Hydrodynamic Modeling of Protoplanetary Disks with GFARGO2

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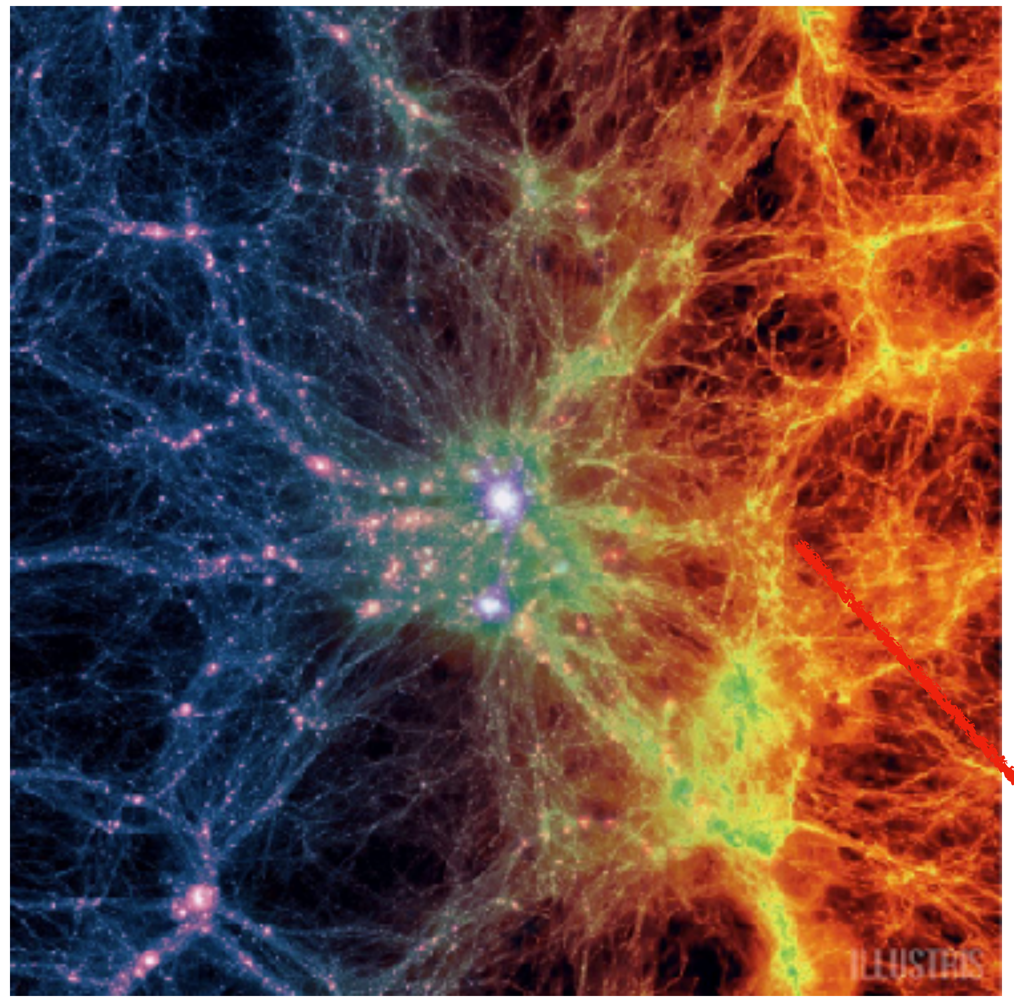
Structure of the Talk

- Astrophysical Context
- Hydrodynamic model (GFARGO2)
- Self-sustaining Vortices
- Advantages of GPU

Astrophysical Context

From large scale structure to planets

10^{13} au

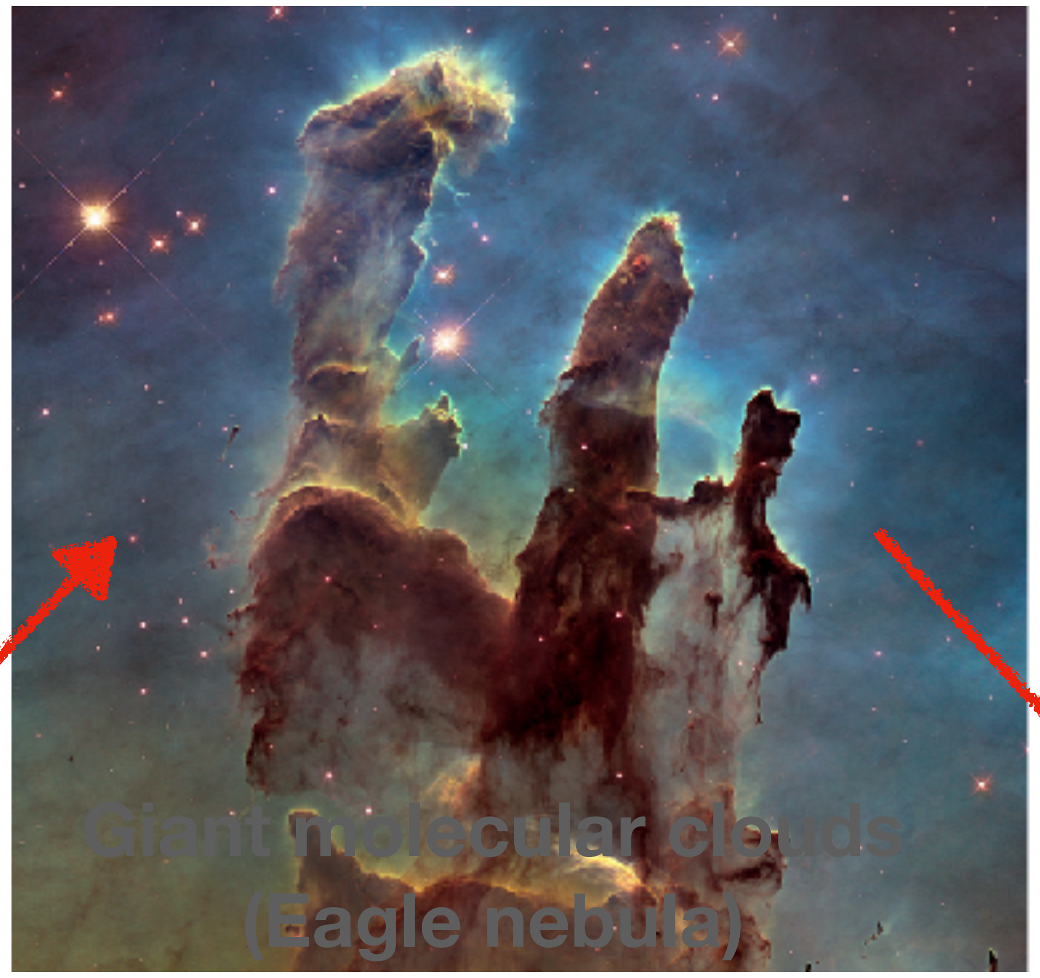


Large-scale structure
(Illustris simulations)

