From molecular clouds to protostellar cores

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Many thanks to: G. Chabrier, P. Marchand, J. Masson (CRAL Lyon)
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N. Vaytet (NBI Copenhagen), R. Teyssier (Zurich)

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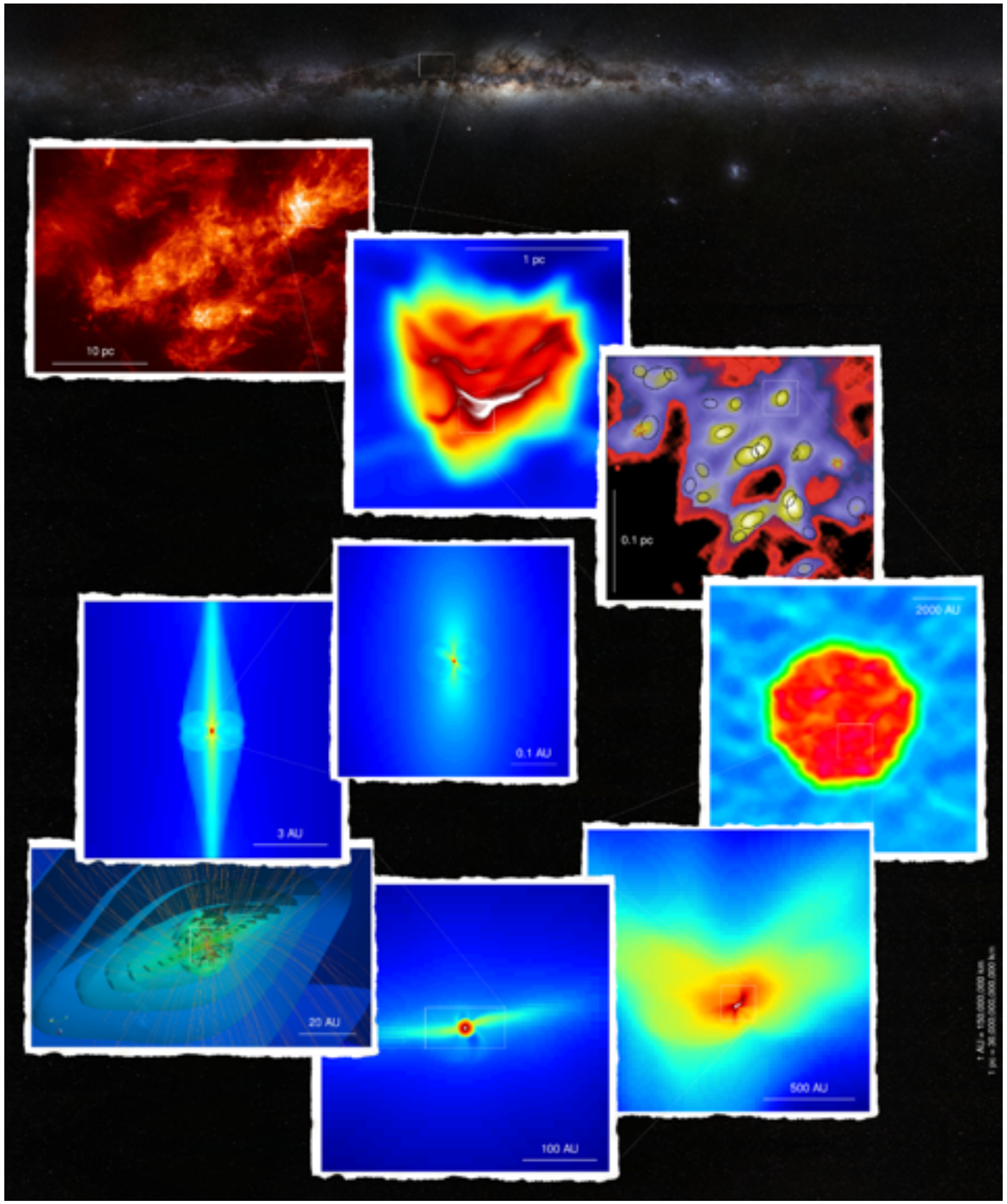
Outline

1. **Introduction**
2. **Molecular clouds**
   - formation
   - evolution

3. **Dense core**
   - formation
   - low mass star evolution sequence
4. **Cluster formation**
   - binary
   - IMF

Star formation: building blocks & challenge



Vaytet et al. (2013)

- from parsec scale (10^{18} cm) to stellar radius (10^{10} cm)

- density: from 1 cm^{-3} to 10^{24} cm^{-3}

- temperature: 10 K - 10^6 K

- ionisation depends on density and temperature… (*ideal vs non-ideal MHD*)

- chemistry, dust grain evolution (*H_2 formation, growth, evaporation*)

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

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)

➡ multifold research field, all processes couple together…

➡ slow progress, but progress

Energy equipartition

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

- **Thermal energy:** $P/k \sim 4000$ K/cm^3

  $\Rightarrow E_{th}=P/(\gamma-1) \sim 10^{-12}$ erg/cm^3

- **Kinetic energy:** Mach number ~ 4

  $\Rightarrow E_{kin}=0.5(\gamma-1)E_{th}\mathcal{M}^2 \sim 5\ E_{th}$

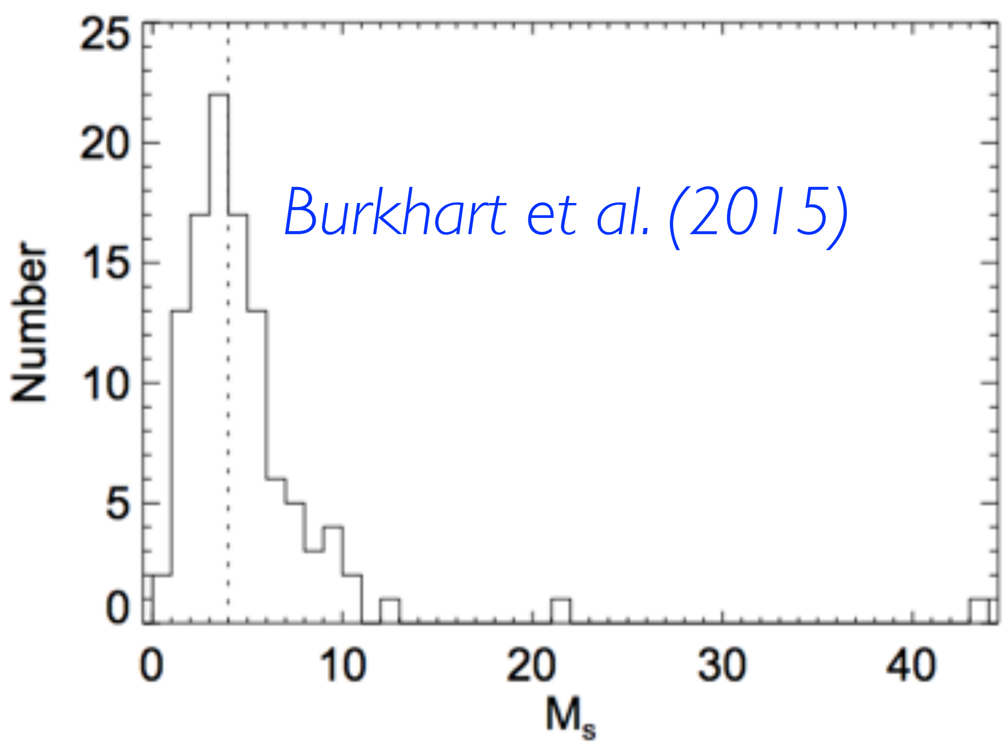


Fig. 3.— Histogram of the sonic Mach number as calculated from the absorption line data for Perseus. The median value is $M_s = 4.0$ and is shown with a straight vertical line.

Energy equipartition

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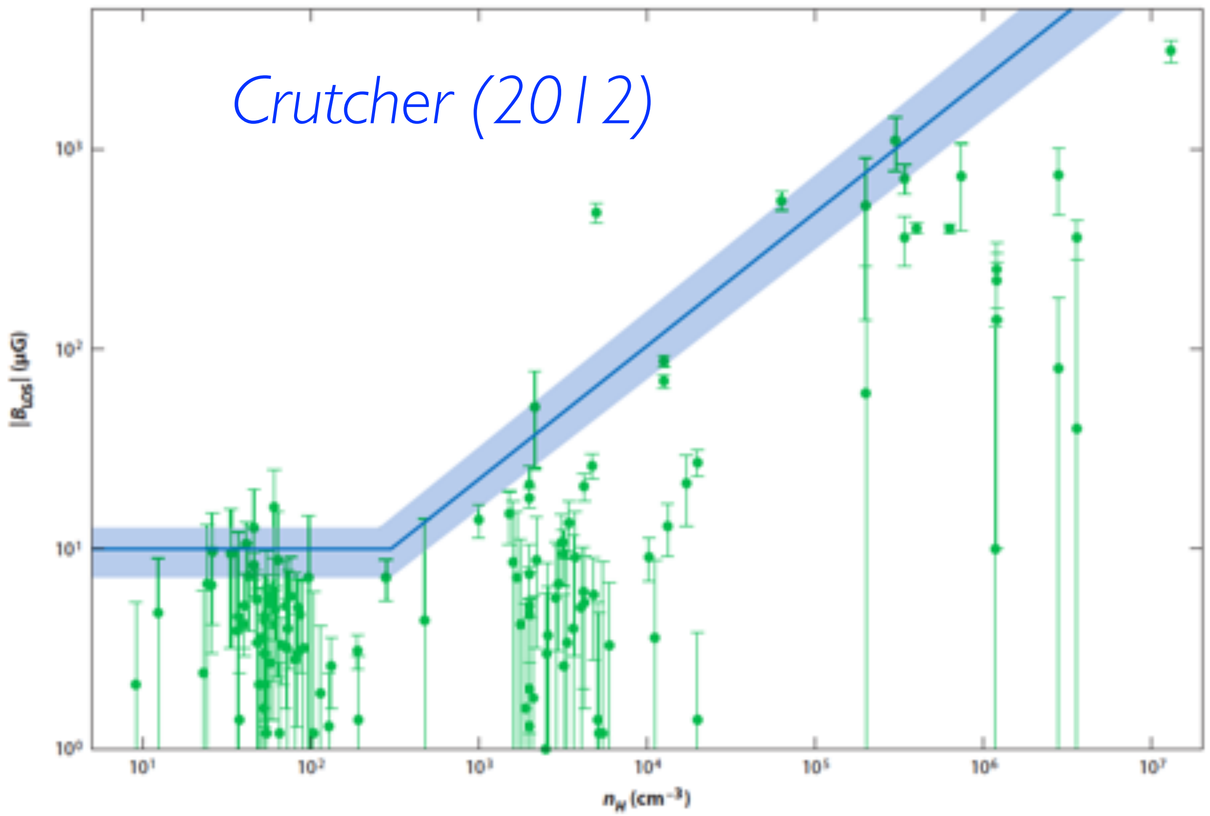
  => $E_{kin}=0.5(\gamma-1)E_{th}\mathcal{M}^2 \sim 5\ E_{th}$

- **Magnetic energy:** B ~ 10 μG

  => $E_{mag}=B^2/(8\pi) \sim 4 \times 10^{-12}$ erg/cm^3



Energy equipartition

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

- Radiation energy

Component of ISRF	Energy density (erg cm^{-3})
Synchrotron	2.7×10^{-18}
CMB	4.19×10^{-13}
Dust emission	5.0×10^{-13}
Nebular emission (bf, ff)	4.5×10^{-15}
Nebular emission (Hα)	8×10^{-16}
Nebular emission (other bb)	10^{-15}
Starlight, $T_1 = 3000$ K	4.29×10^{-13}
Starlight, $T_2 = 4000$ K	3.19×10^{-13}
Starlight, $T_3 = 7000$ K	2.29×10^{-13}
Starlight, power-law	7.11×10^{-14}
Starlight, total	1.05×10^{-12}
Soft X-rays	10^{-17}

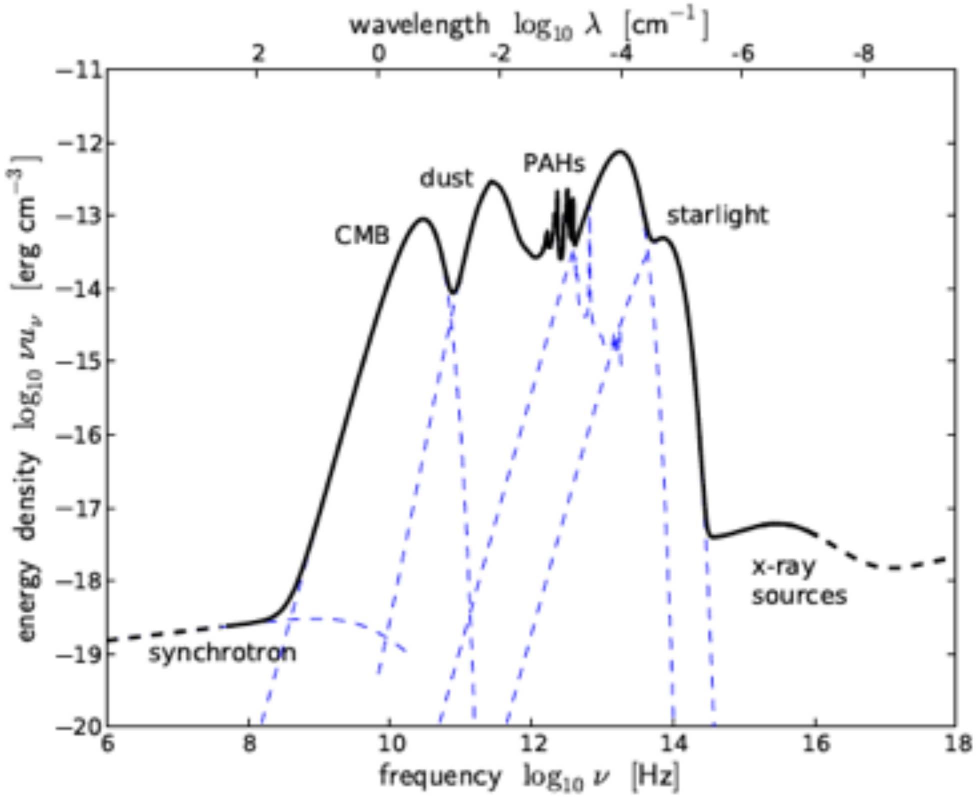


Fig. 1 Schematic sketch of the energy density of the interstellar radiation field at different frequencies. The contributions of the cosmic microwave background (CMB) as well as of old, low-mass and young, high-mass stars are taken to be perfect blackbodies with temperatures 2.73 K, 3500 K, and 18000 K, respectively (see Chakraborty & Fields, 2013). The contributions from dust and PAHs are obtained from Draine & Li (2007). The estimate for the Galactic synchrotron emission is taken from Draine (2011) and the one for the X-ray flux from Snowden et al. (1997). Note that in the vicinity of massive star clusters, the contributions from massive stars can be orders of magnitude larger than the numbers provided here. For further discussions, see for example Draine (2011).

Klessen & Glover (2014)

Molecular cloud evolution

- Molecular clouds are turbulent
  - Power-laws over decades => turbulent cascade?

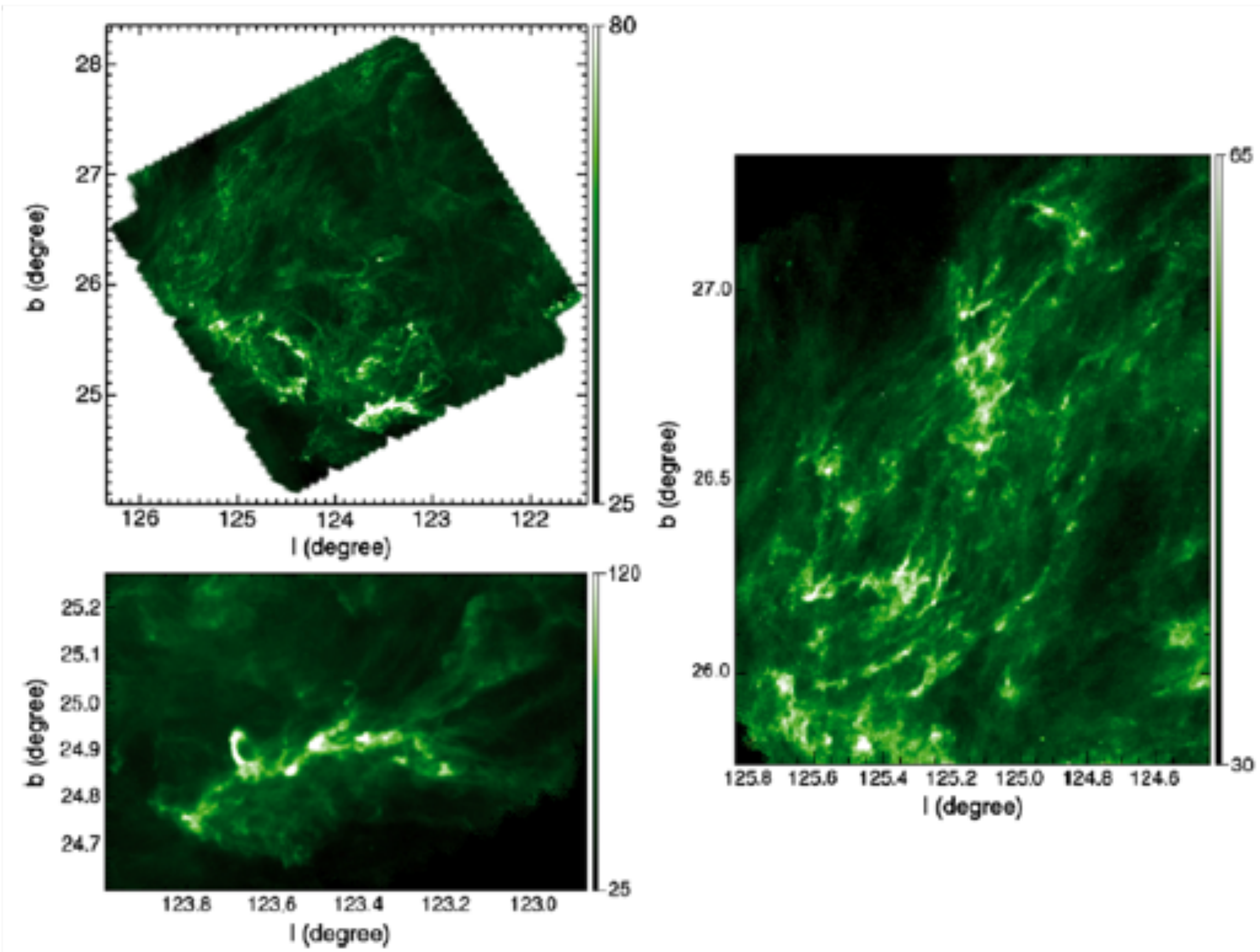
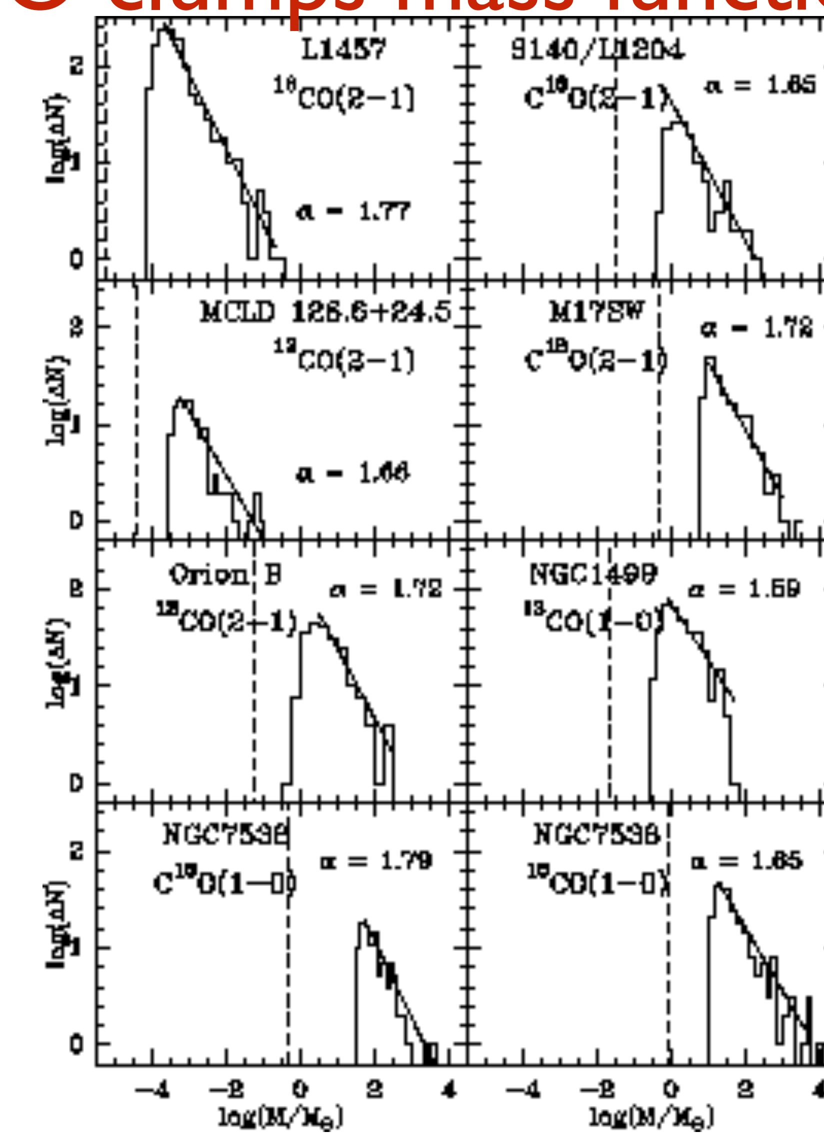


Fig. 11 *Left*: *Herschel*/SPIRE 250 μm map of the Polaris Flare over ~7 pc × 7 pc. Units are MJy sr^{-1} (*top*). Subfield of the region of largest column density discussed in Sect. 3.6 (*bottom*). *Right*: Another subset of regions of lowest column density. Note the brightness difference (from Miville-Deschênes et al. 2010)

CO clumps mass functions



Kramer et al. (1998)

Molecular cloud evolution

- Molecular clouds are turbulent

Klessen (2010)

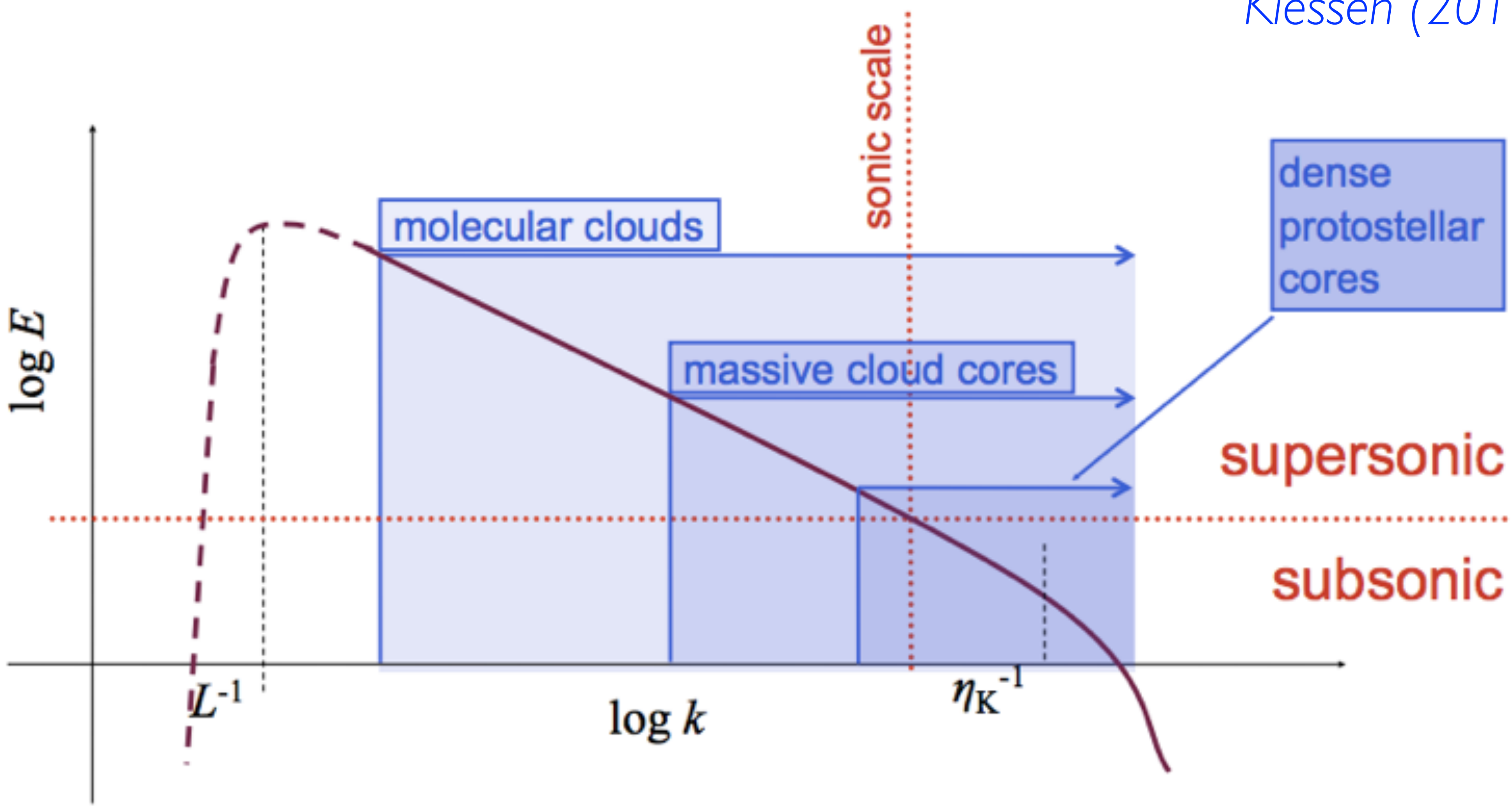


Fig. 2. Simple cartoon picture of the turbulent energy spectrum, i.e. of the kinetic energy carried by modes of different wave numbers k, and their relation to different cloud structures (see also Table 1). Turbulence is driven on large scales comparable to the size L of the cloud and is dissipated on very small scales η_K.

Molecular cloud evolution

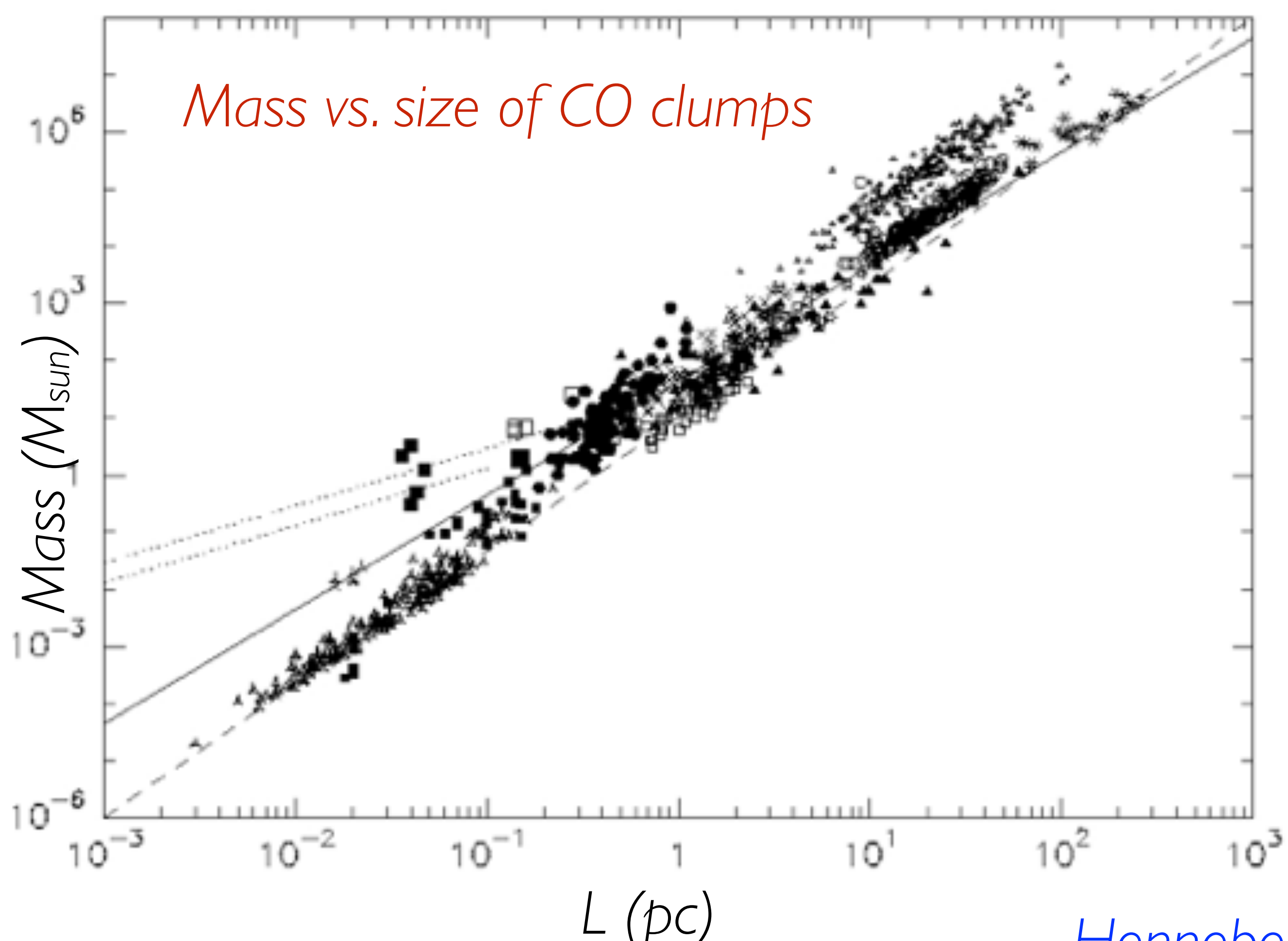
- **Molecular clouds are turbulent**

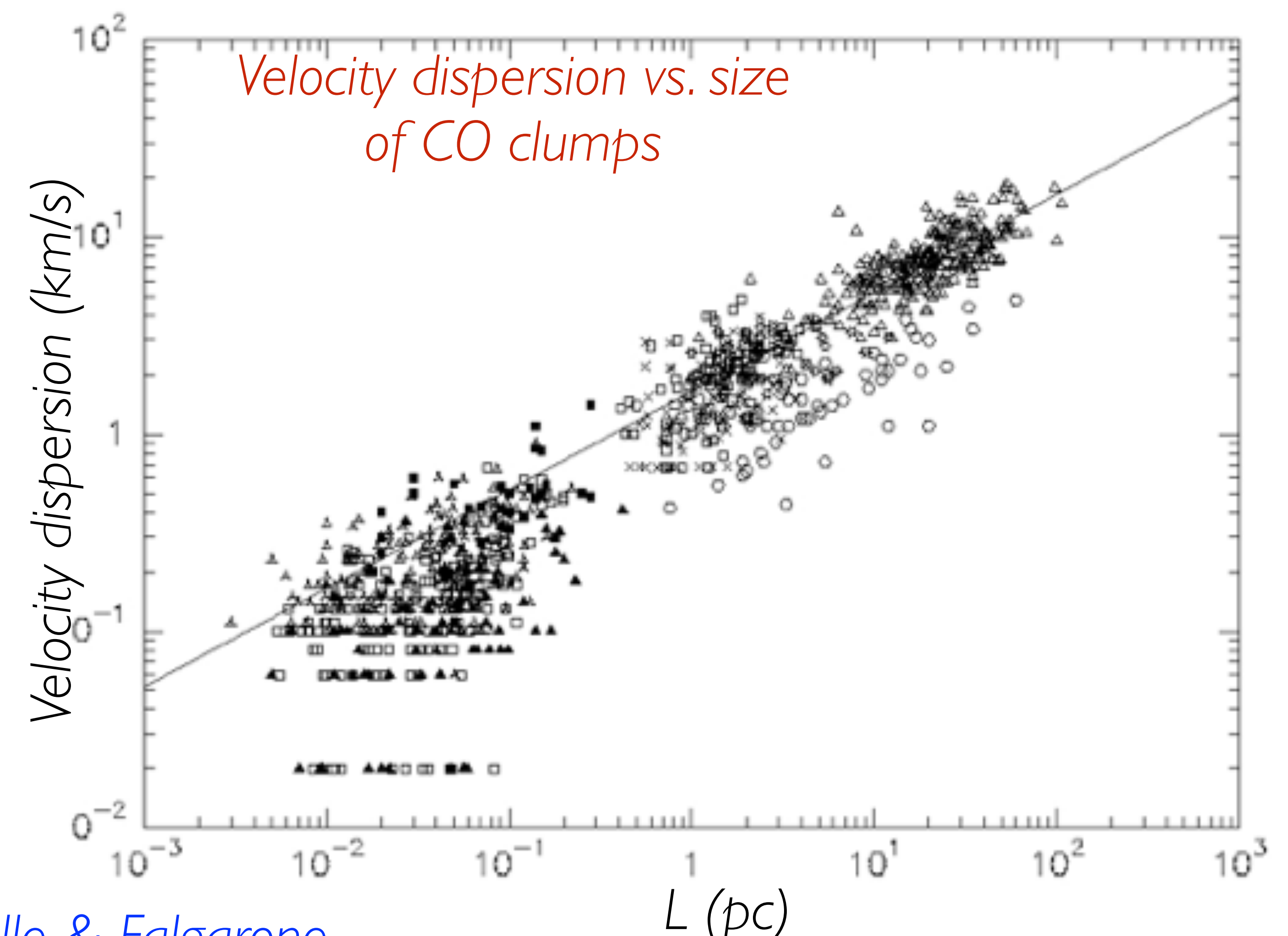
Larson (1981) relations

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

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

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

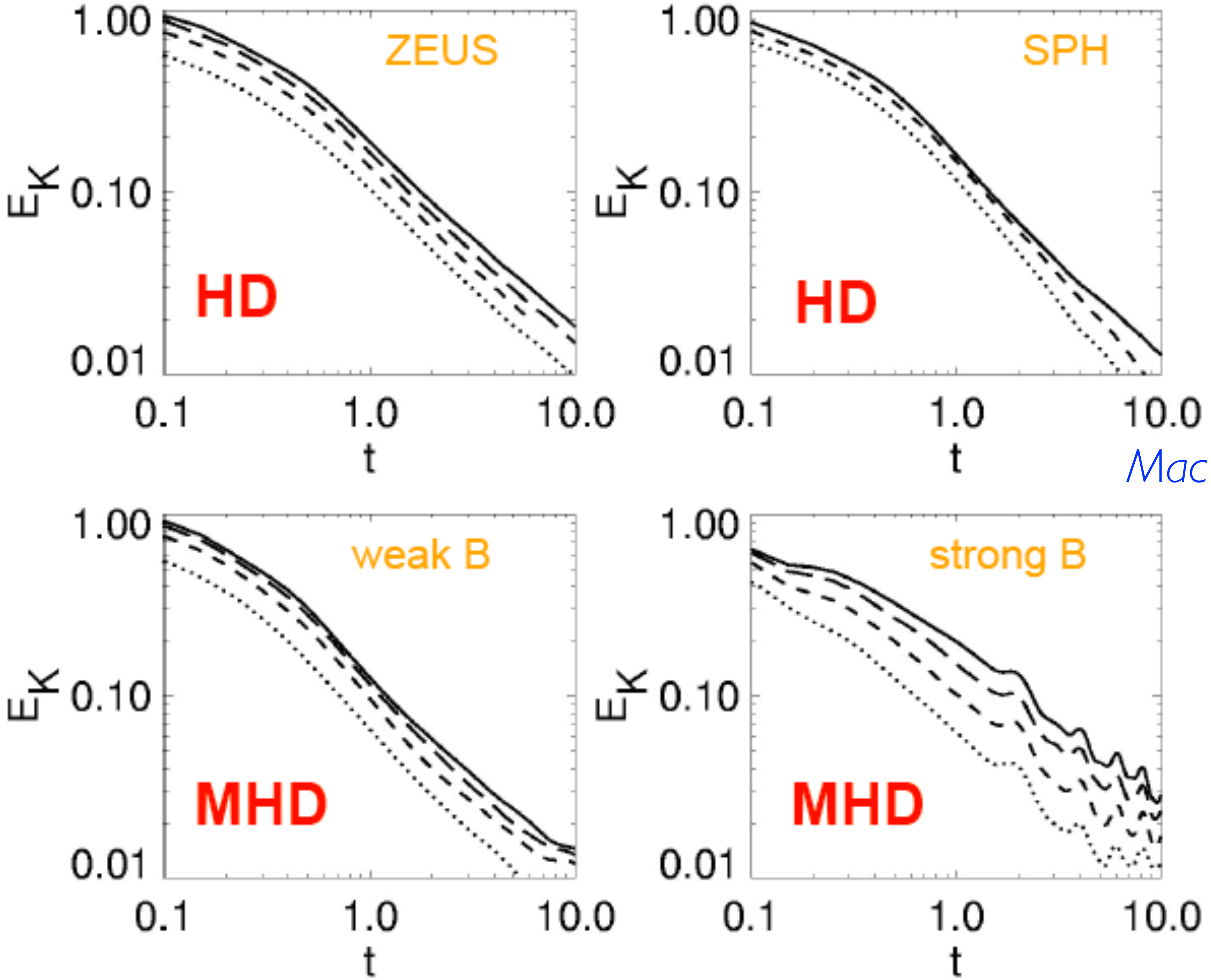




Hennebelle & Falgarone (2012 A&ARA)

Turbulence in molecular clouds

- Energy dissipation



Mac Low et al. (1998)

Energy dissipation

See the discussion in *Klessen & Glover (2014)*

- **Energy dissipation** $L_\mathrm{d}/v_\mathrm{rms}$

  ✓ energy is dissipated in a crossing time

  ✓ dissipation rate: $$\dot{e} = \frac{1/2\rho v_\mathrm{rms}^2}{(L_\mathrm{d}/v_\mathrm{rms})} = \frac{1/2\rho v_\mathrm{rms}^3}{L_\mathrm{d}}$$

  ✓ For typical numbers:

$$\boxed{\dot{e} = 3 \times 10^{-27} \mathrm{erg\ cm^{-3} s^{-1}} \left(\frac{n}{1\ \mathrm{cm^{-3}}}\right) \left(\frac{v_\mathrm{rms}}{10\ \mathrm{km\ s^{-1}}}\right)^3 \left(\frac{L_\mathrm{d}}{100\ \mathrm{pc}}\right)^{-1}}$$

  ✓ energy injection must compensate this dissipation

Source of energy injection

See the discussion in *Klessen & Glover (2014)*

- Different mechanisms, but no definitive answer:
  - ✓ accretion at galactic scales
  - ✓ supernova explosion
  - ✓ spiral arms
  - ✓ gravitational instability
  - ✓ HII region
  - ✓ protostellar jets
- Connect large scale (galaxy) and small scales (protostars) - yet this is another story!

Energy injection

- **Accretion onto the galaxy** (*Klessen & Hennebelle 2010*)
  - ✓ galaxies are fed by gas entering the dark matter halo
  - ✓ needs to replenish the gas content at a rate similar to the SFR (2-4 $M_\odot$/yr)
  - ✓ energy injection rate:

$$\dot{e} = \rho\dot{\epsilon} = \frac{1}{2}\rho\frac{\dot{M}_{\rm in}}{M_{\rm gas}}v_{\rm in}^2$$
$$= 6.2\times10^{-27}\,{\rm erg\,cm^{-3}\,s^{-1}}\left(\frac{n}{1\,{\rm cm^{-3}}}\right)\left(\frac{\dot{M}_{\rm in}}{3\,{\rm M_\odot\,yr^{-1}}}\right)\left(\frac{v_{\rm in}}{220\,{\rm km\,s^{-1}}}\right)^2$$

  - ✓ Only a few percent of this energy input is needed to explain the energy dissipation rate
  - ✓ but… accretion is not steady and the conversion of kinetic to turbulent energy depends linearly on the density contrast

Energy injection

- **Rotation of the galaxy** (*Klessen & Glover 2014*)
  - ✓ **rotation energy can be converted into turbulent energy**
    - spiral arms
    - energy injection rate:

$$\dot{e} \approx G(\Sigma_g/H)^2 L^2 \Omega$$
$$\approx 4 \times 10^{-29} \text{ erg cm}^{-3} \text{ s}^{-1} \times$$
$$\times \left(\frac{\Sigma_g}{10 \text{ M}_\odot \text{ pc}^{-2}}\right)^2 \left(\frac{H}{100 \text{ pc}}\right)^{-2} \left(\frac{L}{100 \text{ pc}}\right)^2 \left(\frac{\Omega}{(220 \text{ Myr})^{-1}}\right)$$

    - magneto-rotational instability (*Balbus & Hawley 1998*)
    - energy injection rate (*Sellwood & Balbus 1999*)

$$\dot{e} = 3 \times 10^{-29} \, \text{erg} \, \text{cm}^{-3} \text{s}^{-1} \left(\frac{B}{3\mu\text{G}}\right)^2 \left(\frac{\Omega}{(220 \, \text{Myr})^{-1}}\right)$$

Energy injection

- Stellar feedback
  - ✓ supernovae

$$\dot{e} = \frac{\sigma_{\rm SN}\xi_{\rm SN}E_{\rm SN}}{\pi R_{\rm sf}^2 H}$$
$$= 3\times10^{-26}\ {\rm erg\ s^{-1}\ cm^{-3}}\times$$
$$\times\left(\frac{\xi_{\rm SN}}{0.1}\right)\left(\frac{\sigma_{\rm SN}}{(100\,{\rm yr})^{-1}}\right)\left(\frac{H}{100\ {\rm pc}}\right)^{-1}\left(\frac{R}{15\ {\rm kpc}}\right)^{-2}\left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right)$$

  - ✓ protostellar jets and outflow

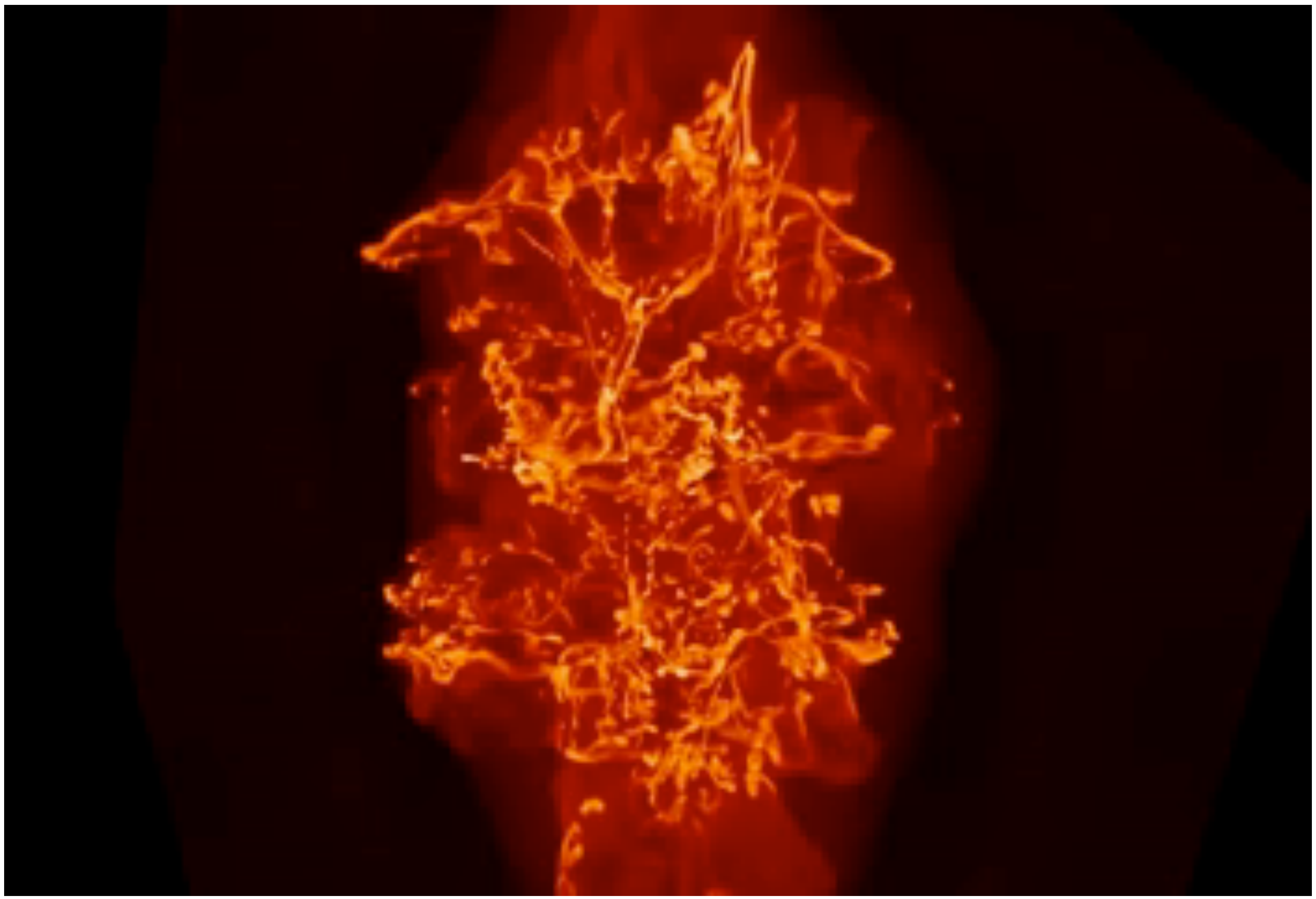
$$L_{\rm jet} = \frac{1}{2}\dot{M}_{\rm jet}\,v_{\rm jet}^2 = 1.3\times10^{32}\,{\rm erg\,s^{-1}}\left(\frac{\dot{M}_{\rm jet}}{10^{-8}\,{\rm M_\odot yr^{-1}}}\right)\left(\frac{v_{\rm jet}}{200\,{\rm km\,s^{-1}}}\right)$$

$$\dot{e} = \frac{1}{2}\xi_{\rm jet}f_{\rm jet}\frac{\dot{M}_{\rm SF}v_{\rm jet}^2}{\pi R^2 H} = \frac{1}{2}f_{\rm jet}\frac{\dot{M}_{\rm SF}v_{\rm jet}\sigma}{\pi R^2 H}$$
$$= 1.4\times10^{-28}\,{\rm erg\,cm^{-3}\,s^{-1}}\times$$
$$\times\left(\frac{f_{\rm jet}}{0.2}\right)\left(\frac{\dot{M}_{\rm SF}}{3\,{\rm M_\odot\,yr^{-1}}}\right)\left(\frac{v_{\rm jet}}{200\,{\rm km\,s^{-1}}}\right)\left(\frac{\sigma}{10\,{\rm km\,s^{-1}}}\right)\left(\frac{H}{100\ {\rm pc}}\right)^{-1}\left(\frac{R}{15\ {\rm kpc}}\right)^{-2}$$

  - ✓ stellar winds? Radiation? Continuous processes, integrated effect would more likely affect the collapsing cloud dynamics

Molecular cloud formation

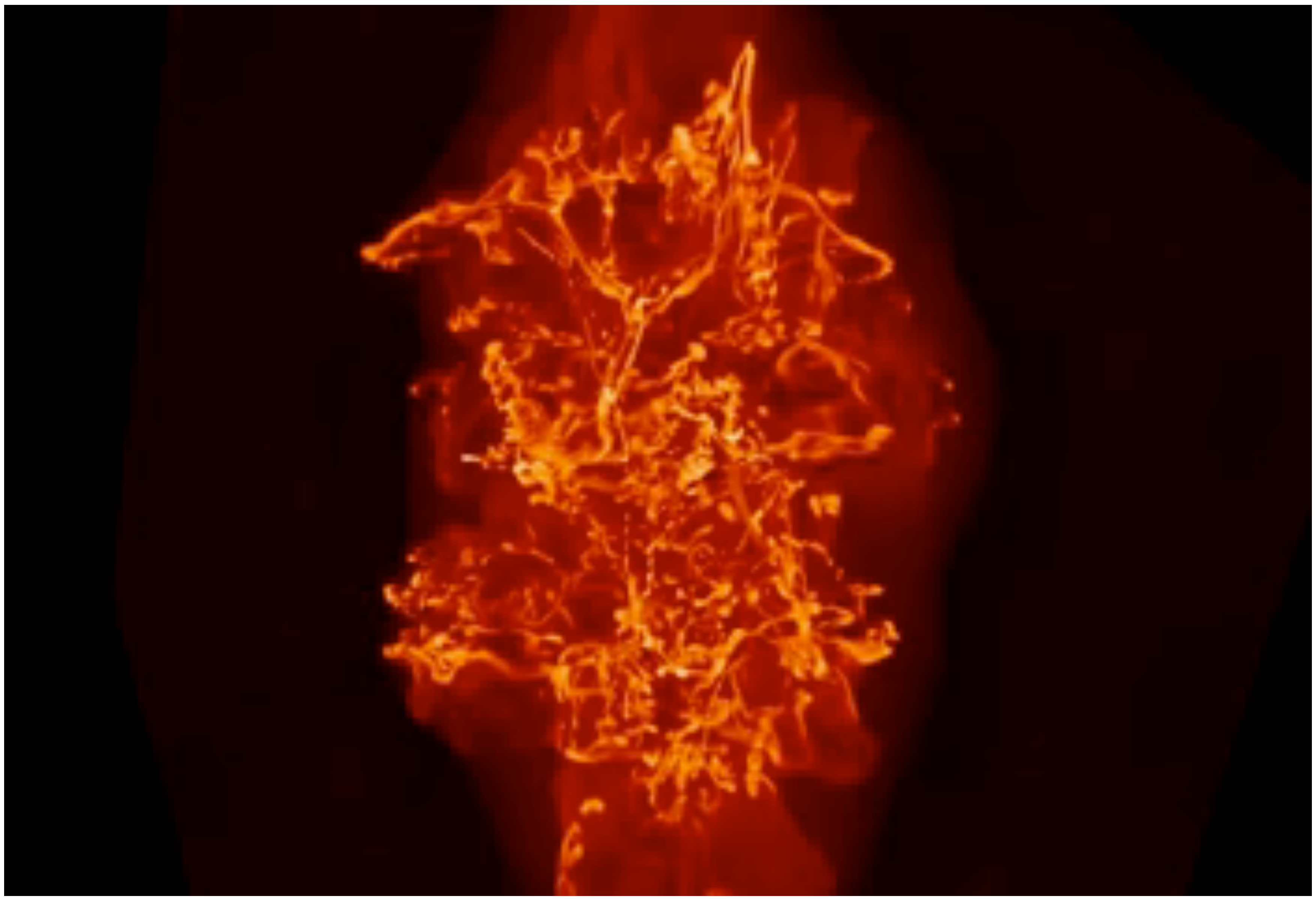
- Colliding flows



Simulation by
Audit & Hennebelle

Molecular cloud formation

- Colliding flows



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Molecular cloud evolution

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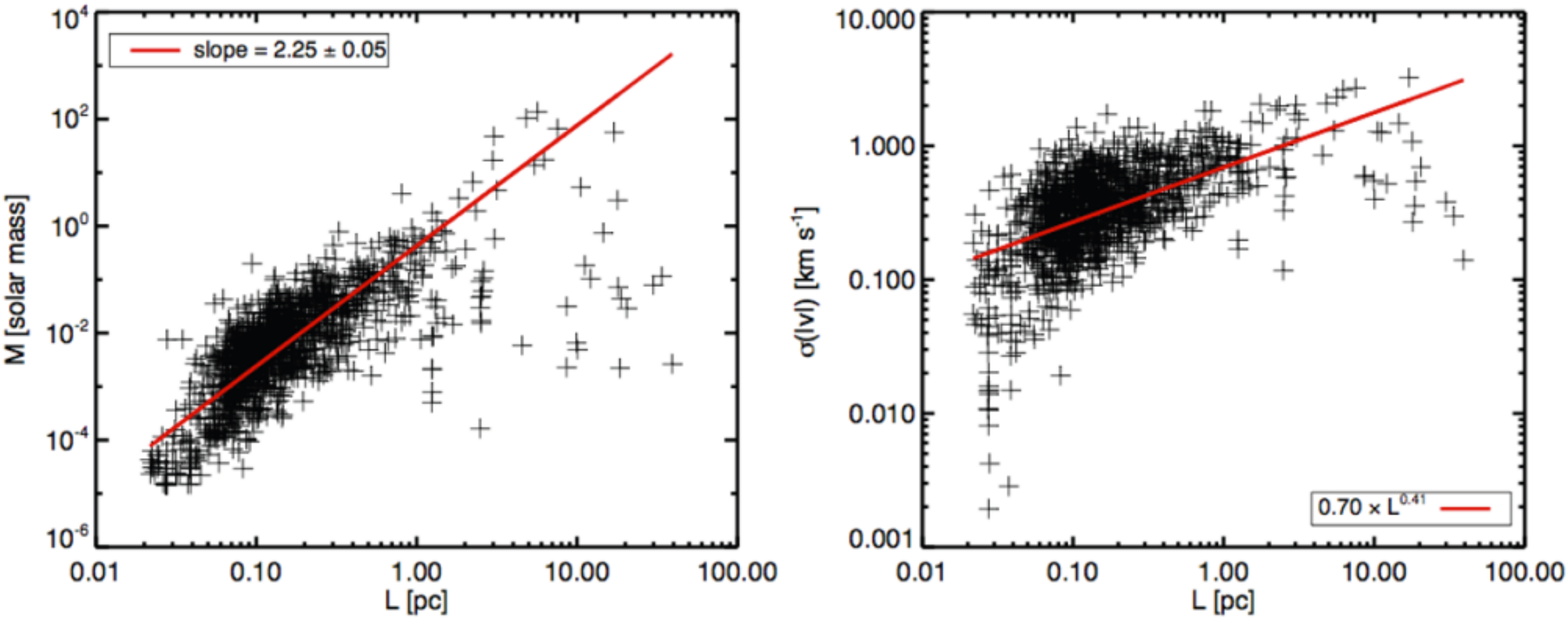


+ mass spectrum similar to the one observed for CO clumps

Saury et al. (2014)

Formation of self-gravitating cores

- **We now consider individual molecular clouds with:**
    - gravity
    - turbulence
    - magnetic field

- **Formation of gravitationally bound structures:**
    - Virial analysis, with only thermal support to balance gravity

$$2\mathcal{T} + \Omega = 0$$

$$M_{\rm crit} \propto \frac{C_{\rm s}^3}{\sqrt{n}}$$

Formation of self-gravitating cores

- **We now consider individual molecular clouds with:**
  - gravity
  - turbulence
  - magnetic field

