Planet Formation in Star-Forming Regions

: from the Solar System to Other Worlds

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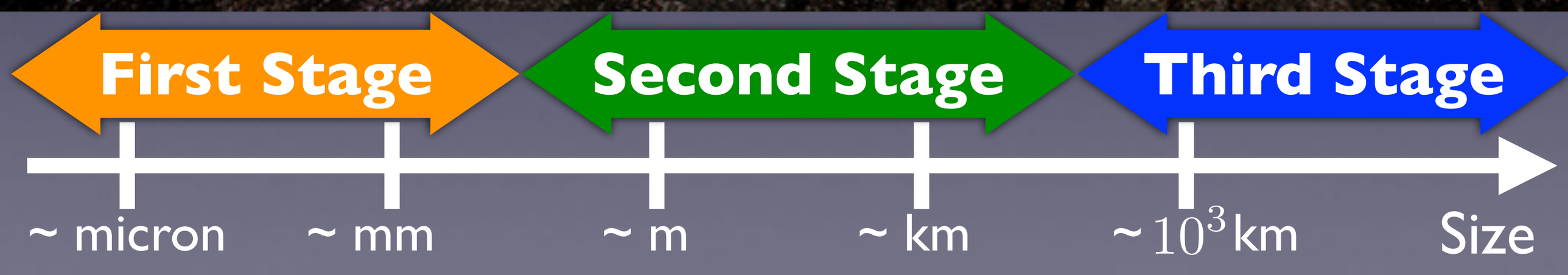
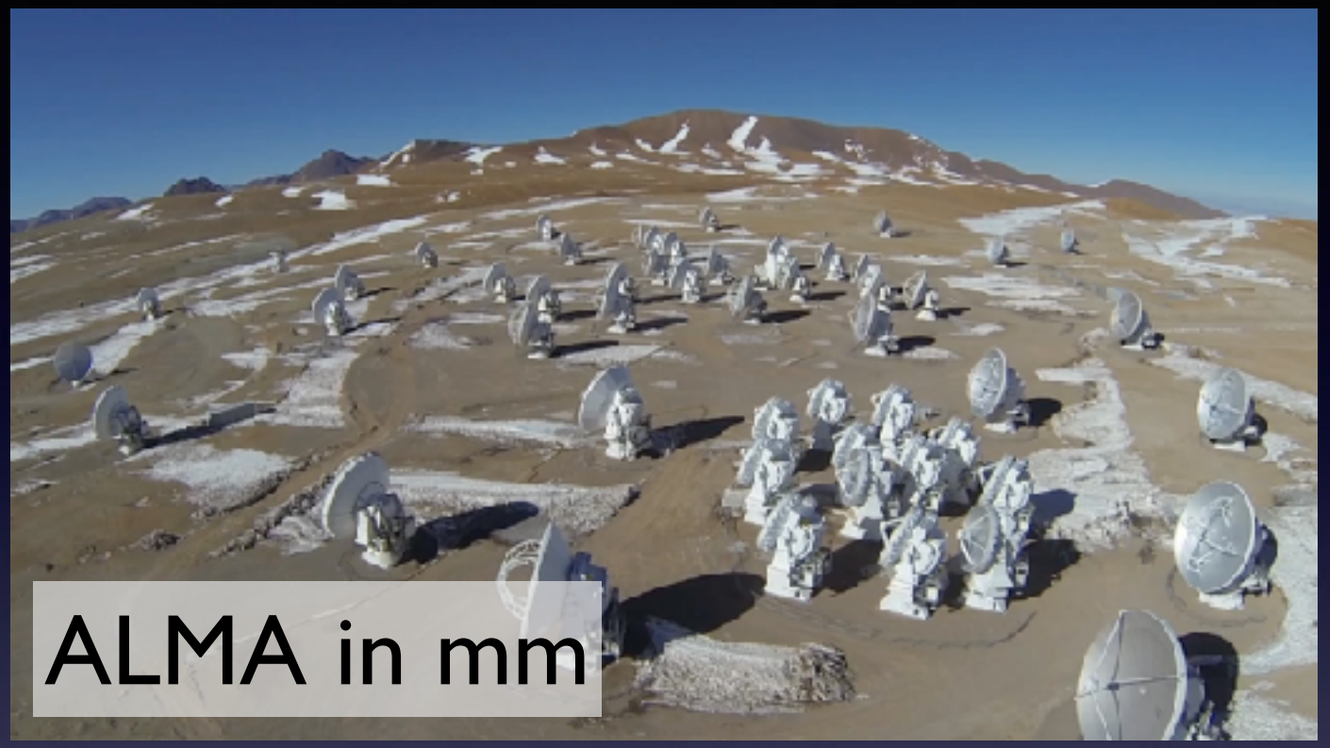
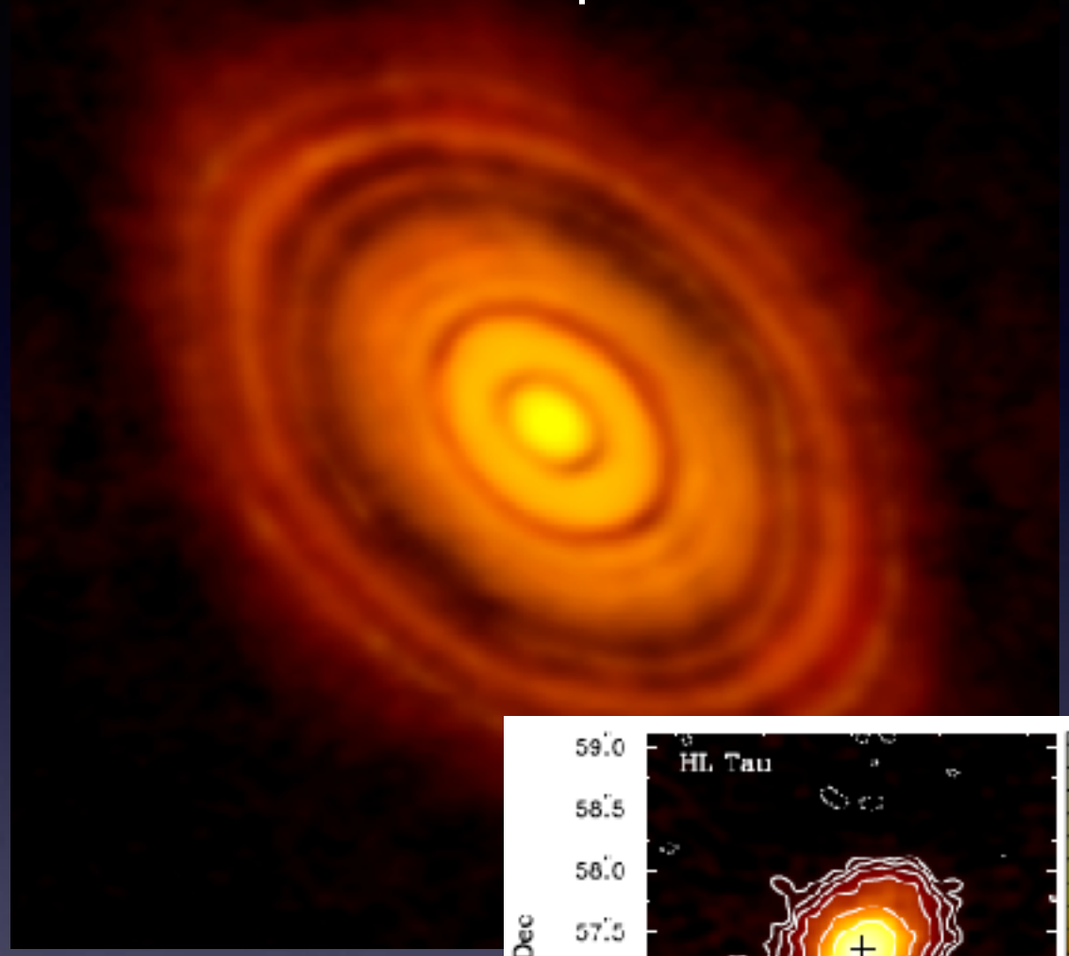
California Institute of Technology



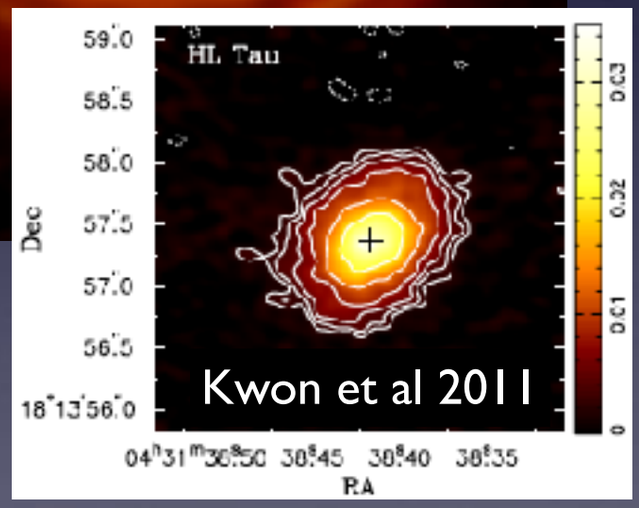
1. Evolution in Astronomical Disk Observations



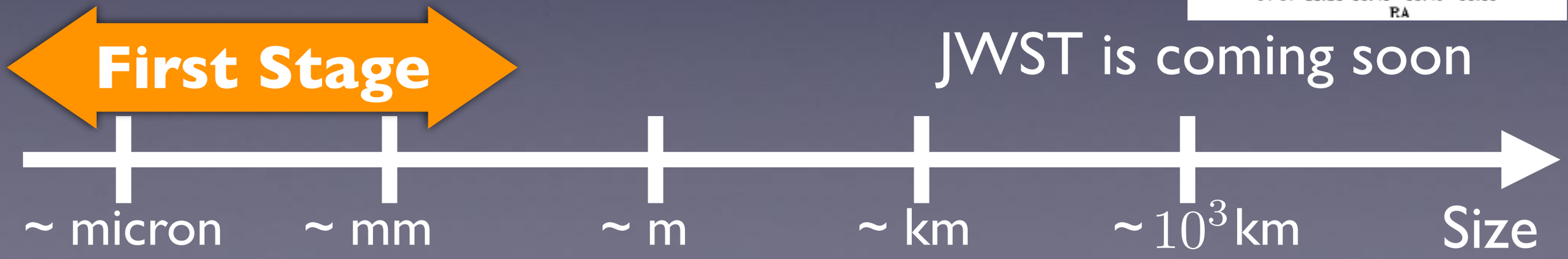
ALMA Partnership et al 2015



We can **see** planet-forming regions

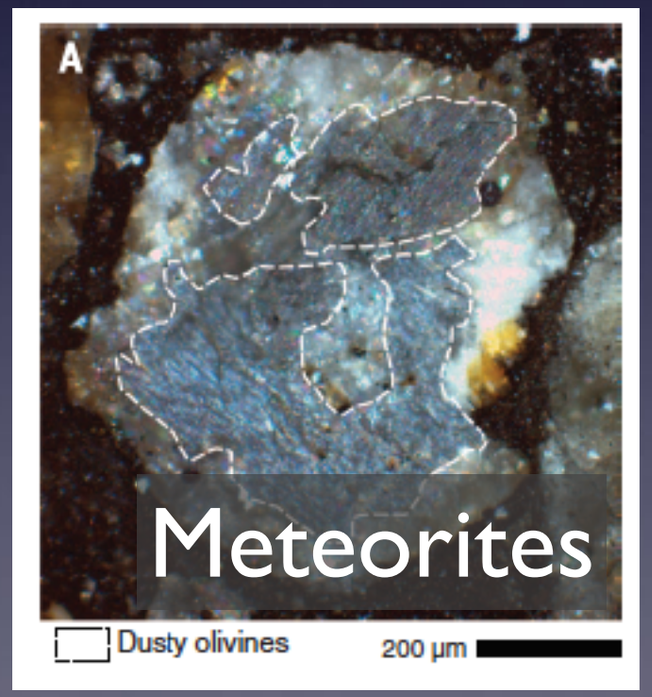


JWST is coming soon



2. Evolution in Space Engineering & Lab Experiments

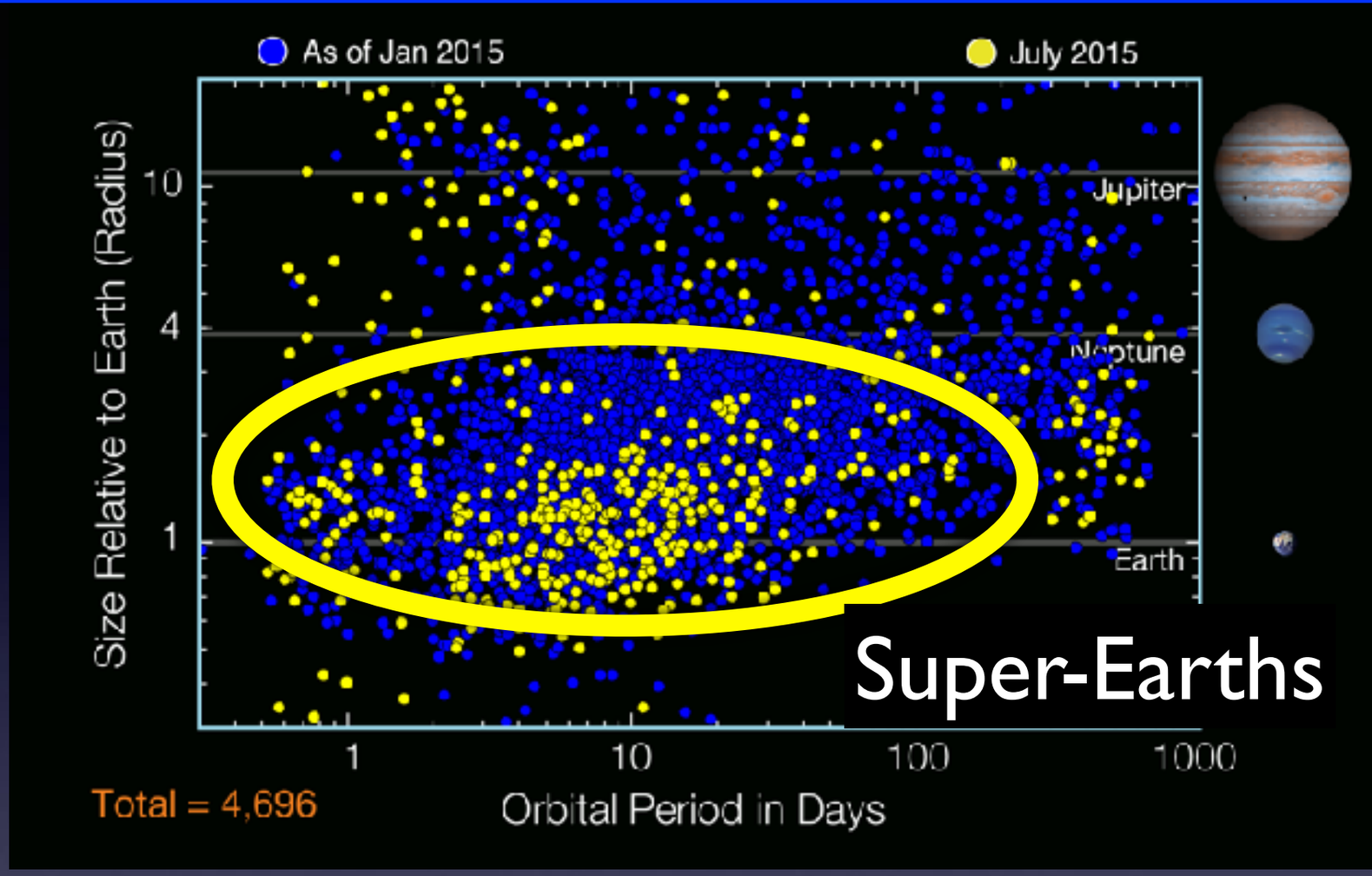
We can **touch** planet-forming materials



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

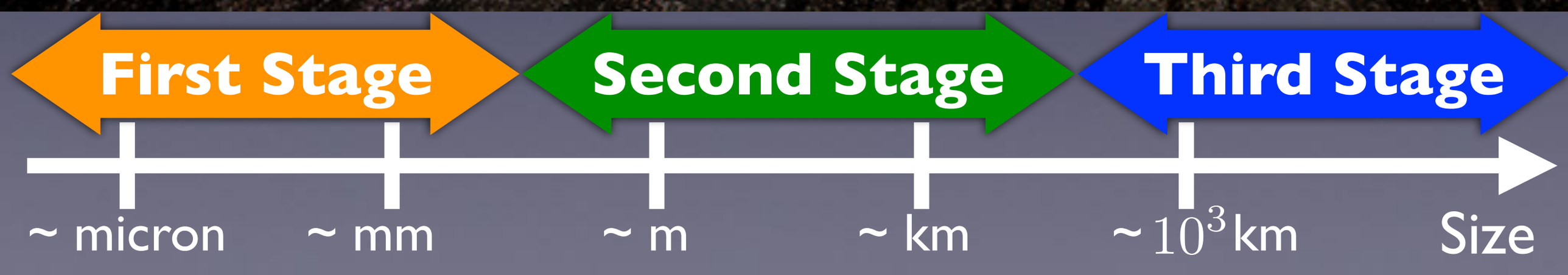
Third Stage

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

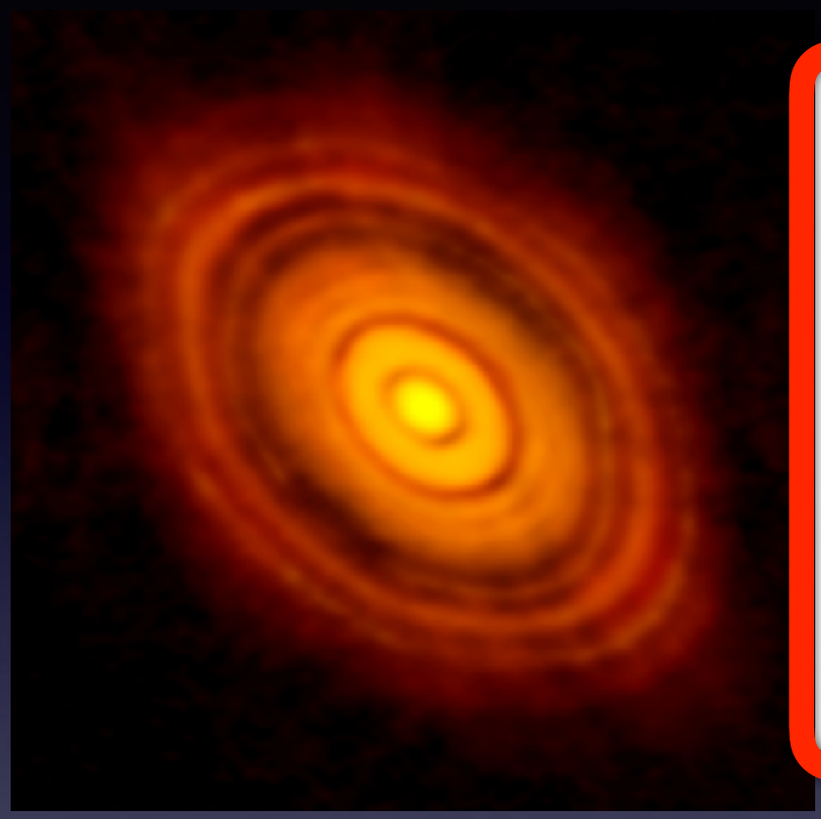
Planet formation: Long journey from dust to planets

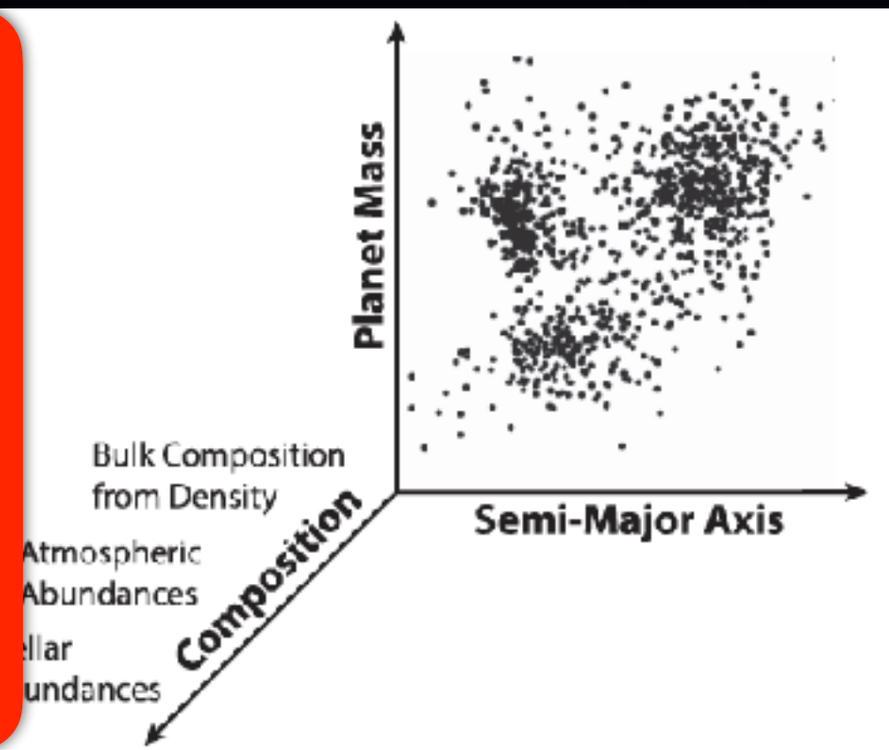
Golden era of (exo)planetary sciences

A Comprehensive Examination of Planet Formation Covering the Full Size Range

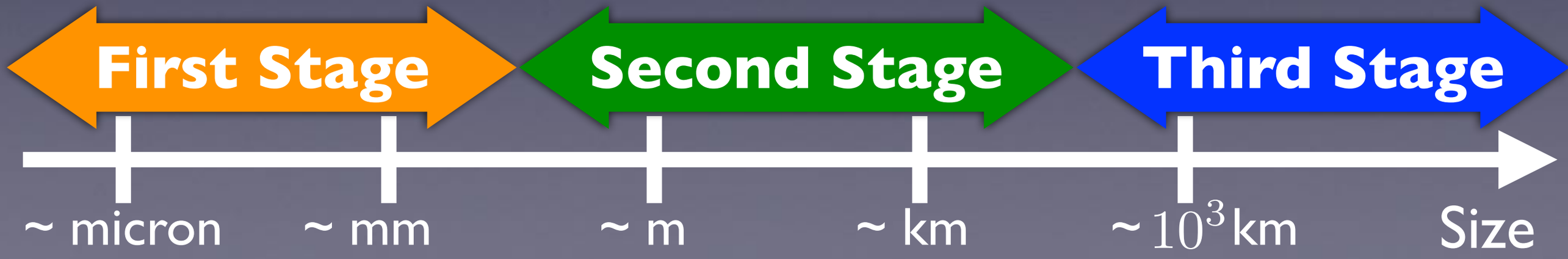


A Comprehensive Examination of Planet Formation





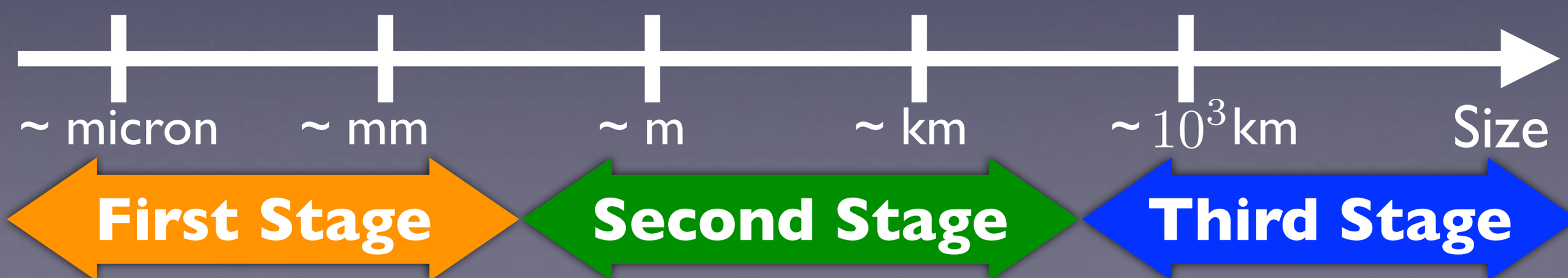
in collaboration with
Shigeru Wakita (ELSI), Yuji Matsumoto (ASIAA), Shoichi Oshino (NAOJ)