10^{9} au

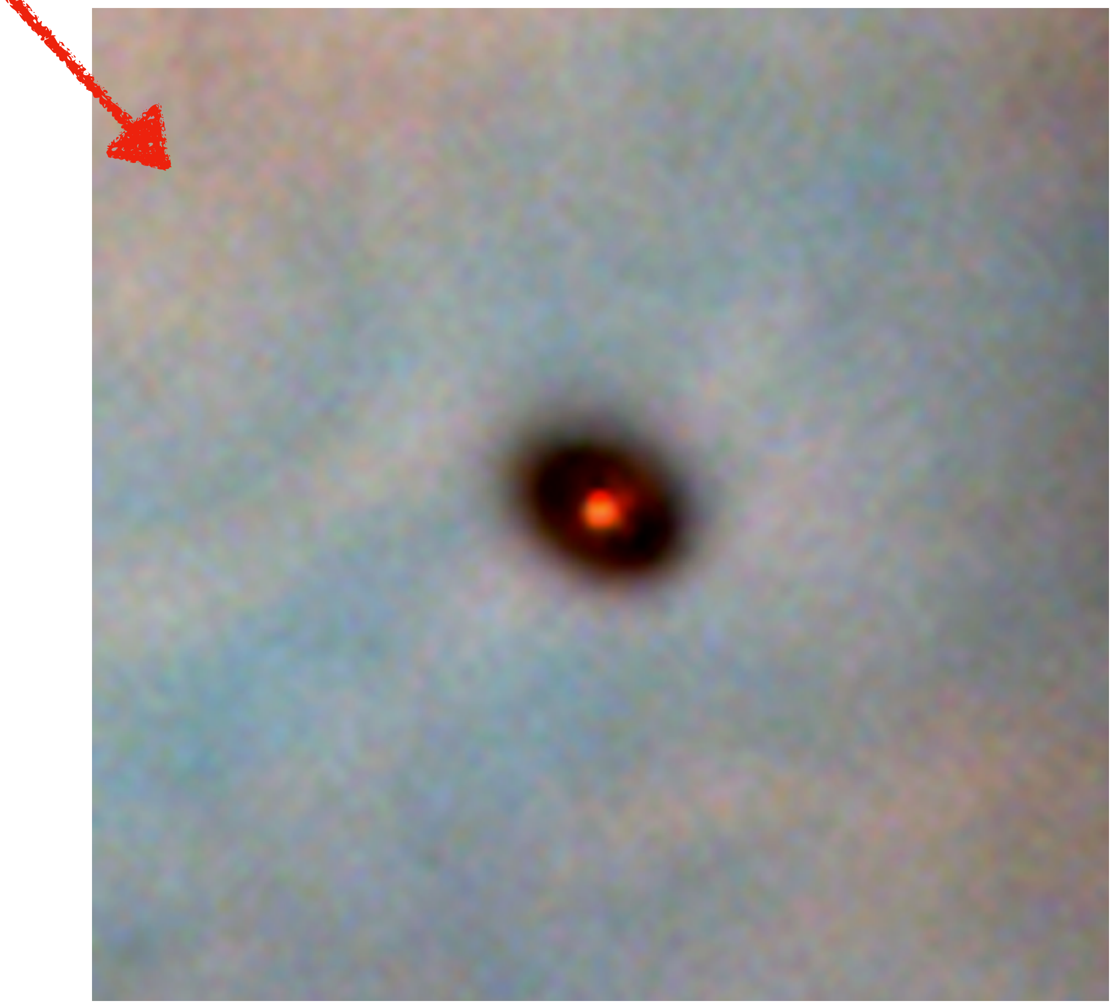
Spiral Galaxy (M81)

10^{6} au



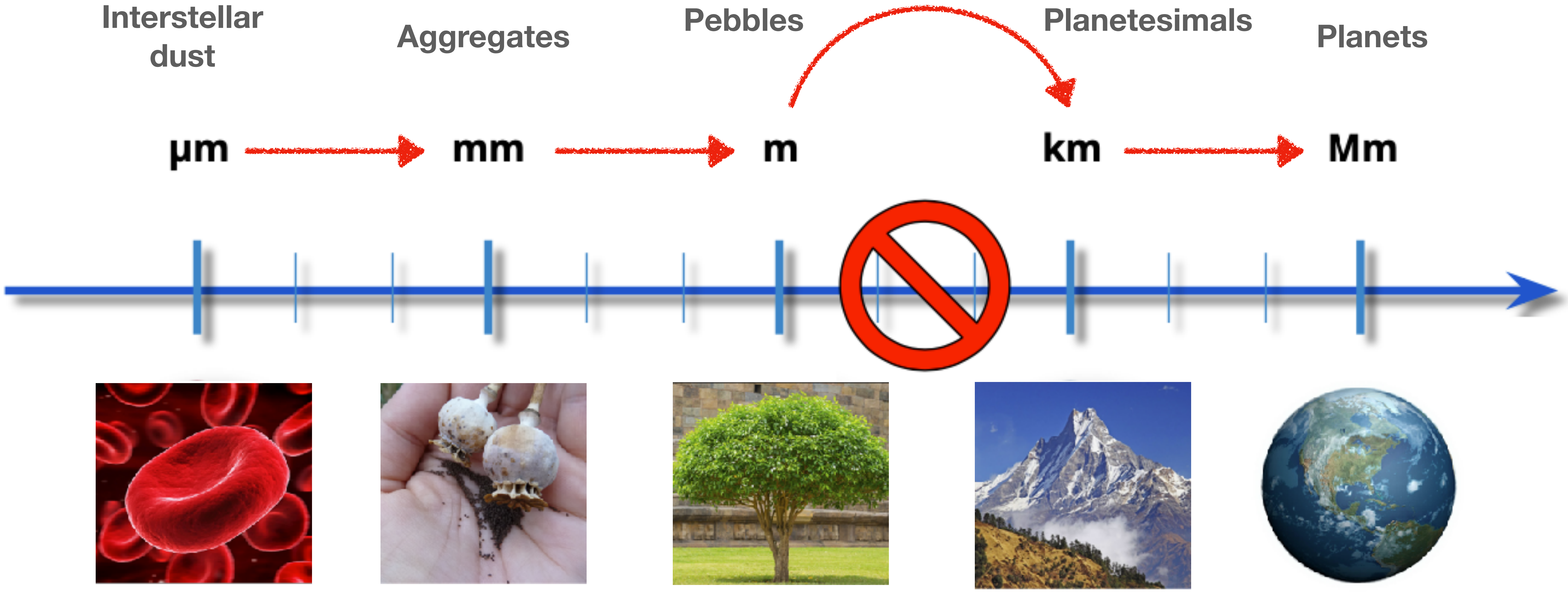
Giant molecular clouds
(Eagle nebula)

10^{3} au



Protoplanetary Disk
(Orion Proplyd)

