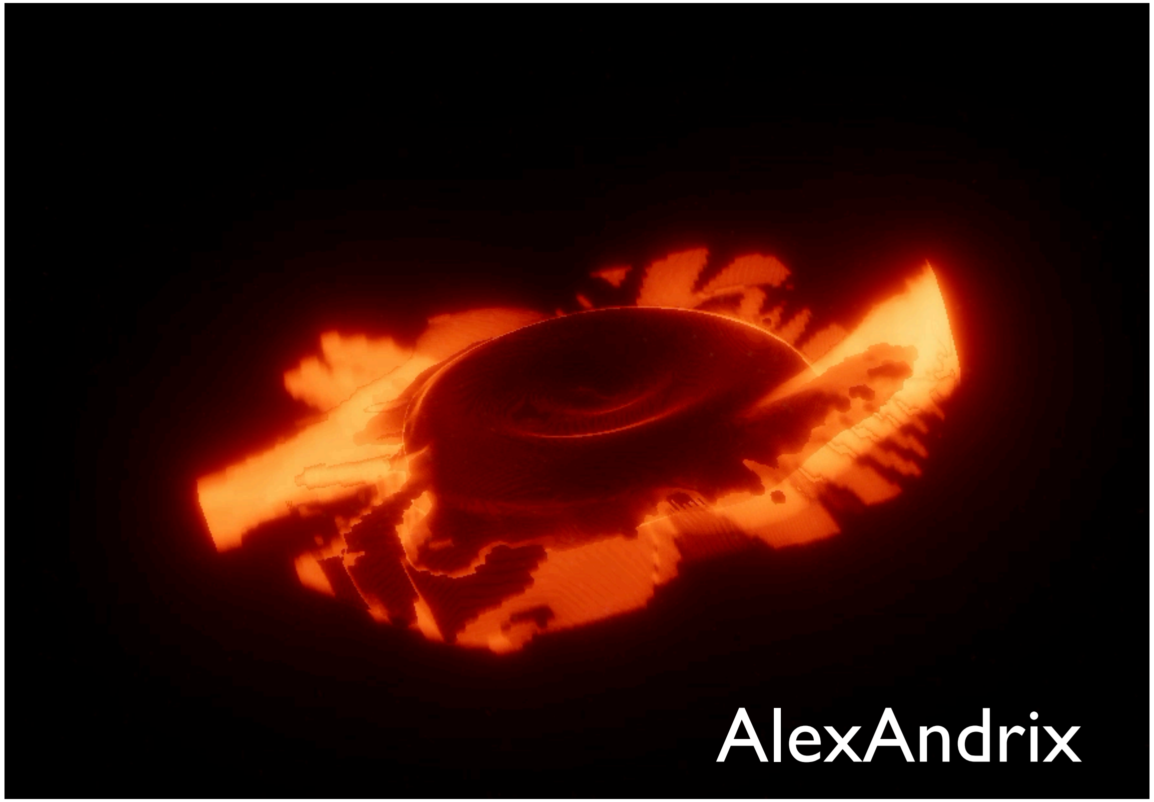
The early stages of star formation: collapse, protostellar disc and protostar



Benoît Commerçon

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CRAL
CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

Outline

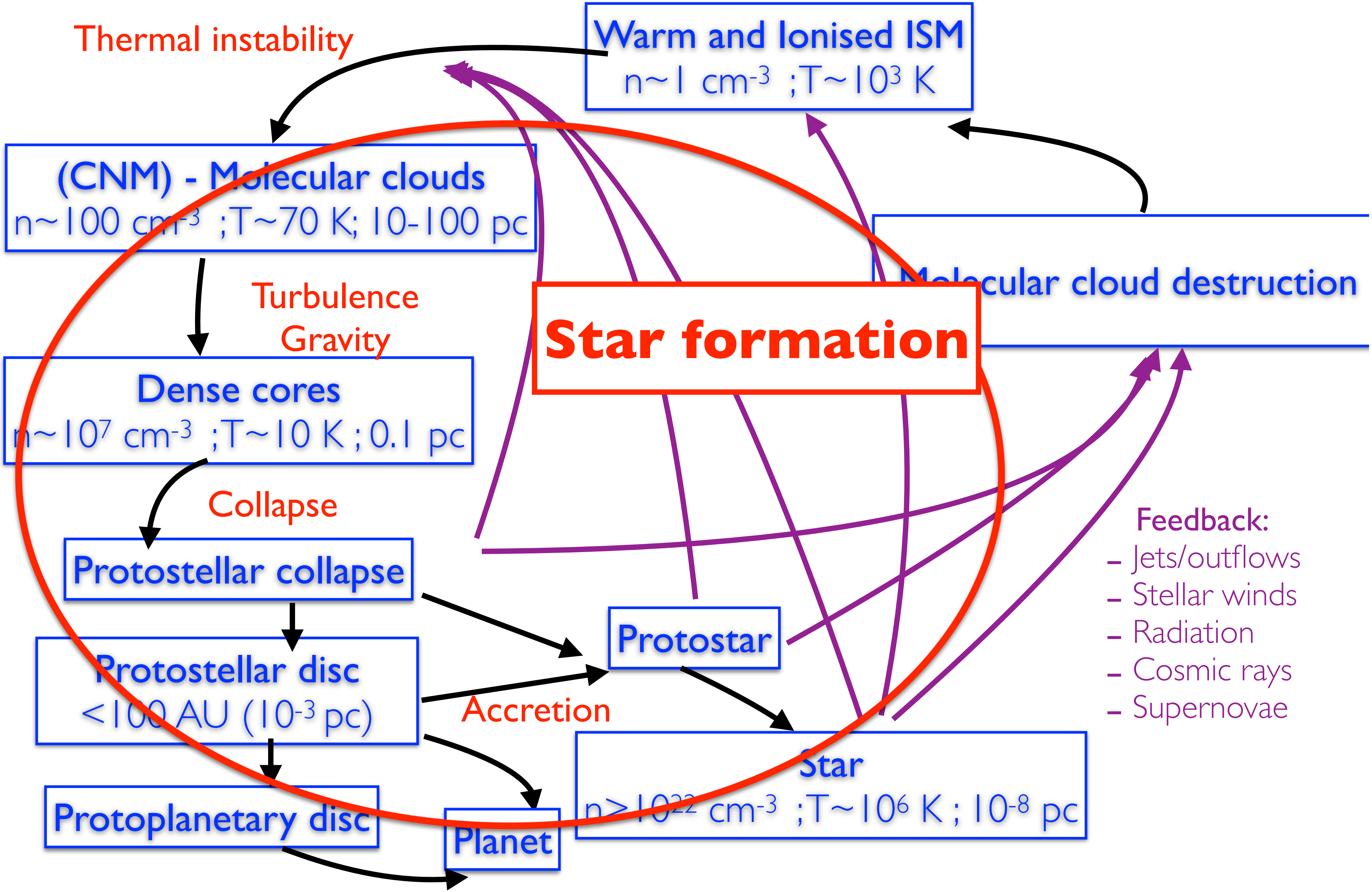
1. Introduction
2. Dense core collapse, disc formation (pc to au)
3. Formation of the protostar (au to $R_{\odot}$)
4. Perspectives

What do we find in the interstellar medium?

- photons at all wavelengths
- gas (mainly H, 10% He and 10^{-4} heavy elements), turbulent
- magnetic fields (from galactic dynamo?)
- dust (solid phase, 1% mass compared to the gas), but (thermo)dynamically important...
- cosmic rays (high energy particles)

$$E_{th}=E_{grav}=E_{kin}=E_{mag}=E_{rad}=E_{cr} \sim 1 \text{ ev/cm}^3$$

Interstellar matter cycle

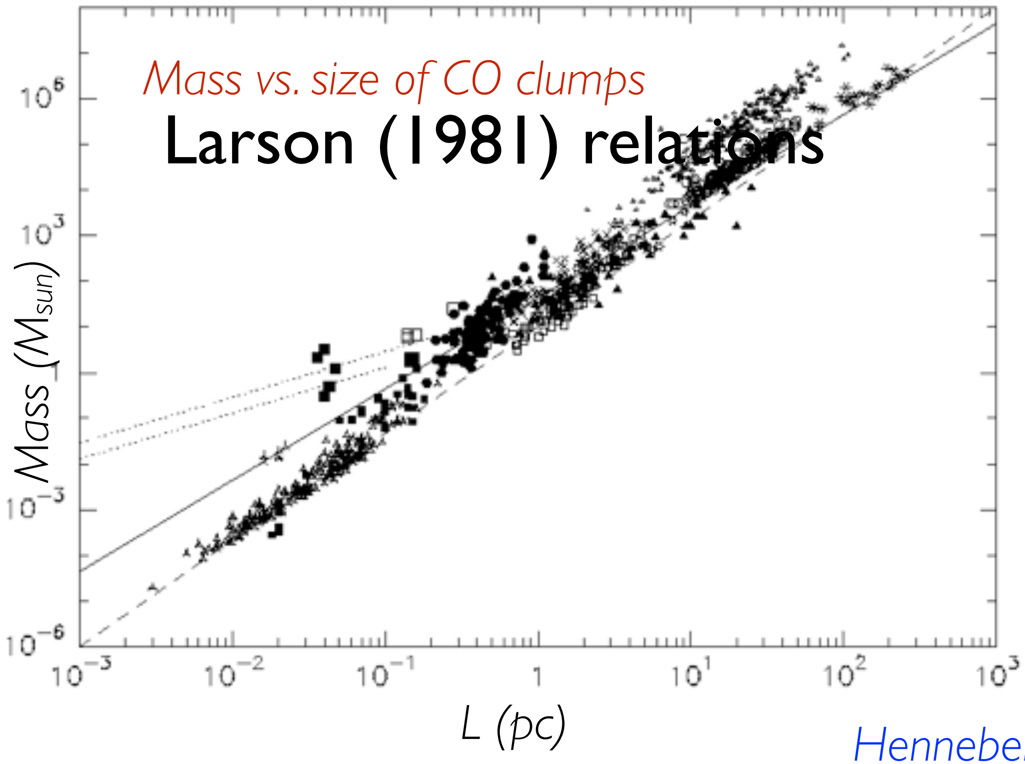


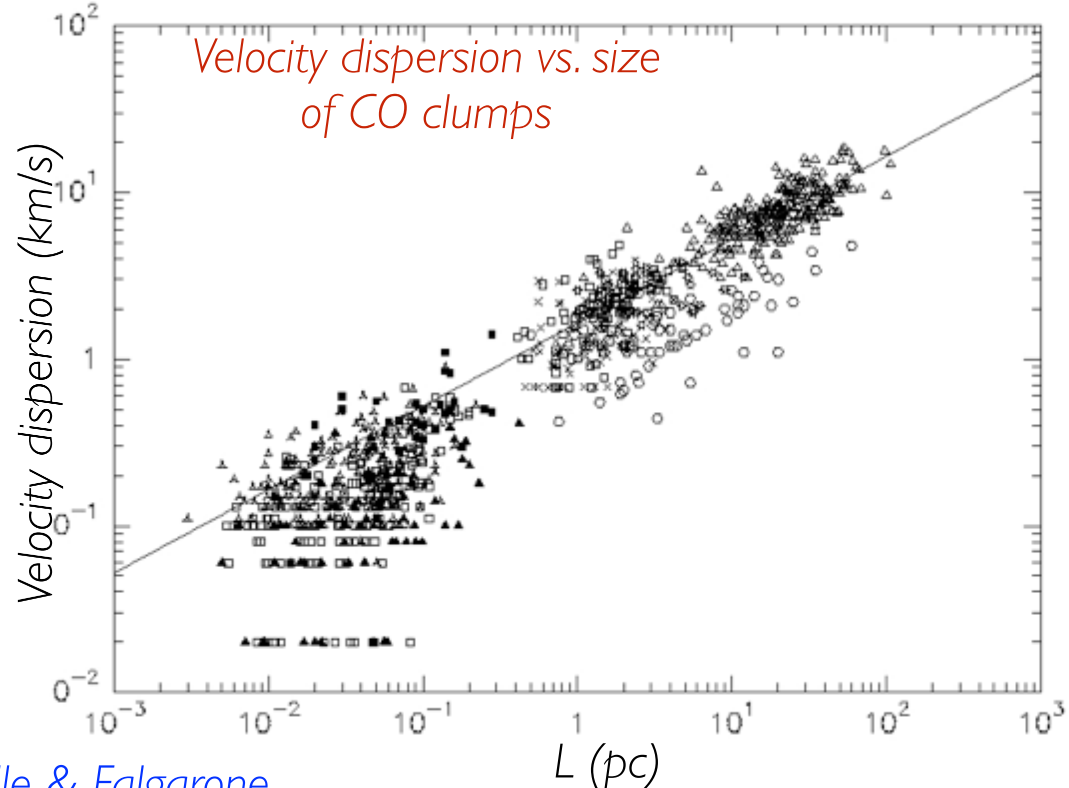
Molecular clouds are turbulent

$$n = 3000\ \mathrm{cm}^{-3}\ \left(\frac{L}{1\ \mathrm{pc}}\right)^{-0.7}$$

$$\Delta v_{\mathrm{NT}} \sim 1\ \mathrm{km\ s}^{-1}\ \left(\frac{L}{1\ \mathrm{pc}}\right)^{0.5}$$

$$\Delta v_{\mathrm{NT}} \sim 1\ \mathrm{km\ s}^{-1}\ \left(\frac{n}{3000\ \mathrm{cm}^{-3}}\right)^{-5/7}$$





Hennebelle & Falgarone (2012 A&ARA)

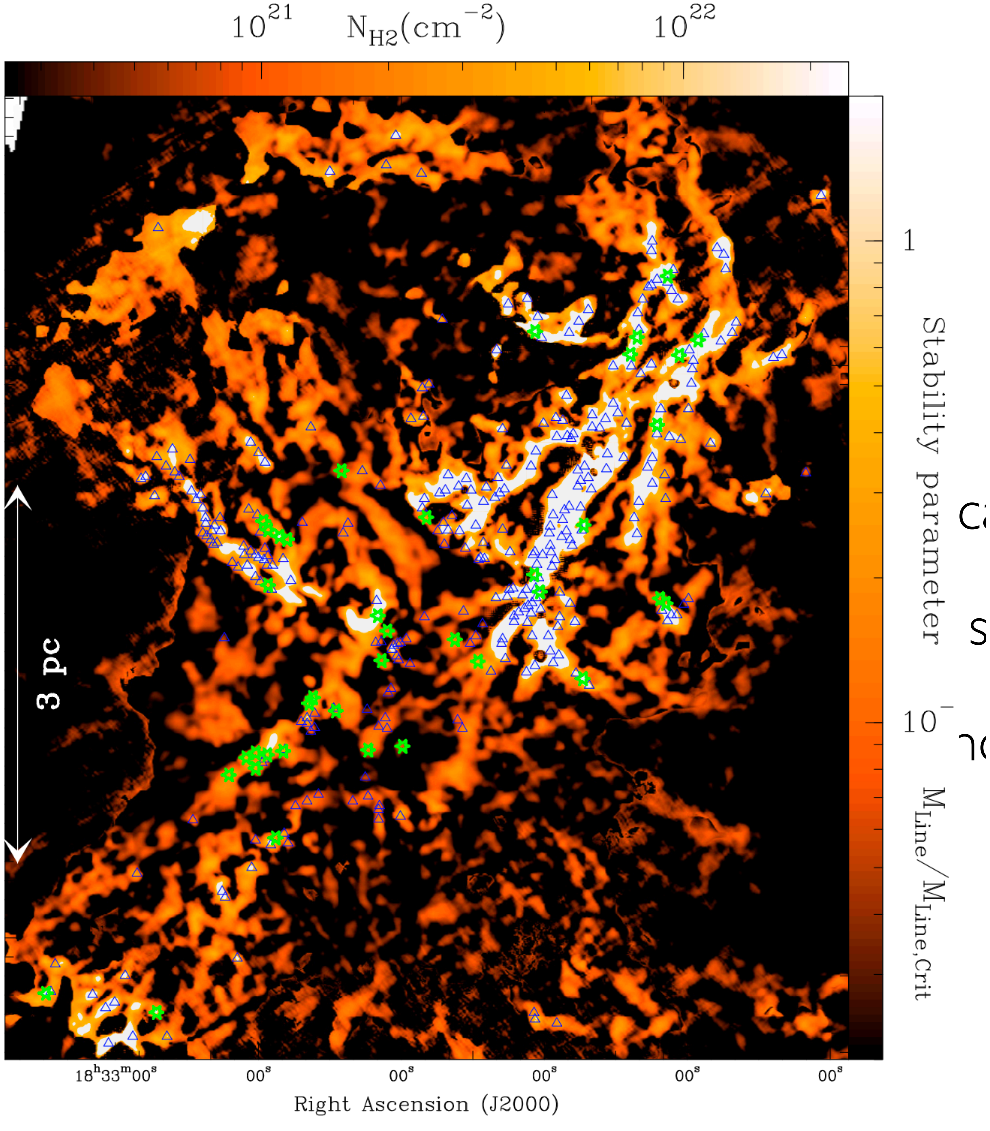
Star formation is inefficient in the MW

- Star formation rate varies in different regions, but the average measured SFR is ~3 $M_\odot$/yr in the Galaxy

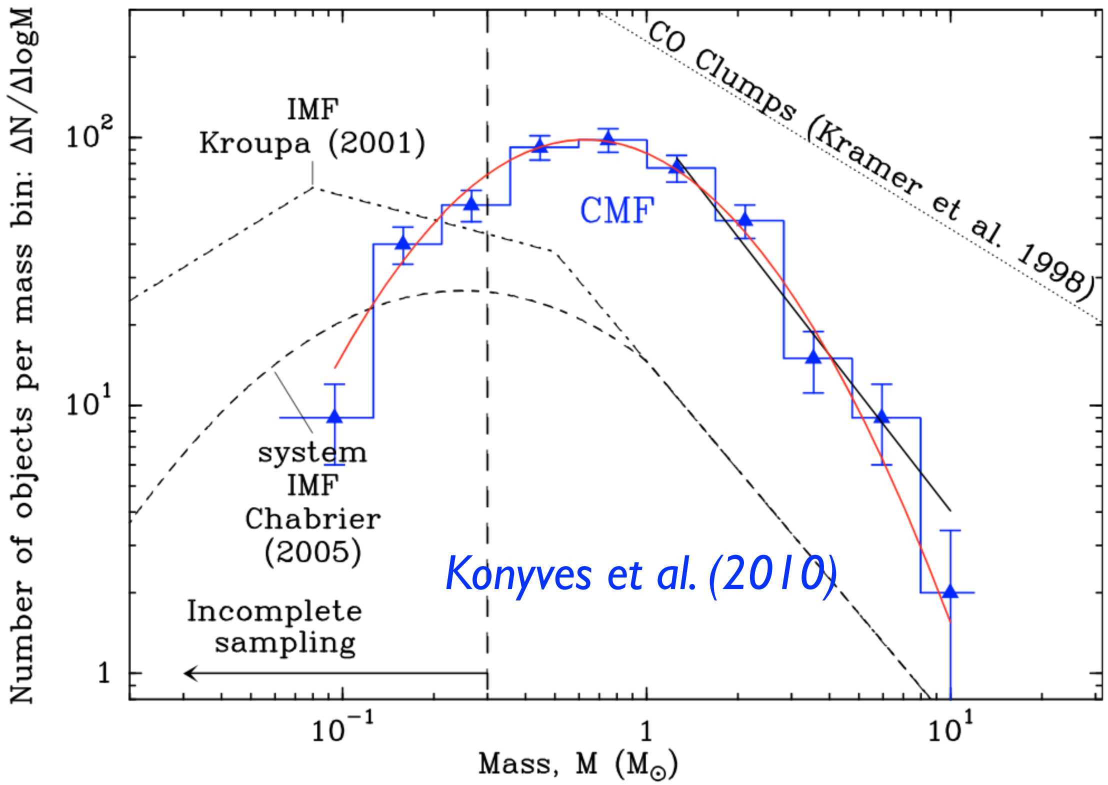
- A simple estimate
  - ✓ M_{gas} ($n > 10^3$ cm^{-3}) in the Galaxy: 10^9 $M_\odot$
  - ✓ Free-fall time

$$t_{ff} = \sqrt{\frac{3\pi}{32 G\rho}} \simeq 6.4 \times 10^6 \text{ yr}$$

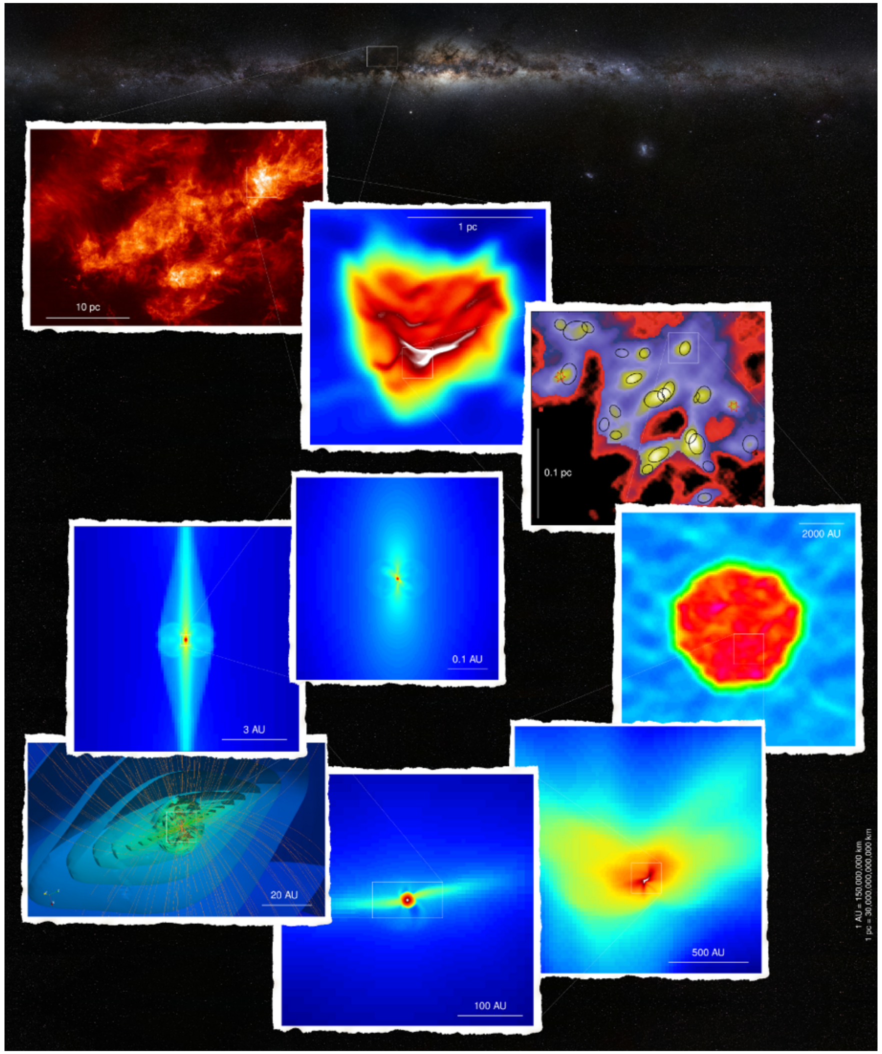
Dense core formation



André et al. (2010)



