Basics of protoplanetary disc structure and dynamics II

Geoffroy Lesur, IPAG, Grenoble

IPAG
Institut de Planétologie
et d'Astrophysique
de Grenoble

Roscoff PNPS JWST School
Oct. 2 2024

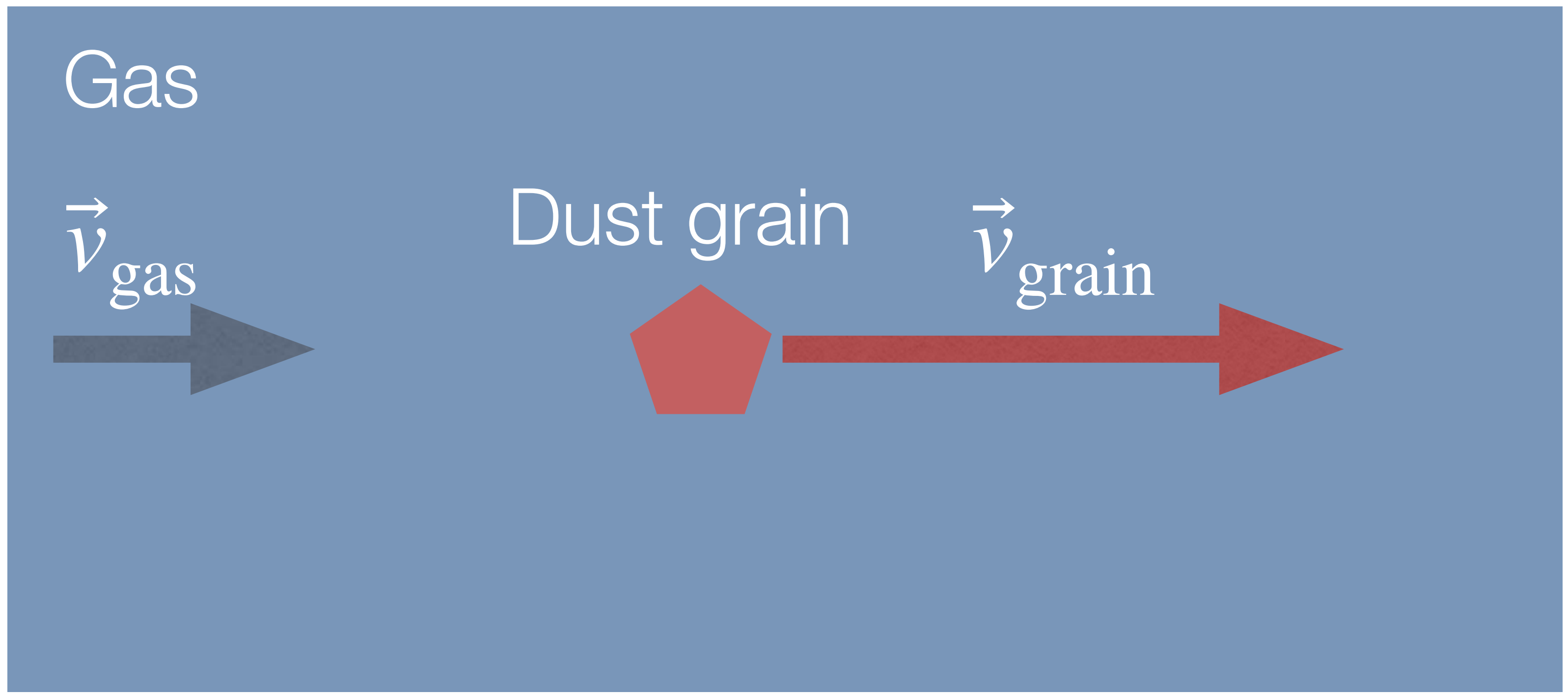
UNIVERSITÉ
Grenoble
Alpes

Outline

- Dust dynamics
  - Radial drift
  - Settling
- Winds
  - Photoevaporation & MHD disc winds
  - MHD wind basics
  - Impact on the secular evolution
  - Wind-dust interaction

Dust & gas dynamics

Dust grains dynamic 101



- The dust grain is coupled to the gas through a drag:

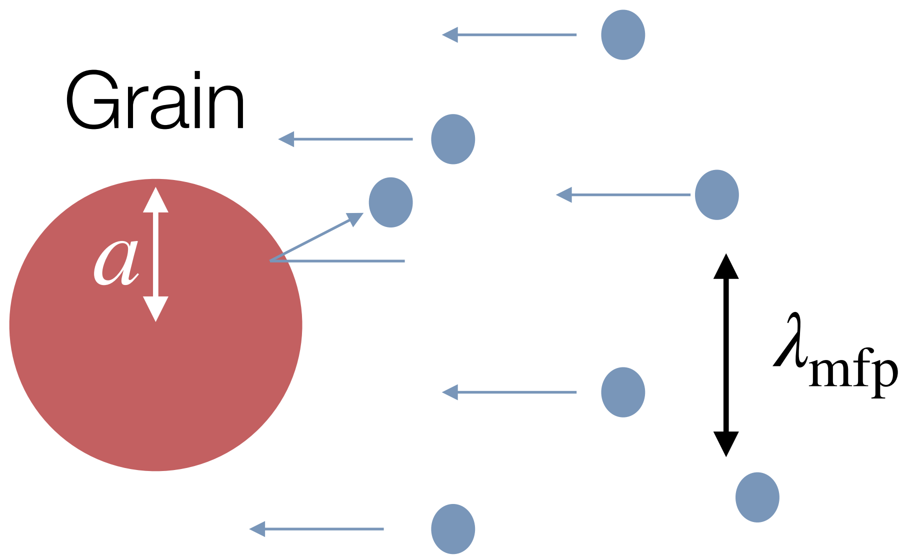
$$m_{\rm grain}\frac{d\vec{v}_{\rm grain}}{dt} = -\frac{m_{\rm grain}}{\tau_s}(\vec{v}_{\rm grain} - \vec{v}_{\rm gas})$$

- This introduces the gain's stopping time τ_s

- In disks, one introduces the Stokes number: $\mathrm{St} = \tau_s \Omega_K$

Relating *St* to the grain size

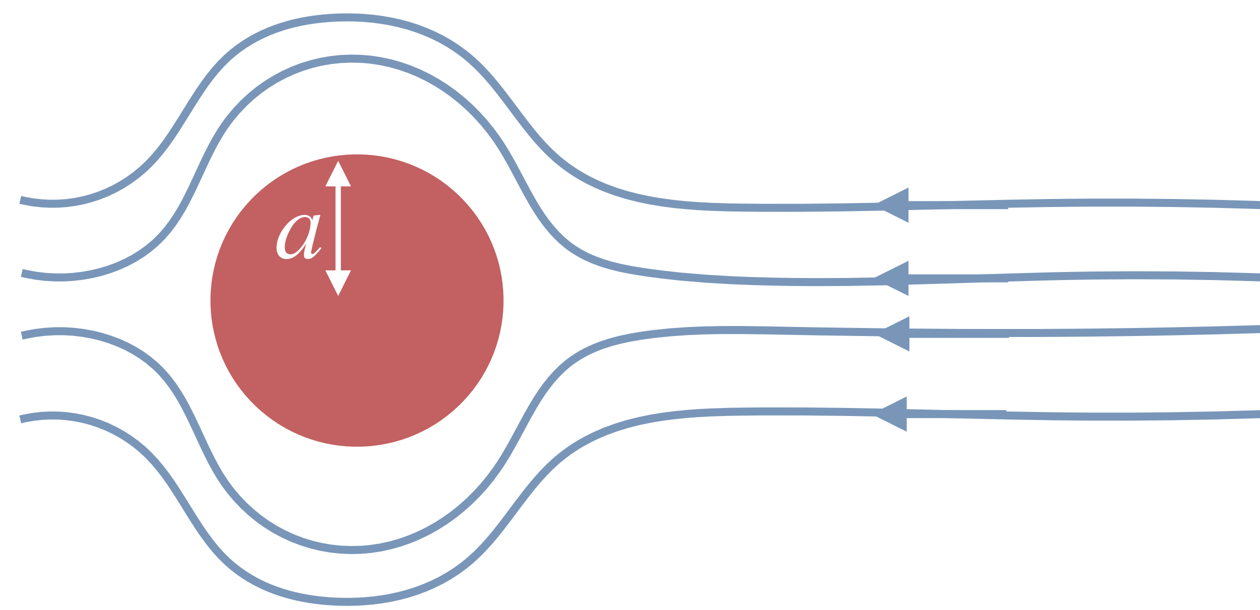
if $a < \lambda_{\rm mfp}$



« Epstein regime »

$$\tau_s = \frac{\rho_{\rm grain} a}{\rho_{\rm gas} c_s}$$

if $a > \lambda_{\rm mfp}$



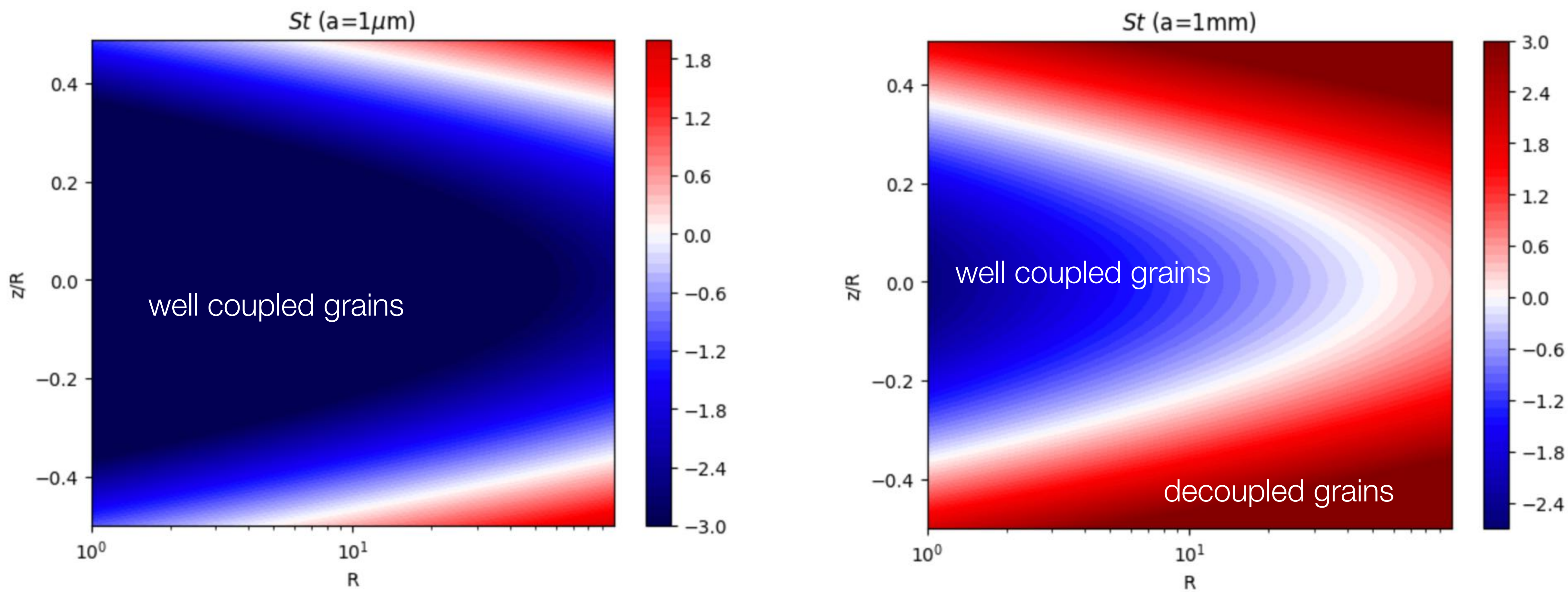
« Stokes regime »

$$\tau_s = \frac{4\rho_{\rm grain} a^2}{9\rho_{\rm gas} c_s \lambda_{\rm mfp}}$$

typically for grains>

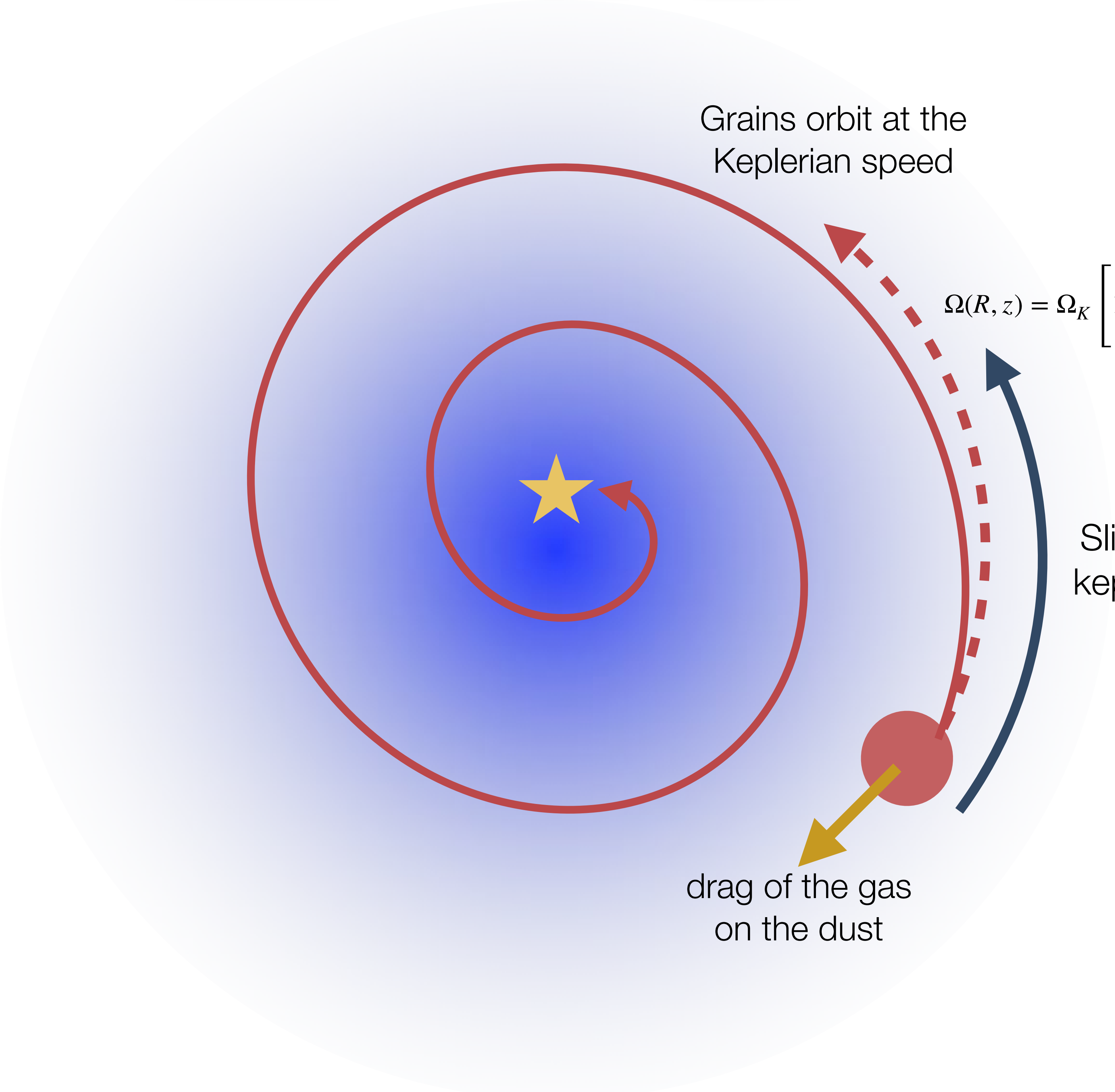
Assumes spherical grains. Fluffy grains typically modelled assuming an « effective » density

Stokes number in actual discs



- Generally speaking, St increases with radius and altitude above the midplane
- 1mm size **spherical** grains have St=1 @ 30 AU

Dust radial drift



$$\Omega(R,z) = \Omega_K \left[1 + (p+q)\left(\frac{H}{R}\right)^2 + q\left(1 - \frac{R}{\sqrt{R^2+z^2}}\right)\right]$$