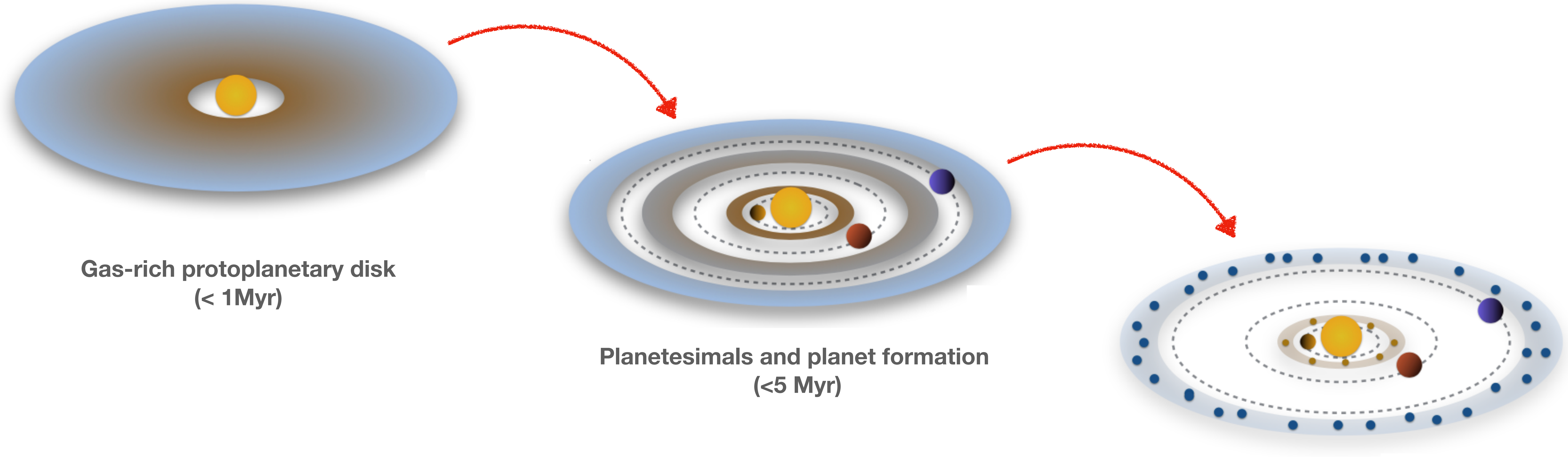
From stardust to planets



Interstellar dust — Aggregates — Pebbles — Planetesimals — Planets

µm → mm → m → km → Mm

Planet formation

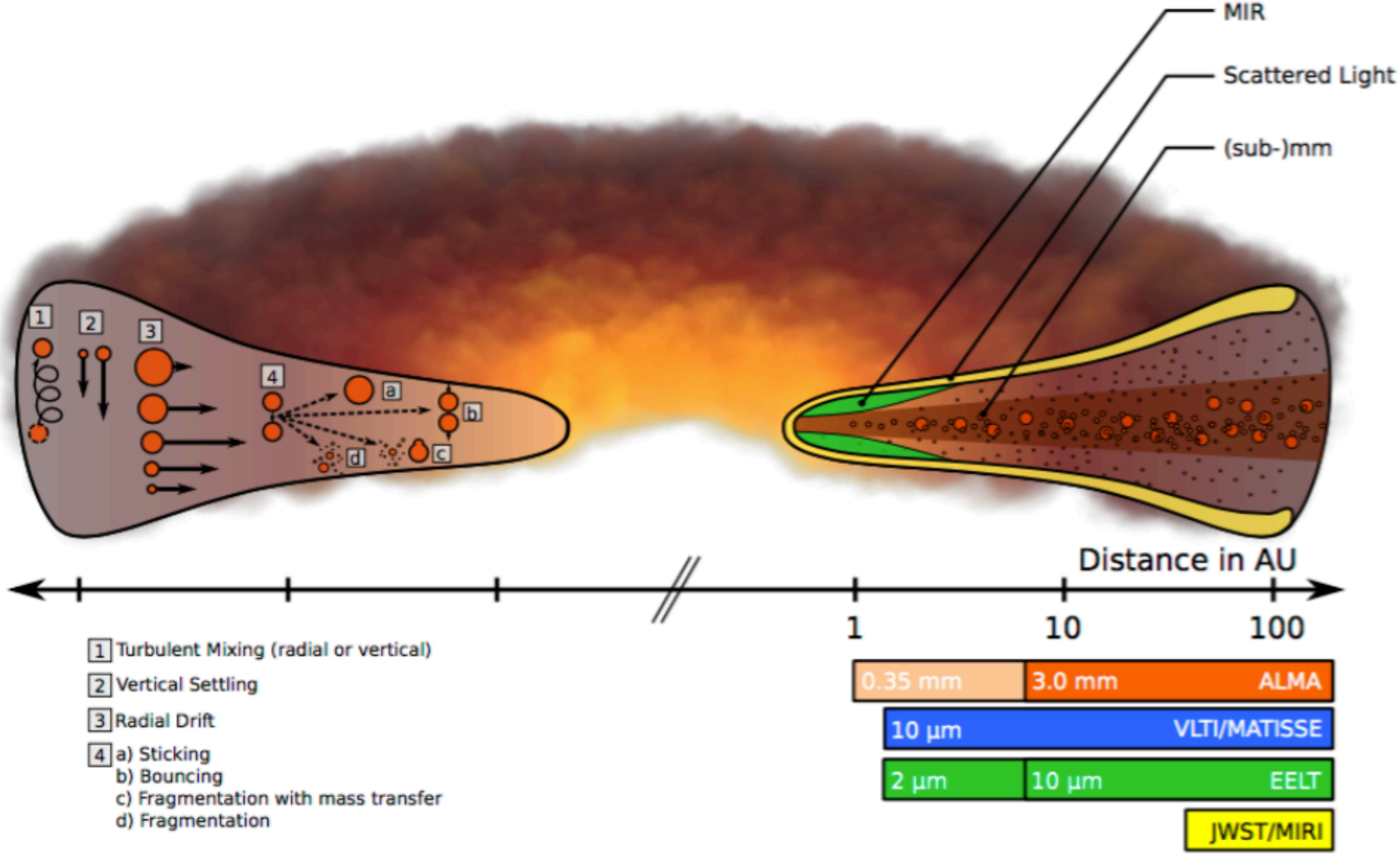


Gas-rich protoplanetary disk
(< 1Myr)

Planetesimals and planet formation
(<5 Myr)

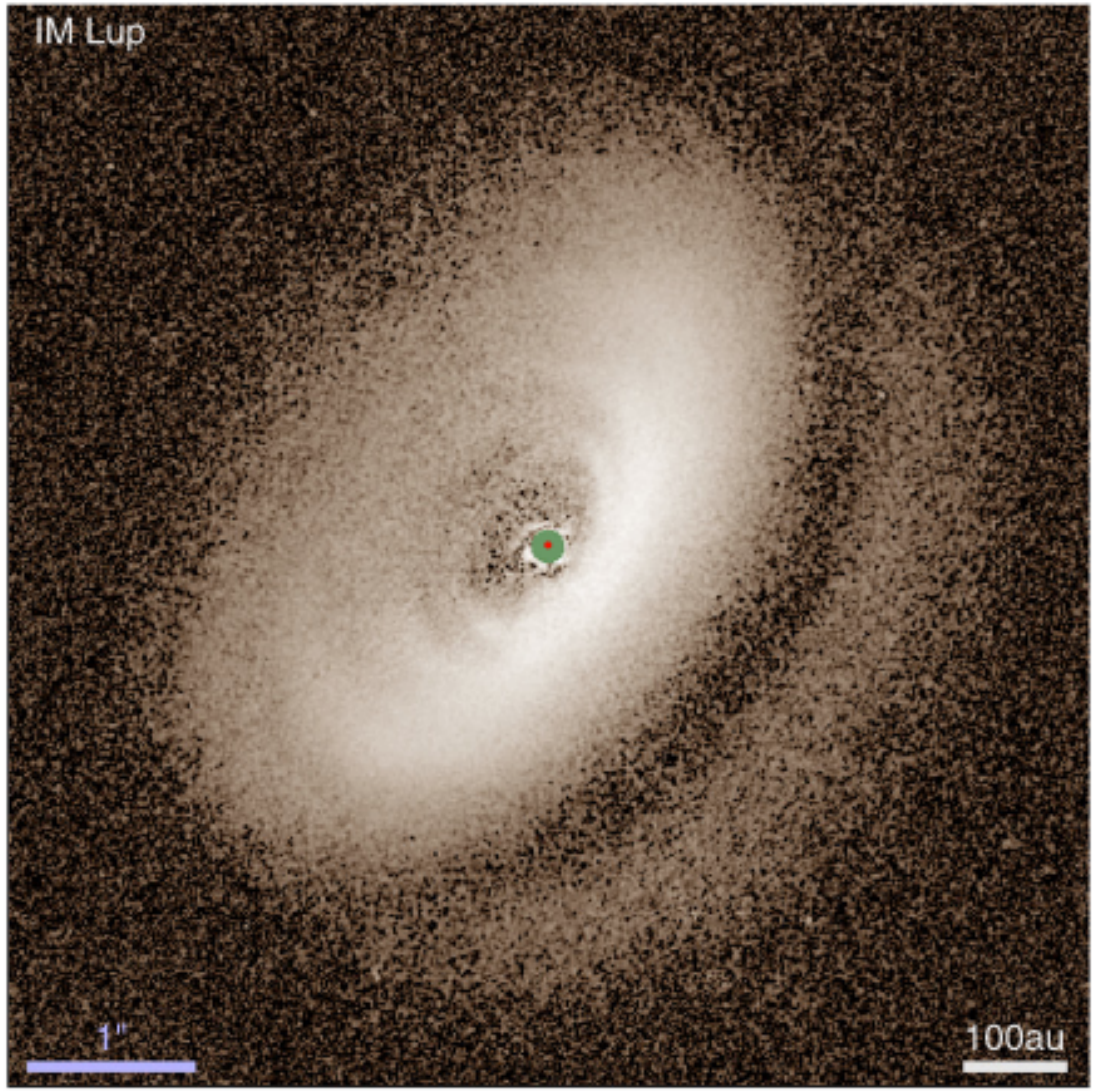
Planetary systems
(~10 Myr)