- **Formation of gravitationally bound structures:**
  - Virial analysis, with only thermal support

$$M_{\rm crit} \sim 1.9 \left(\frac{T}{10~{\rm K}}\right)^{3/2} \left(\frac{n}{10^4~{\rm cm^{-3}}}\right)^{-1/2}~{\rm M_\odot}$$

Formation of self-gravitating cores

- **Turbulence**
  - fluctuations at small scales compared to the Jeans scale

$$C_{\mathrm{s,eff}}^2 \simeq C_{\mathrm{s}}^2 + V_{\mathrm{rms}}^2/3$$

- **Formation of gravitationally bound structures**

$$M_{\mathrm{crit}} \propto \frac{C_{\mathrm{s,eff}}^3}{\sqrt{n}}$$

- **Gravo-turbulent model** (*Hennebelle & Chabrier, Padoan & Nordlund*)

Formation of self-gravitating cores

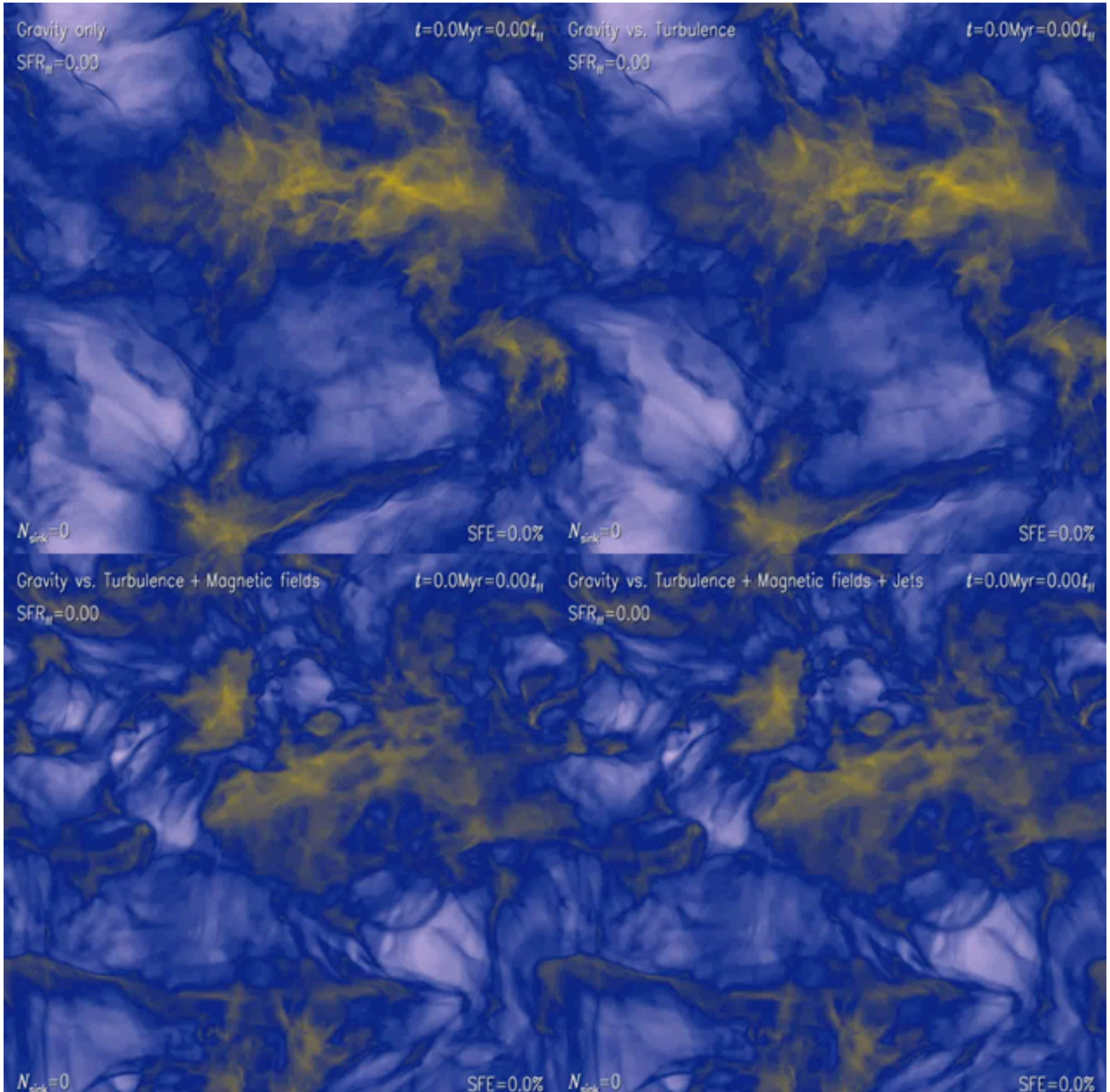
- **Stability in presence of a magnetic field**

$$2\mathcal{T} - 4\pi R^3 P_{\rm ext} - \frac{1}{R}\left(\frac{3}{5}GM^2 - \frac{1}{3}R^4B^2\right) = 0$$

- Critical mass $\qquad M_{\rm c} \sim \left(\frac{5}{9G}\right)^{1/2} \phi_{\rm B}$
- $M>M_c$: "magnetically supercritical" cloud
- Magnetic fields "dilute" gravity:

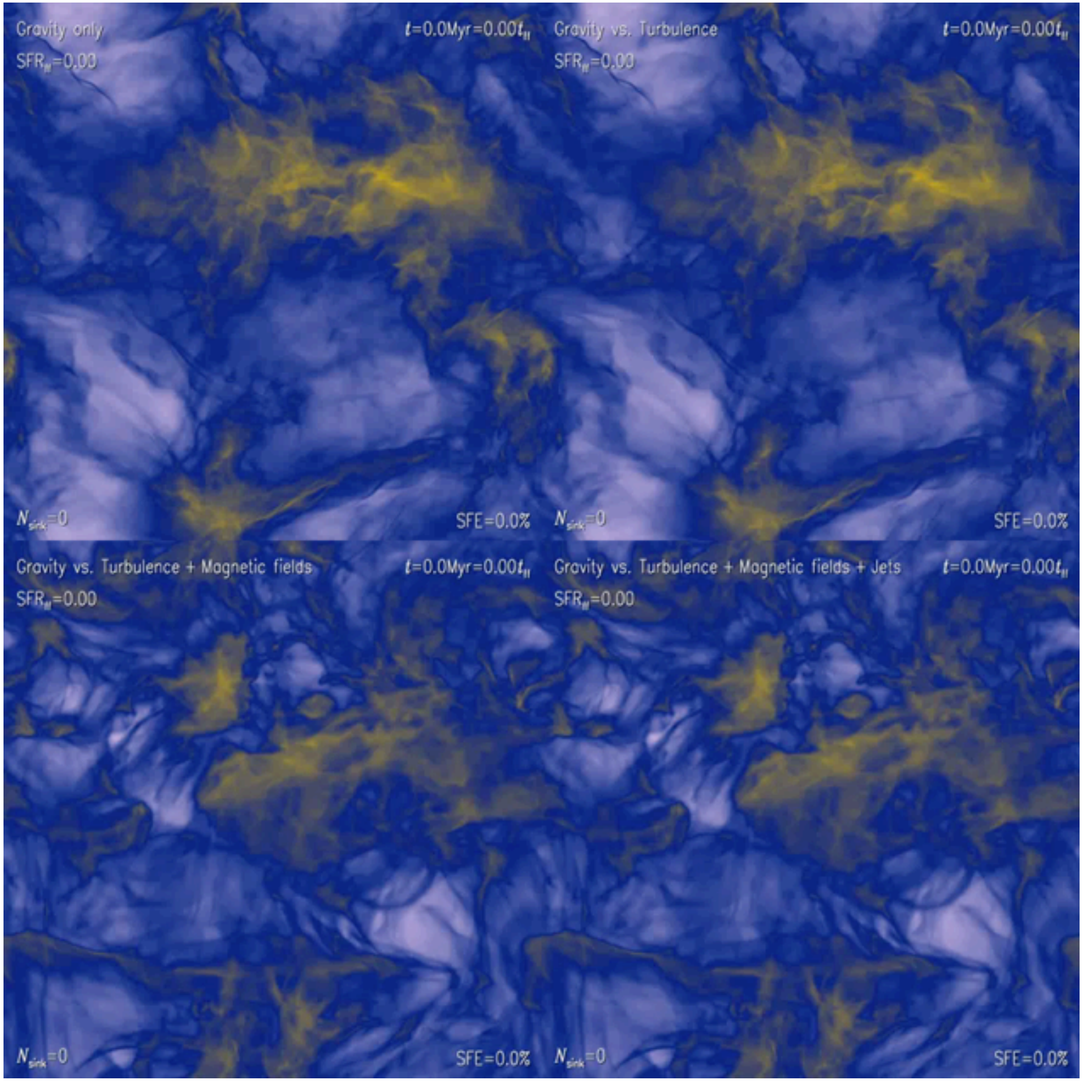
$$2(E_{\rm th} + E_{\rm kin}) + E_{\rm grav}(1-\mu^{-2})$$

Molecular cloud evolution & dense core formation



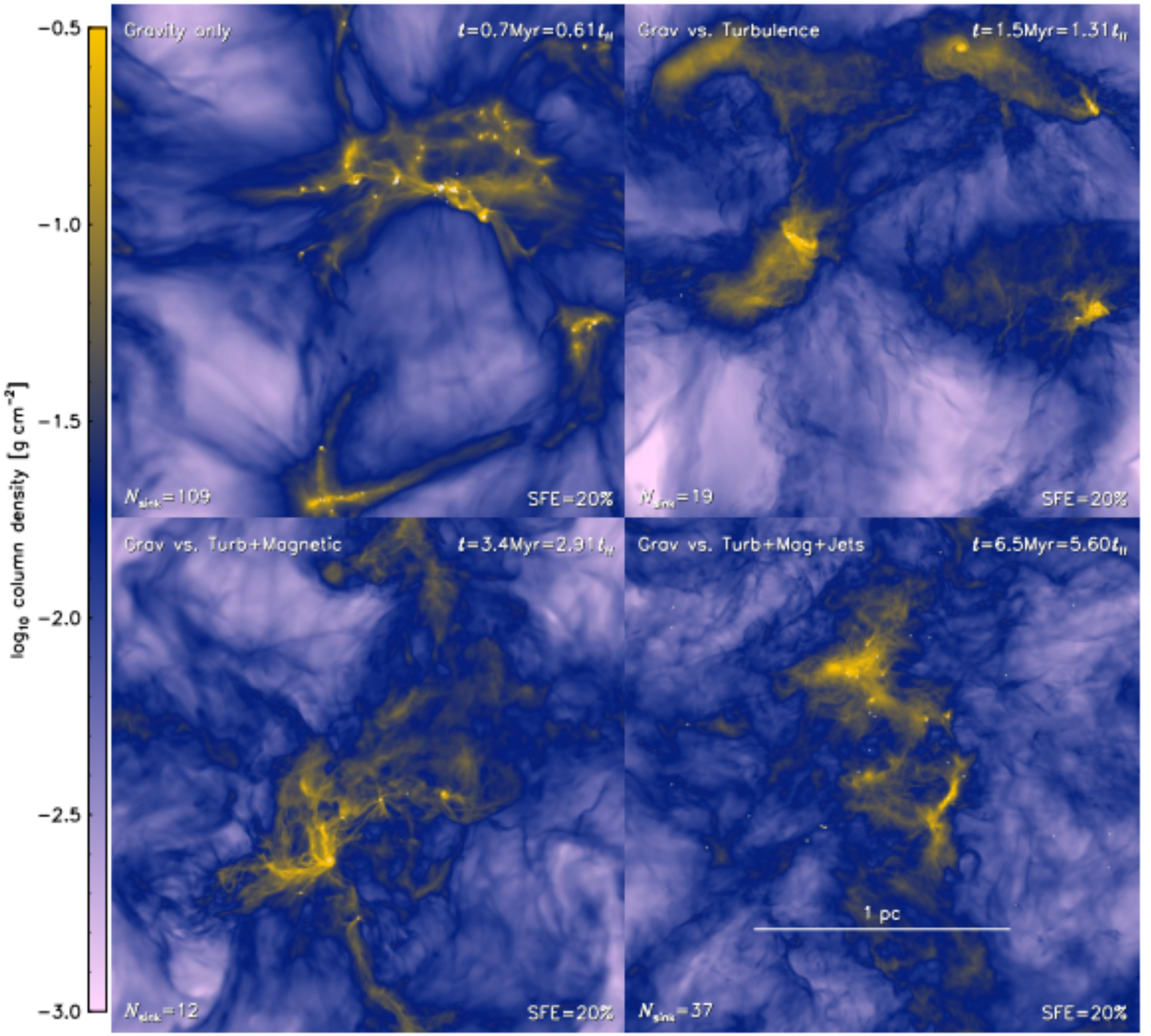
Federrath (2015)

Molecular cloud evolution & dense core formation



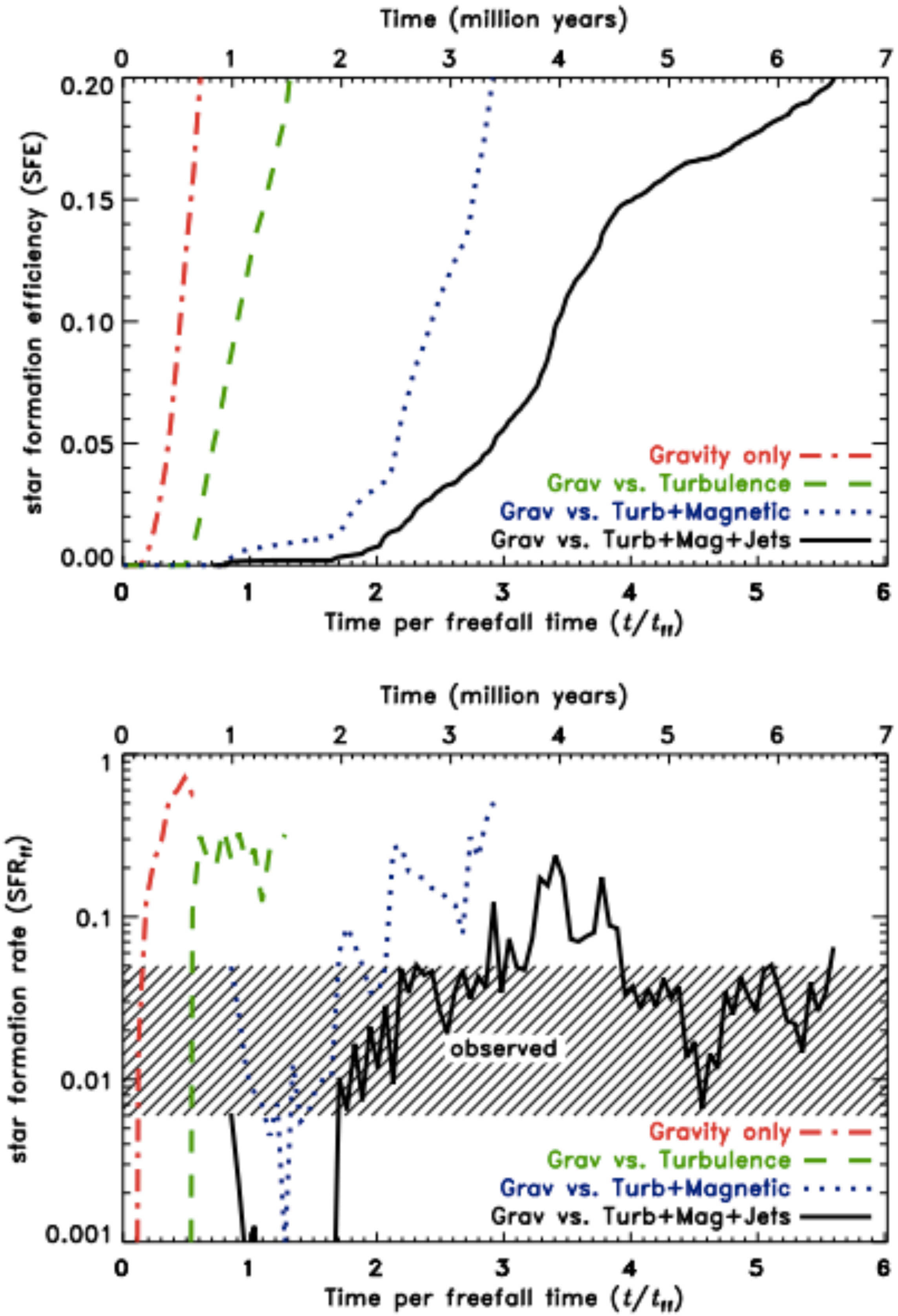
Federrath (2015)

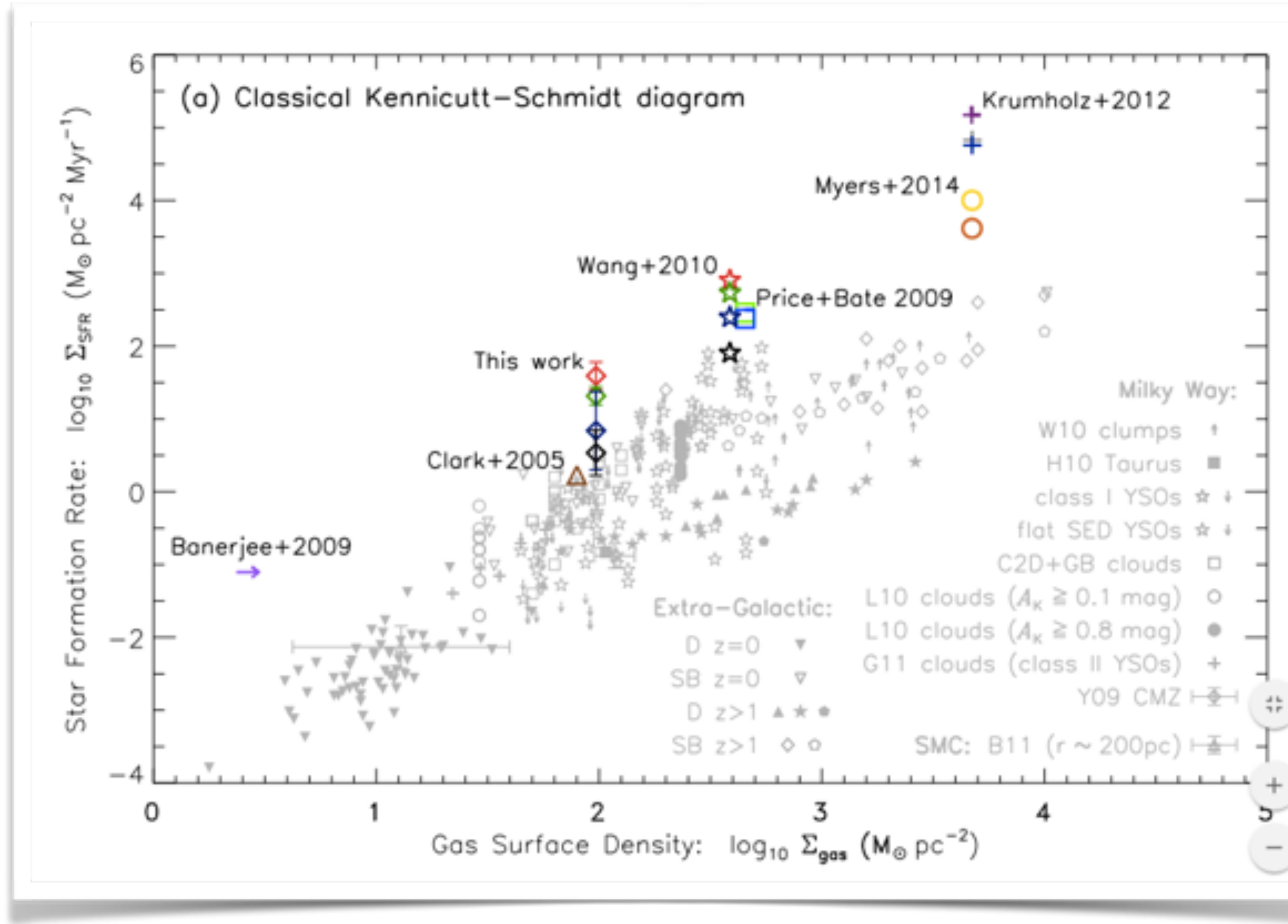
Molecular cloud evolution & dense core formation



Federrath (2015)

Molecular cloud evolution & dense core formation



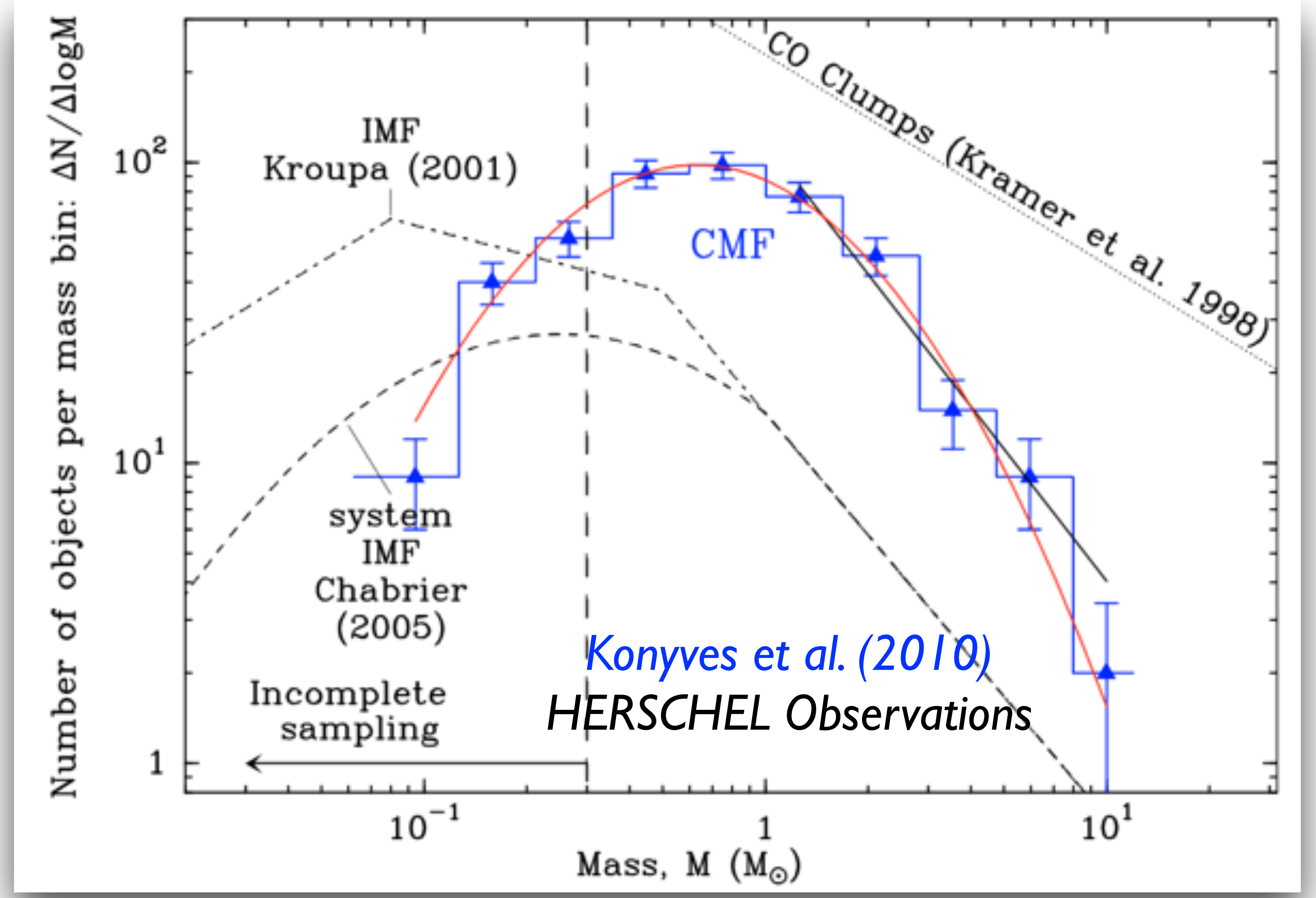


Federrath (2015)

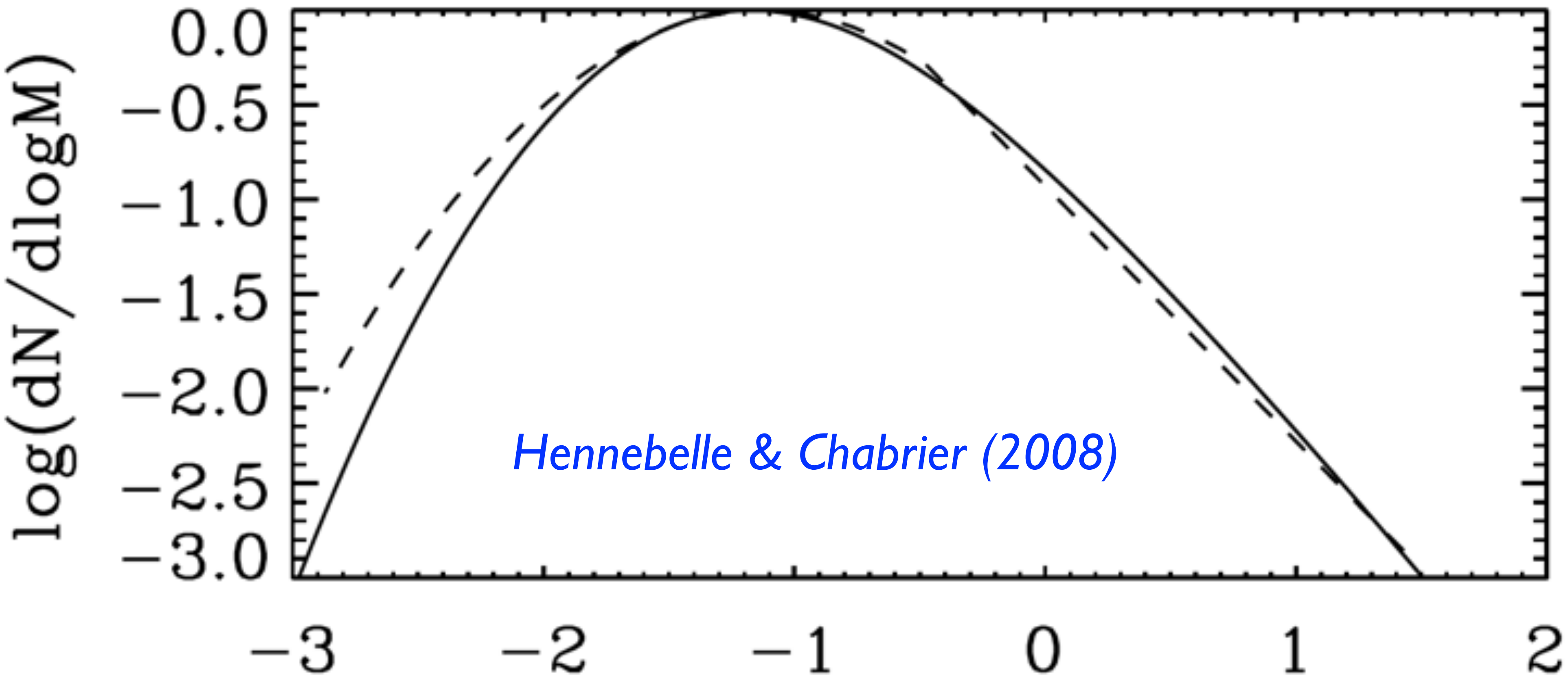
Dense core formation

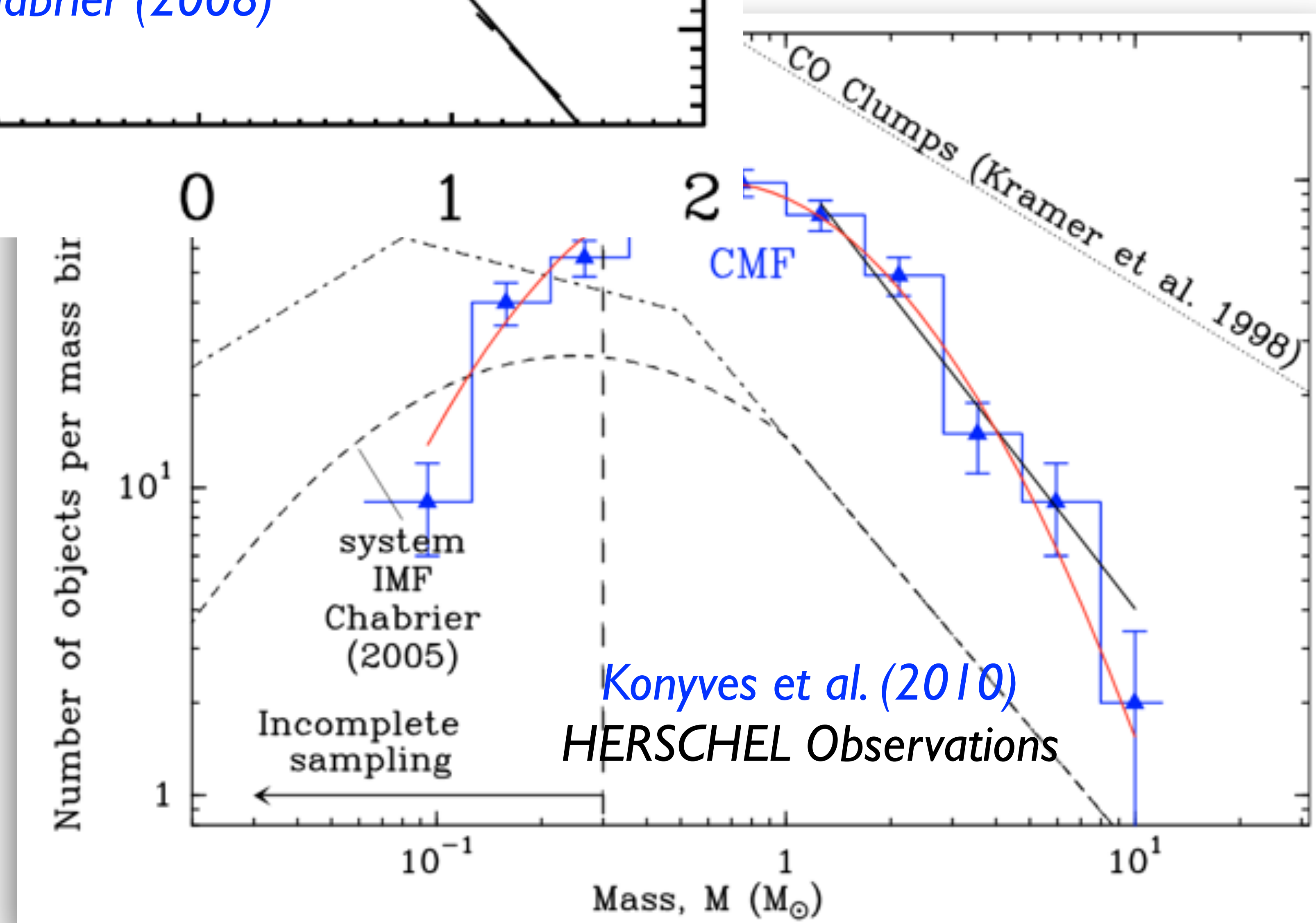
- At the sonic scale for the majority
- Dense core are the progenitors of stars
- 1-1 relation between core mass function and initial stellar mass function?
- Analytical description (e.g., *Hennebelle & Chabrier*)

Barnard 68



Dense core formation

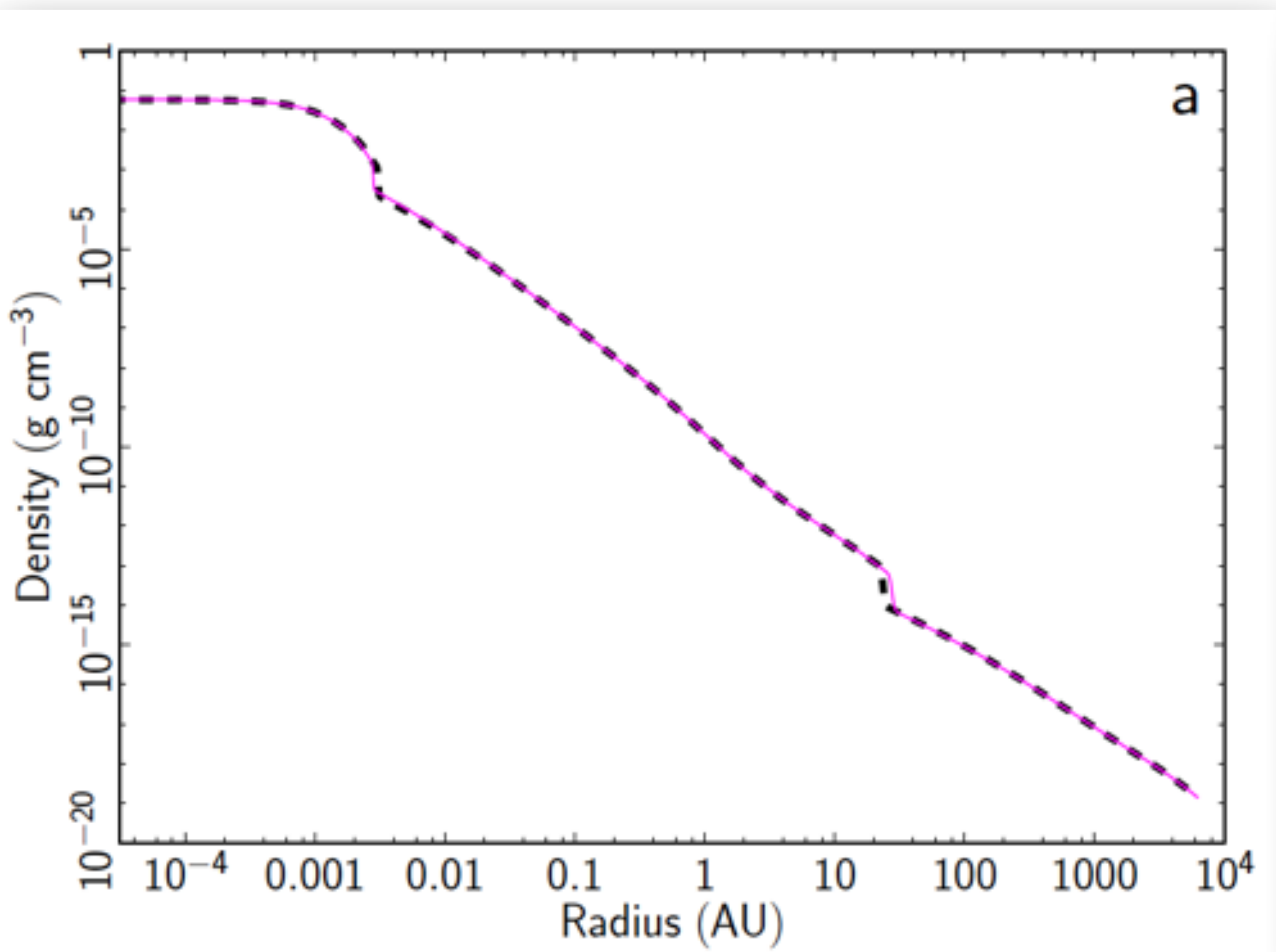


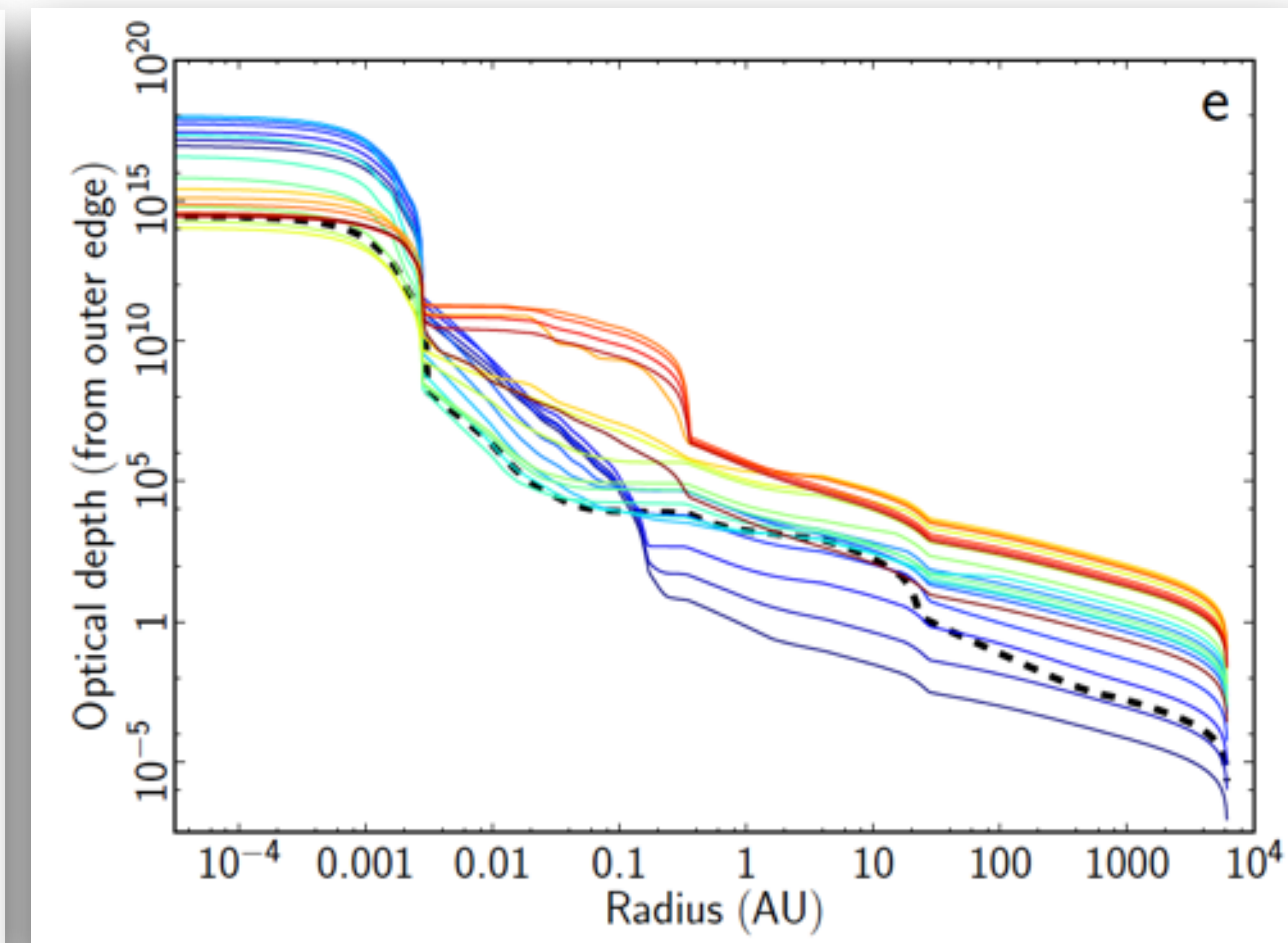


Dense core collapse: the challenge

✓ Follow the dynamics over a wide range of physical scales:

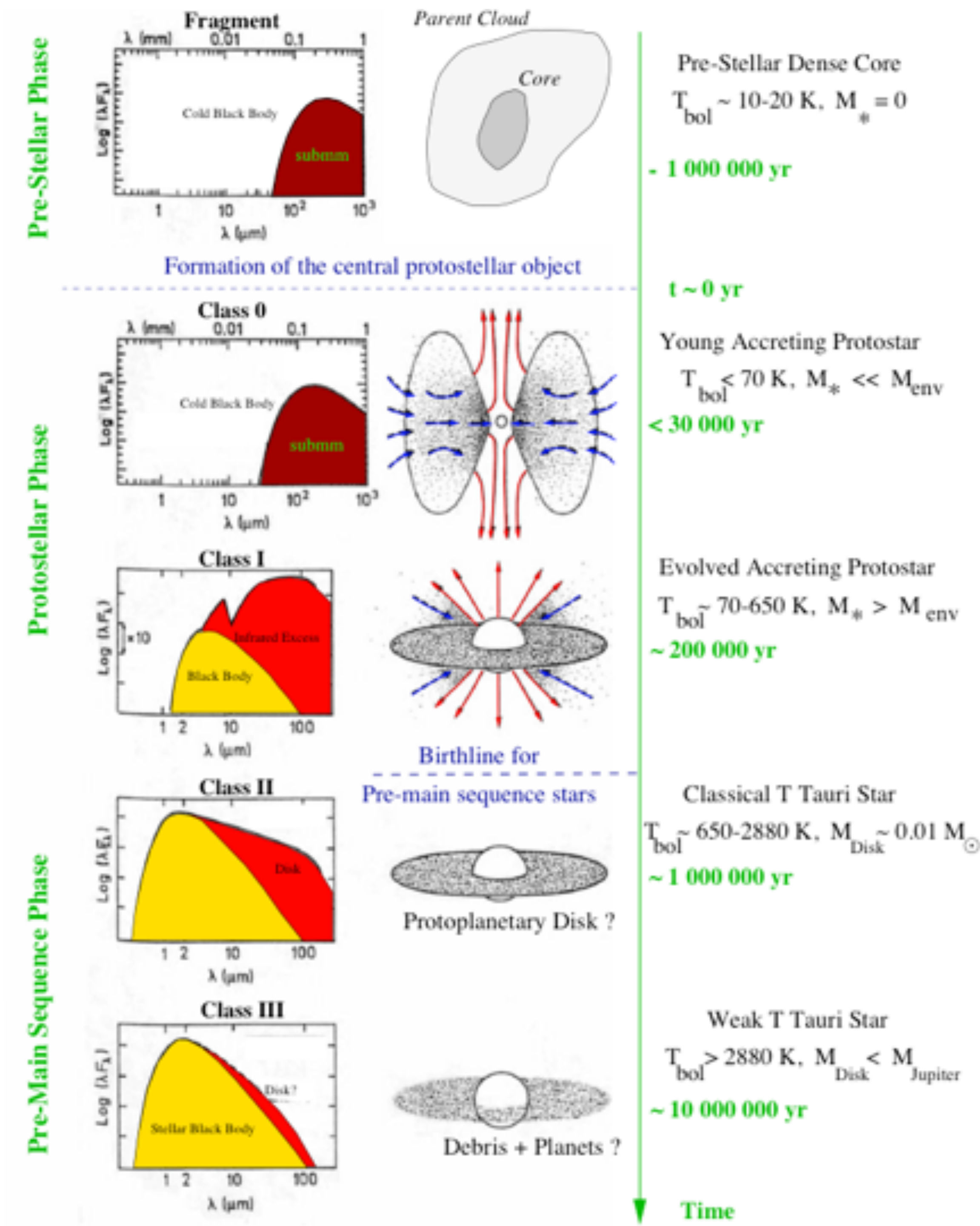
- time scales: free-fall time (~$10^{4,5}$ yr) to second
- spatial scales: parsec to stellar radius
- physical scales: density ranges form 1 cm^{-3} to 10^{24} cm^{-3}





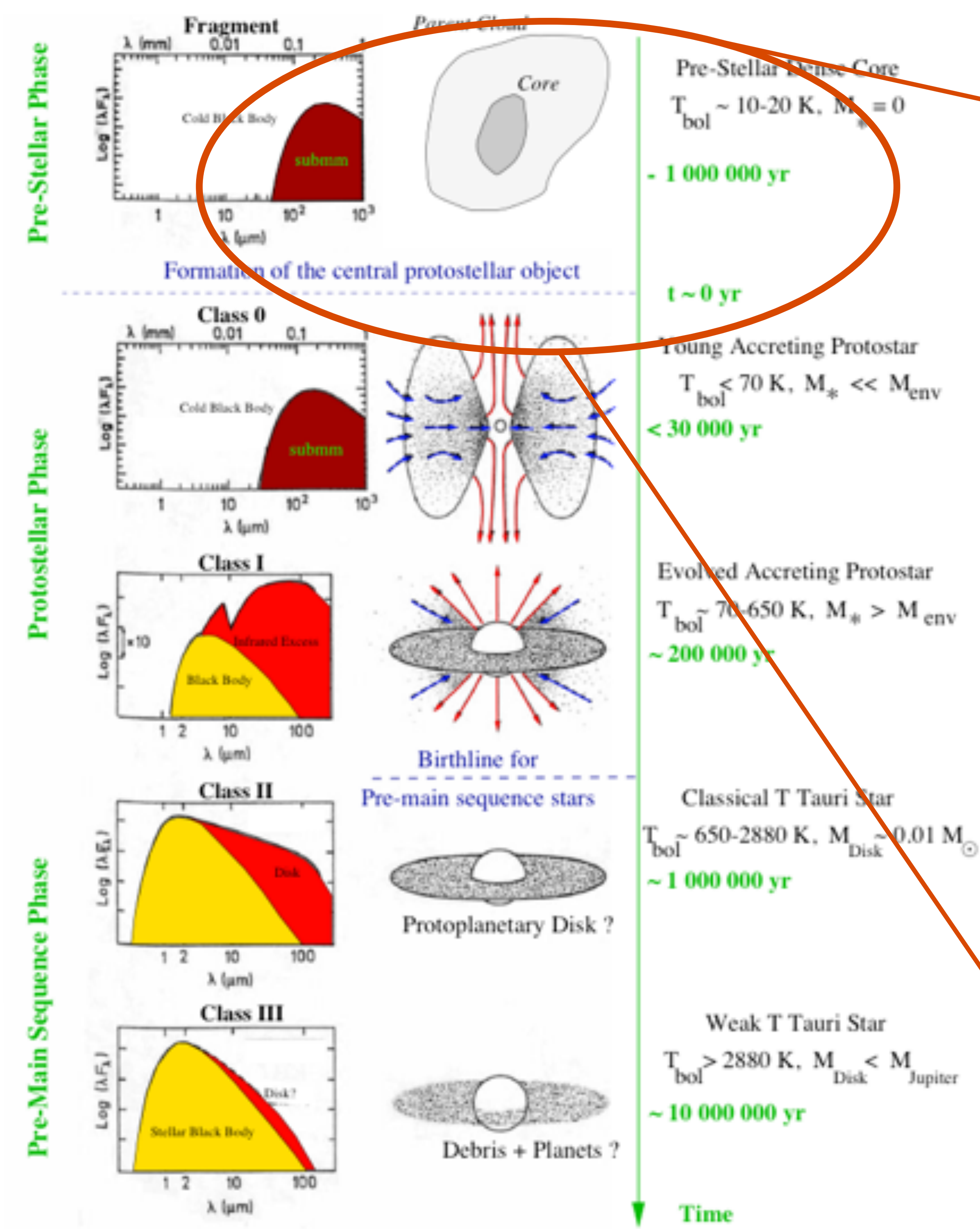
Vaytet et al. (2013)

Star formation evolutionary sequence

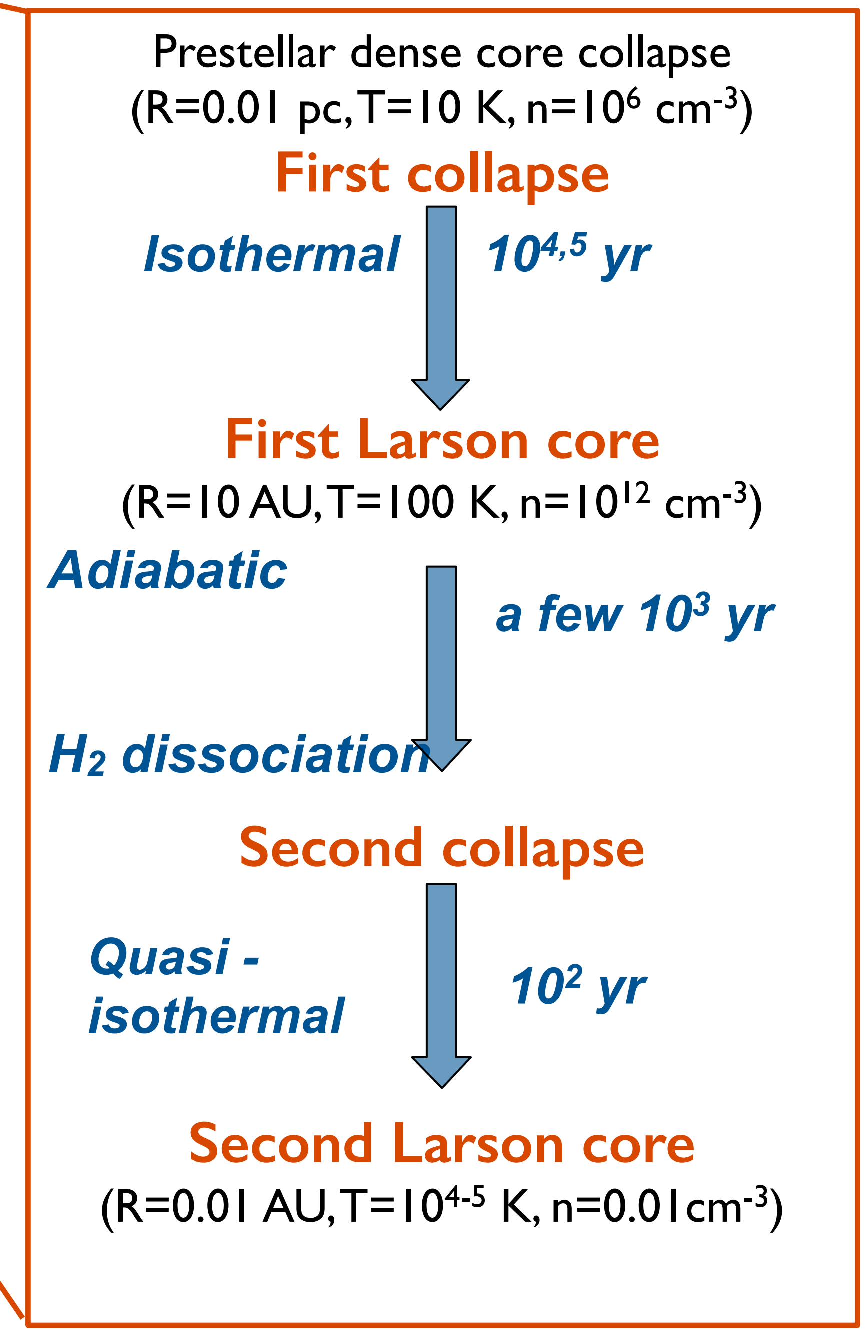


André 2002

Star formation evolutionary sequence

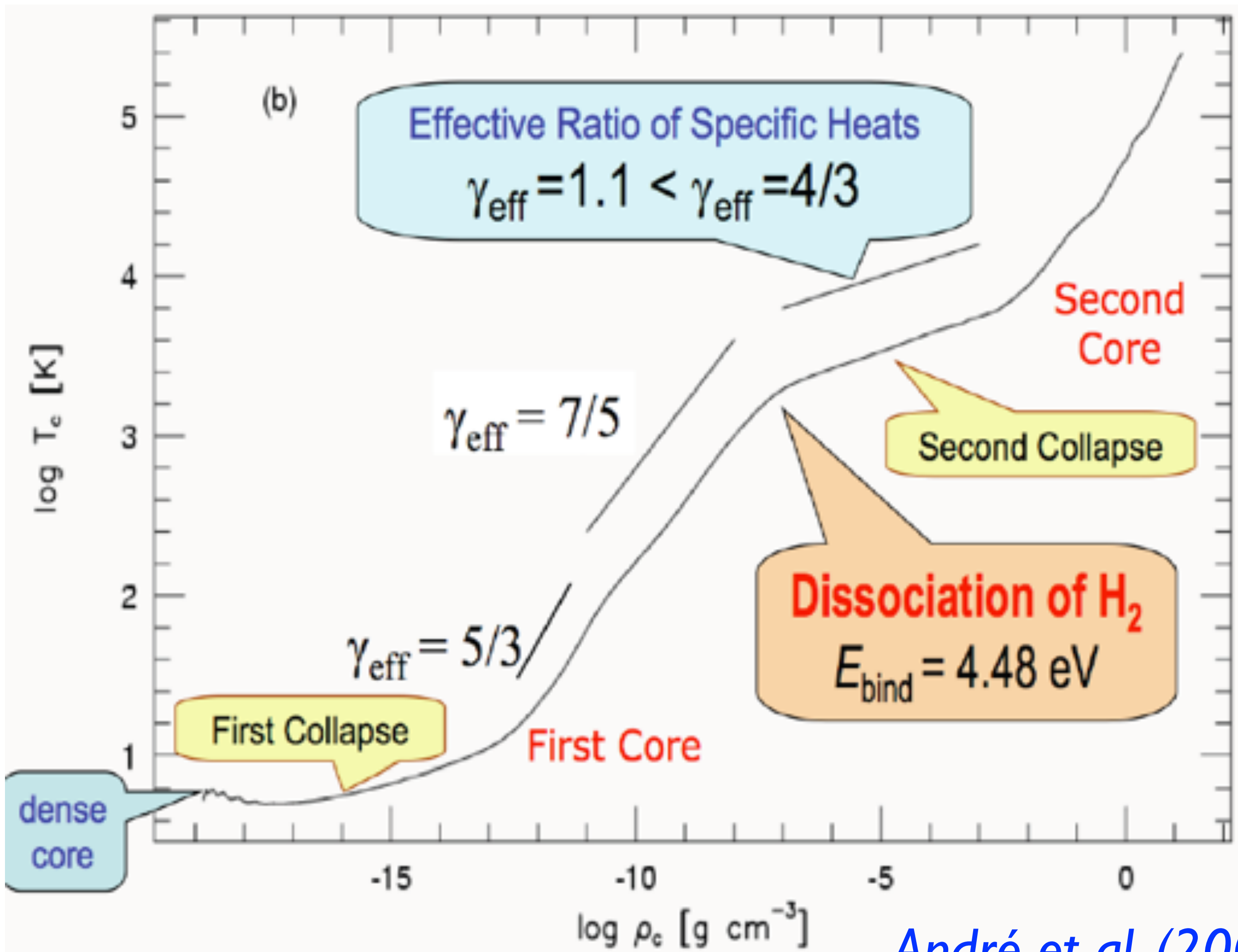


André 2002



Larson (1969)

