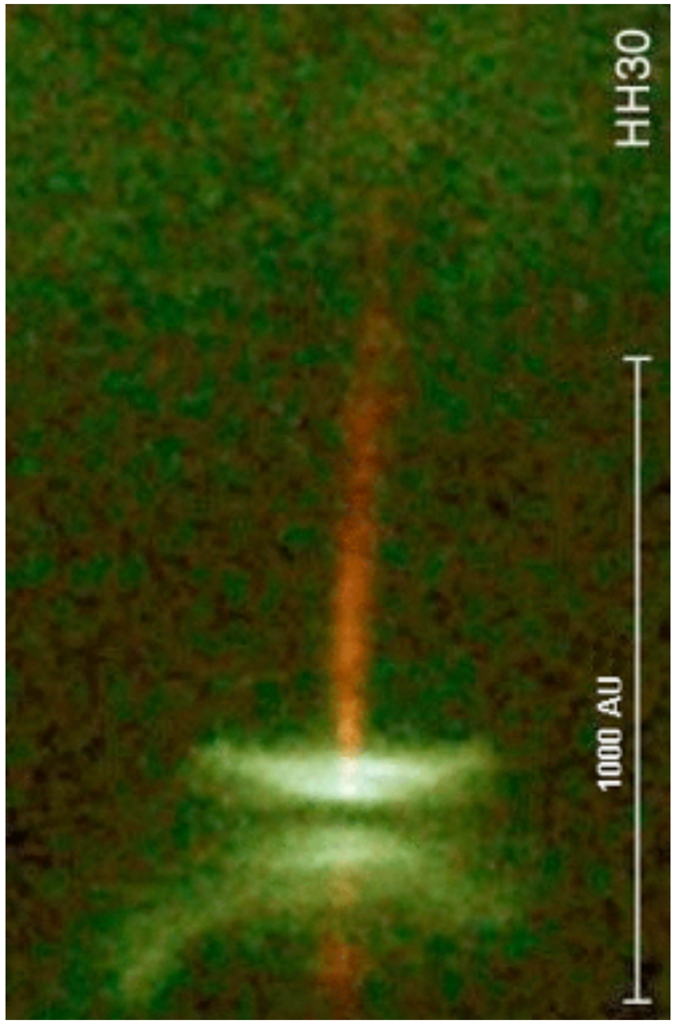
Accretion discs

Geoffroy Lesur (IPAG, Grenoble, France)

Outline

- Accretion discs and jets: what are they
  - Accretion discs in nature
  - Jets in nature
- Accretion disc models
  - Hydrostatic equilibrium
  - Angular momentum transport
  - Linear stability
- A Specific application of the MRI to protoplanetary discs
  - Nonideal MRI
  - Direct detection of turbulence in protoplanetary discs

Protoplanetary discs



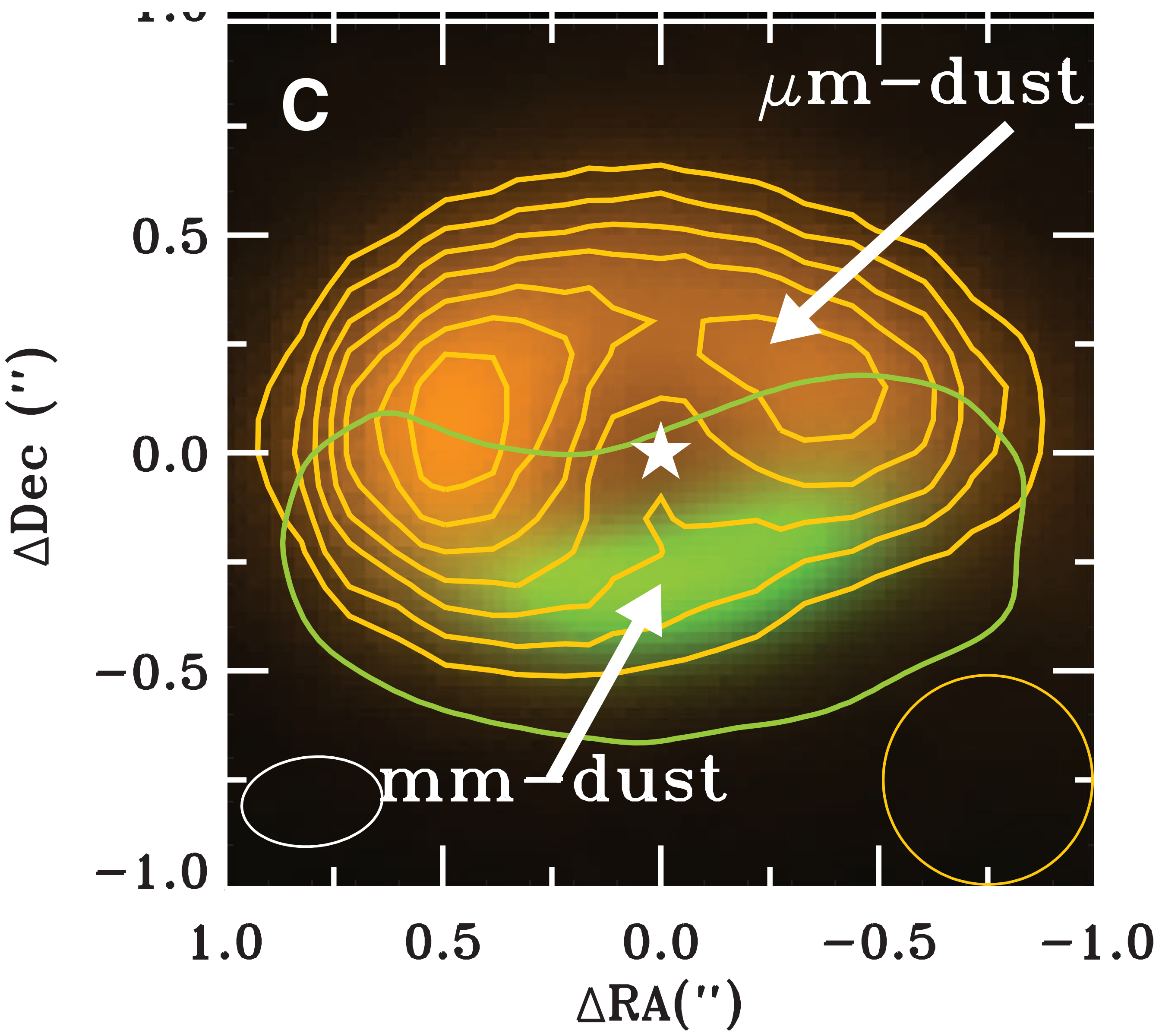
Credit: C. Burrows and J. Krist (STScI),
K. Stapelfeldt (JPL) and NASA

Artist view

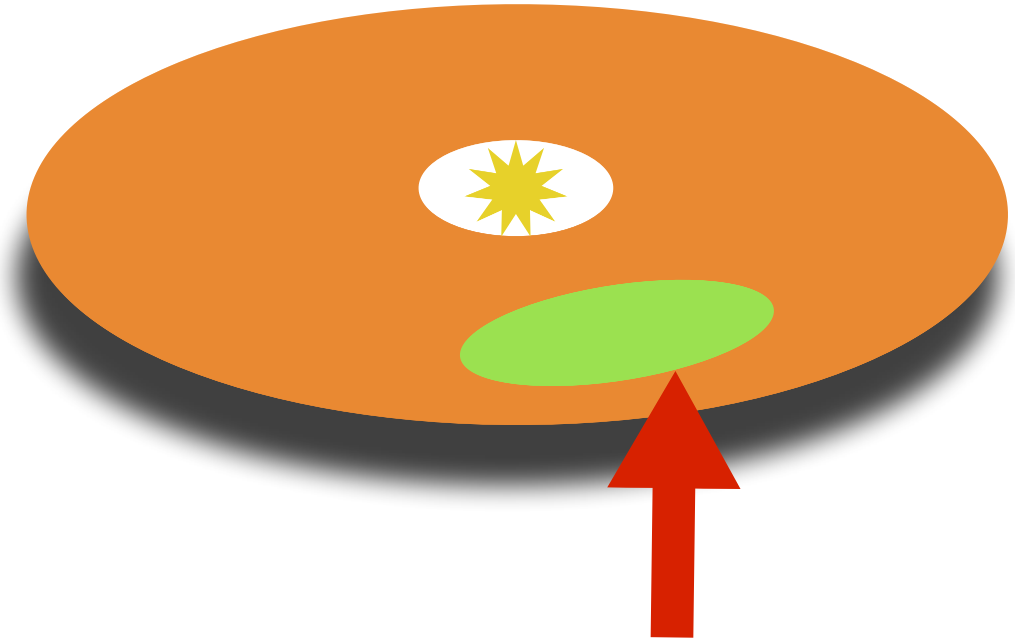
- Size 10^9-10^{13} m
- Central object: young star (10^{30} kg)
- Temperature 10^3-10 K

Structures in protoplanetary discs

I- Vortices



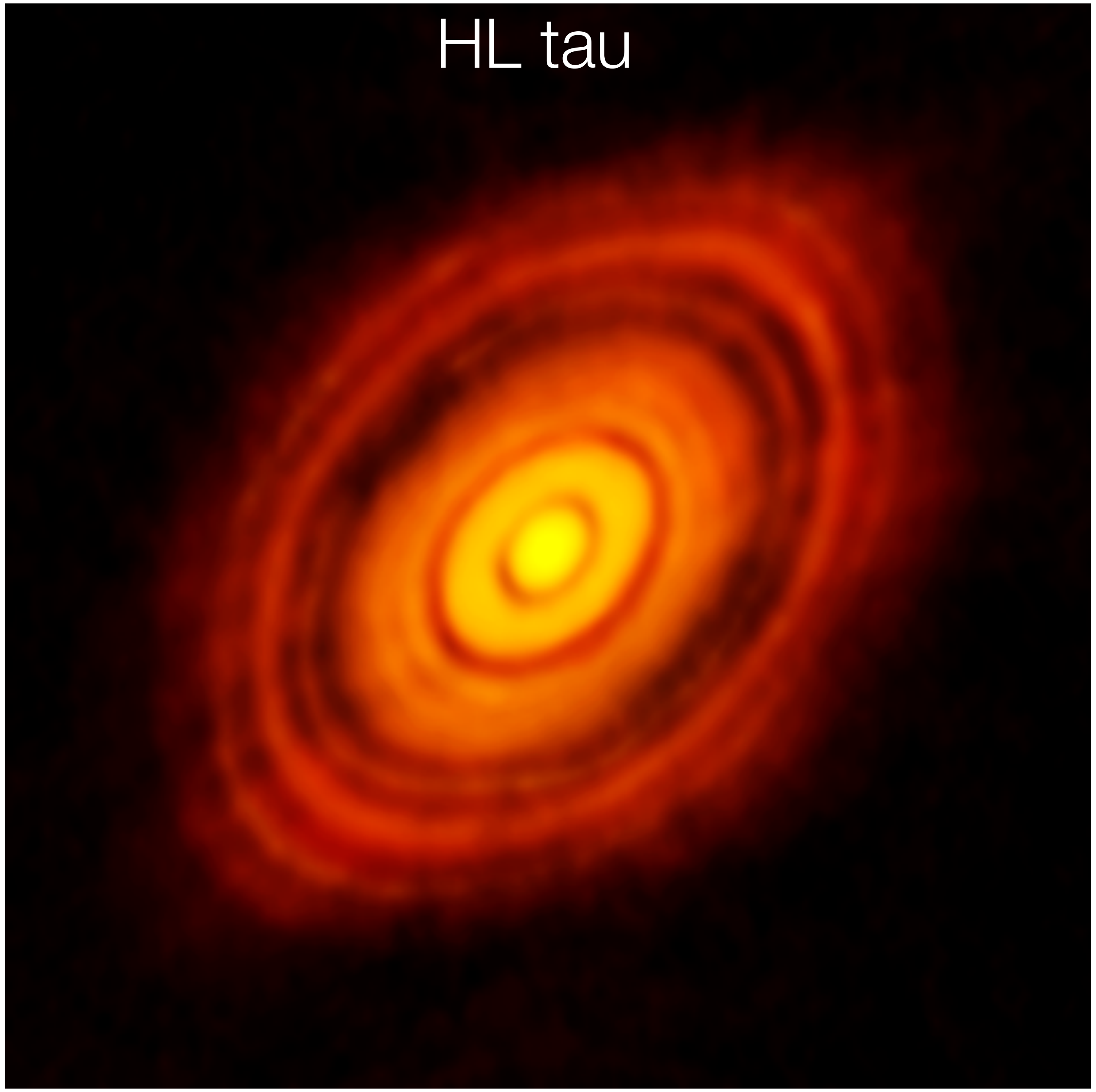
[van-der Marel+ (2013)]