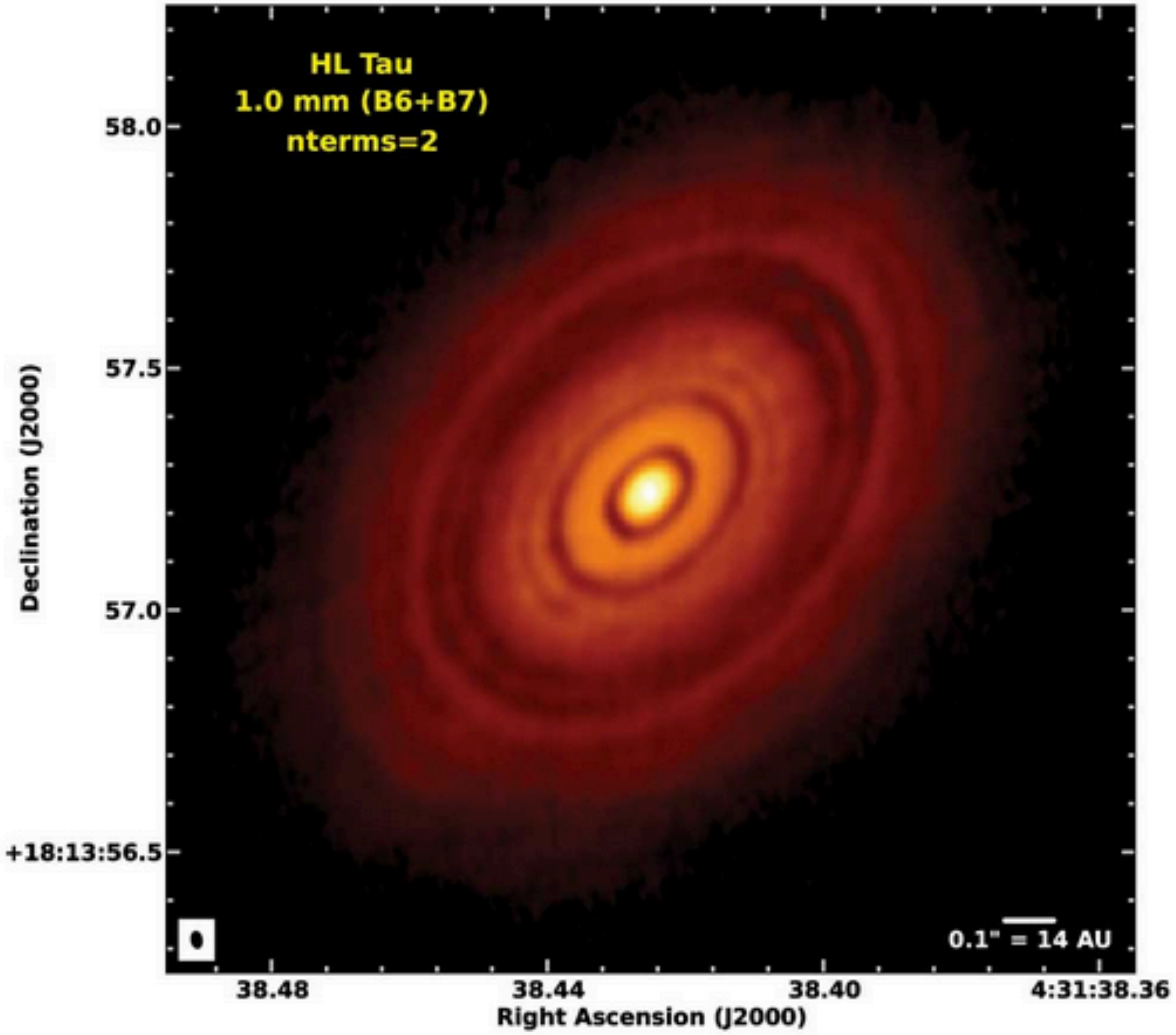
Observations of Protoplanetary Disks



Testi et al. 2014

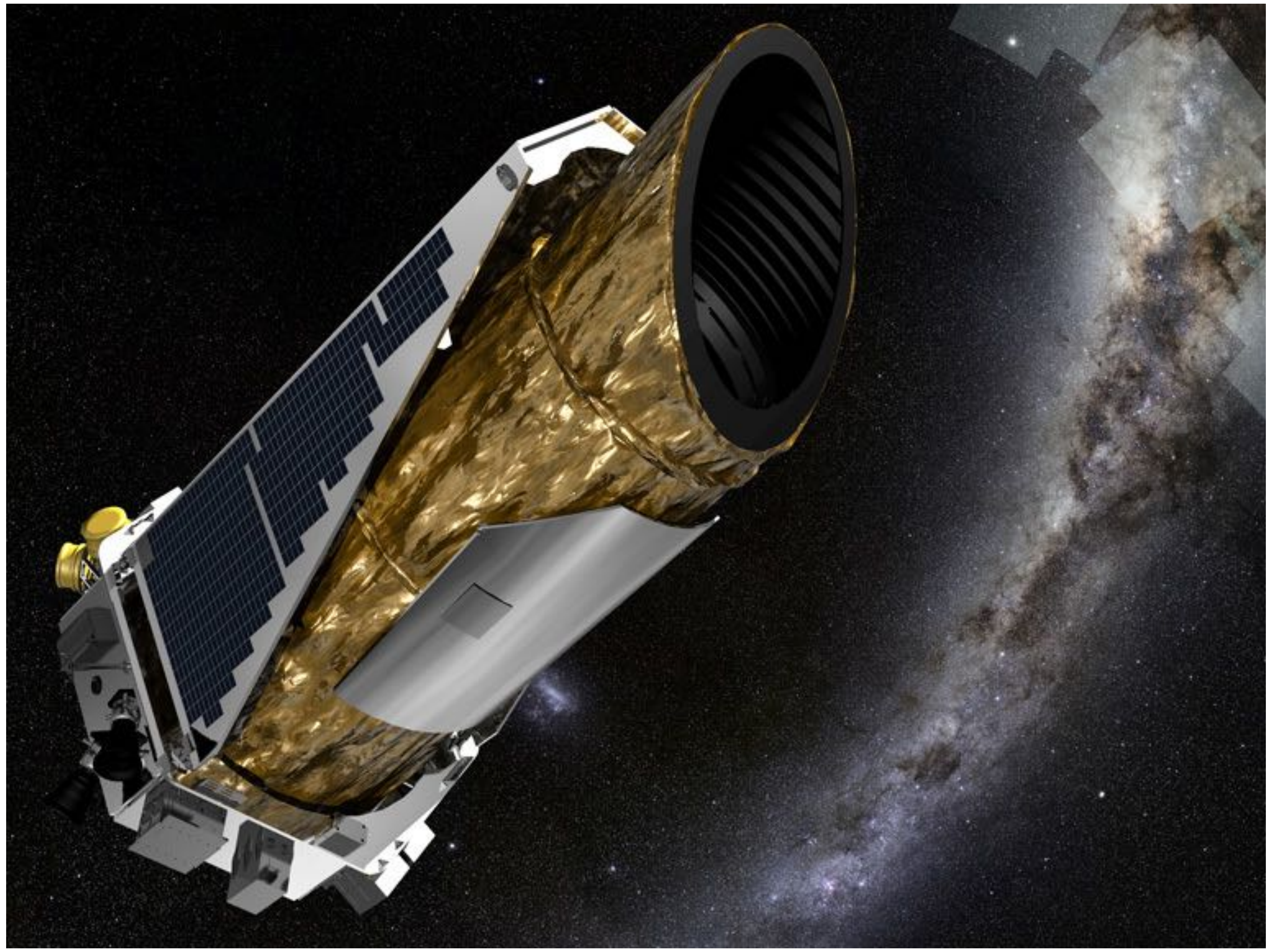
Observations of Protoplanetary Disks

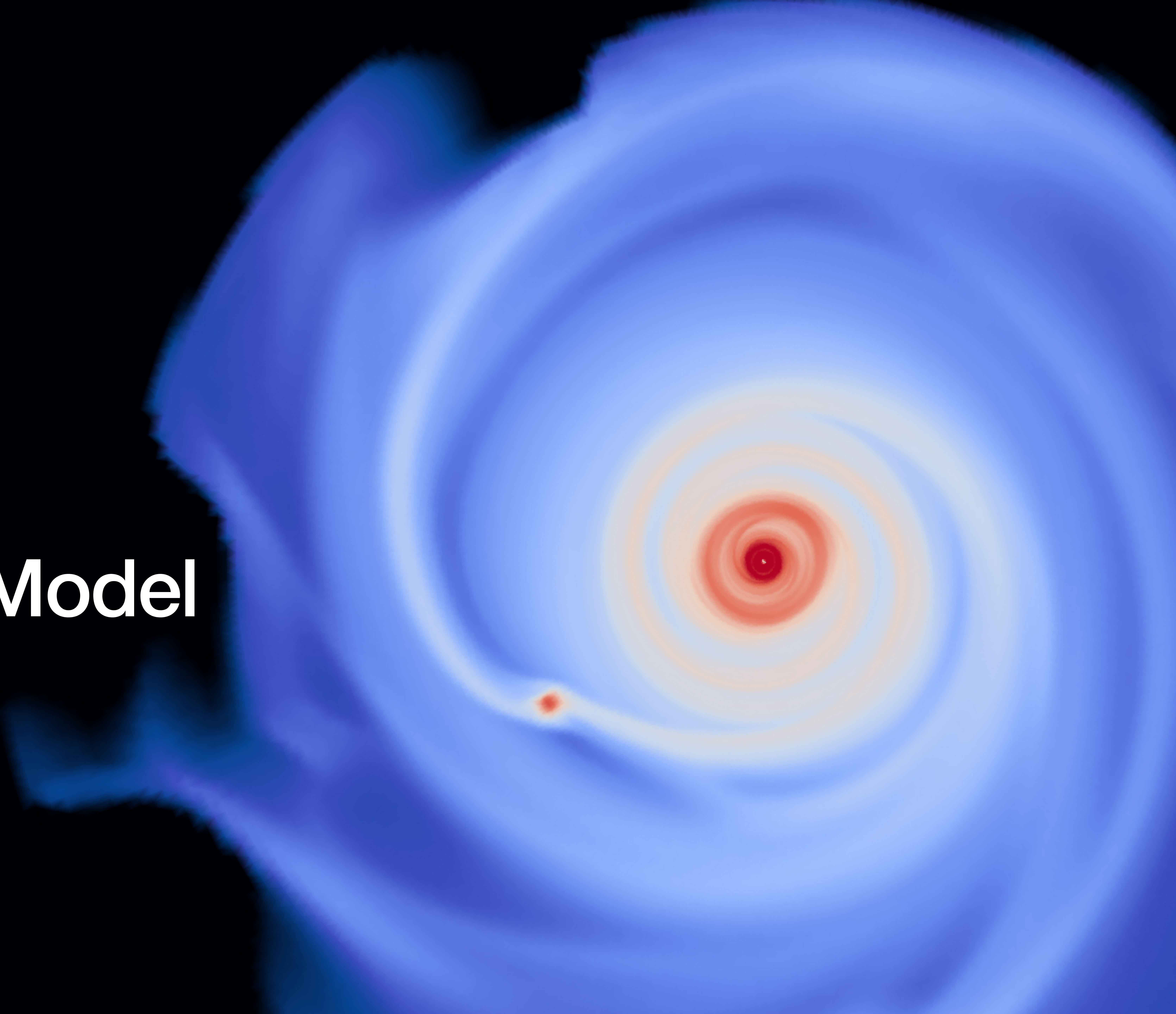




Avenhaus et al. 2018, ALMA Partnership 2014

Observations of Planets





Hydrodynamic Model

Model of a Protoplanetary Disk

- Most mass is in the gas
- Small amount of solids are present in dust
- Partially ionized - MHD effects

Dynamics of gas component

- Continuity equation $$\frac{\partial \Sigma_{\mathrm{g}}}{\partial t} + \nabla \cdot (\Sigma_{\mathrm{g}} \boldsymbol{v}) = 0$$
- Momentum conservation $$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla) \boldsymbol{v} = -\frac{1}{\Sigma_{\mathrm{g}}} \nabla P + \nabla \cdot \boldsymbol{T} - \nabla \Phi - \frac{1}{\Sigma_{\mathrm{g}}} \boldsymbol{f}_{\mathrm{drag}}$$
- Energy equation $$\frac{\partial e}{\partial t} + \nabla \cdot (e \boldsymbol{v}) = -P \nabla \cdot \boldsymbol{v} + Q_{\nu} + Q_{\pm}$$

Dust evolution, EoS and Gravity

- Dust continuity equation $$\frac{\partial \Sigma_{\mathrm{d}}}{\partial t} + \nabla \cdot \Sigma_{\mathrm{d}} \boldsymbol{u} = -\nabla \cdot \boldsymbol{j}$$
- Dust momentum conservation $$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla) \boldsymbol{u} = -\nabla \Phi + \frac{1}{\Sigma_{\mathrm{d}}} \boldsymbol{f}_{\mathrm{drag}} - (\boldsymbol{u} \cdot \nabla) \boldsymbol{j}$$
- Equation of state $$P = (\gamma - 1) e$$
- Gravitational potential $$\Phi_{\mathrm{tot}}(R, \phi) = -G \frac{M_*}{R} + \Phi_{\mathrm{ind}}(R, \phi) + \Phi_{\mathrm{sg}}(R, \phi)$$

GFARGO2 Code

- GPU-based code
- Cylindrical coordinate system
- FARGO (Fast Advection in Rotating Gaseous Objects) algorithm

  > The advection equation is solved in local Keplerian velocity

  > Improves both efficiency (CFL condition) and accuracy (truncation error)
- Conserves mass and angular momentum to machine precision
- Dust pressureless fluid

Barriers for dust growth

- Meter-size (drift) barrier

  > Dust always feels a headwind in gas disk, hence ends up drifting inwards

- Fragmentation barrier

  > Relative velocity between dust particles sets a maximum size limit

Self-Sustaining Vortices

Viscosity in a disk (Magnetorotational instability)

