Disc Formation in Turbulent Cloud Cores

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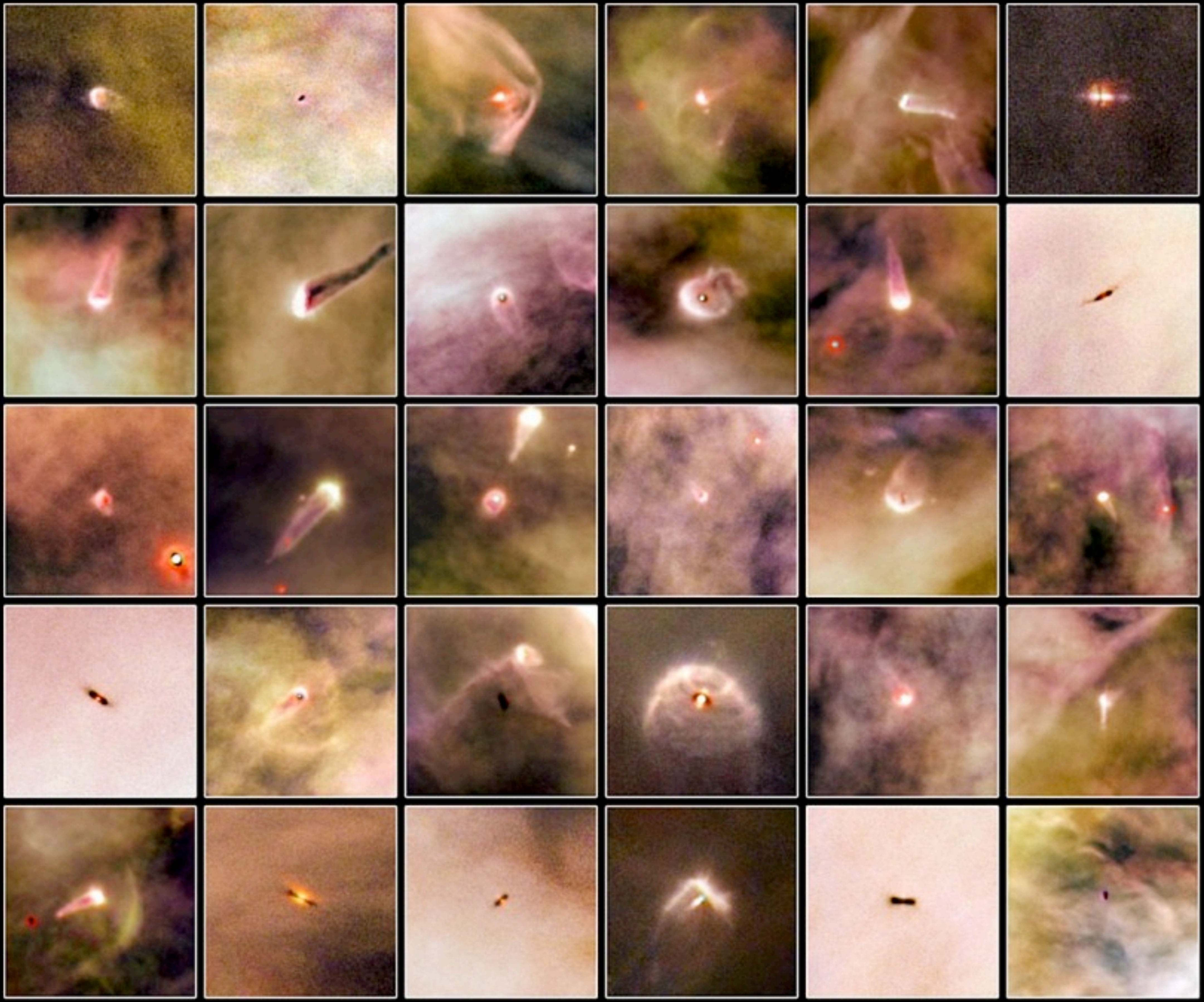
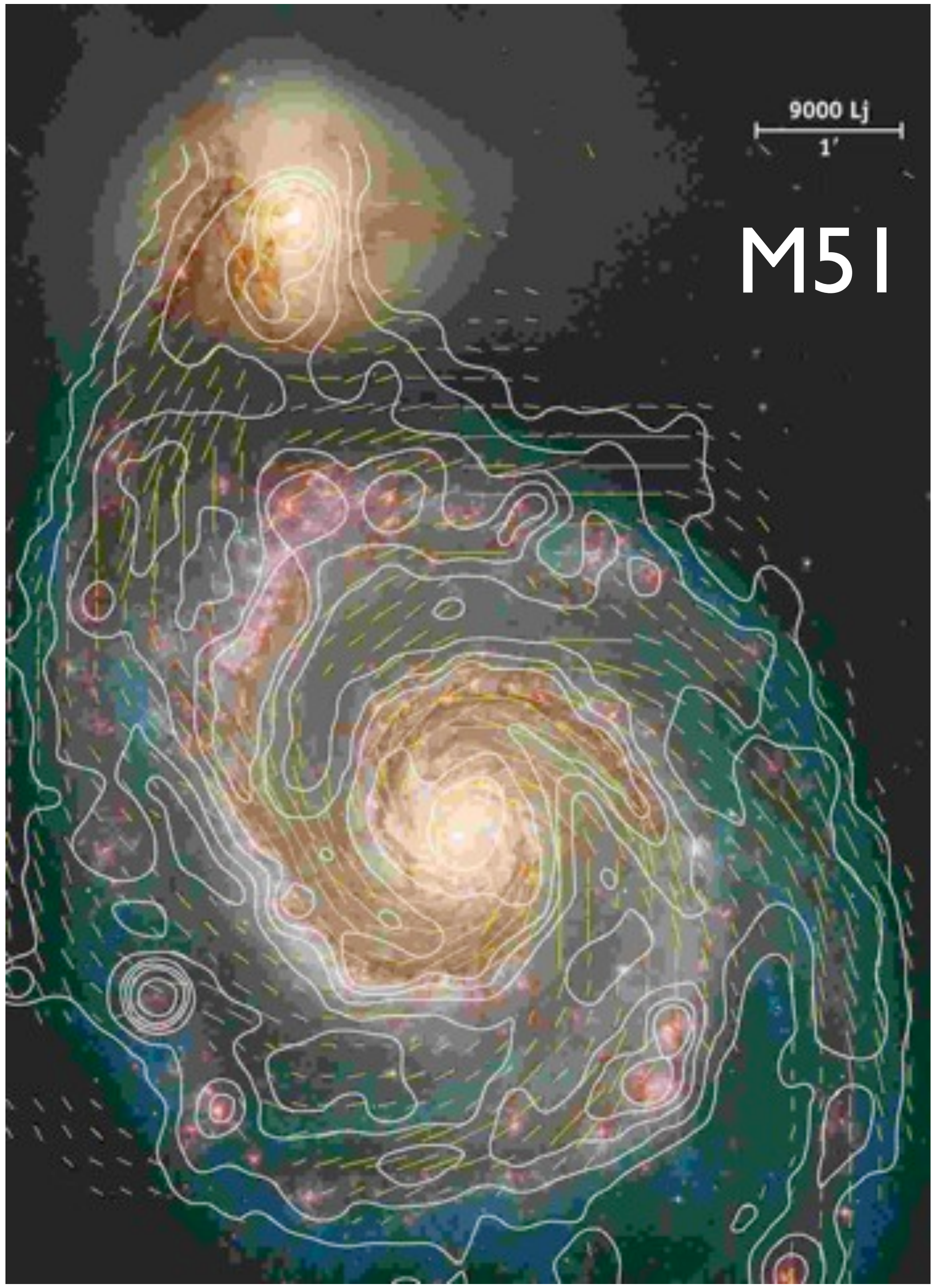


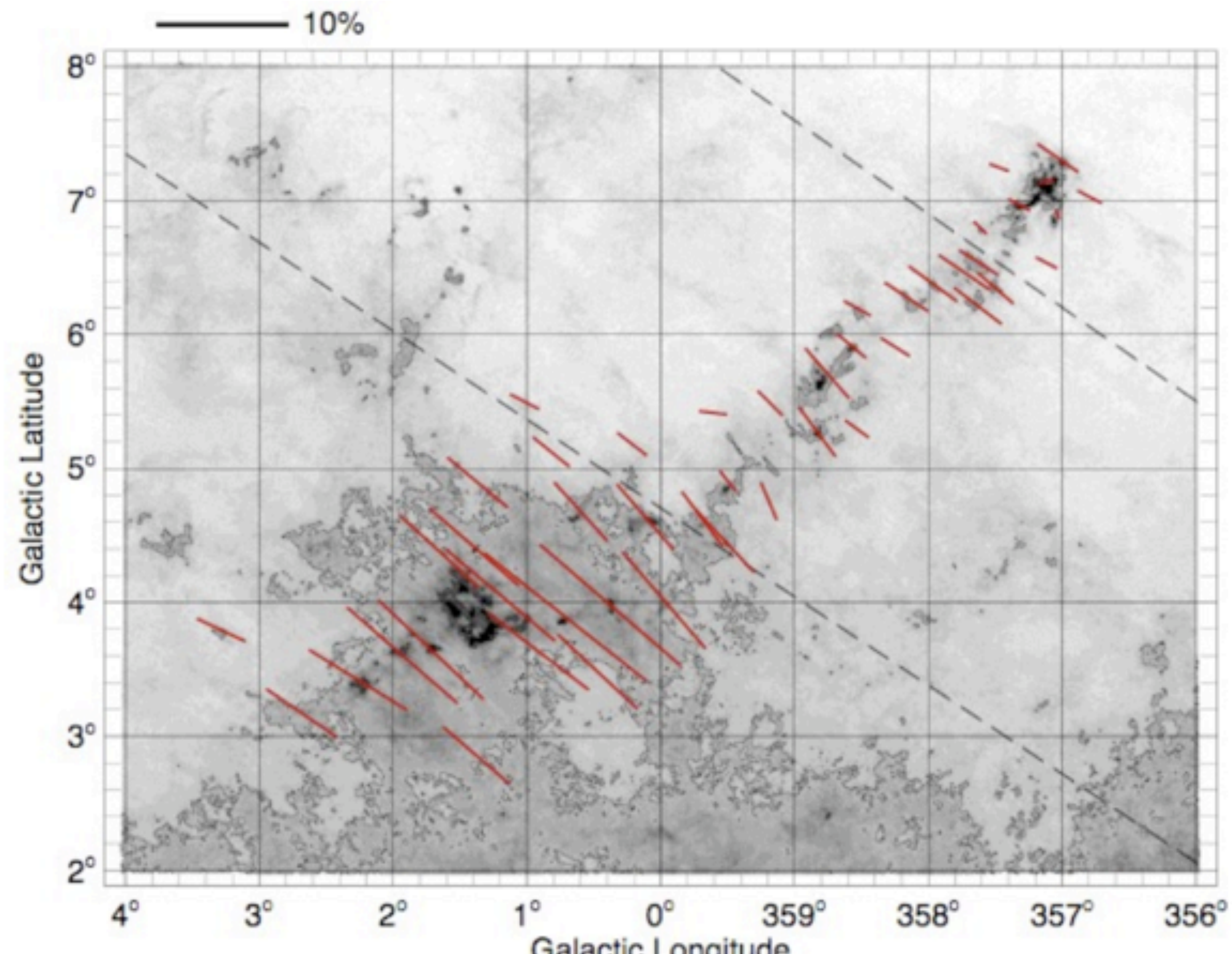
Proplyds (protoplanetary discs) in Orion, *HST*

Magnetic Fields



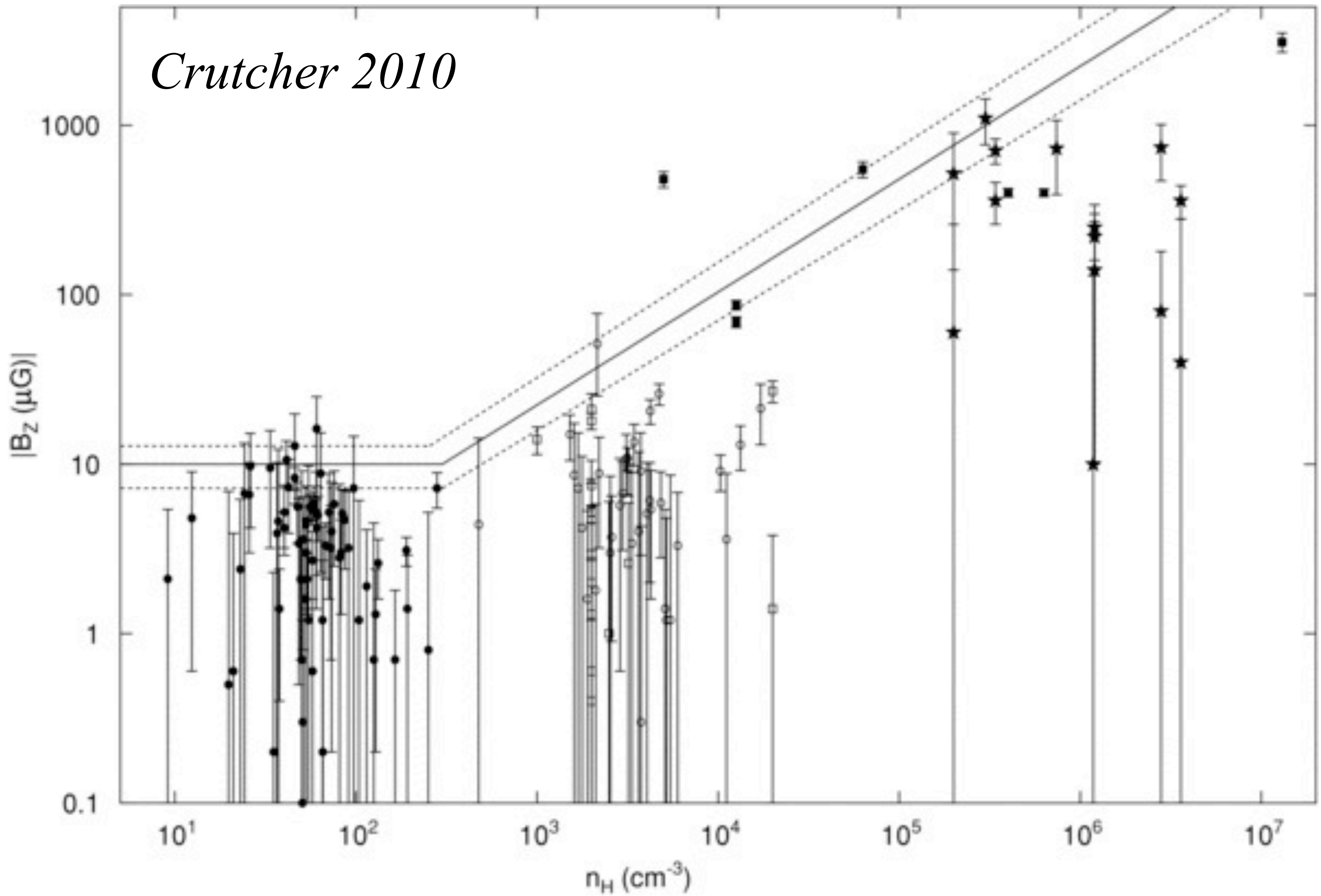
galactic B-fields (e.g. *R.Beck 2001*)
large scale component: $\sim 4\mu G$
total field strength: $\sim 10\mu G$

