Growth and Transport Processes in Protoplanetary Disks

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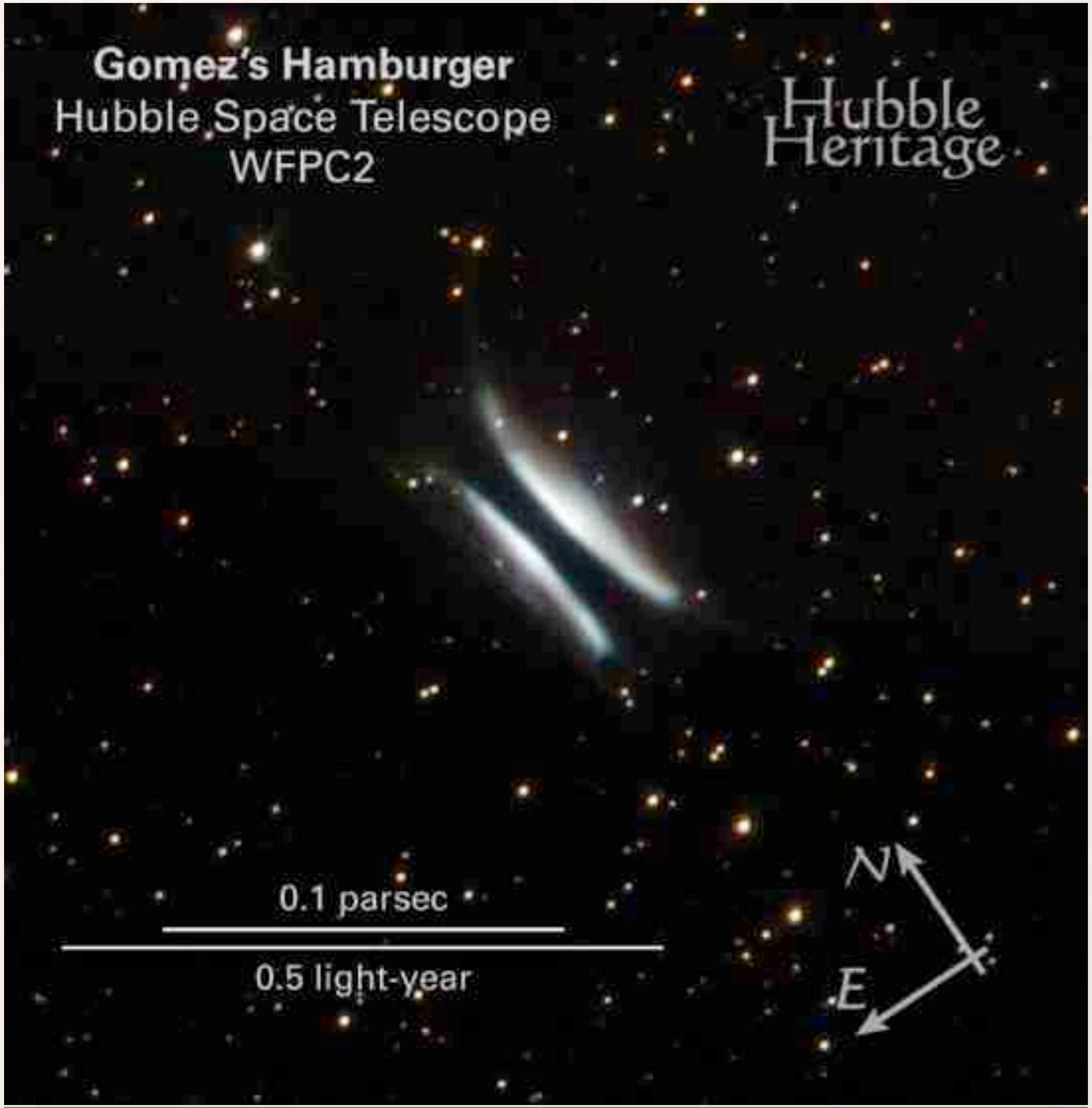
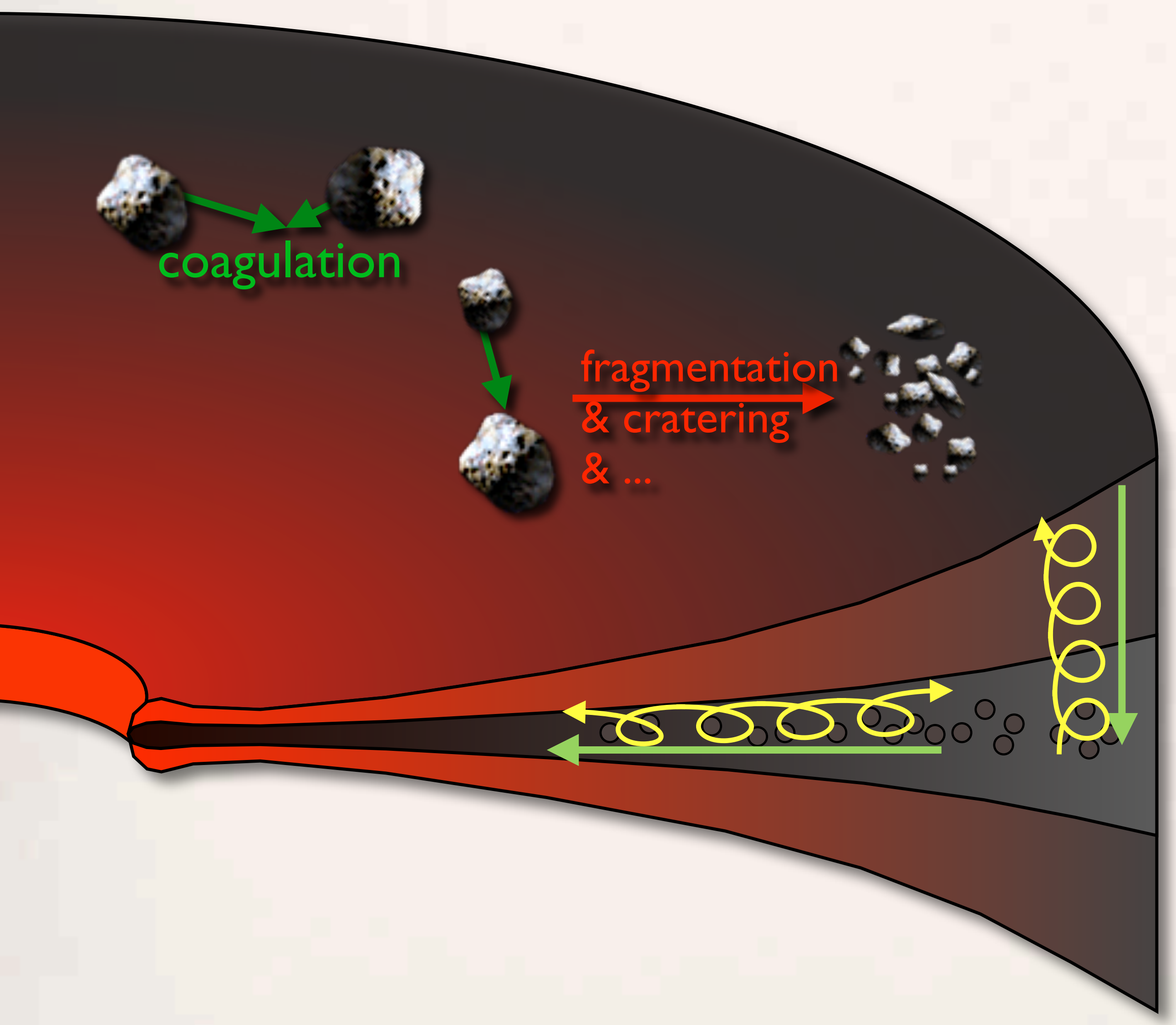
– Introduction –

– Dusty Disks –

- Rich in small dust grains
- Lifetimes of ~ 3 Myrs
- Evolving viscously



– Dust Physics –



- **Vertical Evolution**
  turbulent mixing, settling, dead zones, …
- **Radial (& Azimuthal) Evolution**
  particle drift, mixing, gas drag, meridional flows, turbulent concentration, pressure traps, photophoresis,...
- **Dust Size Evolution**
  sticking, bouncing, fragmentation, compaction, erosion, evaporation, condensation, ...

– Outline –

- Transport Mechanisms
  - Drag Forces
  - Radial Drift
  - Settling & Mixing
- Growth Mechanisms
  - Impact Velocities
  - Collisional Outcomes
- Global Dust Evolution
  - Grain Sizes
  - Dust Surface Densities
  - Transition Disks

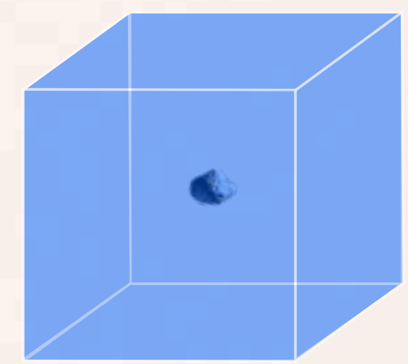
more historical: Dominik, PP V, 2007

– Transport Mechanisms –

– Drag Force –

$$\tau_{\rm stop} = \frac{v}{\dot{v}} = \frac{m\,v}{|F_{\rm drag}|}; \qquad {\rm St} = \frac{\tau_{\rm stop}}{\tau_{\rm orb}} \simeq \frac{a\,\rho_{\rm s}}{\Sigma_{\rm g}}\frac{\pi}{2} \qquad \text{(Stokes number)}$$

St << 1 i.e. $\tau_{\rm fric} \ll \tau_{\rm orb}$



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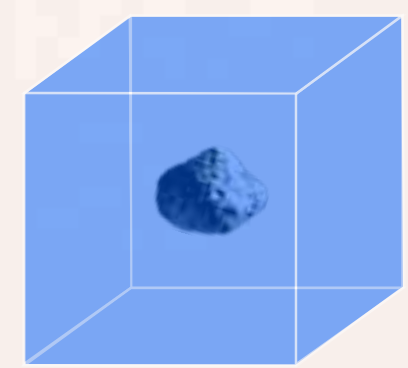

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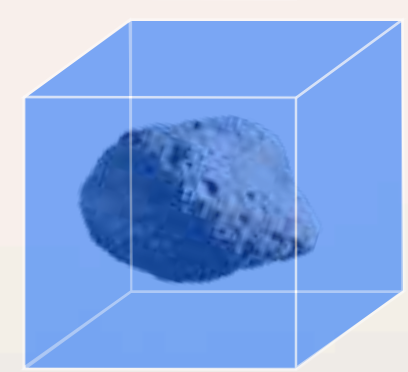

e.g., Whipple (1972)

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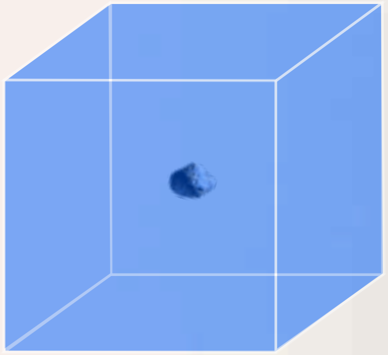

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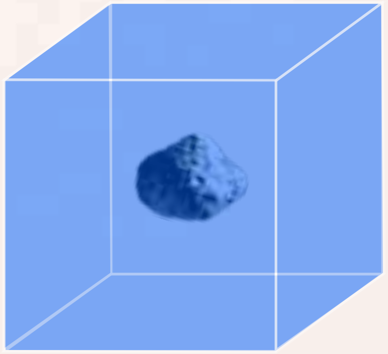

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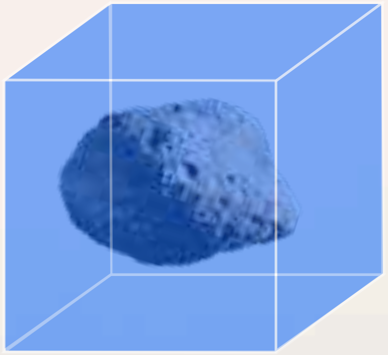

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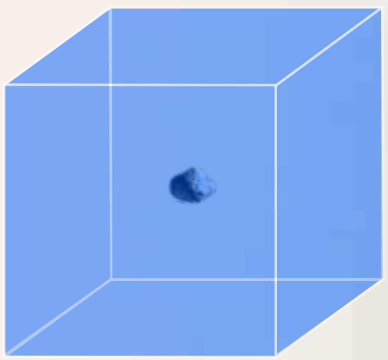

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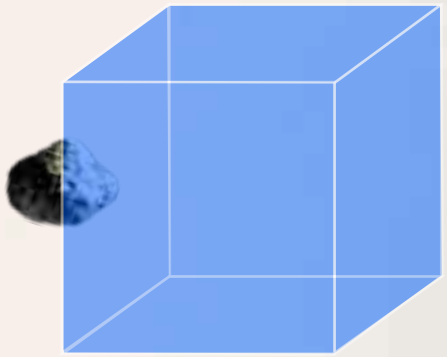

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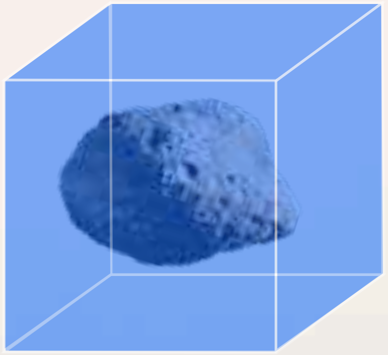

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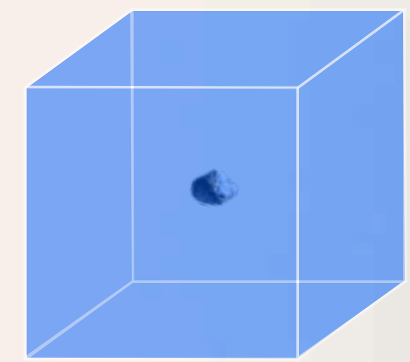

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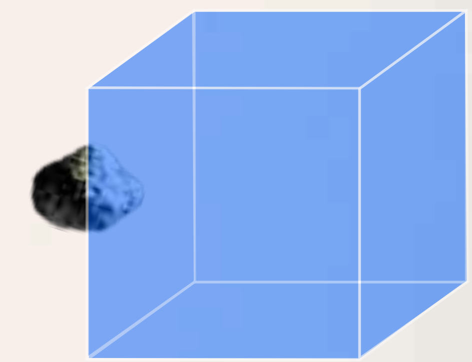

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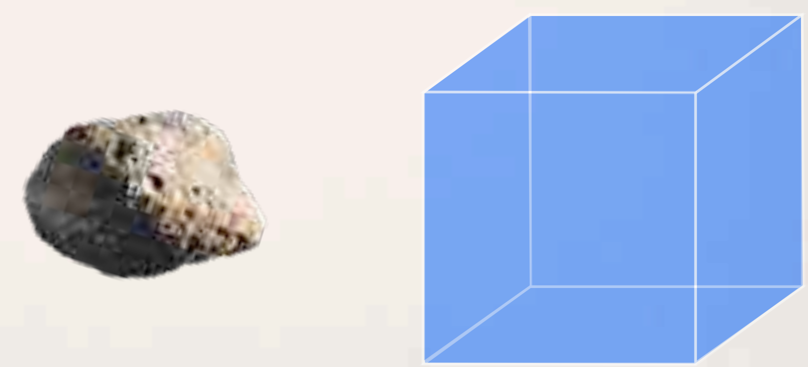
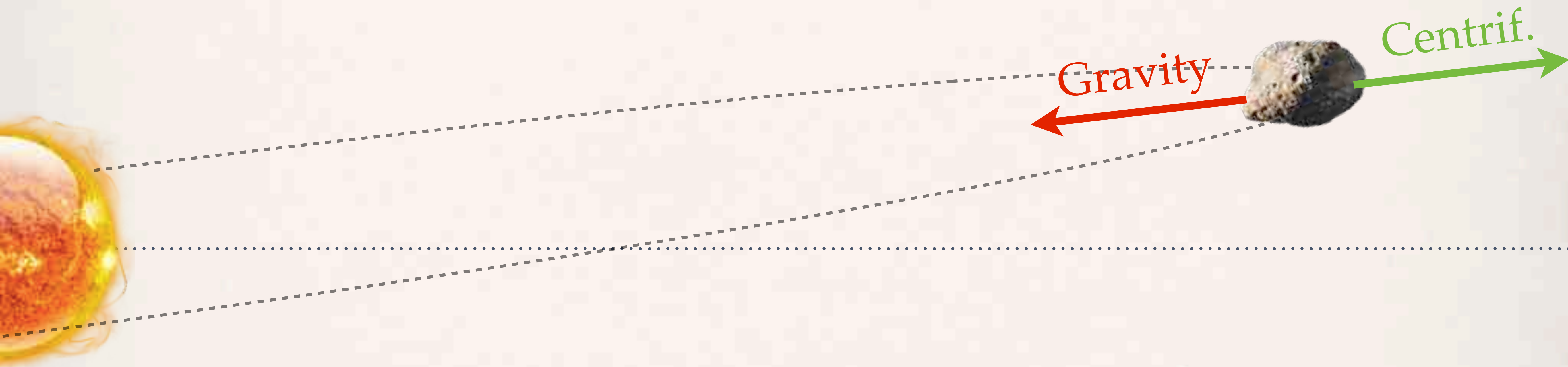


e.g., Whipple (1972)

– Vertical Settling –



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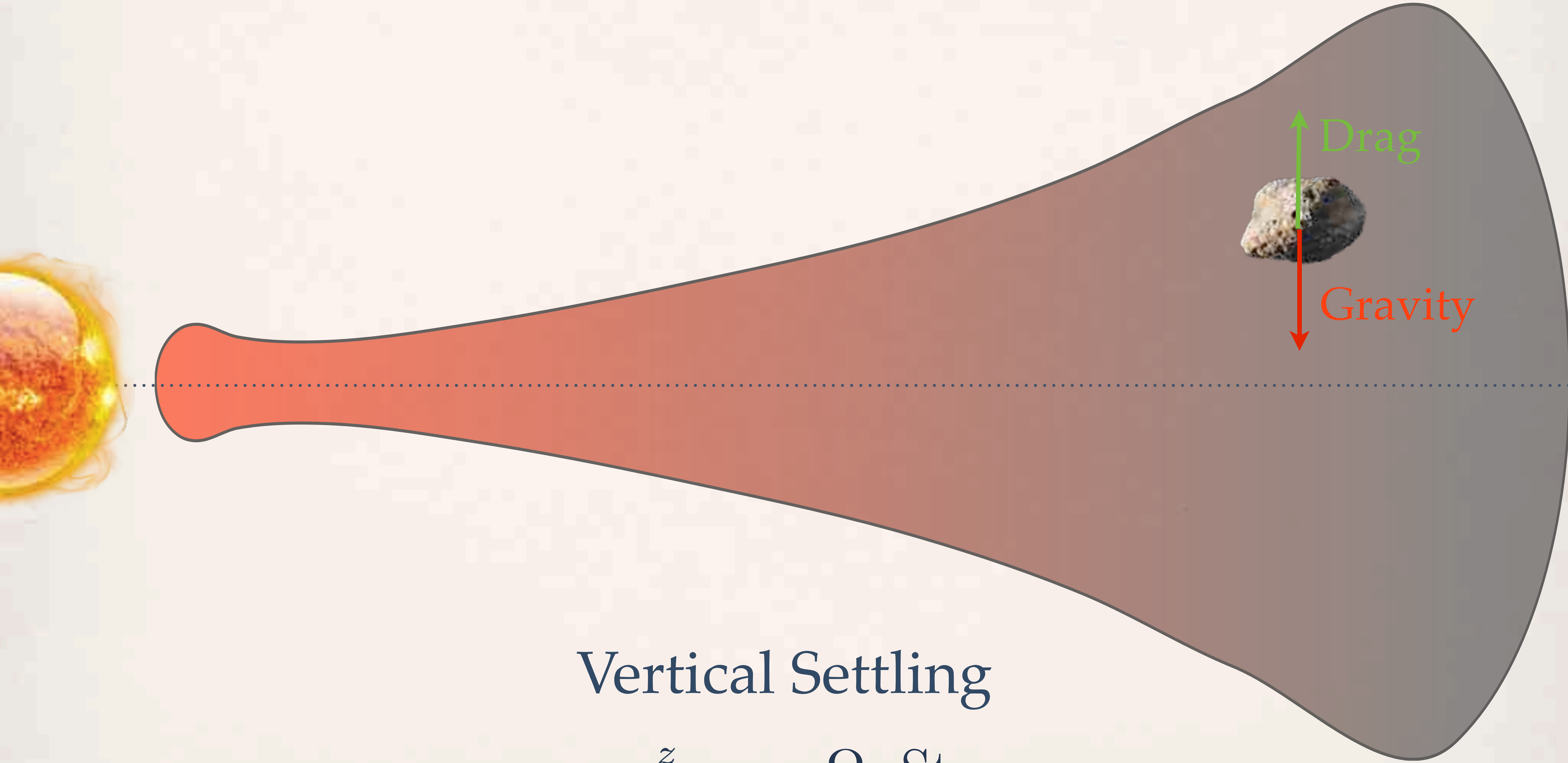

Vertical Settling

$$u_{\rm d}^{z} = -z\Omega_{\rm k}\,{\rm St}$$

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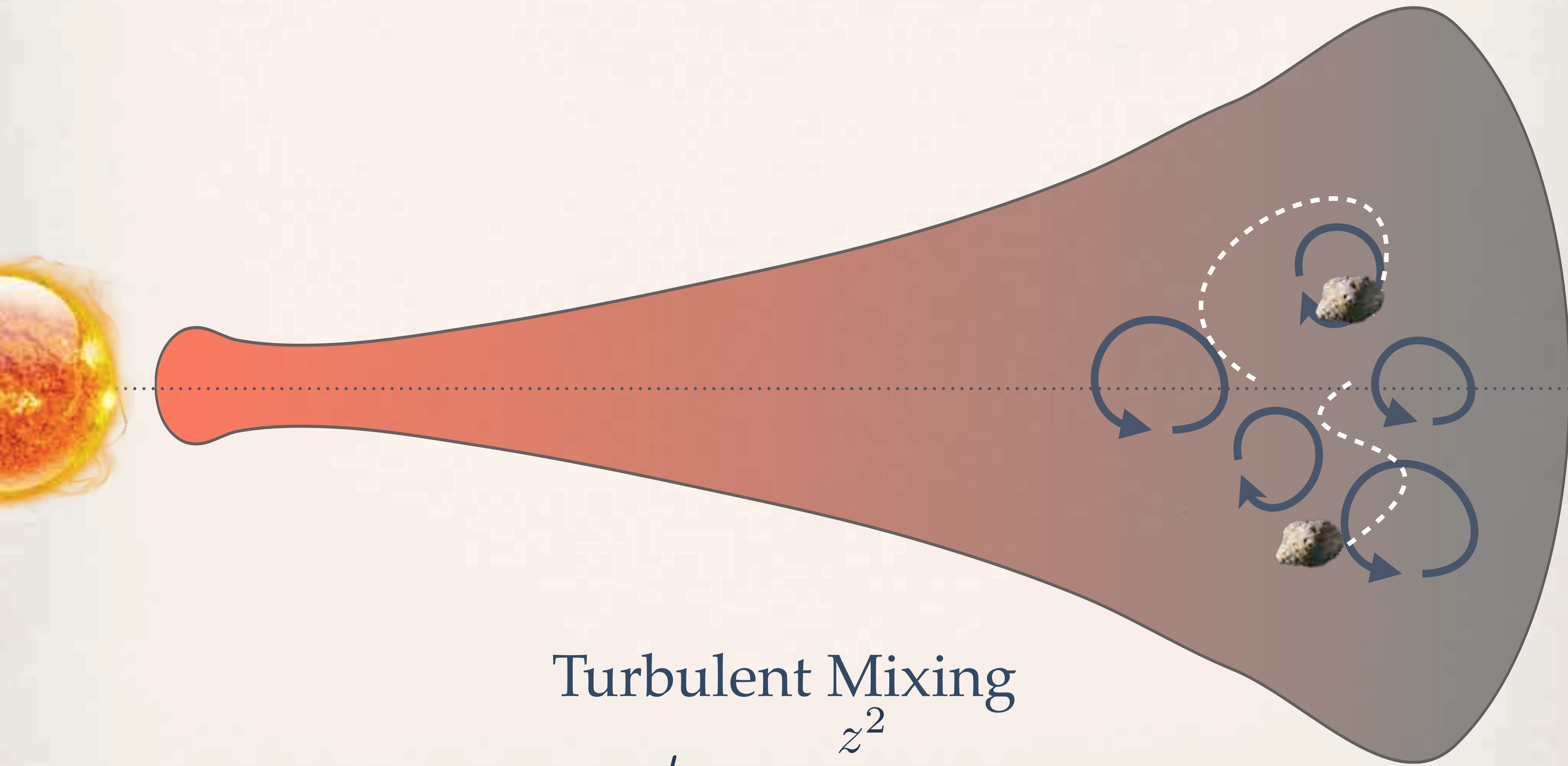


