How to Build the Building Blocks of Planets

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Image: NASA

Outline

- I) Planet formation and protoplanetary disks
- II) The formation of the building bricks of planets

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I) Planet Formation and Protoplanetary Disks

- Disk properties and definitions
- Particle motion & evolution in protoplanetary disks
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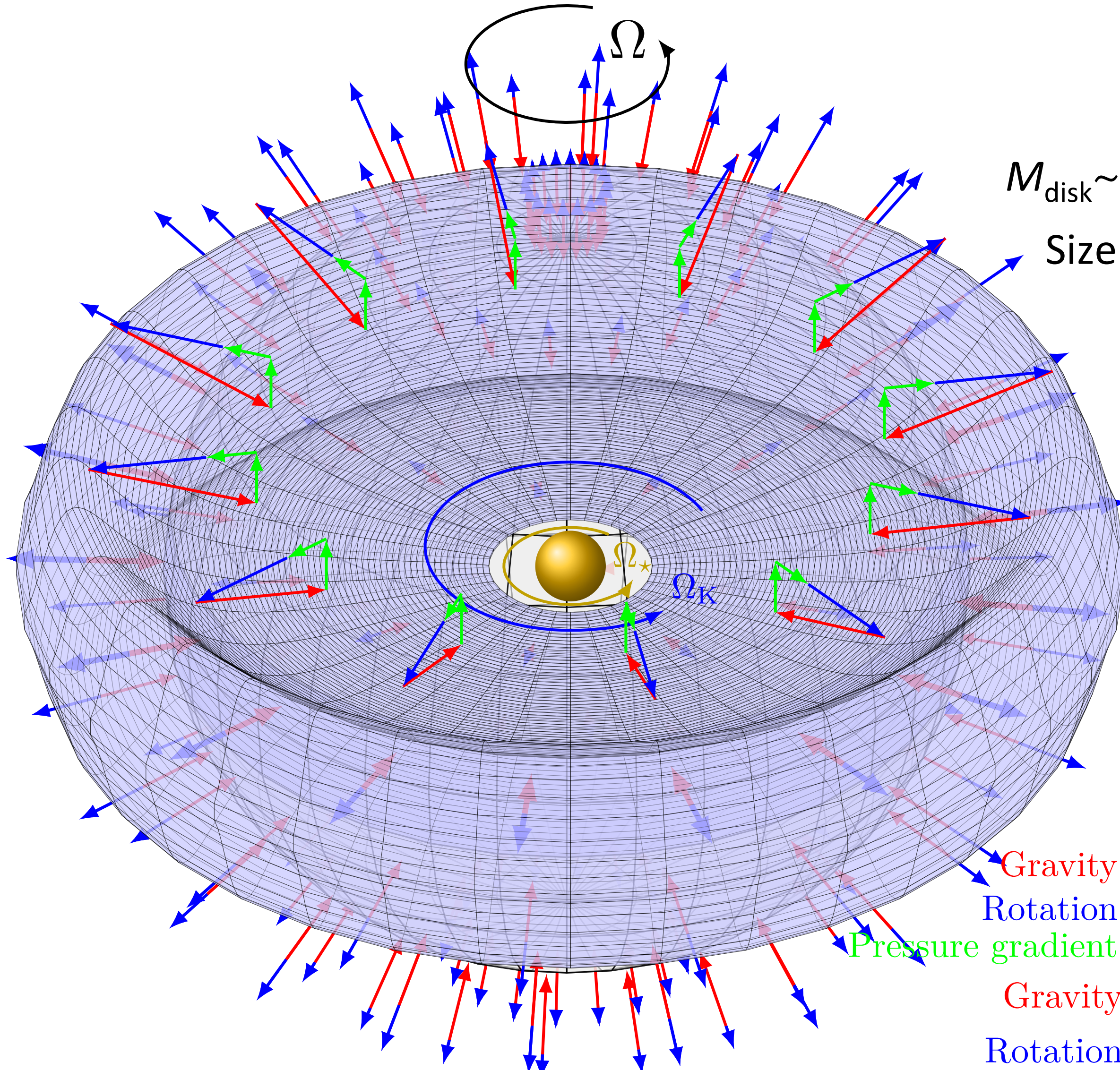
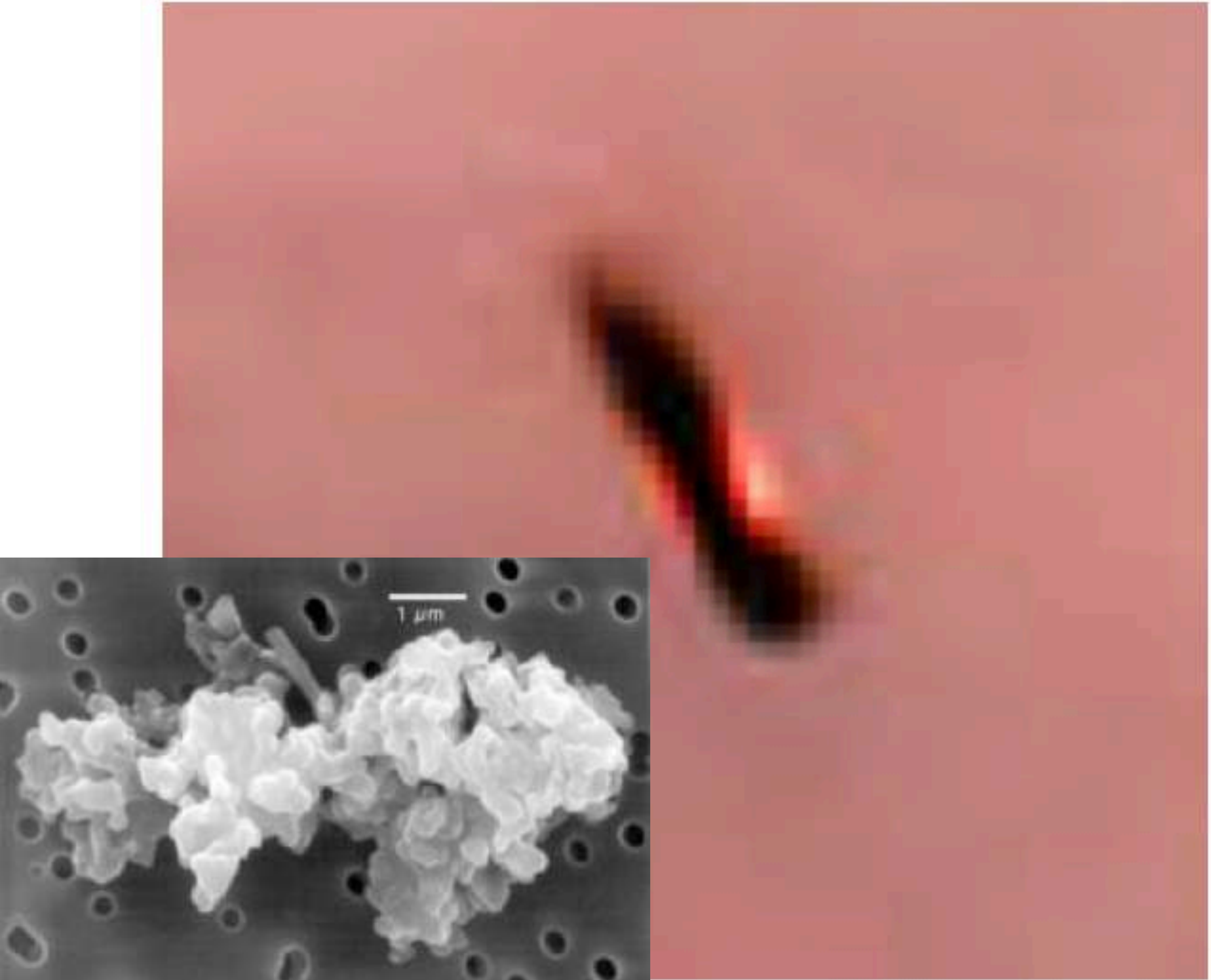
From a Molecular Cloud to a Disk



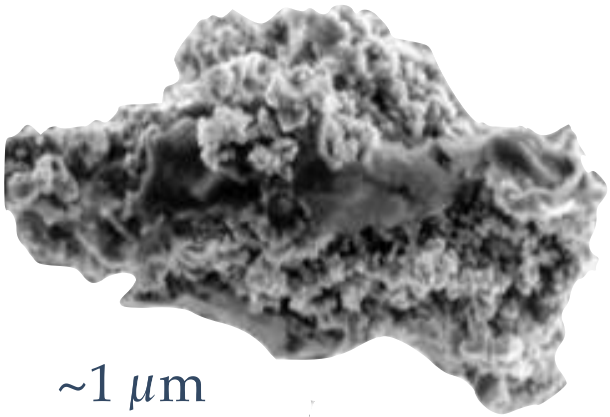
M_{disk}~1%-10% M_{star}

Size typically ~100 AU


1 µm

The Scales

from



~1 μm

to

~13,000 km

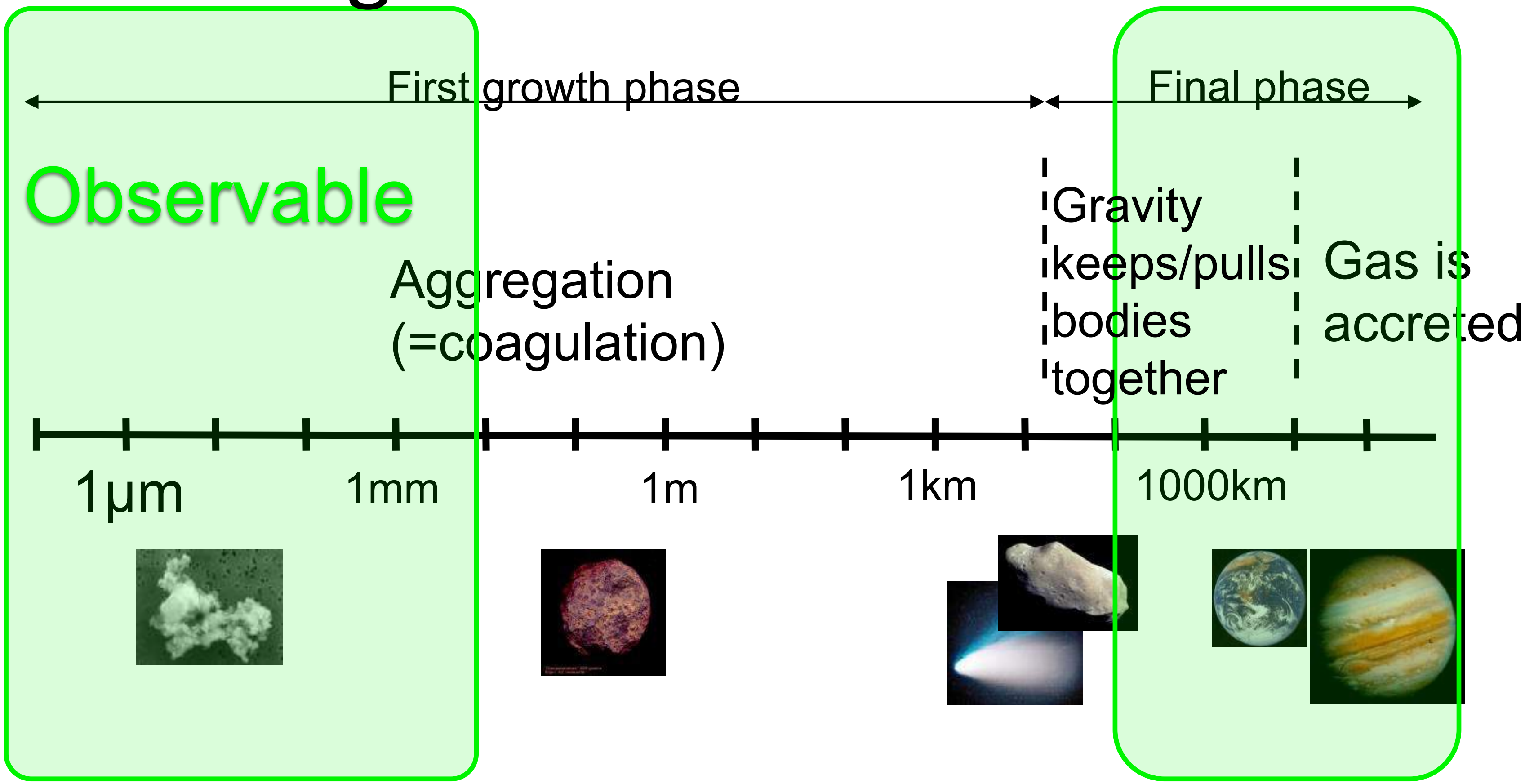
in

~30,000,000,000 km (~100 AU)

or

~140,000 km

The Long Road From Dust to Planets



Covers 13 orders of magnitude in size = 40 (!!) orders of magnitude in mass

Credit: C. Dullemond

Turbulence Model

$\nu_{turb}=\alpha_t h_g c_s$, $0 \leq \alpha_t \leq 1$ (Shakura & Sunyaev 1973)

