The Early Phases of Disc Formation and Disc Evolution

modelling prospective

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Topics

- Angular momentum
- Fragmentation
- Disc-envelope evolution

Initial angular momentum of cores

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

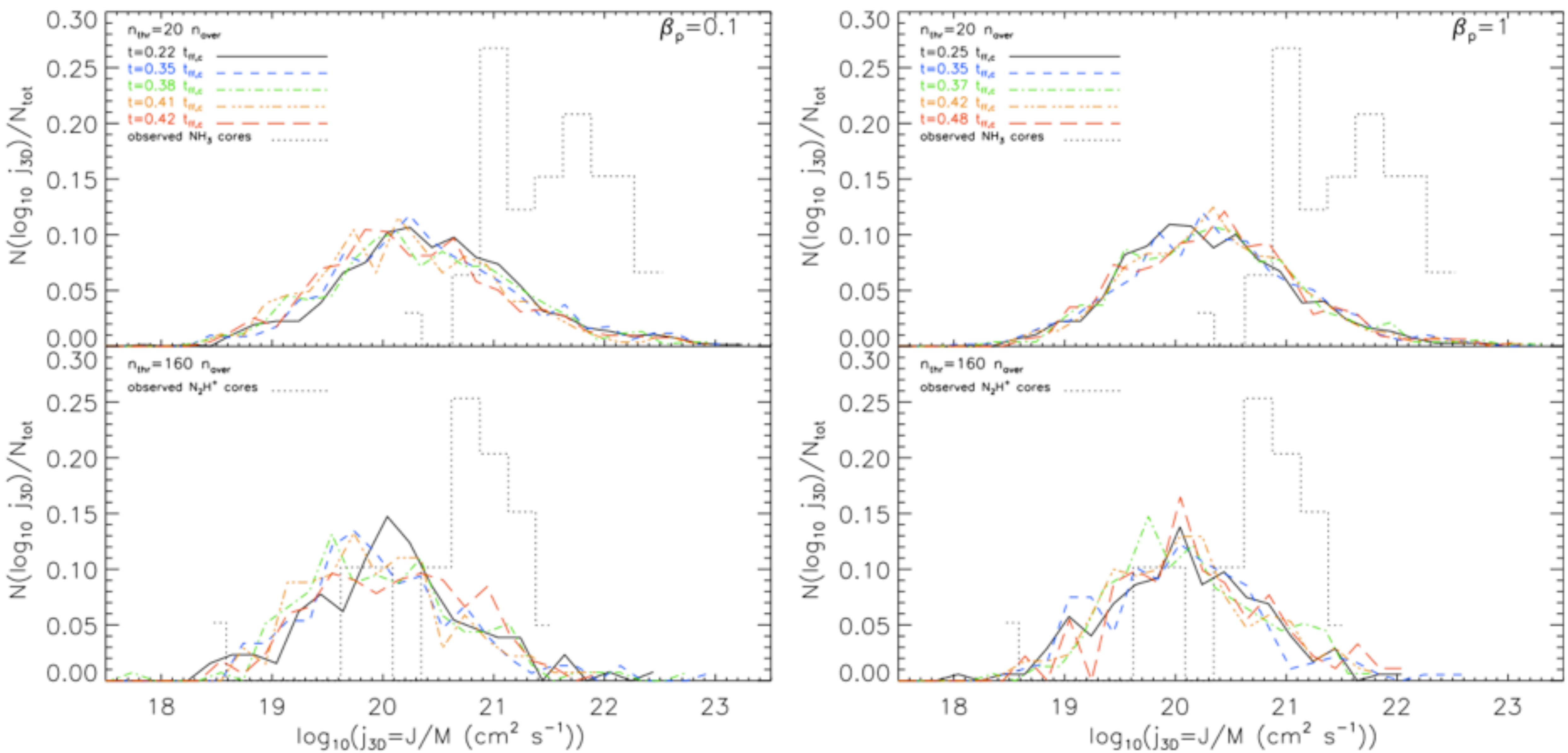
  $$\Omega \sim 10^{-14} - 10^{-13}\ \mathrm{s}^{-1}$$
  $$\Longrightarrow j \sim 10^{21}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$$
  $$\Longrightarrow \beta \sim 0.03 \propto (t_{ff}\,\Omega)^2$$

  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

- Solution: Magnetic Fields
  magnetic braking (*Mouschovias & Paleologou, 1980*)

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Magnetic Fields
$\Longrightarrow$ the mysterious helper for everything?

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Magnetic Fields
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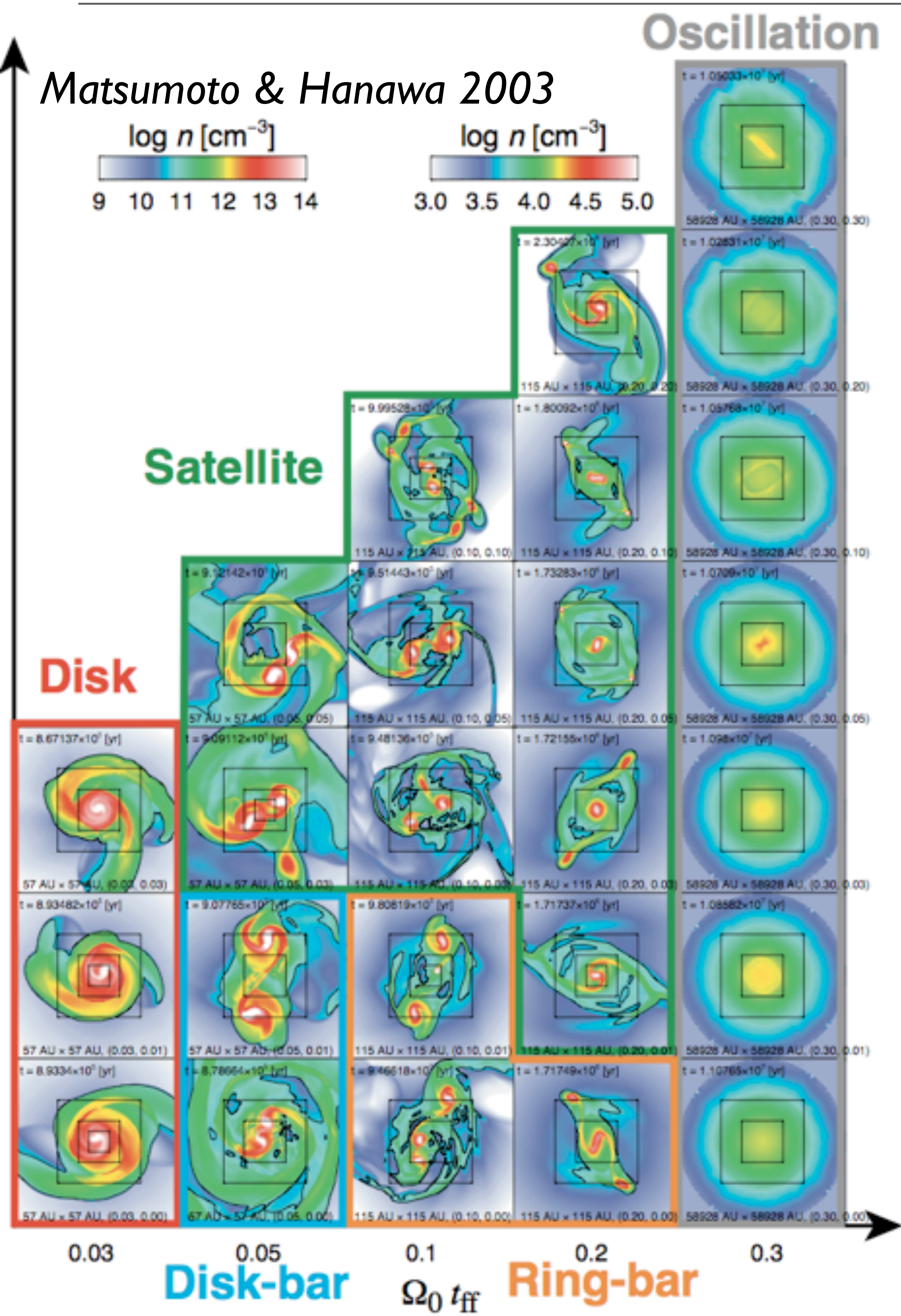
don't ignore Gravitational Torques

Angular Momentum Problem I



The pure hydro cases

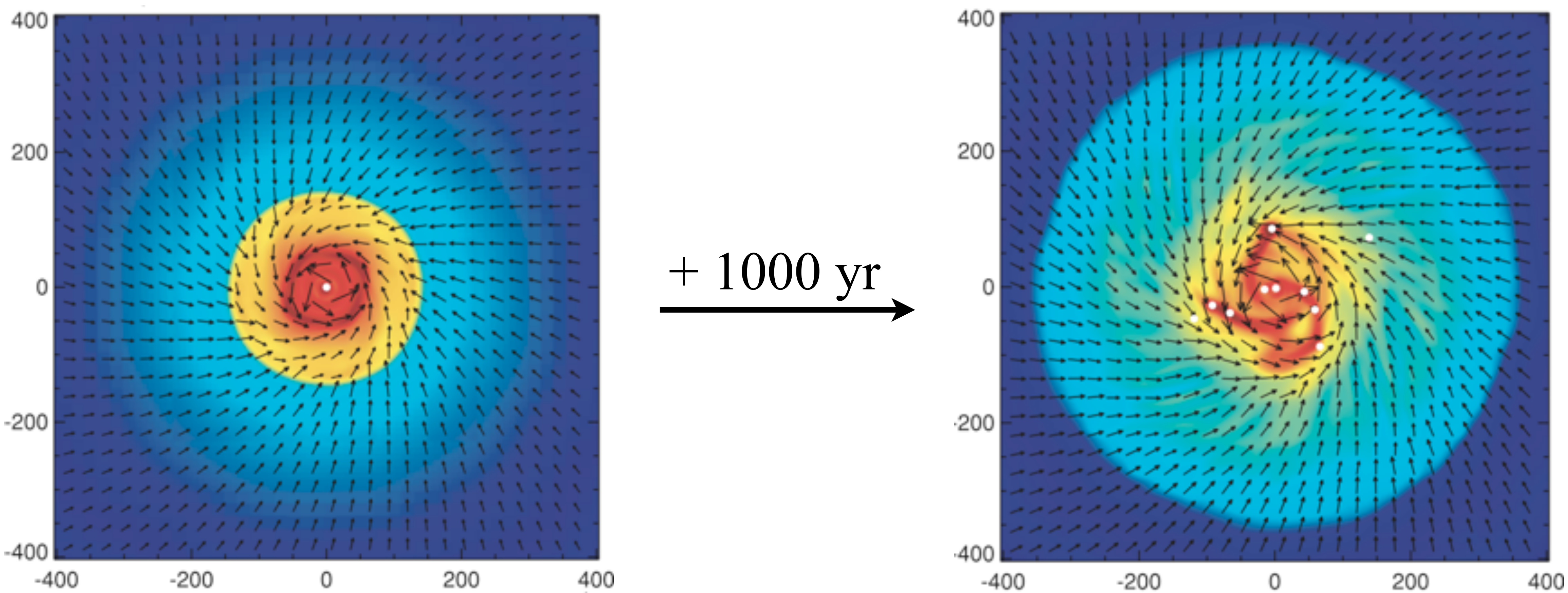
(e.g. Burkert & Bodenheimer 1993, Matumoto & Hanawa 2003, Krumholz et al. 2007, Stamatellos & Whitworth 2009, ...)