Star formation evolutionary sequence



André et al. (2008)

$$M_{\rm Jeans} \propto \rho^{\frac{3}{2}n-2}$$

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

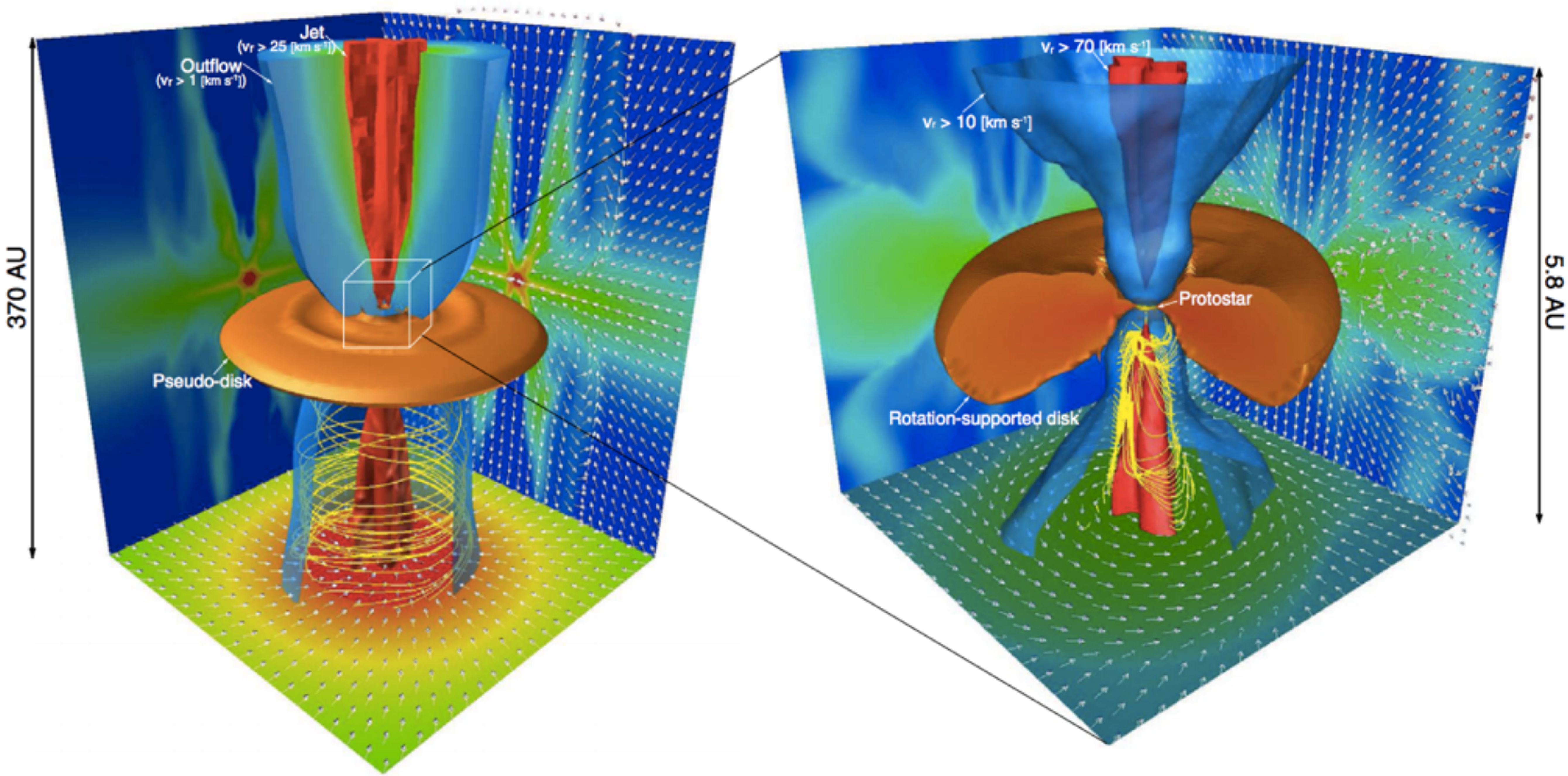
Second collapse

Quasi - isothermal ***10^2 yr***

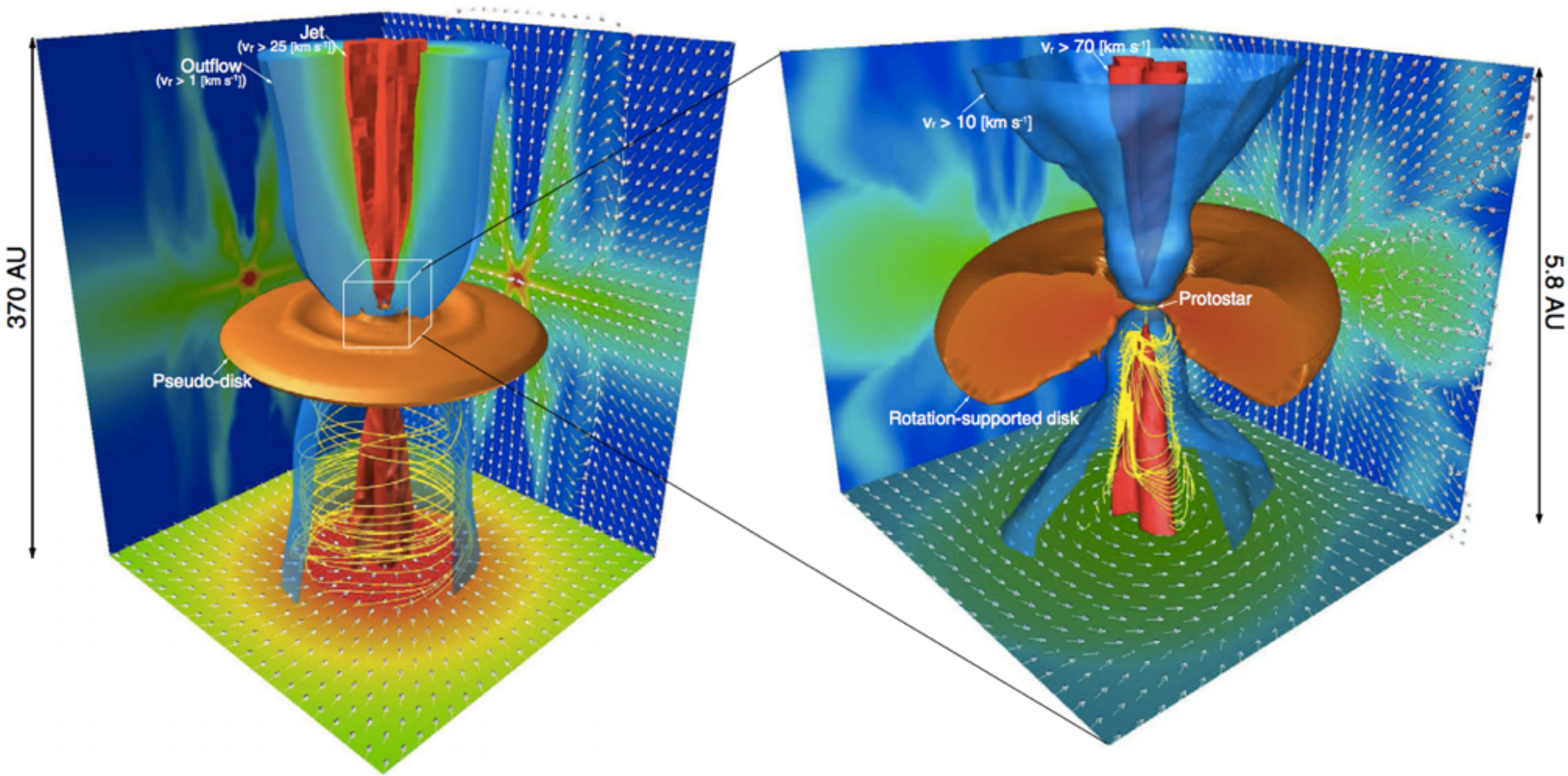
Second Larson core
(R=0.01 AU, T=10^{4-5} K, n=0.01cm^{-3})

Larson (1969)

Protostellar core

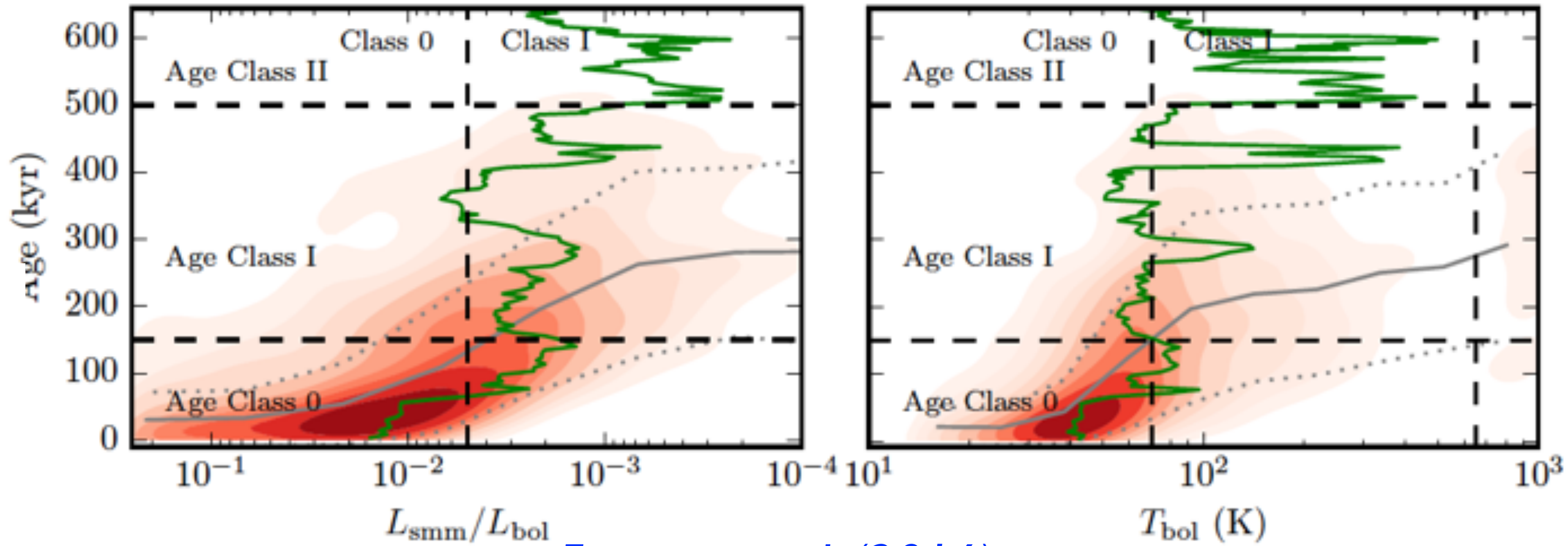


Protostellar core

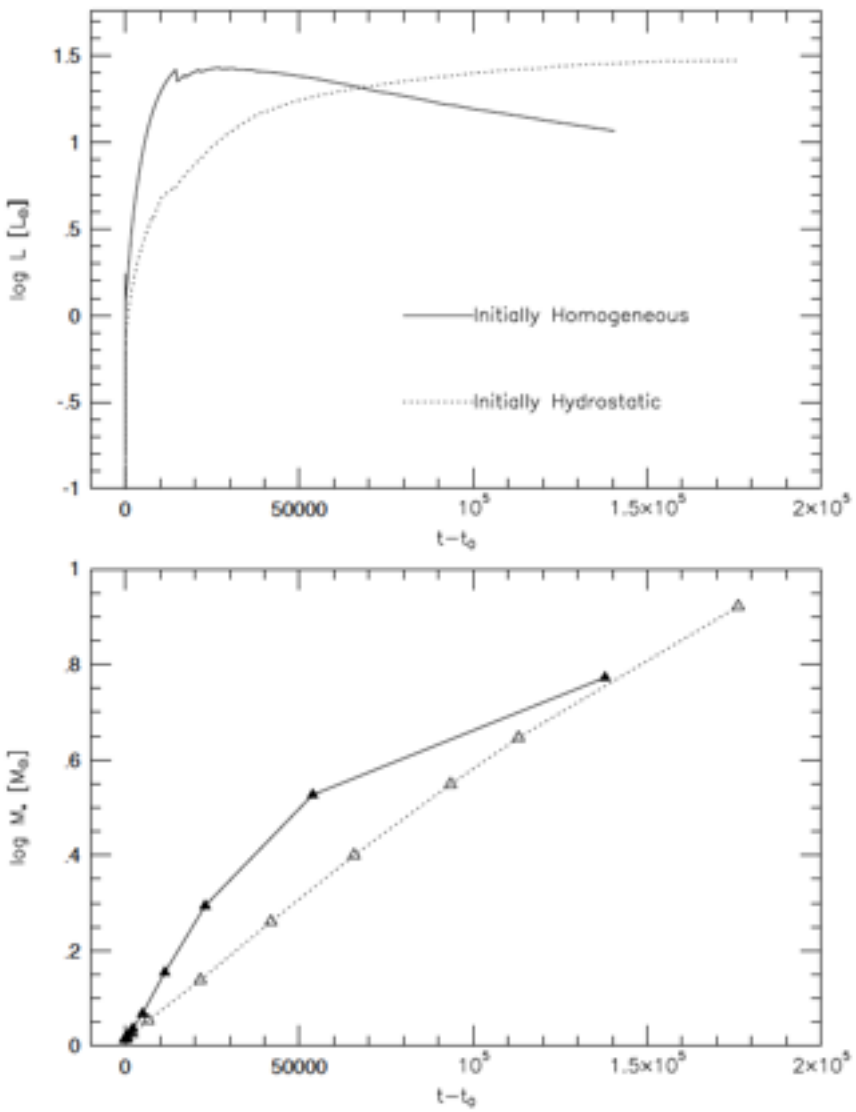


Machida et al.

Luminosity and other evolution tracers



Frimann et al. (2016)



Masunaga et al. (2000)

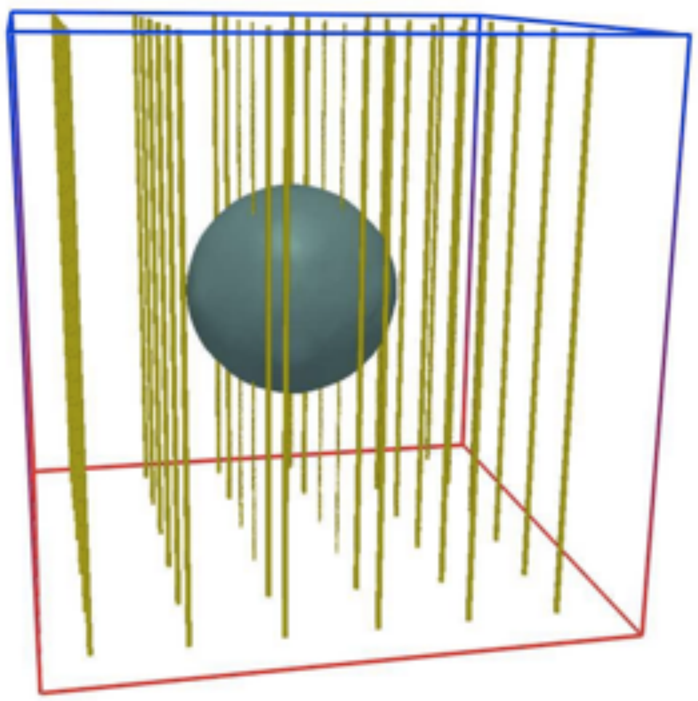
- models match well the distributions of observed tracers
- but… observed quantities do not trace well protostellar ages
- **needs more quantitative analysis and models integrating more physics.**

Numerical experiments

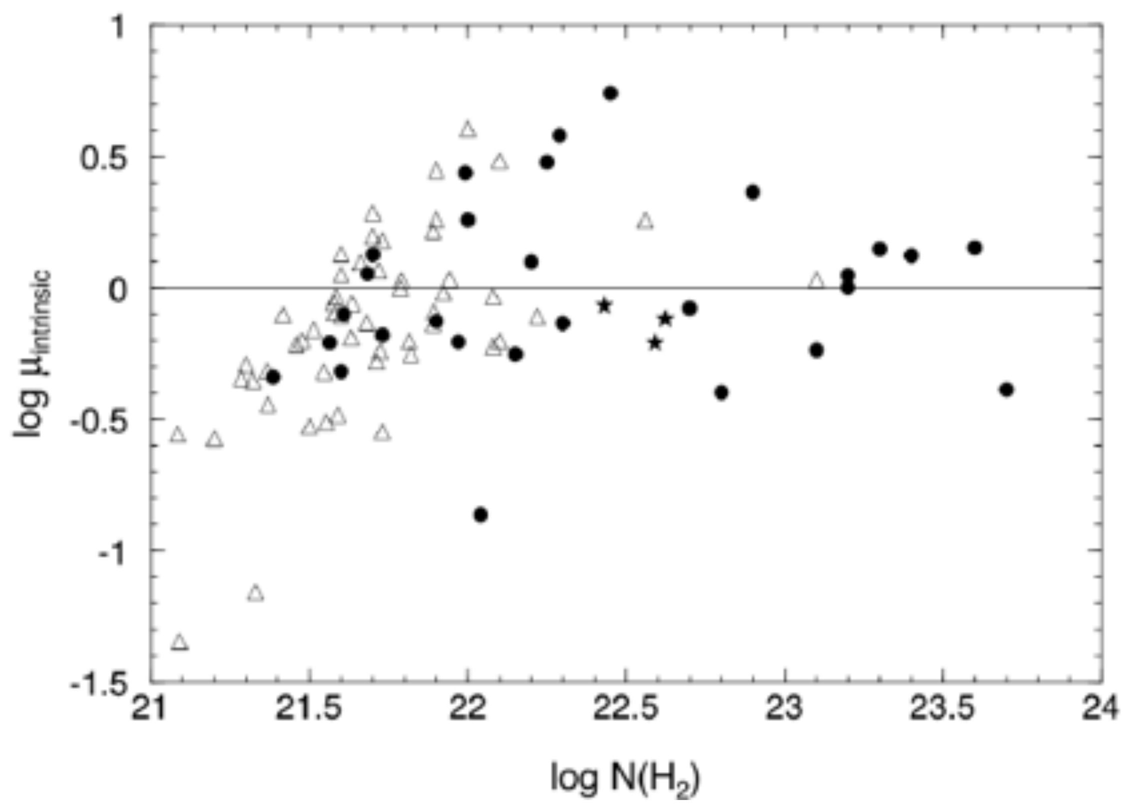
Typical initial conditions:

- 1 $M_\odot$ 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

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



Refinement criterion solely based on the Jeans length



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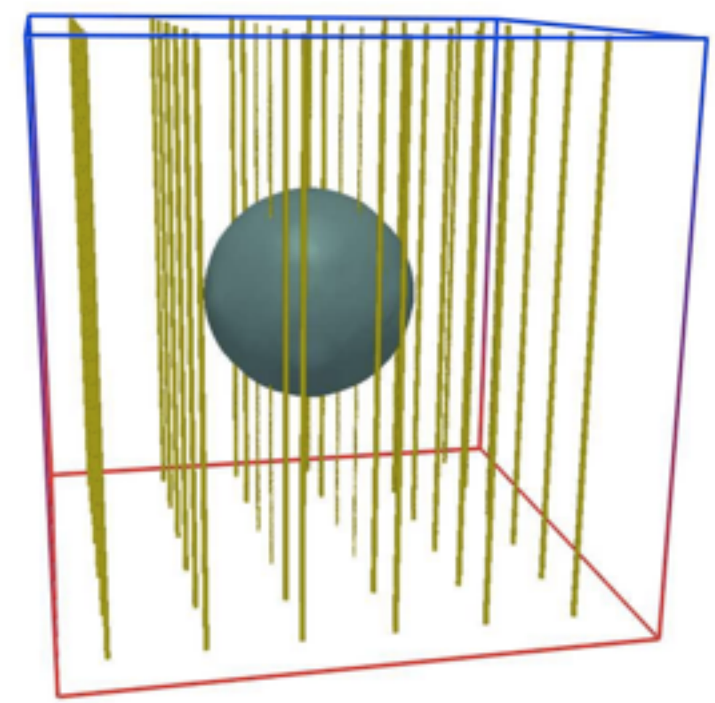
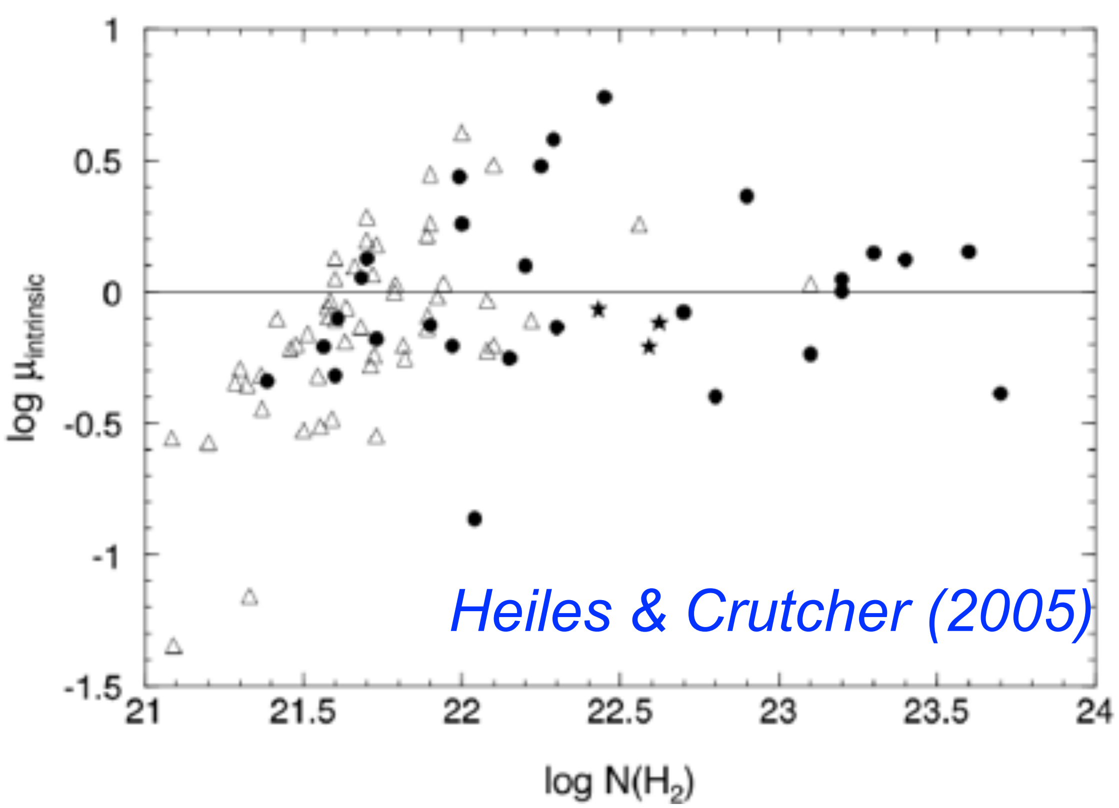


Banerjee & Pudritz (2006)

Refinement criterion solely based on the Jeans length



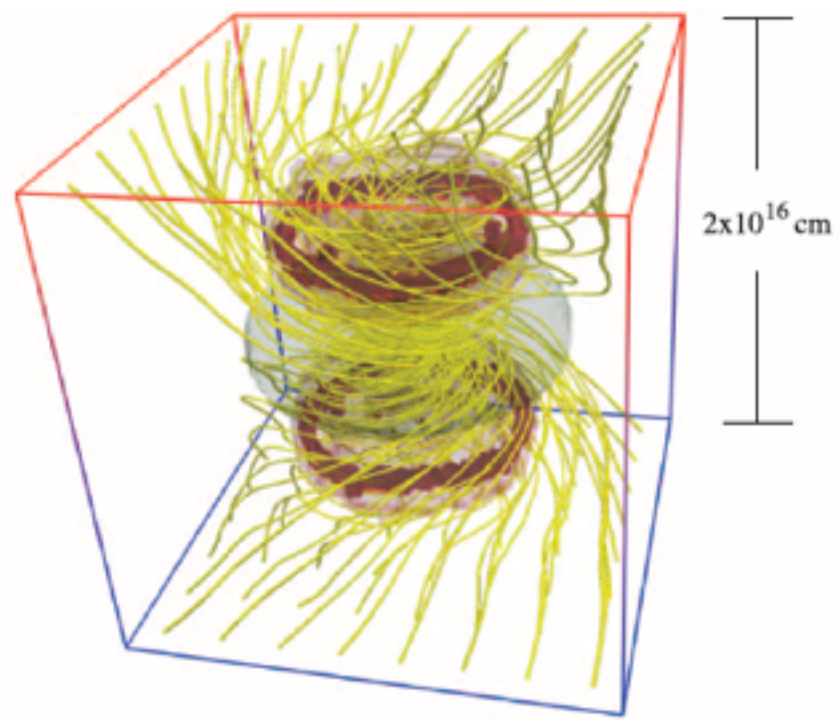
Numerics for star formation

★ **2 numerical methods :**

– **Grid based code (AMR)** : RAMSES code (*Teyssier 2002, Fromang et al. 2006, Commerçon et al. 2011a*), ORION code (*Krumholz et al.*) FLASH code (*Banerjee, Seifried et al.*), etc…

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

➡ **Disadvantages :**
- ✓ (headhach)
- ✓ Eulerian

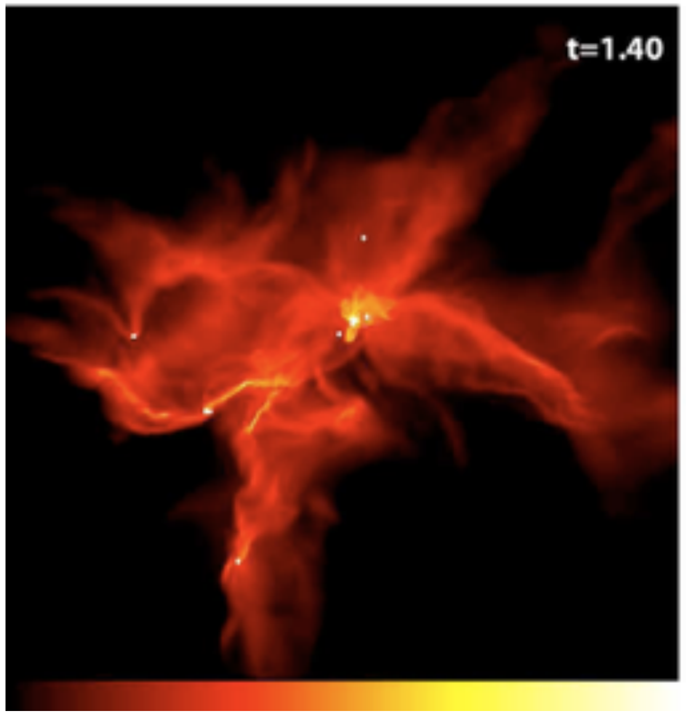


Banerjee & Pudritz 06

– **Lagrangian - SPH** : e.g. Bate & Price (RHD & MHD), Stamatellos et al. 2008 (RHD), etc…

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

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

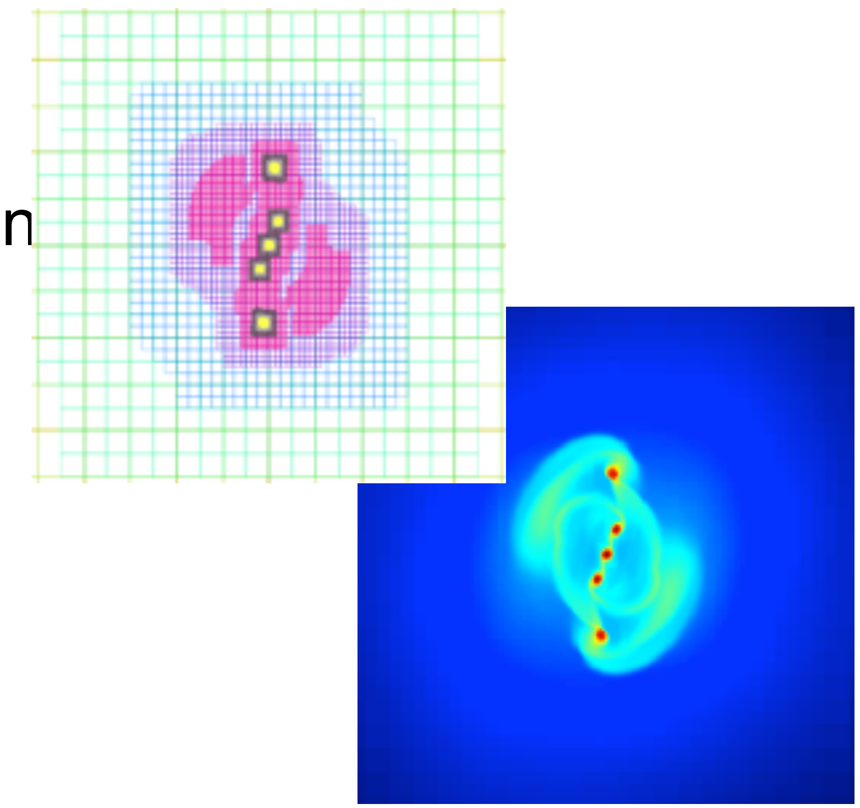


Bate et al. 08

Numerical resolution criteria for SF

★ Gravitational instability ➔ **Jeans** length

AMR : Refinement criteria N_J as a function of the local Jean



$N_J \cdot \Delta x < \lambda_{Jeans}$

↪ Truelove et al. 1997: $N_J \geq 4$

↪ Dynamical criterion

Numerical resolution criteria for SF

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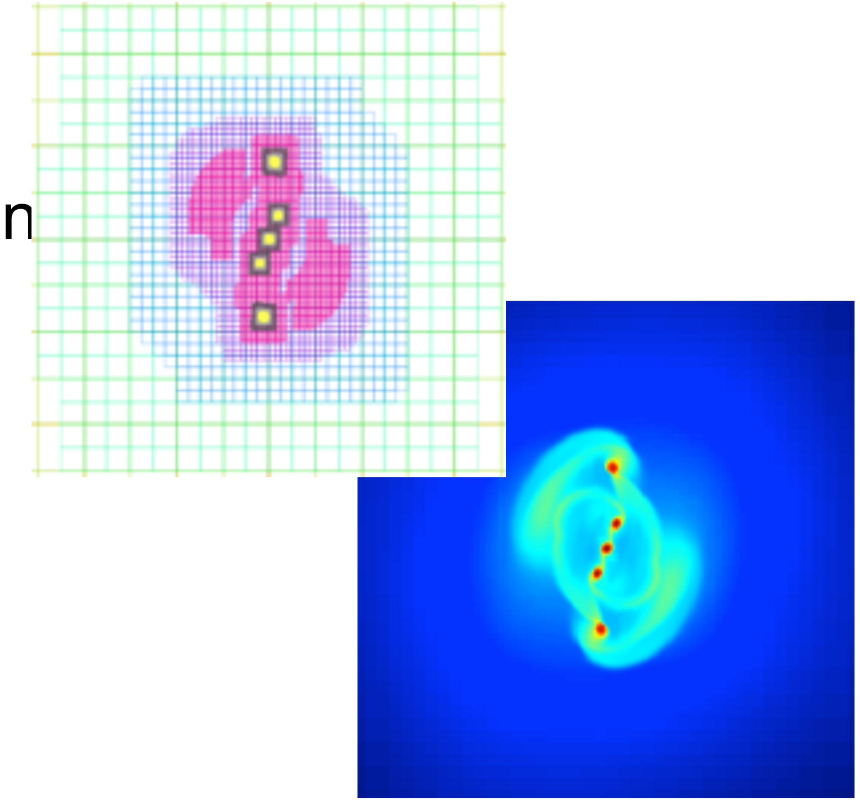

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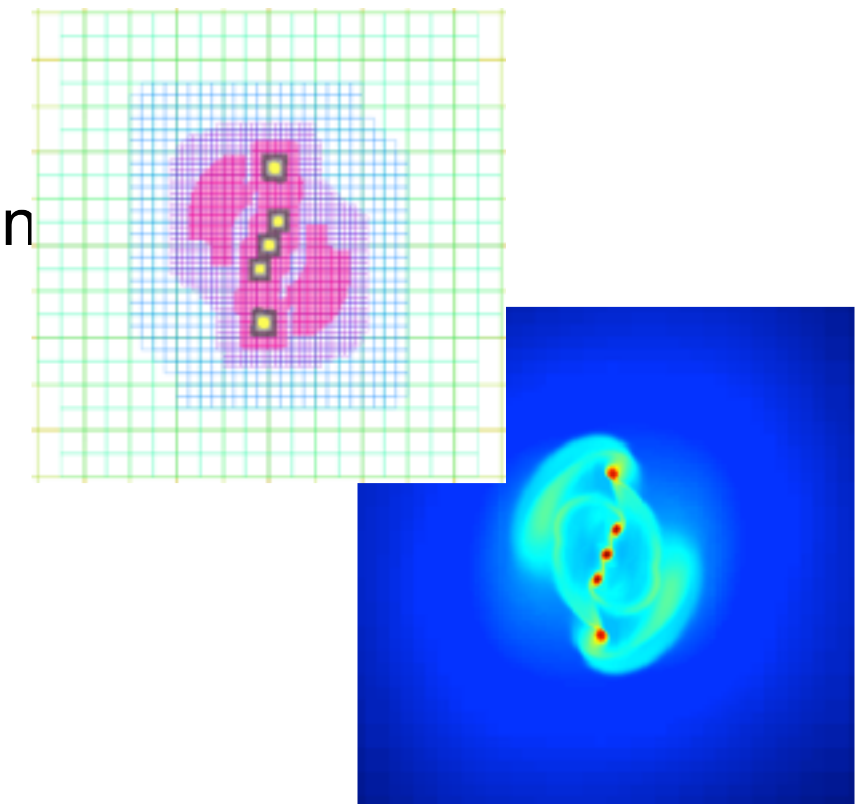

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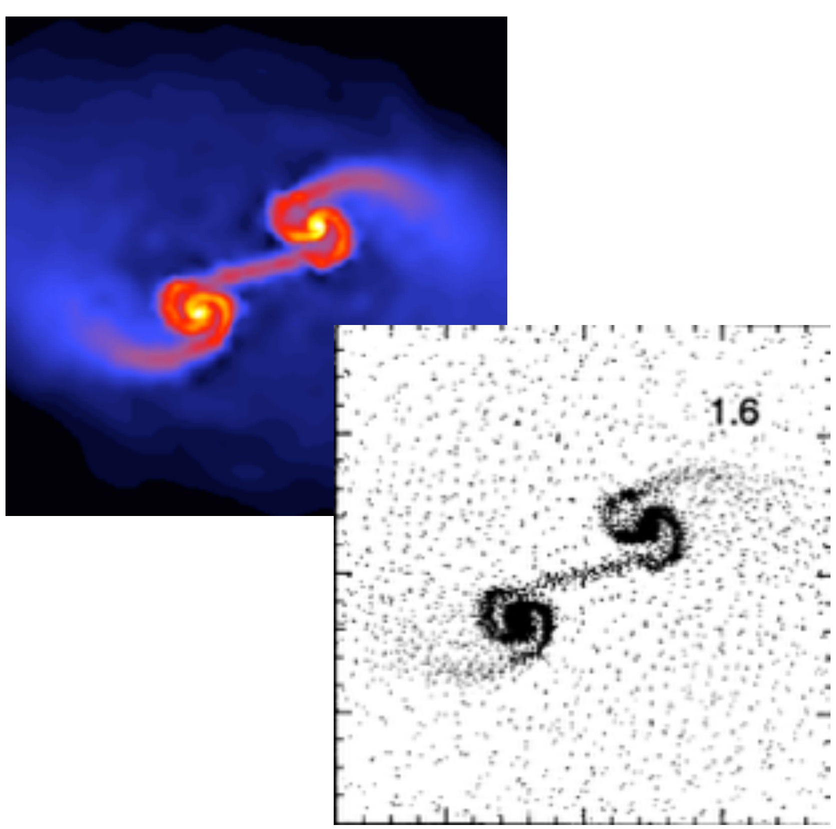
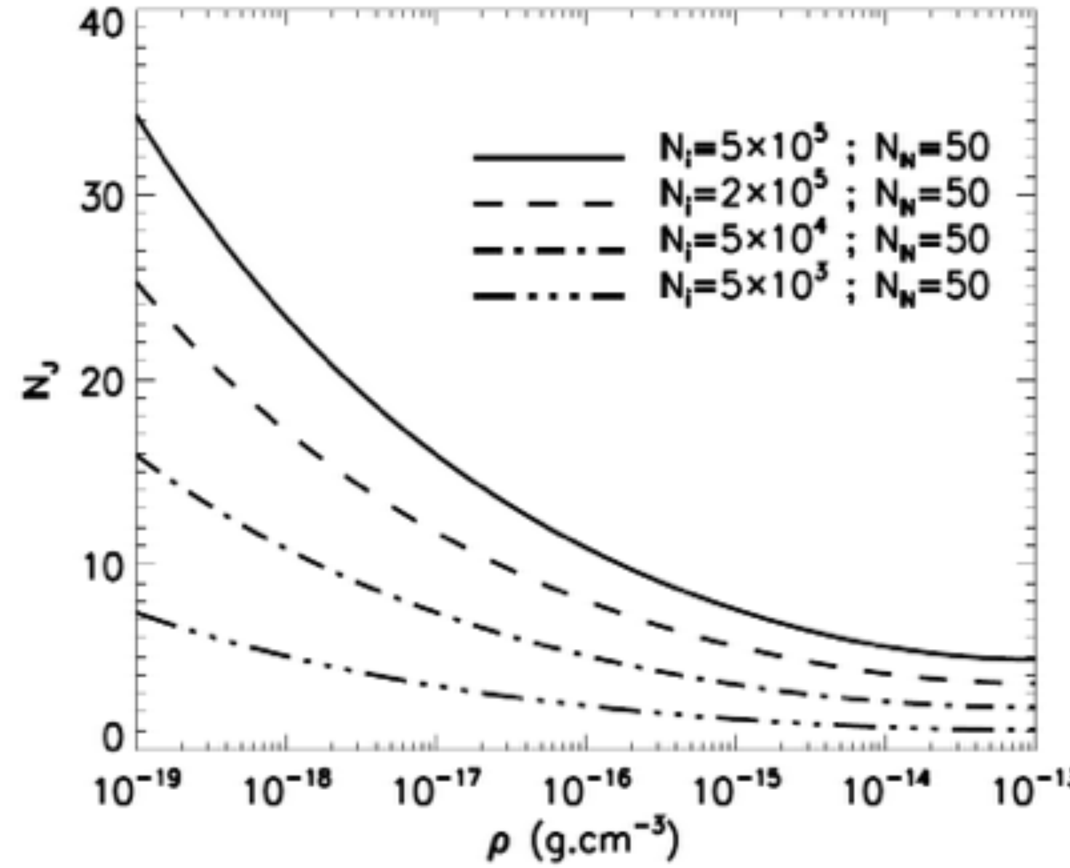


SPH : Total mass of the system particle + 2 N_N (M_{res}) should always be < than the local Jeans mass M_{Jeans} (Bate & Burkert 1997) ➔ static criterion

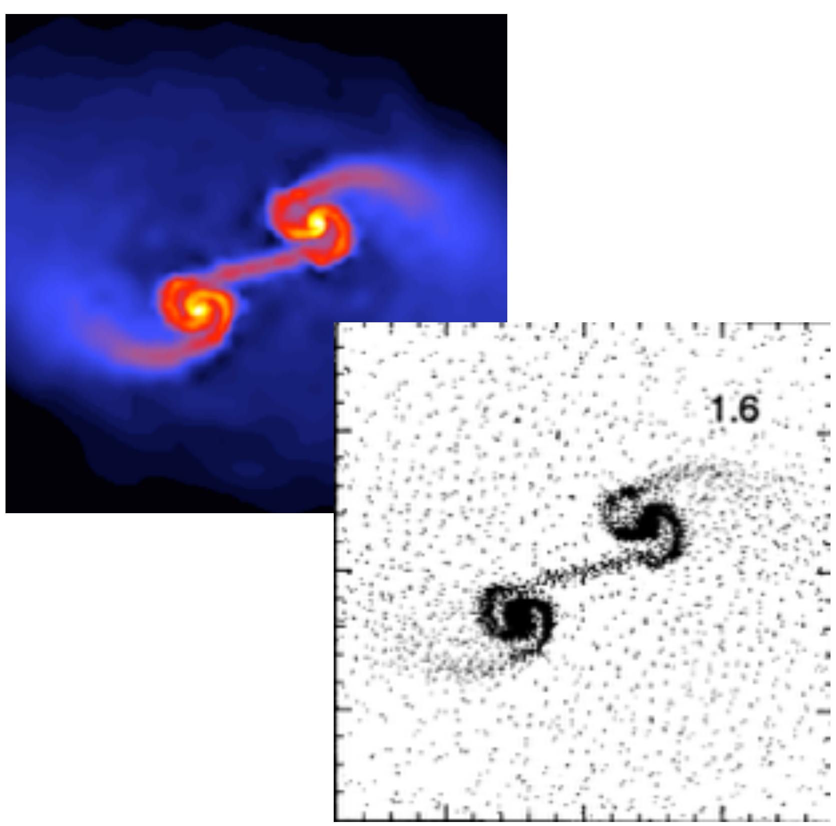
↳ 2 parameters : N_p number of particles

N_N number of neighbors

Numerical resolution criteria for SF



AMR vs. SPH resolution: $N_J^3 = M_{Jeans}/M_{res}$



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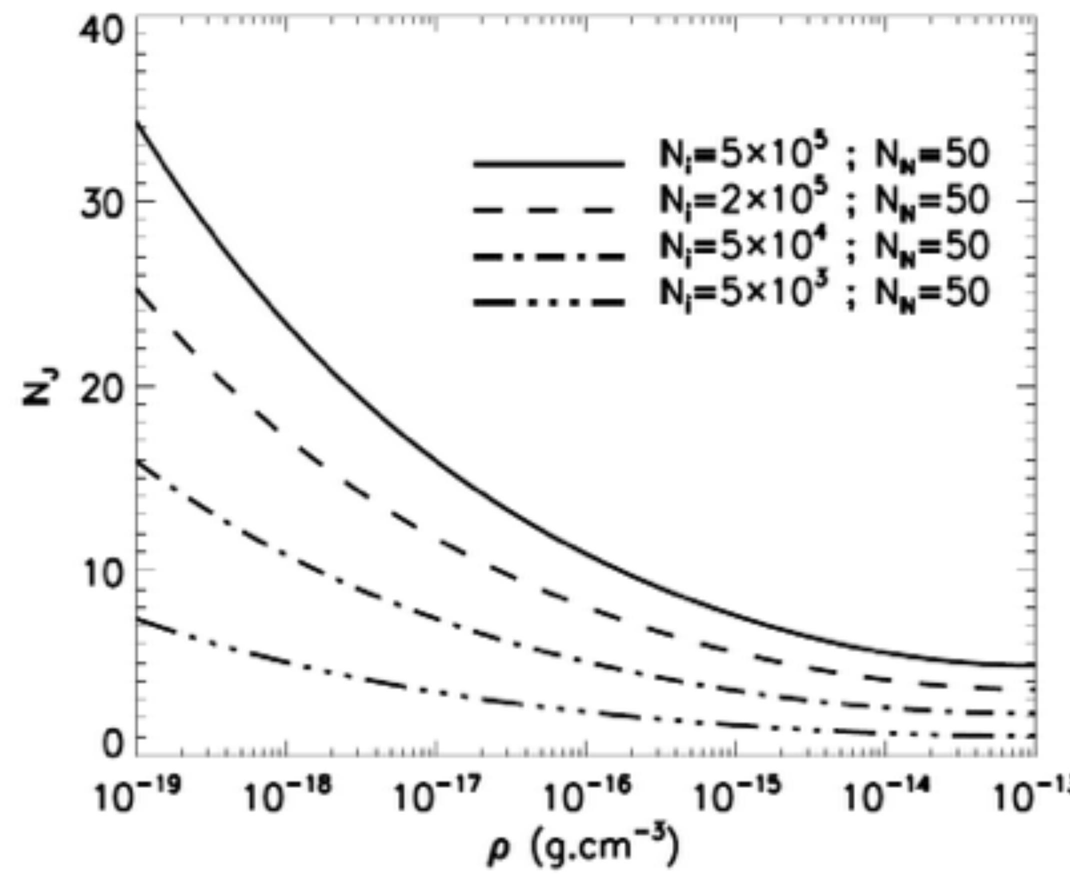


AMR vs. SPH resolution: $N_J^3 = M_{Jeans}/M_{res}$

★ Debate on the accuracy of both methods:

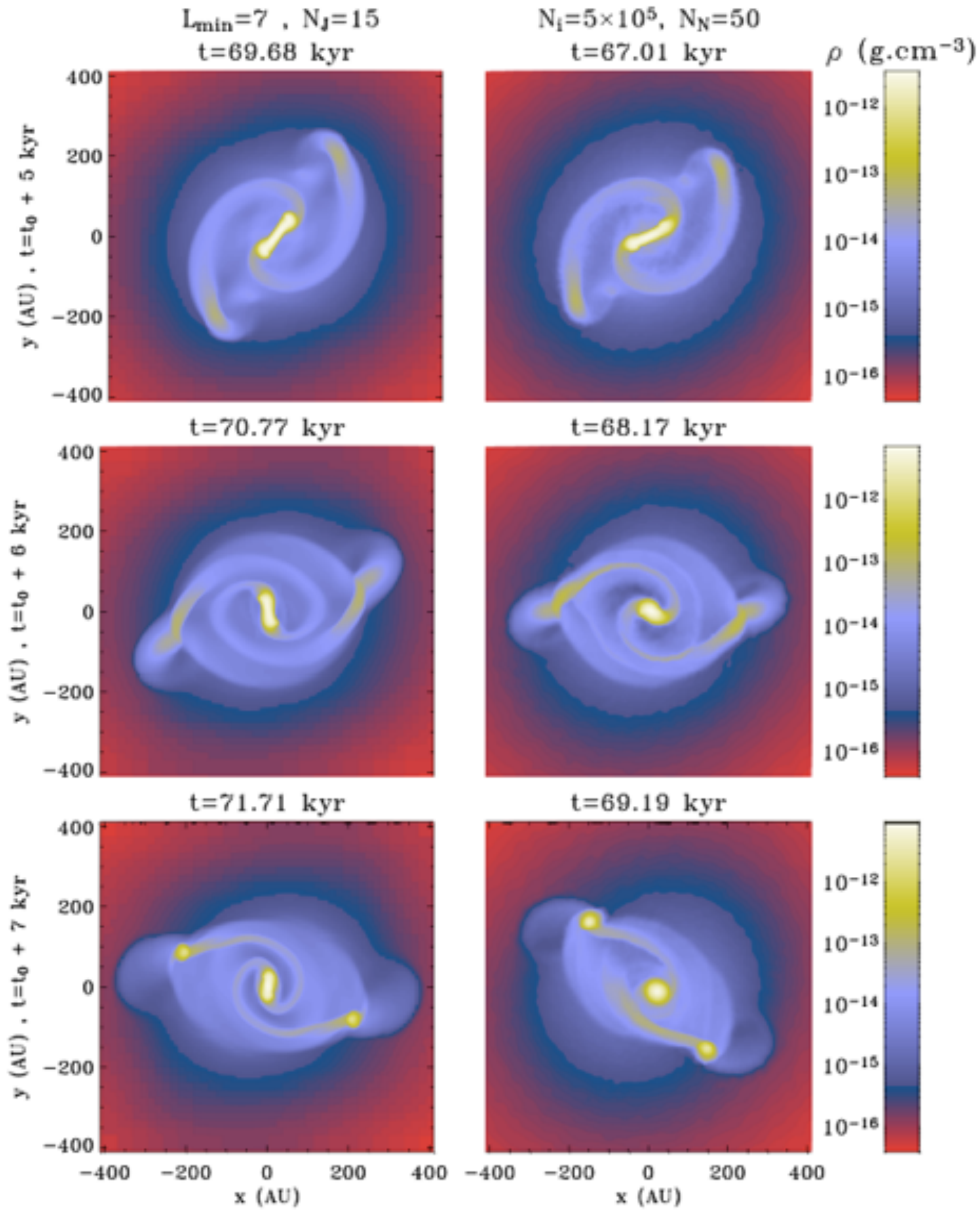
=> Are these methods appropriate for star formation?

=> Are they converging?

☞ Identical initial conditions (uniform density & temperature sphere in solid body rotation, Boss & Bodenheimer test)

☞ Same equations (Euler equation: mass, momentum and total energy + barotropic closure relation)

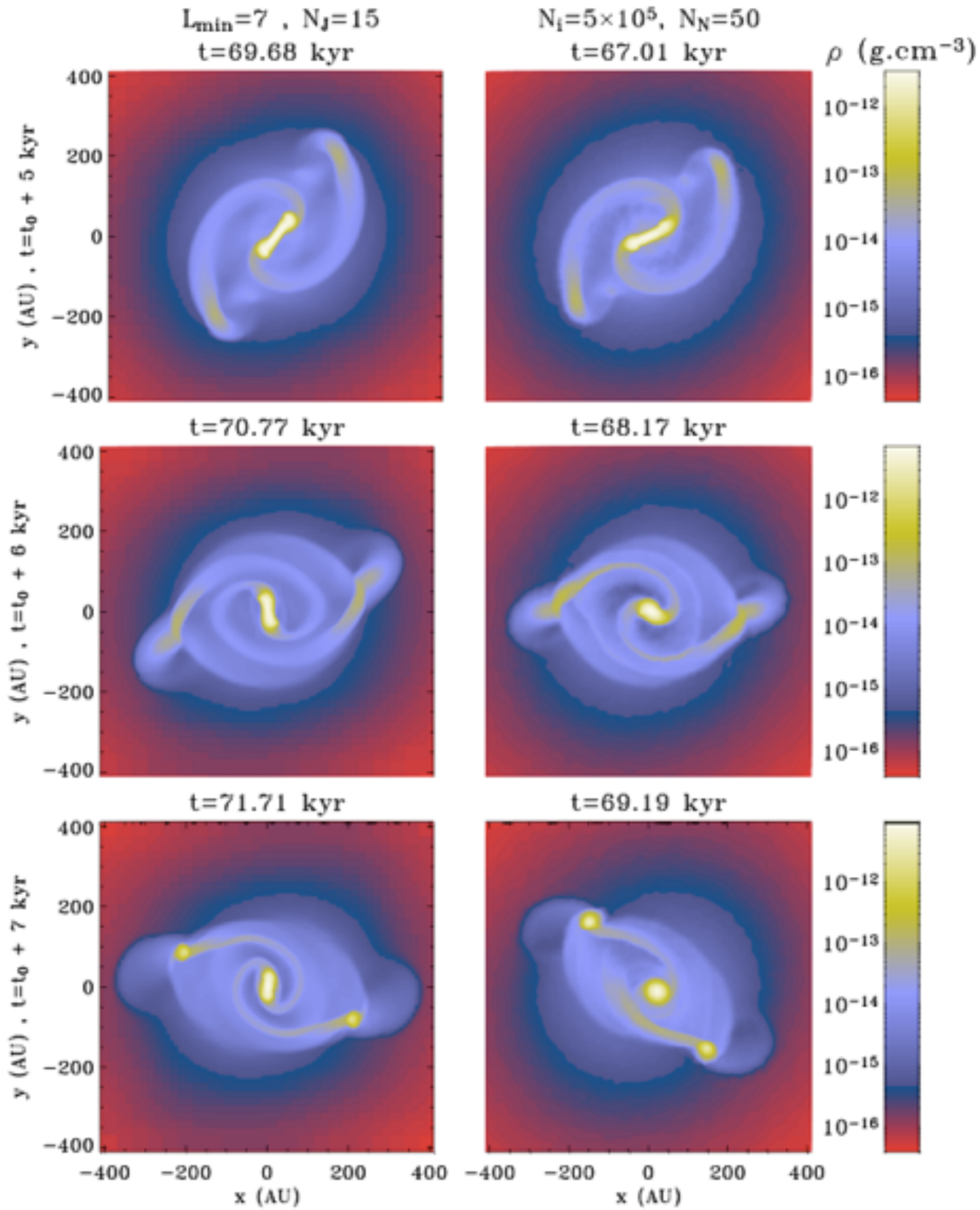
AMR vs. SPH: Convergence



Hydro models

Commerçon et al. 2008

AMR vs. SPH: Convergence



Hydro models

AMR: 64^3 (L_{min}=6) ; ***N_J*=15** !

SPH: N_p=5x10^5 ; N_N=50

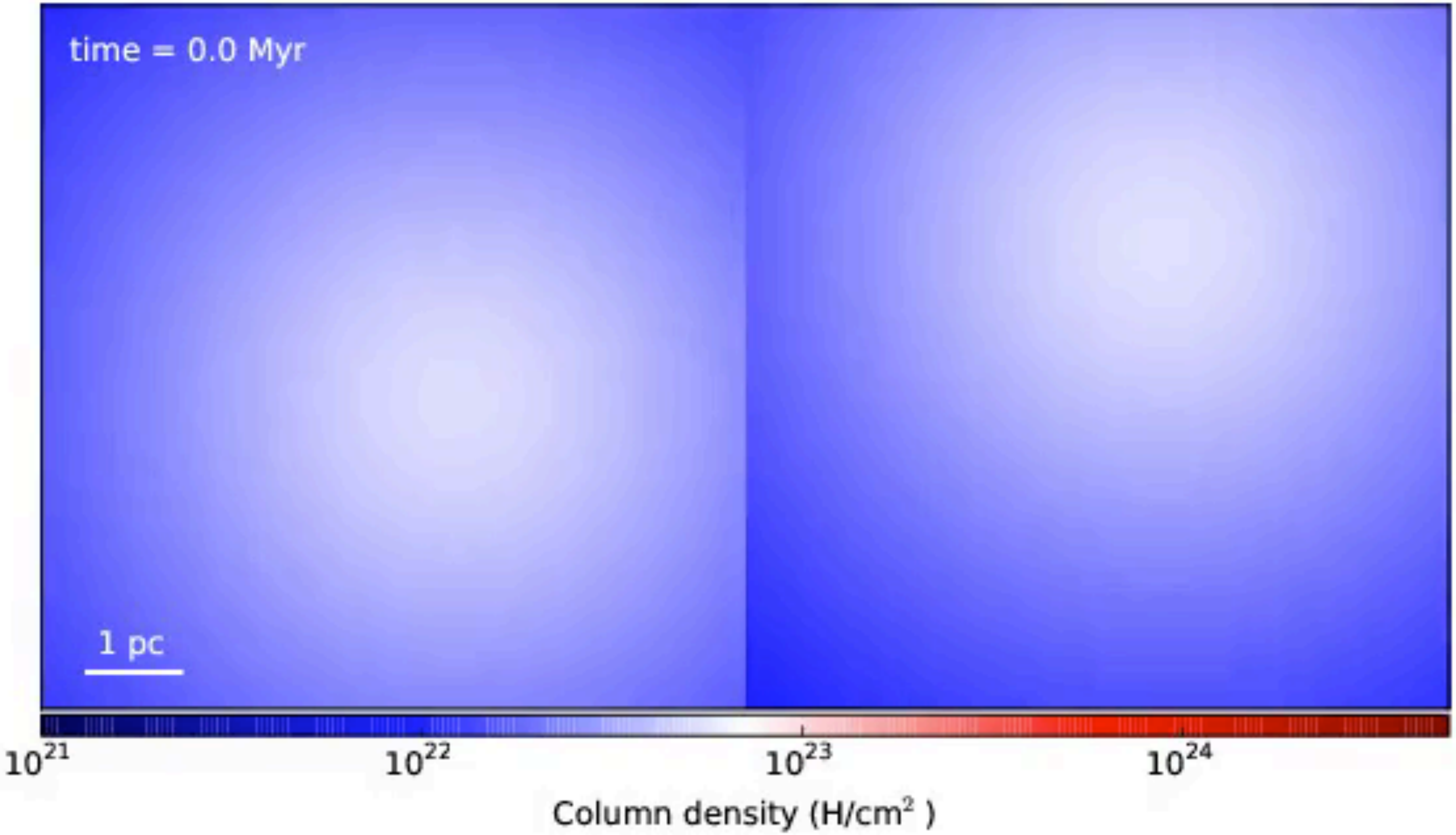
i.e. ~ **5300** particles/Jeans mass !

