Dynamics of planet-forming discs

the role of magnetised winds

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with thanks to

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MHDiscs
Revealing the dynamics of planet-forming discs

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Today's special

Appetisers

Accretion theory in a nutshell

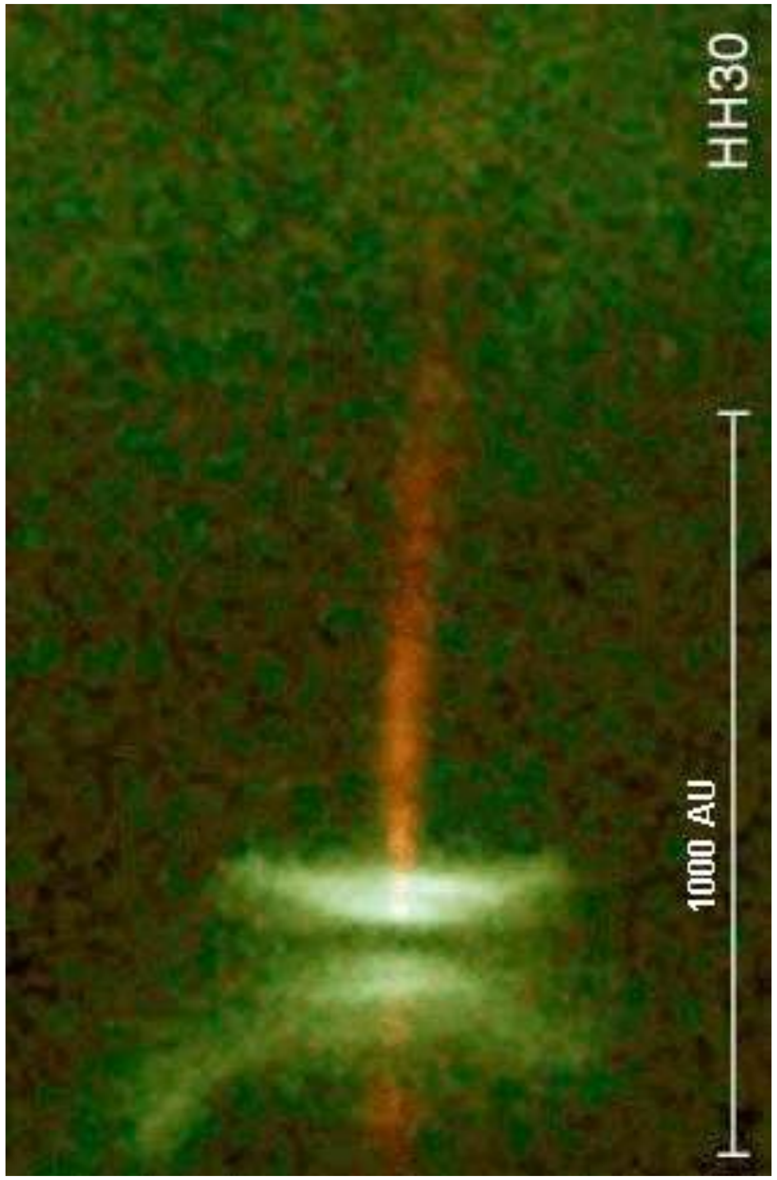
Starters

Observational overview salad

Mains

Magnetised surface winds soufflé

Protoplanetary discs

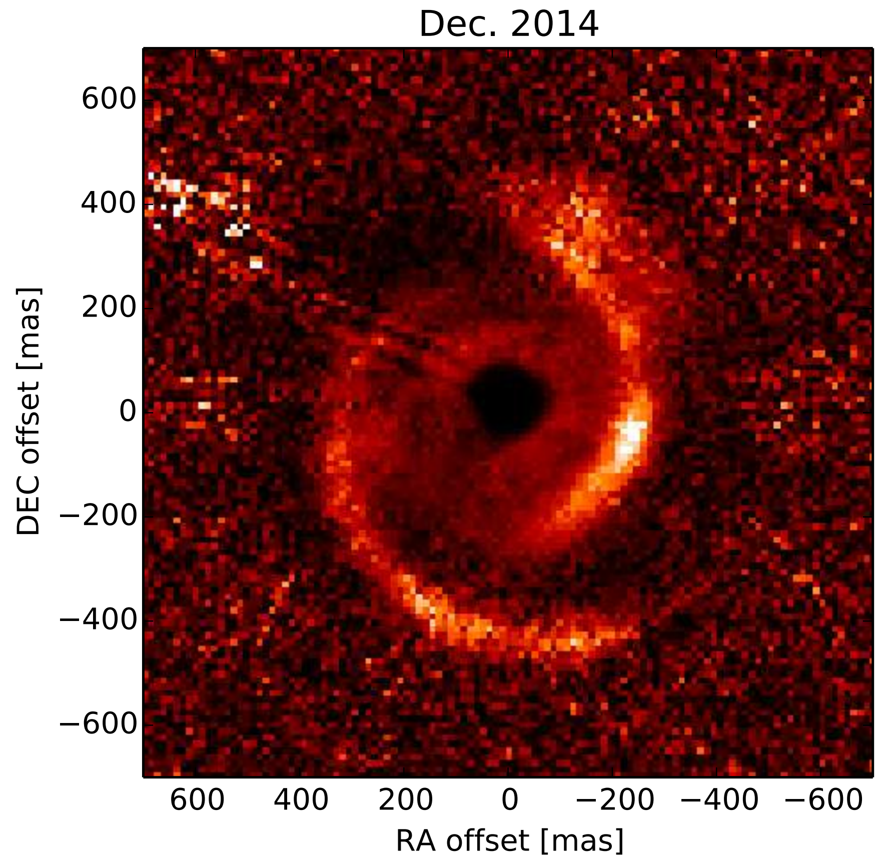


Credit: C. Burrows and J. Krist (STScI),
K. Stapelfeldt (JPL) and NASA

Artist view

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

Structures
In scattered light



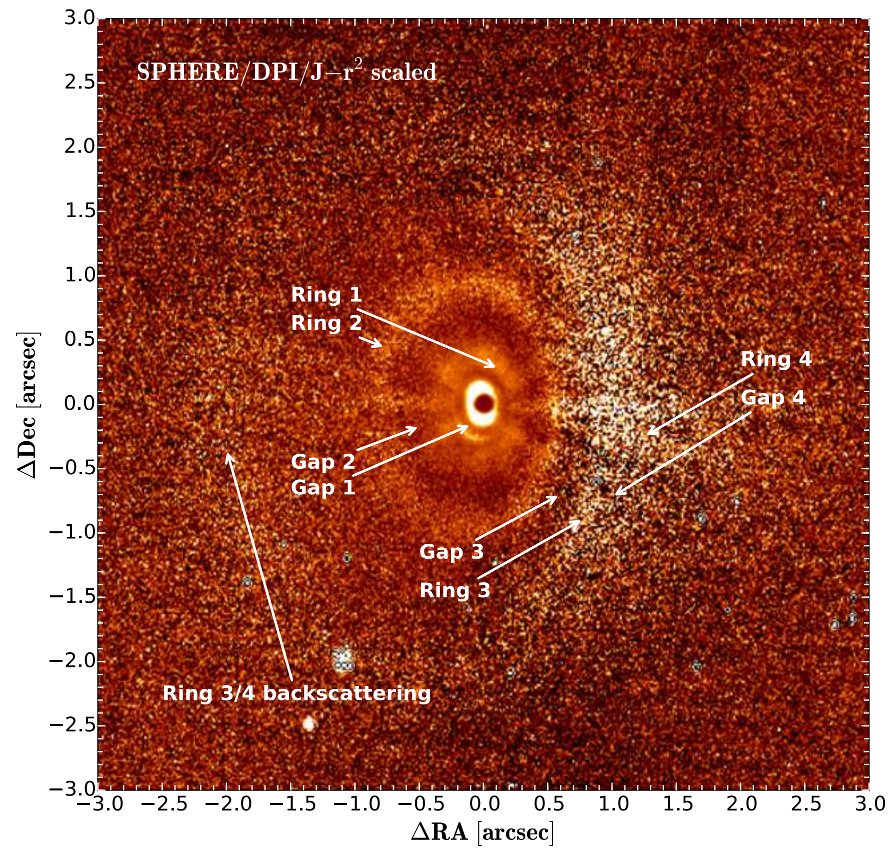


Figure 4: Scattered light images in the near infrared using polarimetric differencital imaging (PDI). Left: spiral structures observed in MWC758, from Benisty et al. (2015). Right: multiple ring structures observed in HD97048, from Ginski et al. (2016).

Structures

In thermal emission from grains

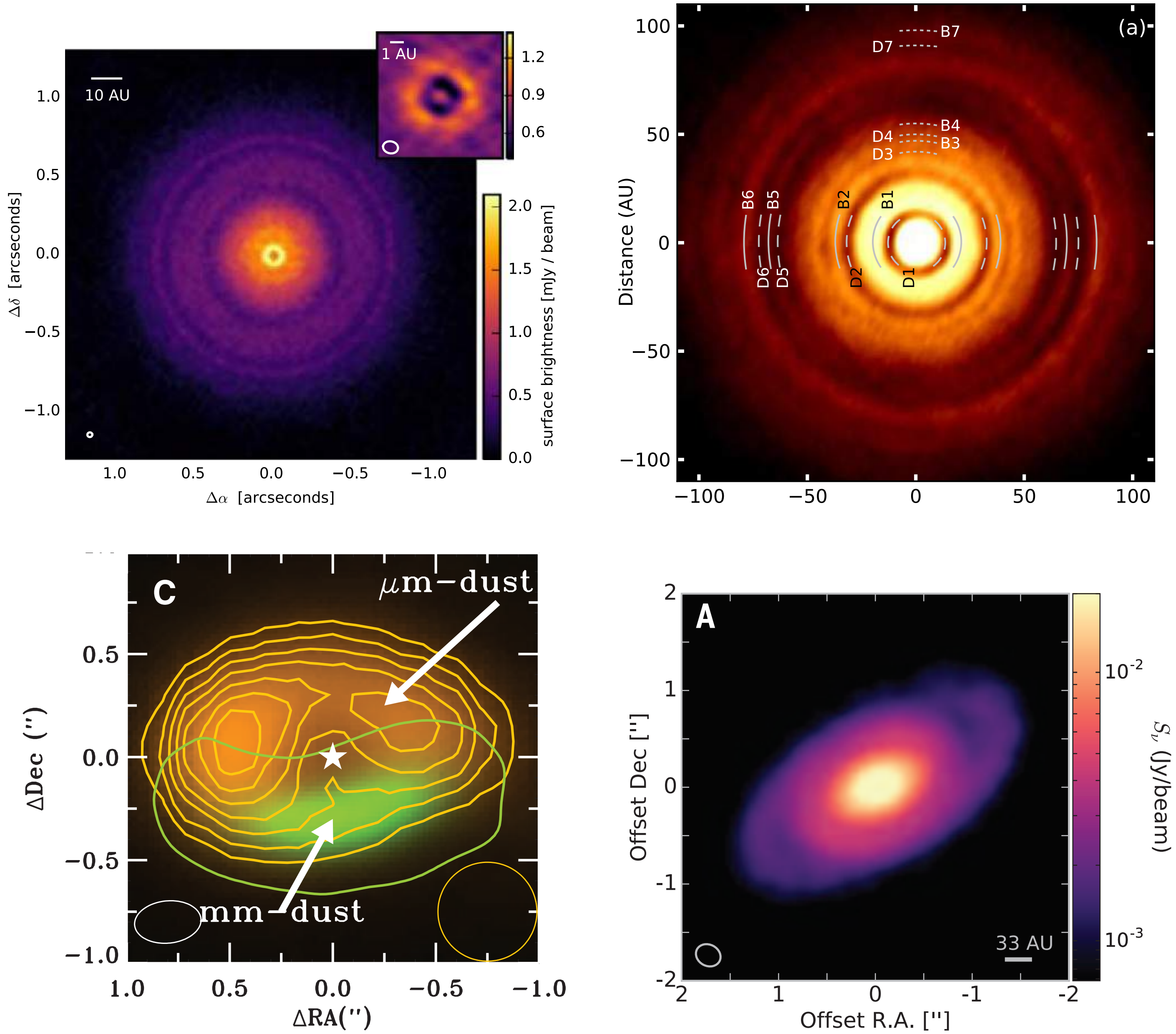
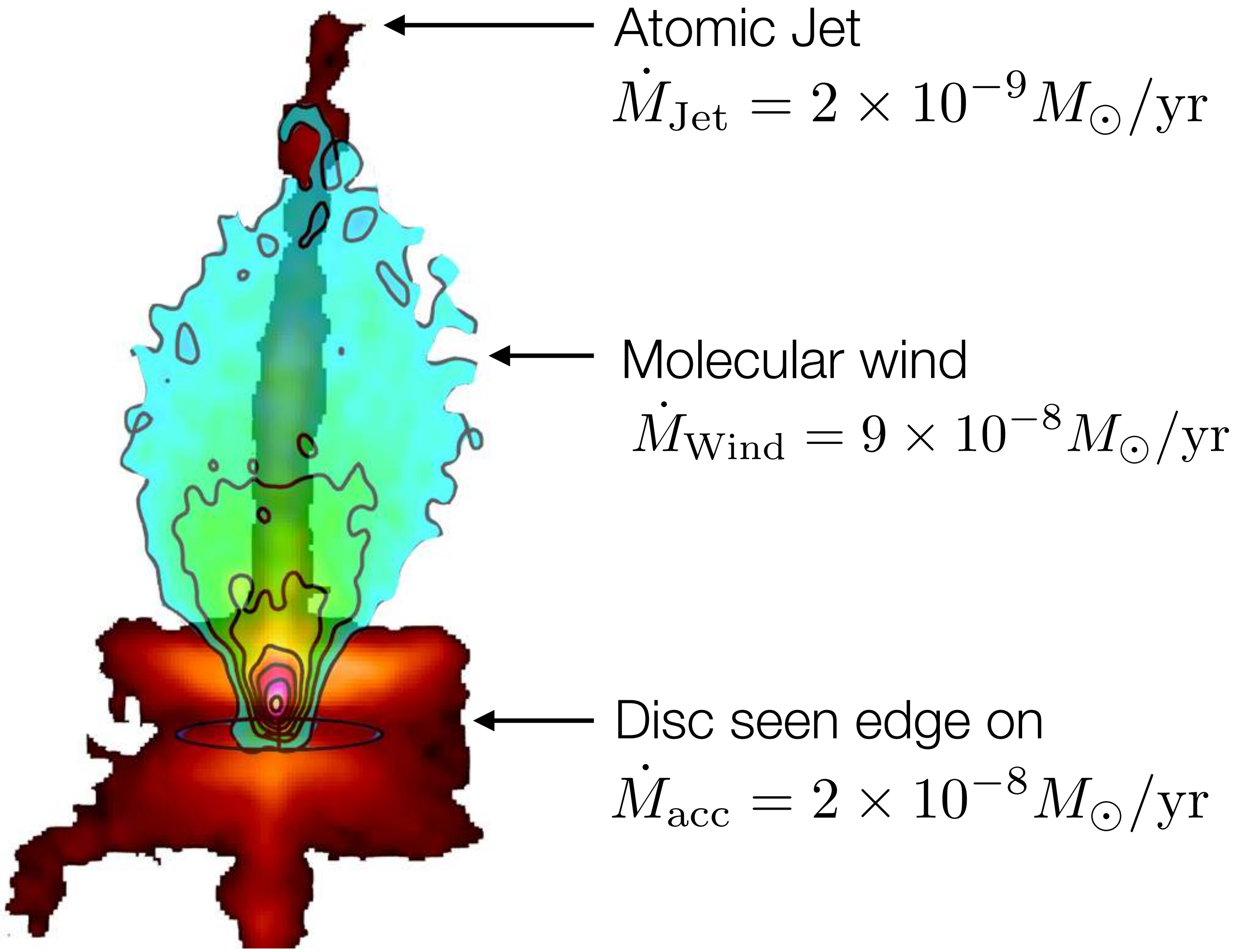


