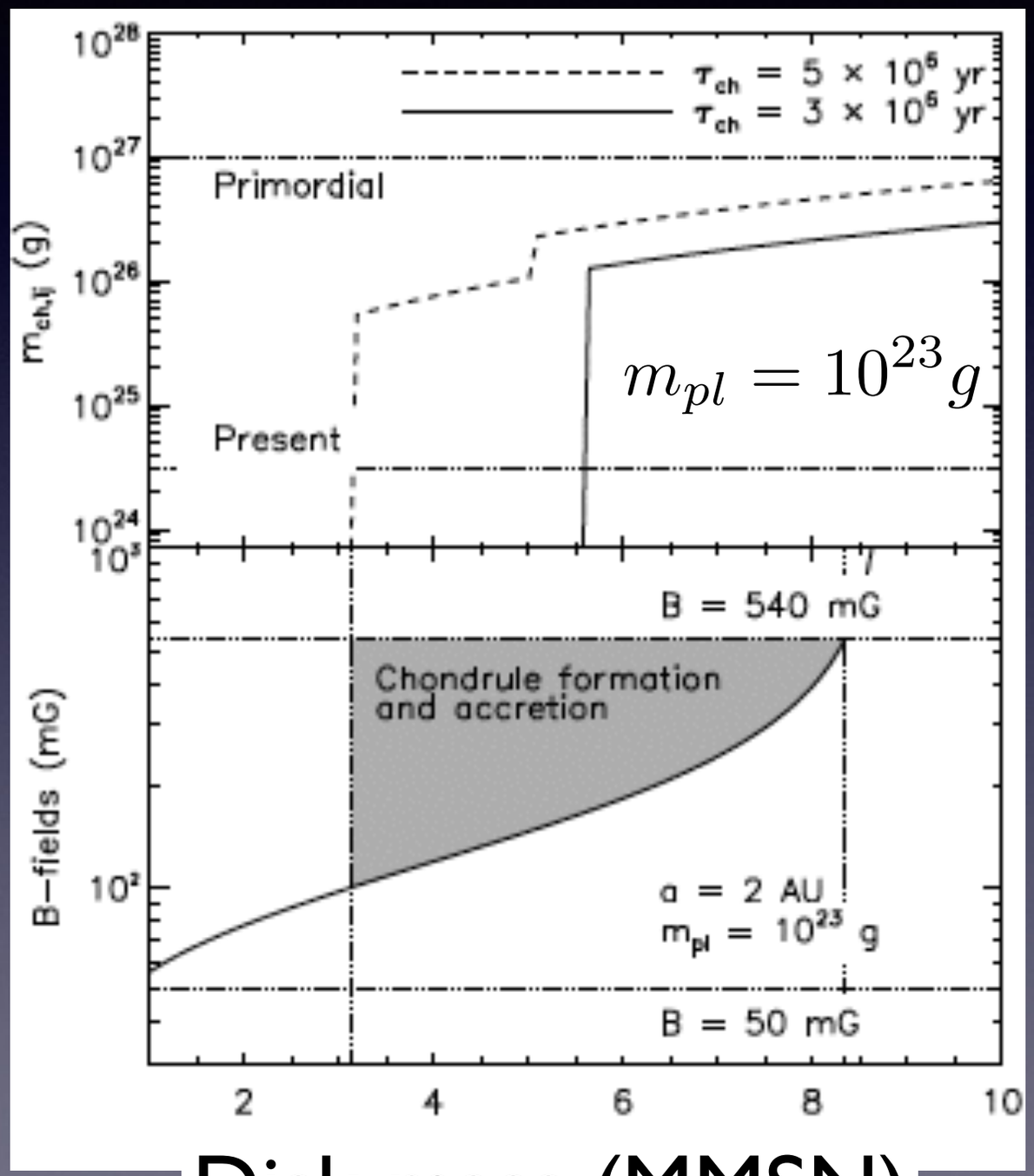
# Forming Chondrites in a Solar Nebula with Magnetically Induced Turbulence




Disk mass (MMSN)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# Fossil Records of the Solar System: Chondrules

abundant in chondrites
(up 80 % in volume)

