Planet Formation in Star-Forming Regions
: from the Solar System to Other Worlds

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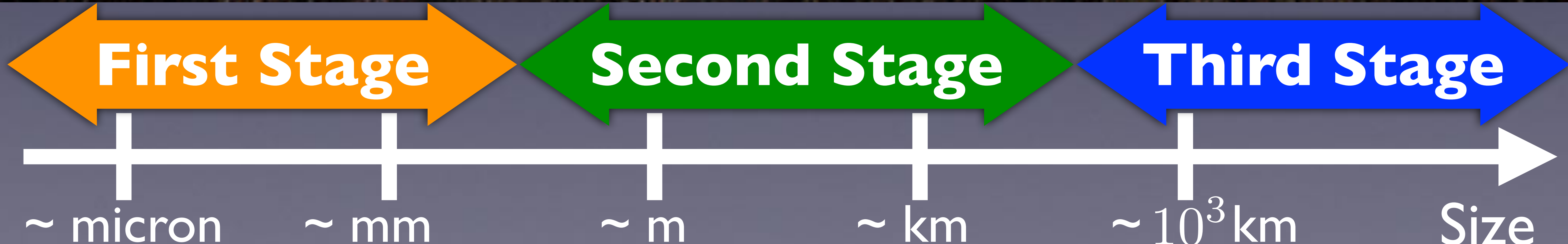
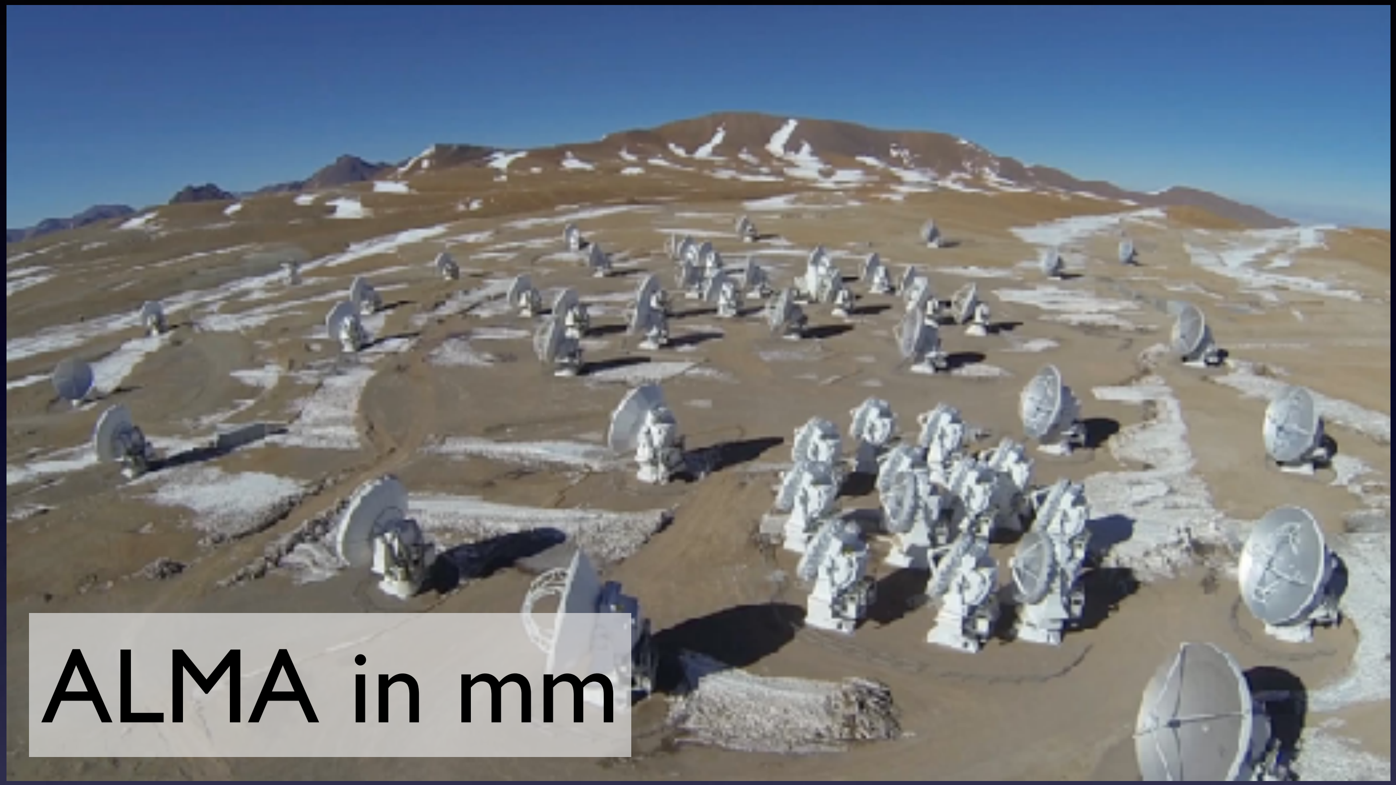
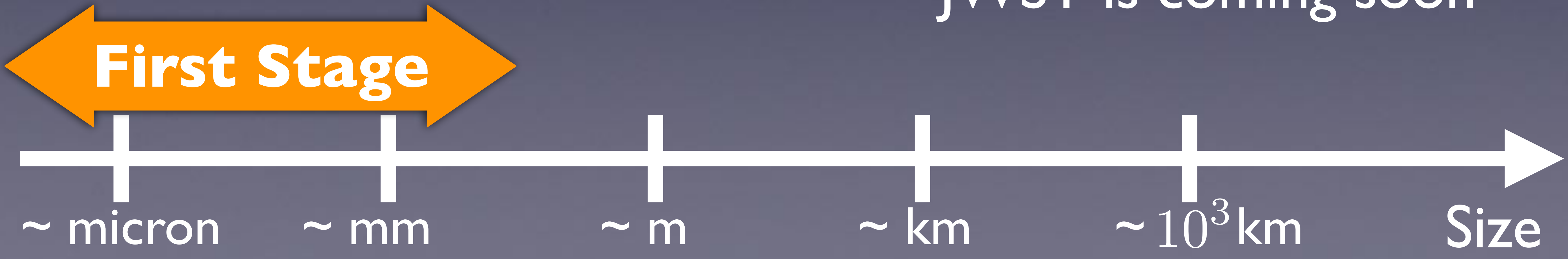


1. Evolution in Astronomical Disk Observations



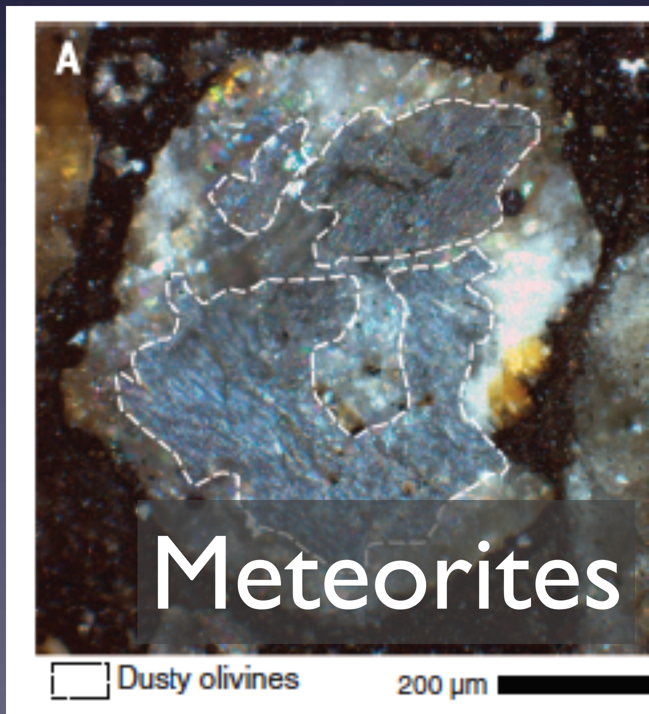
We can **see** planet-forming regions

JWST is coming soon



2. Evolution in Space Engineering & Lab Experiments

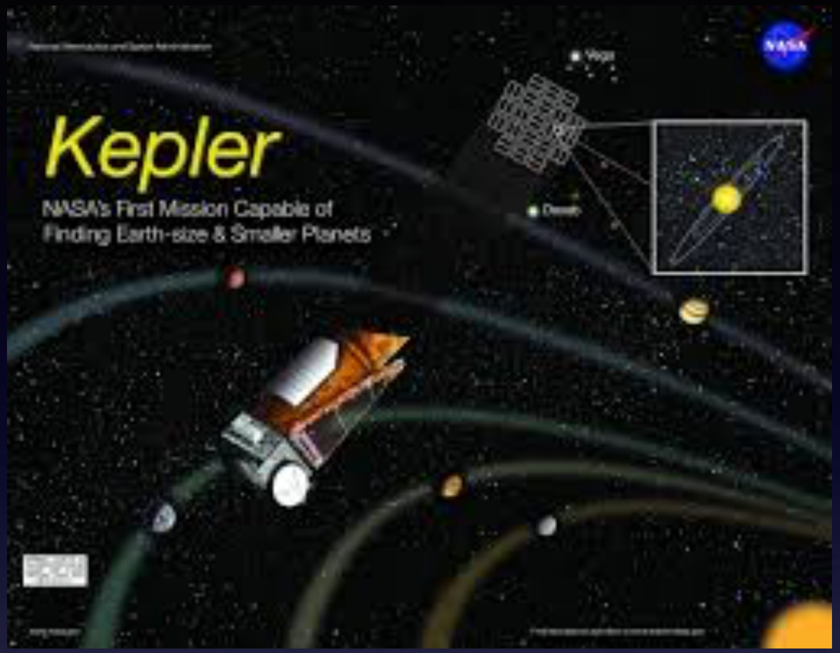
We can **touch** planet-forming materials

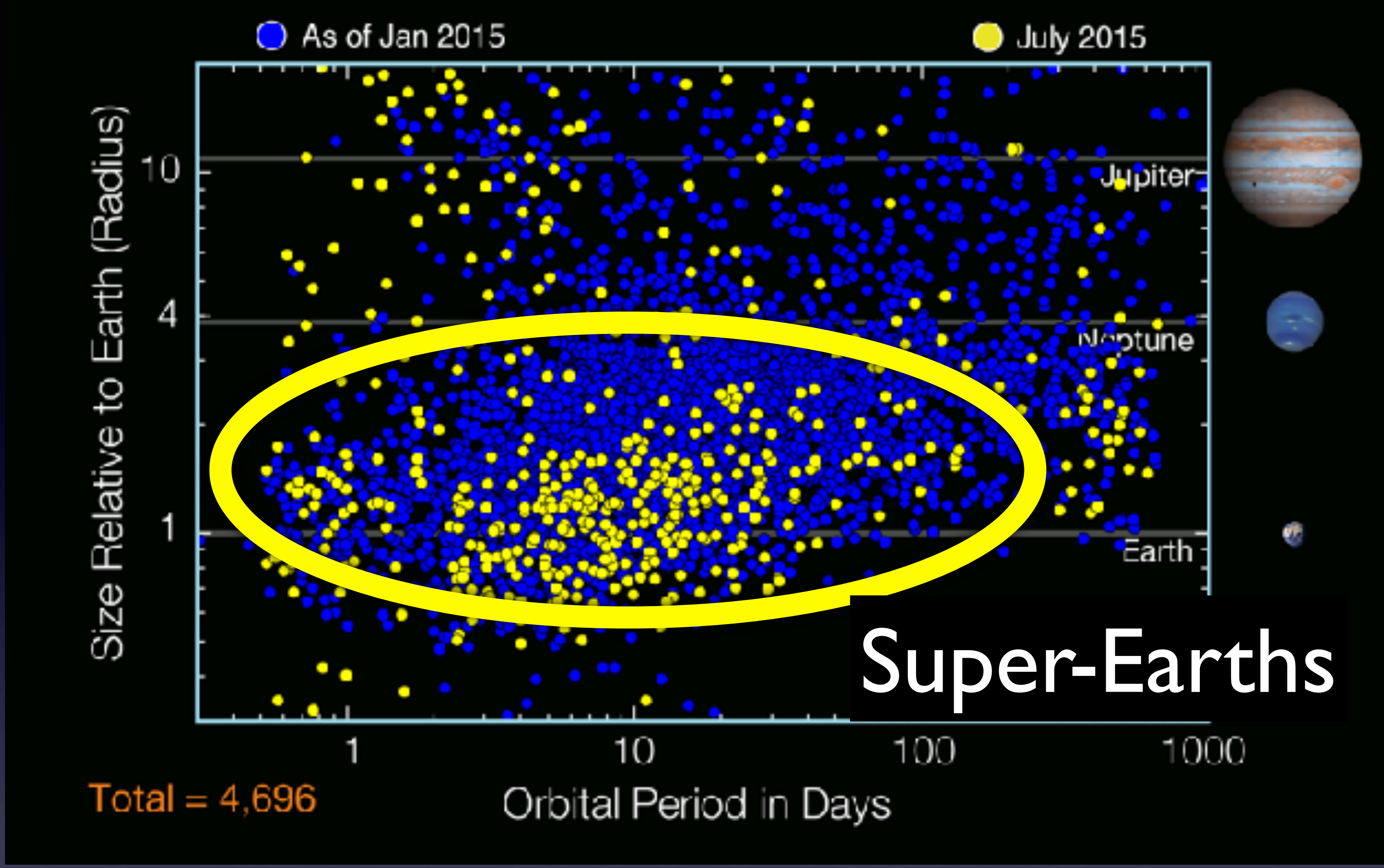


Second Stage

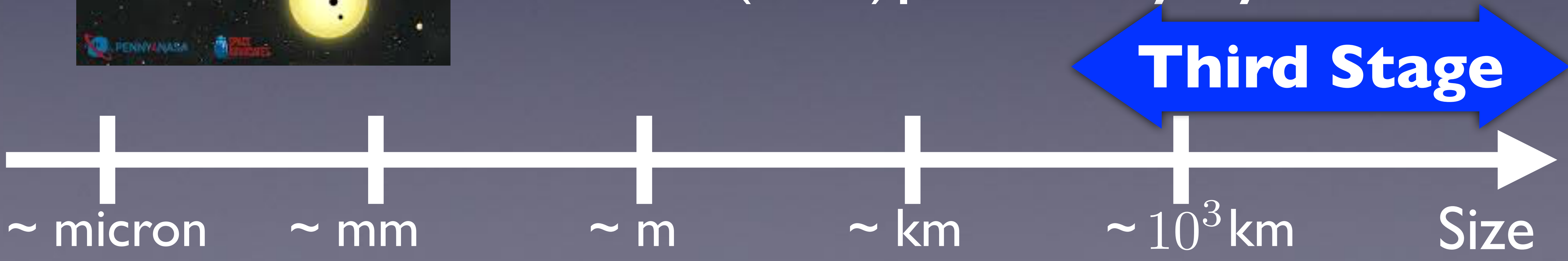
~ micron | ~ mm | ~ m | ~ km | $\sim 10^3$ km | Size

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



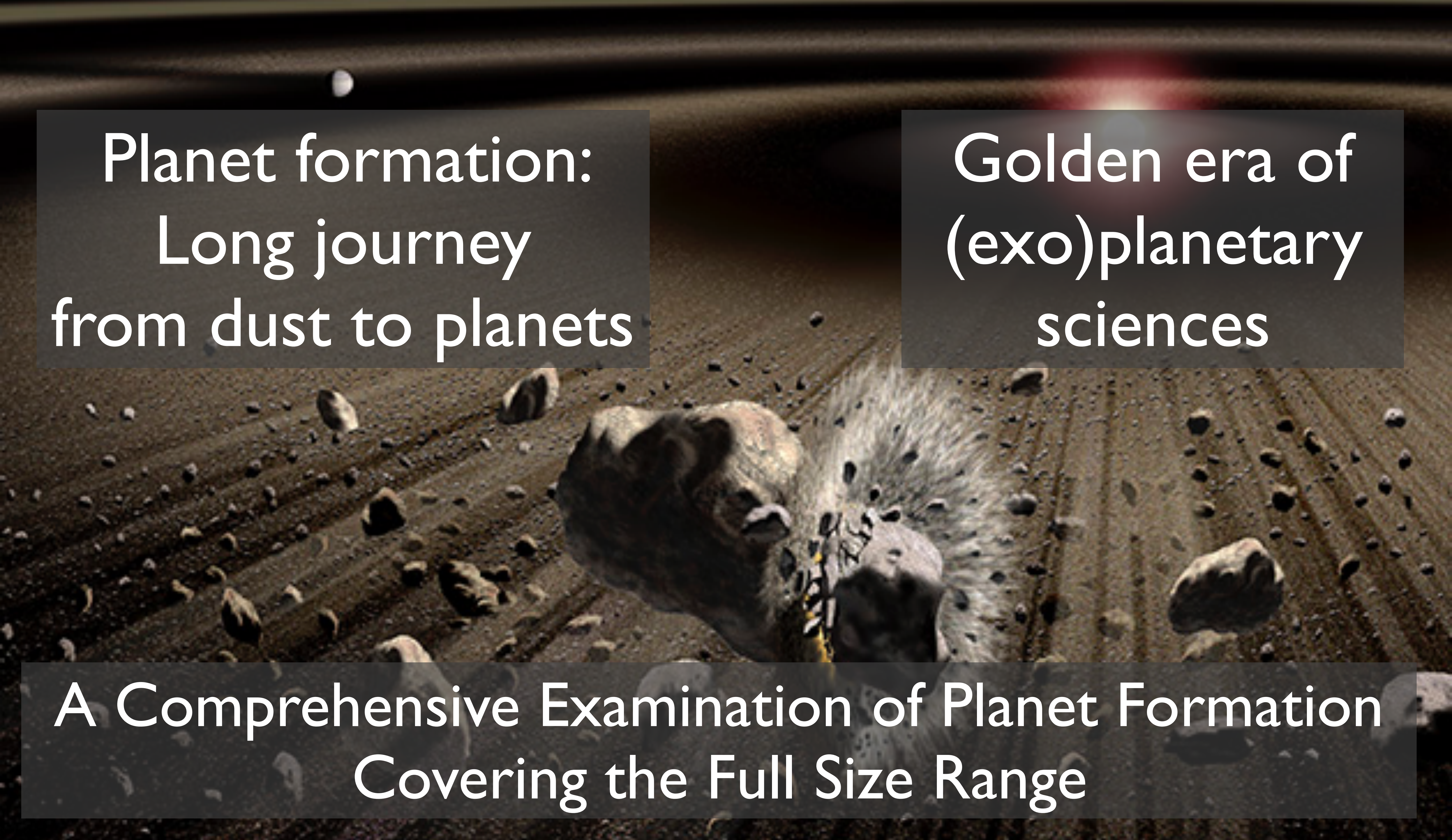


We can **characterize** (exo)planetary systems

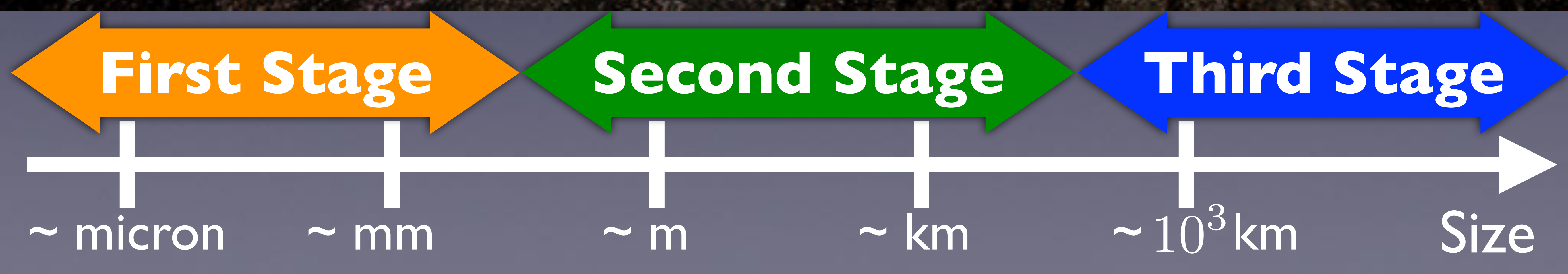


Planet formation:
Long journey
from dust to planets

Golden era of
(exo)planetary
sciences



A Comprehensive Examination of Planet Formation
Covering the Full Size Range



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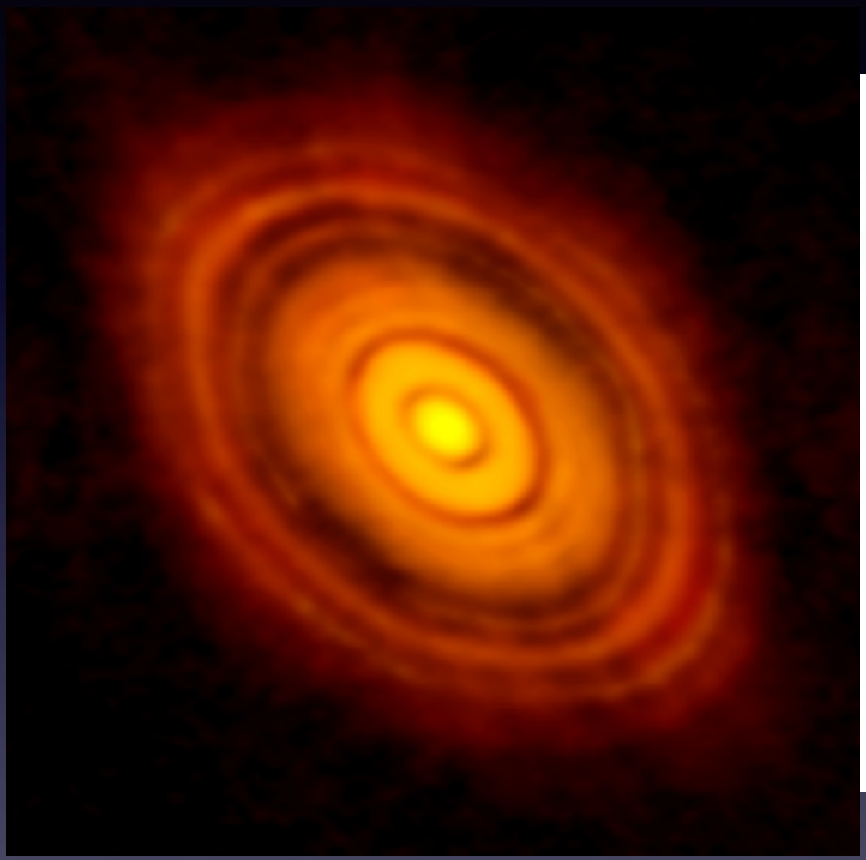
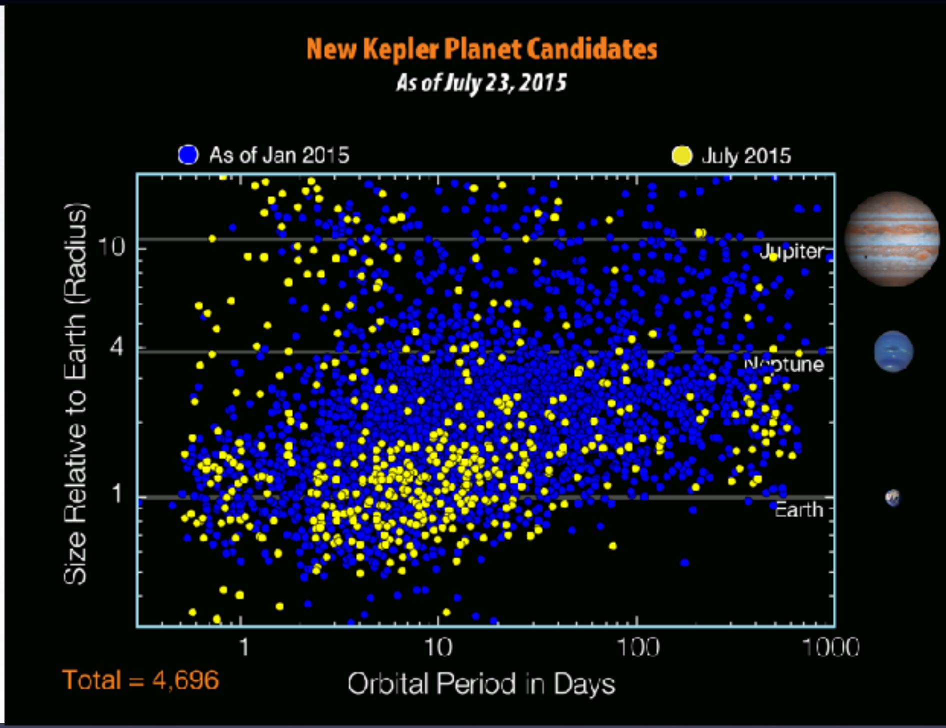
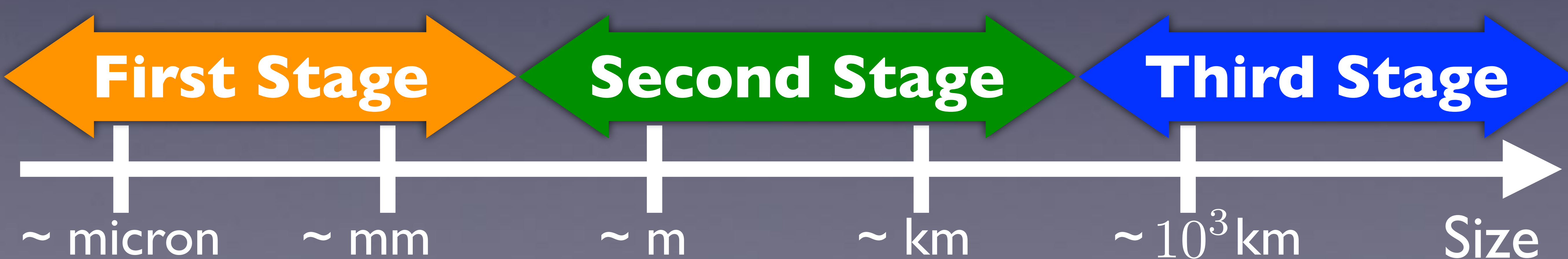
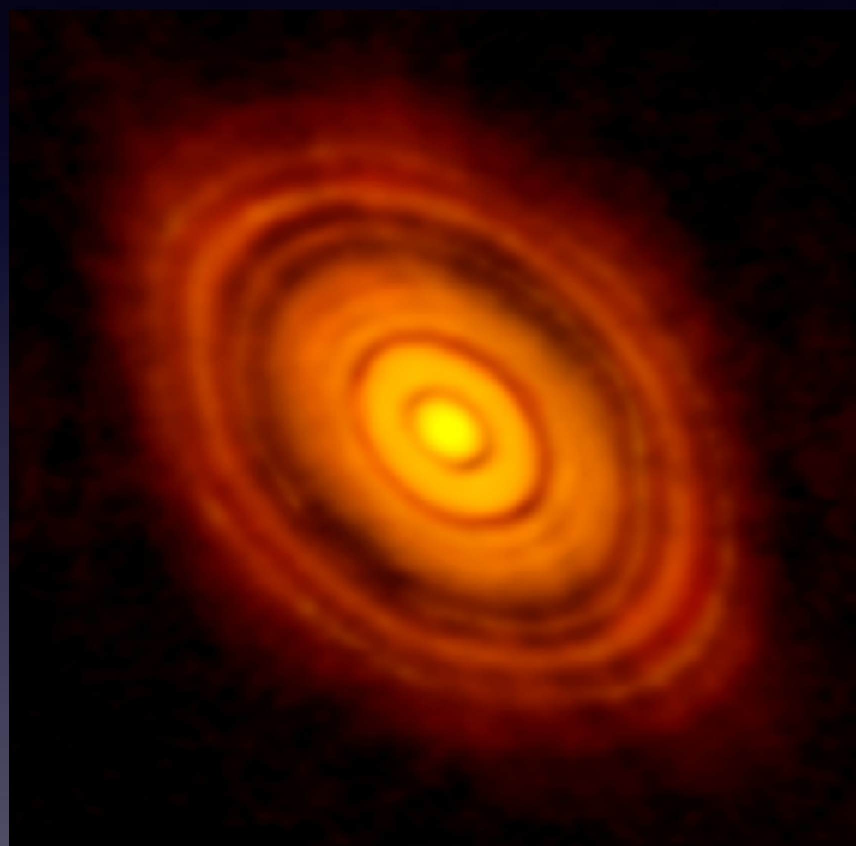
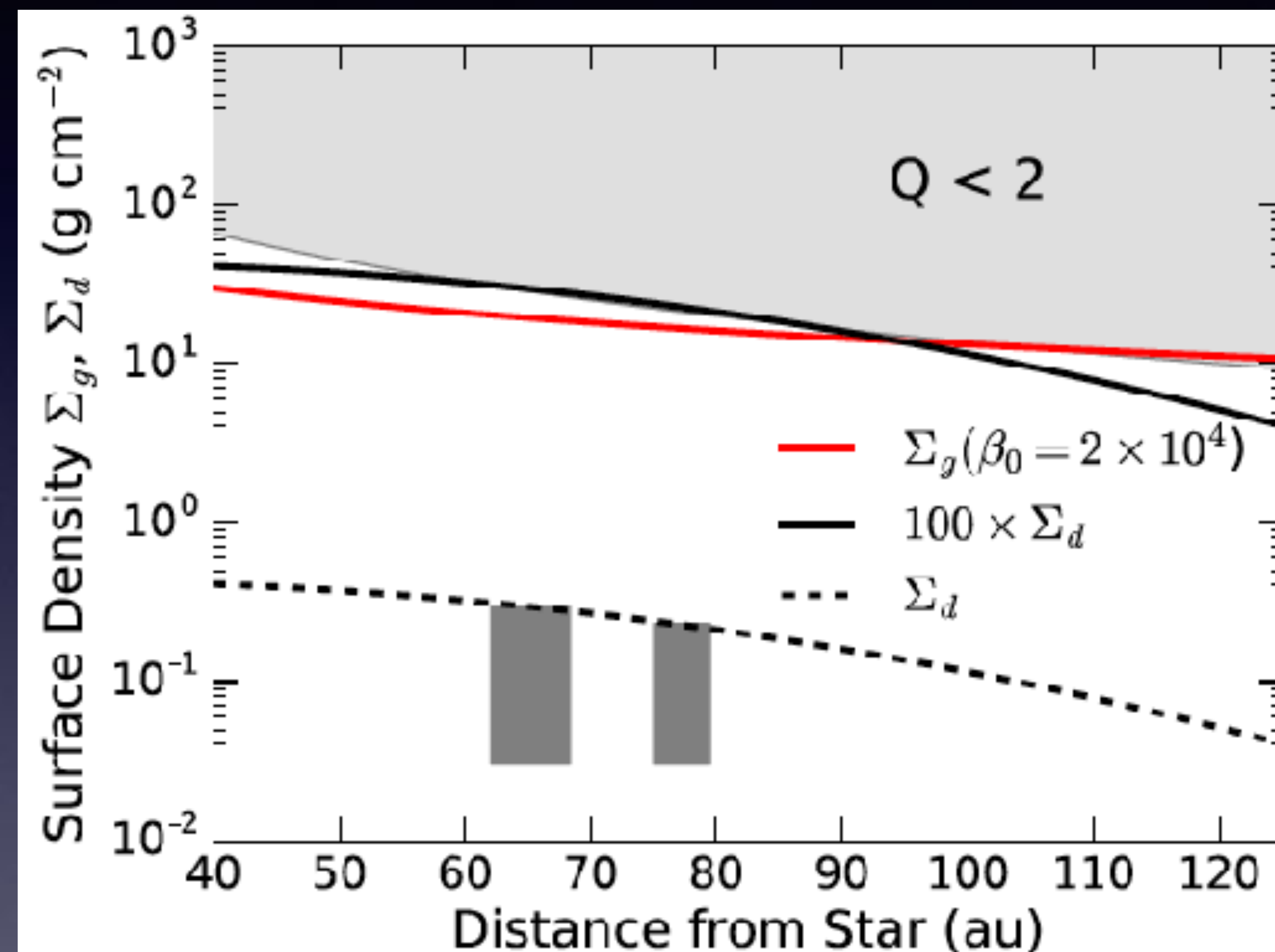






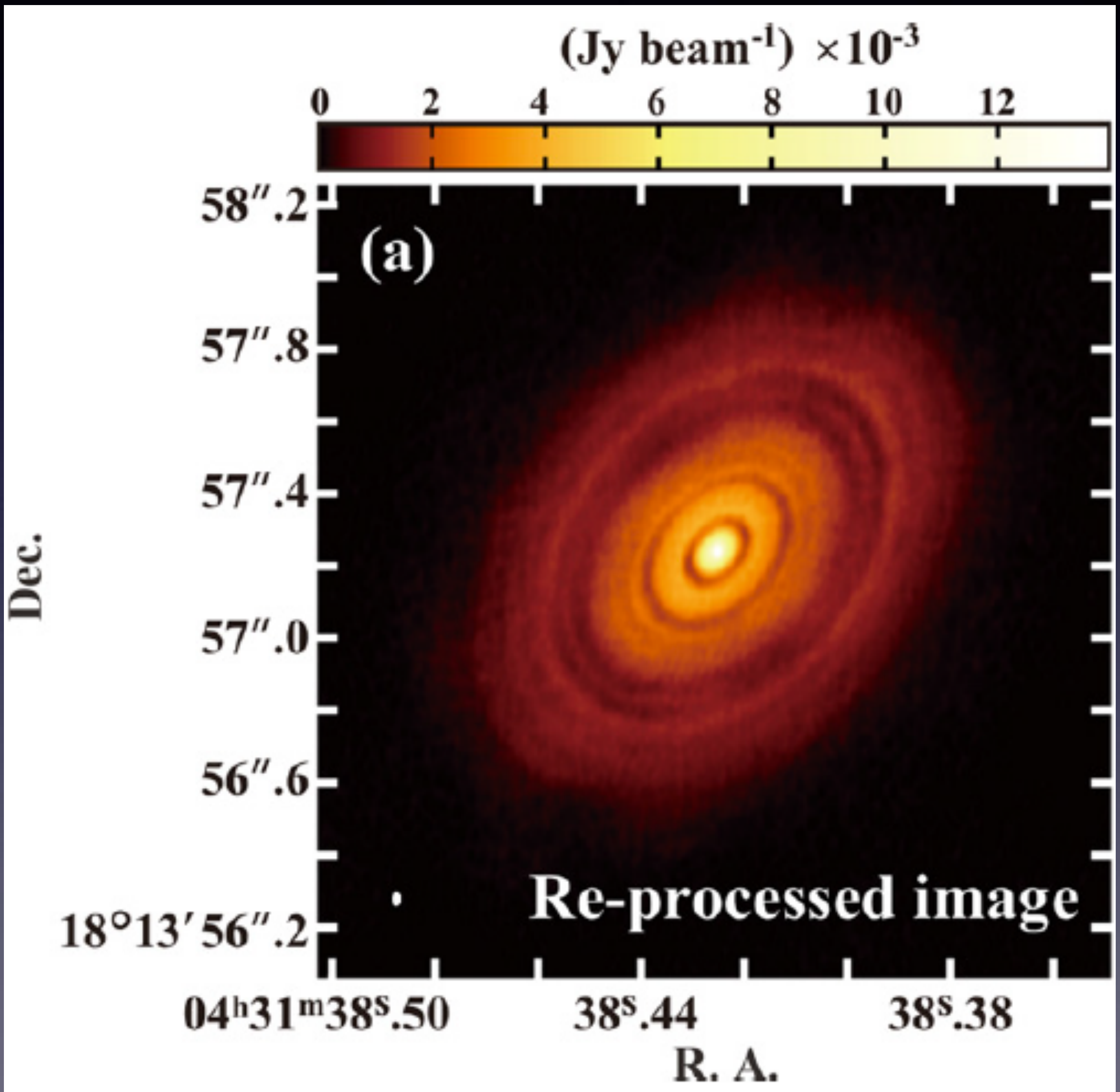
Magnetically Induced Disk Winds and Transport in the HL Tau Disk





Astonishing ALMA Images of HL Tau

ALMA Partnership et al 2015



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!!