[HTML] Black holes in binary systems. Observational appearance.
NI **Shakura**, RA **Sunyaev** - Astronomy and Astrophysics, 1973 - adsabs.harvard.edu
... 338 NI **Shakura** and RA **Sunyaev** Truly "black" objects may be found only in remote binary systems typified by a weak stellar wind from the visible component. I. The General Picture Up to 50 % of stars are in binary systems (Martynov, 1971). **...** Their radiation must ionize and heat neutral interstellar
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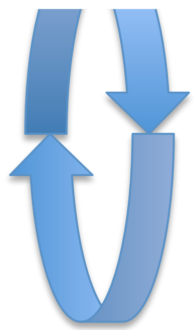
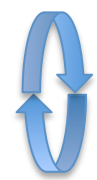


slow



fast

Typical values $\alpha_t \approx 10^{-4}$-10^{-2}
(e.g. Turner+ 2014)

I) Planet Formation and Protoplanetary Disks

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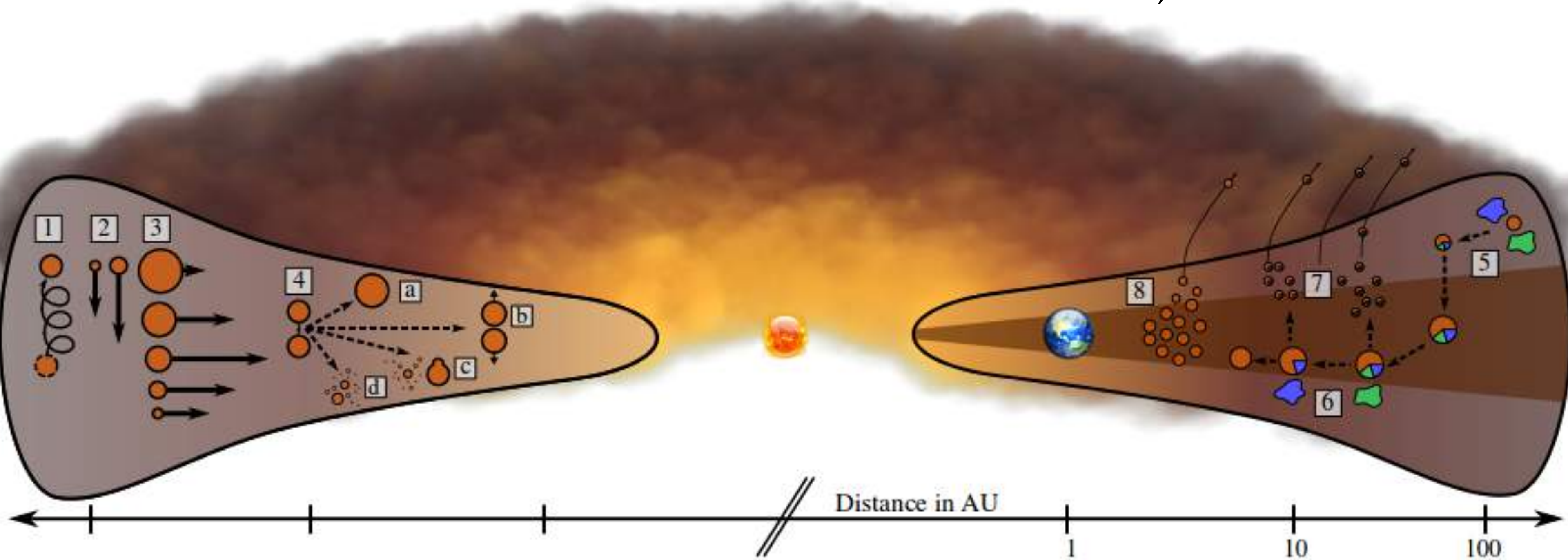
Grain Evolution Processes

Credit: Til Birnstiel; Sun+Earth: Dan Wiersema



[1] Turbulence distributes particles vertically and radially

[2] Growing particles sediment to the mid-plane of the disk

[3] In the outer disk, particles of mm sizes drift quickly inwards

[4] Particle collisions can have many different outcomes
- a) Sticking (= growth)
- b) Bouncing (= growth neutral)
- c) Fragmentation with net growth of the larger body
- d) Fragmentation

[5] Volatile species condense or form on particle surfaces
Particles sediment to the disk mid-plane and drift inward

[6] In the hotter regions, volatiles are released back into the gas phase

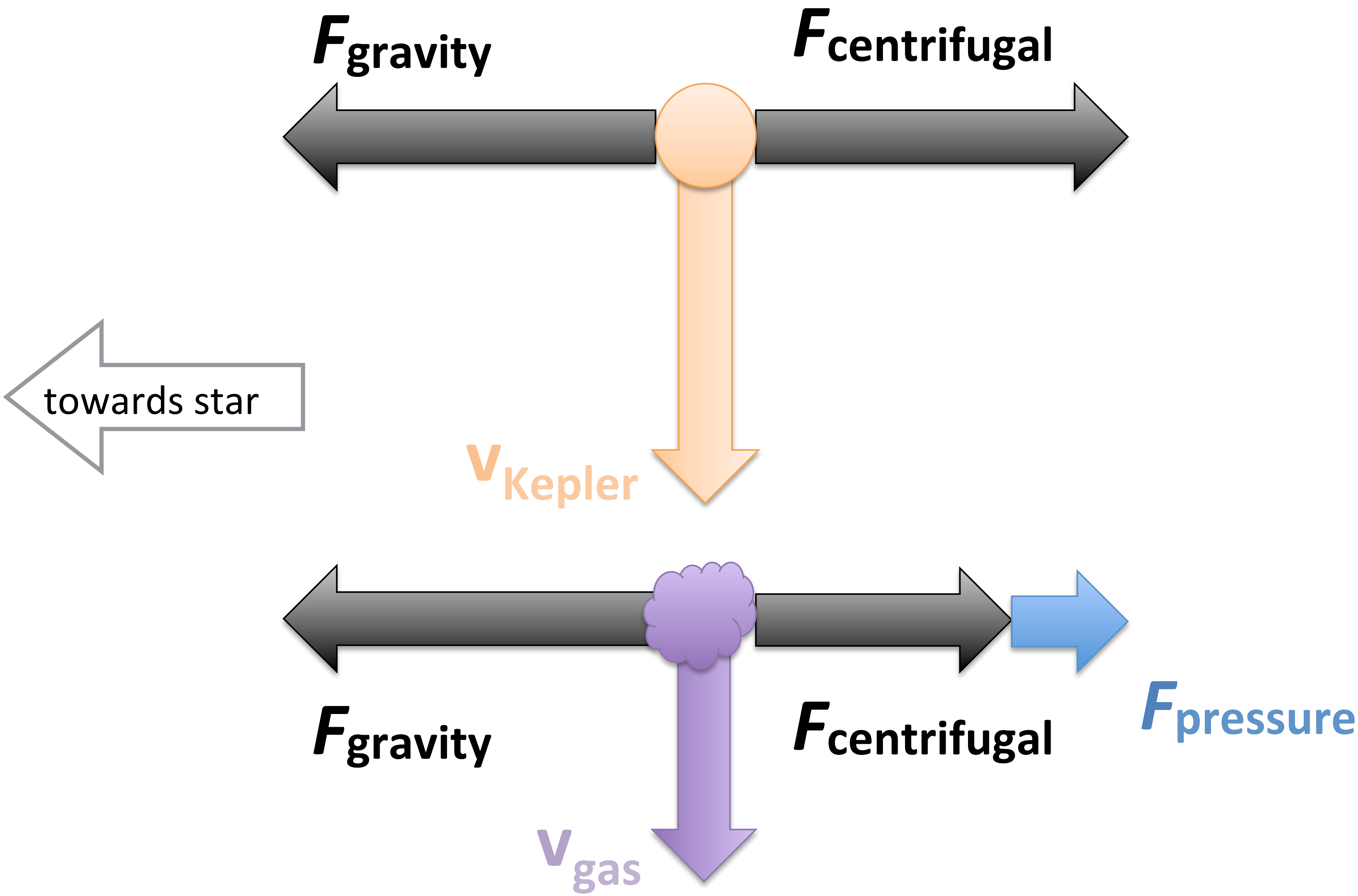
[7] Small fragments can be turbulently mixed up to the disk surface and can be carried away by disk winds

[8] Accumulation of larger particles and planet formation

Example of a Protoplanetary Disk

www.youtube.com/watch?v=p_f6lWWc9jQ

Radial Drift Problem



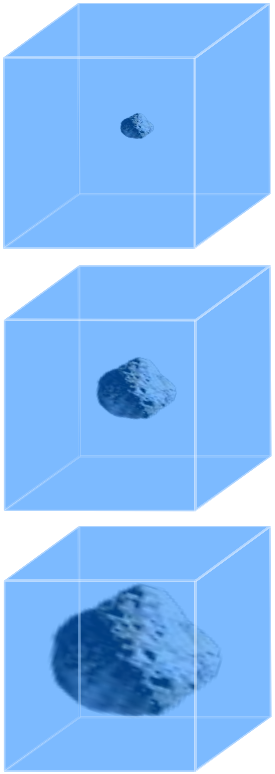
Stokes Number

$$\frac{t_{\rm stop}}{t_{\rm orb}} = t_{\rm stop} \cdot \Omega_{\rm K} \equiv {\rm St} \quad \text{(Stokes number)}$$

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

St ~ 1 i.e. $\tau_{\rm fric} \simeq \tau_{\rm orb}$

St >> 1 i.e. $\tau_{\rm fric} \gg \tau_{\rm orb}$



It's (mostly) not size that matters - it's the Stokes number!

