Direct imaging of giant exoplanets an observers view (with attempted theory context)

Bruce Macintosh

And many other members of the GPI Exoplanet Survey

Mark Marley, Jonathan Fortney, Travis Barman, Eric Nielsen, Rob de Rosa, Jason Wang, Vanessa Bailey, Quinn Konopacky, Jeff Chilcote, JB Ruffio, Alex Maduroricz

Marshall Perrin, Dmitry Savransky,

Eugene Chiang, Paul Kalas, Tom Epsosito, James Graham, et al…

LLNL Postdocs: Jennifer Patience, Mike Fitzgerald, Christian Marois, Quinn Konopacky, Dmitry Savransky

LLNL AO group: Lisa Poyneer, Brian Bauman, Dave Palmer, Scot Olivier, Claire Max, Kevin Baker,

And many others…

Outline

- **Focus: giant (Jupiter-mass or above) planets via direct imaging**
- **Review planet formation – questions and models**
- **What imaging can tell us**
- **The HR8799 system**
- **Planetary atmosphere overviews**
- **Challenges in modeling planets**
- **Gemini Planet Imager**
  - GPI observations of cooler planets
  - How common are giant planets?
- **Future: GPI2**

- **Not so much: optics, small spacecraft, future-future…**

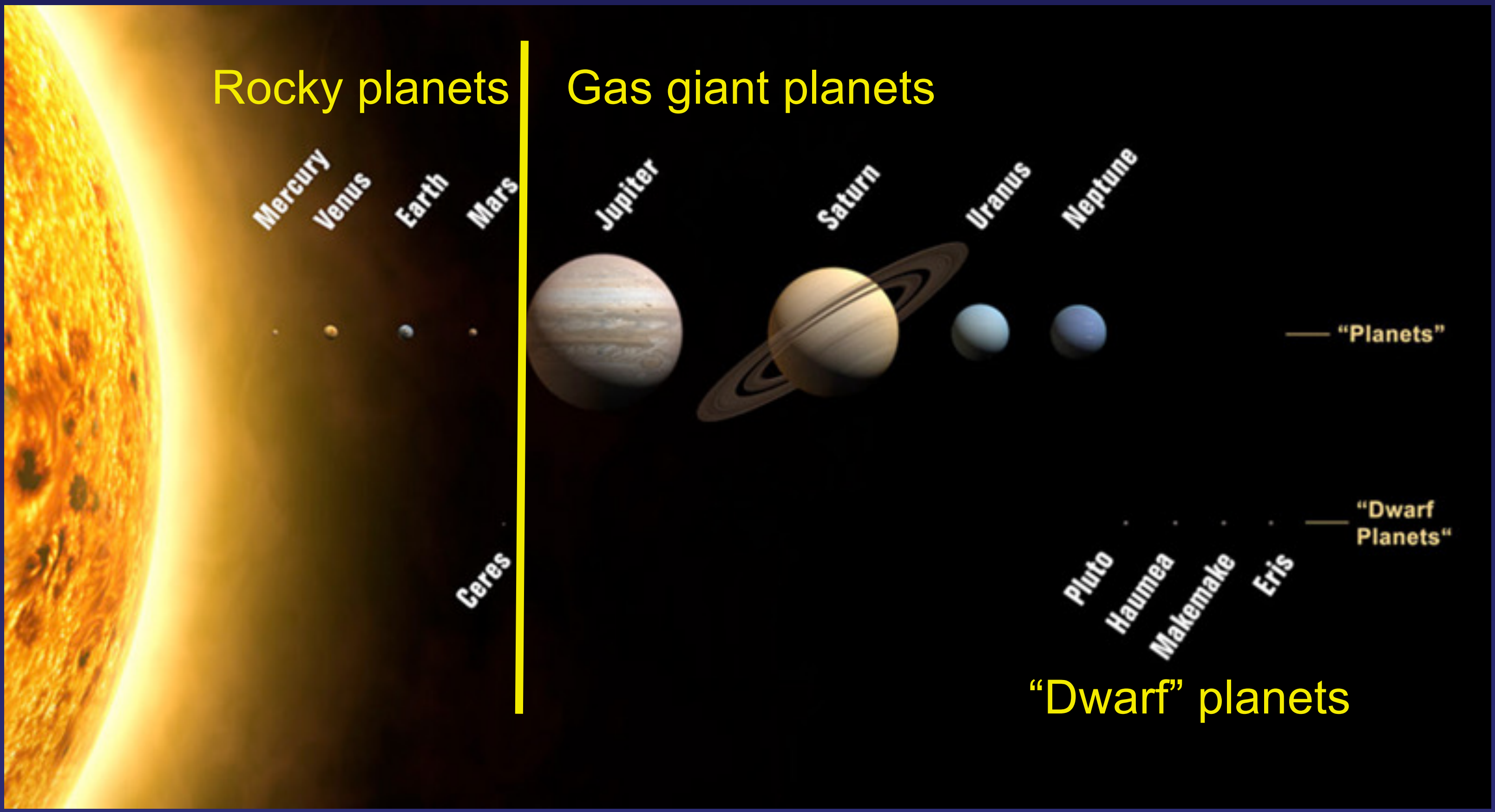
Motivation

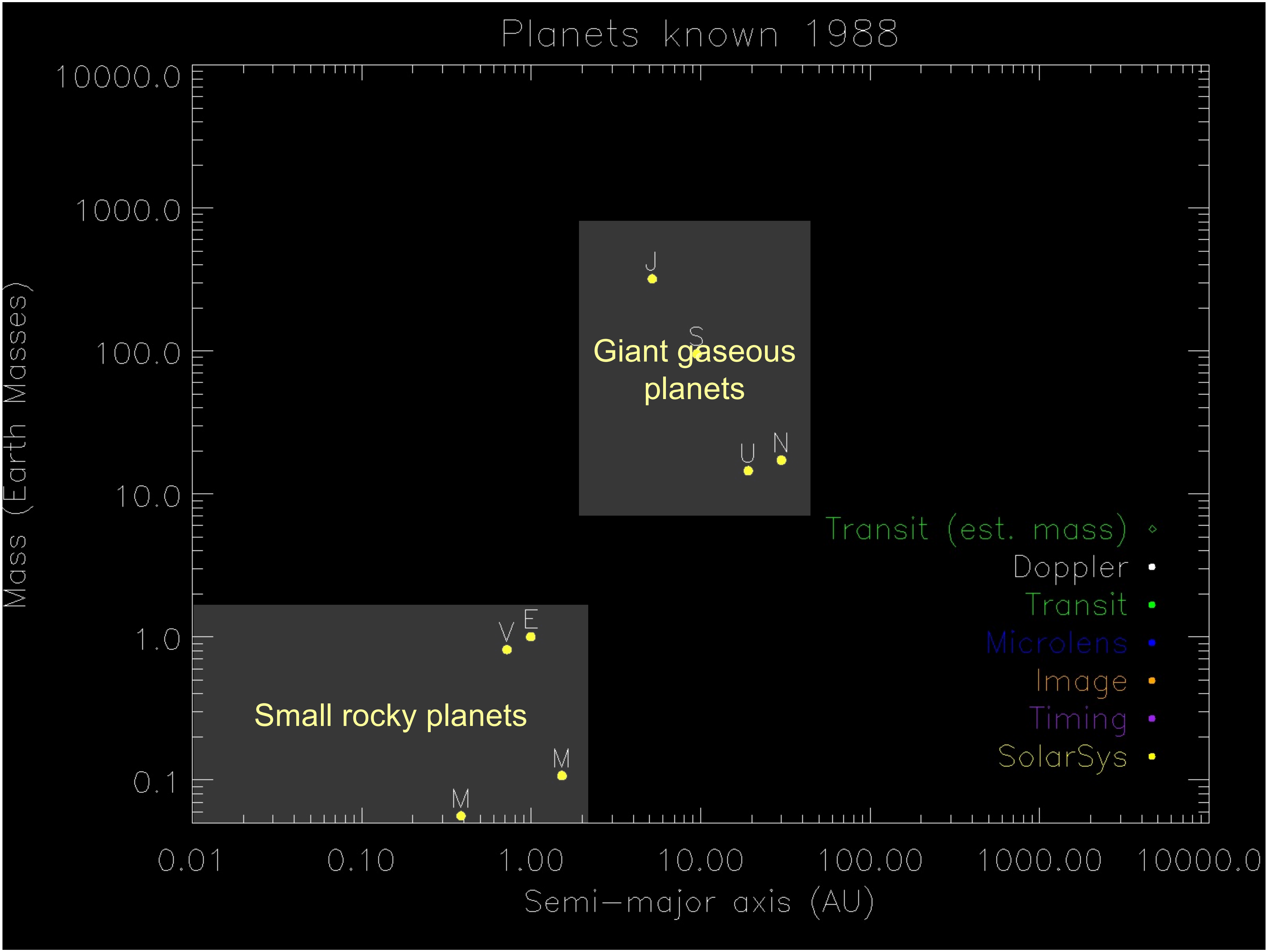
- Direct imaging is a powerful complement to other exoplanet techniques that study inner solar systems
- Giant planets record the formation process of their systems
- Ultimately, imaging with space missions is the best path to studying true Earth analogs

Some important astronomer terminology

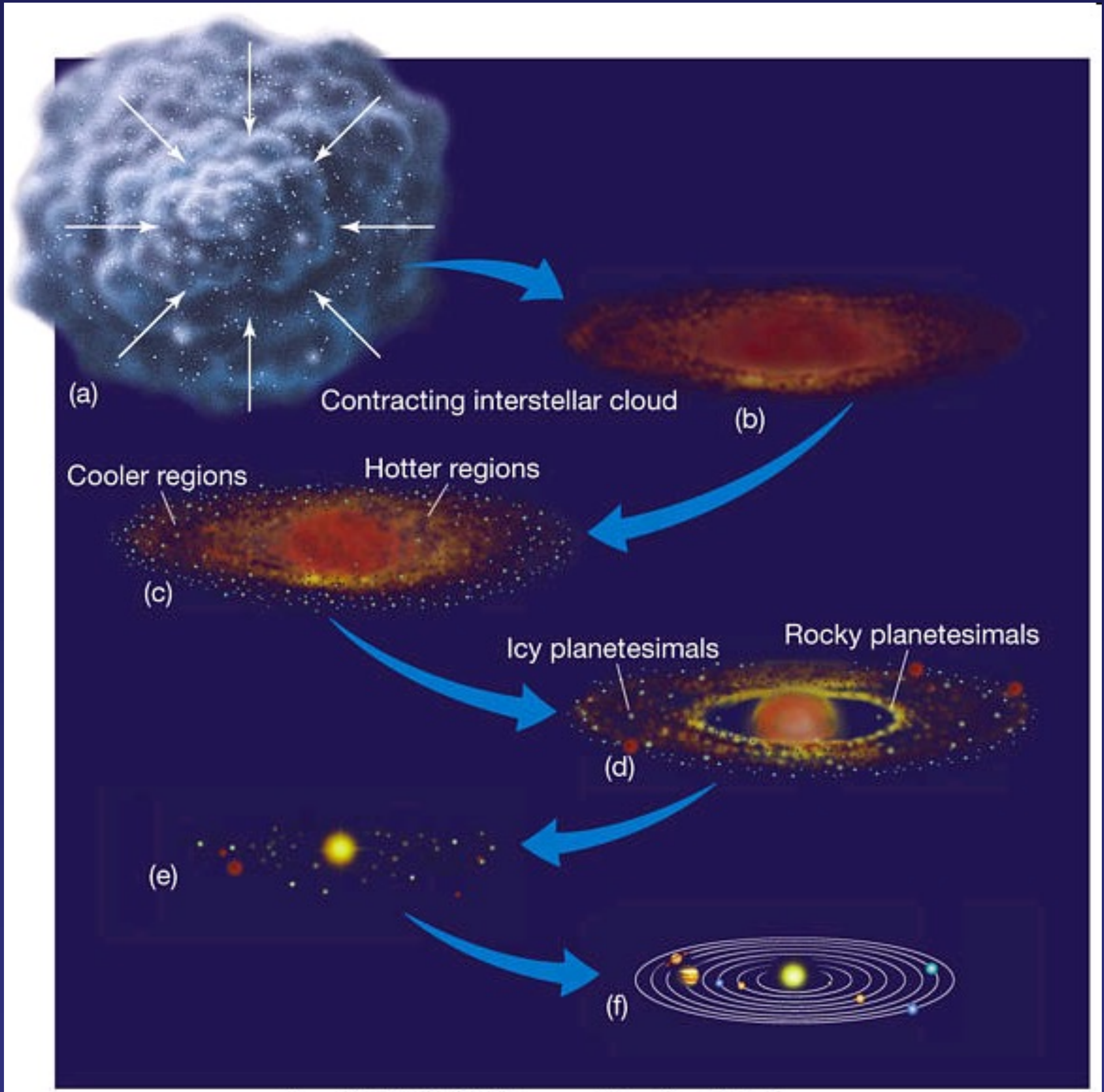
- **Luminosity: the total power radiated by a star or galaxy or planet or space potato.**
  - Units: watts, but often "Solar luminosities" $L_\odot$
- **Flux – power per square meter ("iradiance")**
- **"Metals" – every element that isn't hydrogen or helium**
- **"Metallicity" – fraction of non-H on-He, usually relative to the composition of the sun**
- **Contrast – ratio of brightness between a planet and a star**
- **Astronomical unit (AU) – distance between the Earth and the Sun**
- **Parsec (pc) – 3.26 light years**
- **Mass units – 1 solar mass $M_\odot$ = 1000 Jupiter masses M_J**

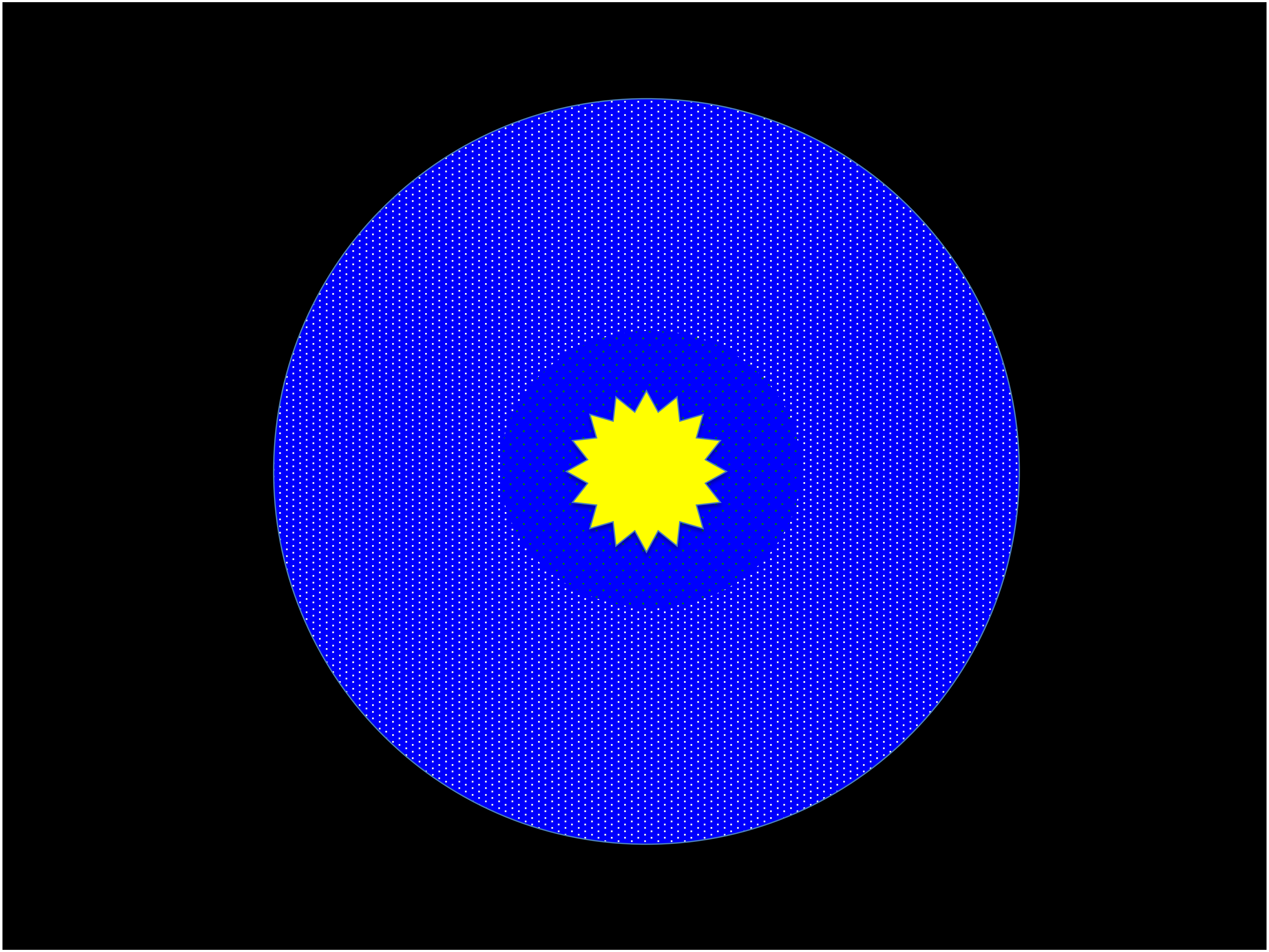
Planets of Our Solar System (2021)

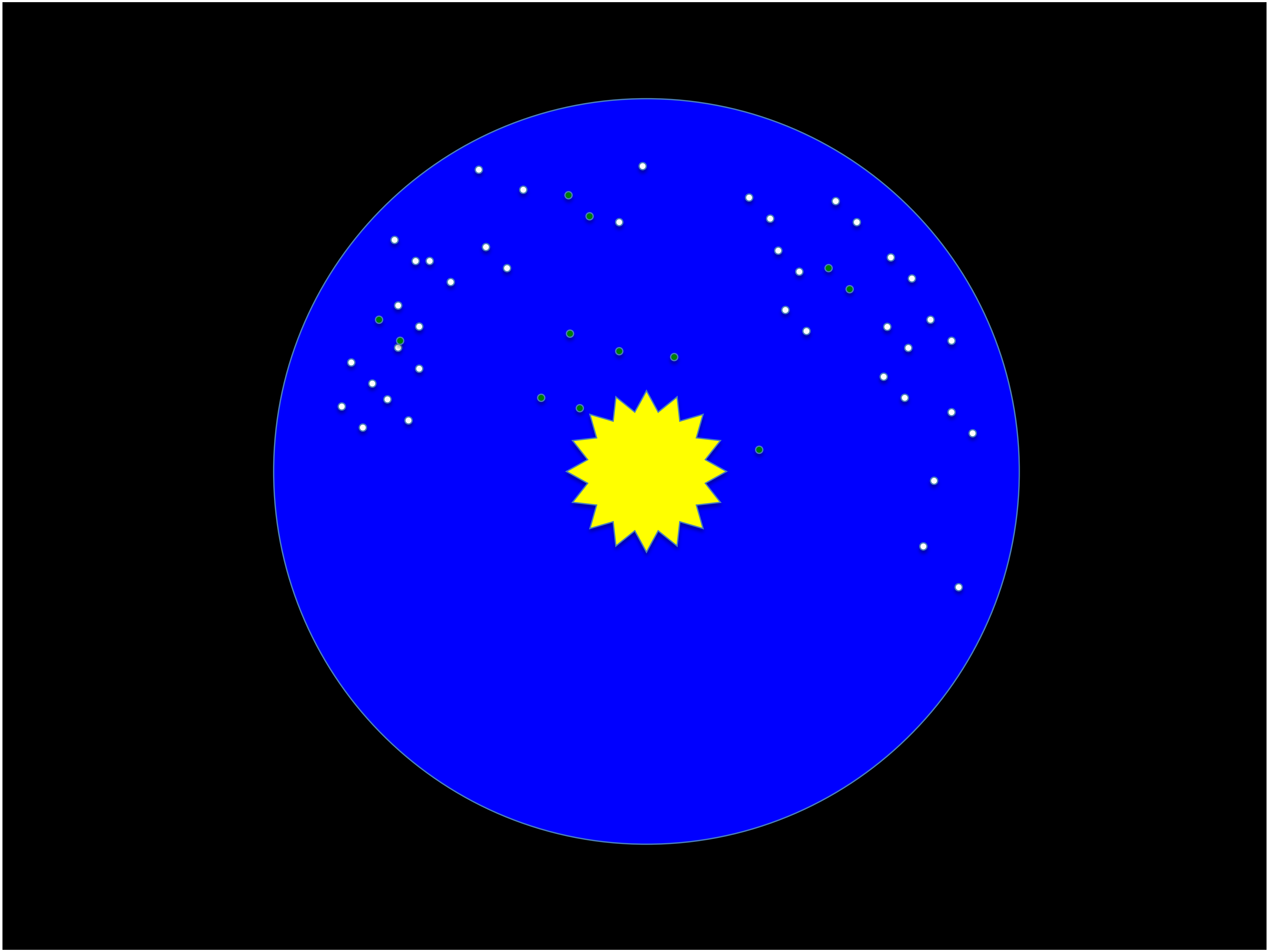


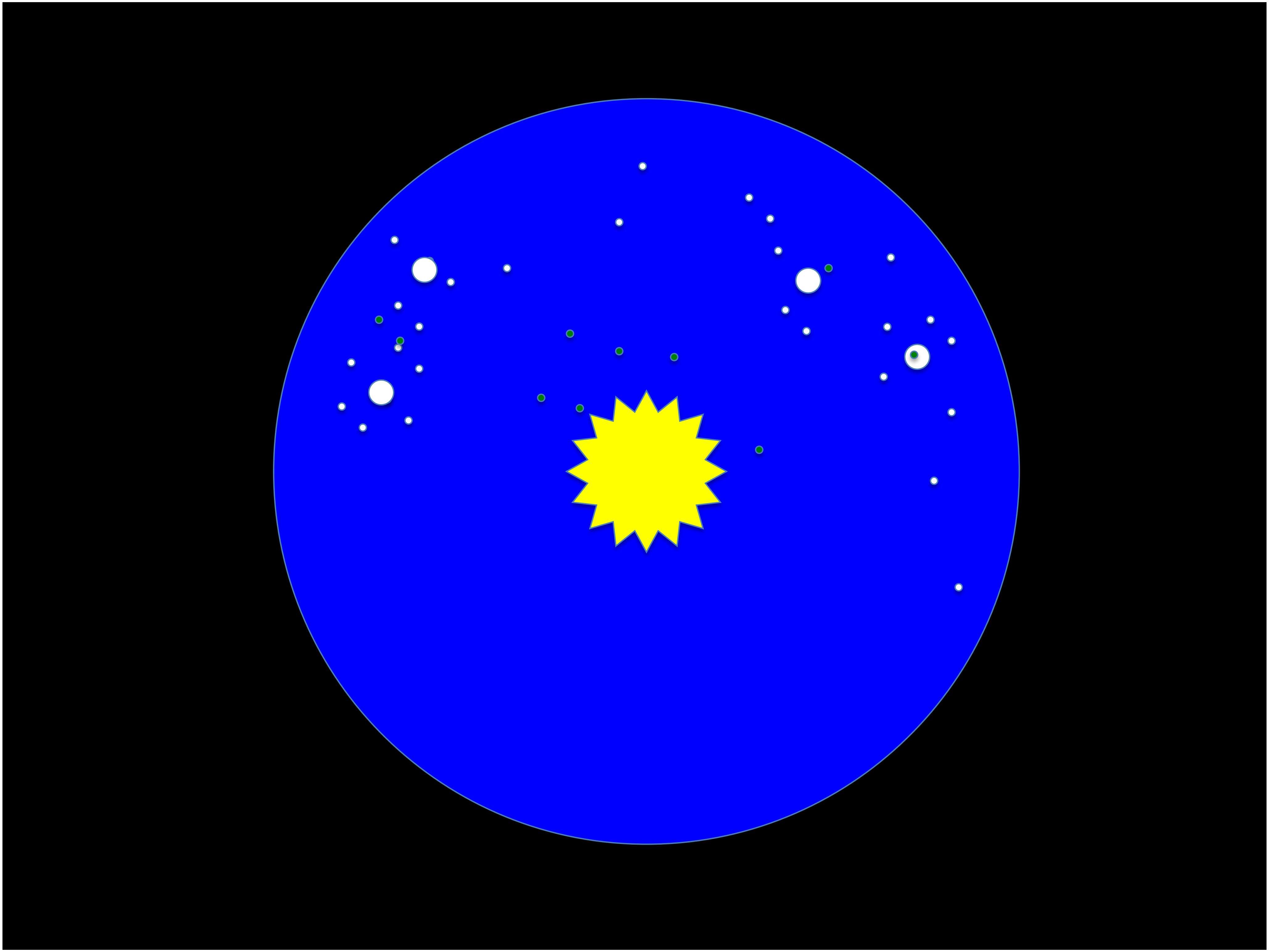

Planets known 1988
Mass (Earth Masses)
10000.0
1000.0
100.0
10.0
1.0
0.1
Semi−major axis (AU)
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
Giant gaseous planets
J
S
U
N
Small rocky planets
V
E
M
M
Transit (est. mass)
Doppler
Transit
Microlens
Image
Timing
SolarSys

