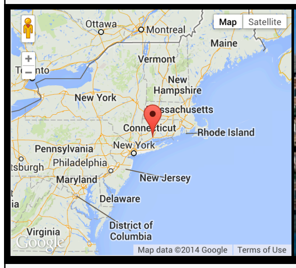
HELIOPHYSICS

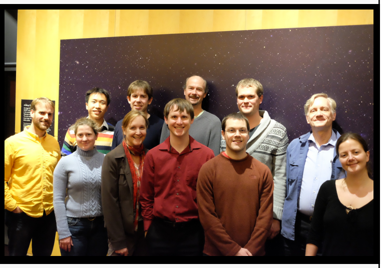
VSP UCAR Visiting Scientist Programs

I. Characteristics of Planetary Systems

II. Insights into Formation

Debra Fischer
Yale University





What does the ensemble of exoplanets tell us about planet formation?

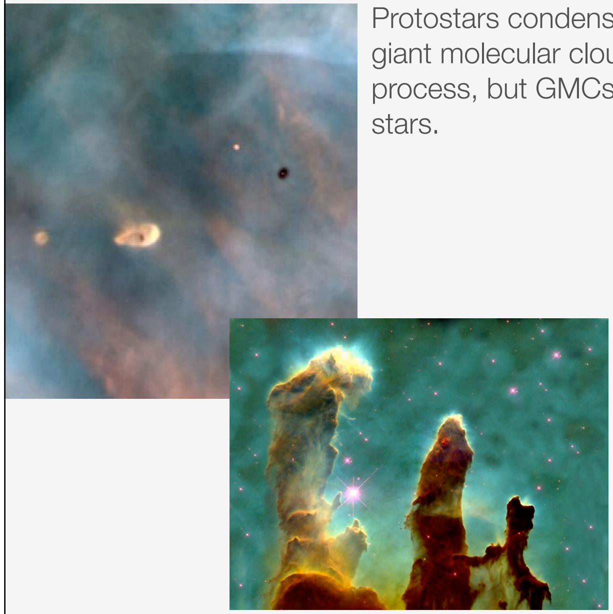
How do exoplanets compare with the solar system?

Do we know η_{EARTH}?

Solar Nebula model

How has the discovery of so many exoplanets impacted our understanding of planet formation?

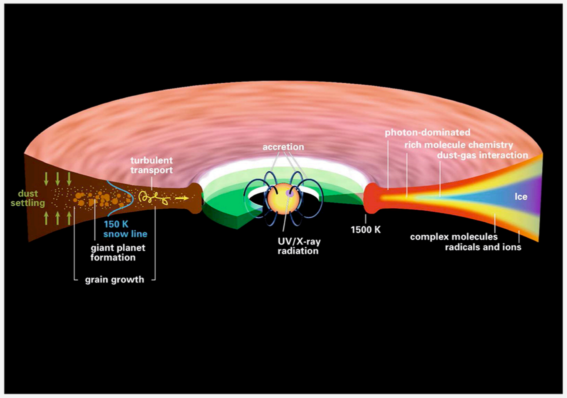
Describe the solar nebula model.
What features of our planetary architecture does this model explain?



Protostars condense (Rayleigh-Jeans criteria) from giant molecular clouds (GMCs). Not a very efficient process, but GMCs can give birth to ~100,000 stars.

The GMC is sculpted by the rapid evolution of massive stars. They contract to the MS and end their short lives (10 Myr) as supernovae, clearing out dust in the GMC as solar type stars are still contracting.

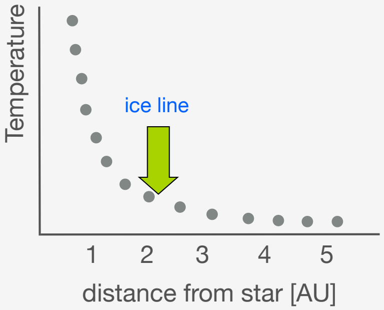
Planet formation theory

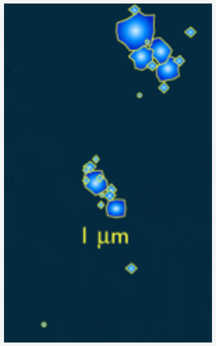


Theory about disk evolution is poorly constrained by observations. This should change with ALMA observations.

Theoretical evolution of the disk (Class II):

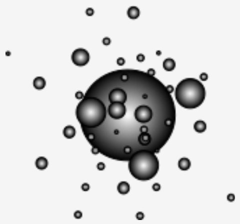
- Dust settles toward midplane, increasing transparency of disk
- Gas becomes hotter than the dust in elevated regions
- Inner disk is too hot for grain growth (~1500K)
- A few AU from the protostar, the disk midplane is cool enough for icy grains to stick and grow.
- gradual clearing of the disk from the upper layers (which shade the midplane) and the inner disk.



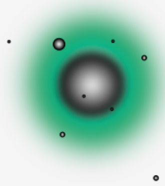


Temperature matters!
Beyond the ice line, grains stick and become the building blocks of planets - planetesimals.

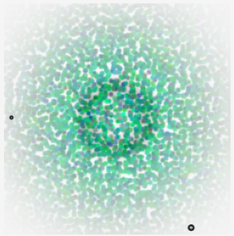
Gas Giant Planet Formation.



Phase I. The growing planet consists mostly of solid material. The planet experiences runaway accretion until the feeding zone is depleted. Solid accretion occurs much faster than gas accretion during this phase.

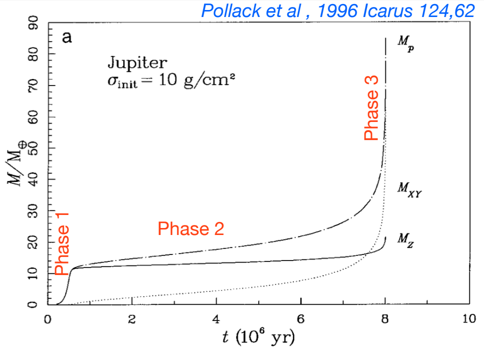


Phase 2. Both solid and gas accretion rates are slow and nearly time independent. This phase governs the overall accretion timescale.

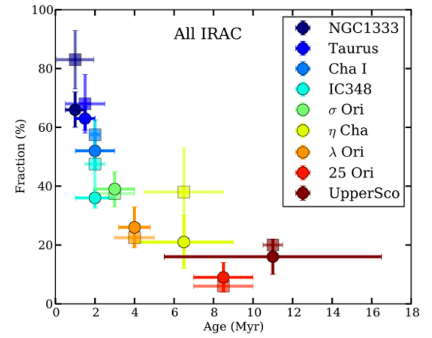


Phase 3. Once the core reaches a mass of ~10 MEarth, runaway gas accretion begins; gas accretion outpaces the accretion of rocky material.

Pollack et al , 1996 Icarus 124,62



The model

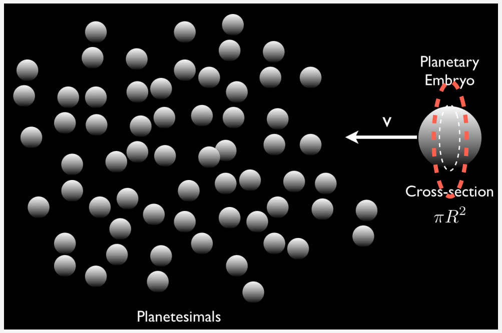


The problem

(disks don't last long enough to reach Phase 3)

The solution: evidence for orbital migration, observed in the ensemble of exoplanets - migration would provide additional feeding zone for more rapid growth and shorter Phase 2.

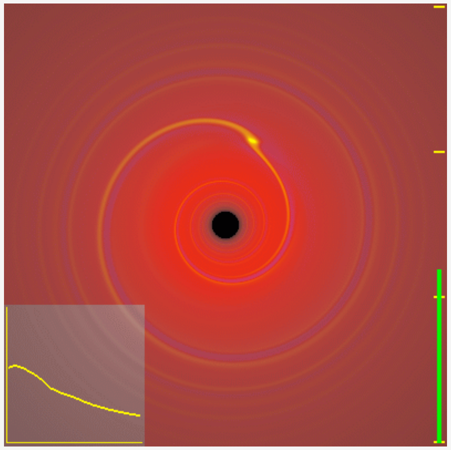
Phase I.



$$\dot{m}_{ij} = \sigma_{ij}\rho_j\delta v_{ij}$$

Planetesimal growth is a “just so” story with convergence to larger particle size as embryo passes through a swarm of planetesimals.

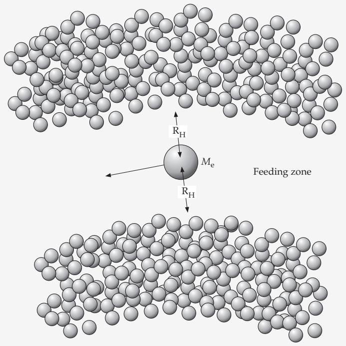
Small guys commonly hit small guys and double their mass. Bigger embryos are rare so the fractional dm/dt is small until gravitational focusing kicks in.



Type 1 migration: planet embedded in the disk (too small to clear a gap); resonances between difference of Keplerian velocities and pattern speed (Linblad resonance) excite spiral wakes in the disk.