Credit: T. Birnstiel

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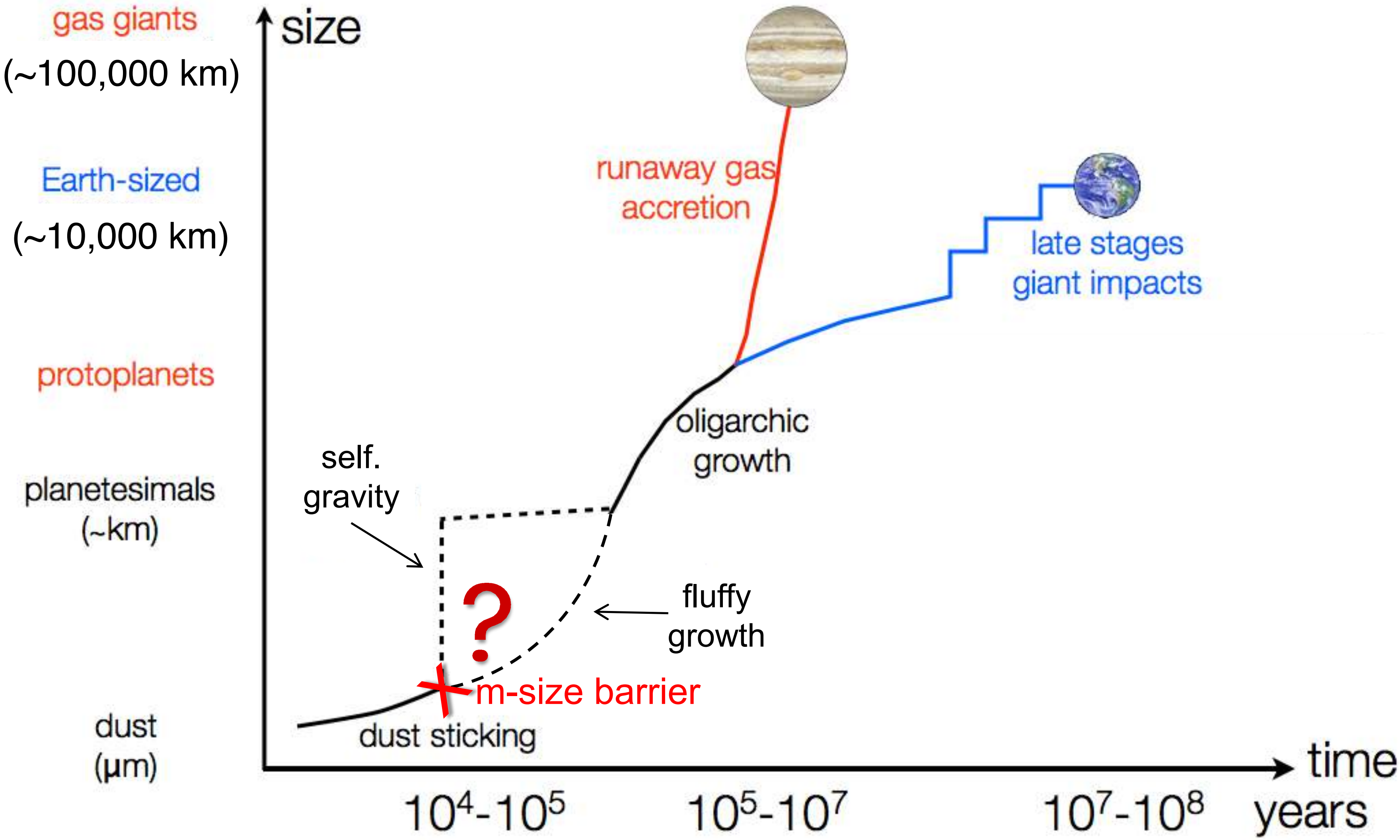
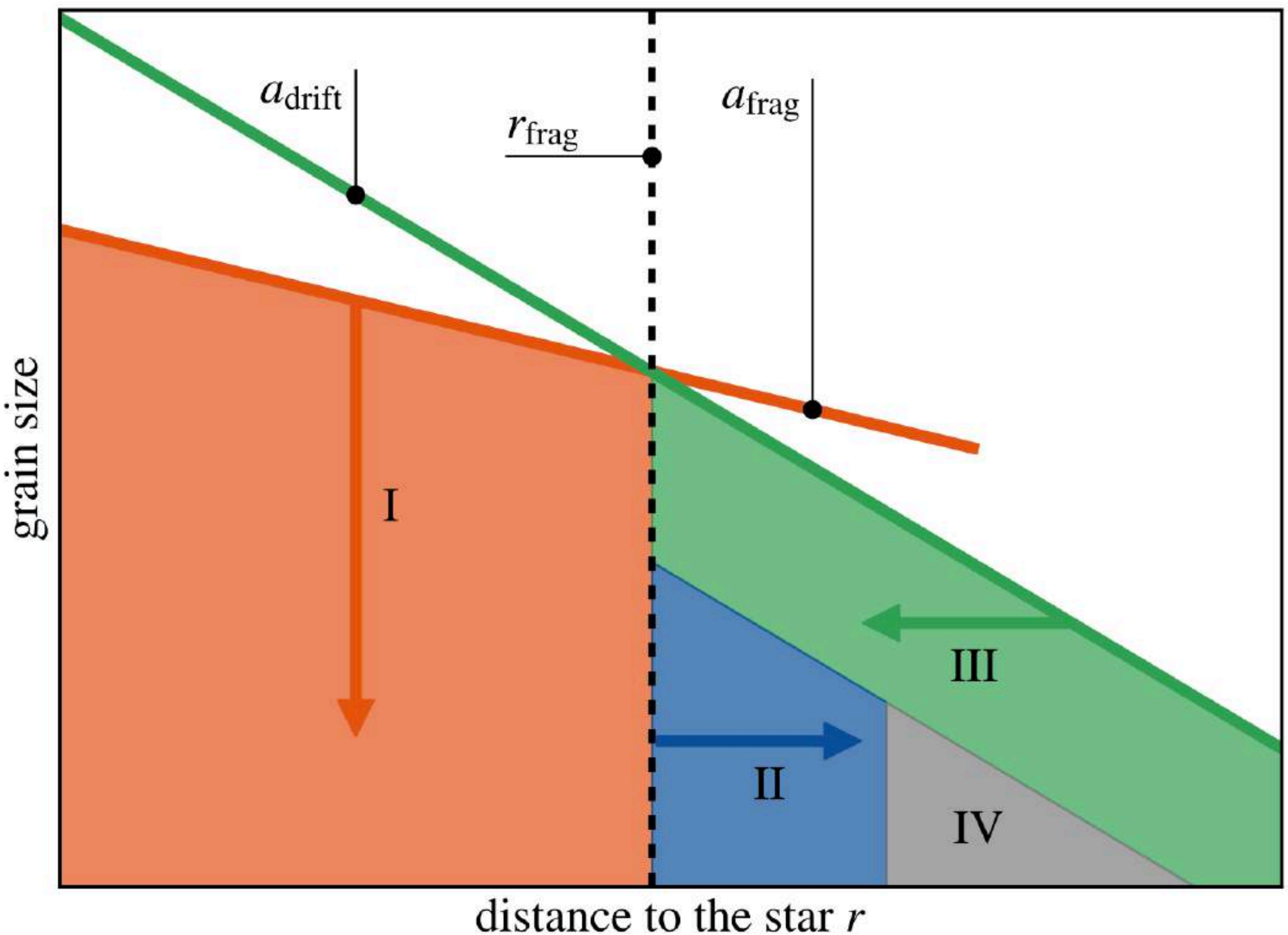
Rough Timescales of Planet Formation



Thanks to A. Morbidelli

Typical Global Size Distribution



I: small particles resupplied by fragmentation

II: delivery of small particles by turbulent radial diffusion

III: growth + drift => top heavy size distribution, smeared out by turbulent radial diffusion

IV: lack of small particles remains

Birnstiel+ 2015

Drift is very fast!

Particles from ~100 AU

drift into the star within

$\sim 10^4$ years!!

Image: A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO)

Then, how do planets form?

1. Stop radial drift
2. Collect dust

} Particle traps

3. Gravitational collapse to planetesimals

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- **Particle trapping** in pressure bumps and the toy **model, leading questions** of the project
- **Planetesimal formation** within our model
- **Constrains on parameters** for the Solar Nebula

Image: Andreas Schreiber

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Image: Andreas Schreiber

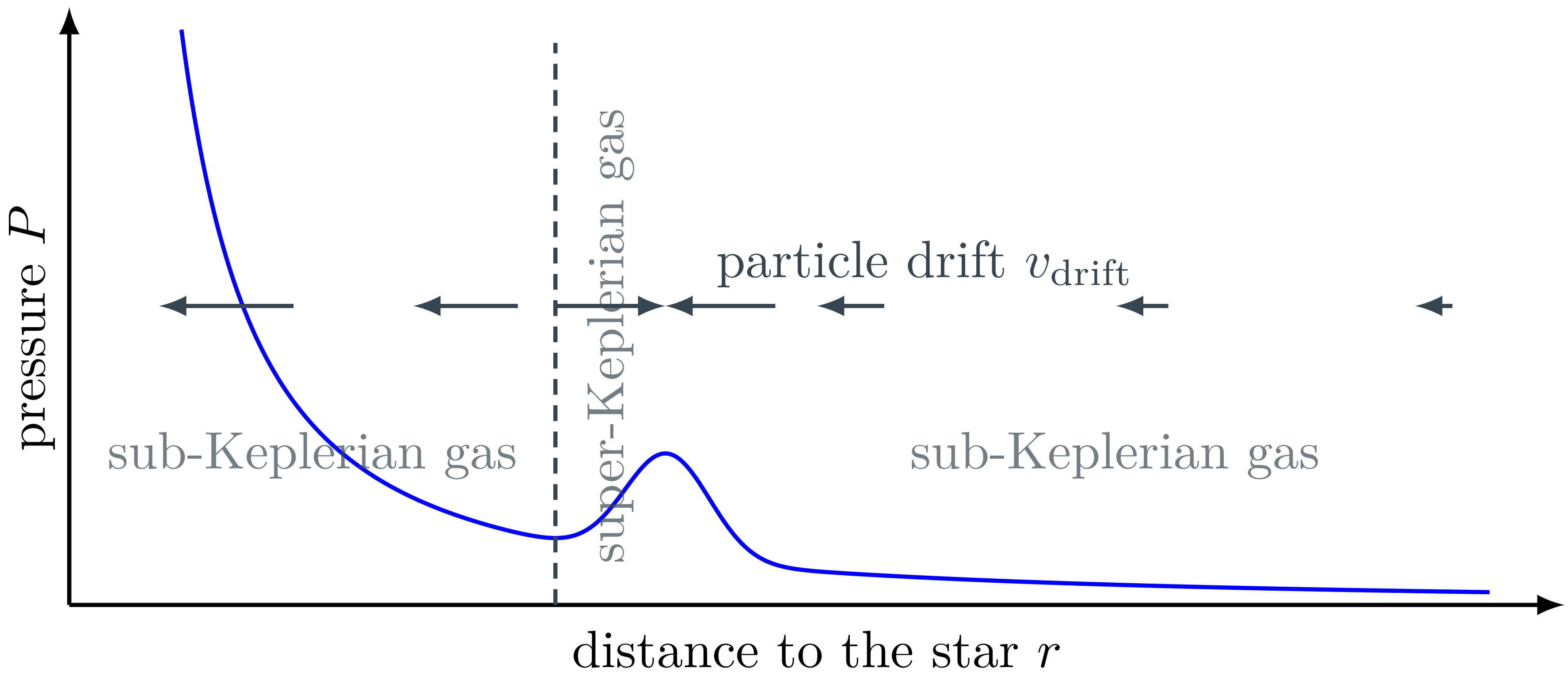
Planetesimals

- infinitesimal planets = building blocks of planets

bound by gravity rather than molecular binding forces (e.g. Van der Waals): >1 km (Benz & Asphaug 1999)

