Non-ideal MHD in planet-forming discs

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Geoffroy Lesur

with thanks to

William Béthune (DAMTP)
Antoine Riols (IPAG)
Matthew Kunz (Princeton)
François Ménard (IPAG)
Jonathan Ferreira (IPAG)
Sébastien Fromang (CEA)

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

cnrs

UNIVERSITÉ Grenoble Alpes

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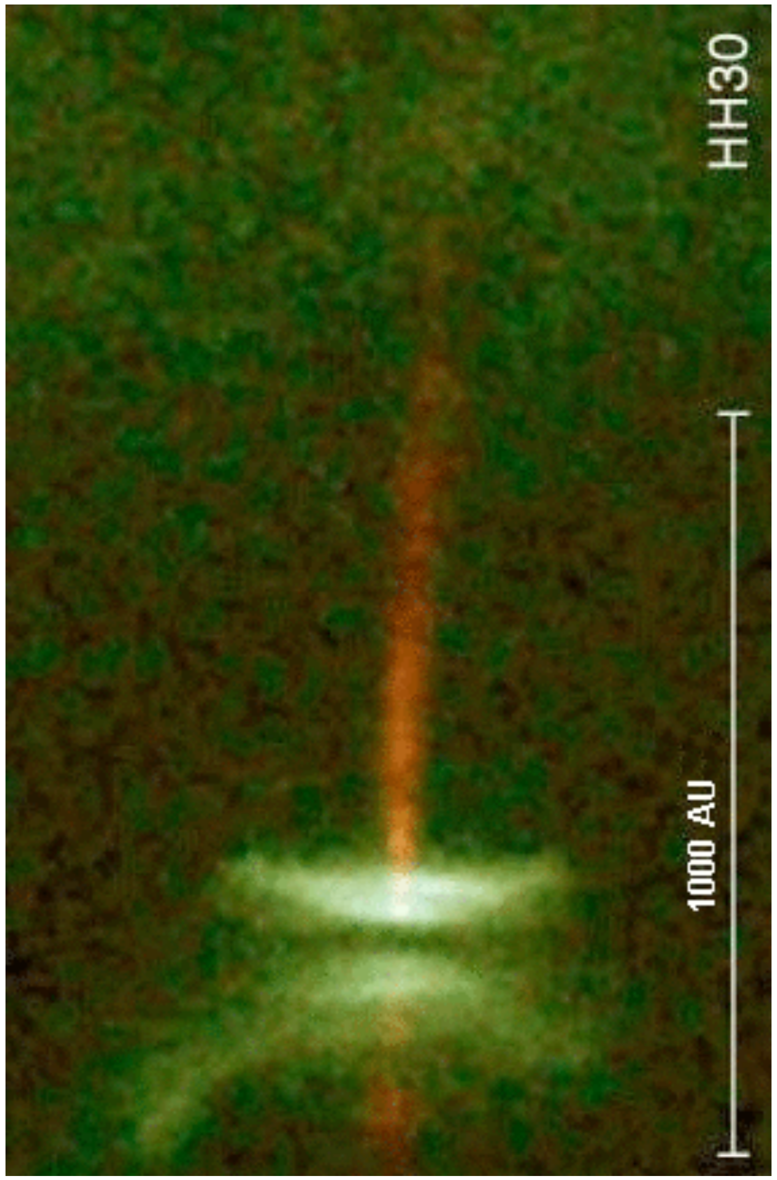
Protoplanetary discs

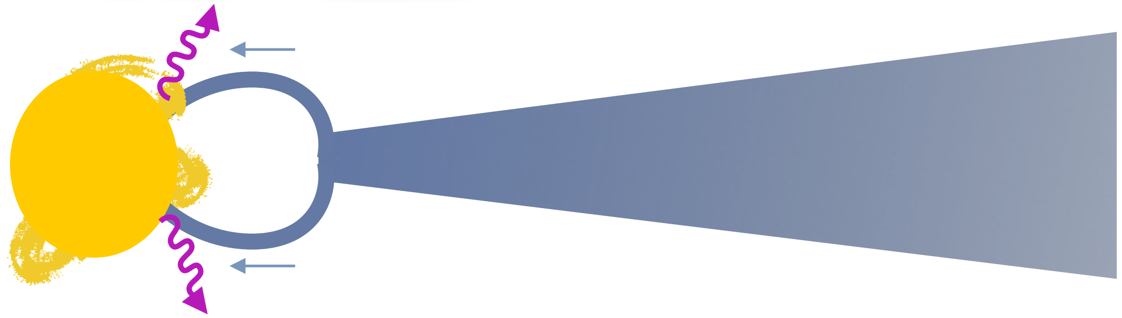


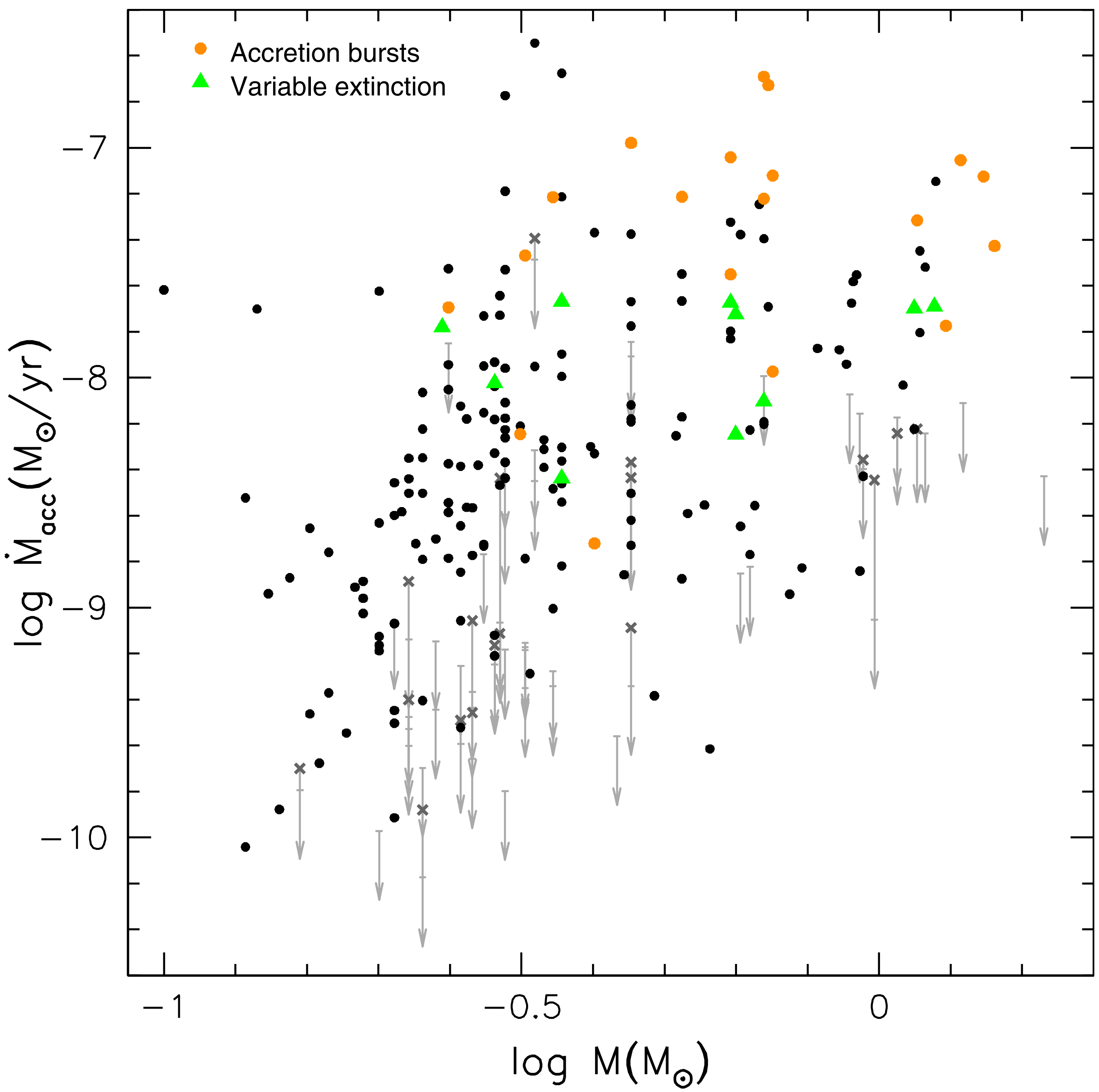
Credit: C. Burrows and J. Krist (STScI),
K. Stapelfeldt (JPL) and NASA

Artist view

- Size: 10^{11}-10^{15} cm (0.1-100 AU)
- Temperature: 10-10^{3} K

Accretion rate onto the stellar surface



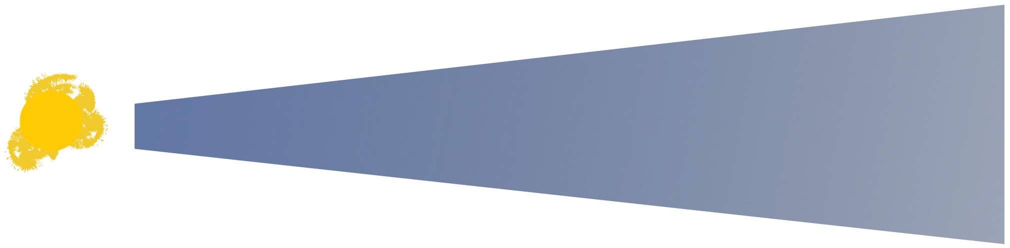


[Venuti+2014]

Historical overview

1970s-1980s

viscous disc theory

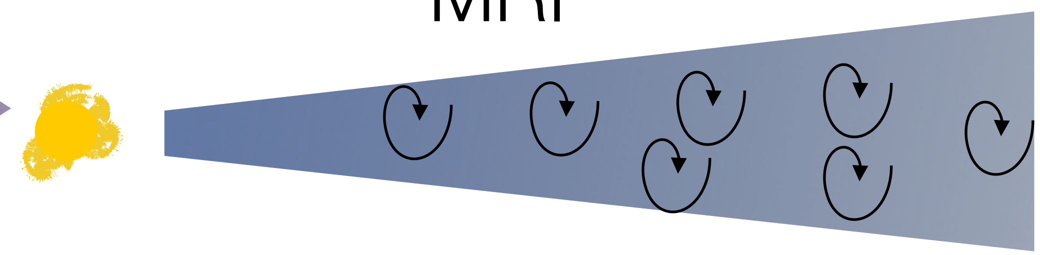


$$\nu_t = \alpha c_s H \quad \text{with} \quad \alpha \simeq 10^{-3}$$

[Shakura & Sunyaev (1973)]

1991

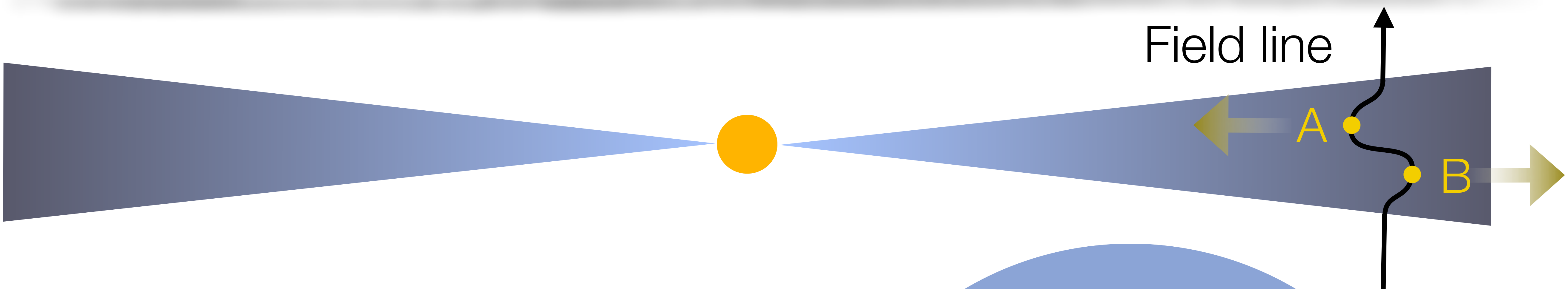
MRI



[Balbus & Hawley 1991]