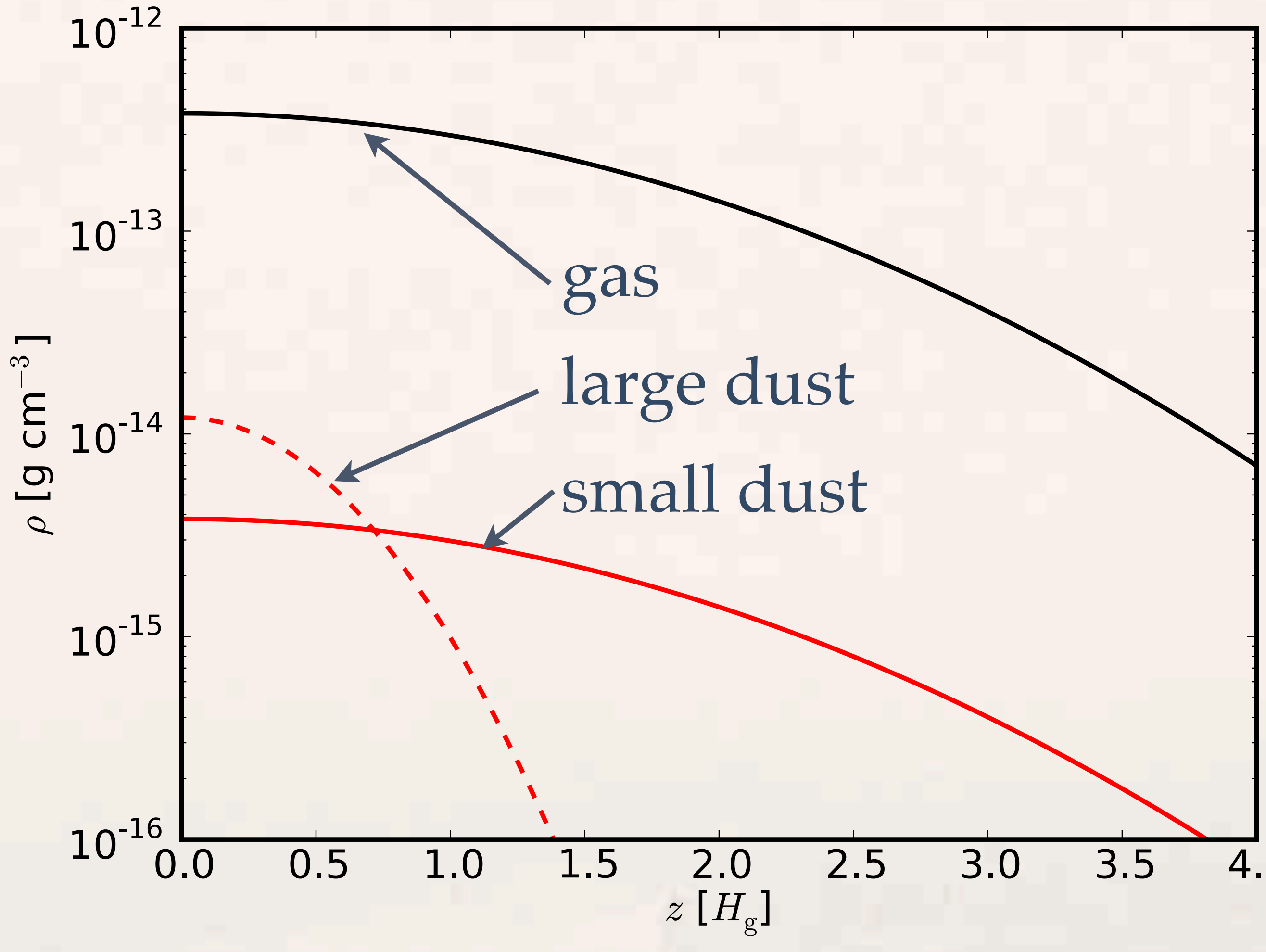
Turbulent Mixing

$$t_{\rm mix} = \frac{z^2}{D}$$

– Vertical Settling –

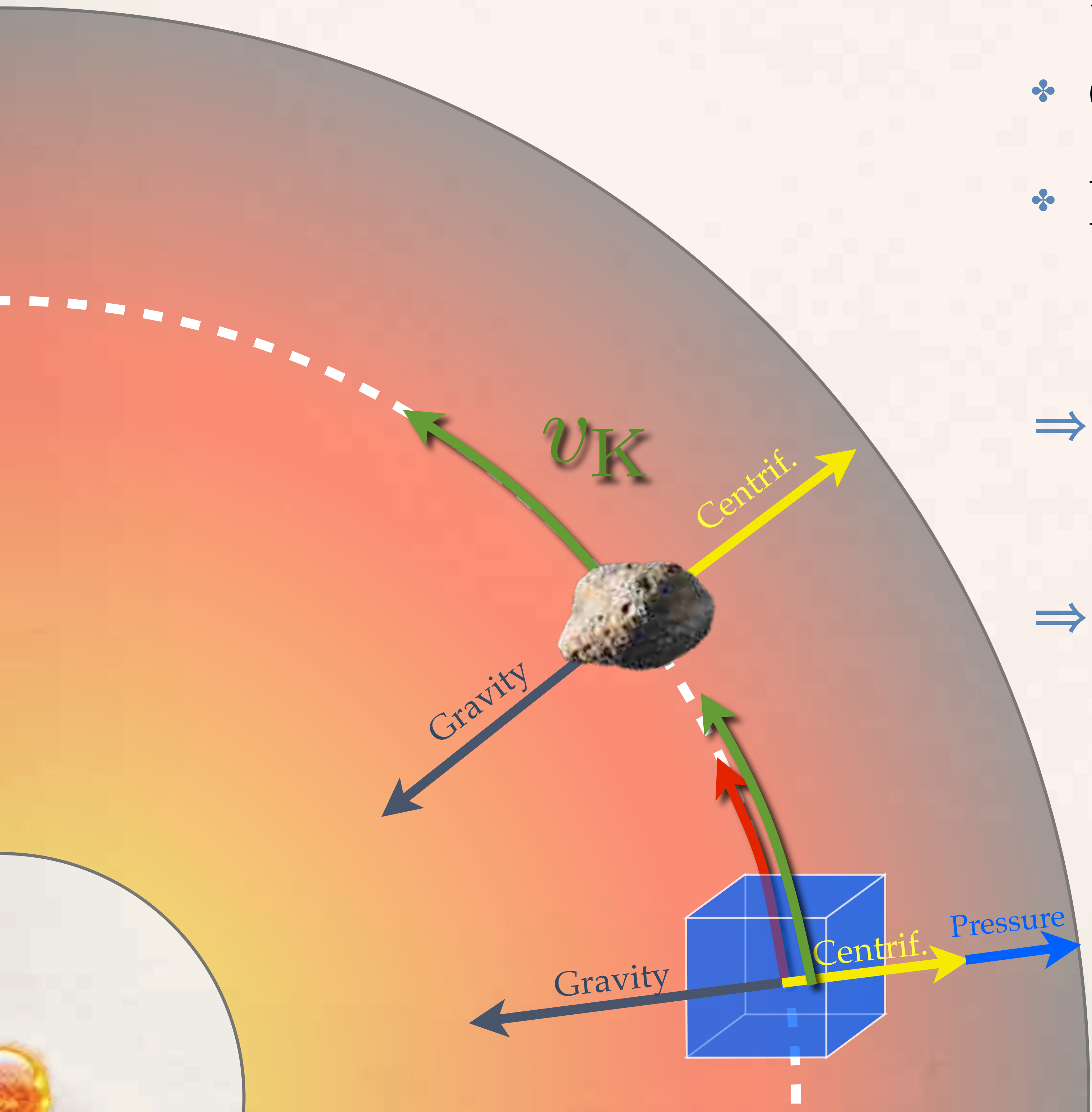
Vertical Settling ⇄ Turbulent Mixing

$$H_{\mathrm{dust}} = \sqrt{\frac{\alpha}{\mathrm{St}}}\, H_{\mathrm{gas}}$$



e.g., Dubrulle et al. (1995)

– Radial Drift –



- Dust: towards Keplerian
- Gas: sub-Keplerian
- Result: headwind

⇒ Angular Momentum Transfer from dust to gas

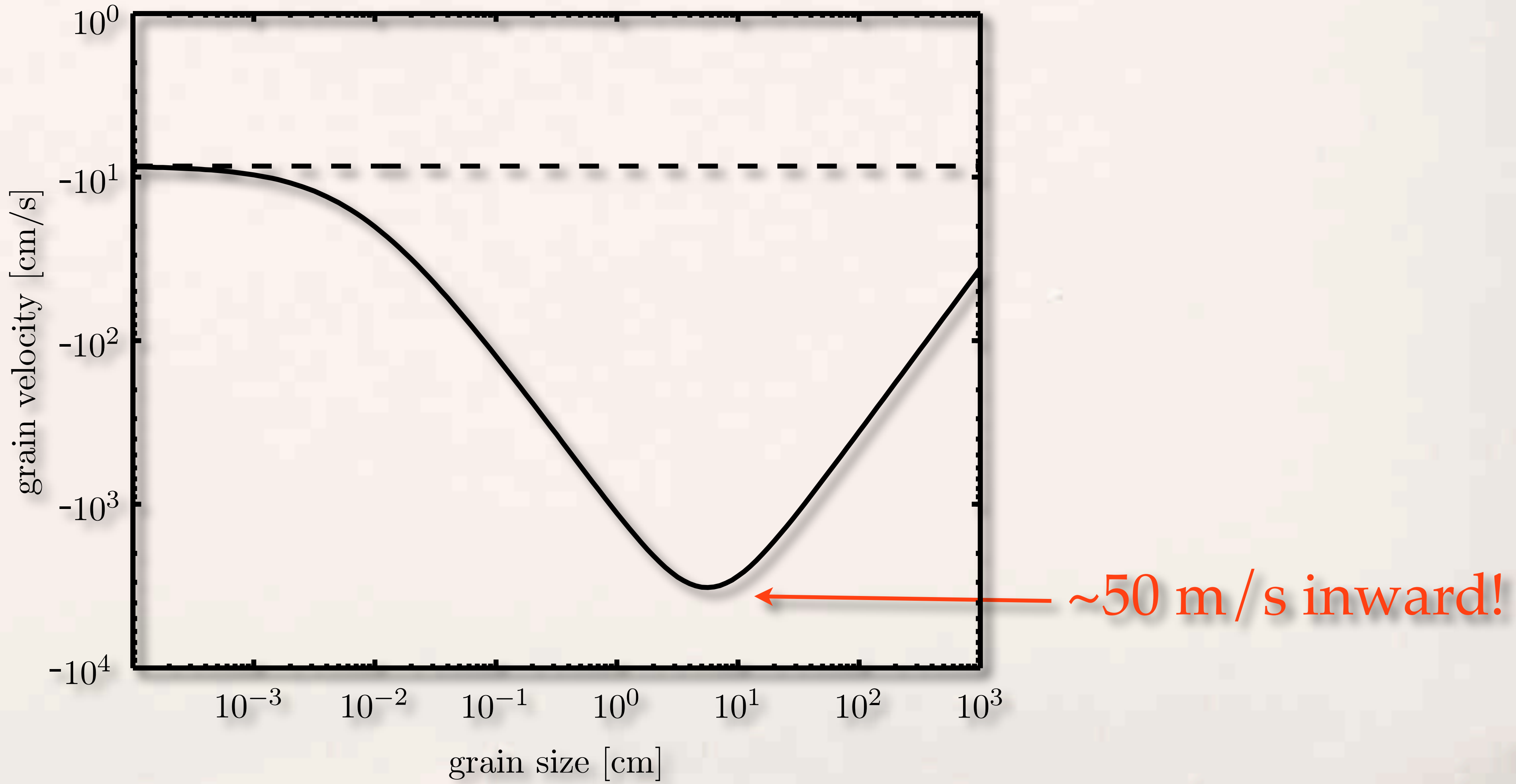
⇒ Orbital Decay

e.g., Weidenschilling (1977)
Nakagawa et al. (1986)

– Radial Drift –

- Drift towards pressure maximum

$$u_r = \frac{1}{\mathrm{St} + \mathrm{St}^{-1}} \frac{c_s^2}{u_k} \frac{d \ln P}{d \ln r}$$



– Summary: Transport –

- Dust is ...

  ... dragged along with gas

  ... mixed by turbulence

- Dust drifts up the pressure gradient:

  ⇒ sedimentation to mid-plane

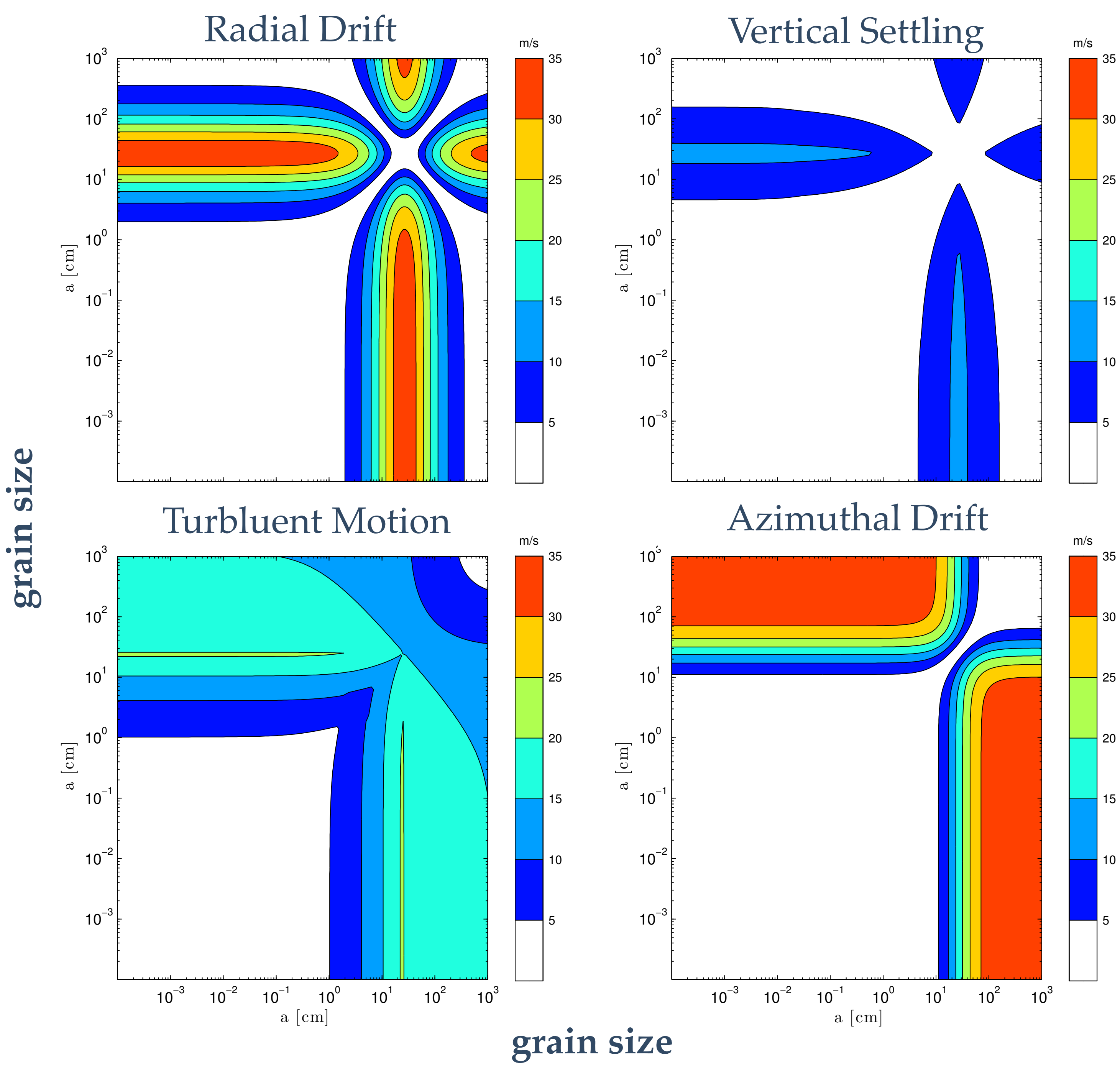
  ⇒ radial drift

All depends on particle size!

– Growth Mechanisms –

Velocities, Outcomes, Codes, & Size Evolution

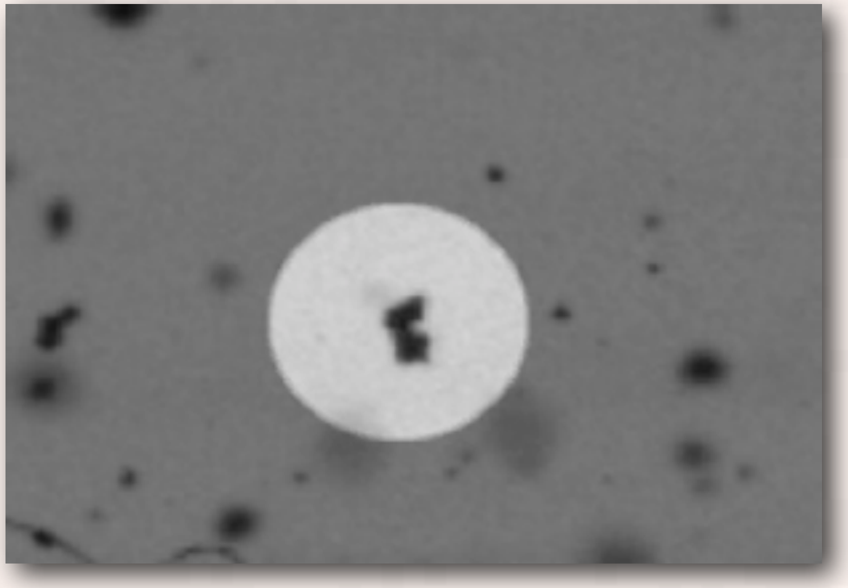
— Relative Velocities —



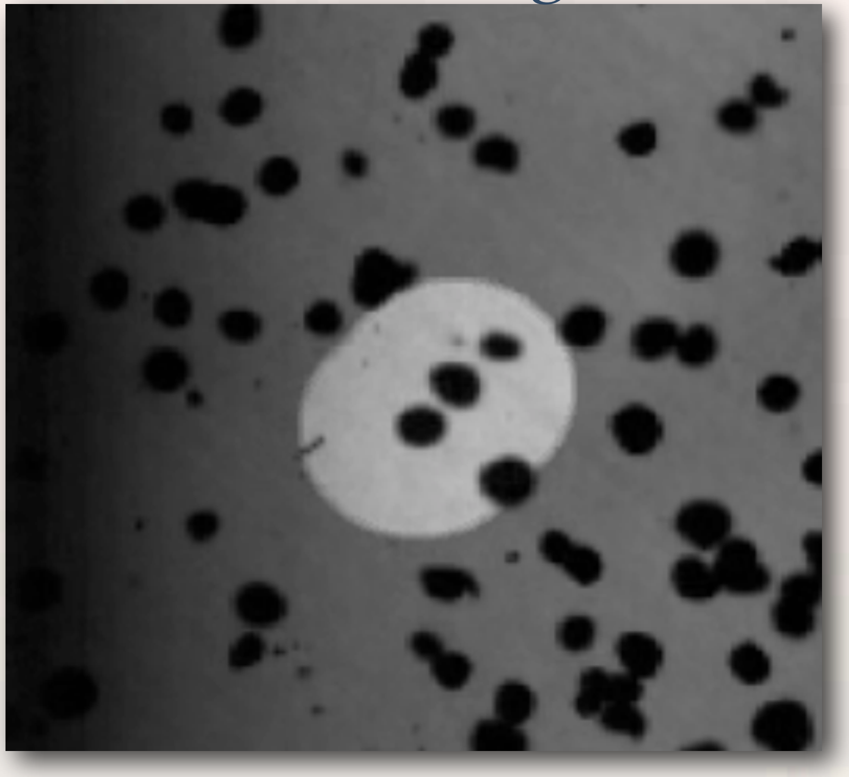
Trend: impact velocity increases with grain size!

– Collisional Outcomes –

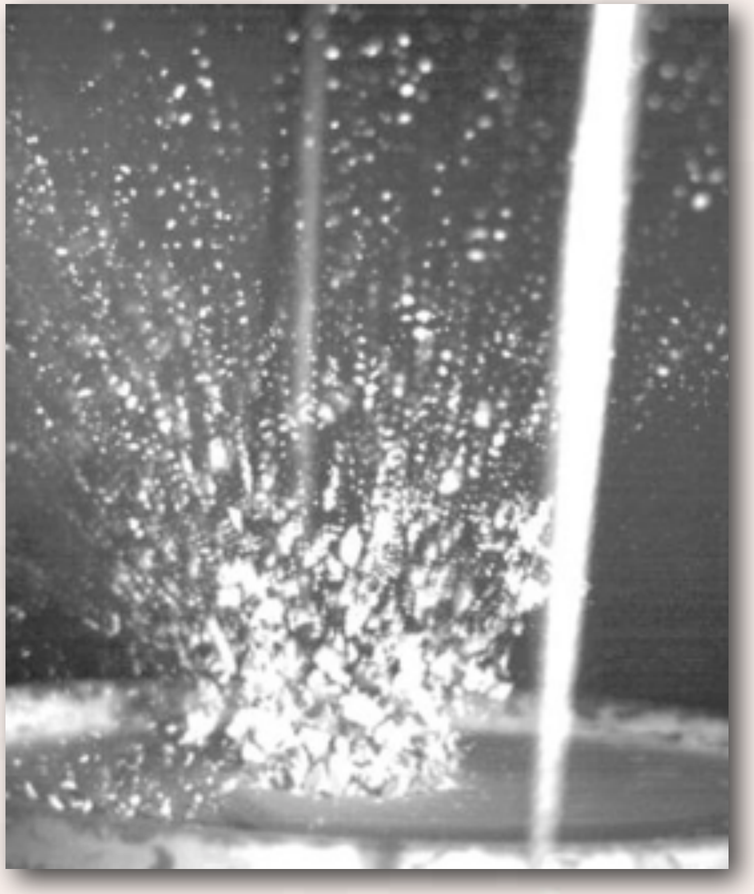
Sticking



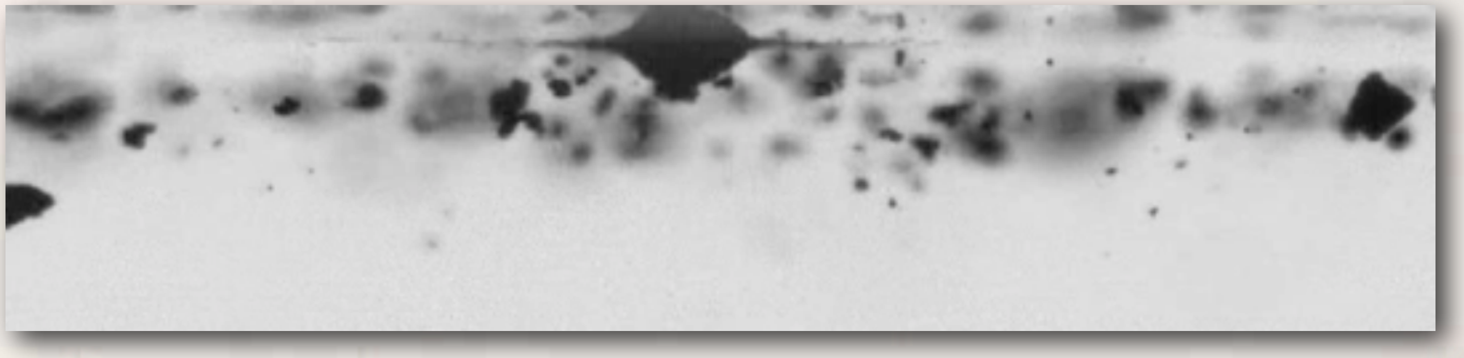
Bouncing



Fragmentation



Mass Transfer

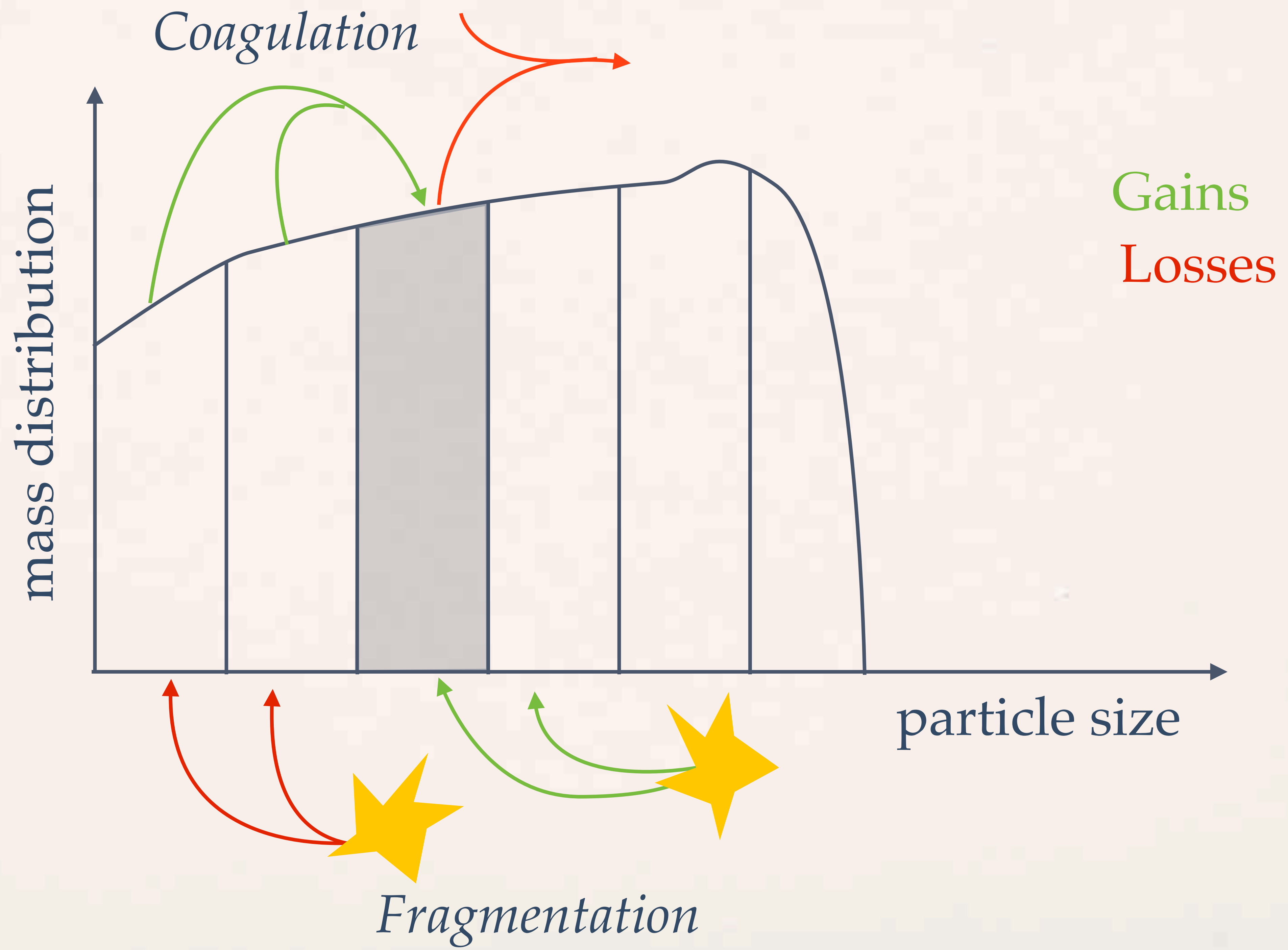


Movies courtesy of J. Blum and collaborators, see e.g. Blum & Wurm 2008, Güttler et al. 2010

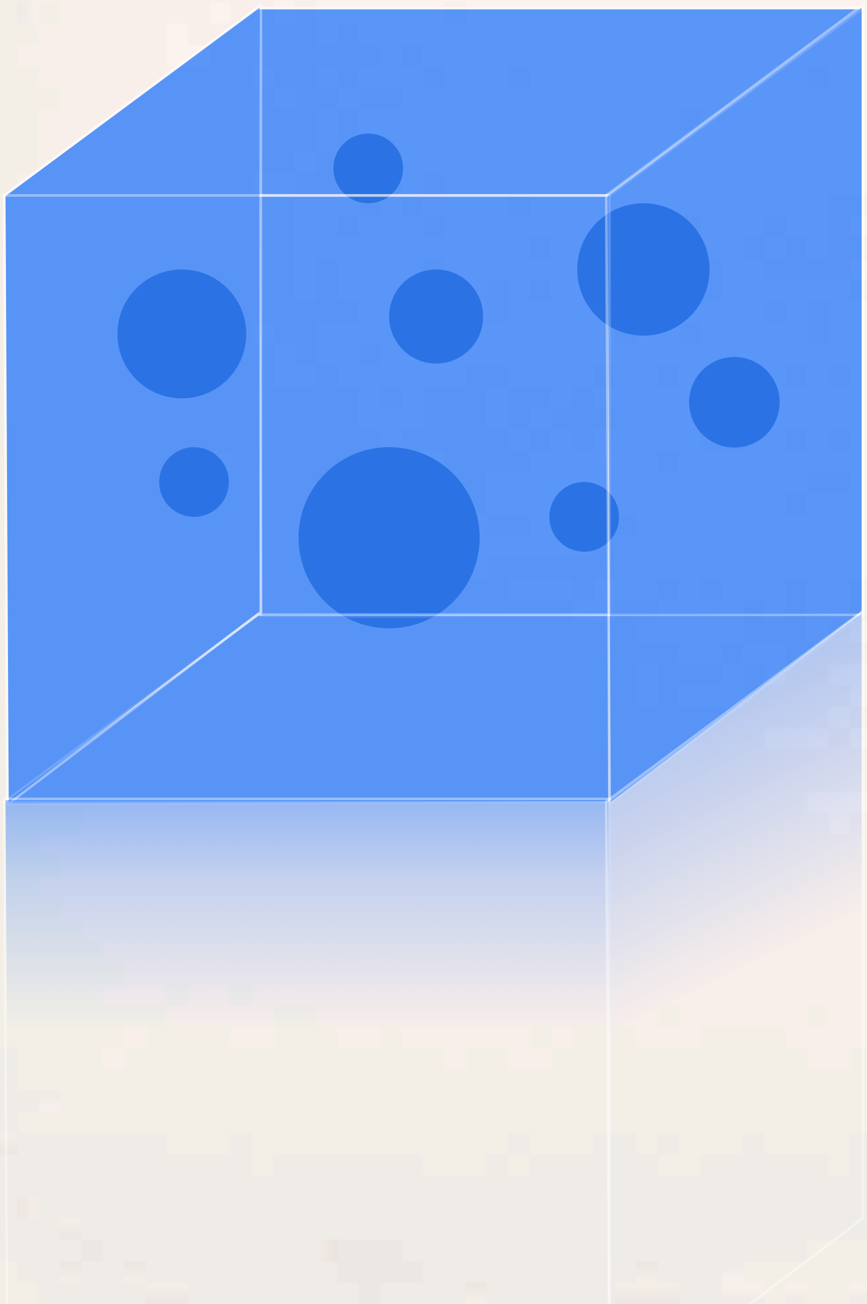
– Numerical Challenges –

- Large parameter space
- Dynamical Range
  - Mass: 20 - 40 orders of magnitude
  - Particle Number: 1 … 10^{26}
  - Collision times (0.1 year) vs. disk life time (3×10^6 years)
- already 0D models can take hours

Coagulation



– Monte Carlo Methods –



Examples:

- Gillespie 1975
- Ormel et al. 2007, ...
- Zsom et al. 2008, ...

Pros:

- Easy to code
- Easy to add properties: porosity, charges, velocity distribution, ...