Star formation: building blocks & challenge



Vaytet et al. (2013)

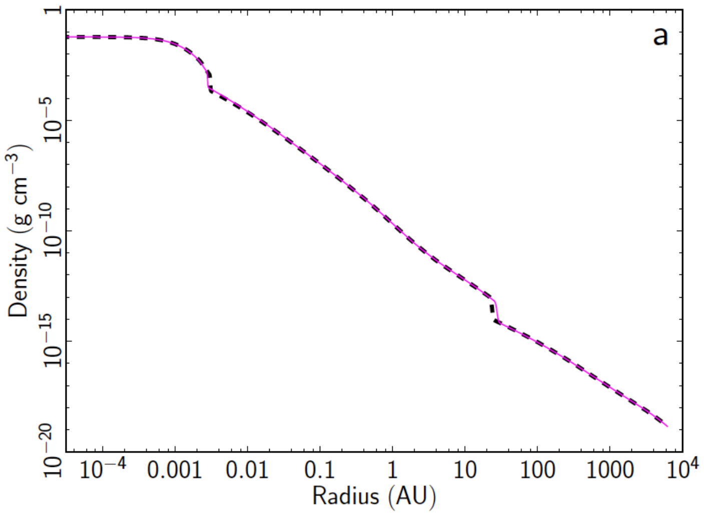
Dynamics over a wide range of scales:

- time: free-fall time (~$10^{4,5}$ yr) to second
- spatial: parsec (10^{18} cm) to stellar radius (10^{10} cm)
- physical: density ranges form 10^4 cm^{-3} to 10^{24} cm^{-3}

- ionisation (*ideal vs non-ideal MHD*)

- chemistry, dust grain evolution

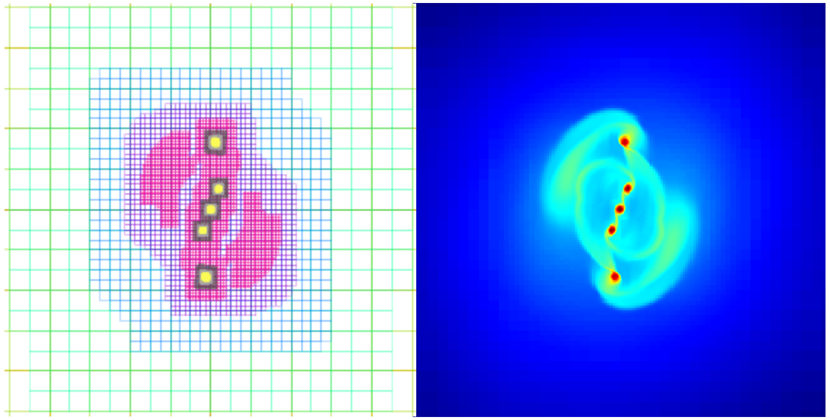
- initial conditions for stellar evolution (*entropy level, magnetic field flux/geometry, angular momentum*)



Numerical tools for star formation

★ 3 numerical methods :

– **Grid based** code - AMR: RAMSES, ENZO, FLASH



➡ Advantages :
- ✓ accuracy
- ✓ shocks
- ✓ refinement criteria

➡ Disadvantages :
- ✓ grid effects
- ✓ Eulerian
- ✓ complex structure

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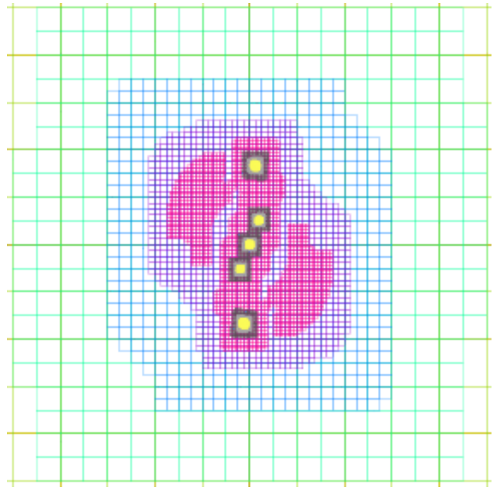

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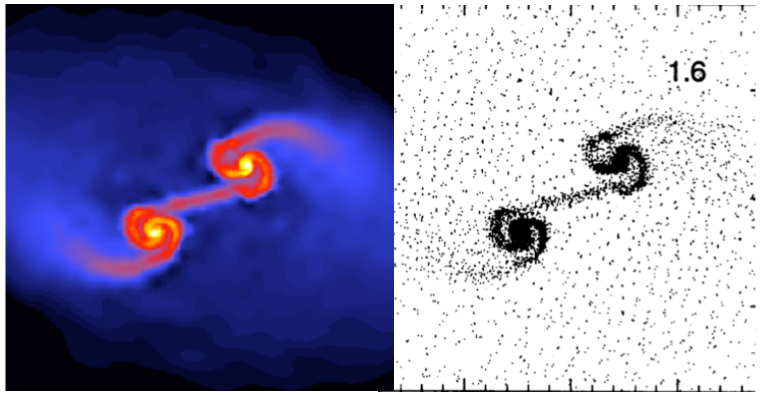
– **Smoothed Particle Hydrodynamics**: GADGET, PHANTOM, GASOLINE

➡ Advantages :
- ✓ Lagrangian
- ✓ naturally adaptive
- ✓ (simpler)

➡ Disadvantages :
- ✓ low density = low resolution
- ✓ noise, dissipative
- ✓ young



Numerical tools for star formation

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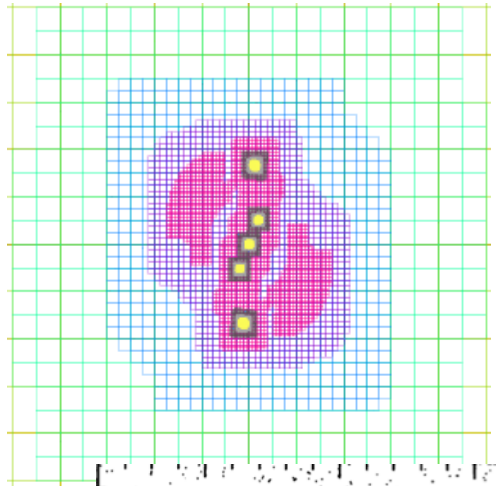

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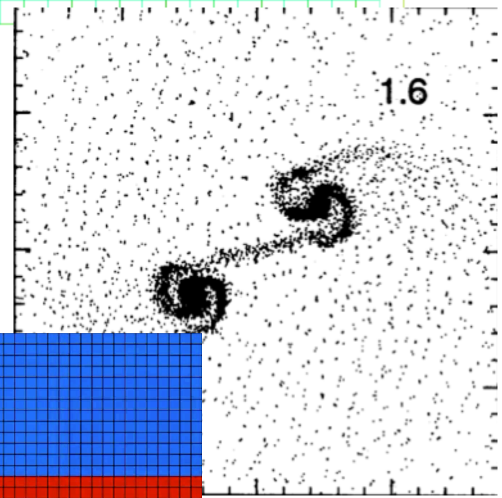

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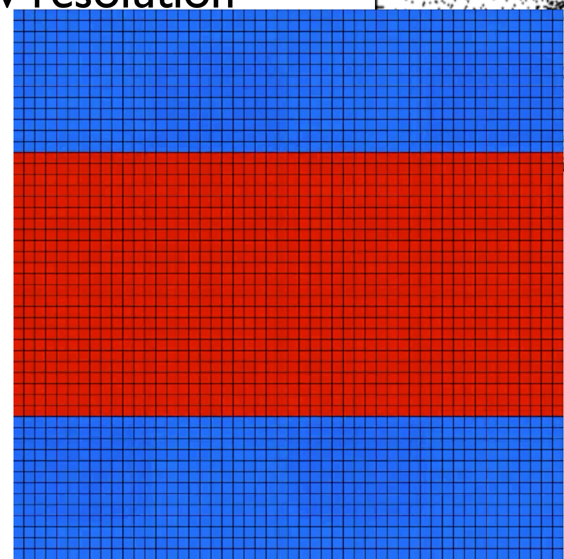
- ✓ young

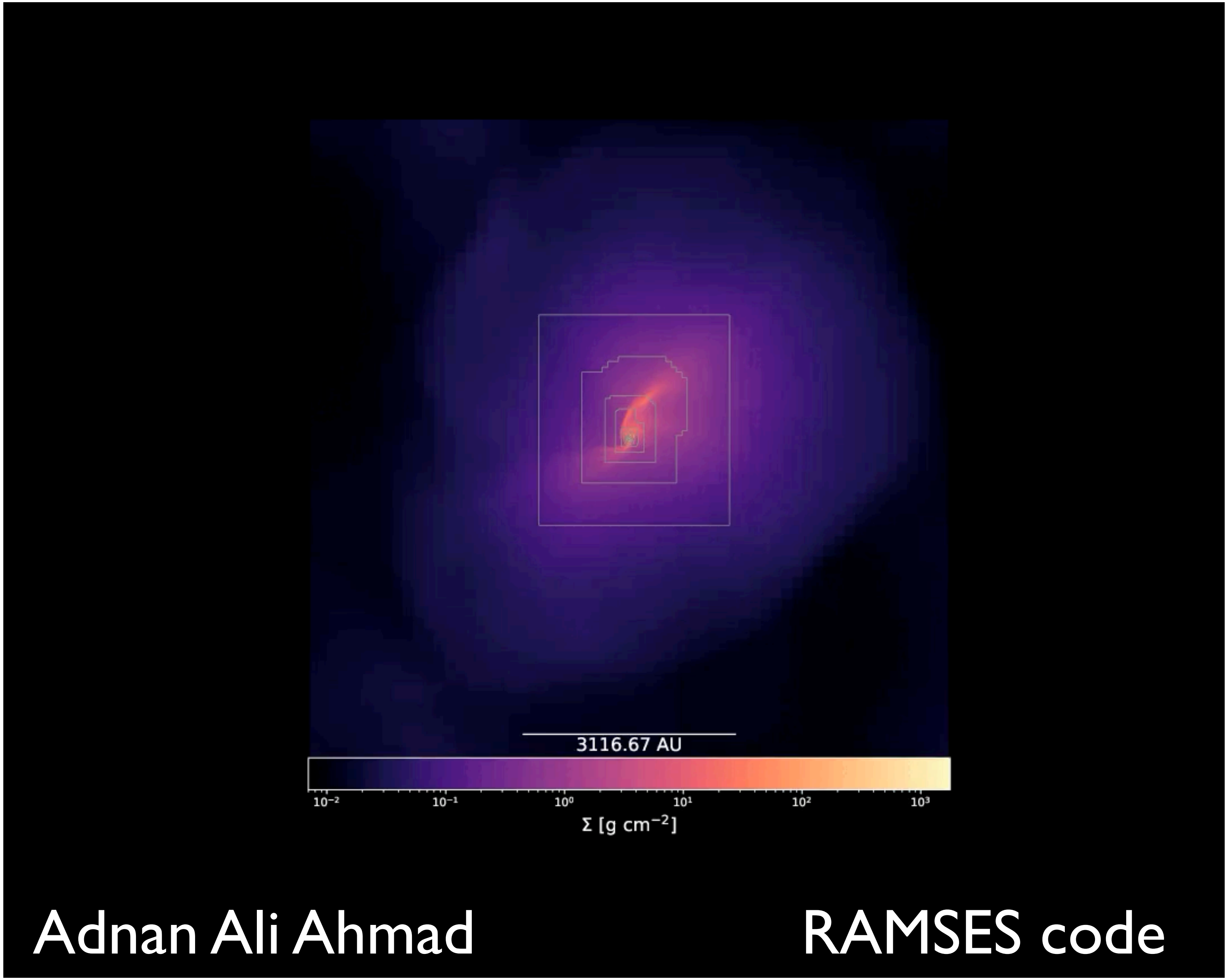
– Mix - Moving mesh: AREPO

➡ Advantages :
- ✓ Lagrangian/Eulerian
- ✓ naturally adaptive

➡ Disadvantages :
- ✓ Tessellation
- ✓ young



Numerical tools for star formation



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Fundamental issues - Angular momentum

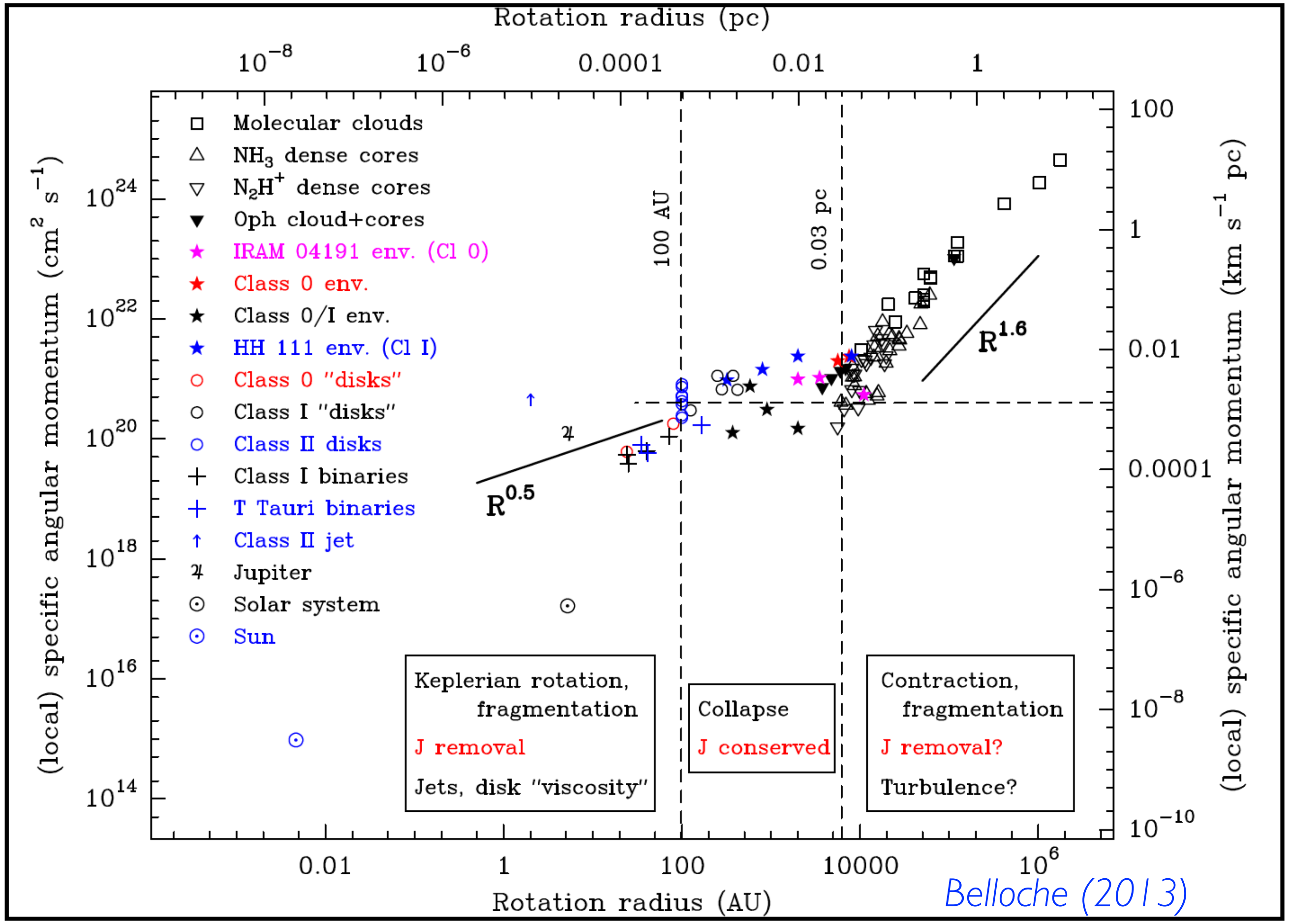
Centrifugal support

Angular momentum conservation

$$j = R_0^2 \omega_0 = R^2 \omega(t)$$

E_{rot}/E_{grav} increases when R decreases

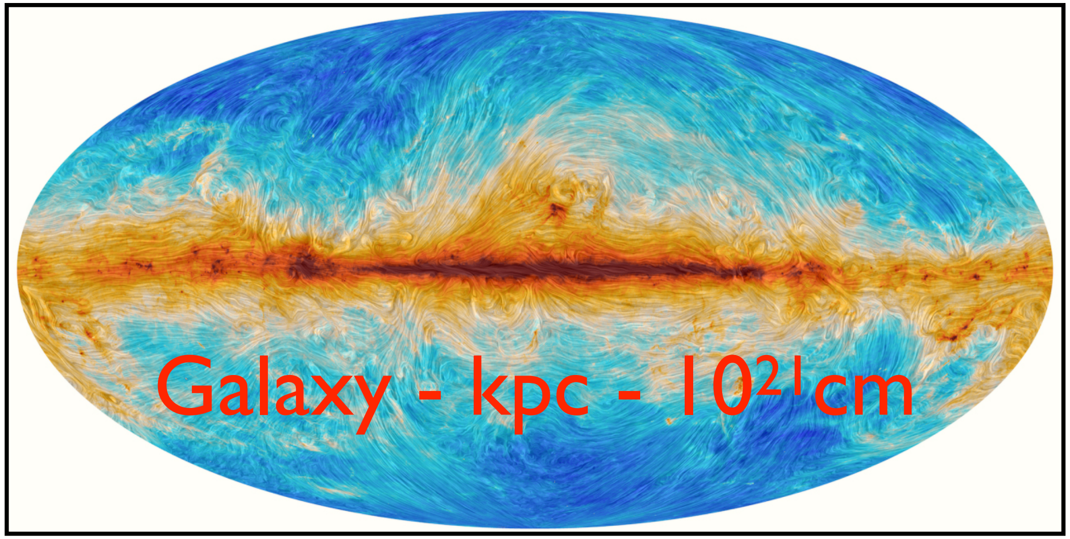
$$\frac{E_{\rm rot}}{E_{\rm grav}} = \frac{MR^2\omega^2}{GM^2/R} \propto \frac{1}{R}$$



Belloche (2013)

A collapsing core must get rid of most of its angular momentum

Magnetic fields are there, at all scales!



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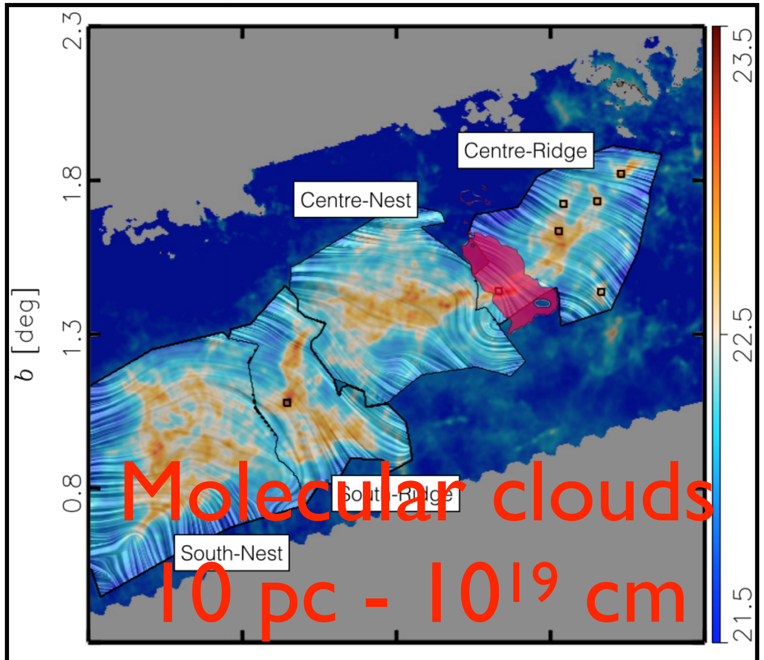
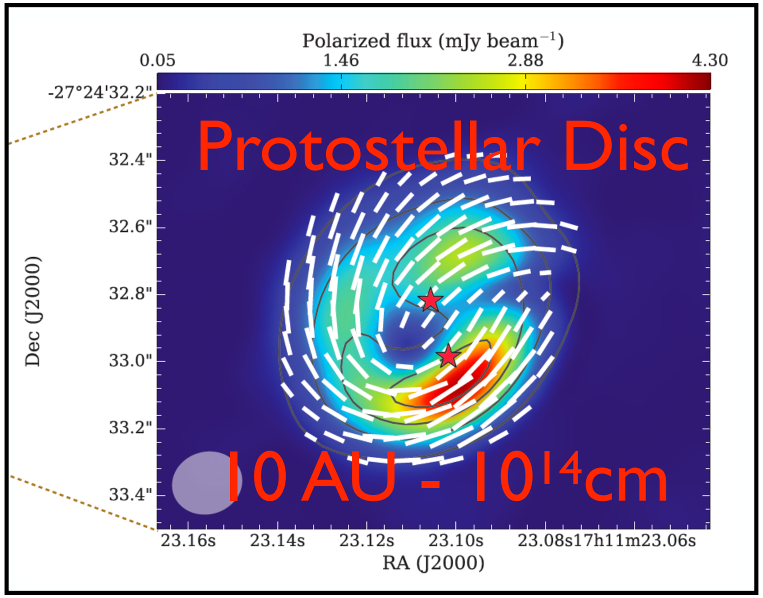
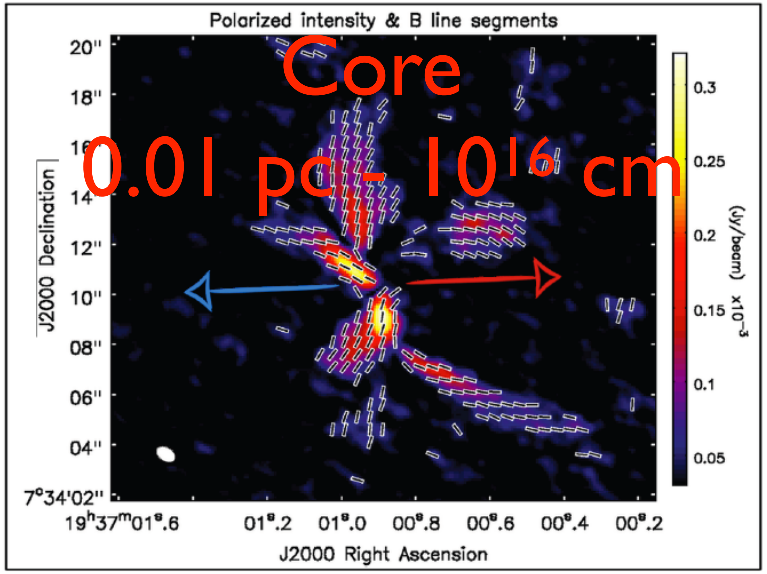


