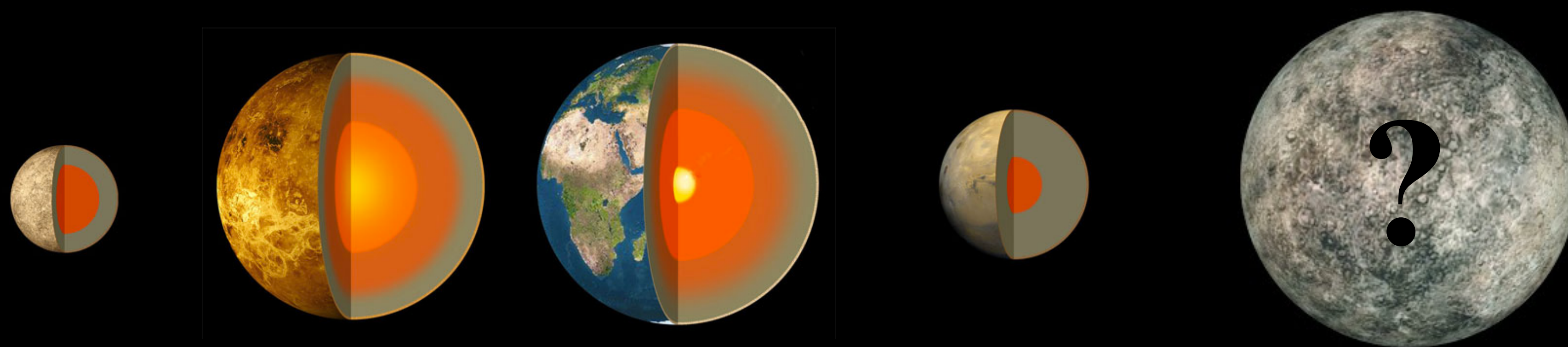
Using Stellar Abundances to Constrain Exoplanet Compositions



[Si/Fe] as a case study

Angie Wolfgang
Penn State
NSF Postdoctoral Fellow