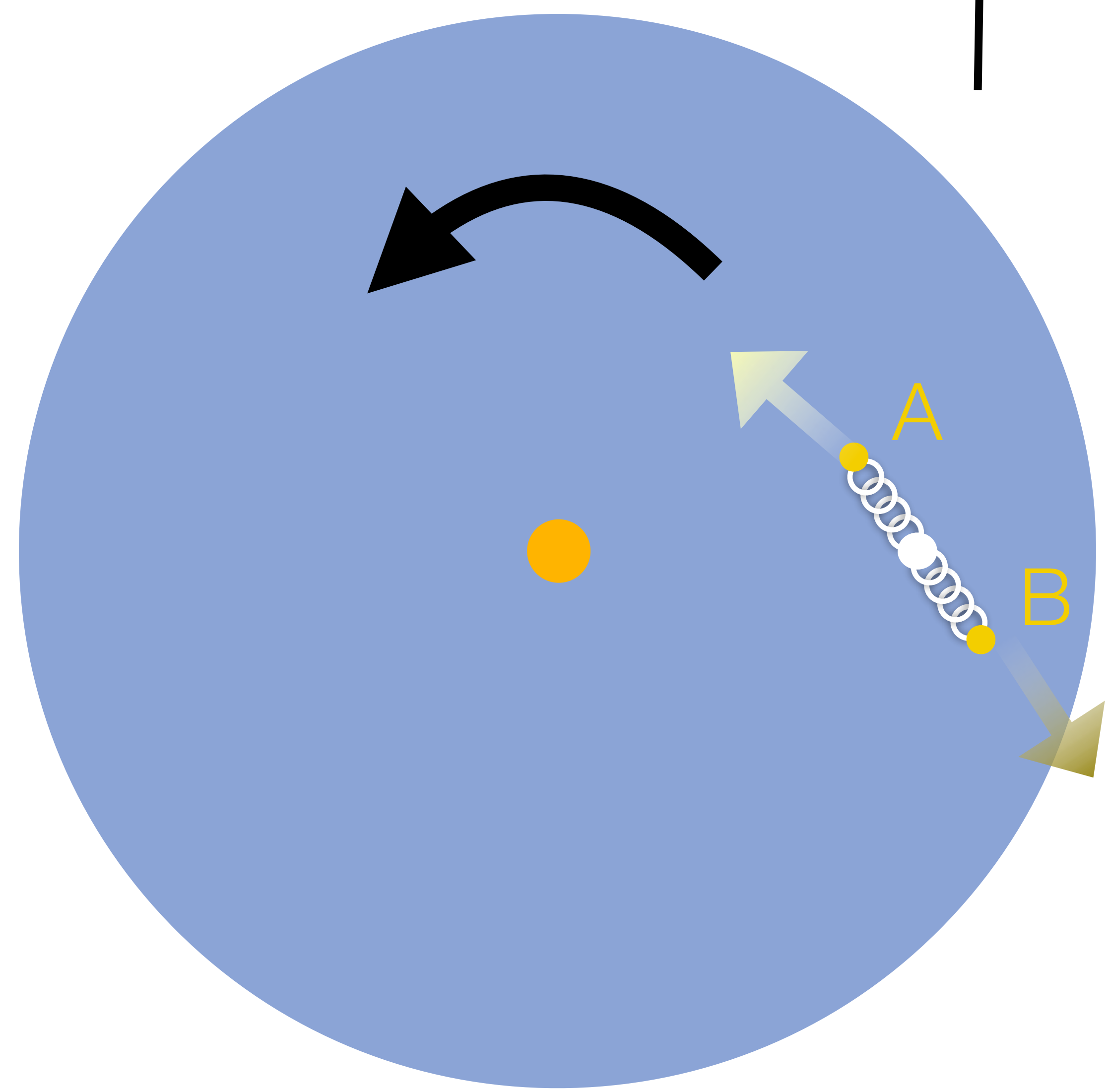
Origin of turbulence in discs
The Magnetorotational instability (MRI)

[Balbus, & Hawley (1991)]
[Balbus (2003)]

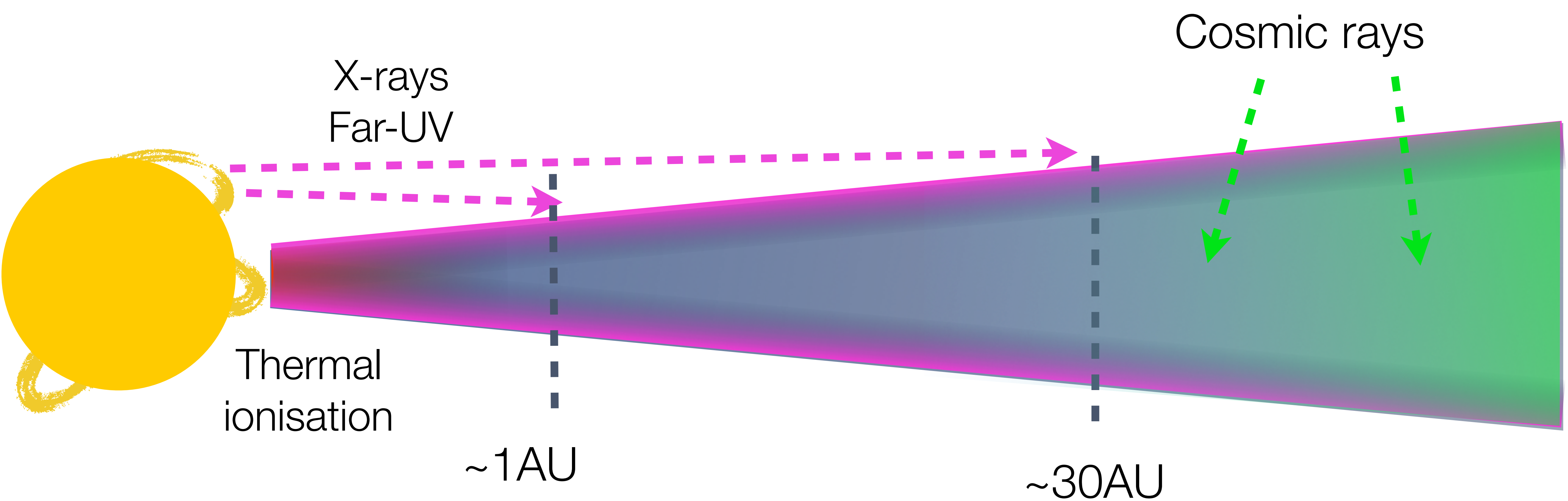


S. Balbus

J. Hawley



Ionisation sources in protoplanetary discs



« non ideal » MHD effects

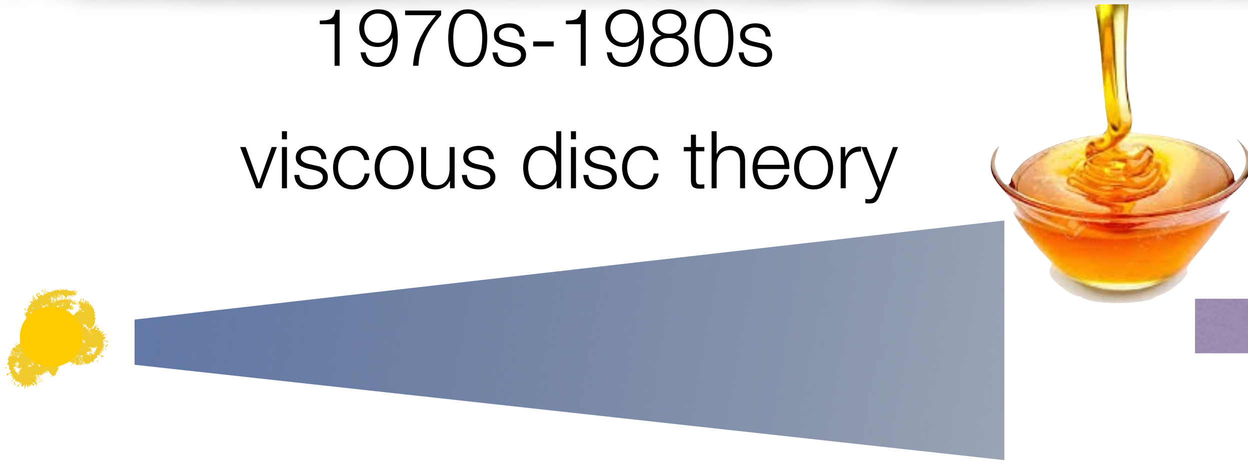
- Ohmic diffusion (electron-neutral collisions)
- Ambipolar Diffusion (ion-neutral collisions)
- Hall Effect (electron-ion drift)

Amplitude of these effects depends strongly on location & composition

Historical overview

1970s-1980s

viscous disc theory



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[Shakura & Sunyaev (1973)]

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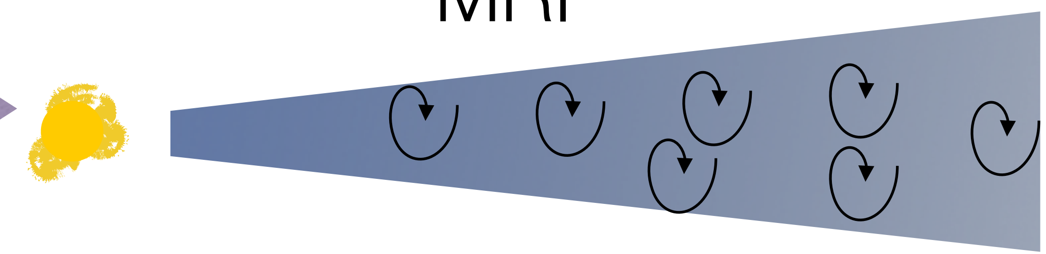
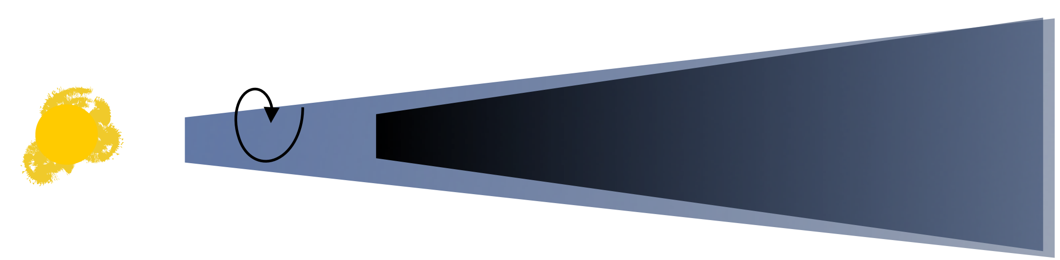


[Balbus & Hawley 1991]

2010



« dead zone »

[Gammie 1996]
[Perez-Beker & Chiang 2011]

Observations

Line broadening

- Emission lines from the gas are broaden by:
  - Keplerian rotation V_k
  - Thermal velocity $v_{\rm th} \simeq c_s \ll V_k$
  - Turbulence $v_{\rm turb} \simeq \sqrt{\alpha} c_s$

Measuring line broadening due to turbulence requires very precise measures/estimates of V_k and c_s