Soler et al. (2017, A&A) - BLASTPol



Alves et al. (2018, A&A) - ALMA



Maury et al. (2018) - ALMA

Fundamental issues - Magnetic flux

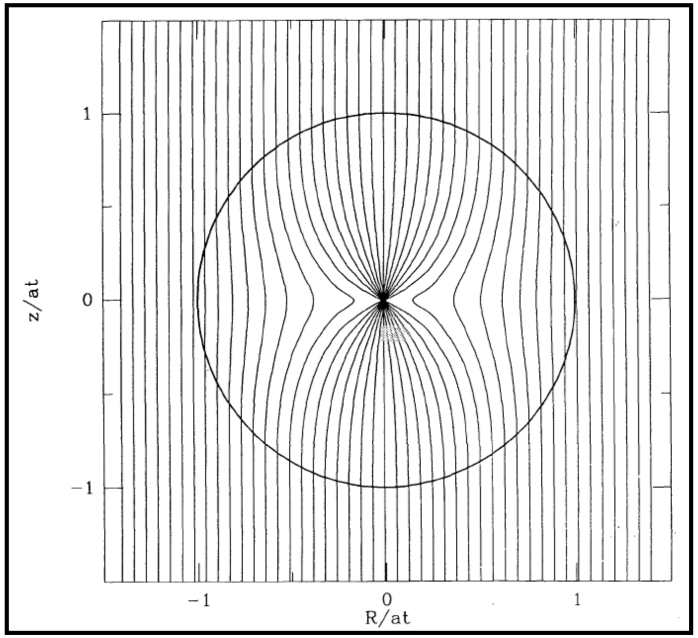
Magnetic support in dense cores

Magnetic flux conservation $\phi \propto BR^2$

E_{mag}/E_{grav} is constant when R decreases

$$\frac{E_{\rm mag}}{E_{\rm grav}} = \frac{B^2 R^3}{GM^2/R} \propto \left(\frac{\phi}{M}\right)^2$$

$\mu = (\phi/M)_{crit}/(\phi/M)$ (observations $\mu \sim 2\text{-}5$)



Galli & Shu (1993)

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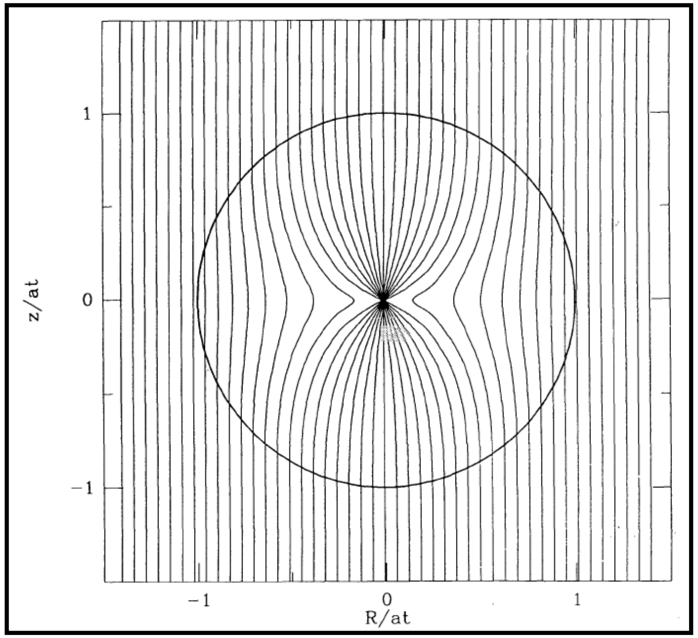


Galli & Shu (1993)

Consider a dense core of initial radius R=0.1 pc and magnetic fields B~ 10 μG

Magnetic flux $\Phi = \pi B R^2 \sim 3 \times 10^{32}$ G cm^2

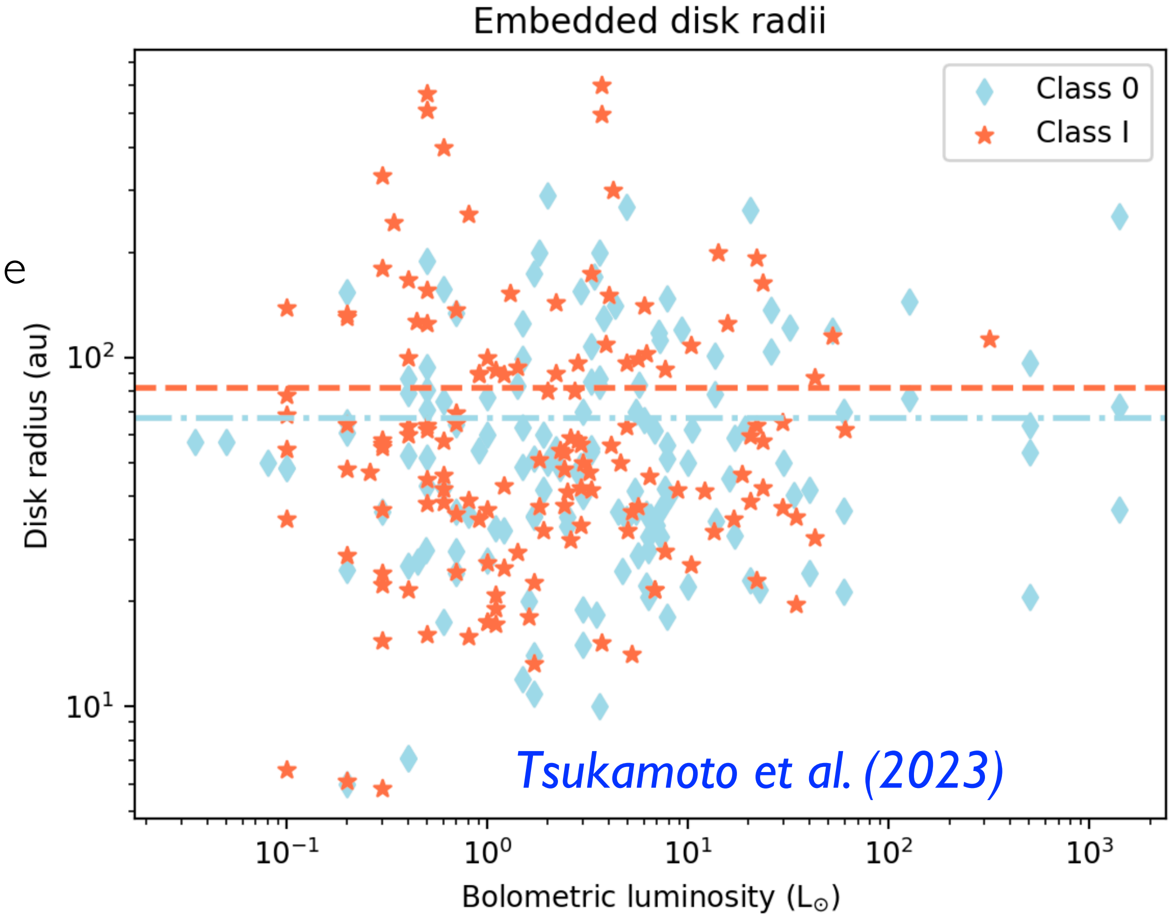
=> if flux is conserved, at a solar radius (6.5×10^{10} cm), **B ~ 10^{10} G**

But Magnetic field in star is observed to be < 10^4 G

A collapsing core must get rid of most of its magnetic flux

Observed disc properties

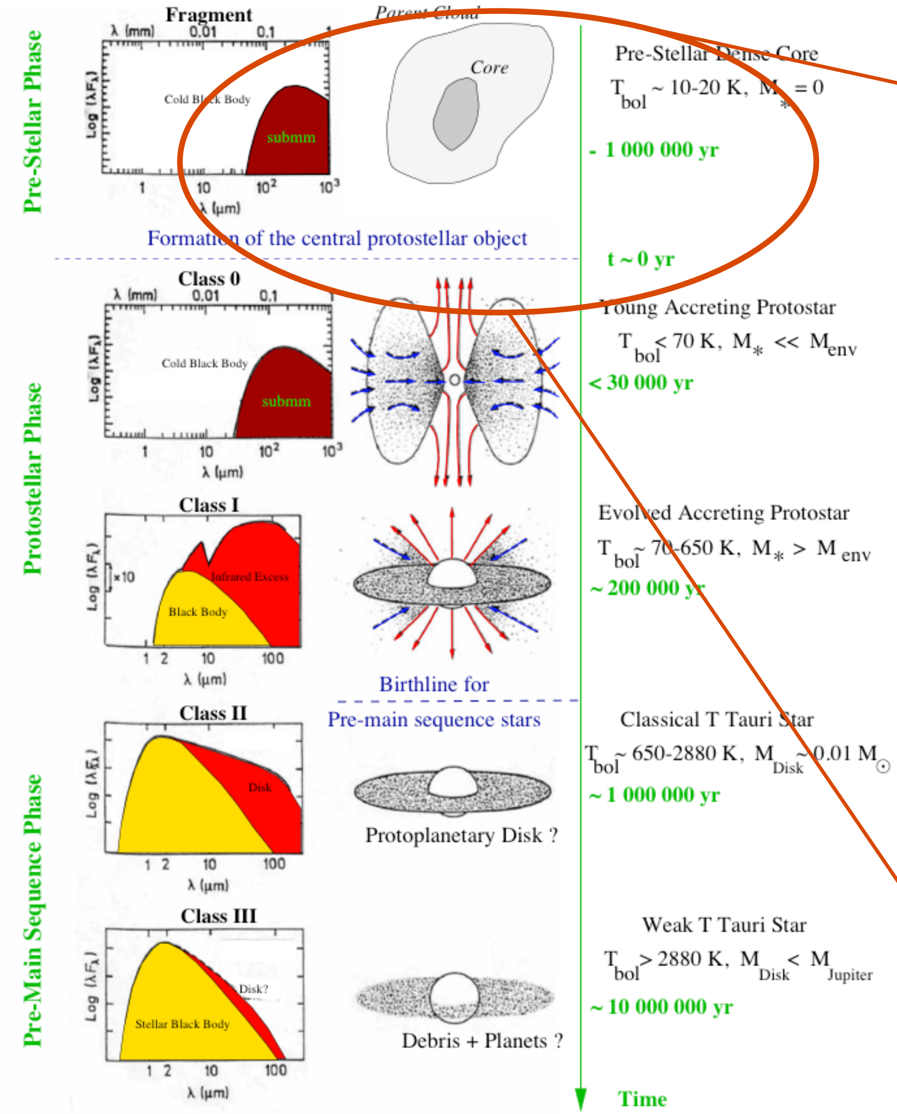
Compilation of Class 0 and Class I protostellar disc radii, from the literature, observed from the dust continuum emission at (sub-)millimeter wavelengths (< 2.7mm)



<u>Assumption</u>: *size of the compact dust emission source corresponds to the gas disc*

Discs are compact: coherent with small angular momentum transmitted, magnetic braking
Trend of increasing radii with age

Star formation evolutionary sequence



André 2002

Prestellar dense core collapse
(R=0.01 pc, T=10 K, n=10^6 cm^{-3})

First collapse

Isothermal ↓ *$10^{4,5}$ yr*

First Larson core
(R=10 AU, T=100 K, n=10^{12} cm^{-3})

Adiabatic ↓ *a few 10^3 yr*

H_2 dissociation

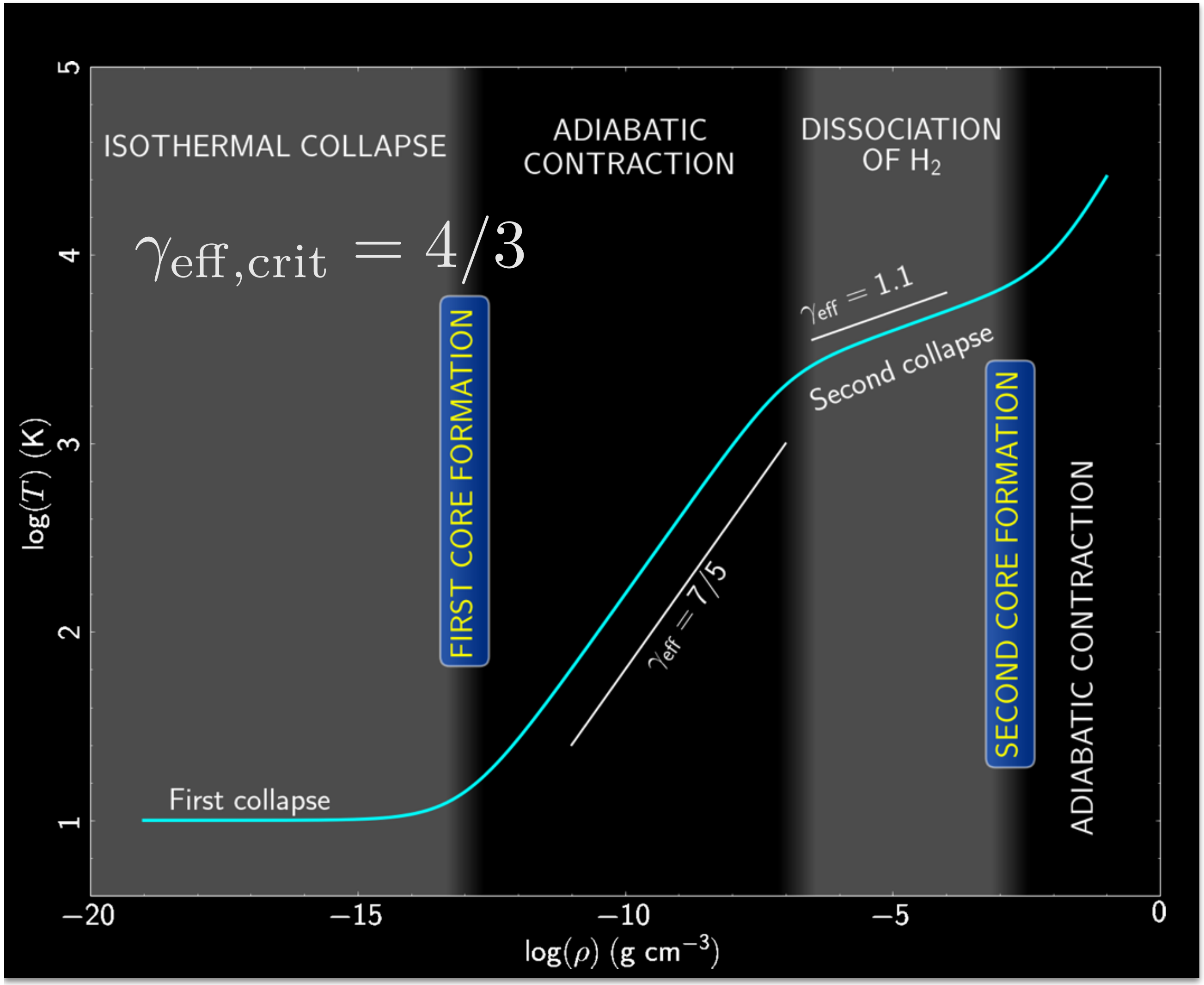
Second collapse

Quasi - isothermal ↓ *10^2 yr*

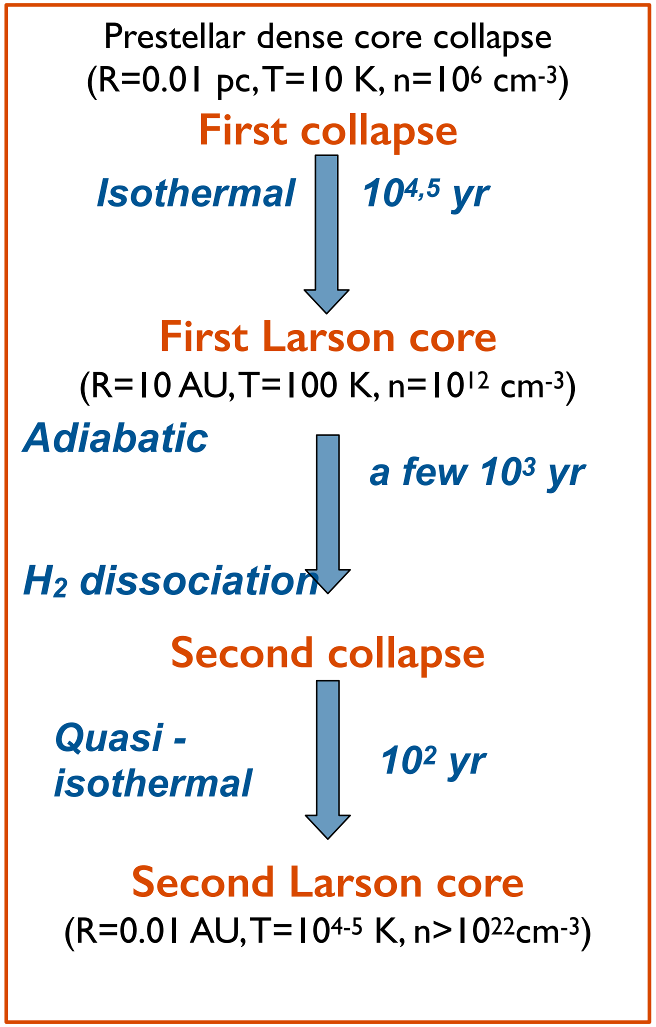
Second Larson core
(R=0.01 AU, T=$10^{4\text{-}5}$ K, n>10^{22}cm^{-3})

Larson (1969)

Star formation evolutionary sequence



Vaytet et al. (2013)

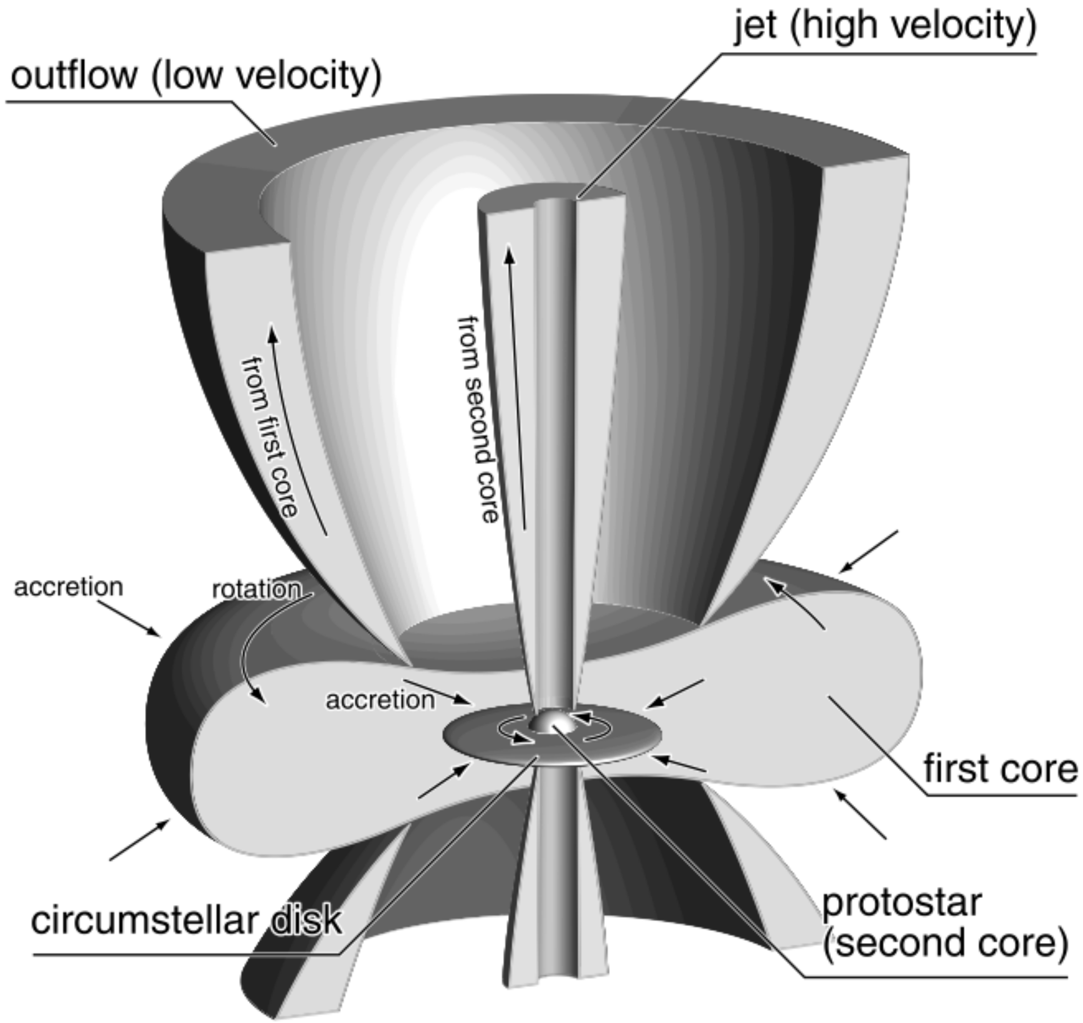


$$M_{\rm Jeans} \propto \rho^{\frac{3\gamma_{\rm eff}}{2}-2} \quad \text{if} \quad P \propto \rho^{\gamma_{\rm eff}}$$

Larson (1969)

Protostar formation

Formation of a very complex structure, with jets, outflows, discs, etc..