Cons:

- low dynamic range, small mass fractions neglected
- slow for non-local simulations or high collisions frequency

– Grid Based Methods –

$$
\begin{aligned}
\frac{\partial f(m)}{\partial t} &= \\
&+\frac{1}{2}\int_0^\infty f(m')\cdot f(m-m')\cdot \\
&\qquad \cdot K(m',m-m')\,dm' \\
&- \int_0^\infty f(m')\cdot f(m)\cdot K(m,m')\,dm' \\
&+\frac{1}{2}\iint_0^\infty f(m')\cdot f(m'')\cdot L(m',m'')\cdot \\
&\qquad \cdot S(m,m',m'')\,dm'\,dm'' \\
&- \int_0^\infty f(m')\cdot f(m)\cdot L(m,m')\,dm'
\end{aligned}
$$

Examples:

- Weidenschilling 1980, ...
- Nakagawa et al. 1981
- Dullemond et al. 2005
- Brauer et al. 2008, ...
- Birnstiel et al. 2009, ...
- Okuzumi et al. 2009, ...

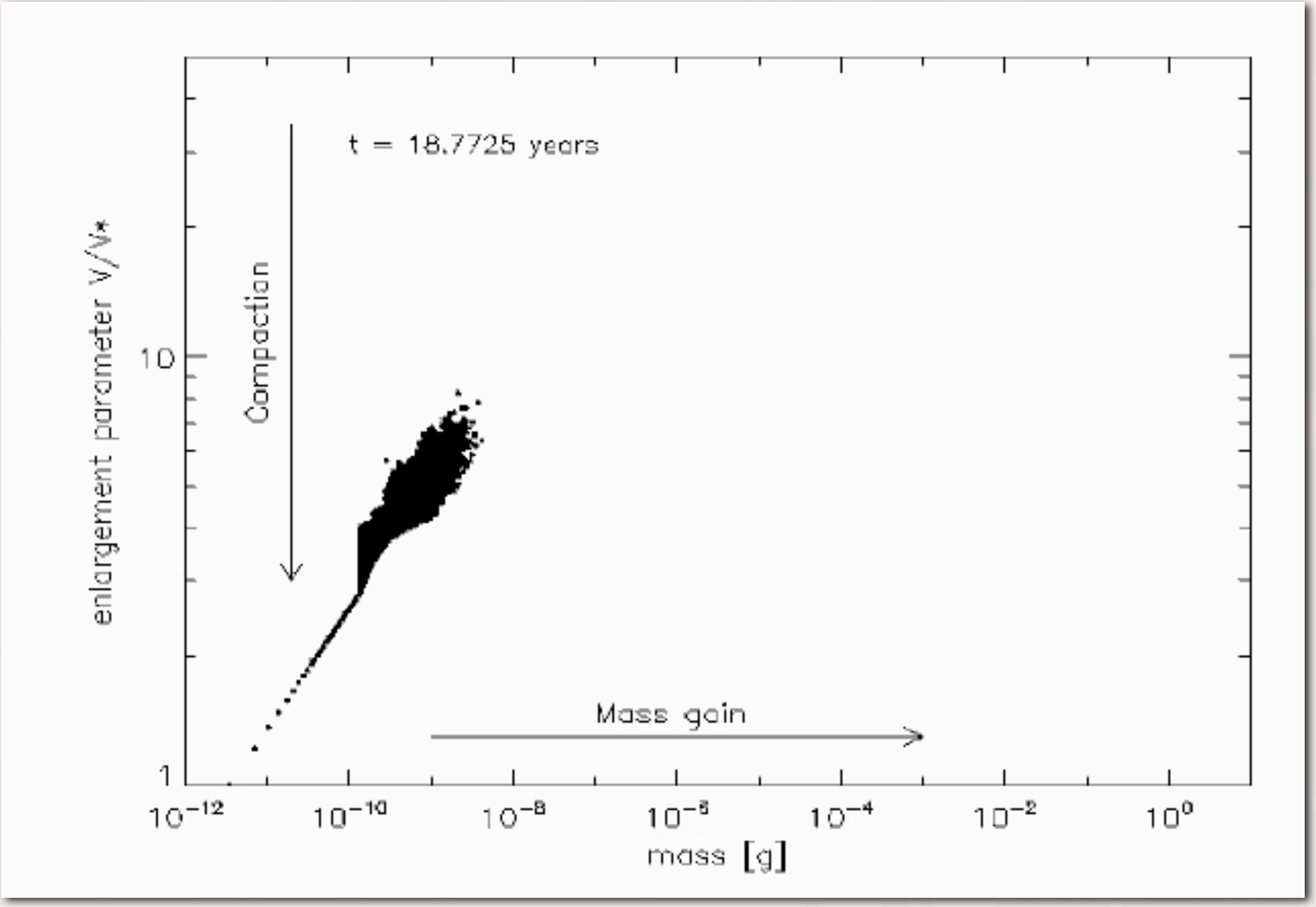
Pros:

- high dynamic range
- implicit integration possible
- fast for multi dimensional simulations

Cons:

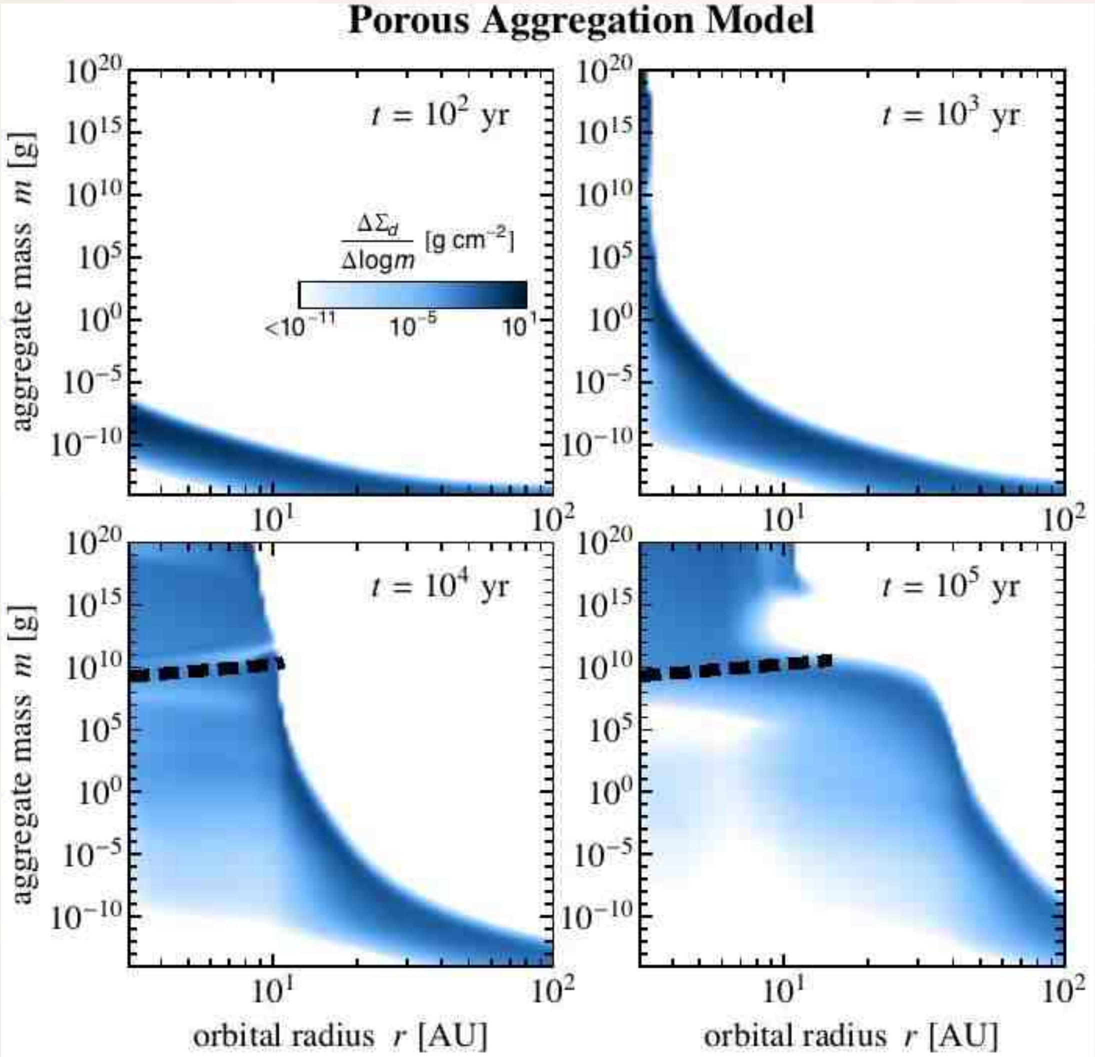
- porosity, charges, velocity distribution: only mean values
- diffusive method, problem with low number statistics

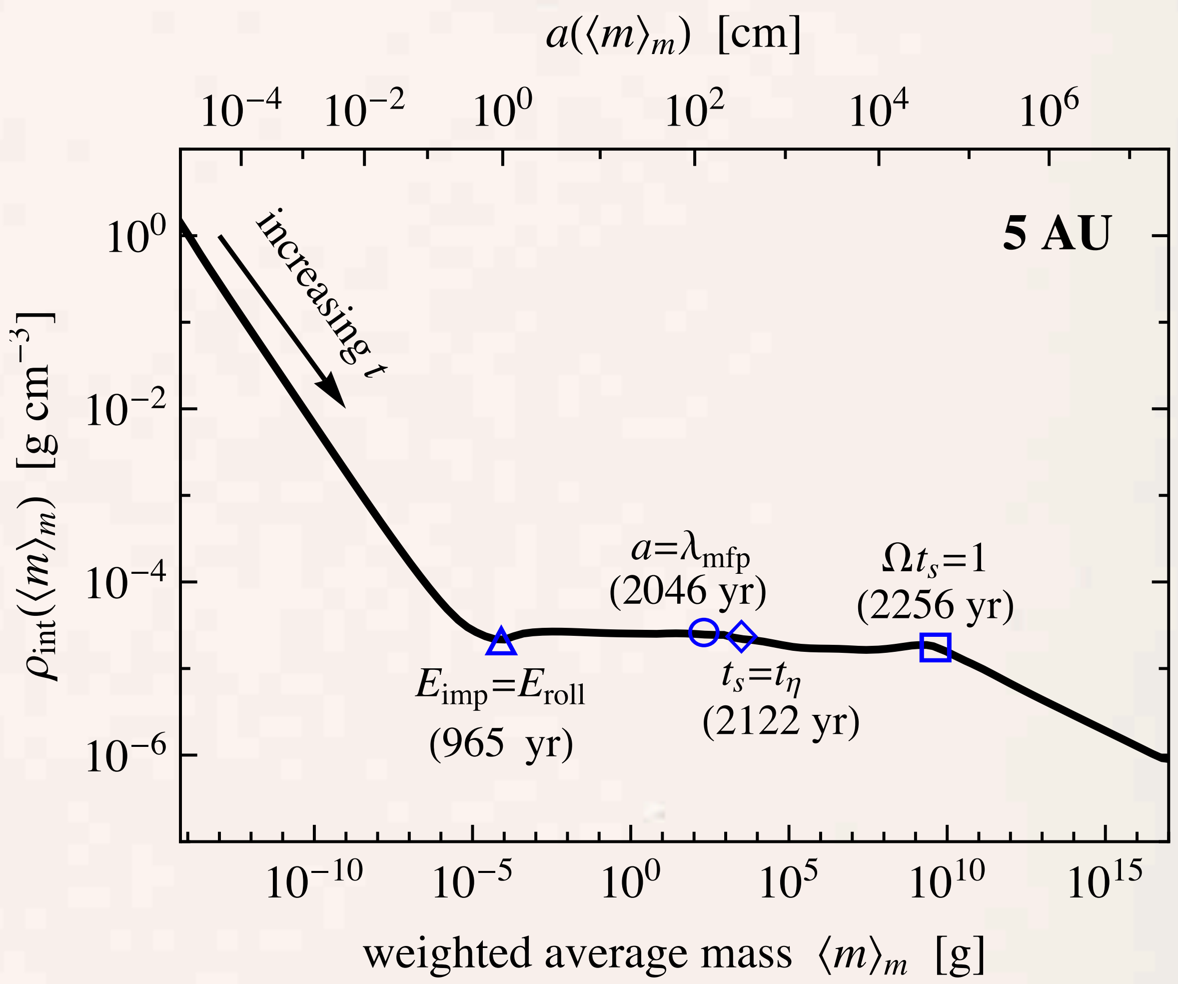
– Bouncing Barrier –



Zsom et al. 2010

– Fractal Growth –

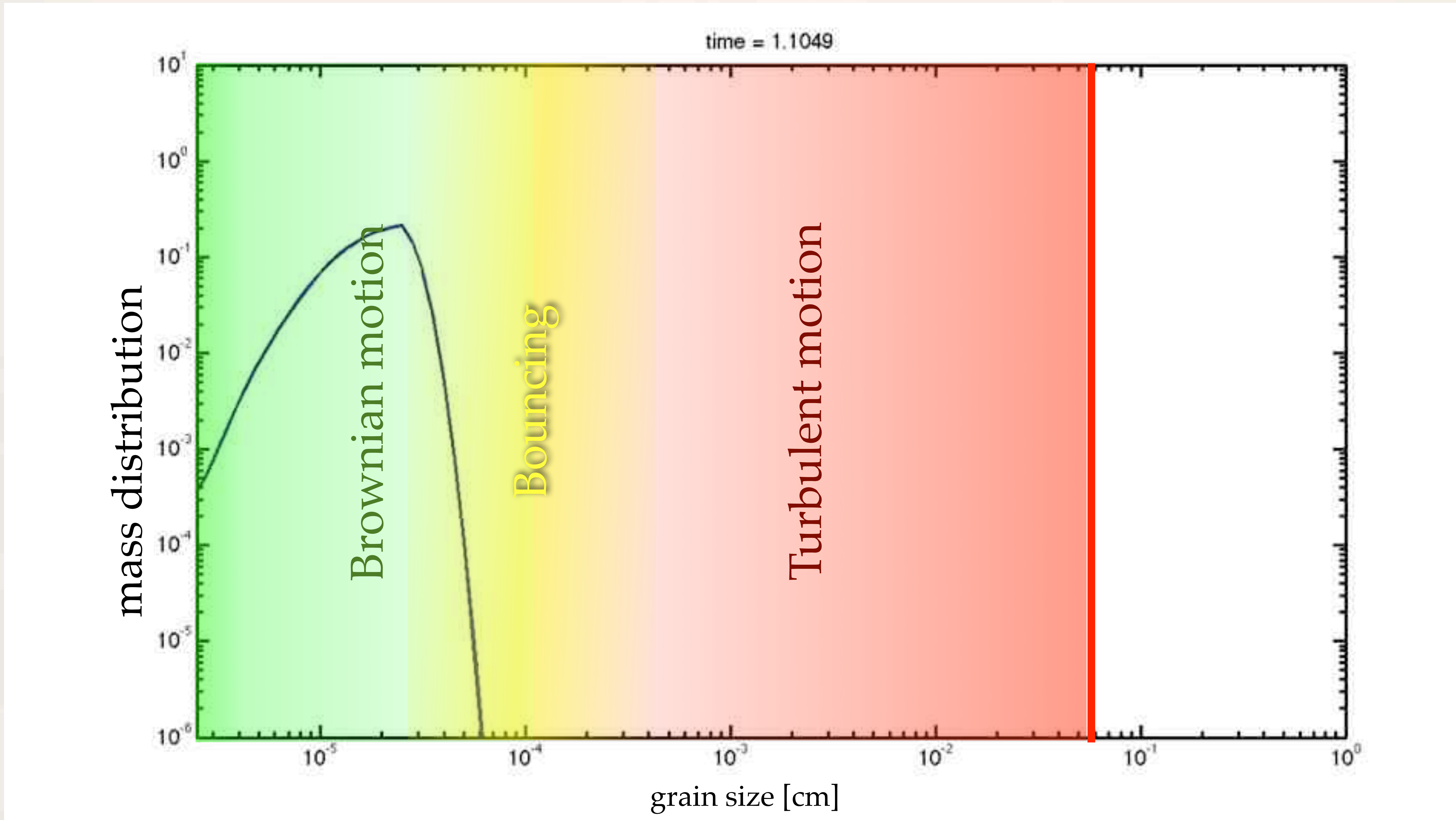




- Fractal particles could break through the drift barrier
- Assumption: icy particles fragment only @ 35 m/s & no significant compaction occurs
- Note: extremely low internal density

Okuzumi et al. 2012

– Growth Barriers –

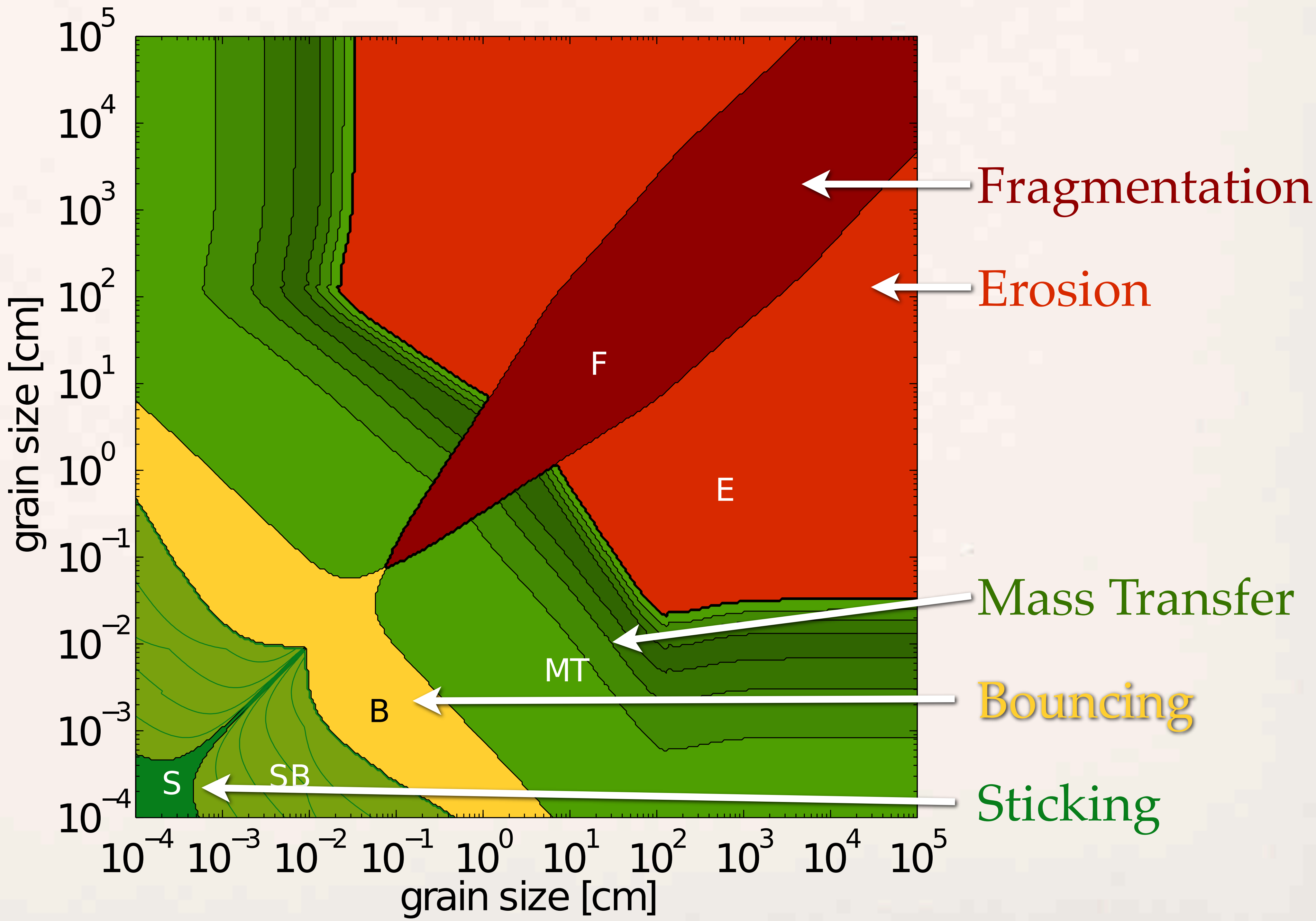


$$\tau_{\mathrm{grow}} \simeq \frac{1}{\epsilon\Omega}$$

e.g. Birnstiel et al. (2011)

– Compact Growth –

take two grain sizes - calculate impact velocity - derive outcome



Windmark, Birnstiel et al. 2012a

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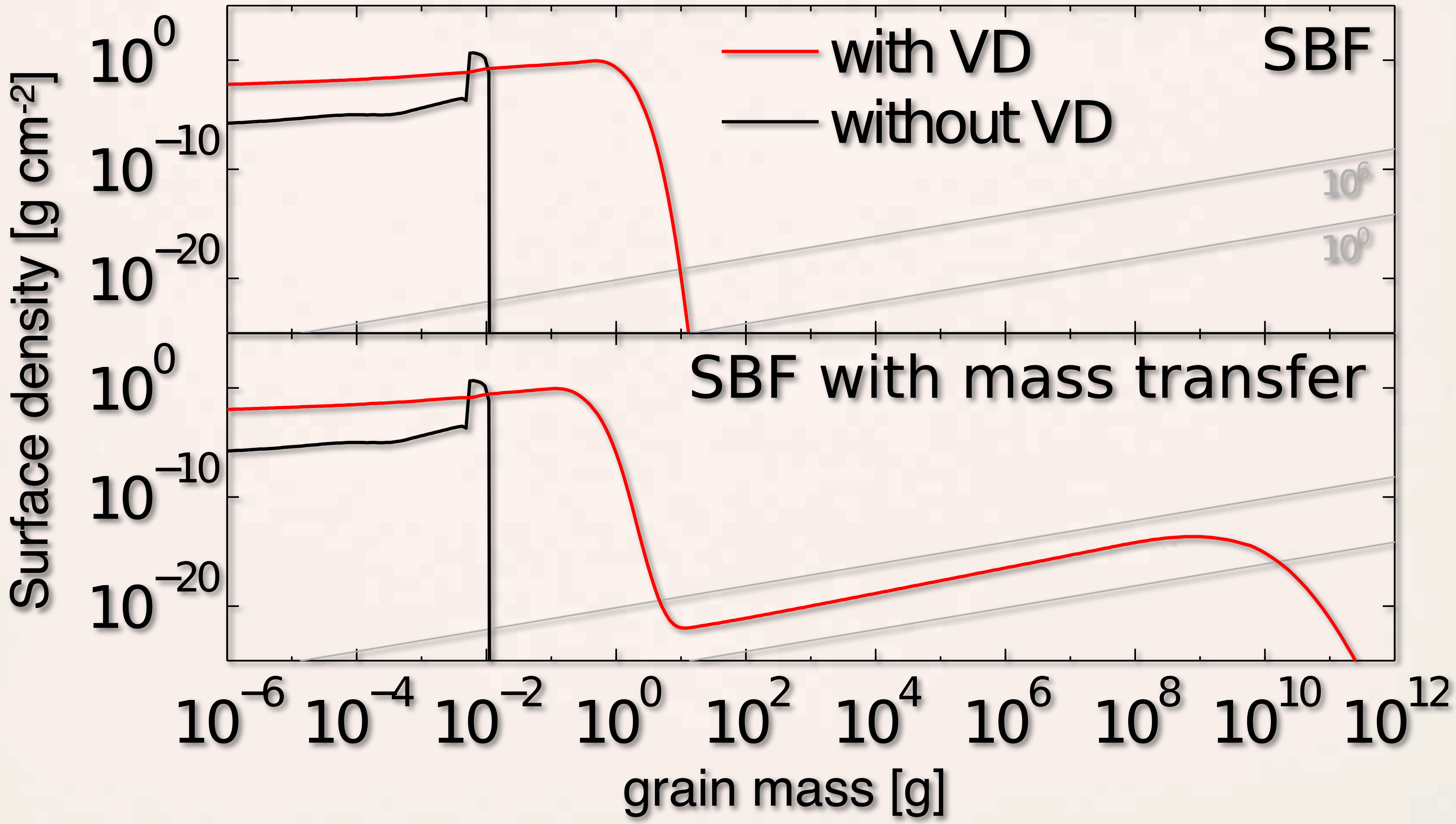


Windmark, Birnstiel et al. 2012b
see also: Garaud et al., 2013

– Summary: Growth –

- Dust is ...
  - ... sticking
  - ... fragmenting
  - ... bouncing
  - ... cratering
  - ... porous
- Several Barriers to Growth
  - ⇒ charging, bouncing, fragmentation, ...
  - ⇒ most can be overcome!