Jonathan Fortney, UC Santa Cruz

Mass, Radius → Compositions

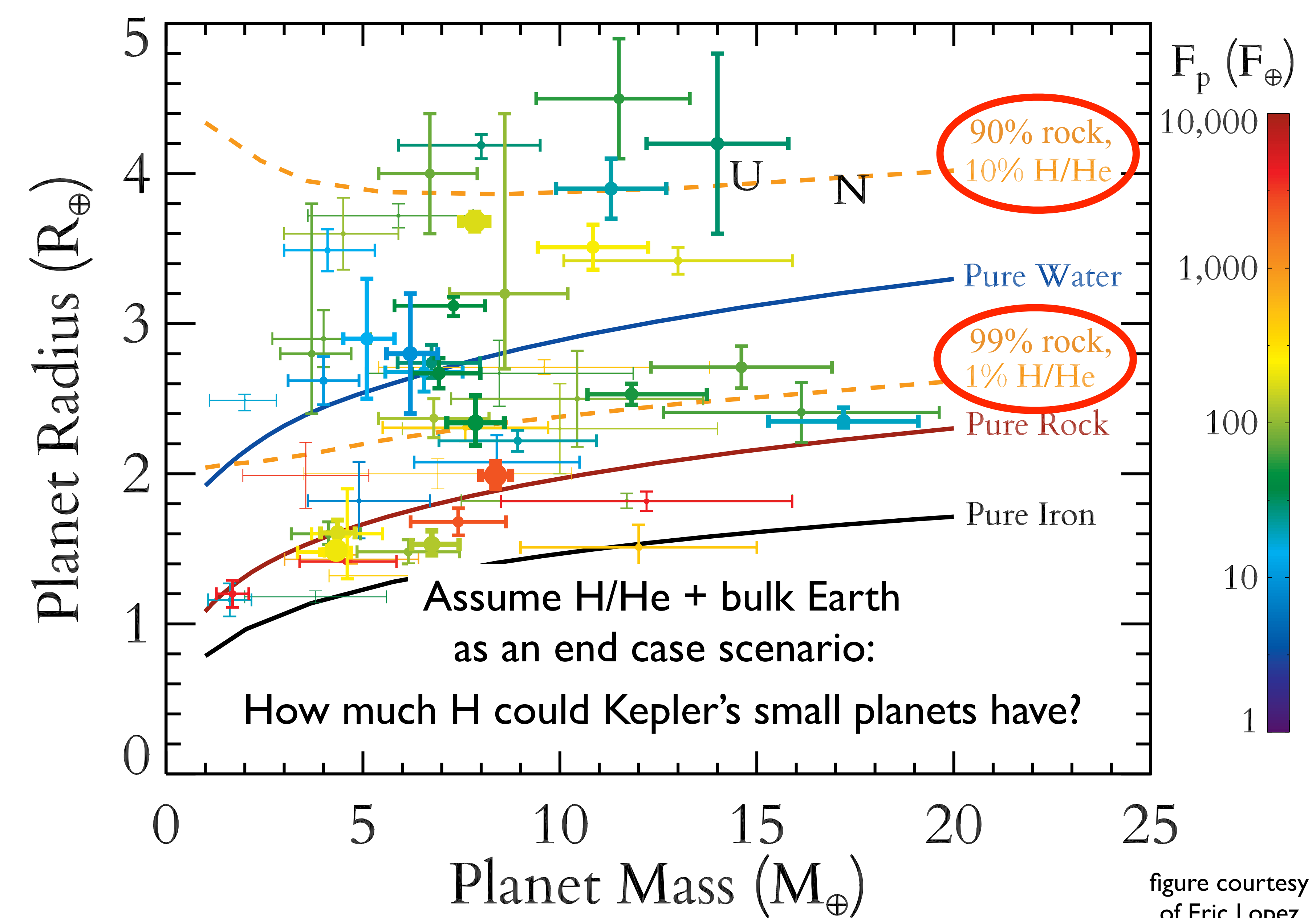
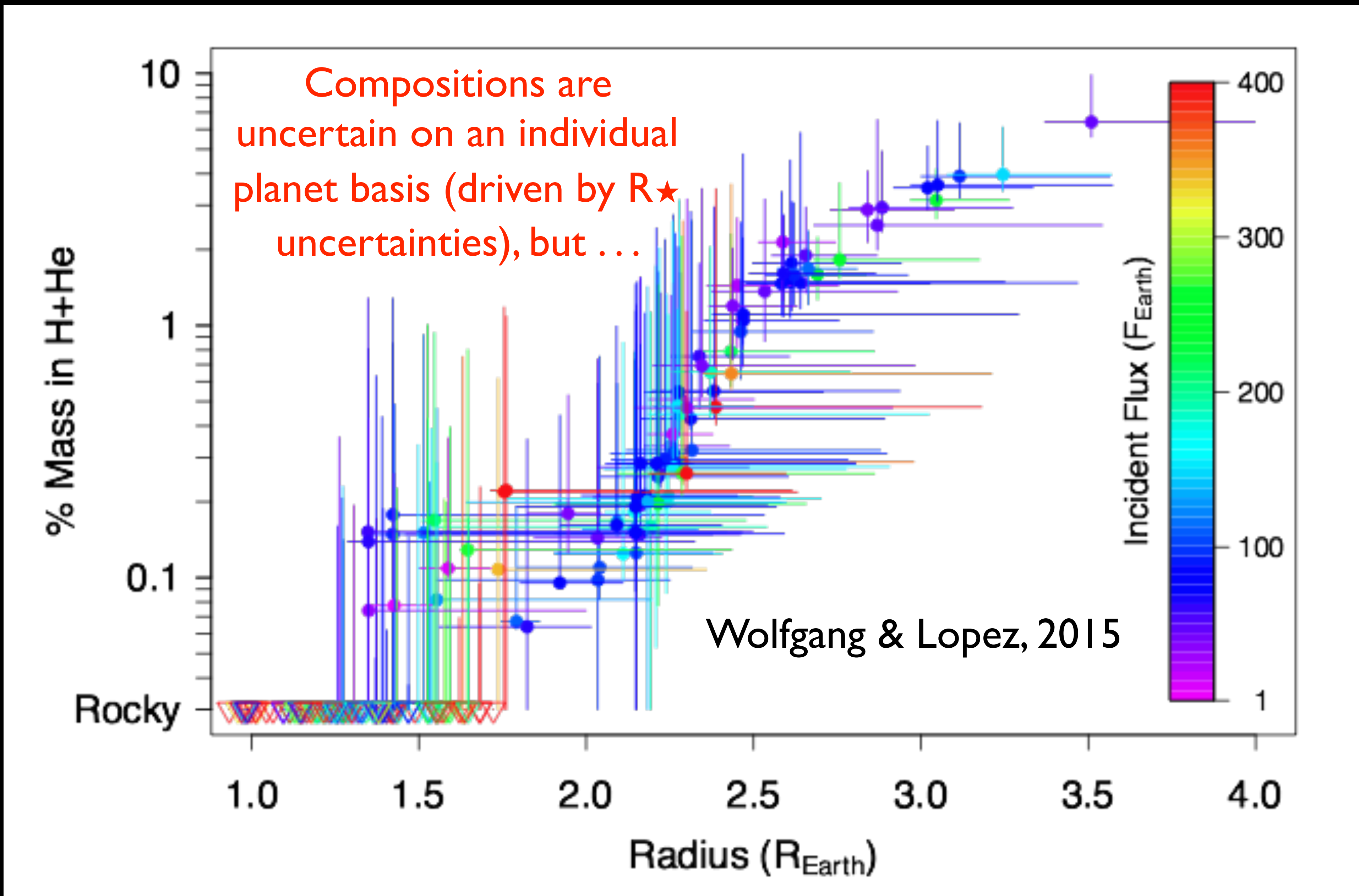
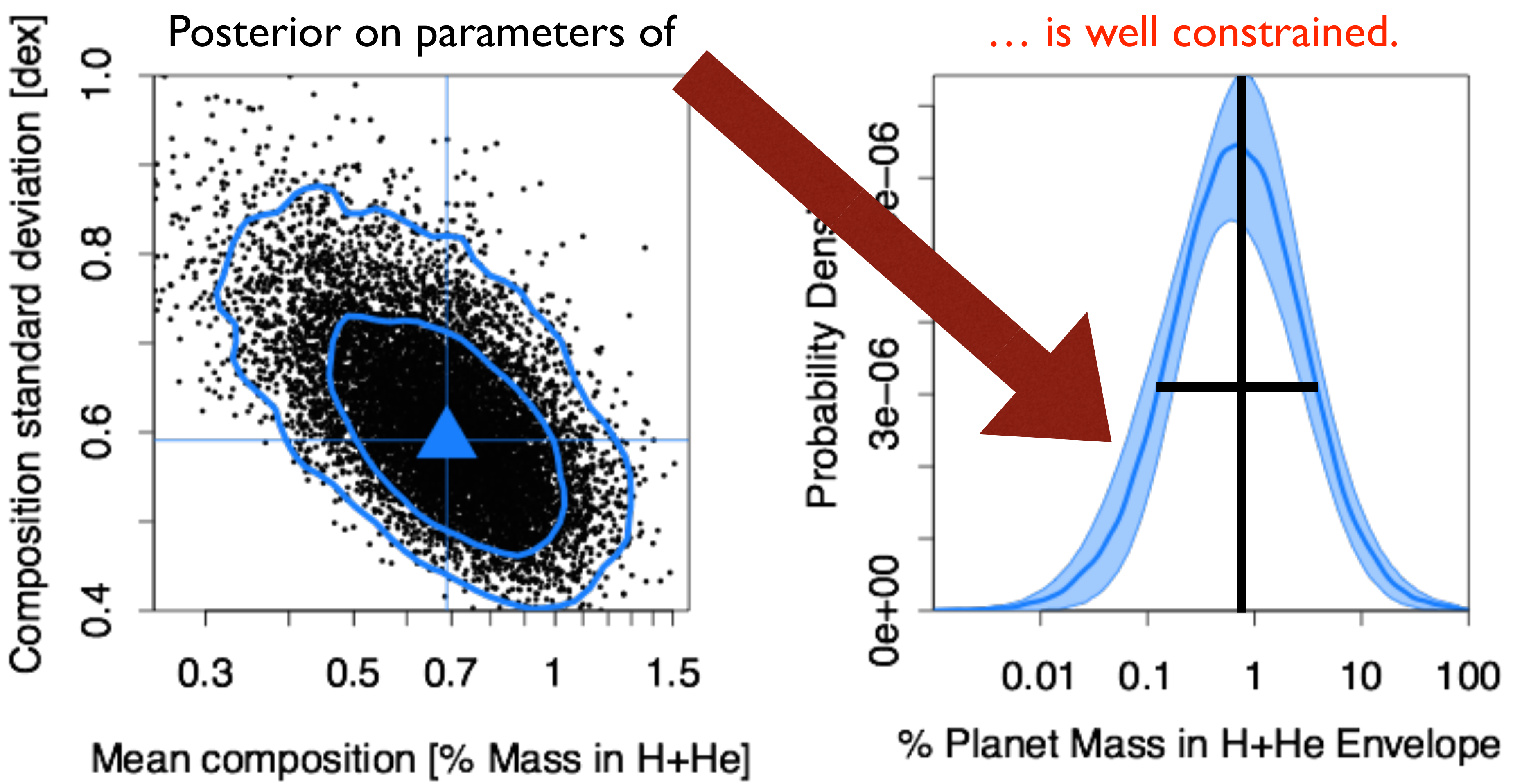