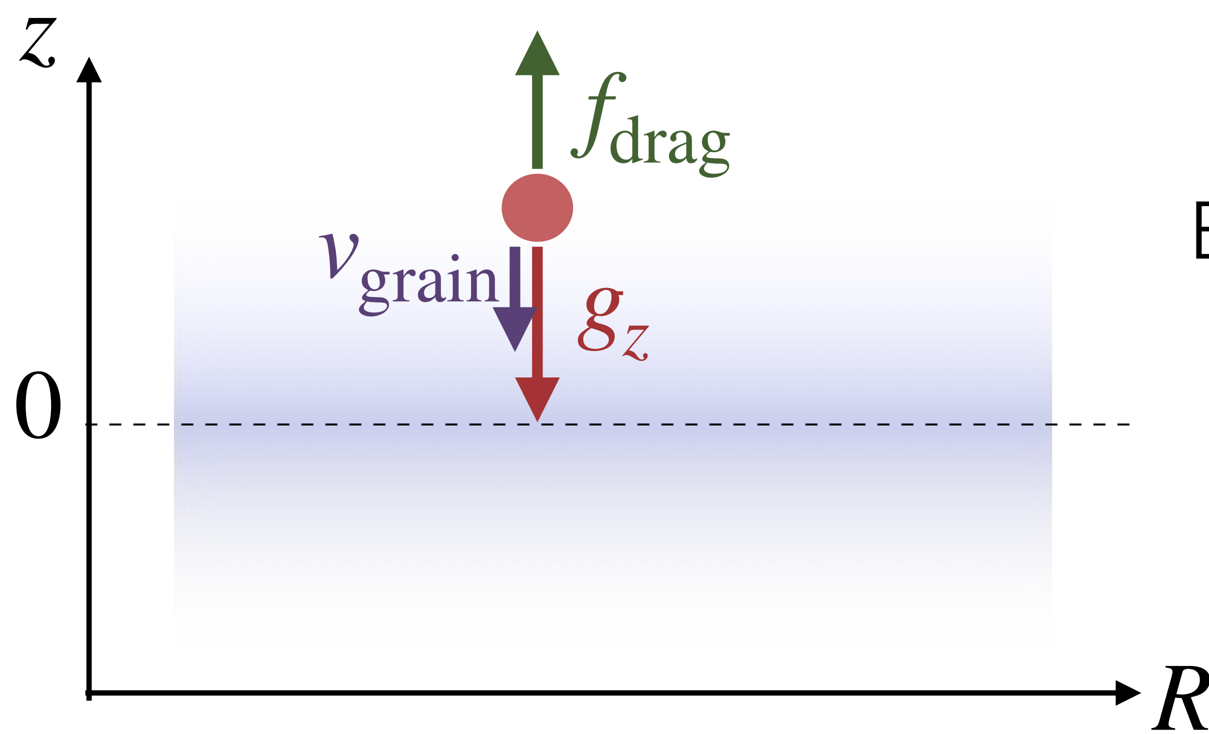
« radial pressure support » = η

$$v_{r,\mathrm{grain}} = -\frac{\eta R \Omega_K}{St + St^{-1}}$$

Maximum drift speed for $St = 1$

As a rule of thumb, grains always drift towards high gas pressure regions

Dust vertical settling



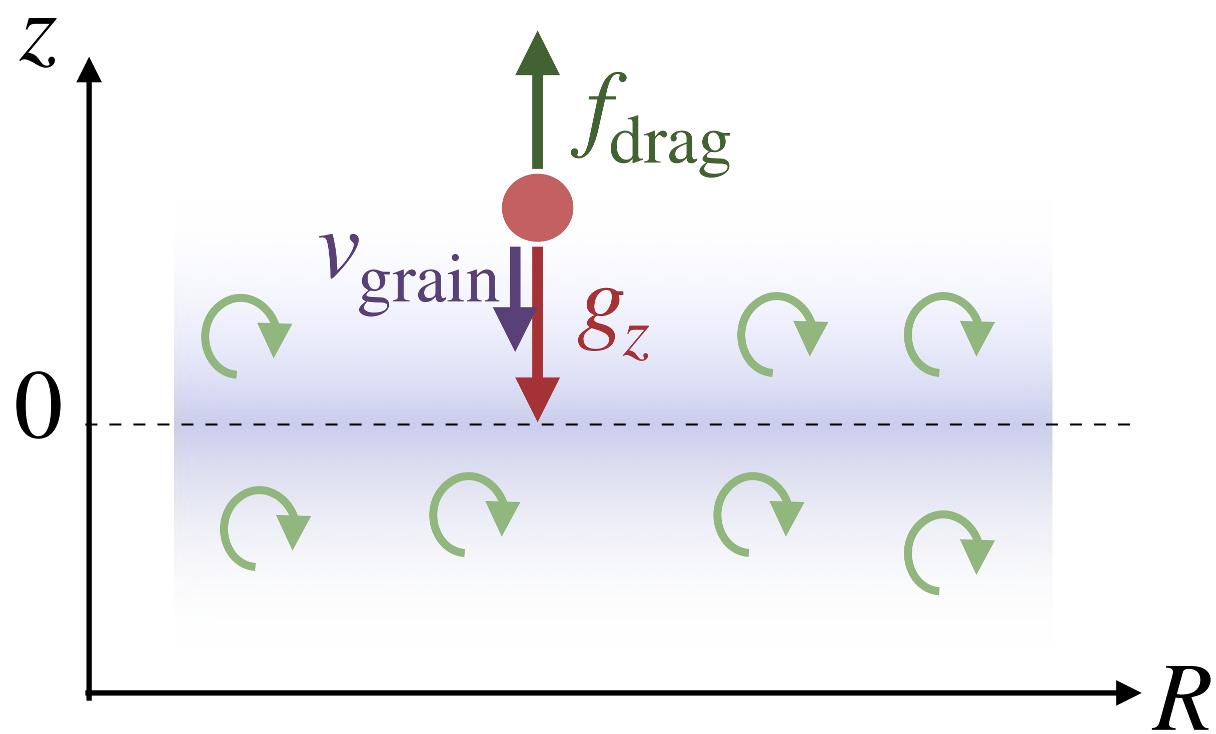
Equation of motion for a grain

$$\ddot{z} = -\Omega_K^2 z - \dot{z}/\tau_s(z)$$

g_z $\quad$ $f_{\rm drag}$

- Grains should settle towards the midplane on a timescale $\tau_{\rm settling} \simeq z/\dot{z} \simeq [\Omega_K St]^{-1}$
- By 1 million years, all grains with $St > 10^{-3}$ @ 100 AU should have settled
- Something's happening to prevent settling of low « ish » St…

Dust turbulent diffusion



Equation of motion for a grain

$$\ddot{z} = -\Omega_K^2 z - \left(\dot{z} - v_{\rm gas}(z,t)\right)/\tau_s(z)$$

g_z — Gas Turbulence

[Youdin & Lithwick 2007]

On can treat the grain population as a « fluid » and write an equation on the dust density

[Dubrulle +1995]

$$\frac{\partial \rho_d}{\partial t} = \frac{\partial}{\partial z}\left(z\Omega_K^2\tau_s(z)\rho_d\right) + \frac{\partial}{\partial z}\left[D_z\rho_g\frac{\partial}{\partial z}\left(\frac{\rho_d}{\rho}\right)\right]$$

Terminal velocity of dust grains

« turbulent diffusion coefficient »

Dust layer thickness

- Result of the advection-diffusion equation for dust grains

$$\rho_d(z) = \rho_d(0)\exp\left(-\frac{z^2}{2H_d^2}\right) \text{ with } \frac{H_d}{H} = \frac{1}{\sqrt{1+\frac{St_0\Omega_K H^2}{D_z}}}$$

St in the disk midplane

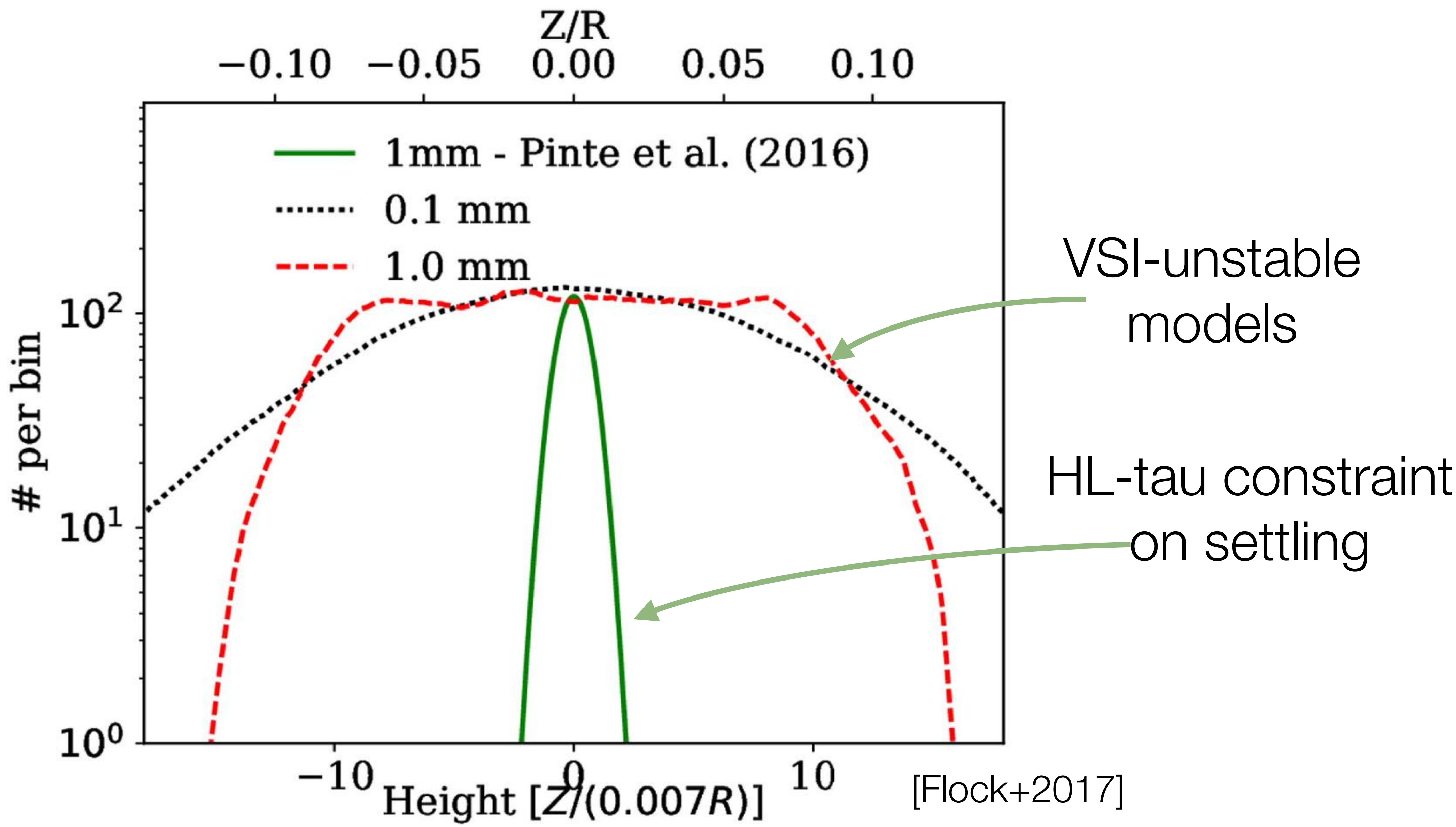
- In the large St limit

$$H_d = H\sqrt{\frac{D_z}{St_0\Omega_K H^2}}$$

- Typical values for vertical dust diffusion
  - MRI: $D_z/\Omega_K H^2 \simeq 5\times 10^{-3}$ (Fromang & Papaloizou 2006)
  - VSI: $D_z/\Omega_K H^2 \sim 0.2$ (Dullemond et al. 2022, but see also Stohl & Kley 2017)
  - GI: $D_z/\Omega_K H^2 \simeq 10^{-2}$ (Riols et al. 2020)

NB: D_z and α can be very different!

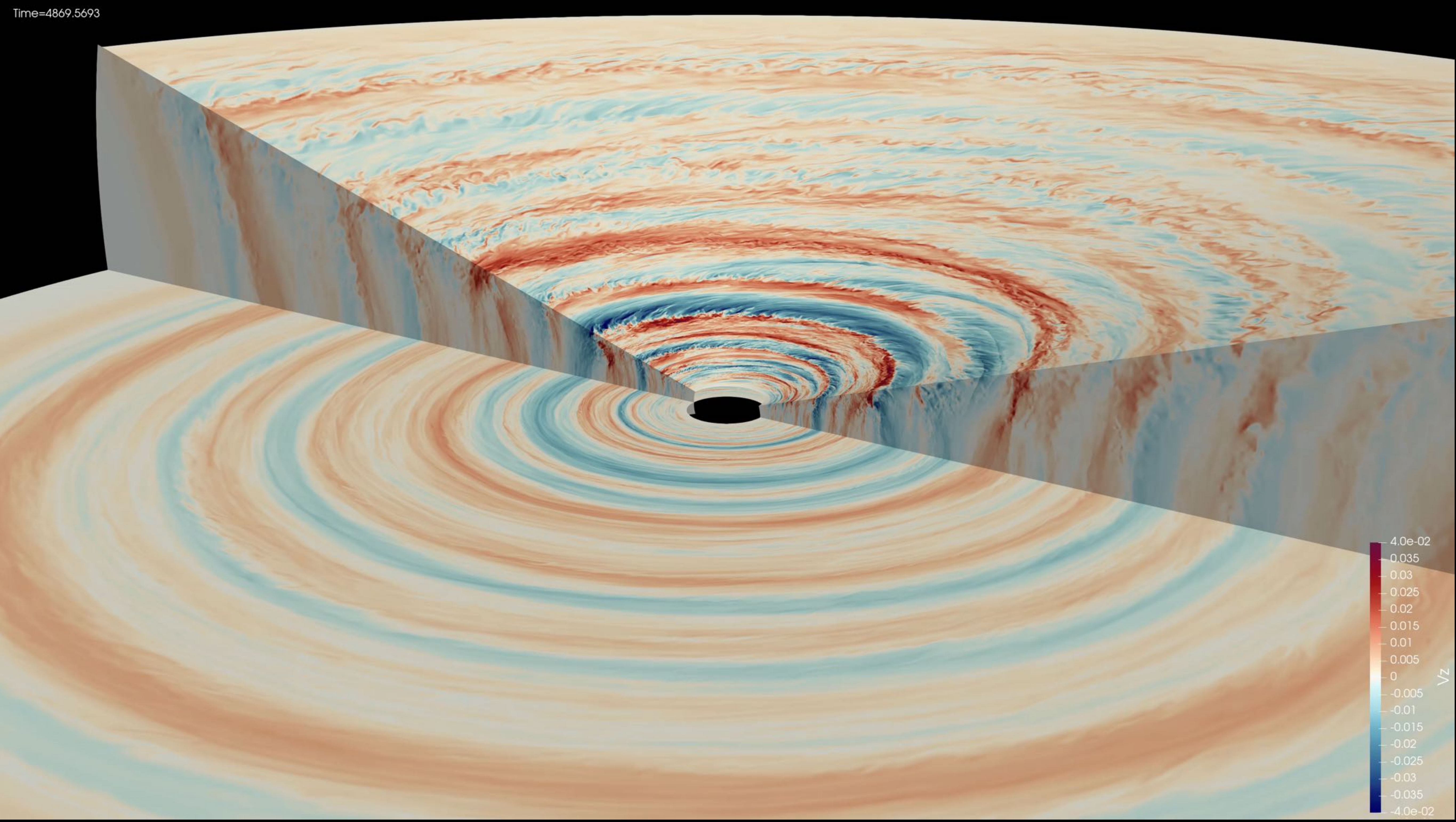
Comparing dust settling models to observations



[Flock+2017]

VSI is excluded from regions where we observe strong settling
[e.g. Villenave+2020, 2024]

Vertical shear instability with multiple dust grains

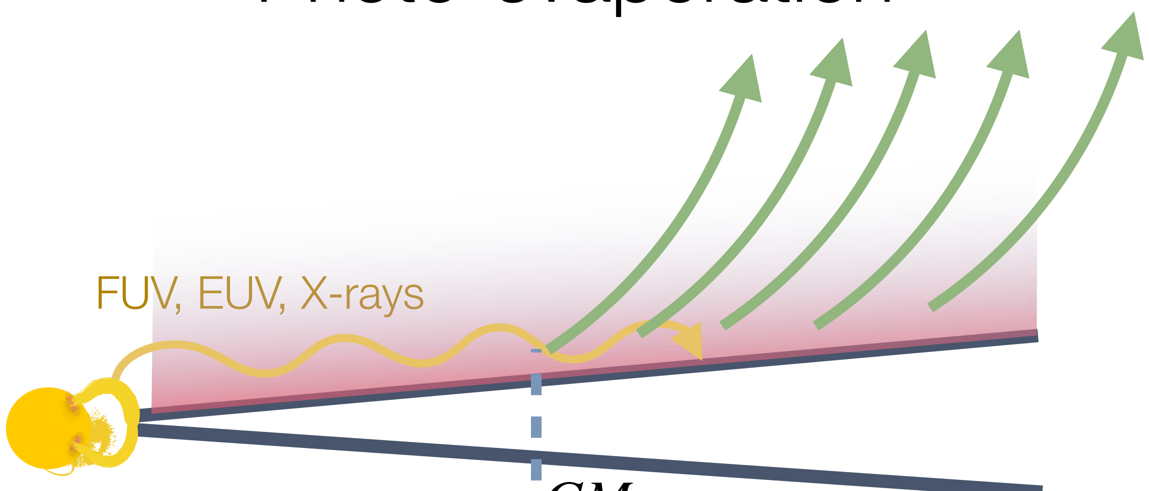


[Lesur & Latter 2025]


DAVID O. SELZNICK'S production of MARGARET MITCHELL'S Story of the Old South
GONE WITH THE WIND
in TECHNICOLOR Starring
CLARK GABLE
as RHETT BUTLER
LESLIE HOWARD
OLIVIA DE HAVILLAND
and presenting
VIVIEN LEIGH
as SCARLETT O'HARA
A SELZNICK INTERNATIONAL PICTURE
DIRECTED BY VICTOR FLEMING
SCREEN PLAY BY SIDNEY HOWARD
A METRO-GOLDWYN-MAYER Release
Music by Max Steiner