The ISM is permeated with magnetic fields



magnetic polarization measurements in the Pipe nebula
F.O.Alves, Franco, Girart 2008

Magnetic Fields

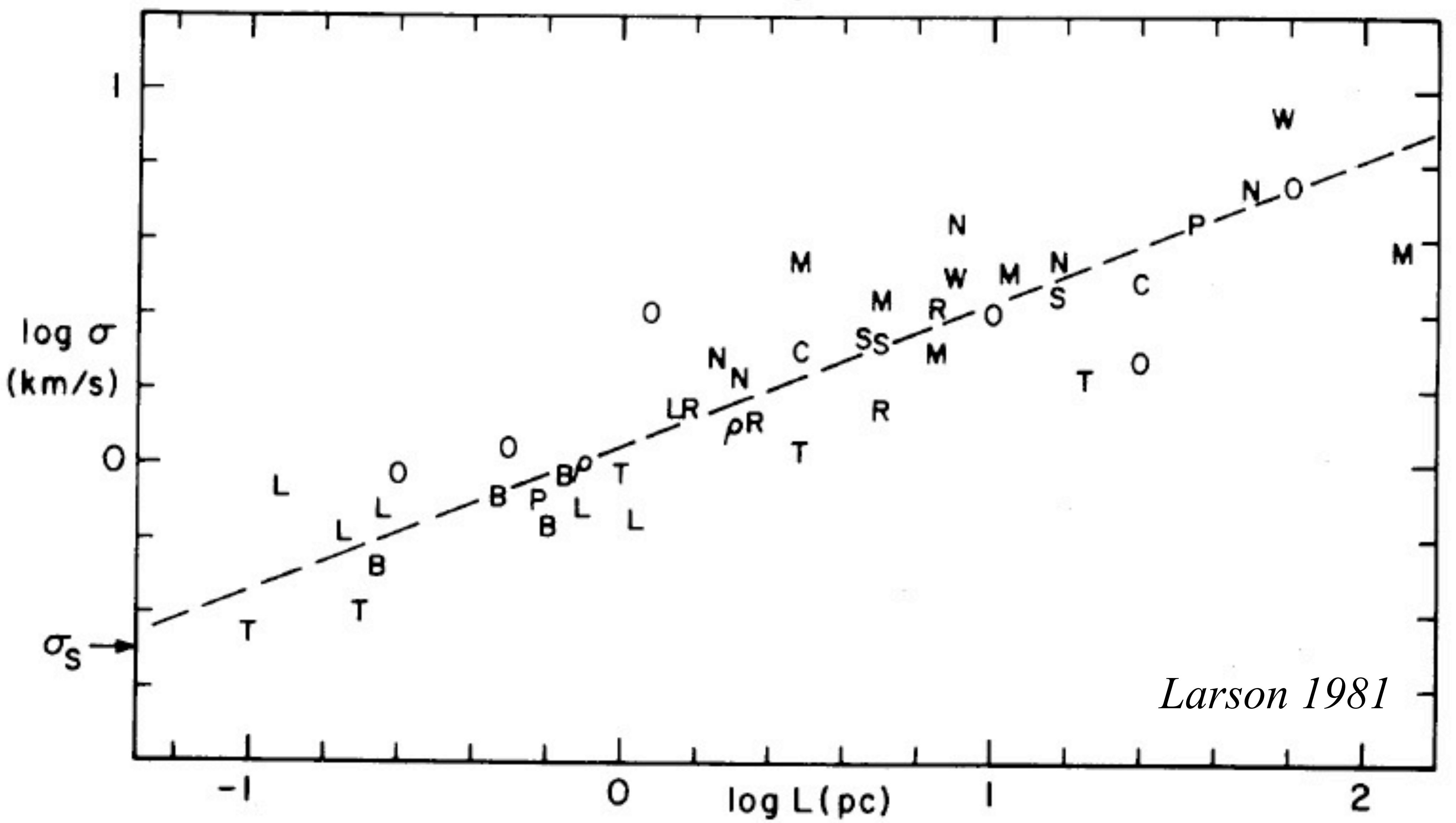


⟹ mass-to-flux ratio for pre-stellar cores:

$$\mu = 2 \ldots 5$$

Turbulence

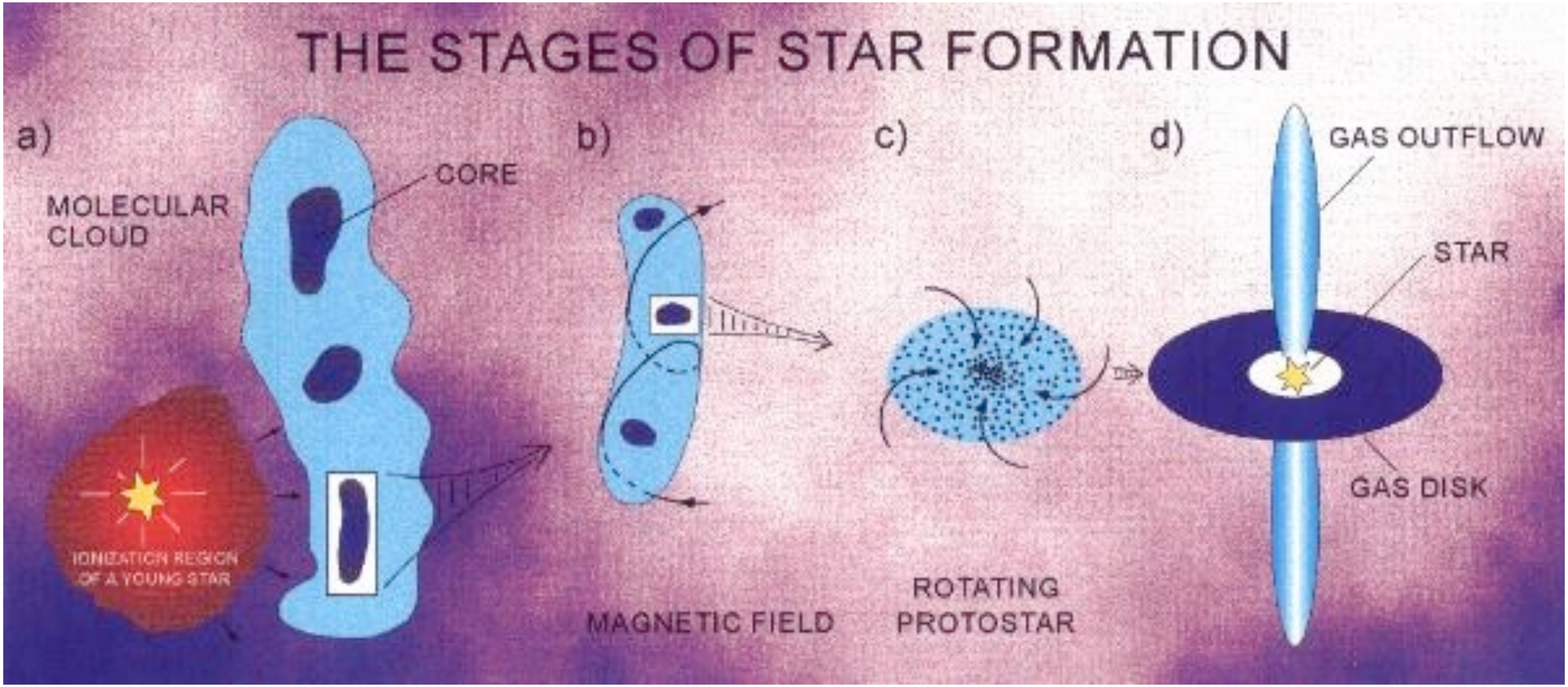
Larson relation: Turbulence in Molecular Clouds



⇒ supersonic high mass cores

⇒ sub-sonic low mass cores (R < 0.1 pc)

Star Formation: Early-type discs



Initial angular momentum of cores

- observational evidence for rotating cores ($R \sim 0.1$ pc)
  e.g. *Goodman et al., 1993*:

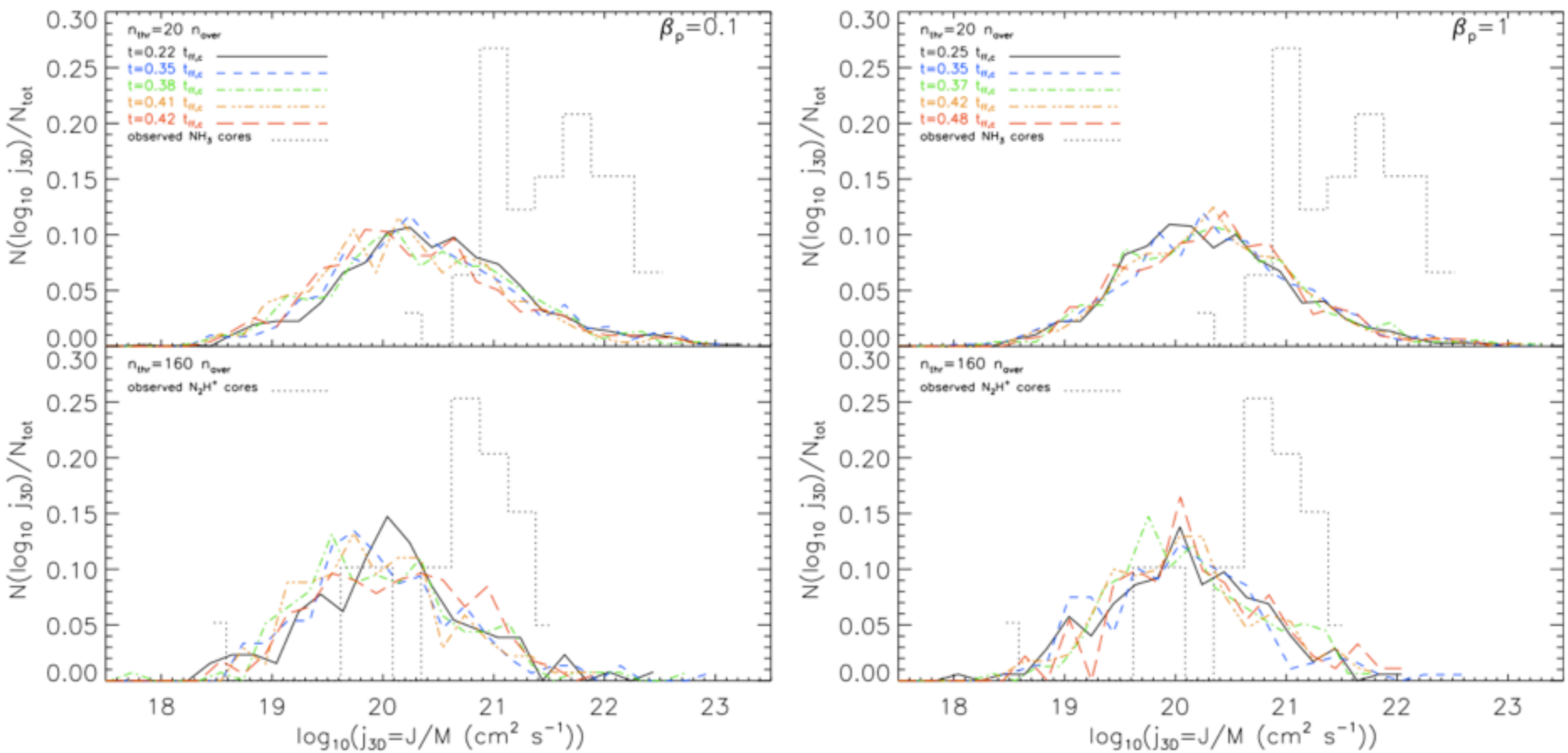
$$\Omega \sim 10^{-14} - 10^{-13}\ \mathrm{s}^{-1}$$
$$\Longrightarrow j \sim 10^{21}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$$
$$\Longrightarrow \beta \sim 0.03 \propto (t_{ff}\,\Omega)^2$$

  but: large scatter

- compare to galactic shear flow: $\Omega \sim 10^{-16} - 10^{-15}\ \mathrm{s}^{-1}$
  $\Longrightarrow$ generated by turbulence (*Barranco & Goodman, 1998*)

Initial angular momentum of cores?

- Dib et al. 2010:
  synthetic observations from simulations overestimate true values by a factor of **8−10**



Angular momentum

- compare to solar system:
  - $j \sim 3\times10^{20}$ cm^2 s^{-1} @ R = 50 AU
  - $j \sim 4\times10^{19}$ cm^2 s^{-1} @ R = 1 AU
  - Sun: $j \sim 10^{16}$ cm^2 s^{-1}

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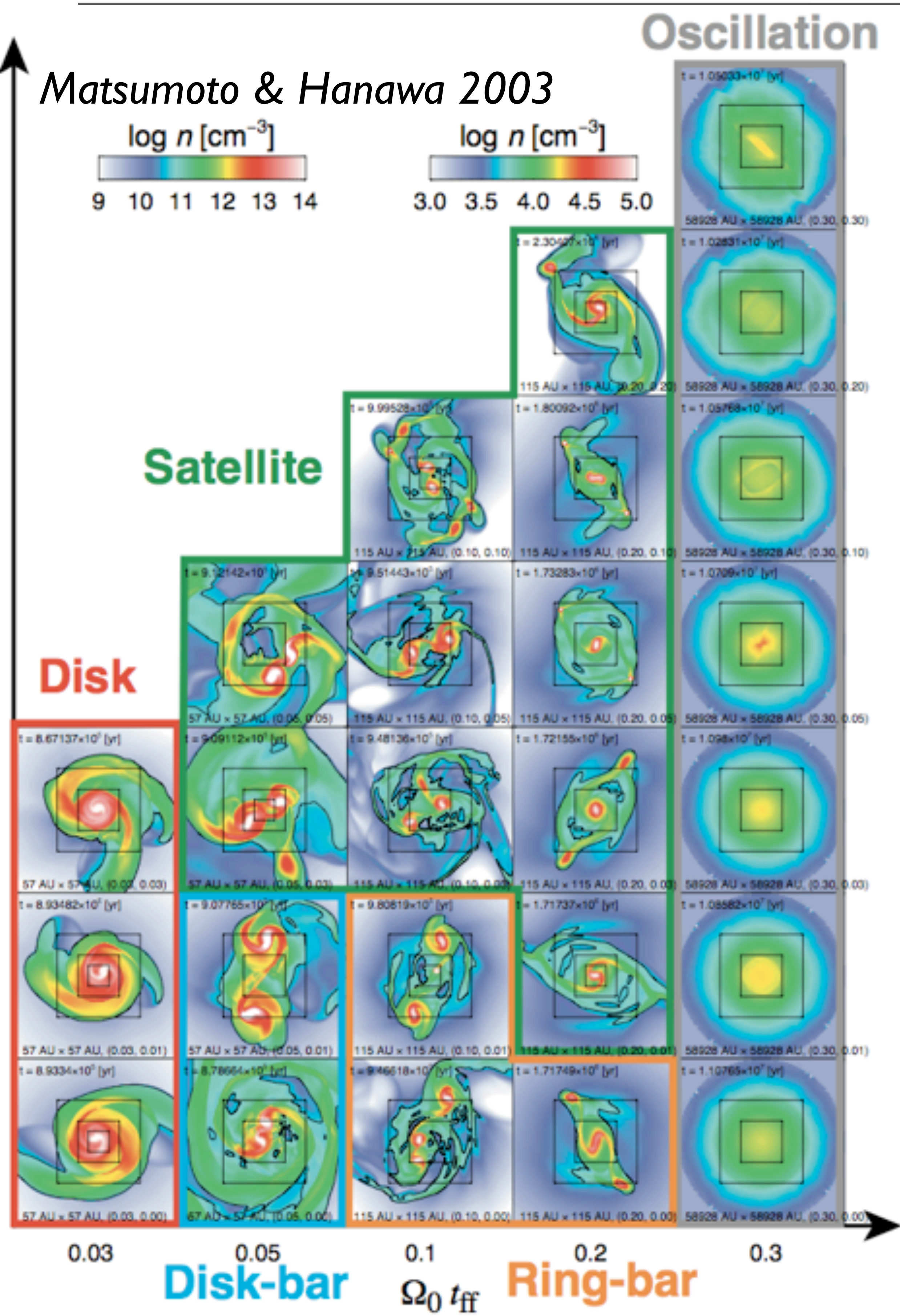
$\Longrightarrow$ angular momentum transport in the disc needed:

angular momentum problem I

Angular Momentum Problem I



The pure hydro cases

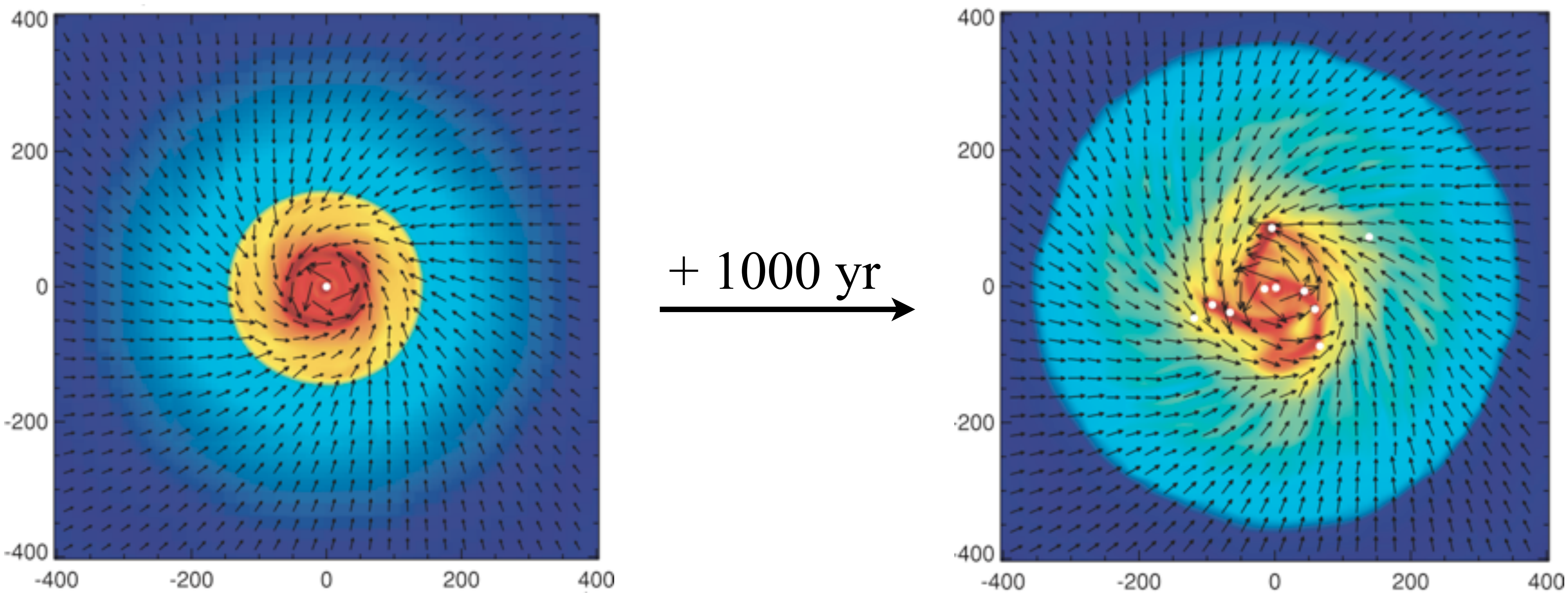
(e.g. Burkert & Bodenheimer 1993, Matumoto & Hanawa 2003, Krumholz et al. 2007, Stamatellos & Whitworth 2009, ...)

$\Longrightarrow$ efficient transport of angular momentum by **gravitational torques**

Angular Momentum Problem I

Collapse of **magnetised**, rotating cloud cores

- weak magnetic fields: $\mu > 10$

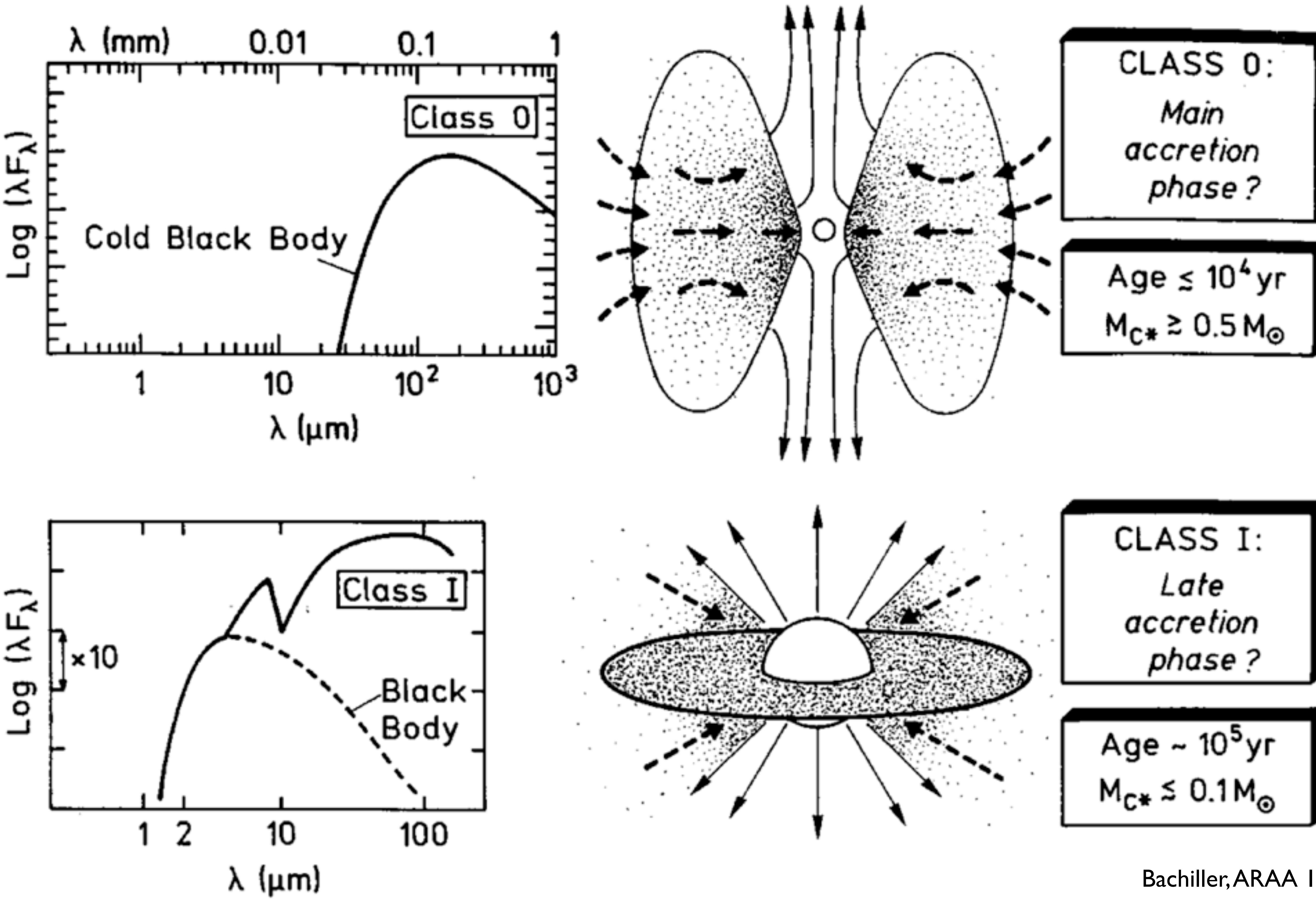


Seifried et al. 2011

$\Longrightarrow$ efficient transport of angular momentum mainly by gravitational torques / fragmenation

$\Longrightarrow$ disc formation & high accretion rates $\sim 10^{-4}\ M_{\odot}/\mathrm{yr}$

Star Formation: Early-type discs



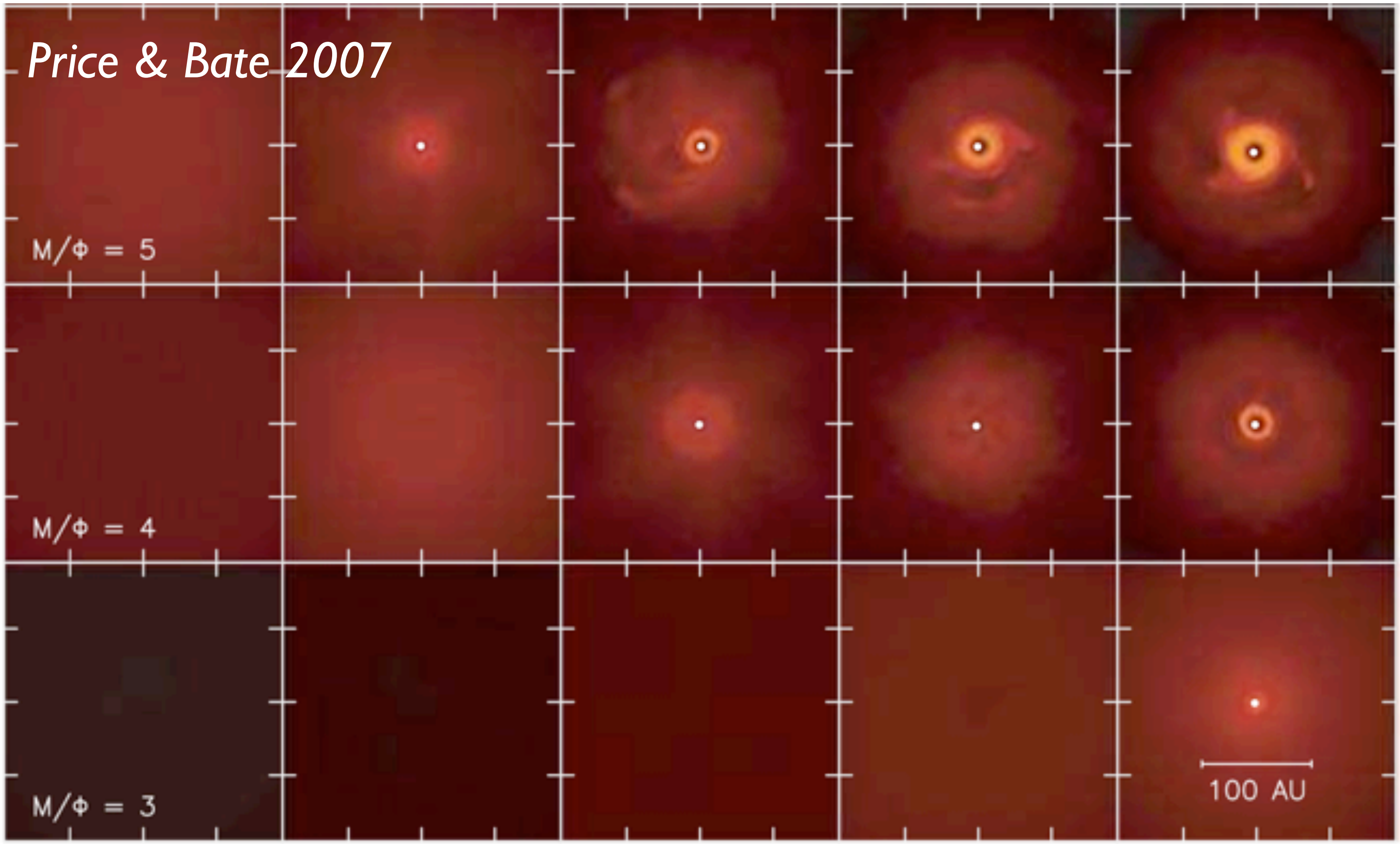
Bachiller, ARAA 1996

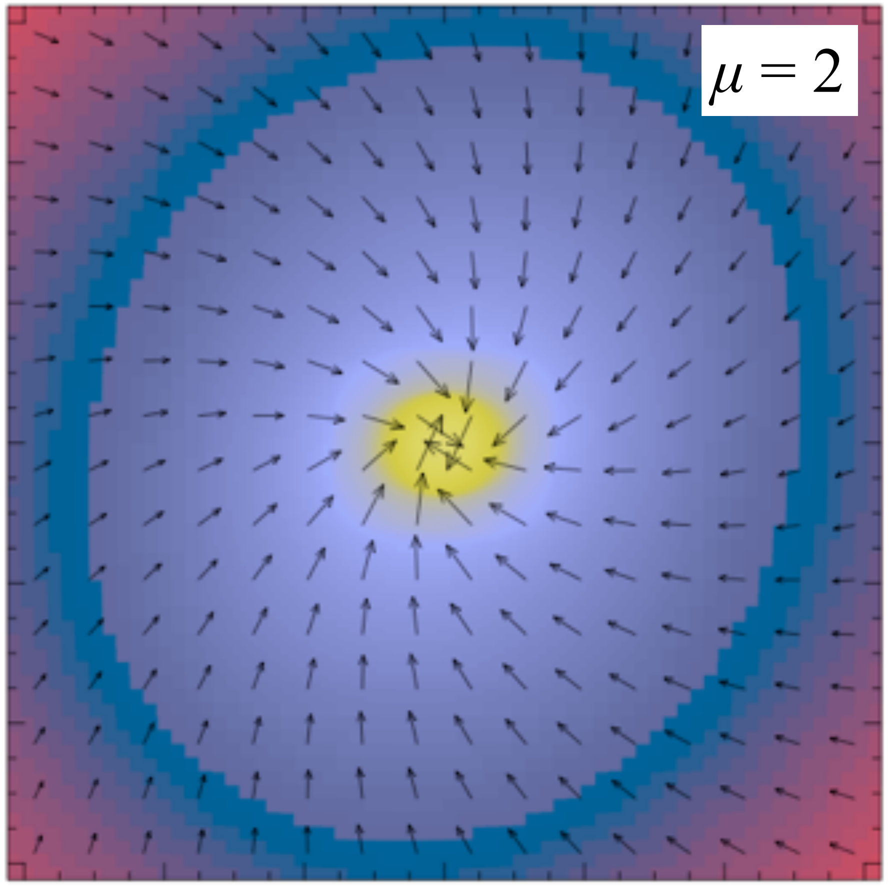
Star Formation: Early-type discs

Collapse of magnetised, rotating cloud cores

- **stronger** magnetic fields: μ < 5 in agreement with observations

(e.g. *Crutcher et al. 2010*)





Hennebelle & Teyssier 2008, ...