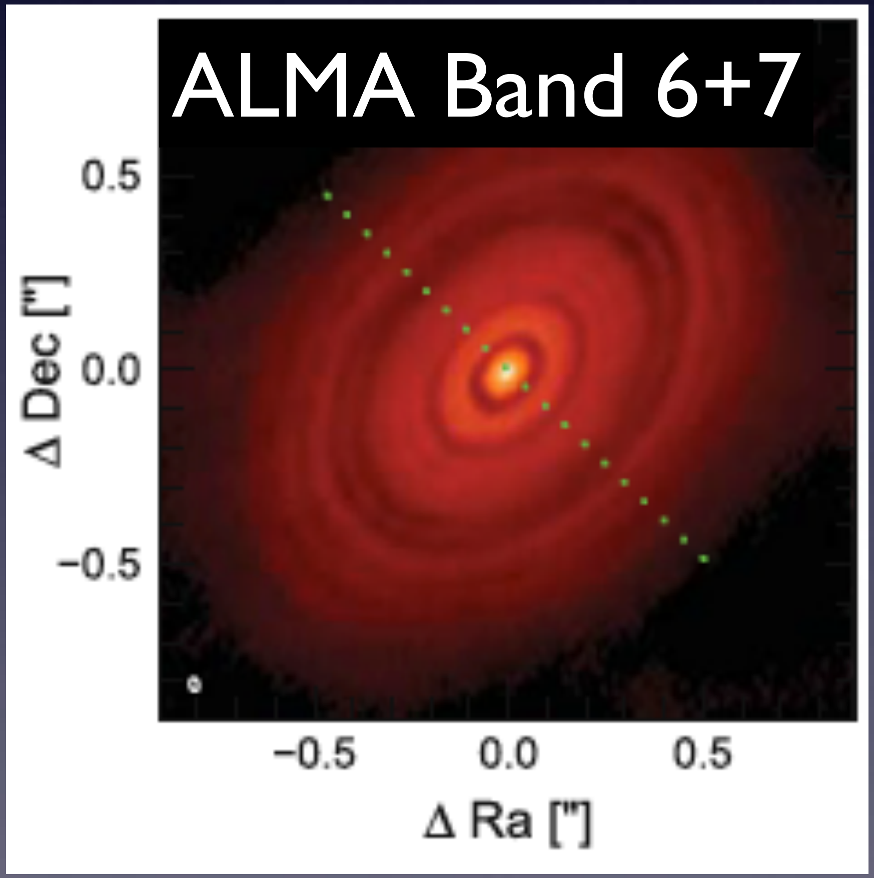
Global Properties of the HL Tau Disk

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

Hayashi et al 1993, Beck et al 2010

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

=> can be explained by MRI and MHD turbulence



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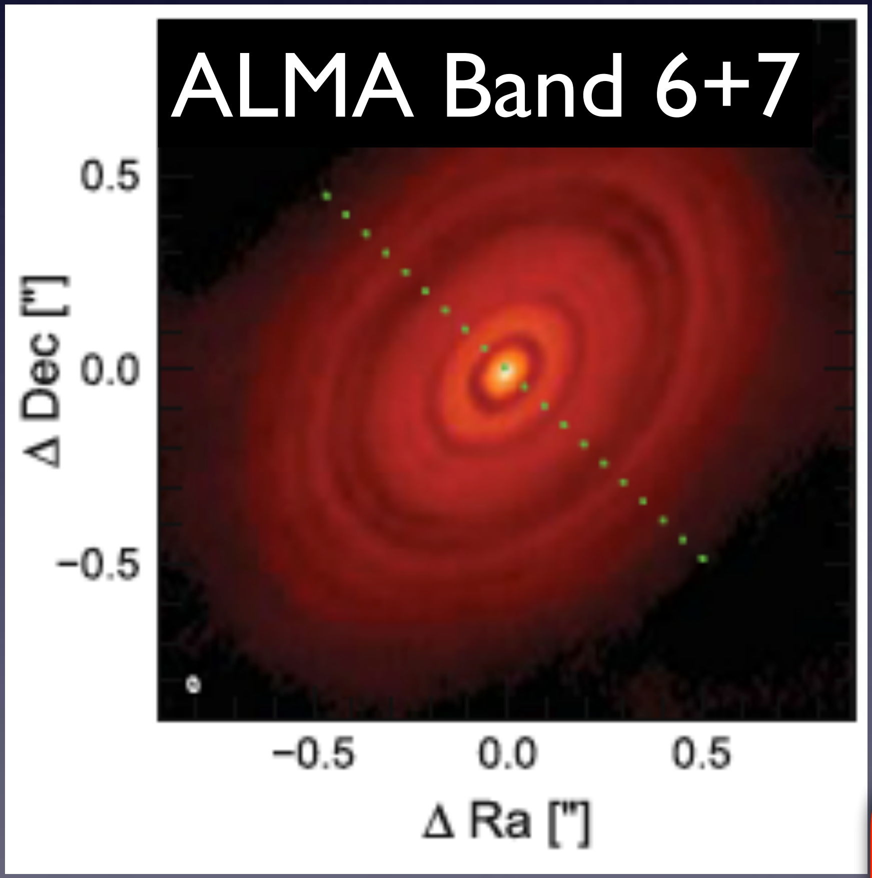
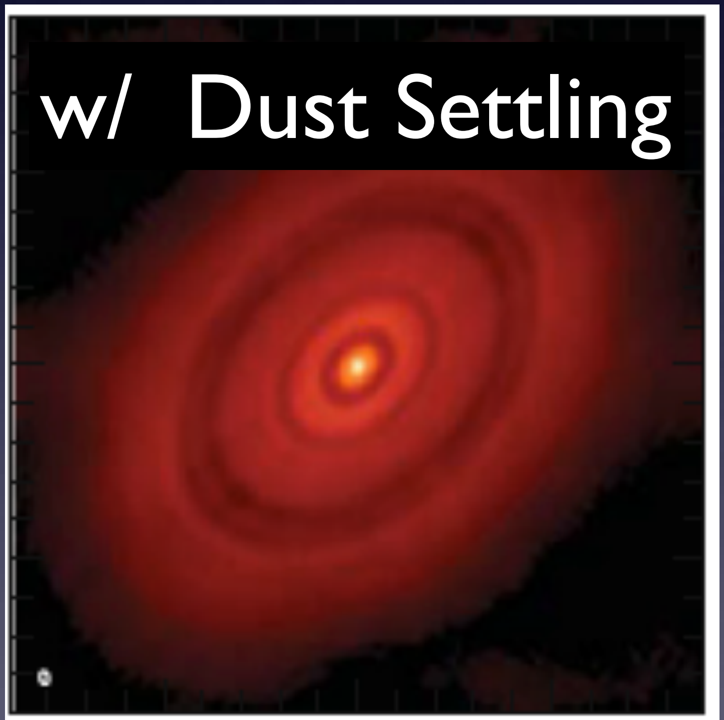




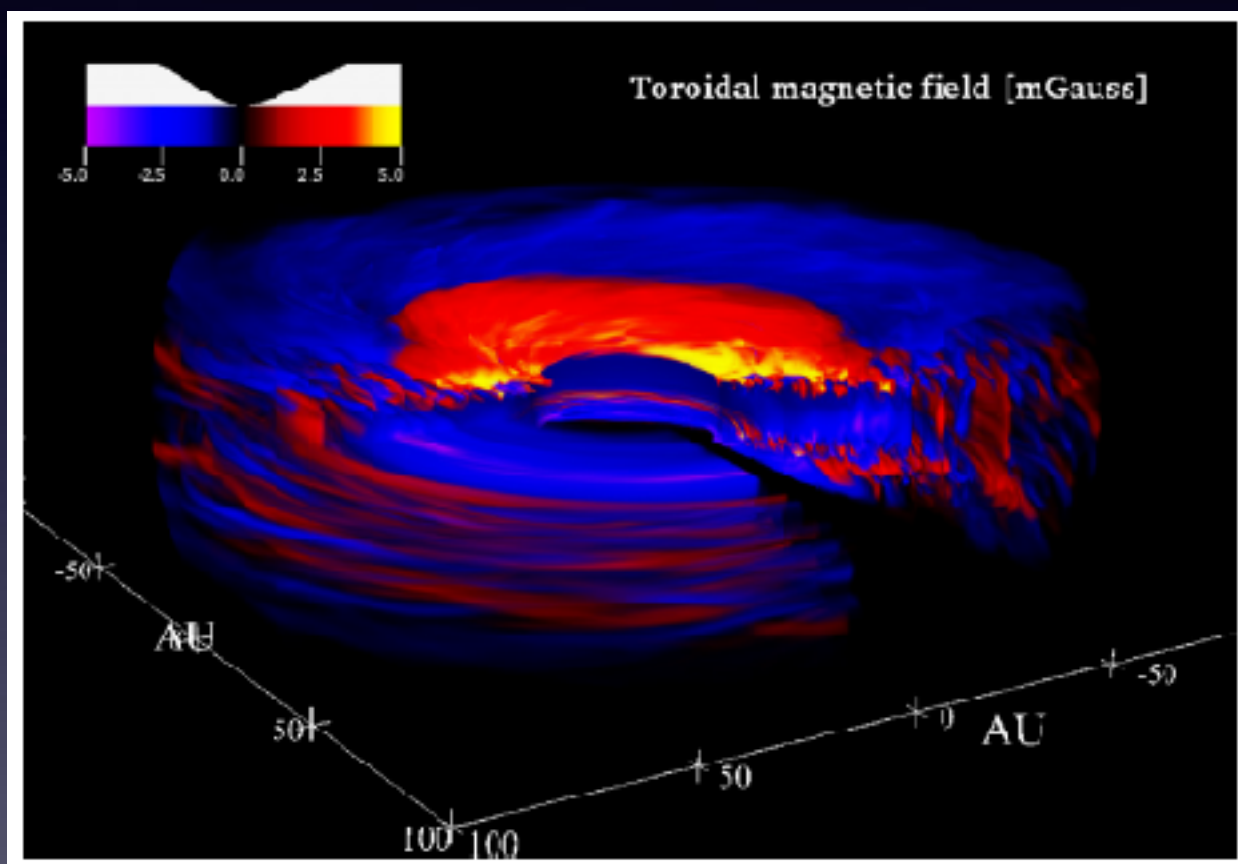
Pinte et al 2016

Vertical dust height ~1au at r =100 au
Local diffusion coefficient : $\sim 10^{-4}$

Magnetically Driven Disk Accretion

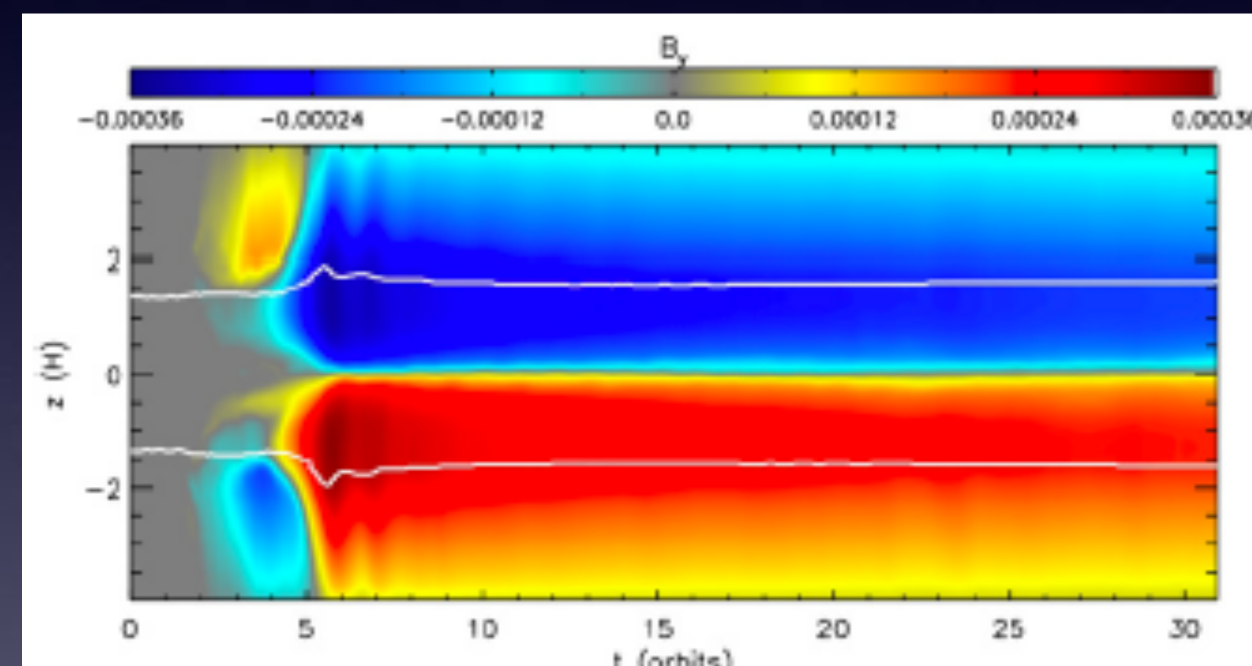
e.g., Armitage et al 2011, Bai & Stone 2013, Turner et al 2014, Suzuki et al 2016

Magnetized Turbulence



Flock et al 2015

Magnetically Induced Disk Winds



Simon et al 2013

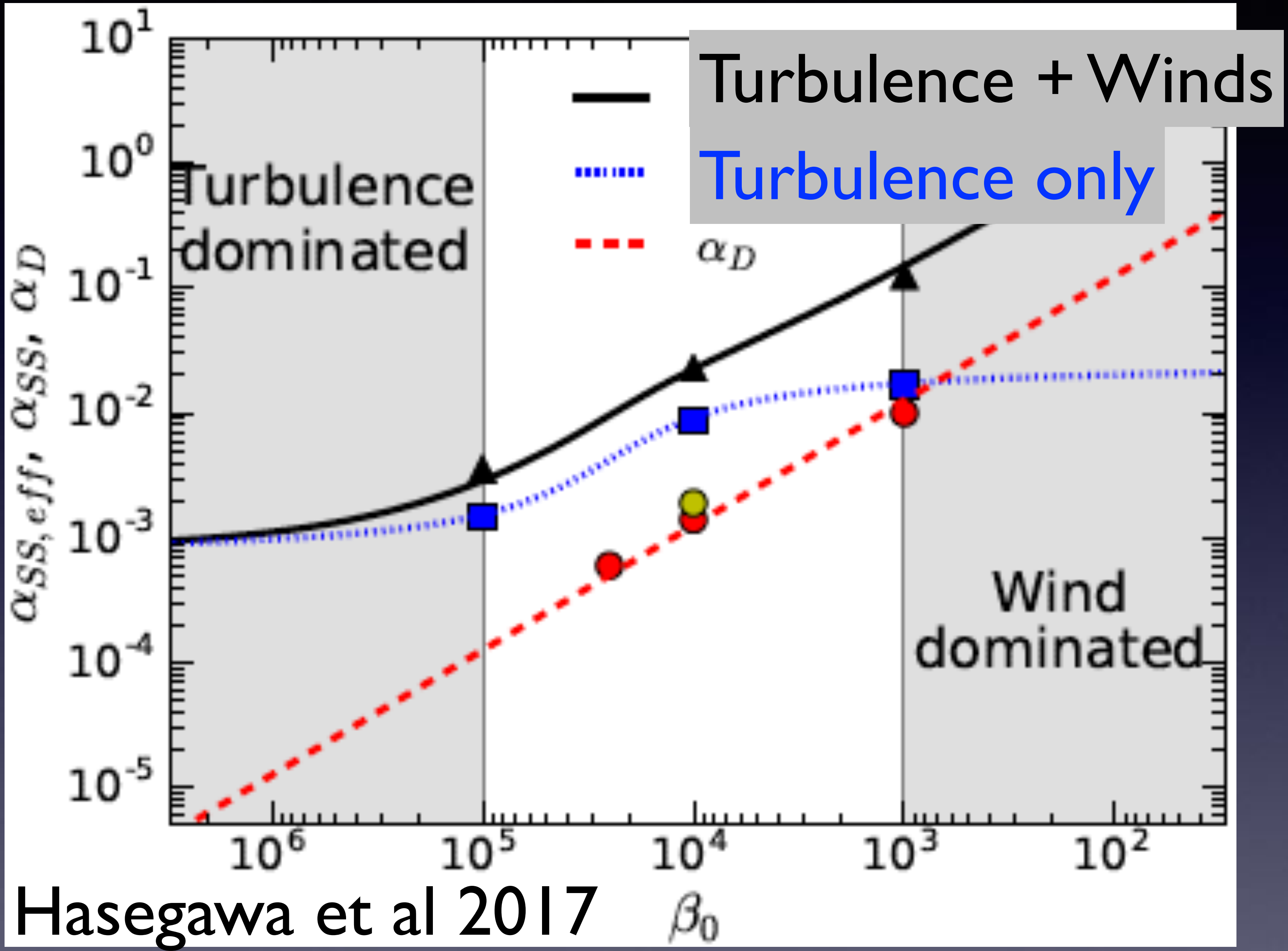
Weak

Strong

B-fields

Magnetically Driven Disk Accretion

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



α_D : vertical mixing of dust

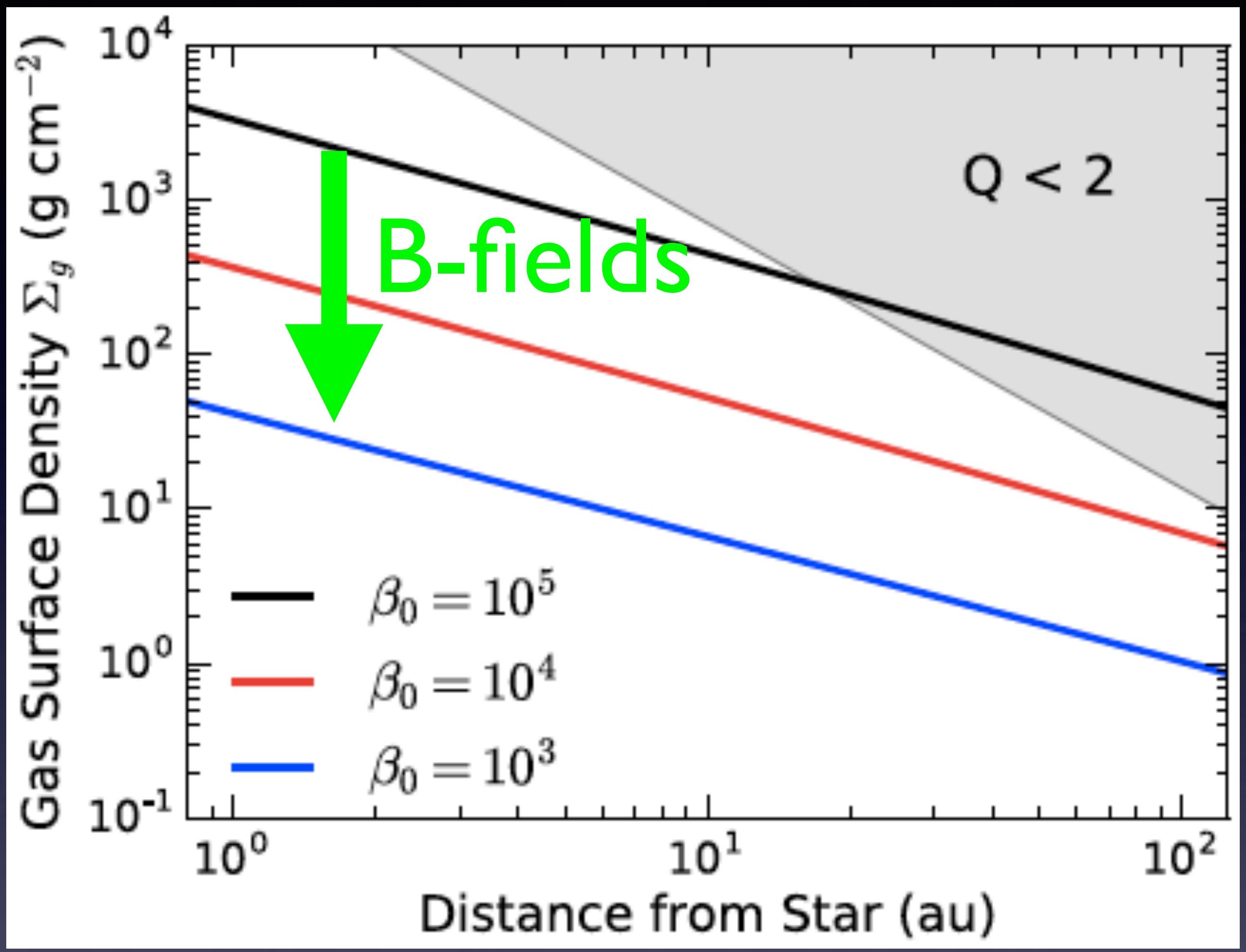
Weak

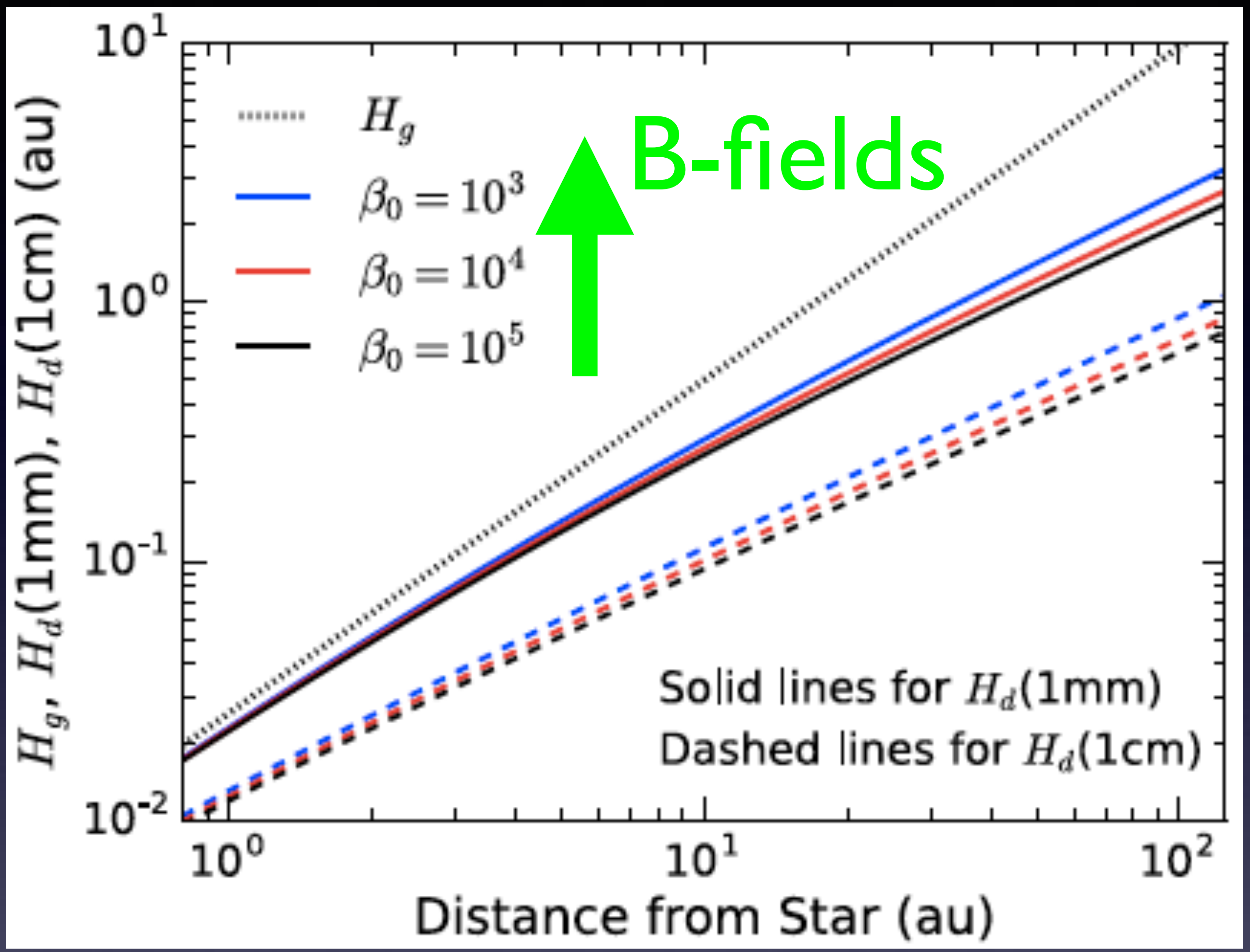
Strong

B-fields

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

Resulting Disk Structures with Disk Winds





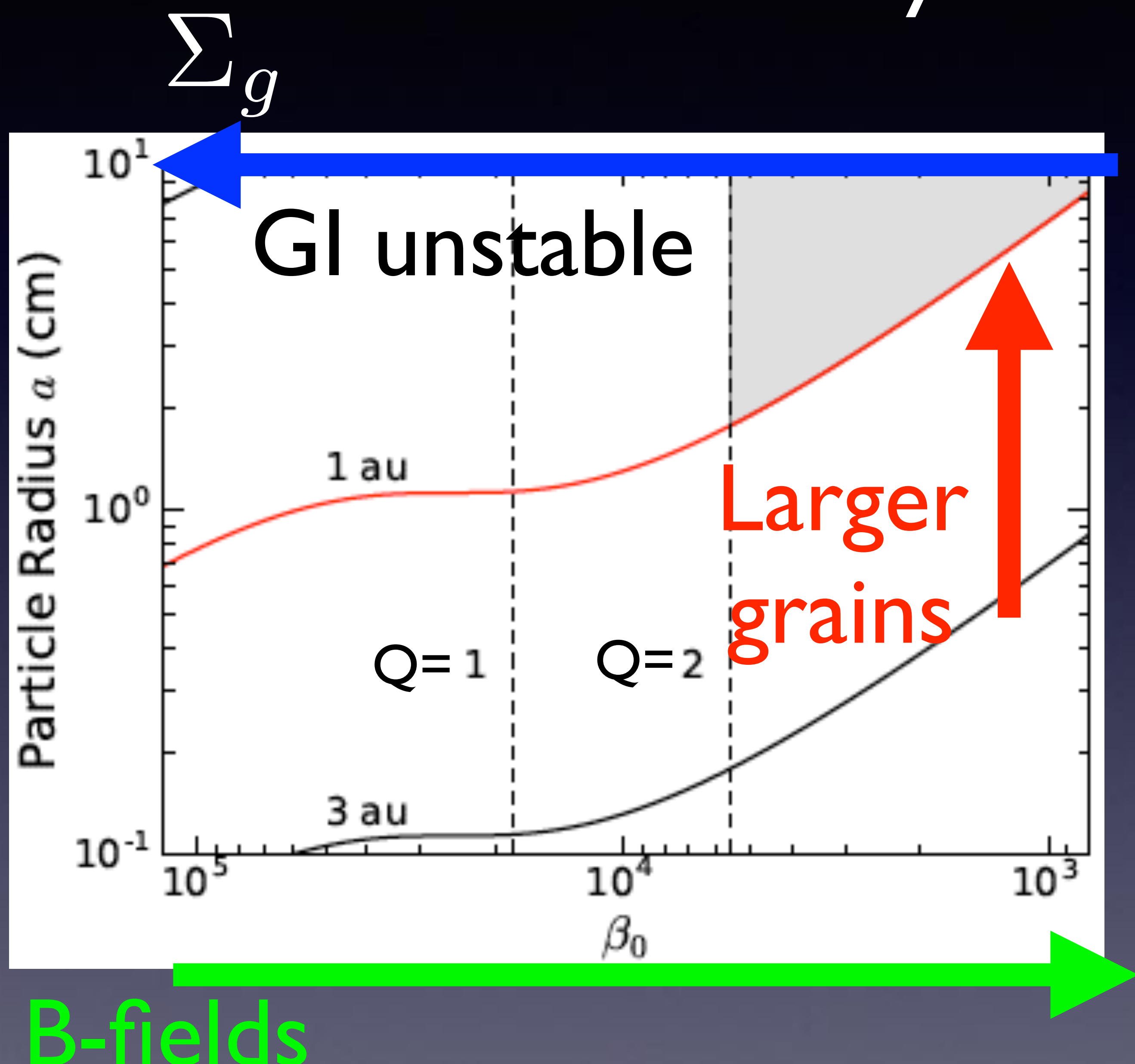
As B-fields are stronger, surface density decreases due to disk winds

Dust scale heights are independent of B-fields

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

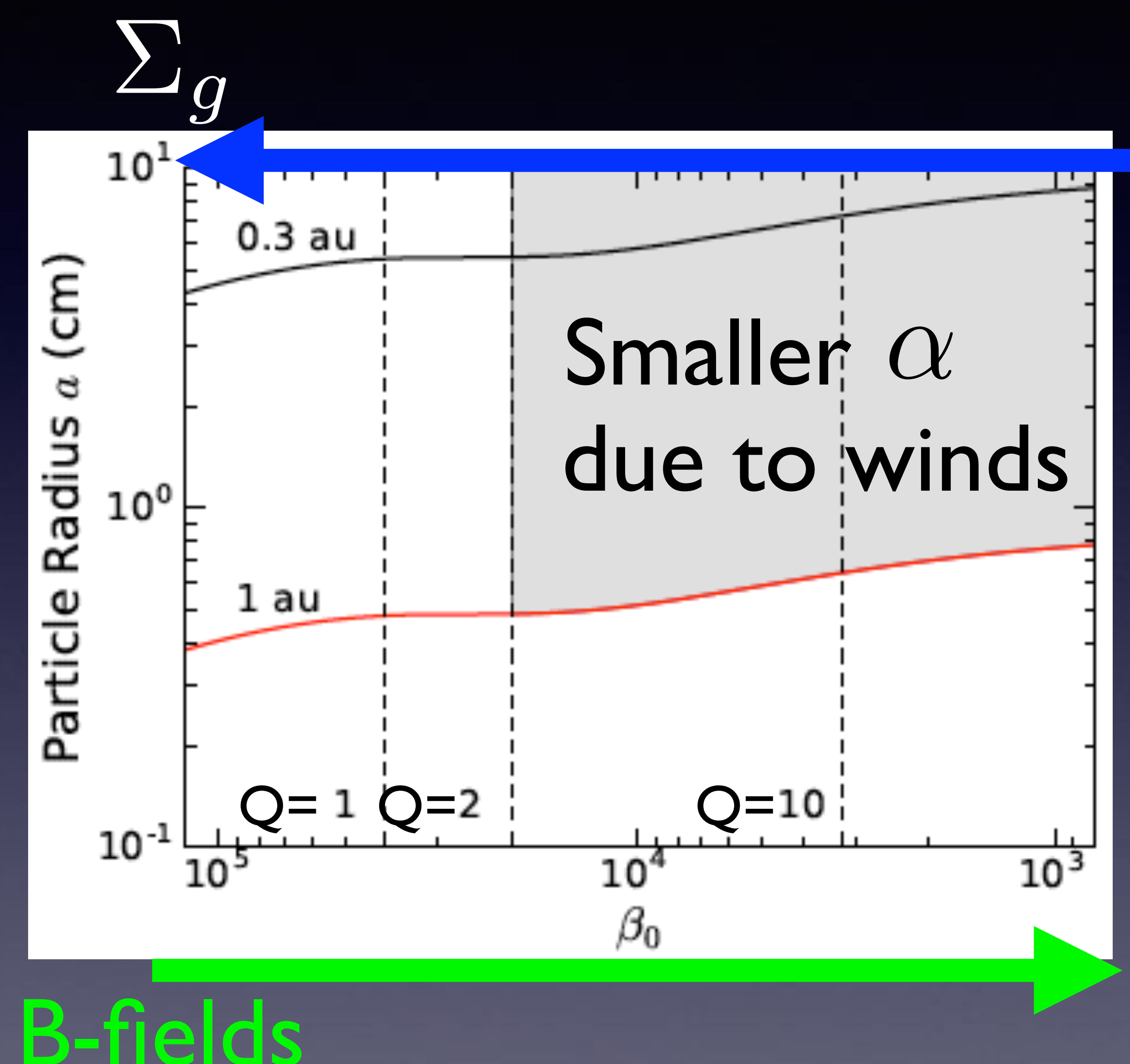
Minimum Size of Dust Particles at r = 100 au

