High-Performance Computing, Planet Formation & Searching for Extrasolar Planets

Eric B. Ford (UF Astronomy)

Research Computing Day
September 29, 2011

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External collaborators include M. Juric (Harvard-Smithsonian Center for Astrophysics) on GPUs, the California Planet Survey team & the entire NASA Kepler Science Team.

Photo: Gabriel Pérez

Planet formation Models

- How did our solar system form?
- How can we the diversity of planetary systems in nature?
- Is our solar system special?

- Growing atoms into giant planets spans ~45 orders of magnitude in mass!
- At least 6 physical processes on timescales spanning ~23 orders of magnitude!

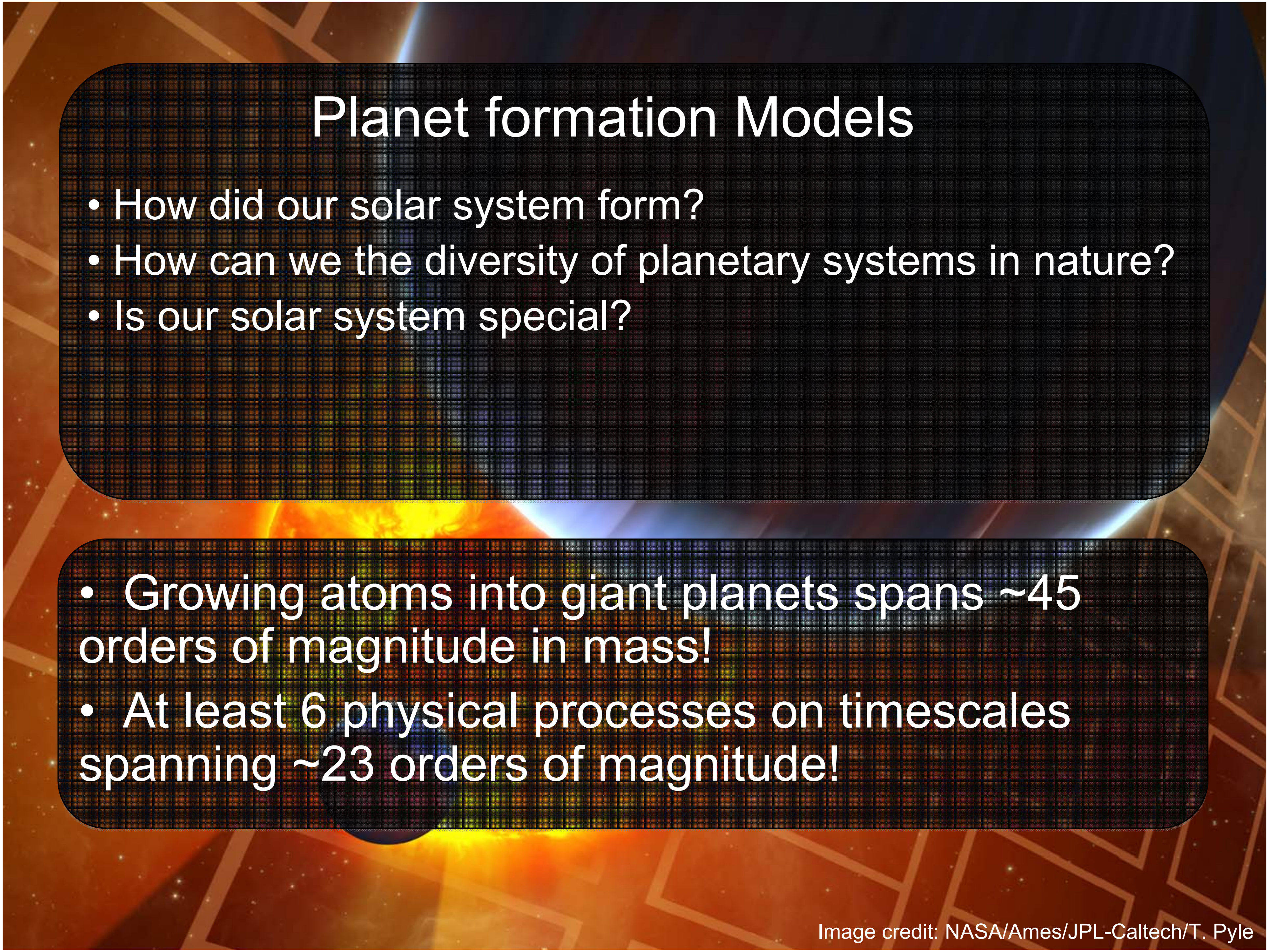


Image credit: NASA/Ames/JPL-Caltech/T. Pyle

Where to Planet Initially Form?

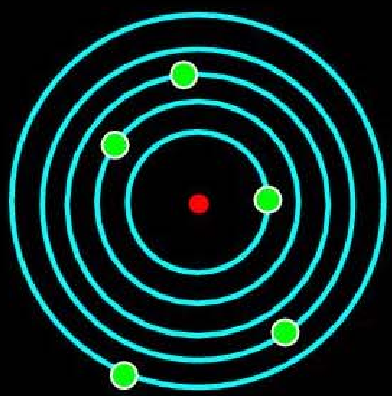


Illustration by E. Chiang

Orbital Migration through Disk

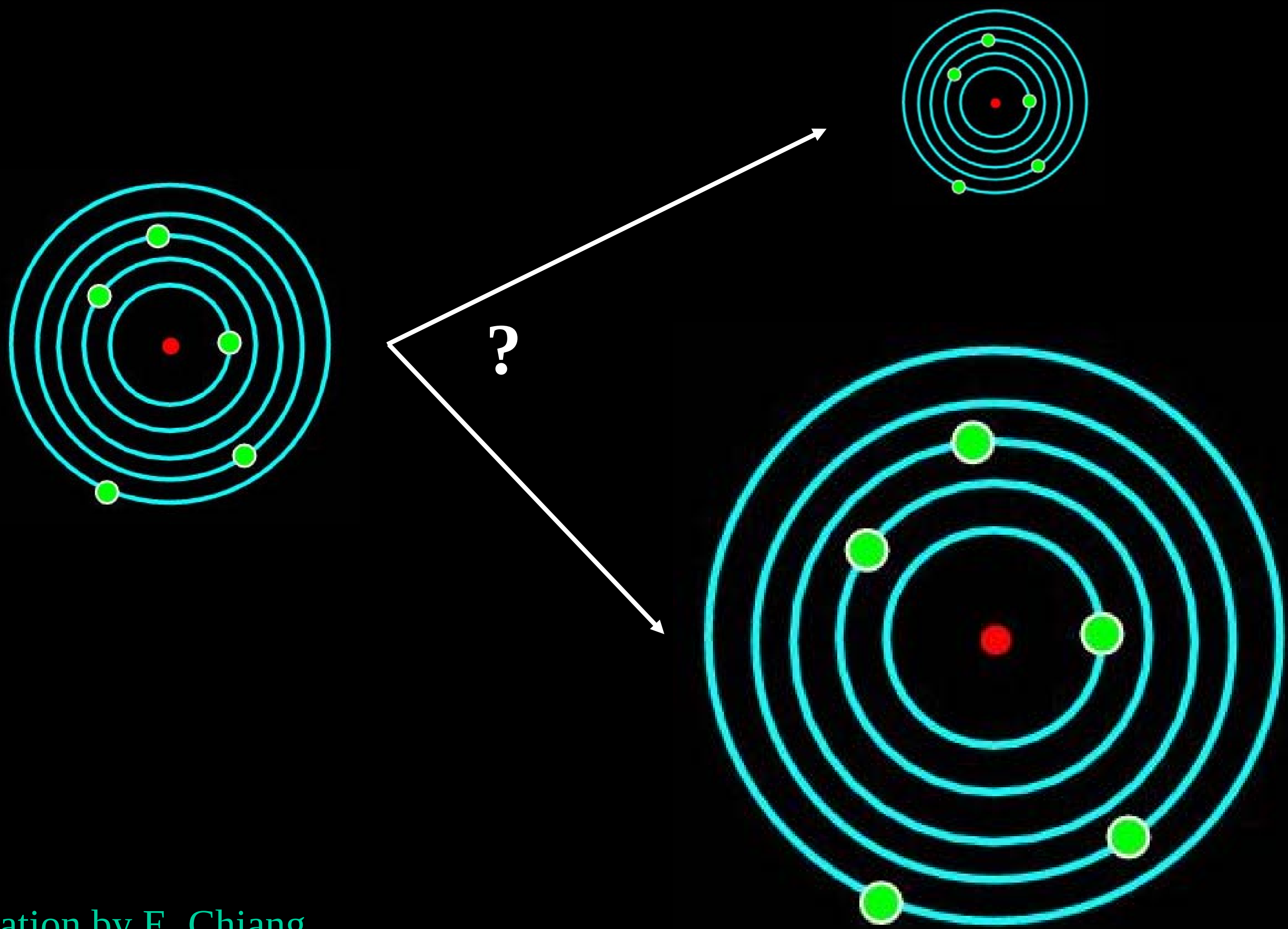


Illustration by E. Chiang

Planet Scattering

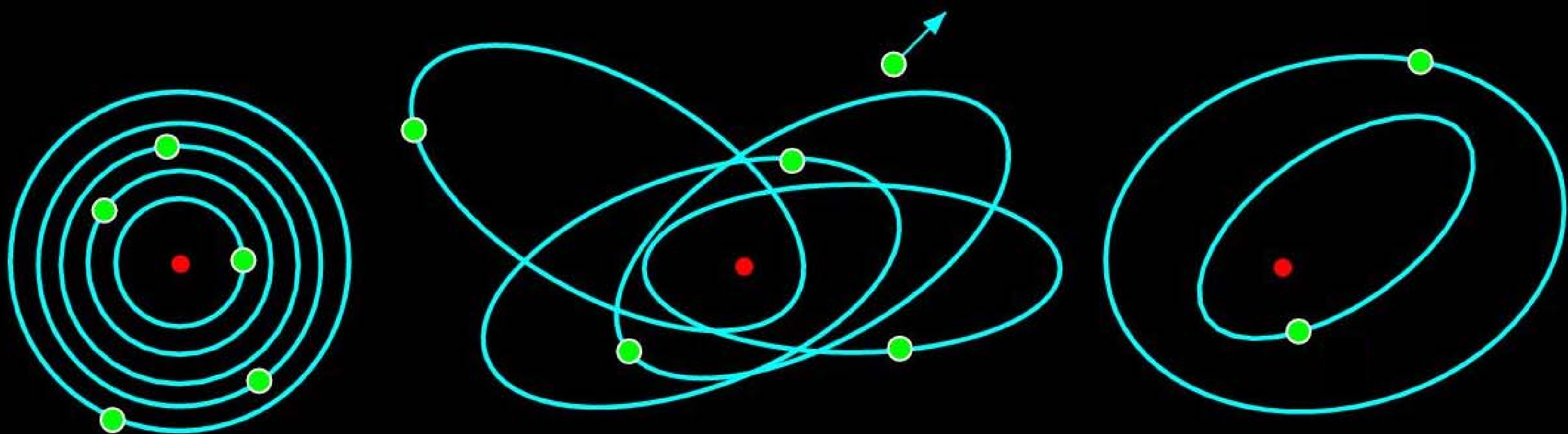
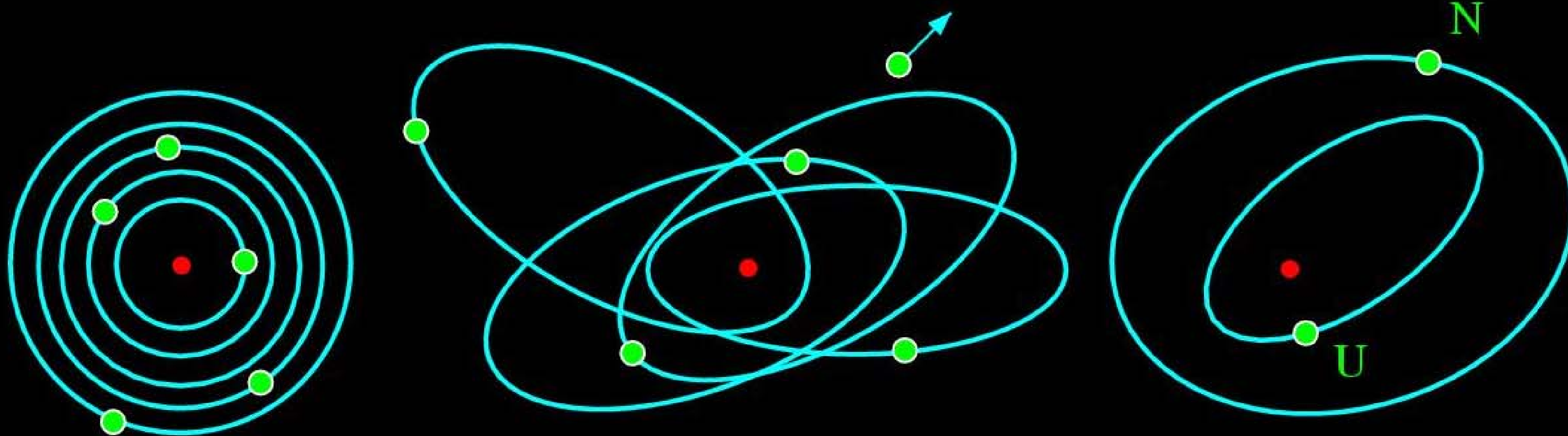
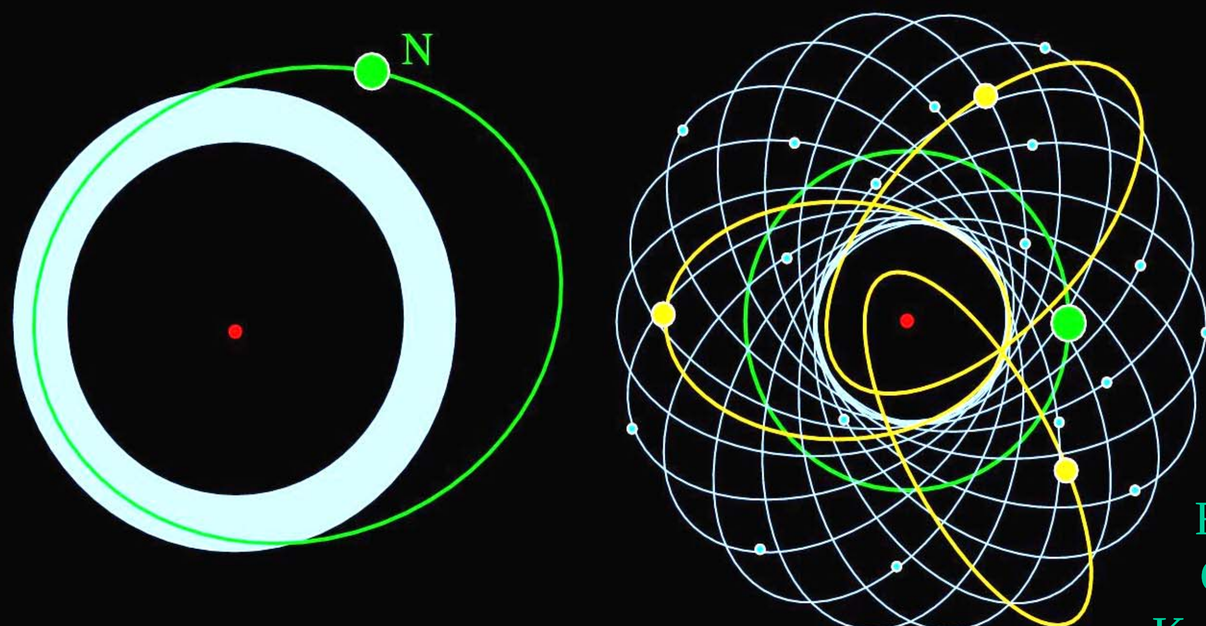


Illustration by E. Chiang

Planetessimal Scattering

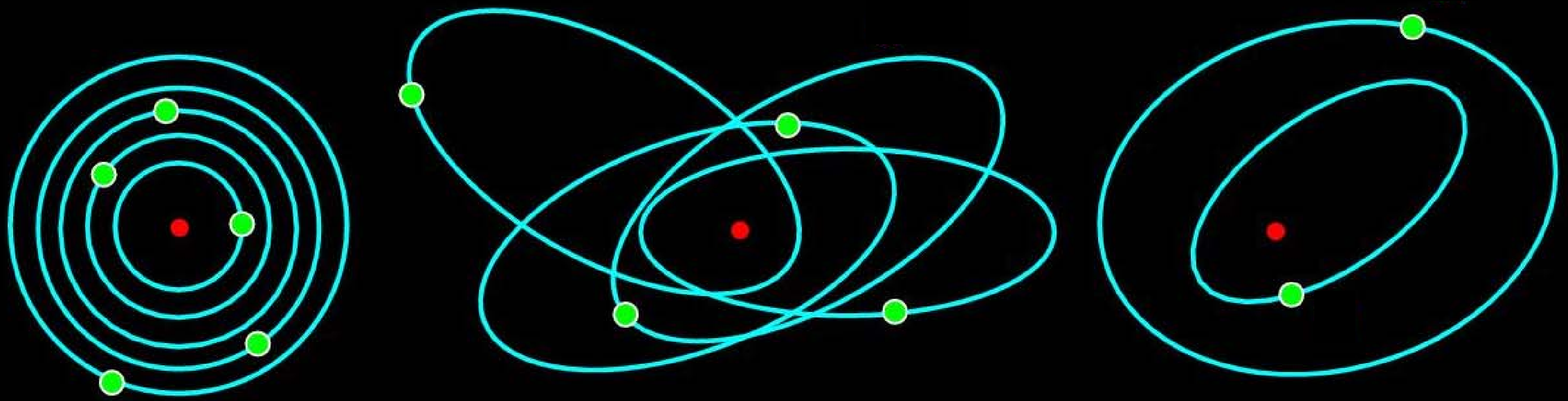




Ford & Chiang 2007
Goldreich et al 2004
Kenyon & Bromley 06
Thommes et al. 99, 02

Illustration by E. Chiang

What Determines Final Orbits?