Figure 5: Top left: Ring-like structures observed in TW Hydra. From Andrews et al. (2016). Top right: multiple ring structure in a deprojected image of HL-Tau from Partnership et al. (2015). Bottom left: horsehoe-like structure observed in Oph IRS 48 at sub-mm wavelengths (green, tracing mm-sized dust) and corresponding scattered light infrared emission (yellow, tracing μm size dust) from van der Marel et al. (2013). Bottom right: spiral structures seen at sub-mm wavelengths in the young and massive disc of Elias 2-27, from Pérez et al. (2016)

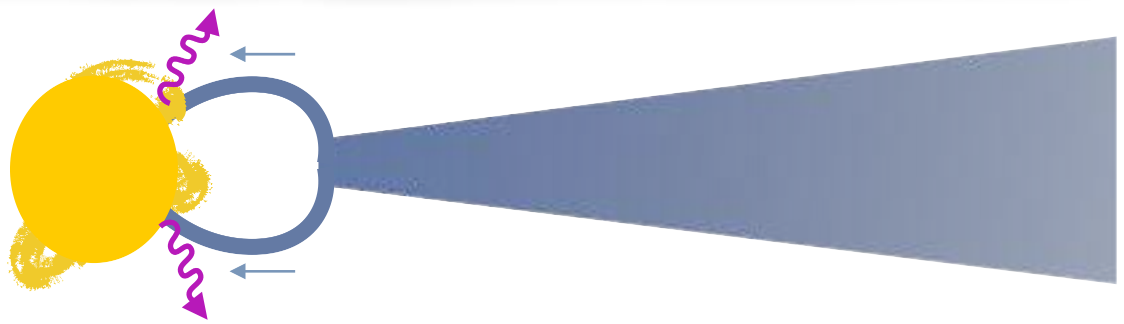
Young disc are often observed in association with outflows

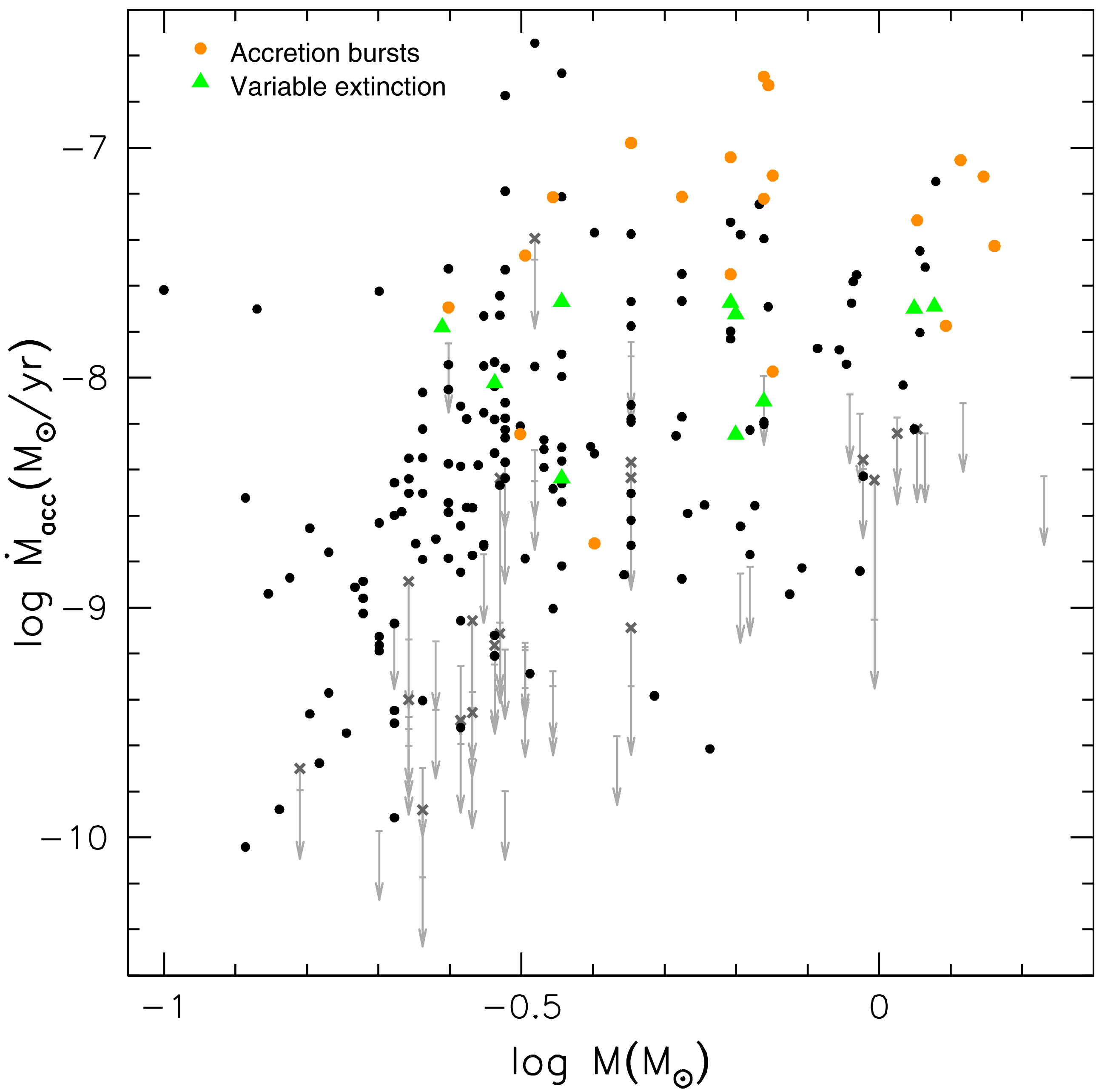


HH30: a disc+jet+wind seen edge on

[Louvet+ 2018]

Accretion rate onto the stellar surface





[Venuti+2014]

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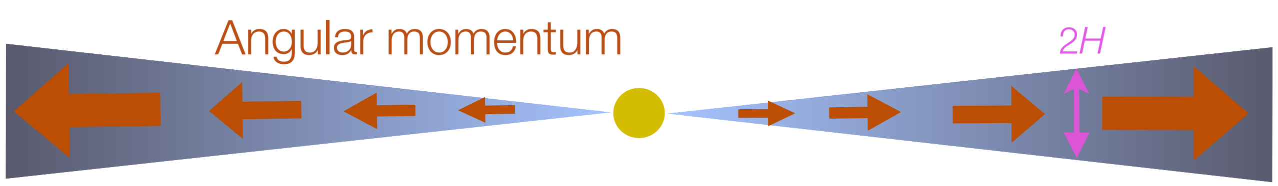
Puddings

Gâteau de Savoie of future projects

Mass accretion requires angular momentum transport

« Viscous » disc



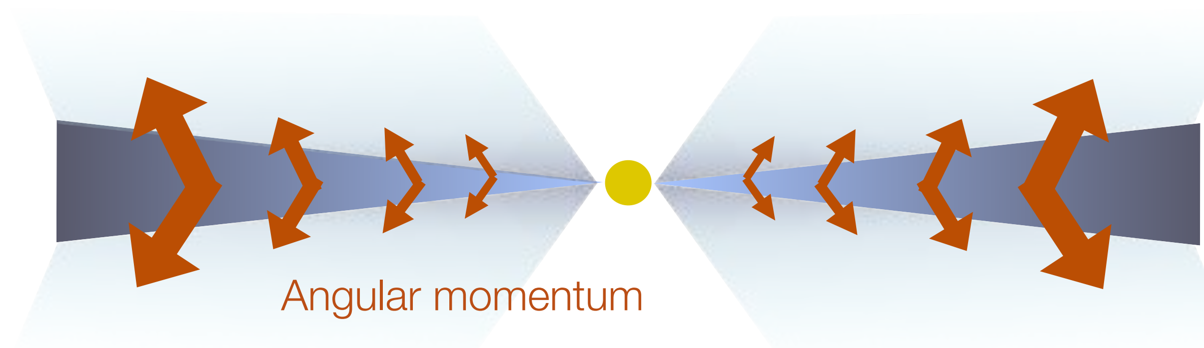
- Angular momentum transported in the disc bulk (via turbulence or waves)
- One defines a « turbulent » viscosity

$$\nu_t = \alpha c_s H$$

«turbulent transport» (α) «sound speed» (c_s) «1/2 disc thickness» (H)

$\alpha \in [10^{-3}, 10^{-1}]$ to explain observed accretion rates

Magnetised wind



- Angular momentum *extracted* from the disc by a magnetic wind
[Blandford & Payne 1982, MNRAS, 199, 883]
- Magnetic field exerts a torque on the disc which generates accretion
(not described by α−disc!)

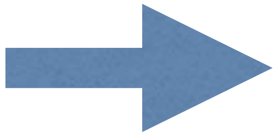
15 years ago, life was « easy »

The United Kingdom was a member of the European Union

George Bush was the US president

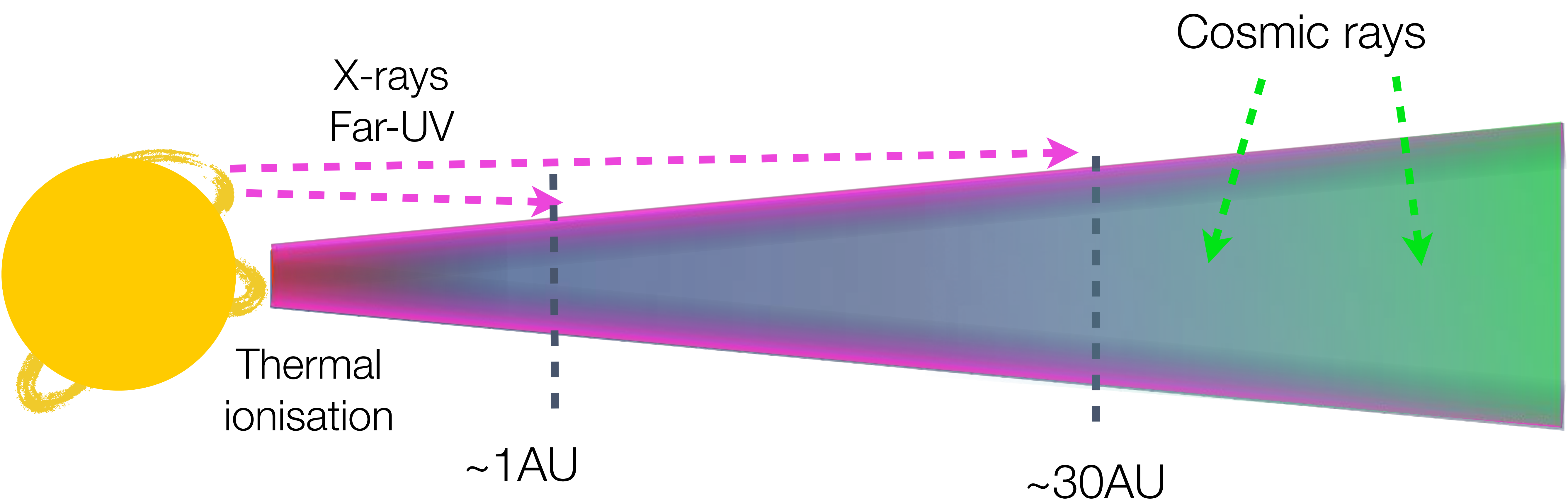
One didn't have to wear masks at all time

Magnetorotational instability
[Balbus & Hawley 1991]