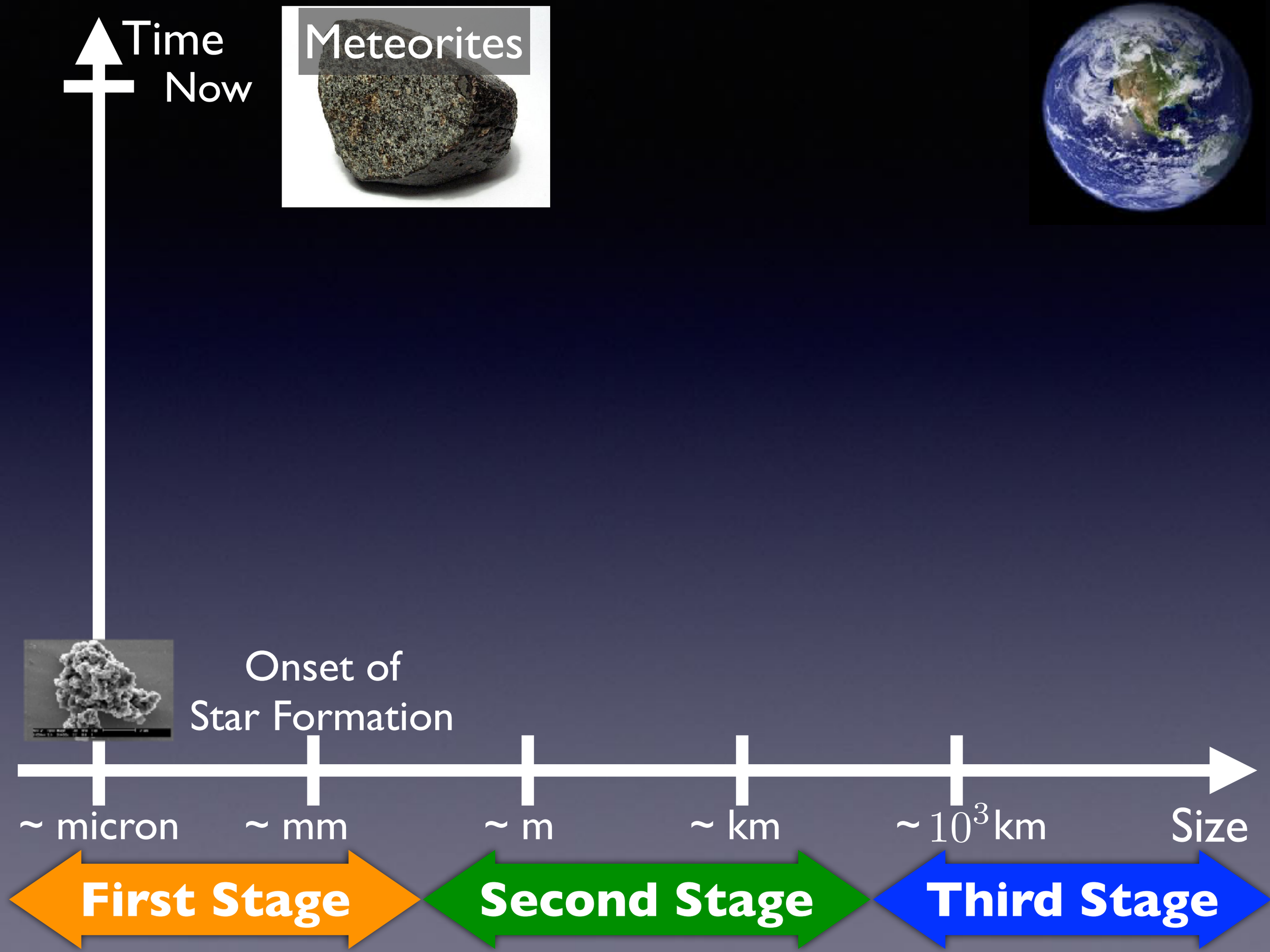


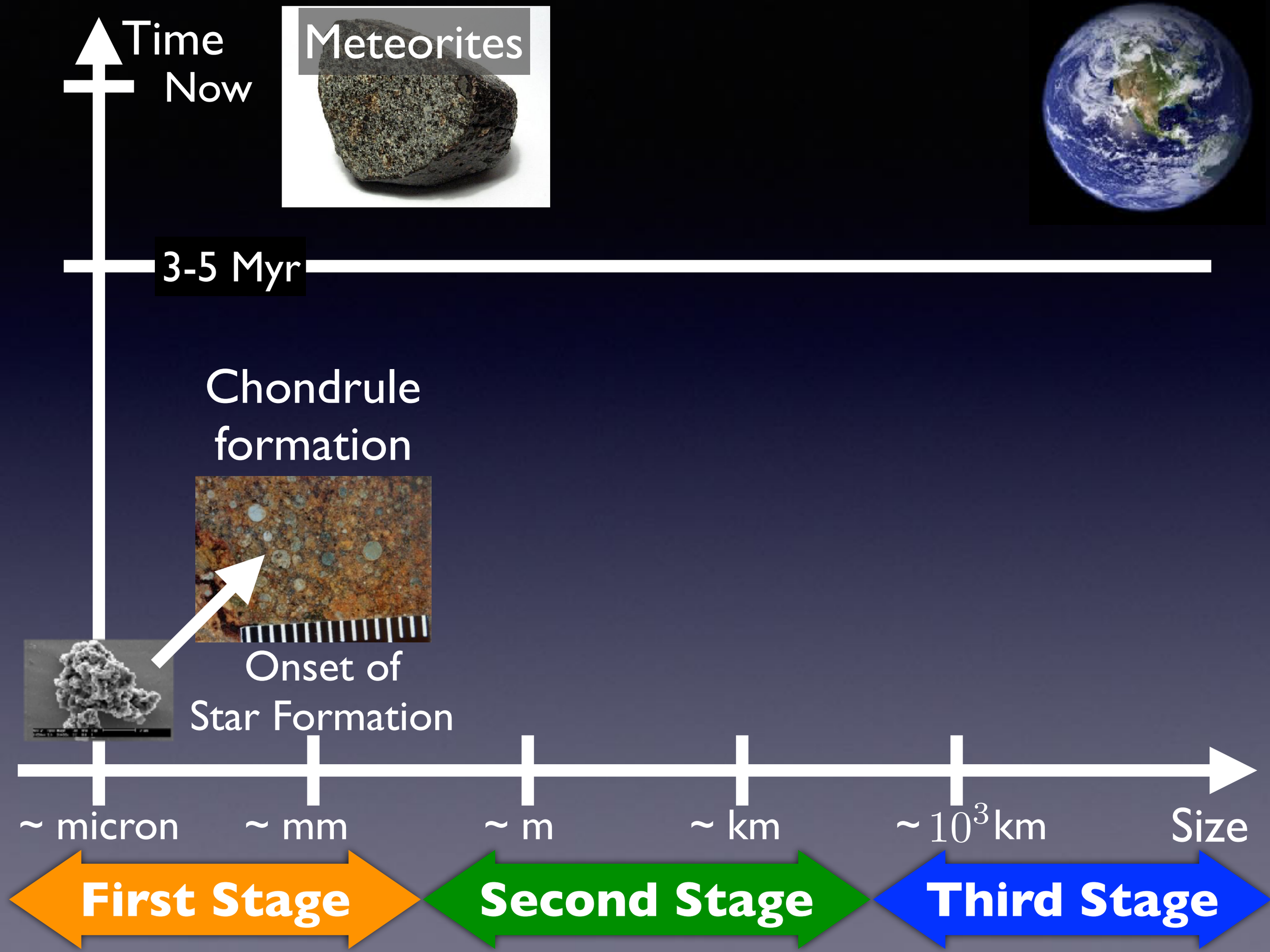
Chondrules: the primitive material in the solar system

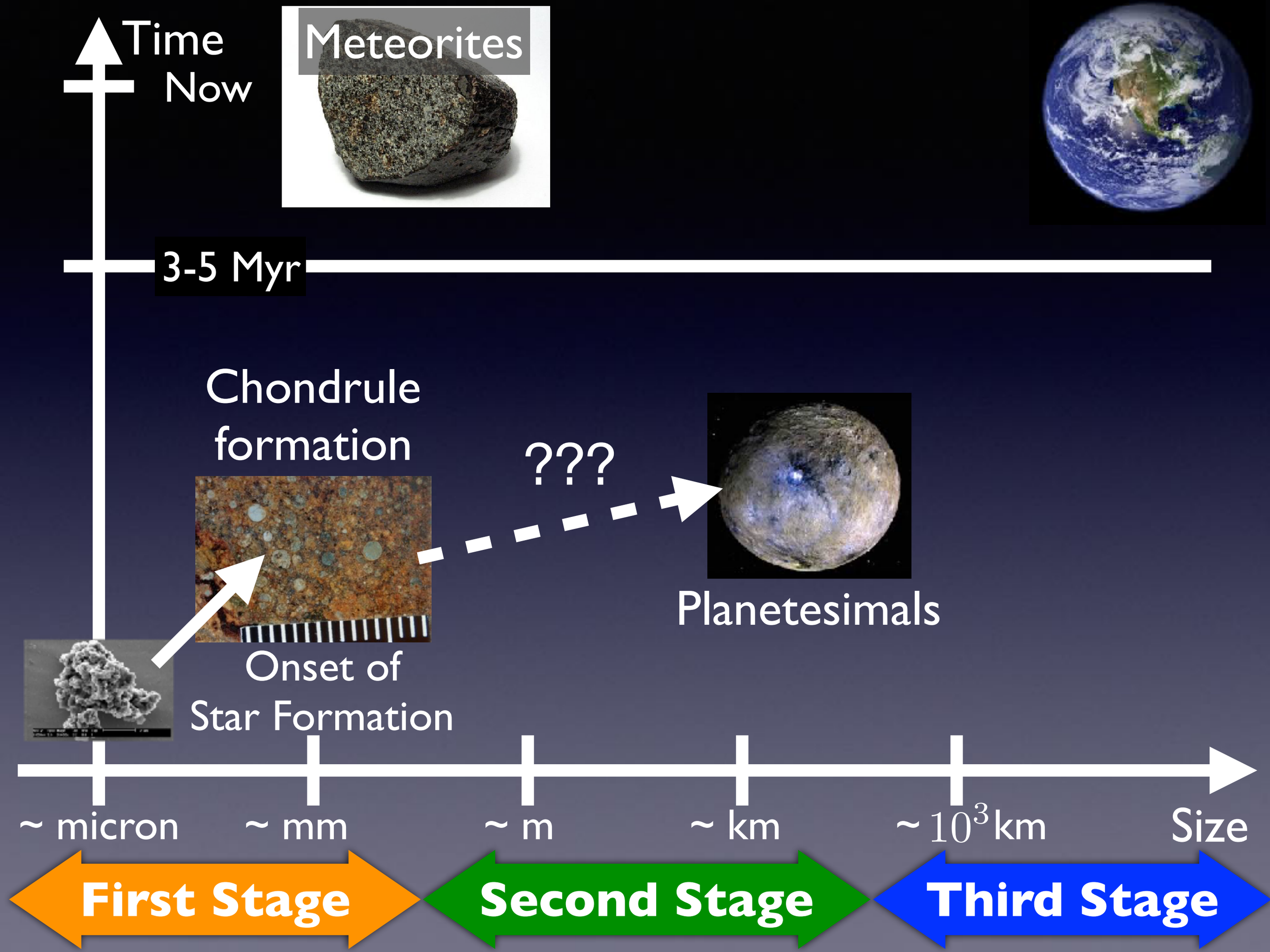
Chondrules are abundant in chondrites that are one class of meteorites

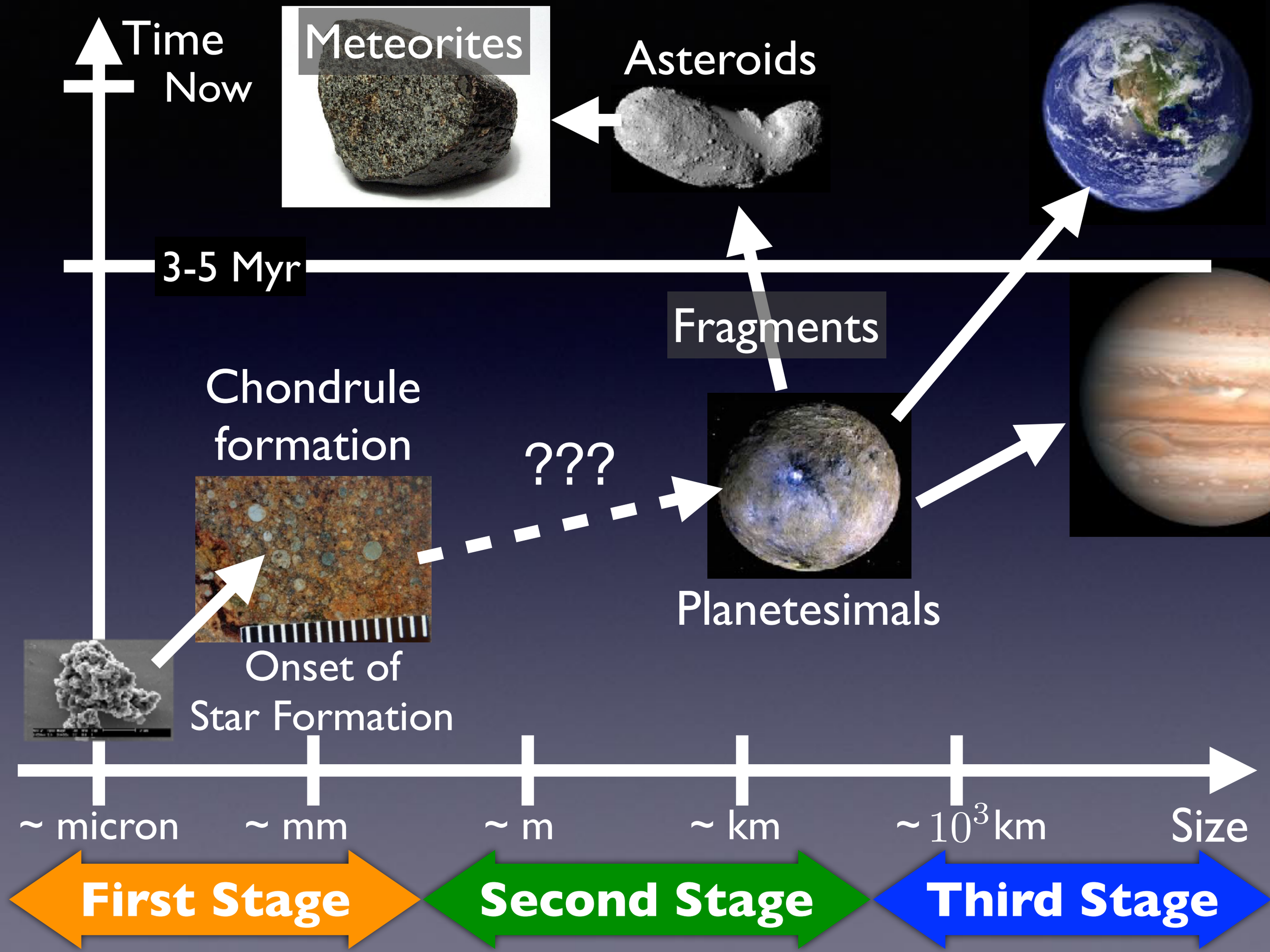
kept forming for **3-5 Myr** after CAI formation began, which is 4.567 Gyr ago

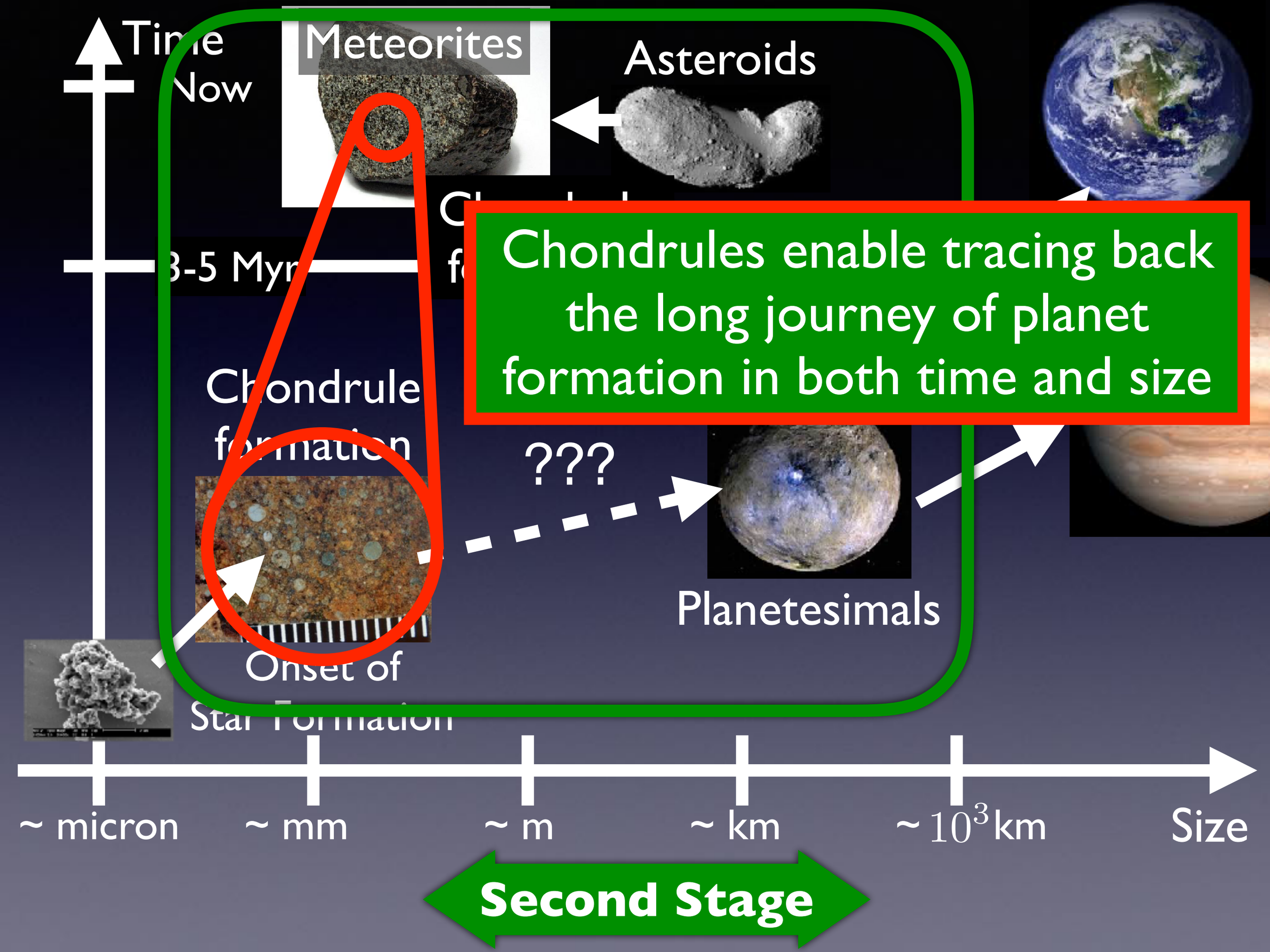

~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
First Stage
Second Stage
Third Stage


Time
Now
Meteorites
Onset of
Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
First Stage
Second Stage
Third Stage


Time
Now
Meteorites
3-5 Myr
Chondrule formation
Onset of Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
First Stage
Second Stage
Third Stage


Time
Now
Meteorites
3-5 Myr
Chondrule formation
???
Planetesimals
Onset of Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
First Stage
Second Stage
Third Stage


Time
Now
Meteorites
Asteroids
3-5 Myr
Fragments
Chondrule formation
???
Planetesimals
Onset of Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
First Stage
Second Stage
Third Stage


Time
Now
Meteorites
Asteroids
3-5 Myr
Chondrule formation
???
Planetesimals
Onset of Star Formation
Chondrules enable tracing back the long journey of planet formation in both time and size
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
Second Stage

Current Picture of Planet Formation

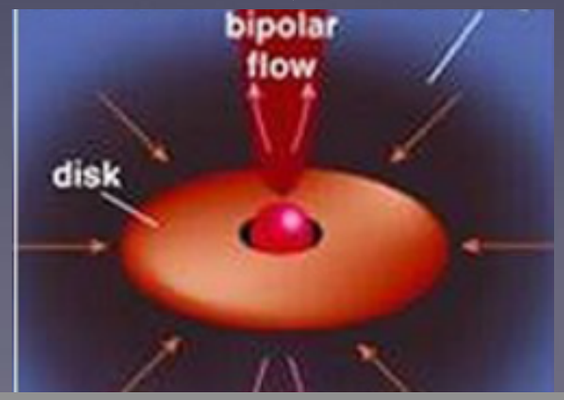
e.g., Hayashi 1981

NIR image of
Hubble Space Telescope

The Eagle Nebula
(d ~ 2000 pc)

Molecular Clouds

Gravitational
collapse

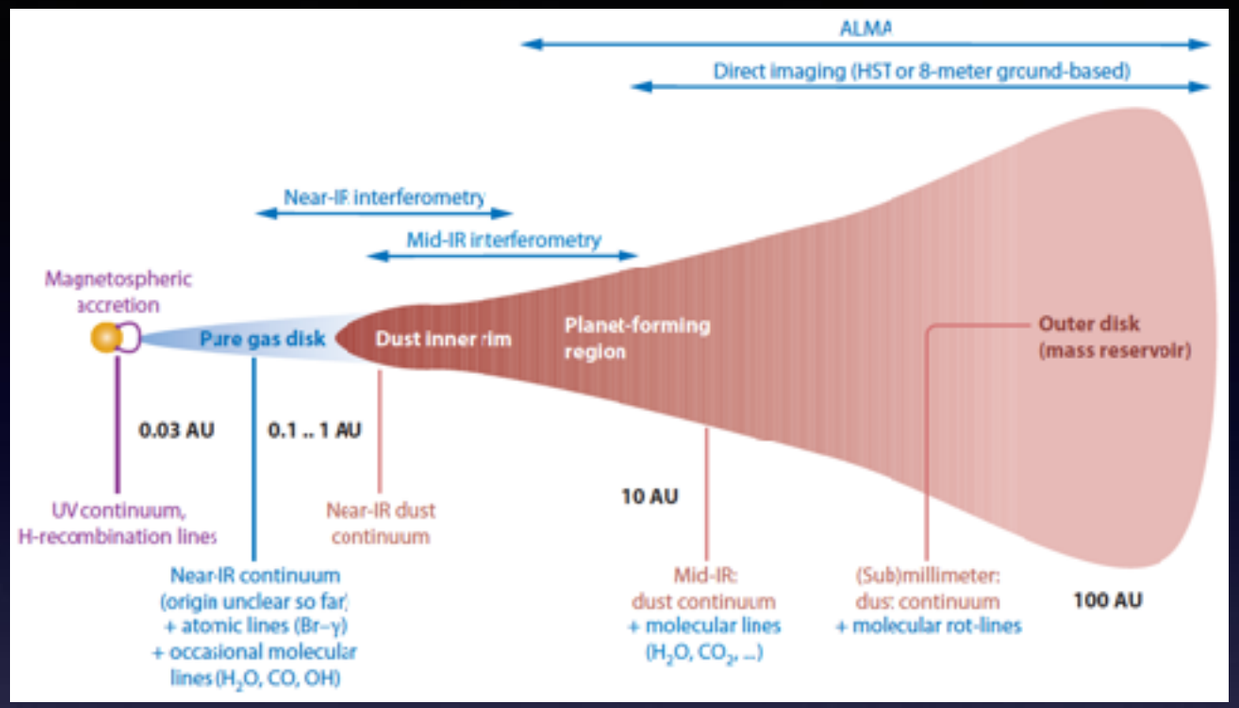


Circumstellar Disks

1 pc $= 3 \times 10^{18} cm$

Current Picture of Planet Formation

e.g., Hayashi 1981



$$M_{disk} \sim 10^{-2} M_{\odot}$$

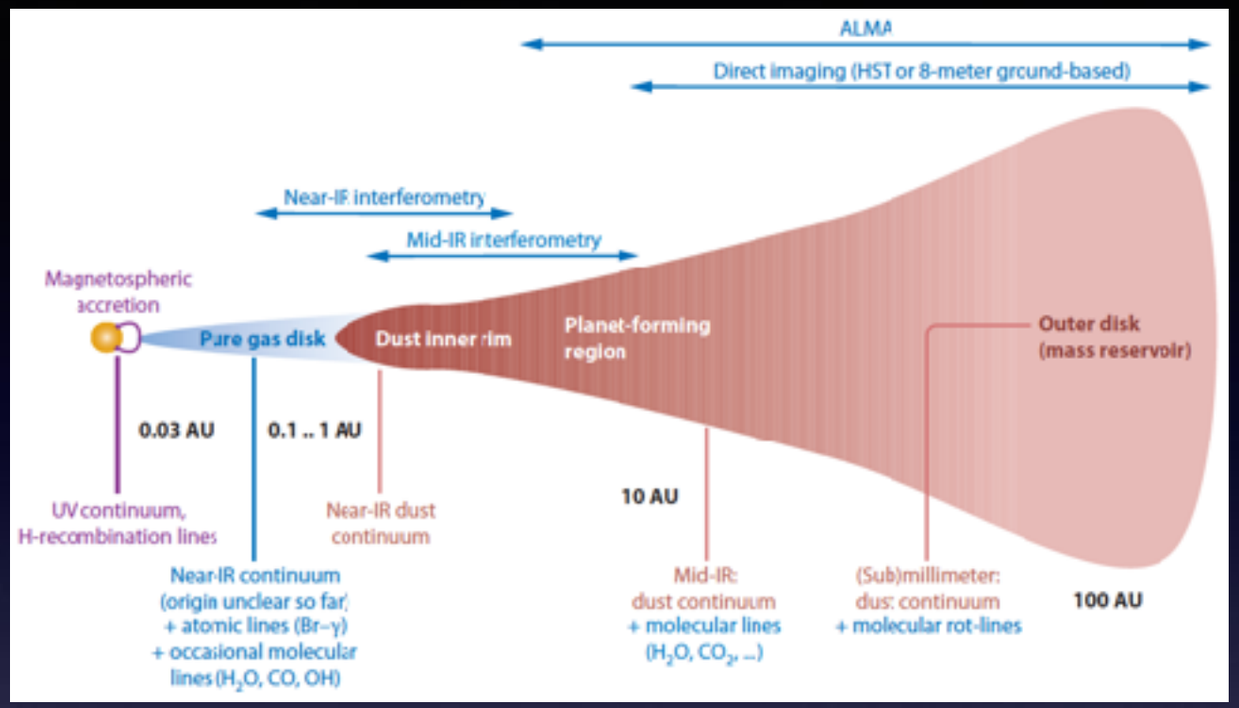
(: ~ 99% of gas and ~ 1% of dust)

$$\tau_{disk} \sim 10^{6} - 10^{7} yr$$

Disks are turbulent possibly by magnetic fields

Current Picture of Planet Formation

e.g., Hayashi 1981



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Disks are turbulent possibly by magnetic fields