$\Longrightarrow$ 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

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

see also: Allen et al. 03, Matsomoto & Tomisaka 04, Machida et al. 05, Hennebelle & Fromang 08, Kuiper 11, Commercon et al. 10, Rosen et al. 12, ...

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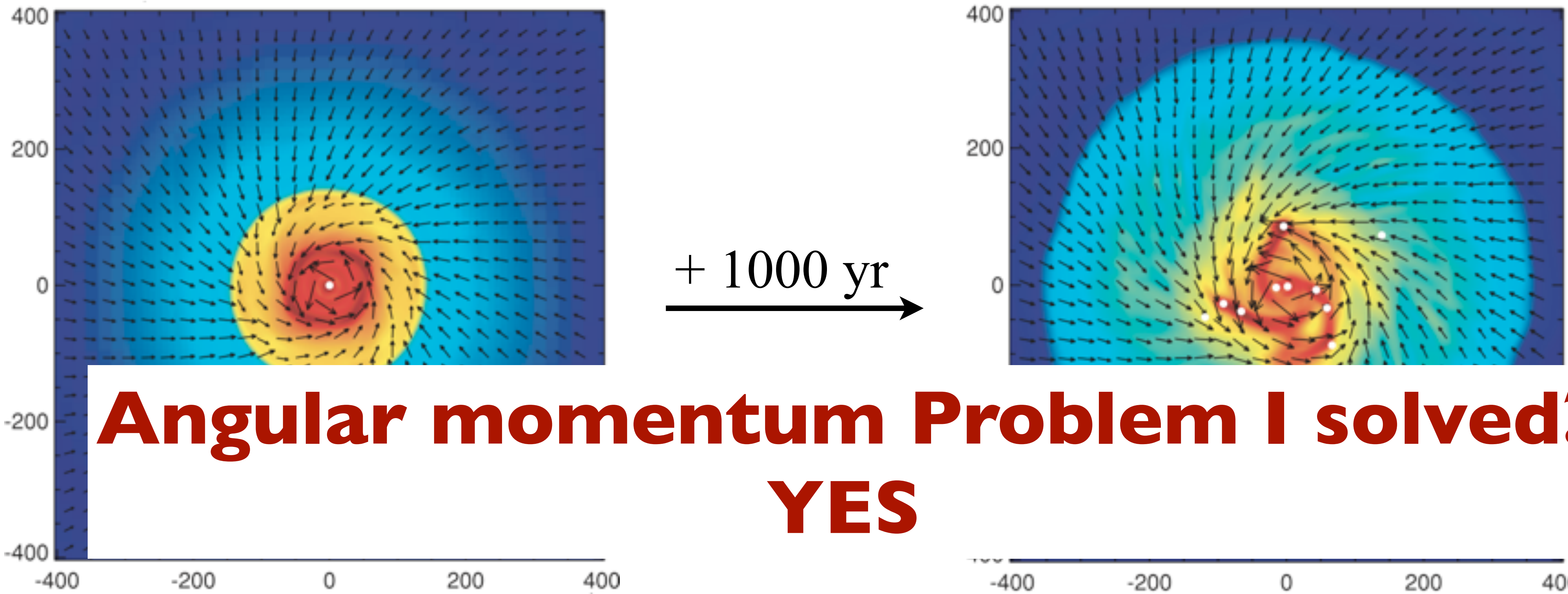

Angular momentum Problem I solved?
YES

Seifried et al. 2011

⟹ efficient transport of angular momentum
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⟹ disc formation & high accretion rates $\sim 10^{-4}\ M_\odot/\mathrm{yr}$

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Angular Momentum Problem II

Collapse of magnetised, rotating cloud cores

- **stronger** magnetic fields: $\mu < 5$ in agreement with observations

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

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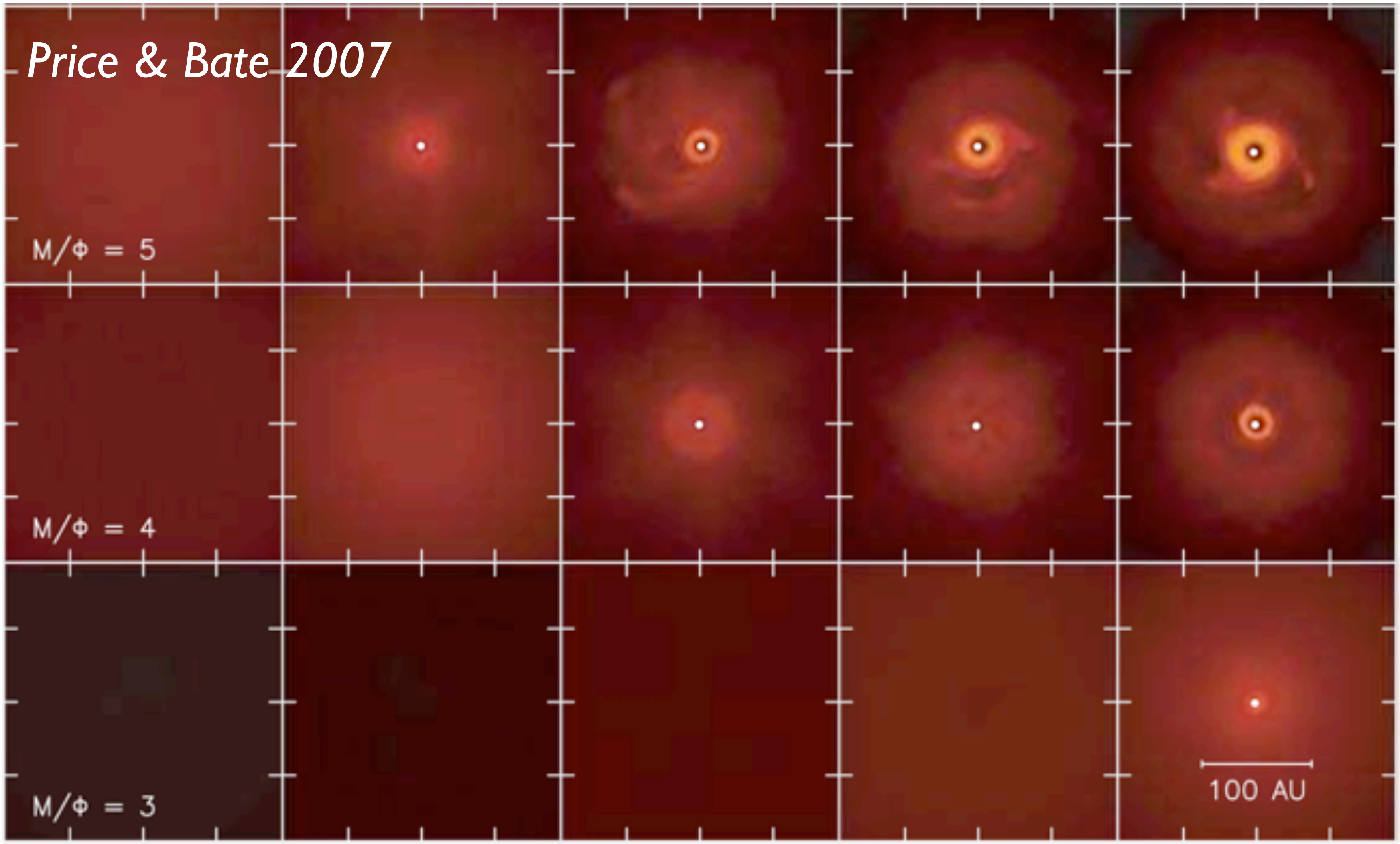

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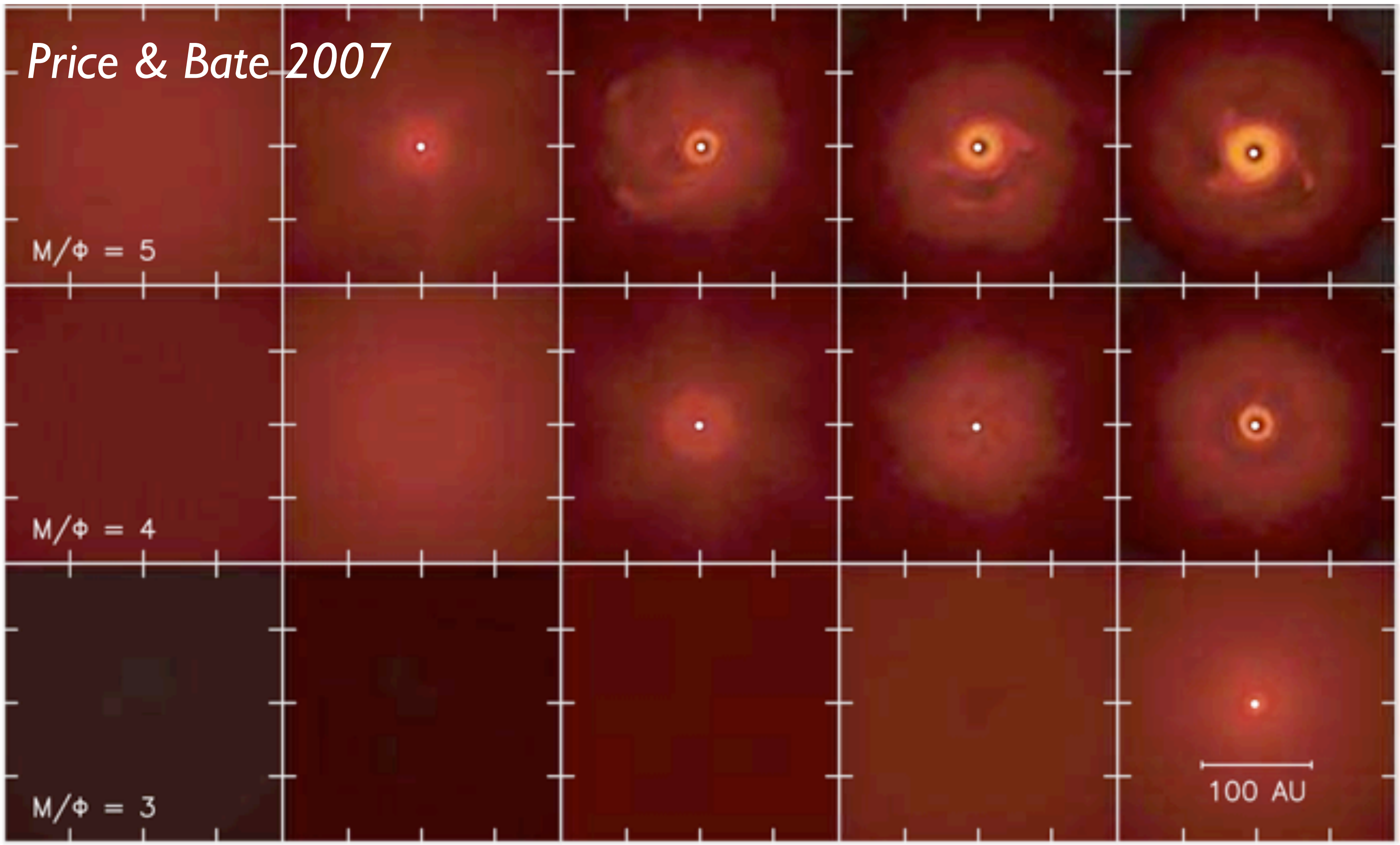

see also: Allen et al. 2003, Hennebelle & Teyssier 2008, Li et al. 2011, Seifried et al. 2011, ...