Machida et al. (2010)

Protostar formation

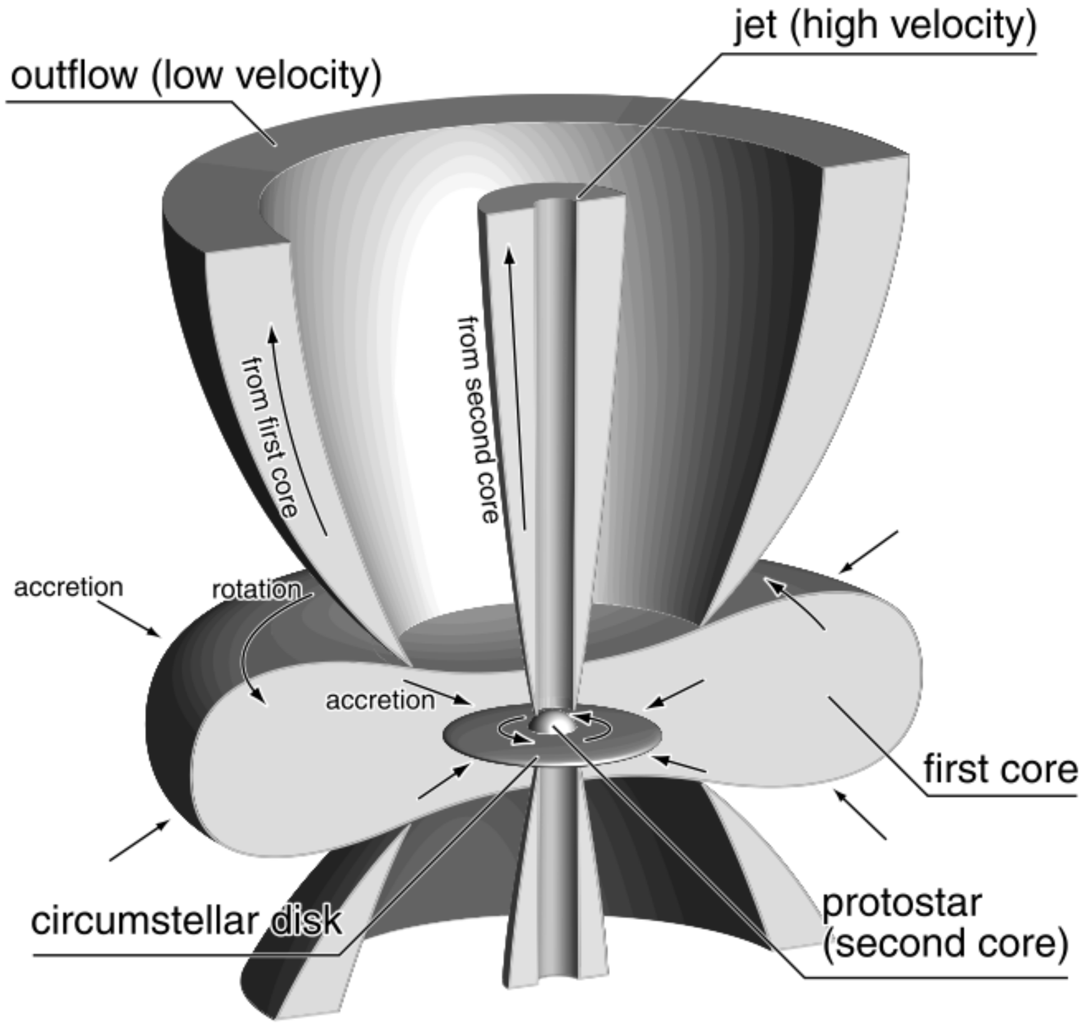
Formation of a very complex structure, with jets, outflows, discs, etc..

What about Bfield evolution?

When does the disc form? Does it fragment?

What are the initial conditions in the protostar?

➡ Implications for planet formation



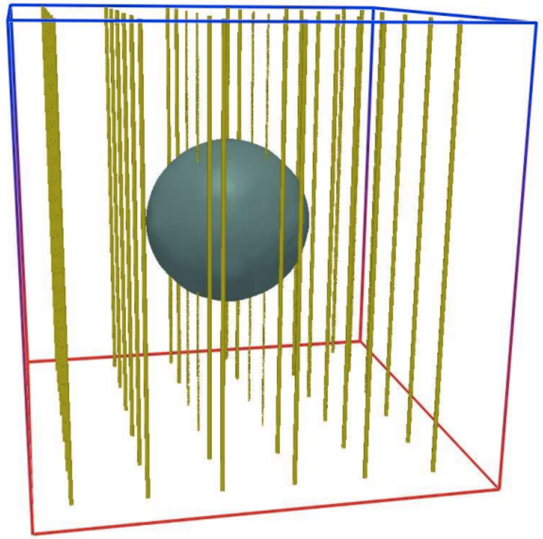
Machida et al. (2010)

Numerical experiments

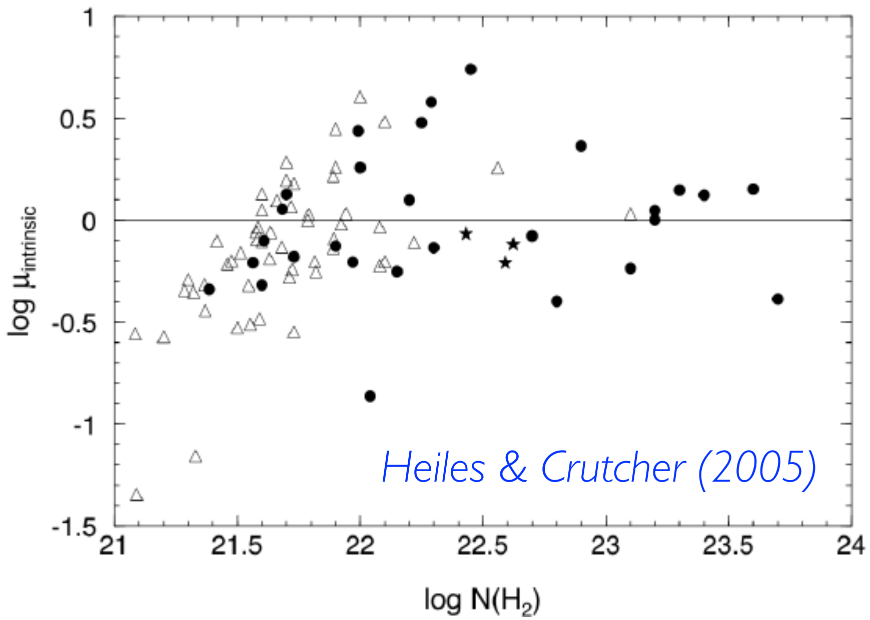
Typical initial conditions:

- 1 - 100s $M_\odot$ isolated dense core
- uniform / BE-like density profile
- uniform temperature (10 K, $\alpha = E_{th}/E_{grav}$)
- solid body / differential rotation ($\beta = E_{rot}/E_{grav}$)
- m=2 density perturbation / turbulent velocity field
- organised magnetic field

$\mu = (\phi/M)_{crit} / (\phi/M)$ (observations $\mu \sim 2\text{-}5$)



Banerjee & Pudritz (2006)

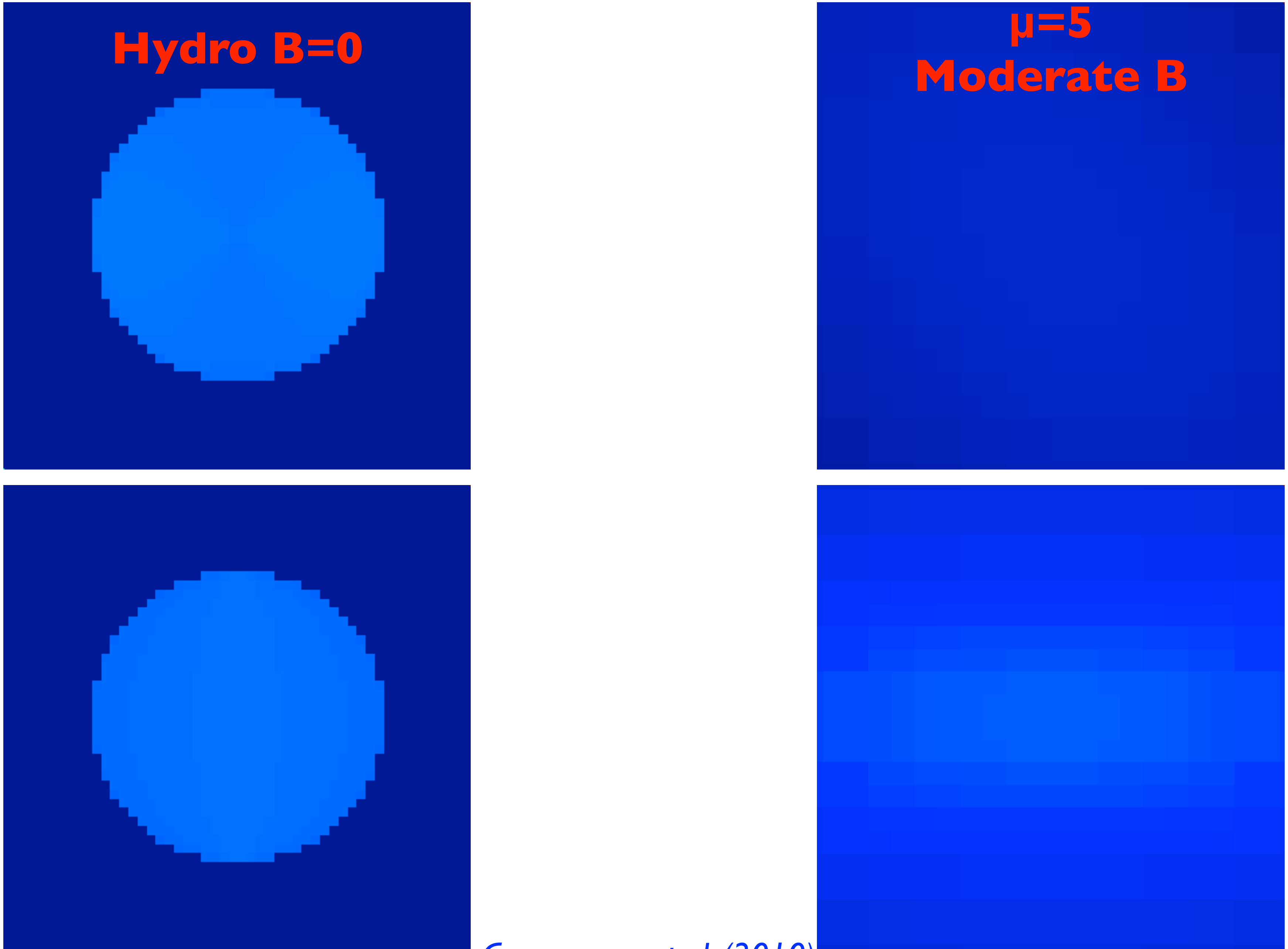


Heiles & Crutcher (2005)

State-of-the-art in early 2010s: ideal MHD

equatorial plane

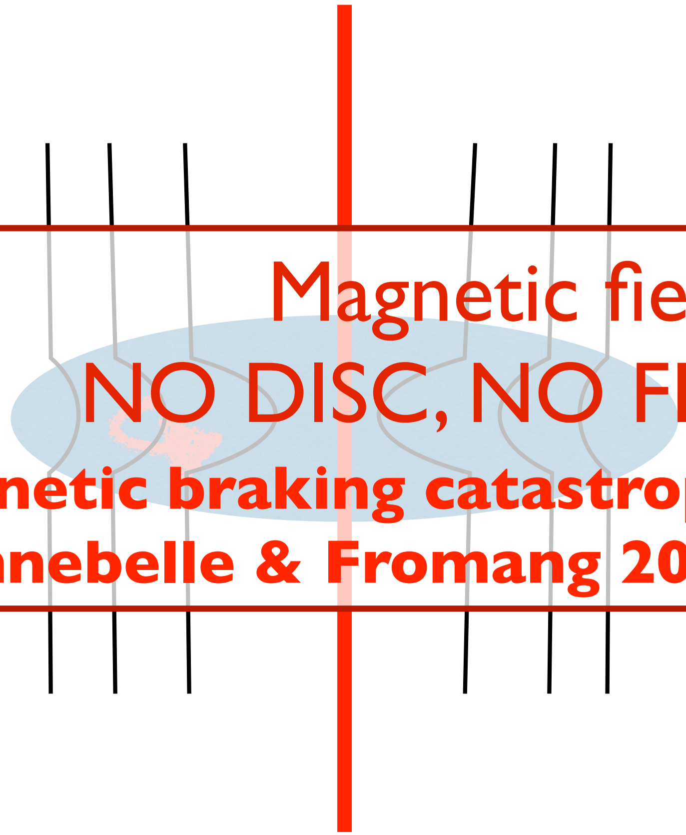
yz - plane



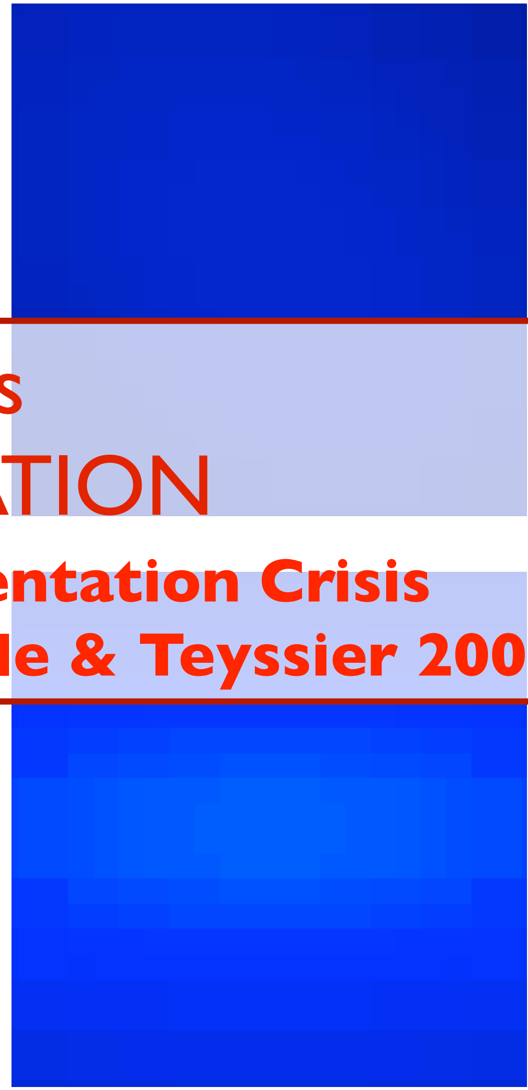
Commerçon et al. (2010)

State-of-the-art in early 2010s: ideal MHD

Magnetic braking



μ=5
Moderate B



Magnetic field dominates

NO DISC, NO FRAGMENTATION

Magnetic braking catastrophe & Fragmentation Crisis
(e.g., Hennebelle & Fromang 2008, Hennebelle & Teyssier 2008)

Commerçon et al. (2010)

Non-ideal MHD

Ohmic diffusion   Hall effect   Ambipolar diffusion

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times \left[\mathbf{u} \times \mathbf{B} - \eta_\Omega \mathbf{J} - \frac{\eta_\mathrm{H}}{||\mathbf{B}||} \mathbf{J} \times \mathbf{B} + \frac{\eta_\mathrm{AD}}{||\mathbf{B}||^2} \mathbf{J} \times \mathbf{B} \times \mathbf{B} \right] = 0$$

Direct effects:

- rearrangement of magnetic field lines
- reconnection
- magnetic flux diffusion

But to compute resistivity, one needs

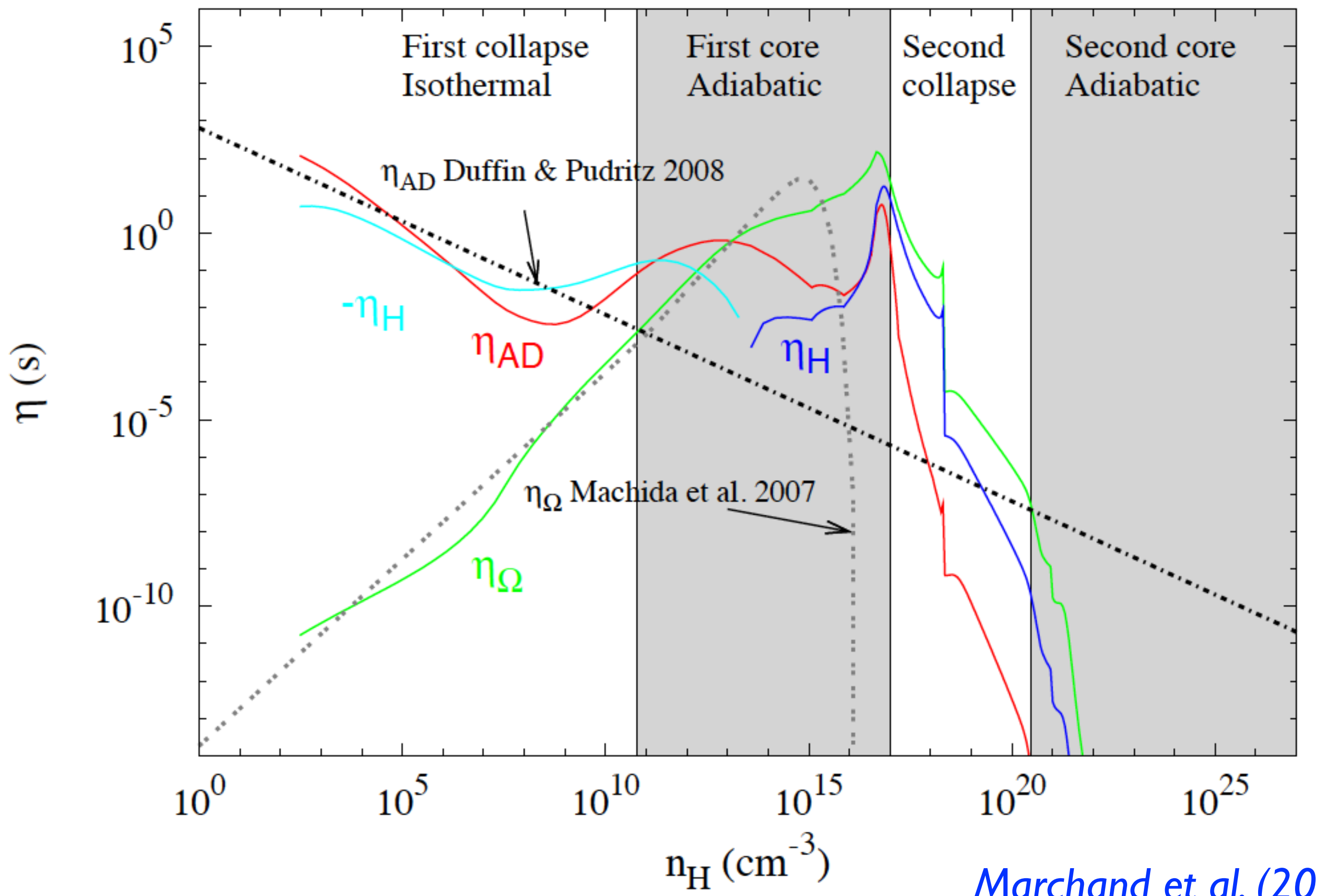
gas-grain chemistry

dust grain population properties

Non-ideal MHD

Ohmic diffusion Hall effect Ambipolar diffusion

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times \left[\mathbf{u} \times \mathbf{B} - \eta_\Omega \mathbf{J} - \frac{\eta_\mathrm{H}}{||\mathbf{B}||} \mathbf{J} \times \mathbf{B} + \frac{\eta_\mathrm{AD}}{||\mathbf{B}||^2} \mathbf{J} \times \mathbf{B} \times \mathbf{B} \right] = 0$$

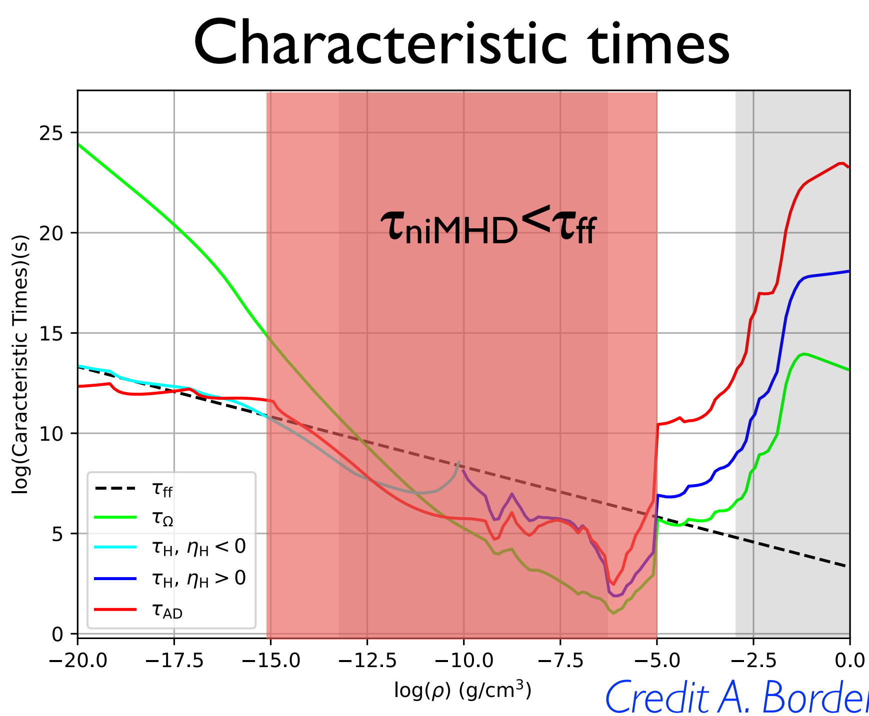


Marchand et al. (2016)