⟹ ***too*** efficient magnetic braking

⟹ ***no*** disc formation

Star Formation: Early-type discs

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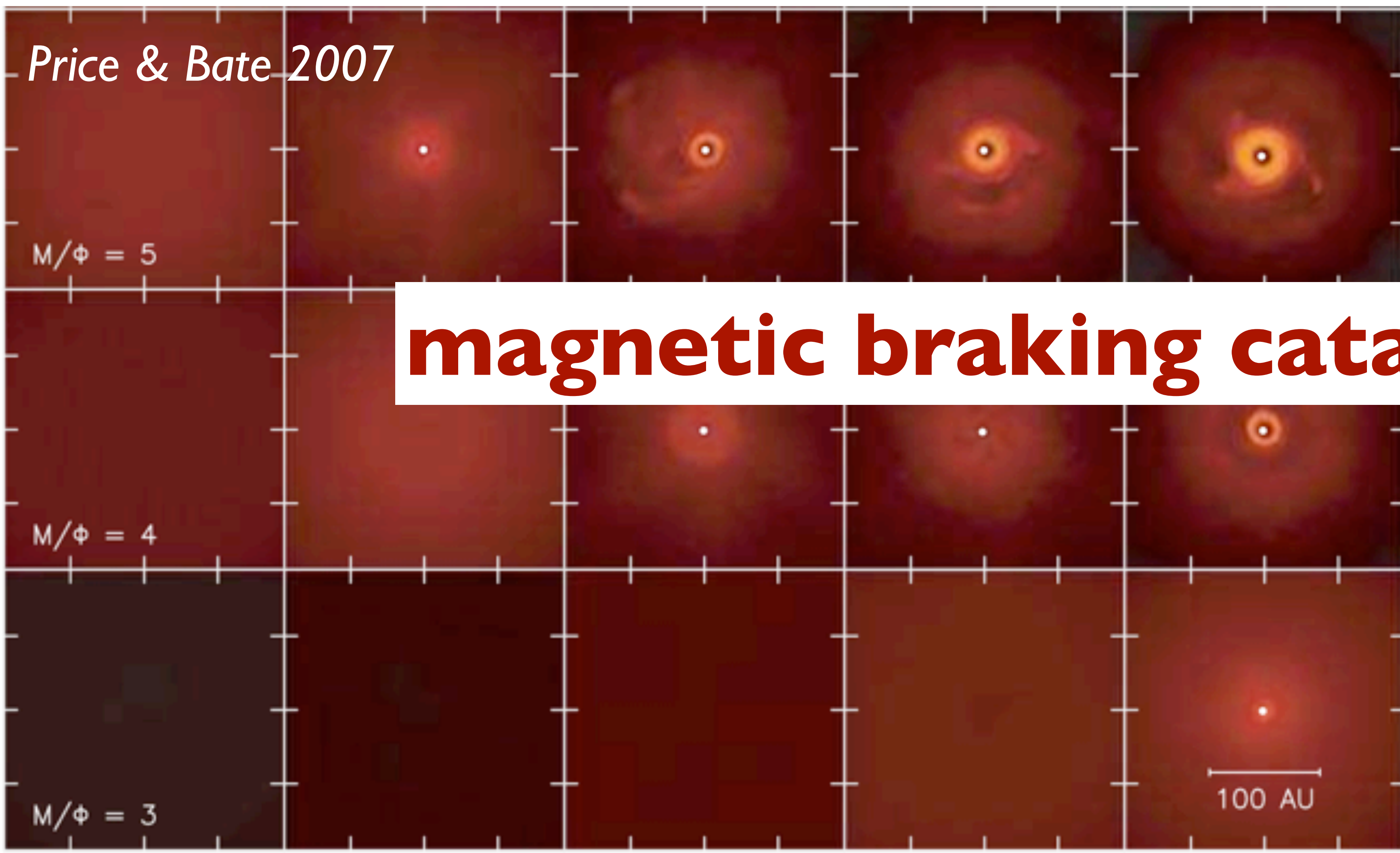
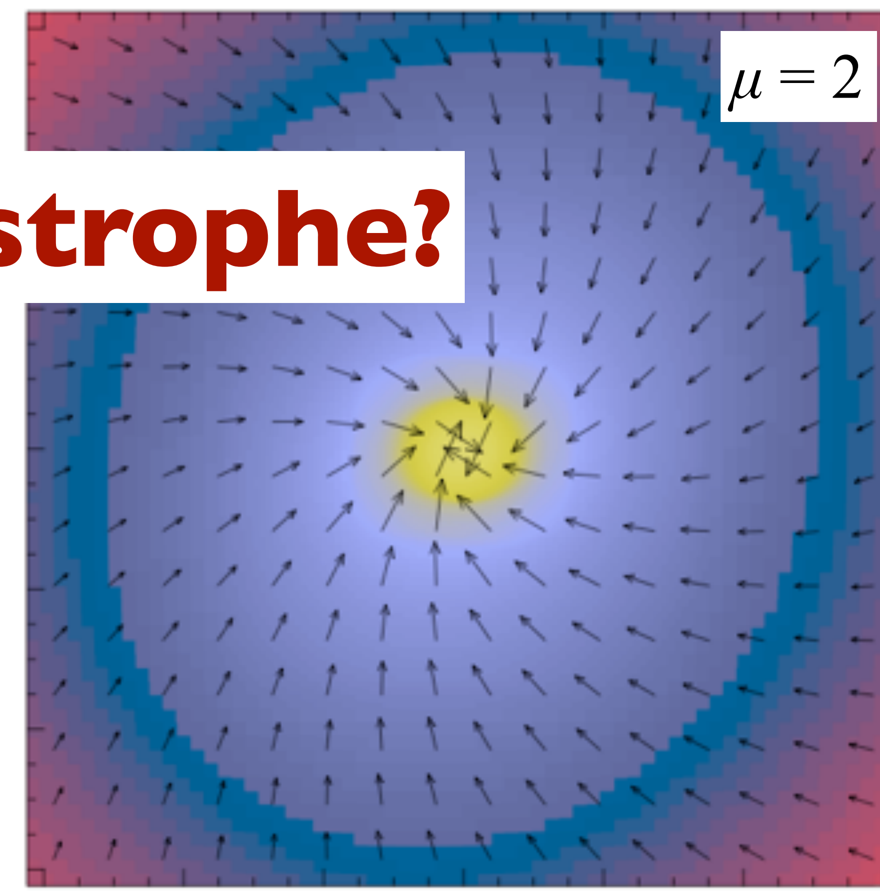


magnetic braking catastrophe?



Hennebelle & Teyssier 2008, ...

$\Longrightarrow$ ***too*** efficient magnetic braking

$\Longrightarrow$ ***no*** disc formation

Angular Momentum Problem II

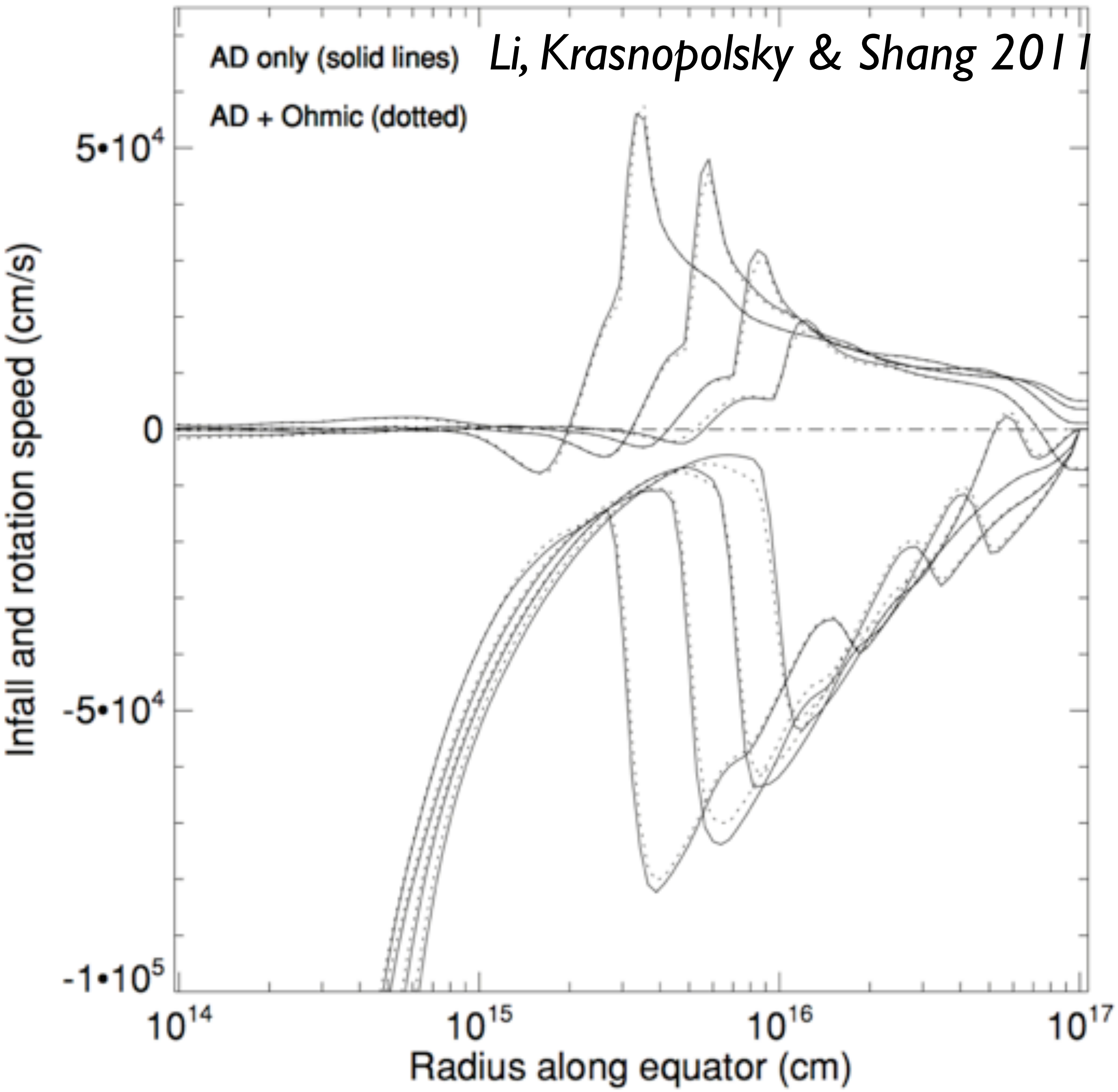
Solutions?

- flux loss by:
  - Ohmic resistivity (*Dapp & Basu 2011, Krasnopolsky et al. 2010*)
  - ambipolar Diffusion (*Duffin & Pudritz 2008, Li et al. 2011*)
  - turbulent reconnection (*Lazarian & Vishniac 1999, Santos-Lima et al. 2012*)
- Hall effect (*Krasnopolsky et al. 2011*)
- Outflows from small discs

Angular Momentum Problem II

⟹ Non-ideal MHD and reconnection active only at small scales/high density

⟹ not effective enough to reduce magnetic braking



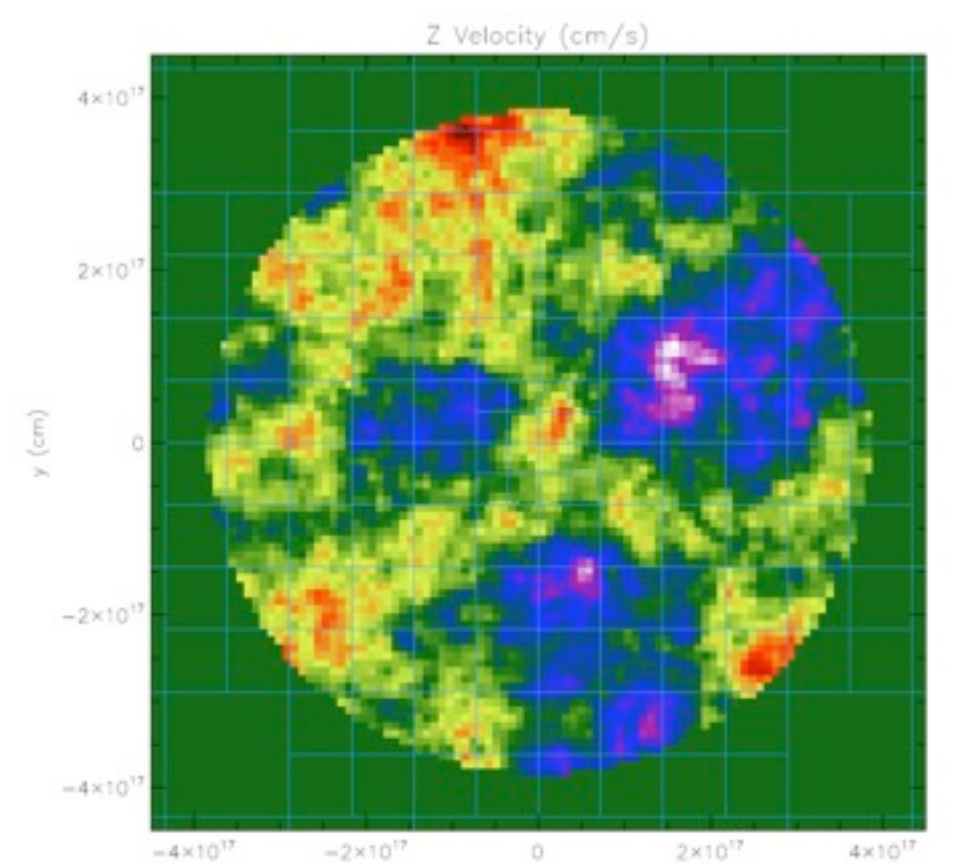
⟹ *Li, Krasnopolsky & Shang 2011:*
"The problem of catastrophic magnetic braking that prevents disk formation in dense cores magnetized to realistic levels remains unresolved"

