Planet Formation in Star-Forming Regions

: from the Solar System to Other Worlds

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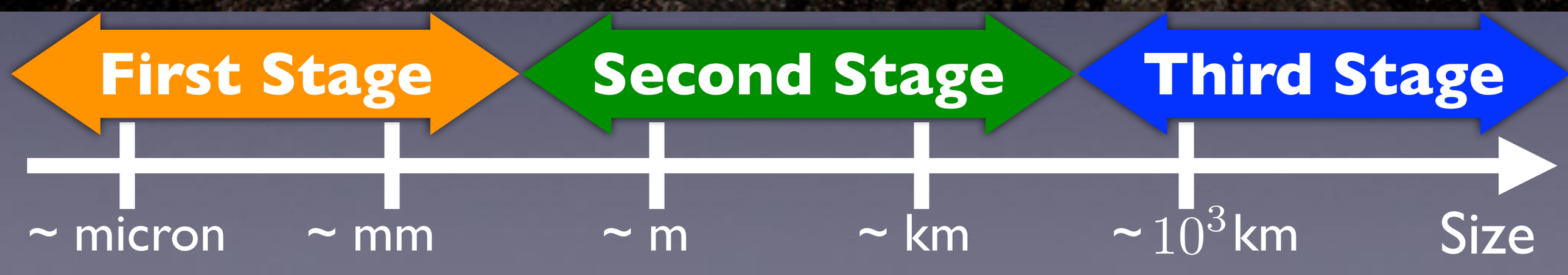
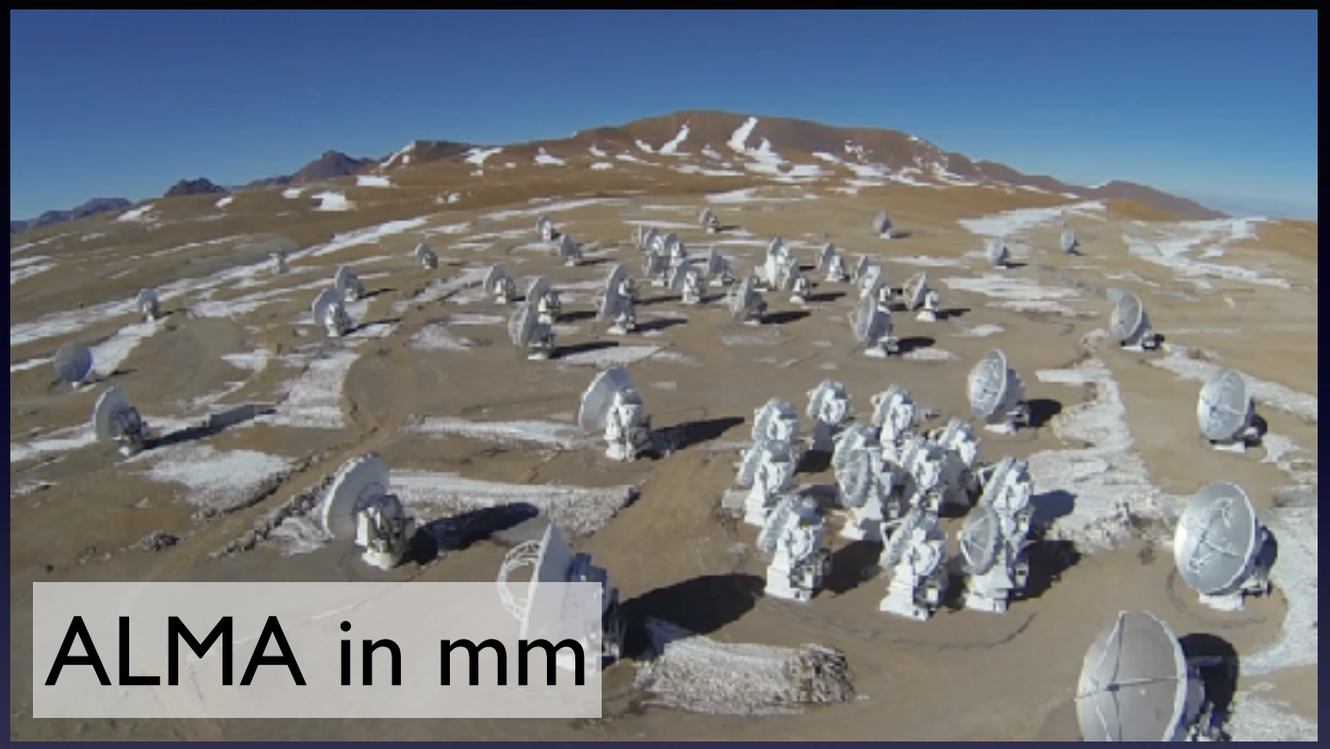
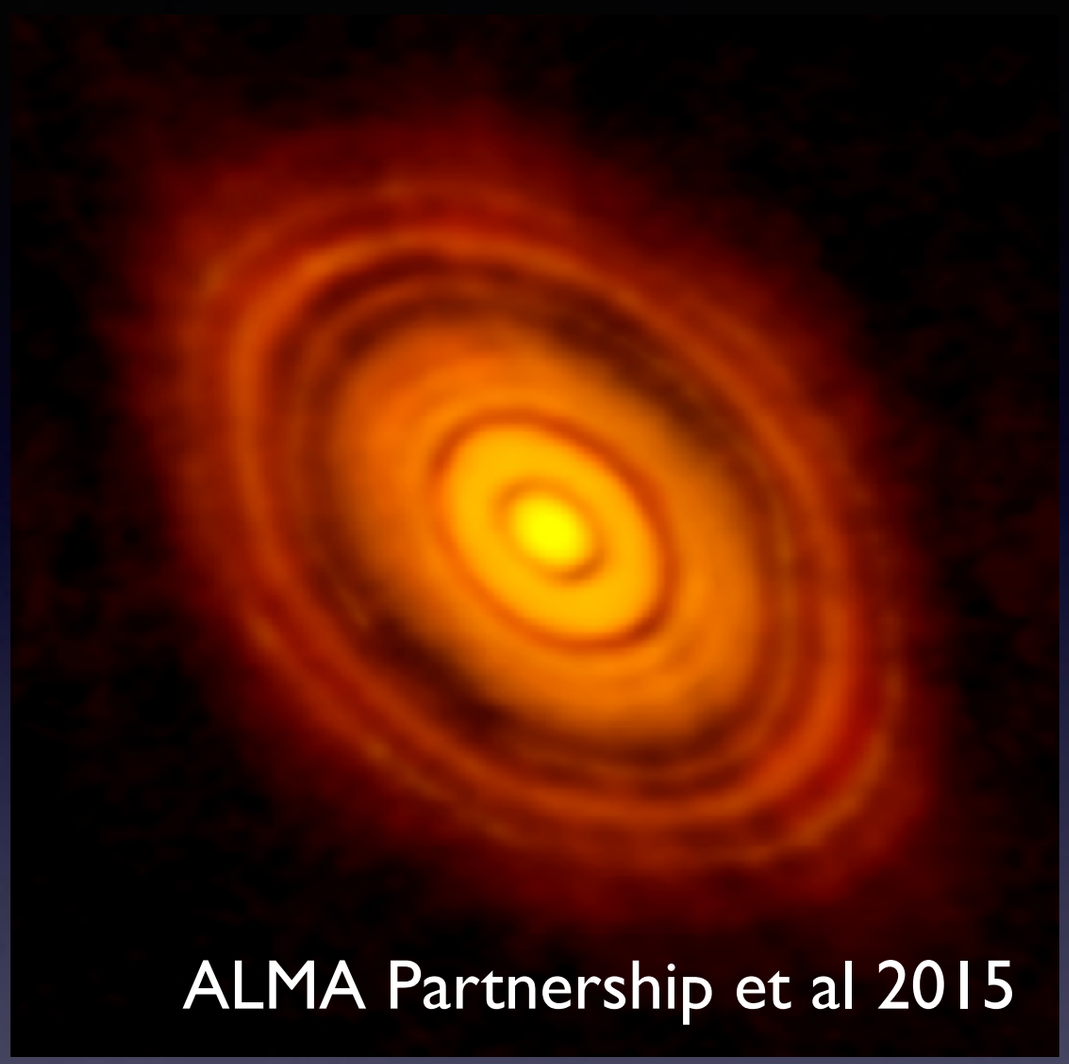
California Institute of Technology



1. Evolution in Astronomical Disk Observations



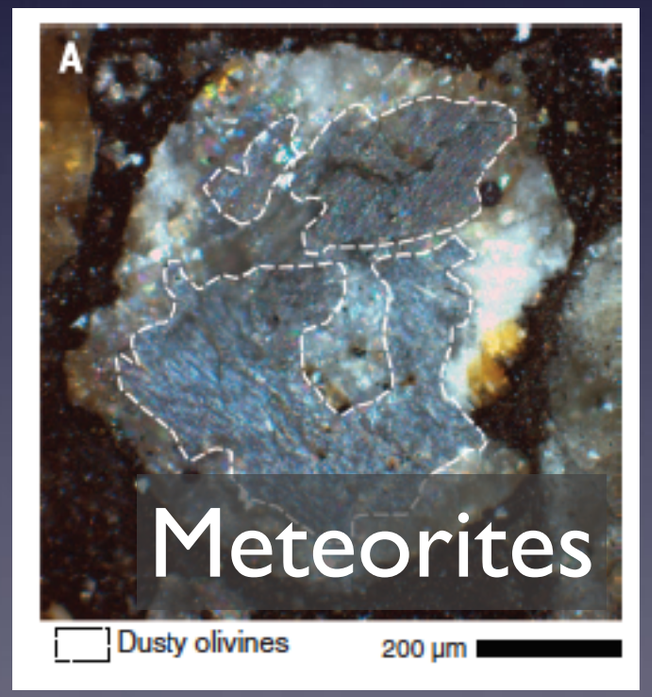

ALMA Partnership et al 2015

We can **see** planet-forming regions

JWST is coming soon

2. Evolution in Space Engineering & Lab Experiments

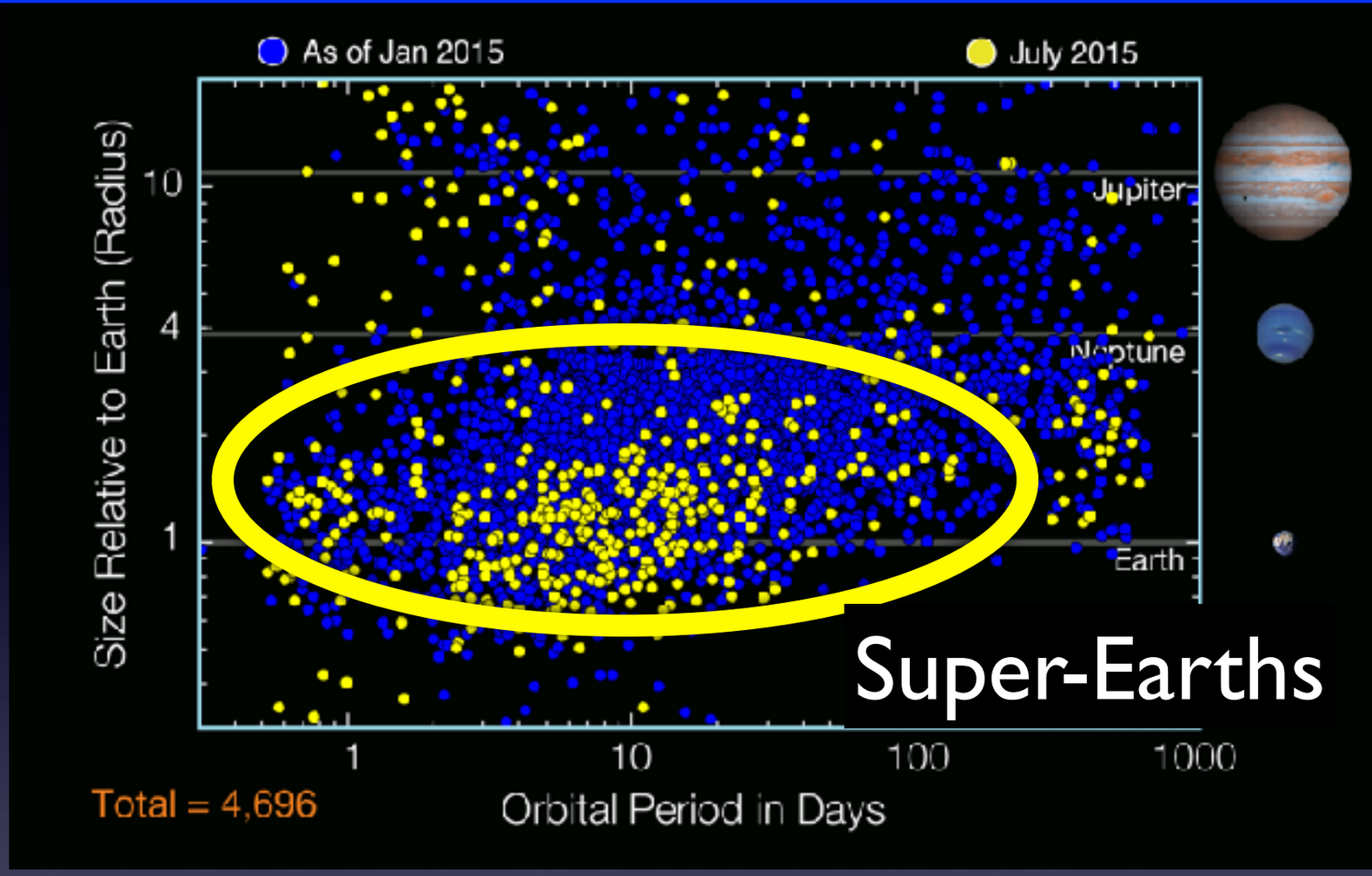
We can **touch** planet-forming materials



Second Stage

~ micron ~ mm ~ m ~ km ~ 10^3 km Size

3. Evolution in the Number of Known (exo)Planets



We can **characterize** (exo)planetary systems

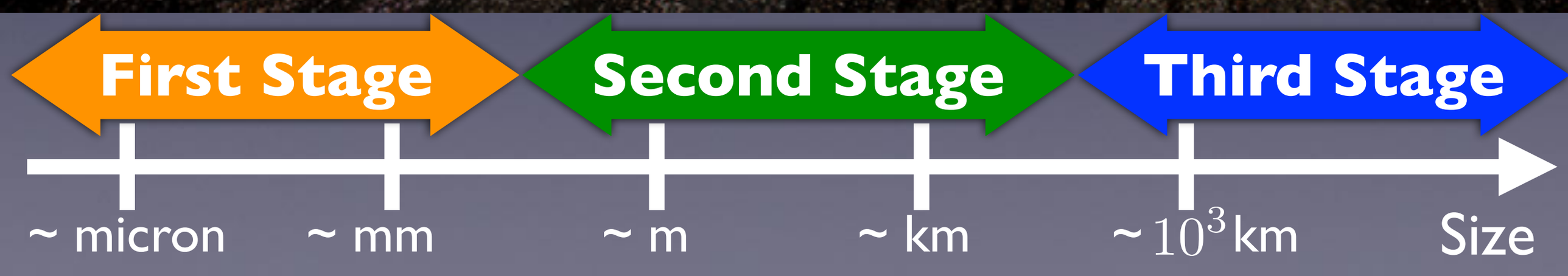
Third Stage

~ micron ~ mm ~ m ~ km ~ 10^3 km Size

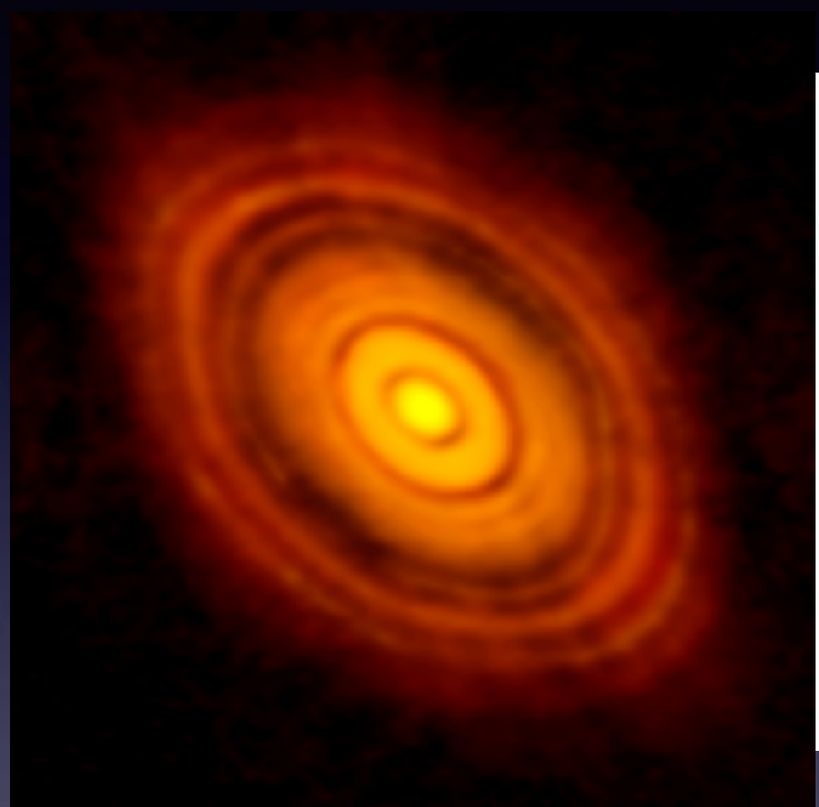
Planet formation: Long journey from dust to planets

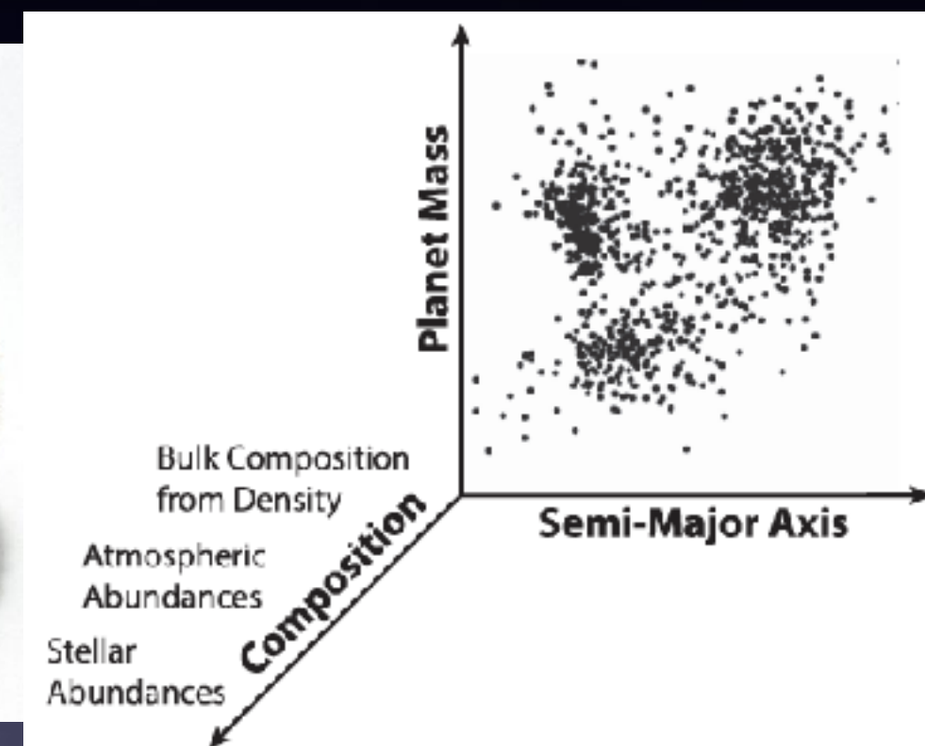
Golden era of (exo)planetary sciences

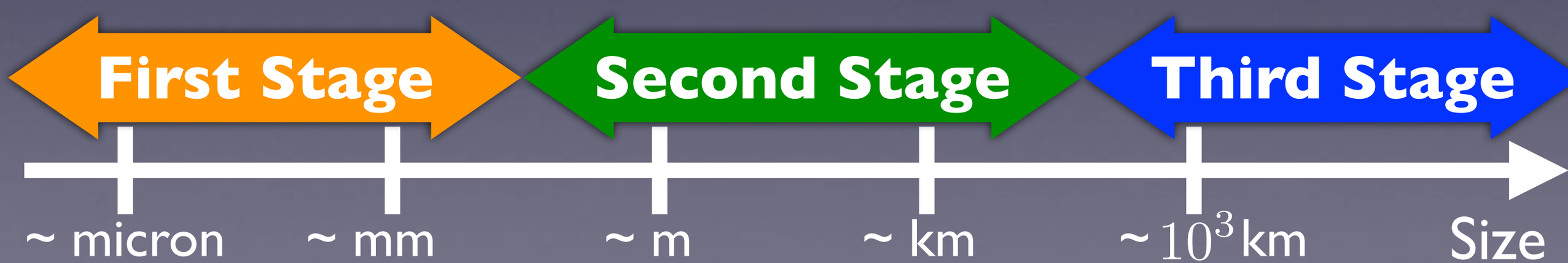
A Comprehensive Examination of Planet Formation Covering the Full Size Range



A Comprehensive Examination of Planet Formation







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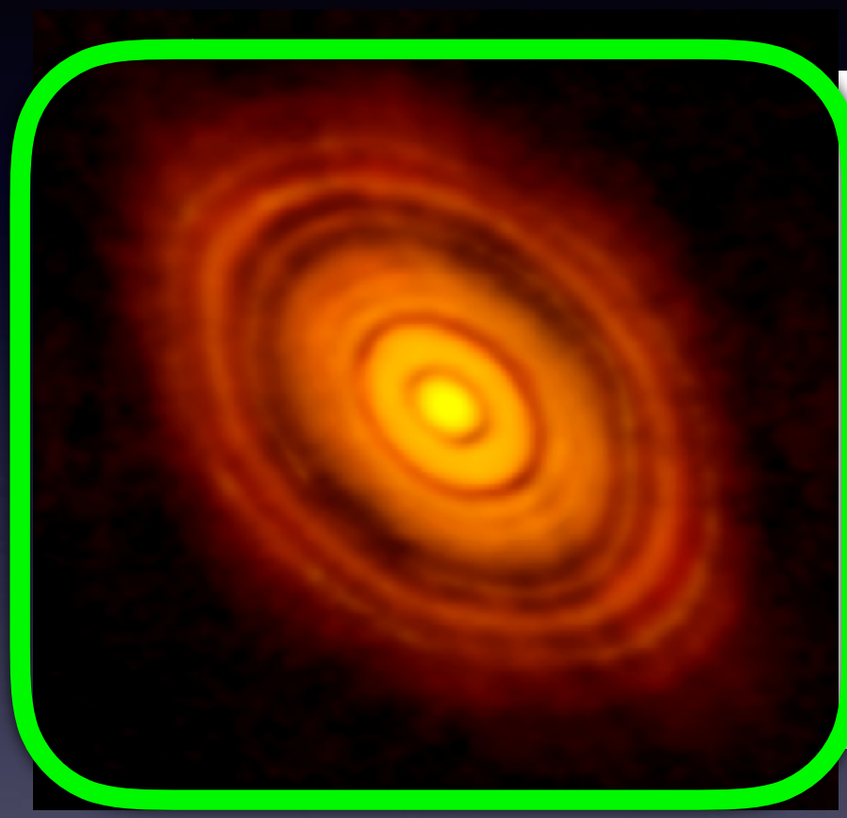
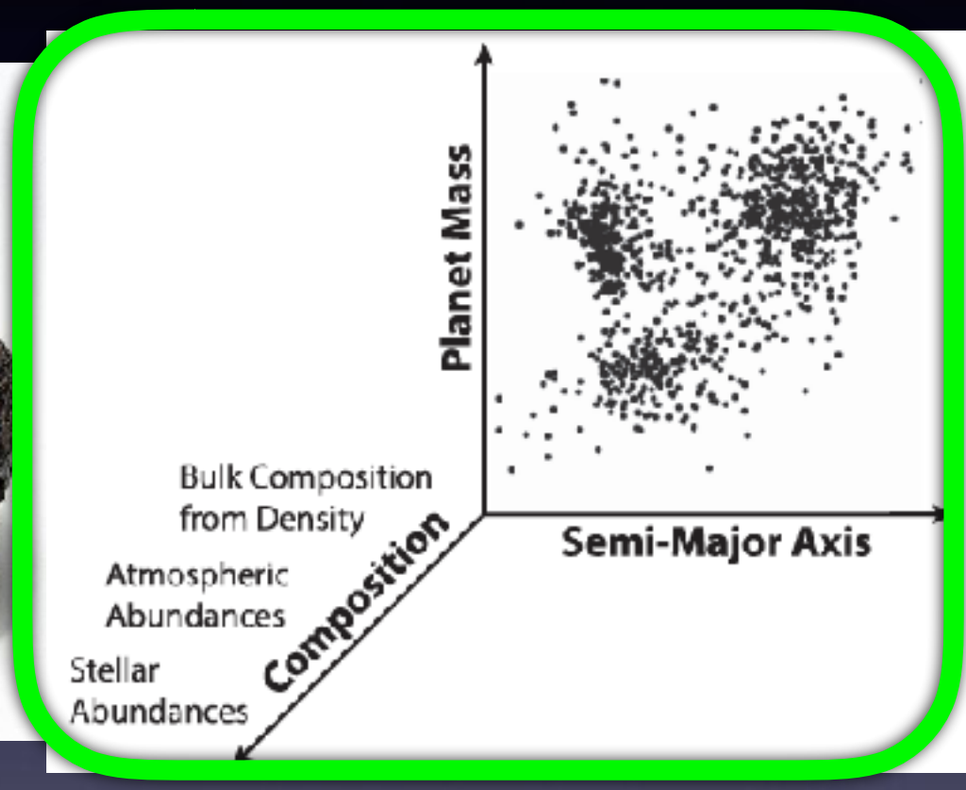
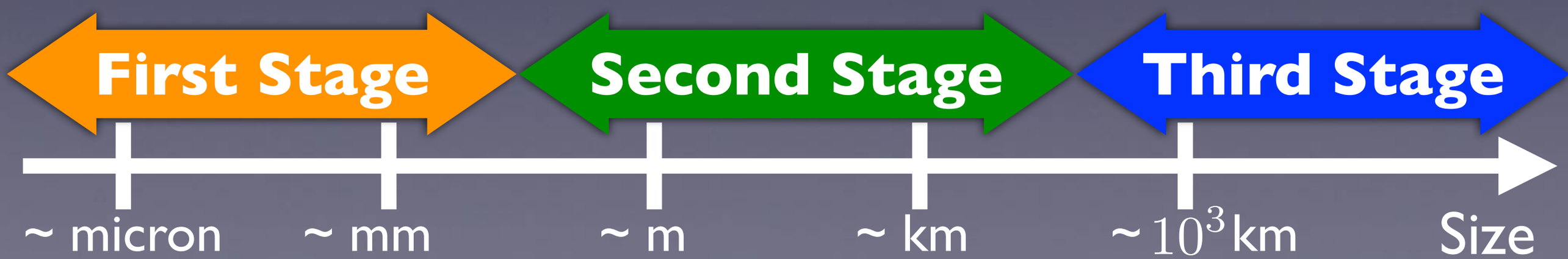
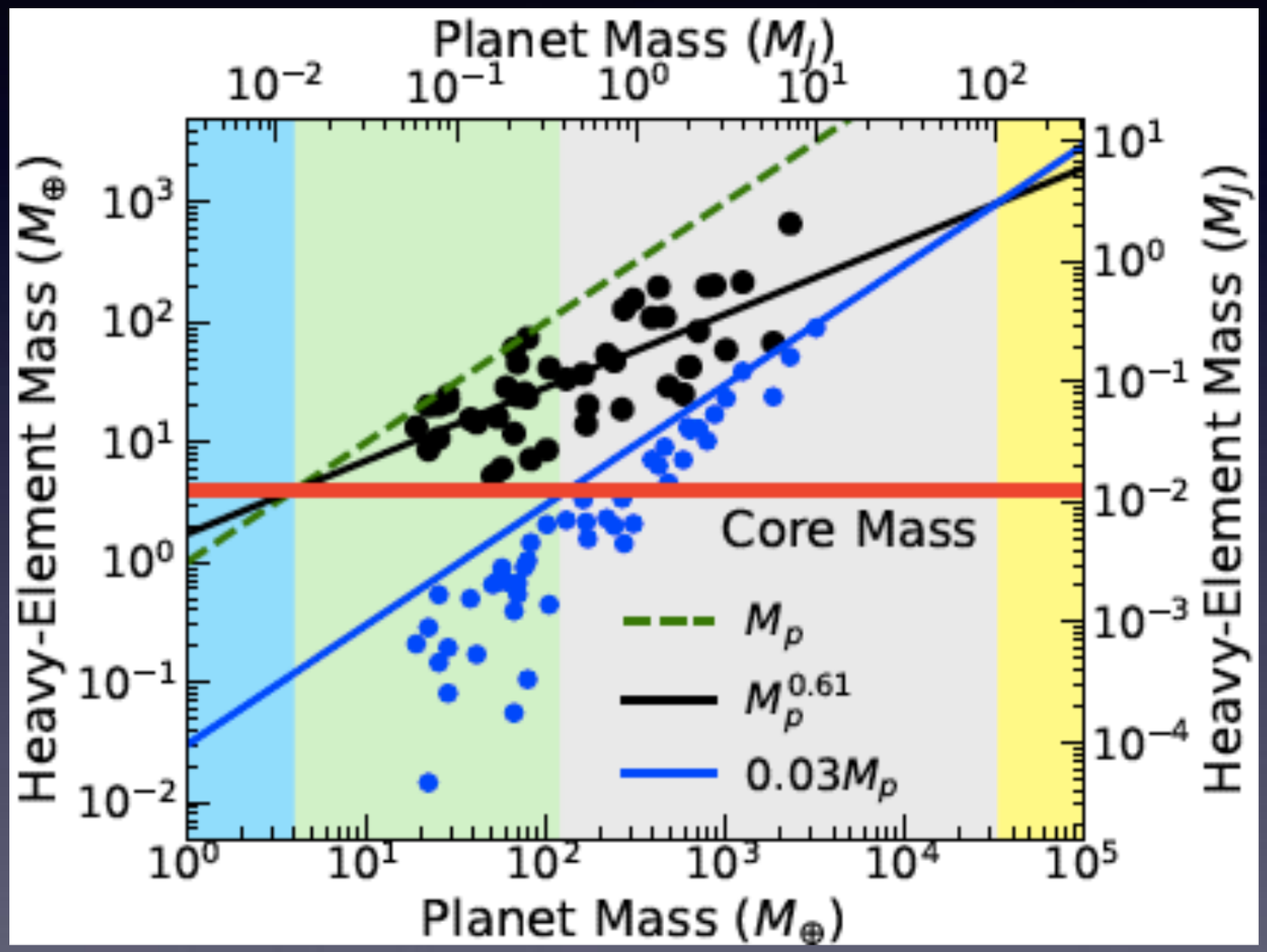
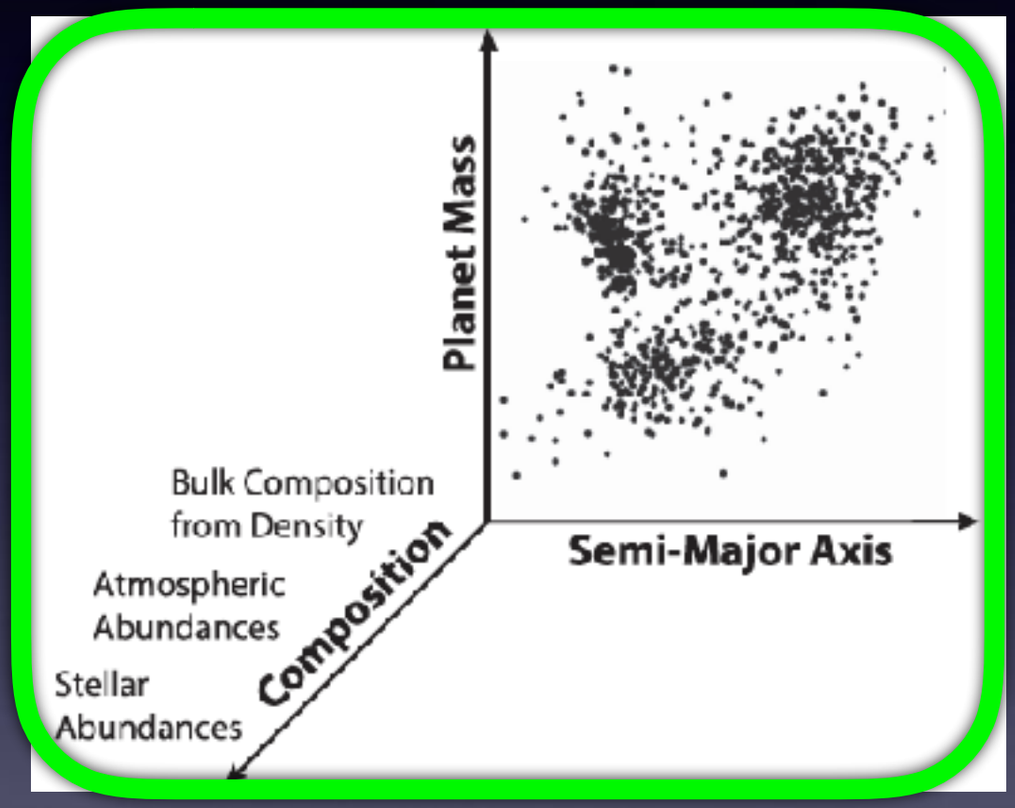