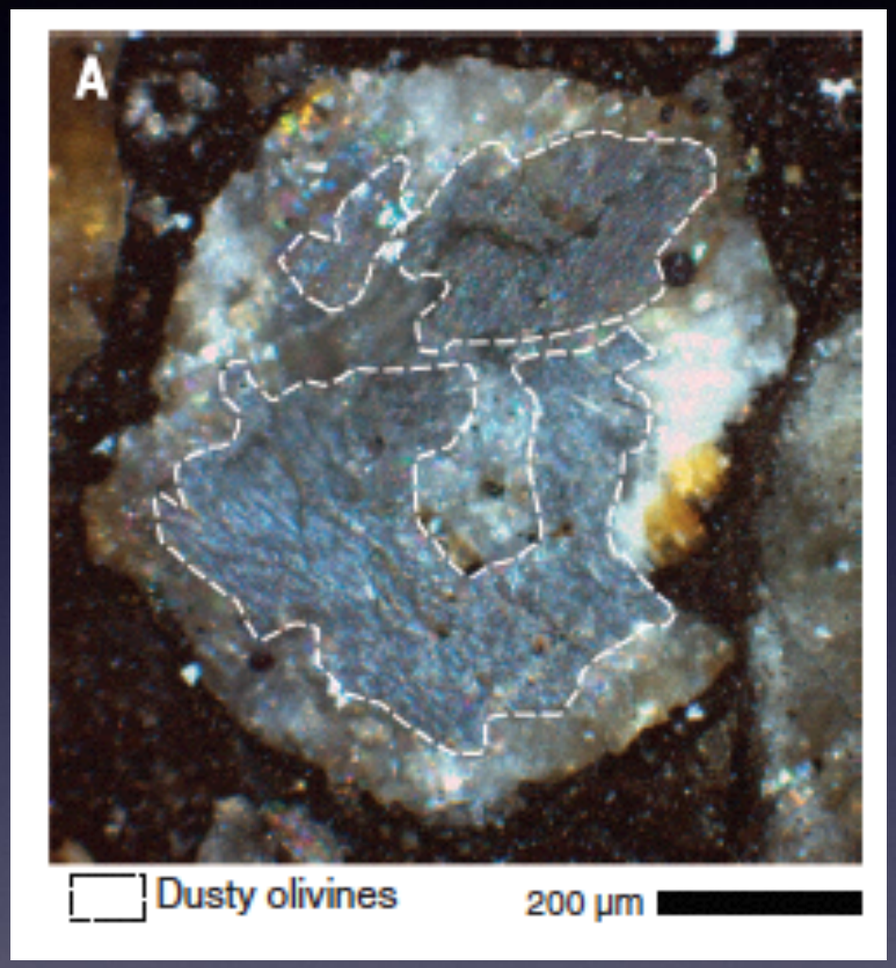
~1mm sized spherical particles

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

# New information: magnetic fields in the nebula



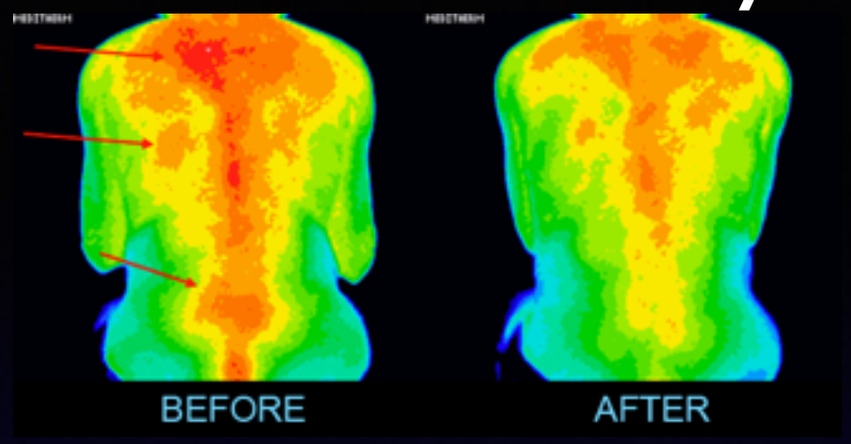

Fu et al 2014

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

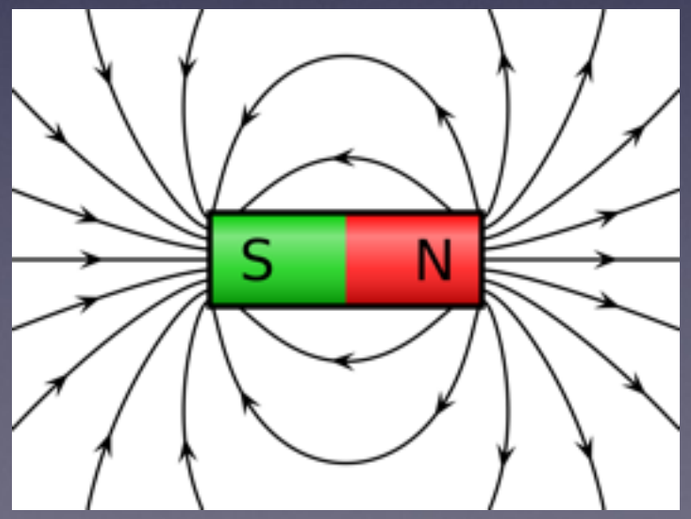
Thermal History




Abundance

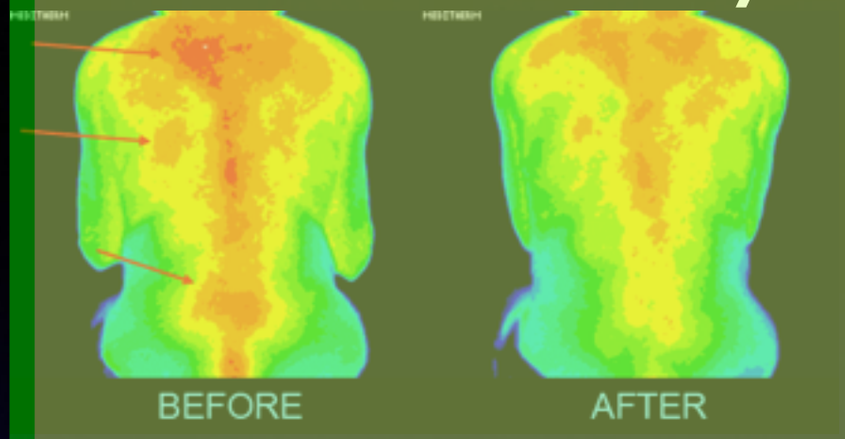
# Chondrule Formation & Accretion

Timescale




B-fields

Thermal History



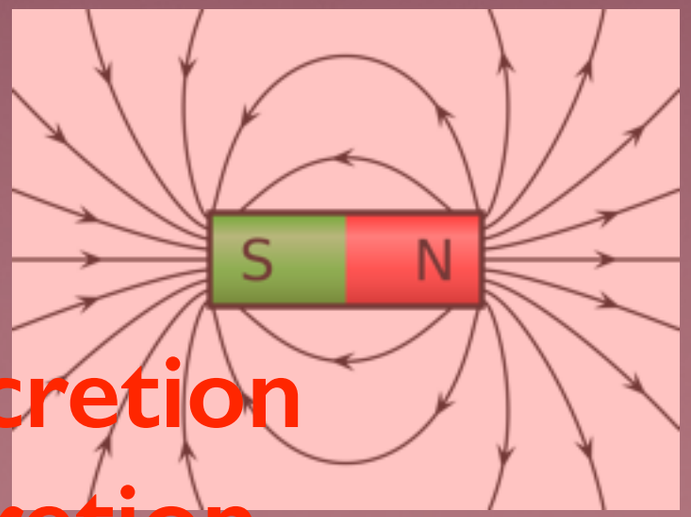

Abundance

Chondrule Formation
& Accretion

**Chondrule Formation**
**= Impact Jetting**

Timescale

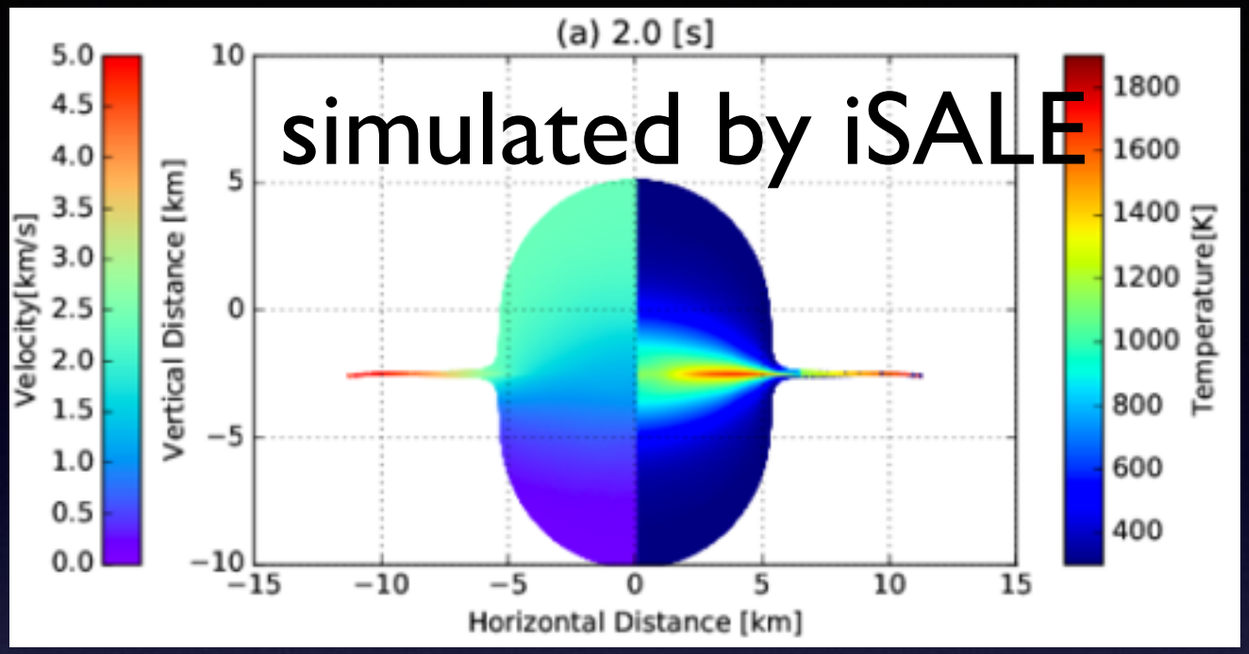
**Chondrule Accretion**
**= Pebble Accretion**