– Global Dust Evolution –

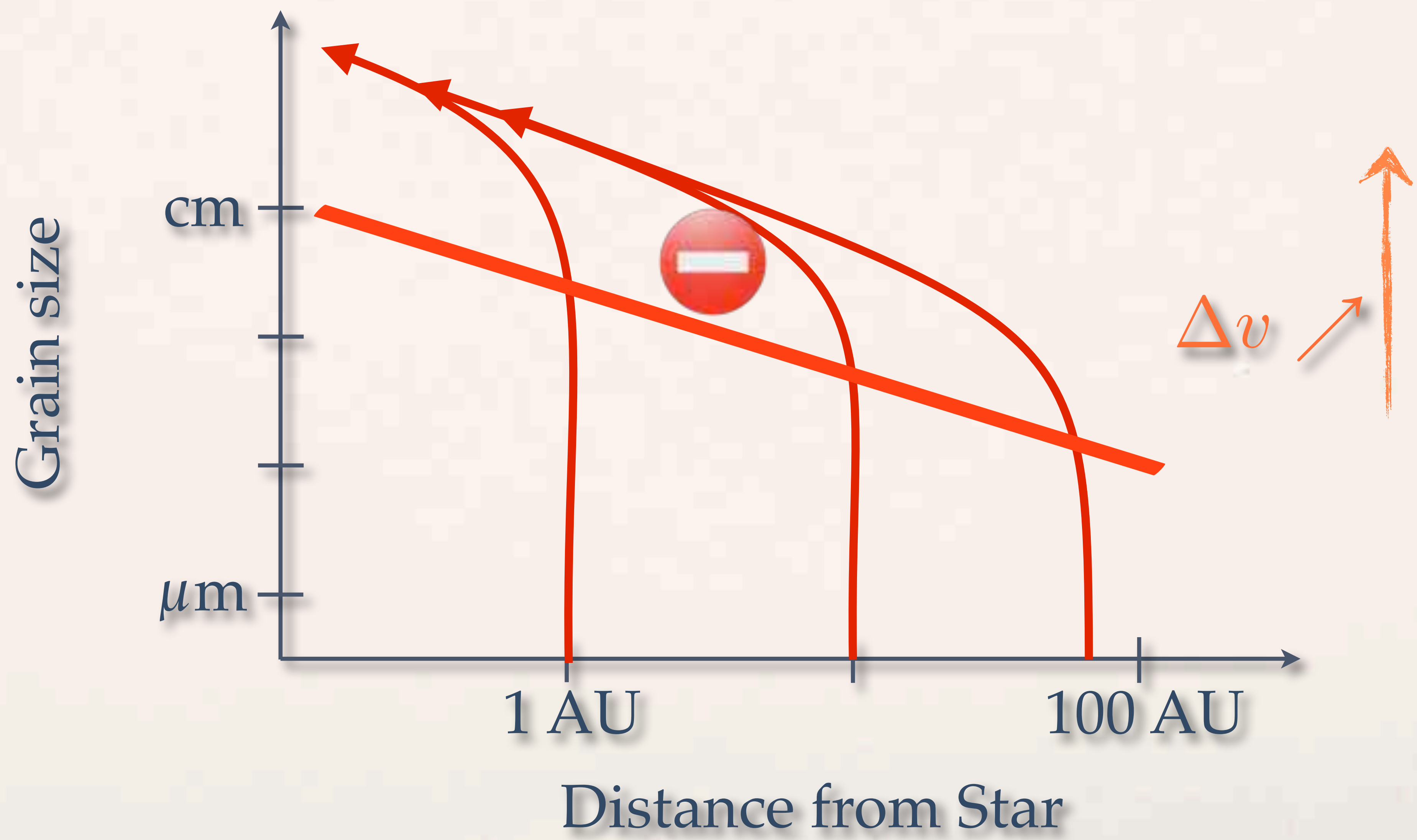
I. Grain Sizes and Surface Densities

– Rules of Thumb –

- Rule 1: the larger the grain, ...
  a) ... the larger its *inward drift velocity*
  b) ... the larger the *collision velocity*
- Rule 2: $\tau_{\rm grow} \simeq \dfrac{1}{\epsilon\Omega}$
- Rule 3: particles drift to higher pressure

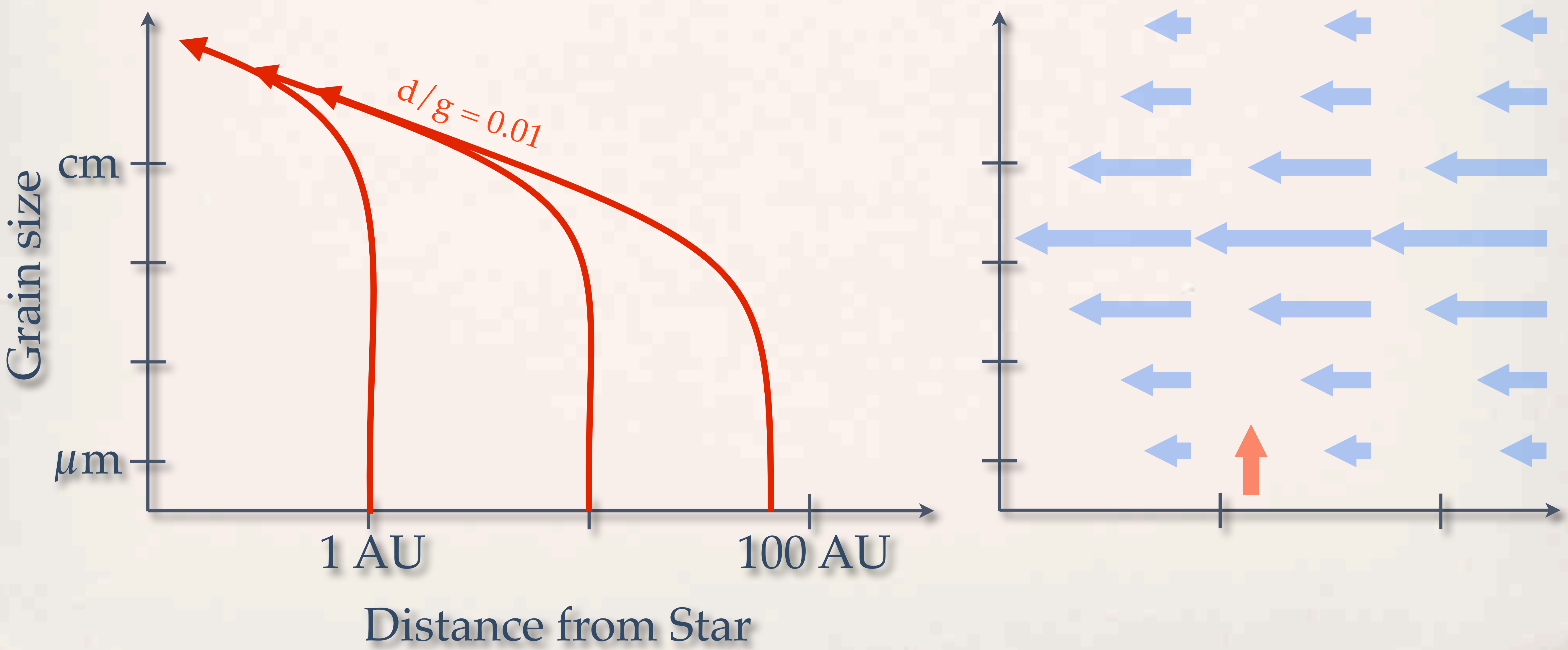
– Dust Evolution in a Nutshell –

- Rule 1: the larger the grain, ...
  - ... the larger its *inward drift velocity*
  - ... the larger the *turbulent collision velocity*



– Dust Evolution in a Nutshell –

- Rule 2: lower dust-to-gas ratio = slower growth



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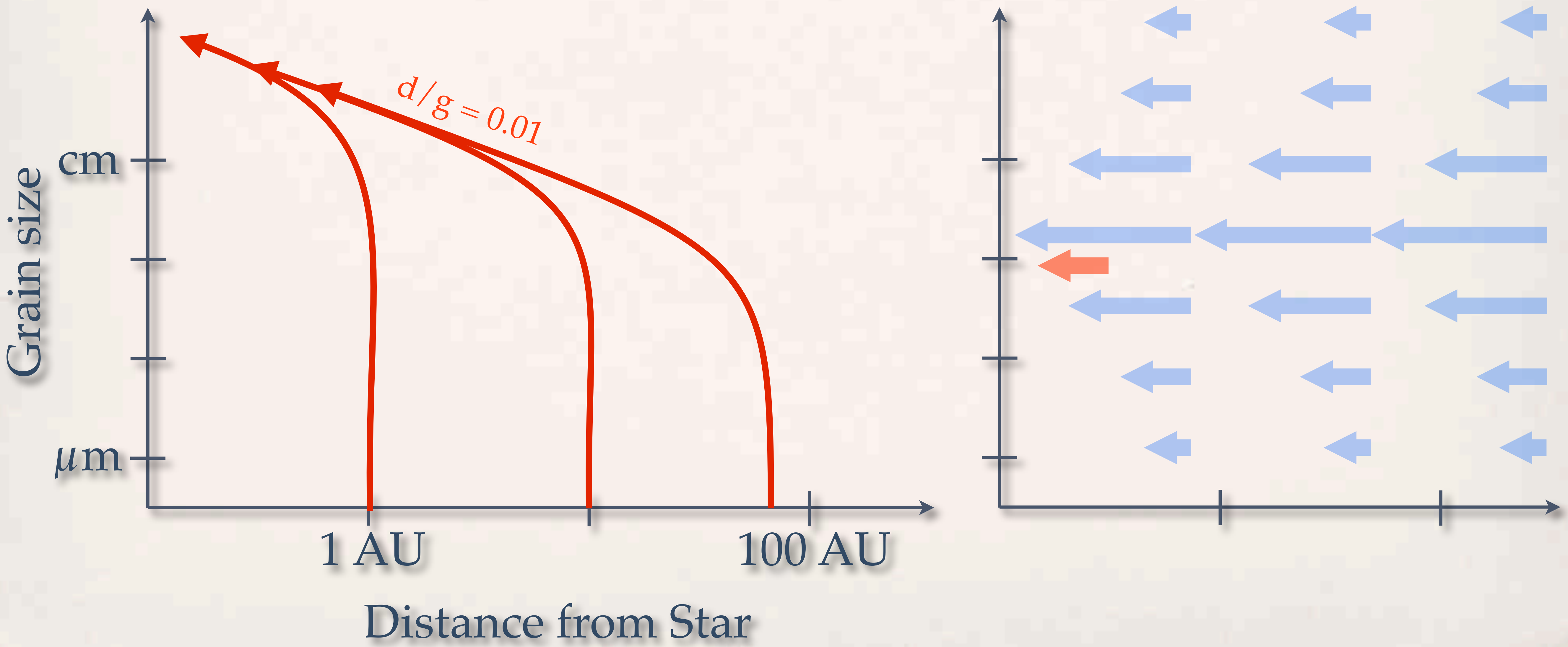

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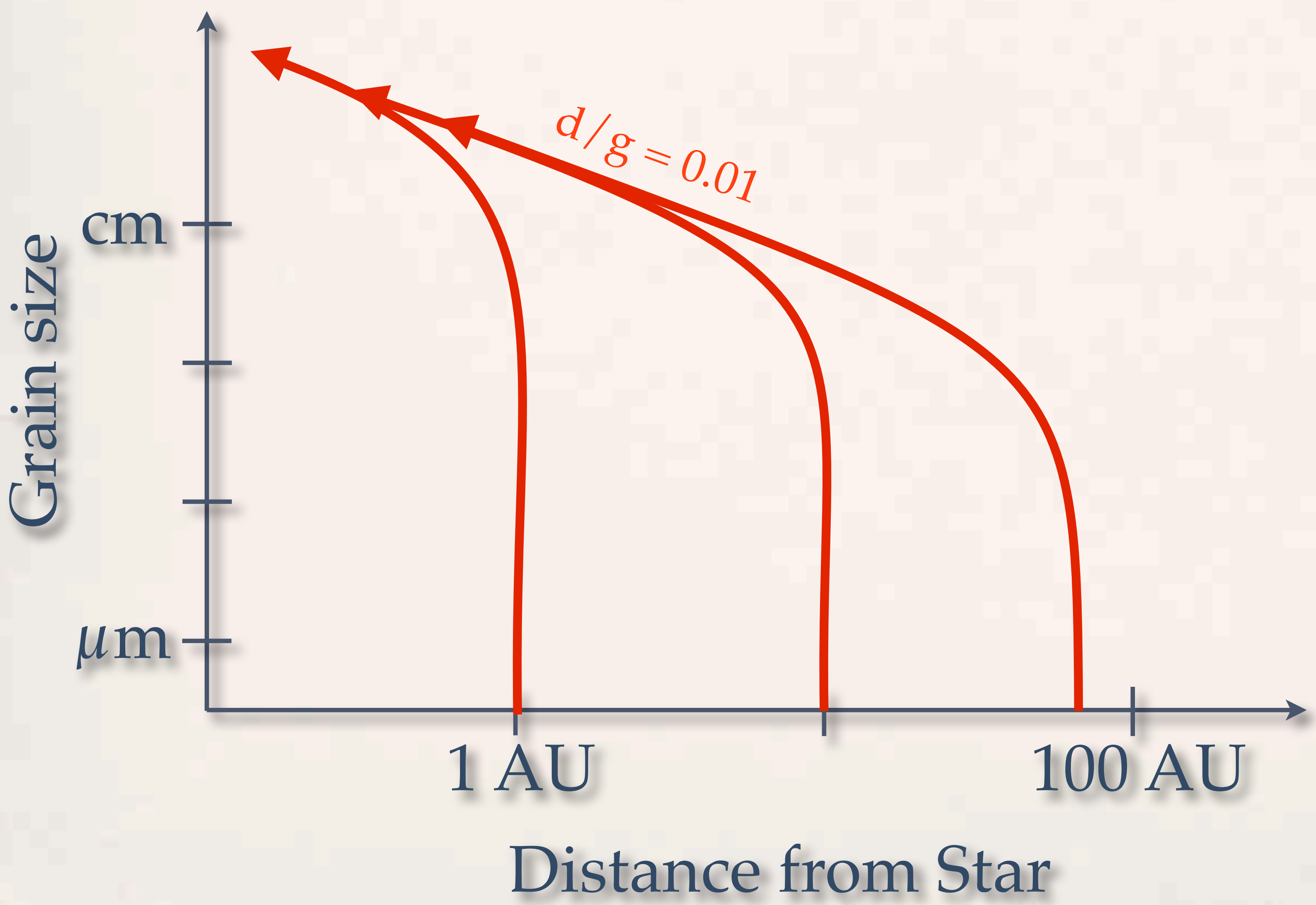

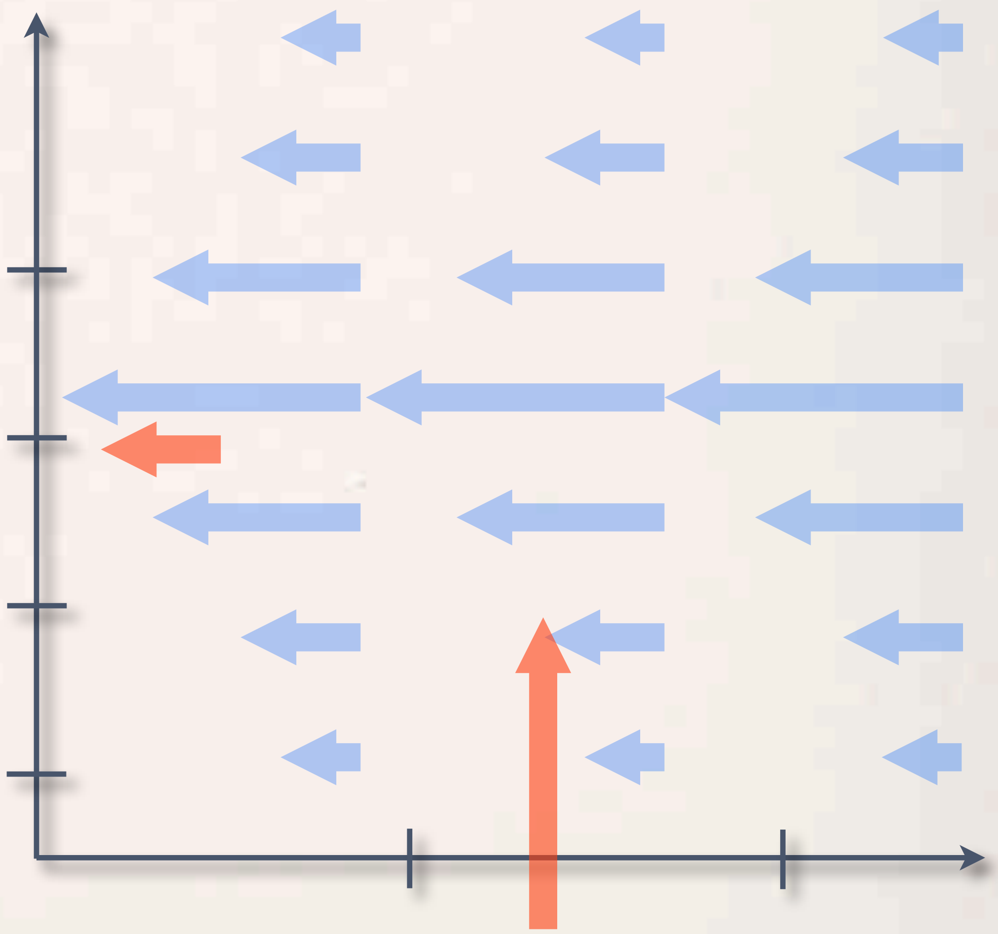

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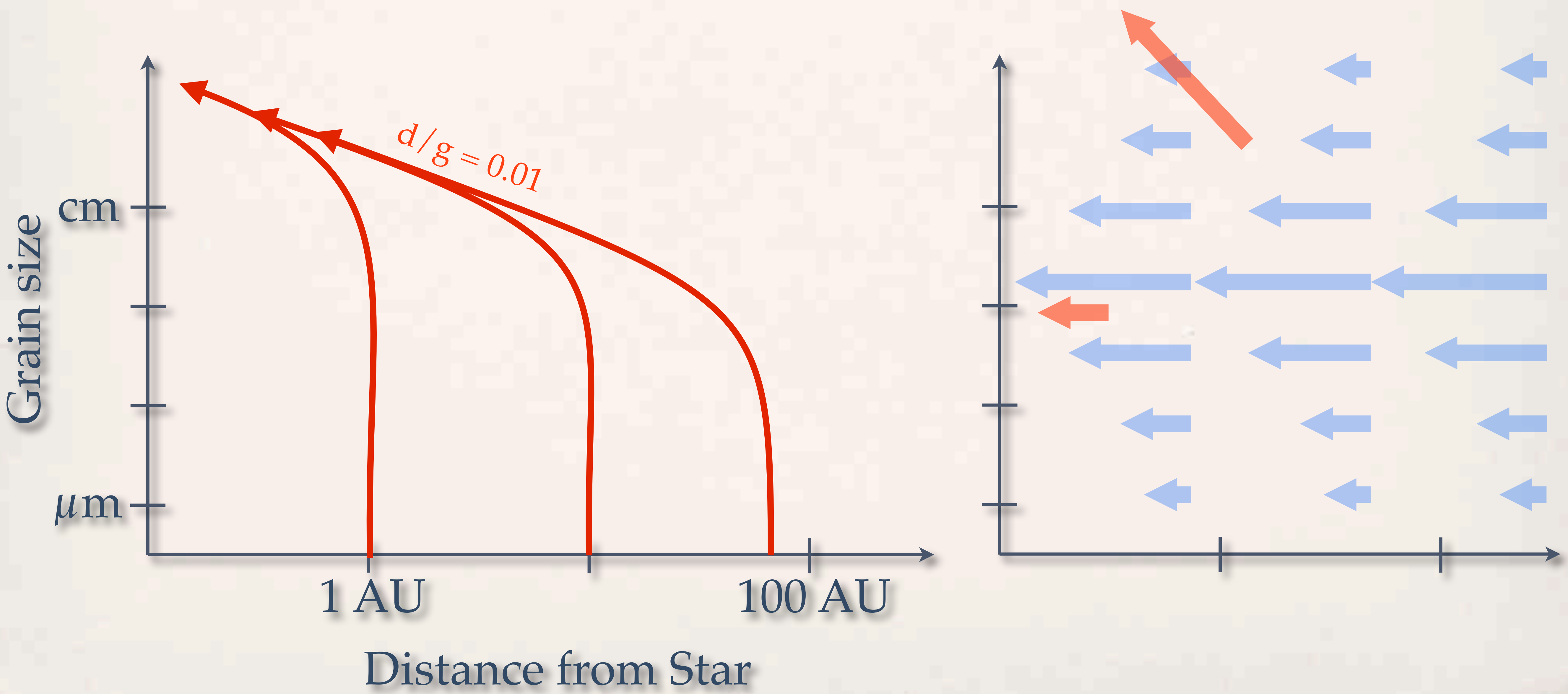

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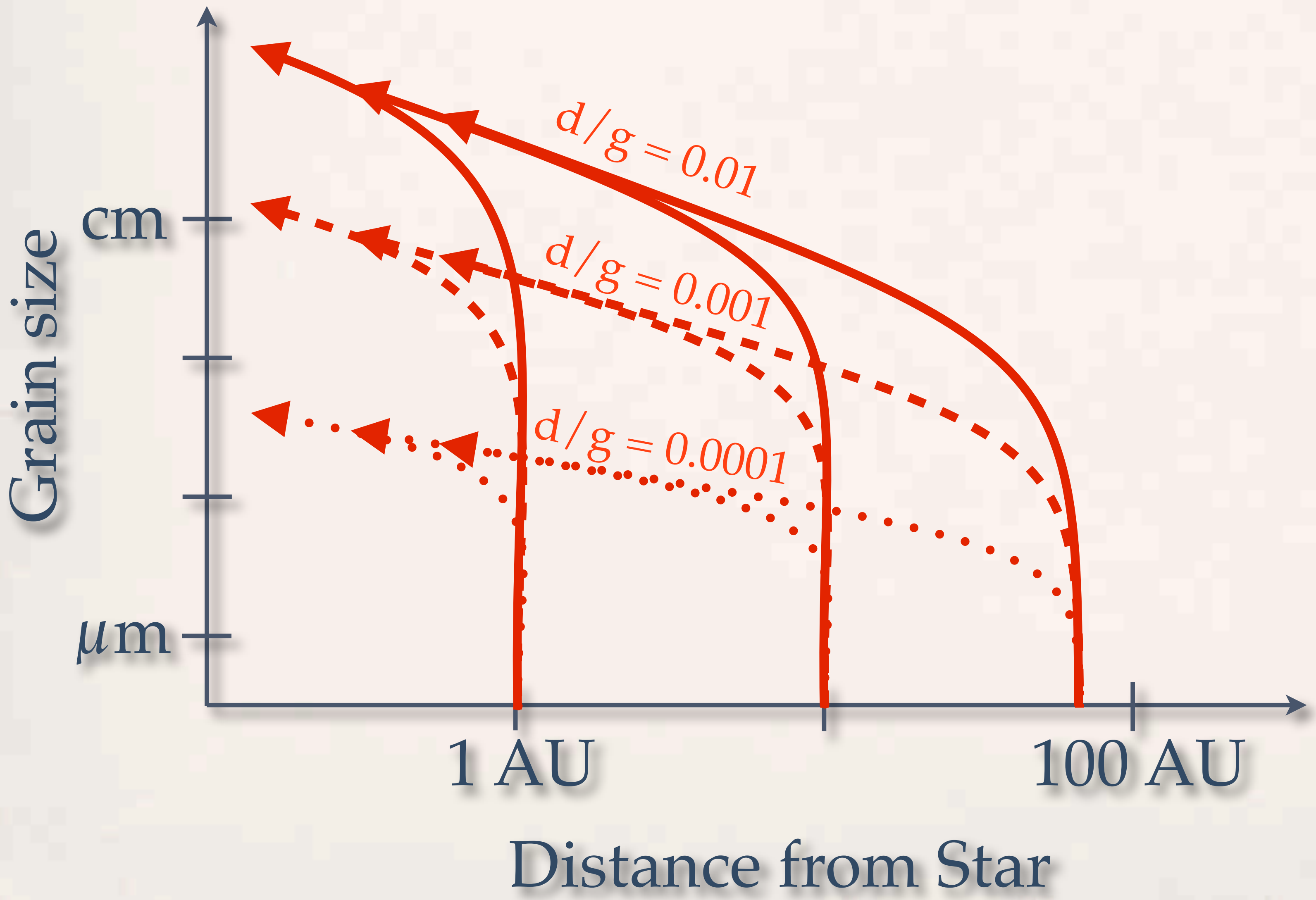
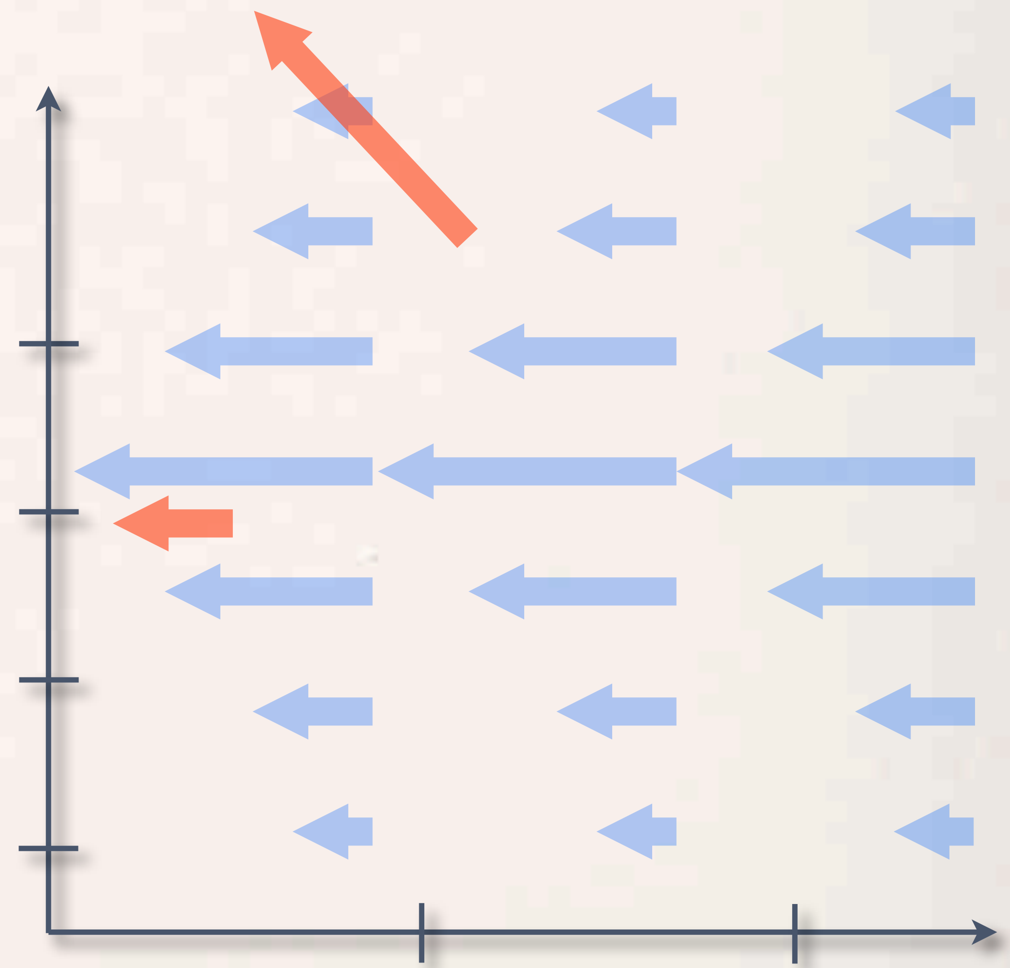




– Size Barriers –

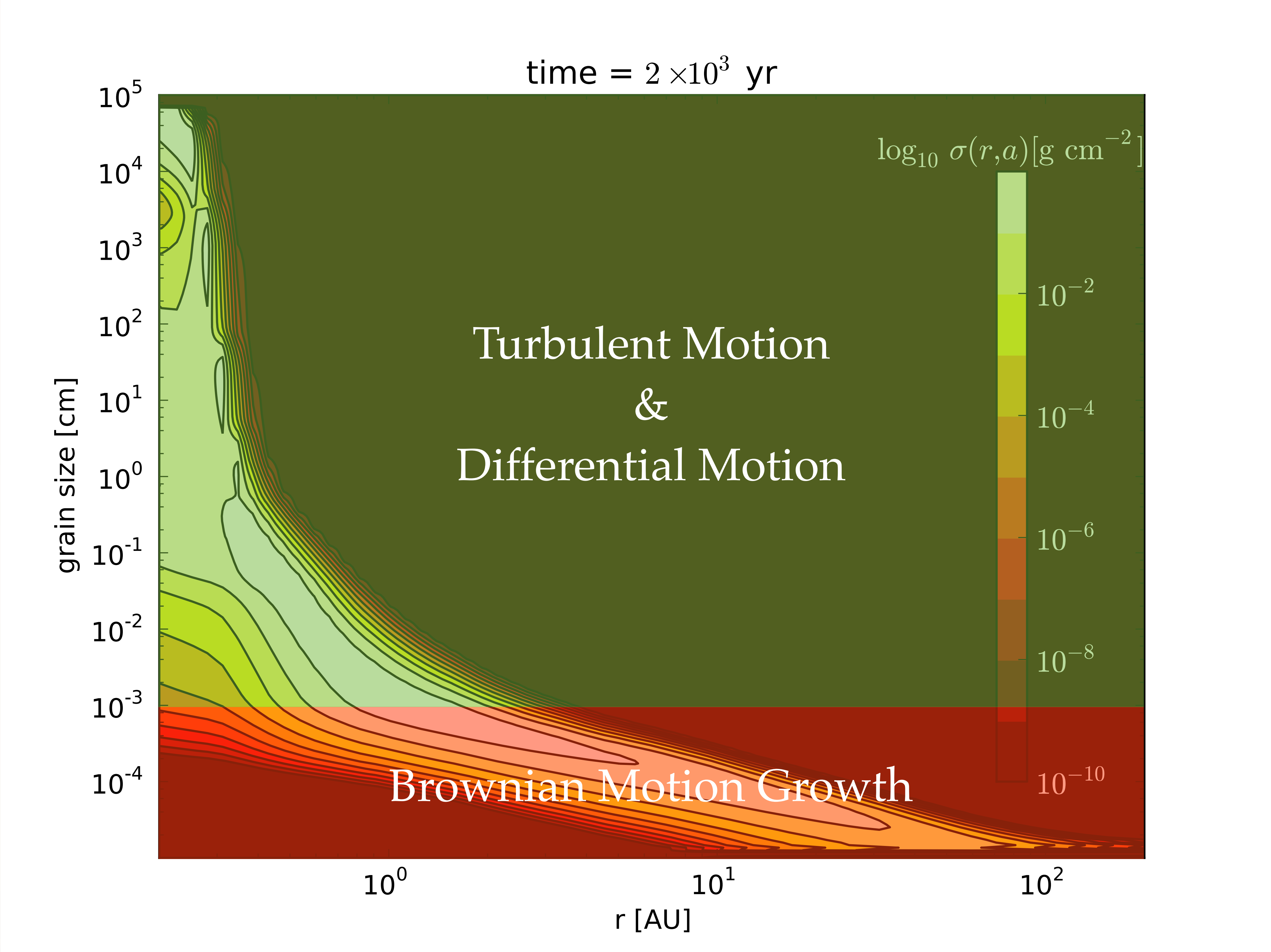
$$a_{\rm frag} \simeq 0.06 \, \frac{\Sigma_{\rm g}}{\rho_{\rm s} \alpha} \, \frac{u_{\rm f}^2}{c_{\rm s}^2}$$

$$a_{\rm drift} \simeq \frac{\Sigma_{\rm dust}}{\pi \, \rho_{\rm s}} \, \frac{V_{\rm k}^2}{c_{\rm s}^2} \, \gamma^{-1}$$