The disk structure exerts a torque on the growing protoplanet. Typically, the outer disk is more massive and exerts a larger torque, moving the protoplanet inward. However, outward migration is also predicted.

Phase 2.



The endpoint of solid growth occurs when the embryo has gathered all planetesimals within the gravitationally focused reach.

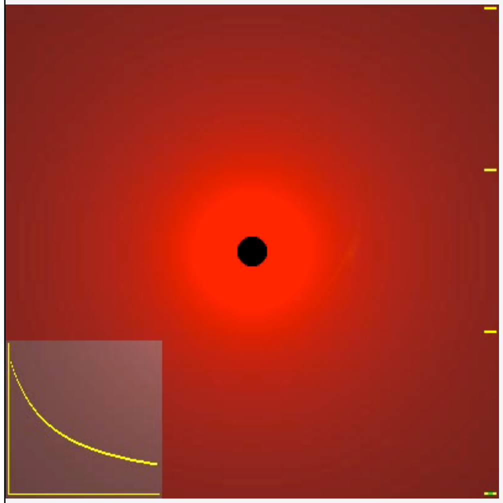
Outside of this maximum "zone of influence" orbits around the embryo are unstable due to tidal effects of the star - this defines the "Hill sphere radius"

$$R_H = a_e\left(\frac{M_e}{3M_*}\right)^{1/3}$$

$a_e =$ *orbital radius of embryo*

Hill sphere radius is the region where gravitational effects from the planet (embryo) dominate over the star.

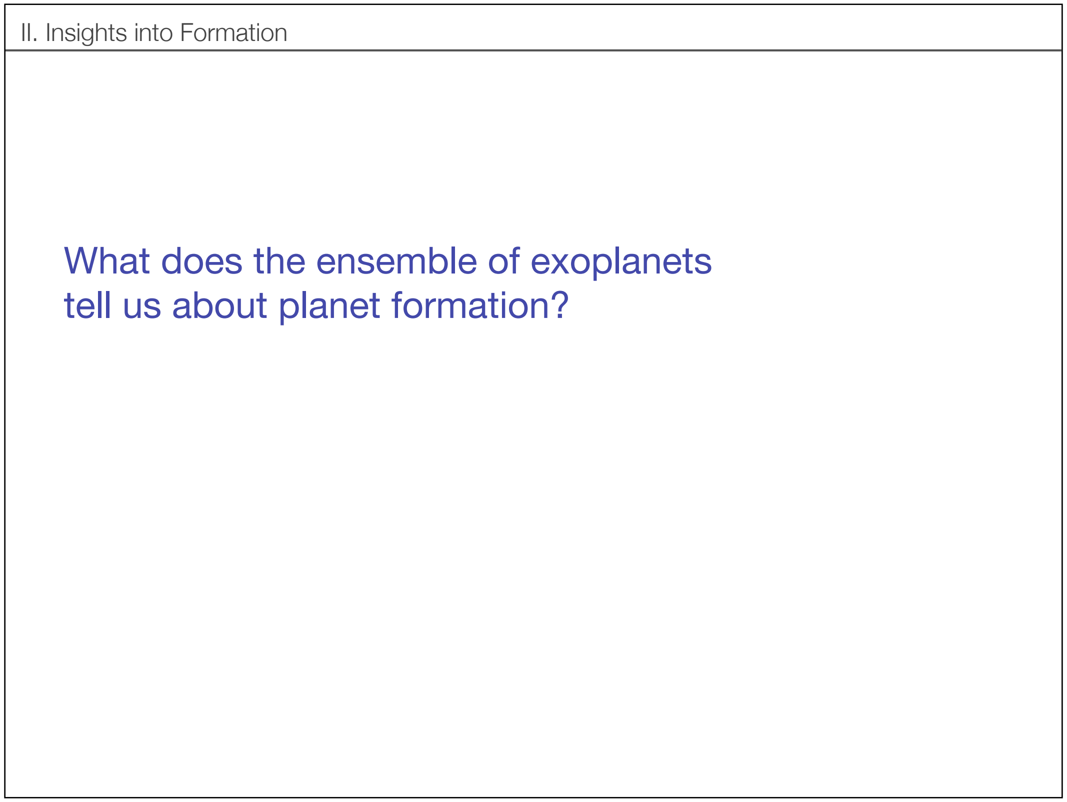
Often the condition for accretion used by theorists; particles in N-body simulations are accreted if they come within a Hill radius.



Disks evolve from Type I to Type II.

Type II migration: planet clears a gap in the disk, the aerodynamic drag disappears.

Do migrating planets sweep up most interior planets?
What stops migration?



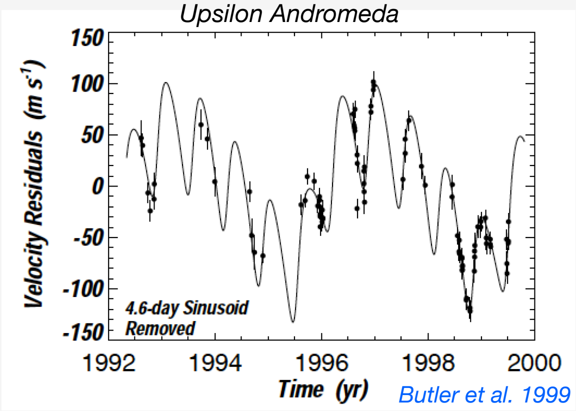
II. Insights into Formation

What does the ensemble of exoplanets tell us about planet formation?

In fact, the pile-up is sharper than seen here.

Large population of planets with periods between 2-3 d, not clear why there should be such a sharp peak here.

1. Planets migrate and end up in “packed” configurations.



Butler et al. 1999

Three coherent signals:

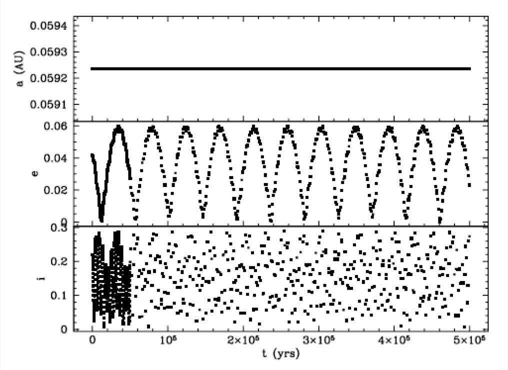
P_b = 4.6171d
$M_b$sini = 0.72 M_{Jup}

P_c = 242 d
$M_c$sini = 1.98 M_{Jup}

Orbital migration

P_d = 1270 d
$M_d$sini = 4.11 M_{Jup}

Rivera & Lissauer (2000) carried out dynamical simulations to place constraints on eccentricity, sin i, mutual inclination, additional (undetected) planets.



Rivera & Lissauer (2000)

Numerical integration of Ups And b; stable for 500,000 yrs and eccentricity oscillates between 0 and 0.06.

Exoplanet insights: dynamical fullness

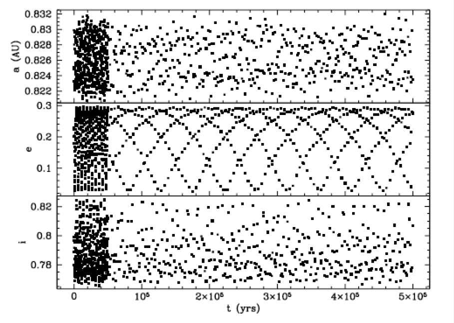


FIG. 1c

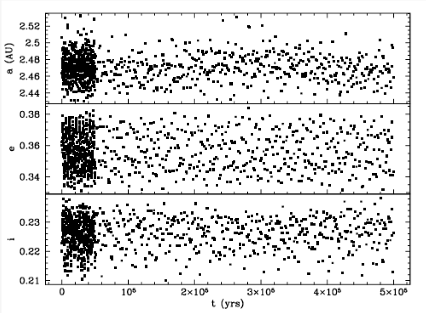


FIG. 1d *Rivera & Lissauer (2000)*

Ups And c, ecc 0 - 0.3

Ups And d, ecc 0.34 - 0.38

Do our solar system planets show a time-varying exchange of orbital eccentricity?

Exoplanet insights: dynamical fullness

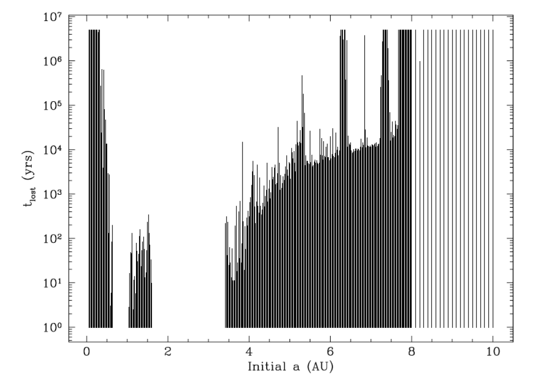


FIG. 4a

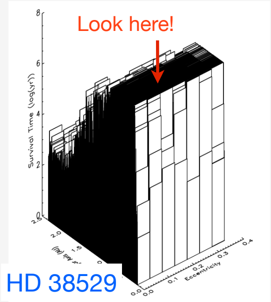
Rivera & Lissauer (2000) also placed test particles on circular orbits at intervals of 0.02 AU between planets b and d (and every 0.2AU beyond d out to 8AU) in the Ups And planetary system.