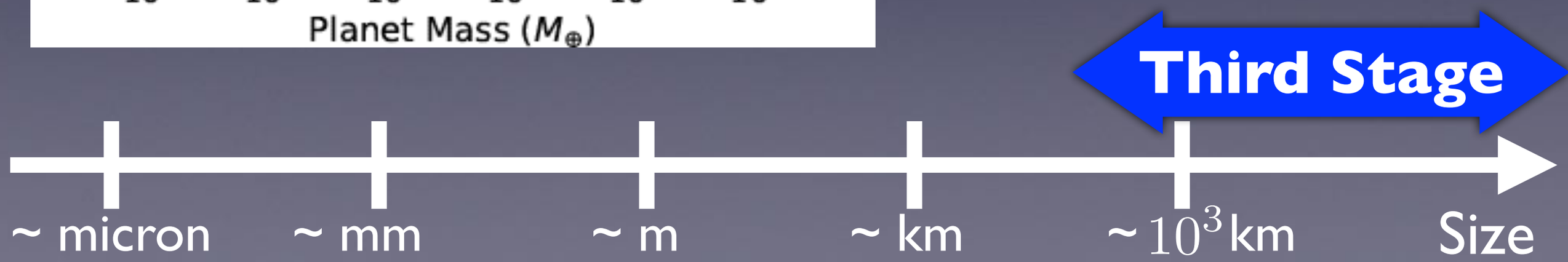




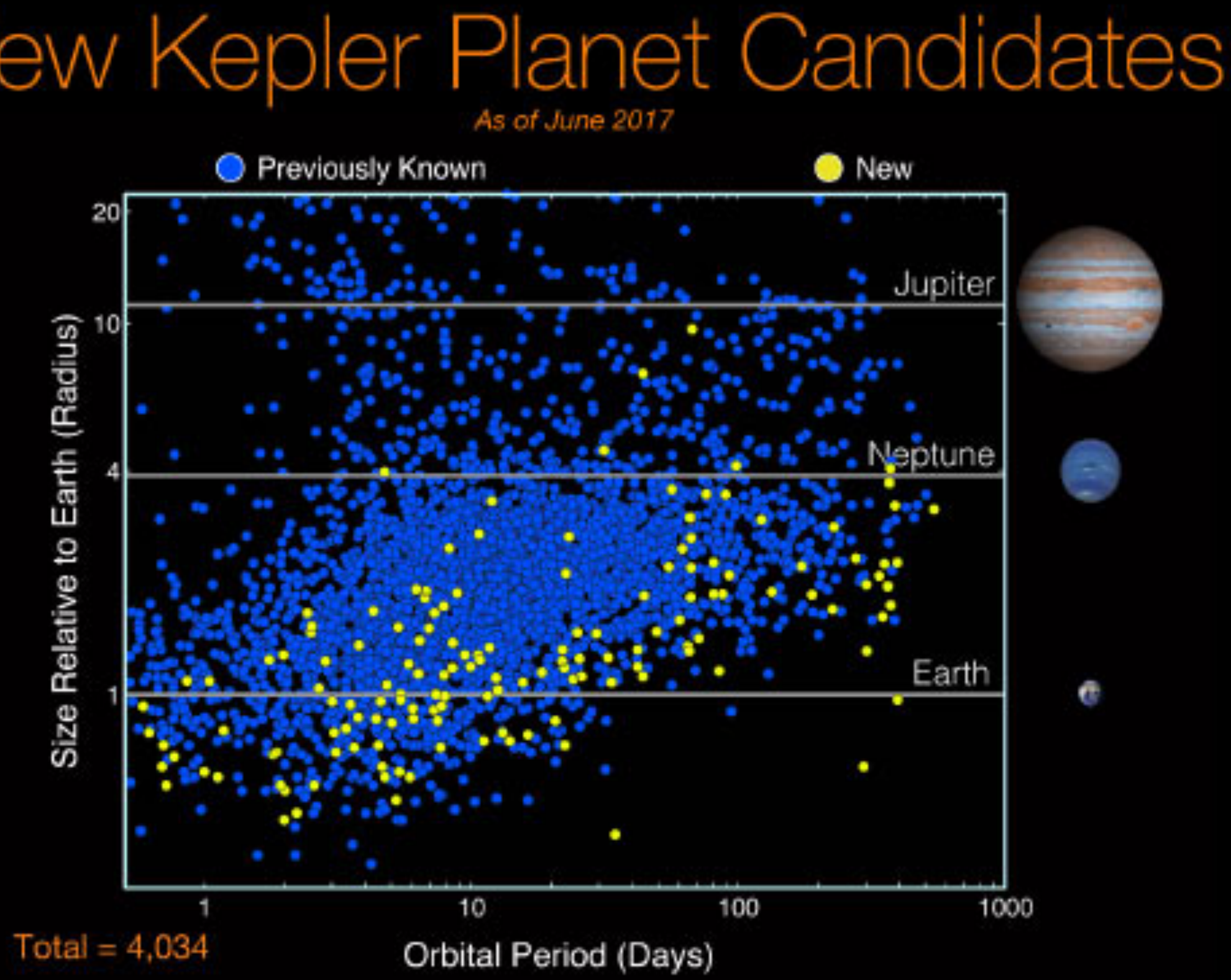
The Origin of the Total Heavy Element in Observed Exoplanets



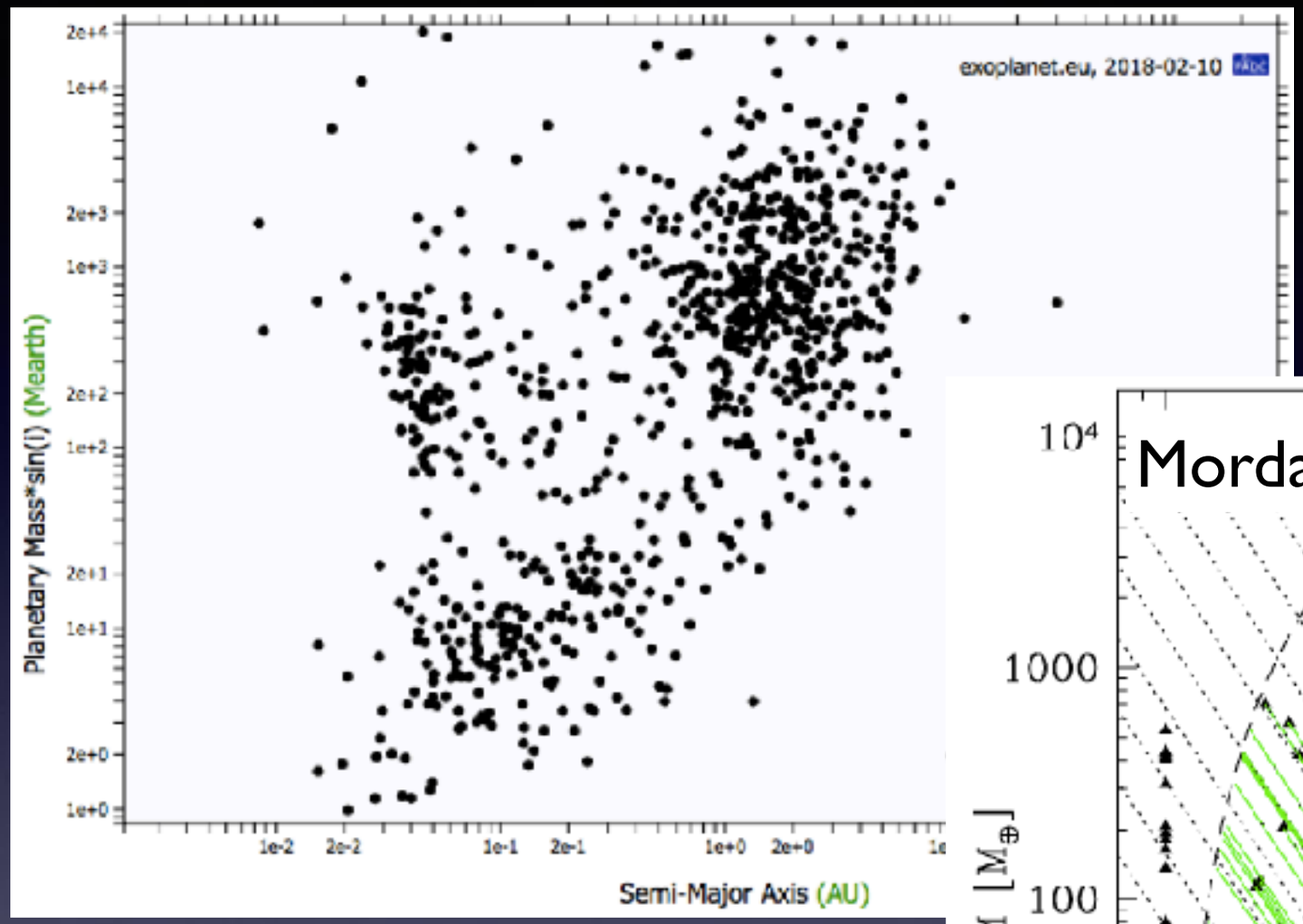


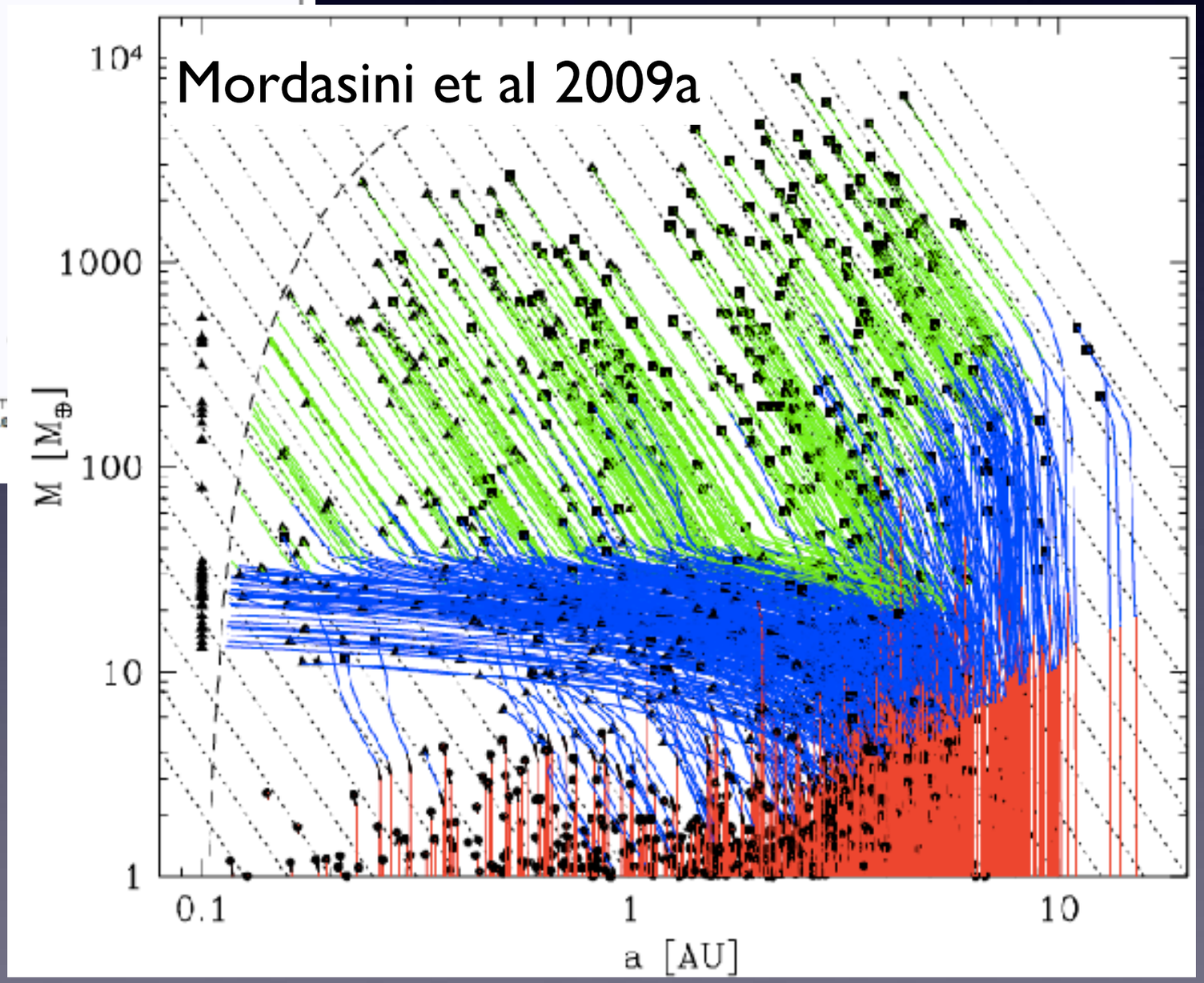


Exoplanets are Ubiquitous in Our Galaxy



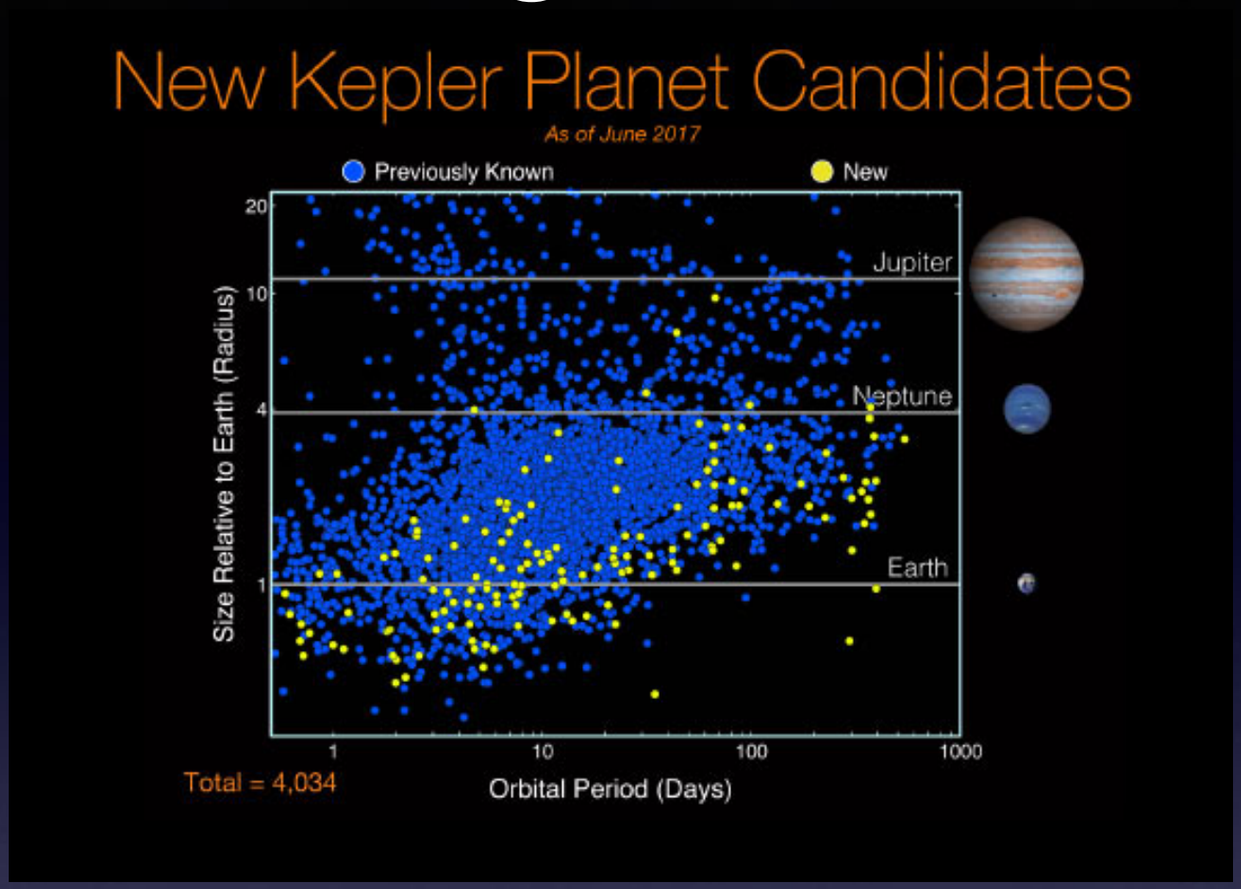
Background 1: How do Planets form?

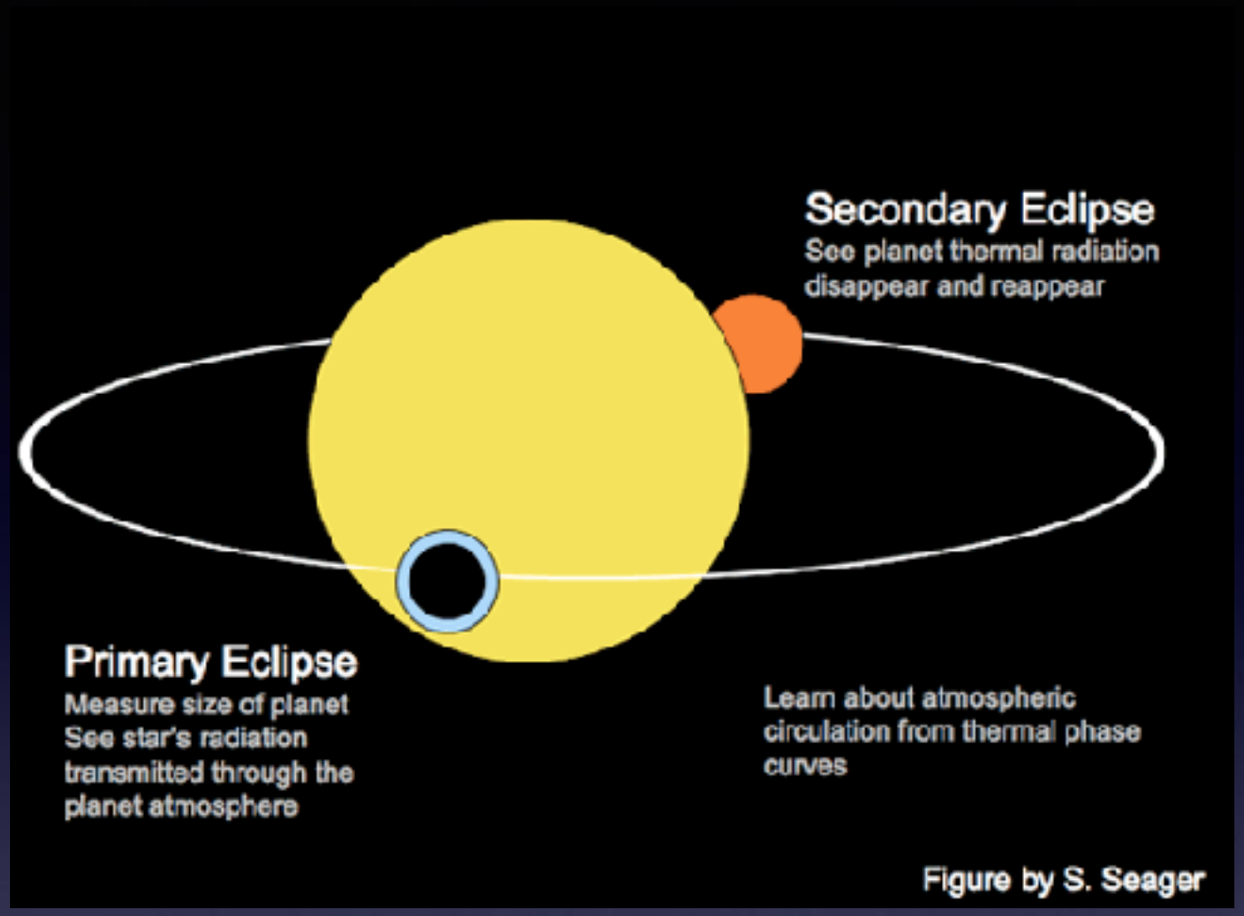




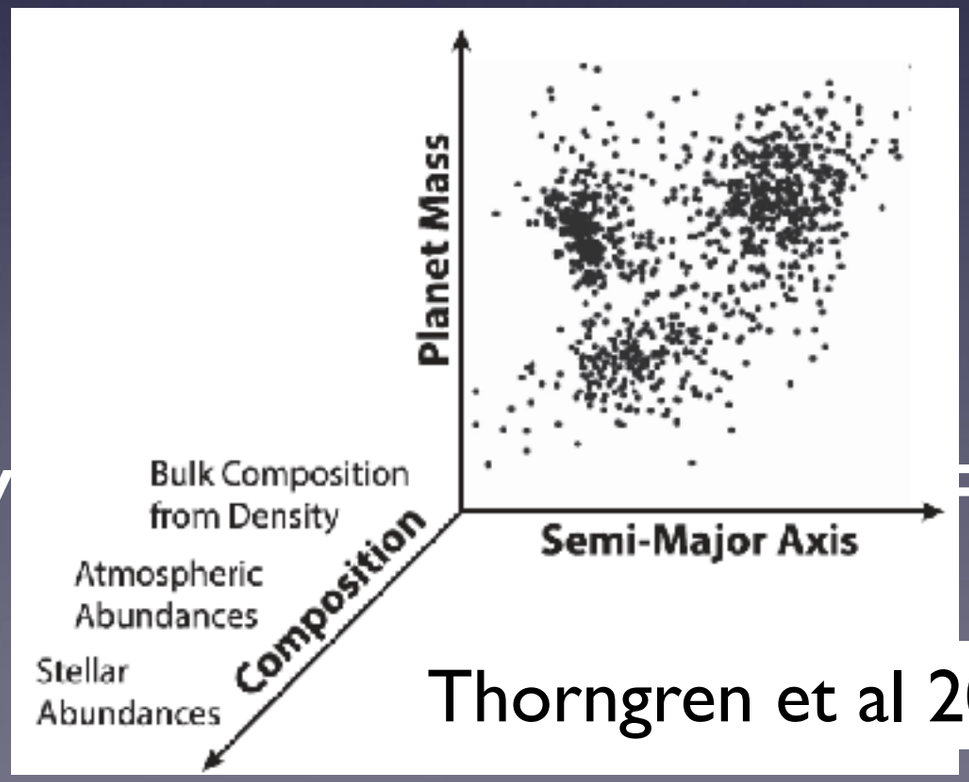
The planet mass-semimajor axis can be observed

Background 2: How do Planets form?





