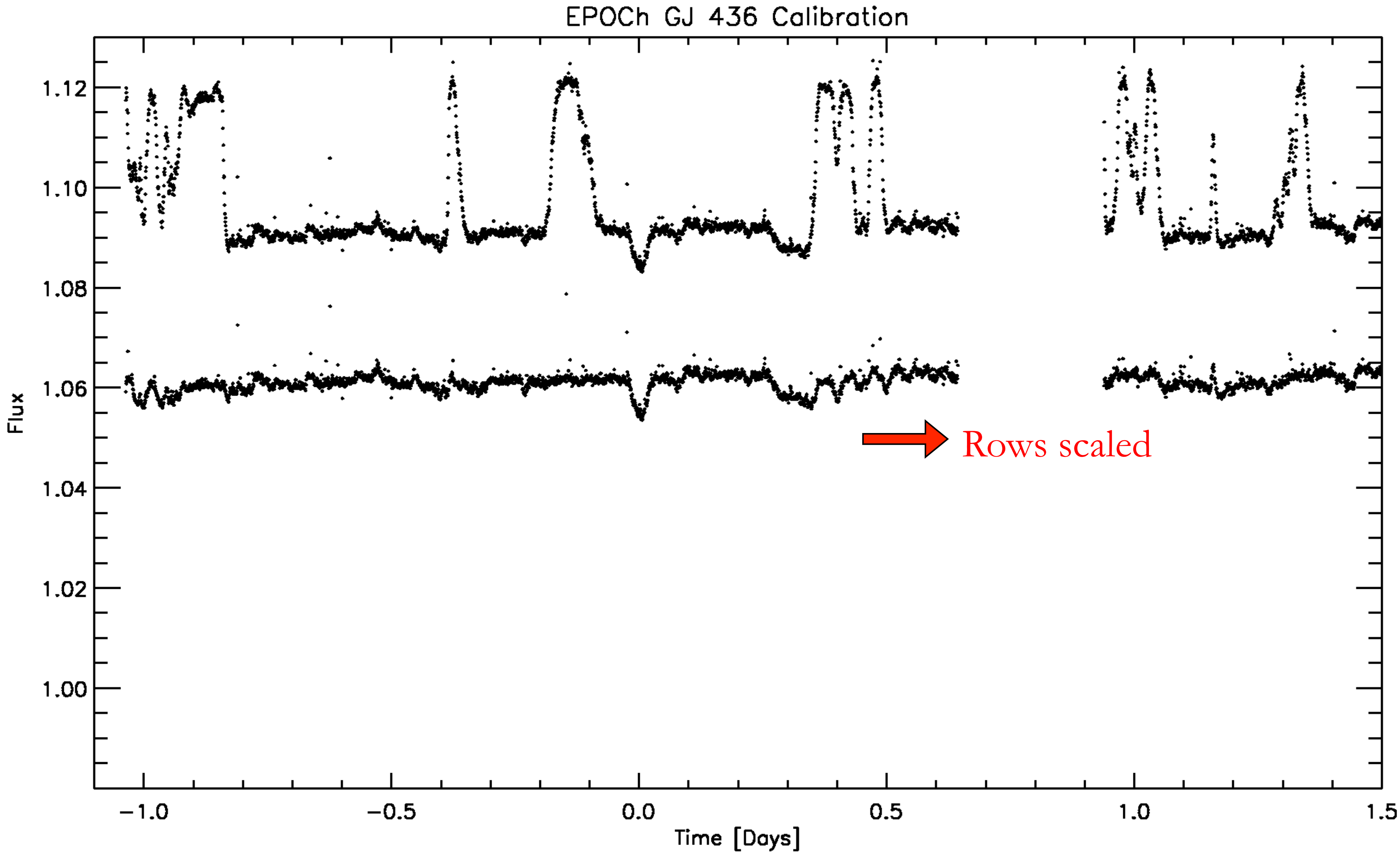
- Calibrated images via Cornell/UMD
- Major systematic: pointing jitter!
- Current photometric noise in 50-s integration = 1.5-1.9 times the Poisson noise limit