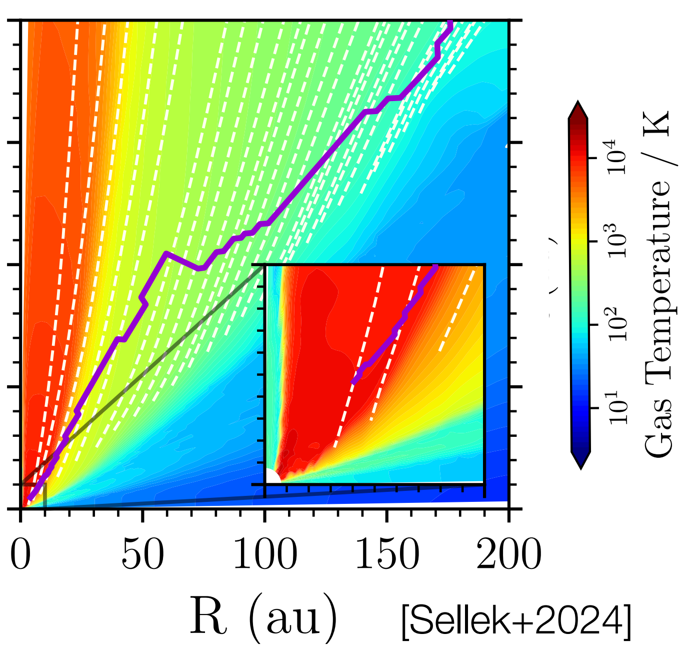
Two types of wind

Photo-evaporation



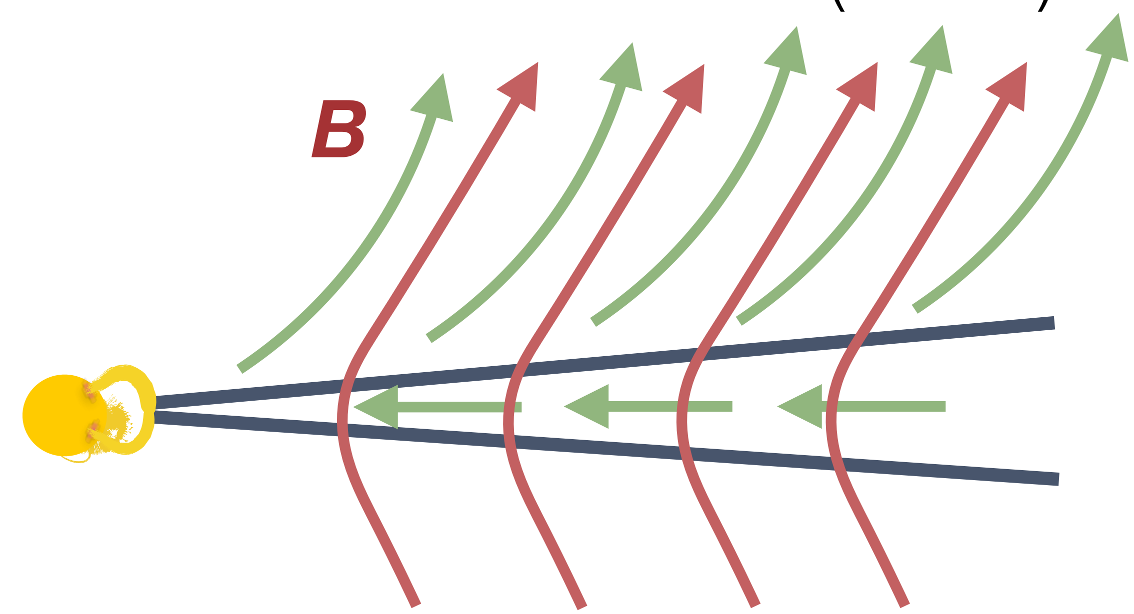
$$R_g = \frac{GM_*}{c_s^2}$$

- Driven by heating of the disc surface by high energy radiation from the star
- Launched at radii larger than R_g [Shu+1993, Hollenbach+1994]
- Typical $\dot{M}_{\rm wind} \simeq 10^{-9} M_\odot/{\rm yr}$

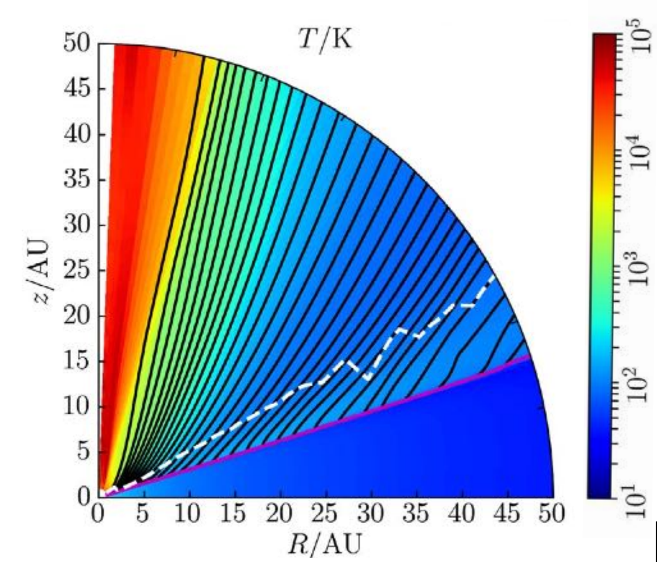


[Sellek+2024]

MHD disk wind (MDW)

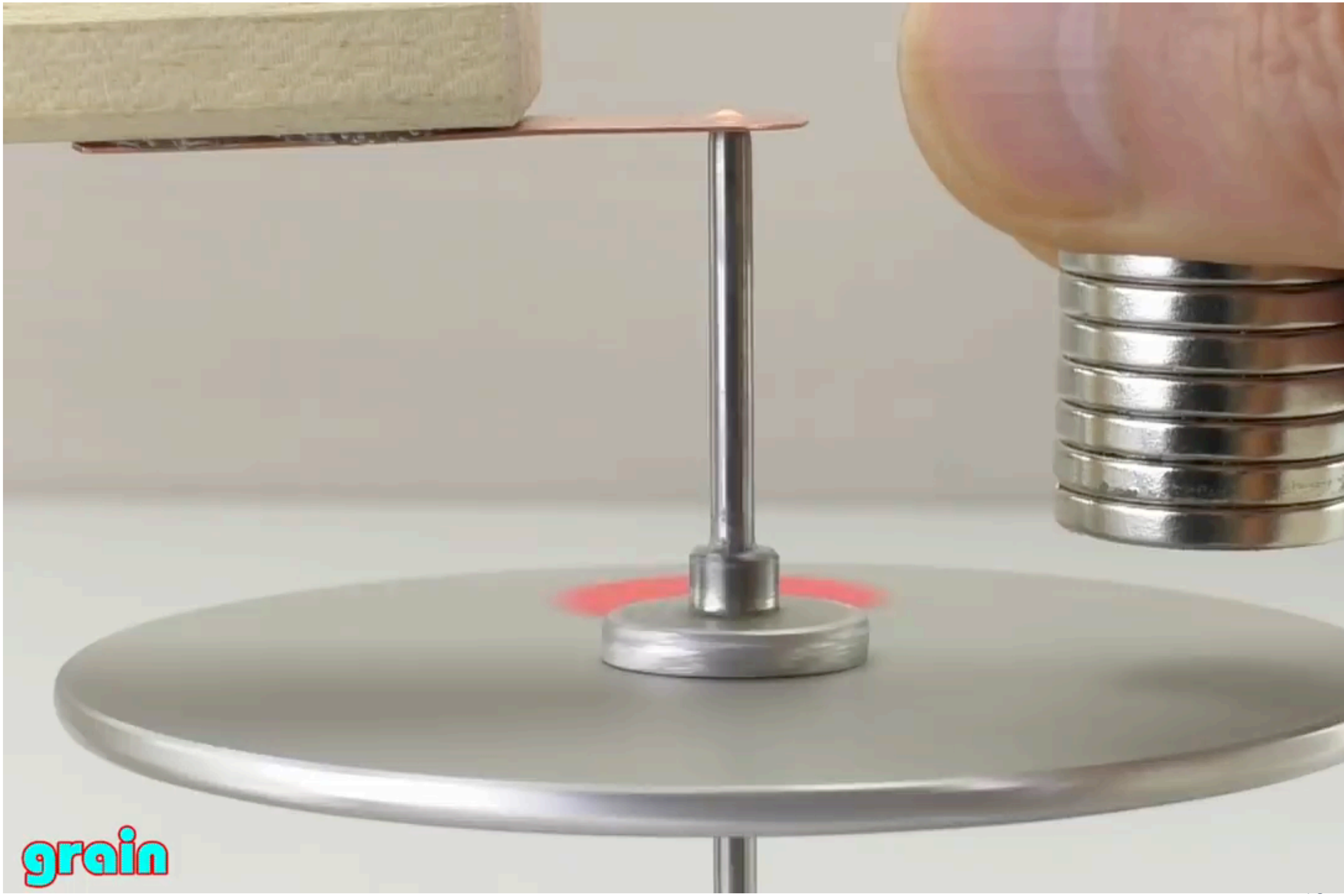


- Driven by the accretion energy released by the disk
- Requires a large-scale B field [Ferreira & Pelletier 1993,1995]
- Typical $\dot{M}_{\rm wind} \simeq 10^{-8} M_\odot - 10^{-7} M_\odot/{\rm yr}$

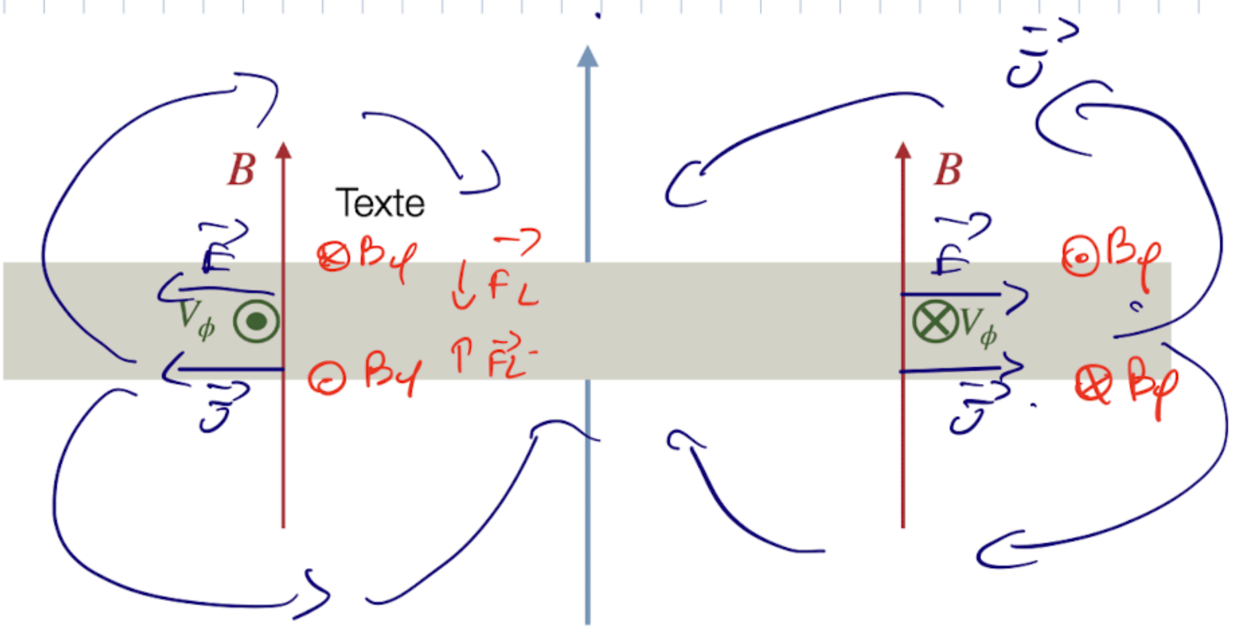


[Wang+2019]

A little experiment



Internals of magnetic breaking



Induction : $\vec{E} = \frac{\vec{v} \times \vec{B}}{c}$.

Ohm's law $\vec{E} = \frac{4\pi}{c^2} \eta \vec{J}$ →

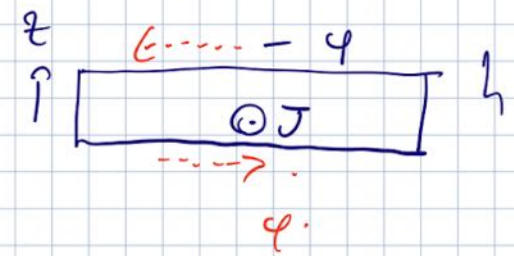
Lorentz force $\vec{F}_L = \frac{\vec{J} \times \vec{B}}{c} = \frac{c^2}{4\pi\eta} \vec{E} \times \vec{B}$.

$$\vec{F}_L = -\frac{c}{4\pi\eta} v_\varphi B \vec{e}_\varphi$$

→ Magnetic Breaking due to the radical current

⇒ Induced magnetic field:

$$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c} \vec{J}$$



$$-2 L_\varphi B_\varphi = \frac{4\pi}{c} J_R L_\varphi h$$

$$B_\varphi = -\frac{2\pi}{c} J_R h.$$

This induced field implies an additional component to the lorentz force!

$$\vec{F}_L = \vec{J}_R \times \vec{B}_\varphi = -\frac{2\pi}{c} J_R^2 h.$$

→ The disc is compressed!

If the disc is compressed, it must be compressed by something (action ⟺ reaction).

Closing currents!

Back to the accretion problem

$$\frac{\partial \Sigma}{\partial t} + \frac{1}{R}\frac{\partial}{\partial R} R\overline{\rho v_r} + \left[\rho v_z\right]_{z=-h}^{+h} = 0$$

$\equiv \zeta \Omega_K \Sigma$ « mass loss parameter »

$$\overline{\rho v_r}\frac{\partial}{\partial R}\Omega R^2 + \frac{1}{R}\frac{\partial}{\partial R}R^2\left[\overline{\rho v_\phi v_r} - \frac{\overline{B_\phi B_r}}{4\pi}\right] + R\left[\rho v_\phi v_z - \frac{B_\phi B_z}{4\pi}\right]_{z=-h}^{+h} = 0$$

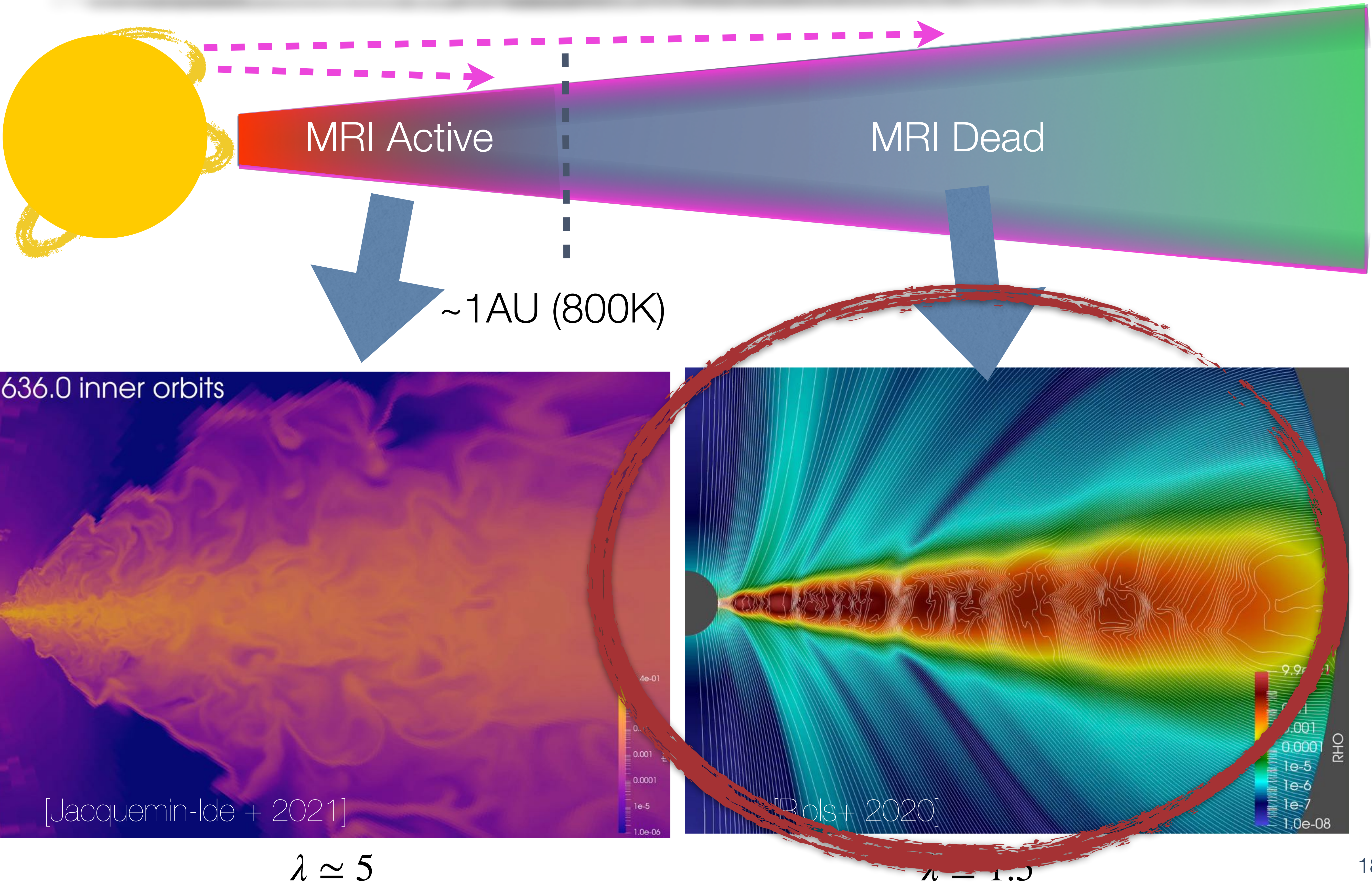
accretion

$\equiv \alpha \overline{P}$ « viscous alpha parameter »

$\equiv \zeta(\lambda - 1)\Sigma R \Omega^2$ « magnetic lever arm »