- CONVERGENCE!

Commerçon et al. 2008

Star cluster formation

Lee, Hennebelle, Geen et al.



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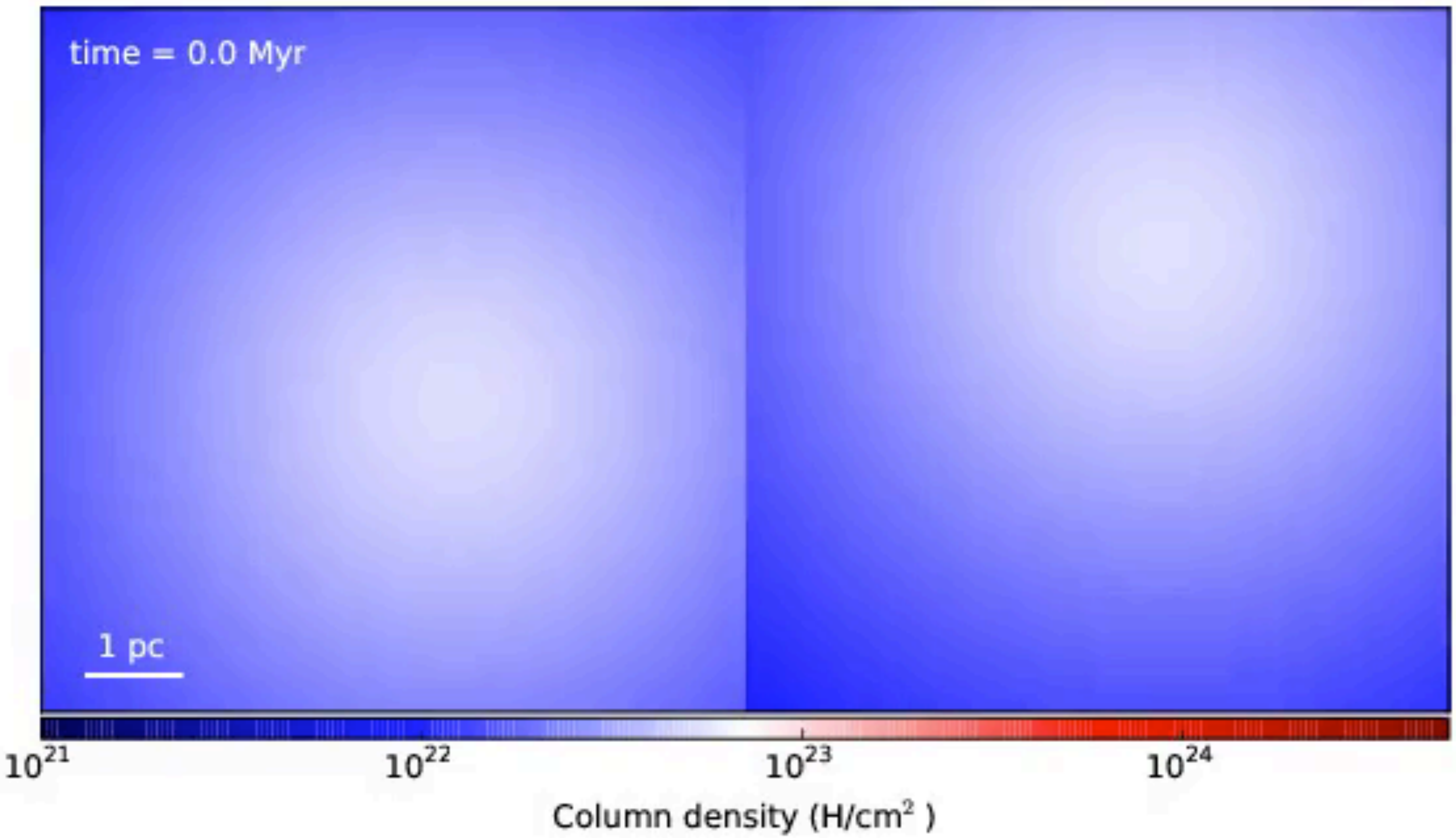
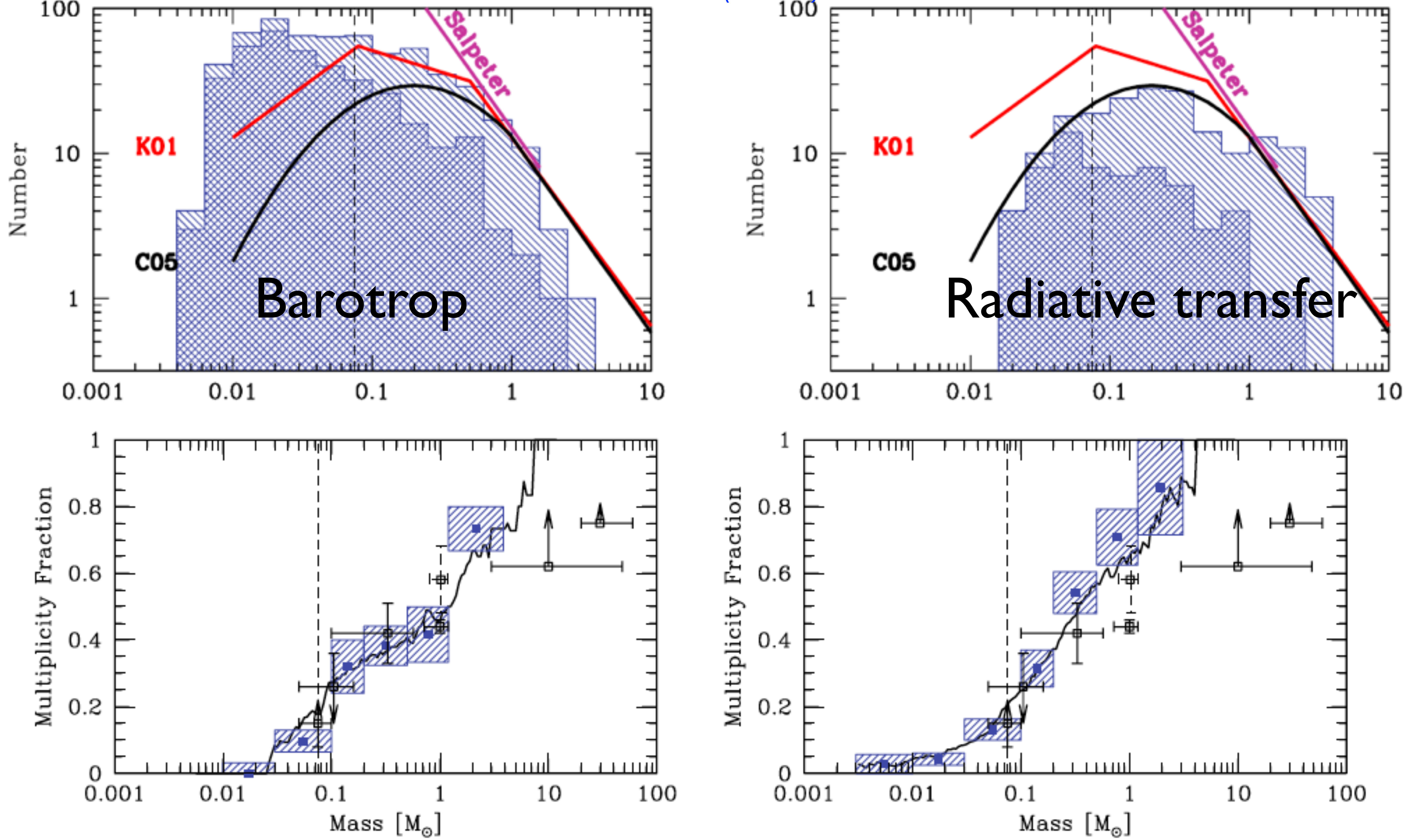


Star cluster formation

Bate (2012)



Formation of the protoplanetary disc

Benoît Commerçon - Anaëlle Maury

Centre de Recherche Astrophysique de Lyon

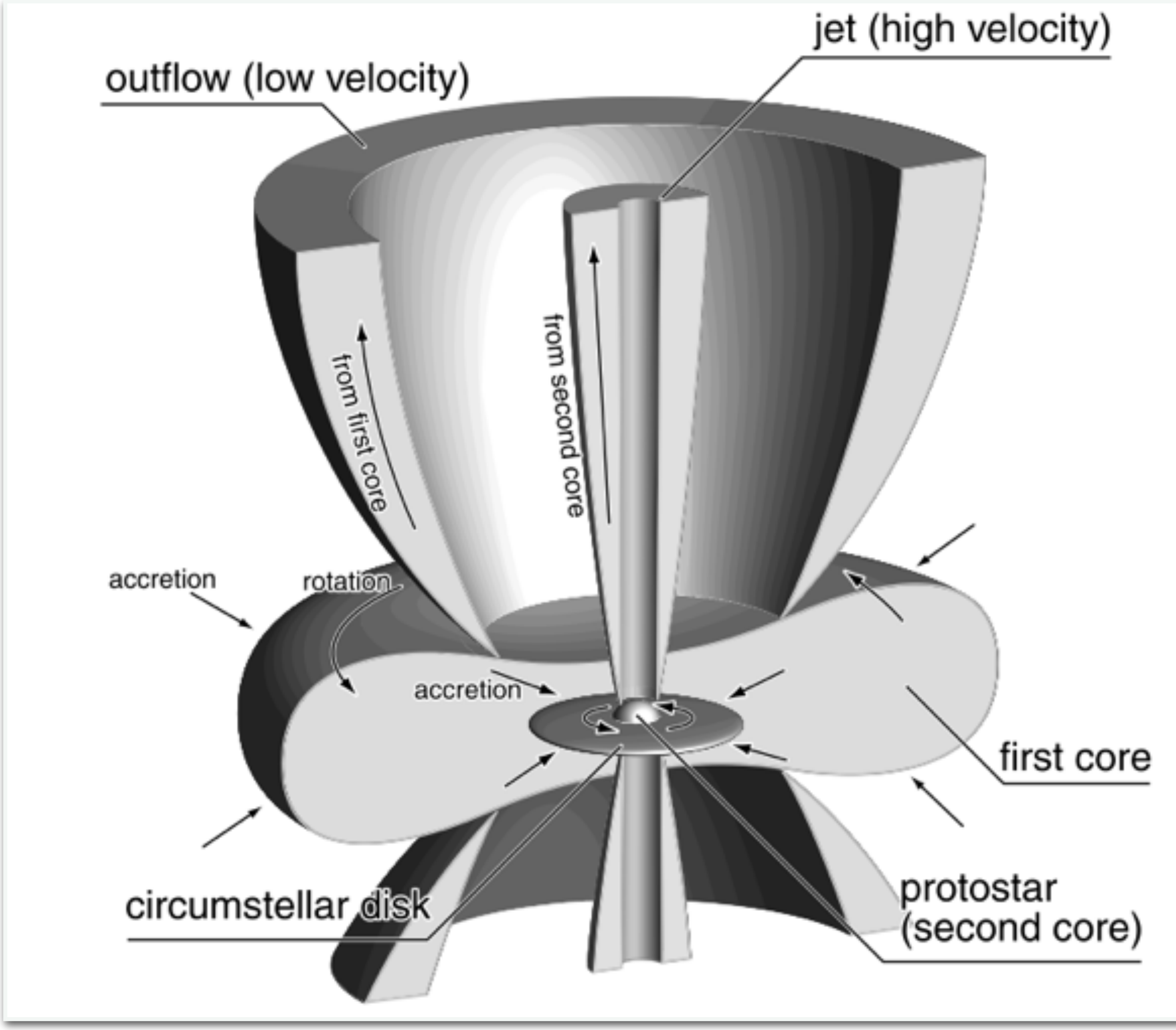
CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

Outline

1. **Introduction**
2. **Non ideal MHD**
   - chemistry
   - ideal vs. non-ideal MHD
3. **Disc formation**
   - properties
   - evolution
4. **Chemistry and dynamics**
5. **Comparison with observations**

Protostar formation

- Formation of a very complex structure, with jets, outflows, discs, etc..
- Disc formation depends highly on MHD effects...
- Chemistry, cosmic rays have to be taken into account to estimate ionization
- When does the disc form? Does it fragment?



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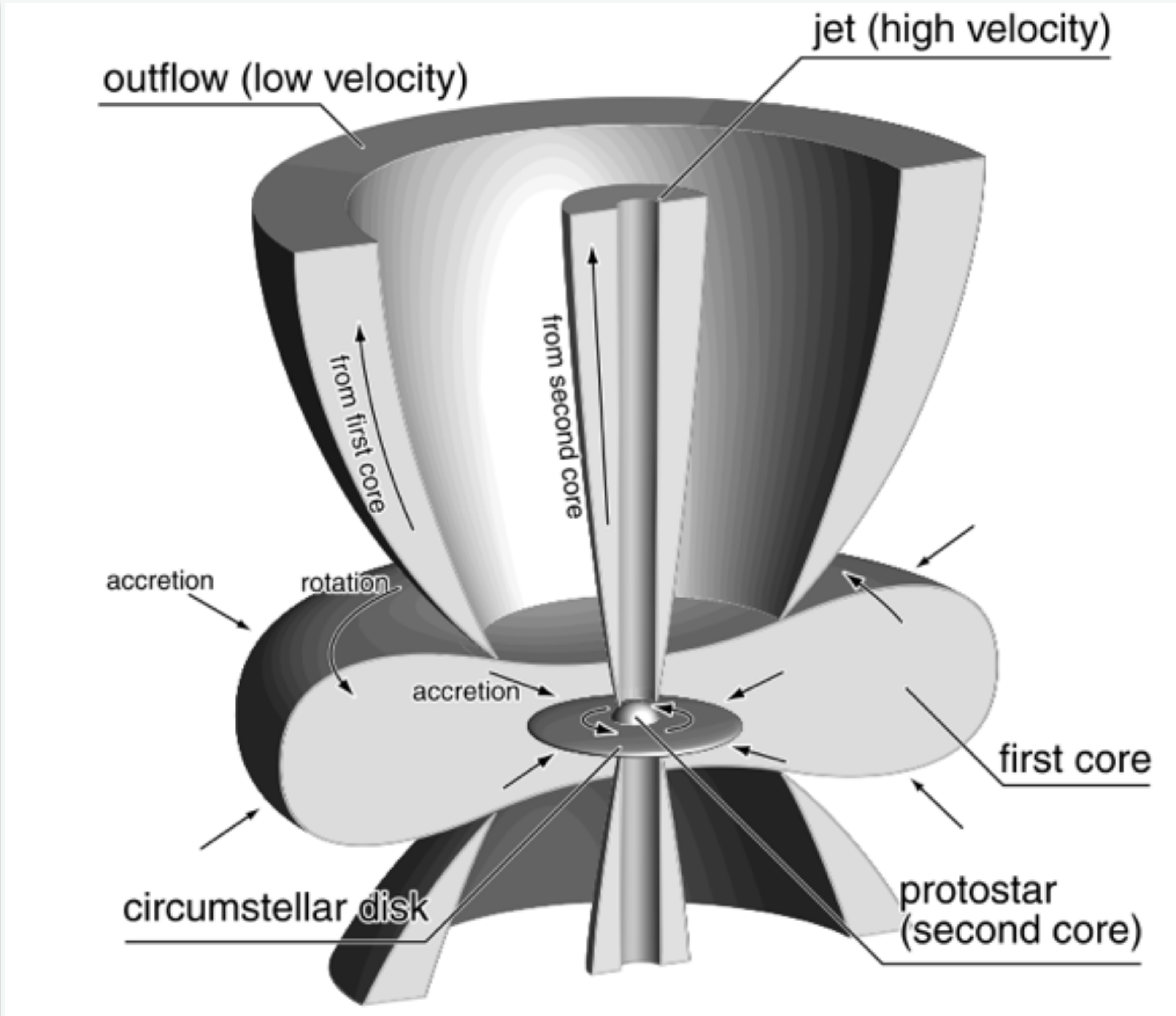

Machida et al. (2010)

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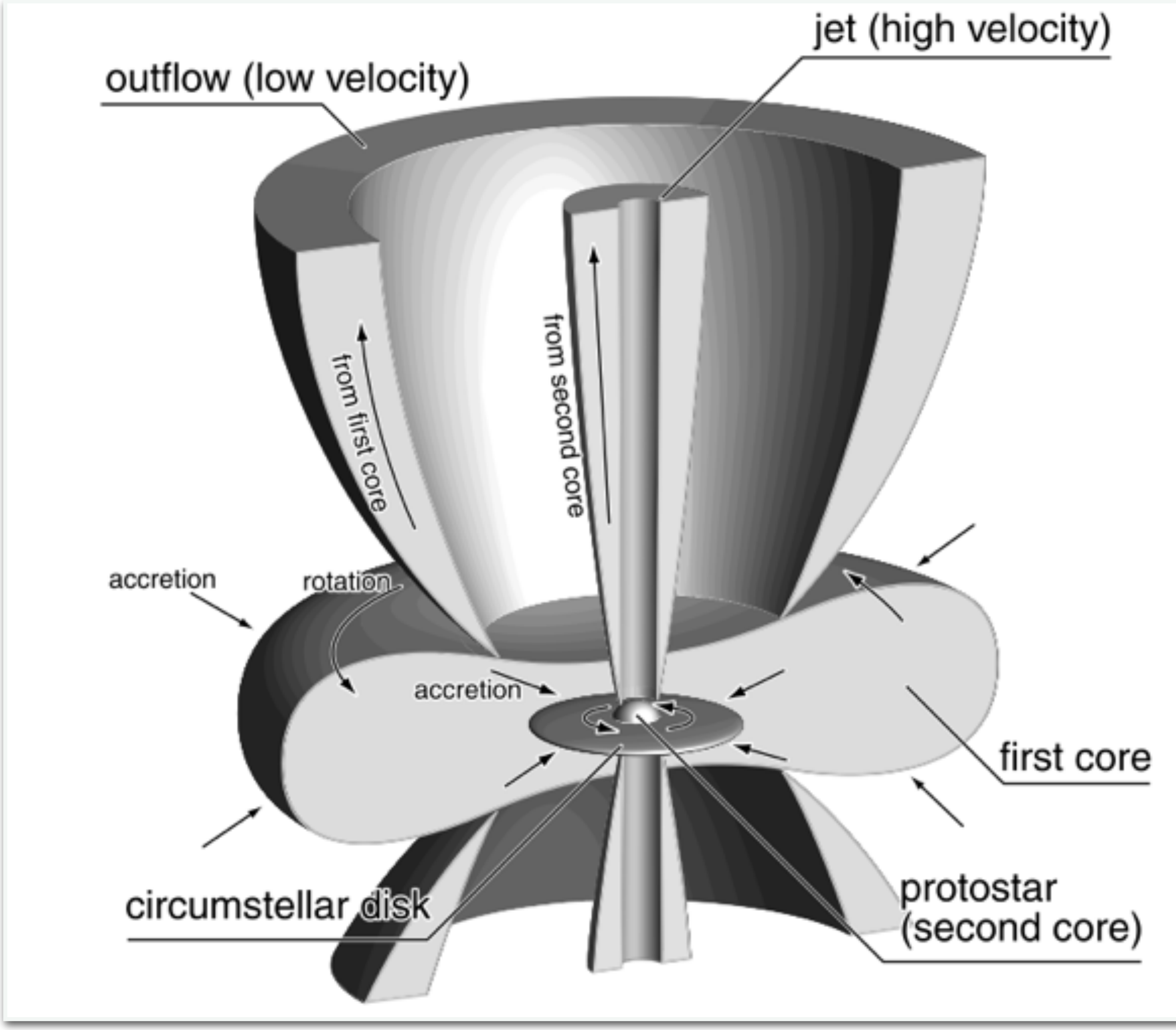
➡ Implications for planet formation



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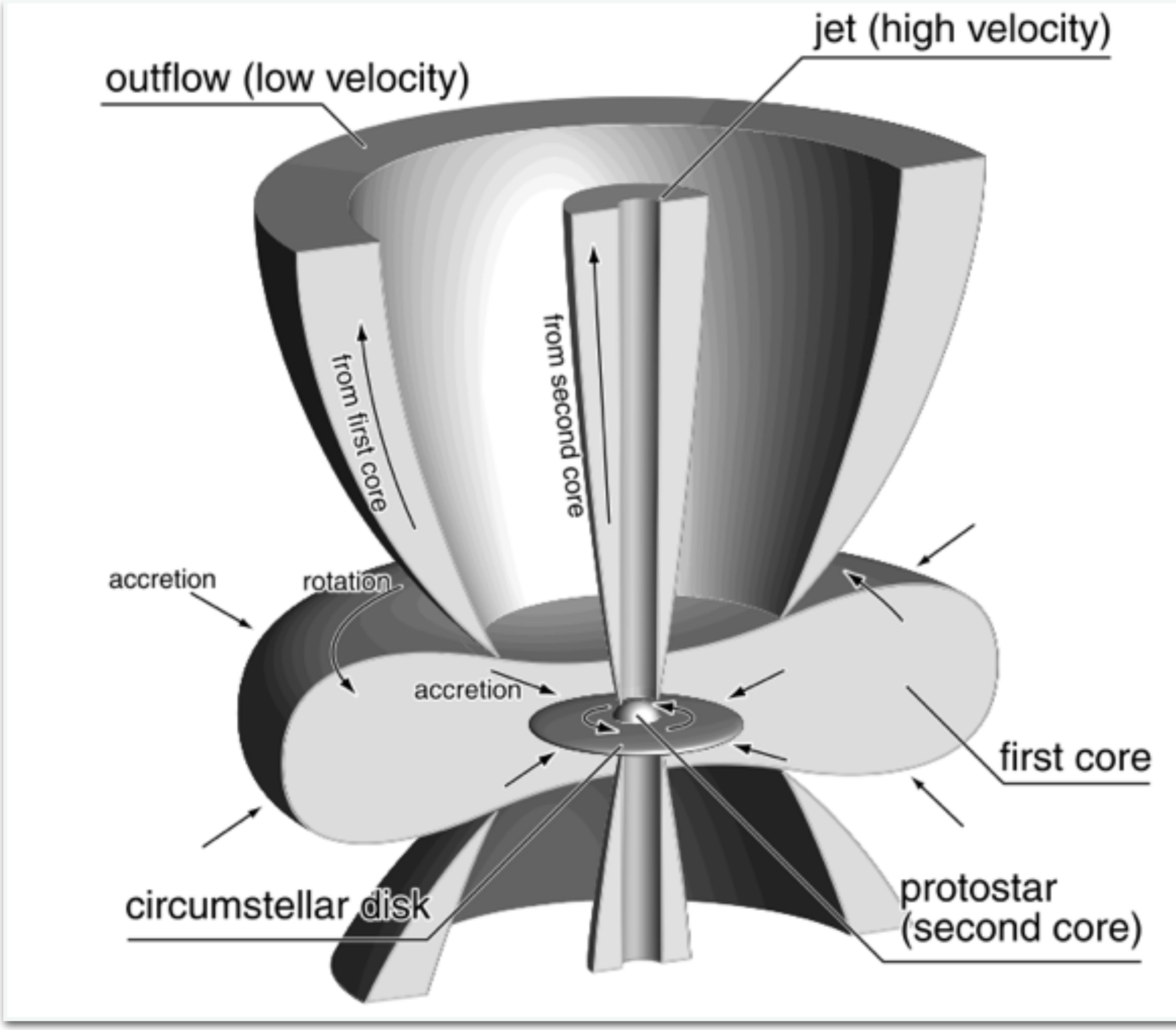


Machida et al. (2010)

Effect of magnetic fields and rotation

Consider a dense core of initial radius R, mass M and temperature T

Thermal support

- E_{th}/E_{grav} decreases when R decreases

$$\frac{E_{\rm th}}{E_{\rm grav}} = \frac{3M/m_p kT}{2GM^2/R} \propto R$$

Centrifugal support

- Angular momentum conservation
- E_{rot}/E_{grav} increases when R decreases

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

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

Magnetic support

- Magnetic flux conservation
- E_{mag}/E_{grav} is constant when R decreases

$$\phi \propto BR^2$$

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

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

Effect of magnetic fields and rotation

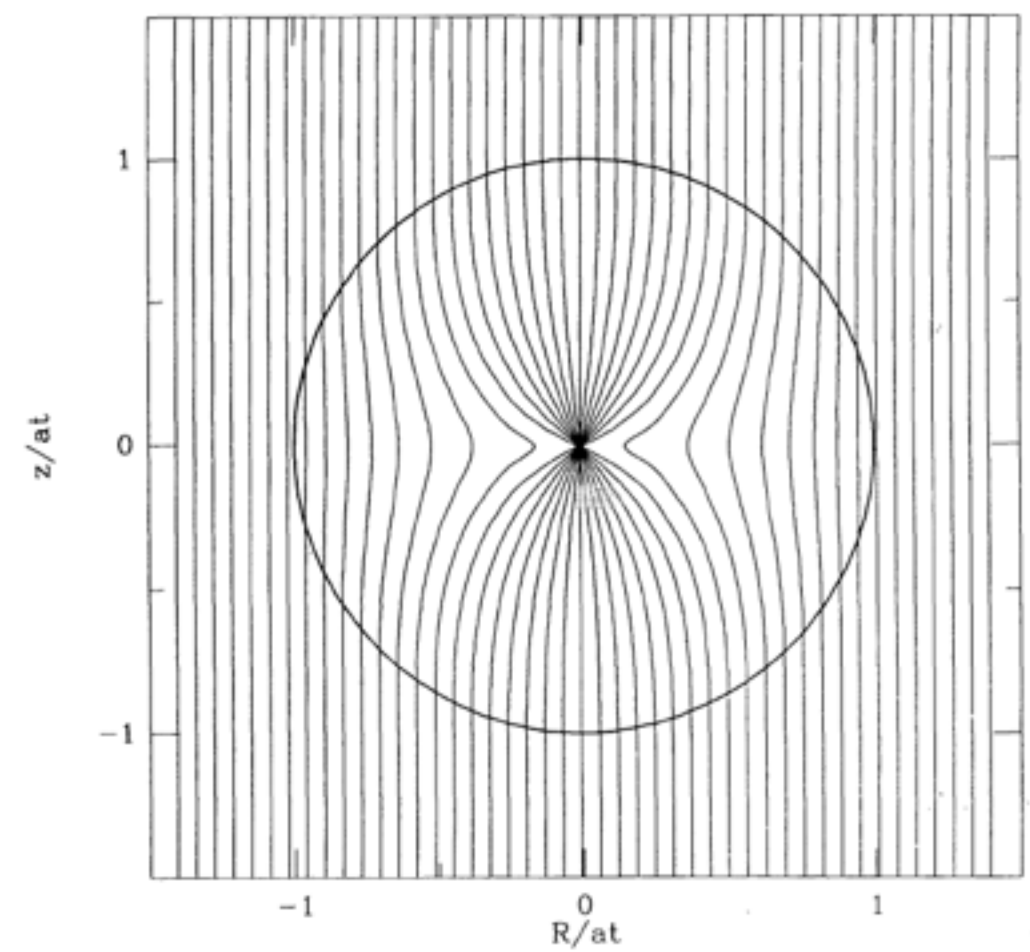
Consequences:

Centrifugal forces become dominant

- flattening of the envelope
- formation of a centrifugally supported disc

Magnetic forces stay comparable to gravity

- flattening of the envelope
- NO formation of a supported structure
- formation of a pseudo-disc (Galli & Shu 1993)

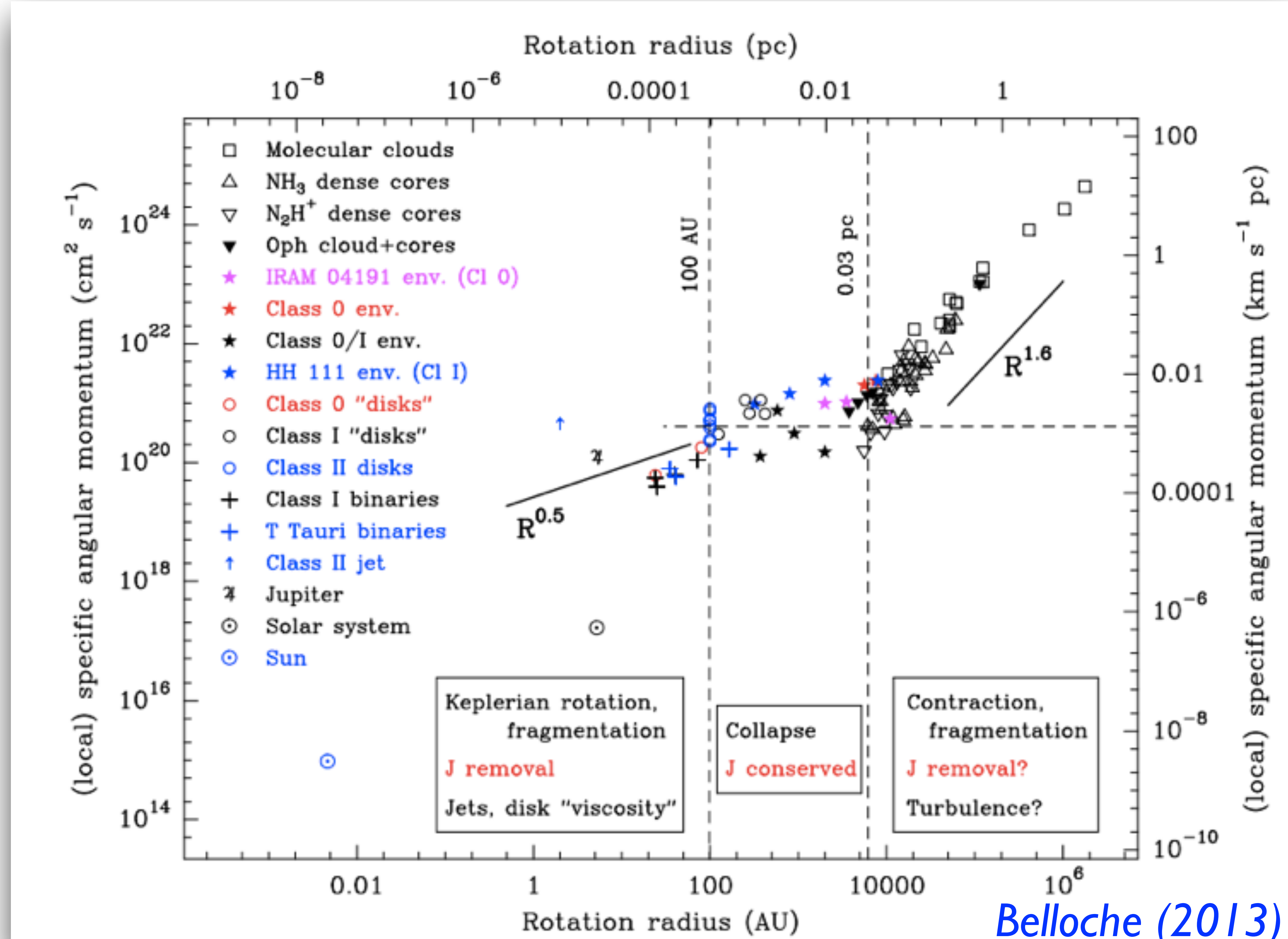


Galli & Shu 1993

Magnetic fields brakes the cloud

- transfer angular momentum from the inner part to the envelop

Angular momentum conservation



Belloche (2013)

Magnetic flux problem

Consider a cloud of initial radius R=0.1 pc, B~ 10 μG

- ✓ Magnetic flux $\Phi=\pi BR^2 \sim 3\times10^{32}$ G cm^2
- ✓ if flux is conserved, at a solar radius (6.5×10^{10} cm), B~ 10^{10} G

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

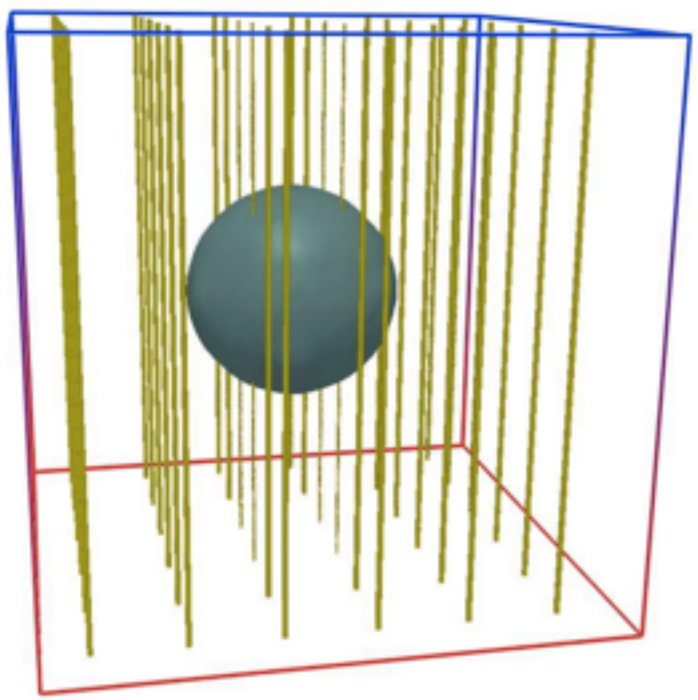
=> Magnetic flux as to be removed or transported away during gravitational collapse

Numerical experiments

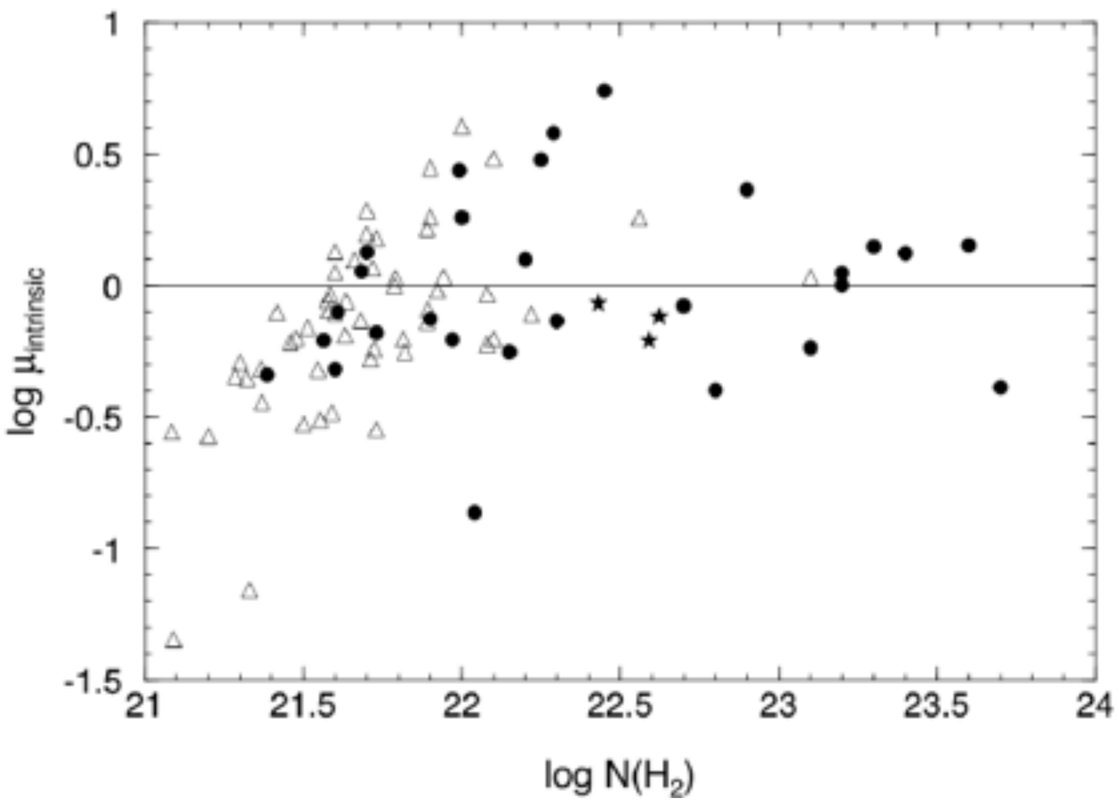
Typical initial conditions:

- 1 $M_\odot$ 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

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



Refinement criterion solely based on the Jeans length



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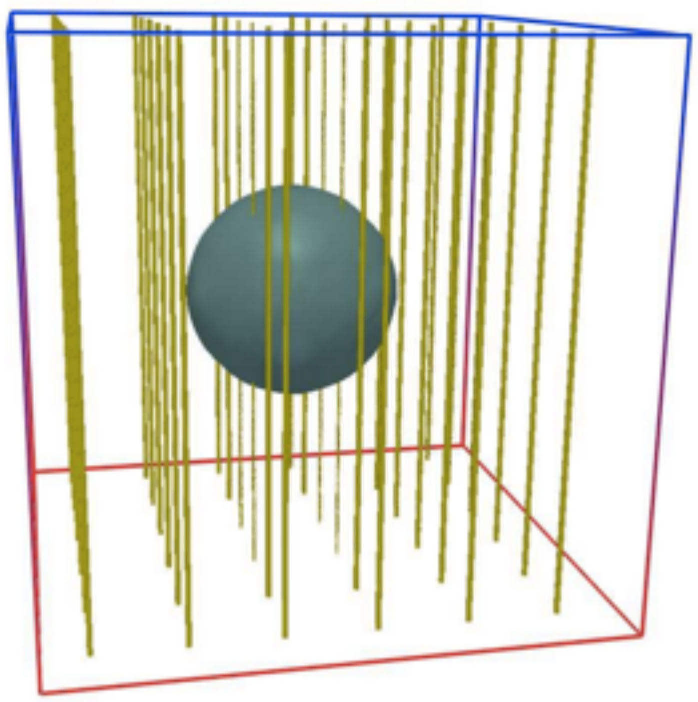

Banerjee & Pudritz (2006)

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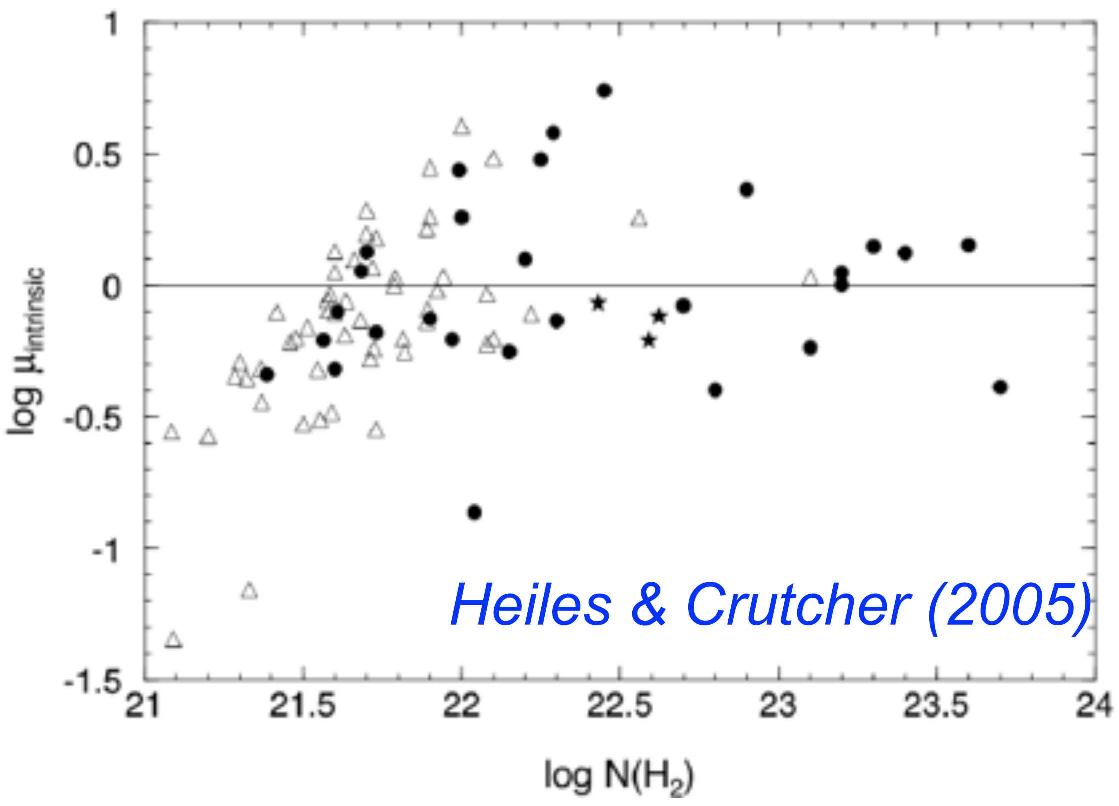


Heiles & Crutcher (2005)

State-of-the-art

3D dynamical models make step-by-step necessary developments

- magnetic fields: ideal and non ideal MHD
- radiation hydrodynamics
- chemodynamics, but no retroaction
- cosmic rays
- inclusion of different feedback processes

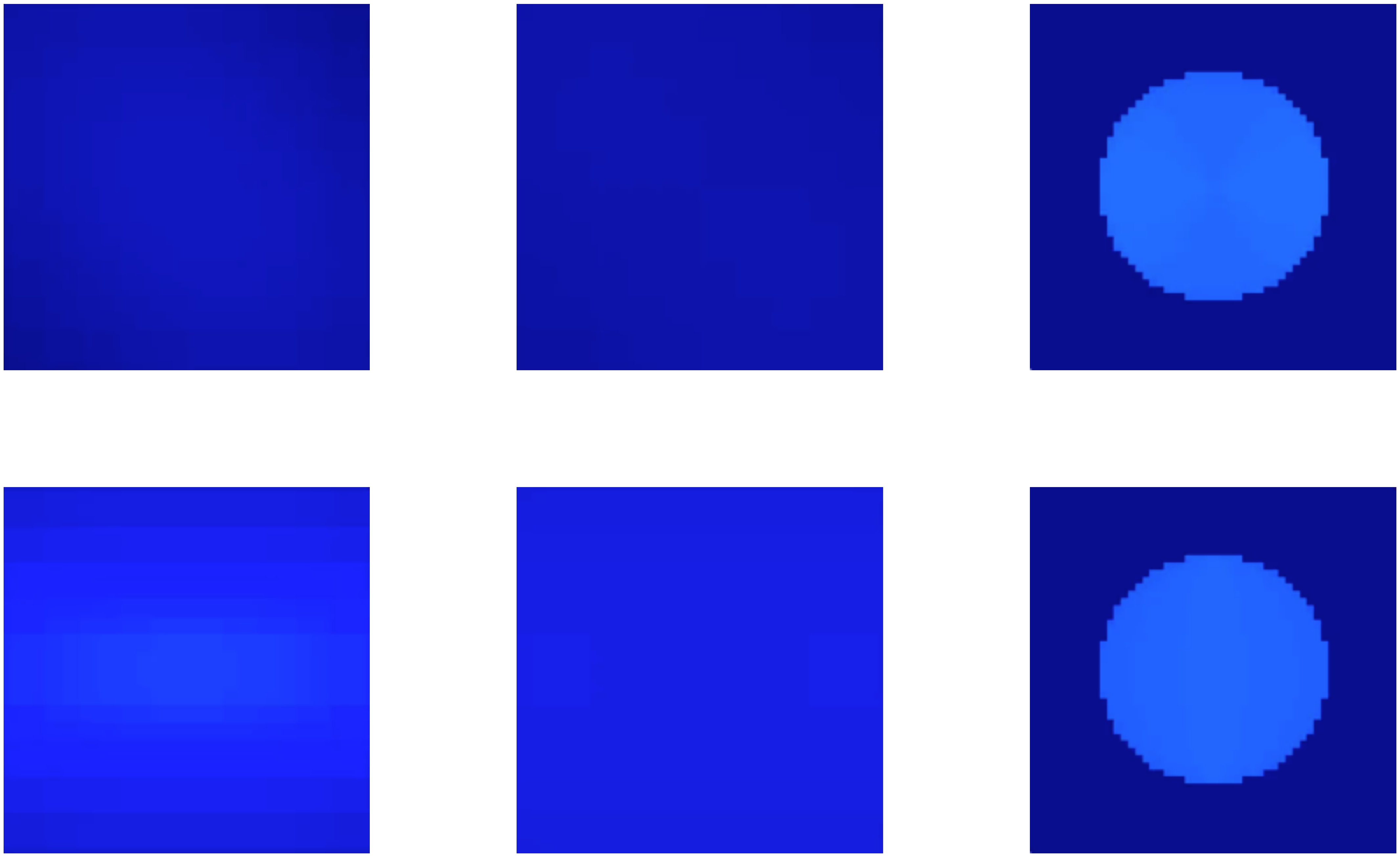
$$
\begin{cases}
\partial_t \rho + \nabla \cdot [\rho \mathbf{u}] = 0 \\
\partial_t \rho \mathbf{u} + \nabla \cdot [\rho \mathbf{u} \otimes \mathbf{u} + P\mathbb{I} - \mathbf{B} \otimes \mathbf{B}] = -\lambda \nabla E_{\mathrm{r}} \\
\partial_t E_{\mathrm{T}} + \nabla \cdot [\mathbf{u}\,(E_{\mathrm{T}} + P) + \mathbf{B}(\mathbf{B} \cdot \mathbf{u})] = -\mathbb{P}_{\mathrm{r}} \nabla : \mathbf{u} - \lambda \mathbf{u} \nabla E_{\mathrm{r}} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_{\mathrm{R}}} \nabla E_{\mathrm{r}} \right) \\
\partial_t E_{\mathrm{r}} + \nabla \cdot [\mathbf{u} E_{\mathrm{r}}] = -\mathbb{P}_{\mathrm{r}} \nabla : \mathbf{u} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_{\mathrm{R}}} \nabla E_{\mathrm{r}} \right) + \kappa_{\mathrm{P}} \rho c (a_{\mathrm{R}} T^4 - E_{\mathrm{r}}) \\
\partial_t \mathbf{B} + \nabla \times \left[\mathbf{u} \times \mathbf{B} - \frac{\mathbf{J} \times \mathbf{B}}{e n_{\mathrm{e}}} + \frac{[(\nabla \times \mathbf{B}) \times \mathbf{B}] \times \mathbf{B}}{\gamma_{\mathrm{AD}} \rho \rho_{\mathrm{i}}} - \frac{\mathbf{J}}{\sigma_{\|}} \right] = 0
\end{cases}
$$

Influence of the magnetization (ideal MHD)

MU=5 Strong B | **MU=20 Weak B** | **Hydro B=0**

equatorial plane

yz - plane



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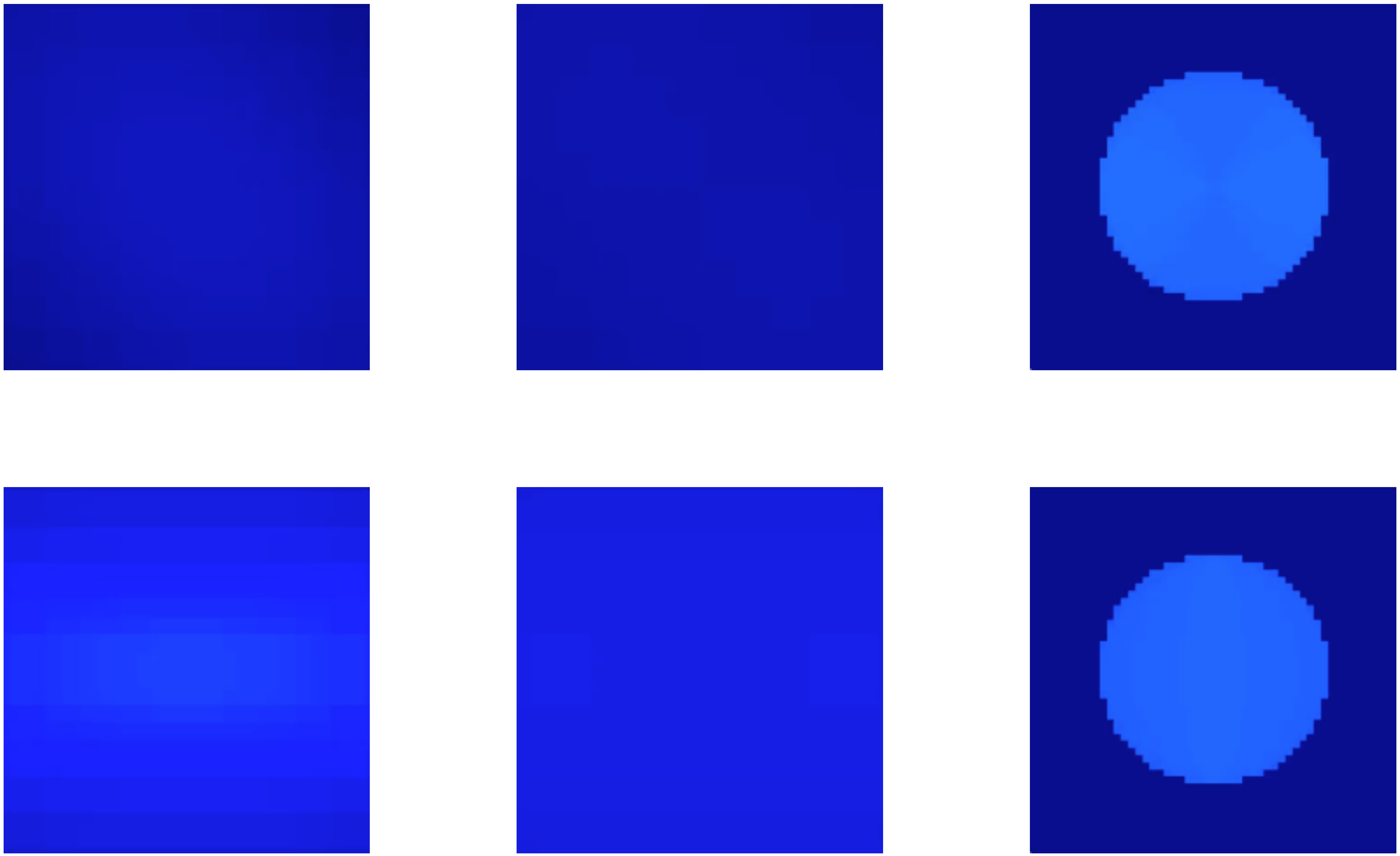

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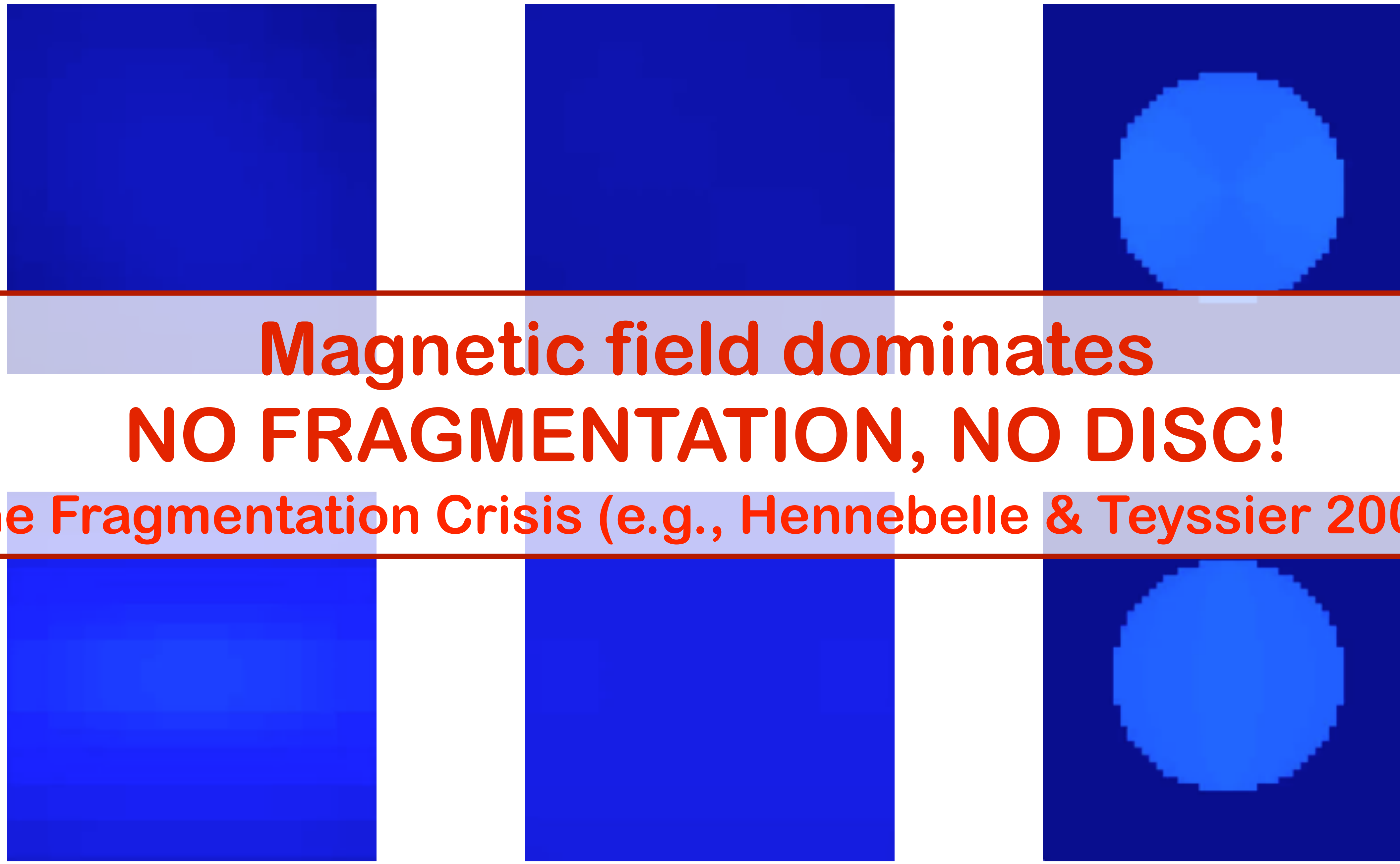
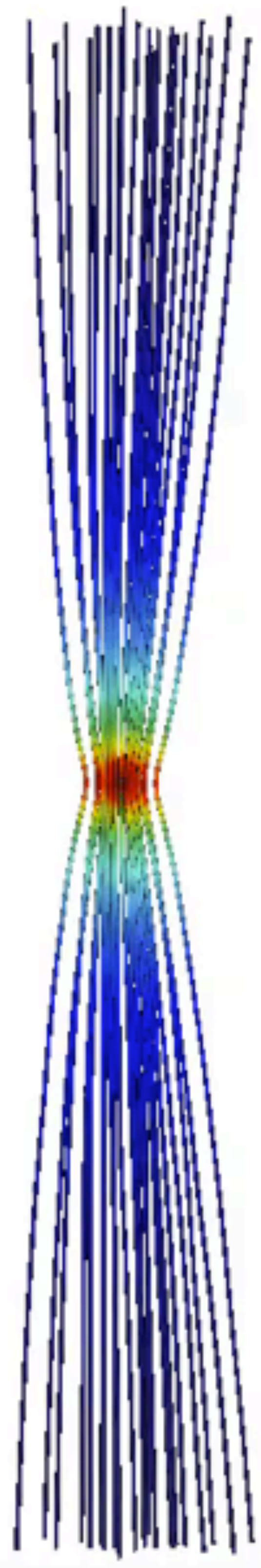


Magnetic field dominates

NO FRAGMENTATION, NO DISC!