Turbulence only



20 mm-sized dust is needed to reproduce ALMA image

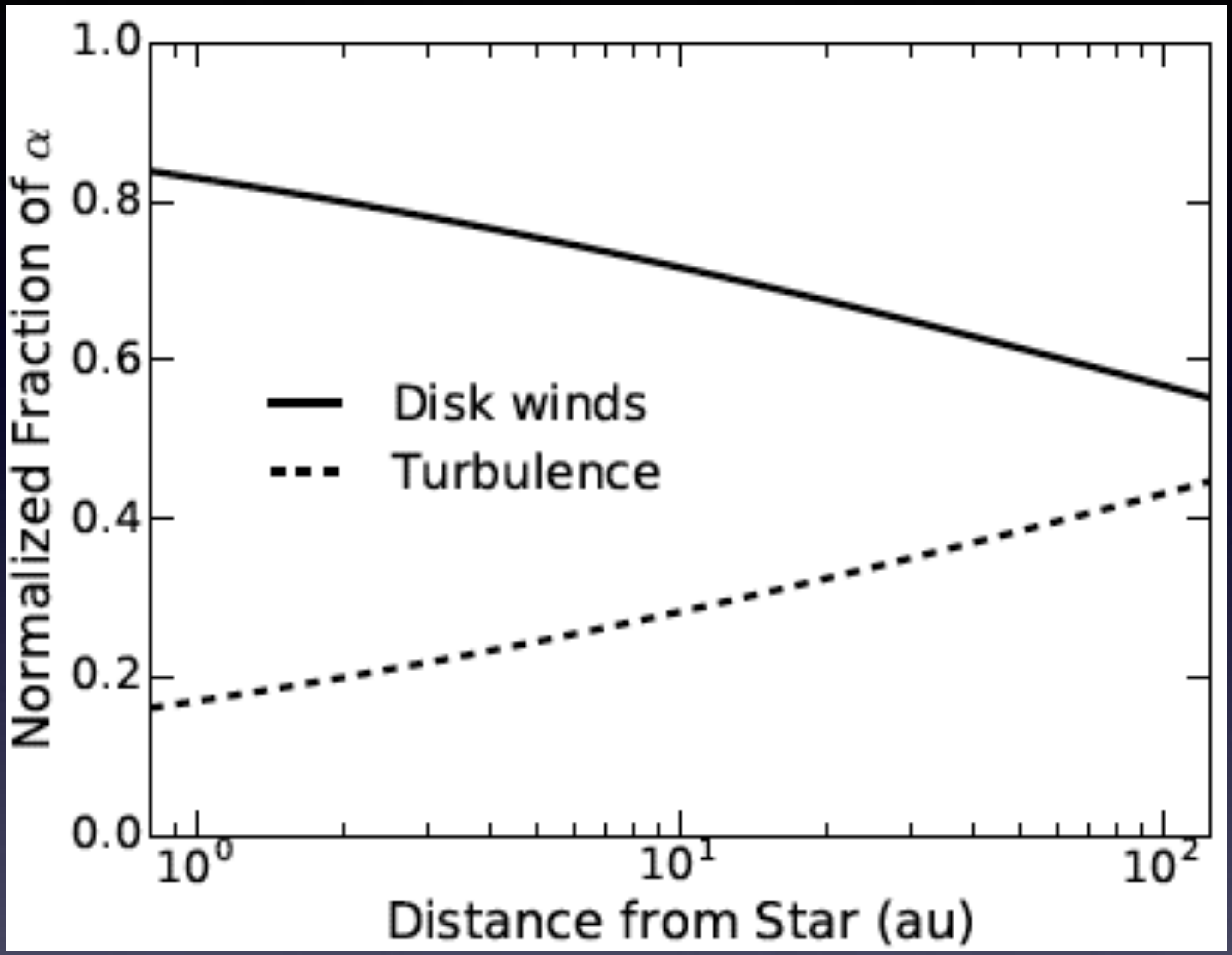
Turbulence + Winds

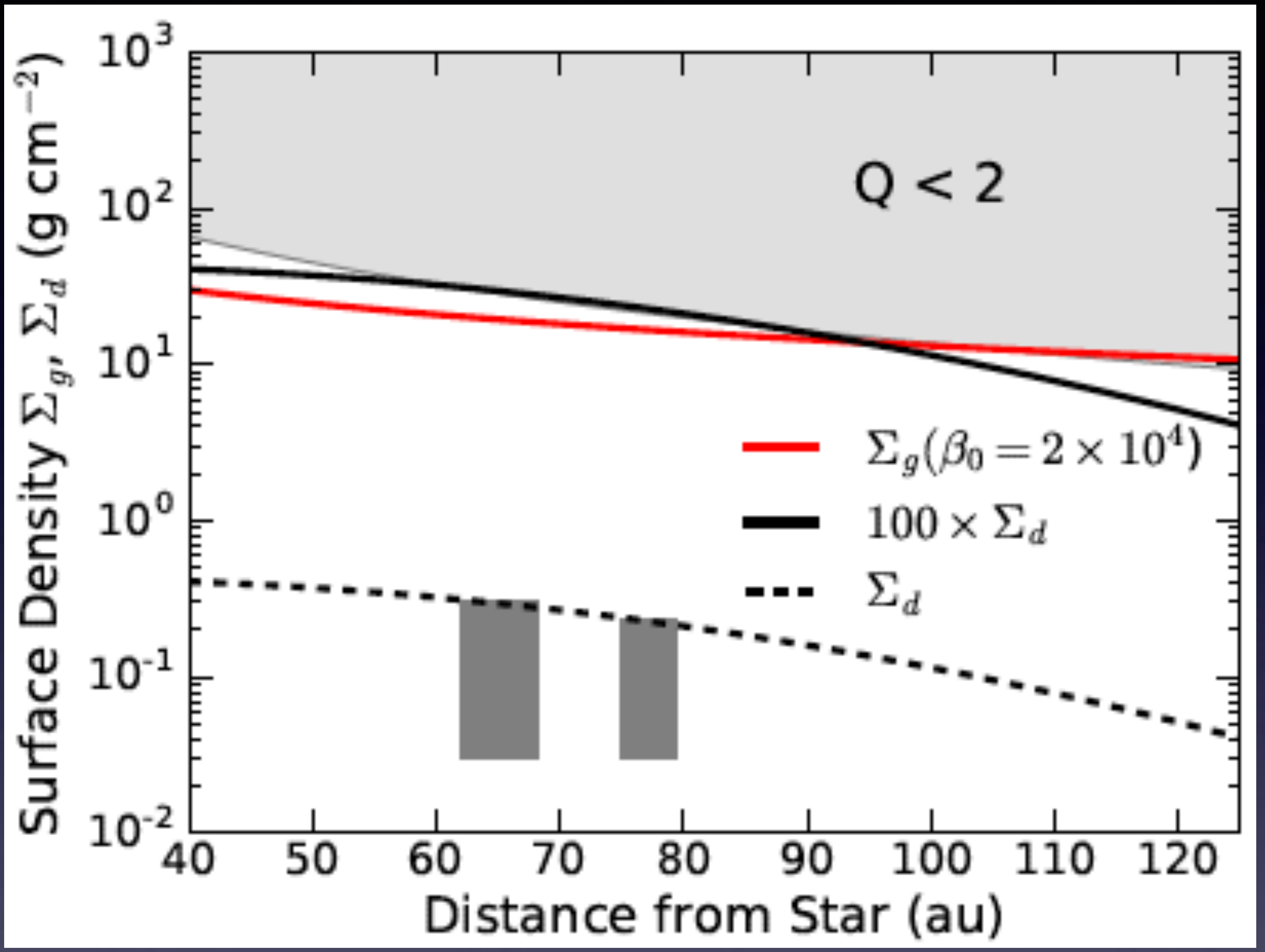


4 mm-sized dust is needed to reproduce ALMA image

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

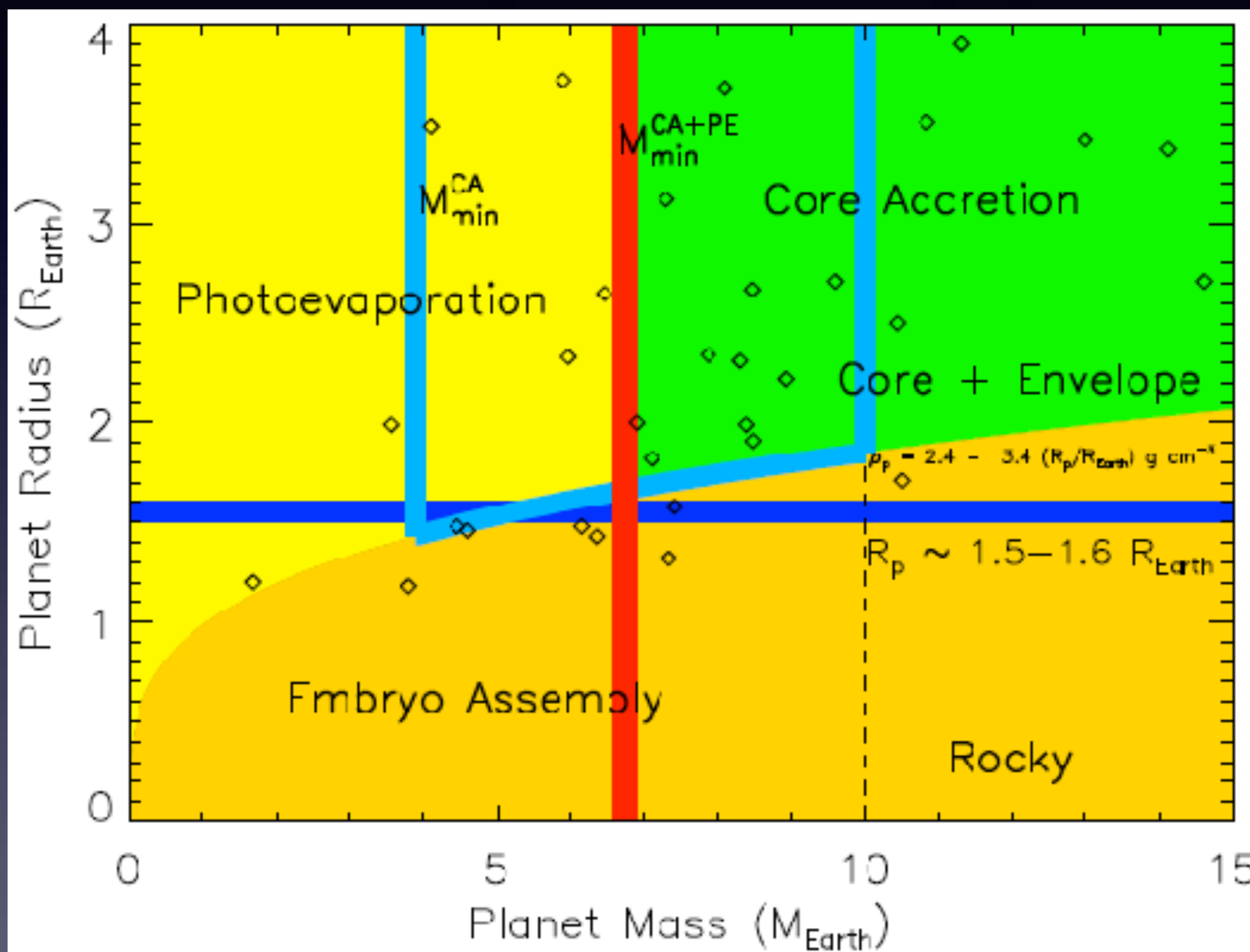
The gas-to-dust rate varies along the distance from the star (lower in the inner region & higher in the outer region)

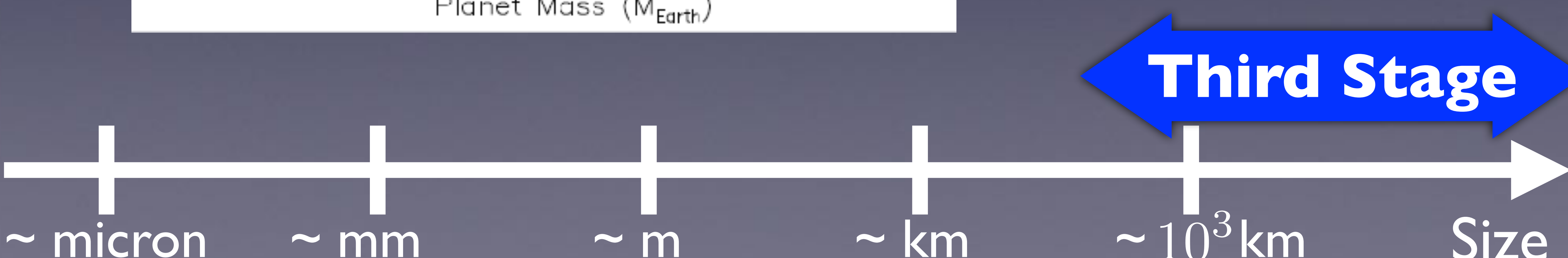
Summary

Hasegawa et al 2017, ApJ, 845, 31

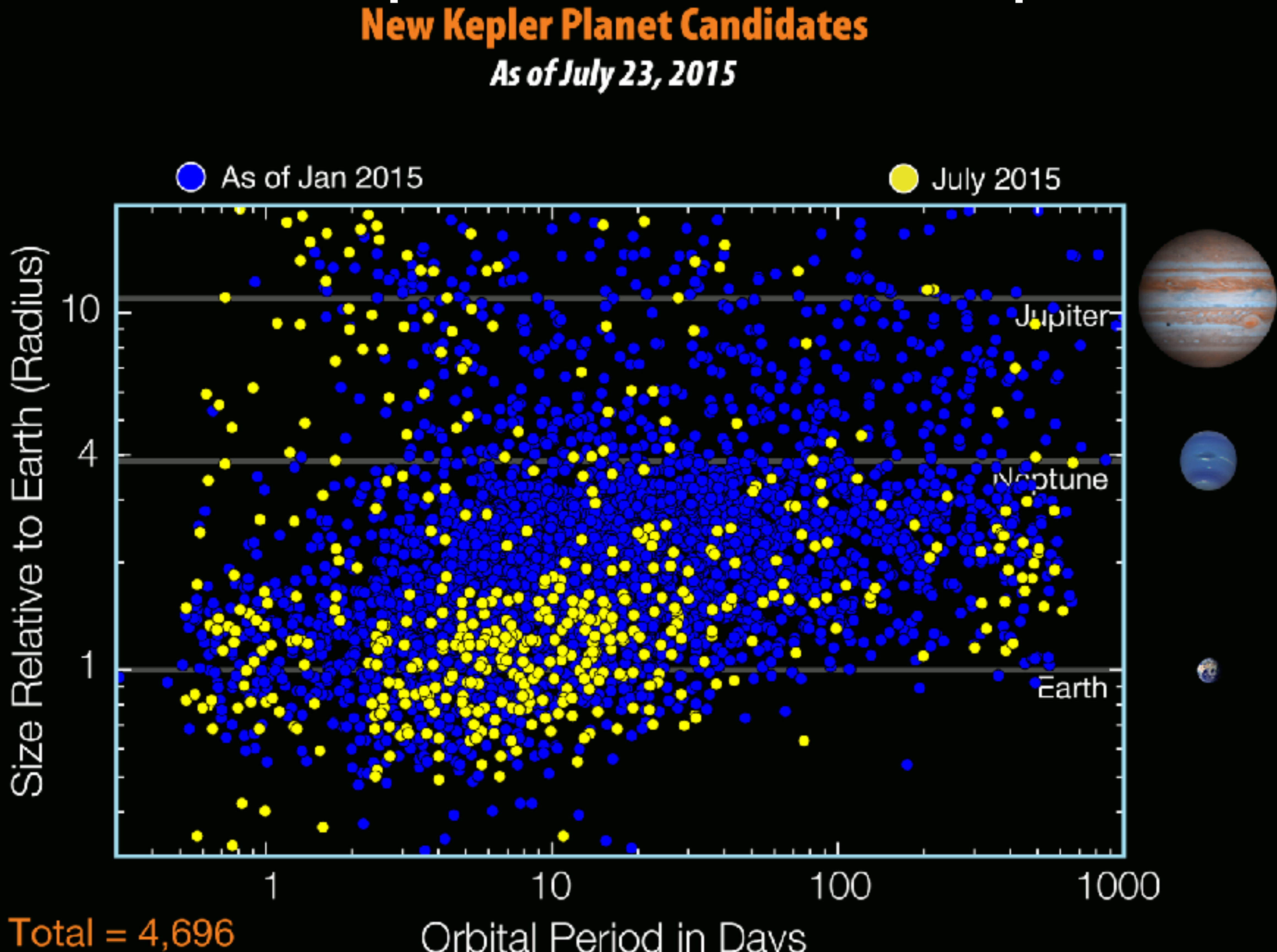
- ALMA observations of the HL Tau disk can advance our understanding of disk evolution
- Subsequent radiative transfer modeling suggests a higher degree of dust settling for the actively accreting disk
- Developed the simple, semi-analytical model, taking into account magnetically induced disk winds
- 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 the birthplace of planets and to fully identify the origins of observed multiple gaps in the HL Tau disk

Super-Earths as Failed Cores in Orbital Migration Traps



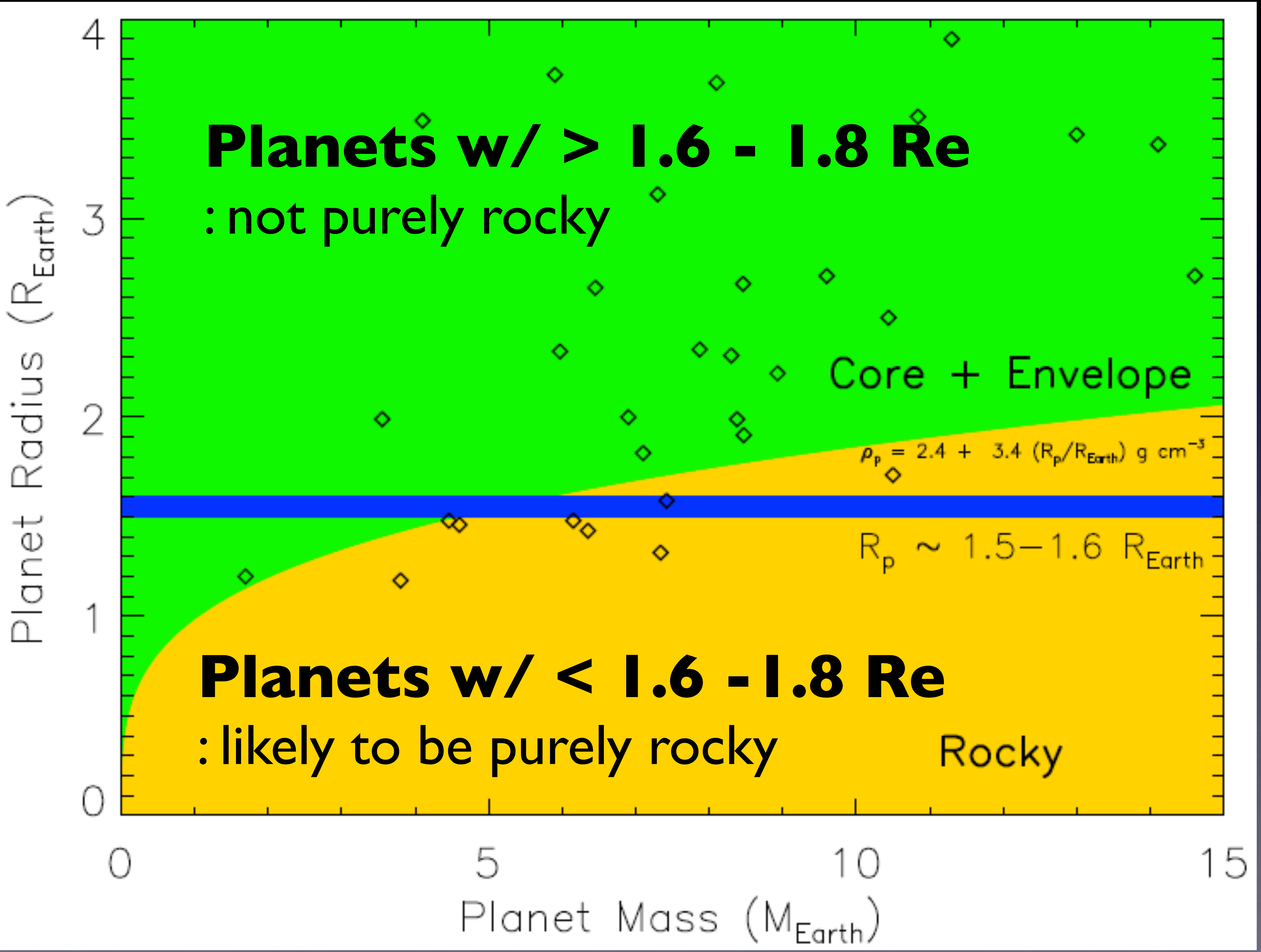


Close-in Super-Earths are Ubiquitous

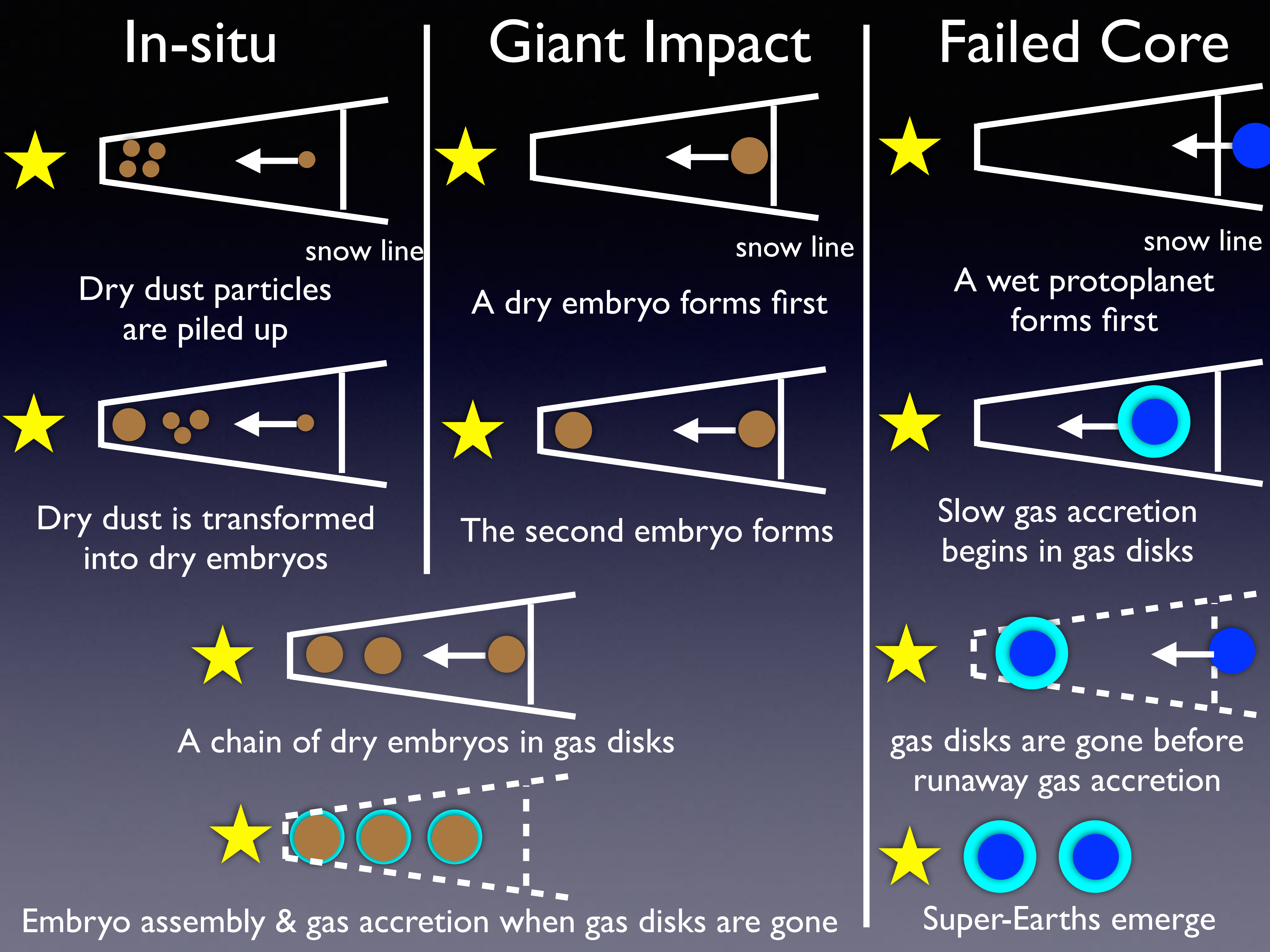


Properties of Observed Super-Earths

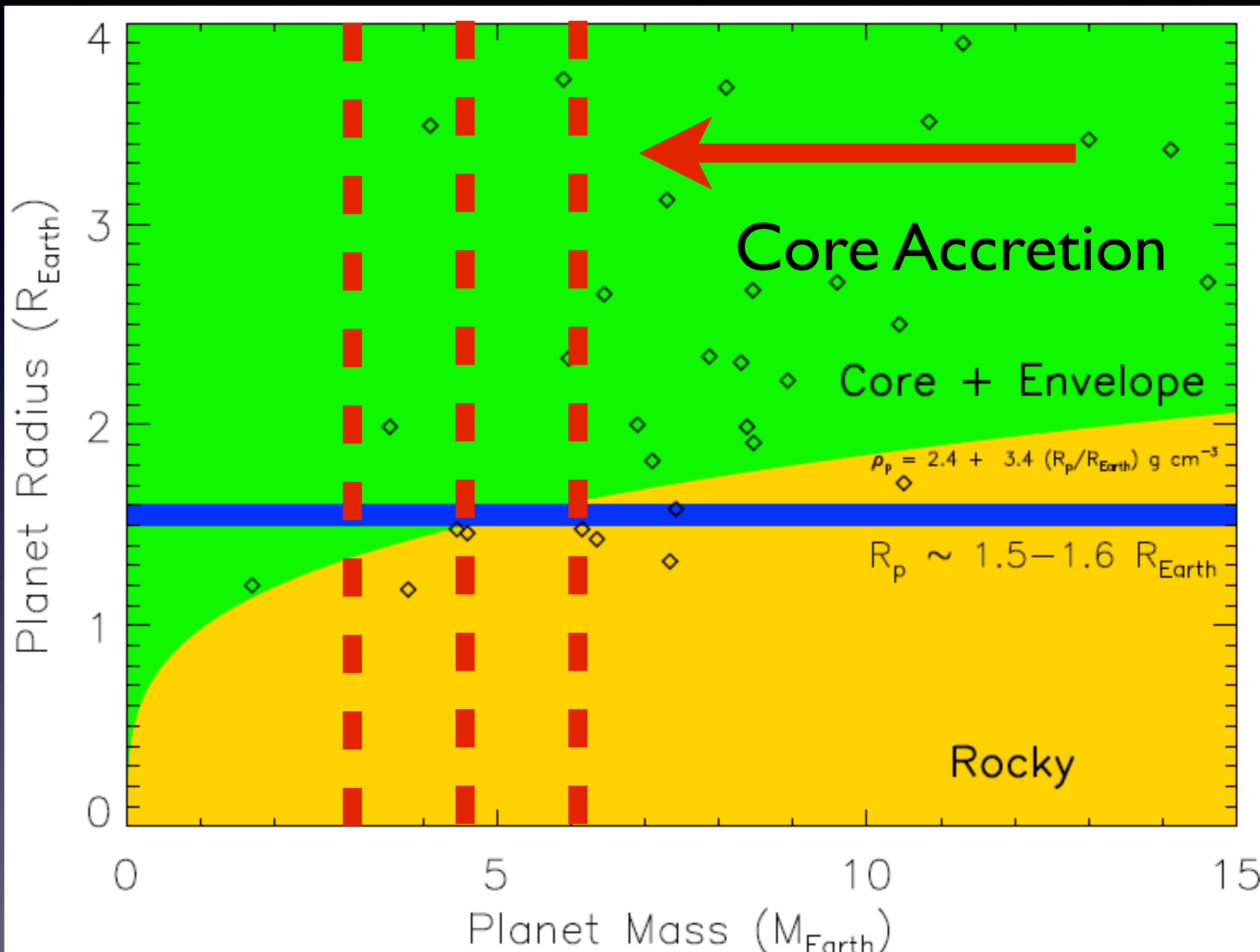
e.g., Weiss & Marcy 2014, Marcy et al 2014, Rogers 2015, Wolfgang & Lopez 2015, Gettel et al 2016, Jontof-Hutter et al 2016



Sub-set of samples from Weiss & Marcy 2014
(mass measurements better than 2-sigma)

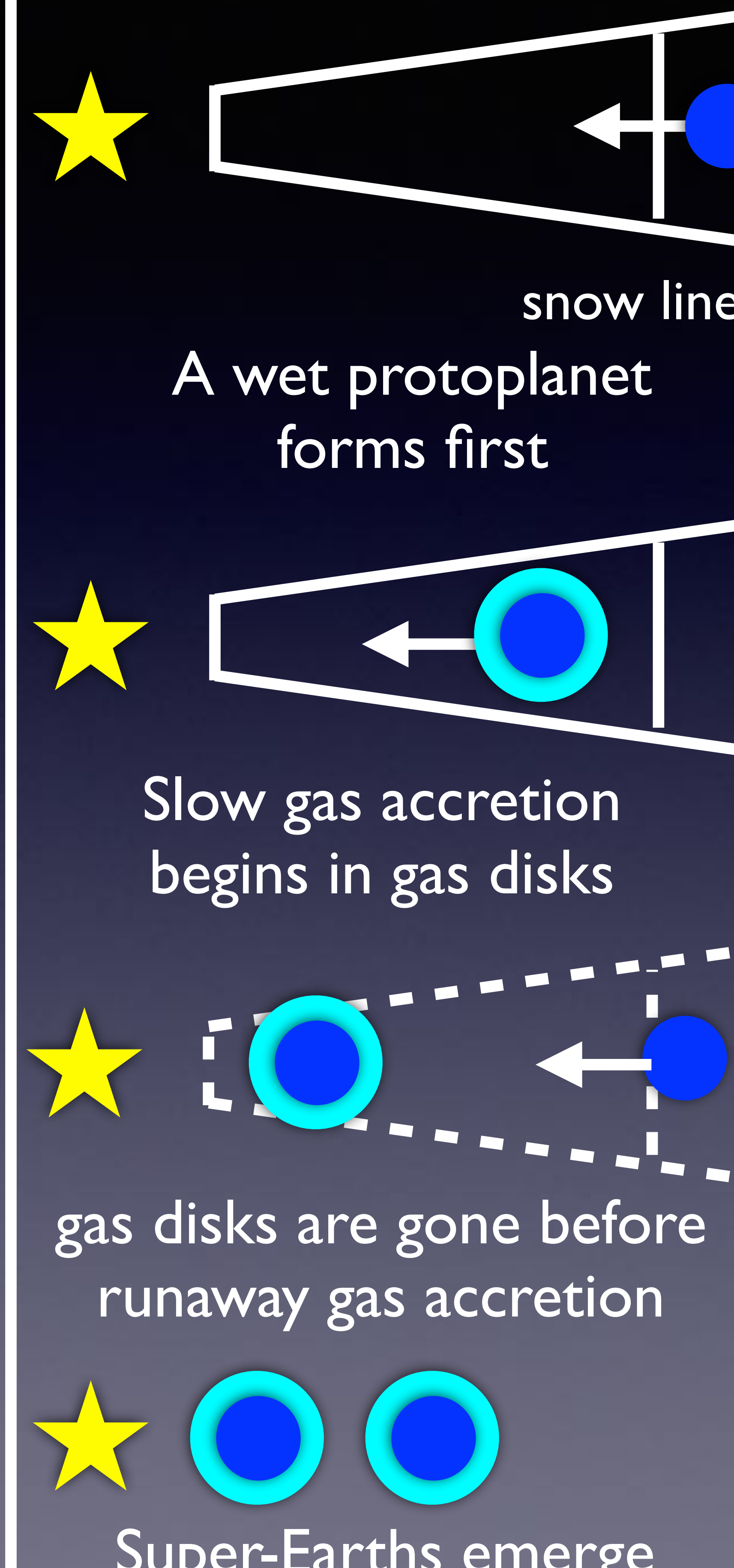

In-situ
Giant Impact
Failed Core
snow line
Dry dust particles are piled up
snow line
A dry embryo forms first
snow line
A wet protoplanet forms first
Dry dust is transformed into dry embryos
The second embryo forms
Slow gas accretion begins in gas disks
A chain of dry embryos in gas disks
gas disks are gone before runaway gas accretion
Embryo assembly & gas accretion when gas disks are gone
Super-Earths emerge

A scaled-down version of gas giant formation



What is the minimum mass of planets formed by core accretion??