A wind introduces 2 new parameters: ζ and λ

Two « flavours » of MHD wind

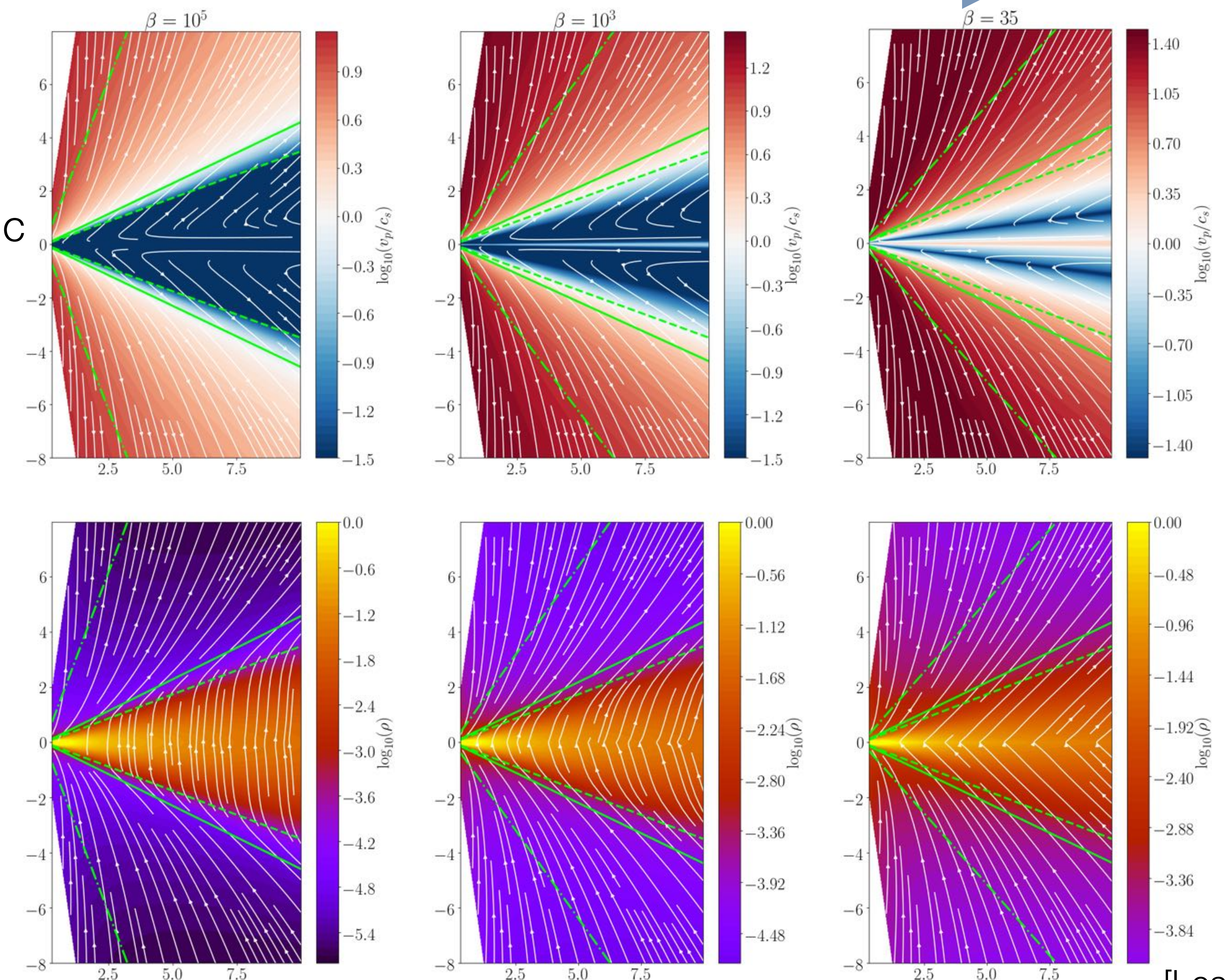


A sample of MHD disc winds

increasing field strength

Streamlines & sonic mach number

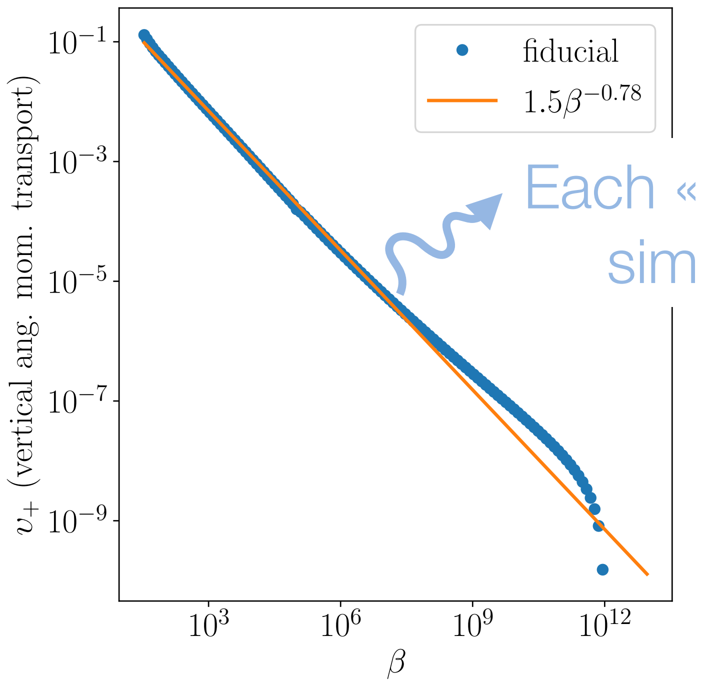
Fieldlines & gas density



[Lesur 2021]

Fig. 2. Flow topology in the fiducial run (ambipolar diffusion only $\Lambda_A = 1$). Top row: poloidal streamlines (white) and log of the sonic Mach number. Bottom row: poloidal field and log of density, normalised so that the midplane density at $R = 1$ is unity. Note that the colour scales are identical between the columns. From left to right the disc magnetisation increases: $\beta = 10^5$; 10^3 ; 35. The green lines denotes critical lines of the flow: Alfv'enic (plain) and fast magnetosonic (dot-dashed). The green dashed line represents the disc "surface" where the flow becomes ideal, arbitrarily located at $z = 3.5h$ for all of the solutions.

Relating accretion, ejection and field strength



Each « dot » is a simulation

Scaling laws from self-similar simulations [Lesur 2021]
https://github.com/glesur/PPDwind

Accretion rate

surface density

$$\dot{M}_{\mathrm{acc}} = 1.6\times 10^{-8}\left(\frac{\Sigma_0 R_{10\,\mathrm{a.u}}^{-1/2}}{10\,\mathrm{g.cm^{-2}}}\right)^{0.22}\left(\frac{M}{M_\odot}\right)^{-0.28}\left(\frac{\varepsilon}{0.1}\right)^{-0.78}\left(\frac{B_{z0}R_{10\,\mathrm{a.u}}^{-5/4}}{1\,\mathrm{mG}}\right)^{1.56} M_\odot/\mathrm{yr}$$

Disc aspect ratio (H/R)

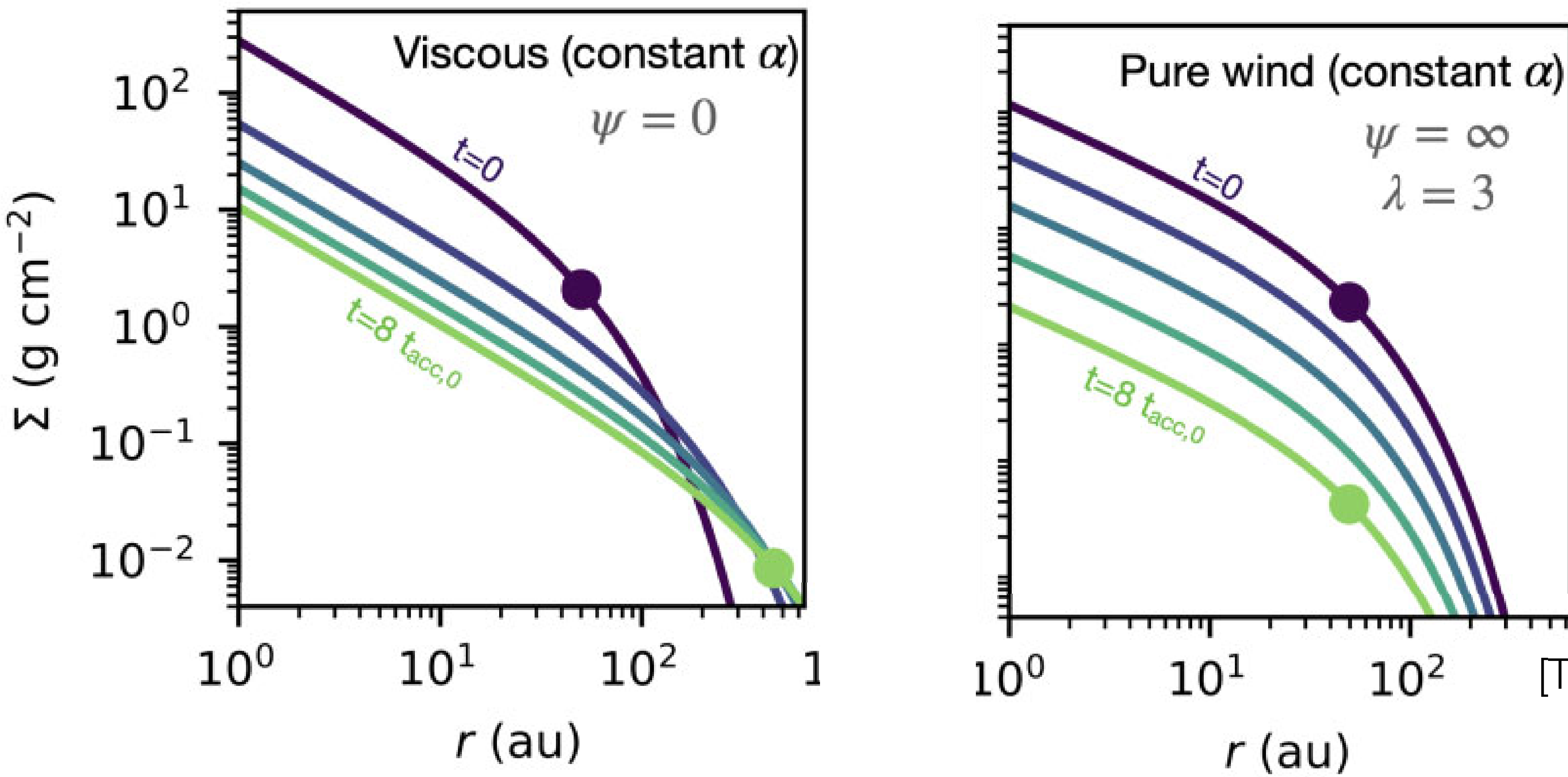
$$\dot{M}_{\mathrm{wind}} = 1.07\,\dot{M}_{\mathrm{acc}}\left(\frac{\Sigma}{10\,\mathrm{g.cm^{-2}}}\right)^{0.09}\left(\frac{B_z}{1\,\mathrm{mG}}\right)^{-0.18}$$

- Mass accretion is mostly controlled by the magnetic field intensity and depends *only weakly* on Σ
- Mass loss rate is approximately equal to mass accretion rate.

→ The big unknown for a predictive theory is $B_z(R,t)$

Impact on disc evolution

In MHD disk winds, the angular momentum is « extracted » vertically, so there is no radial expansion



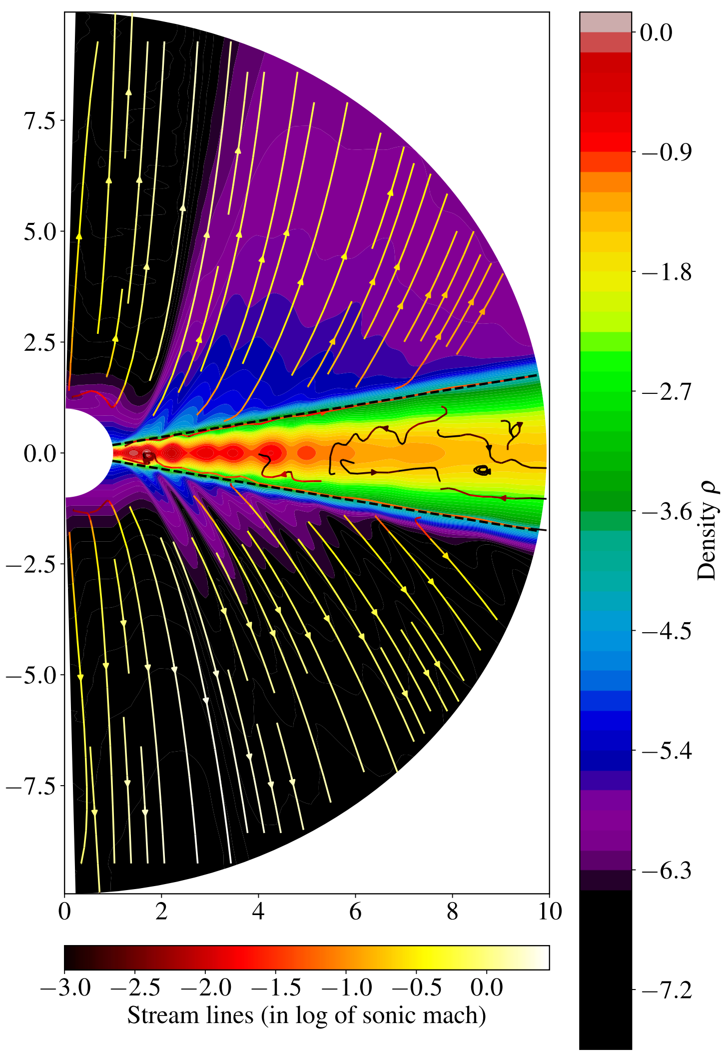
[Tabone+2022]

… or maybe there is (Yang & Bai 2021)