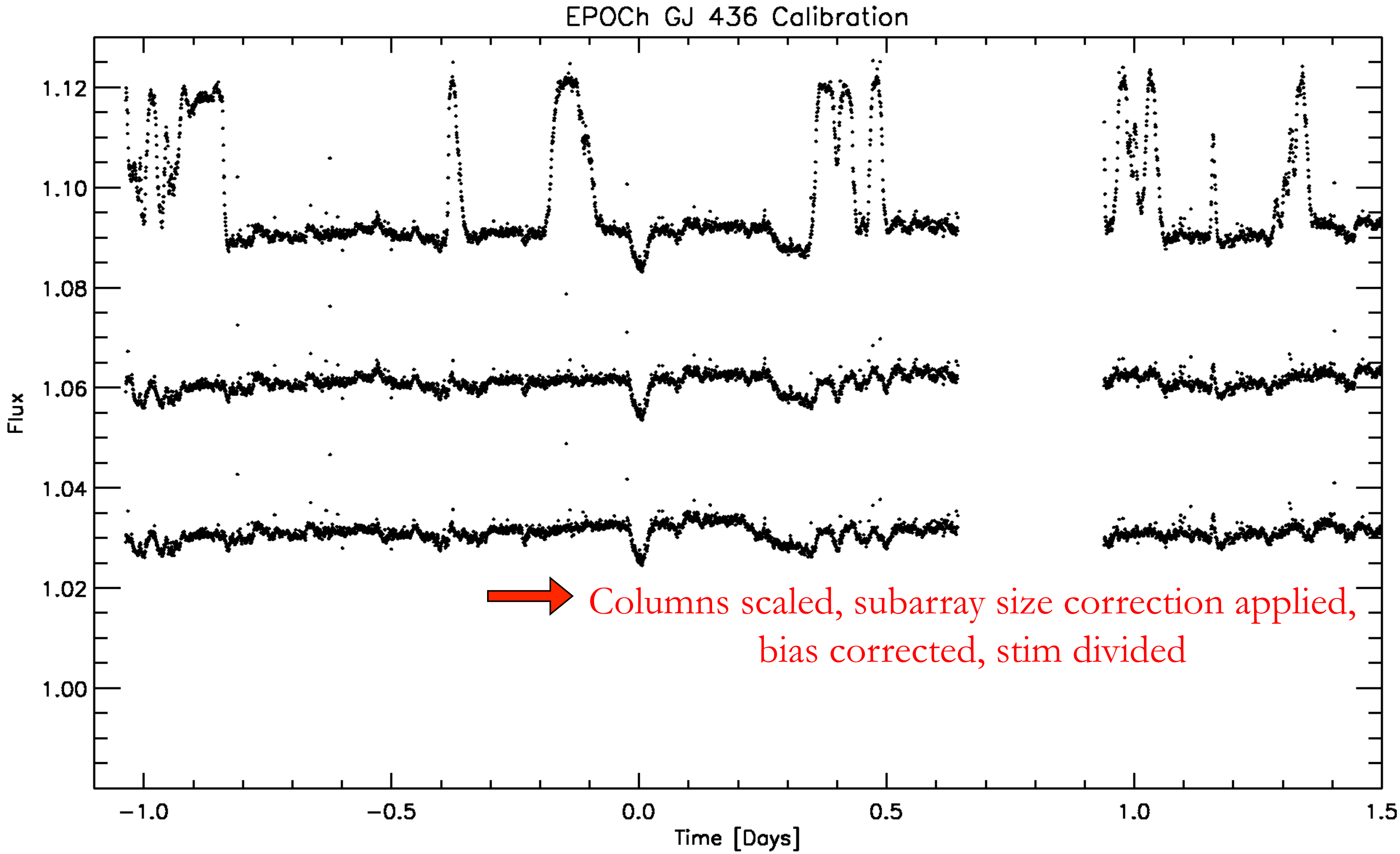
EPOCh Calibration



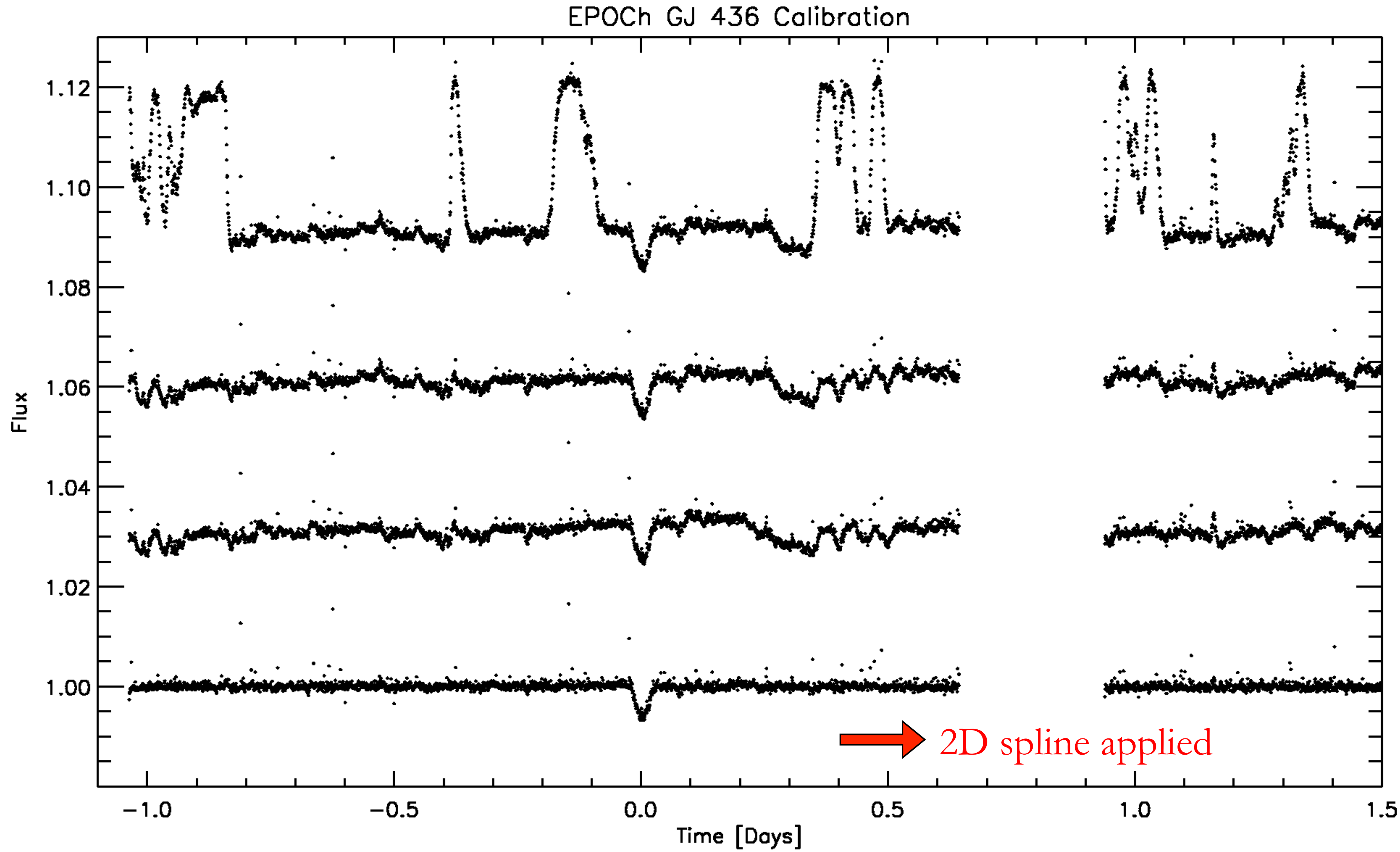
EPOCh Calibration



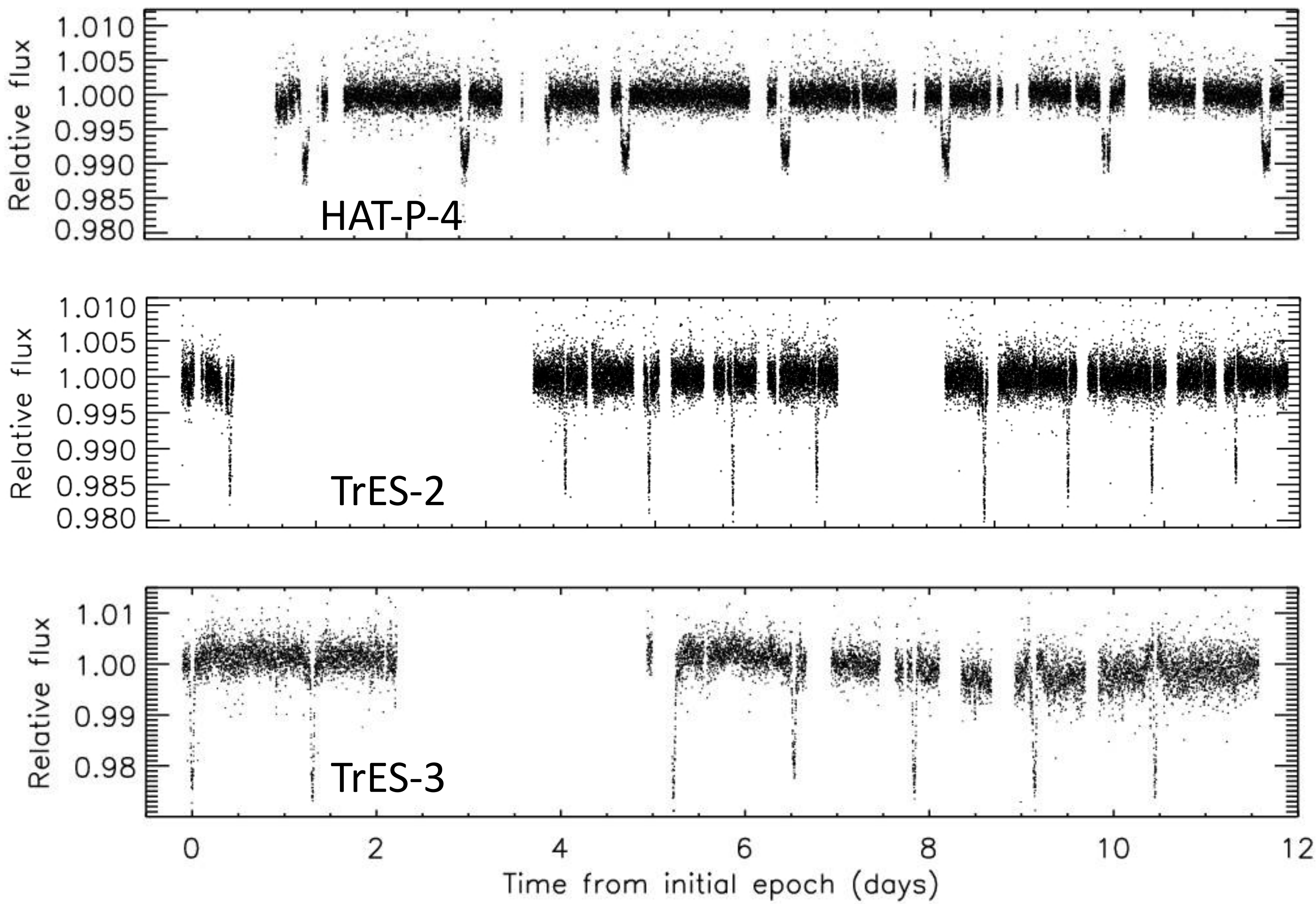
EPOCh Calibration



EPOCh Calibration



Photometry



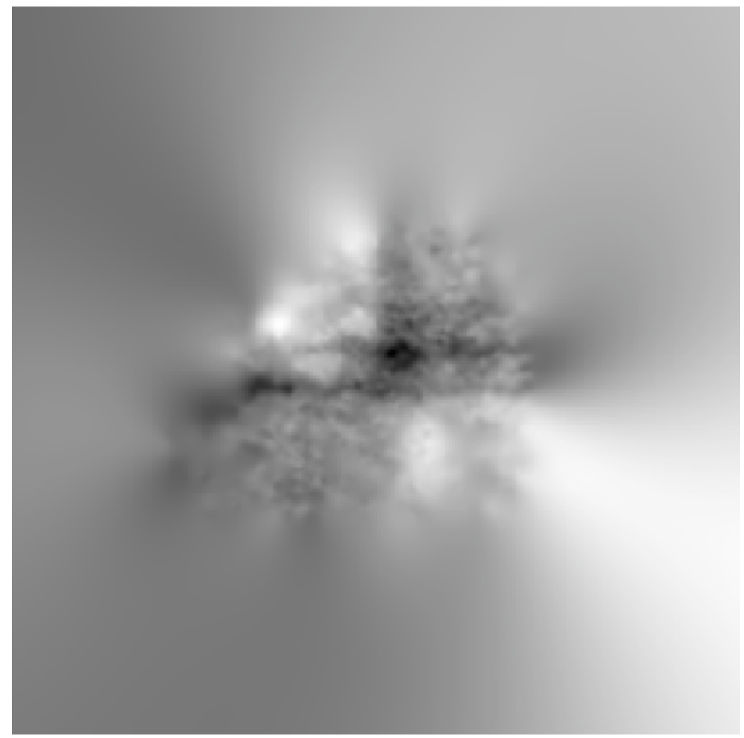
HAT-P-4
TrES-2
TrES-3
Relative flux
1.010
1.005
1.000
0.995
0.990
0.985
0.980
1.01
1.00
0.99
0.98
0
2
4
6
8
10
12
Time from initial epoch (days)

EPOXI Major Results

- GJ 436 (Ballard et al, in press)
  - Refined system parameters
  - New set of transit times
  - Ruled out additional transiting planets with 95% confidence interior to GJ 436b (>1.25Rearth) and to periods up to 8.5 days (>2.0Rearth)
- HAT-P-7 (Christiansen et al, 2010)
  - Refined system parameters
  - New set of transit times
  - 'Confirmed' the Kepler secondary eclipse depth measurement in the optical
- HAT-P-4, TrES-3, TrES-2, WASP-3 (Christiansen et al, submitted)
  - Refined system parameters, new sets of transit times

Lessons Learned...

- Stability, stability, stability
  - Repeatability
  - 'World's most expensive thermometer'
  - Prefer the star to stay in the field of view
- Calibration!
  - Pre-launch can be insufficient
- Photons, photons, photons
  - Obvious but critical when shoe-horning instruments/ projects into transit work
- Fast response required
  - Time is (lots of) money



The EPOXI View of Earth

Nick Cowan (University of Washington)

KITP (May 18, 2010)

Looking for Water

- Water in atmosphere?
  - H_2O vapor
  - Variable cloud cover
- Water on surface?
  - Color of oceans
  - Glint of oceans
  - Polarization from oceans