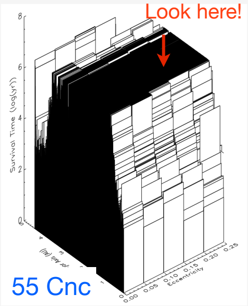
All test particles were lost in 10^8 years, leading them to conclude that the current system was dynamically full and additional planets were unlikely in the inner 8 AU of this system.

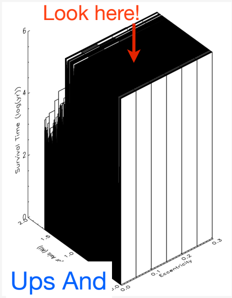
Is our own solar system dynamically packed?

(meaning that it is not likely that additional planets could be dropped into the s.s. and survive in stable orbits)

Exoplanet insights: dynamical fullness







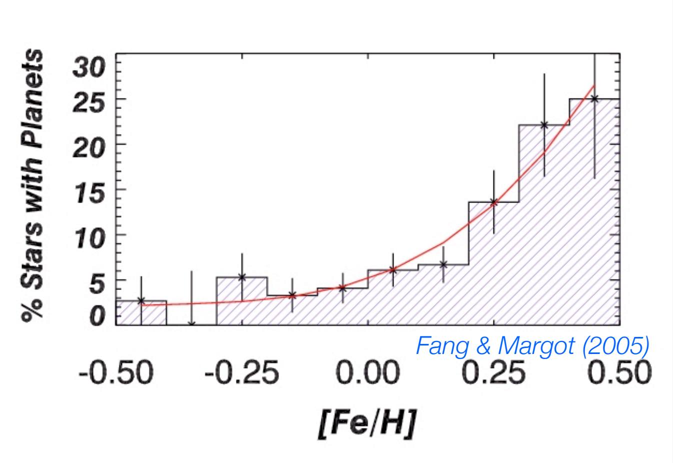
Barnes & Raymond (2004)

Searched known multi-planet systems (Doppler detections) for dynamically stable zones where exoplanets might survive.

Hypothesis: planet formation is an efficient process that leads to packed planetary systems (PPS).
Test: run numerical integrations with test particles at steps of 0.002 AU and eccentricity steps of 0.05.

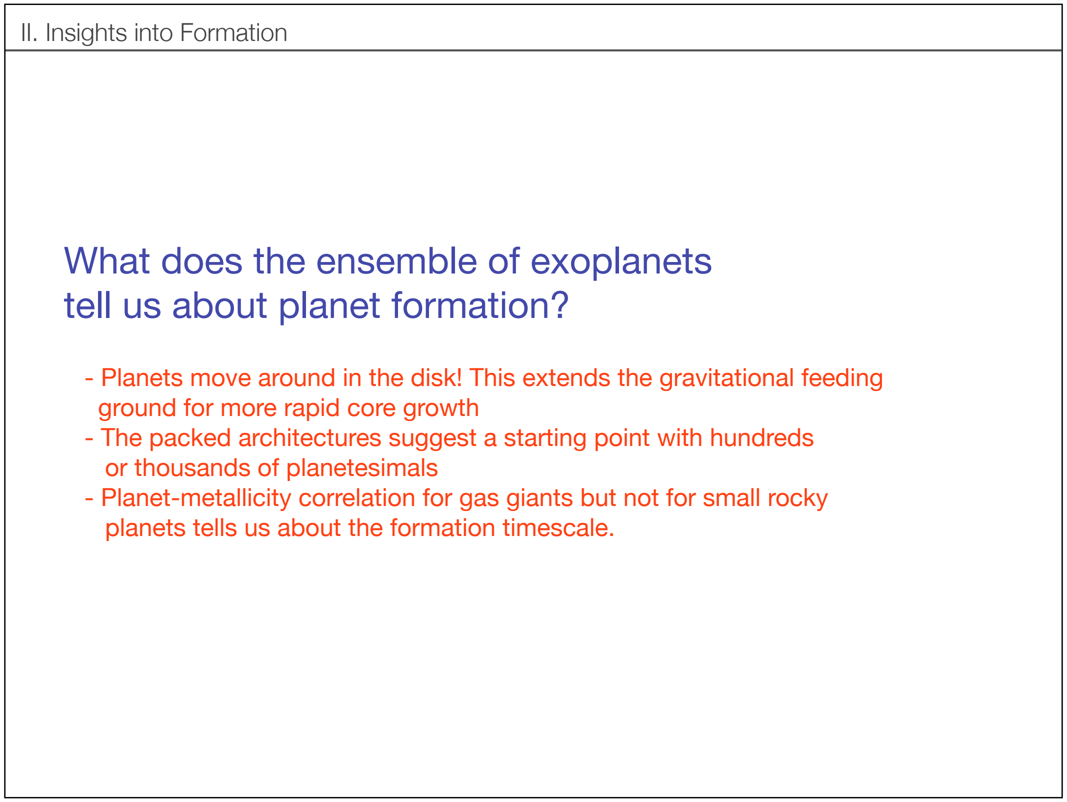
Finding: three of the multi-systems had regions where test particles survived longer than 10 Myr. However, they had not accounted for planet-planet interactions, which further destabilized the “empty” zones.

2. Planet-metallicity correlation.



Fang & Margot (2005)

Planet-metallicity correlation: metals increase the surface density at the midplane of the protoplanetary disk, accelerating the accretion rate so that cores form while gas is still present in the disk.



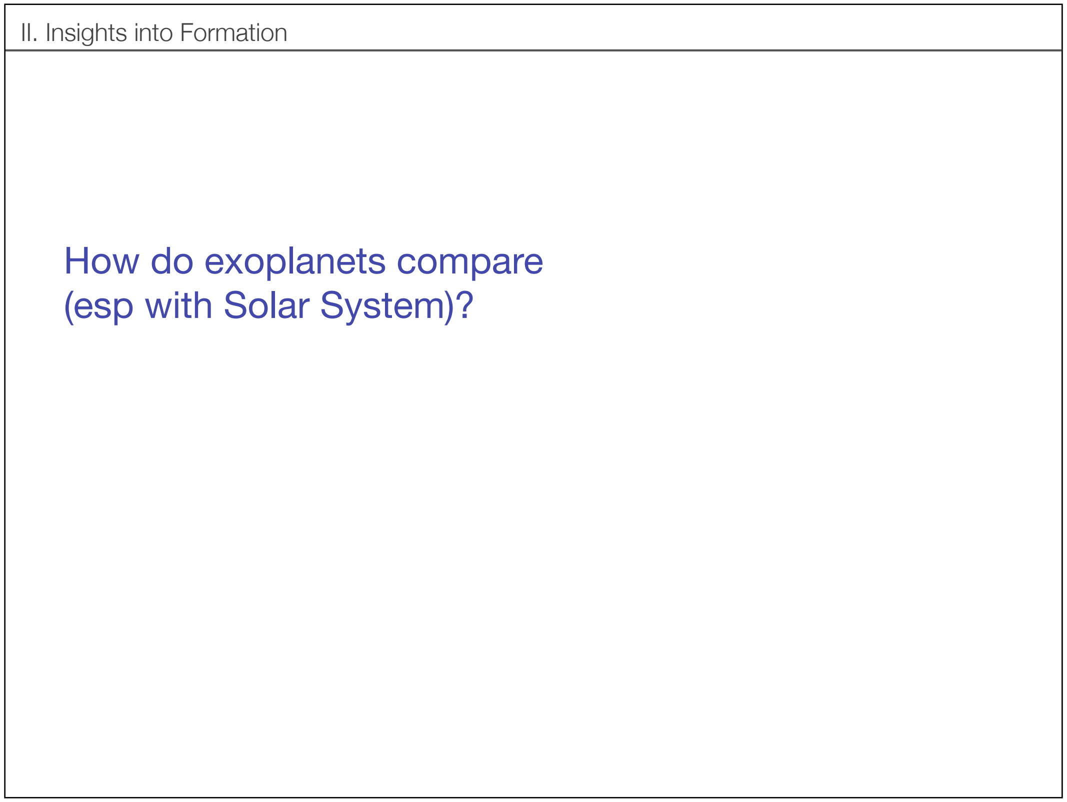
II. Insights into Formation

What does the ensemble of exoplanets tell us about planet formation?

- Planets move around in the disk! This extends the gravitational feeding ground for more rapid core growth
- The packed architectures suggest a starting point with hundreds or thousands of planetesimals
- Planet-metallicity correlation for gas giants but not for small rocky planets tells us about the formation timescale.

In fact, the pile-up is sharper than seen here.

Large population of planets with periods between 2-3 d, not clear why there should be such a sharp peak here.



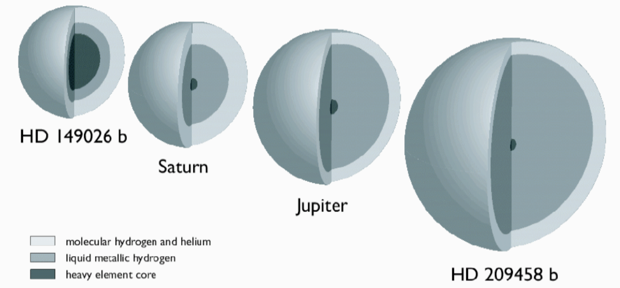
II. Insights into Formation

How do exoplanets compare
(esp with Solar System)?