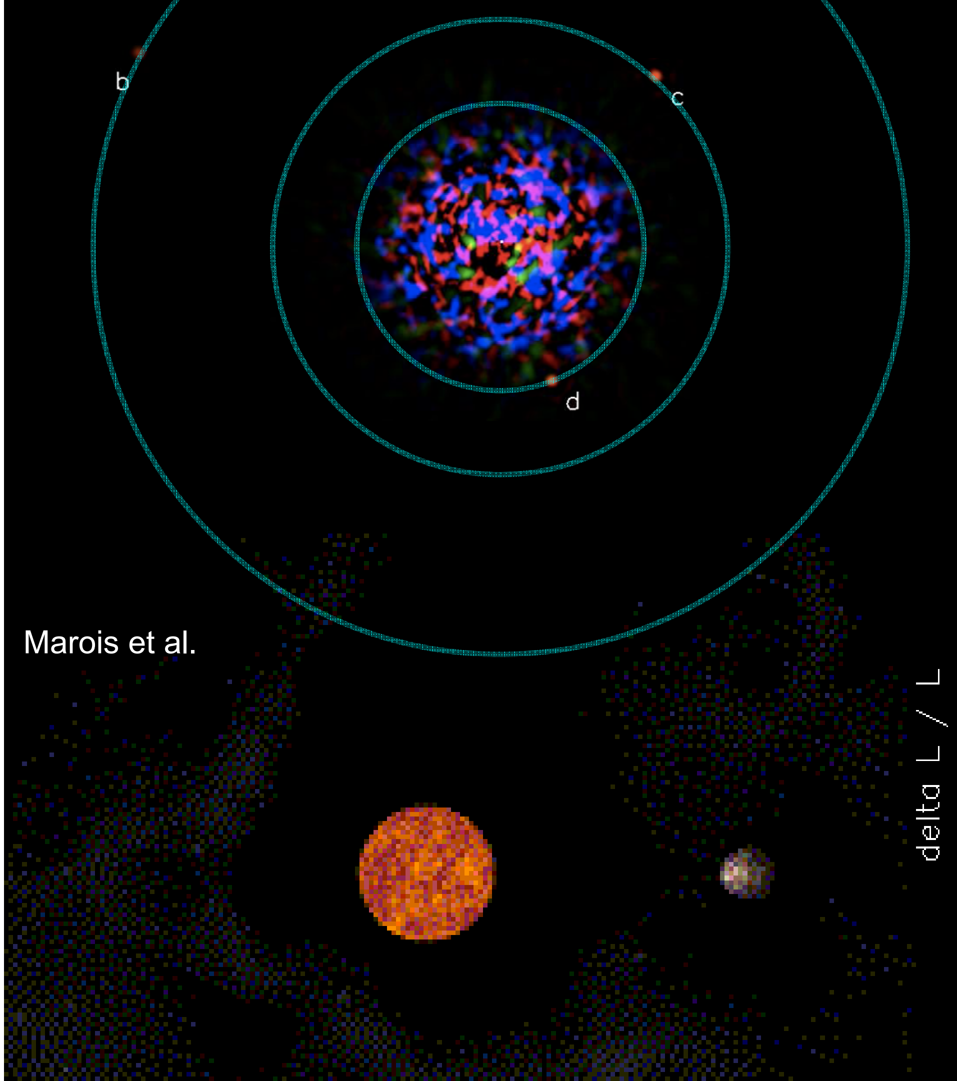


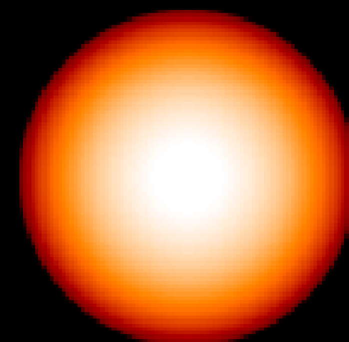
Difference in architectures of systems with:

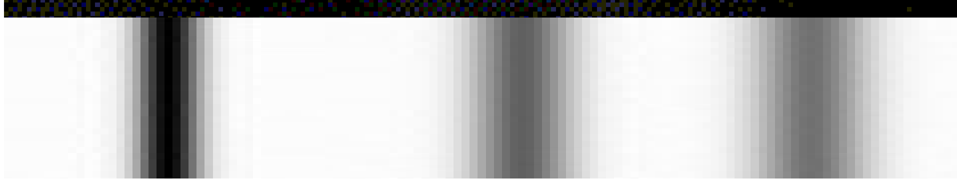
- Giant planets only?
- Low-mass planets only?
- Both giant & low-mass planets?

Illustration by E. Chiang

Exoplanet Discovery Techniques







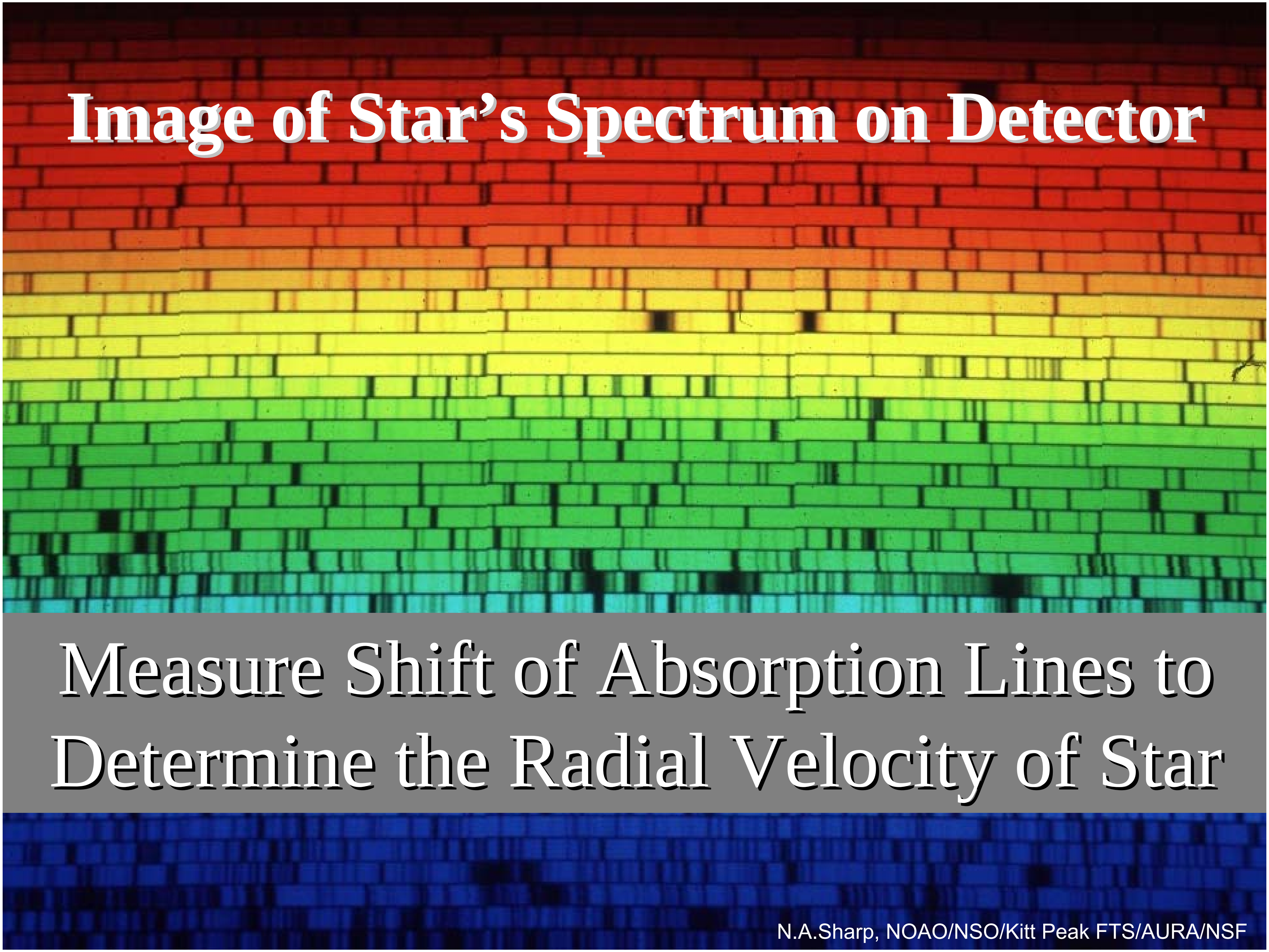
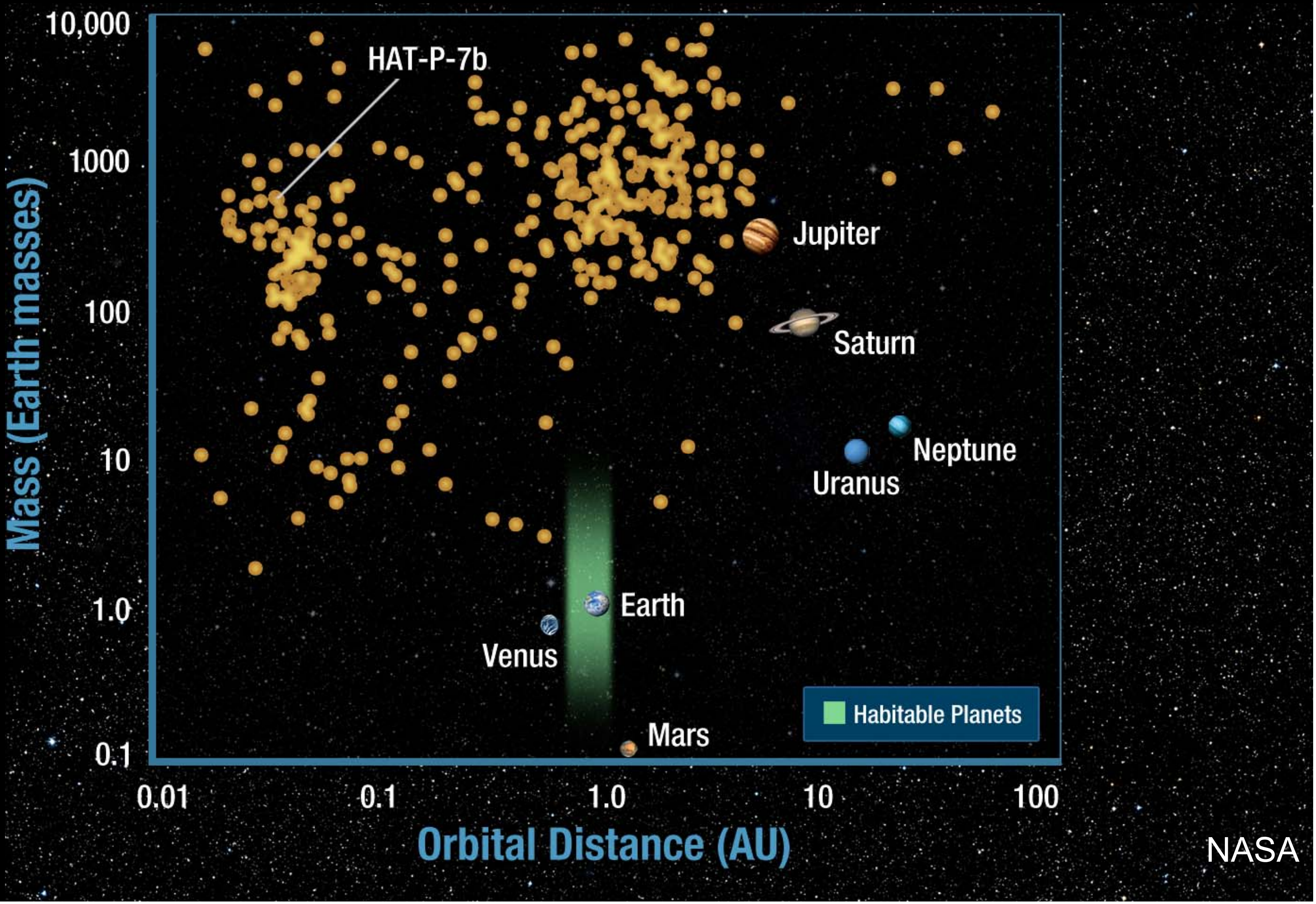


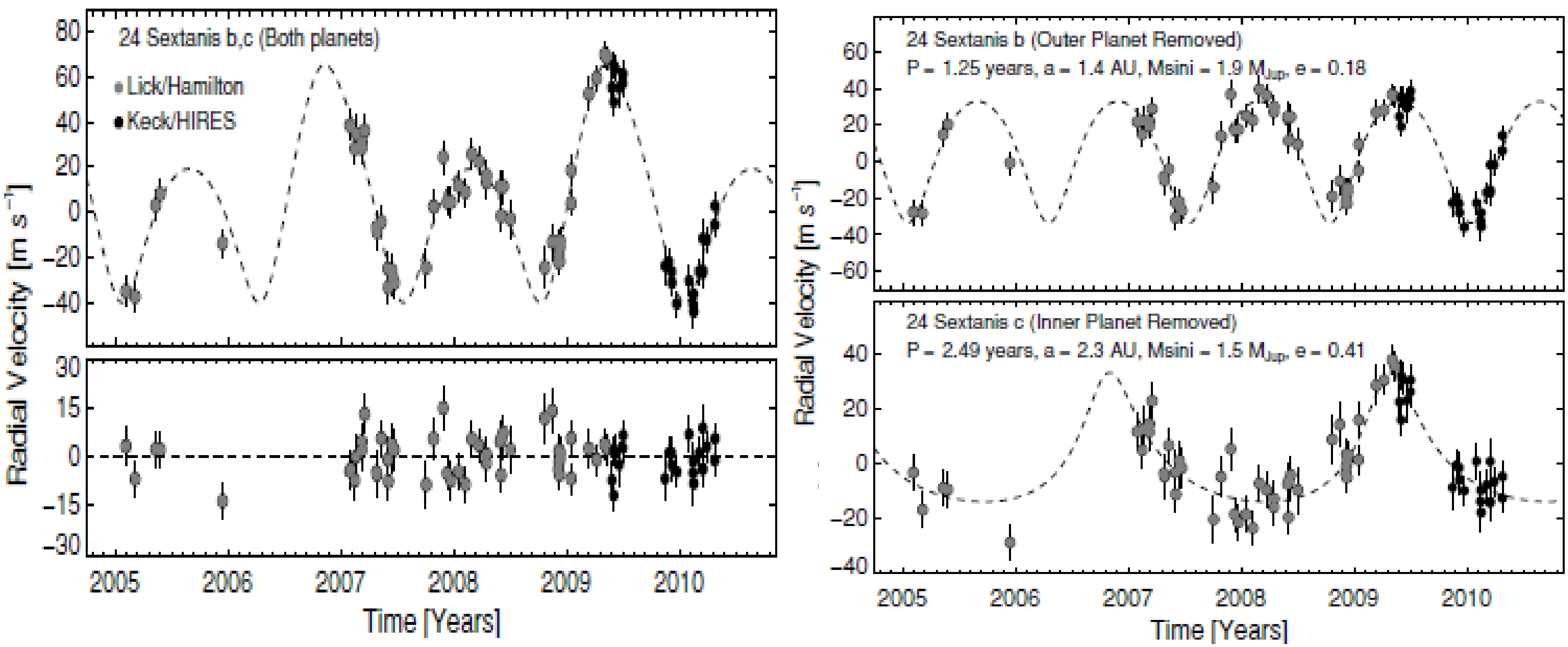
Image of Star's Spectrum on Detector
Measure Shift of Absorption Lines to Determine the Radial Velocity of Star
N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Census of Exoplanets (w/ Doppler observations)