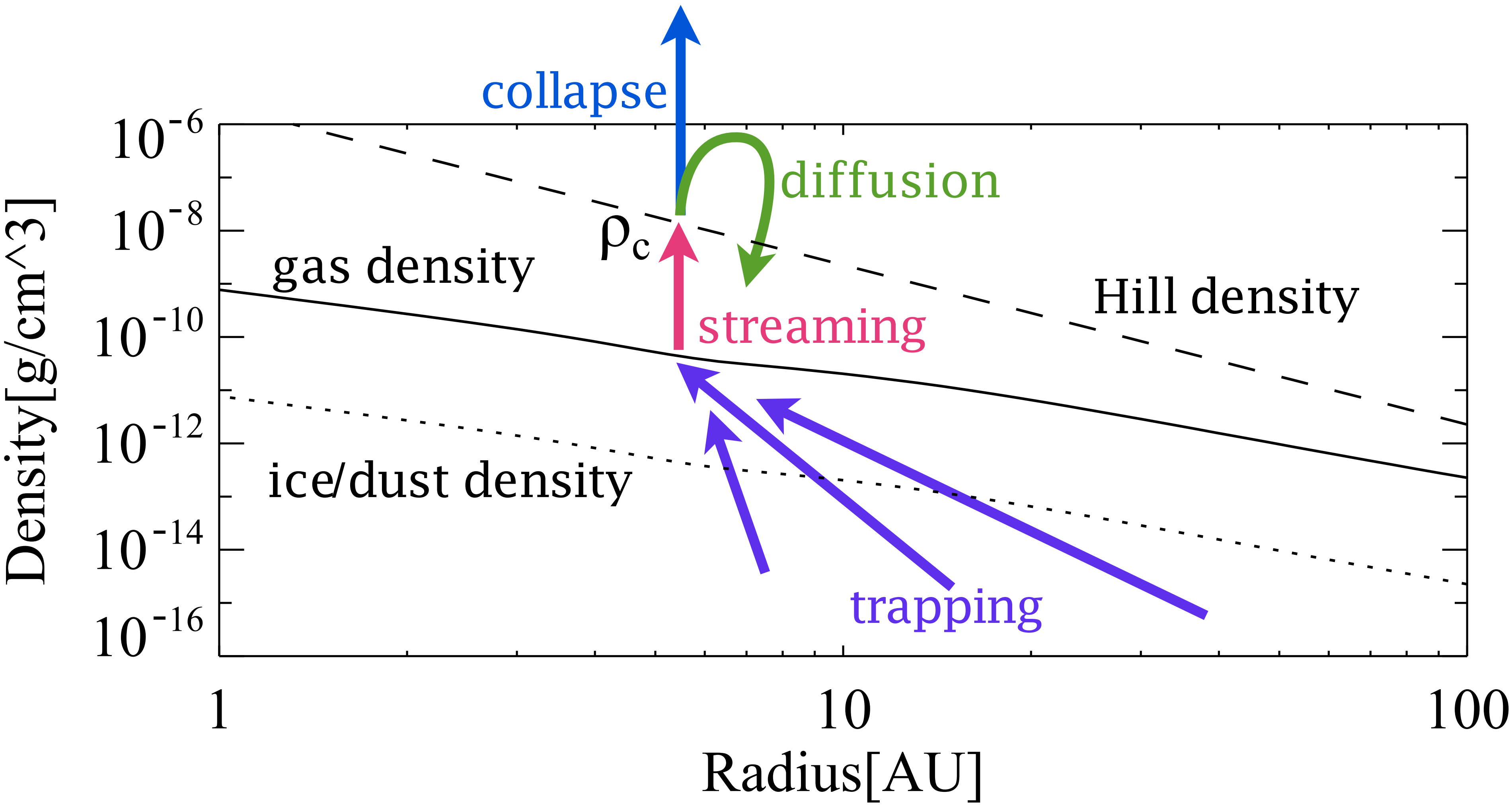
Image: Andreas Schreiber

Particle Trapping in Pressure Bumps

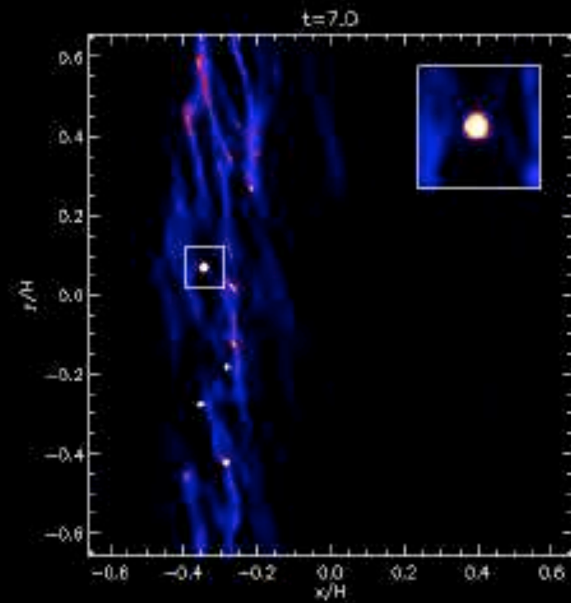


Idea: Whipple 1972

Condition for Planetesimal Formation



Thanks to Hubert Klahr & Andreas Schreiber



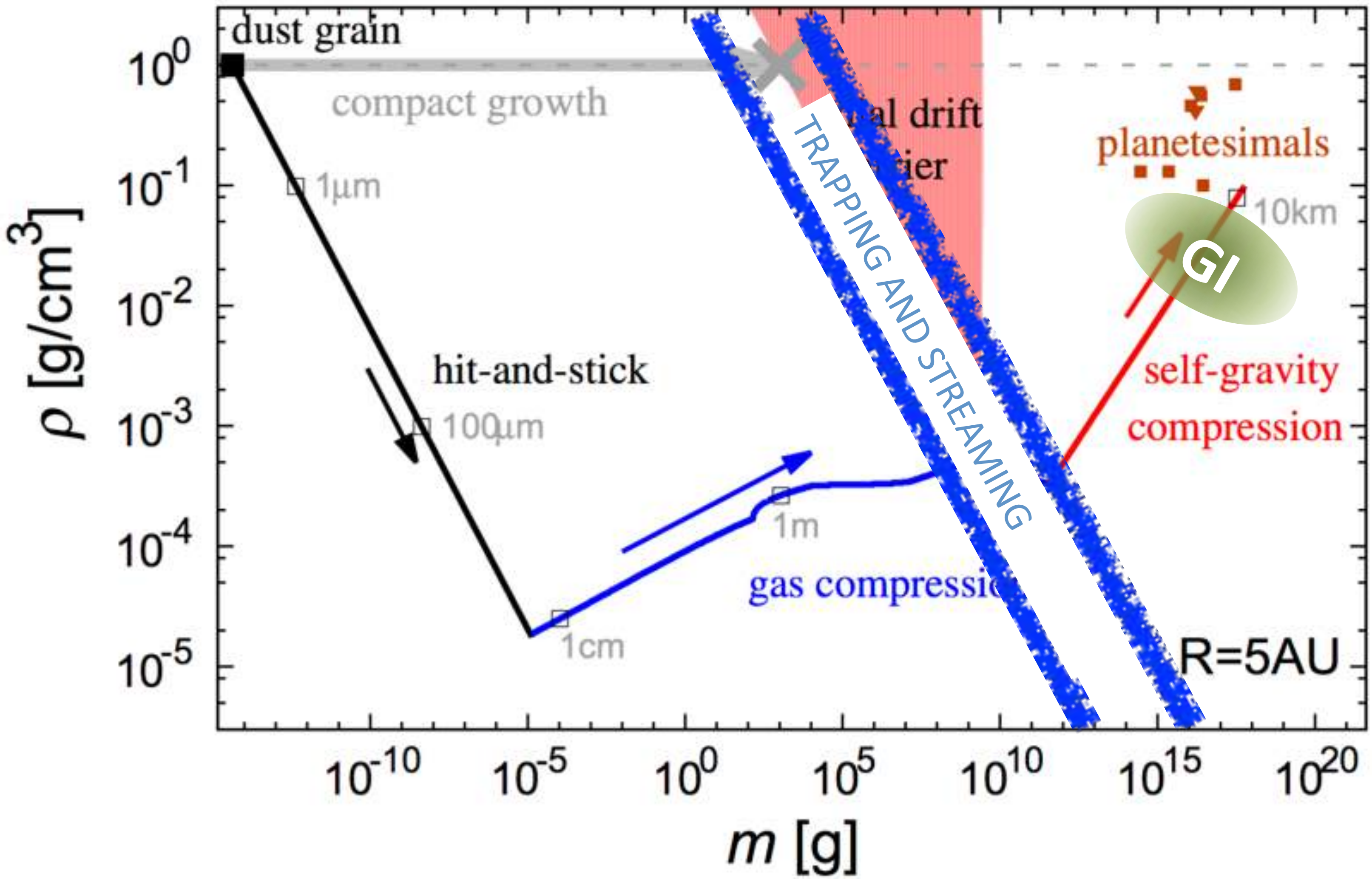
Rapid planetesimal formation in turbulent circumstellar discs

Nature, vol. 448, p. 1022-1025

A. Johansen[1], J. Oishi[2], M.-M. Mac Low[2,1], H. Klahr[1], Th. Henning[1], A. Youdin[3]
[1]Max-Planck-Institut für Astronomie, Heidelberg
[2]American Museum of Natural History, New York
[3]CITA, University of Toronto, Canada

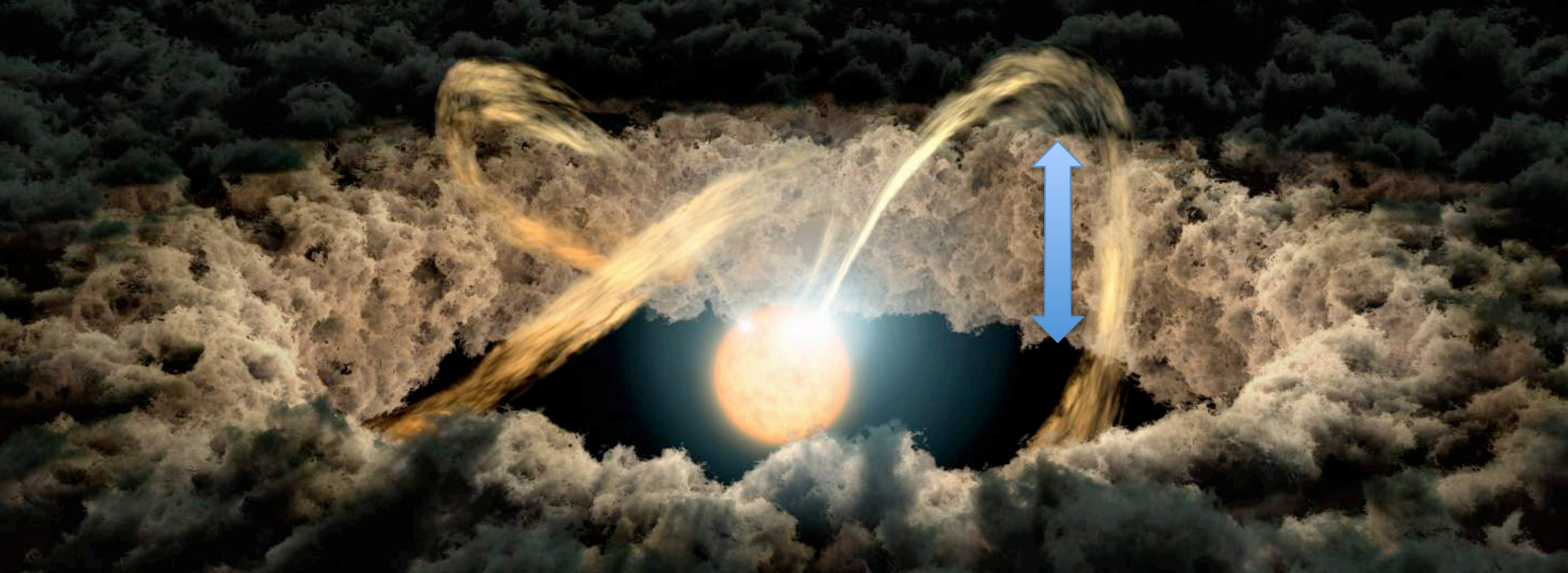
Credit: Johansen, Oichi, MacLow, Klahr, Henning & Youdin, 2007, Nature

Can coagulation cross the streaming regime?



Kataoka+ 2013

Column/Surface Density



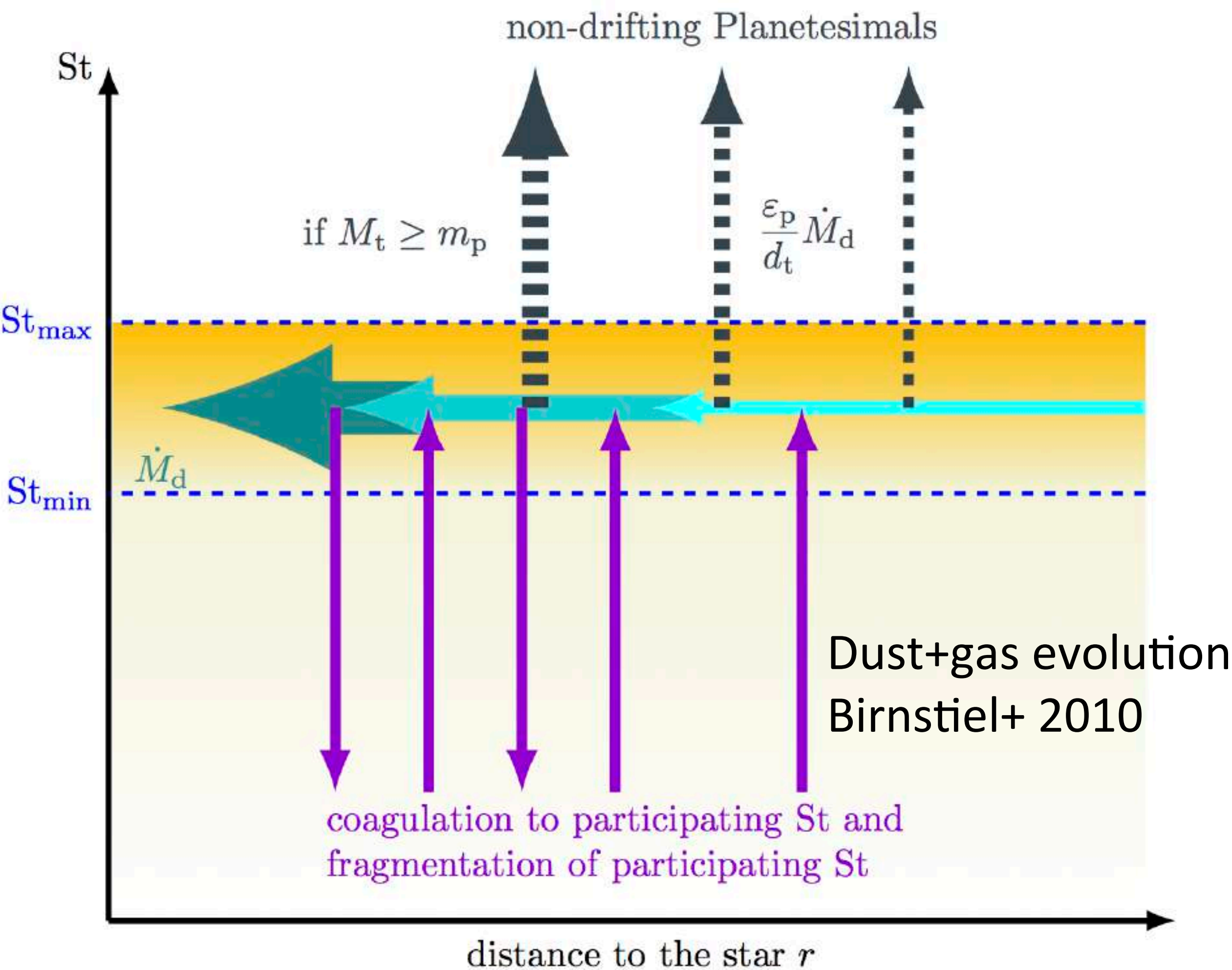
$$\Sigma = \int_{-\infty}^{\infty} \rho \, \mathrm{d}z$$

Image: NASA

Leading Questions

- Where and when do planetesimals form? How does the surface density profile look like, $\Sigma_p(r)$?
- Can we exclude certain parameter ranges of our model for the Solar Nebula?

