Radial Mixing of Grains and Precursors of Planetesimals

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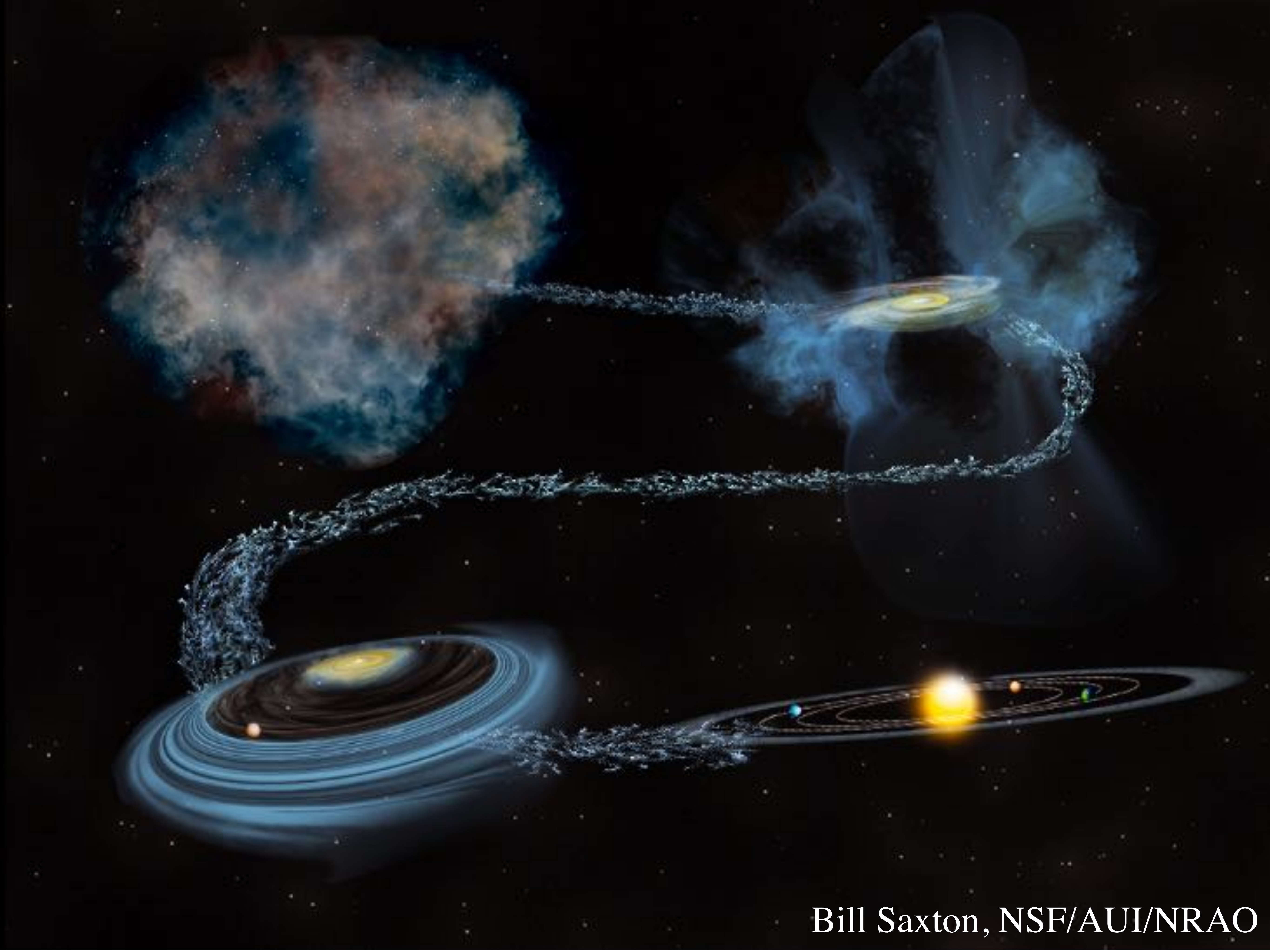
EOS-NExSS

Outline

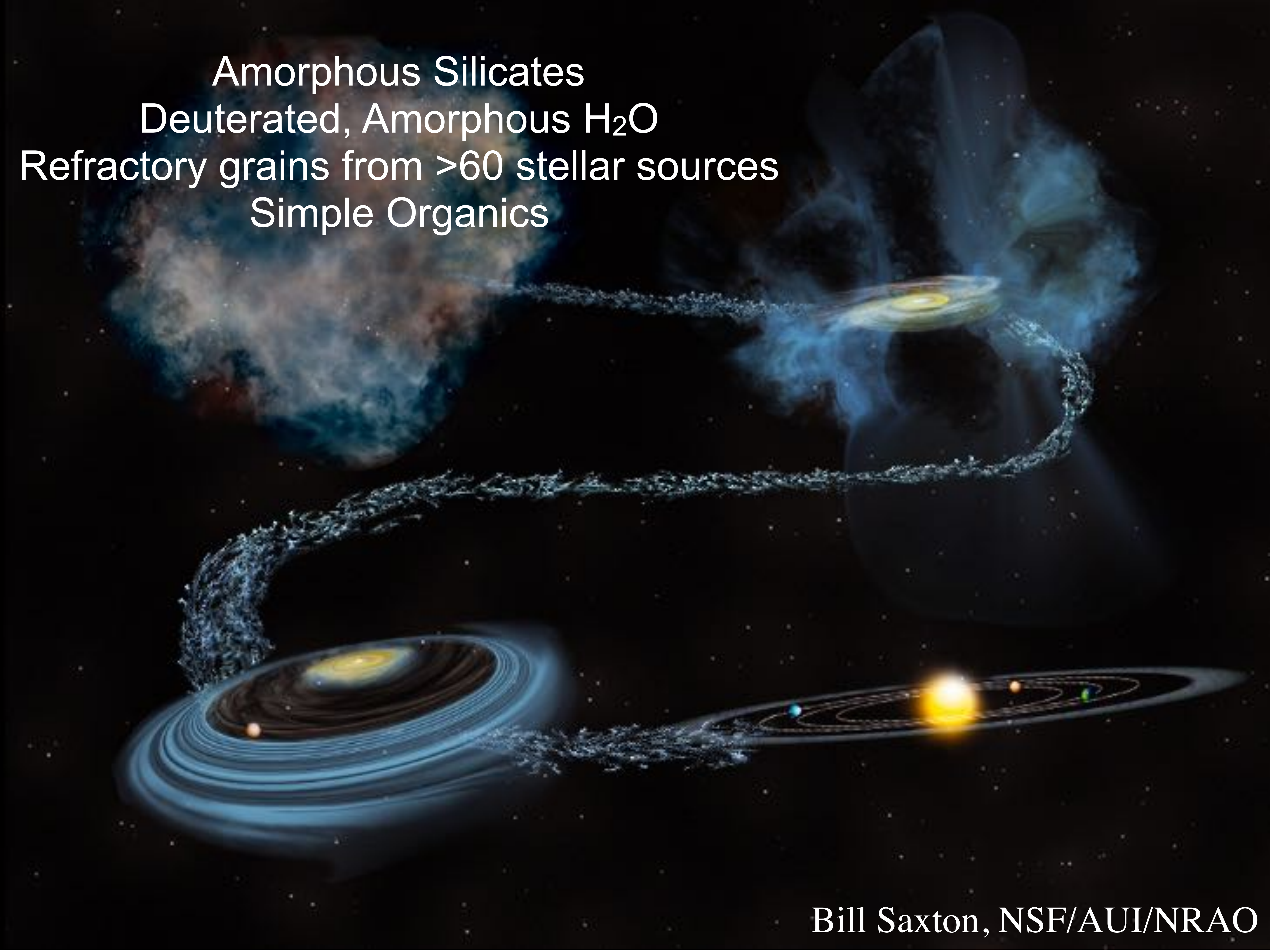
- Observations of Primitive Materials in the Solar System and other Protoplanetary Disks
  - Evidence of Dynamics and Mixing
- Dynamical Evolution of Solids and Gas in Protoplanetary Disks
- Protoplanetary Disk Evolution: Knowns and Unknowns
  - Dynamic Evolution
  - Alpha Disk; GI
  - Jets and MHD Winds
- Putting the Story Together Vertical Dynamics + Radial Extrapolation

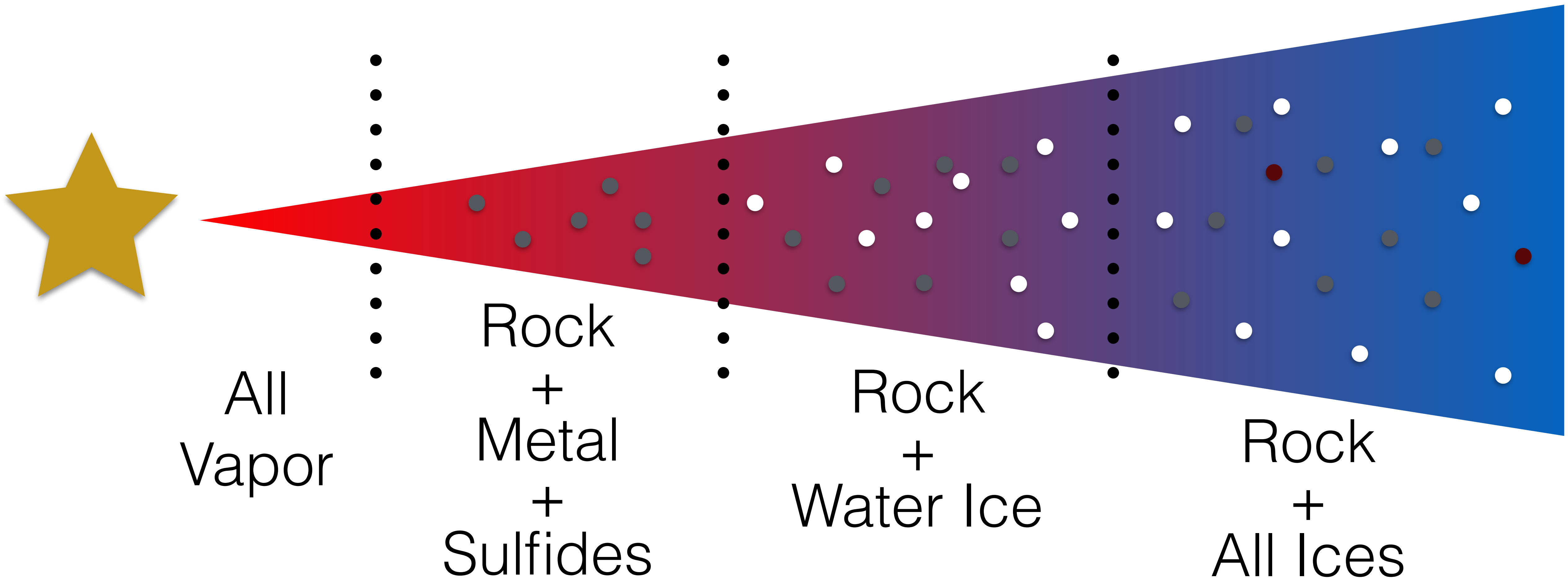


Bill Saxton, NSF/AUI/NRAO

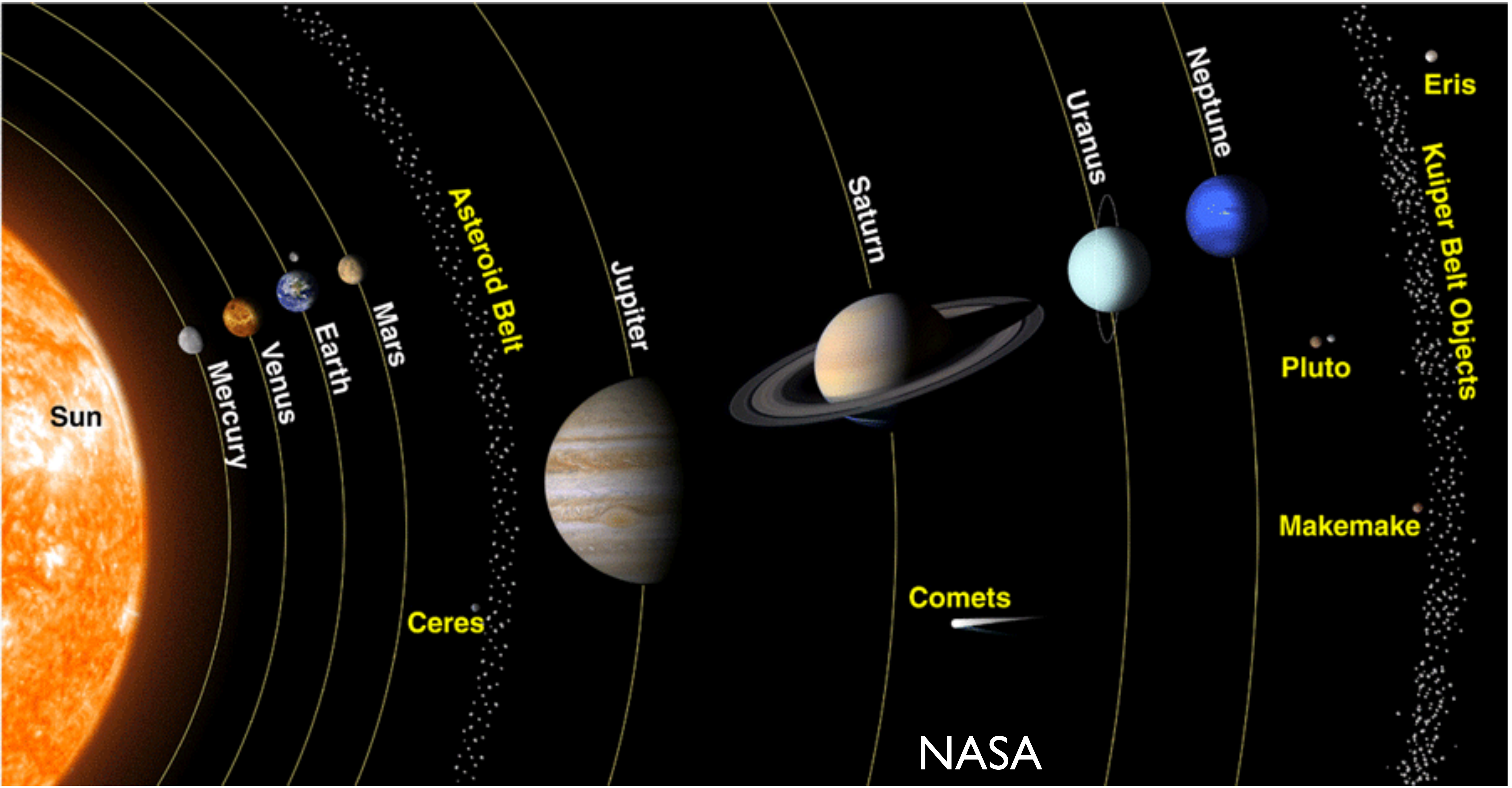

Dennis di Cicco/Sean Walker


Dennis di Cicco/Sean Walker

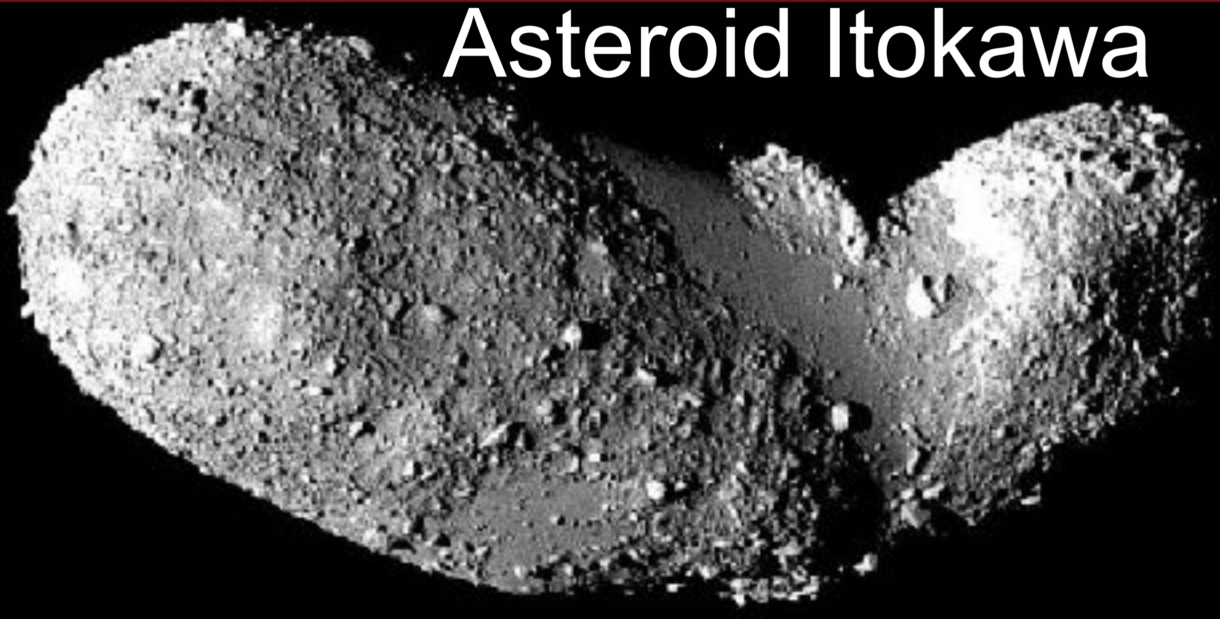

Amorphous Silicates
Deuterated, Amorphous H_2O
Refractory grains from >60 stellar sources
Simple Organics
Bill Saxton, NSF/AUI/NRAO


All
Vapor
Rock
+
Metal
+
Sulfides
Rock
+
Water Ice
Rock
+
All Ices

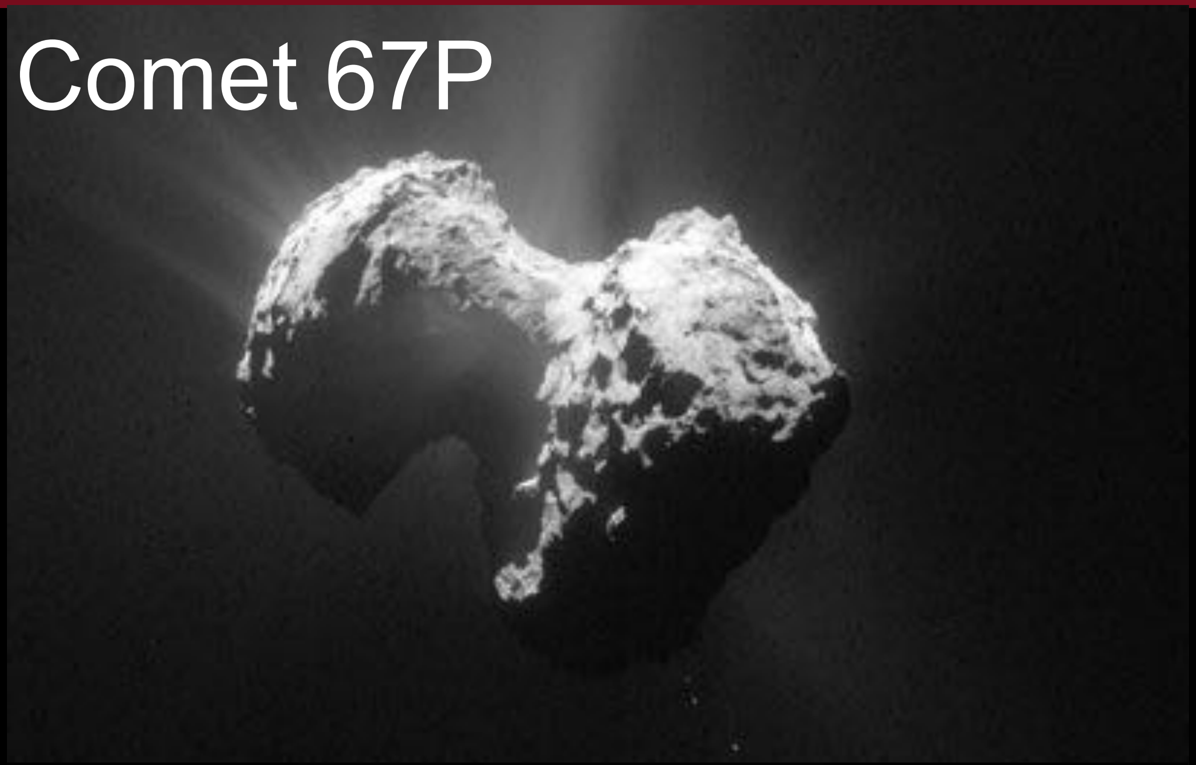
Our Solar System is a fossil record of planet formation…we just have to know where to look.



Primitive bodies record the physical/chemical environments present during planet formation.



Asteroid Itokawa



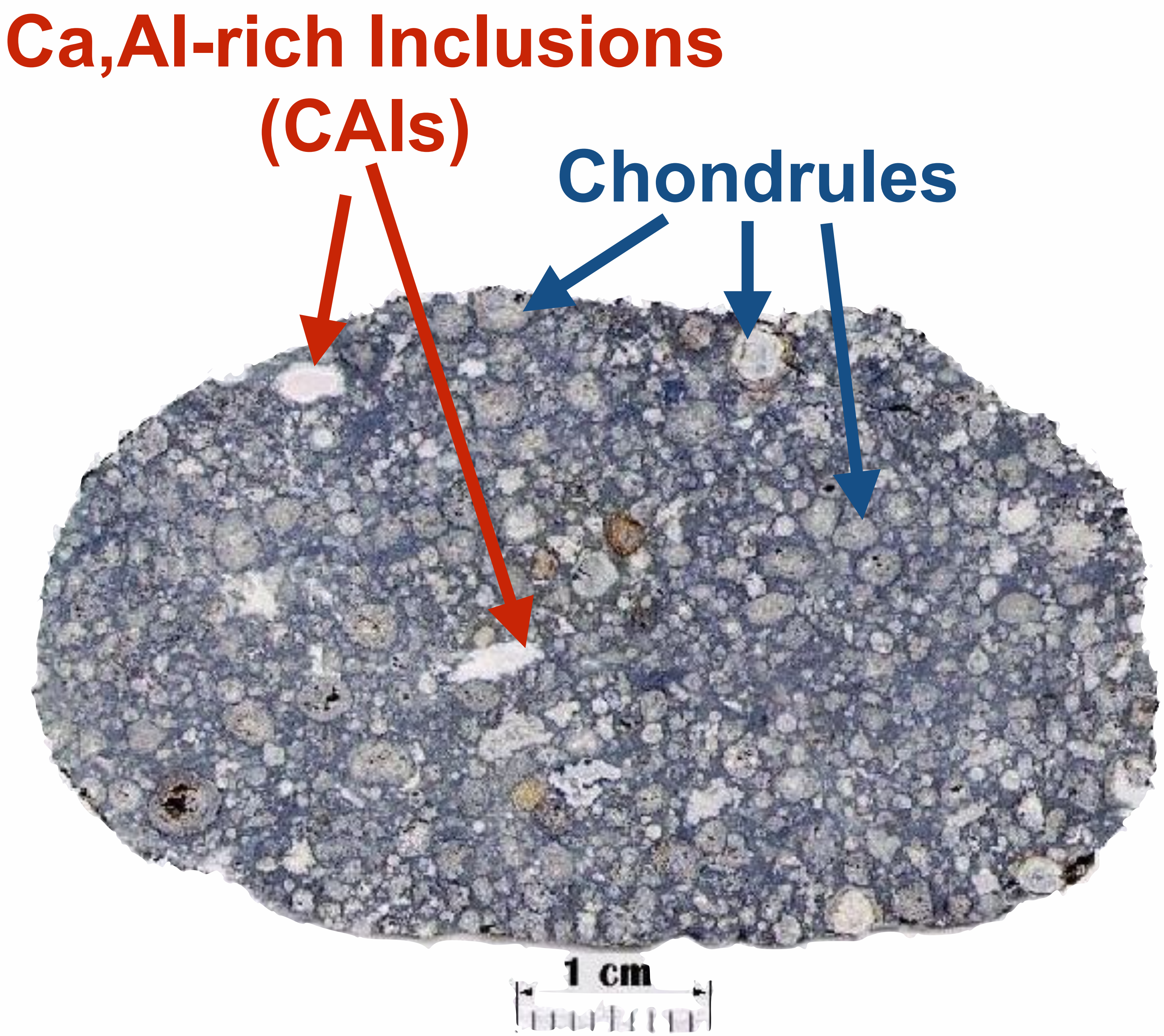
Comet 67P

Asteroid Ceres

Comet Wild 2

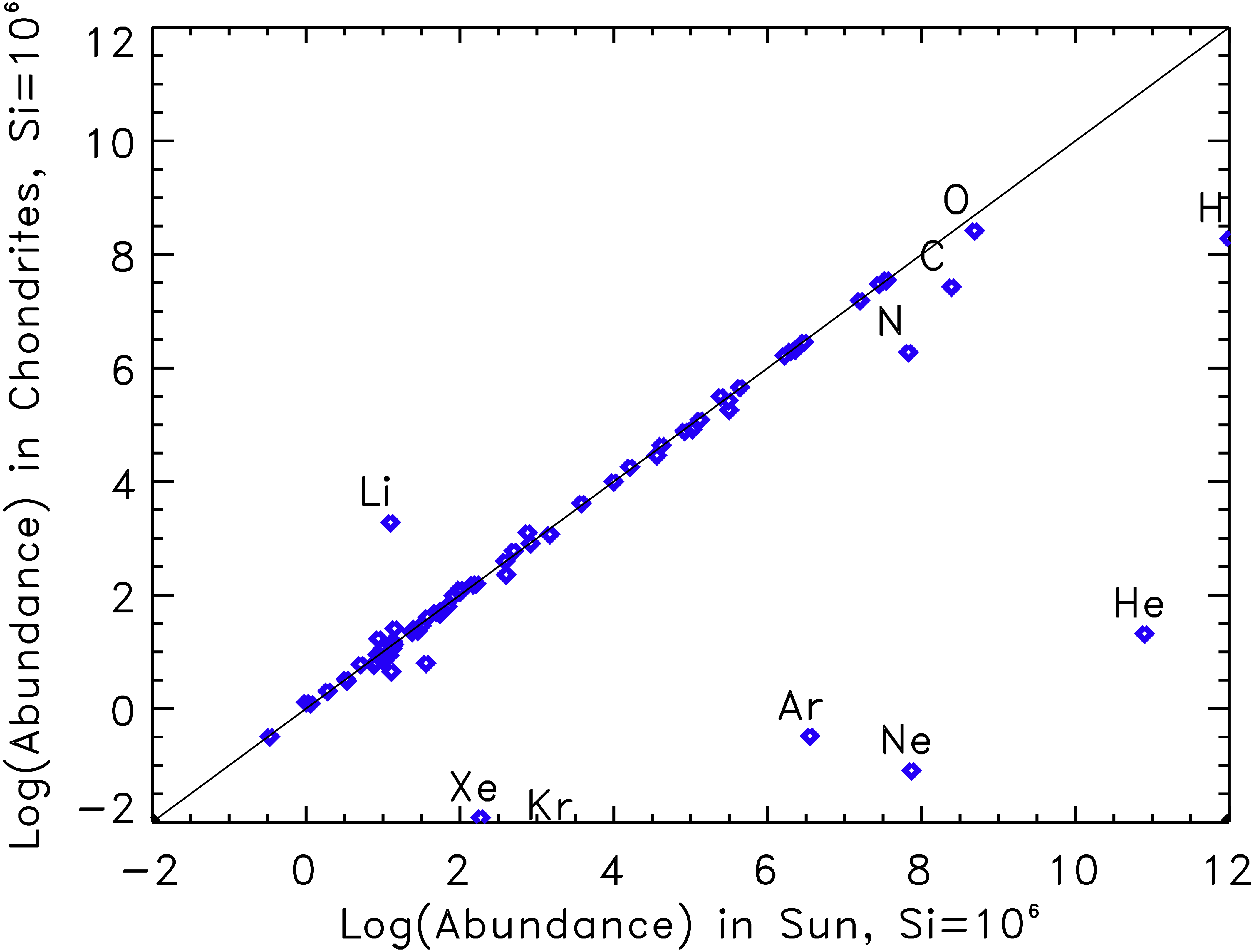
Primitive samples are naturally delivered to Earth on a regular basis.

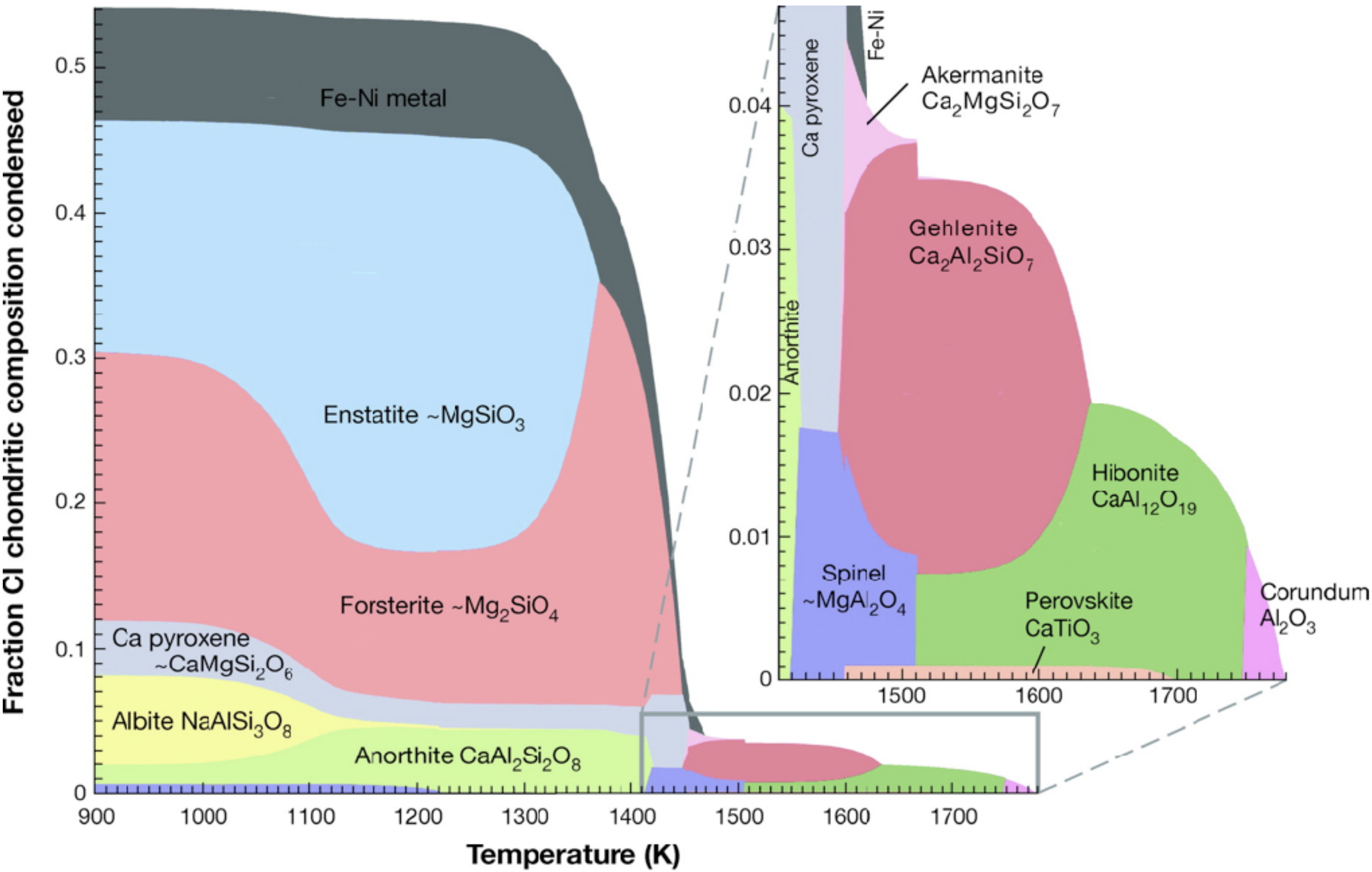
Chondritic samples provide detailed clues about the early stages of planet formation.



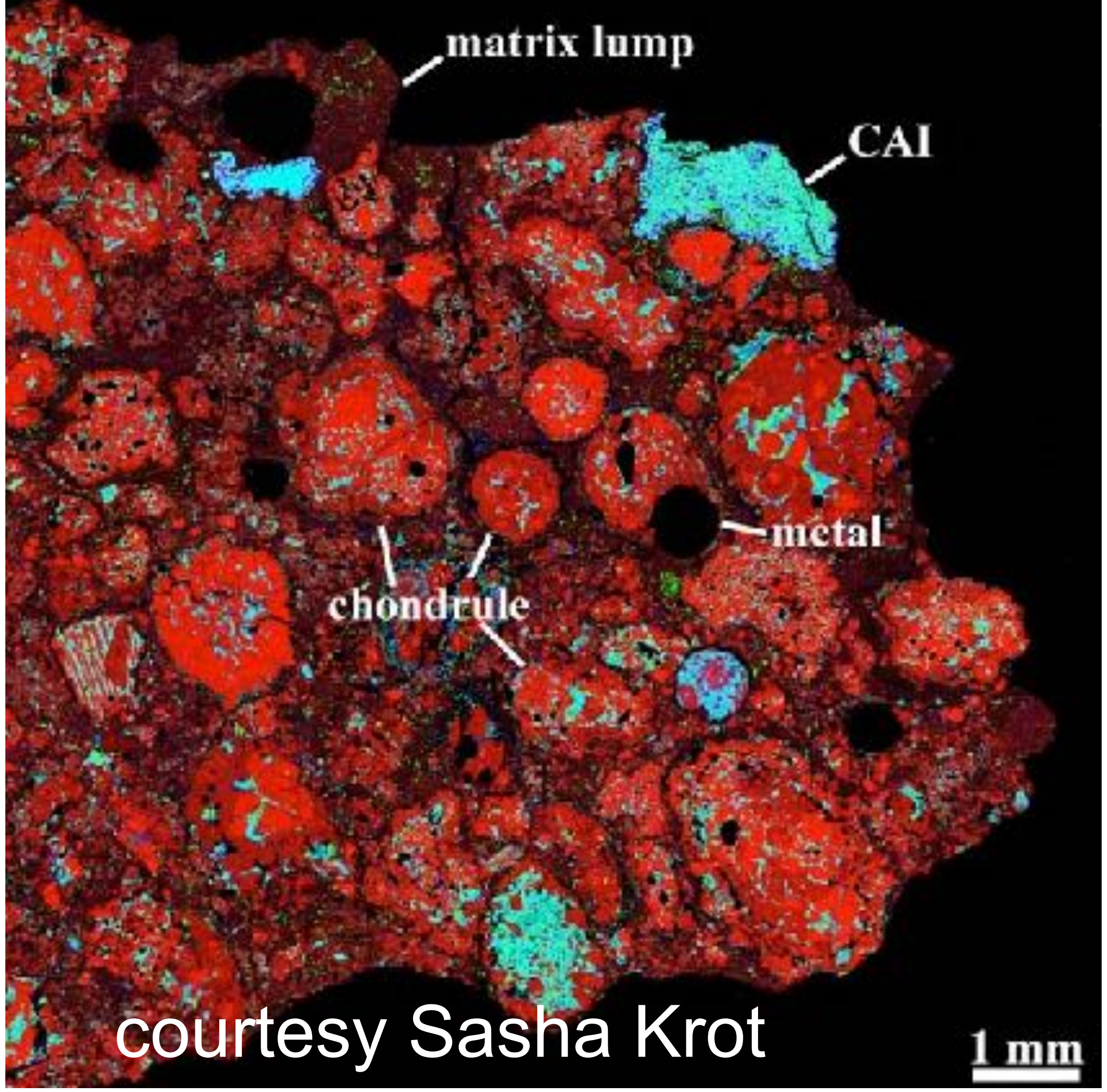
Allende Meteorite

Chondritic Composition





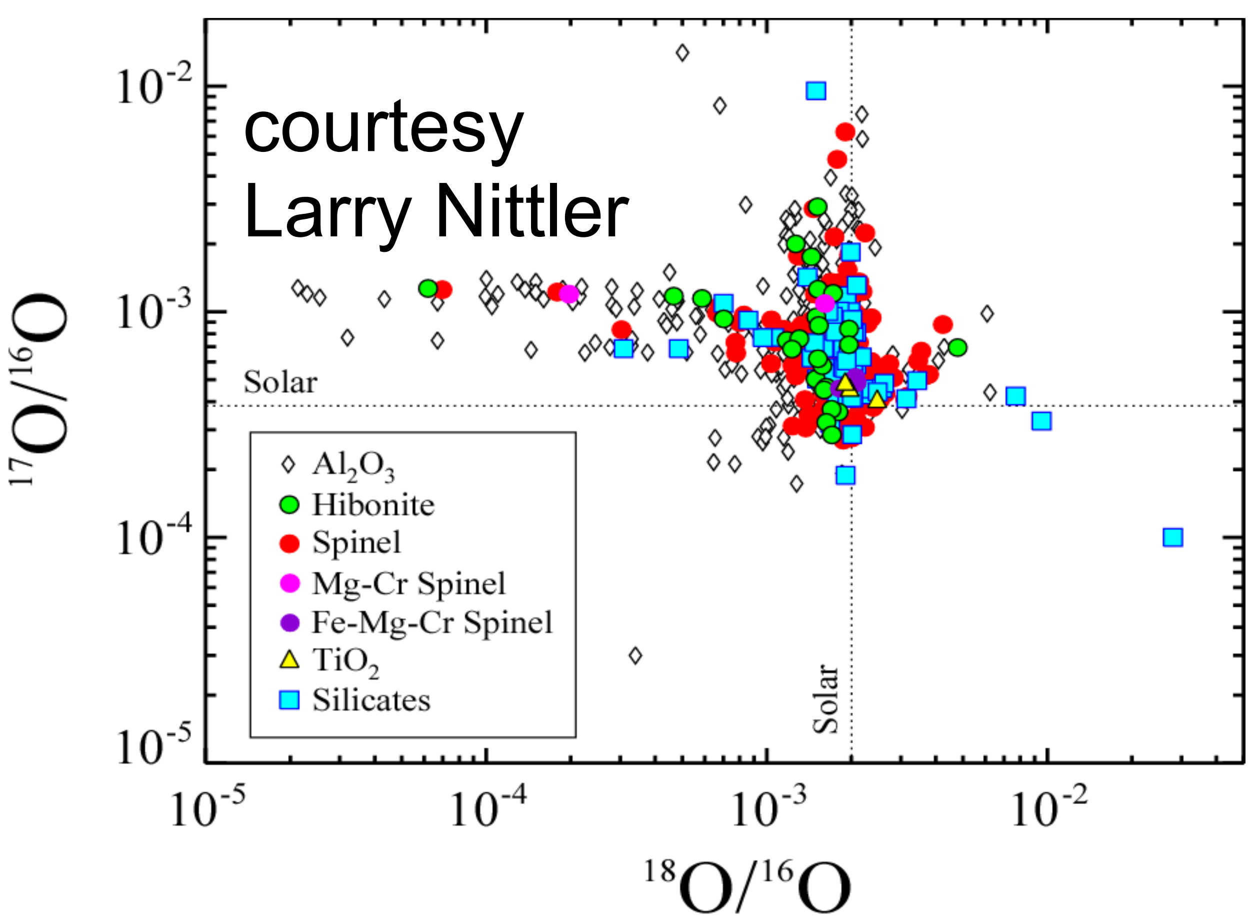
Equilibrium chemistry at constant pressure

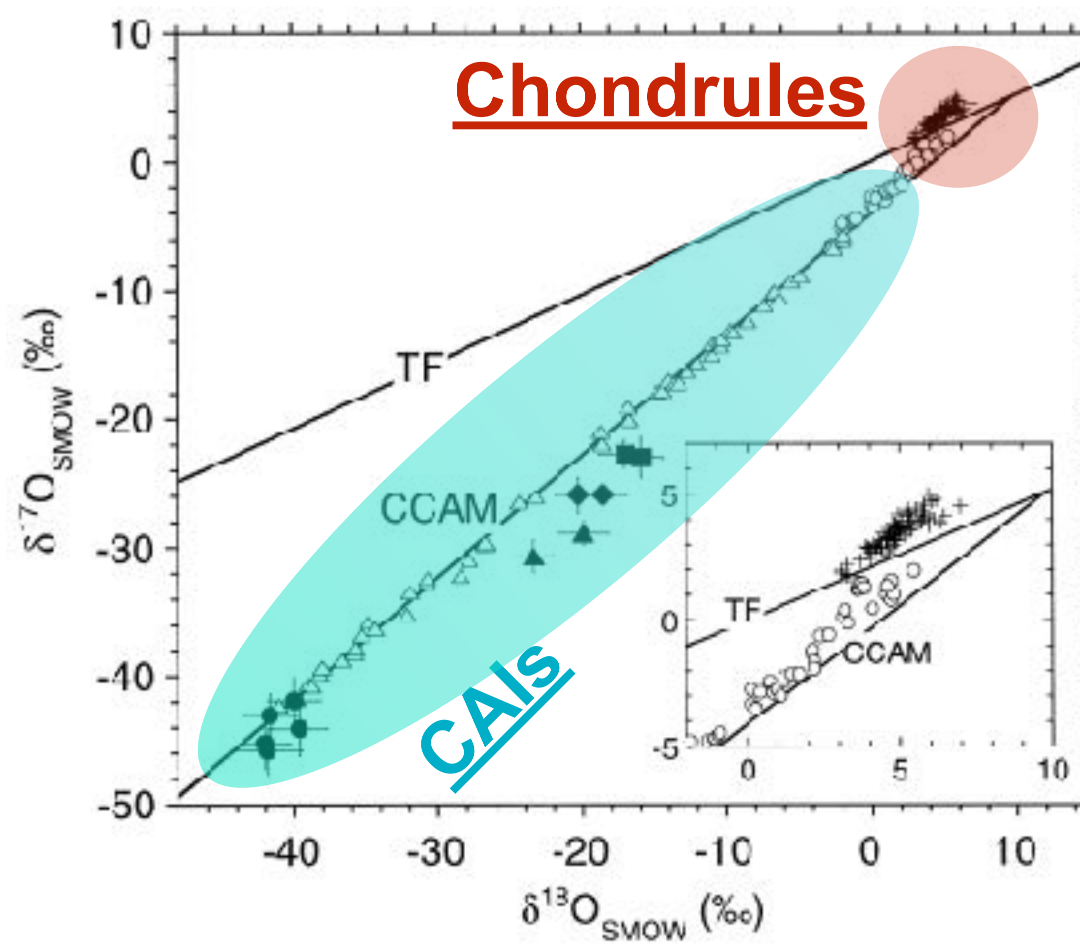


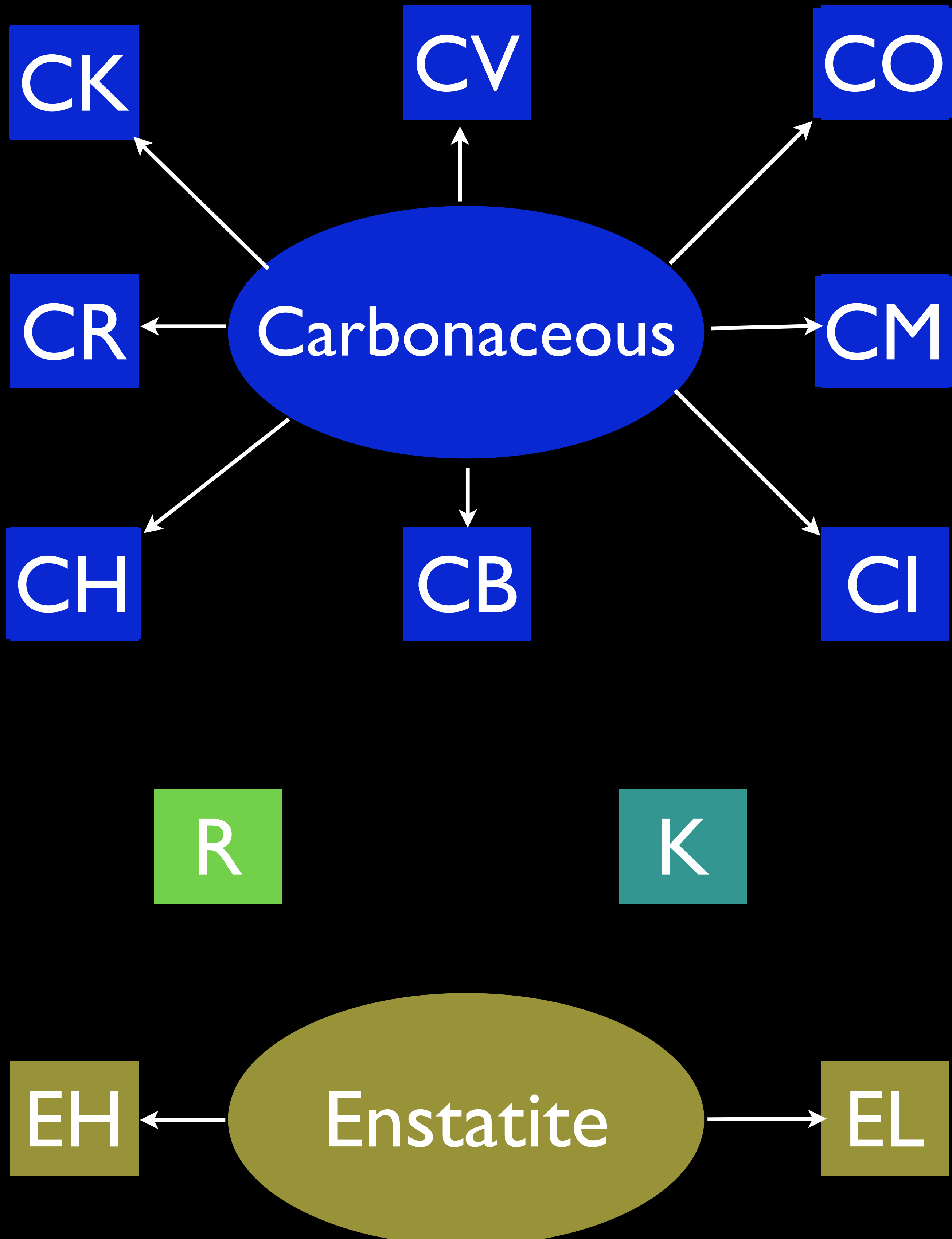
CAIs: Ca, Al-rich,
Minerals form at T>1500 K

Chondrules: Mg, Fe rich
Melted at T~1700-2100 K
Cooled at 10-1000 K/hr

Matrix: Everything else
- -Organics
- -Amorphous Silicates
- -Crystalline Silicates
- -Presolar grains

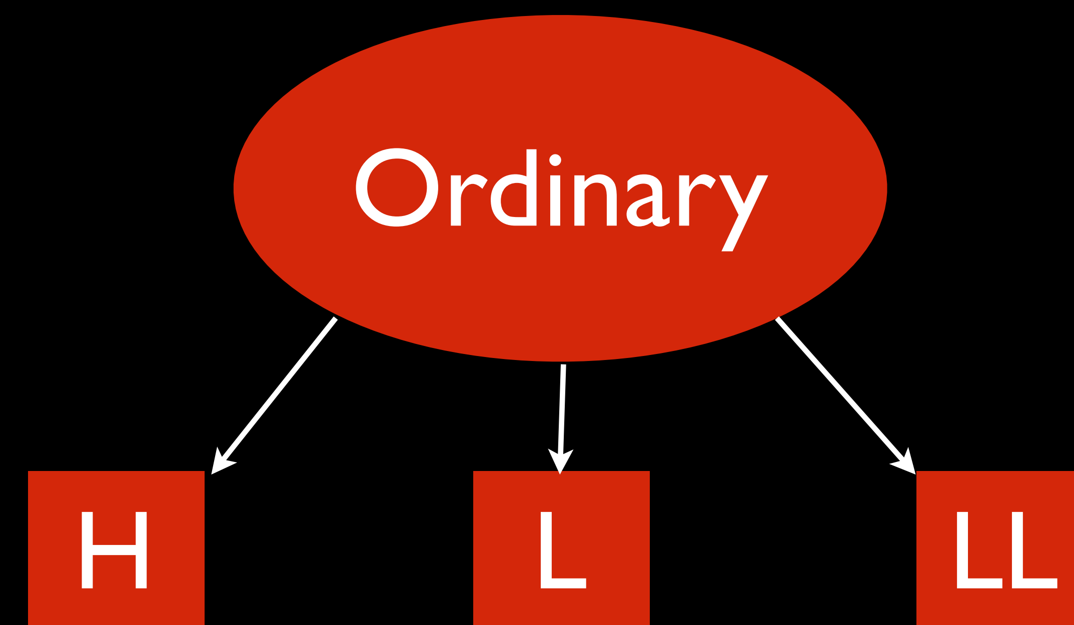




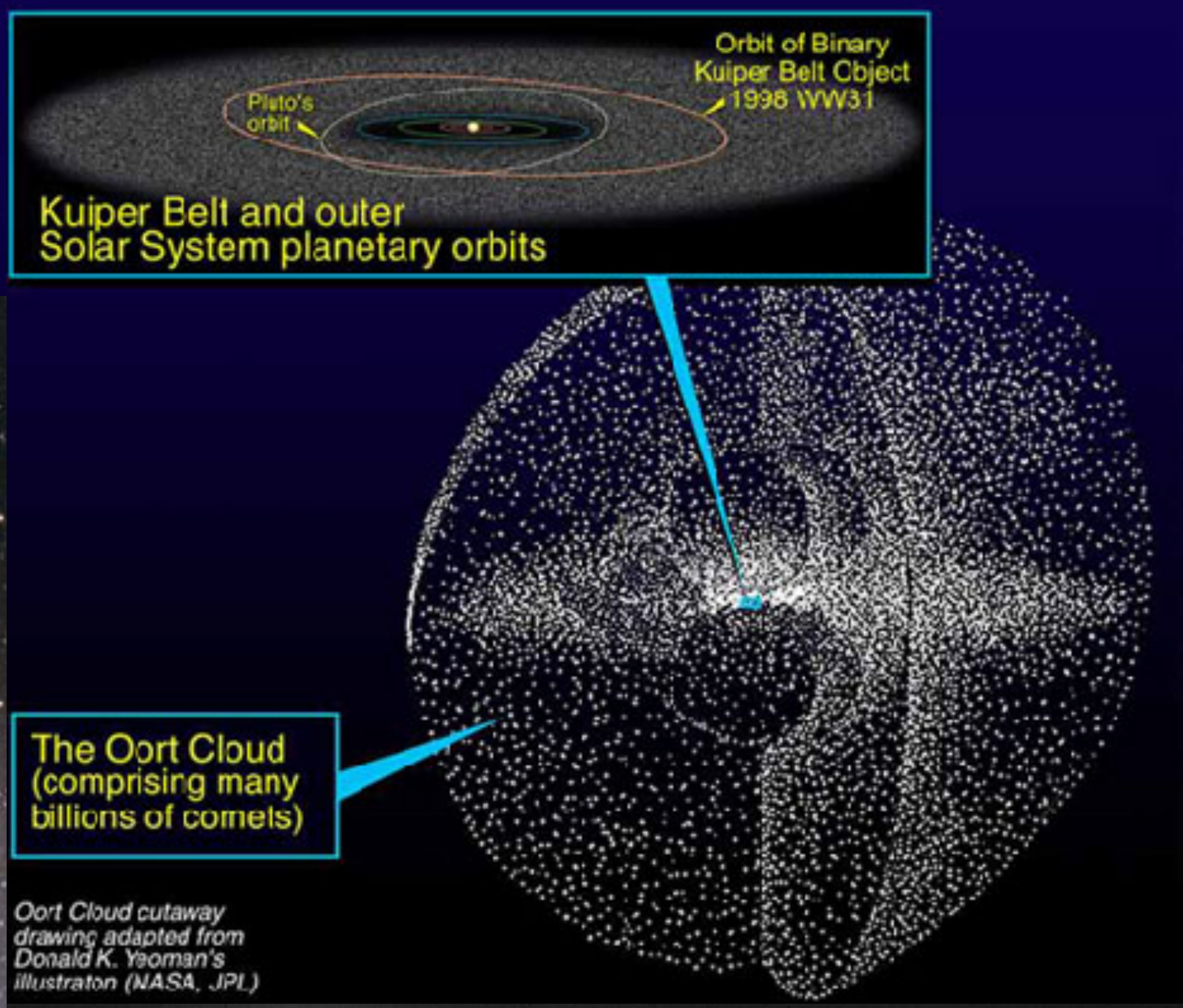


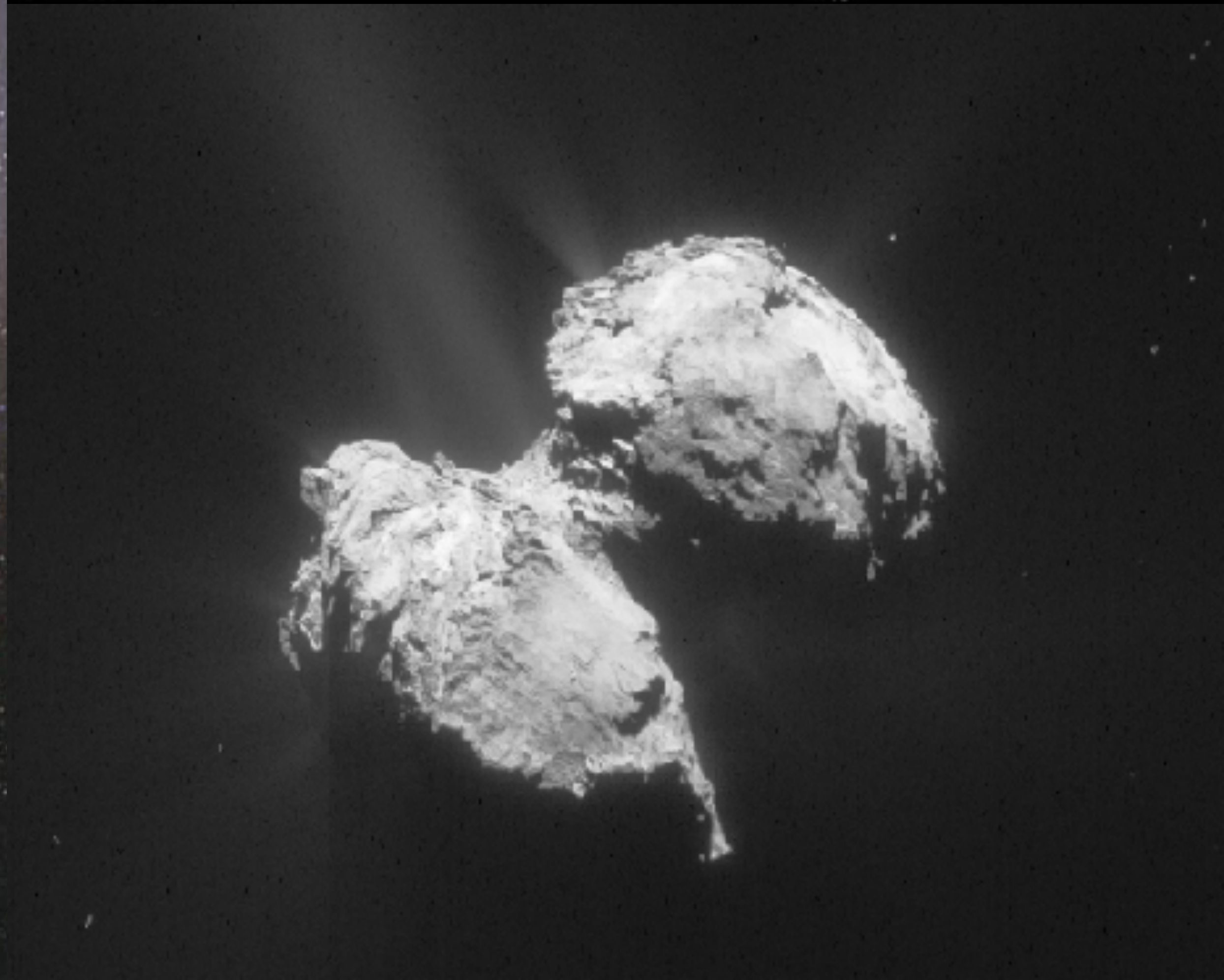
There are actually 3 classes of chondrites, and 15 different groups.