See talks on observations
by Luca Ricci & Laura Pérez

e.g., Birnstiel et al. 2012a

– Just Grain Growth –



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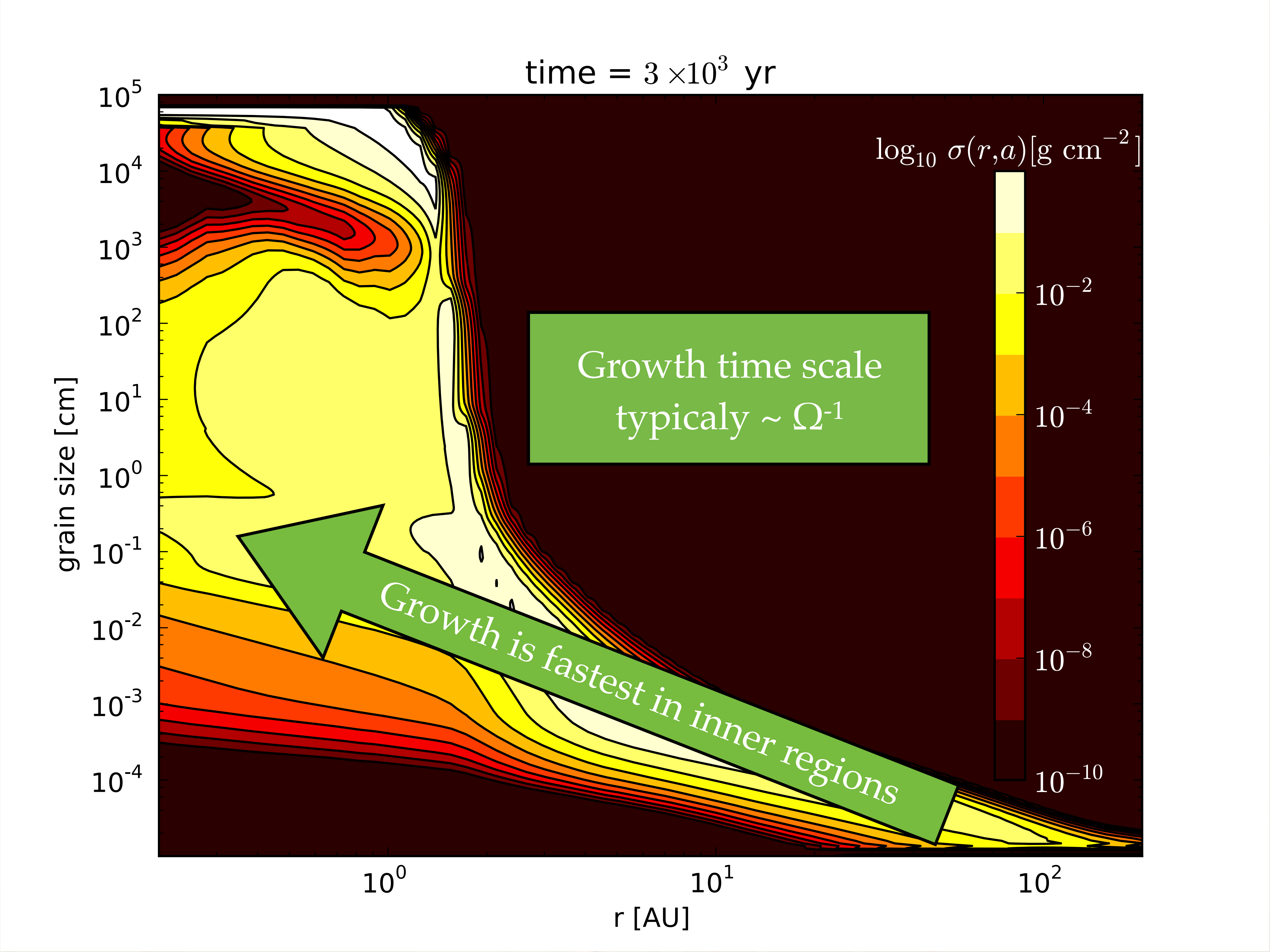

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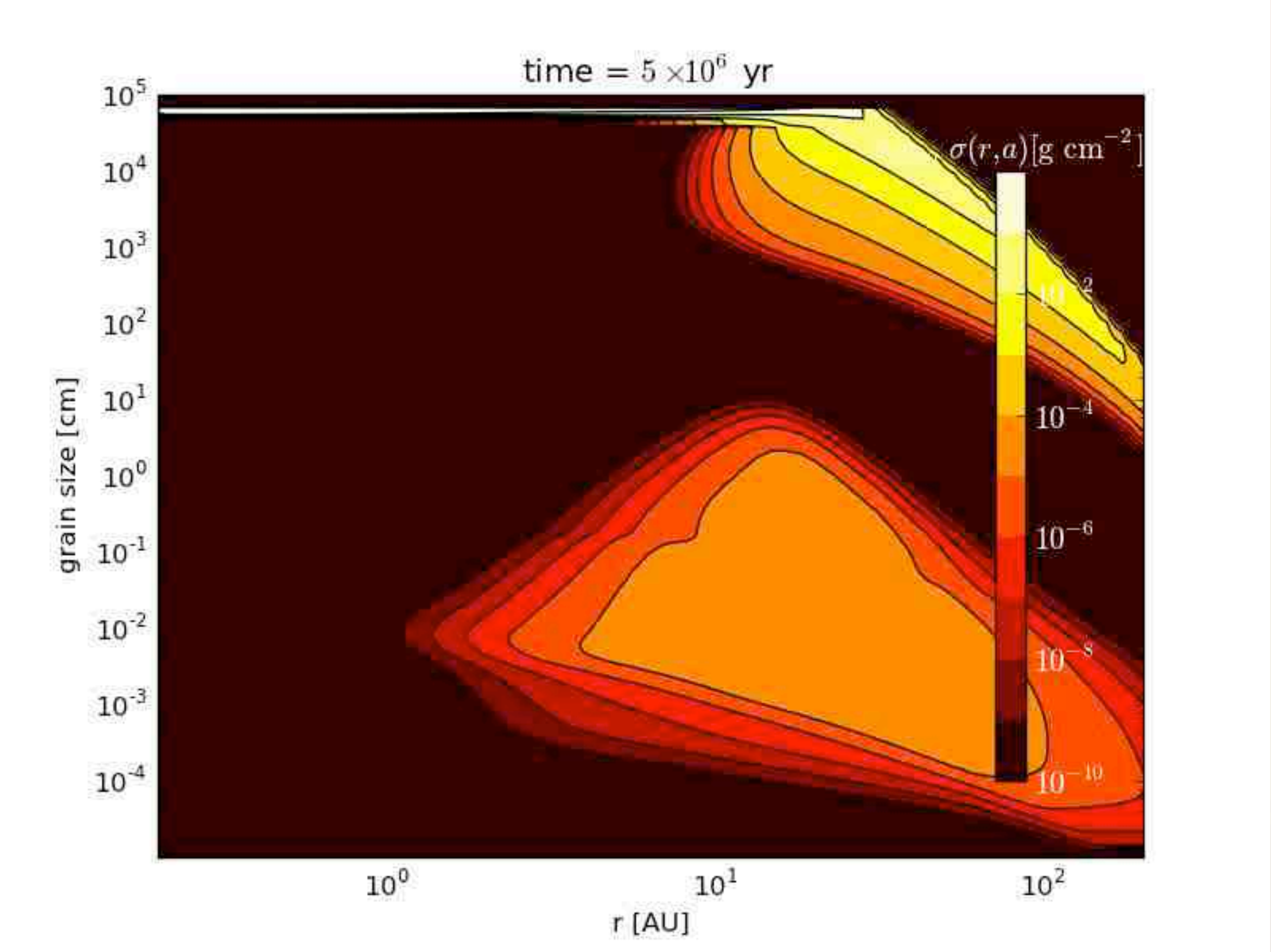
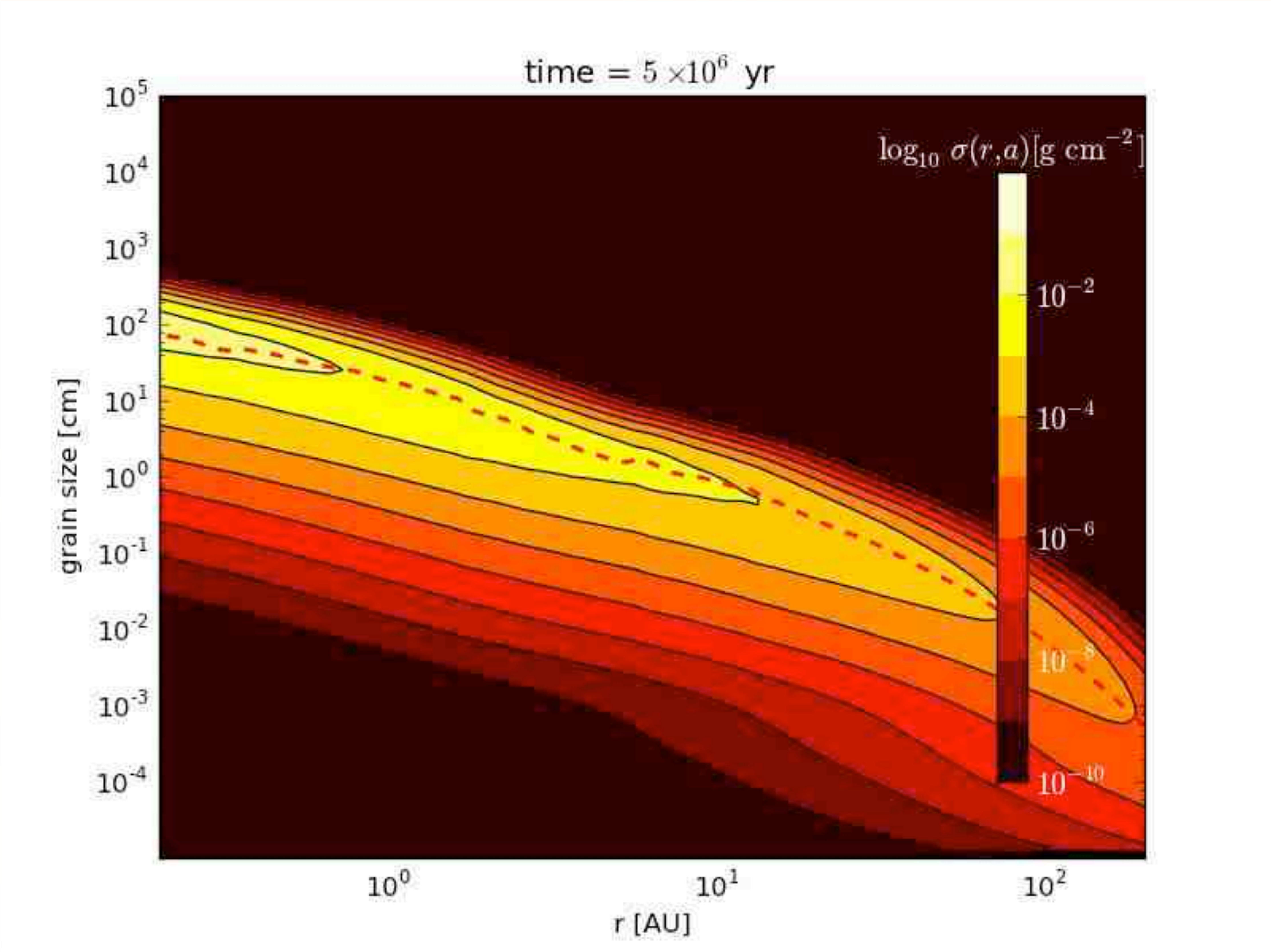
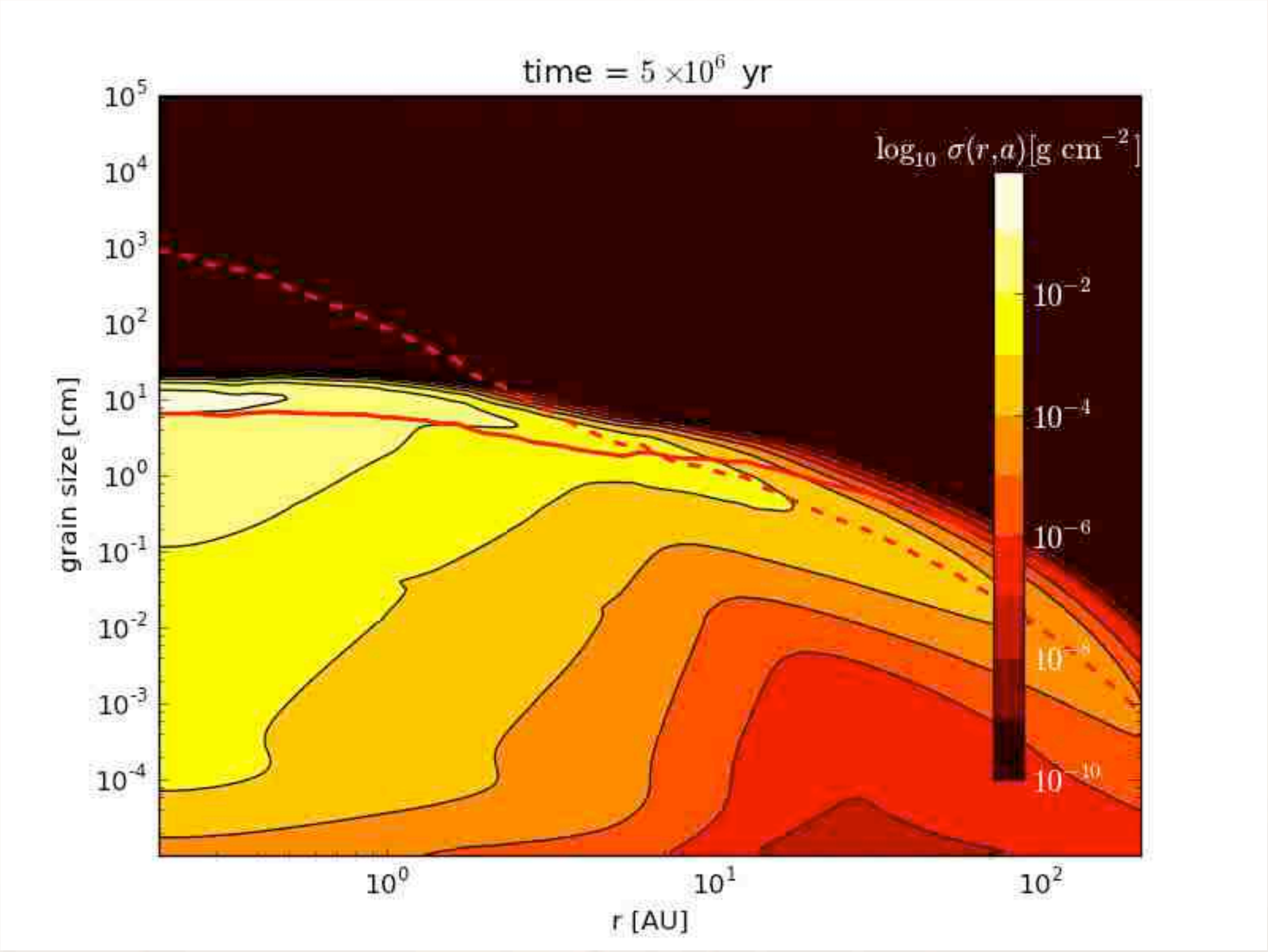


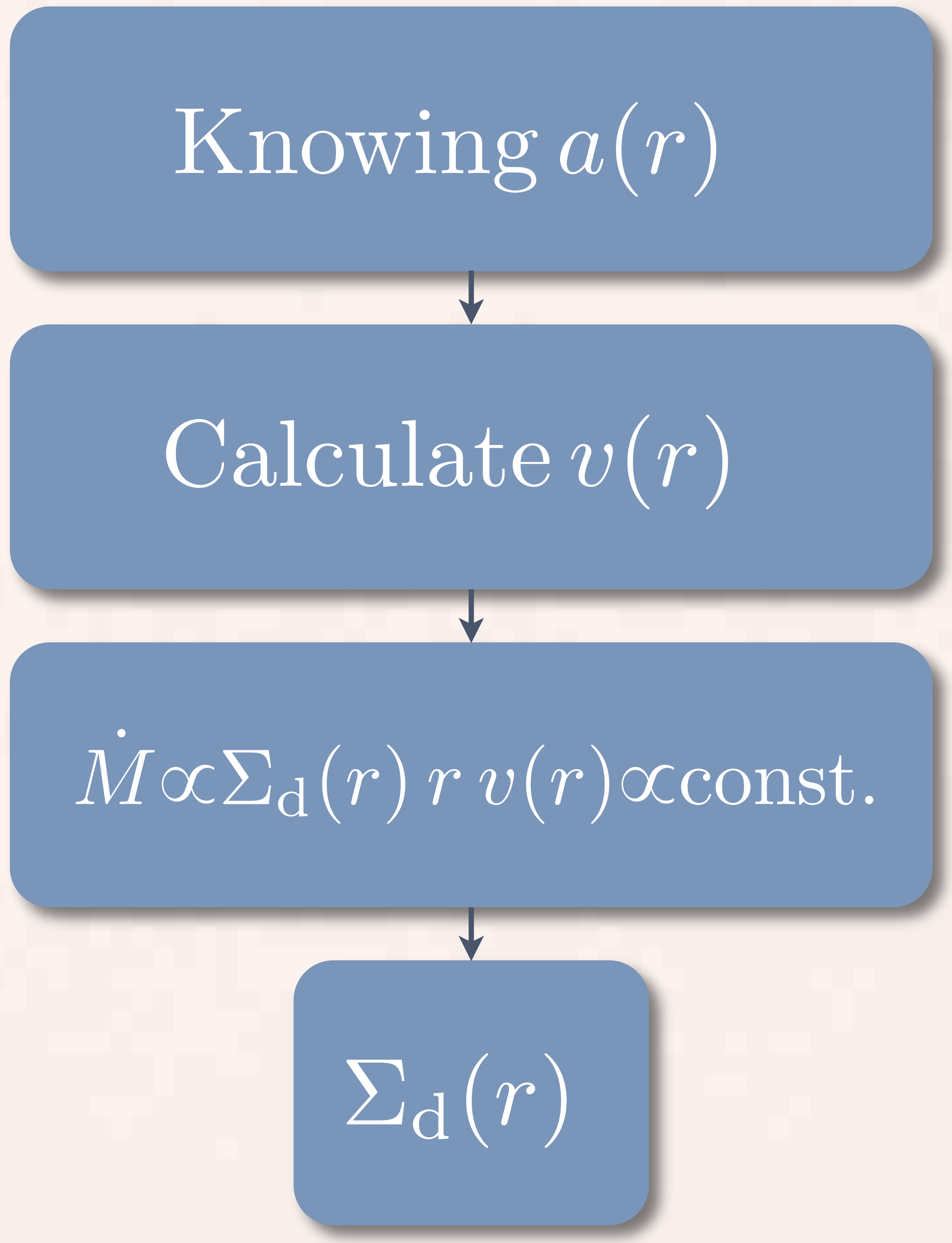
– Grain Growth & Drift –



– Growth & Drift & Fragmentation –



– Surface Density –



– Surface Density –

From basic principles (Birnstiel et al. 2012):

$$\Sigma_{\mathrm{drift}} \propto \sqrt{\frac{\Sigma_{\mathrm{gas}}}{r^2\,\Omega_{\mathrm{k}}}} \propto r^{-\frac{3}{4}}$$

$$\Sigma_{\mathrm{frag}} \propto \frac{\alpha_{\mathrm{t}}\,\Omega_{\mathrm{k}}}{v_{\mathrm{frag}}^2\,\gamma} \propto r^{-\frac{3}{2}}$$

Note
Not *directly* dependent on the (uncertain) drift rate, the relative importance is what counts!

– Surface Density –

From basic principles (Birnstiel et al. 2012):

$$\Sigma_{\mathrm{drift}} \propto r^{-\frac{3}{4}}$$ ← outer or old disk

$$\Sigma_{\mathrm{frag}} \propto r^{-\frac{3}{2}}$$ ← inner disk: MMSN

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$$\Sigma_{\rm frag} \quad \propto \quad r^{-\frac{3}{2}} \leftarrow \text{inner disk: MMSN}$$

Weidenschilling '77, Hayashi '81: $\boldsymbol{r}^{-1.5}$

Chiang & Laughlin '13: $\boldsymbol{r}^{-1.6}$

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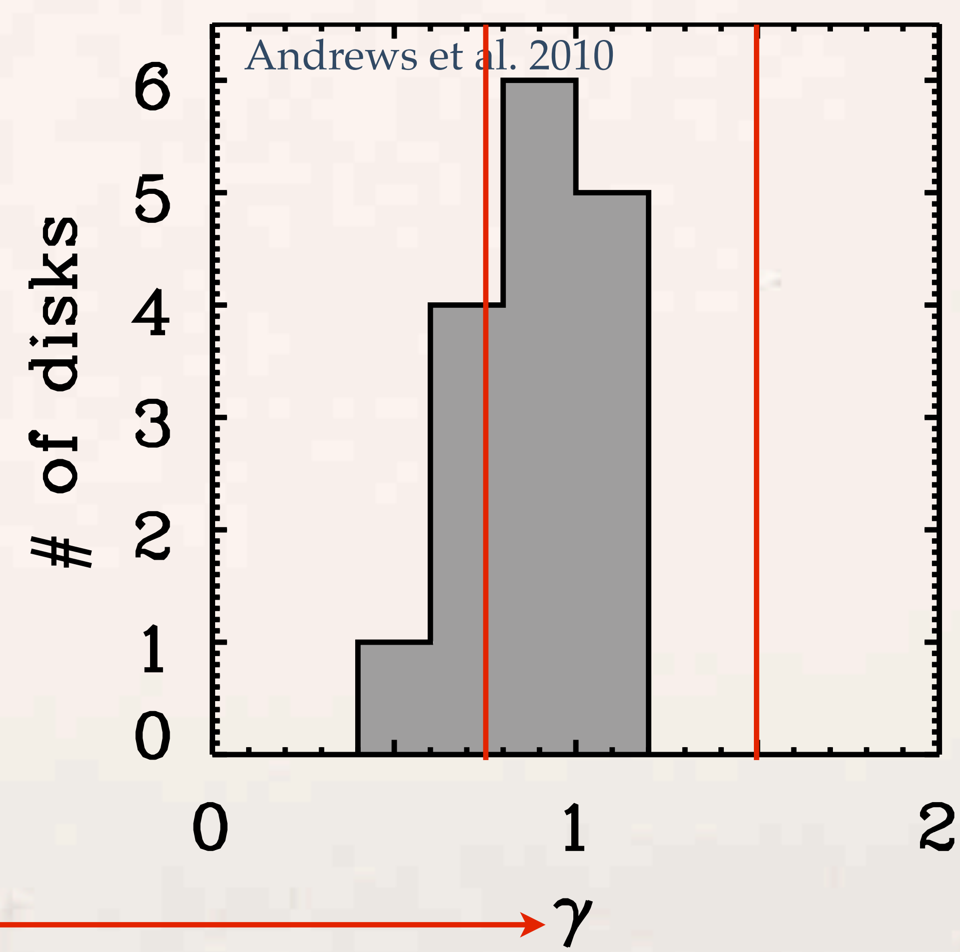
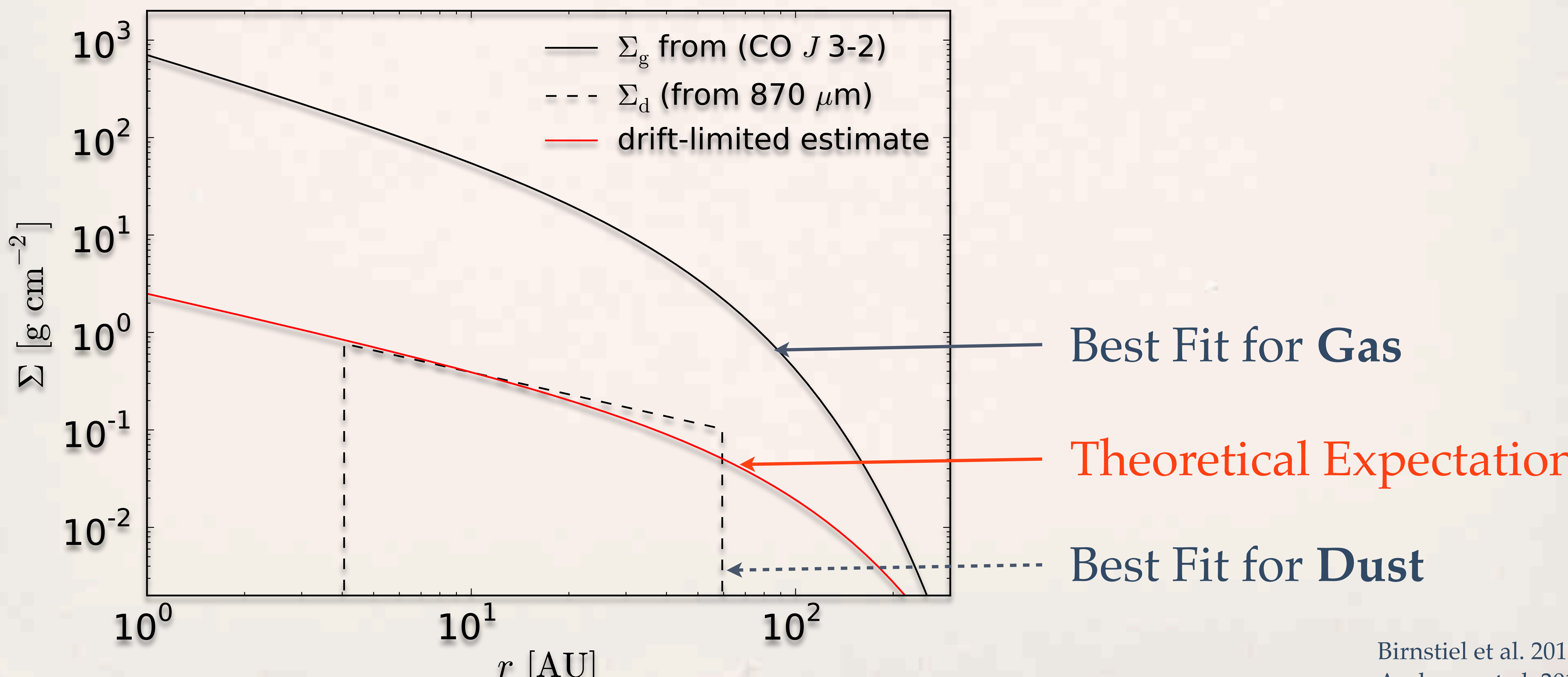


– Surface Density –

$$\Sigma_{\rm drift} \propto \sqrt{\frac{\Sigma_{\rm gas}}{r^2\,\Omega_{\rm k}}} \propto r^{-\frac{3}{4}}$$



Birnstiel et al. 2012
Andrews et al. 2012

– Issue of Timescales –

$$\tau_{\mathrm{drift}} \simeq \frac{r}{v_{\mathrm{d}}} \simeq \frac{1}{\mathrm{St}\,\gamma} \left(\frac{H}{r}\right)^{-2} \text{orbits}$$

Particles drift inward in a few 100 orbits!