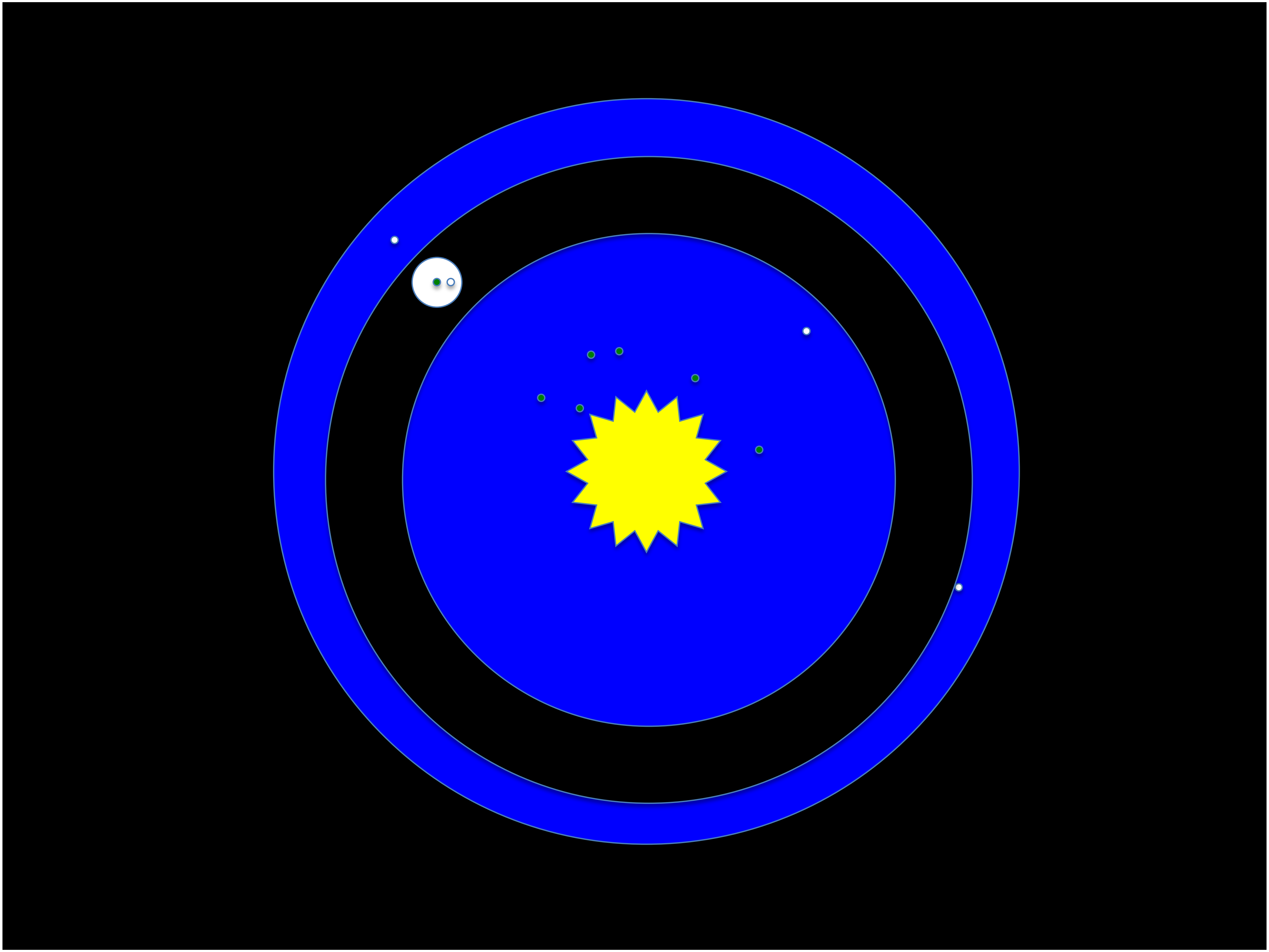
Star and planet formation steps

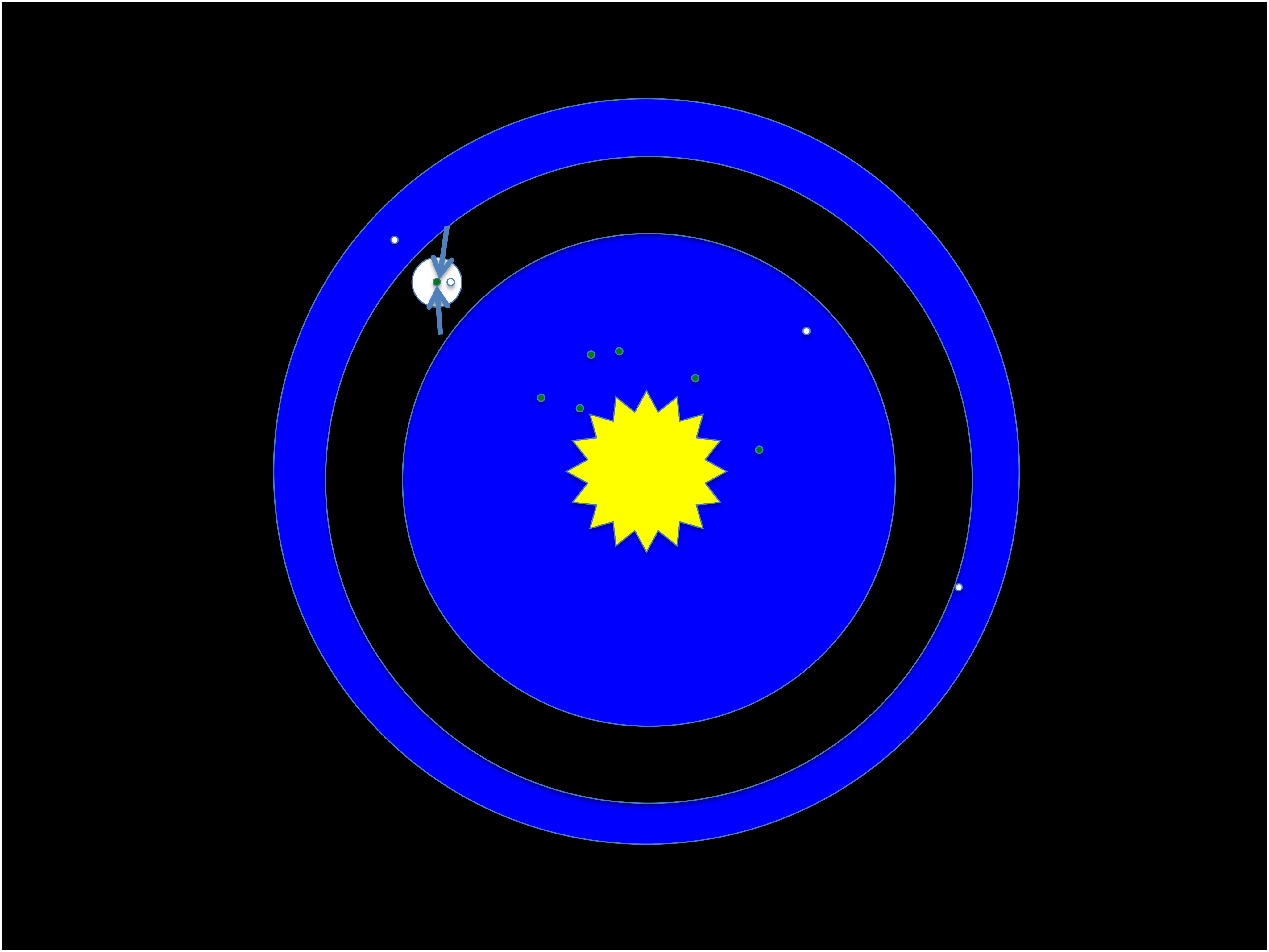


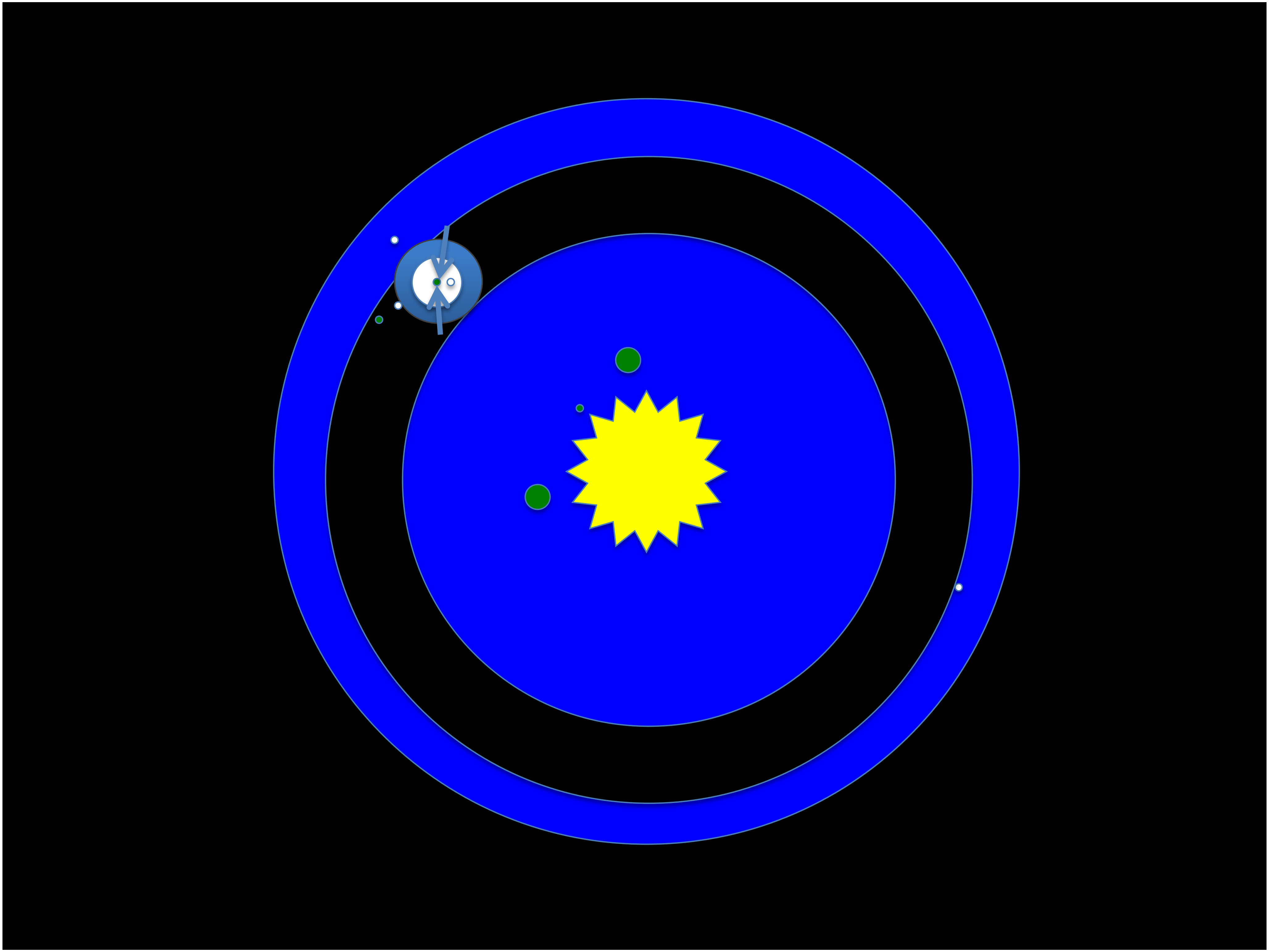


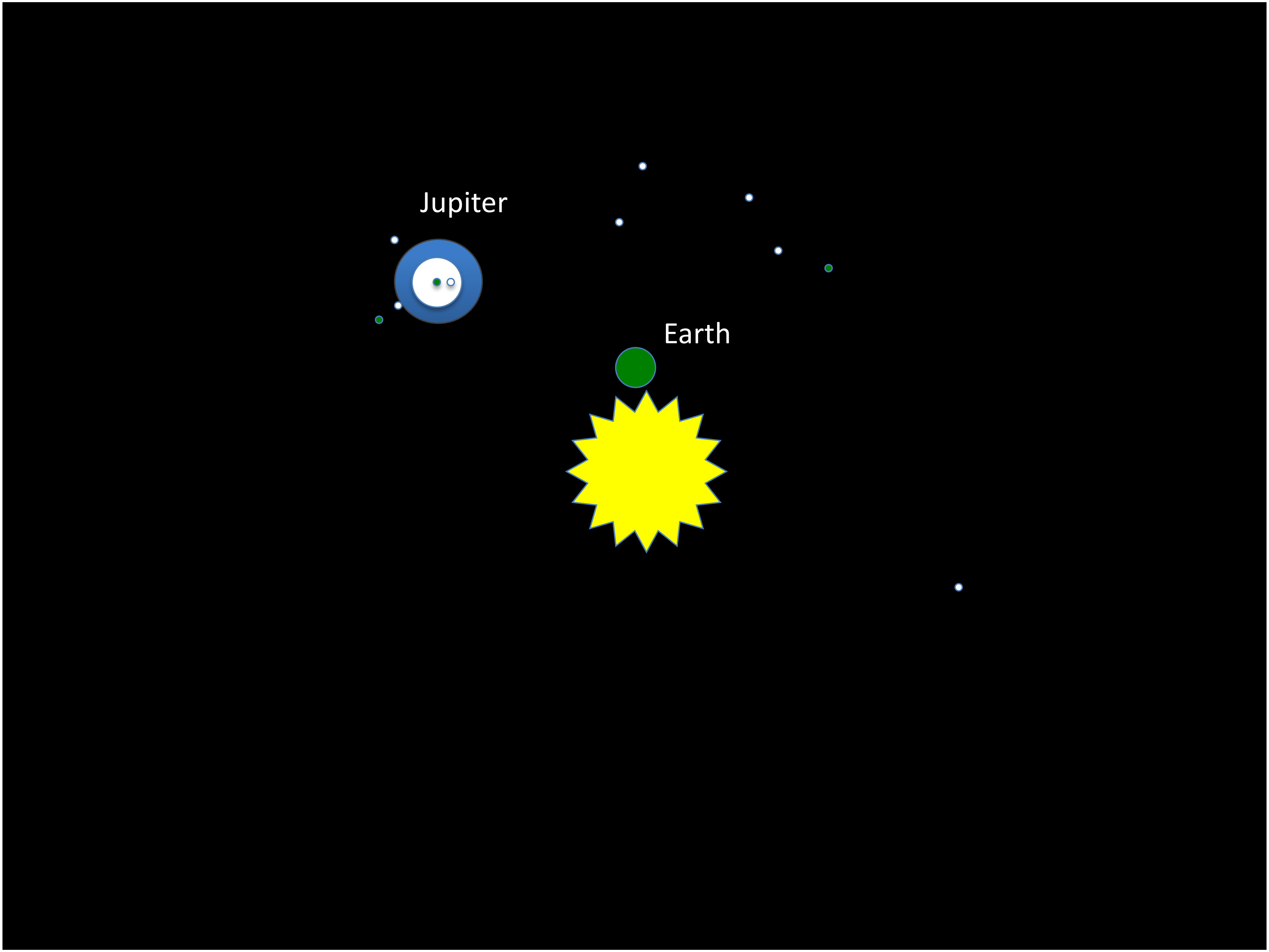


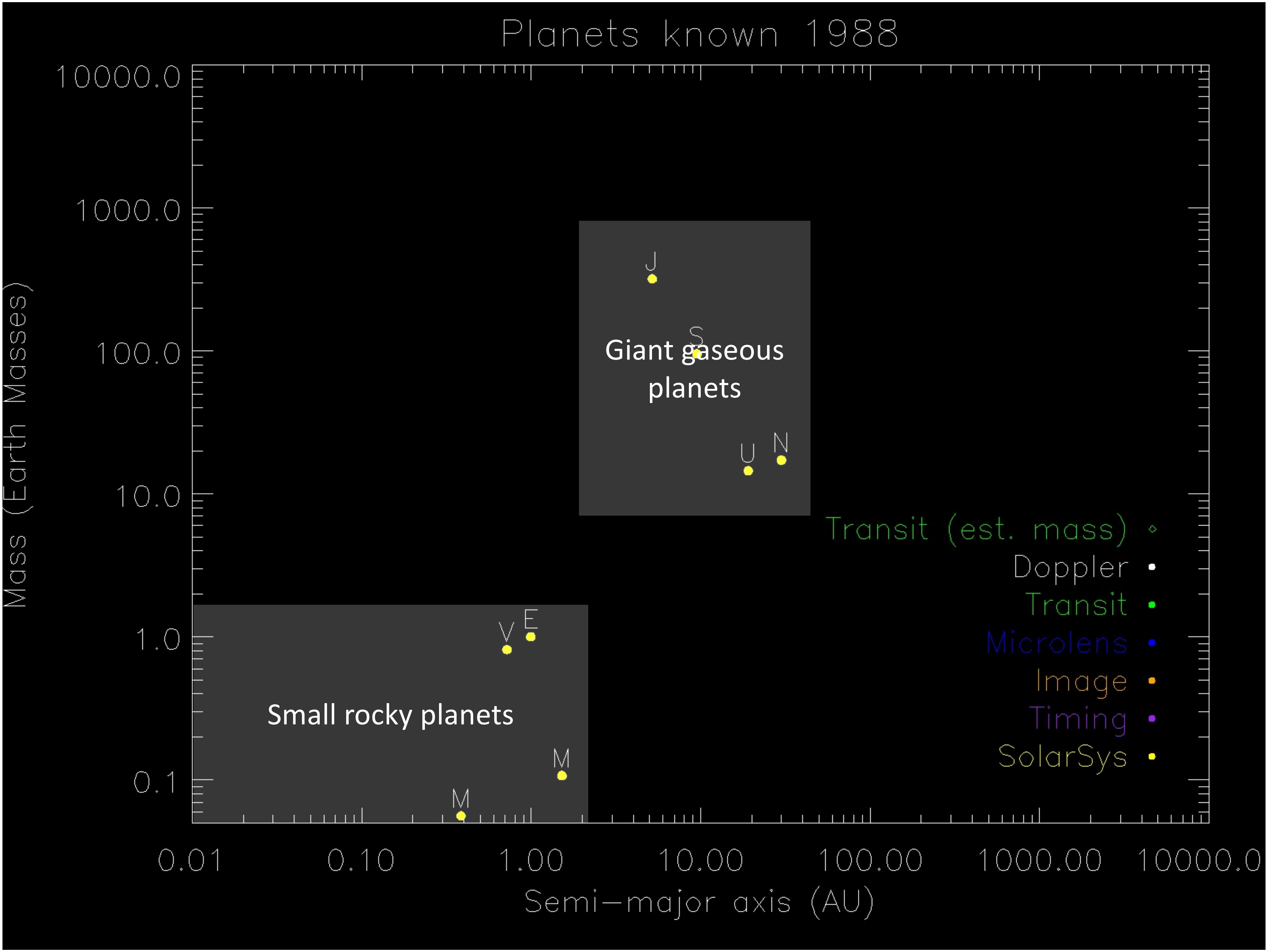




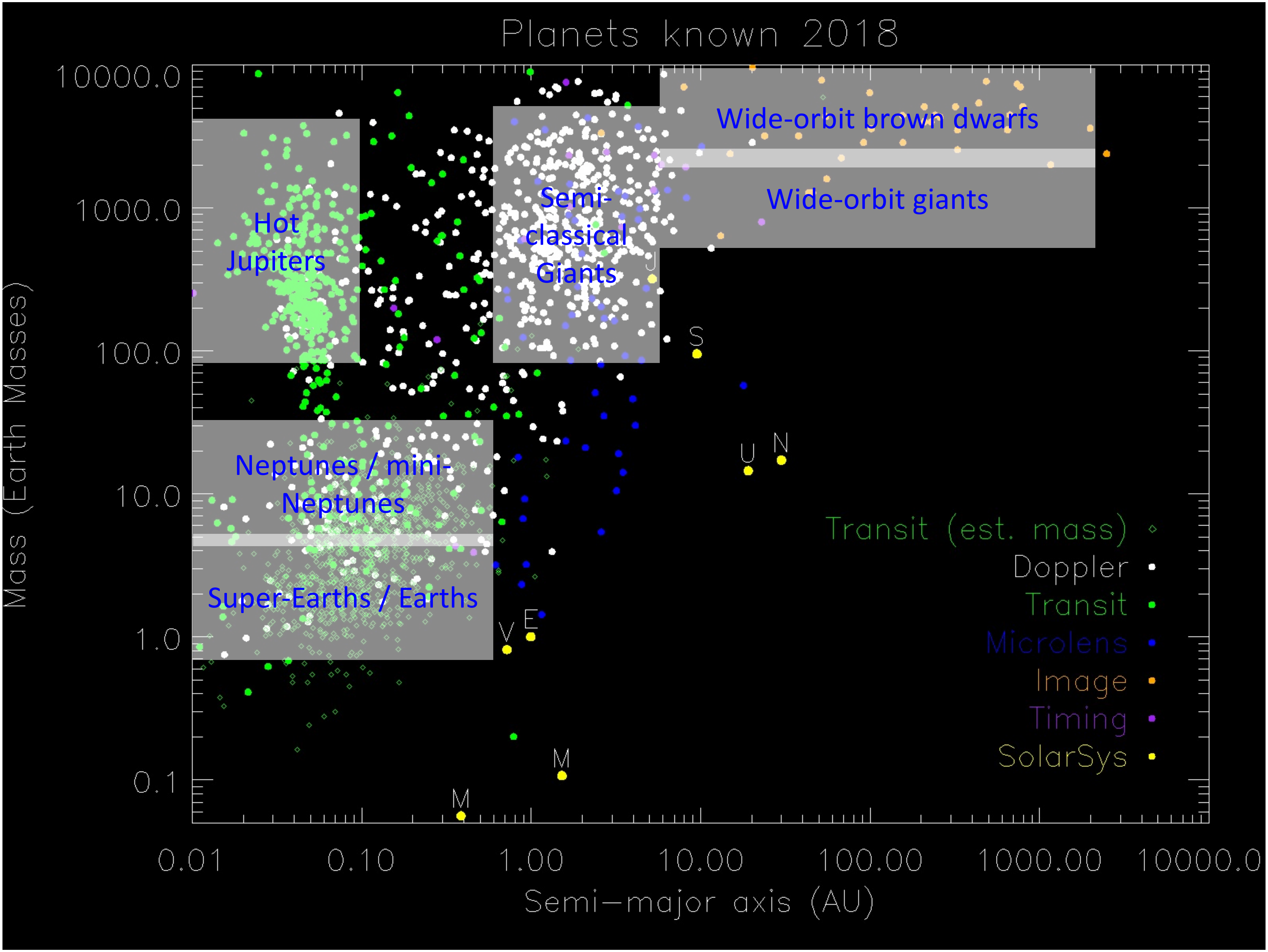


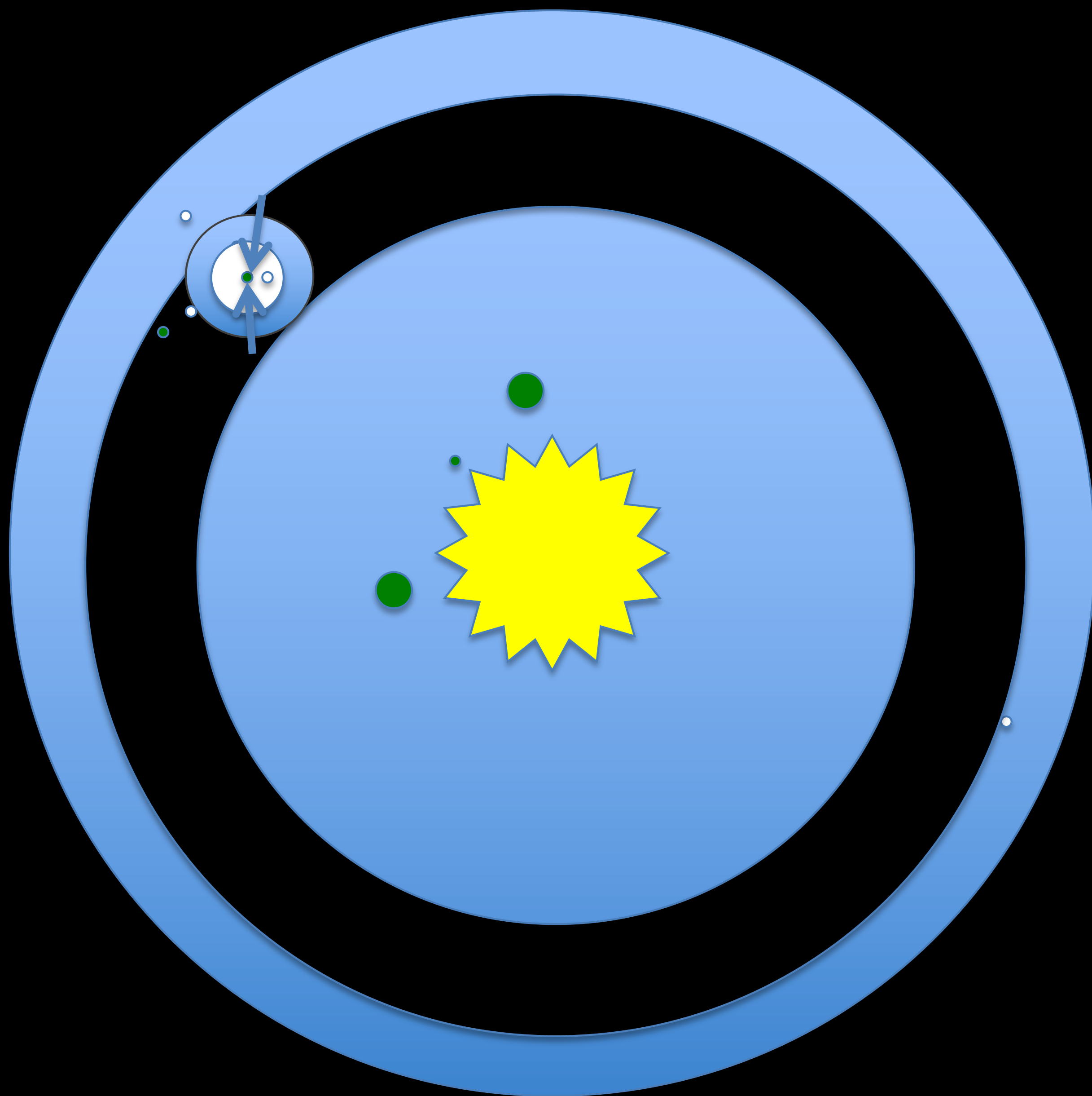


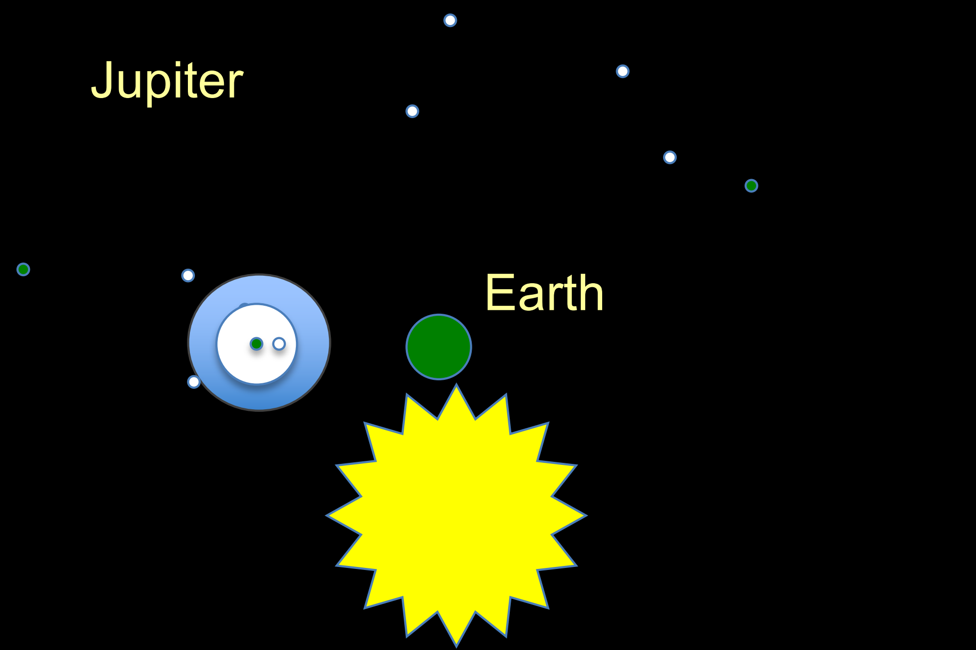

Jupiter
Earth



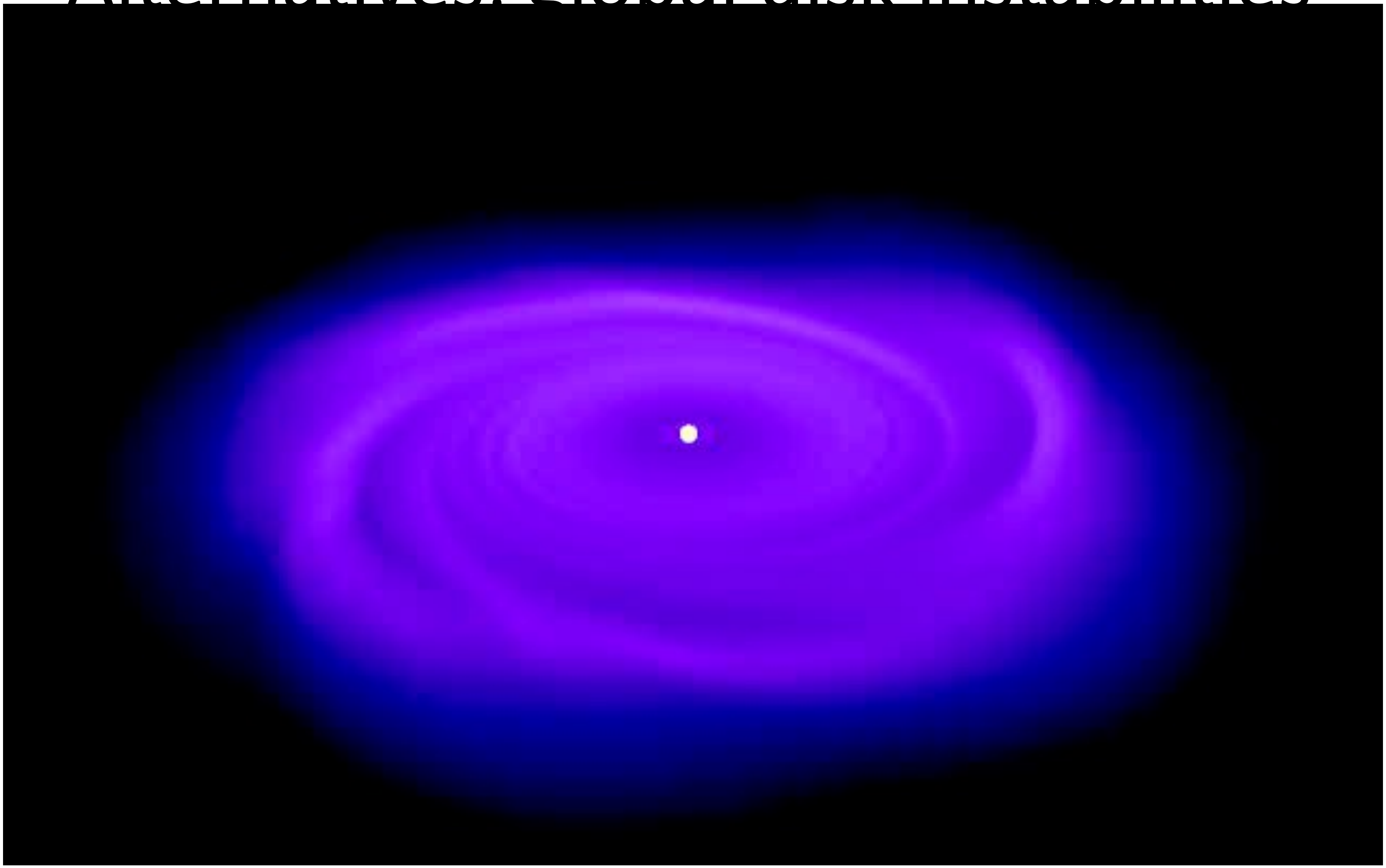
Planets known 1988
Mass (Earth Masses)
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
Semi−major axis (AU)
Giant gaseous planets
Small rocky planets
J
S
U
N
V
E
M
M
Transit (est. mass)
Doppler
Transit
Microlens
Image
Timing
SolarSys


Planets known 2018
Mass (Earth Masses)
Semi−major axis (AU)
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
Hot Jupiters
Semi-classical Giants
Wide-orbit brown dwarfs
Wide-orbit giants
Neptunes / mini-Neptunes
Super-Earths / Earths
J
S
U
N
V
E
M
M
Transit (est. mass)
Doppler
Transit
Microlens
Image
Timing
SolarSys

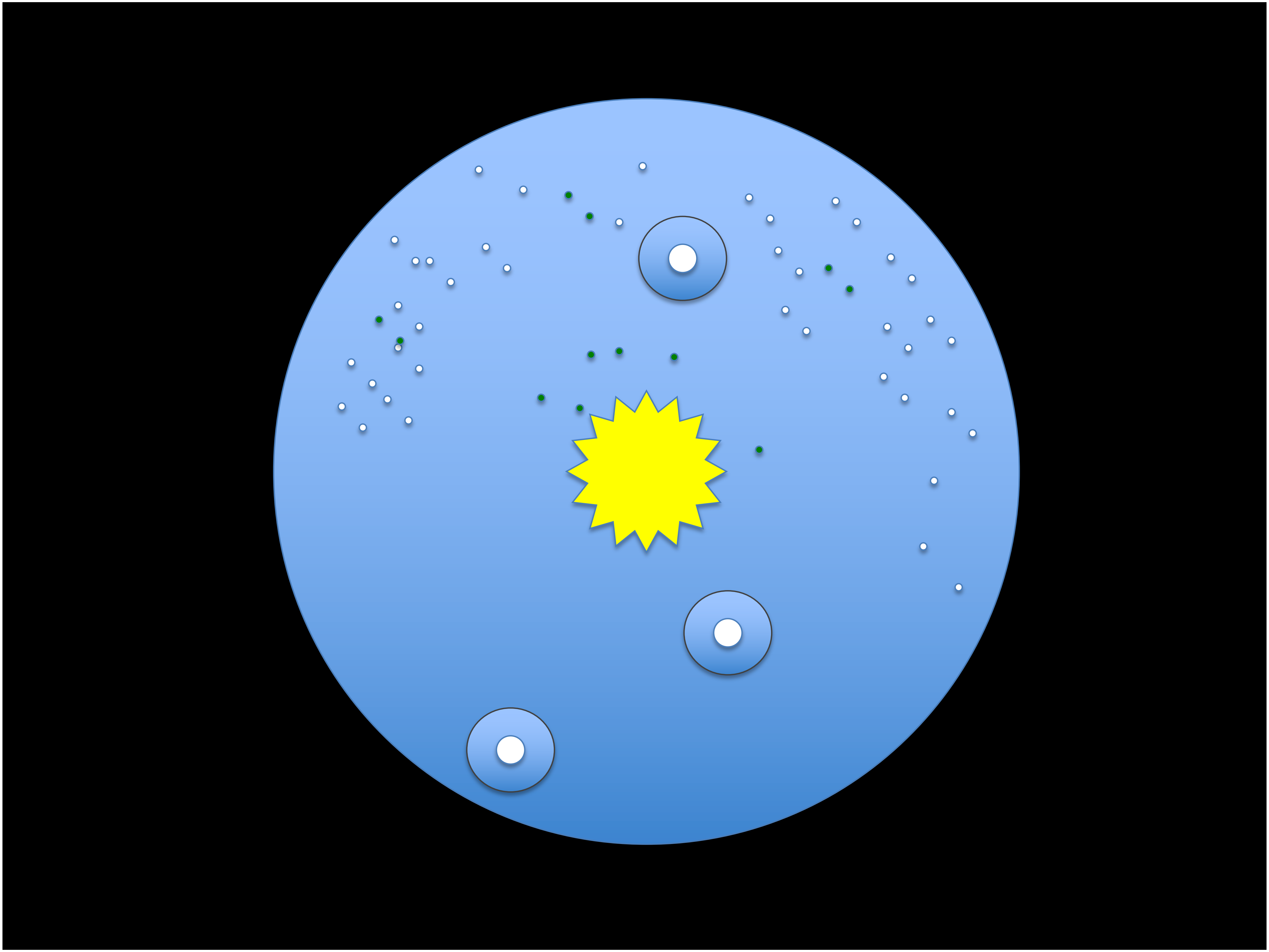



Jupiter
Earth

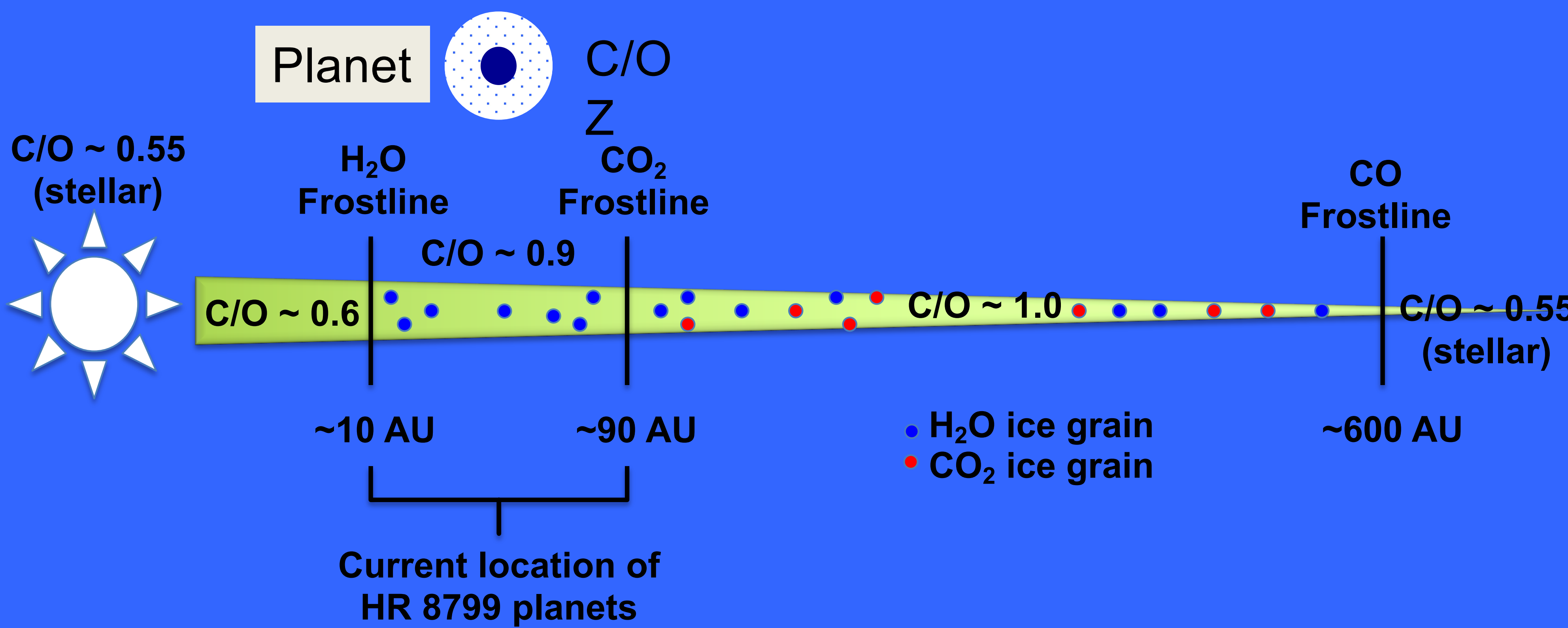
Alternatives: global disk instabilities



- Animation from Mayer et al

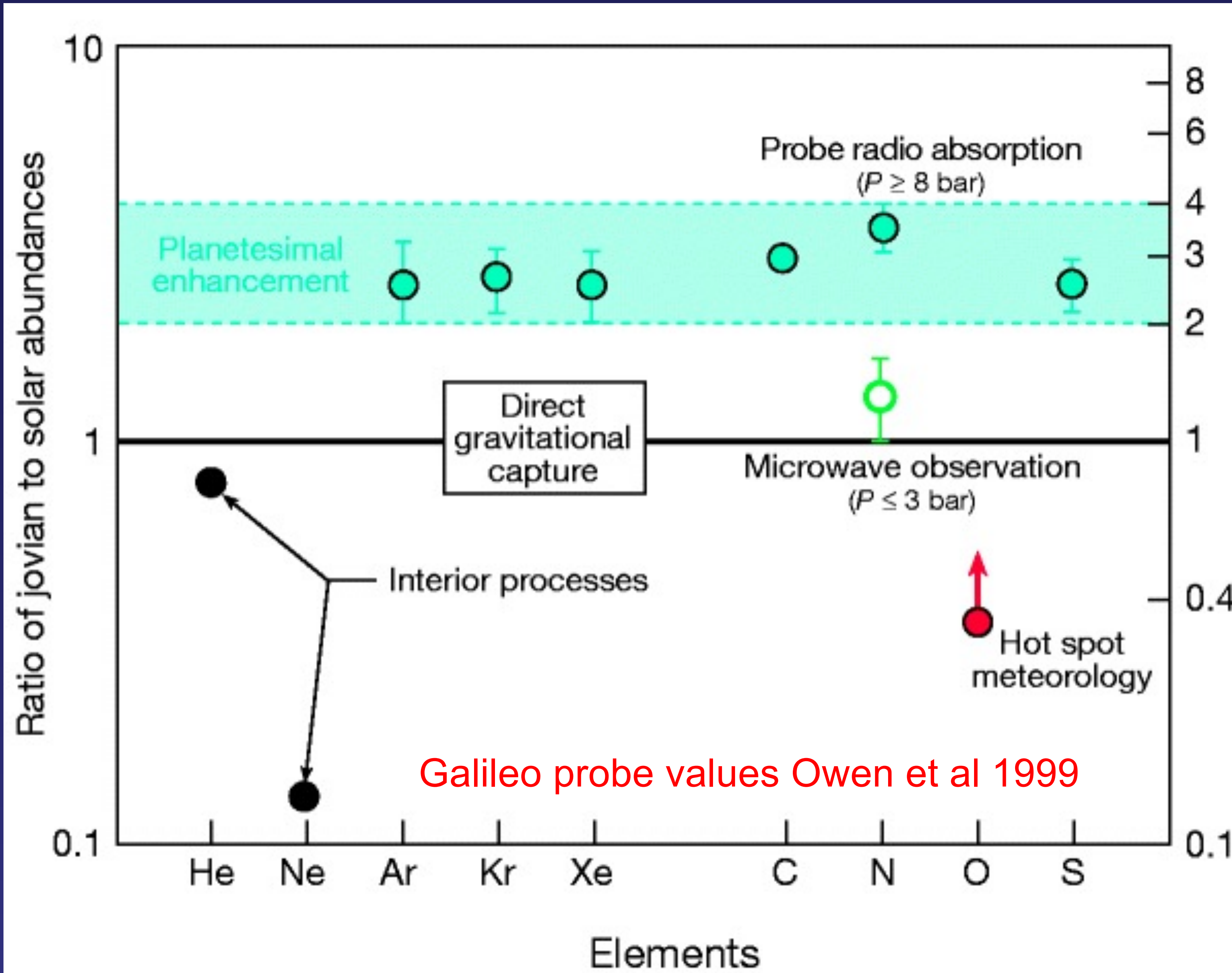


Gas disk and solid material have different carbon / oxygen / hydrogen ratios

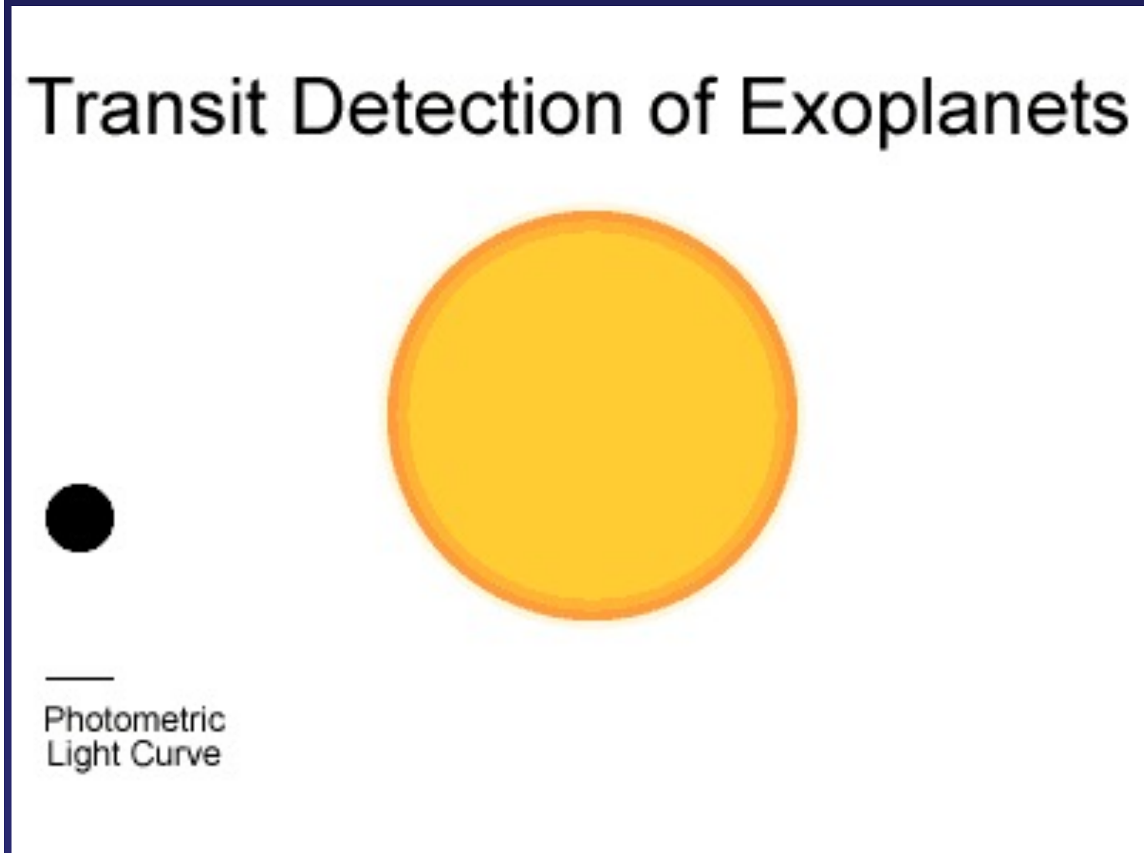


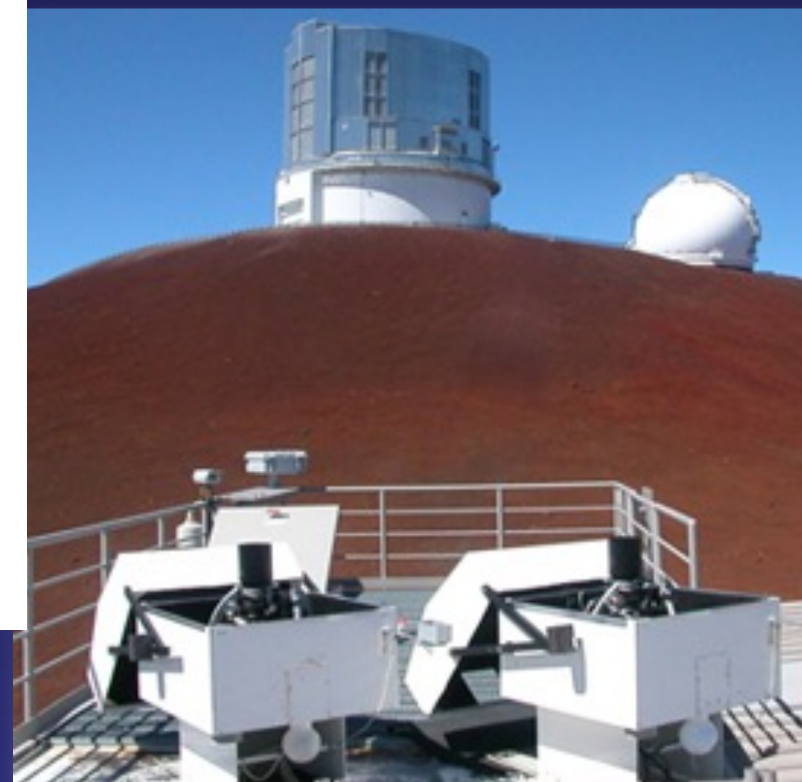
After Konopacky/Macintosh after Oberg&Murray-Clay