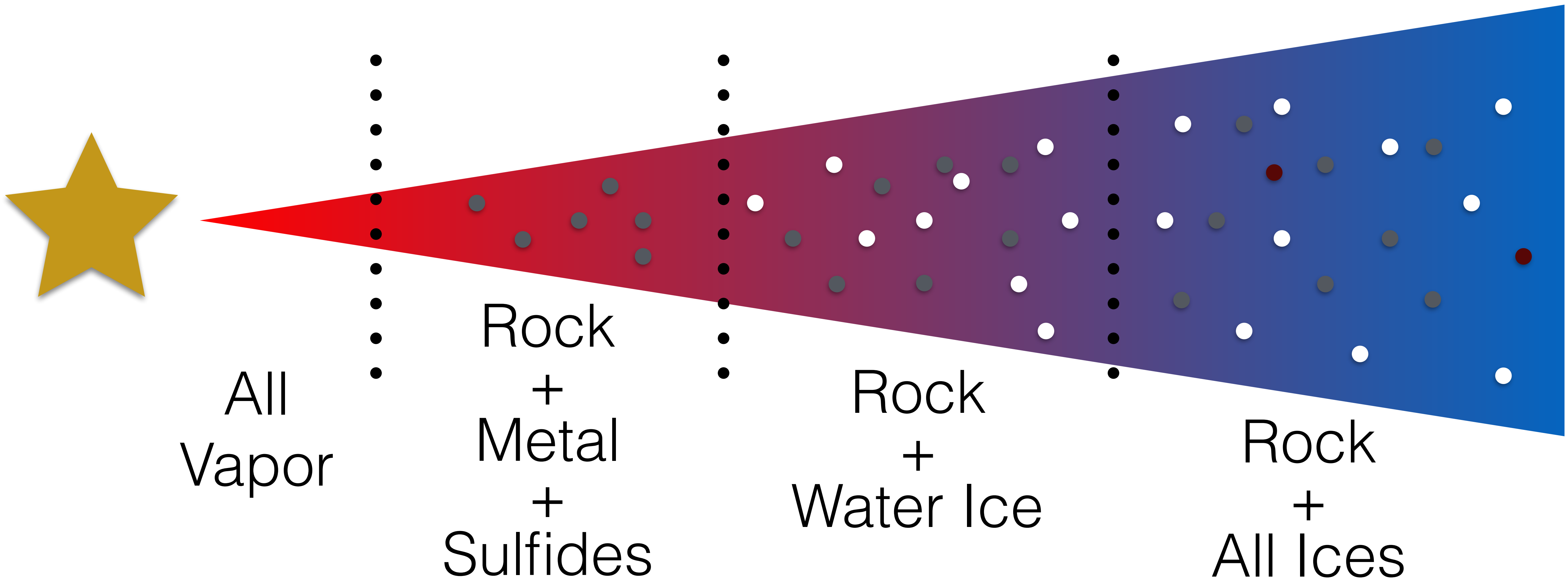
Distinguishing features: petrology, chemical composition, and oxygen isotope ratios.



Comets: Records of the outer Solar System



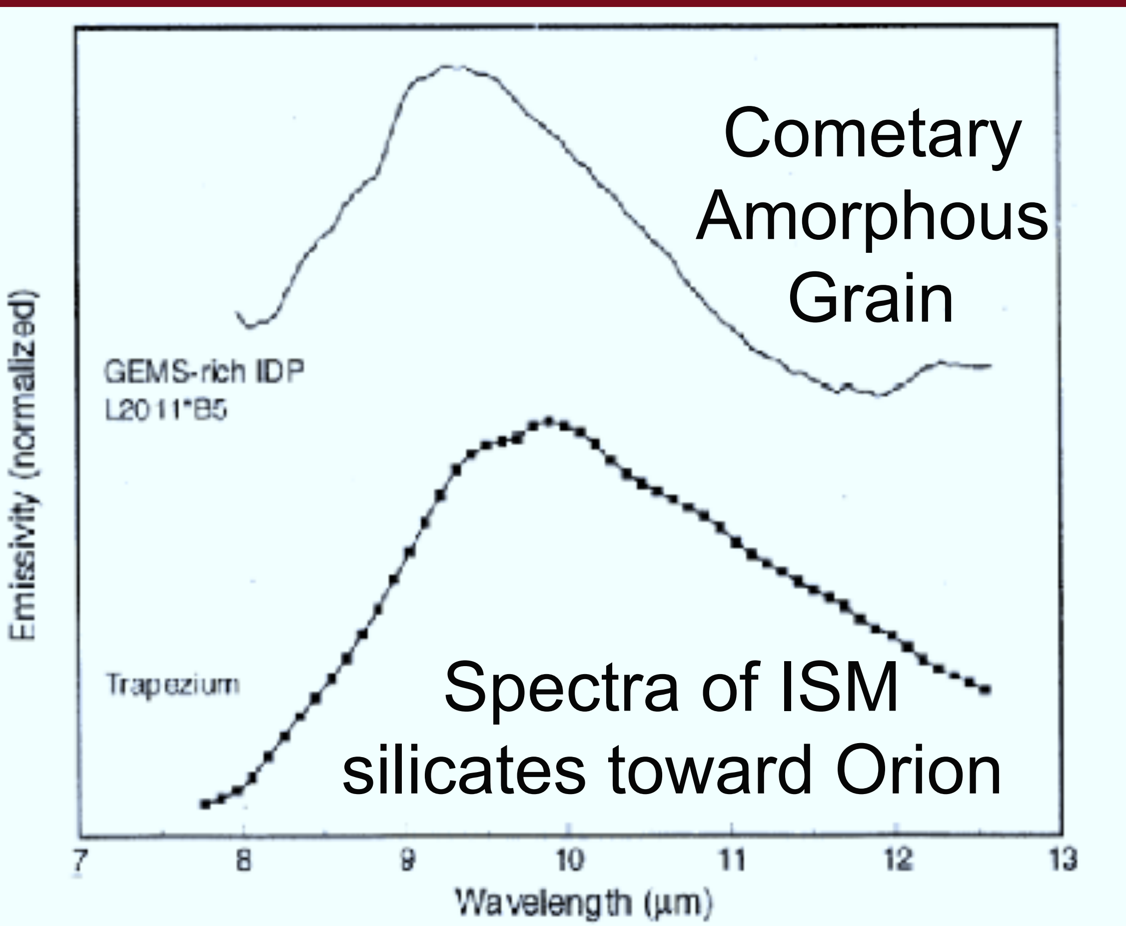


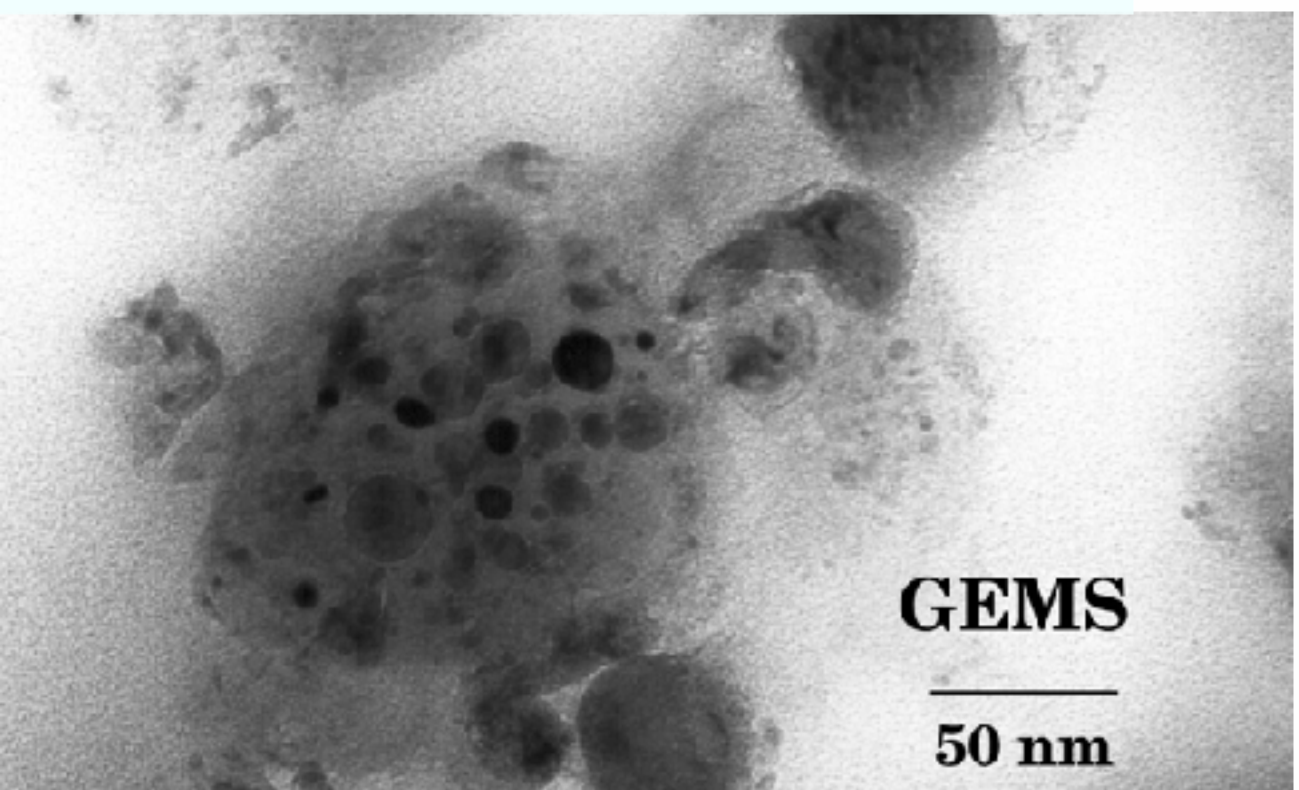


Comet Formation Region: Out beyond the water condensation temperature where T<120-150 K.

Too low for significant alteration of planetary materials. Long expected to be composed of Interstellar Materials.

Comets contain abundant crystalline silicates.





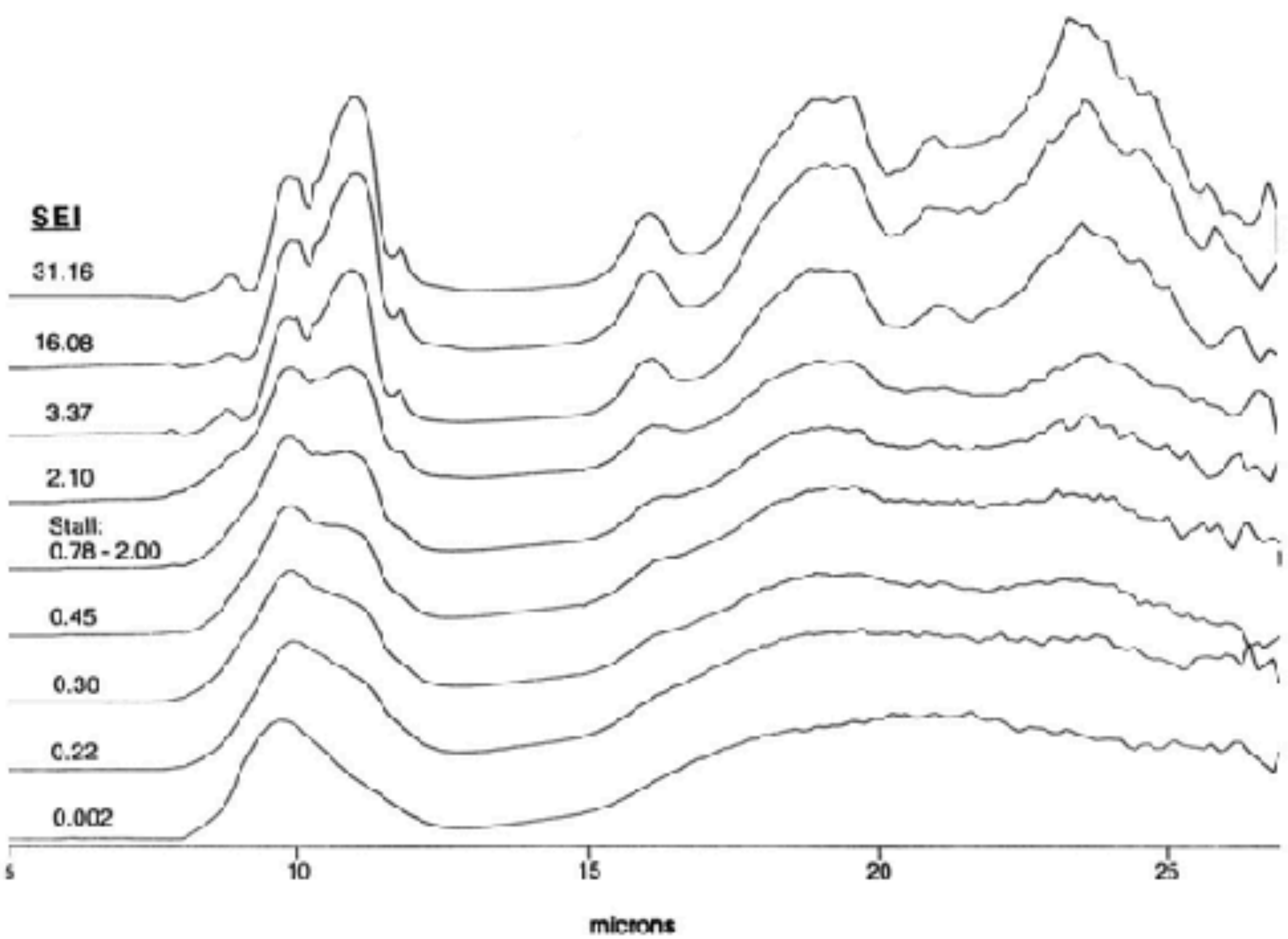
Crystalline silicates indicate significant exposure of cometary materials to high temperatures.

Bockelee-Morvan+ 2002

Table 1. Relative mass fractions of silicates in comet C/1995 O1 (Hale-Bopp).

Date	r_h [AU]	Cry Ol	Cry Pyr	Am Ol	Am Pyr	Cry Tot[a]	Reference
7 Oct. 1996	2.8	0.22	0.08	–[b]	0.72	0.30	Crovisier et al. (2000)
		0.50	–[b]	0.10	0.40	0.50	Colangeli et al. (1999)[c]
11 Apr. 1997	0.93	0.33	0.20	0.31	0.13	0.54	Wooden et al. (1999)
		0.08	0.80[d]	0.08	0.03	0.88	Wooden et al. (1999)[e]
28 Dec. 1997	3.9	0.22	0.14	–[b]	0.64	0.56	Crovisier et al. (2000)

Time at T>~1000 K



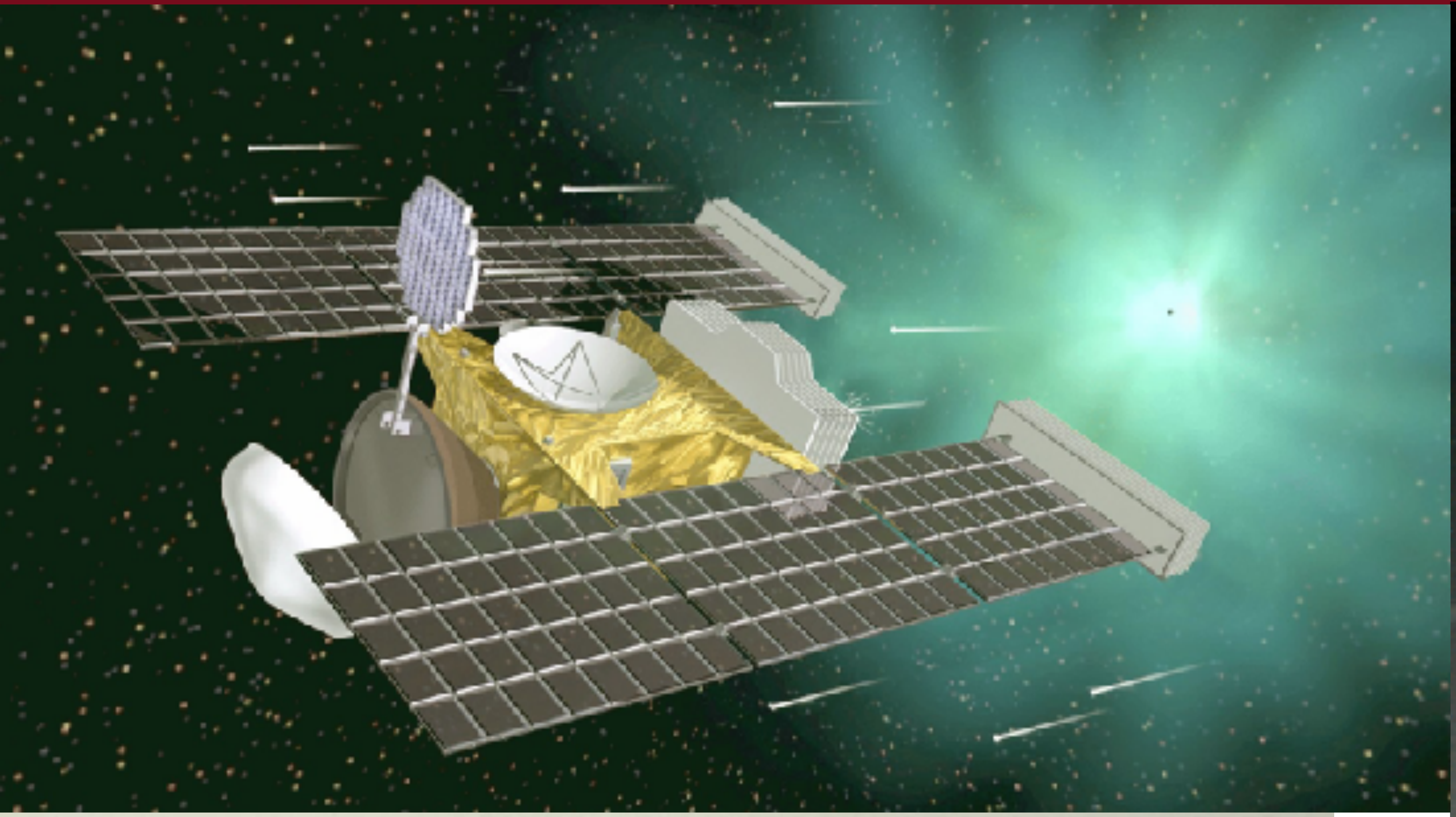
Hallenbeck+ 2000

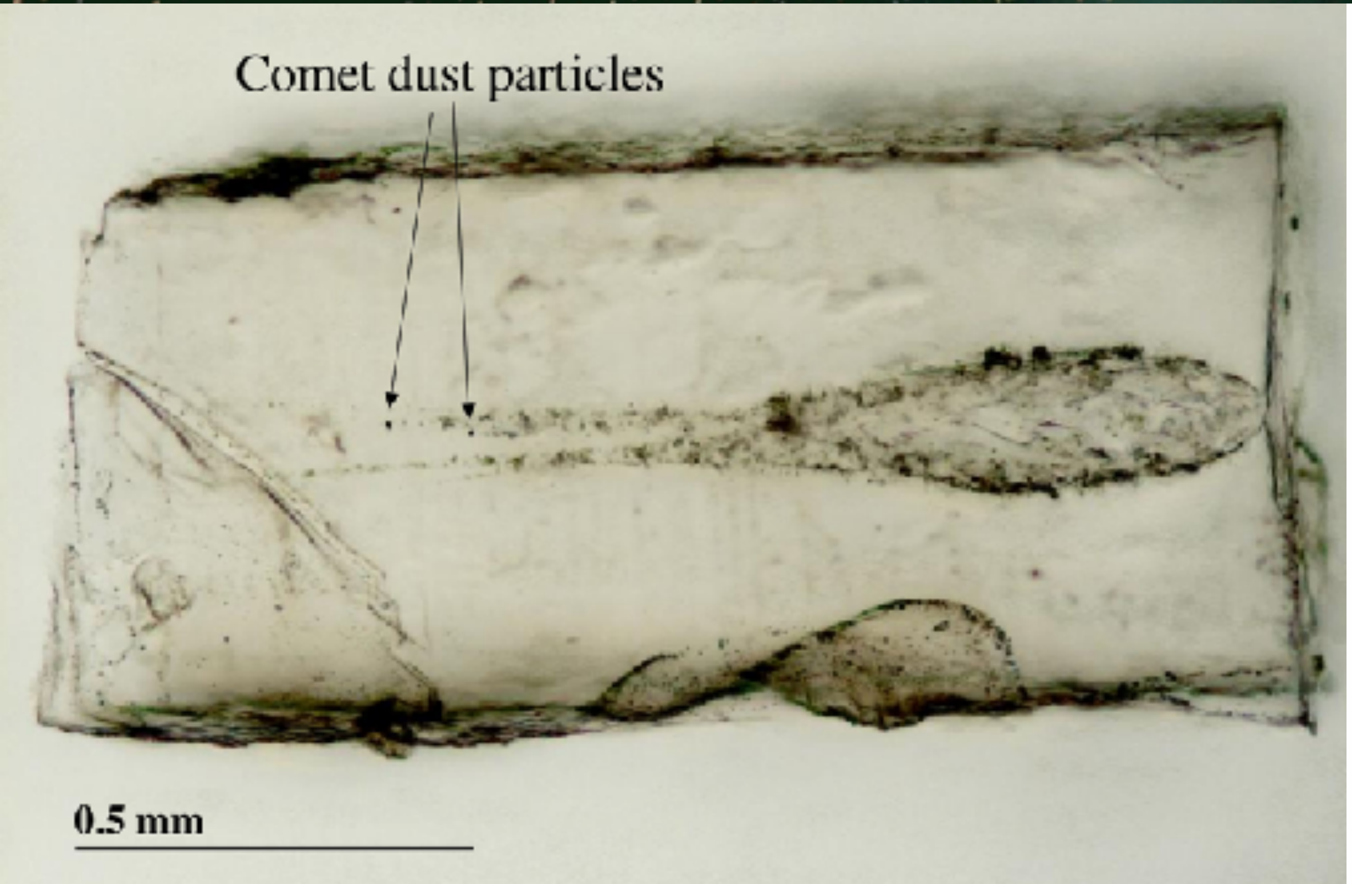
Amorphous grains exposed to ***T>800-1000 K*** anneal to become crystalline.

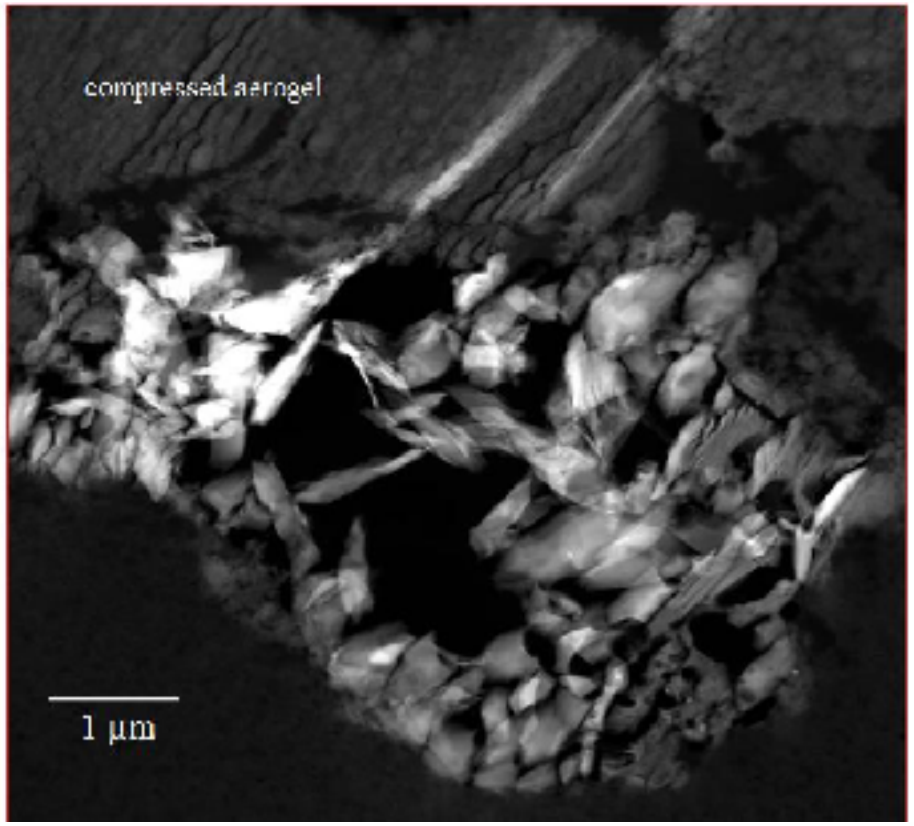
-Locally Produced?

-Transported Outward?

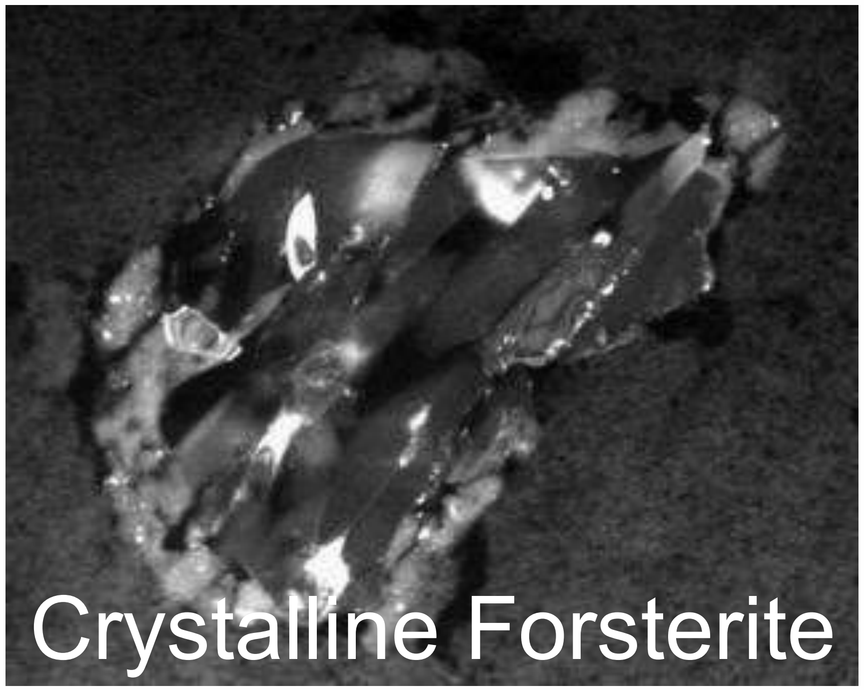
Stardust: NASA's Comet Sample Return



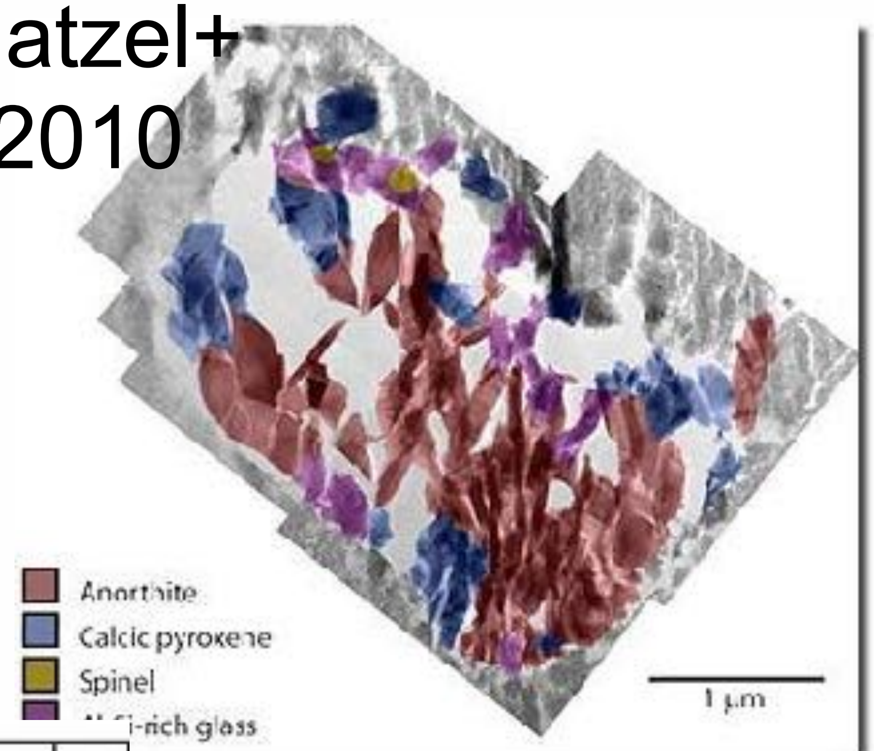




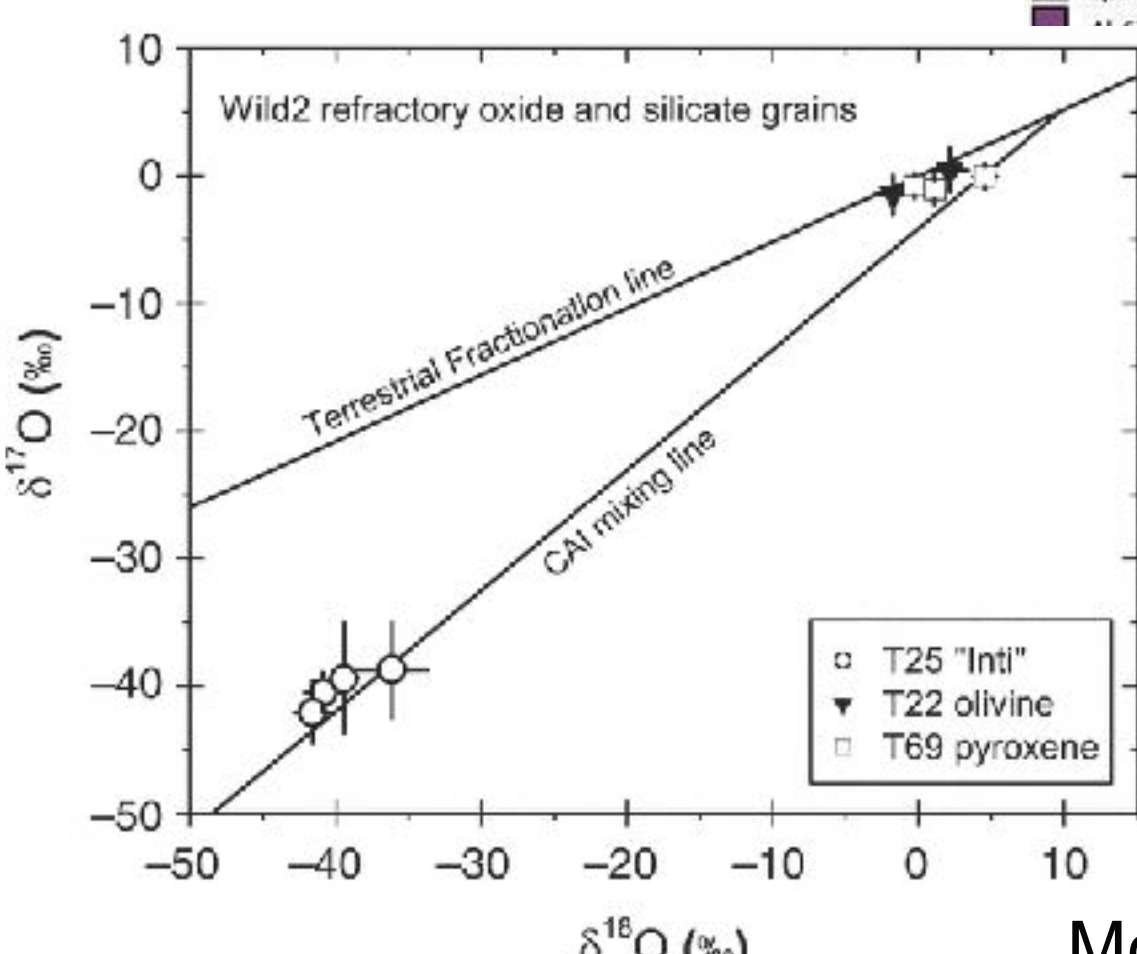
High-temperature phases in comets appear cogenetic with chondritic materials.

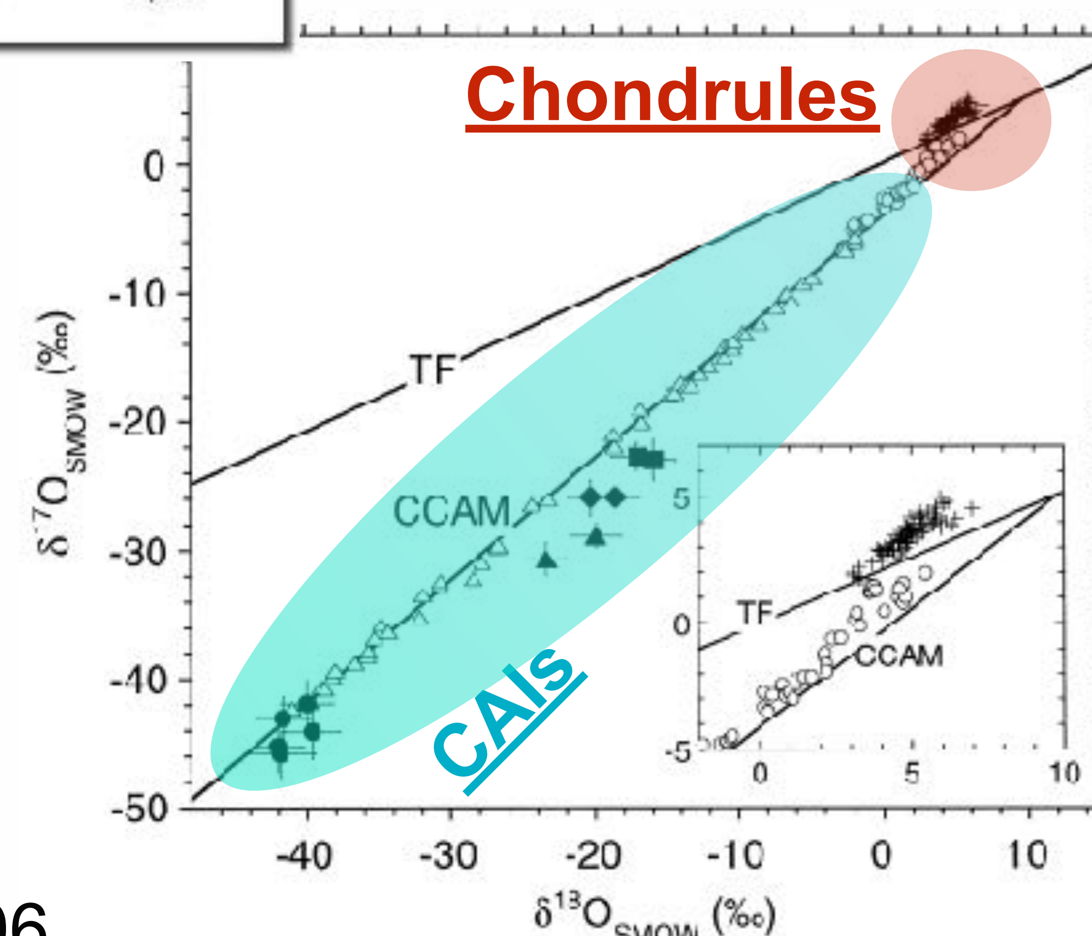


Matzel+ 2010



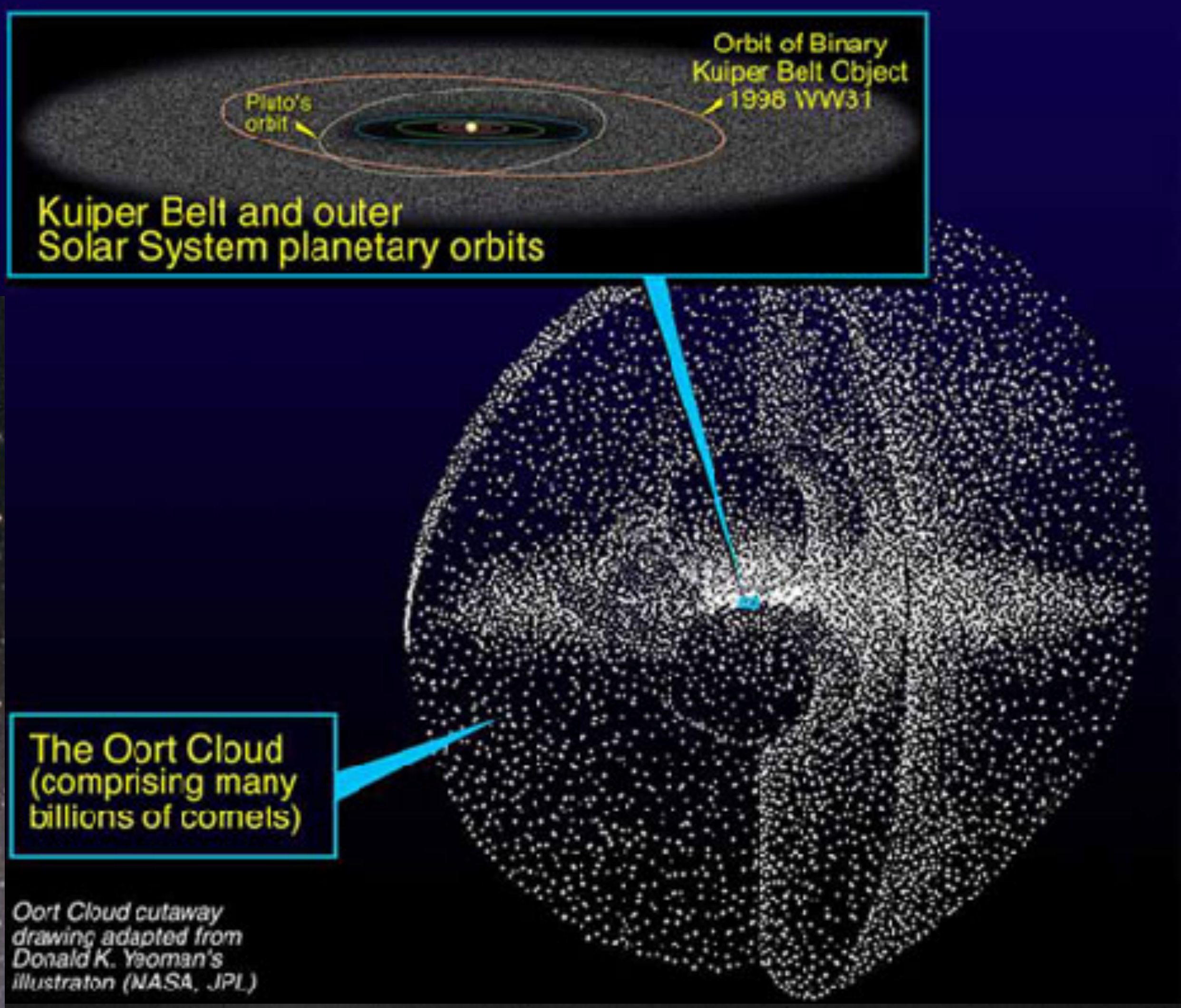
Stardust samples of comet Wild 2 look like the stuff we find in chondritic meteorites.

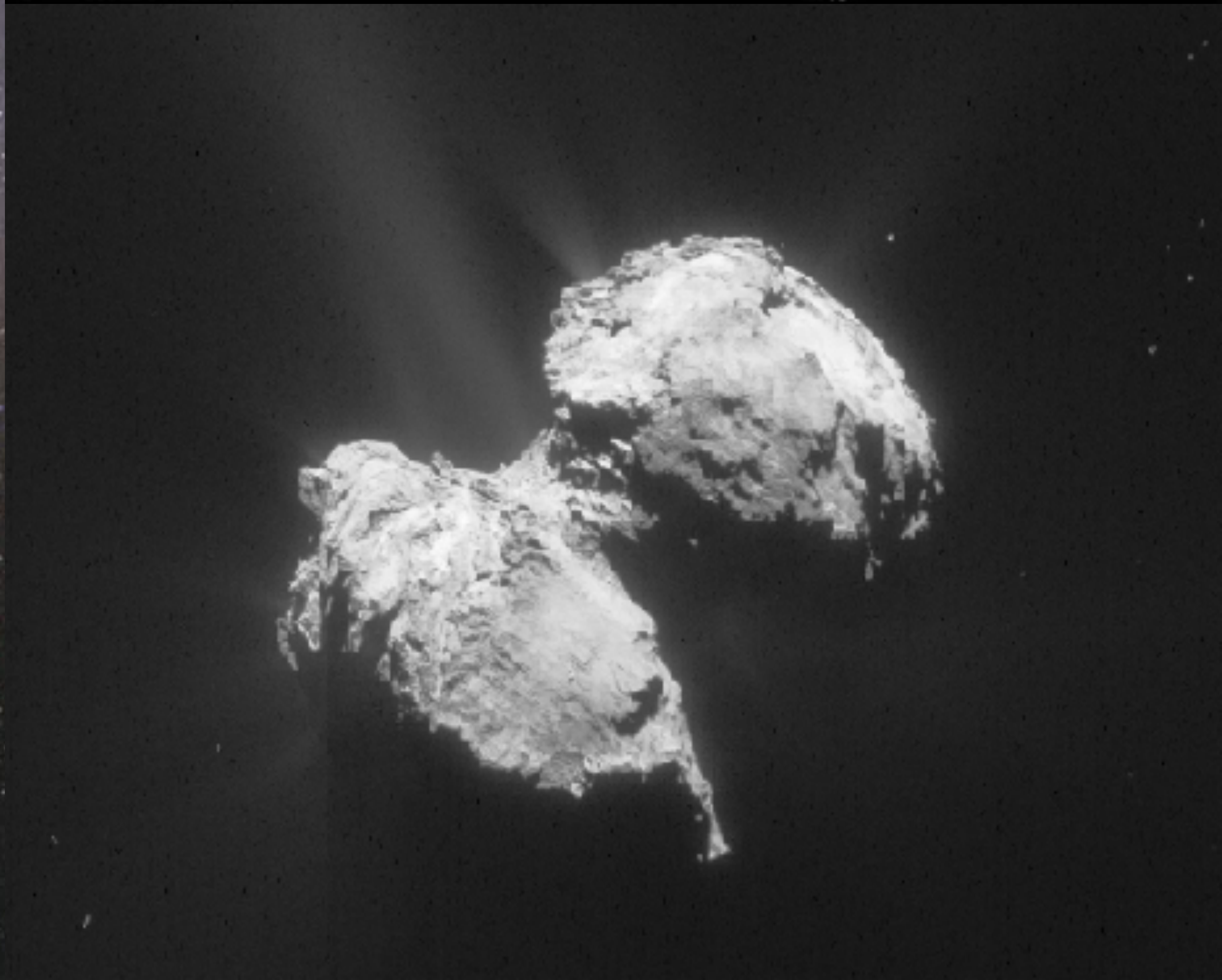




McKeegan+ 2006

Water also tells a story…





Deuterium abundances can be used as a thermometer.