Parameter study of collapsing cores

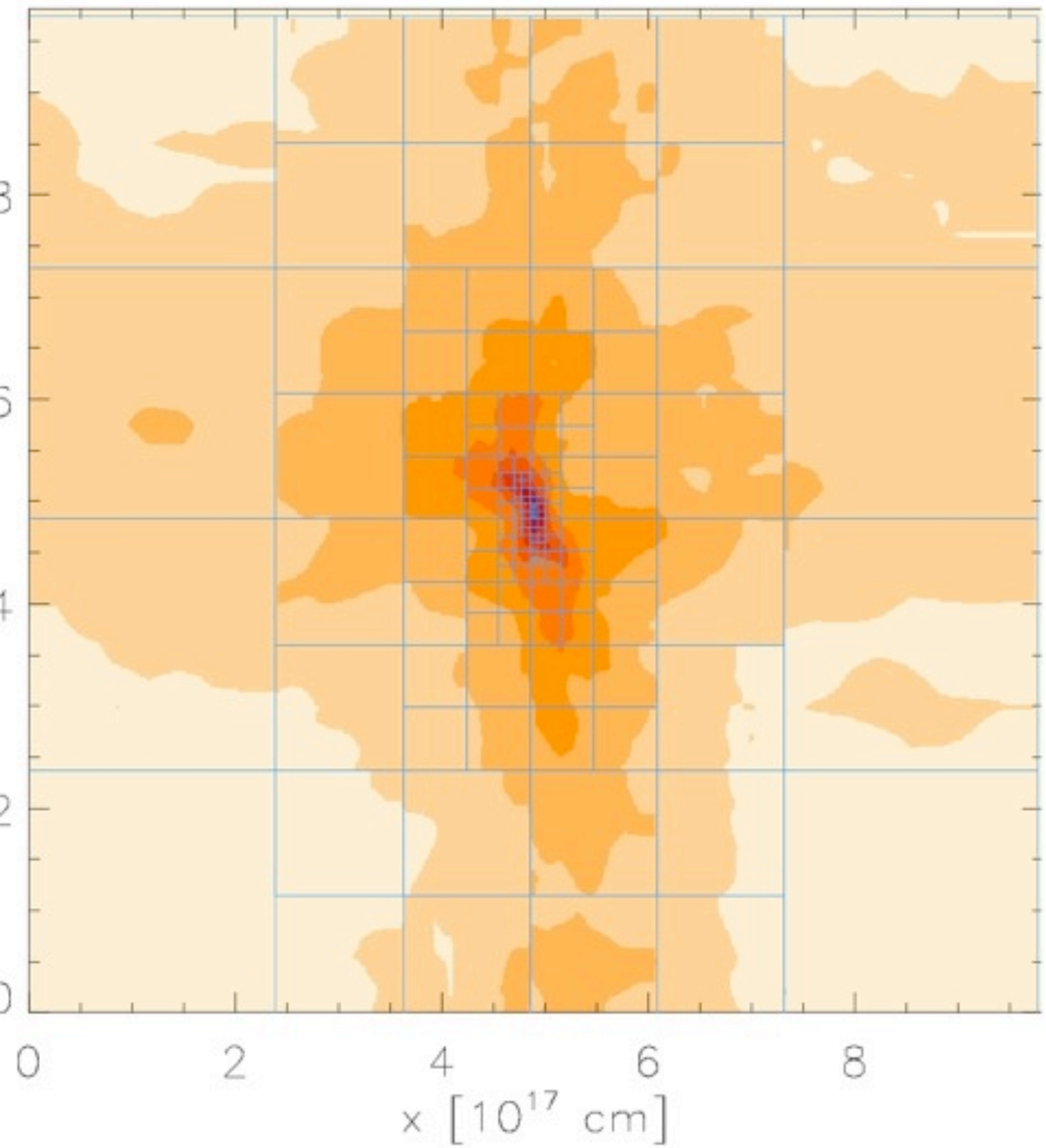
Seifried, et al. 2013

Run	$m_{\rm core}$ ($M_\odot$)	$r_{\rm core}$ (pc)	μ	Rotation	Ω (10^{-13} s^{-1})	$\beta_{\rm turb}$	Turbulence seed	p	$M_{\rm rms}$	$t_{\rm sim}$ (kyr)
2.6-NoRot-M2	2.6	0.0485	2.6	No	0	0.087	A	5/3	0.74	15
2.6-Rot-M2	2.6	0.0485	2.6	Yes	2.20	0.087	A	5/3	0.74	15
2.6-NoRot-M100	100	0.125	2.6	No	0	0.084	A	5/3	2.5	15
2.6-Rot-M100	100	0.125	2.6	Yes	3.16	0.084	A	5/3	2.5	15
2.6-Rot-M100-B	100	0.125	2.6	Yes	3.16	0.084	B	5/3	2.5	15
2.6-Rot-M100-C	100	0.125	2.6	Yes	3.16	0.084	C	5/3	2.5	15
2.6-Rot-M100-p2	100	0.125	2.6	Yes	3.16	0.084	A	2	2.5	15
2.6-NoRot-M300	300	0.125	2.6	No	0	0.12	A	5/3	5.0	10
2.6-Rot-M1000	1000	0.375	2.6	Yes	1.90	0.081	A	5/3	5.4	10

- low + high mass cores
- strong magnetic field
- with/without global rotation
- sub-/supersonic **turbulence**



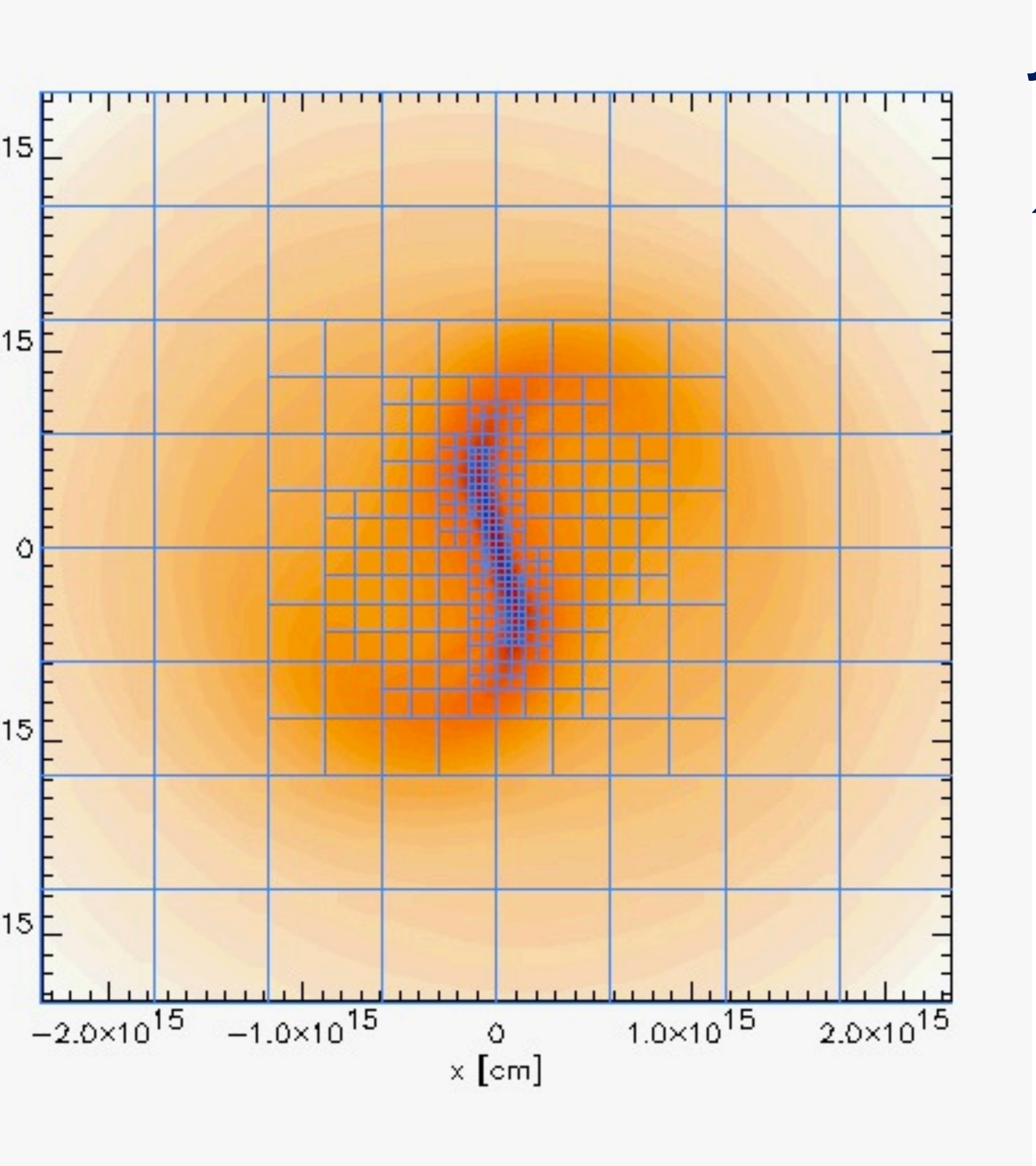
Numerical Method: FLASH Code



**Alliance Center for Astrophysical Thermonuclear Flashes (ASC), University of Chicago*

- 3D grid-based MHD integrator for parallel computing (MPI)
- Hydro solvers: PPM, Kurganov
- MHD solvers:
  - 8Wave (Roe-type)
  - **Bouchut**-type
  - also: unsplit scheme, staggered mesh
- Gravity:
  - multigrid
  - multipole
  - **tree-based**
  - periodic or isolated BCs
- Multi-physics:
  - heating/cooling
  - radiation
  - **sink particles**
- **AMR**: block structured (PARAMESH)
- Refinement on own choice (e.g. gradient, curvature, density, **Jeans-criterion**, etc.)

Numerical Method: FLASH Code



Jeans-criterion:
minimum resolution to resolve the Jeans-length (*Truelove et al. 1997*):

$$N = \lambda_J / \Delta x \geq 4$$

- only sufficient to prevent numerical fragmentation
- **higher** resolution necessary to resolve internal structures
  Turbulence ~ 30 grid cells
  (e.g. *Federrath et al. 2010*)

Jeans-length: $\lambda_{\mathrm{J}} = \sqrt{\frac{\pi \, c_{\mathrm{s}}^2}{G_N \, \rho}}$

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Seifried, et al. 2013

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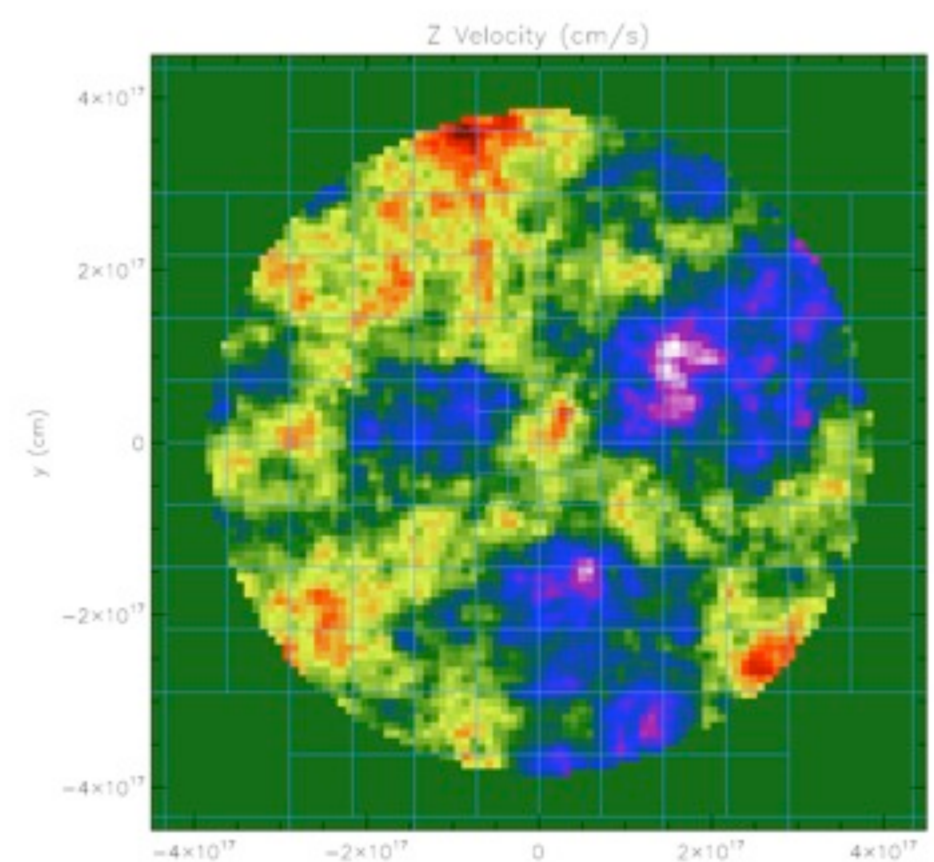
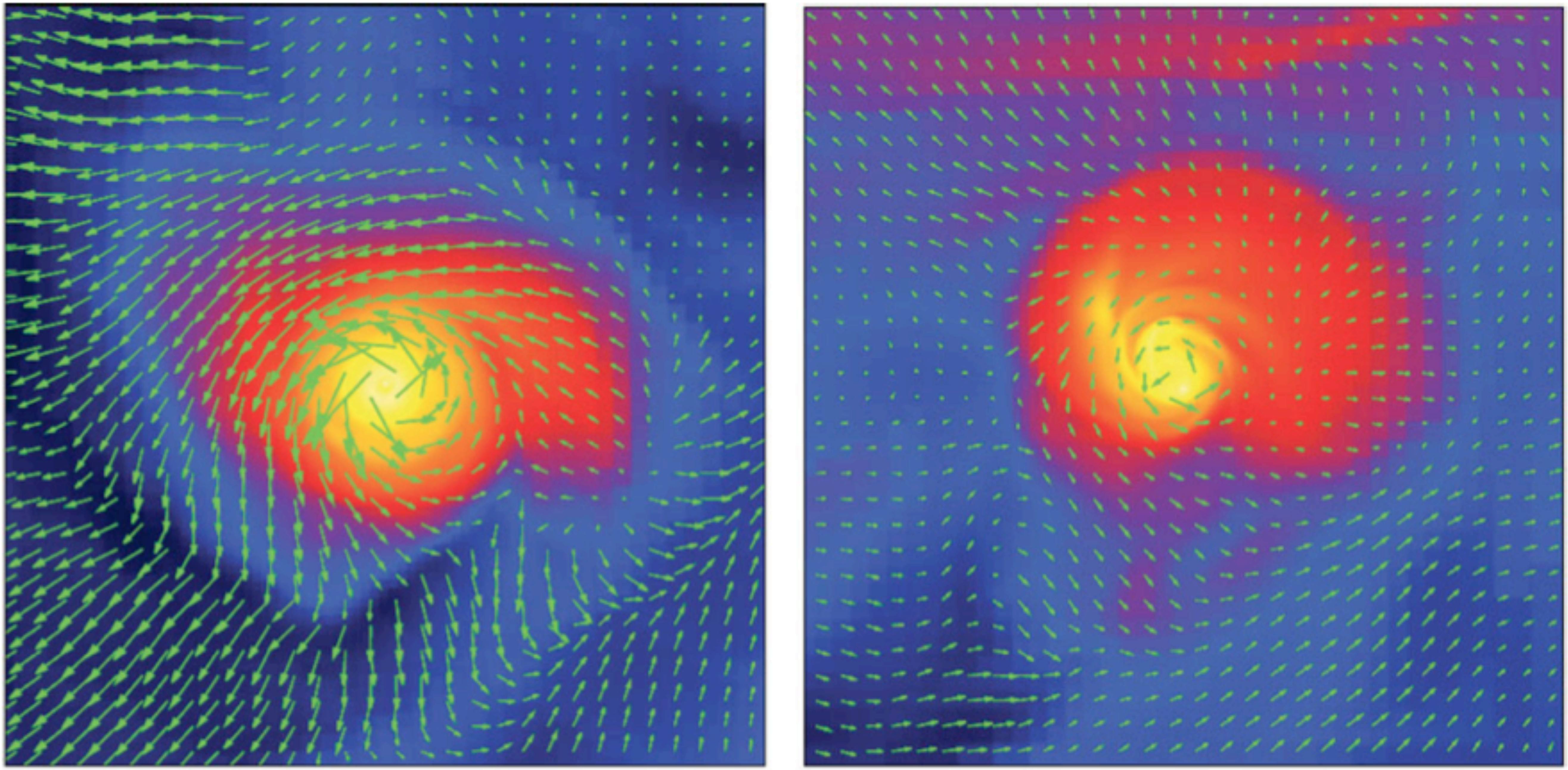
- low + high mass cores
- strong magnetic field
- with/without global rotation
- sub-/supersonic **turbulence**