- Shakura Sunyaev Kinematic viscosity

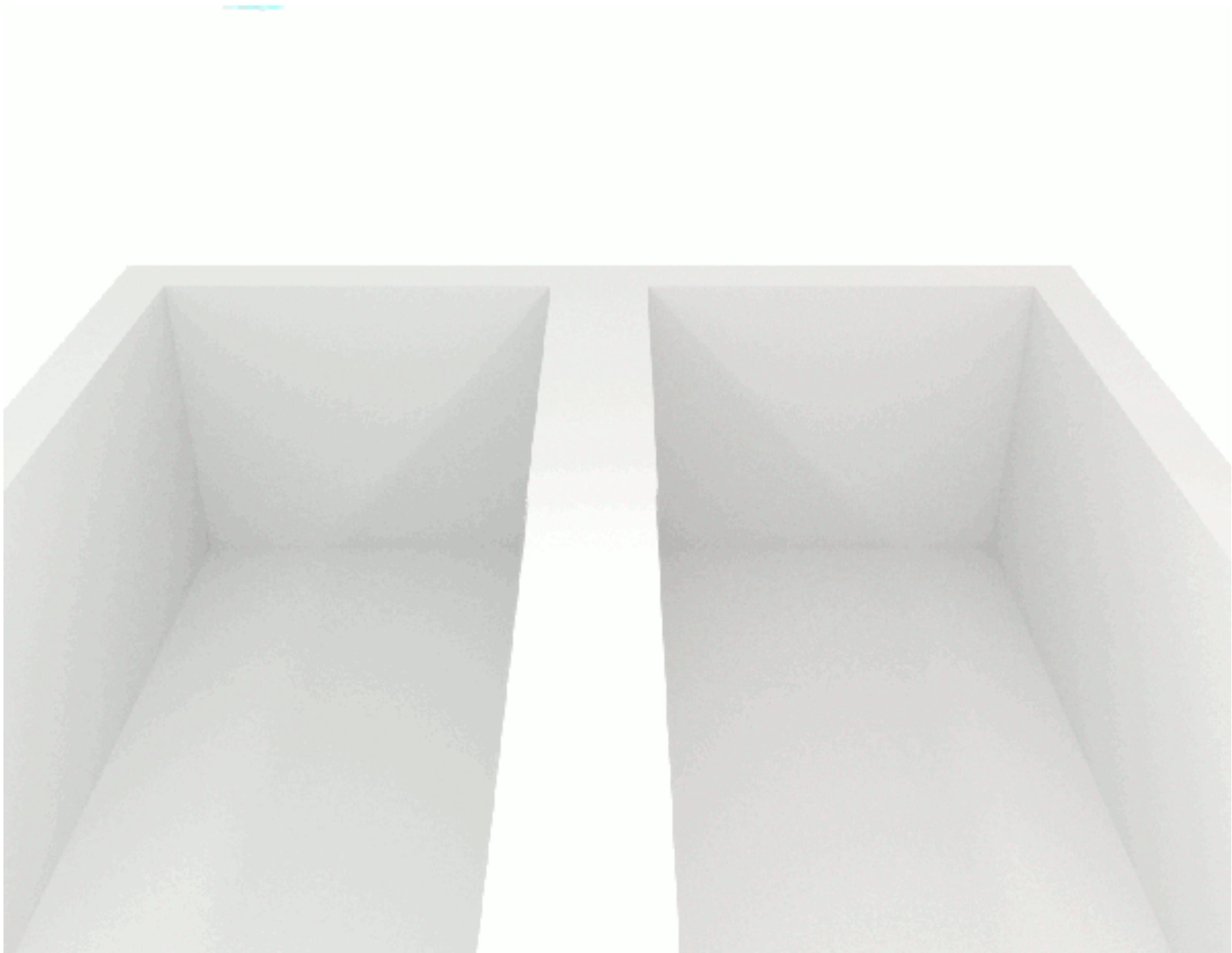
$$\nu = \alpha \frac{c_{\mathrm{s}}^2}{\Omega_{\mathrm{K}}}$$

- Assume dust particles adsorb electrons & ions

$$\alpha = \alpha_{\mathrm{bg}} \left(\frac{\Sigma_{\mathrm{d}}}{\Sigma_{\mathrm{d}}^0}\right)^{\phi_{\mathrm{d}}} \left(\frac{\Sigma_{\mathrm{g}}}{\Sigma_{\mathrm{g}}^0}\right)^{\phi_{\mathrm{g}}}$$