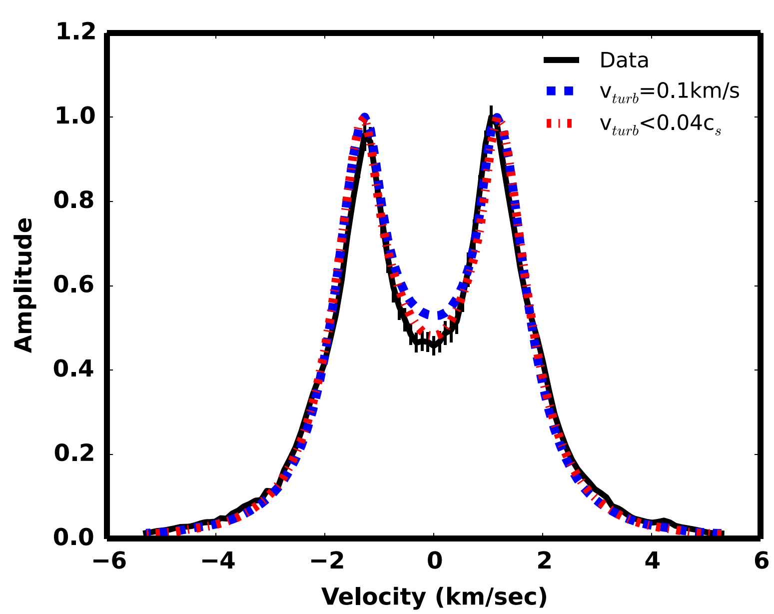
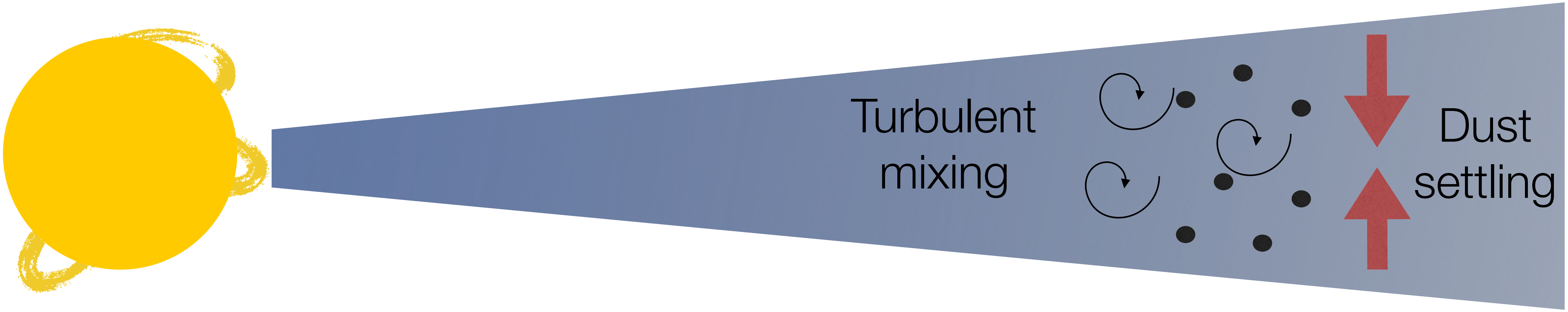


Figure 6. CO(3-2) high resolution spectra (black line) compared to the median model when turbulence is allowed to move toward very low values (red dotted–dashed lines) or when it is fixed at 0.1 km s^{-1} (blue dashed lines). All spectra have been normalized to their peak flux to better highlight the change in shape. The models with weak turbulence provide a significantly better fit to the data despite the fact that the turbulence is smaller than the spectral resolution of the data.

[Flaherty+2015]

Turbulence velocity smaller than 0.04 c_s

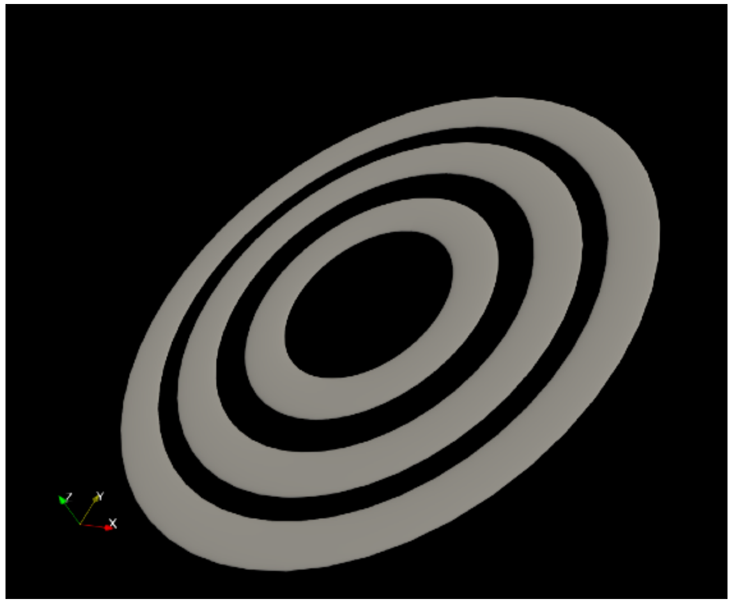
Dust settling (I)

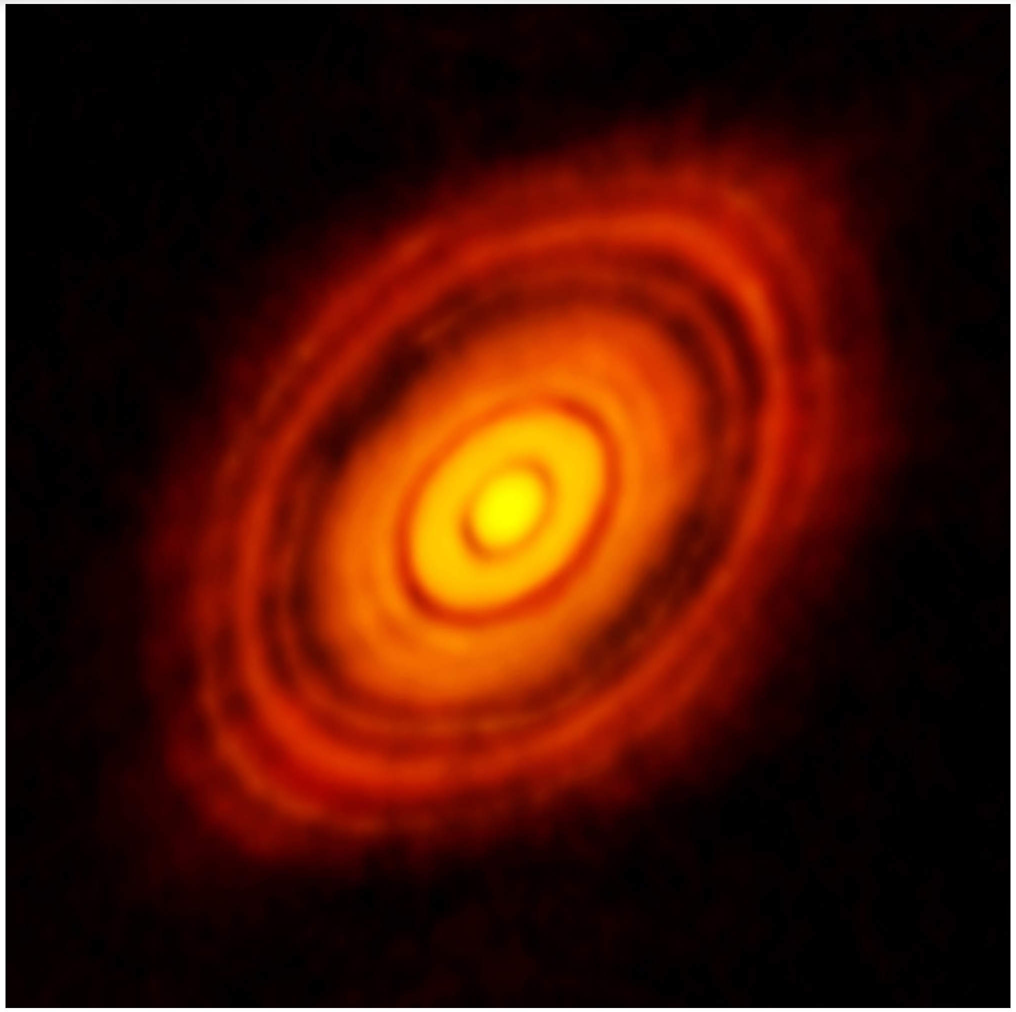


The thickness of the dust layer depends on the competition between settling and turbulent mixing

Dust settling (III)

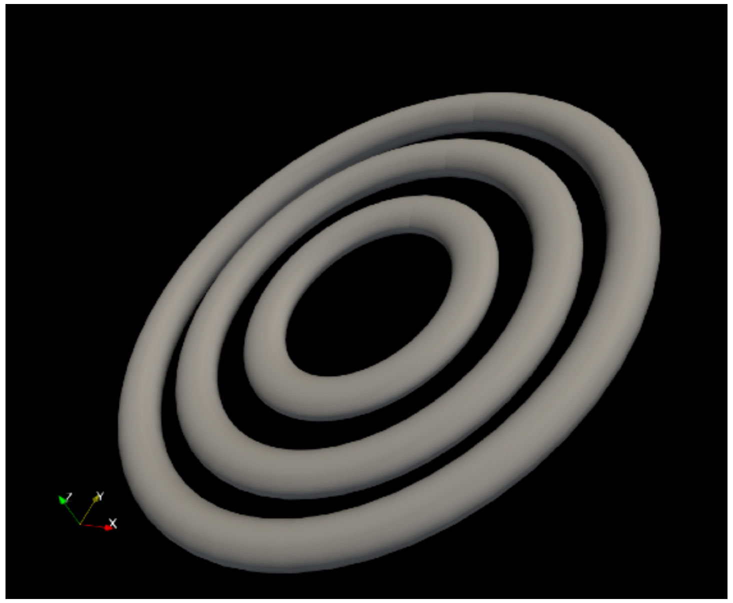
Thin disc model





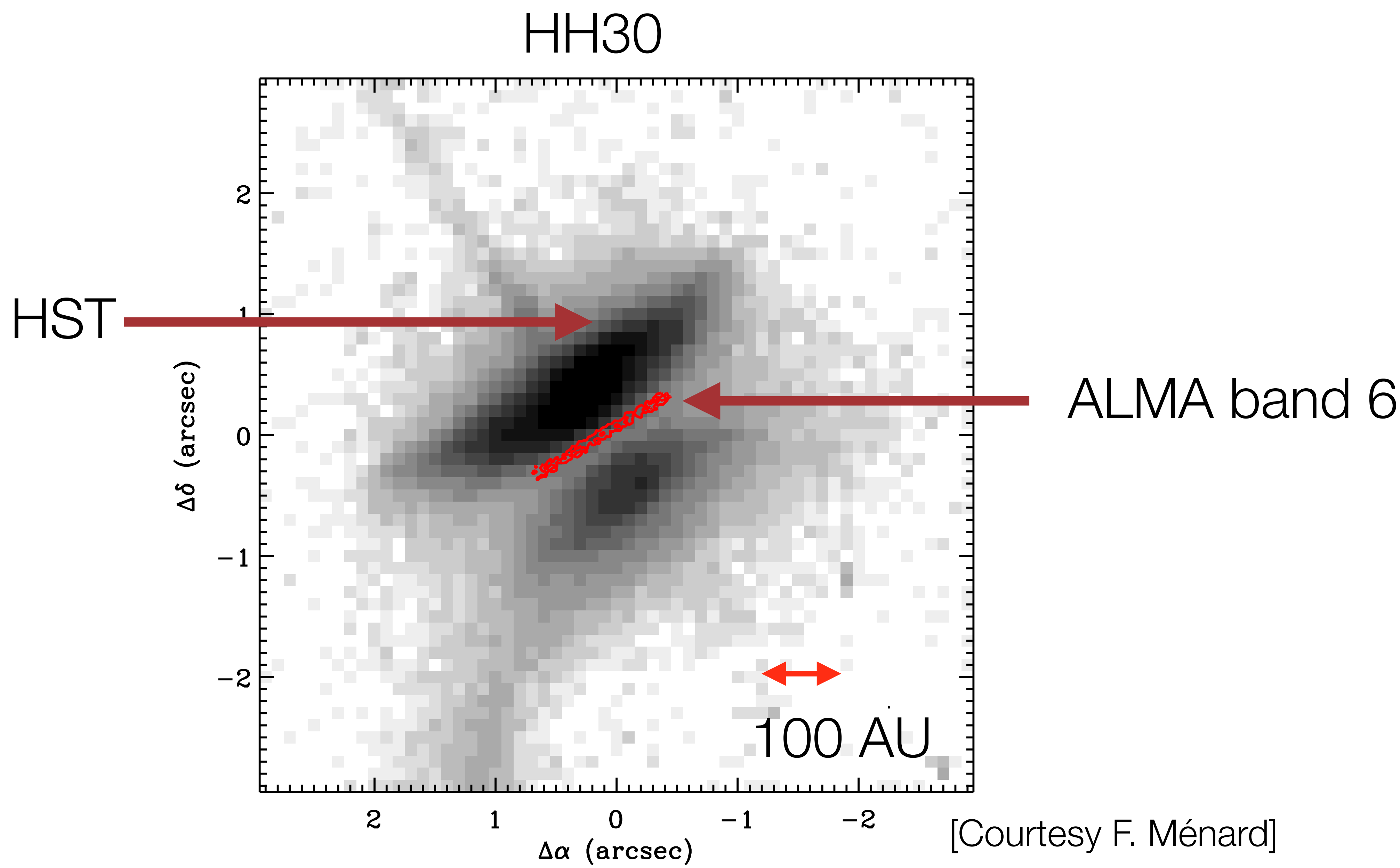
HL tau, as seen by ALMA observatory
[ALMA partnership 2015]

Thick disc model



- HL tau dust disc is very thin (H/R<0.01) [Pinte+2016]
- Very strong settling

Dust settling
in edge on discs



[Courtesy F. Ménard]

mm-sized dust grains are strongly settled → low level of turbulence

Summary: Failure of the turbulent disc model

Theoretical

Discs are very weakly ionised

→ "Non-ideal" MHD effects

→ MHD turbulence too weak to explain observed accretion rates
[Turner+2014, PPVI]

Observational

- Turbulent line broadening (CO, DCO+) smaller than expected from MHD turbulence
  [Flaherty+2015, 2017]
- Vertical dust settling stronger than expected from MHD turbulence [Pinte+2016]

→ Turbulence (if it exists) is much weaker than anticipated in the turbulent disc model

Key questions

- What drives accretion in protoplanetary discs?
- Which process is responsible for the large scale structures we observe?