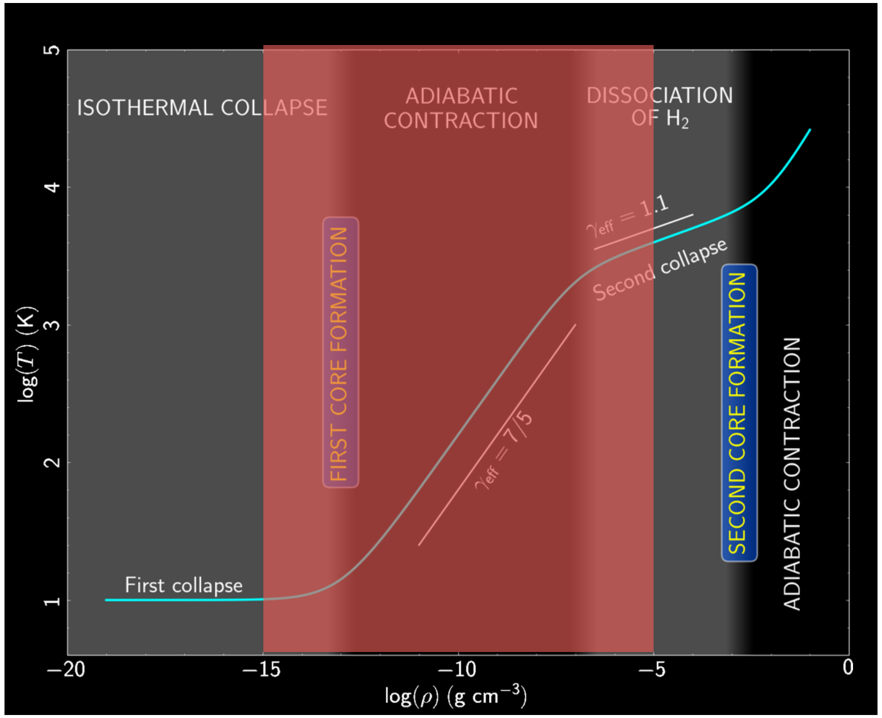
Non-ideal MHD

Ohmic diffusion Hall effect Ambipolar diffusion

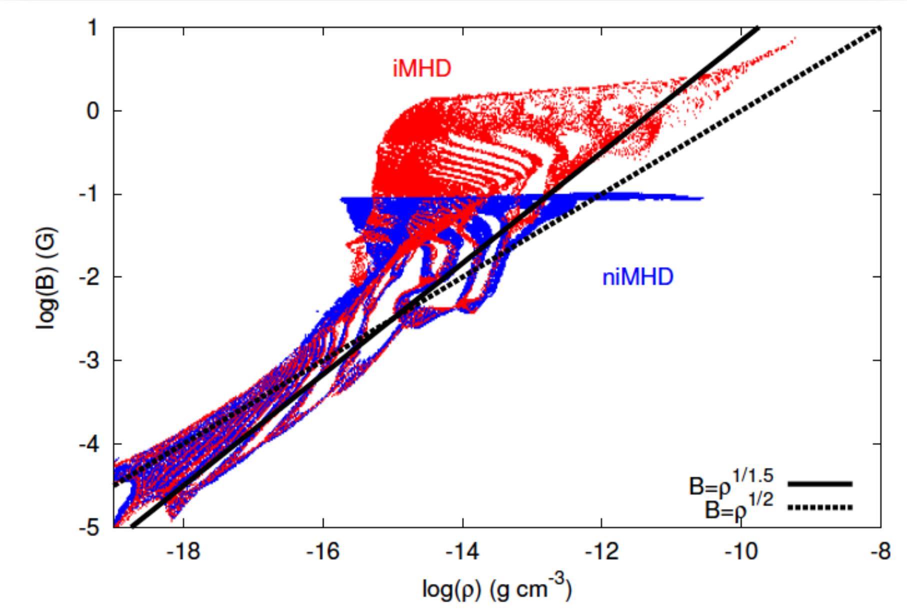
$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times \left[\mathbf{u} \times \mathbf{B} - \eta_\Omega \mathbf{J} - \frac{\eta_{\rm H}}{||\mathbf{B}||} \mathbf{J} \times \mathbf{B} + \frac{\eta_{\rm AD}}{||\mathbf{B}||^2} \mathbf{J} \times \mathbf{B} \times \mathbf{B} \right] = 0$$



Credit A. Borderies



1 M⊙: Ambipolar diffusion



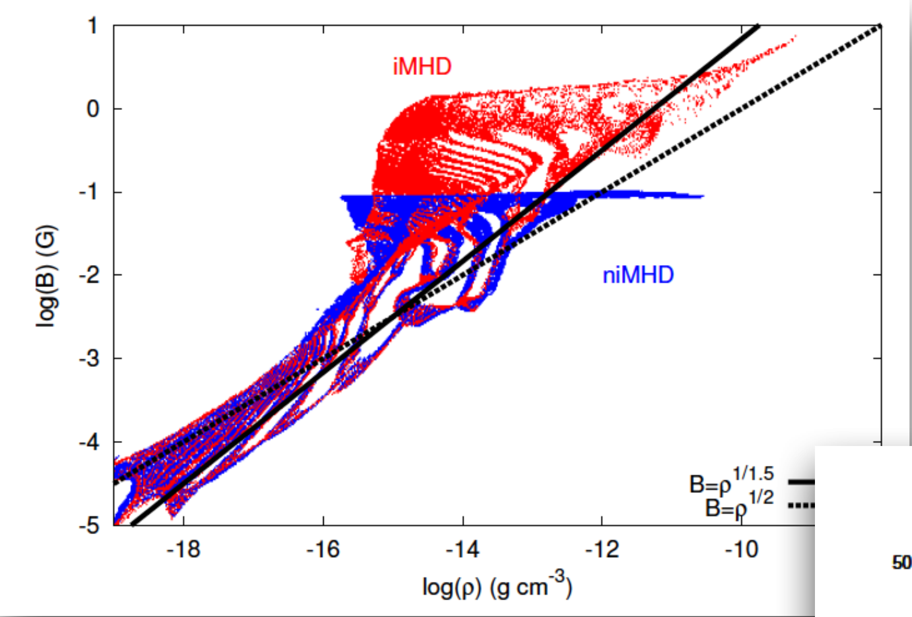
- formation of a **plateau** at B~0.1G
- **reorganisation** of magnetic field lines (essentially **poloidal**)

=> **reduced magnetic braking**

=> solution to the magnetic flux problem

Masson et al. (2016)

1 M⊙: Ambipolar diffusion



- formation of a **plateau** at B~0.1G
- **reorganisation** of magnetic field lines (essentially **poloidal**)

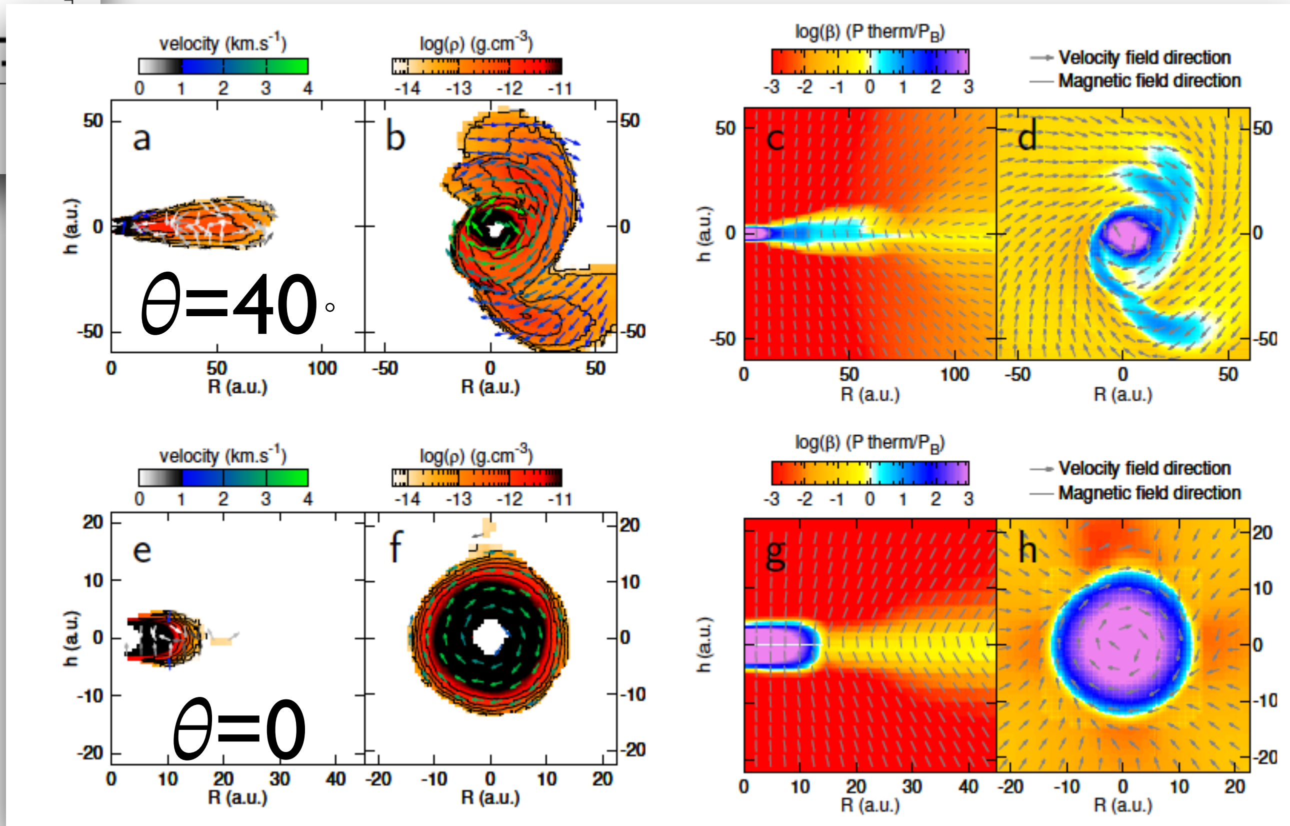
=> **reduced magnetic braking**

=> solution to the magnetic flux problem

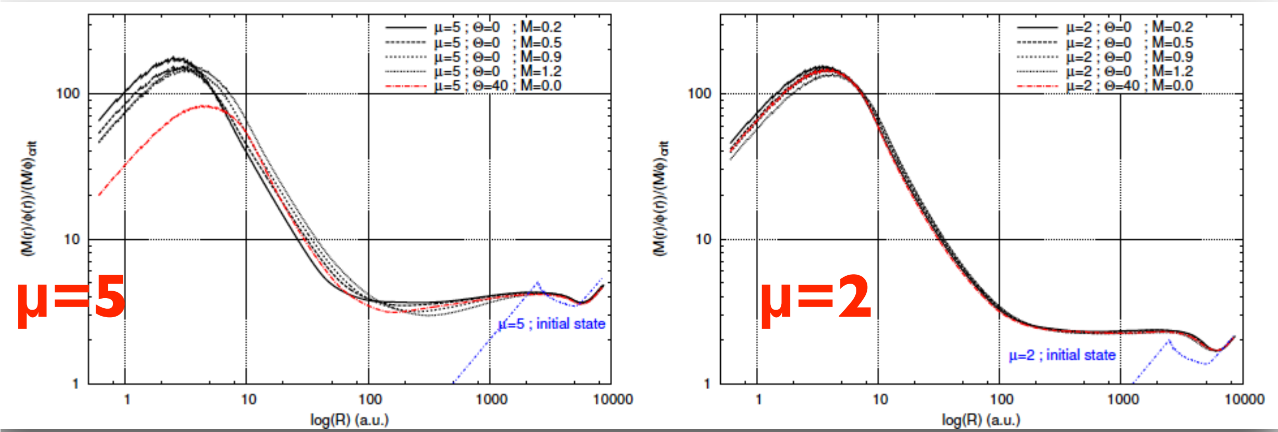
- Rotationally supported disc formation (**R ~ 50 AU**) - consistent with obs.
- **P_{therm}/P_{mag}>1** within discs
- **vertical** magnetic field in the disc

=> initial conditions for protoplanetary discs studies

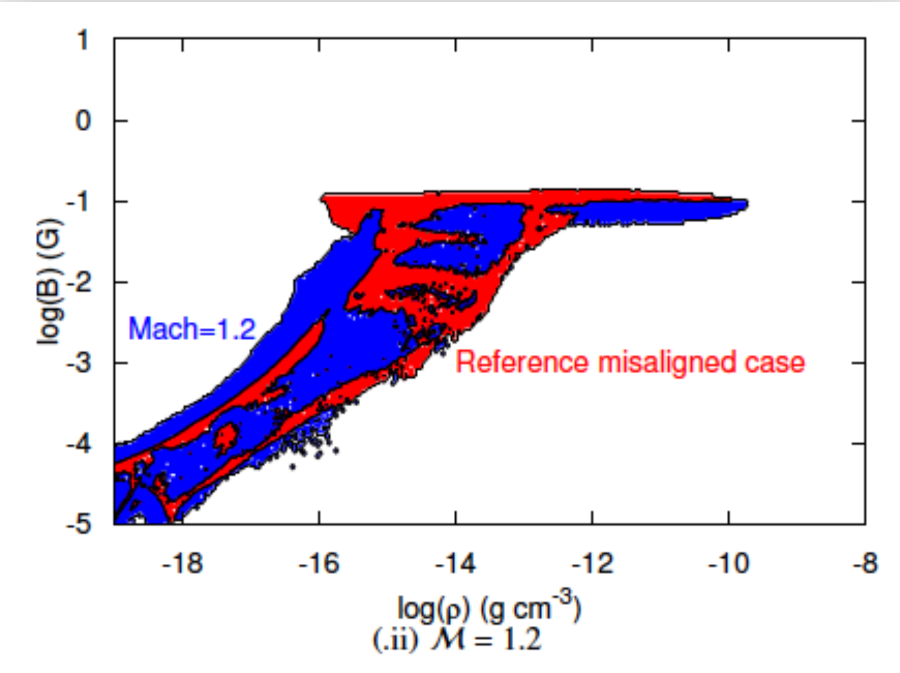
Masson et al. (2016)

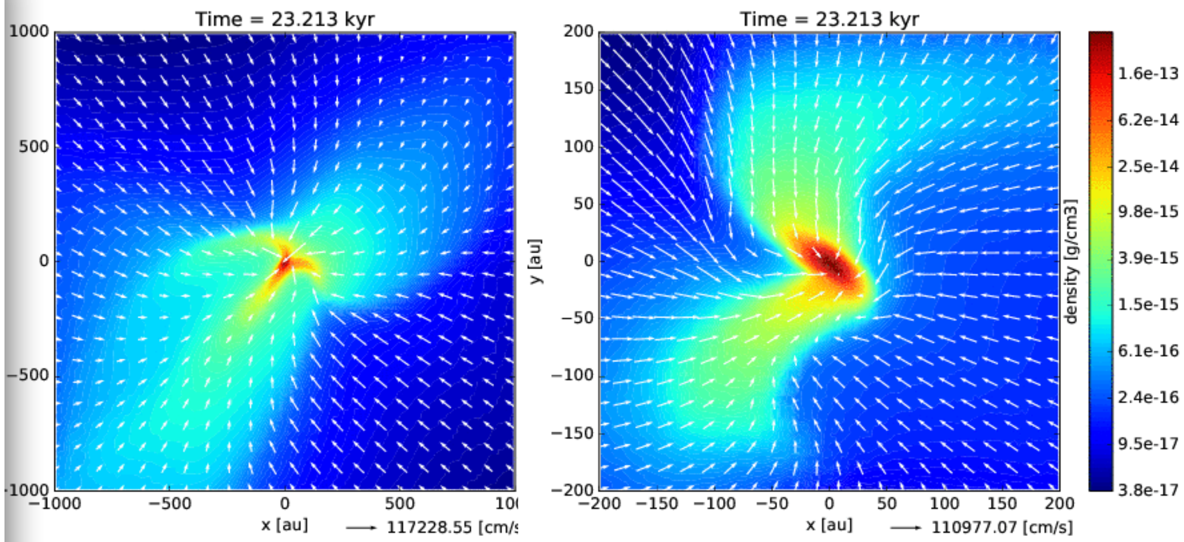


1 M⊙: Turbulence and ambipolar diffusion



- magnetisation & disc size **does not depend** on turbulence level, nor on the initial magnetic field amplitude

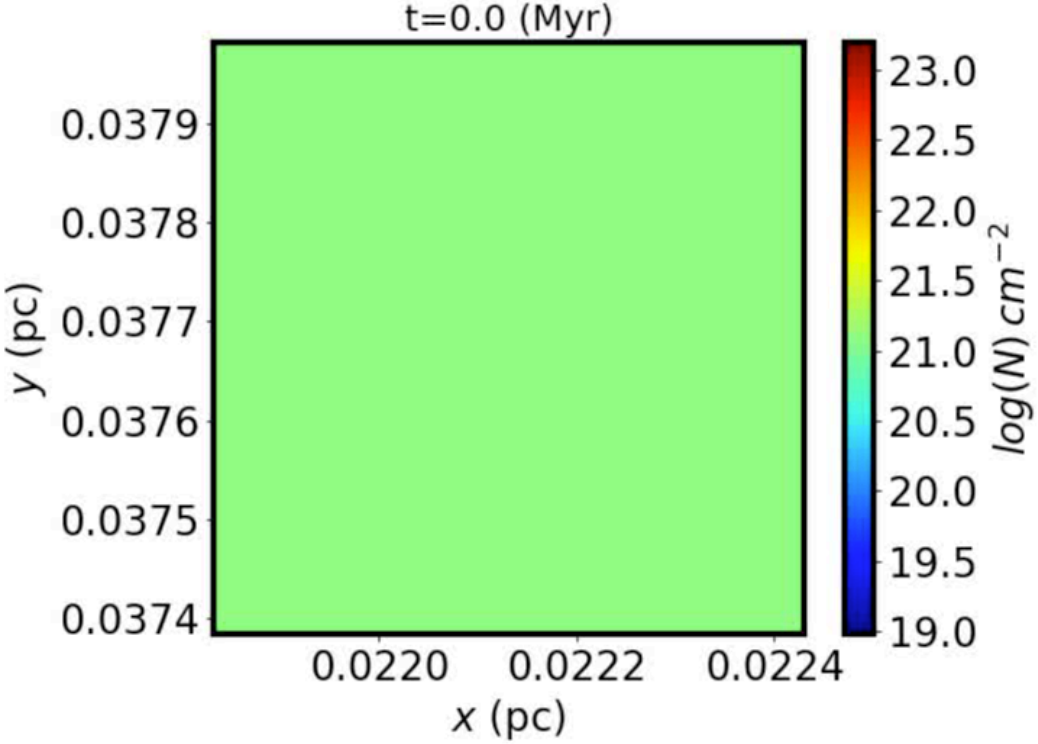




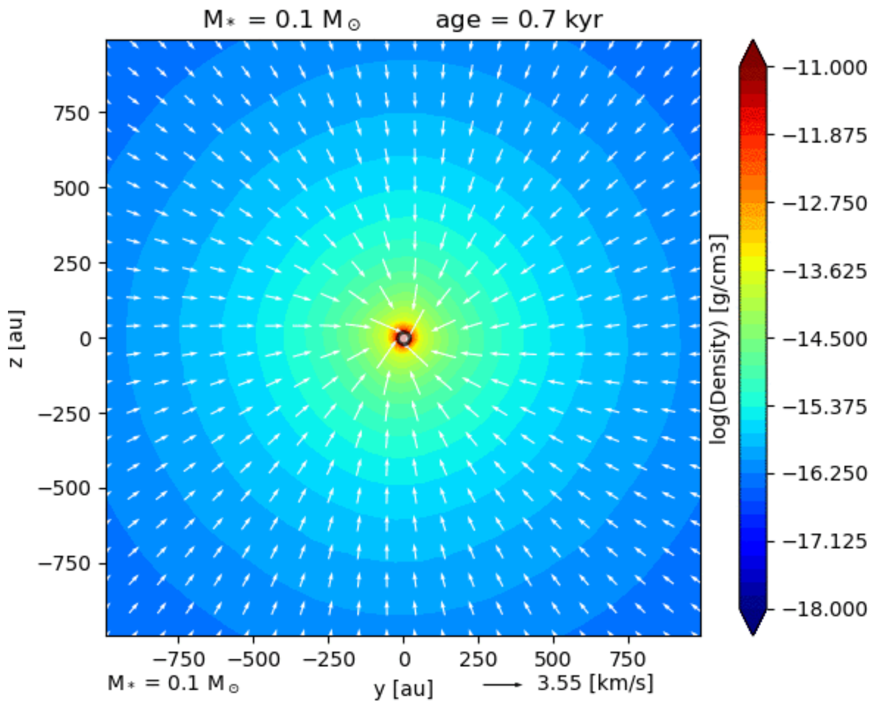
Convergence!

Long time integration

Low-mass core - 1M$_\odot$	Massive core - 100 M$_\odot$
100 kyr!	70 kyr



Hennebelle et al. (2020)



Commerçon et al. (2021)

Magnetically regulated disc size with AD

Hennebelle et al. (2016)

$$\tau_{\rm far} \simeq \frac{B_\phi h}{B_z v_\phi} \qquad \tau_{\rm br} \simeq \frac{\rho v_\phi 4\pi h}{B_z B_\phi}$$

$$\tau_{\rm diff} \simeq \frac{4\pi h^2}{c^2 \eta_{\rm AD}} \frac{B_z^2 + B_\phi^2}{B_z^2} \simeq \frac{4\pi h^2}{c^2 \eta_{\rm AD}} \qquad \tau_{\rm rot} \simeq \frac{2\pi r}{v_\phi}$$

$$r_{\rm d,AD} \simeq 18\ {\rm au} \times \delta^{2/9} \left(\frac{\eta_{\rm AD}}{0.1\ {\rm s}}\right)^{2/9} \left(\frac{B_z}{0.1\ {\rm G}}\right)^{-4/9} \left(\frac{M_{\rm d} + M_*}{0.1\ M_\odot}\right)^{1/3}$$

- disc size **does not depend** on turbulence level
- weak dependance on the mass

VS.