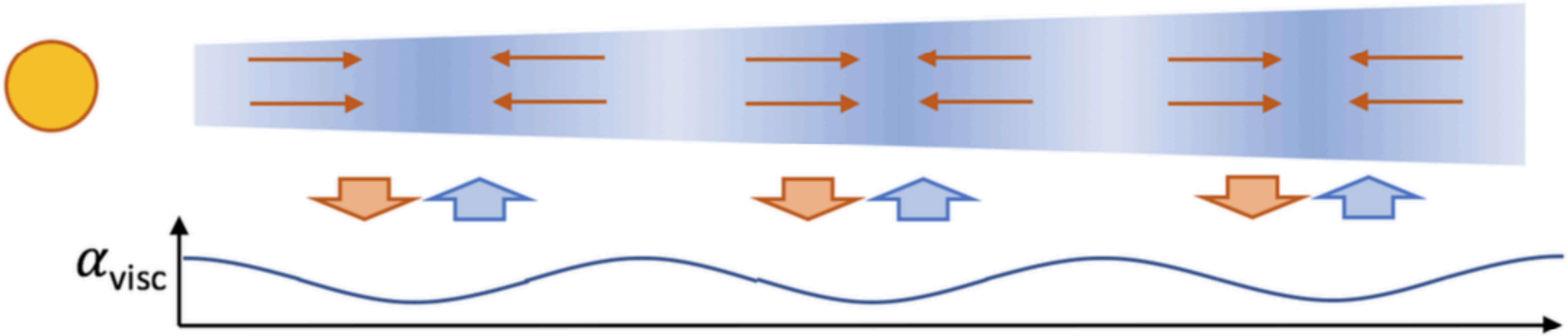
$$\phi_{\mathrm{d}} = -1$$

$$\phi_{\mathrm{g}} = 1$$



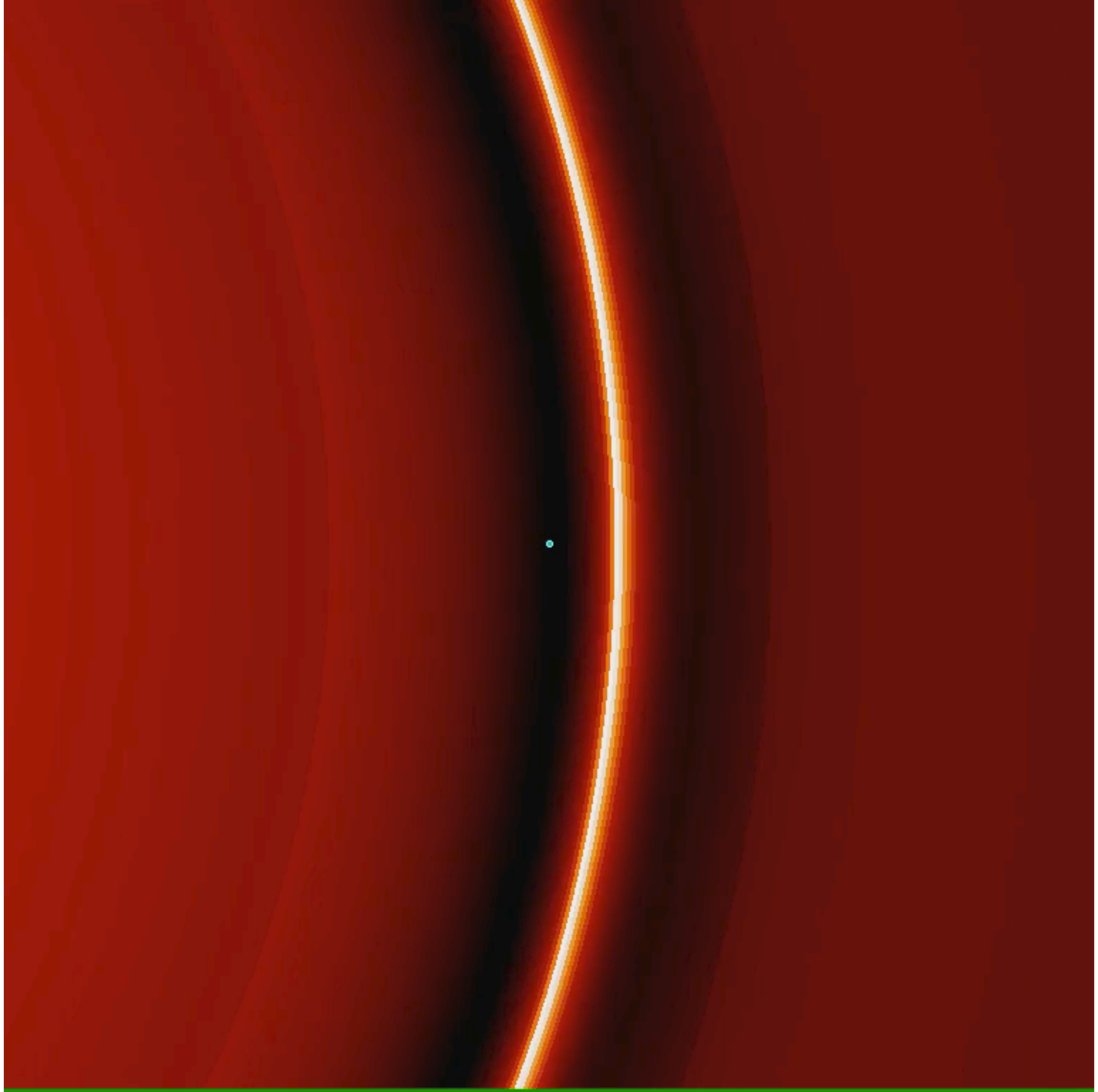
By Synapticrelay - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=50627718