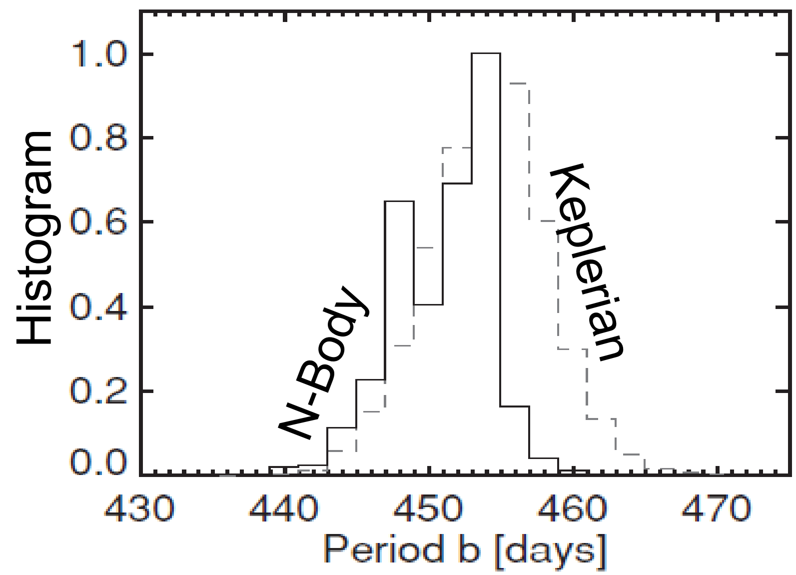
NASA

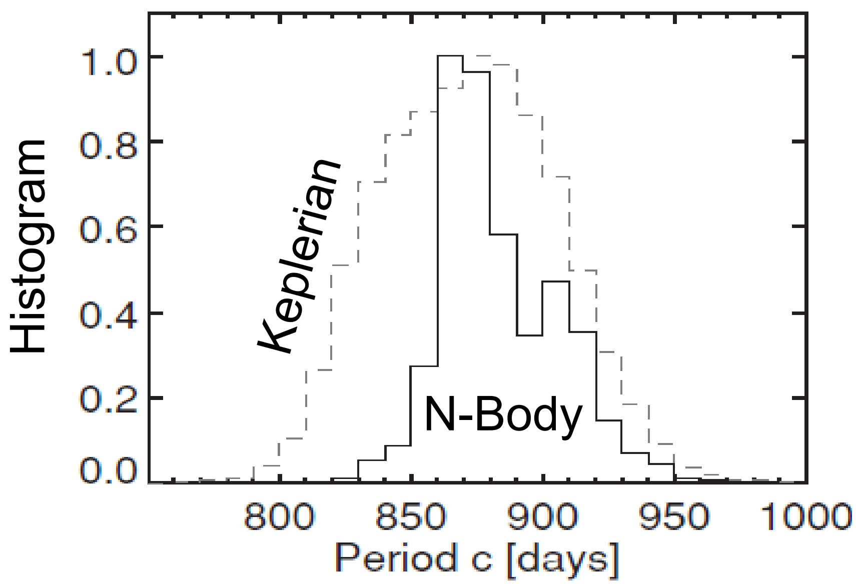
Two Planet System Discovered by Doppler Technique (24 Sextans)

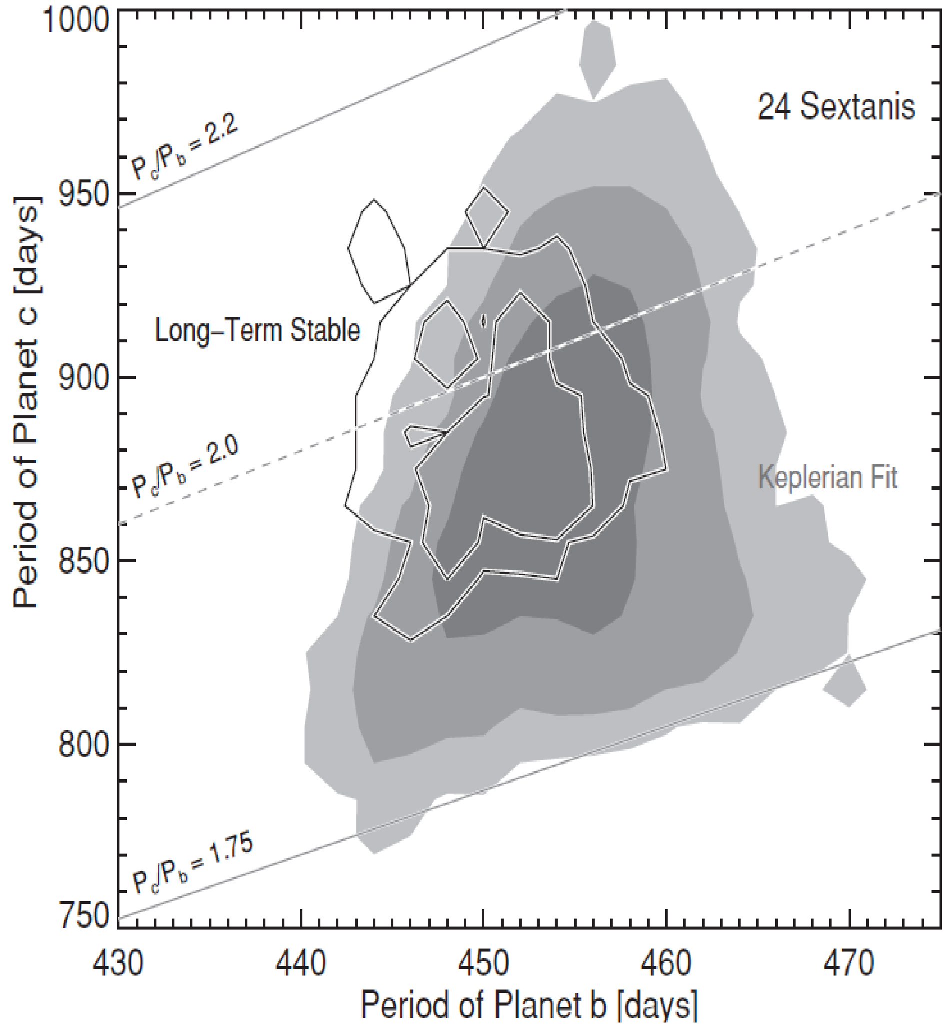


Johnson et al. 2011

Uncertainty in Orbital Periods (24 Sextans)





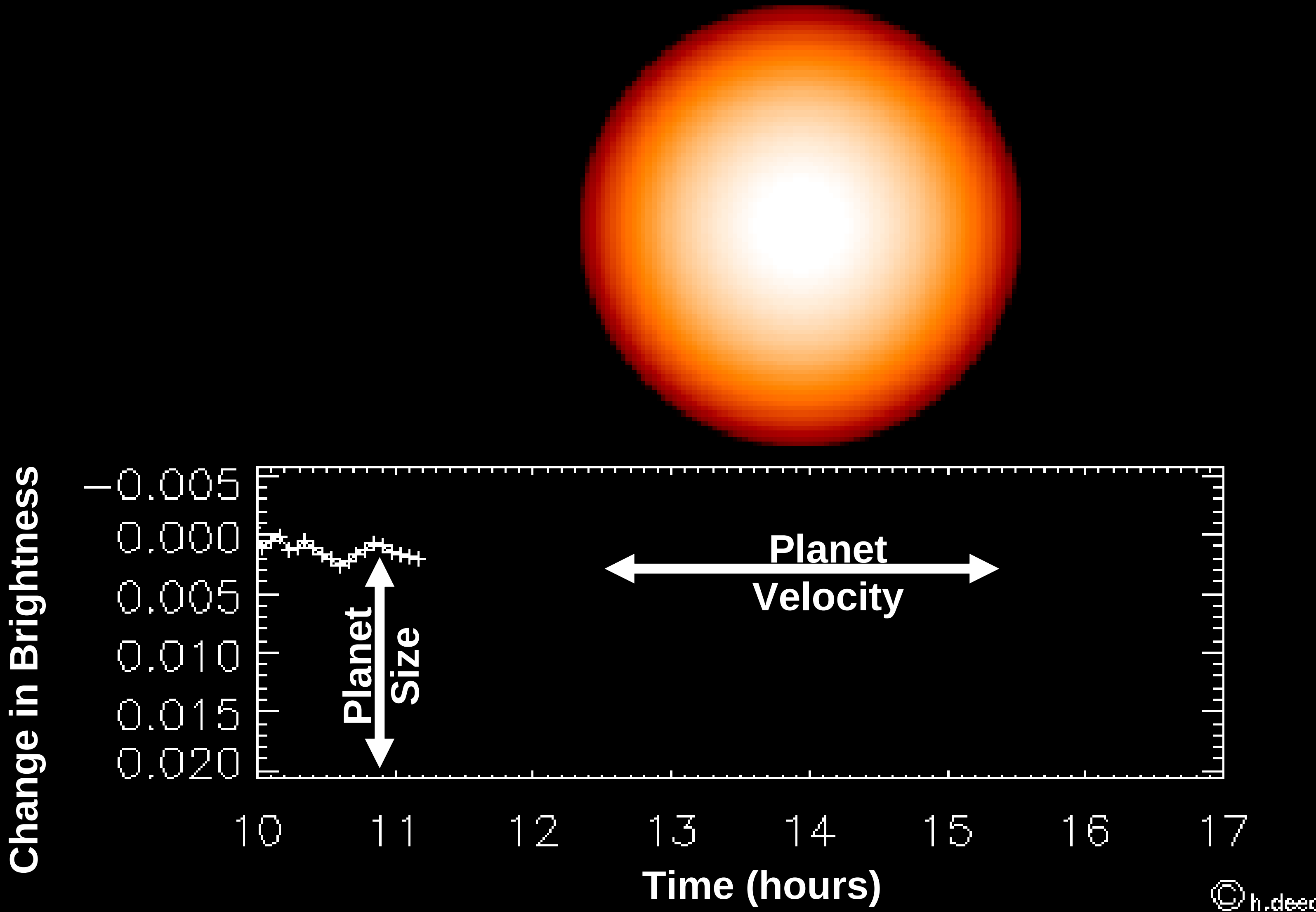


Johnson et al. 2011

Computational Challenge

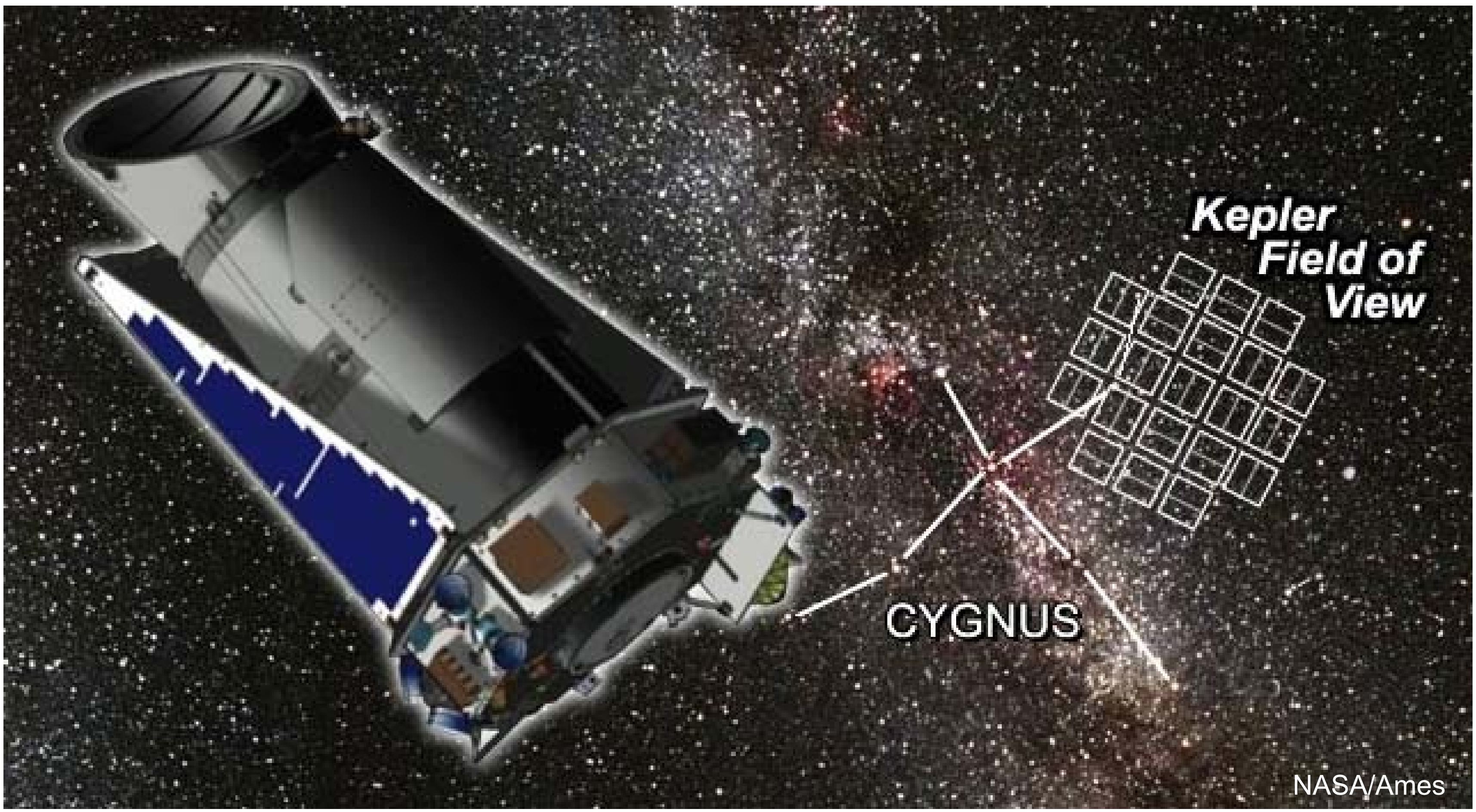
- Analyzing radial velocity (or other) observations of extrasolar planetary systems with multiple planets.
  - parameter estimation via Markov chain Monte Carlo
  - ~$7xN_{planets}$ model parameters
  - ~10^7-10^{10} model evaluations
  - Parallelized via Differential Evolution MCMC
  - Also want to test models for long-term stability
  - Ideally, automated, with estimates updated each time a new observation is obtained
- Need algorithms that efficiently explore high-dimensional parameter space
- Conventionally use clusters w/ OpenMP
- Moving to Graphics Processing Units