Jupiter's abundances reflect formation process

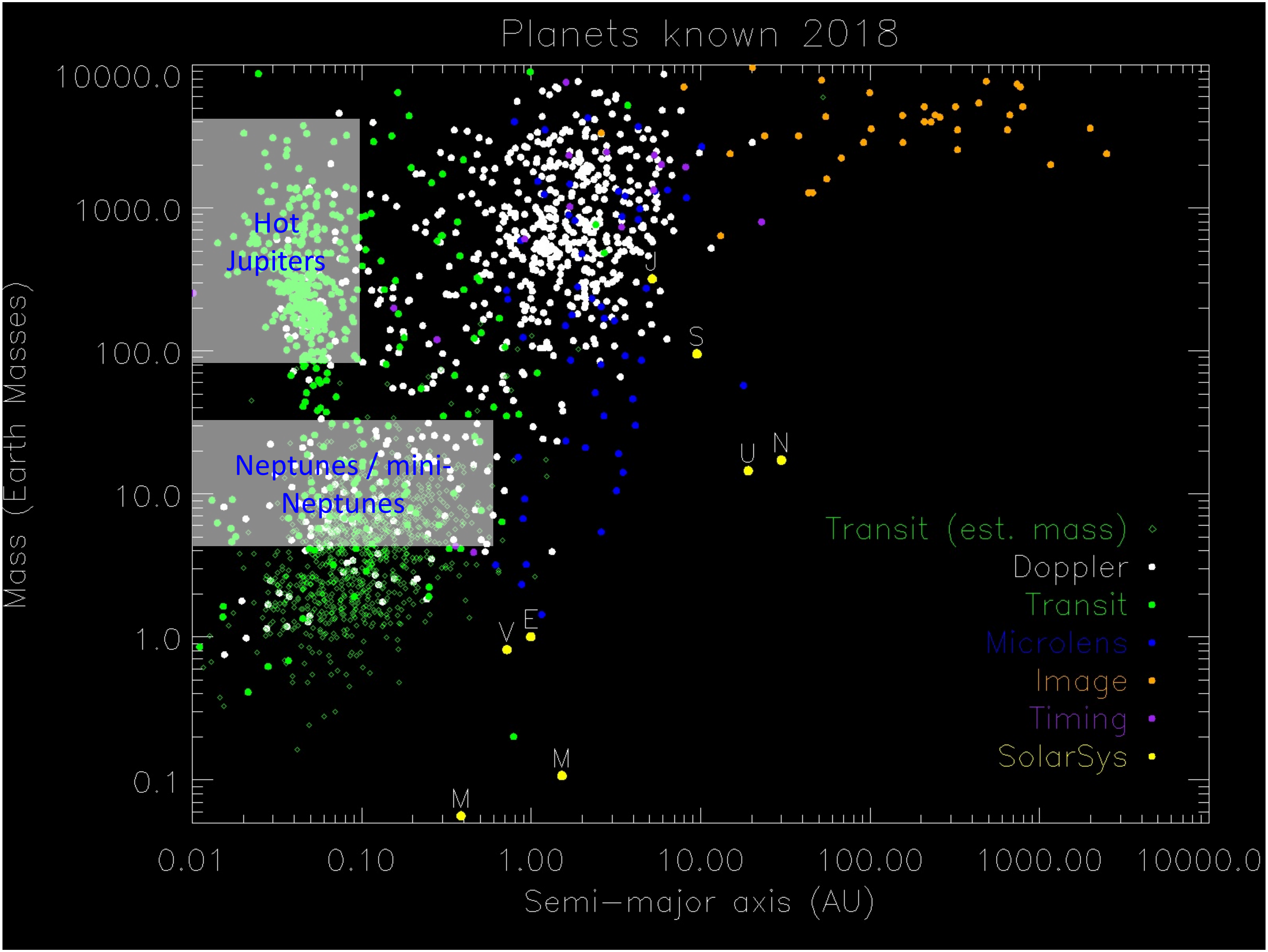


Transiting extrasolar planets



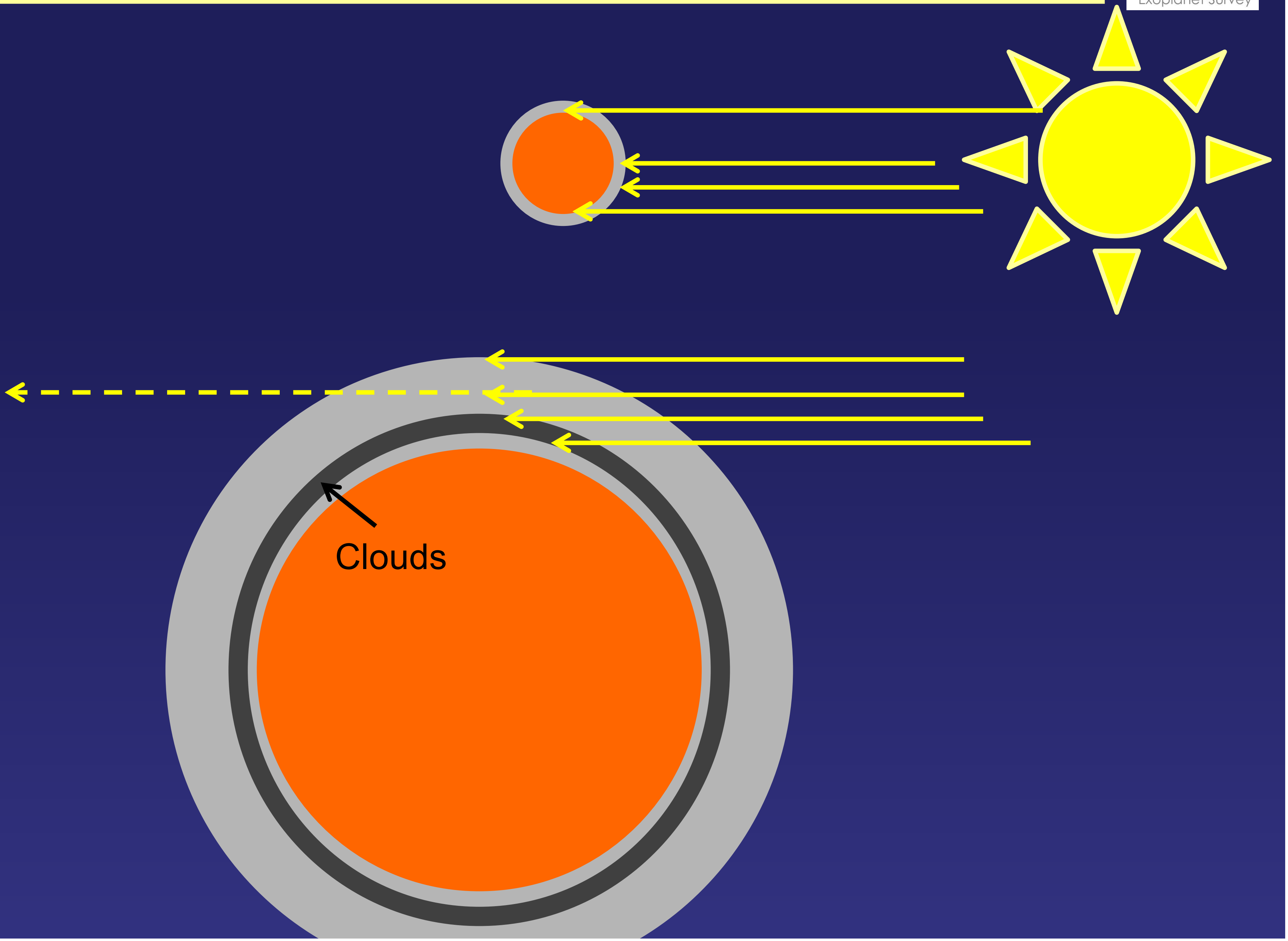


Signal easy to measure even with 11-cm telescope

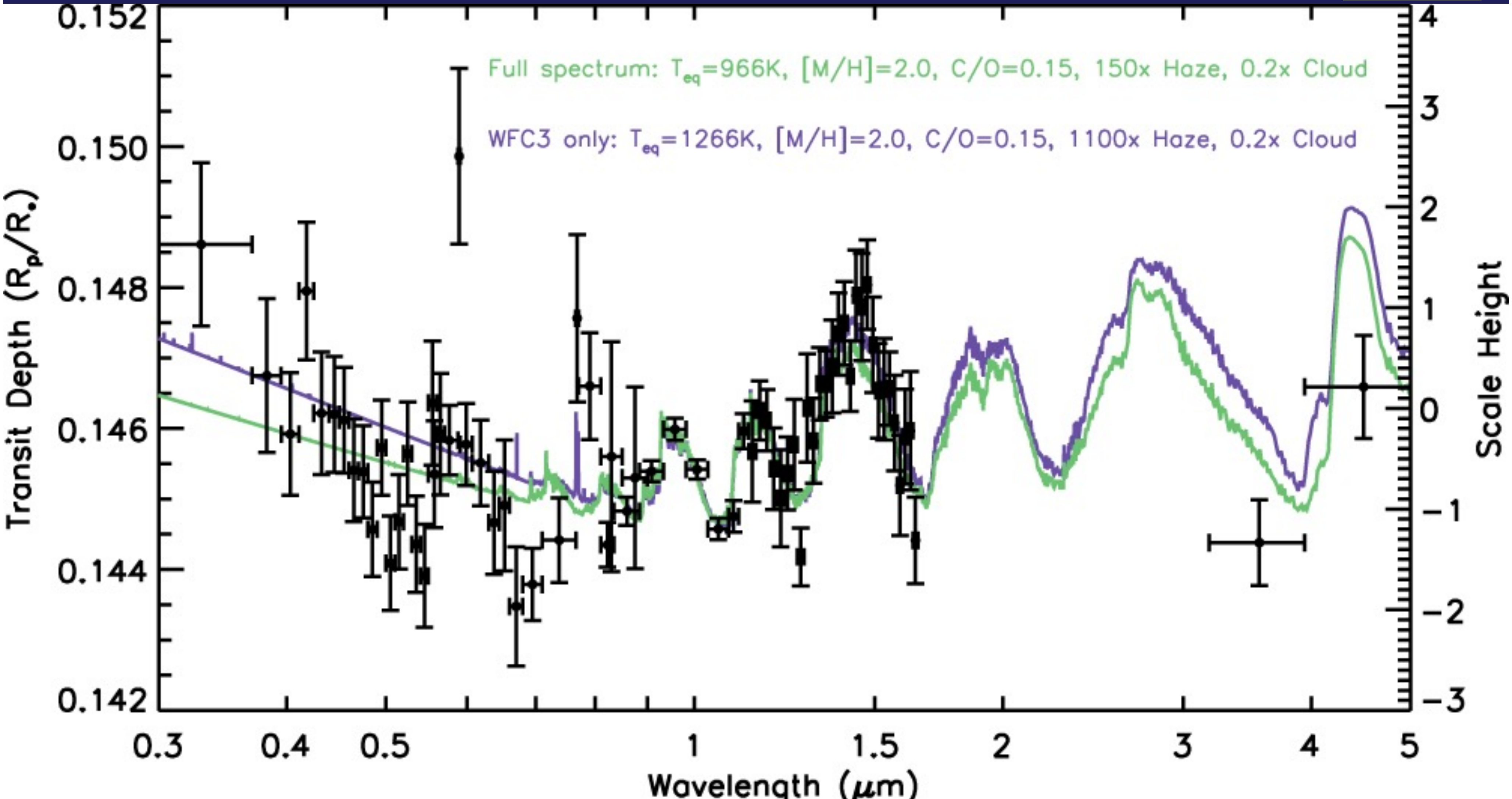


Planets known 2018
Mass (Earth Masses)
10000.0
1000.0
100.0
10.0
1.0
0.1
Semi−major axis (AU)
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
Hot Jupiters
Neptunes / mini-Neptunes
J
S
U
N
V
E
M
M
Transit (est. mass)
Doppler
Transit
Microlens
Image
Timing
SolarSys

Transit spectroscopy probes upper atmosphere



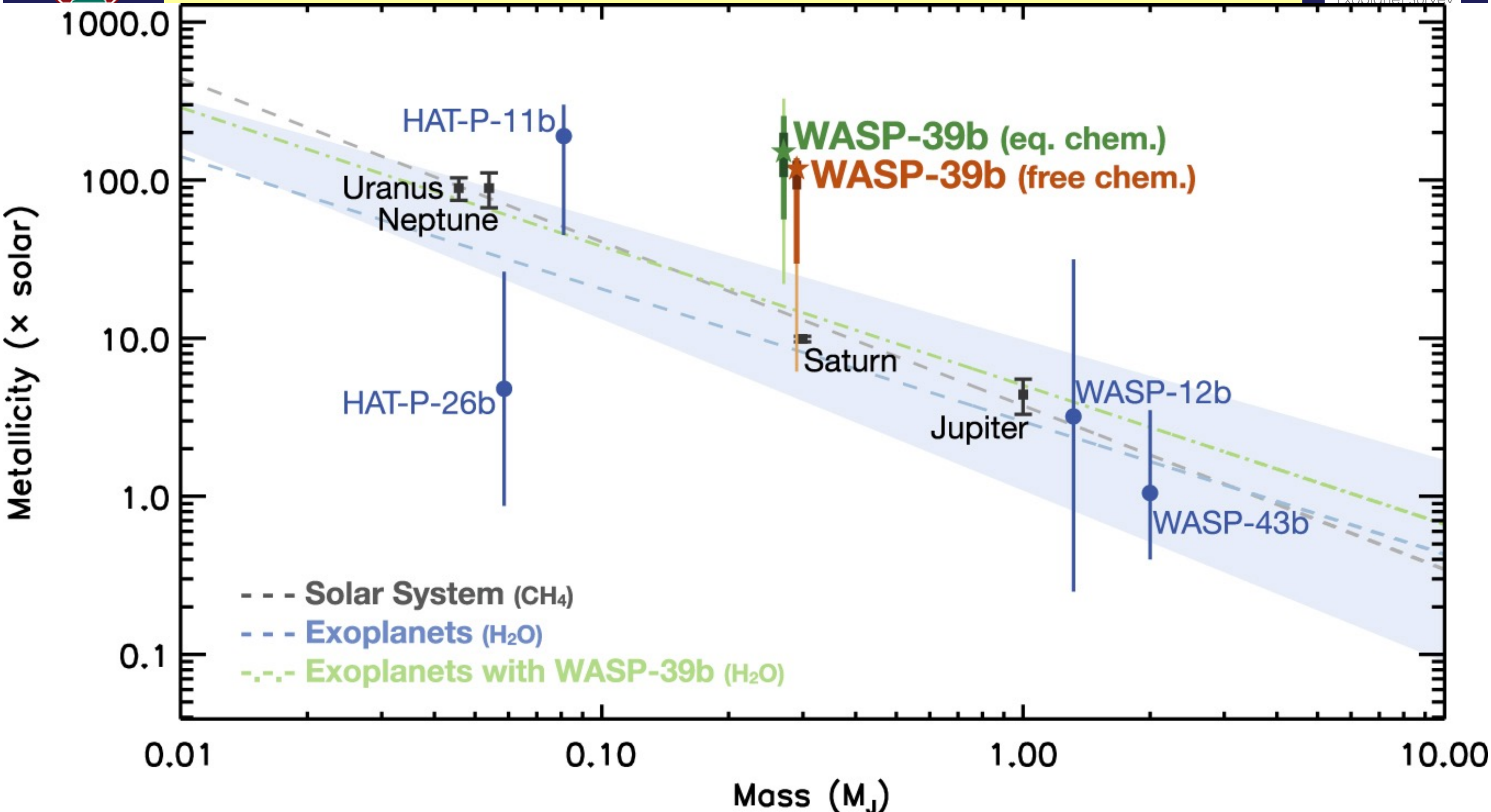
Transmission spectrum of hot jupiter WASP-39b (water features)



Model fits require x100 solar abundance of heavy elements but very sensitive to cloud assumptions

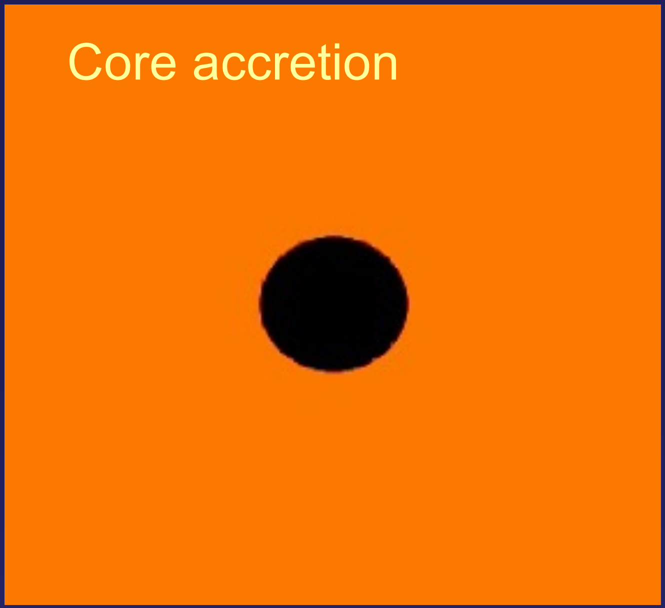
Wakeford et al 2018

"Hot Jupiter" metallicity somewhat consistent with solar system…



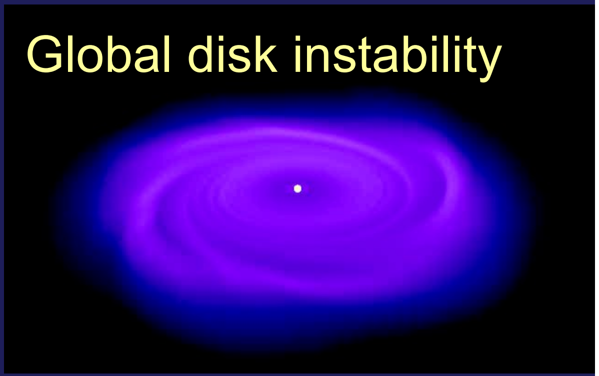
Planet formation pathways predict different properties

Core accretion



Gravitational planet scattering

Global disk instability

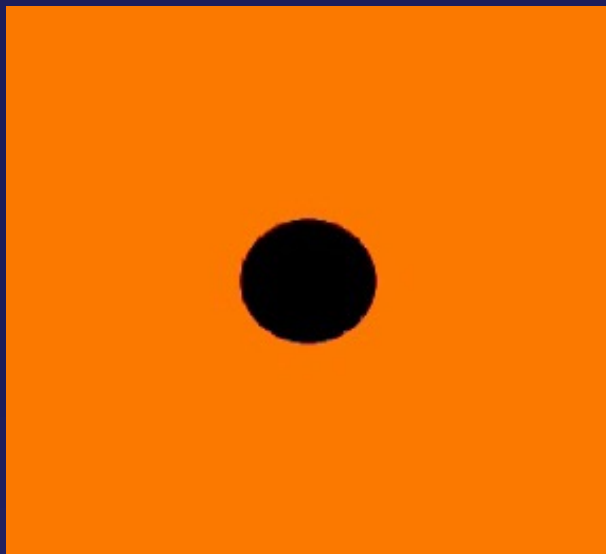


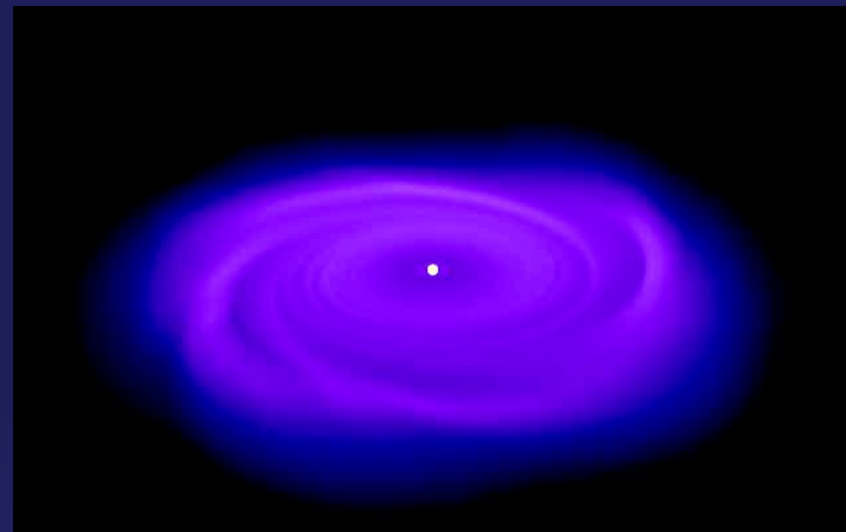
- Generally circular orbits
- Planets inside ice line
- More low-mass

- Elliptical orbits unless later circularized
- Multiple planets

- Very massive planets or BDs
- Wide orbits
- Multiplanet ?

Formation predictions: composition

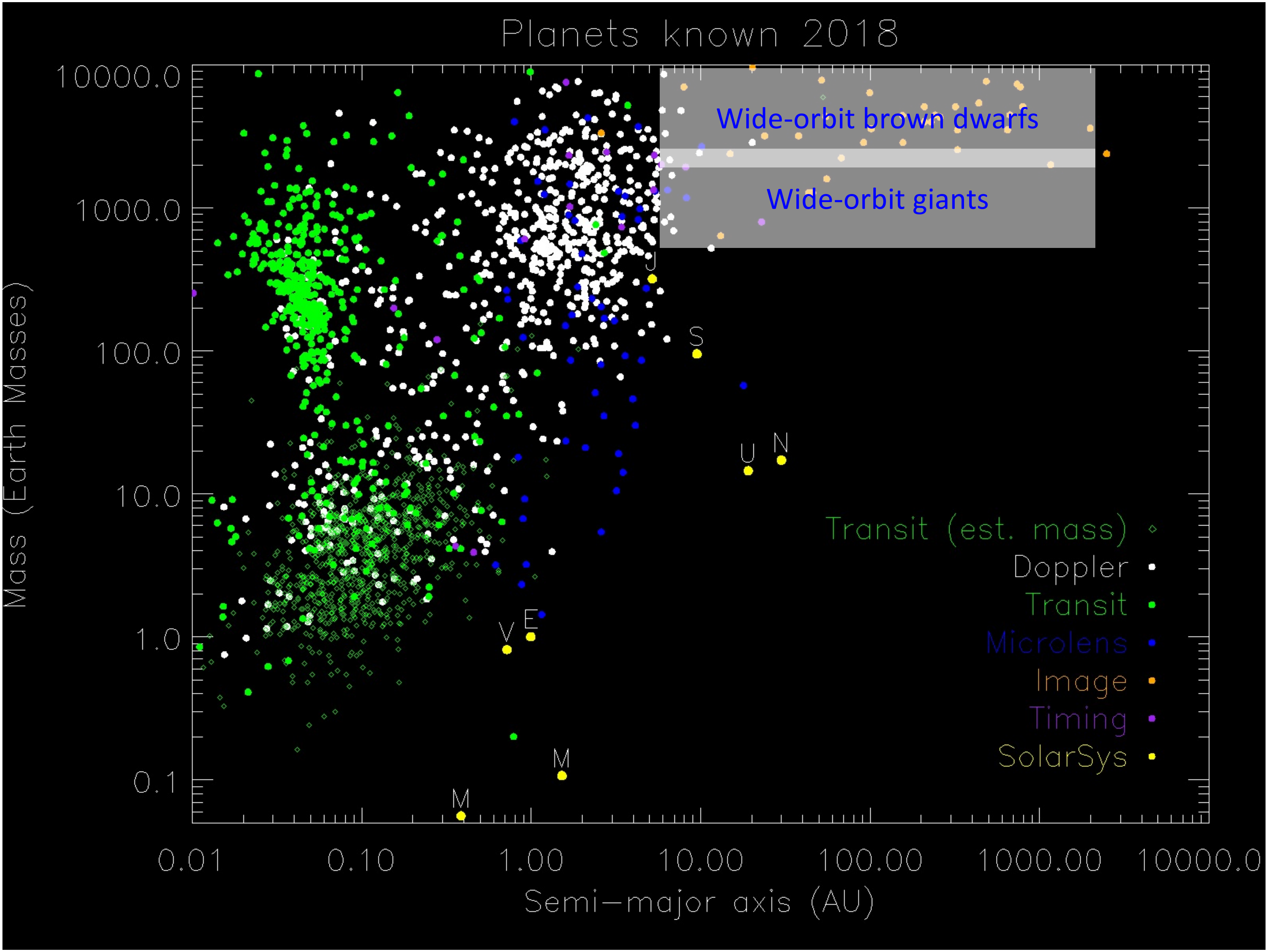




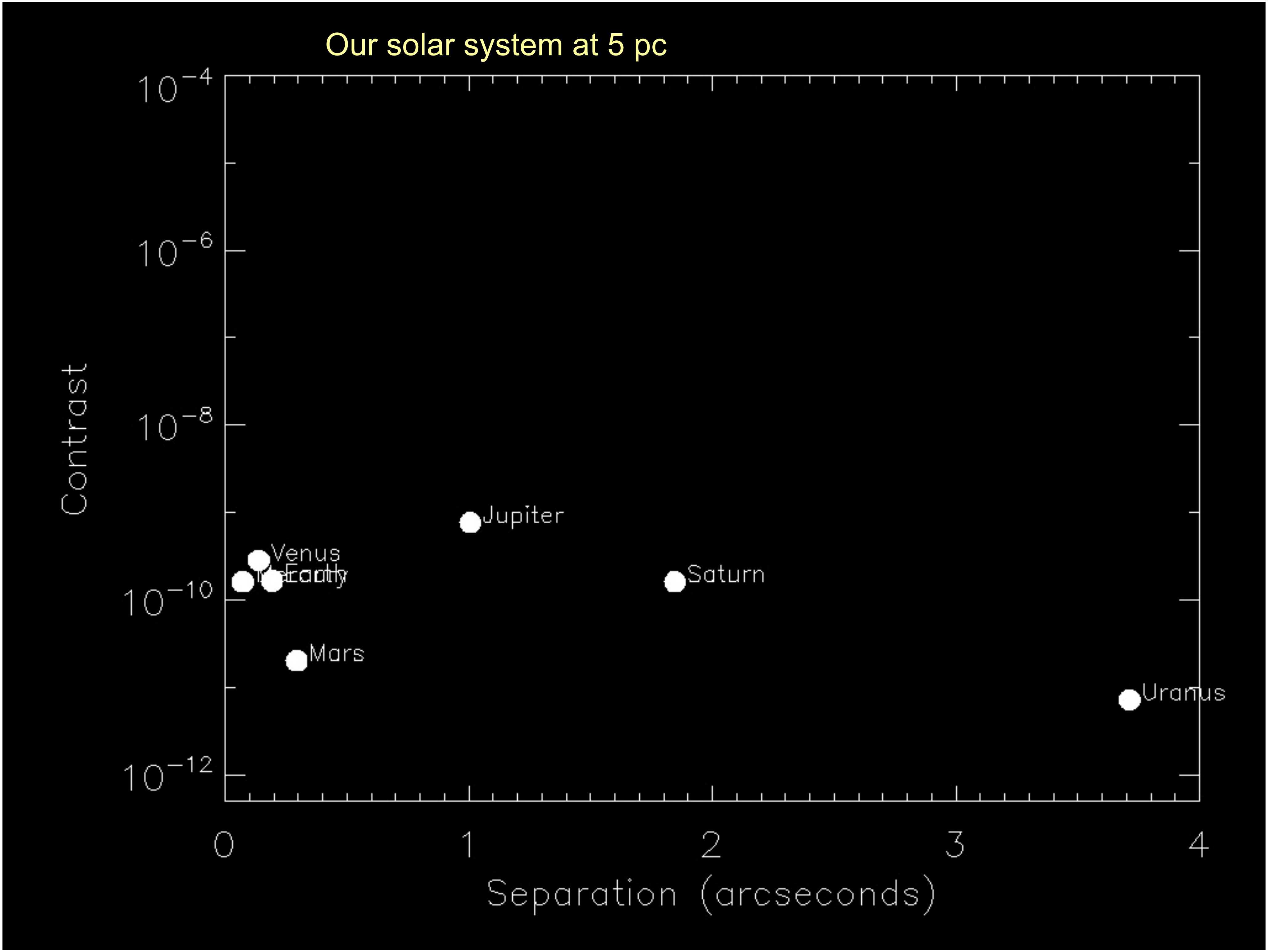
- Enhanced (or modified…) metallicity due to preferential accretion of solids
- Colder planets?

- Stellar metallicity
- High-entropy planets

Dog Break 1

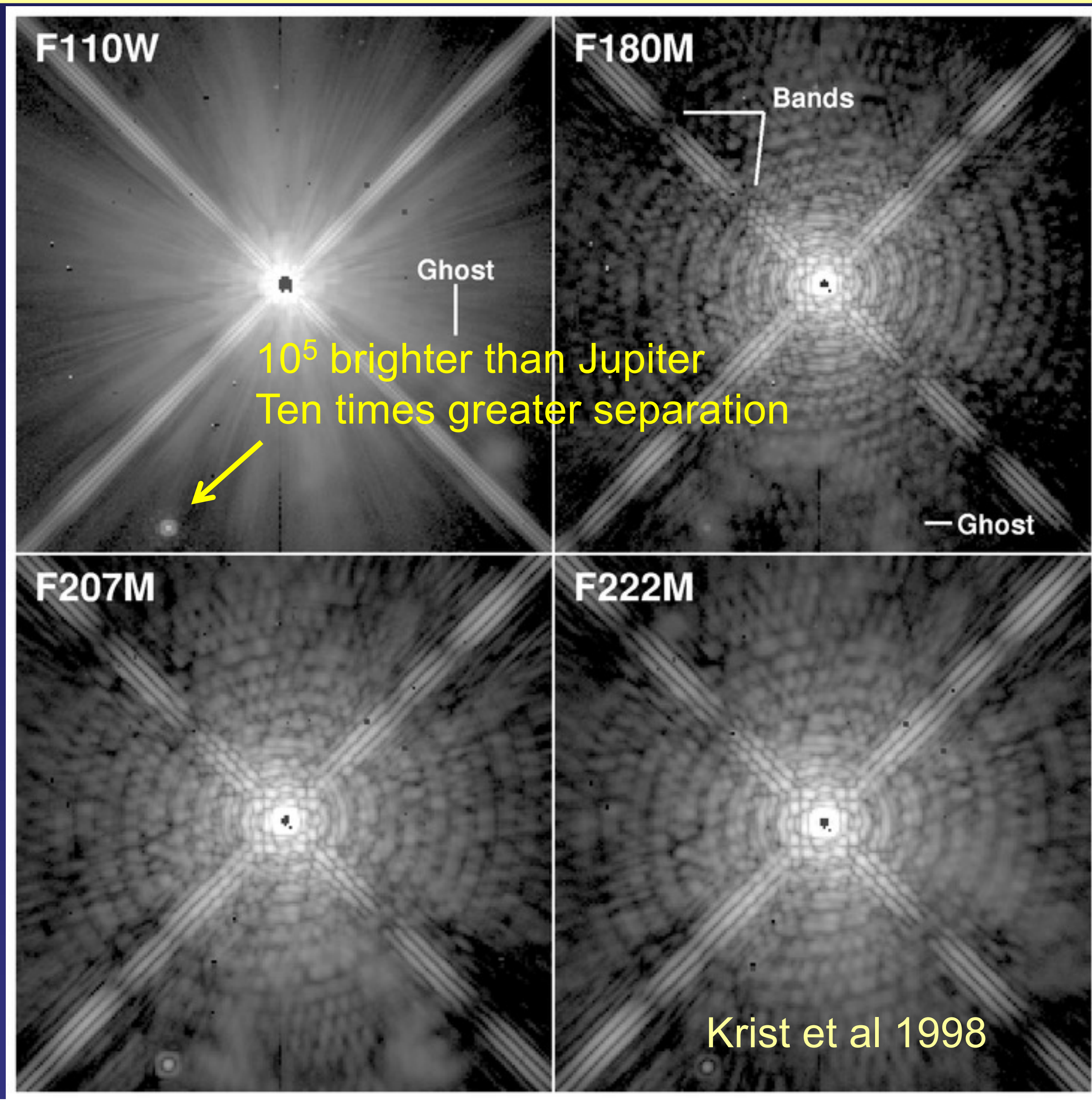


Planets known 2018
Wide-orbit brown dwarfs
Wide-orbit giants
Mass (Earth Masses)
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
Semi−major axis (AU)
J
S
U
N
V
E
M
M
Transit (est. mass)
Doppler
Transit
Microlens
Image
Timing
SolarSys



Our solar system at 5 pc
Contrast
Separation (arcseconds)
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
0
1
2
3
4
Jupiter
Venus
Earth
Mercury
Saturn
Mars
Uranus

Hubble Space Telescope IR Point Spread Functions (PSF)

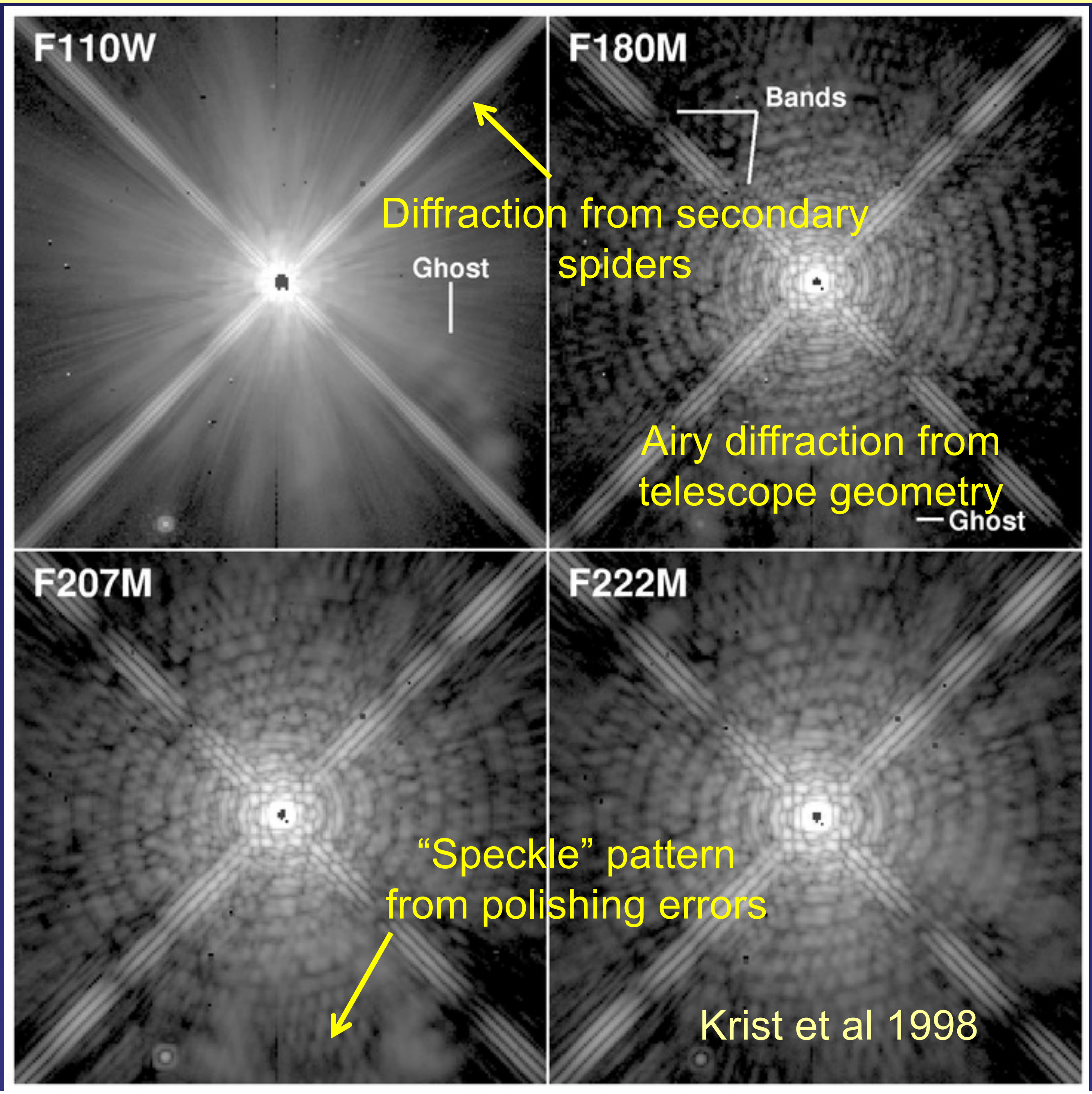


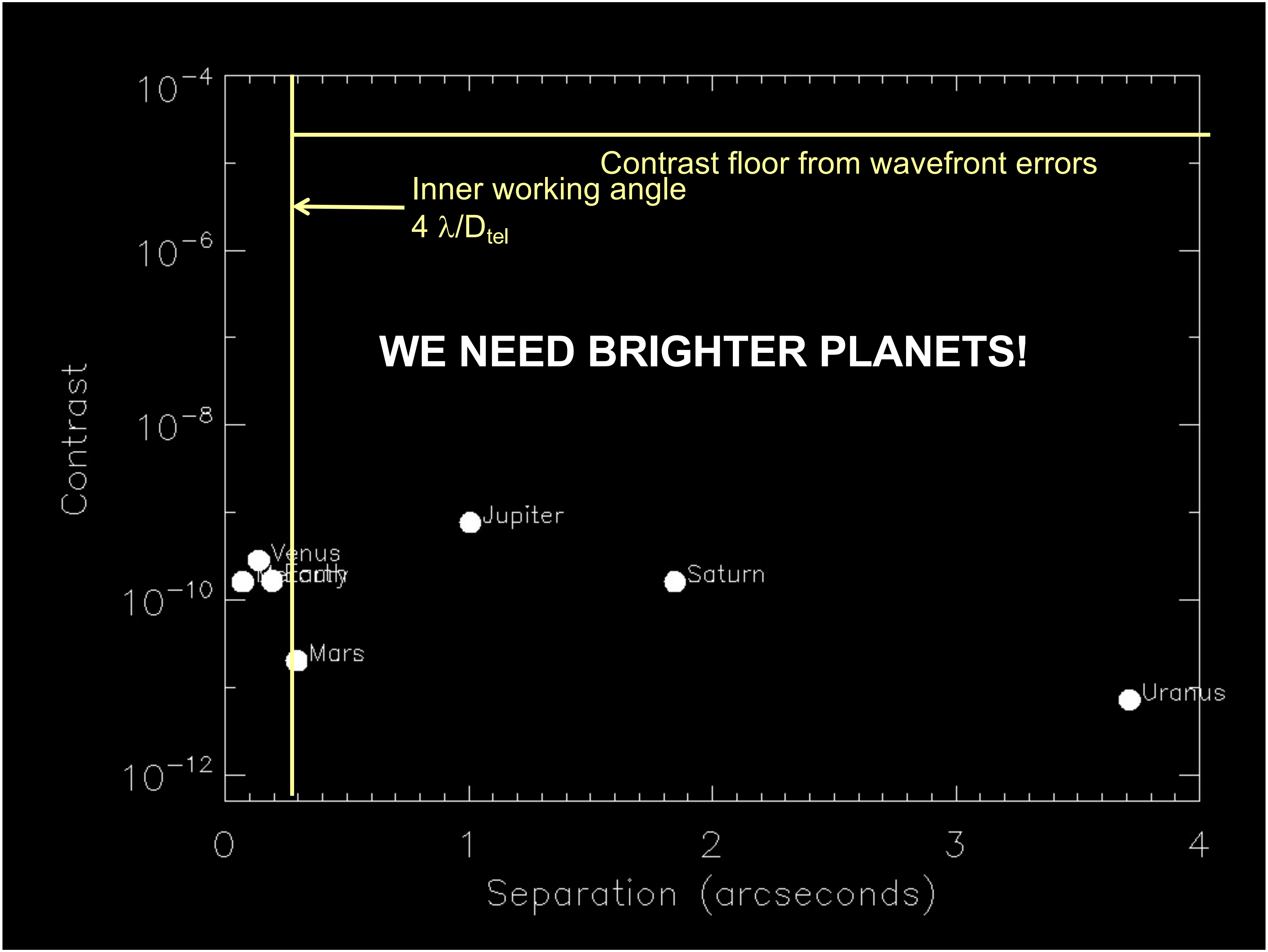
10^5 brighter than Jupiter
Ten times greater separation