⟹ *too* efficient magnetic braking

⟹ *no* disc formation

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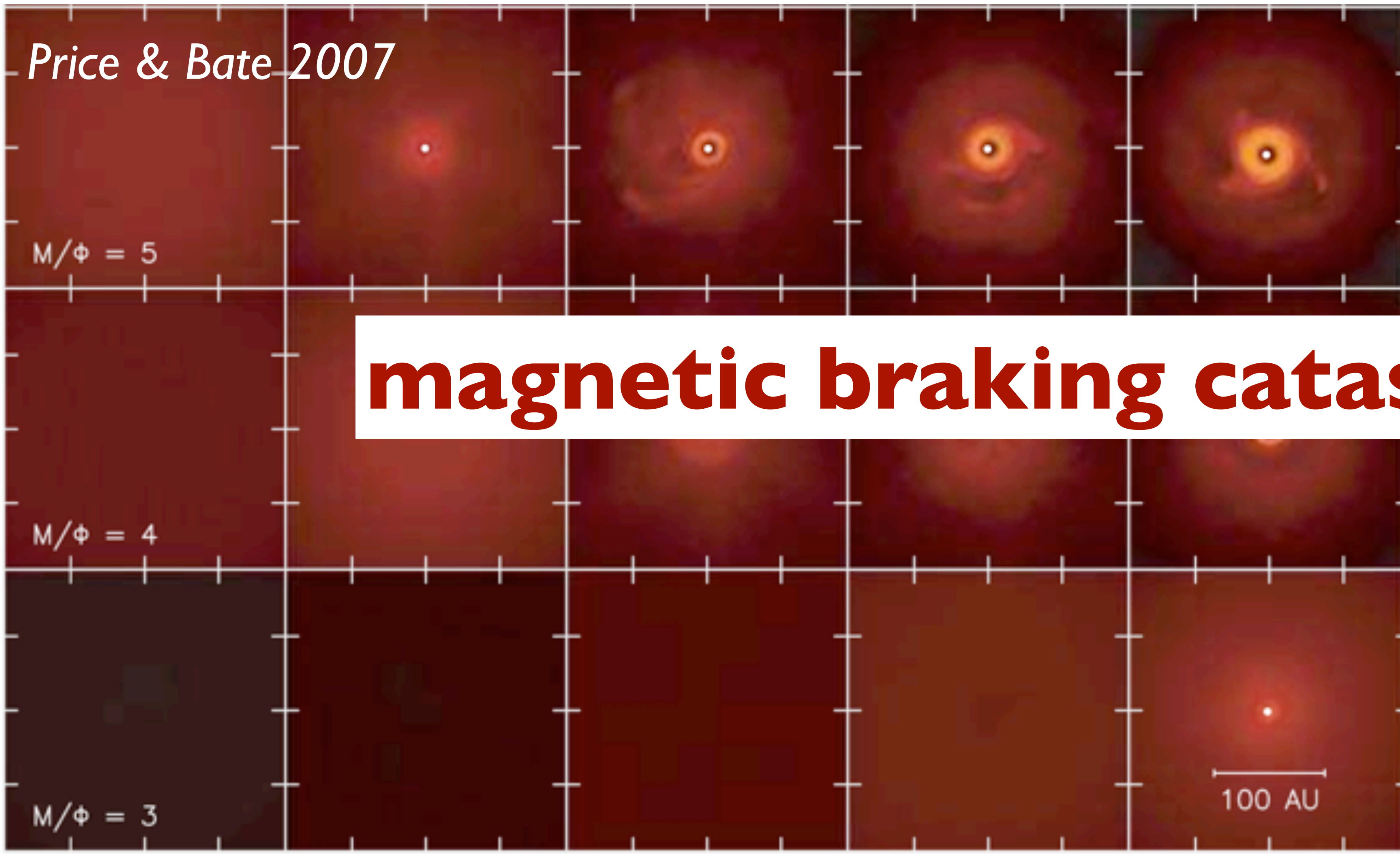


magnetic braking catastrophe?

see also: Allen et al. 2003, Hennebelle & Teyssier 2008, Li et al. 2011, Seifried et al. 2011, ...

$\Longrightarrow$ *too* efficient magnetic braking

$\Longrightarrow$ *no* disc formation

Angular Momentum Problem II

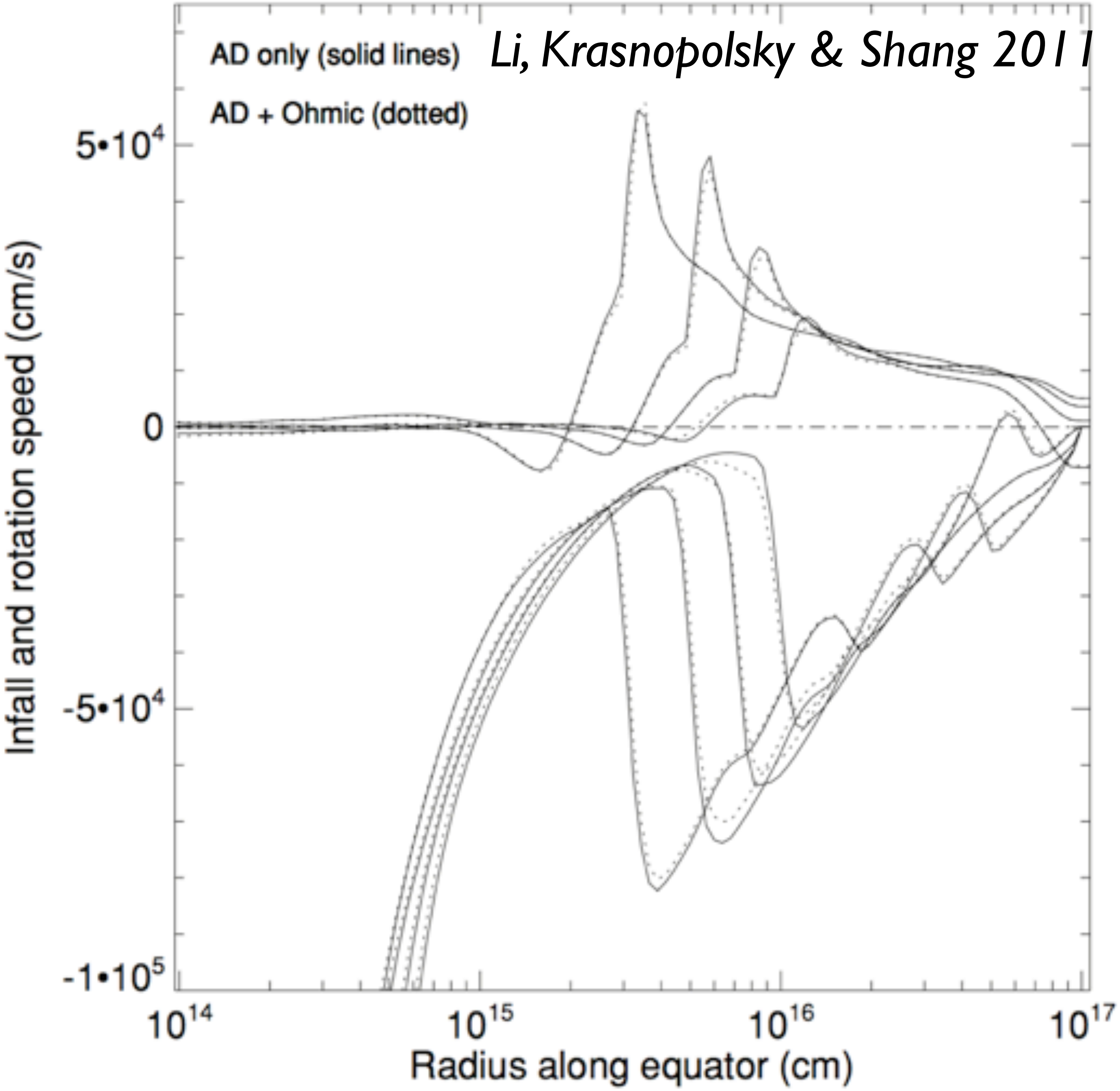
Solutions?

- 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, see also Poster 16)
- Hall effect (Krasnopolsky et al. 2011)
- Outflows from small discs (Zhi-Yun Li's talk)