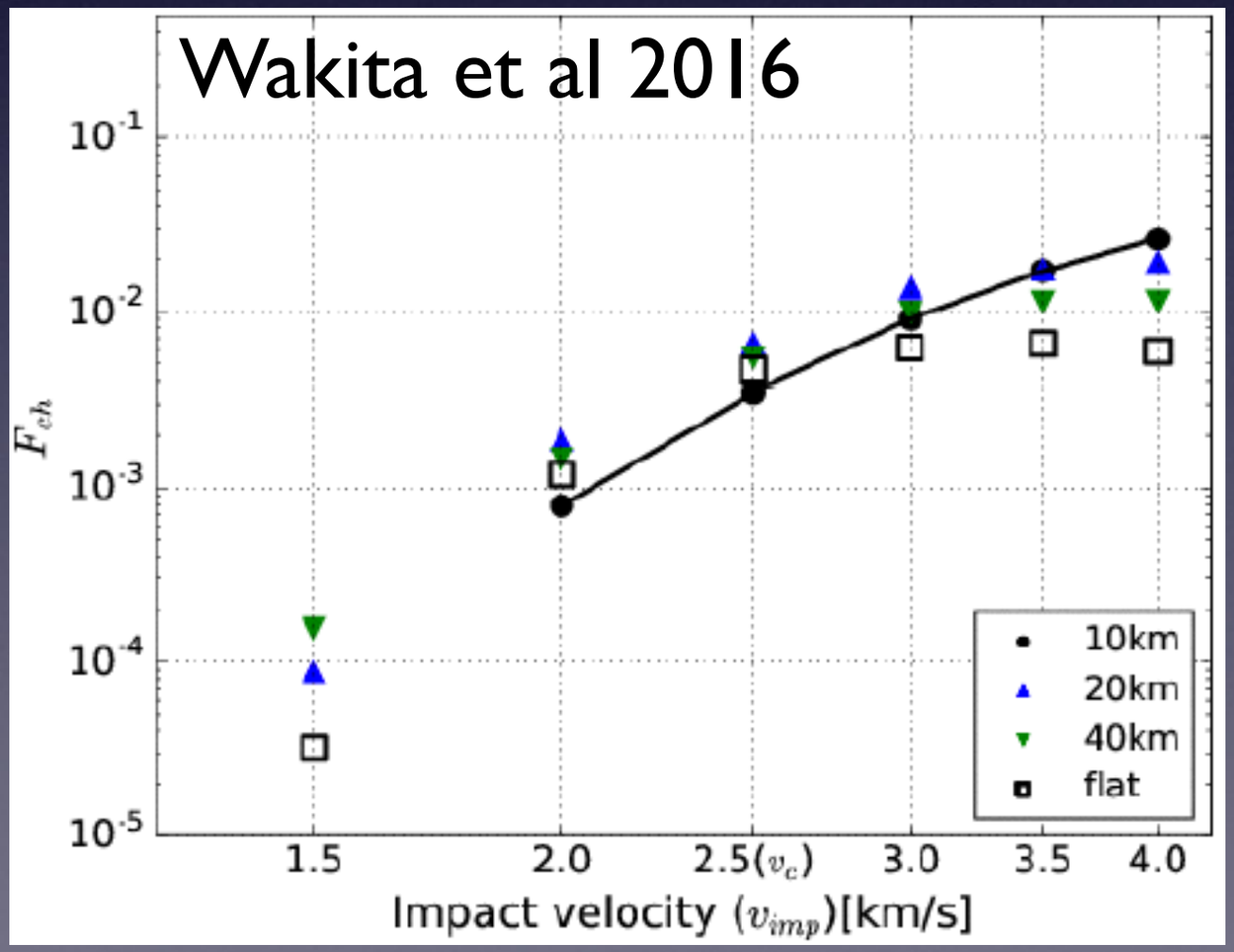

B-fields

# Key idea: impact jetting

e.g., Johnson et al 2015



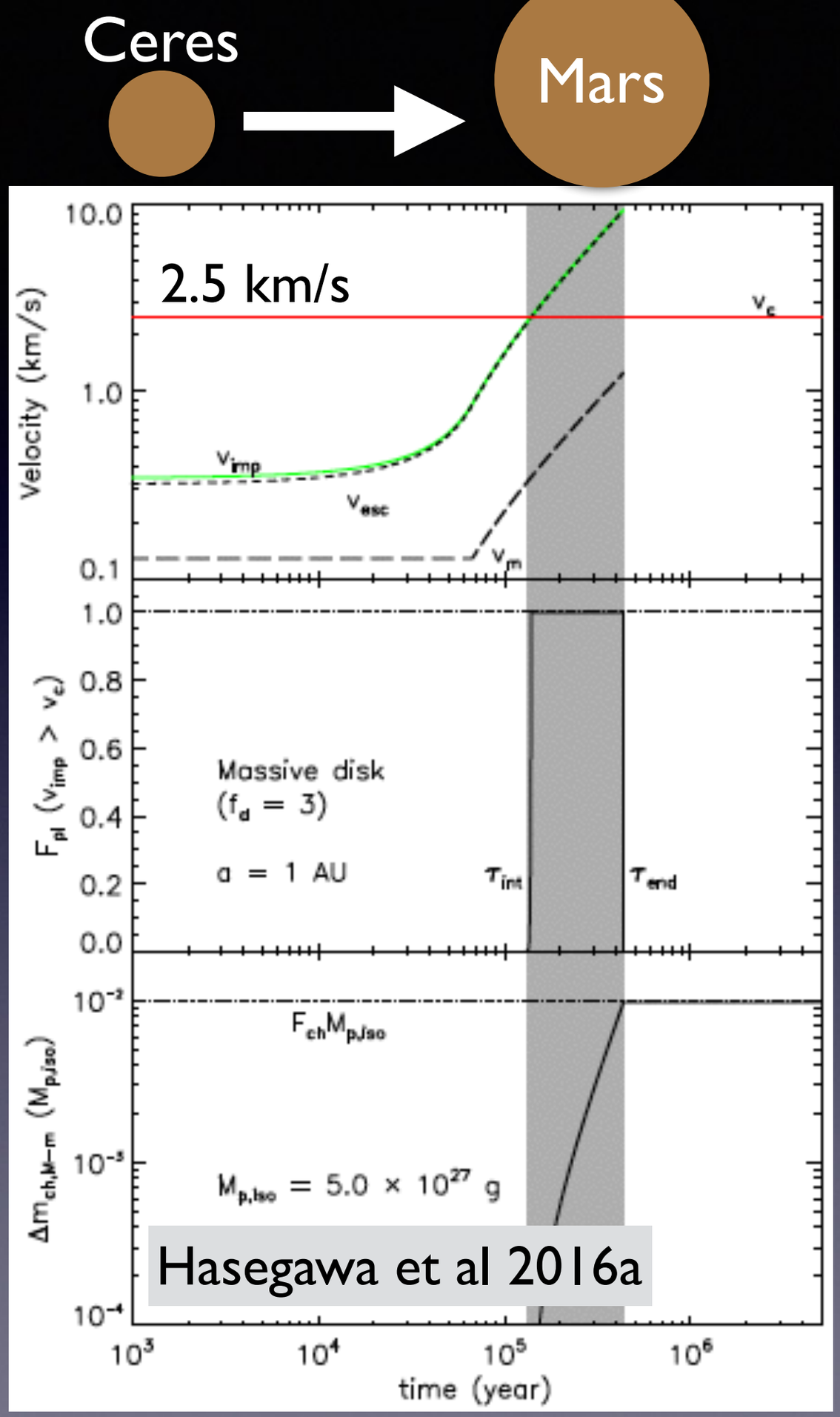

A planetesimal with r = 5km collides with a planetesimal or a protoplanet




Some materials melt, and are ejected from the system

Such ejected materials may be a progenitor of chondrules

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