Krist et al 1998

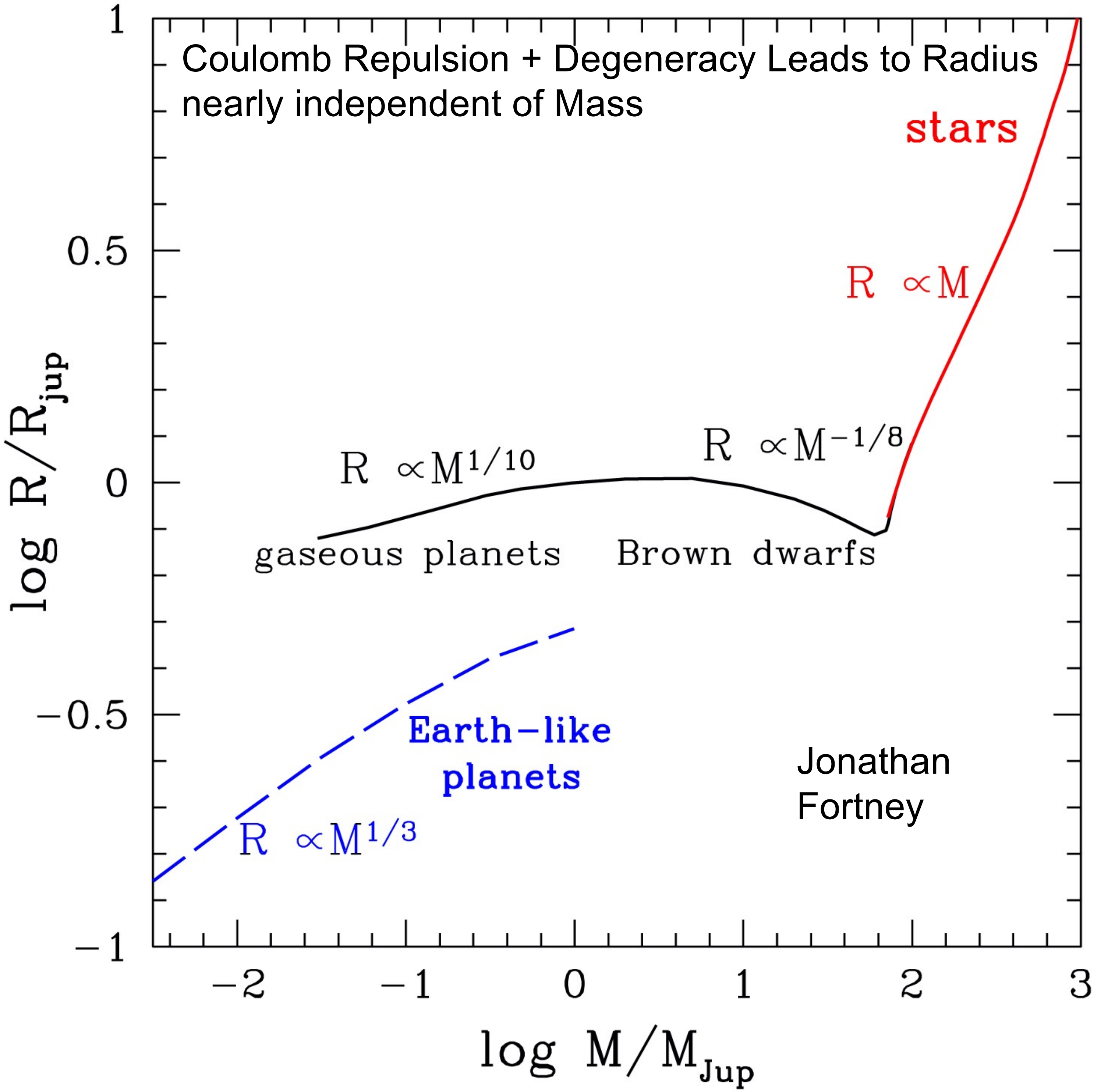
Exoplanet Survey

Hubble Space Telescope infrared Point Spread Functions (PSF)

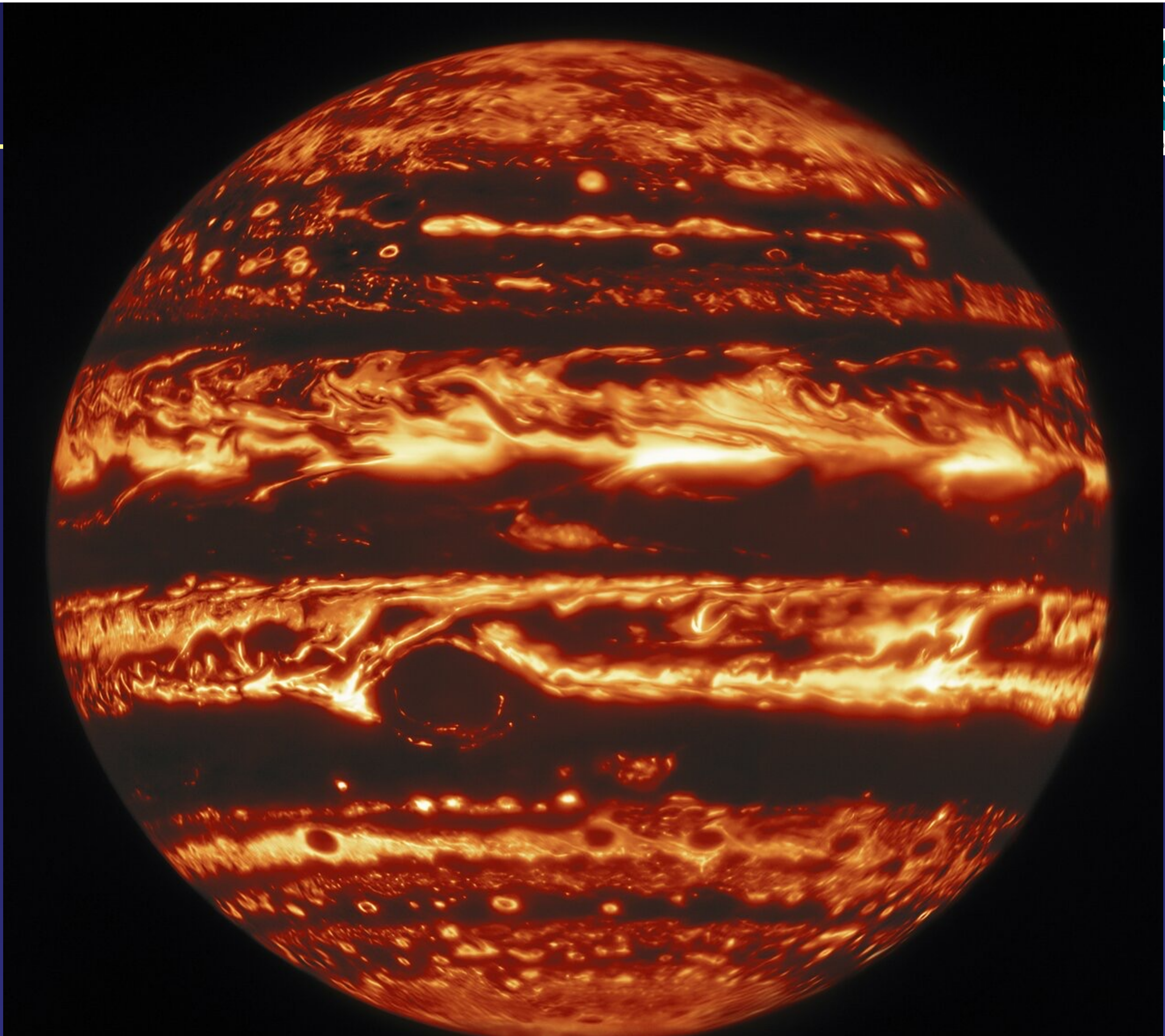




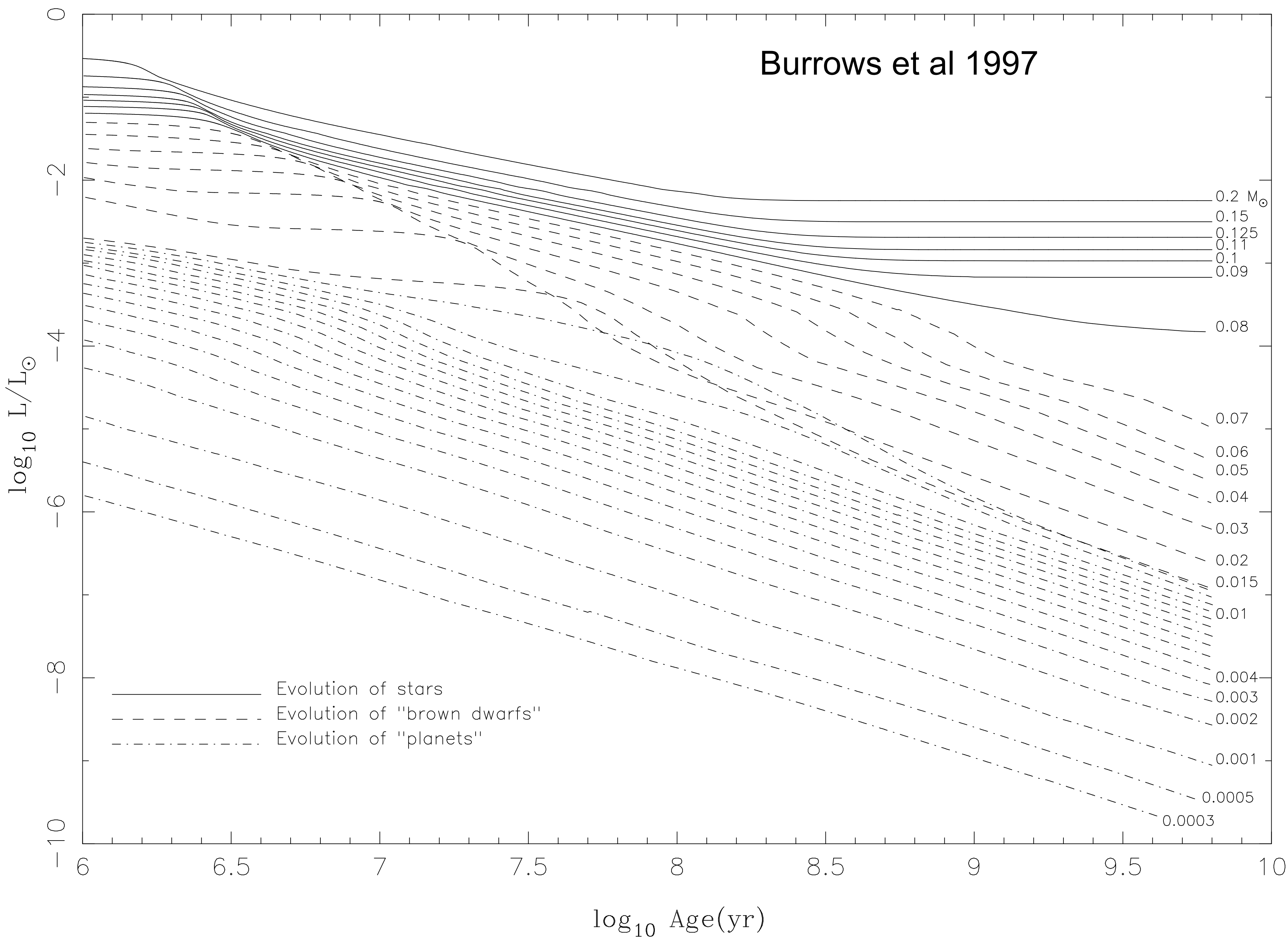
Contrast floor from wavefront errors
Inner working angle
4 λ/D_tel
WE NEED BRIGHTER PLANETS!
Contrast
10^-4
10^-6
10^-8
10^-10
10^-12
Jupiter
Venus
Earth
Saturn
Mars
Uranus
0
1
2
3
4
Separation (arcseconds)

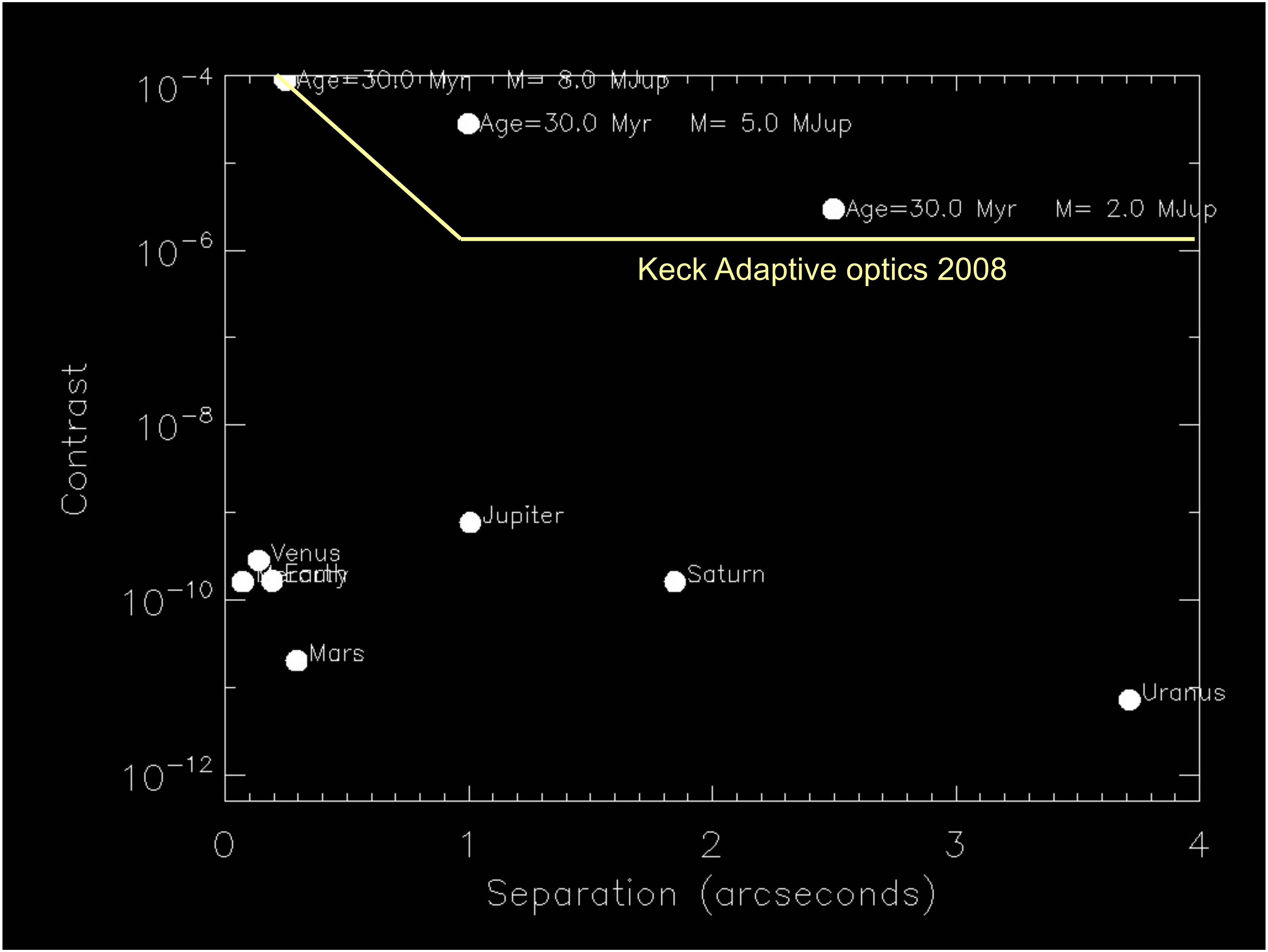


Coulomb Repulsion + Degeneracy Leads to Radius nearly independent of Mass
stars
$R \propto M$
$R \propto M^{-1/8}$
$R \propto M^{1/10}$
gaseous planets
Brown dwarfs
Earth-like planets
$R \propto M^{1/3}$
Jonathan Fortney
$\log R/R_{jup}$
$\log M/M_{Jup}$
1
0.5
0
−0.5
−1
−2
−1
0
1
2
3



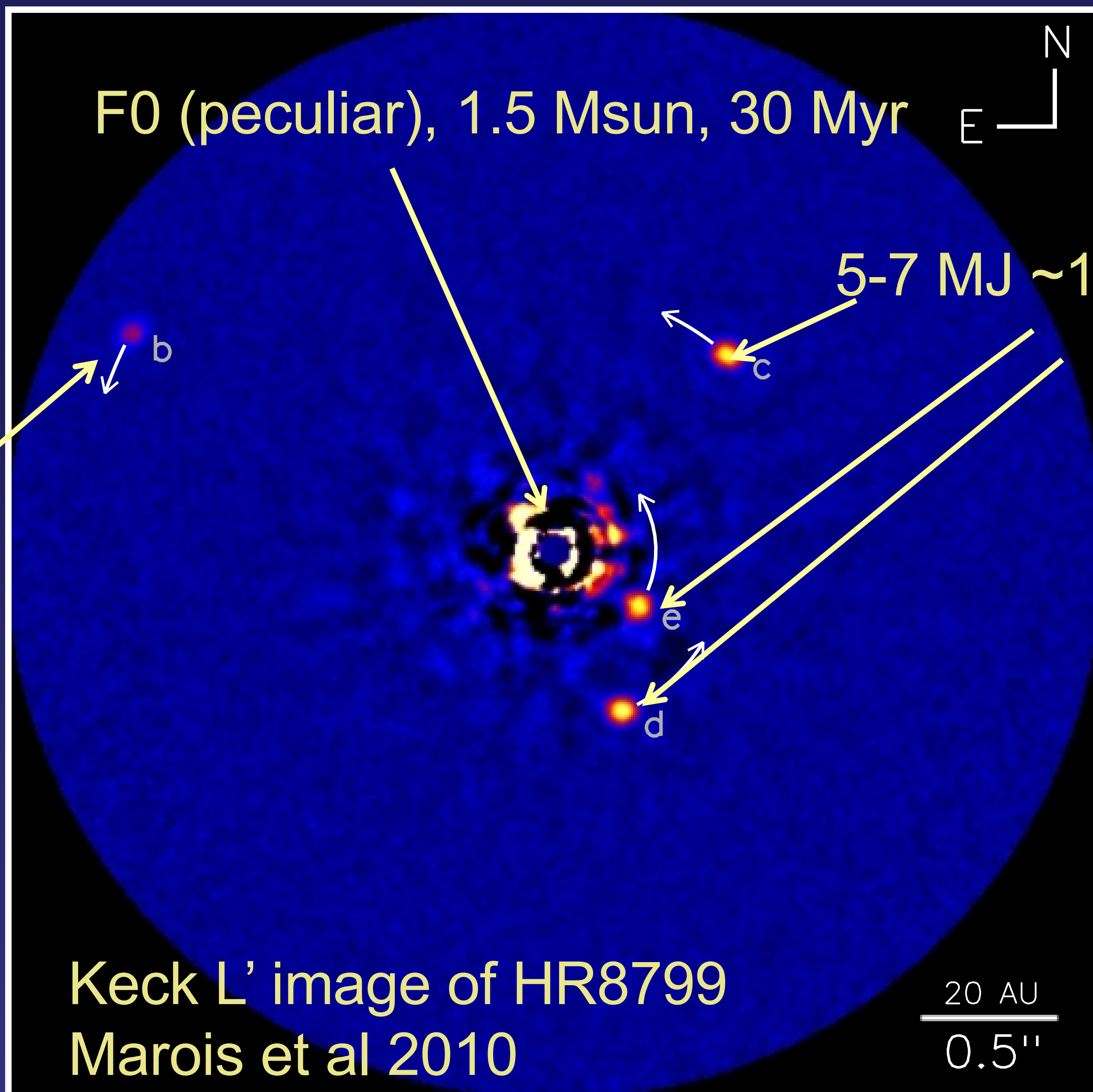
HST and Gemini: https://noirlab.edu/public/news/noirlab2116/


Burrows et al 1997
0.2 $M_\odot$
0.15
0.125
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.015
0.01
0.004
0.003
0.002
0.001
0.0005
0.0003
Evolution of stars
Evolution of "brown dwarfs"
Evolution of "planets"
$\log_{10} L/L_\odot$
$\log_{10}$ Age(yr)
0
−2
−4
−6
−8
−10
6
6.5
7
7.5
8
8.5
9
9.5
10



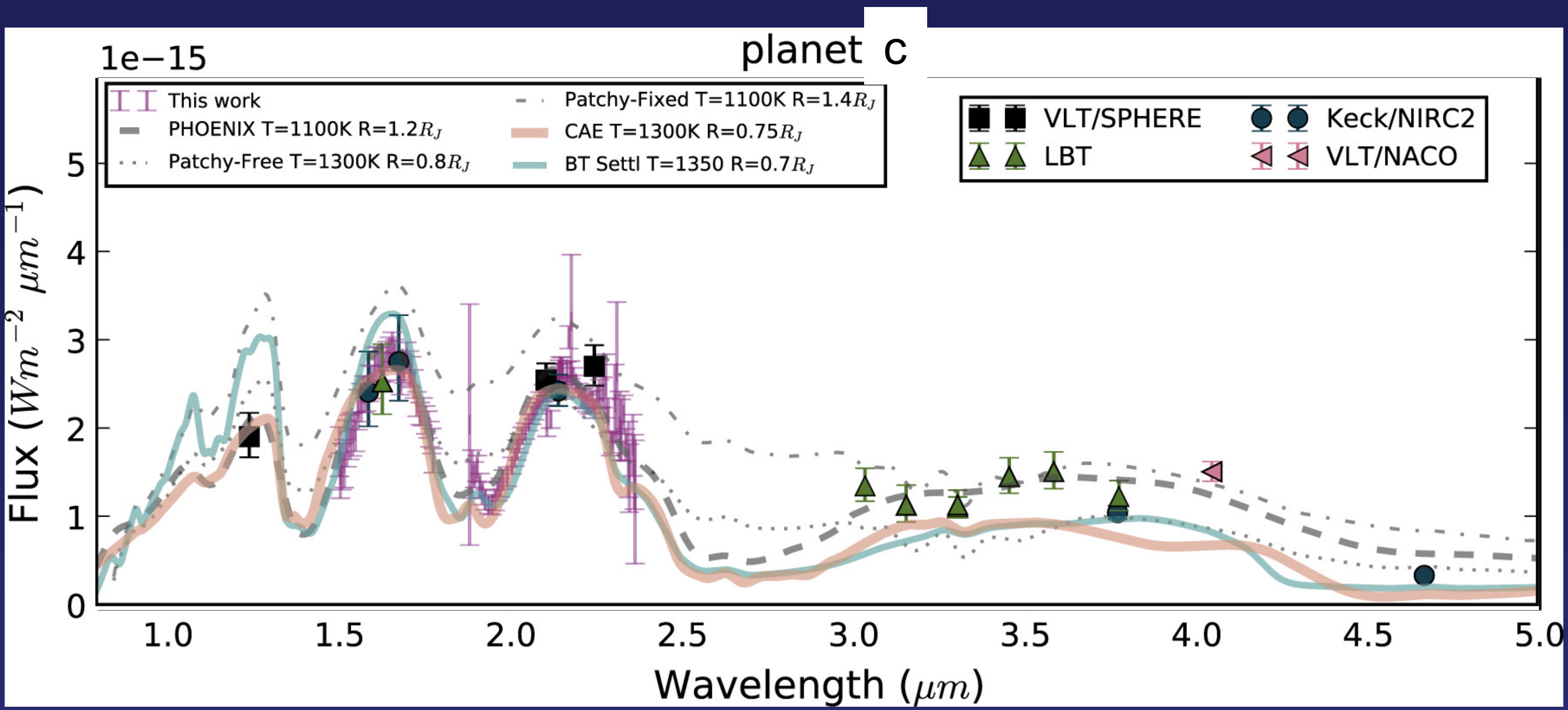
Age=30.0 Myr M= 8.0 MJup
Age=30.0 Myr M= 5.0 MJup
Age=30.0 Myr M= 2.0 MJup
Keck Adaptive optics 2008
Jupiter
Venus
Earth
Saturn
Mars
Uranus
Contrast
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
0
1
2
3
4
Separation (arcseconds)

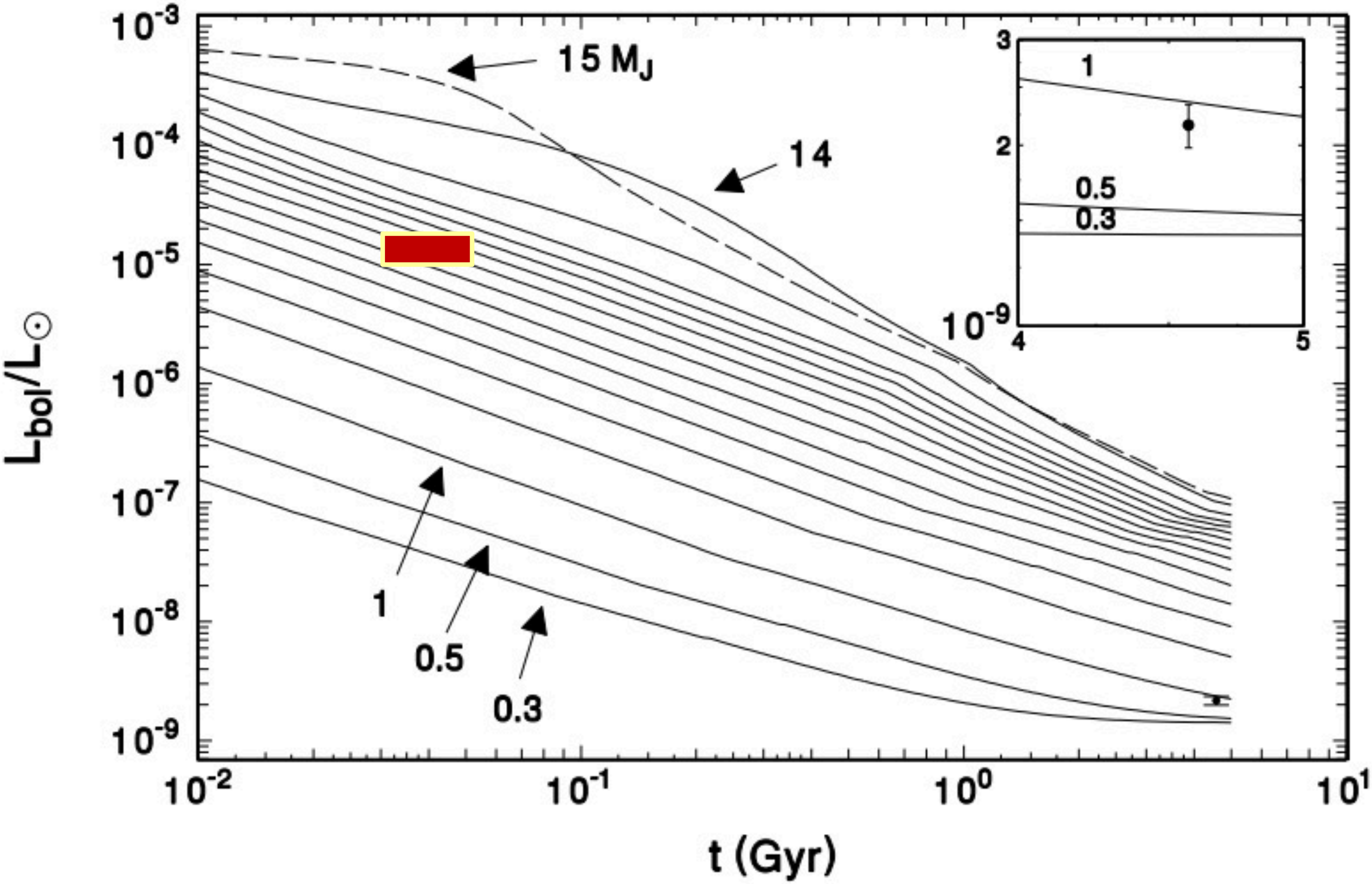
HR8799 system



2009 – 2016

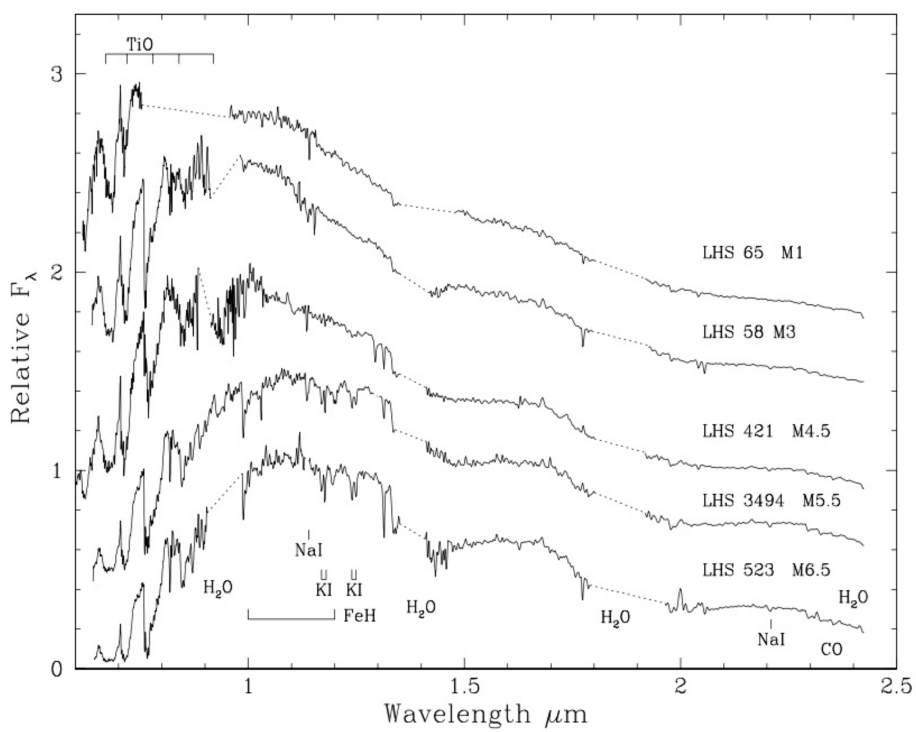
We have a good estimate of the total flux





Luminosity and age allow estimate of mass. (Modern values 5-7 MJ)

Stellar spectra



deeper
hotter
denser

L- to M dwarf transition

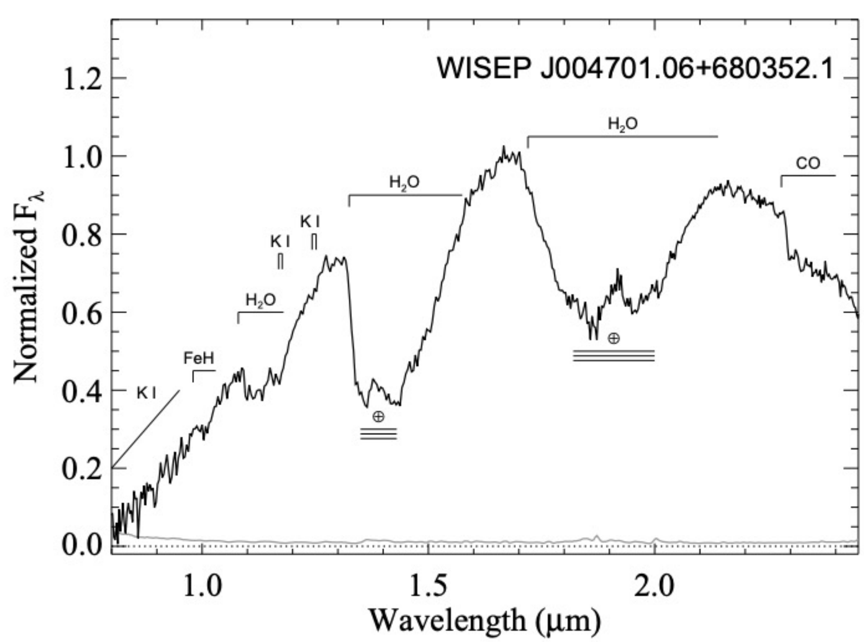
Cool stars (2000 K)

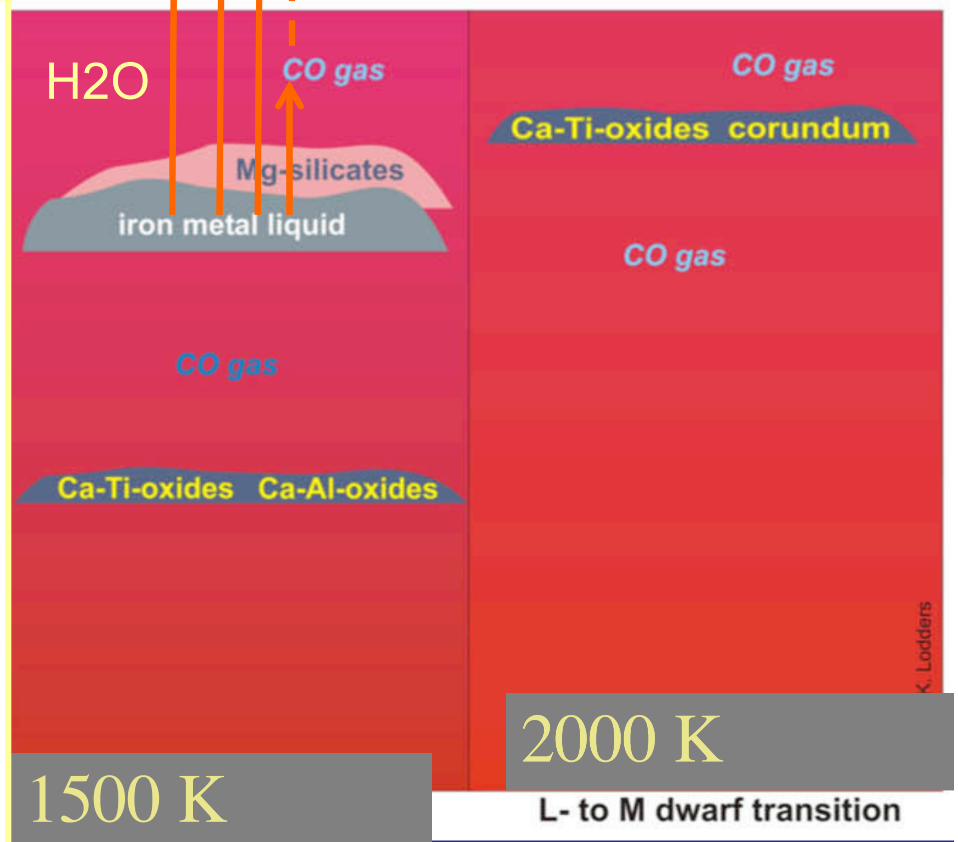
Atmosphere of HR8799 planets

Spectrum shows
CH4, H2O

Spectrum shows
H2, H2O, CO

deeper
hotter
denser



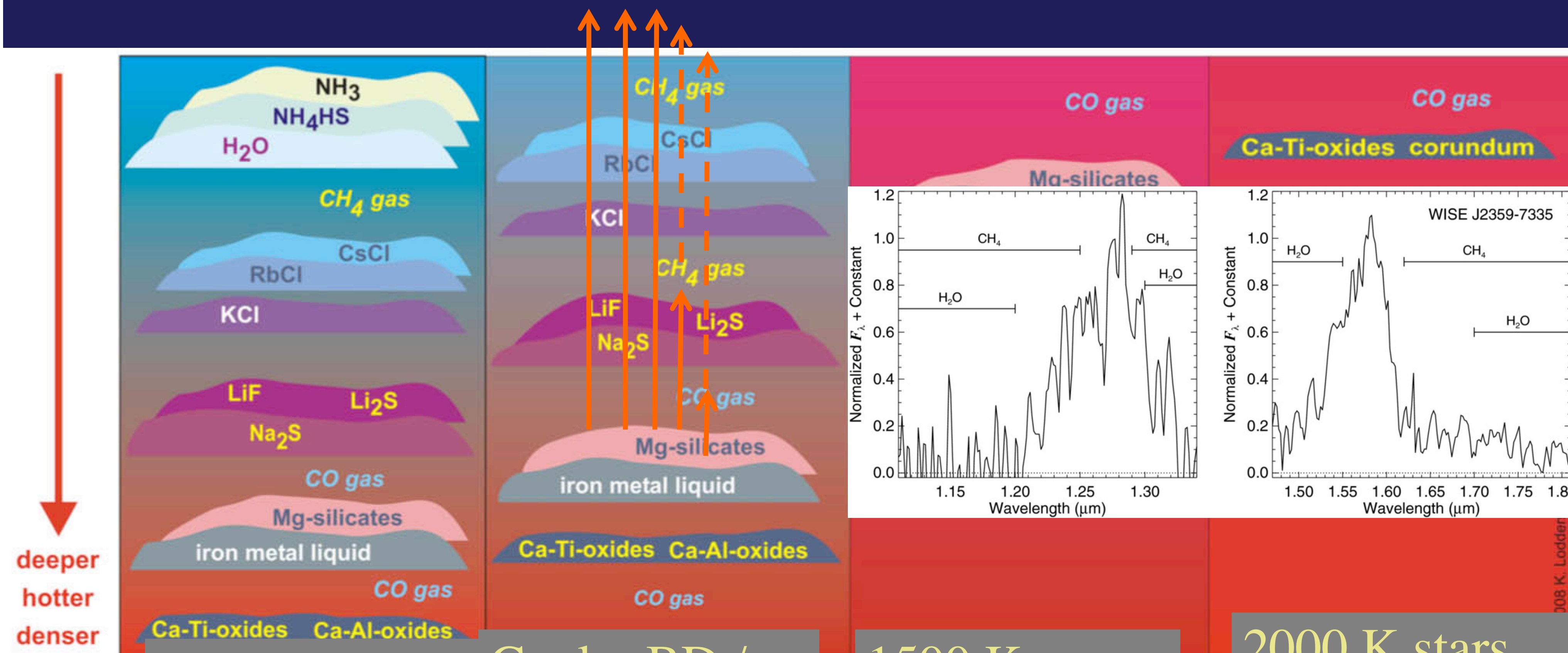


Burgasser et al. 2009 white paper / after Lodders & Fegley 2006

Atmosphere of HR8799 planets

Spectrum shows
CH4, H2O

Spectrum shows
H2, H2O, CO



Jupiter

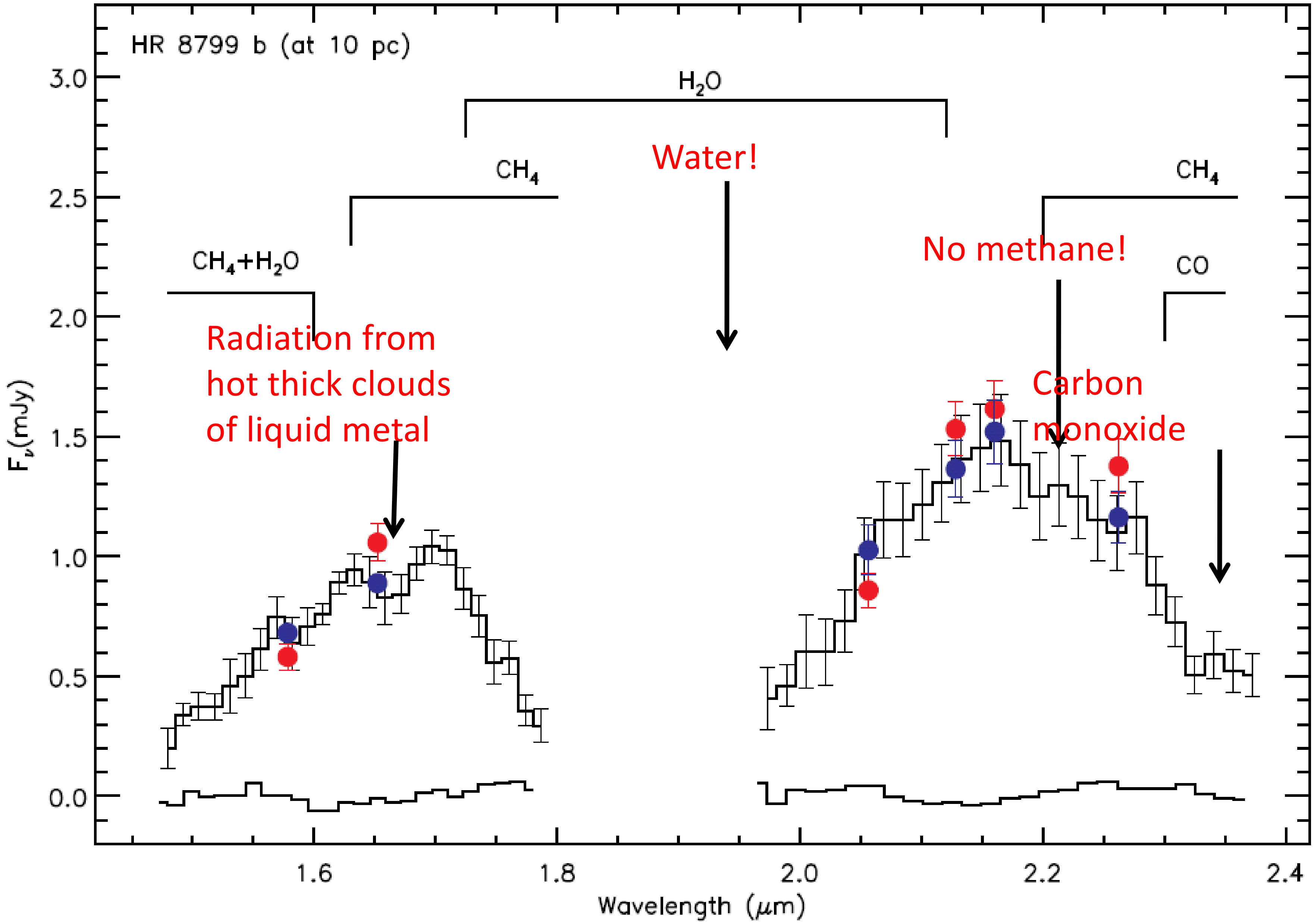
Cooler BD / planets

1500 K brown dwarfs

2000 K stars

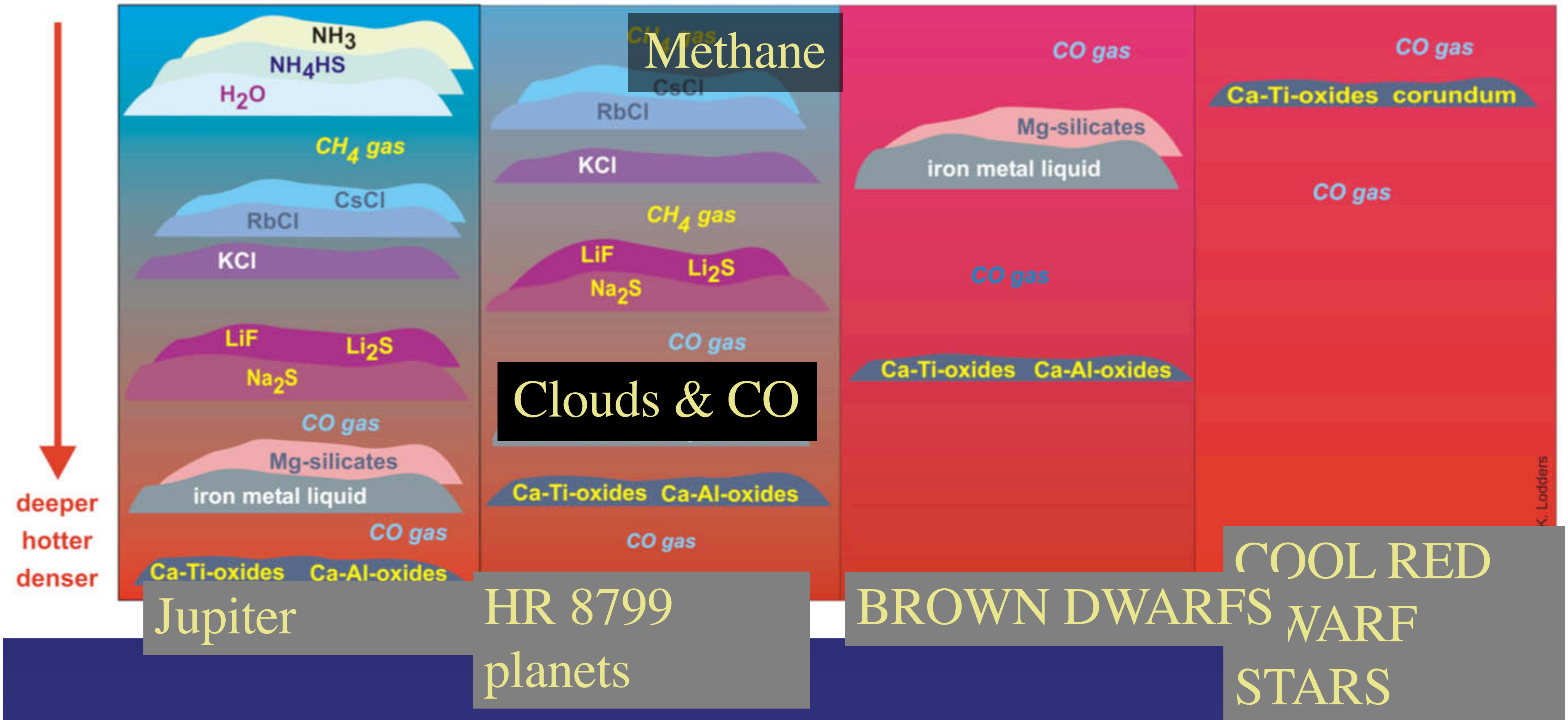
Burgasser et al. 2009 white paper / after Lodders & Fegley 2006