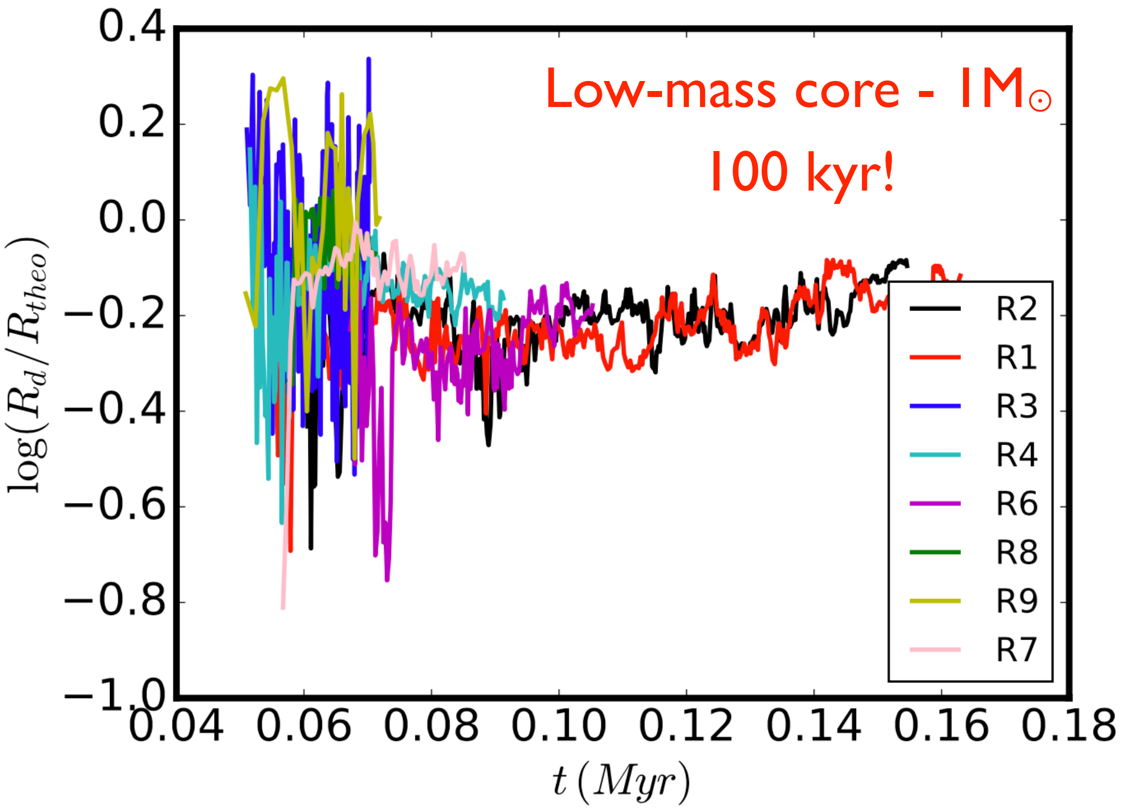
$$r_{\rm d,hydro} \simeq \frac{\Omega_0^2 R_0^4}{4\pi/3\rho_0 R_0^3 G} = 3\beta R_0 = 106\ {\rm AU}\ \frac{\beta}{0.02} \left(\frac{M}{0.1\,{\rm M}_\odot}\right)^{1/3} \left(\frac{\rho_0}{10^{-18}{\rm g\,cm^{-3}}}\right)^{-1/3}$$

Magnetically regulated disc size with AD

$$r_{\rm d,AD} \simeq 18\ \mathrm{au} \times \delta^{2/9} \left(\frac{\eta_{\rm AD}}{0.1\ \mathrm{s}}\right)^{2/9} \left(\frac{B_z}{0.1\ \mathrm{G}}\right)^{-4/9} \left(\frac{M_{\rm d}+M_*}{0.1\ M_\odot}\right)^{1/3}$$

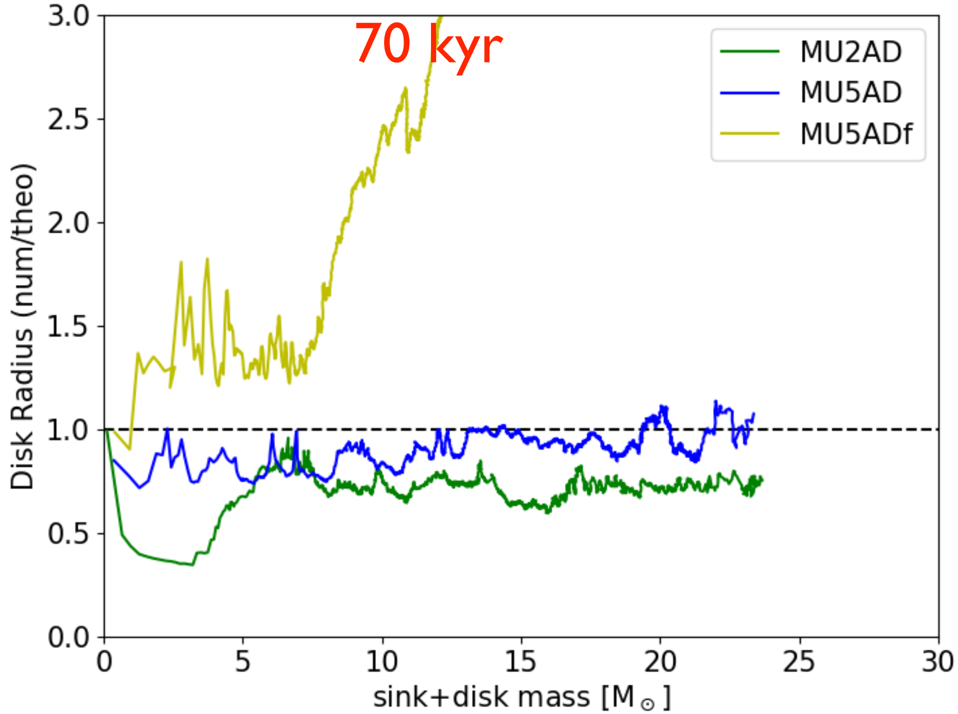
Hennebelle et al. (2016)

- very good agreement between the analytical and experimental values
- disc size **does not depend** (too much) **on initial conditions**



Hennebelle et al. (2020)

Massive core - 100 M☉



Commerçon et al. (2021)

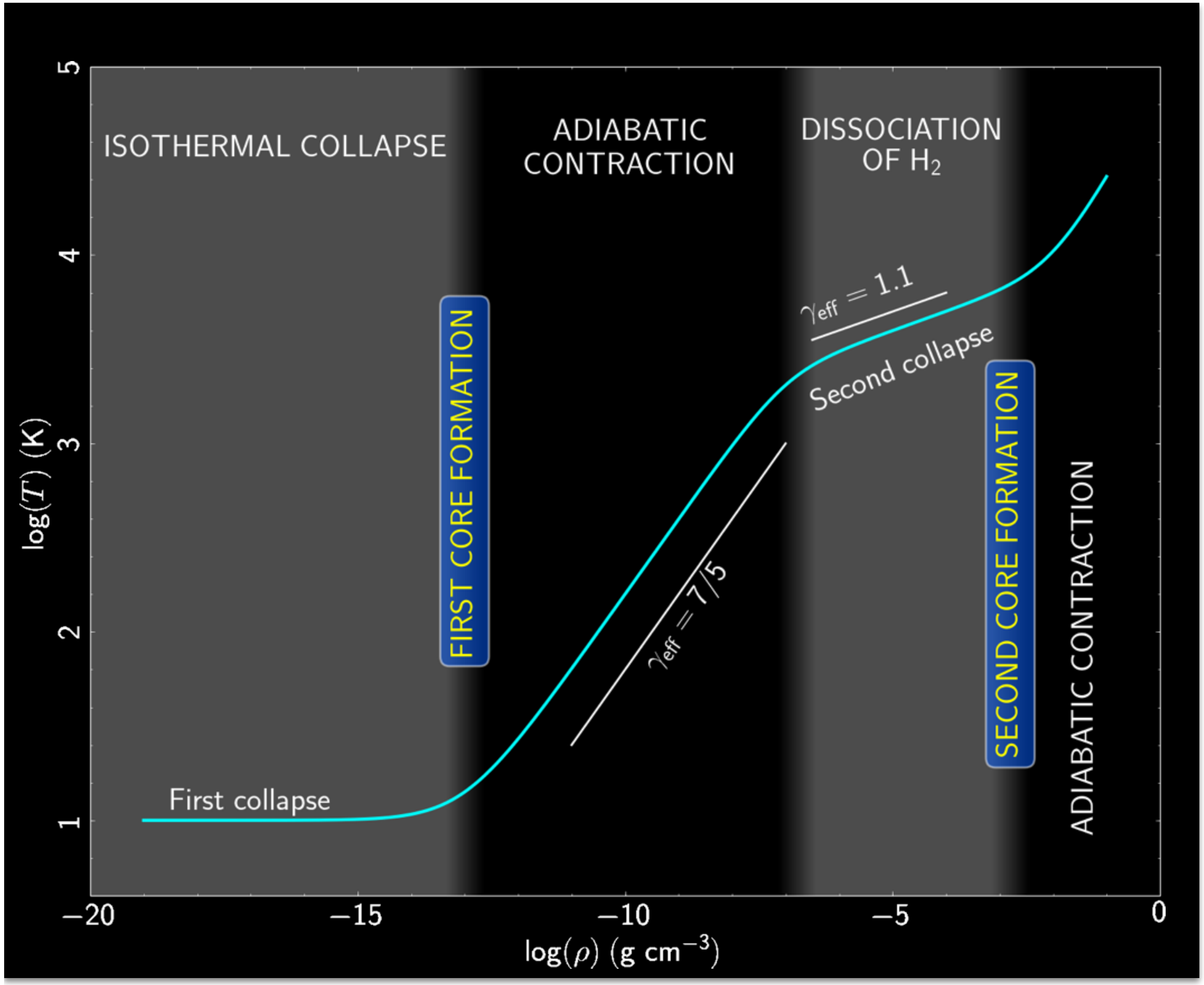
Take away I

- ✓ Disc formation is regulated by non-ideal processes
- ✓ Magnetic regulation works for low- and high-mass protostar formation
- ✓ Prediction of magnetic fields properties at disc (au) scales

Outline

1. Introduction
2. Dense core collapse, disc formation (pc to au)
3. **Formation of the protostar (au to $R_\odot$)**
4. Observations
5. Perspectives

Star formation evolutionary sequence



Vaytet et al. (2013)

$$M_{\mathrm{Jeans}} \propto \rho^{3\gamma_{\mathrm{eff}}-4}$$

Prestellar dense core collapse
(R=0.01 pc, T=10 K, n=10^6 cm^{-3})

First collapse

Isothermal ↓ ***$10^{4,5}$ yr***

First Larson core

(R=10 AU, T=100 K, n=10^{12} cm^{-3})

Adiabatic ↓ ***a few 10^3 yr***

H_2 dissociation

Second collapse

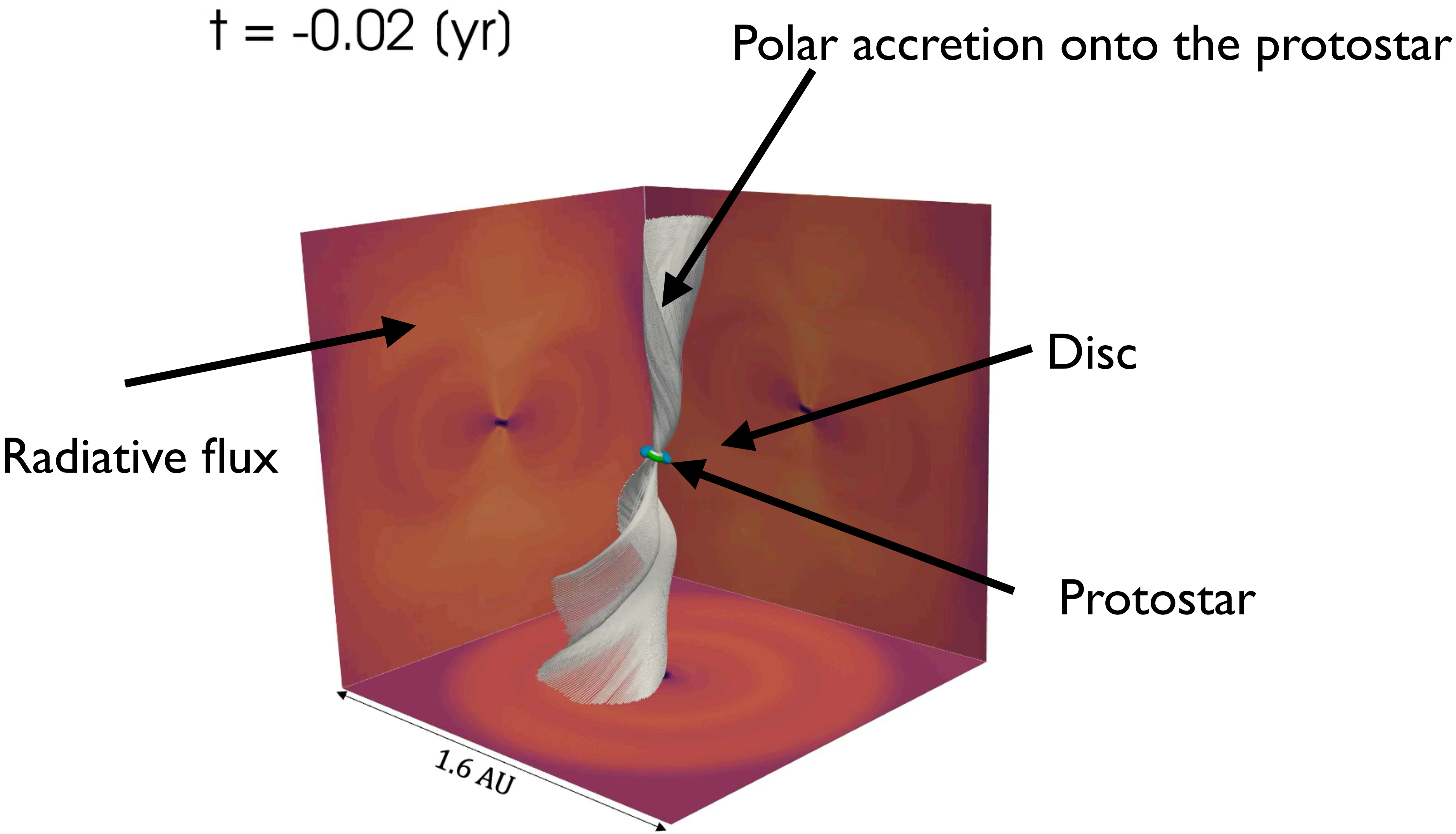
Quasi - isothermal ↓ ***10^2 yr***

Second Larson core

(R=0.01 AU, T=10^{4-5} K, n=0.01cm^{-3})

Larson (1969)

Sub-au disc evolution - hydro + rotation



Ahmad et al. (2024)

Disc quickly expands to au size

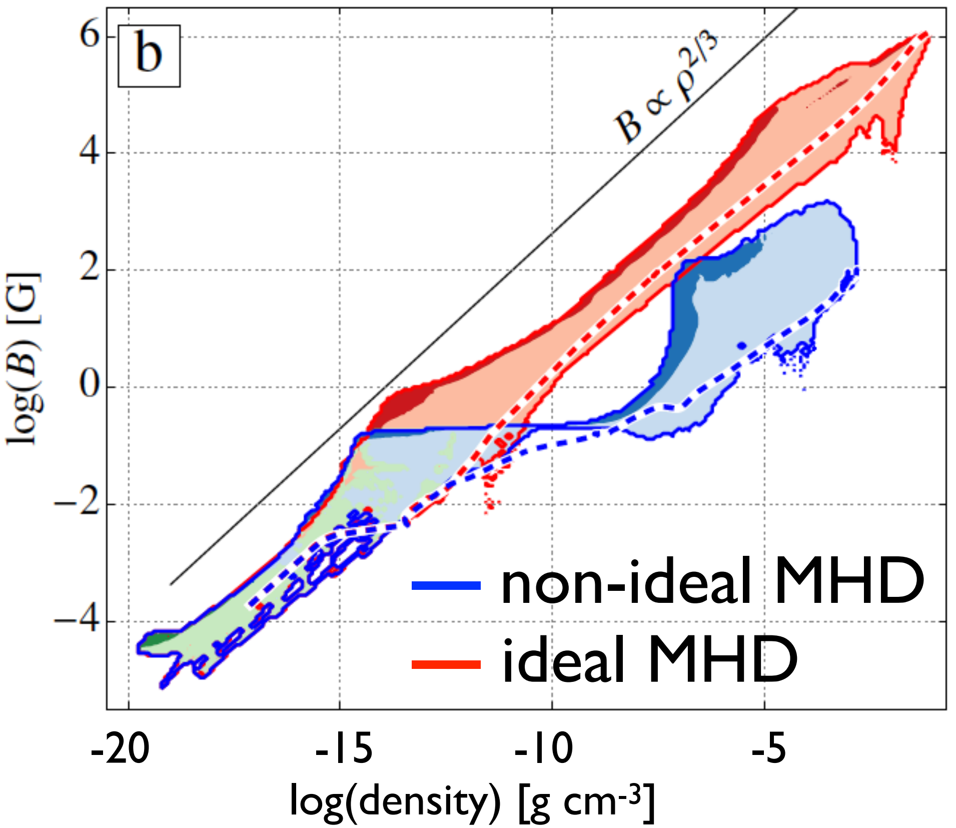
Second collapse with (non-ideal) MHD

- Ohmic + ambipolar diffusion
- non-ideal gas EOS

Vaytet et al. (2018)

Saumon, Chabrier & Von Horn (1995)

- maximum resolution : $\Delta x \sim 8 \times 10^{-5}$ AU (21 AMR levels)



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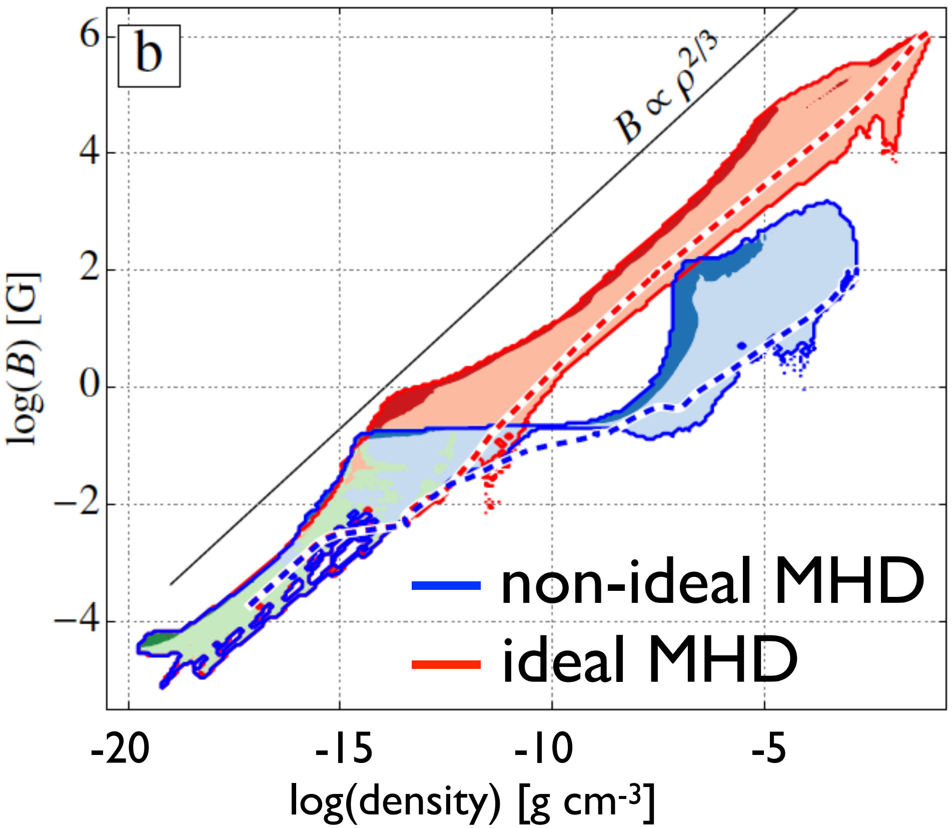
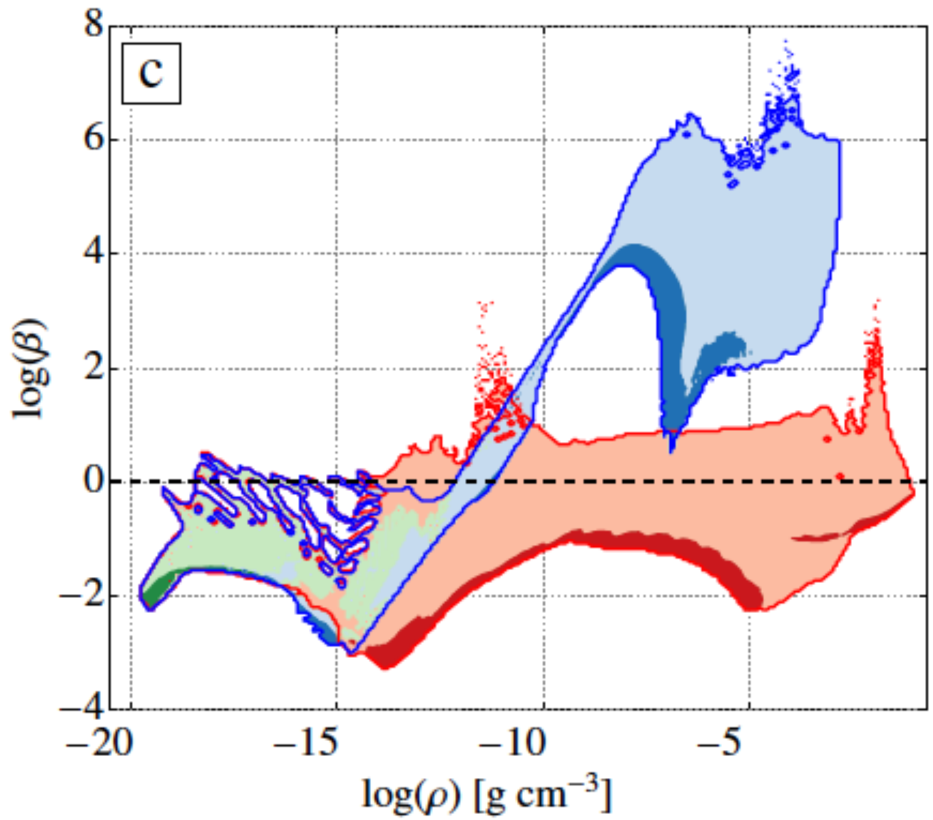