- resolution: 1.2 AU

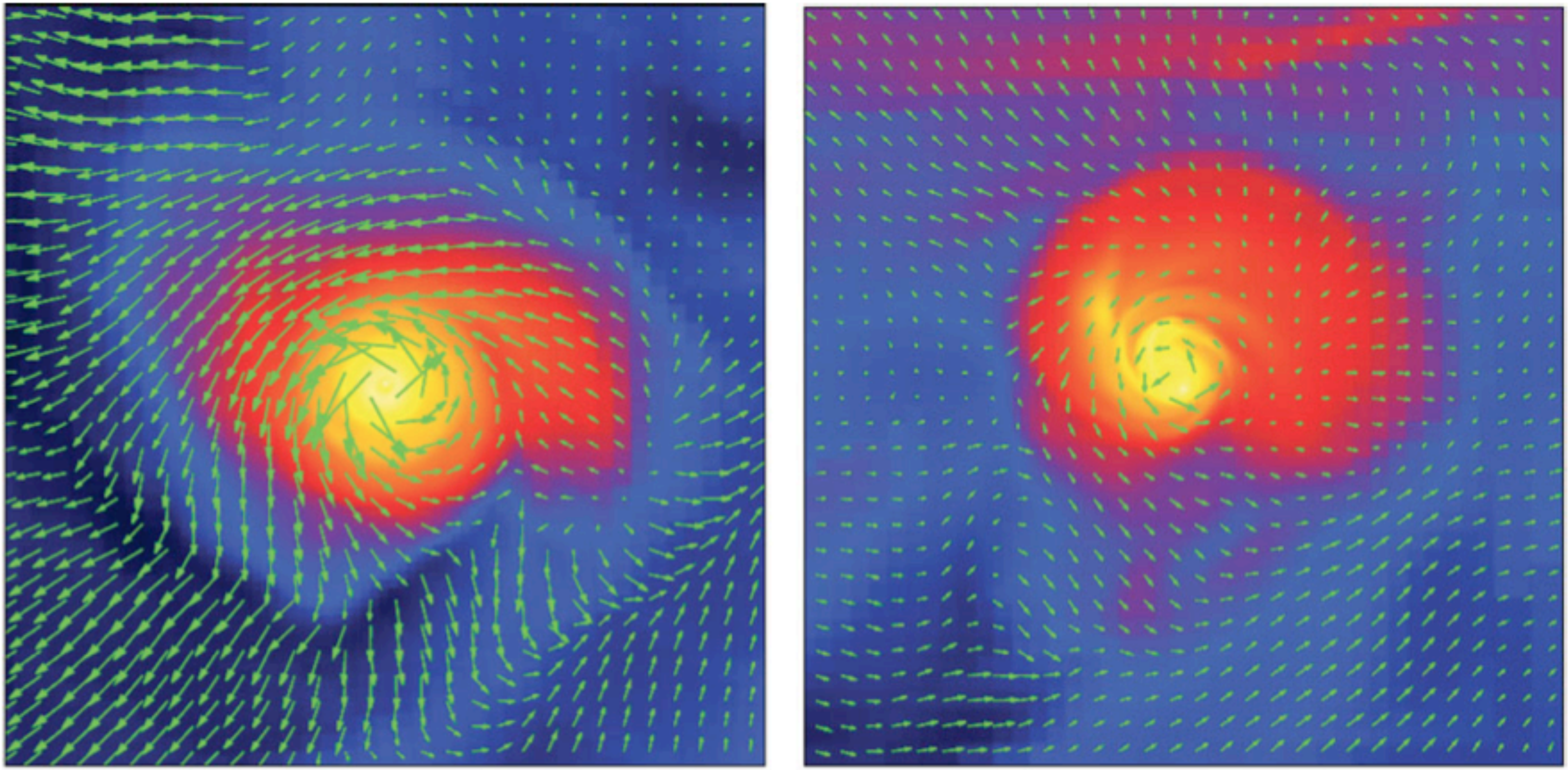


Collapse of Turbulent Cores



Seifried, RB, Pudritz, Klessen 2012

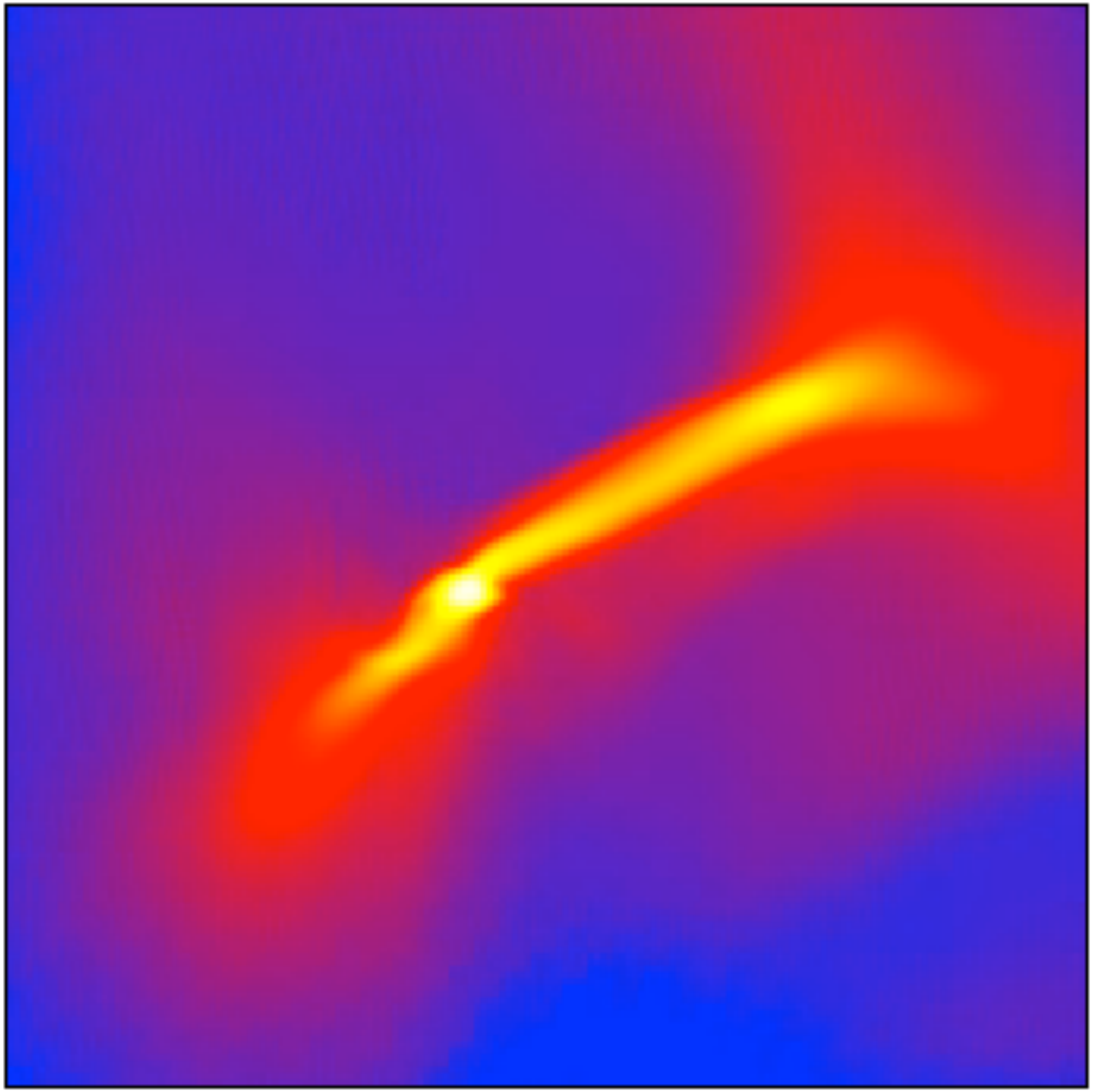
Collapse of Turbulent Cores



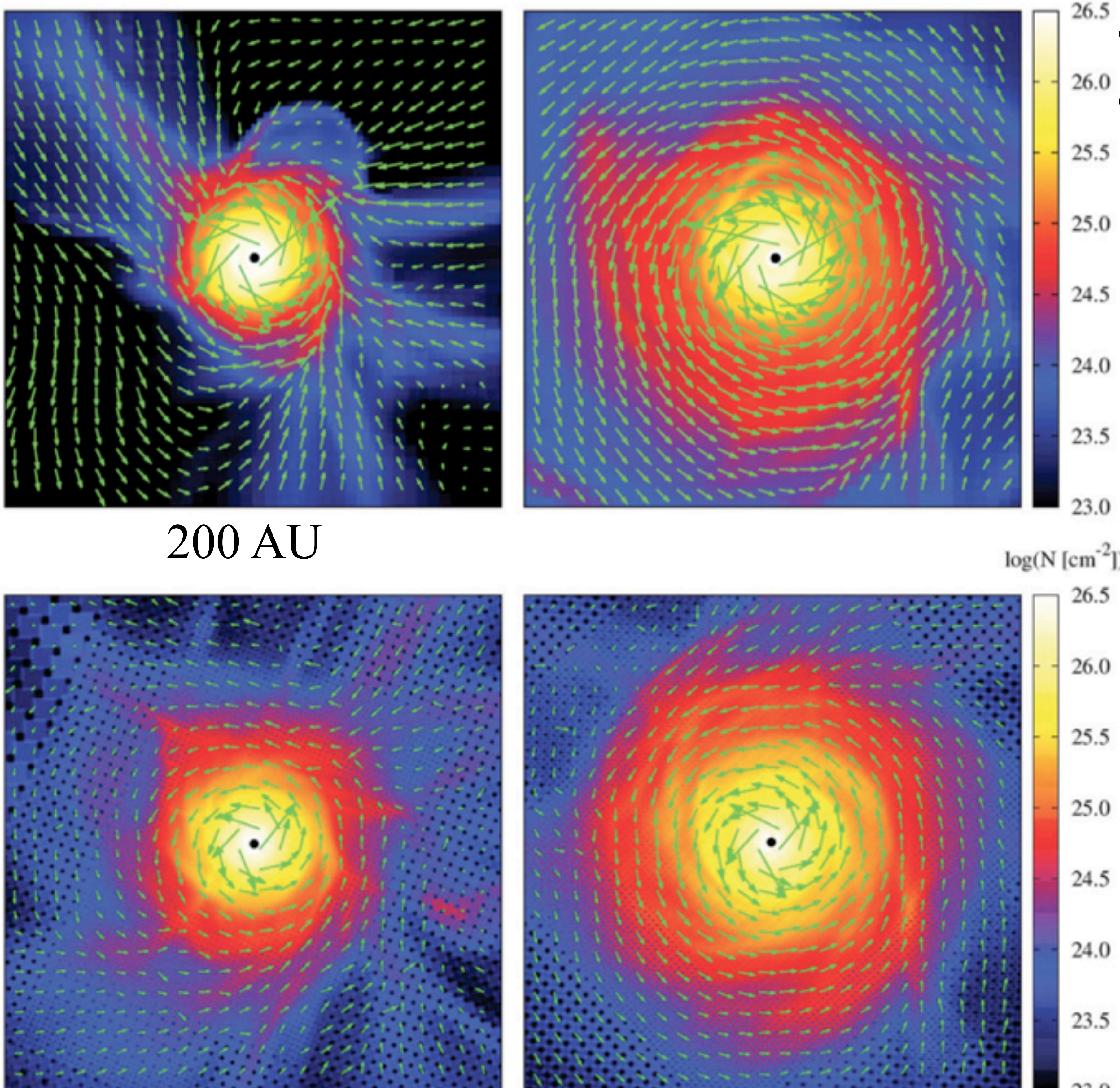
Seifried, RB, Pudritz, Klessen 2012

$\Longrightarrow$ discs "reappear"

Collapse of Turbulent Cores



Collapse of Turbulent Cores

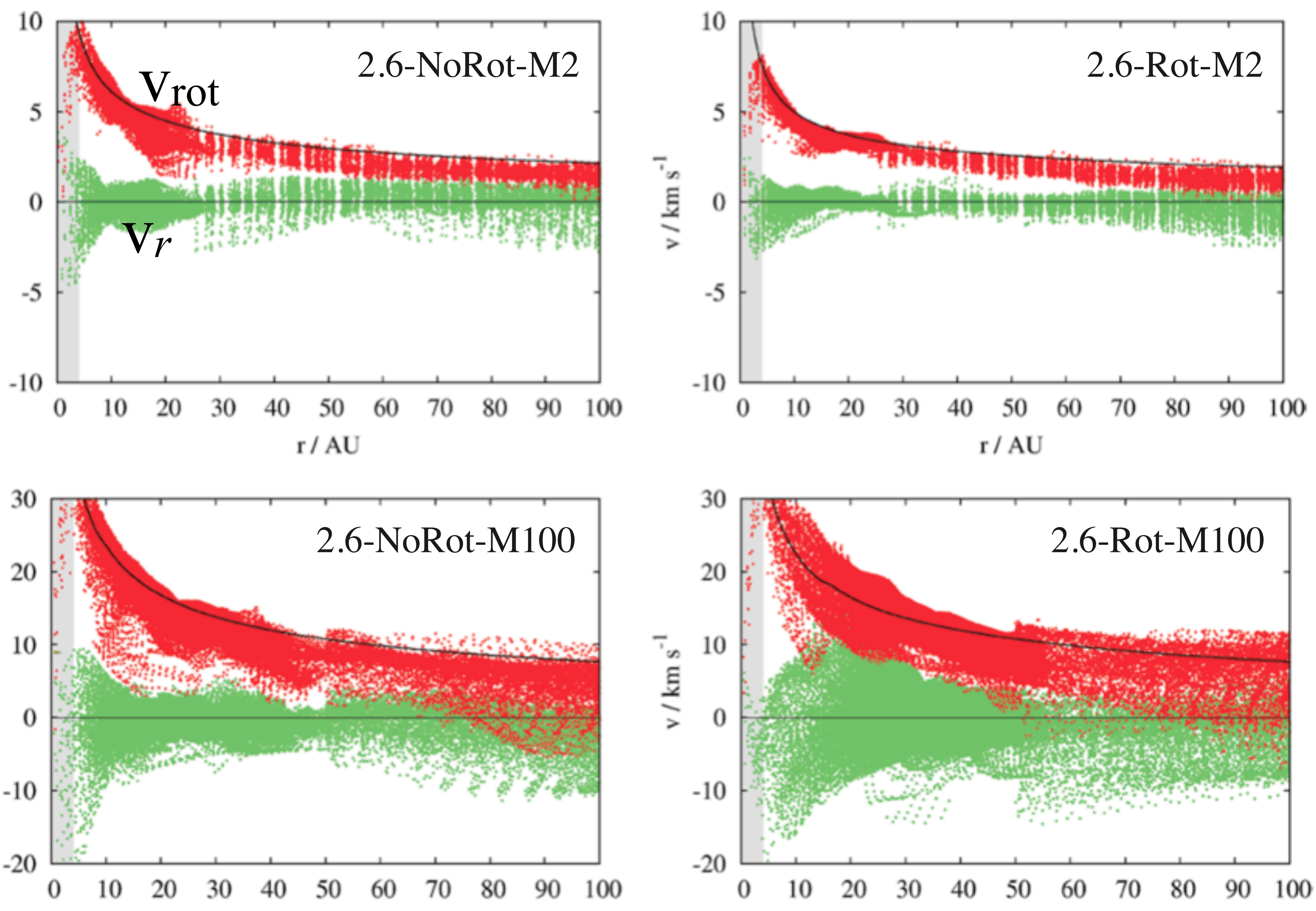


- low mass cores
- strong magnetic field: $\mu = 2.6\ \mu_{crit}$
- transonic turbulence $Ma = 0.74$
- **no** global rotation
- with global rotation