Spectrum of HR8799b – cool but looks hot



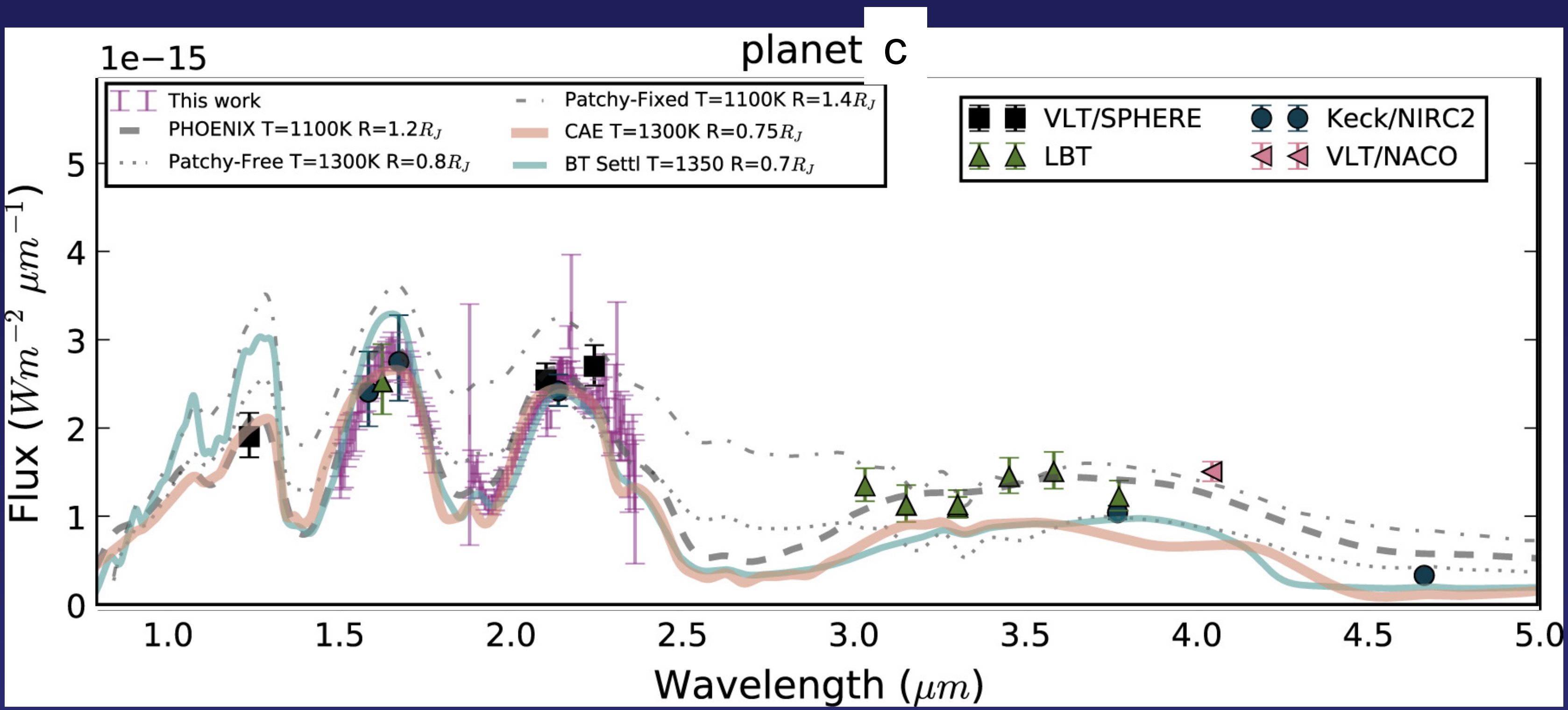
Clouds, circulation and chemistry complicate interpretaiton

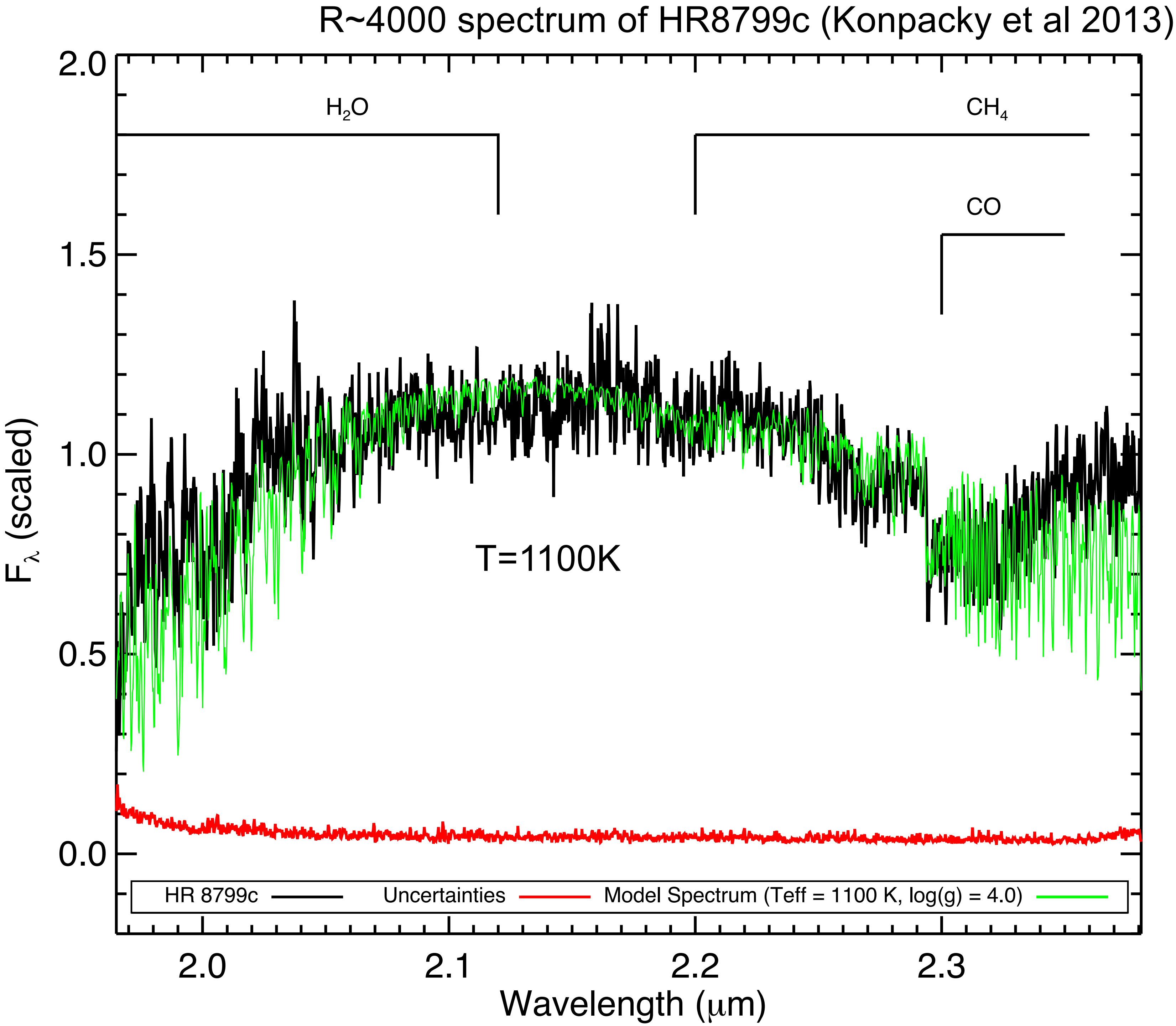
Some evidence of high carbon and oxygen abundance



Burgasser et al. 2009 white paper / after Lodders & Fegley 2006

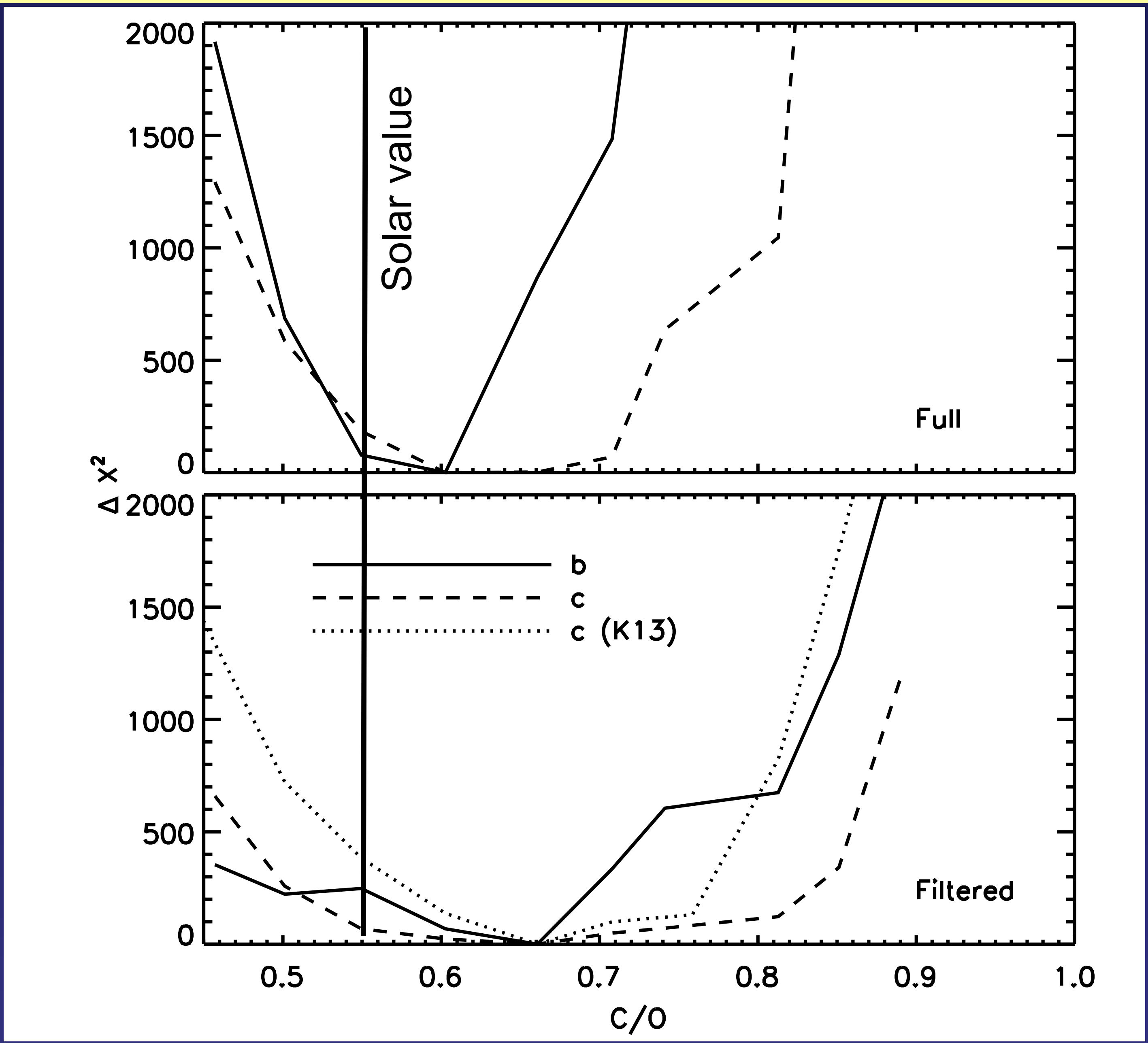
Models often give high temperatures and small radii





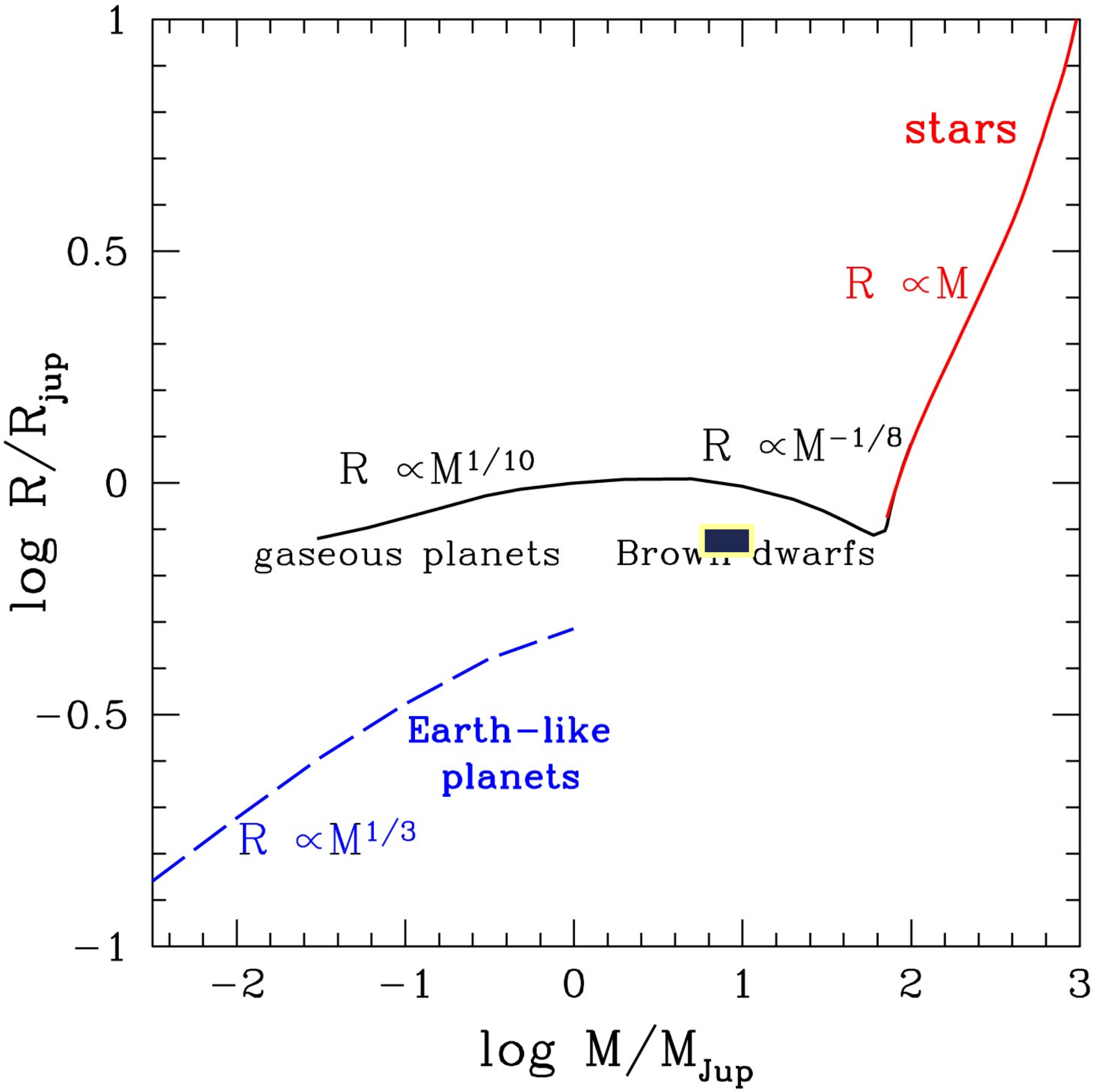
gpi Exoplanet Survey

Measured C/O ratios slightly higher than solar

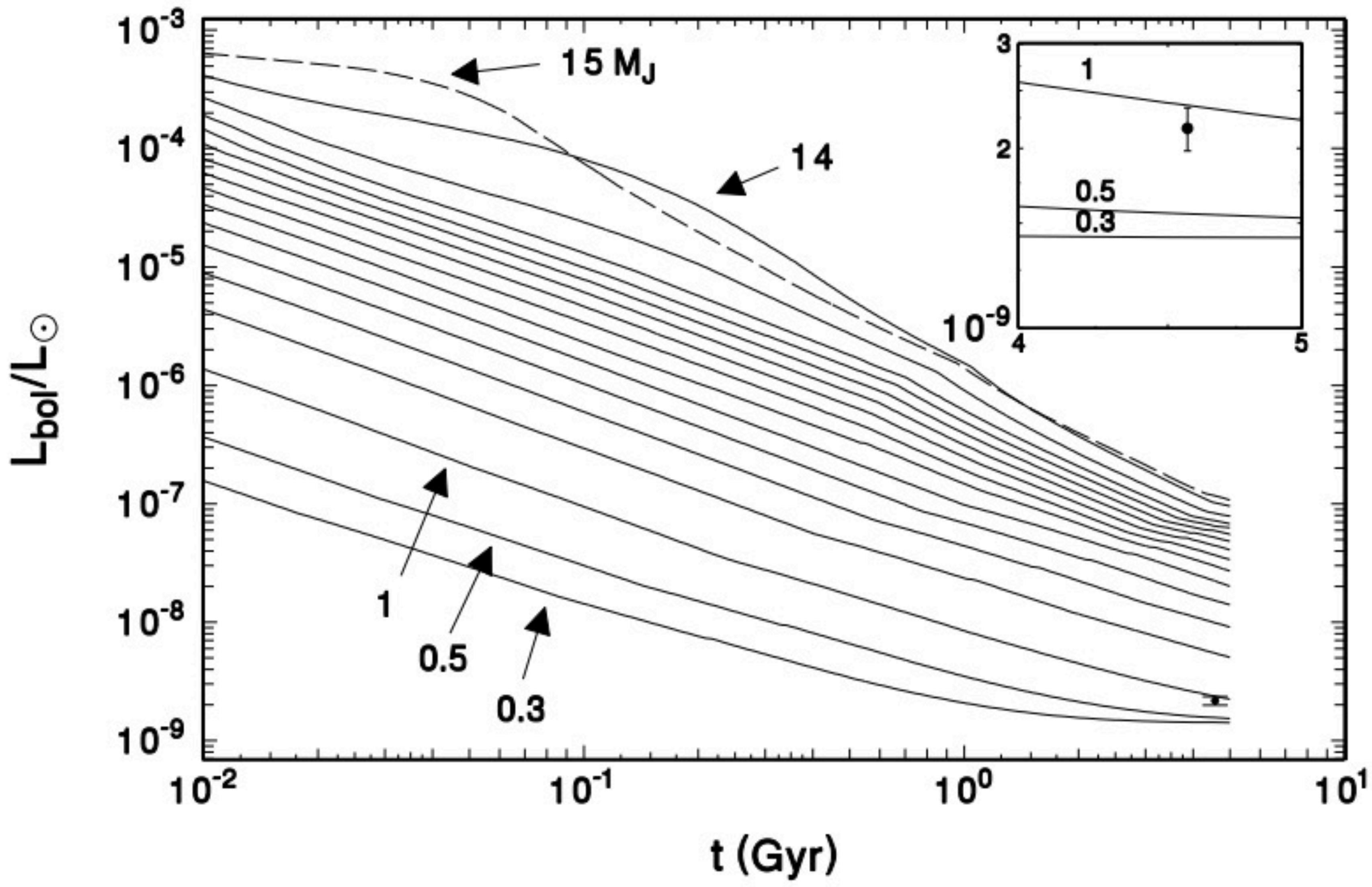


Barman et al 2015

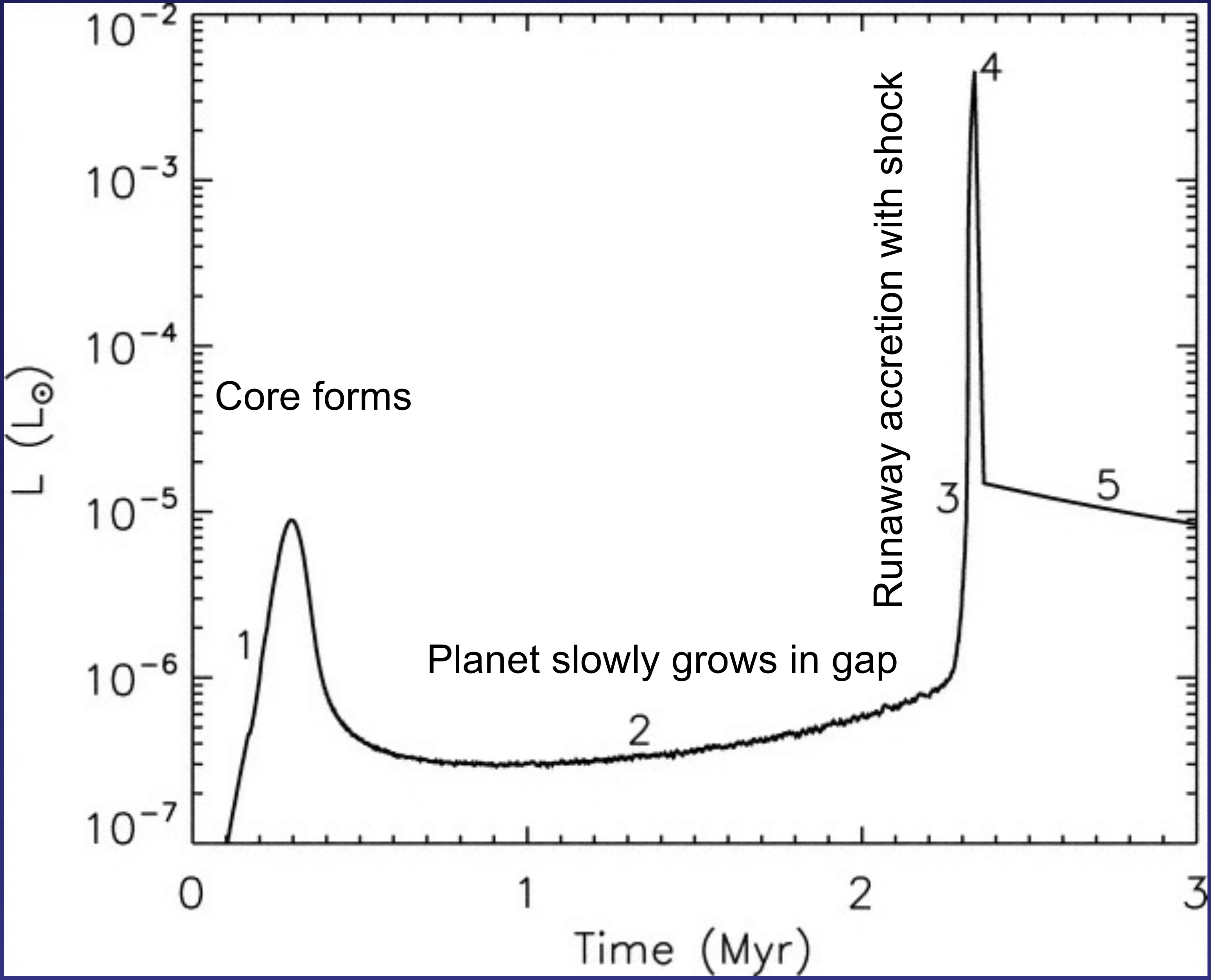
Models consistently underpredict radii of these young planets



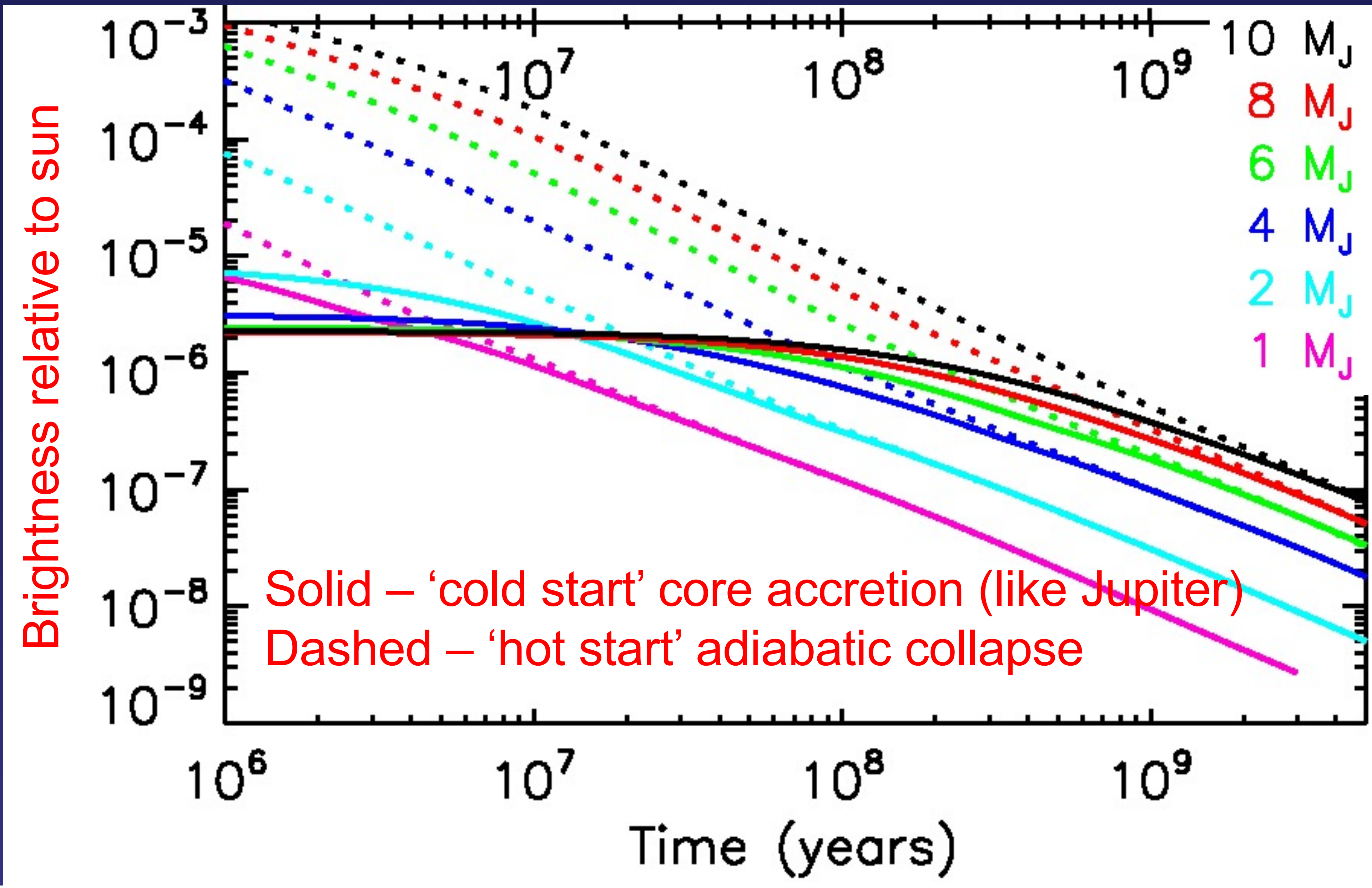
But what about initial conditions?



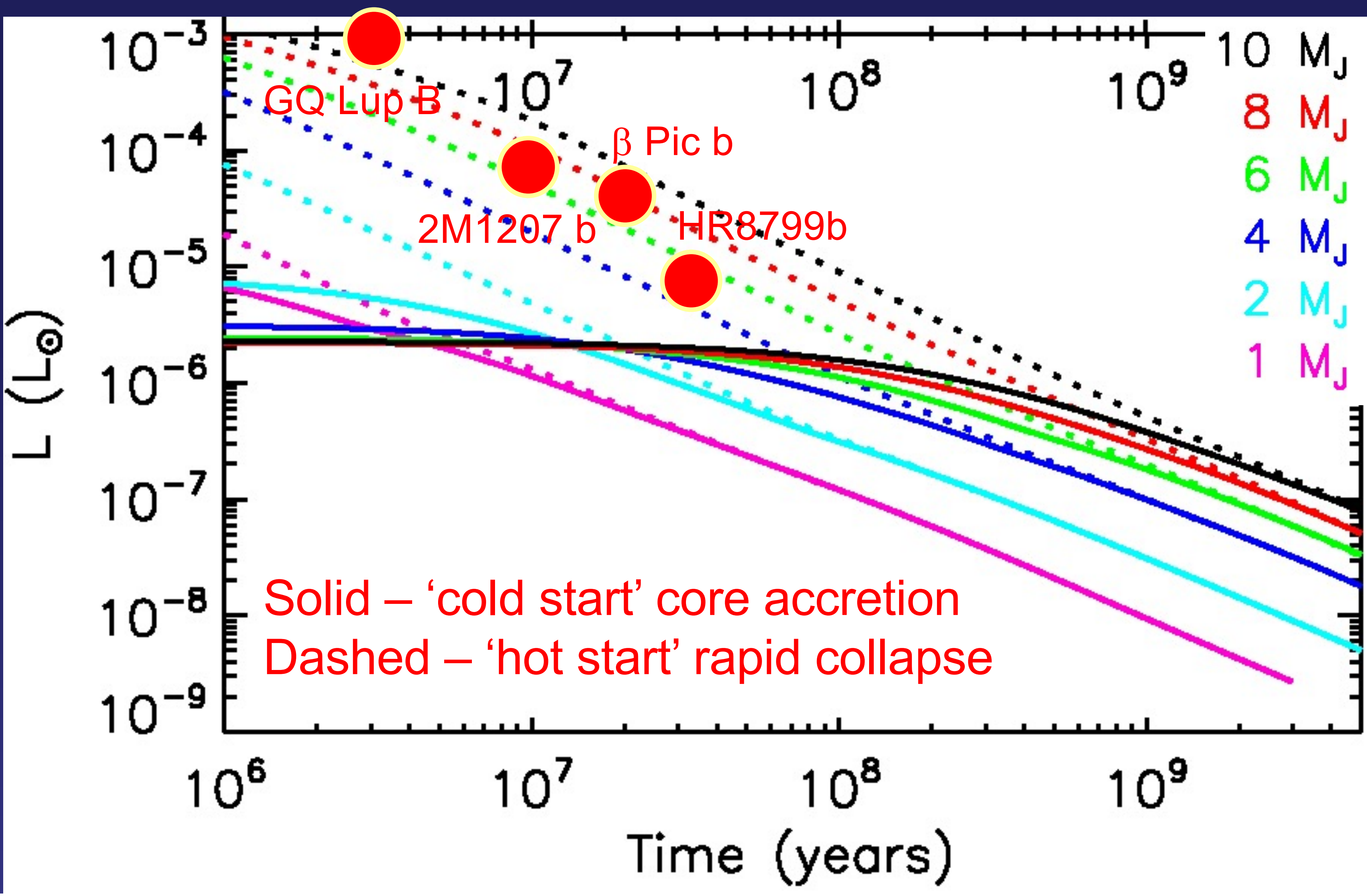
Adding realistic accretion of mass (Marley et al 2006)



Complication or opportunity: brightness depends on formation mechanism



Most directly imaged planets look “hot”?