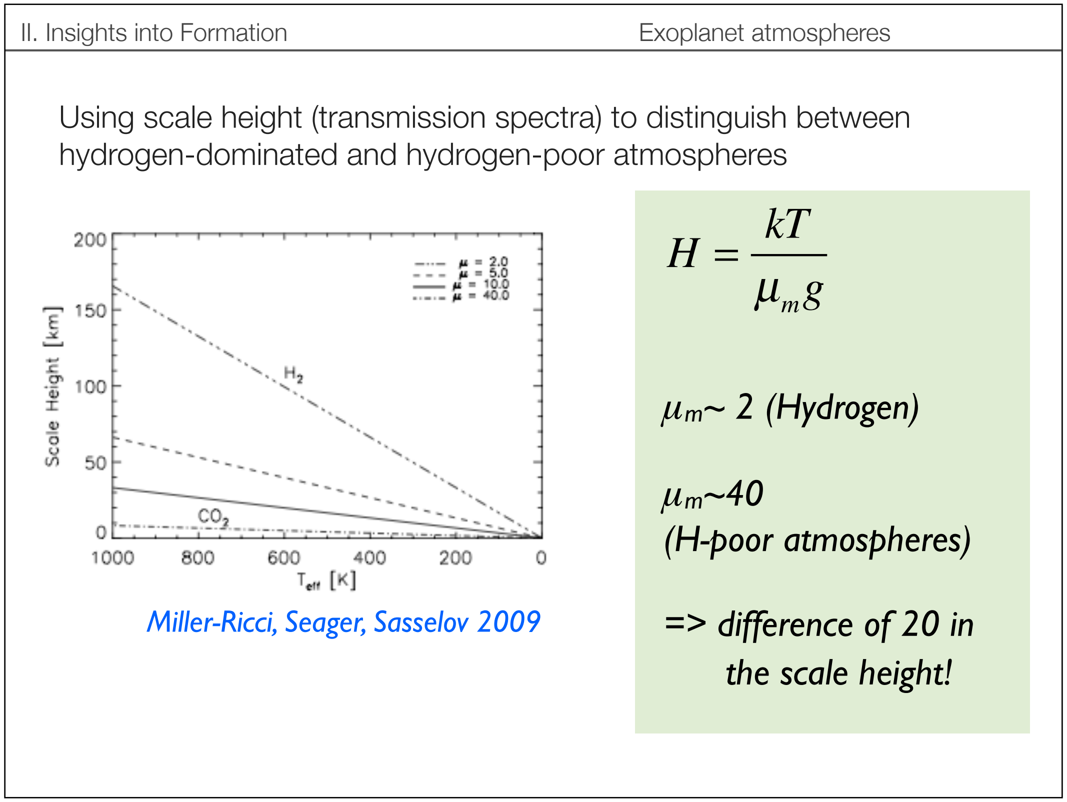
In fact, the pile-up is sharper than seen here.

Large population of planets with periods between 2-3 d, not clear why there should be such a sharp peak here.

Exoplanet interior structure



Models allow us to determine interior structure of unseen planets orbiting stars hundreds of light years away.
The combination of mass and radius gives a unique 2-layer model.



Using scale height (transmission spectra) to distinguish between hydrogen-dominated and hydrogen-poor atmospheres

Miller-Ricci, Seager, Sasselov 2009

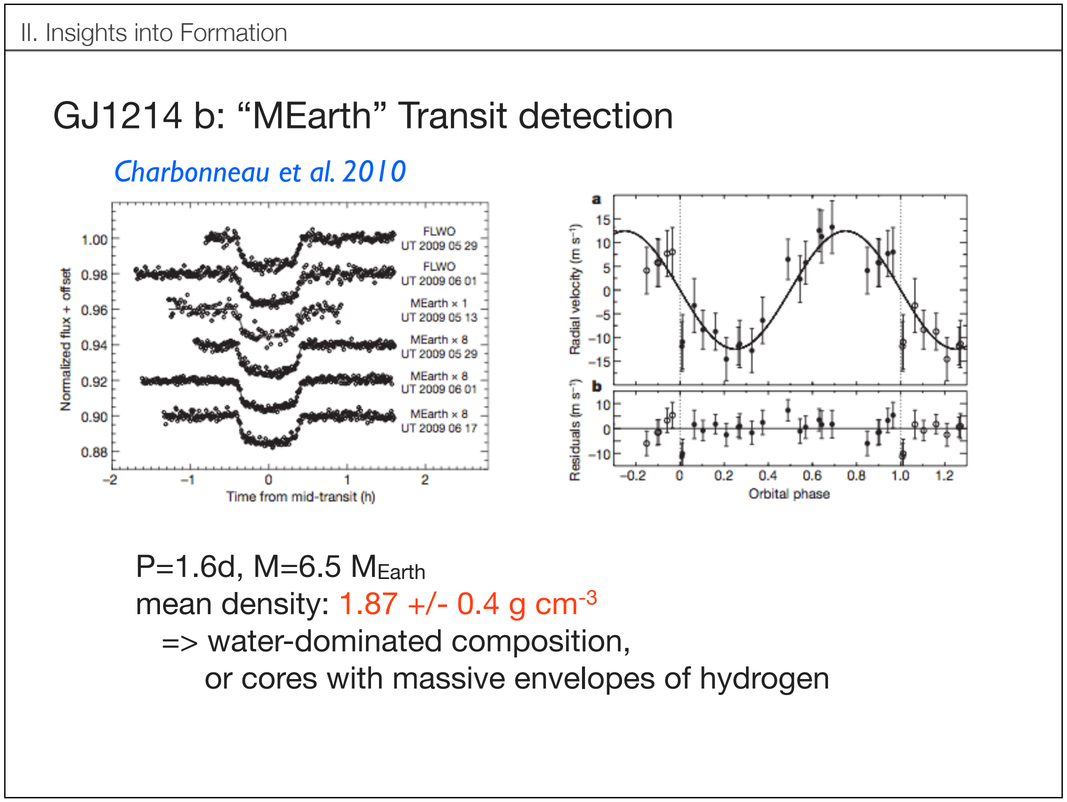
$$H = \frac{kT}{\mu_m g}$$

μ_m~ 2 (Hydrogen)

μ_m~40
(H-poor atmospheres)

=> difference of 20 in the scale height!

This will make it easier to characterize H-rich atmospheres (stronger transmission spectrum)

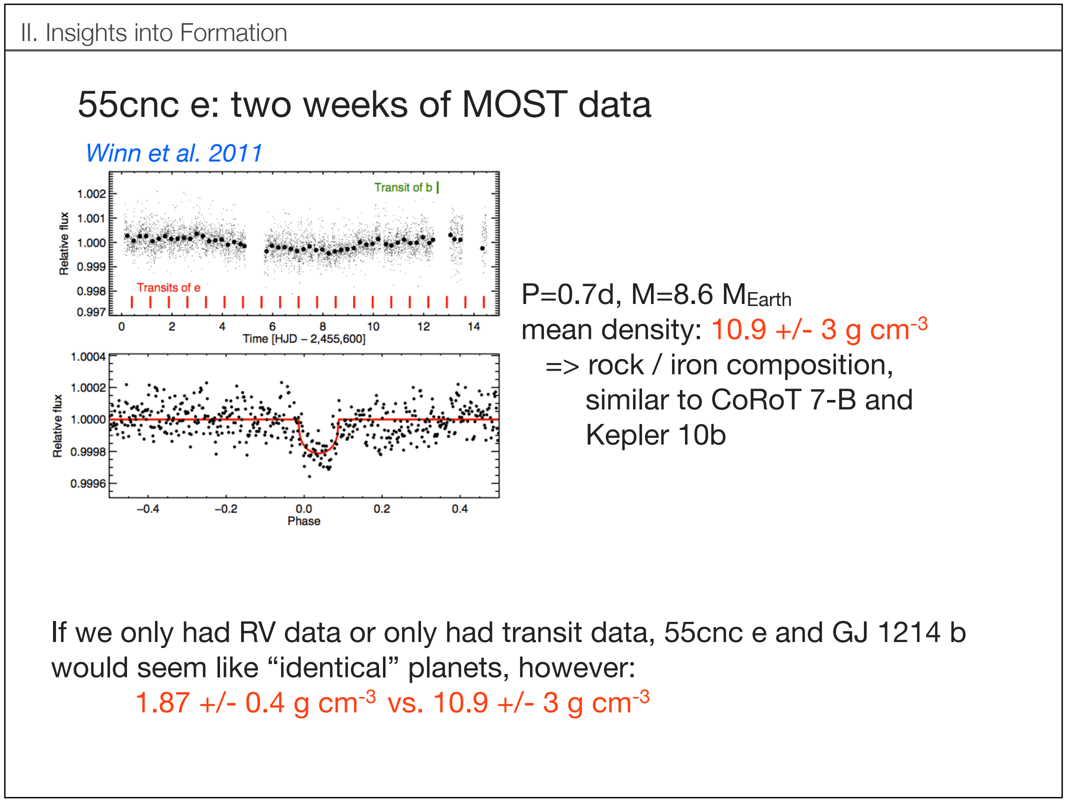


GJ1214 b: “MEarth” Transit detection

Charbonneau et al. 2010

P=1.6d, M=6.5 M_{Earth}
mean density: 1.87 +/- 0.4 g cm^{-3}
=> water-dominated composition,
or cores with massive envelopes of hydrogen

A poster child: transiting planet around an M dwarf. Dramatically different density than 55 cnc e.