The Planetesimal Model



- 0<ε<1: efficiency parameter
- d(r): trap distance
- M_t: trapped mass within 1 trap lifetime
- m_p: planetesimal mass

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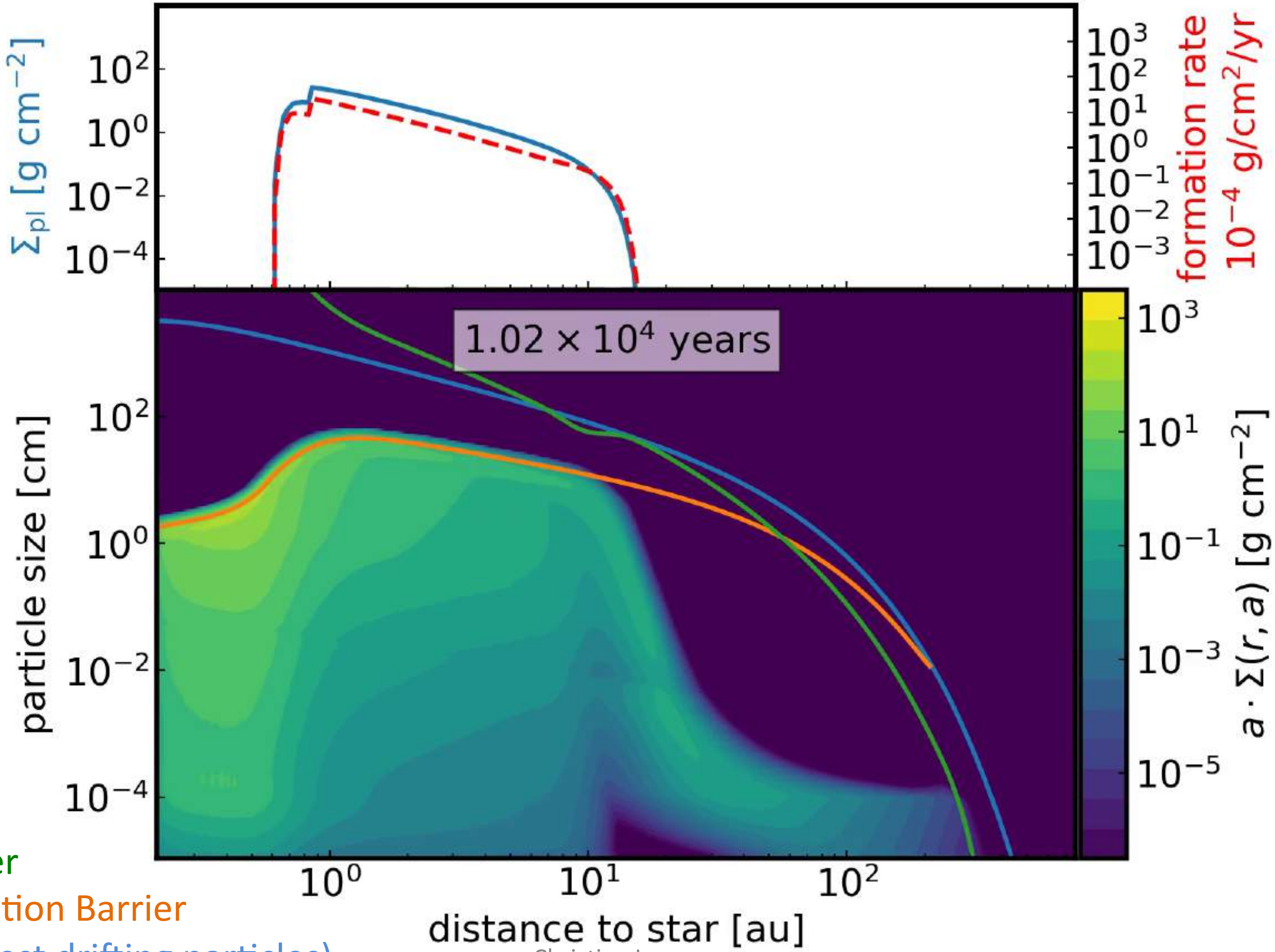
Image: Andreas Schreiber

Comments on Simulations

- Saturation/stagnation around 1 Myr
- Viscously evolving disk (dispersal)
- No…
  - photoevaporation (sink term for the gas)
  - planetesimal collisions (2nd generation planetesimals)
  - pebble accretion (Ormel & Klahr 2010)

Typical Evolution, $\boldsymbol{\alpha_t=10^{-3}}$, $M_{disk}=0.05M_\odot$, $r_c=35AU$, $\varepsilon=0.1$



Drift Barrier

Fragmentation Barrier

St = 1 (fastest drifting particles)

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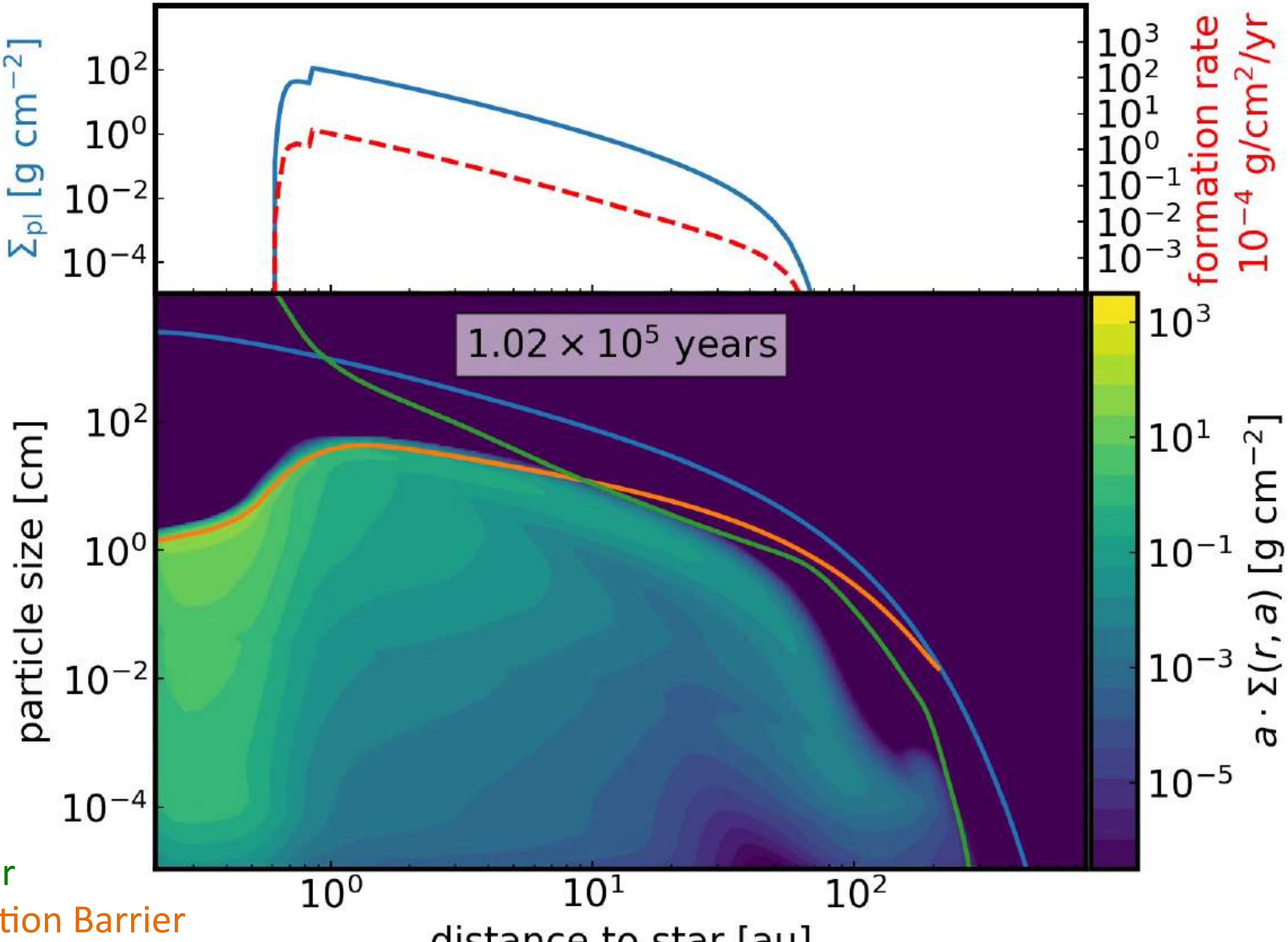