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

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

Angular Momentum Problem II

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Solution: Turbulence

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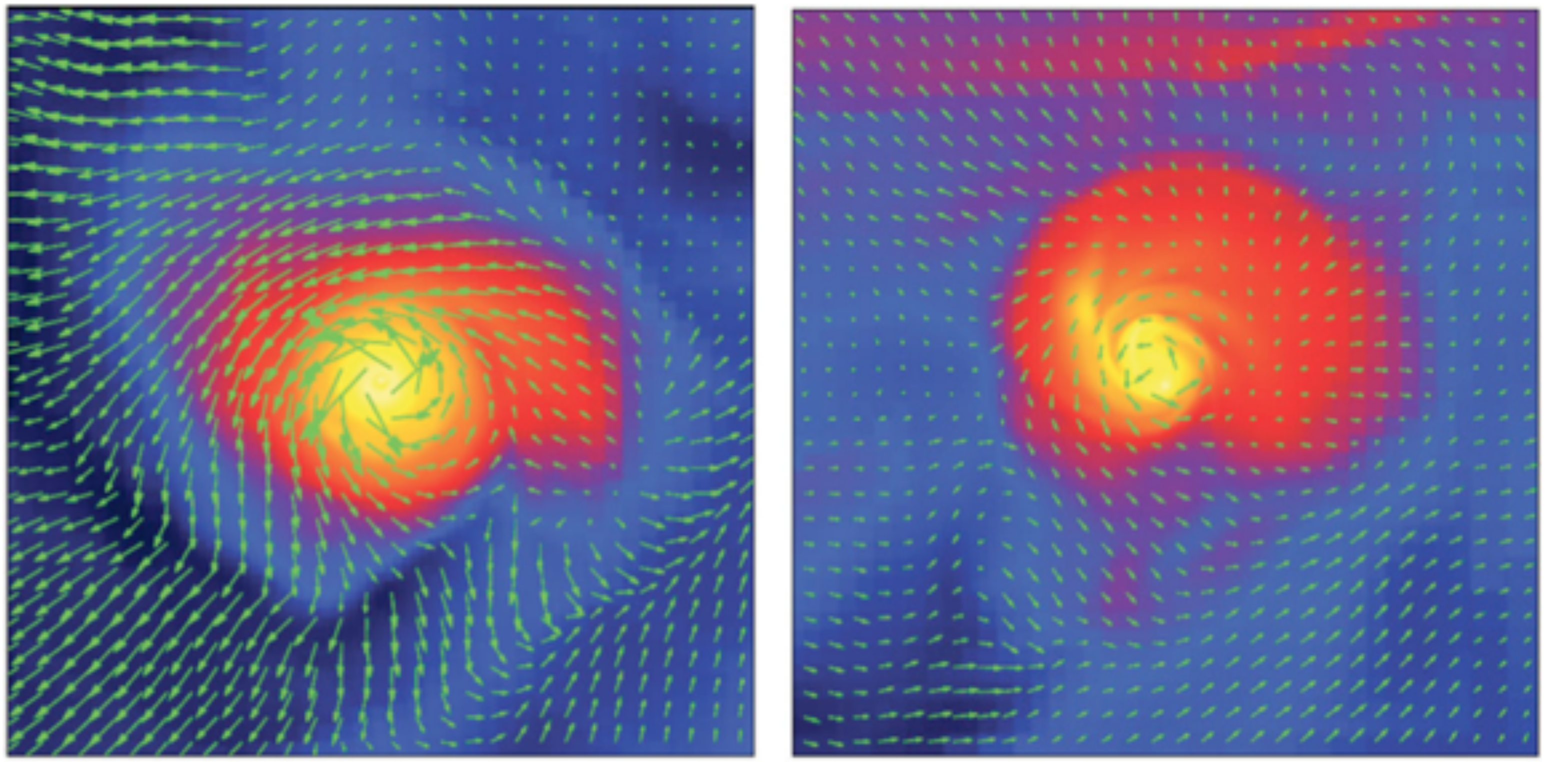
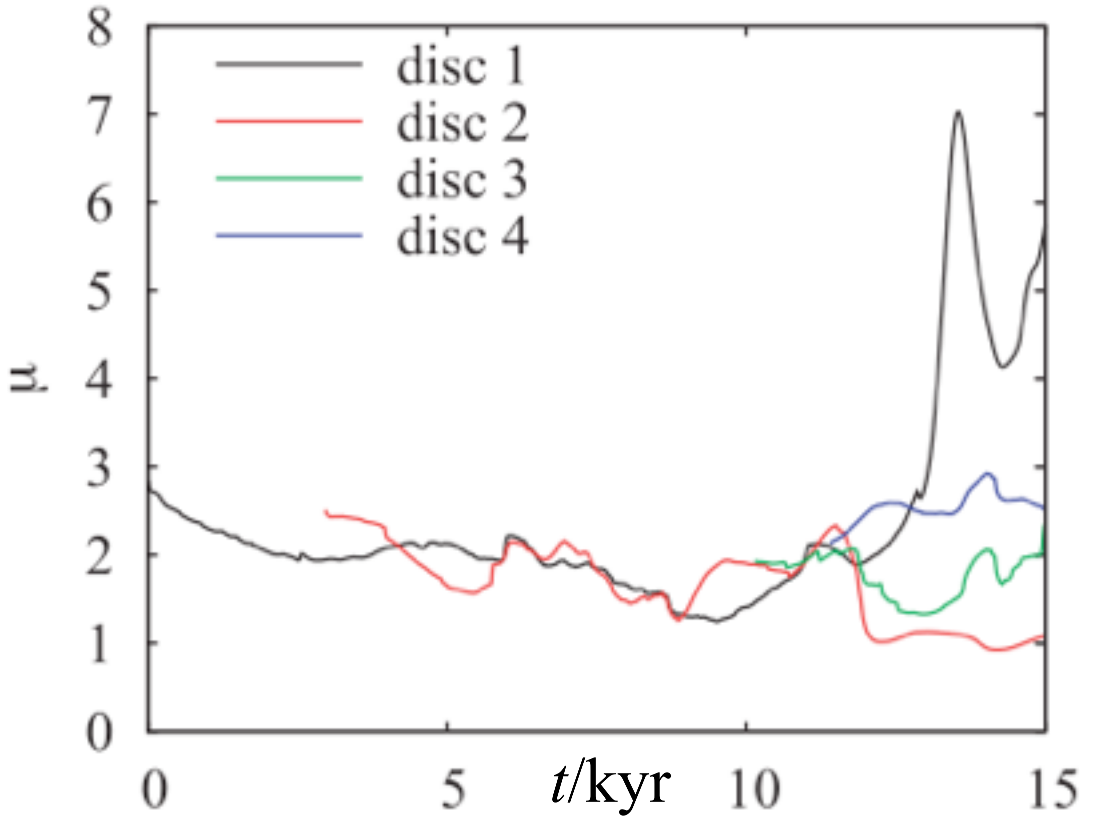
$\Longrightarrow$ the other mysterious helper for everything?

Angular Momentum Problem II

Solution: **Turbulence**



Seifried, RB, Pudritz, Klessen 2011, see also Daniel's Poster 26



- large, replenished local angular momentum by shear flows & filaments
- initial large-scale coherent field becomes distorted
- no flux loss

Fragmentation

- Key to generate binary & multiple systems: other mechanism (e.g. capture) seem to fail (e.g. Bodenheimer et al., PP IV 2000)

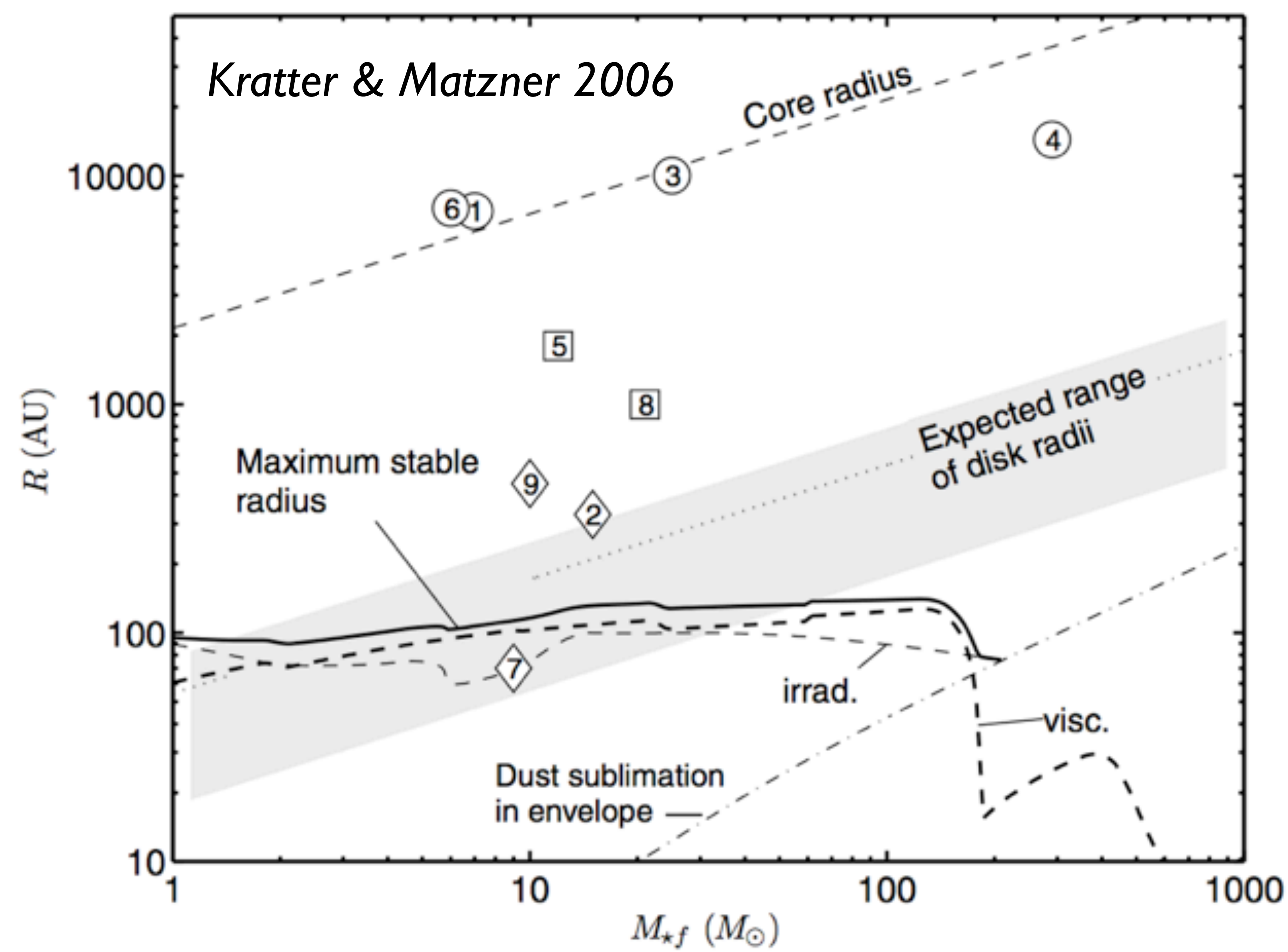
- What determines fragmentation, i.e Q_{Toomre}?

Fragmentation

Massive discs/massive star formation

- From one-zone calculations:

  $\Longrightarrow$ discs with R > 150 AU will fragmentation around stars with $M \sim 5\ \mathrm{M}_\odot$