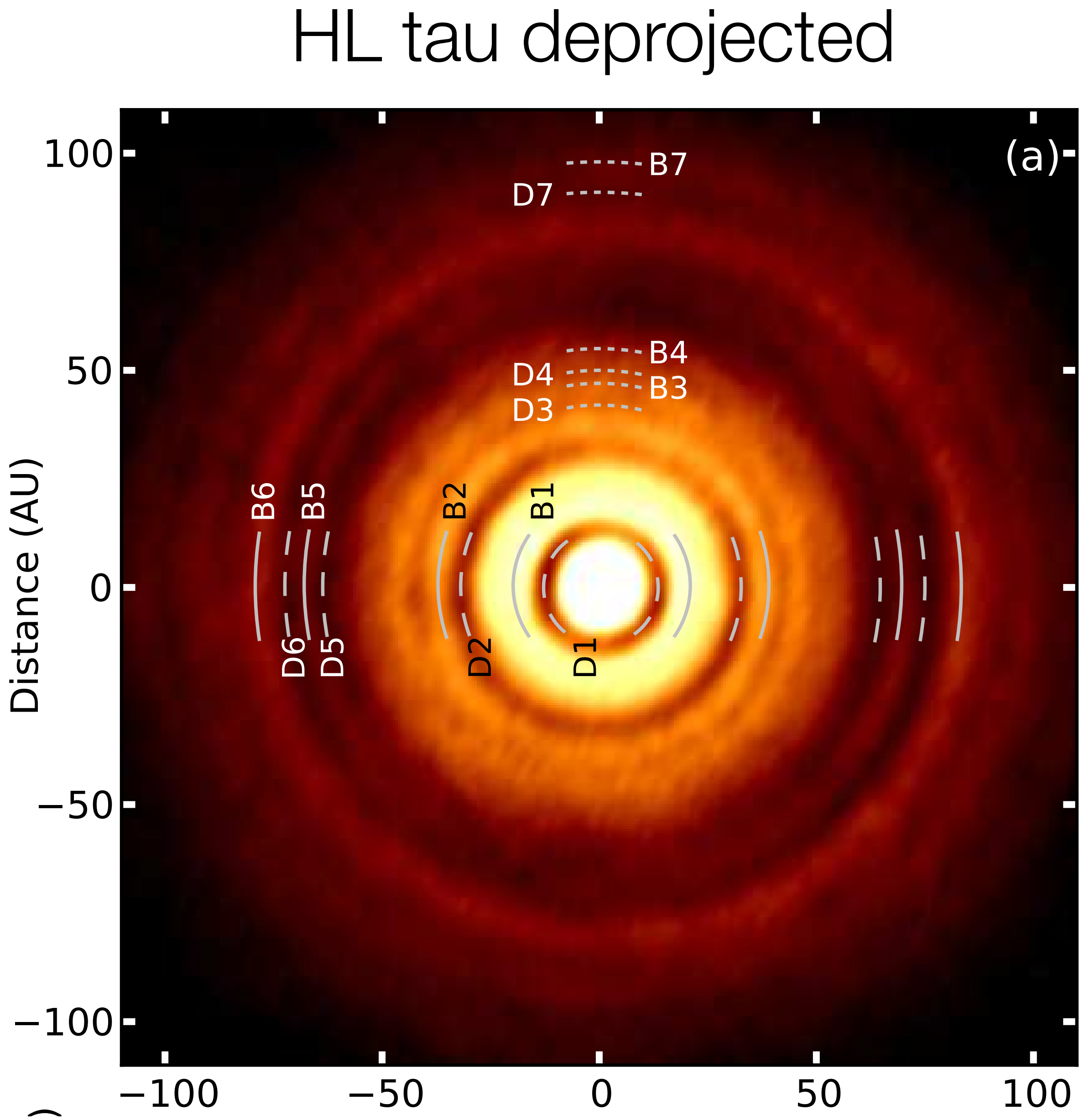
Giant anticyclonic vortex

Structures in protoplanetary discs

II- Rings

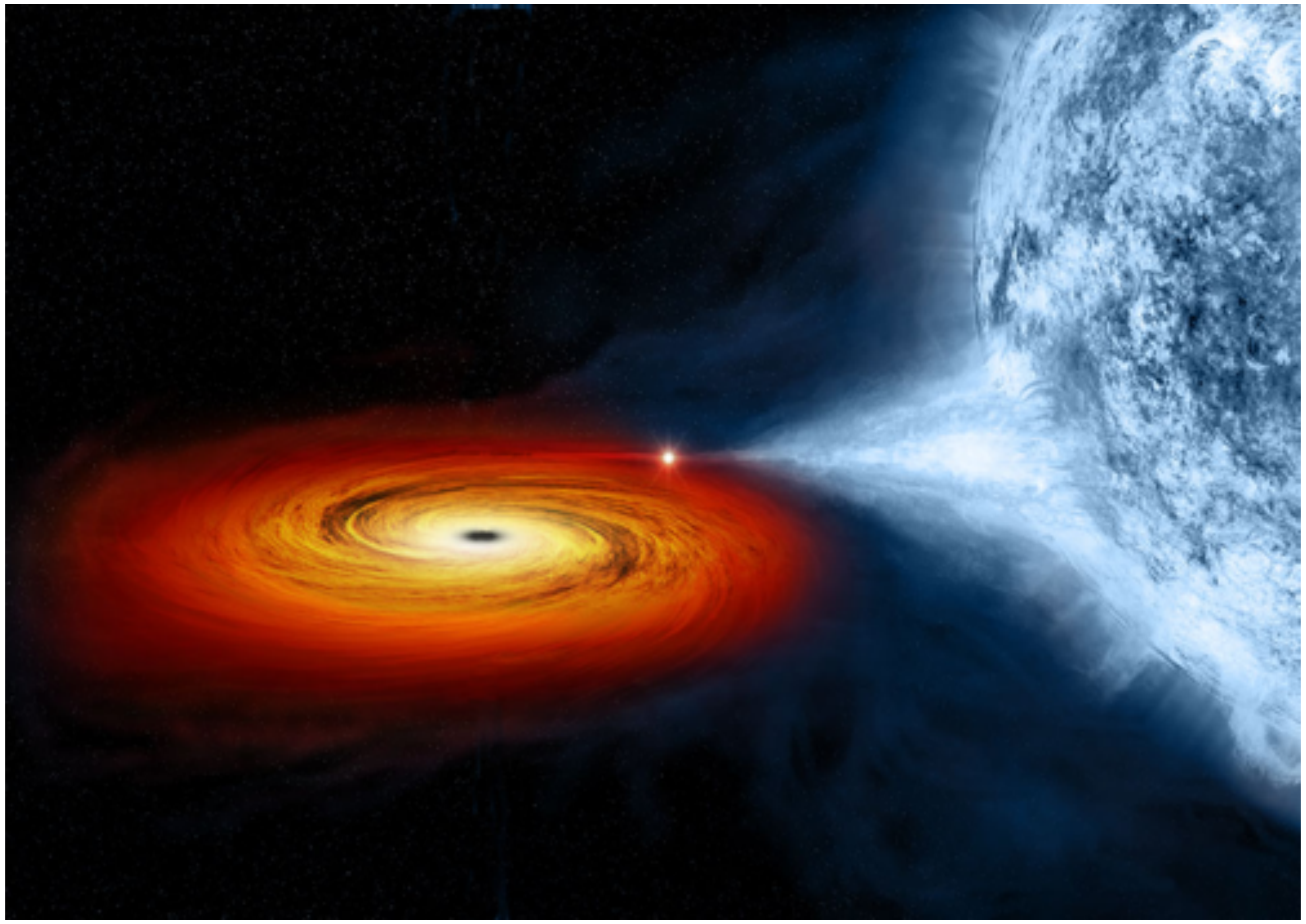


ALMA (ESO/NAOJ/NRAO)
Press release 6 Nov. 2014



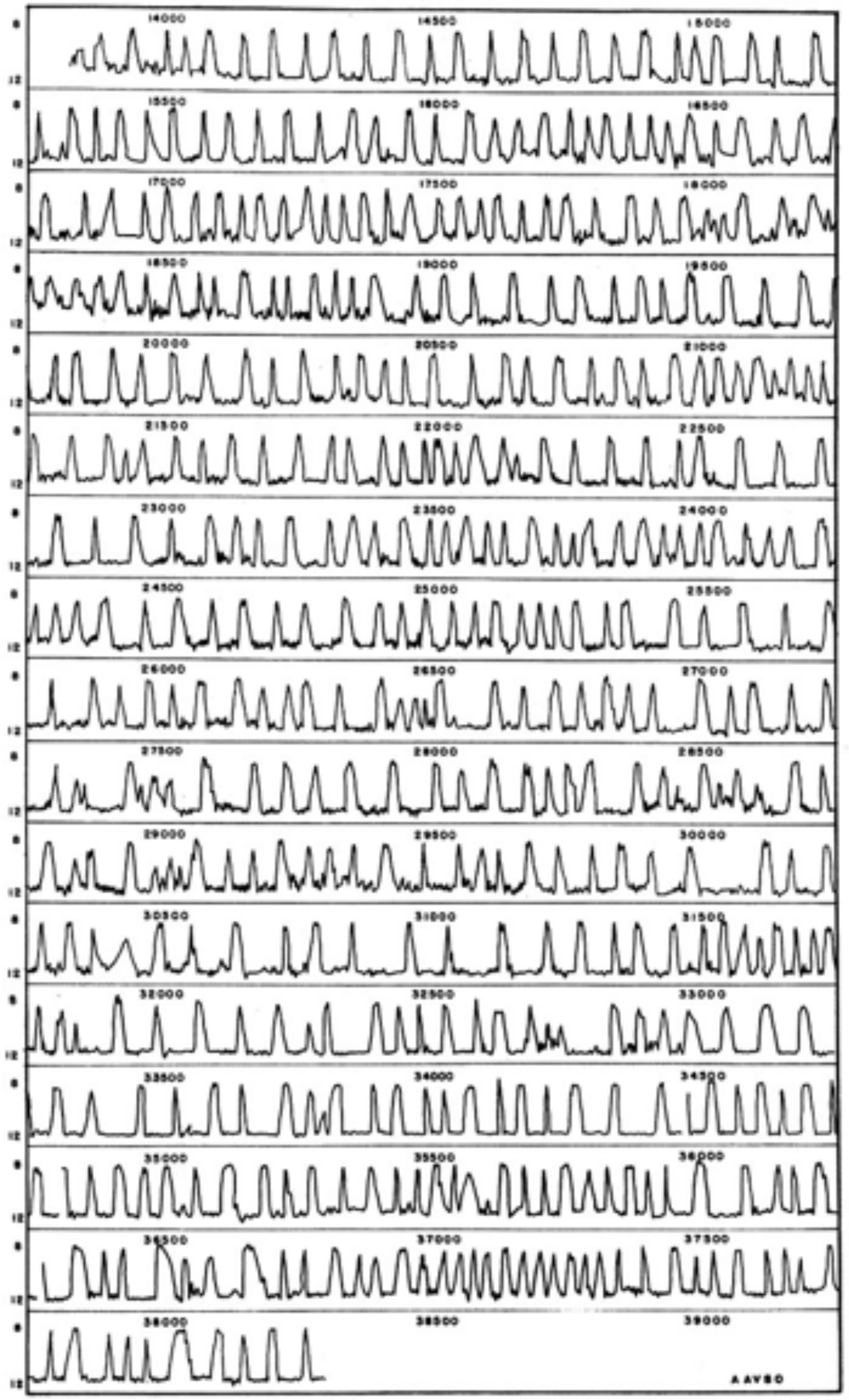
[Brogan+2015]

Compact binaries



Artist view

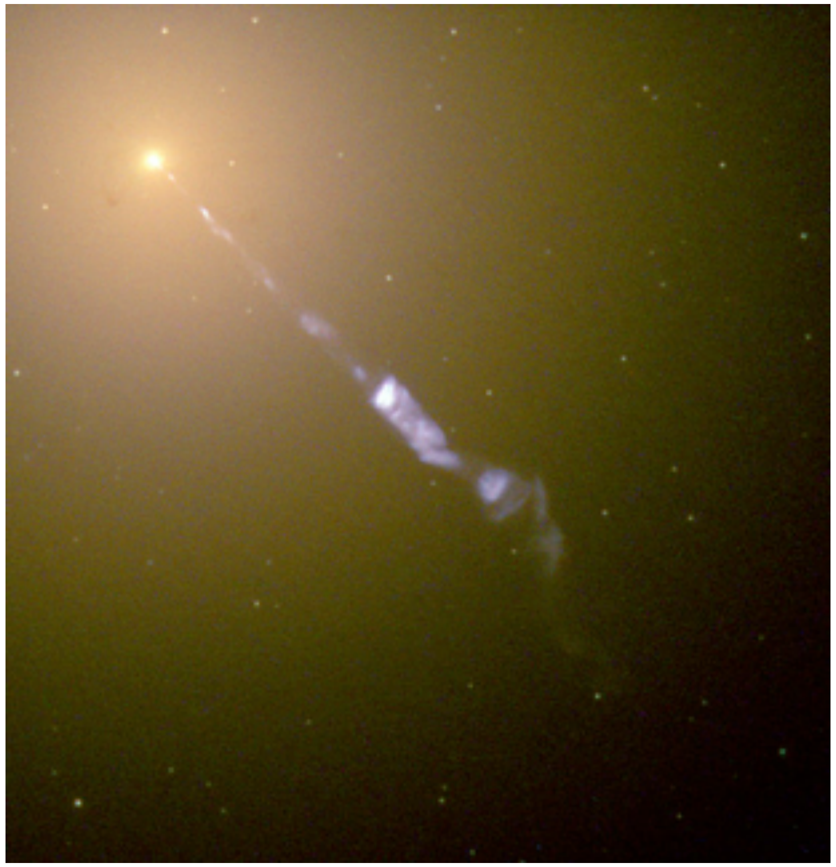
- Size 10^4-10^8 m
- Central object: white dwarf, neutron star, black hole (10^{30} kg)
- Temperature 10^5-10^3 K