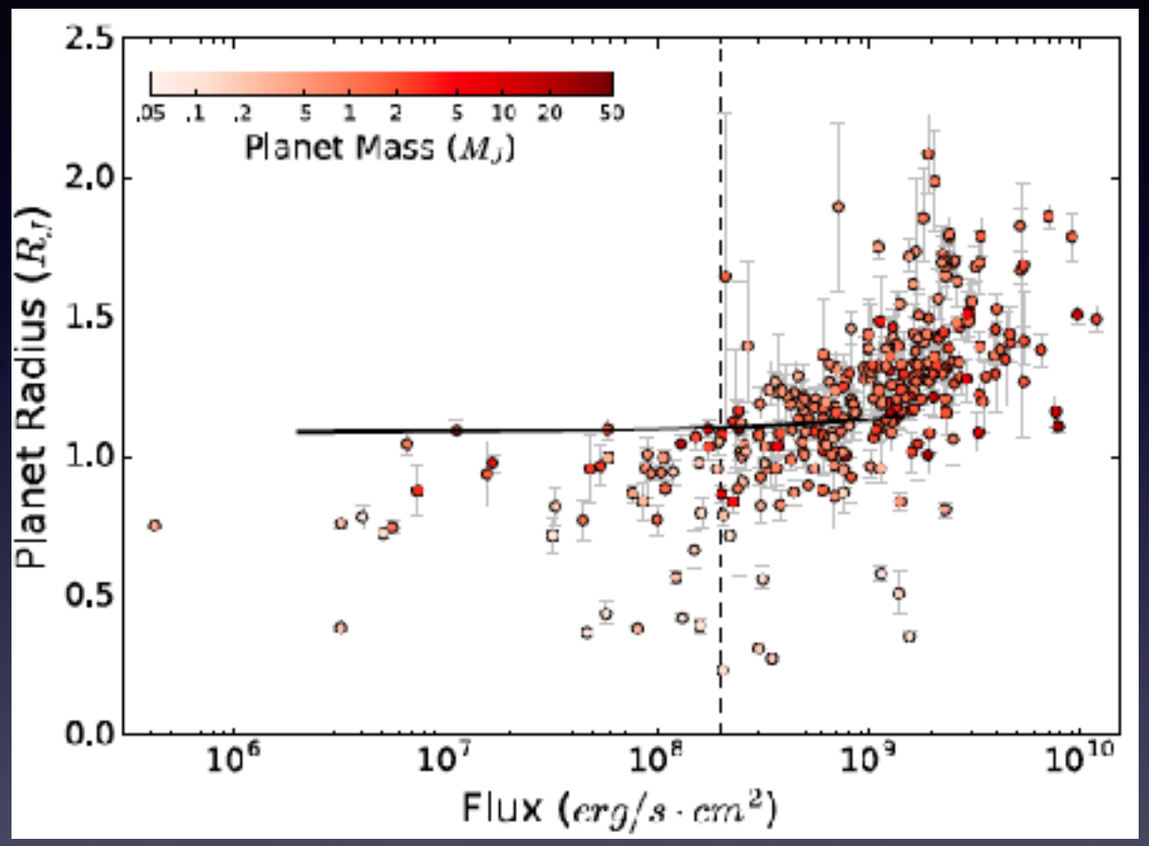
The planet radius can be observed => the bulk density

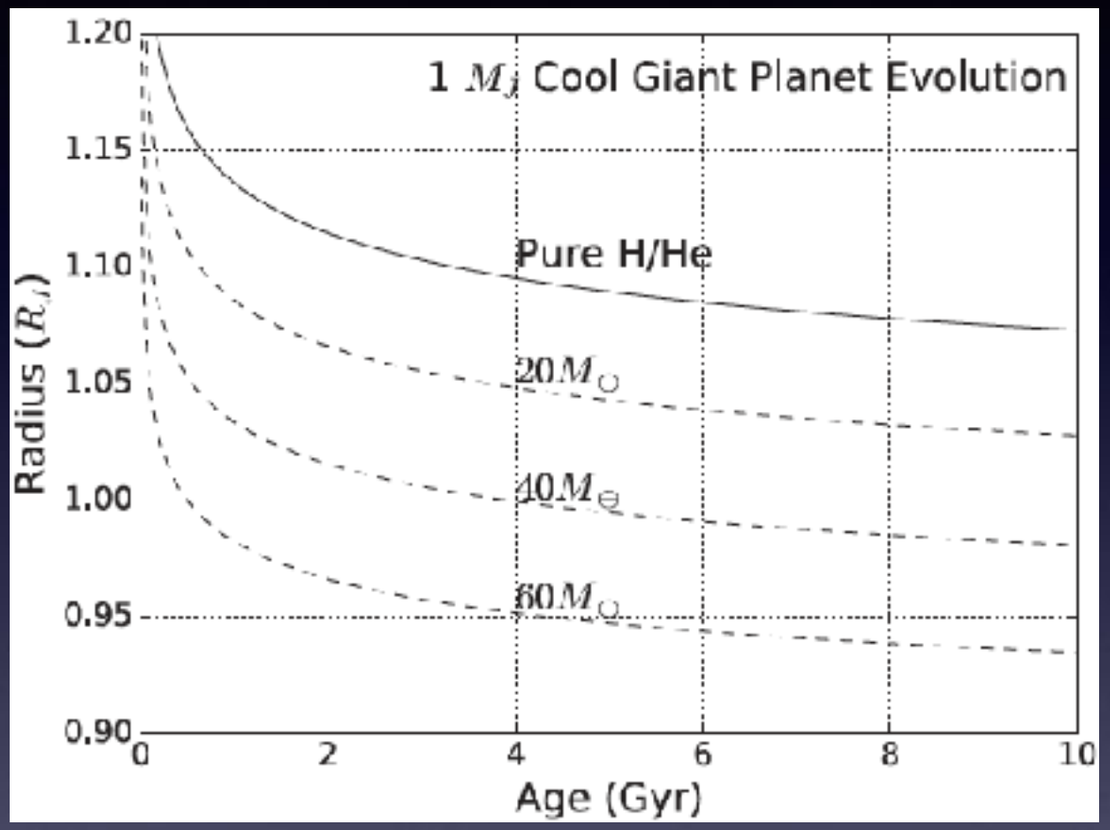


Thorngren et al 2016

The atmosphere can be observed => the composition

Estimate of the heavy element mass in observed exoplanets

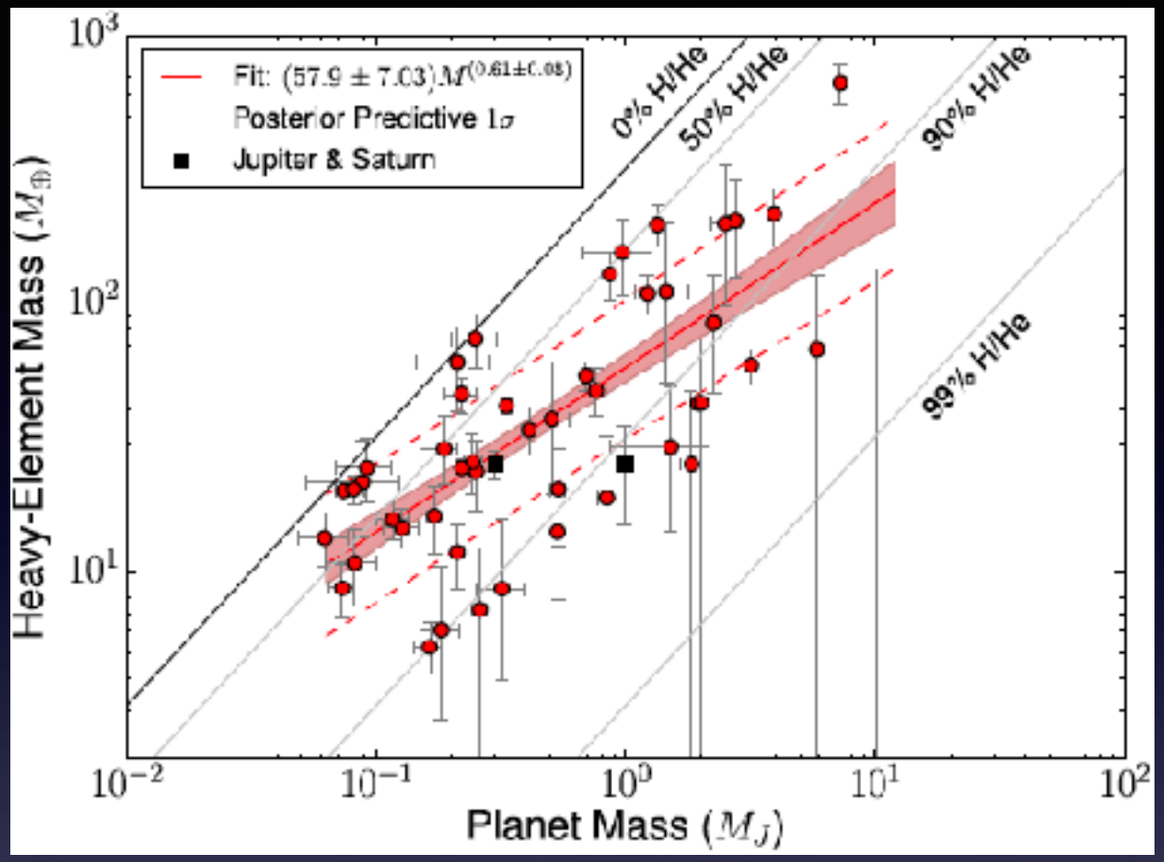


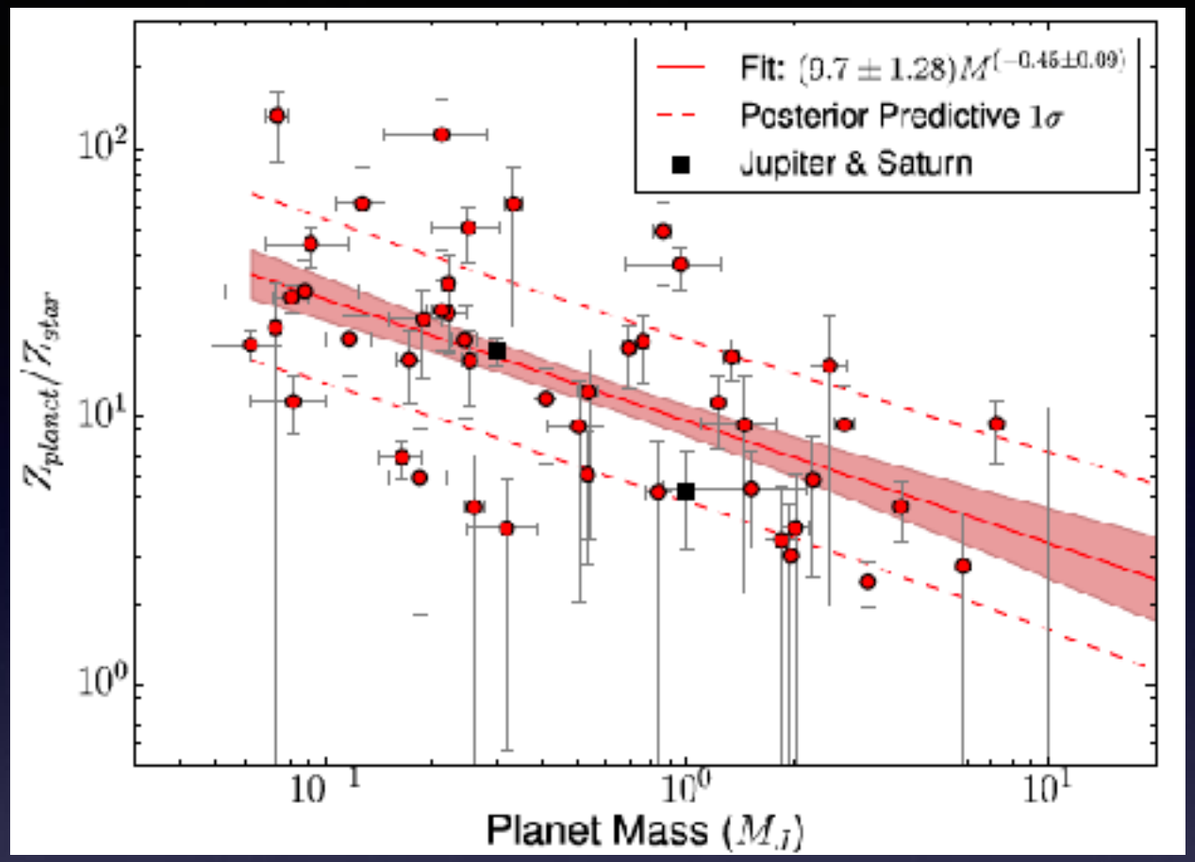


Target selection: relatively cool close-in exoplanets

Compute the radius evolution of planets,
by distribute heavy elements in cores and atmospheres

Results of Thorngren et al 2016





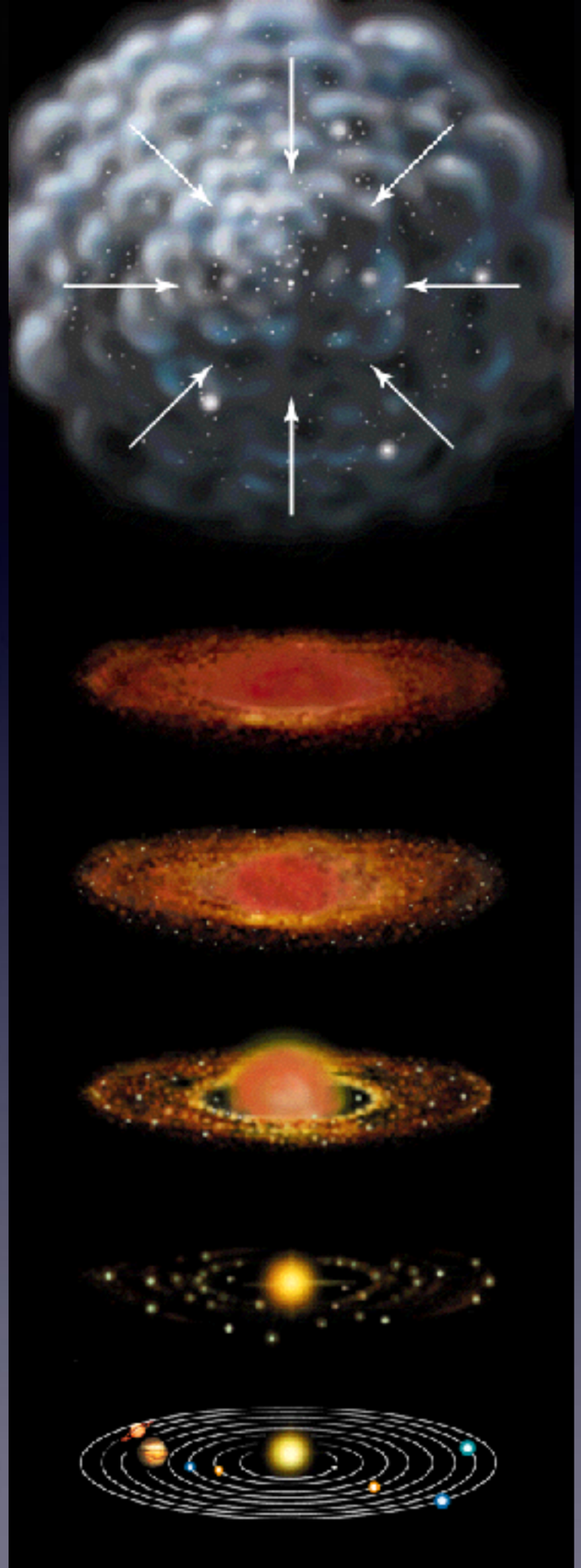
$$M_Z \propto M_p^\gamma \text{ with } \gamma = 0.61 \approx 3/5$$

$$\frac{Z_p}{Z_s} = \frac{M_Z}{M_p}\frac{1}{Z_s} \propto M_p^\alpha \text{ with } \alpha = -0.45 \approx -2/5$$

$\alpha \approx \gamma - 1$ => M_Z and M_p are almost independent of Z_s

M_Z : the total heavy element mass in planets with the mass of M_p

Z_s : the metallicity of the host star



Current Picture of Planet Formation

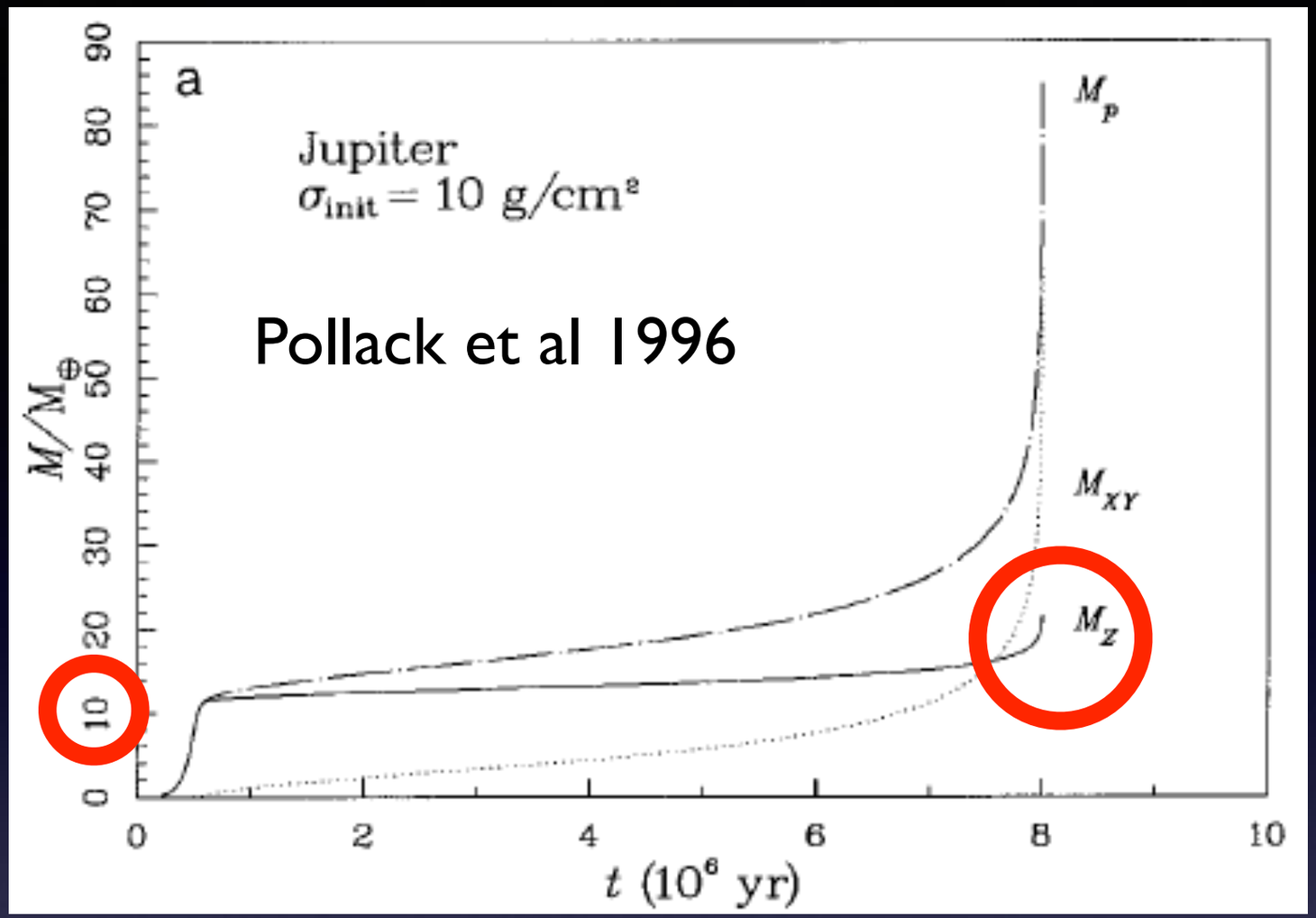
e.g., Hayashi 1981

Planet formation is a natural outcome of star formation

The natal disk is composed of gas and solids

Planetary systems form in the disk around the central star

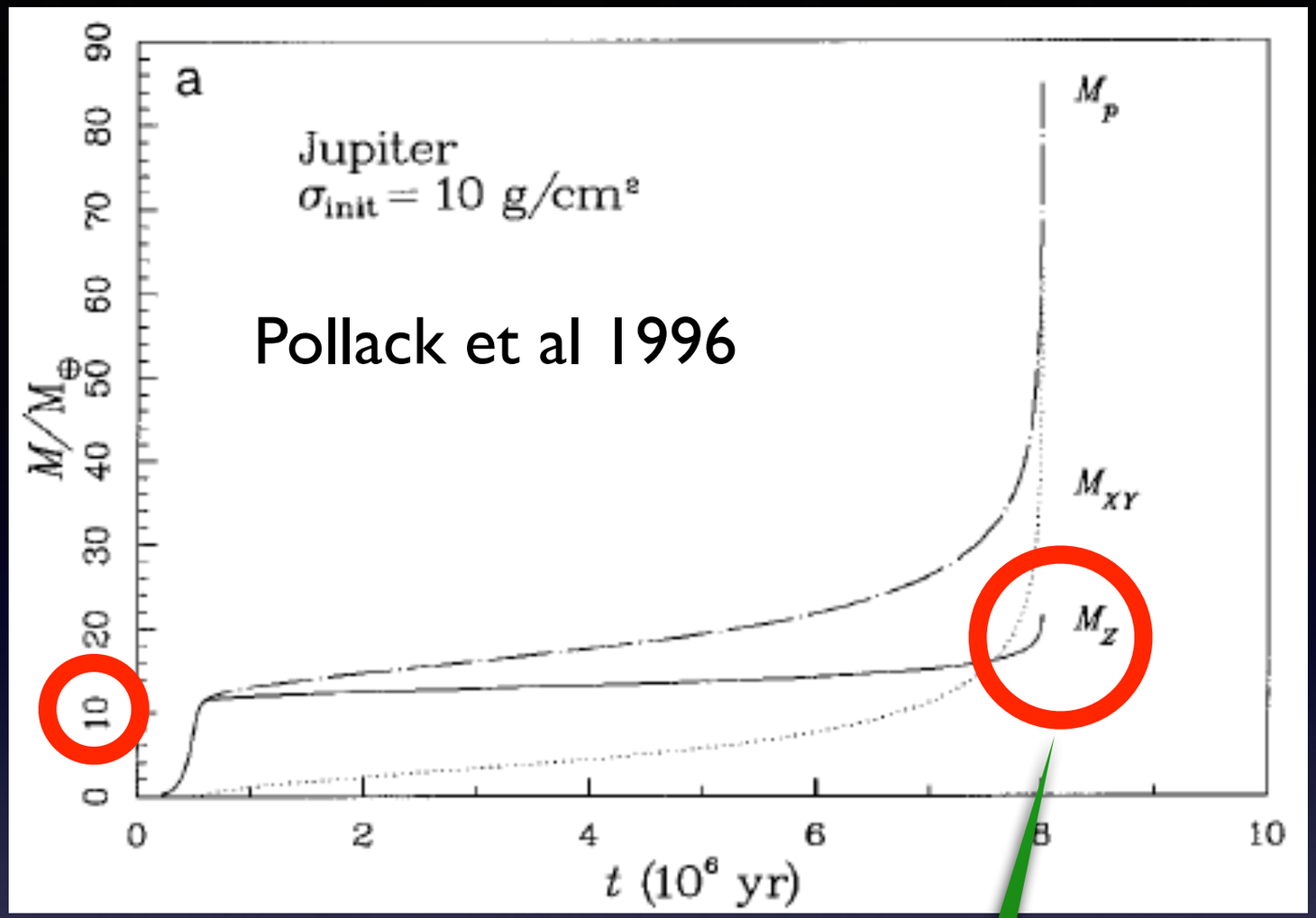
Planet Formation via Core Accretion: Accretion of Gas and Solids