Shadow of a Distant Planet

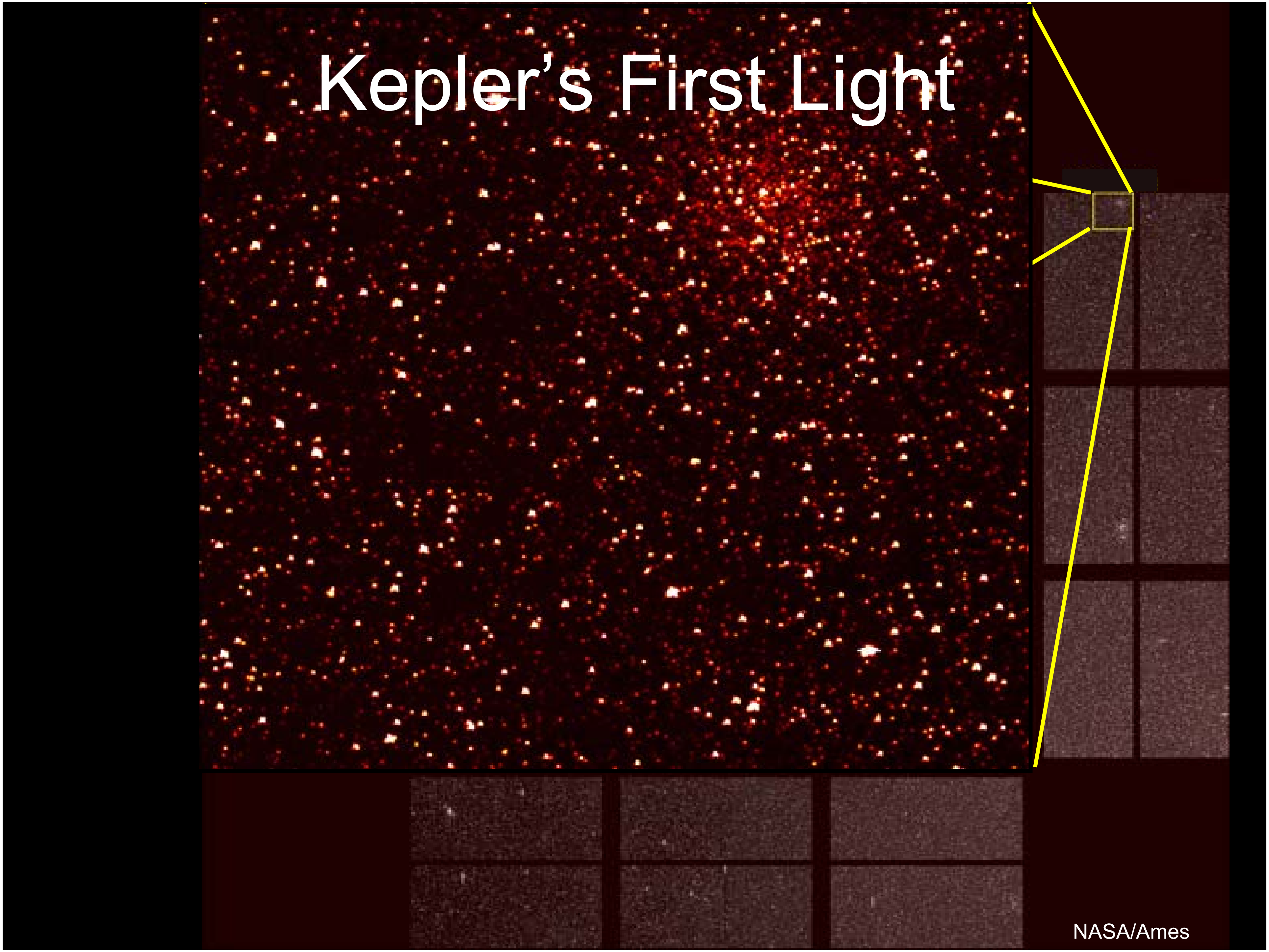


Kepler Mission

- NASA, photometry of >150,000 stars
- Looking for Earth-like planets in transit
- 50μmag in 6 hours; 30 minute cadence
- First ~210 days went public last week

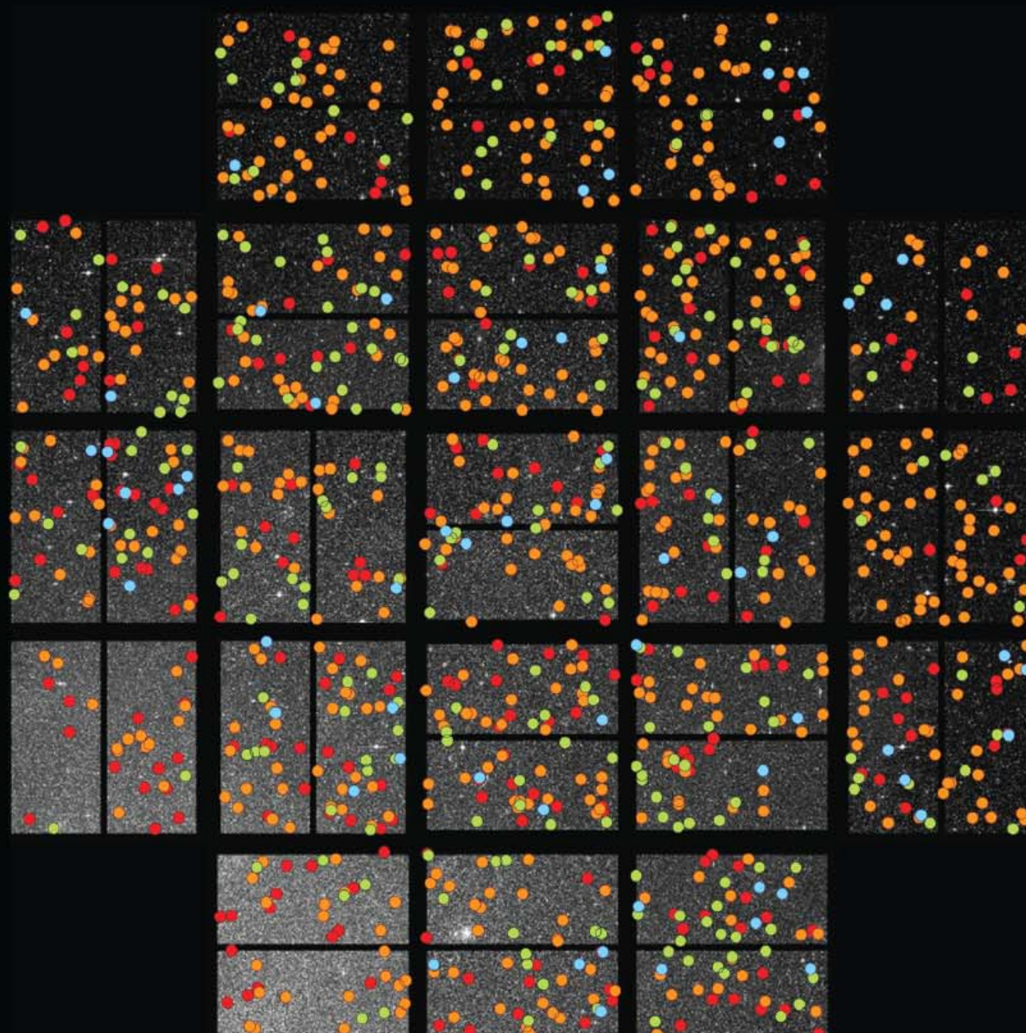


Kepler's First Light



NASA/Ames

Locations of Kepler Planet Candidates



Earth-size

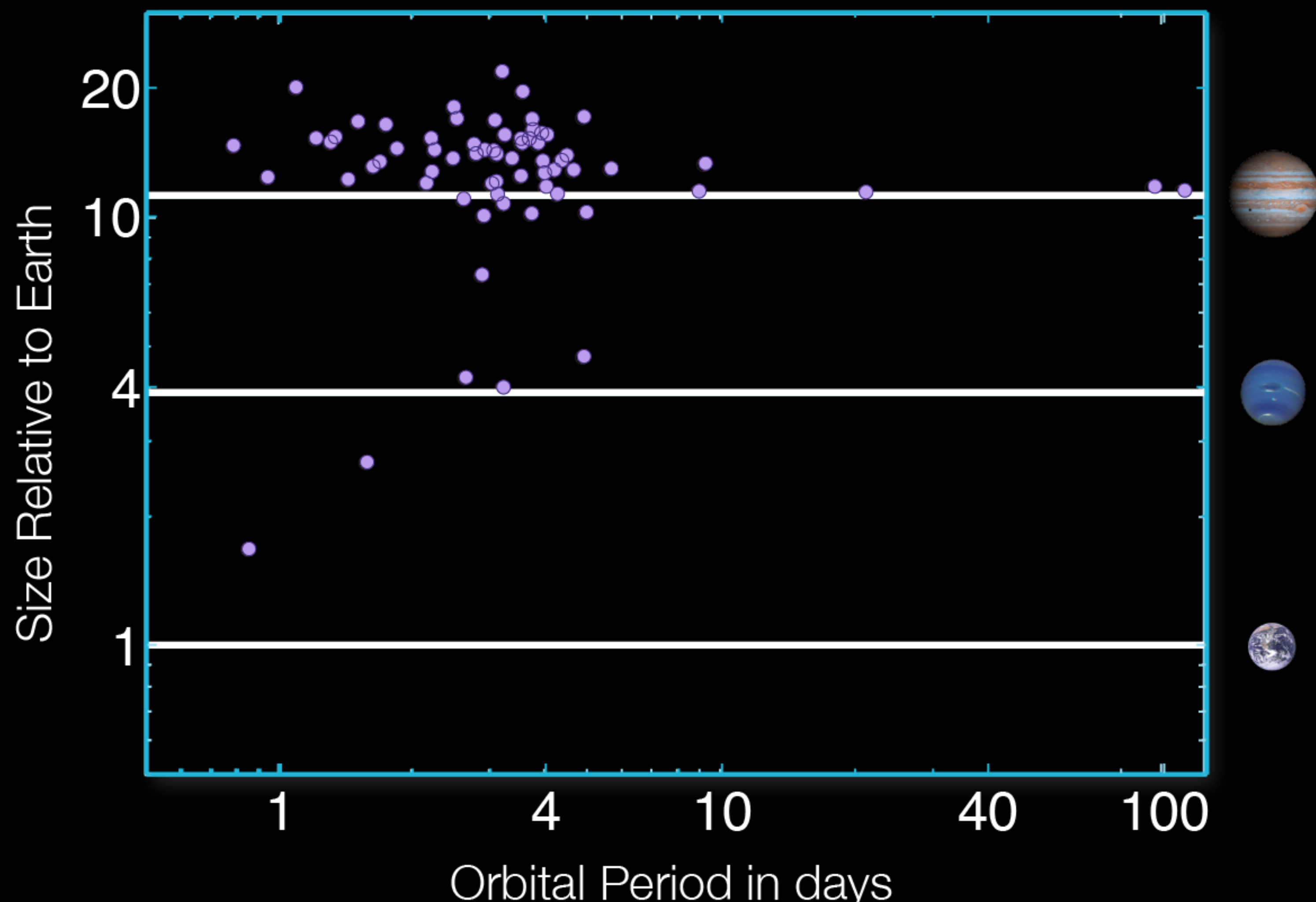
Super-Earth size
1.25 - 2.0 Earth-size

Neptune-size
2.0 - 6.0 Earth-size

Giant-planet size
6.0 - 22 Earth-size

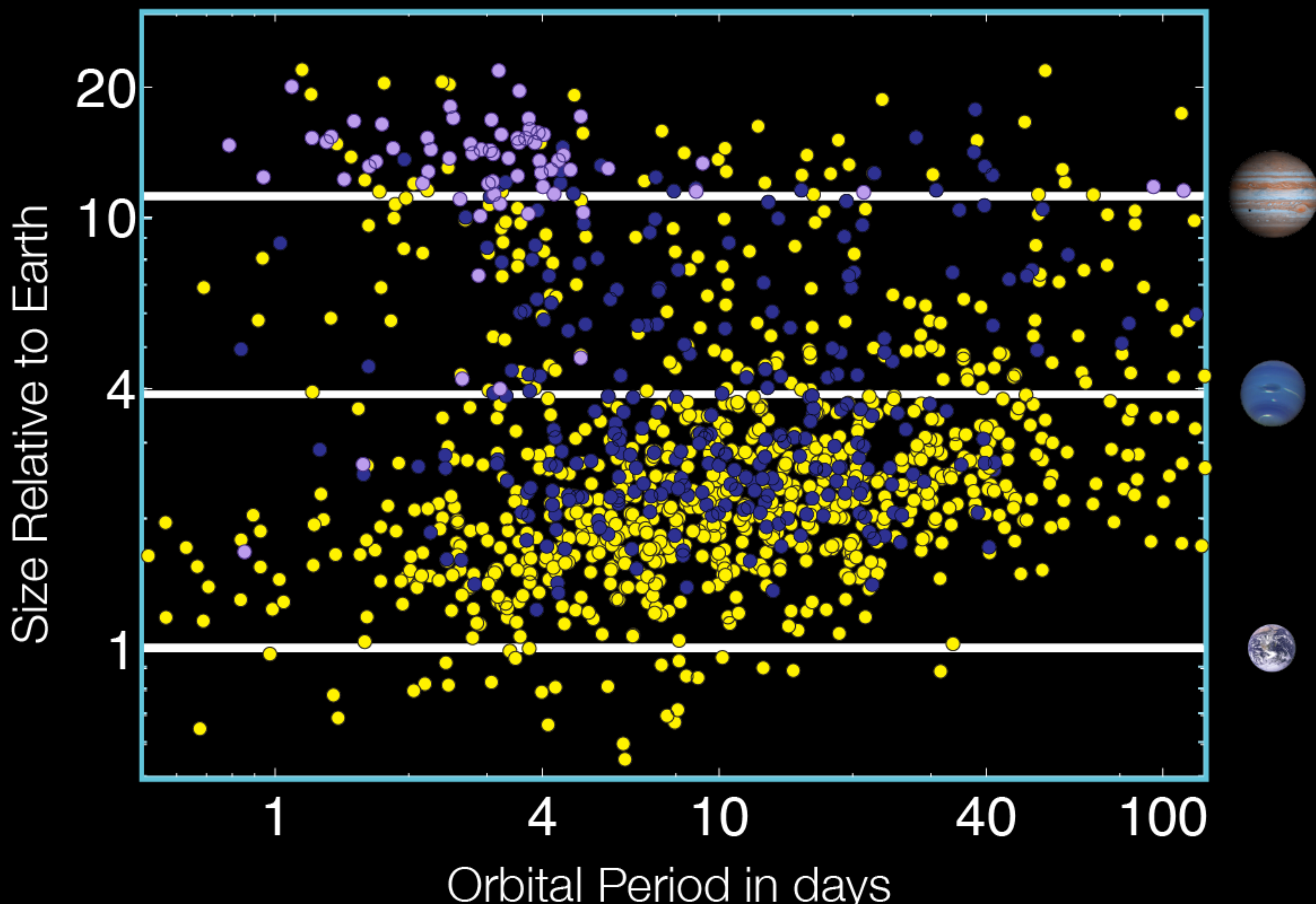
NASA/Ames

Pre-Kepler Transiting Planets - 2009



NASA/Ames

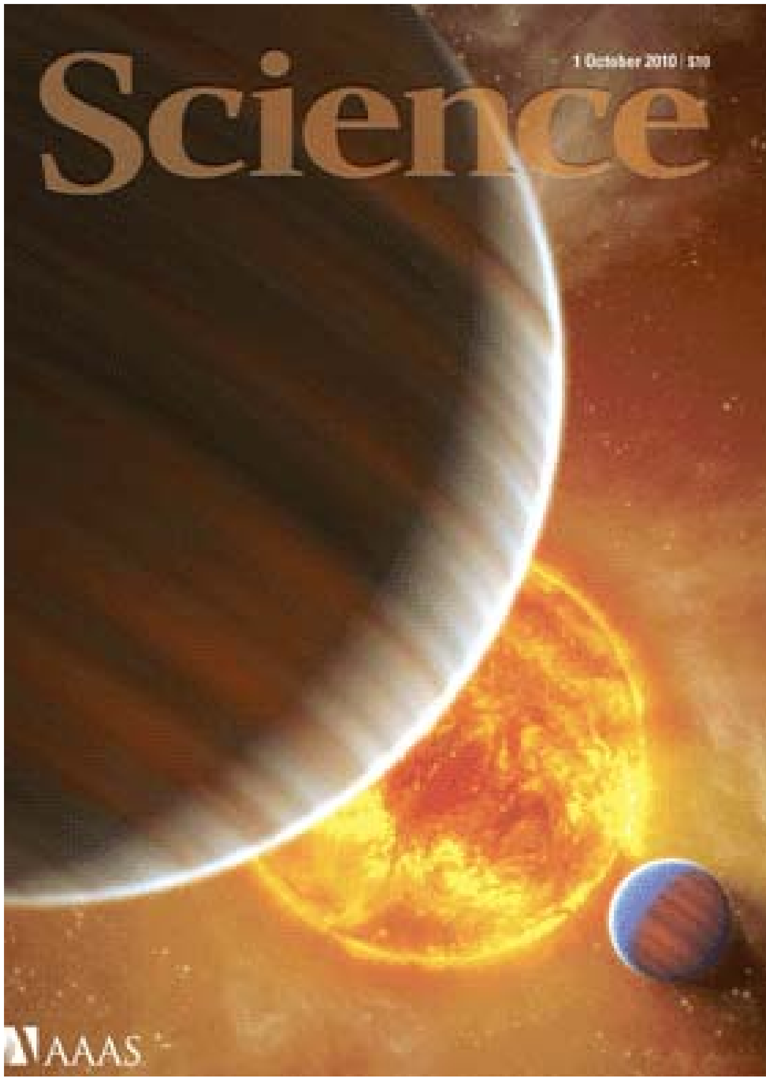
Kepler Candidates as of February 1, 2011