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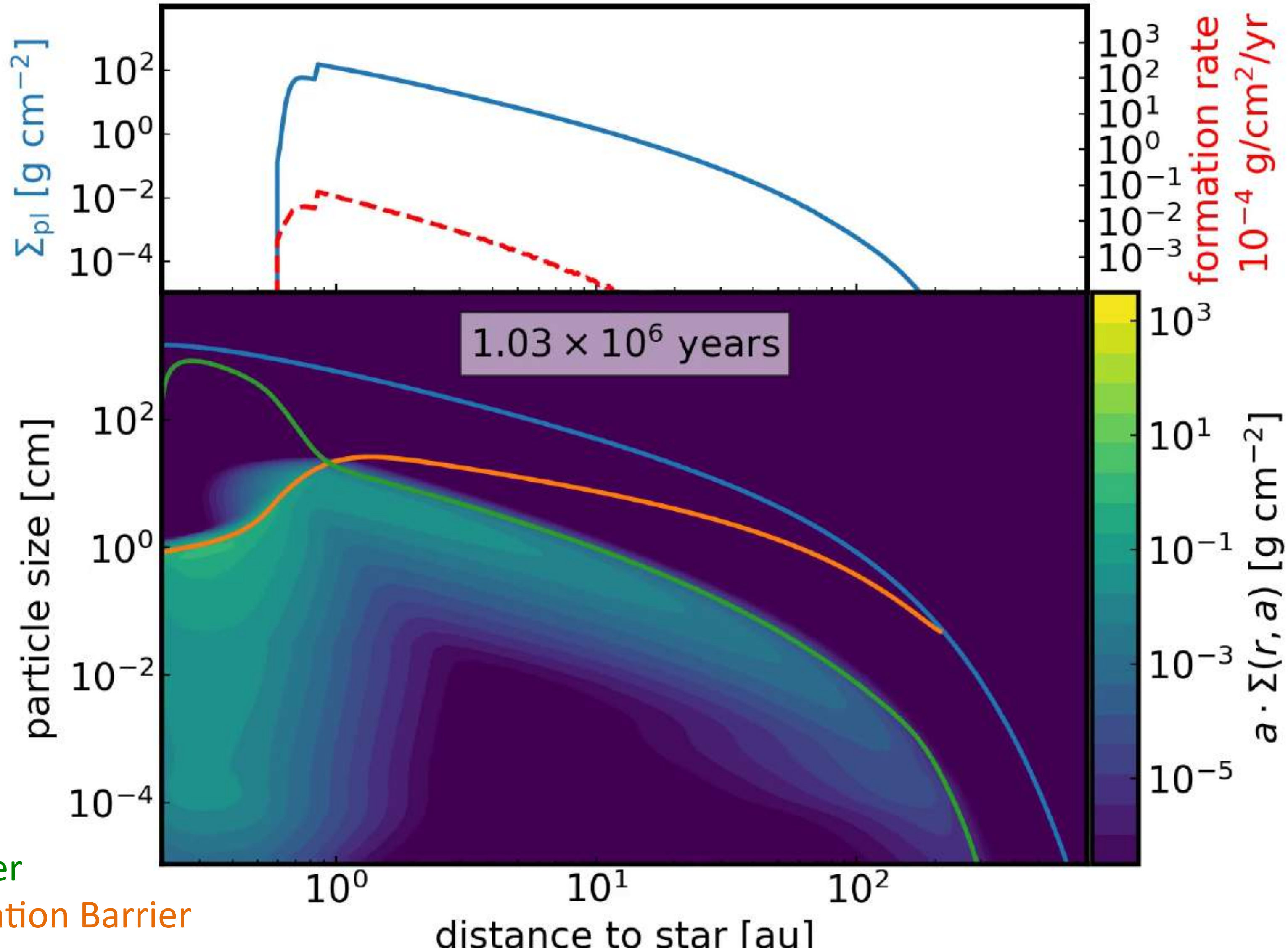
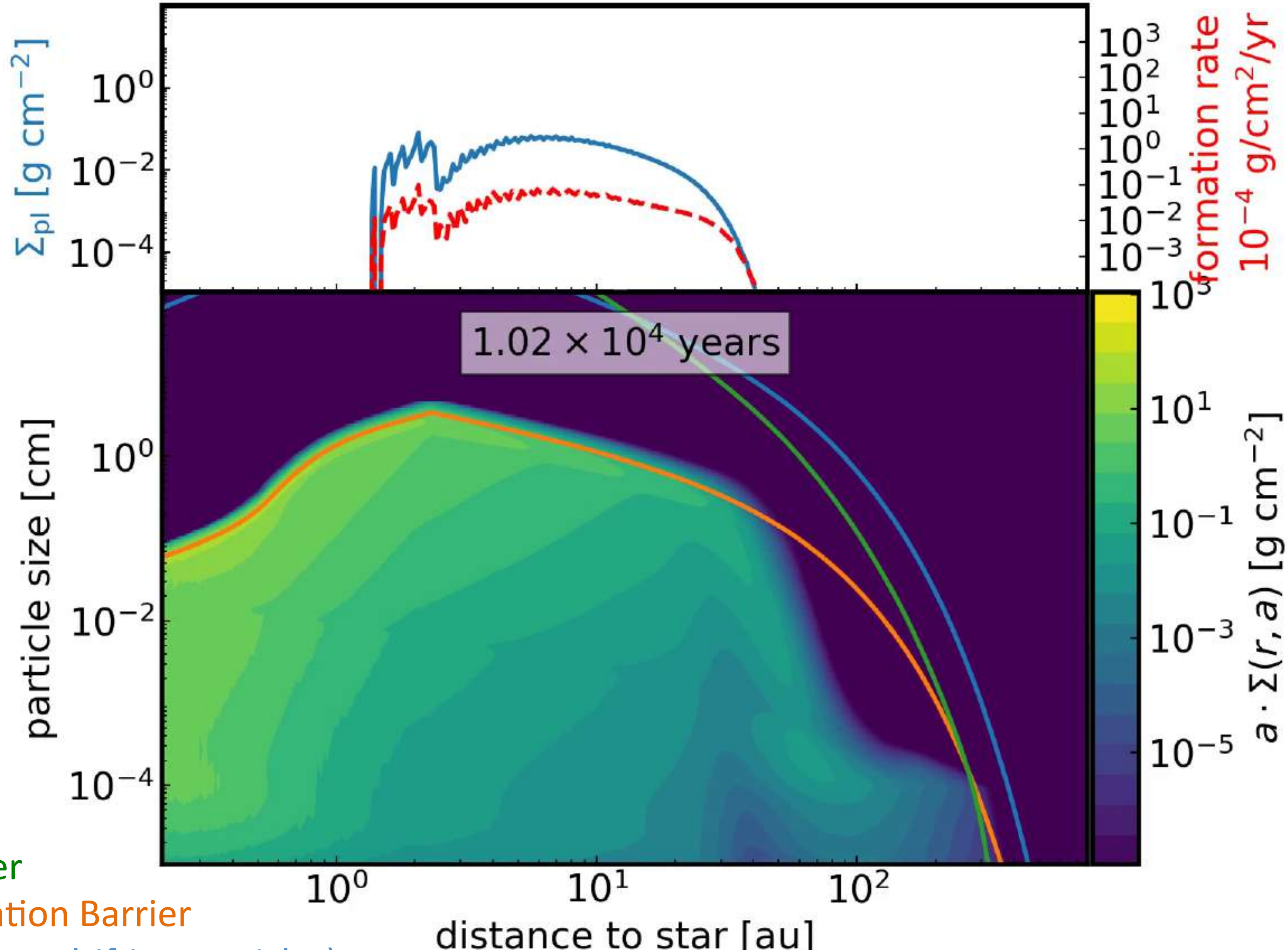


Drift Barrier
Fragmentation Barrier
St = 1 (fastest drifting particles)

Typical Evolution, $\boldsymbol{\alpha_t}$=**10^{-2}**, M_{disk}=0.05$M_\odot$, r_c=35AU, ε=0.1



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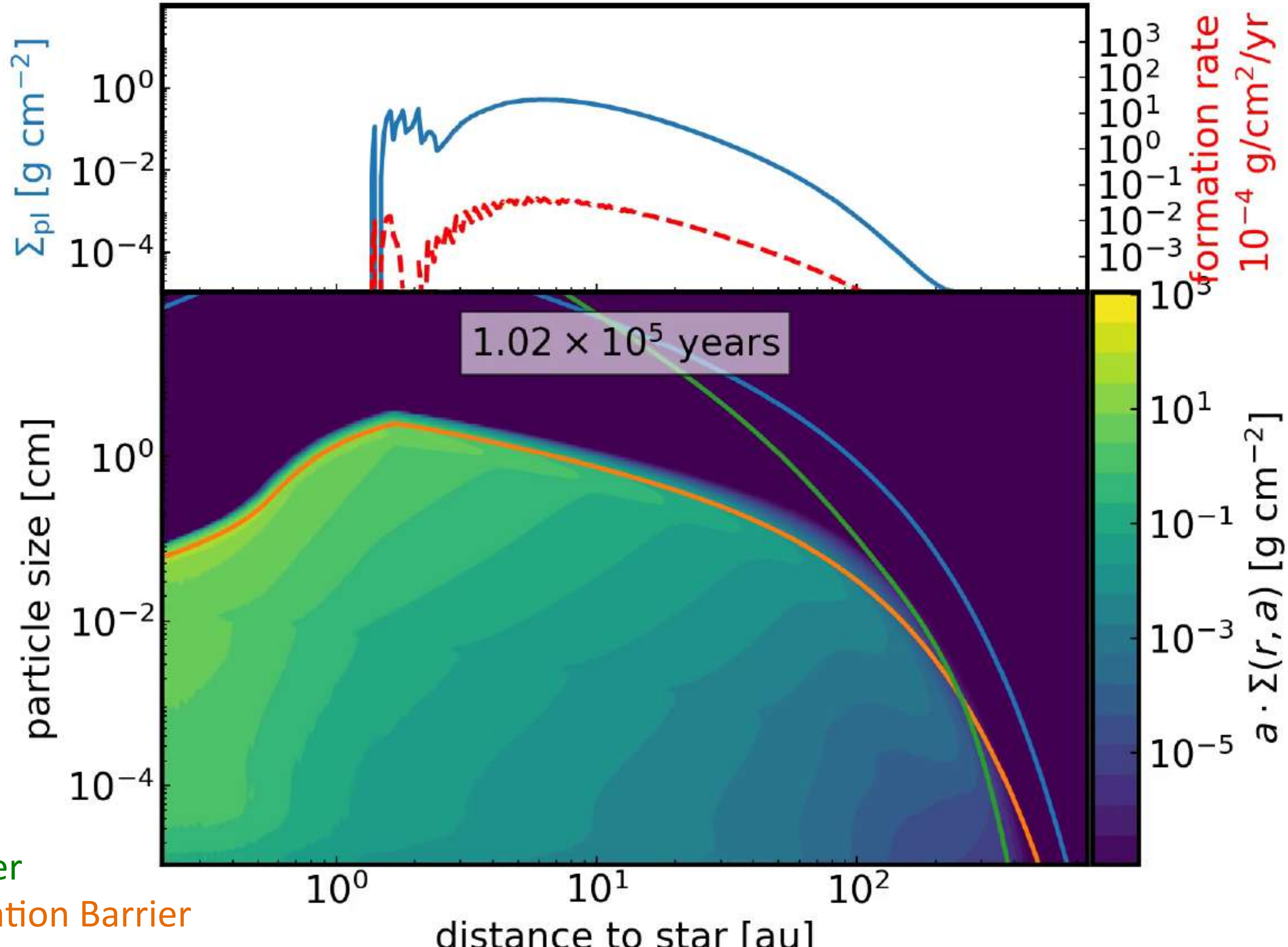

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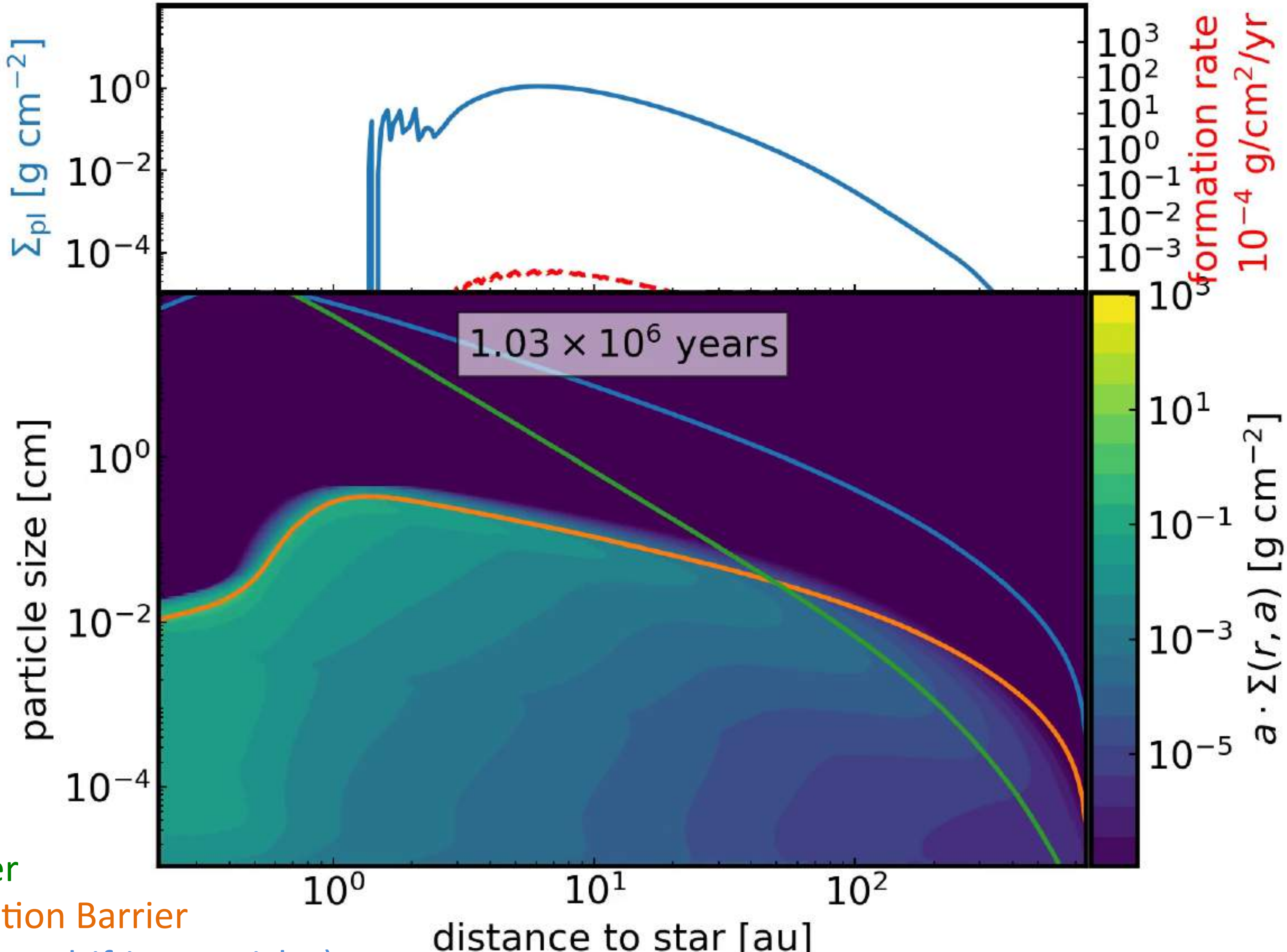