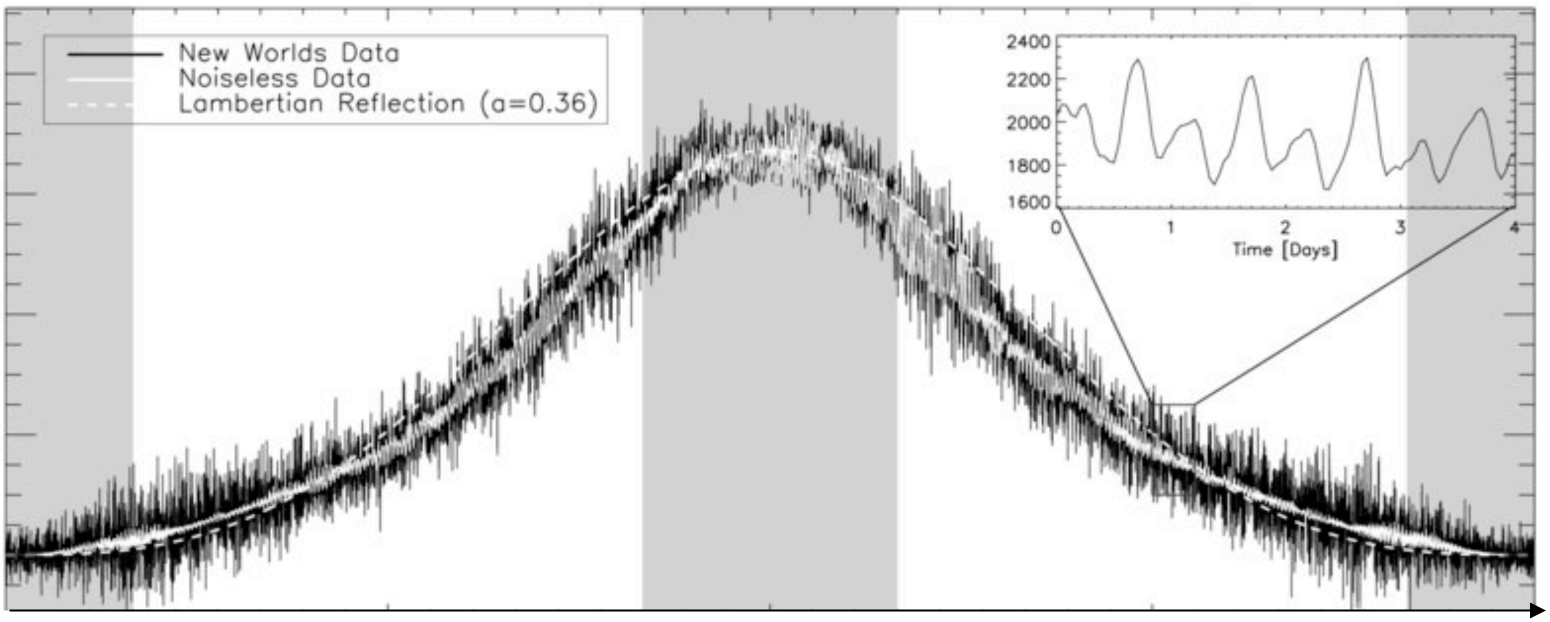
Long-Exposure Spectroscopy

Yearly Variability

Daily Variability

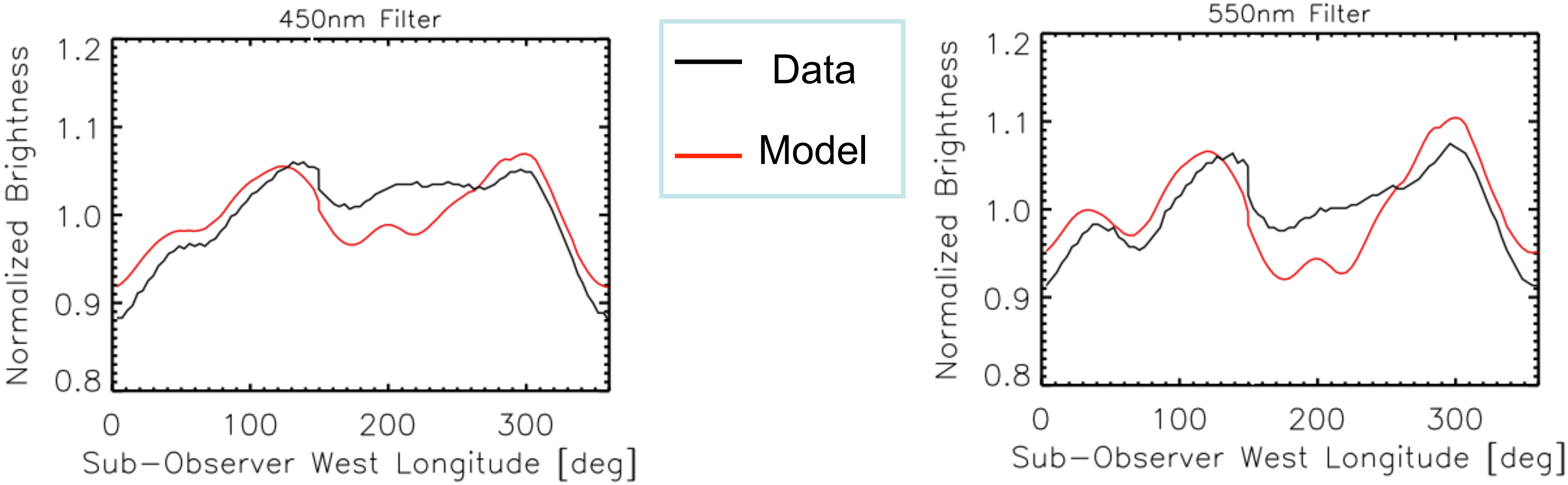
Orbital & Rotational Variability

flux

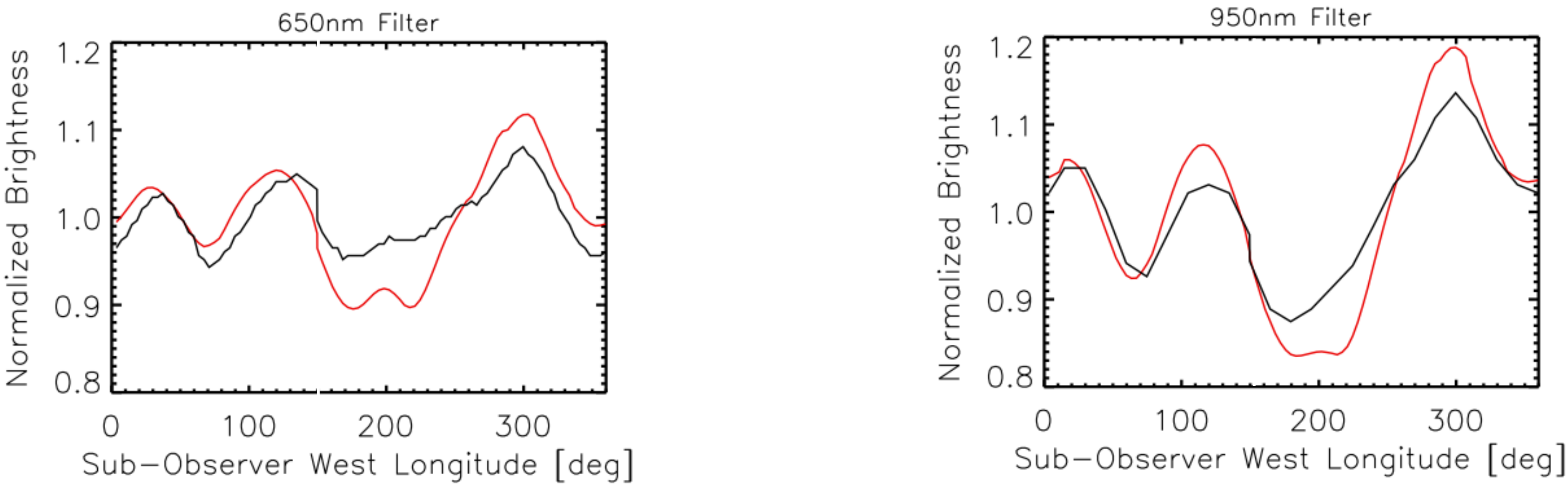


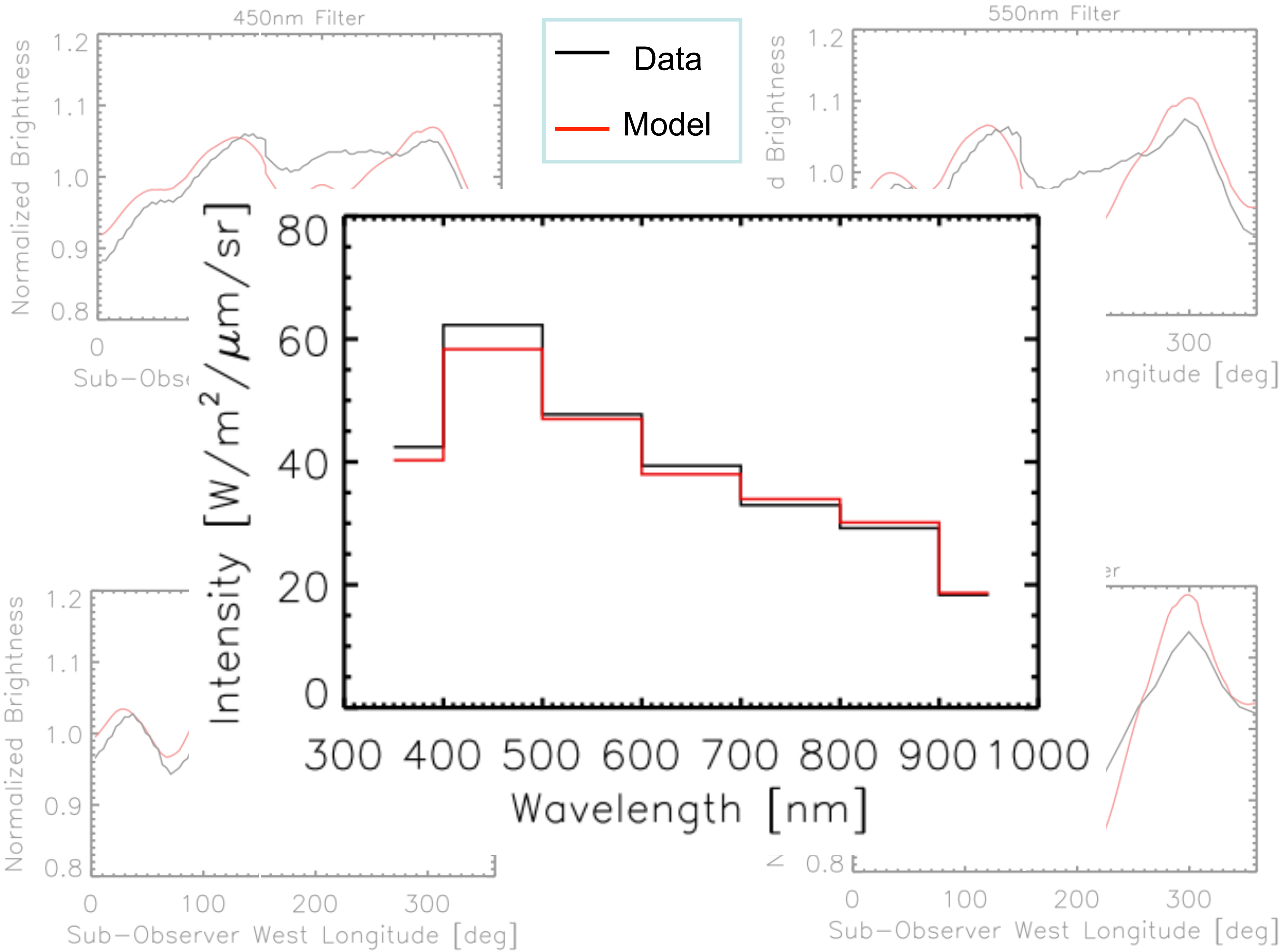
Oakley & Cash (2009)

- Will **not** know A_0 (degenerate with R_p)
- **Will** measure $A(t)/A_0$ and $A(\lambda)/A_0$



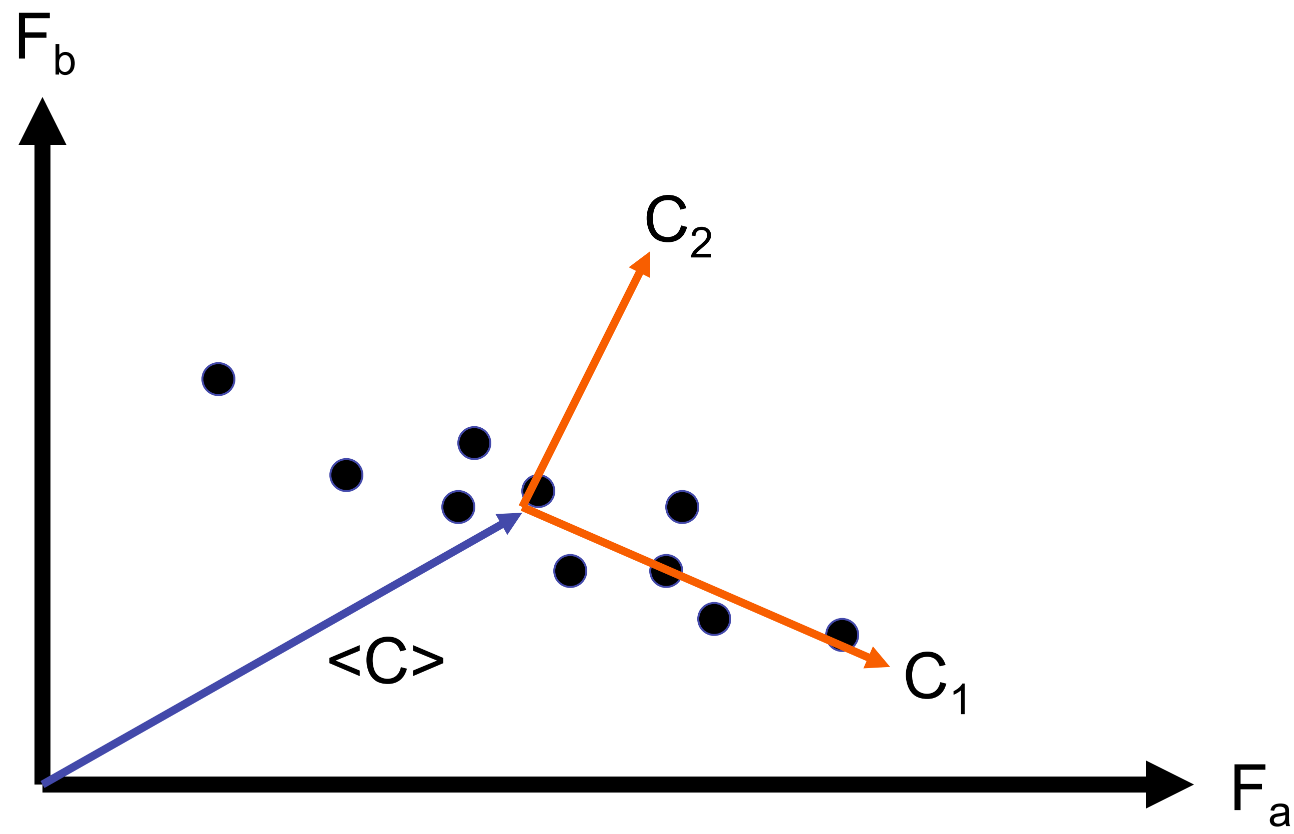
Light Curves June 5th, 2008
(Robinson et al. 2010)



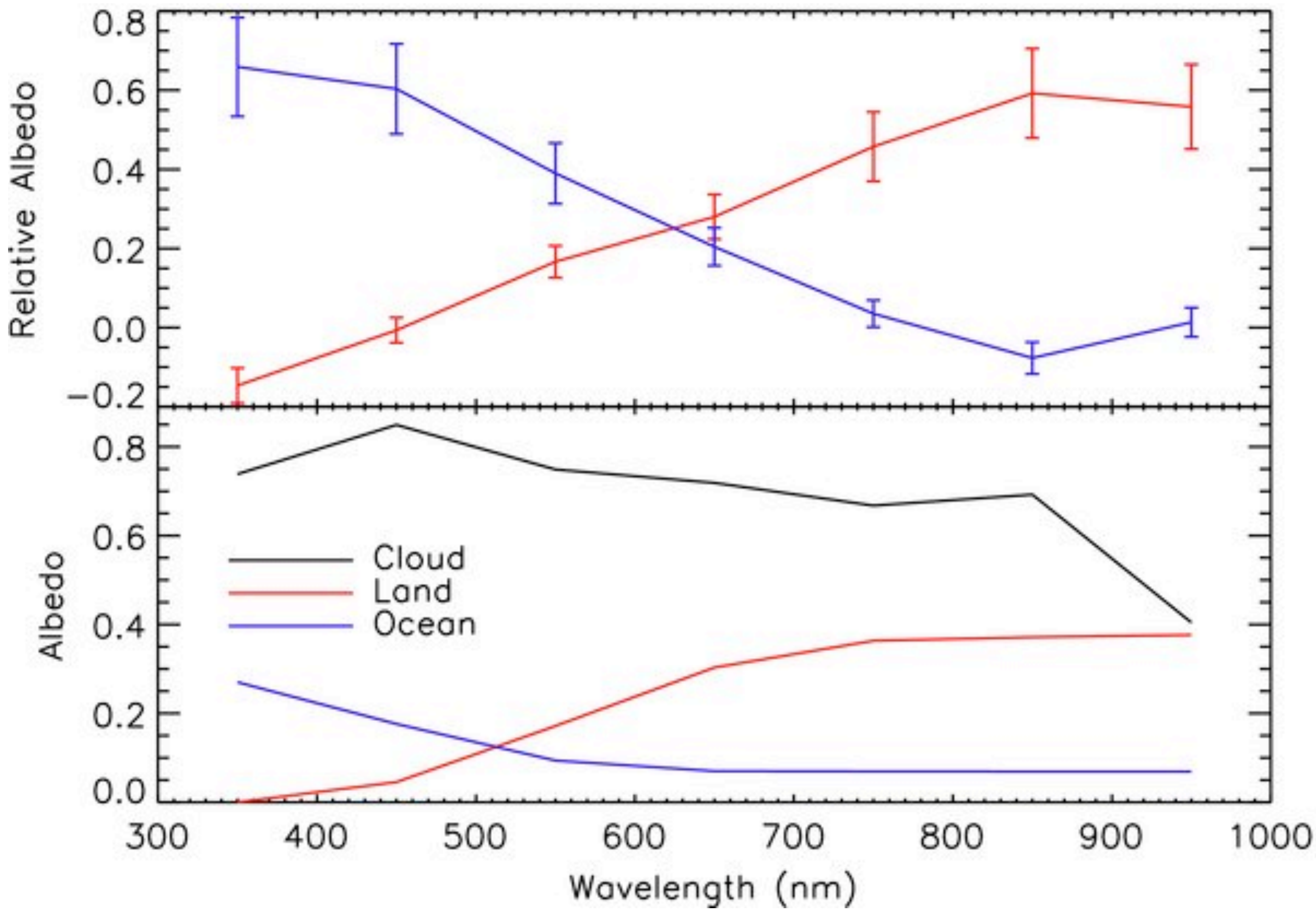


450nm Filter
550nm Filter
Data
Model
Intensity [W/m^2/μm/sr]
Wavelength [nm]
Normalized Brightness
Sub−Observer West Longitude [deg]