Hasegawa et al 2016a

# Lots of collisions occur when protoplanets form

Protoplanets form via runaway/oligarchic growth

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

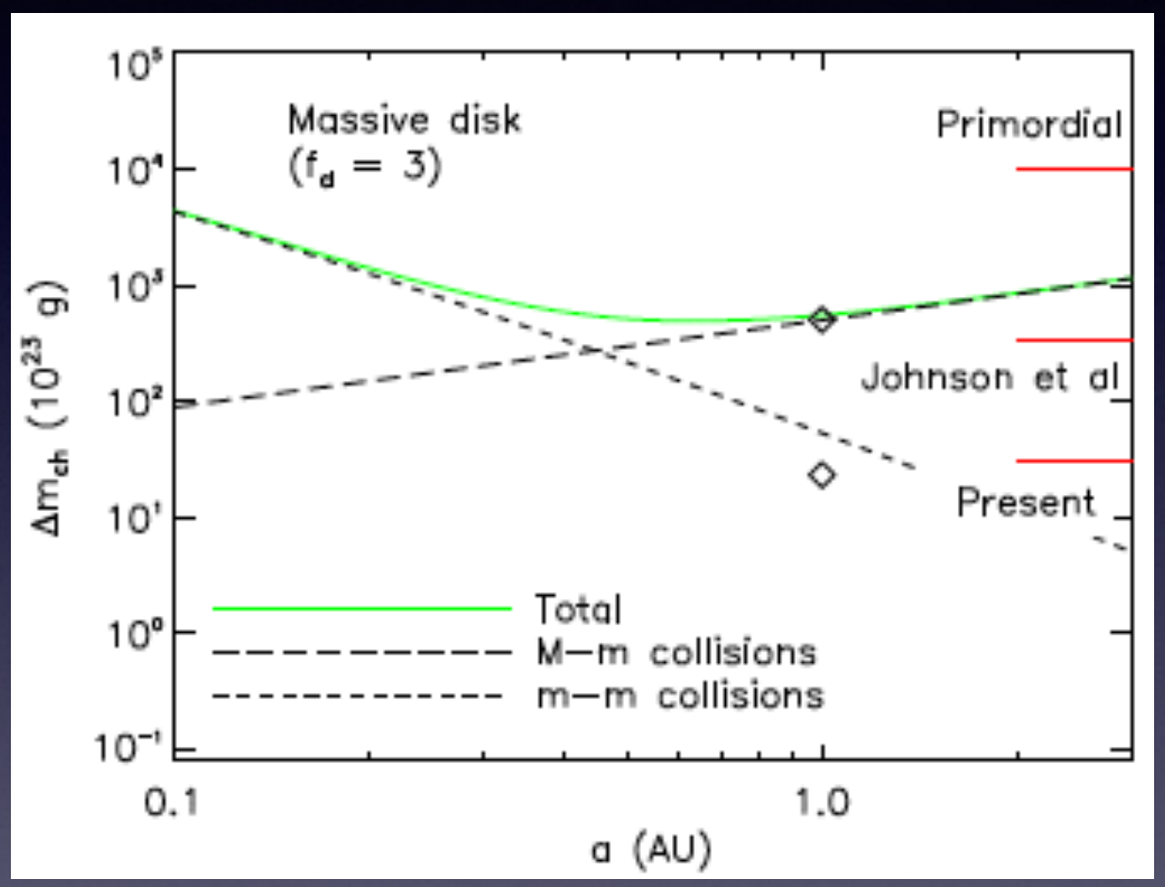
Chondrule-forming collisions occur at the hatched region

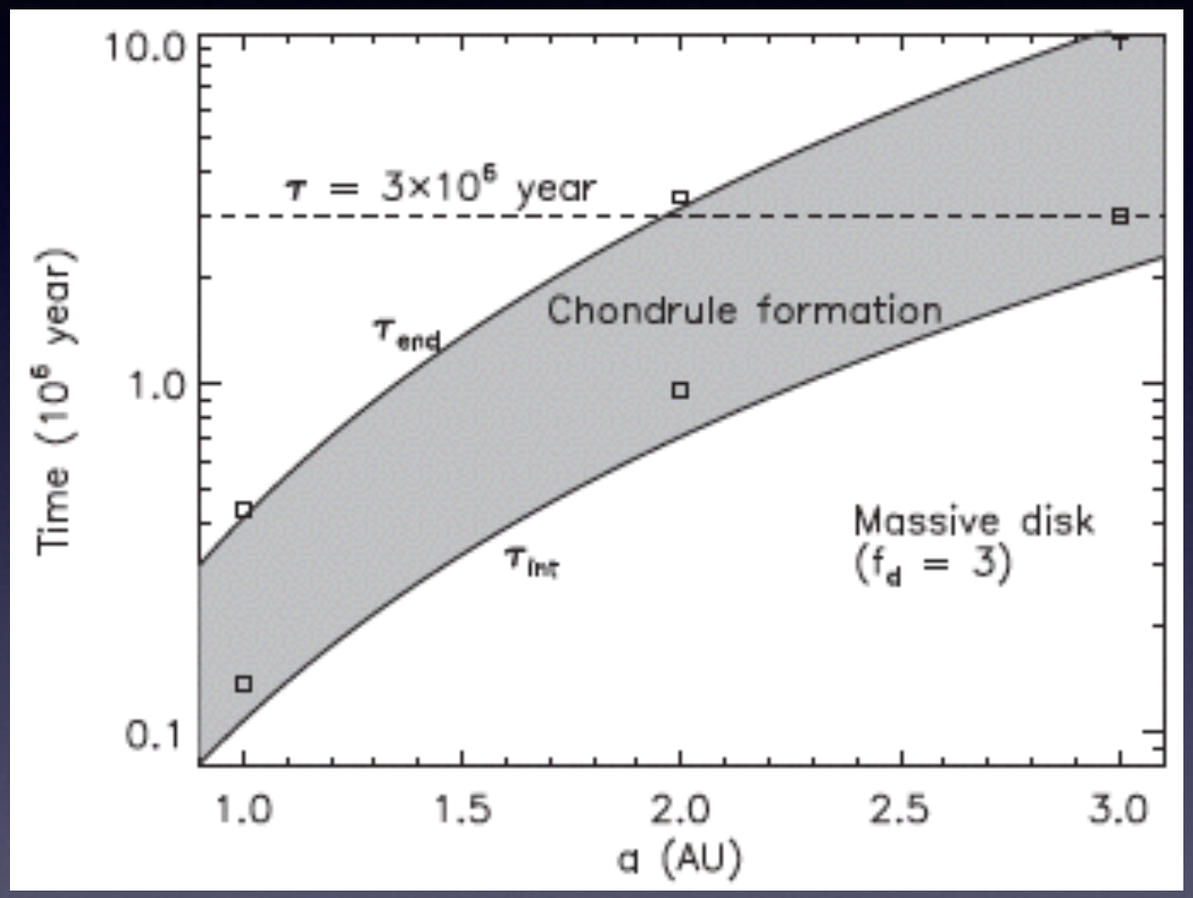
The total chondrule abundance is 1 % of the protoplanet mass