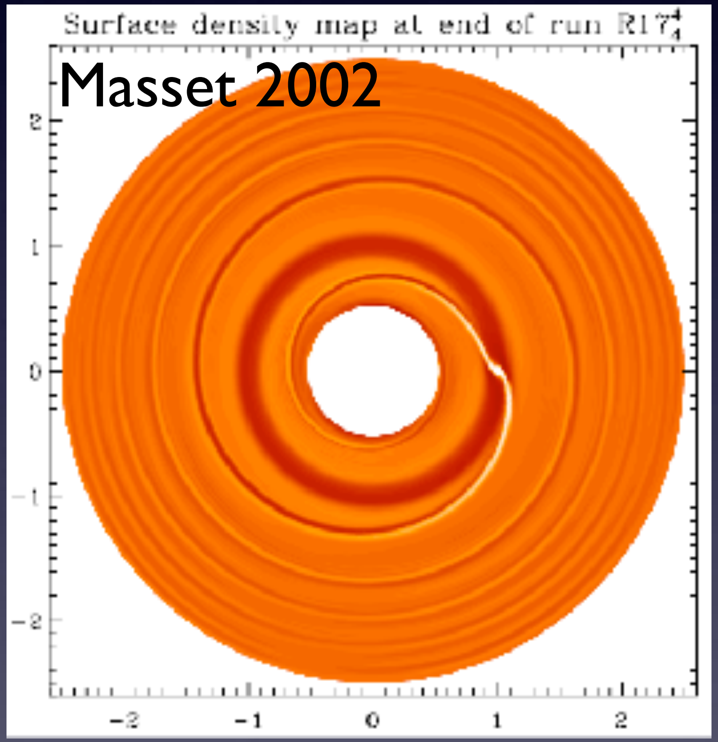
Failed Core

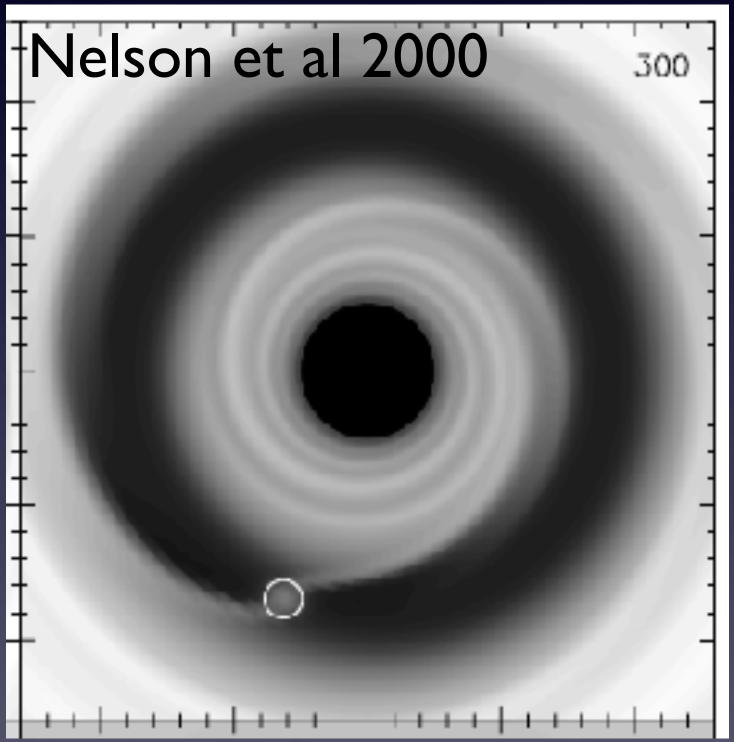


Key Idea: Planetary Migration in Gas Disks

e.g. Goldreich & Tremaine 1980, Ward 1986, Lin & Papaloizou 1986, Nelson et al 2000, Masset 2001, 2002, Tanaka et al 2002, Baruteau & Masset 2008, Paardekooper et al 2010, 2011

Planetary Migration = Angular Momentum Transfer between Planets and Gas Disks





Type I migration (no gap)

: effective for low mass planets such as terrestrial planets & cores of gas giants

Type II migration (gaps)

: effective for massive planets such as Jovian planets

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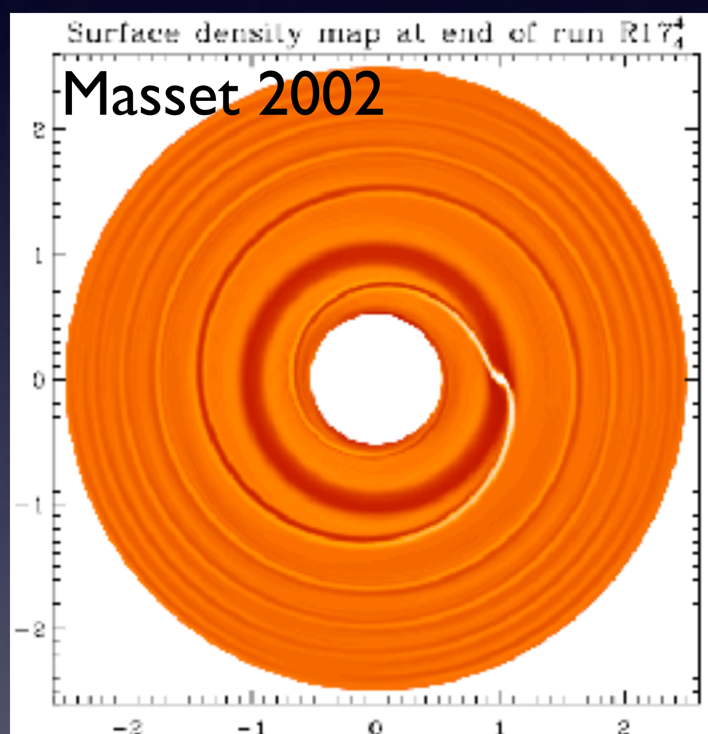
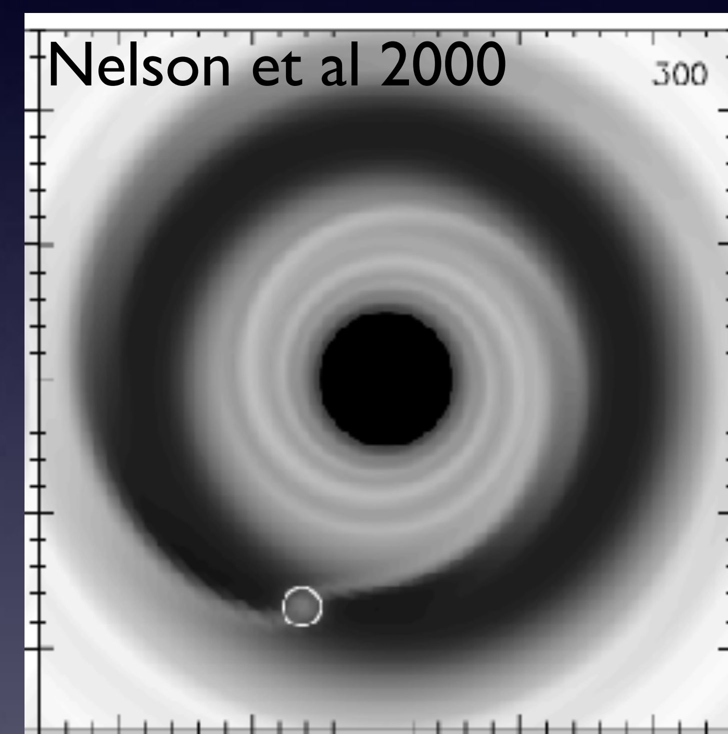
Plan … tum

Tra … sks

Both modes of migration have some problems





Type I migration (no gap)

: effective for low mass planets such as terrestrial planets & cores of gas giants

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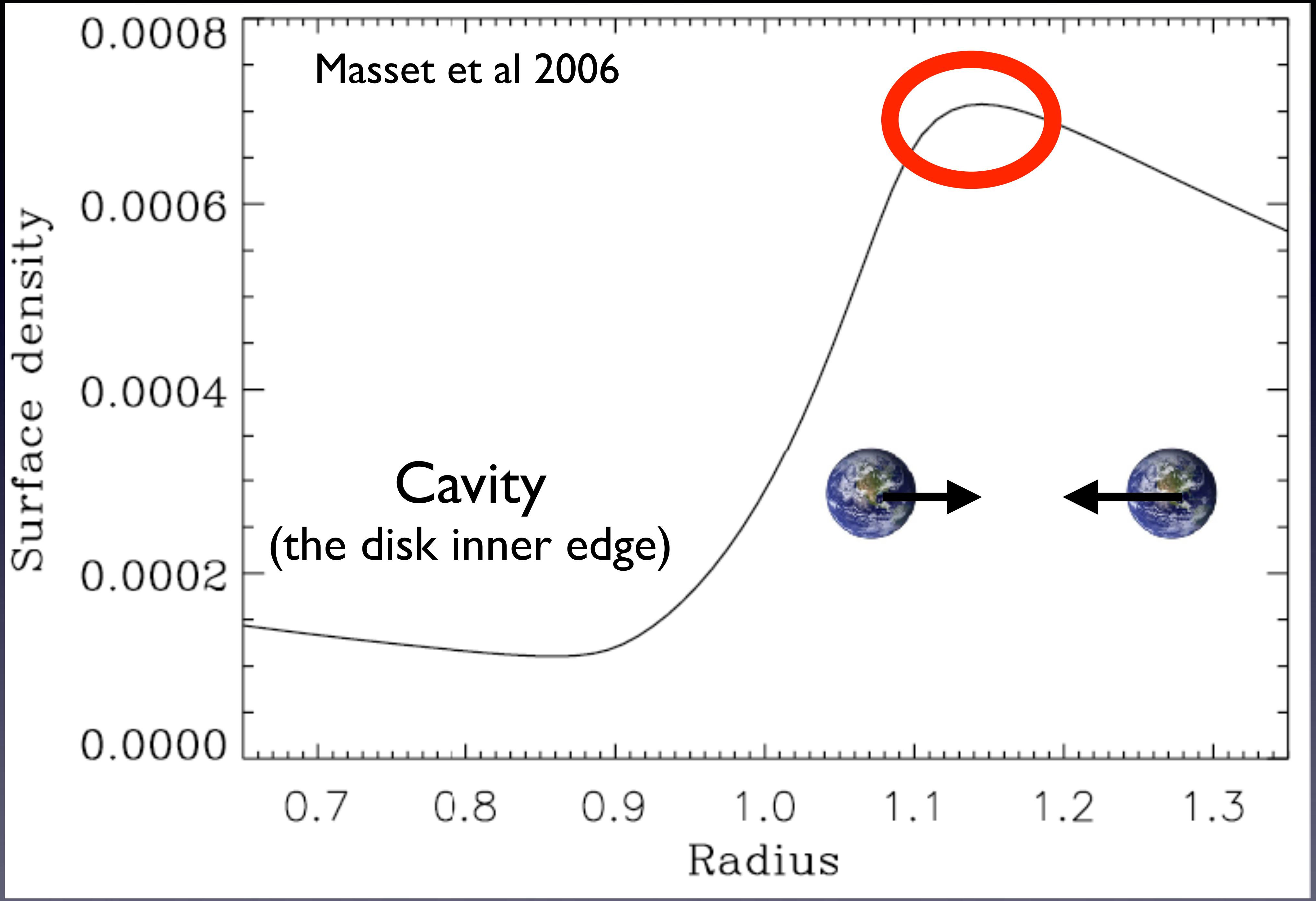
: effective for massive planets such as Jovian planets

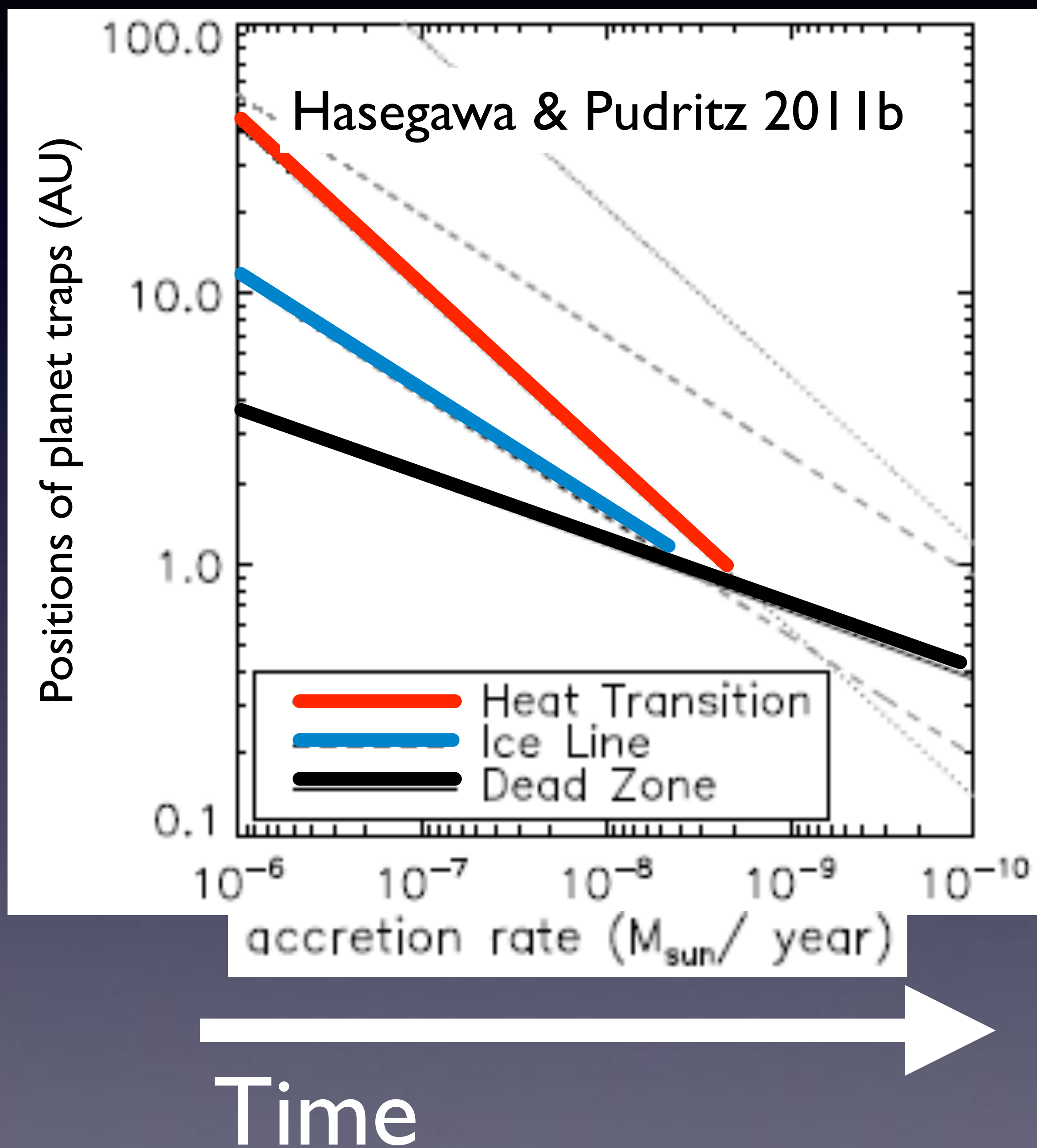
A Potential Solution to Type I Migration

e.g., Masset et al 2006, Hasegawa & Pudritz 2011b



Planet Traps = Disk Structures where the Net Torque becomes Zero (i.e. Dead Zones, Ice Lines, etc..)

Fundamental Properties of Planet Traps



Multiple Traps in Single Disks

: the outer edge of dead zones, ice lines, heat transitions

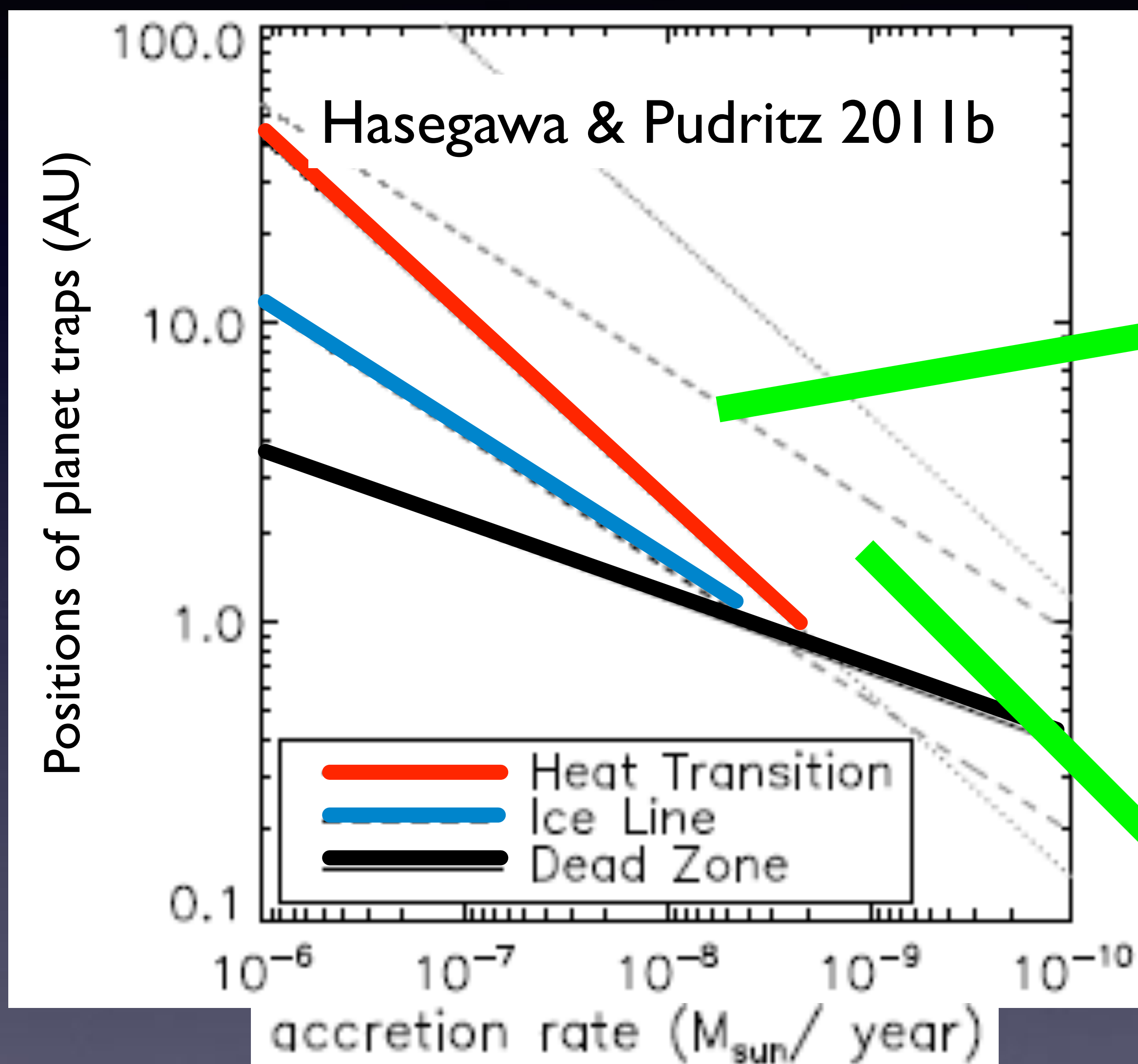
Locations of Traps are Specified by Disk Evolution

Mass Dependence of Traps

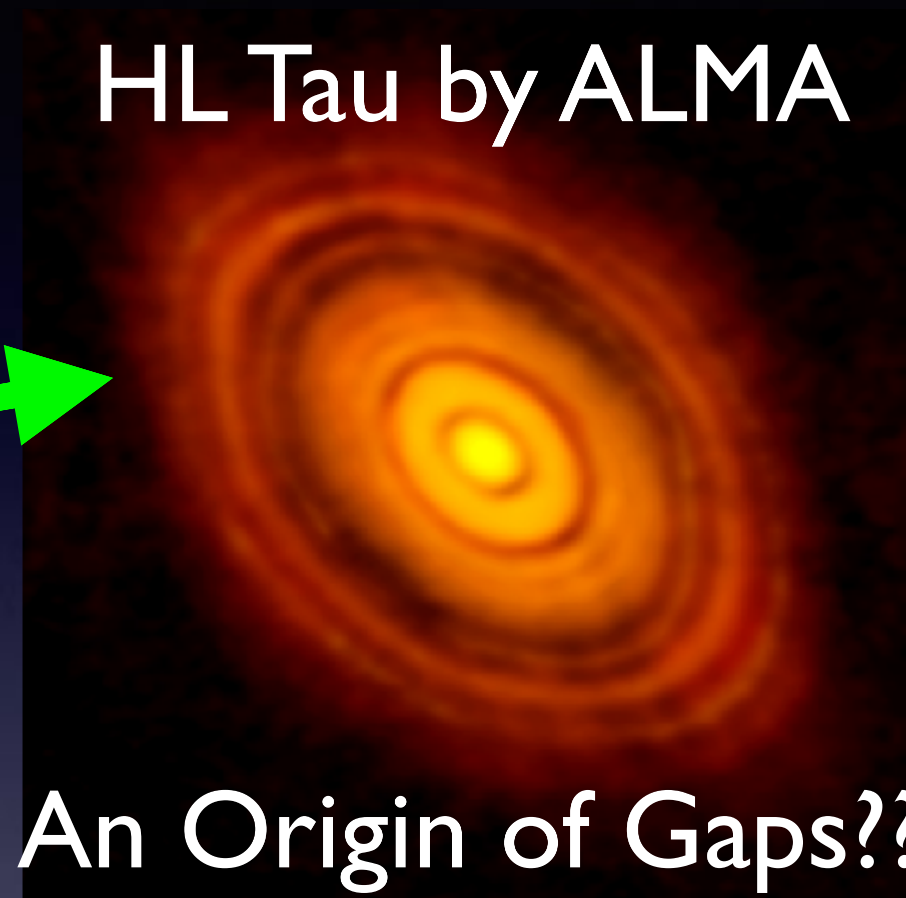
: planet traps are effective until protoplanets obtain the gap-opening mass & undergo type II migration

Planets Form Locally at Traps (r > 1 AU) Before Type II Migration

Fundamental Properties of Planet Traps

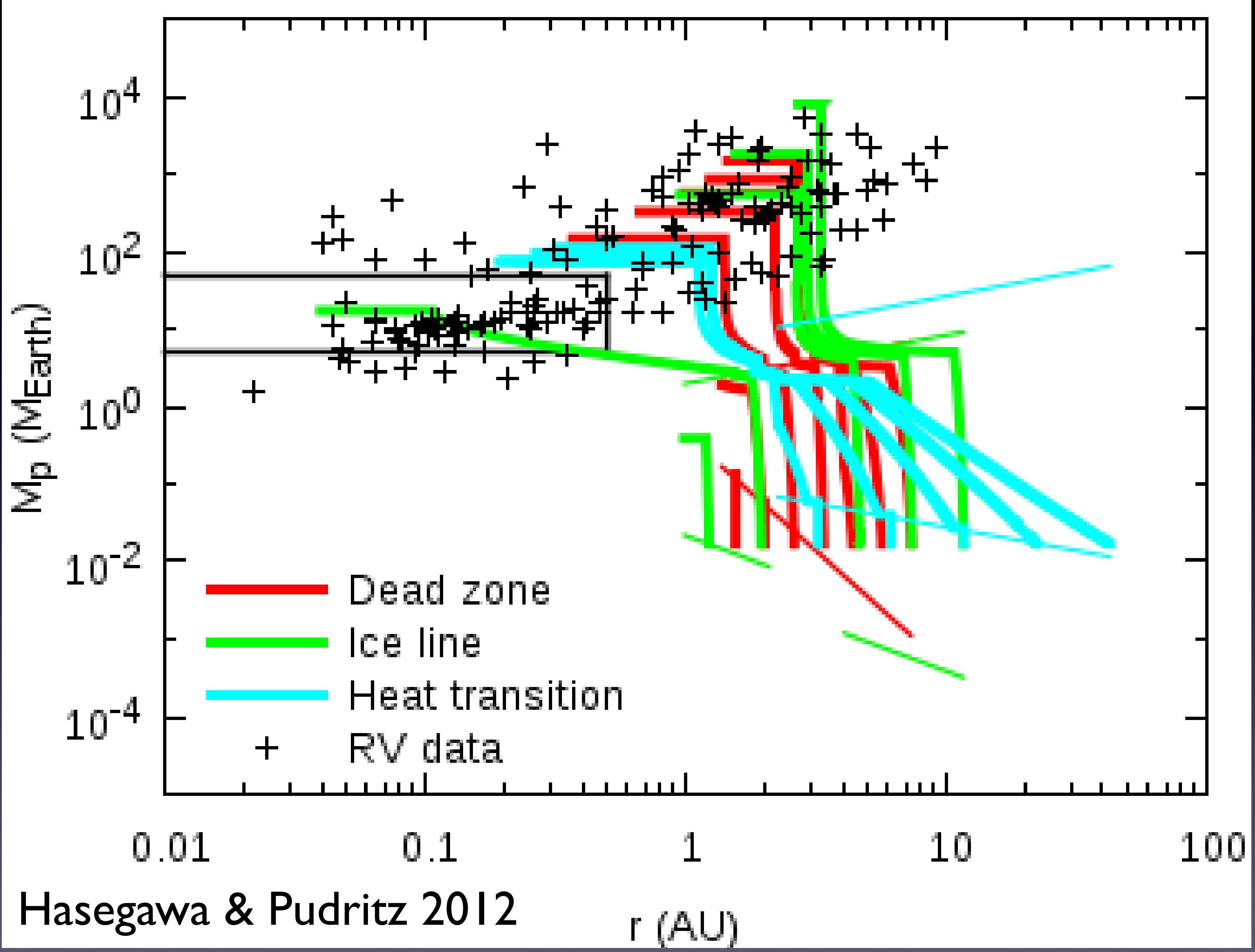


Time



Initial Conditions for N-body Dynamics

Result 1: Evolutionary Tracks of Trapped Planets



Hasegawa & Pudritz 2012

Disk Evolution

e.g., Hartmann et al 1998

+

Planetary Migration (Orbital Evolution)

Planet Traps & Type II

+

Core Accretion (Mass Growth)

e.g., Pollack et al 1996

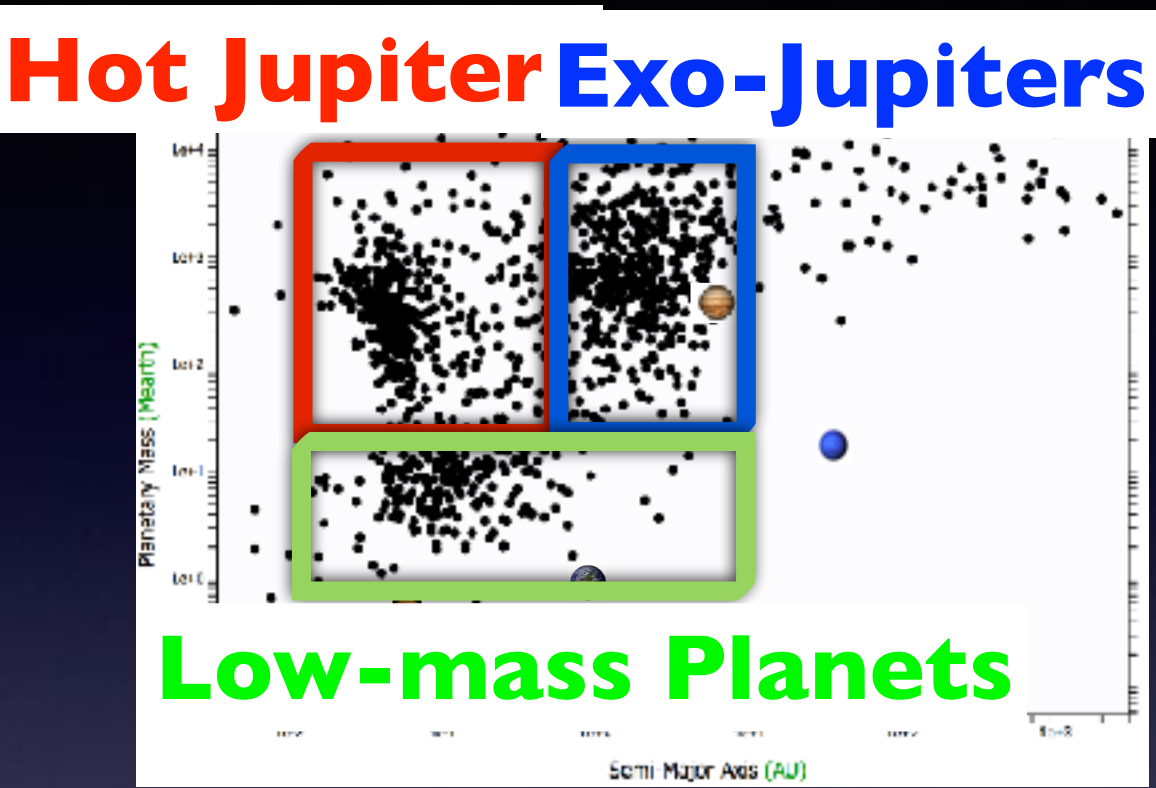
End-Points of Tracks Line-up with the RV Data

Planet-planet interaction is not included

Result 2: Statistical Analysis for Computed Tracks

Hasegawa & Pudritz 2013

Partition the Diagram



Calculate Planet Formation Frequencies (PFFs)

$$PFFs \equiv \sum_{\eta_{acc}} \sum_{\eta_{dep}} \frac{N(\eta_{acc}, \eta_{dep})}{N_{int}}$$

$$\times w_{mass}(\eta_{acc}) w_{lifetime}(\eta_{dep})$$

Weight functions related to disk observations

	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF	~ 7.6 %	~ 25.3 %	~ 10.2 %	43.1%

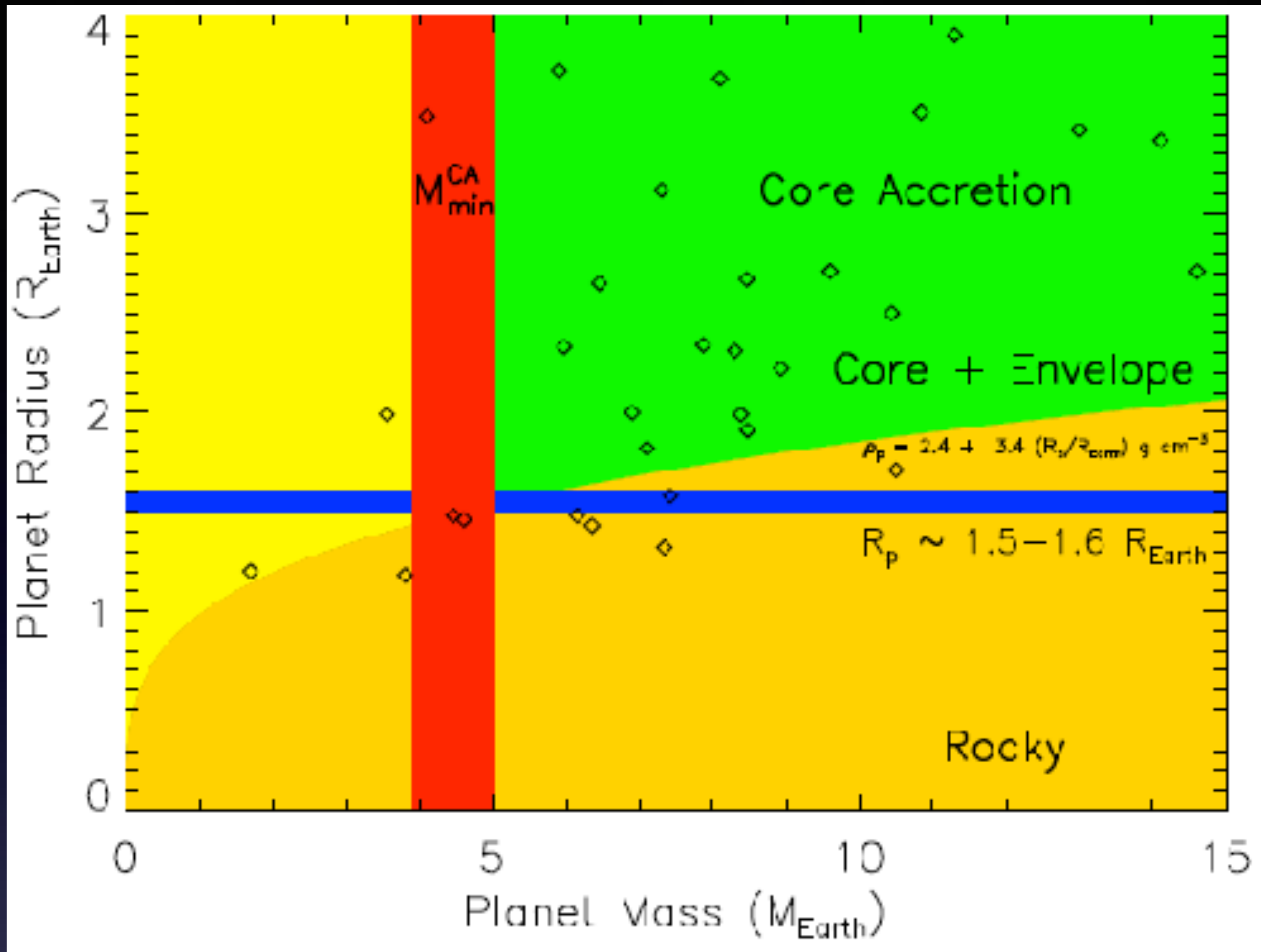
The Observational Trend of Massive Planets can be Reproduced

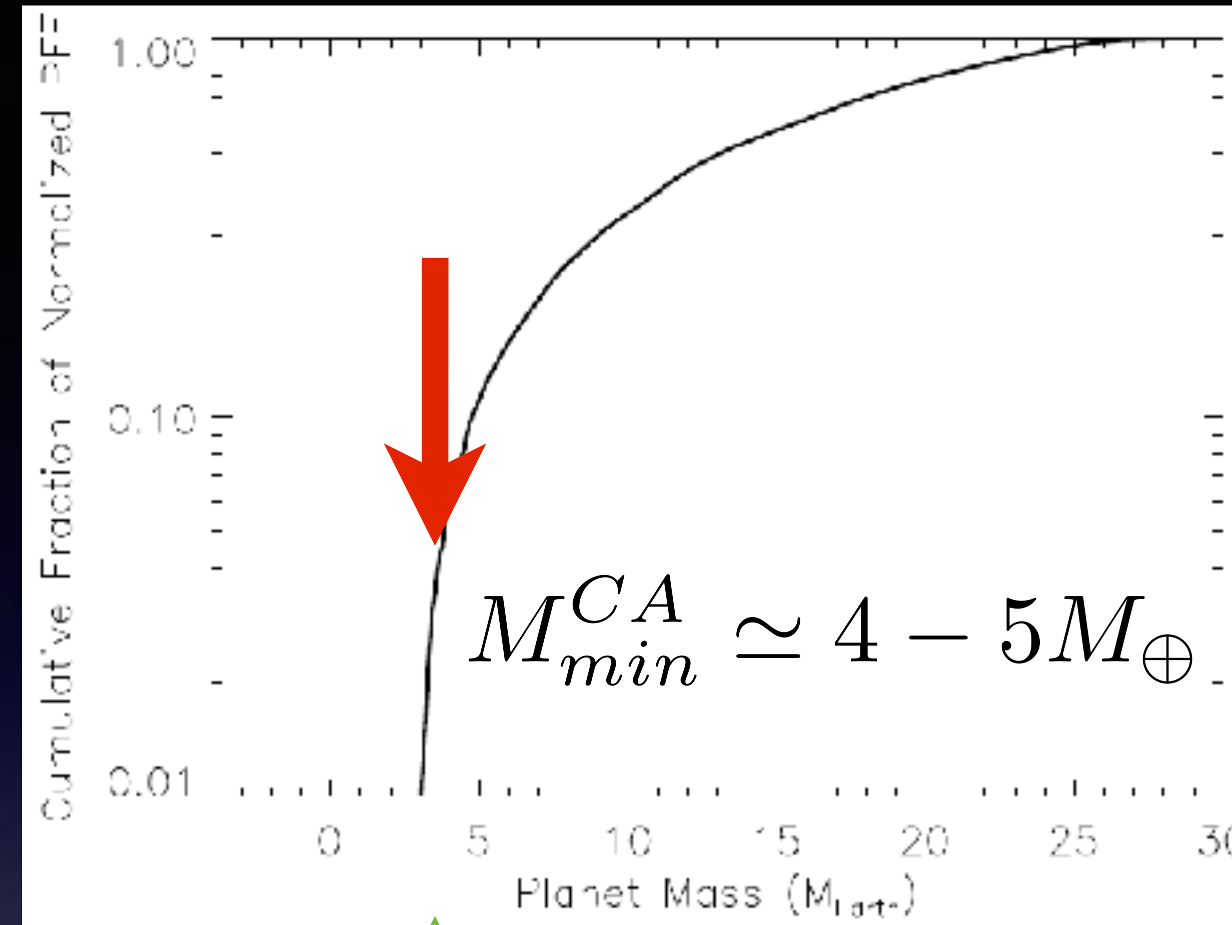
Other Formation Mechanisms are Needed for Super-Earths

The Minimum Mass of Planets Formed by Core Accretion at Planet Traps:

	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF	~ 7.6 %	~ 25.3 %	~ 10.2 %	43.1%

A Considerable Fraction of Close-in Super-Earths can be Formed as Failed Cores of Gas Giants (Mini-Gas Giants)