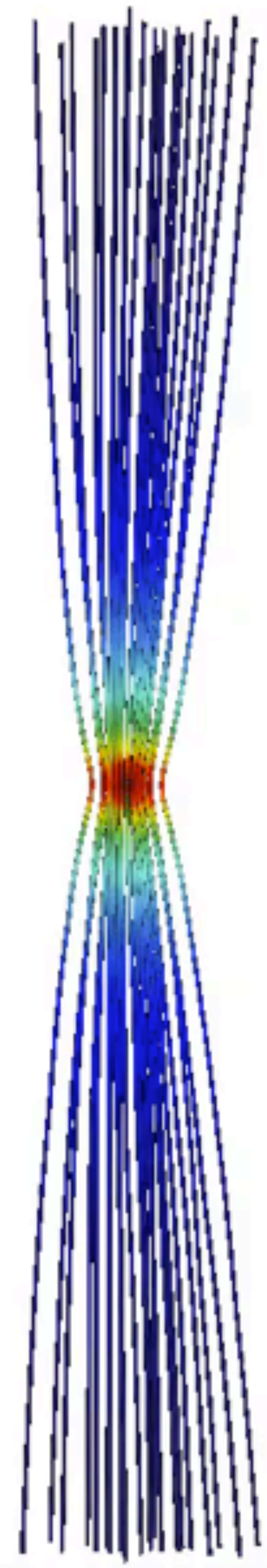
The Fragmentation Crisis (e.g., Hennebelle & Teyssier 2008)

Dense core collapse



Movie by Marc Joos

Dense core collapse



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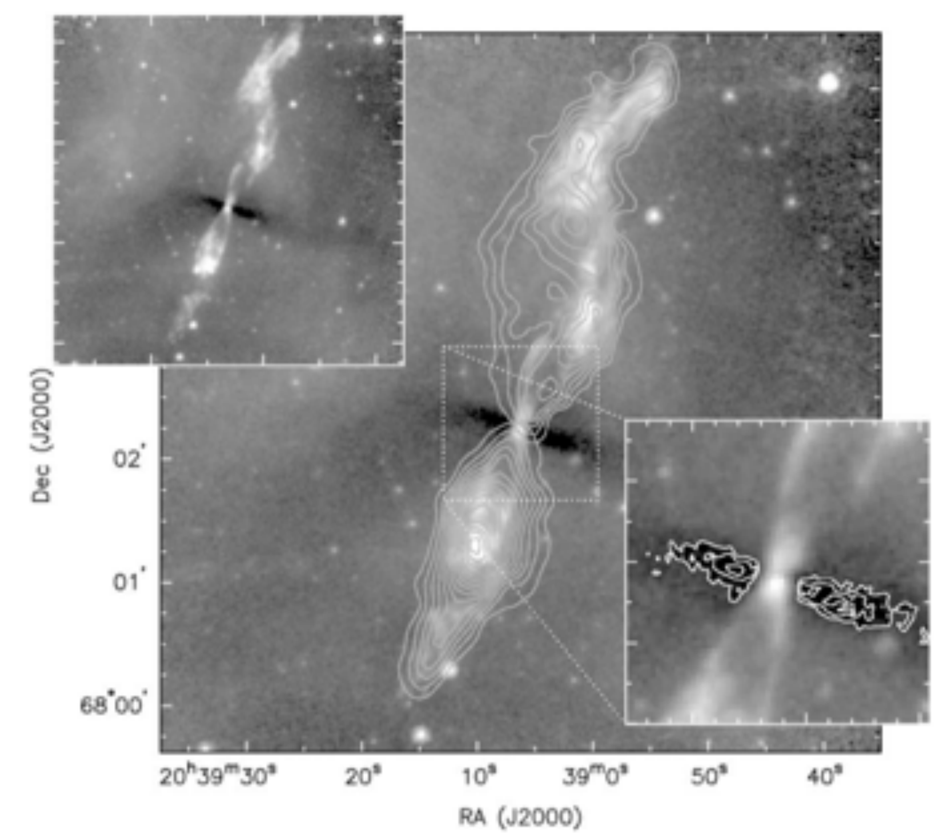

Looney et al. 2007

Disc formation in magnetised cores

- **Late formation**
  - end of class 0, $M_{env} << M_{env,0}$ (e.g., *Machida & Hosokawa 2013*)

- **Misalignment**
  - no reason for the rotation axis and the magnetic field to be aligned (e.g., *Hull et al. 2013*)
  - reduces magnetic braking efficiency (e.g. *Hennebelle & Ciardi 2009, Joos et al. 2012, Li et al. 2013*)

- **Turbulent diffusion**
  - reconnection events fast with Ohmic diffusion only, collective effect at larger scale (e.g. *Santos Lima et al. 2012, Joos et al. 2013, Seifried et al. 2013*)

- **Non-ideal MHD**
  - Ohm dissipation (*Tomida et al. 2013, 2015, Machida et al.*)
  - Hall effect (*Krasnopolsky et al. 2011, Tsukamota et al. 2015, Wurster et al. 2016*)
  - ambipolar diffusion (*Tsukamota et al. 2015, Wurster et al. 2016*)

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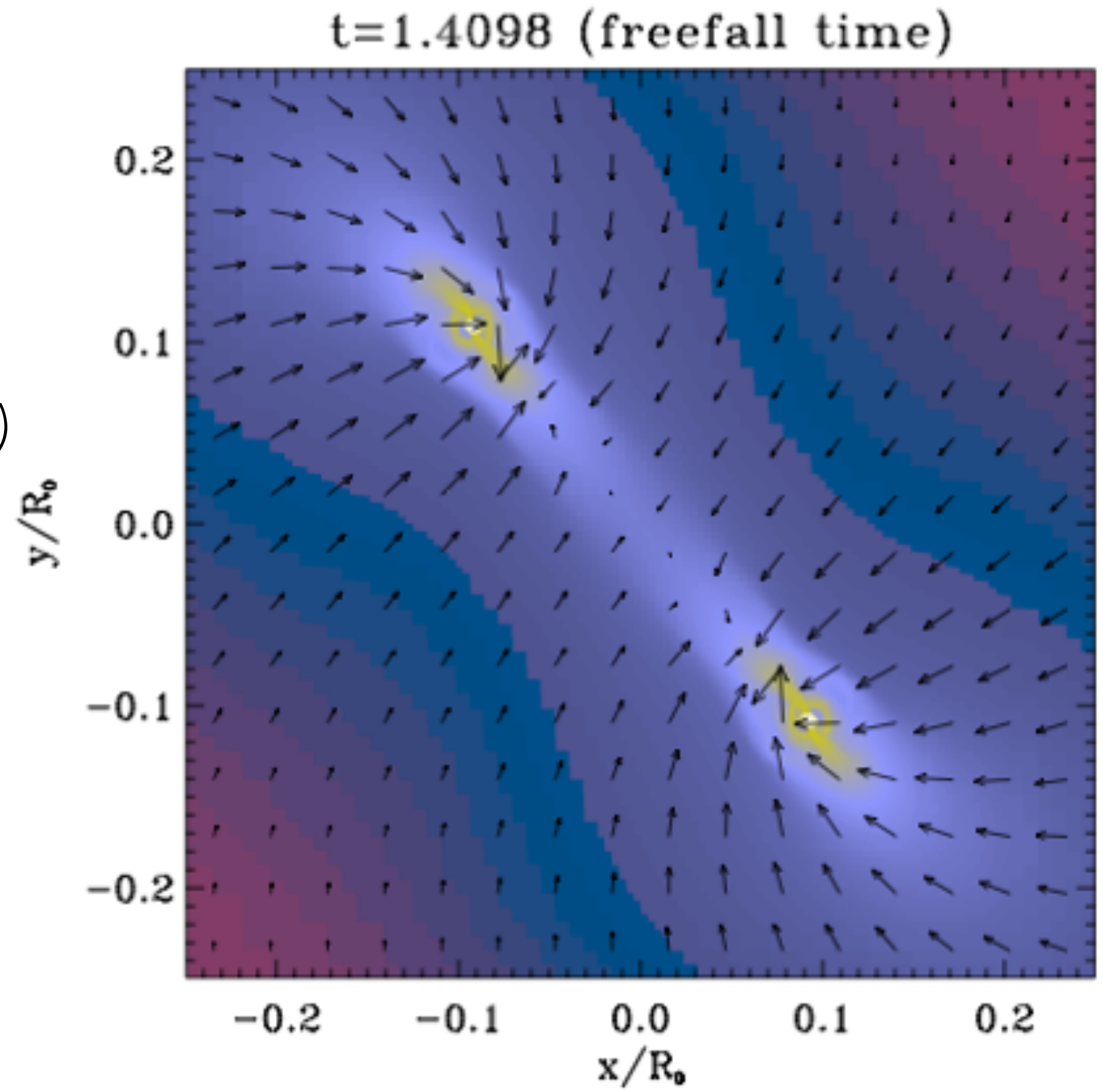
  - ambipolar diffusion (*Tsukamota et al. 2015, Wurster et al. 2016*)

Solve the fragmentation crisis

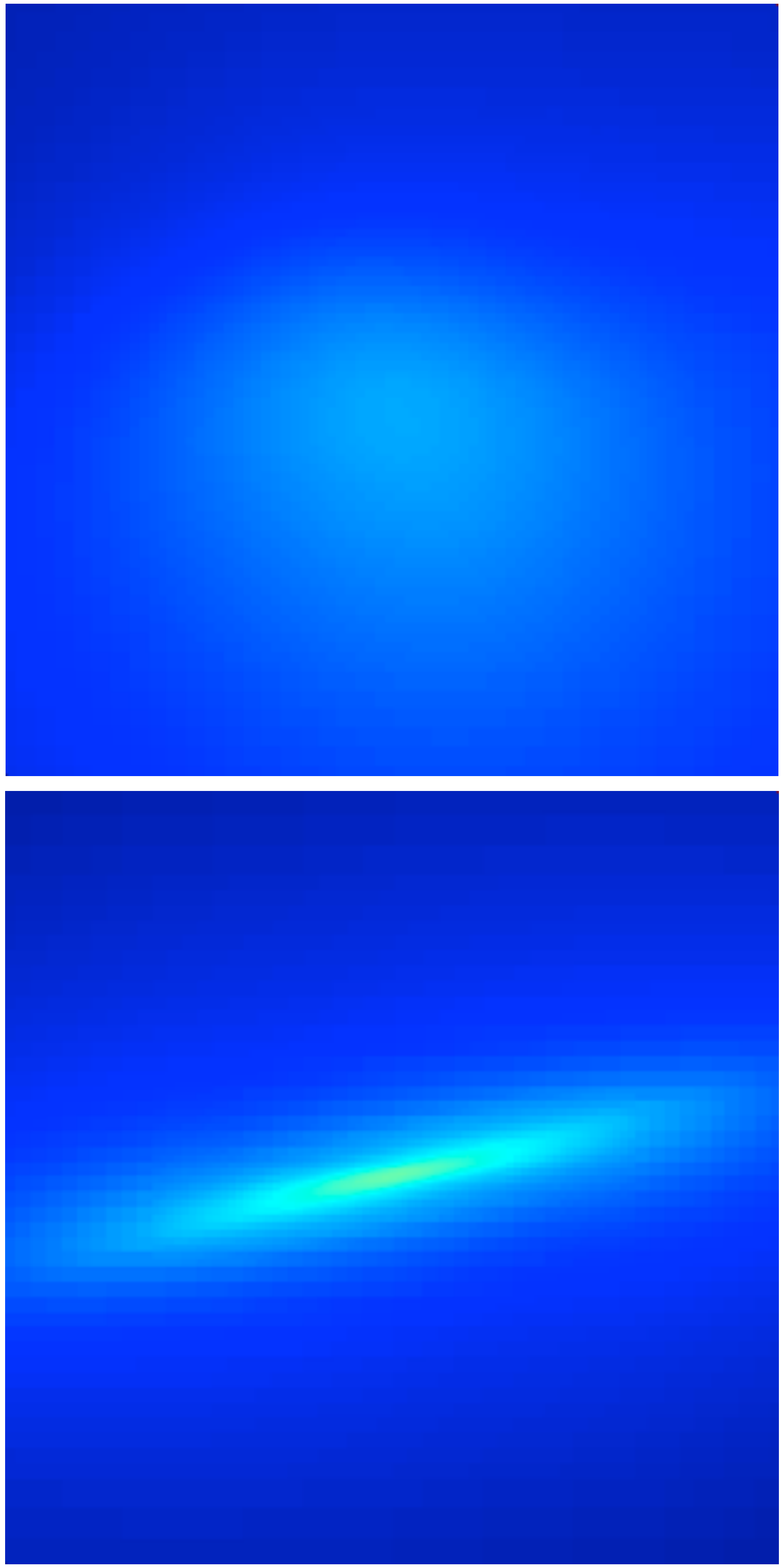
- **Large scale fluctuations**
  (e.g. *Hennebelle & Teyssier 2008, Price & Bate 2007*)
  - could explain wide binaries

Amplitude perturbation *A*=0.5



Influence of misalignment

- Large scale fluctuations
- **Angle B/rotation axis**
  (*Hennebelle & Ciardi 2009, Joos et al. 2012*)



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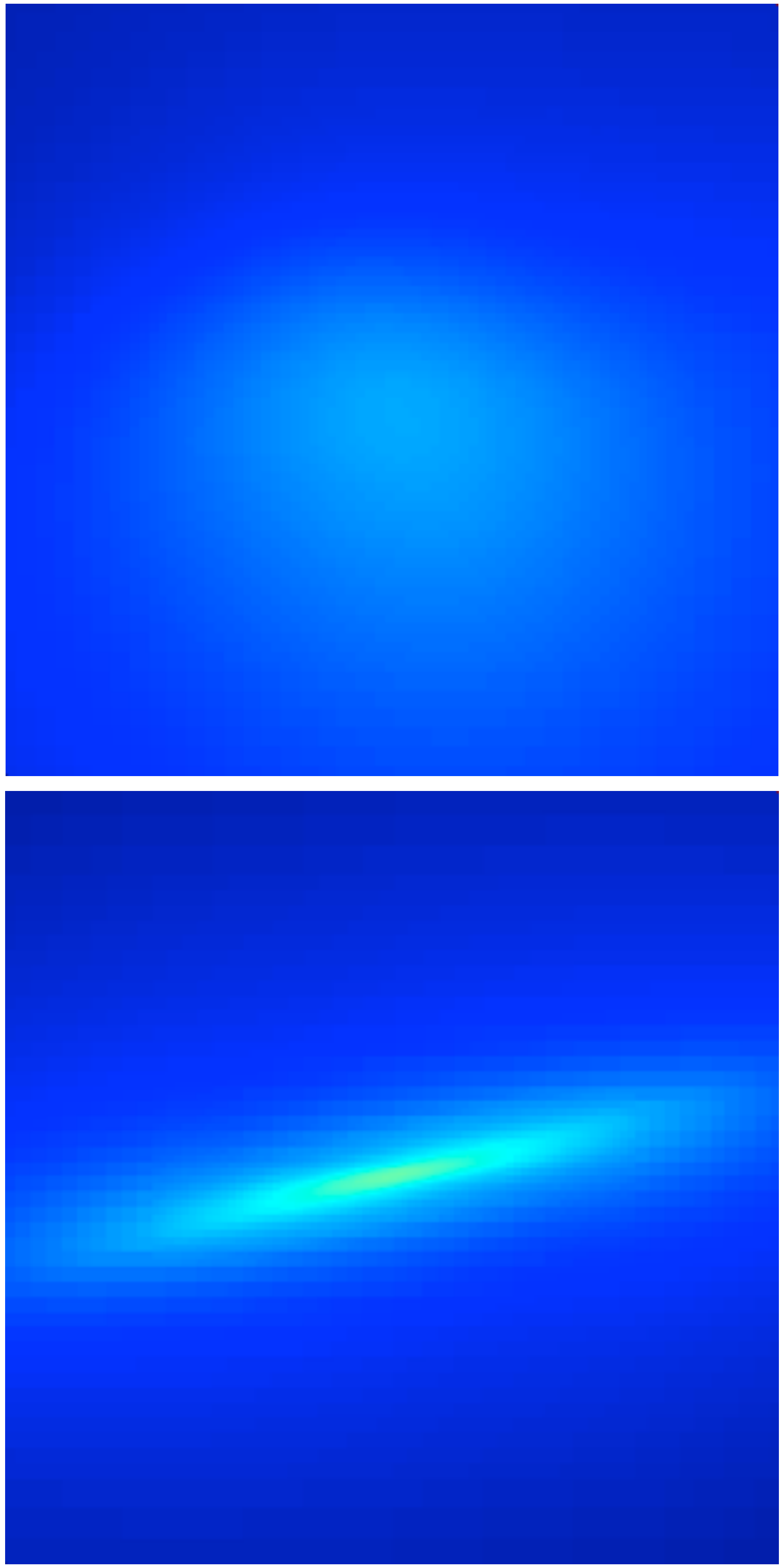
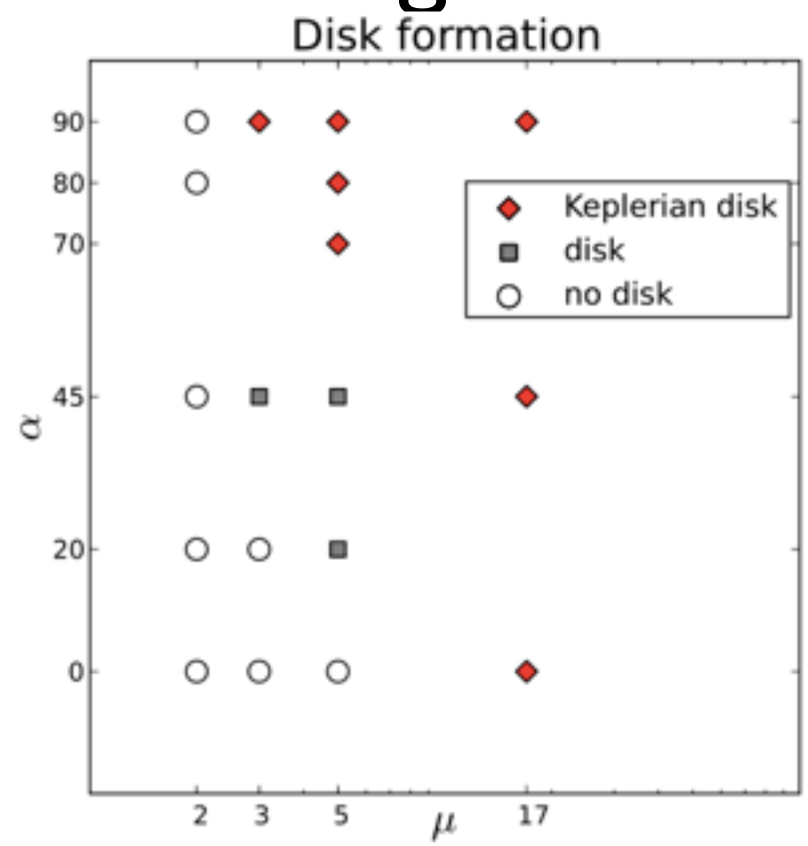
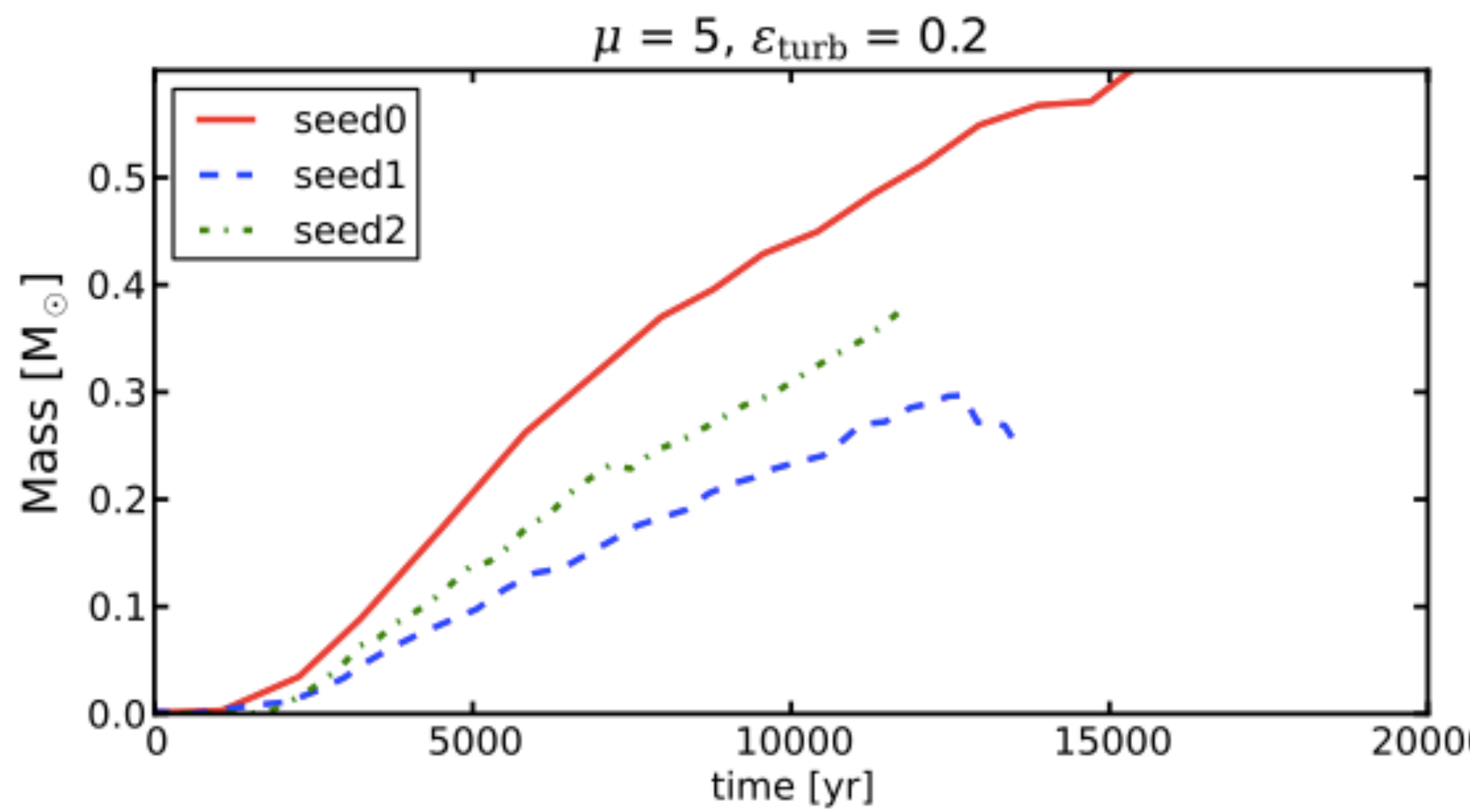


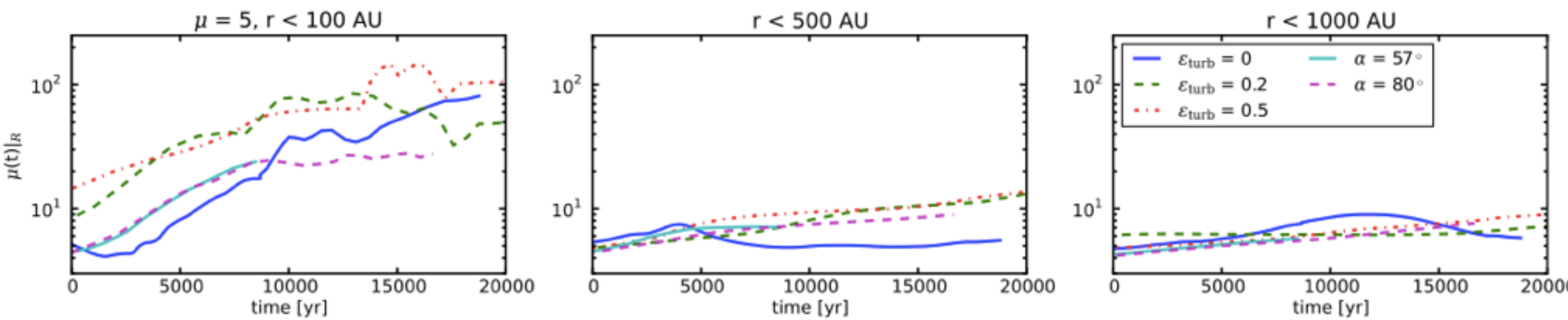
Influence of turbulence and misalignment

Misalignement



Turbulence

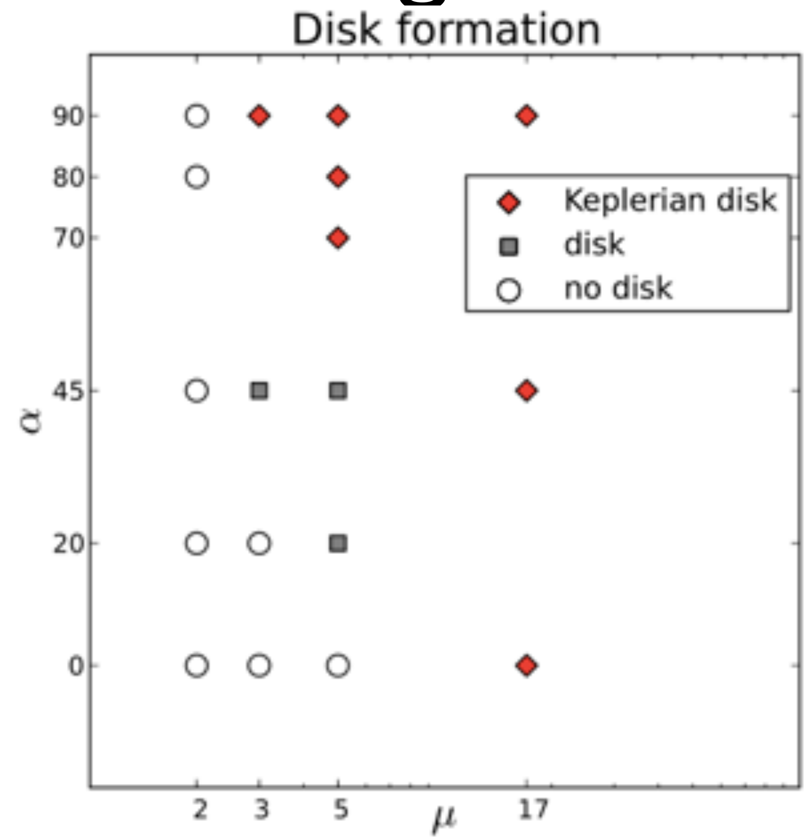




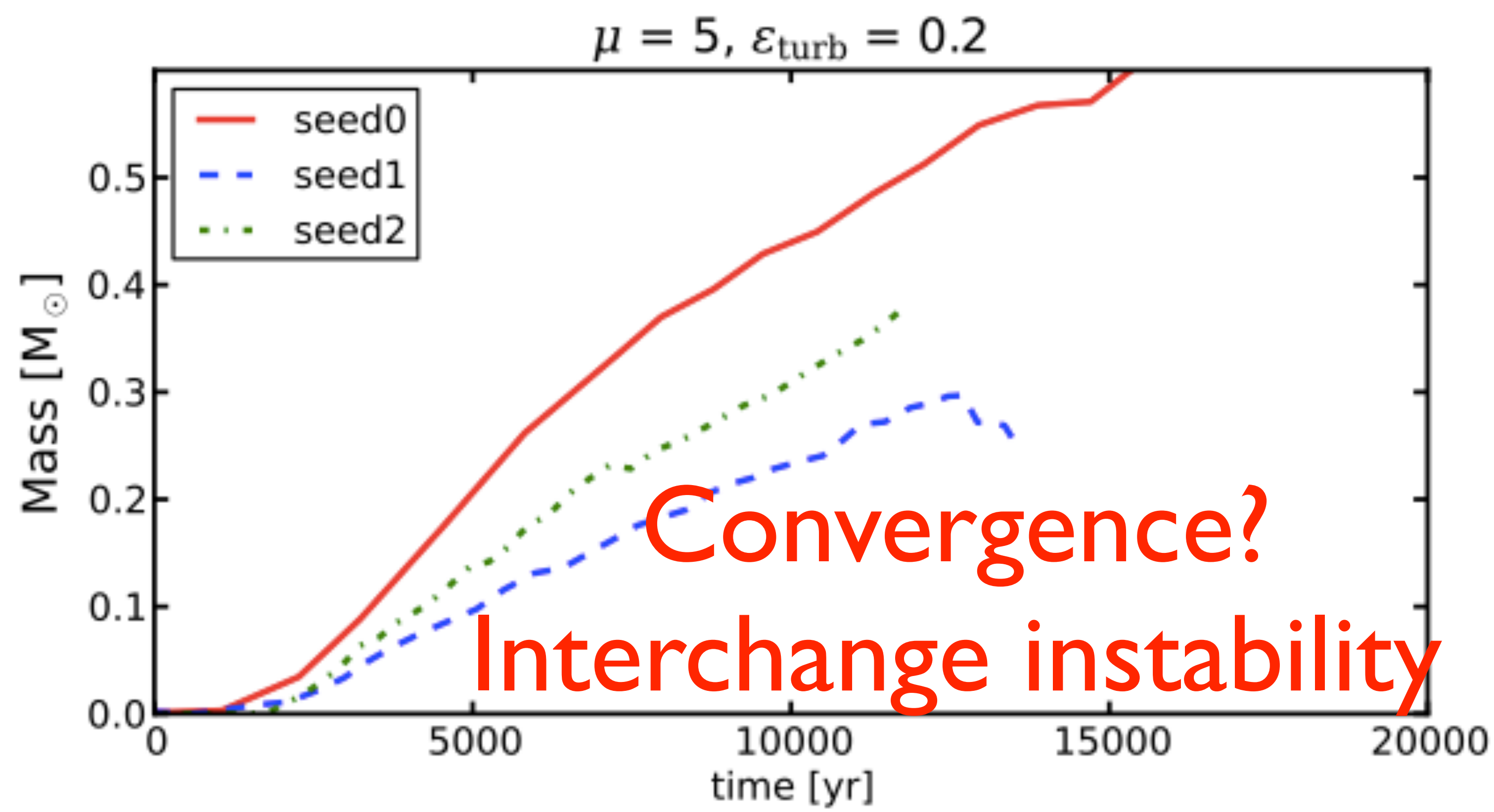
Joos et al. (2012, 2013)
Ciardi & Hennebelle (2011)

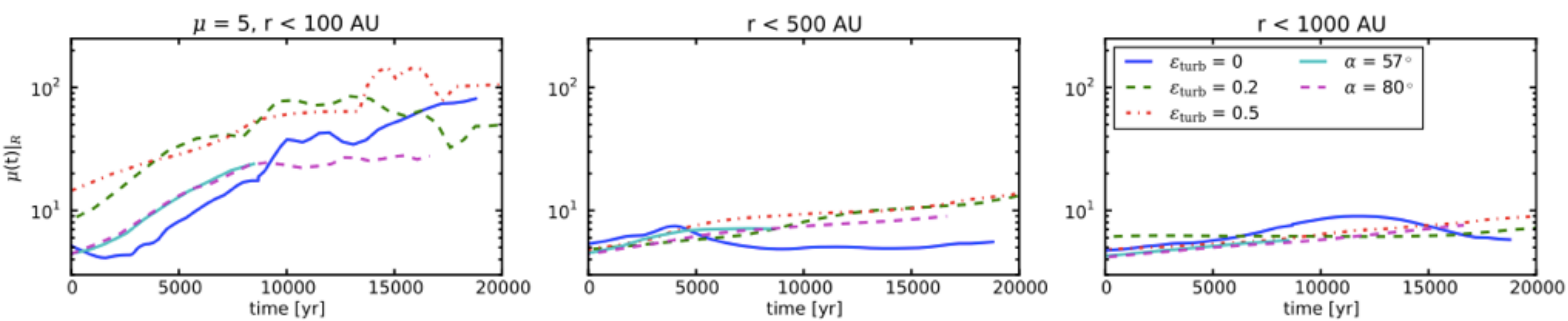
Influence of turbulence and misalignment

Misalignement



Turbulence





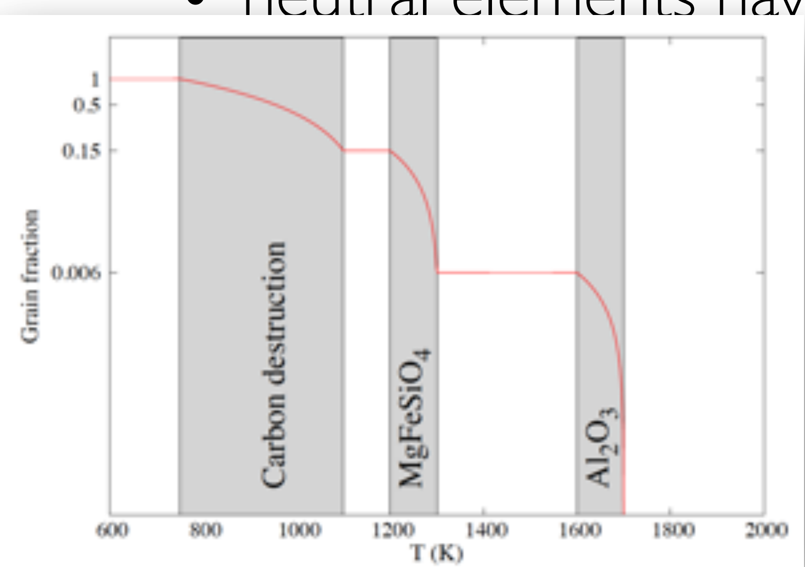
Joos et al. (2012, 2013)
Ciardi & Hennebelle (2011)

Equilibrium chemistry for non-ideal MHD

✓ **Reduced chemical network dedicated for ionisation (based on the work by *Umebayashi & Nakano 1990*)**

- H, He, C, O, metallic elements (Fe, Na, Mg, etc..)
- H^+, $H_3{}^+$, He^+, C^+, molecular and metallic ions
- bins in the dust grains size distribution (G, G^+, G^-)
- dust evaporation at T>800 K
- thermal ionisation of potassium (T>1000 K)
- neutral elements have constant abundances

Reaction	α	β	γ
$H^+ + O \rightarrow H + O^+$	6.86×10^{-10}	0.26	0
$H^+ + O_2 \rightarrow H + O_2^+$	2.00×10^{-9}	0.00	0
$H^+ + M \rightarrow H + M^+$	1.10×10^{-9}	0.00	0
$He^+ + H_2 \rightarrow He + H^+ + H$	3.70×10^{-14}	0.00	35
$He^+ + CO \rightarrow He + C^+ + O$	1.60×10^{-9}	0.00	0
$He^+ + O_2 \rightarrow He + O^+ + O$	1.10×10^{-9}	0.00	0
$H_3^+ + CO \rightarrow H_2 + HCO^+$	1.36×10^{-9}	−0.14	0
$H_3^+ + O \rightarrow H_2 + OH^+$	7.98×10^{-10}	−0.16	0
$H_3^+ + O_2 \rightarrow H_2 + O_2H^+$	9.30×10^{-10}	0.00	0
$H_3^+ + M \rightarrow H_2 + H + M^+$	1.10×10^{-9}	0.00	0
$C^+ + H_2 \rightarrow CH_2^+ + h\nu$	2.00×10^{-16}	0.00	0
$C^+ + O_2 \rightarrow CO^+ + O$	3.42×10^{-10}	0.00	0
$C^+ + O_2 \rightarrow CO + O^+$	4.54×10^{-10}	0.00	0
$C^+ + M \rightarrow C + M^+$	1.10×10^{-9}	0.00	0
$m^+ + M \rightarrow m + M^+$	2.90×10^{-9}	0.00	0
$H^+ + e^- \rightarrow H + h\nu$	3.50×10^{-12}	−0.75	0
$He^+ + e^- \rightarrow He + h\nu$	5.36×10^{-12}	−0.5	0
$H_3^+ + e^- \rightarrow H + H + H$; $\rightarrow H_2 + H$	2.34×10^{-8}	−0.52	0
$C^+ + e^- \rightarrow C + h\nu$	2.36×10^{-12}	−0.29	0
$m^+ + e^- \rightarrow m_1 + m_2$	2.40×10^{-7}	−0.69	0
$M^+ + e^- \rightarrow M + h\nu$	2.78×10^{-12}	−0.68	0
$H_2 \rightarrow H_2^+ + e^-$	1.2×10^{-17}		
$H_2 \rightarrow H^+ + H + e^-$	2.86×10^{-19}		
$He \rightarrow He^+ + e^-$	6.58×10^{-18}		



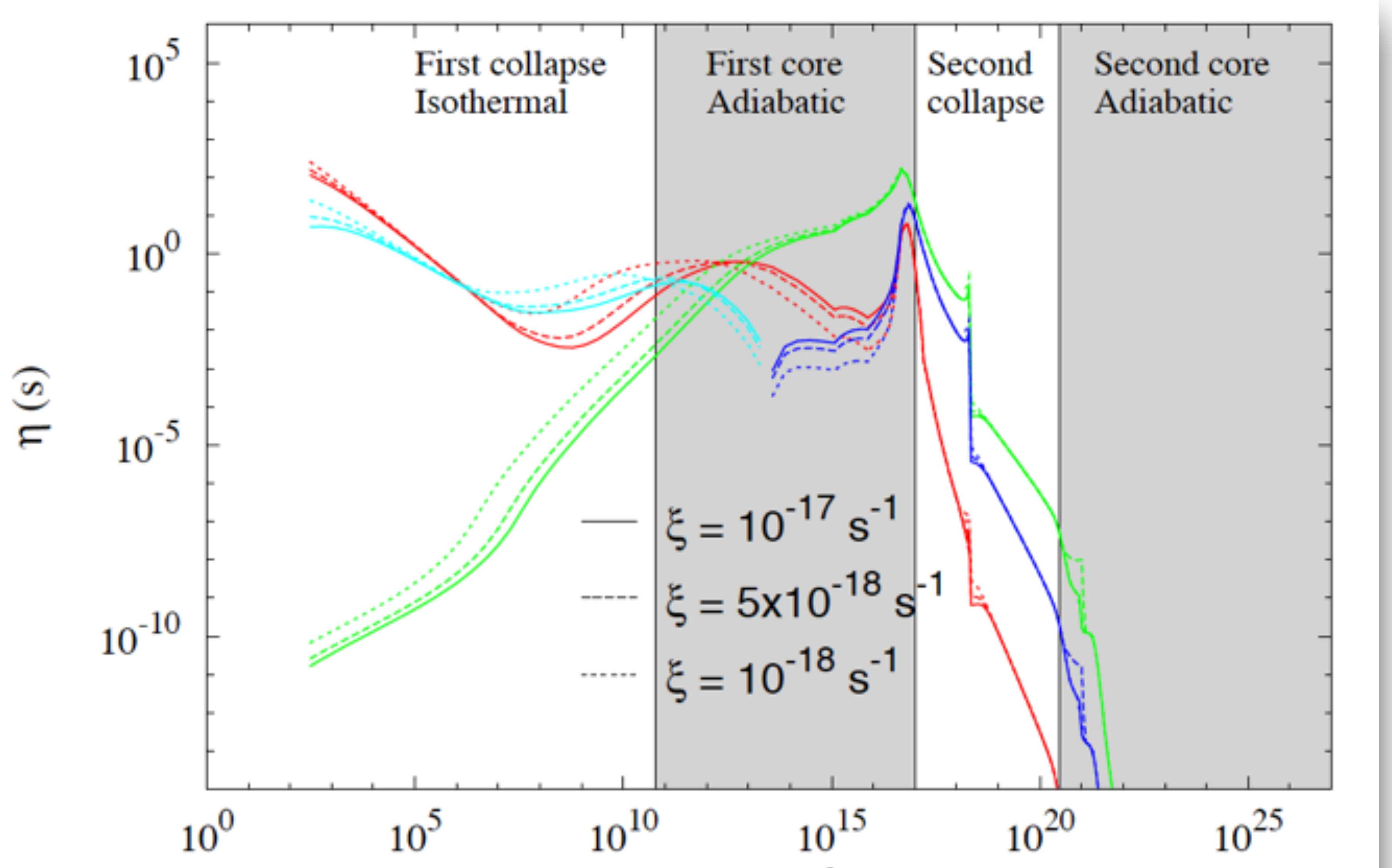
✓UMIST database for gas species (*McElroy et al. 2013*)
✓*Kunz & Mouschovias (2009)* for interactions with and between grains

✓ **Goal: compute a 3D table of abundances:**

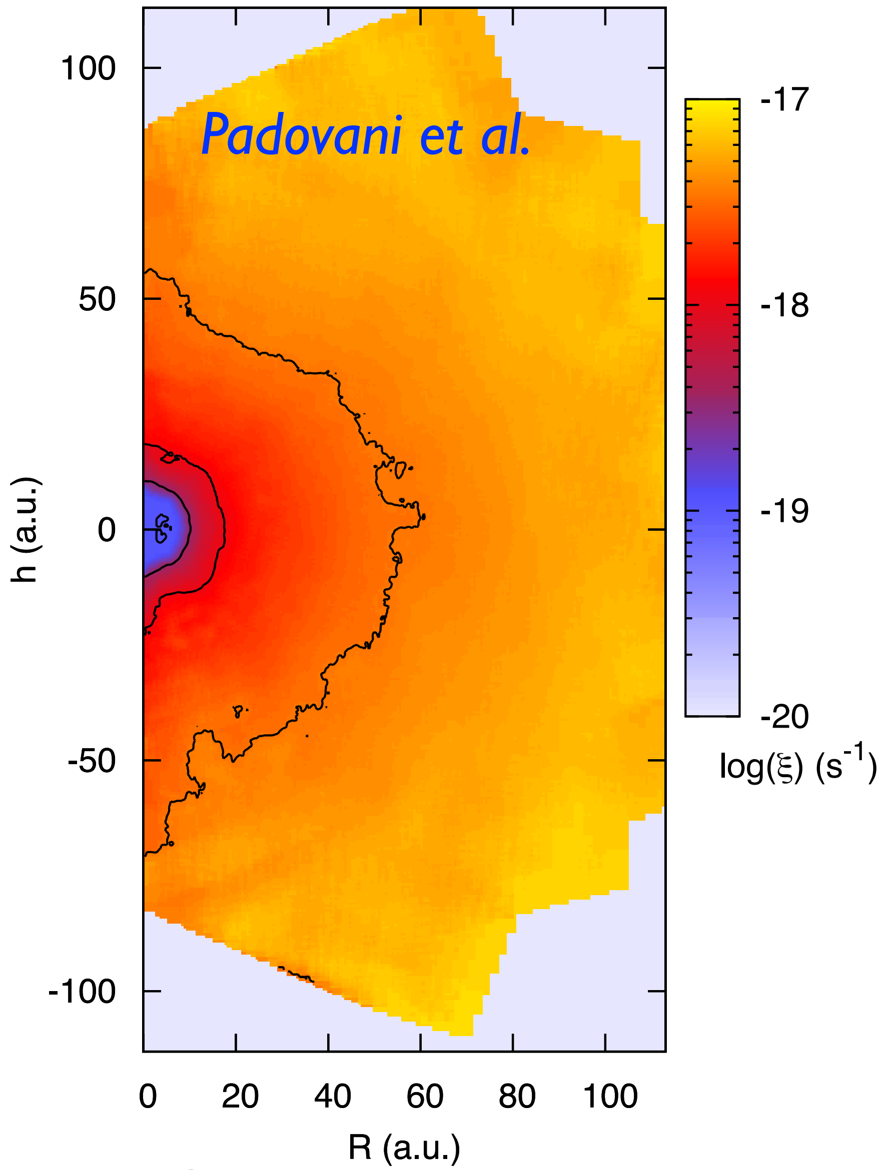
- depends on temperature, density and CR ionisation
- used on-the-fly in 3D calculations to compute resistivities

Marchand et al. (2016)

Equilibrium chemistry for non-ideal MHD: results



https://bitbucket.org/pmarchan/chemistry



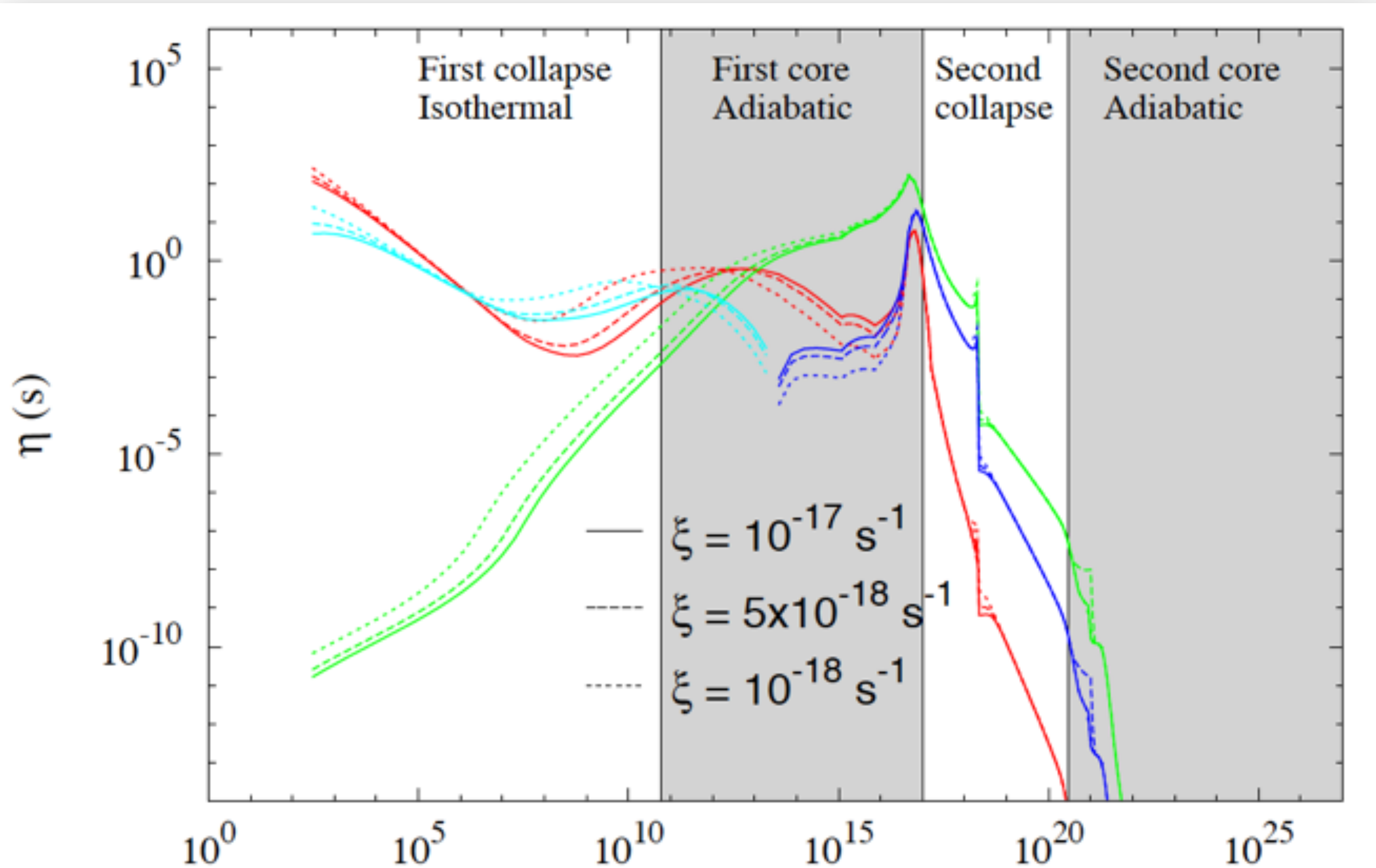
CR ionisation rate in the core interior

1/ **Grain** is the most important parameter

2/ Needs at least 20 bins in dust grain size distribution to converge…

Marchand et al. (2016)

Equilibrium chemistry for non-ideal MHD: results



https://bitbucket.org/pmarchan/chemistry

$$\eta_\Omega = \frac{1}{\sigma_\parallel},$$

$$\eta_H = \frac{\sigma_H}{\sigma_\perp^2 + \sigma_H^2},$$

$$\eta_{AD} = \frac{\sigma_\perp}{\sigma_\perp^2 + \sigma_H^2} - \frac{1}{\sigma_\parallel},$$

$$\sigma_\parallel = \sum_i \sigma_i,$$

$$\sigma_\perp = \sum_i \frac{\sigma_i}{1 + (\omega_i \tau_{in})^2},$$

$$\sigma_H = -\sum_i \frac{\sigma_i \omega_i \tau_{in}}{1 + (\omega_i \tau_{in})^2}.$$

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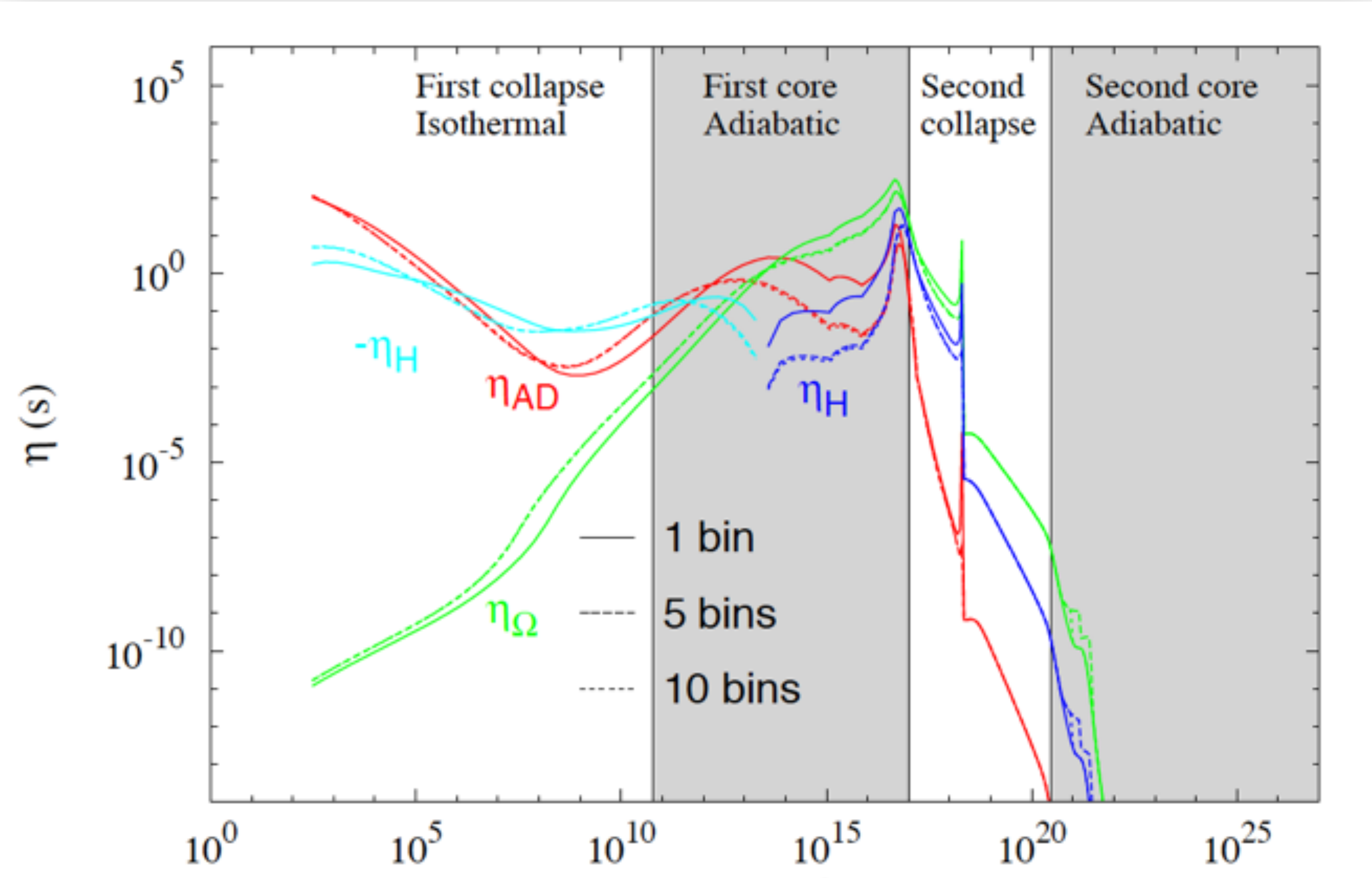

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1/ **Grain** is the most important parameter
2/ Needs at least 10 bins in dust grain size distribution to converge…

Marchand et al. (2016)

Applications: effect of ambipolar diffusion

Generalised Ohm's law

$$
\begin{aligned}
\frac{\partial \mathbf{B}}{\partial t} =& \nabla \times \Bigg[\mathbf{v} \times \mathbf{B} \\
& - \eta_{\Omega} (\nabla \times \mathbf{B}) \qquad \text{Ohmic diffusion} \\
& - \eta_{H} \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{B} \right\} \qquad \text{Hall effect} \\
& - \eta_{AD} \frac{\mathbf{B}}{B} \times \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{B} \right\} \Bigg] \qquad \text{ambipolar diffusion}
\end{aligned}
$$

Applications: effect of ambipolar diffusion

Generalised Ohm's law

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \Big[\mathbf{v} \times \mathbf{B}$$

$$- \eta_\Omega (\nabla \times \mathbf{B})$$ Ohmic diffusion

$$- \eta_H \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{B} \right\}$$ Hall effect

$$- \eta_{AD} \frac{\mathbf{B}}{B} \times \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{B} \right\} \Big]$$ ambipolar diffusion