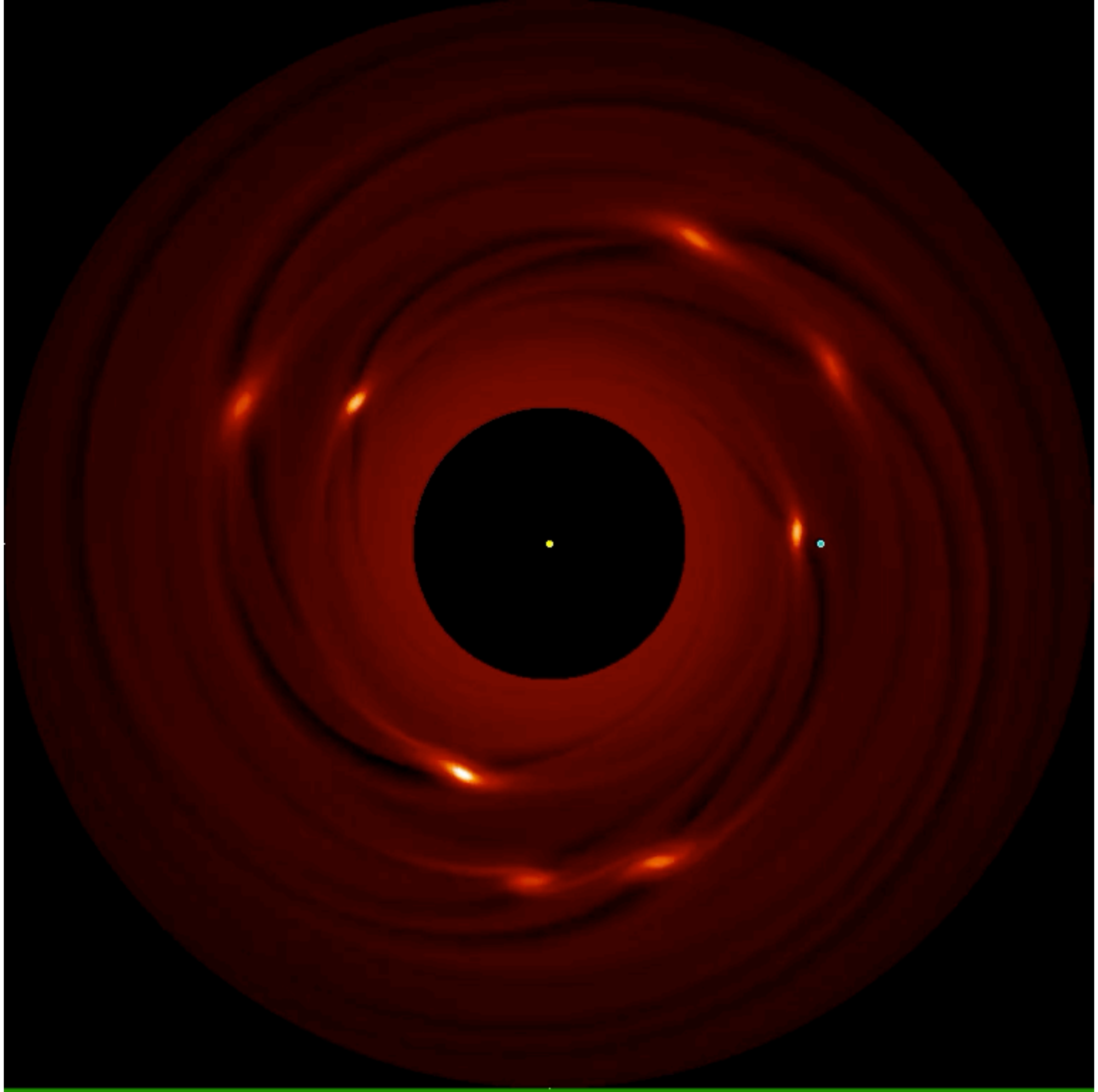
Viscous Ring Instability



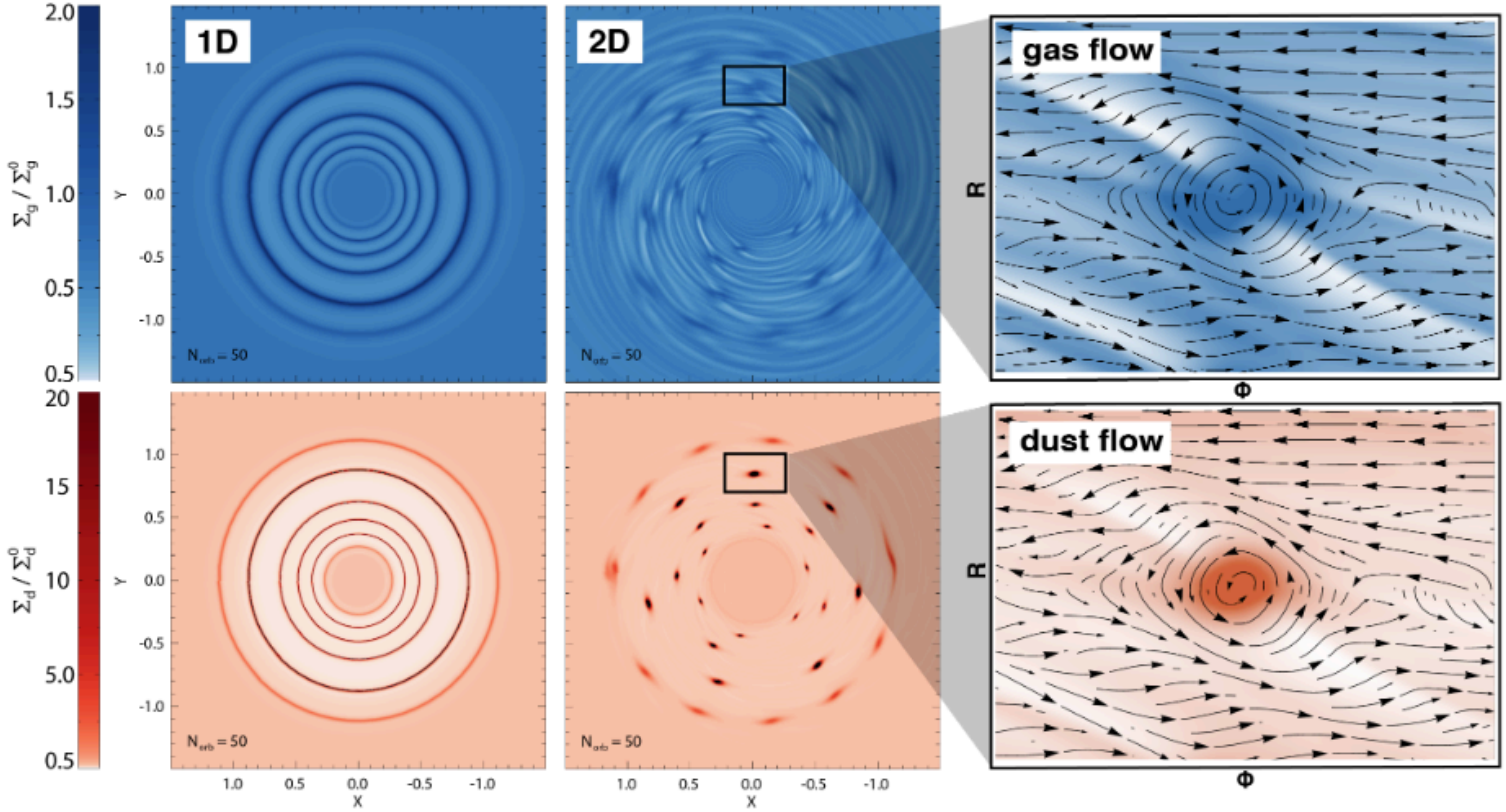
- Perturbation in dust reduces viscosity
- This accumulates gas
- Dust drifts towards gas pressure maximum
- Positive feedback

Dullemond & Penzlin 2017





Regály, Kadam, & Dullemond (2020)



Why are the results important?

- The vortices are secularly stable for 1000s of orbits
- Drift barrier is overcome
- Fragmentation barrier is overcome (high dust-to-gas density ratio)
- Collect a significant amount of dust (0.1 - 10 M_E)
- Simple physically motivated model

GPUs


GEFORCE RTX
GIGABYTE
GEFORCE RTX
GIGABYTE
GEFORCE RTX
GIGABYTE
GEFORCE RTX
GIGABYTE
WORKSTATION

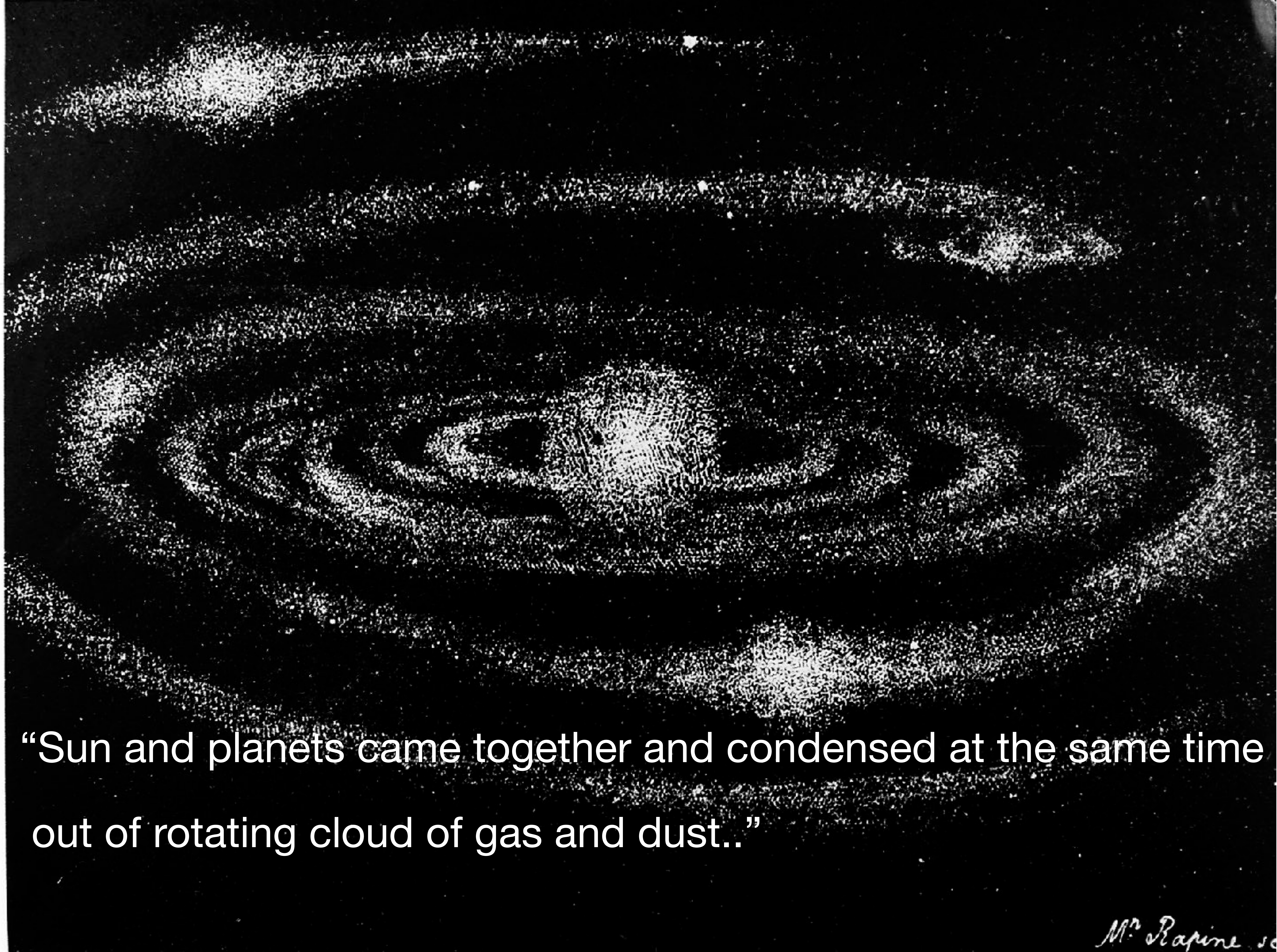
Role of GPUs

- Need to solve several PDEs, calculate several fields, gravity is expensive
- Fast: ~12 hours for a simulation (1024 x 512 on Nvidia Tesla K80)
- Energy efficient: ~300 W
- Tested on Nvidia Tesla C2075 (2x slower), Volta 100 (2x faster)
- Future of computational astrophysics

THE NEBULAR
HYPOTHESIS OF
LAPLACE

—See p. 102

Pierre-Simon Laplace
(1749-1827)



“Sun and planets came together and condensed at the same time out of rotating cloud of gas and dust..”