Principal Component Analysis



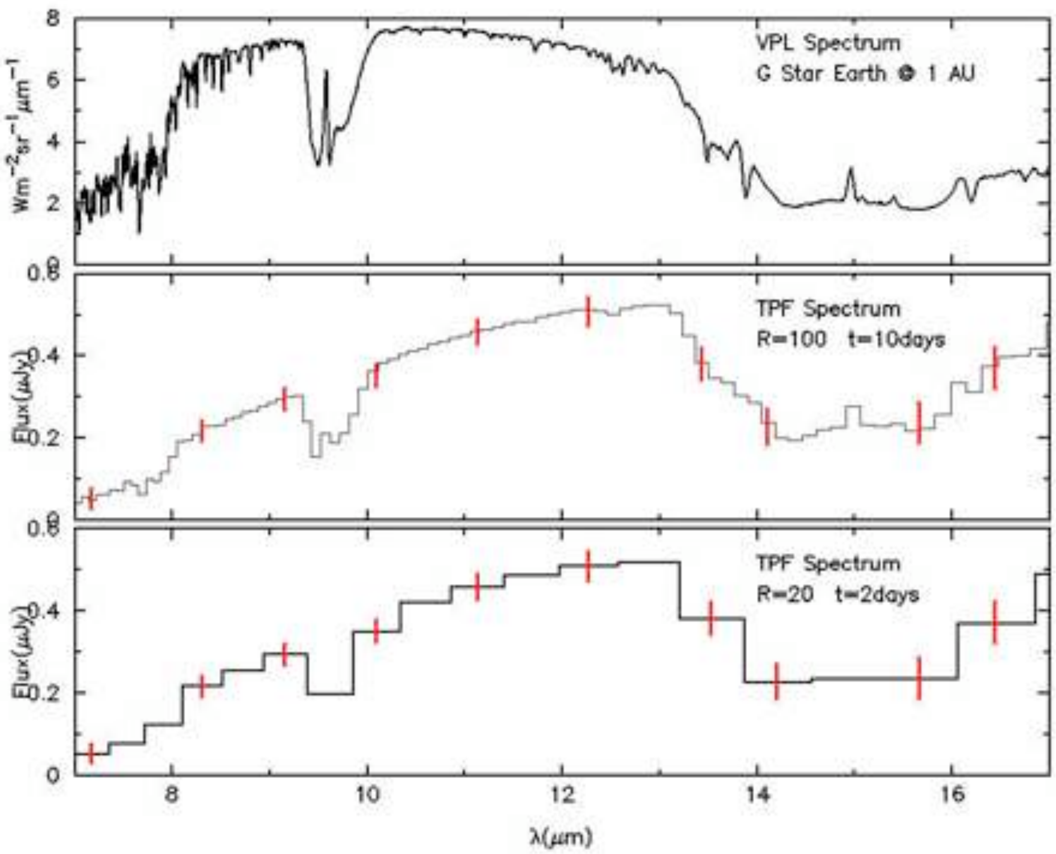
Time Averaged Spectrum: Eigencolors



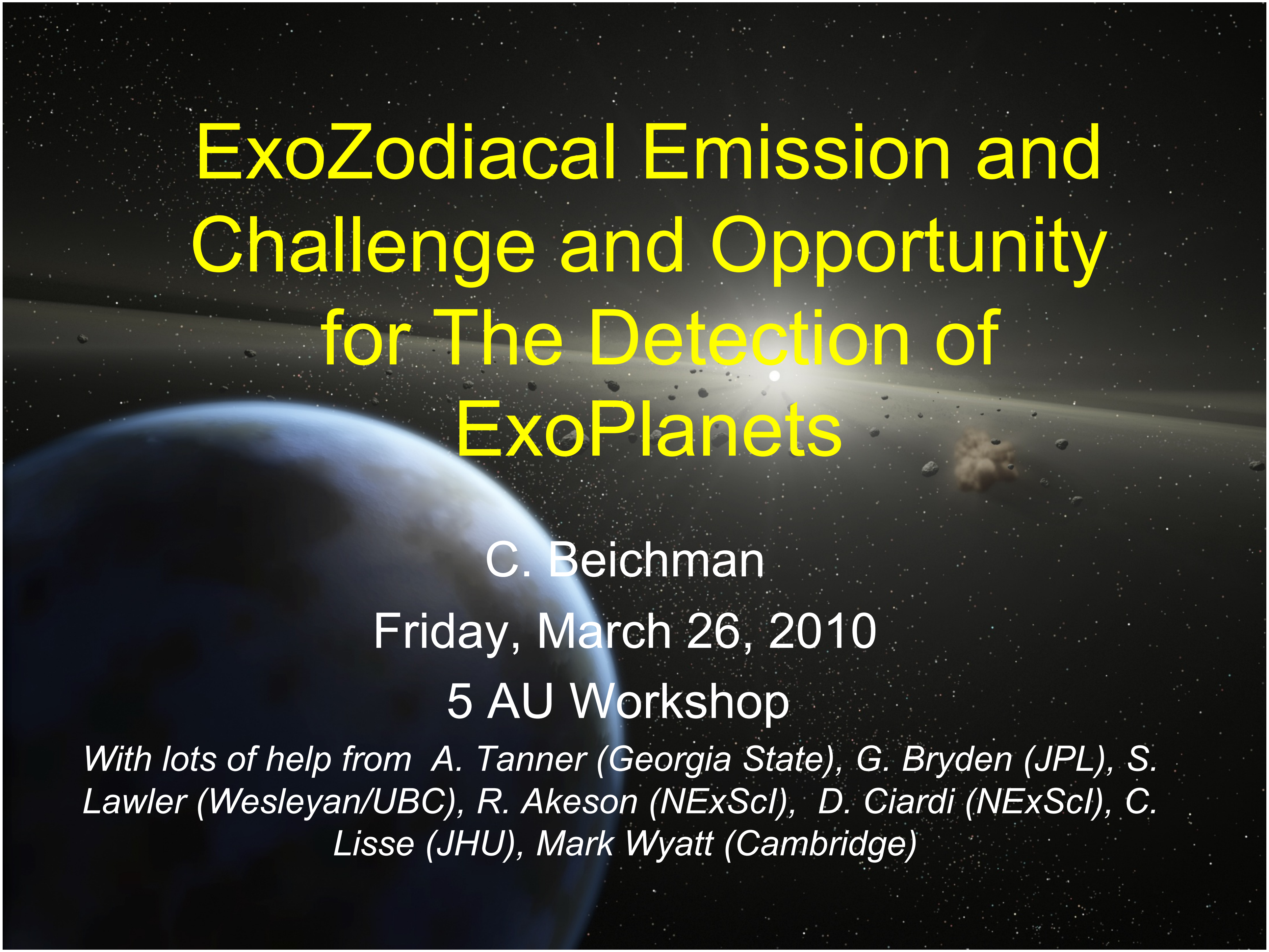
Cowan et al. (2009)

Conclusion

Time-Resolved, Multi-Band Photometry Complements Time-Averaged Spectroscopy



From VPL



ExoZodiacal Emission and Challenge and Opportunity for The Detection of ExoPlanets

C. Beichman

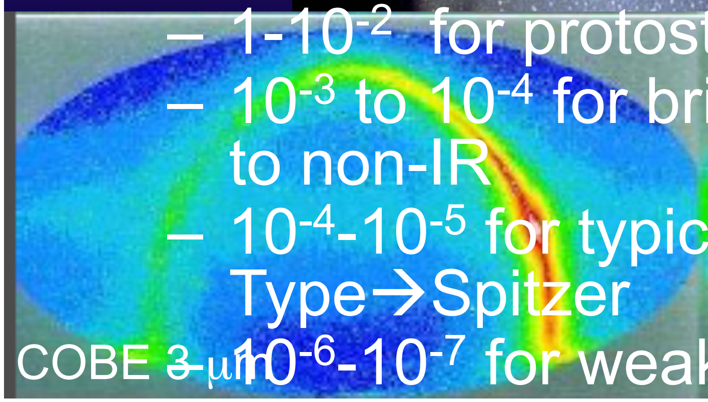
Friday, March 26, 2010

5 AU Workshop

With lots of help from A. Tanner (Georgia State), G. Bryden (JPL), S. Lawler (Wesleyan/UBC), R. Akeson (NExScI), D. Ciardi (NExScI), C. Lisse (JHU), Mark Wyatt (Cambridge)

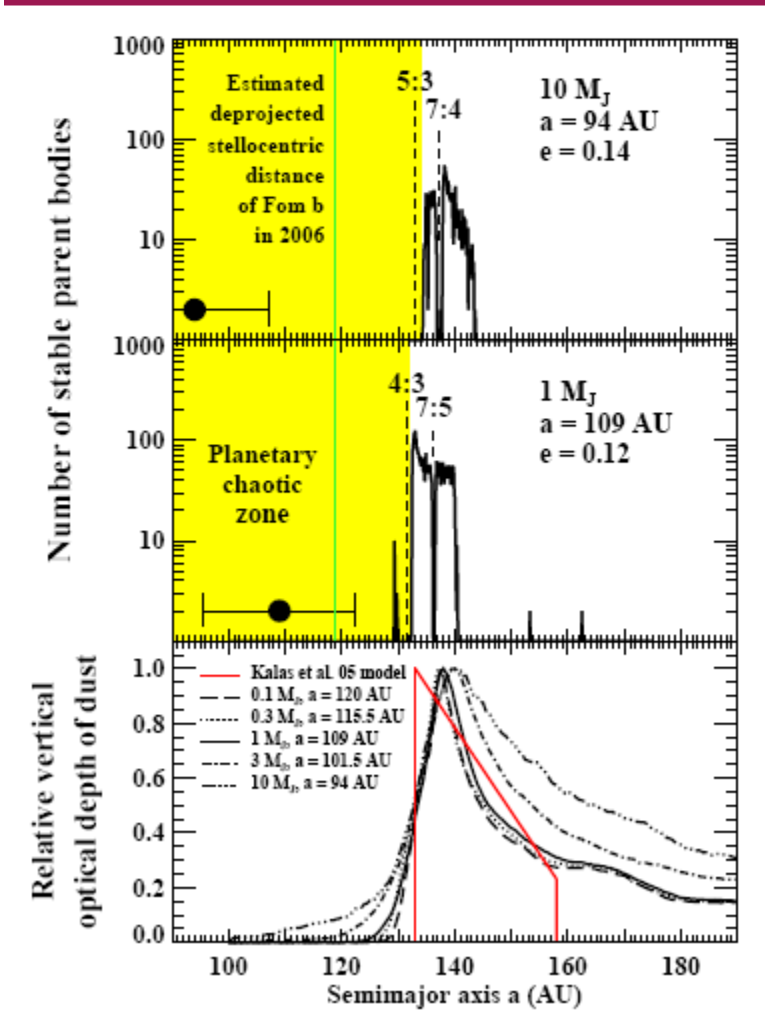
Debris Disks and Formation of Planets

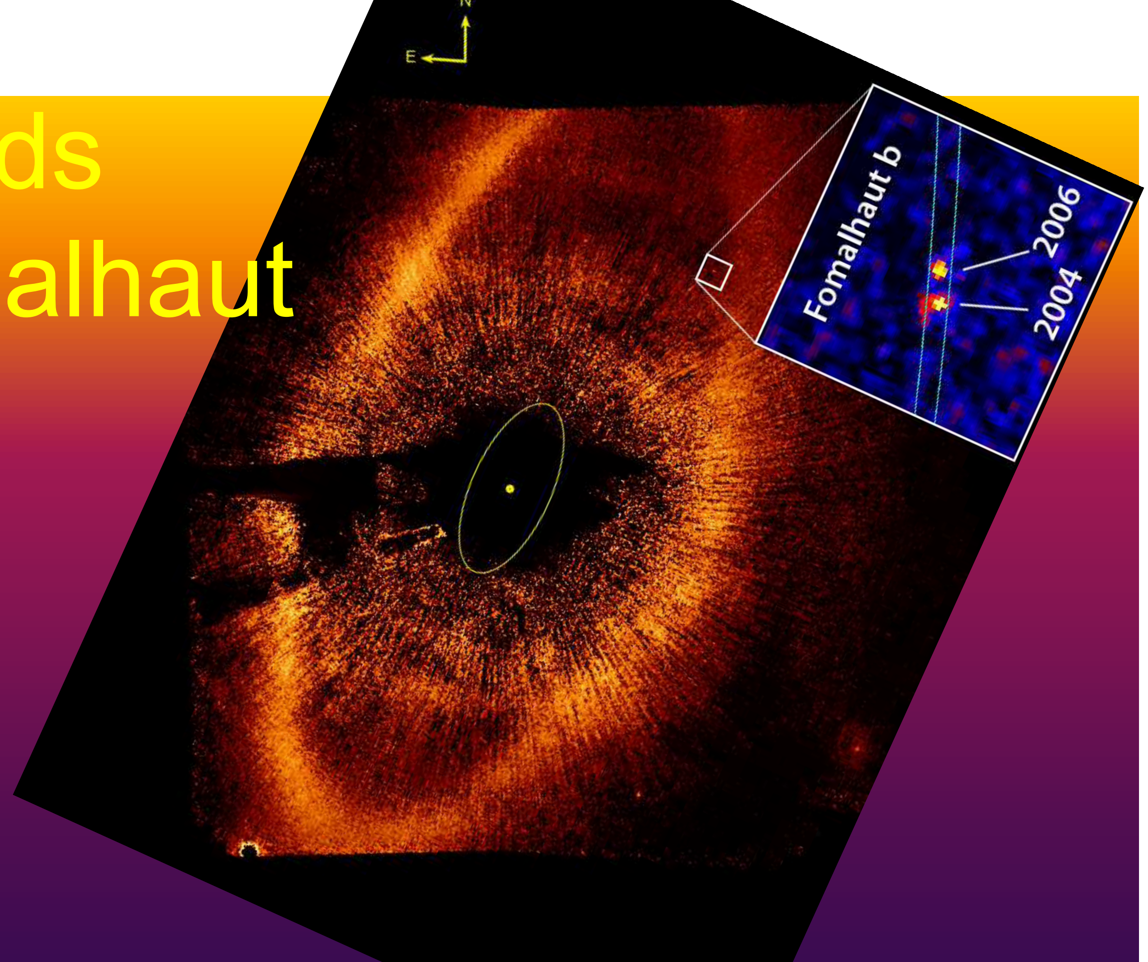
- Prediction of debris disks by Witteborn et al (Icarus 1982)
  - "Accretion models of planet formation and the early cratering history of the solar system suggest that planet formation is accompanied by a cloud of debris resulting from accumulation and fragmentation. A rough estimate of the infrared luminosities of debris clouds is presented for comparison with measured 10-micron luminosities of young stars. New measurements of 13 F, G, and K main-sequence stars of the Ursa Major Stream, which is thought to be about 270-million years old, place constraints on the amount of debris which could be present near these stars."
- IRAS discoveries followed in 1984 (Aumann, Gillett et al)
- Fractional luminosity, Ld/L*, a convenient metric
  - $1\text{-}10^{-2}$ for protostars & classical T Tauri stars
  - 10^{-3} to 10^{-4} for brightest, youngest (?) disks --- accessible to non-IR
  - $10^{-4}\text{-}10^{-5}$ for typical disks --- IRAS& ISO for early Sp Type→Spitzer
  - $10^{-6}\text{-}10^{-7}$ for weak disks like solar system


COBE 3 μm

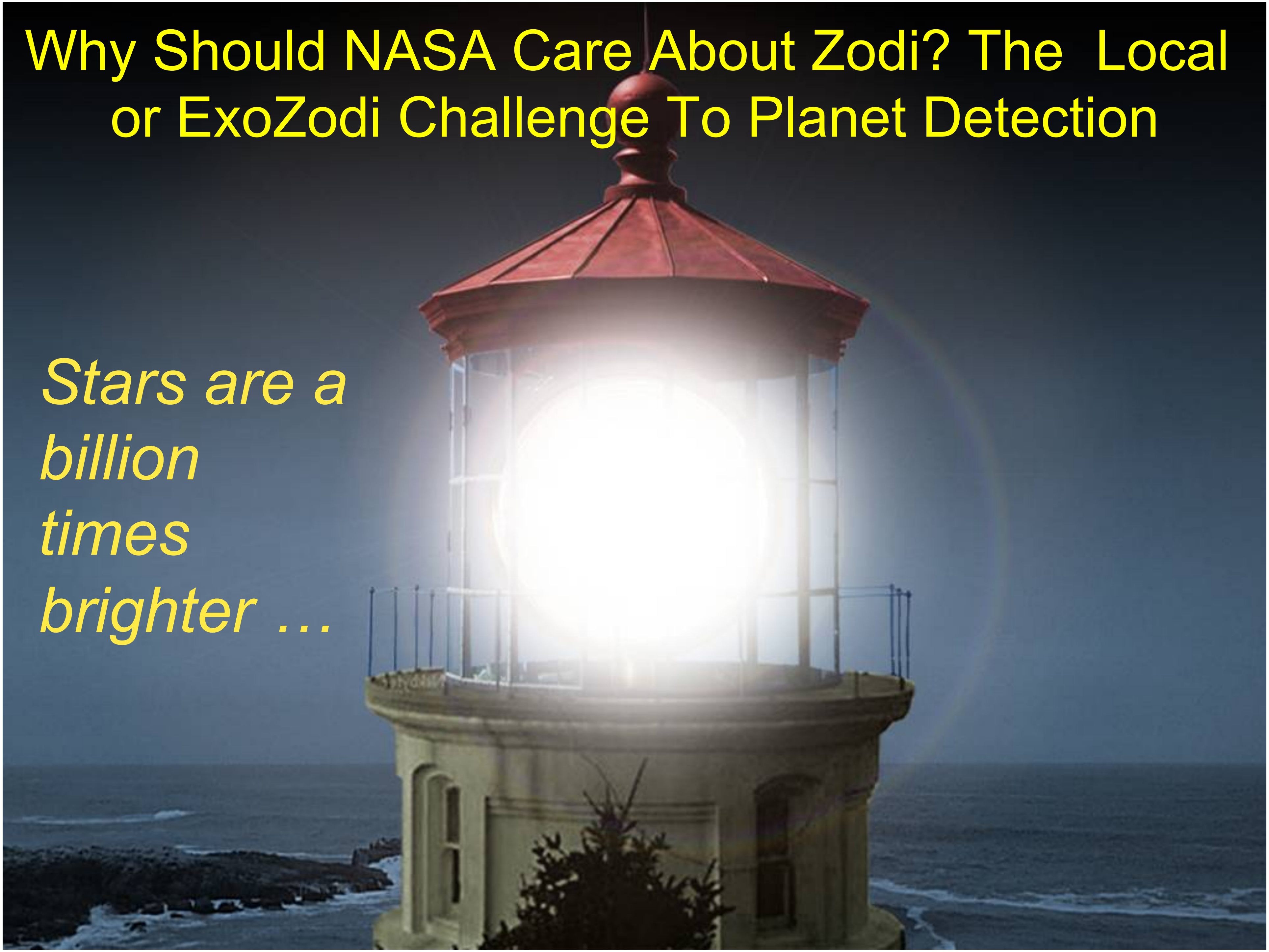

COBE 25 μm

HST/Keck Finds Cause of Fomalhaut Disk Offset





- Kalas et al (2009) directly detect Fomalhaut-b at 115 AU, e~0.13
- Common Proper Motion and orbital motion (1.4 AU in 1.7 yr)➔P=872 yr
- Quasi-dynamical mass: M<u><</u> 3 MJup to avoid disrupting/spreading disk