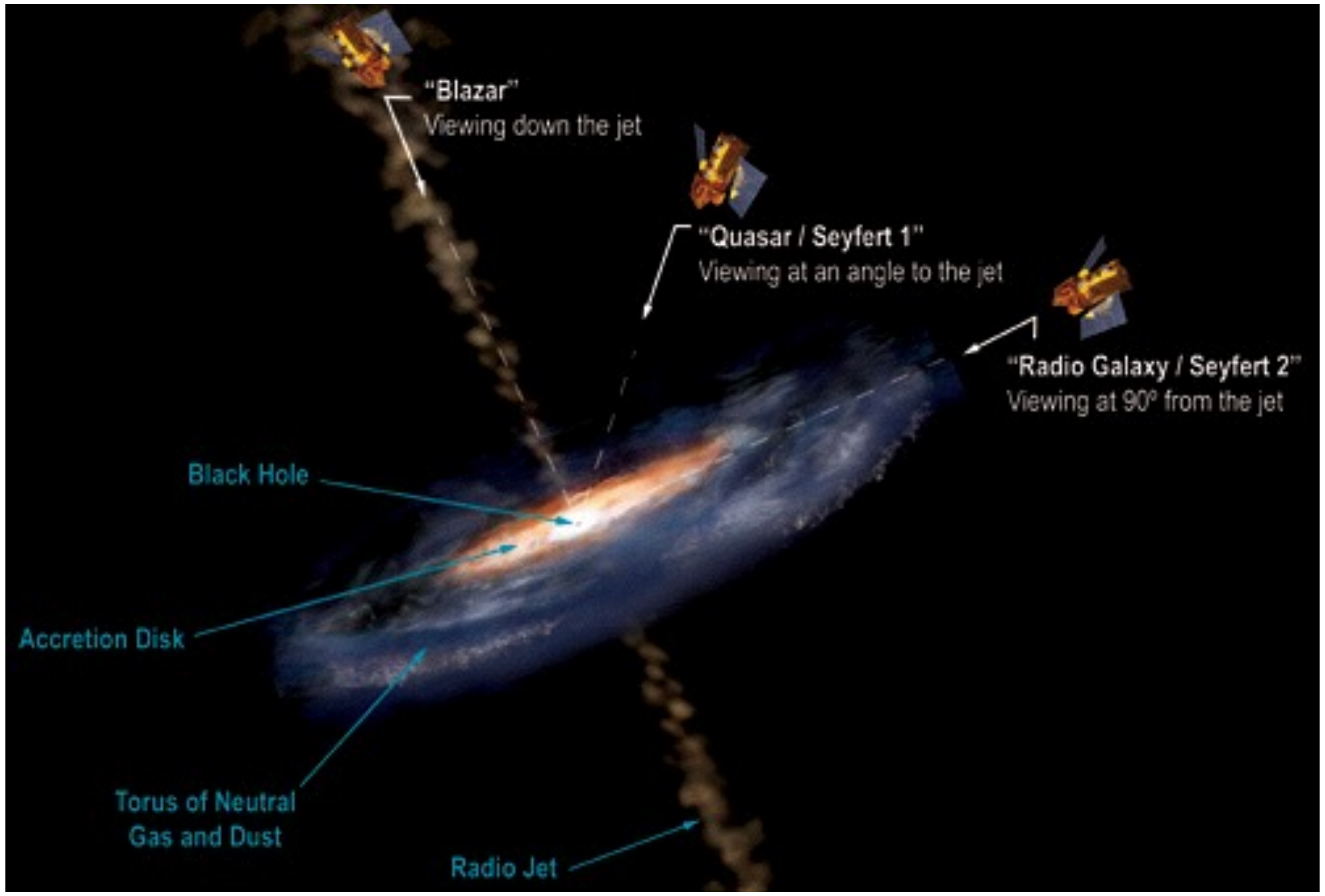
LIGHT CURVE OF SS CYGNI

1896 — 1963

Active galactic nuclei (blazars, quasars…)

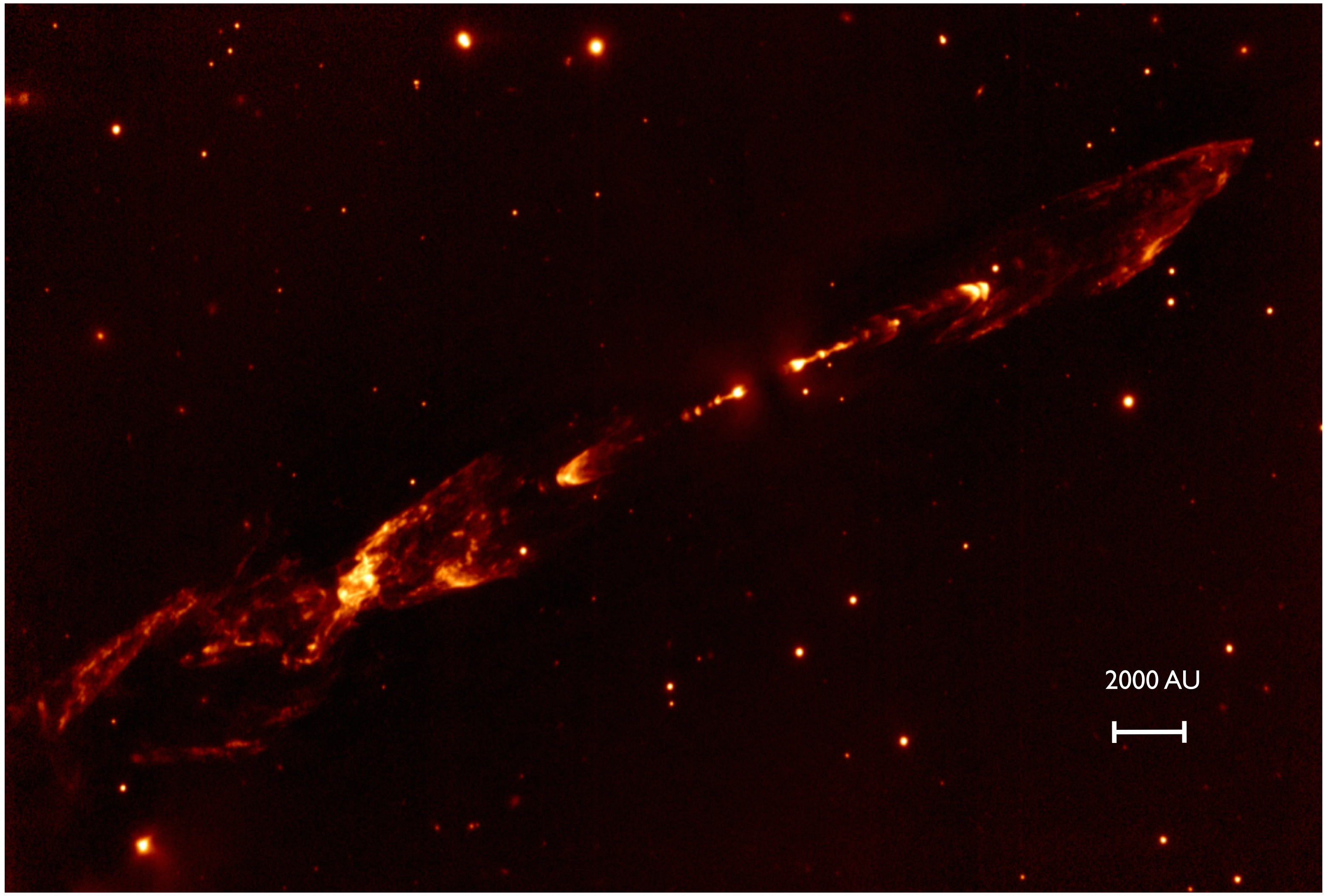


M87

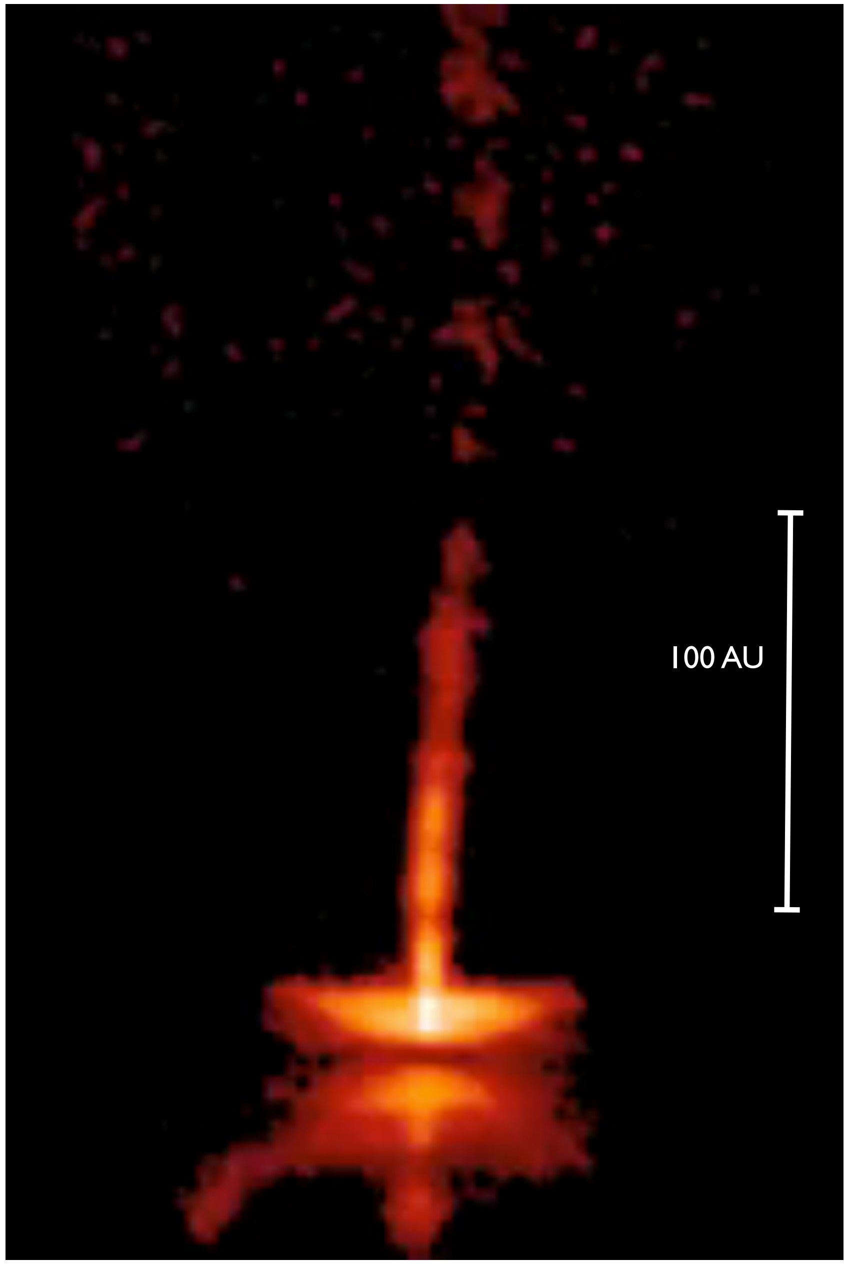


- Size 10^{10}-10^{15} m
- Central object: black hole (10^{36}-10^{39} kg=10^{6}-10^{9} M_{sun})
- Temperature 10^{5}-10^{2} K