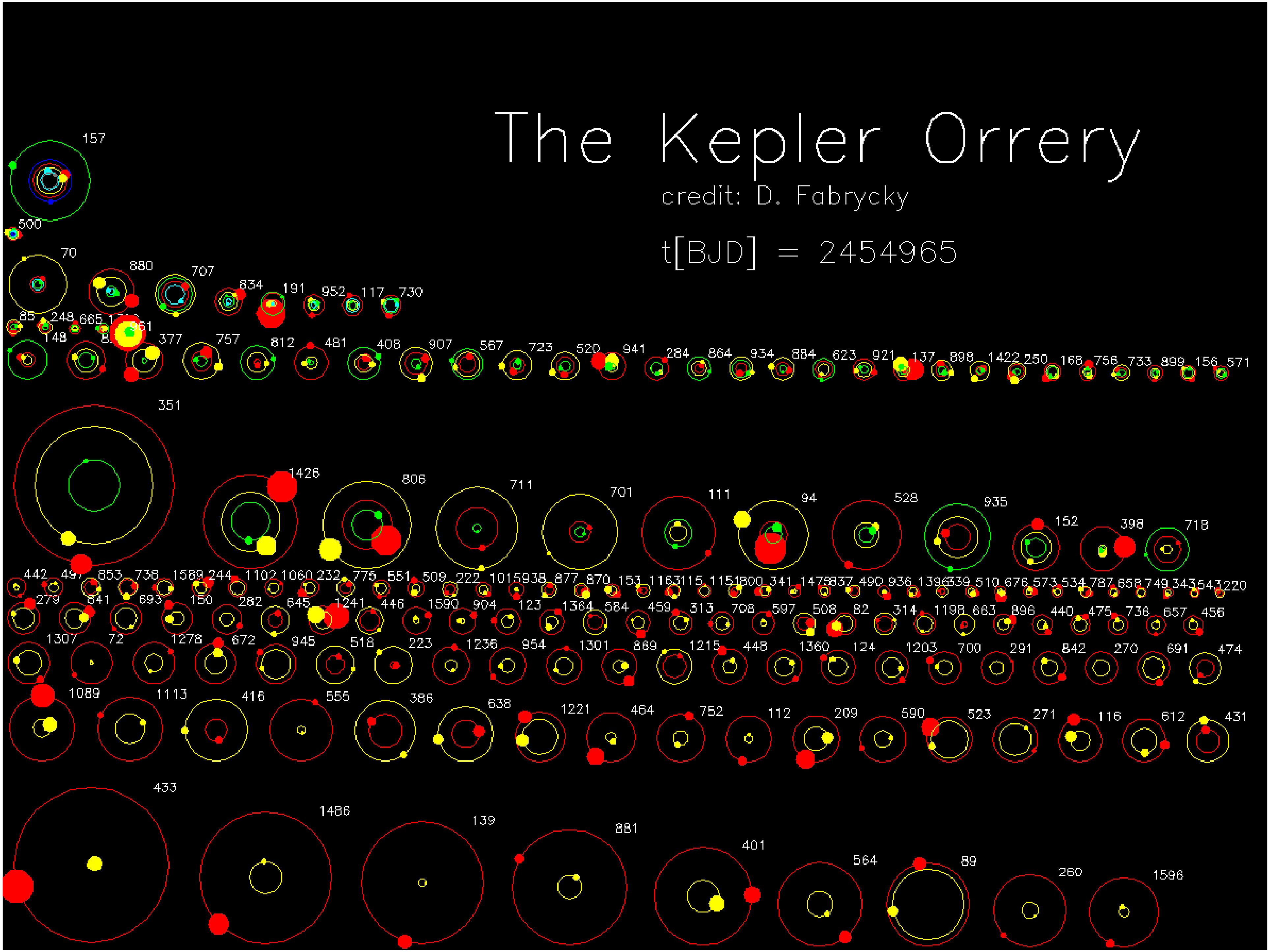


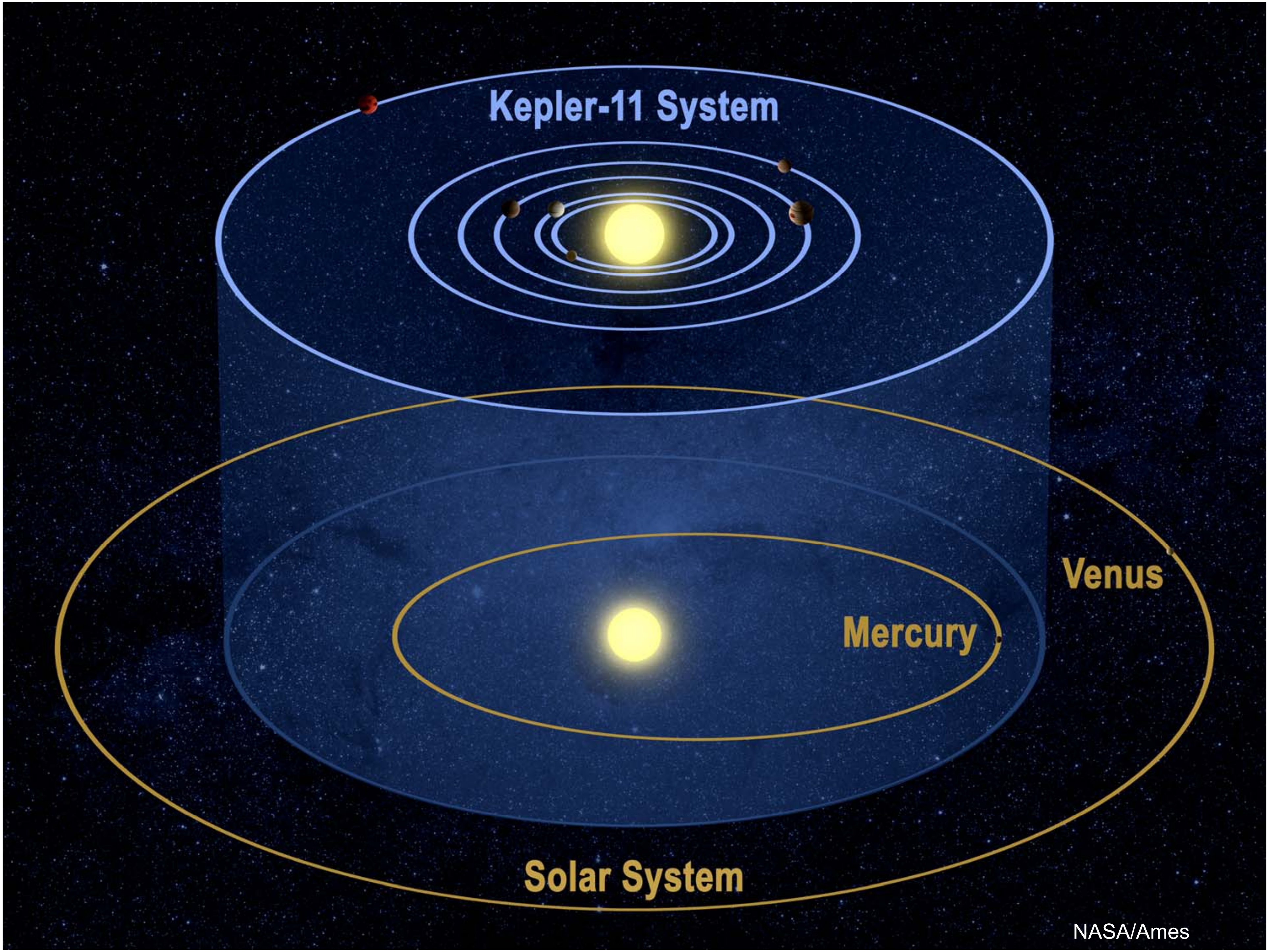
NASA/Ames

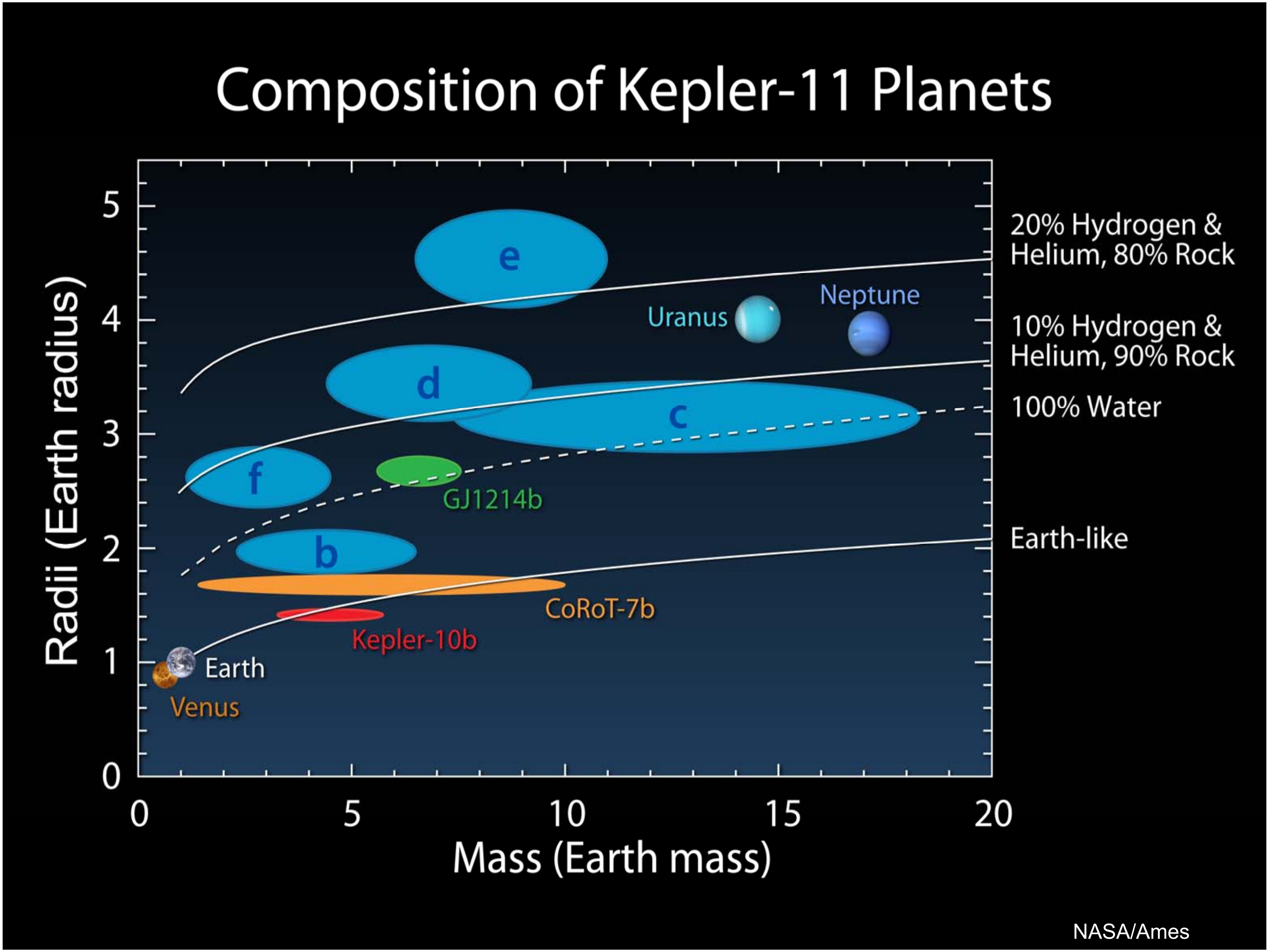
Kepler’s Abundance of Riches

Kepler-9 b-d   Kepler-10b   Kepler-11 b-g



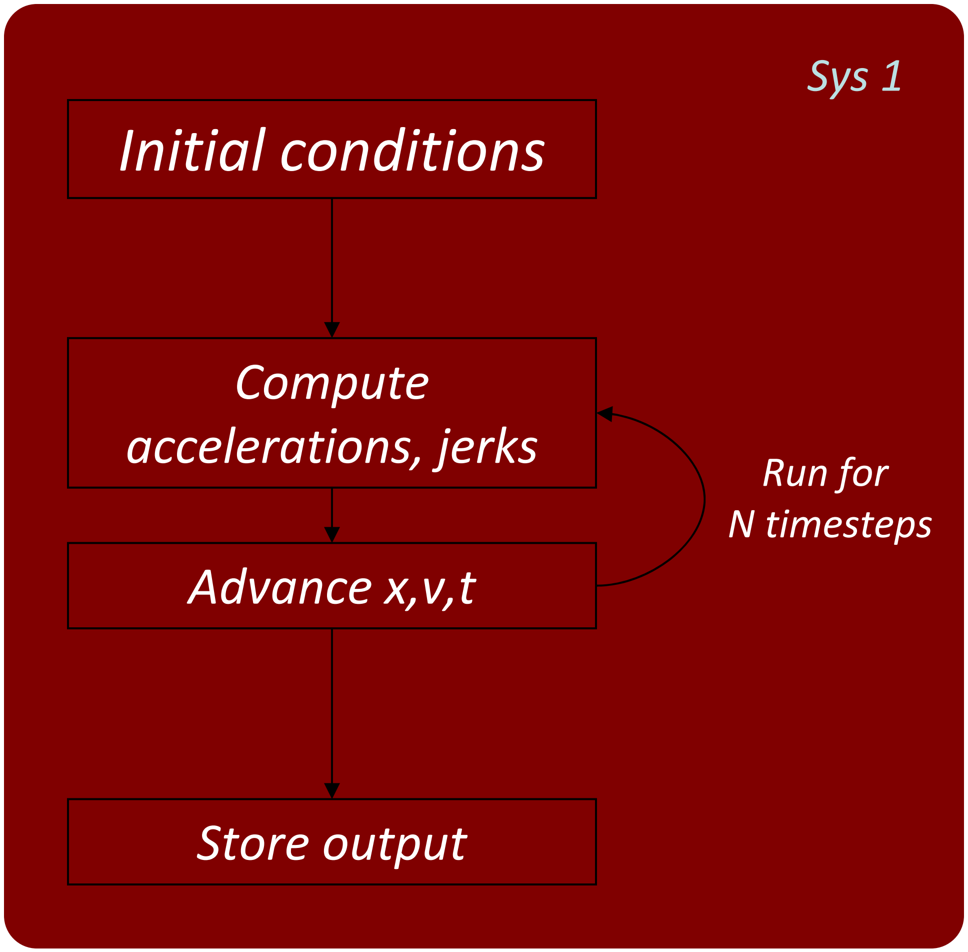

The Kepler Orrery
credit: D. Fabrycky
t[BJD] = 2454965


Kepler-11 System
Venus
Mercury
Solar System
NASA/Ames

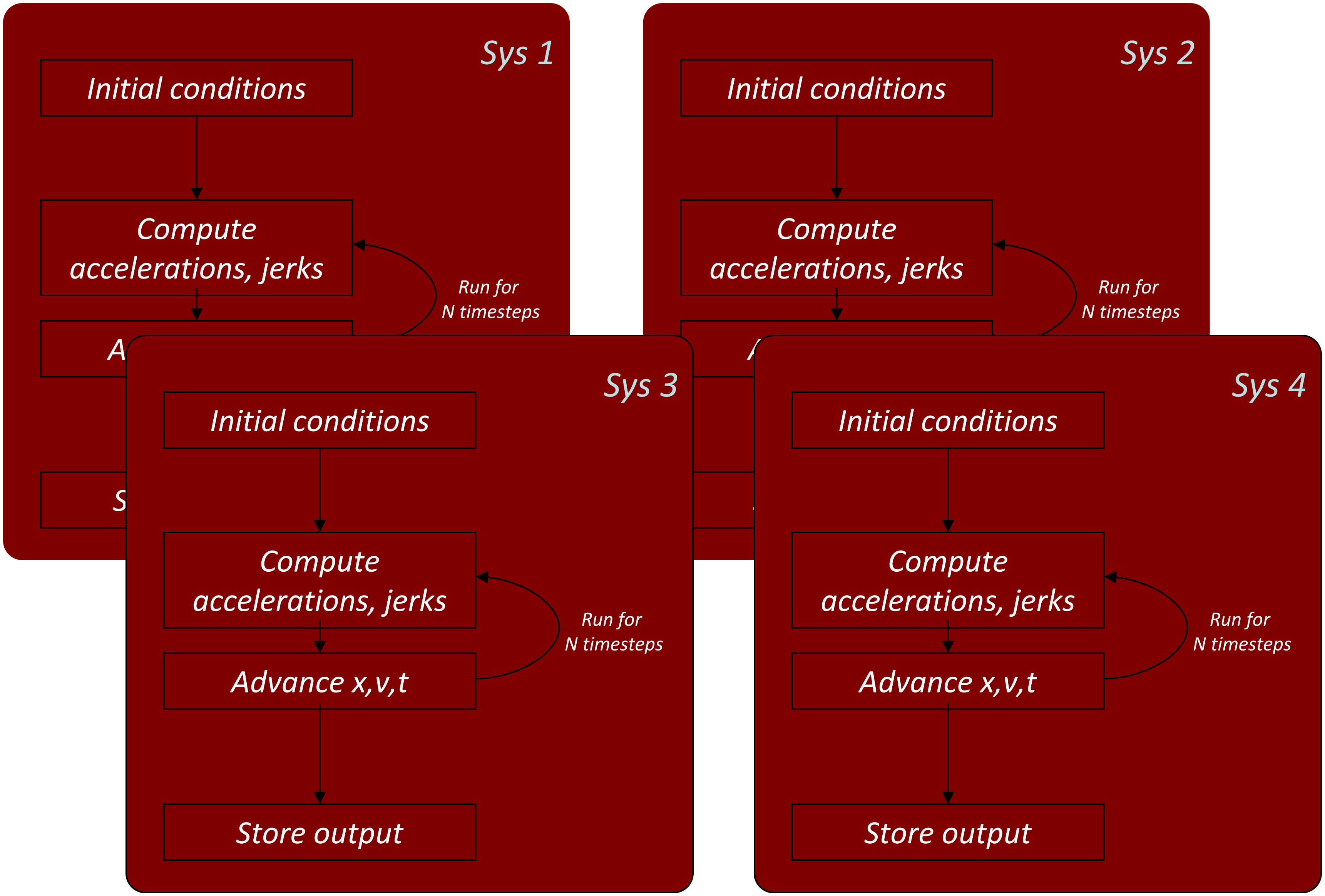


Composition of Kepler-11 Planets
Radii (Earth radius)
Mass (Earth mass)
0
1
2
3
4
5
0
5
10
15
20
e
d
c
f
b
GJ1214b
CoRoT-7b
Kepler-10b
Earth
Venus
Uranus
Neptune
20% Hydrogen & Helium, 80% Rock
10% Hydrogen & Helium, 90% Rock
100% Water
Earth-like
NASA/Ames

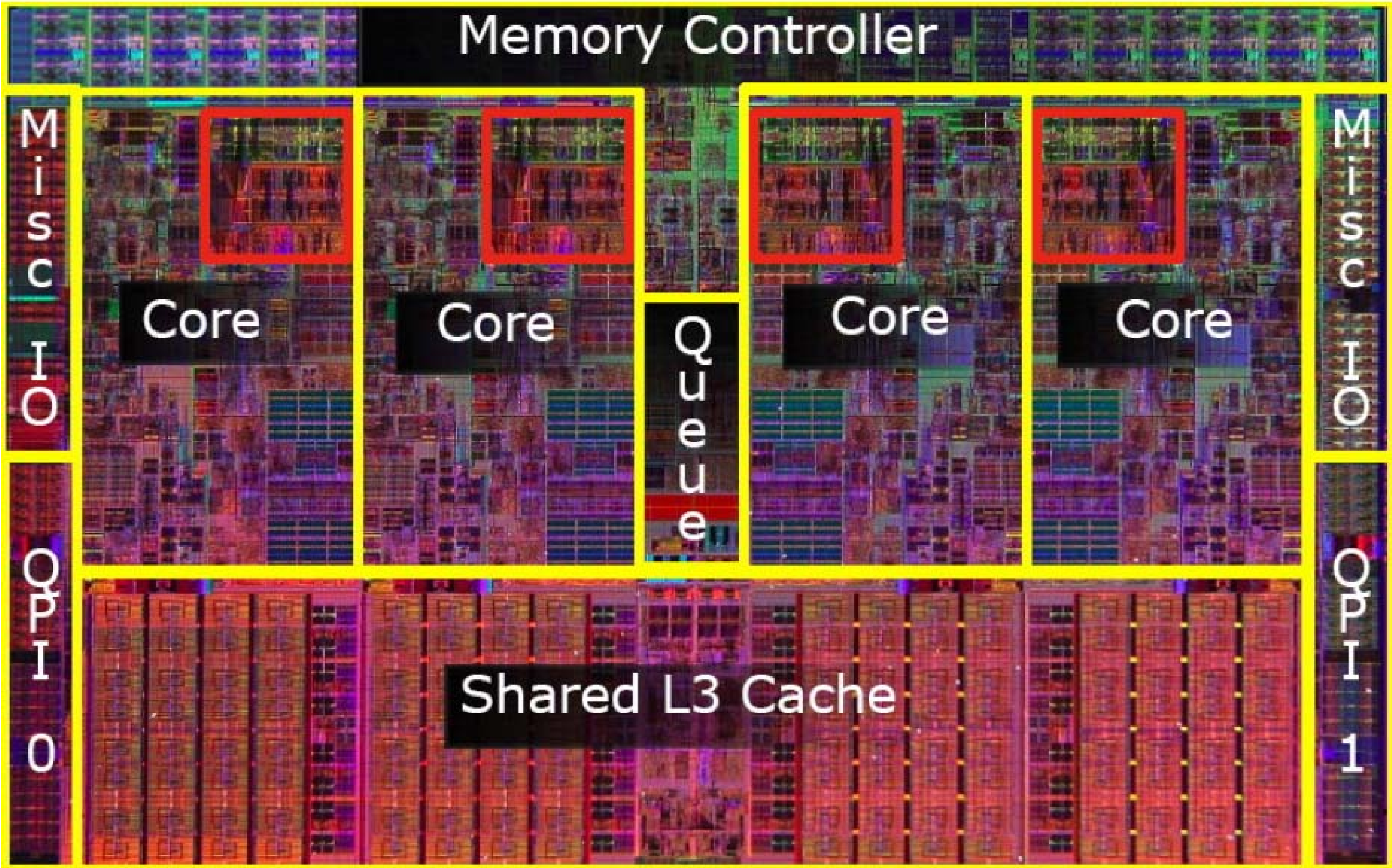
A Simple CPU Implementation



CPU parallelization (trivial: run N=N_{cores} jobs at a time)



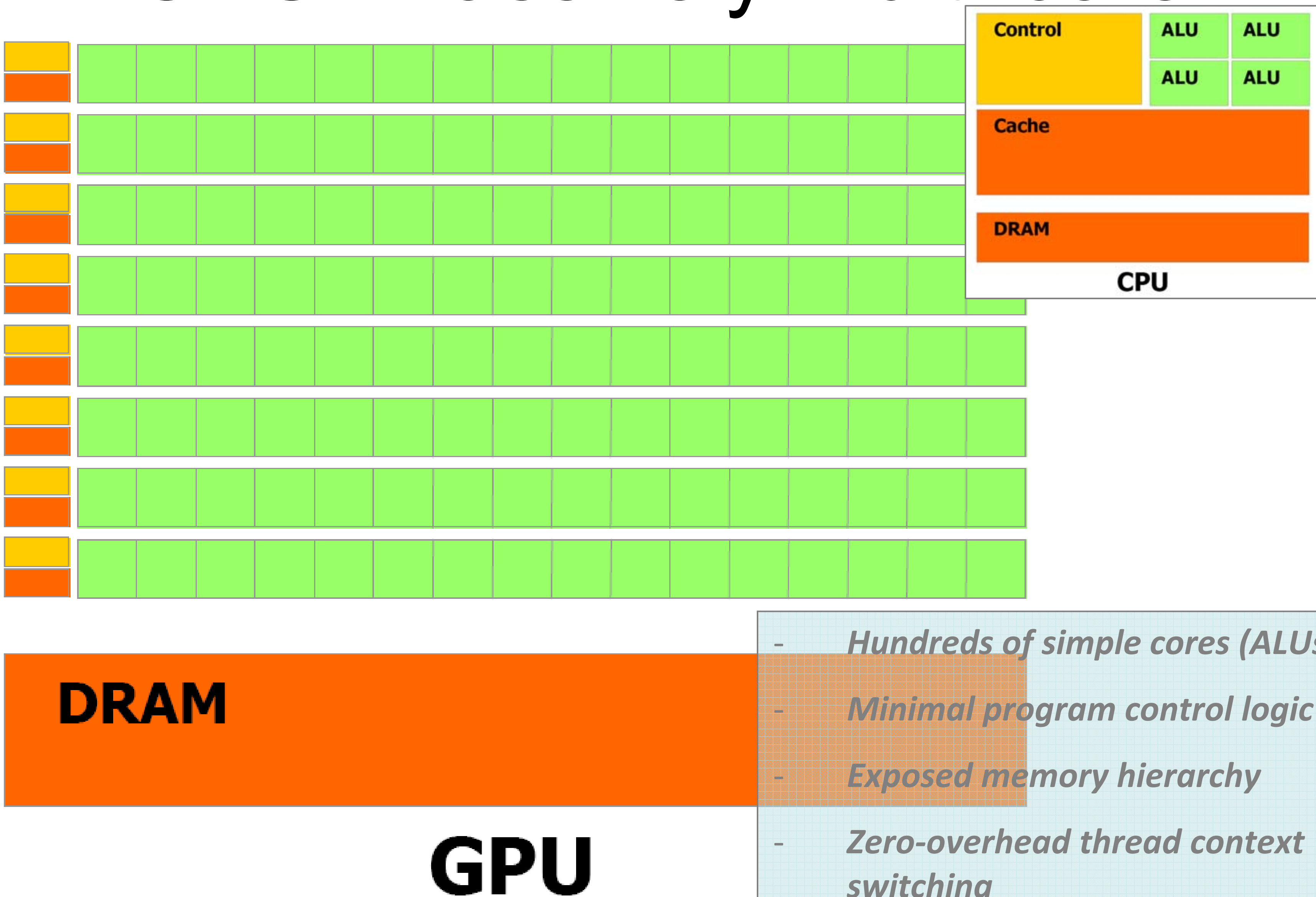
What is in a Intel Core i7?



~0.1% Devoted to Floating Point Arithmetic!

Intel Corp.

GPU: Massively Multi-core

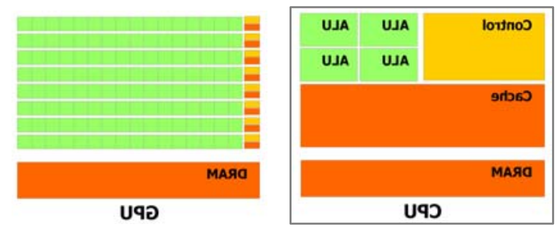


- Hundreds of simple cores (ALUs)
- Minimal program control logic
- Exposed memory hierarchy
- Zero-overhead thread context switching