Applications: effect of ambipolar diffusion

Generalised Ohm's law

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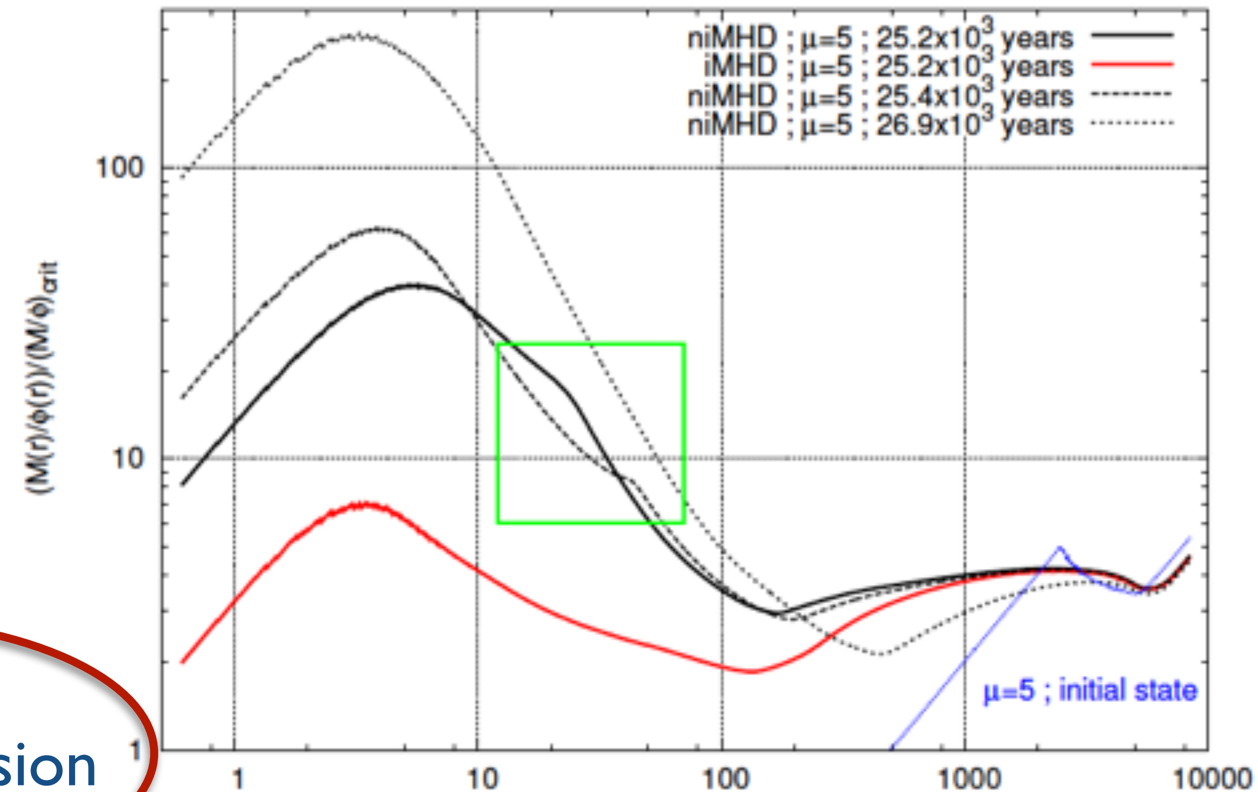
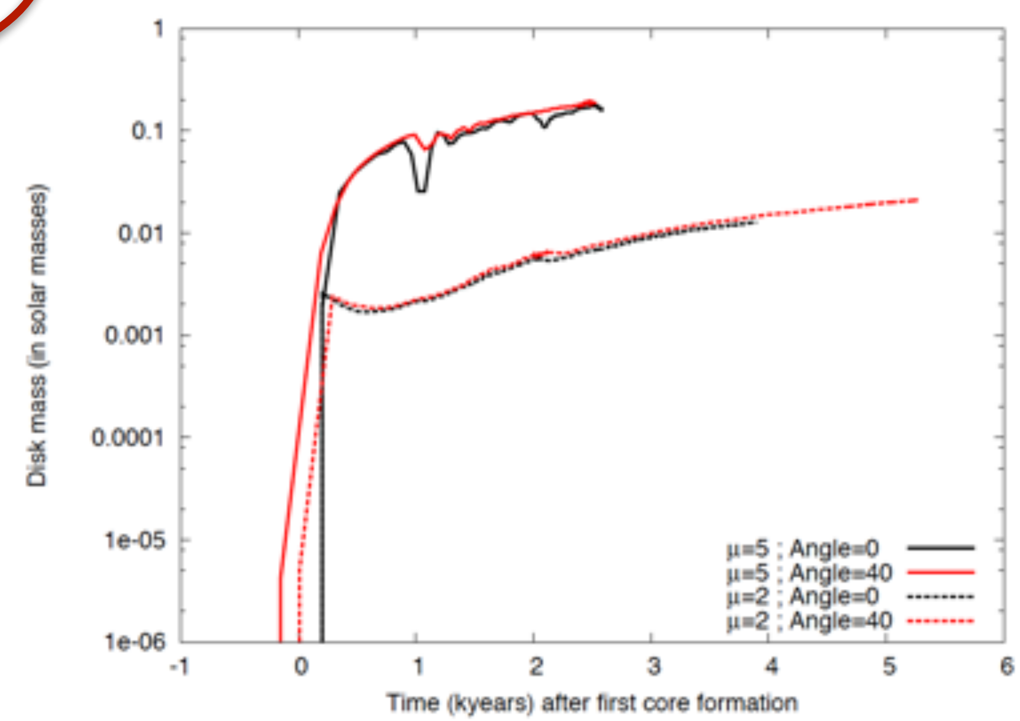
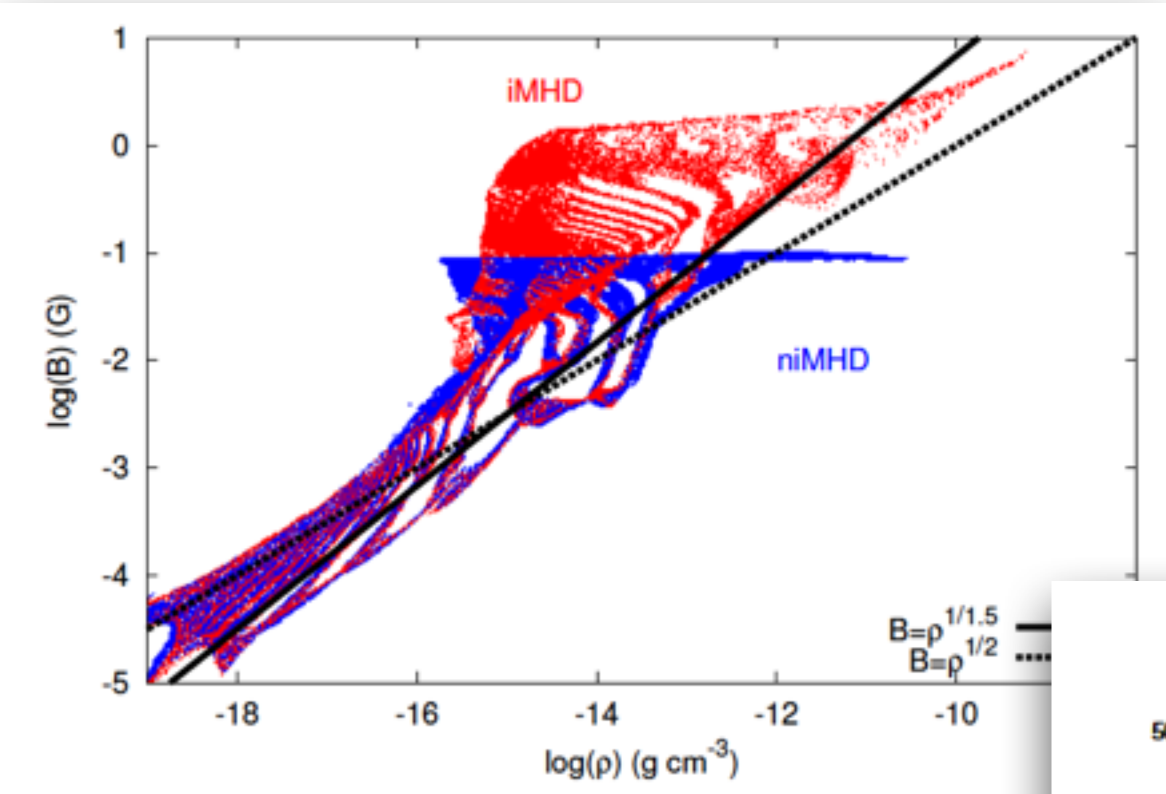




Masson et al. (2016)

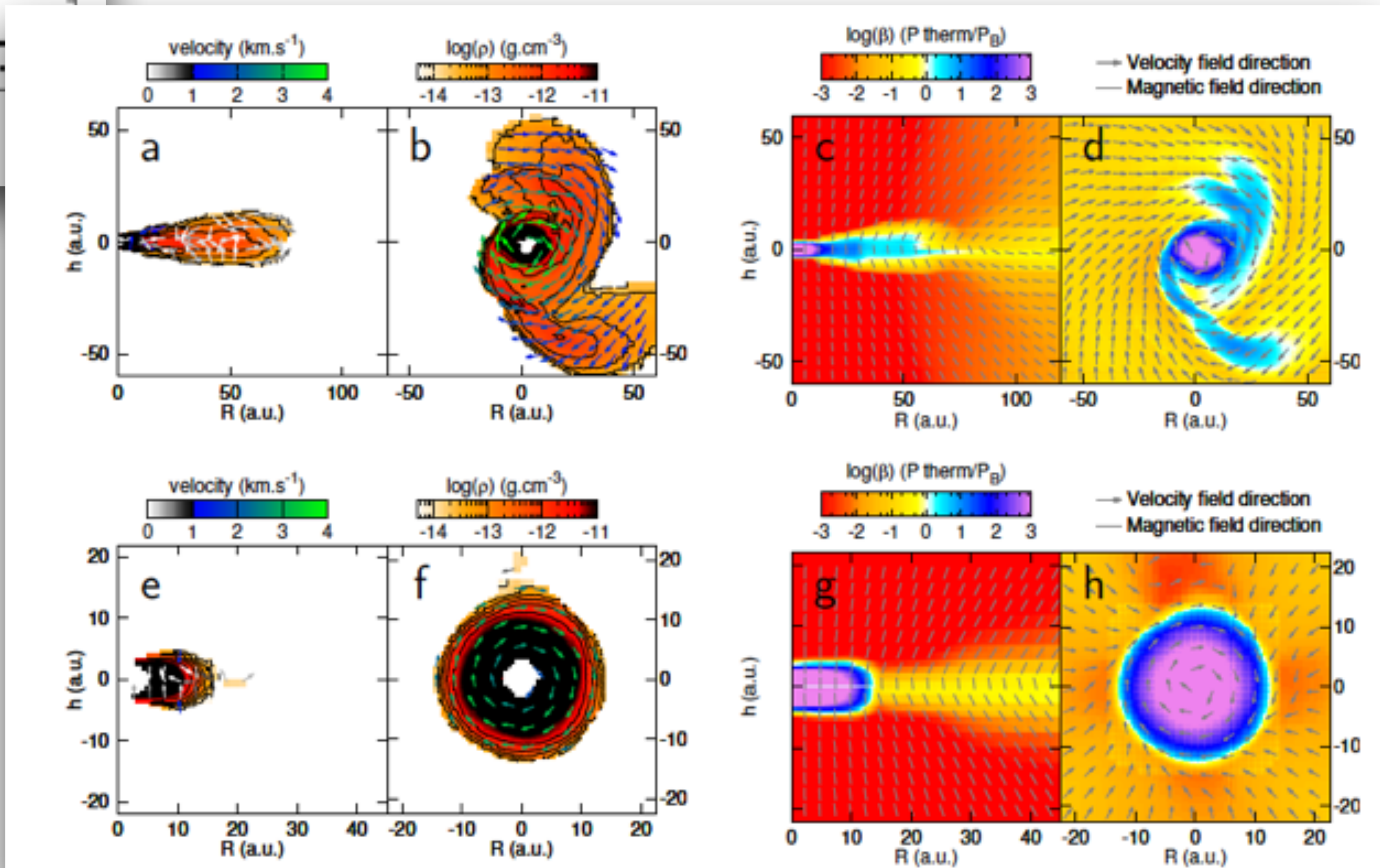
Applications: effect of ambipolar diffusion



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

=> **reduced magnetic braking**

- mass and radius of first core do not change
- **weaker outflows** compared to ideal MHD



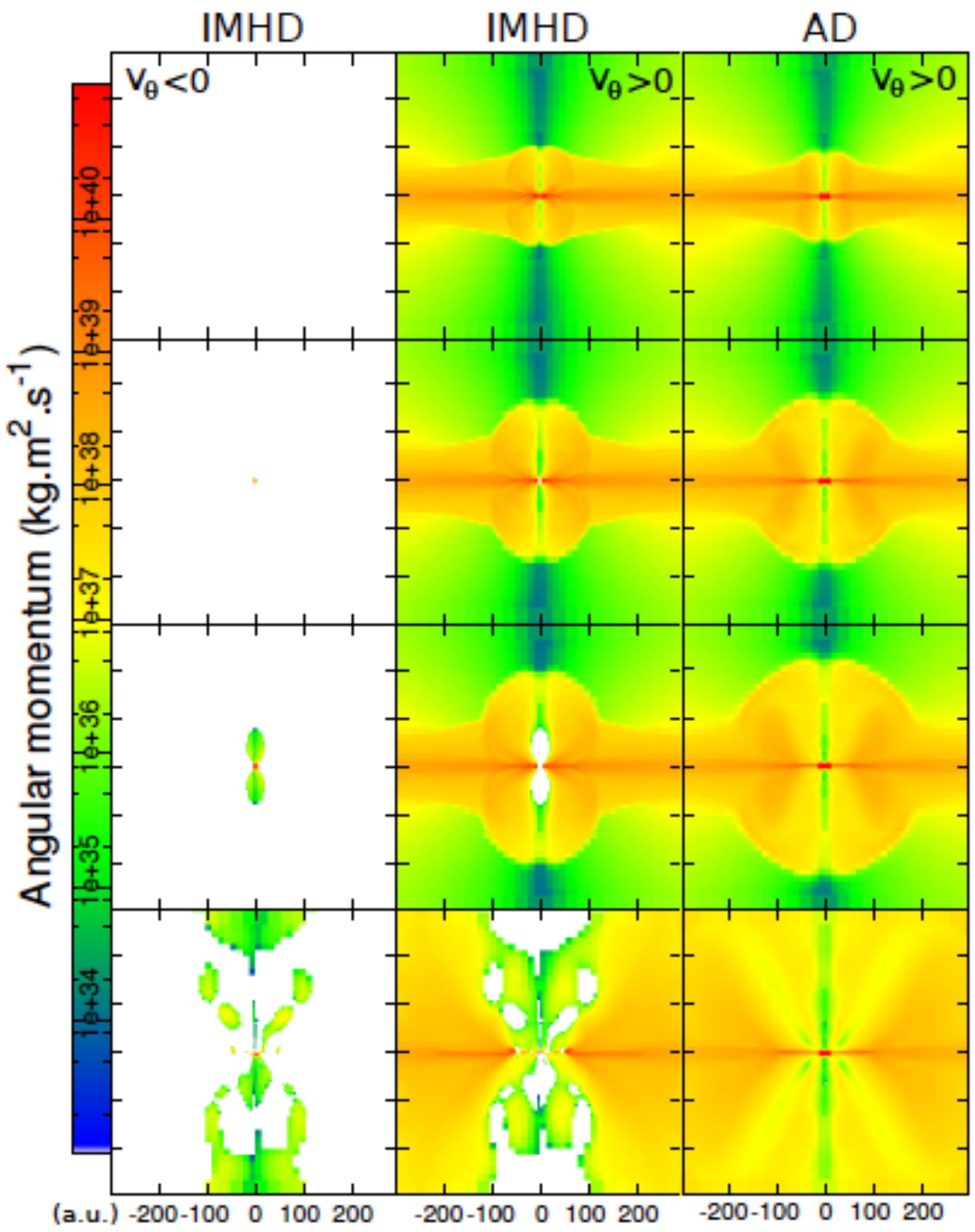
- Rotationally supported disc formation (**R ~ 50 AU**) - consistent with obs.
- disc size **depends** on misalignment
- **P_{therm}/P_{mag}>1** within discs
- **poloidal** magnetic field

=> initial conditions for protoplanetary discs studies

Masson et al. 2016

Influence of non-ideal MHD

Rotation and interchange instability



- reduce magnetic braking (suppress counter-rotation found in ideal MHD)

Influence of non-ideal MHD

Rotation and interchange instability

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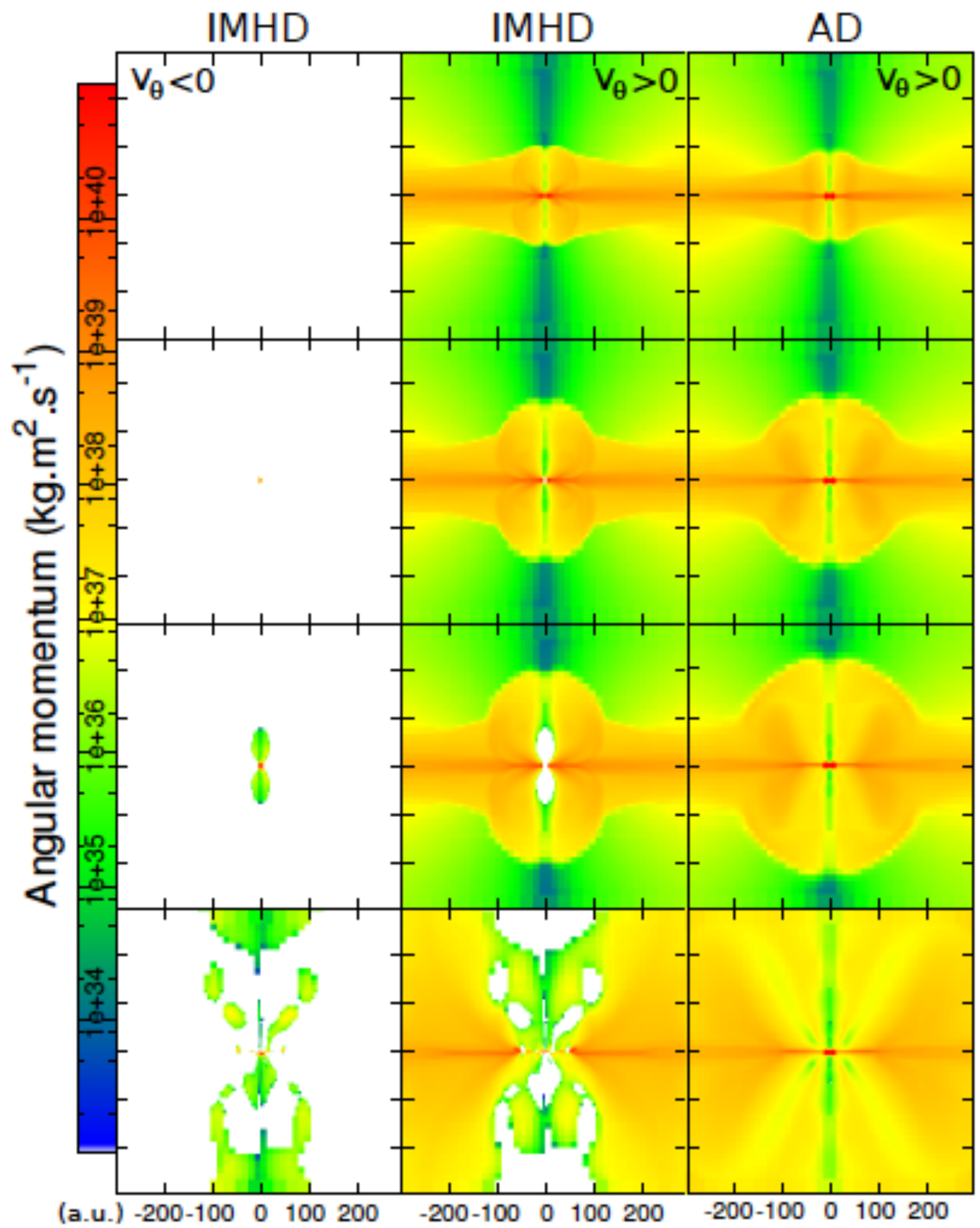


Masson et al. in prep

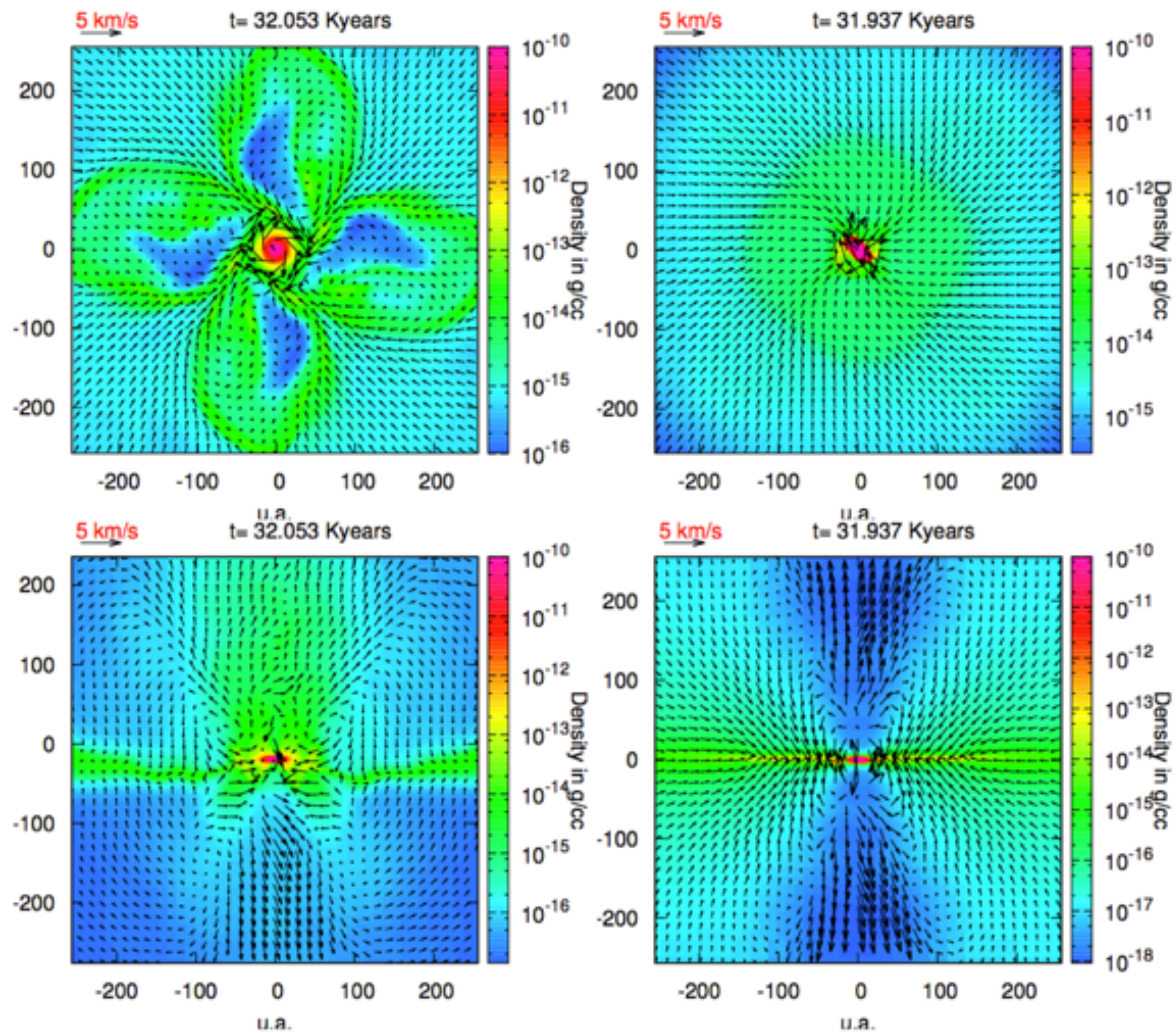
Influence of non-ideal MHD

Disc formation and interchange instability

- reduce magnetic braking (suppress counter-rotation found in ideal MHD)

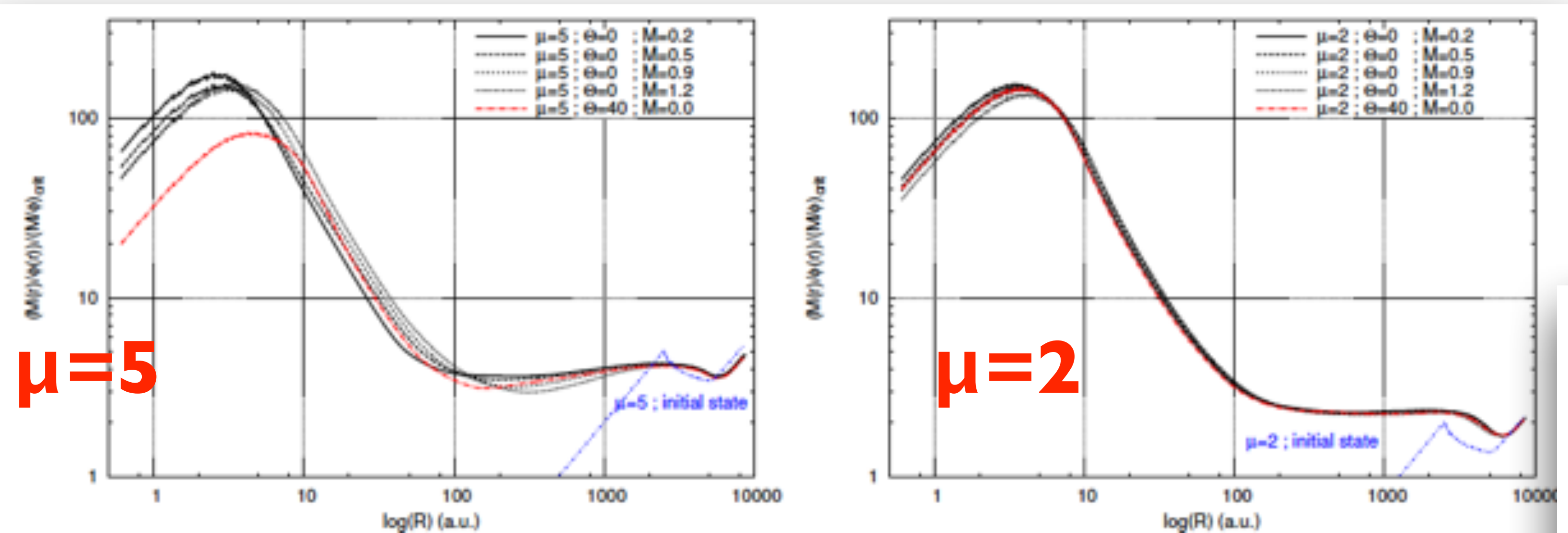
- similar qualitative results in the turbulent case
but
- magnetic pressure is greatly reduced in the disc with AD
- changes at the first core scale
- diffusion is *controlled*

Ideal **Ambipolar diffusion**



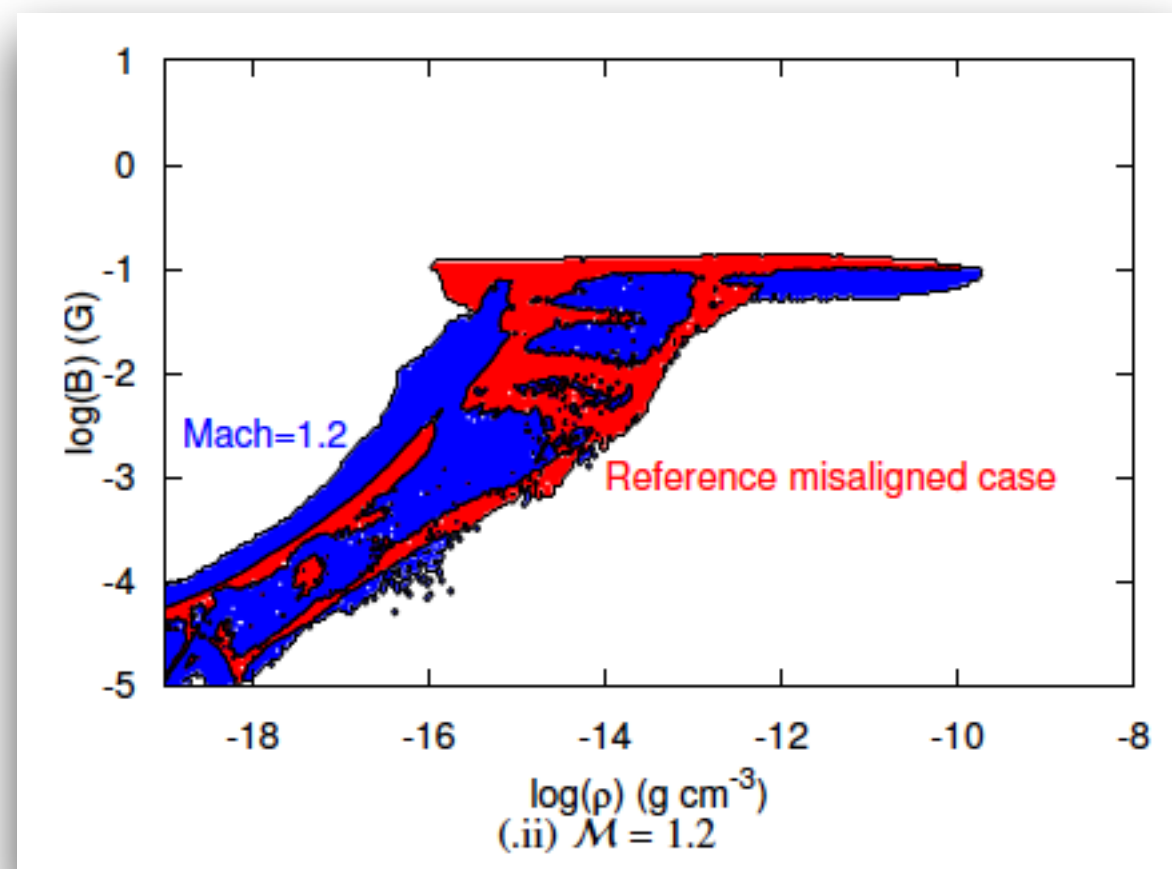
J. Masson PhD

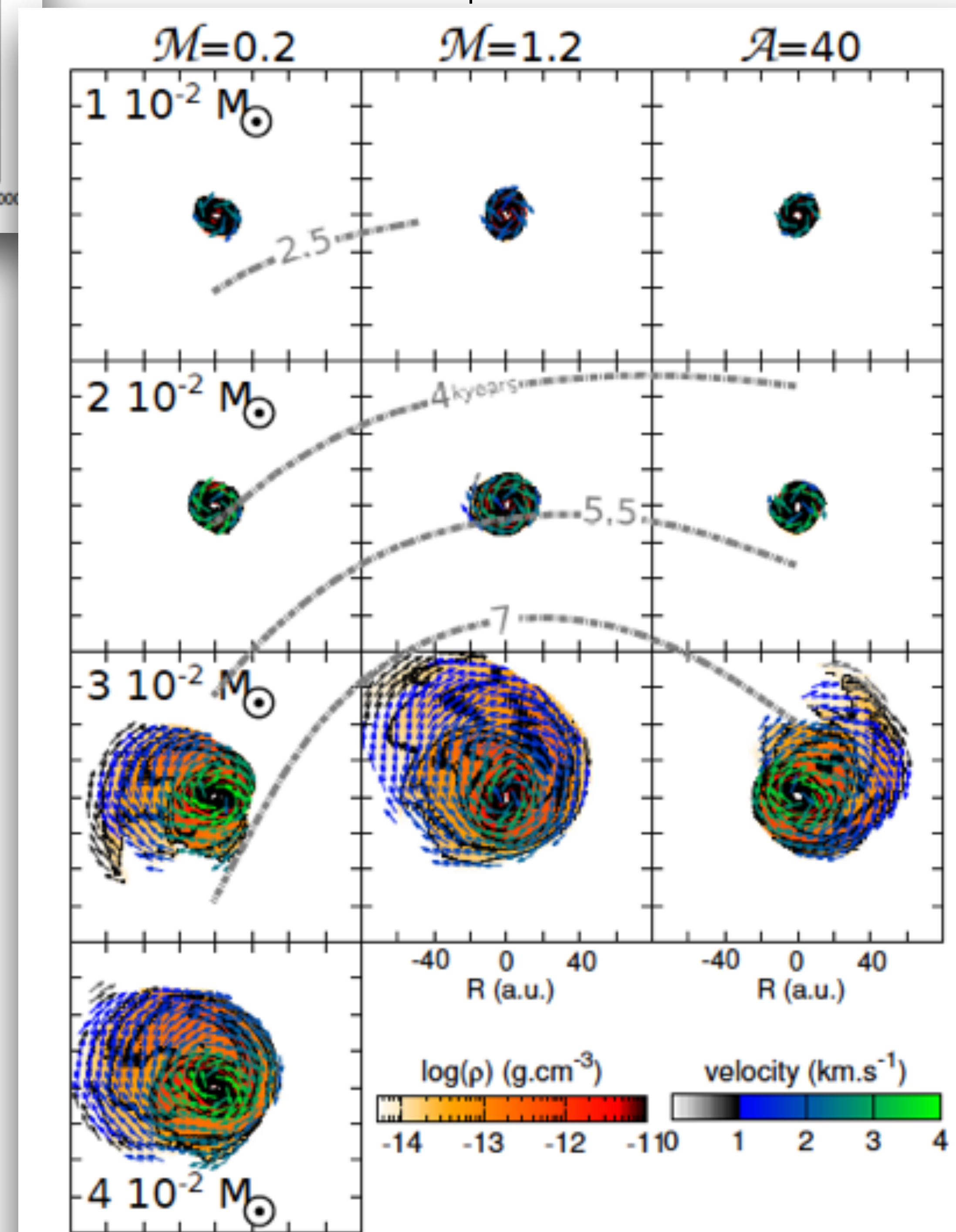
Turbulence & ambipolar diffusion



- disc size **does not depend** on turbulence level

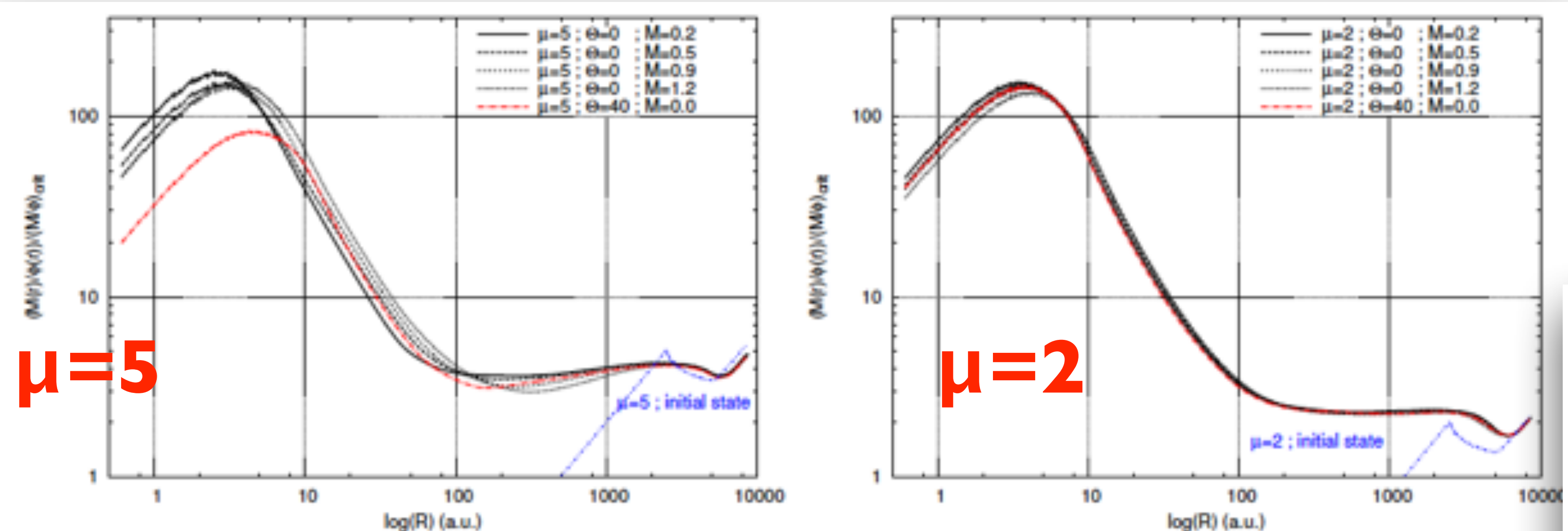
=> combination between turbulent diffusion and ambipolar diffusion?





Masson et al. in prep.

Turbulence & ambipolar diffusion



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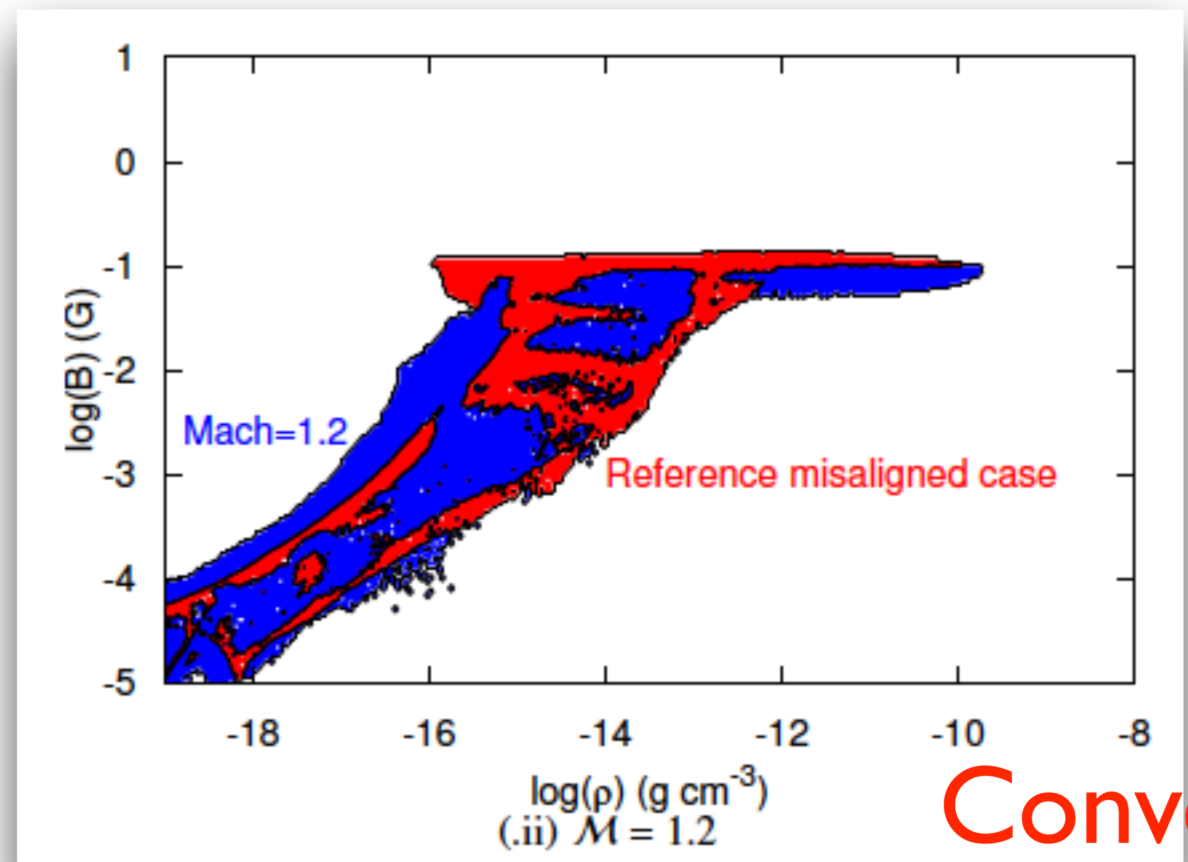
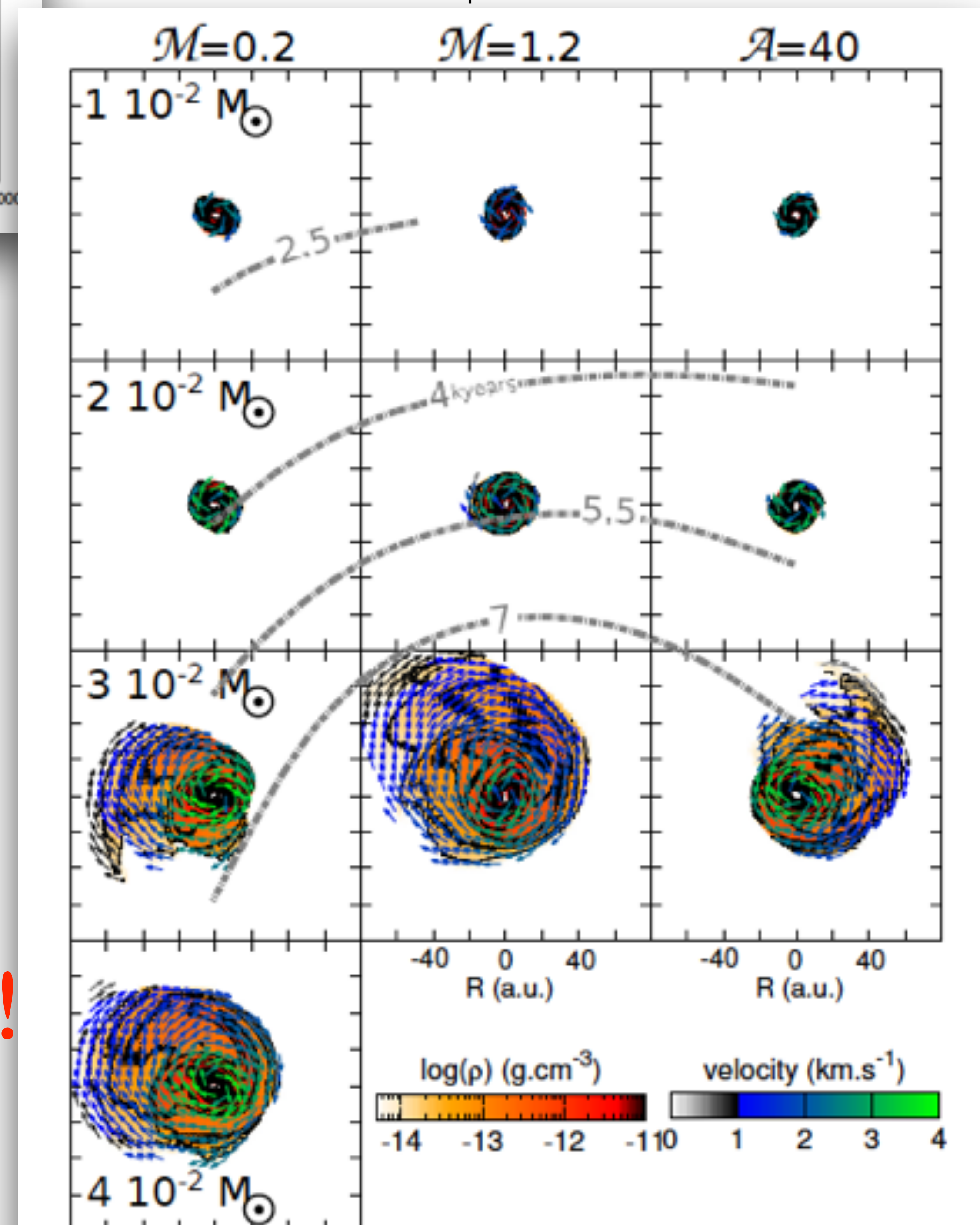
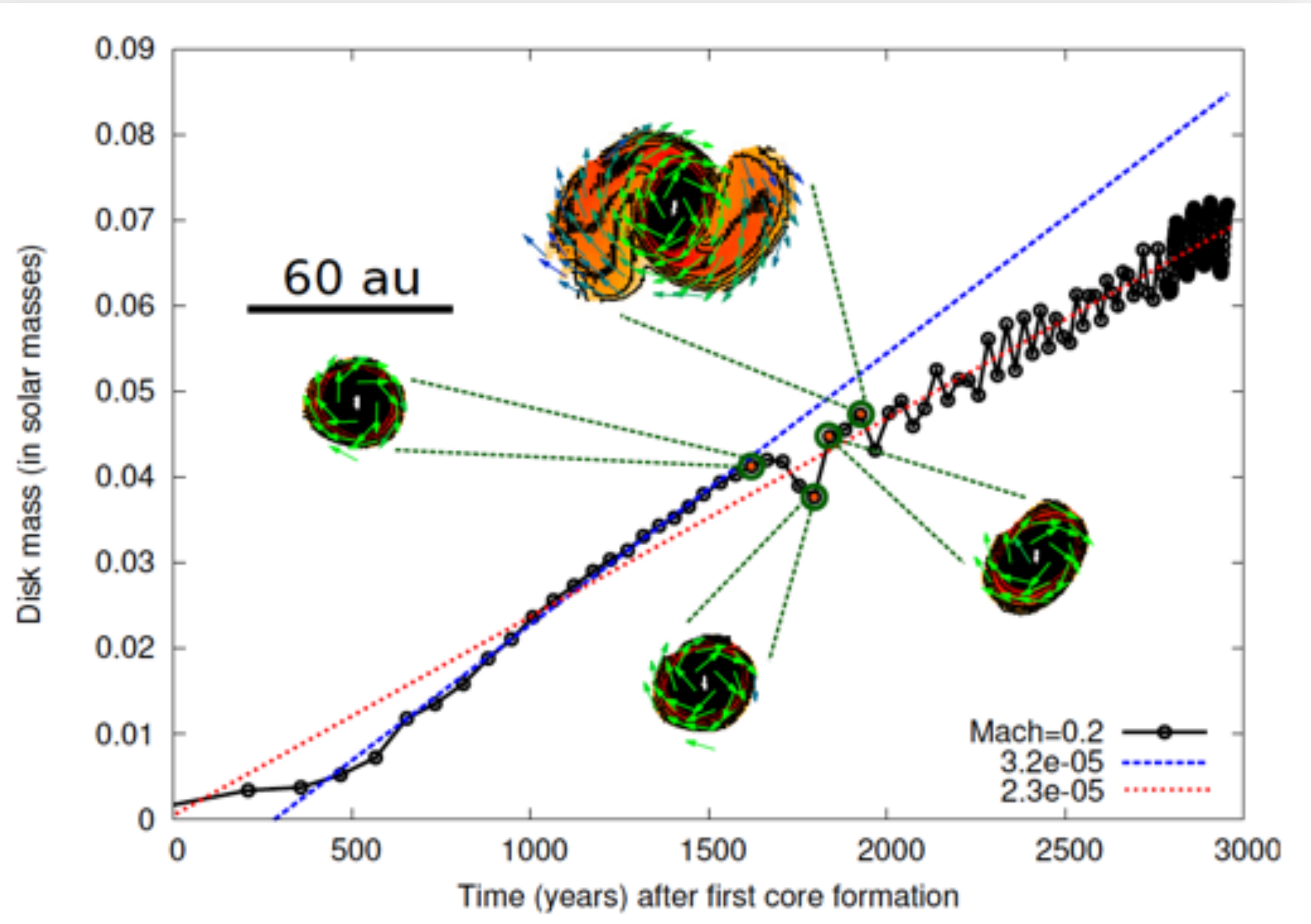




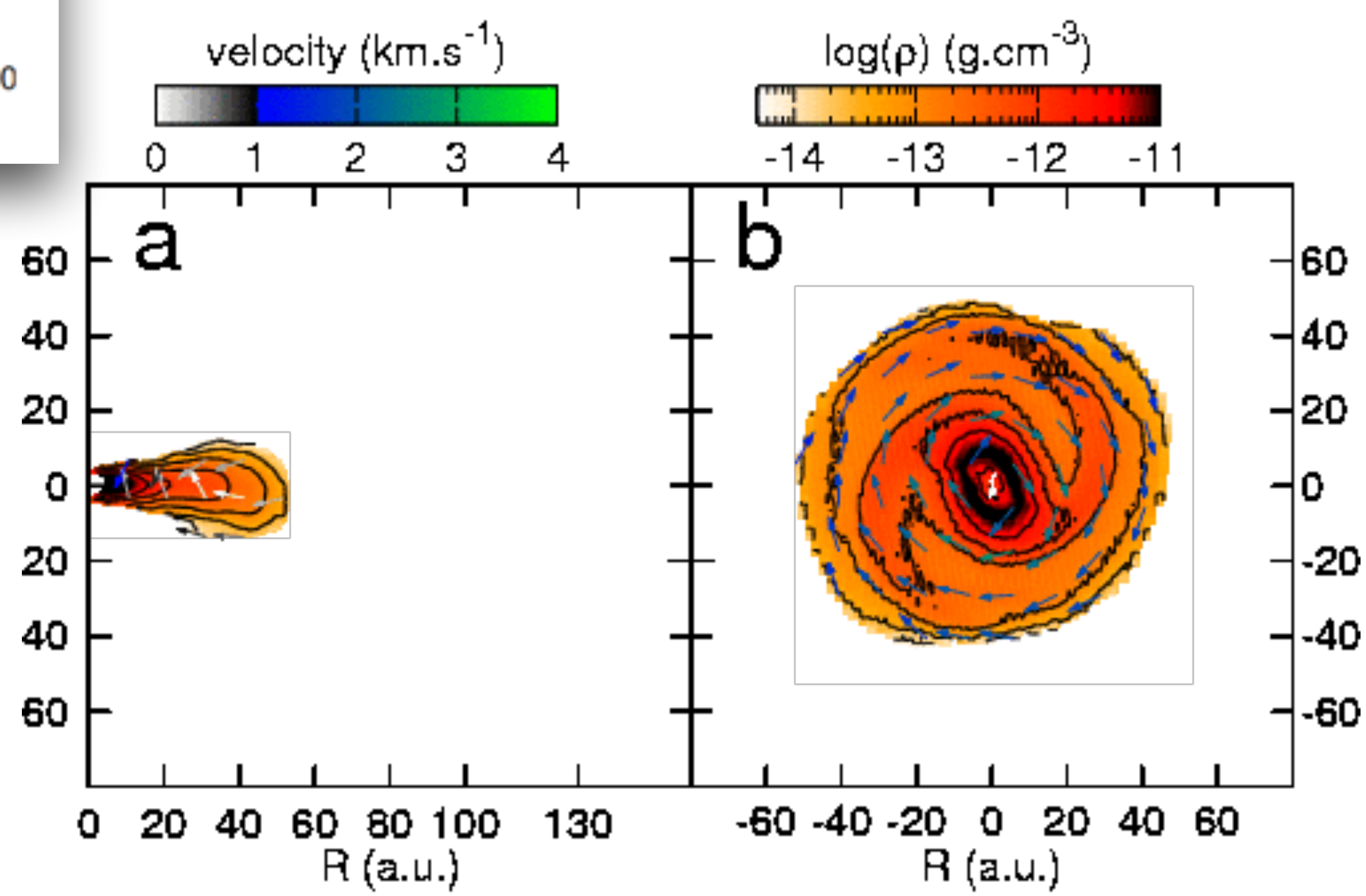
Convergence!

Masson et al. in prep.

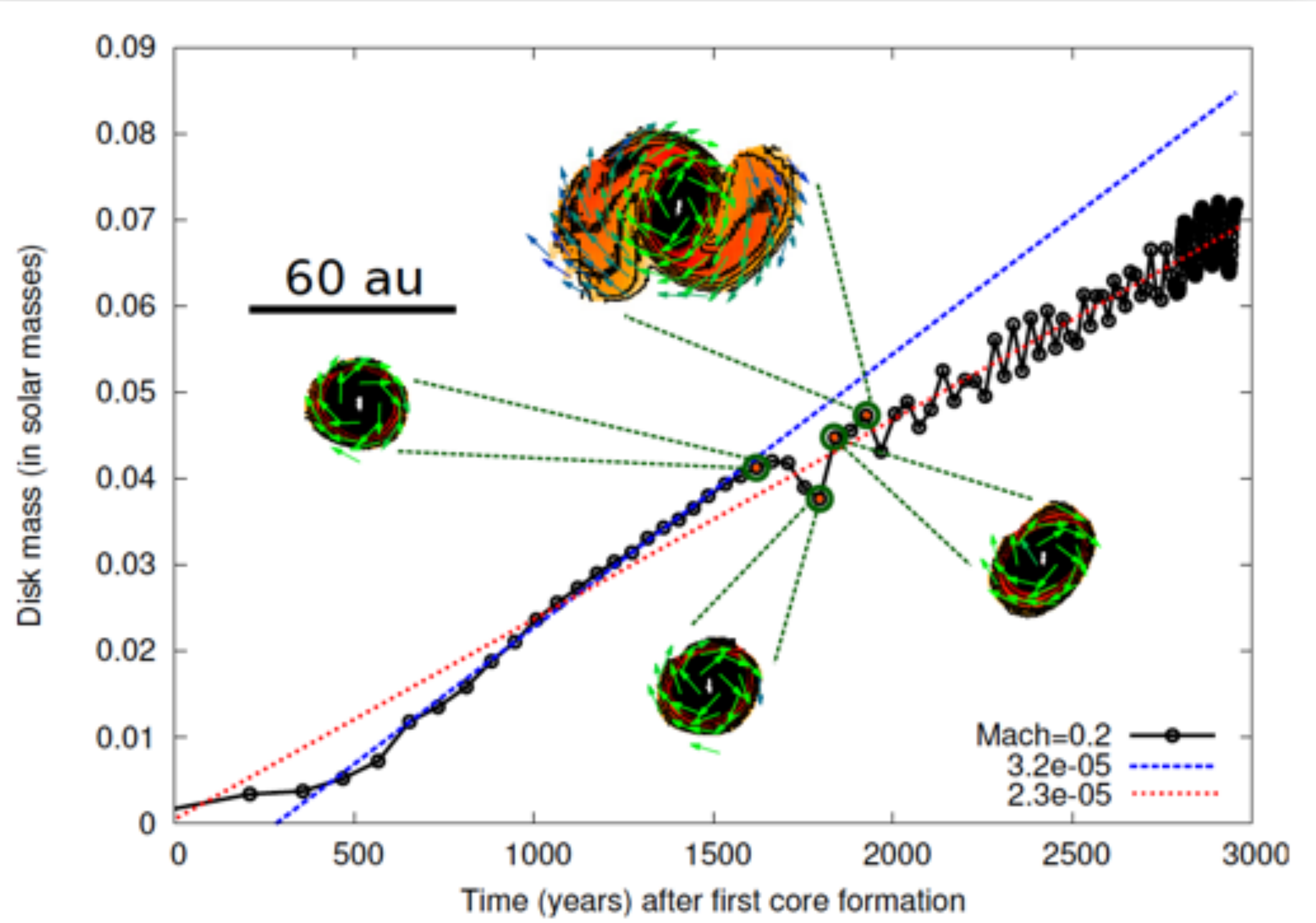
Late evolution



Masson et al. in prep.