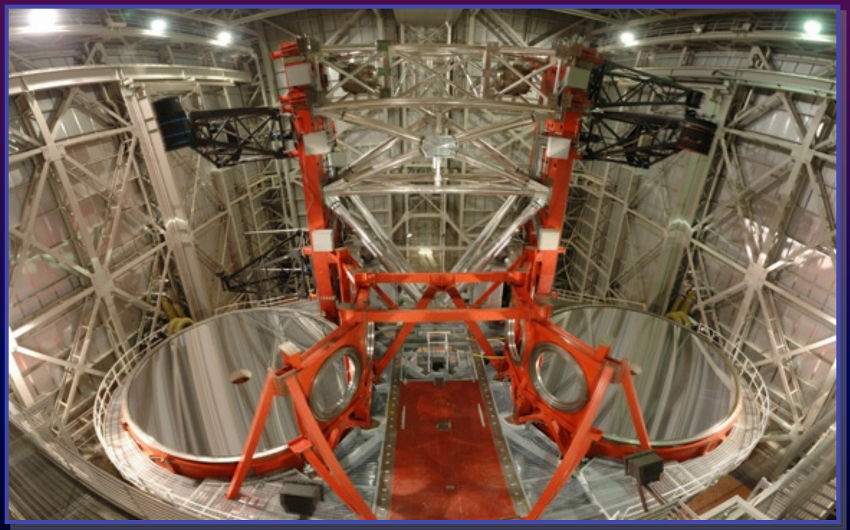
Why Should NASA Care About Zodi? The Local or ExoZodi Challenge To Planet Detection
Stars are a billion times brighter …

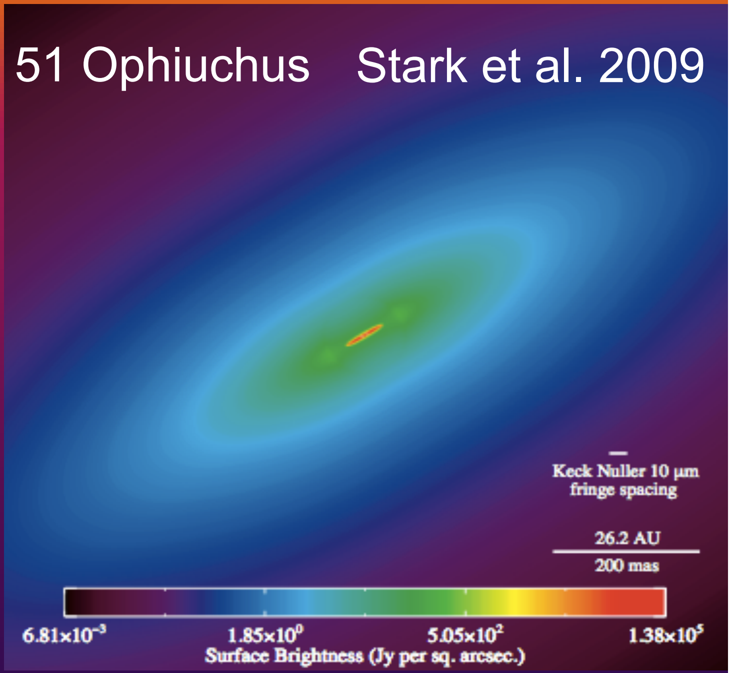

…than the planet
…hidden
in the glare.


Like this firefly.
Hidden in the
Exo Zodi Fog

Next Steps in EZ Research

- Spitzer (even JWST) limited by photometric accuracy
- Interferometers null star signal to reveal disk: 10 mas resolution with Keck → 0.1-1 AU
- Keck ExoZodi survey of nearby stars
  - Hinz, Kuchner, Serabyn





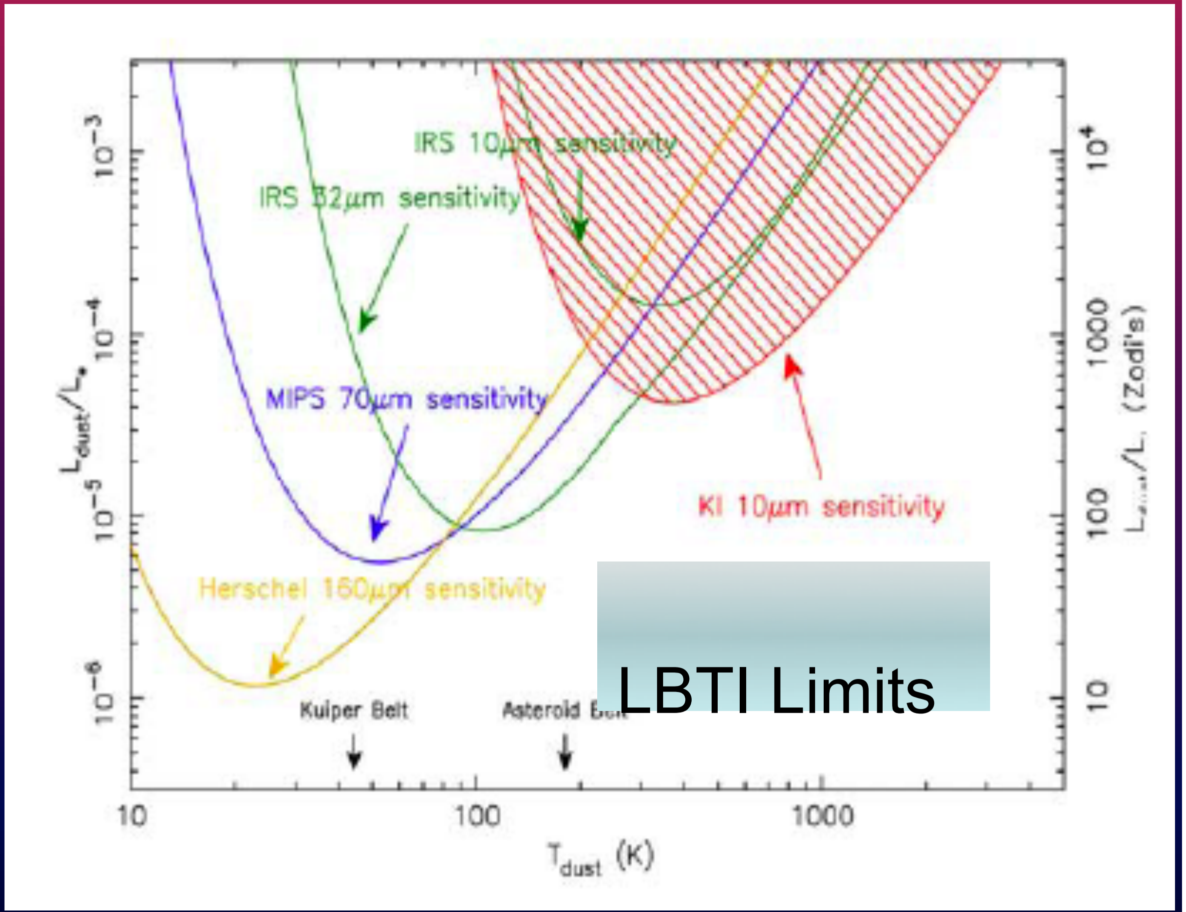
Fit Spitzer, Keck-I, MIDI with 2 dust clouds:

1) inner ring of large grains ("birth ring")
2) small particles (maybe β meteoroids)

LBTI will reach ~10 zodi (5-10x KI)

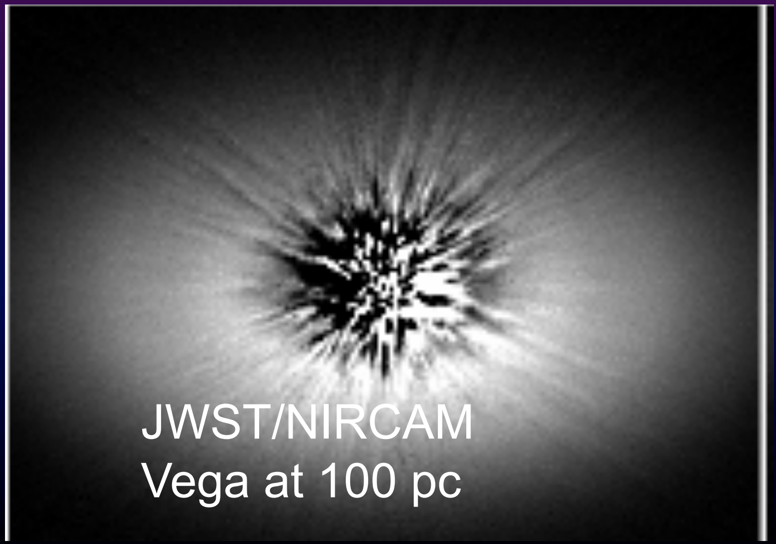
Ground-based Zodi Survey Prospects

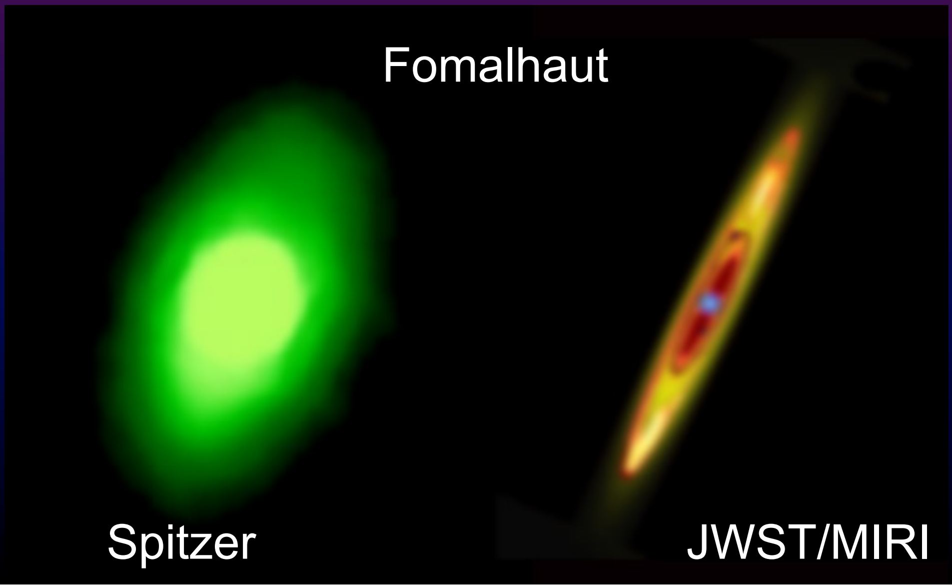
- Space-based (Spitzer, JWST) cannot get below 1000 Zodi at 10 μm
- Ground based observations at few hundred Zodi, 3-4x Spitzer
- LBTI will go below 100 SS, perhaps as low as 10 SS, approaching TPF limit
- Modest extrapolation with theory may satisfy concerns