NVIDIA Corp.

GPU Design: Graphics Processing Units Heritage

- All cores execute the same program on different data
  - Process large streams of data with small, independent, arithmetic intensive, programs
    - E.g., transforming the pixels of an image
    - Transforming geometry in 3D games
    - Shading polygons 3D games



NVIDIA Corp.

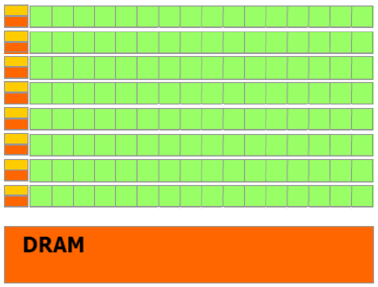
- Lots of raw computational power
    - 80% of GPU transistors are devoted to math
    - Fast basic arithmetic
    - Hardware implementation of common transcendental functions (e.g., sin, cos, exp, ln, …)

- Excellent overlap with needs of typical scientific codes

GPU Challenges

- Programming (human time overhead)
- Is problem highly parallelizable?
- Branching (special cases, collisions, binaries, etc.)
- Memory latency (want lots of computation on relatively few numbers)
- CPU <-> GPU Data Transfers
- Speed up kernel by x100, other parts of code become significant
- Keeping up with the times (new architectures)

Simiple GPU parallelization
(slightly nontrivial: $N \sim 16 \times N_{cores}$ jobs in 1 process)