Numerical technics

Numerical method

I- PLUTO- a finite volume shock-capturing code

Equations of motion

$$\partial_t \rho + \boldsymbol{\nabla} \cdot \rho \boldsymbol{u} = 0,$$

$$\partial_t \rho \boldsymbol{u} + \boldsymbol{\nabla} \cdot \left[\rho \boldsymbol{u} \boldsymbol{u} + c_\mathrm{s}^2 \rho + \boldsymbol{B}^2/2 - \boldsymbol{B} \otimes \boldsymbol{B} \right] = -2\rho \boldsymbol{\Omega} \times \boldsymbol{u} + \rho \boldsymbol{g},$$

$$\partial_t \boldsymbol{B} + \boldsymbol{\nabla} \times \left[\boldsymbol{u} \times \boldsymbol{B} + \eta_\mathrm{O} \boldsymbol{J} + \eta_\mathrm{H} \boldsymbol{J} \times \hat{\boldsymbol{B}} - \eta_\mathrm{A} \boldsymbol{J} \times \hat{\boldsymbol{B}} \times \hat{\boldsymbol{B}} \right] = 0$$

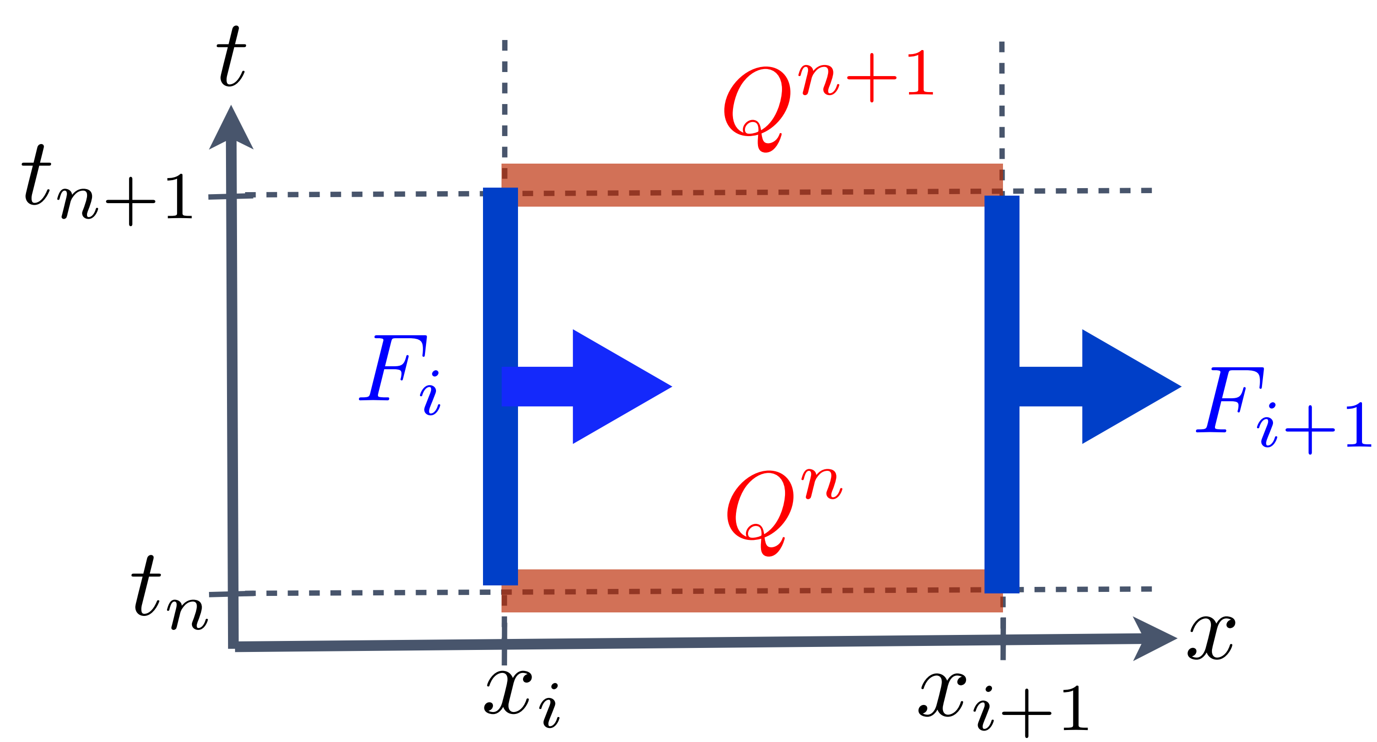
$$\boldsymbol{\nabla} \cdot \boldsymbol{B} = 0$$

General conservative form

$$\partial_t Q + \boldsymbol{\nabla} \cdot \boldsymbol{F}(Q) = 0$$

Integrate in space and time:

$$Q_i^{n+1} = Q_i^n + dt(F_{i+1}^n - F_i^n)$$



Flux are computed solving a Riemann problem
[Mignone+ 2007, A&A 170:228]

Numerical method

II- PLUTO- features & scalability

- Code in ANSI C
- Solve HD/MHD/RelHD/RelMHD equations
- Open source (http://plutocode.ph.unito.it/)
- MPI parallelisation

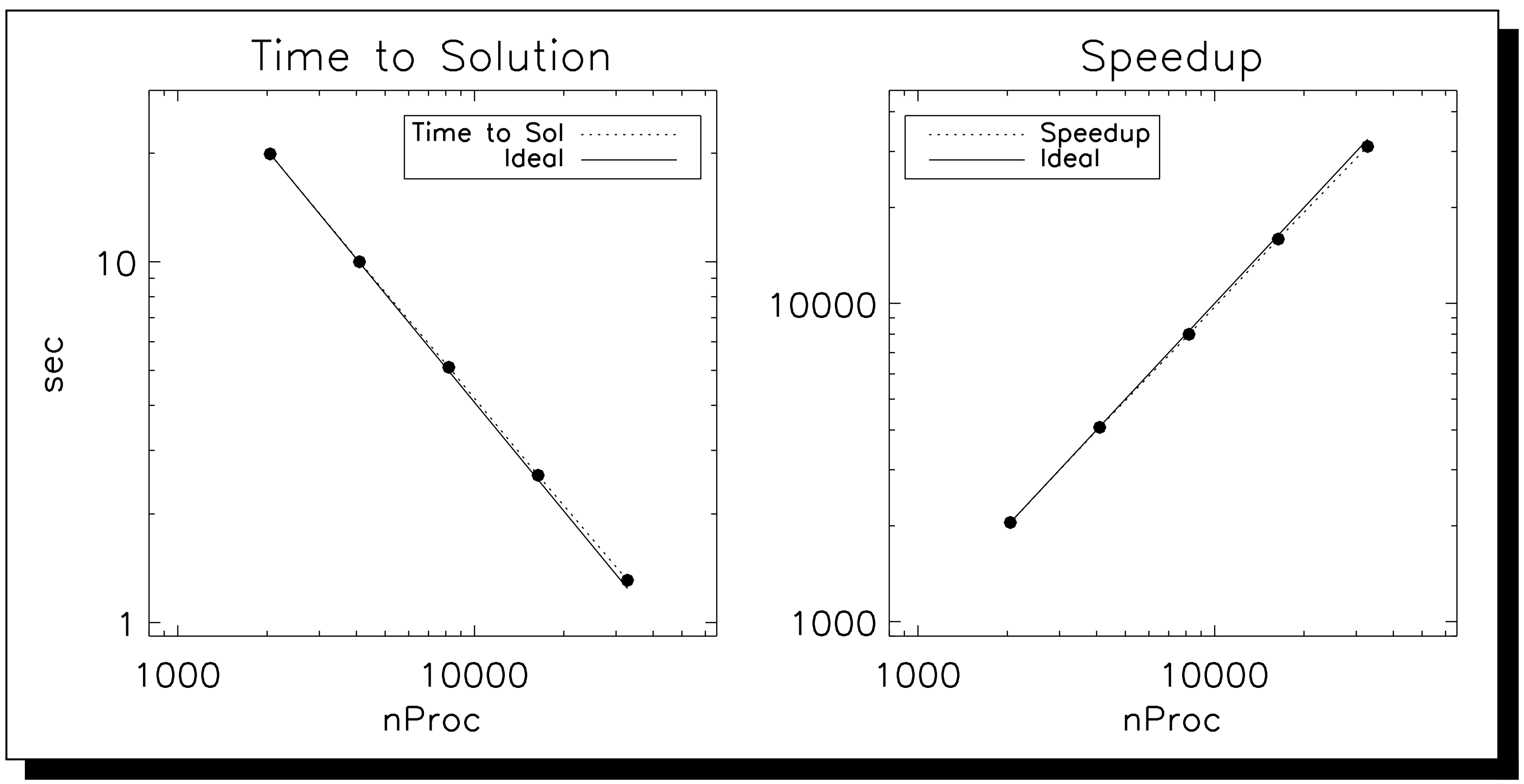


Figure 1.1: Strong scaling of PLUTO on a periodic domain problem with 512^3 grid zones. Left panel: average execution time (in seconds) per step vs. number of processors. Right panel: speedup factor computed as T_1/T_N where T_1 is the (inferred) execution time of the sequential algorithm and T_N is the execution time achieved with N processors. Code execution time is given by black circles (+ dotted line) while the solid line shows the ideal scaling.

[PLUTO user guide]

very good scalability up to 30 000 cores

Numerical method

III- Non ideal effect constrains

Hall effect drives whistler waves

- whistler wave speed $c_w \propto 1/\Lambda$
- CFL stability condition on whistler waves implies:

$$\Delta t < \frac{\Delta x}{c_w^{\max}} \propto \Delta x^2$$

- Hall cannot be treated implicitly (nonlinear term)