Seifried, et al. 2013

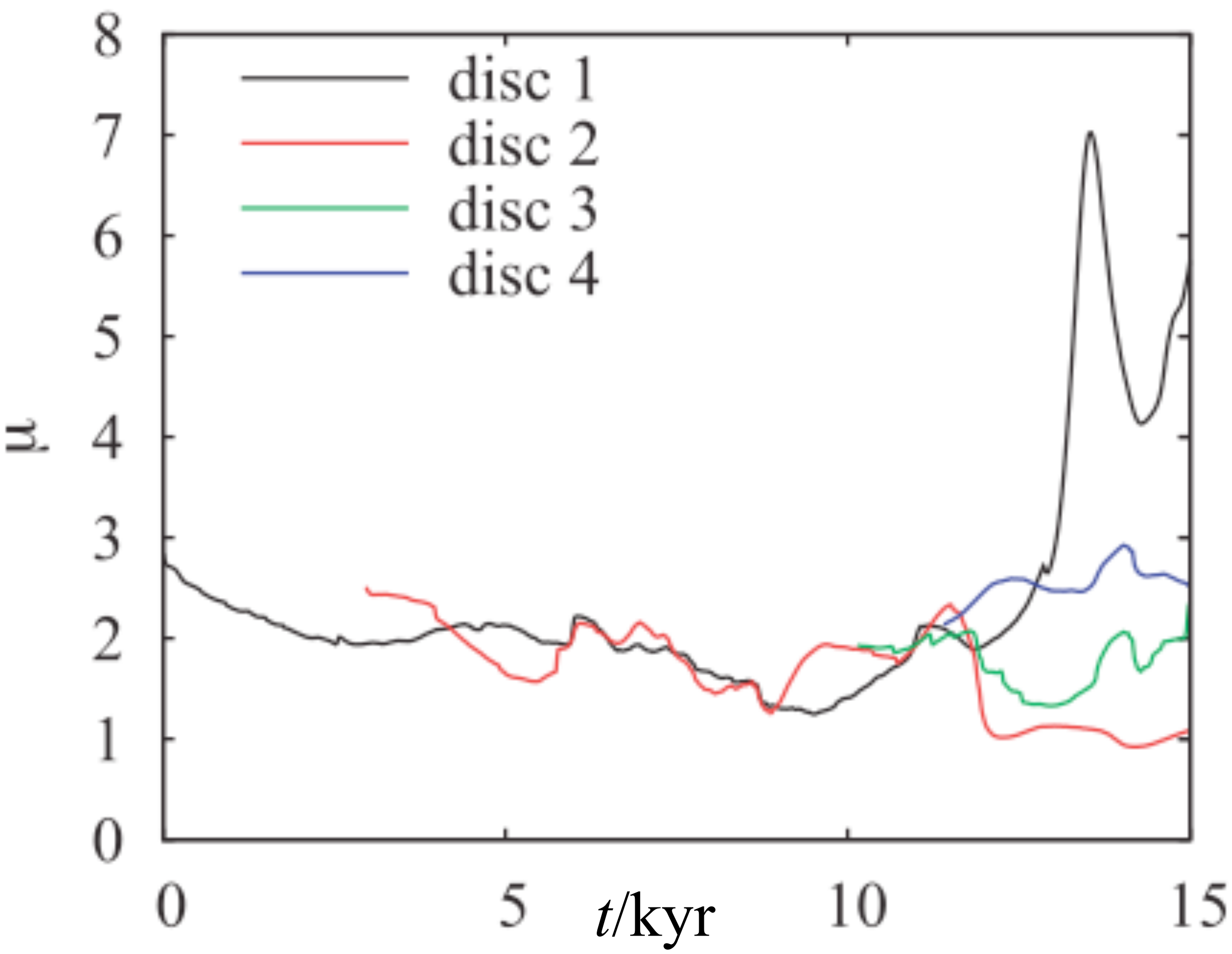
Collapse of Turbulent Cores

velocity structure

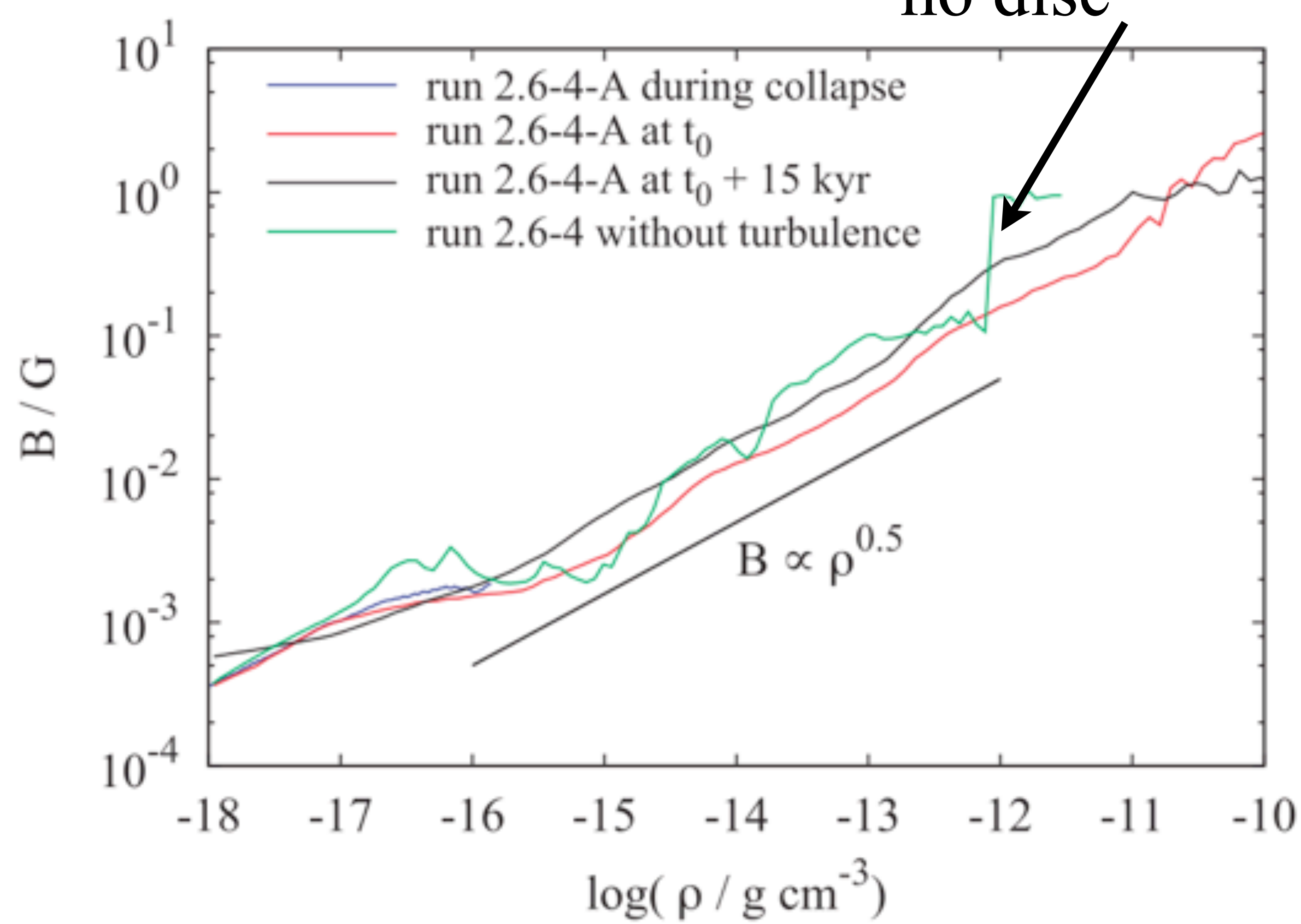


Collapse of Turbulent Cores

due to flux loss?



no turbulence
no disc



Collapse of Turbulent Cores

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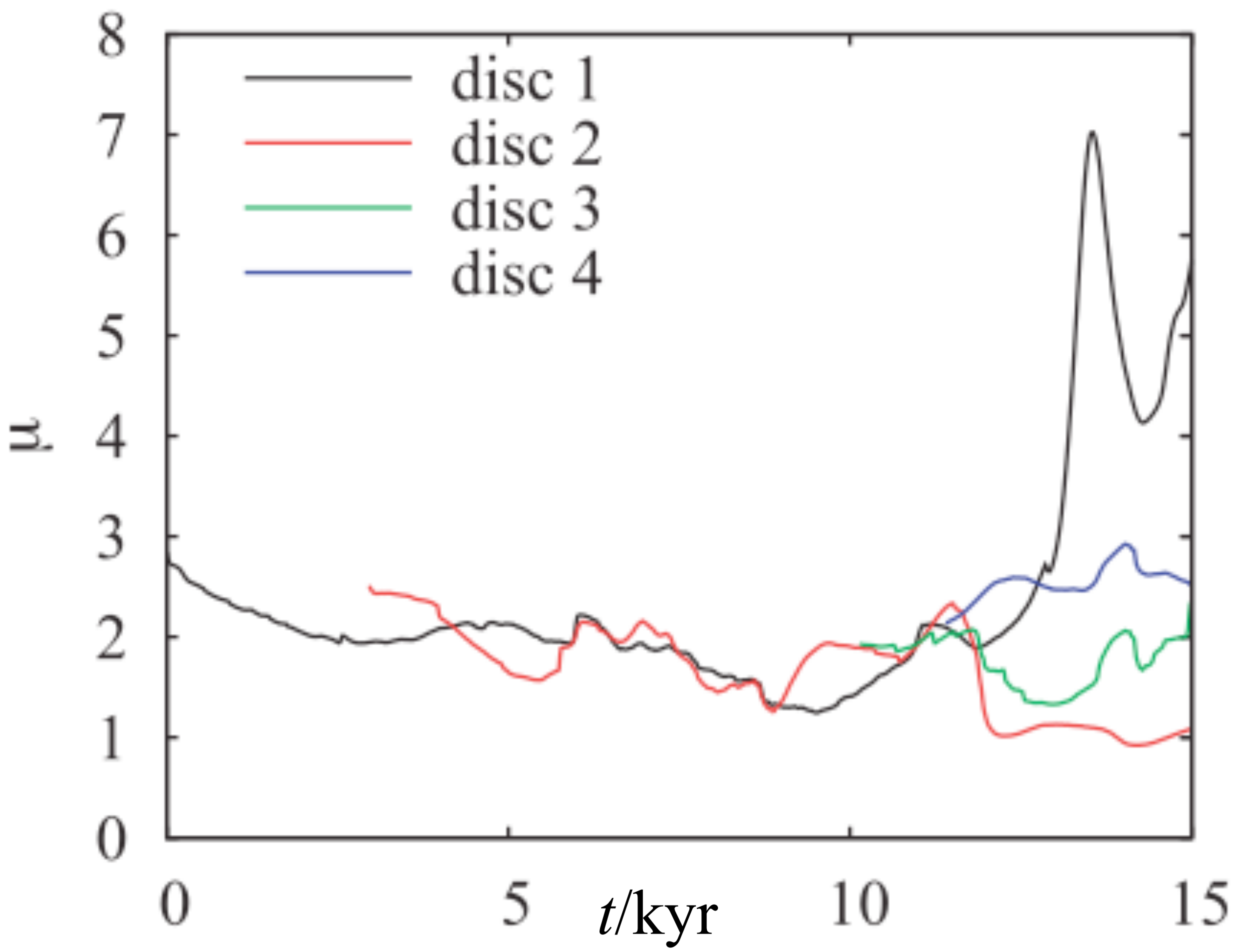
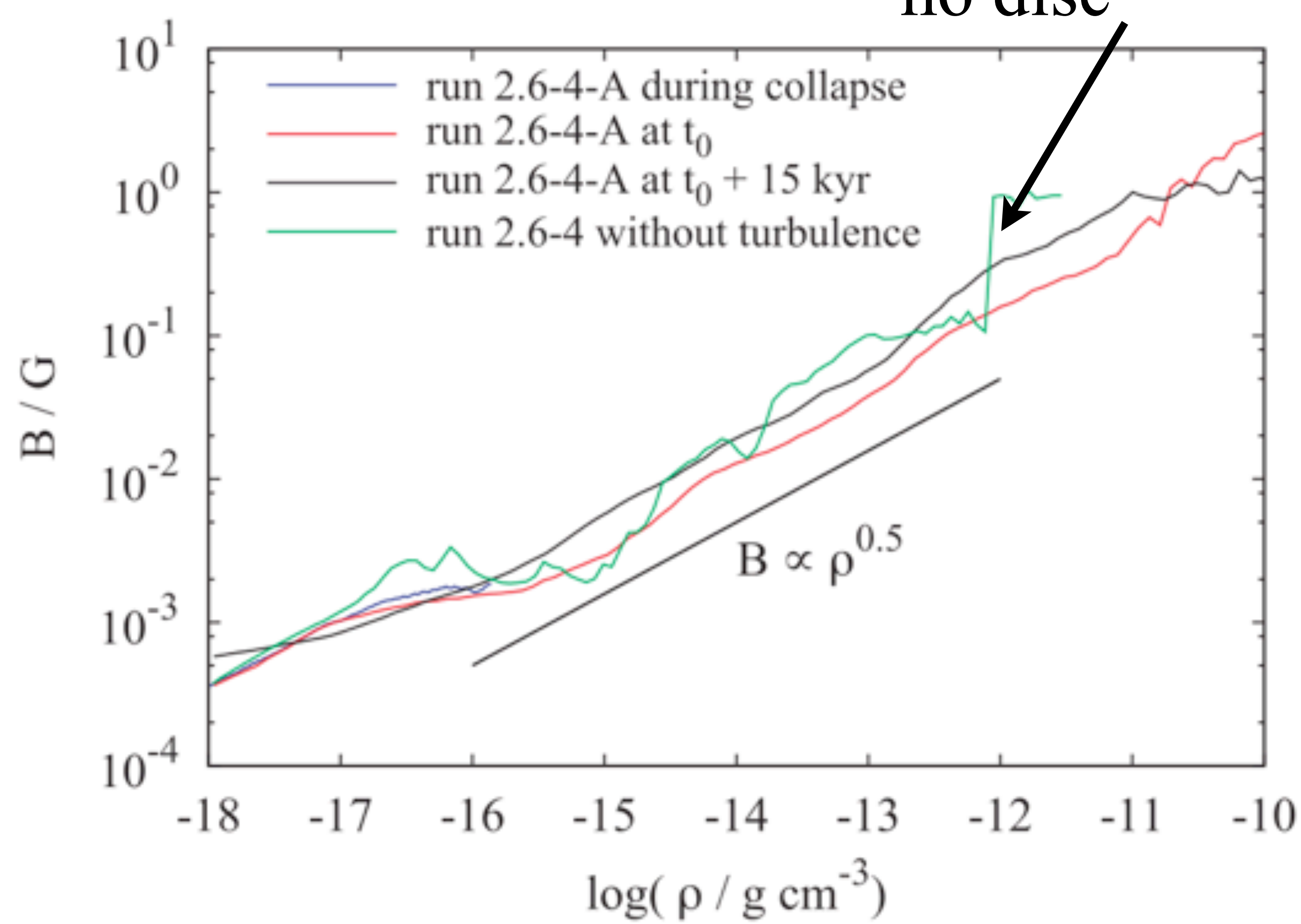
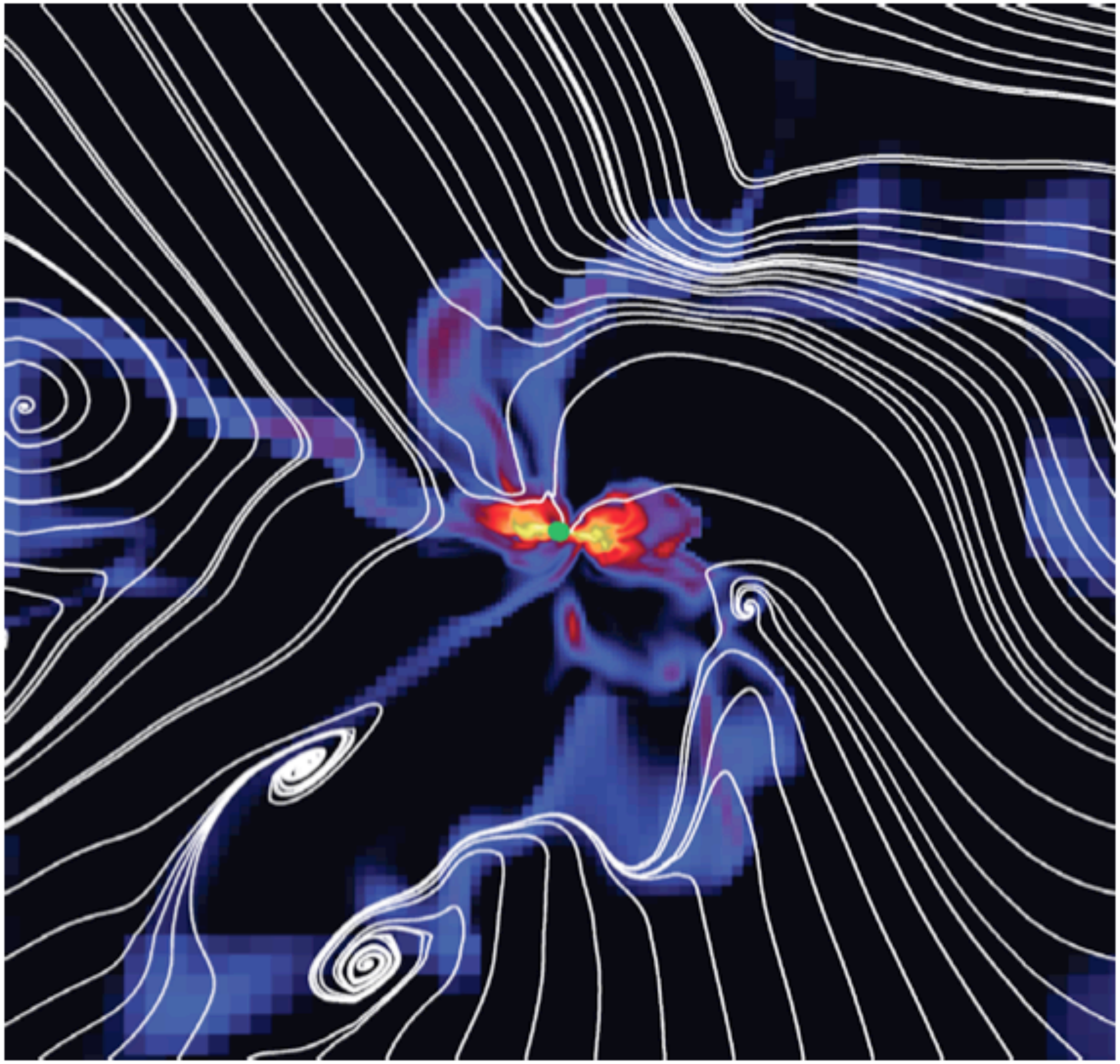