$M_{core} \simeq 10 M_\oplus$

M_Z increases at the final formation stage

Planet Formation via Core Accretion: Accretion of Gas and Solids



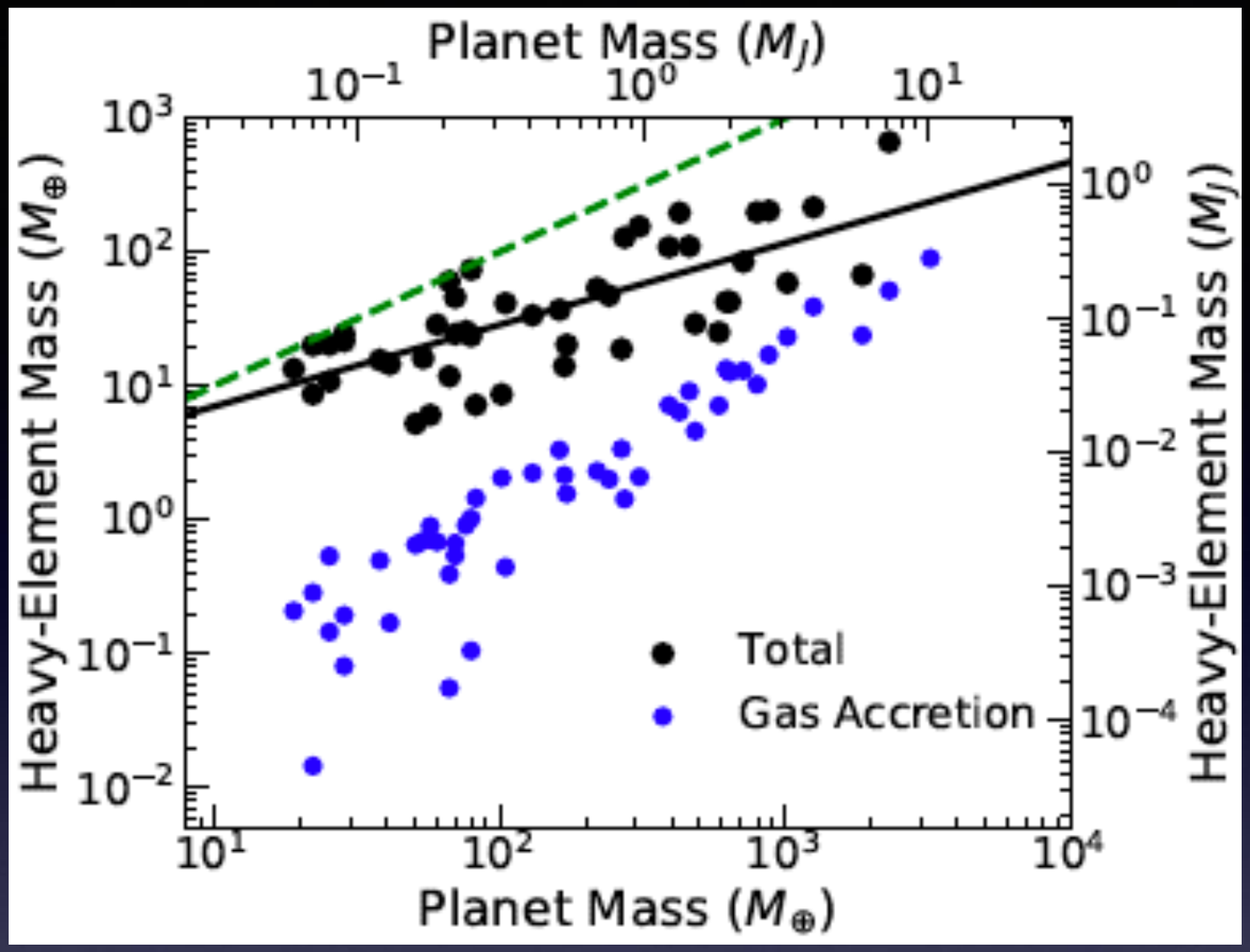
$$M_p = M_{XY} + M_Z$$

$$M_Z = M_{core} + M_{pl} + M_{pe} + M_{Z,gas}$$

Planetesimals

Pebbles

dust in gas



$$M_{Z,gas} = Z_s M_{XY}$$

Contribution arising from gas accretion is negligible

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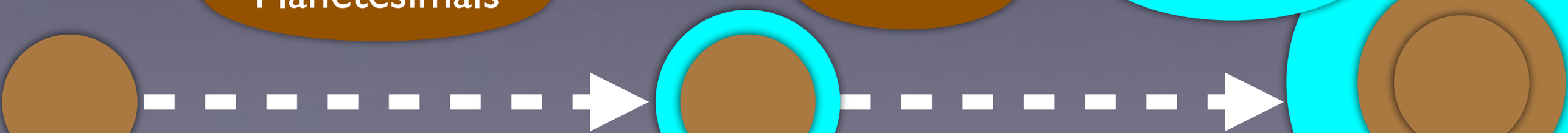
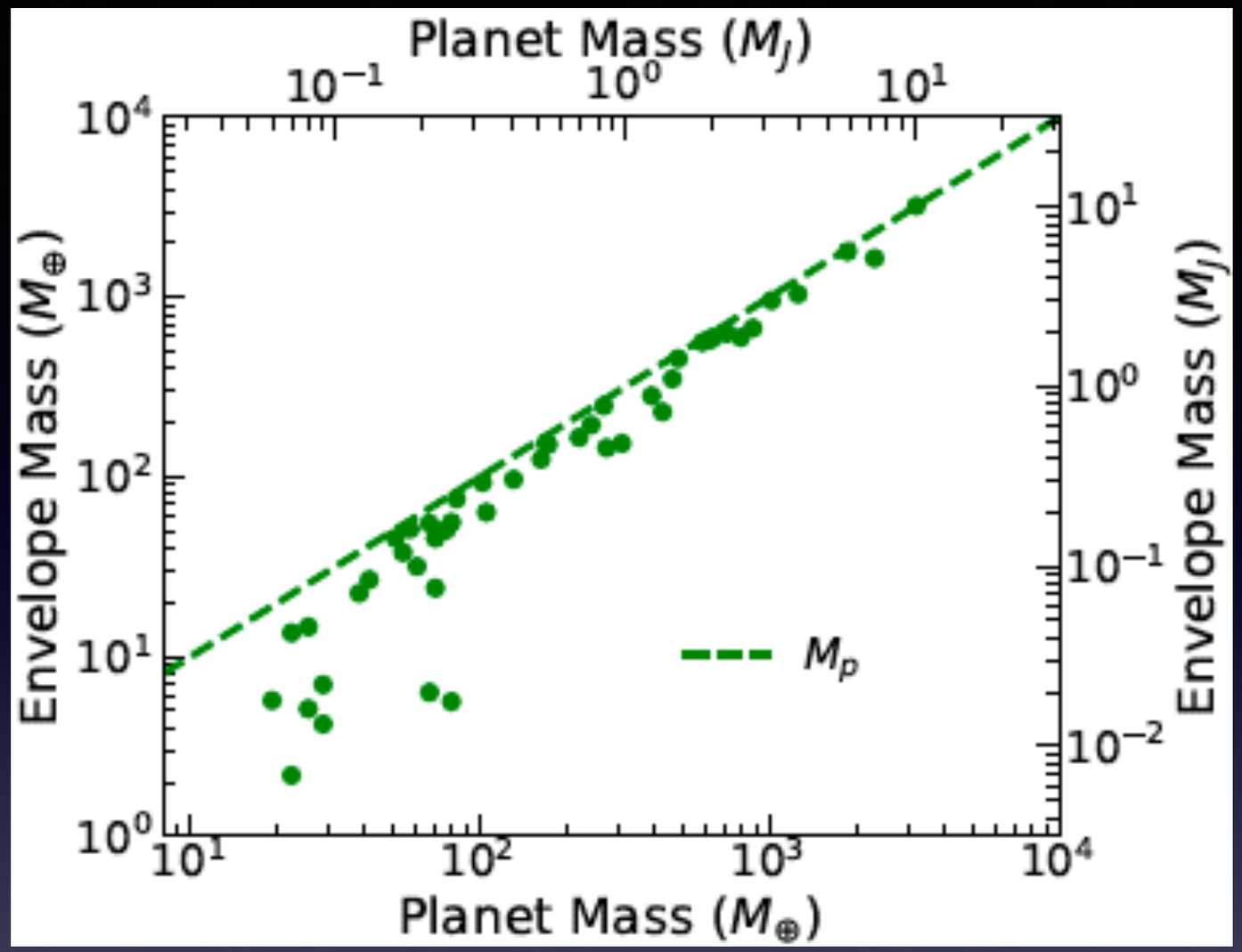




$$M_{Z,gas} = Z_s M_{XY}$$

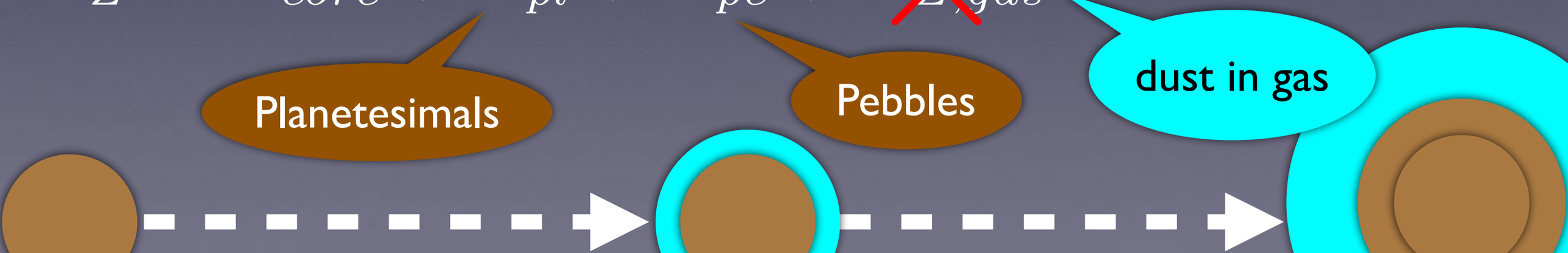
Contribution arising from gas accretion is negligible

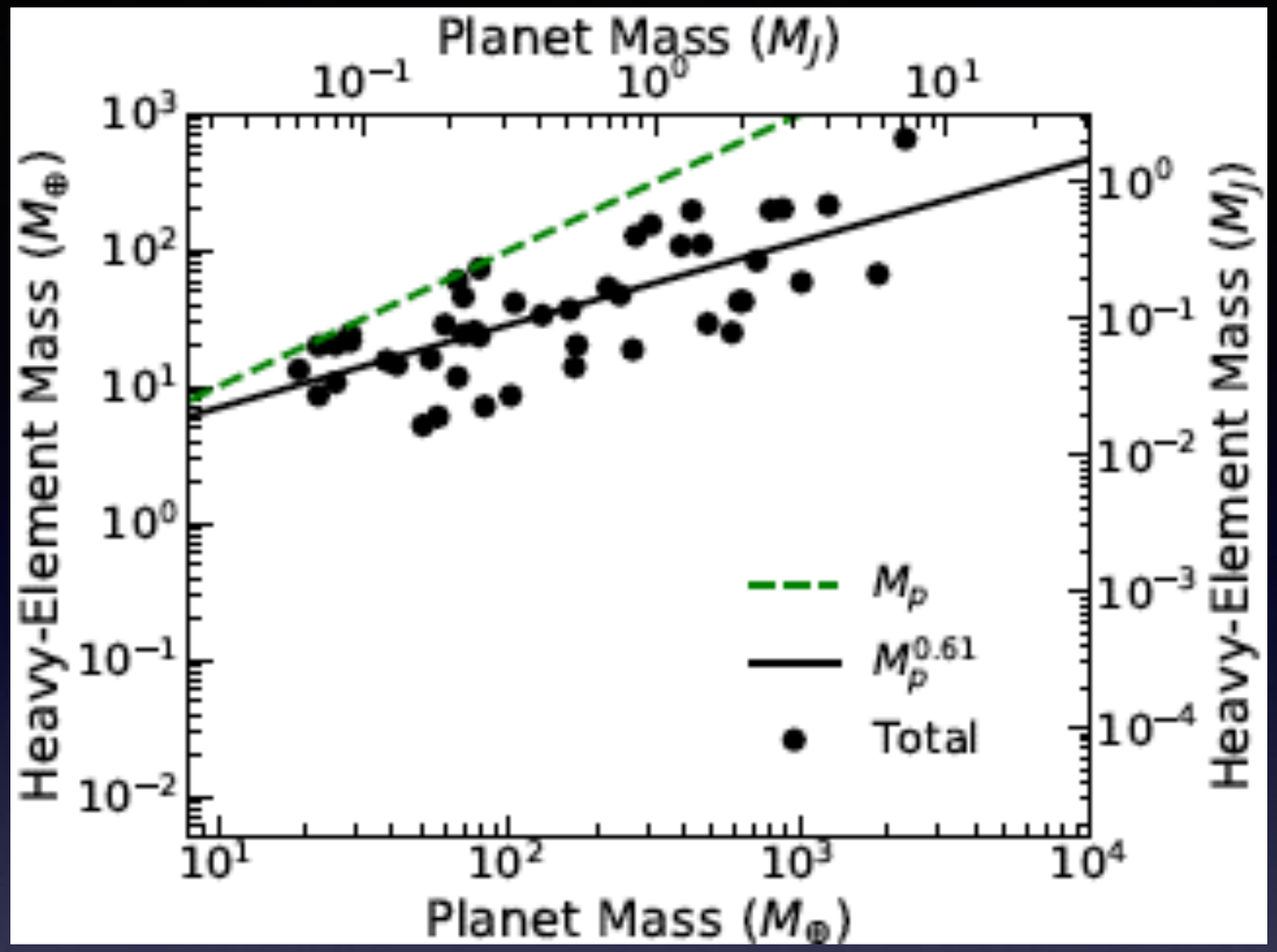
Runaway gas accretion occurred for planets with $M_p > 100 M_\oplus$

Some mechanisms are needed for postponing runaway gas accretion

$$M_p = \boxed{M_{XY}} + M_Z$$

$$M_Z = M_{core} + M_{pl} + M_{pe} + \cancel{M_{Z,gas}}$$





M_{core} is determined by disk parameters for both planetesimal & pebble accretion

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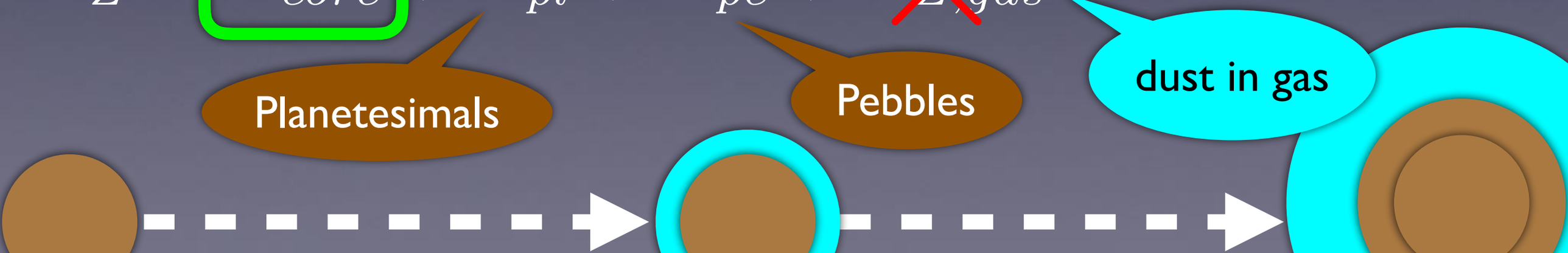

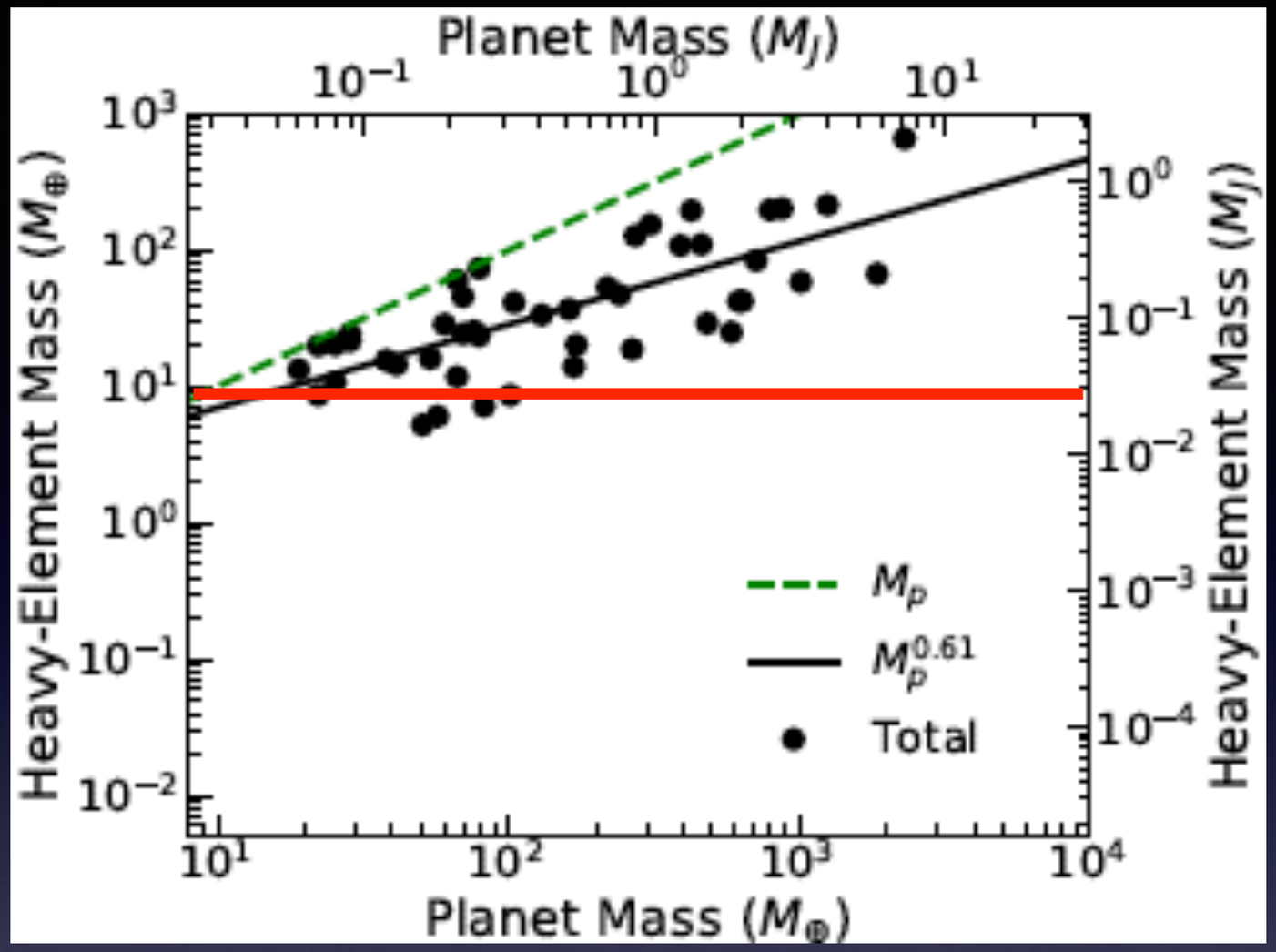

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M_{core} is independent of M_p for both scenarios

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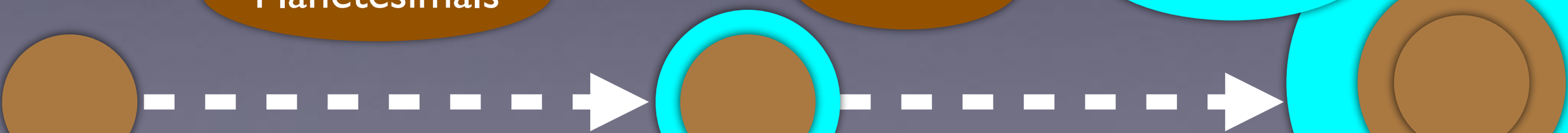

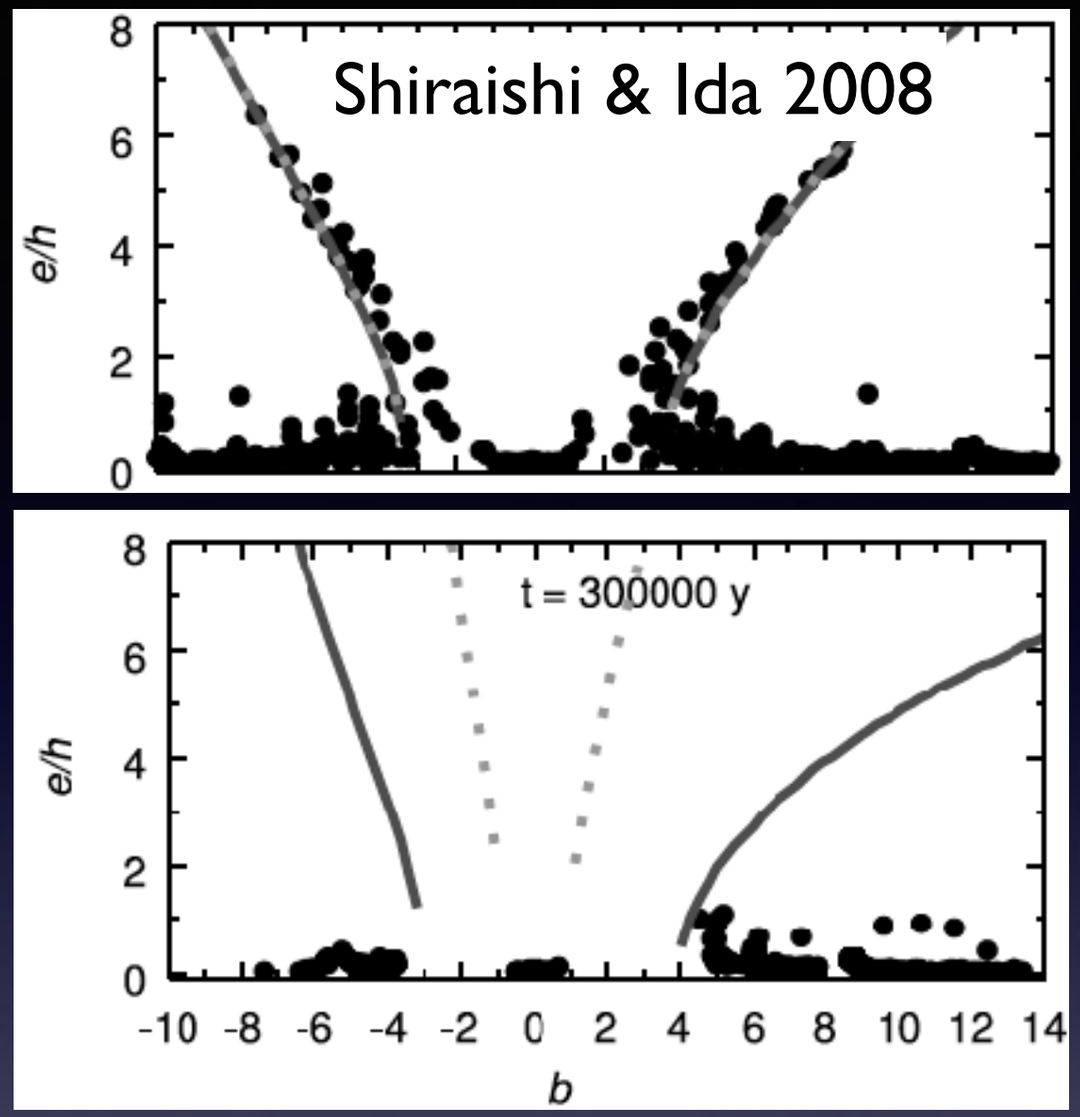

The spatial distribution of planetesimals is the key, which is determined by the gravitational interaction with a protoplanet

$M_Z \simeq M_{pl} \propto M_p^{1/3}$ with no gap in planetesimal disks

$M_Z \simeq M_{pl} \propto M_p^{3/5}$ with gaps in planetesimal disks

$$M_p = M_{XY} + M_Z$$

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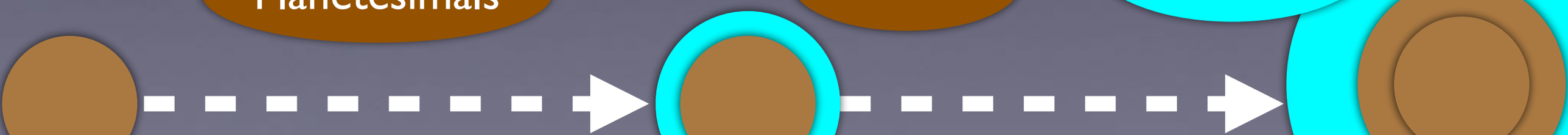

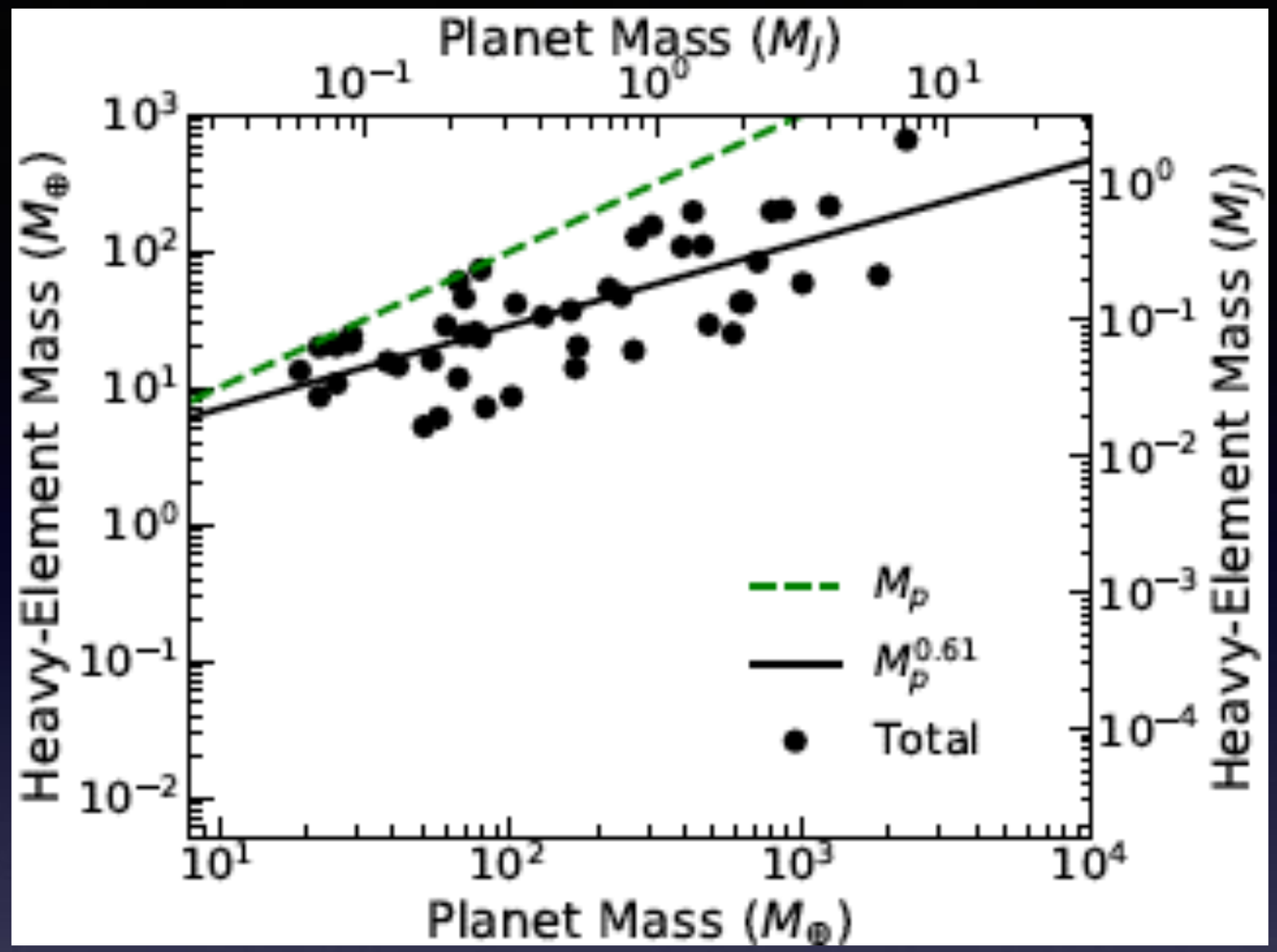

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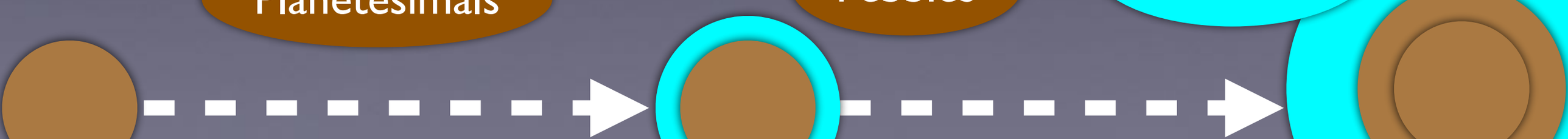