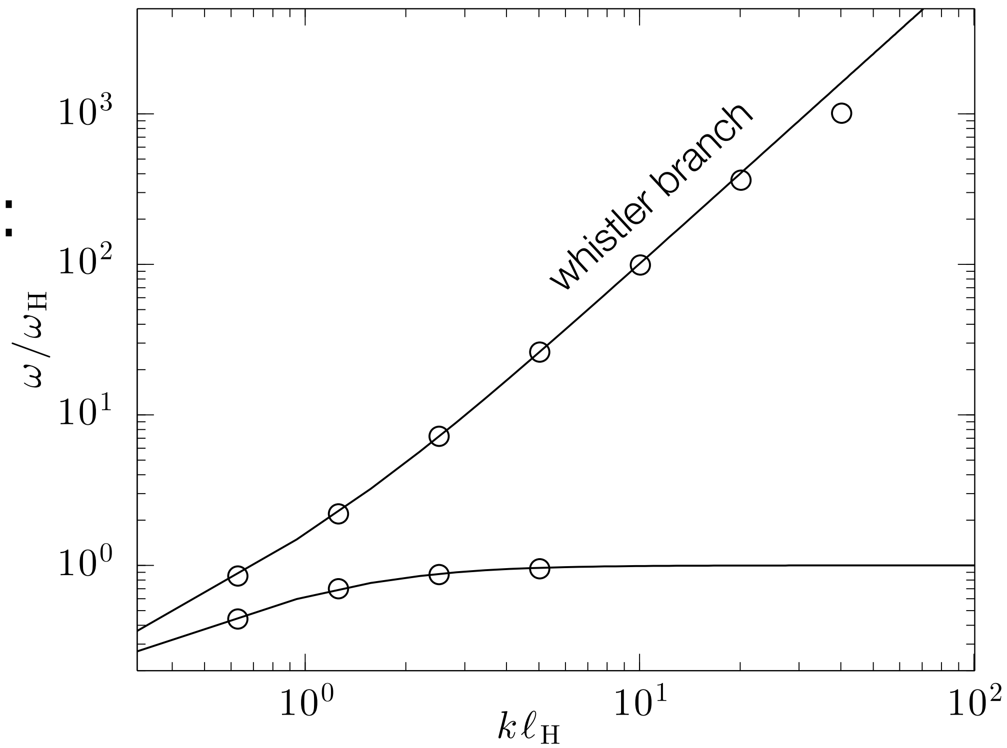


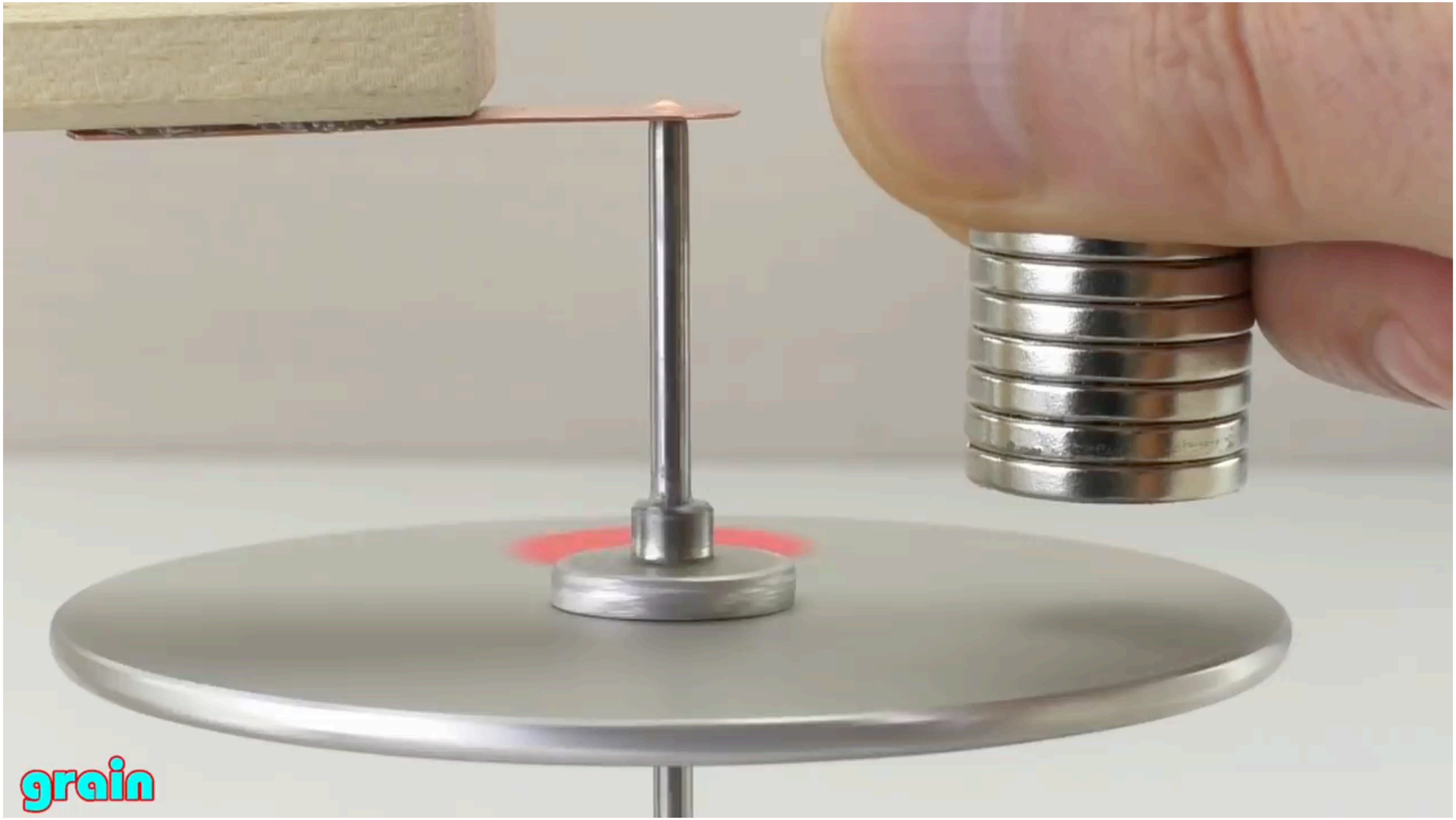
Fig. A.1. Dispersion relation for whistler waves. Black line: analytical prediction; circles: eigenfrequencies measured in PLUTO using our implementation of the Hall effect.

[Lesur+2014]

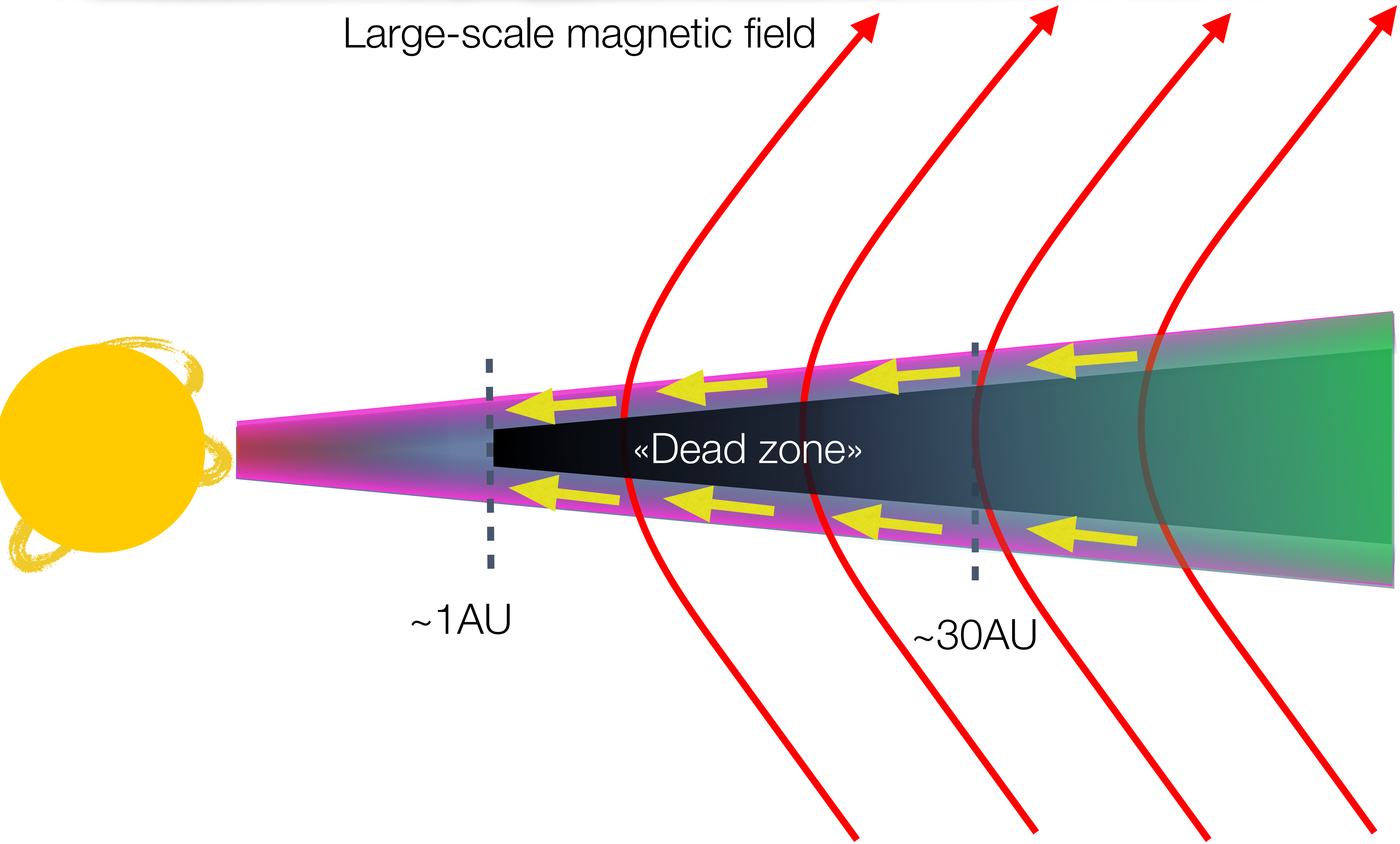
Simulations including the Hall effect are very costly, even at moderate resolution (many time steps)