figure courtesy of Eric Lopez

Sub-Neptunes: ~1% Mass in H/He



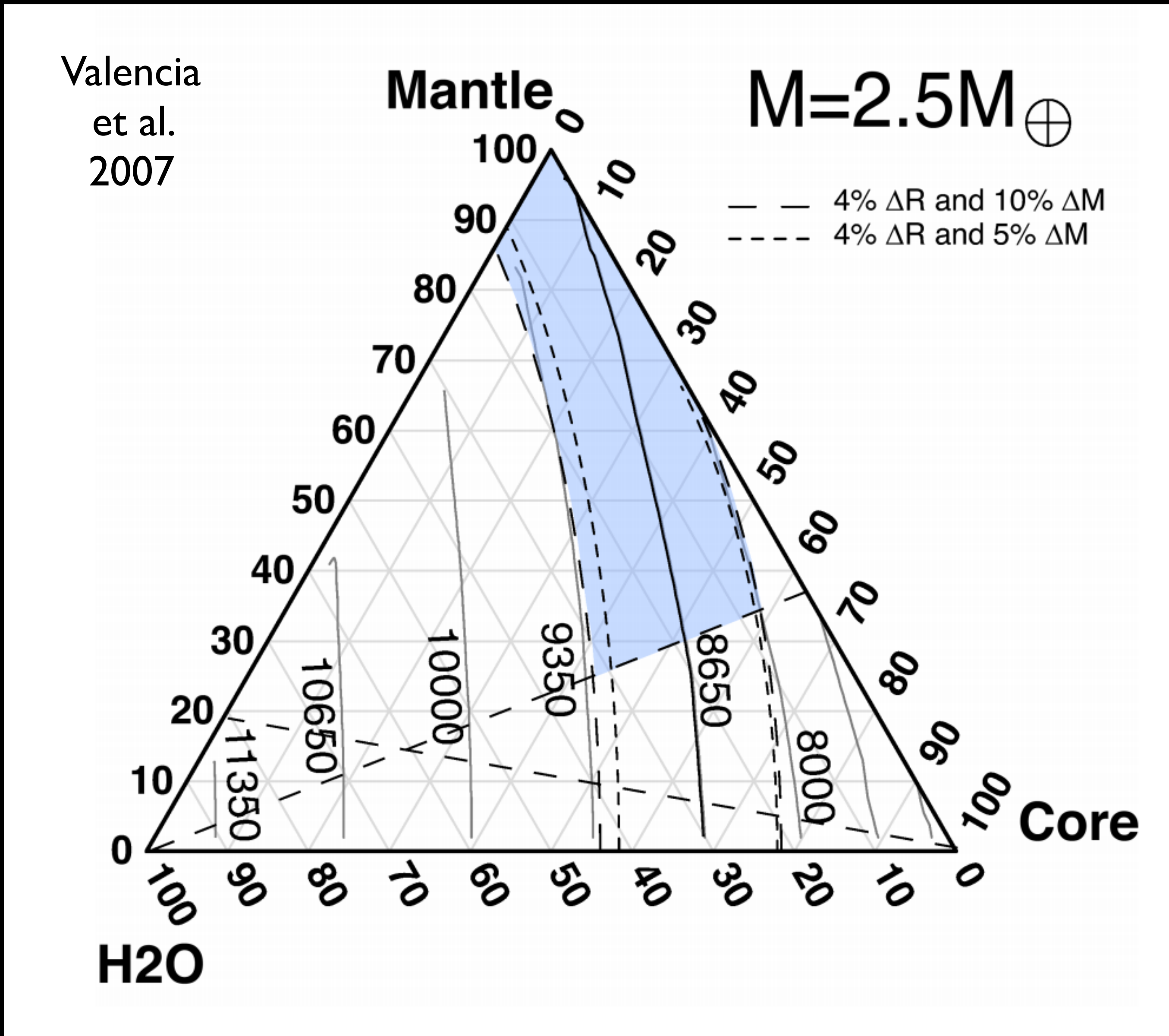
Population Distribution of Compositions



~ 1% envelope mass fractions are the most likely

Most sub-Neptunes have envelope fractions between 0.1 - 10%

But Depends on Assumed Structure



Inferring planetary compositions from M, R becomes a degenerate problem with > 2 layers:

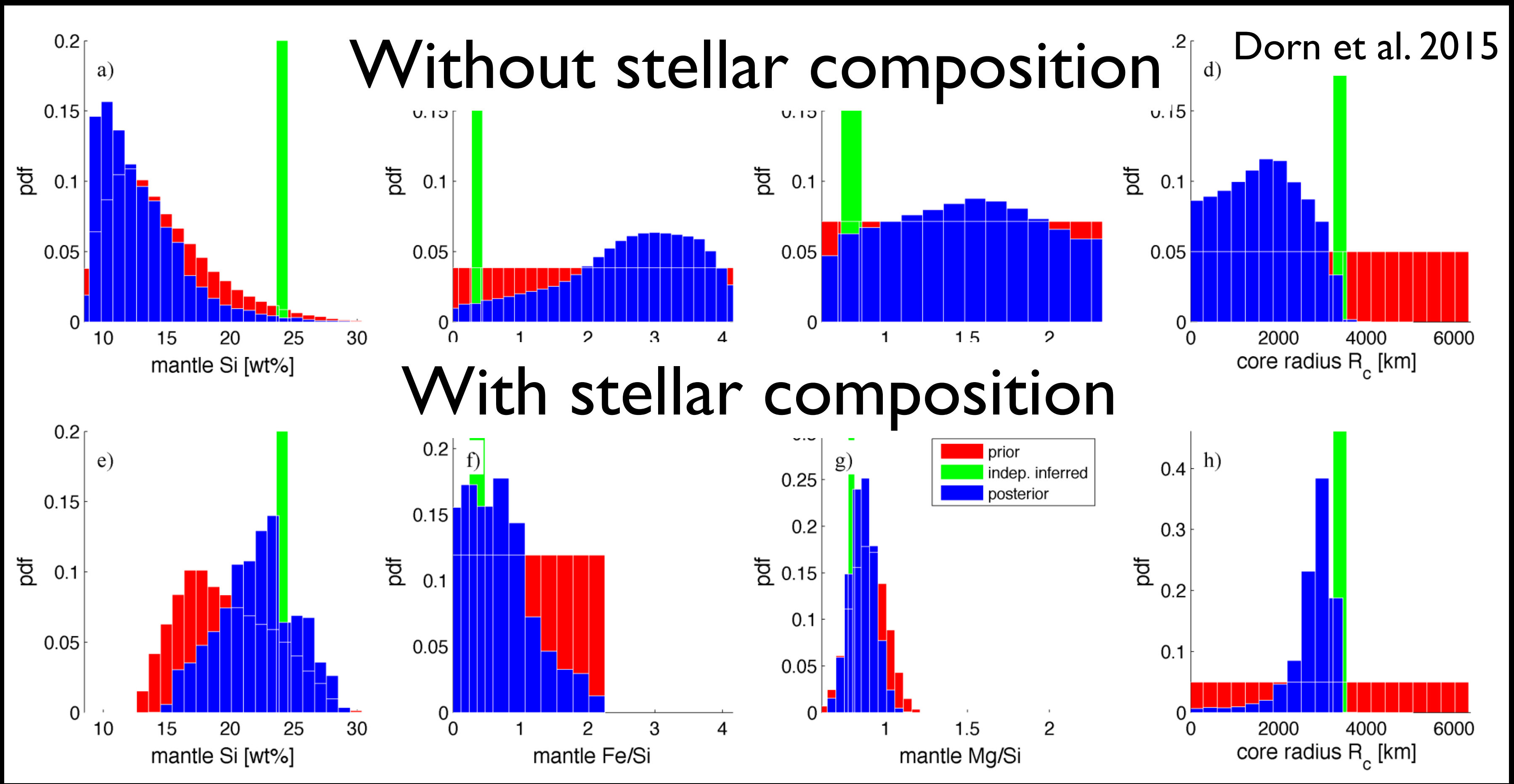
Many compositions give the same mass and radius.

Invoke the Star-Planet Connection

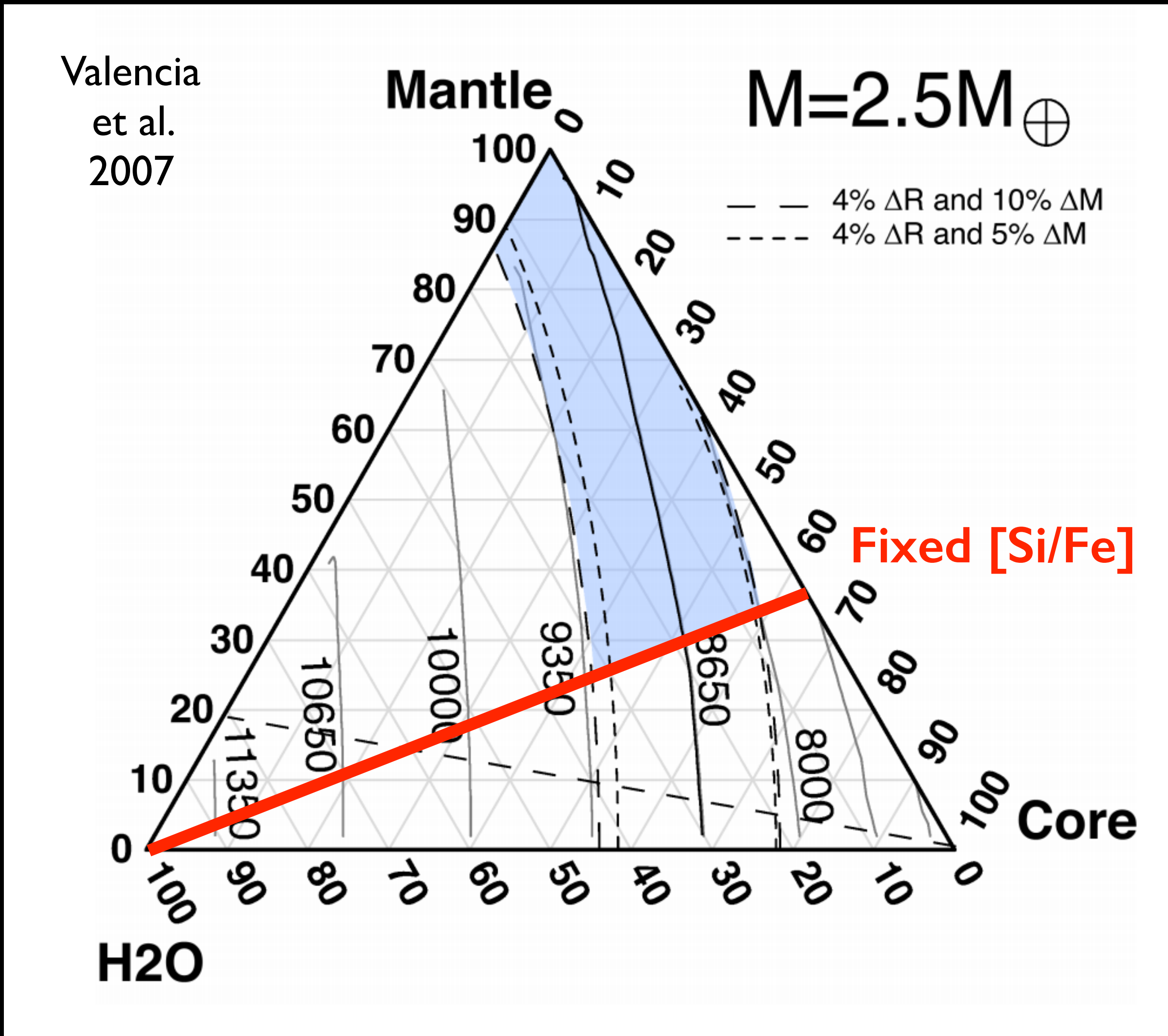
The protostar accretes material from the disk; planets form in that disk.