At 1 au, $n \sim 10^{14} cm^{-3}$

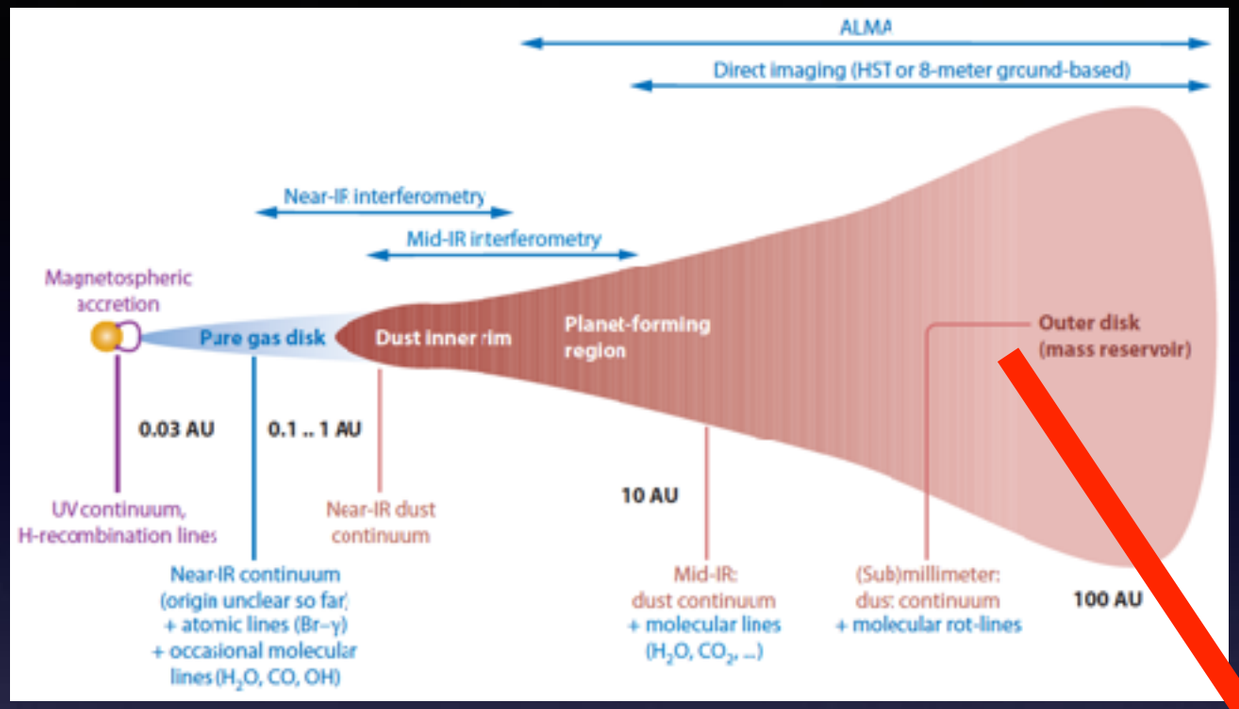
$T \sim 300K$

cf) the atmosphere of the Earth,

At 1 bar, $n \sim 10^{19} cm^{-3}$

Current Picture of Planet Formation

e.g., Hayashi 1981



$$M_{disk} \sim 10^{-2} M_{\odot}$$

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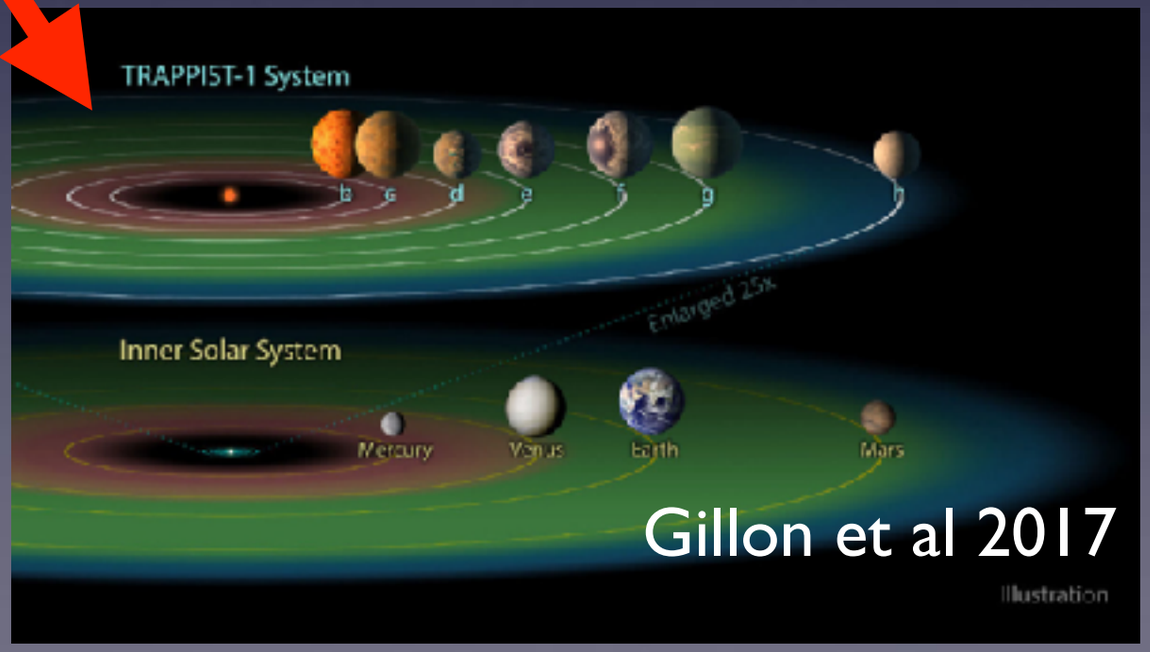
Disks are turbulent possibly by magnetic fields

10 -100 Myr



Gillon et al 2017

At 1 au, $n \sim 10^{14} cm^{-3}$

$T \sim 300K$

cf) the atmosphere of the Earth,

At 1 bar, $n \sim 10^{19} cm^{-3}$

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

abundant in chondrites
(up to 80 % by volume)

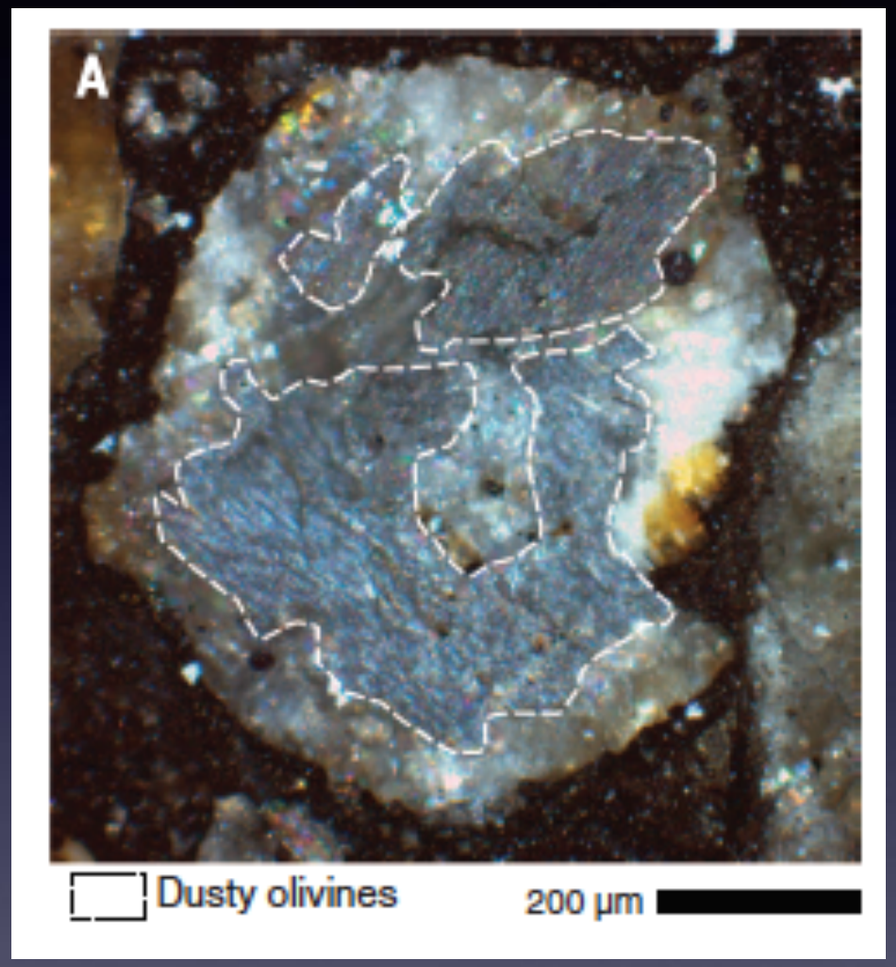
~1mm sized spherical particles
formed as molten droplets
of silicate (T ~ 1800K)

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)



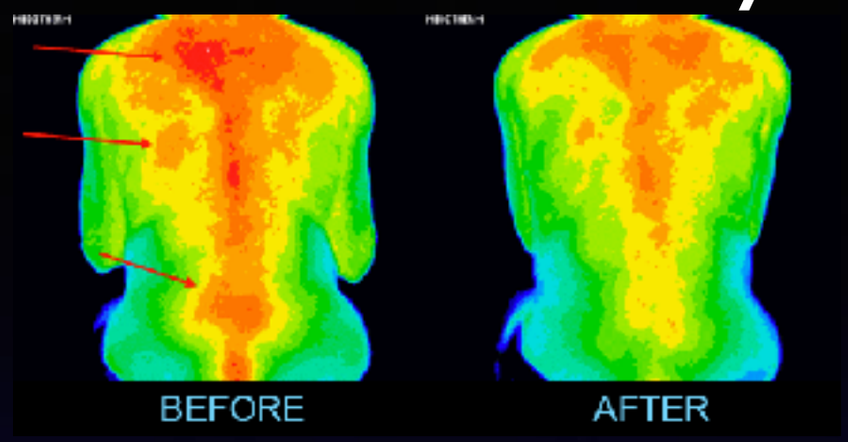
Fu et al 2014

Semarkona meteorite
: primitive, ordinary chondrite

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

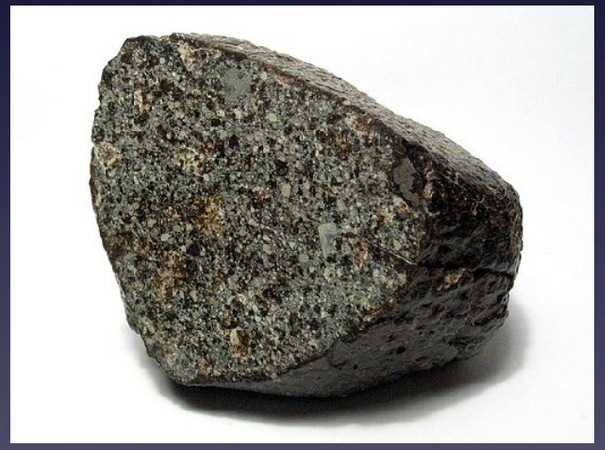
B-fields in the solar nebula were ~ 50 - 540 mG
=> Level of turbulence in the nebula can be estimated!!

Thermal History

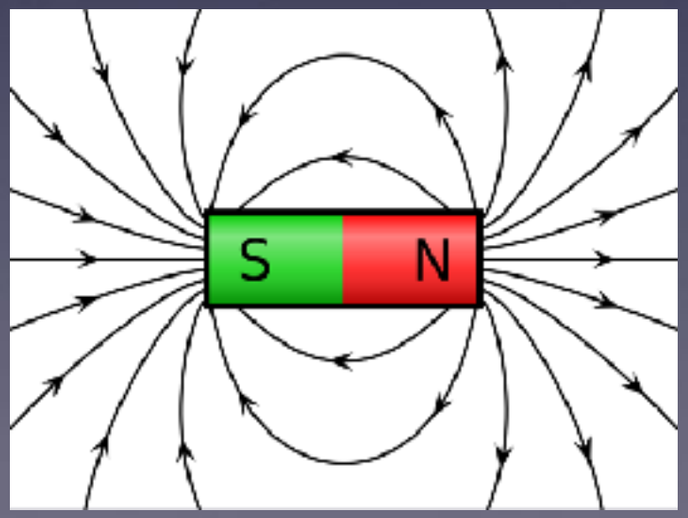


Abundance

Chondrule Formation & Accretion

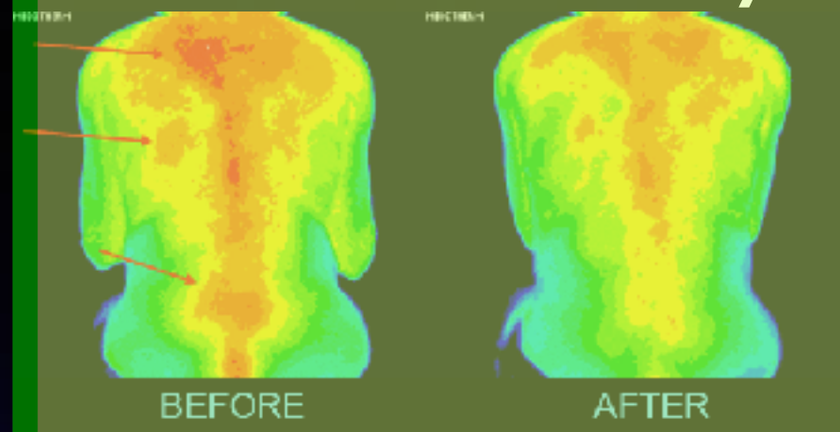


Timescale



B-fields

Thermal History



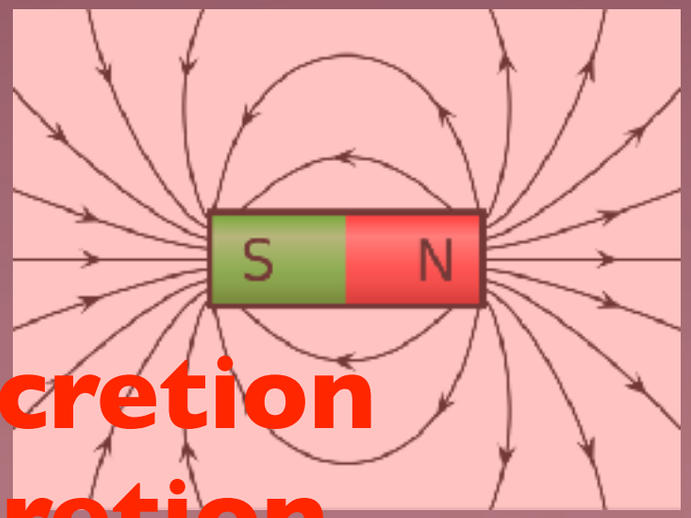
Abundance

Chondrule Formation
& Accretion

Chondrule Formation
= Impact Jetting

Timescale

Chondrule Accretion
= Pebble Accretion

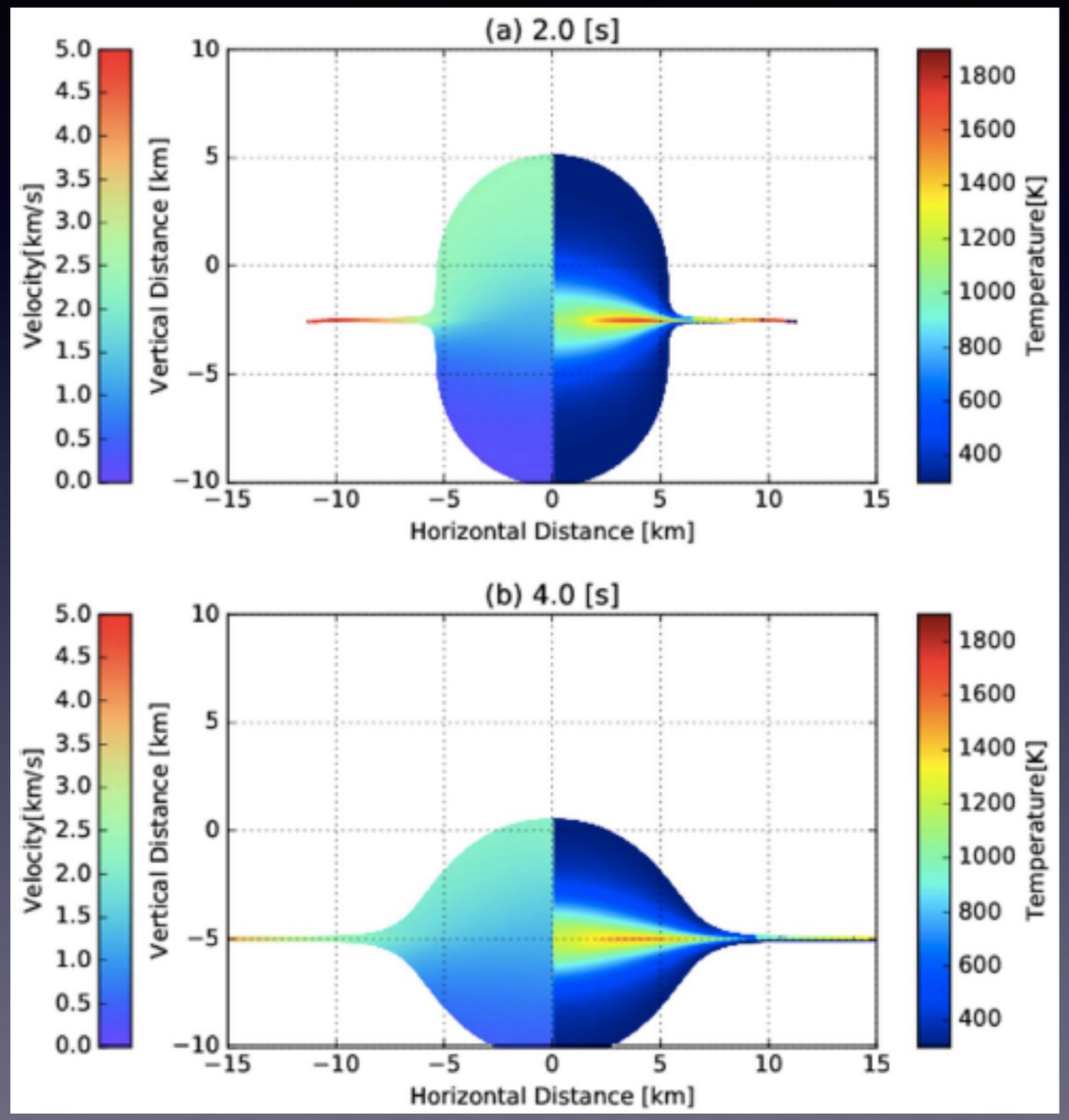


B-fields

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

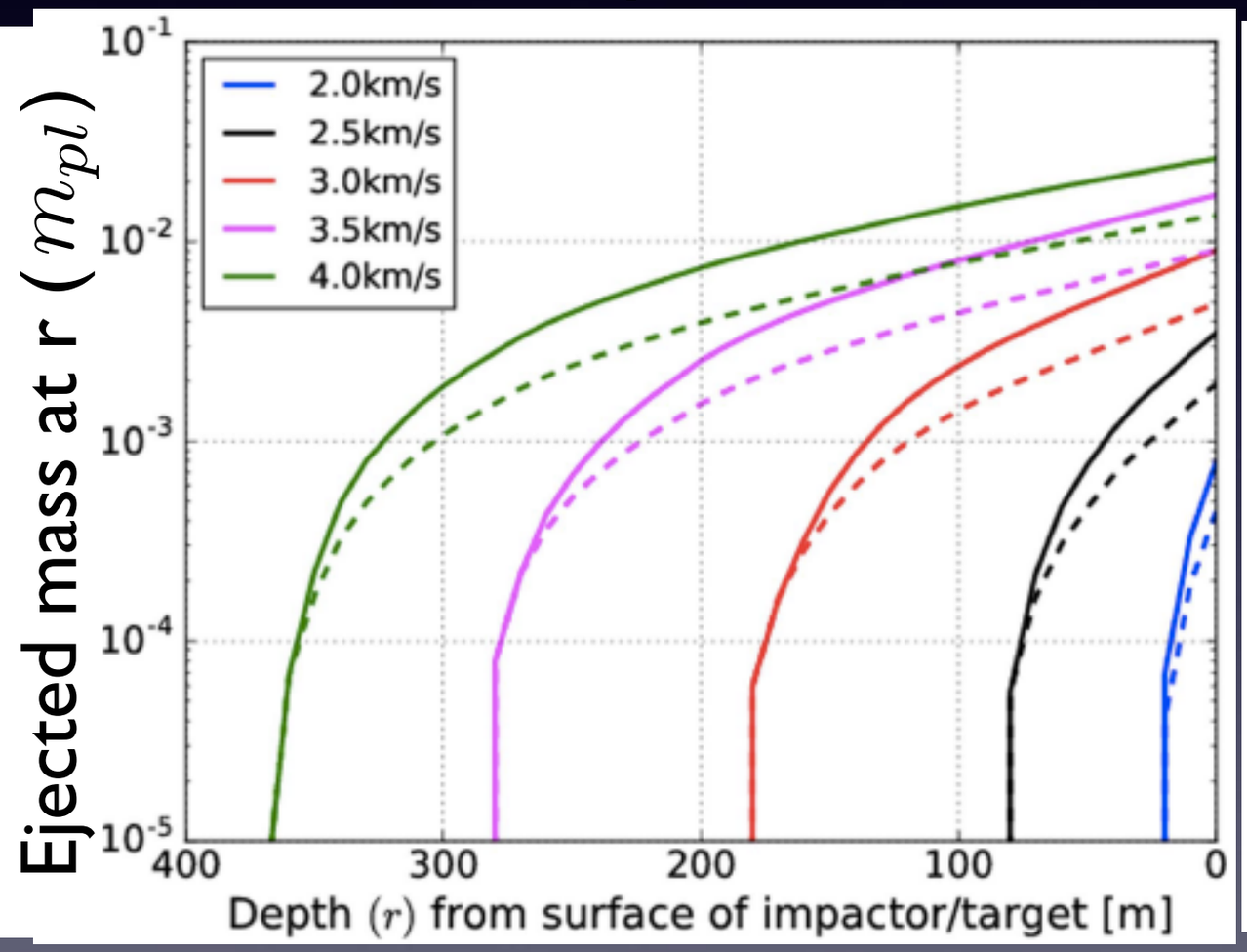
Some materials melt, and are ejected from the system