Towards a new paradigm

A little experiment

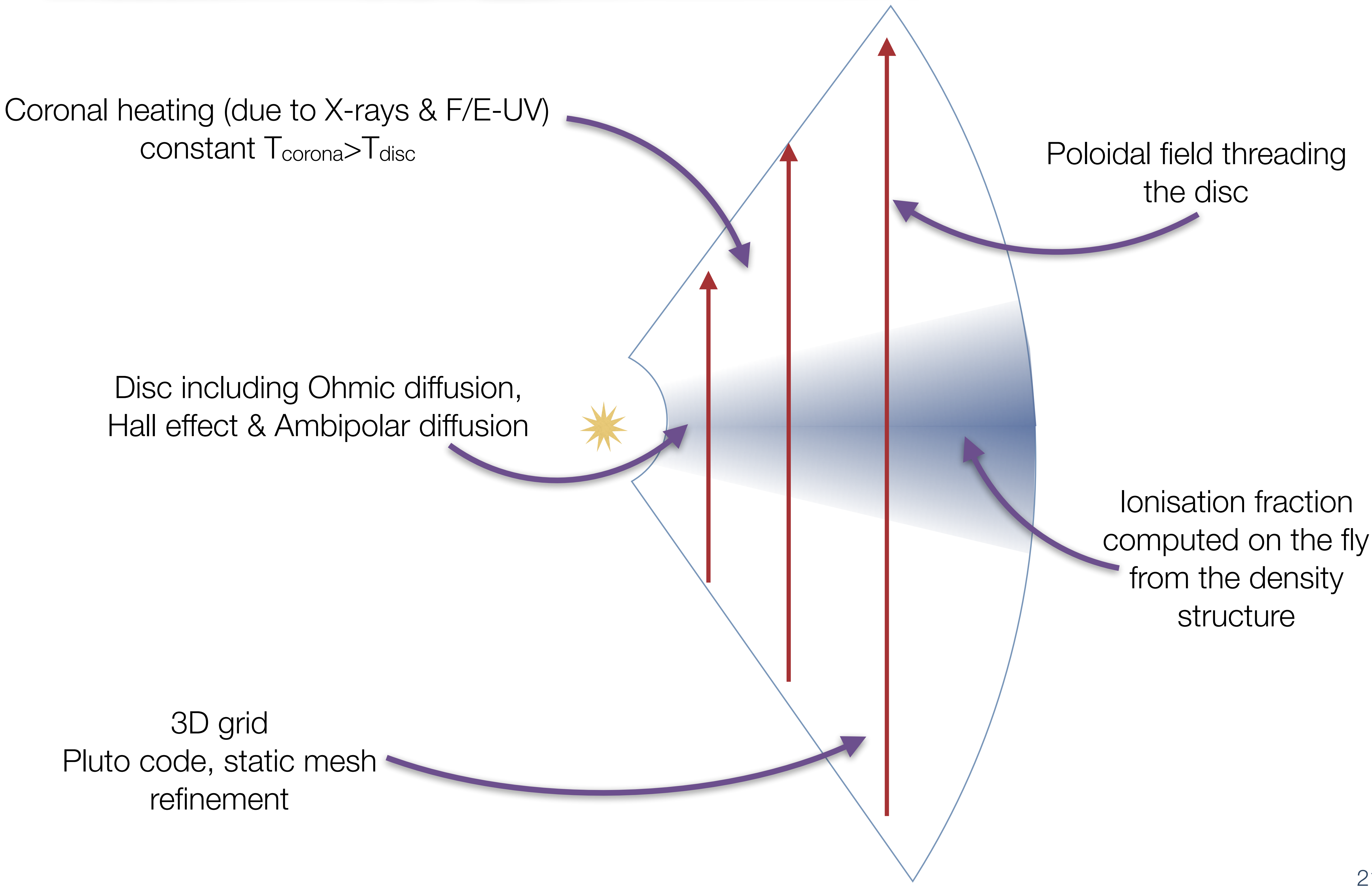


An alternative solution: wind-driven accretion



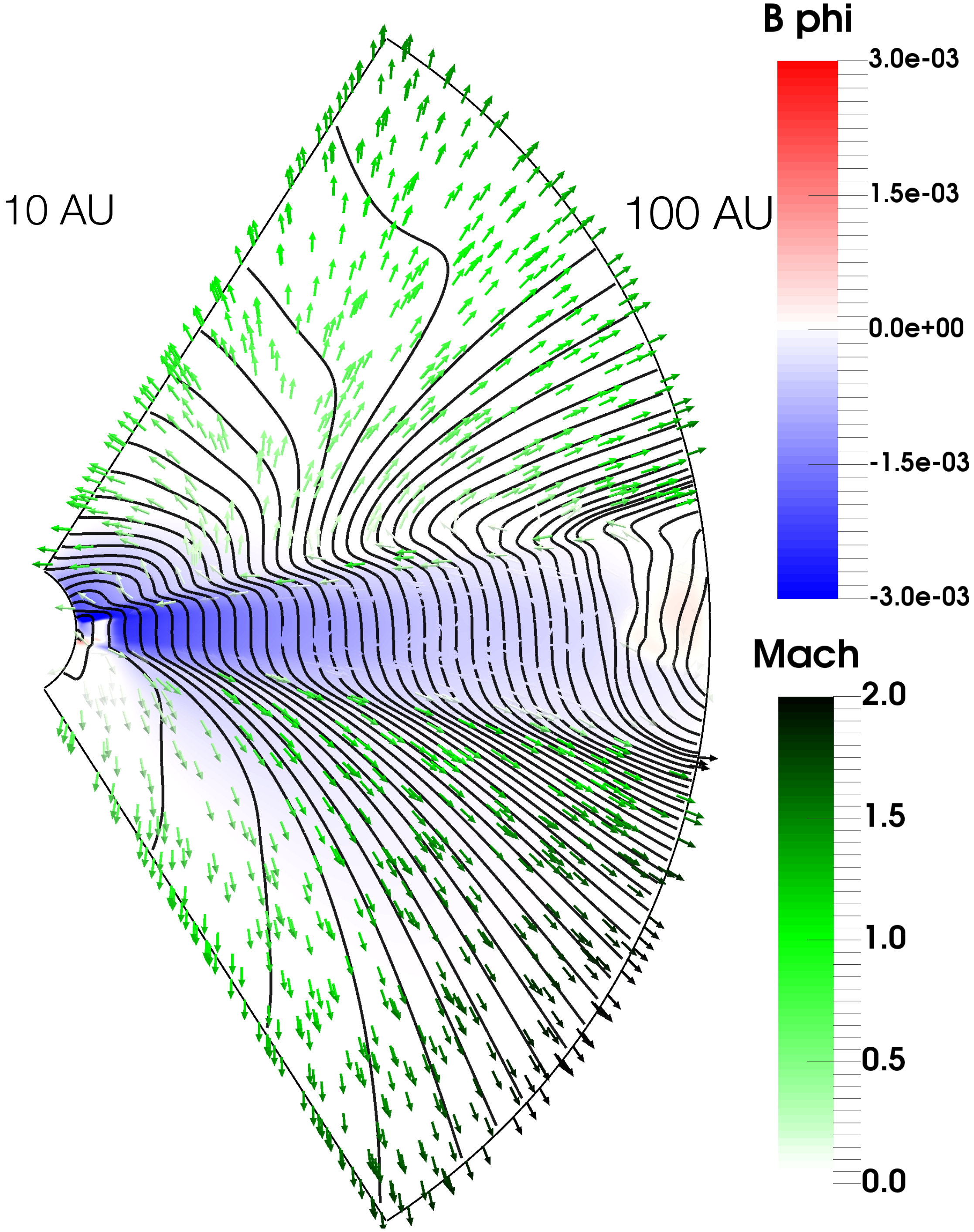
[Bai+ 2013, Lesur+ 2014, Simon+ 2015]

Global simulations
Numerical setup

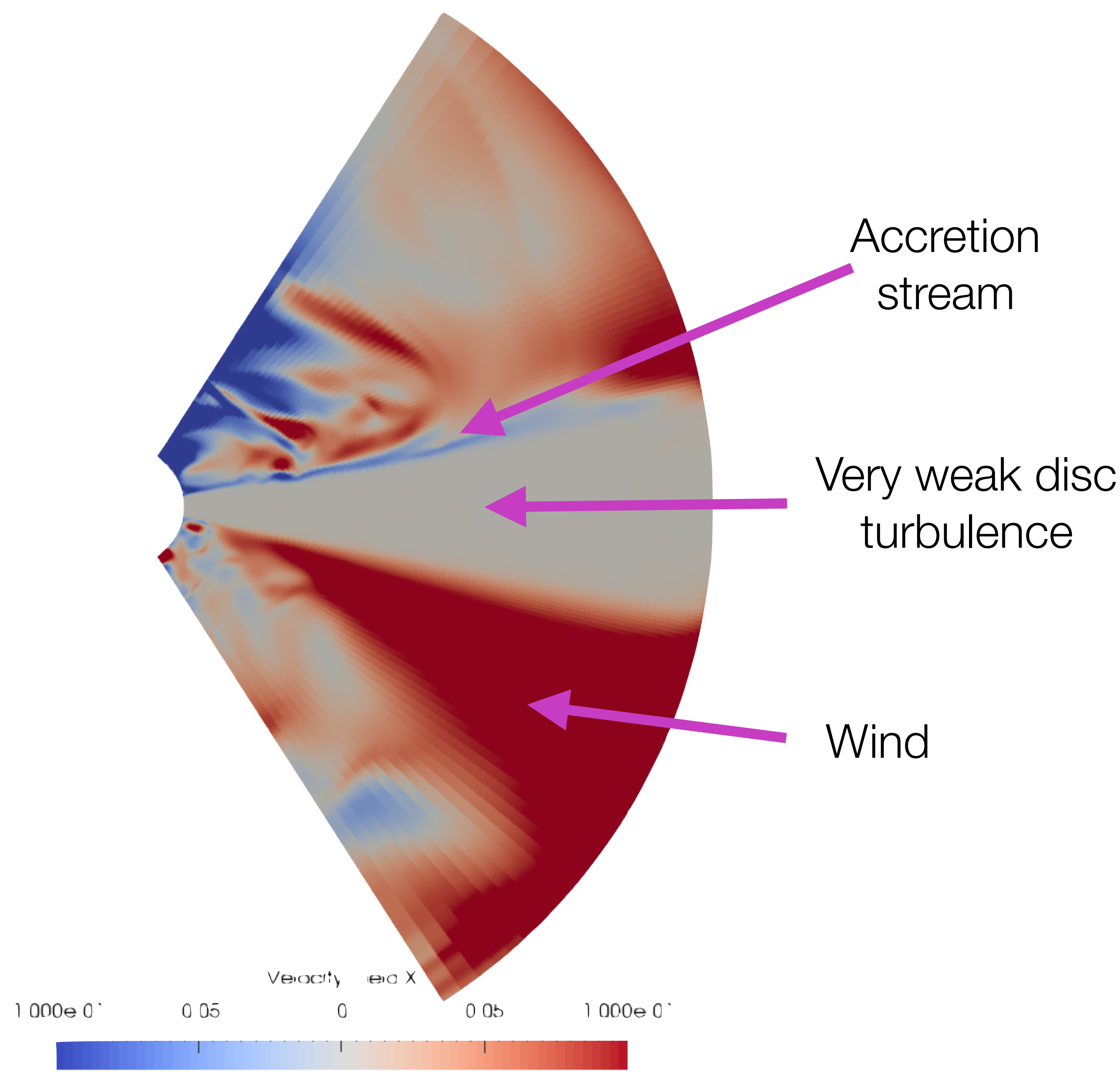


Global Geometry

Magnetic field topology



Radial velocity



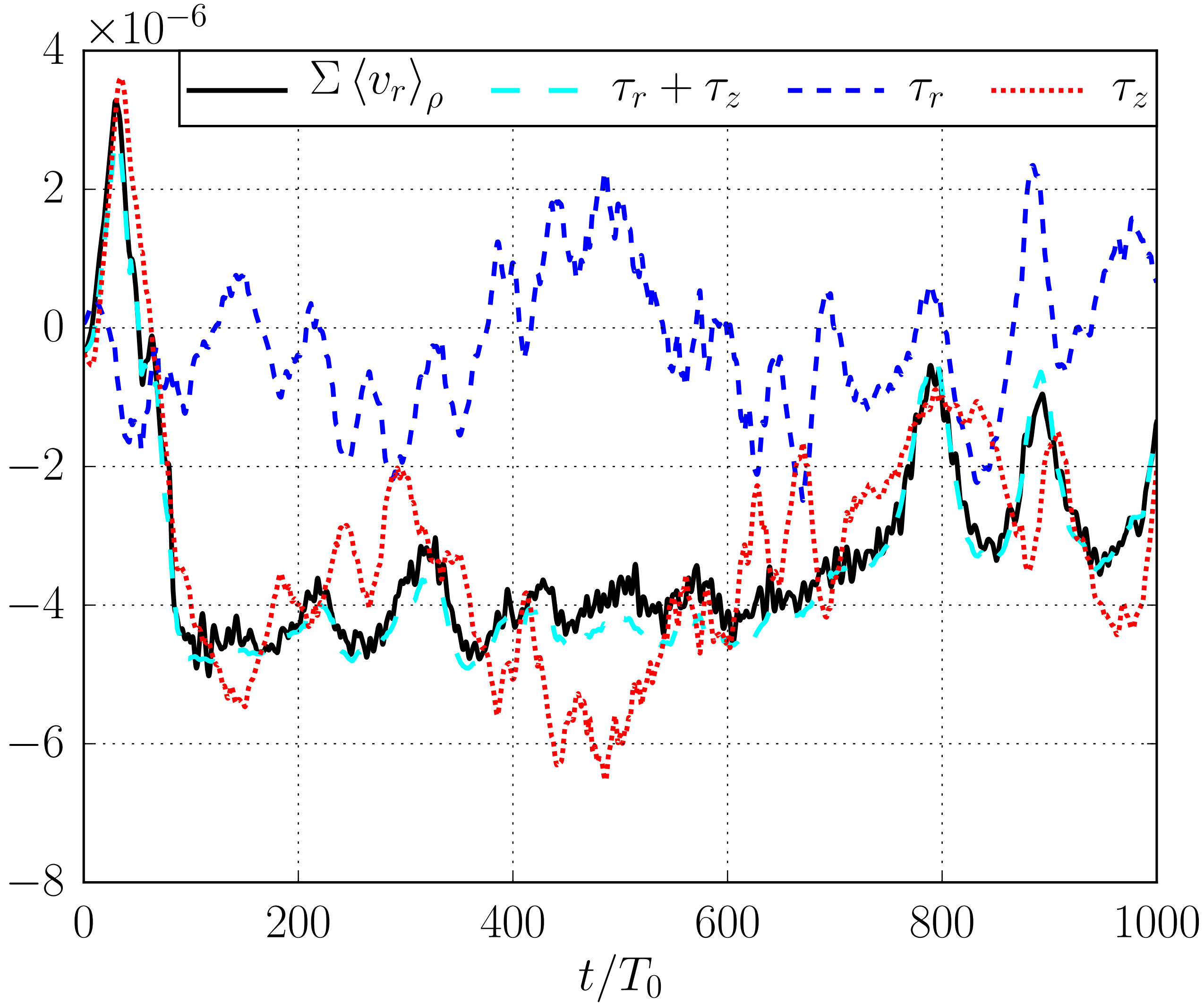
[Béthune, Lesur & Ferreira 2017]