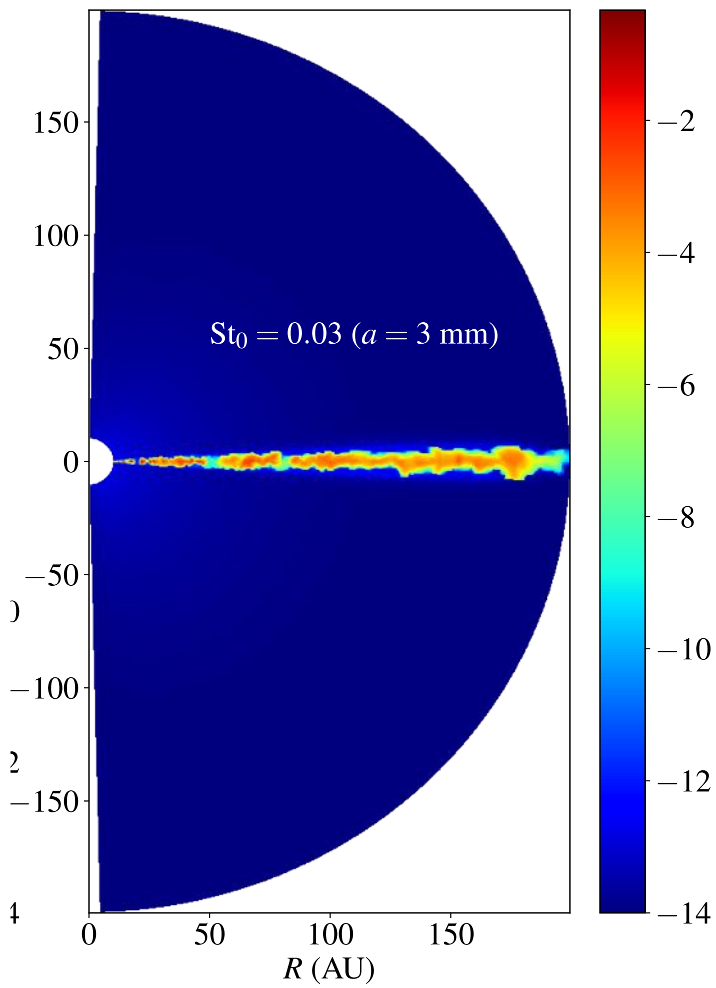
Dust Dynamics in wind-driven disc

Dust Settling

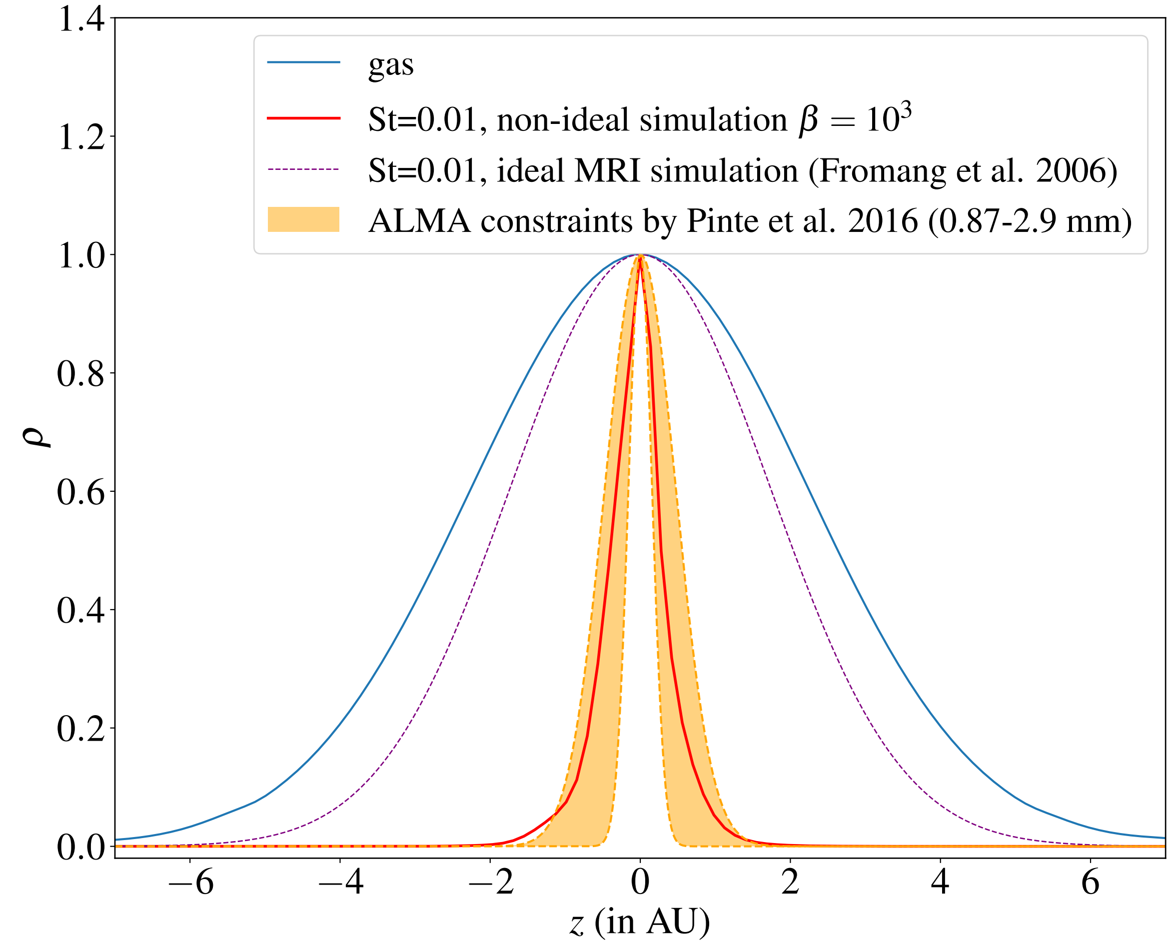
gas



dust grains



vertical density profiles

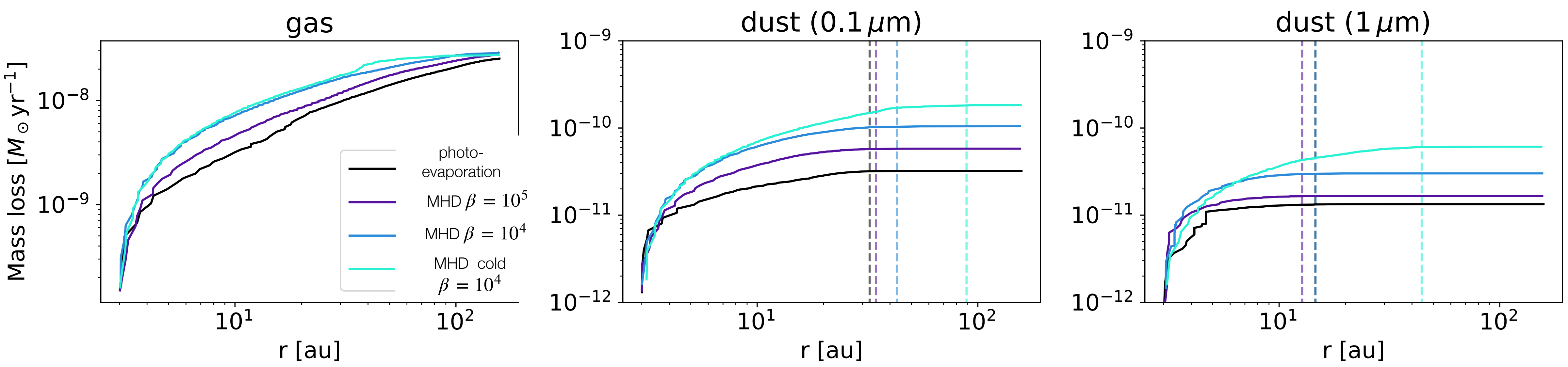


[Riols & Lesur 2019, Riols+2020]

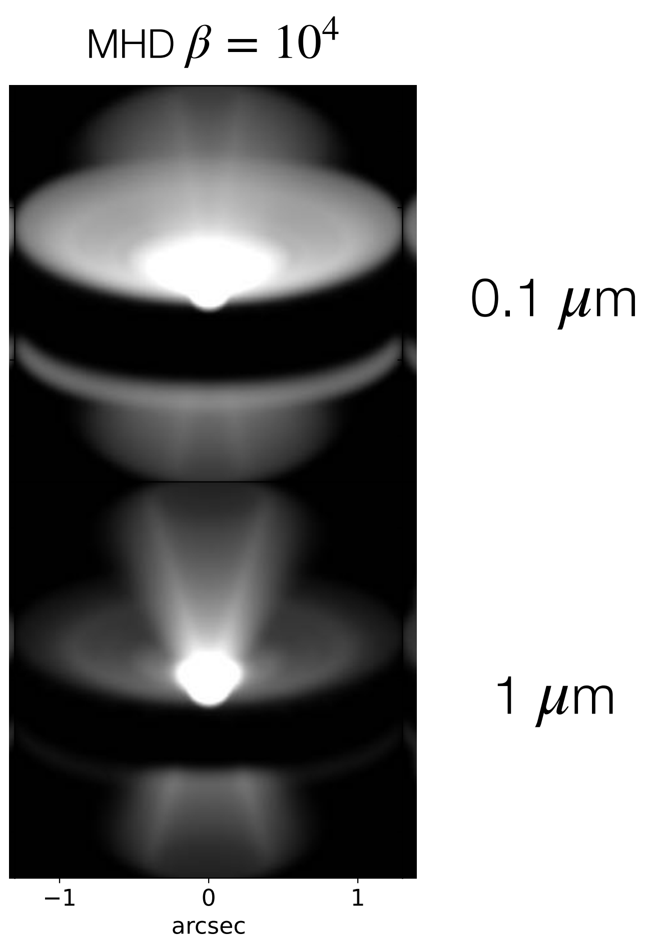
Observed dust settling is compatible with a wind-driven accretion disc

Dust grain entrainment

[Rodenkirch & Dullemond 2022]

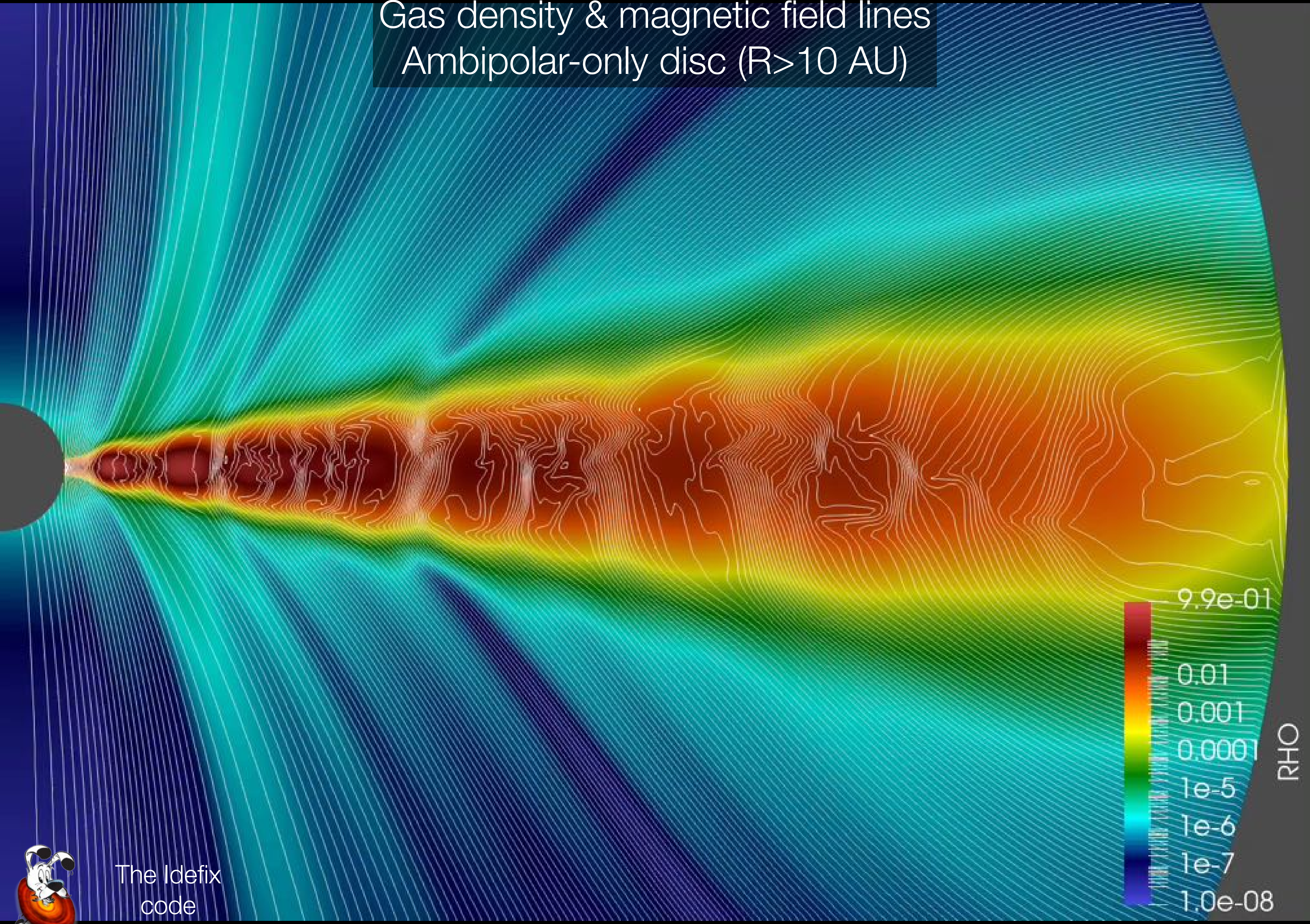


- Maximum entrained dust size ~a few μm
- Mostly in the inner regions (dust settling outside)
- Appears as a faint conical emission in synthetic observations



H band image

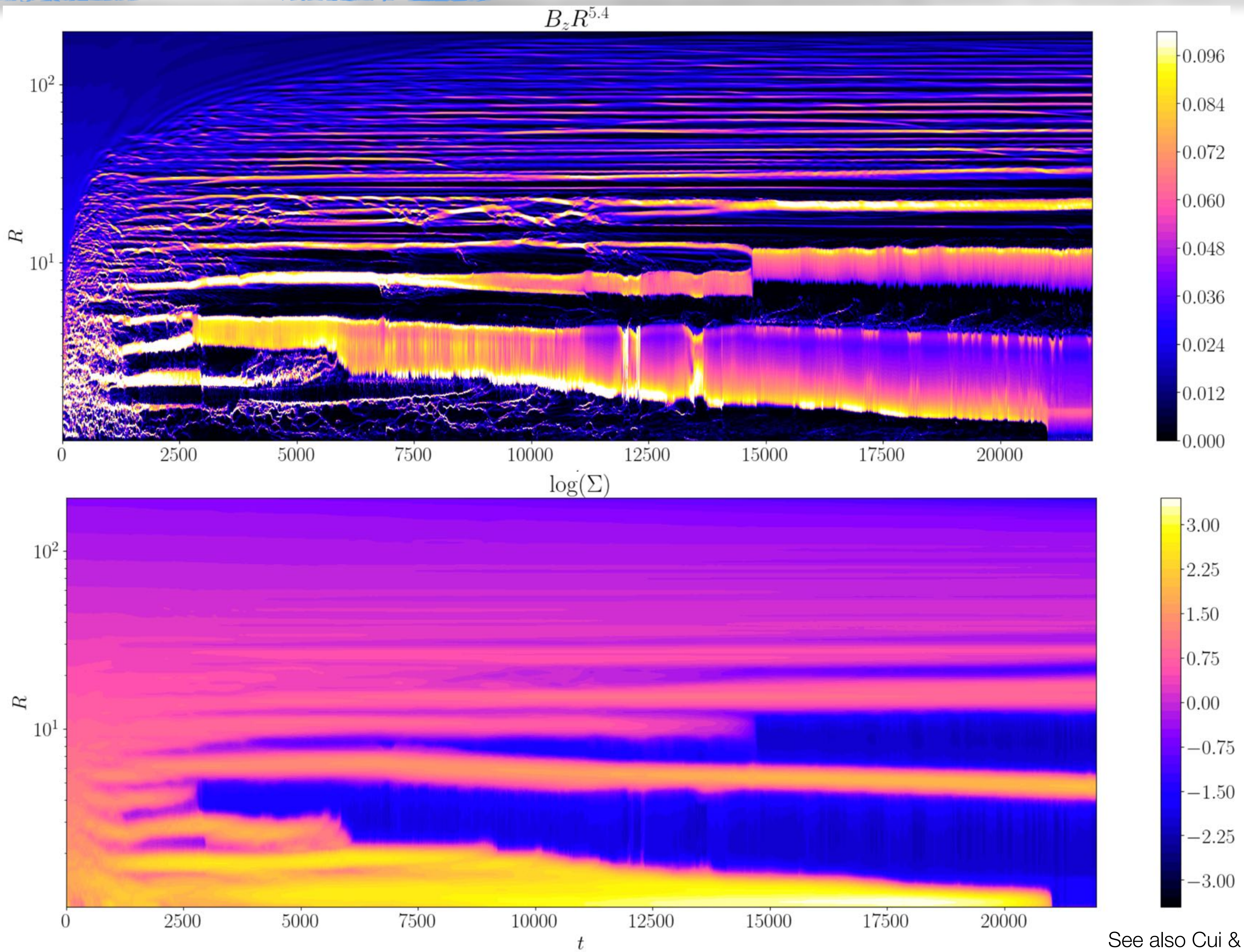
Gas density & magnetic field lines
Ambipolar-only disc (R>10 AU)



The Idefix code

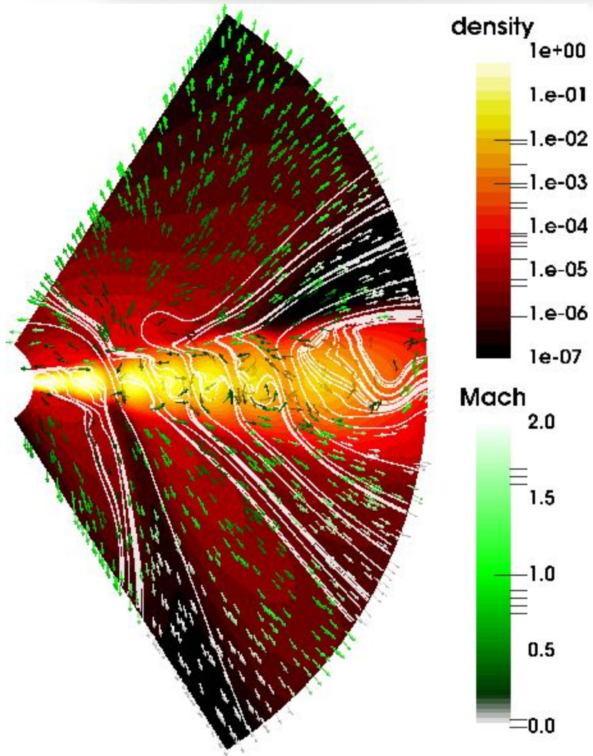
[Lesur+2023]

Temporal evolution

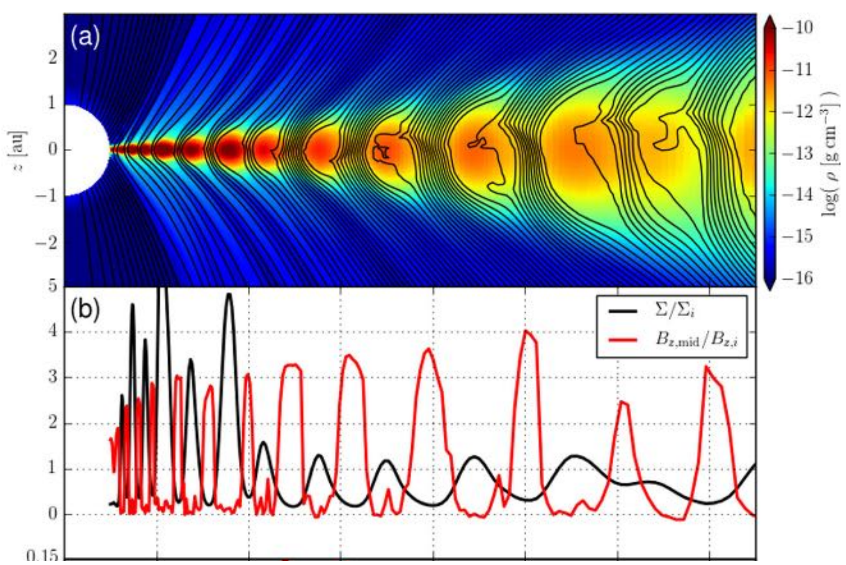


See also Cui & Bai 2021

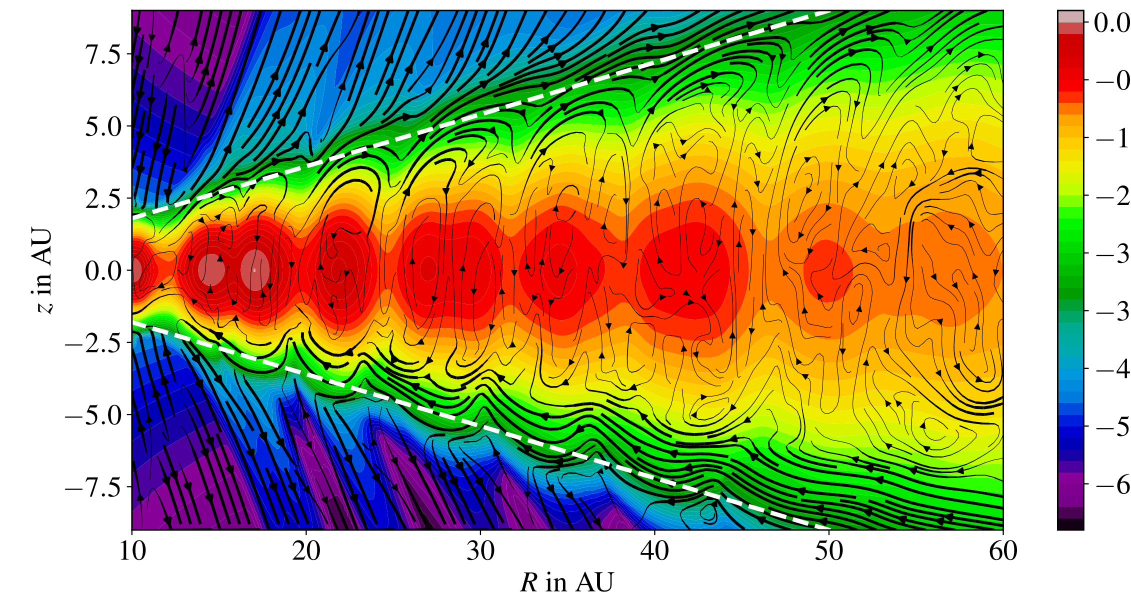
Spontaneous structure formation in « windy » disc