 α

Viscous disc model was justified by MRI-driven turbulence

Ionisation sources in protoplanetary discs

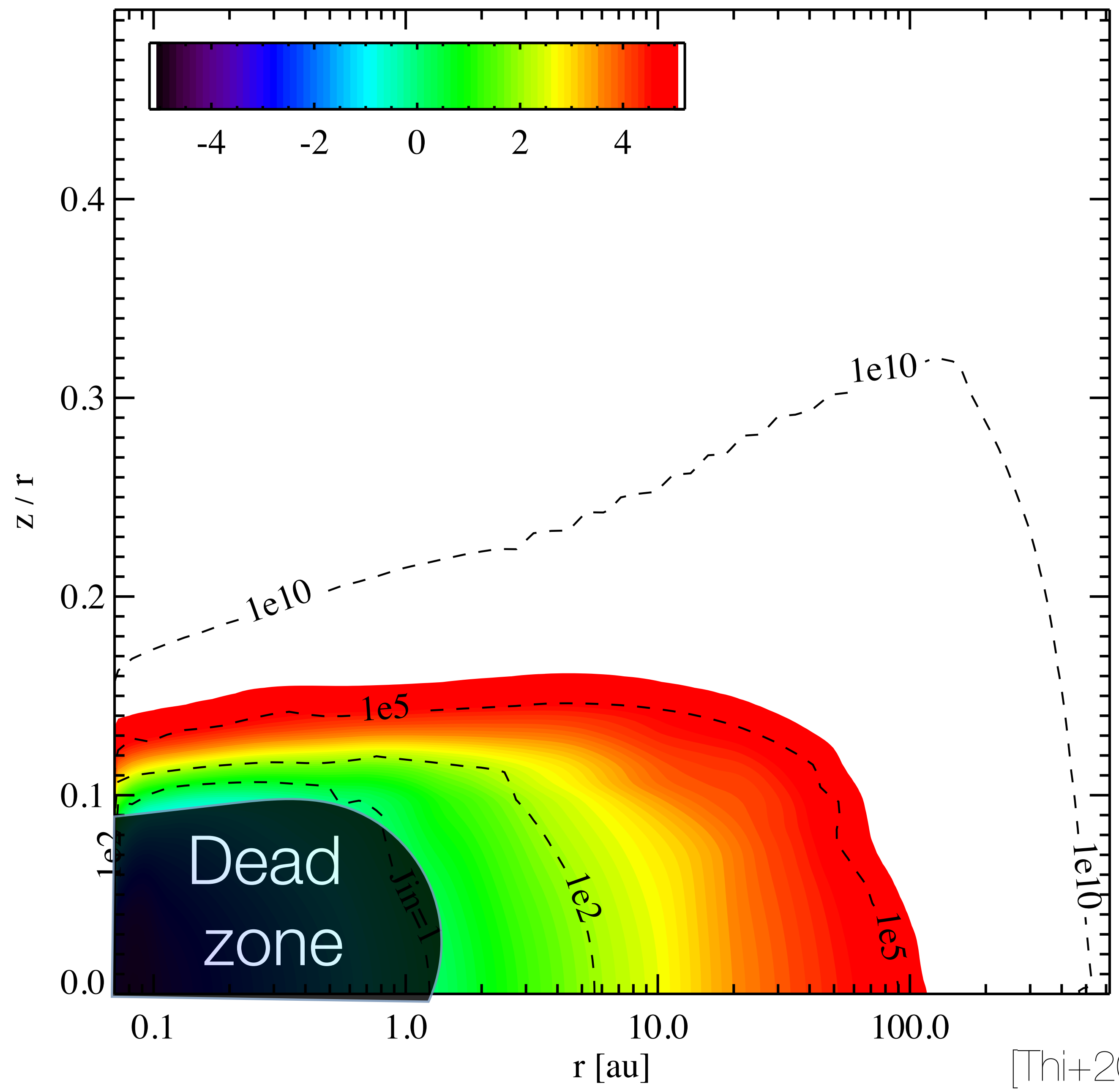


« non ideal » MHD effects

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

Amplitude of these effects depends strongly on location & composition

Ohmic resistivity

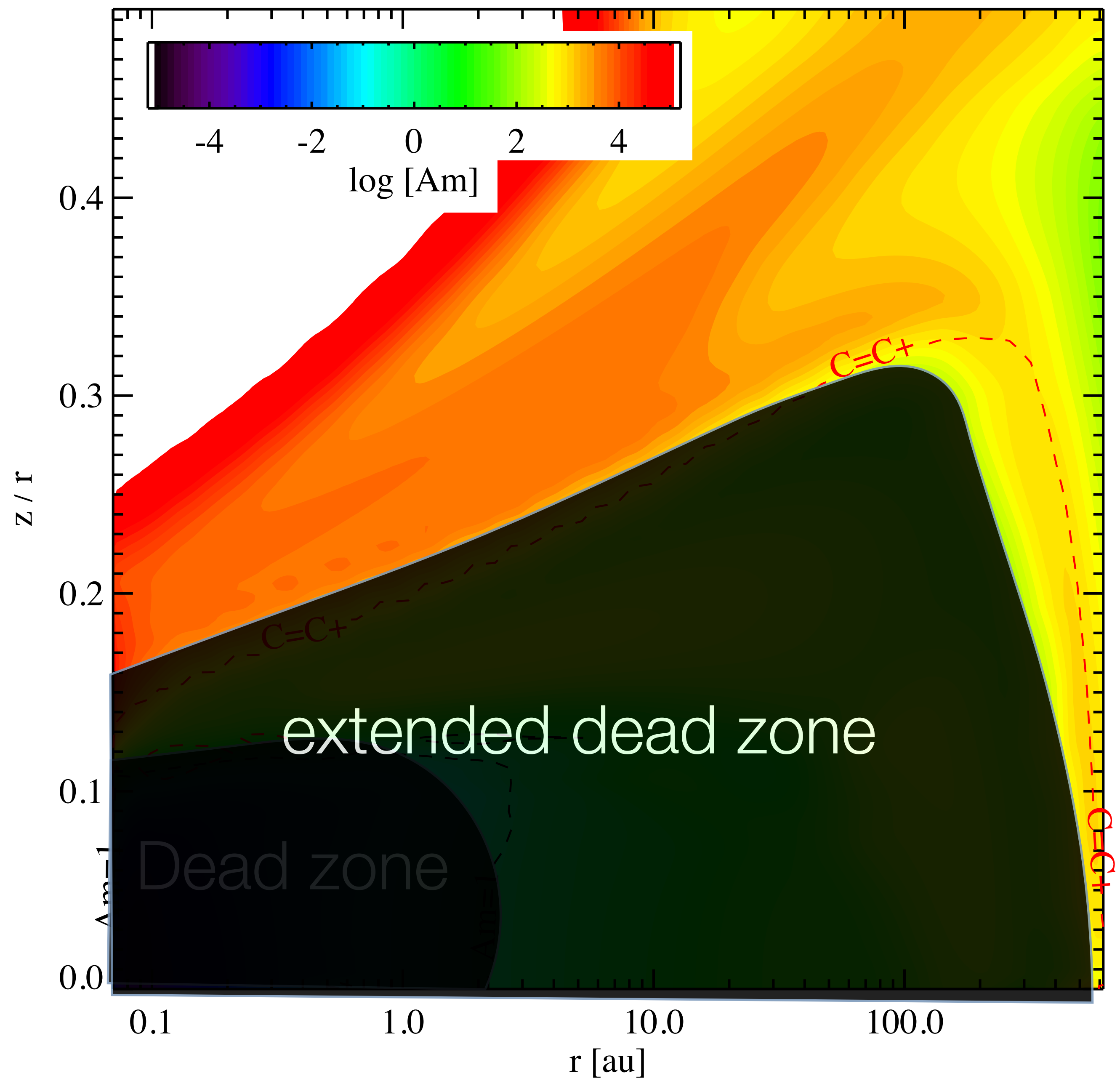


[Thi+2018]

MRI-driven turbulence is stabilised when Rm<1 [Jin 1996]

➡ « Historical » dead zone [Gammie 1996]

Ambipolar diffusion



[Thi+2018]

→ Am<100 → MRI is suppressed [Perez-Becker & Chiang 2011]

Discs are too diffusive to sustain MHD turbulence.

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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

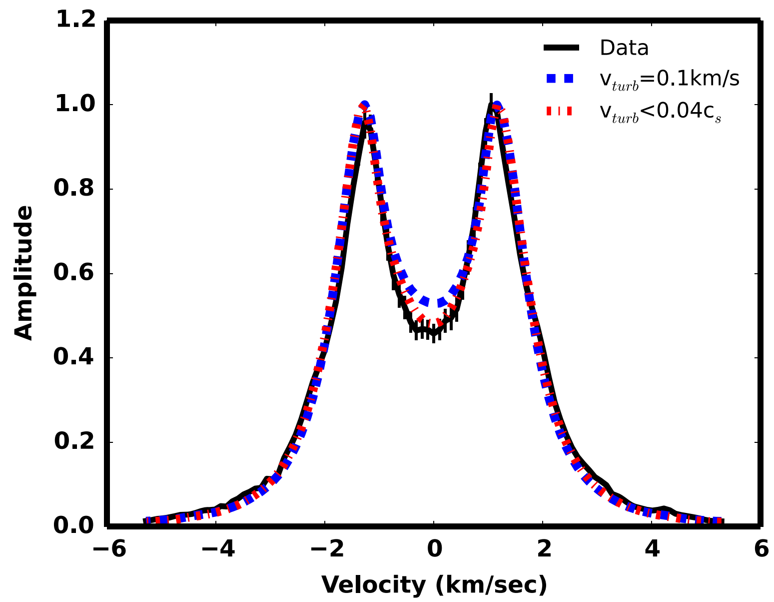
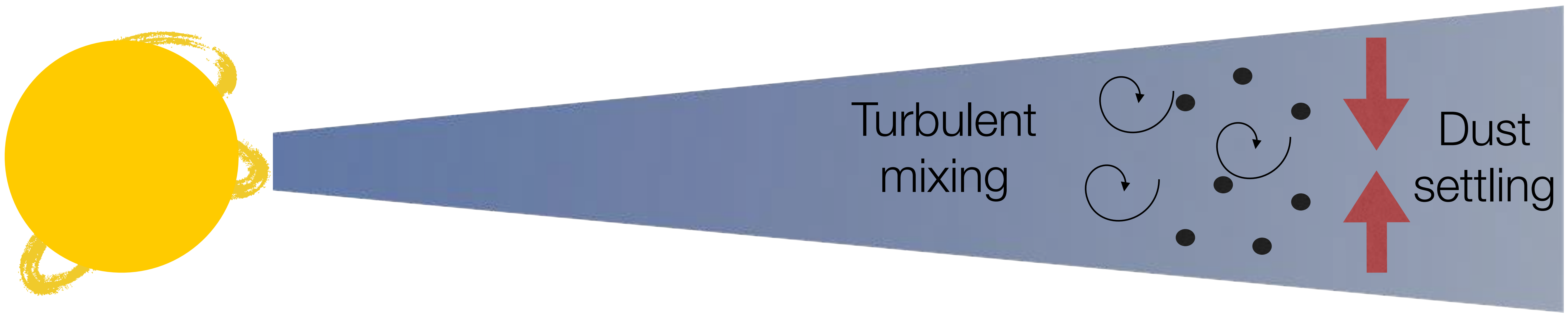


Figure 6. CO(3-2) high resolution spectra (black line) compared to the median model when turbulence is allowed to move toward very low values (red dotted–dashed lines) or when it is fixed at 0.1 km s^{-1} (blue dashed lines). All spectra have been normalized to their peak flux to better highlight the 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)



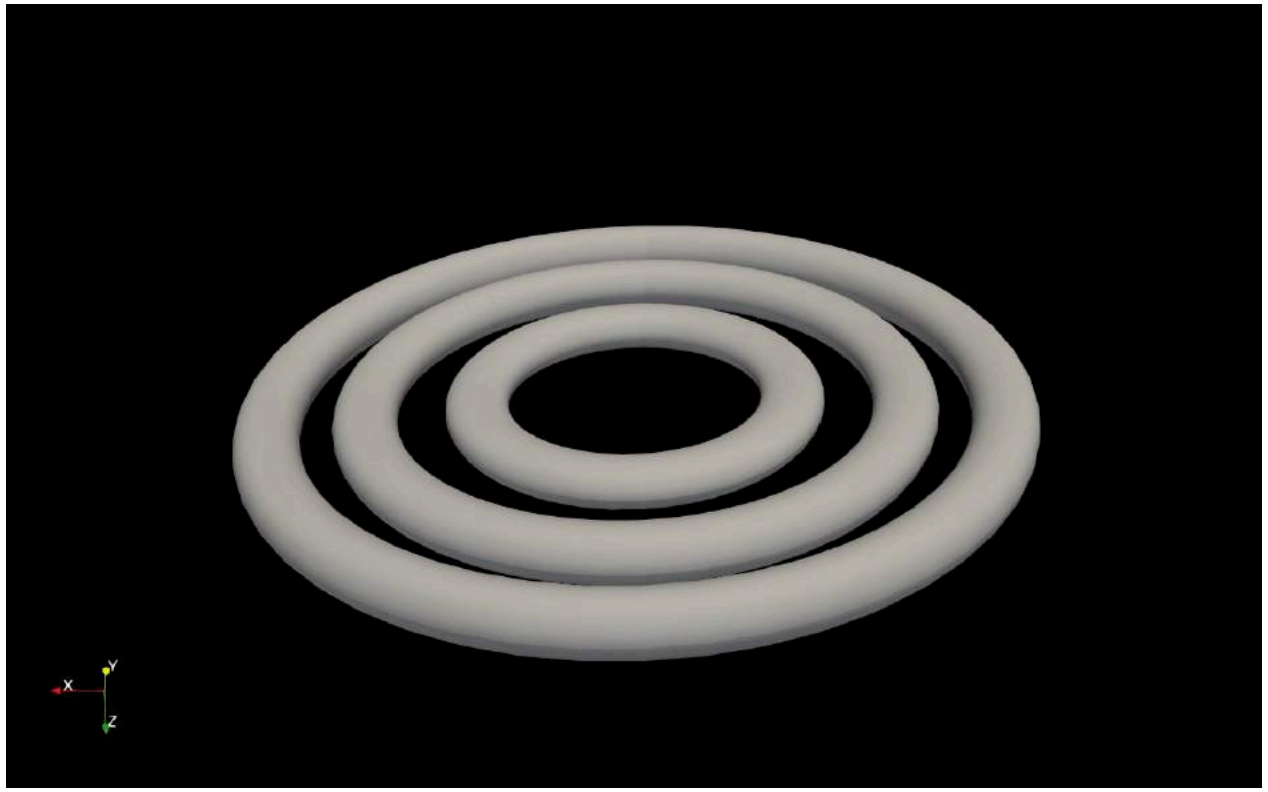
The thickness of the dust layer depends on the competition between settling and turbulent mixing