II. Insights into Formation

55cnc e: two weeks of MOST data

Winn et al. 2011

P=0.7d, M=8.6 M_{Earth}

mean density: 10.9 +/- 3 g cm^{-3}

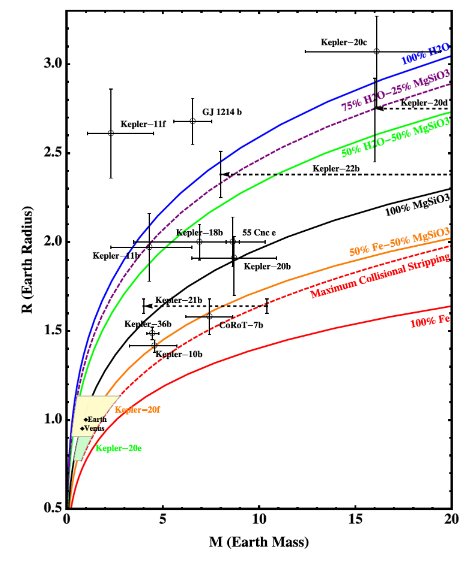
=> rock / iron composition,
similar to CoRoT 7-B and
Kepler 10b

If we only had RV data or only had transit data, 55cnc e and GJ 1214 b would seem like “identical” planets, however:

1.87 +/- 0.4 g cm^{-3} vs. 10.9 +/- 3 g cm^{-3}

55 Cnc: the system that keeps on giving – authors note that this is a star you can go out into your backyard and see at night.

II. Insights into Formation



Mass radius curves for mass fractions:

100% H_2O

75% H_2O - 25% $MgSiO_3$

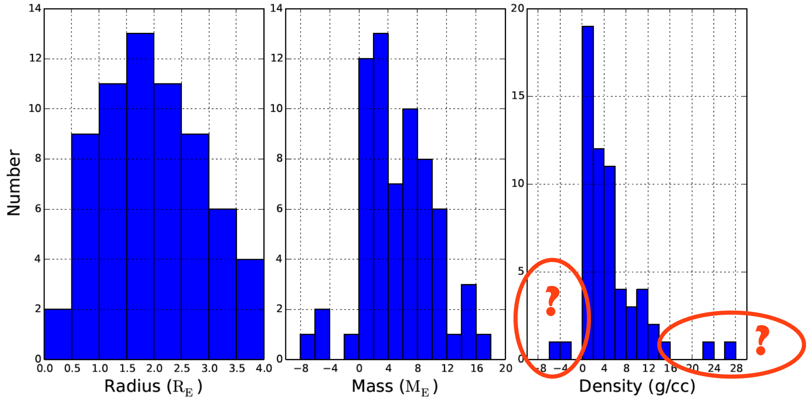
50% H20 - 50% $MgSiO_3$

Pure $MgSiO_3$

50% Fe - 50% $MgSiO_3$

Pure Fe

Statistical mass, radius, density of 65 exoplanets

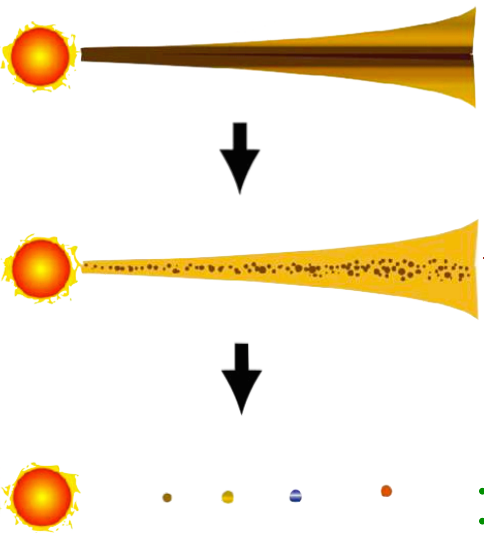


Marcy et al. 2014

No RV detections. Statistical analysis allows negative RV amplitudes in posterior distribution.

Improved mass measurements (more precise Doppler measurements) would improve density calculation,

What determines the composition of terrestrial planets?



1. Solids condense out of disk and grow into dust grains and pebble sized aggregates.

- Initial elemental abundances
- Disk thermal structure
- Chemical reactions
- Transport of material w/in disk

2. Planetesimals form and grow.

- Timing of planetesimal formation
- Migration of planetesimals
- Migration of giant planets

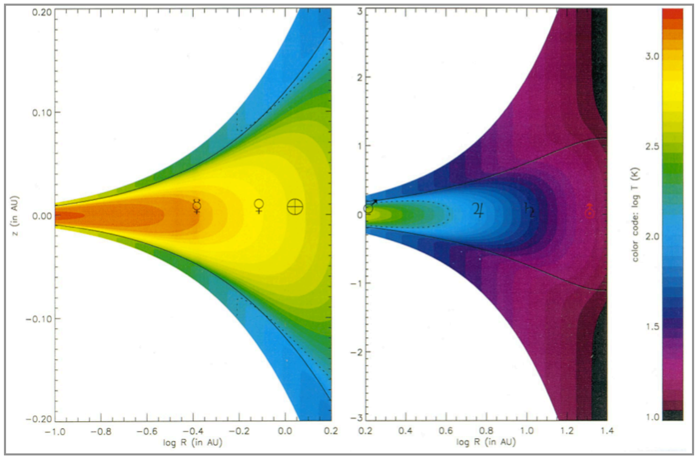
3. Embryos scatter and collide with each other and eventually grow into planets.

- Planet feeding zone
- Giant collisions

http://www.planet.sci.kobe-u.ac.jp/study/list/astrophysics/index_e.html

Disk Structure

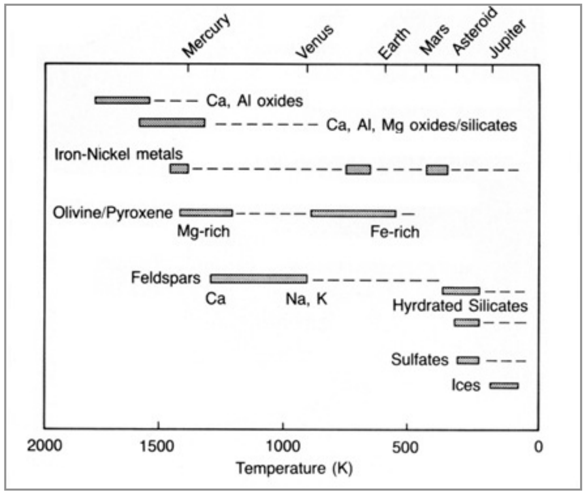
Start with a model T-P profile and assumed chemical composition (e.g., solar) ... but, at what time? The disk is evolving.



Hersant et al. 2001

Disk Structure
Equilibrium Chemistry

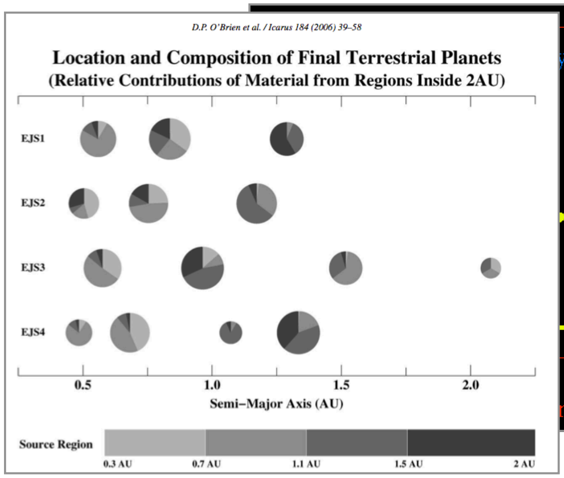
Given the T-P profile, condensation temperatures for refractory and volatile elements as f(radius).



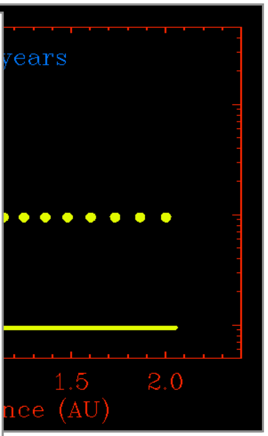
(Bond 2010)

Disk Structure
Equilibrium Chemistry
Disk Evolution

Then tag the planetesimals with equilibrium chemistry compositions and let the system dynamically interact.