- Hydrogen (H) is the most abundant element
- Deuterium (D) has an abundance 100,000 times below that of hydrogen (relic from big bang)

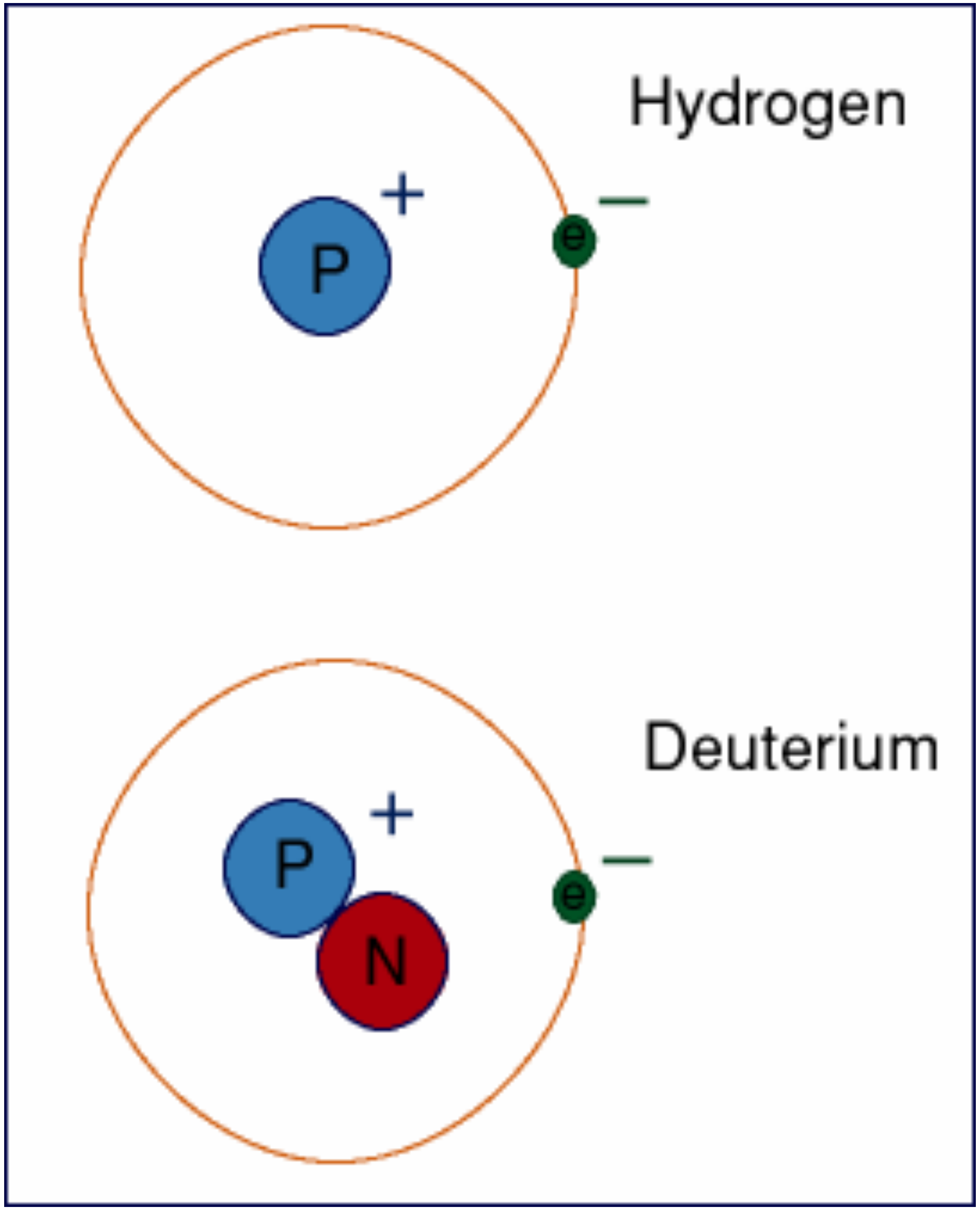
➡ at low temp. ($T < 50$ K) chemistry favors transfer of D as opposed to H

➡ if $T < 50$ K then

$HDO/H_2O > D/H$

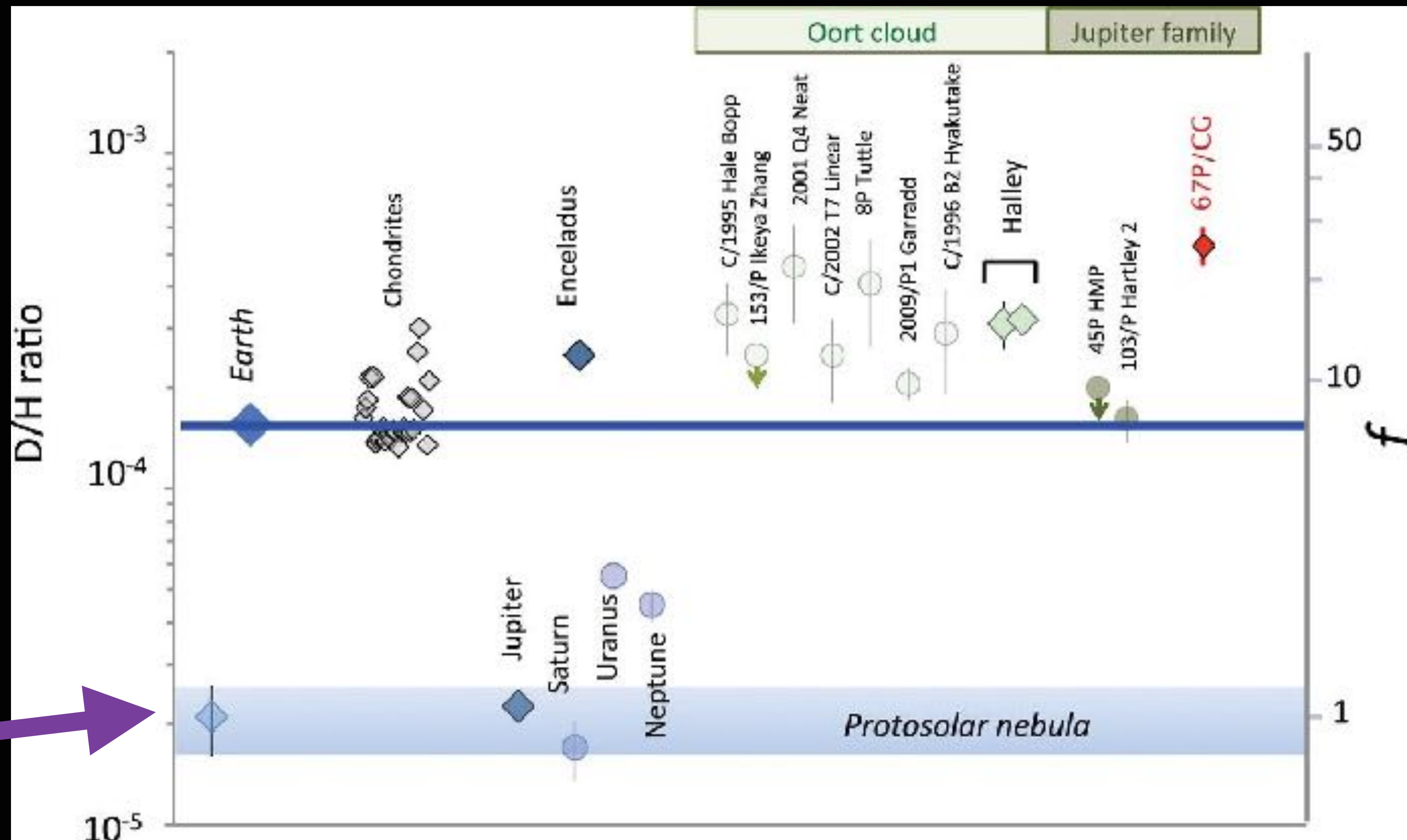
➡ if $T > 50$ K then

$HDO/H_2O = D/H$



D/H Ratios in the Solar System record where water was formed.

Any water on this line formed at T>50 K

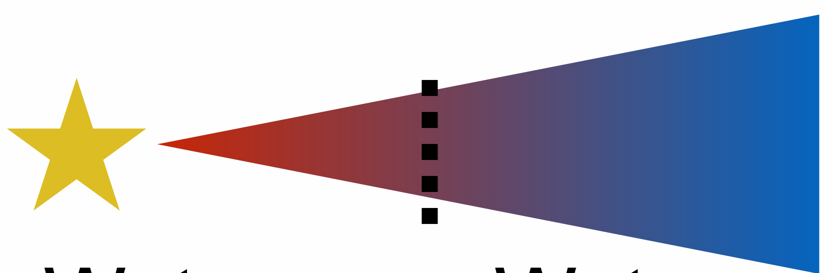


- *Some water, throughout the Solar System, formed at very low temperatures - T < 50 K*

Water would be subjected to dynamical redistribution along with solids.

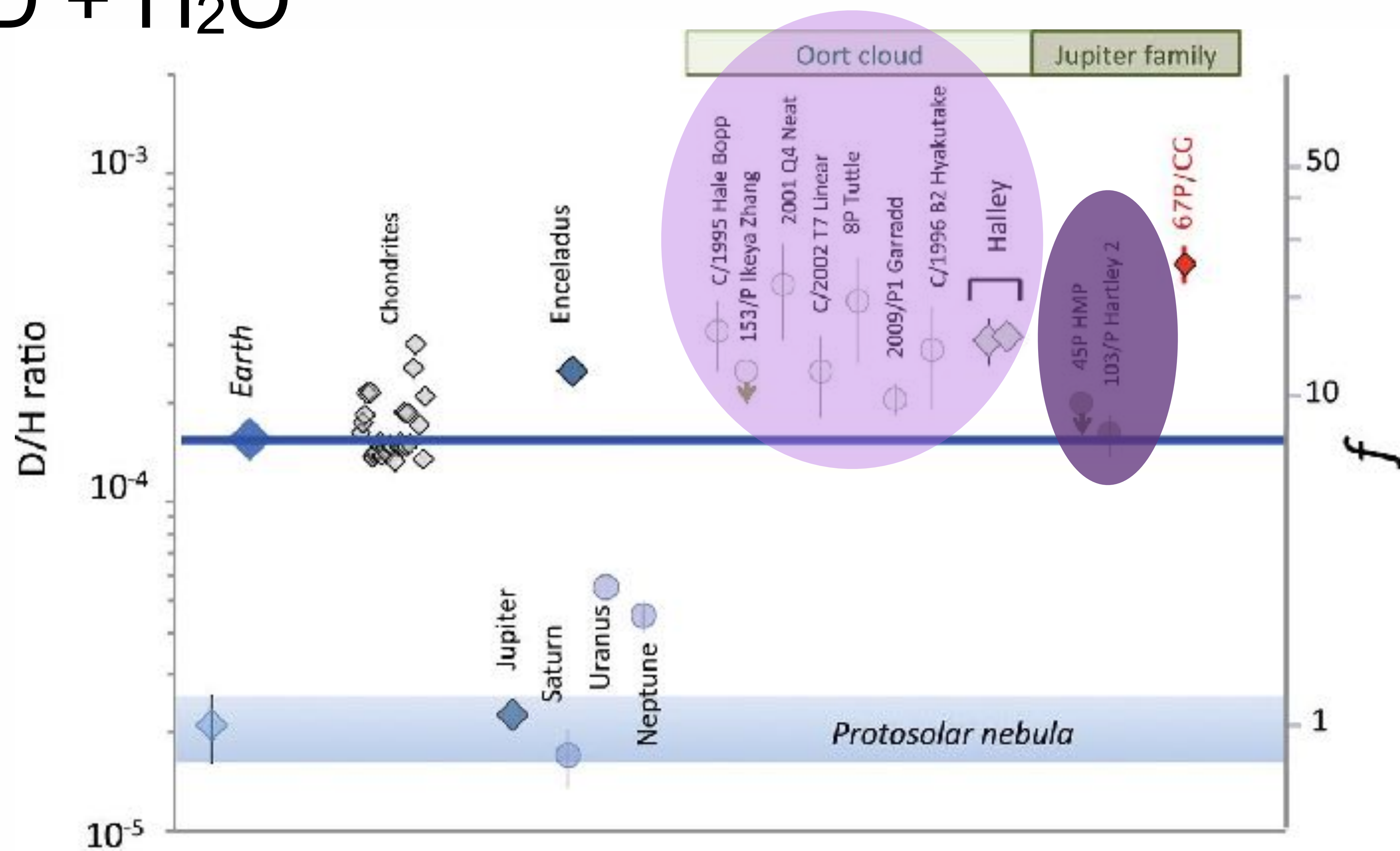
$$H_2 + HDO \rightleftarrows HD + H_2O$$

T>400 K



Water Vapor

Water Ice



Lots of variation seen in D/H among primitive bodies.

Variations must be due to some dynamic process.

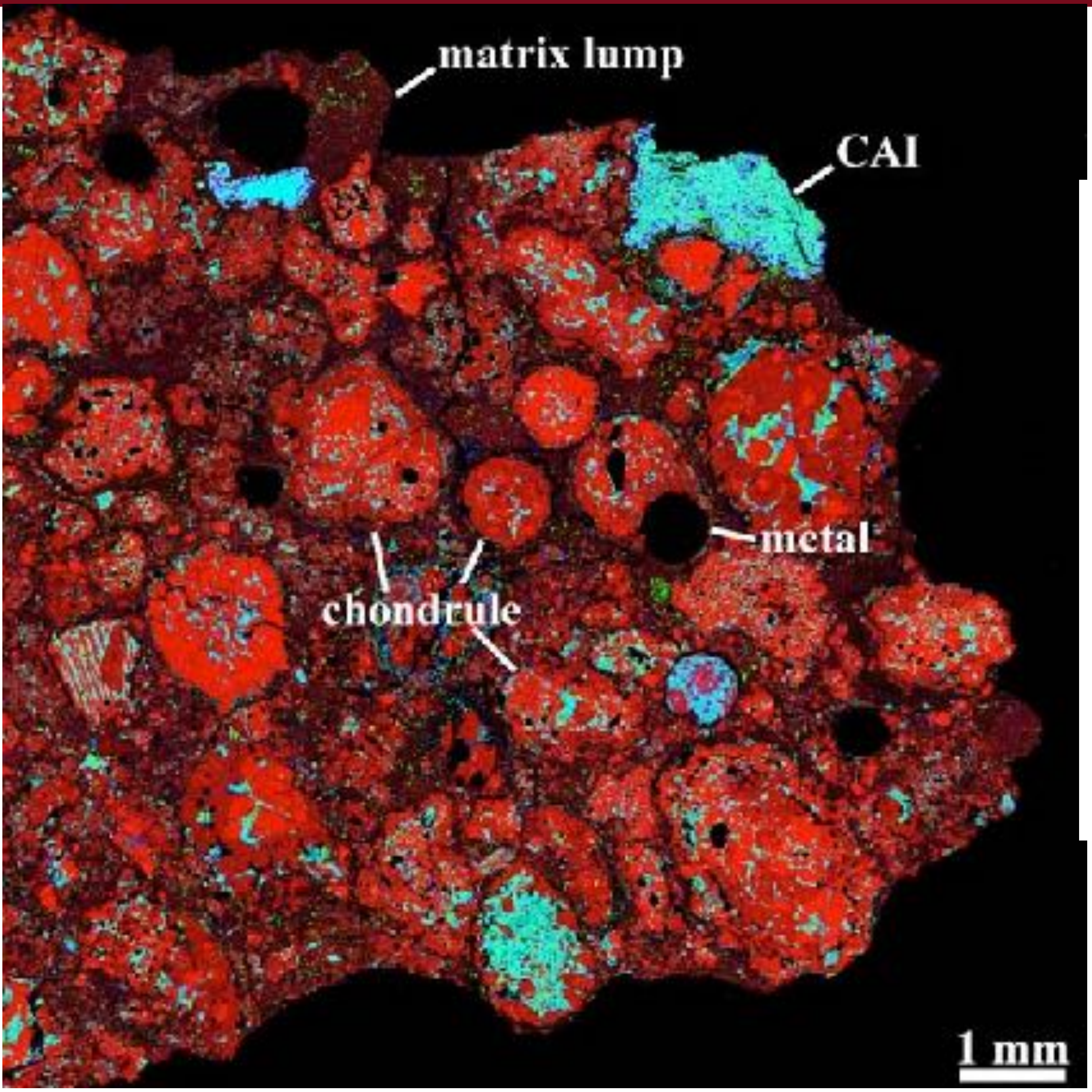
Highest D/H: 5×10^{-4} (Altwegg+ 2015)

Protosolar D/H: 2×10^{-5}

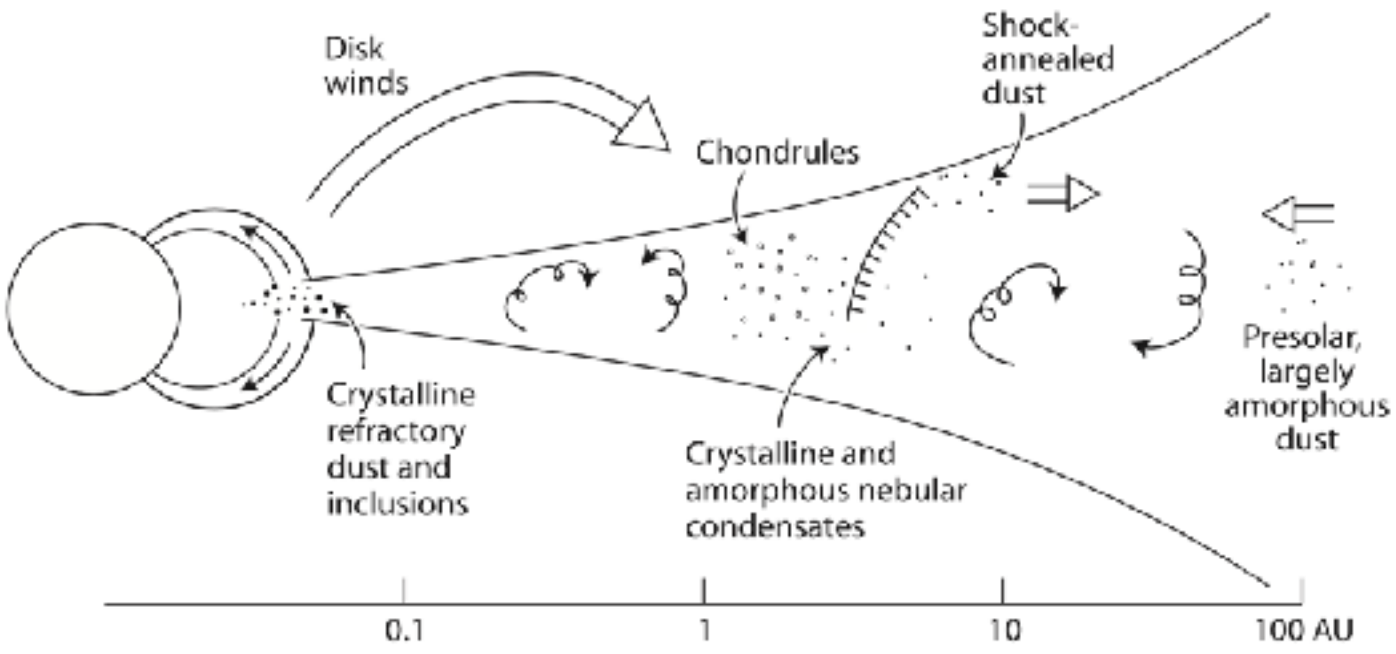
>40% of water from high T

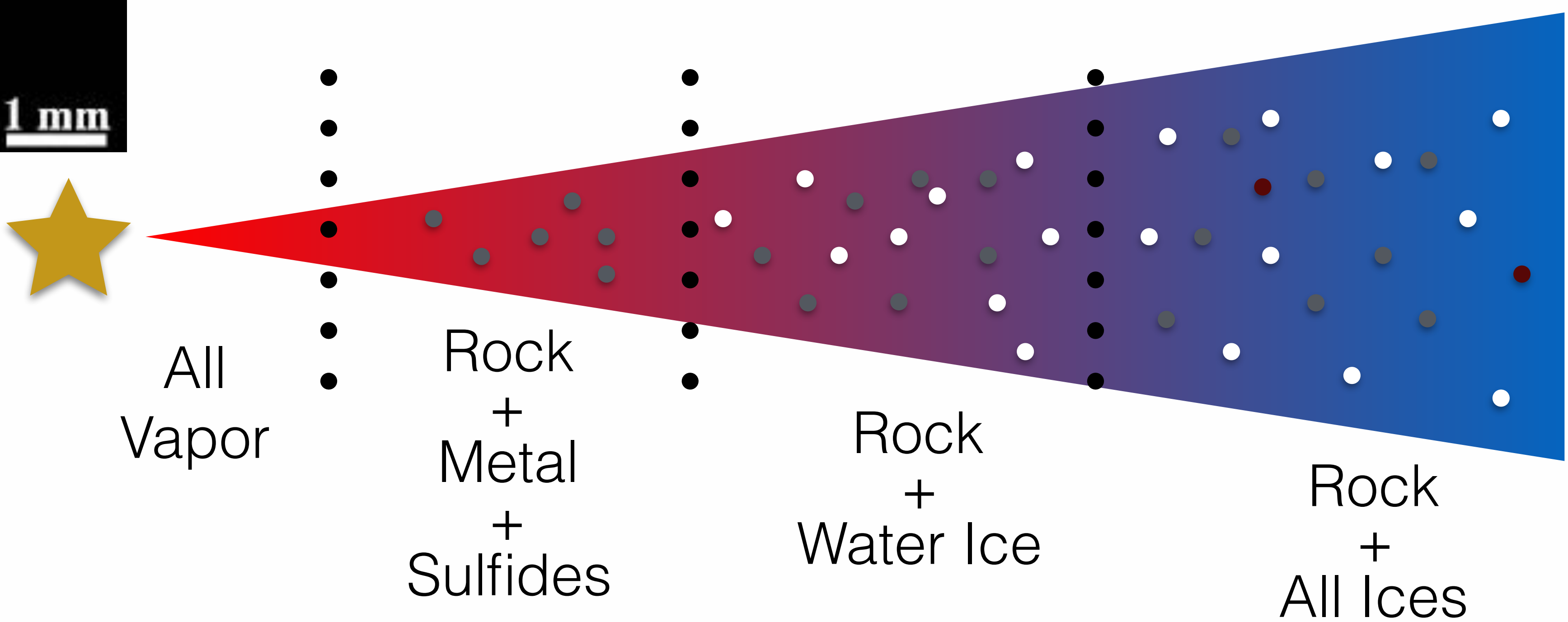
>70% of water from high T

Take Away: Planetesimals are mixtures of materials that were processed to various degrees in different regions of the solar nebula.



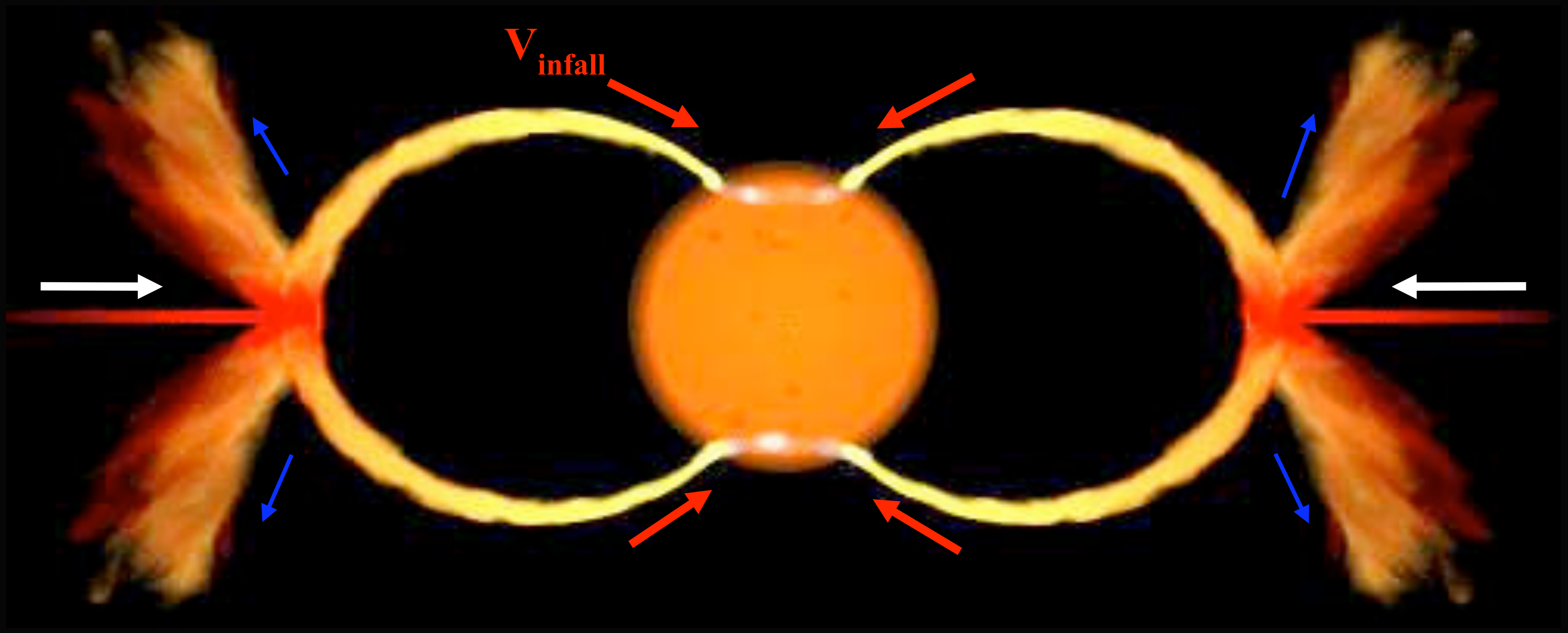
Scott and Krot (2005)





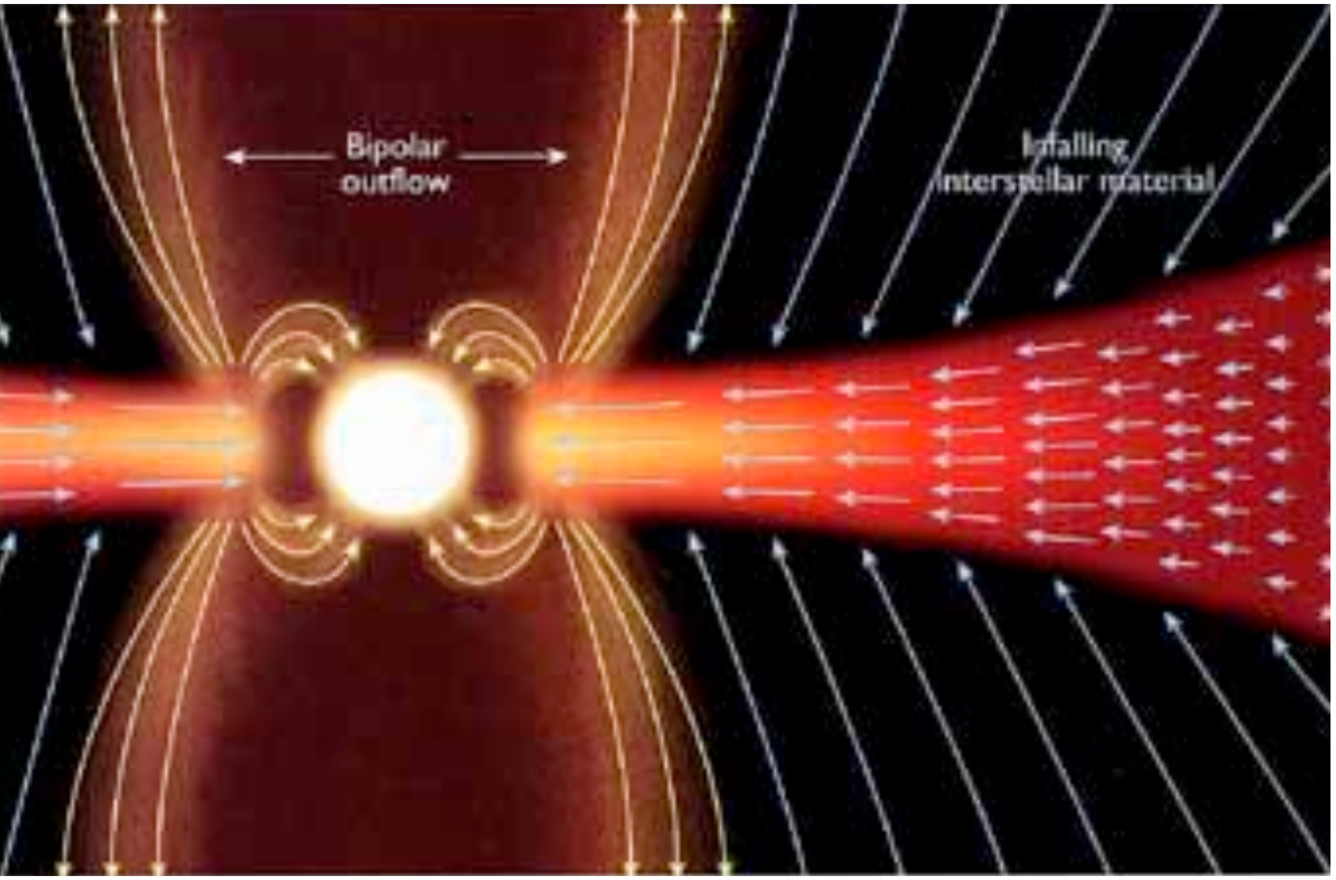
Bill Saxton, NSF/AUI/NRAO

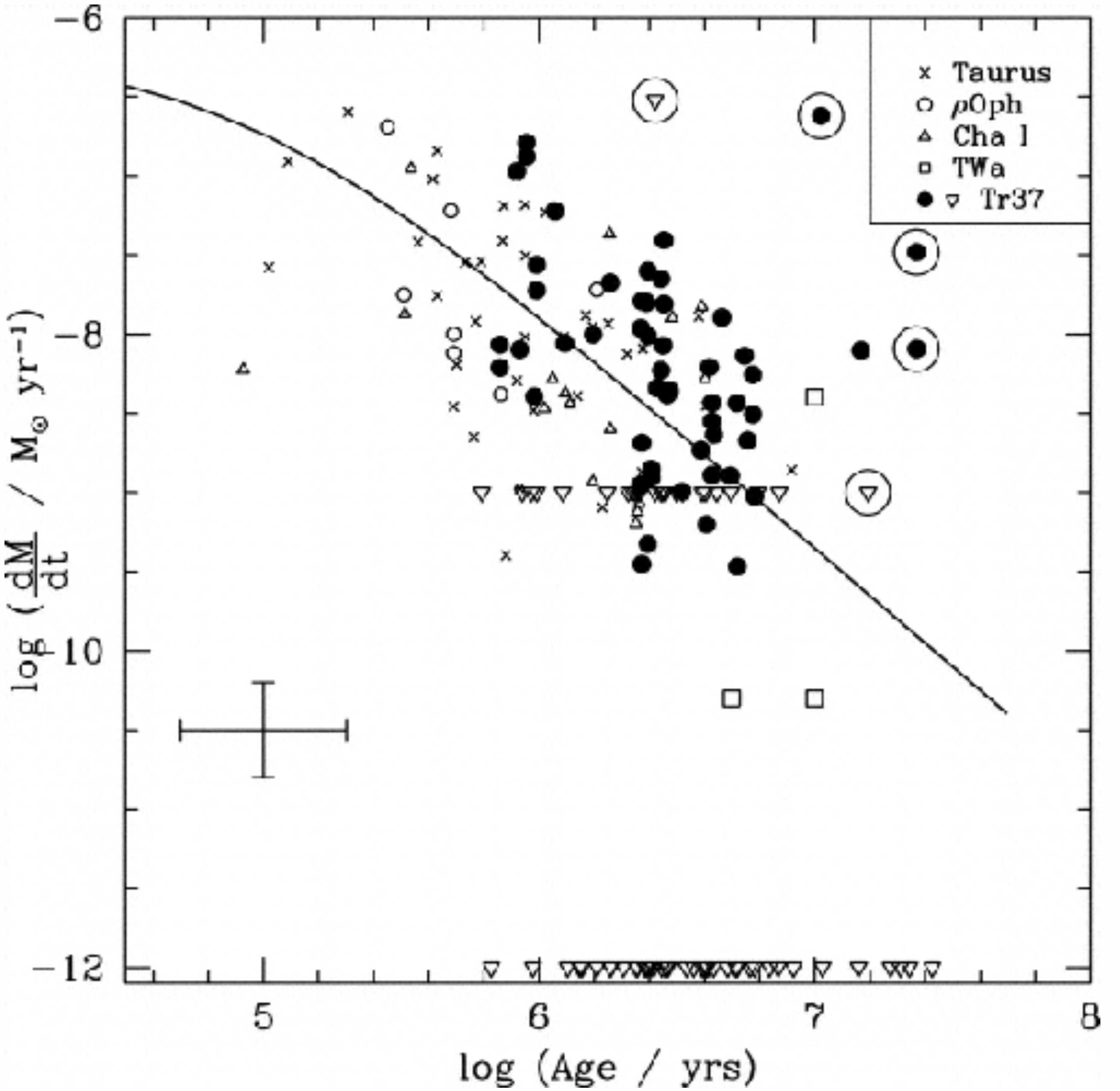
Magnetospheric accretion



- ballistic motion along magnetic field lines
  - $V_{infall} \sim (GM_*/R_*)^{1/2}$
- most disk material accreted onto star, ~10% lost in wind
  - emission produced in the flow can be used to trace disk mass accretion rate

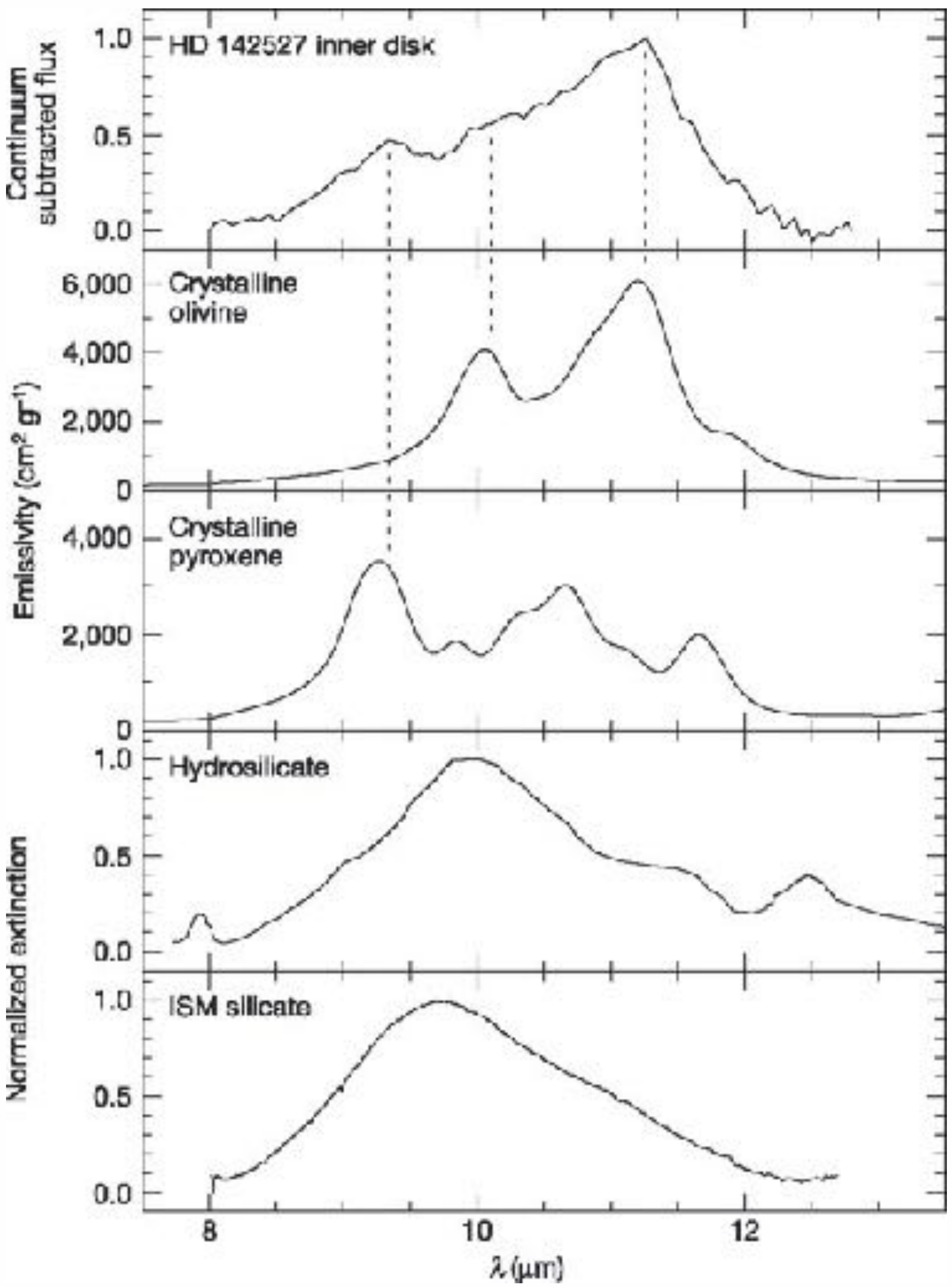
Protoplanetary Disk Properties



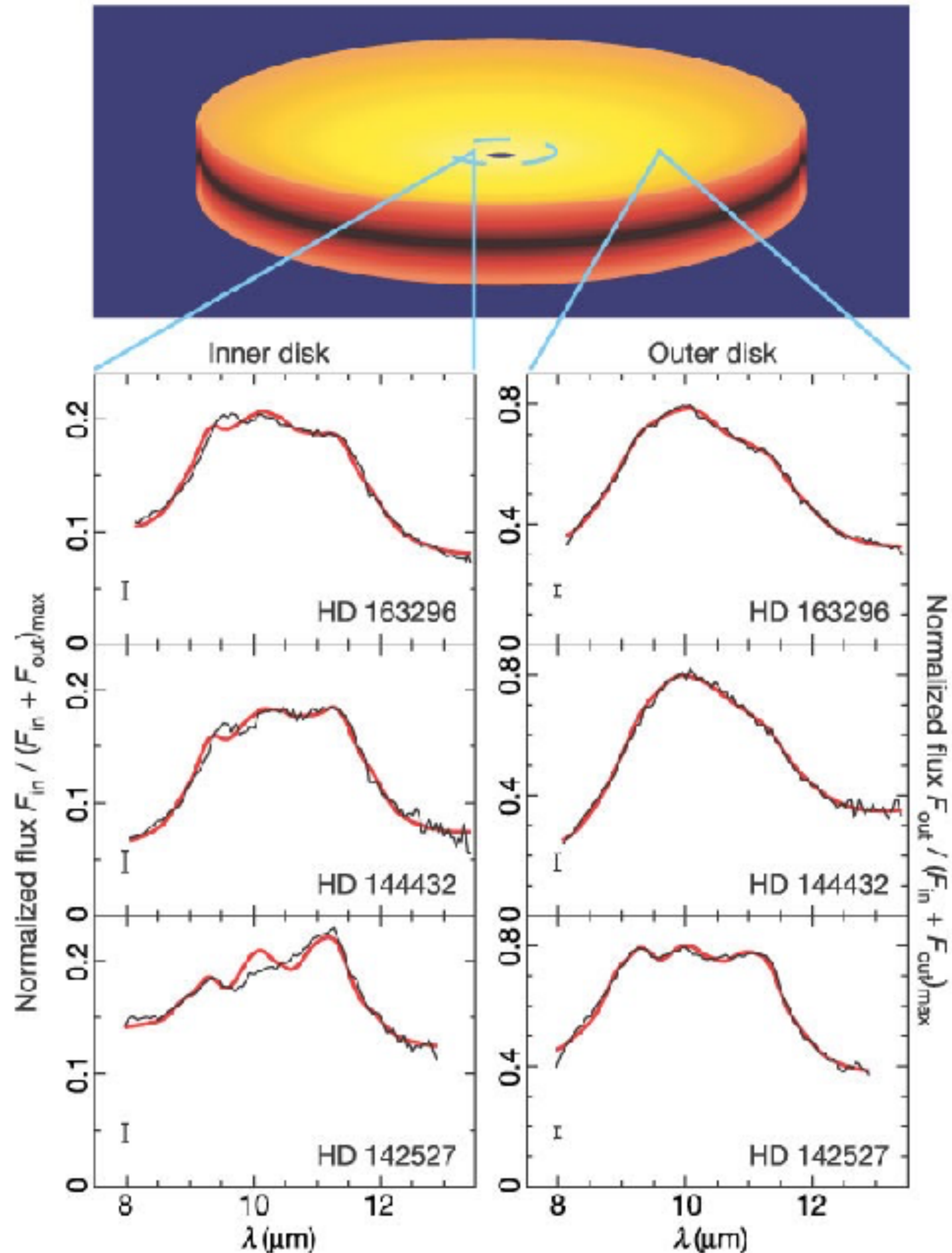


Protoplanetary disks are active objects, through which mass and angular momentum are transferred as part of the last stages of pre-main sequence evolution of the central star.

Signs of radial mixing/transport are found in other disks as well.

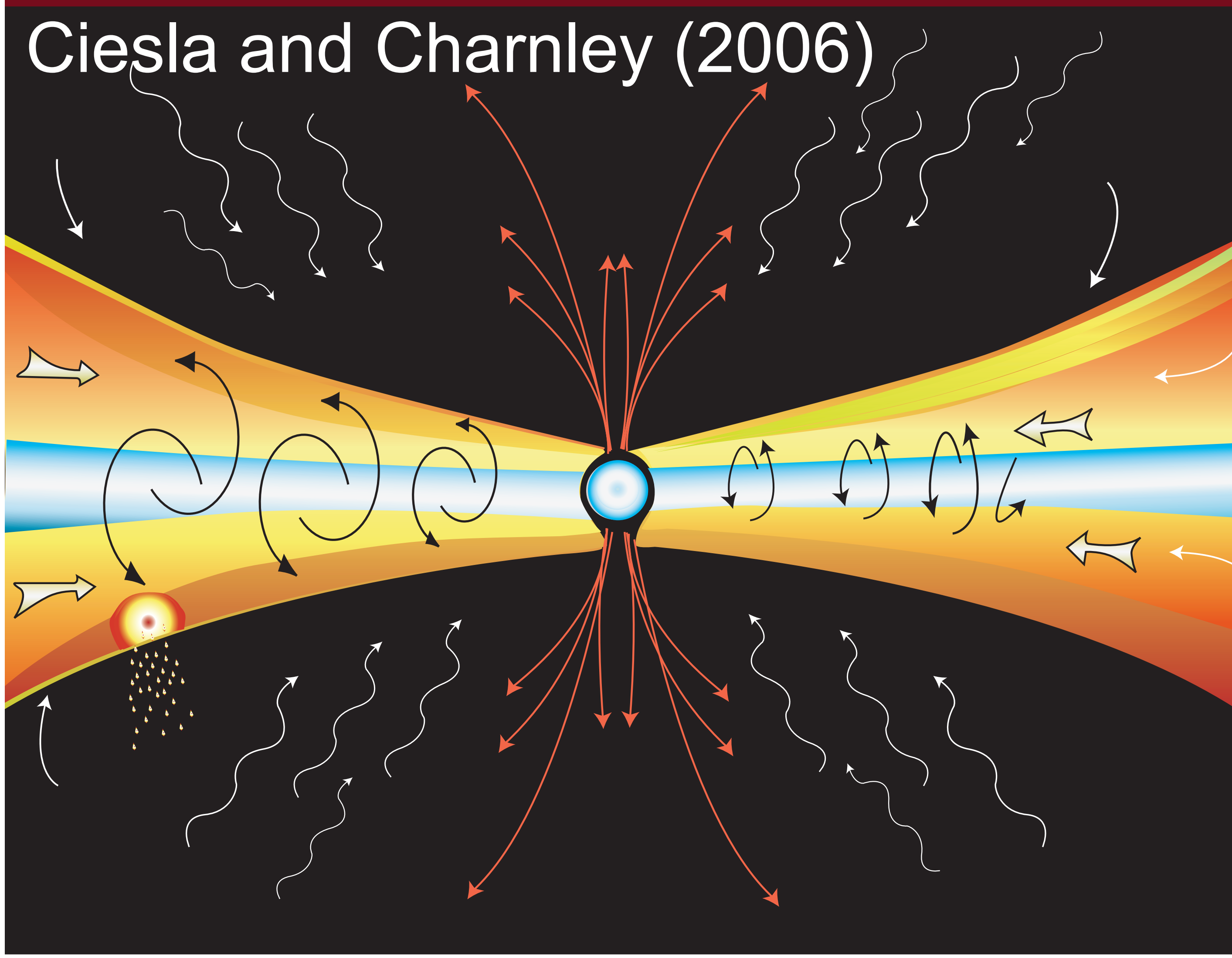


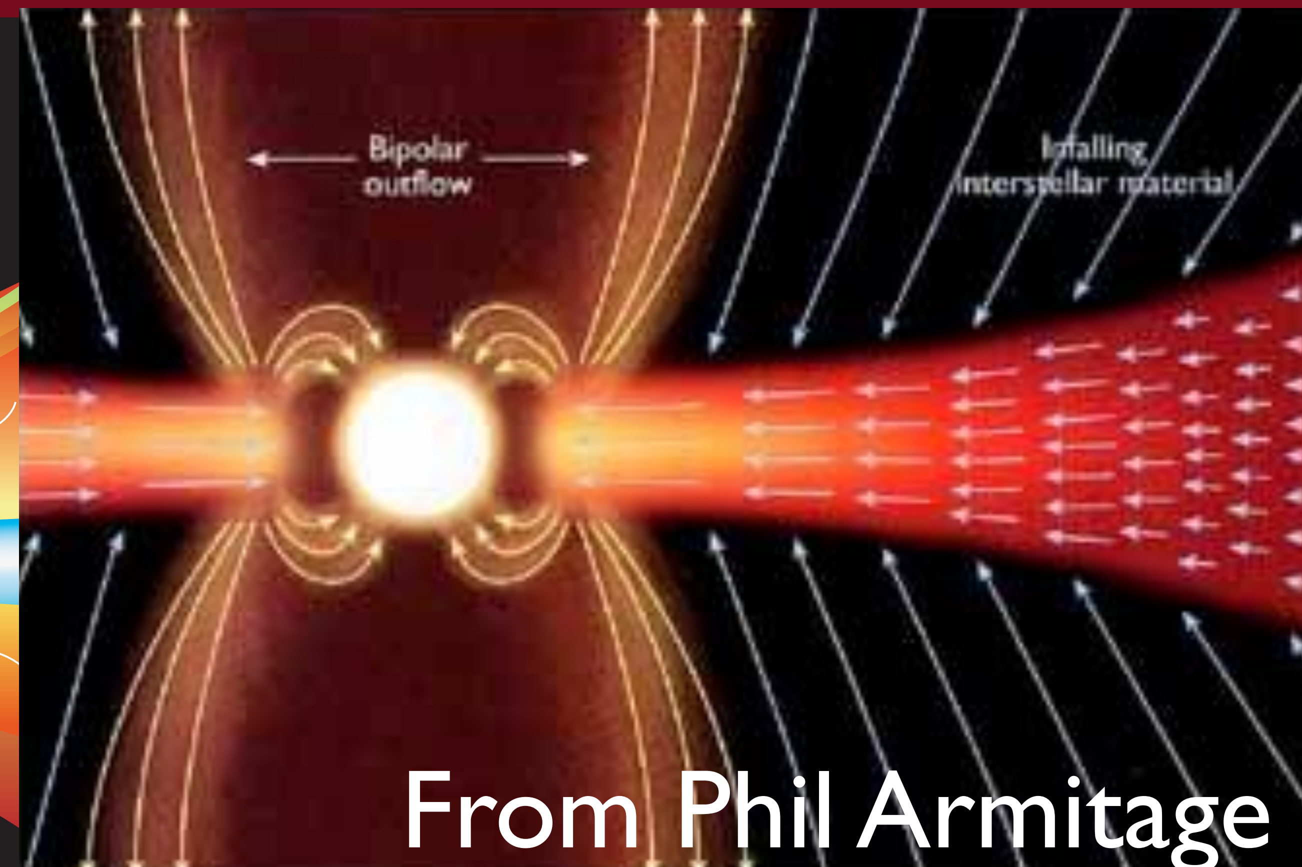
van Boekel (2004)



Dust and Gas Dynamics in Protoplanetary Disks

The picture that emerged was that the solar nebula was a dynamic place.


Ciesla and Charnley (2006)



From Phil Armitage

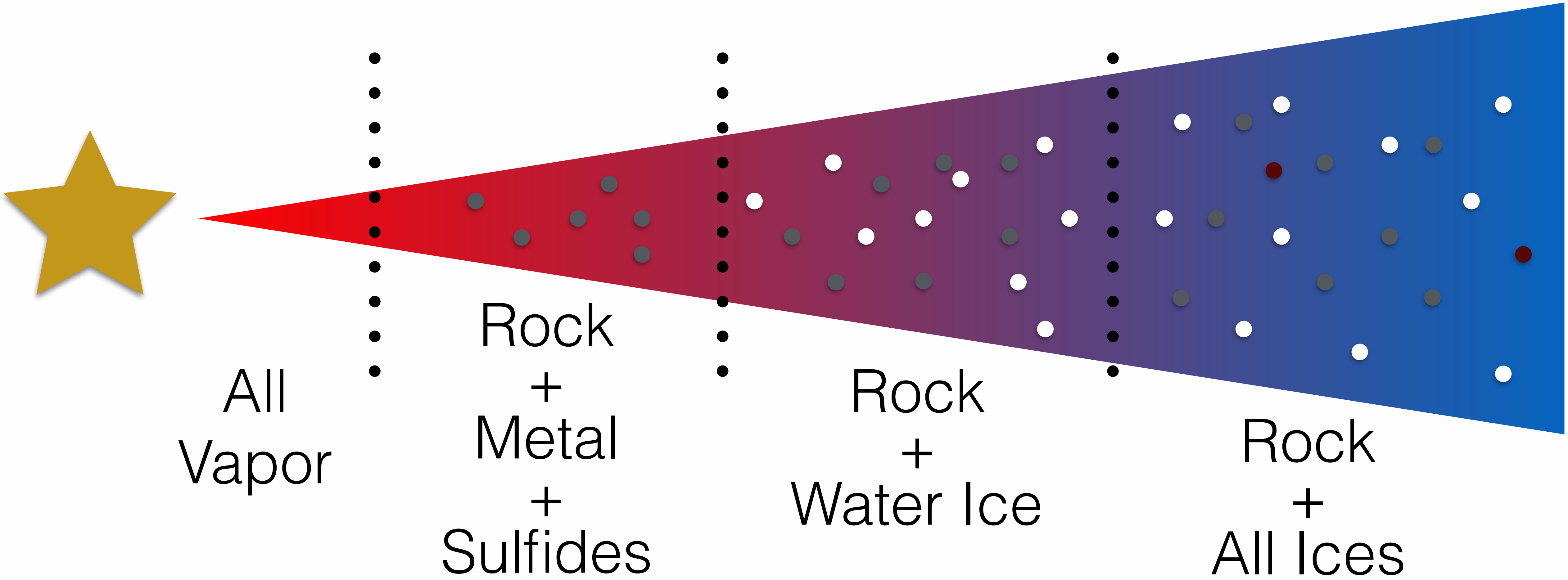
Materials from different environments are intimately mixed on centimeter scale.