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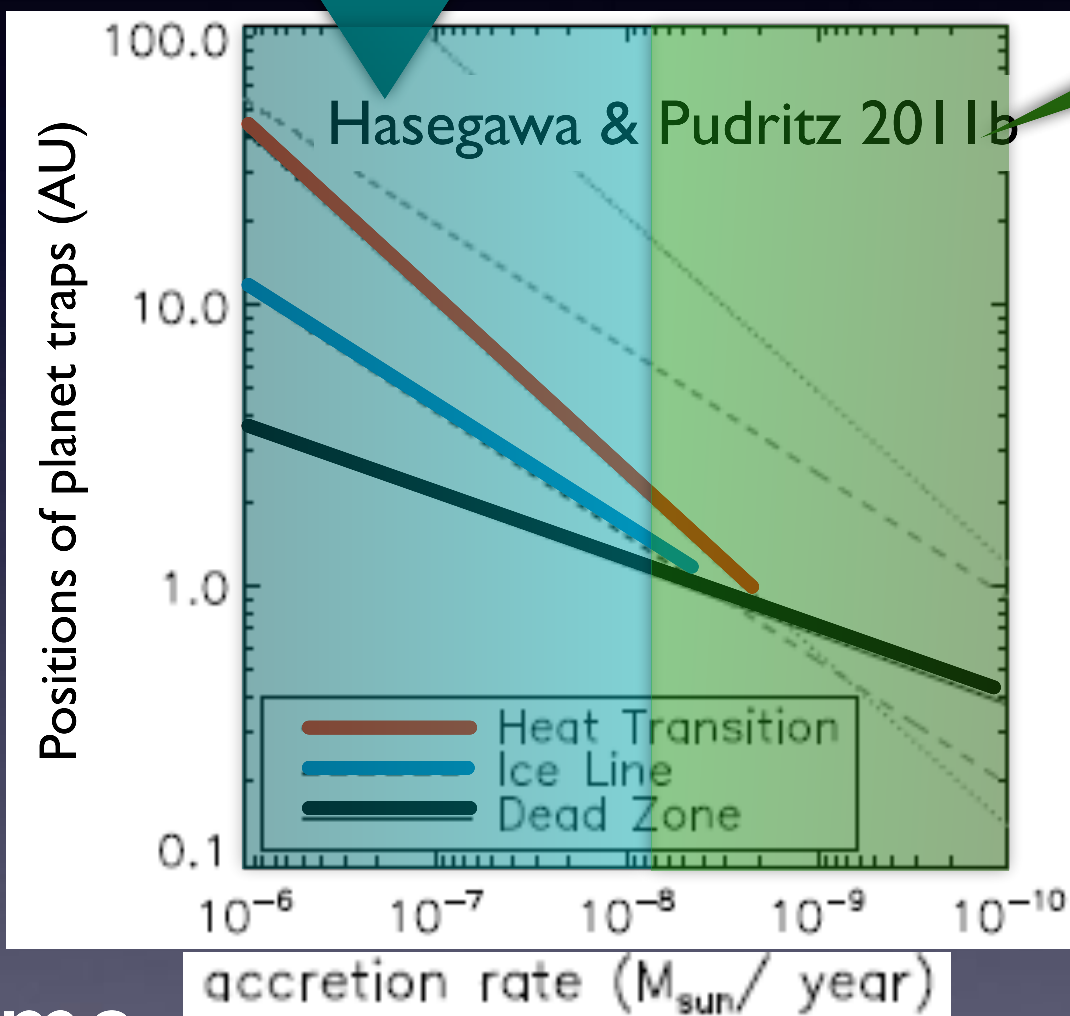
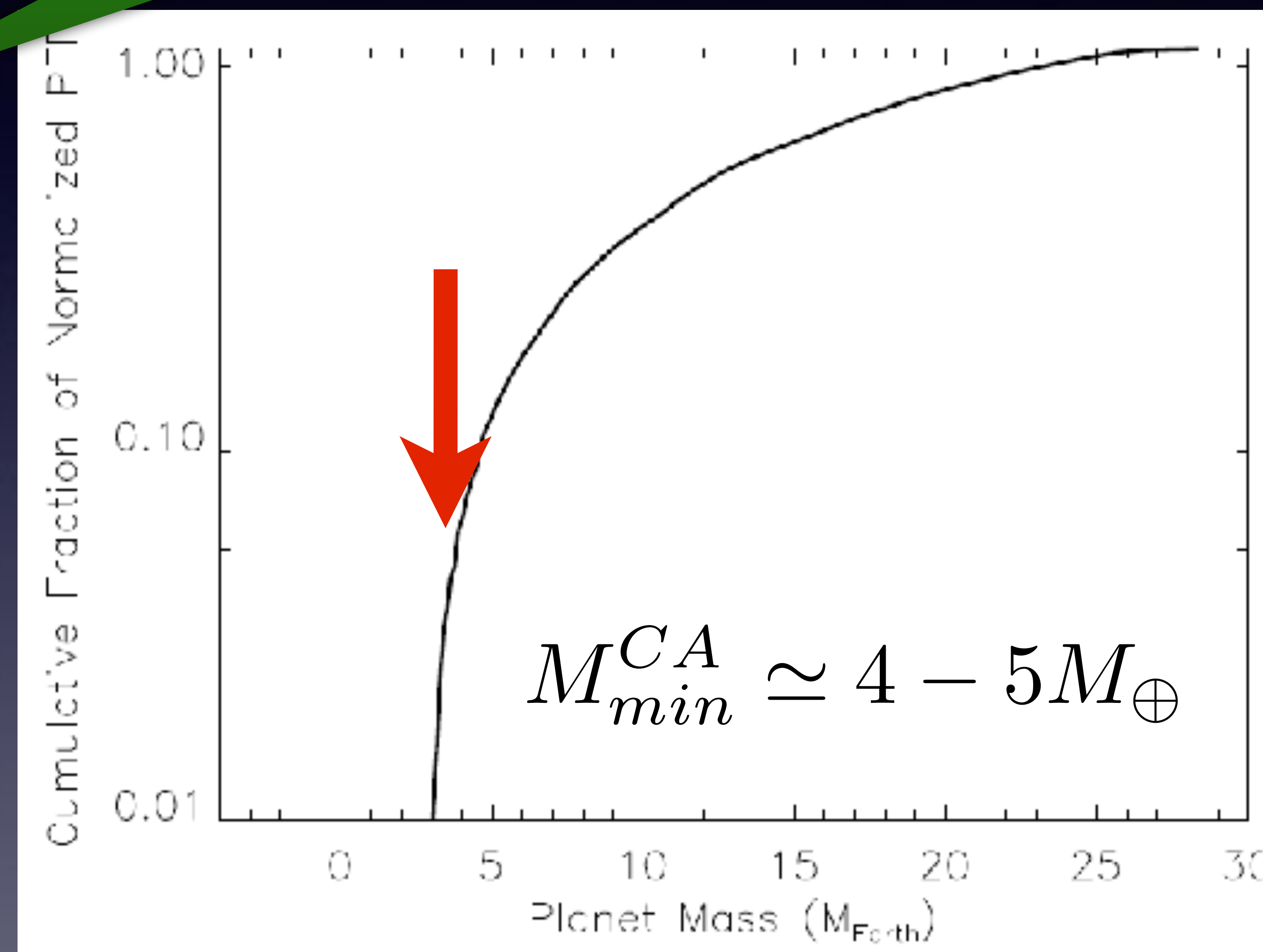
Switching of Migration Modes at $M_{min}^{CA} \simeq 4-5M_{\oplus}$

Planet Traps (Type I Migration)
:Transport Forming Planetary Cores
from Large Orbital Radii to >1 AU

Type II Migration (w/ a Gap)
:Transport the Cores
from r > 1 AU to r < 1 AU



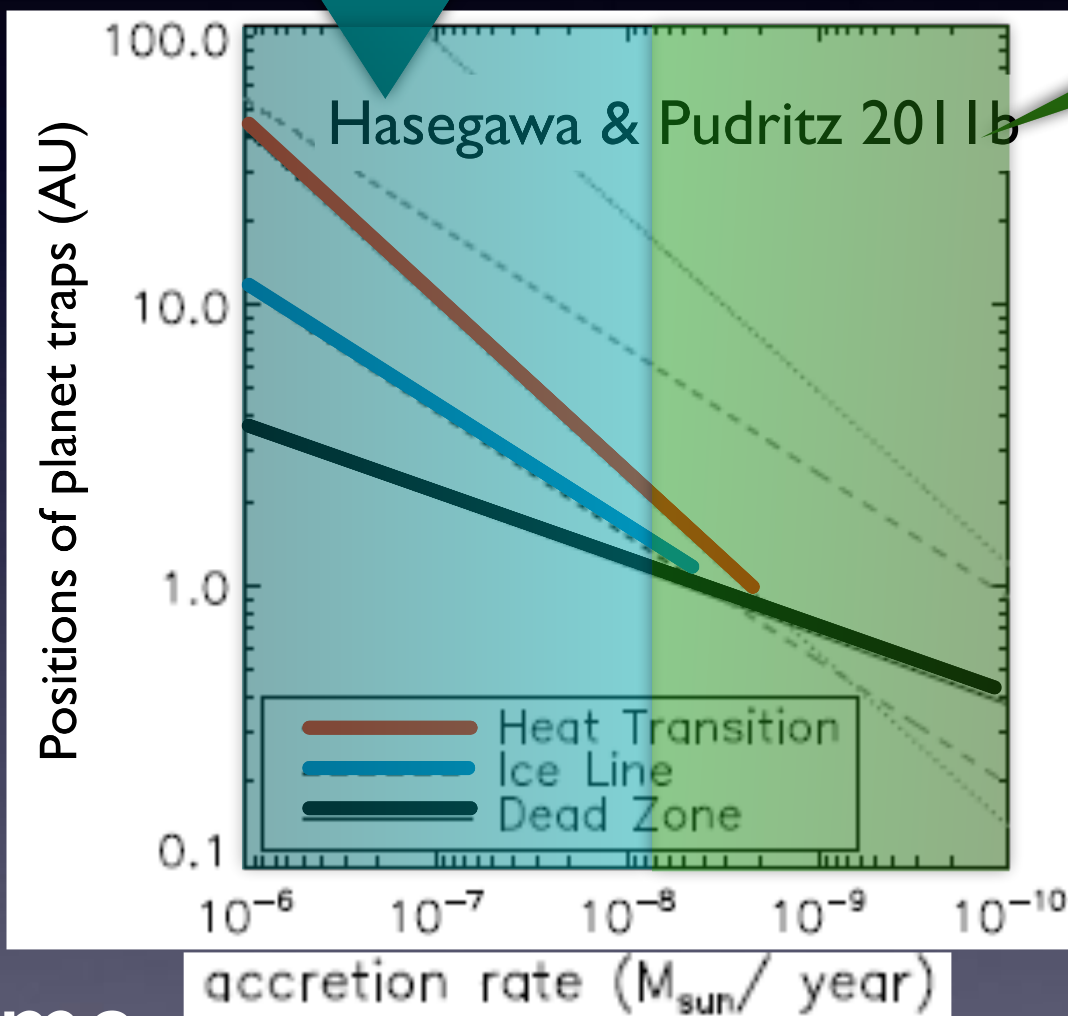
Time



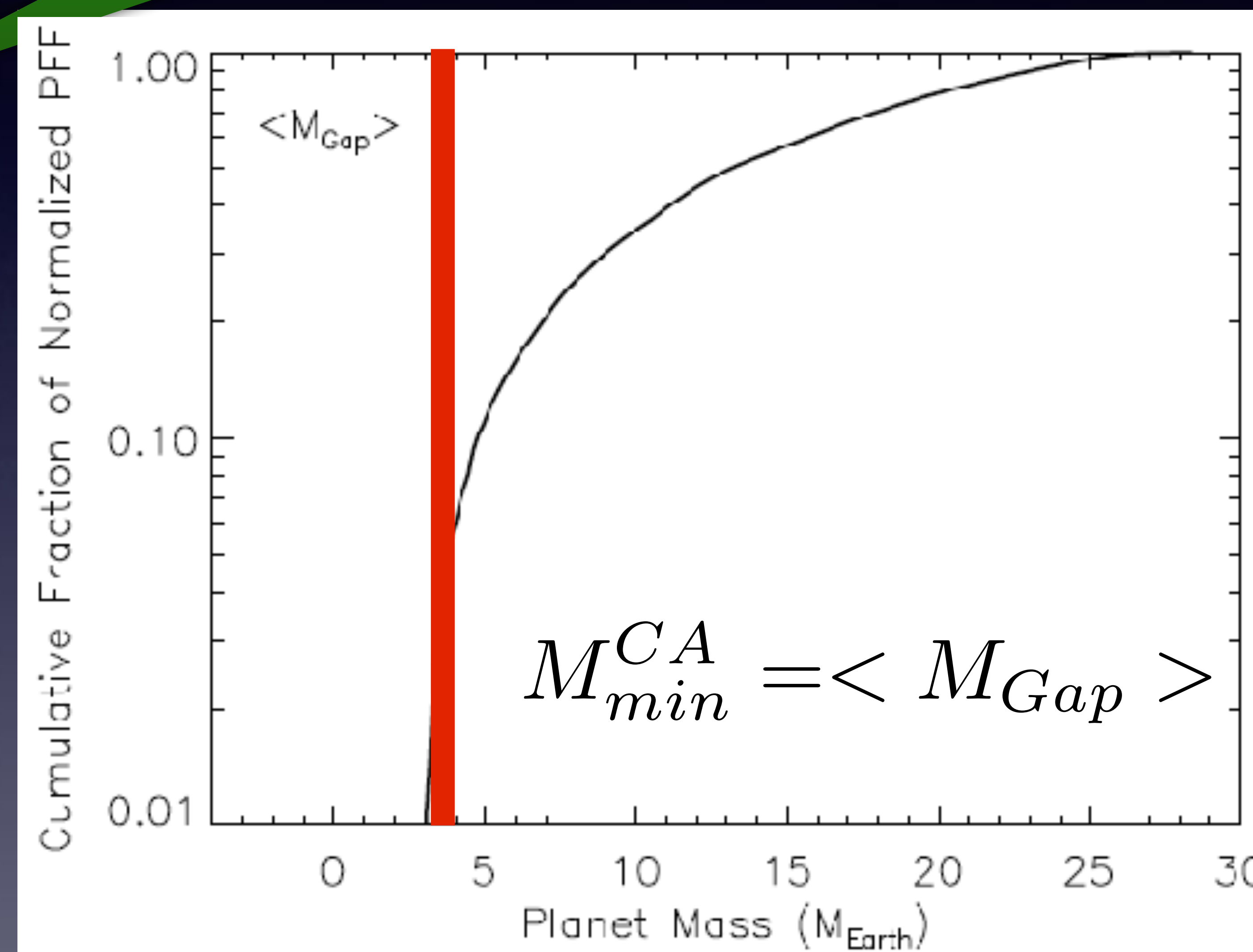
Switching of Migration Modes at $M_{min}^{CA} \simeq 4 - 5 M_{\oplus}$

Planet Traps (Type I Migration)
: Transport Forming Planetary Cores from Large Orbital Radii to >1 AU

Type II Migration (w/ a Gap)
: Transport the Cores from r > 1 AU to r < 1 AU



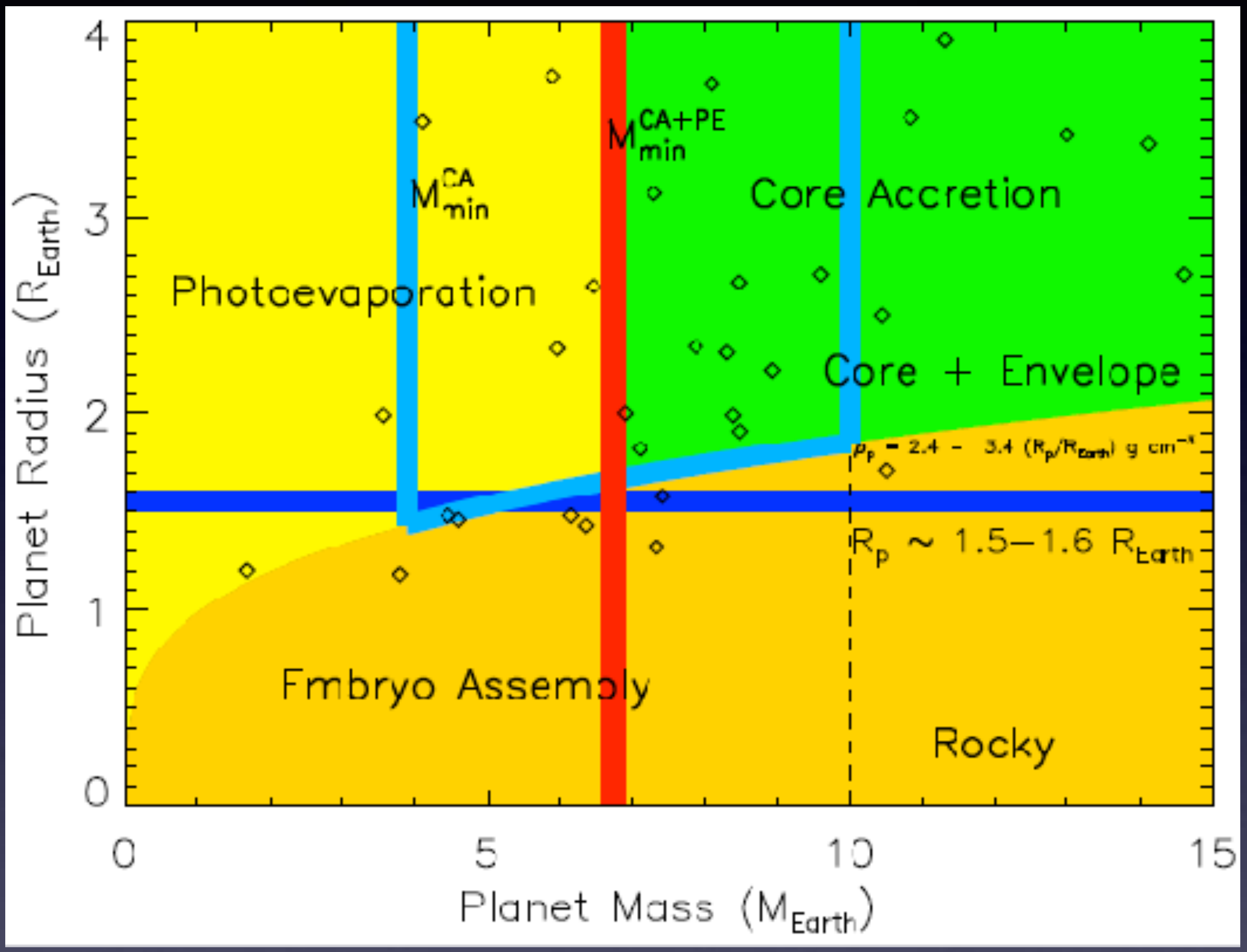
Time

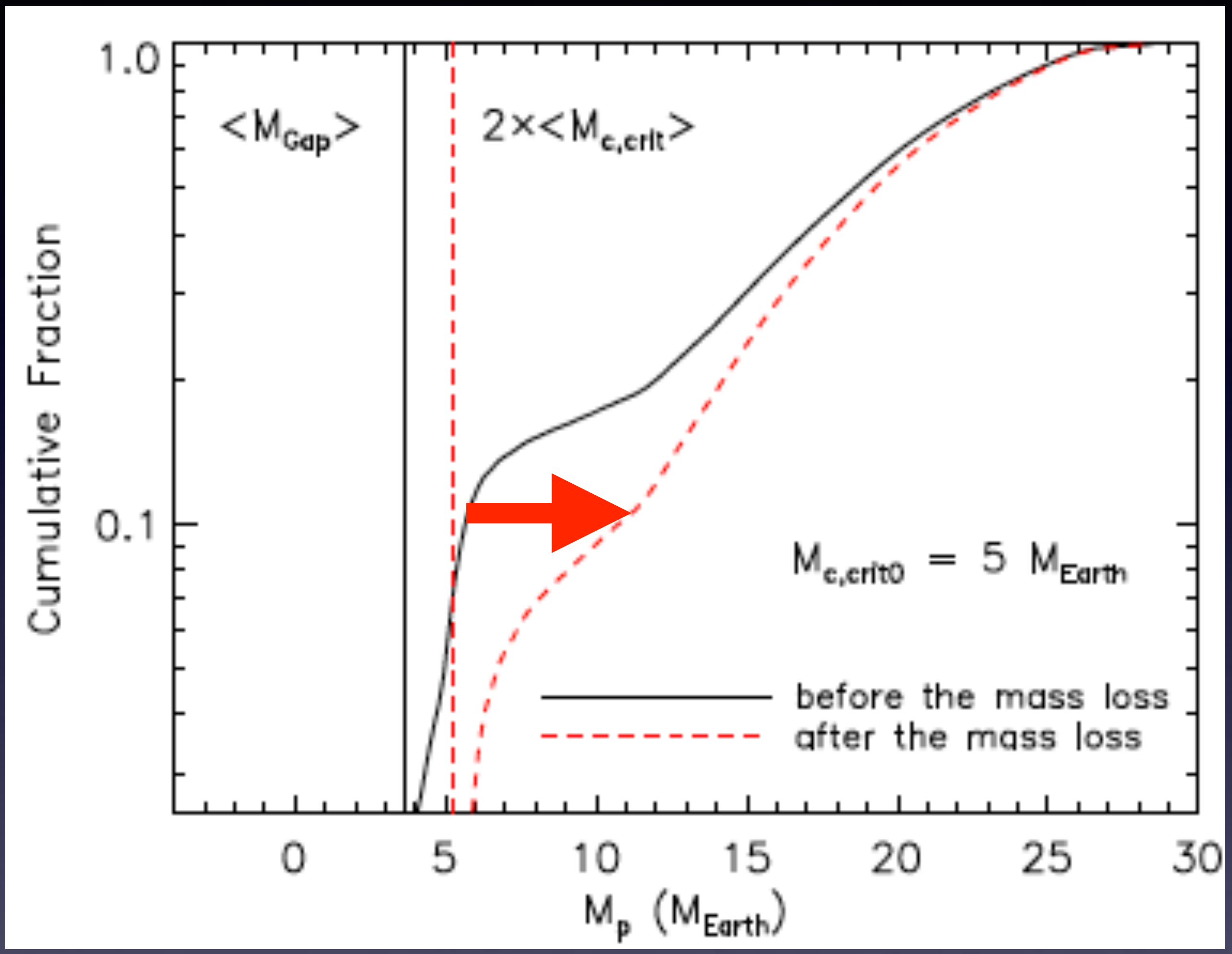


$\langle M_{Gap} \rangle$ = the Mean Value of the Gap-Opening Mass for Close-in Super-Earths

The Effect of Atmospheric Escape

Hasegawa 2016





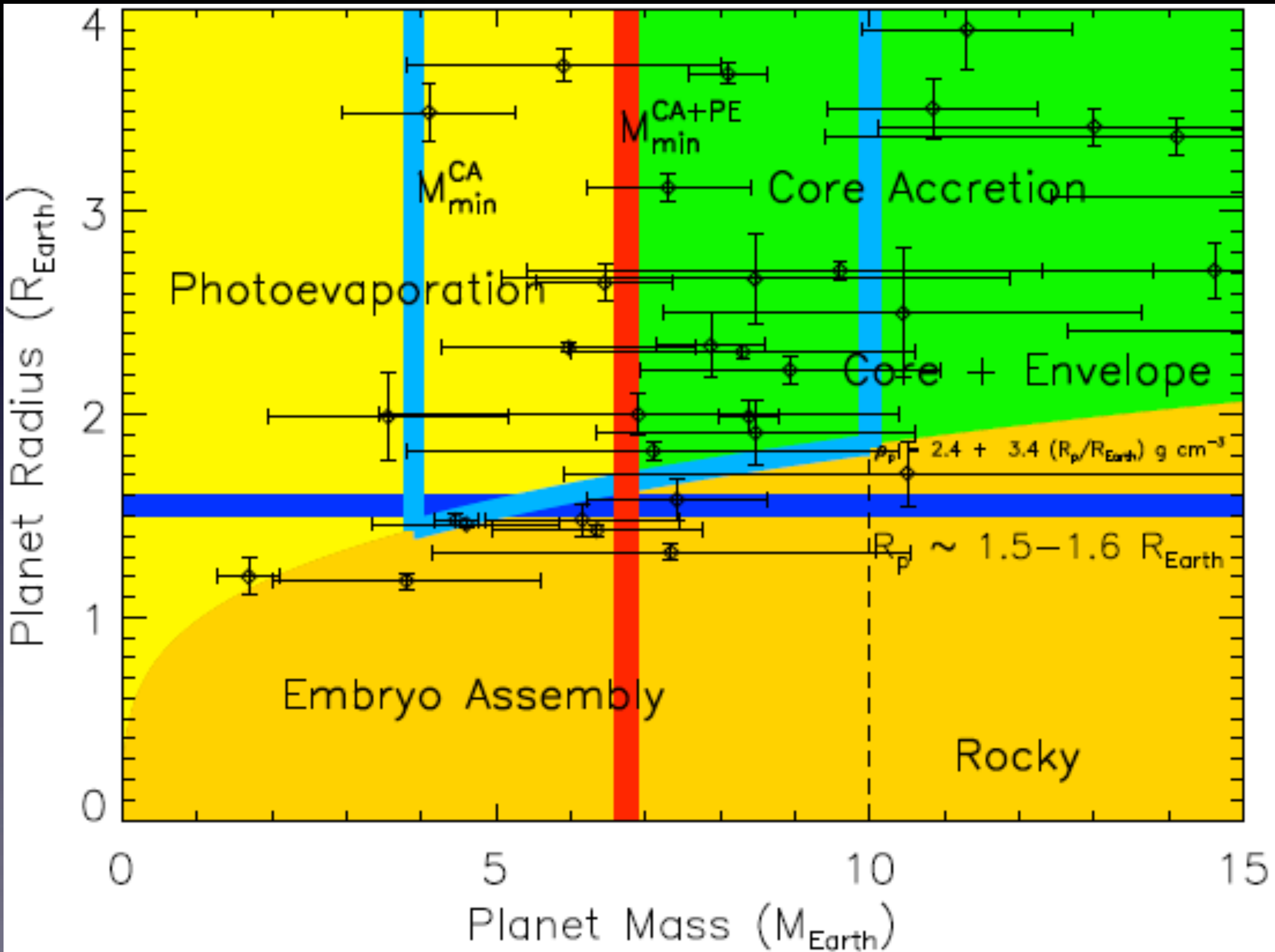
The Mass-Radius Diagram Divides into a Number of Regions, and can Specify the Formation Histories of Close-in Super-Earths

Photoevaporative Mass Loss Increases M_{min}^{CA} of $\sim 5M_{\oplus}$ to M_{min}^{CA+PE} of $\sim 7M_{\oplus}$ by Stripping the Gas Envelopes

Lopez & Fortney 2013

Exoplanet "Phase" Diagram

Hasegawa 2016

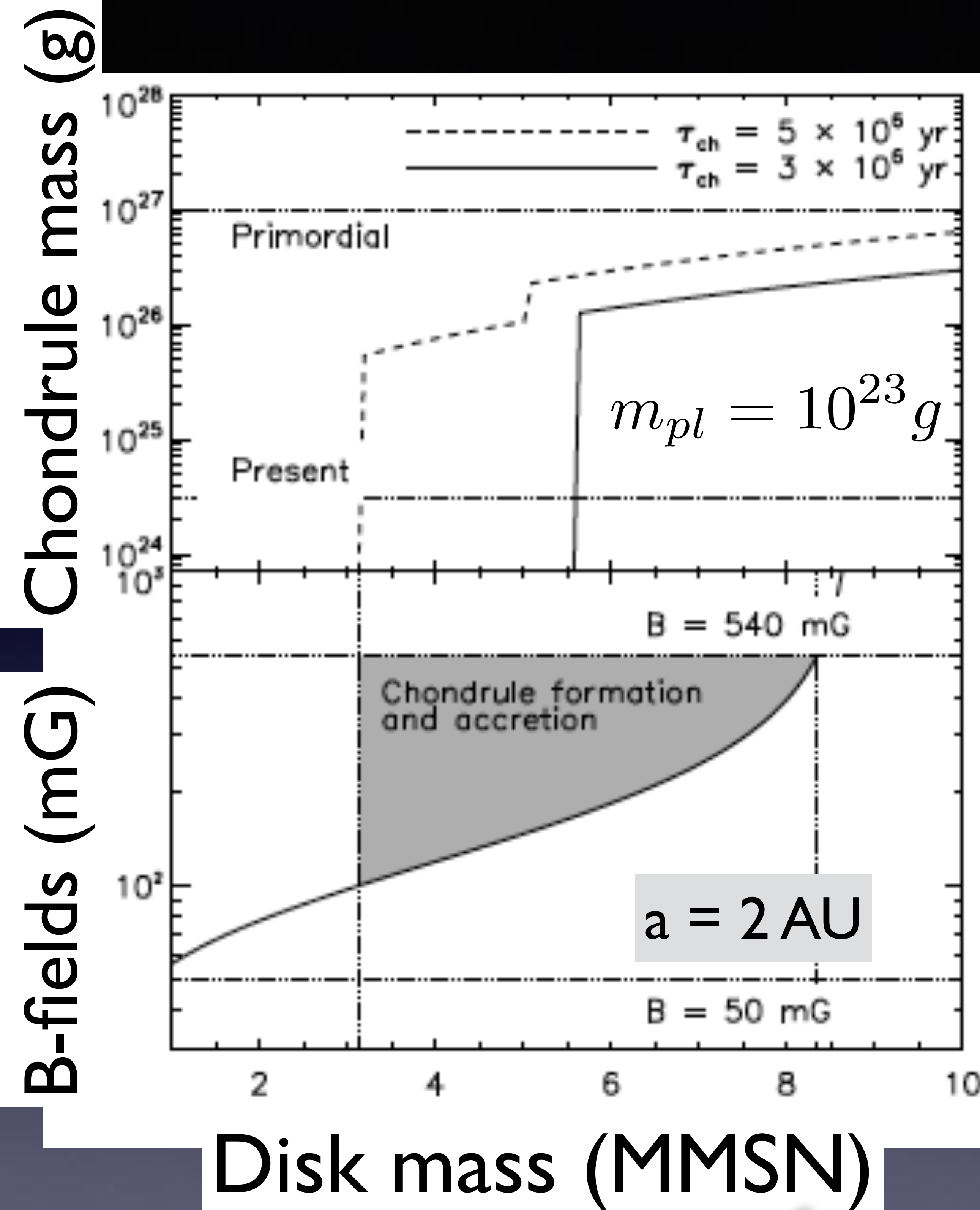


Summary

Hasegawa 2016, ApJ, 832, 83

- Close-in super-Earths are the most abundant population in the current exoplanet observations, and their formation mechanisms are unclear
- A population synthesis model is developed, focusing on Type I migration traps (dead zone, ice line, heat transition)
- Planet traps may be important to reproduce the trend of observed massive exoplanets, and for some fractions of observed close-in super-Earths
- Switching of migration modes determines the minimum mass of super-Earths formed by our model, which is $M_p > 4\text{-}5\ M_{Earth}$
- Our model suggests that the mass-radius diagram can serve as an exoplanet "phase" diagram

Impact Jetting and the Origin of Ordinary Chondrites



Chondrules: the primitive material formed in the Solar Nebula (disk)

abundant in chondrites
(up to 80 % by volume)

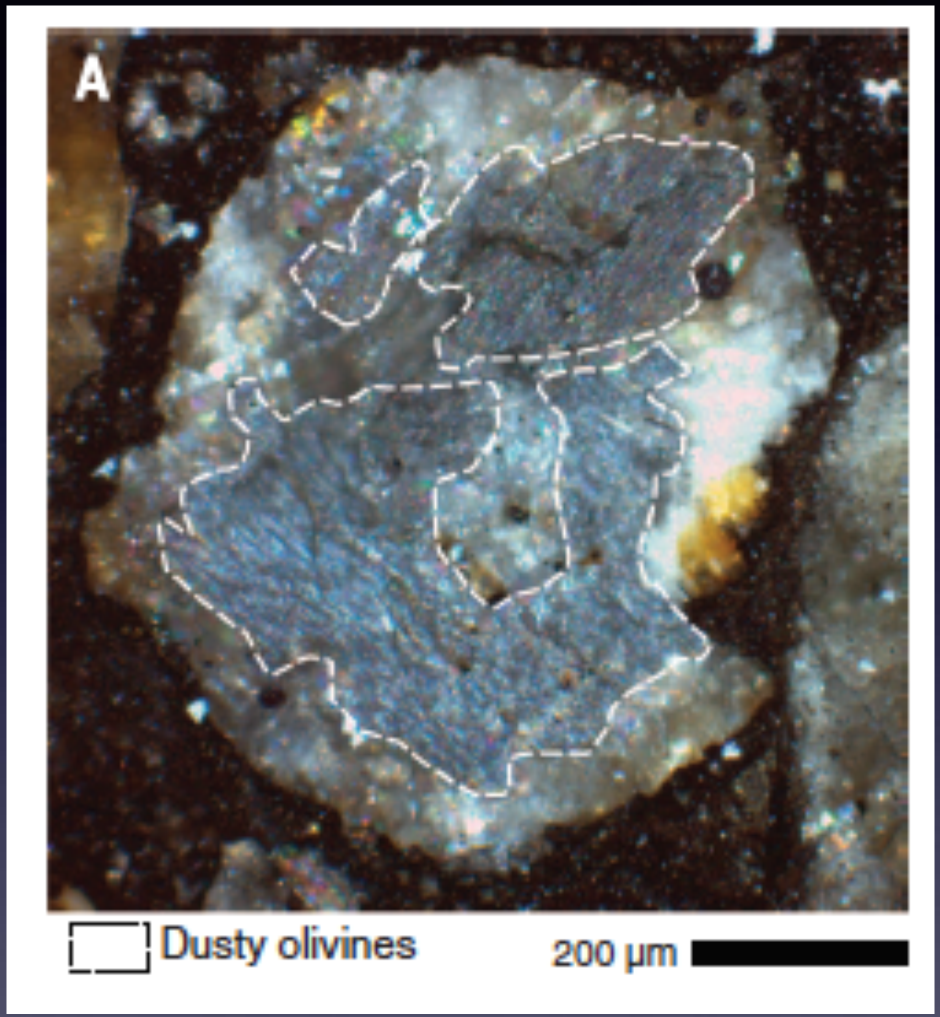
~1mm sized spherical particles formed as molten droplets of silicate (T ~ 1800K)

the cooling rate is
~ 10 - 1000 K per hour
(the nebular gas is needed)

kept forming for 3-5 Myr after CAI formation began, which is 4.567 Gyr ago

cf) Mars formed at ~2 Myr after CAI formation

New information from lab experiments : magnetic fields in the nebula (disk)



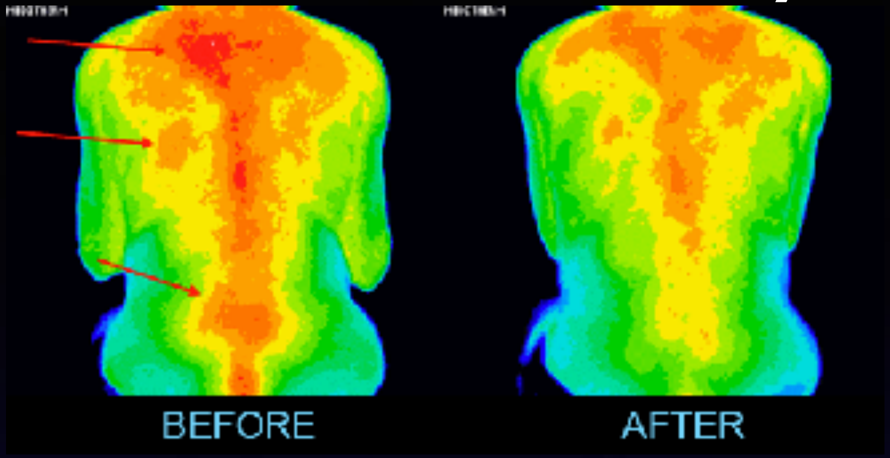
Fu et al 2014

Semarkona meteorite
: primitive, ordinary chondrite

Both thermoremanent magnetization & its direction
=> olivine-bearing chondrules were magnetized in the solar nebula

B-fields in the solar nebula were ~ 50 - 540 mG
=> Level of turbulence in the nebula can be estimated!!