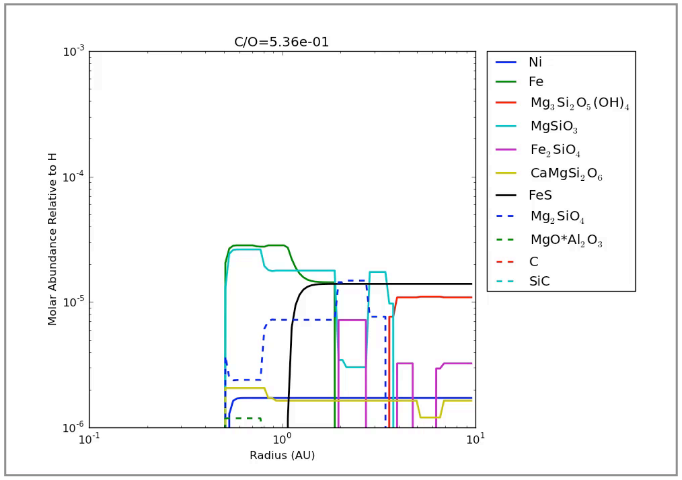
O'Brien et al 2006, Icarus



Bond et al 2010, 2012

Disk Structure
Equilibrium Chemistry
Disk Evolution

For C/O ratios > 1.0 the planetesimals become C-rich.
Such high C/O may be rare (Sun C/O = 0.5).



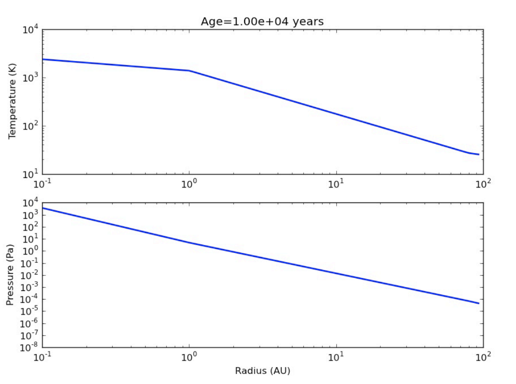
Moriarty, Madhusudhan & Fischer 2014

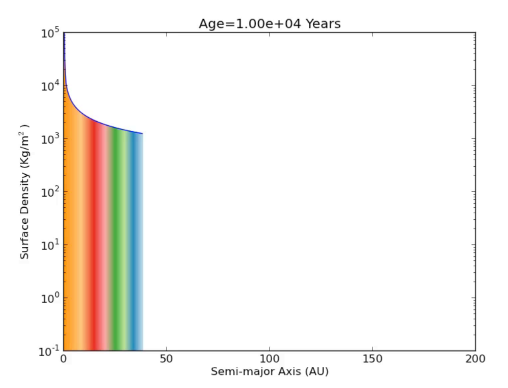
Disk Structure
Equilibrium Chemistry
Disk Evolution

Sequential condensation (disk evolves)

Temperature and pressure change as the disk evolves.

Surface density evolves as material is transported inward.



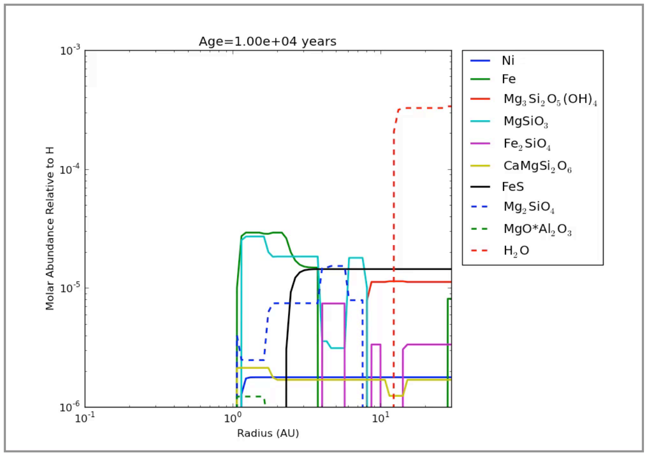


Moriarty, Madhusudhan & Fischer 2014

II. Insights into Formation

Disk Structure
Equilibrium Chemistry
Disk Evolution

Therefore, equilibrium chemistry evolves in the disk.

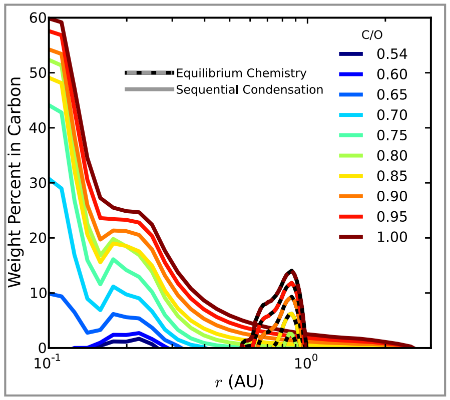


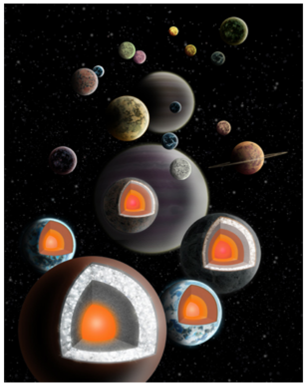
Moriarty, Madhusudhan & Fischer 2014

II. Insights into Formation

Disk Structure
Equilibrium Chemistry
Disk Evolution

Result of Sequential Condensation:
can get “carbon planets” for lower C/O of 0.65. Why do we care?
Thermal properties different by factor of two; implications for energy transport, plate tectonics, habitability.

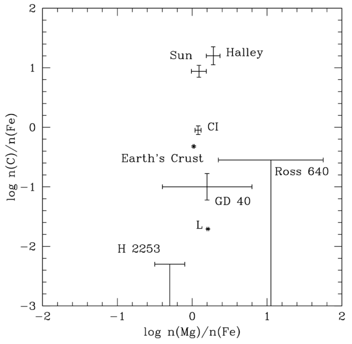




Moriarty, Madhusudhan & Fischer 2014

II. Insights into Formation

Interior composition is difficult to confirm observationally.
If stellar C/O ratio > 0.8 then likely that close-in planets have graphite / diamond interior layers.



Jura (2006)

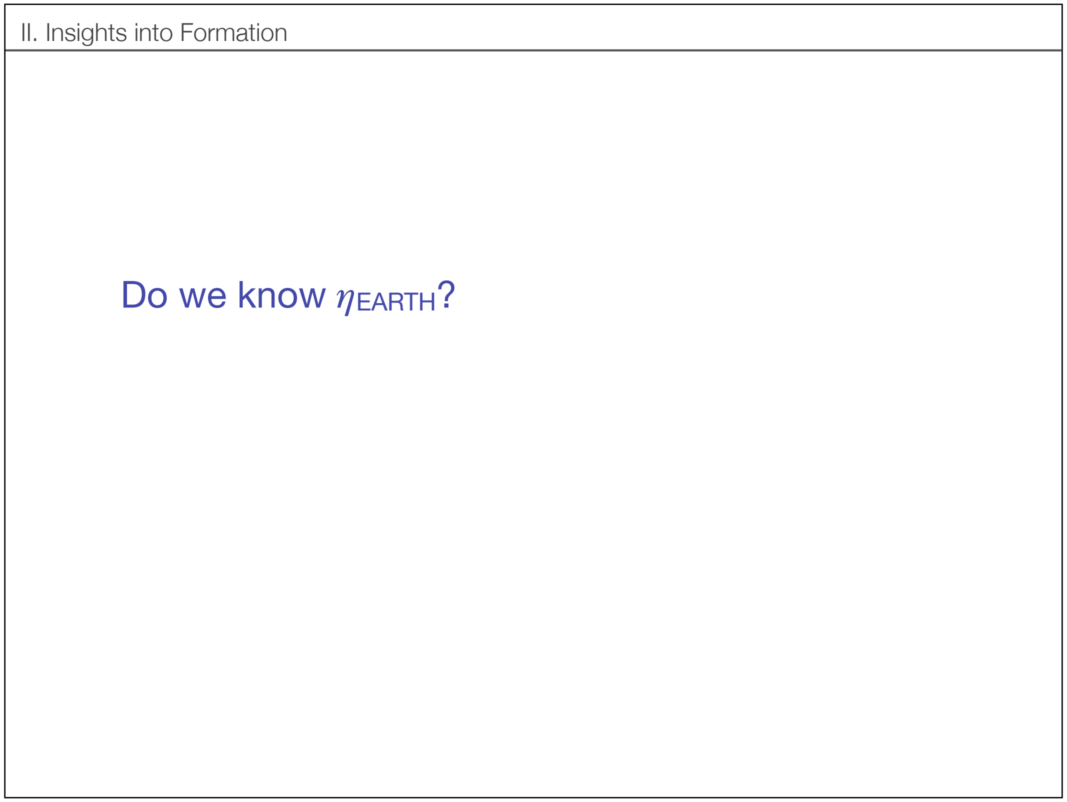
However, the white dwarf pollution spectra do not seem to support the existence of C-rich planets! Only see Earth-mantle pollution (O, Fe, Si, Mg)

- Perhaps C/O > 0.6 are rare.
- Perhaps inner planets disrupted during the giant phase - not available for accretion onto the WD.

Main point: in addition to wide range of density, there may be a wide range of chemical composition with impact on planet habitability.

How do exoplanets compare (esp with Solar System)?

- Multi-planet systems common
- New Category: Super Earths
- Wide diversity in density and chemical compositions



II. Insights into Formation

Do we know η_{EARTH}?

In fact, the pile-up is sharper than seen here.

Large population of planets with periods between 2-3 d, not clear why there should be such a sharp peak here.