Jets in protoplanetary discs

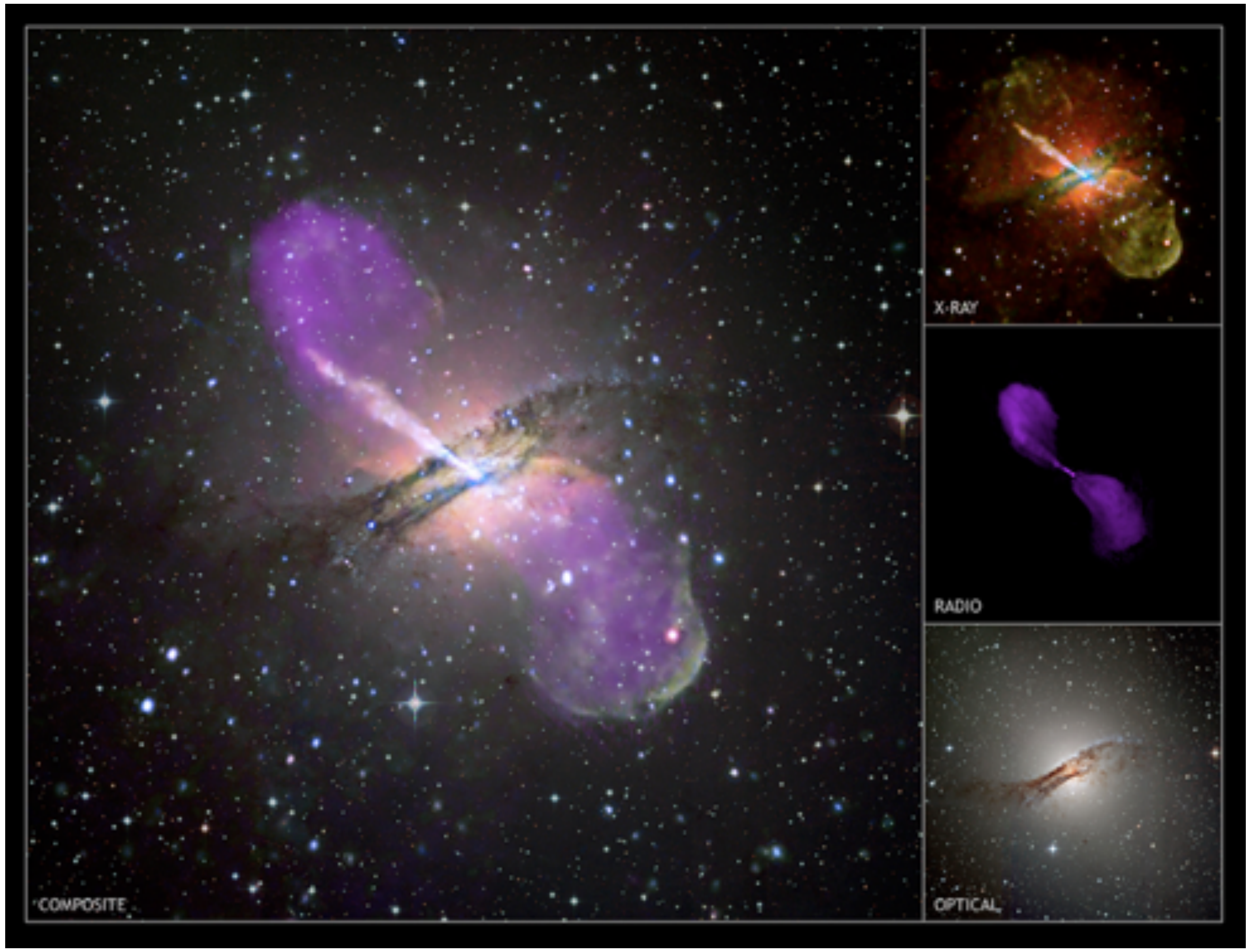


HH212

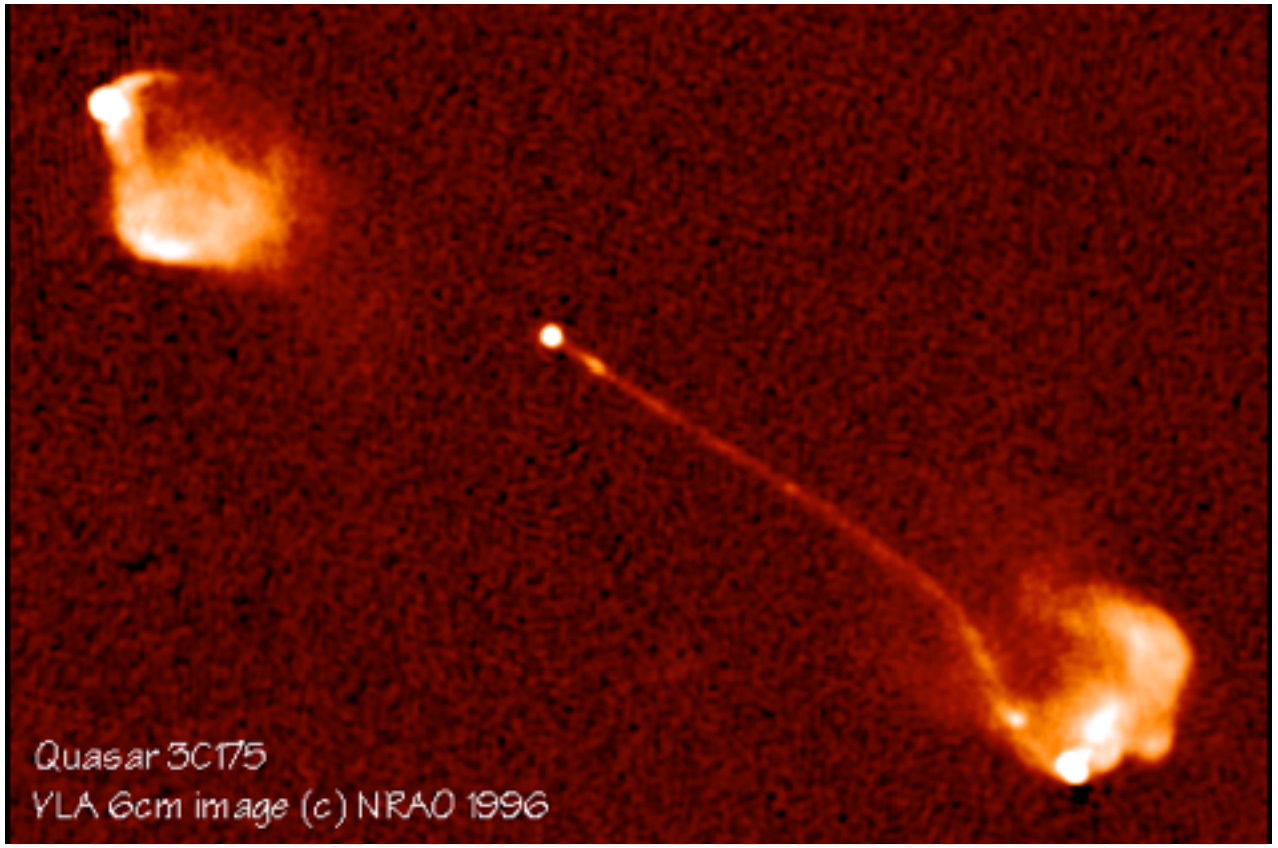


HH30

Jets in AGNs



Centaurus A



Quasar 3C175

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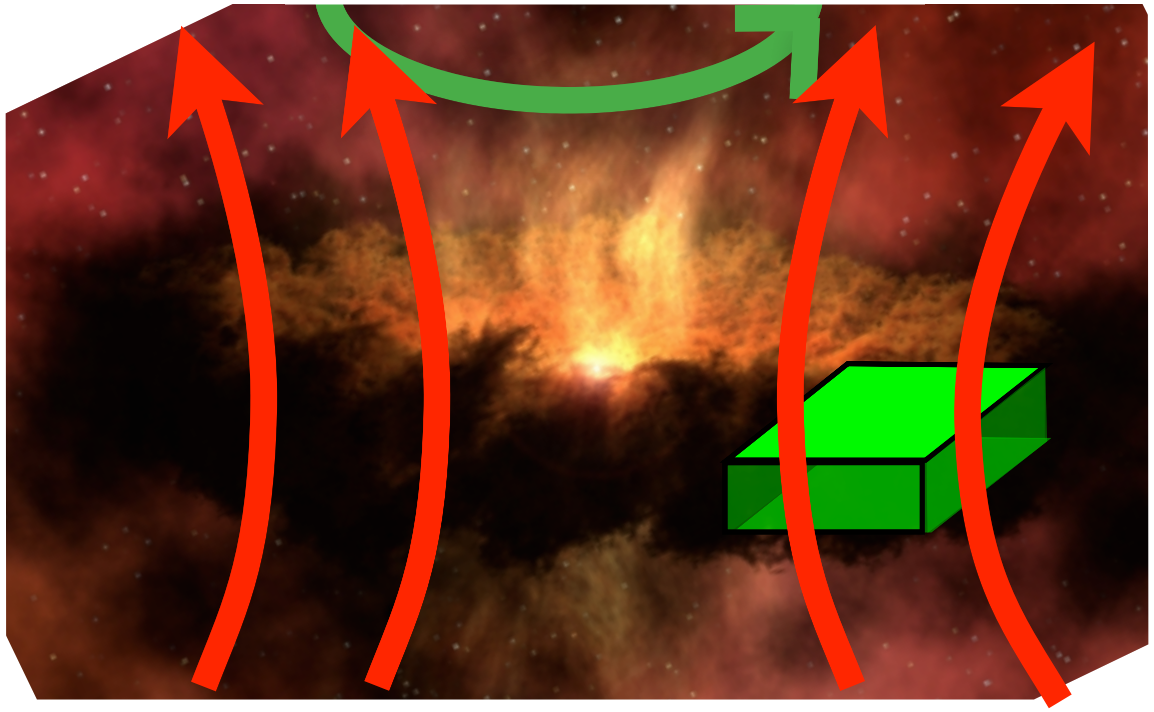
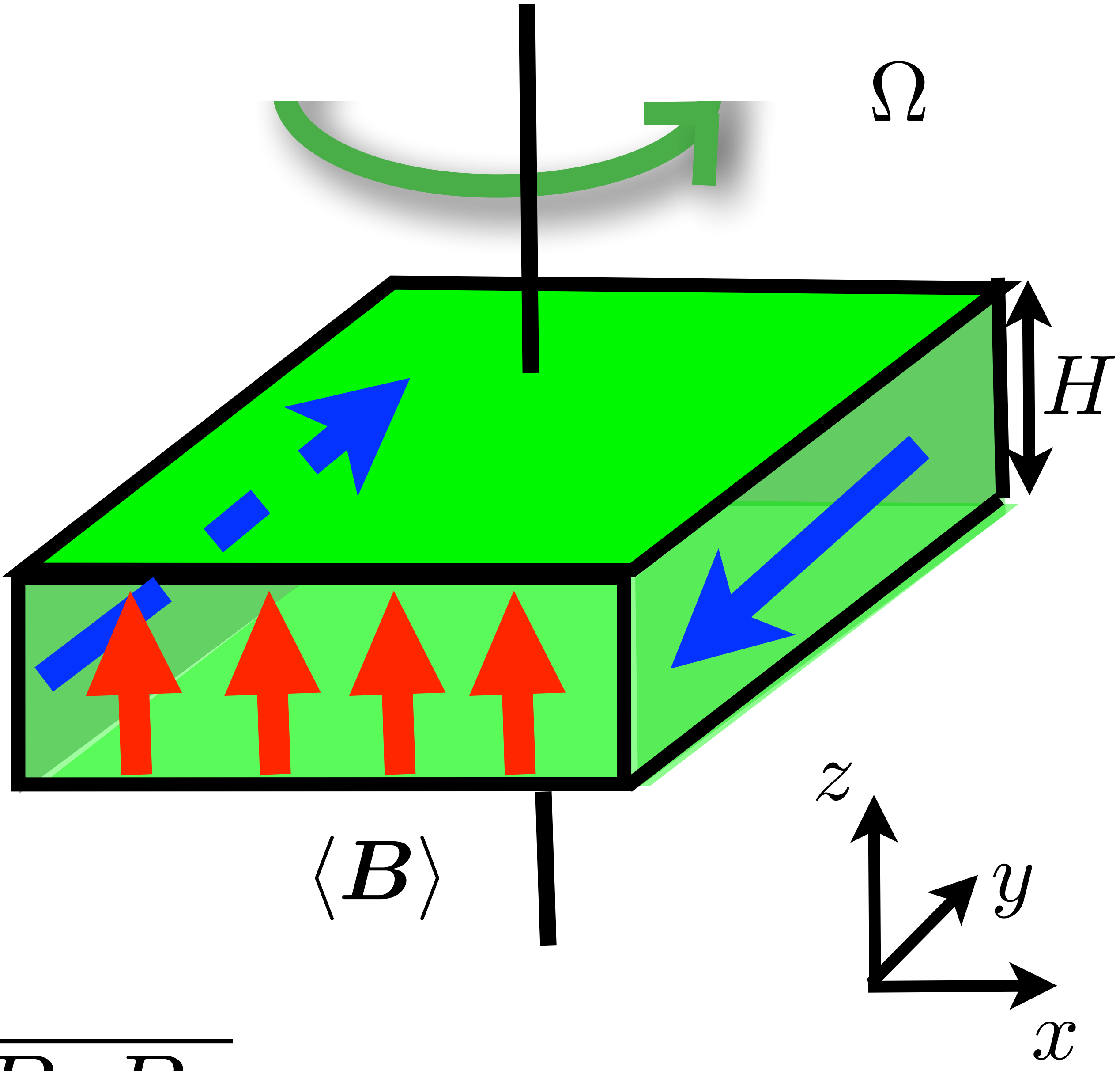
Nonlinear evolution of the MRI

The shearing box model

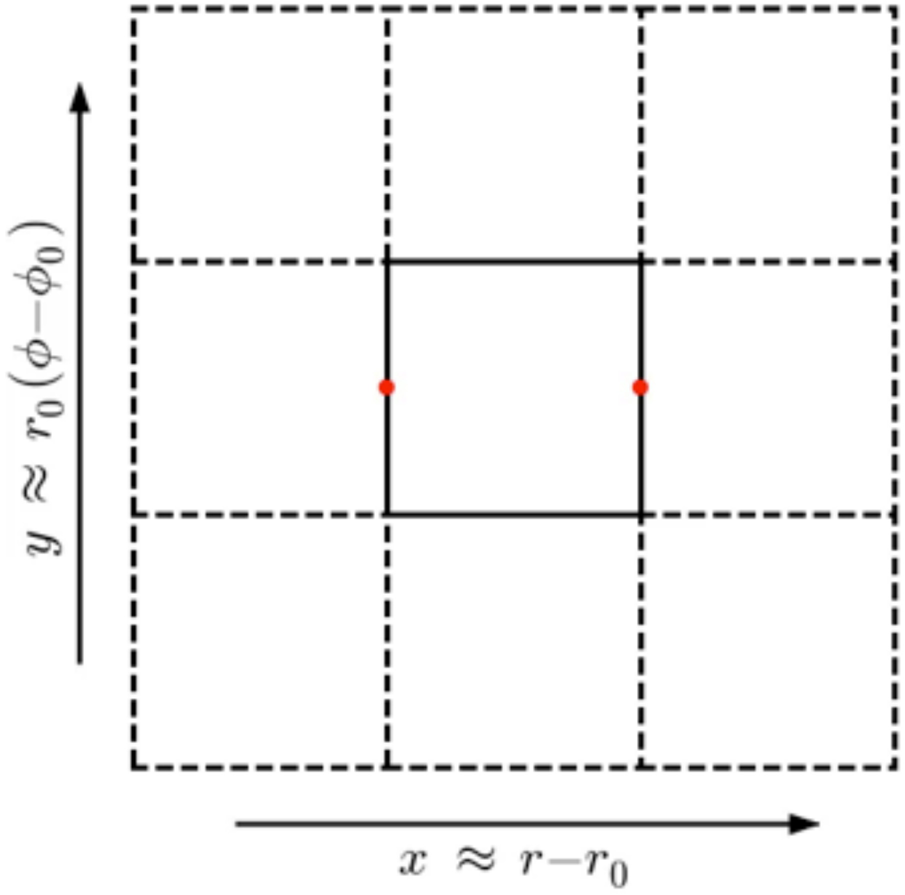




$$\alpha = \frac{\overline{\rho v_x v_y - B_x B_y}}{\overline{\rho}\Omega^2 H^2}$$

Boundary conditions

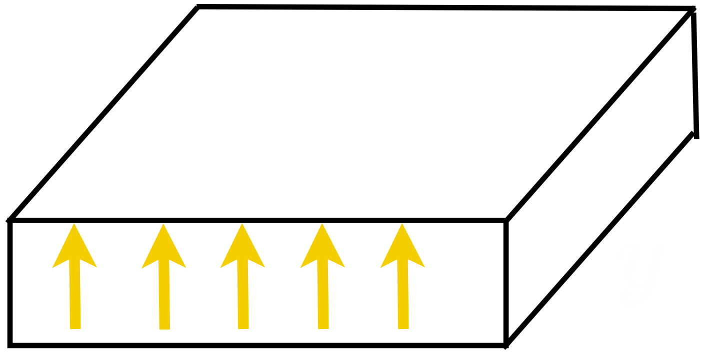
- Use shear-periodic boundary conditions= «shearing-sheet»
- Allows one to use a sheared Fourier Basis
- periodic in y and z (non stratified box)