Inner Solar System materials are found in comets from outer Solar System.

Protoplanetary disks transport mass for periods of Myr as final stages of pre-main sequence evolution of central star.

High temperature components found in outer regions of other protoplanetary disks.

Disk Structure



$$\Sigma\left(r\right)=\Sigma_0\left(\frac{r}{1\ \mathrm{AU}}\right)^{-p}$$

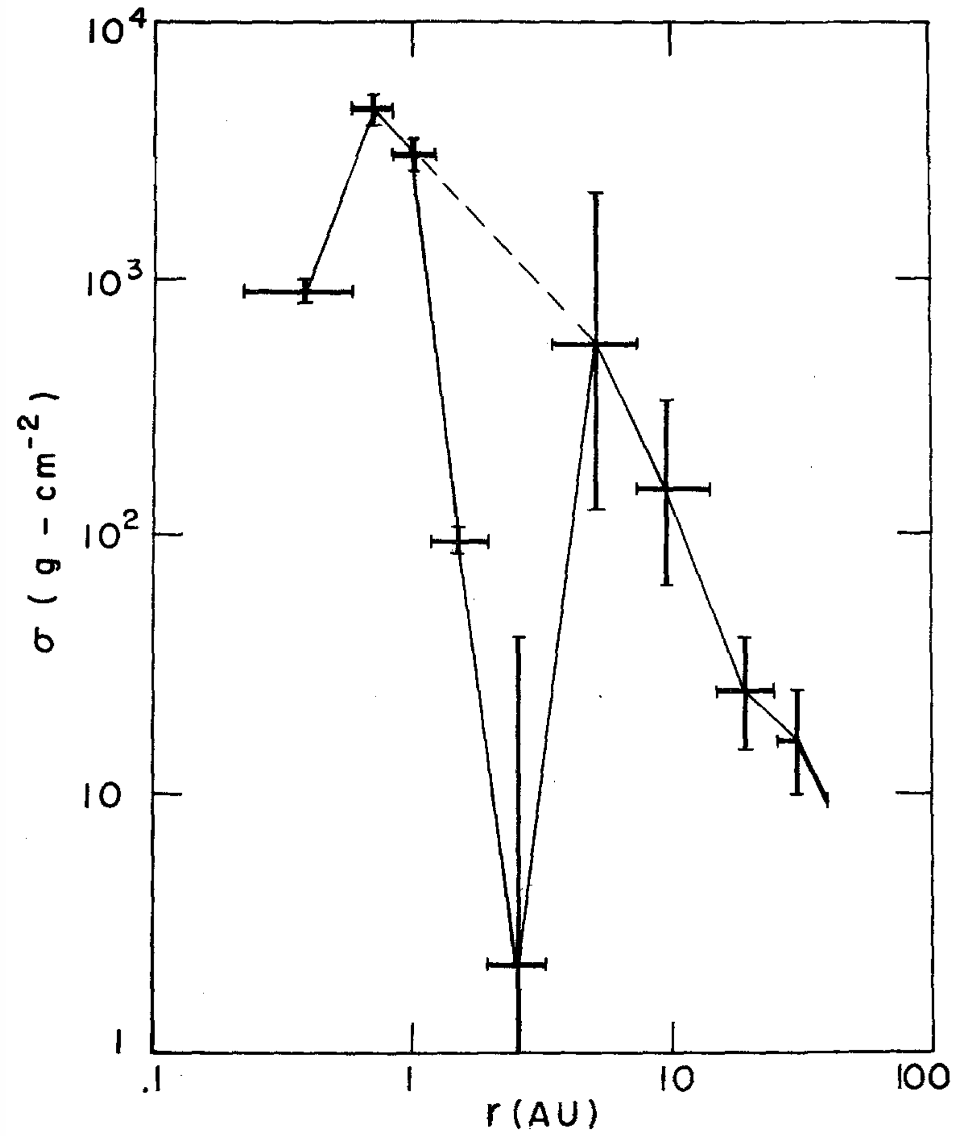
$$T\left(r\right)=T_0\left(\frac{r}{1\ \mathrm{AU}}\right)^{-q}$$

The vertical thickness of the disk is small when compared to radial extent, so it is often treated as a 1D object in terms of evolution.

Minimum Mass Solar Nebula

Planetary zones: masses and surface densities

	Mass ($M_\oplus$)	Fe mass fraction	Solar comp. mass ($M_\oplus$)	Zone limits (AU)	Surface density (g cm^{-2})
Mercury	0.053	0.62	27	0.22	880
Venus	0.815	0.35	235	0.56	4750
Earth	1	0.38	320	0.86	3200
Mars	0.107	0.30	27	1.26	95
Asteroids					
present	0.0005	0.25	0.1	2.0	0.13
original	0.15?		30		40
				3.3	
Jupiter	318	–	600–12 000	7.4	120–2400
Saturn	95	–	1000–6000	14.4	55–330
Uranus	14.6	–	700–2000	24.7	15–40
Neptune	17.2	–	800–2000	35.5	10–25

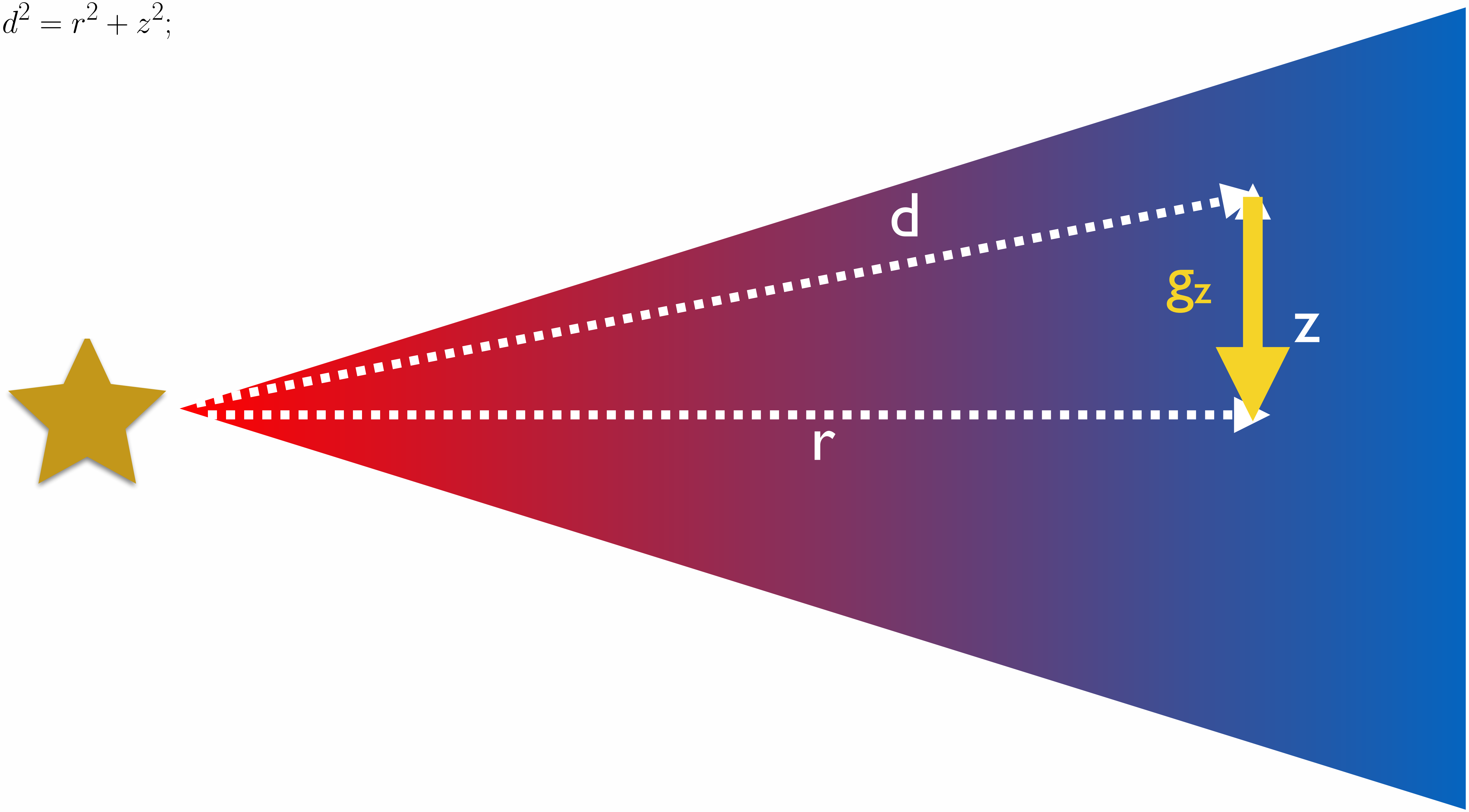


$$\Sigma(r) = 1700 \left(\frac{r}{1\ \mathrm{AU}}\right)^{-\frac{3}{2}}\ \mathrm{g\ cm^{-2}}$$

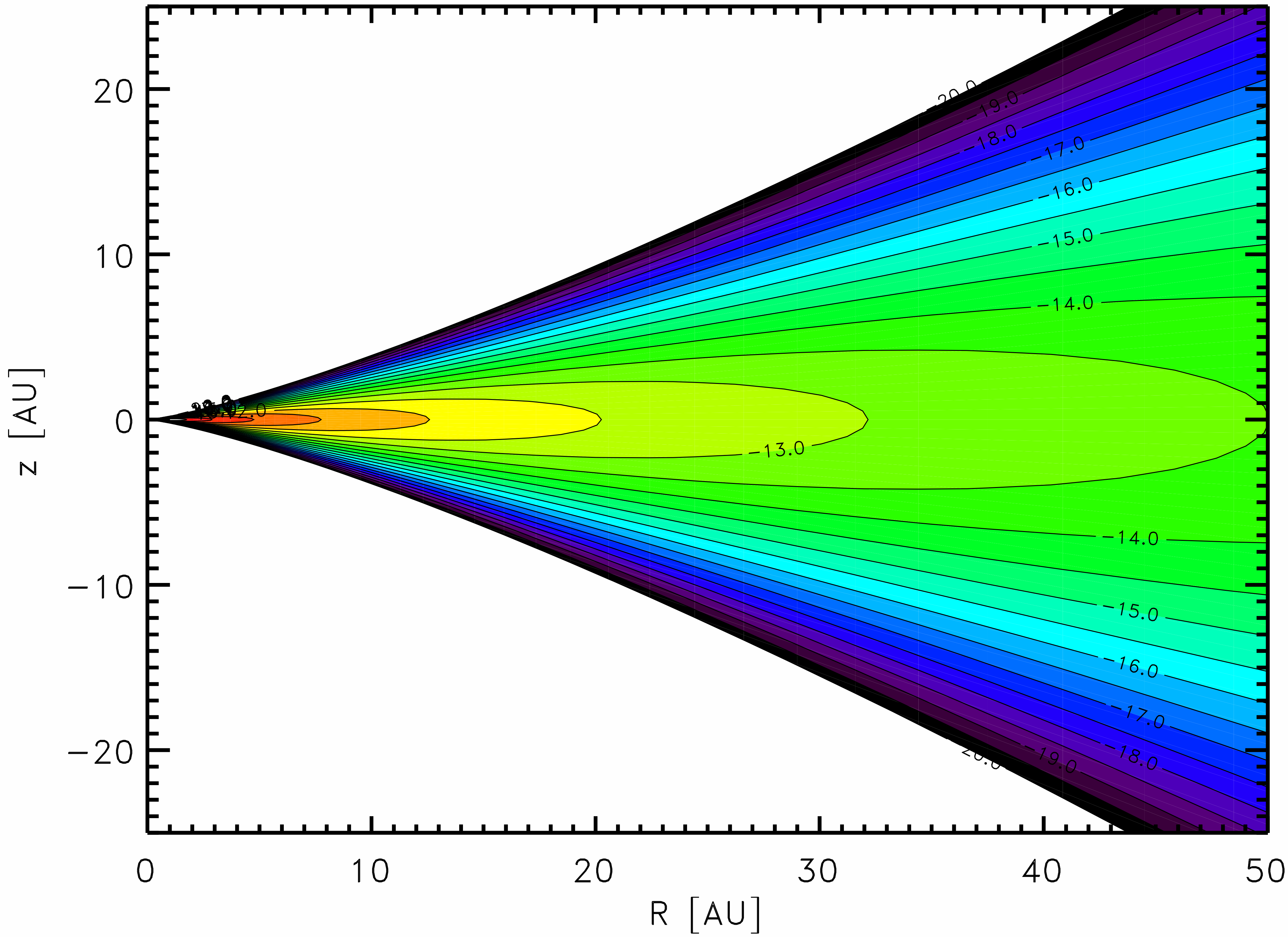
$$T(r) = 280 \left(\frac{r}{1\ \mathrm{AU}}\right)^{-\frac{1}{2}}\ \mathrm{K}$$

Vertical Structure

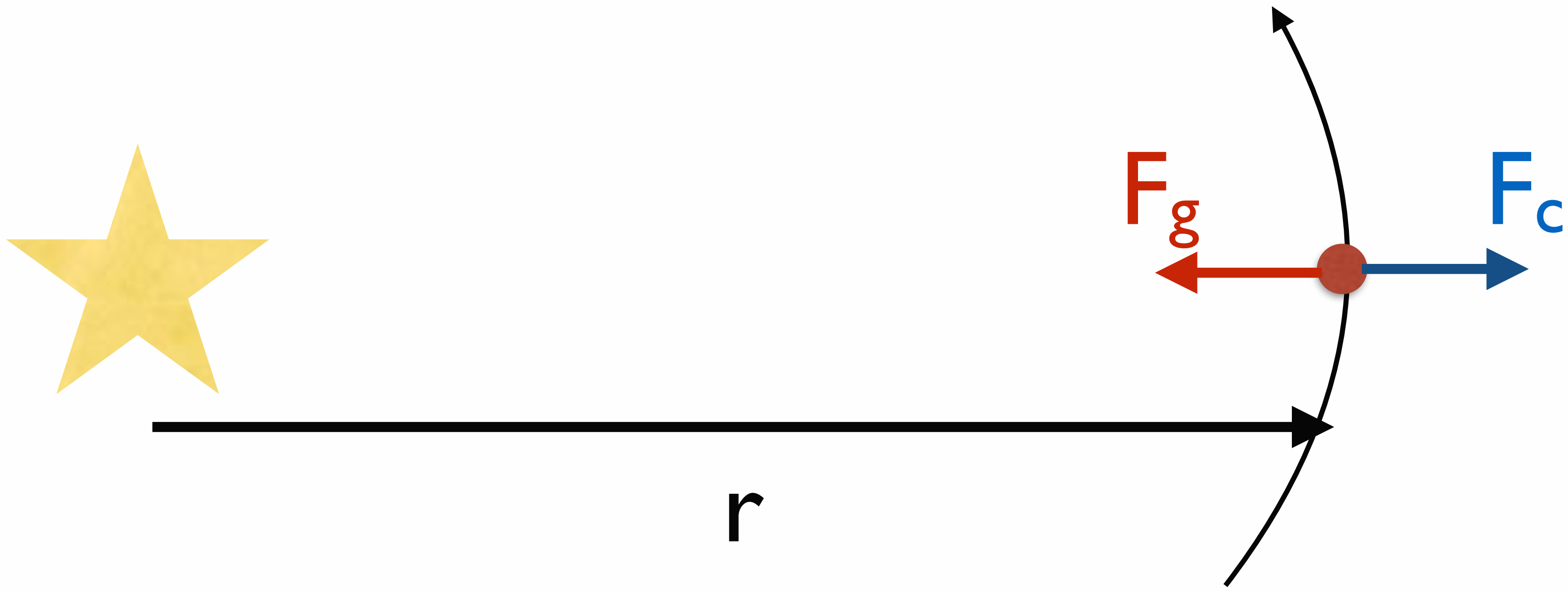
$d^2 = r^2 + z^2;$



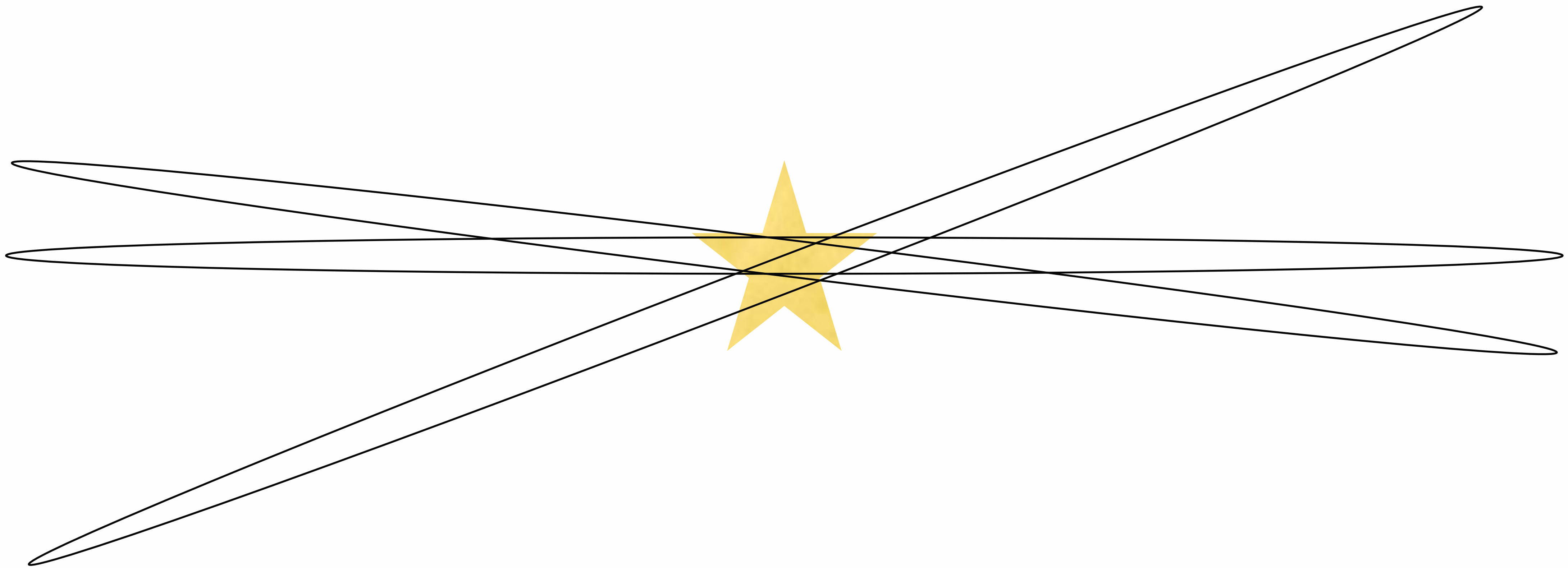
Density Map of a Protoplanetary Disk



Solid Dynamics



$$\frac{GM_\odot}{r^2} = \frac{v^2}{r}$$



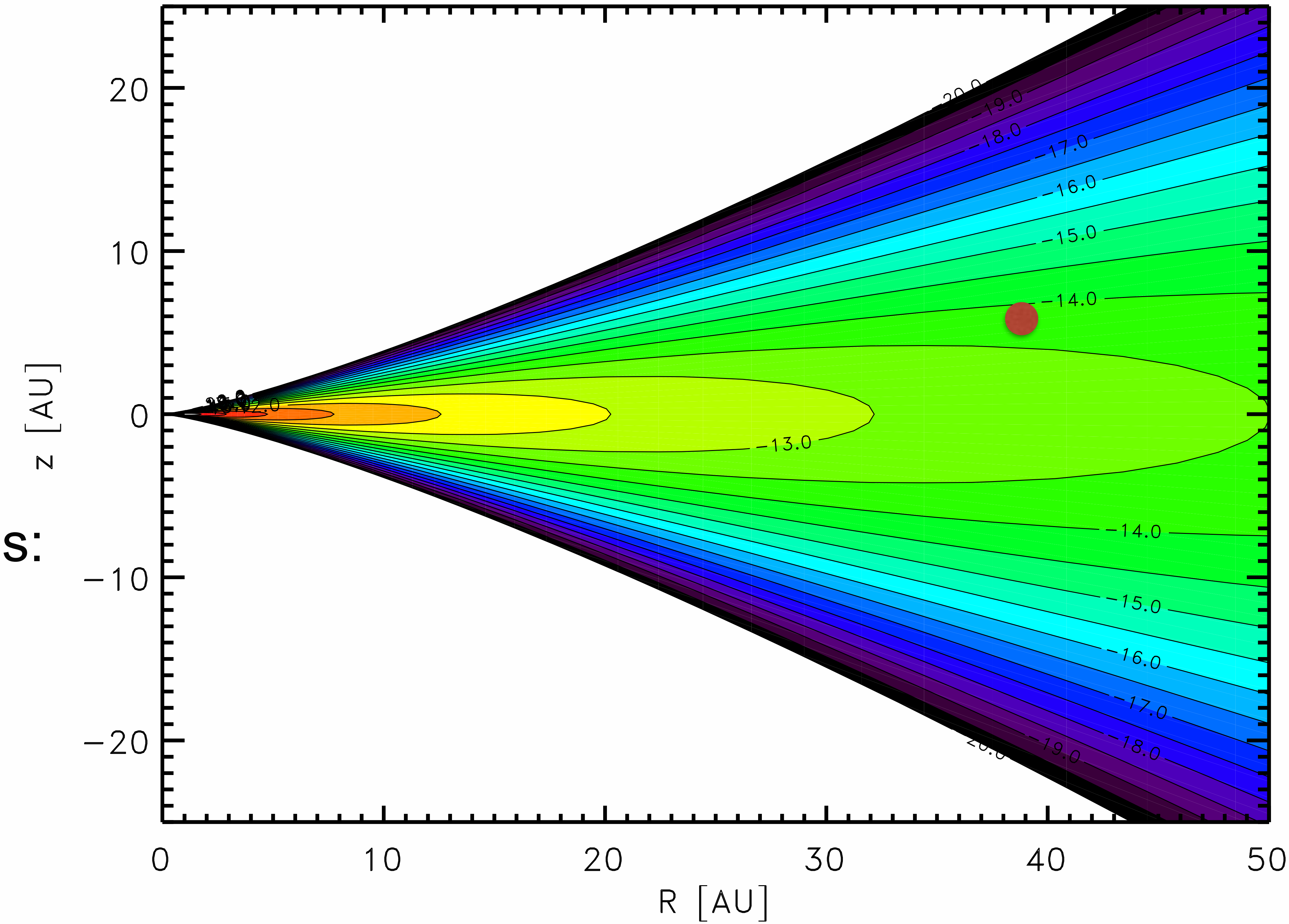
Particle motions are affected by the gas.

$$t_s = \frac{mv}{F_D}$$

$$F_D = \frac{4}{3}\pi a^2 c_s \rho_g v$$

$$m = \frac{4}{3}\pi a^3 \rho_m$$

$$t_s = \frac{a\rho_m}{\rho_g c_s}$$



Planetesimals:
$t_s \Omega_K >> 1$

Dust:
$t_s \Omega_K << 1$

Pebbles:
$t_s \Omega_K \sim 1$

Vertical settling: small particles “fall” toward the midplane.

$$F_z = -mg_z$$

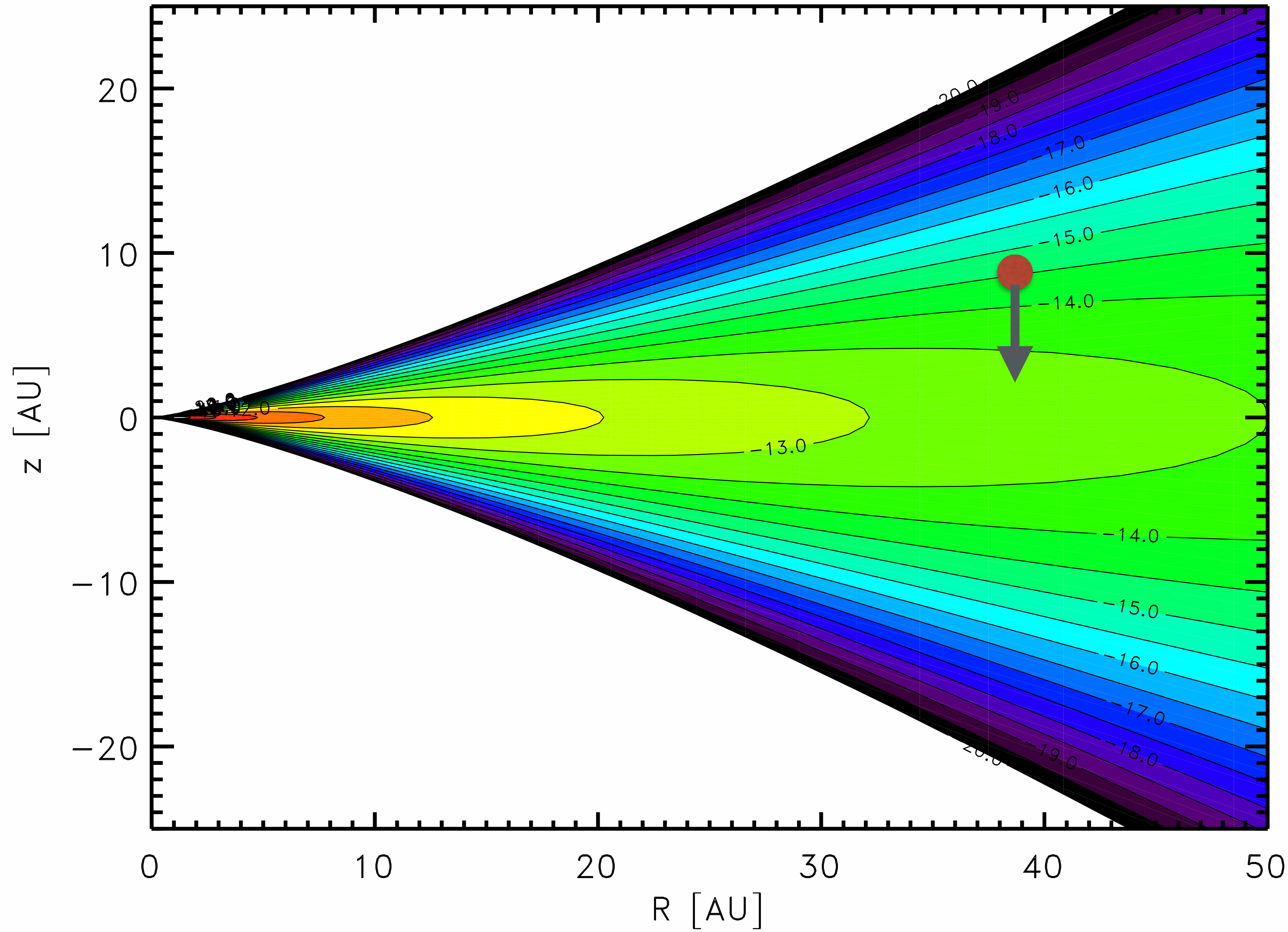
$$F_z = -\frac{GM_\odot m}{r^2}\frac{z}{r}$$

$$F_z == -m\Omega_K^2 z$$

$$F_D = \frac{4}{3}\pi a^2 c_s \rho_g v_z$$

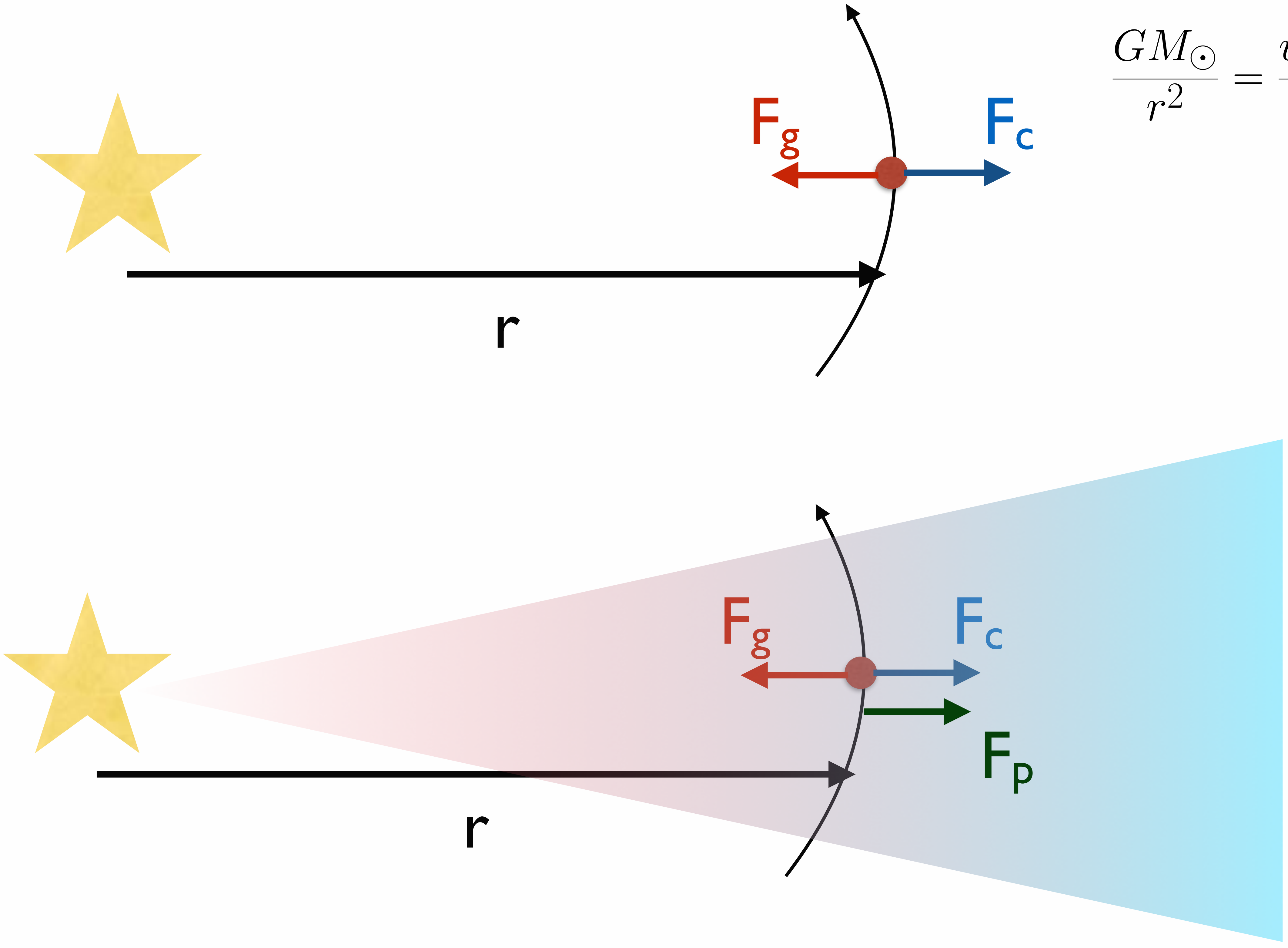
$$v_z = -\Omega_K^2 t_s z$$

$$t_{sett} = \frac{z}{|v_z|} = \left(t_s \Omega_K^2\right)^{-1}$$



Radial Structure: pressure

$$\frac{GM_\odot}{r^2} = \frac{v^2}{r}$$

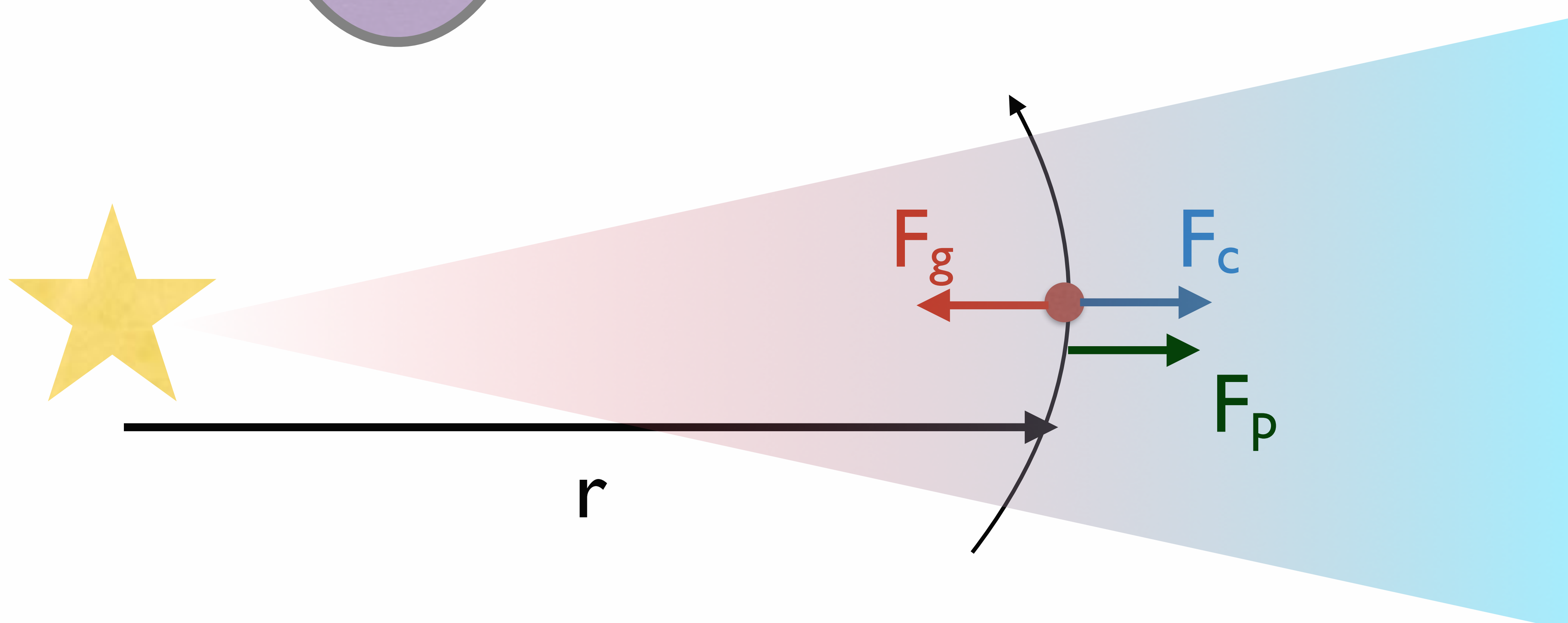


Radial Structure: pressure

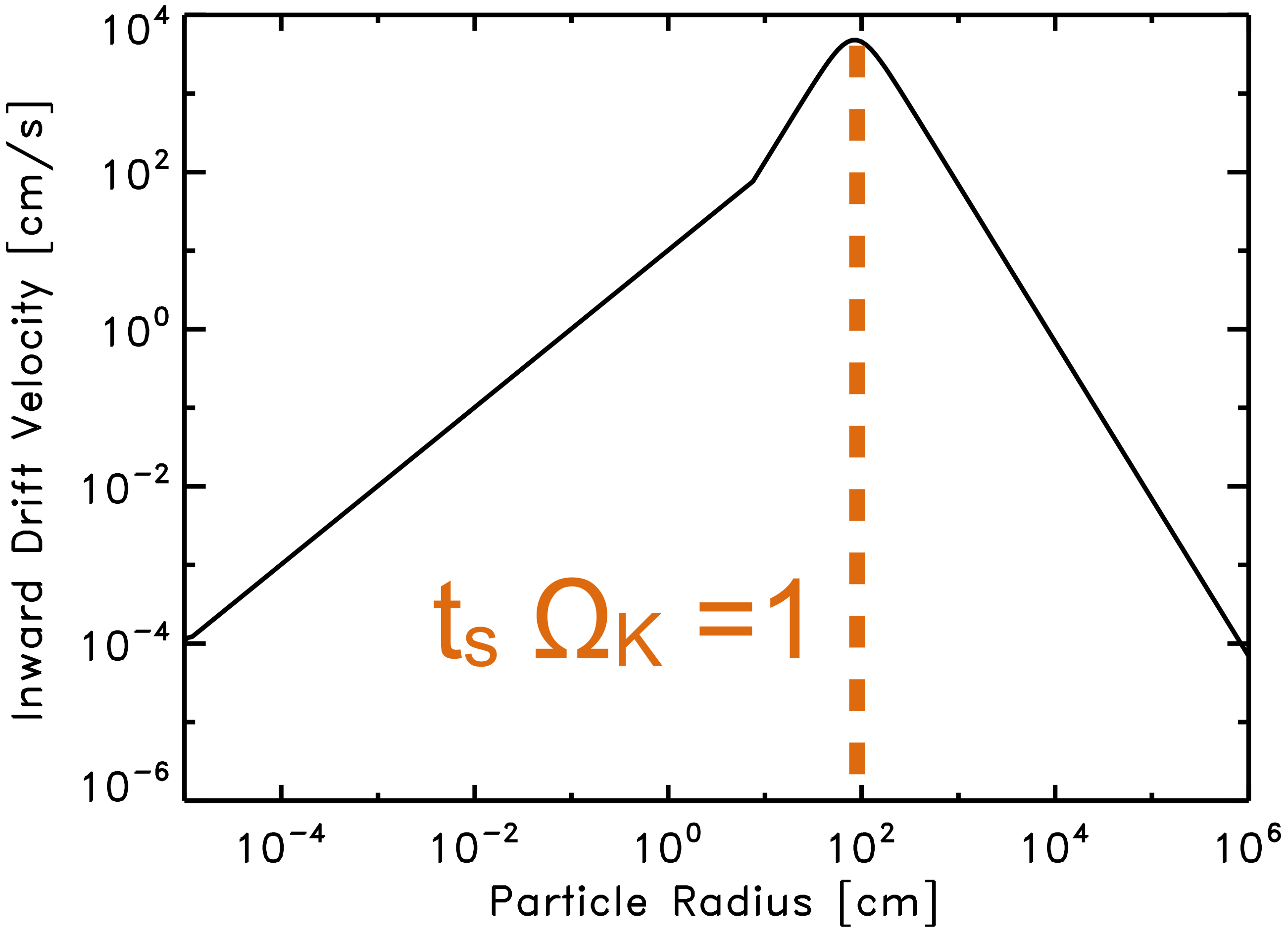
$$F_c = F_g + F_p$$

V_{solid} - V_{gas} ~ 10-100 m/s

$$\frac{v^2}{r} = \frac{GM_\odot}{r^2} + \frac{1}{\rho_g}\frac{\partial P}{\partial r}$$

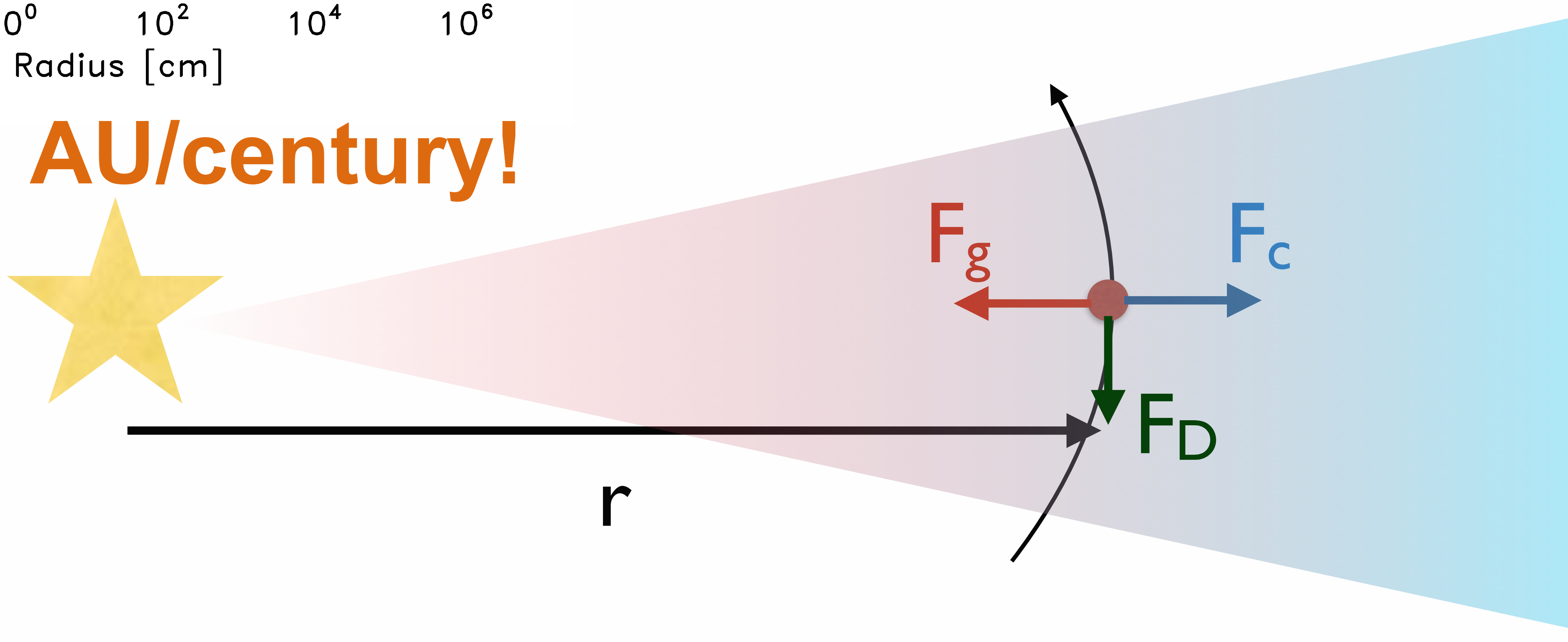


Gas Drag--Solid-Gas Separation



Solids will experience a "head wind" as they orbit the star, causing them to drift inwards with time.

~50 m/s or ~1 AU/century!

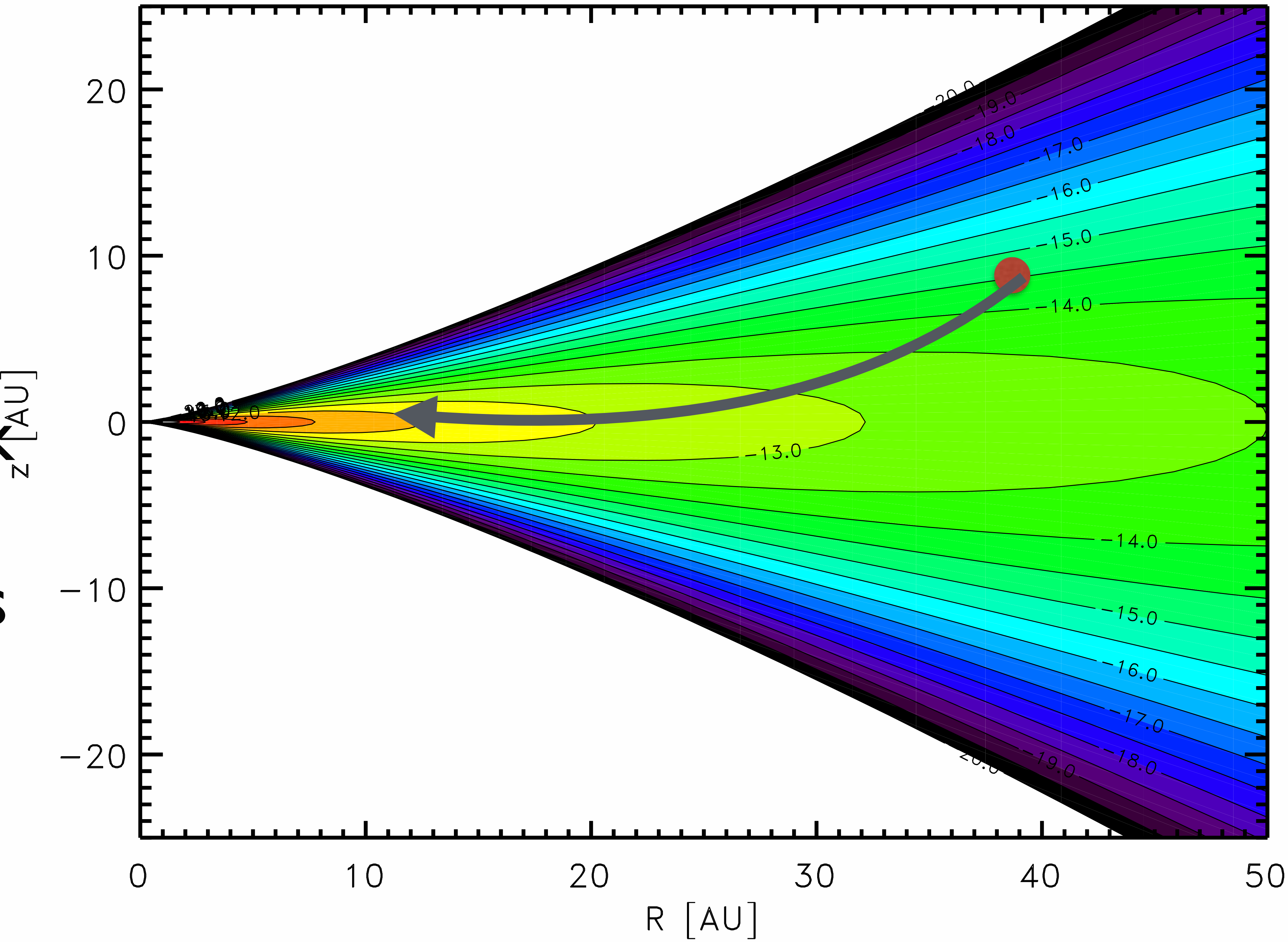


Solids settle and migrate inwards with time. How do we get outward transport?

Photophoresis

Jets above Disk

Disk Dynamics



Photophoresis requires direct radiation from the star to drive dust outward.

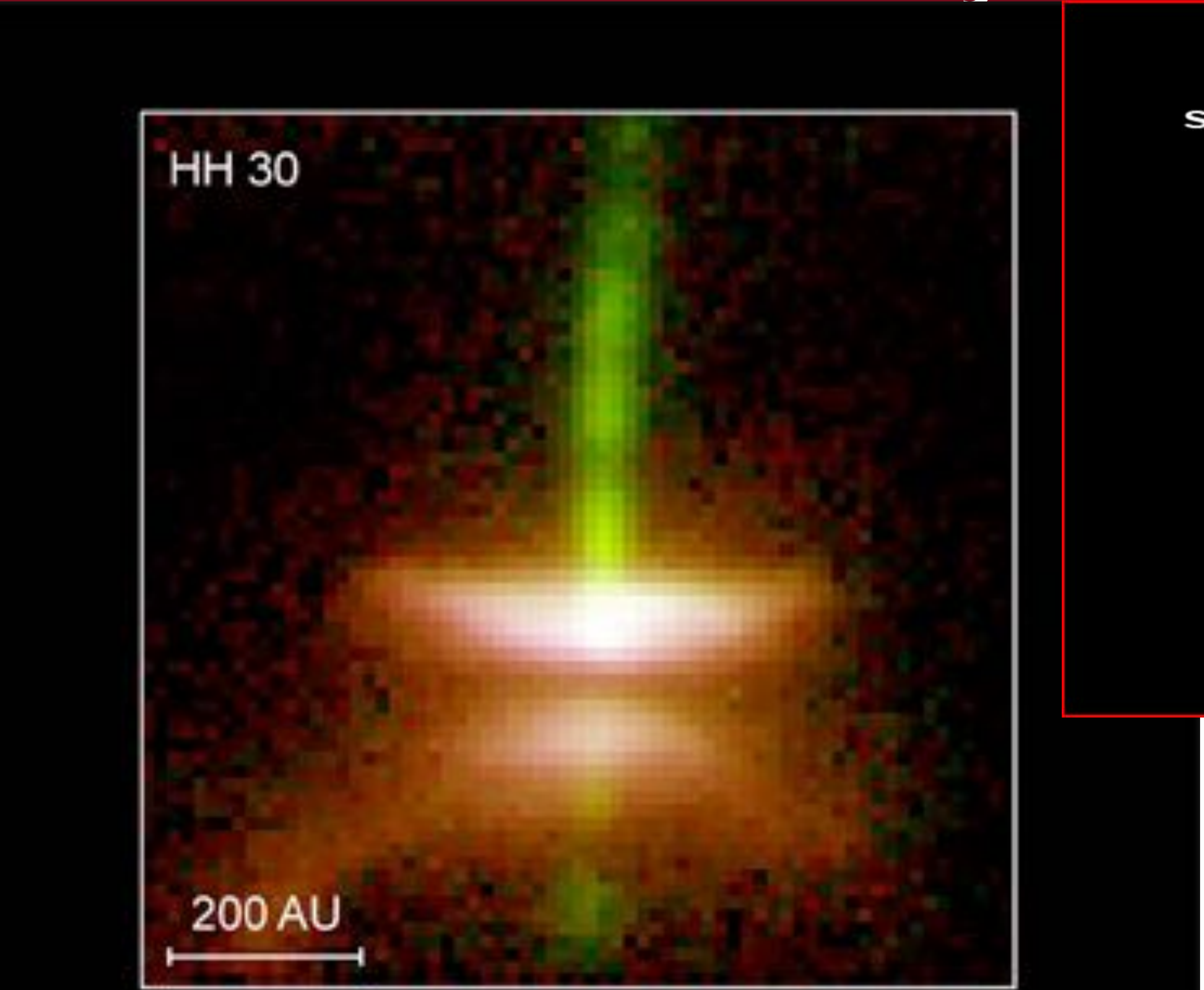
Crookes Radiometer

Photons from star heat one side of particle more than other.

Gas molecules bounce off grain surface with higher velocity, imparting more momentum. This leads to outward drift.