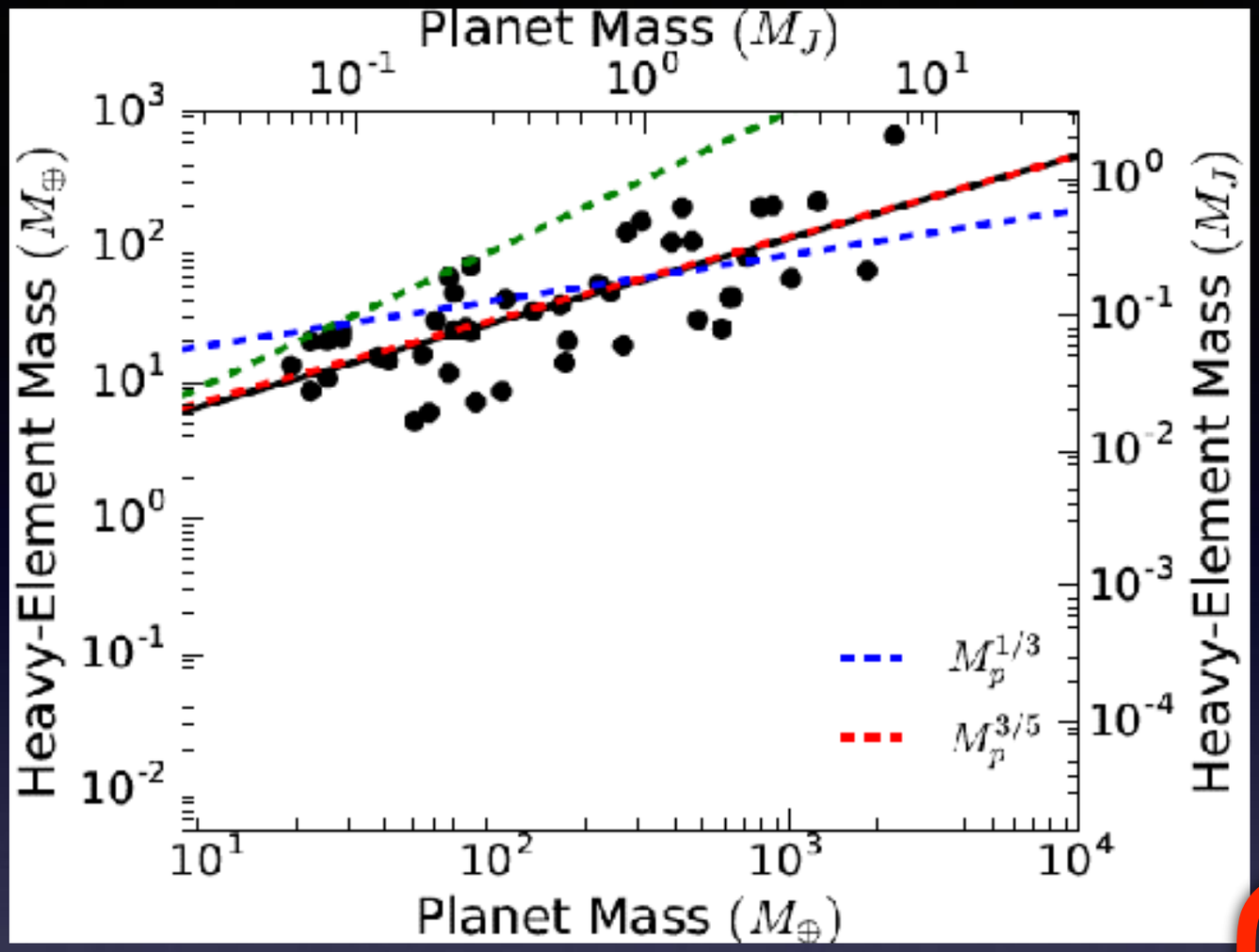

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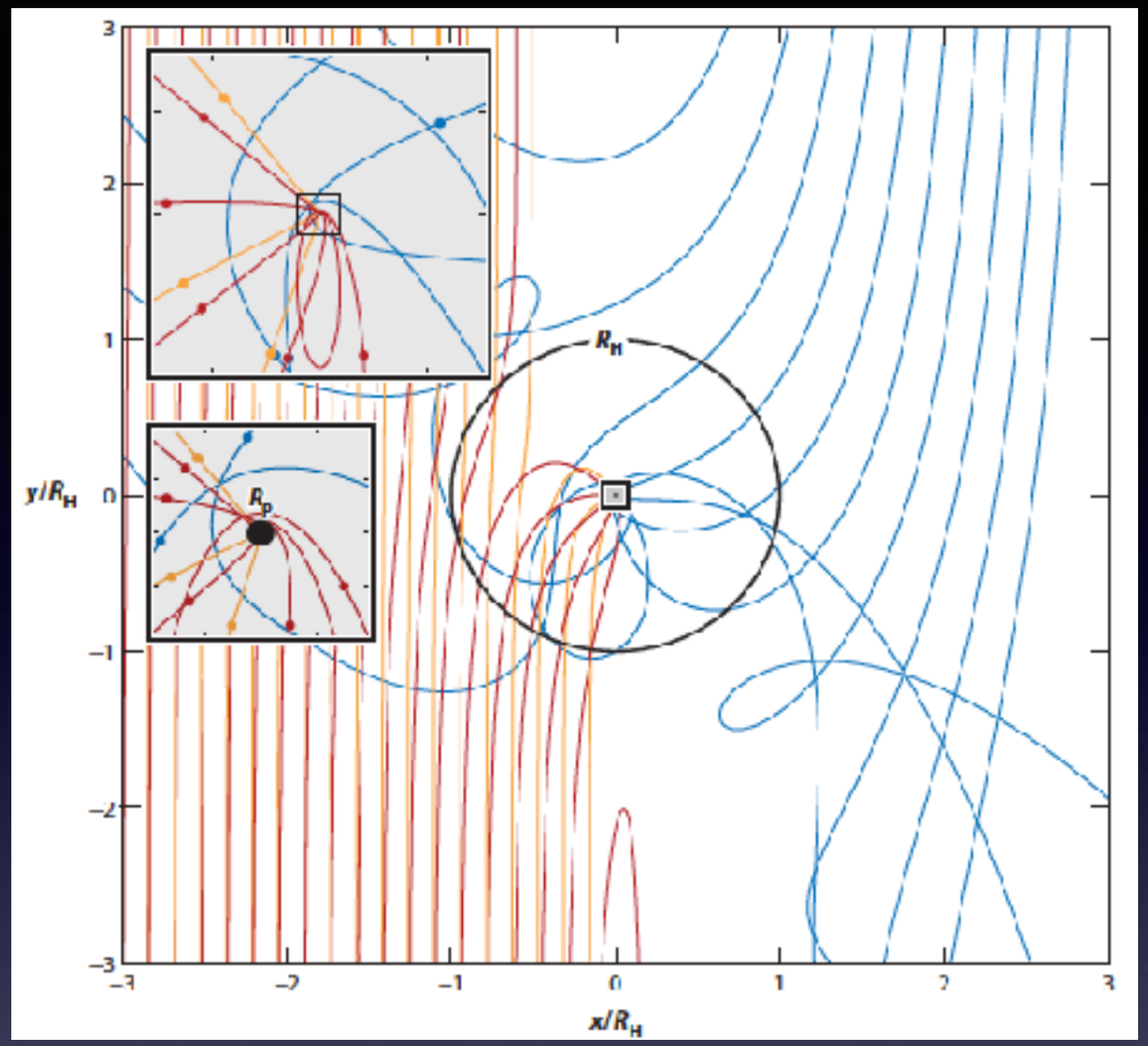

Understanding of pebble accretion is premature

e.g., Johansen & Lambrechts 2017

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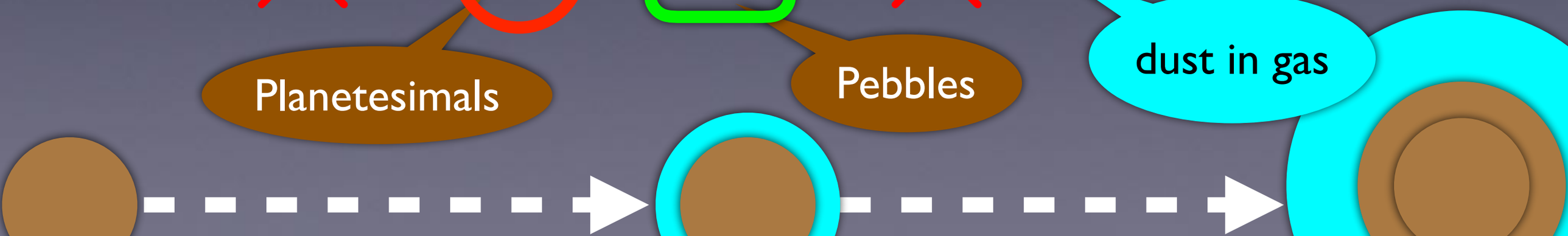

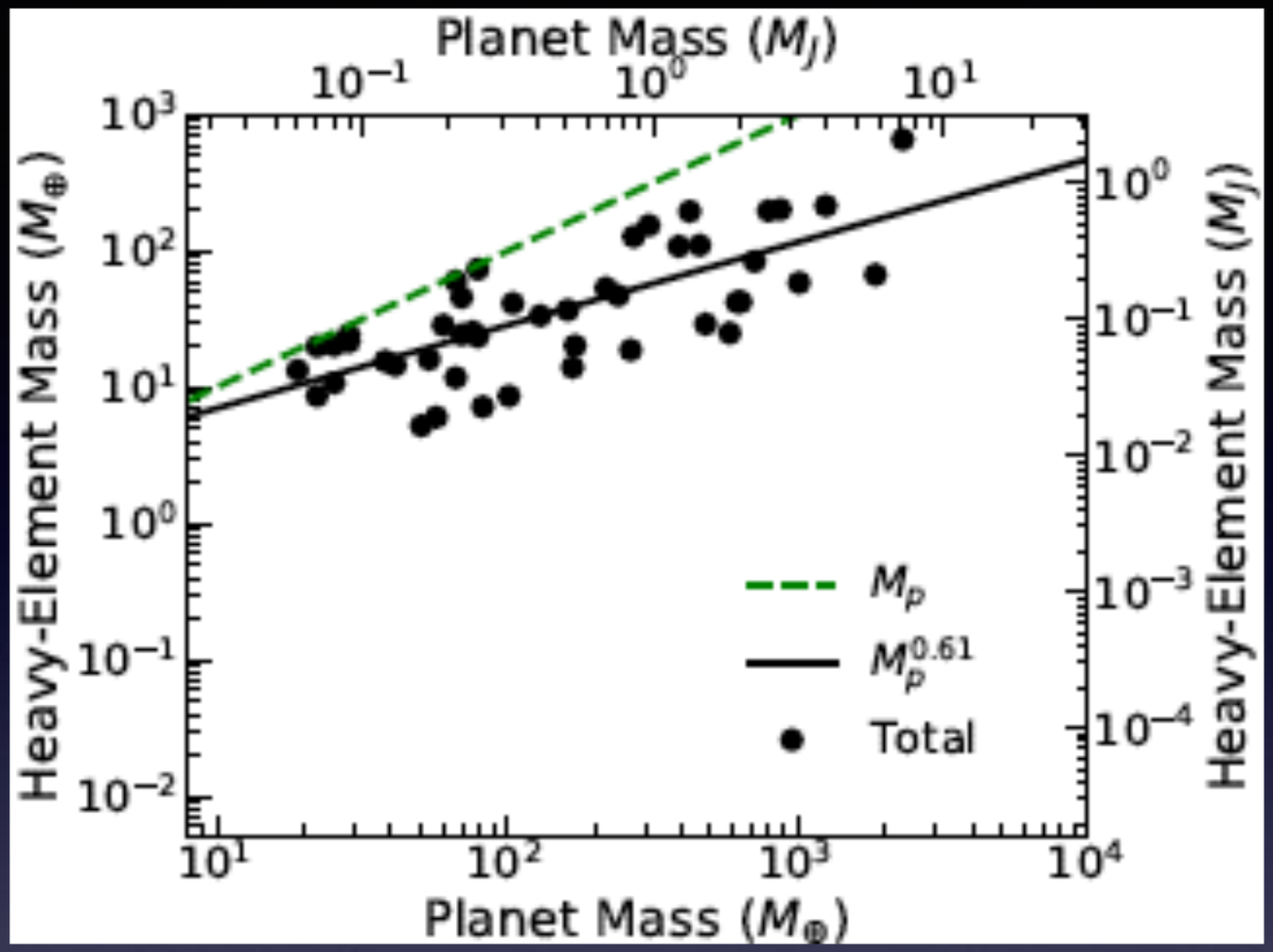

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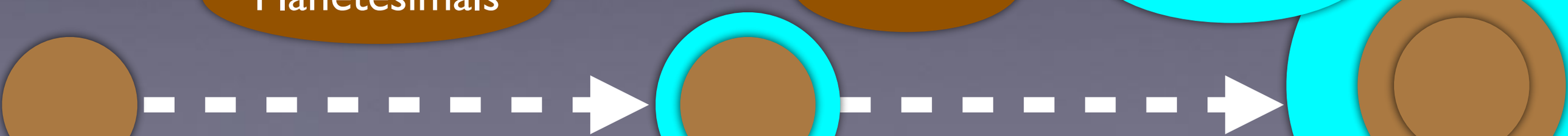

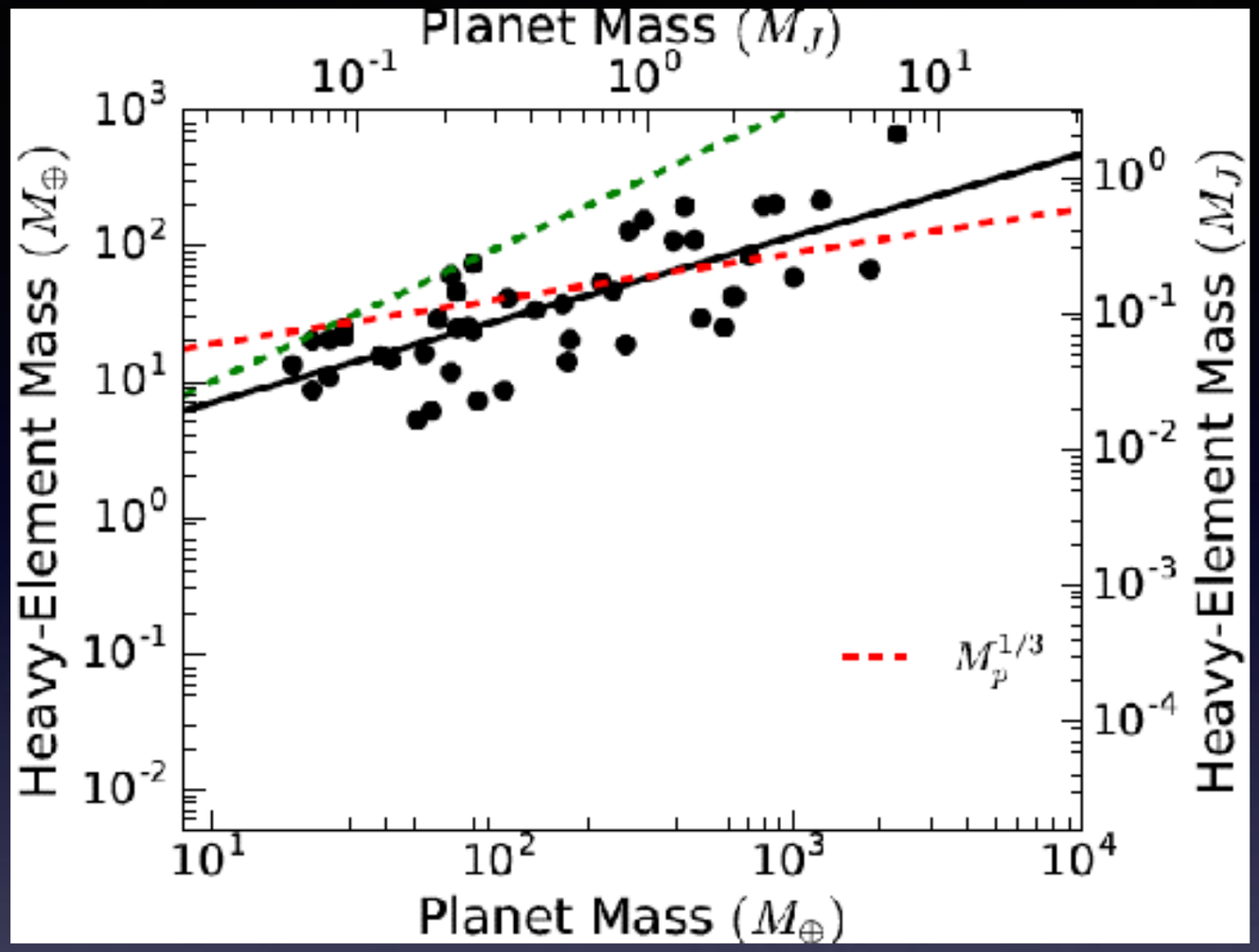

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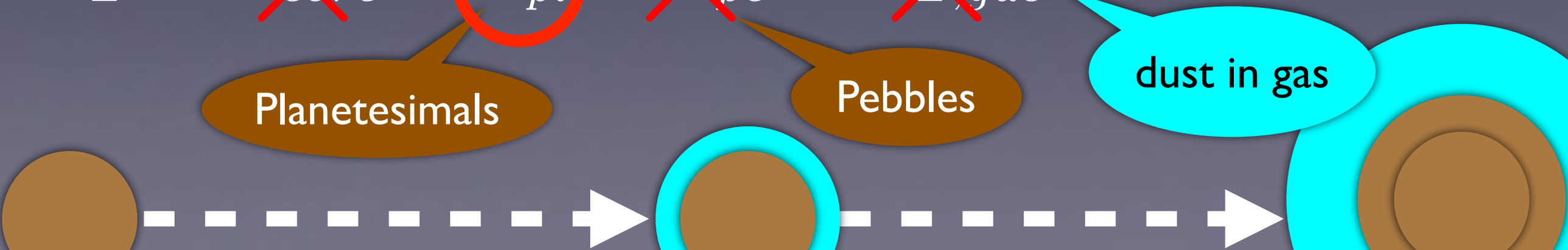
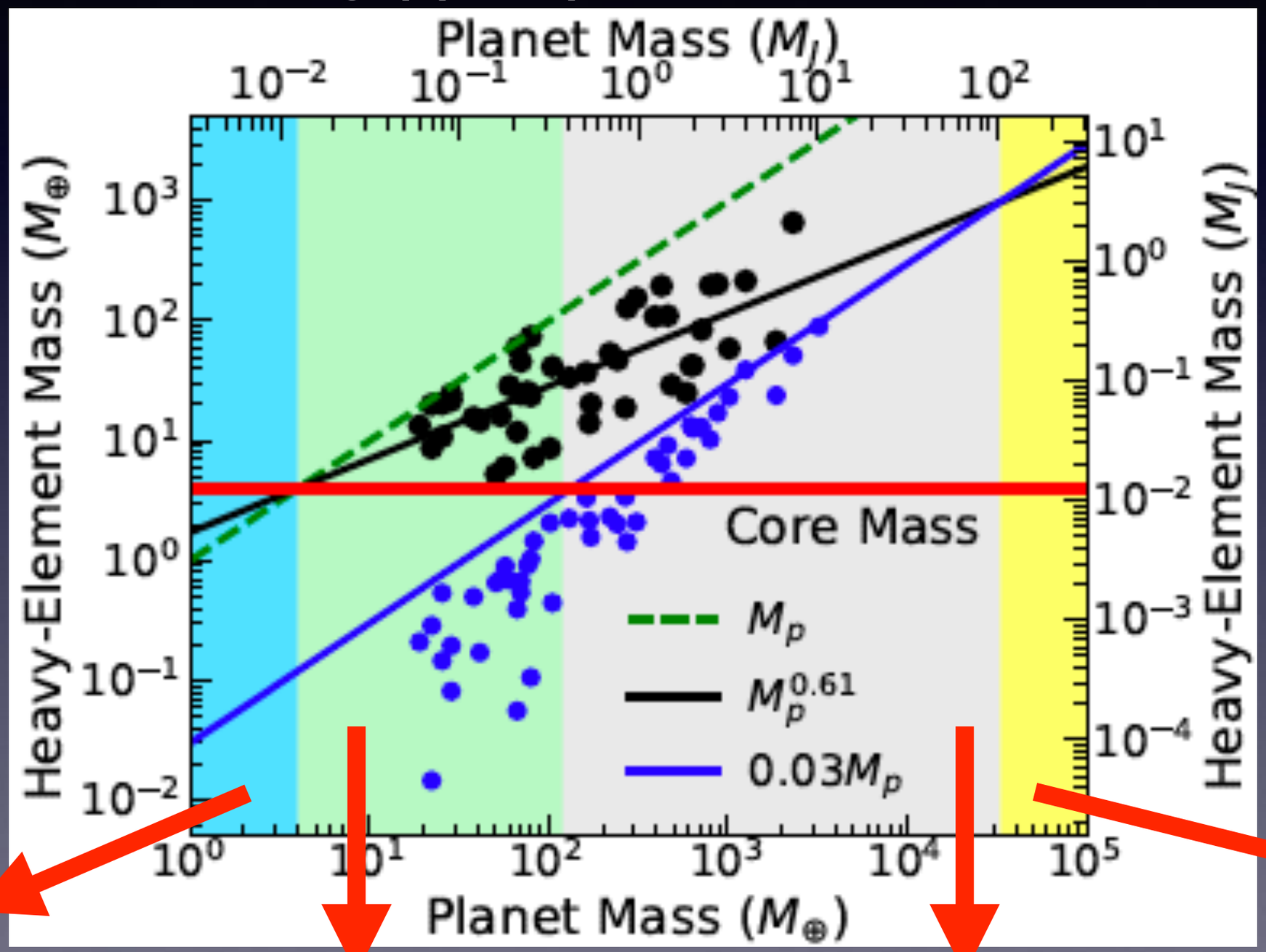


The total heavy elements are determined by the final stage of planet formation

At the stage, solids are accreted onto planets from gapped planetesimal disks



Rocky (super)Earths

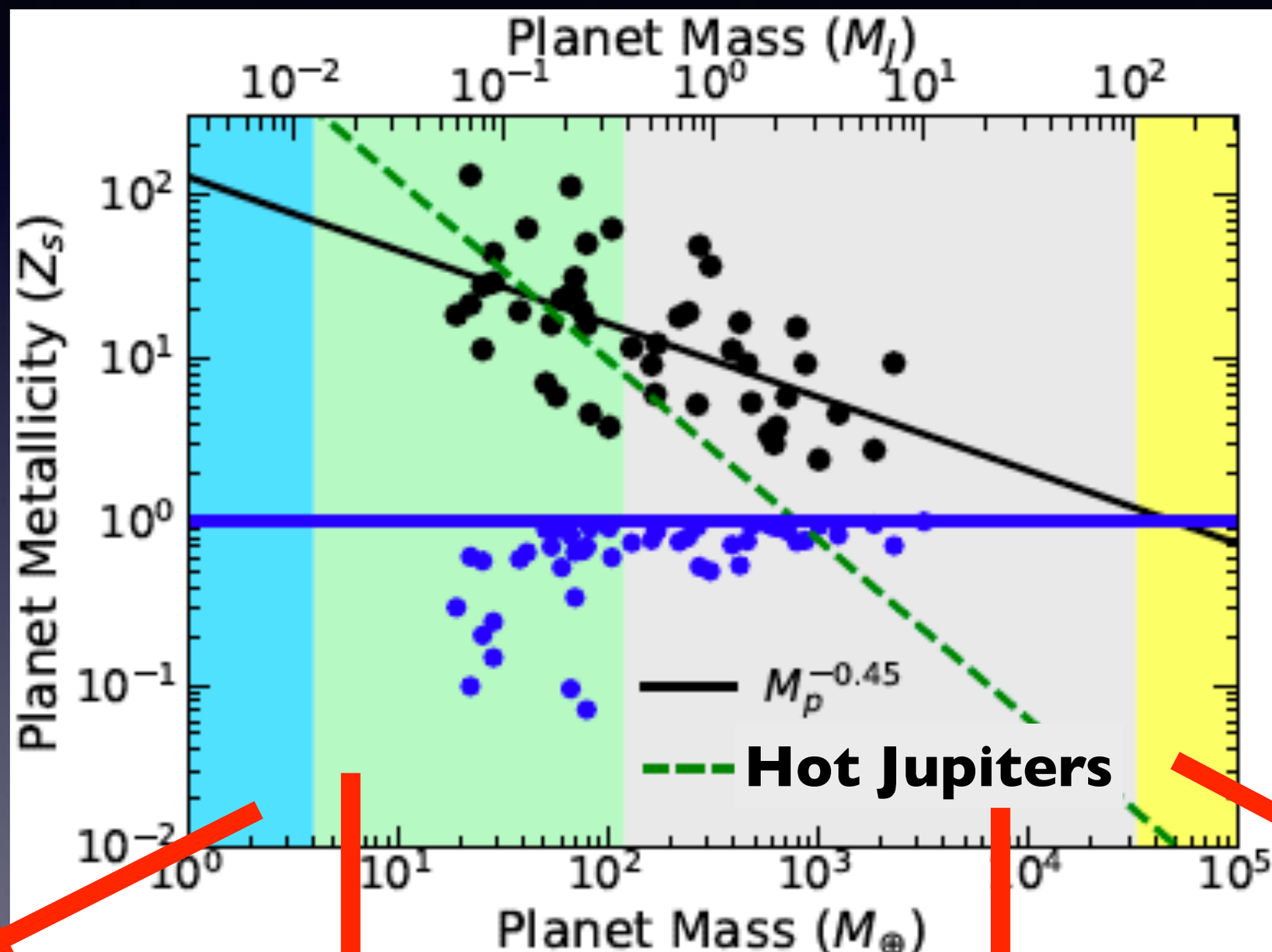
Gas-poor sub-giants

Gas-rich giants

Stars

Evolution of atmospheric metallicity can be explored, comparing hot and warm Jupiters

Planetary cores might be fully dissolved into their atmospheres for gas-poor sub-giants