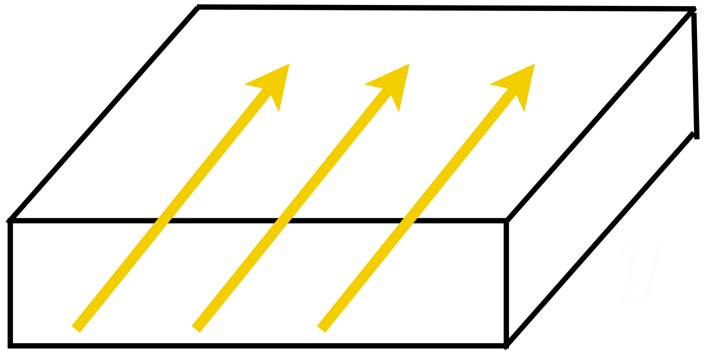
Courtesy T. Heinemann

Mean vertical and toroidal fields are conserved

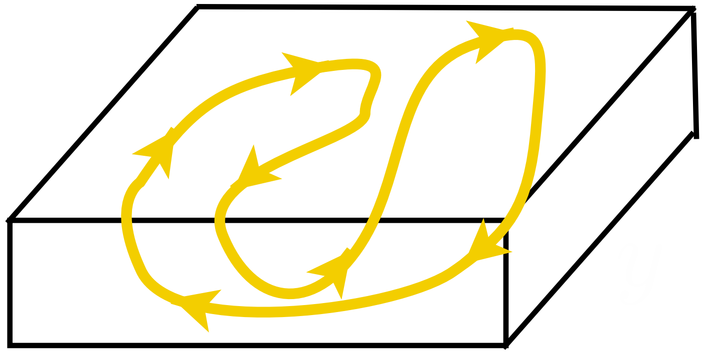
mean vertical field



mean toroidal field

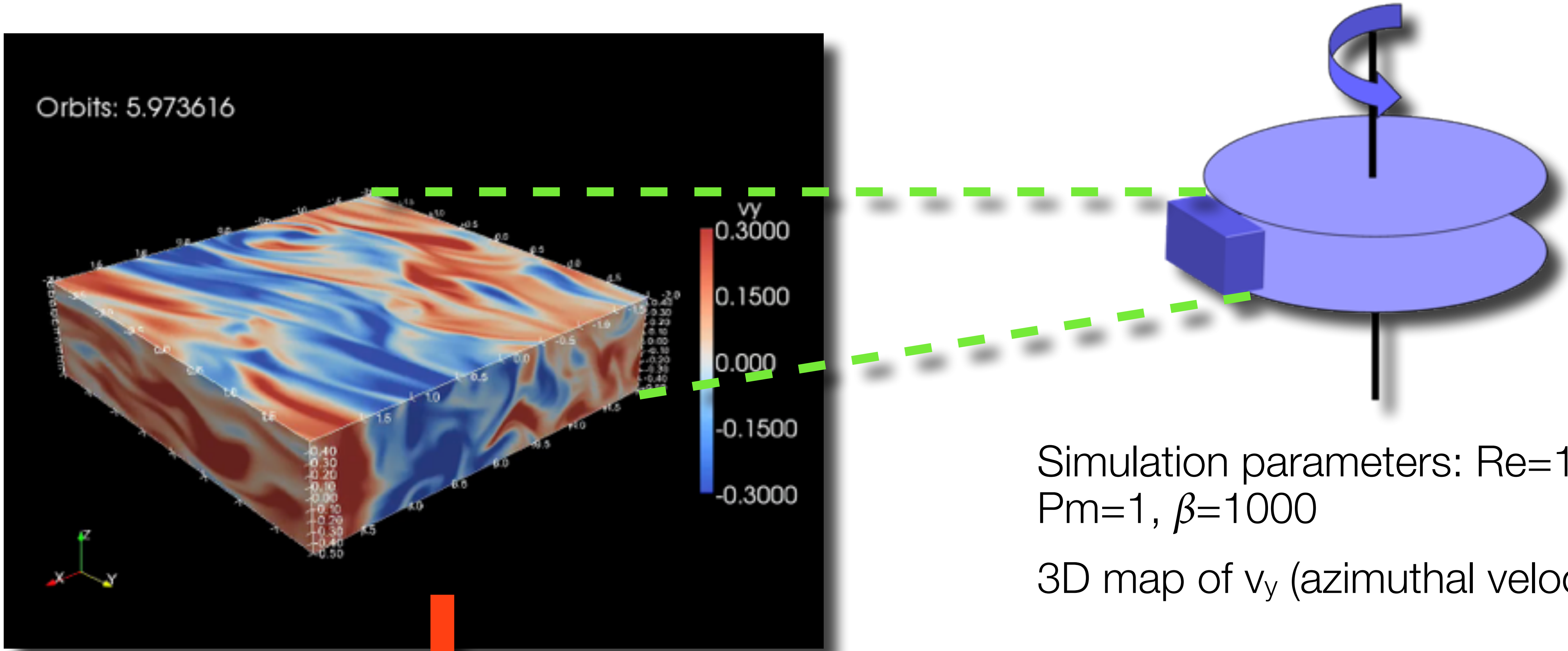


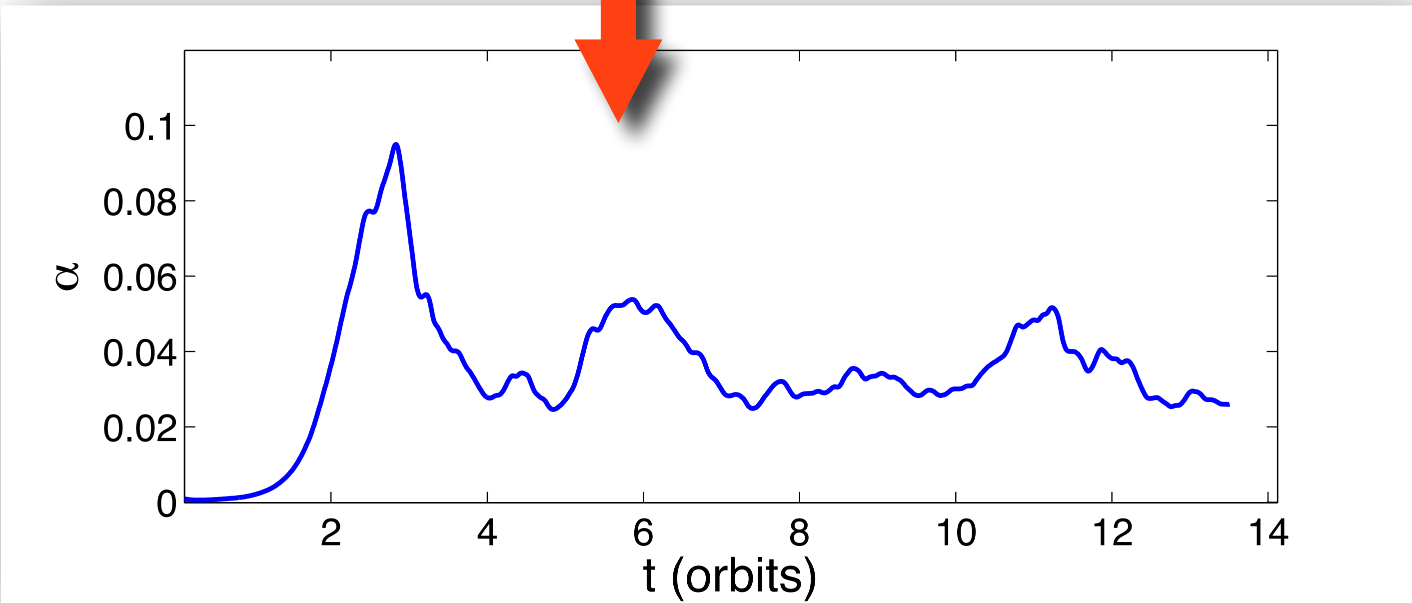
zero mean field



Mean vertical field case

Typical simulation





Simulation parameters: Re=1000, Pm=1, β=1000

3D map of v_y (azimuthal velocity)

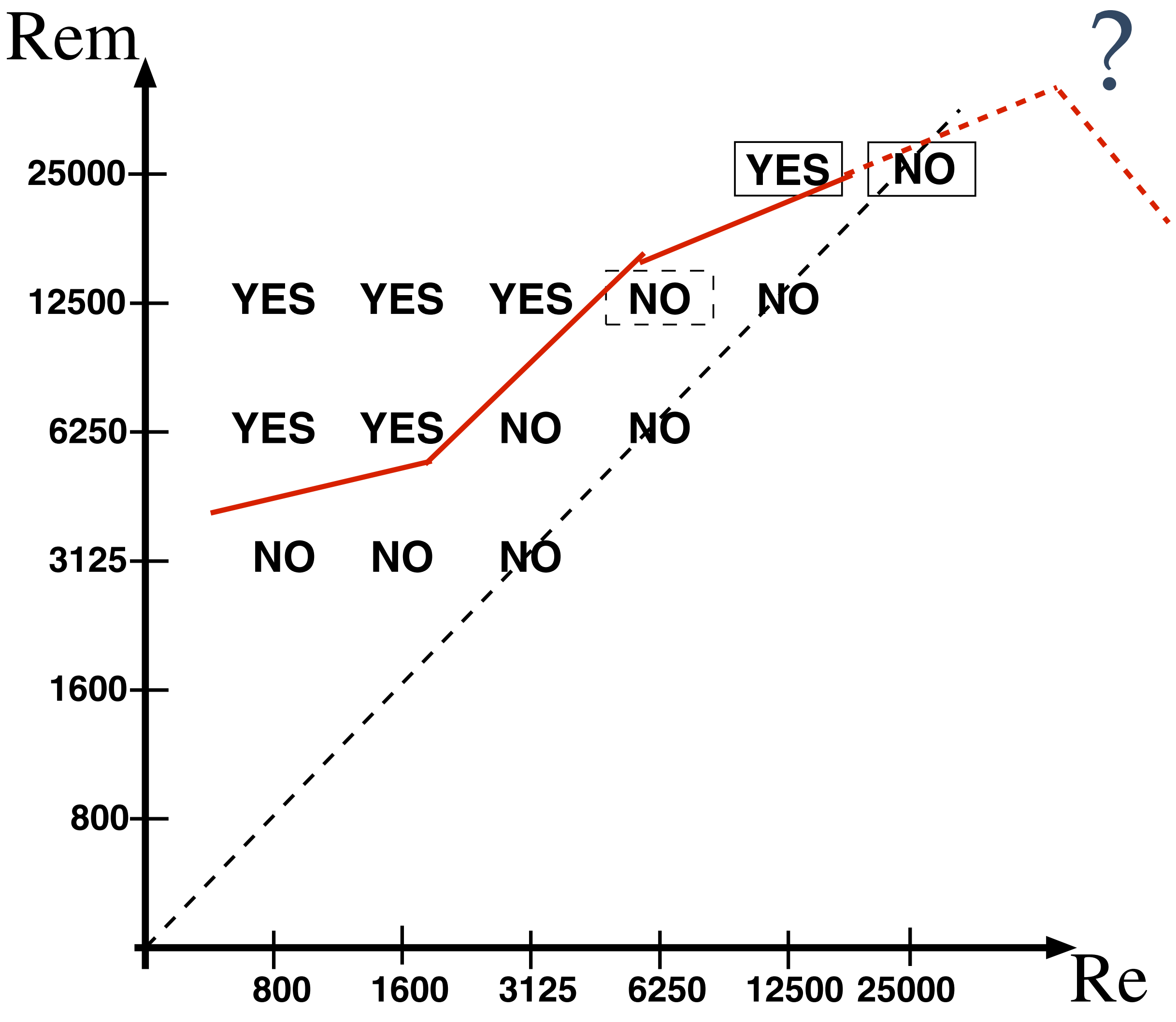
Zero mean field case =“MRI dynamo”

MRI Simulations

zero mean field shearing box=dynamo

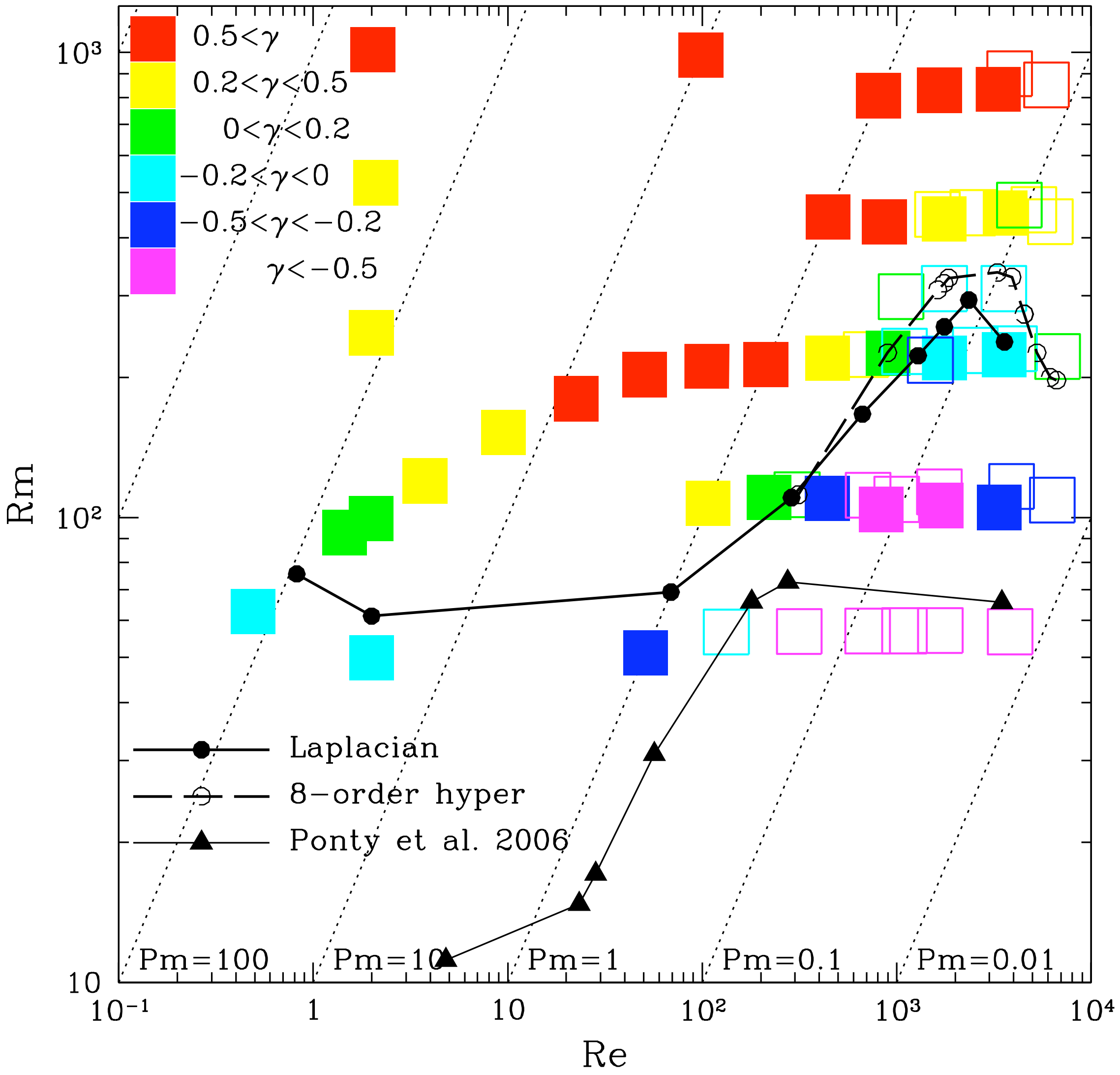
Zero net flux MRI

[Fromang+ 2007]



Small scale dynamo

[Schekochihin+ 2006]