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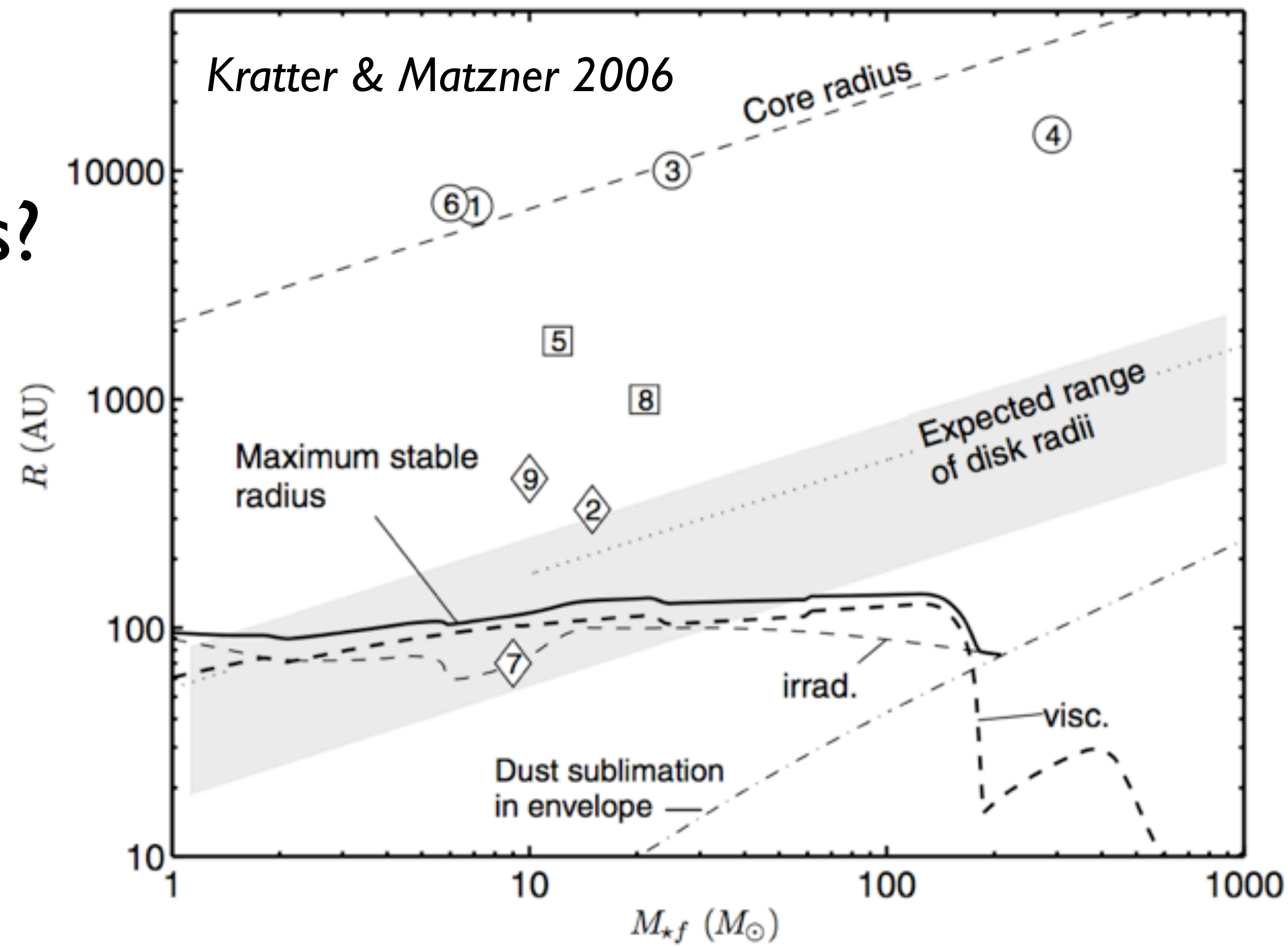
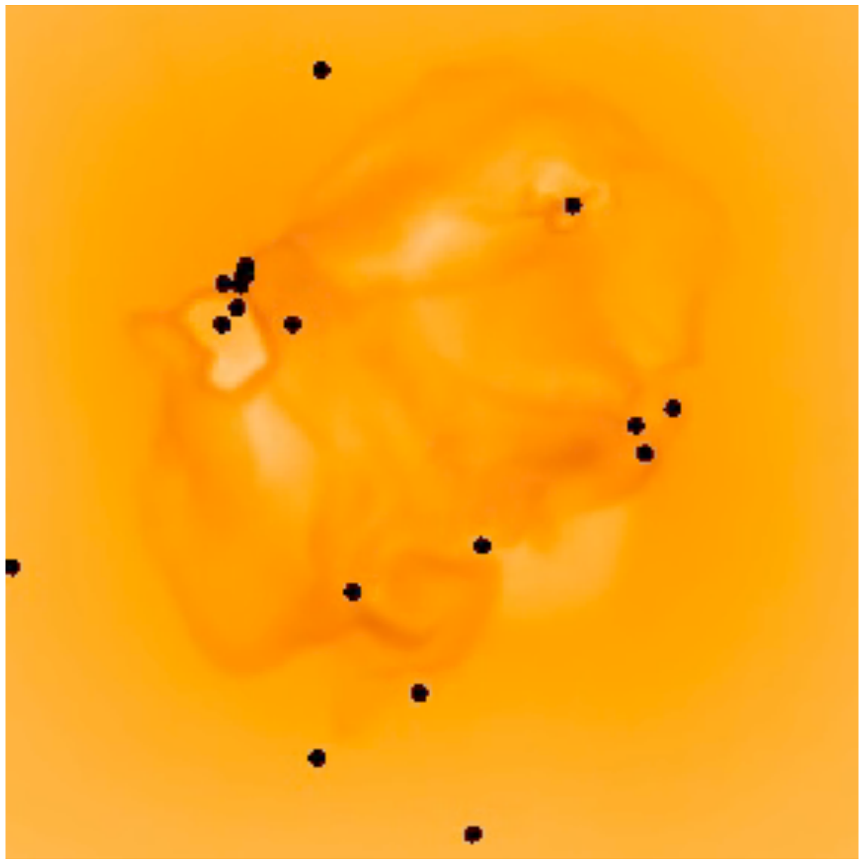
- how many fragments?
- binary/multiple fraction?

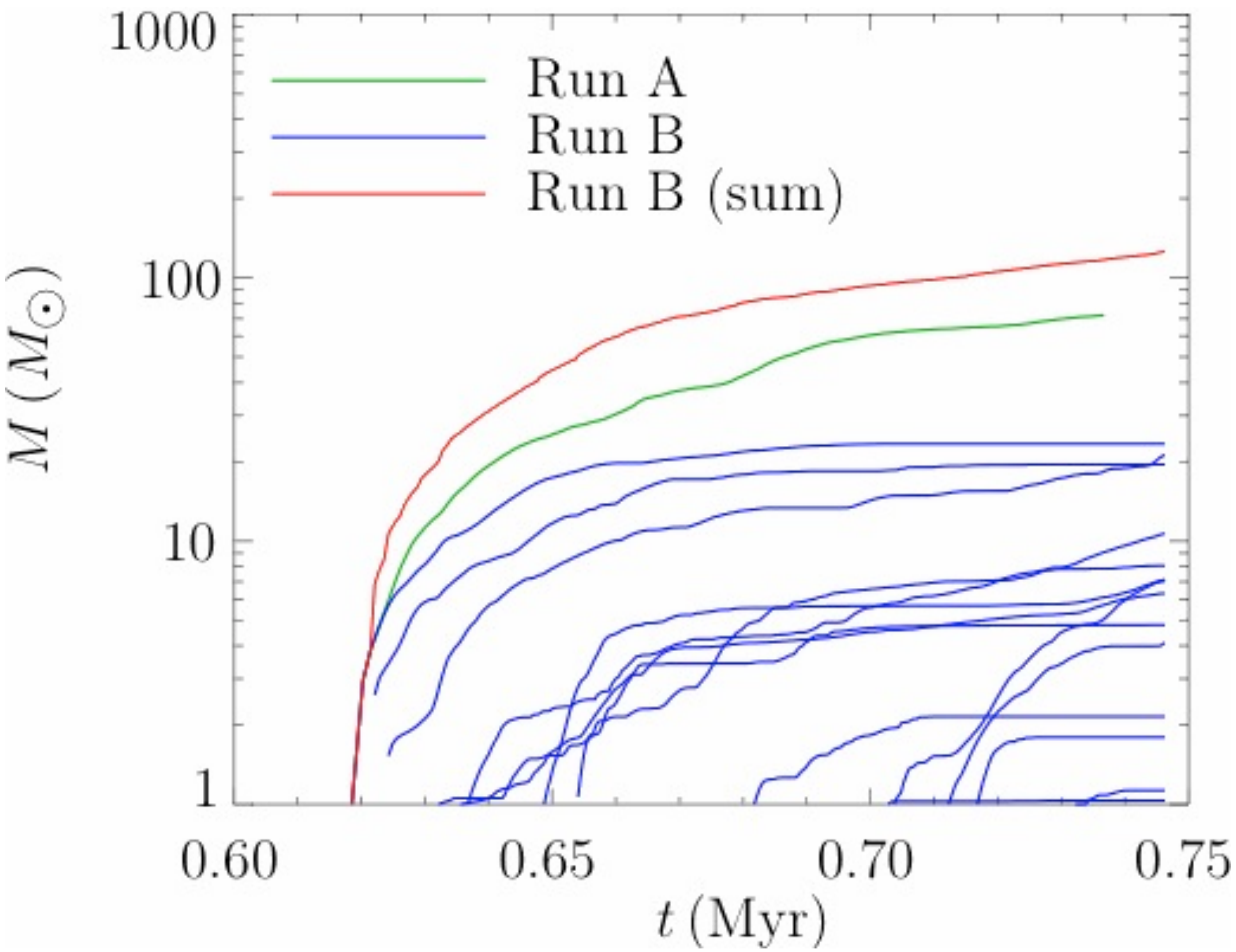


Fragmentation

Kratter & Matzner 2006: "Fragmentation may starve accretion in massive stars, especially above this limit, and is likely to create swarms of small, coplanar companions."