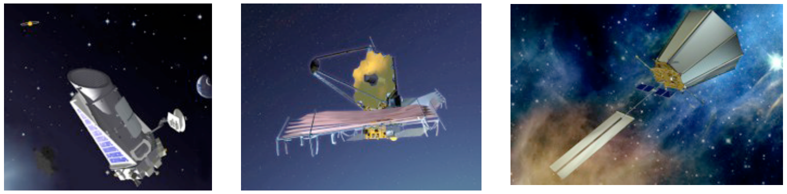
Do we now know η_{Earth} from Kepler data?

η_{Earth} = fraction of stars with Earth-sized planets in the habitable zone.

Why do we want that number?

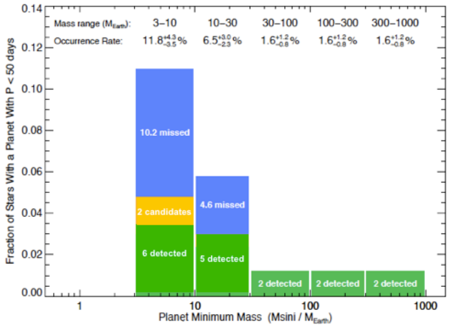
It tells us the number of stars we need to survey to find habitable planets => what size space telescopes needed !

Kepler and beyond.................



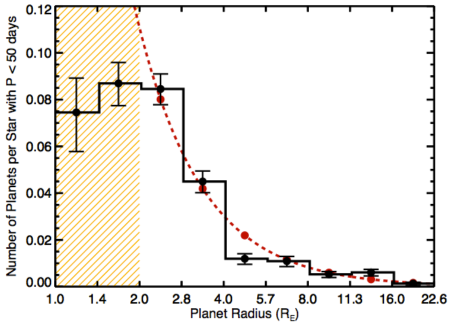
For short-period (< 50 day) planets

RV's: low mass planets common



Howard et al. 2010

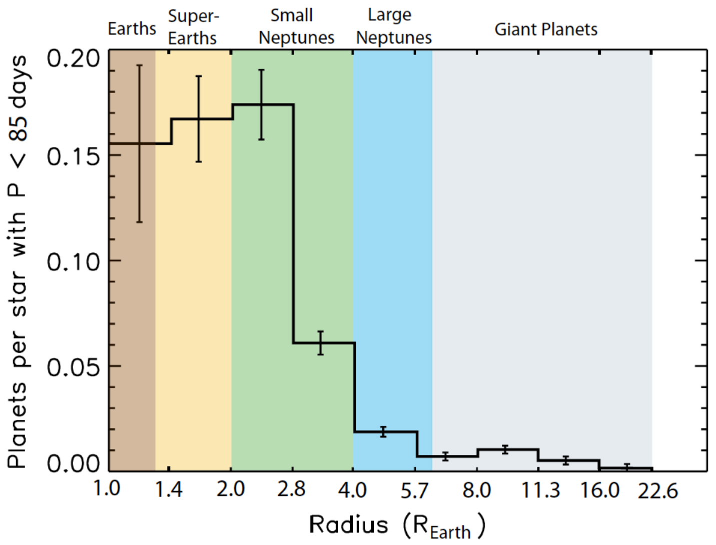
Kepler: Small planets common



Howard et al. 2012

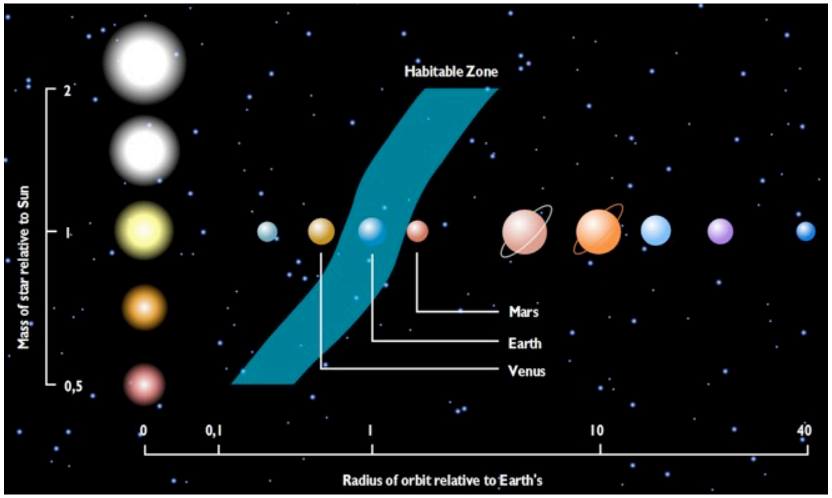
Four times as many Neptunes as Jupiters.
Seven times as many superEarths as Jupiters!

For short-period (< 85 day) planets



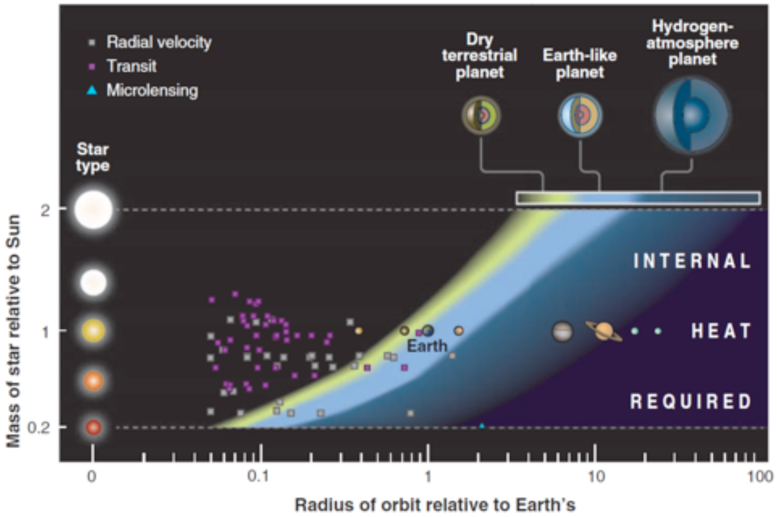
Fressin et al. 2013 ApJ 766, 81

Do we now know η_{Earth} from Kepler data?



HZ is the circumstellar region where a terrestrial planet can maintain liquid water on the surface.

Do we now know η_{Earth} from Kepler data?



Dry “land” planets have an advantage over planets with oceans. They can re-emit more IR radiation because air is unsaturated and the dry stratosphere limits hydrogen escape.

Do we now know η_{Earth} from Kepler data?

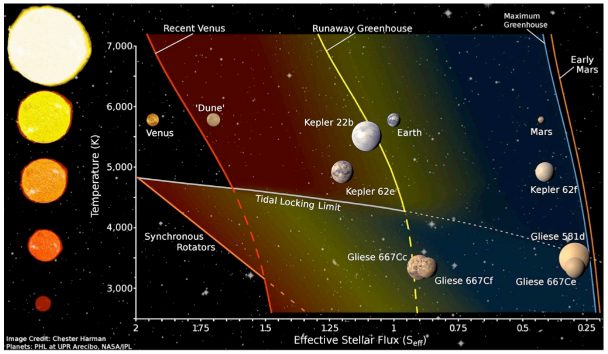


Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

Because of uncertainties in albedo, revise the HZ as f(L_{STAR})

- Greenhouse gases absorb and re-emit much of the outgoing IR.
- The Wien peak for Mdwarfs is in the IR, making their HZ wider.

Do we now know η_{Earth} from Kepler data?

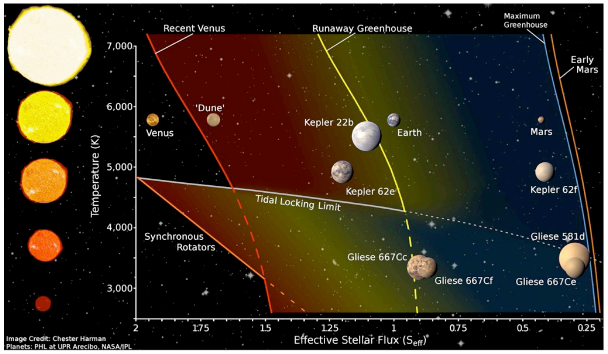
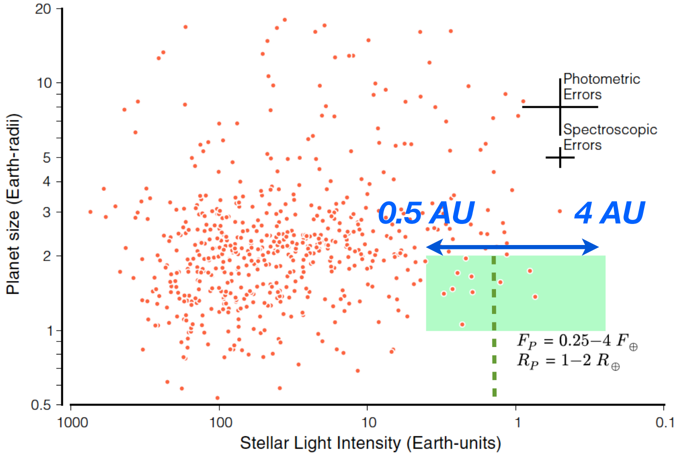


Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

Because of uncertainties in planetary albedo,
Kopparapu et al. (2013) revise the HZ as f(L_{STAR})

Inner and outer boundaries are empirical:
Venus lost water ~1 Gya and Mars lost water 3.8 Gya

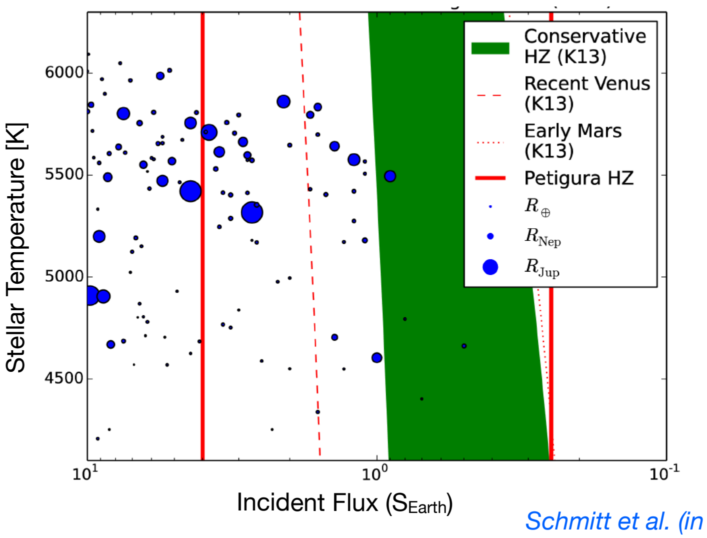
Do we now know η_{Earth} from Kepler data?