Compositions of planets correlate with compositions of their stars (?)

Exoplanet composition models now incorporate stellar composition:



How does $[Si/Fe]_{pl} = [Si/Fe]_\star$ help?



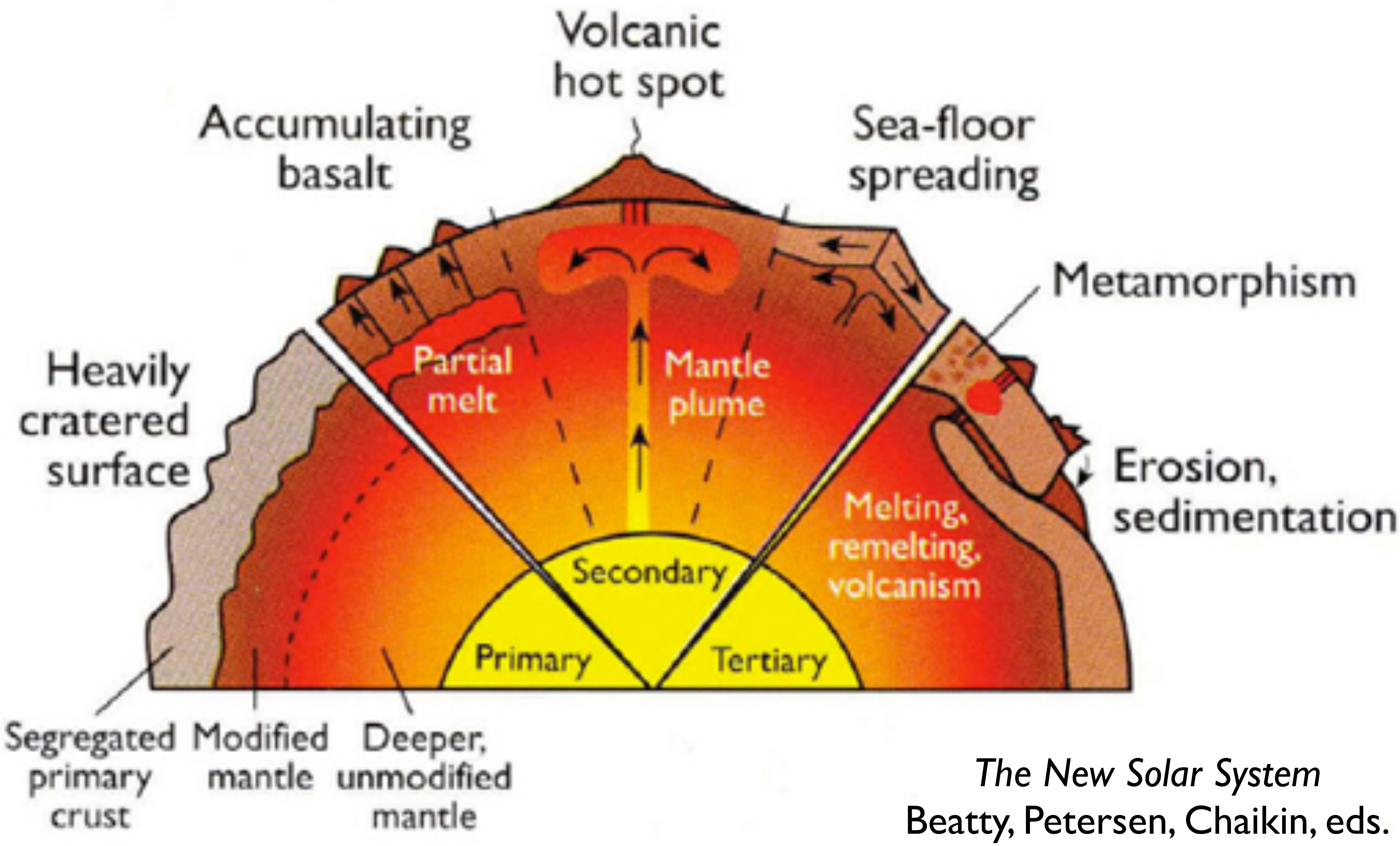
Inferring planetary compositions from M, R becomes a degenerate problem with > 2 layers:

Many compositions give the same mass and radius.

Assuming a [Si/Fe] helps limit possibilities.

Why talk about Si, Fe?

Composition of interior affects interior-surface interactions and the resulting atmosphere: Which volatiles? How much?

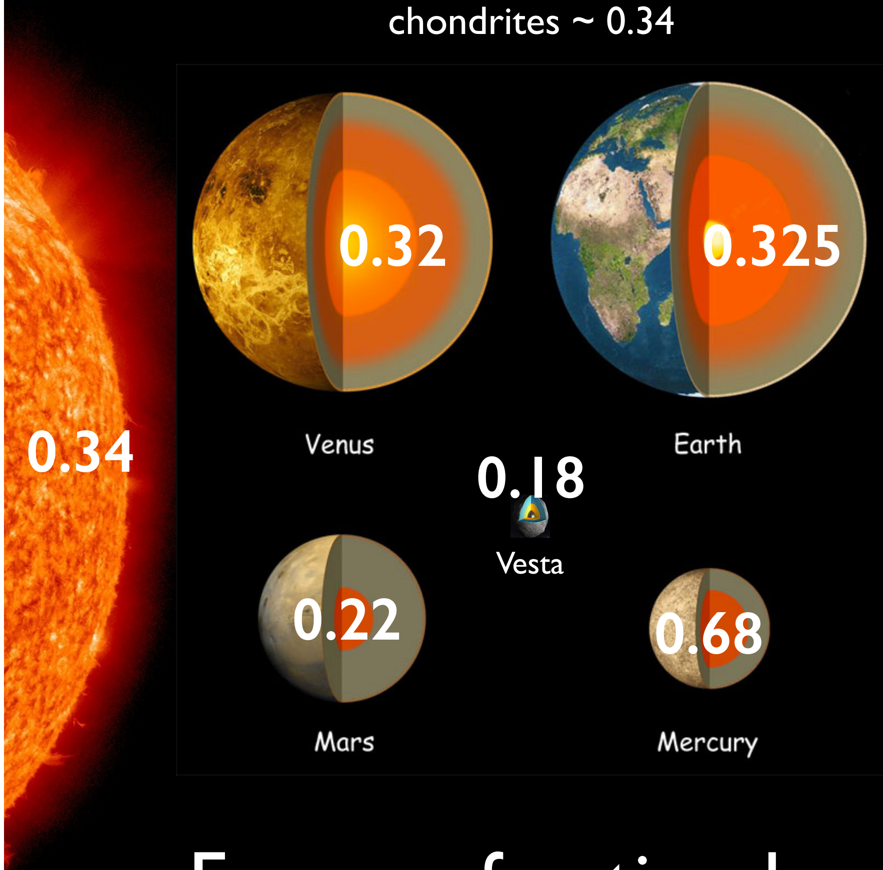


The New Solar System
Beatty, Petersen, Chaikin, eds.