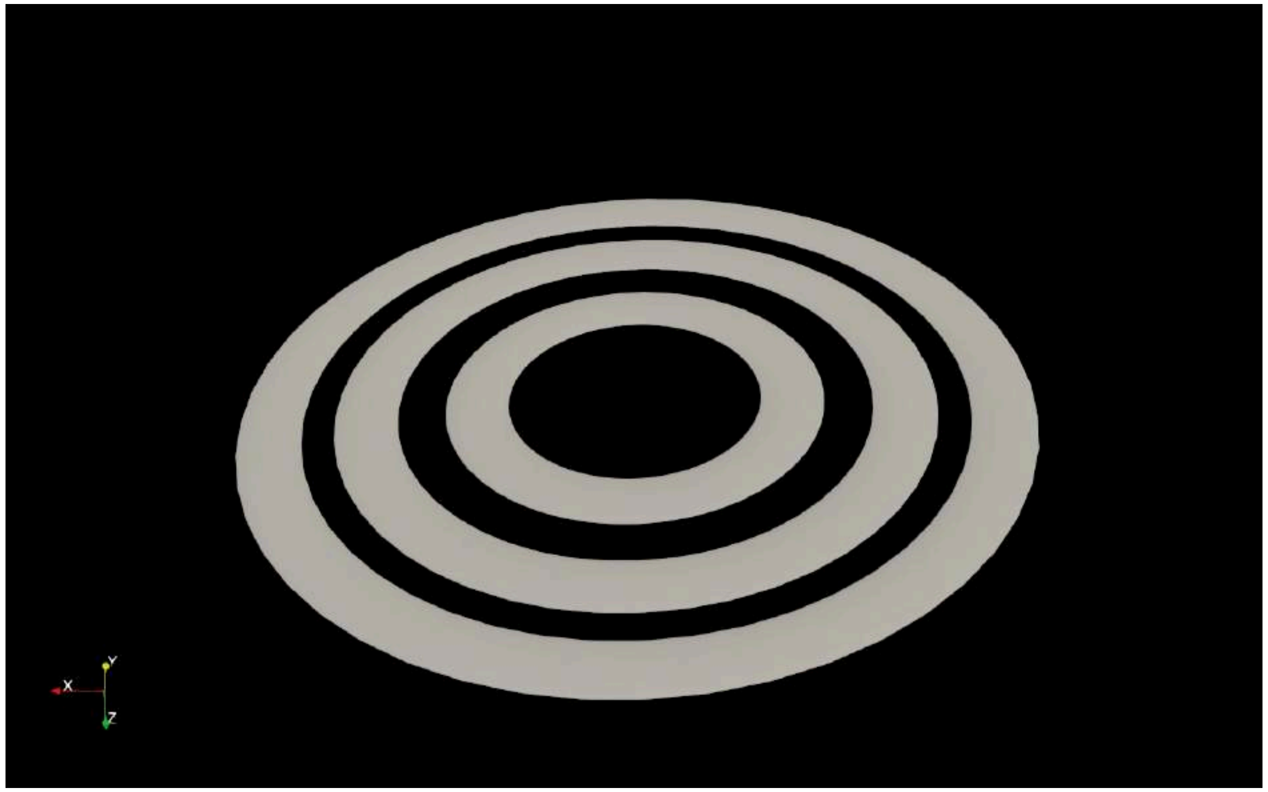
Dust settling (II)

Assume the disc is organised into rings

Thick dust disc

Thin dust disc

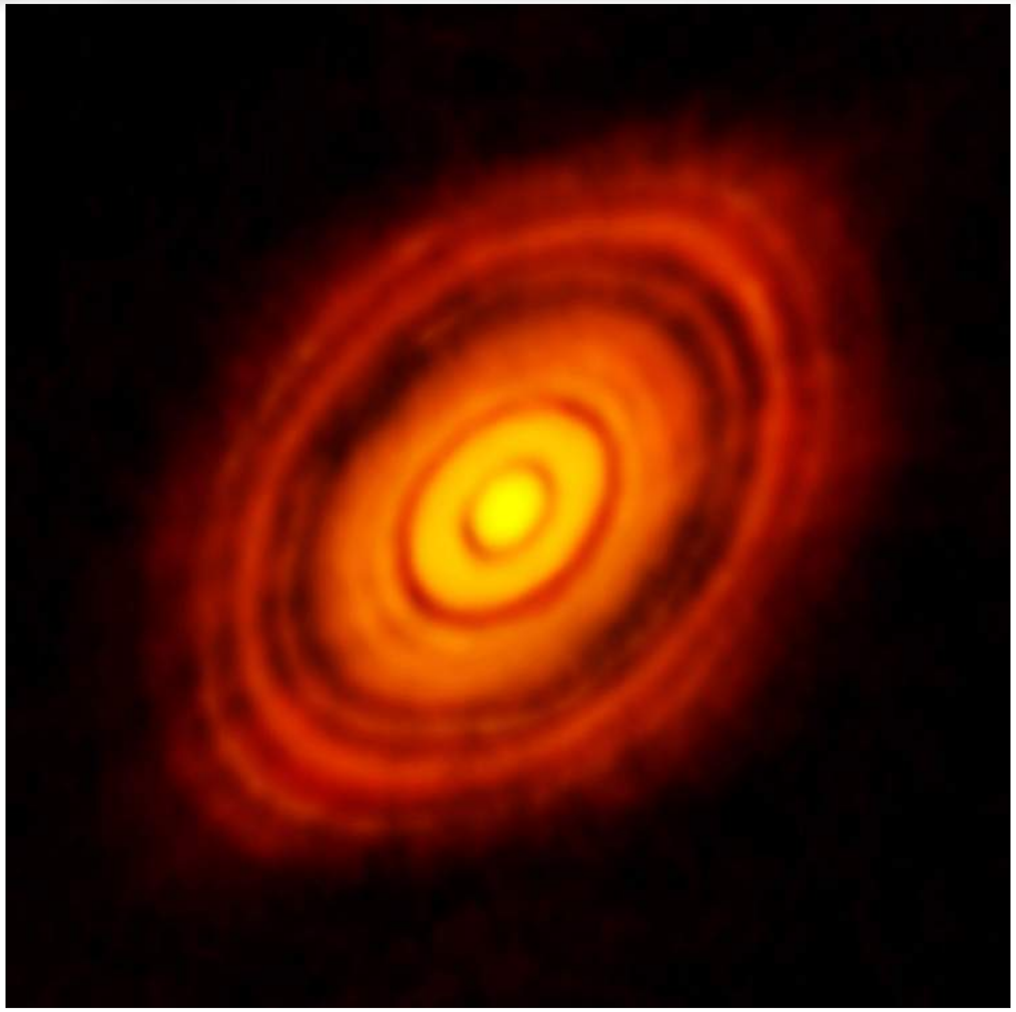




In a thick disc seen inclined, the dark bands are strongly non-axisymmetric

Dust settling (III)

Thin disc model

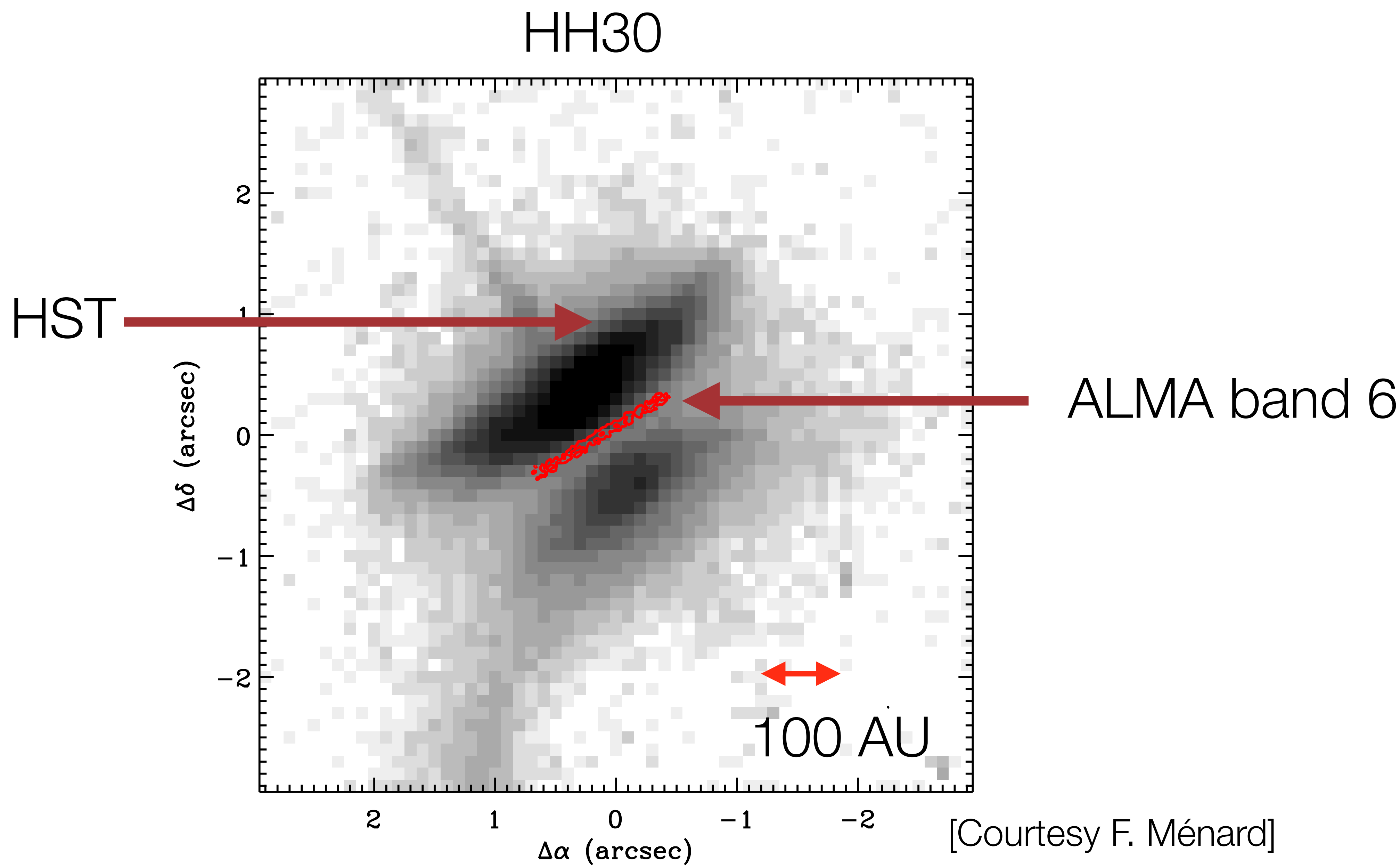


HL tau, as seen by ALMA observatory
[ALMA partnership 2015]

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?