Late evolution



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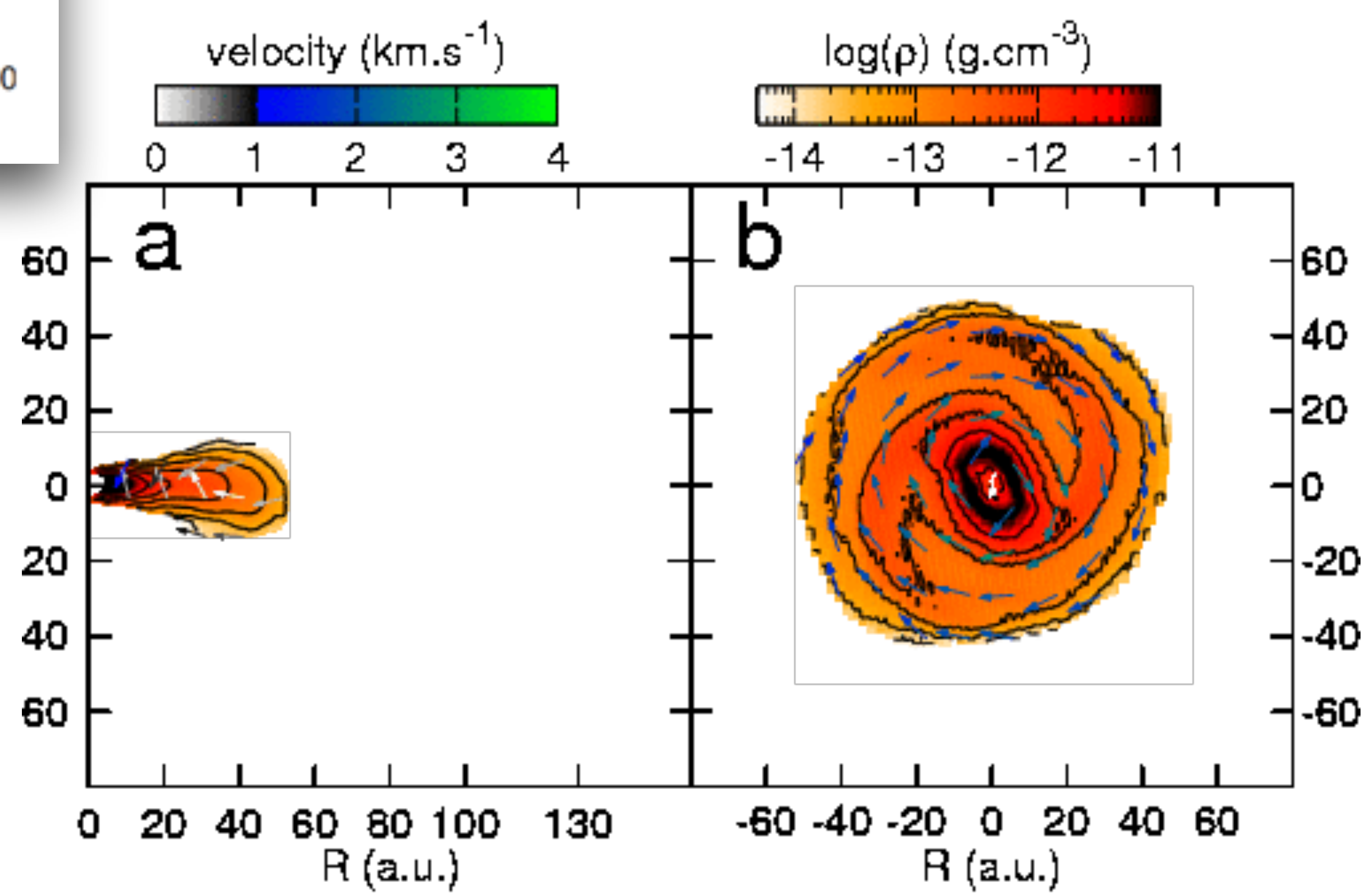

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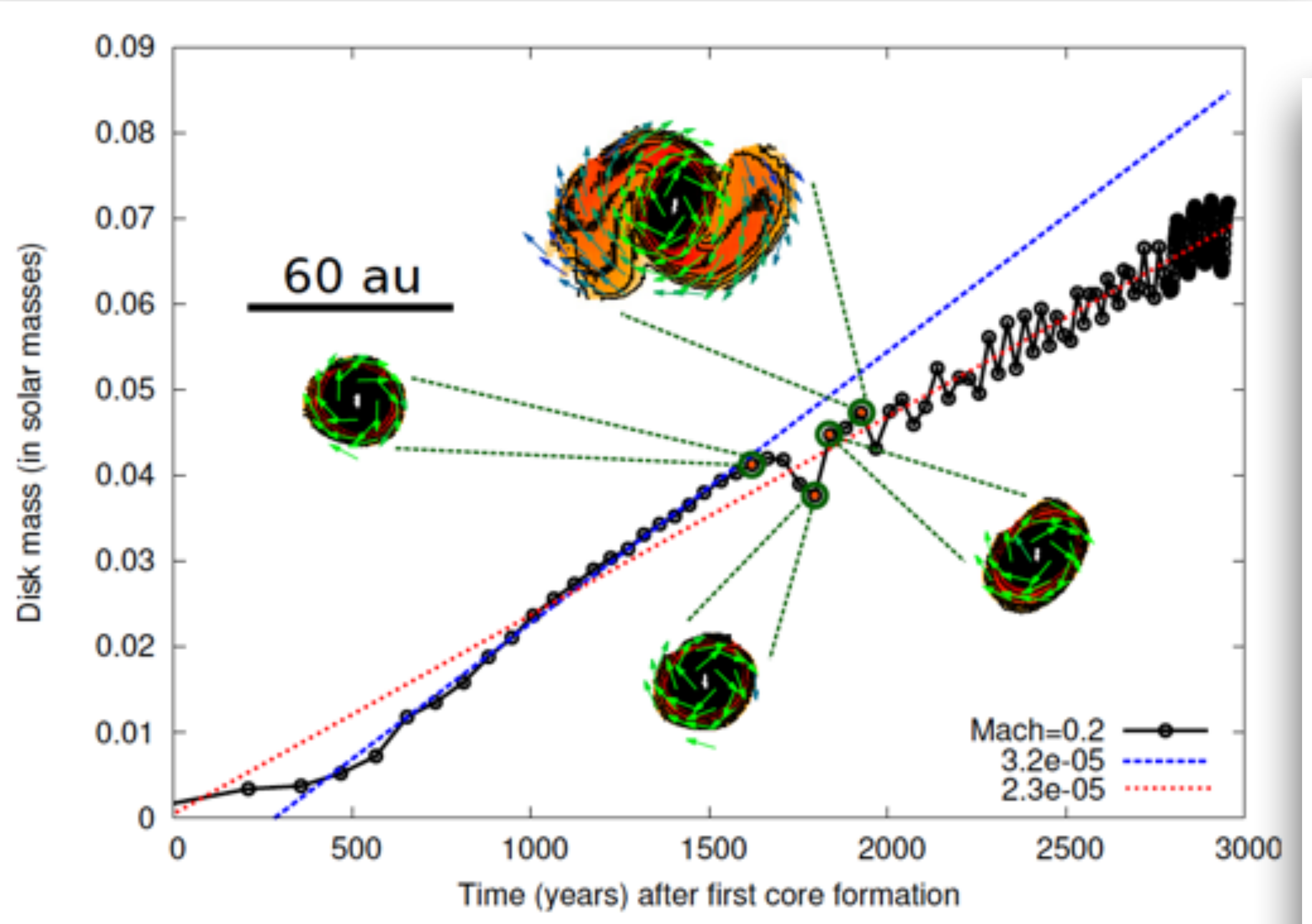

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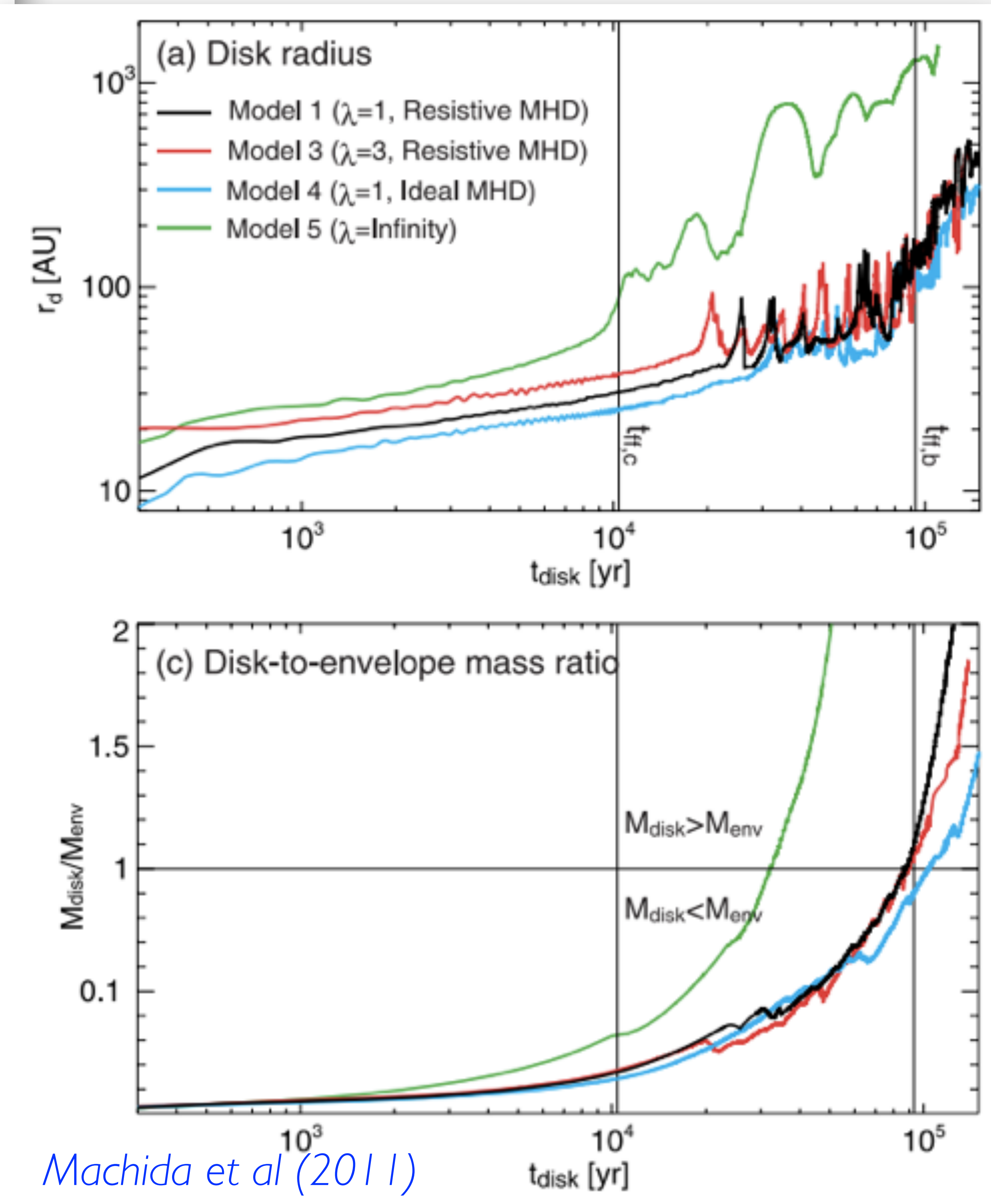

Machida et al (2011)

Magnetically regulated disc size with AD

Hennebelle et al. (2016)

$$\tau_{\rm far} \simeq \frac{B_\phi h}{B_z v_\phi}$$

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

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

$$\tau_{\rm rot} \simeq \frac{2\pi r}{v_\phi}$$

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

- 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

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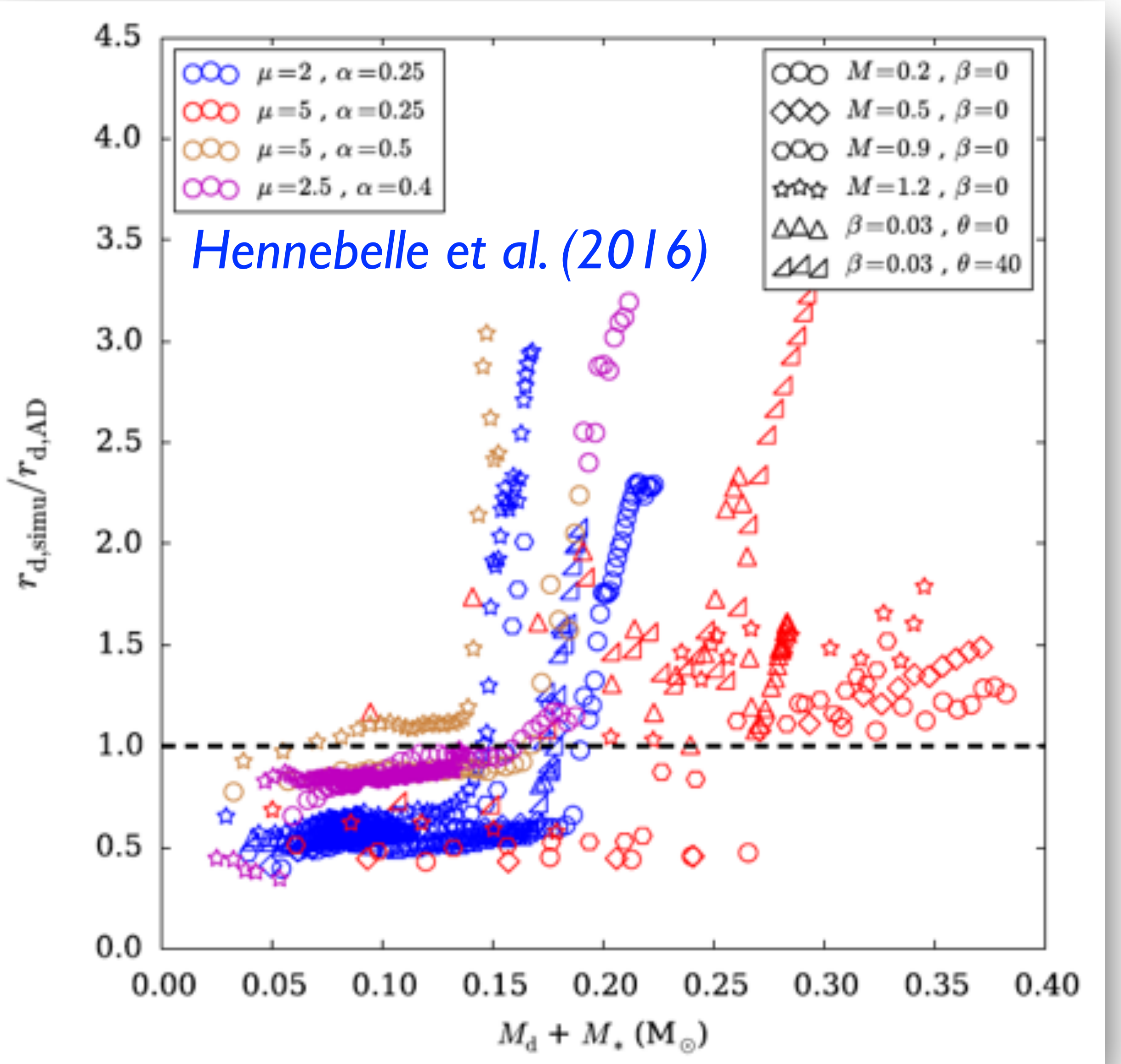
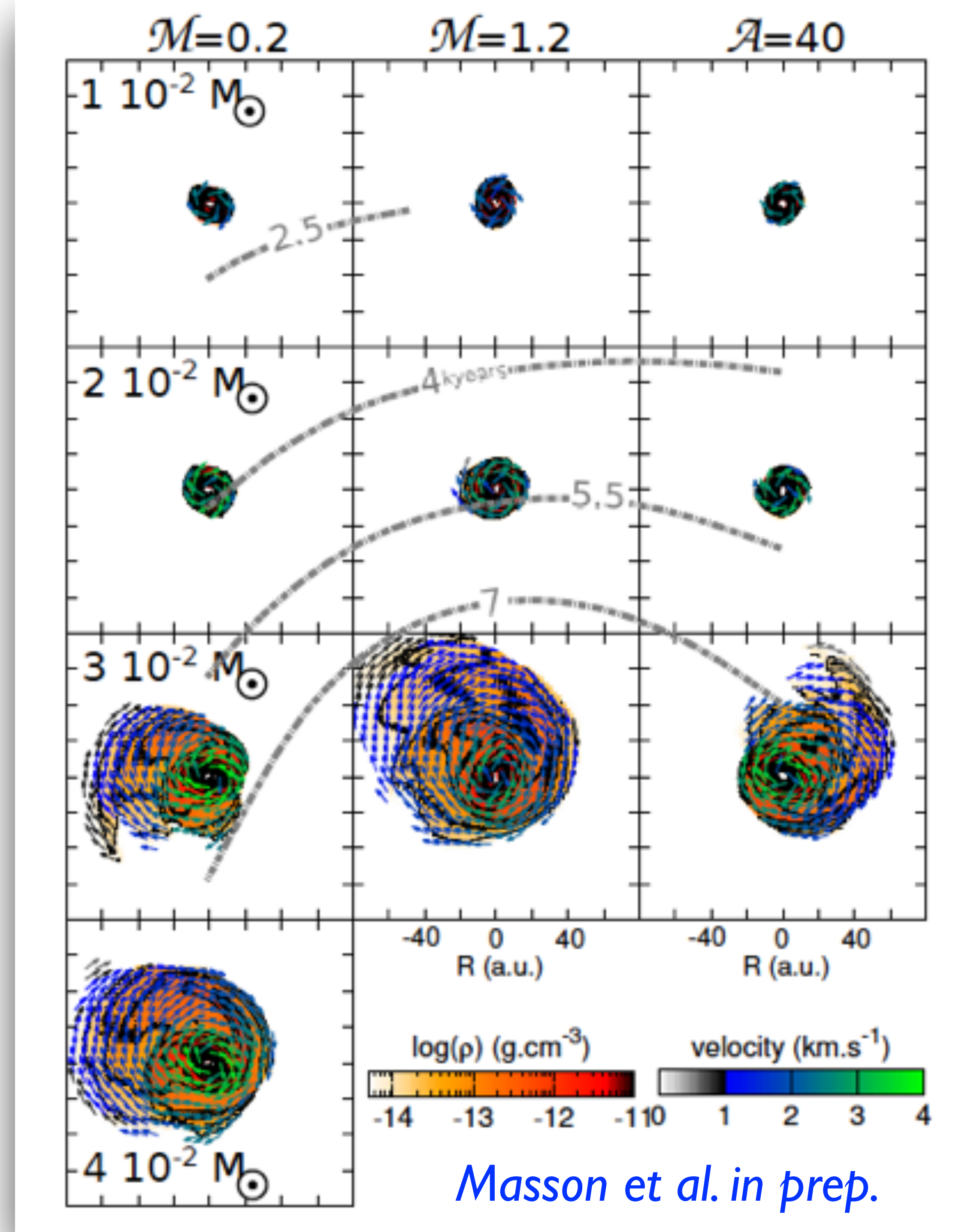


Hennebelle et al. (2016)



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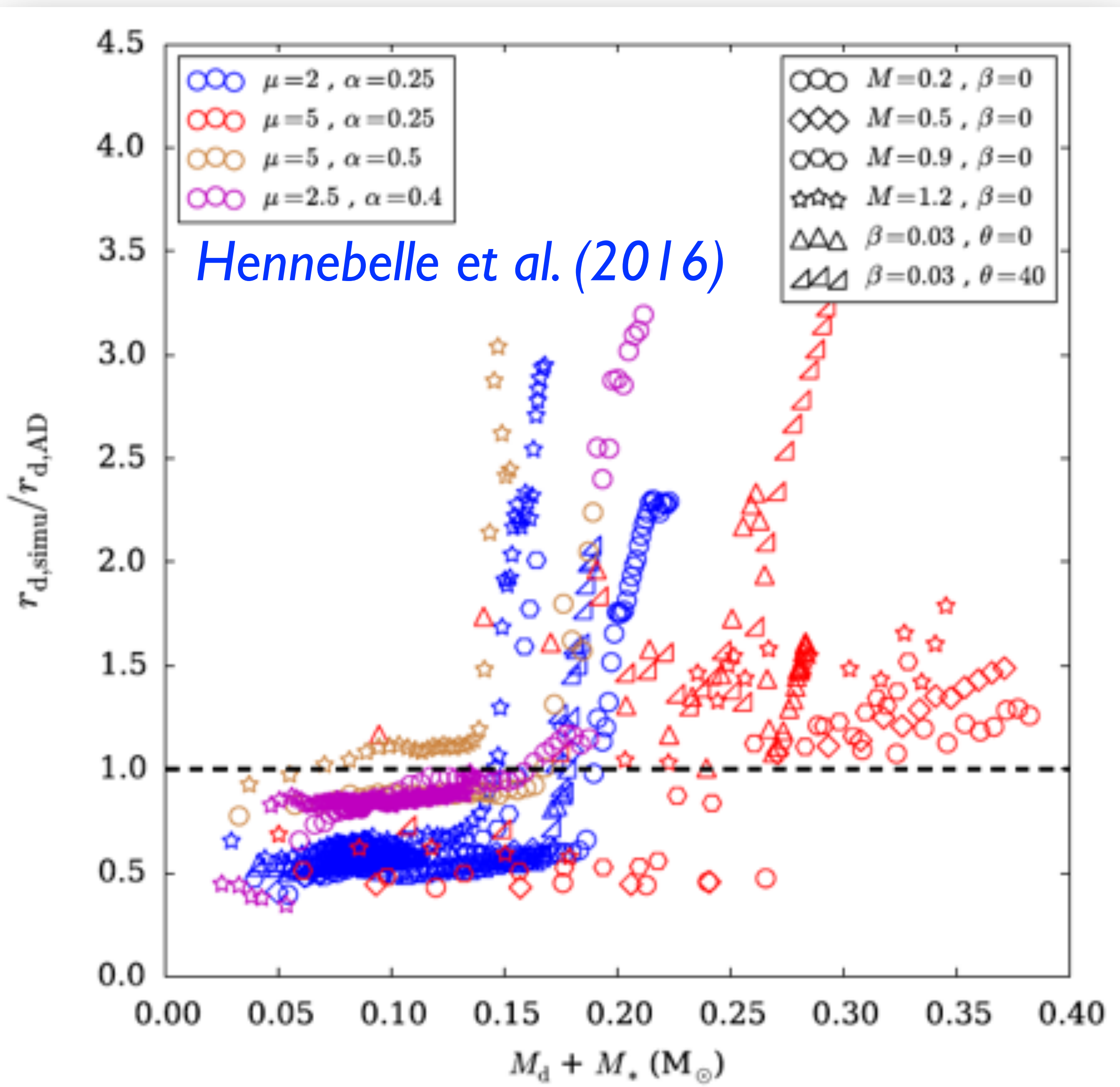
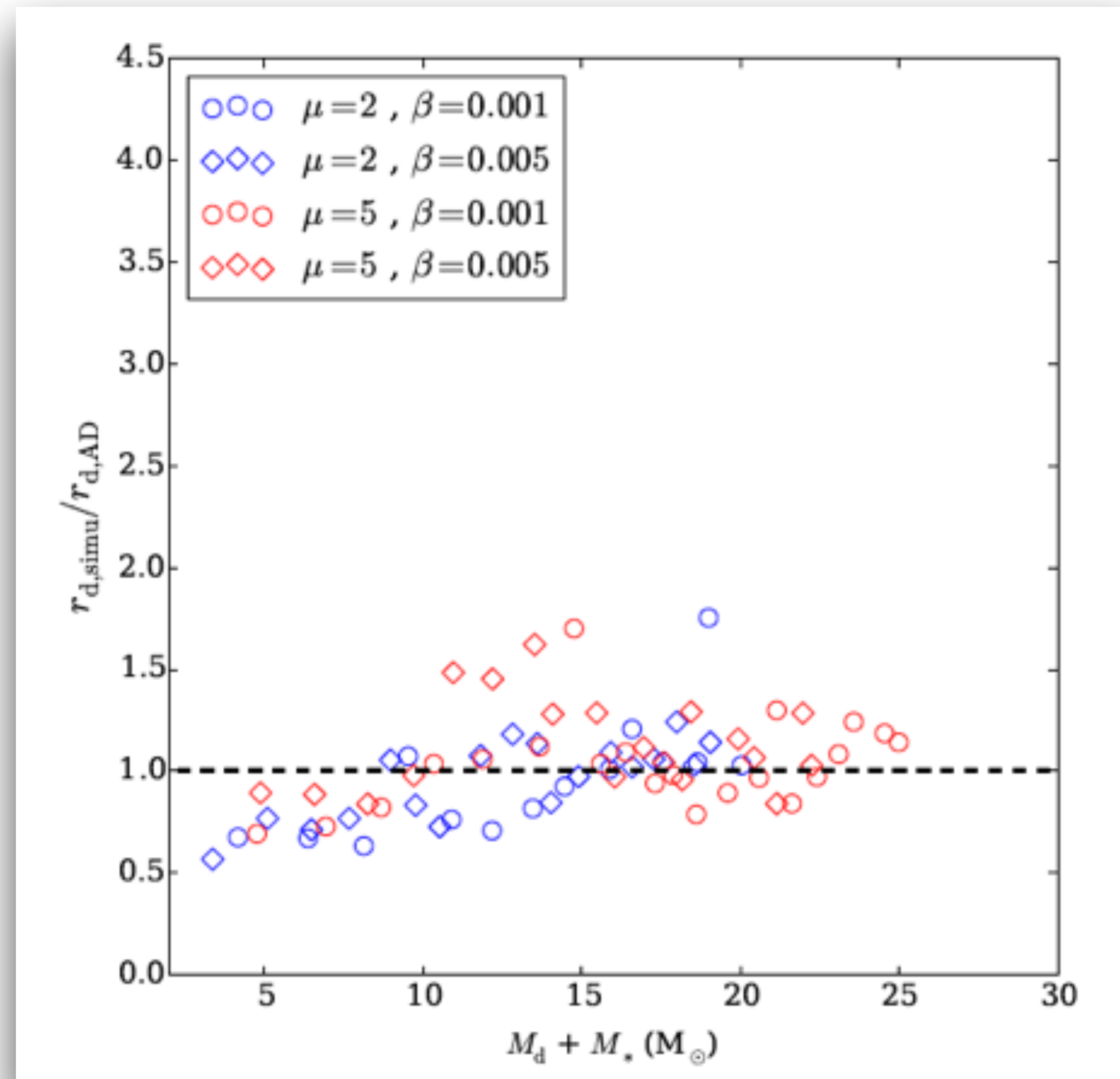
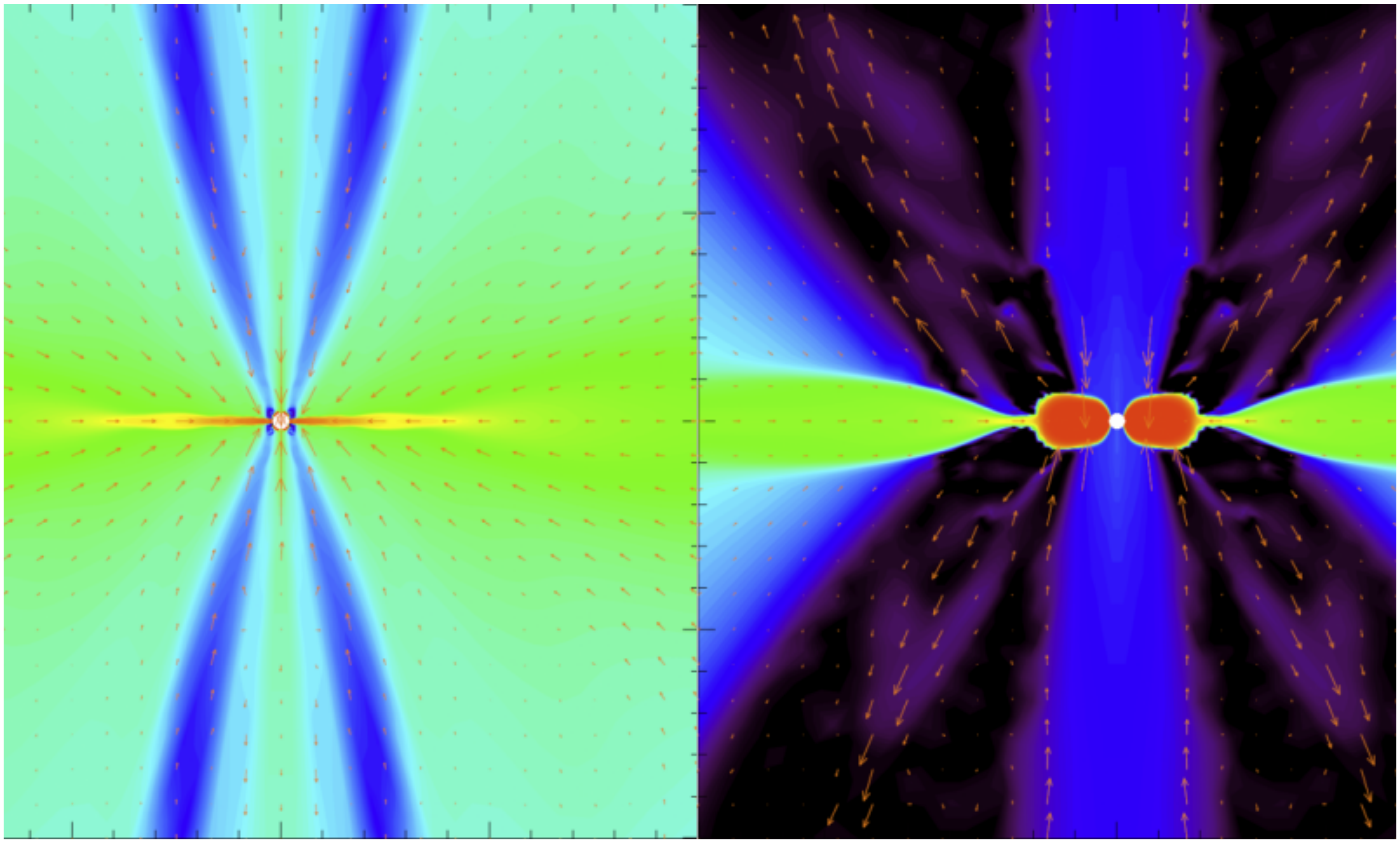




✓ Works for massive stars as well!

Effect of dust grains



Small grains
standard MRN
amin = 0.005 μm, amax = 0.25 μm

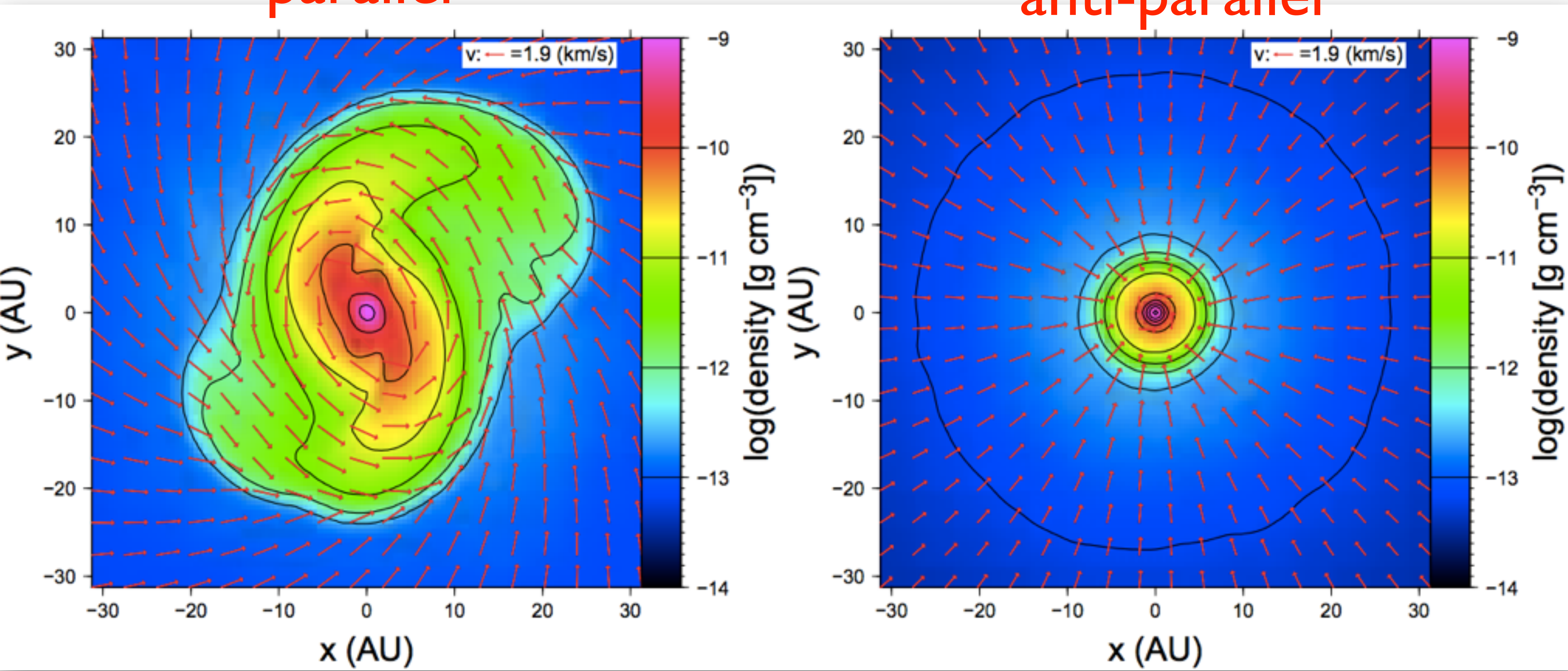
Large grains
truncated MRN
amin = 0.1 μm, amax = 0.25 μm

Zhao et al (2016)

Hall effect

parallel

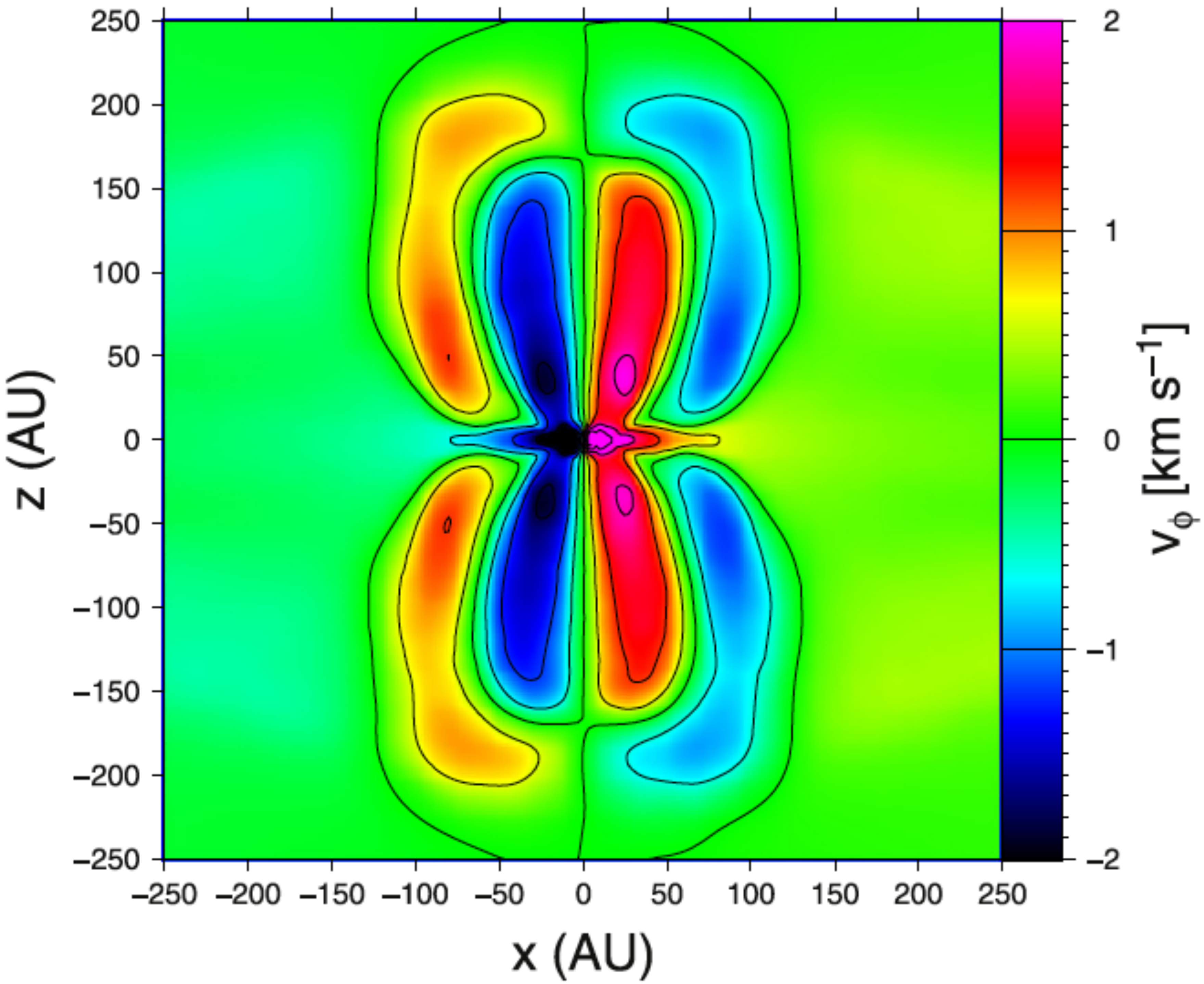
anti-parallel



- Hall effect depends on the magnetic field orientation
- Bi-modality of disc properties
- non-aligned configuration?

Tsukamoto et al. (2015)

Hall effect

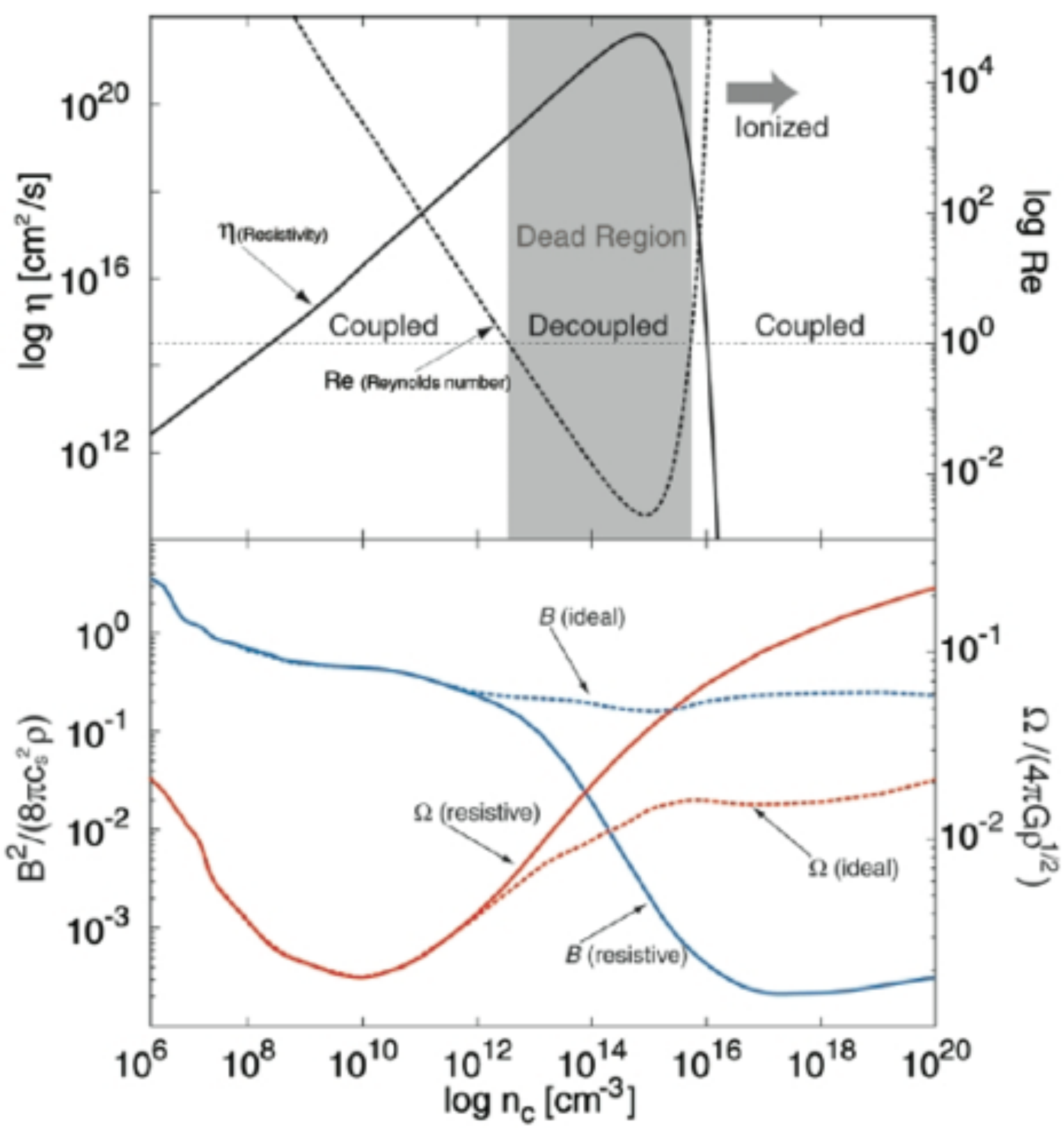


Tsukamoto et al. (2015)

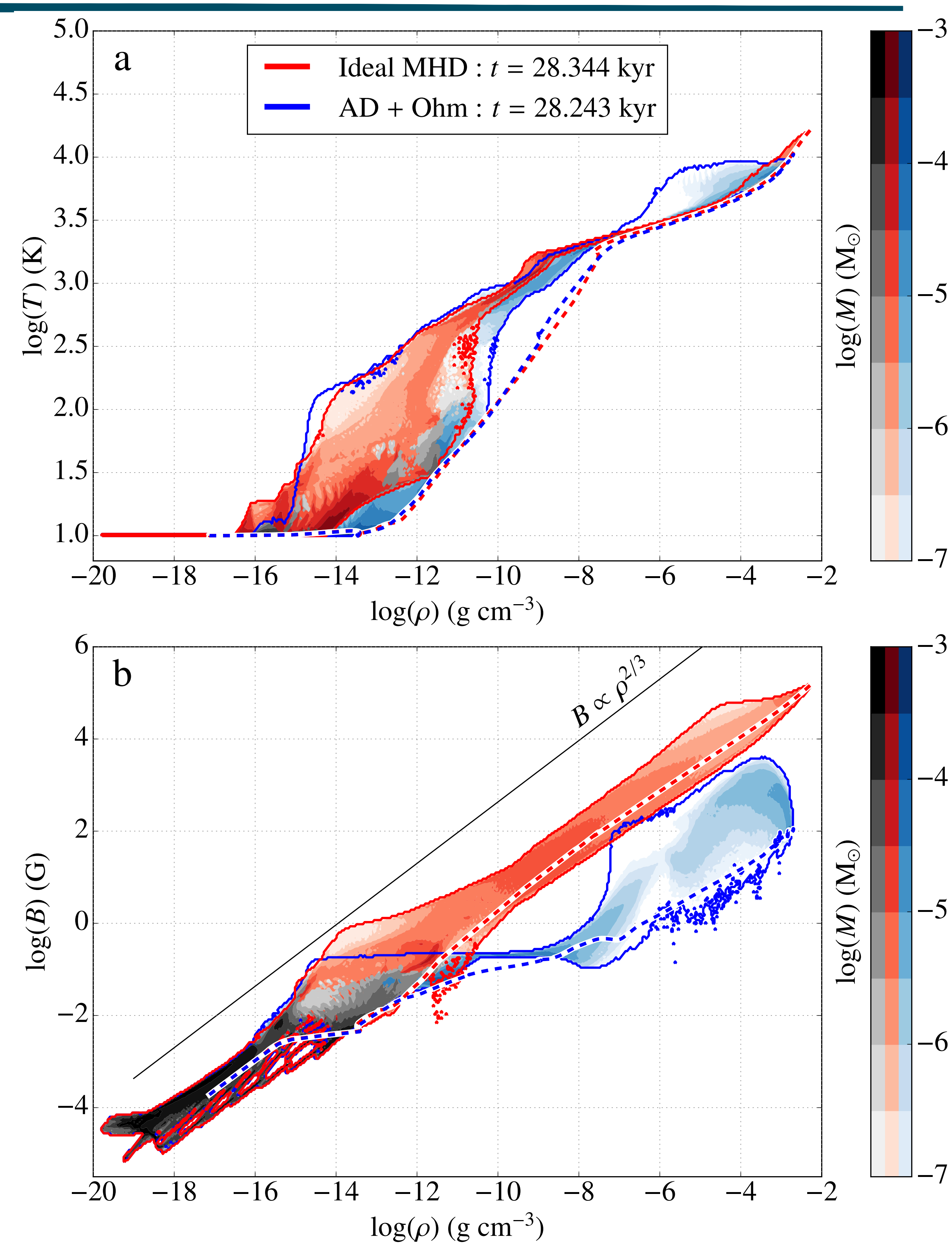
- Counter-rotating envelope

2nd collapse

Magnetic flux reduced by ~3 orders of magnitude only with ambipolar diffusion and Ohmic diffusion

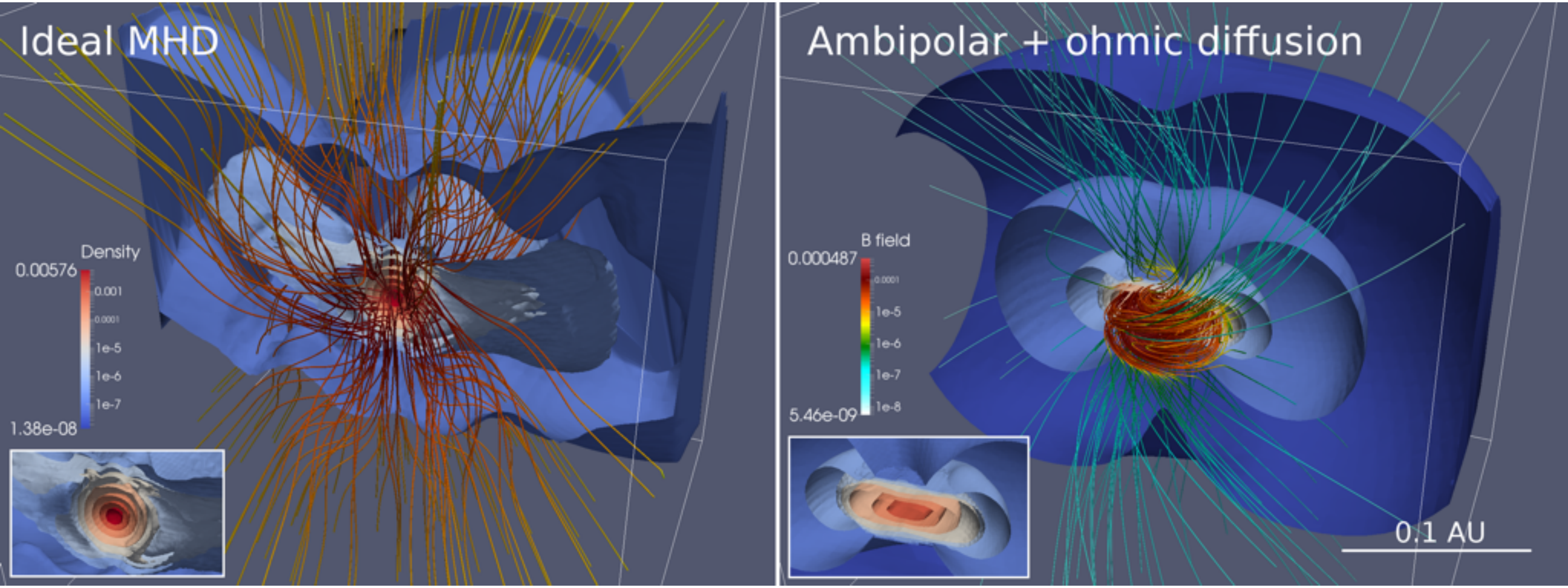


Machida et al (2008)



Vaytet et al (in prep.)

2nd collapse

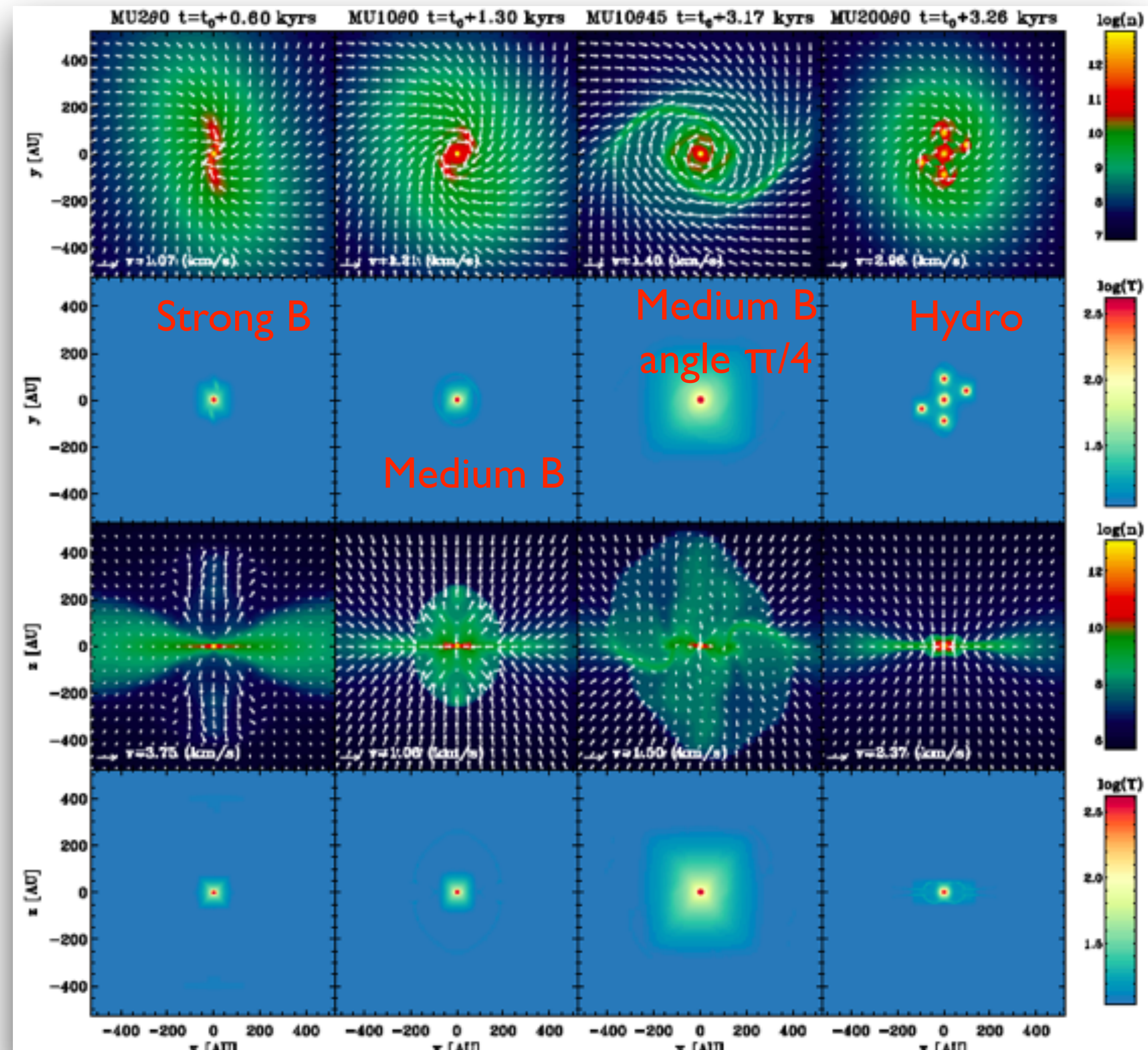


Vaytet et al (in prep.)