Global simulations
Accretion mechanism

$$\Sigma\langle v_r\rangle_\rho = -\frac{1}{\partial_r\left[r\langle v_\varphi\rangle\right]}\left(\frac{1}{r}\partial_r\left[2r^2H(r)\langle\mathcal{T}_{r\varphi}\rangle\right] - r\left[\langle\mathcal{T}_{z\varphi}\rangle\right]_{-H}^{+H}\right)$$

Angular momentum transported radially in the disc $= \tau_r$

Angular momentum extracted by the wind $= \tau_z$



wind-driven accretion

$$\dot{M}_{\rm acc} = 1.1 \times 10^{-7}\, M_\odot.\mathrm{yr}^{-1}$$

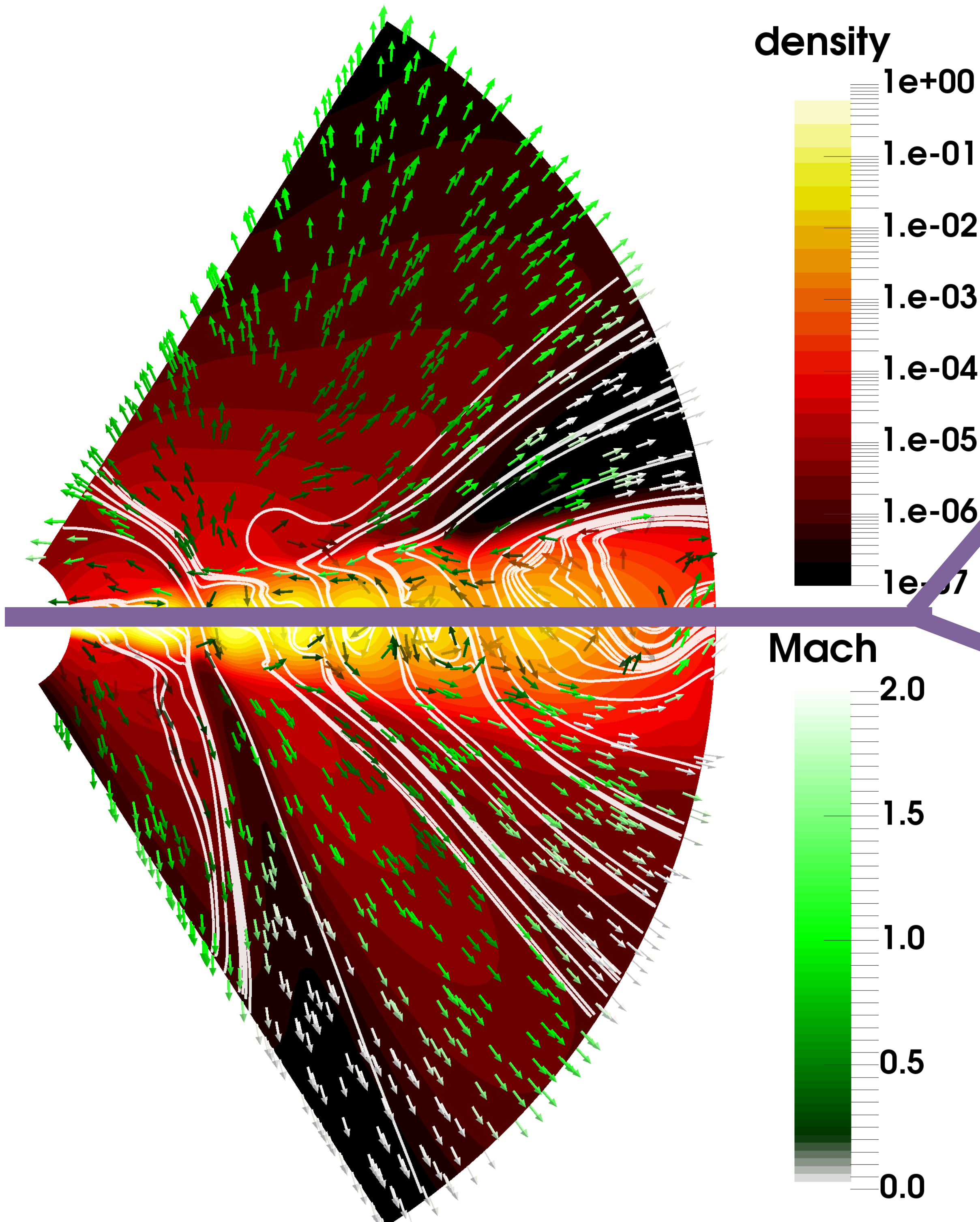
@50 au

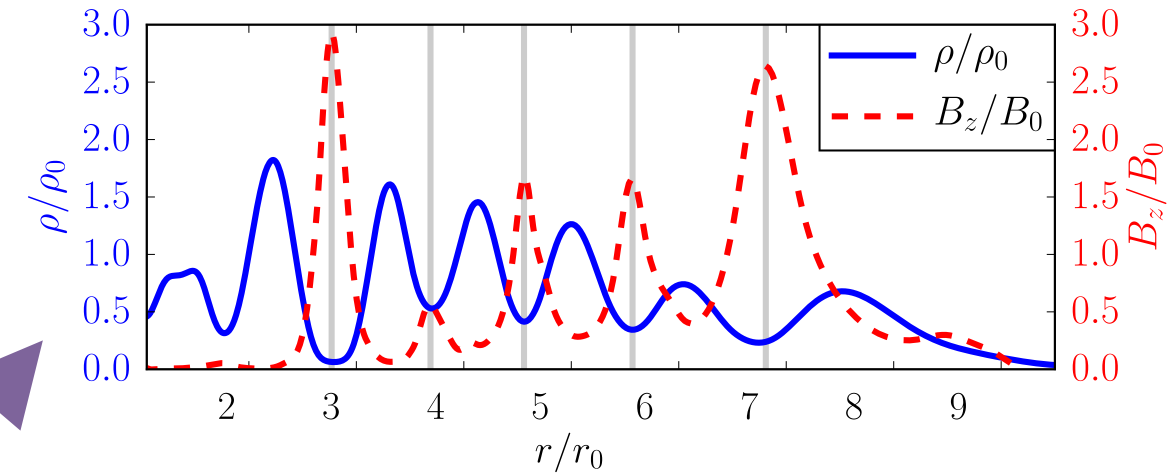
$$\dot{M}_{\rm wind} = 2.3 \times 10^{-7}\, M_\odot.\mathrm{yr}^{-1}$$