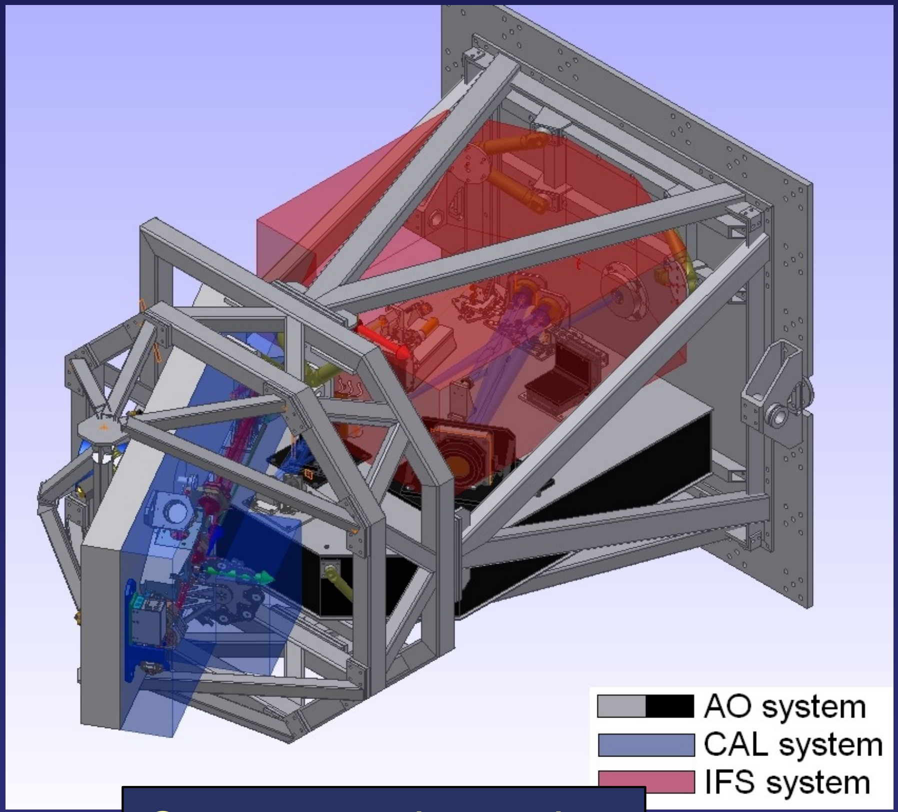


Getting to lower mass and closer planets: The Gemini Planet Imager

Data pipeline (Montreal, UofT, STScI)

Infrared integral field spectrograph (UCLA & U. Montreal) makes images and spectra of planets

Superpolished mirrors, clean-room optics

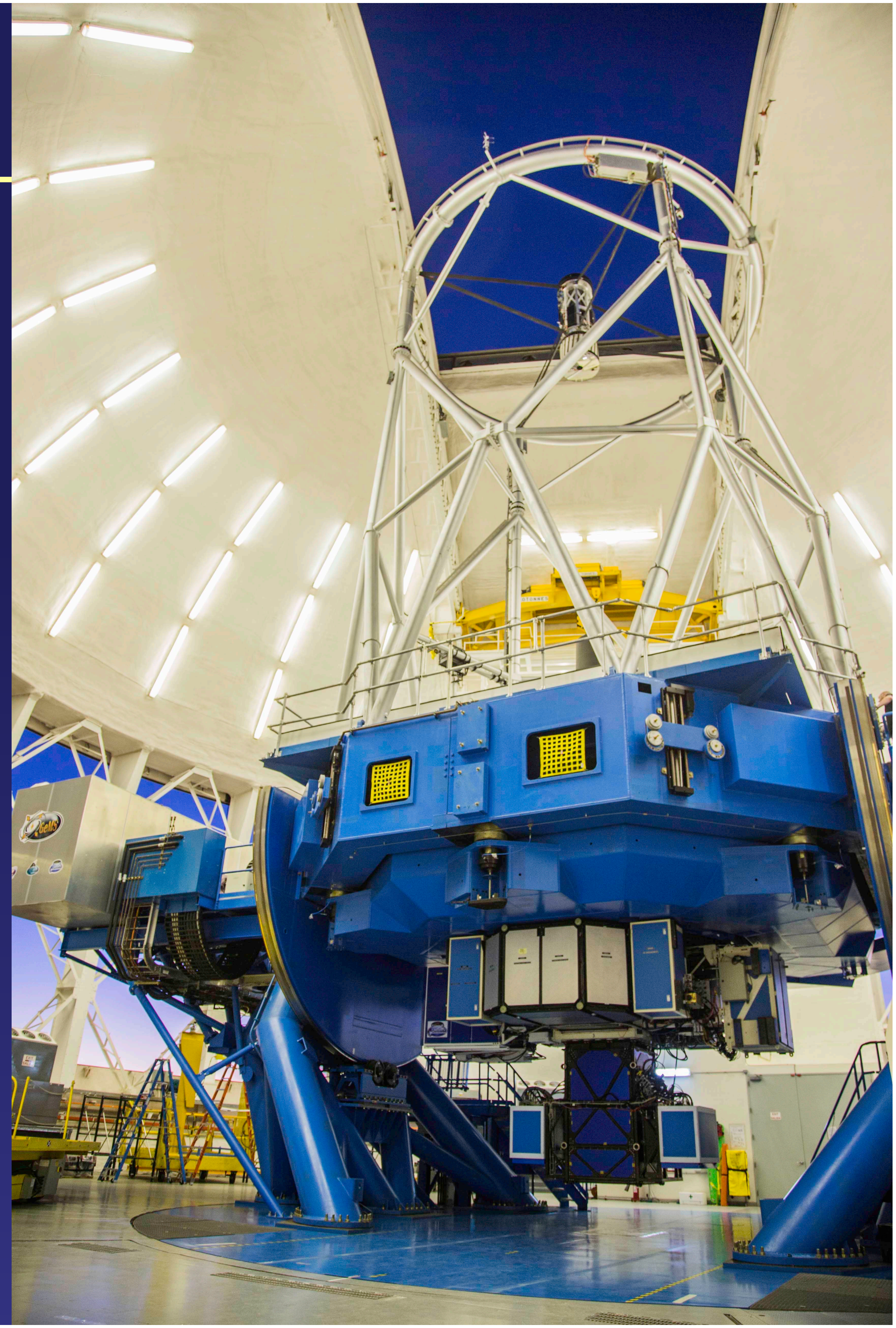


Mechanical structure and top-level software (NRC Canada) holds and connects subsystems

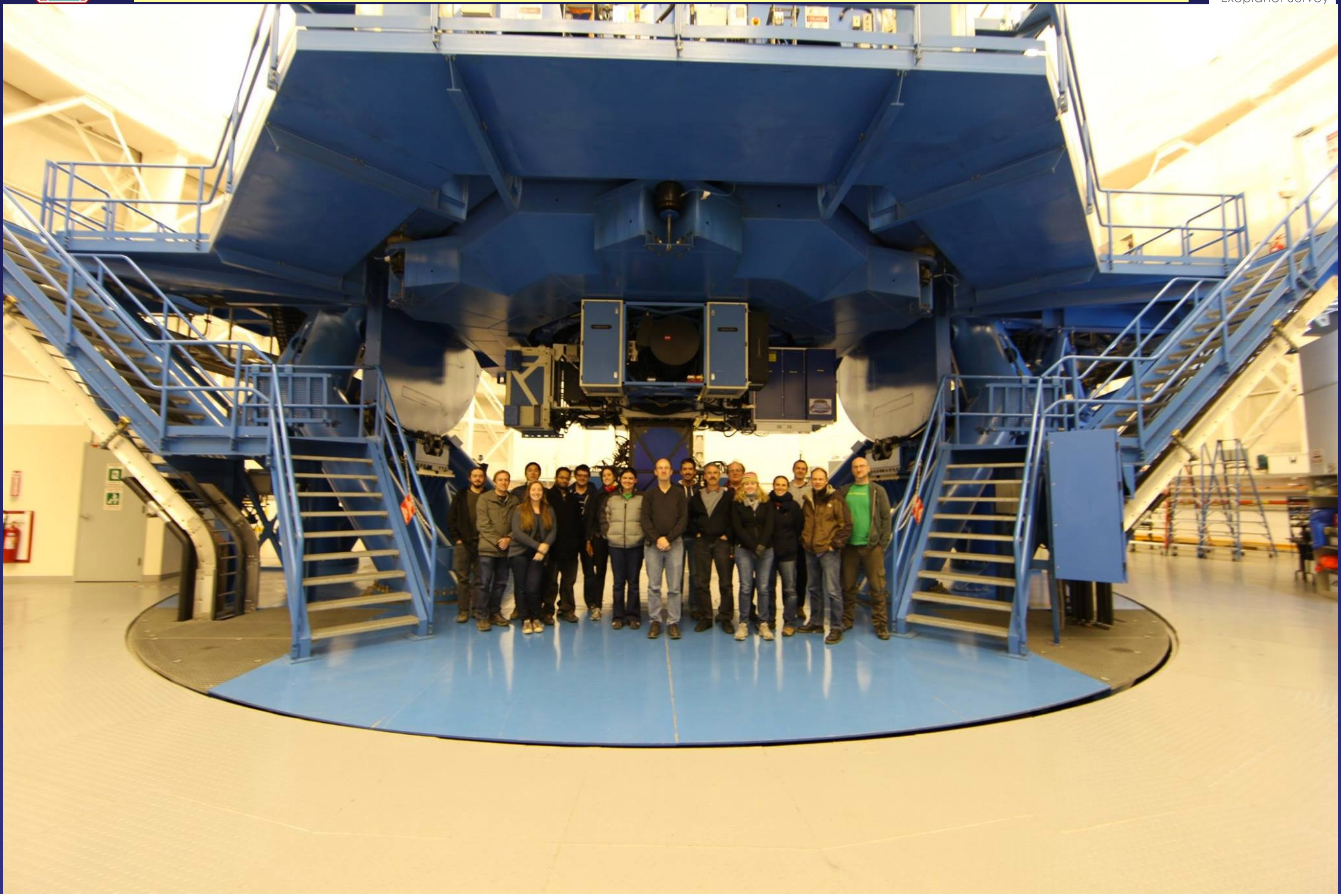
Adaptive optics system (LLNL) corrects for atmospheric turbulence and optical imperfections

Coronagraph masks (AMNH) block diffracted light from the star

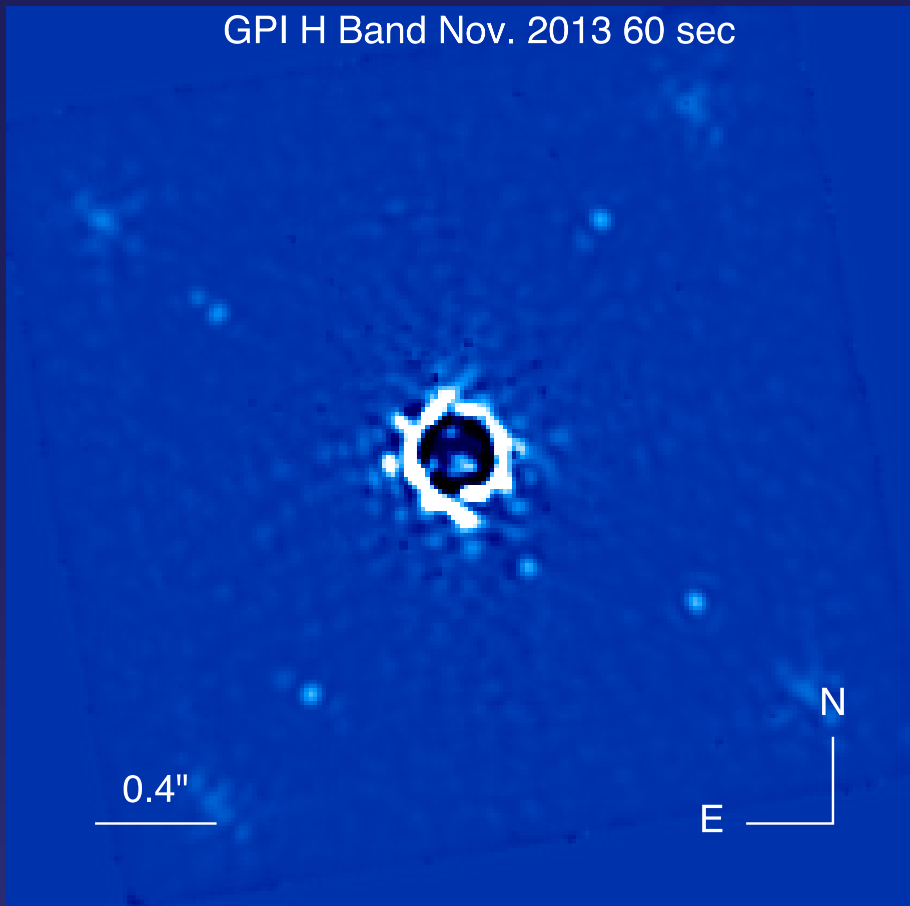
Project management: LLNL


First light: November 2013


GPI team (2014)

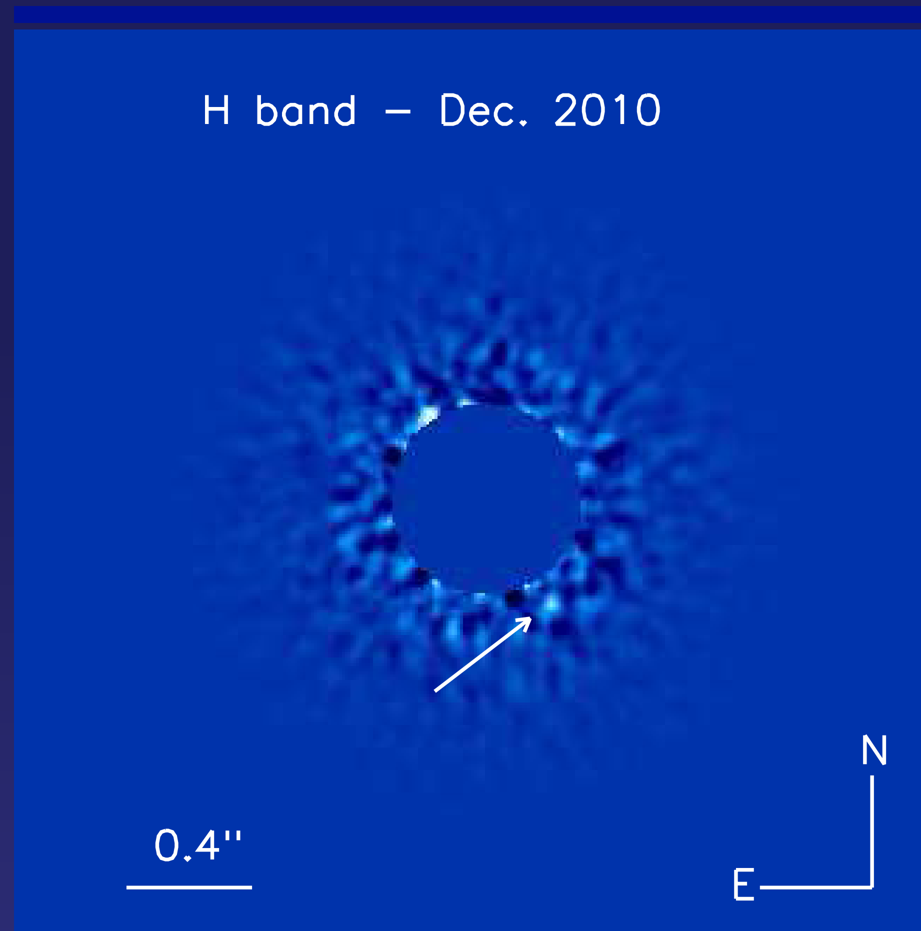


First light: Beta Pictoris b



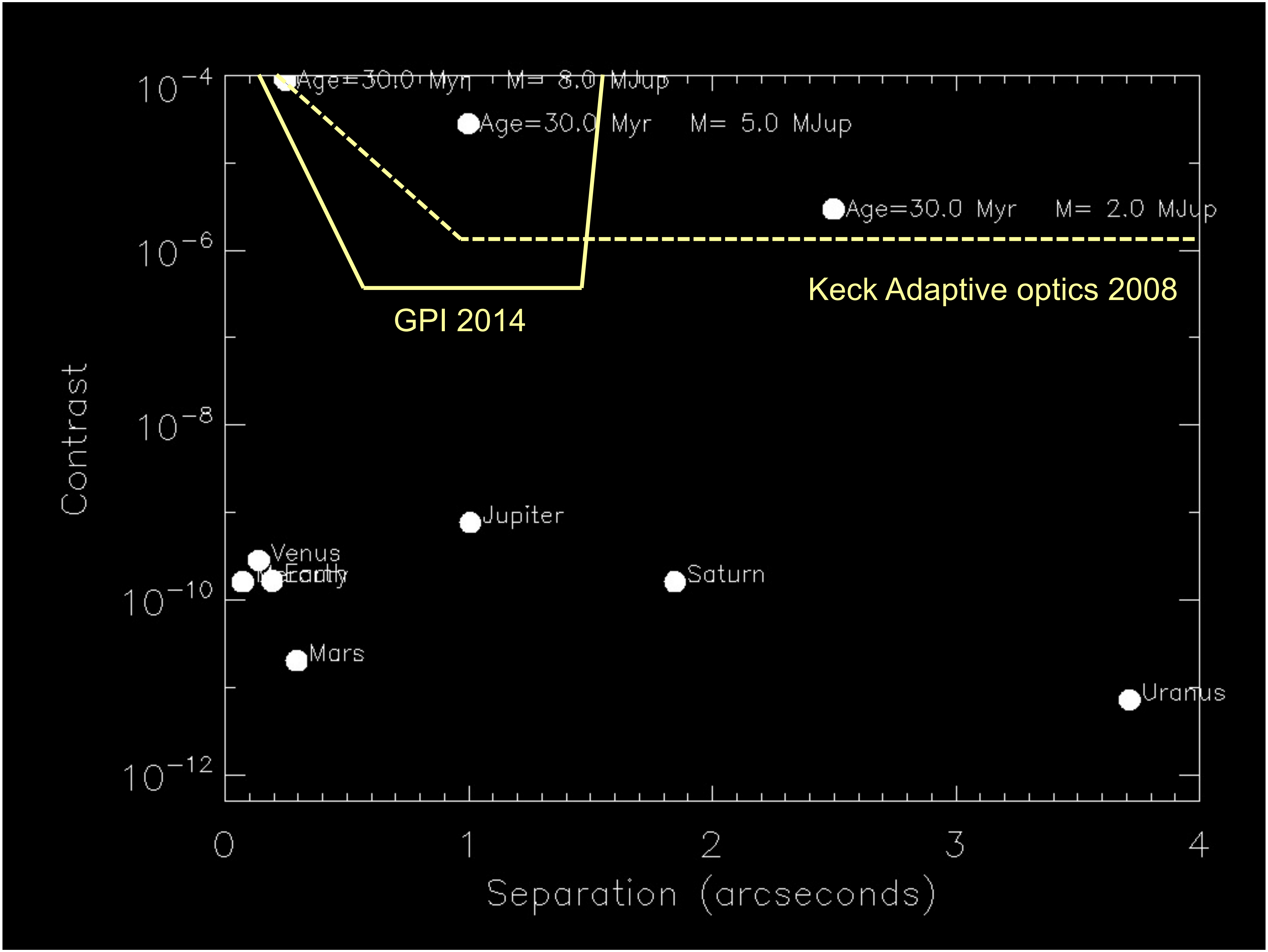
Gemini Planet Imager

60 seconds



Gemini NICI

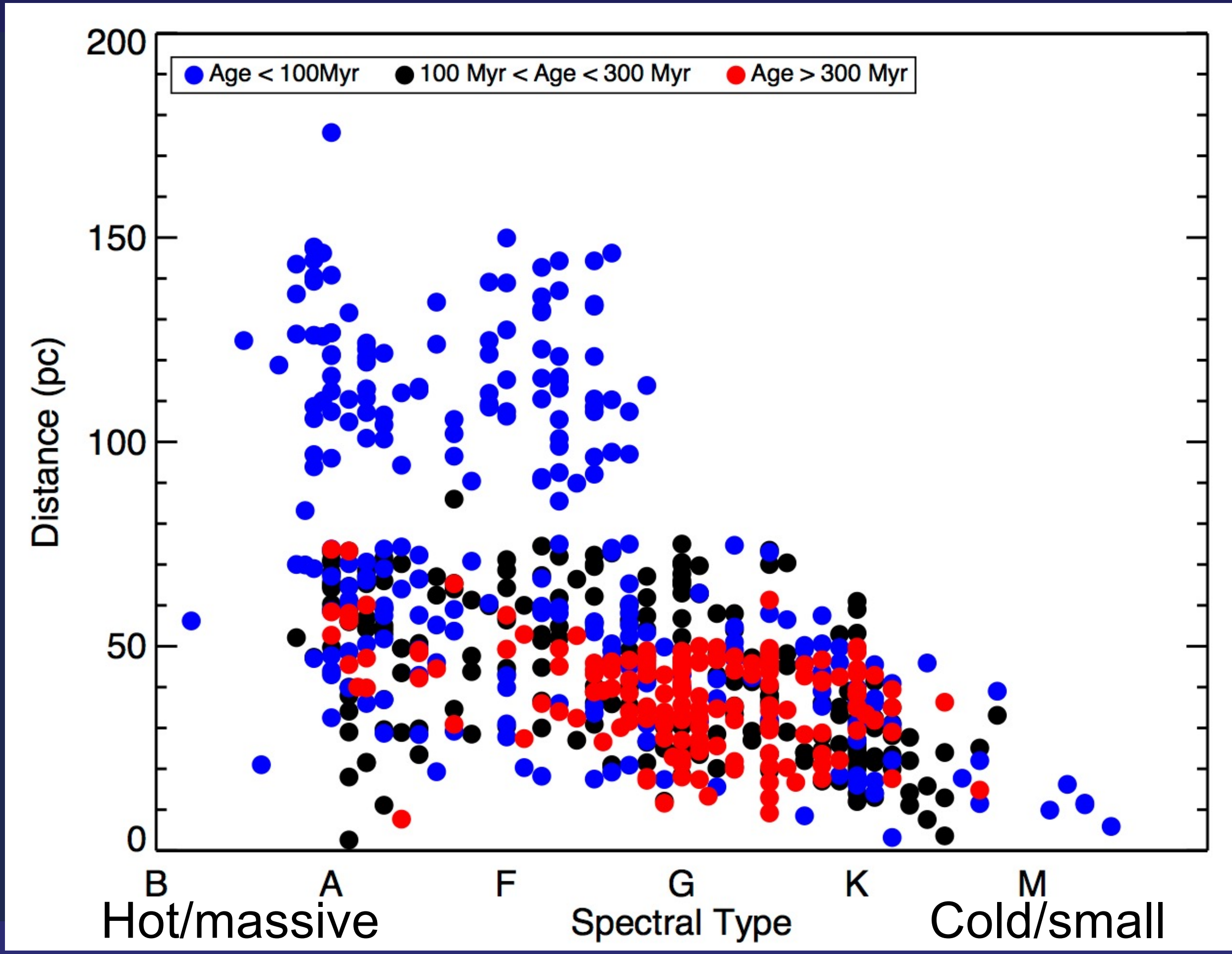
3952 seconds



Age=30.0 Myr M= 8.0 MJup
Age=30.0 Myr M= 5.0 MJup
Age=30.0 Myr M= 2.0 MJup
Keck Adaptive optics 2008
GPI 2014
Jupiter
Venus
Earth
Saturn
Mars
Uranus
Contrast
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
0
1
2
3
4
Separation (arcseconds)

Gemini Planet Imager Exoplanet Survey: 2014-2018*

- Target: 600 stars
- Final survey: 532 stars @ 1 hr each
- Deep spectra of 10 planets and brown dwarfs
- Extensive disk observations (Kalas, Esposito, Perrin, et al.)



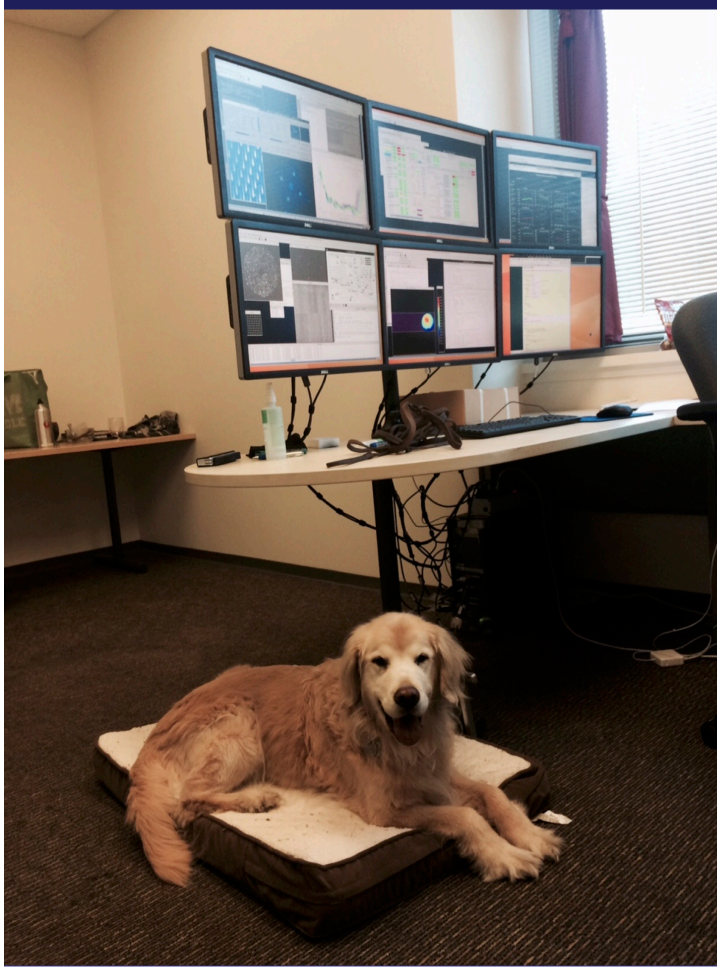
*Some followup in 2019

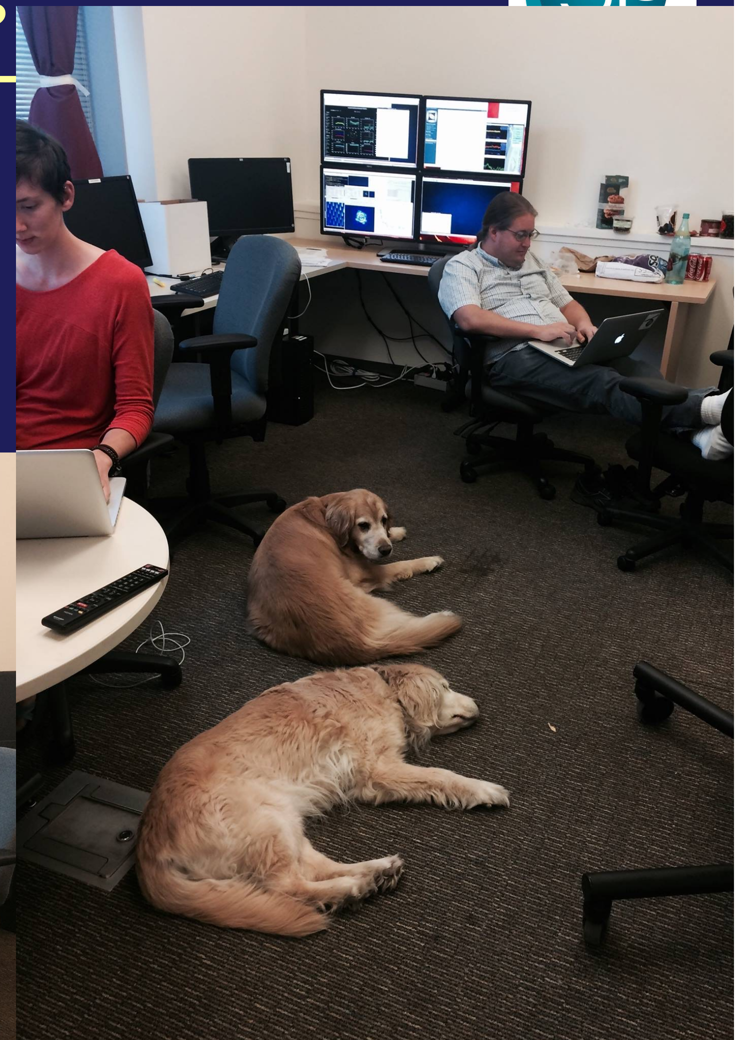
The GPI team (a subset)

Jonathan Aguilar, S. Mark Ammons, Pauline Arriaga, Etienne Artigau, Vanessa Bailey, Travis Barman, Steve Beckwith, Celia Blain, Sarah Blunt, Sebastian Bruzzone, Joanna Bulger, Ben Burningham, Adam S. Burrows, Eric Cady, Christine Chen, Eugene Chiang, Jeffrey K. Chilcote, Tara Cotten, Ian Czekala, Rebekah I. Dawson, Robert J. De Rosa, Ruobing Dong, René Doyon, Zachary H. Draper, Gaspard Duchêne, Thomas M. Esposito, Daniel Fabrycky, Michael P. Fitzgerald, Katherine B. Follette, Jonathan J. Fortney, BJ Fulton, Benjamin Gerard, Stephen Goodsell, James R. Graham, Alexandra Z. Greenbaum, Pascale Hibon, Sasha Hinkley, Lea Hirsch, Justin Hom, Andrew Howard, Tara Hufford, Li-Wei Hung, Patrick Ingraham, Rebecca Jensen-Clem, Mara Johnson-Groh, Paul Kalas, Quinn Konopacky, David Lafreniere, James E. Larkin, Samantha Lawler, Eve Lee, Jinhee Lee, Jonathan Lin, Michael Line, Bruce Macintosh, Jerome Maire, Franck Marchis, Mark S. Marley, Christian Marois, Brenda C. Matthews, Stanimir Metchev, Max Millar-Blanchaer, Caroline V. Morley, Katie M. Morzinski, Ruth Murray-Clay, Eric L. Nielsen, Andrew Norton, Rebecca Oppenheimer, David W. Palmer, Rahul Patel, Jenny Patience, Marshall D. Perrin, Charles Poteet, Lisa A. Poyneer, Laurent Pueyo, Roman R. Rafikov, Abhijith Rajan, Julien Rameau, Fredrik T. Rantakyrö, Bin Ren, Emily Rice, Malena Rice, Patricio Rojo, Jean-Baptiste Ruffio, M. T. Ruiz, Dominic Ryan, Maissa Salama, Didier Saumon, Dmitry Savransky, Adam C. Schneider, Jacob Shapiro, Anand Sivaramakrishnan, Inseok Song, Rémi Soummer, Melisa Talis, Sandrine Thomas, Gautam Vasisht, David Vega, J. Kent Wallace, Jason J. Wang, Kimberly Ward-Duong, Sloane J. Wiktorowicz, Schuyler G. Wolff, Joe Zalesky, Ben Zuckerman

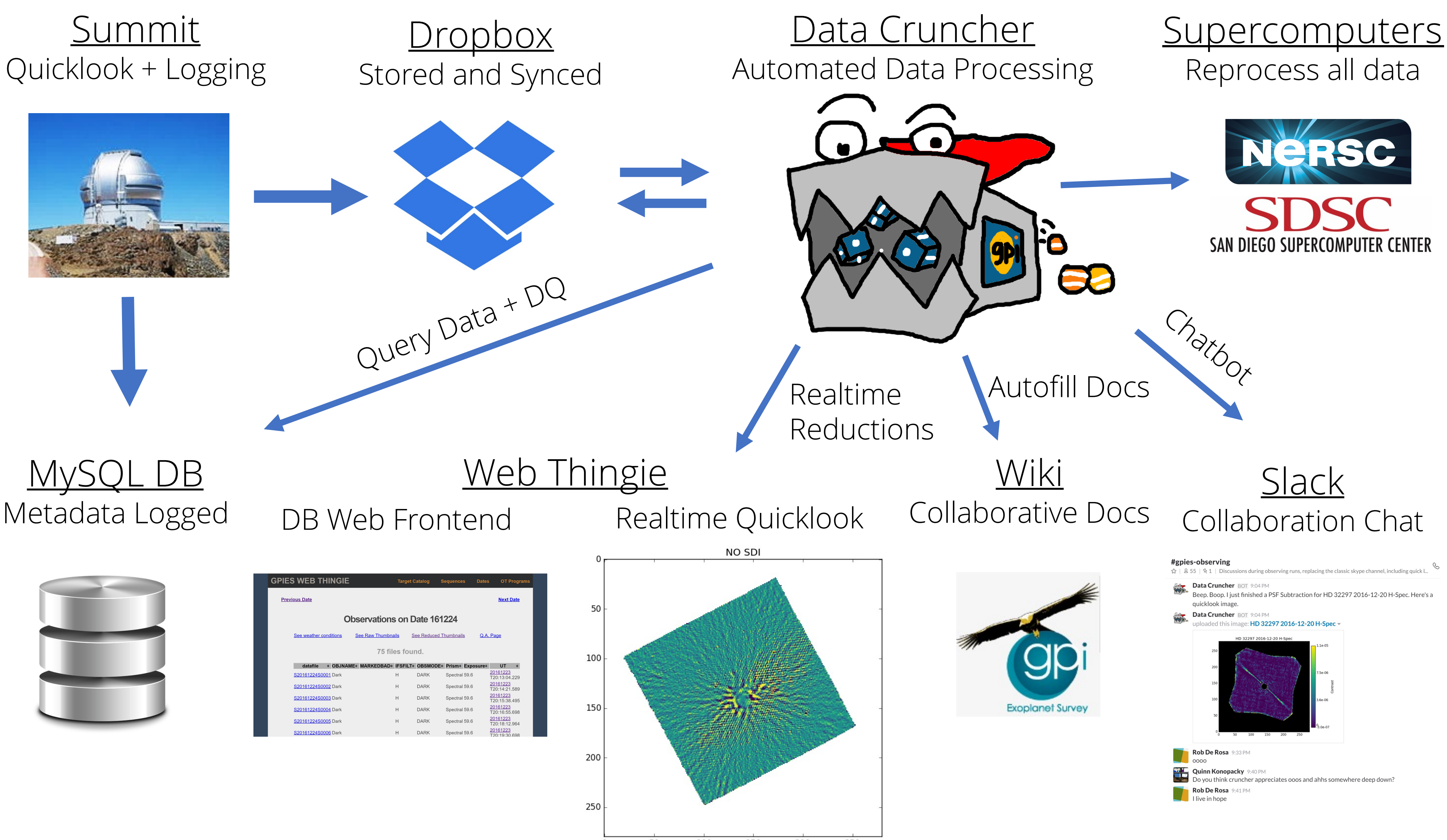
Telescope puppies

Eric Nielsen
Vanessa Bailey
Persi
Kala



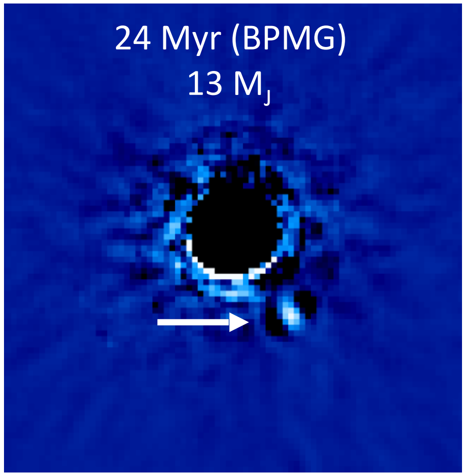


The GPIES Data Infrastructure



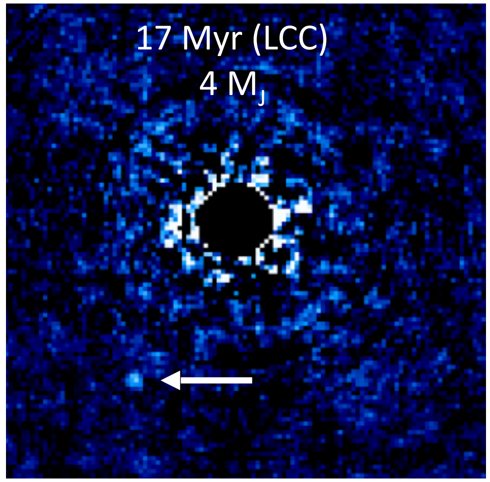
Wang et al. 2018

6 planets and 4 brown dwarfs



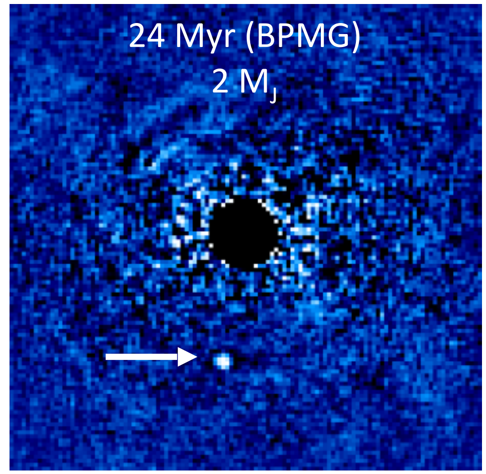
β Pic b

Chilcote et al. (2015, 2017)
Wang et al. (2016)



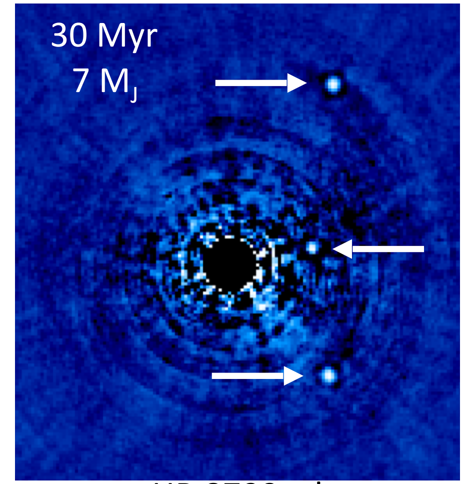
HD 95086 b

Rameau et al. (2016)
De Rosa et al. (2016)



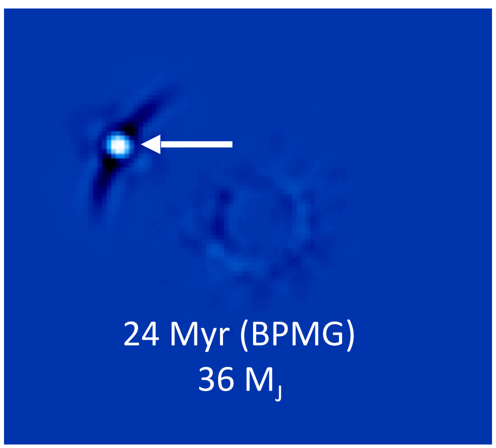
51 Eri b

Macintosh et al. (2014)
Rajan et al. (2017)



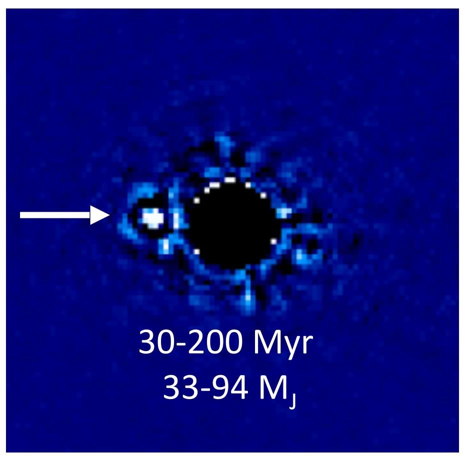
HR 8799 cde

Ingraham et al. (2014)
Greenbaum et al. (2018)



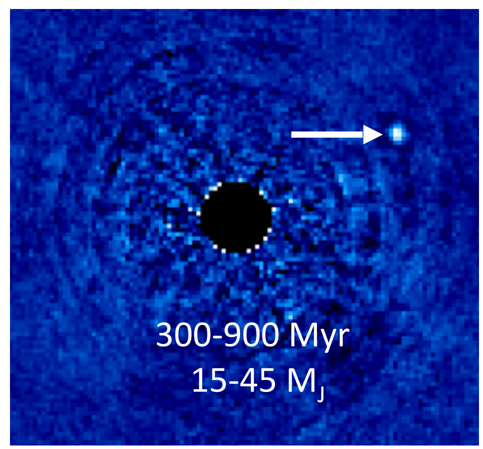
PZ Tel B

Ryan et al. (in prep.)