Such ejected materials may be a progenitor of chondrules

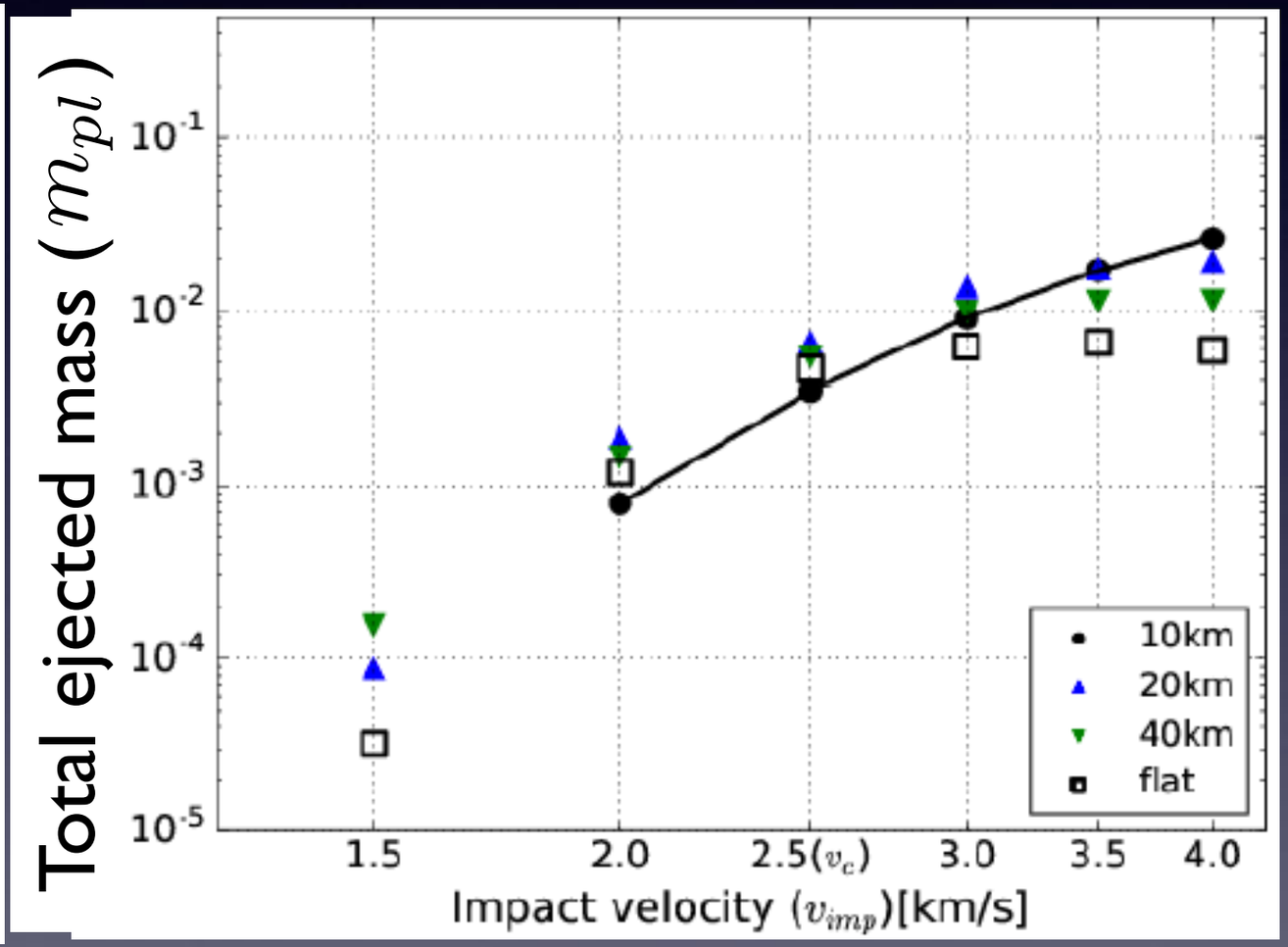
Parameter Study

Wakita et al 2017

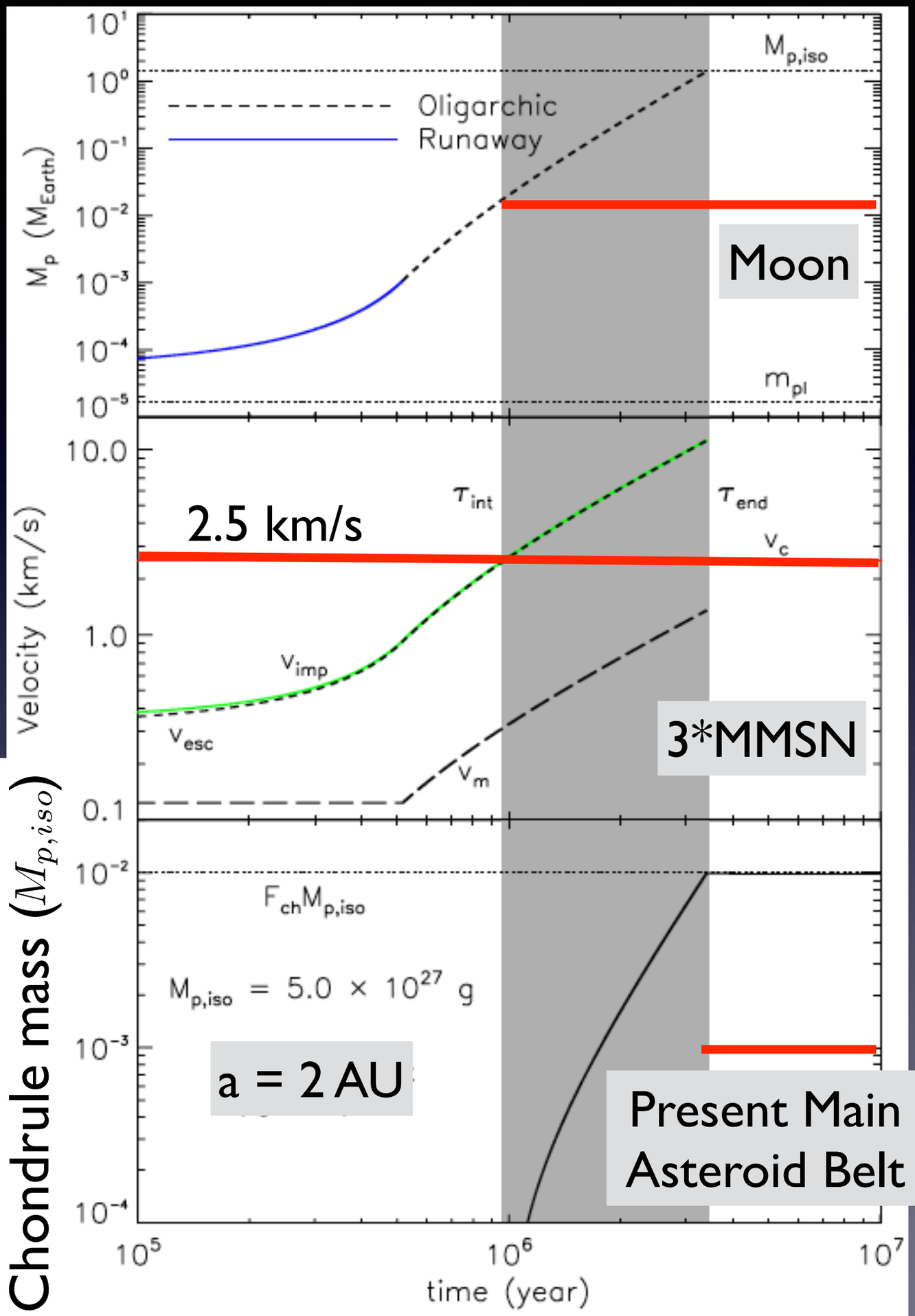
Collisions between 10 km sized planetesimals



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

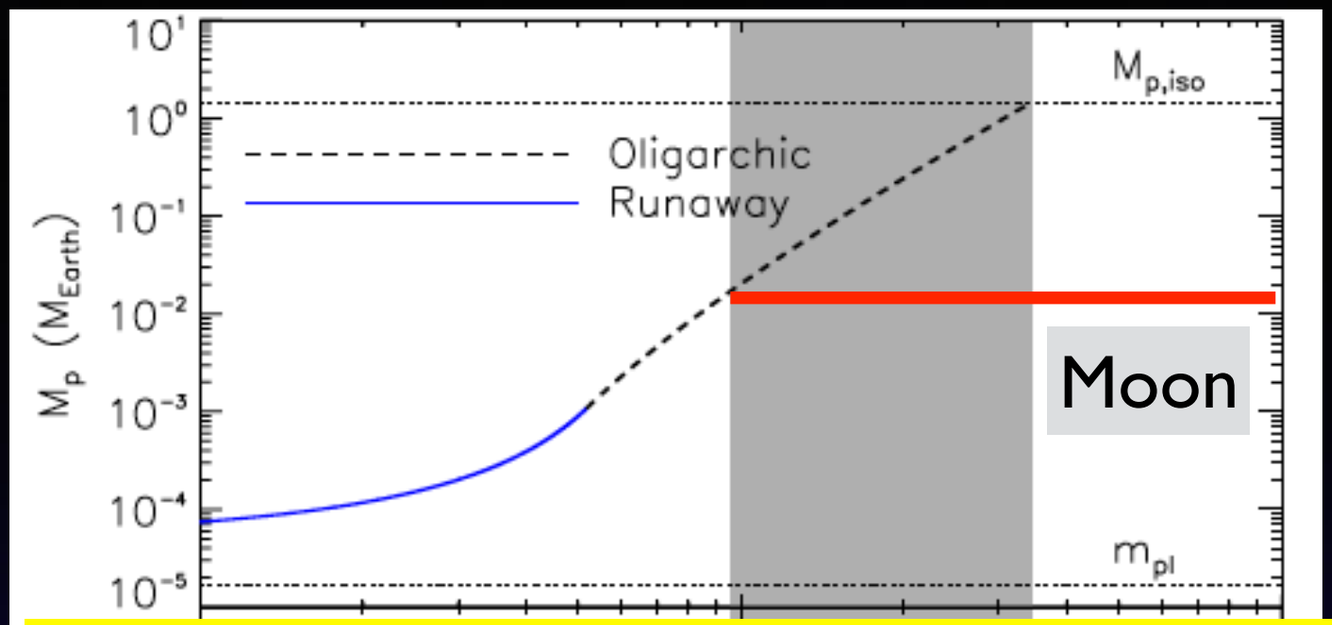
Chondrule-forming collisions occur at the hatched region

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

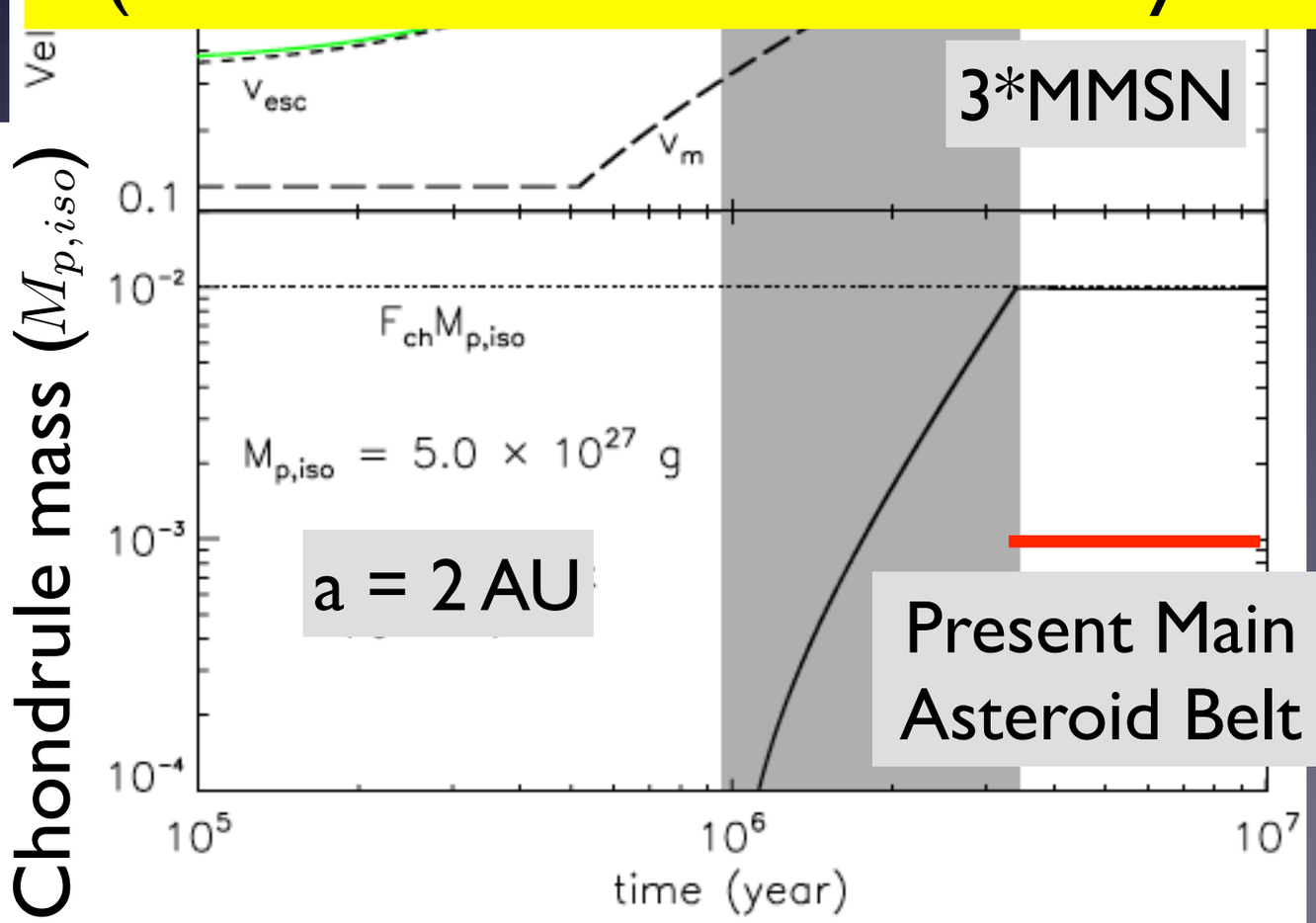
Hasegawa et al 2016a



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)



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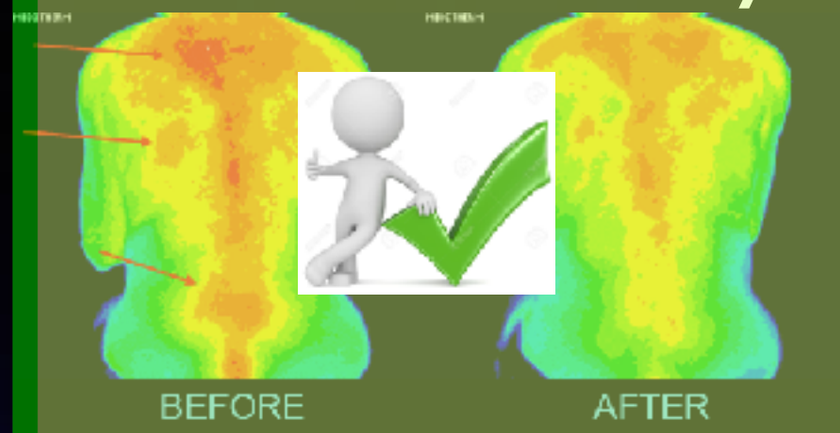
Thermal History



Abundance

Chondrule Formation
& Accretion

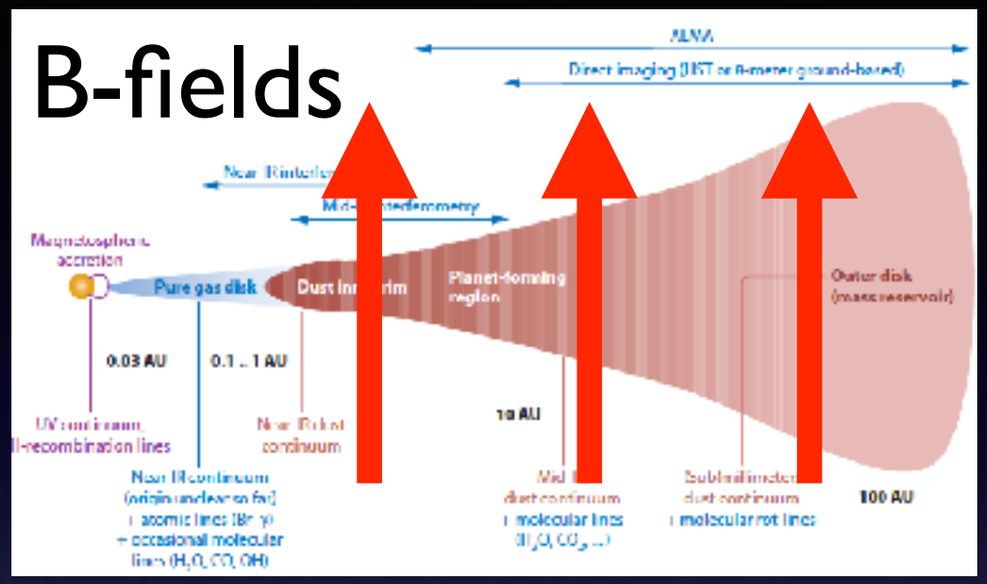
Chondrule Formation
= Impact Jetting

Timescale

B-fields

Chondrule Accretion
= Pebble Accretion

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



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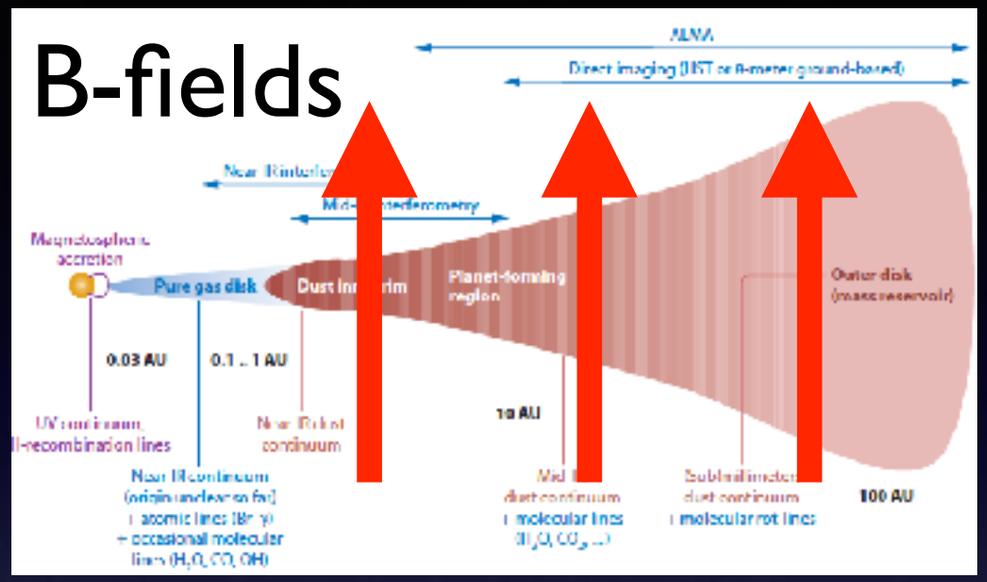
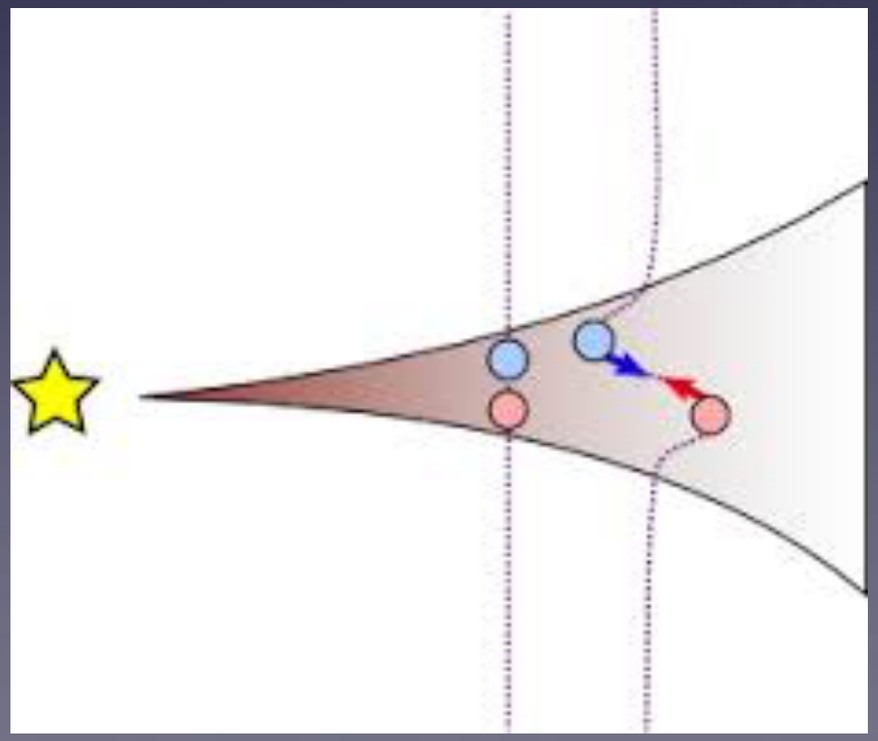
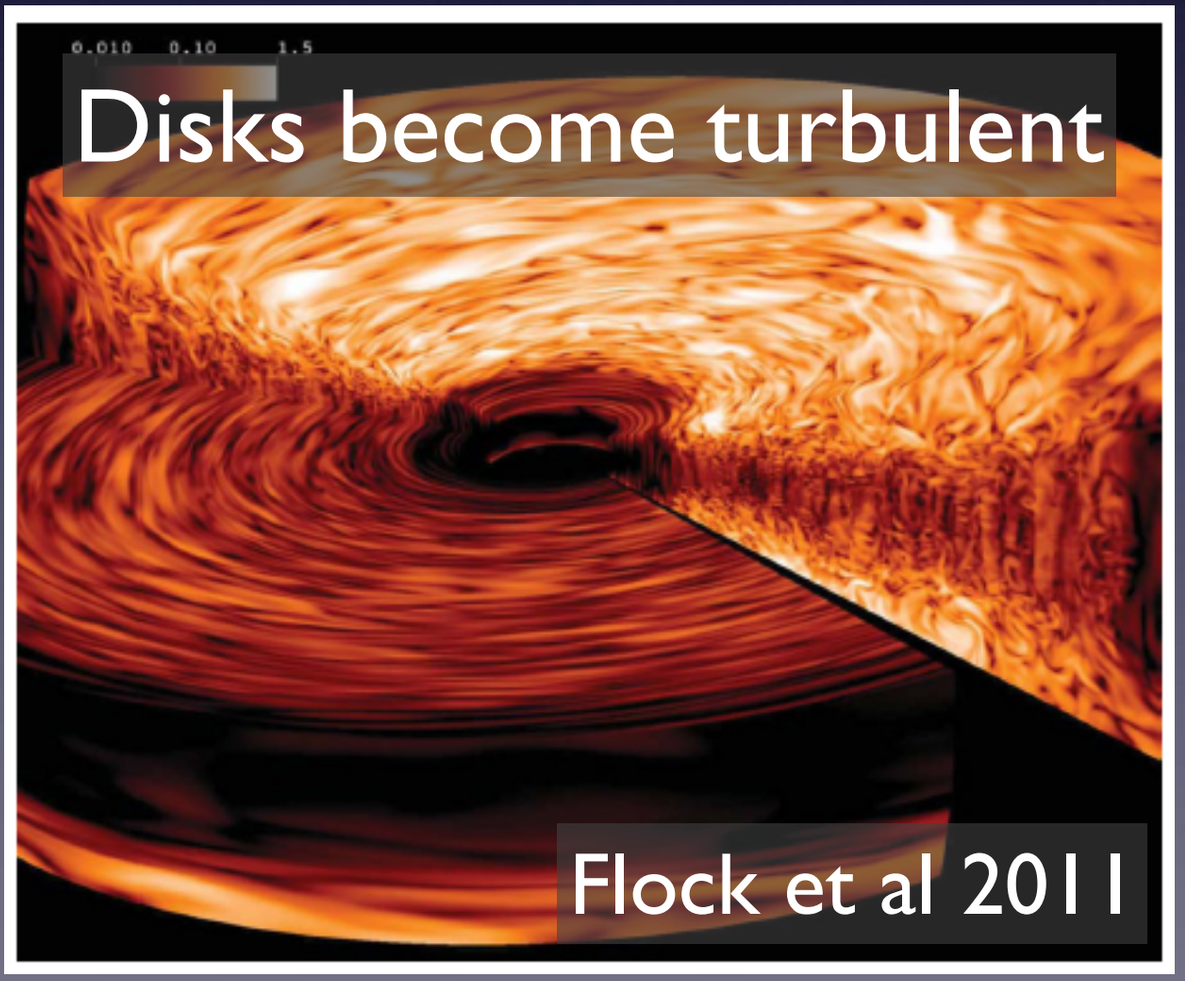