Peters et al. 2010

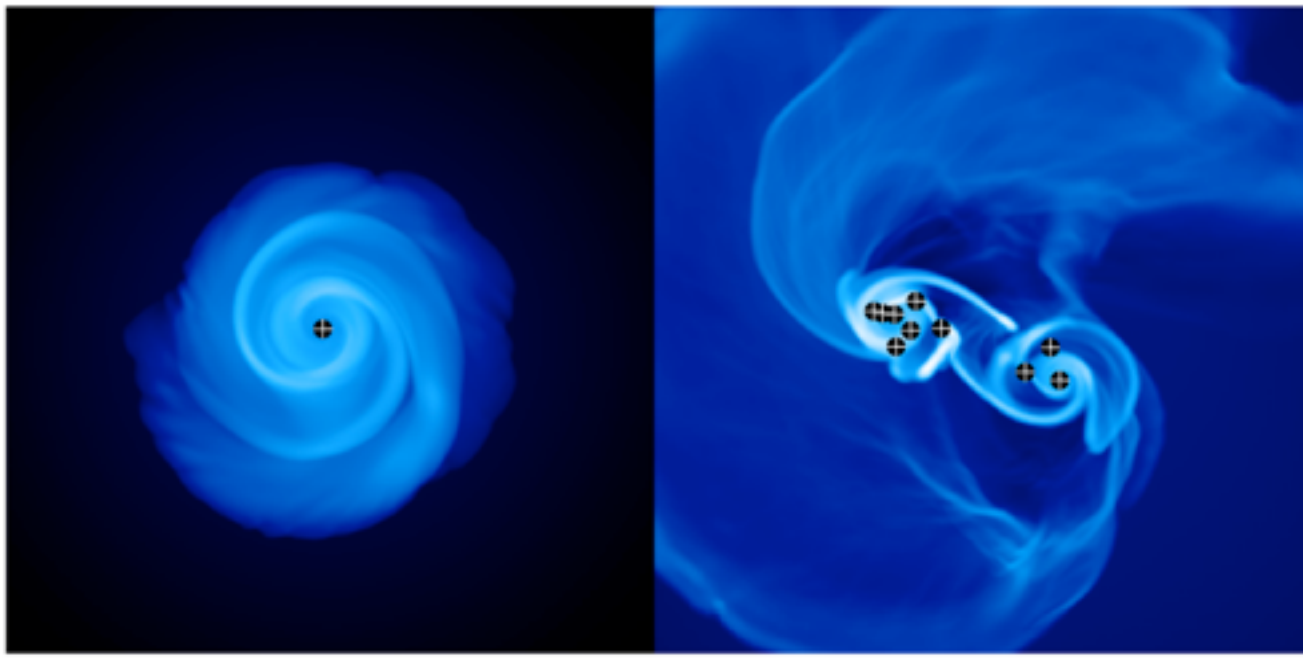


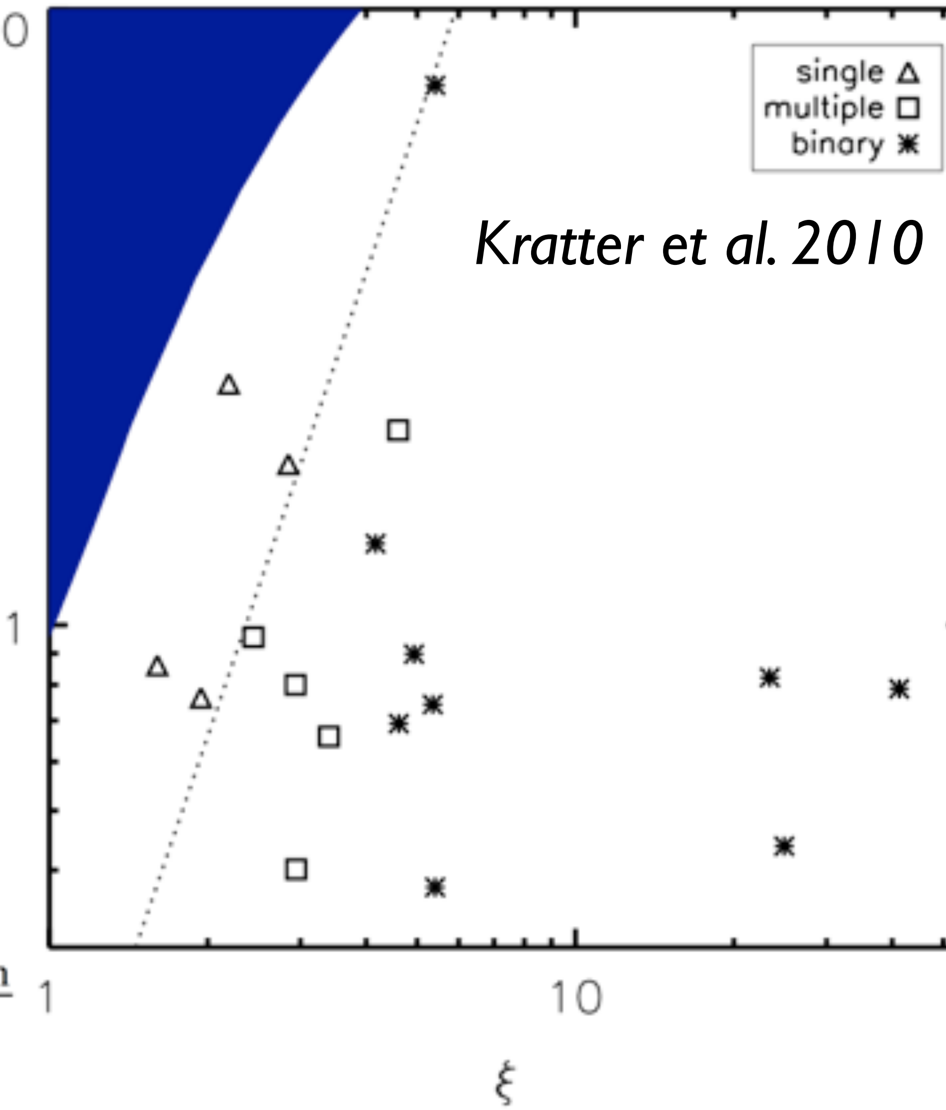
$\Longrightarrow$ Fragmentation induced starvation (FIS)

Fragmentation

Massive discs/massive star formation

- Parameter study: 3D hydro simulations





- thermal parameter: $\xi = \frac{\dot{M}_{\rm in} G}{c_{s,d}^3}$
- rotational parameter: $\Gamma = \frac{\dot{M}_{\rm in}}{M_{*d}\Omega_{k,\rm in}} = \frac{\dot{M}_{\rm in}\langle j\rangle_{\rm in}^3}{G^2 M_{*d}^3}$

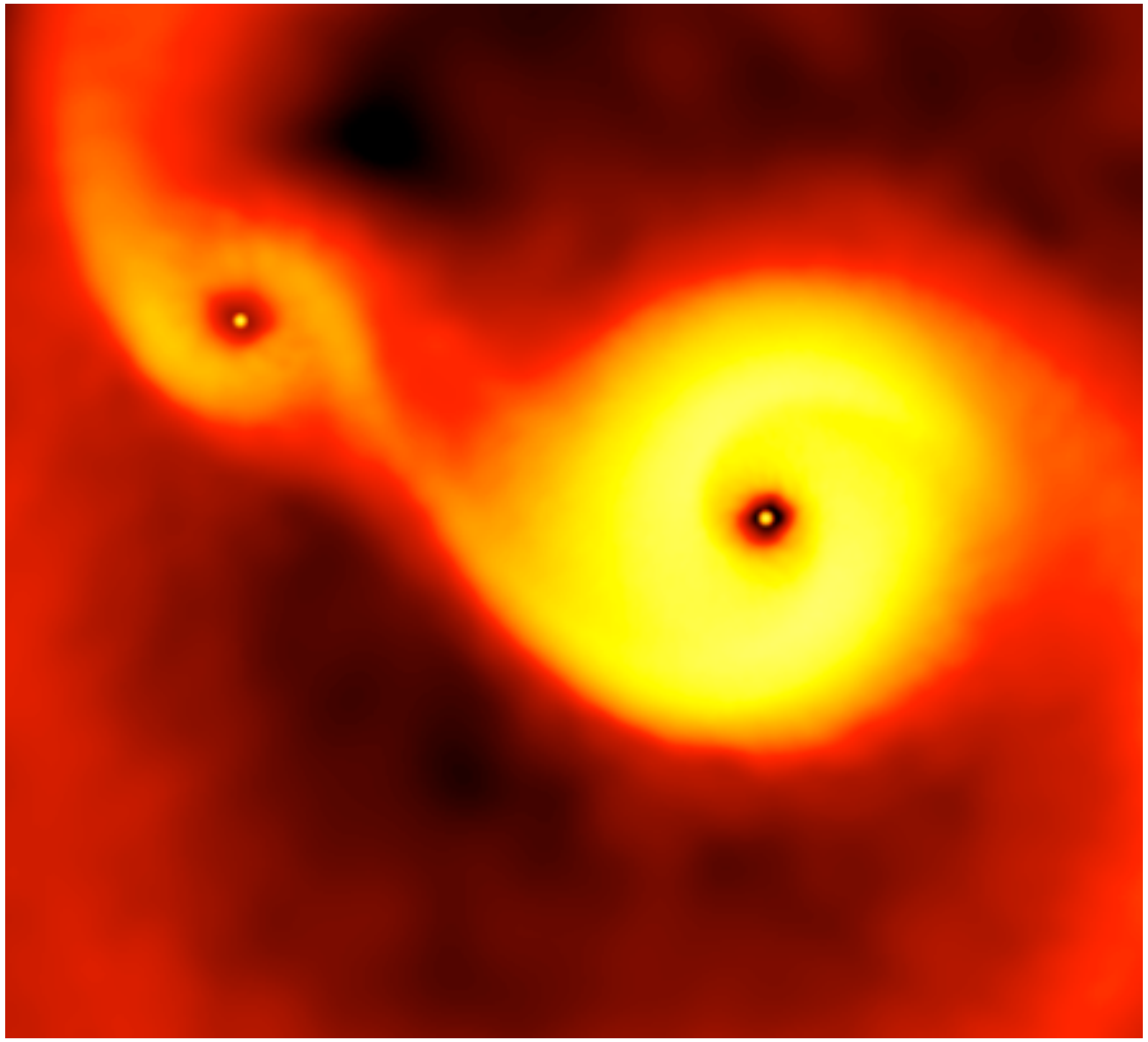
$\Longrightarrow$ gravitational torques are the main driver for fragmentation

$\Longrightarrow$ maximum stable discs: $M_{\rm disc} \sim 0.5\ M_{\rm total}$

Fragmentation

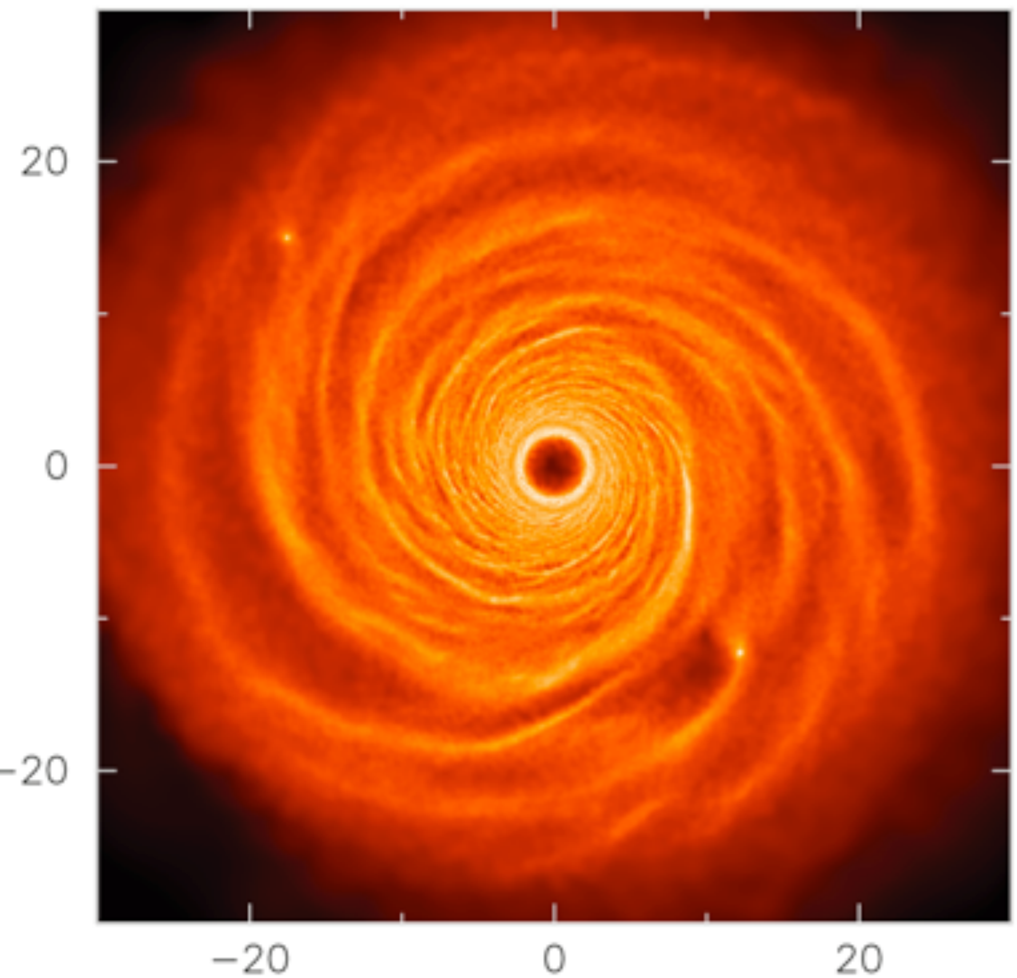
Discs from turbulent environments:

- discs generated in turbulent environment survive such violent environment (*Paul Clark, 2009*)
- properties:
  - massive $M_{disc}/M_{star} > 0.1$
  - sizes: few 100 AU - 2000 AU
  - prone to fragment