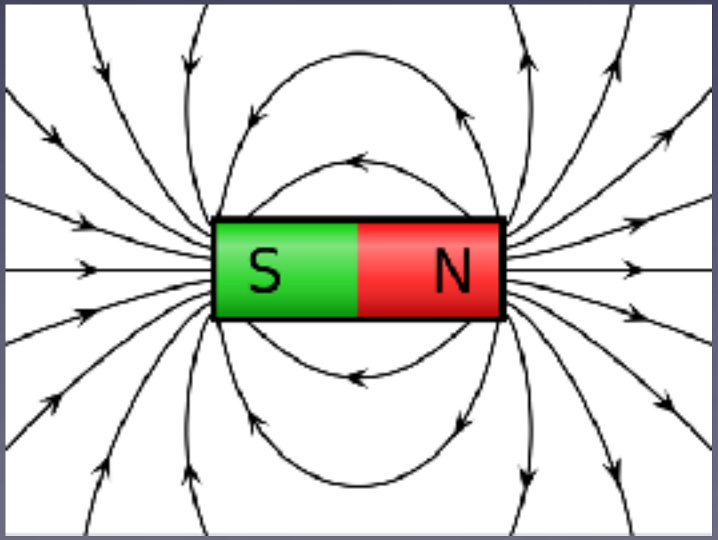
Thermal History



Abundance

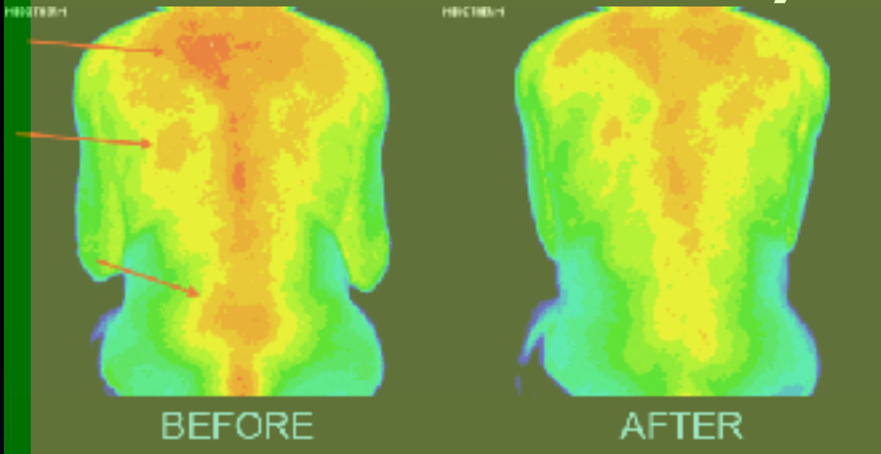
Chondrule Formation
& Accretion

Timescale



B-fields

Thermal History

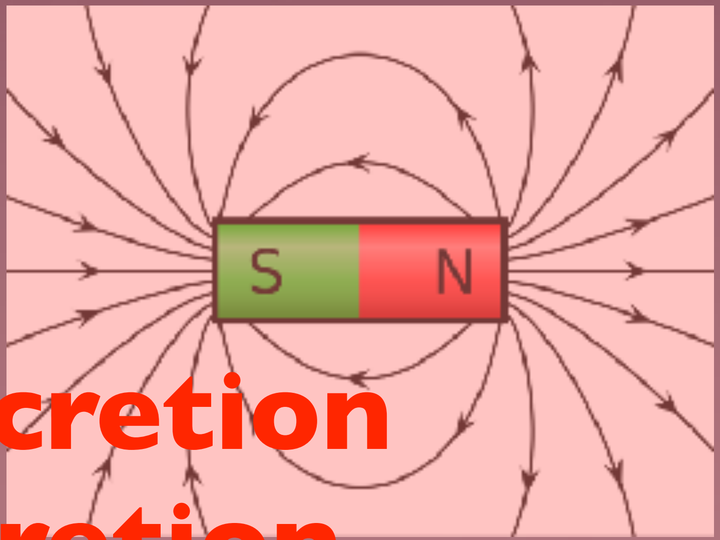


Abundance

Chondrule Formation
& Accretion

Chondrule Formation
= Impact Jetting

Timescale



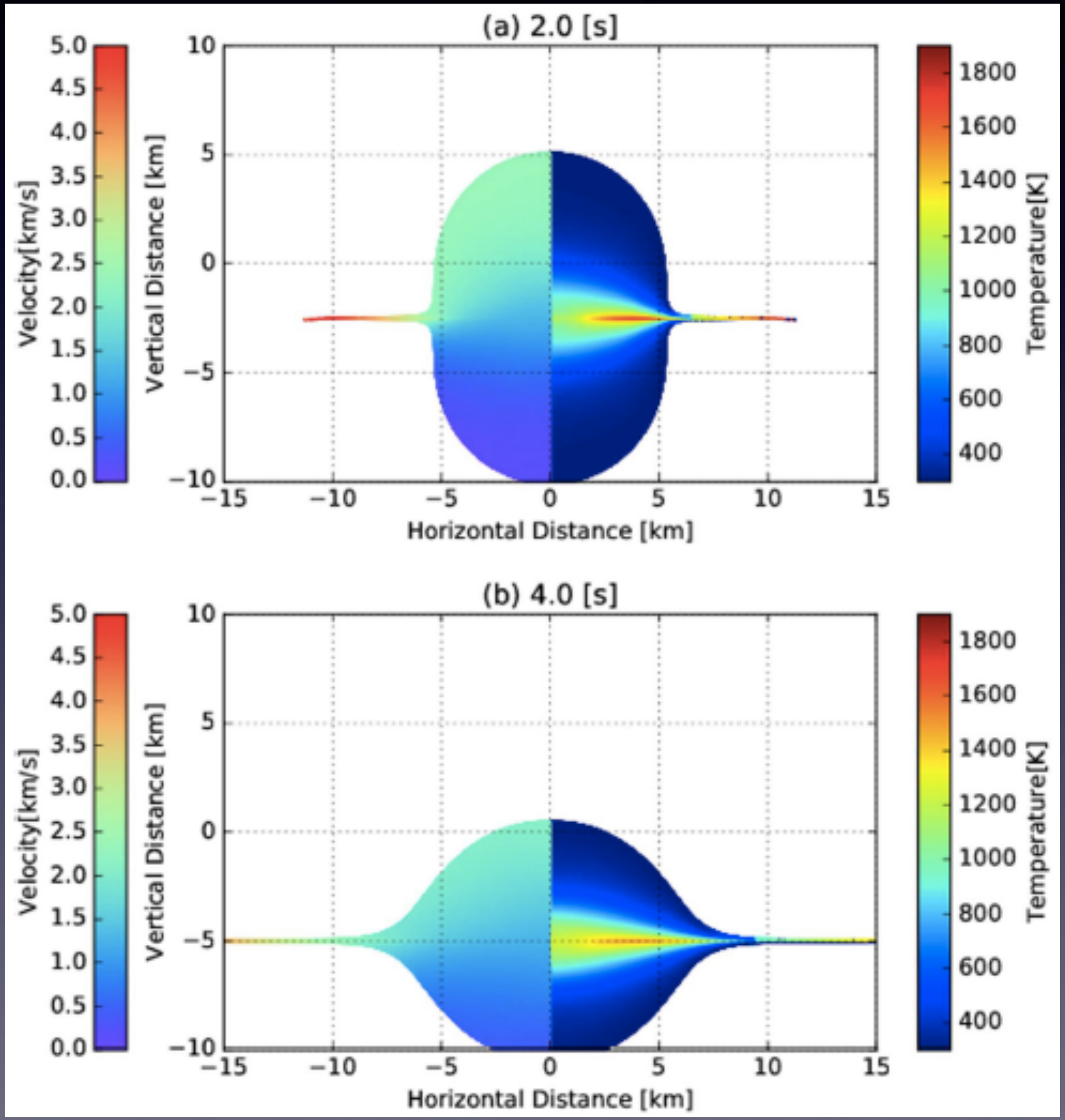
Chondrule Accretion
= Pebble Accretion

B-fields

Key idea: impact jetting

e.g., Johnson et al 2015

iSALE simulations



Wakita et al 2017

A planetesimal with r = 5km collides with a planetesimal or a protoplanet

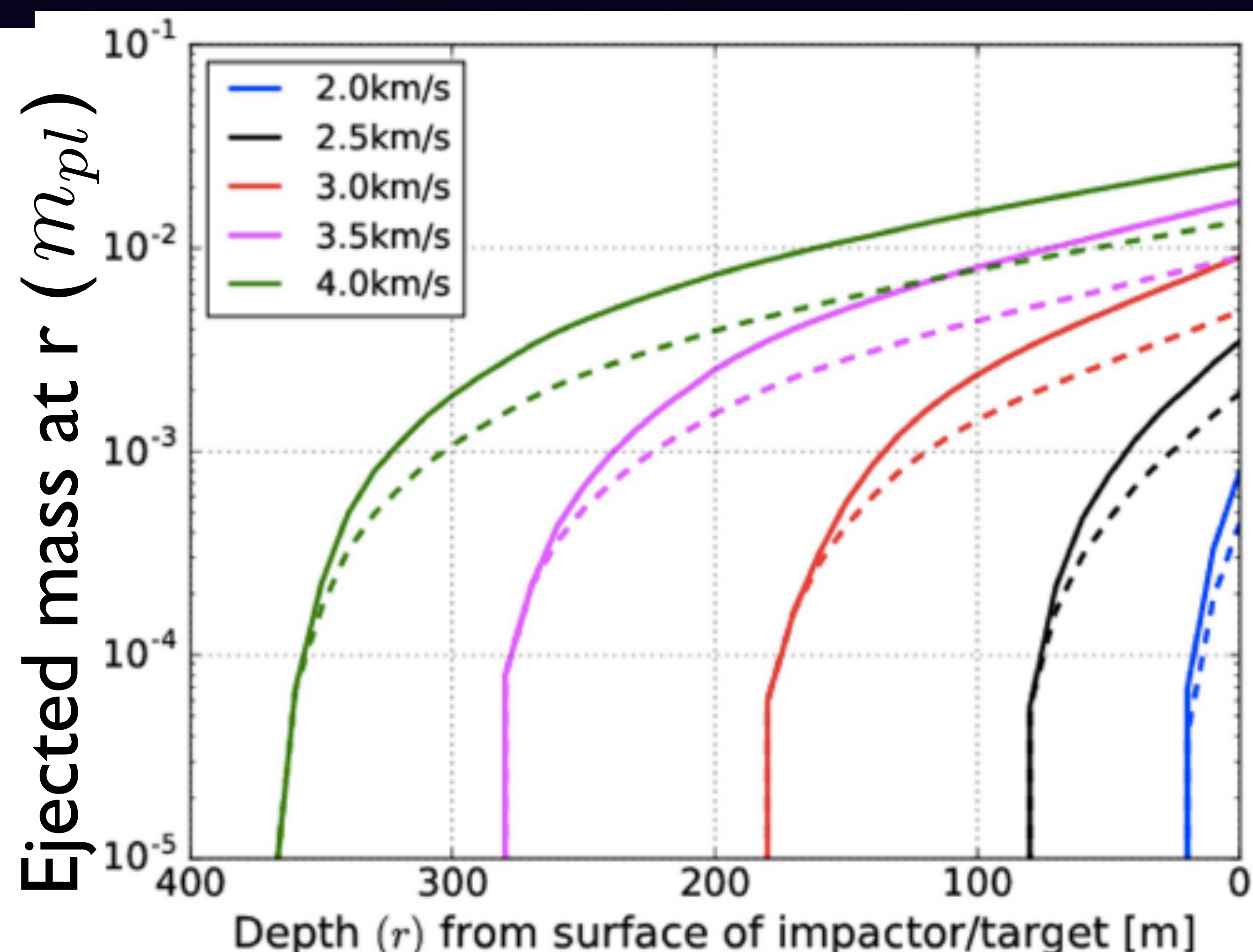
Some materials melt, and are ejected from the system

Such ejected materials may be a progenitor of chondrules

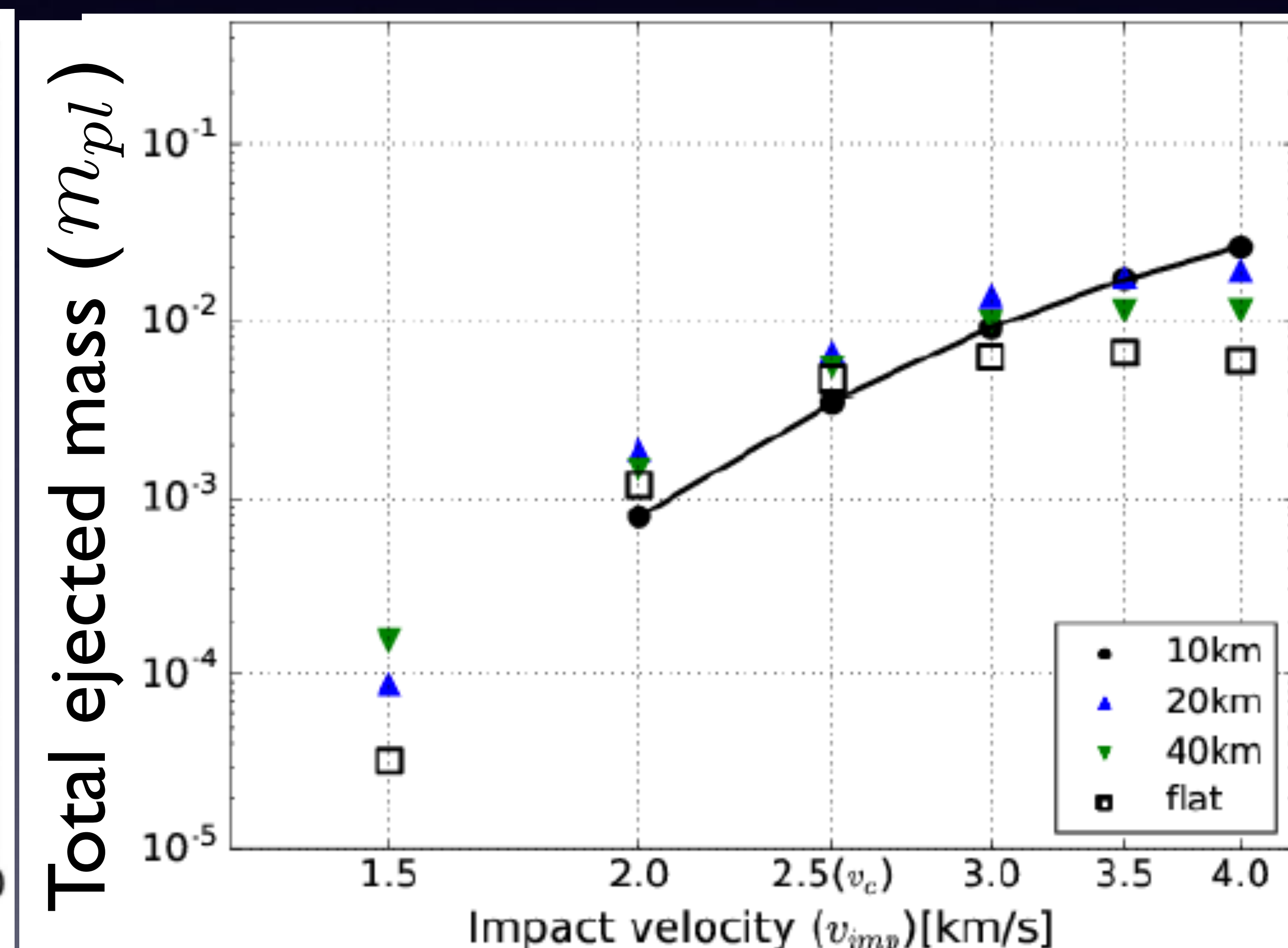
Parameter Study

Wakita et al 2017

Collisions between 10 km sized planetesimals



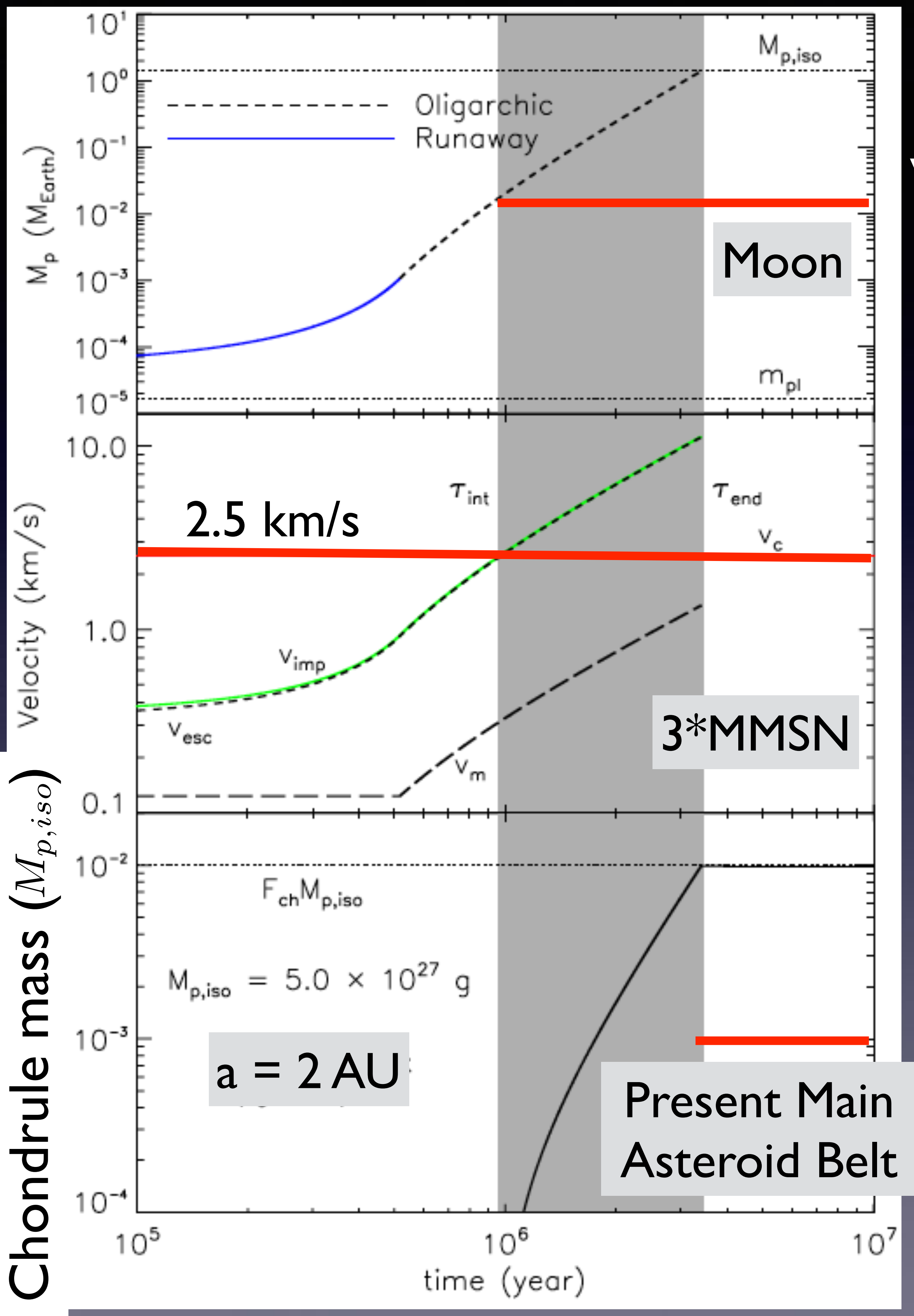
Collisions with various setups



Total ejected mass is about 1% of impactors' mass when v > 2.5 km/s

Lots of collisions occur when protoplanets form

Hasegawa et al 2016a



Protoplanets form via runaway/oligarchic growth

Impact velocity of 2.5 km/s is achieved in the oligarchic phase

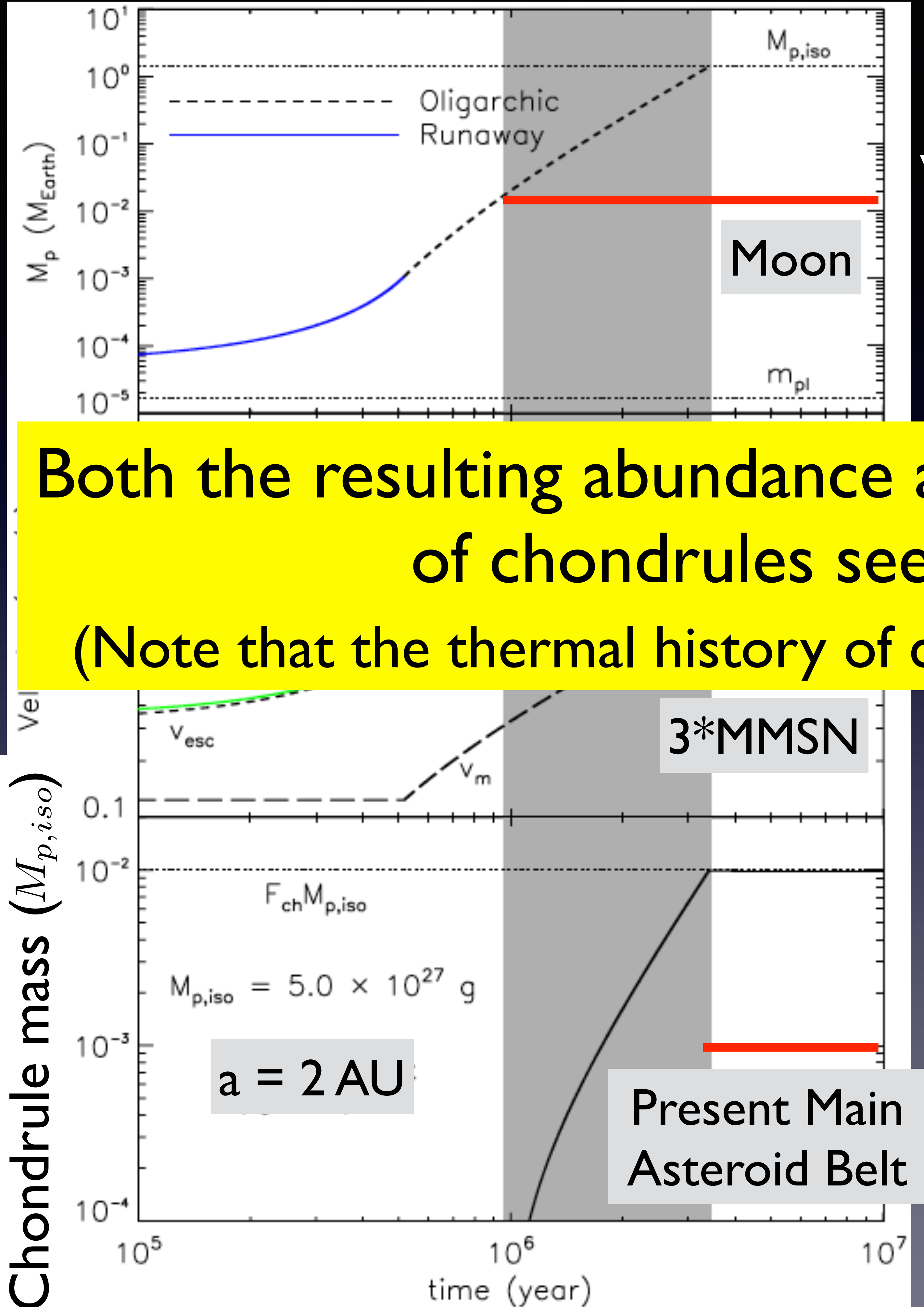
Chondrule-forming collisions occur at the hatched region

The total chondrule abundance is 1 % of the protoplanet mass

MMSN =
the Minimum Mass of the Solar Nebula

Lots of collisions occur when protoplanets form

Hasegawa et al 2016a



Protoplanets form via

Both the resulting abundance and the formation timescale of chondrules seem reasonable!!

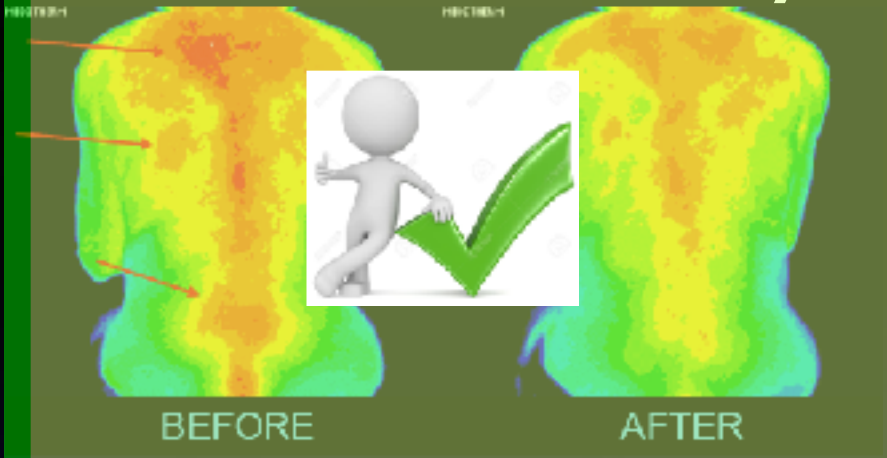
(Note that the thermal history of chondrules is also probably fine)

Chondrule-forming collisions occur at the hatched region

The total chondrule abundance is 1 % of the protoplanet mass

MMSN =
the Minimum Mass of the Solar Nebula

Thermal History



Abundance

Chondrule Formation
& Accretion

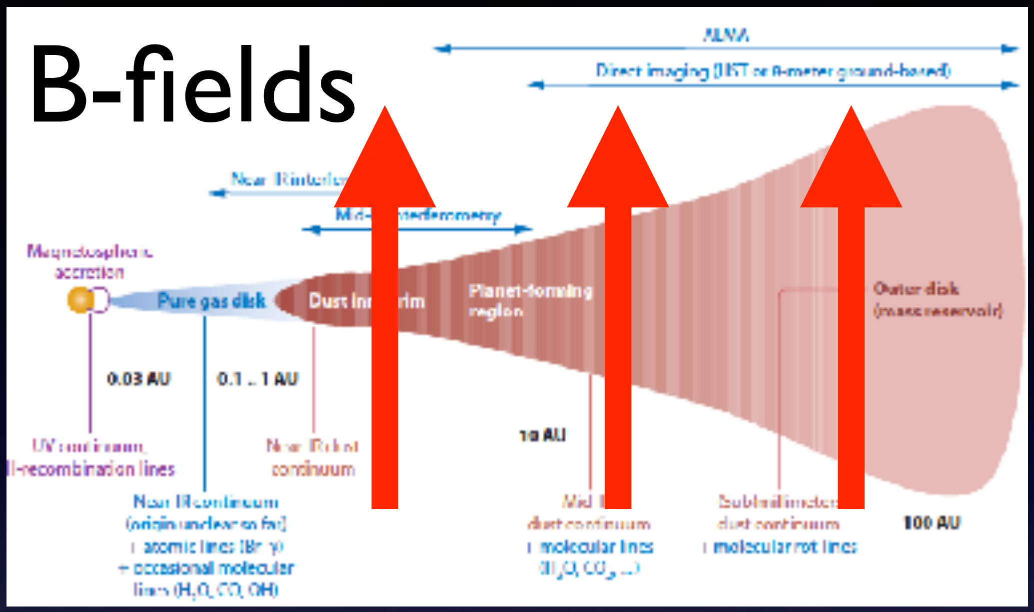
Chondrule Formation
= Impact Jetting

Timescale

Chondrule Accretion
= Pebble Accretion

B-fields

Lab results (magnetic fields) come into play!!!



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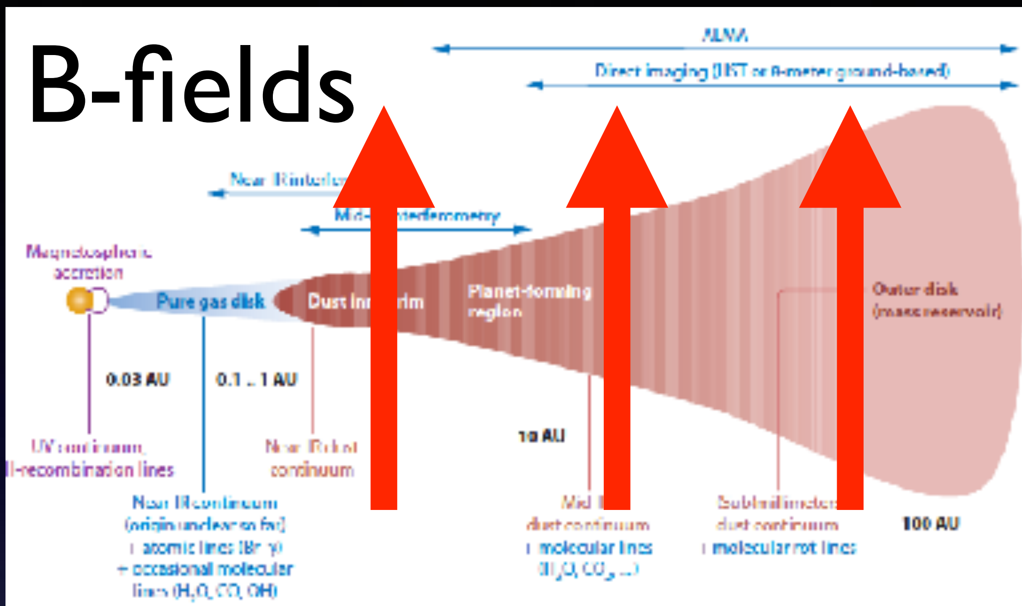
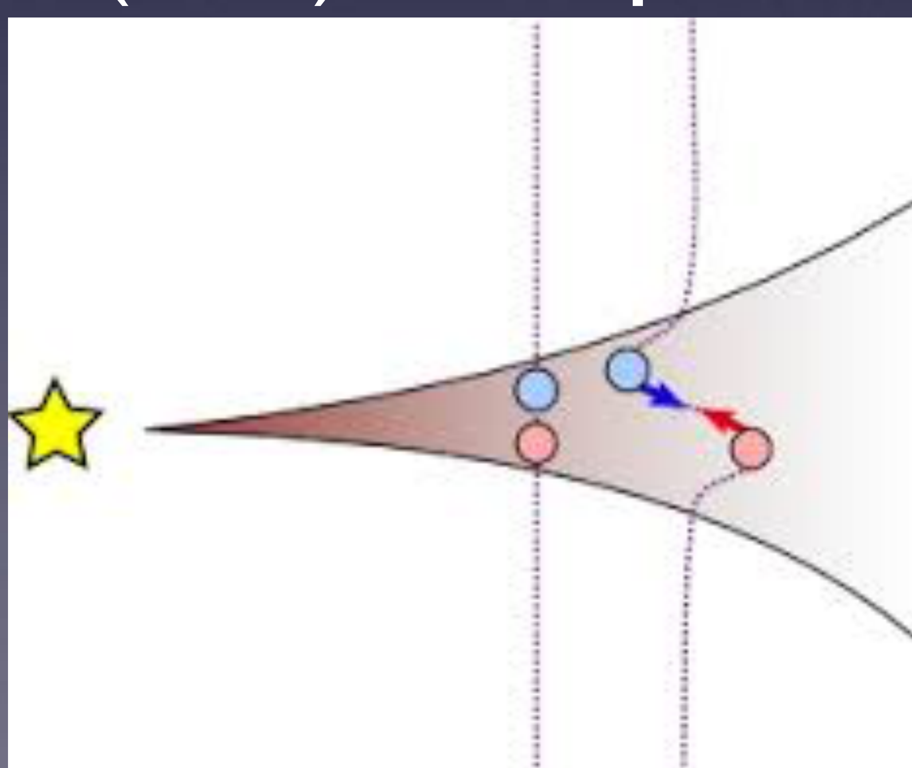
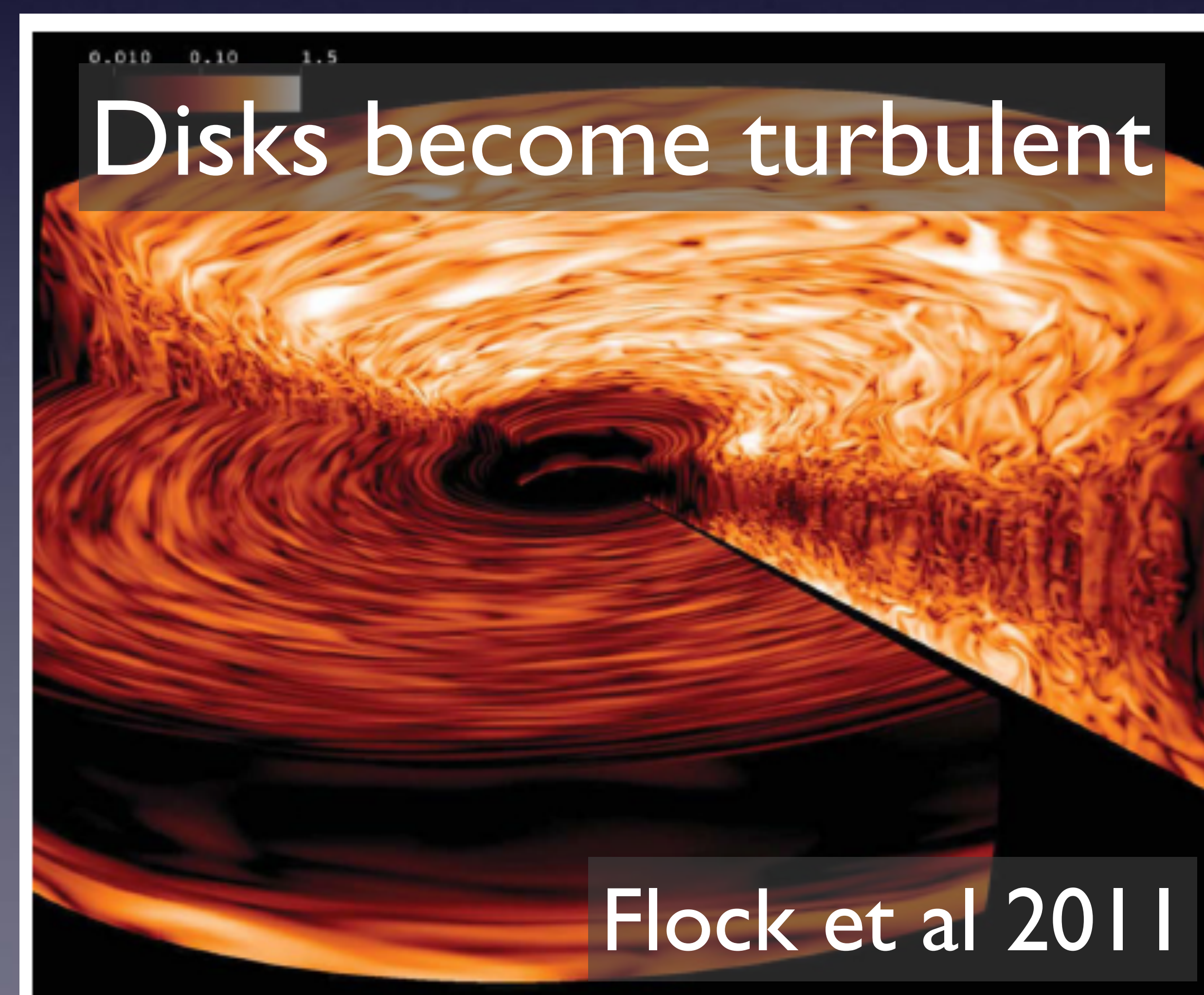