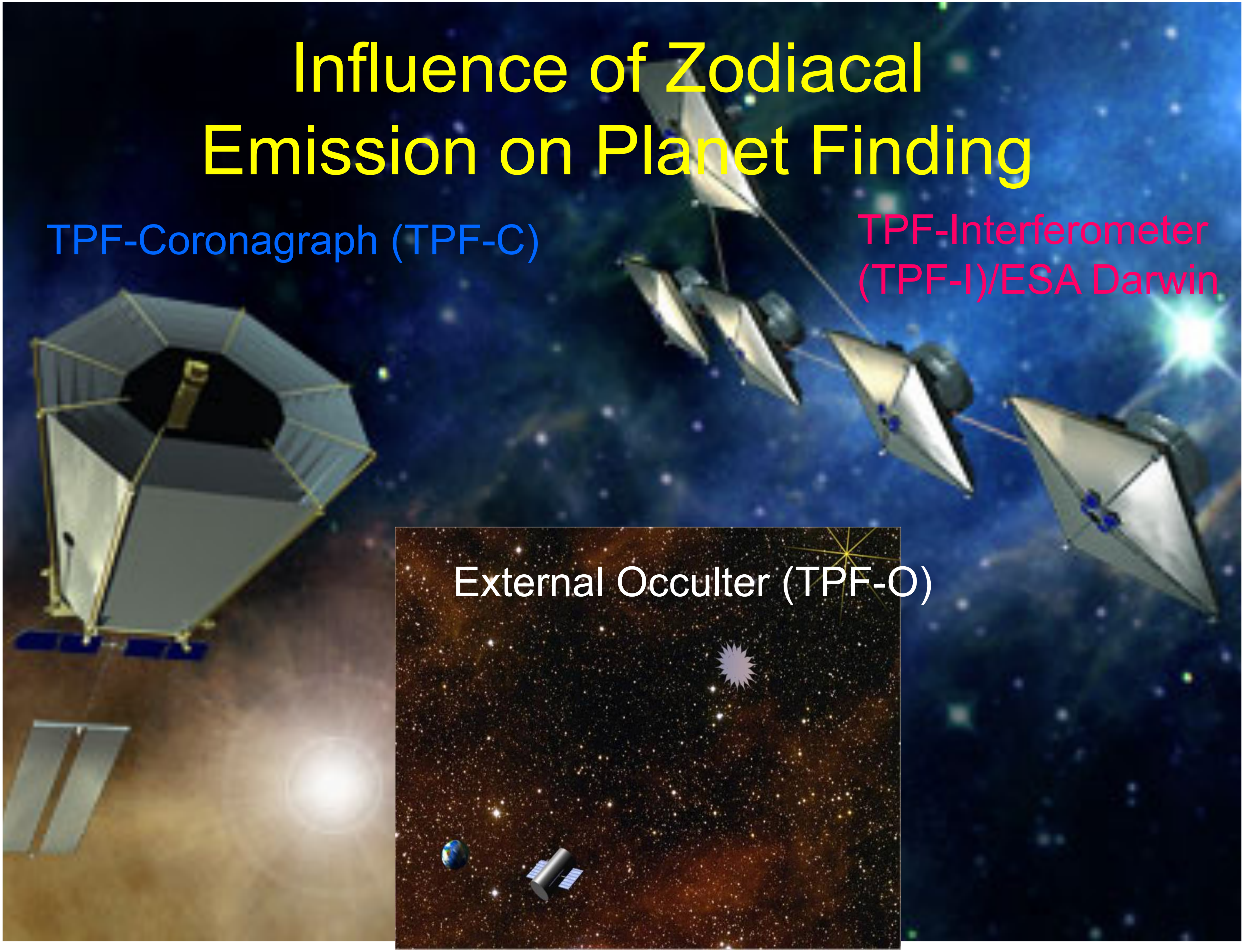


Future Capabilities

- Herschel/SCUBA-2 will map dozens of resolved systems, probing cold dust (160 um) 3-10x more sensitive/resolution than Spitzer
- JWST/MIRI and NIRCAM will give resolved, spectroscopic maps of brightest, biggest disks allowing detailed study of structure, including composition gradients

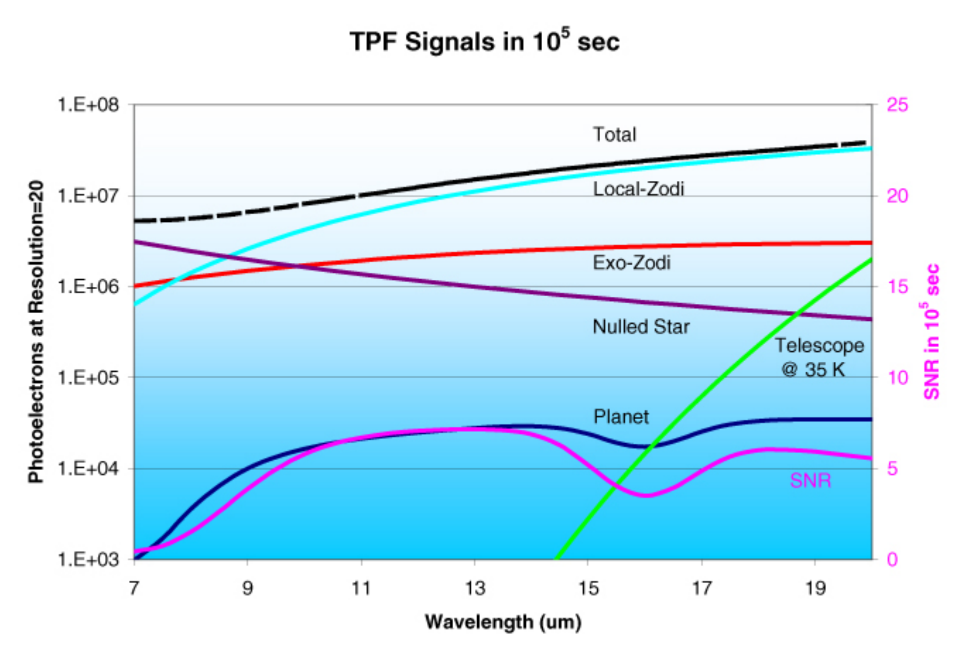





Influence of Zodiacal
Emission on Planet Finding
TPF-Coronagraph (TPF-C)
TPF-Interferometer
(TPF-I)/ESA Darwin
External Occulter (TPF-O)

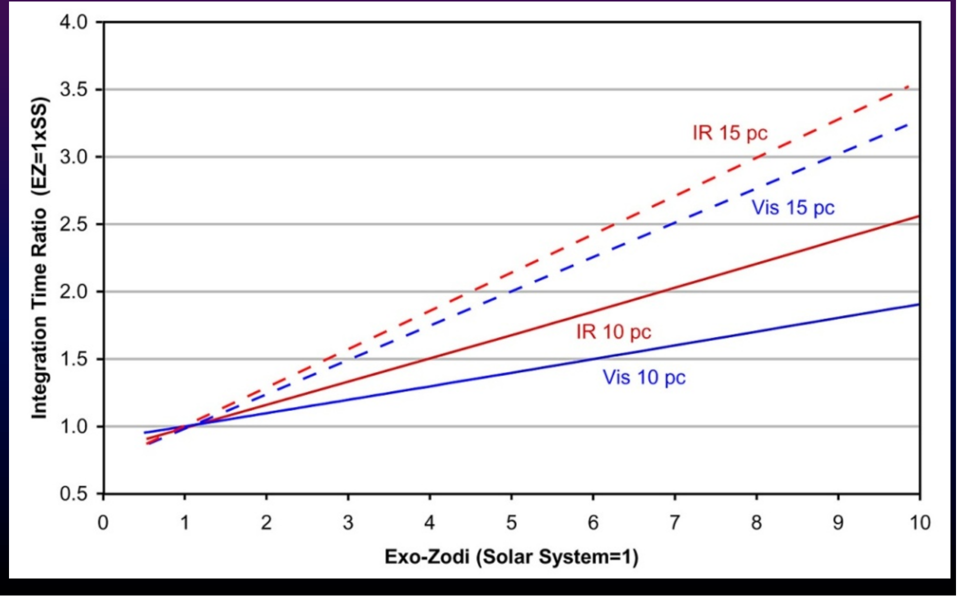
Zodi Problem for Earth-Detection

- Local zodiacal important noise source---put observatory at 5 AU (Leger et al)



- Photon noise from EZ can overwhelm planet
- Total EZ ~300 x planet Solar System Zodiacal cloud

- EZ signal within single pixel (~λ/D) significant for >10 zodi for either visible or IR



What Could We Learn About ExoZodi From Local Zodi

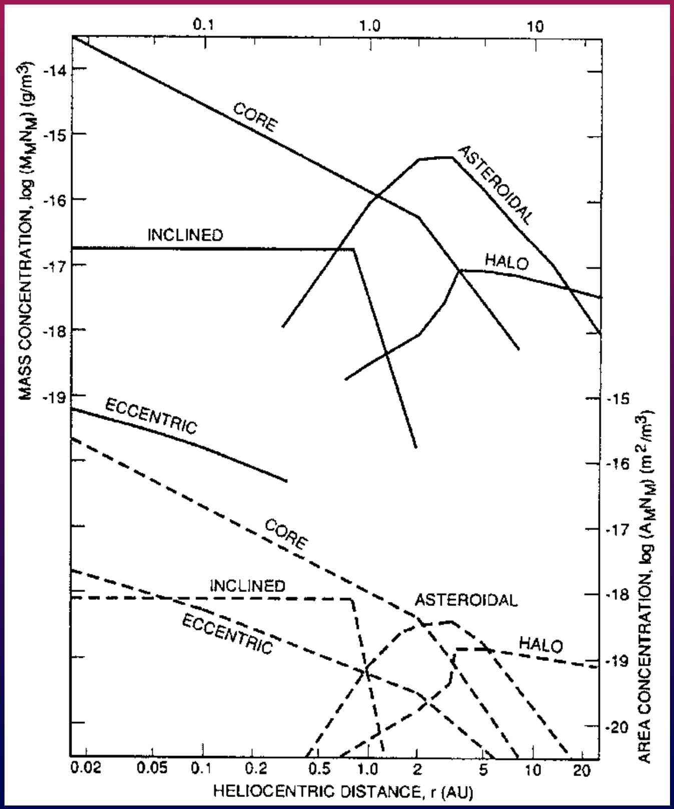
- Proposed mission in 1996---good idea then, still compelling now
- Know more about EZ than LZ, particularly beyond 1-3 AU
  - Steepness of drop-off at asteroid belt→ origin of material
  - Physical properties of dust from in situ measurements and spectroscopy
- Site Survey for future observatories

A Proposal for a Discovery Class Mission:
The Local Zodiacal Mapper (LZM)
Submitted 11 December, 1996

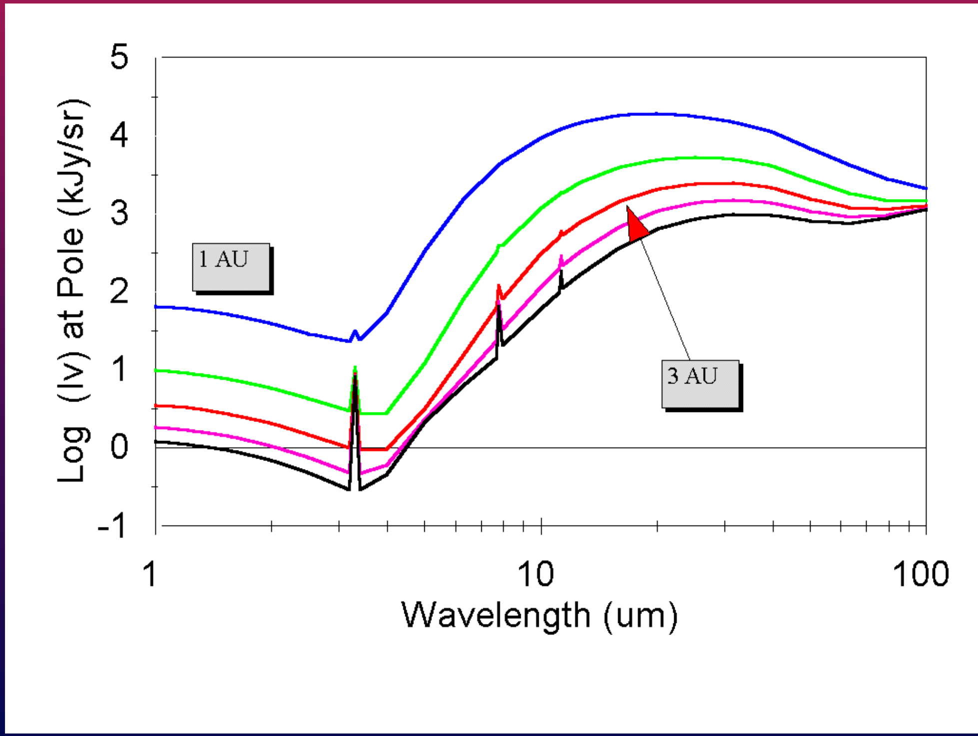
Table 4. Science Team Roles

Role	Team Member
Solar System structures, Zodiacal cloud modeling, Relation to exo-zodi clouds	Backman Beichman Dermott Leger Reach Sykes
CIRB Theory and Analysis	Mather Phinney Wright
Cirrus	Boulanger Cutri Helou
Science Operations	Cutri Van Buren
Instrument	Beichman Gautier Herter Mather Moseley
Data Processing	Beichman Helou Van Buren
	Wright
Outreach and Education	Backman Sykes

In Situ Studies of the Local Zodi



The mass and surface area estimated for different constituents of the solar system as a function of heliocentric distance. LZM would make direct measurements of the scattered and re-radiated emission from these objects and constrain their properties (Divine 1993).



A model based on IRAS and COBE data obtained at 1 AU (Reach et al. 1996) is used to predict the sky brightness at other distances from the Sun. Curves go from 1 to 5 AU from top to bottom and include zodiacal and cirrus emission. Cirrus features are seen at 3.3, 7.7 and 11 µm.