MagnetoRotational Instability (MRI) can operate

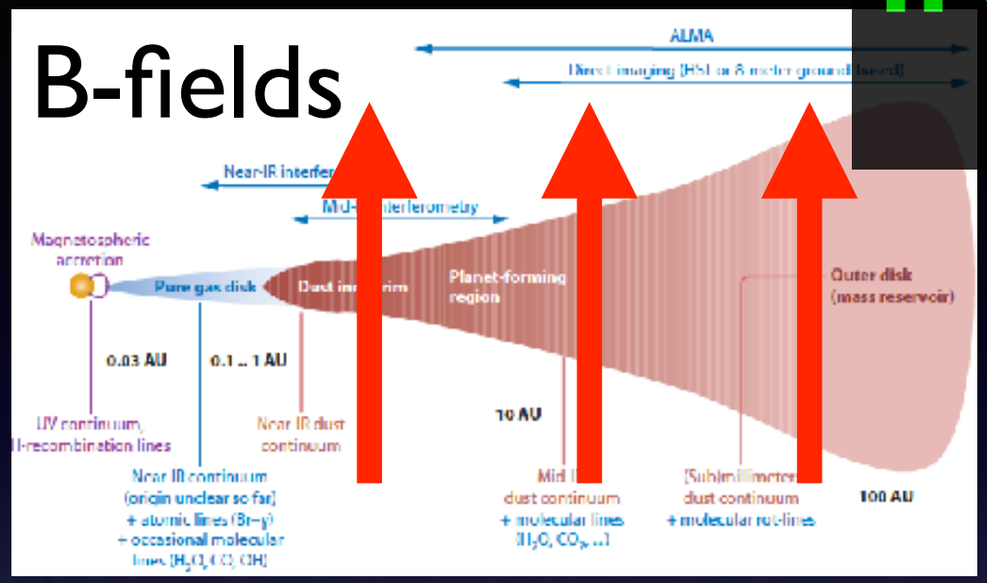


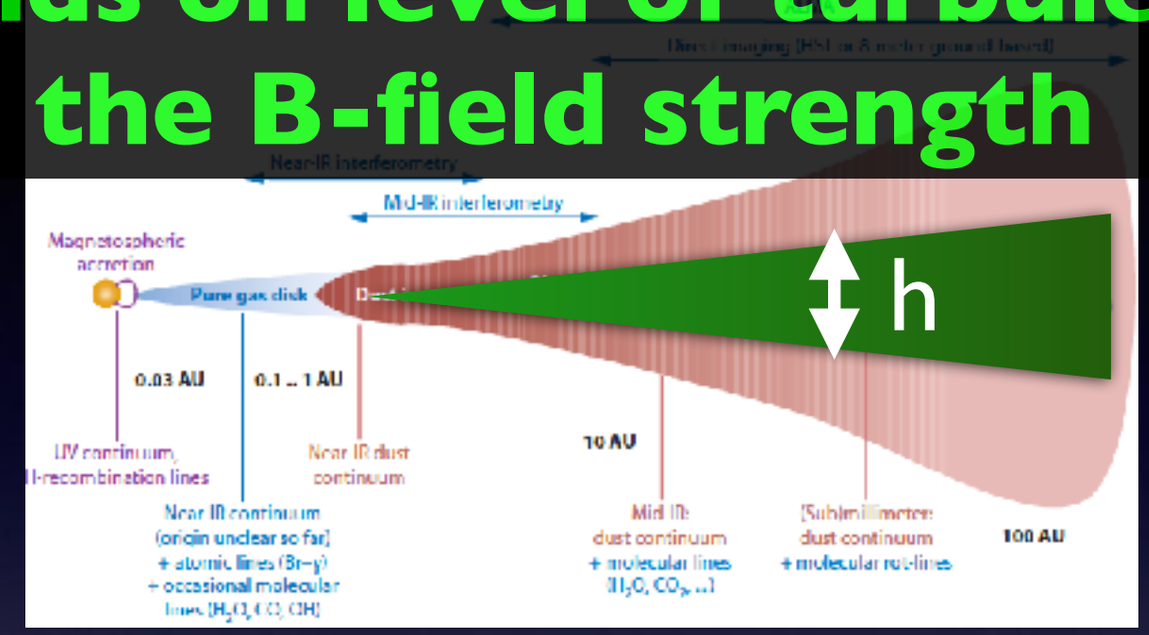


Lab results (magnetic fields) come into play!!!

h depends on level of turbulenc

so the B-field strength





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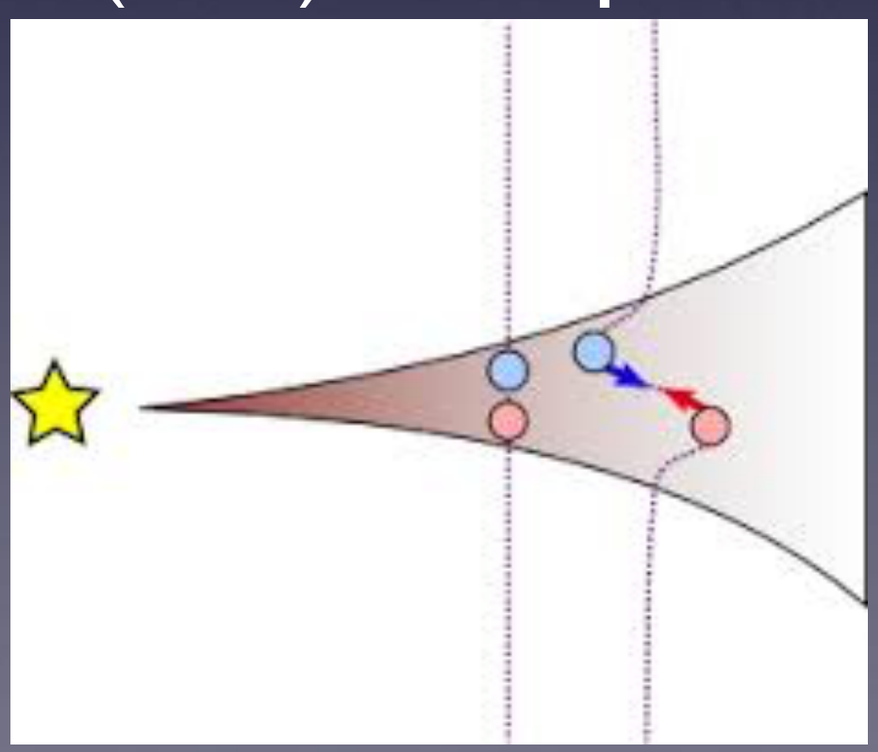
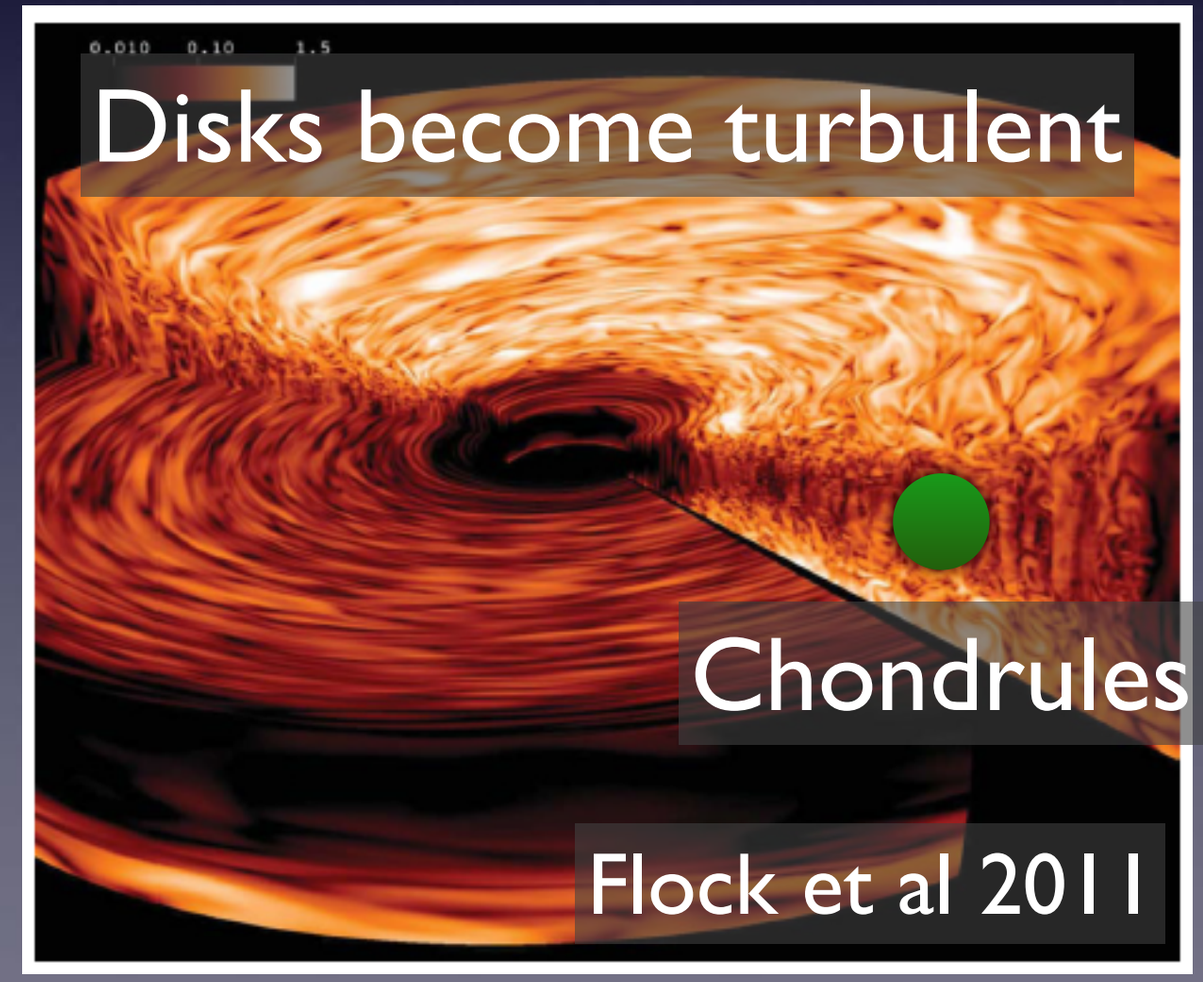
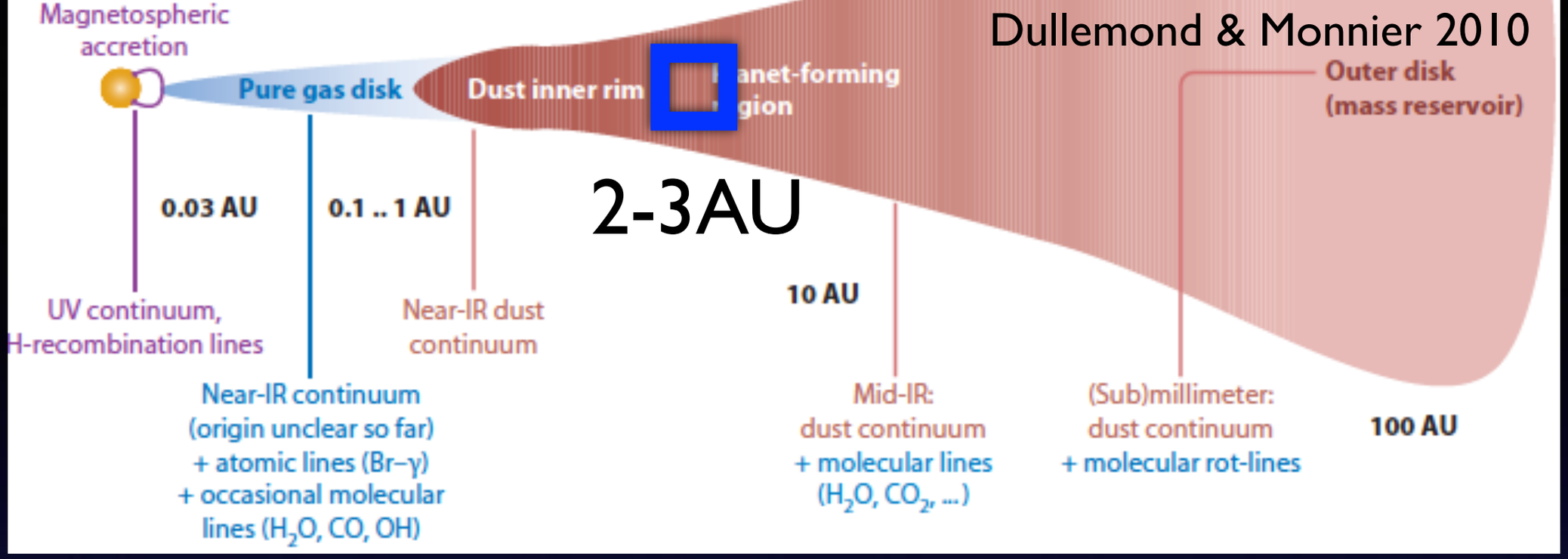
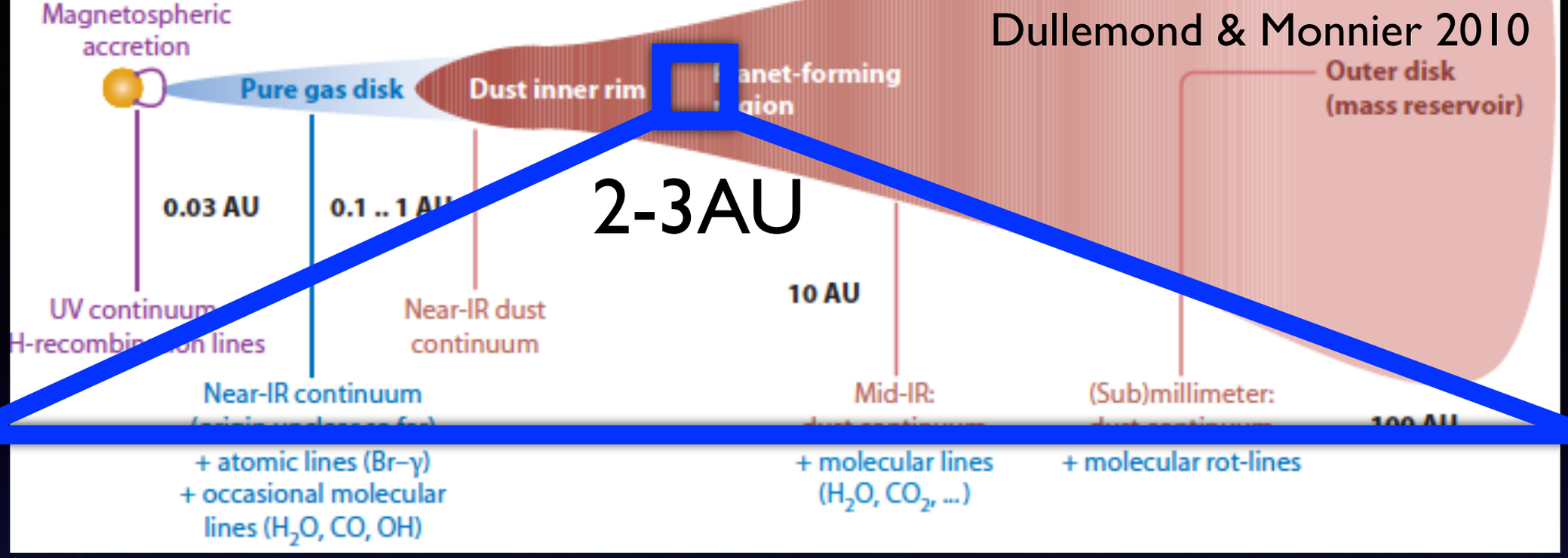
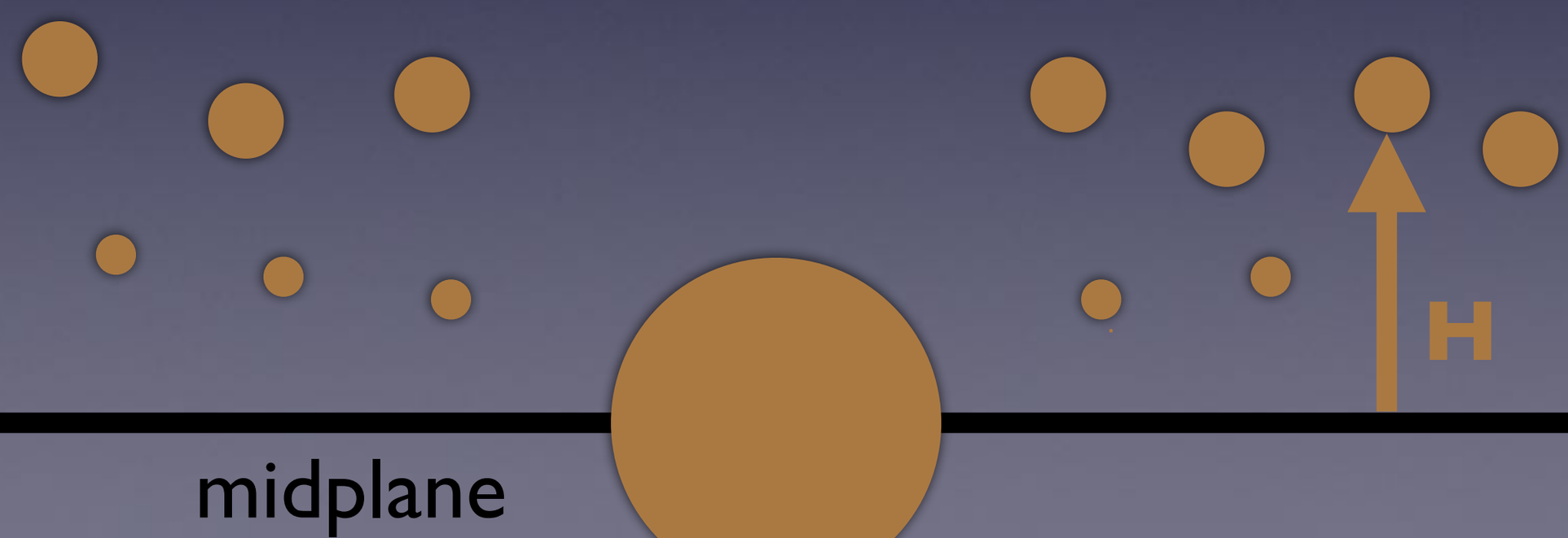


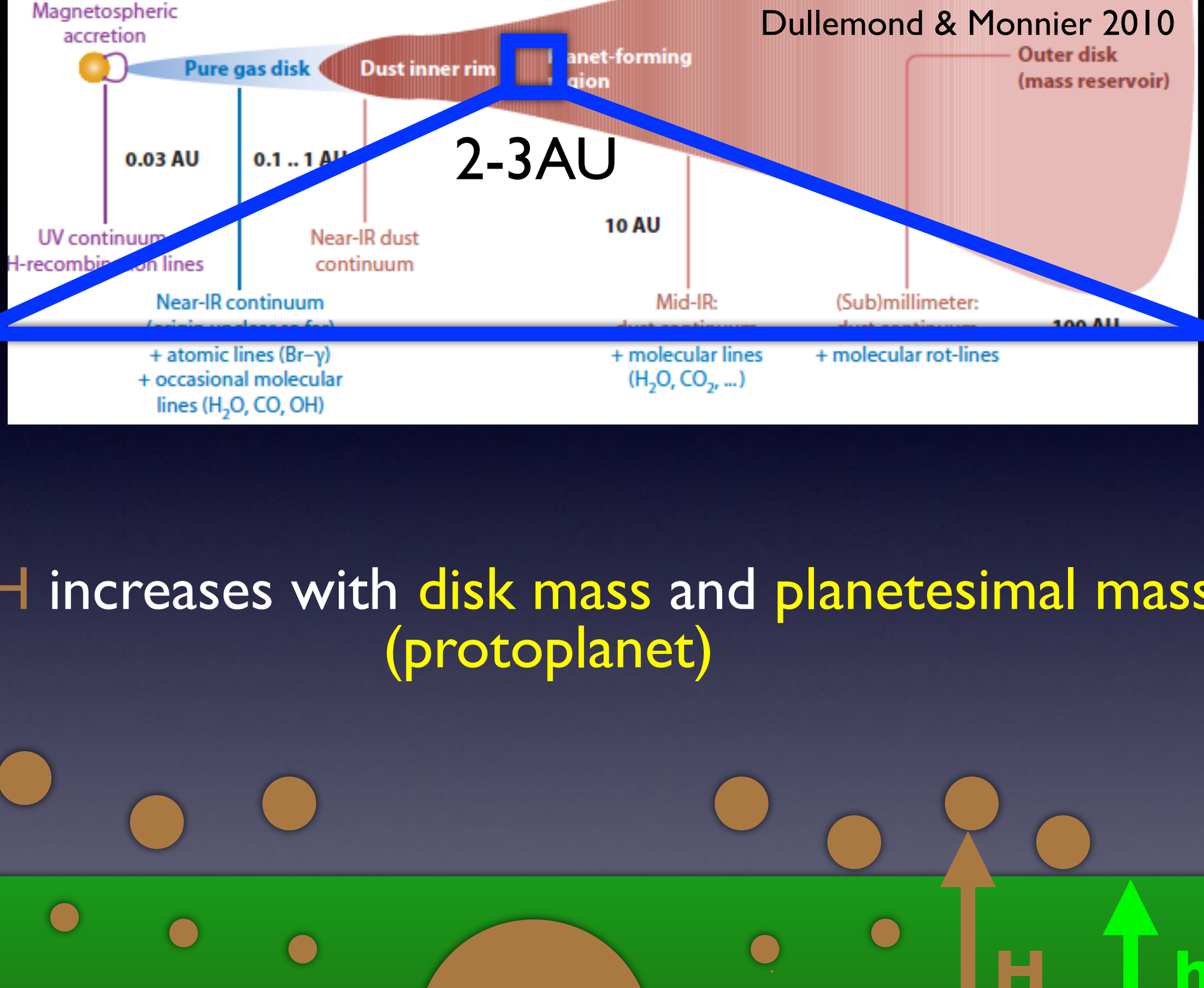



Dullemond & Monnier 2010
Magnetospheric accretion
Pure gas disk
Dust inner rim
anet-forming gion
Outer disk (mass reservoir)
2-3AU
0.03 AU
0.1 .. 1 AU
10 AU
100 AU
UV continuum, H-recombination lines
Near-IR dust continuum
Near-IR continuum (origin unclear so far) + atomic lines (Br–γ) + occasional molecular lines (H_2O, CO, OH)
Mid-IR: dust continuum + molecular lines (H_2O, CO_2, ...)
(Sub)millimeter: dust continuum + molecular rot-lines