Turbulent resistivity effect ? [Riols+2015]

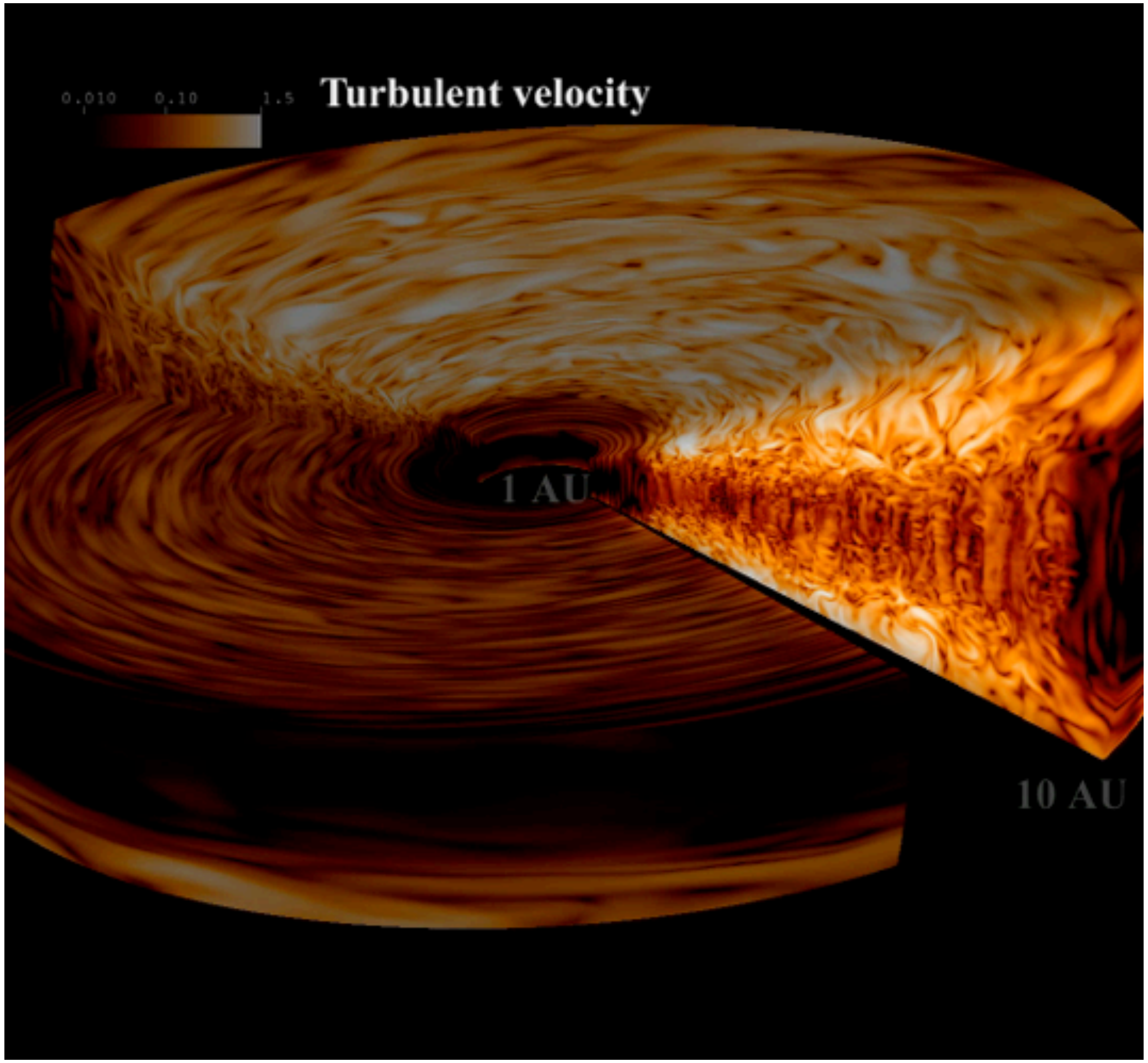
See also J. Walker's talk on Thursday

MRI Simulations
Global simulations

Global simulations are consistent with box simulations *in the same conditions*

$$\alpha \sim 10^{-3}\text{—}10^{-2}$$

[Hawley+ (1995) ; Fromang & Nelson (2006) ; Sorathia+ (2012)]



[Flock+ 2011]

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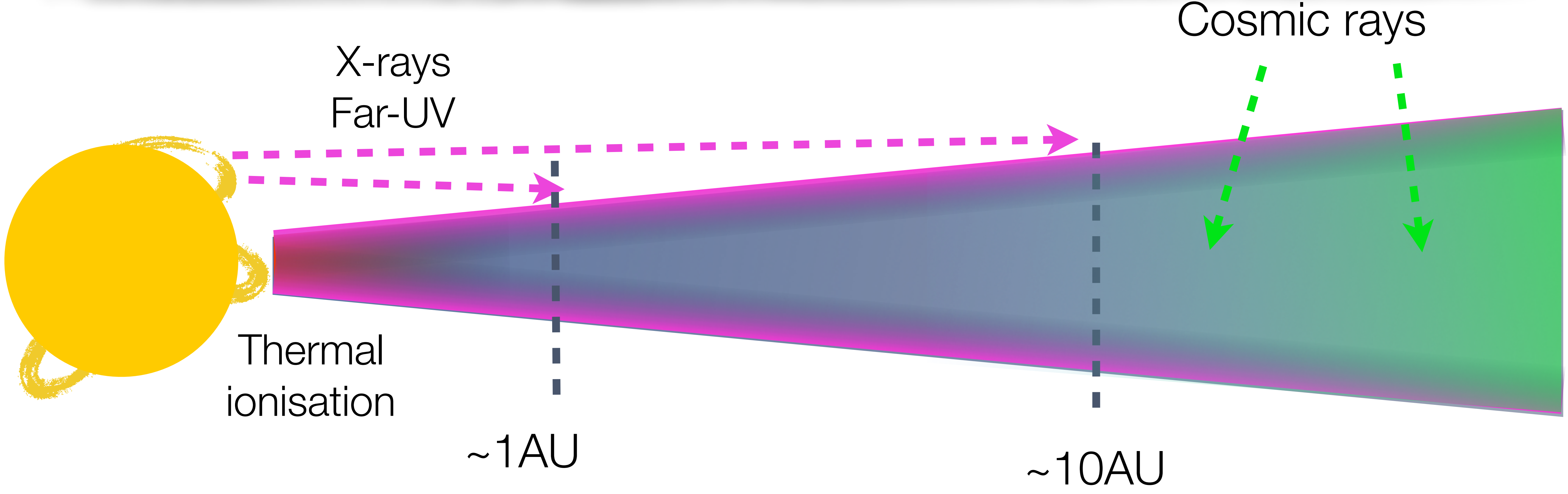
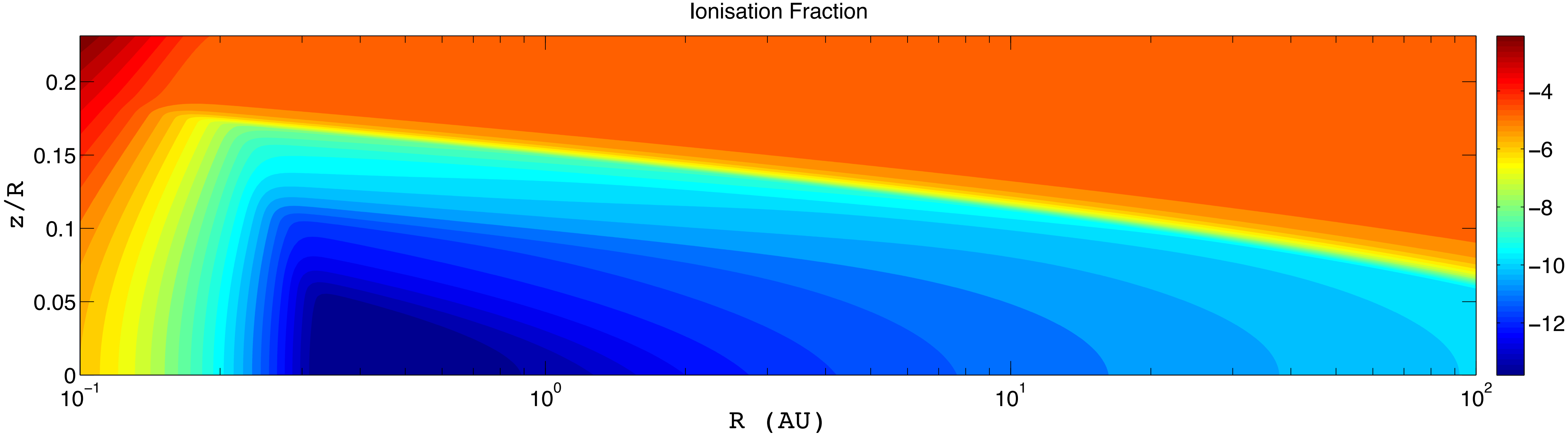
The MRI in protoplanetary discs

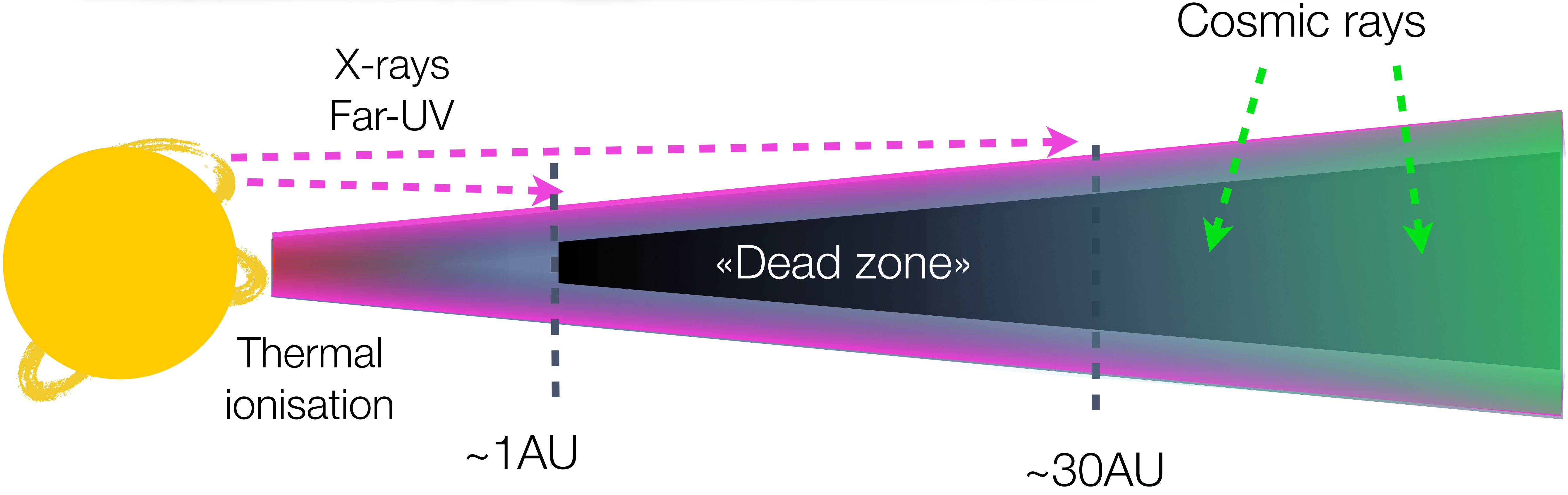
Ionisation sources in protoplanetary discs





Protoplanetary disc plasmas are dominated by neutrals

Dead zone in protoplanetary discs



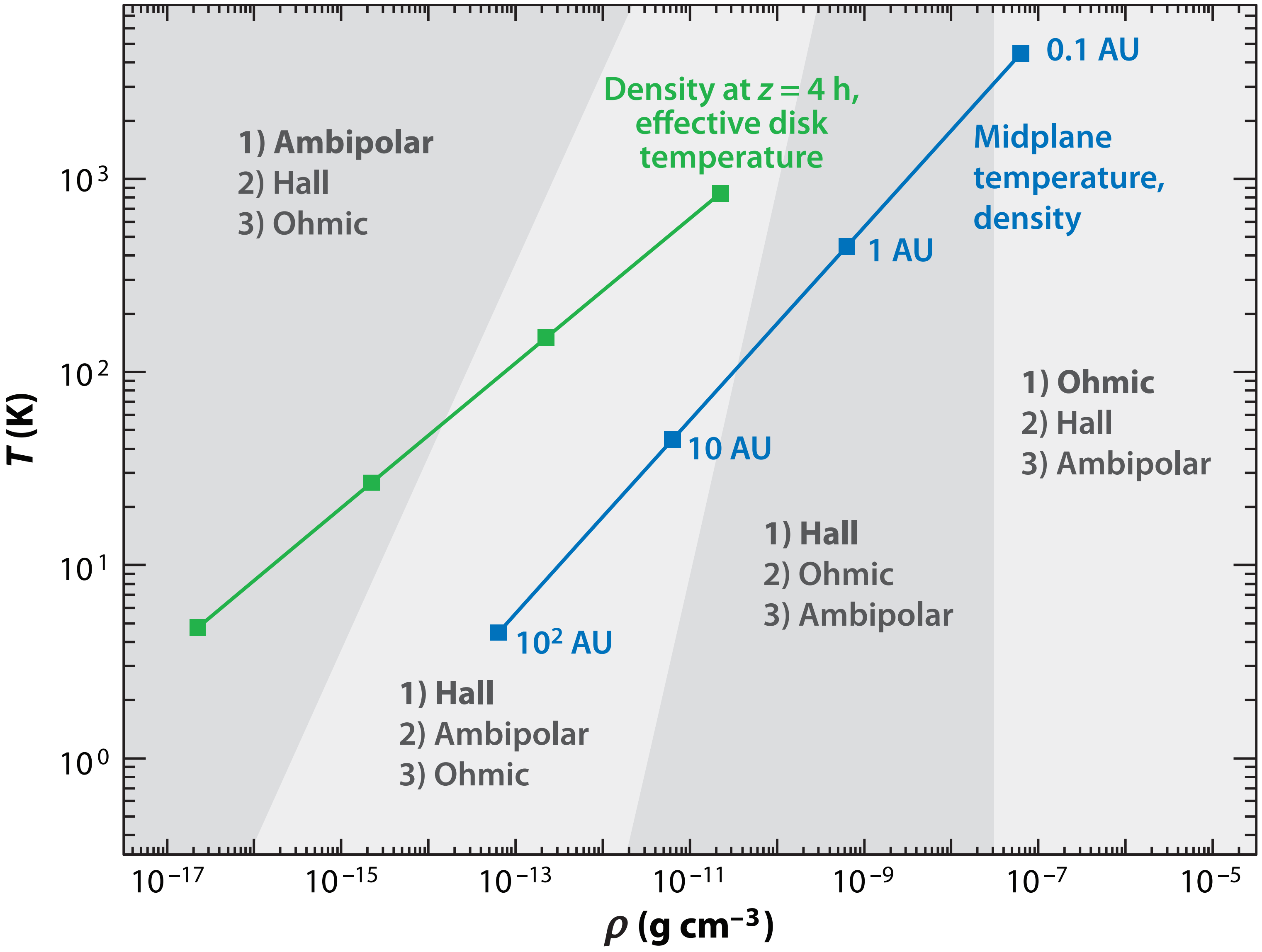
3 non ideal effects enter the scene

- Ohmic diffusion (collisions between electrons and neutrals)
- Ambipolar Diffusion (collisions between ions and neutrals)
- Hall Effect (drift between electrons and ions)