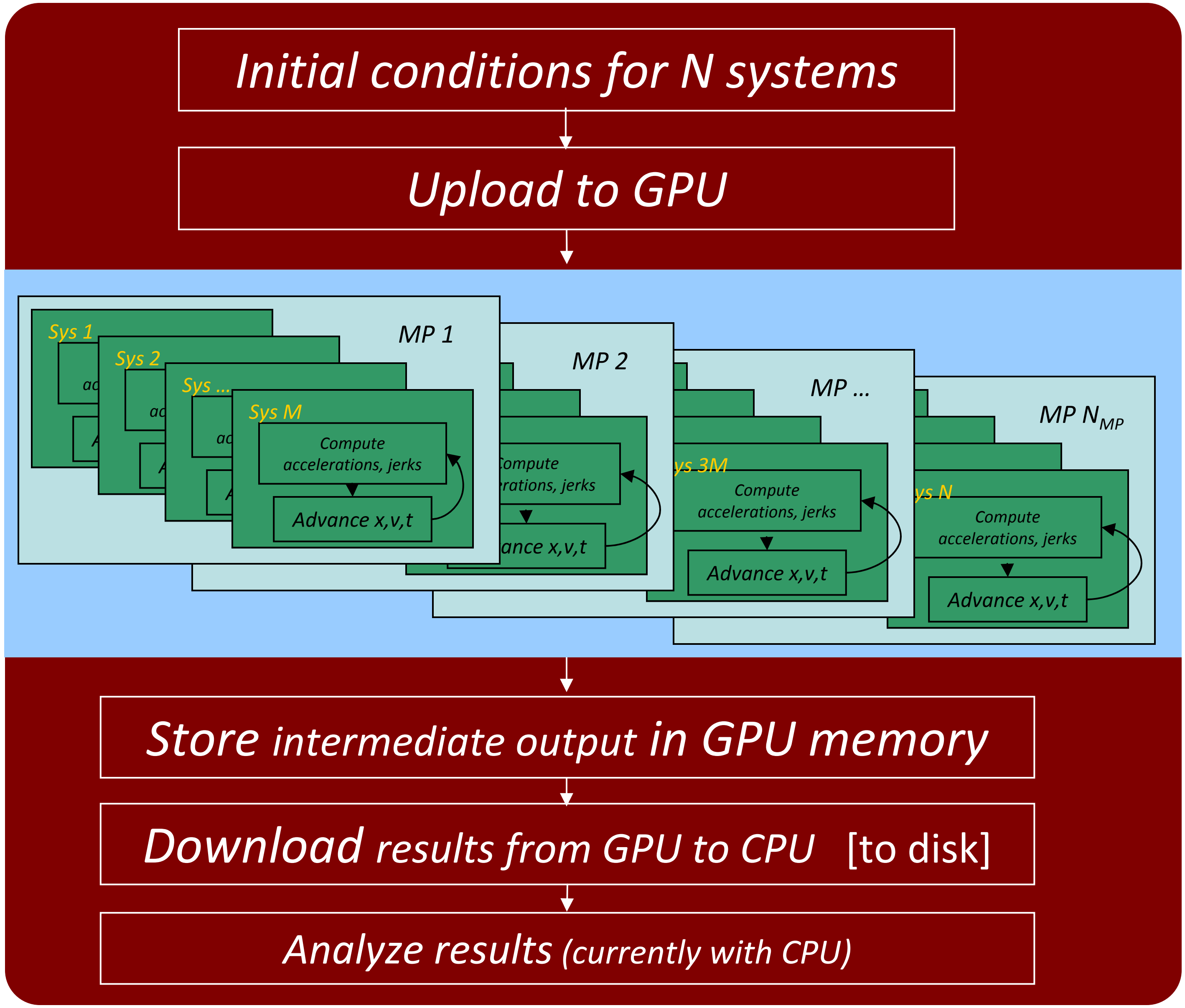
Separate device

All cores run the same program

Easy to parallelize as 1 system/thread

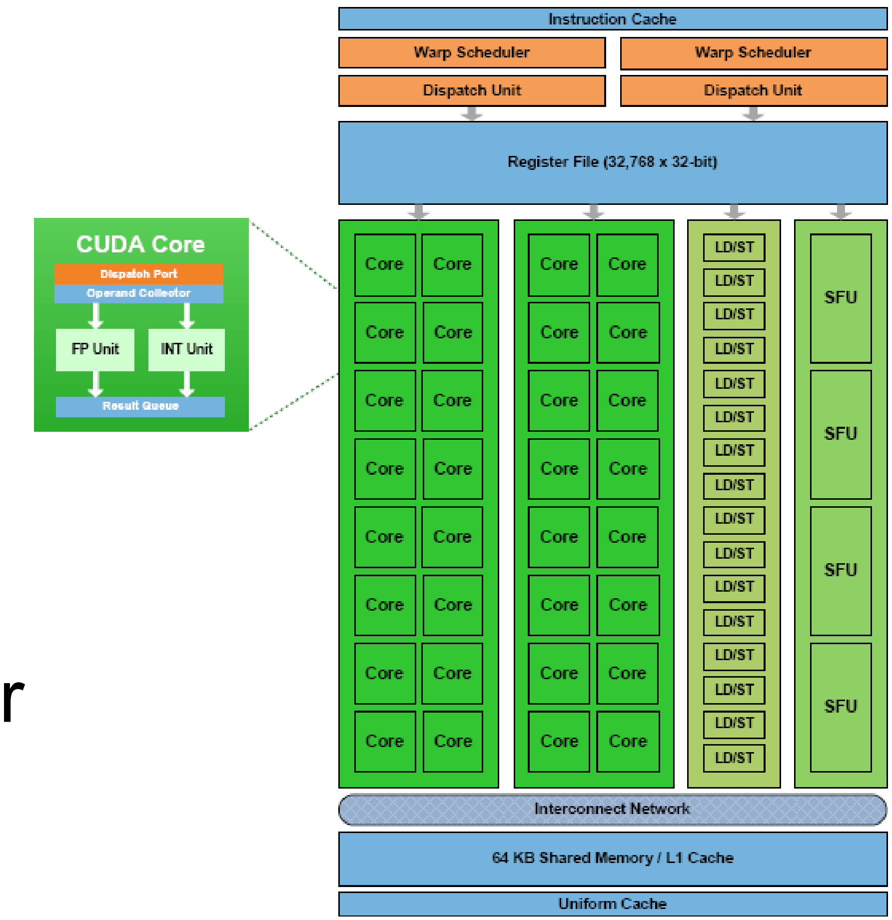
Pack N>4,000 jobs into 1 process to hide memory latency & achieve large speed-ups

Simple integration algorithms



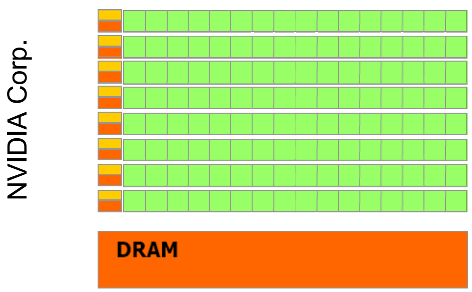
GPUs keep getting better: Fermi

- “Upto 8x faster double precision” (750 GFLOPS)
- 512 (vs 240) cores
- 4 Special Function Units per multiprocessor (vs 1)
- Increase shared memory
- On GPU memory cache
- Atomic ops 5-20x faster
- Fewer registers per core
- Favors algorithms w/ finer grained parallelization



NVIDIA Corp.

High Performance GPU parallelization (challenging: $N \sim few \times N_{cores}$ jobs in 1 process)

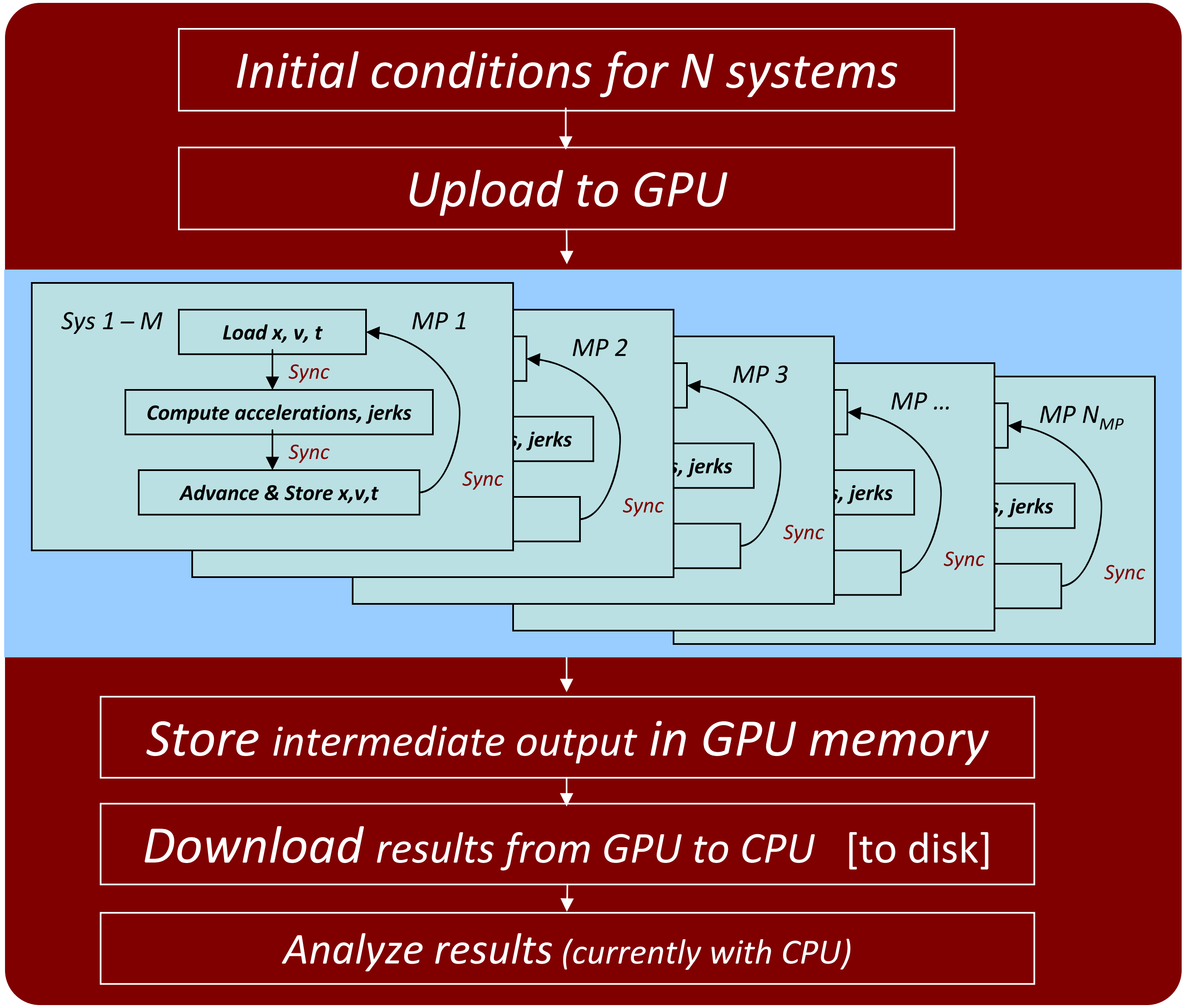


All multiprocessors (MPs) run the same program, each for M systems

Parallelize each step optimally, for finer parallelization

Achieve large speed-ups with only ~1,000 jobs

More complex integration algorithms



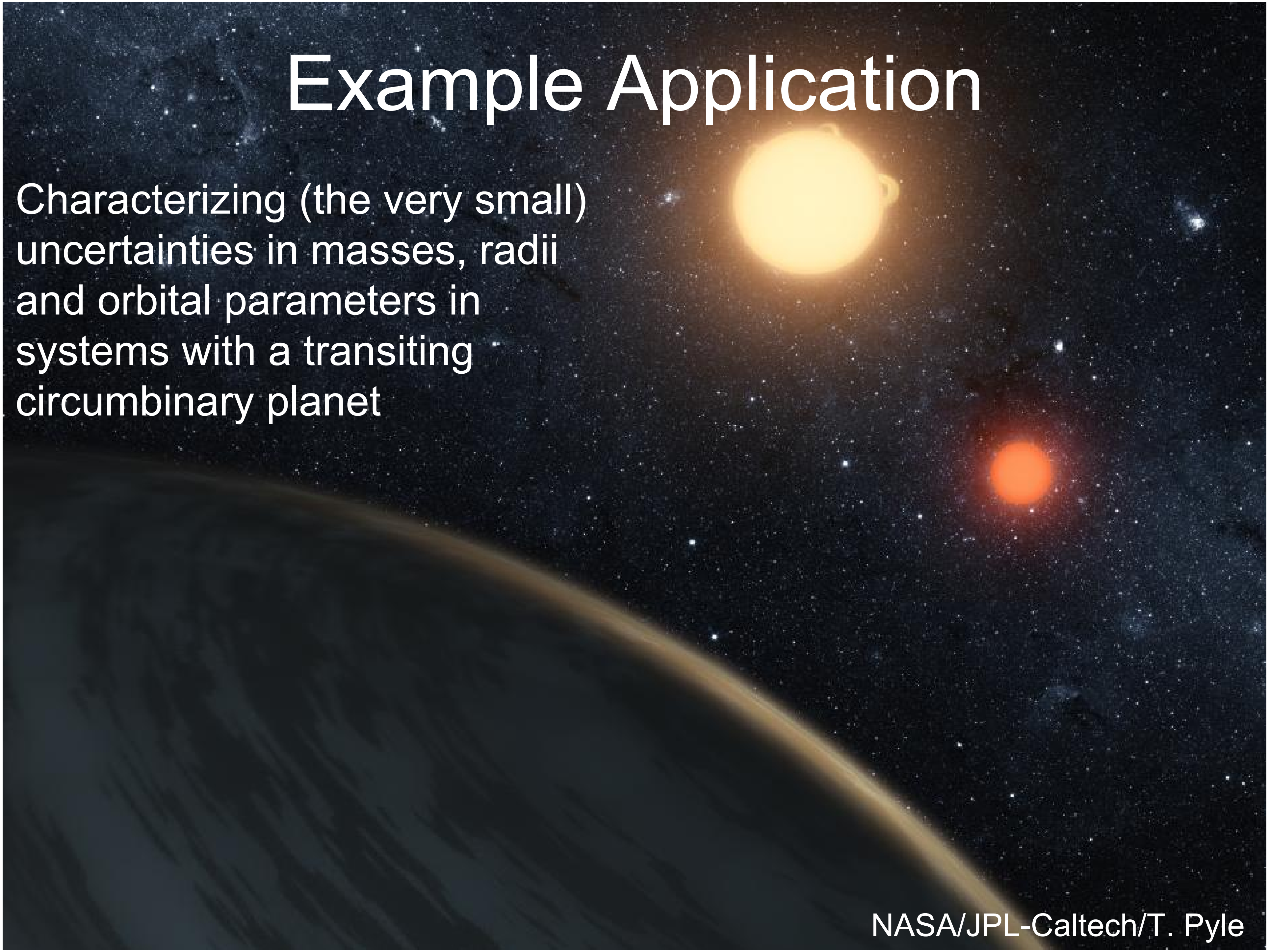
A Moment of Zen…

- “About GPUs, this is NOT…”
- This is about CPUs, 5 years from now
- We must:
  - (Re)learn how to code for 1000-core, shared memory machines
  - Have the basic tools to efficiently use them (e.g., ODE and N-body solvers)

- Obtaining 10-100x speedup NOW doesn’t hurt either ☺
- For more about Swarm-NG http://www.astrogpu.org/

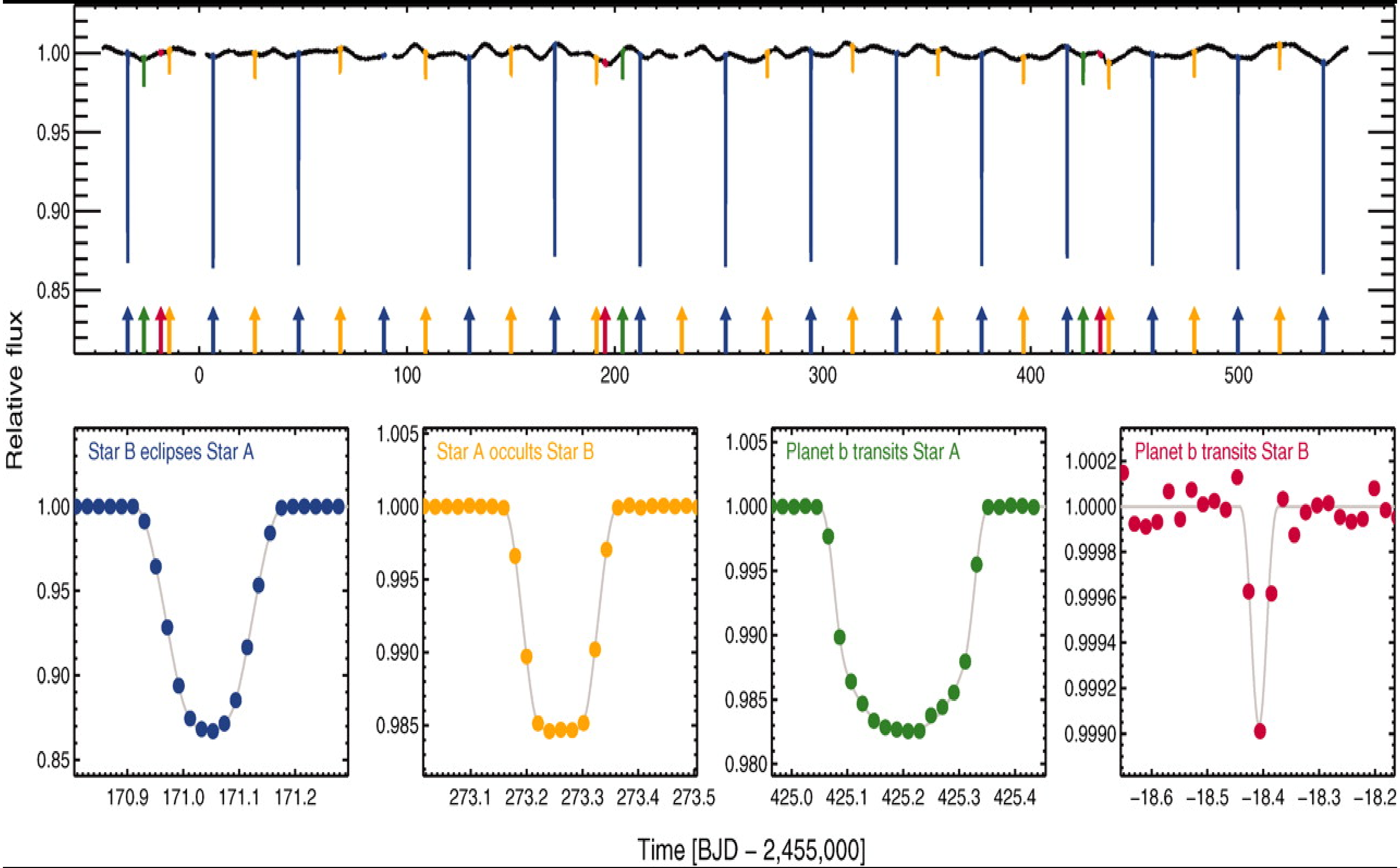
Example Application

Characterizing (the very small) uncertainties in masses, radii and orbital parameters in systems with a transiting circumbinary planet