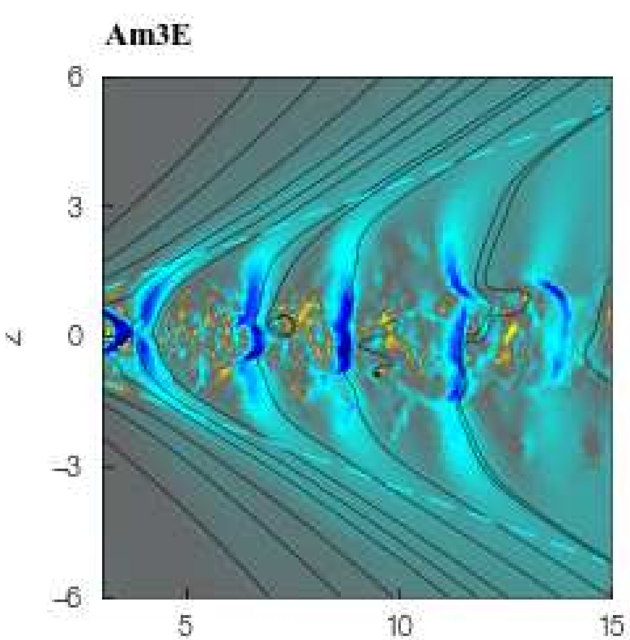
[Béthune+2017]



[Suriano+2018]



[Riols+2020]



[Cui & Bai 2021]

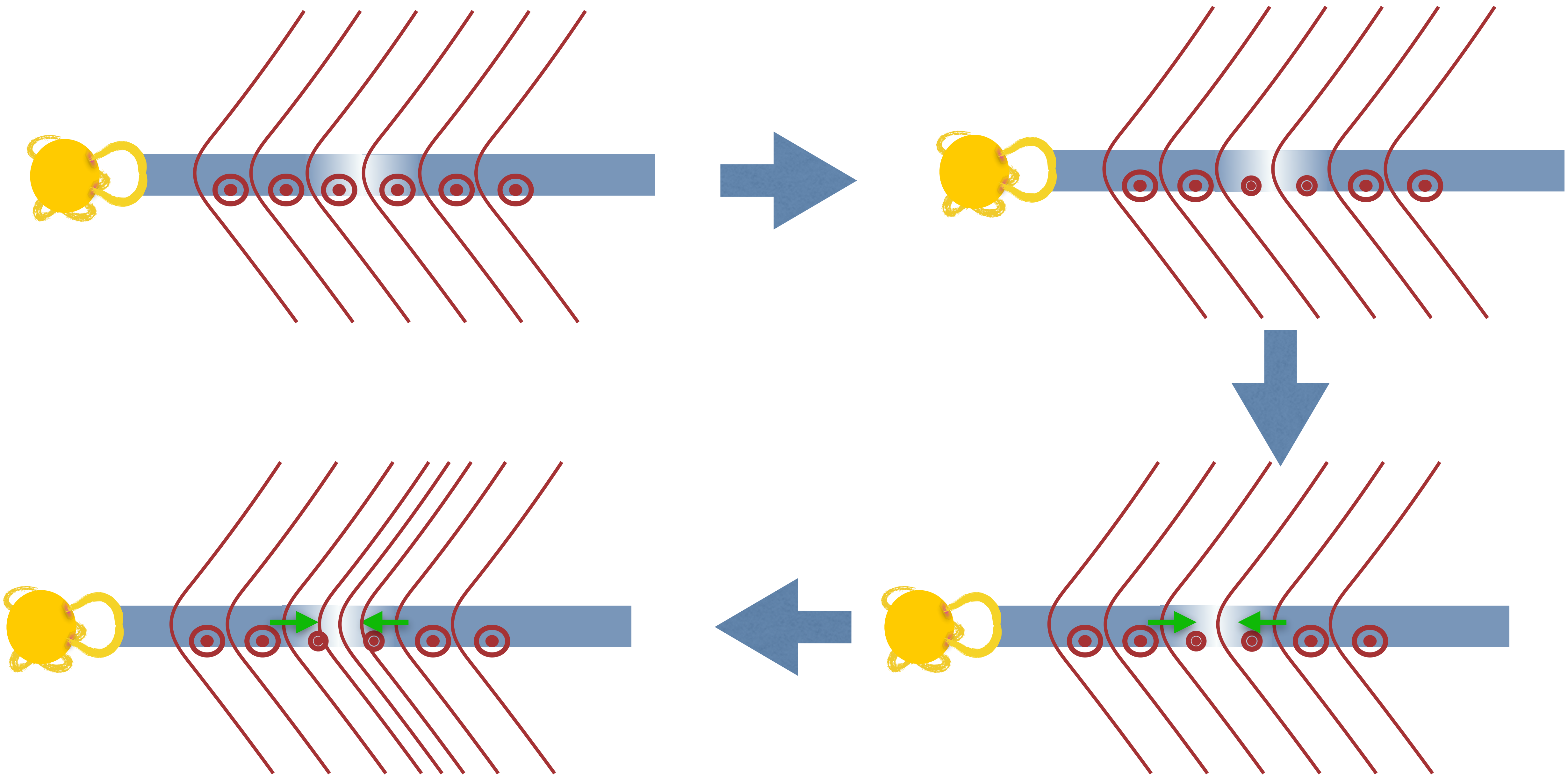
Common ingredients are

- Ambipolar diffusion (valid for R>~5AU)
- Large scale magnetic field (fossil field?) B≥a few mG @ 10 AU ($\beta \lesssim 10^4$)

A feedback loop

Consider a small density deficit

It induces a reduction in B_φ^2

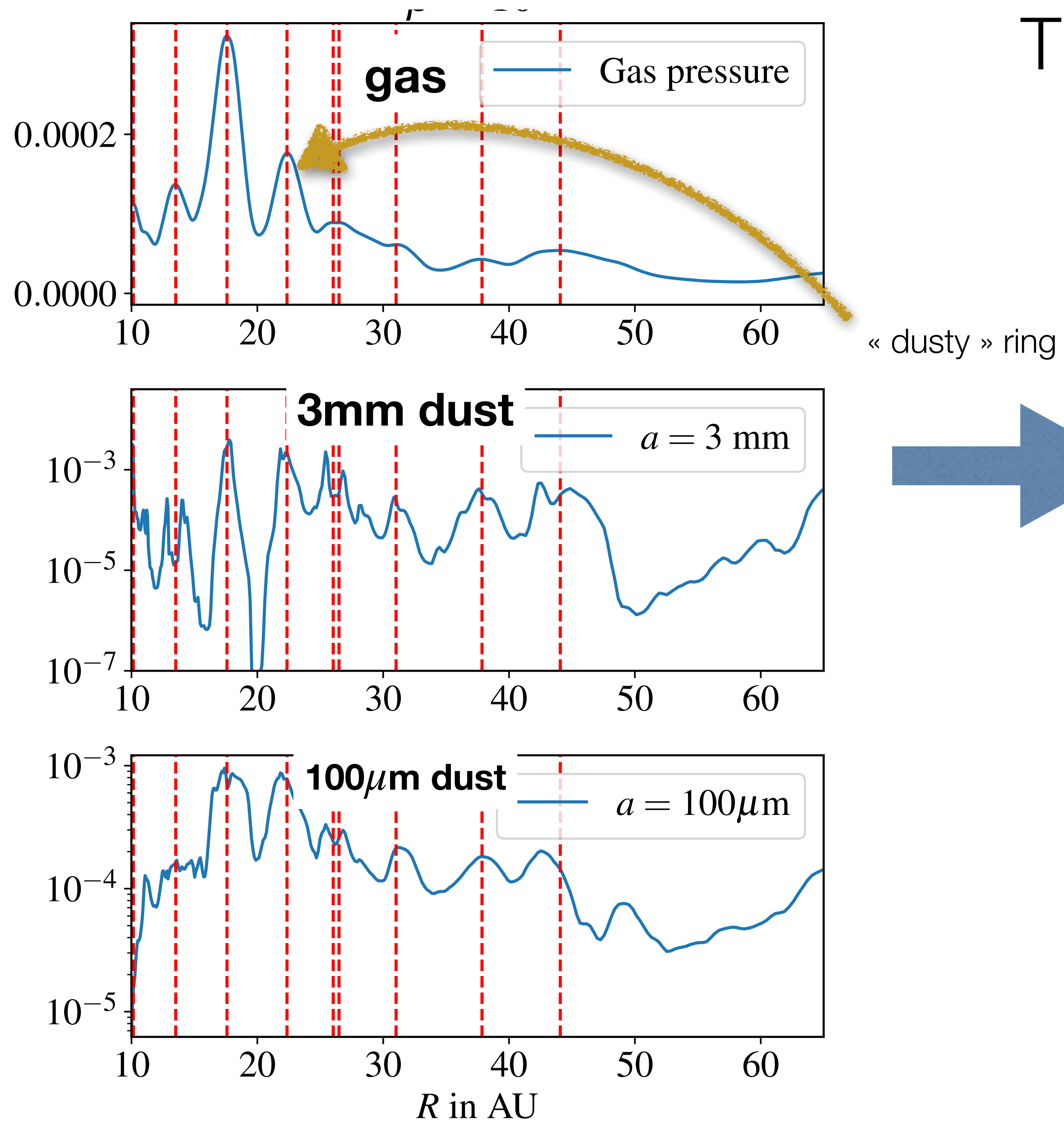


This drags poloidal magnetic field lines towards the gap until magnetic pressure equilibrium is reached

The magnetic pressure deficit triggers an ion drift towards the « gap »

MHD-driven rings are observable

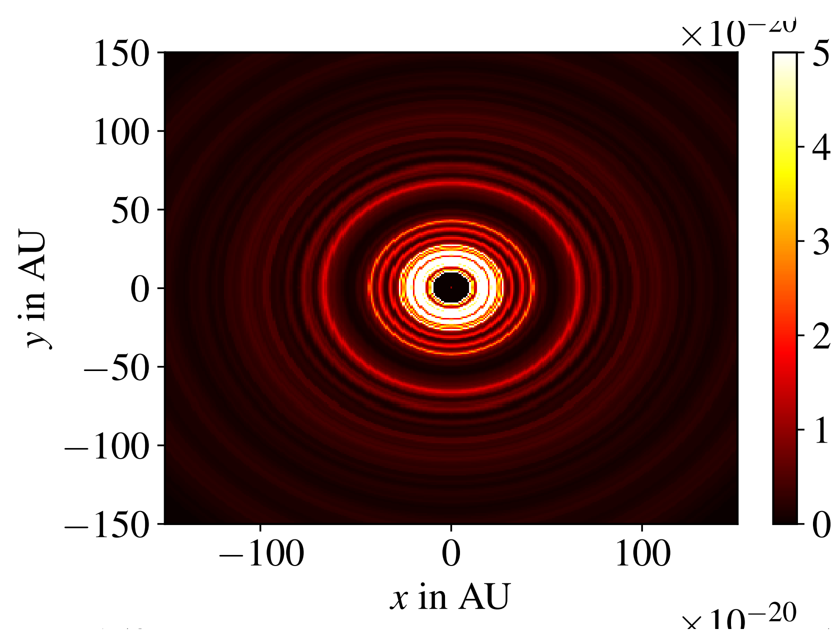
[Riols+2020]



The « gas rings » produced by winds are steady-state pressure bumps

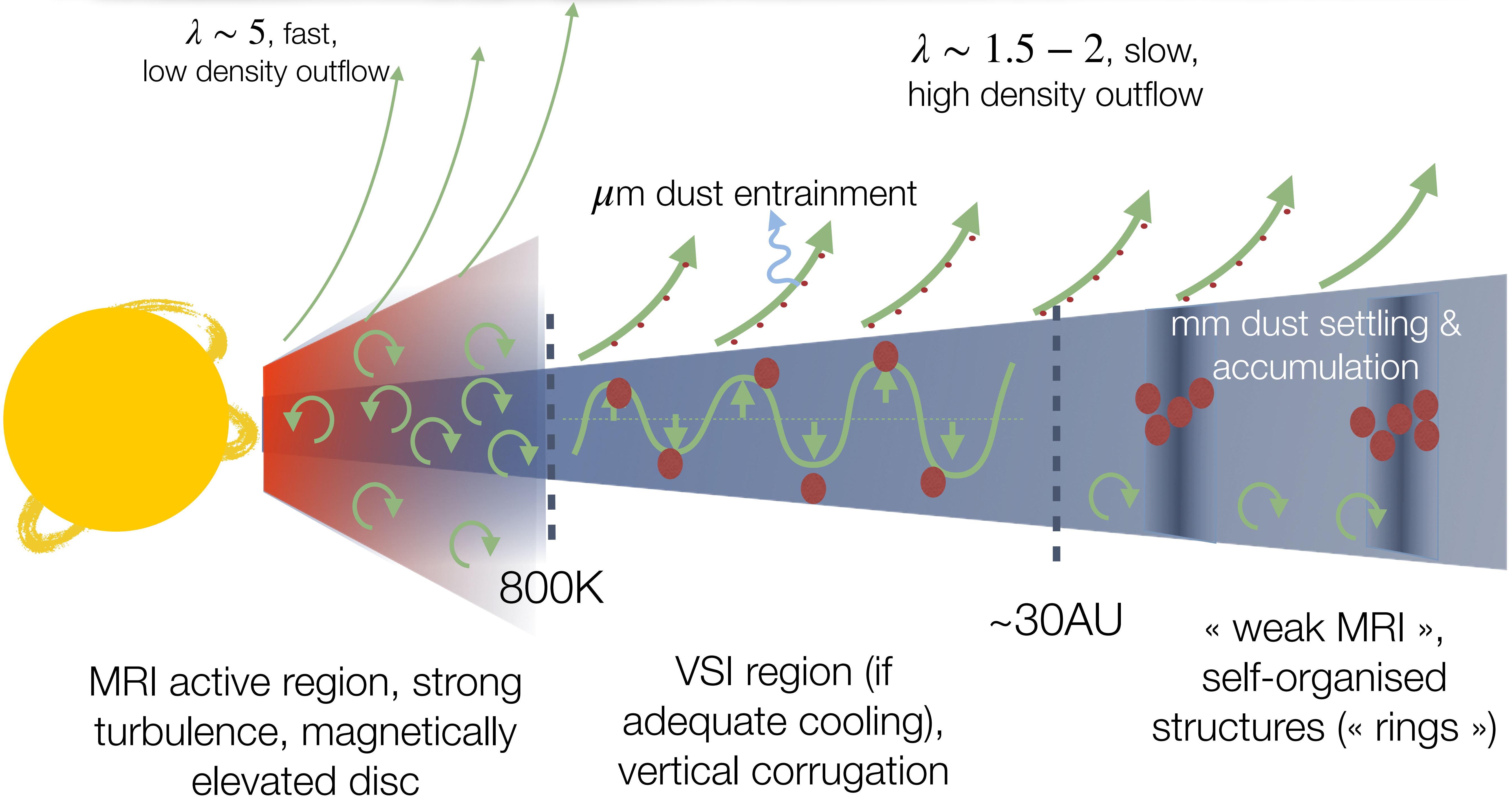
They act as dust traps

Synthetic ALMA image @1mm



MHD wind spontaneously create visible dust ring structures

Summary

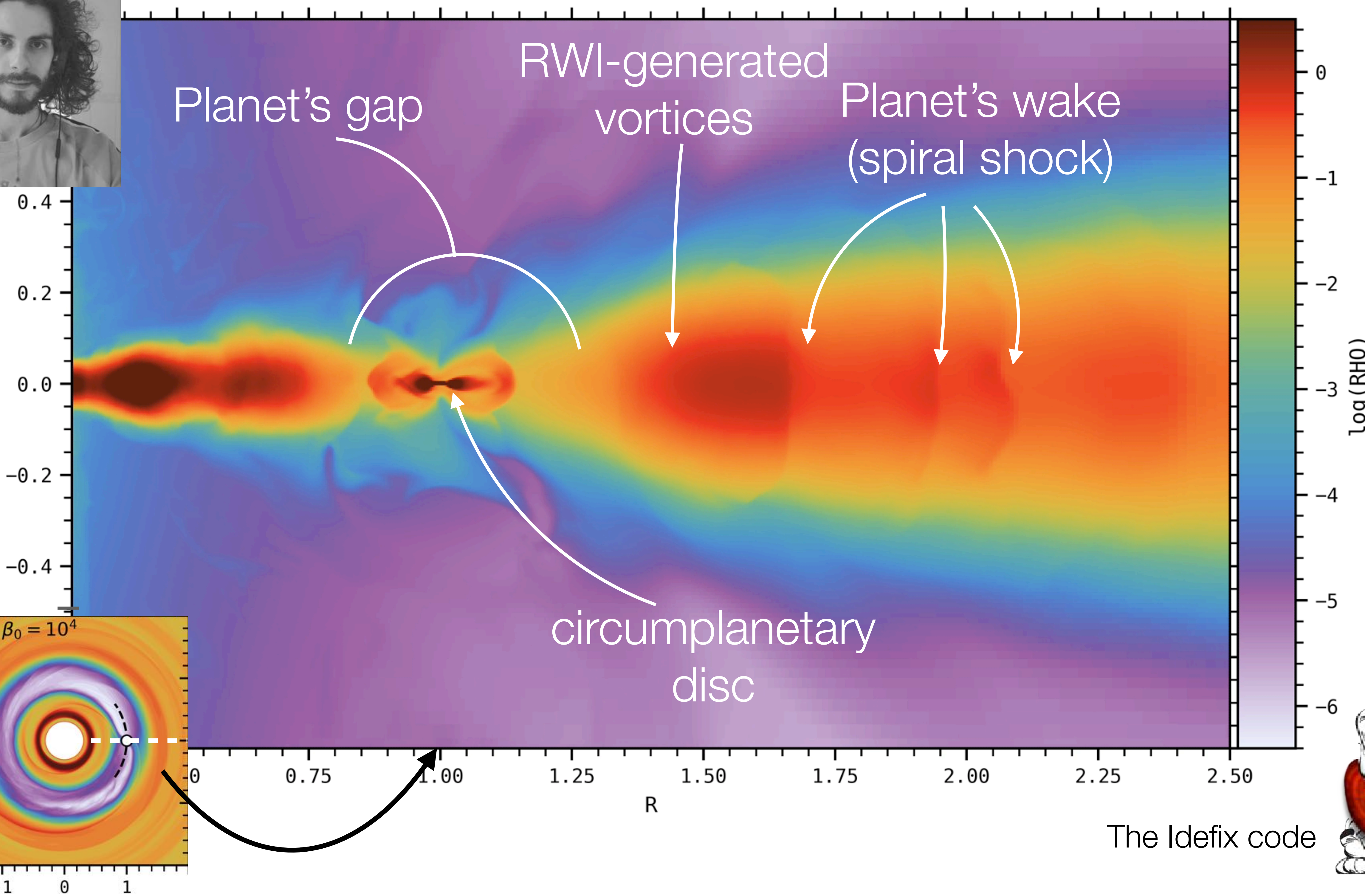


$\lambda \sim 5$, fast,
low density outflow
$\lambda \sim 1.5 - 2$, slow,
high density outflow
μm dust entrainment
mm dust settling &
accumulation
800K
~30AU
MRI active region, strong turbulence, magnetically elevated disc
VSI region (if adequate cooling), vertical corrugation
« weak MRI », self-organised structures (« rings »)