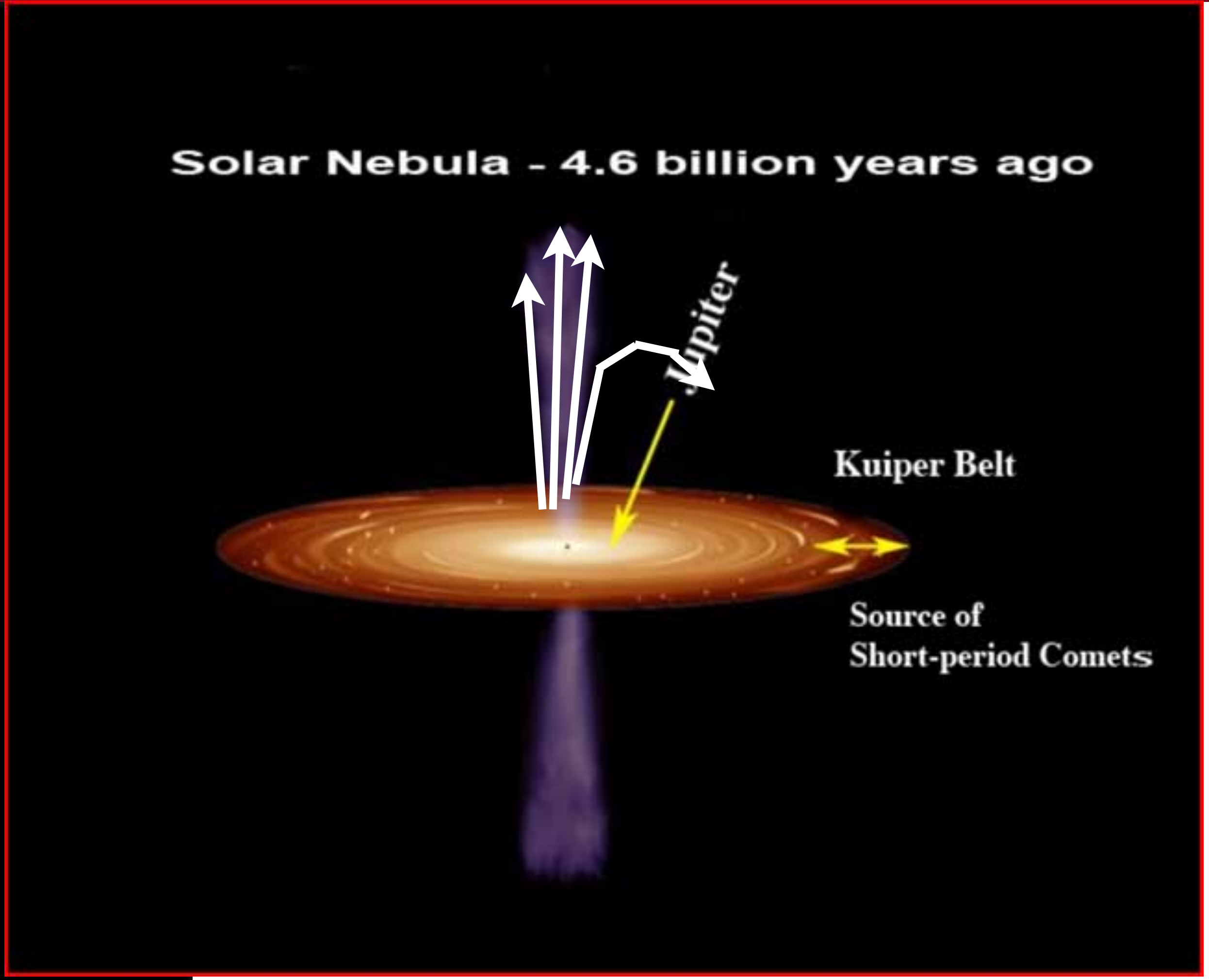
Kraus and Wurm 2005; Haack+ 2006; Wurm+ 2007;Cuello+ 2016

Jet models suggest materials were carried ballistically above the disk.



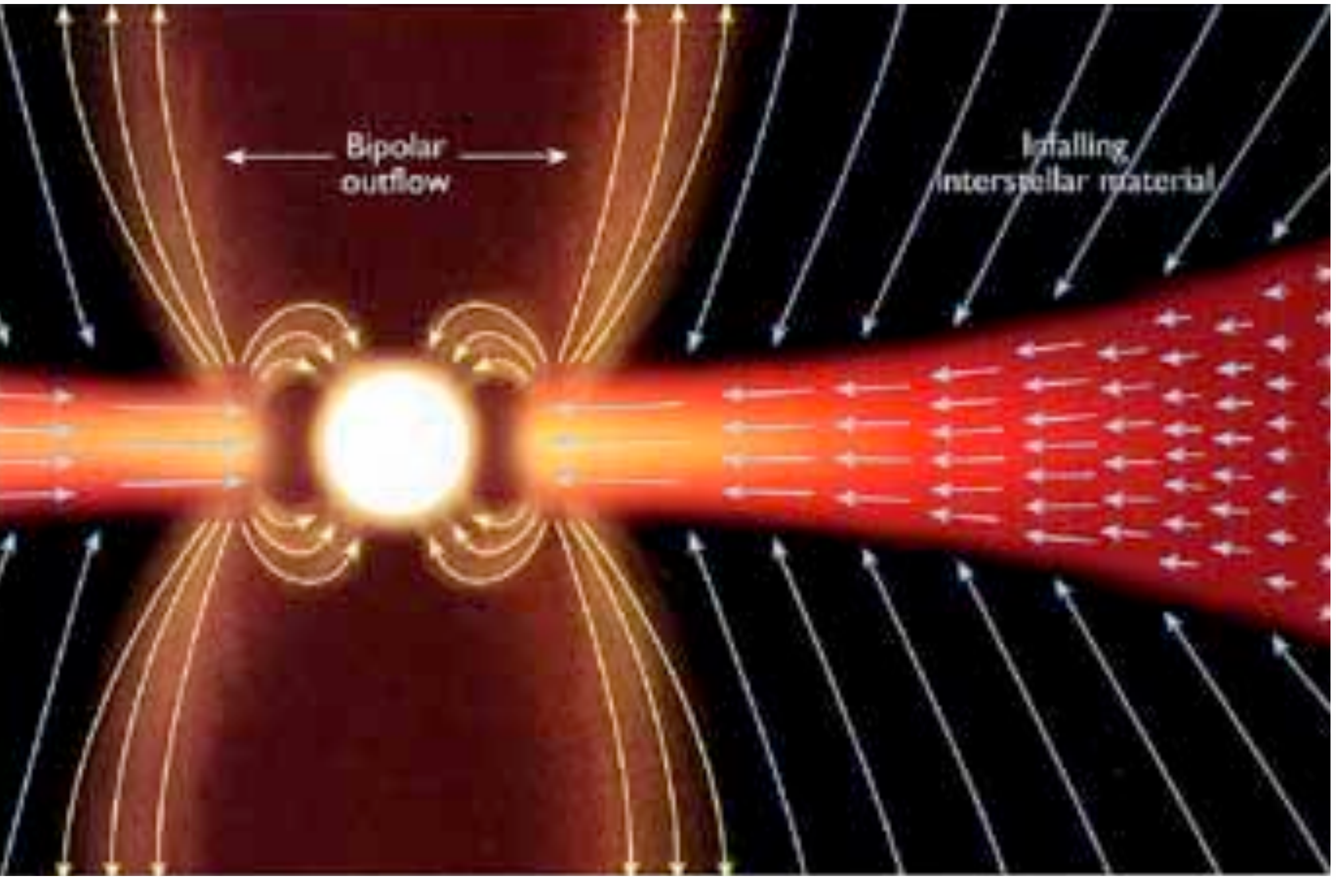
Disks around Young Stars

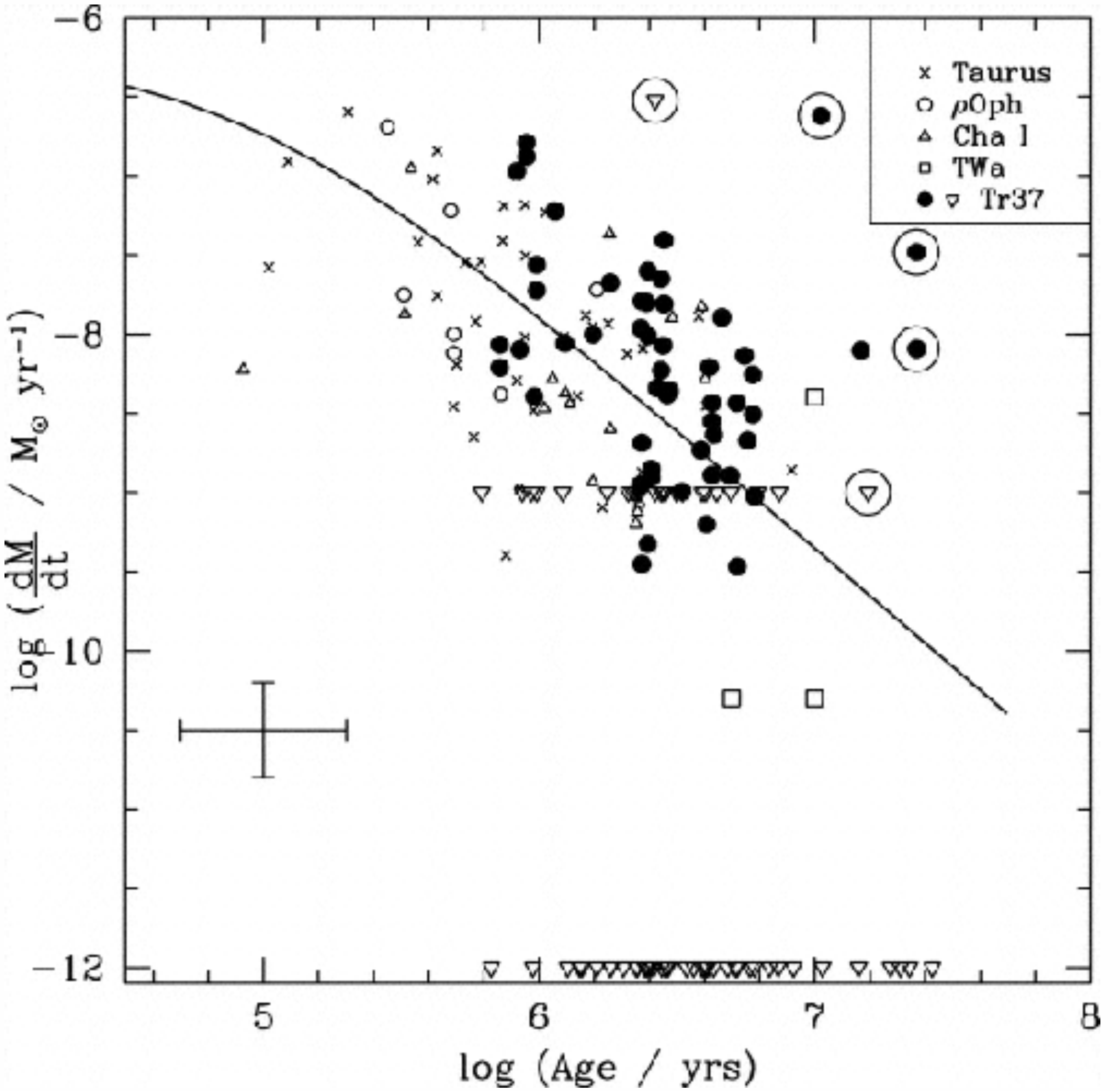
Hubble Space Telescope • WFPC2



Works for refractory dust, but will it work for water?

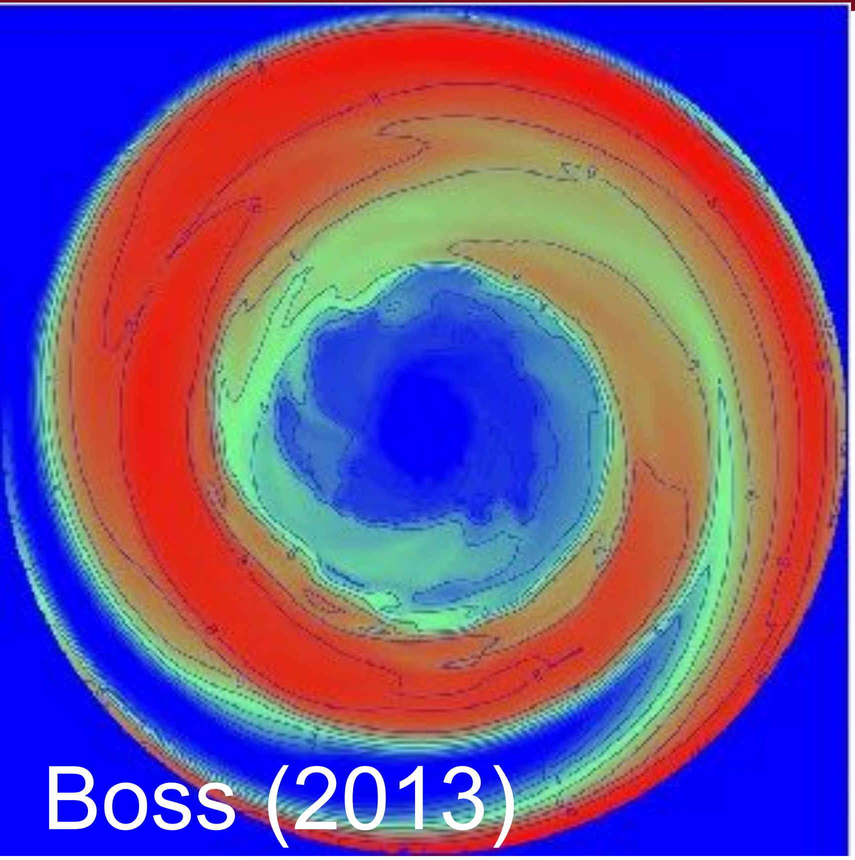
Remember, disks are dynamic themselves.



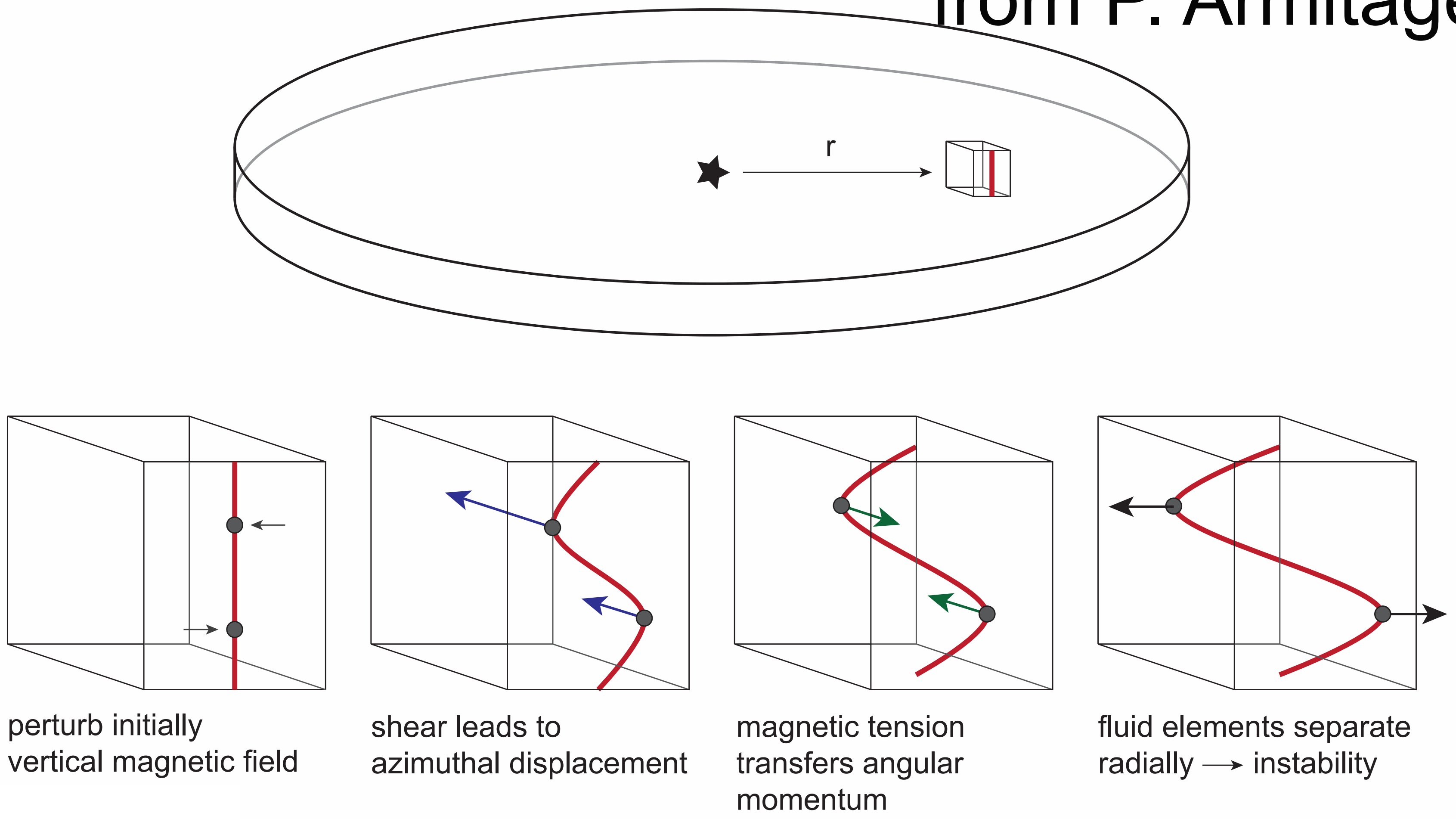


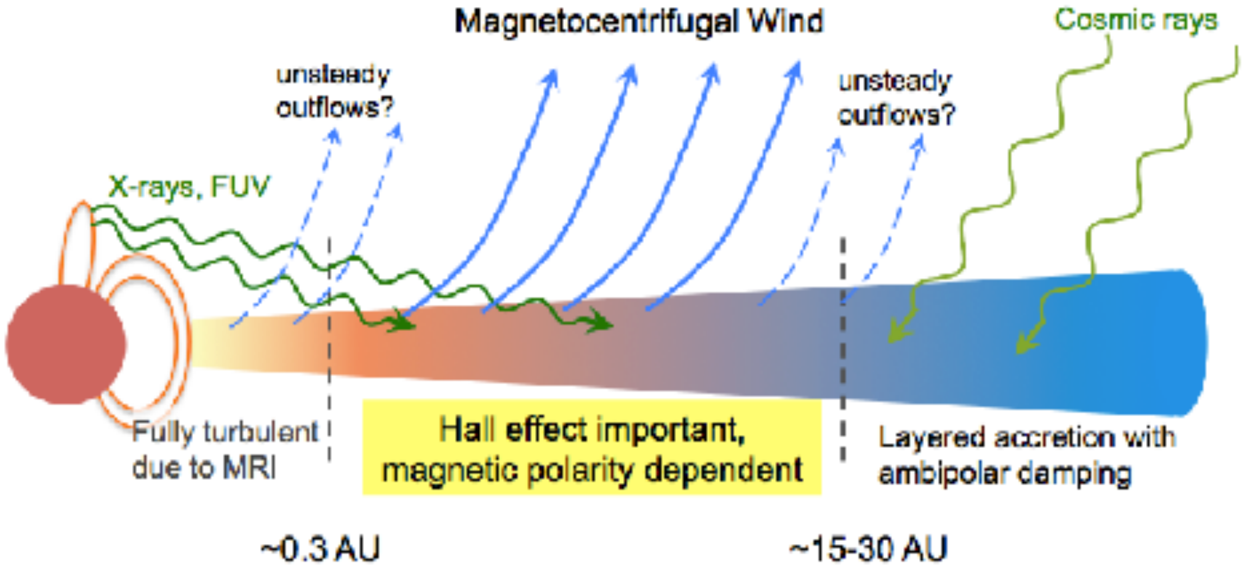
Mass is accreted from the disk onto the star over periods of millions of years. This leads to large-scale movement of disk materials.

How materials were redistributed in the disk is controlled by how the disk evolves.



from P. Armitage

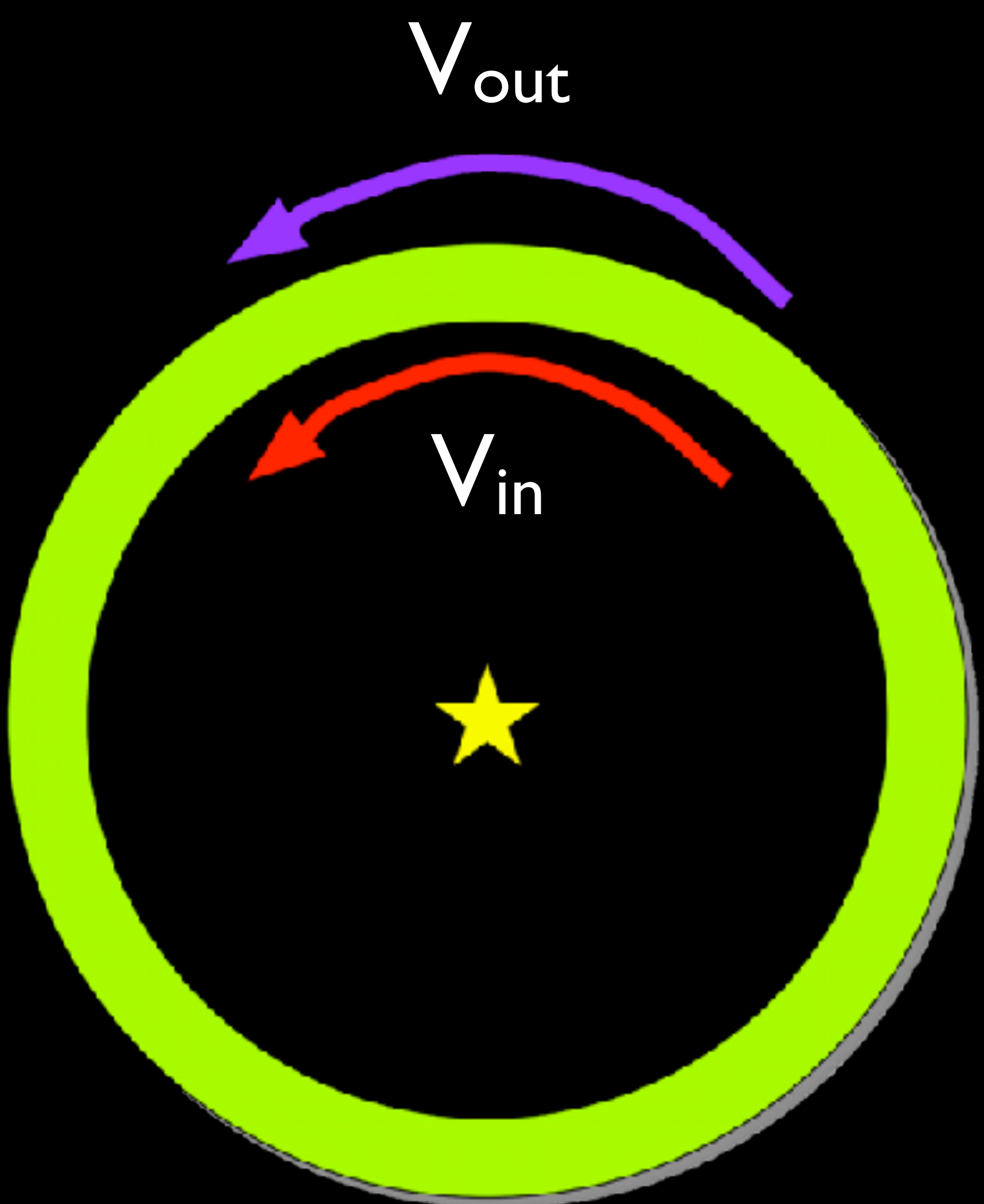




Bai (2014)

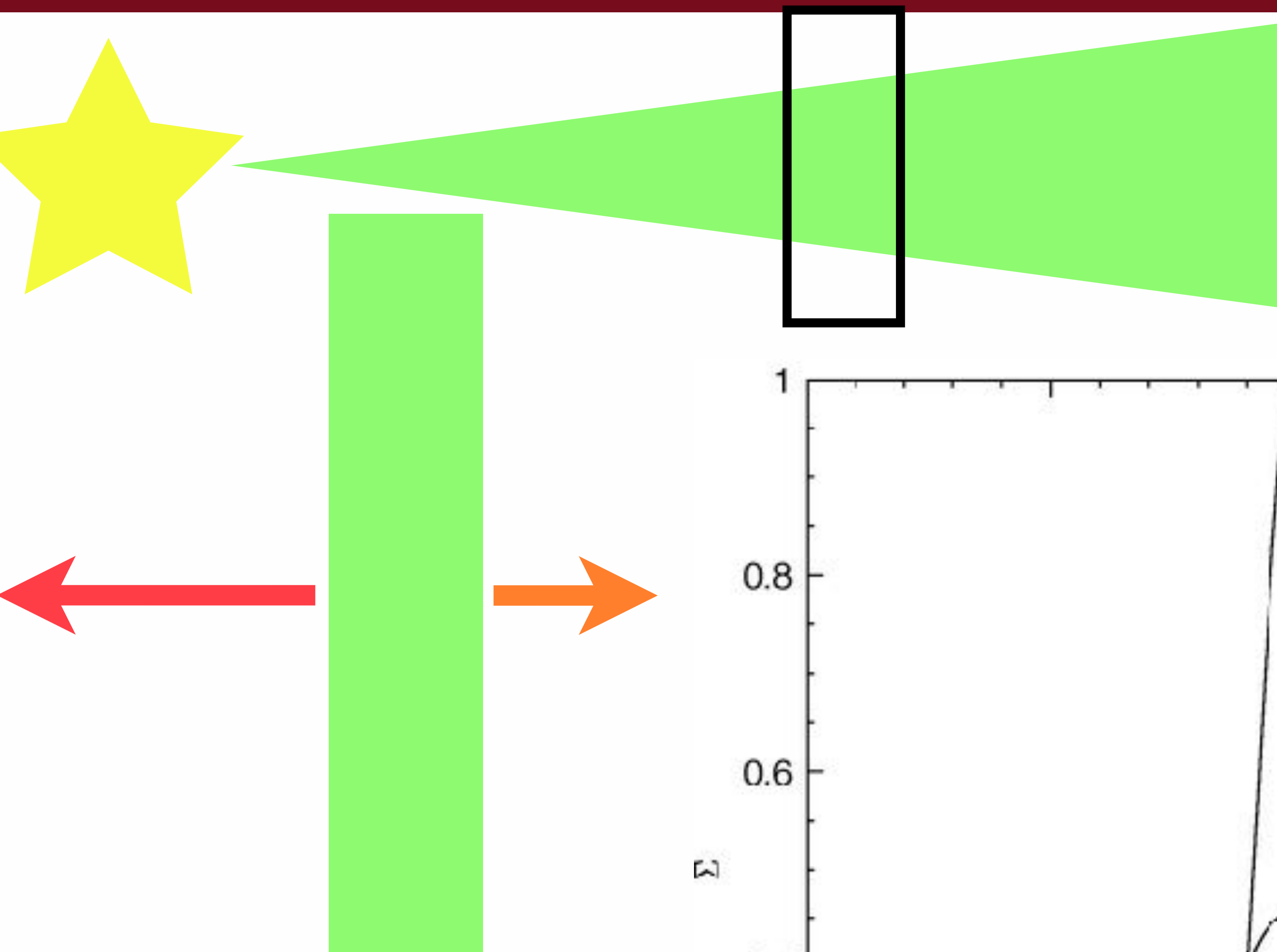
Gravitational or magnetohydrodynamic interactions result in forces between disk parcels, allowing angular momentum to be transferred within the disk.

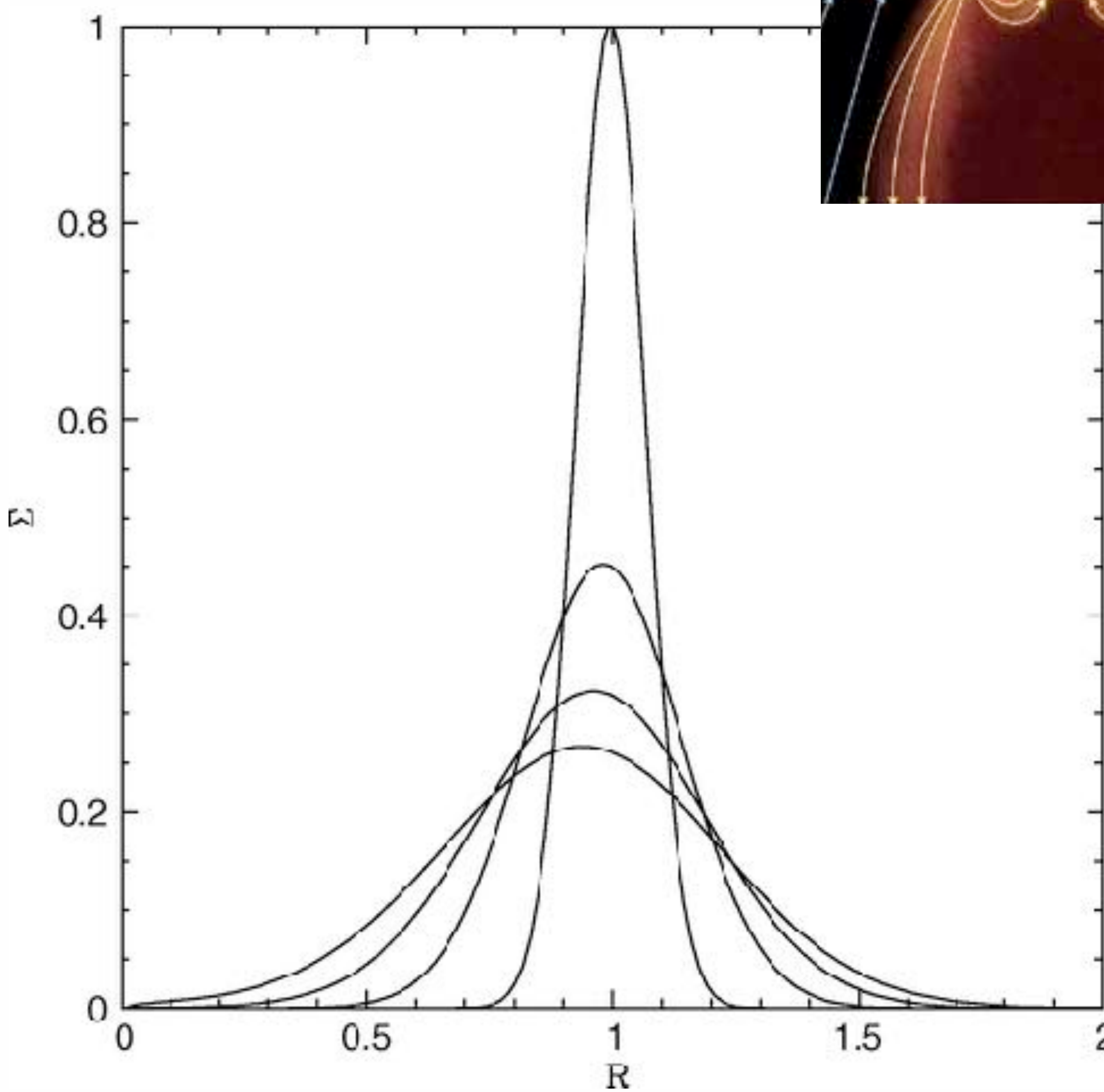
Viscous Disk Model

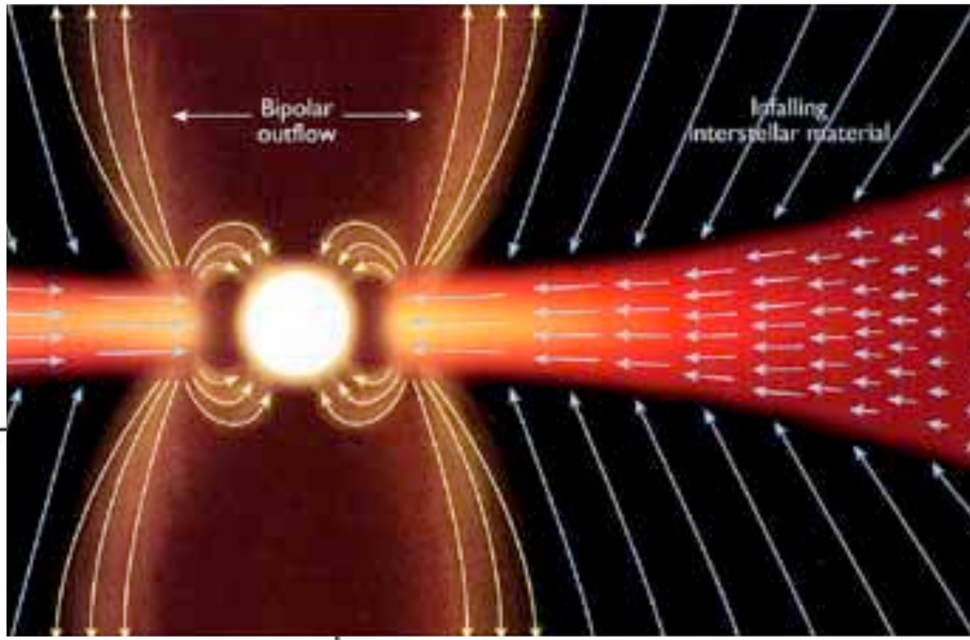


- Disk is considered to be turbulent and viscous.
- $V_{out} < V_{in}$
- Viscous stresses largely drive mass inward, with some being pushed outward to conserve angular momentum.
- Viscosity taken to be $\nu = \alpha c_s H$

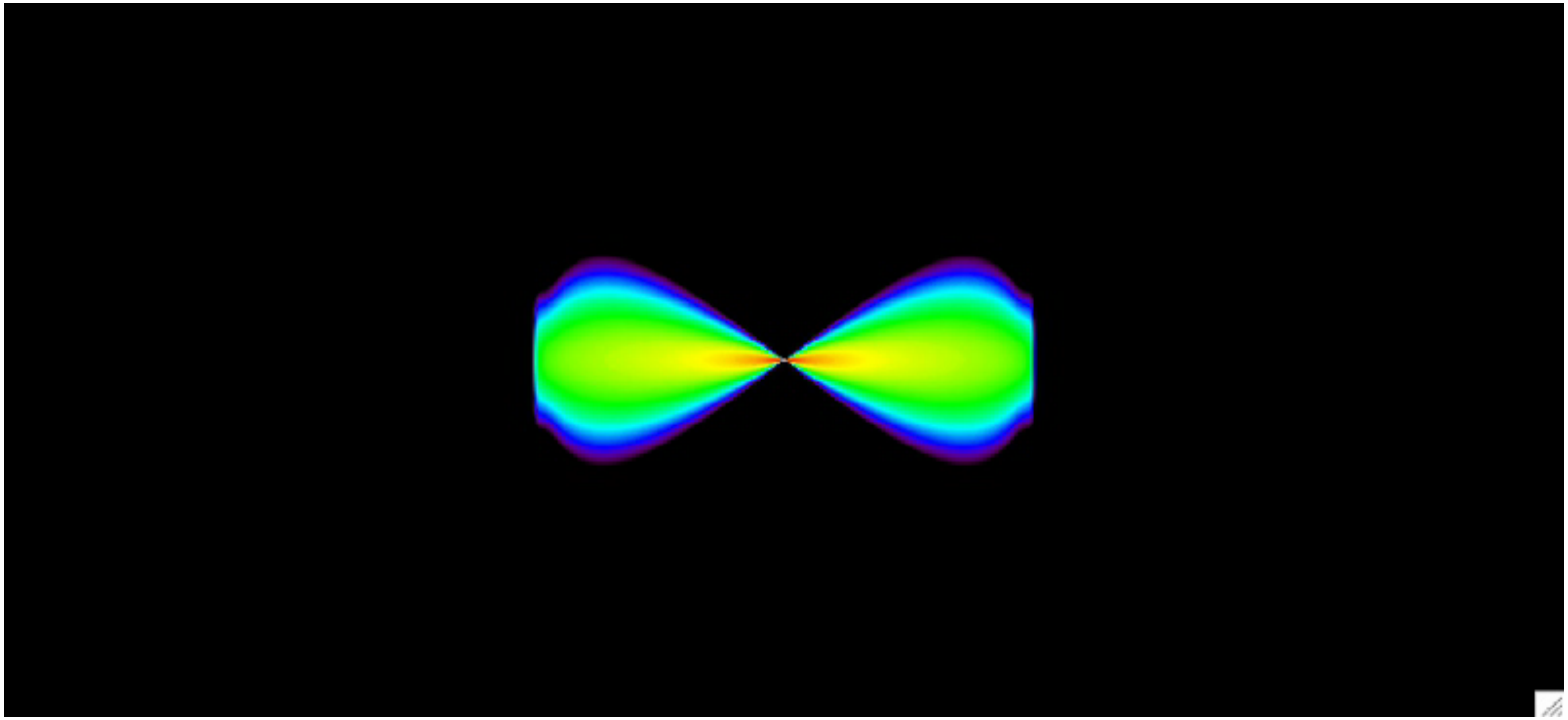
The principles of disk evolution: mass in, angular momentum out.





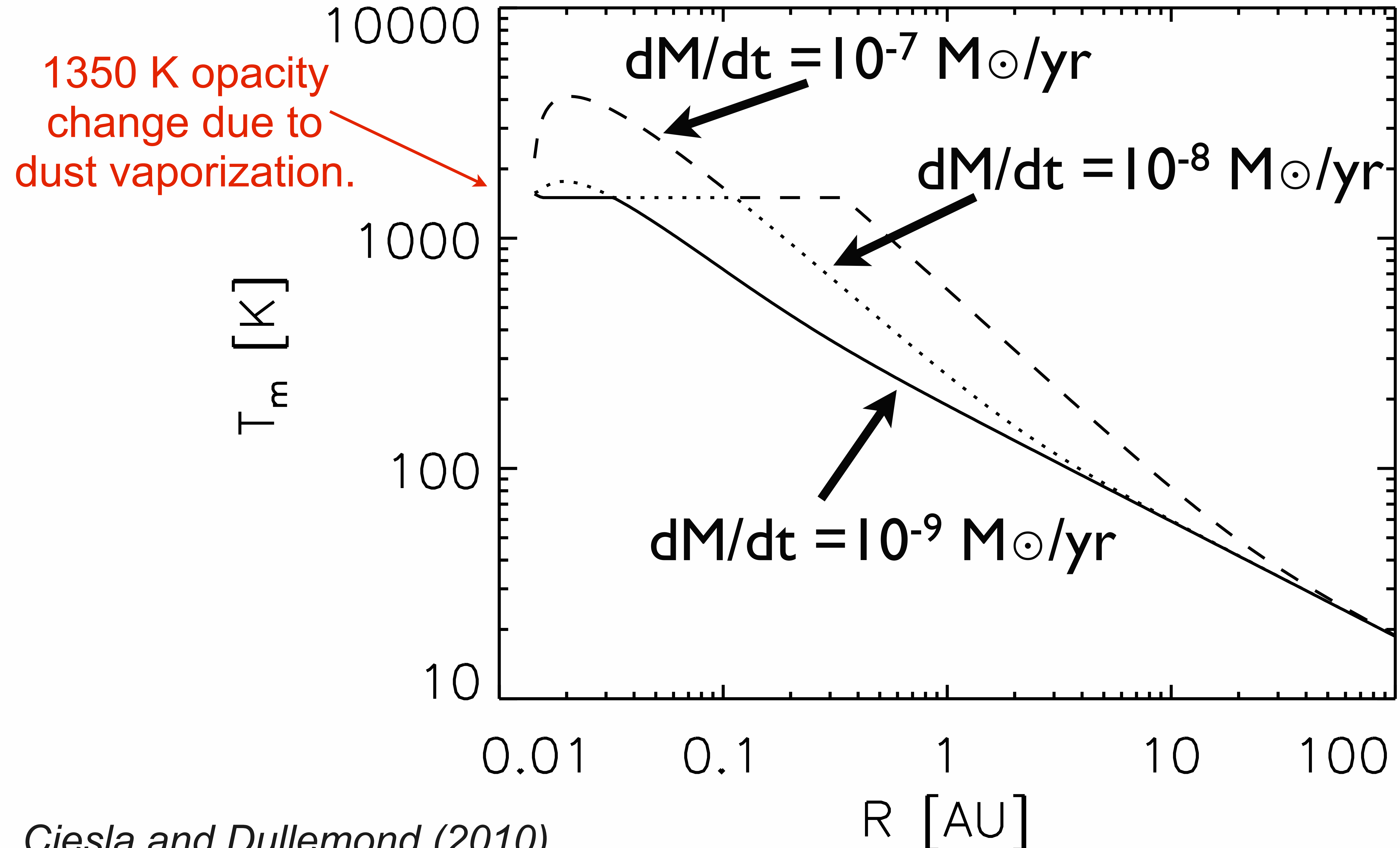


Disks are constantly evolving in response to mass/angular momentum transport.



As gas flows toward/away from disk, solids are entrained in flow, and carried with it.

Disk Thermal Evolution



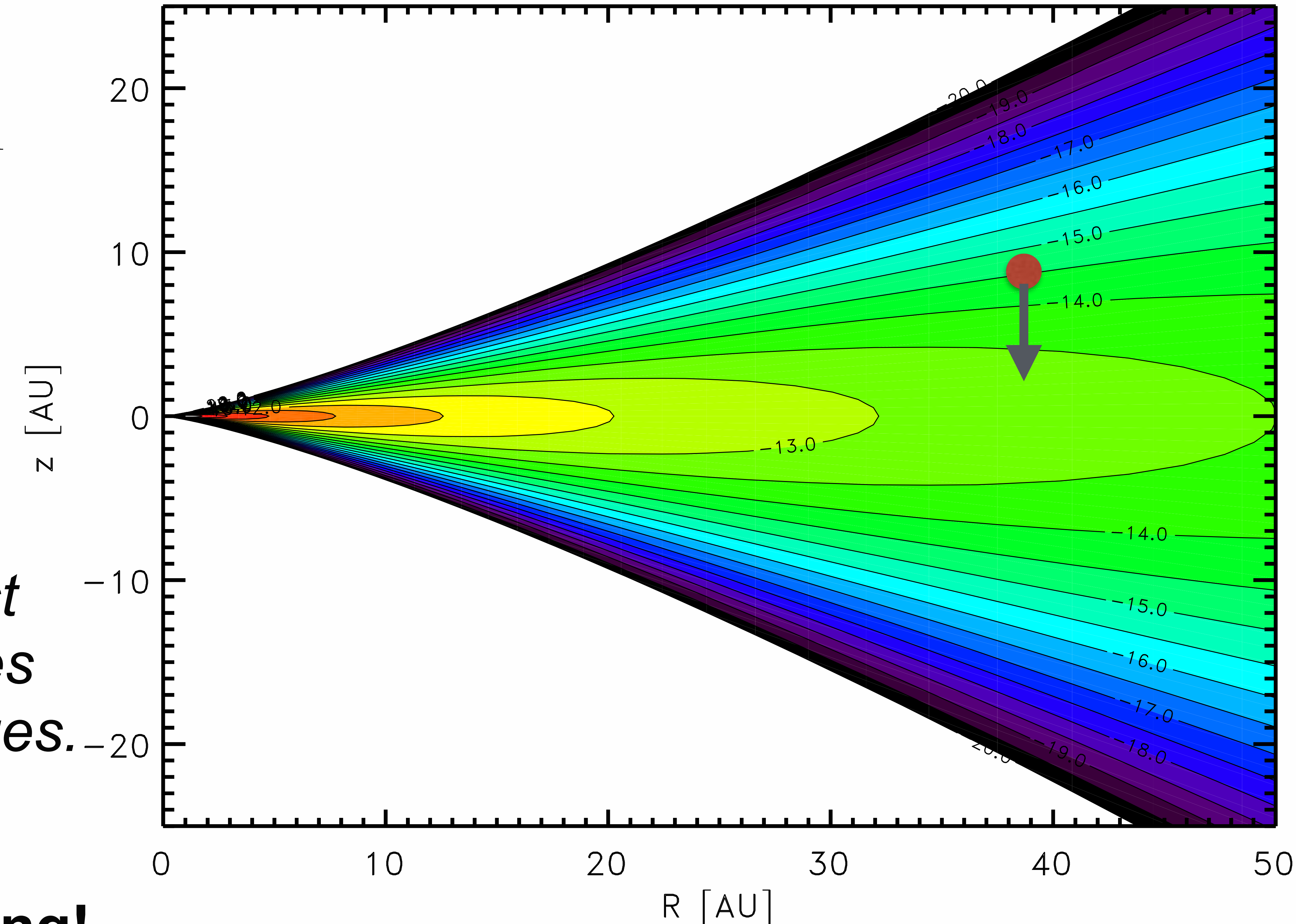
Ciesla and Dullemond (2010)

Vertical settling: small particles "fall" toward the midplane.

$$t_{sett} = \frac{z}{|v_z|} = \left(t_s \Omega_K^2\right)^{-1}$$

$t_{sett} \sim 10^5$ yrs

But disks are seen with dust at high altitudes at much later ages.



=> Upward mixing!

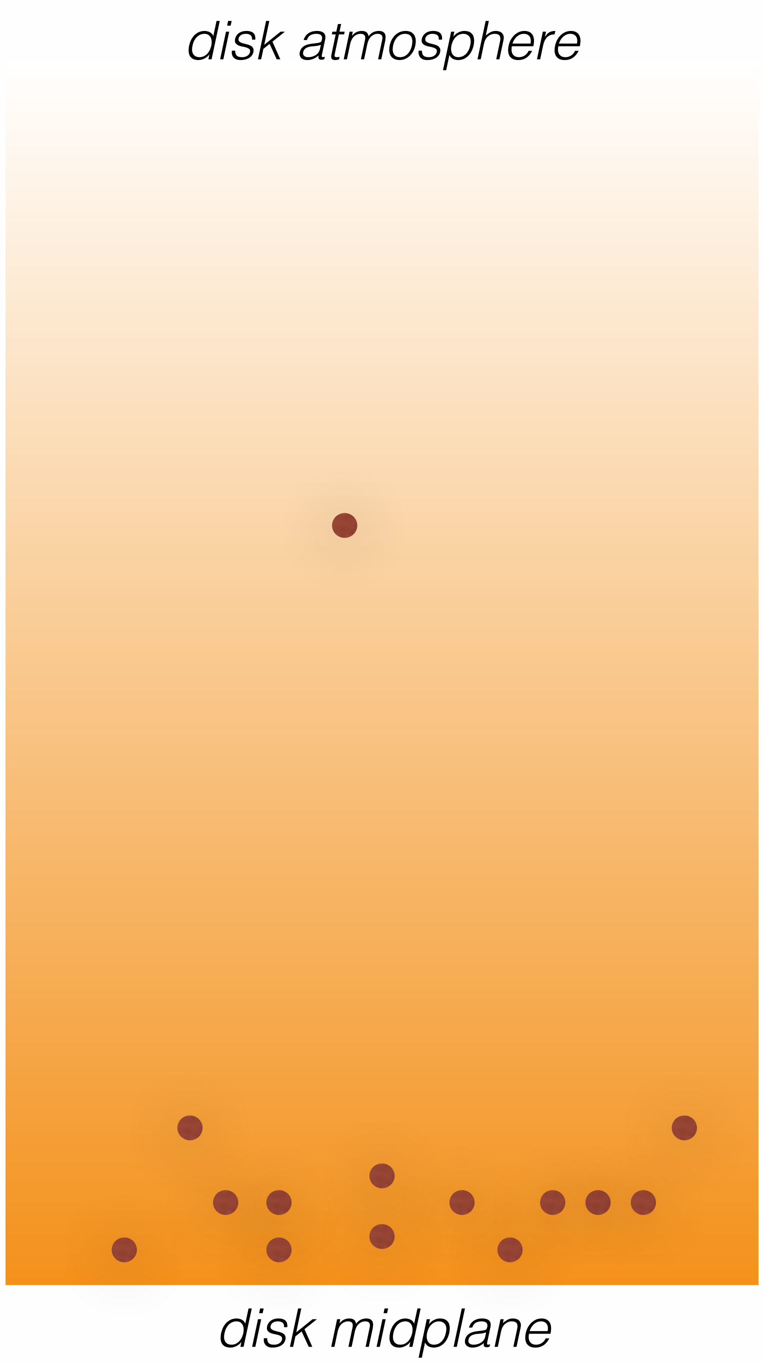
Vertical mixing offsets settling.