Rocky (super)Earths

Gas-poor sub-giants

Gas-rich giants

Stars

Summary

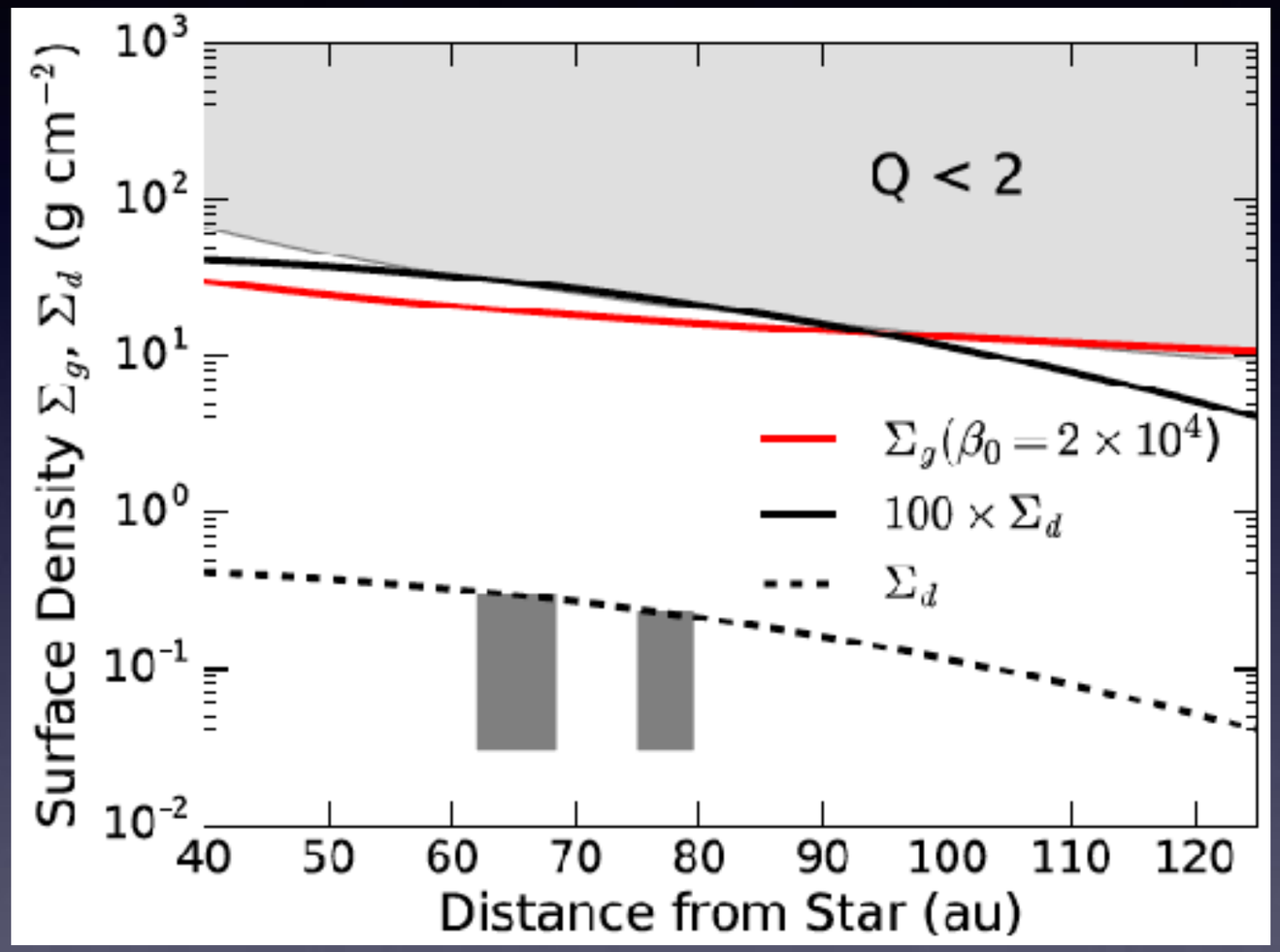
Hasegawa et al. 2018, submitted

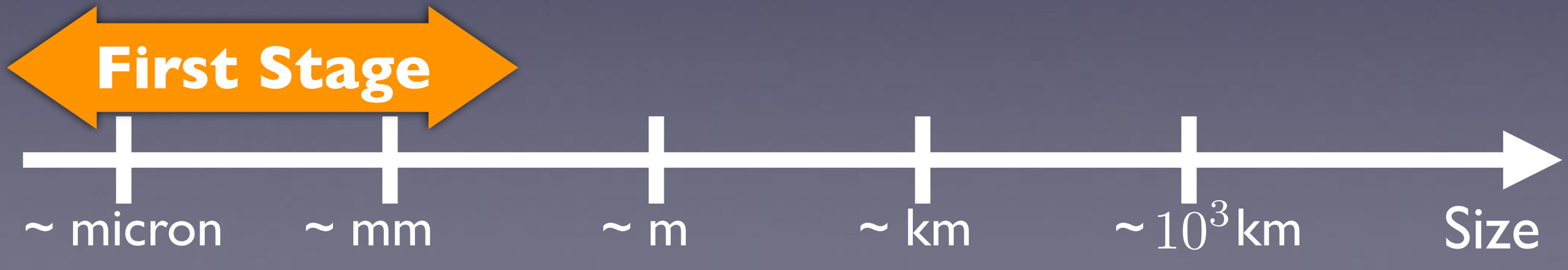
- Formation mechanisms of observed exoplanets are better constrained, by taking into account planet mass, orbital period, and planet composition
- Observed warm Jupiters tend to have correlations:

$$M_Z \propto M_p^{3/5} \qquad \frac{Z_p}{Z_s} = \frac{M_Z}{M_p}\frac{1}{Z_s} \propto M_p^{-2/5}$$

- Our results indicate that the contribution (dust) arising from gas accretion is negligible
- Runaway gas accretion is postponed until $M_p > 100 M_\oplus$
- Accretion of solids from gapped planetesimal disks can reproduce the above trends better
- We propose a classification of observed exoplanets

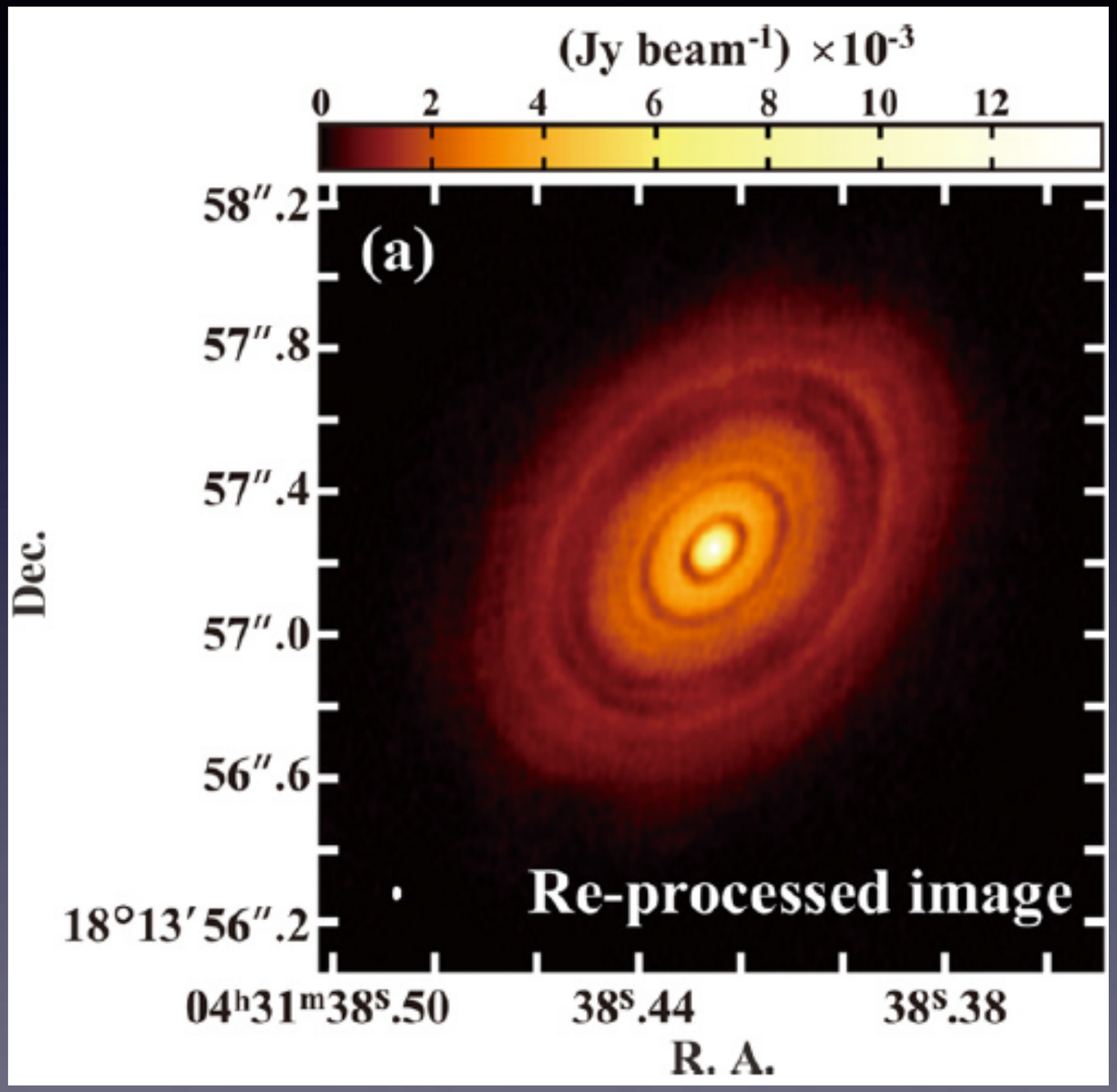
Magnetically Induced Disk Winds and Transport in the HL Tau Disk





Astonishing ALMA Images of HL Tau

ALMA Partnership et al 2015,
also see Akiyama YH et al 2016



HL Tau : a Class I/II YSO
: ~140 pc (< 1 Myrs)

Nearly concentric
multiple gaps in
the dust thermal emission

Potential signature of
planet formation

The origin of observed gaps is not identified yet!!

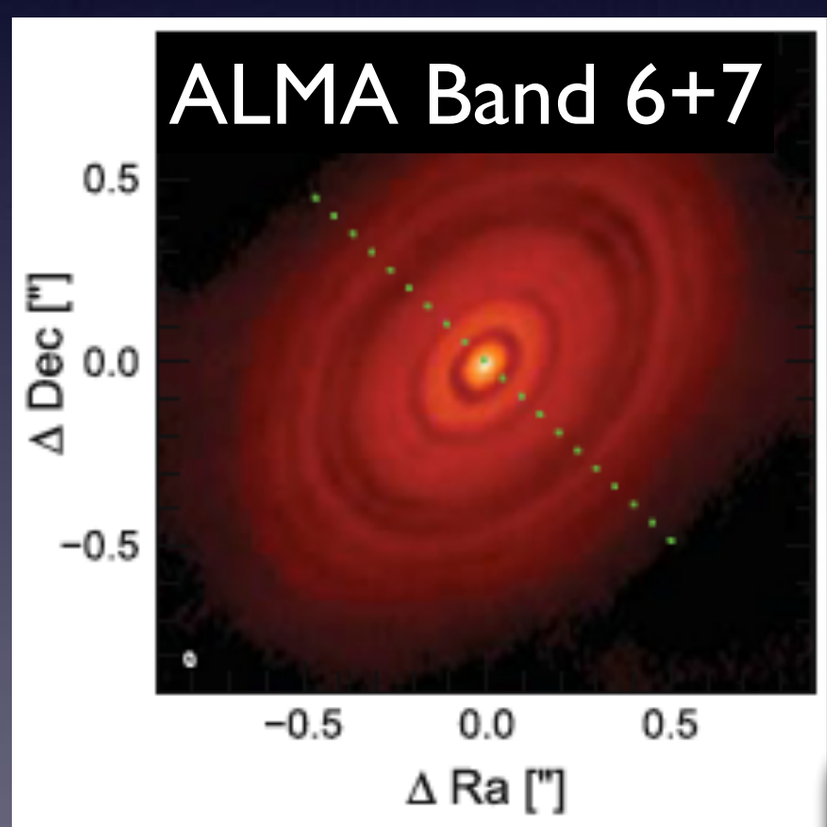
Global Properties of the HL Tau Disk

Disk accretion rate $\simeq 10^{-7} - 10^{-6}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$

Hayashi et al 1993, Beck et al 2010

Global diffusion coefficient : $\alpha_{\mathrm{GL}} \simeq 10^{-2} - 10^{-1}$

=> can be explained by MRI and MHD turbulence



Pinte et al 2016

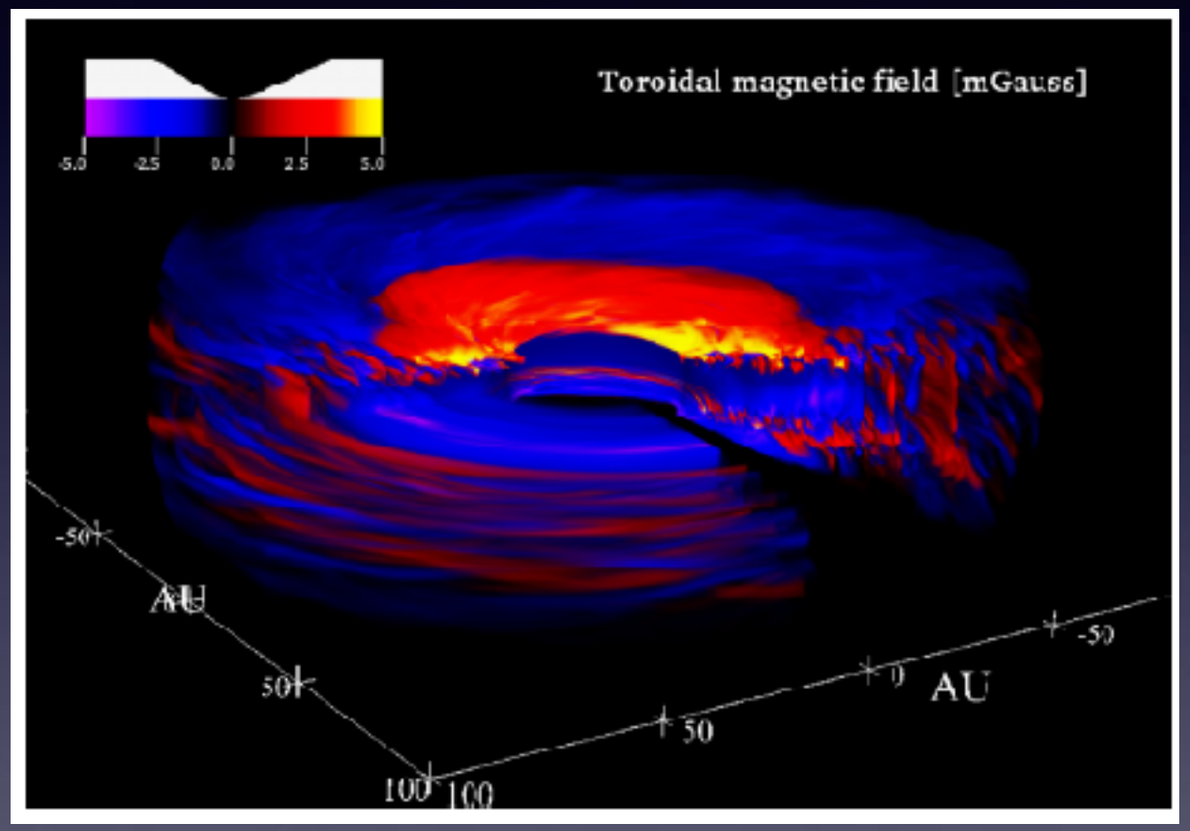
Vertical dust height: ~1au at r =100 au

Local diffusion coefficient: $\alpha_{\mathrm{LC}} \sim 10^{-4}$

Magnetically Driven Disk Accretion

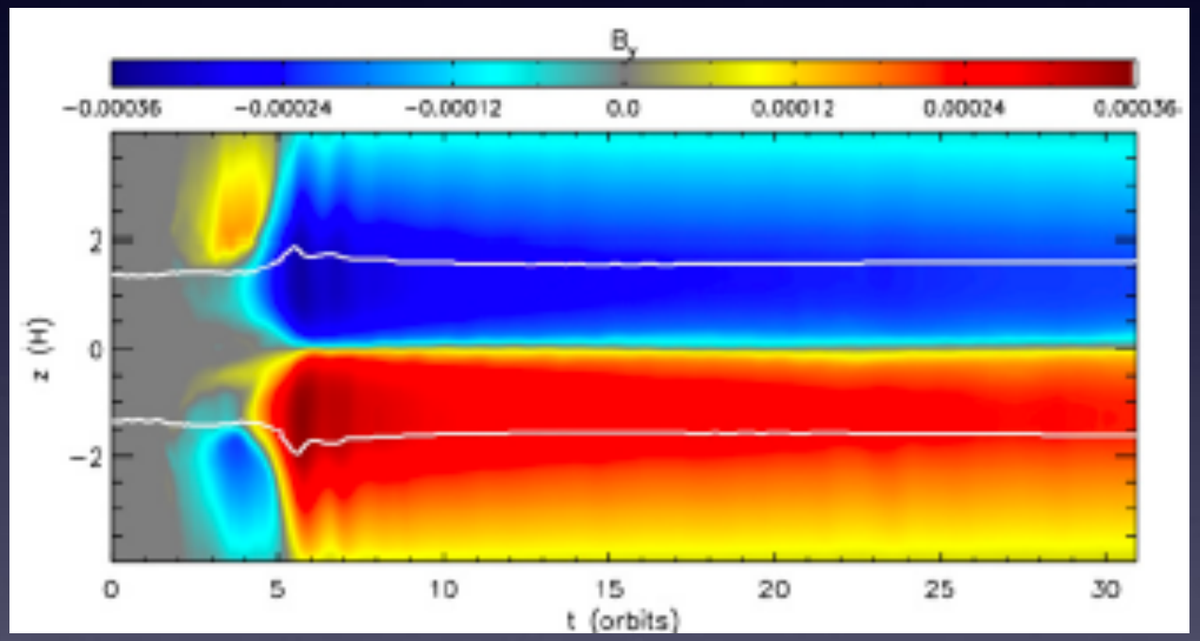
e.g., Armitage et al 2011, Bai & Stone 2013, Turner et al 2014, Suzuki et al 2016

Magnetized Turbulence



Flock et al 2015

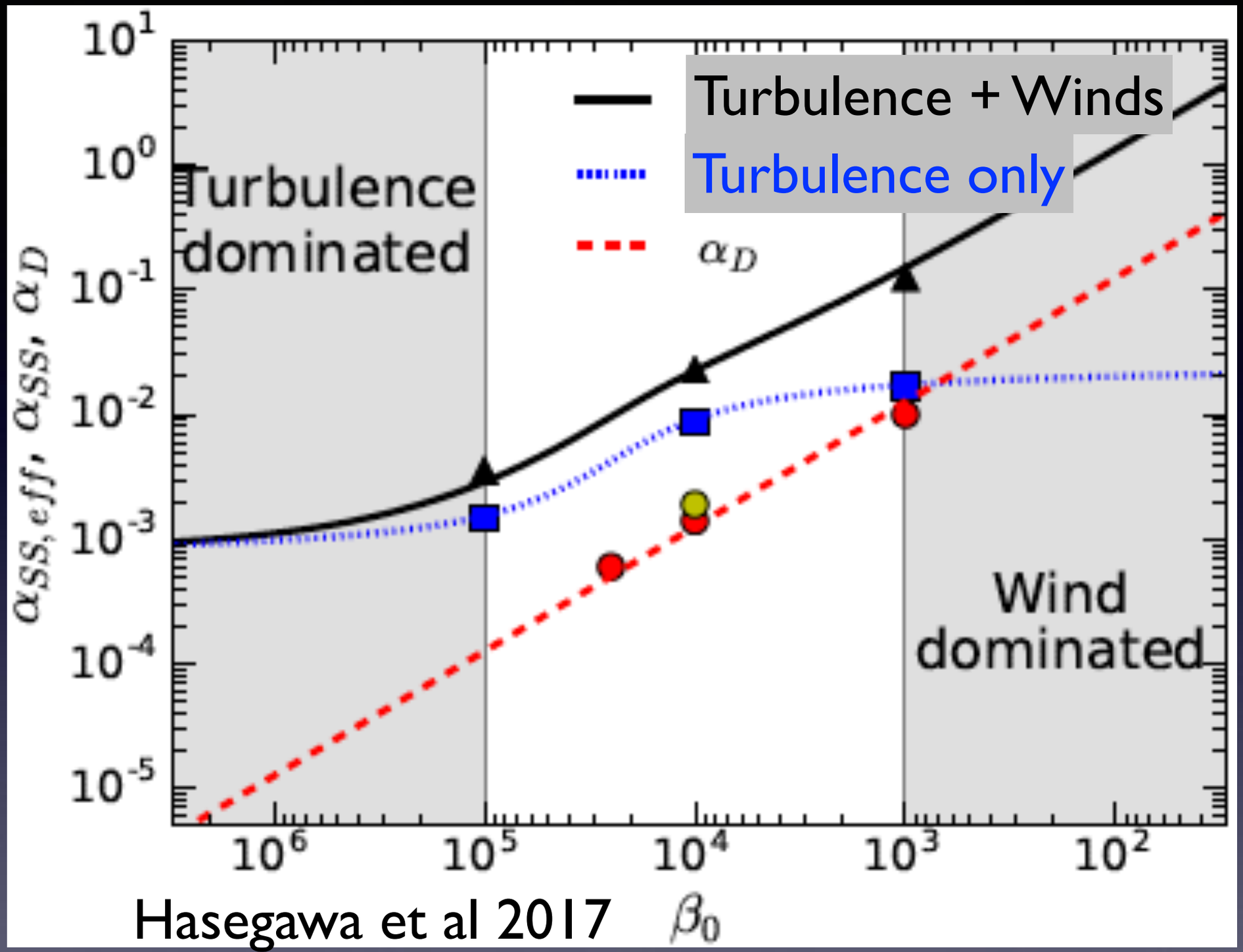
Magnetically Induced Disk Winds



Simon et al 2013

Weak → Strong

B-fields



Hasegawa et al 2017

α_D : vertical mixing of dust

Weak → Strong

B-fields

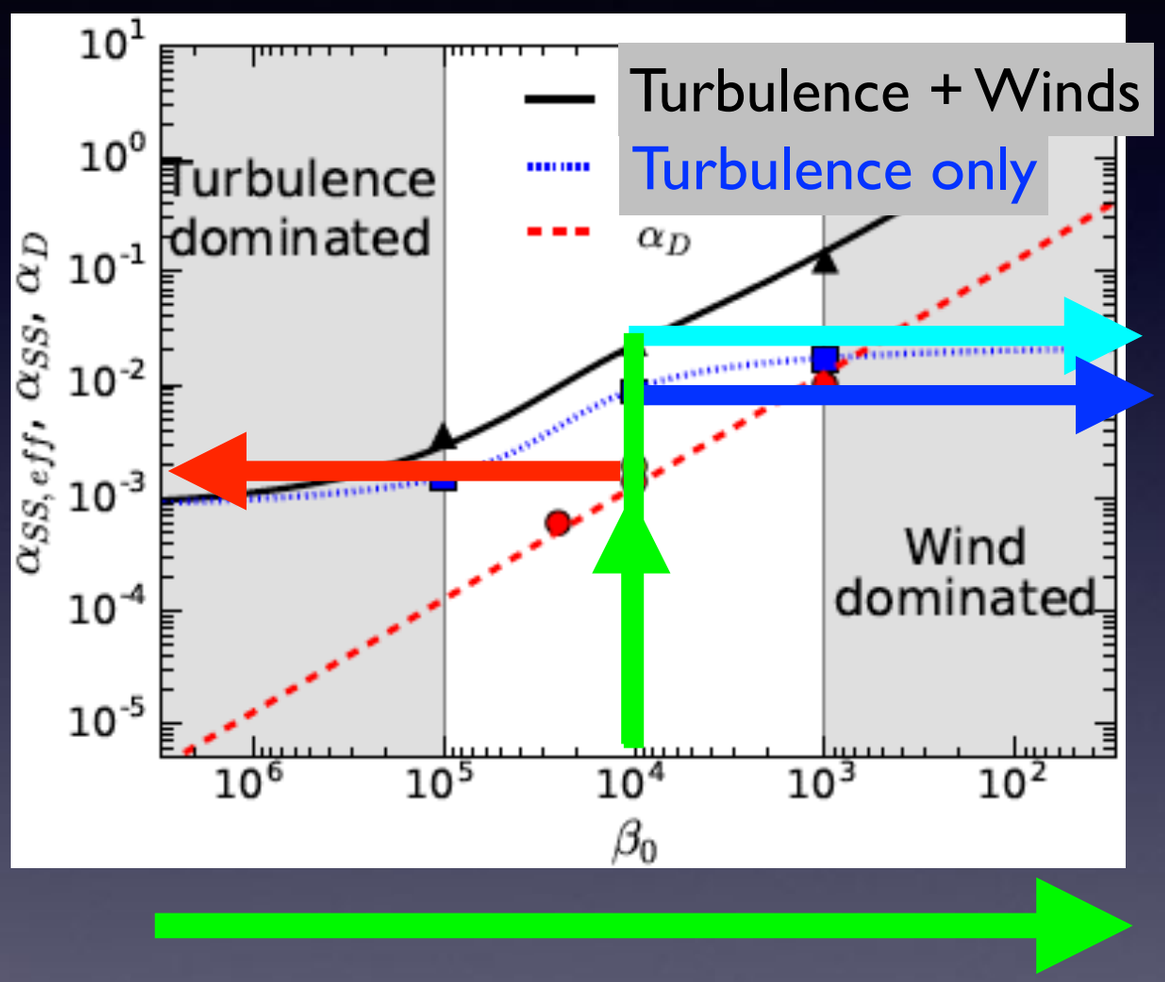
Simulation results from Simon et al 2013, Zhu et al 2015 are used