Amplitude of these effects depends strongly on location & chemistry

Non-ideal protoplanetary discs

[Kunz & Balbus 2003]
[Armitage 2011]



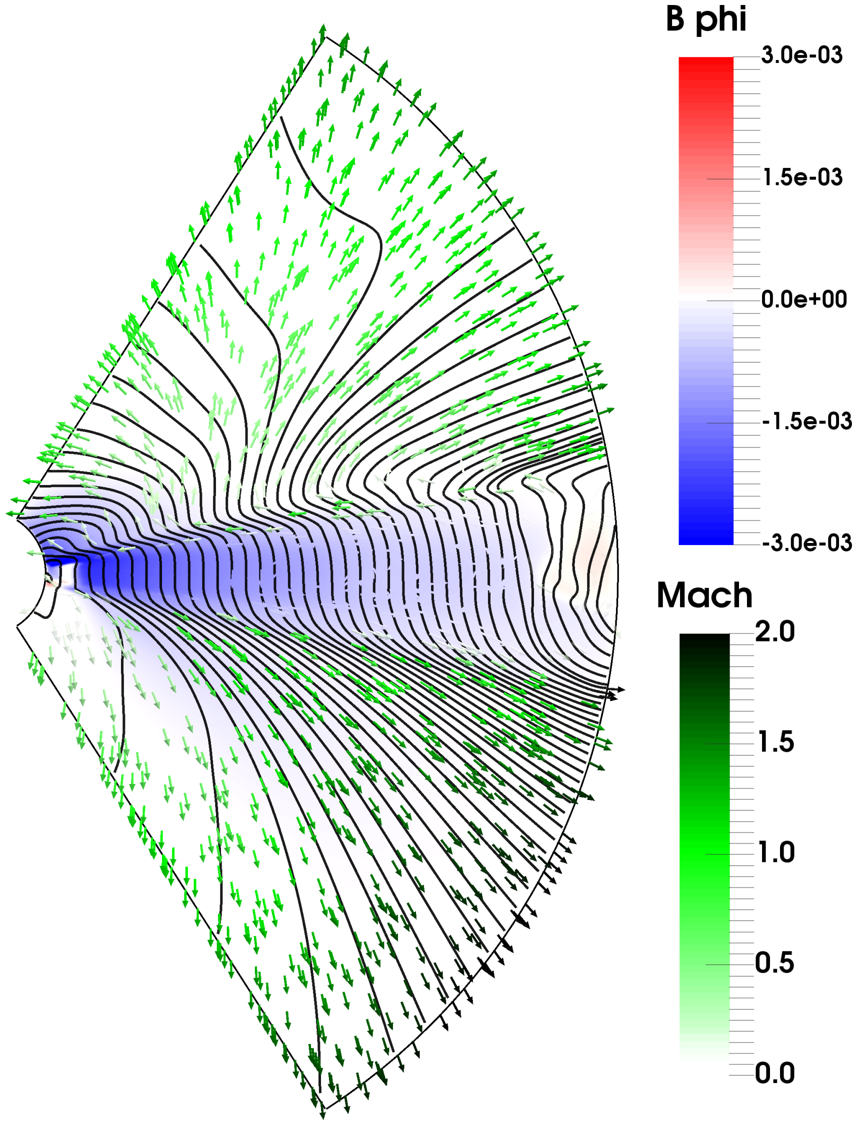
NB: strongly depends on grain size and metallically

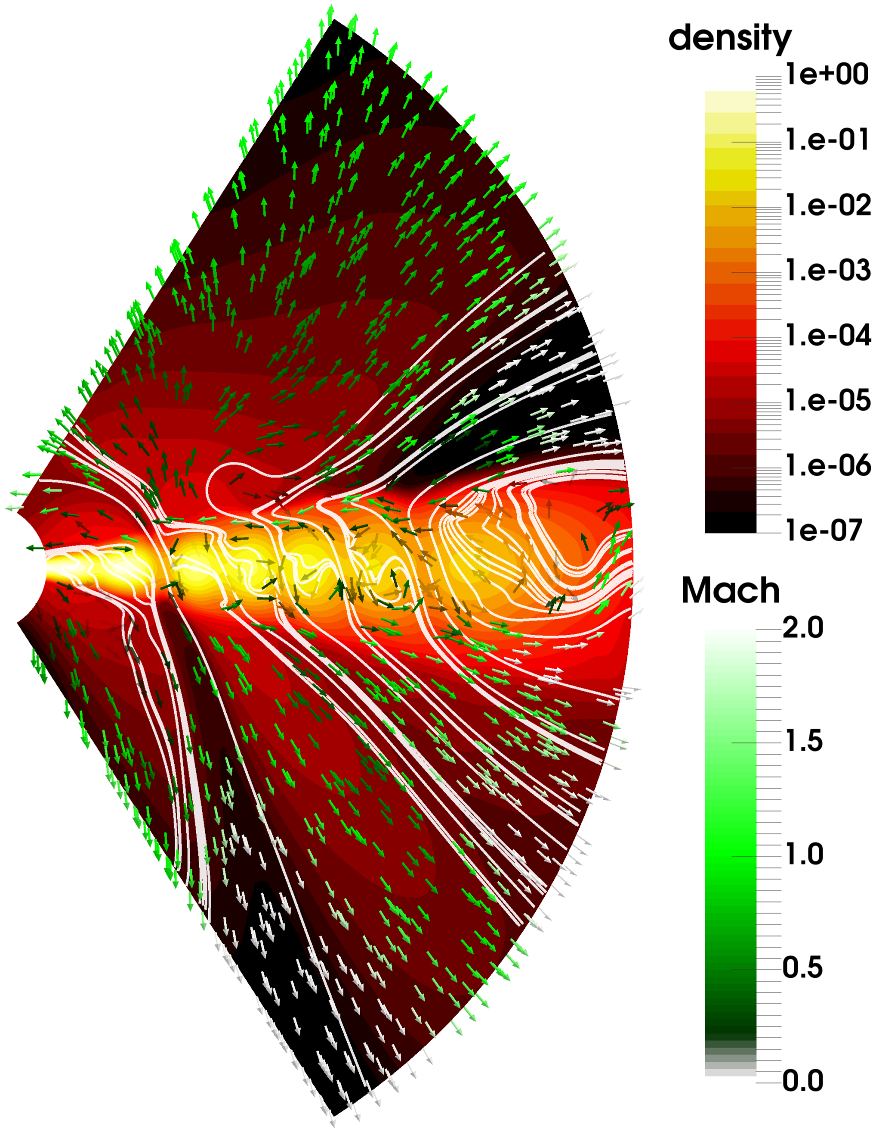
Hall effect dominates in most of the disc midplane
Ambipolar diffusion dominates in the upper layer

weak ionisation regions

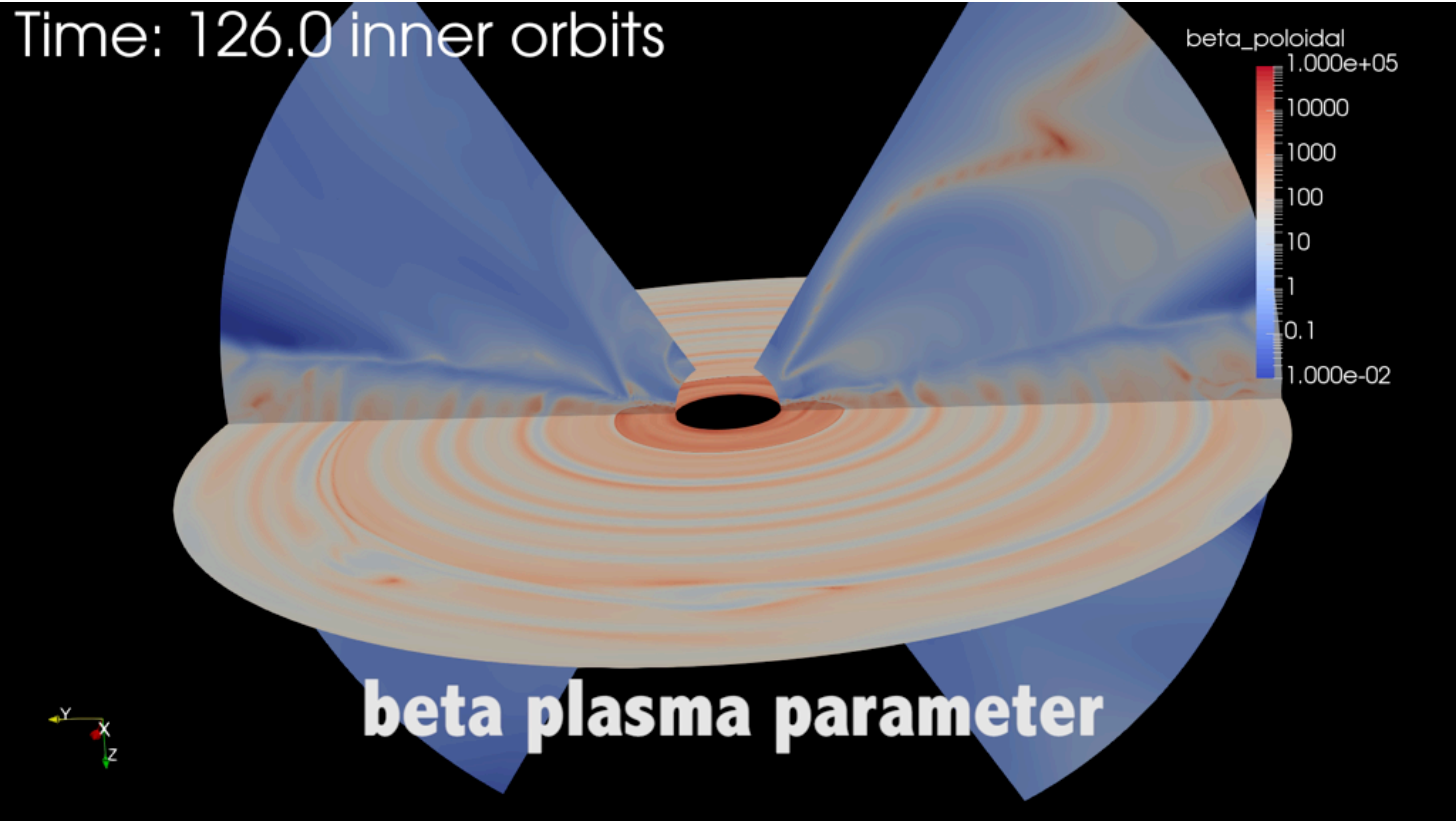
Wind-driven accretion

[Béthune+2017]





- Surface layer is sufficiently ionised to drive a wind
- Wind extract angular momentum and generates accretion
- Self organisation instead of turbulence in the midplane



[Béthune+2017]

Detecting the MRI in protoplanetary discs

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 of V_k and c_s

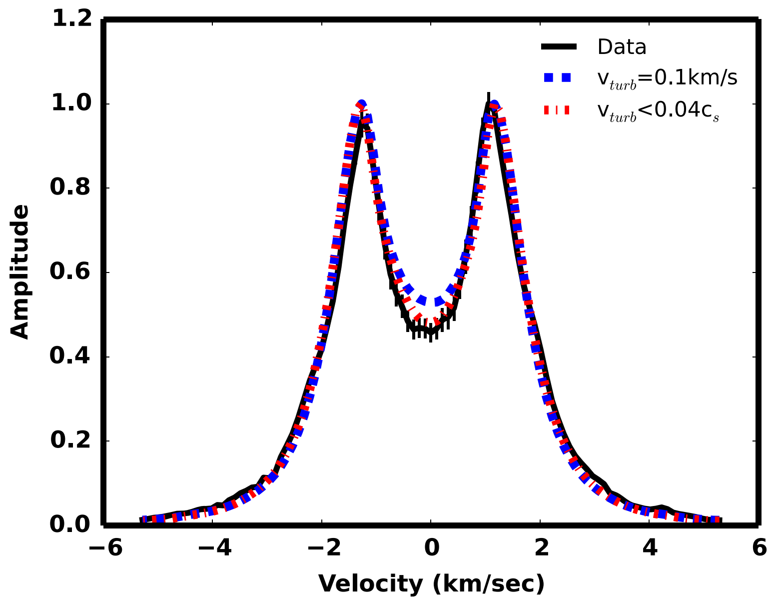


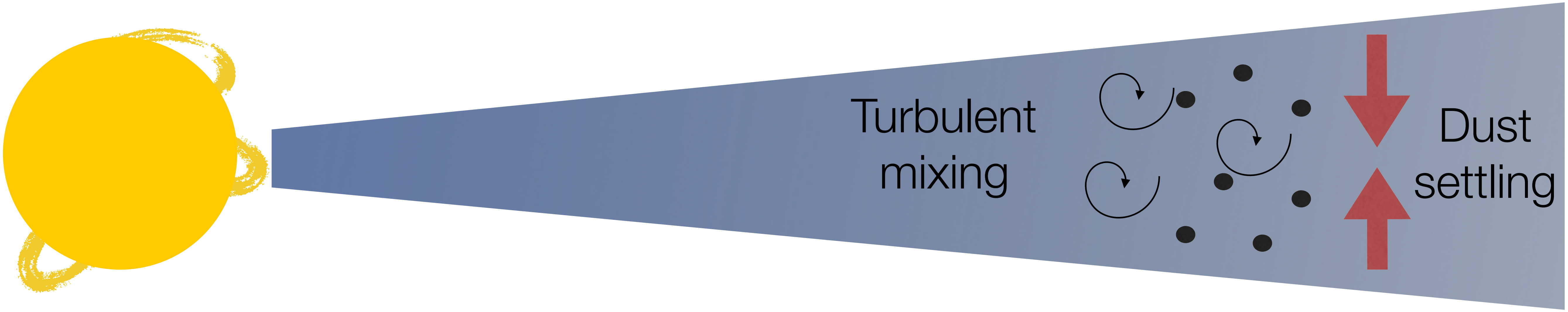
Figure 6. CO(3-2) high resolution spectra (black line) compared to the median model when turbulence is allowed to move toward very low values (red dotted–dashed lines) or when it is fixed at 0.1 km s^{-1} (blue dashed lines). All spectra have been normalized to their peak flux to better highlight the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

$$\alpha \lesssim 10^{-4}$$

Dust settling (I)