Possible Solution

Pressure Bumps

$$u_{\mathrm{r}} = \frac{1}{\mathrm{St} + \mathrm{St}^{-1}} \frac{c_{\mathrm{s}}^2}{u_{\mathrm{k}}} \frac{\mathrm{d}\ln P}{\mathrm{d}\ln r}$$

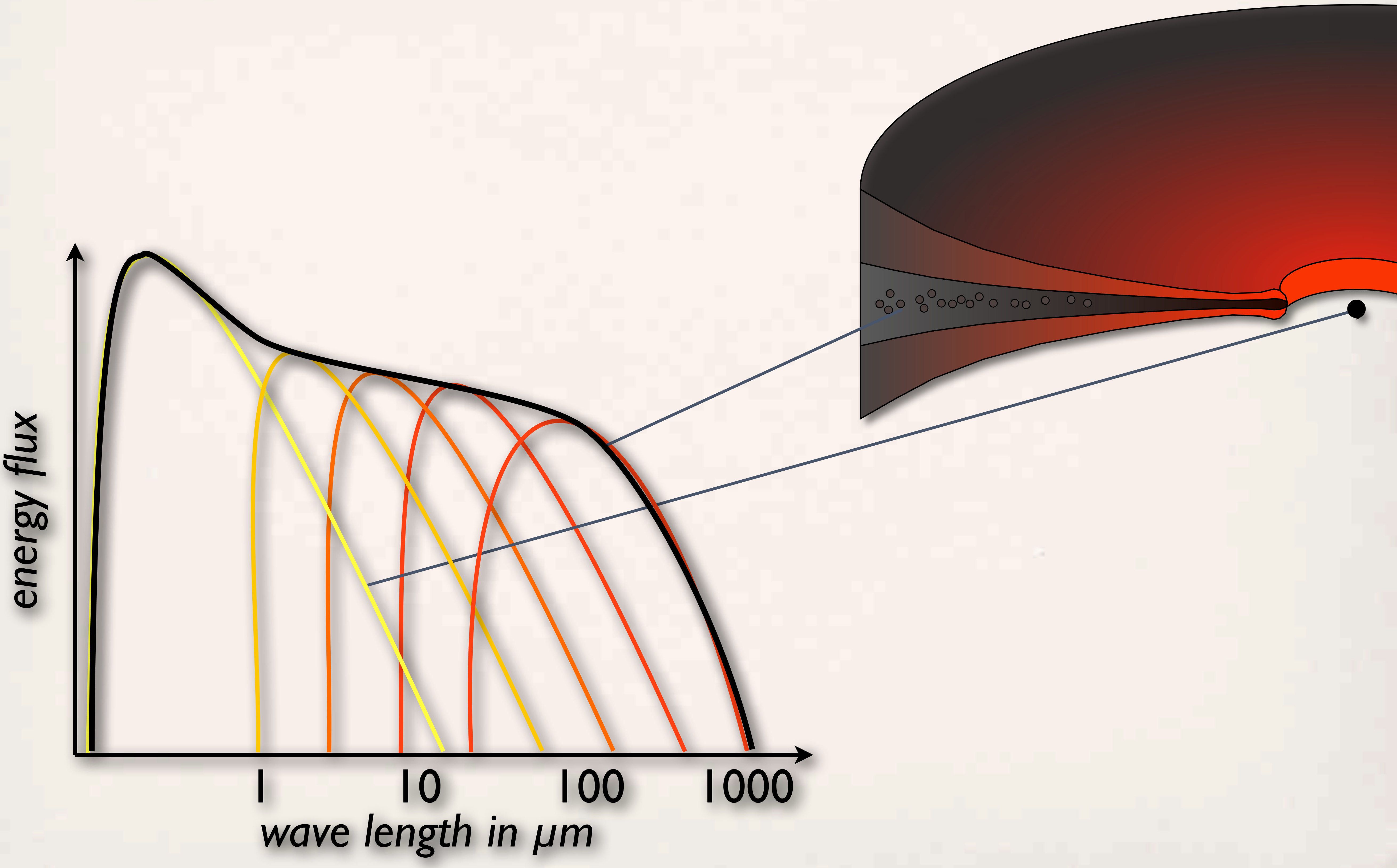
See Talk by Luca Ricci

e.g.
Klahr & Henning 1997
Kretke & Lin 2007
Brauer 2008
...

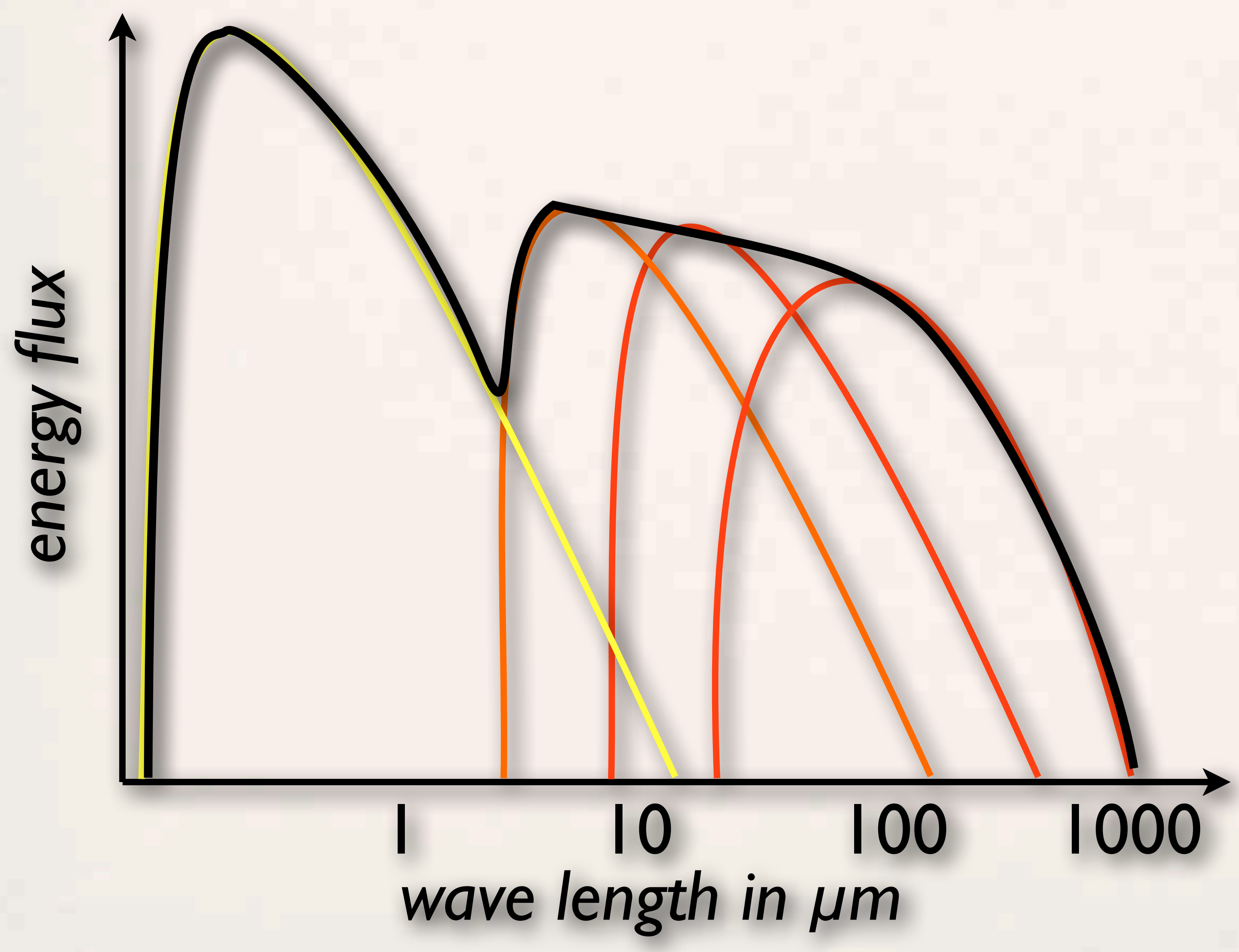
– Global Dust Evolution –

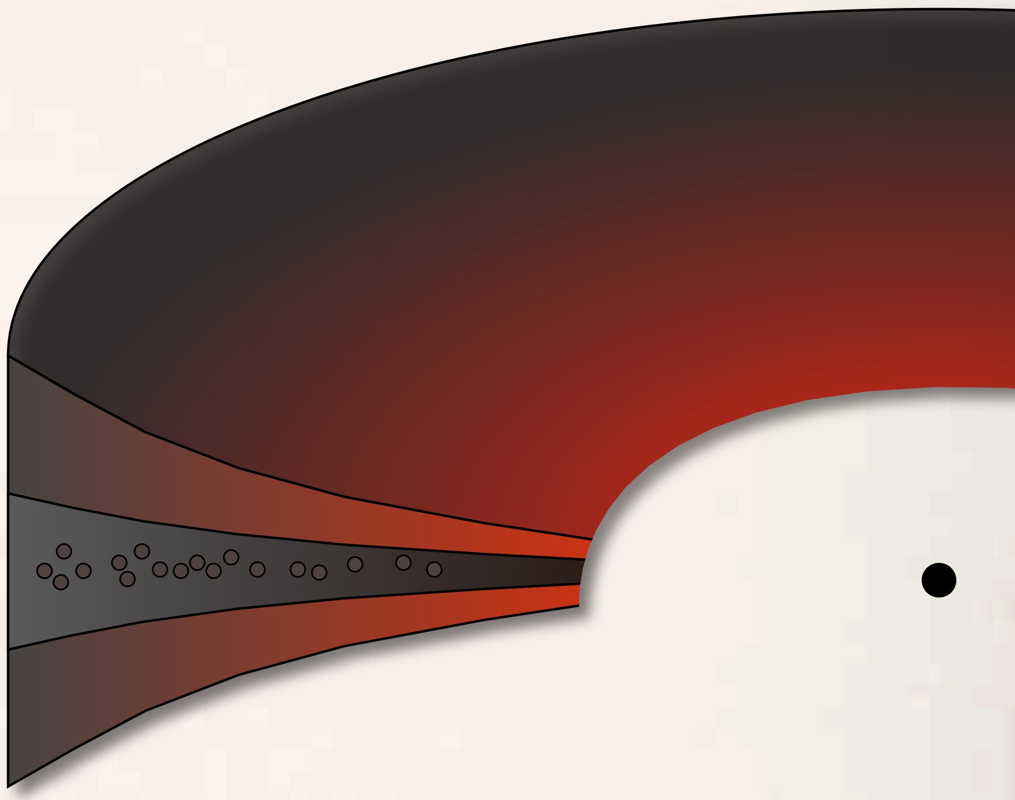
II. Transition Disks

– SED –

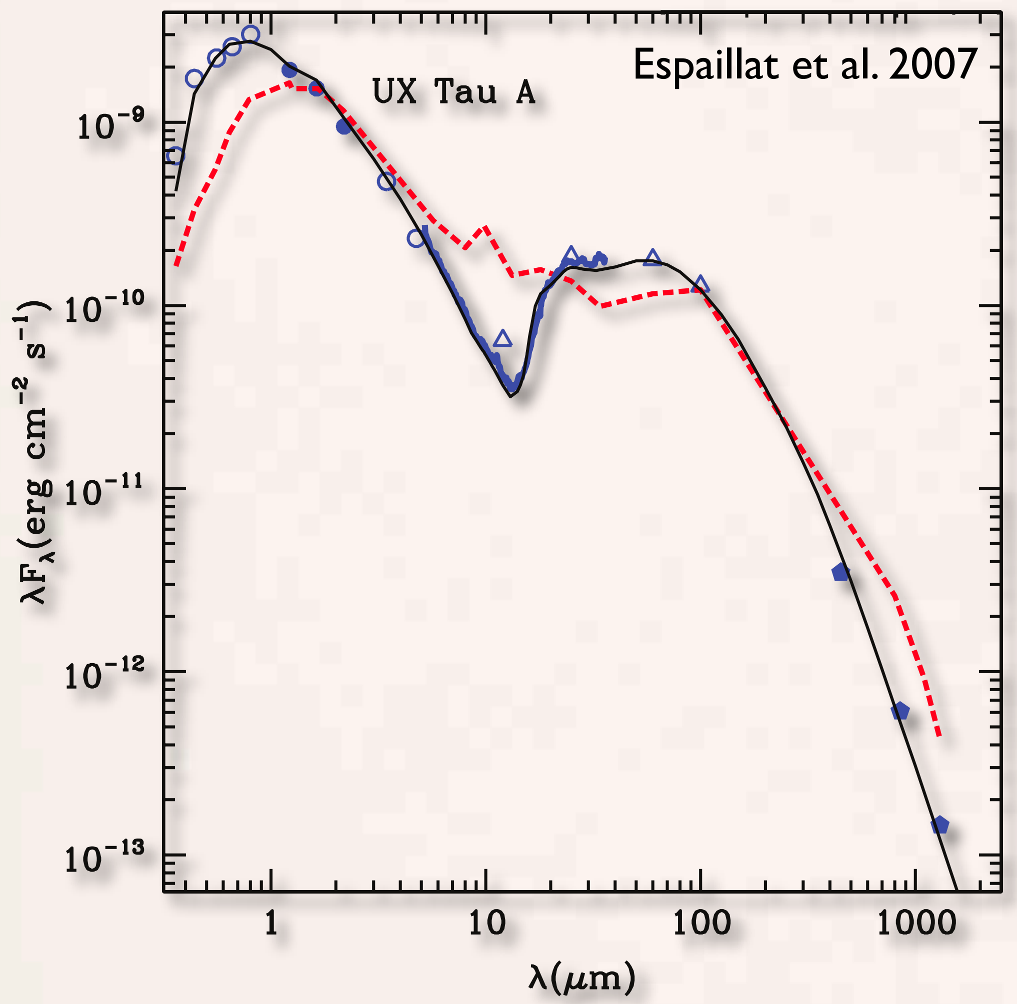


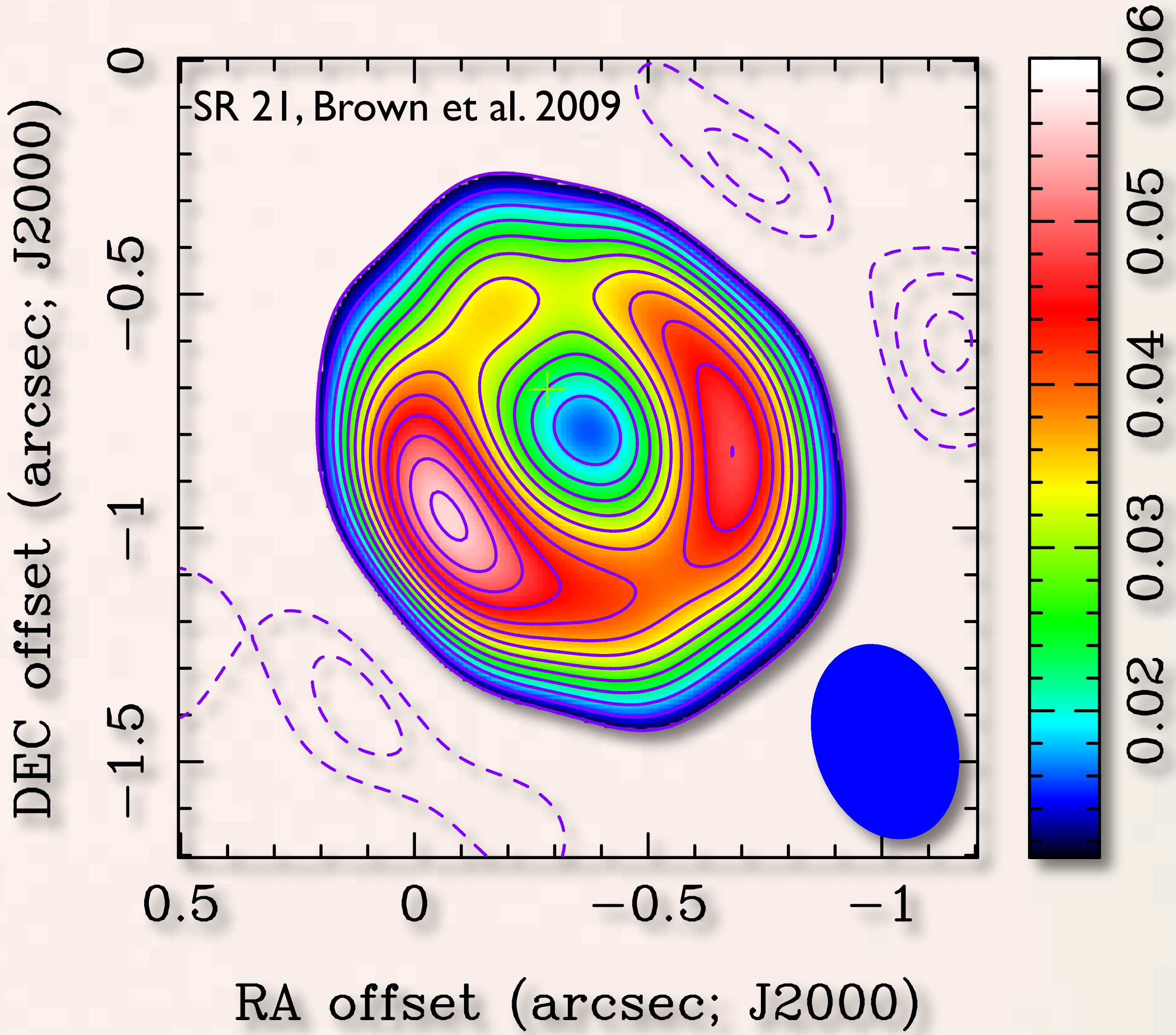
– SED –





– Properties of Transition Disks –

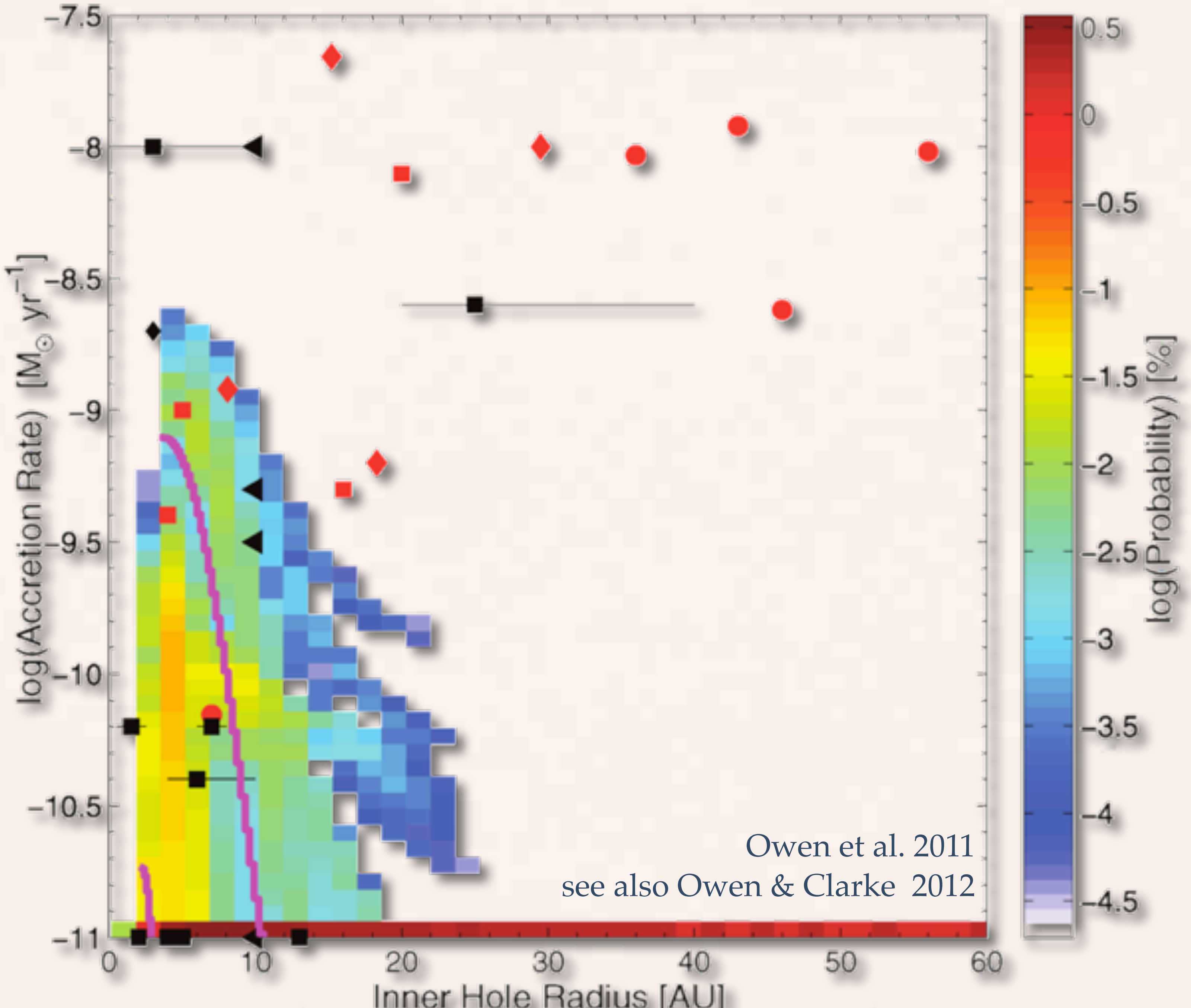




- not all TDs have a TD-like SED
- transition disk fraction*: > 1/3
- obs. median hole size: 35 AU
- wide range of accretion rates