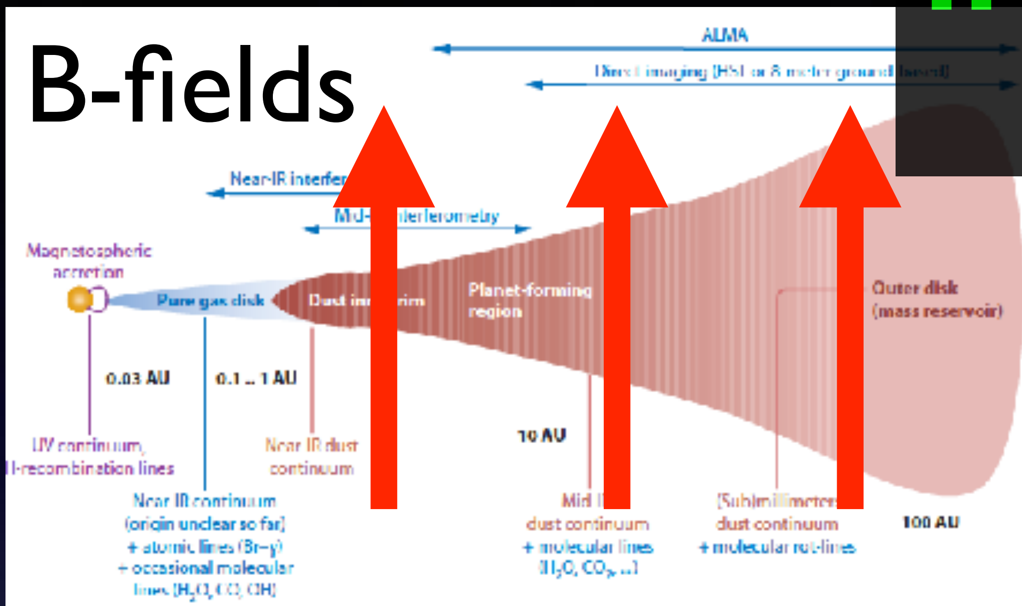
MagnetoRotational Instability (MRI) can operate

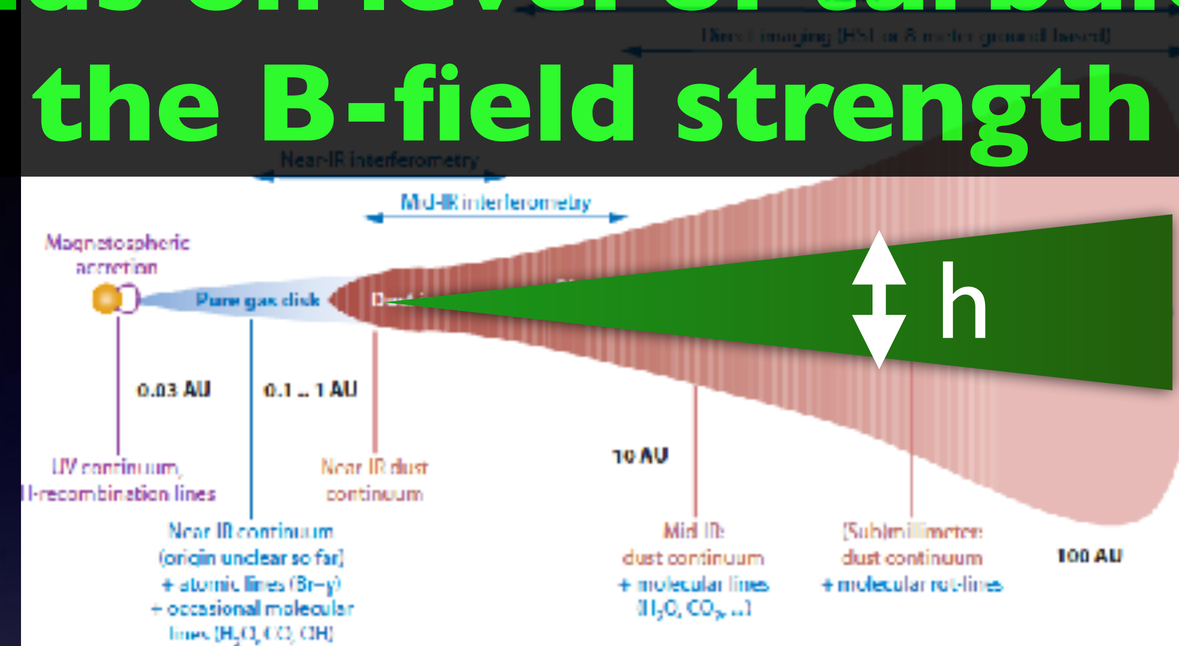




Lab results (magnetic fields) come into play!!!

h depends on level of turbulence so the B-field strength





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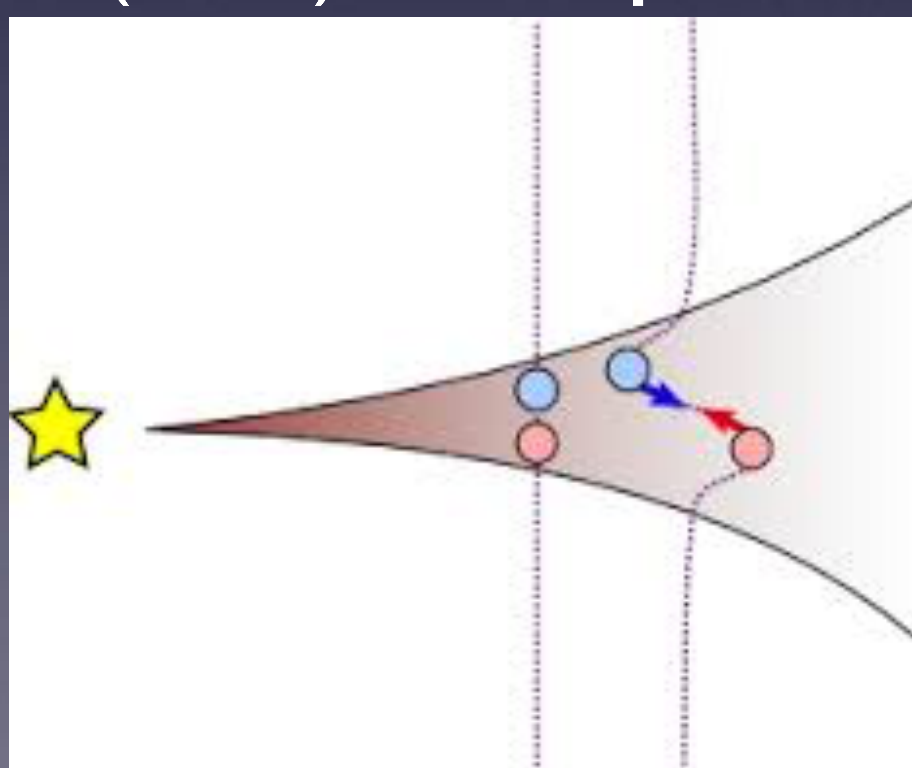
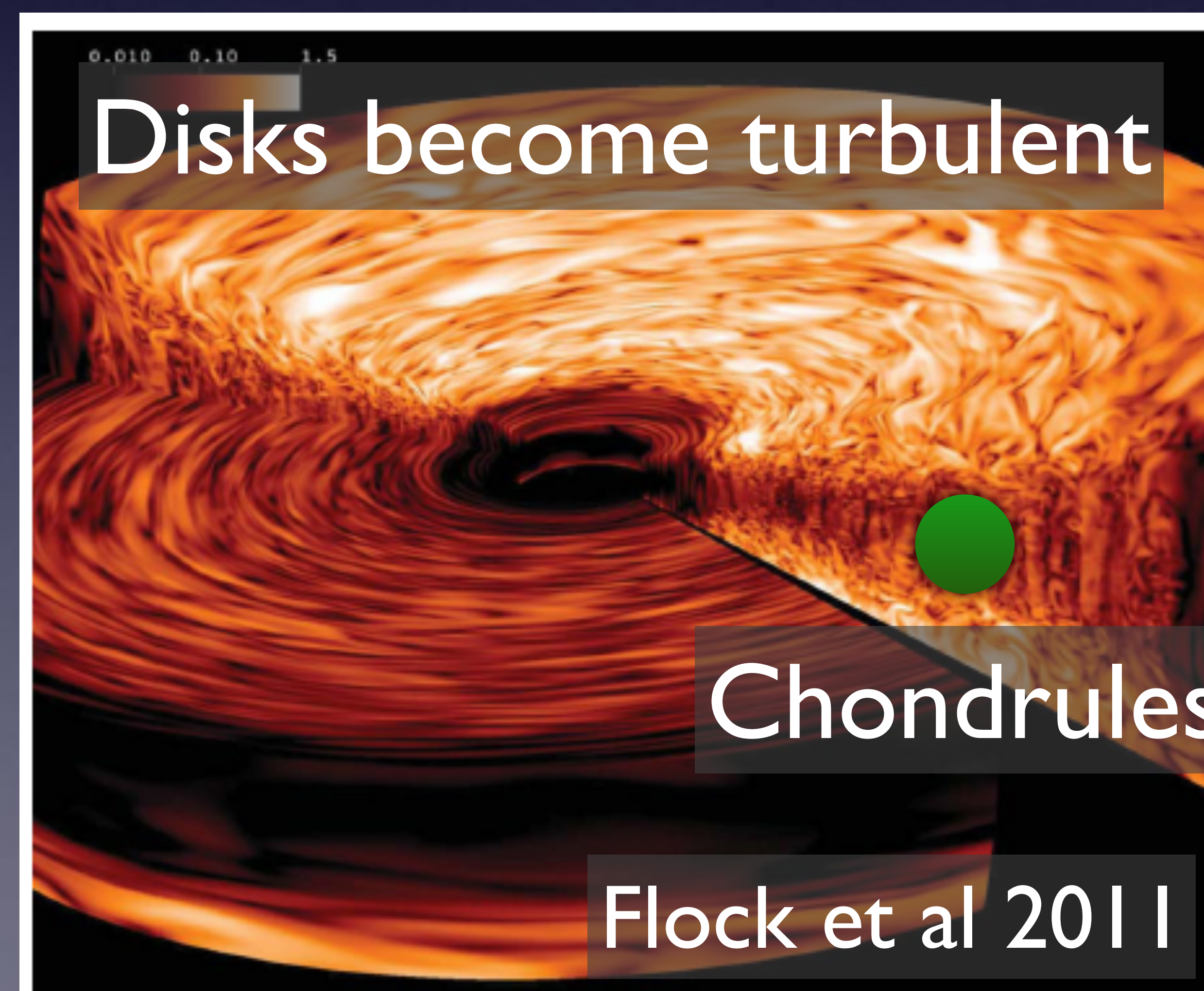
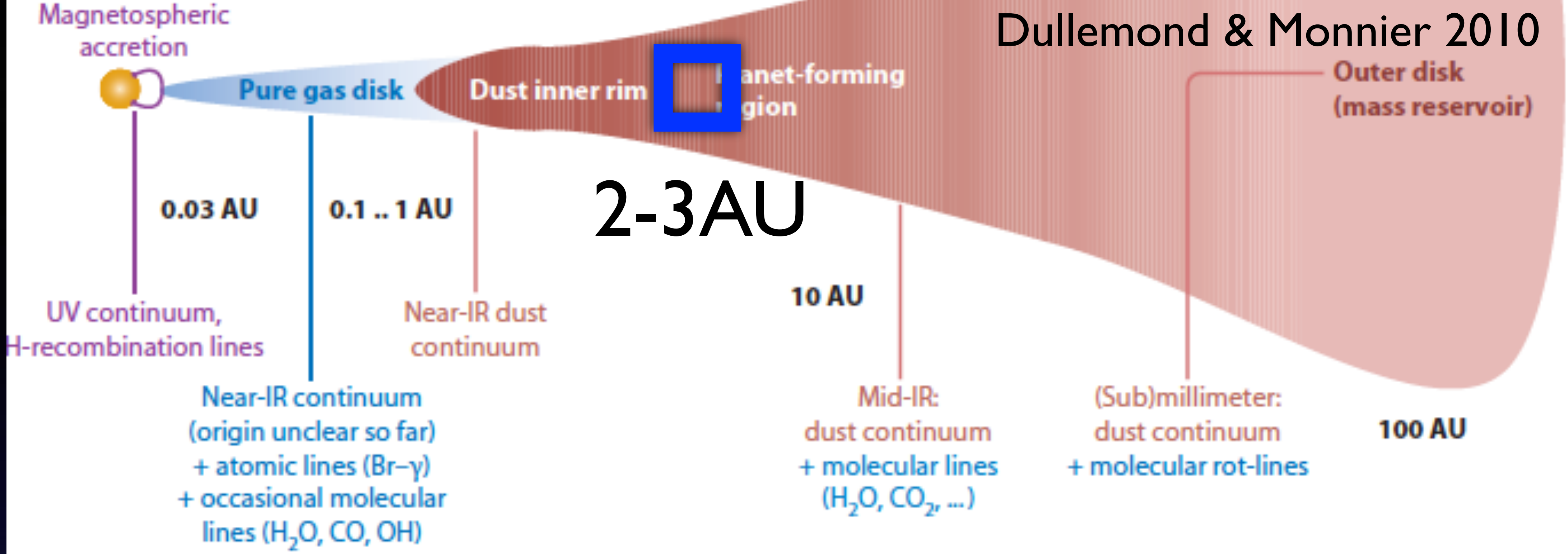
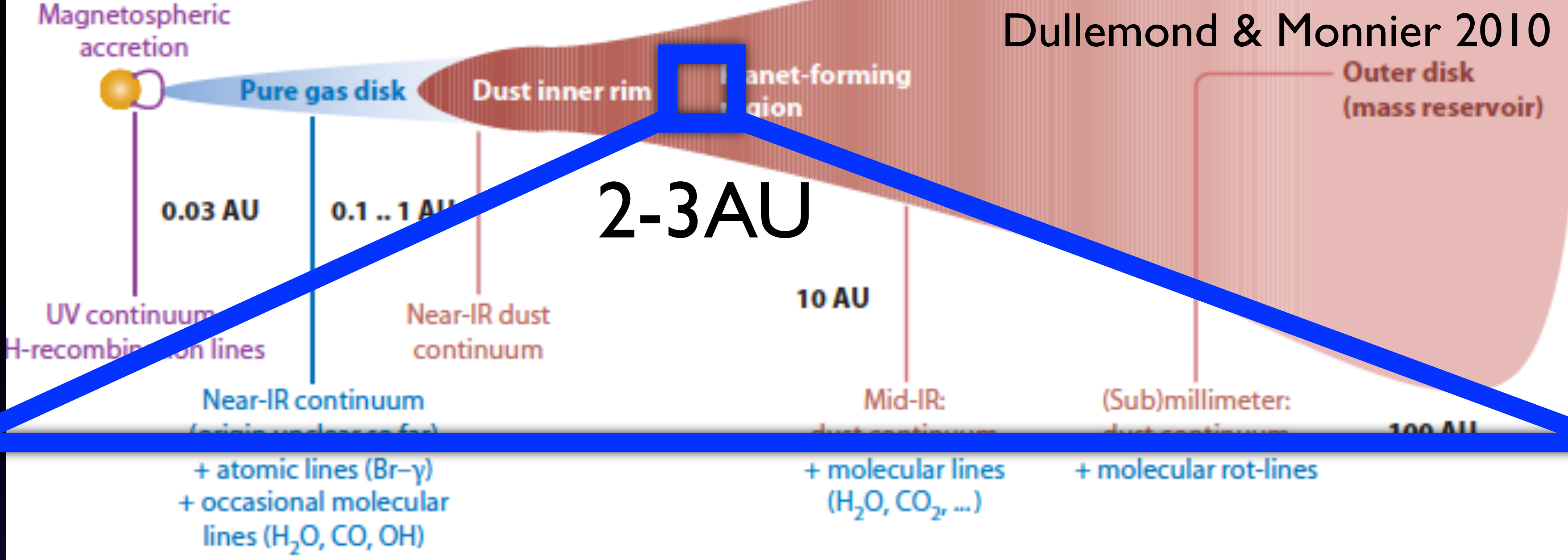


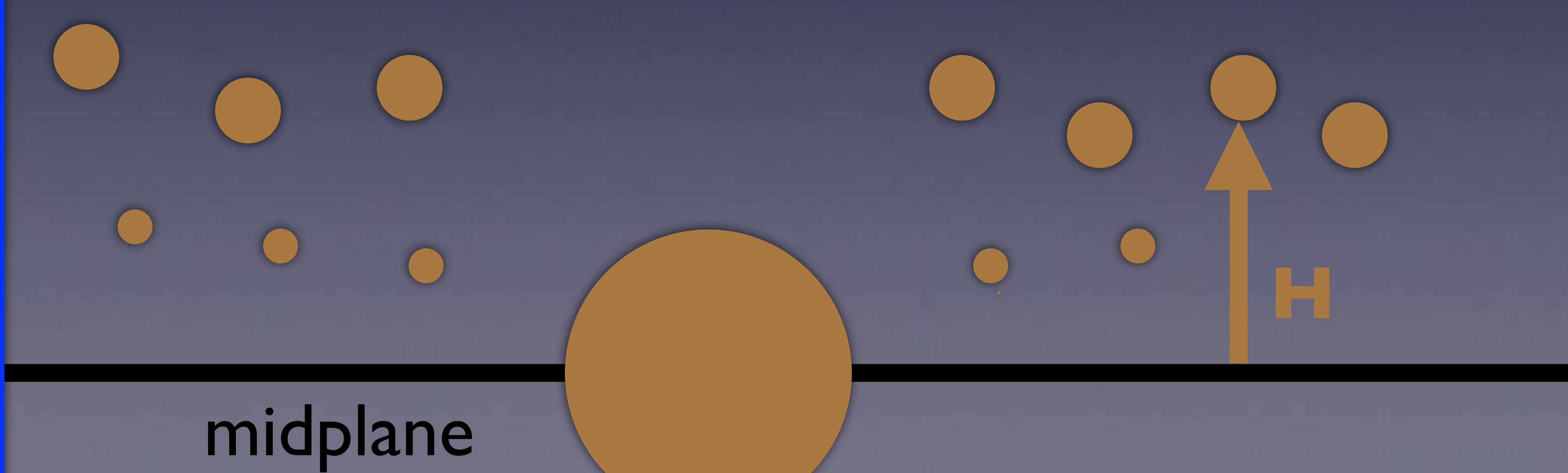


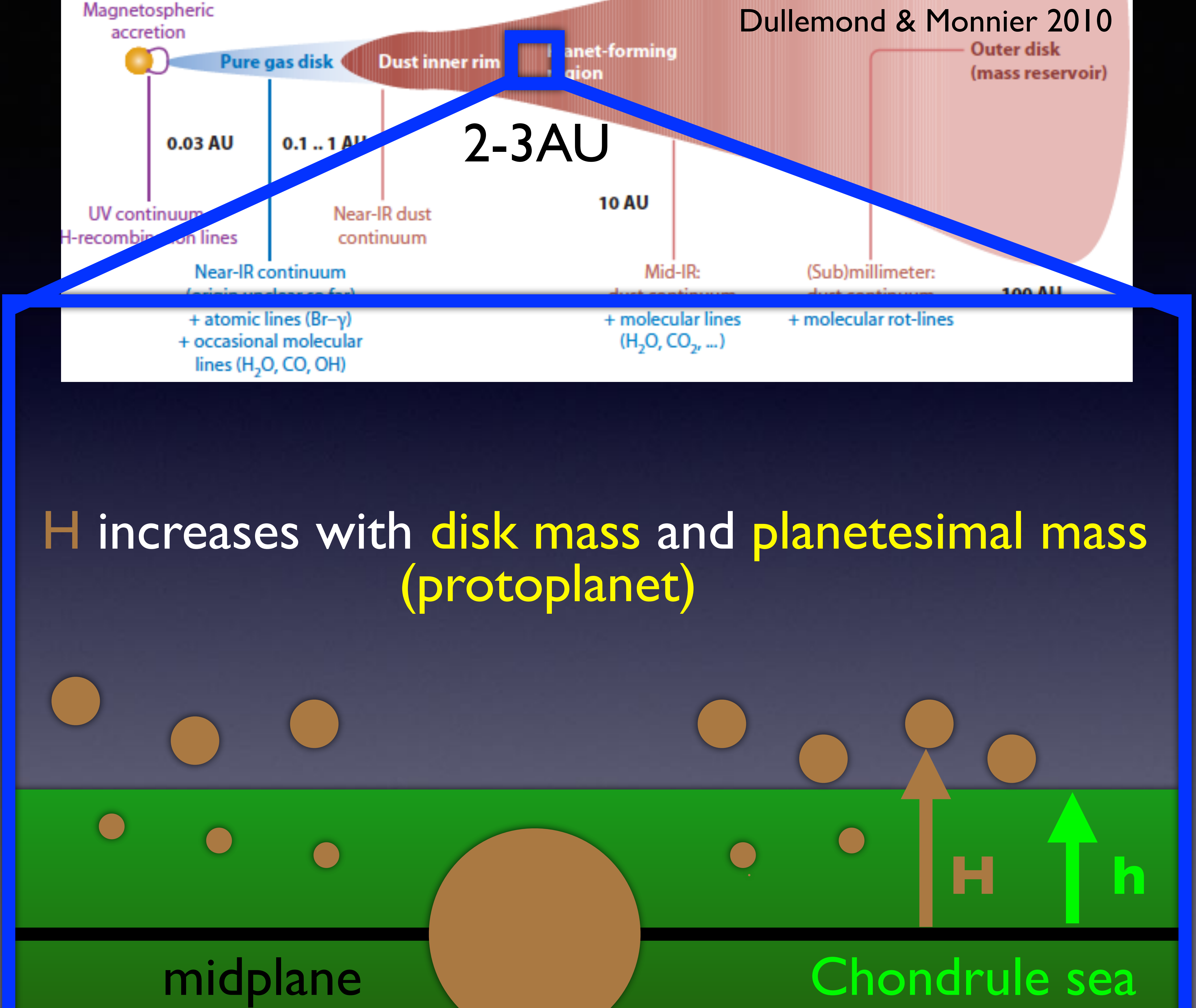


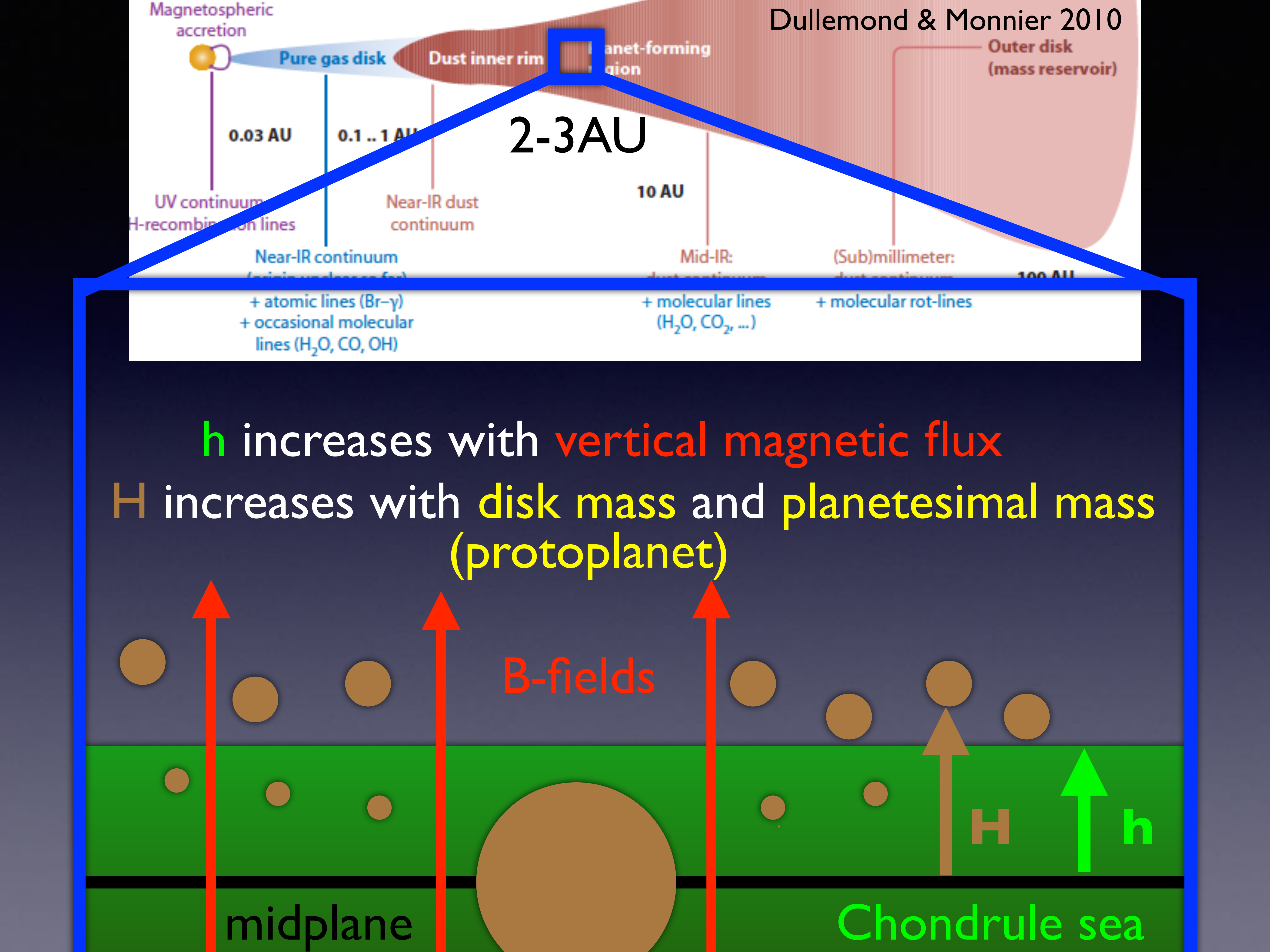
Dullemond & Monnier 2010



H increases with disk mass and planetesimal mass (protoplanet)




Dullemond & Monnier 2010
Magnetospheric accretion
Pure gas disk
Dust inner rim
Outer disk (mass reservoir)
2-3AU
0.03 AU
0.1 .. 1 AU
10 AU
UV continuum
Near-IR dust continuum
Near-IR continuum
Mid-IR:
(Sub)millimeter:
+ atomic lines (Br–γ)
+ occasional molecular lines (H_2O, CO, OH)
+ molecular lines (H_2O, CO_2, ...)
+ molecular rot-lines
H increases with disk mass and planetesimal mass (protoplanet)
H
h
midplane
Chondrule sea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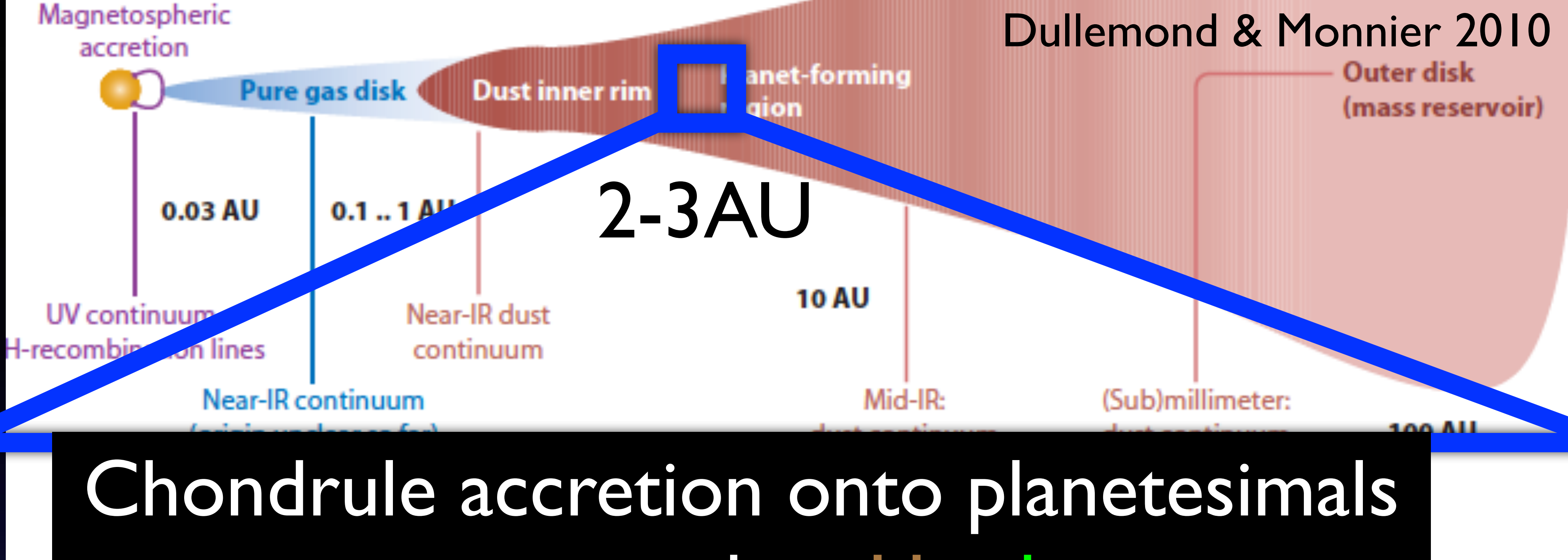
h increases with vertical magnetic flux
H increases with disk mass and planetesimal mass (protoplanet)
B-fields
H
h
midplane
Chondrule sea

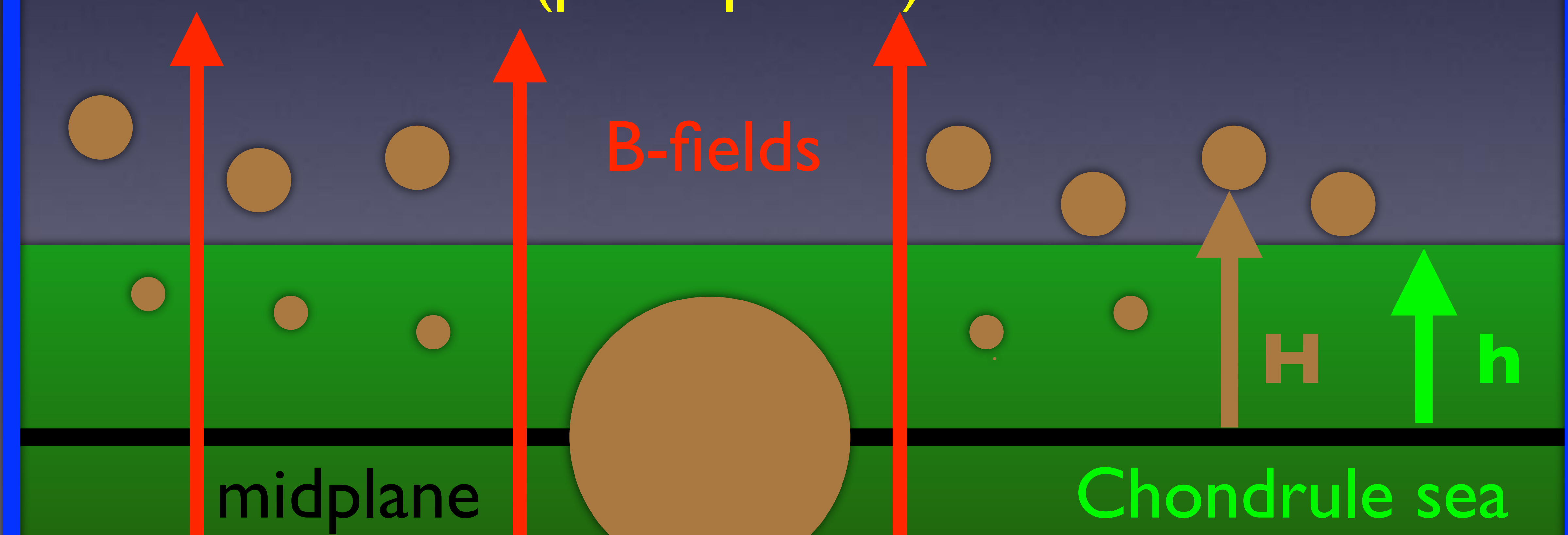


Chondrule accretion onto planetesimals occurs when $H < h$

Lesion et al 2015

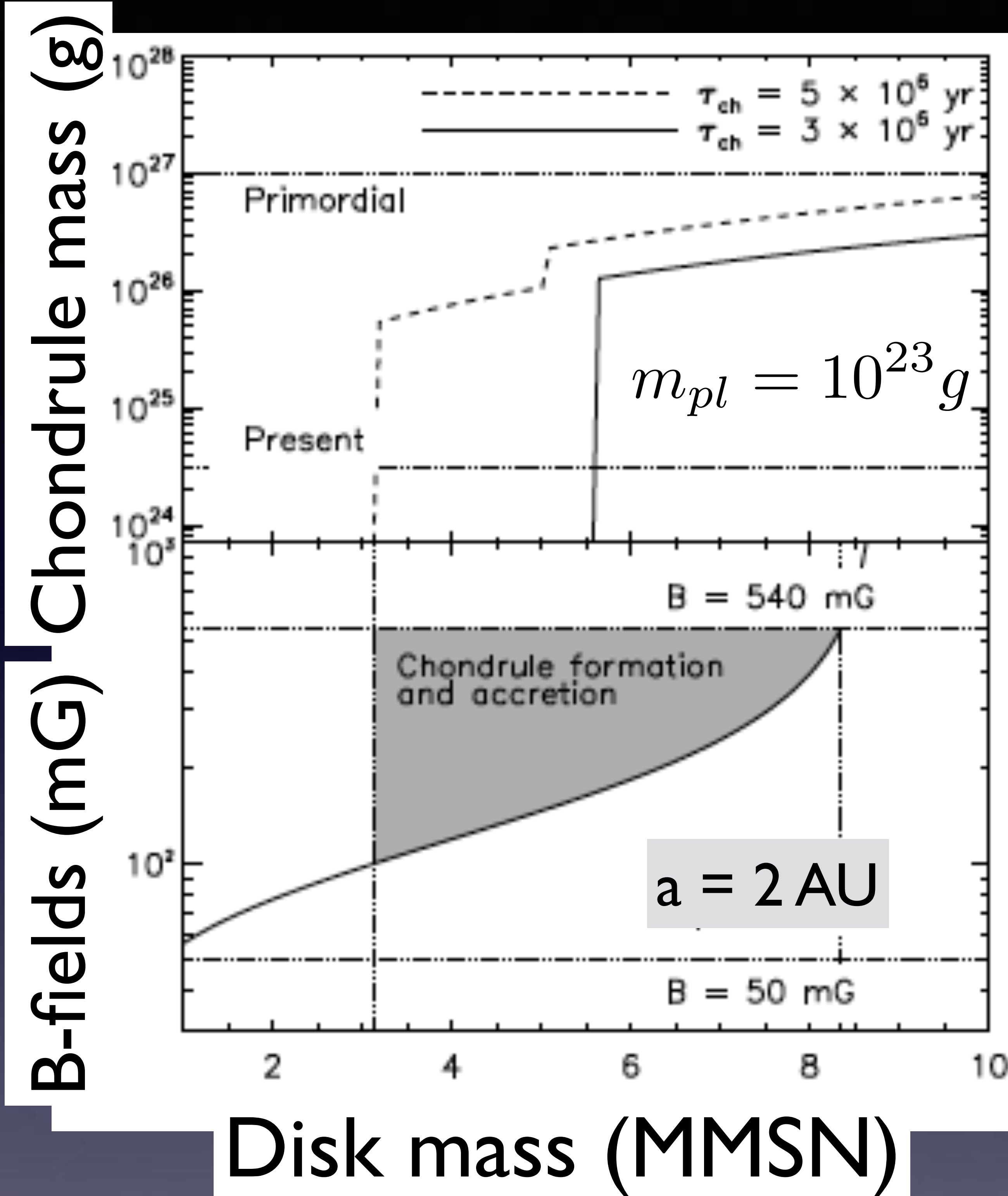
h increases with vertical magnetic flux

H increases with disk mass and planetesimal mass (protoplanet)