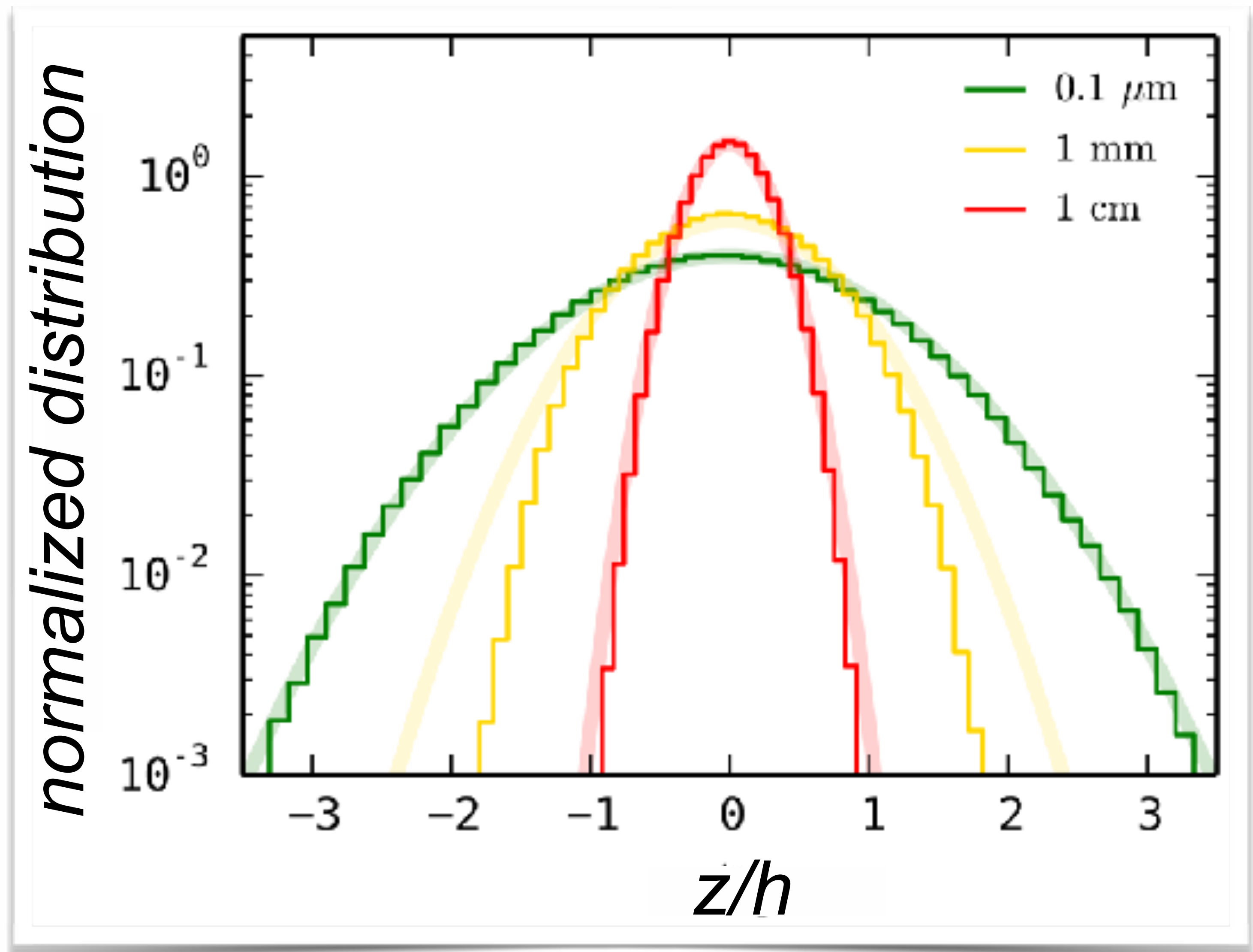
$$\frac{\partial \rho_i}{\partial t} = \frac{\partial}{\partial z}\left(\rho_g D \frac{\partial C_i}{\partial z}\right) - \frac{\partial}{\partial z}(\rho_i v_z)$$

$D = \alpha c_s H$

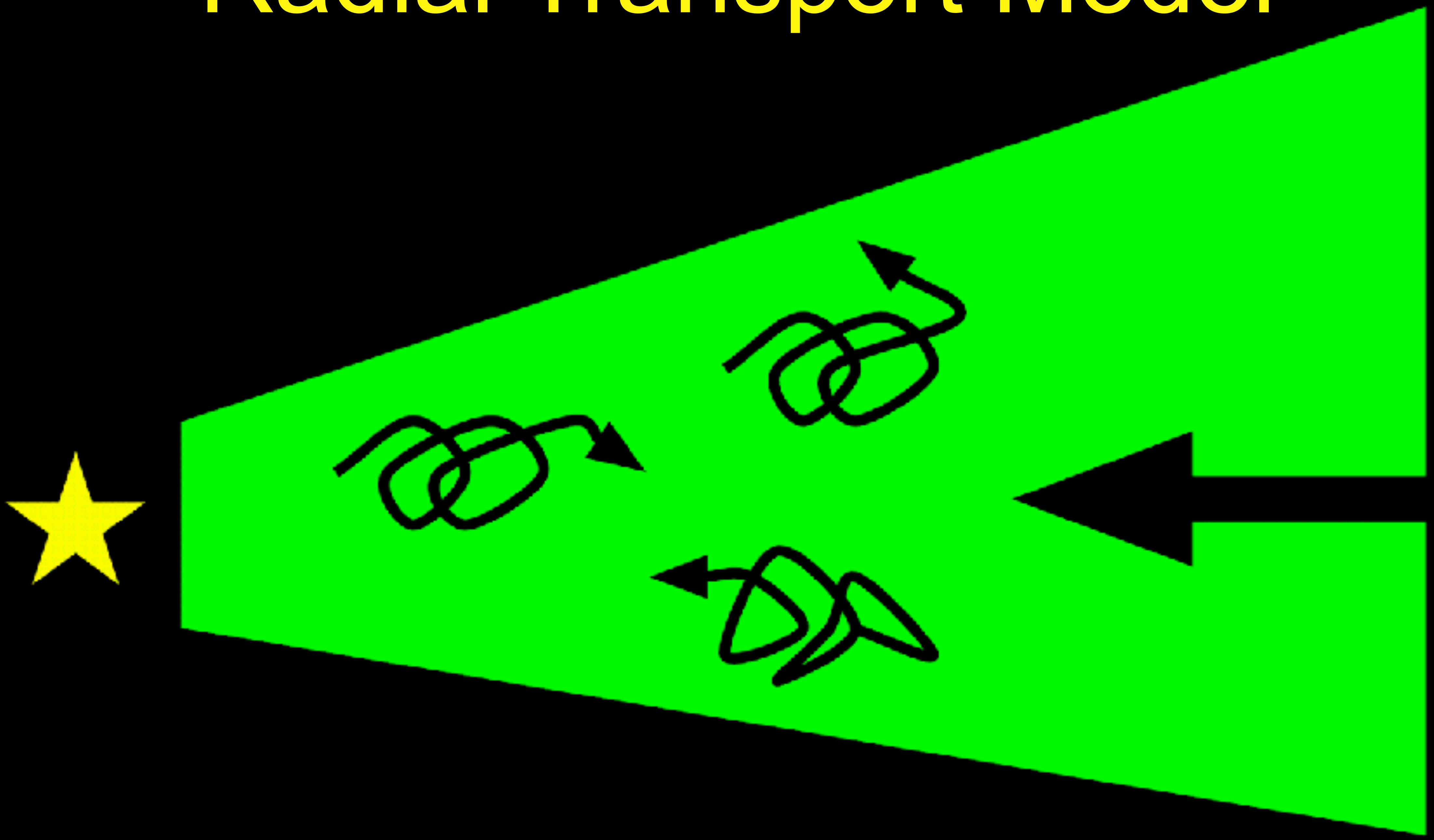
$C_i = \rho_i / \rho_g$

$$\frac{h_\mathrm{d}}{h_\mathrm{g}} \approx \sqrt{\frac{\alpha}{\alpha + \Omega t_s}\left(\frac{1+\Omega t_s}{1+2\Omega t_s}\right)}$$



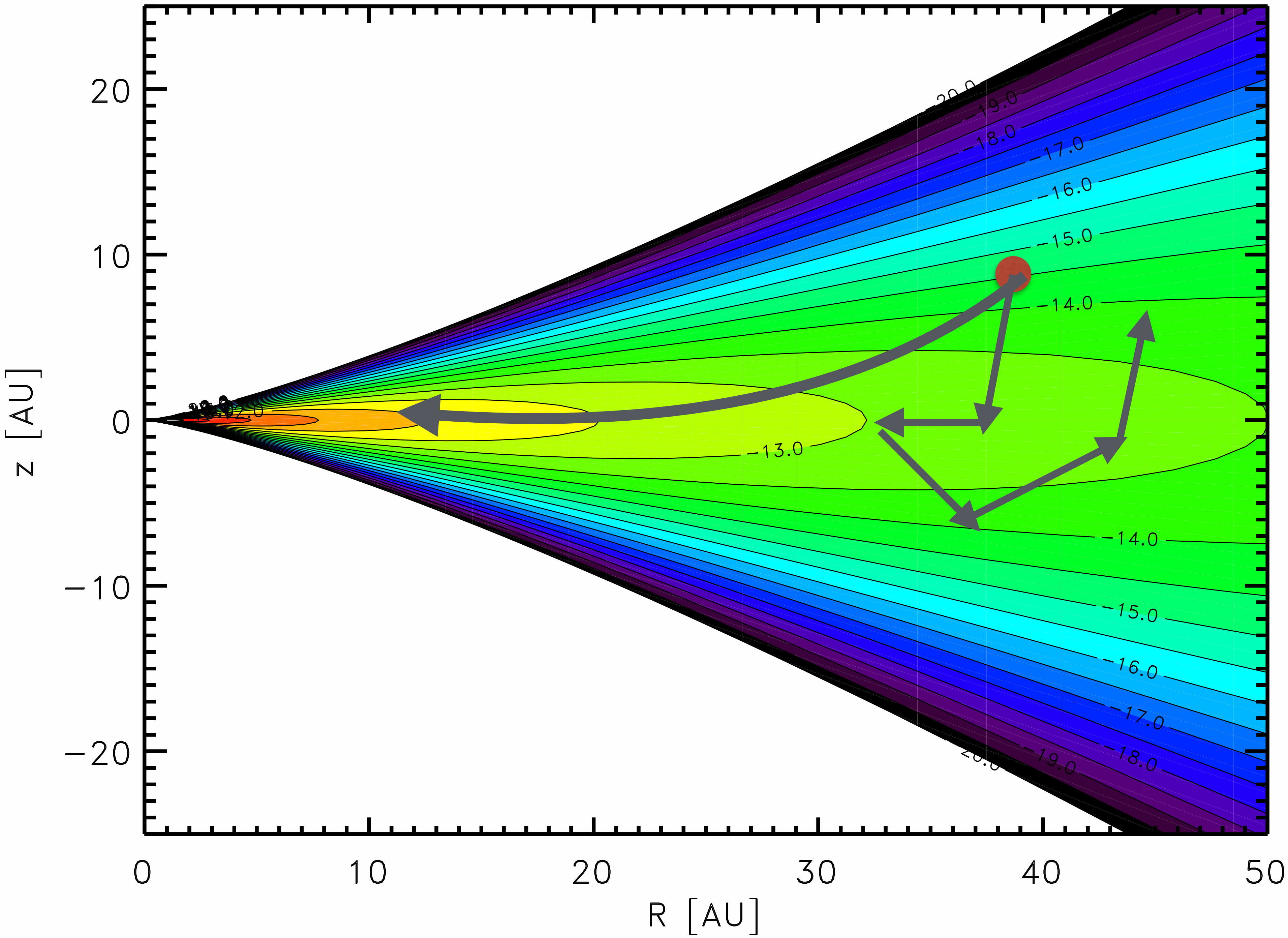


Radial Transport Model



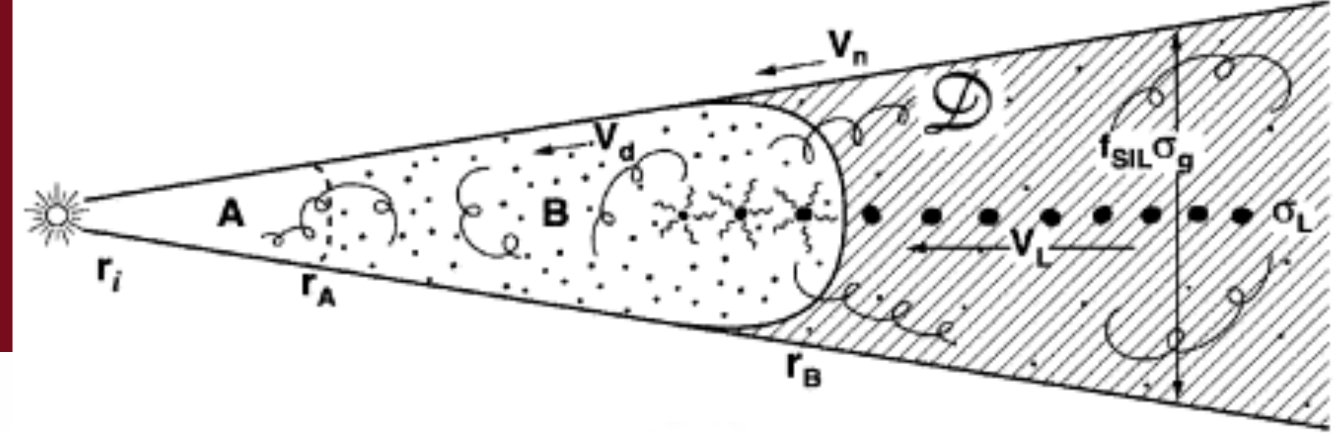
$$\frac{\partial \Sigma_i}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\Sigma D\frac{\partial}{\partial r}\left(\frac{\Sigma_i}{\Sigma}\right)\right) - \frac{1}{r}\frac{\partial}{\partial r}\left(r v_r \Sigma_i\right).$$

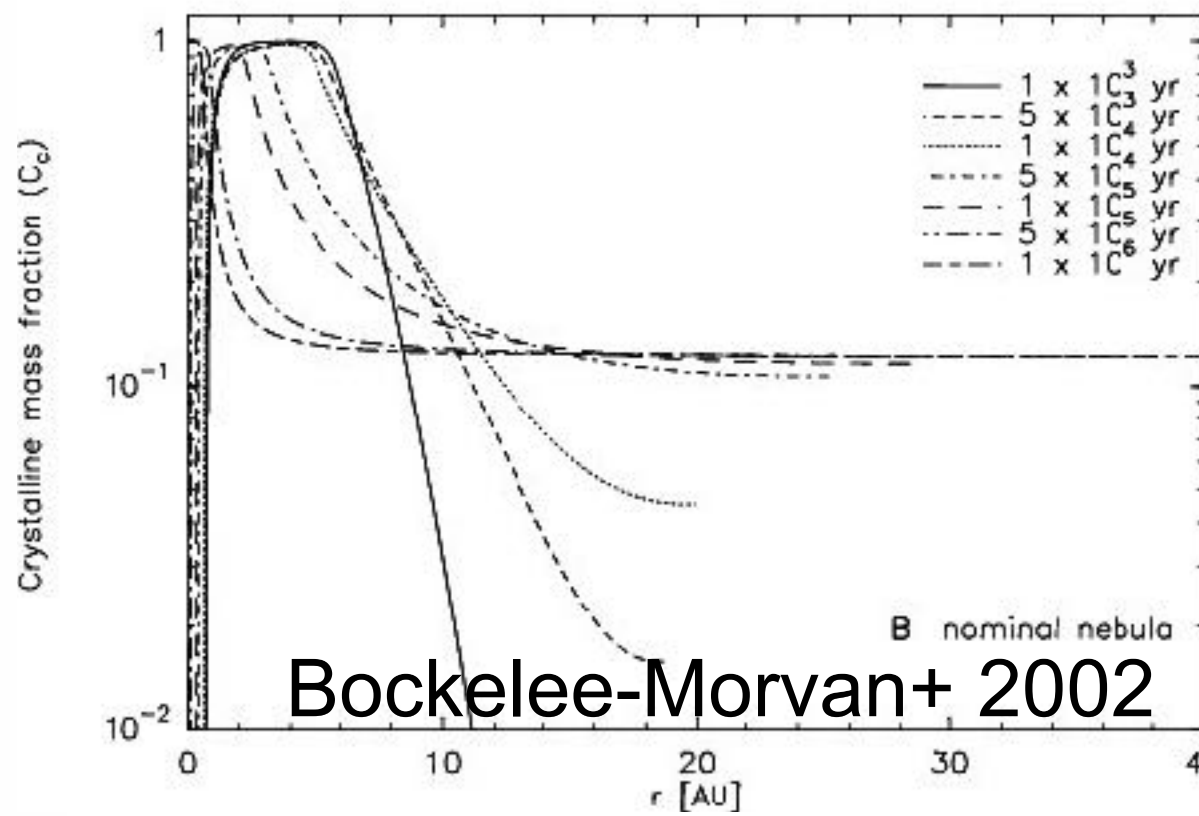
Diffusion leads particles to follow random paths through the disk.

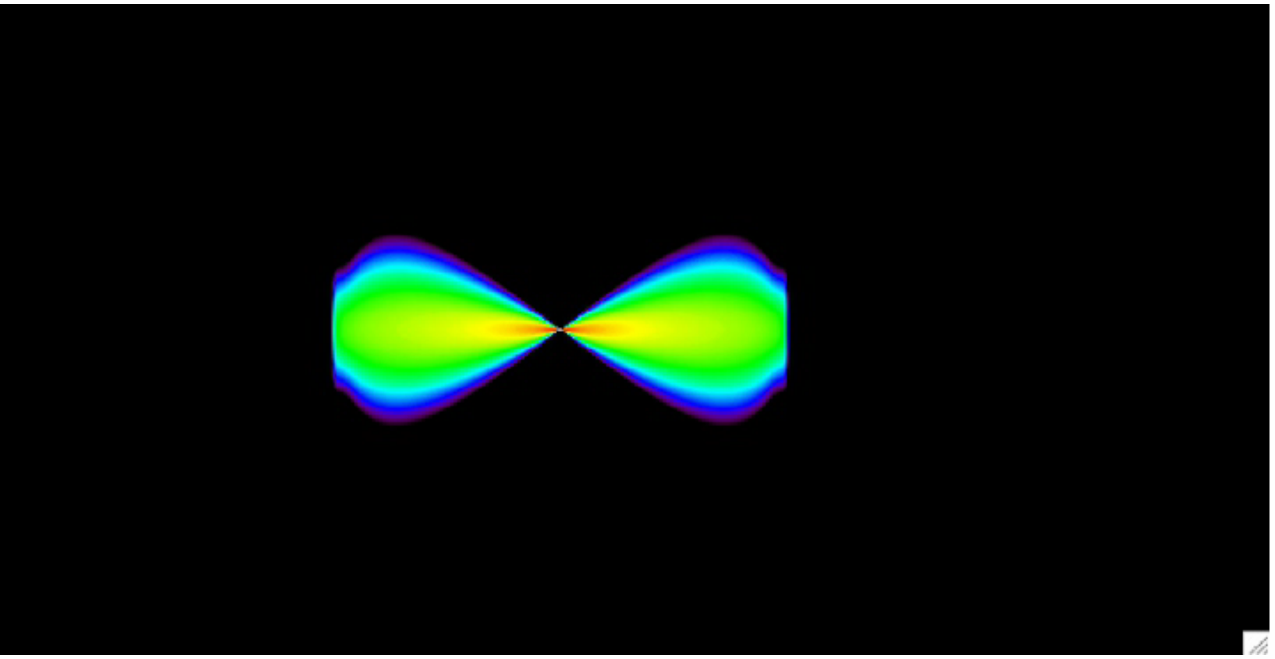


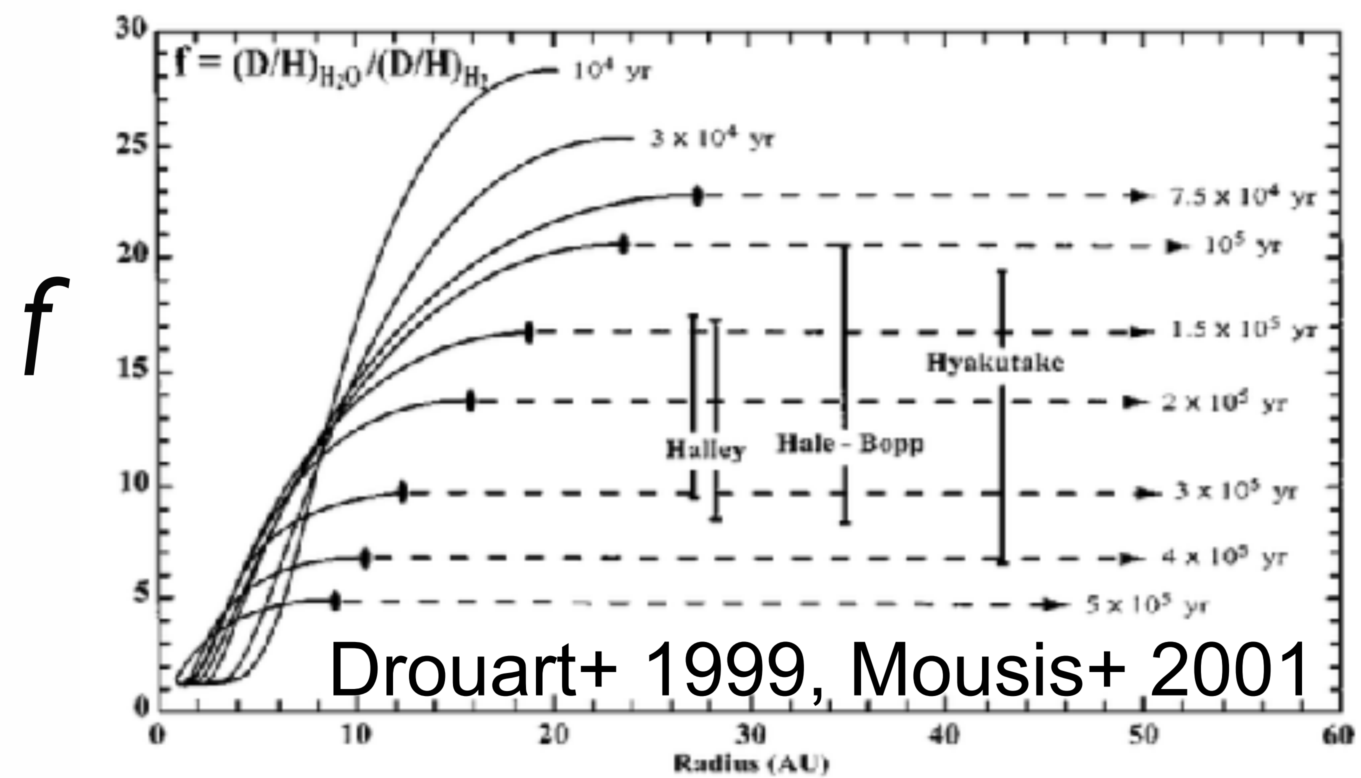
Outward transport

- High temperature materials formed in regions where viscous dissipation led to appropriate temperatures.
- Carried outward by radial expansion of the disk + outward diffusion

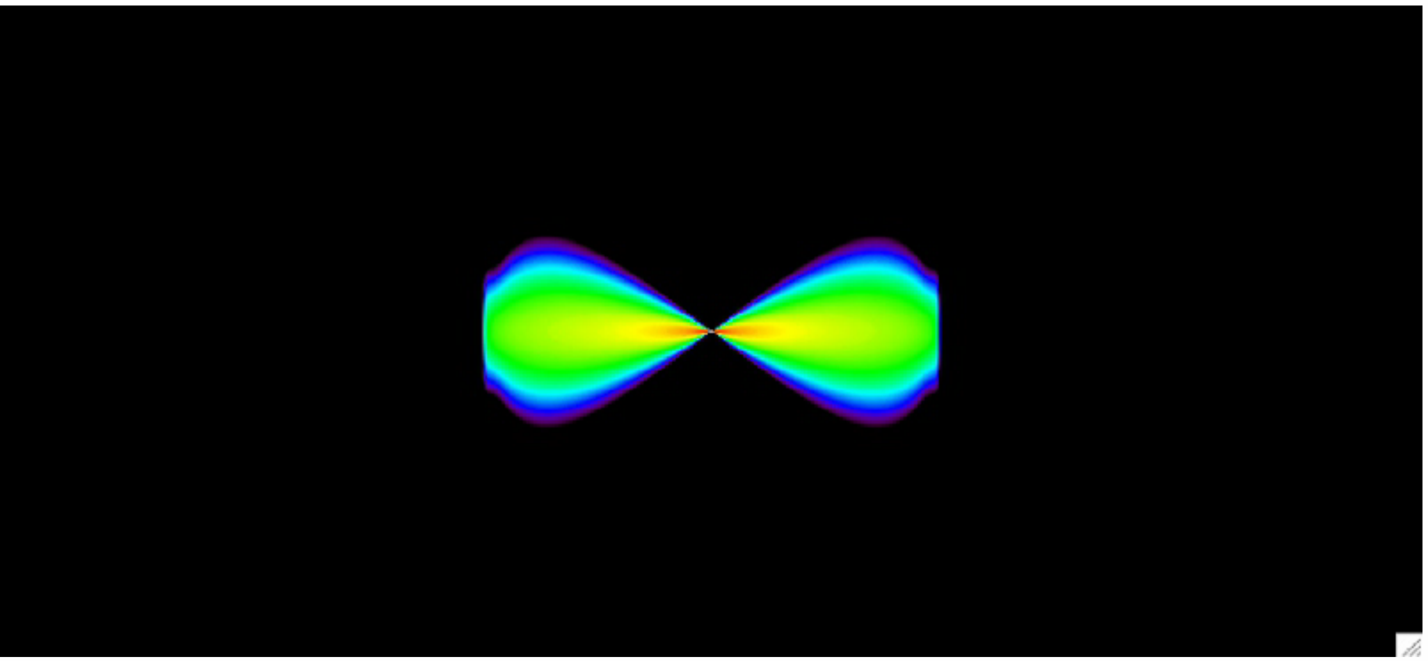


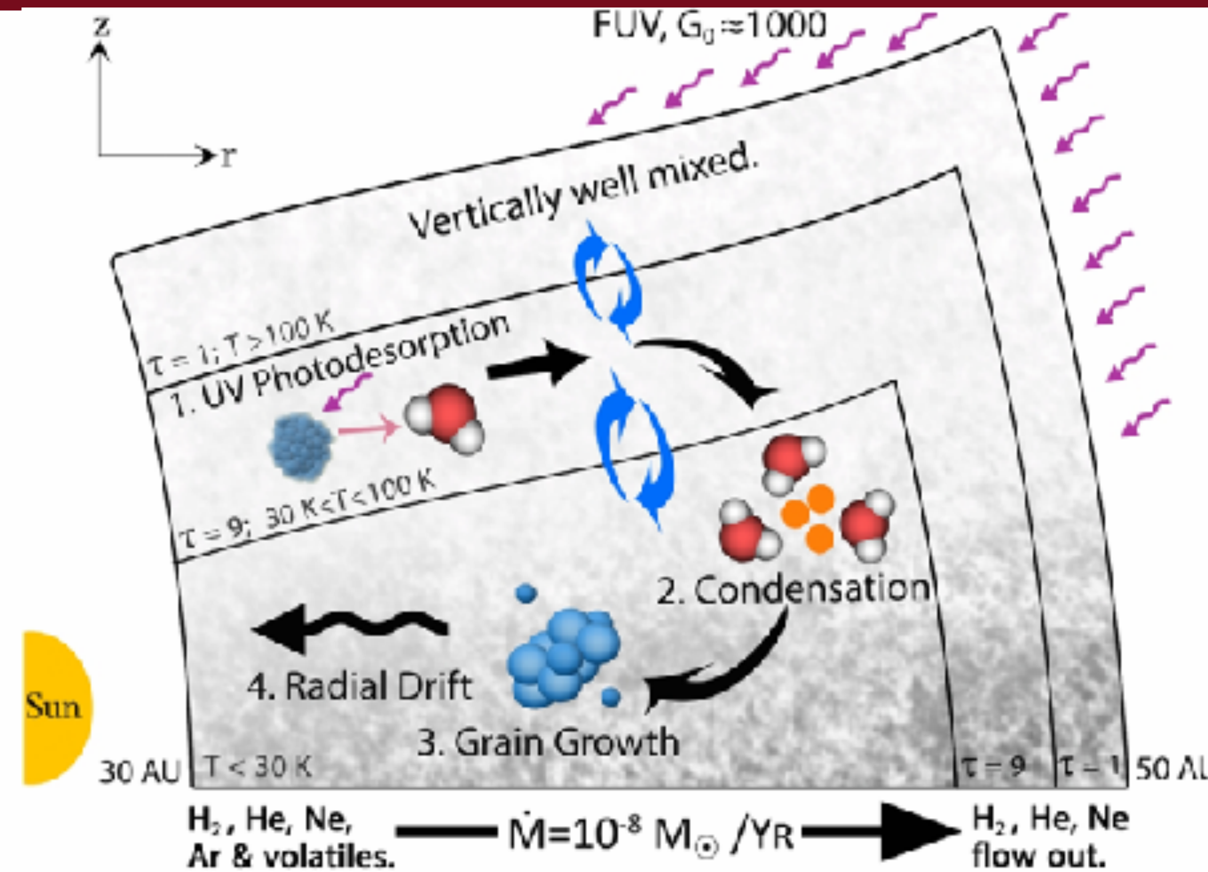




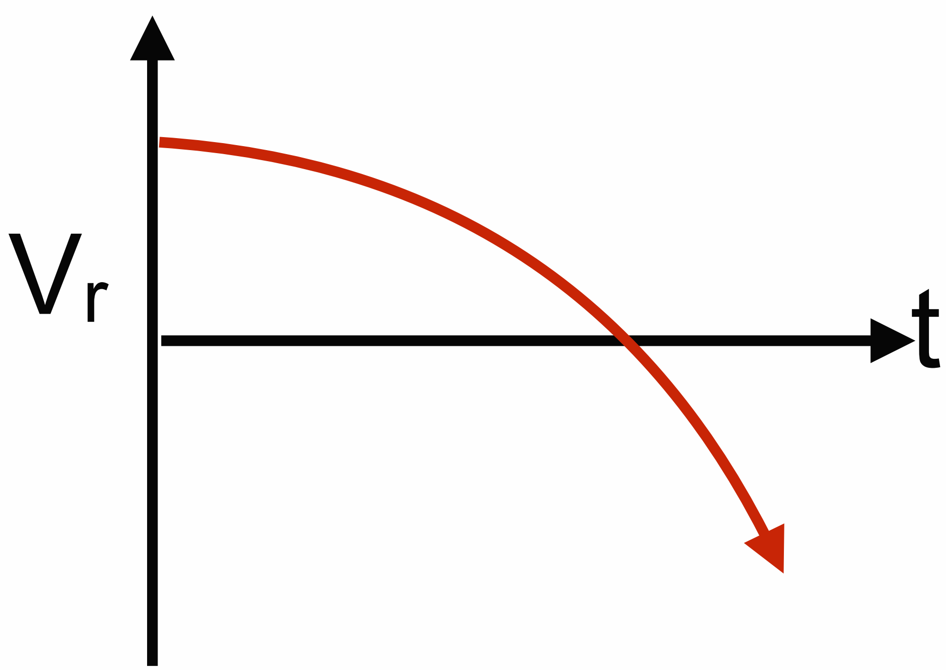


Extent of outward transport depends on details of disk evolution.

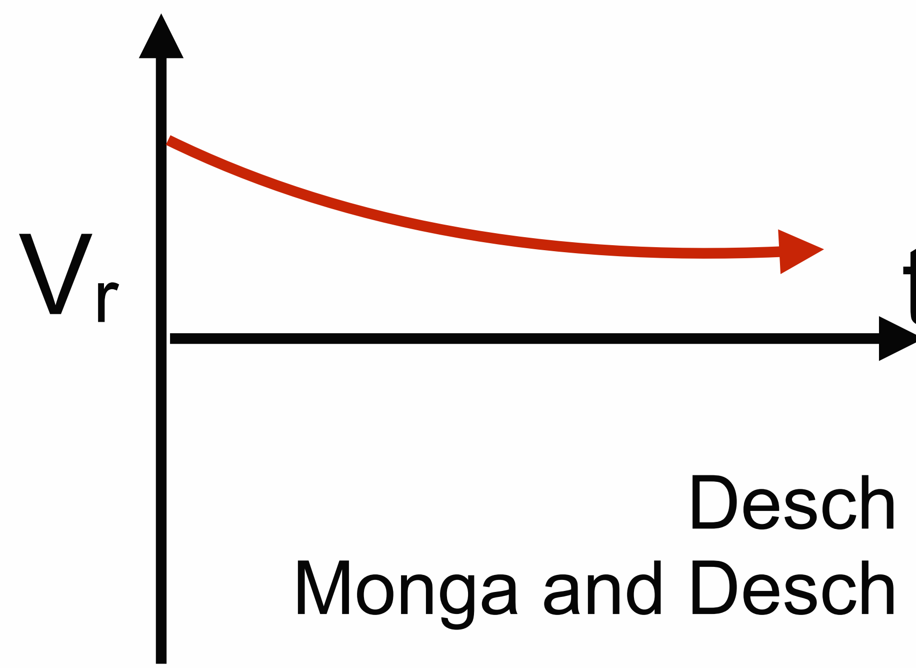




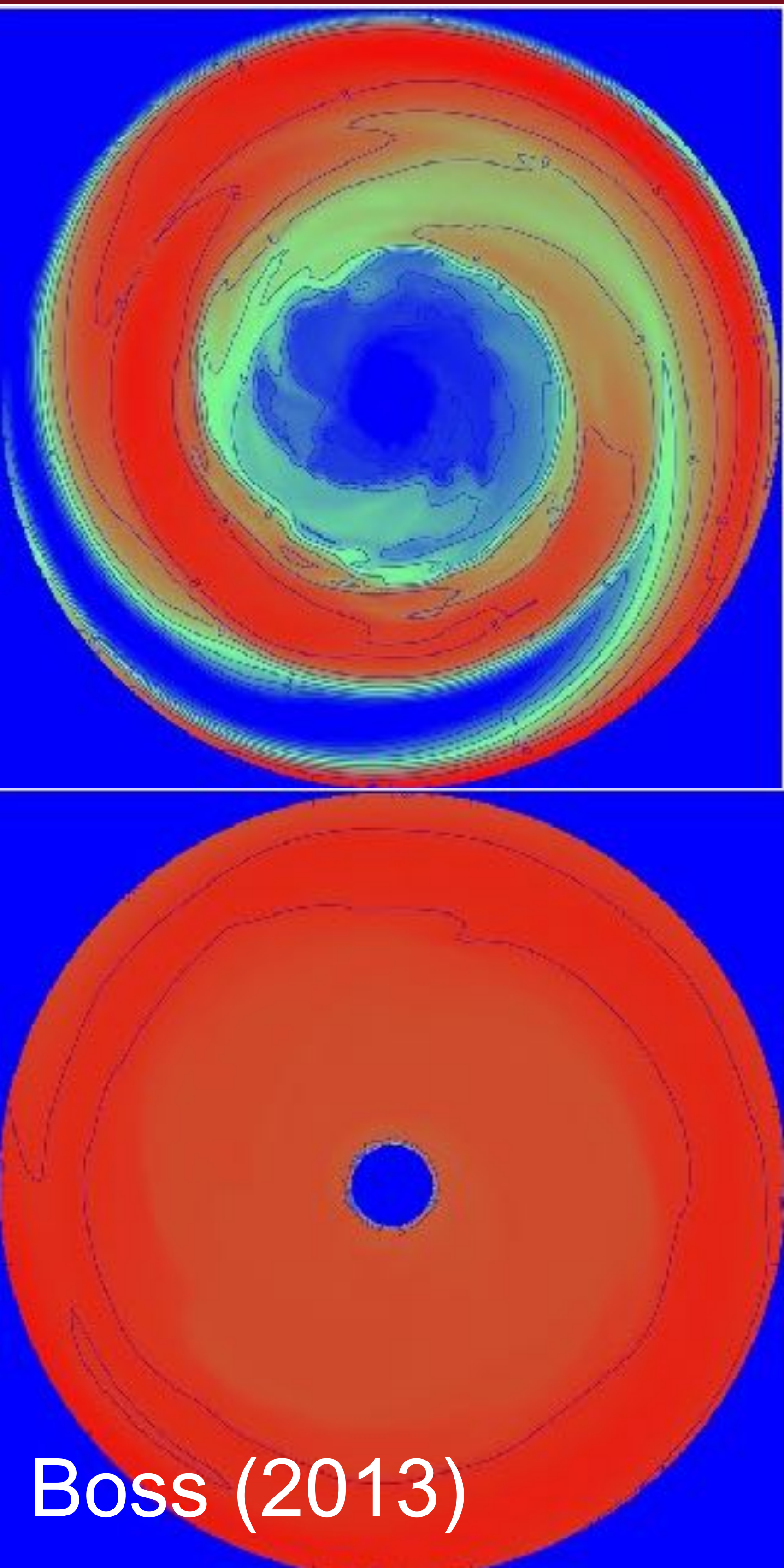
Standard viscous disk:

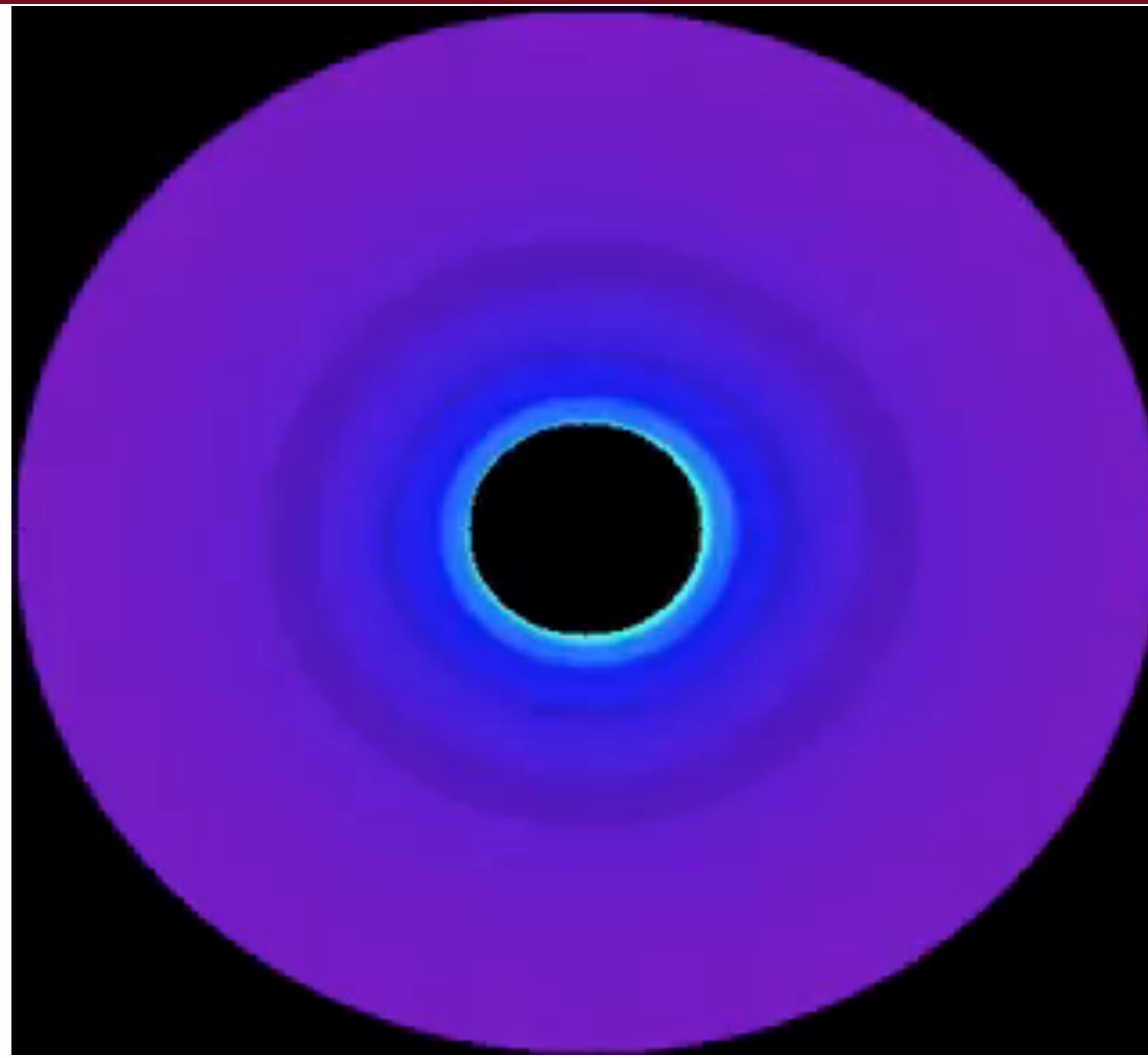


"Decretion Disk"



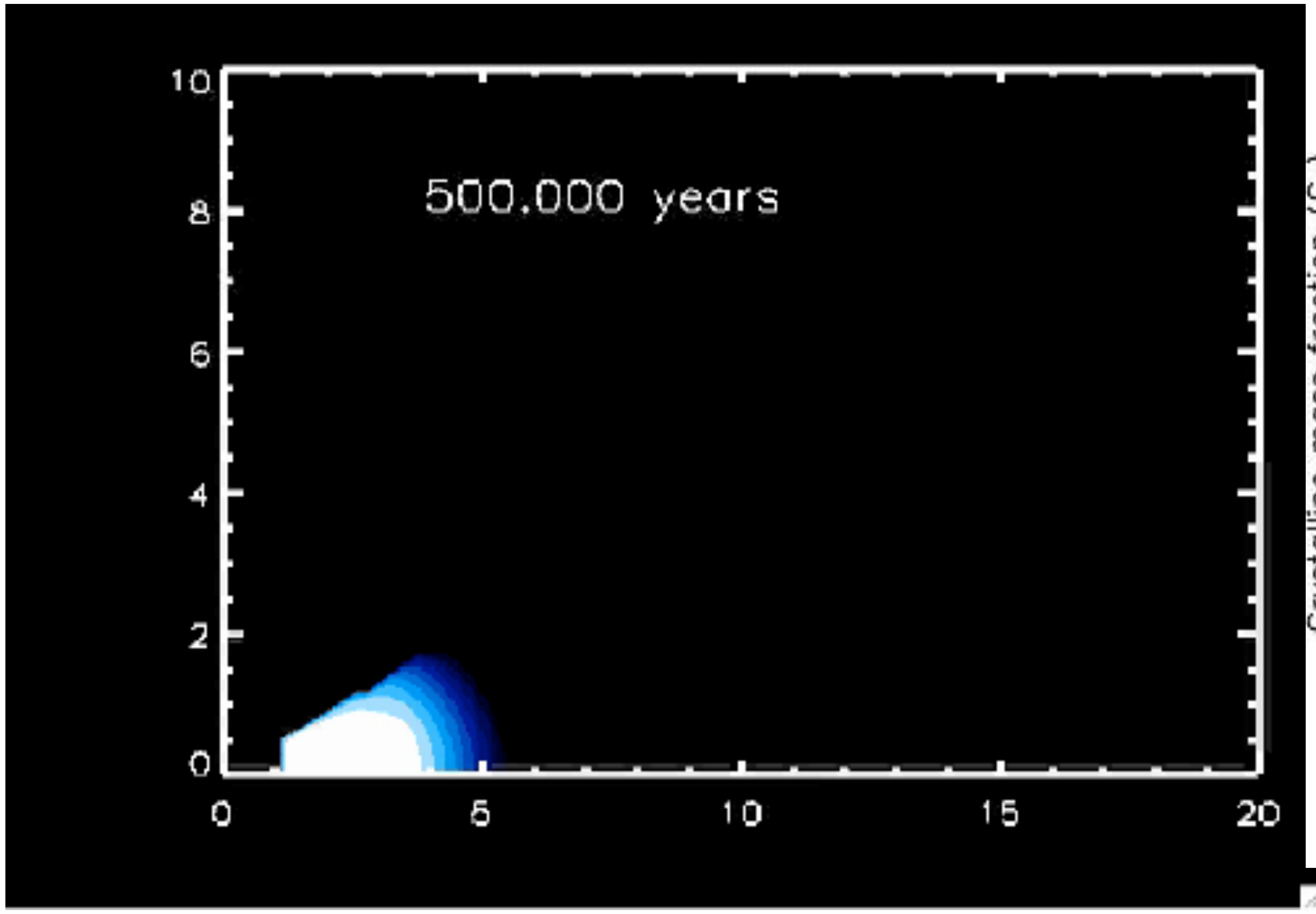
Desch (2007)
Monga and Desch (2015)

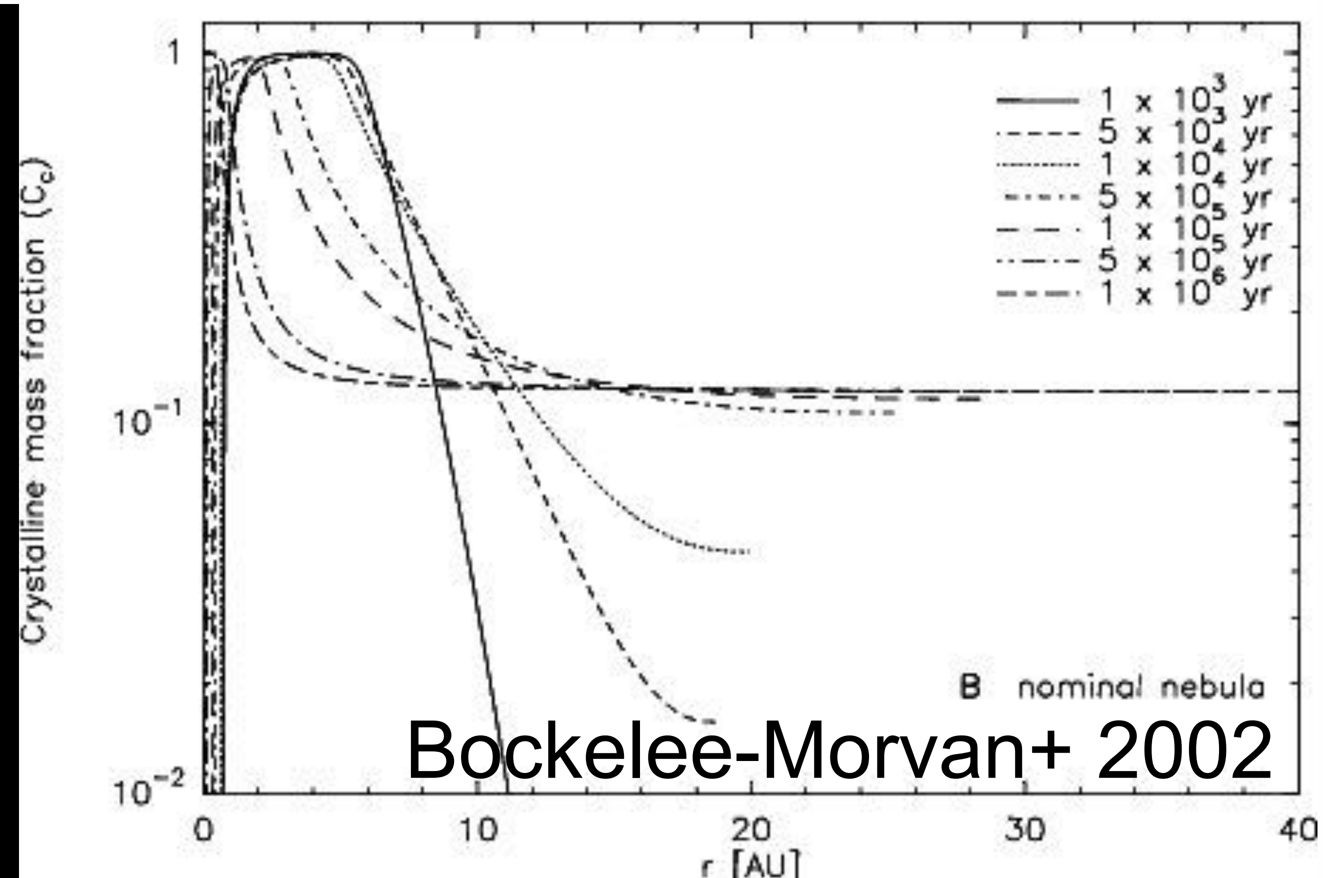




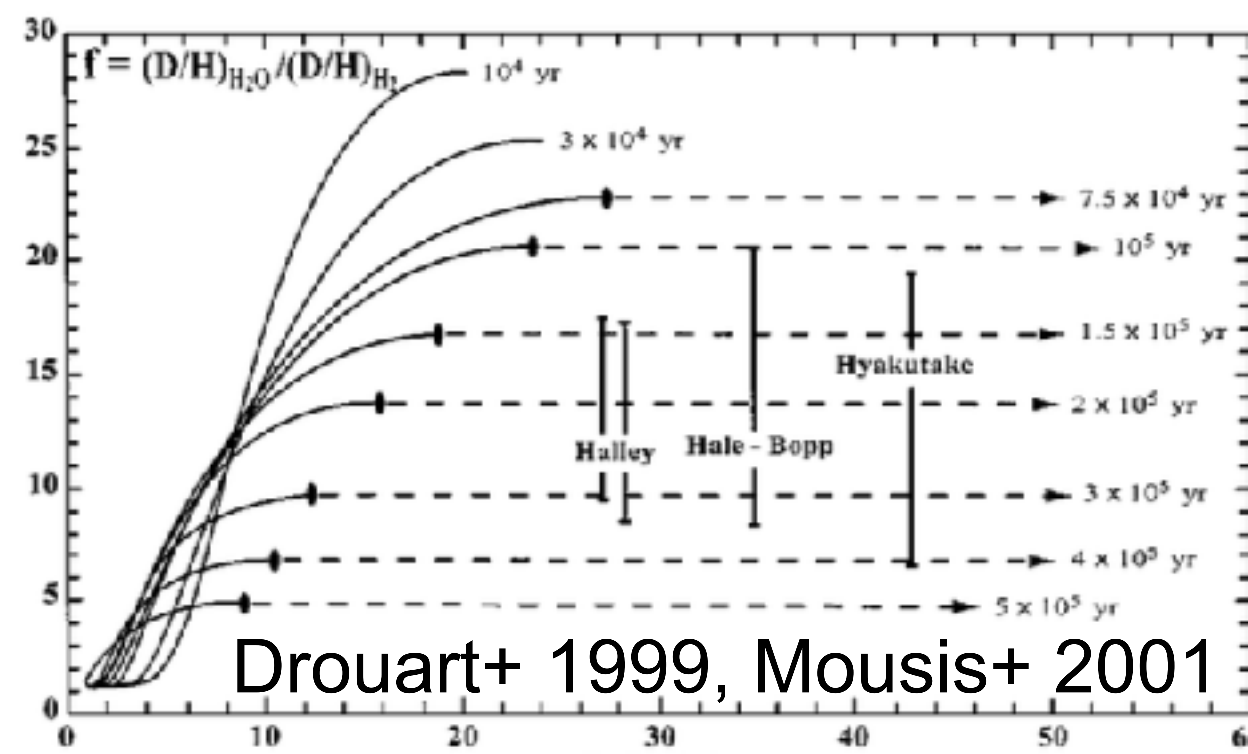
Alan Boss Simulation

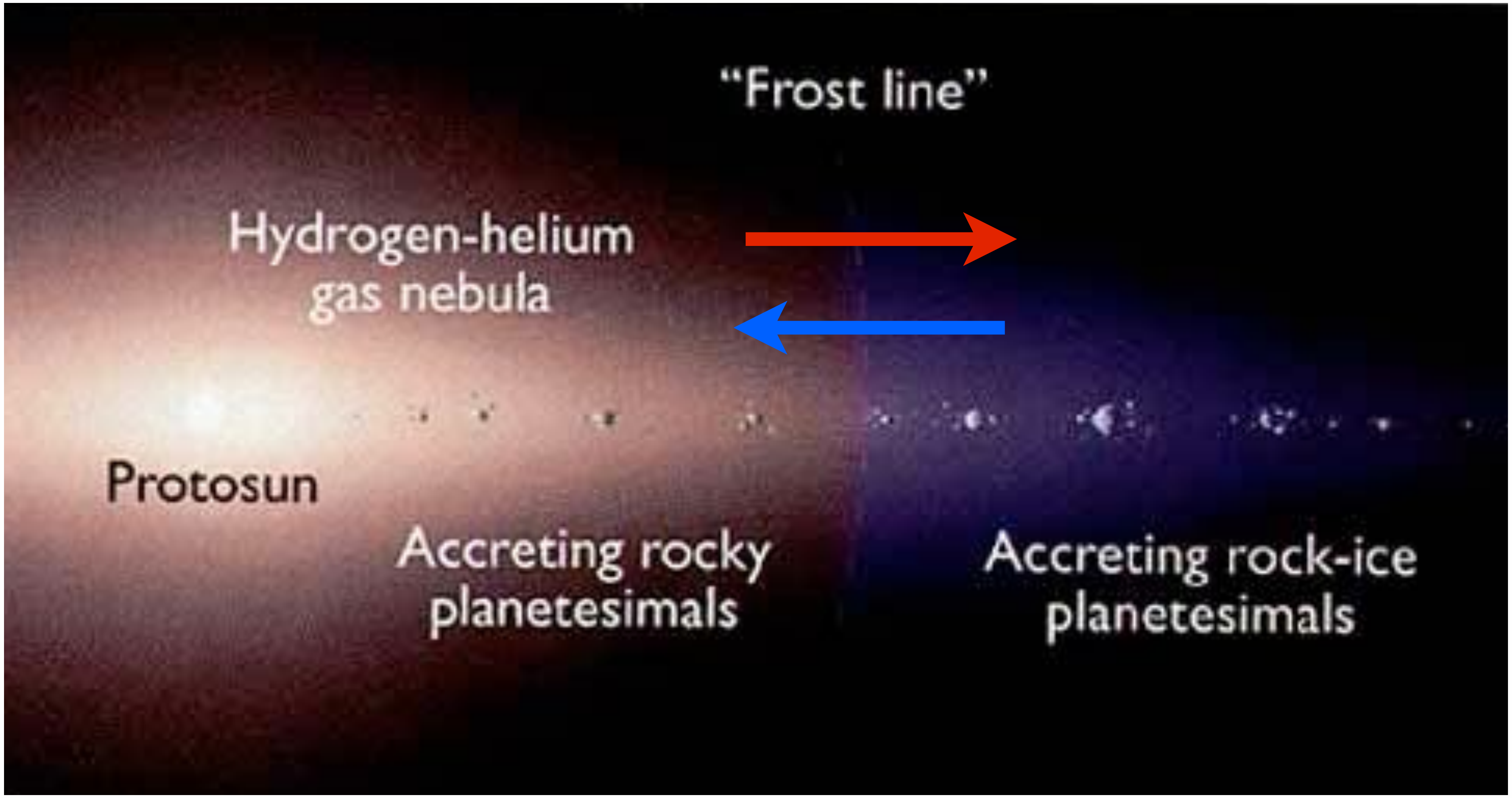
Dynamical models thus far have focused on *ensemble* distributions.