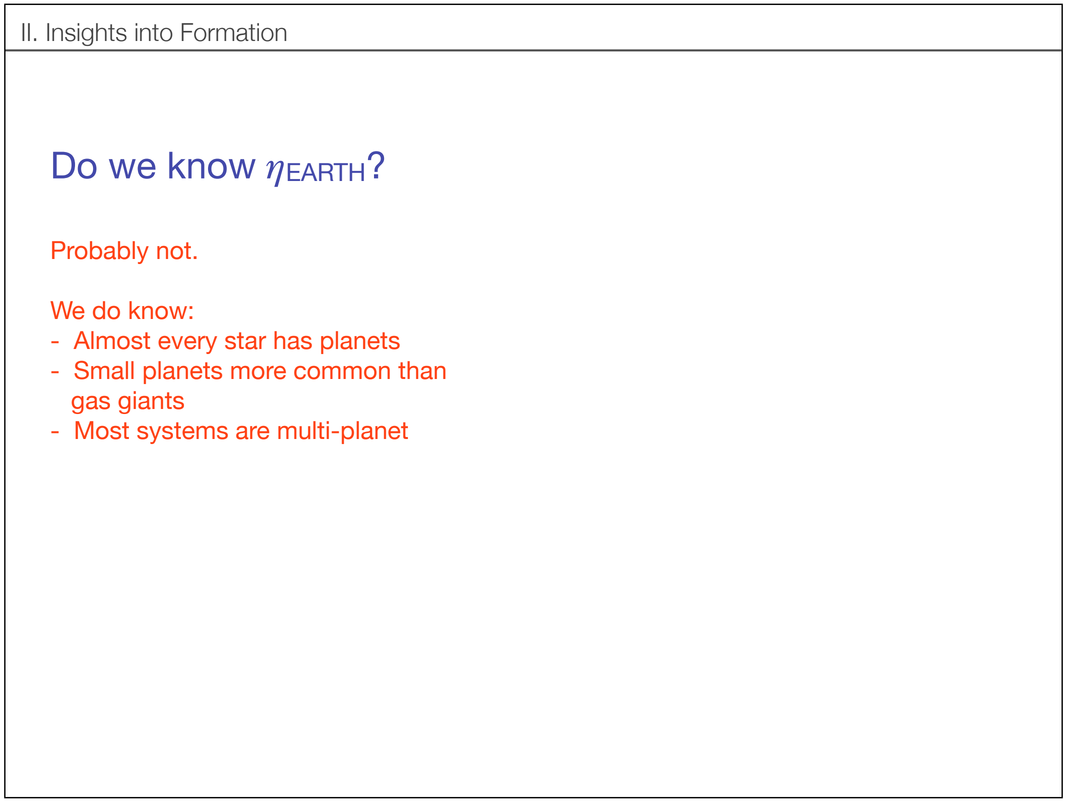
Petigura et al. (2013) PNAS

Do we now know η_{Earth} from Kepler data?

Somewhere between 10 - 40% depending on extrapolation assumptions.



Schmitt et al. (in prep)



Do we know η_{EARTH}?

Probably not.

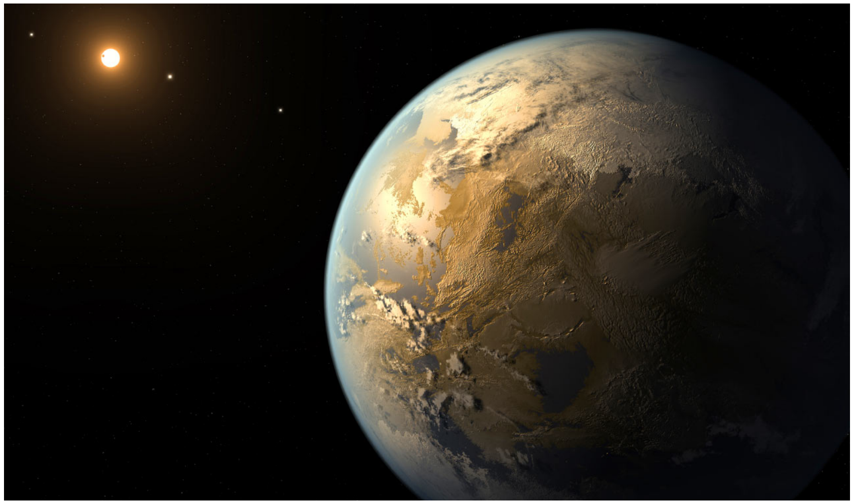
We do know:
- Almost every star has planets
- Small planets more common than gas giants
- Most systems are multi-planet

In fact, the pile-up is sharper than seen here.

Large population of planets with periods between 2-3 d, not clear why there should be such a sharp peak here.

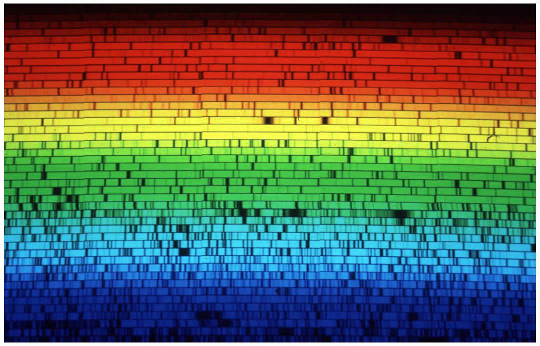
Paradigm shift: Kepler discoveries

“Practically all Sun-like stars have planets”

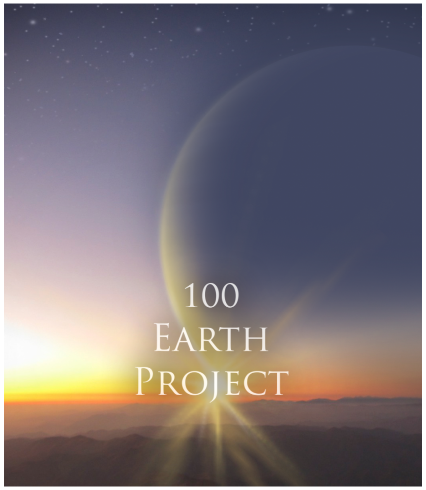


2010 Decadal Survey: "Our view of the universe has changed dramatically. Hundreds of planets of startling diversity have been discovered orbiting distant suns."

Recommended technology development to improve Doppler precision to 10 cm/s.



100 Earths Project

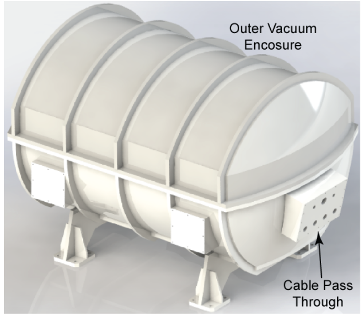


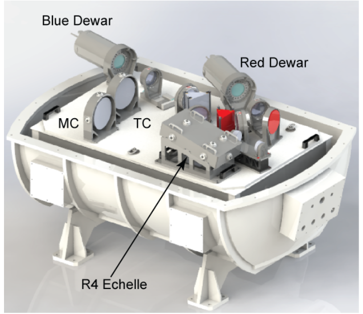
If we keep using the same instruments we've used in the past, we will get the same results (1 m/s precision).

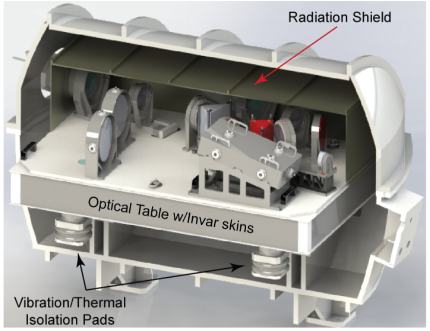
Time to design instruments that are fundamentally different for Doppler searches.

100 Earths Project: EXPRES-0

The goal is to build an instrument that can distinguish stellar “noise” from Doppler line shifts. NSF MRI proposal was just selected for funding.







100 Earths Project: at the DCT