The abundance and the timescale are obtained

# Resultant abundance and timescales

Hasegawa et al 2016a

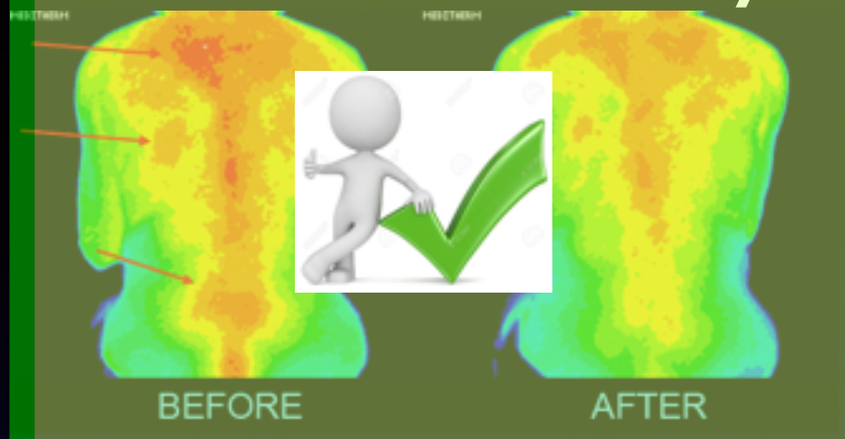



Both values seem reasonable!!

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

Thermal History




Abundance

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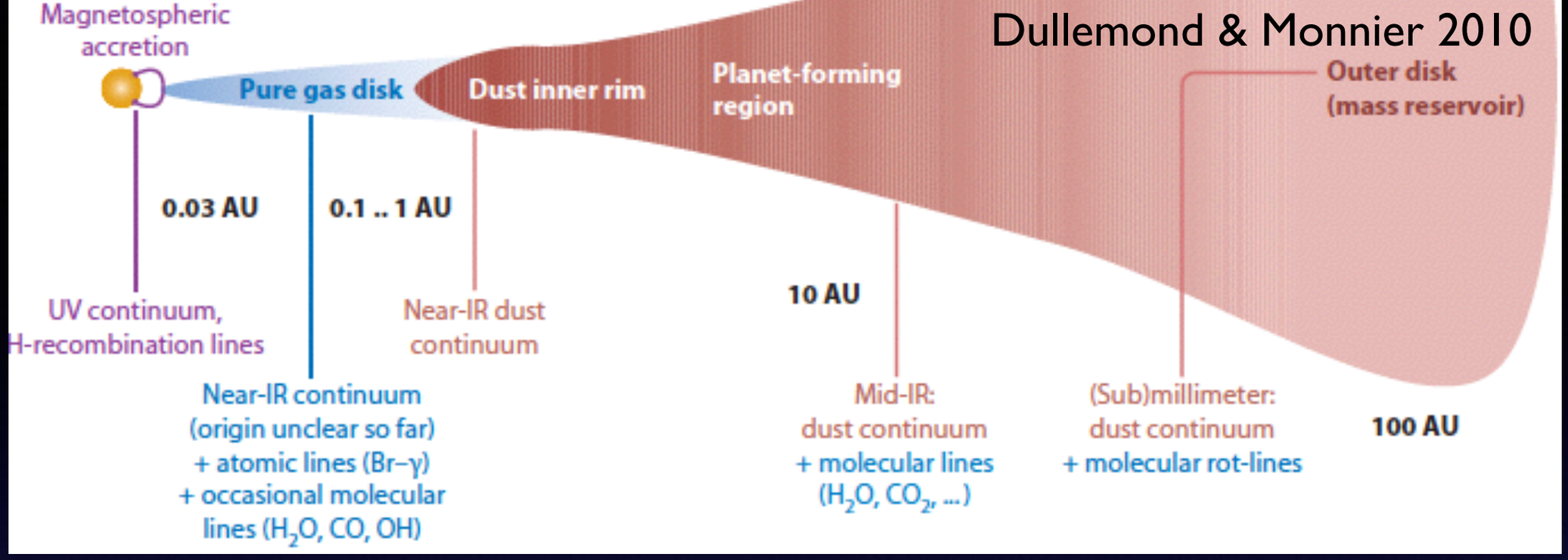
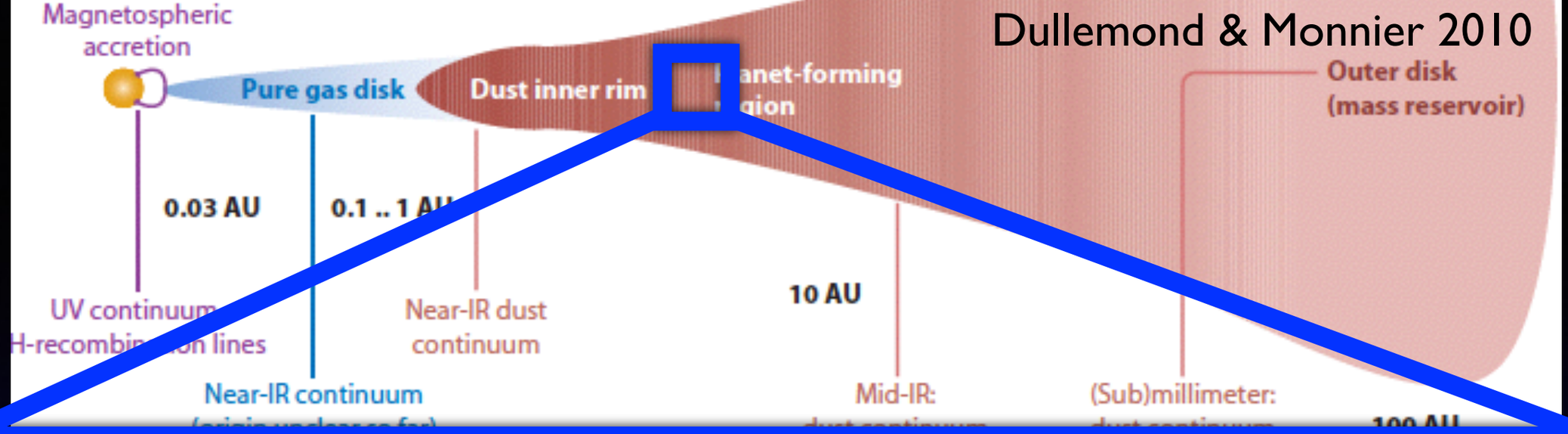
B-fields


Dullemond & Monnier 2010
Magnetospheric accretion
Pure gas disk
Dust inner rim
Planet-forming region
Outer disk (mass reservoir)
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