What about the observations?

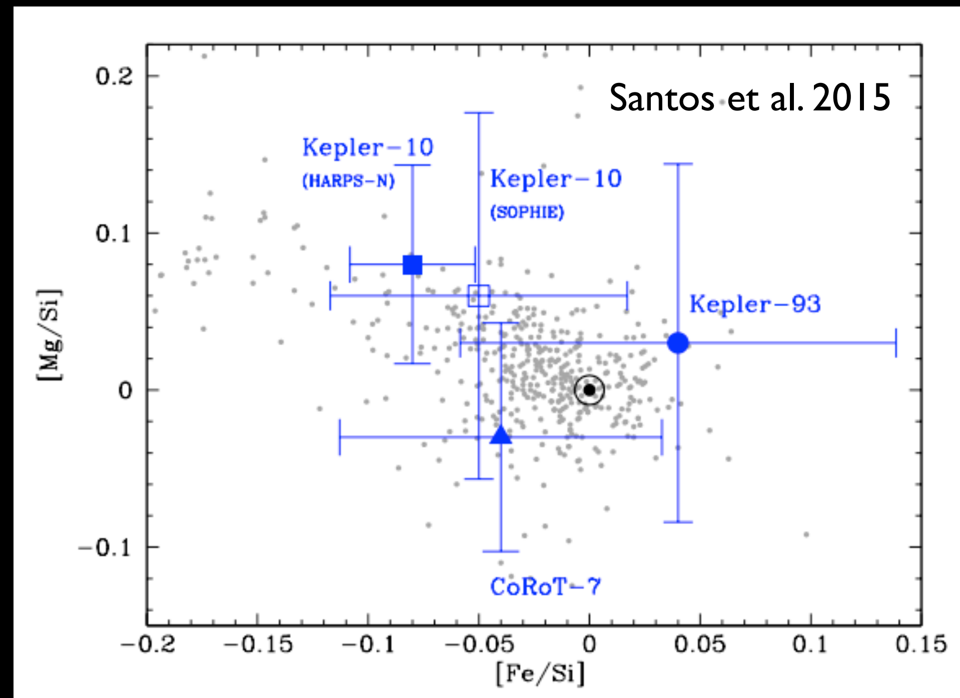
Solar System iron mass fractions:

chondrites ~ 0.34



Fe mass fraction has significant variation across terrestrial bodies

[Fe/Si] for exoplanets:



Planet iron/rock mass fraction agrees with stellar iron abundance . . . but large error bars!

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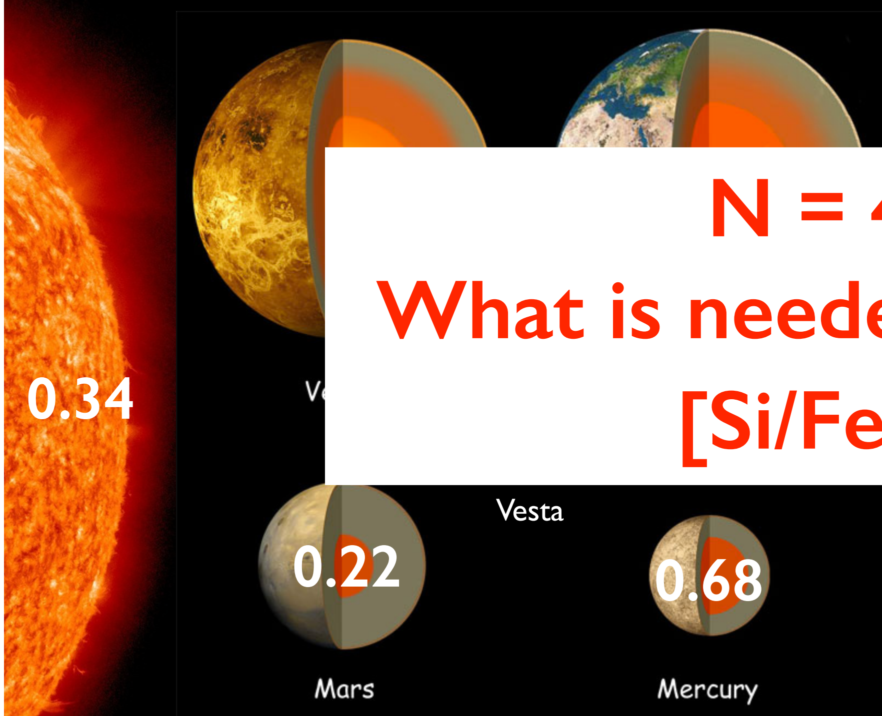

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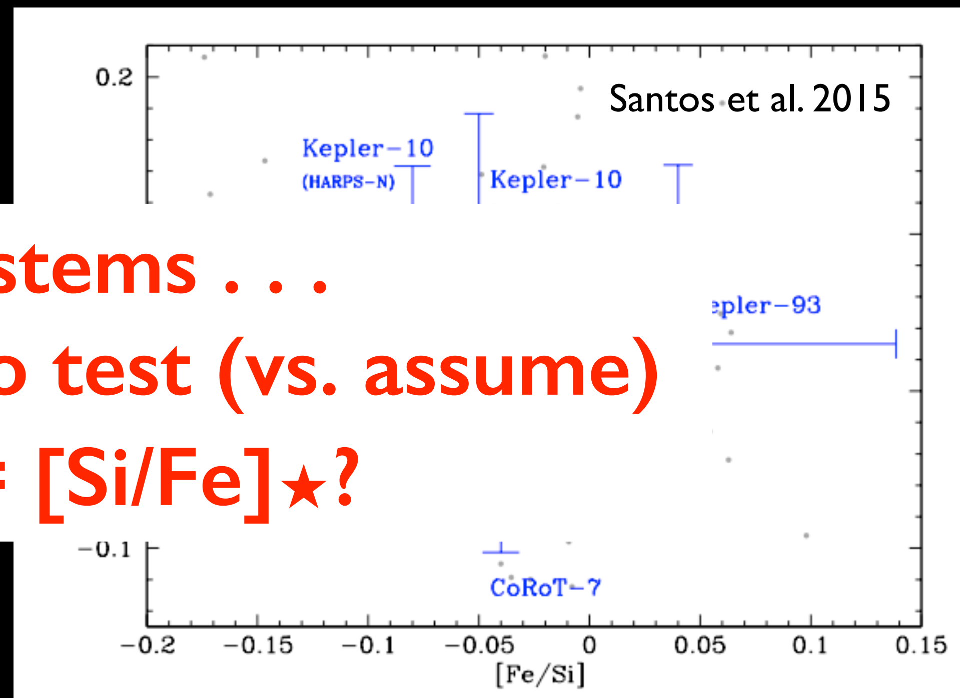

Planet iron/rock mass fraction agrees with stellar iron abundance . . . but large error bars!

N = 4 systems . . .

What is needed to test (vs. assume)

$[Si/Fe]_{pl} = [Si/Fe]_{\star}$?

Transiting Exoplanet Survey Satellite:

Launches 2018: find planets around nearby stars

Then: follow up from ground to get precise masses

Goal: fill out M-R space; understand planet compositions

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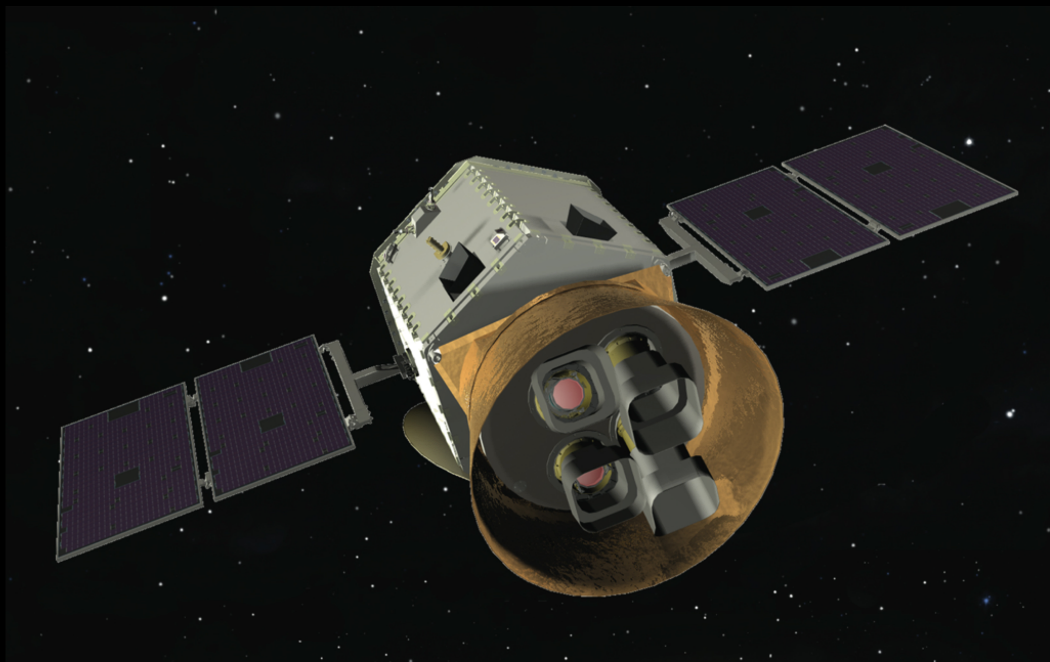

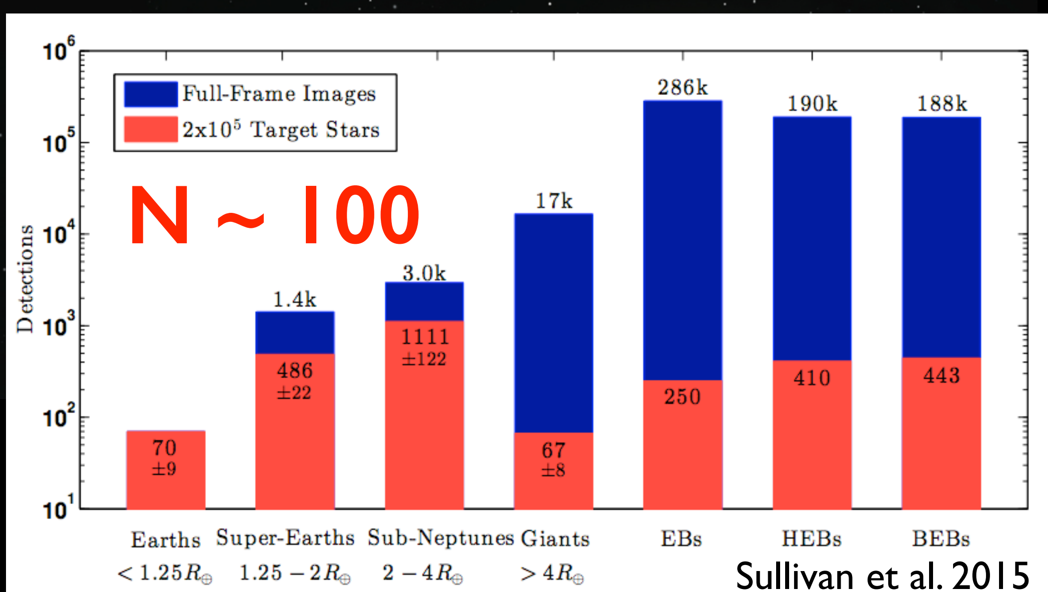

Launches 2018: find planets around nearby stars

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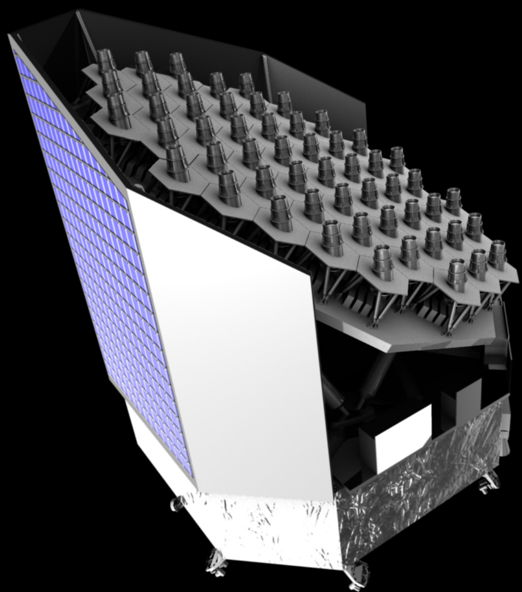
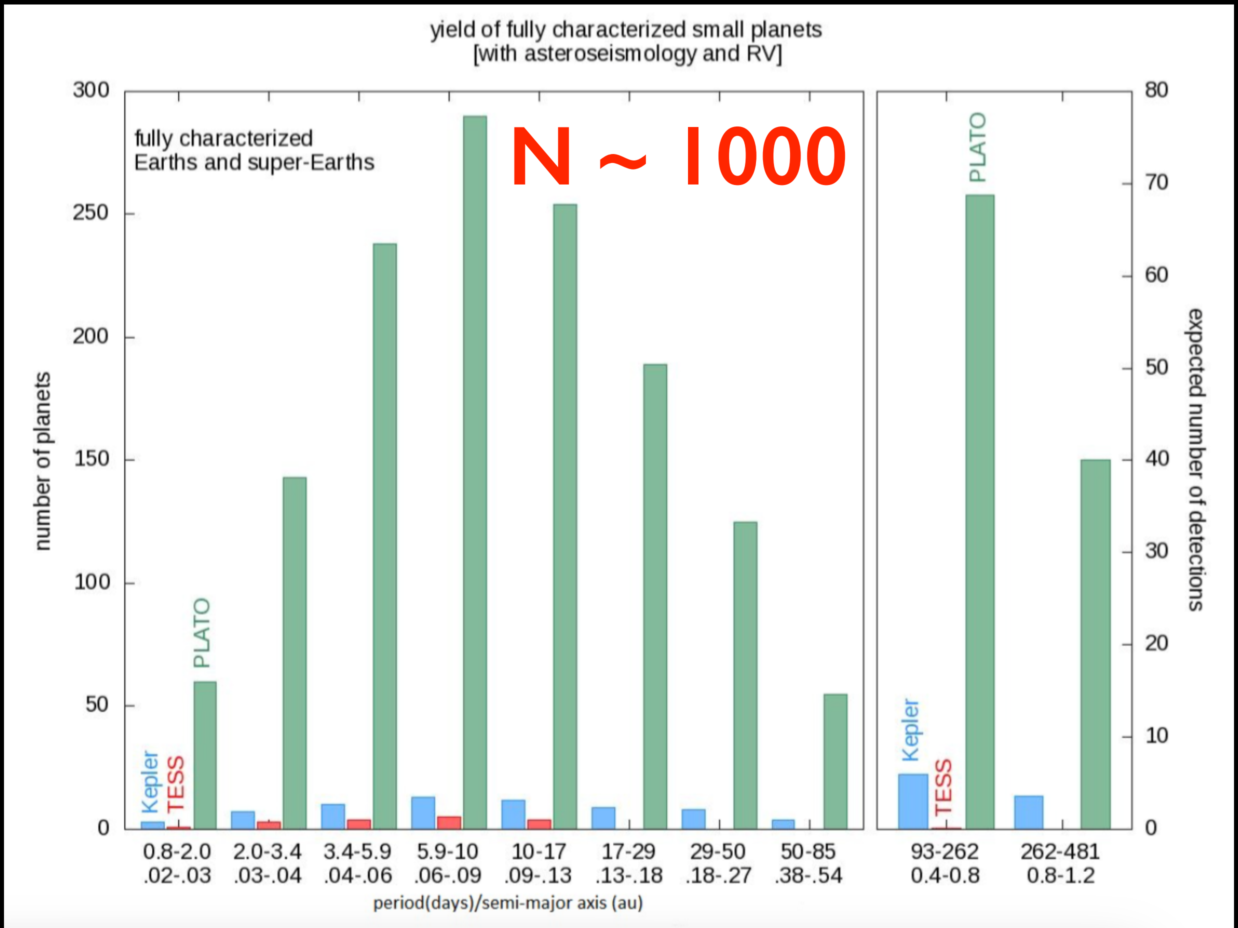
PLAnetary Transits & Oscillations of stars:



Goal:

statistical planet characterization with asteroseismology



ESA M-class,
4-year mission,
target launch
2026

Framing the Question

Do rocky planet compositions actually correlate with the refractory abundances of their host stars?