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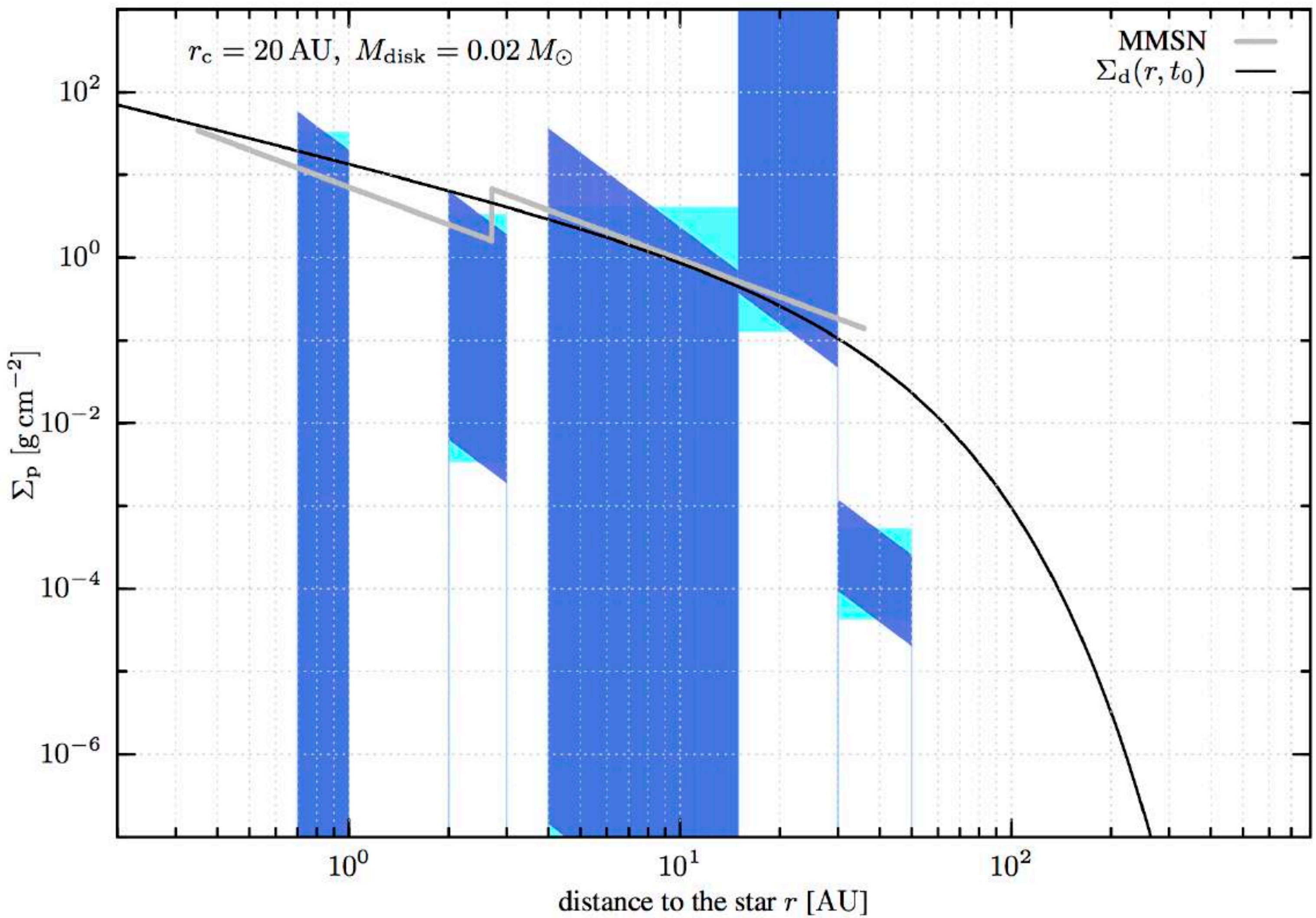
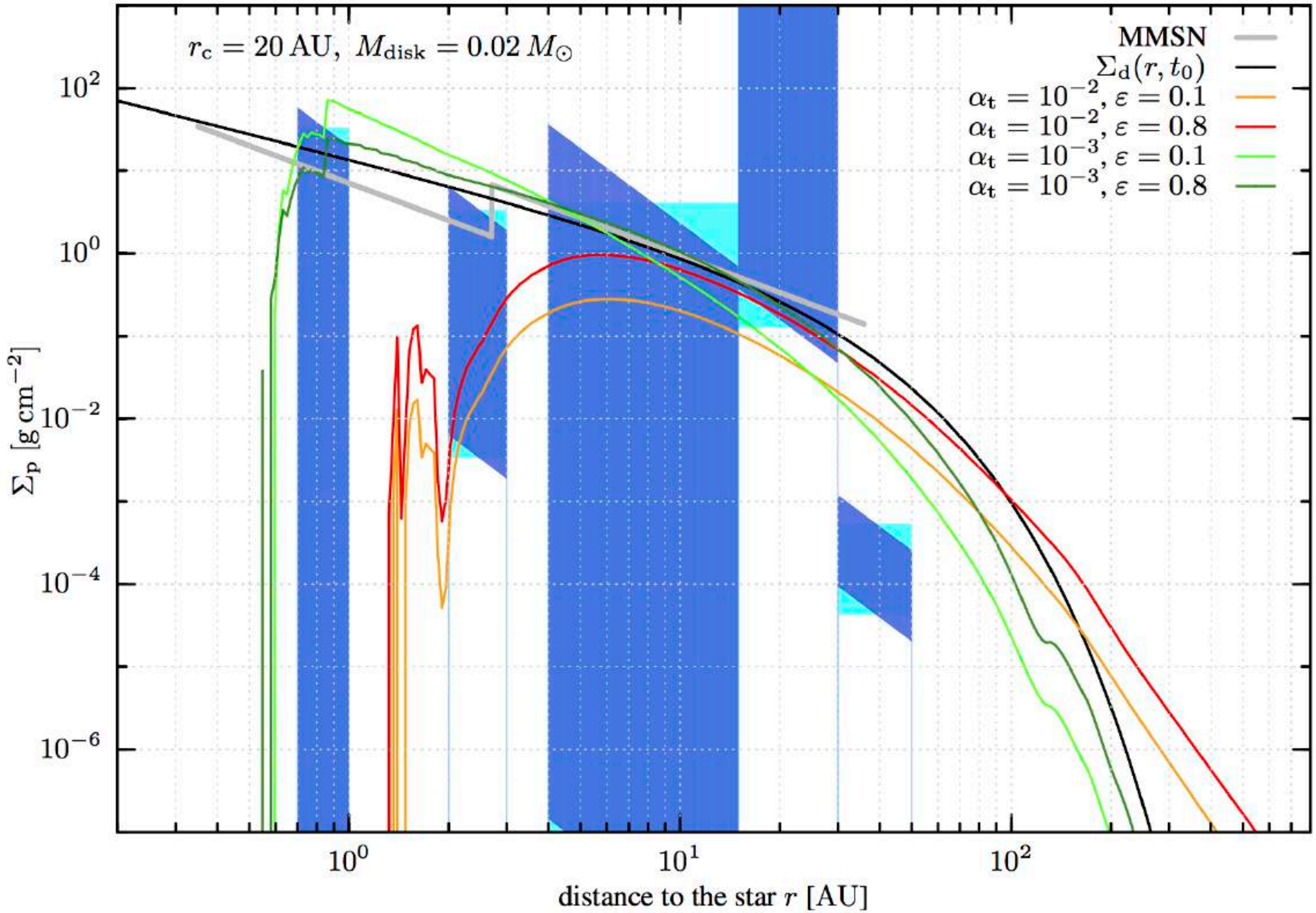
Image: Andreas Schreiber