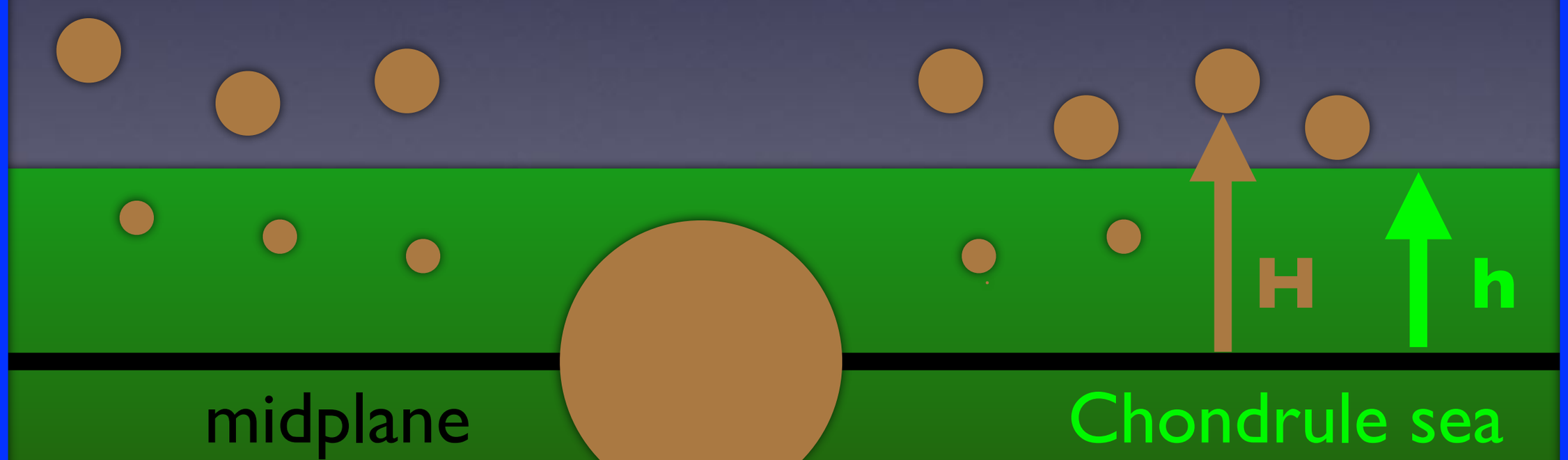


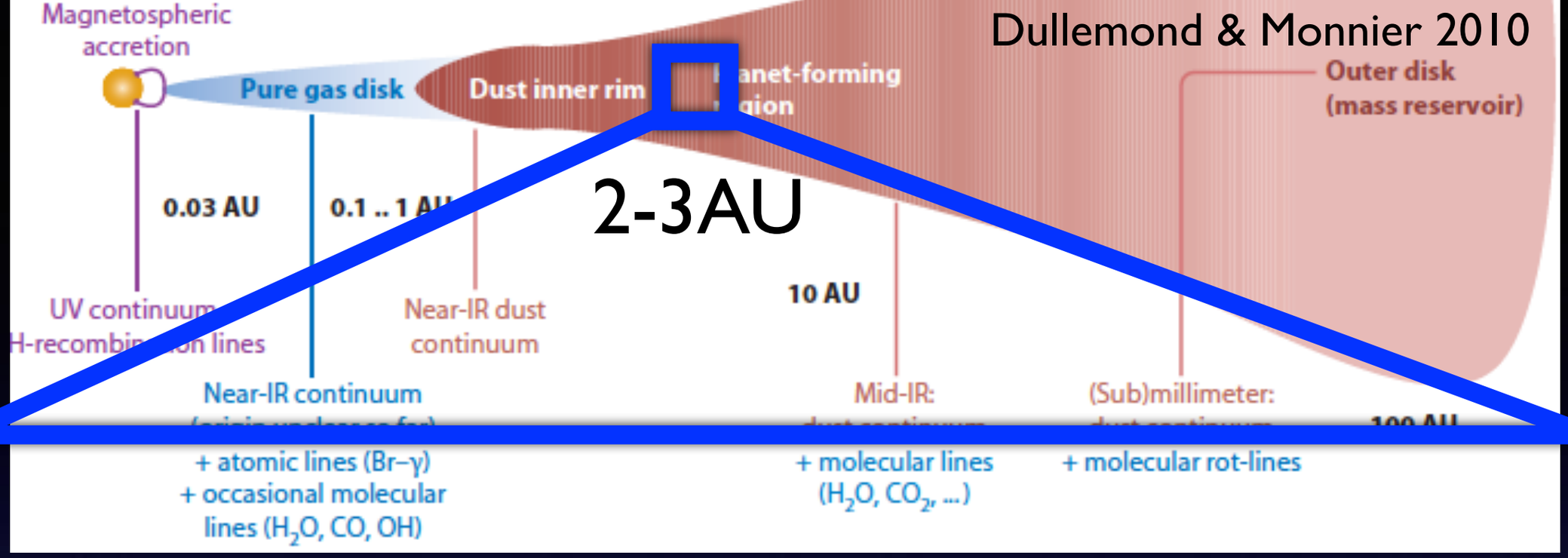
H increases with disk mass and planetesimal mass (protoplanet)





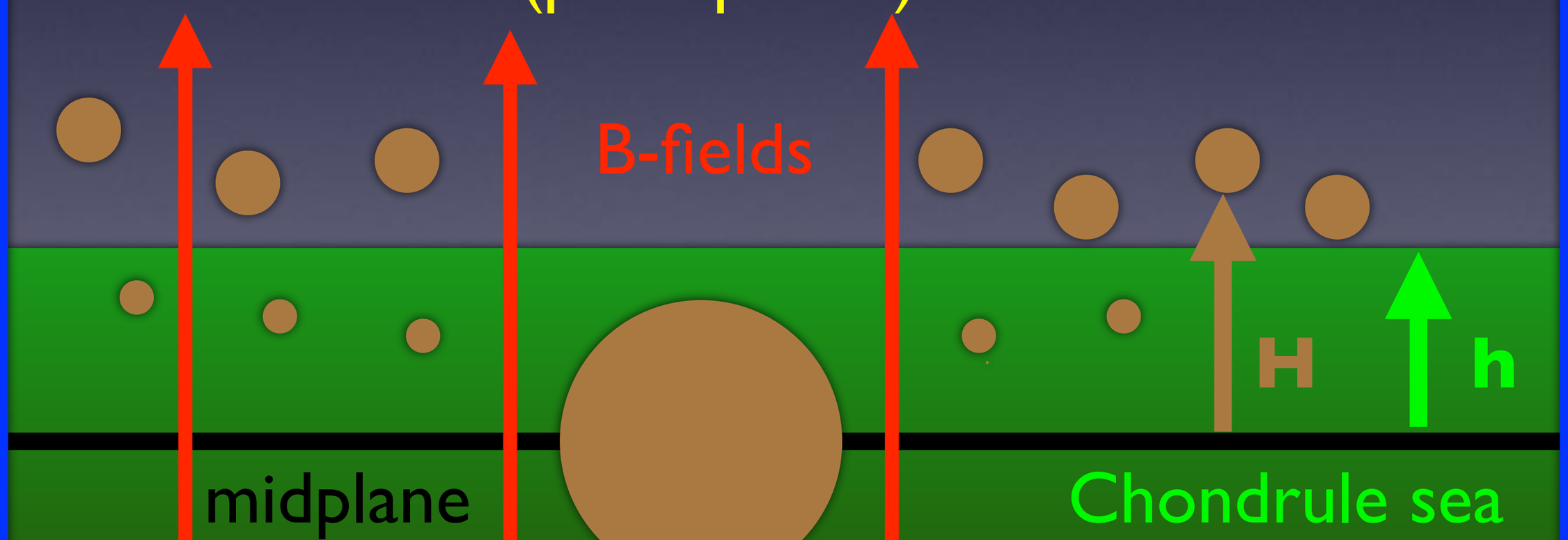
H increases with disk mass and planetesimal mass (protoplanet)

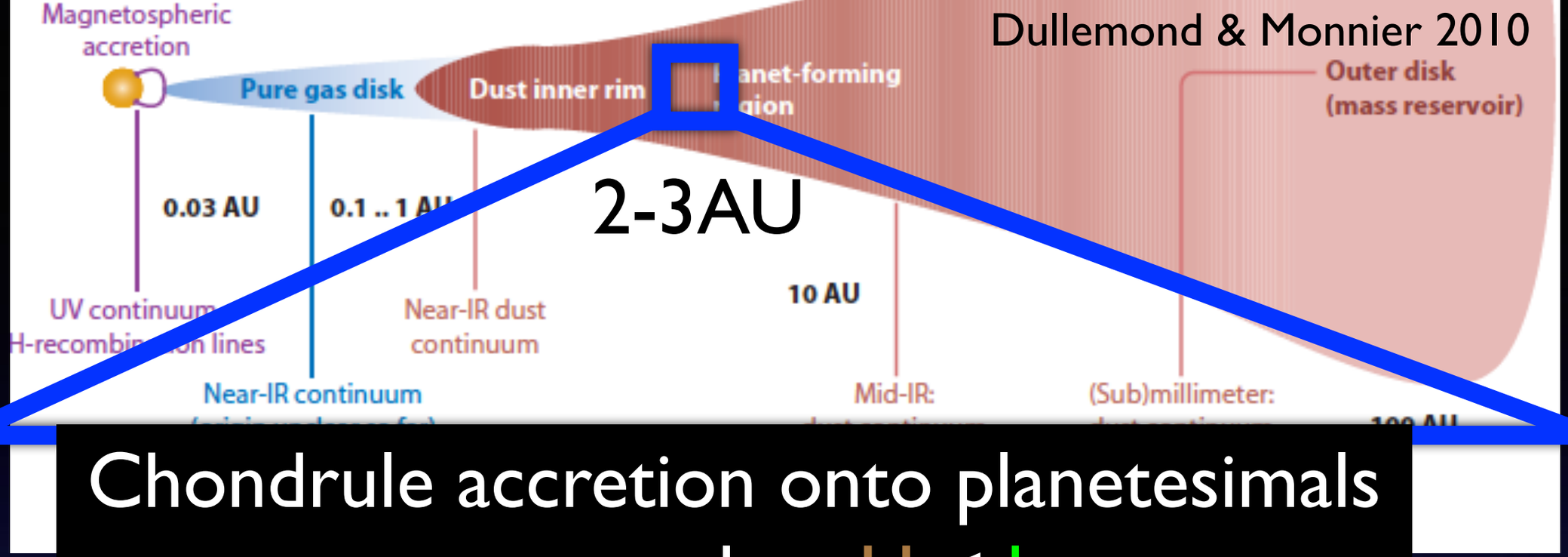




h increases with vertical magnetic flux

H increases with disk mass and planetesimal mass (protoplanet)



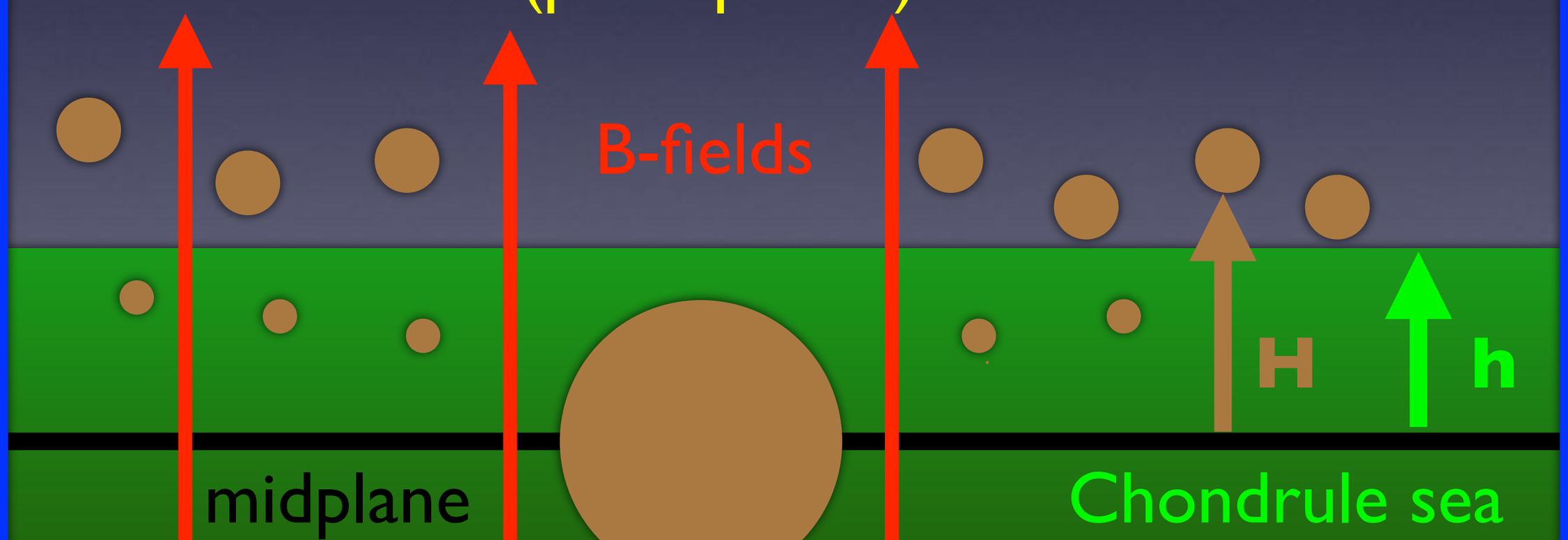


Chondrule accretion onto planetesimals occurs when H < h

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

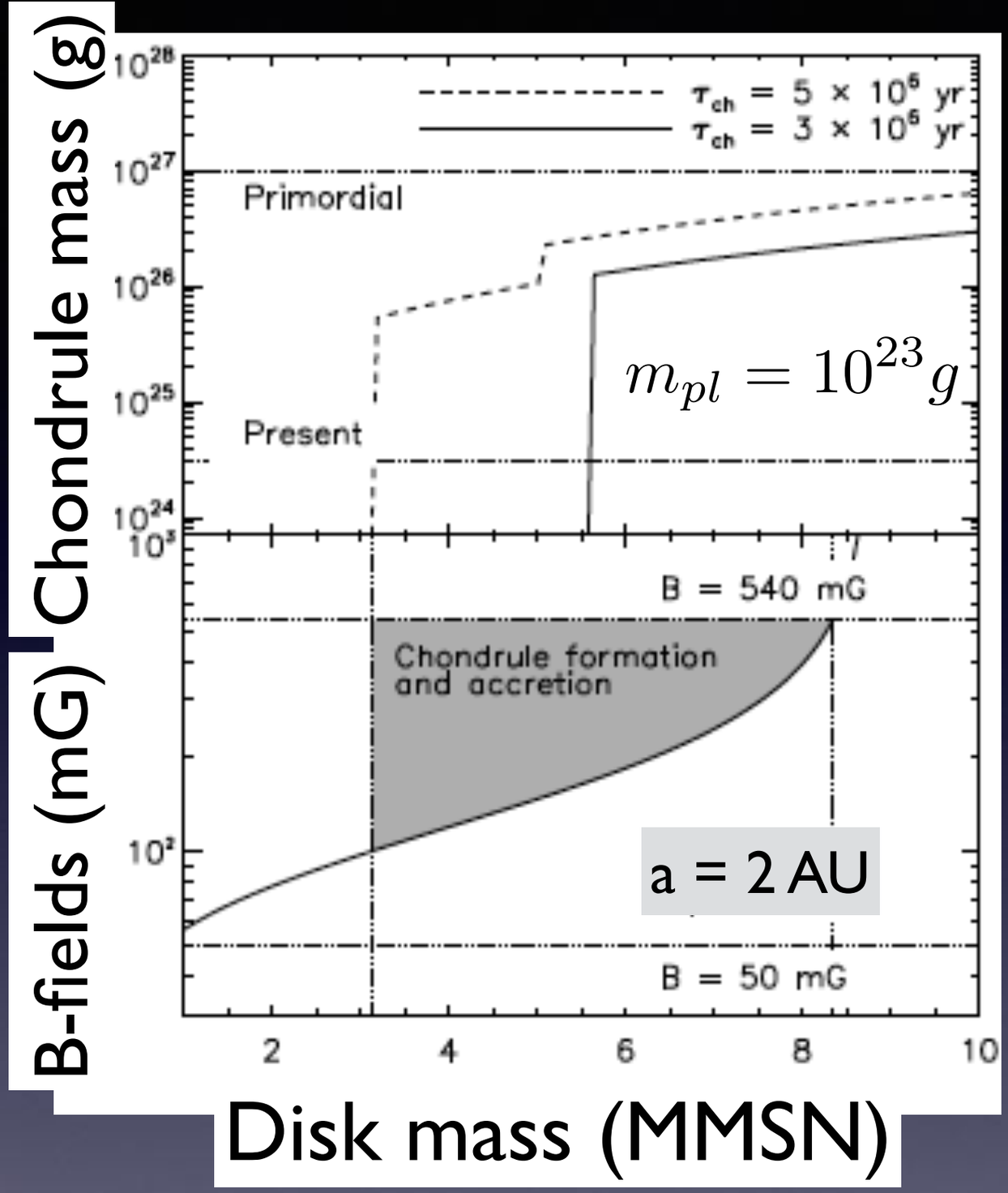
Disk mass (MMSN)

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

Total chondrule mass

Minimum value of B-fields for chondrule accretion

Disk mass (MMSN)



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

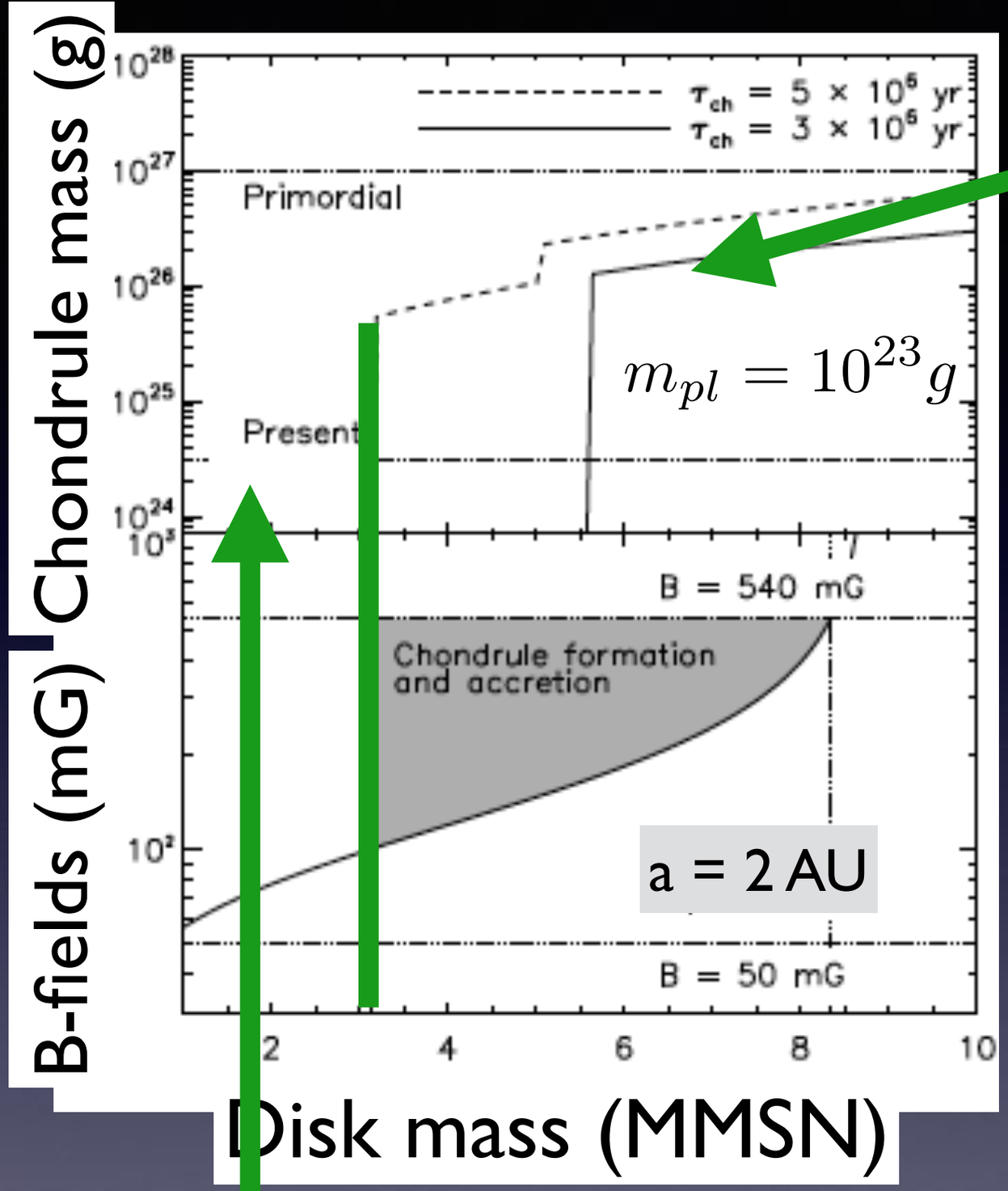
Total chondrule mass

Minimum value of B-fields for chondrule accretion

Disk mass (MMSN)

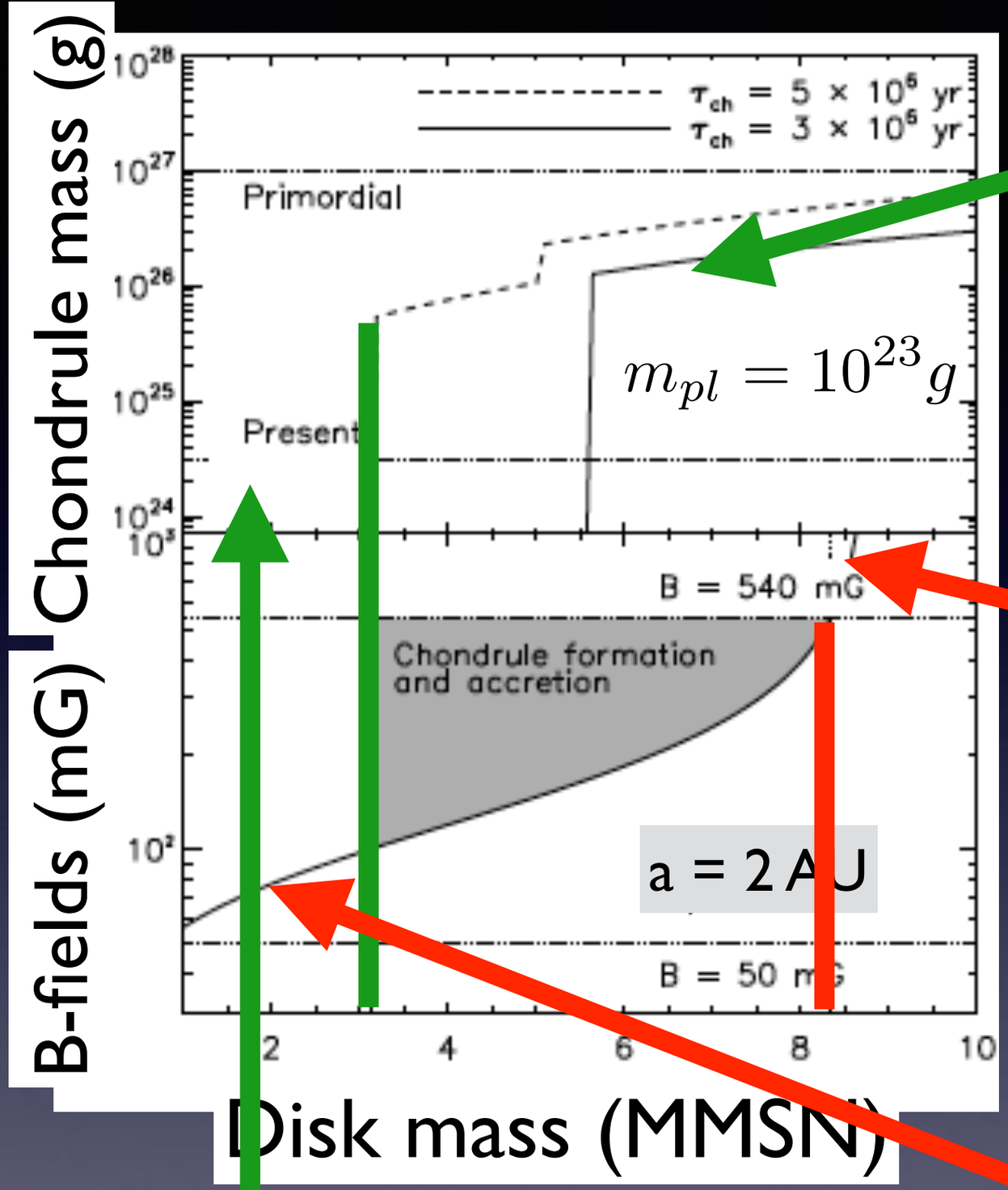
Hasegawa et al 2016b

A large number of chondrules form in massive disks



No chondrule formation due to a low disk mass

Hasegawa et al 2016b



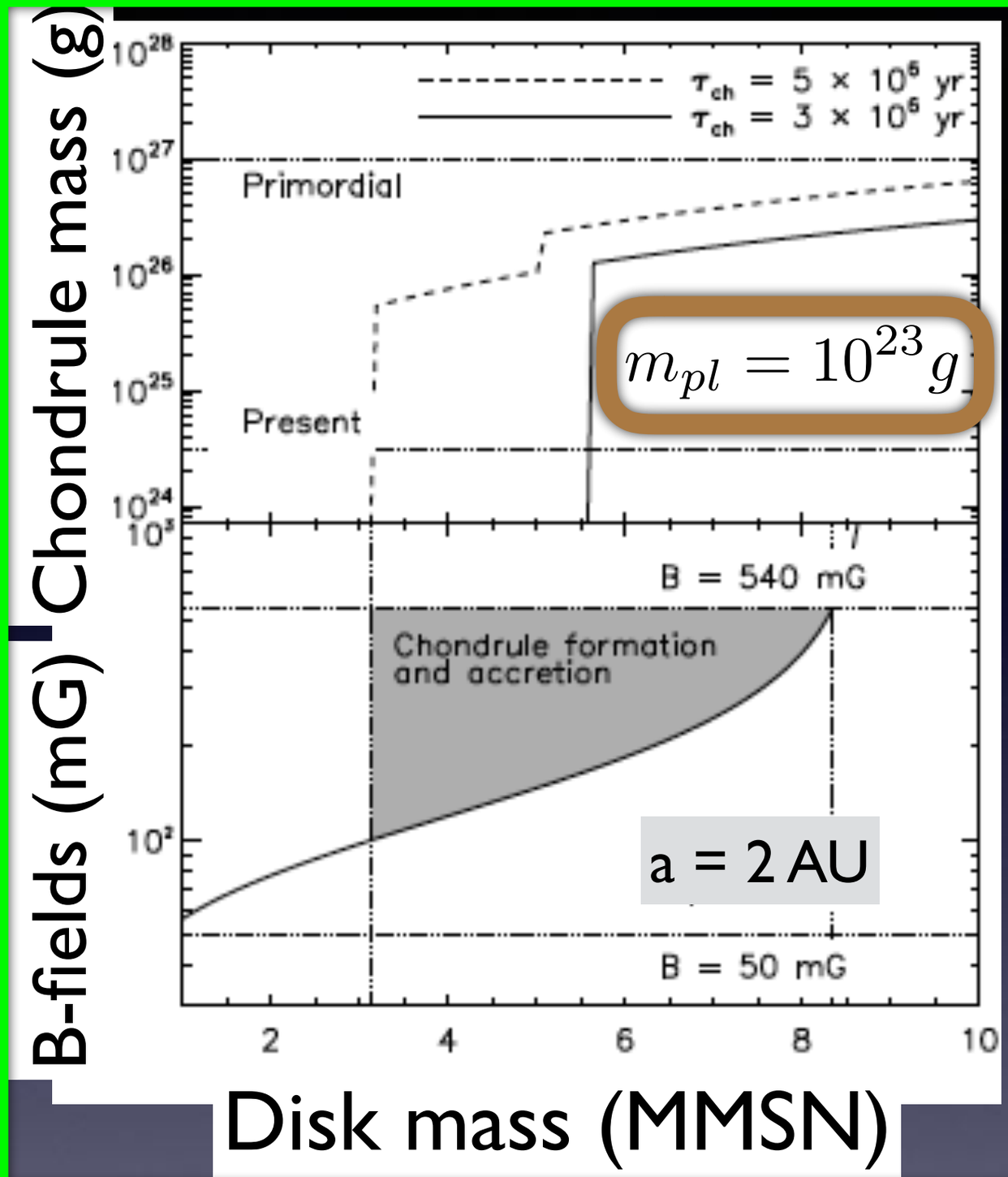
A large number of chondrules form in massive disks