* for mm-bright disks. See Andrews et al. 2011

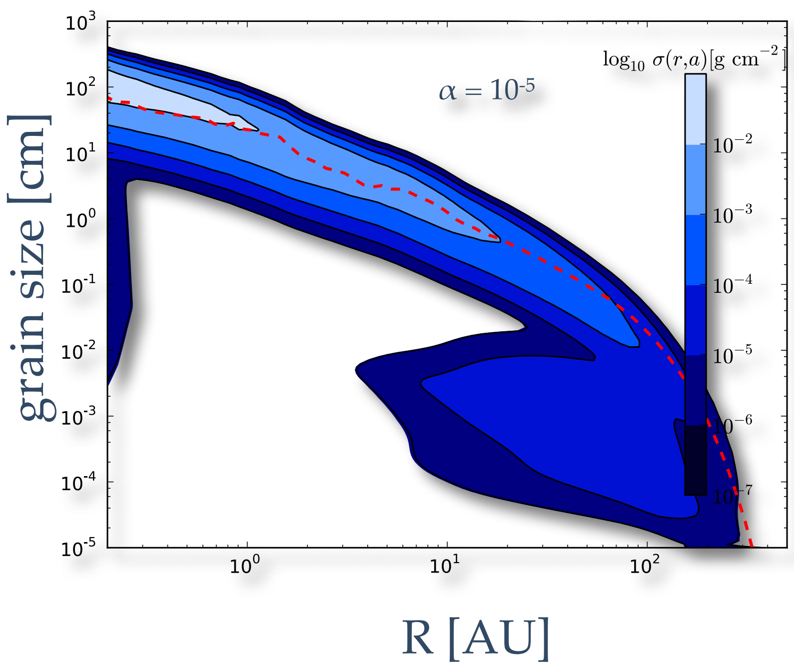
– Photoevaporation –



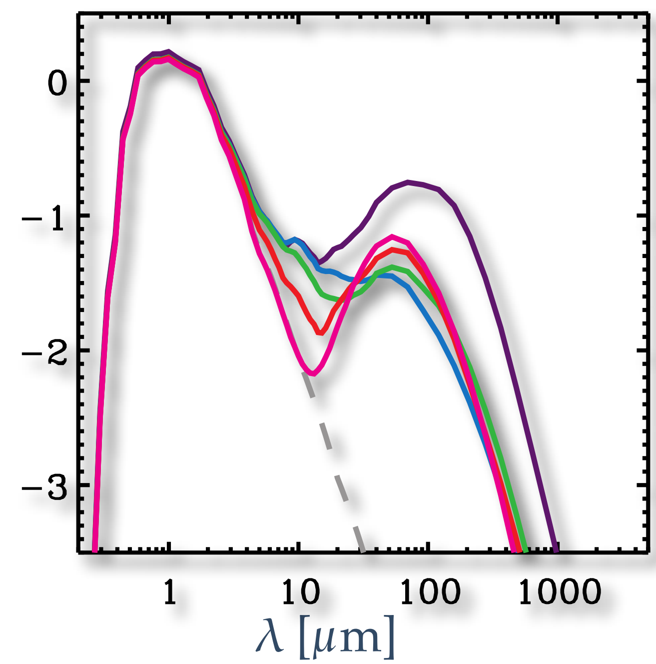
Talk: B. Ercolano
Poster: G. Rosotti

– Grain Growth? –

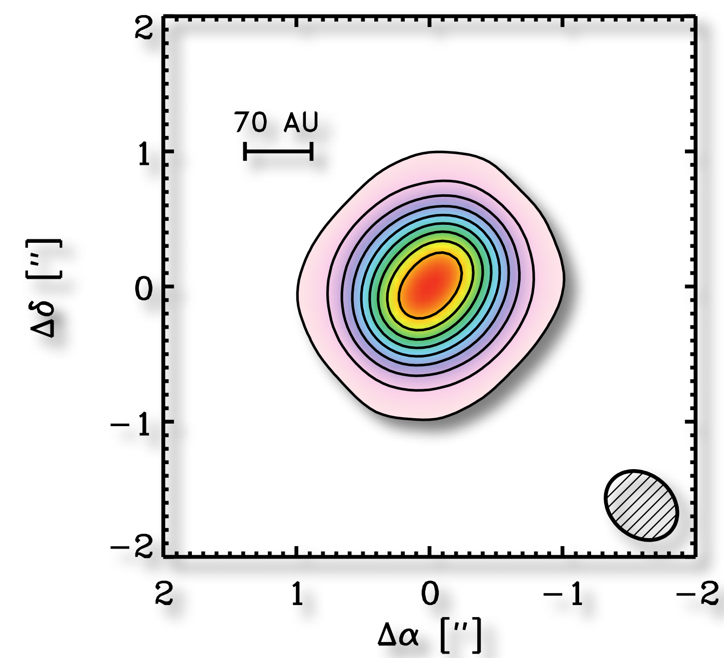
Dust Model



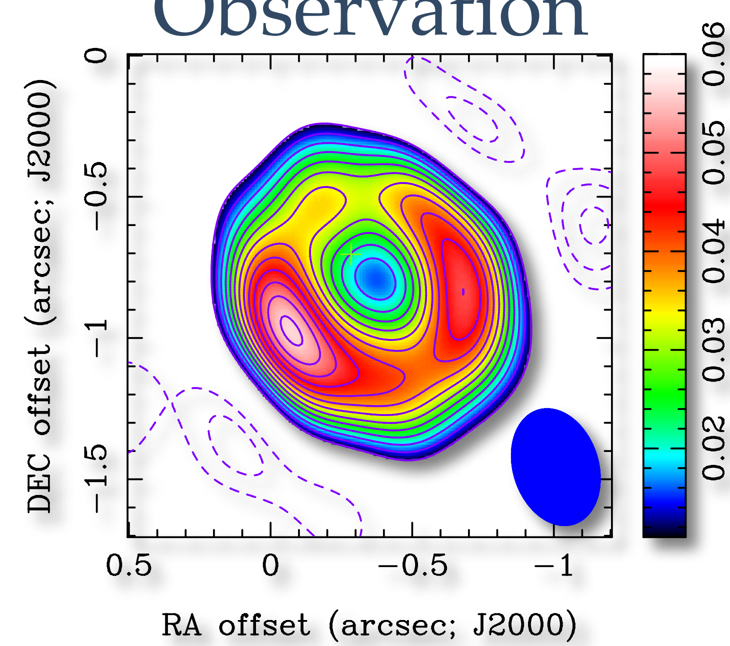
Model SED



Model Image



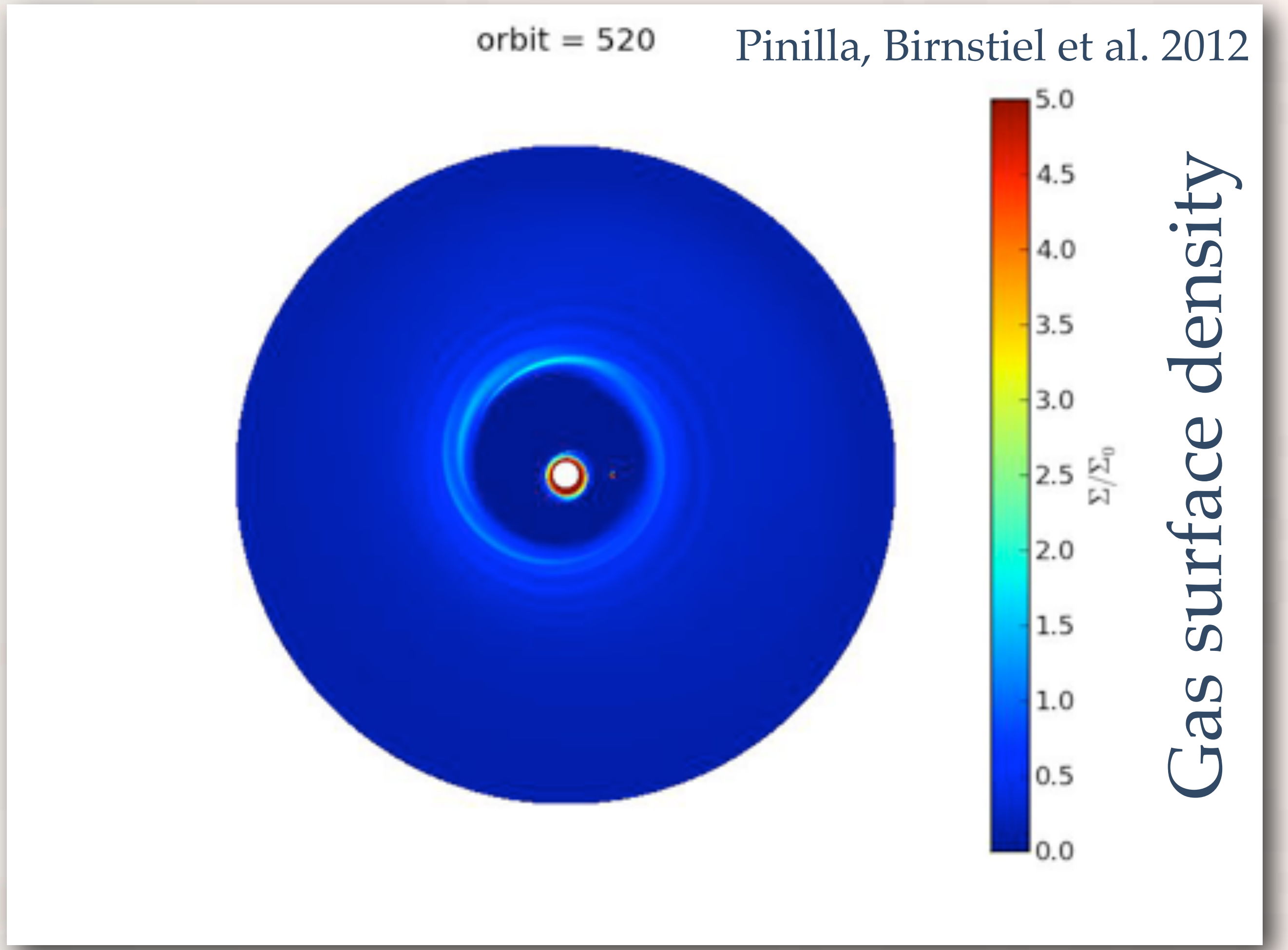
Observation

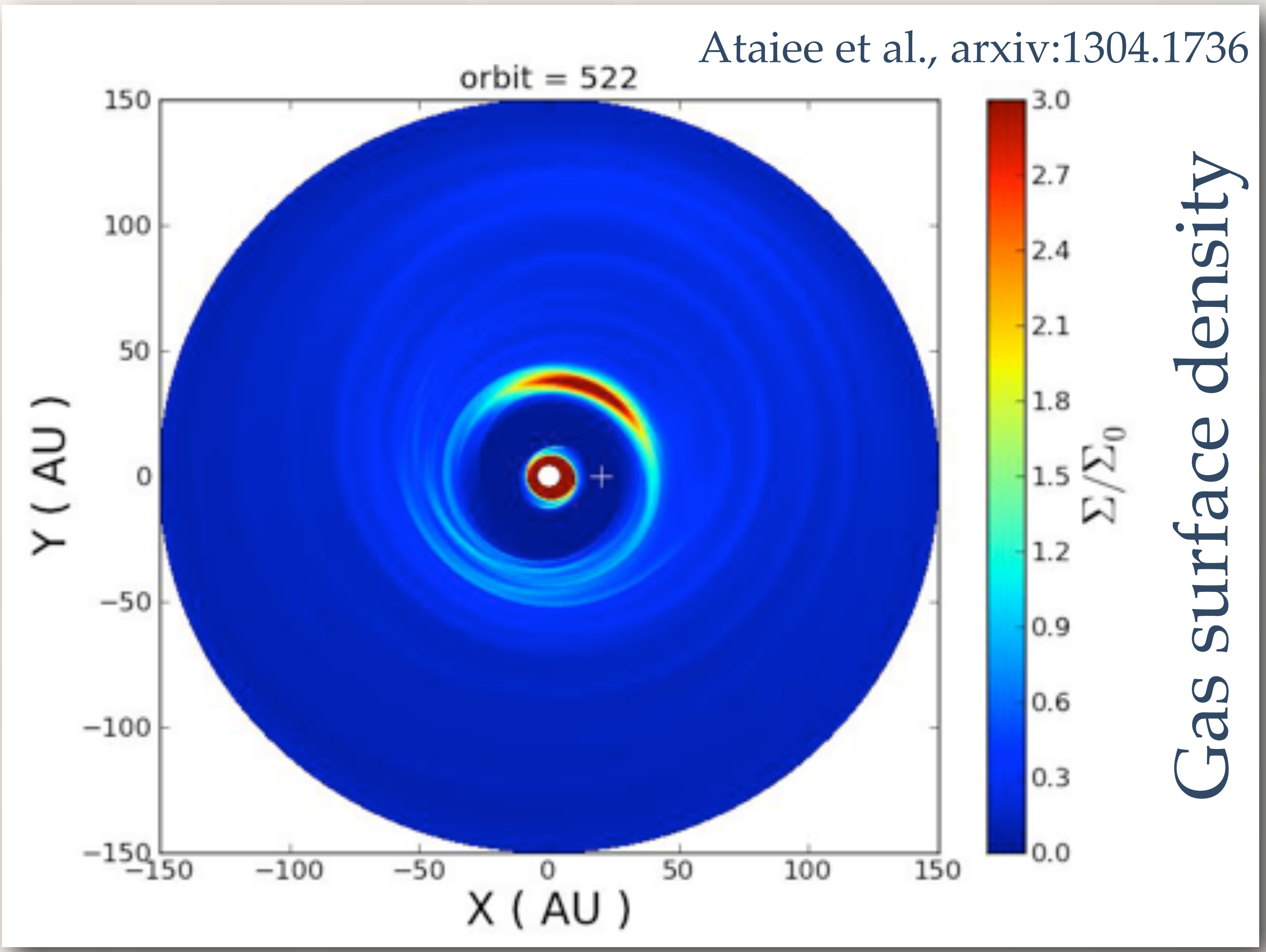


Brown et al. 2009

Birnstiel, Andrews, Ercolano 2012

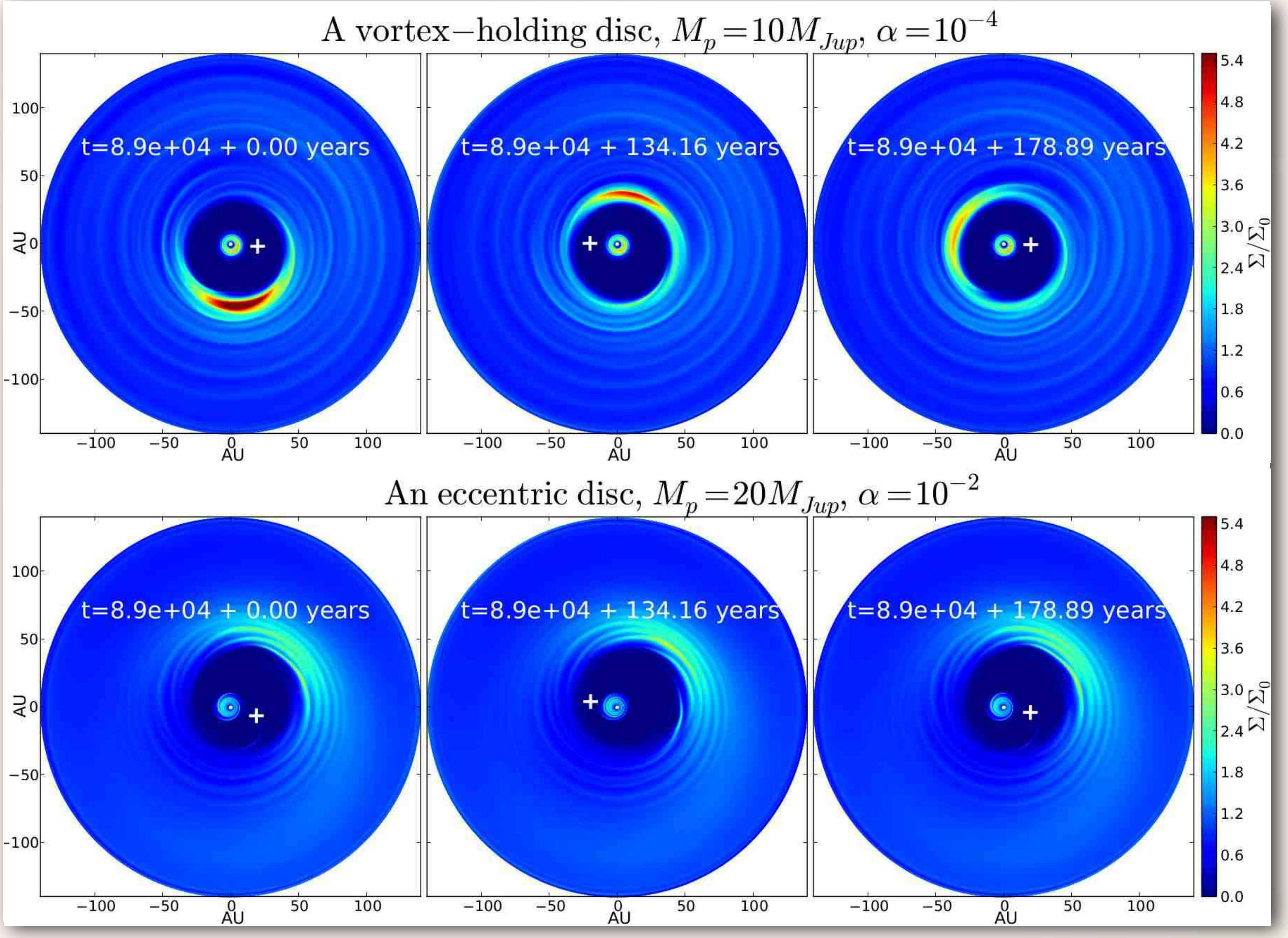
– Planets & Instabilities –





see also:
Goldreich et al.
H. Li et al.,
F. Masset et al.,
A. Crida et al.,
W. Lyra et al.,
...

– Planets & Instabilities –



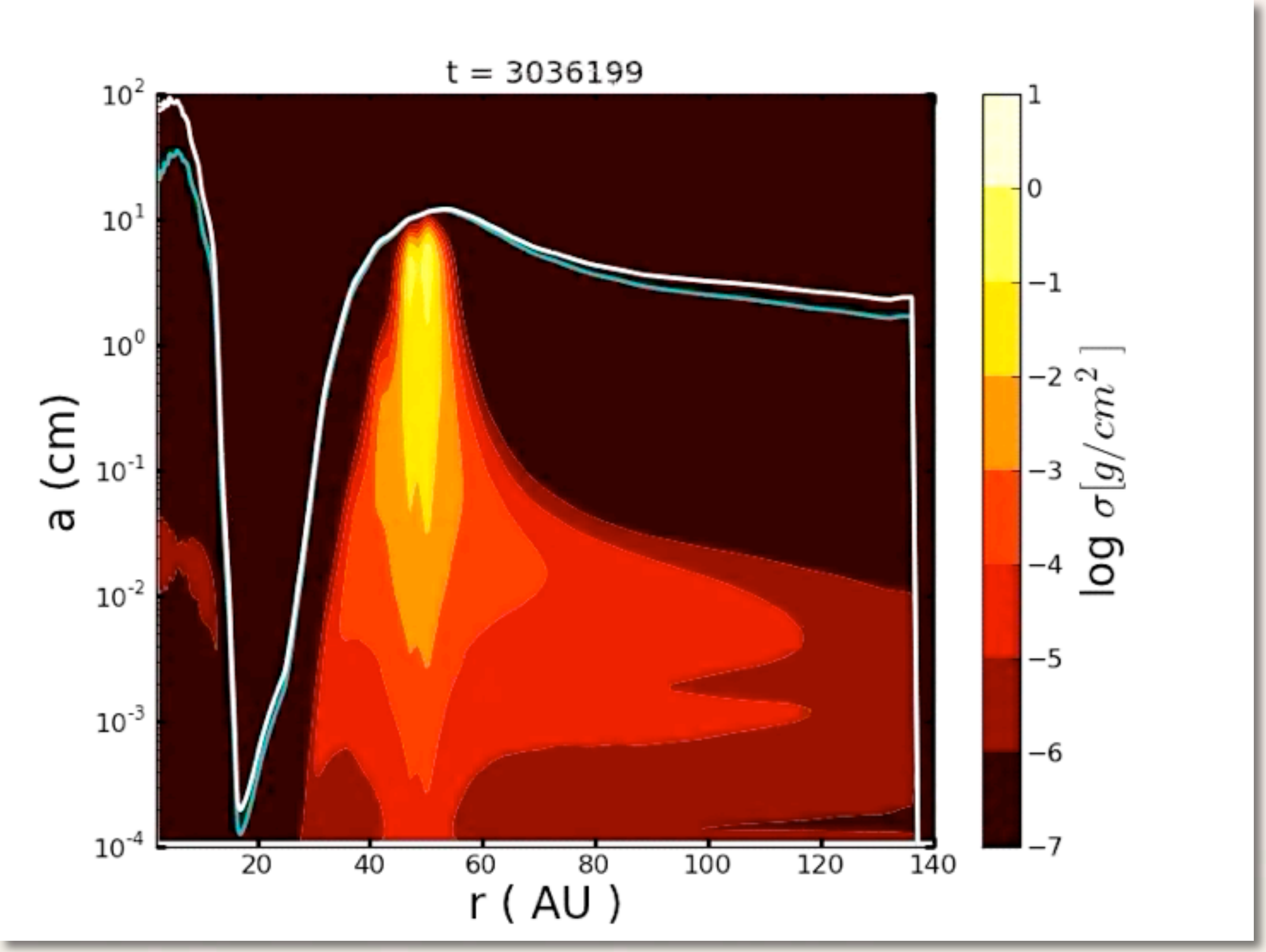
Ataiee et al., arxiv:1304.1736

trapping

no trapping

see also:
H. Li et al.,
F. Masset et al.,
A. Crida et al.,
G. Lesur et al.,
W. Lyra et al.,
...

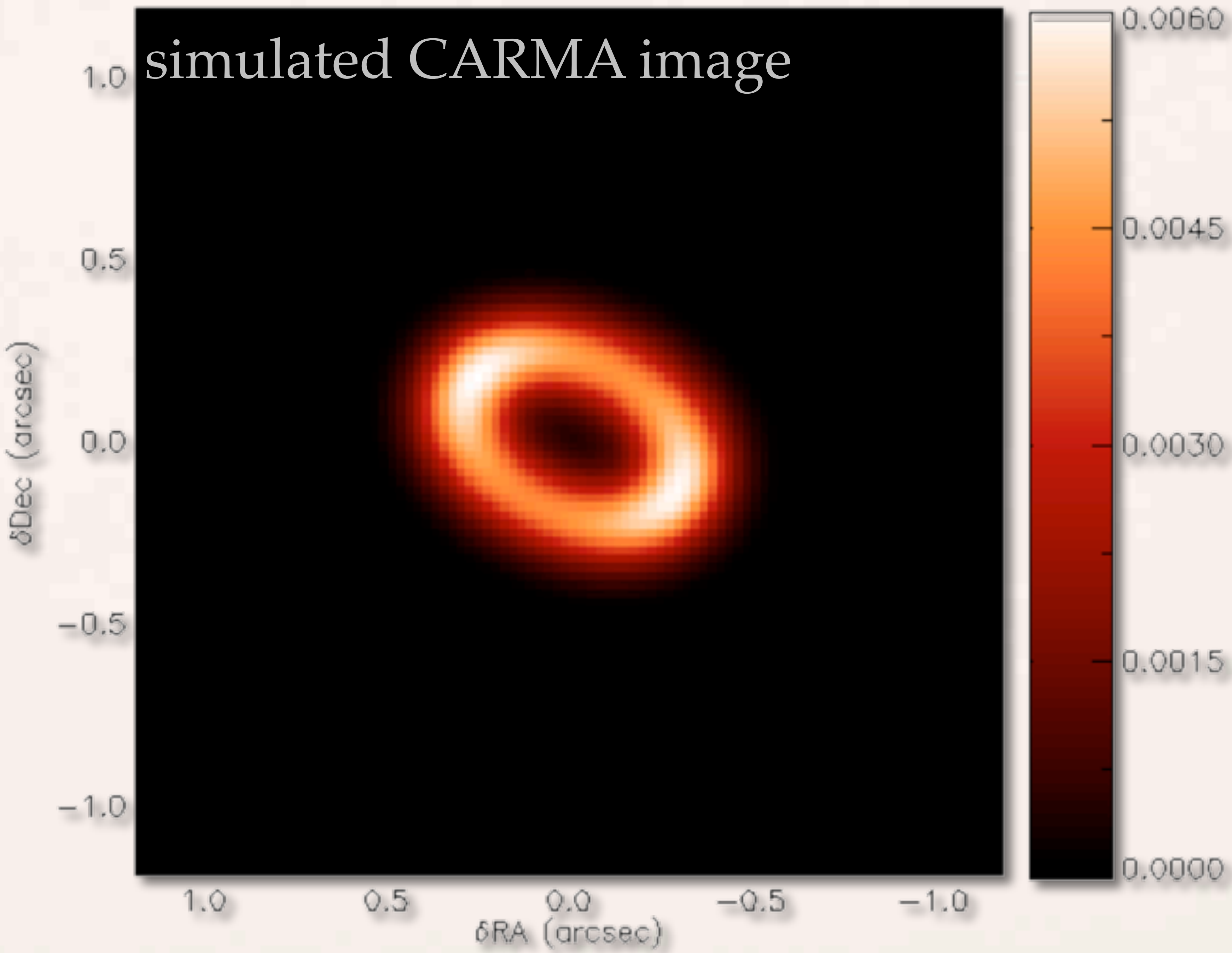
– Dust Filtration –



Pinilla, Birnstiel et al. 2012

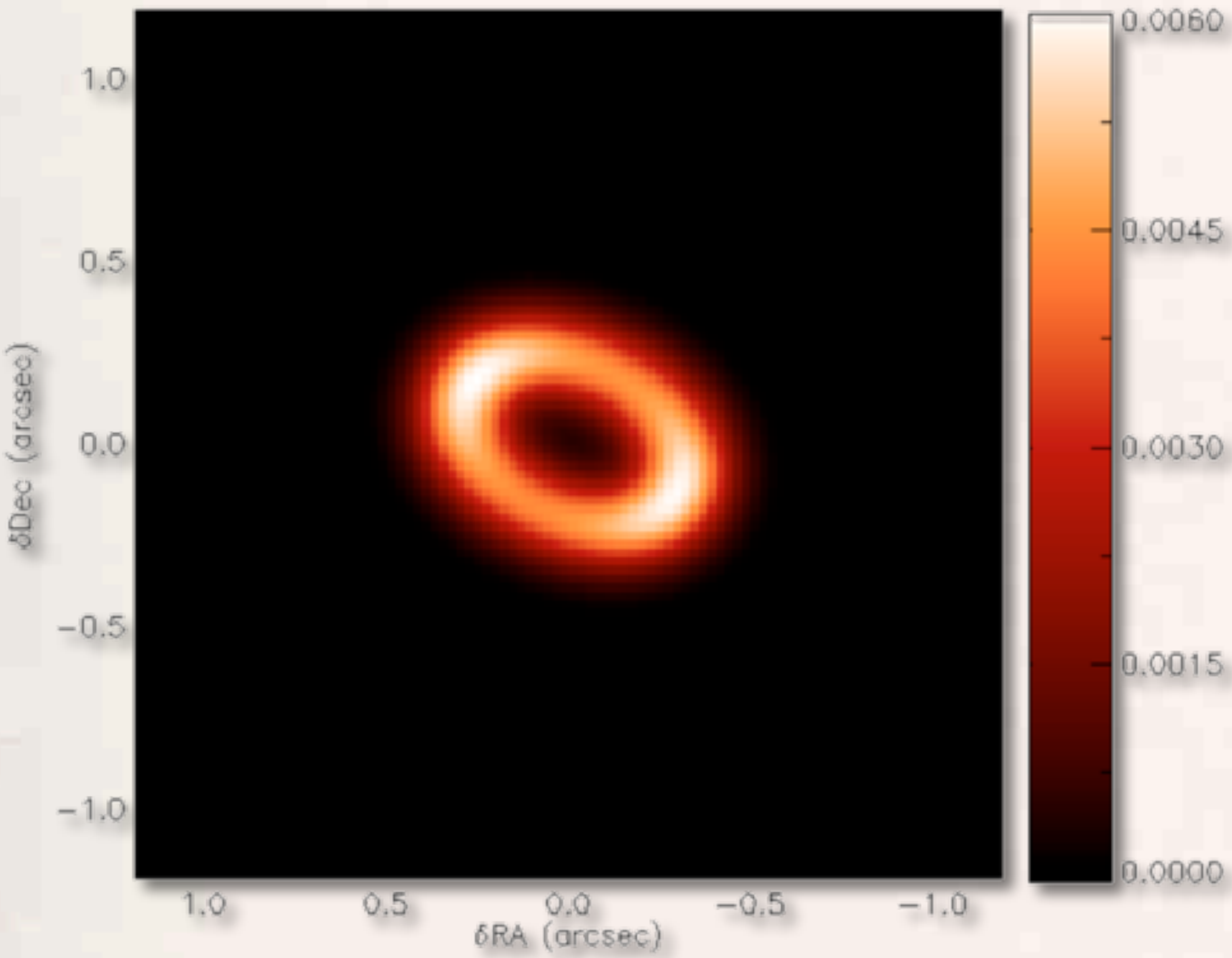
see also:
Rice et al. 2006
Zhu et al. 2012