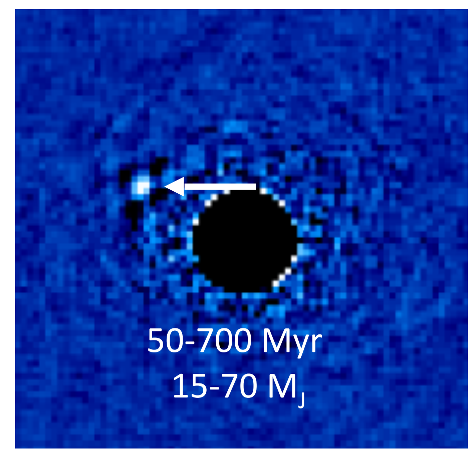
HD 984 B

Johnson-Groh et al. (2017)



HR 2562 B

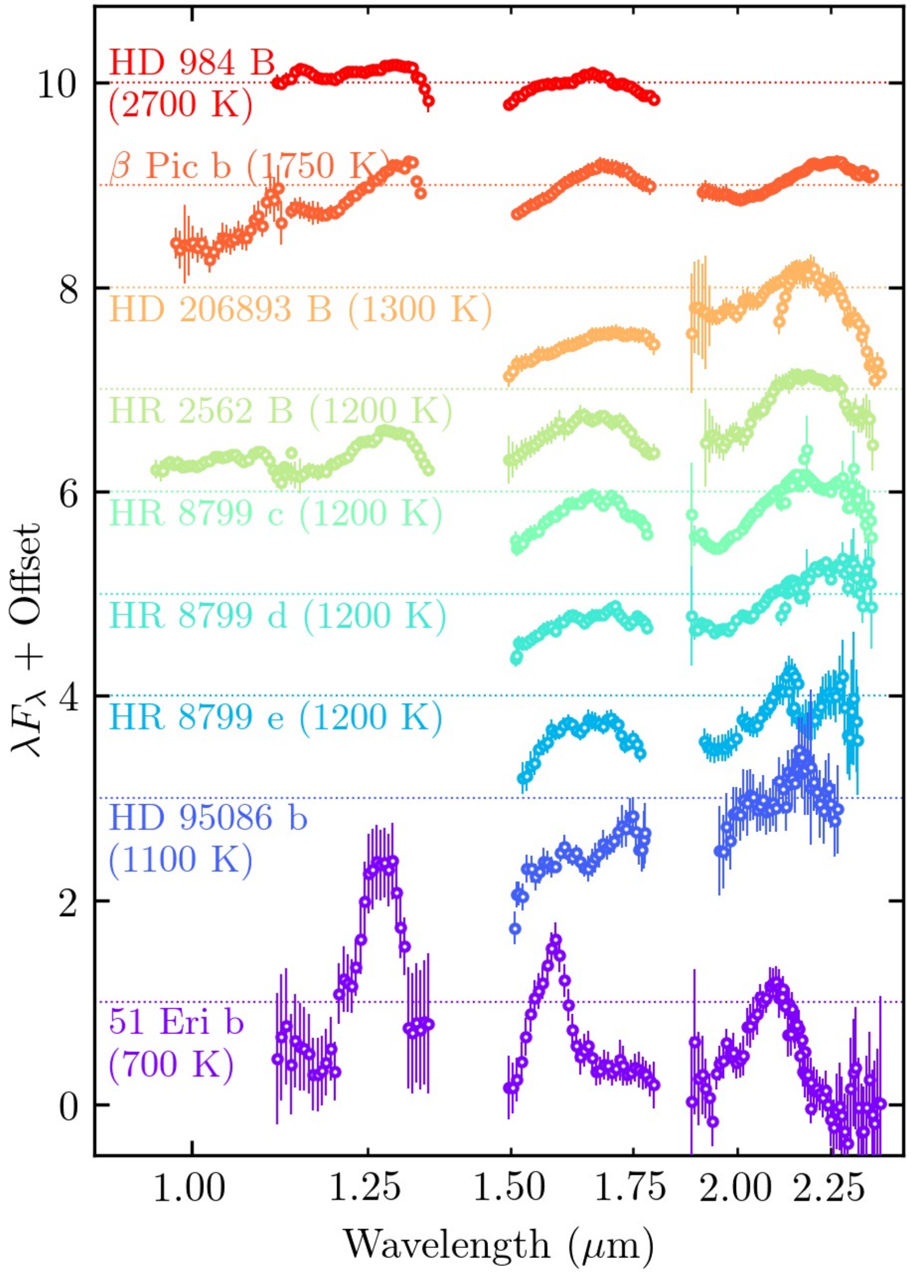
Konopacky et al. (2016)

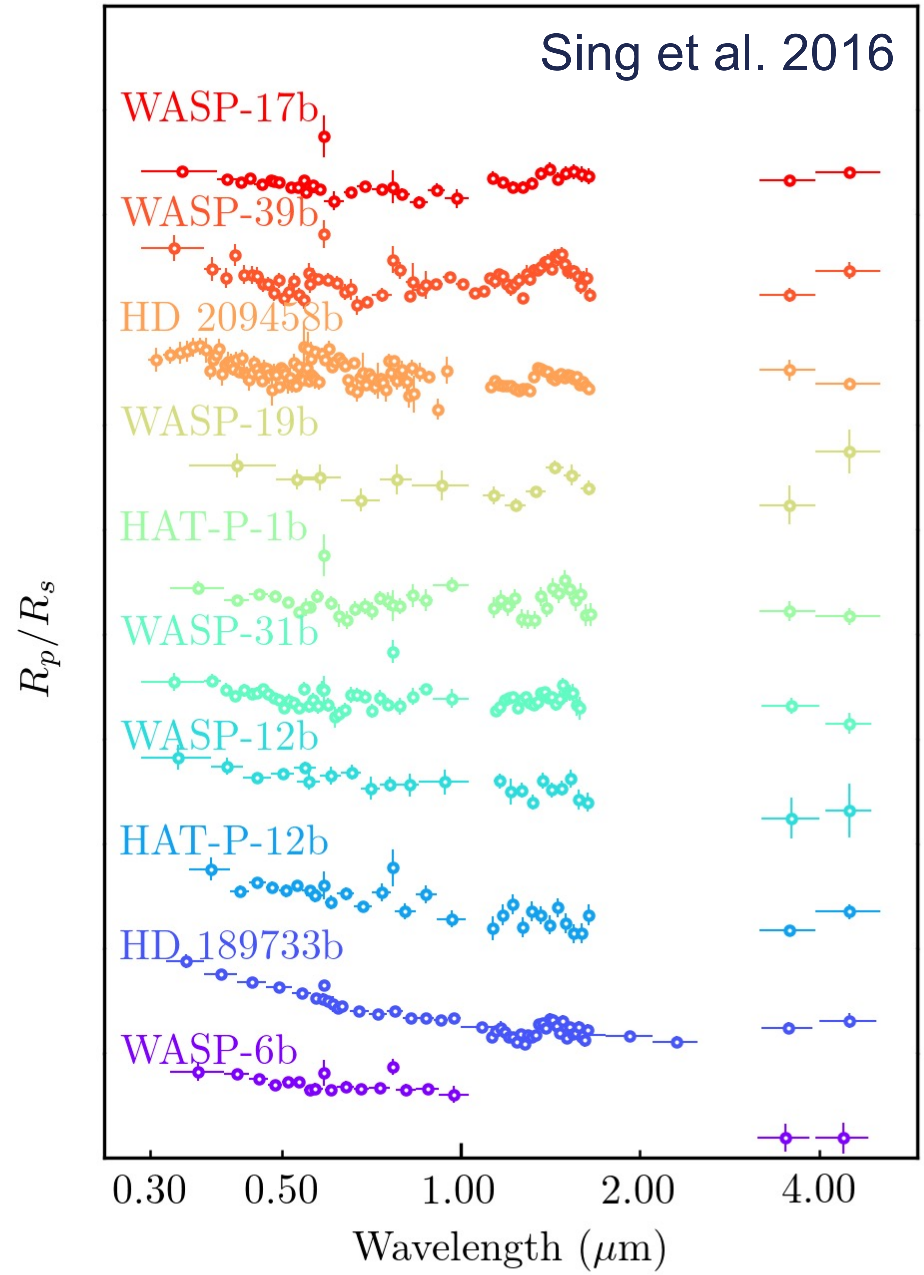


HD 206893 B

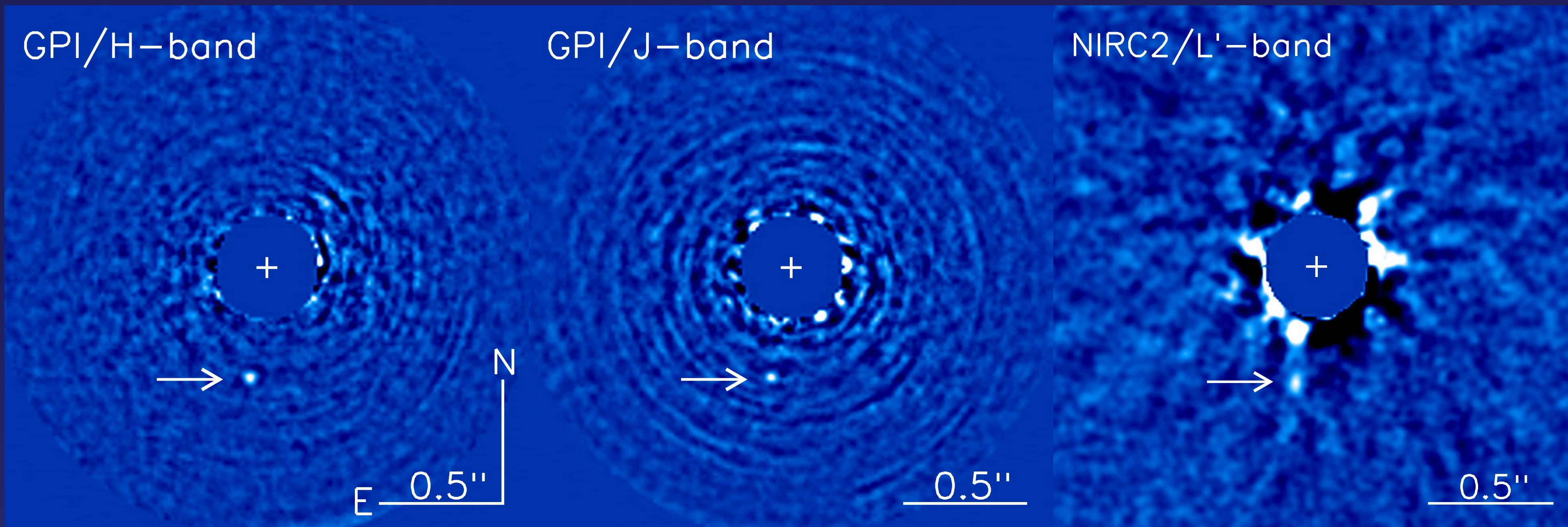
Ward-Duong et al. (2018)

GPIES Spectral Library



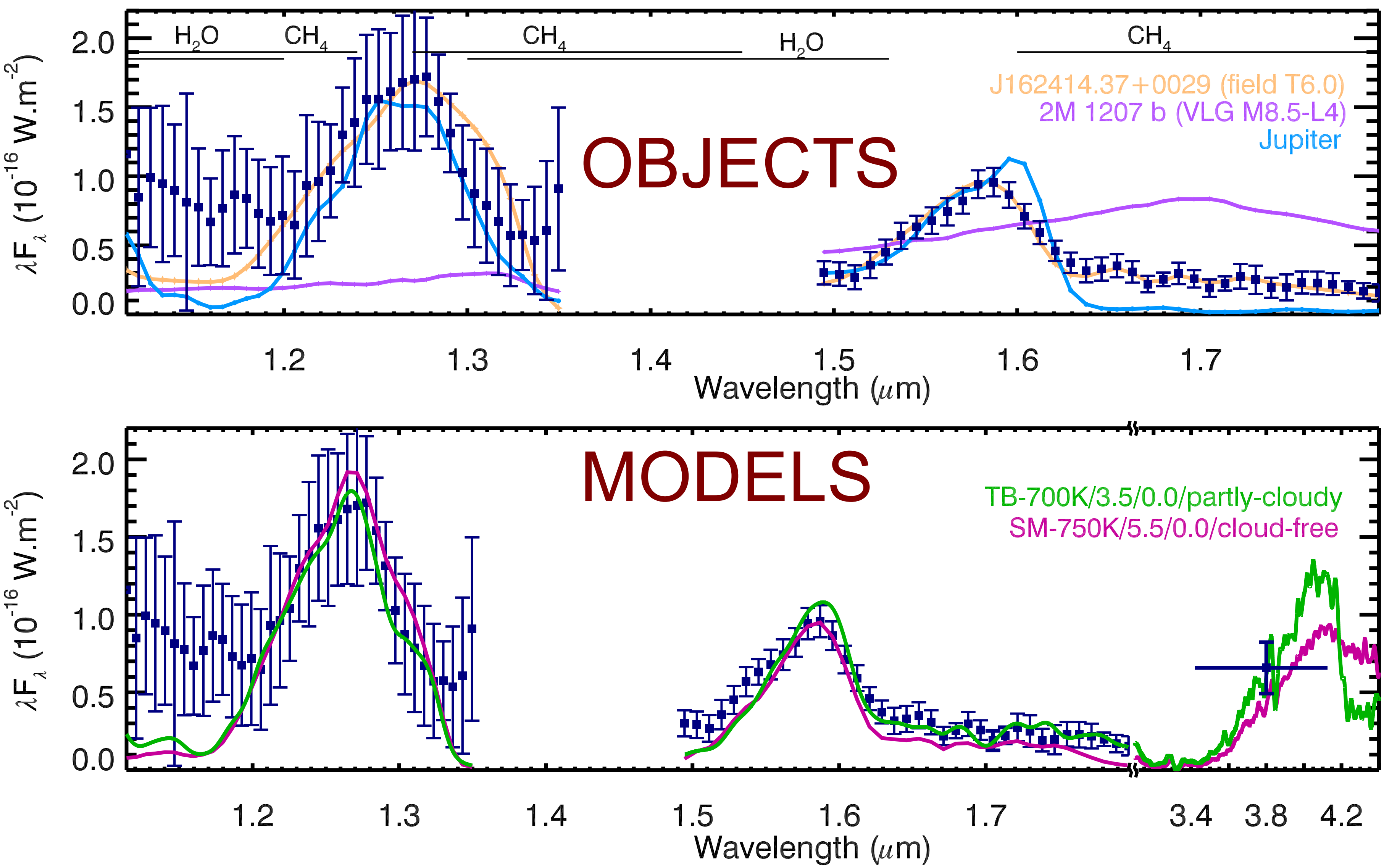


51 Eridani b: Macintosh et al 2015



Star is 20 million years old
Planet orbits at ~14 AU

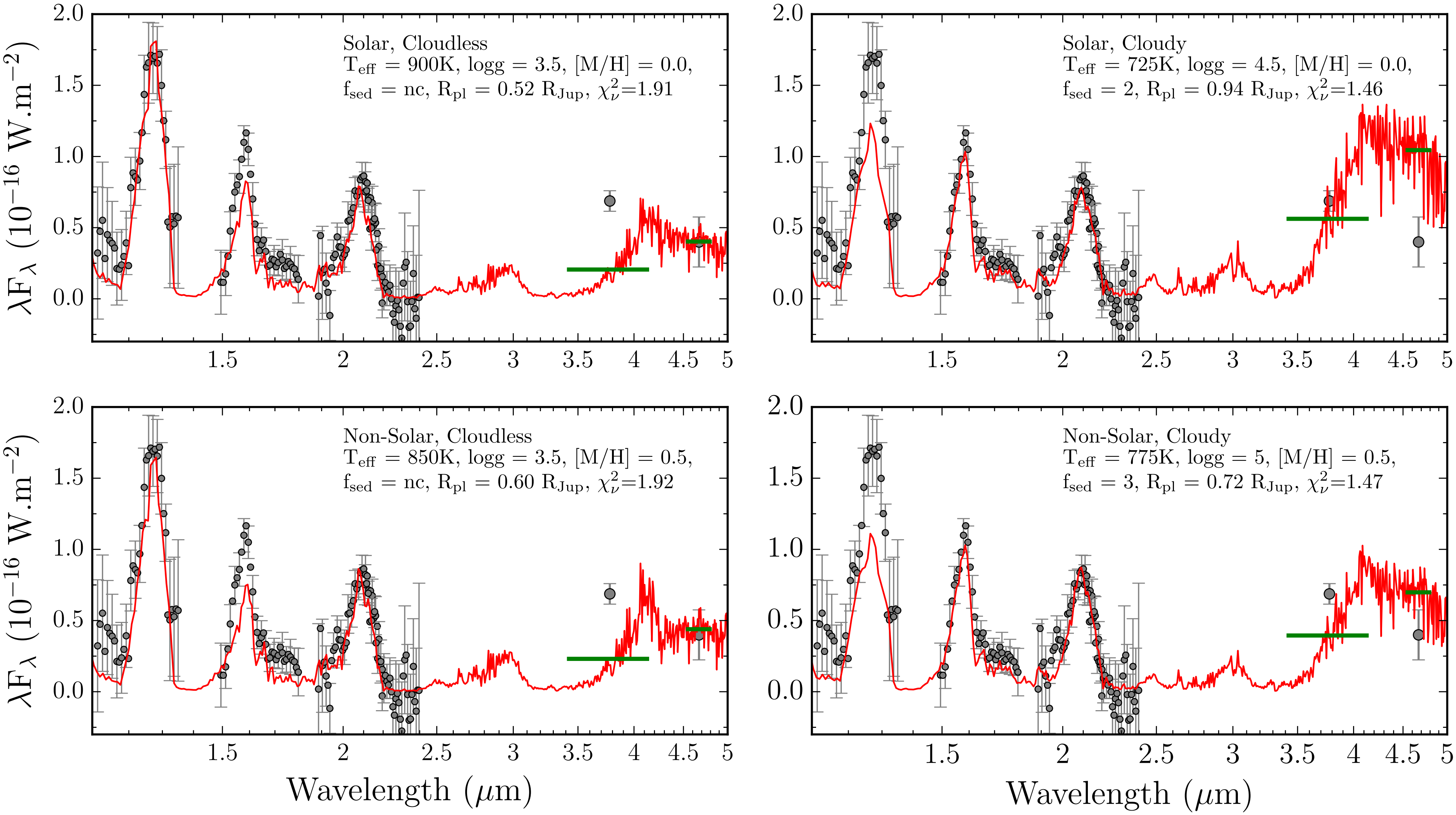
51 Eri b – getting to be more Jupiter-like



Modeling by Mark Marley, Didier Saumon, Travis Barman

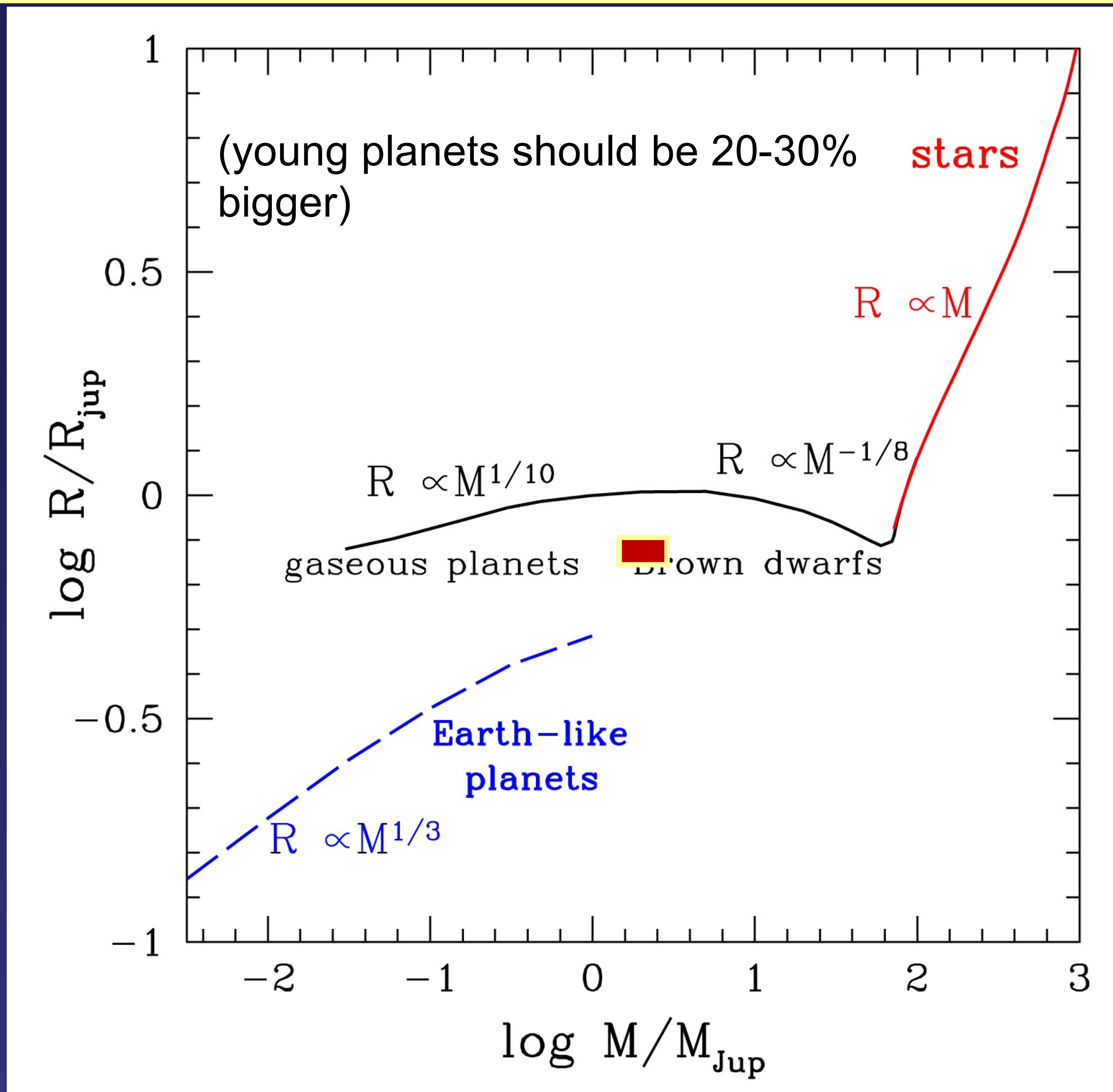
“Partly cloudy” 750K model

Model first require high metallicity , salt and sulfide clouds(Rajan et al 2017)



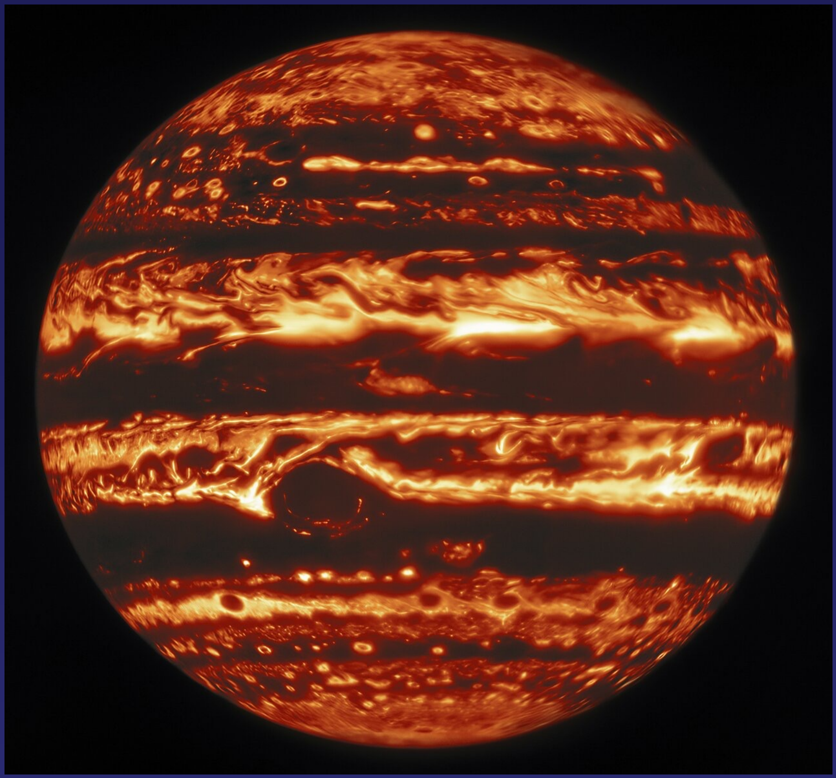
But radii still coming out too small…

Model fits still tend towards small radii

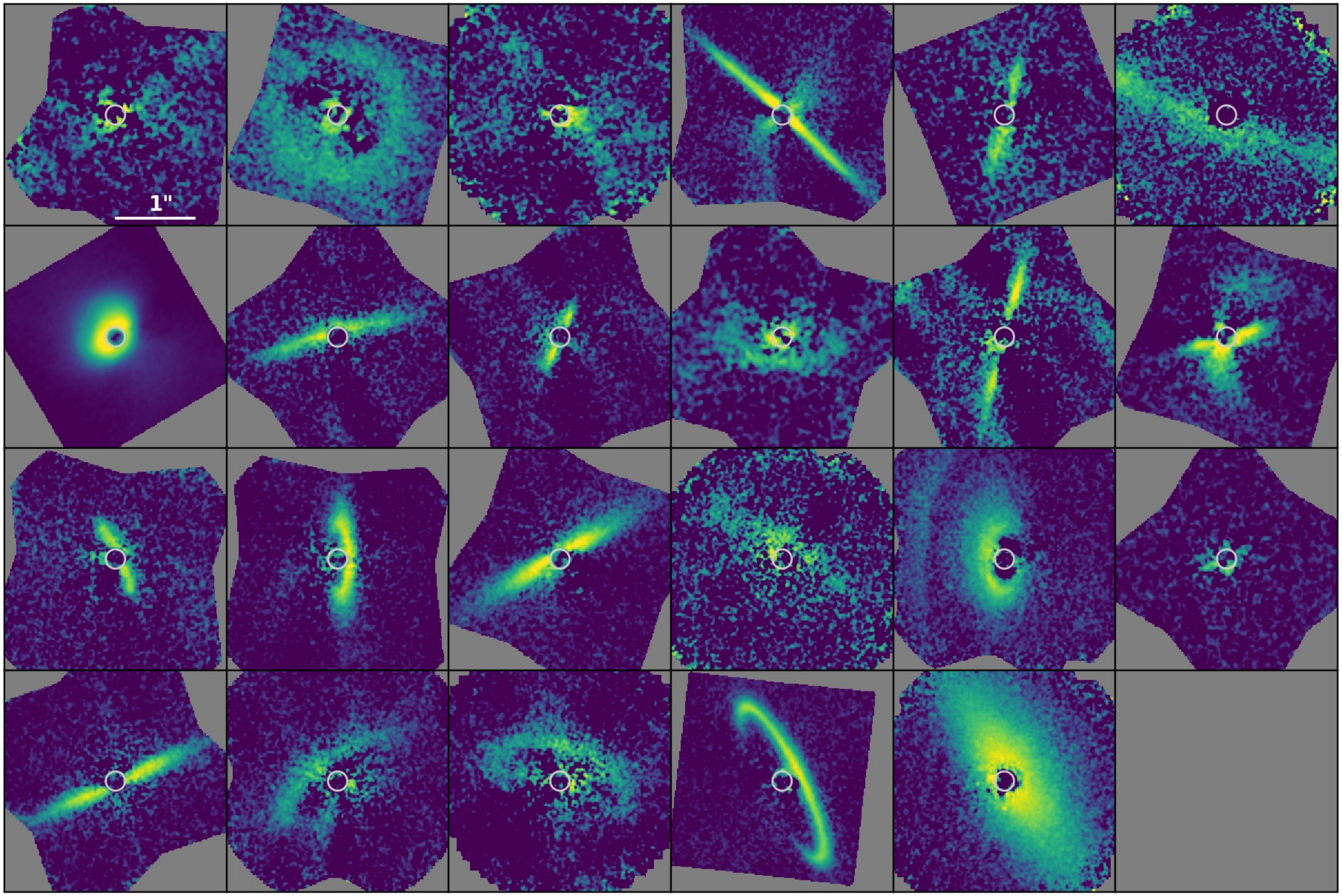


Radius dichotomy

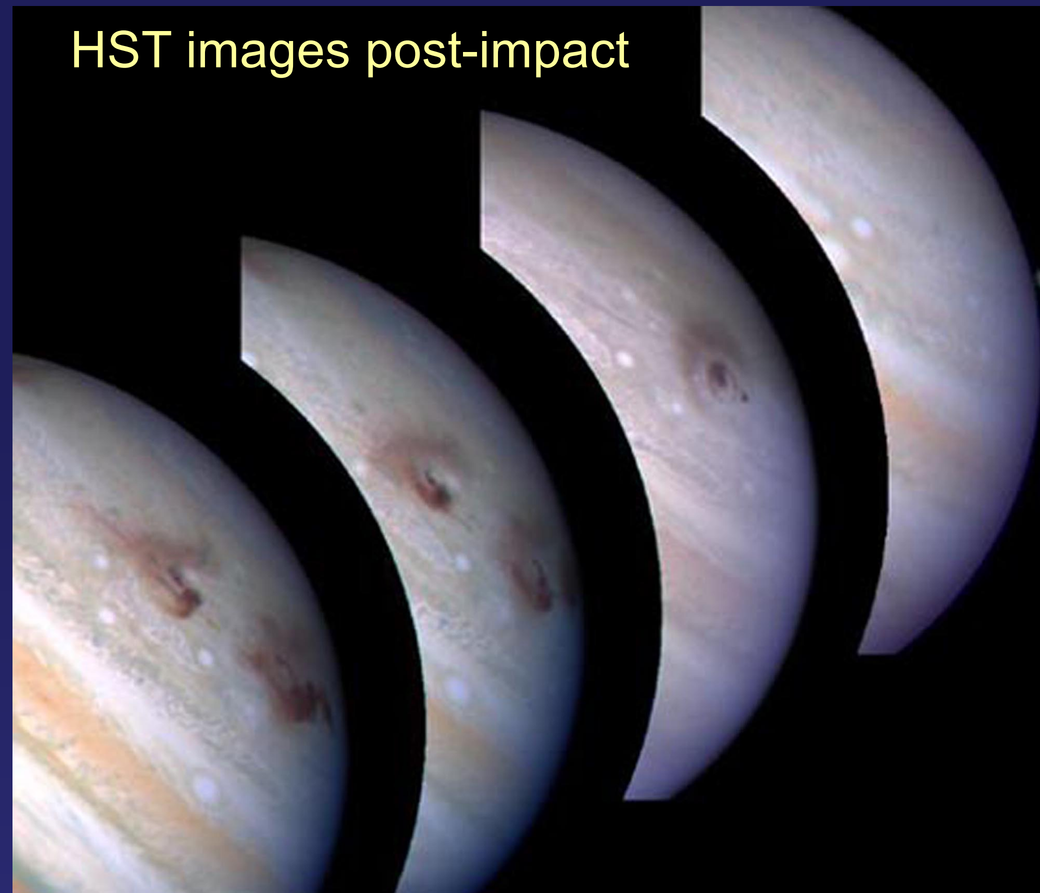
- **Equation of state?**
  - Probably not? Also radii of older cold planets are better predicted
- **Core mass?**
  - A dense non-hydrogen core would both make the planets smaller
- **Atmosphere models**
  - If the models are over-estimating the effective temperature of the planet they will over-estimate the flux per unit area and hence under-estimate the radius
  - Treatment of clouds, chemistry, vertical circulation
  - Additional sources of opacity?



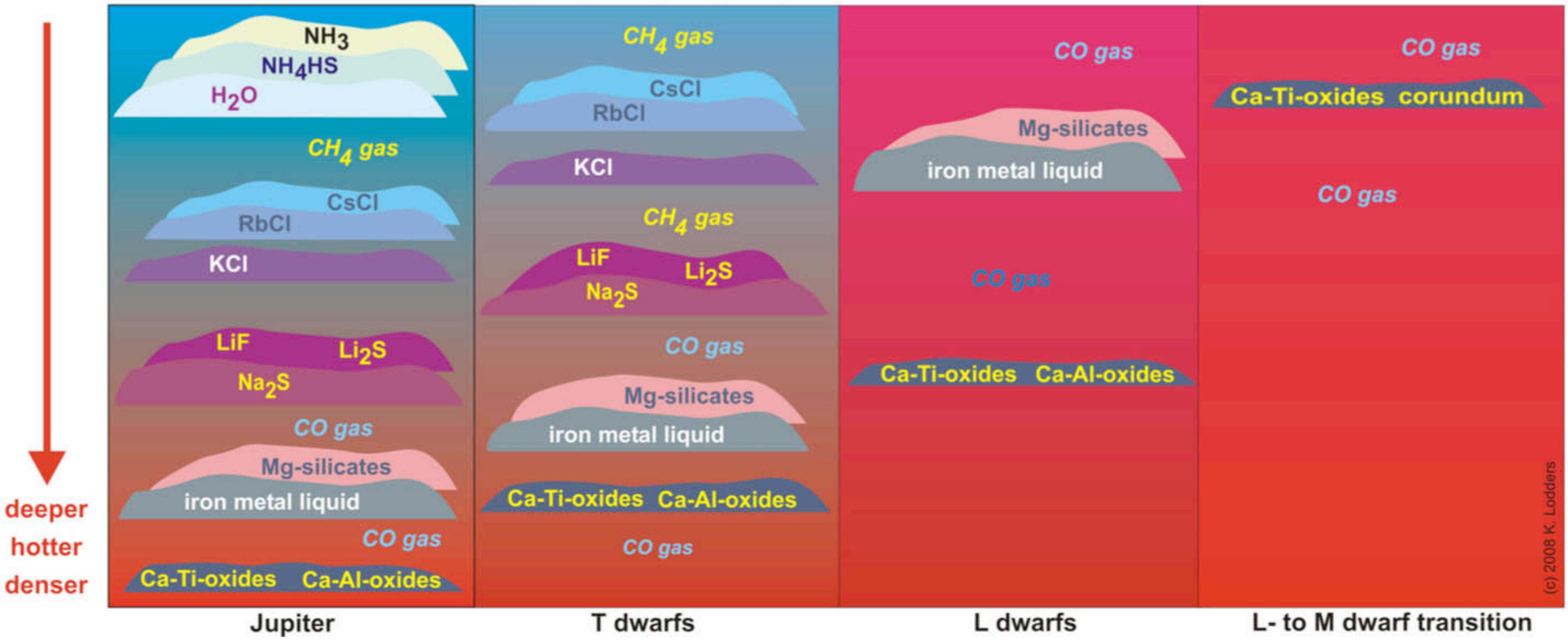
Many young stars are surrounded by massive asteroid/comet belts



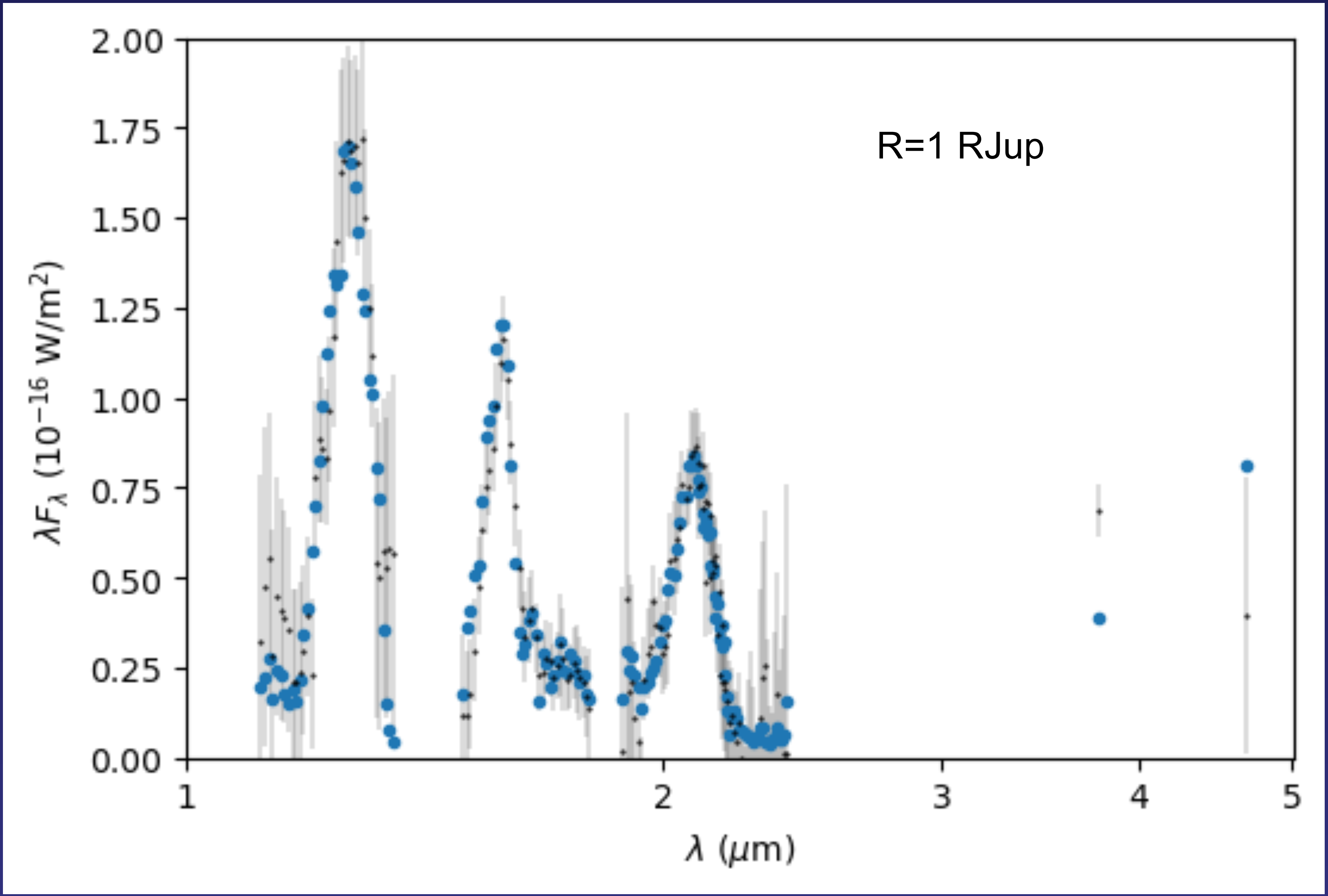
Comet Shoemaker-Levy 9 impact



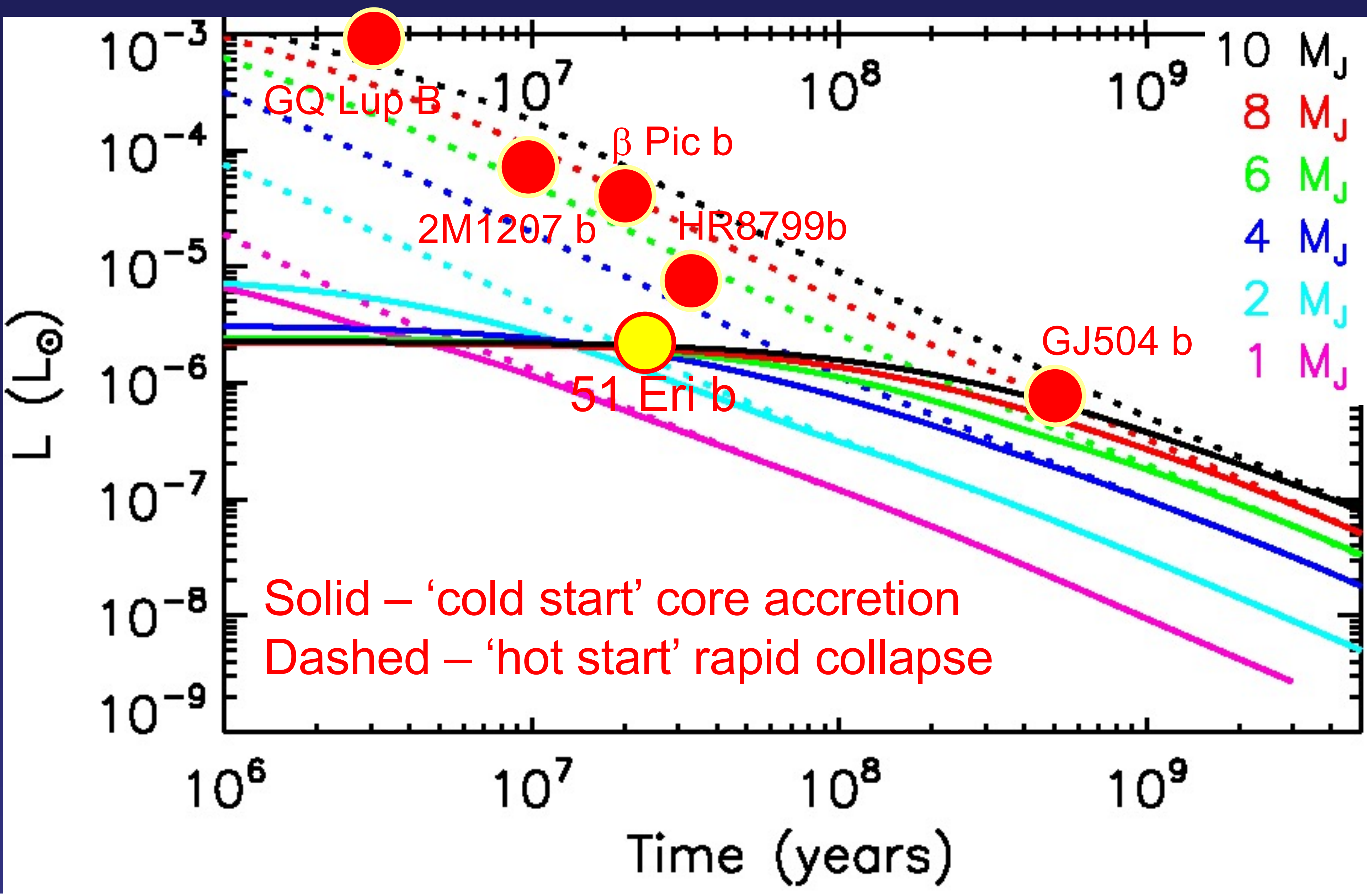
Adding a “rain” of dust into planet models