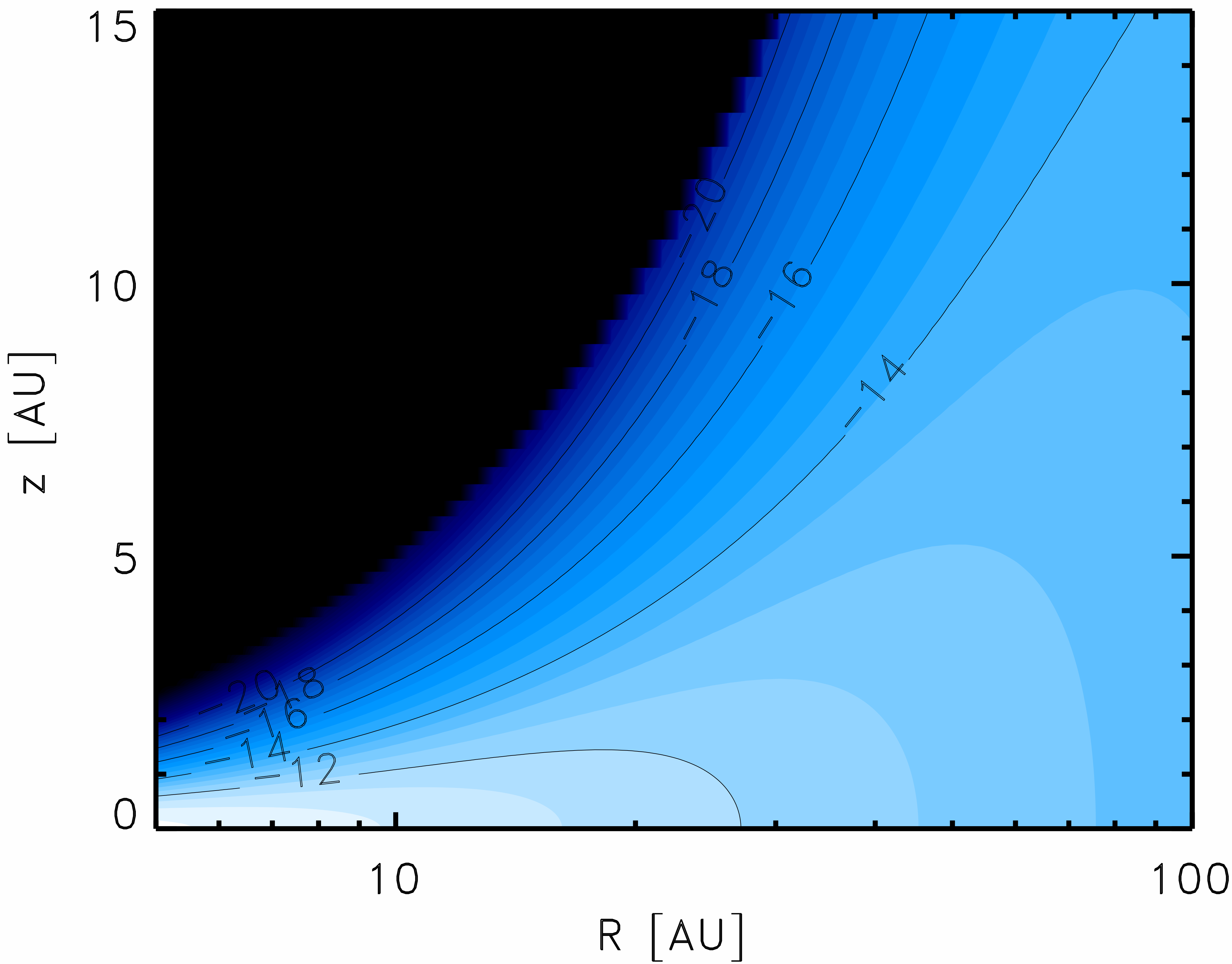
D/H in water should correlate with silicate crystallinity or high temp components in comets. This could serve as test for transport methods in disks.



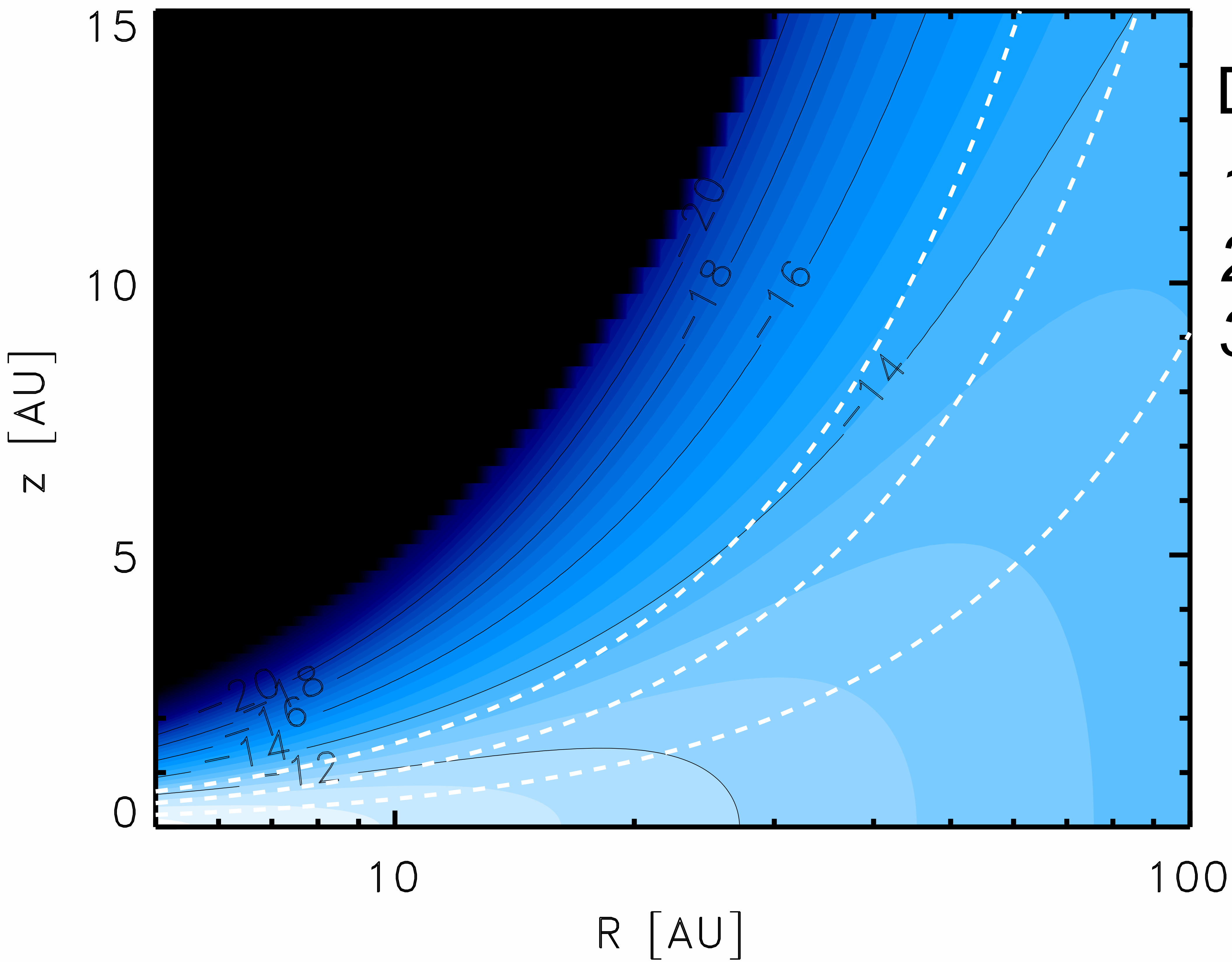


"Frost line"
Hydrogen-helium
gas nebula
Protosun
Accreting rocky
planetesimals
Accreting rock-ice
planetesimals

Protoplanetary Disk Structure



Protoplanetary Disk Structure

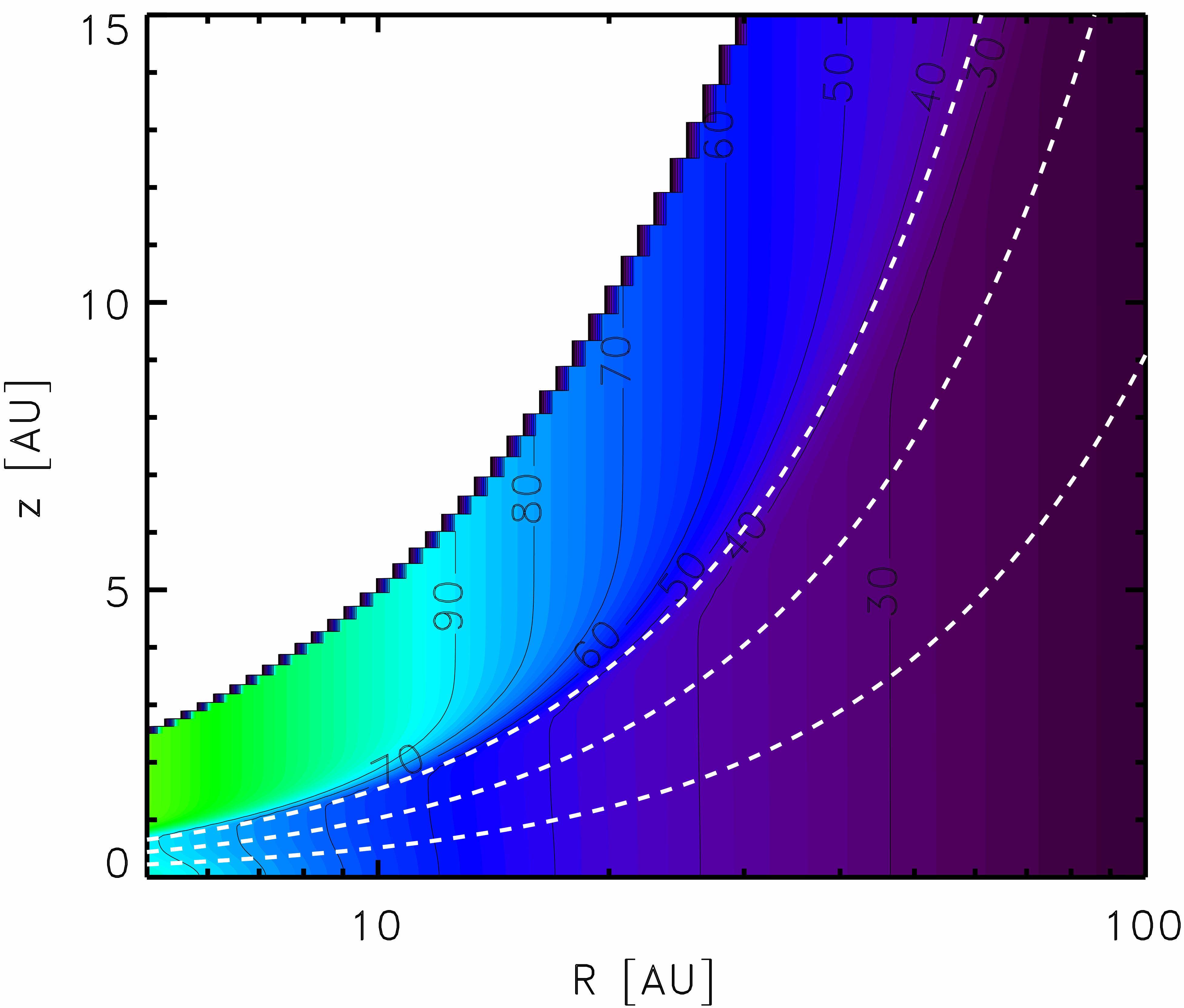


Mass Distribution:

1H: 68.27%
2H: 95.45%
3H: 99.94%

Can also be thought of as residence times

Temperatures



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1H: 68.27%
2H: 95.45%
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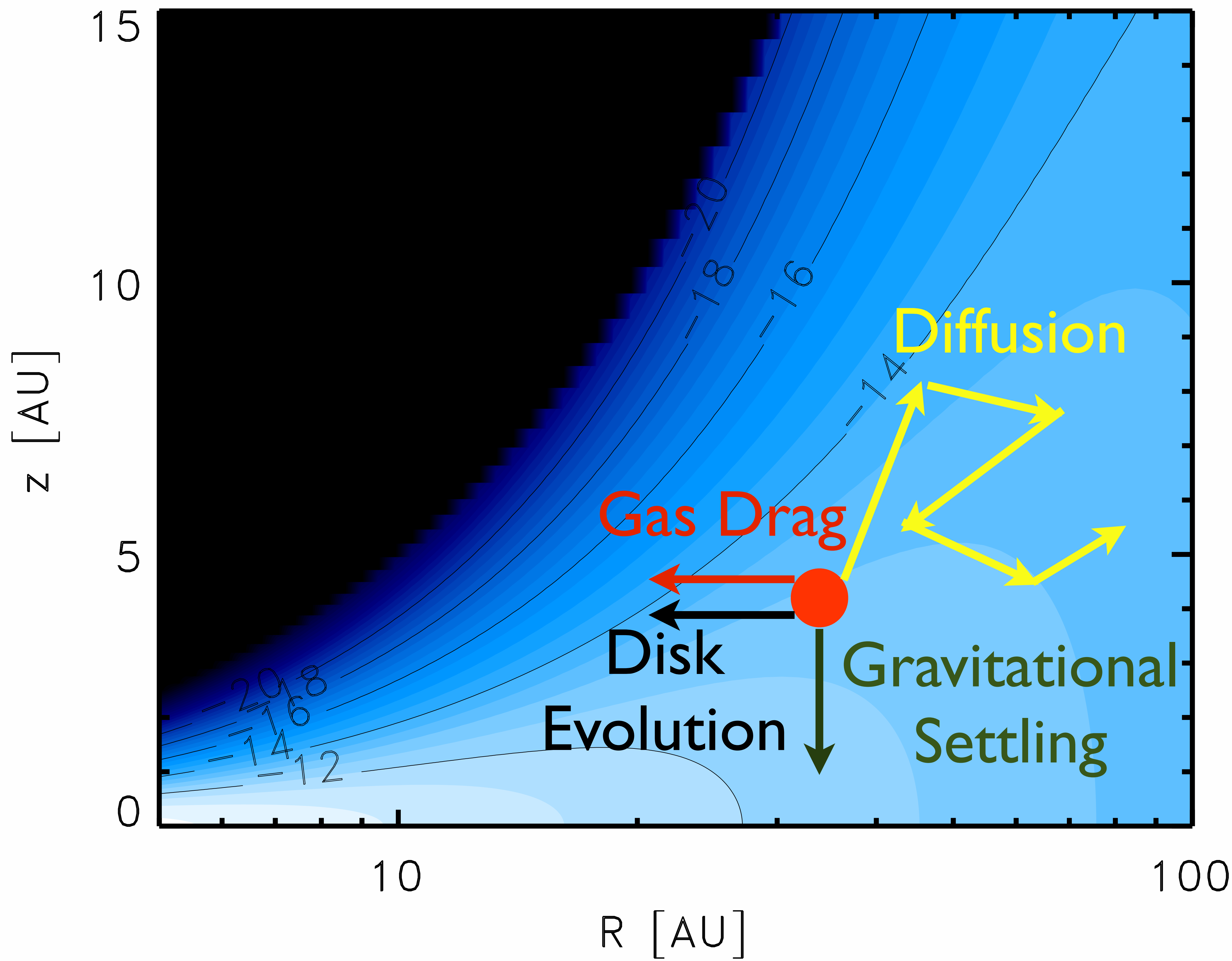
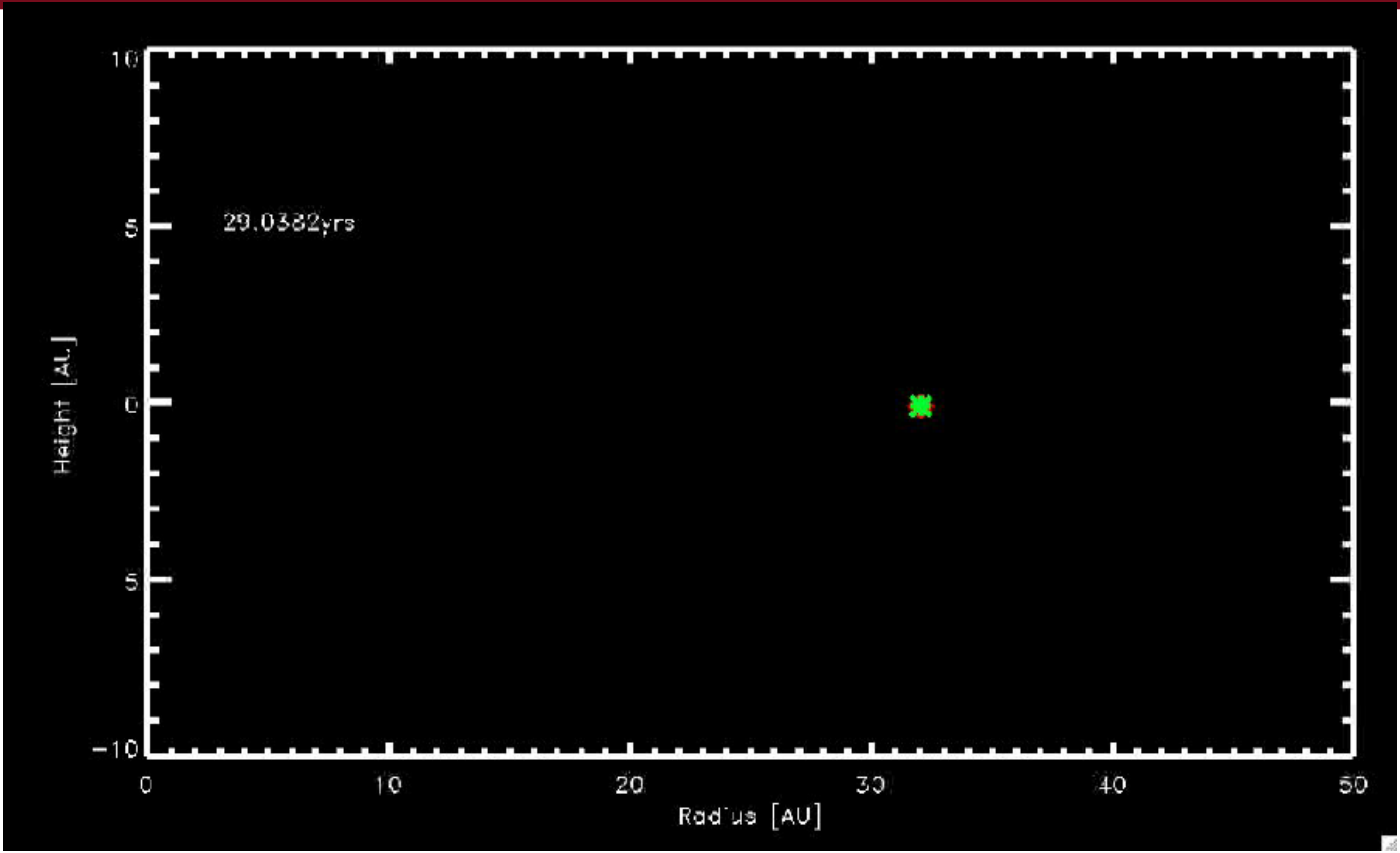
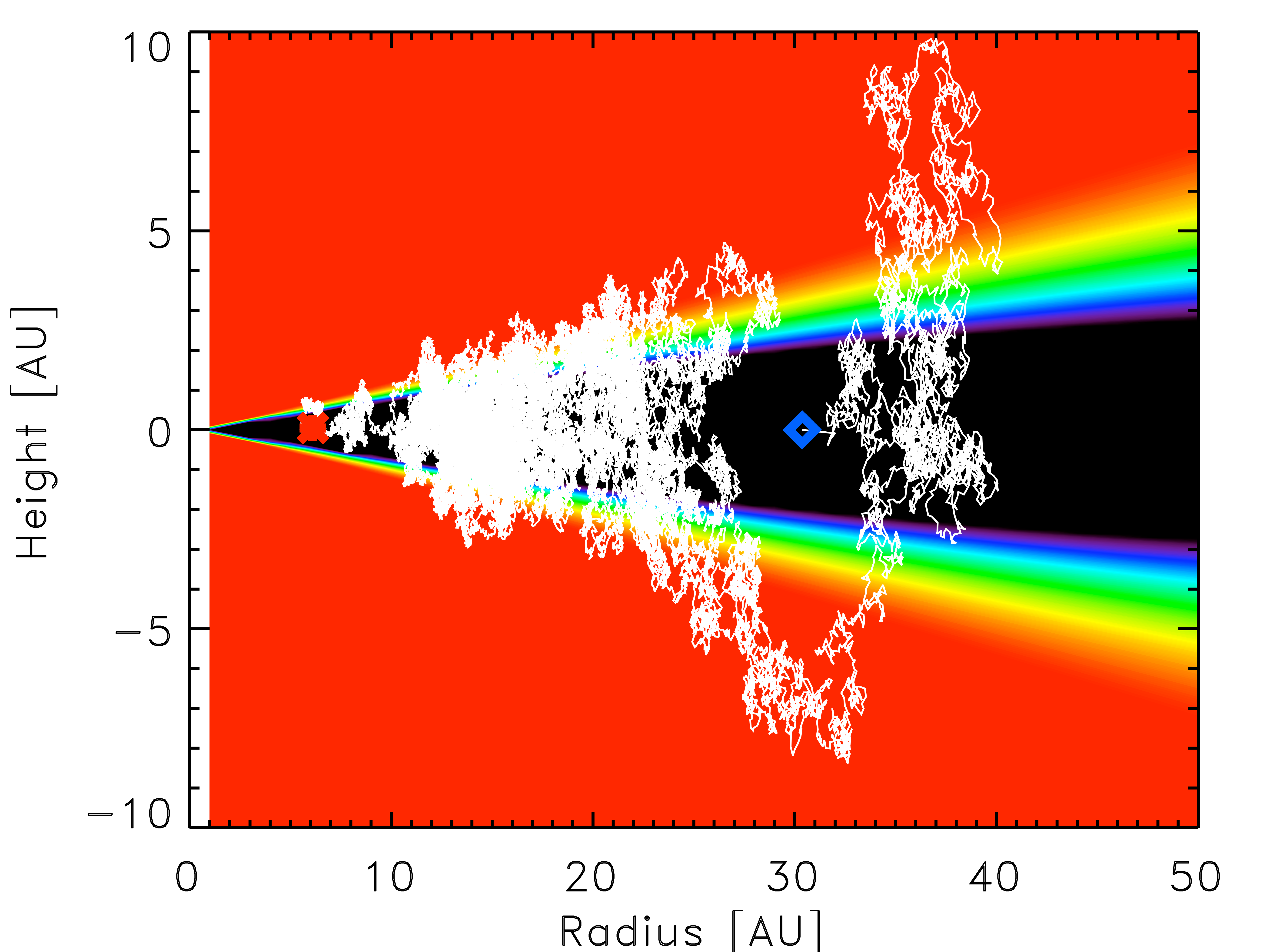
Can also be thought of as residence times

The Basic Idea...



Example of a Particle Path

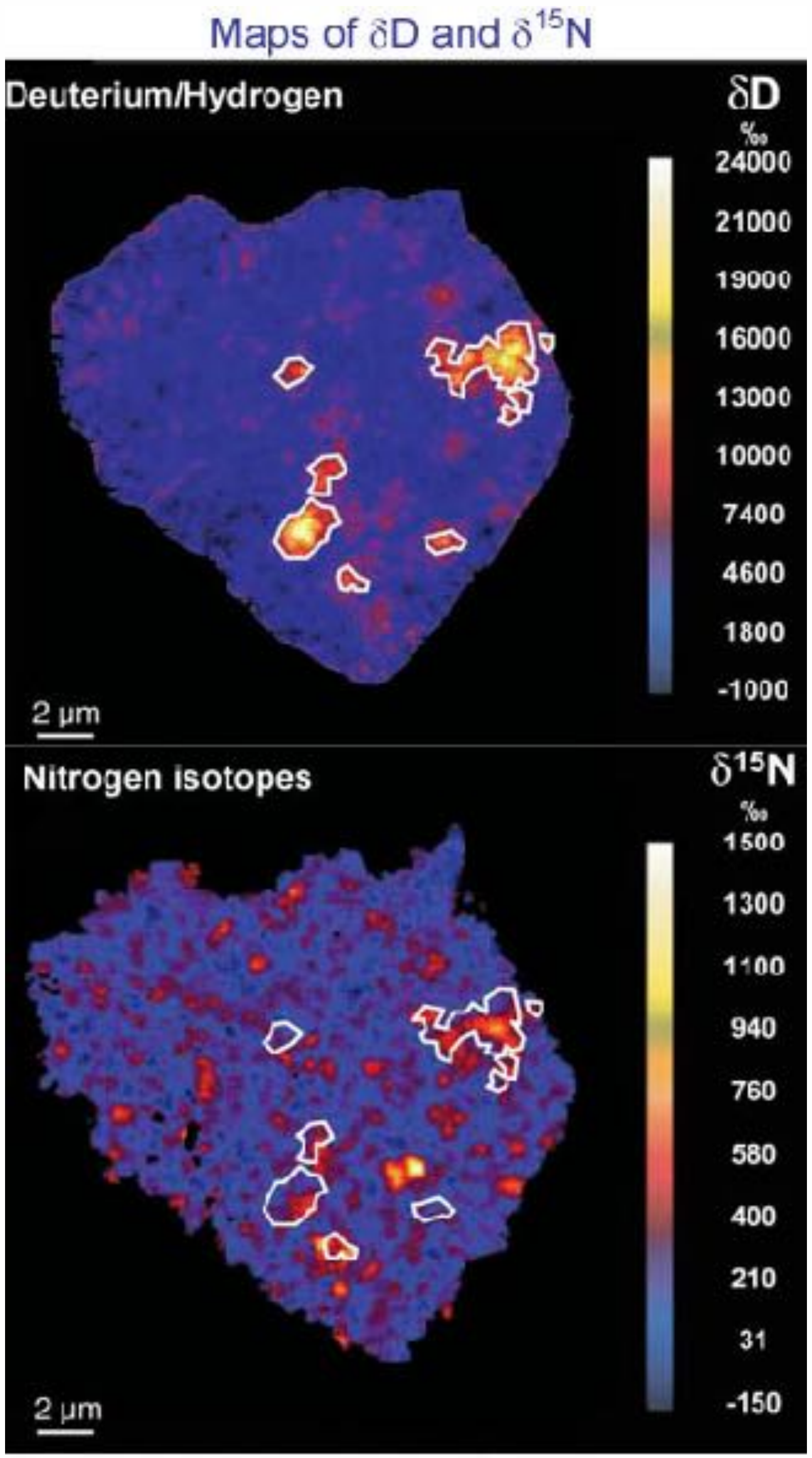




Height [AU]
Radius [AU]
10
5
0
−5
−10
0
10
20
30
40
50

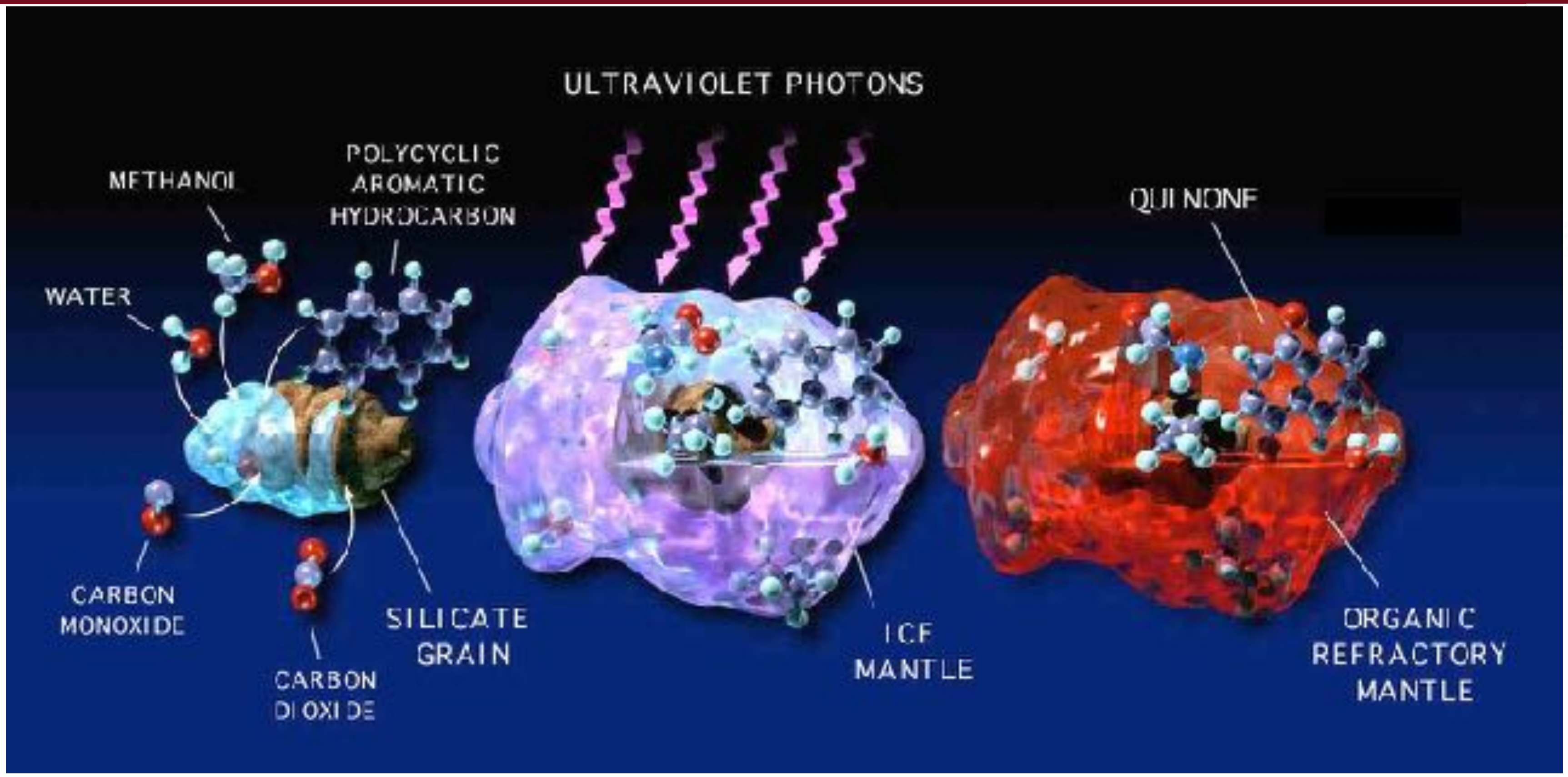
Solar System Organics

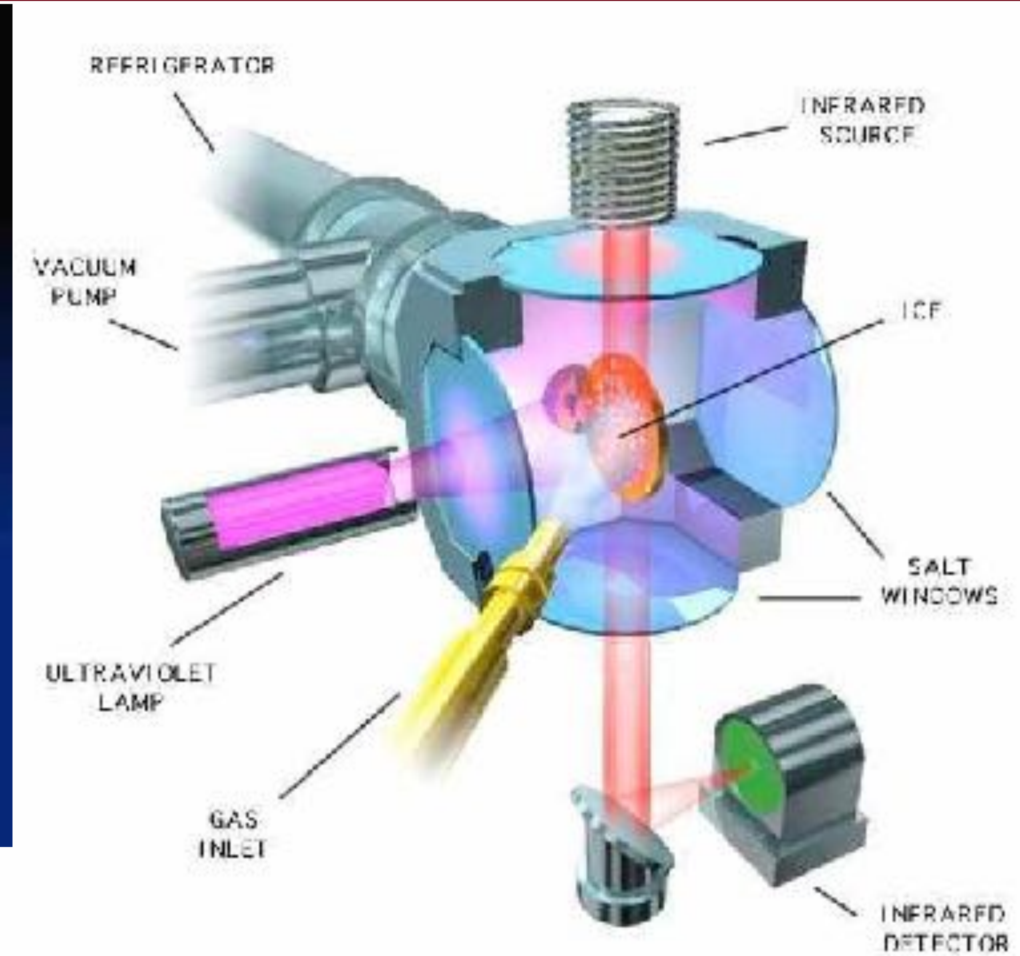
- Organic molecules widely observed in meteorites and cometary samples
  - Well mixed in the solar system
- Traditional explanation of their origin:
  - Strecker synthesis in aqueous environment on a parent body
  - UV Irradiation of ices in the ISM
- Anomalous isotope ratios, i.e. D/H or $^{15}N/^{14}N$, favor formation in cold environments, providing support for irradiation origin



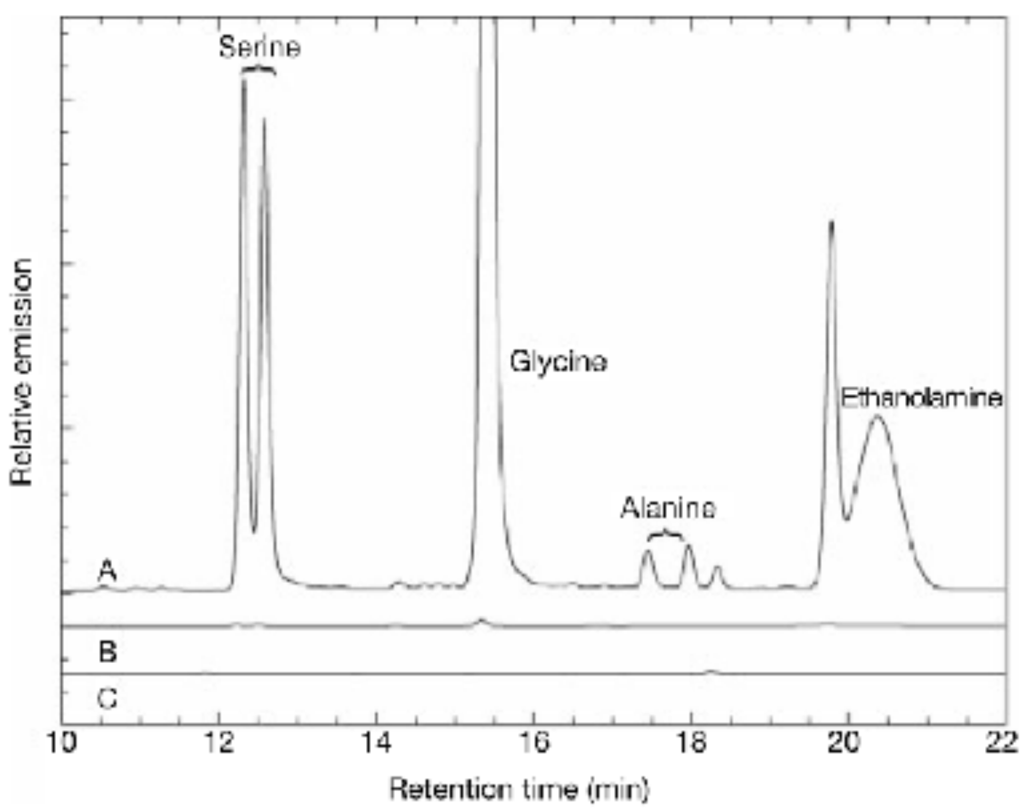
(From Busemann *et al.*, 2006, *Science*, v. 312, p. 728.)

Organic Synthesis Experiments





CLOUD SIMULATION CHAMBER



<u>Bernstein et al (2002)</u>

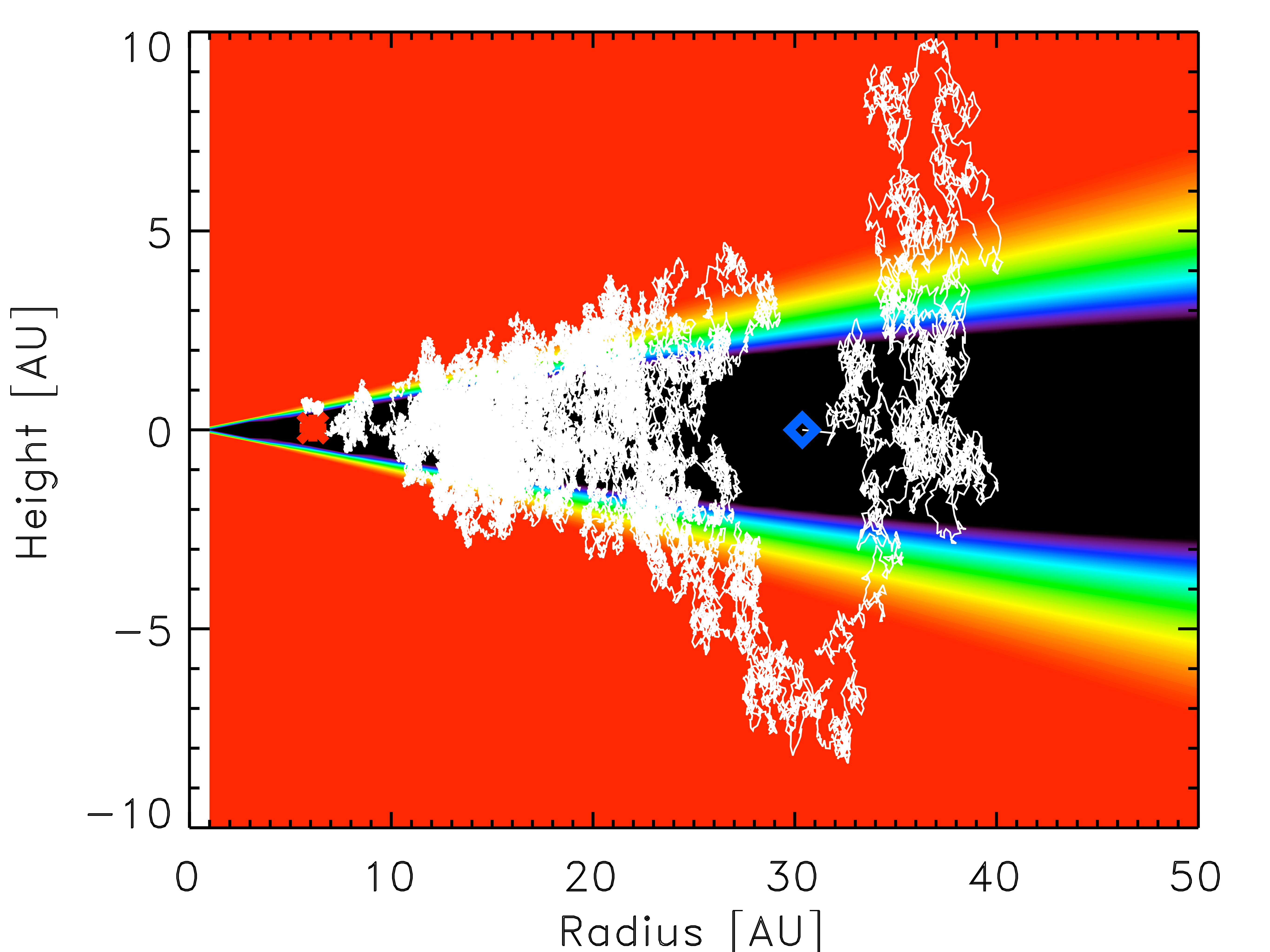
4×10^{18} photons/cm^2

~10^{11} photons/1 micron grain

~1 photon/ice molecule

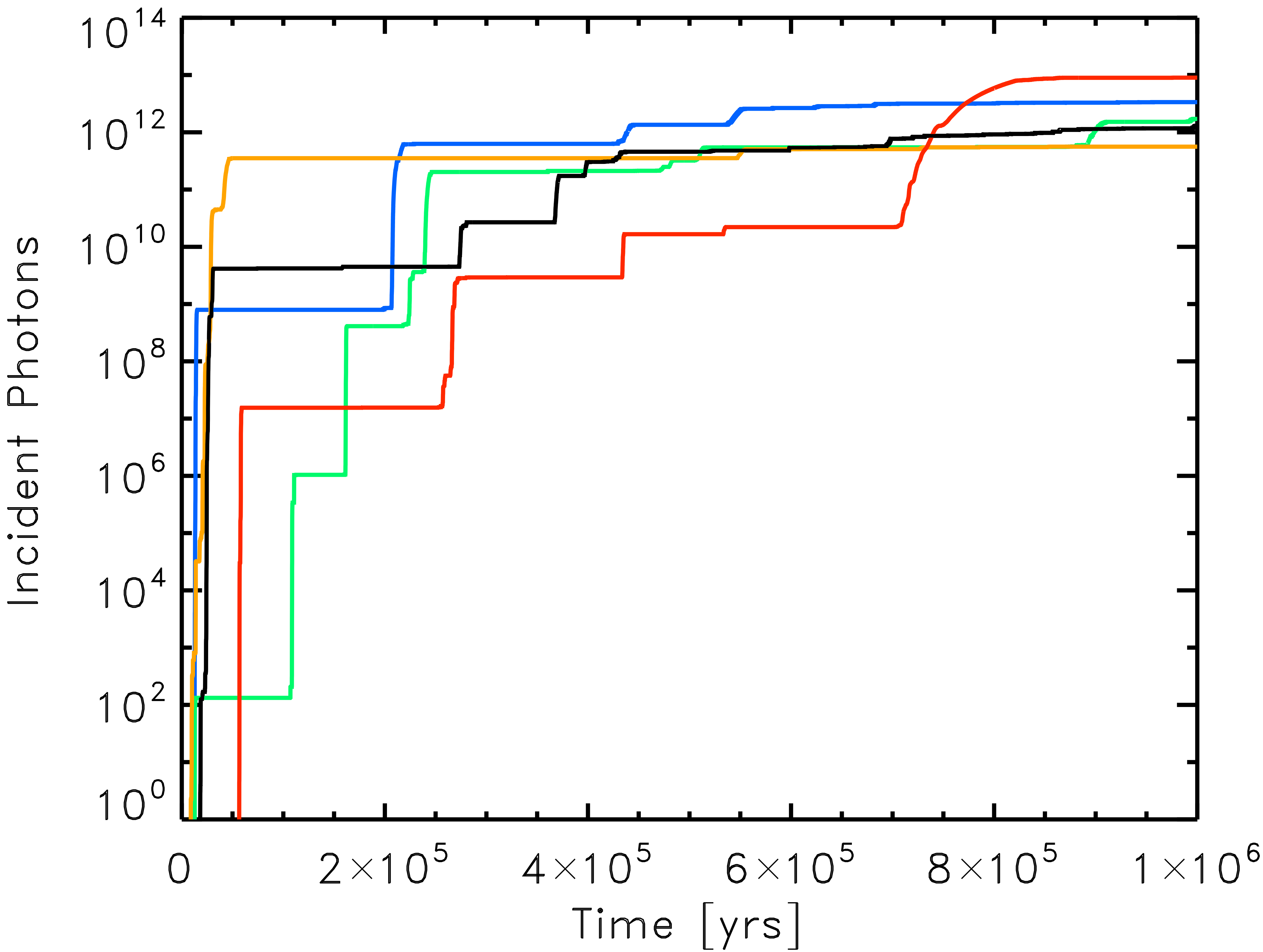
$H_2O:CH_3OH:NH_3:HCN$

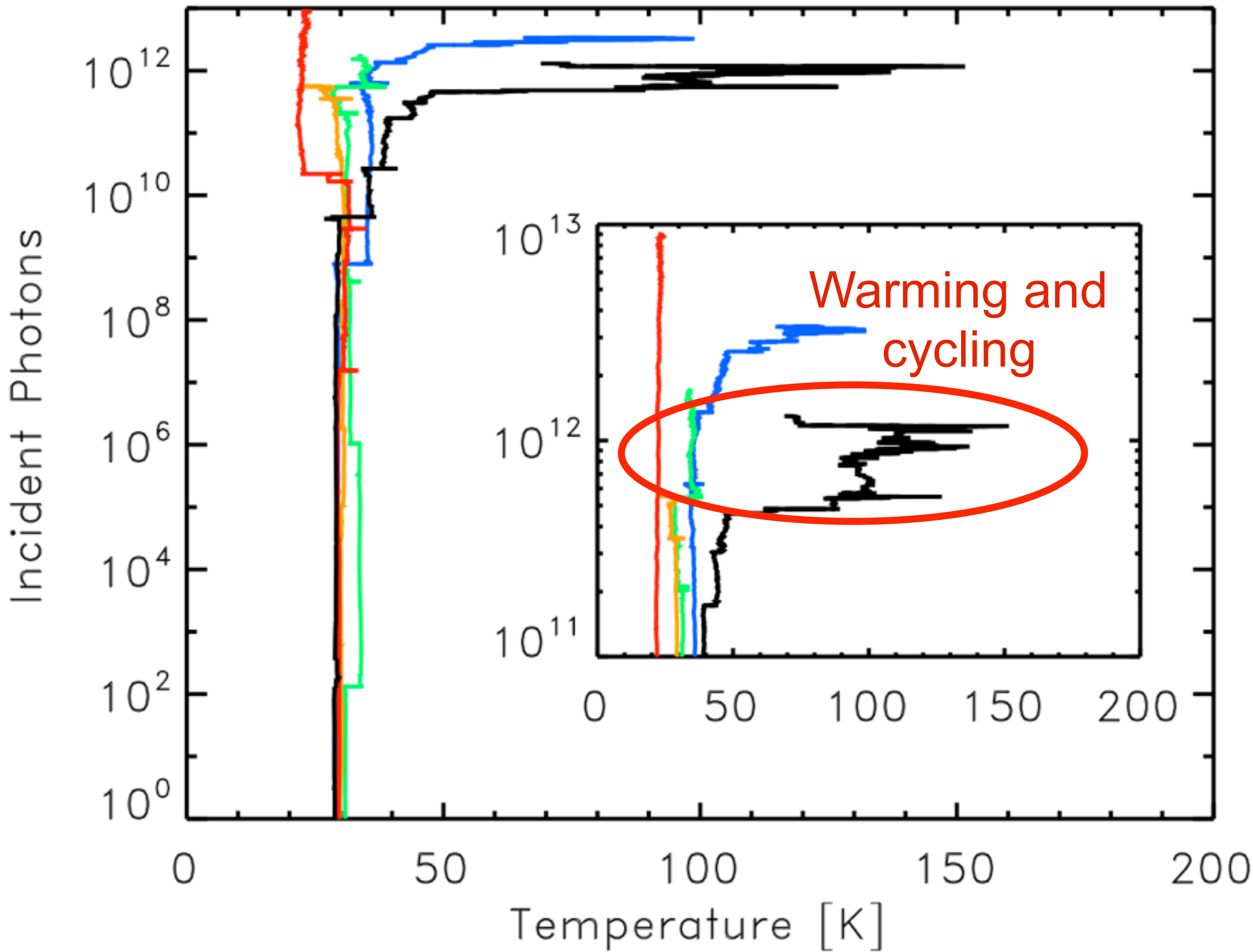
20:2:1:1



10
5
0
−5
−10
Height [AU]
0
10
20
30
40
50
Radius [AU]