Astrophysics with Solar System Missions and The New Horizon Case

Mario R. Perez
NASA Headquarters
Astrophysics Division
05.19.2010

Exoplanet Science Measurements from Solar System Probes
Workshop – Kavli Institute for Theoretical Physics - UCSB

Legacy

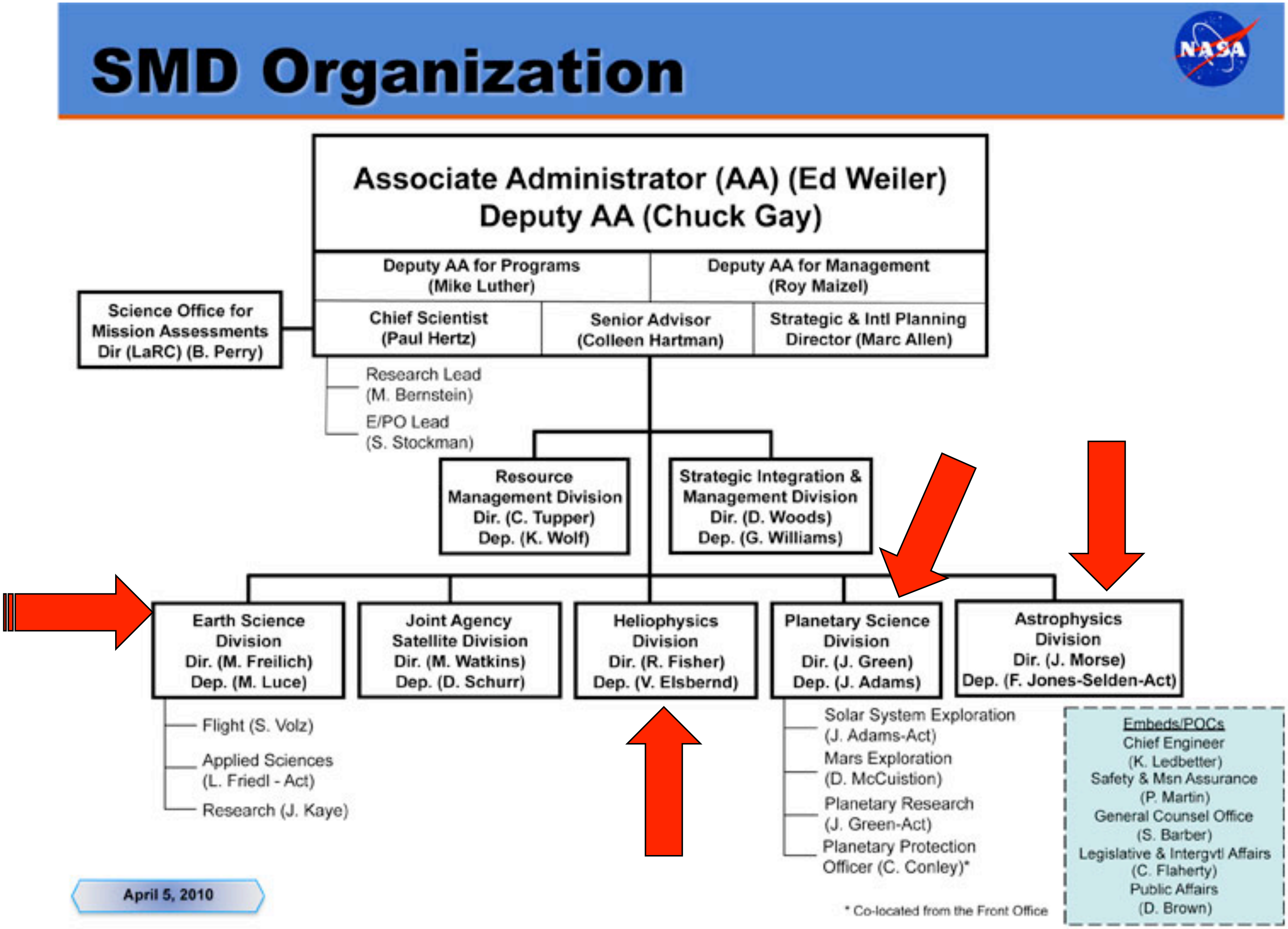
- From the beginning, space flight has attempted to accomplish science objectives. These accomplishments were either serendipitous or had some modest goals.
  - Starting with 1962 rocket flights, gamma-ray and x-ray detectors observed the fluorescence of the Moon; detected x-ray background and Sco X-1.
  - In 1967-1973 the Vela satellites discovered gamma-ray bursts.
  - In 1967 OSO-3 discovered x-ray flares and background detection.
  - In the APOLLO era many discoveries: UV imaging, cosmic ray data, limits on violation of GR, etc. (*"Man's Role in the National Space Program,"* Committee on Aeronautical and Space Sciences).
- See graphical topical review by Virginia Trimble, presented at the workshop *"**View from 5 AU**"* (UC Irvine, March 25/26, 2010 at http://www.physics.uci.edu/5AU/)
- The most successful and well-known results of planetary probes observing astronomical targets are from Voyager 1 and 2 (UVS: 500-1700 Å) of ultraviolet spectra of galactic sources.

Current Motivation

- The current institutional need can be summarized or enunciated as: **"Better utilization of NASA Assets."**
- This effort will require better coordination within NASA, among the Science, Exploration, Aeronautics, and Space Operation Directorates.
- Future space missions may not have to be "chemically pure" regarding the central goal or the Directorate or Division of origin.
- Cross Directorate or Division missions currently are not discouraged neither are encouraged, however, they could be excellent examples of better utilization of space resources. (But "not encouraged" = forbidden)

Astrophysics Division

Divisions at SMD



Astrophysics Division Themes

Science Goals

- There are many new science objectives, which are being identified for investigations at large heliocentric distances, **d > 5 - 40 AU**.
- These notional objectives map well into the three astrophysics science themes (examples):
  - **Exoplanet Exploration**
    - Nature, distribution and origin of the dust and exo-zodi in a HZ; transits, microlensing events, Kuiper belts objs
  - **Cosmic Origins**
    - Study of diffuse light in our Galaxy
  - **Physics of the Cosmos**
    - Detecting the signature of recombination via measurements of the extragalactic background

Recent Events

- **EPOXI** – The extended mission of Deep Impact (Planetary Division; PI: Mike A'Hearn, UMd) has been dedicated to do astronomical measurements by doing remote sensing of exoplanets and of the Earth, as an exoplanet analog, Drake Deming, PI EPOCH, GSFC. Microlensing parallax observations in Oct., 2009.

- **Cassini** – NASA competed investigations to conduct astronomical observations. A PI team was awarded a grant to secure data and analyze parallax images of star fields.

- **Rosetta** - ESA mission – In September 2009, there was a request to NASA HQ to secure time critical observations of a **"microlens parallax"** event solicited by colleagues at OSU. Good reception by ESA but unsuccessful due to operational constraints of the mission.

- **Focus Initiative.** About a year ago, Jon Morse, Division Director, assigned an Mario Perez to investigate using planetary probes to conduct cruise science observations. Several missions have been contacted.

Astrophysics Division

Planetary Missions

- **Dawn** – PI will not consider doing any astrophysical observations (in cruise phase?)

- **New Horizons** – PI was interested in exploring options (see next few viewgraphs).

- **Juno** – Will be launched in August 2011. First PI mission that was selected invoking three Science Decadal Surveys (i.e., Astrophysics, Planetary and Heliophysics => High relevance for NASA). Juno is a joint mission between the ***Heliophysics and the Planetary Divisions.***

Pending Decisions After Many Negotiations

From NH:

1. The PI will form a group to more carefully assess the possibility of using NH for astrophysics objectives.
2. NH Management and HQ will setup a meeting in the Sep-Nov 2010 timeframe, to discuss this topic further, after the group identified in (1) has completed its task.

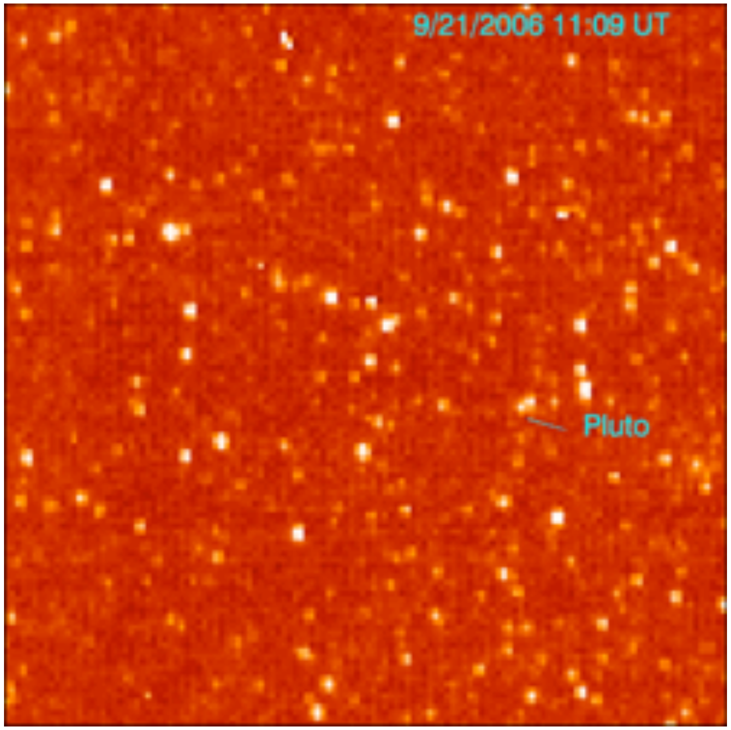
From HQ:

1. Depending on the availability of funds (research grants and NH operations), a decision will be made regarding competing some limited cruise science as a ROSES element.

Cruise Astrophysics with NH

Cruise Science

- Possible astronomical observations for a few days/hours in years:
  - 2012, 2013, and 2014
  - 3-axis stabilized every other year
- **Instruments of Interest:**
  - Imagers (LORRI, MVIC)
  - UV Spectrograph (Alice)



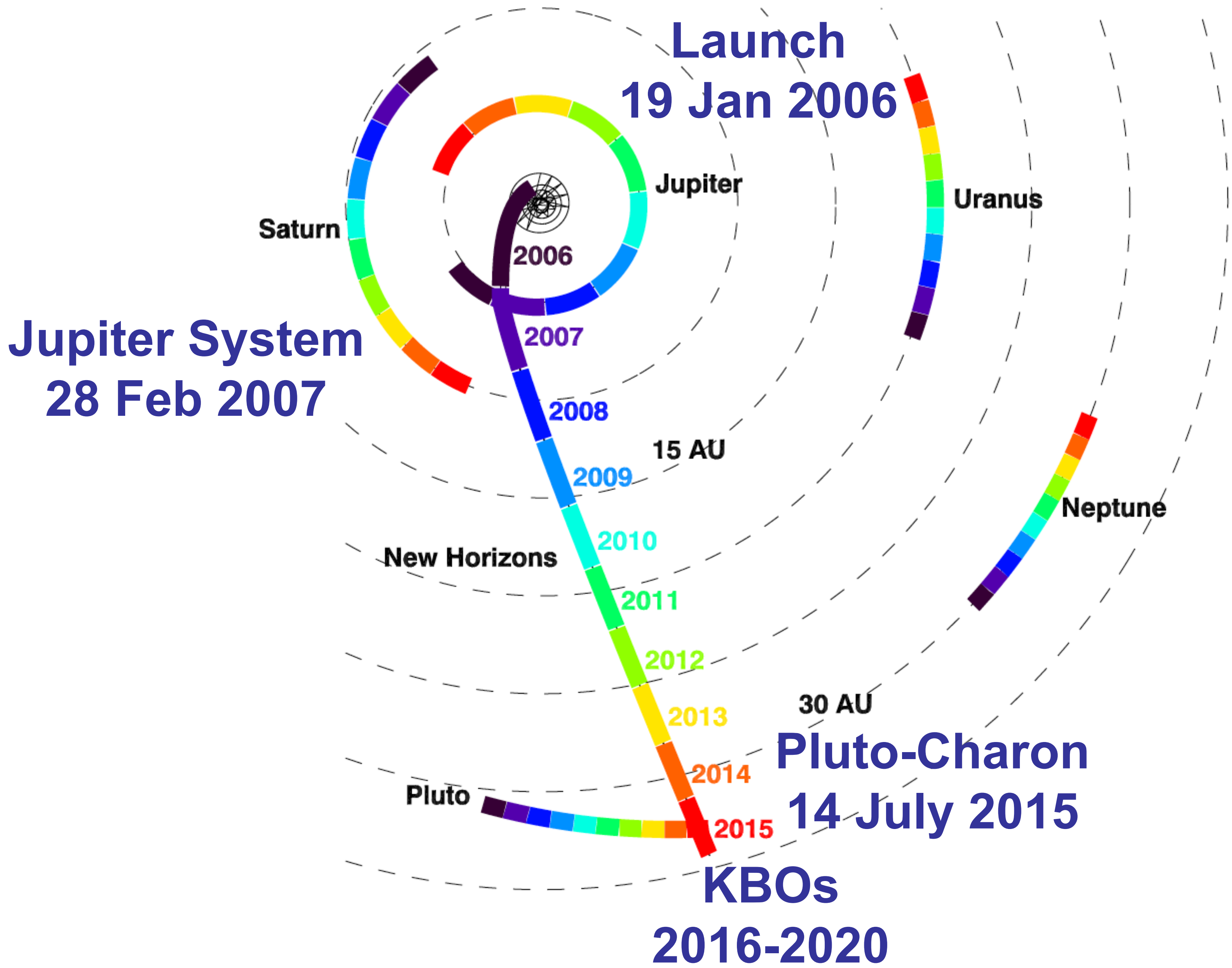
First Pluto sighting from New Horizons (September 21–24, 2006)

Extended Mission

- After Encounter with Pluto in 2016, NH could be willing to do additional astrophysics observations