$[Si/Fe]_{pl} = a*[Si/Fe]_{\star} + b$

(current assumption: a = 1, b = 0)

How well would we know the correlation parameters given the future data?

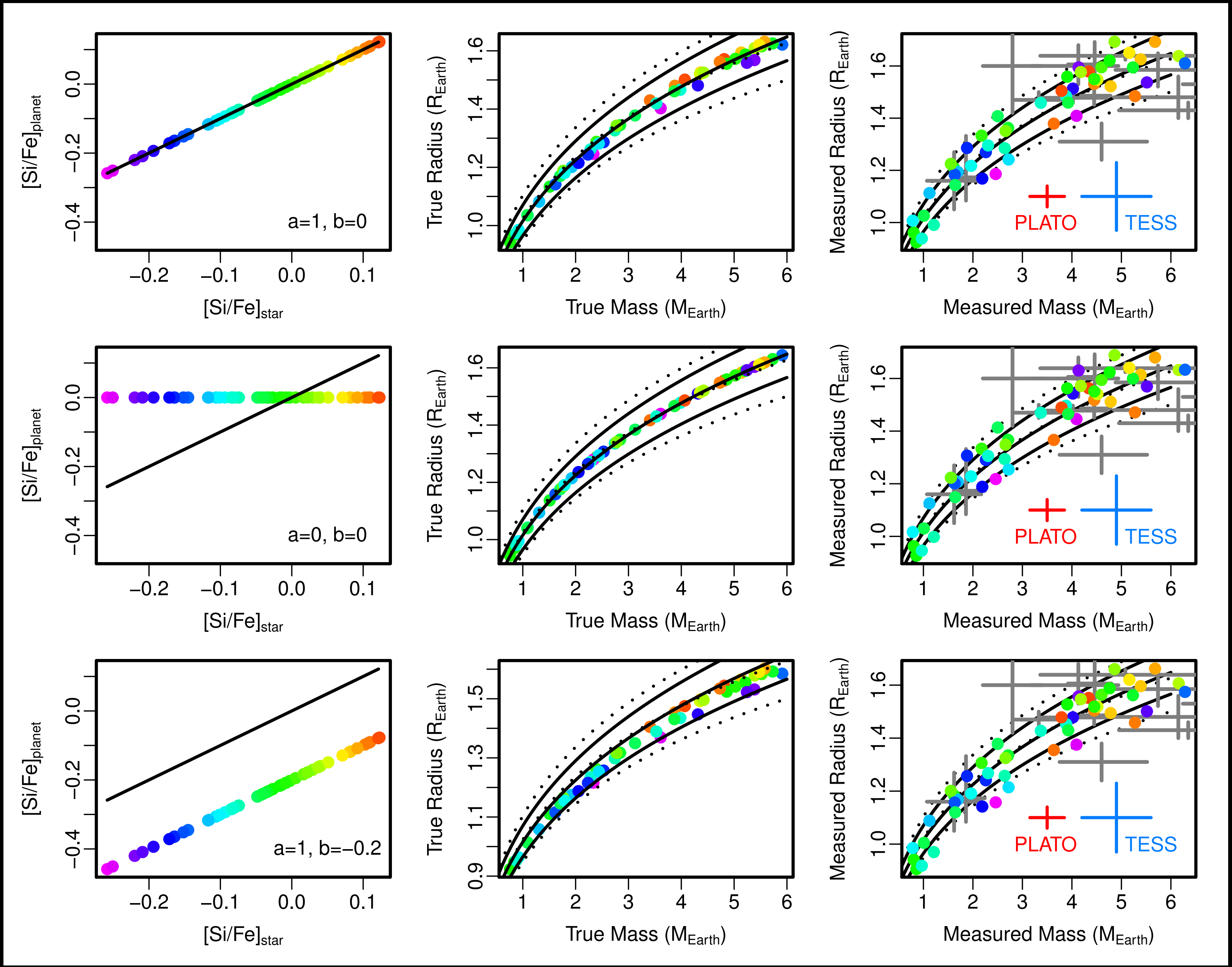
1) Generate population assuming a=1, b=0.
($[Si/Fe]_{pl}$ → rock/iron + internal structure → M, R)

2) Apply error bars to simulate uncertain M, R, [Si/Fe].

3) Perform hierarchical inference to get m, b constraints.

Simulating [Si/Fe] for star & planets

What number and quality of observations do we need to test $[Si/Fe]_{pl}$ = $[Si/Fe]_\star$ with TESS and PLATO?



Results

How well would we know the correlation parameters given the quality of the future data?

TESS:

σ_M = 20%

σ_R = 10%

$\sigma_{[Si/Fe]}$ = 0.1

(current techniques)

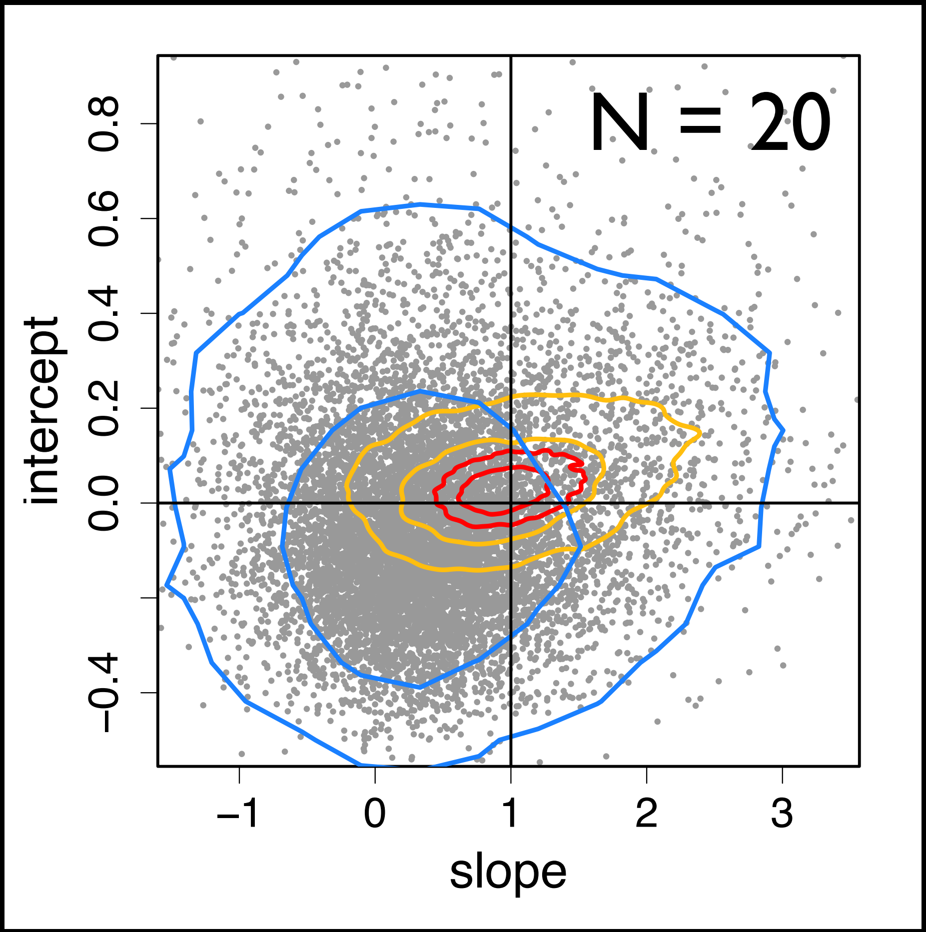
PLATO

σ_M = 10%

σ_R = 3%

$\sigma_{[Si/Fe]}$ = 0.05

(asteroseismology, improvements in stellar atmosphere modeling)



Gaia + 30 cm/s RVs

σ_M = 5%

σ_R = 1%

$\sigma_{[Si/Fe]}$ = 0.05

(Gaia parallaxes, next-generation radial velocity instrumentation, improvements in stellar atmosphere modeling)