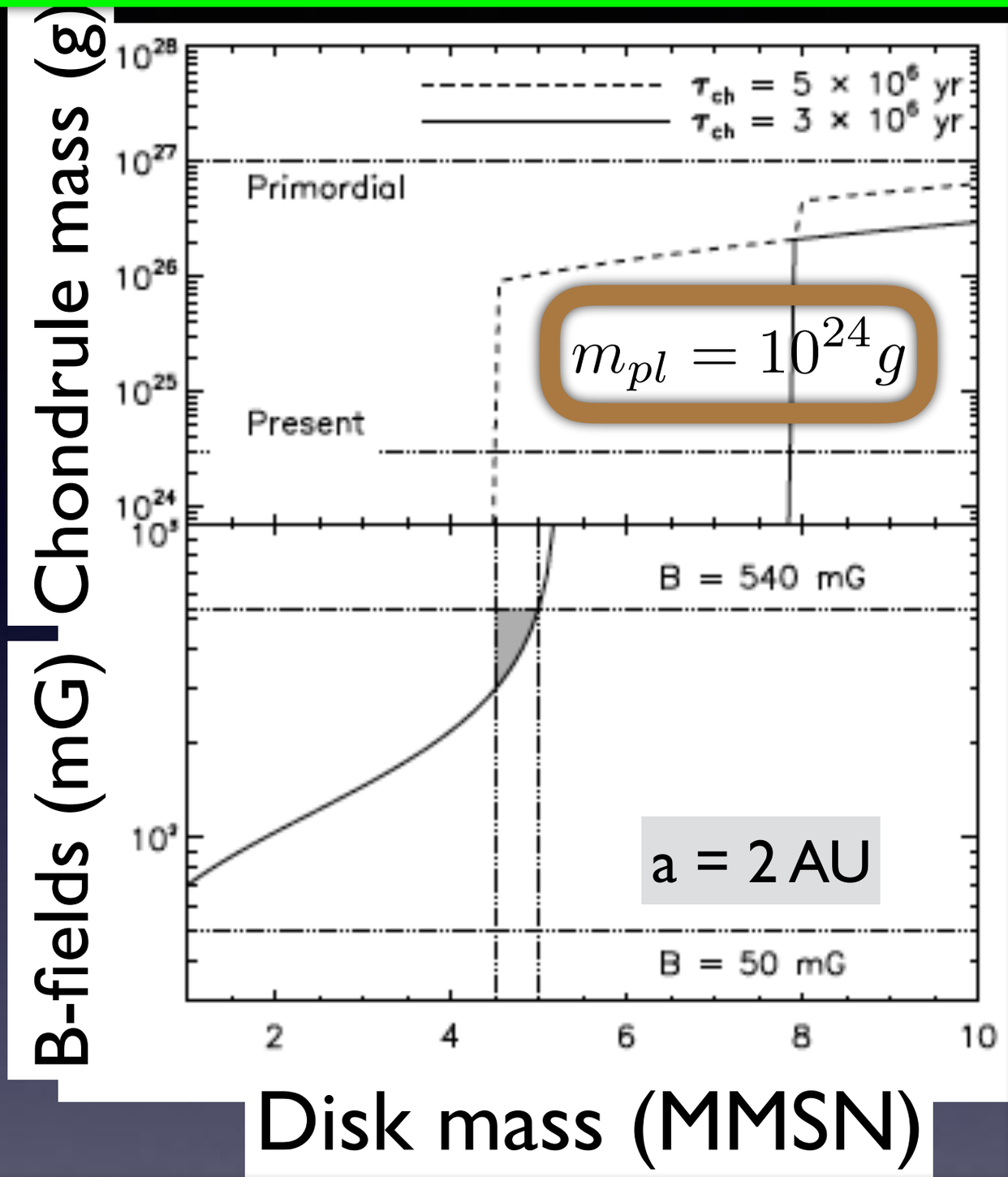
A very strong magnetic field is needed for chondrules to have the same height as planetesimals

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

No chondrule formation due to a low disk mass

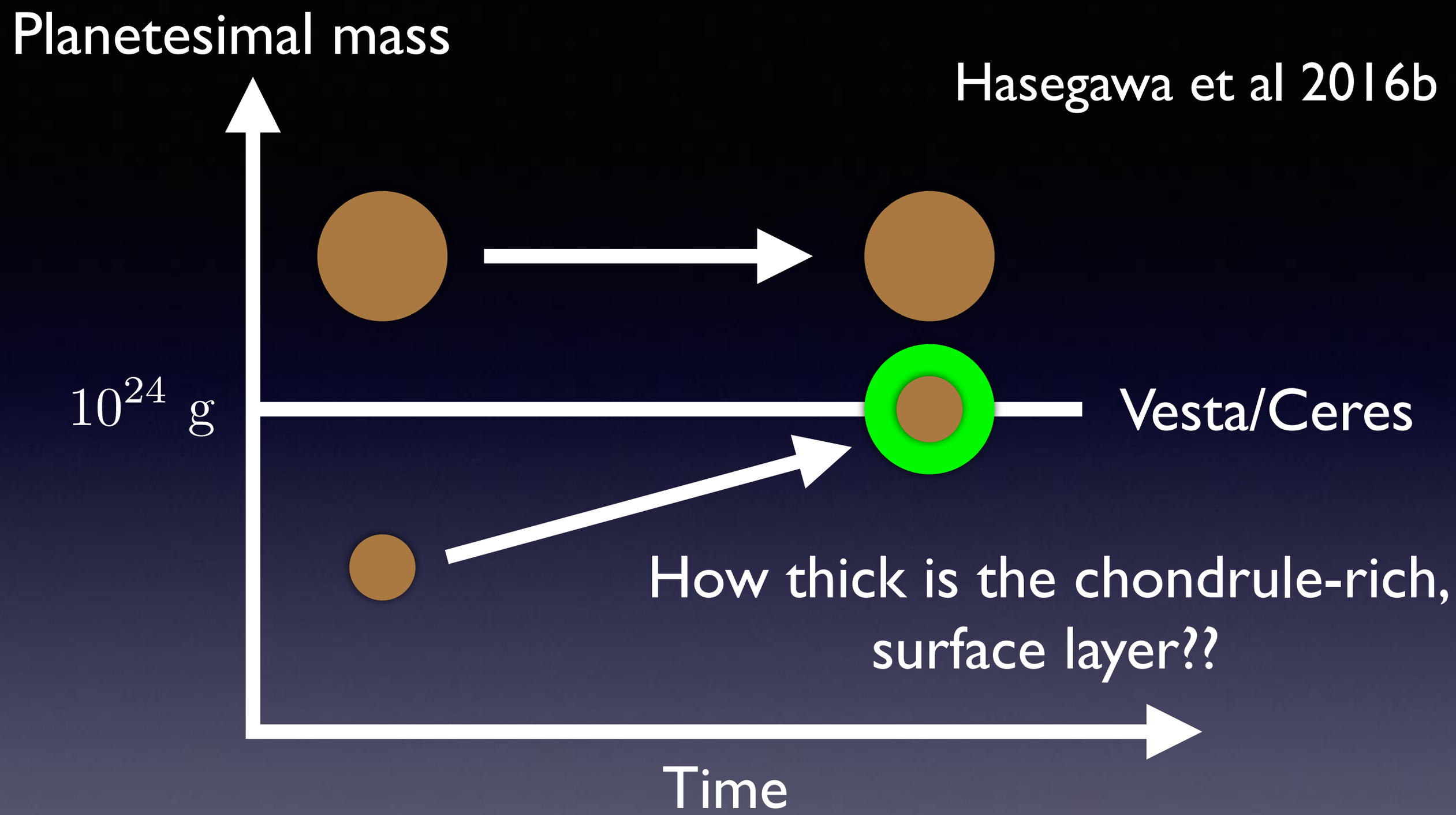
Hasegawa et al 2016b





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

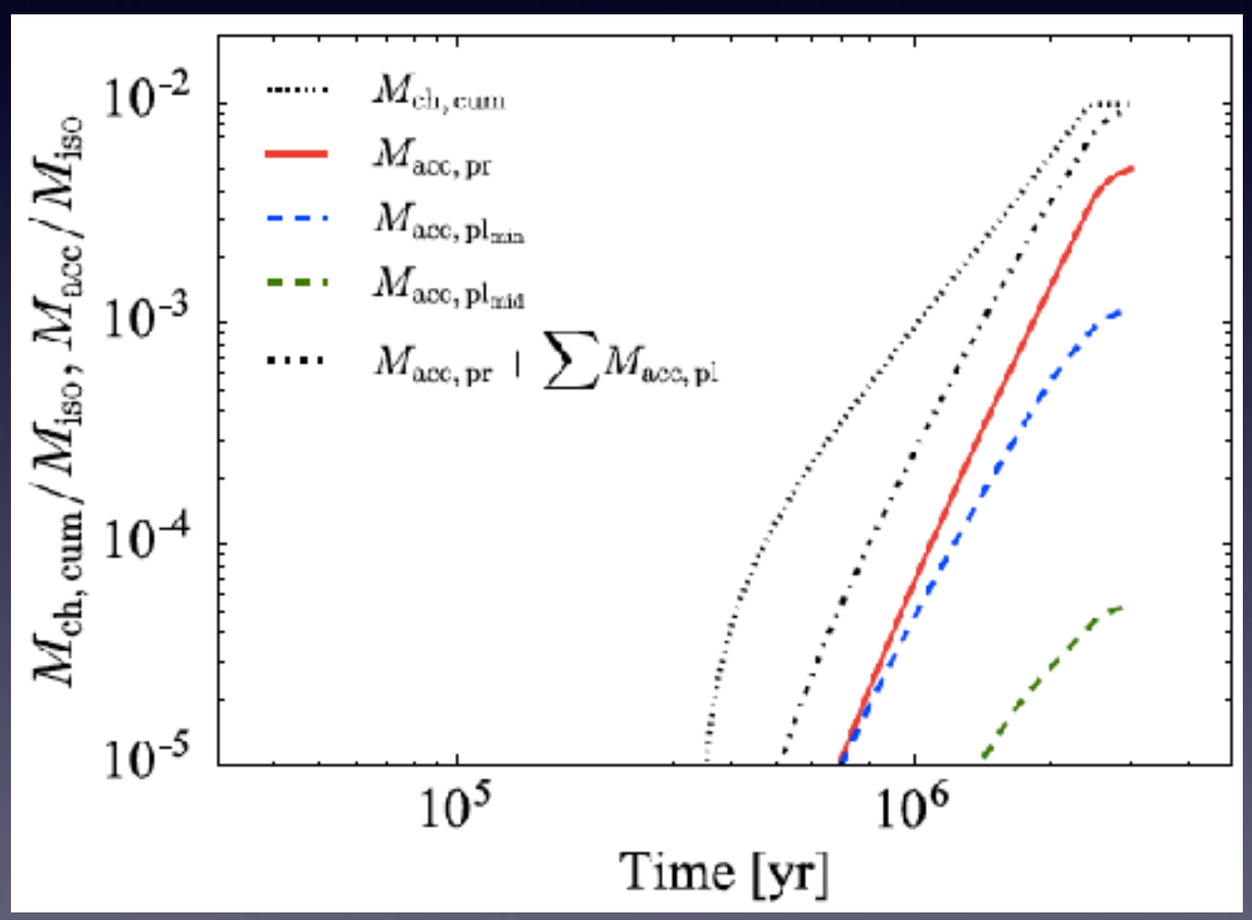


Our model needs a first generation of planetesimals that trigger impact jetting and serve as parent bodies to accrete chondrules

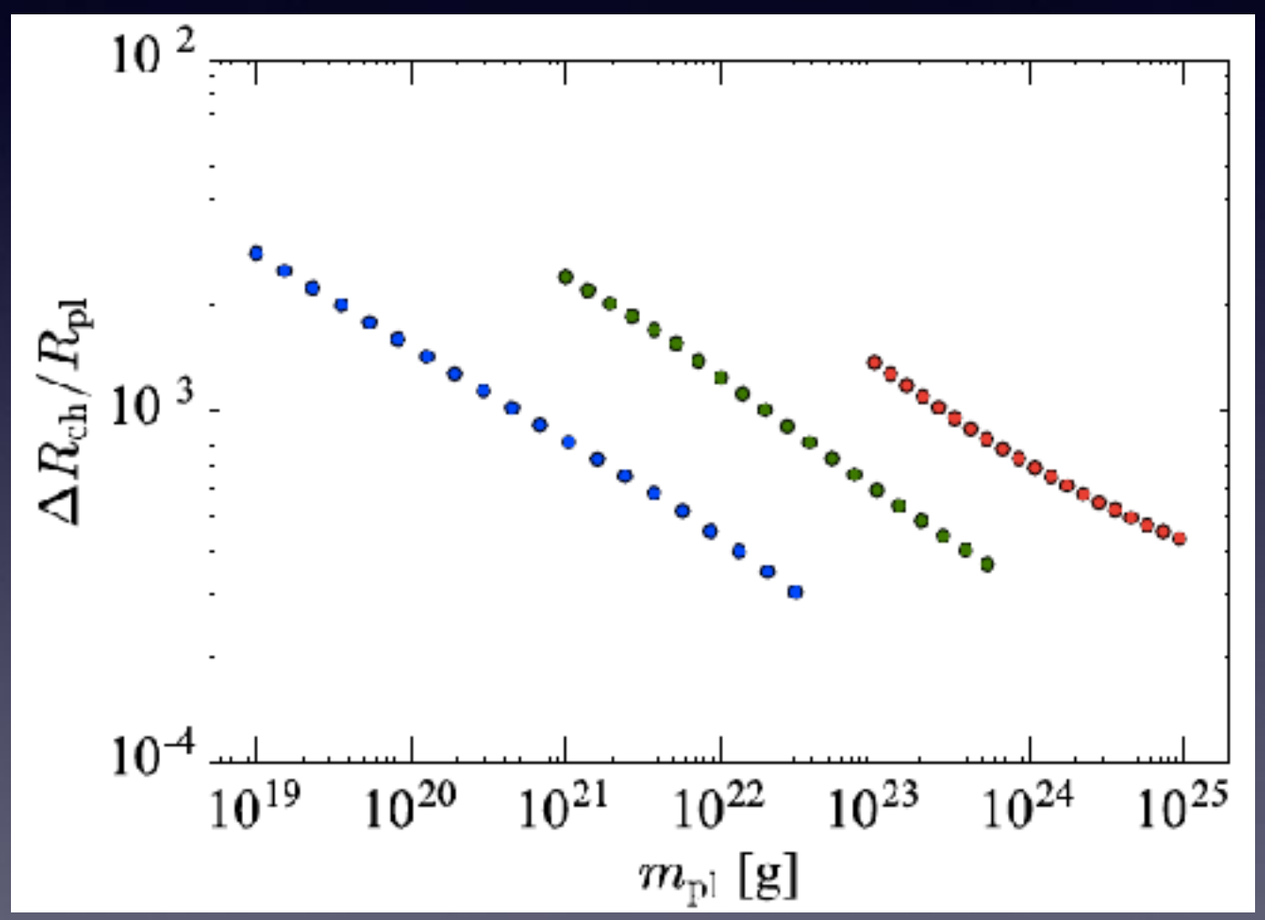
Chondrule Accretion onto Existing Planetesimals

Matsumoto et al 2017

Time evolution of chondrule accretion

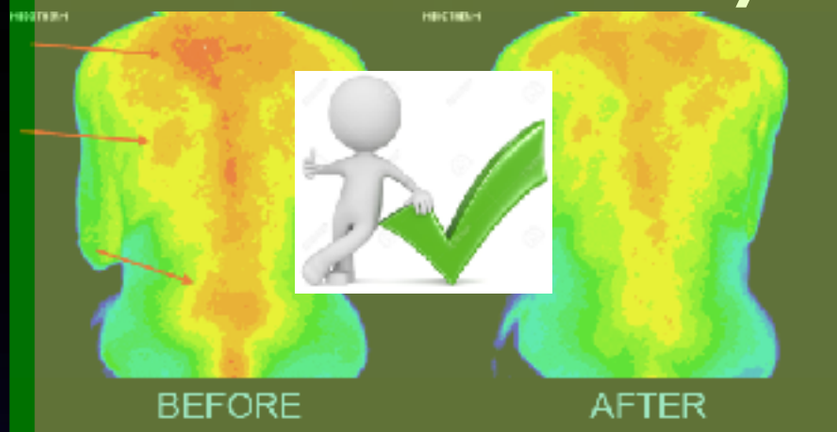


Parameter study



Chondrule-rich surface layer is
~ 0.3 km for 230km-sized planetesimals

Thermal History



Abundance

Chondrule Formation
& Accretion

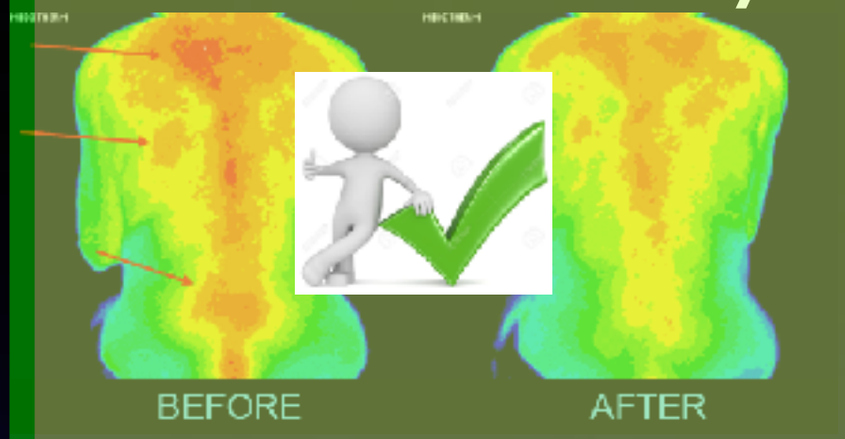
Chondrule Formation
= Impact Jetting

Timescale

Chondrule Accretion
= Pebble Accretion

B-fields

Thermal History



Abundance

Chondrule Formation

A great mixture of lab experiments, numerical simulations of collisions theory of planet formation, & disk physics

Timescale

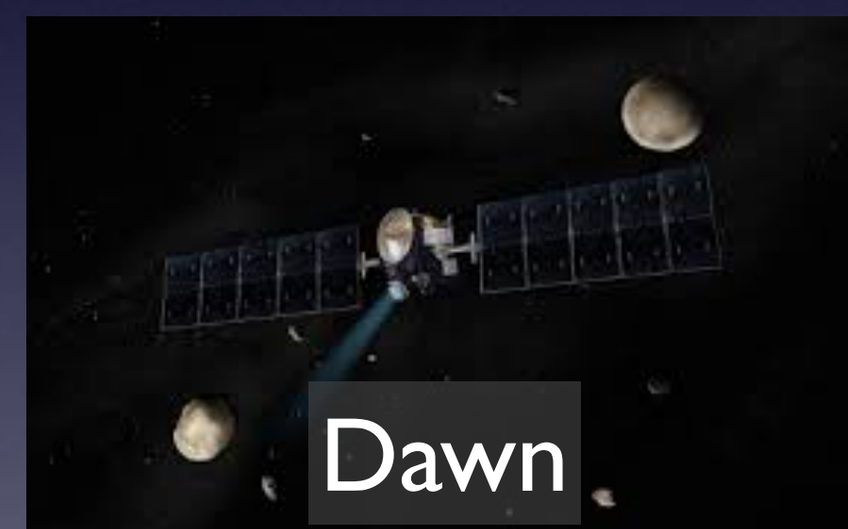
Chondrule Accretion = Pebble Accretion

B-fields

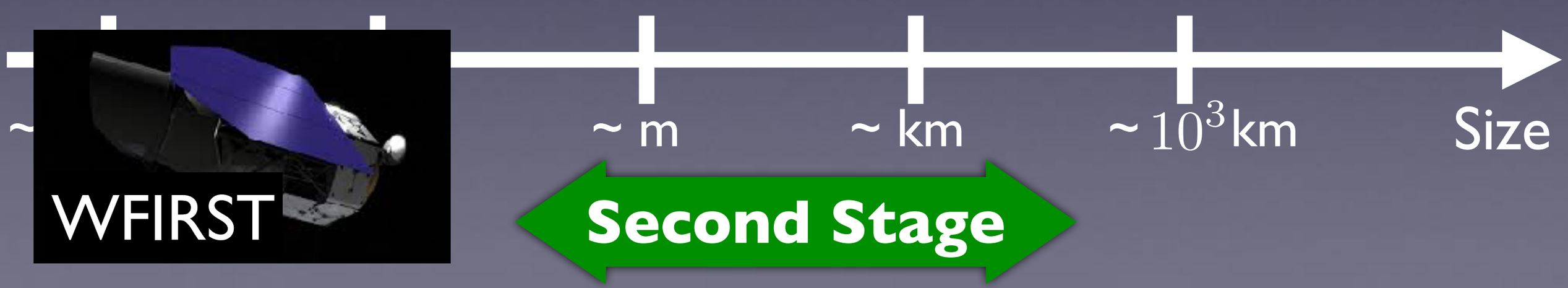
Planetesimal Formation & Origins of Asteroids