Supplementary material

Planet-disc-wind interaction in action

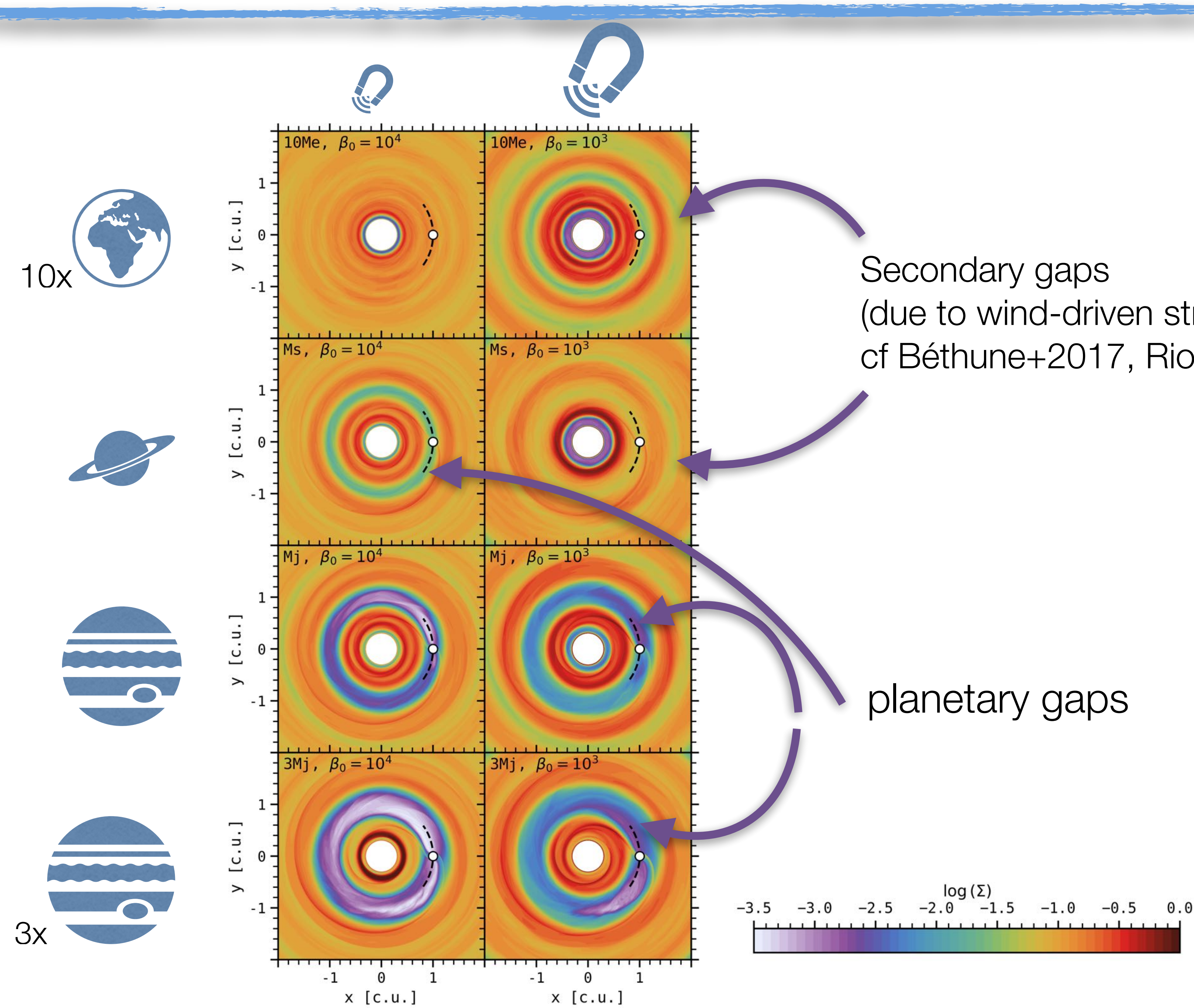
[Wafflard-Fernandez & Lesur 2024]



The Idefix code

Gap opening by embedded planet in a windy disk

[Wafflard-Fernandez & Lesur 2024]

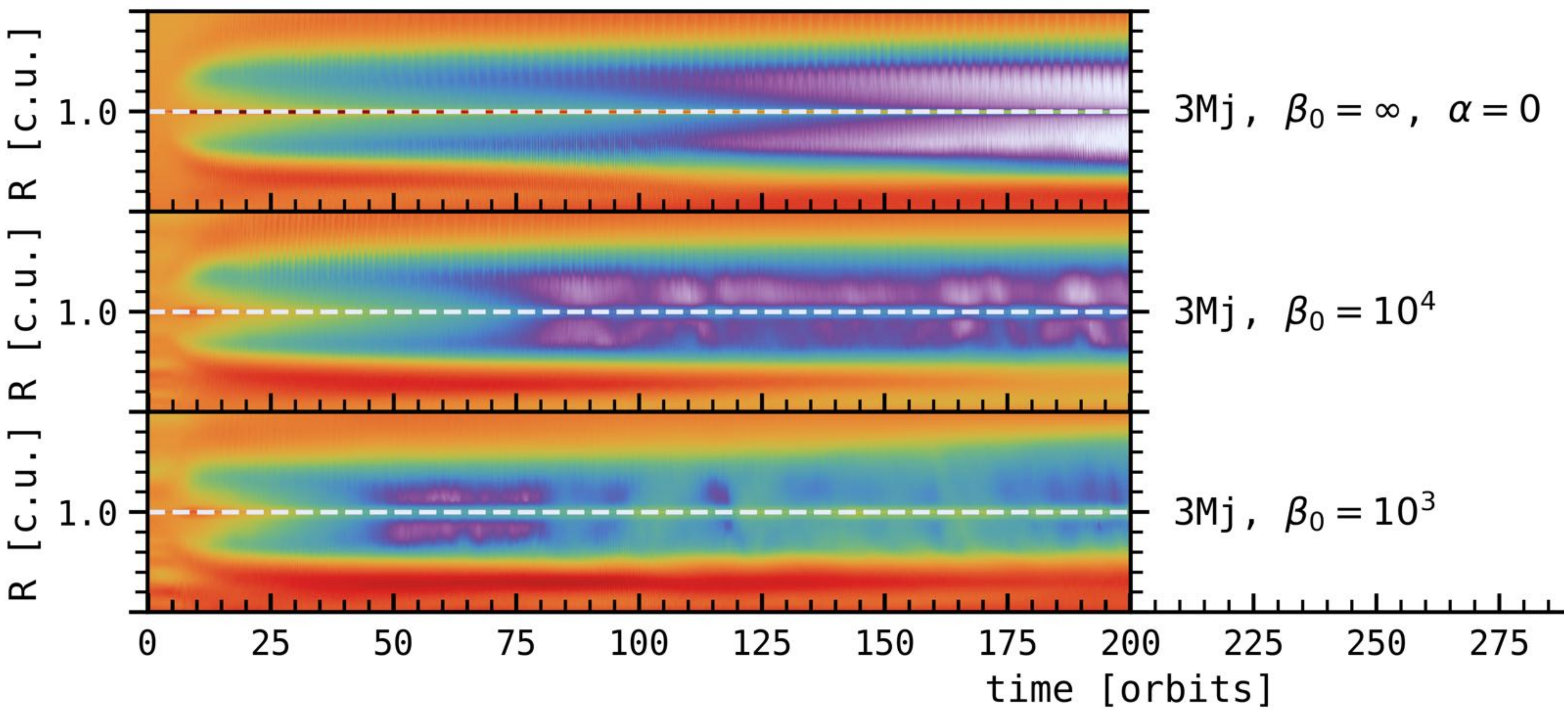


Secondary gaps
(due to wind-driven structure formation
cf Béthune+2017, Riols+2020)

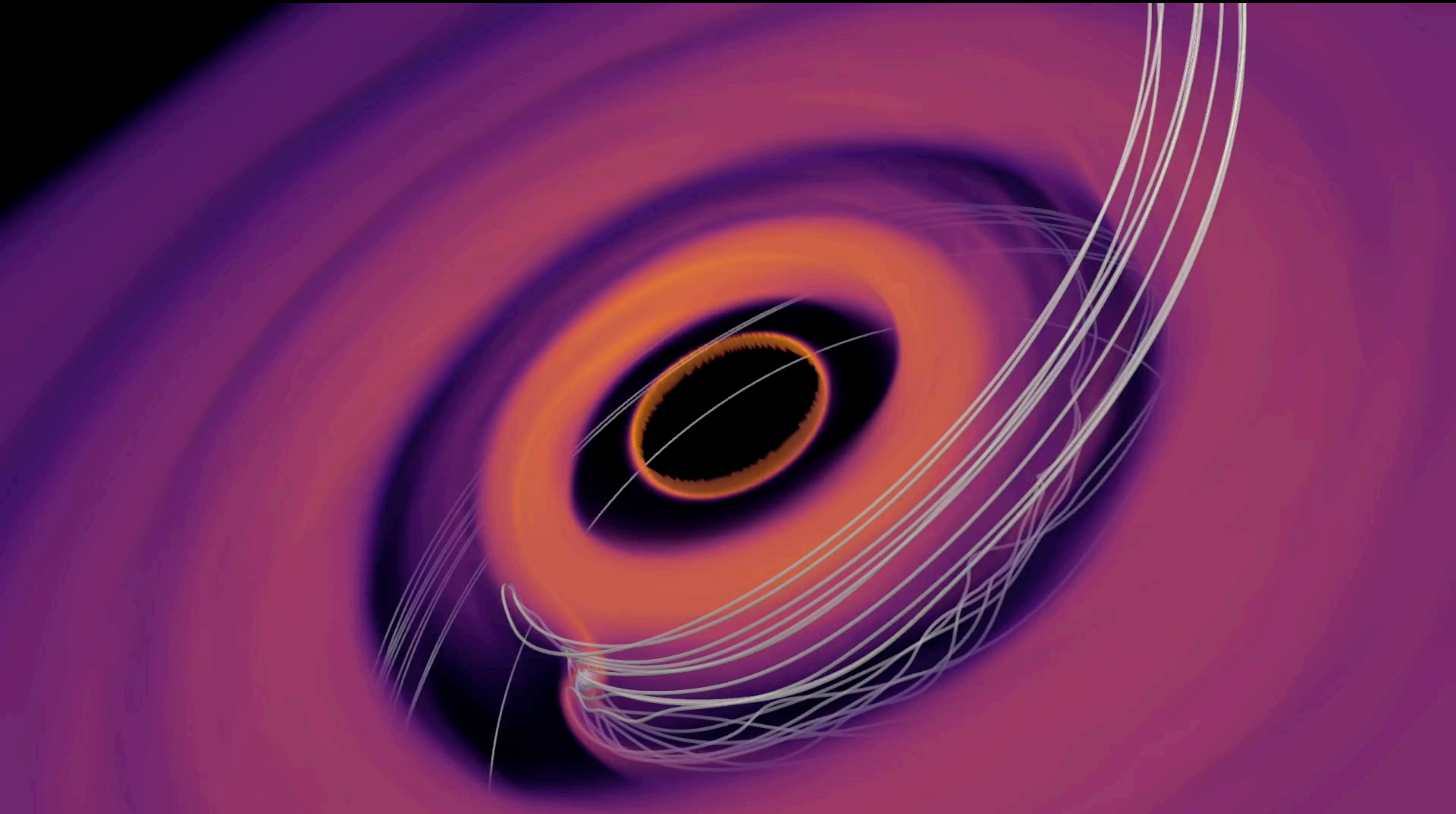
planetary gaps

- Planets still open gaps
- Gap opening criterion and depth depends on the field strength

Gap morphology



- Magnetised gaps become asymmetric as time goes on
- Stronger field amplifies the effect



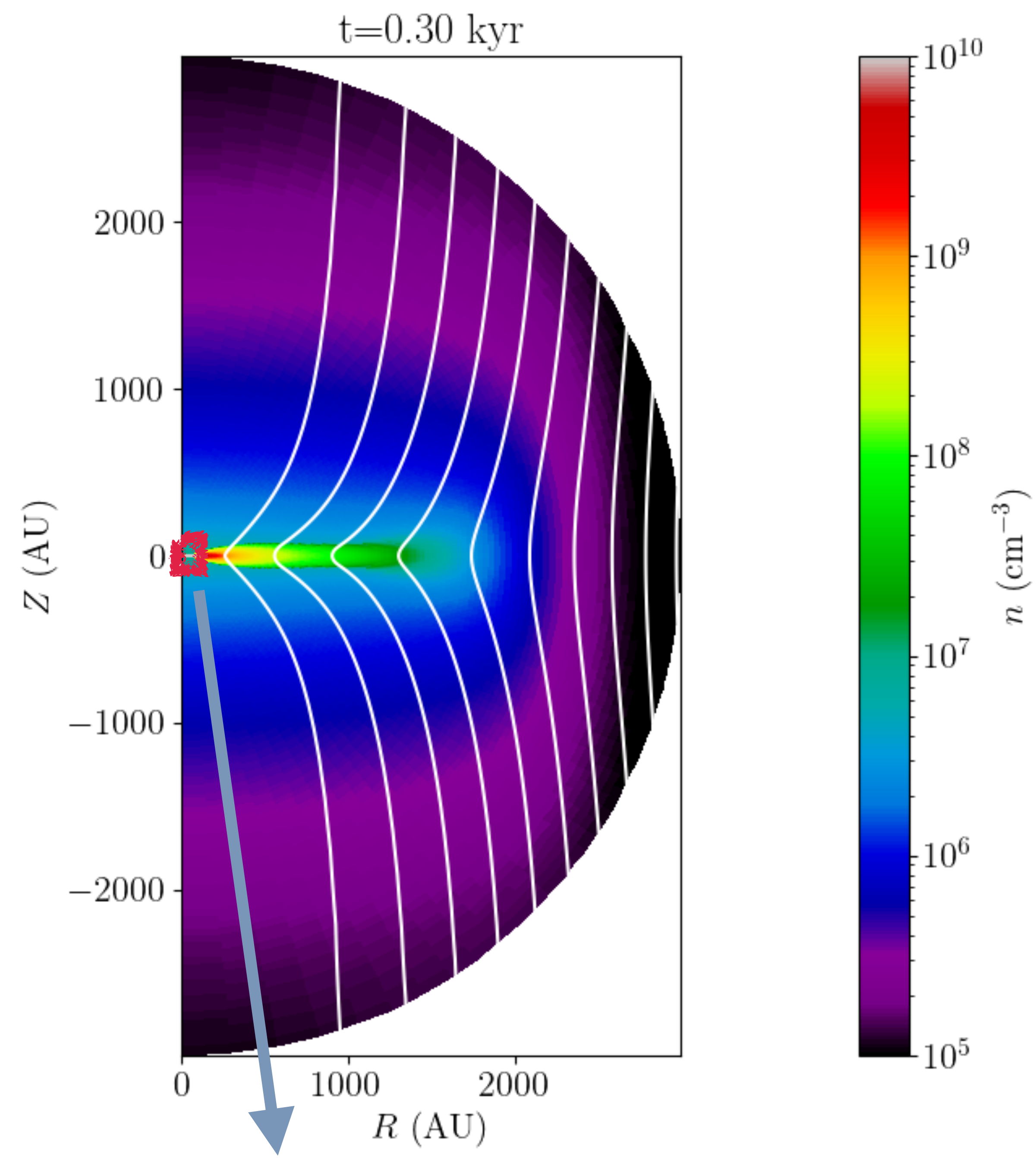
Wafflard-Fernandez & Lesur 2024

A collapsing core


Jonah Mauxion

- Chemical network to account for non-ideal effects [Ohmic & Ambipolar]
- Setup inspired from Masson et al. (2016):
    - Start from a uniformly rotating supercritical $1\ \mathrm{M}_{\odot}$ core
    - initial $R_{\rm core}$= 2500 au
    - Barotropic EOS : $T \propto T_0 \sqrt{1 + \left(\frac{n}{n_{cr}}\right)^{4/5}}$
    - $n_{cr} = 10^{11}\ \mathrm{cm}^{-3} \Leftrightarrow 1^{st}$ hydrostatic core