Results

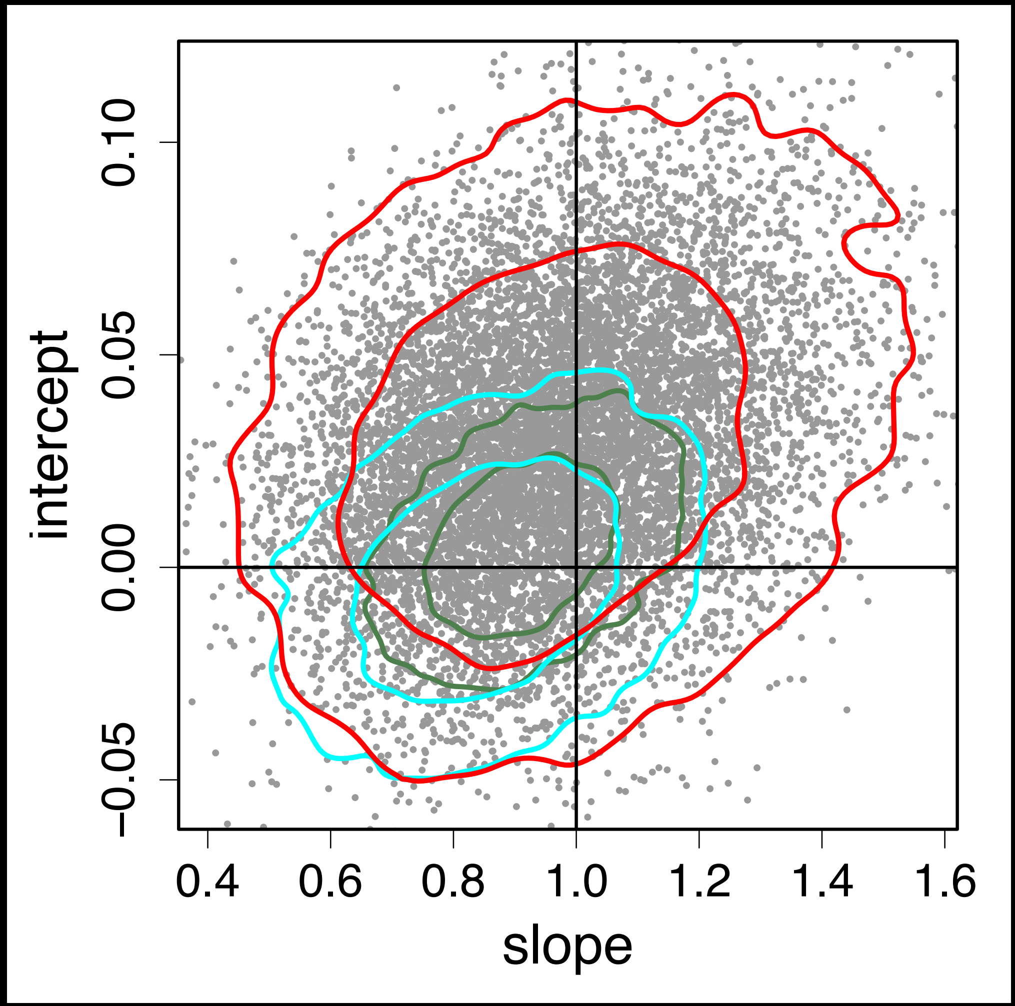
How well would we know the correlation parameters given the size of the future dataset?

Gaia + 30 cm/s RVs:

$\sigma_M = 5\%$

$\sigma_R = 1\%$

$\sigma_{[Si/Fe]} = 0.05$



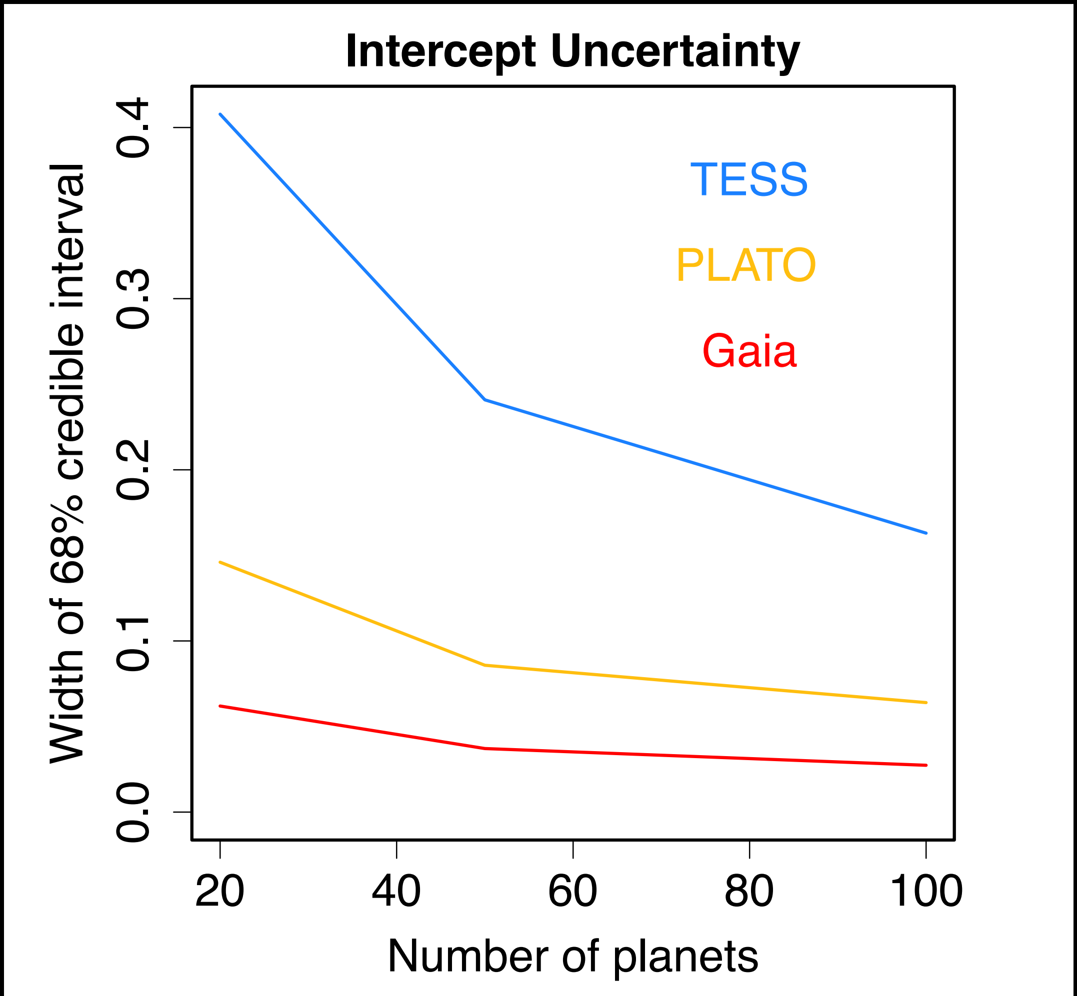
N = 20

N = 50

N = 100

But intercept interesting too!

If stellar [Si/Fe] is systematically offset from planet rock mass fraction, then giant impacts could be important for exo-Earths!



How well can we constrain intercept?

With radii constrained to 1-3% and masses constrained to < 5%, could find systematic differences between $[Si/Fe]_{pl} - [Si/Fe]_{\star} \sim 0.05$

Conclusions

Composition distribution of Kepler's sub-Neptunes:
the typical 1 < R_{Earth} < 4 planet has ~1% mass in H+He envelope;
95% have envelope fractions between 0.1% and 10 %

BUT this **result is non-unique** when constrained by mass and radius.
Modelers are using **stellar abundances to break degeneracies.**

Empirically testing $[Si/Fe]_{pl} = [Si/Fe]_{\star}$ is possible with
1% errors on R_{pl} (Gaia is needed)

Lower precision datasets could test for systematic offsets in stellar [Si/Fe] versus planet rock mass fraction (rmf), which can probe the **prevalence of giant impacts** on a population level.

Stay tuned for a 2030 thesis near you!!