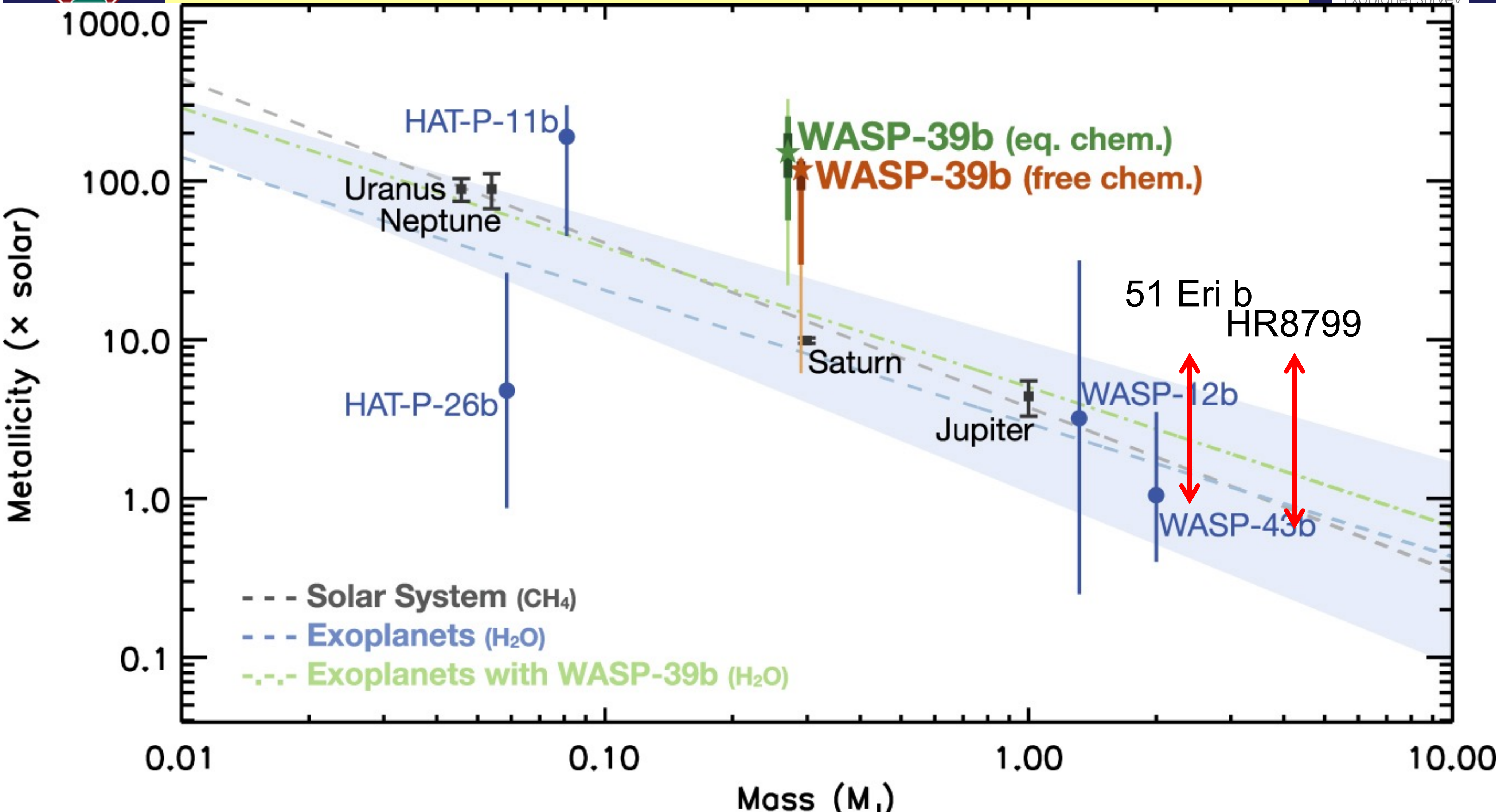
“Dust rain” model (Madurowicz, Bathala, Marley, Macintosh)

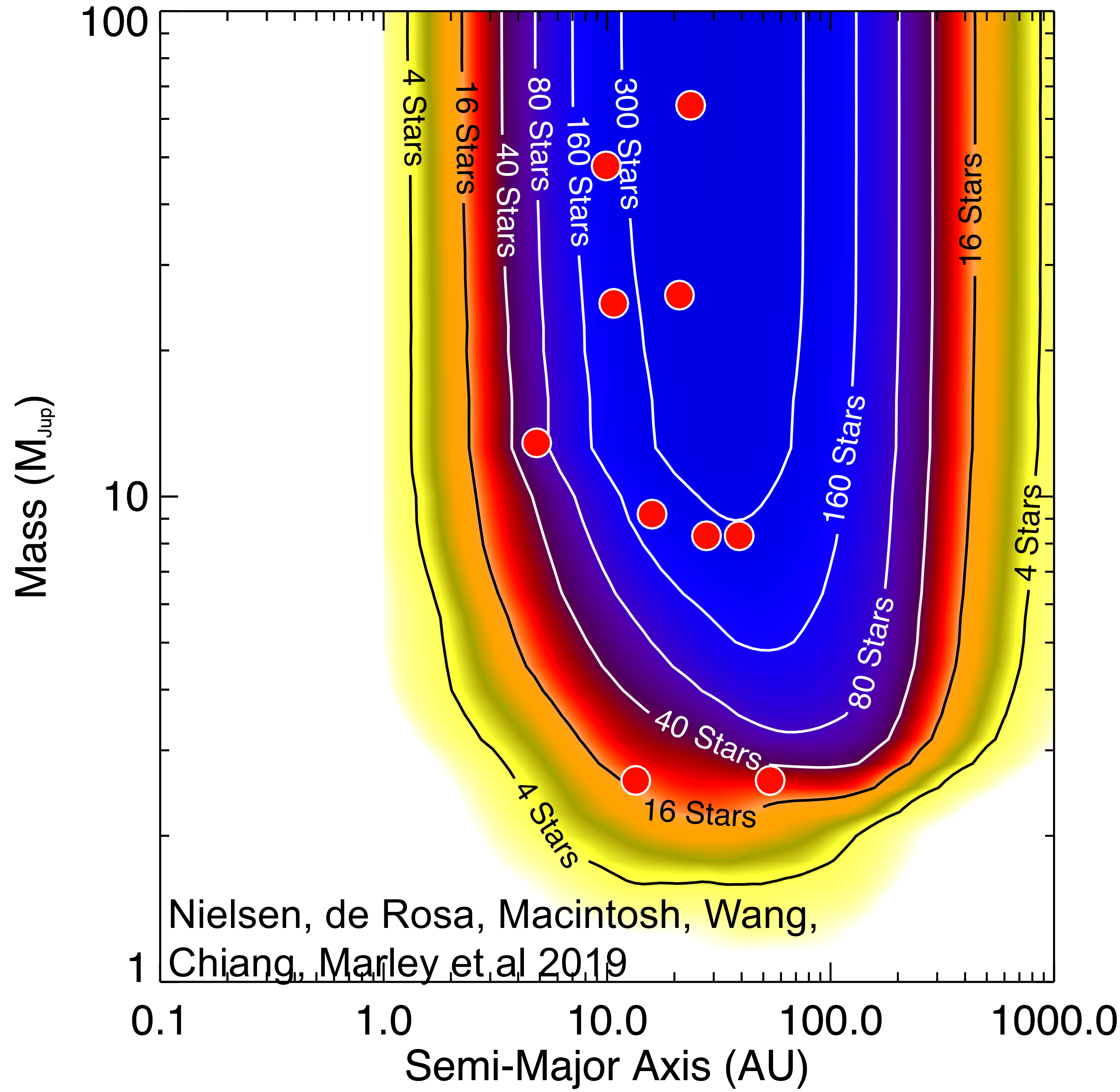


51 Eri b consistent with cold Jupiter-like formation but most others "hot"



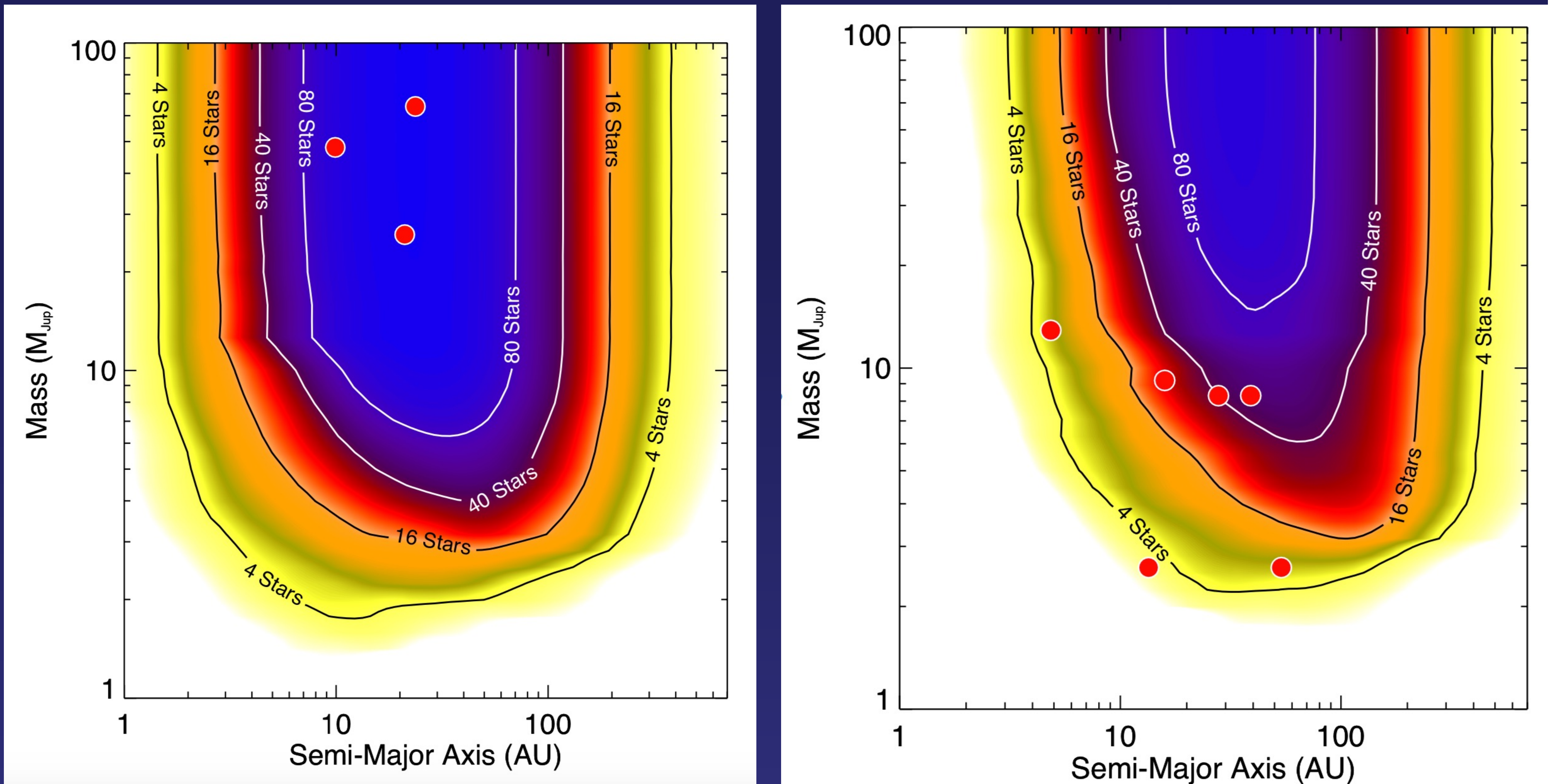
Direct imaged planet metallicities are consistent with trend but uncertain





Mass (M_{Jup})
100
10
1
0.1
1.0
10.0
100.0
1000.0
Semi-Major Axis (AU)
4 Stars
16 Stars
40 Stars
80 Stars
160 Stars
300 Stars
160 Stars
80 Stars
40 Stars
16 Stars
4 Stars
16 Stars
4 Stars
Nielsen, de Rosa, Macintosh, Wang,
Chiang, Marley et al 2019

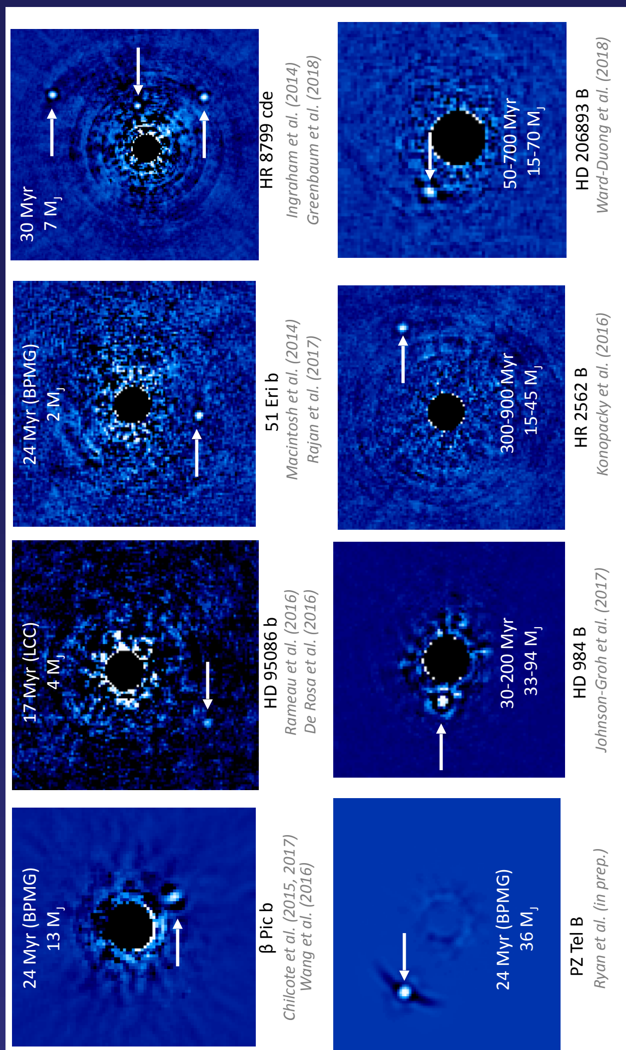
Wide-orbit giant planets much more common around high-mass stars

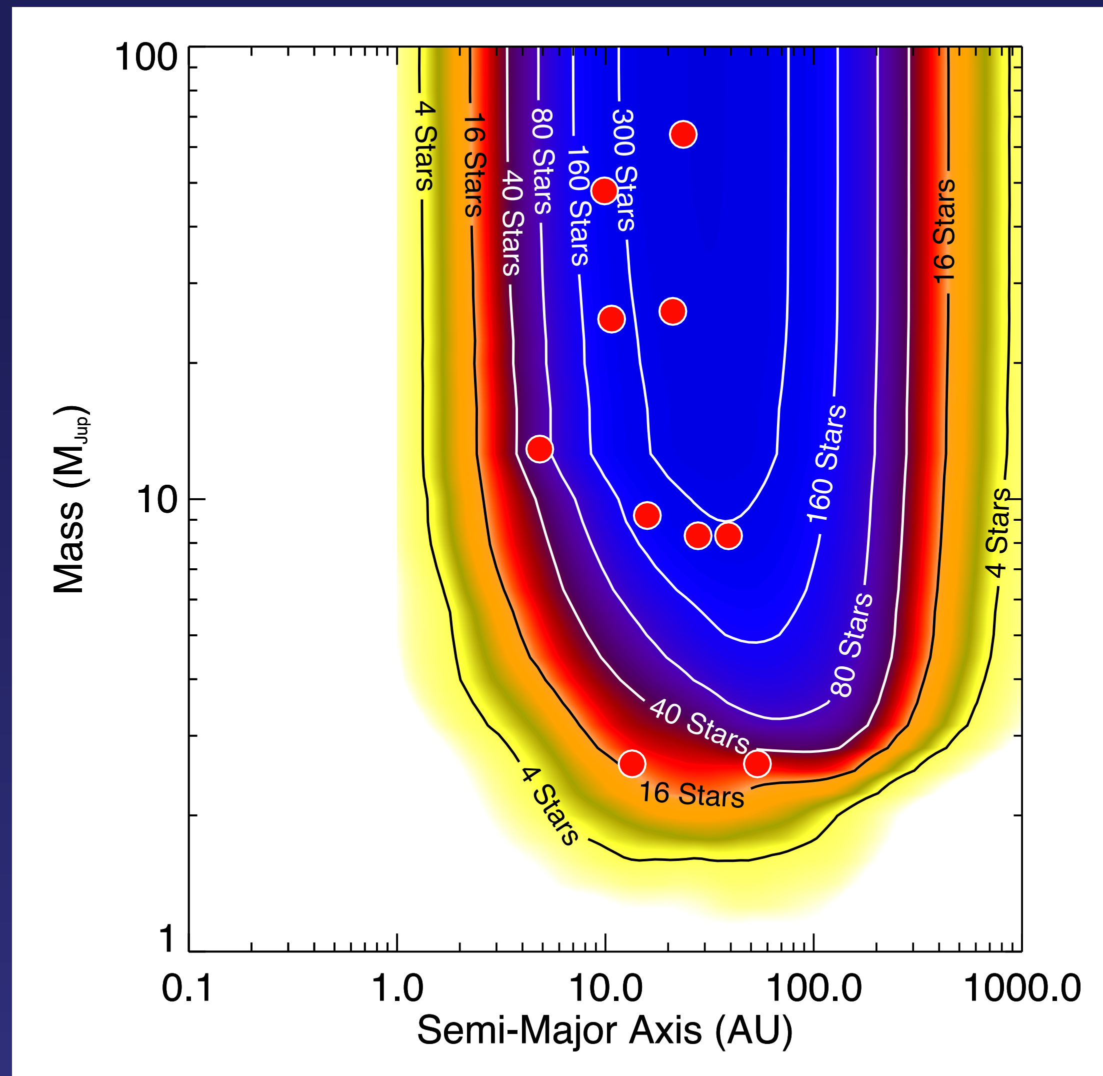


Mass < 1.5 Msun
Giant planets < 25% of stars

Mass > 1.5 Msun
Giant planets ~1 per star

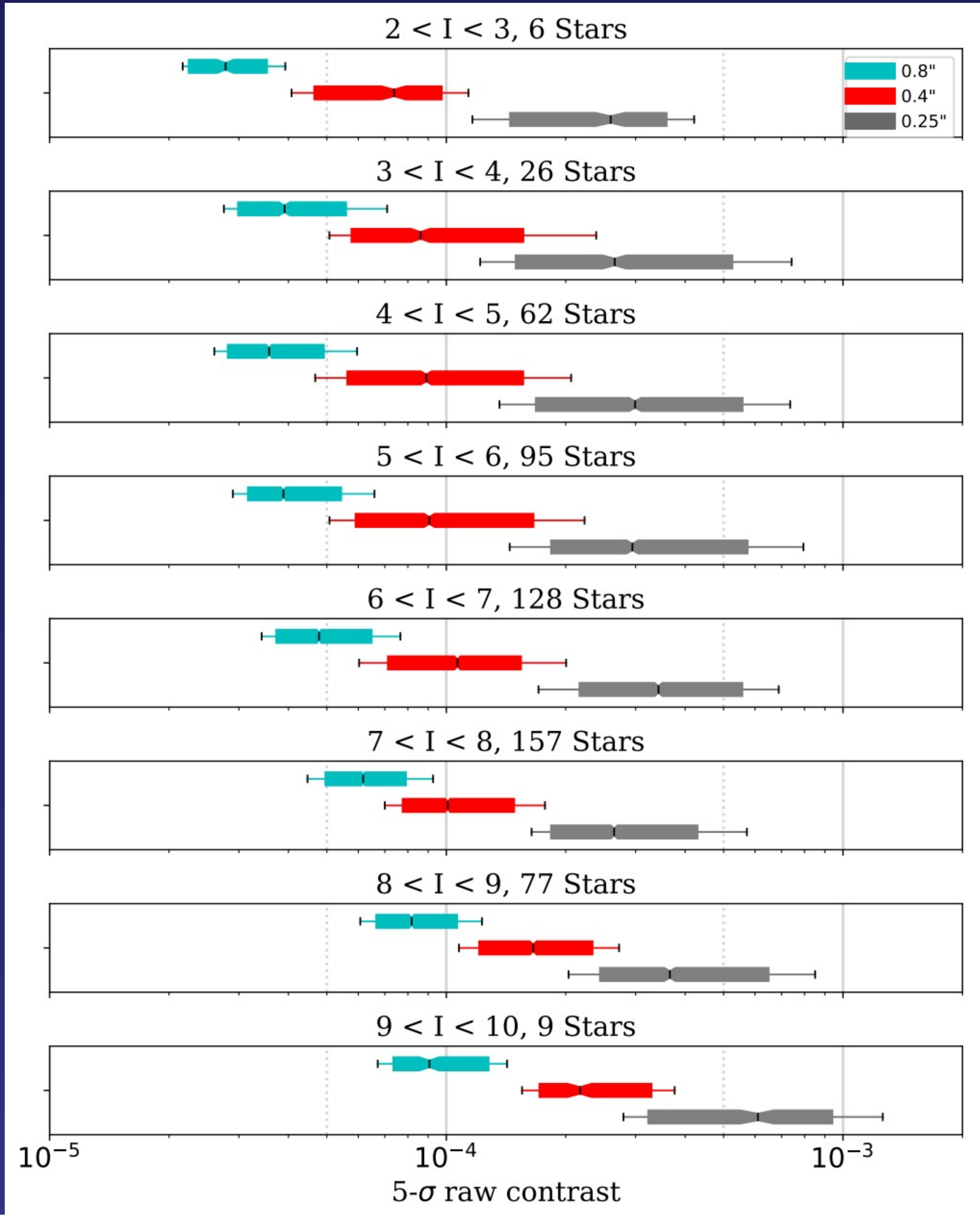
We need more planets!



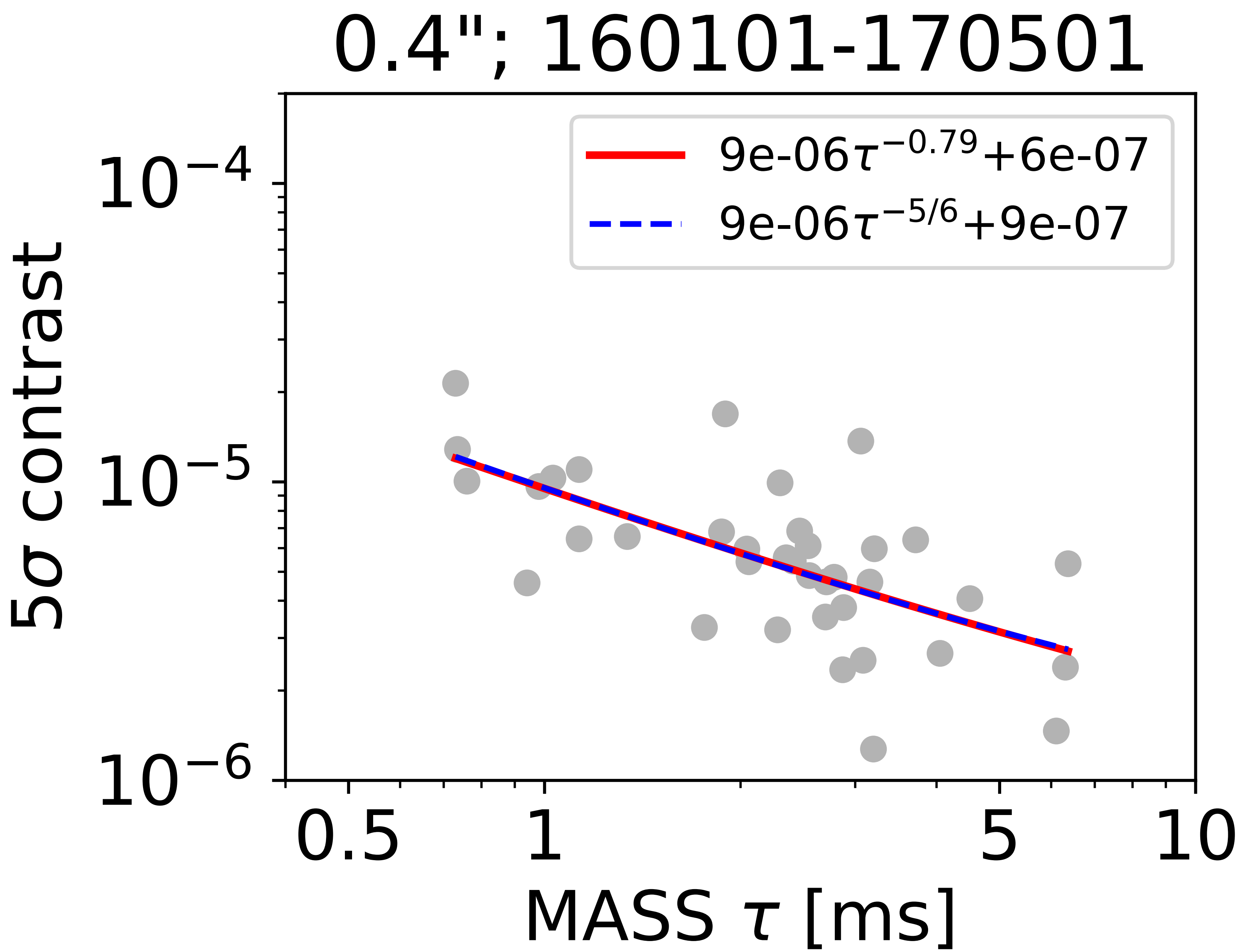


GPI Performance modeling and evaluation (Bailey, Poyneer et al)

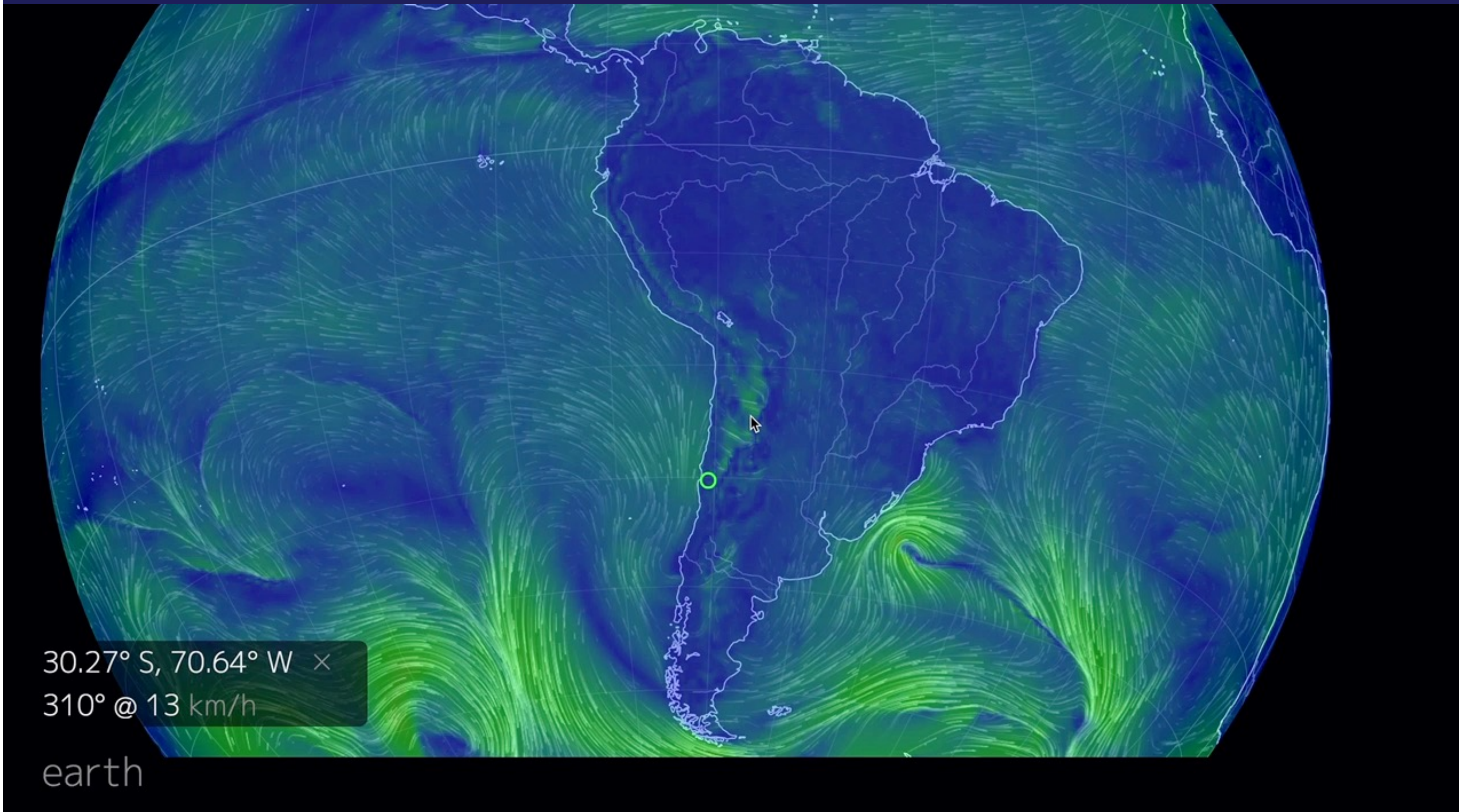
- Empirical multiparameter fit to contrast vs telemetry
- 25,000 raw 60-min images
- 500 combined datasets
- Extension of work in Bailey et al 2016



Strongest contrast predictor: atmospheric coherence time $\tau = 0.3\ r_0 / v_{wind}$

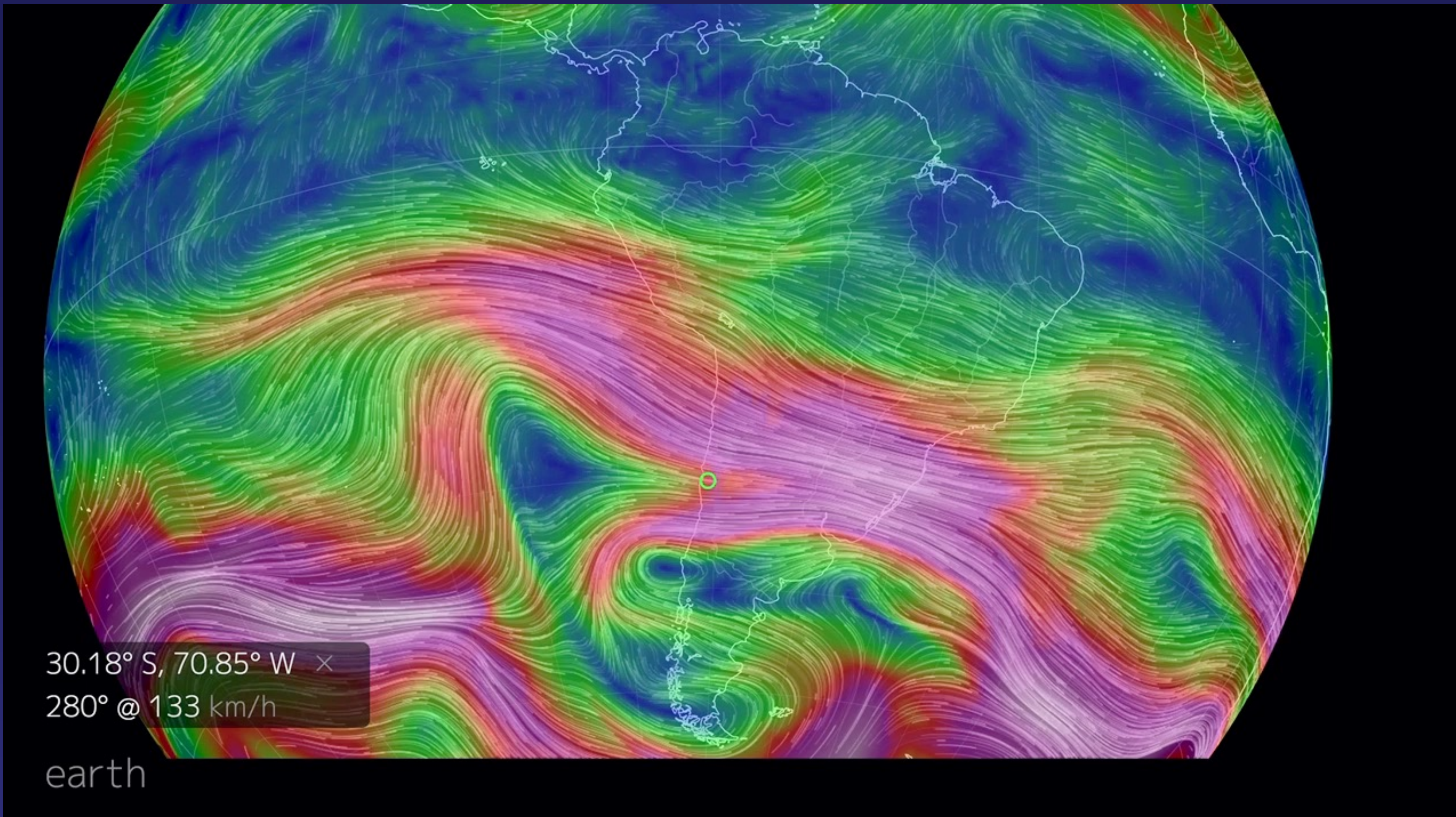


Surface winds: 0-40 km/h



earth.nullschool.net

Jet stream winds 130 km/h



Madurowicz et al 2018

Other limitations

- GPI limited to bright / nearby stars
- Operations complexity
- Very few young stars left in the southern sky

gpi

Exoplanet Survey

gpi2

GPI 2.0 – A Facility-Class High Contrast Imaging System in the North for the 2020s

- Upgrade led by Jeff Chilcote (ND) and Quinn Konopacky (UCSD) with Bruce Macintosh, Dmitry Savransky, Marshall Perrin and GPI team
- Funded by NSF (ND) and HSF (UCSD)
- Upgrade begins ~~2020B~~, 2021 “first” light ~~2022~~ 2023

UC San Diego

GEMINI OBSERVATORY
Exploring the Universe, Sharing its Wonders

GPI2 upgrade baseline

- Upgraded photon-counting pyramid wavefront sensor to allow operation on fainter stars
- New fast realtime computer reduce effective delay from ~1.8 to ~0.5 ms
- Enhanced coronagraphic masks with smaller inner working angle (<0.1”) or higher throughput
- Broadband spectrograph mode for simultaneous JHK observations
- Enhanced software environment to provide fast, efficient queue observing

Some conclusions and platitudes

- **Direct imaging with current technology probes a unique piece of planet phase space – wide-orbit, high-entropy/energy massive planets**
- **Discoveries test planet formation models**
- **Shows the need for new details in atmosphere modeling**
  - Clouds, dust, initial entropy…
- **Near-future: GPI2 extending our target sample to lower-mass and younger planets**
- **James Webb Space Telescope adding longer-wavelength data and lower-mass / older warm planets**
- **Mid-future: Mature Jupiter analogs with space coronagraphs like Nancy Grace Roman telescope**
- **Far-future: Earths?**