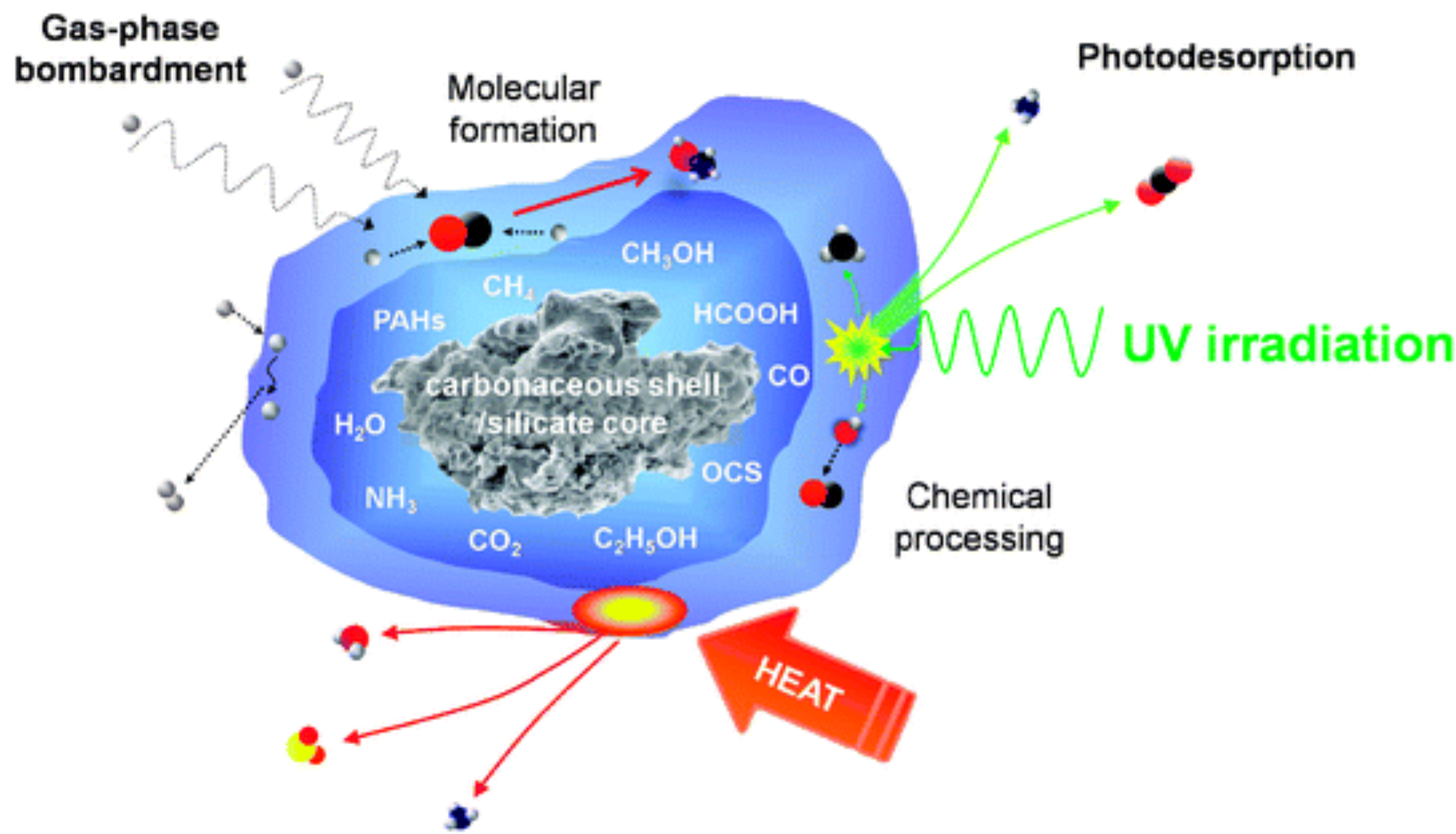
Assuming $F_0 = 1G_0$ (χ=1; ~10^8 photons/cm^2/s)





Incident Photons
Temperature [K]
Warming and cycling

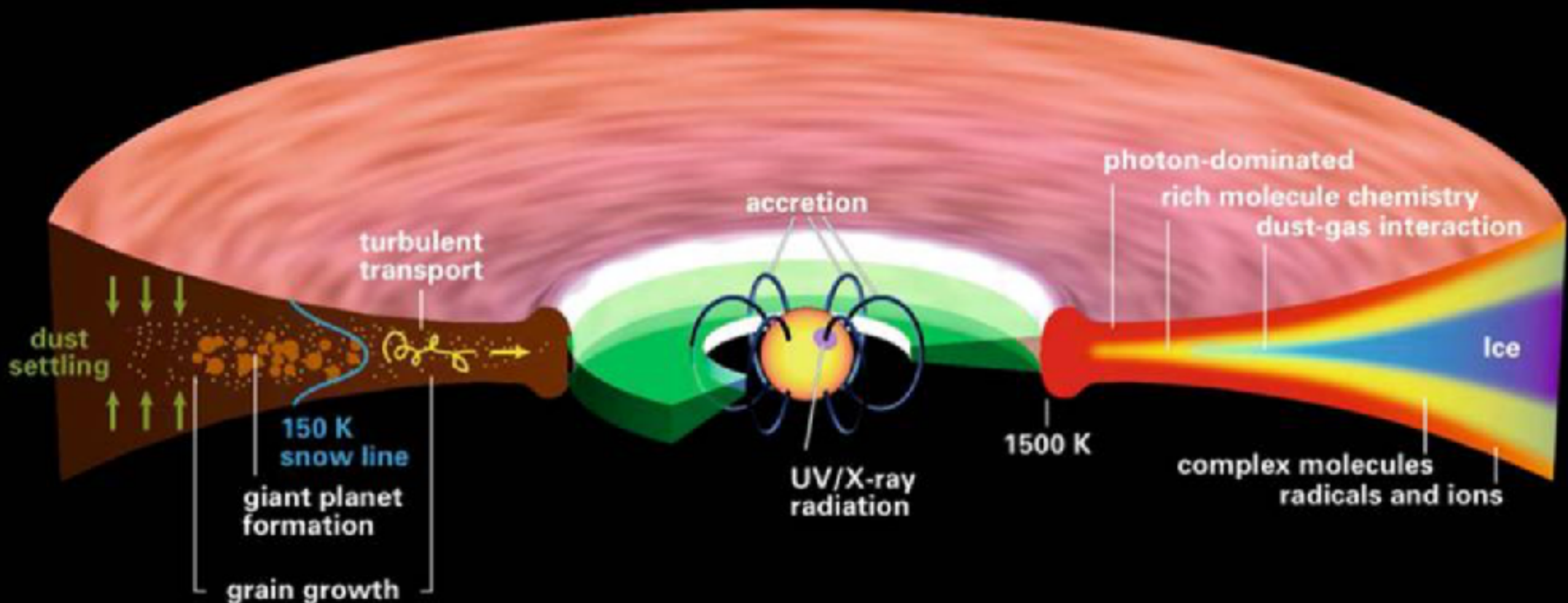
The dynamics of the disk led to significant chemical processing of ices in the outer solar nebula.



Physical processing of the ices and molecules also occurs, having further chemical consequences...

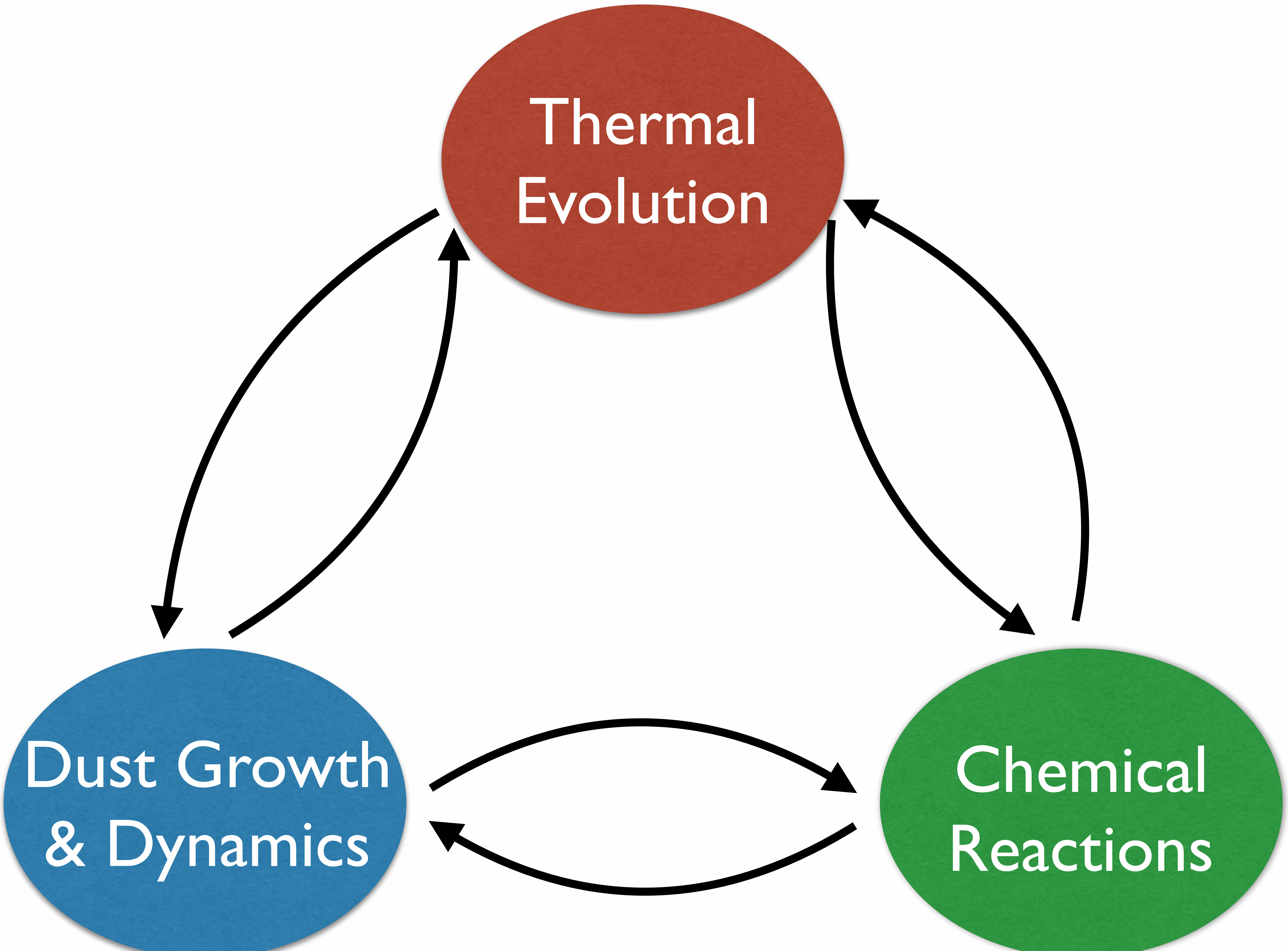
The physical and chemical evolution of planetary materials are intimately coupled.

Henning and Semenov (2013)

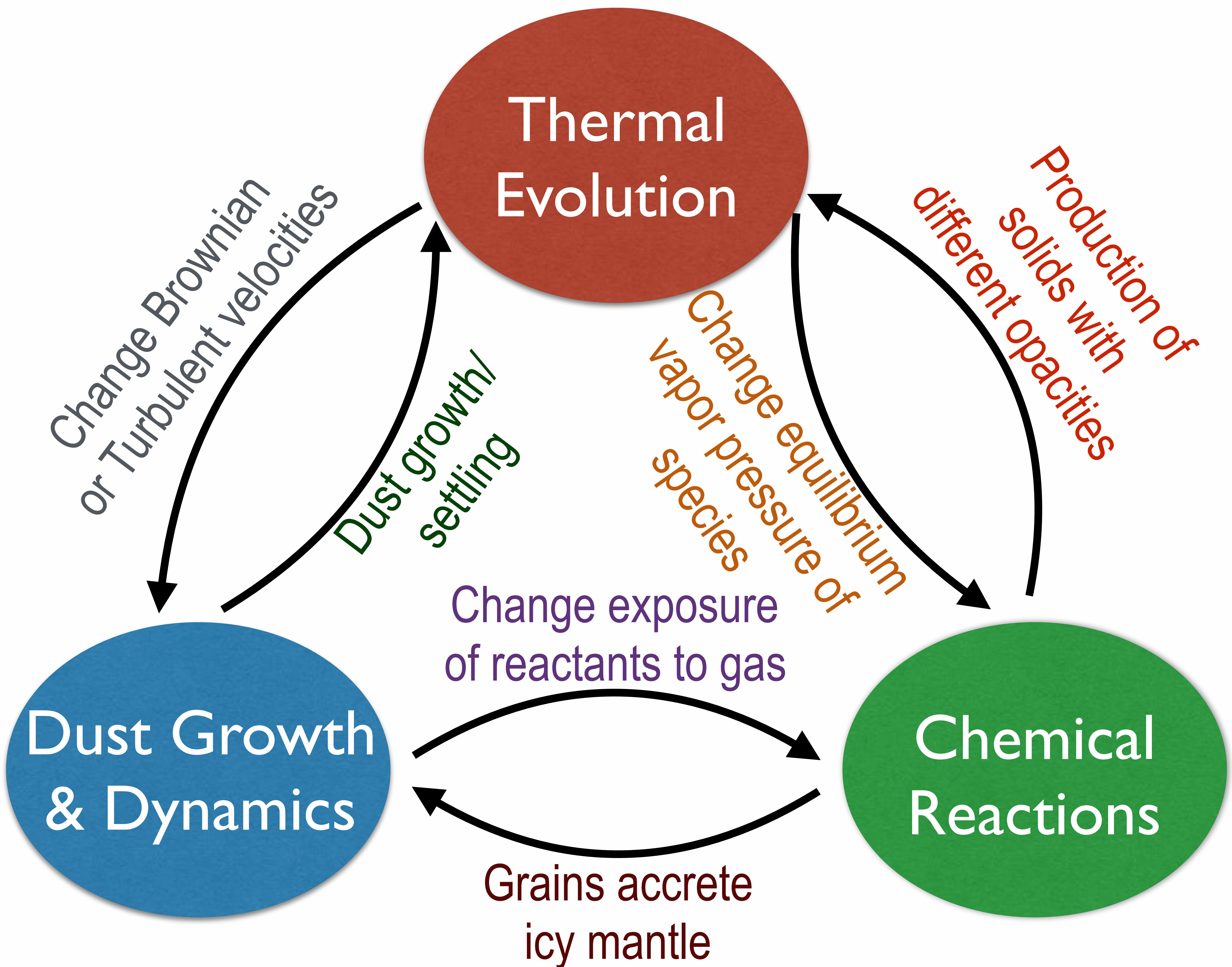


Comets and planetesimal compositions are shaped by a suite of processes that act at one time.

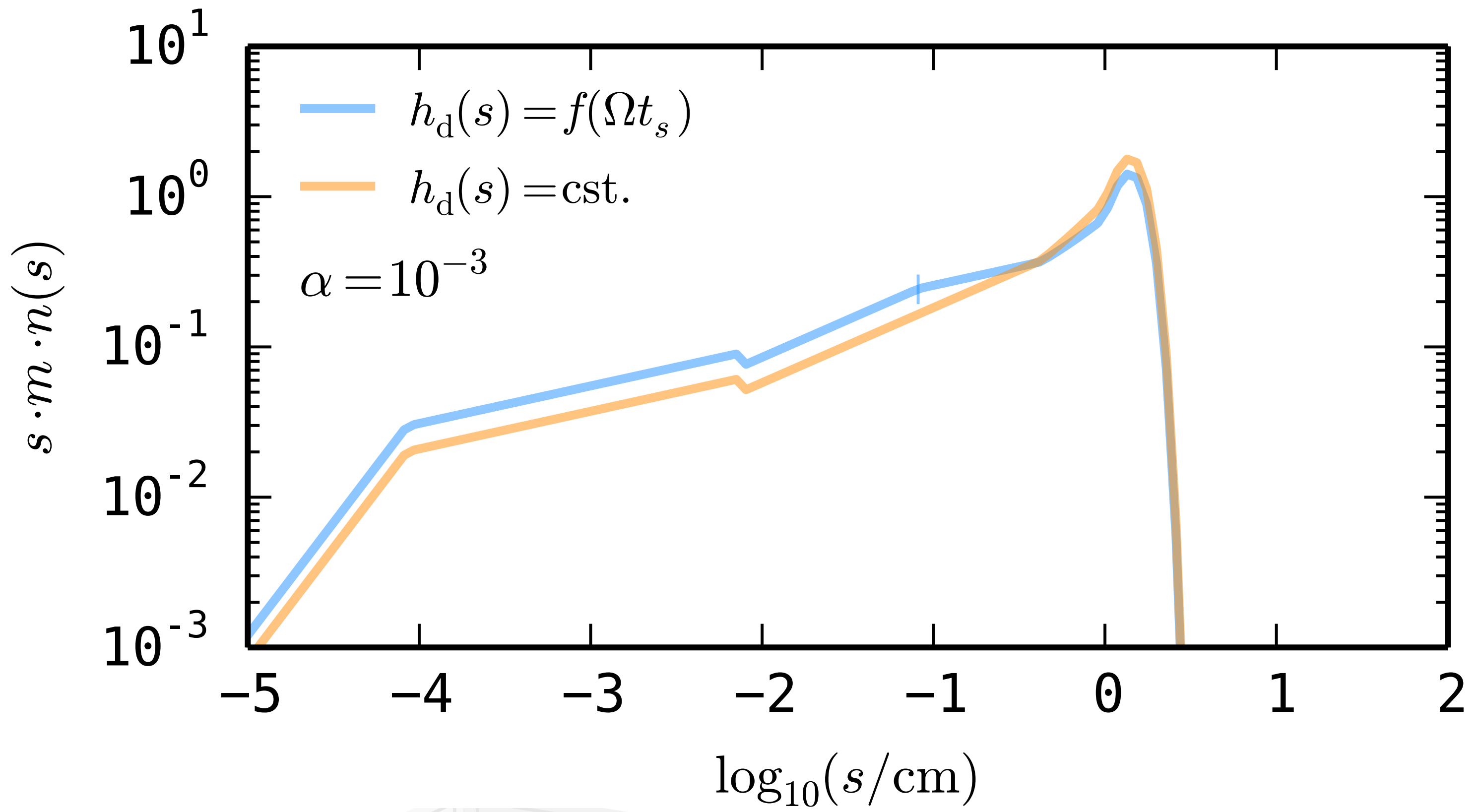
Studying primitive materials requires understanding the feedbacks that exist in protoplanetary disks.



Studying primitive materials requires understanding the feedbacks that exist in protoplanetary disks.

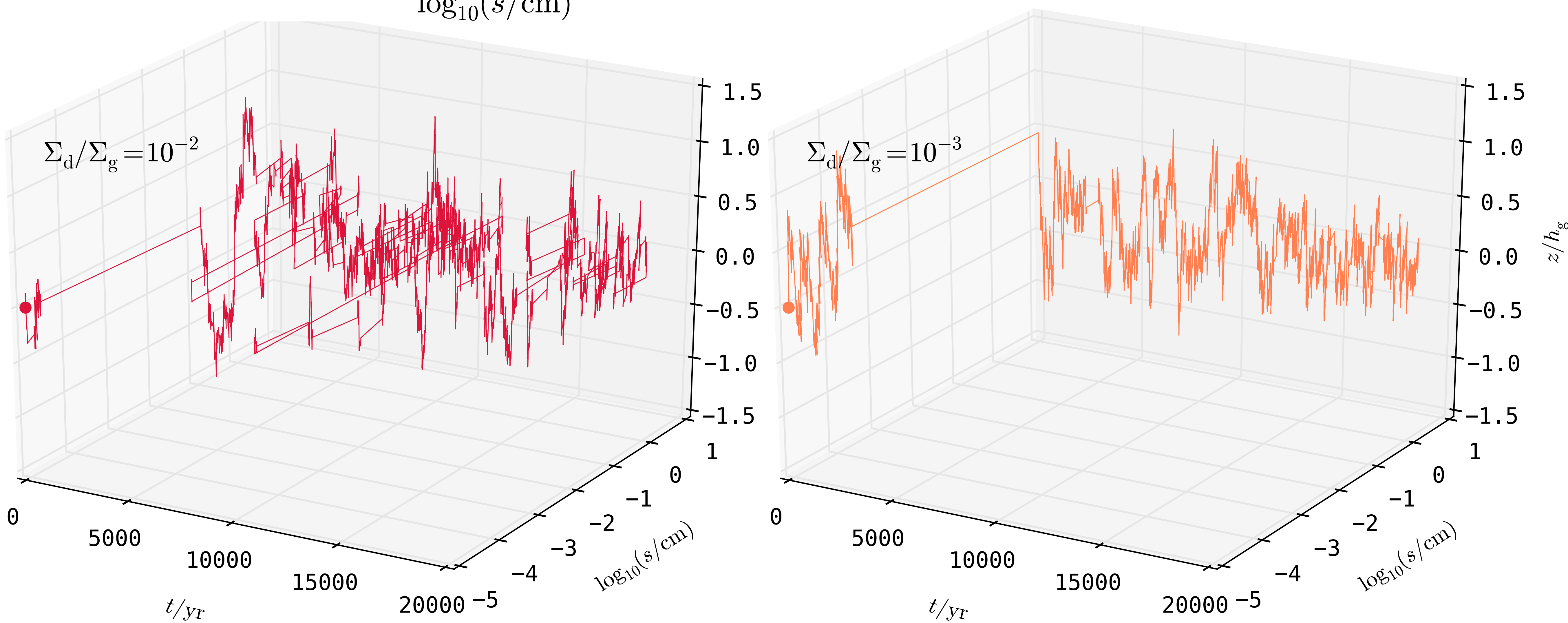


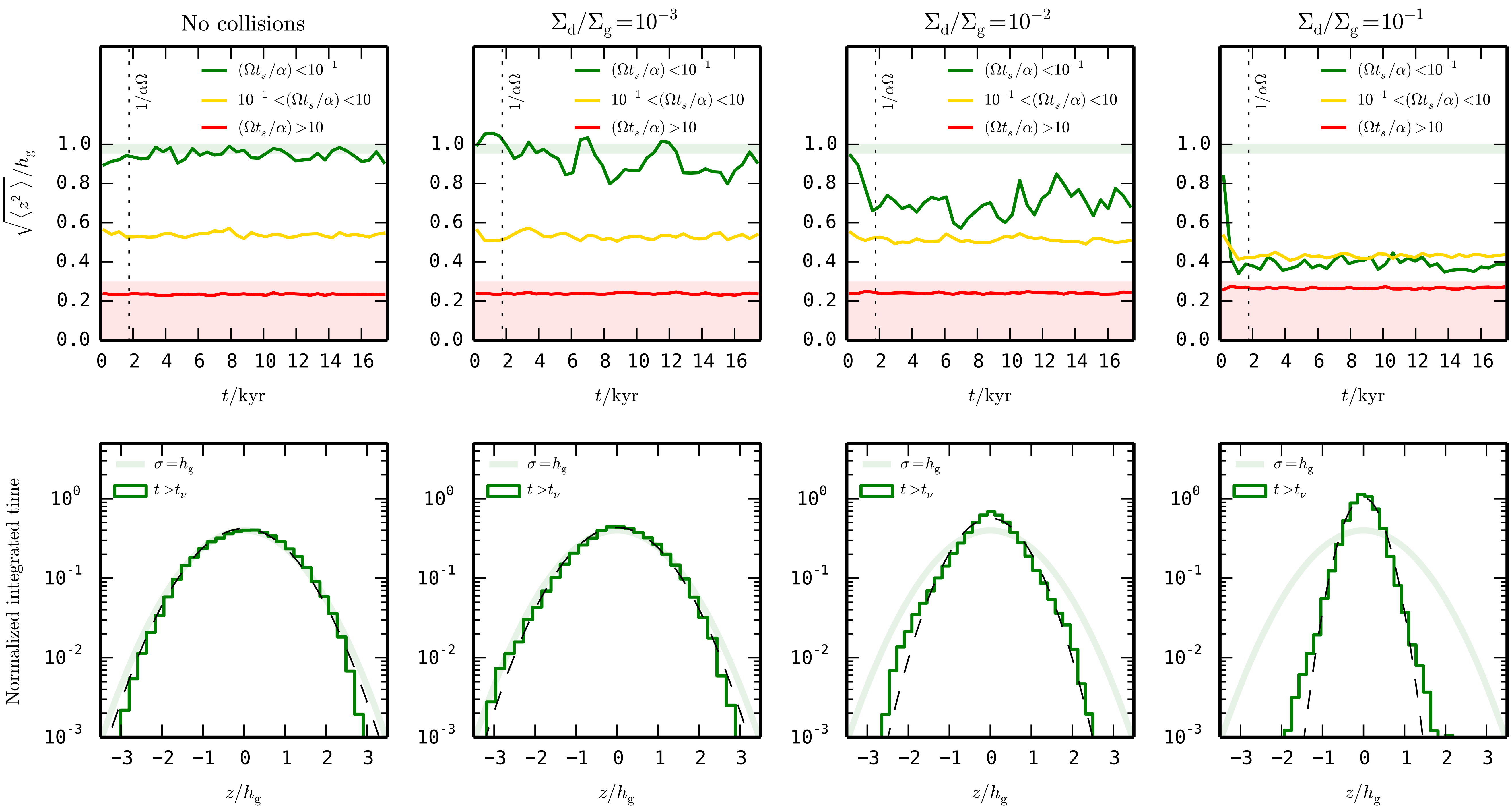
Krijt and Ciesla (submitted)



Particle growth generally reduces the mobility of small grains.

When dust/gas ratios are lowered, particles can move as we previously treated.



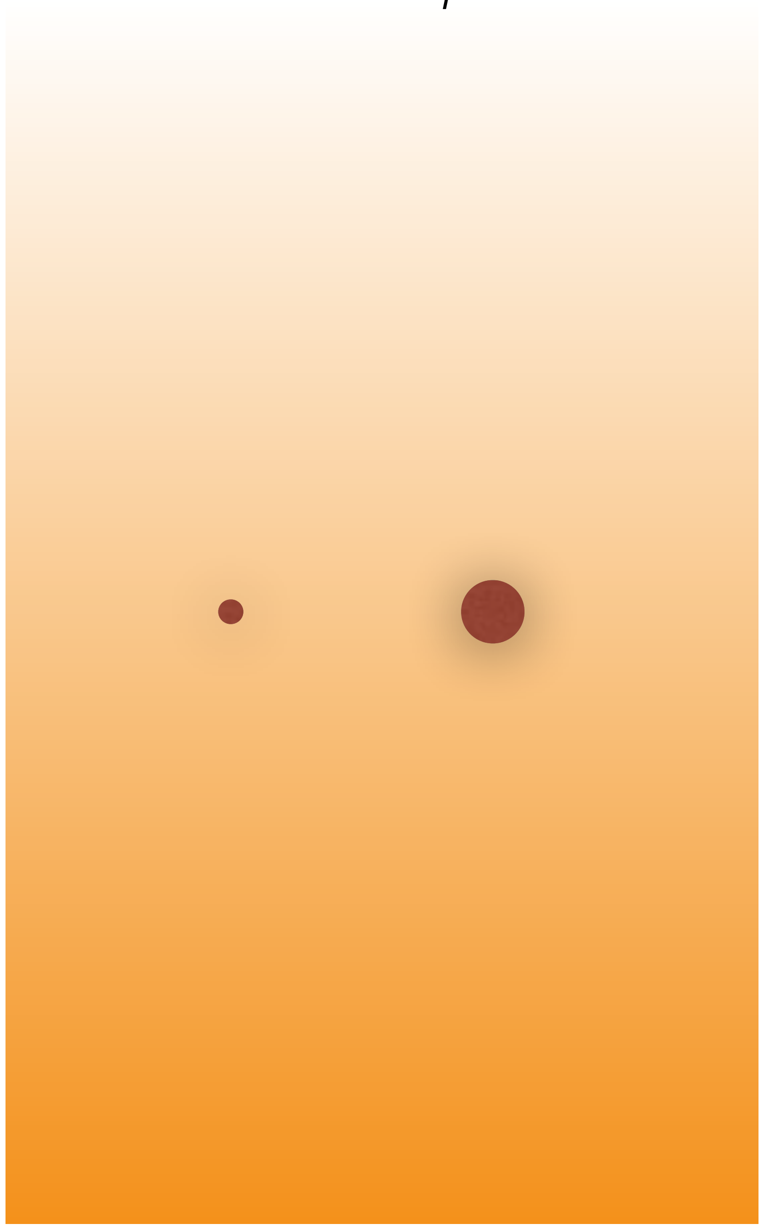


No collisions
$\Sigma_d/\Sigma_g = 10^{-3}$
$\Sigma_d/\Sigma_g = 10^{-2}$
$\Sigma_d/\Sigma_g = 10^{-1}$
$(\Omega t_s/\alpha) < 10^{-1}$
$10^{-1} < (\Omega t_s/\alpha) < 10$
$(\Omega t_s/\alpha) > 10$
$1/\alpha\Omega$
$\sqrt{\langle z^2 \rangle}/h_g$
t/kyr
$\sigma = h_g$
$t > t_\nu$
Normalized integrated time
z/h_g

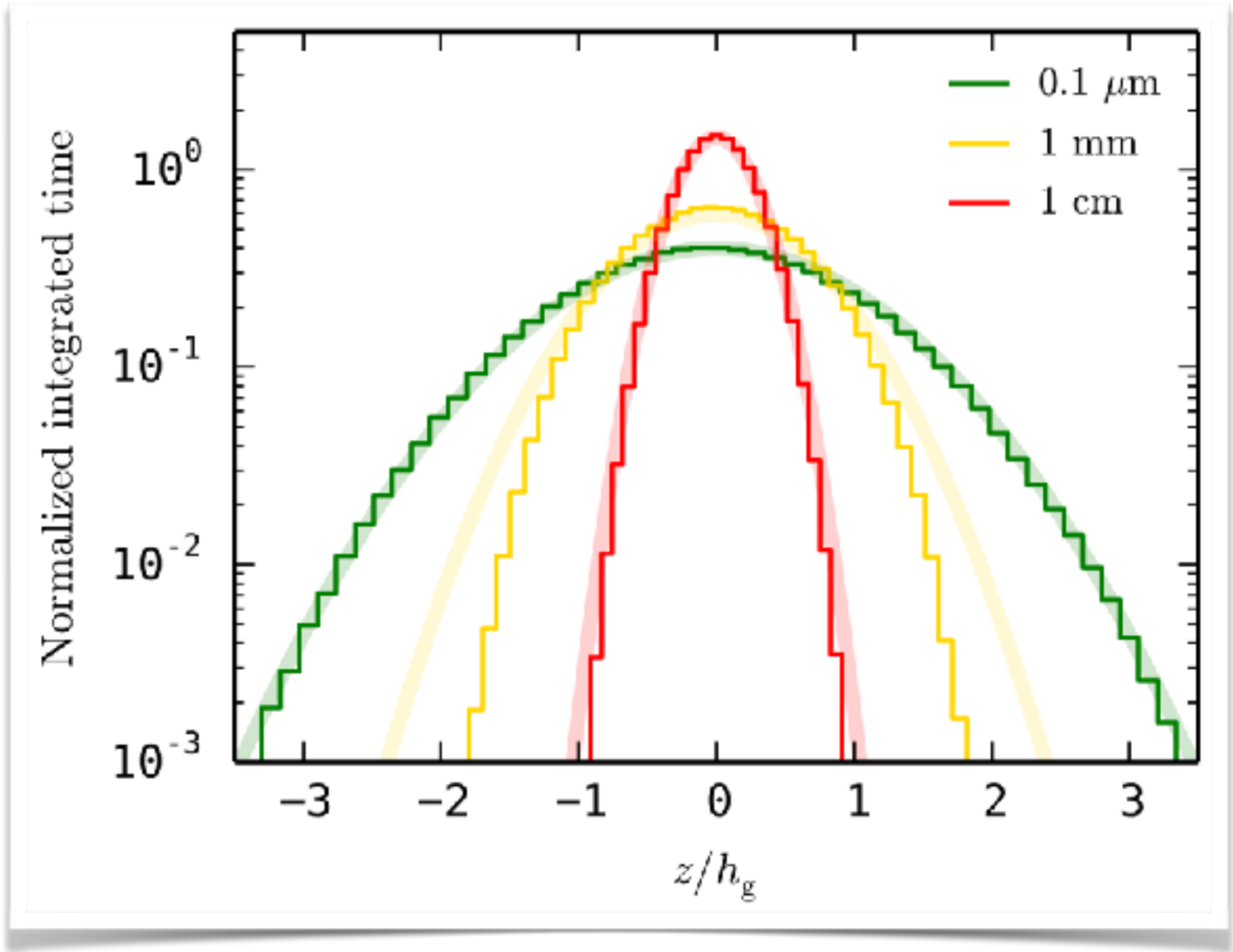
The dynamical evolution of solids depends strongly on their size.

$$\frac{h_\mathrm{d}}{h_\mathrm{g}} \approx \sqrt{\frac{\alpha}{\alpha + \Omega t_s}\left(\frac{1+\Omega t_s}{1+2\Omega t_s}\right)}$$

disk atmosphere

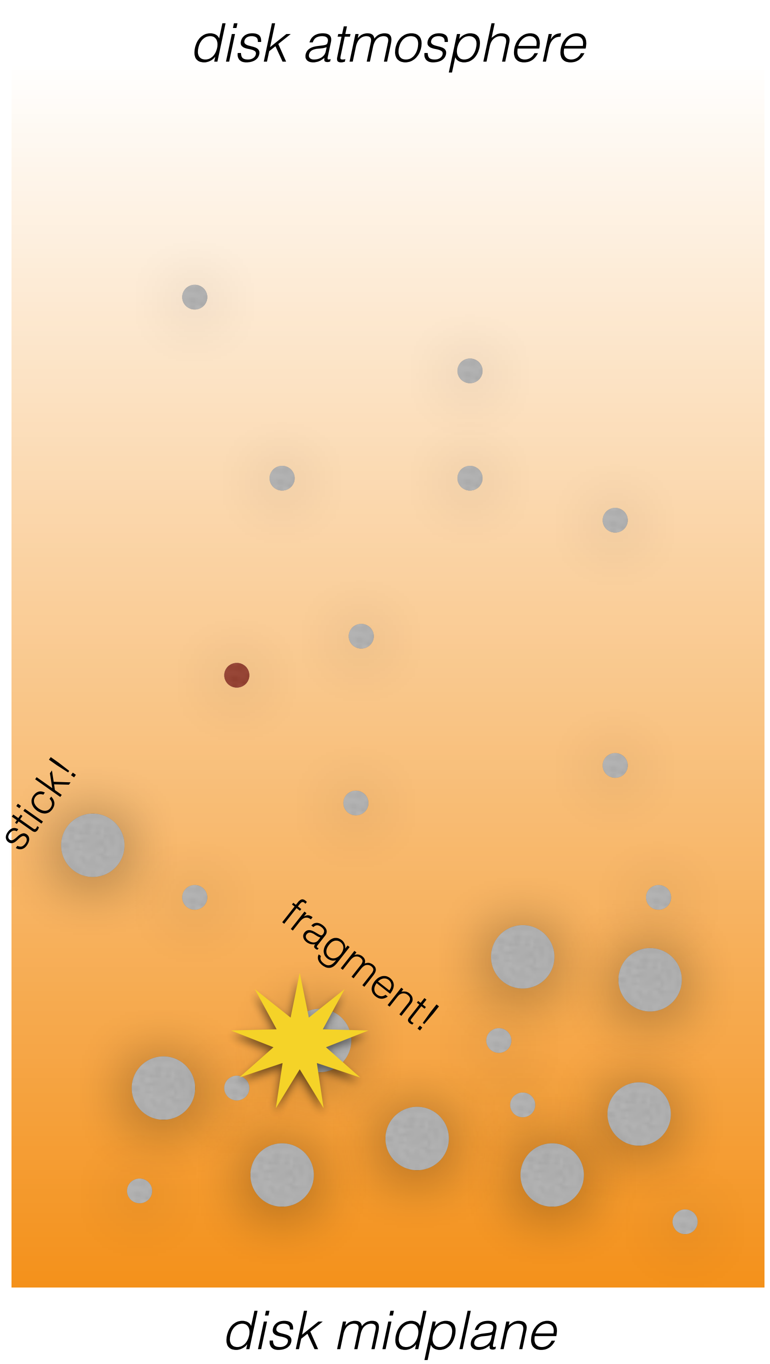


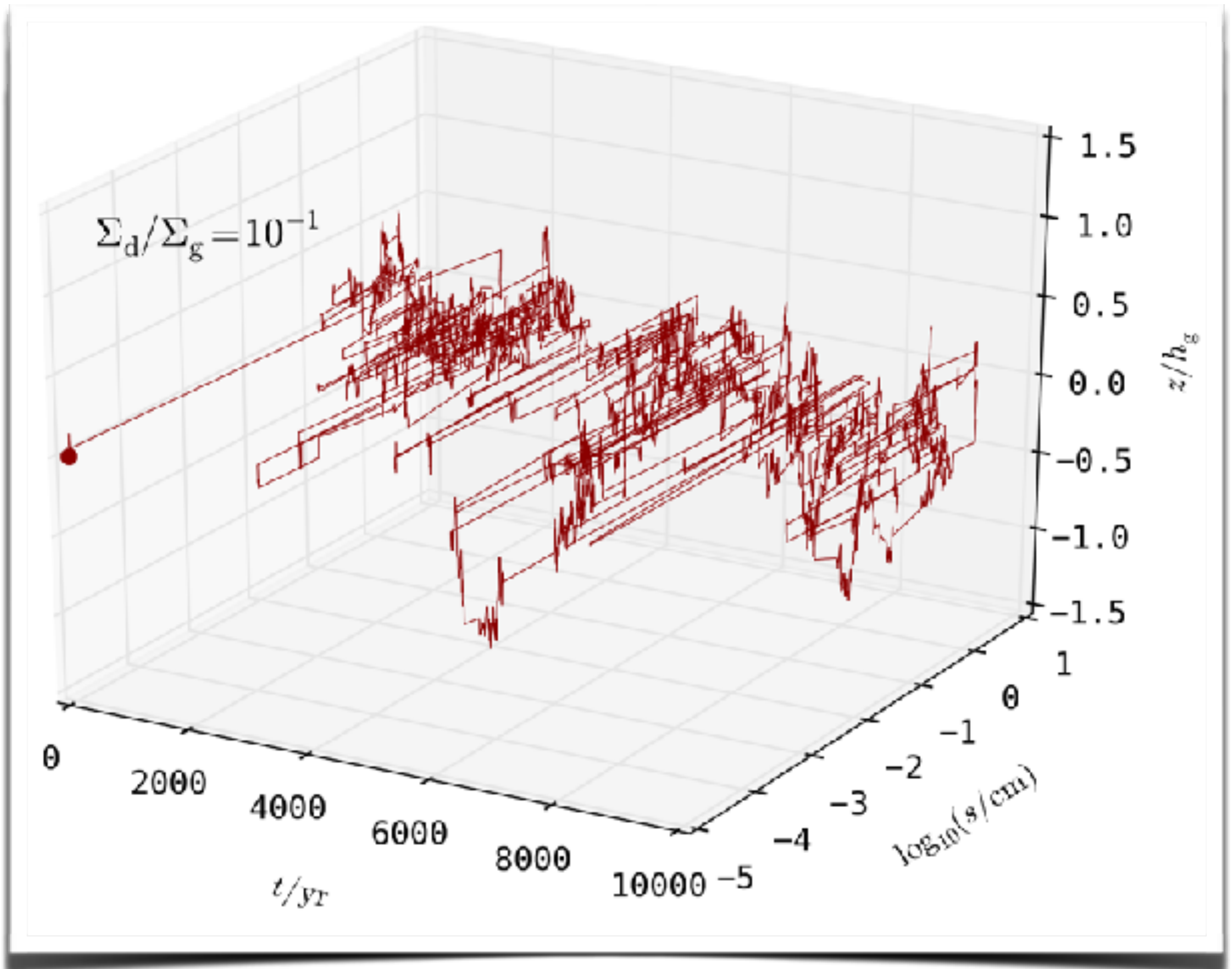
disk midplane



Ciesla (2010,2011)
Ciesla and Sandford (2012)
Charnoz et al. (2015)

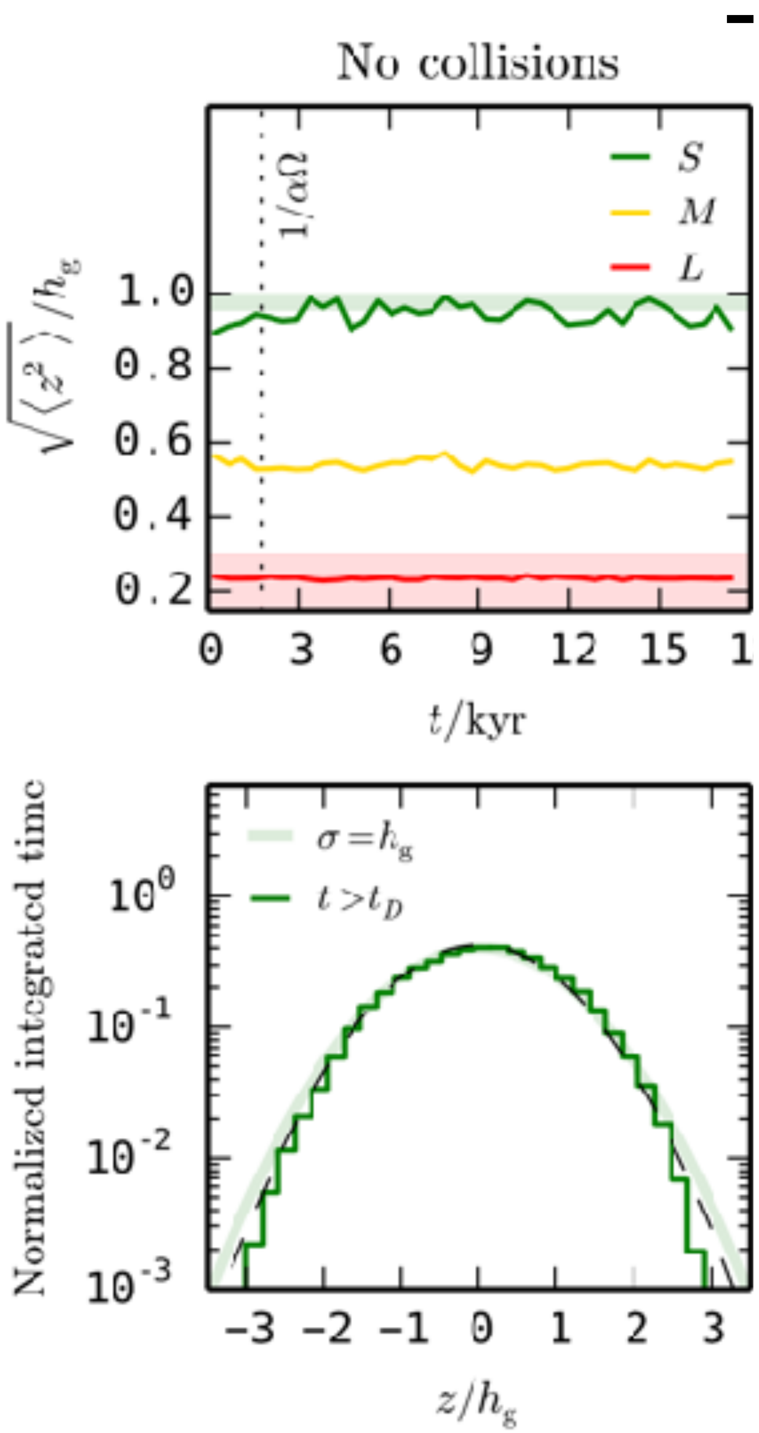
In addition to turbulence and gravitational settling, ***particle collisions*** will determine the vertical distribution of solid species.





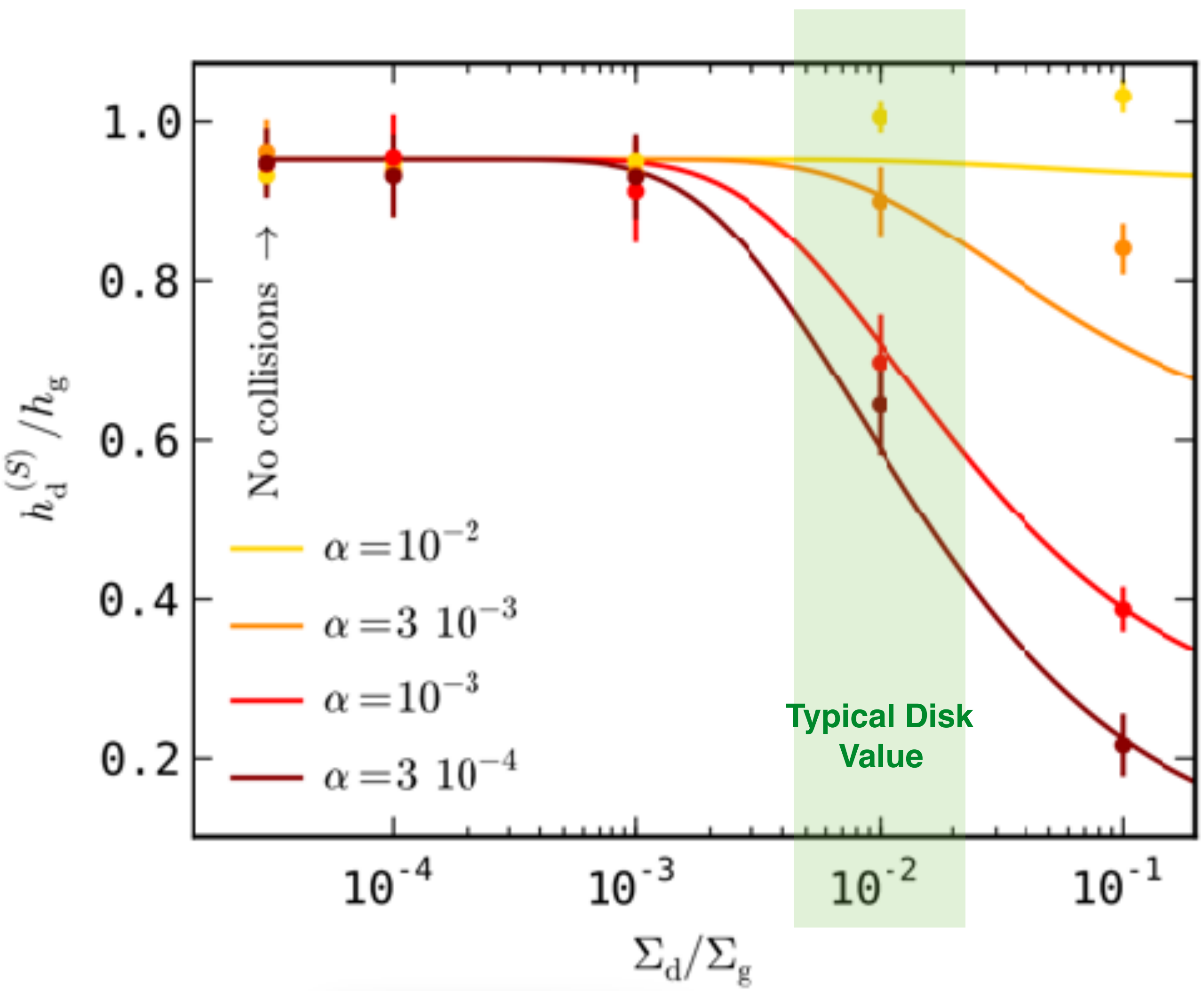
Size distribution from
Birnstiel et al. (2011)

Krijt & Ciesla (2016)



No collisions
$1/\alpha\Omega$
S
M
L
$\sqrt{\langle z^2 \rangle}/h_g$
1.0
0.8
0.6
0.4
0.2
0
3
6
9
12
15
1
t/kyr
Normalized integrated time
$\sigma = h_g$
$t > t_D$
10^0
10^{-1}
10^{-2}
10^{-3}
-3
-2
-1
0
1
2
3
z/h_g

The effect of trapping increases with increasing dust/gas ratio and decreasing diffusivity.



Strength of trapping is inversely correlated with dimensionless parameter:

$$\Phi = \frac{t_{sw}}{t_D} \sim \alpha \left(\frac{\Sigma_d}{\Sigma_g}\right)^{-1}.$$

which is lowest in regions with low turbulence and high dust contents.

Vertical mixing is not as efficient as previously believed, allowing for vertical gradients in the properties of the dust.

That is: Dust at protoplanetary disk surfaces likely does not represent bulk properties of dust at disk interior.

Krijt & Ciesla (2016)

Take home message: Chemical evolution and physical evolution are coupled.

- Small bodies in our Solar System record a dynamic solar nebula, consistent with what is seen in other protoplanetary disks.
    - All chemical compounds would have experienced significant excursions.
- In a dynamic nebula, materials would constantly be in motion. **Primitive materials do not record individual formation environments.**
    - Particles are not incorporated into planetesimals at the same region that they were formed/created.
    - Despite being incorporated into planetesimals at the disk midplane, solids can be carried to high altitudes prior to accretion, leading to exposure to high energy particles and radiation.
    - Chemical evolution of primitive materials will be determined by their integrated paths through the disk. *Every grain would have a unique path and a unique processing history.*
- The record of meteoritic materials and protoplanetary disks may have a complicated relationship as dust growth traps grains near the midplane, and out of view of observations.