Given that

$$\dot{M}, c_{\rm s}^2(\propto T_d),\ \Omega(\propto \sqrt{M_*})$$

1. Gas surface density

$$\Sigma_{\rm g} = \frac{\dot{M}\Omega}{3\pi\alpha_{\rm GL}c_{\rm s}^2}$$



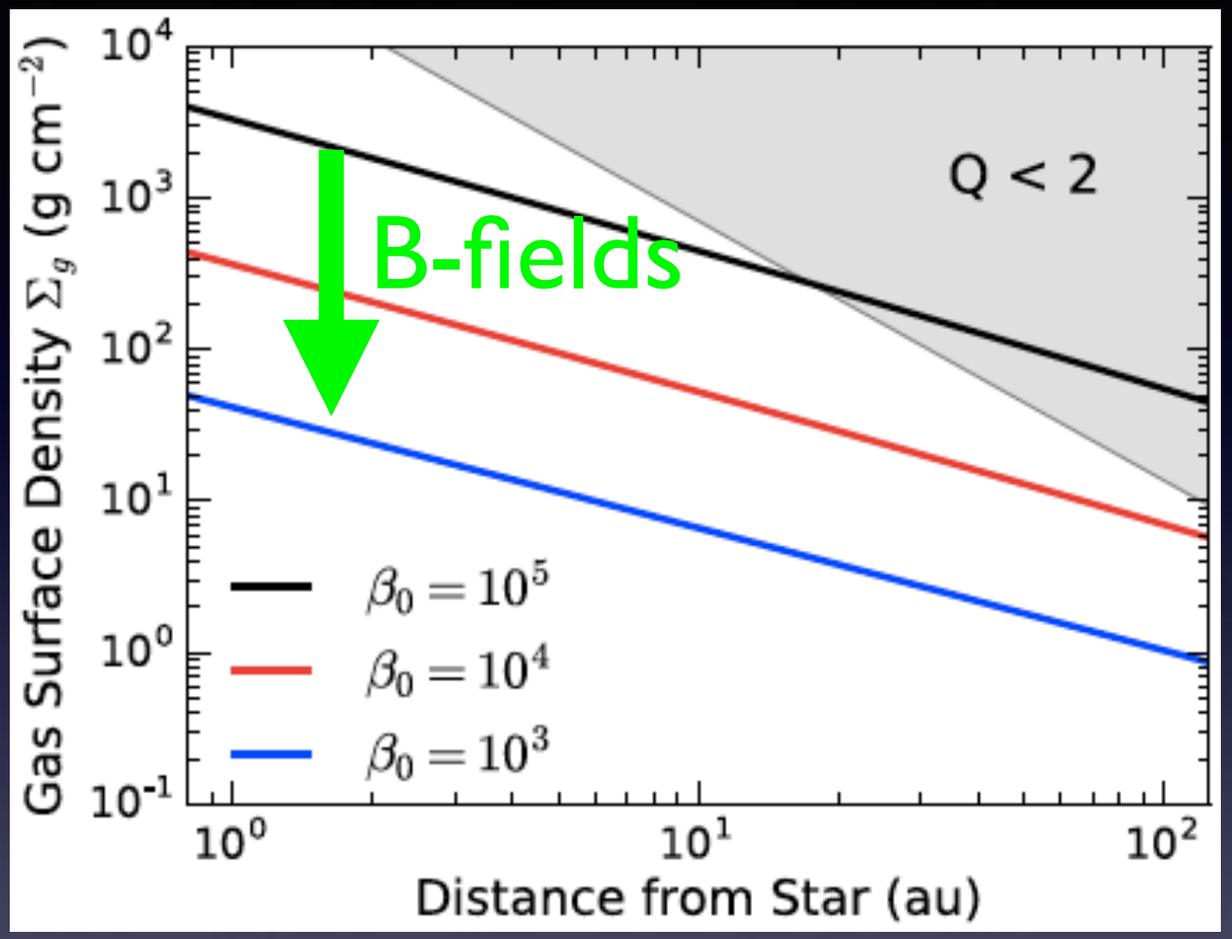
B-fields

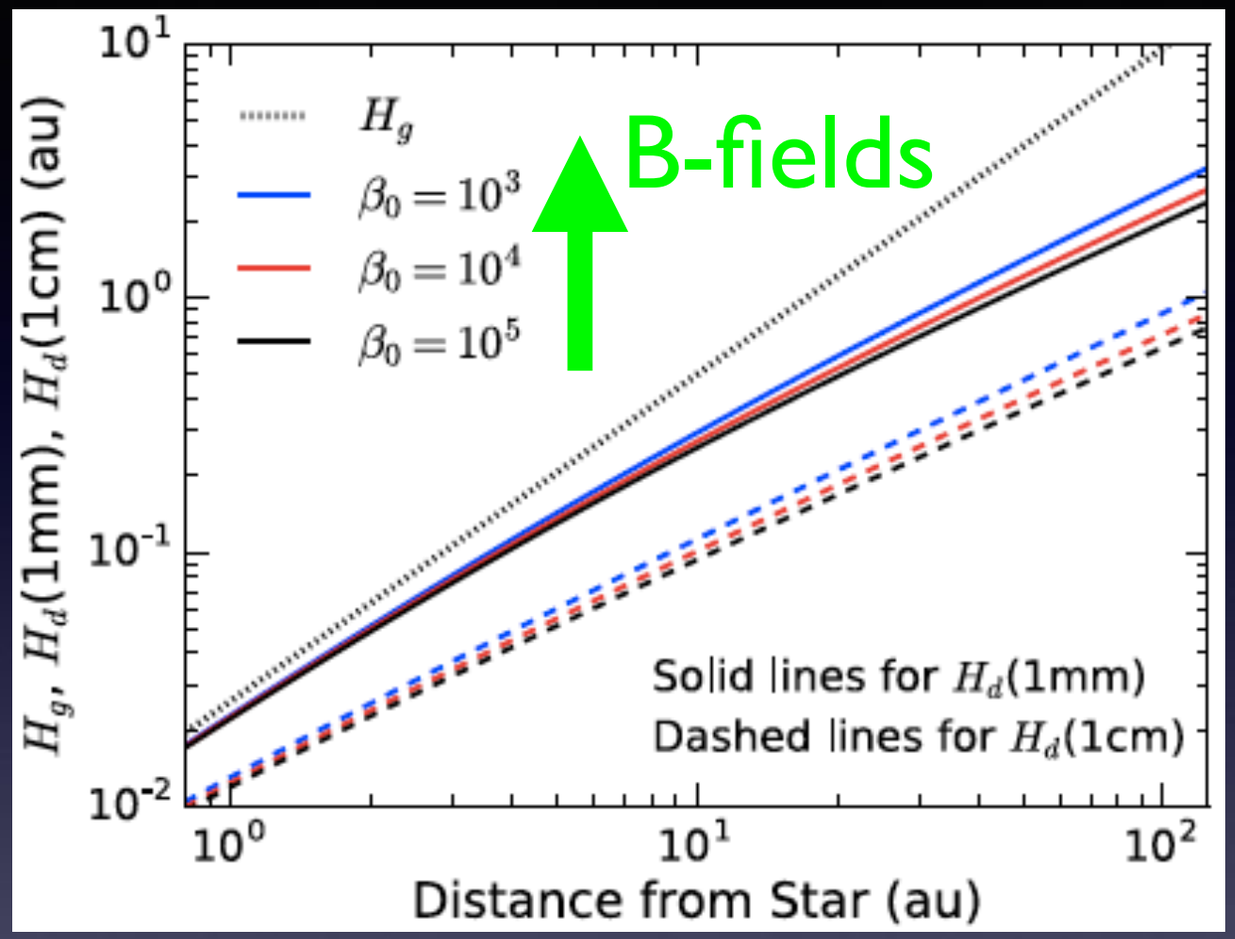
2. Dust height

$$H_{\rm d} = \left(1 + \frac{St}{\alpha_D}\right)^{-1/2} H_{\rm g}$$

$$St \propto \frac{a}{\Sigma_{\rm g}}$$

Resulting Disk Structures with Disk Winds





As B-fields are stronger, surface density decreases due to disk winds

Dust scale heights are independent of B-fields

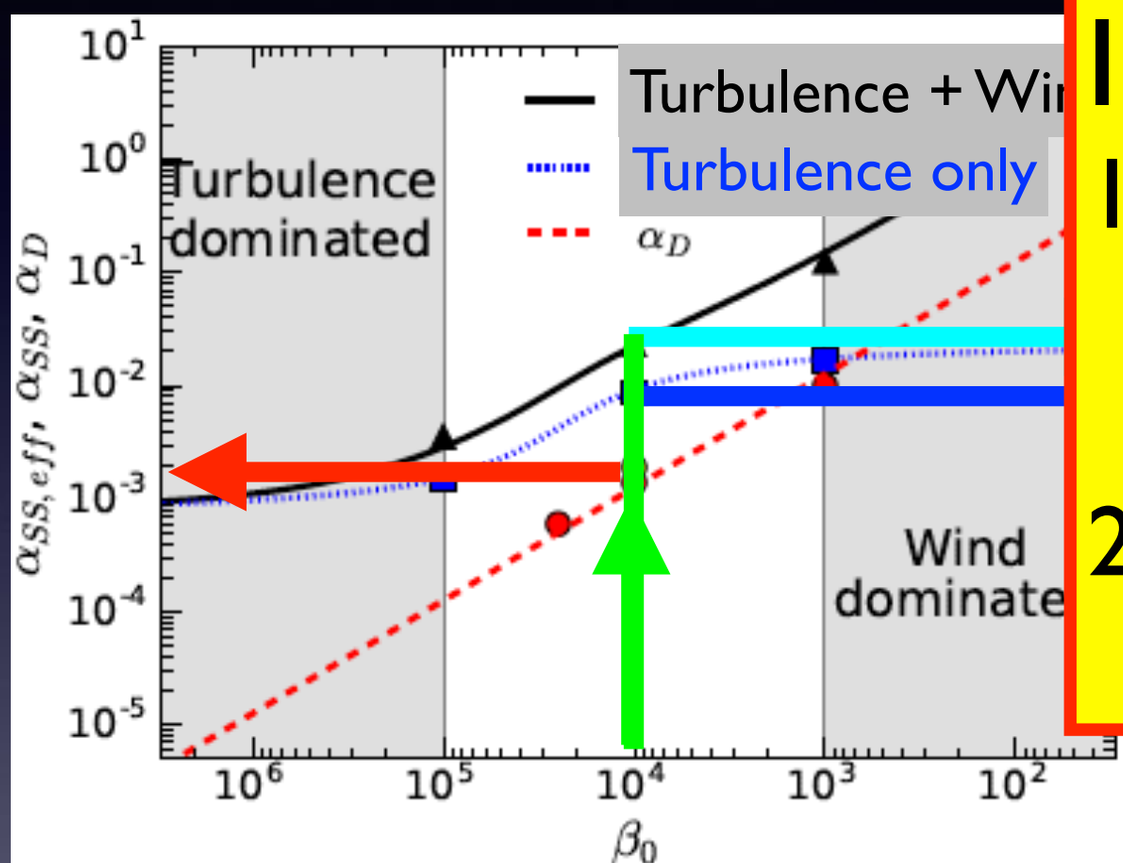
Results are obtained for given values of disk accretion rate, disk temperature

Given that

$$\dot{M}, c_{\rm s}^2(\propto T_d),\ \Omega(\propto \sqrt{M_*})$$

1. Gas surface density

$$\Sigma_{\rm g} = \frac{\dot{M}\Omega}{3\pi\alpha_{\rm GL}c_{\rm s}^2}$$



B-fields

Inversely solve the problem

1. Find α_D (or β_0) with $H_{\rm d} = 1$ au at $r = 100$ au

2. Find $\alpha_{\rm GL}$ (or β_0) with $\Sigma_{\rm g}$ that satisfies marginally GI

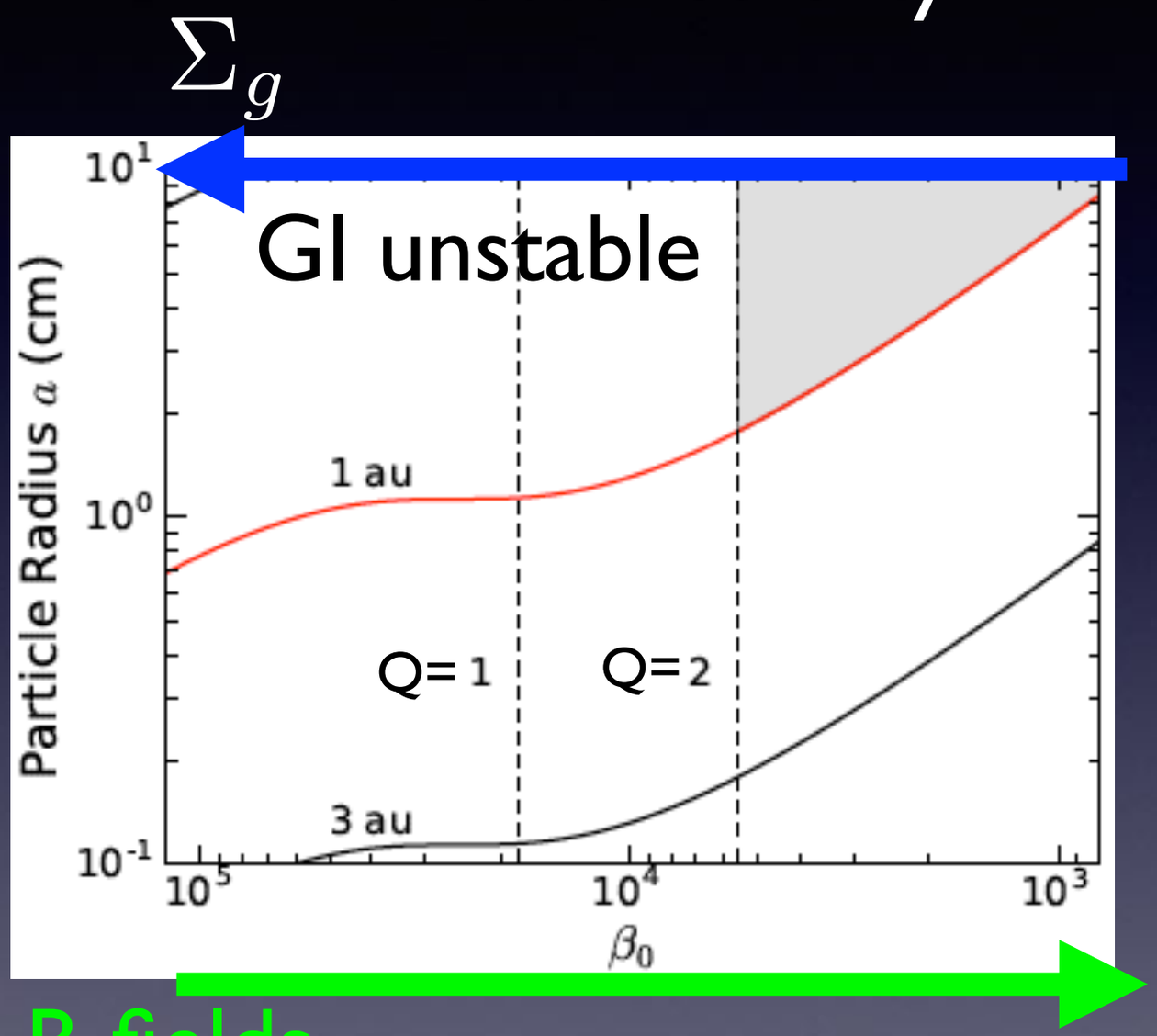
2. Dust height

$$H_{\rm d} = \left(1 + \frac{St}{\alpha_D}\right)^{-1/2} H_{\rm g}$$

$$St \propto \frac{a}{\Sigma_{\rm g}}$$

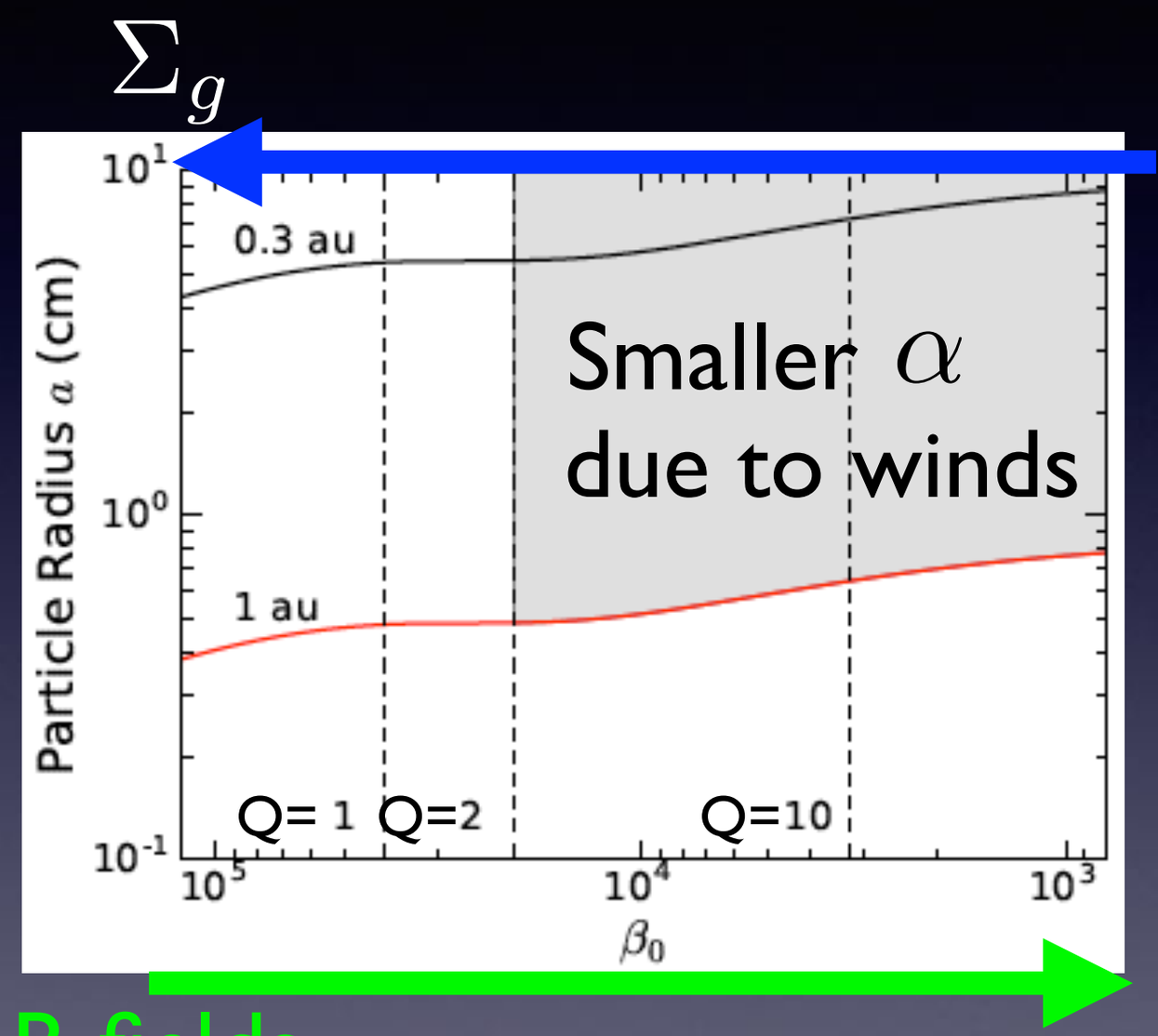
Minimum Size of Dust Particles at r = 100 au

Turbulence only



20 mm-sized dust is needed to reproduce ALMA image

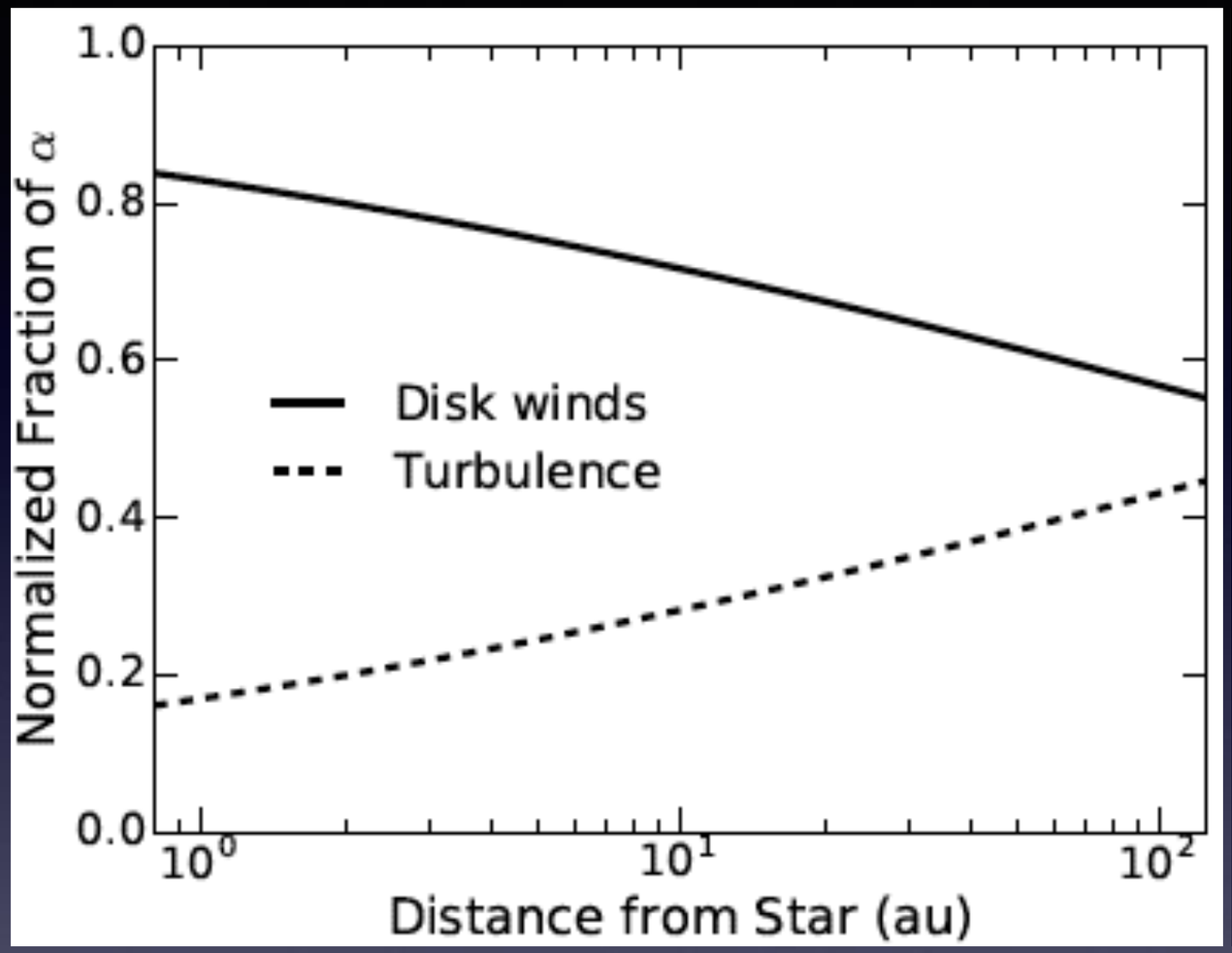
Turbulence + Winds

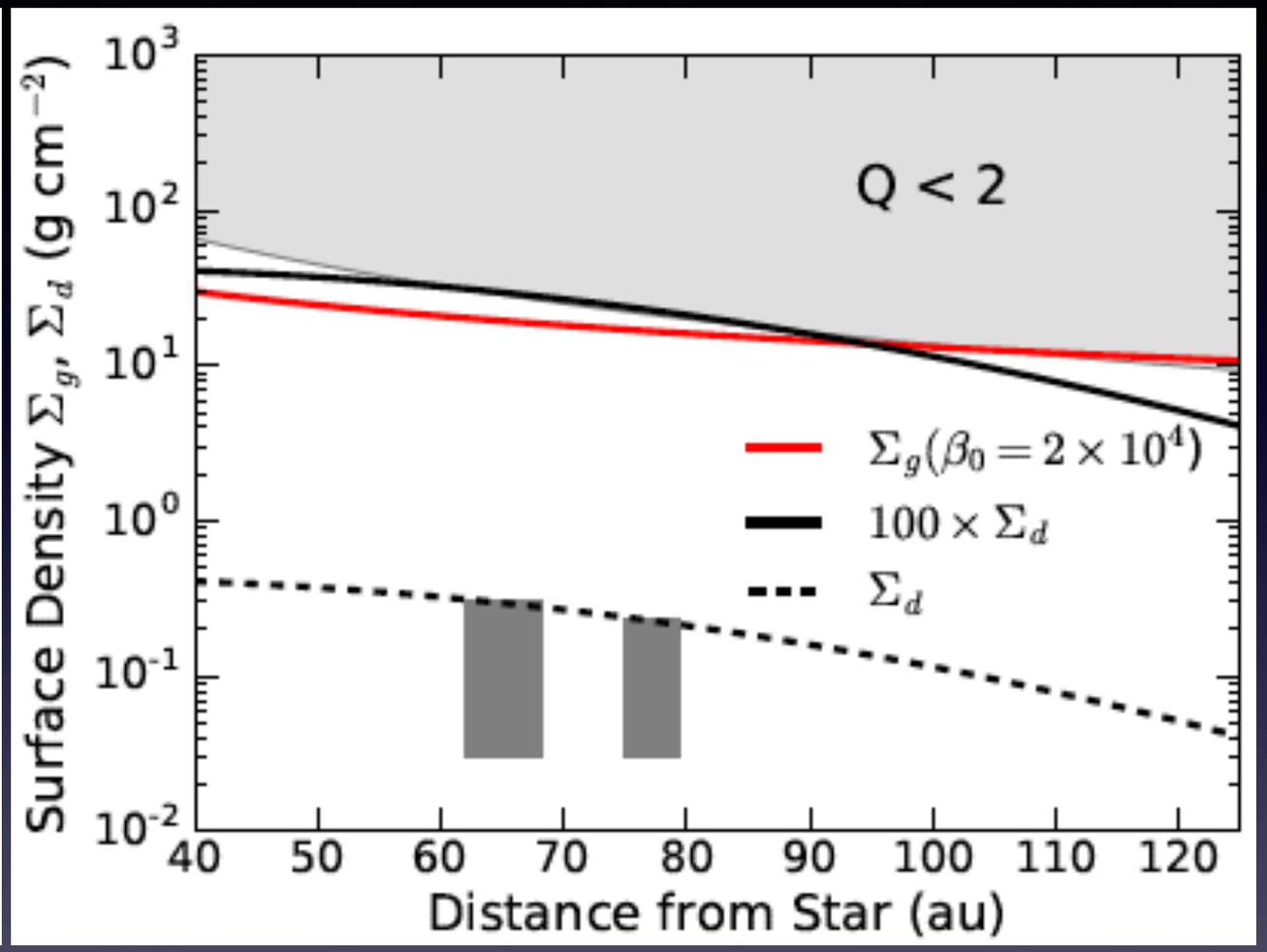


4 mm-sized dust is needed to reproduce ALMA image

Results are obtained for given values of disk accretion rate, disk temperature

Resulting Global Structure of the HL Tau Disk

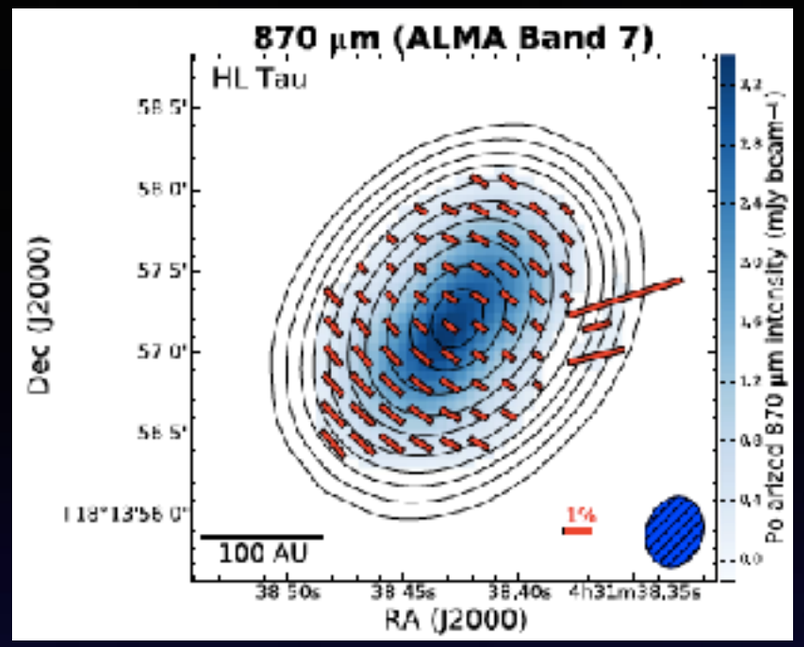




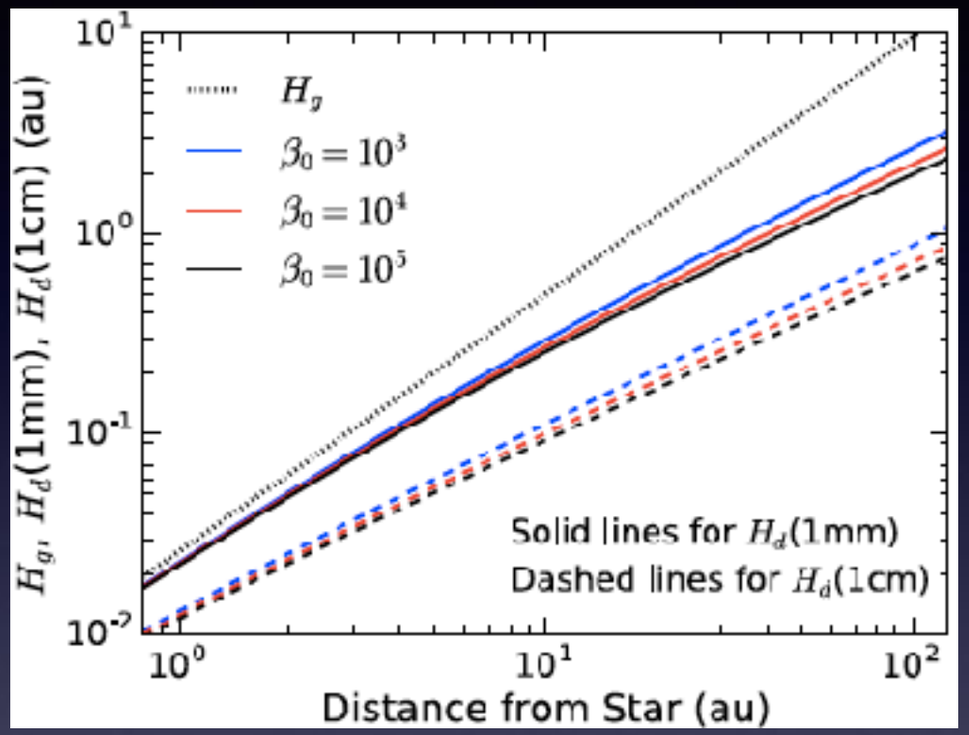
Disk winds transport the most of angular momentum (50-80 %) across the entire region of the disk