Magnetic flux reduced by ~3 orders of magnitude with **non-ideal MHD**

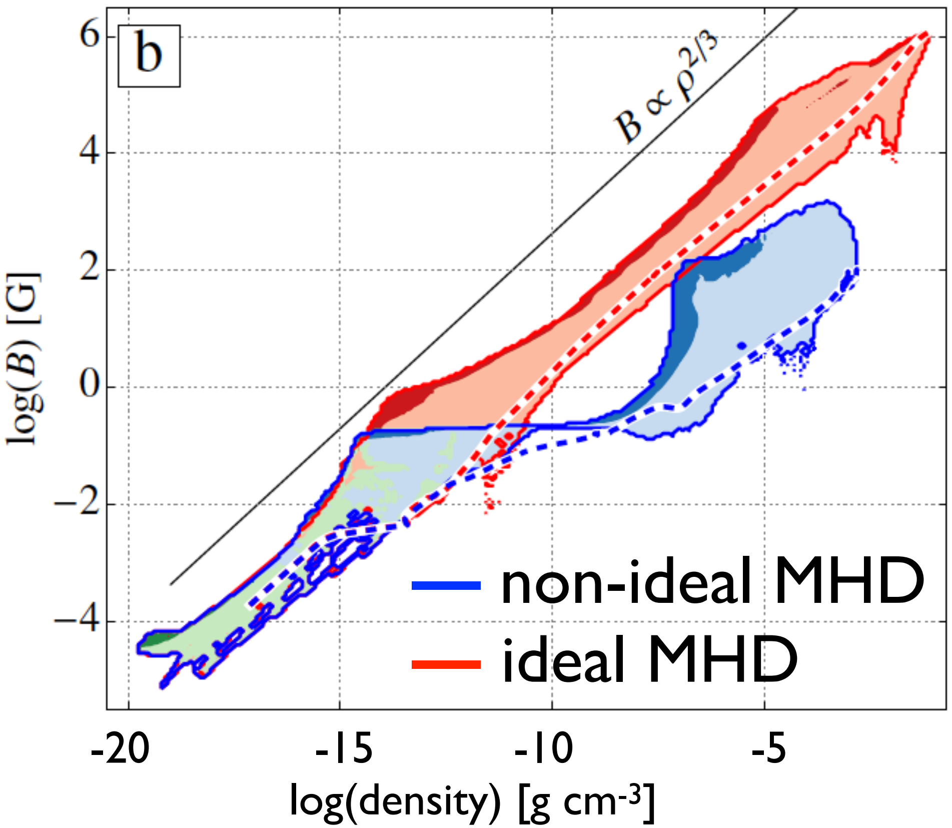
Second collapse with (non-ideal) MHD

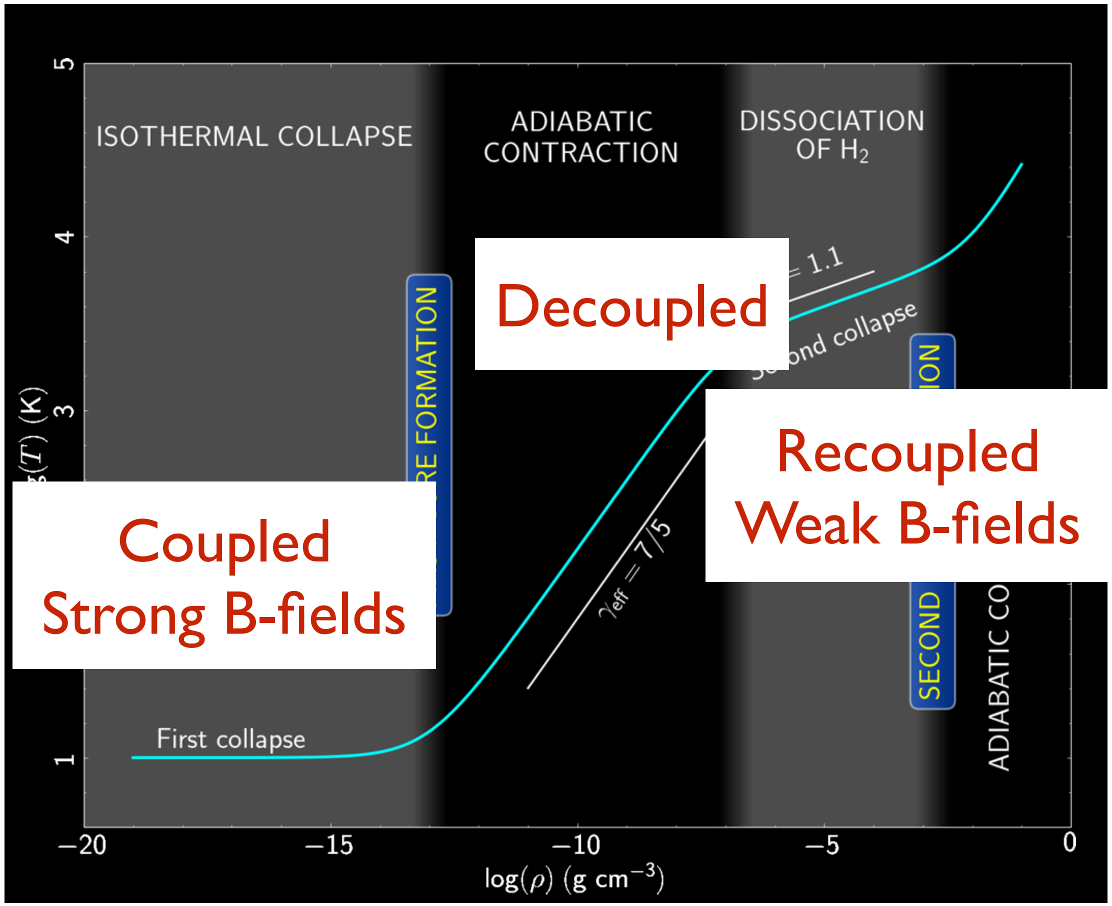
- Ohmic + ambipolar diffusion
- non-ideal gas EOS

Vaytet et al. (2018)

Saumon, Chabrier & Von Horn (1995)

- maximum resolution : Δx~8x10^{-5} AU (21 AMR levels)

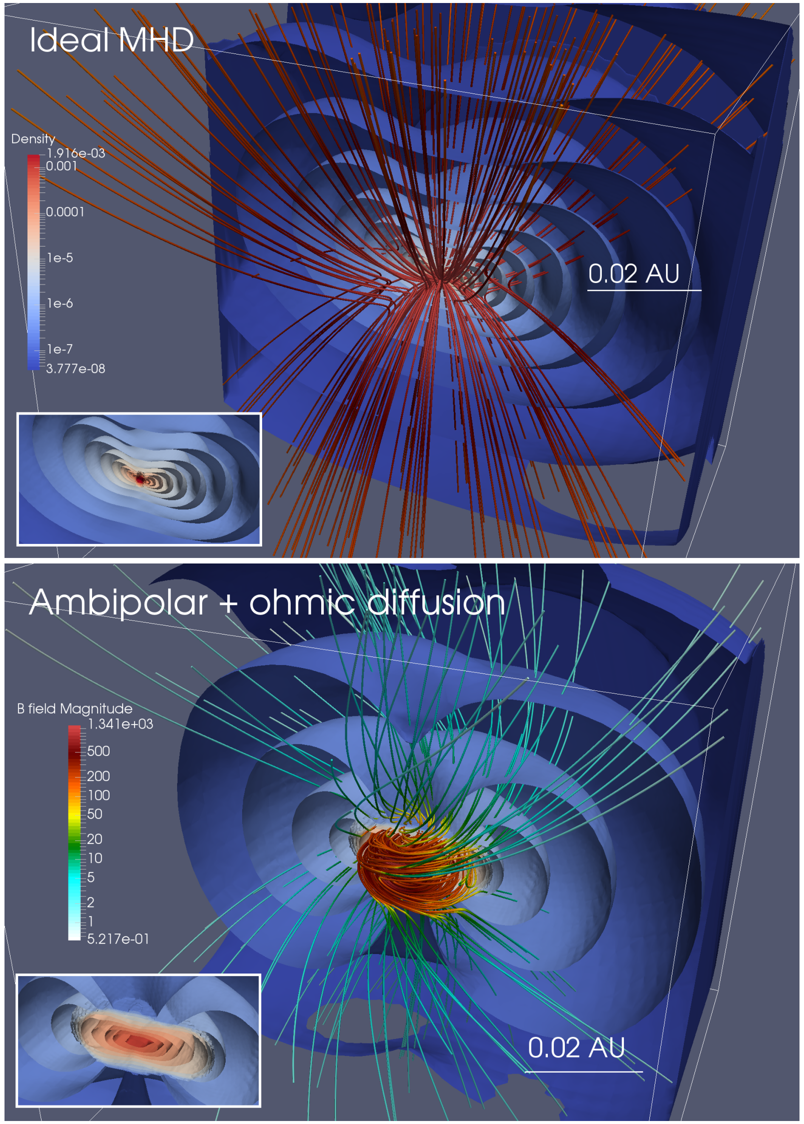




Magnetic flux reduced by ~3 orders of magnitude with **non-ideal MHD**

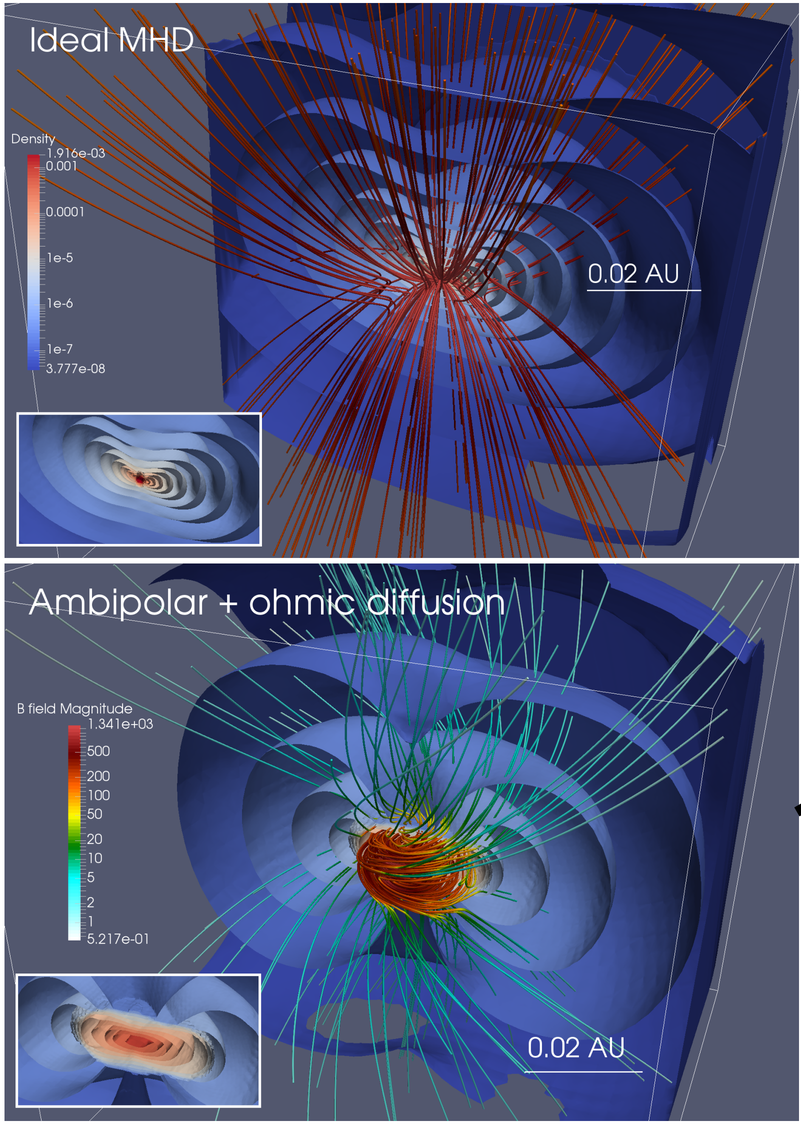
Second collapse - B-field morphology

Vaytet et al. (2018)



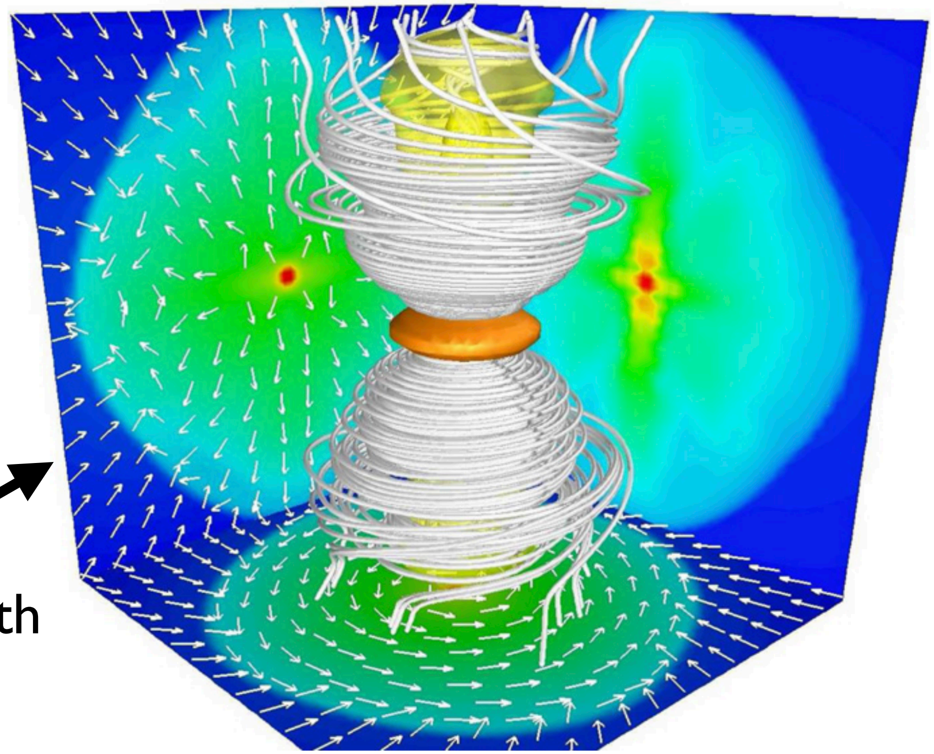
Second collapse - jet launching

Vaytet et al. (2018)



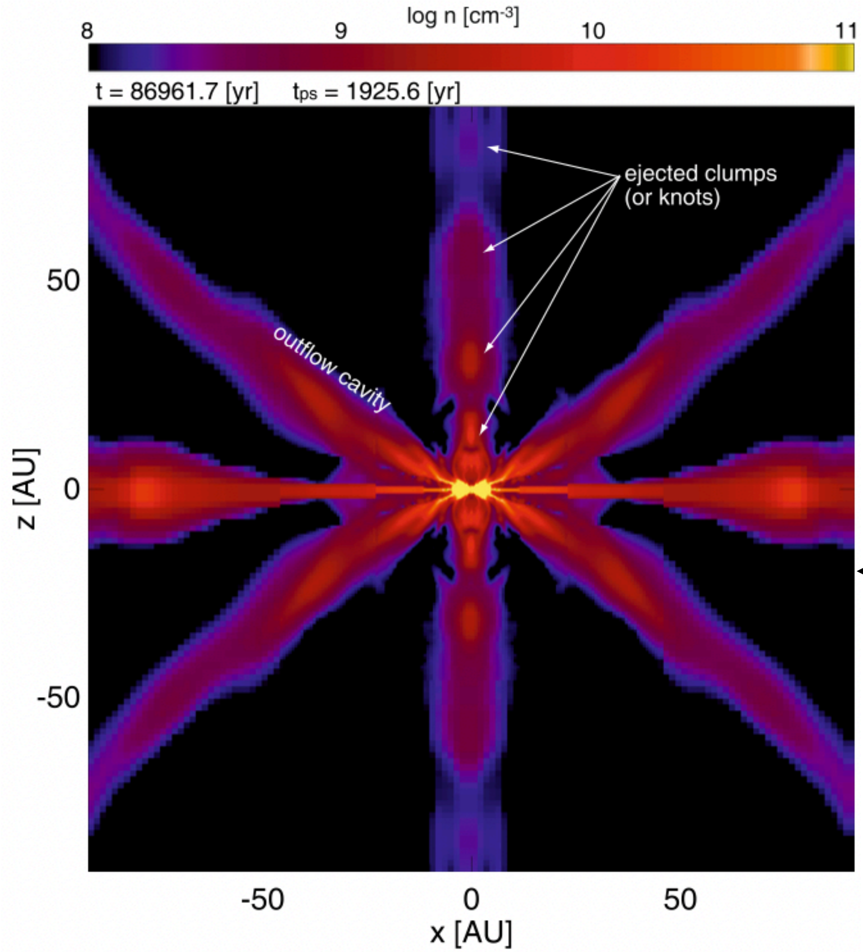
A month

Tomida et al. (2013)



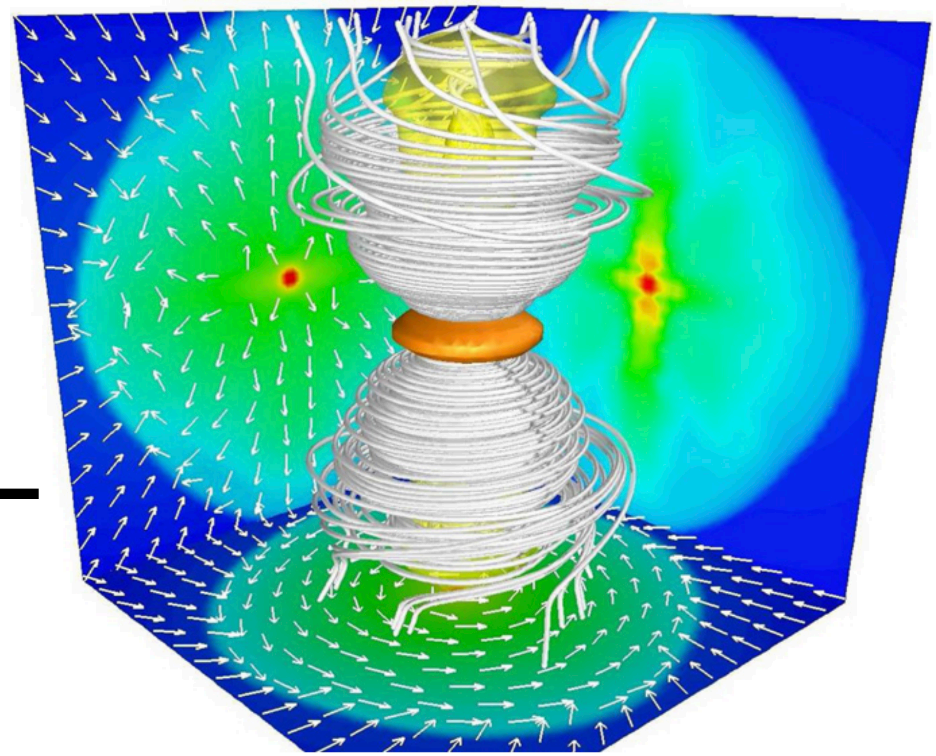
Towards jet and outflow

Machida & Basu (2019)



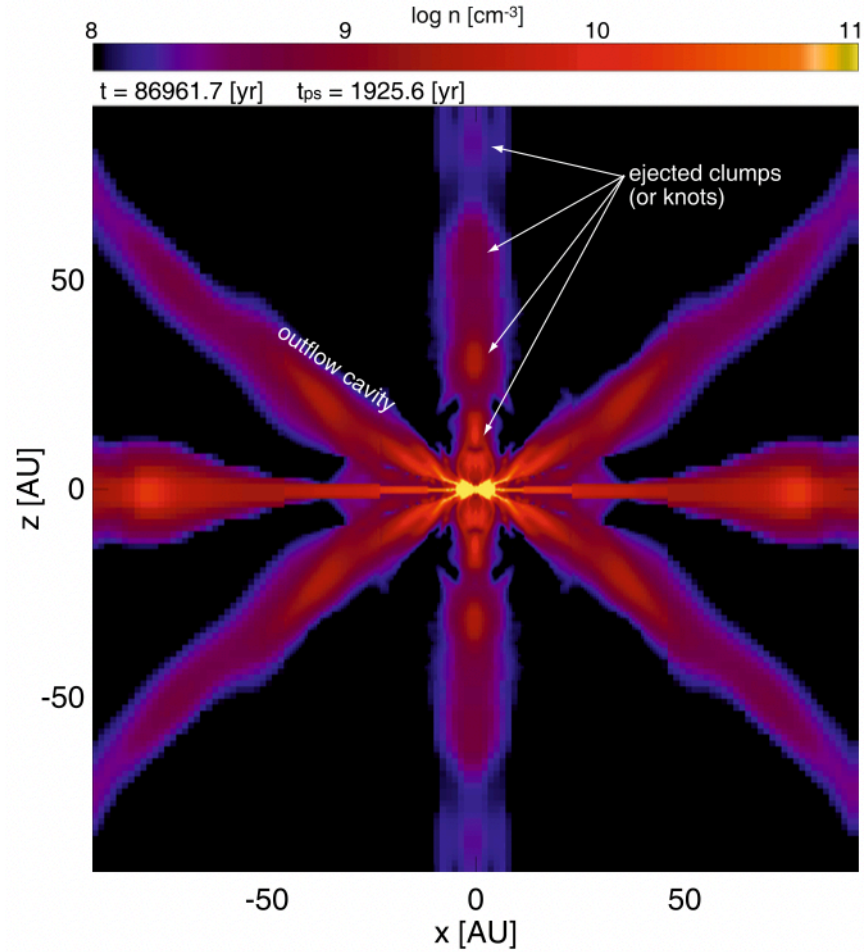
2000 years

Tomida et al. (2013)

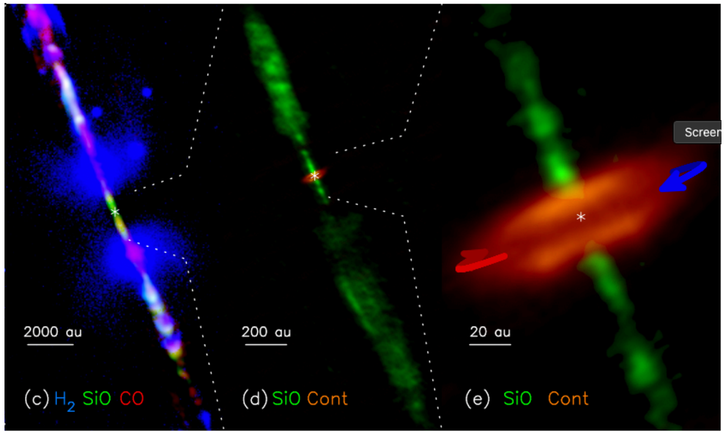


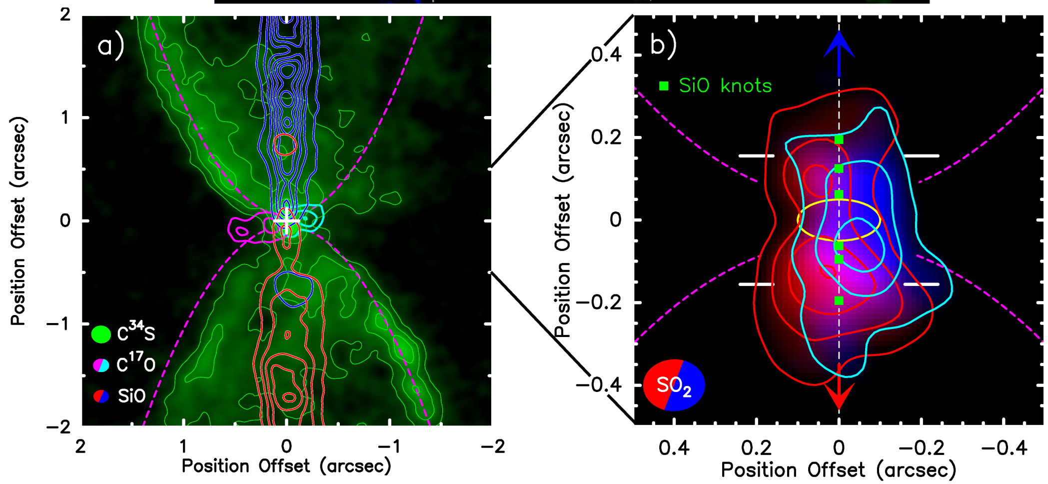
Towards jet and outflow

Machida & Basu (2019)



Lee et al. (2020)