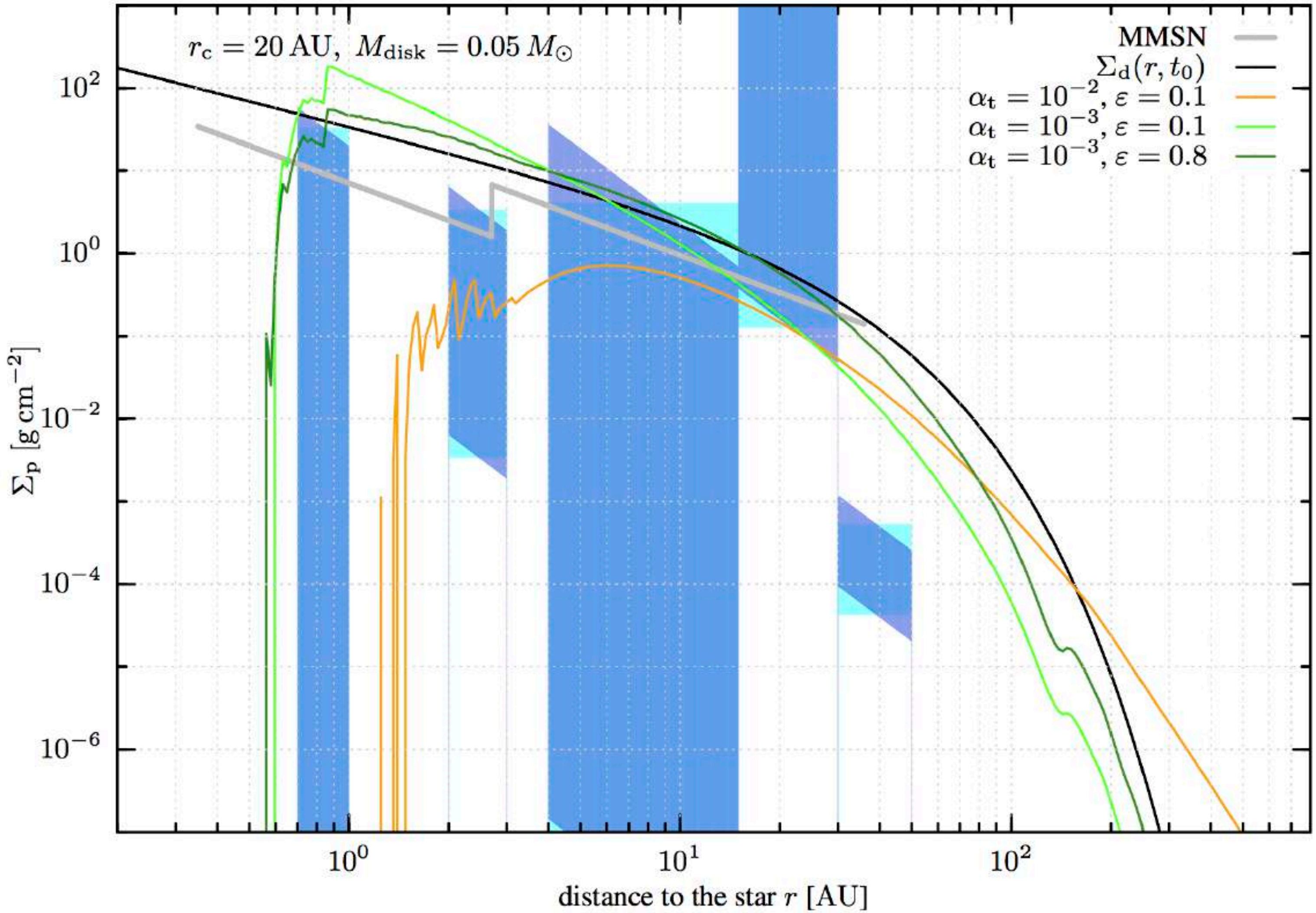
Results (1), small & light



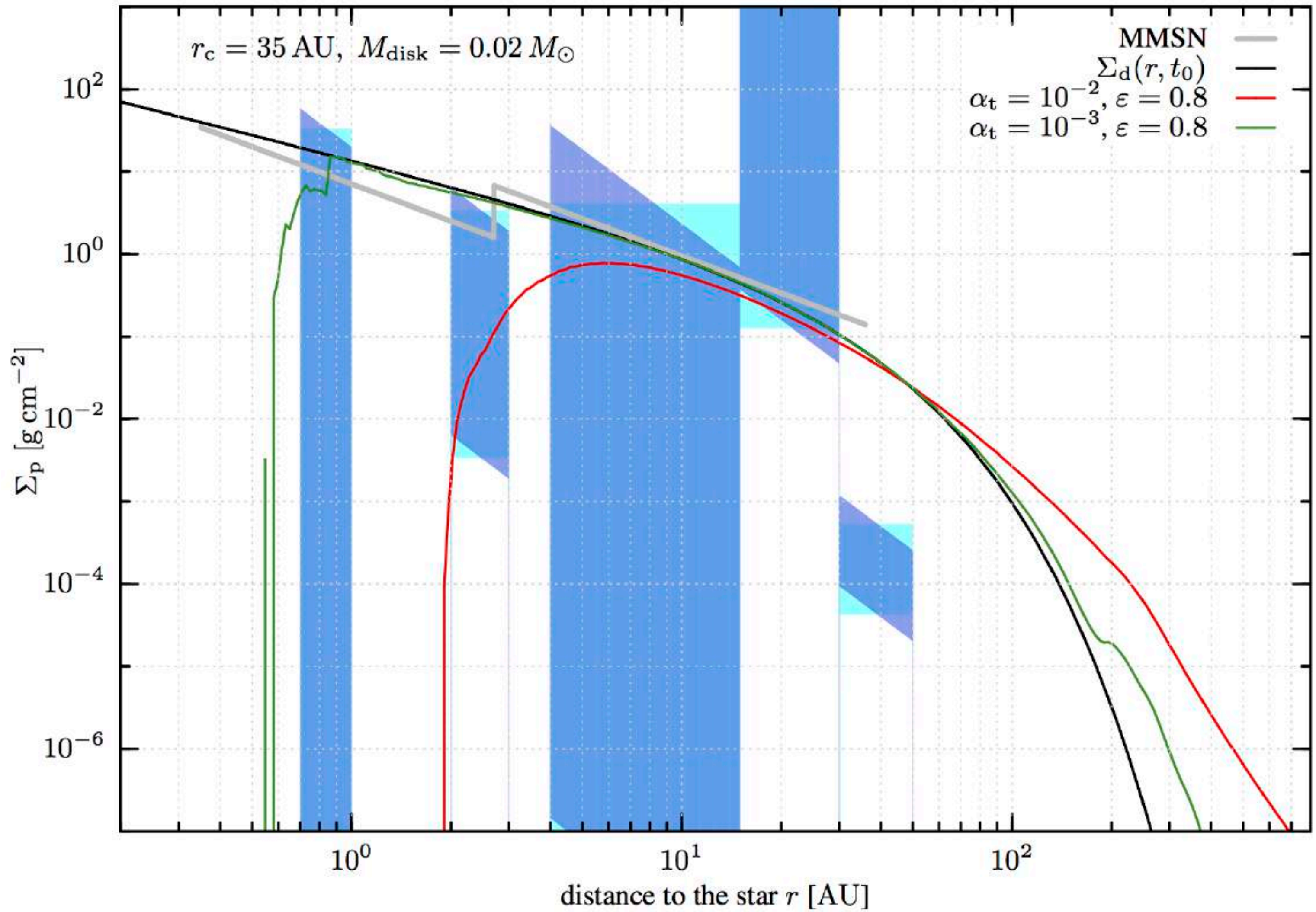
Results (1), small & light



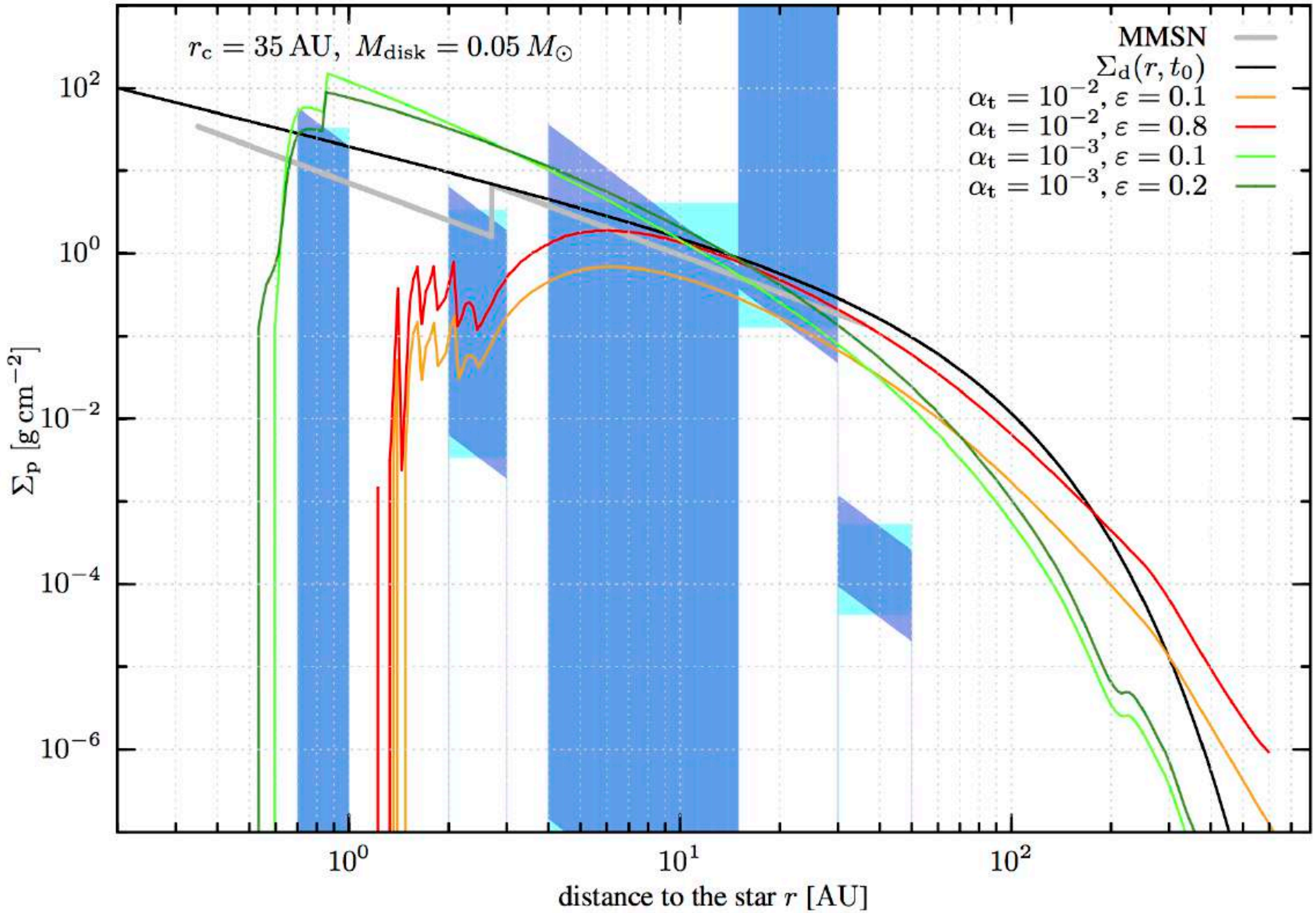
Results (2), small & heavy



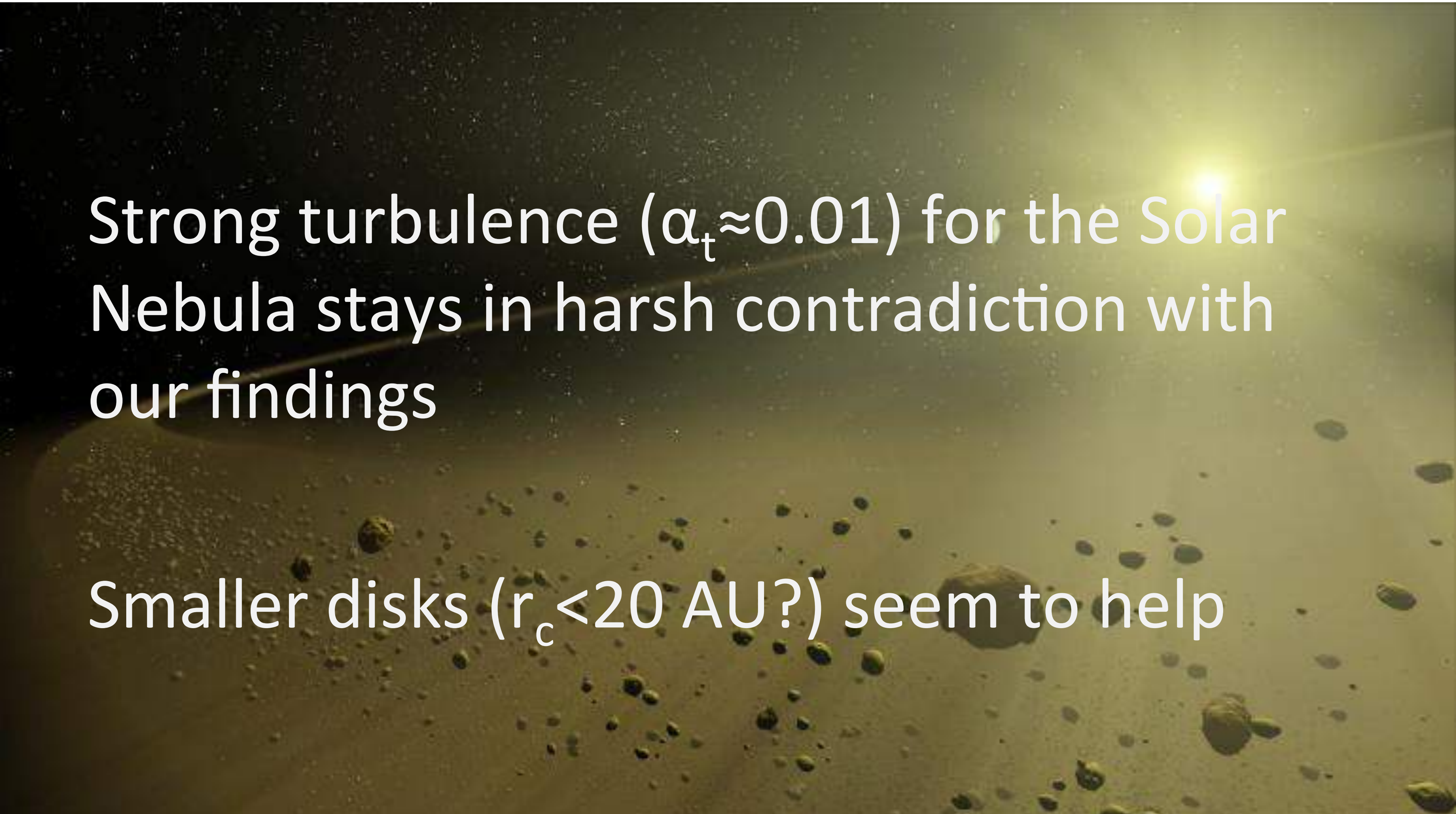
Results (3), large & light



Results (4), large & heavy



Conclusion



Strong turbulence ($\alpha_t \approx 0.01$) for the Solar Nebula stays in harsh contradiction with our findings

Smaller disks ($r_c < 20$ AU?) seem to help

Credit: California Institute of Technology

Outlook

- Pebble accretion (Ormel & Klahr 2010), mm-cm sized particles onto planetesimals
- Planetesimal-planetesimal interactions (leading to fragmentation & growth), N-Body
- Experiment with trap formation time and check other model parameters, fit the outer disk

Credit: Kouji Kanba

Summary

- Novel model: planetesimals via pebble trapping, directly linked to pebble flux

- Difficult to get a radial planetesimal profile with $\alpha_t \approx 10^{-2}$ allowing the formation of our planets in the Solar System

- Further physics has to be included (ptes-ptes collisions, photoevaporation, pebble accretion, temperature model, trap formation model…)