Astrophysics Division

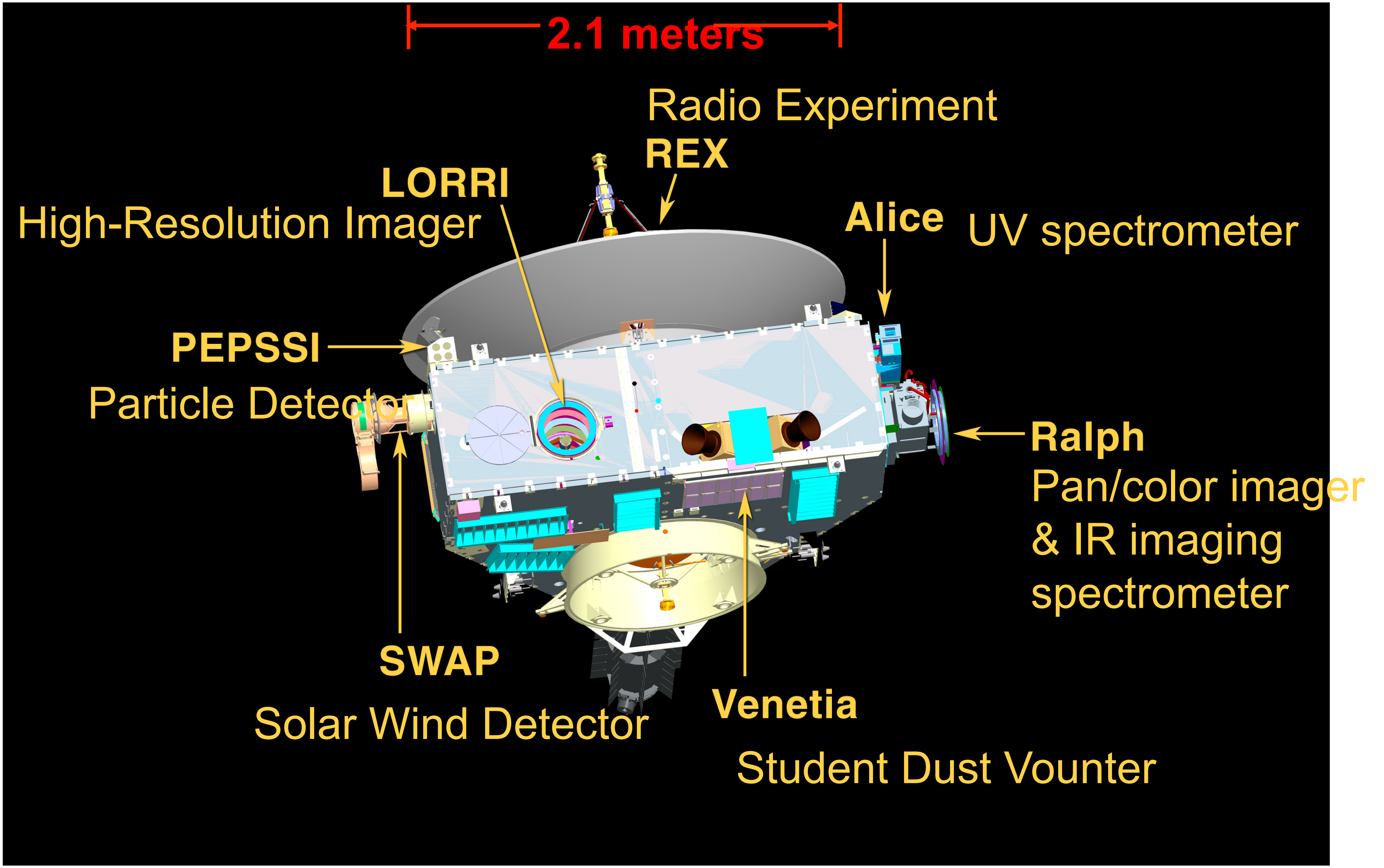
New Horizons Trajectory



Instrument Characteristics

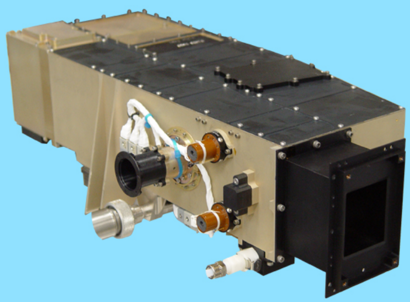
Alice	UV Spectrometer	➢ 46.5-188.0 nm, 0.3 nm resolution ➢ FOV 4° x 0.1° "slot" and 2° x 2° "box", 5 mrad/pixel ➢ airglow & occultation capabilities
Ralph/ MVIC	Multispectral Visible Imaging Camera (pan/color imager)	➢ Panchromatic (350-850 mm) & 4-color (Blue, Red, CH_4, Near-IR) ➢ FOV 5.7° x 0.15° or 5.7° x scan length, 20 microrad resolution
Ralph/ LEISA	Linear Etalon Imaging Spectral Array (IR Imaging spectrometer)	➢ 1.25-2.50 micron at R=240 and 2.10-2.25 micron at R = 550 ➢ FOV 0.9° x 0.9° (scanned), 62 microrad/pixel
LORRI	LOng-Range Reconnaissance Imager (High-Resolution Imager)	➢ Panchromatic (350-850 nm) ➢ FOV 0.29° x 0.29°, 5 microrad/pixel ➢ 1024 x 1024 CCD, 12 bit, texp = 1ms – 30s in 1ms steps ➢ S/N=7 for V=12 in 100ms and for V=17.5 in 10s (4x4 rebin)
REX	Radio science EXperiment (Uplink, Radiometery)	➢ Part of telecommunications systems, with 2.1 m antenna ➢ X-band (7.182 GHz uplink, 8.438 GHz downlink)
SWAP	Solar WInd at Pluto (solar wind detector)	➢ 0.25-7.5 KeV. RPA: 0.5V (<1.5 keV), ESA: $\Delta E/E=0.4$ (>1.4 keV) ➢ FOV 200° x 10°
PEPSSI	Pluto Energetic Particle Spectrometer Science Investigation (particle detector)	➢ e^-: 25-500 KeV, Protons: 40-500 KeV, CNO: 150-1000 KeV ➢ FOC 160° x 12°, 25° x 12° resolution
SDC	In Situ Dust Counter	➢ 0.10 m^2 active area, ➢ Threshold Mass ~10^{-12} gram (~1 micron)

NH Spacecraft & Instruments

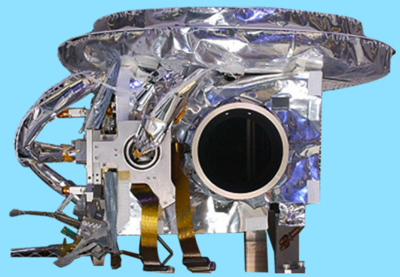


Astrophysics Division

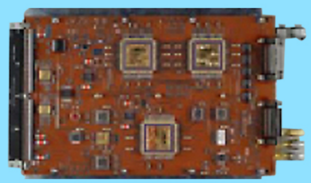
NH Instruments



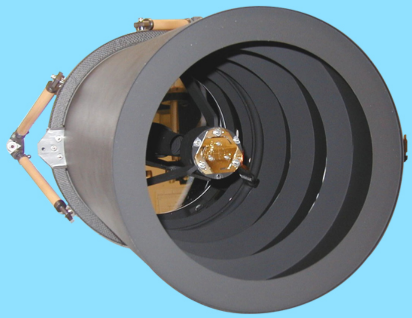
Alice UV Spectrograph, 46.5-188 nm,
Mass 4.15 kg, Power 3.6 W



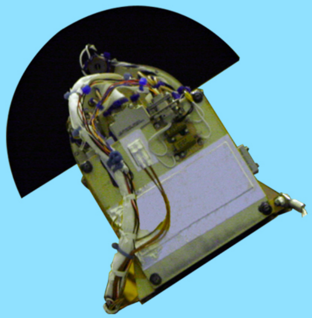
Ralph Visible Color Imager (MVIC)
and IR Spectral Imager (LEISA),
Mass 10.67 kg, Power 6.74 W



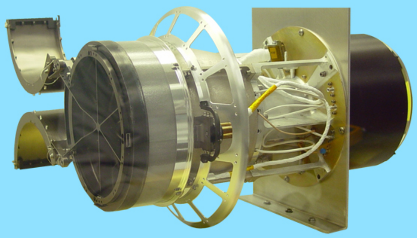
Radio Experiment (REX), Antenna (2.1 m)
+ Processing Card (0.1 kg, 2.1 W)



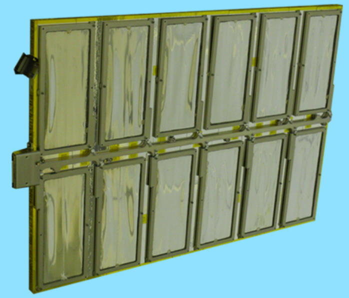
Long Range Reconnaissance Imager
(LORRI), Panchromatic Visible Imager,
Mass 9.03 kg, Power 4.6 W



Pluto Energetic Particle Spectrometer
Science Investigation (PEPSSI),
Mass 1.48 kg, Power 2.45 W



Solar Wind at Pluto (SWAP),
Mass 3.3 kg, Power 2.84 W



Venetia Burney Student Dust Counter
(VB-SDC), Mass 1.69 kg, Power 6.4 W

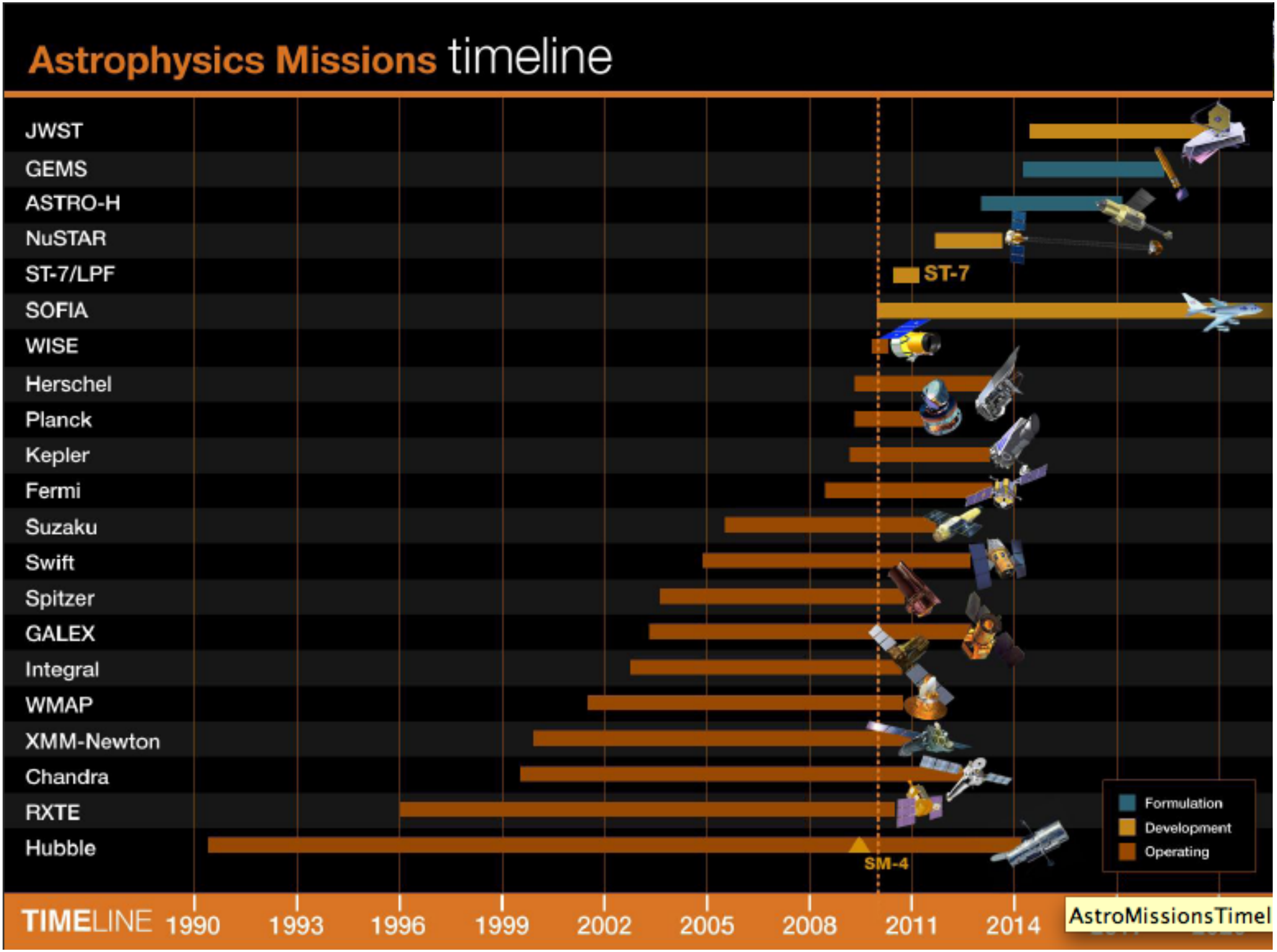
NH Operations Plan

- Most of the year NH is in “hibernation”
  - G&C system powered off
  - S/C spinning with high gain antenna pointed approximately at Earth
  - Weekly beacon tones, less frequent telemetry contacts (biweekly, monthly, …)
  - Instruments powered off, except Student Dust Counter (SDC)
  - Integrated Electronics Module (IEM; computer) is on
- **Annual Checkouts (ACOs) conducted annually**
  - First two ACOs in fall, now during summer
  - **Approximately 2 months of activities, including ~2 weeks of 3-axis activities**
  - Sometimes (alternate years) have “slimmed down” ACOs with no 3-axis
- Precessions
  - Exit hibernation briefly (~10 days) to reorient spacecraft for optimal high gain antenna pointing during hibernation
- *Currently considering possibility of operating PEPSSI and SWAP (particle instruments not requiring 3-axis) during hibernation because of high return for* ***heliophysics science***

Constraints for "Astrophysics Support"

- NH has *small* Ops Team (~10 FTE) with hands full already running NH, planning and executing ACOs, and planning and testing the Pluto Encounter activities
  - **Astrophysics objectives would require additional MOPS support (money)**
- Certain resources are limited and must be managed:
  - Thruster cycles (need to maintain enough margin for Pluto and KBOs)
  - Fuel (hydrazine needed for Pluto activities, for TCMs to target KBOs)
  - Data downlink (max downlink rate is ~2 kbps and DSN time is limited)
- Operating the imagers (LORRI and/or Ralph) or the UV spectrograph (Alice) *before* the Pluto Encounter may increase the risk that they may fail or have reduced performance (e.g., less sensitivity)
  - Alice Team is already concerned about too many counts from photocathode
- ***After* the Pluto Encounter, there should be more flexibility for performing Astrophysics objectives during the Extended Mission**
  - **Cruise Science must still fit within the available resources and risk posture, as set by NASA's Planetary Science Division**


XMM-Newton (ESA)
Swift
Suzaku (JAXA)
FERMI
INTEGRAL (ESA)
GALEX
RXTE
Herschel (ESA)
Planck (ESA)
WMAP
Hubble
Kepler
Chandra
Spitzer
March 17, 2010


Astrophysics Missions timeline
JWST
GEMS
ASTRO-H
NuSTAR
ST-7/LPF
SOFIA
WISE
Herschel
Planck
Kepler
Fermi
Suzaku
Swift
Spitzer
GALEX
Integral
WMAP
XMM-Newton
Chandra
RXTE
Hubble
ST-7
SM-4
Formulation
Development
Operating
TIMELINE
1990
1993
1996
1999
2002
2005
2008
2011
2014
AstroMissionsTimel

Path Forward Ideas

– **Future hybrid or mixed missions with two or more SMD Divisions involved; Planetary/Heliophysics/Earth Science Divisions**
  - Upcoming Opportunities: Discovery, New Frontiers, Explorer
– **Example: Program - "Characterizing the Earth as an Exoplanet"**
  - Potential Divisions involved: Heliophysics (Living with a Star), Earth Sciences, Planetary & Astrophysics
– **Missions of Opportunities within Astrophysics**
  - To fund and support instrumentation for NASA and ESA Planetary Probes
- **What about DOE and DoD space missions?**
  - Dual Science and Global Situational Awareness
– **Get the science drivers for astrophysics at *d > 5-40 AU,* enunciated by a panel of the National Academy of Sciences**