Dynamical chemical evolution w tracer particles

- 10^6 tracer particles & store position, temperature & density
- 1 $M_\odot$ dense core collapse with 3 different magnetisation and 1 different angle
- Compute the chemistry using the Bordeaux **NAUTILUS** full gas-grain chemistry code (655 species, >6000 reactions)
- 50 000 CPU hours for chemistry

✓ Access to the 3D abundances within the collapsing dense cores
✓ Account for hysteresis effects



Hincelin et al. (2013)
Hincelin et al. (2016)

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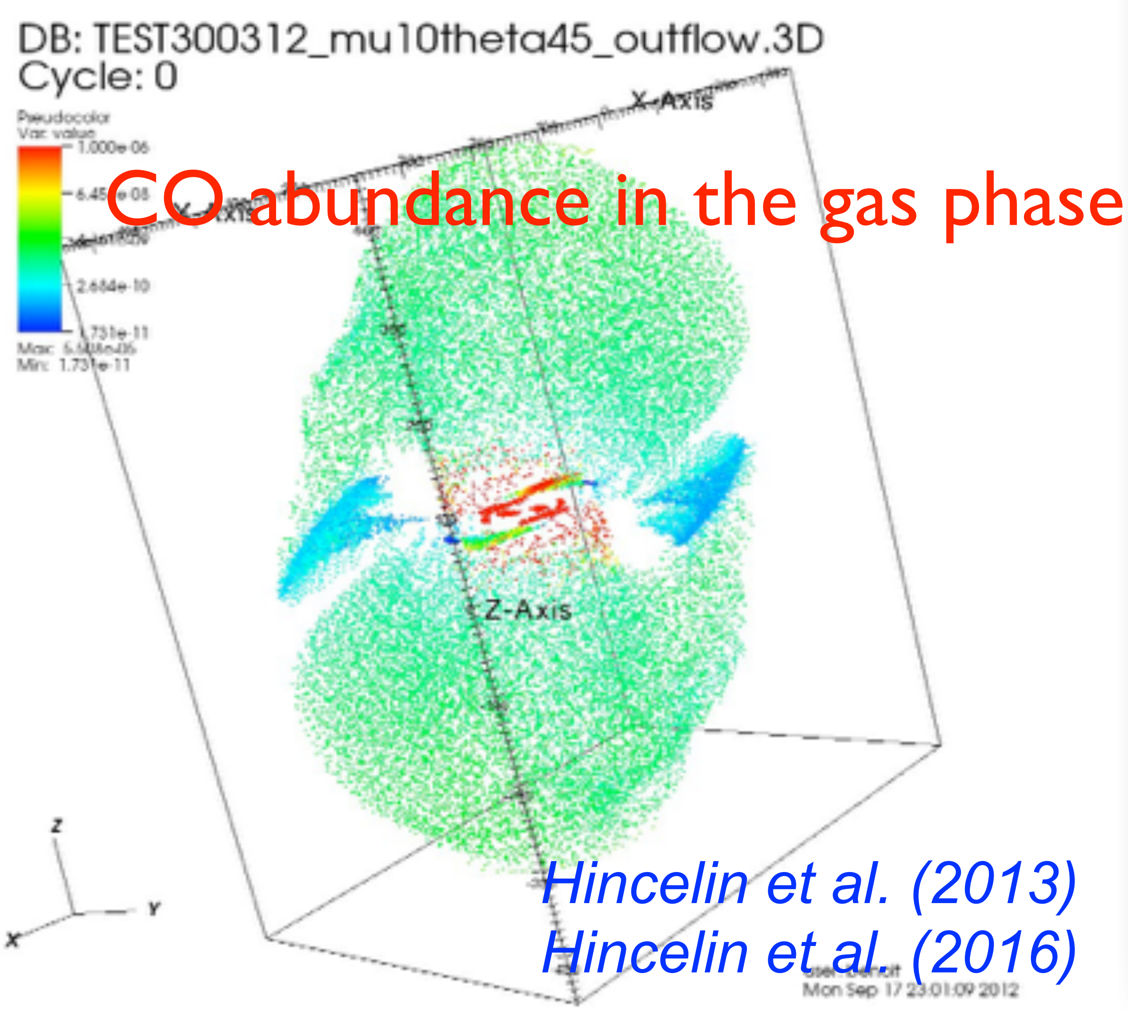

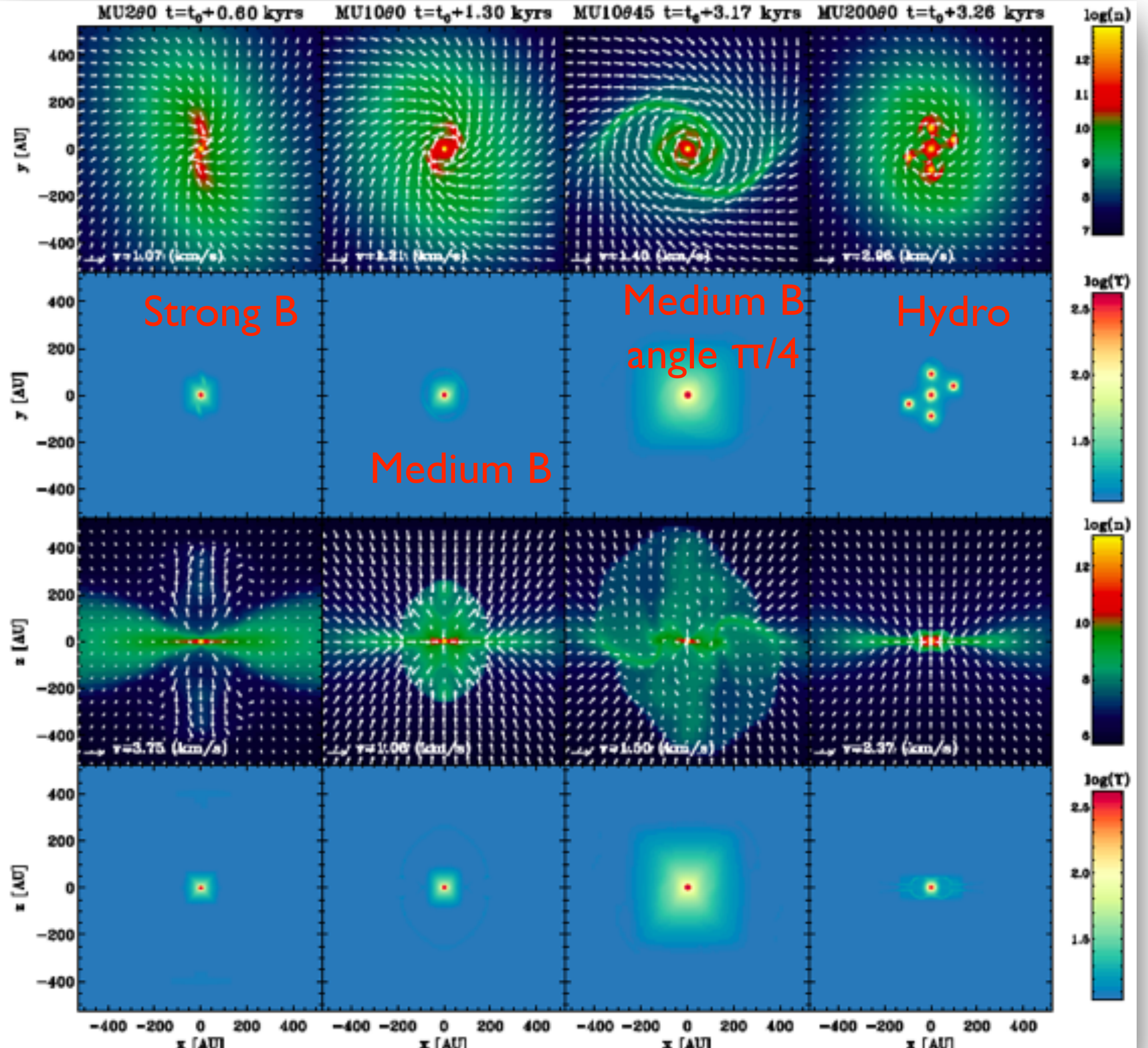

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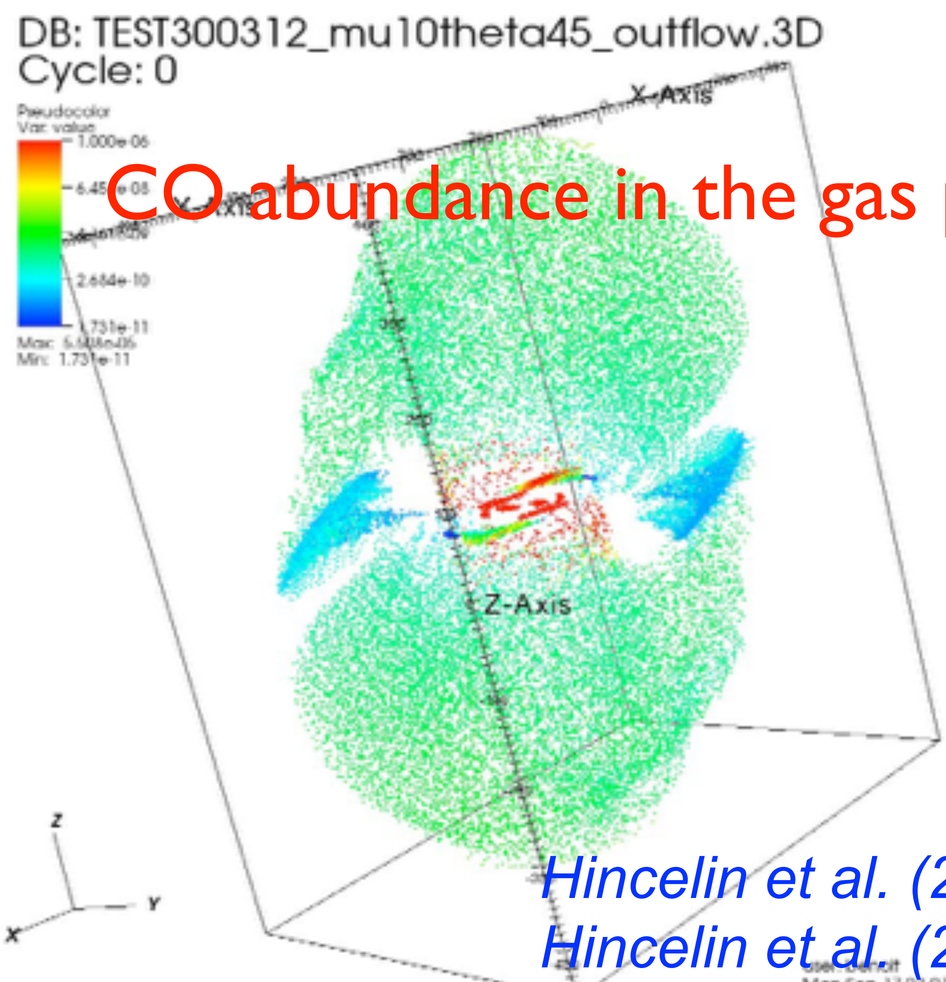
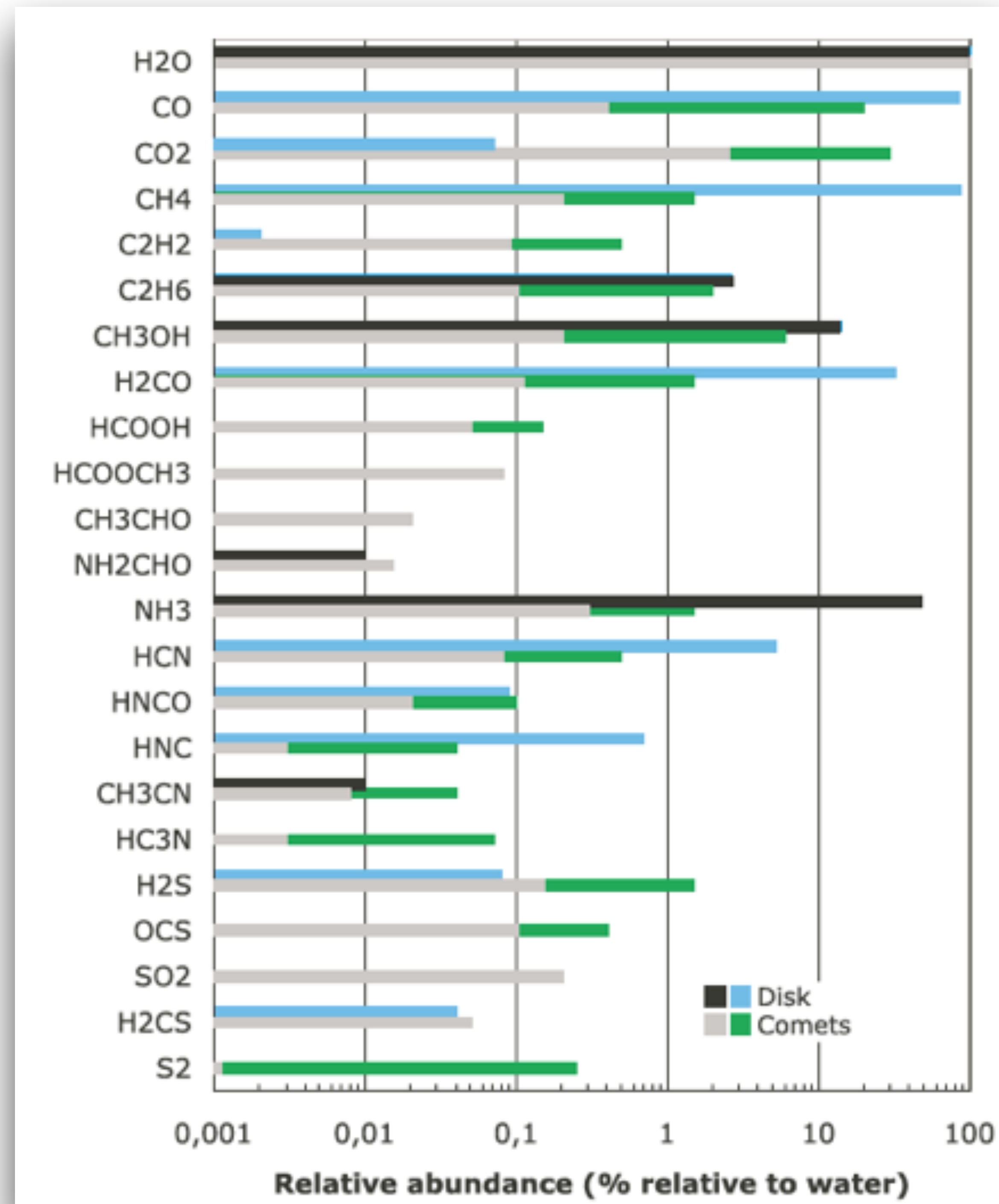


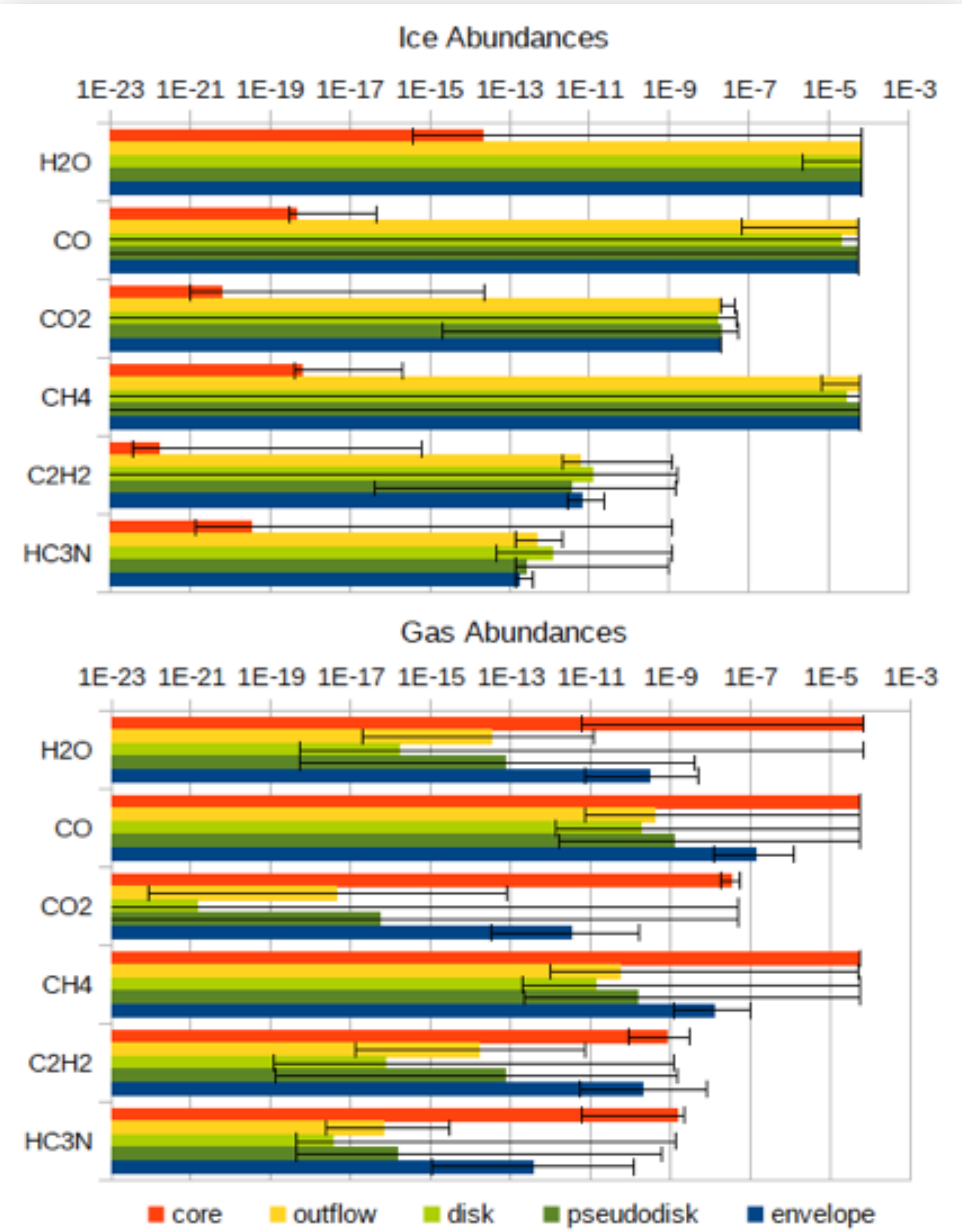
CO abundance in the gas phase

Hincelin et al. (2013)
Hincelin et al. (2016)

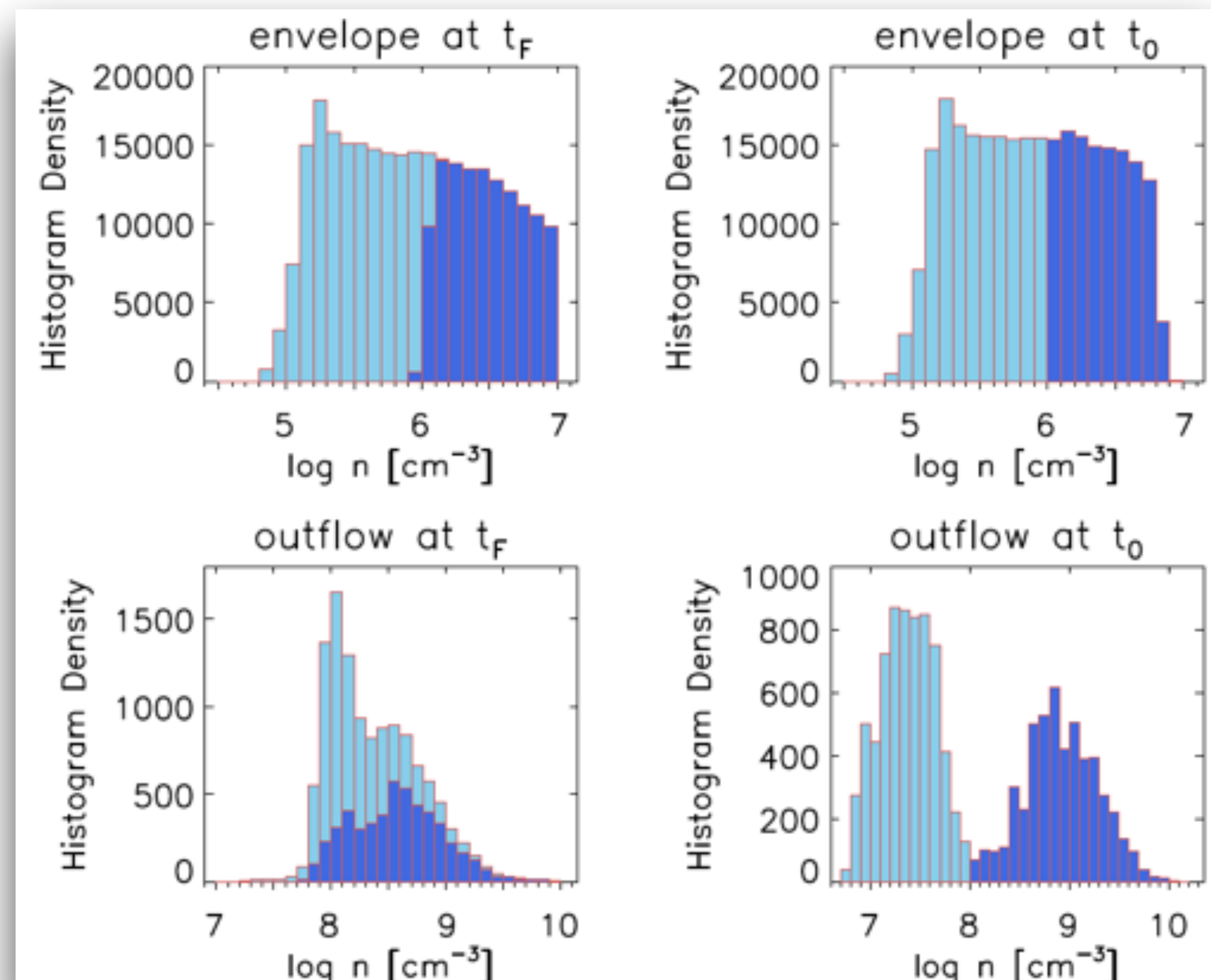


Dynamical chemical evolution w tracer particles

- **total abundance (gas+ice)** unchanged from the parent cloud to the disc;
- **mixing** of particles with **different histories**;
- **tracers identification** of the different **components**: core, disc, pseudo-disc, outflow, and envelop



Hincelin et al., 2016
see also Ruaud et al.



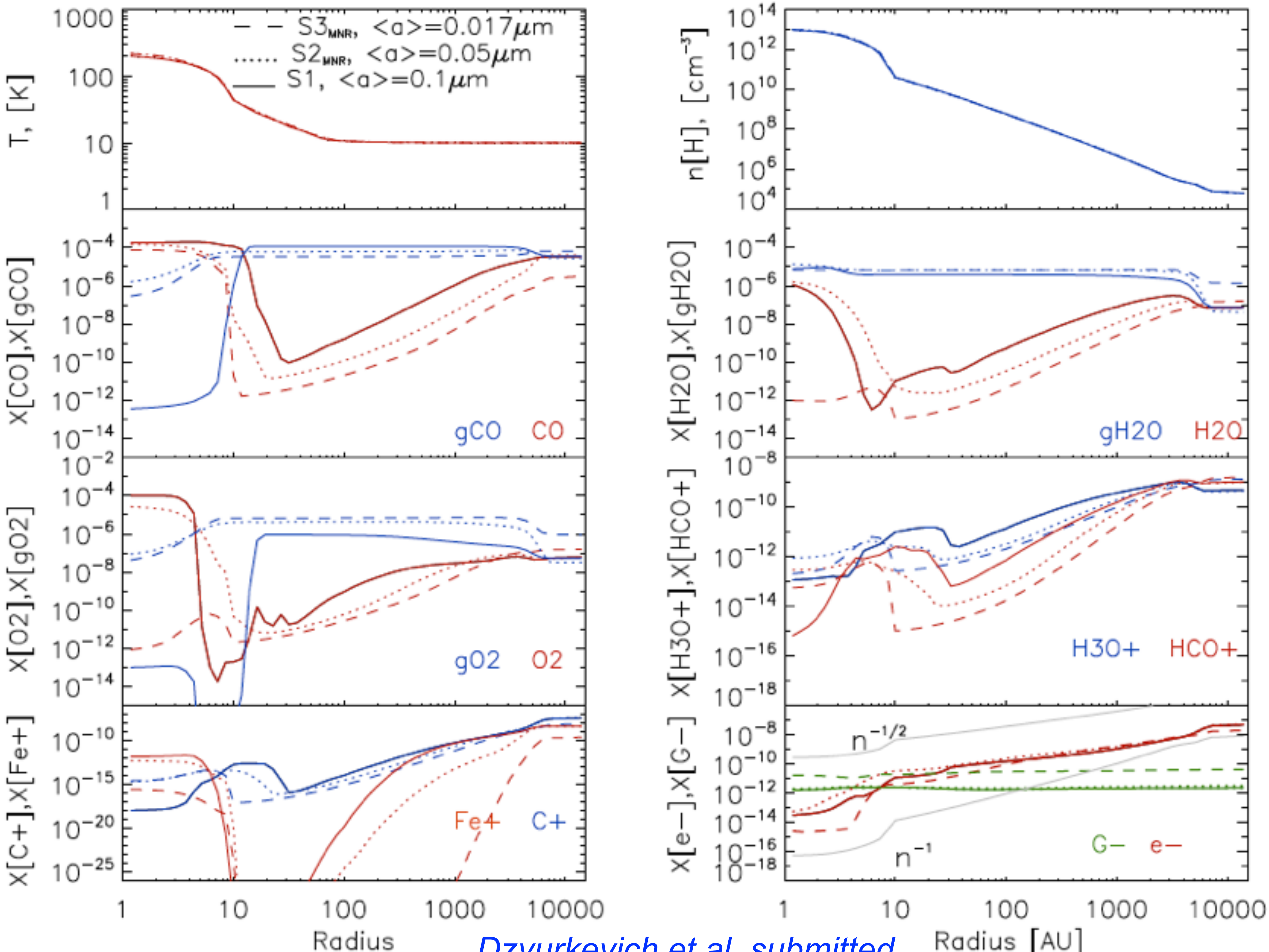
Chemo-dynamical models

- reduced chemical network designed for H-C-O chemistry, from the **CHOC_STAT** code (*Lesaffre, Pineau des Forets, Flower et al.*)
- chemical species are advected in **RAMSES** and chemistry is solved after each hydro timestep
- no retroaction of the chemistry on the dynamics yet…
- N=56 species (51 + 5 for the dust core refractory material)
- ~230 reactions: gas-phase, recombination, photodissociation and ionisation, CR desorption and ionisation, gas-grain interaction (adsorption, desorption, charge transfer)

Neutral species														
H	H_2	He	C	CH	CH_2	CH_3	CH_4	O	O_2	OH	H_2O	CO	CO_2	Fe
Ionized species														
H^+	H_2^+	H_3^+	He^+	C^+	CH^+	CH_2^+	CH_3^+	CH_4^+	CH_5^+	O^+	O_2^+	OH^+	H_2O^+	H_3O^+
CO^+	HCO^+	Fe^+												
Core species														
O^{**}	Si^{**}	Mg^{**}	Fe^{**}	C^{**}										
Mantle species														
H^*	H_2^*	He^*	C^*	CH^*	CH_2^*	CH_3^*	CH_4^*	O^*	O_2^*	OH^*	H_2O^*	CO^*	CO_2^*	Fe^*
Grains														
G	G^+	G^-												

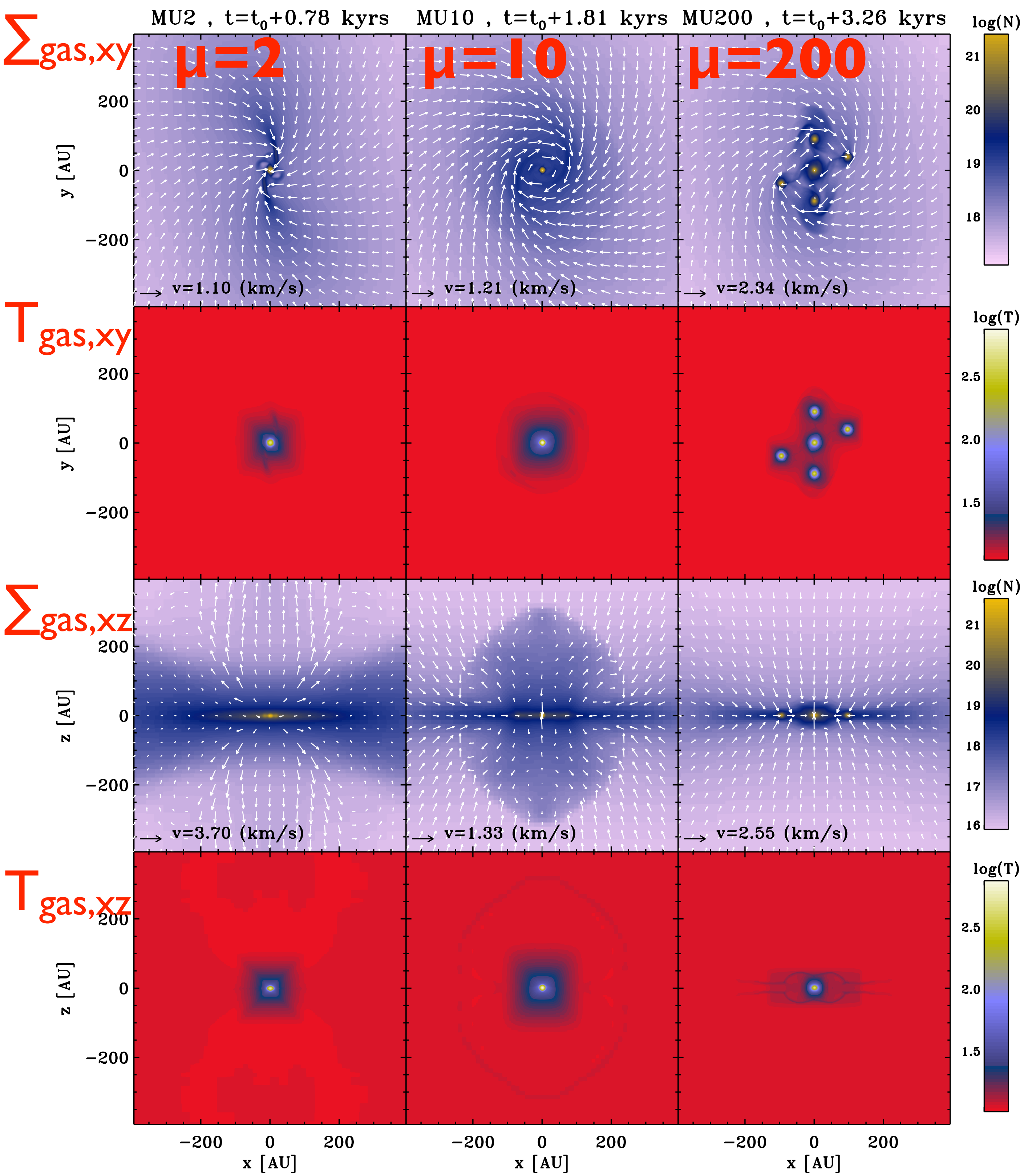
Dzyurkevich et al. submitted

Spherical collapse: effects of dust grain size



Dzyurkevich et al. submitted

Towards synthetic observations



- 3 representative cases
  - *MU2*: pseudo-disc + outflow
  - *MU10*: disc + pseudo-disc + outflow
  - *MU200*: disc + fragmentation

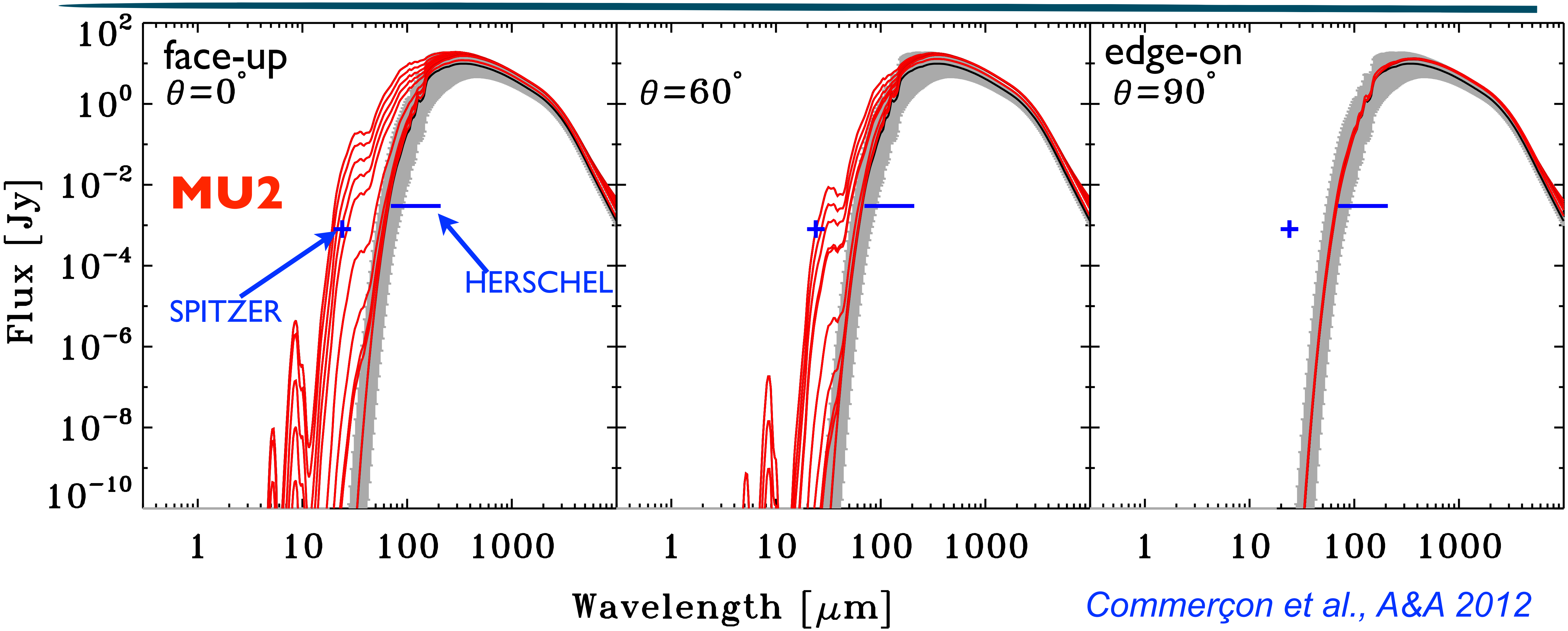
- First core lifetime:

MU2	*MU10*	*MU200*
1.2 kyr	3 kyr	> 4 kyr

- Images & SED computed with the radiative transfer code **RADMC-3D**, developed by C. Dullemond (ITA Heidelberg)
- $T_{dust} = T_{gas}$ (given by the RMHD calculations)

Commerçon, Launhardt, Dullemond & Henning, A&A 2012

SED - Do we see a first core signature?



Commerçon et al., A&A 2012

- *Objects at 150 pc, 3000 AU x 3000 AU region*
- *Prestellar core = initial conditions (black line)*
- Emission in the FIR => **HERSCHEL, SPITZER**
- But similar SEDs in the MU200 model, i.e. **with a disc**!

=> Issues in SED-fitting models for early Class 0?

Help to select first core candidates & to distinguish starless cores and first cores

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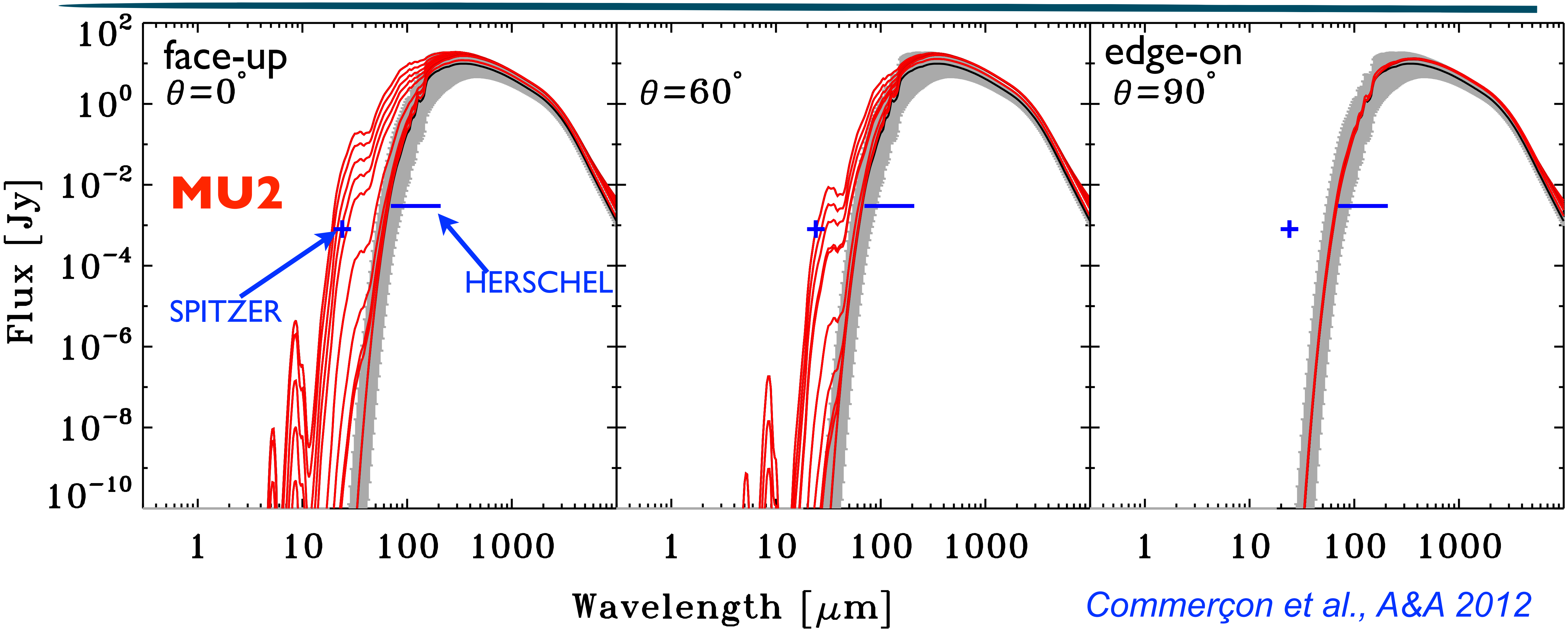

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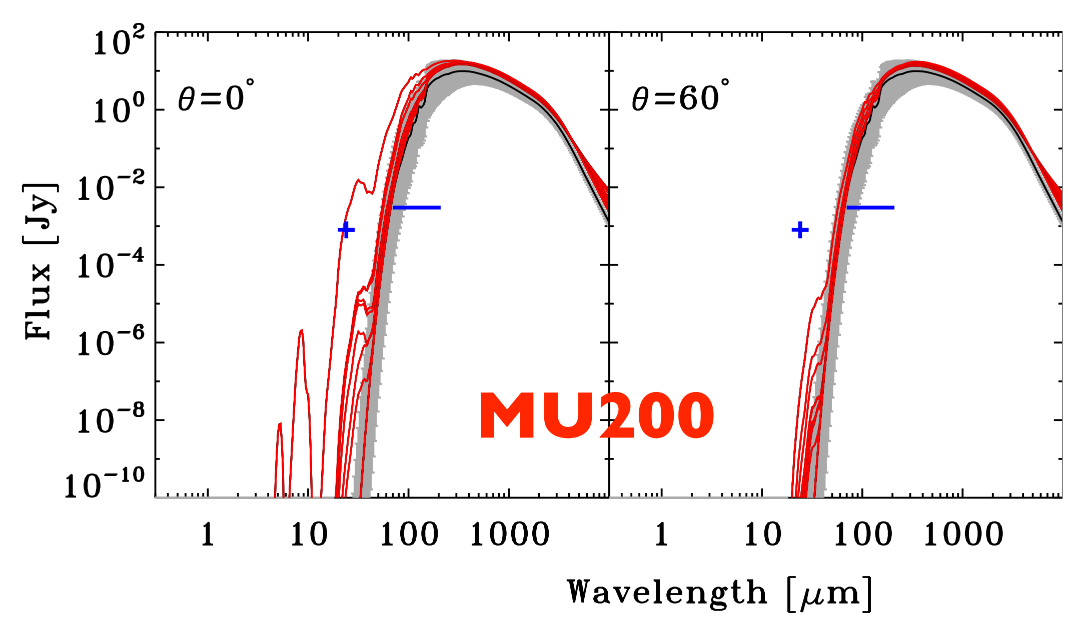
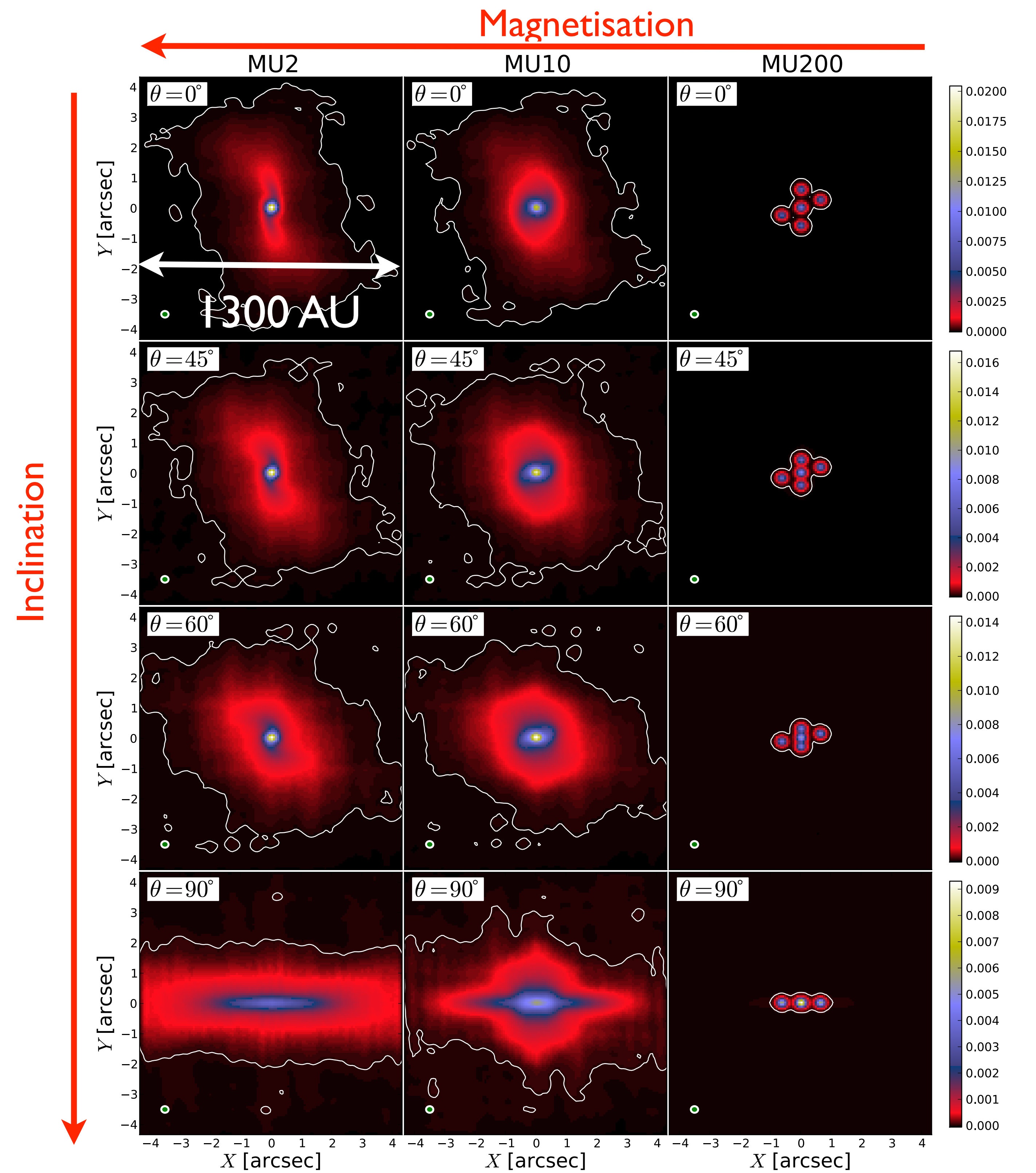


Synthetic ALMA dust emission maps

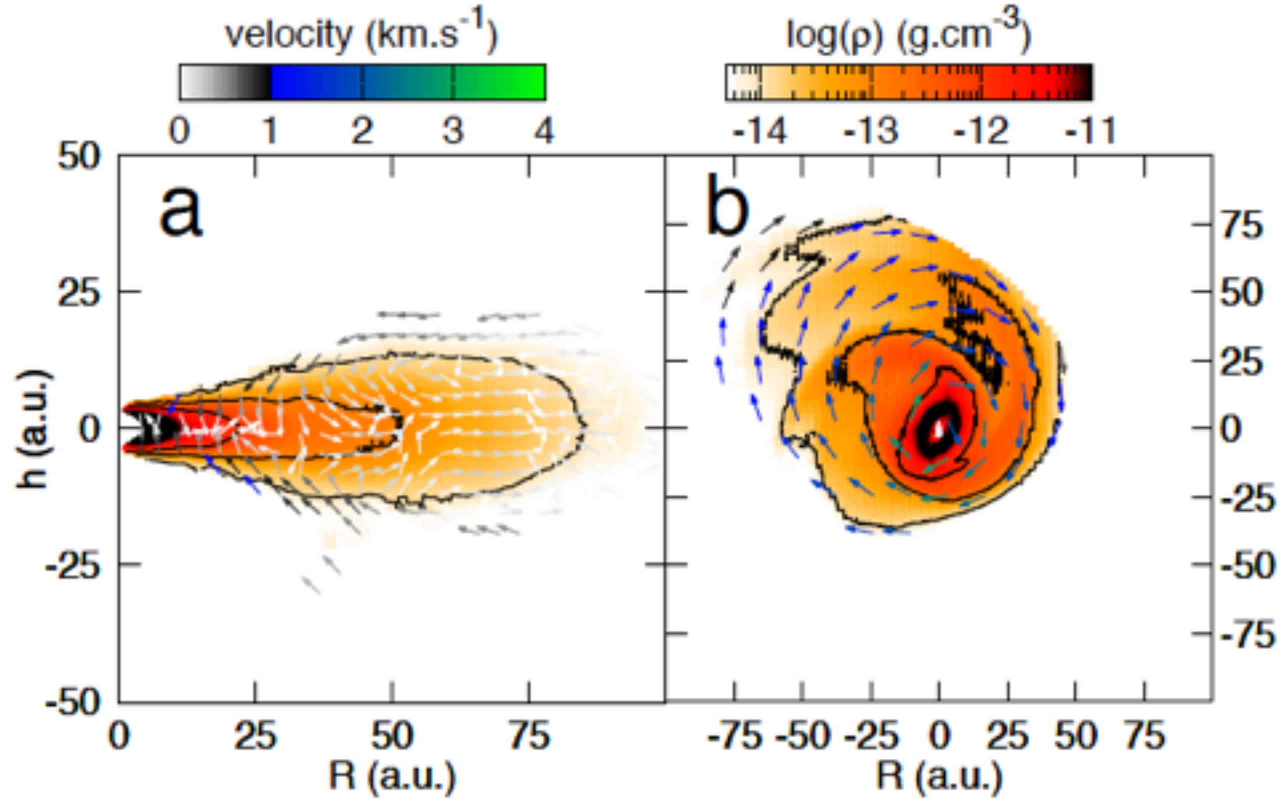
ALMA Band 3 Config 20 @150 pc

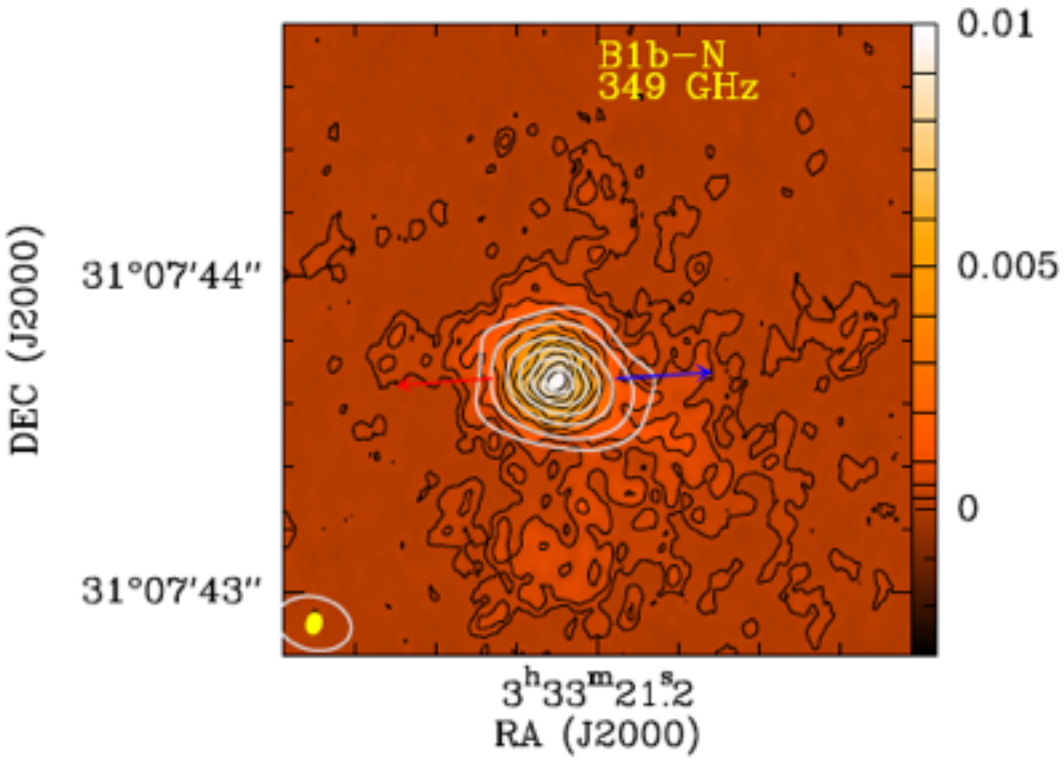
Commerçon, Levrier et al. A&A, 2012

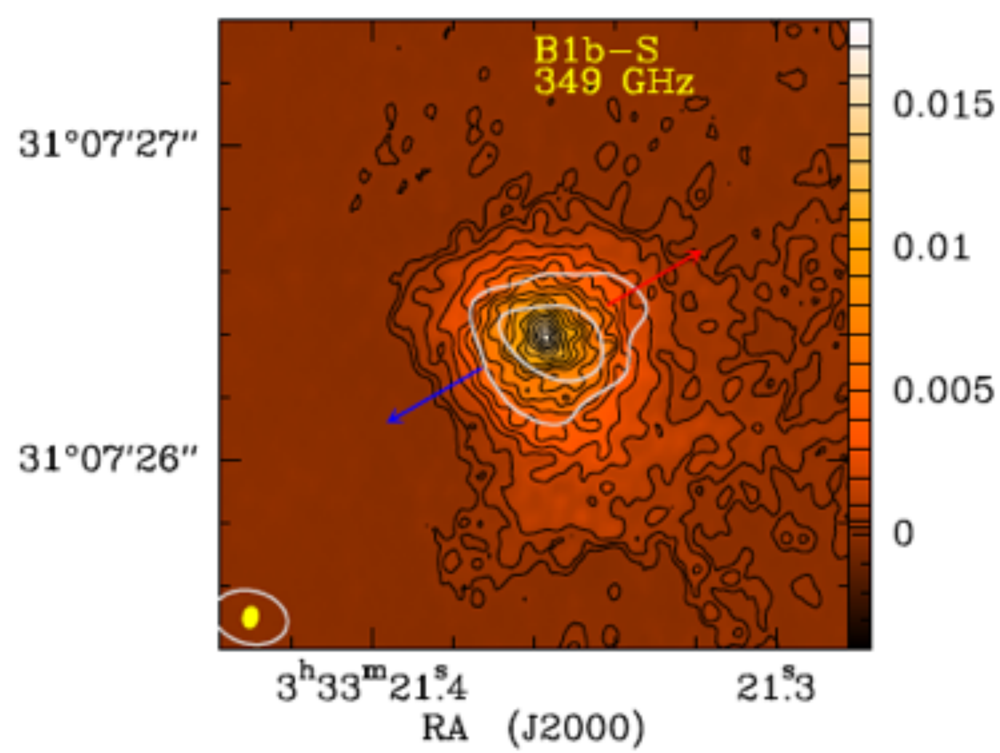


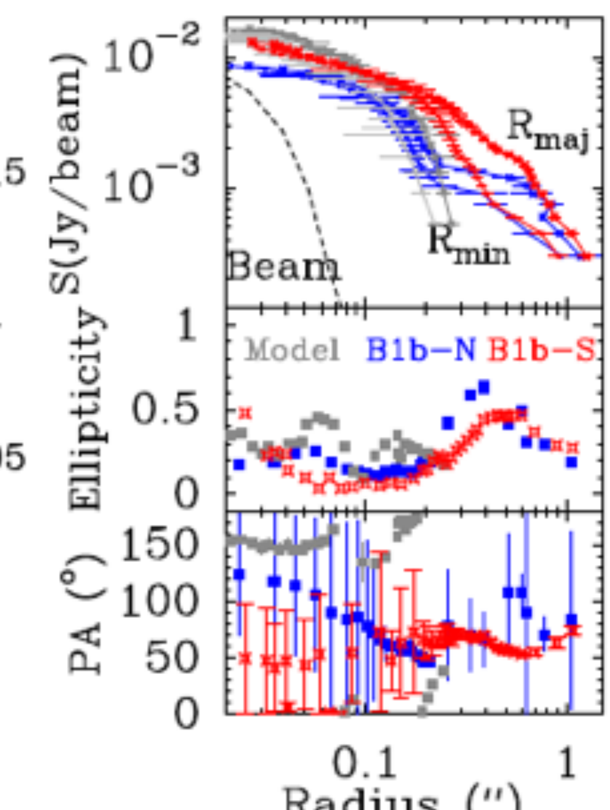
Comparison with real ALMA observations

- Source Barnard 1b-N: first core candidate
- ALMA 0.06'' @ 350 GHz (~15 AU)
- data compatible with collapse model ($\mathscr{M}$=1.2 ; μ=2)
- data compatible with disc growth with time







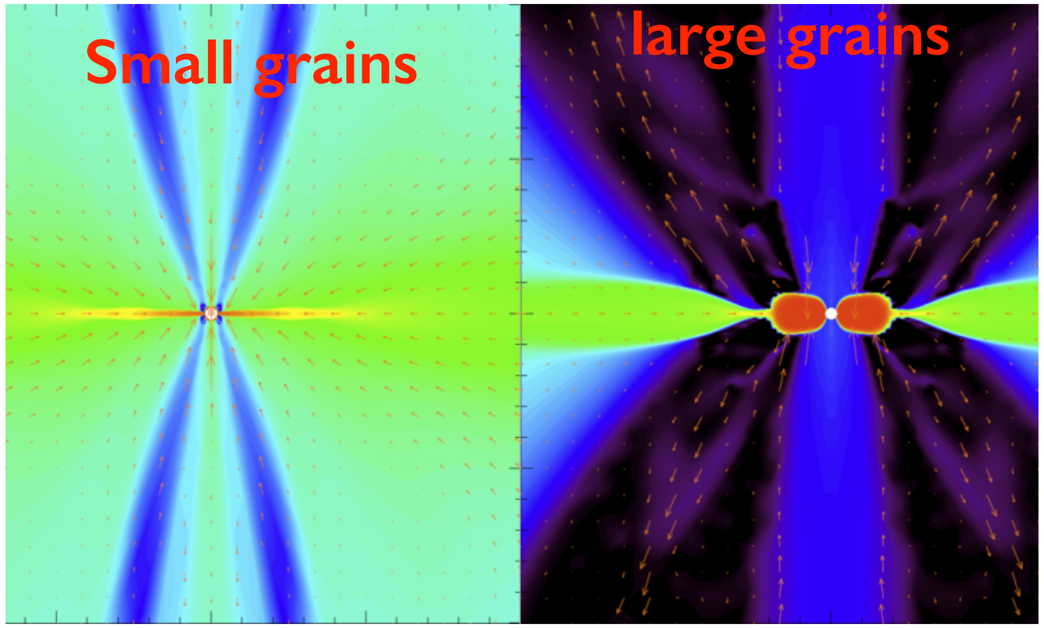


Gérin et al. A&A, subm.

What is next?

- **Follow the dust dynamics at all scales**
  - dust growth
  - dust charge
  - gas-to-dust ratio

Zhao et al (2016)



- **Couple the process**
  - magneto hydrodynamics: chemistry + dust + magnetic resistivities
  - radiation hydrodynamics: chemistry + dust + opacities
  - track cosmic rays ionisation
  - inclusion more feedback processes (jets, wind, CR acceleration)

- **Couple the scales**
  - galaxy evolution to molecular clouds (e.g., Renaud et al. 2013)
  - self-regulated ISM, from diffuse ISM to collapsing dense cores (Hennebelle et al.)
  - protoplanetary disc evolution with accreting envelop

Take away

We are getting closer, but….

- large uncertainties on gas-grain chemistry for ionisation
- coupling with magnetic fields poorly constrained
- dust evolution?
- second Larson core: a challenge for computational astrophysics

What we need:

✓ constraints on the dust
✓ systematic parameter studies
✓ synthetic observations: dust, line emission, polarisation

THANK YOU

Astrosim school