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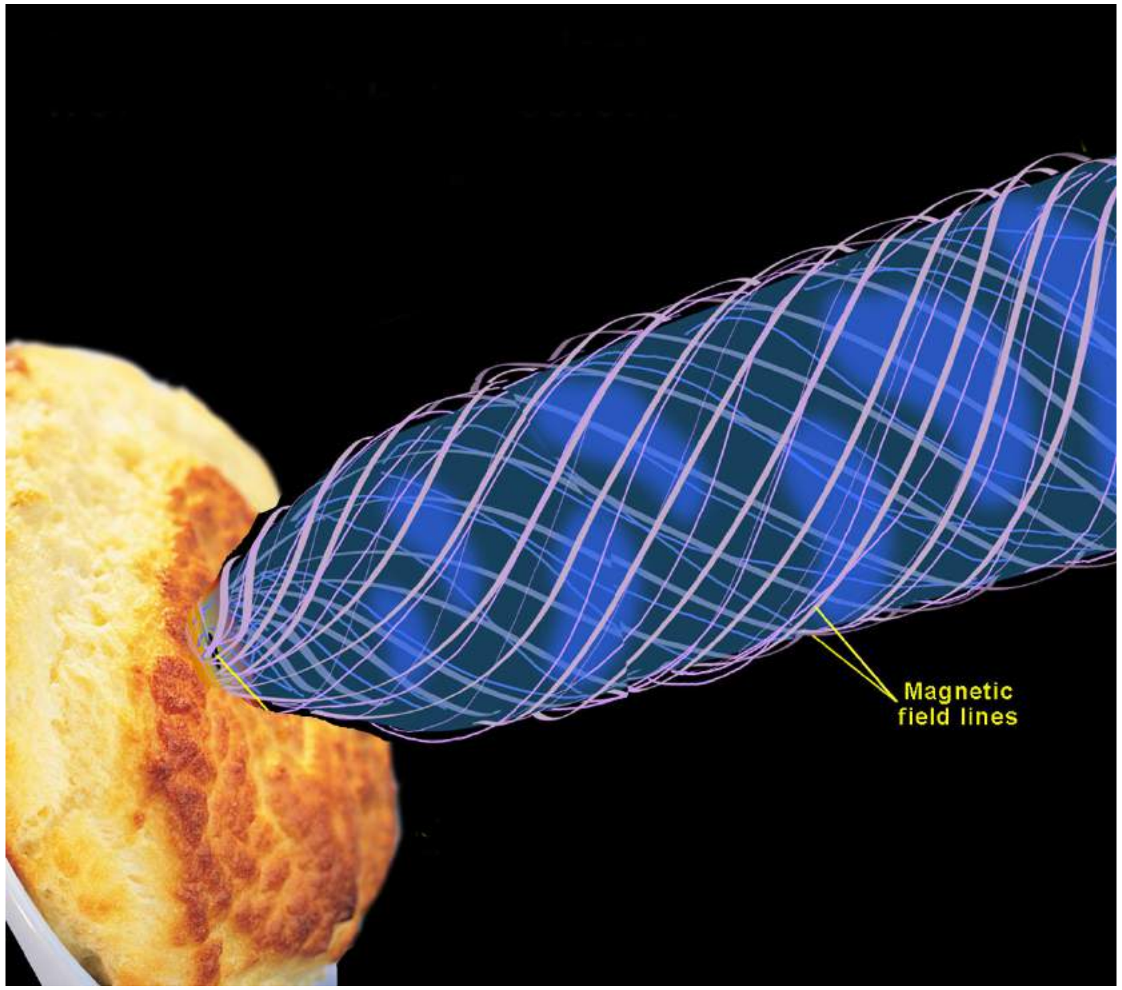
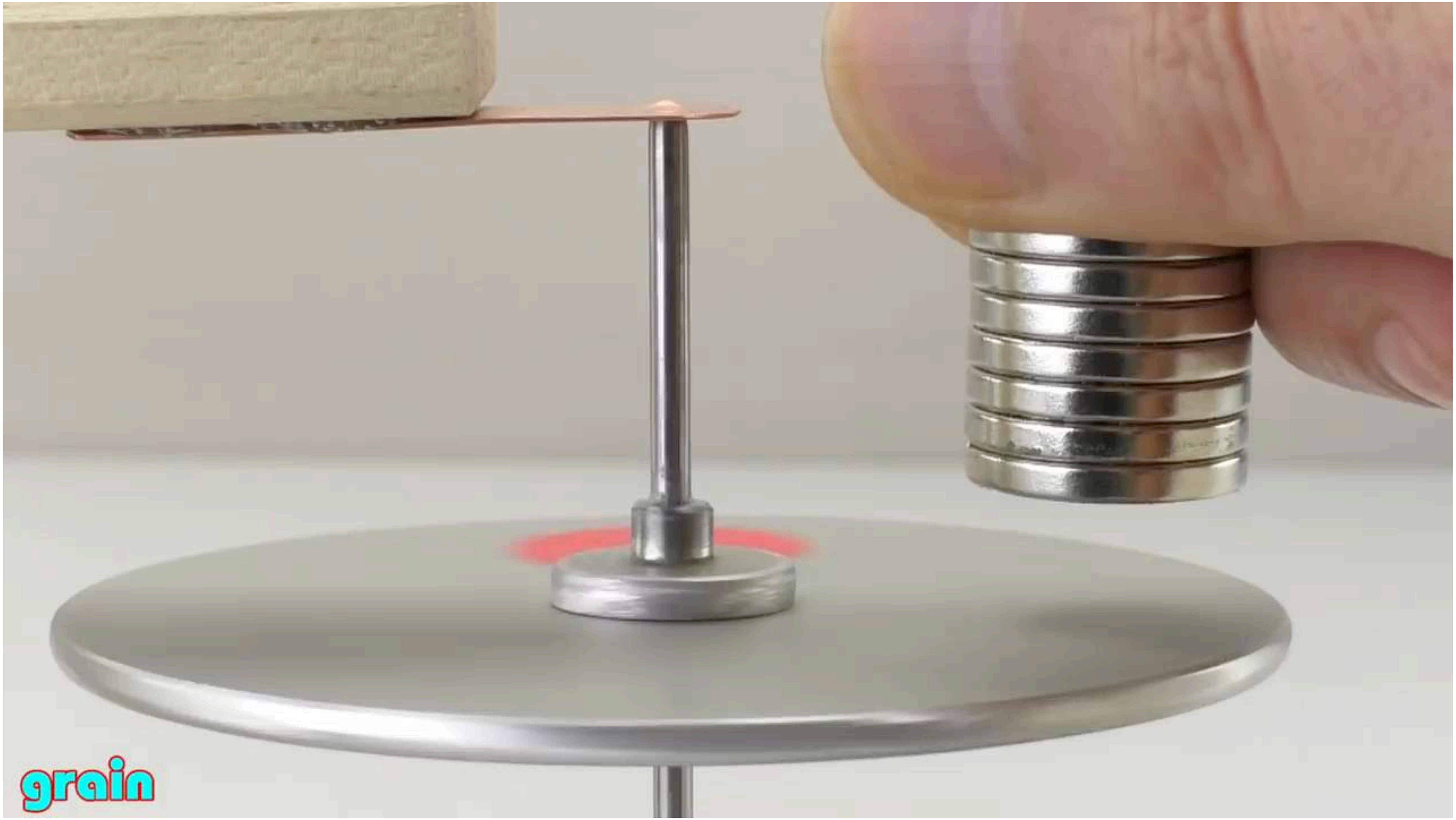
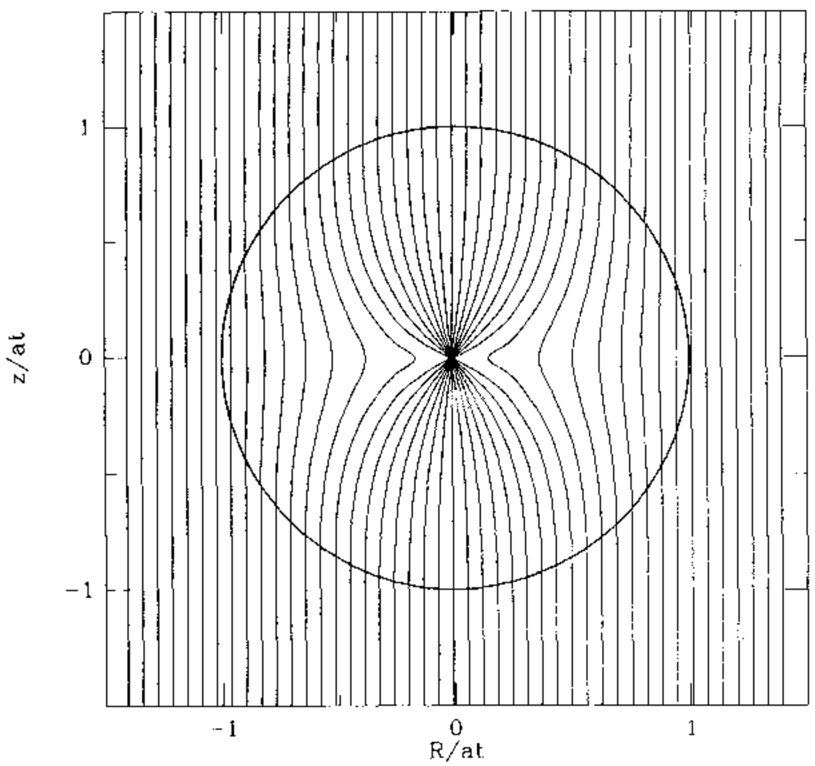


A little experiment

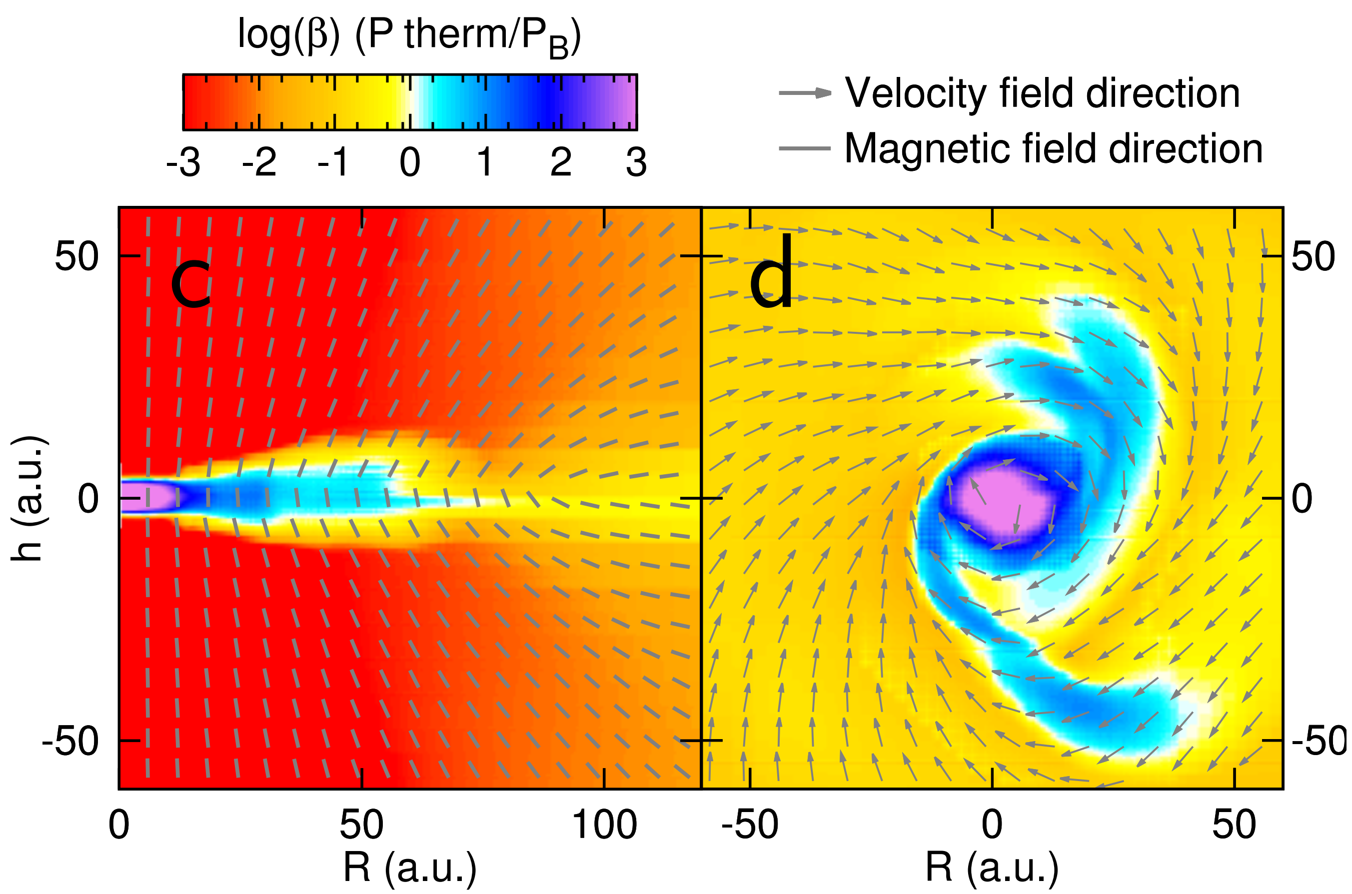


Origin of a large scale field

Collapse calculation (initial phases of star+disc formation)



Galli & Shu 1993

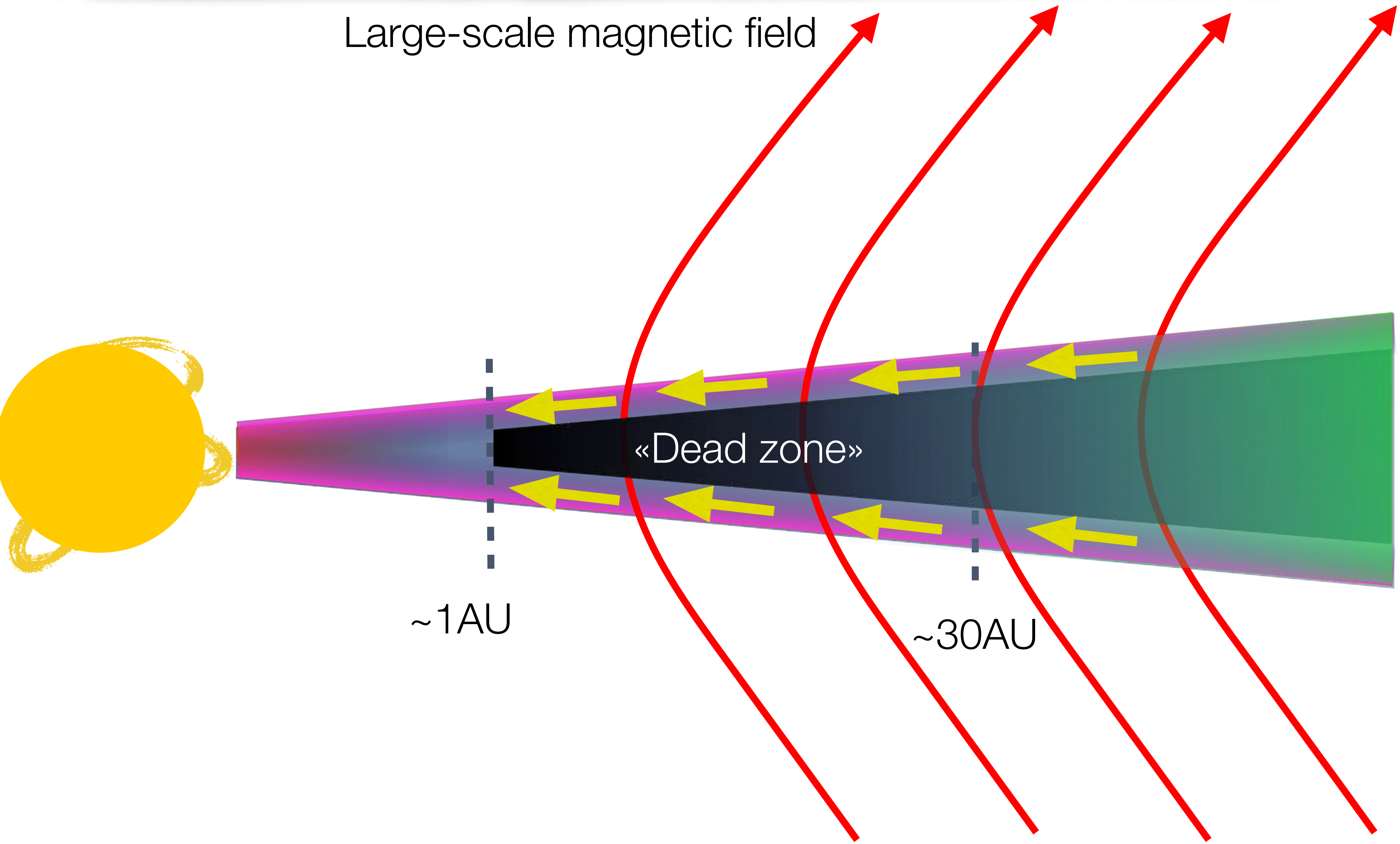


side view

top view

Masson+ (2016)