- Anisotropic infall and a flattening of the core
- Field line deformation that acquire the classic hourglass shape
- Field line dragging



Let's zoom in

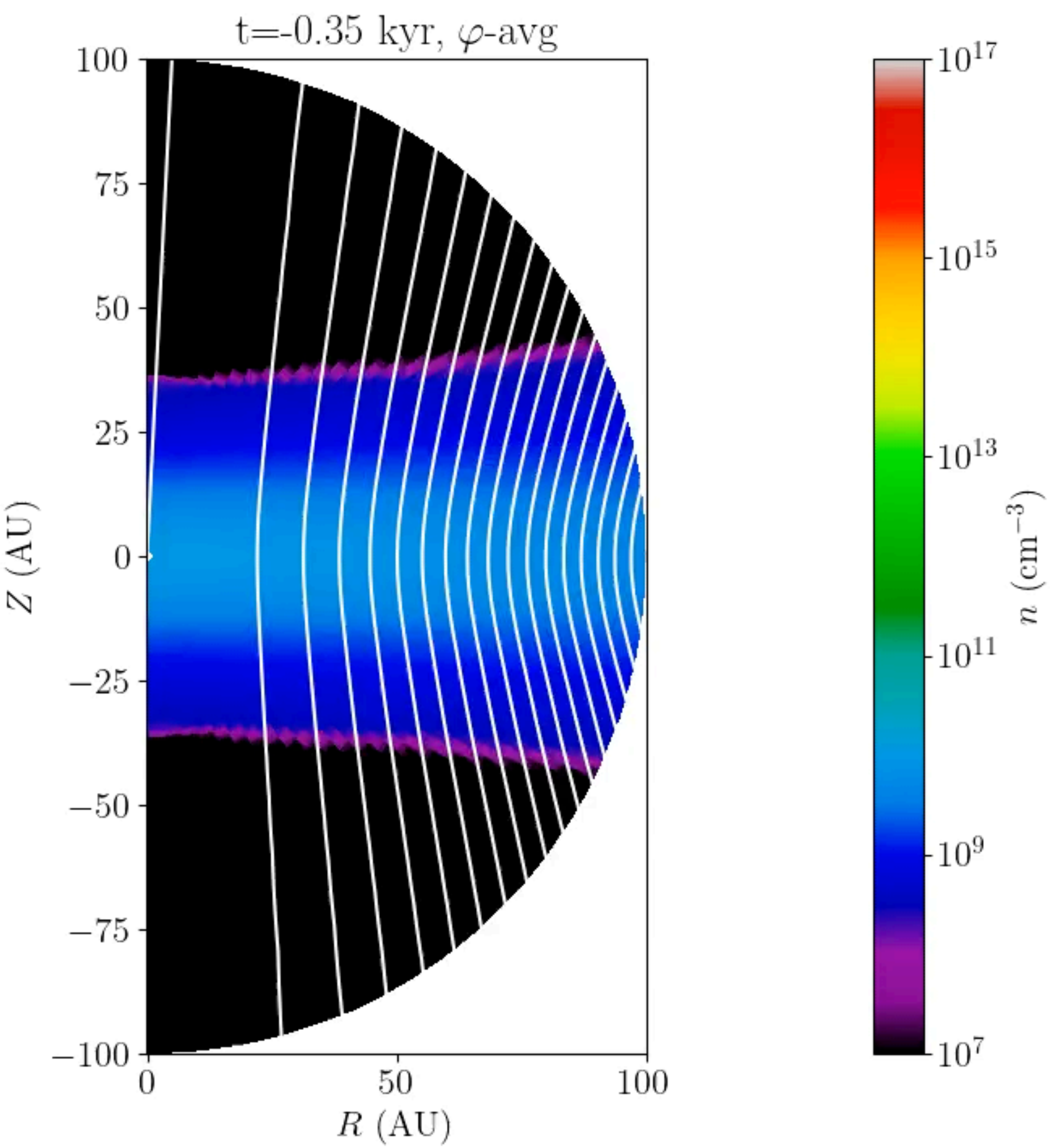
Long timescale evolution

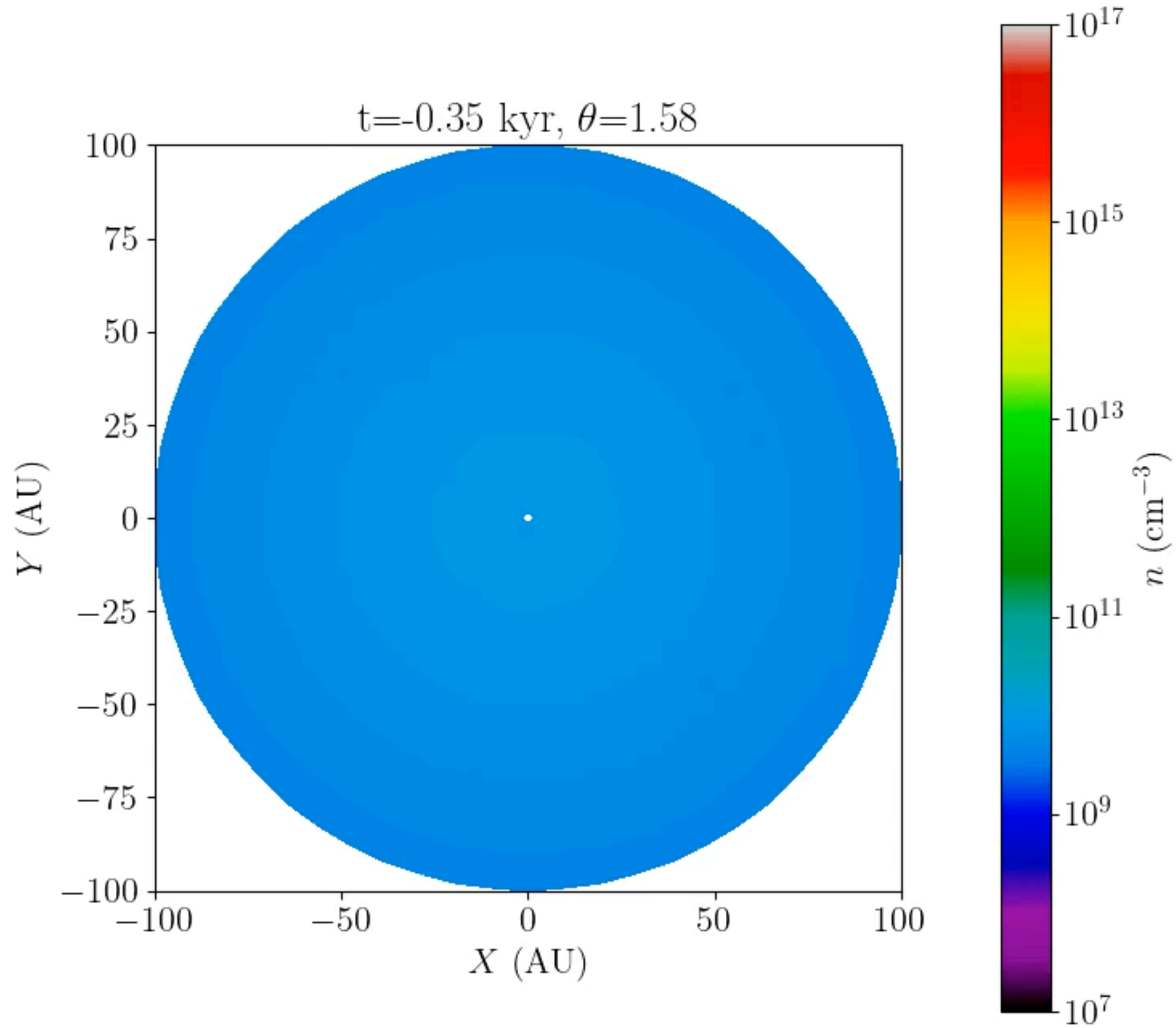
Jonah Mauxion

edge-on view

Top view

[Mauxion+2024]

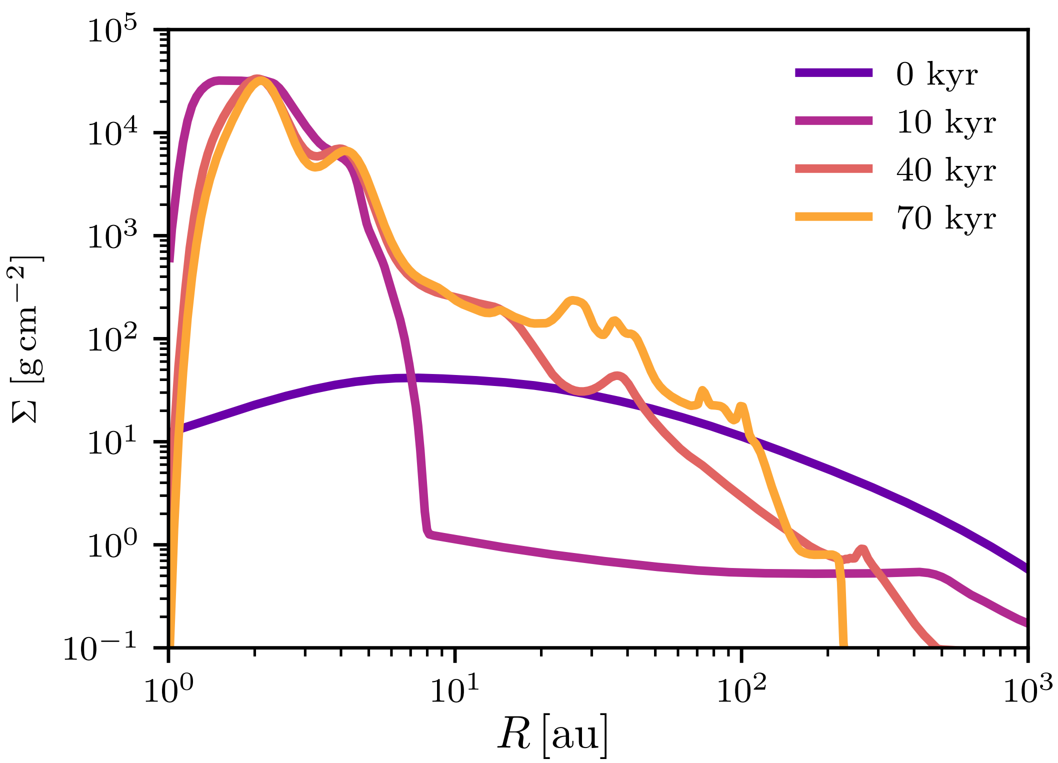




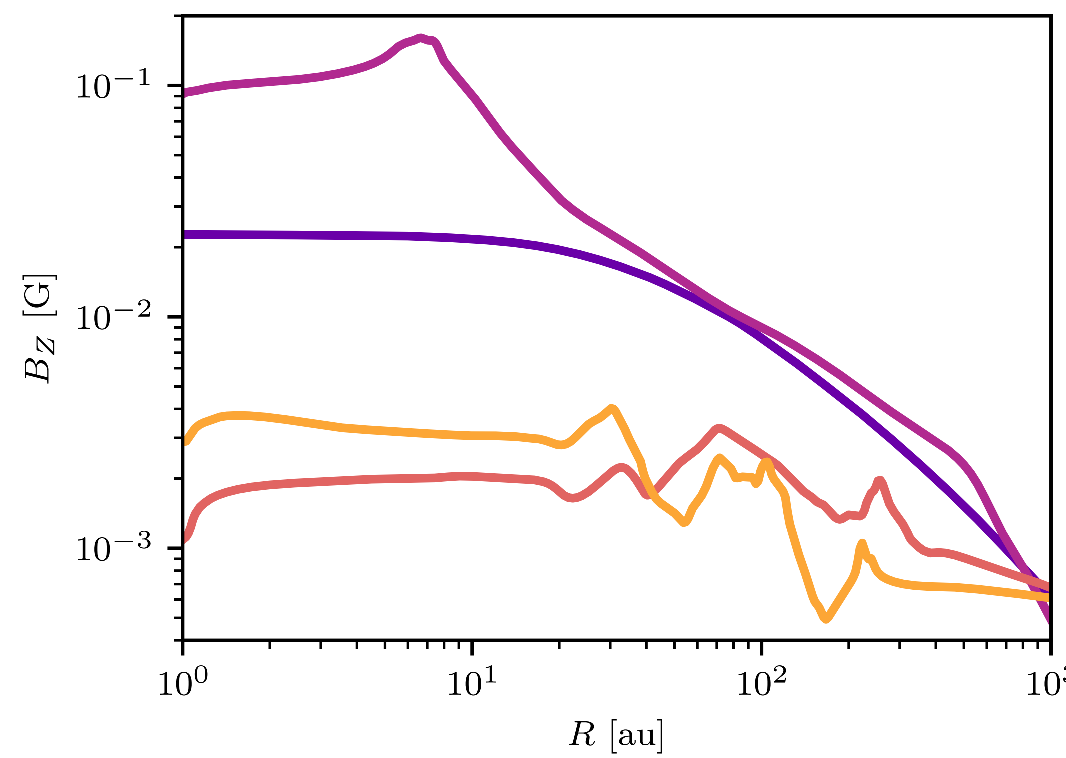
Long timescale evolution (cont’d)


Jonah Mauxion

[Mauxion+ 2024]

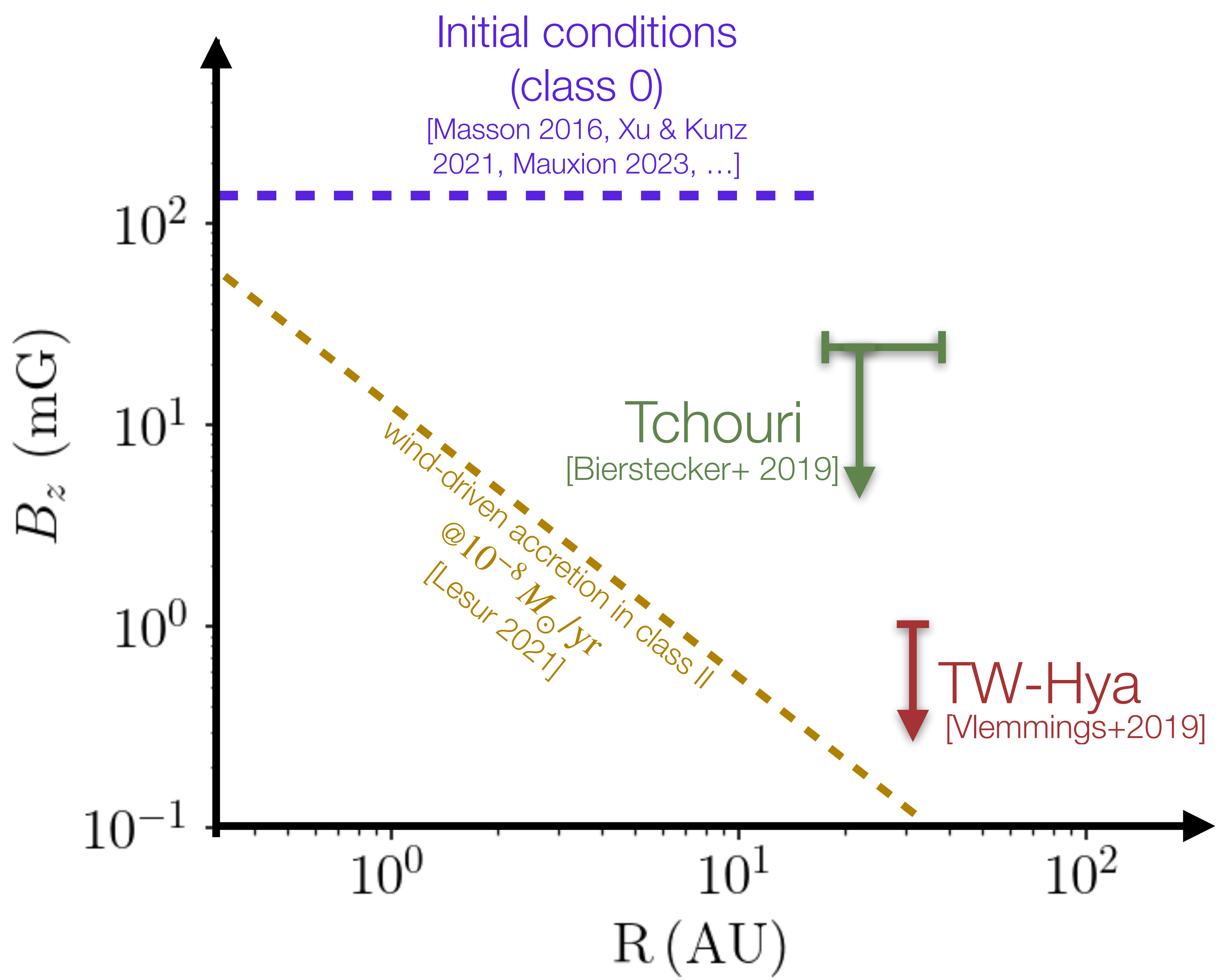


Surface density
evolves into a steep power-law



B field decays down to 1mG
(compatible with obs limits)

Constraining the large scale field



B must decay by ~10^2 at 10 AU from class 0 to class II