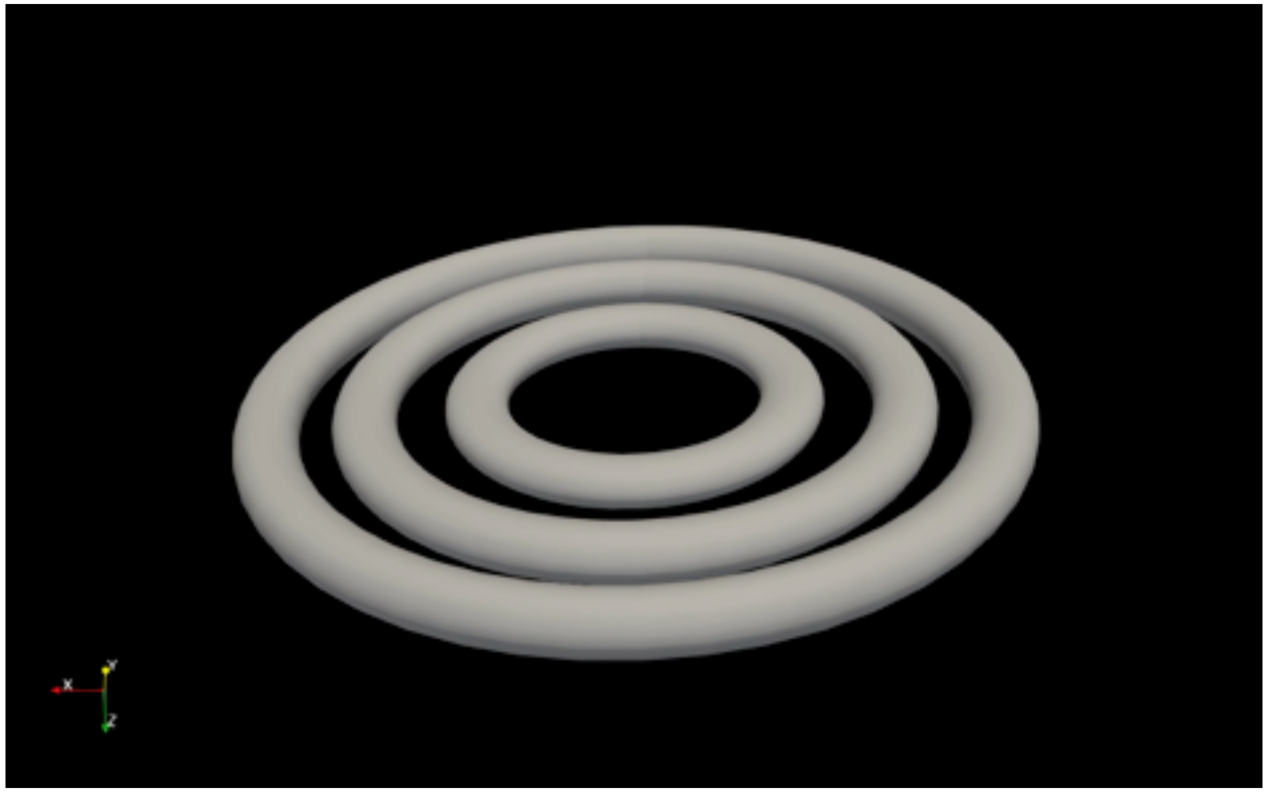


→ The thickness of the dust layer depends on the competition between settling and turbulent mixing

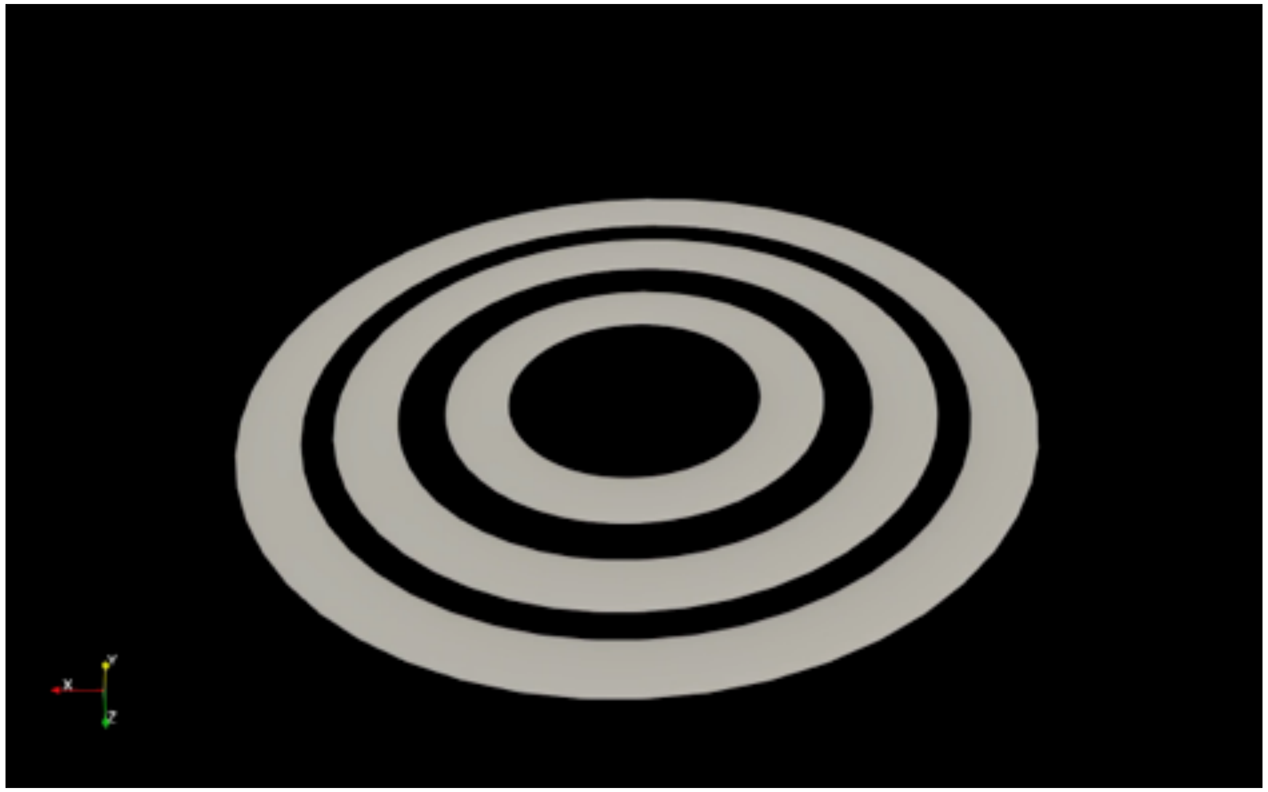
Dust settling (II)

Assume the disc is organised into rings

Thick dust disc



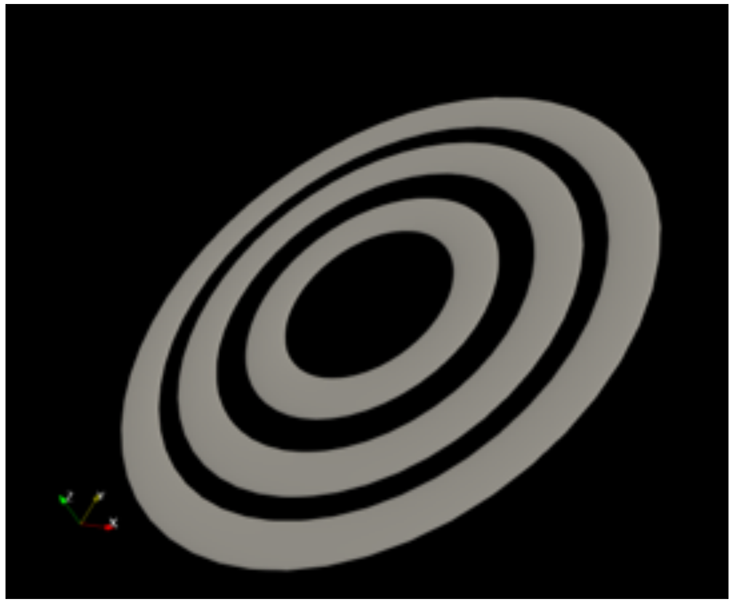
Thin dust disc

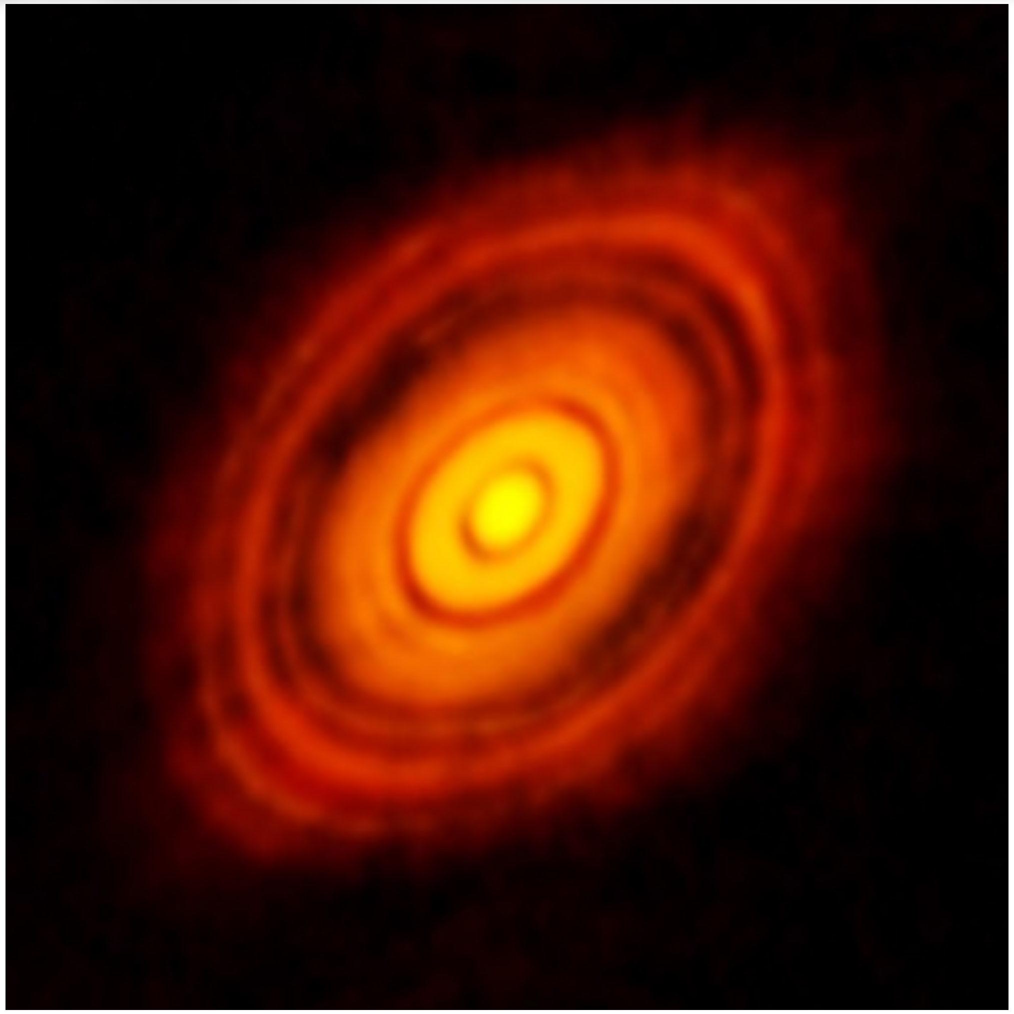


In a thick disc seen inclined, the dark bands are strongly non-axisymmetric

Dust settling (III)

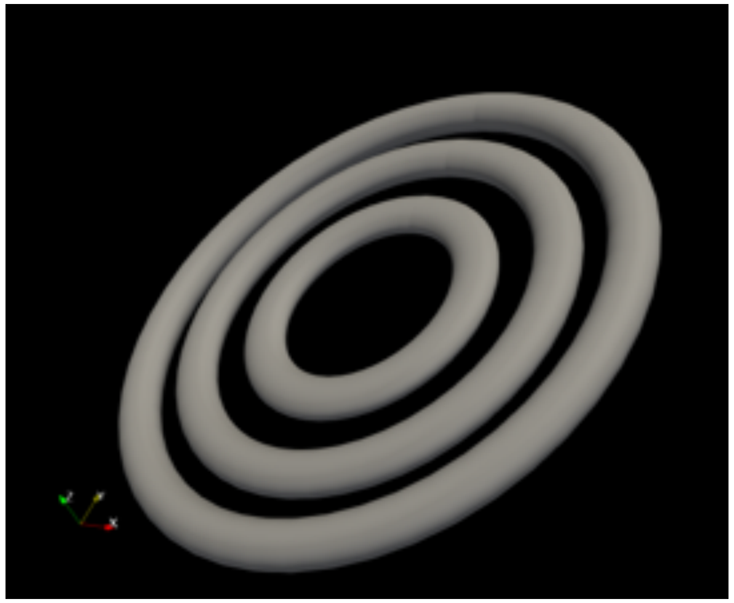
Thin disc model





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 (H/R gas=0.1) → low level of turbulence

The end

thank you for your attention