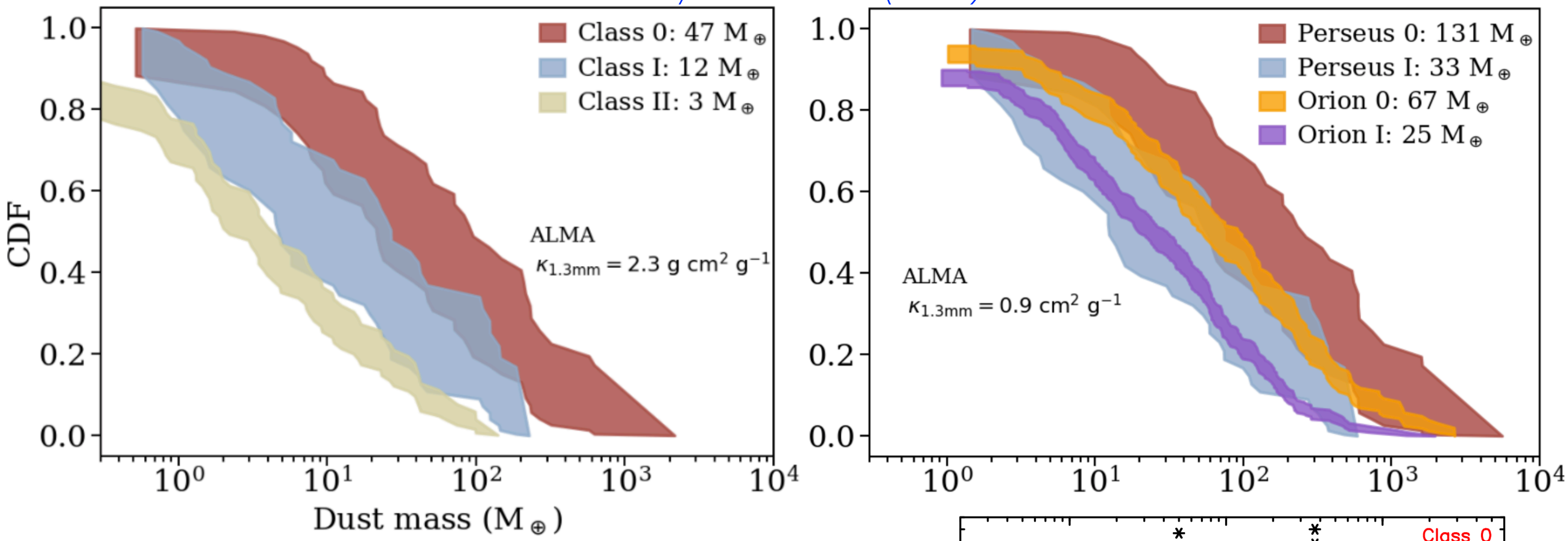
Tabone et al. (2017, 2020)

Take away II

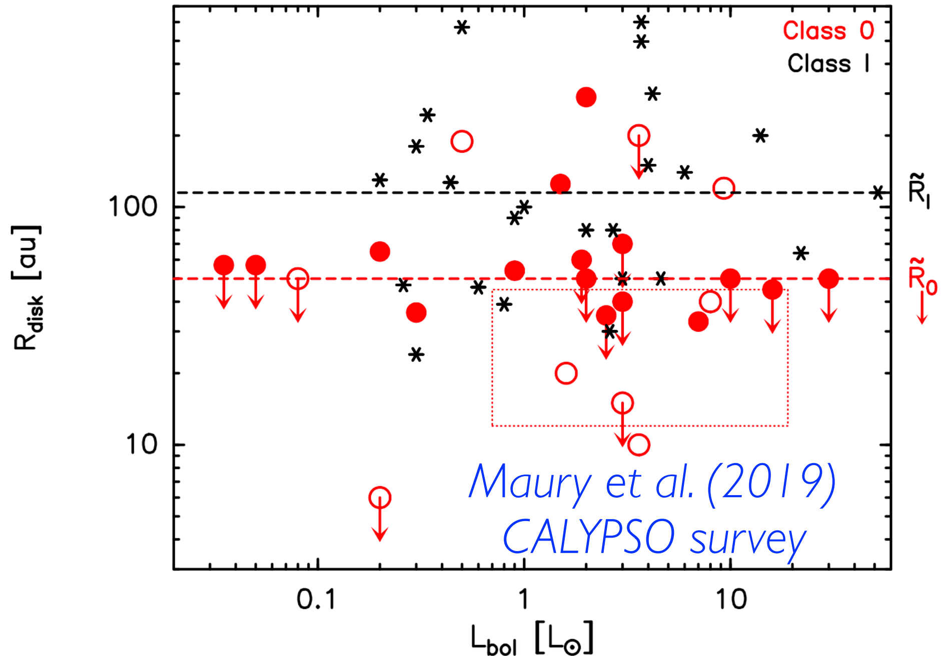
- ✓ Disc and protostar formation and early evolution highly dependent on the physics included
- ✓ Angular momentum and magnetic flux problems have a solution
- ✓ Non ideal MHD is required
- ✓ Robustness of the predictions of magnetic properties in class 0 protostars?

Disc radius evolution

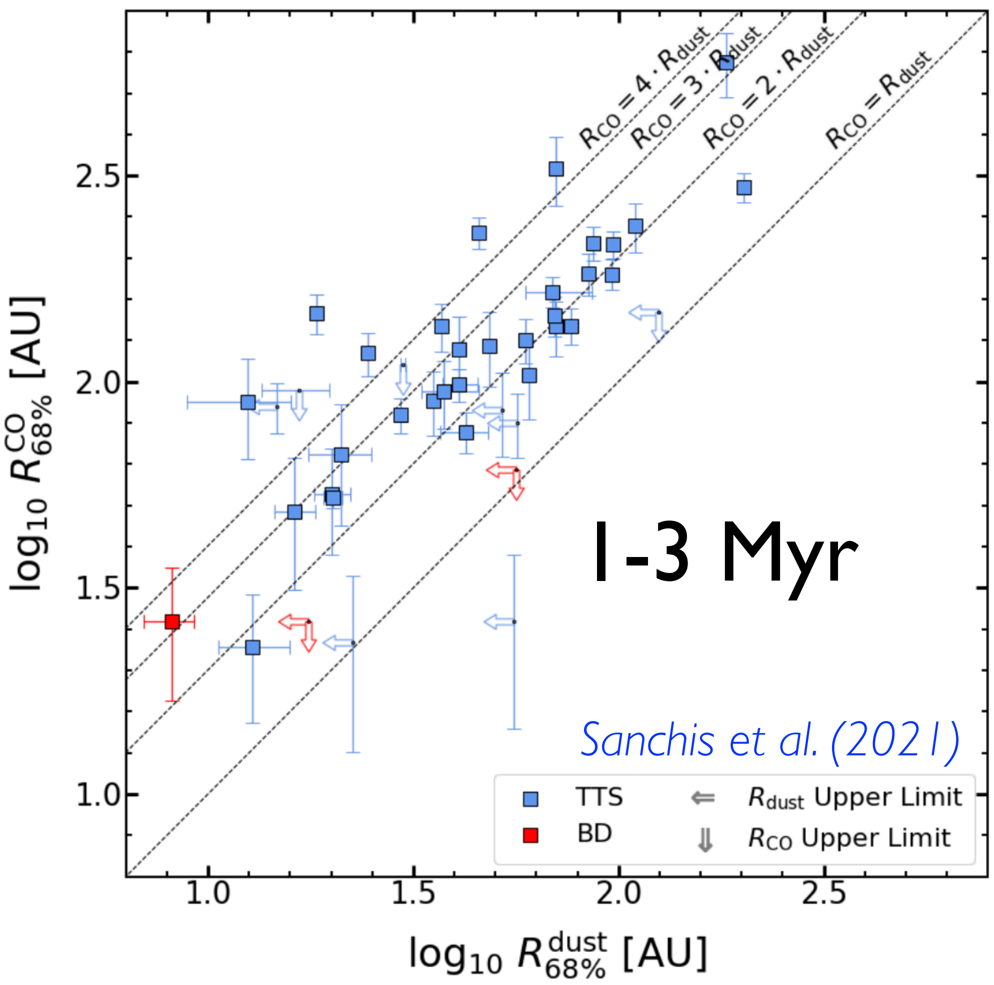
Tychoniec et al. (2020)

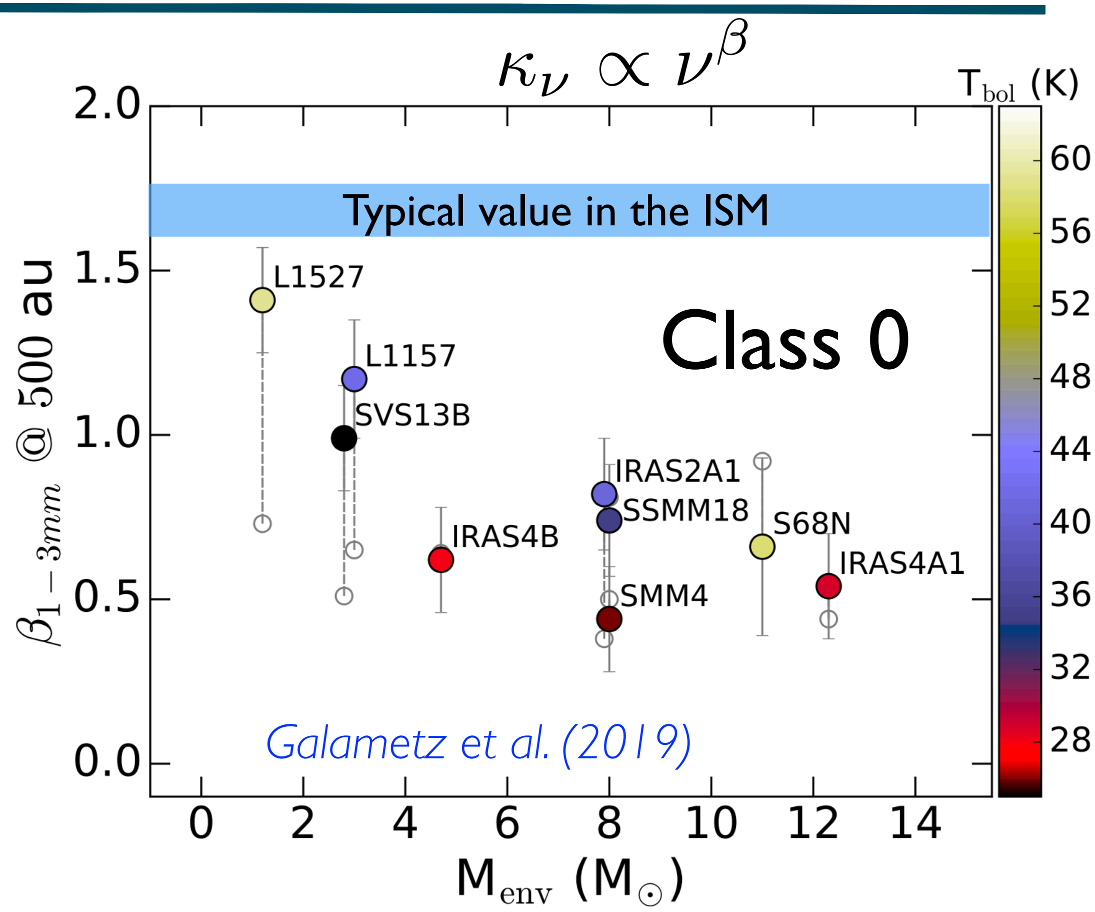


Disc mass decreases with time
Disc radius increases with time
Disc size compatible with niMHD
(*Lebreuilly+21*)



Evidences of dust evolution





- Gas disc is 2-3 times larger than the dust discs
- Discs are enriched in dust compared to the ISM
- Evidence of large grains

Dust grains drift and grow!

Gas-dust dynamical coupling

Drag force

$$\mathbf{F}_{\mathrm{g/d}} = -\frac{m_{\mathrm{grain}}}{t_{\mathrm{s}}}(\mathbf{v}_{\mathrm{d}} - \mathbf{v}_{\mathrm{g}})$$

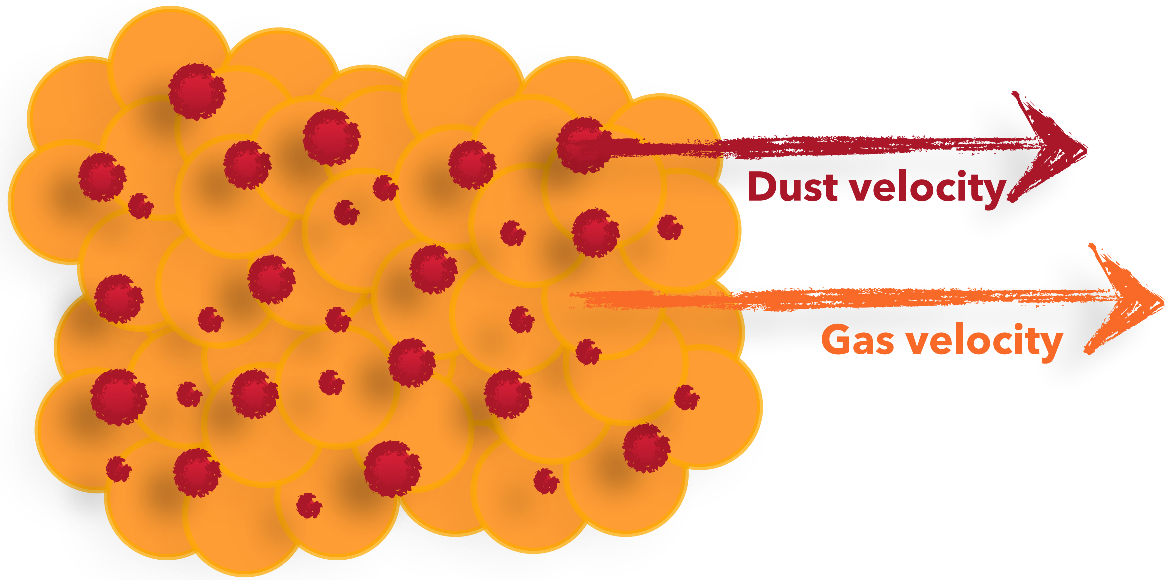
Stopping time (Epstein 1924)

$$t_{\mathrm{s}} = \sqrt{\frac{\pi\gamma}{8}} \frac{\rho_{\mathrm{grain}}}{\rho} \frac{s_{\mathrm{grain}}}{c_{\mathrm{s}}}$$

Coupling with the gas (Stokes number)

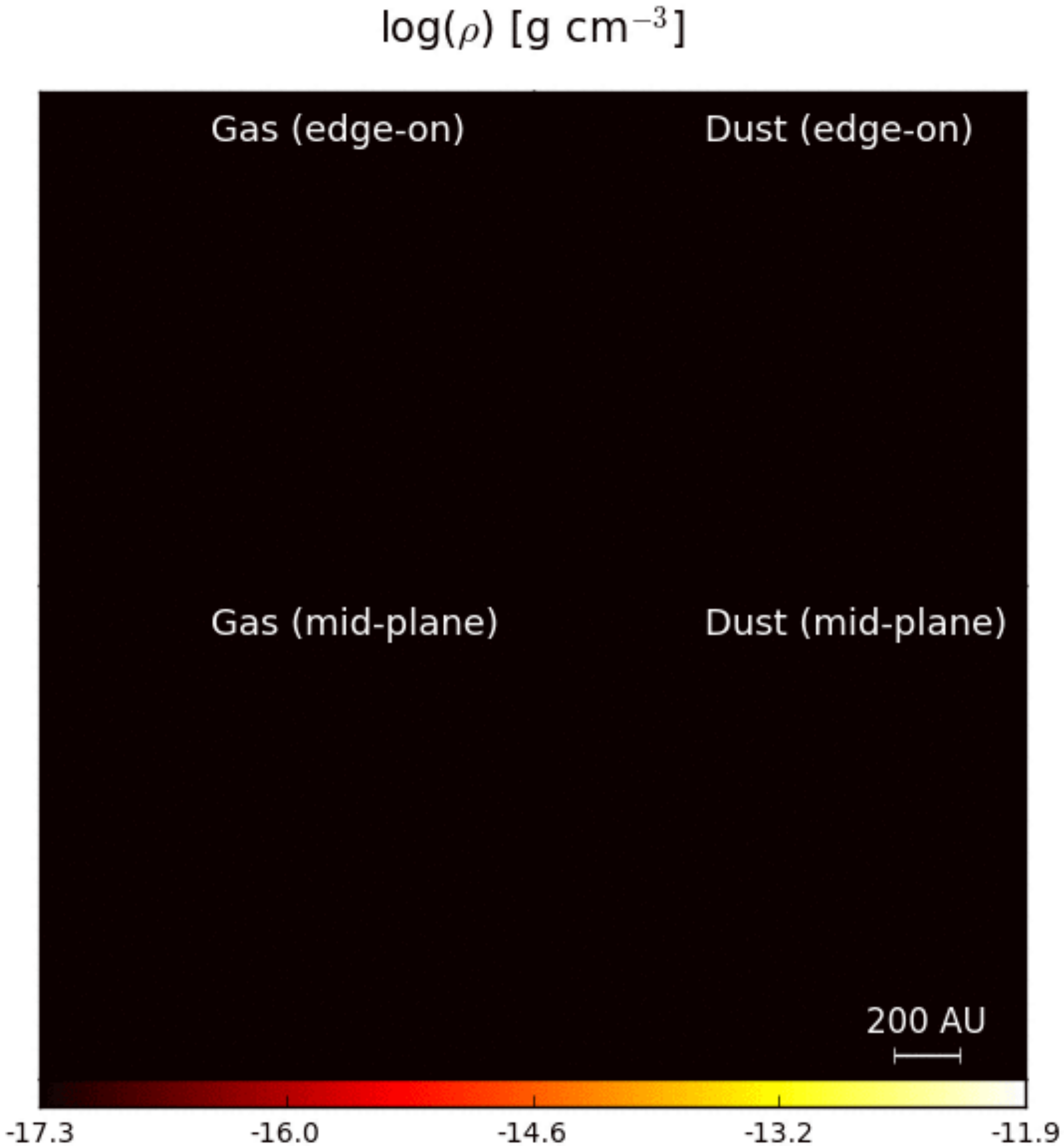
$$\mathrm{St} \equiv \frac{t_{\mathrm{s}}}{t_{\mathrm{dyn}}}$$

- If St<1, strong coupling
- If St>1, poor coupling



Lebreuilly et al. (2019, 2020)
Dust in RAMSES

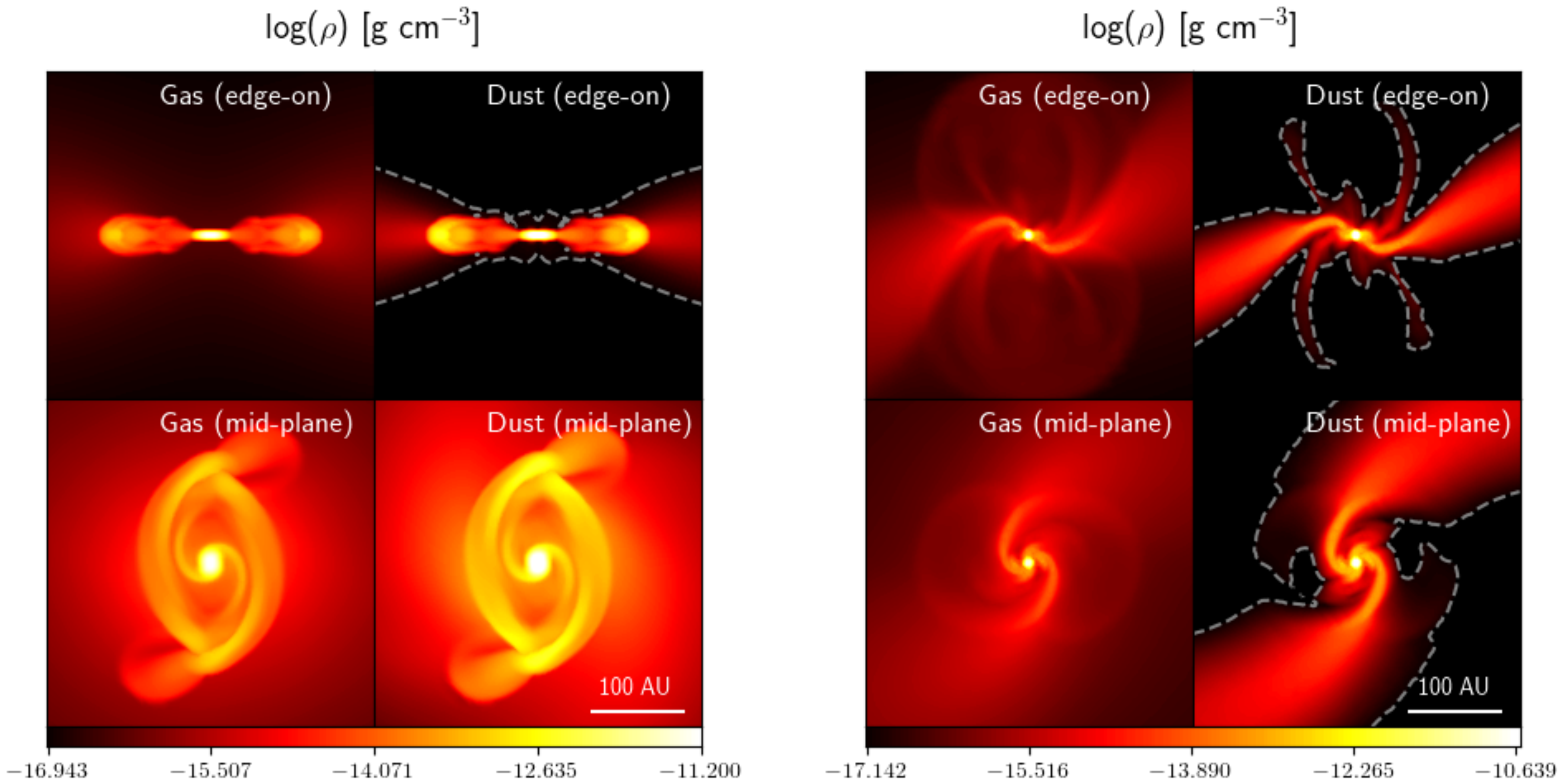
Collapse with dust and gas dynamical coupling



Hydro

Lebreuilly et al., 2020

Collapse with dust and gas dynamical coupling



Hydro

Ideal MHD

Lebreuilly et al., 2020

Conclusion

- ✓ Discs are back with non ideal MHD
- ✓ Non-ideal MHD cannot be ignored: it is a solution to the **magnetic flux** and **angular momentum** problems!
- ✓ Second core disc quickly **expands** to AU size
- ✓ Magnetic fields of **1kG** at birth

Perspectives

- Long term integration at sub-au scale => GPU acceleration?
- Dust evolution is key