$m_{pl} = 10^{23} g$
Total chondrule mass
Minimum value of B-fields for chondrule accretion
Disk mass (MMSN)

$m_{pl} = 10^{24} g$
Total chondrule mass
Minimum value of B-fields for chondrule accretion
Disk mass (MMSN)



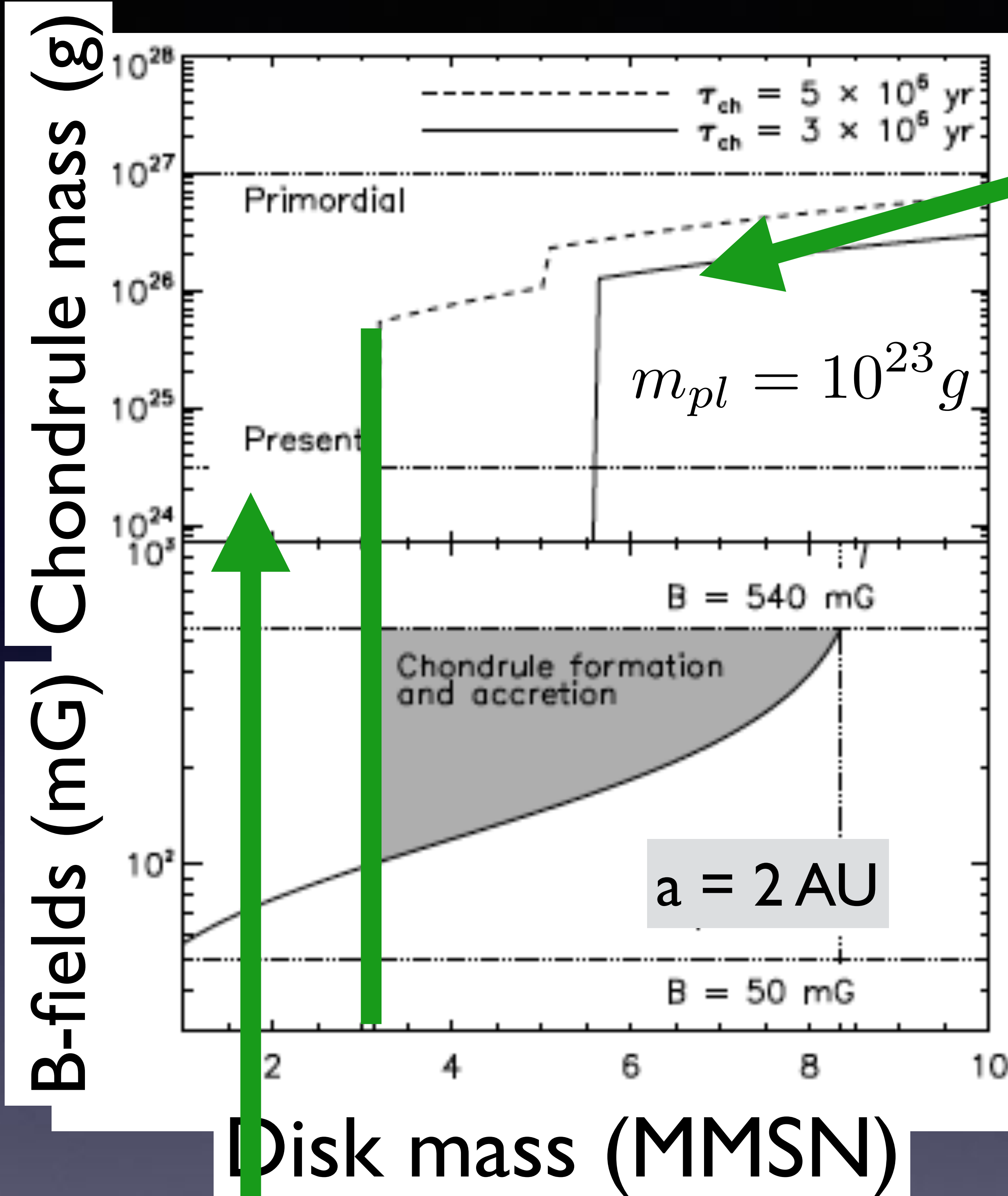
$$m_{pl} = 10^{24} g$$

Total chondrule mass

Minimum value
of B-fields for
chondrule accretion

Disk mass (MMSN)

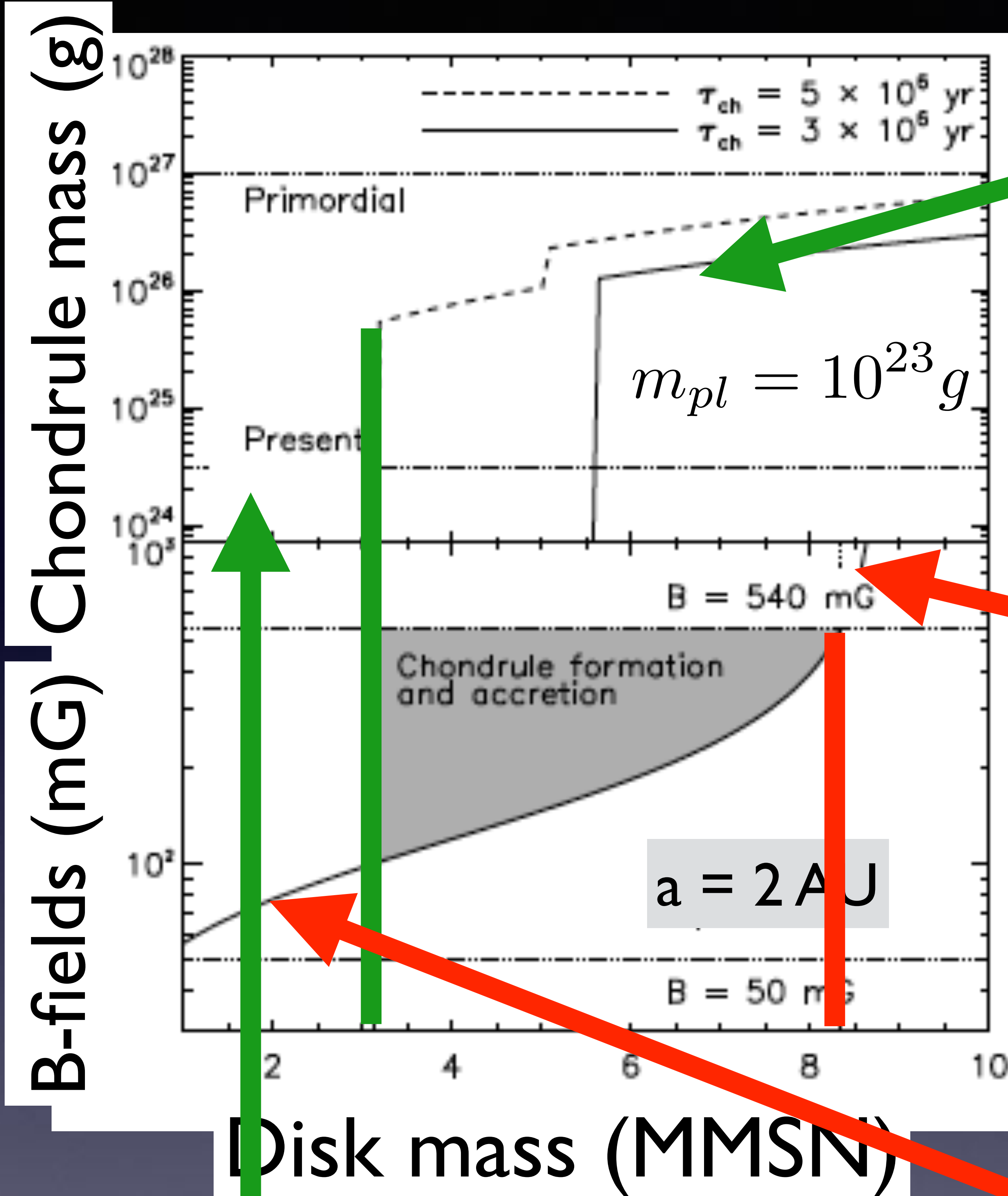
Hasegawa et al 2016b



A large number of chondrules form in massive disks

No chondrule formation due to a low disk mass

Hasegawa et al 2016b



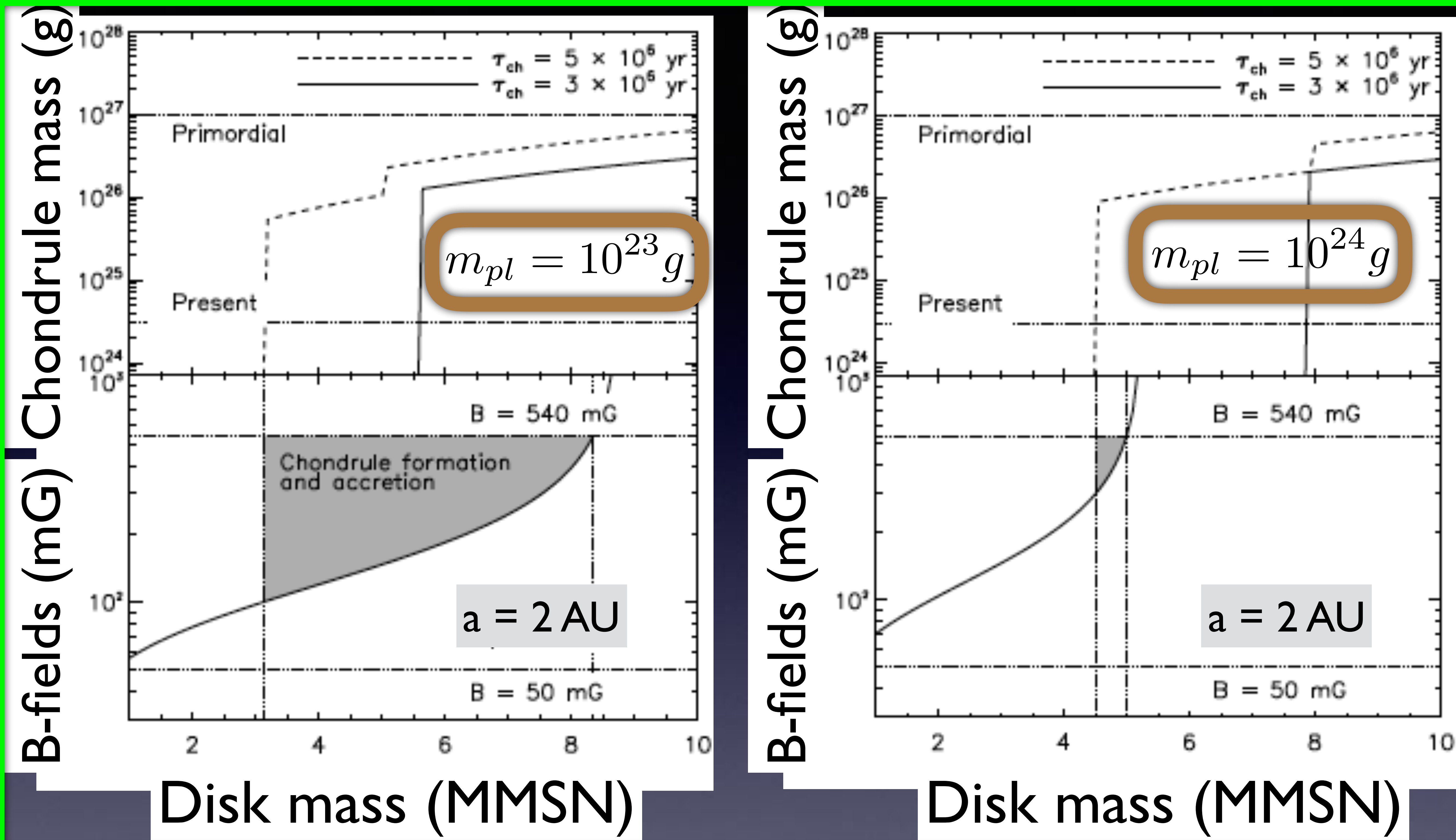
A large number of chondrules form in massive disks

A very strong magnetic field is needed for chondrules to have the same height as planetesimals

Planetesimals can reside in the chondrule sea, but no chondrules indeed

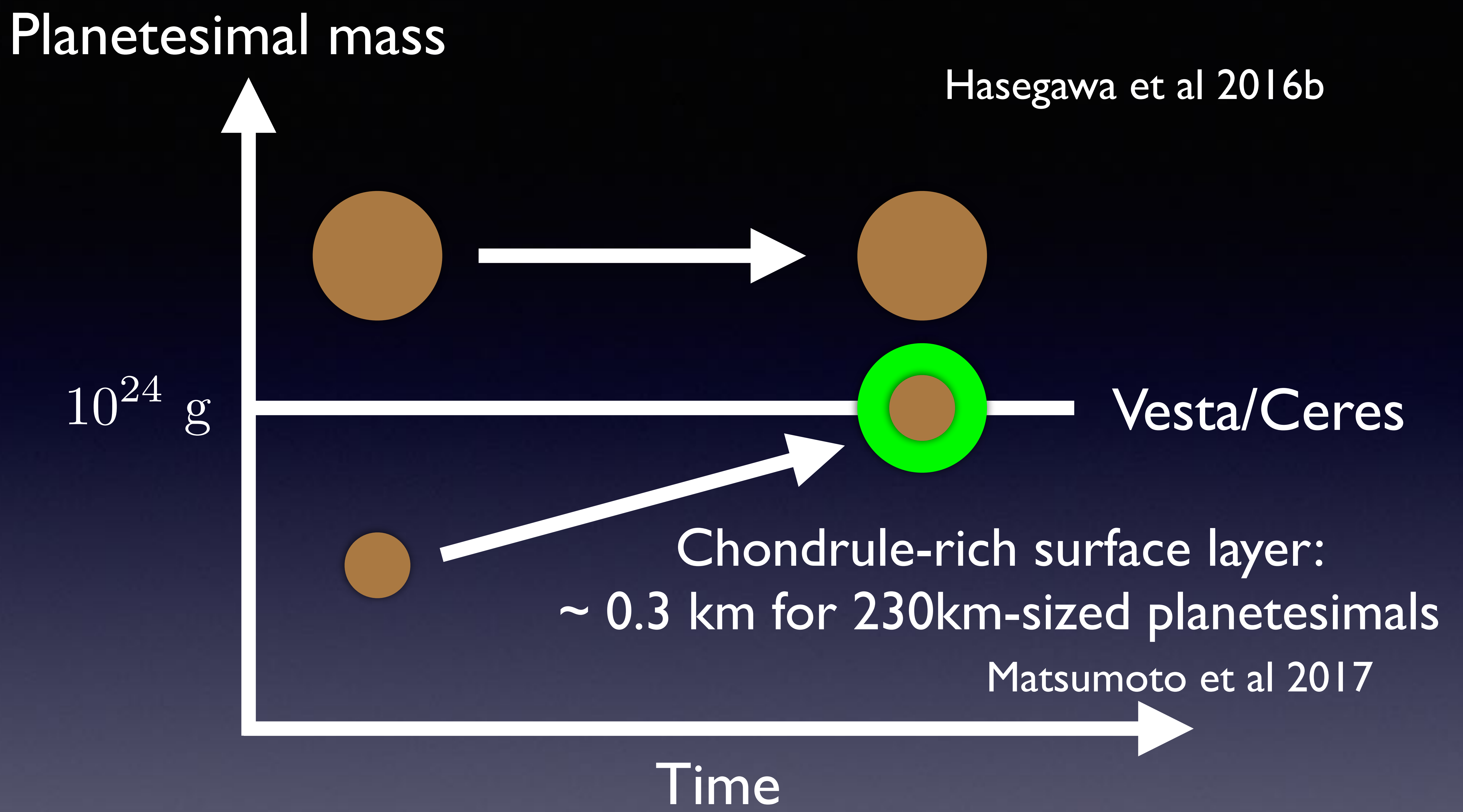
No chondrule formation due to a low disk mass

Hasegawa et al 2016b



All the currently available meteorite data can be satisfied
when the disk mass is < 5 MMSN
the planetesimal mass is < 10^{24} g

Hasegawa et al 2016b



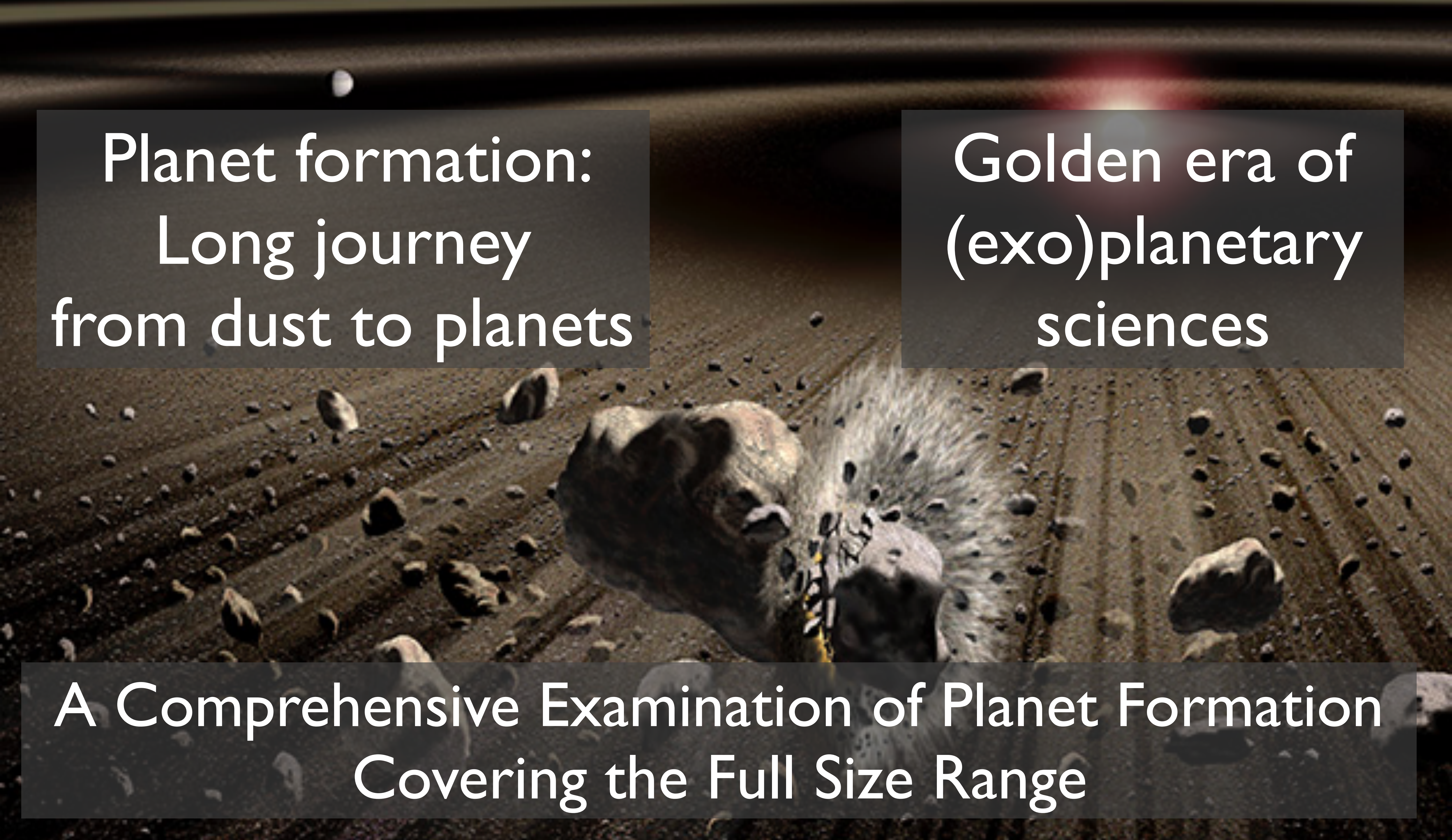
Our model needs a first generation of planetesimals
that trigger impact jetting and
serve as parent bodies to accrete chondrules

cf) Mars formed at ~2 Myr after CAI formation

Summary

Hasegawa et al 2016a, ApJ, 816, 9
Hasegawa et al 2016b, ApJ, 820, L12

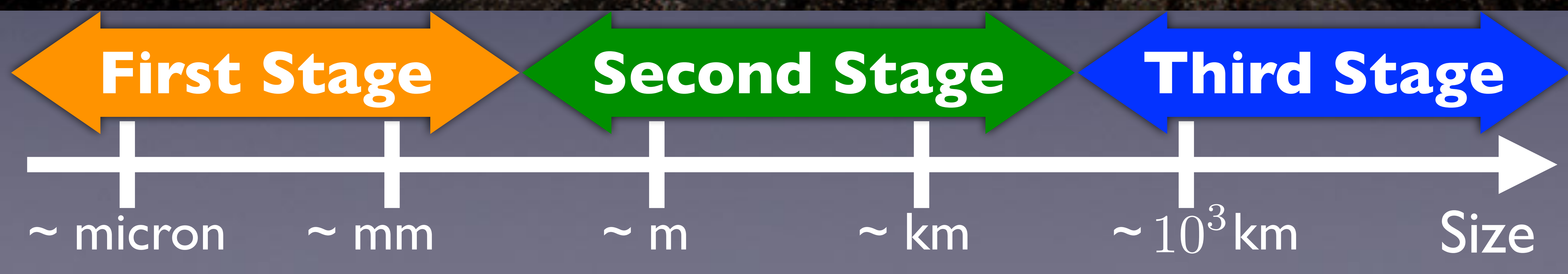
- Primitive meteorites contain fossil records of the solar system
- Coupling of impact jetting with subsequent chondrule accretion is a promising scenario to account for the currently available meteorite data
- all the requirements can be met when the disk mass is < about 5 MMSN and the planetesimal mass is < about 10^{24} g
- Our model implies that only primordial asteroids that were originally smaller than 500 km in radius may have a chondrule-rich surface layer (~ 0.3 km)!!
- The upper limit of the planetesimal mass is comparable to that of Vesta/Ceres, and current observations/missions may provide an invaluable opportunity to verify our scenario!!



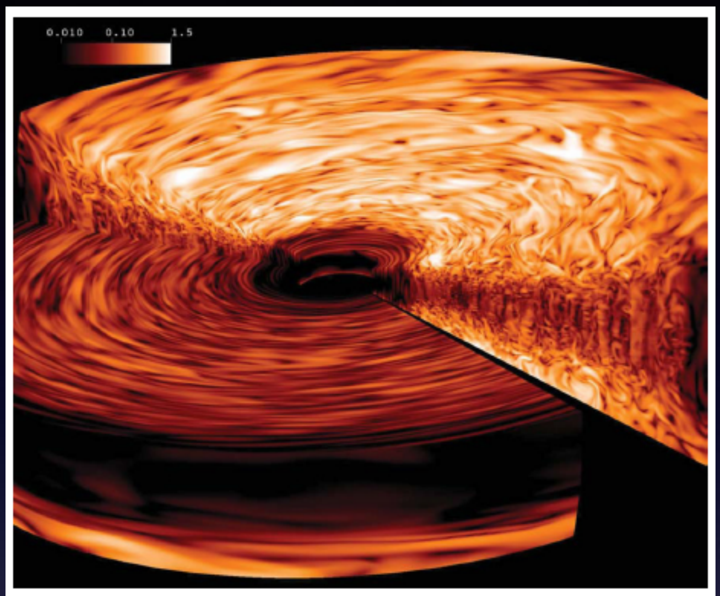
Planet formation:
Long journey
from dust to planets

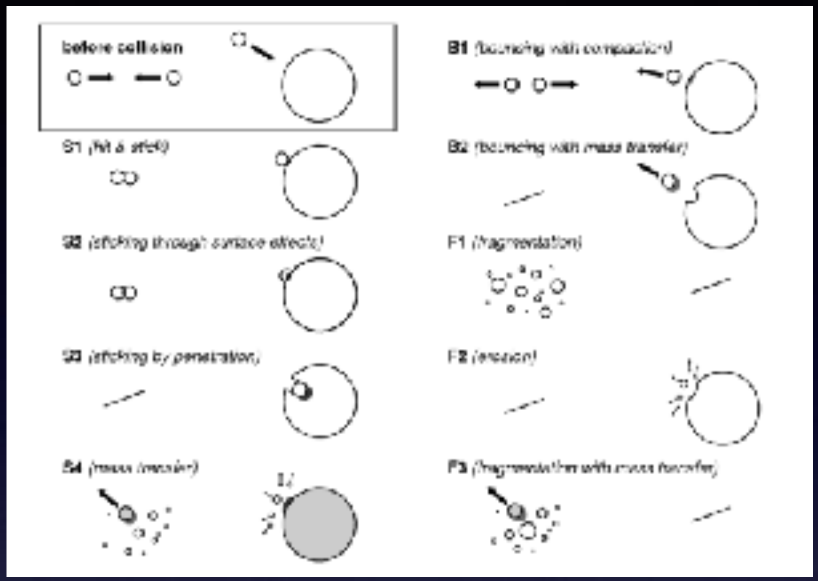
Golden era of
(exo)planetary
sciences

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 2017 in prep

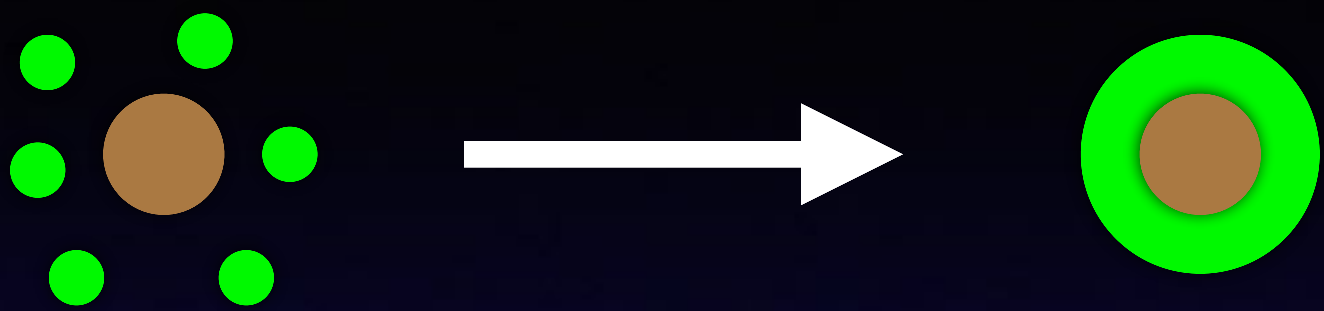
We will **infer** the distribution of planet-forming materials in disks

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

First Stage

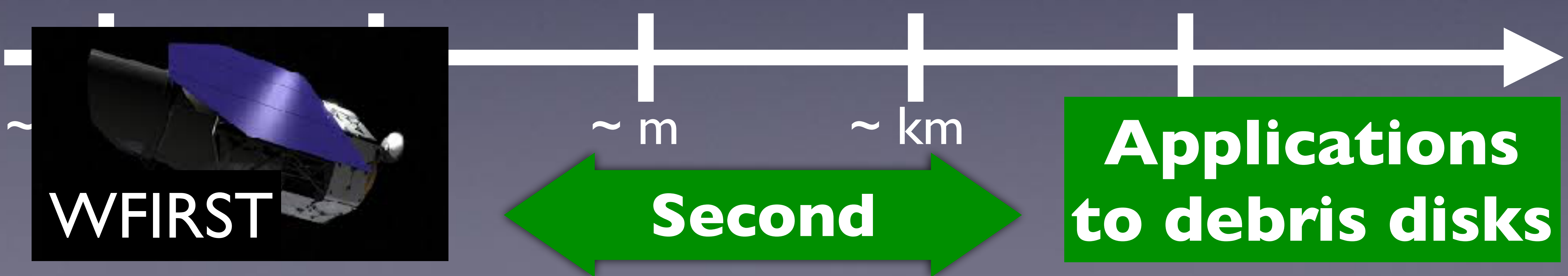
Planetesimal Formation & Origins of Asteroids

Scenario 1: Chondrule accretion

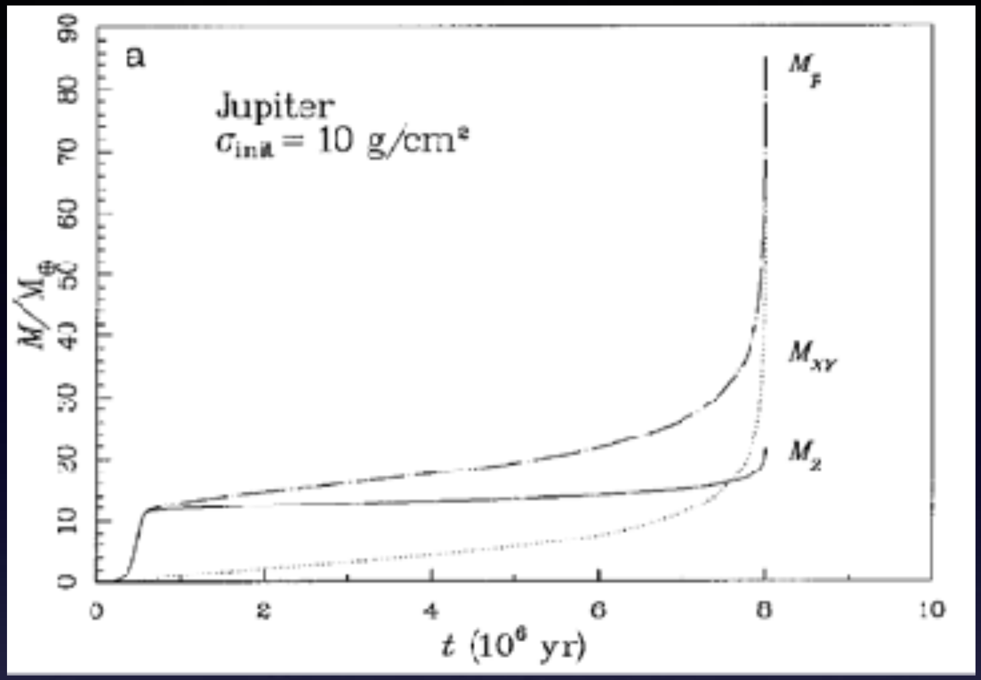


Scenario 2: Chondrule accumulation

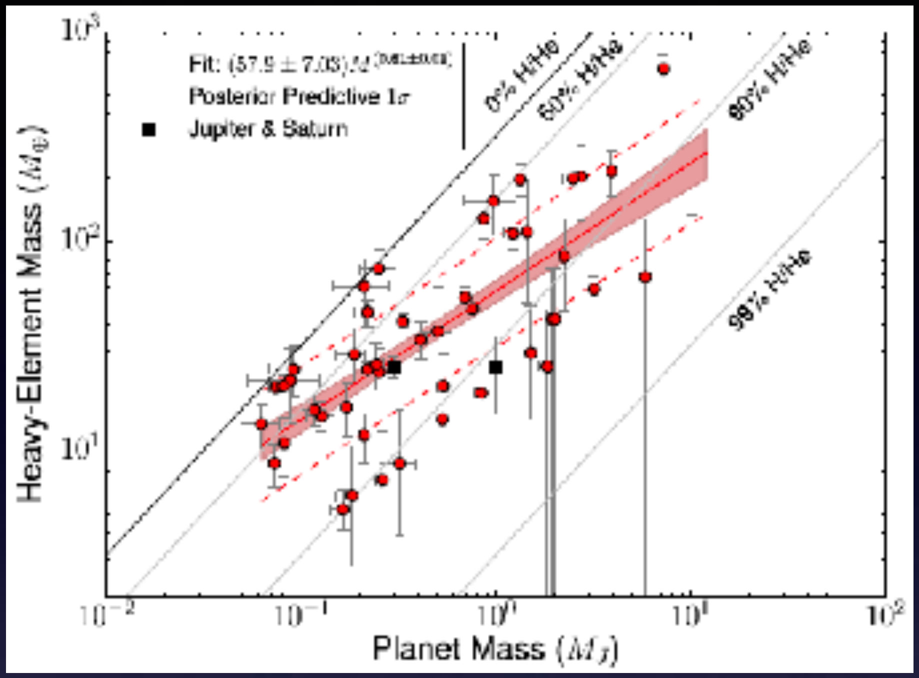
We will **identify** formation mechanism(s) of planetesimals



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

$\sim 10^3$km

Size

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, three projects are discussed, which include a theoretical modeling of the HL Tau disk, chondrule formation and accretion, and the mass-radius diagram of close-in planets
- 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