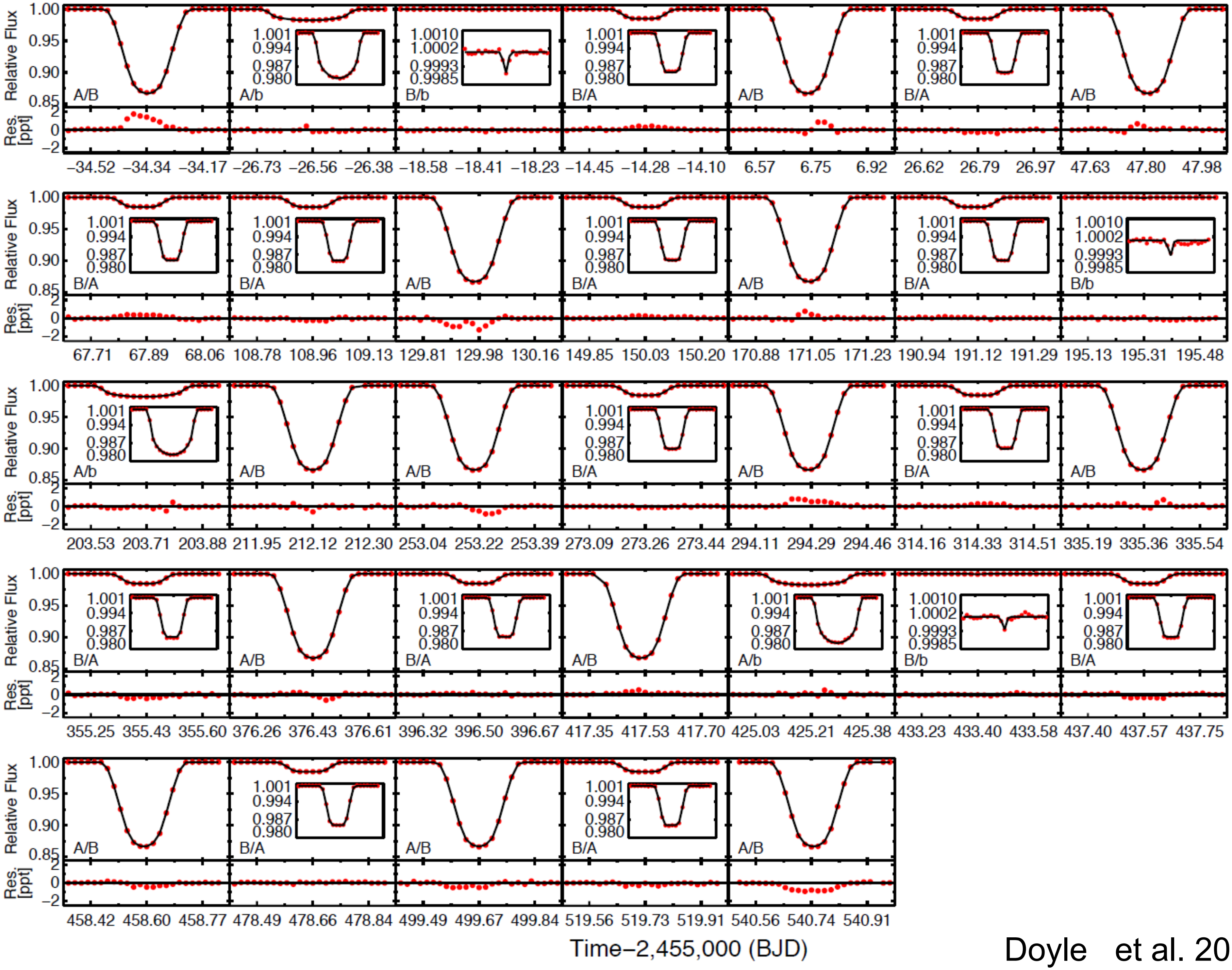


NASA/JPL-Caltech/T. Pyle

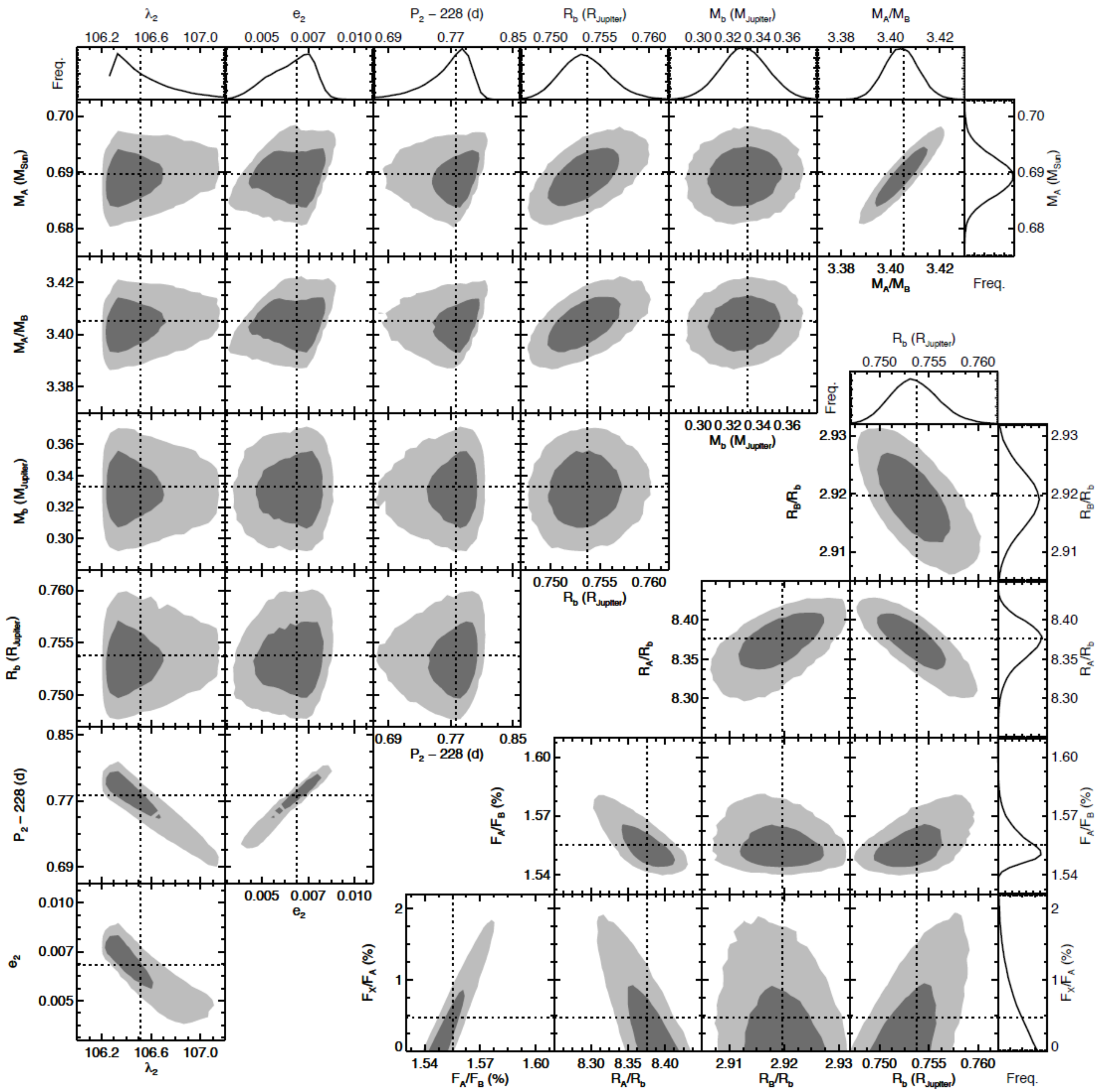
Kepler-16



Doyle et al. 2011



Doyle et al. 2011

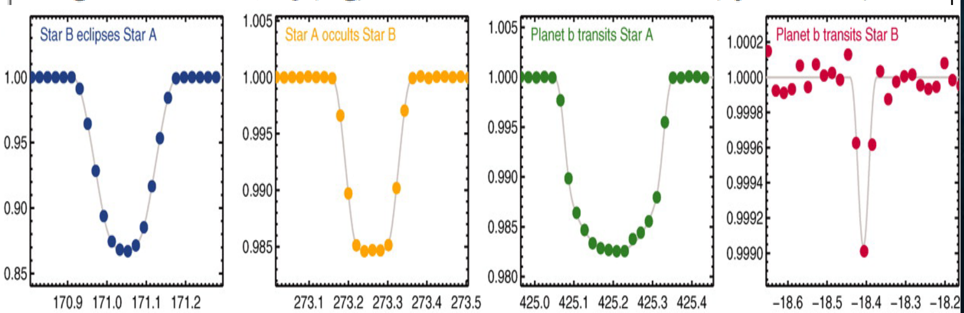


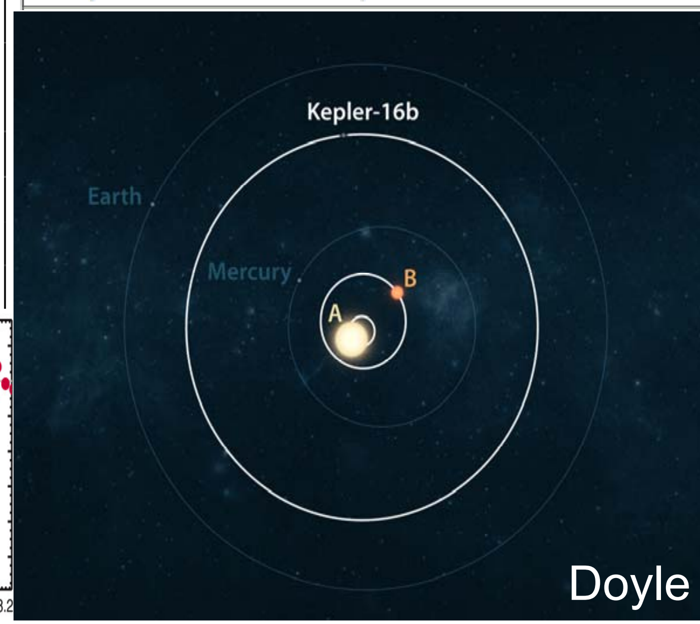
Doyle et al. 2011

Precise Masses & Radii

Parameter	Value and Uncertainty
Star A	
Mass, M_A ($M_\odot$)	$0.6897^{+0.0035}_{-0.0034}$
Radius, R_A ($R_\odot$)	$0.6489^{+0.0013}_{-0.0013}$
Mean Density, ρ_A (g cm^{-3})	$3.563^{+0.017}_{-0.016}$
Surface Gravity, $\log g_A$ (cgs)	$4.6527^{+0.0017}_{-0.0016}$
Effective Temperature, $T_{\rm eff}$ (K)	4450 ± 150
Metallicity, [m/H]	-0.3 ± 0.2
Star B	
Mass, M_B ($M_\odot$)	$0.20255^{+0.00066}_{-0.00065}$
Radius, R_B ($R_\odot$)	$0.22623^{+0.00059}_{-0.00053}$
Mean Density, ρ_B (g cm^{-3})	$24.69^{+0.13}_{-0.15}$
Surface Gravity, $\log g_B$ (cgs)	$5.0358^{+0.0014}_{-0.0017}$
Binary star orbit	
Period, P_1 (day)	$41.079220^{+0.000078}_{-0.000077}$
Semi-major axis length, a_1 (AU)	$0.22431^{+0.00035}_{-0.00034}$
Eccentricity, e_1	$0.15944^{+0.00061}_{-0.00062}$
Argument of Periapse, ω_1 (deg)	$263.464^{+0.026}_{-0.027}$
Mean Longitude, λ_1 (deg)	$92.3520^{+0.0011}_{-0.0011}$
Inclination, i_1 (deg)	$90.3401^{+0.0016}_{-0.0019}$
Longitude of Nodes, Ω_1 (deg)	$\equiv 0$ (by definition)

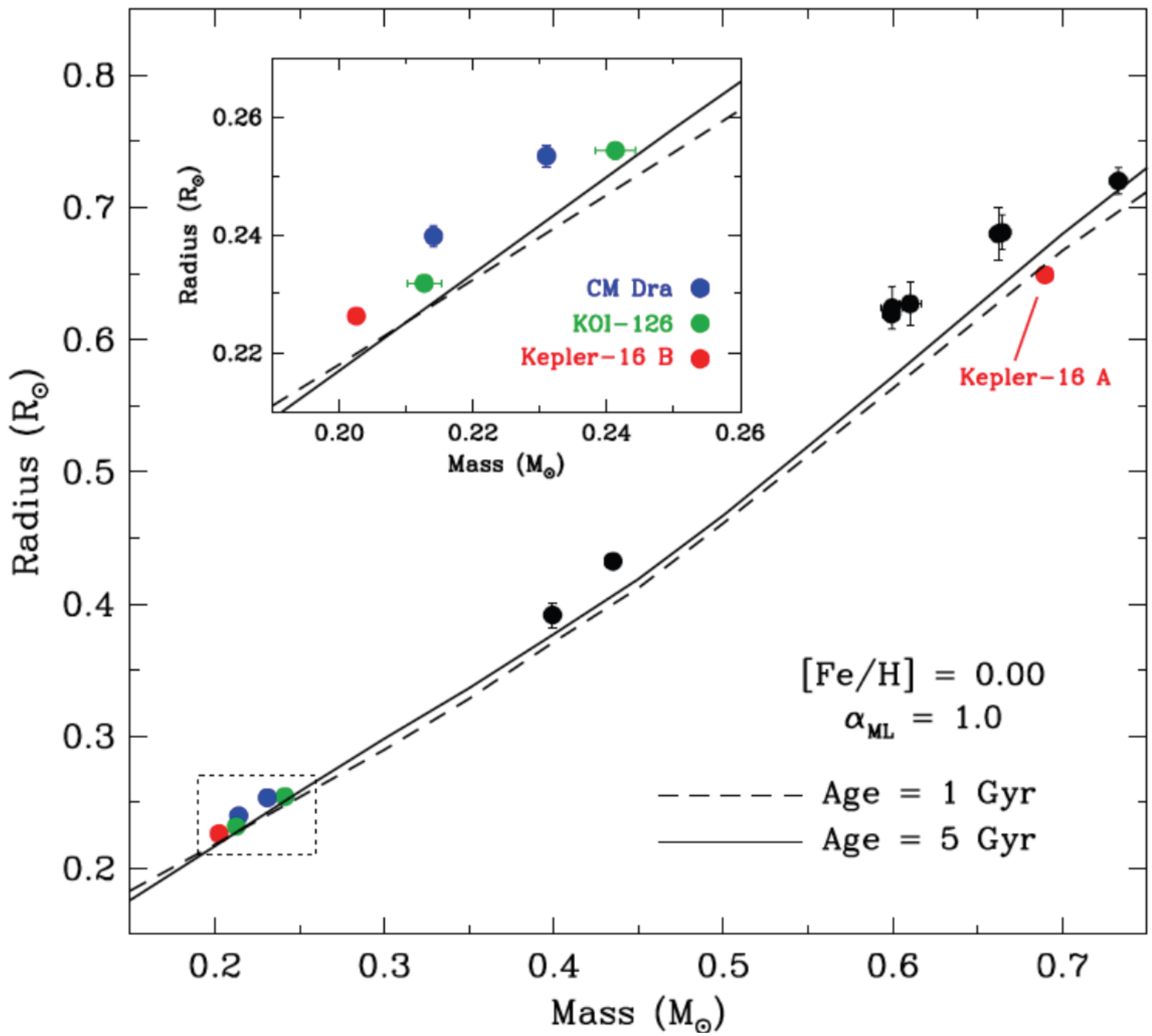
Parameter	Value and Uncertainty
Planet b	
Mass, M_b ($M_{\rm Jupiter}$)	$0.333^{+0.016}_{-0.016}$
Radius, R_b ($R_{\rm Jupiter}$)	$0.7538^{+0.0026}_{-0.0023}$
Mean Density, ρ_b (g cm^{-3})	$0.964^{+0.047}_{-0.046}$
Surface Gravity, g_b (m s^{-2})	$14.52^{+0.70}_{-0.69}$
Circumbinary planet orbit	
Period, P_2 (day)	$228.776^{+0.020}_{-0.037}$
Semi-major axis length, a_2 (AU)	$0.7048^{+0.0011}_{-0.0011}$
Eccentricity, e_2	$0.0069^{+0.0010}_{-0.0015}$
Argument of Periapse, ω_2 (deg)	$318.^{+10.}_{-22.}$
Mean Longitude, λ_2 (deg)	$106.51^{+0.32}_{-0.16}$
Inclination, i_2 (deg)	$90.0322^{+0.0022}_{-0.0023}$
Longitude of Nodes, Ω_2 (deg)	$0.003^{+0.013}_{-0.013}$





Doyle et al. 2011

Exquisite Precision in Mass & Radius



Winn et al. 2011

Questions