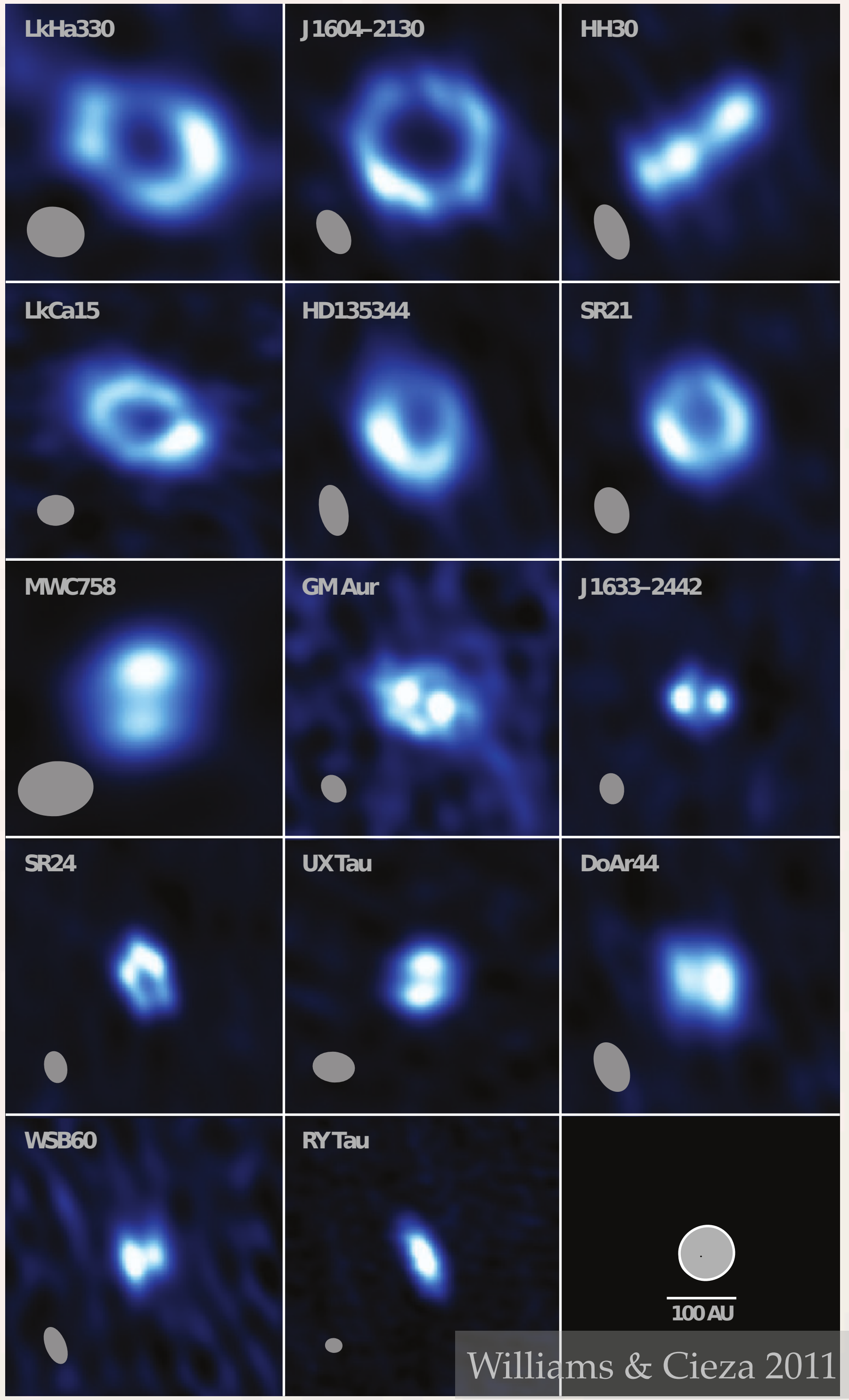
– Planets & Instabilities –



Pinilla, Birnstiel et al. 2012

– Planets & Instabilities –

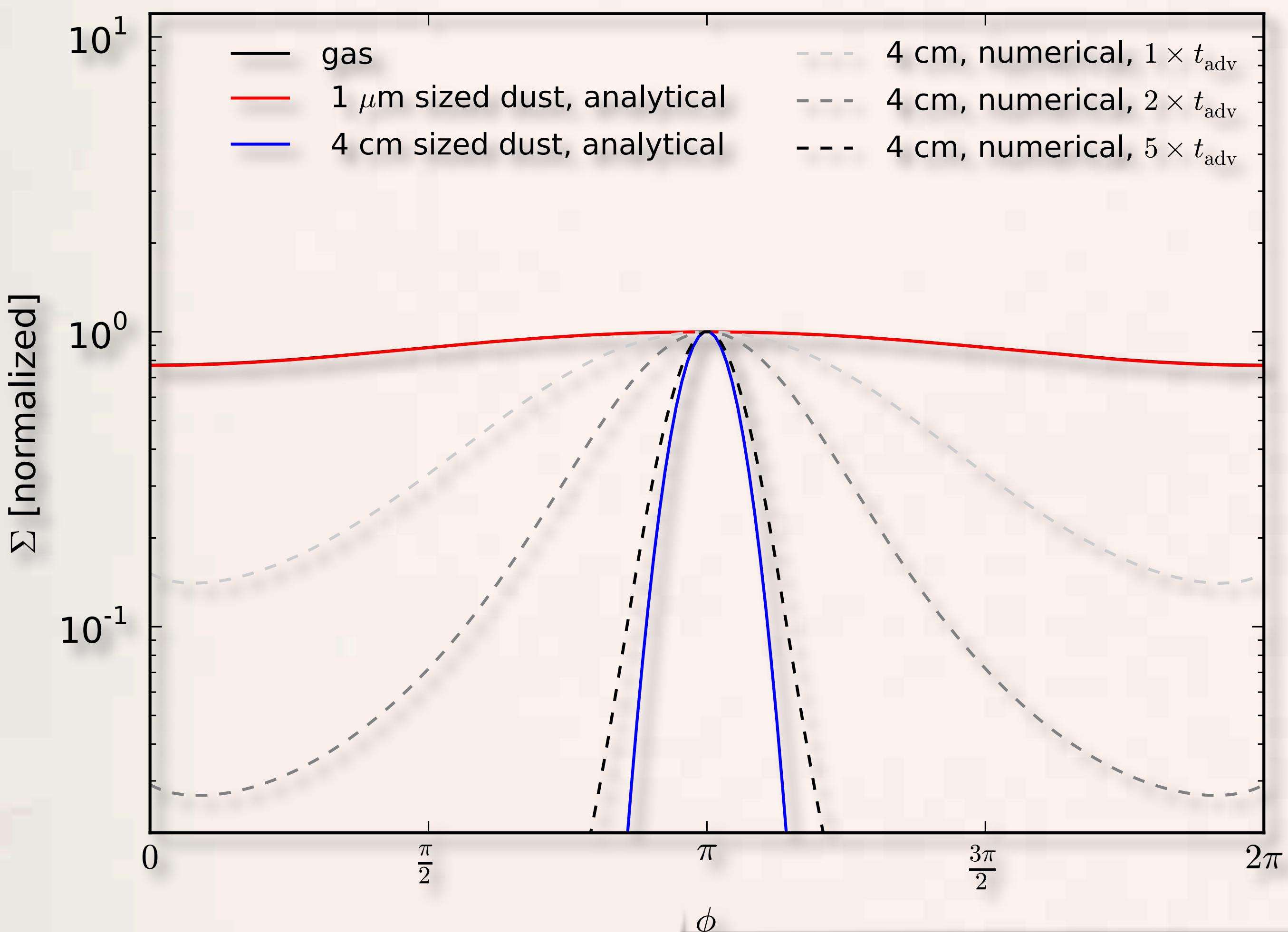


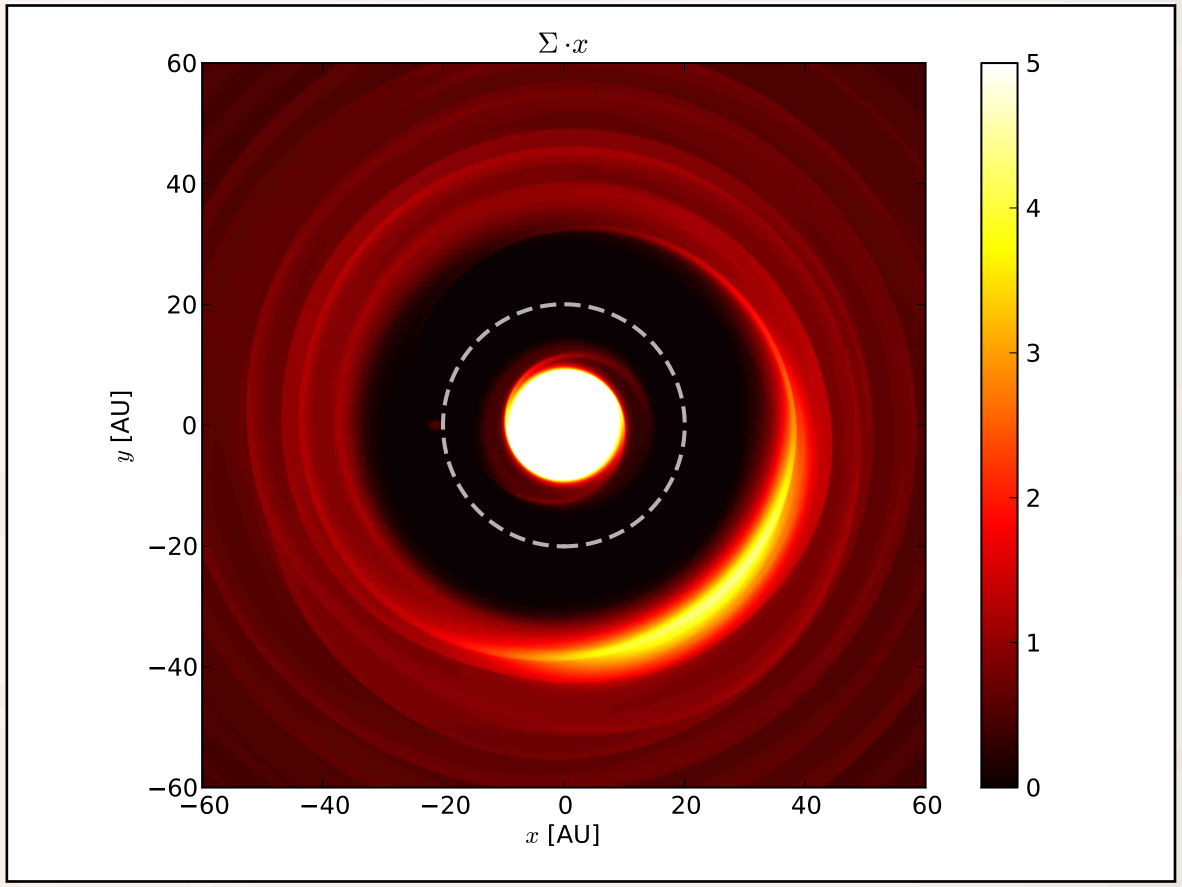


Pinilla, Birnstiel et al. 2012

– Asymmetries –

Birnstiel et al. 2013





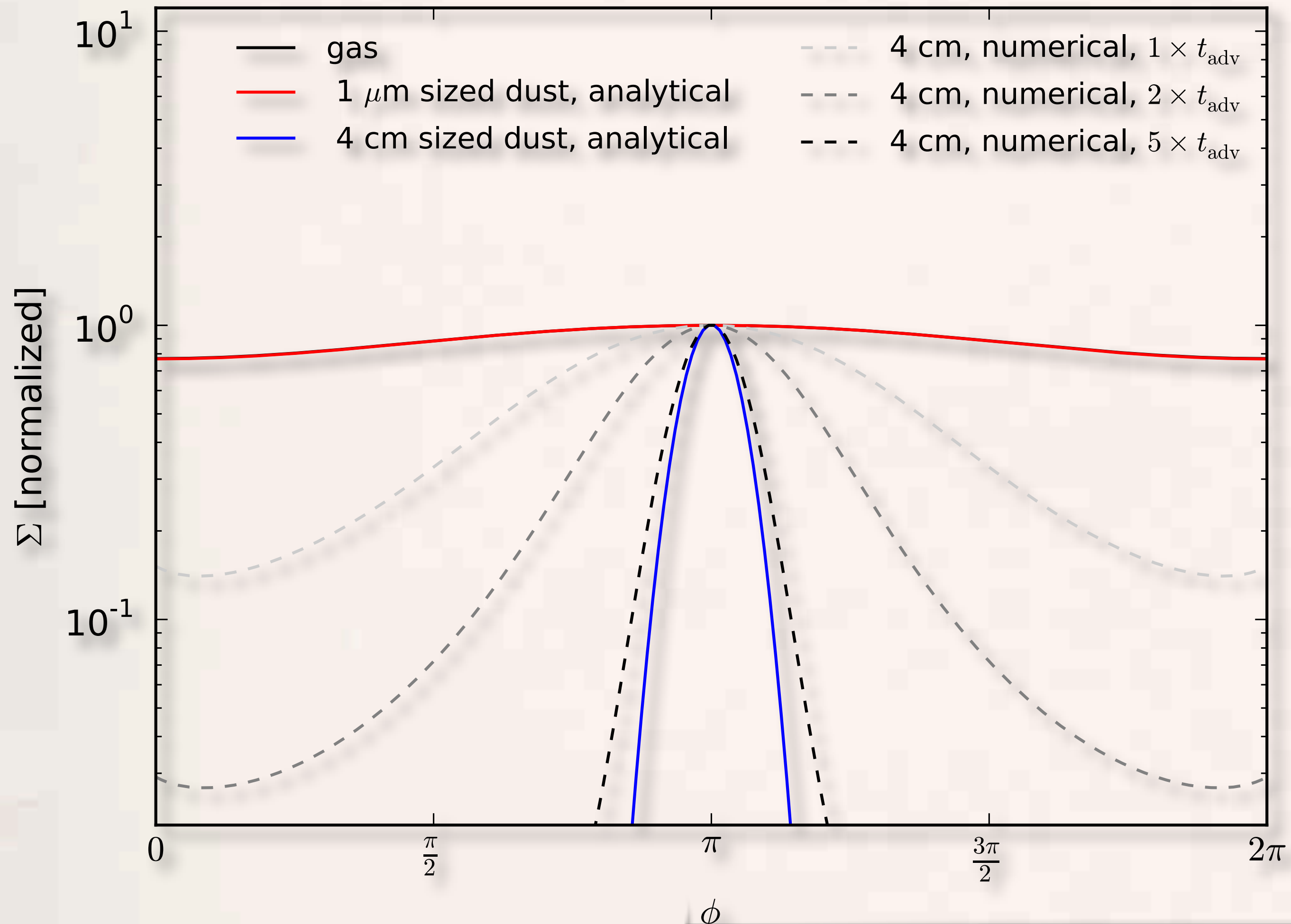
Collaboration with Li & Li

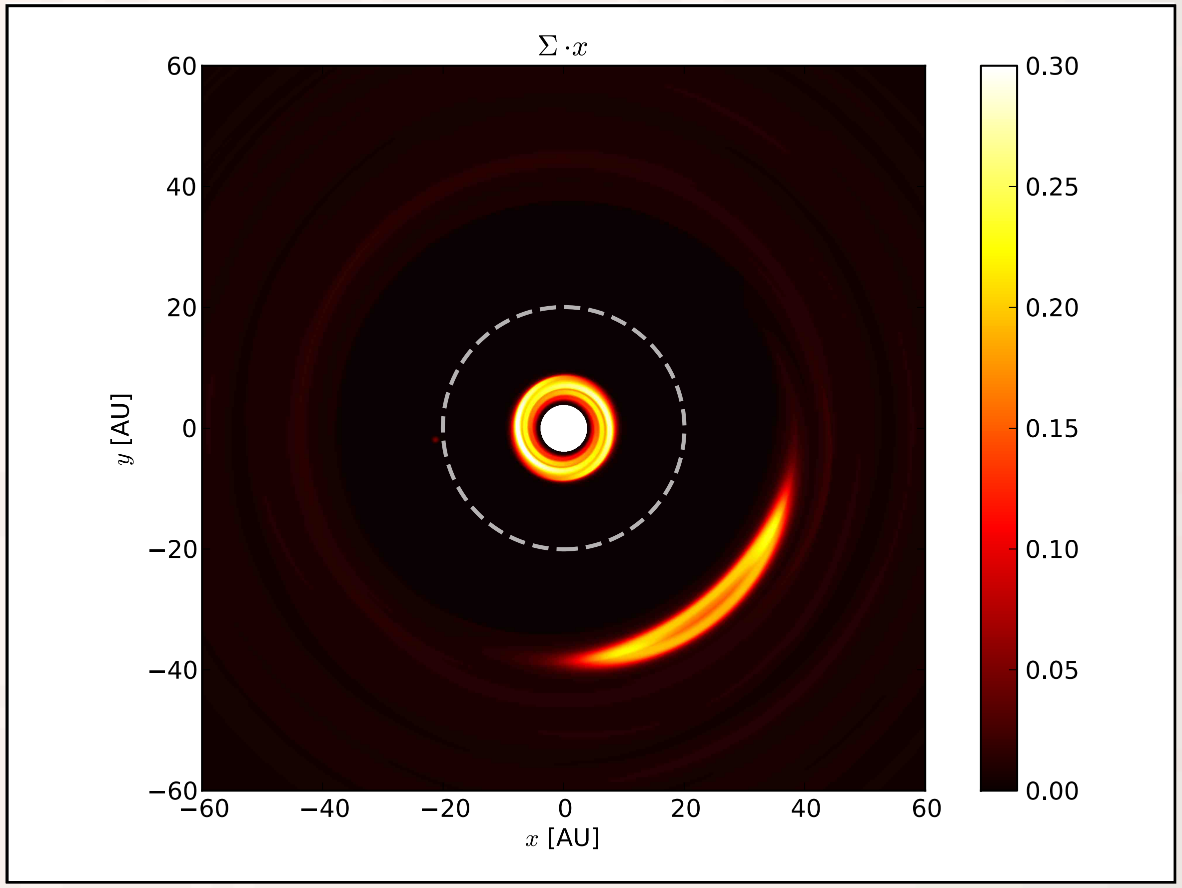
Talks:

N. v. d. Marel	S. Wolf	A. Isella
S. Casassus	F. Ménard	S. Maddison

– Asymmetries –

Birnstiel et al. 2013





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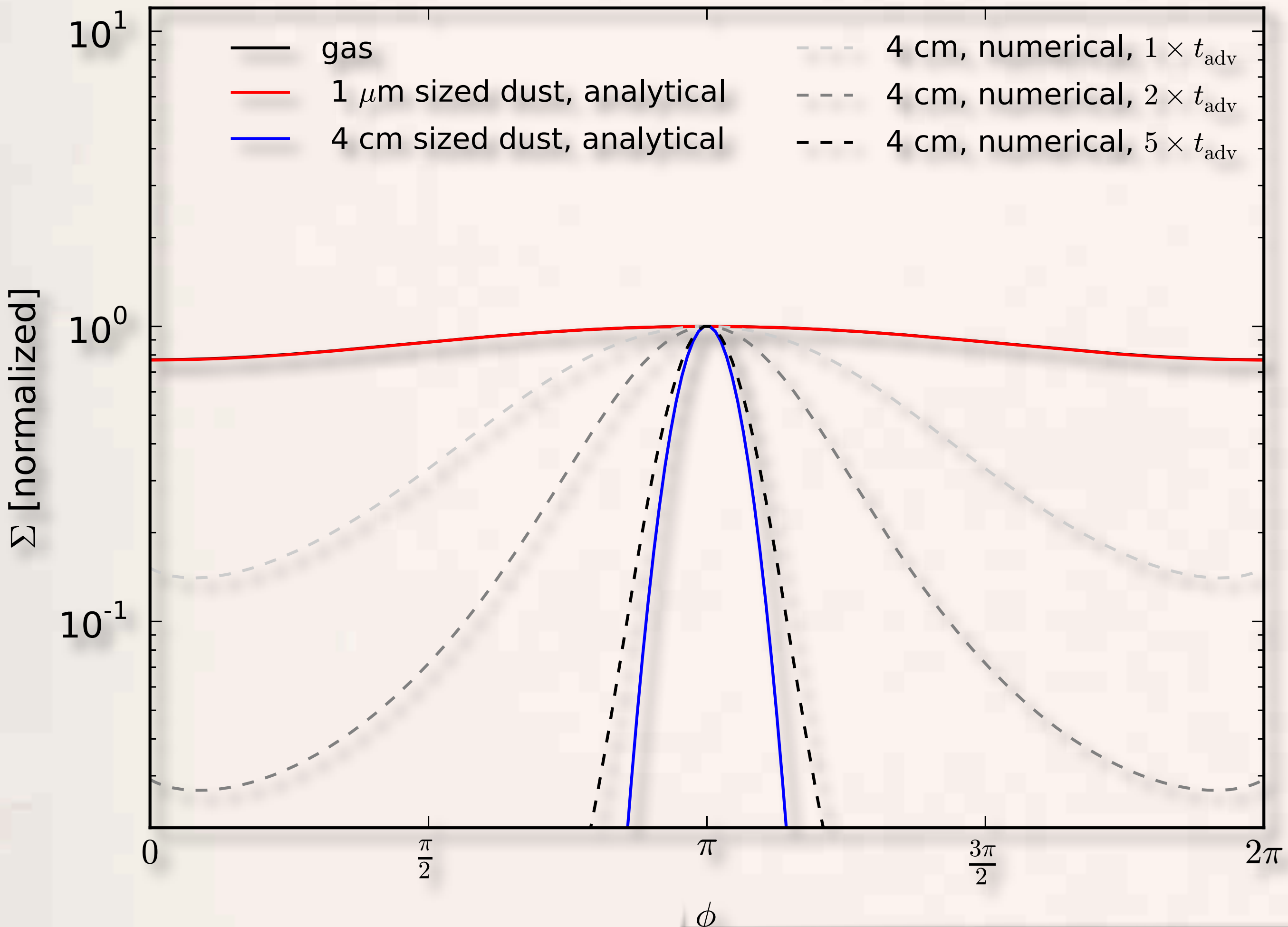

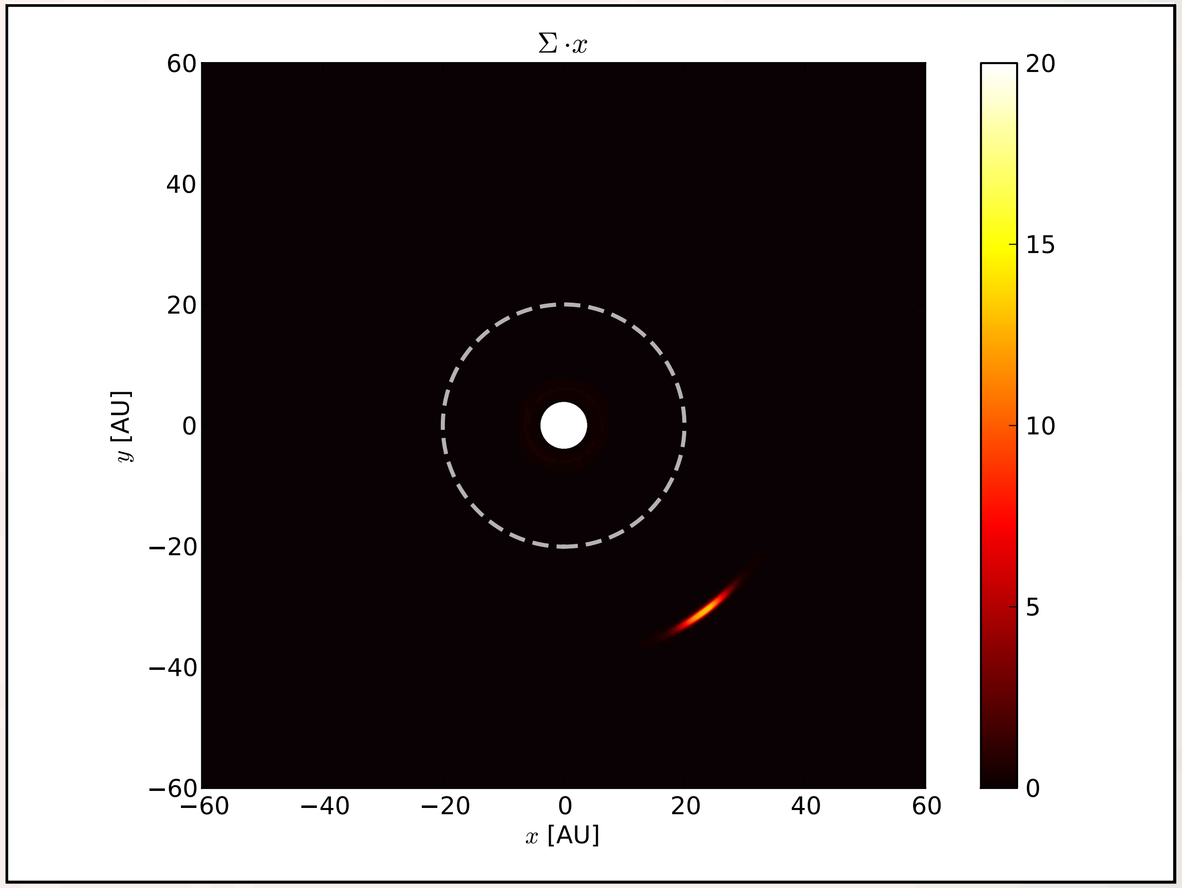

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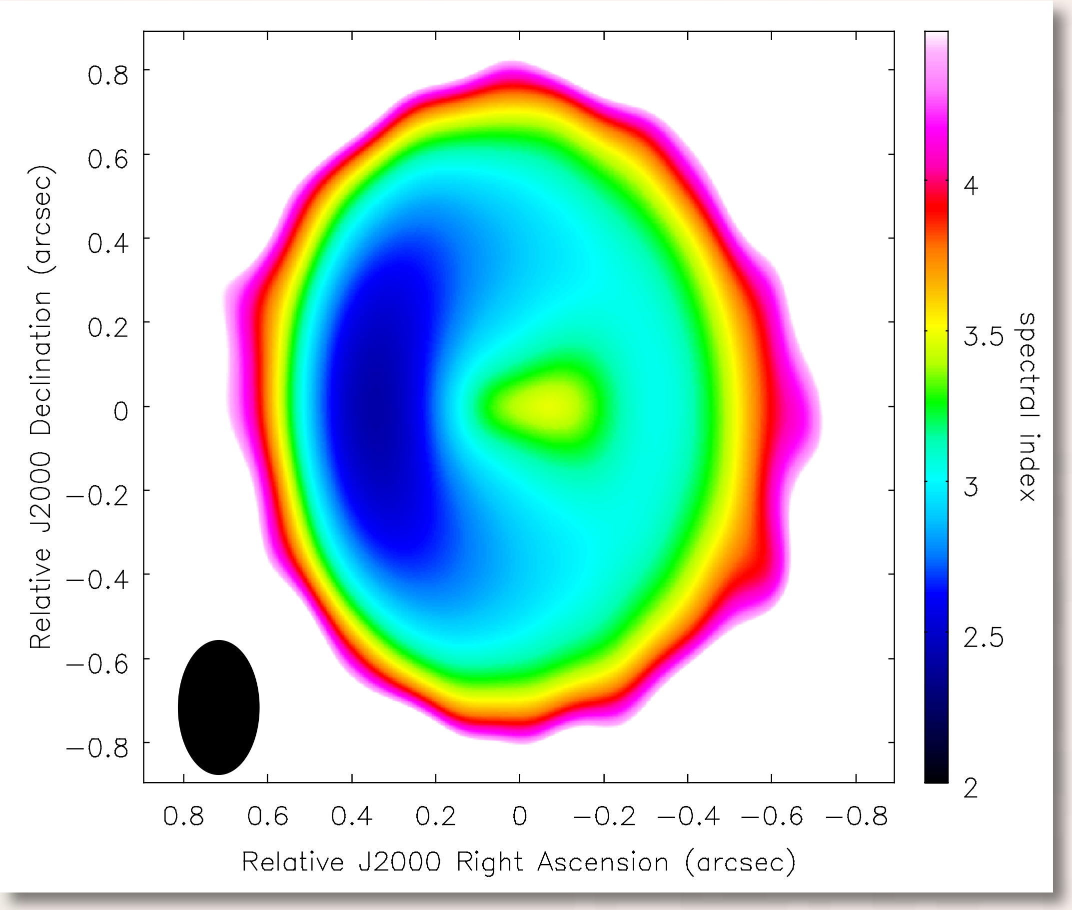

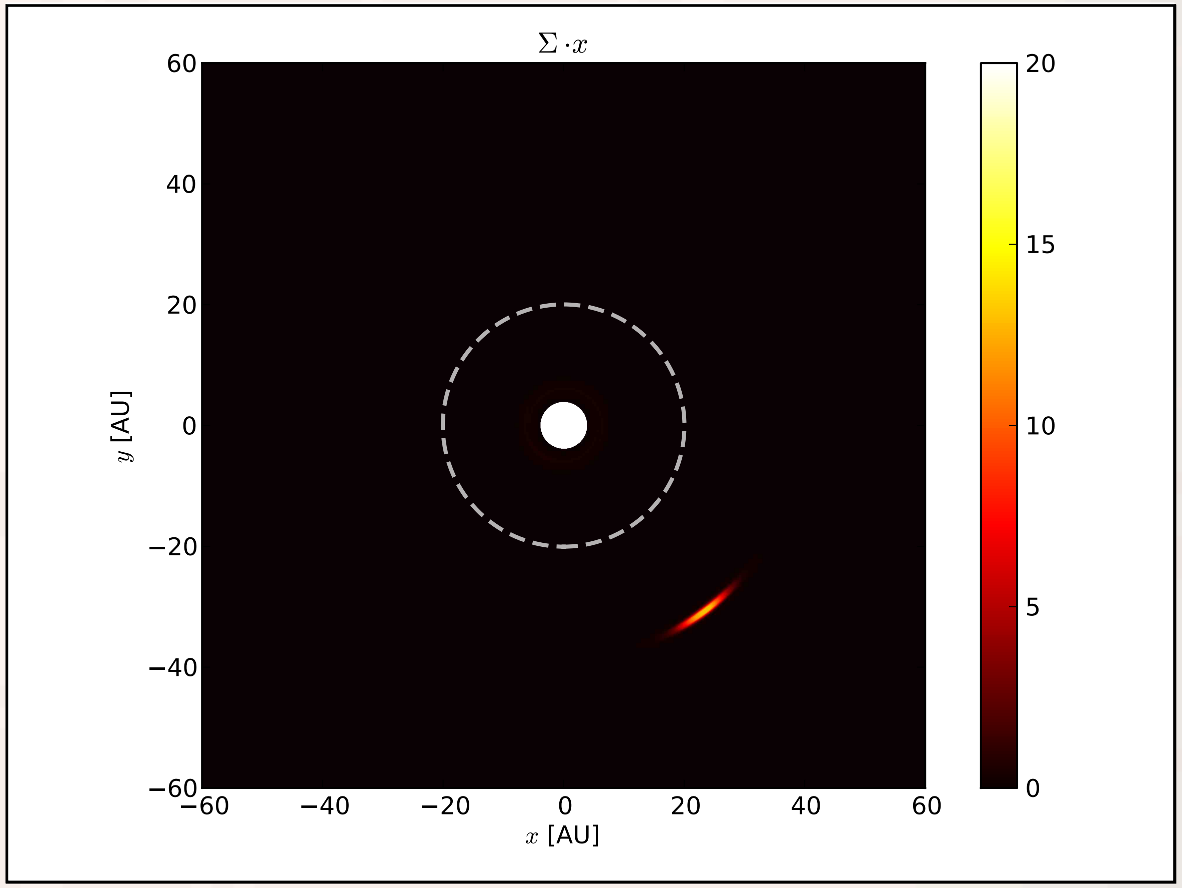

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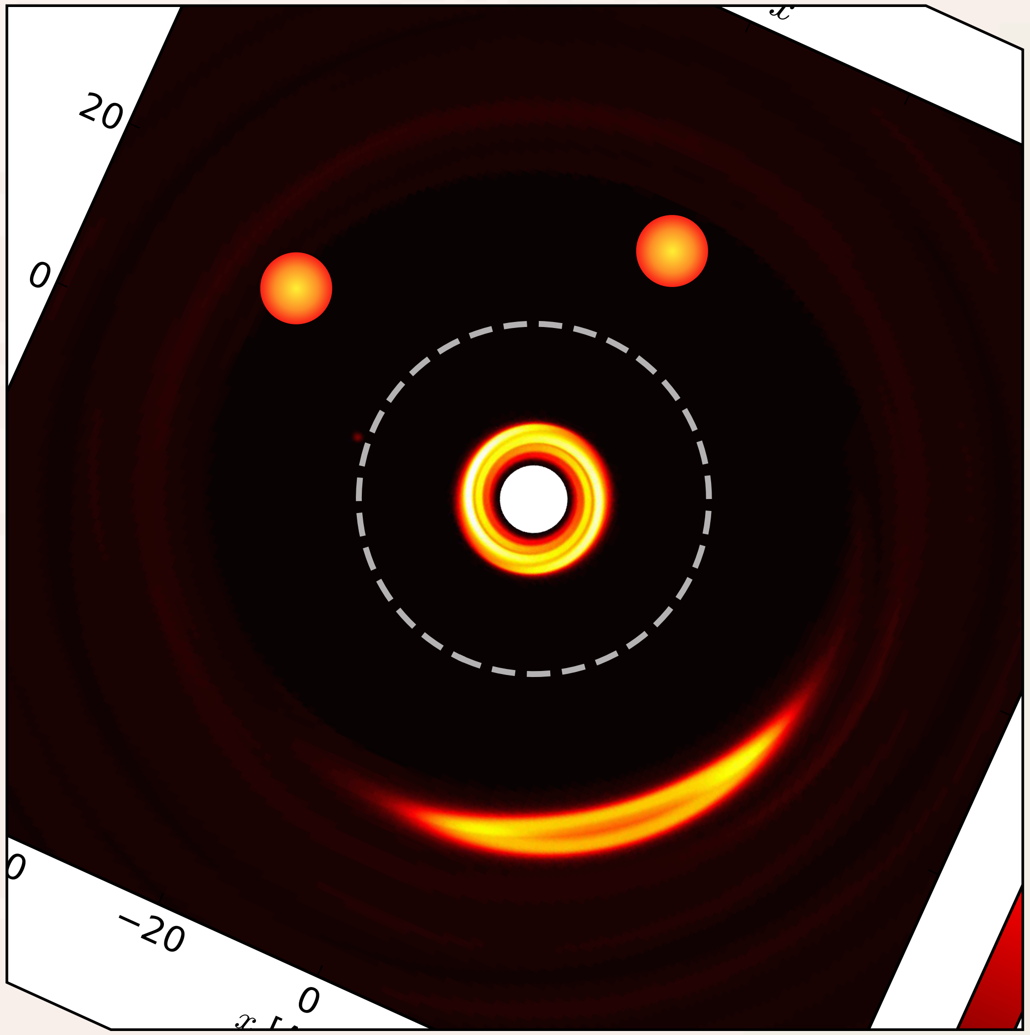
S. Wolf
A. Isella
S. Casassus
F. Ménard
S. Maddison

– Summary –

- radial drift problem
  - supported by some observations
  - not supported by others → *L. Riccis Talk*
  - time scale problem? missing physics?
- analytical grain sizes a(r)
  - larger grains in the inner regions
  - different physical cases: drift vs. fragmentation
  - observationally testable → *L. Pérez Talk*
- analytical surface densities $\Sigma_{dust}(r)$
  - $\Sigma_{dust} \neq \Sigma_{gas}$!
  - inner regions: MMSN / MMEN
  - outer regions: → *L. Pérez Talk*
- Dust Filtration potentially explains features of transition disks
- Watch out for ALMA



Thanks for your attention!