$\Longrightarrow$ only little flux loss

Collapse of Turbulent Cores

Magnetic field structure

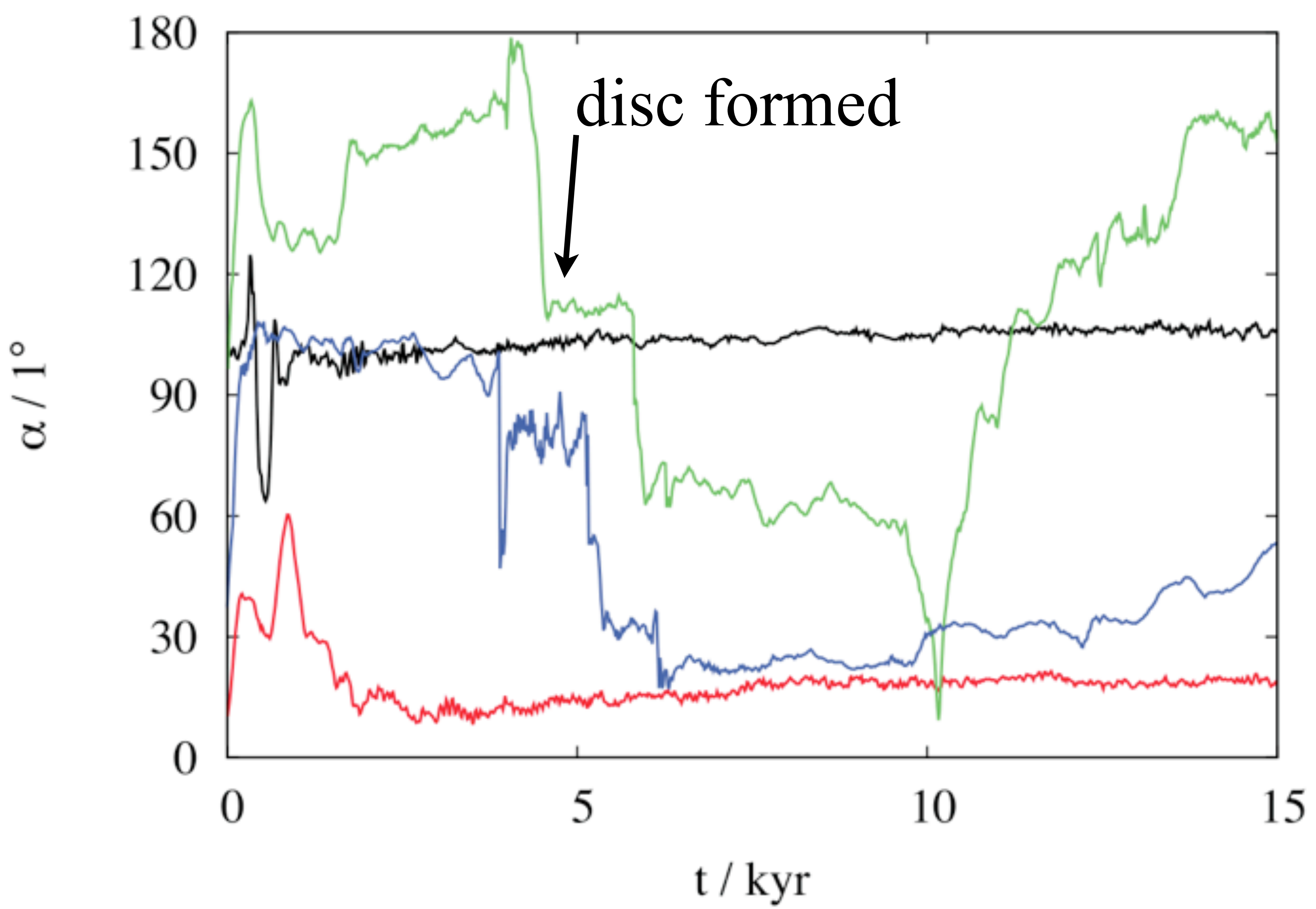


Collapse of Turbulent Cores

rotation vs. magnetic field orientation

$\Longrightarrow$ inclined rotation helps to form discs?

(*Hennbelle & Ciardi 2009, Joos et al. 2012*)



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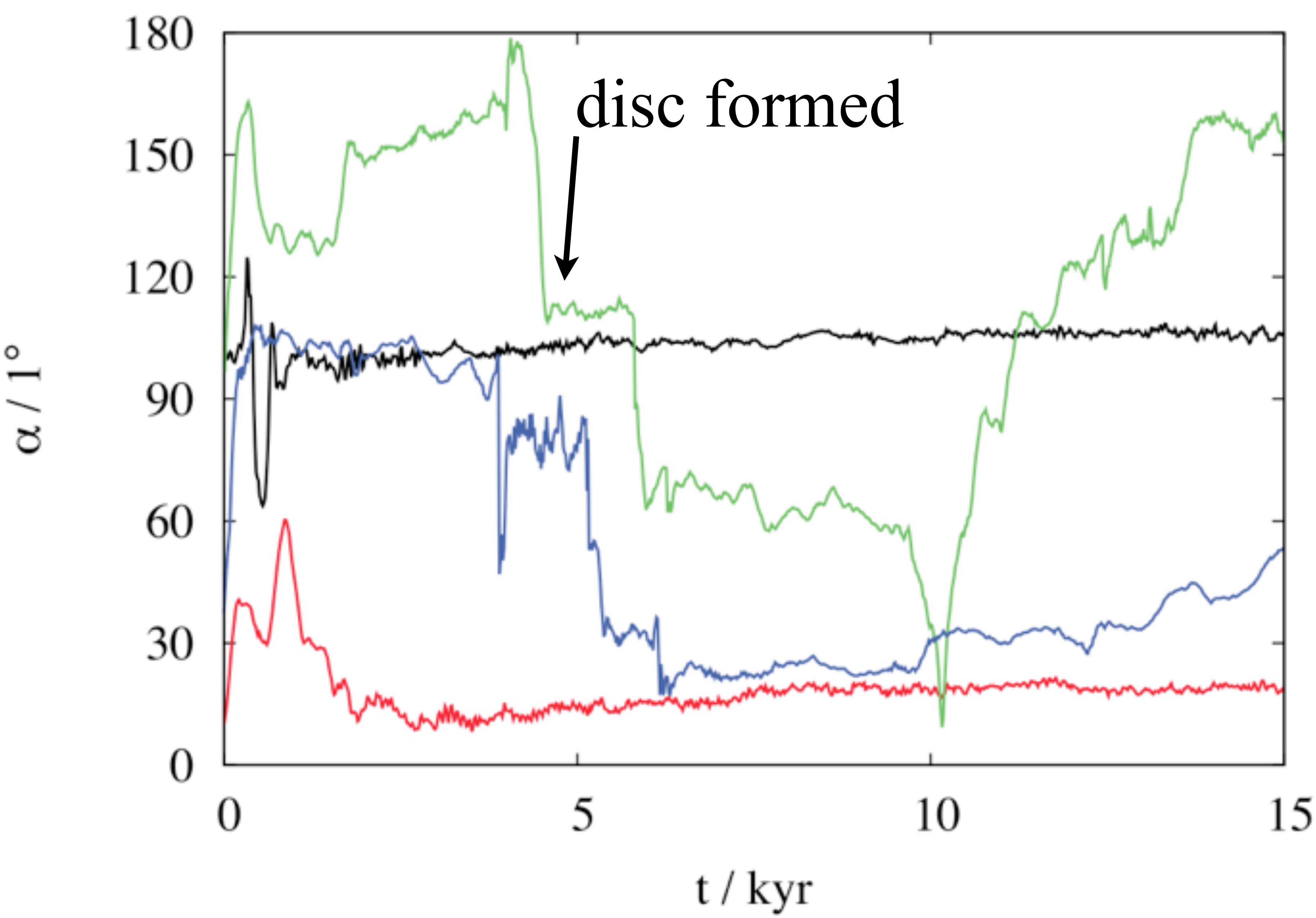
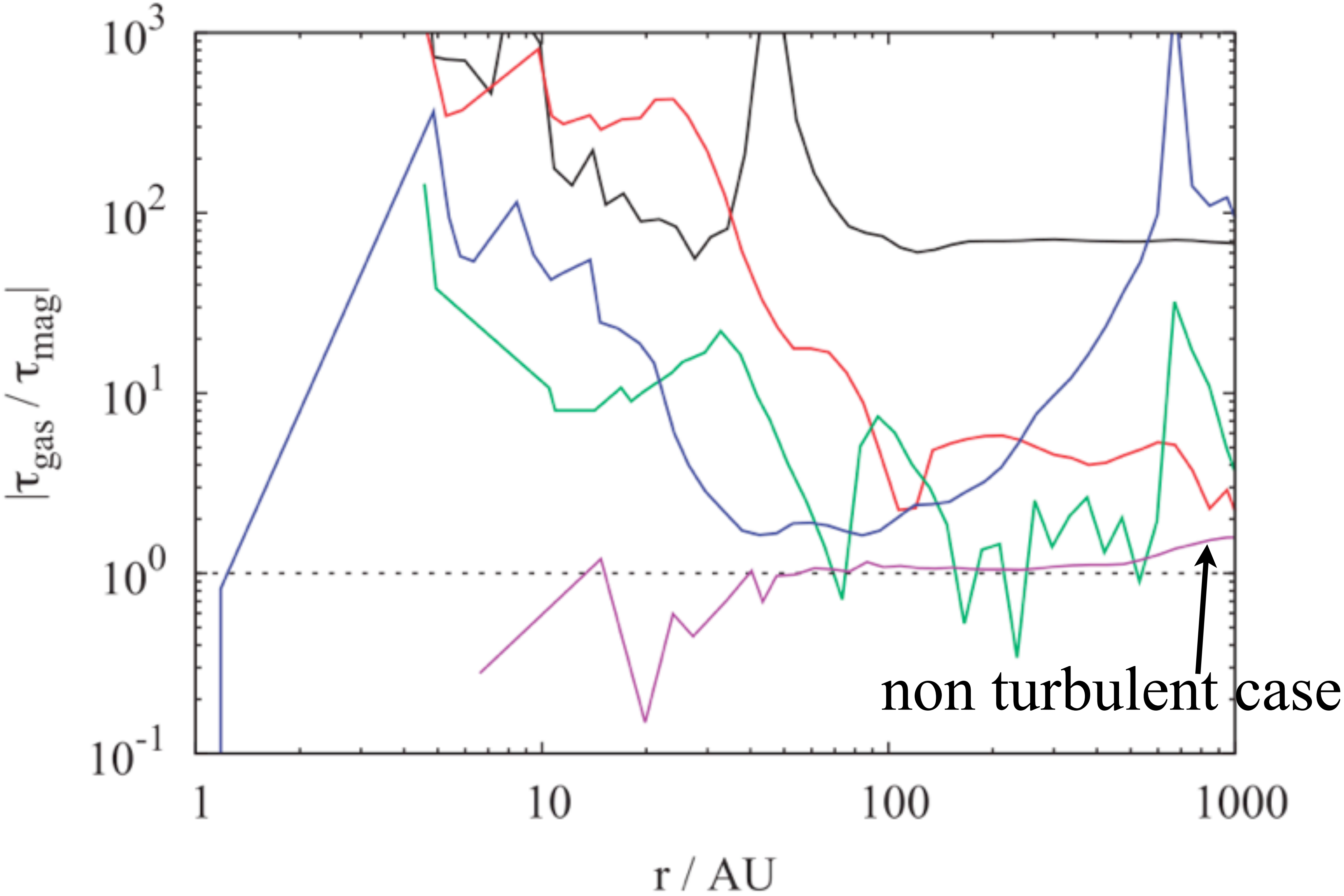


$\Longrightarrow$ but no large scale magnetic field component

Collapse of Turbulent Cores

Torques



Summary

- It is easy to form discs
- Angular momentum is efficiently transported during disc formation by gravitational torques
- Magnetic braking catastrophe only for unrealistic ICs