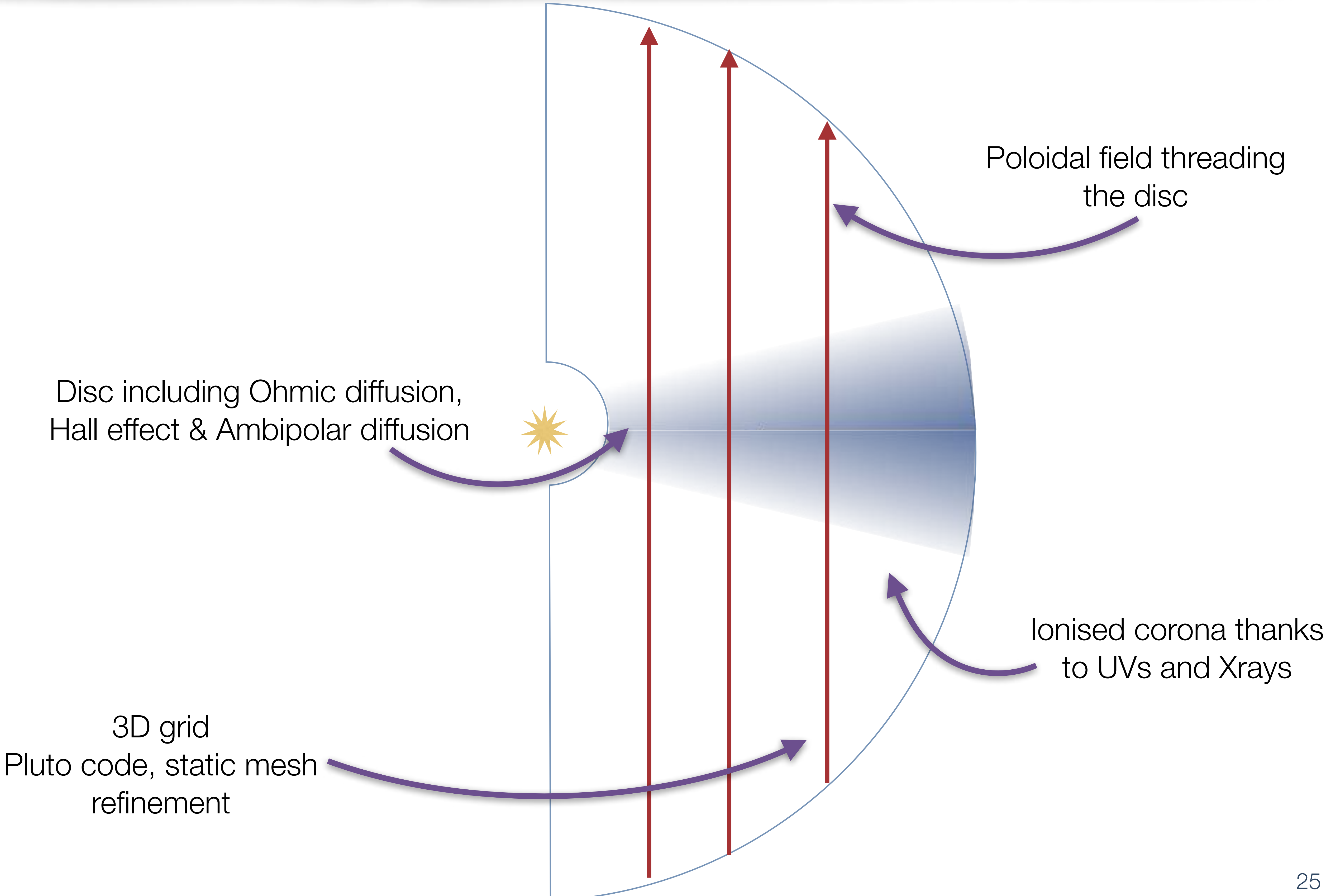
Wind-driven accretion in dead zones



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

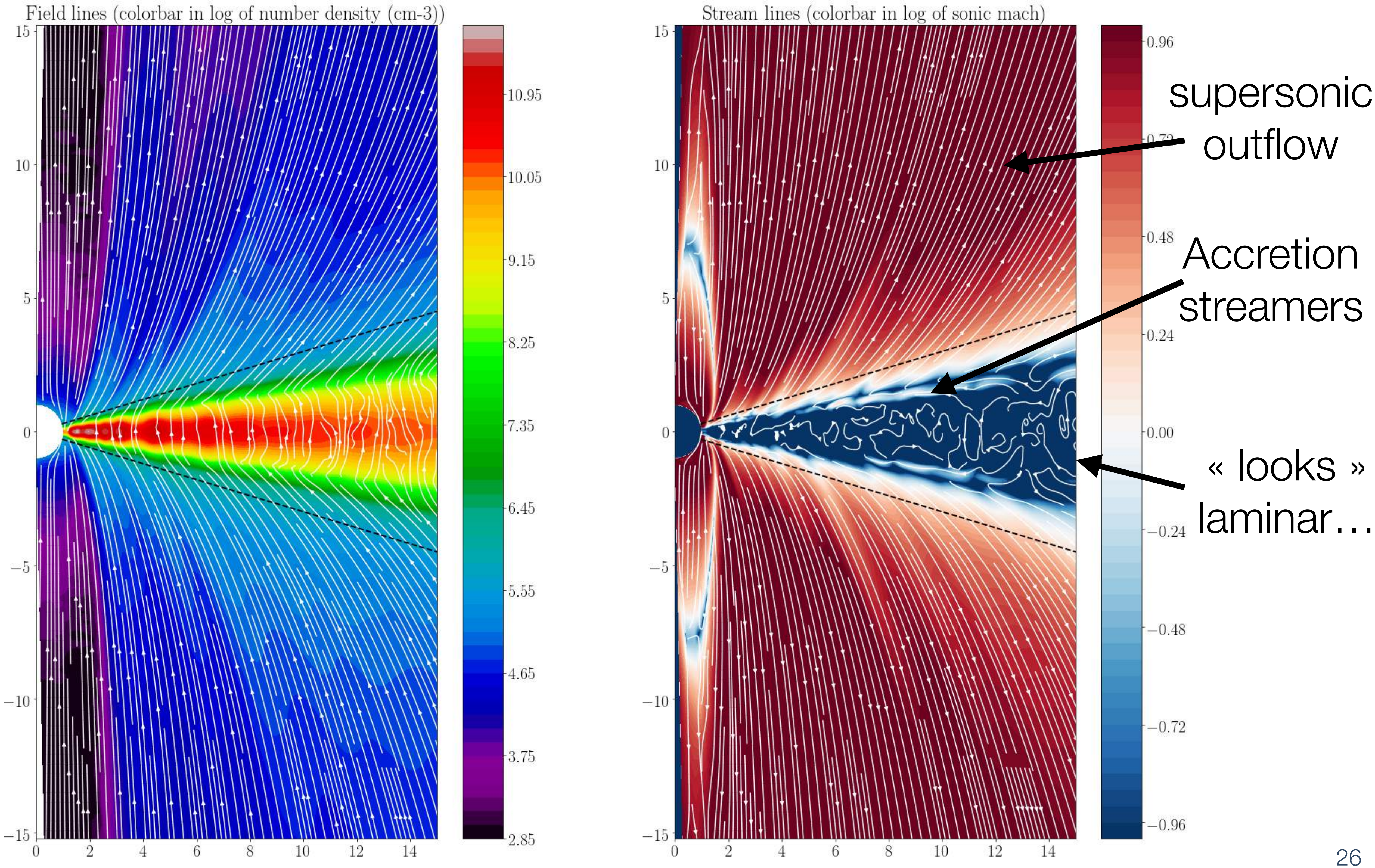
Global simulations

Numerical setup



Global picture

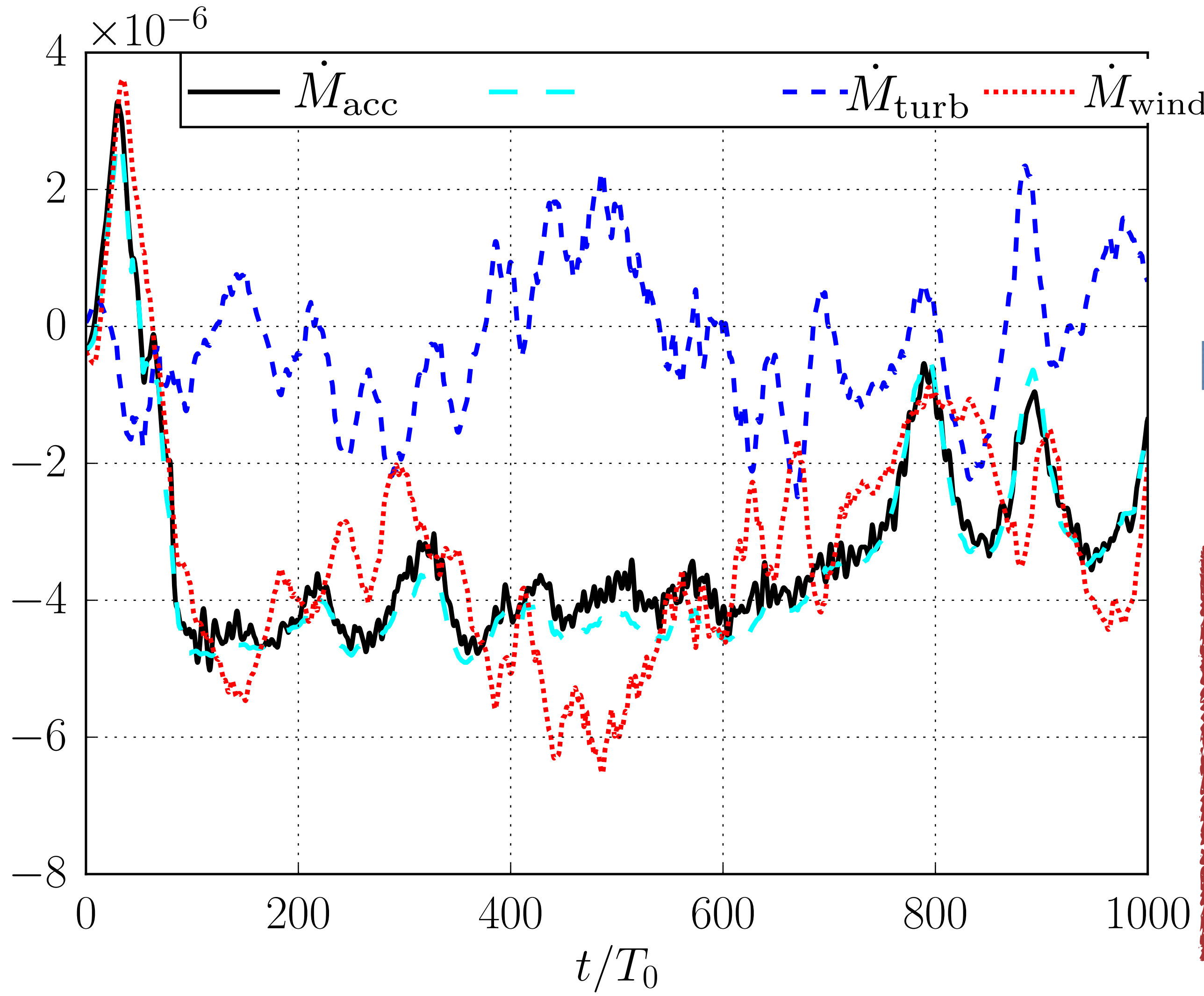
$\beta_p = 10^4, \ \mathrm{Am}_{\mathrm{mid}} = 1$ average from t=1700 orbits to t=2400 orbits



Global simulations
Accretion mechanism

$$\dot{M}_{\mathrm{acc}} = \dot{M}_{\mathrm{turb}} + \dot{M}_{\mathrm{MHD\ wind}}$$

Total accretion rate — « Turbulence » contribution — MHD wind contribution



→ wind-driven accretion

$$\dot{M}_{\mathrm{acc}} = 1.6\times10^{-8}\left(\frac{\Sigma}{10\,\mathrm{g.cm^{-2}}}\right)^{0.22}\left(\frac{R}{10\,\mathrm{A.U.}}\right)^{2.08}\left(\frac{M}{M_\odot}\right)^{-0.28}\times\left(\frac{\varepsilon}{0.1}\right)^{-0.78}\left(\frac{B_z}{1\,\mathrm{mG}}\right)^{1.56} M_\odot/\mathrm{yr.}$$

[Lesur 2021]

Accretion rate is mostly controlled by the poloidal field strength

Ejection efficiency

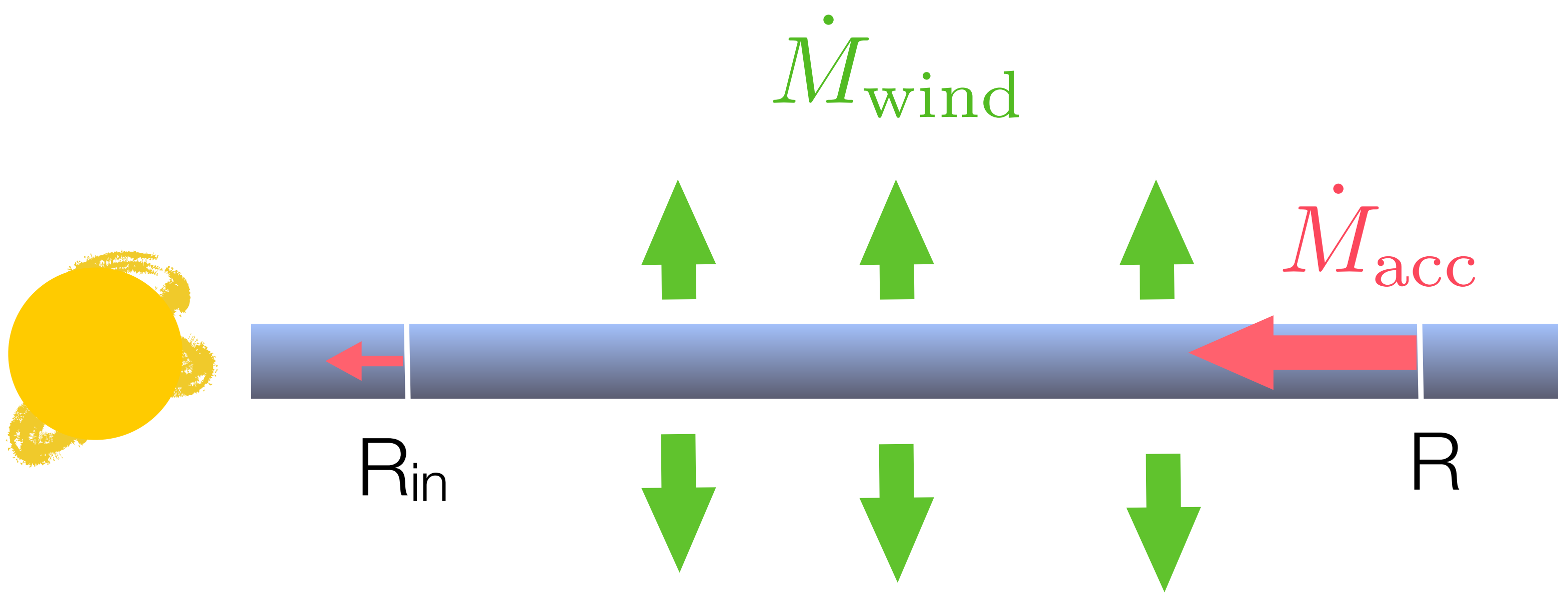
- Wind mass loss rate defined as

$$\dot{M}_{\rm wind} = 2\pi \int_{R_{\rm in}}^{R} {\rm dR}\, R[\rho u_z]_{\rm surface}$$