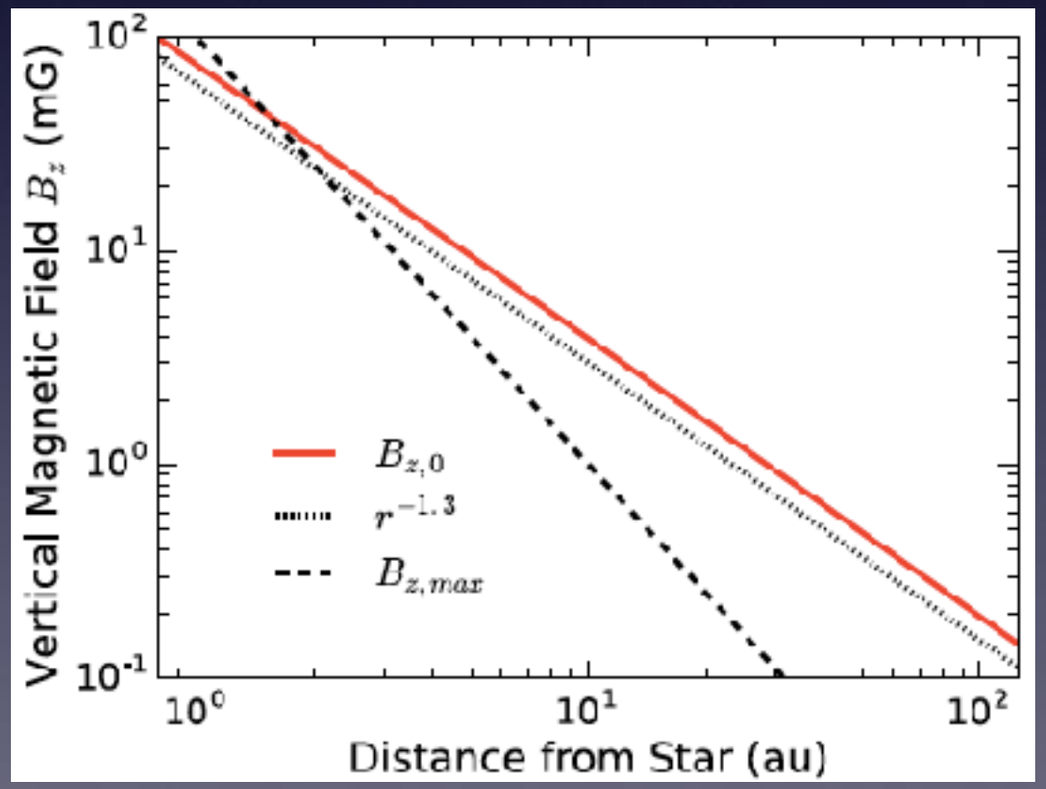
The gas-to-dust rate varies along the distance from the star (lower in the inner region & higher in the outer region)

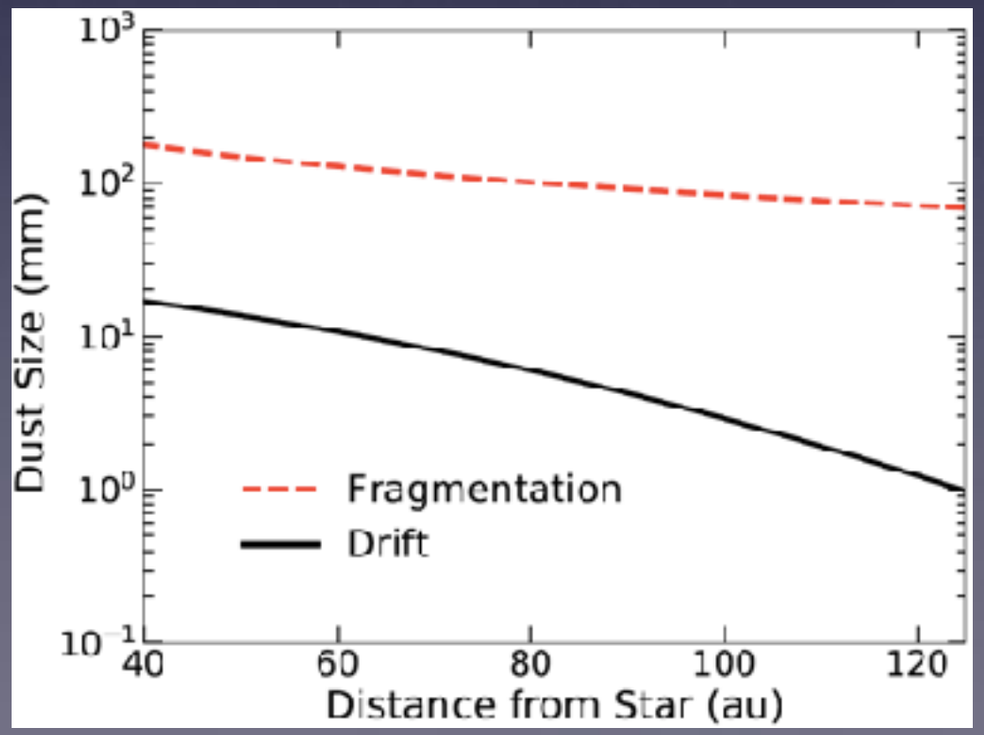
Next Step1: Application to Polarization (Preliminary)



Kataoka et al 2017, Stephens et al 2017



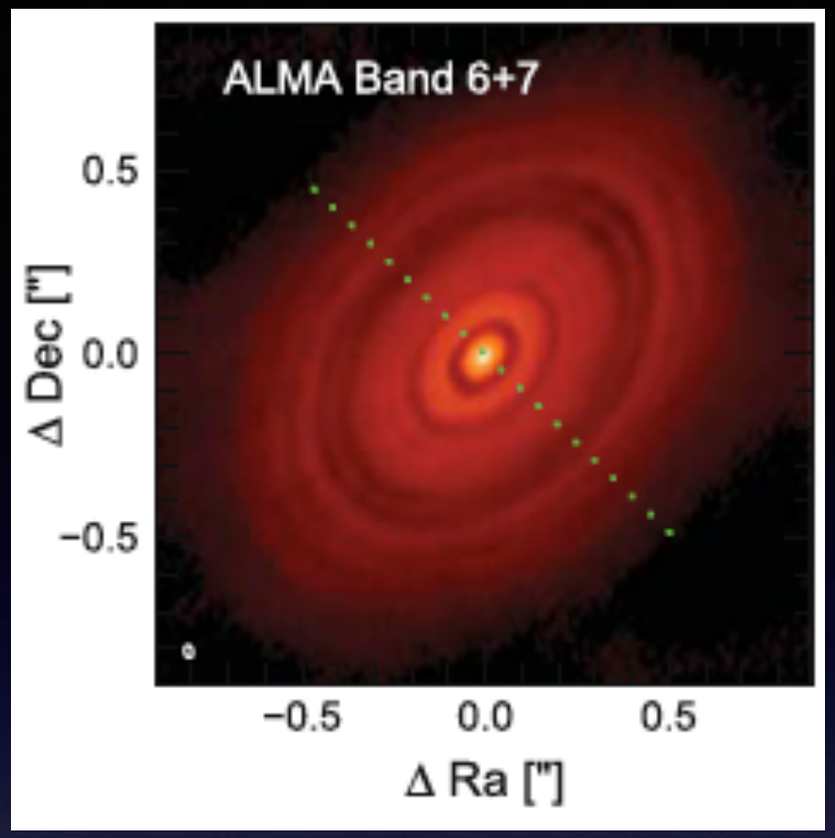


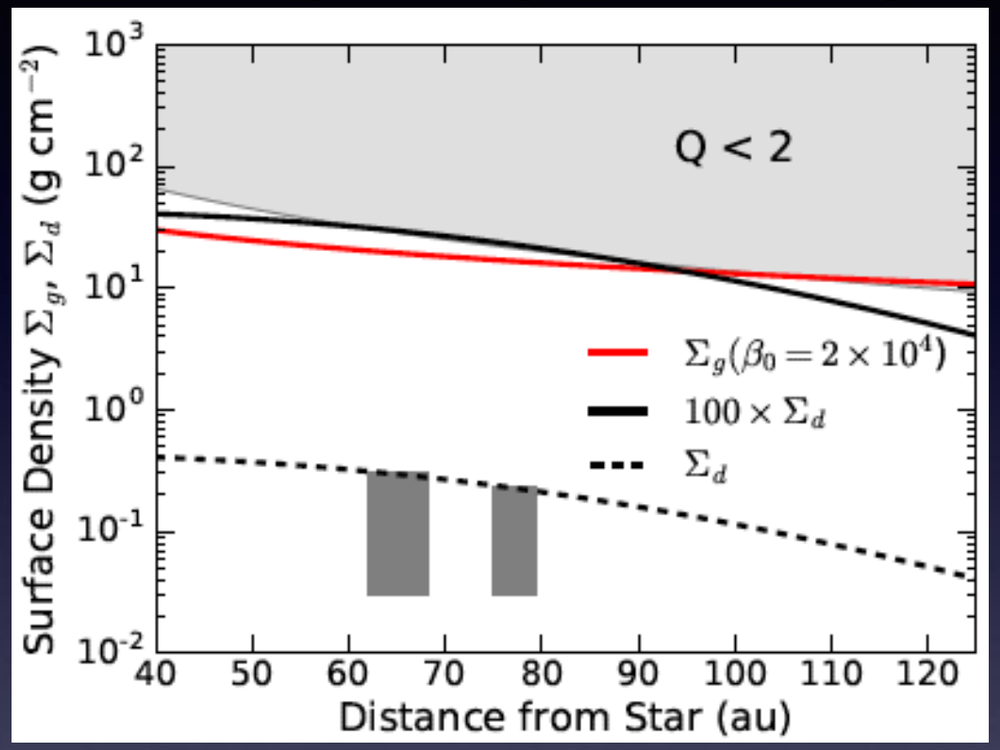


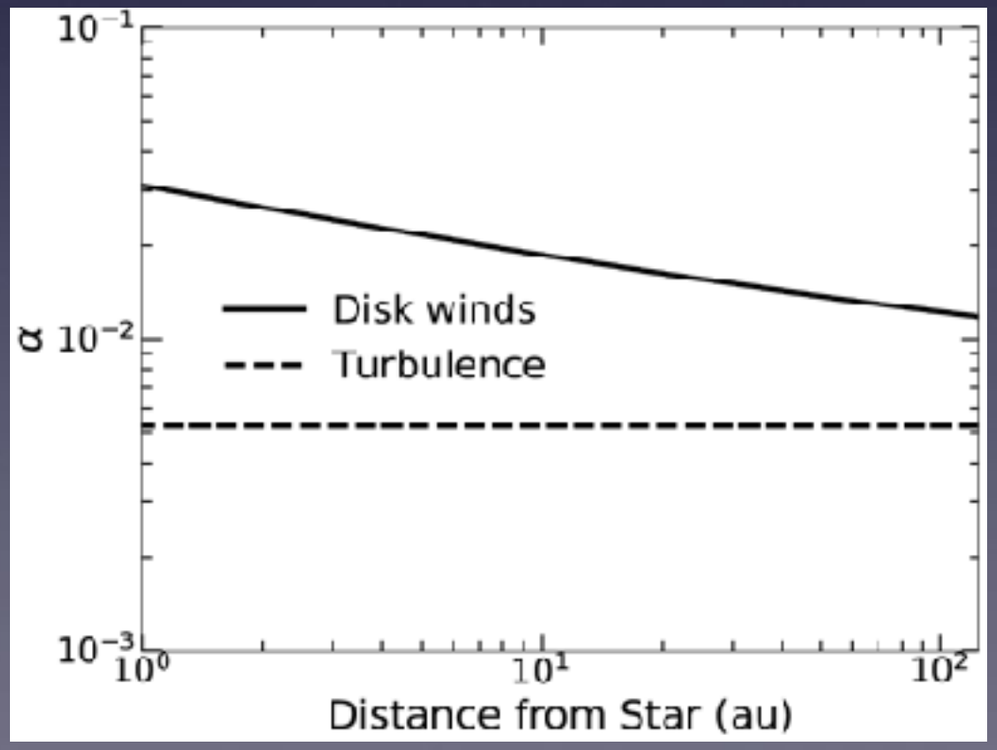
JVLA data will be combined, too

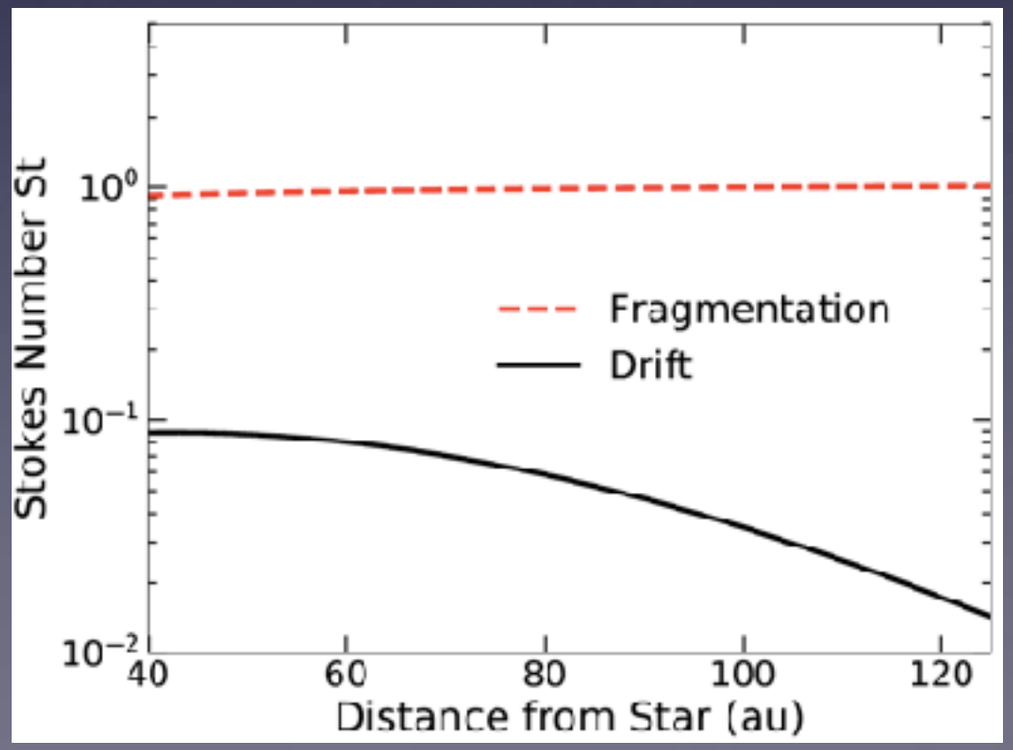
Carrasco-Gonzalez et al 2016

Next Step 2: Application to Thermal emission (Origins of gaps)









Summary

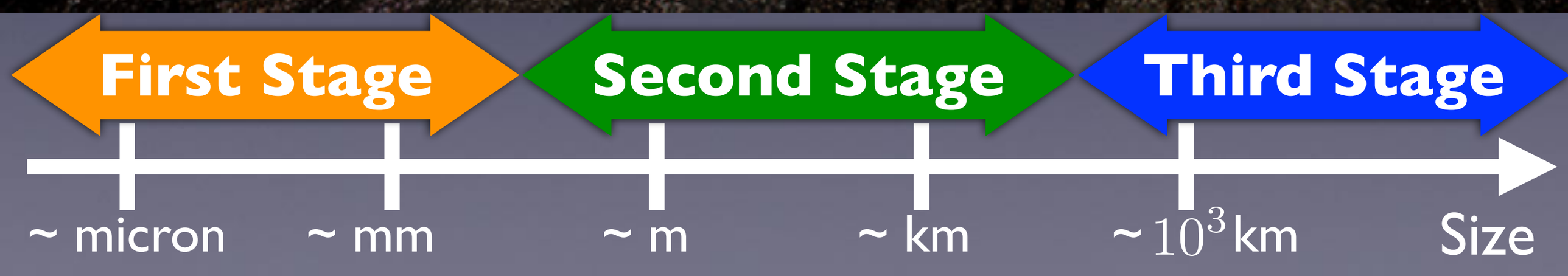
Hasegawa et al 2017, ApJ, 845, 31

- ALMA observations of the HL Tau disk can advance our understanding of **disk evolution**
- Subsequent radiative transfer modeling suggests a higher degree of dust settling for the actively accreting disk
- Developed the simple, semi-analytical model, taking into account magnetically induced disk winds
- Our results indicate the importance of **magnetically induced disk winds** to fully reproduce the global configuration
- Followup work will be performed to obtain a better understanding of **polarization observations** and to fully

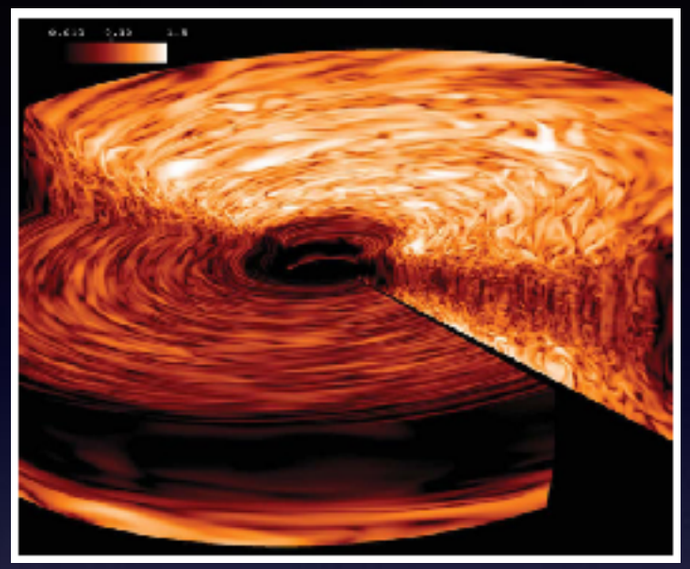
Planet formation: Long journey from dust to planets

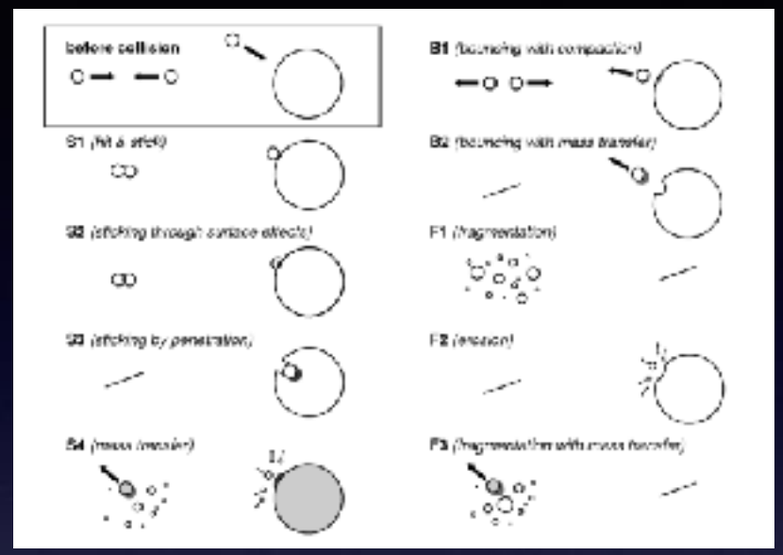
Golden era of (exo)planetary sciences

A Comprehensive Examination of Planet Formation Covering the Full Size Range



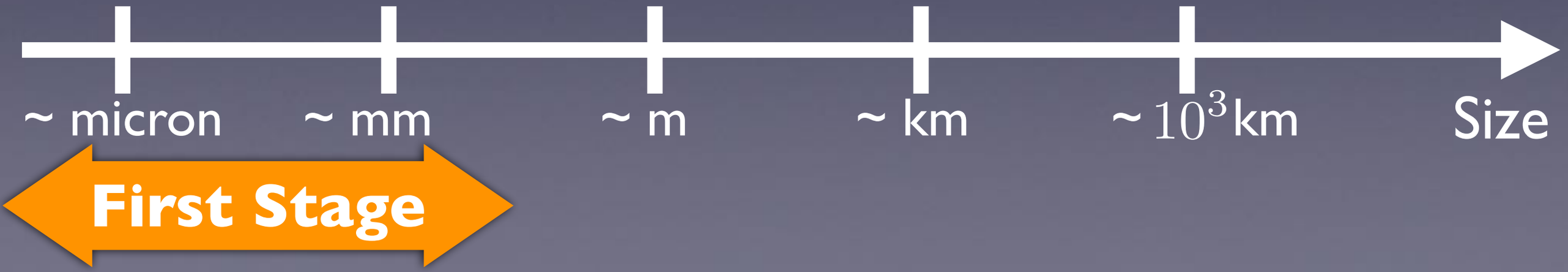
Numerical Modeling of Dust Growth in Turbulent Disks





Flock et al 2011 Sengupta et al 2018 submitted

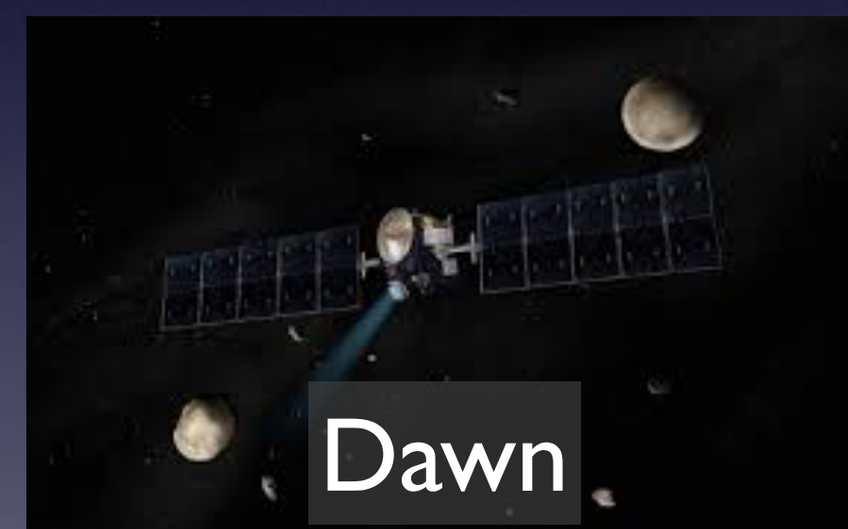
We will **infer** the distribution of planet-forming materials in disks



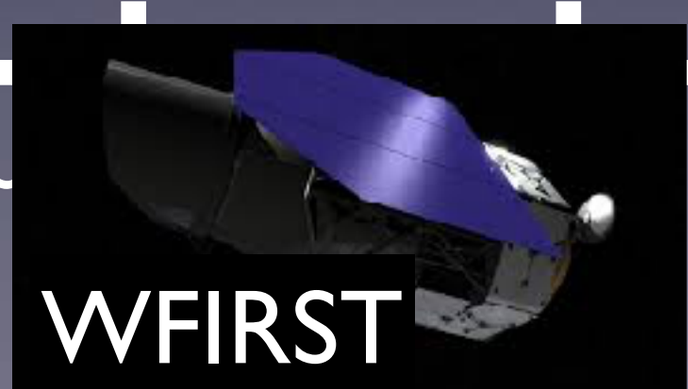
Planetesimal Formation & Origins of Asteroids

Scenario 1: Chondrule accretion

Scenario 2: Chondrule accumulation



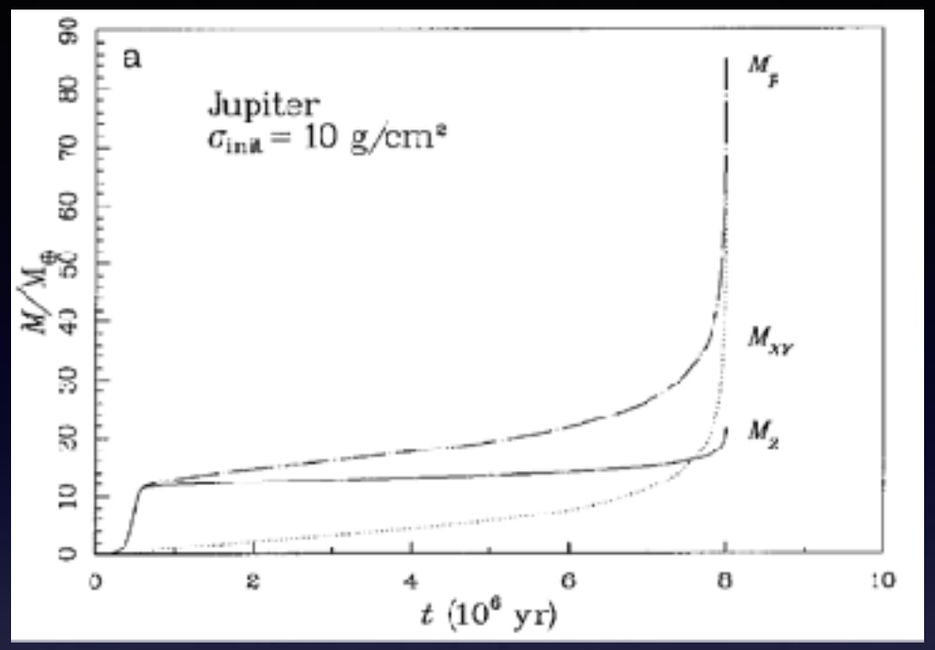
We will **identify** formation mechanism(s) of planetesimals



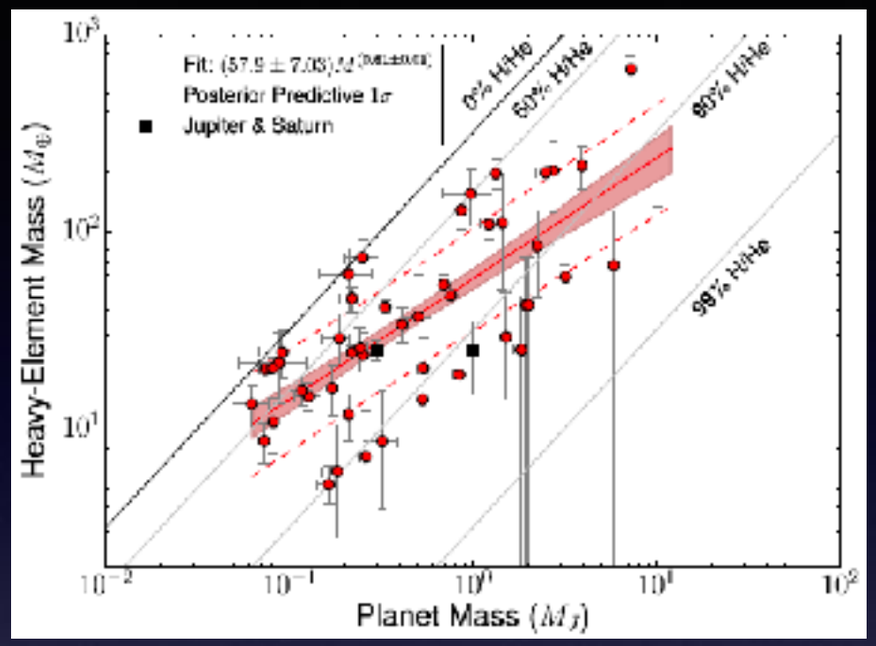
Second Stage

Applications to debris disks

Gas Accretion onto Cores & Origins of Super-Earths



Pollack et al 1996



Thorngren et al 2016

FINESSE

We will **link** formation mechanisms of (exo)planets to their atmosphere

Applications to the Origin of the Solar System

Third Stage

Summary

- Planet formation is the long journey from small dust grains to large planets
- A number of important advances in planet formation over full range of scales
- As examples, the origin of heavy elements in observed exoplanets and theoretical modeling of the HL Tau disk are discussed
- further synergies between planetary and exoplanetary sciences will be undertaken to draw a better picture of planet formation and examine the origin of the solar and extrasolar planetary systems