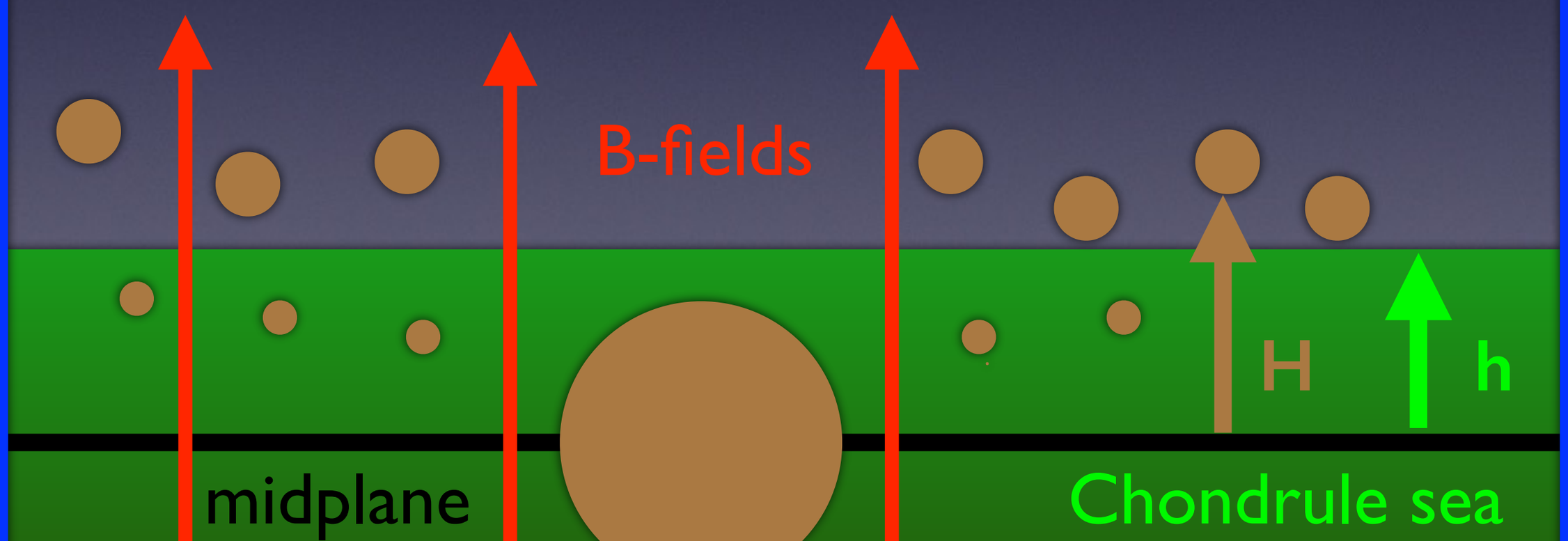


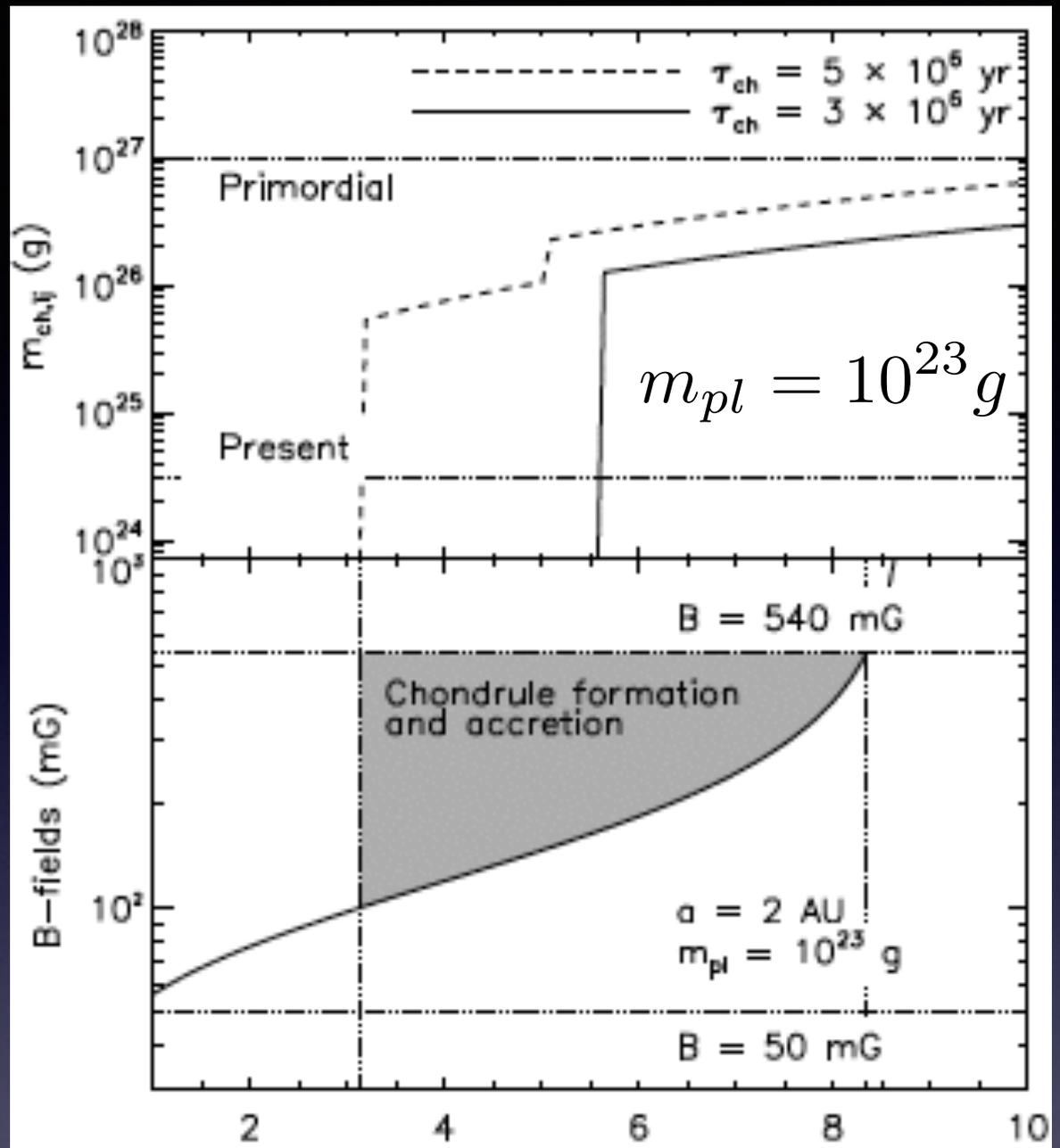

# Chondrule accretion occurs when H < h

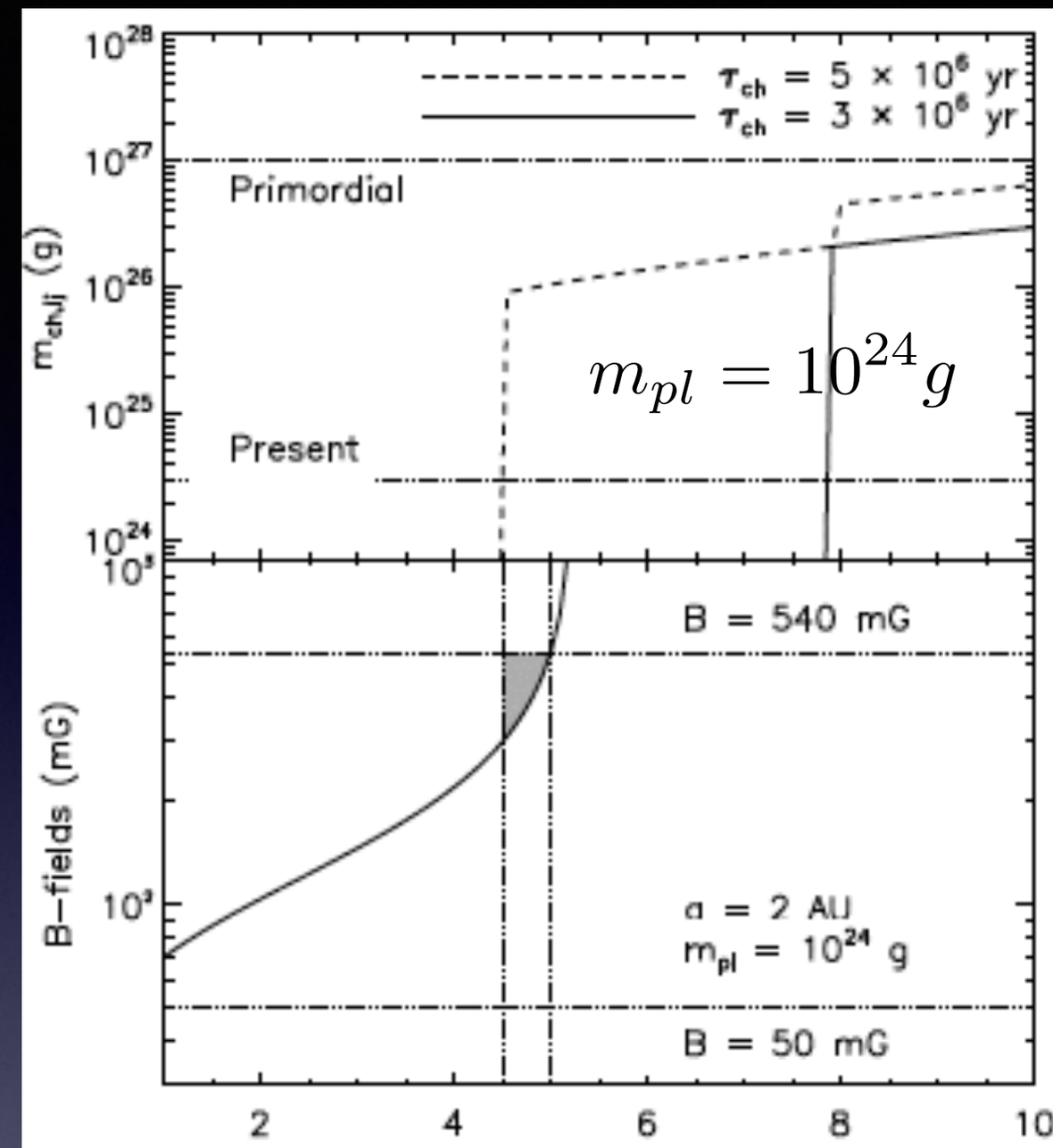
Lesion et al 2015

h increases with vertical magnetic flux

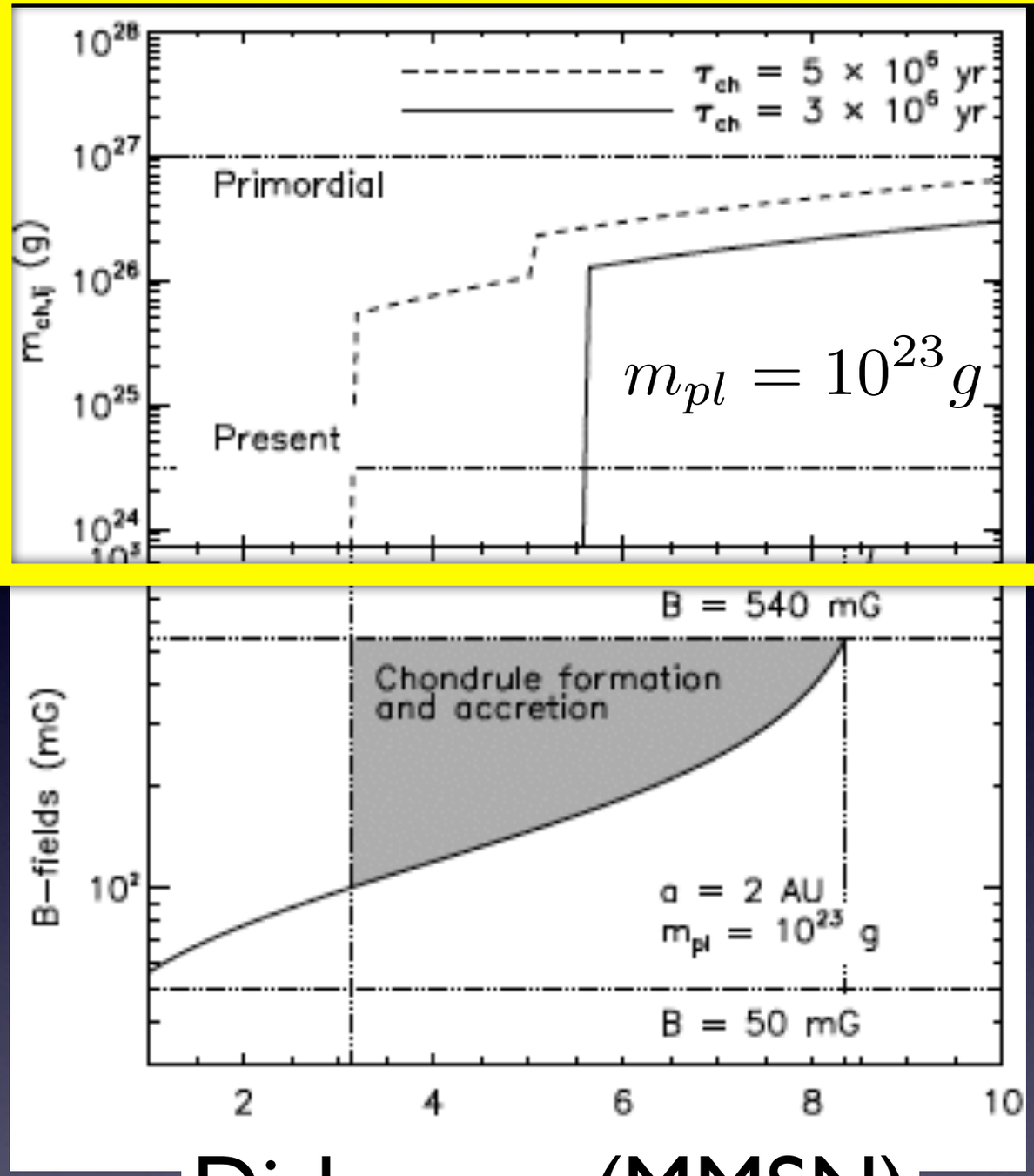
H increases with disk mass and planetesimal mass