- Ejection efficiency is

$$\xi = \frac{2\pi R^2[\rho u_z]_{\rm surface}}{\dot{M}_{\rm acc}}$$

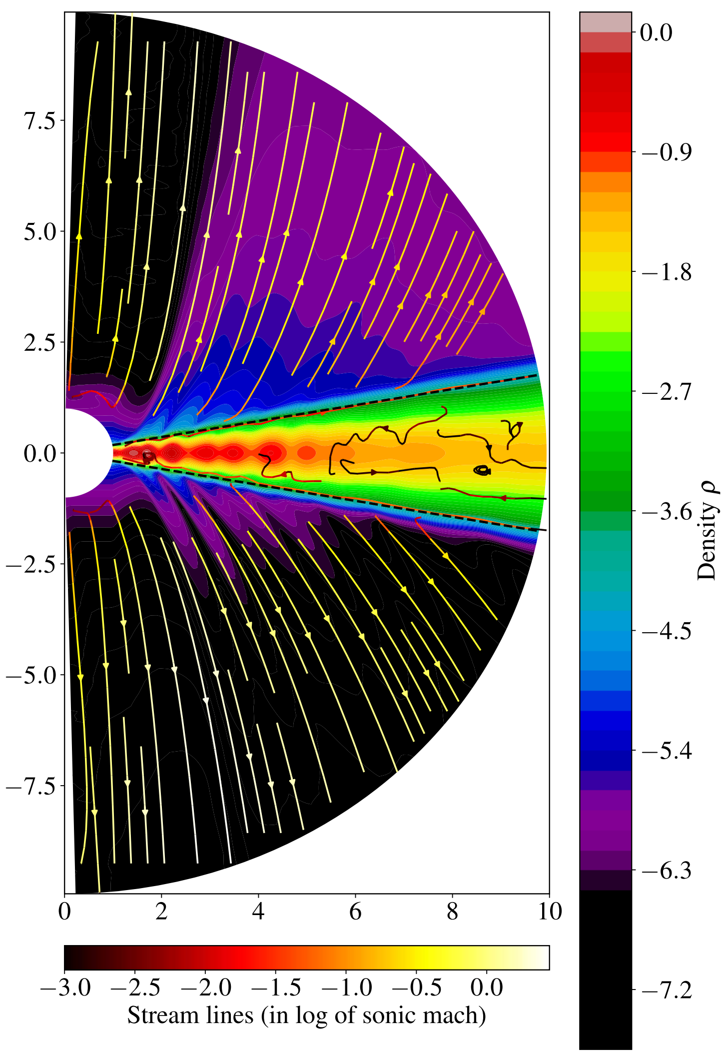
- Typically have $\xi = 0.2$—1
[Béthune+2017, Bai 2017, Wang+2018, Lesur 2021]



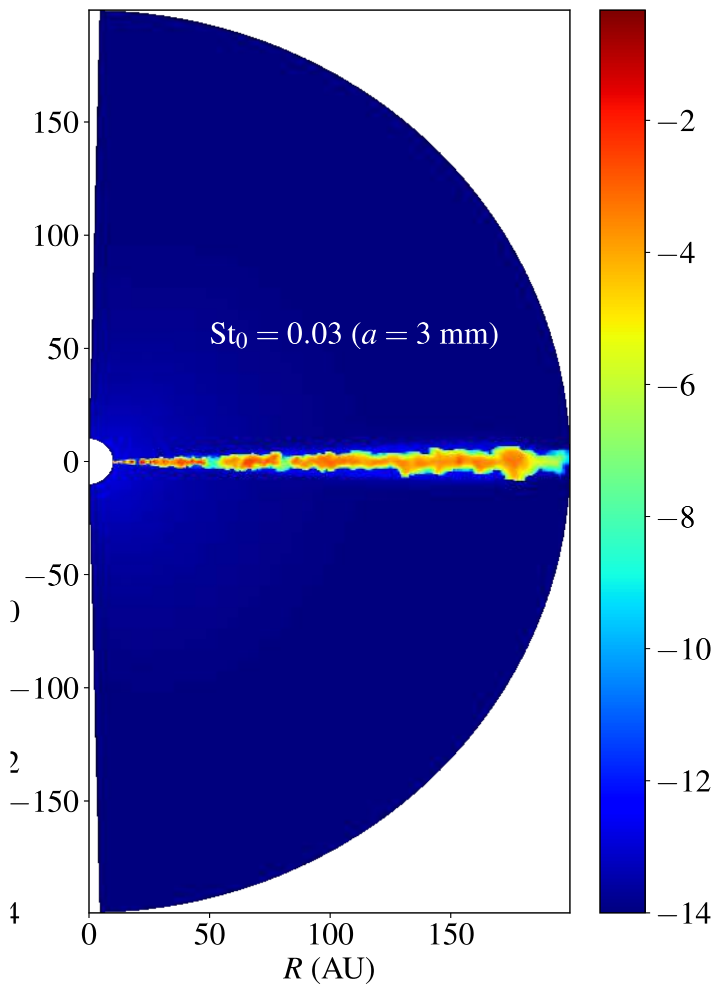
Mass accretion rate onto the star can be significantly smaller than the wind mass loss rate

Dust Dynamics

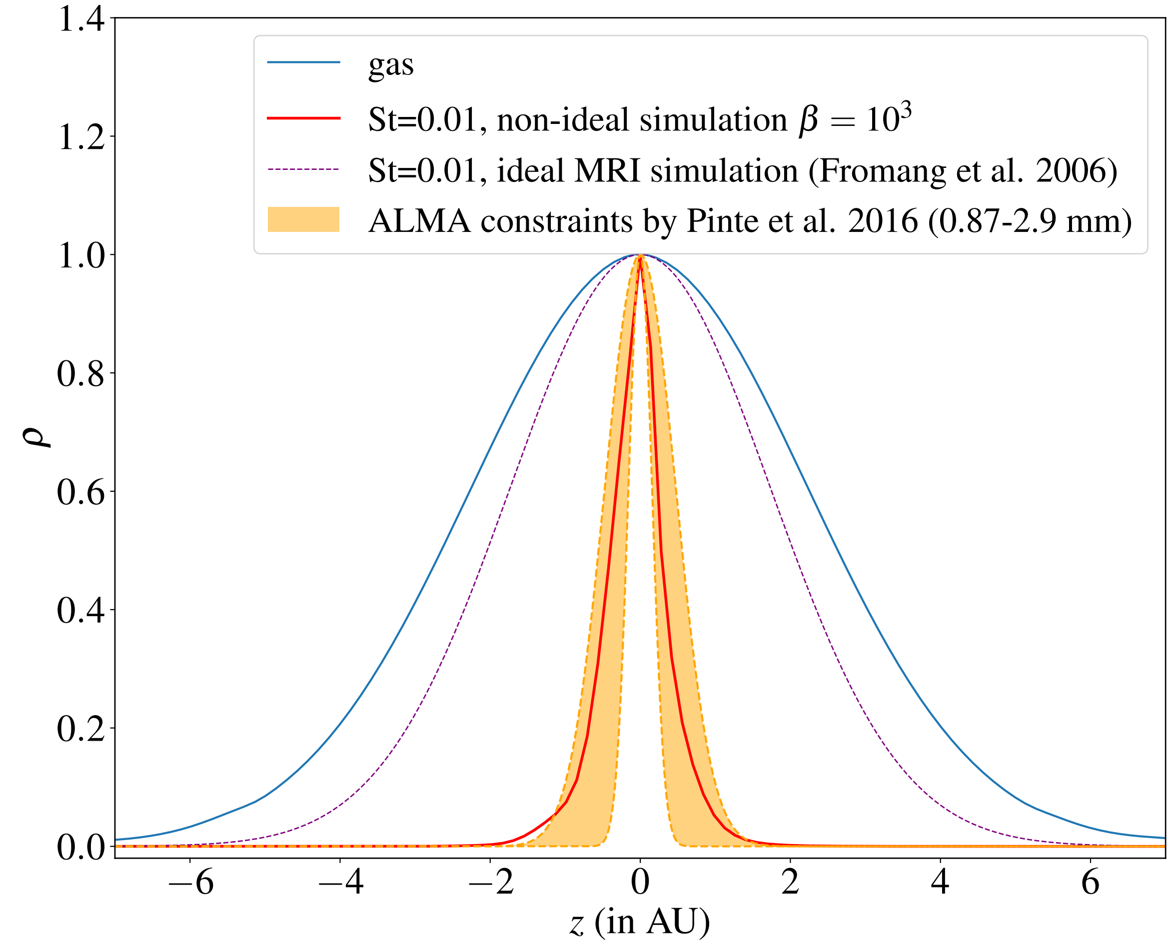
gas



dust grains

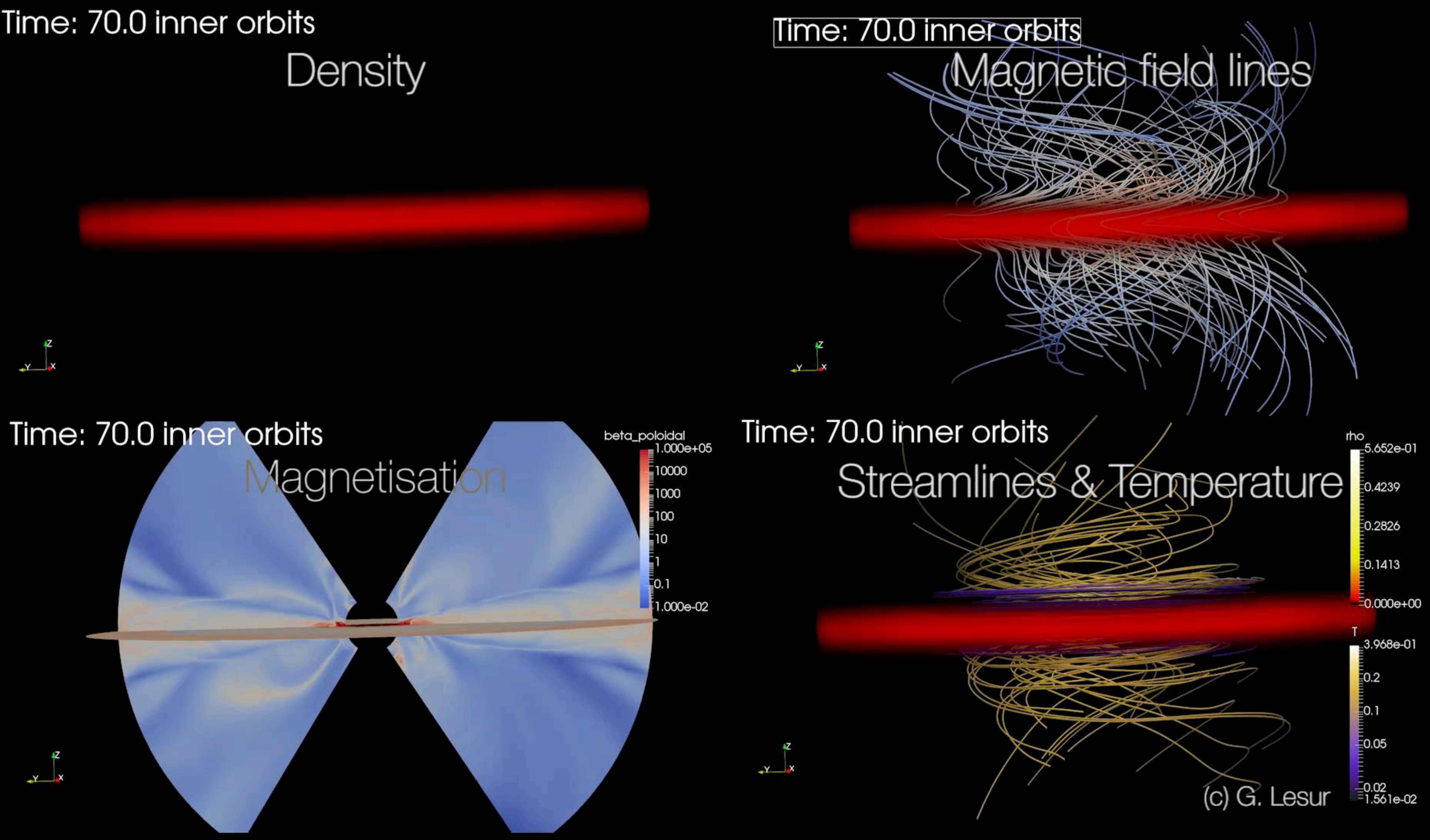


vertical density profiles



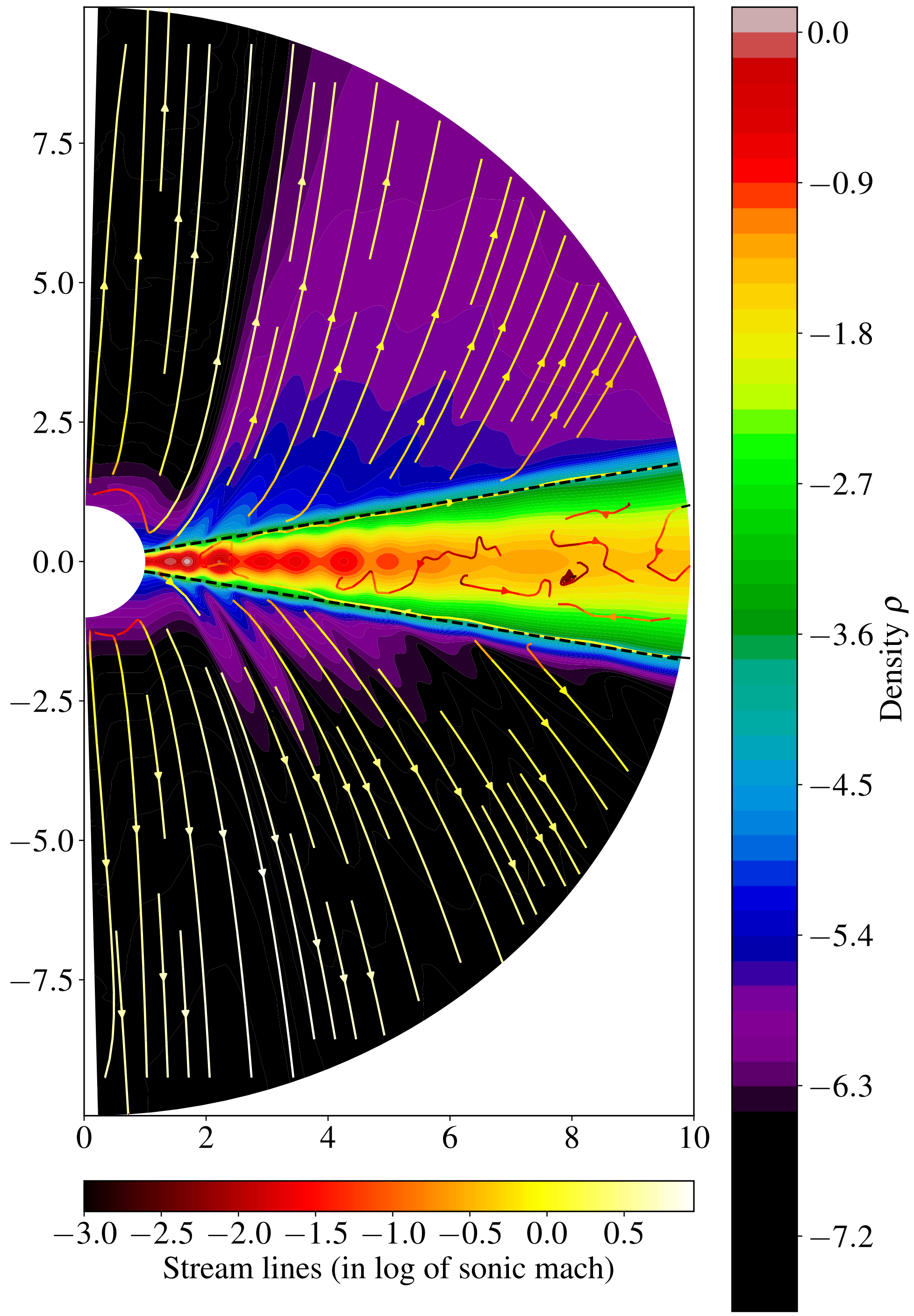
[Riols & Lesur 2019, Riols+2020]