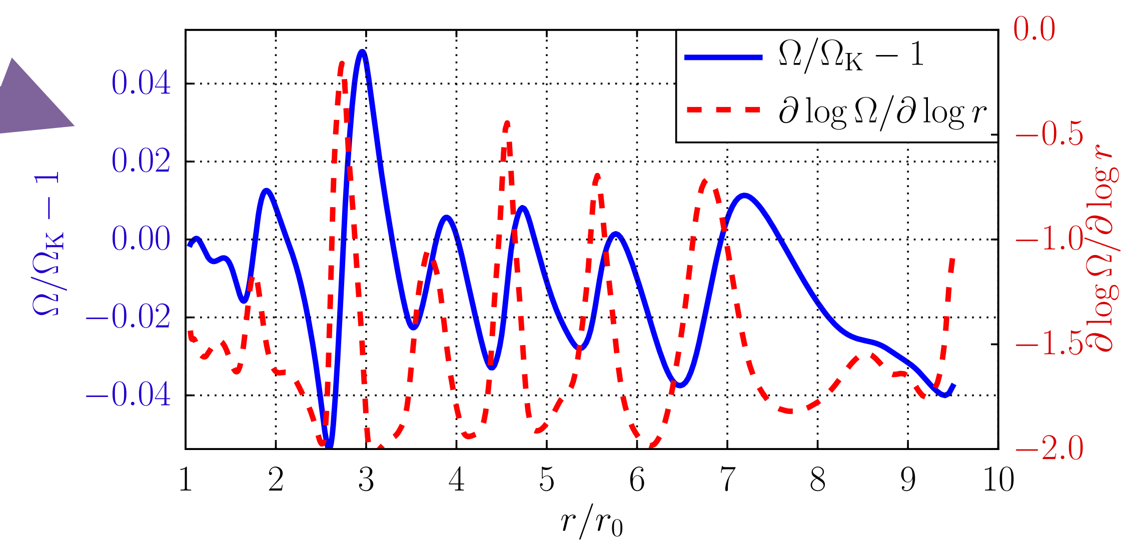
@10-100 au

Self-organisation

In wind-emitting discs

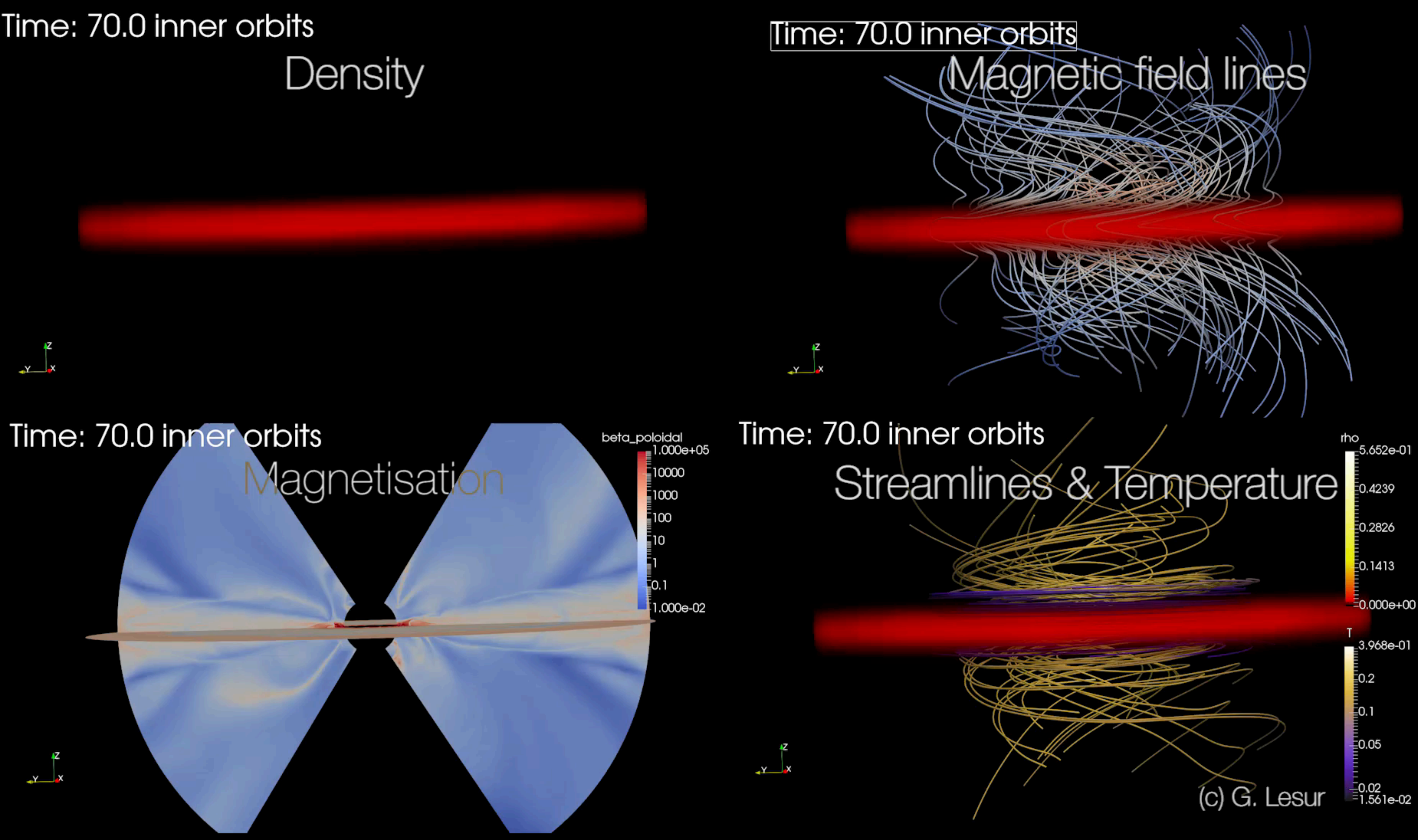




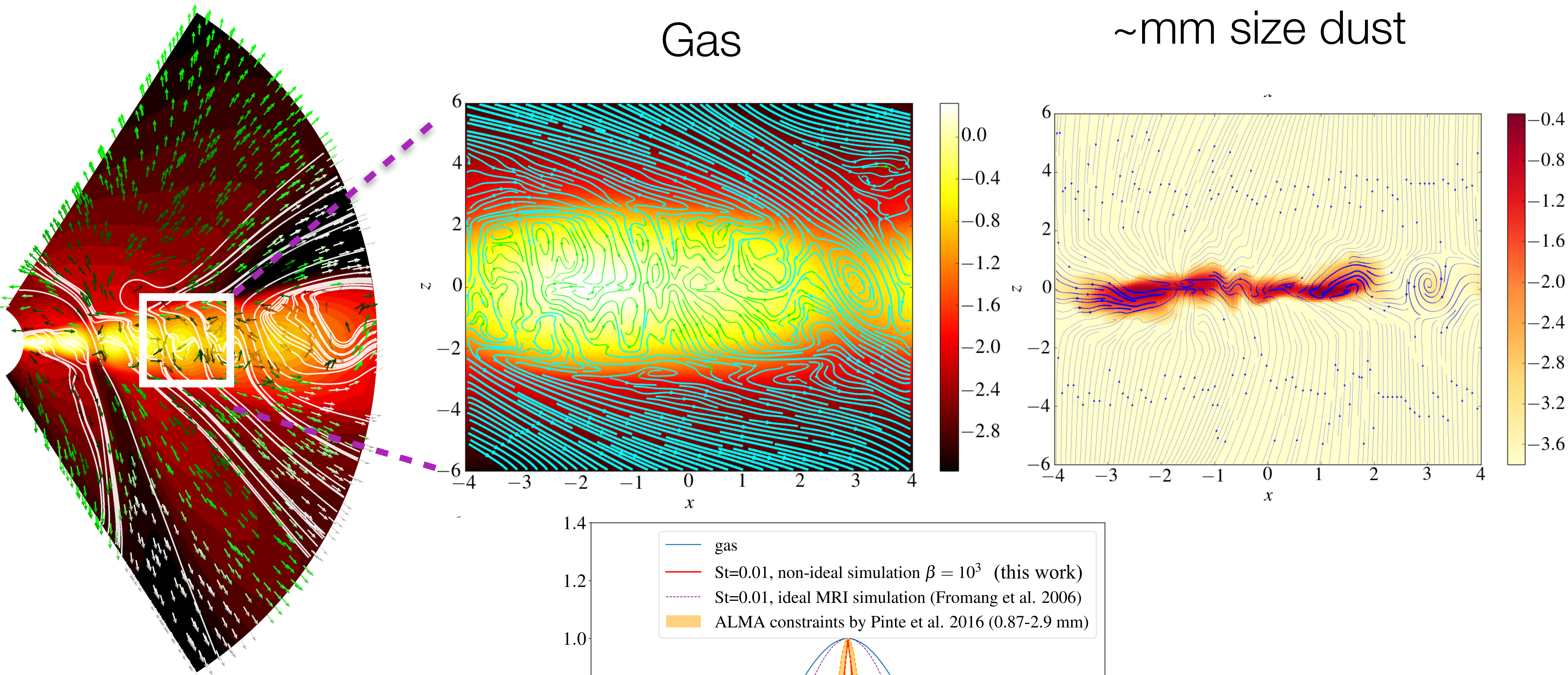


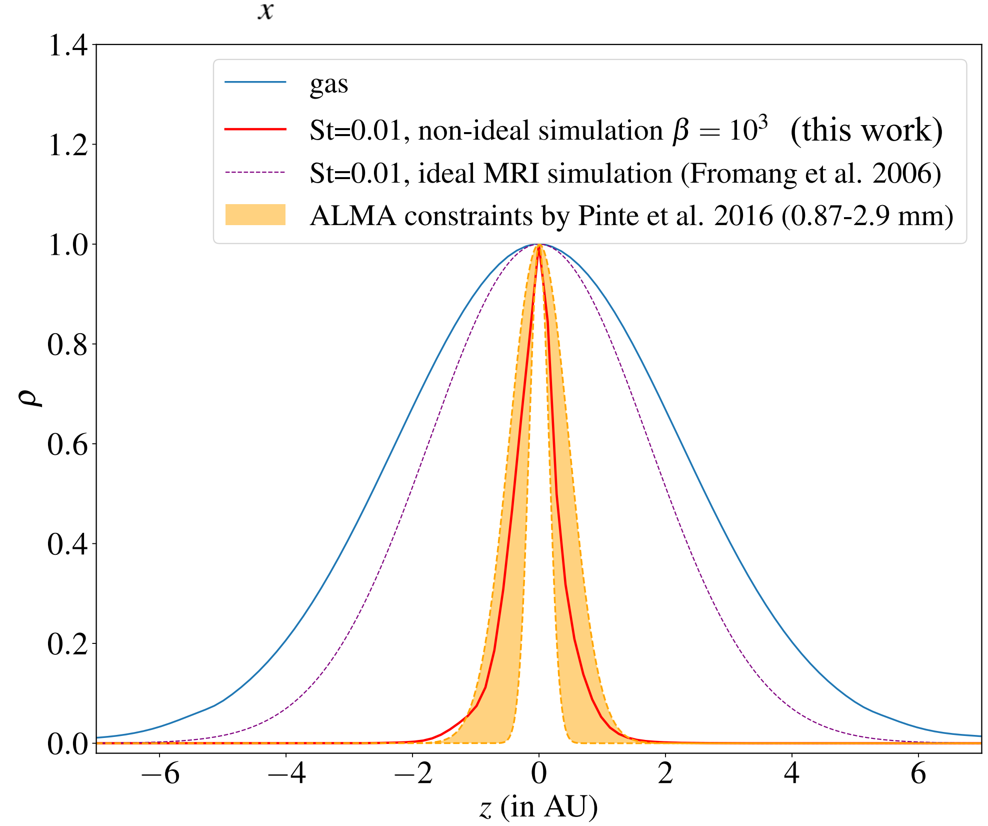
Magnetic structure spontaneously creates density & pressure “bumps”

[see also Kunz & Lesur 2013, Bai & Stone 2014]


Time: 70.0 inner orbits
Density
Time: 70.0 inner orbits
Magnetic field lines
Time: 70.0 inner orbits
Magnetisation
beta_poloidal
1.000e+05
10000
1000
100
10
1
0.1
1.000e-02
Time: 70.0 inner orbits
Streamlines & Temperature
rho
5.652e-01
0.4239
0.2826
0.1413
0.000e+00
T
3.968e-01
0.2
0.1
0.05
0.02
1.561e-02
(c) G. Lesur

Dust Dynamics @ 30 AU

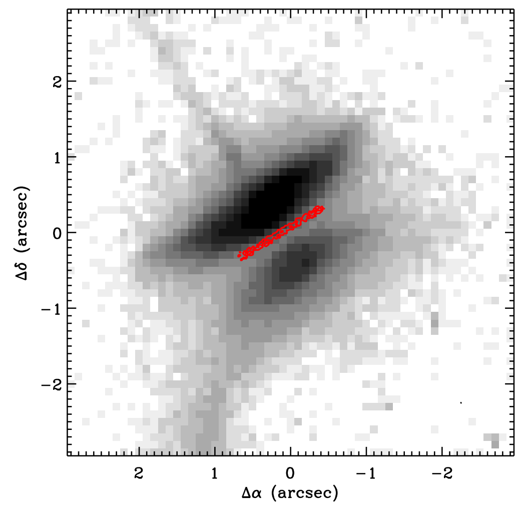




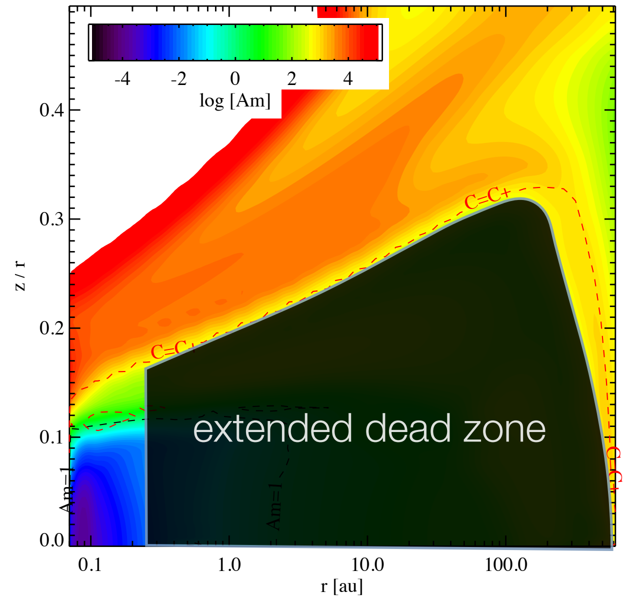
[Riols & Lesur 2018]

Conclusions and take home message

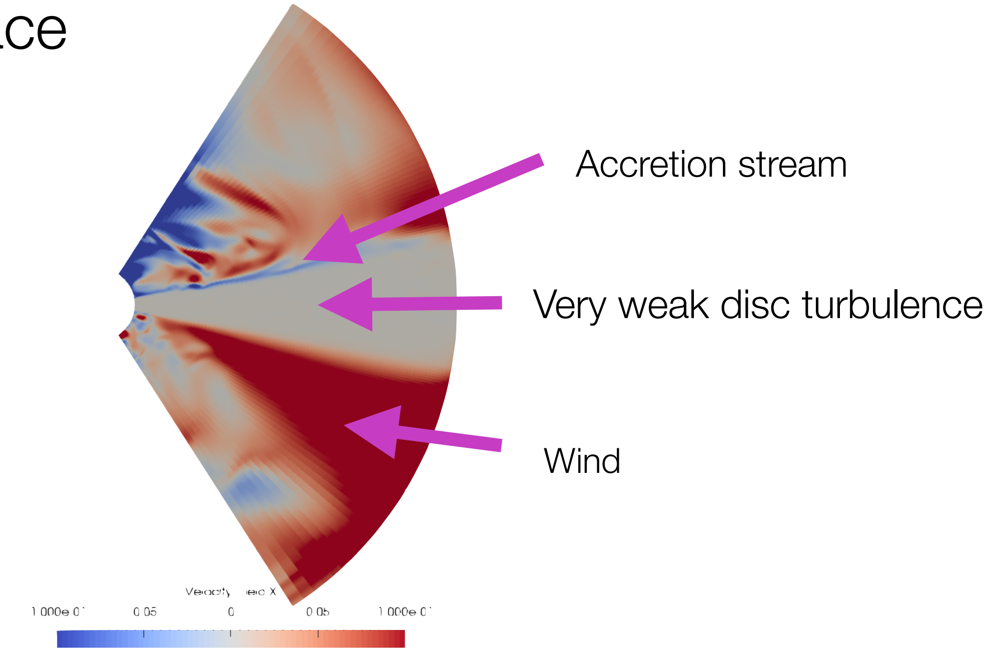
- Observations indicates that discs are weakly turbulent, but are accreting



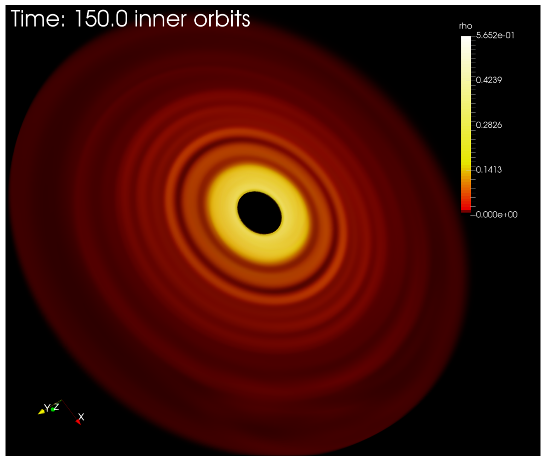
- The inclusion of all non-ideal MHD effects leads to an extended dead zone. Only the disc surface « sees » magnetic fields.



- It is possible to reconcile observed accretion rates and lack of turbulence, with a magnetised wind launched from the ionised surface



- Self-organisation is a natural *consequence* of surface winds, which could explain some of the observed « ring » features



Prospective for HPC

- Need for fast methods for non-ideal MHD effects (sub-cycling on GPUs?, but needs development and testing. Who does it? who maintains it?)
- Lots of data (several TB for each run). In-lab visualisation becomes problematic. Long time storage not necessary.
- Need a place to « experiment » (Mésocentres?)