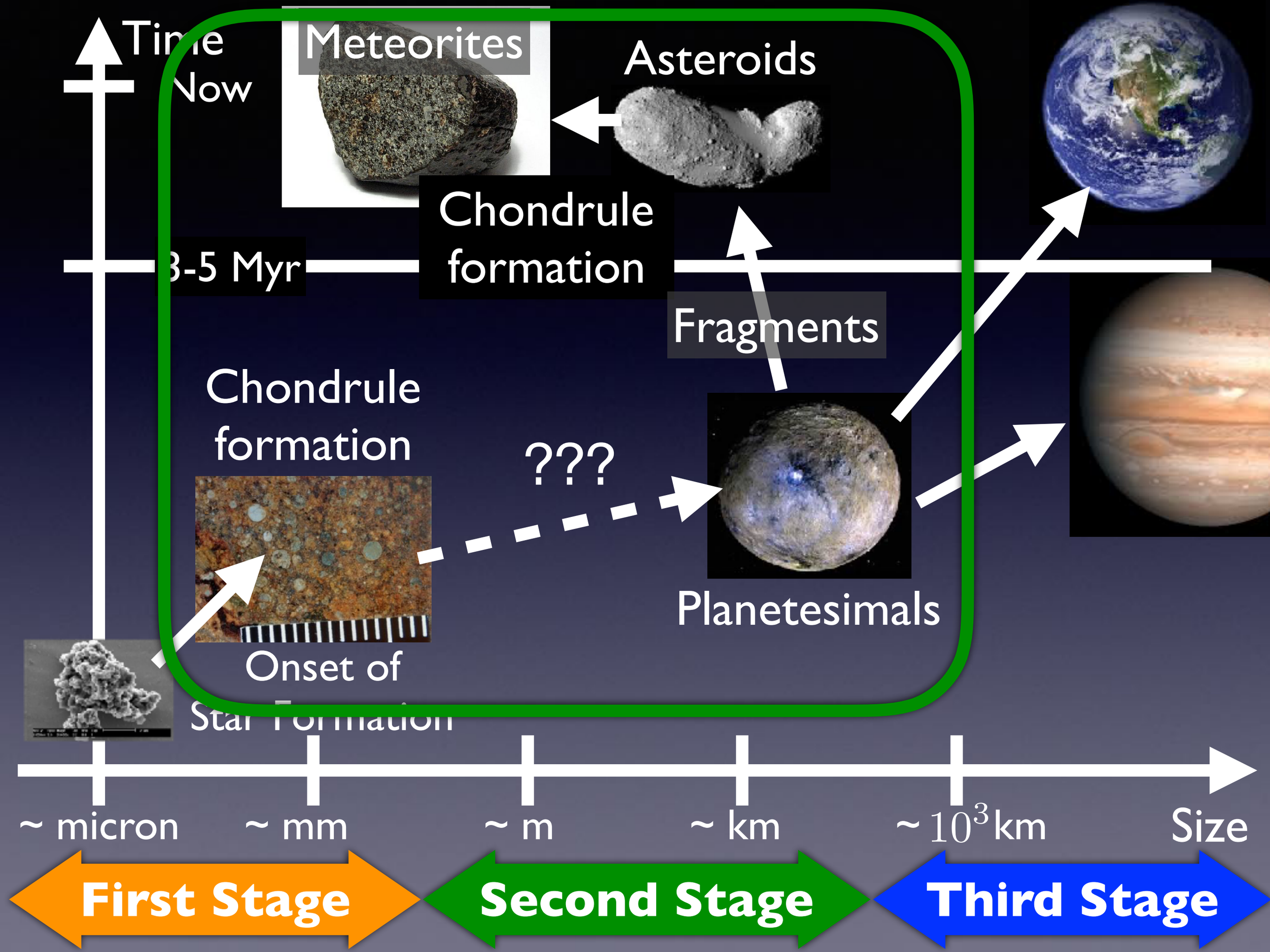
Scenario 1: Chondrule accretion

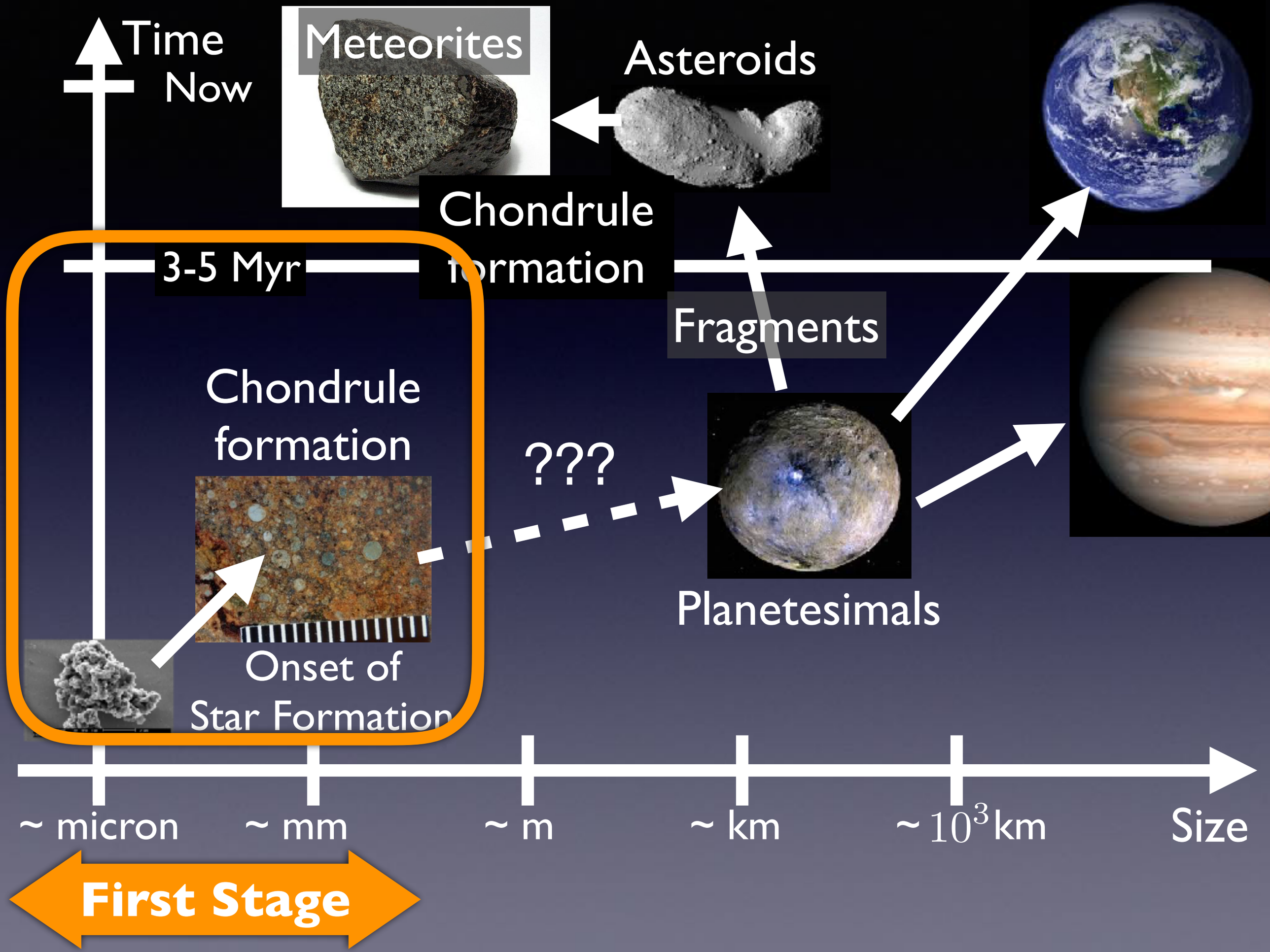
Scenario 2: Chondrule accumulation



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




Time
Now
Meteorites
Asteroids
Chondrule formation
3-5 Myr
Fragments
Chondrule formation
???
Planetesimals
Onset of
Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
First Stage
Second Stage
Third Stage


Time
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Meteorites
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Chondrule formation
3-5 Myr
Fragments
Chondrule formation
???
Onset of Star Formation
Planetesimals
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
First Stage

Magnetically Induced Disk Winds and Transport in the HL Tau Disk

ALMA image of HL Tau

ALMA Partnership et al 2015

Key Observed Features

: a high disk accretion rate

: efficient dust settling Pinte et al 2016

Our Disk Model

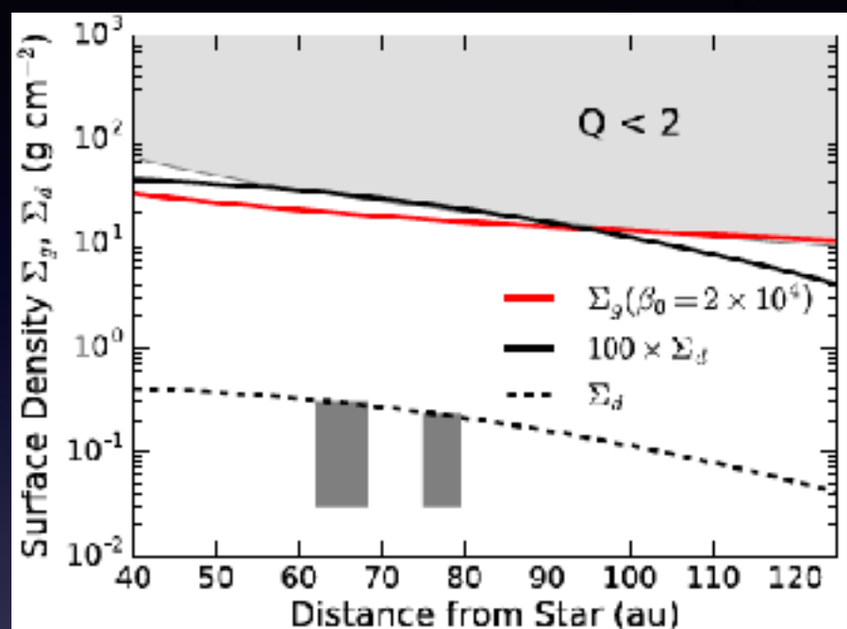
: magnetized turbulence and magnetically induced disk winds

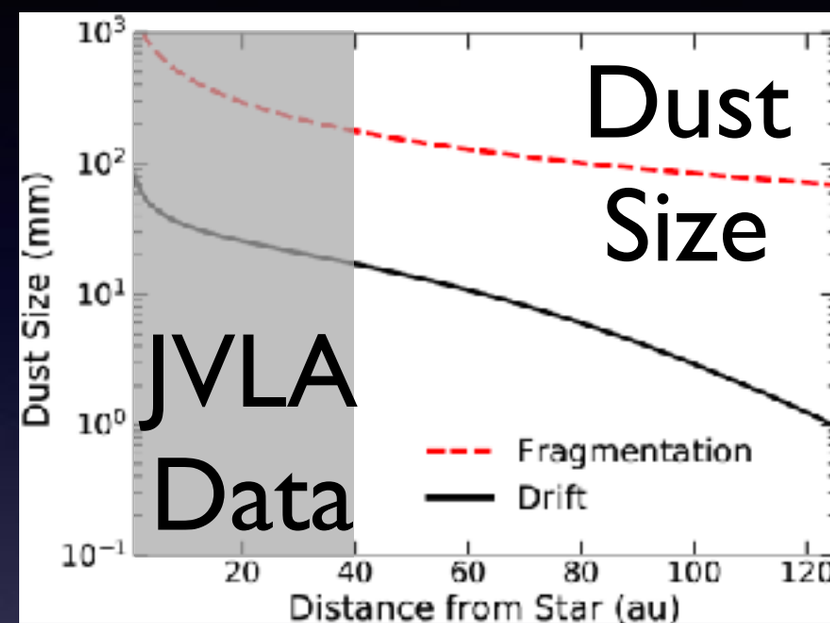
Hasegawa et al 2017

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

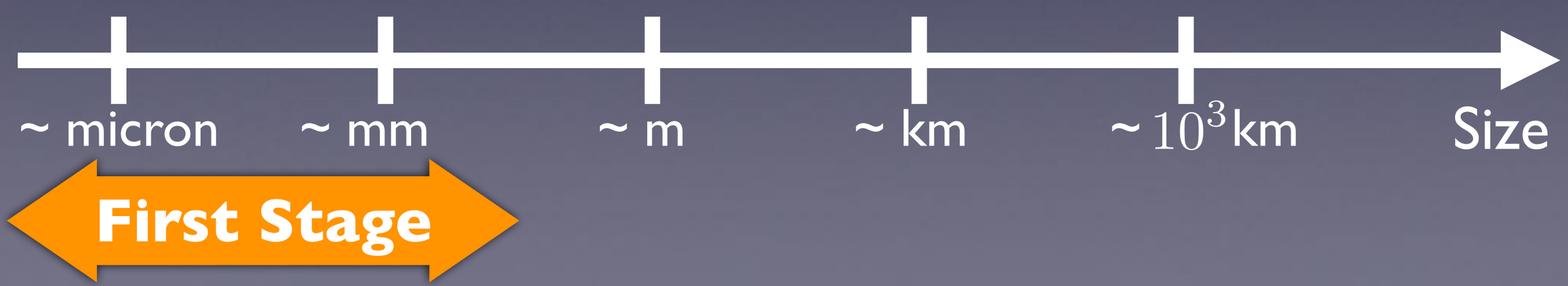
First Stage

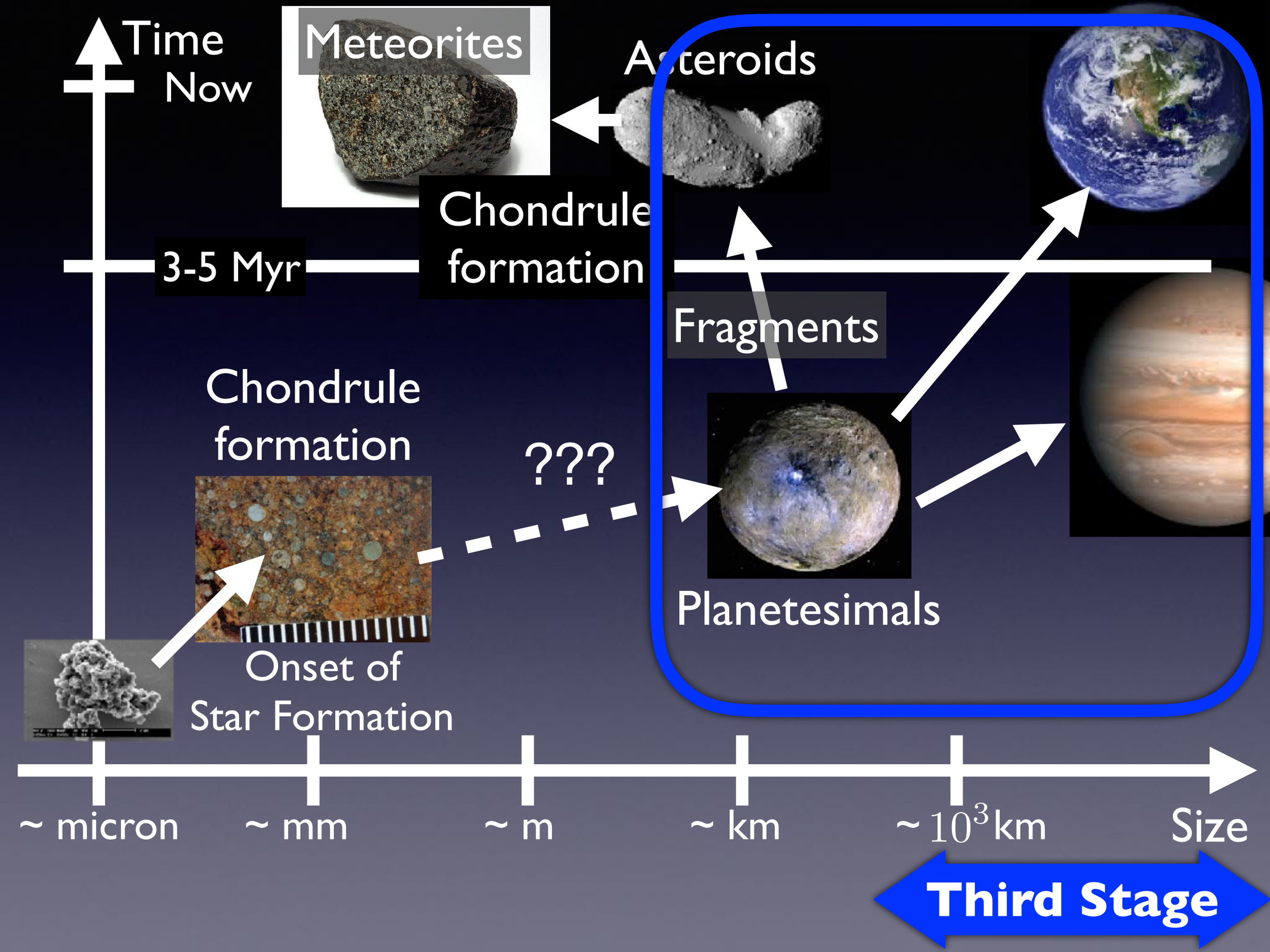
Coupling of Disk Observations with Dust Growth Models



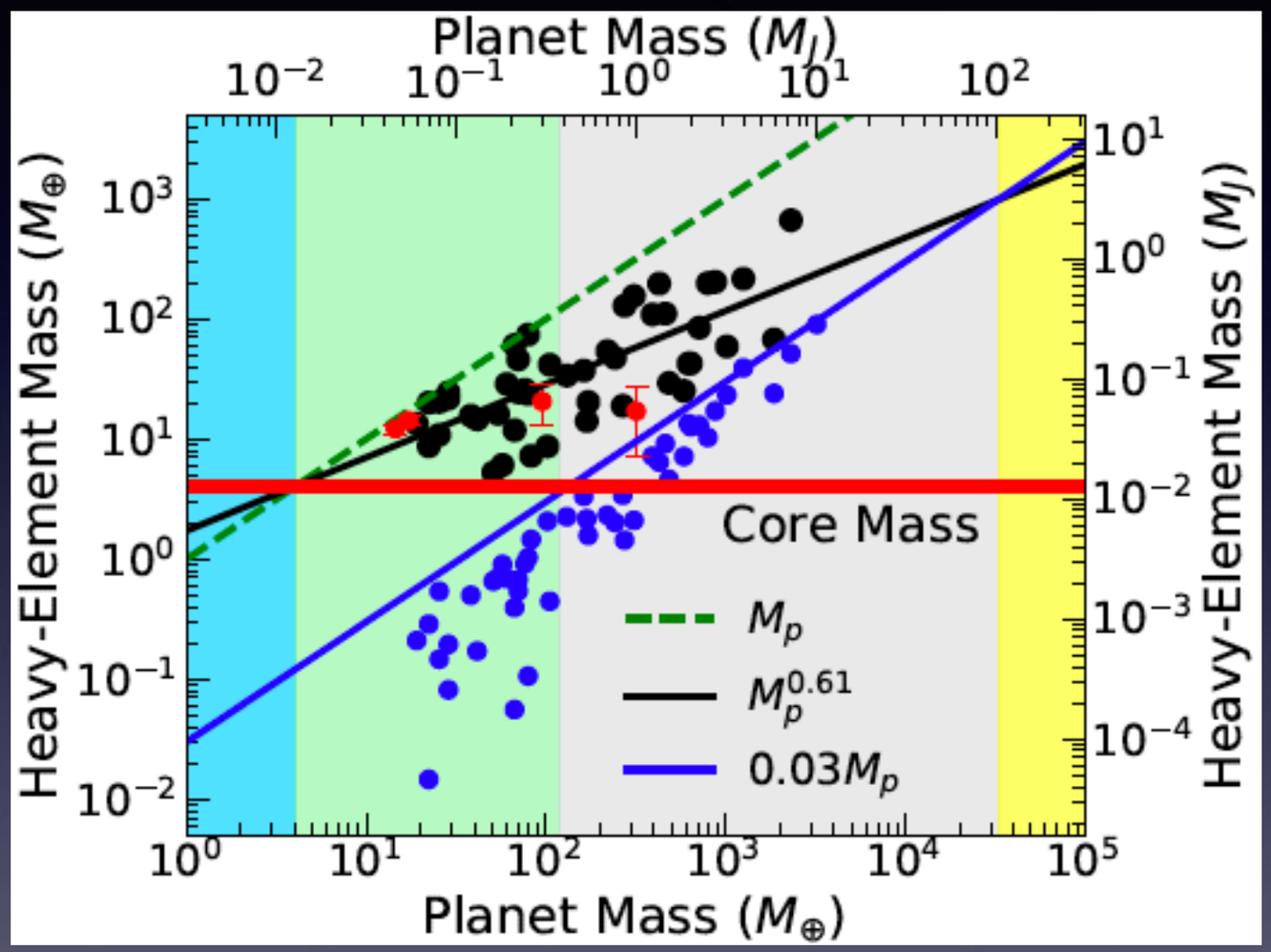


We will **specify** the distribution of planet-forming materials in disks




Time
Now
Meteorites
Asteroids
Chondrule formation
3-5 Myr
Fragments
Chondrule formation
???
Planetesimals
Onset of Star Formation
~ micron
~ mm
~ m
~ km
~ 10^3 km
Size
Third Stage

Origin of the Heavy Element Content Trend in Giant Planets



Estimate of the total heavy element mass

: focus on warm Jupiters

Thorngren et al 2016

Planetesimal accretion

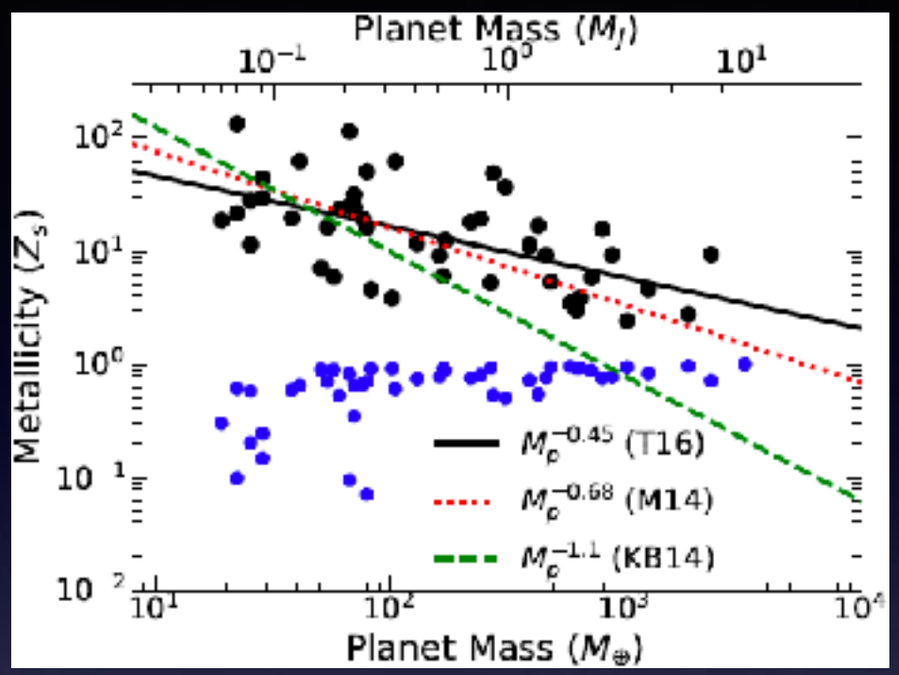
: solid accretion from gapped planetesimal disks

Hasegawa et al 2018

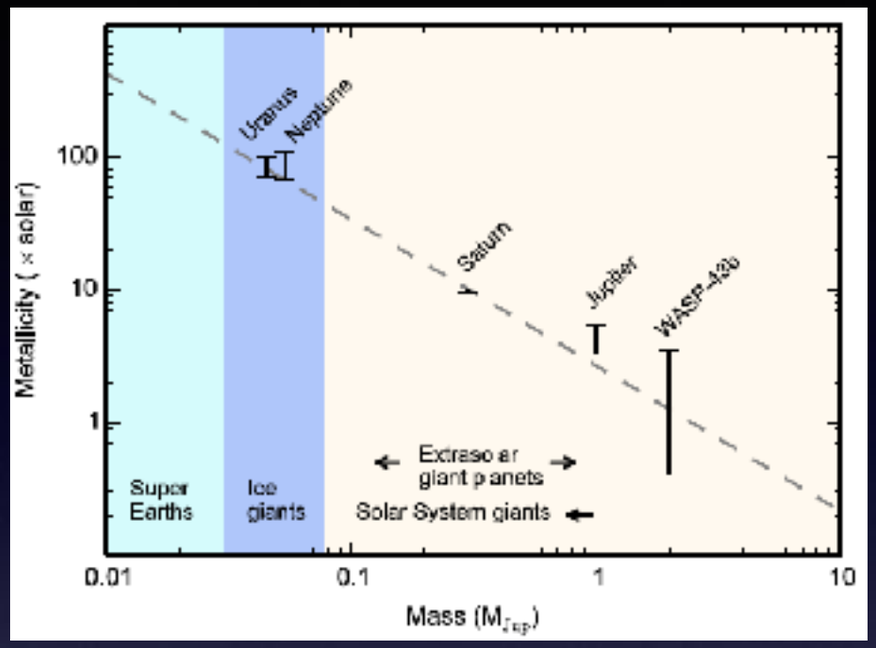
~ micron ~ mm ~ m ~ km ~ 10^3 km Size

Third Stage

Coupling of Exoplanet Observations with Planet Formation Theory



Hasegawa et al 2018



Kreidberg et al 2014

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

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

Third Stage

Summary

- Planet formation is the long journey from small dust grains to large planets
- A number of astonishing progresses allow a comprehensive examination of planet formation, covering the fill size range
- As an example, chondrule formation and accretion are discussed, focusing on the impact jetting scenario
- This scenario can account for a number of the currently available meteorite data, and may be useful for the sample return missions
- 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