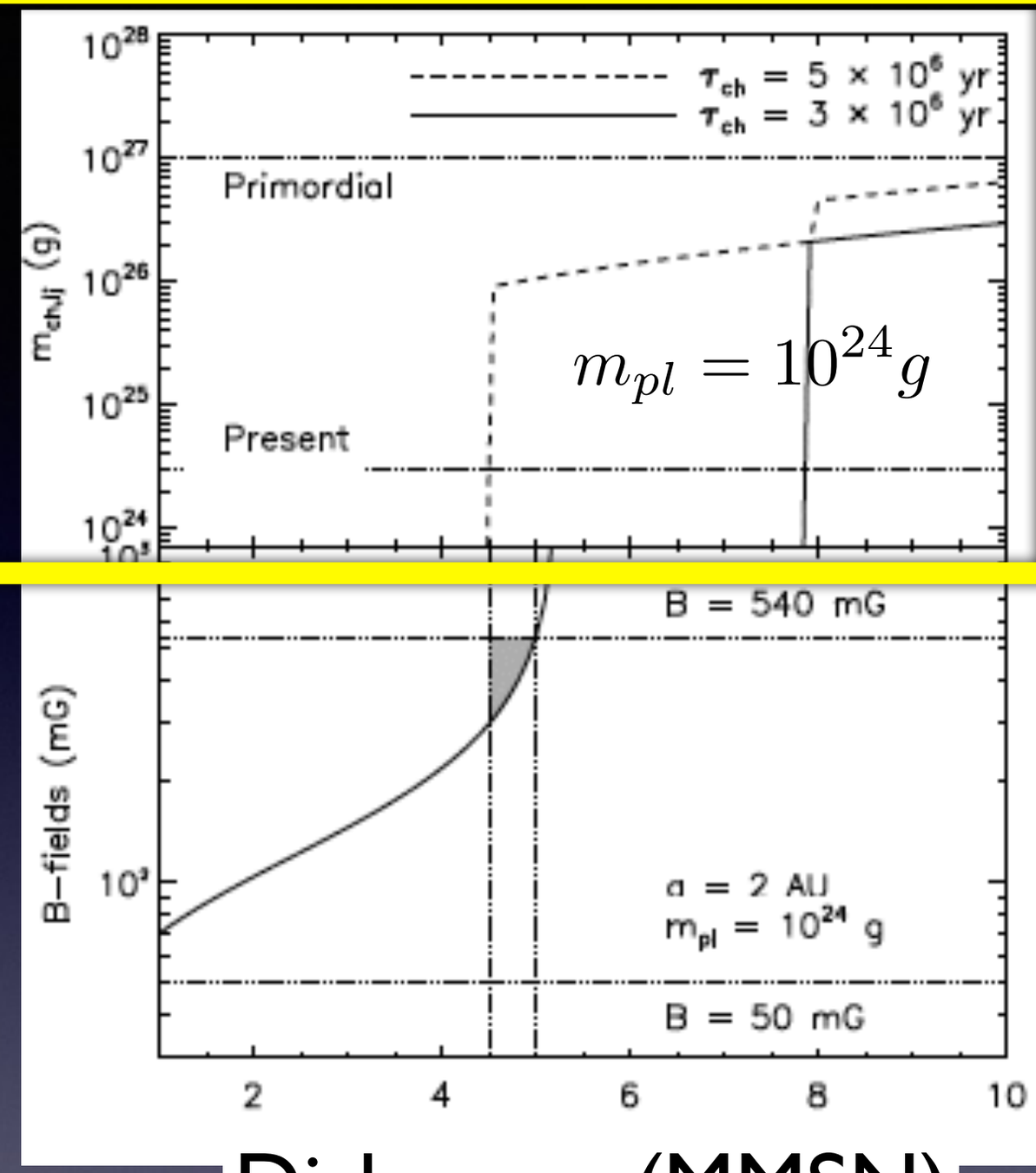




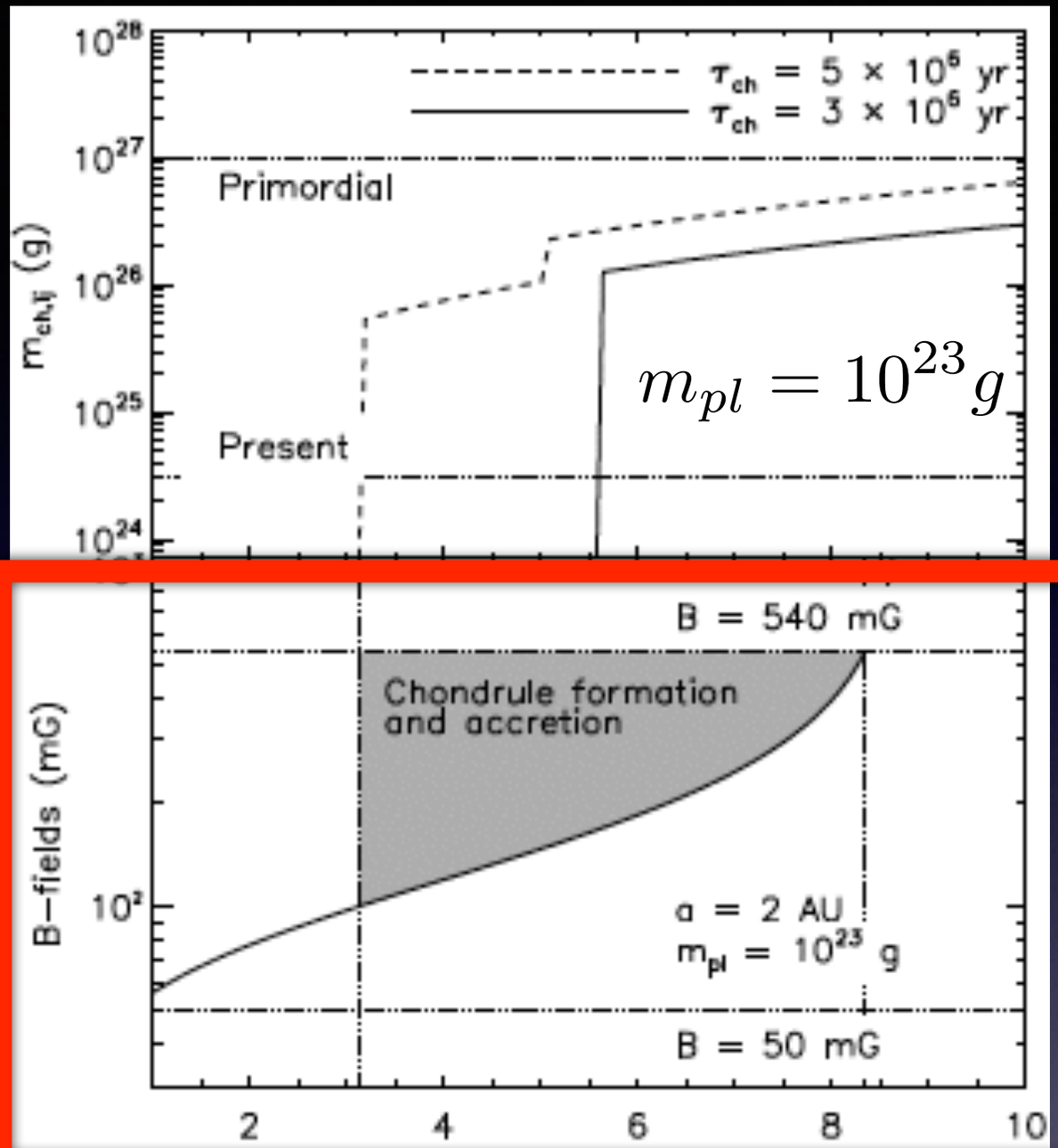

Hasegawa et al 2016b

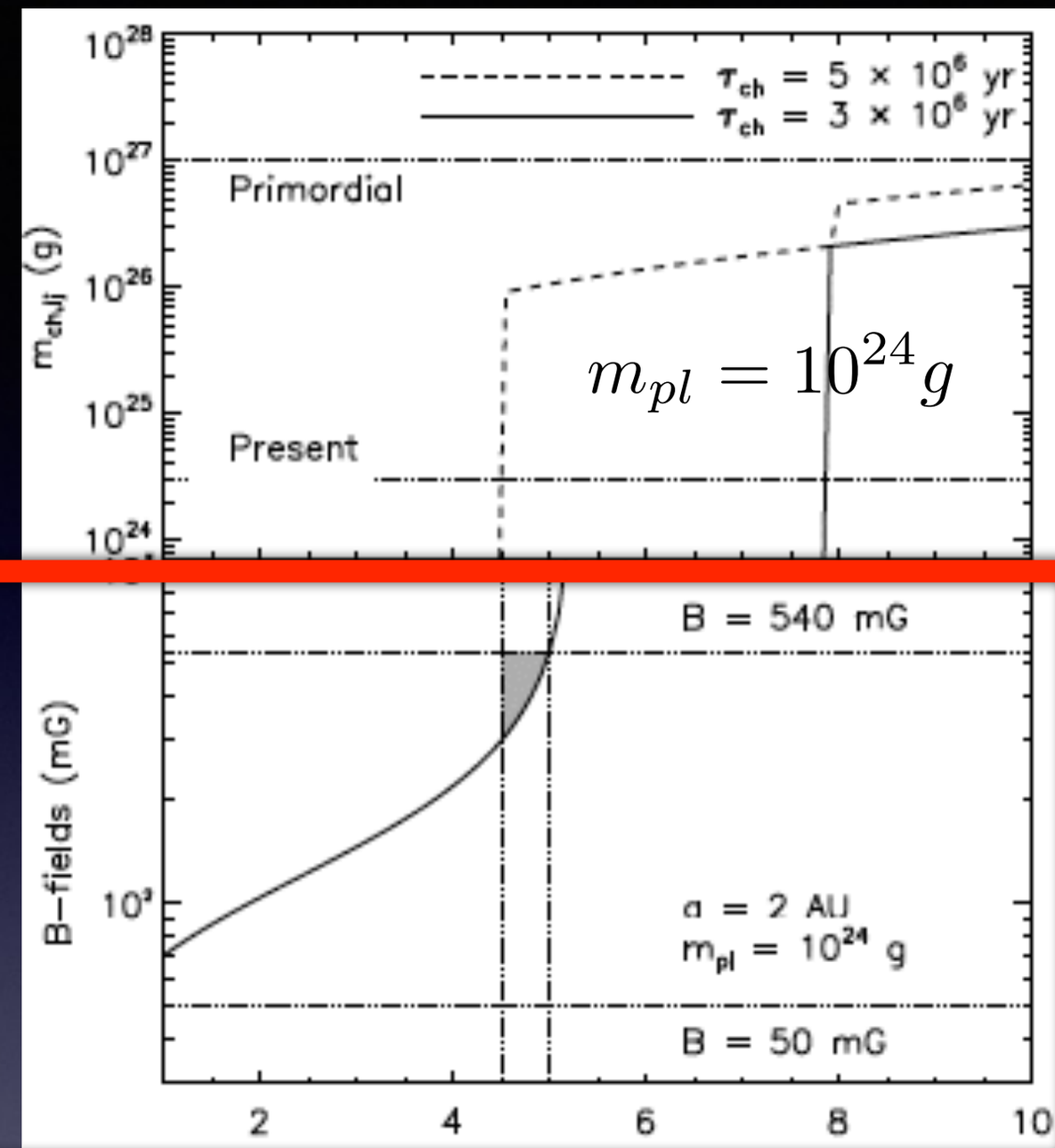



A high disk mass is needed for
a short formation time & massive planetesimals

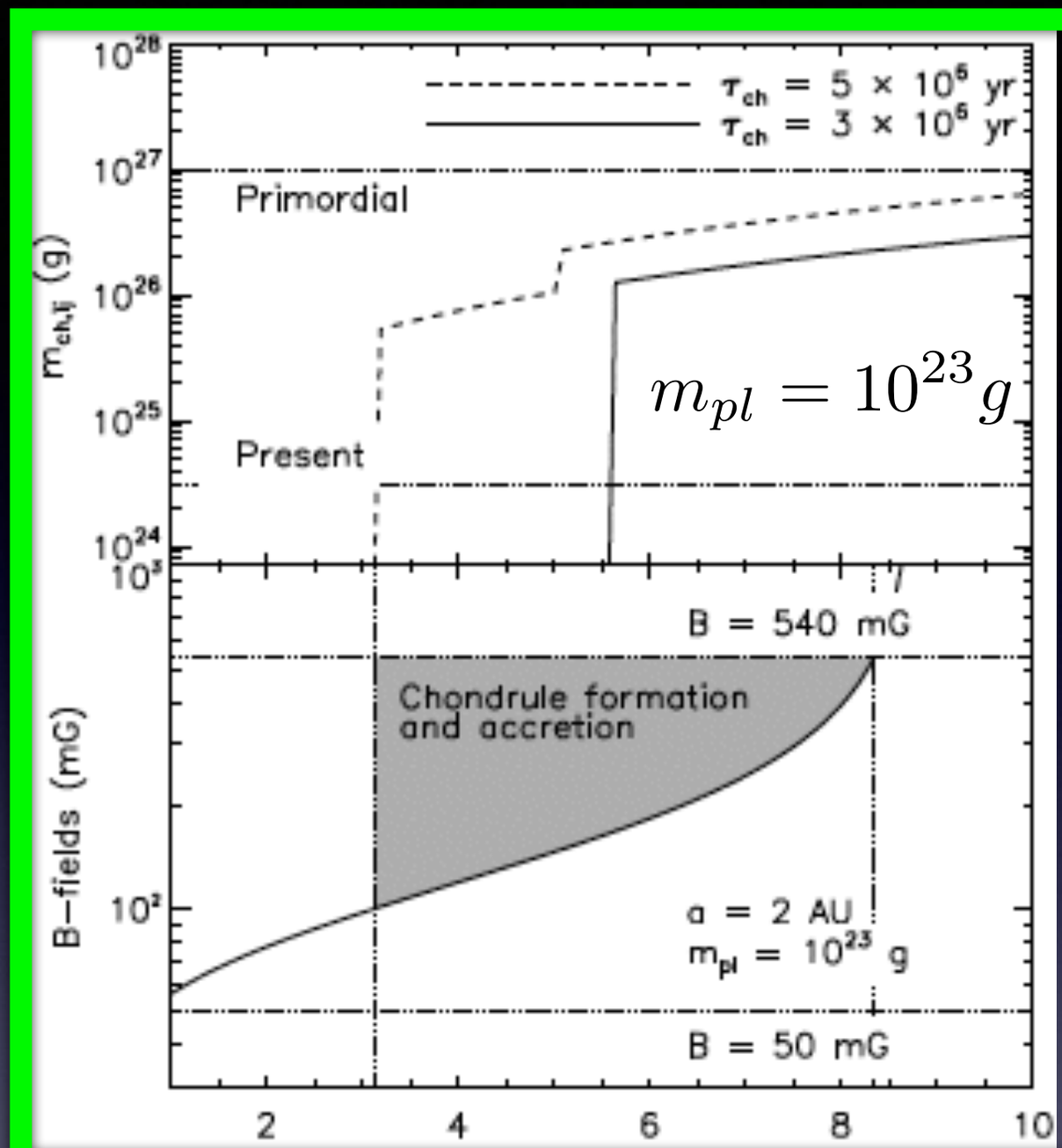
Hasegawa et al 2016b



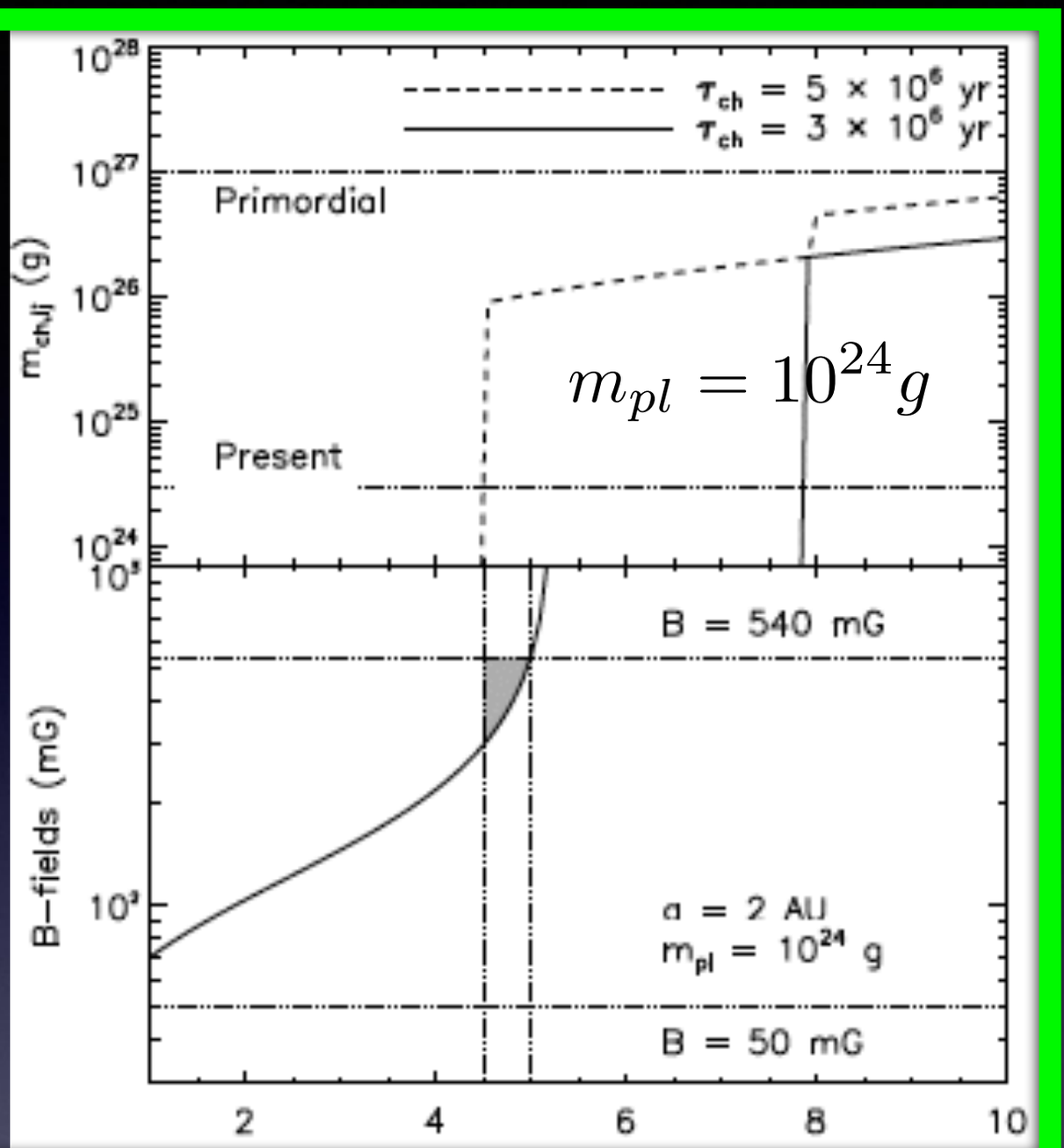




A strong B-field is needed for
massive disks and massive planetesimals

Hasegawa et al 2016b




Disk mass (MMSN)




Disk mass (MMSN)

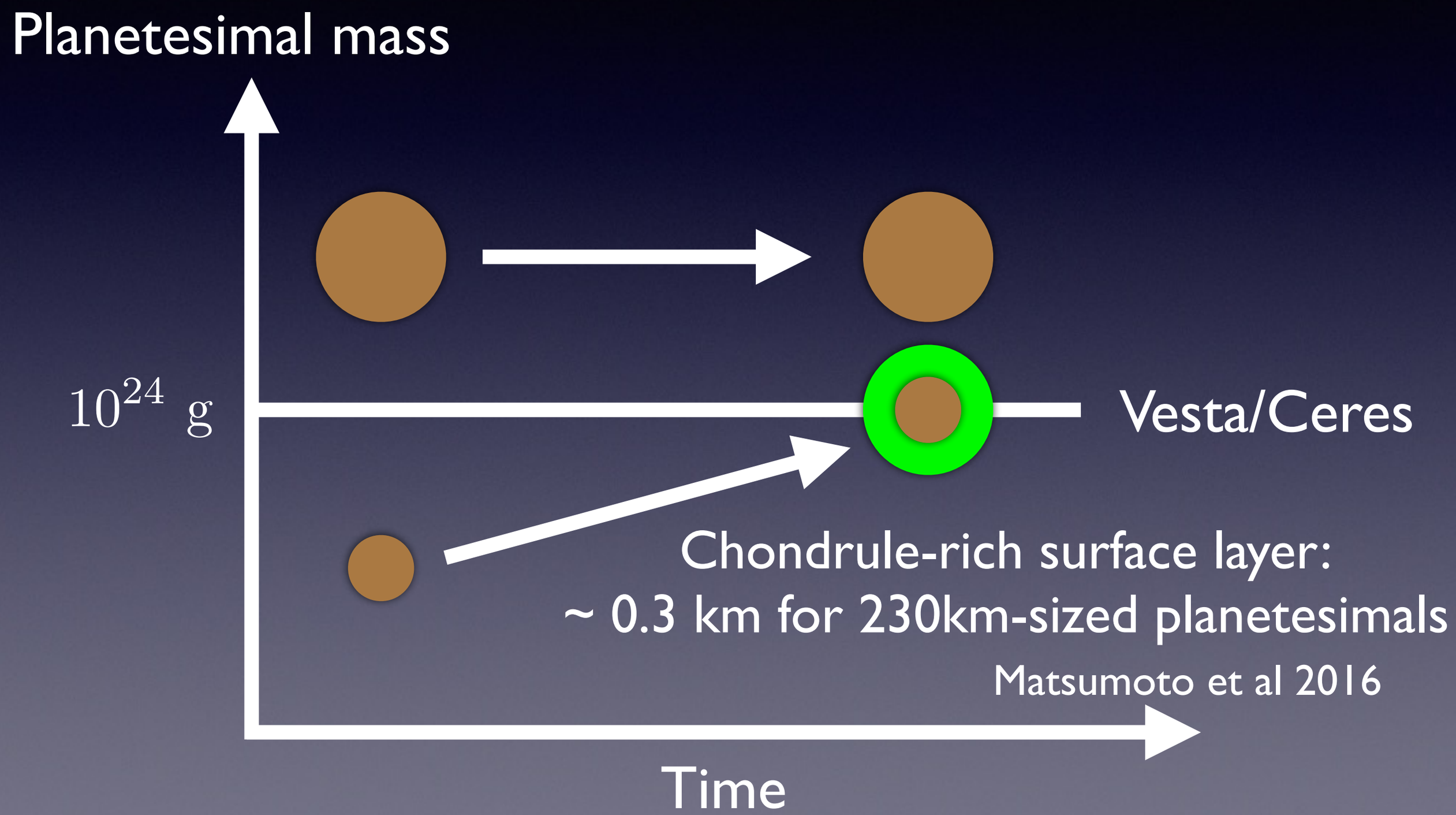
All the currently available meteorite data can be satisfied when the disk mass is < 5 MMSN

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

Hasegawa et al 2016b



# Summary

Hasegawa et al 2016a, ApJ, 816, 9
Hasegawa et al 2016b, ApJ, 820, L12
Matsumoto et al 2016, ApJ, submitted
Wakita et al 2016, ApJ, to be submitted

- 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!!
- The upper limit of the planetesimal mass is comparable to that of Vesta/Ceres, and future observations/missions may provide an invaluable opportunity to verify our scenario!!