Levels of turbulence in models are compatible with observed dust settling

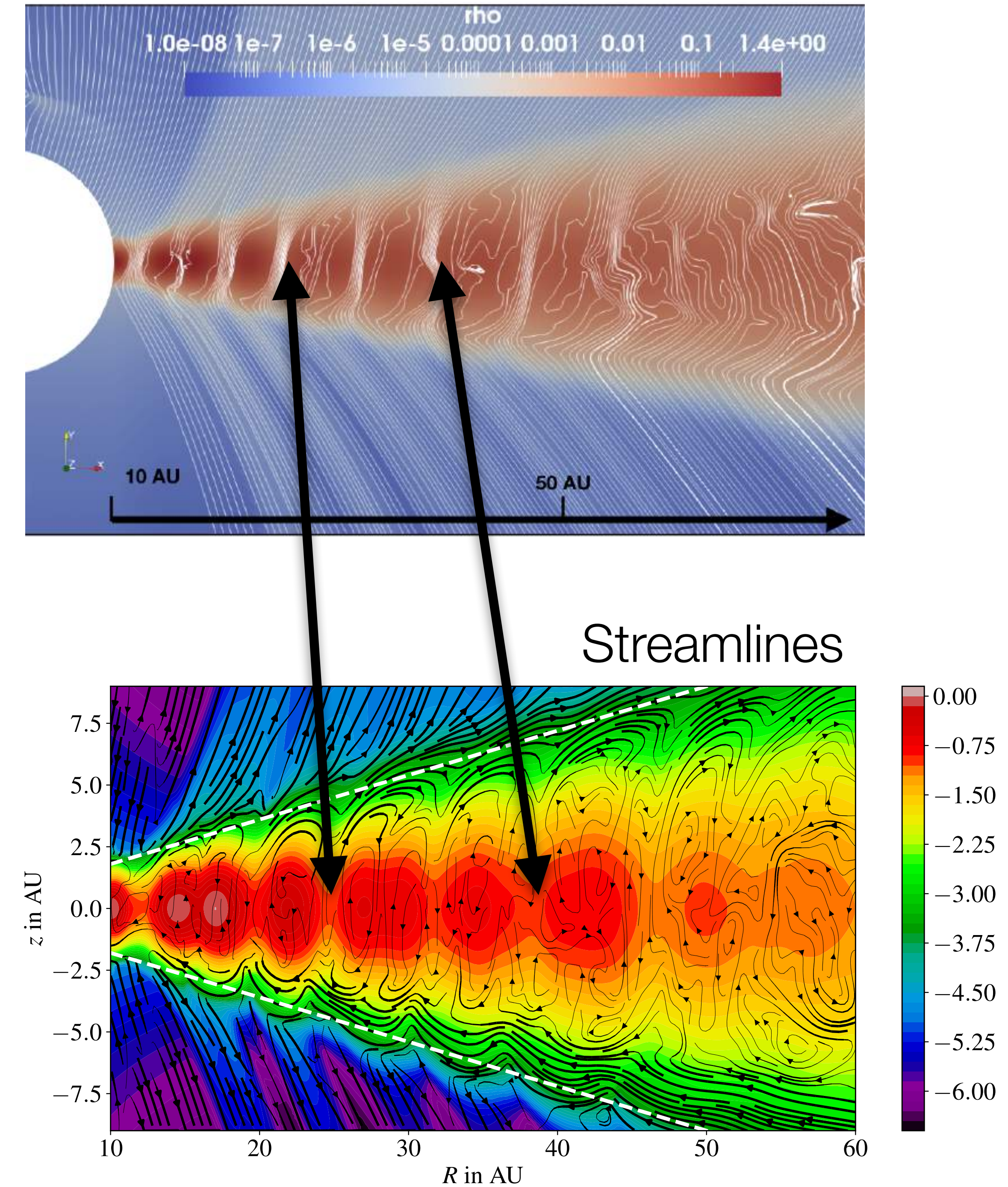

Time: 70.0 inner orbits
Density
Time: 70.0 inner orbits
Magnetic field lines
Time: 70.0 inner orbits
Magnetisation
beta_poloidal
1.000e+05
10000
1000
100
10
1
0.1
1.000e-02
Time: 70.0 inner orbits
Streamlines & Temperature
rho
5.652e-01
0.4239
0.2826
0.1413
0.000e+00
T
3.968e-01
0.2
0.1
0.05
0.02
1.561e-02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

Self-organisation

In wind-emitting discs



Magnetic field lines

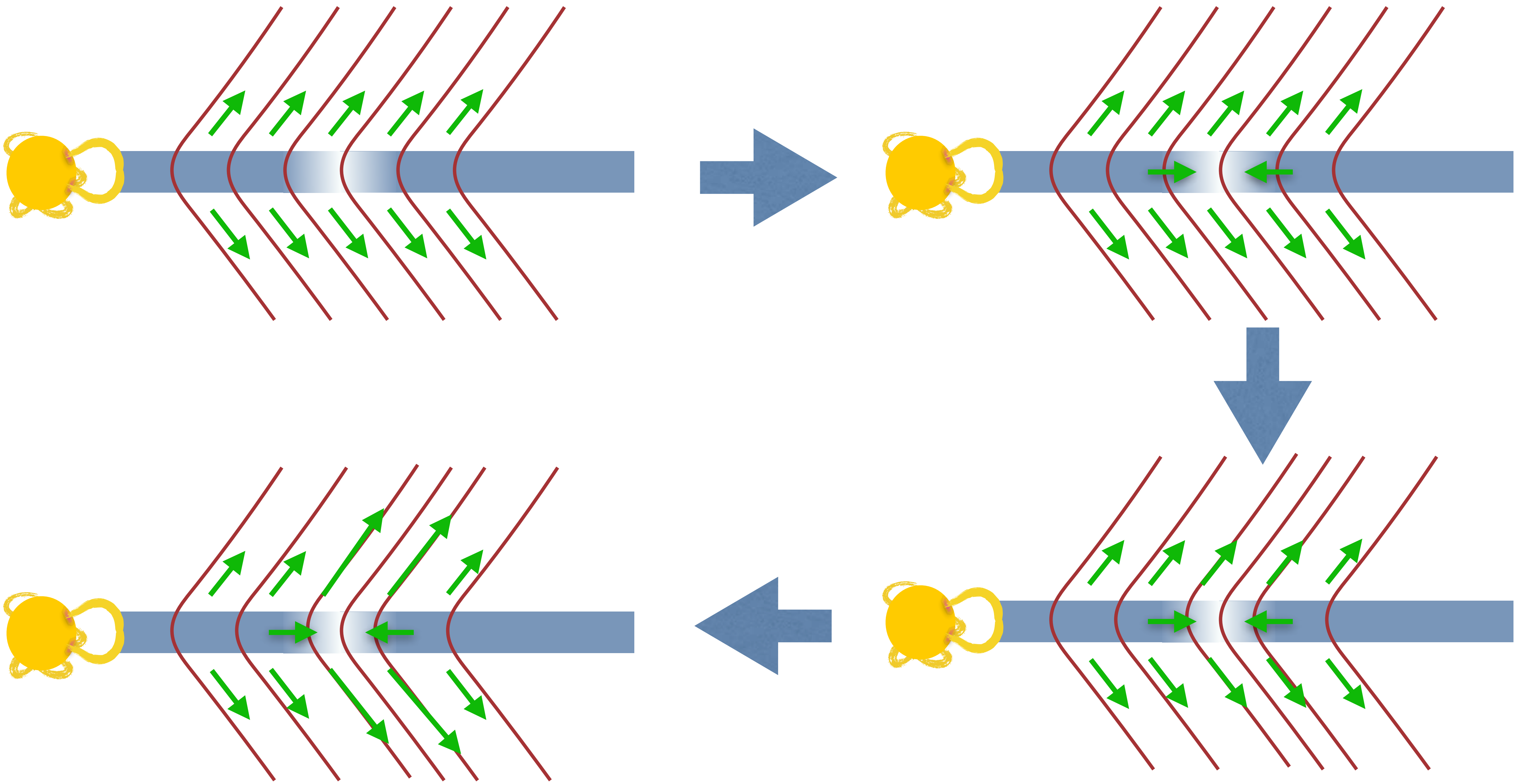


[Riols+2020]

Physical interpretation ?

Consider a small density deficit

This induces a radial flow which tend to fill the deficit



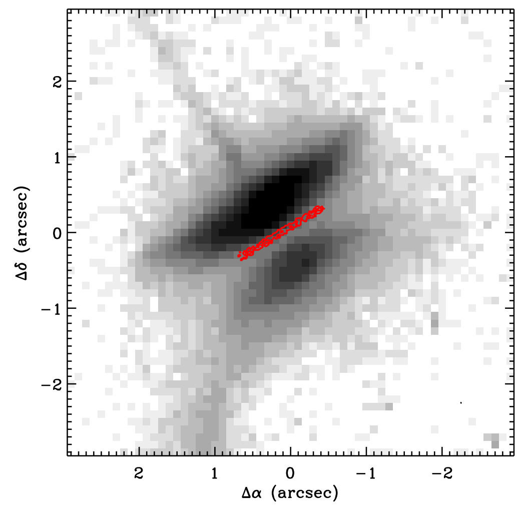
The increased magnetic flux enhance the mass loss in the outflow, which empties the initial density deficit

The radial flow advects both mass and poloidal field lines

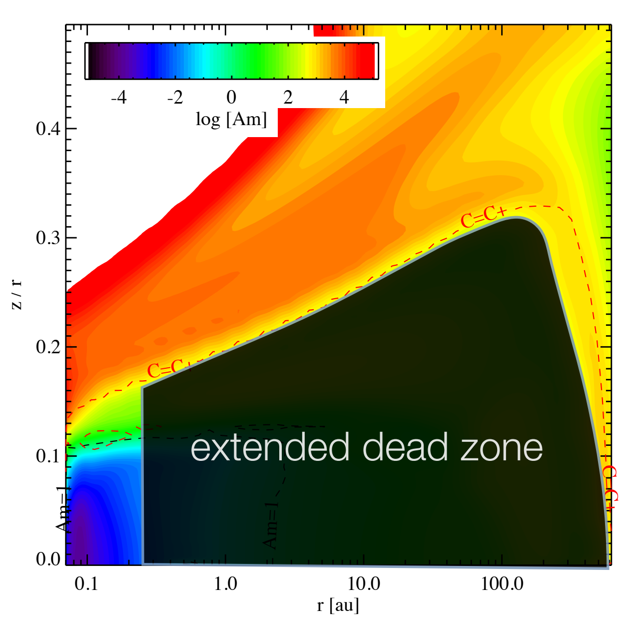
[Riols & Lesur 2019]

Conclusions and take home message

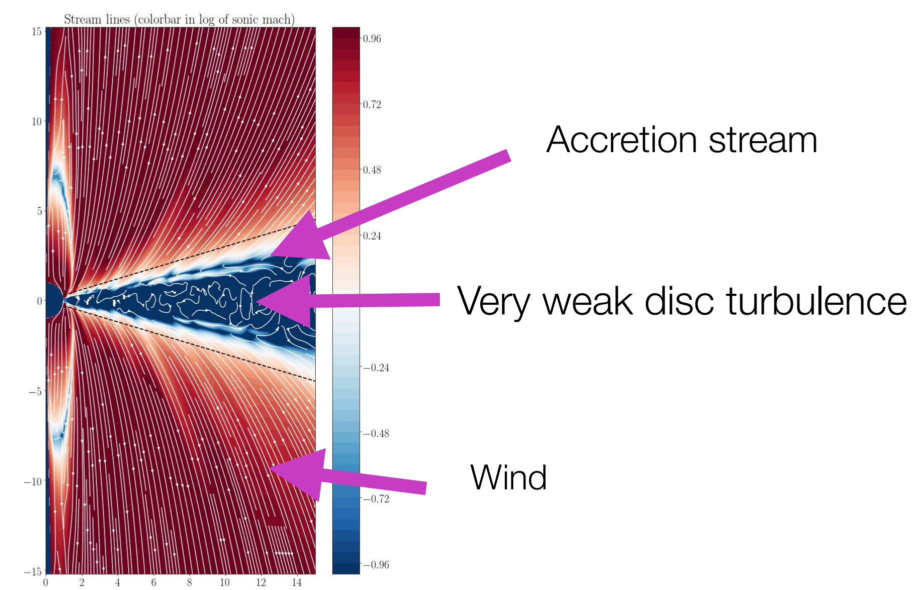
- Observations indicates that discs are weakly turbulent, but are accreting



- 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