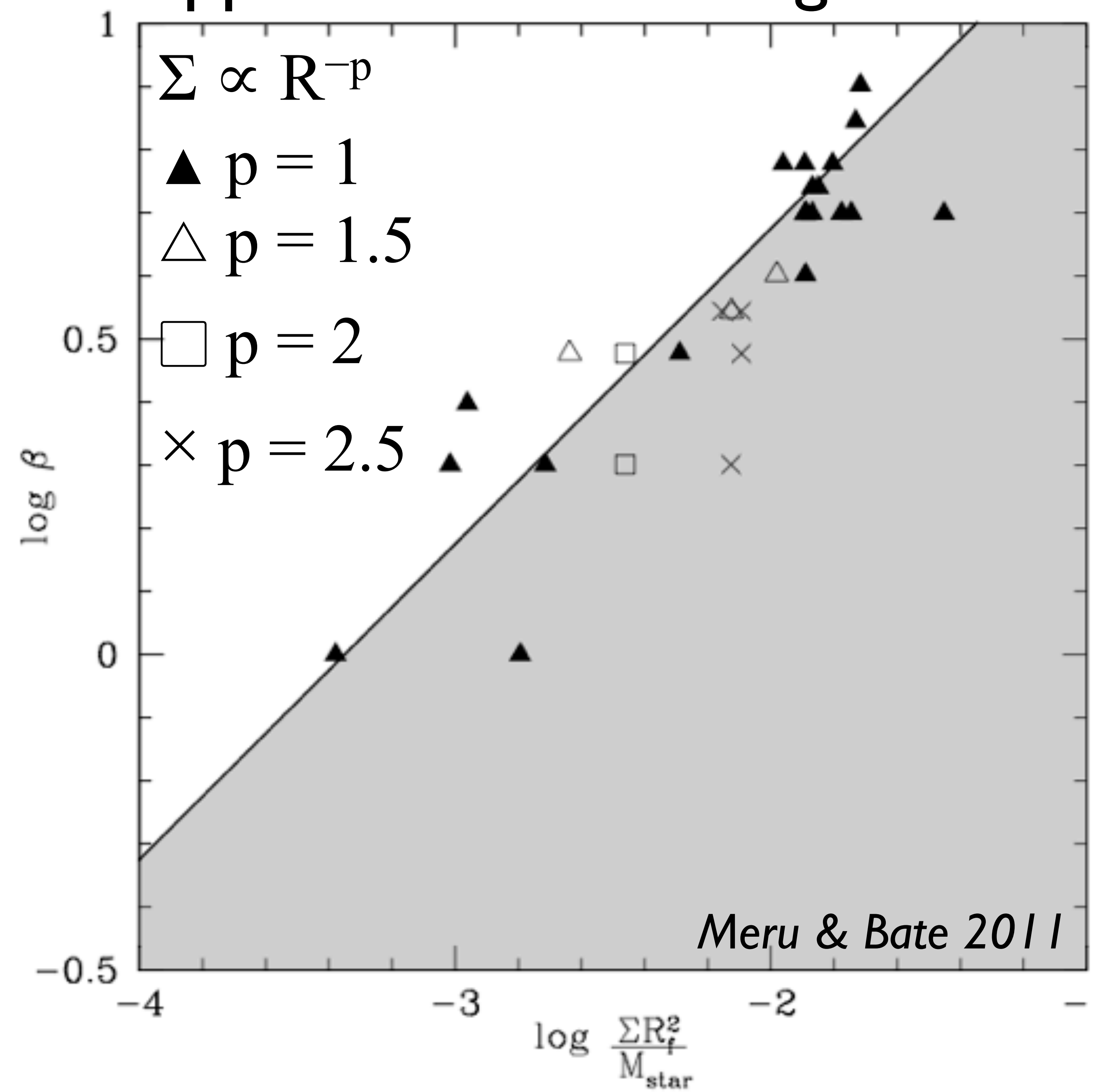


Fragmentation

- dependency on initial disc profile
- 3D Simulations: $M_{\rm star} = 1\ \mathrm{M}_\odot$, $M_{\rm disc} = 0.1\ \mathrm{M}_\odot$



appearance of fist fragment:



$\Longrightarrow$ initial density profile:
crucial parameter

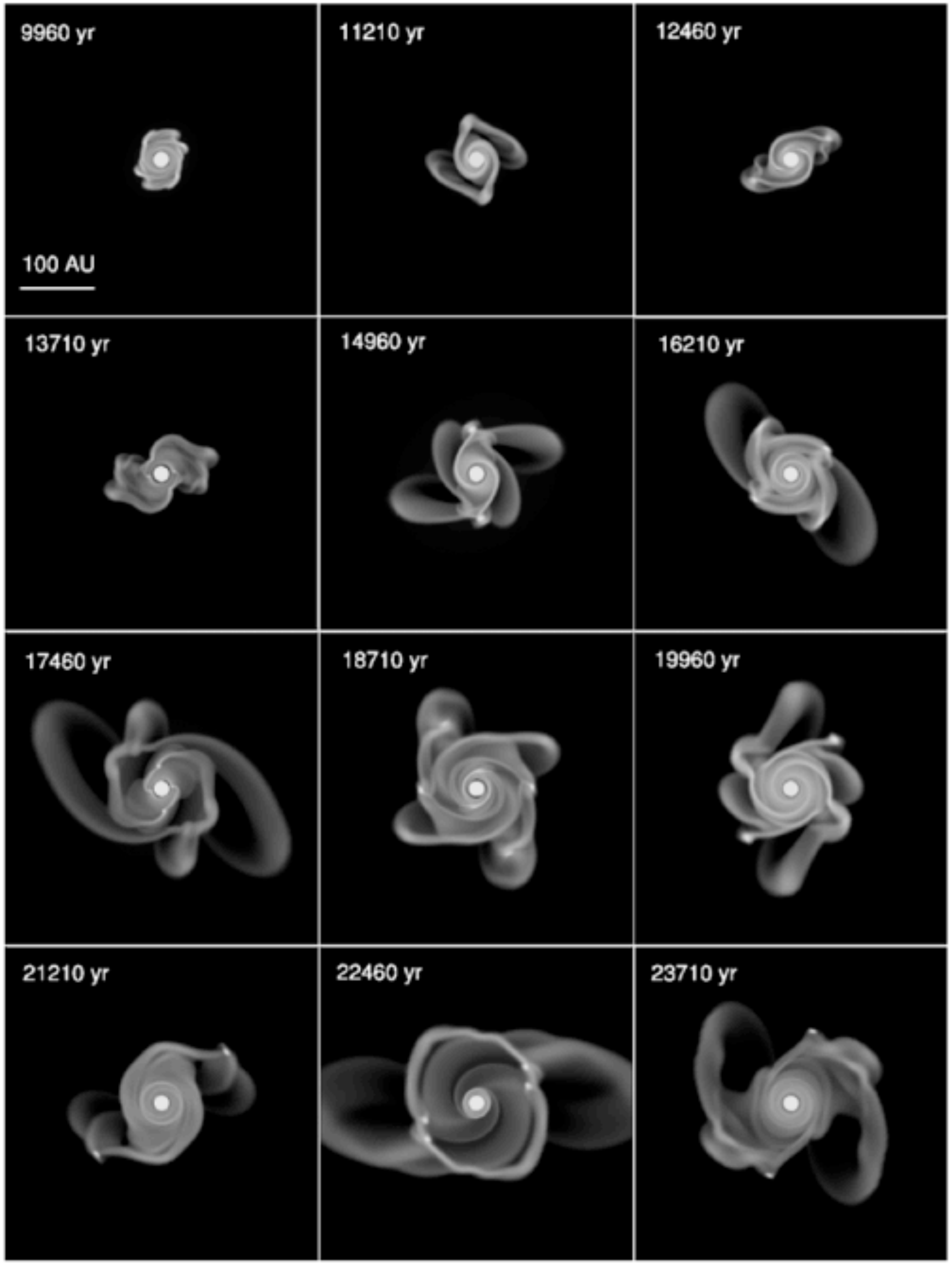
Fragmentation

Is there a “right” disc density profile?

- e. g. the minimum solar nebular model $\Sigma \propto R^{-1.5}$ (Hayashi, 1981)?

- Kuchner, 2004: $\Sigma \propto R^{-2\pm0.5}$ from planets in extrasolar systems

Fragmentation



Vorobyov & Basu, 2005

- collapse of a rotating, magnetised cloud core
- thin disc approximation to follow the evolution

$\Longrightarrow$ accretion bursts:

$\sim 10^{-4}\, M_{\odot}/yr$

\+ steady accretion:

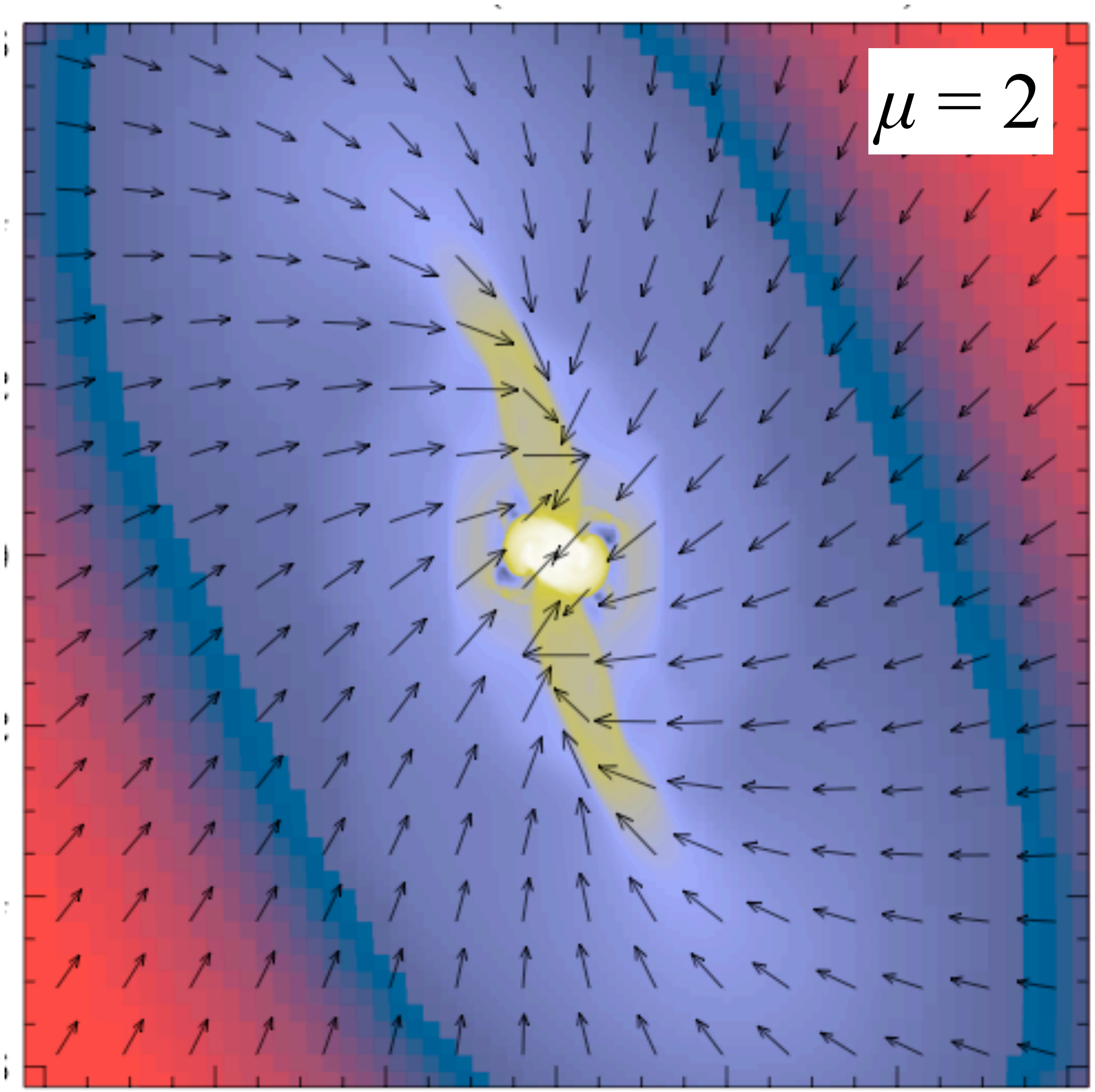
$\sim 10^{-6}\, M_{\odot}/yr$

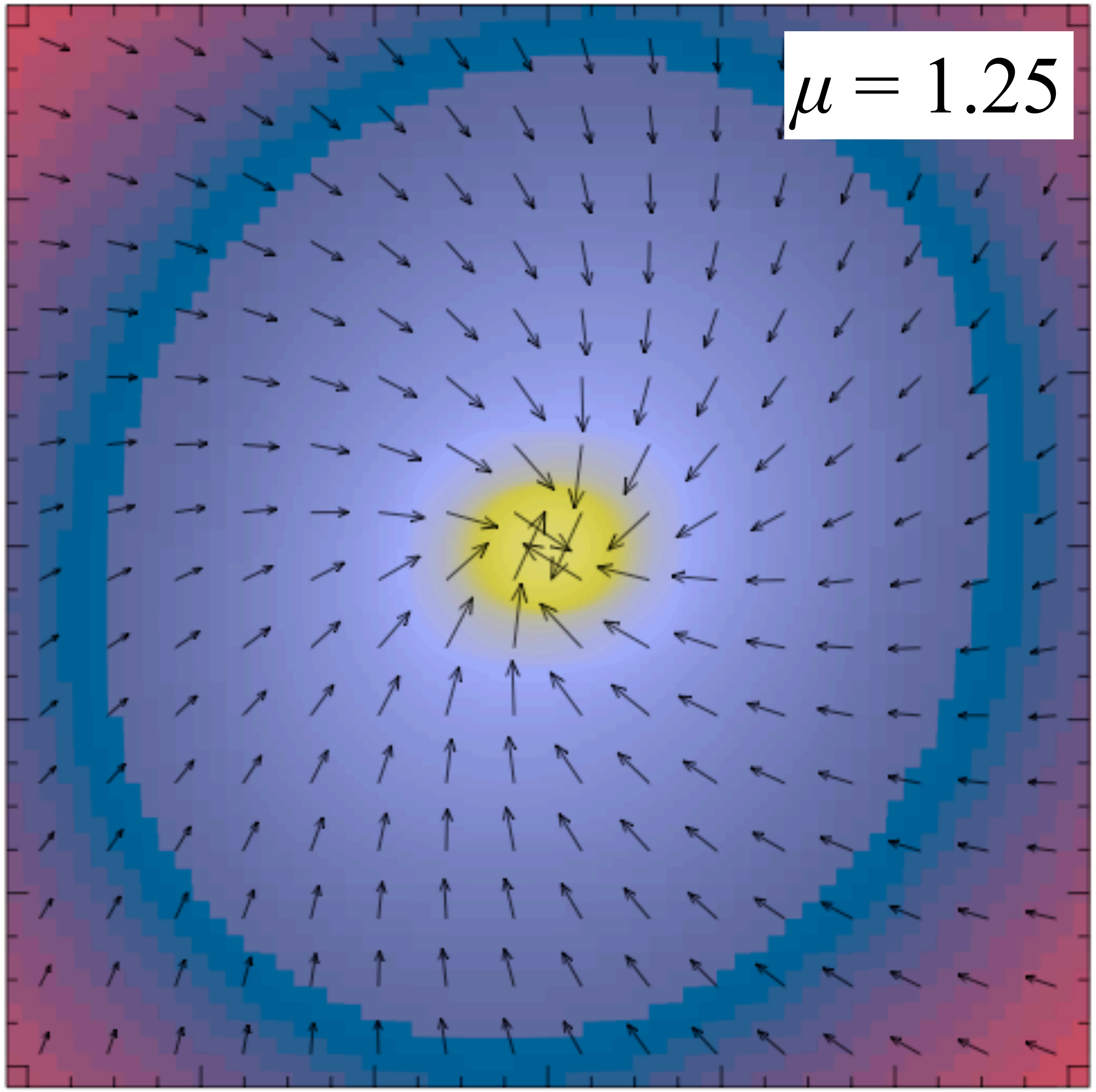
$\Longrightarrow$ next talk by Eduard

Magnetic fields?

Fragmentation crisis?

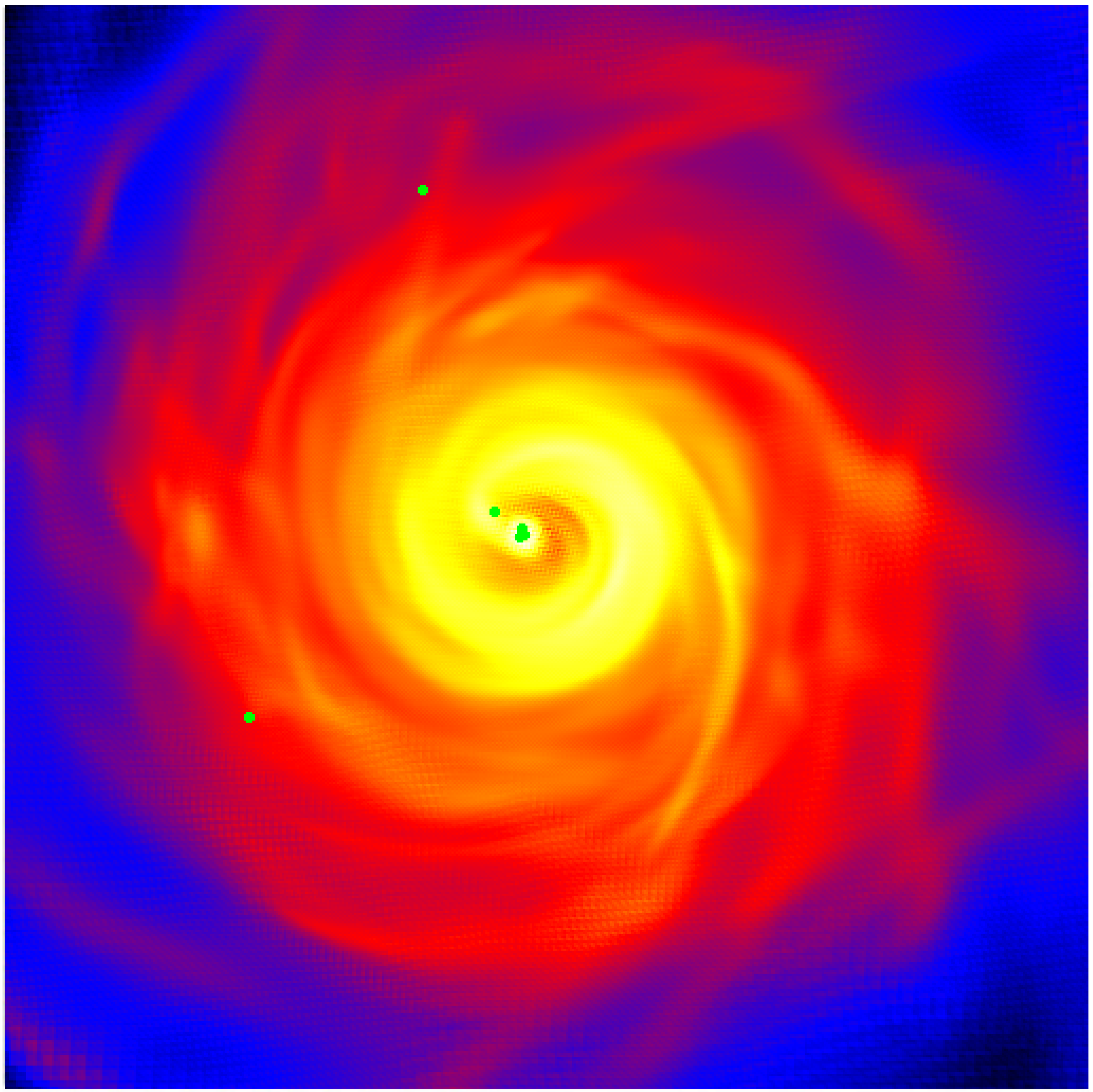
- Hennebelle & Teyssier 2008:
  binary fraction too low for μ < 5

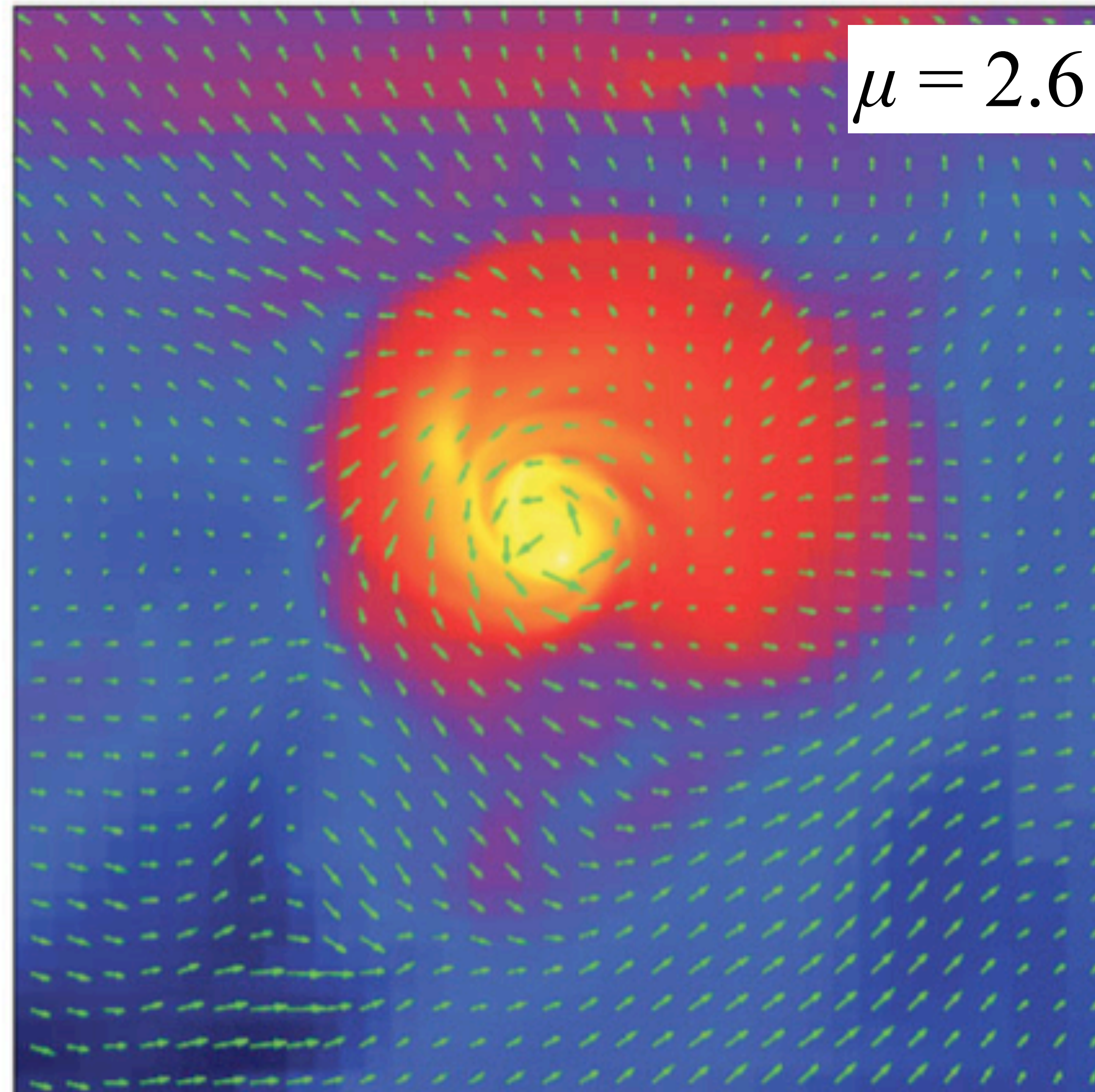




Fragmentation crisis?

Solution: **Turbulence**



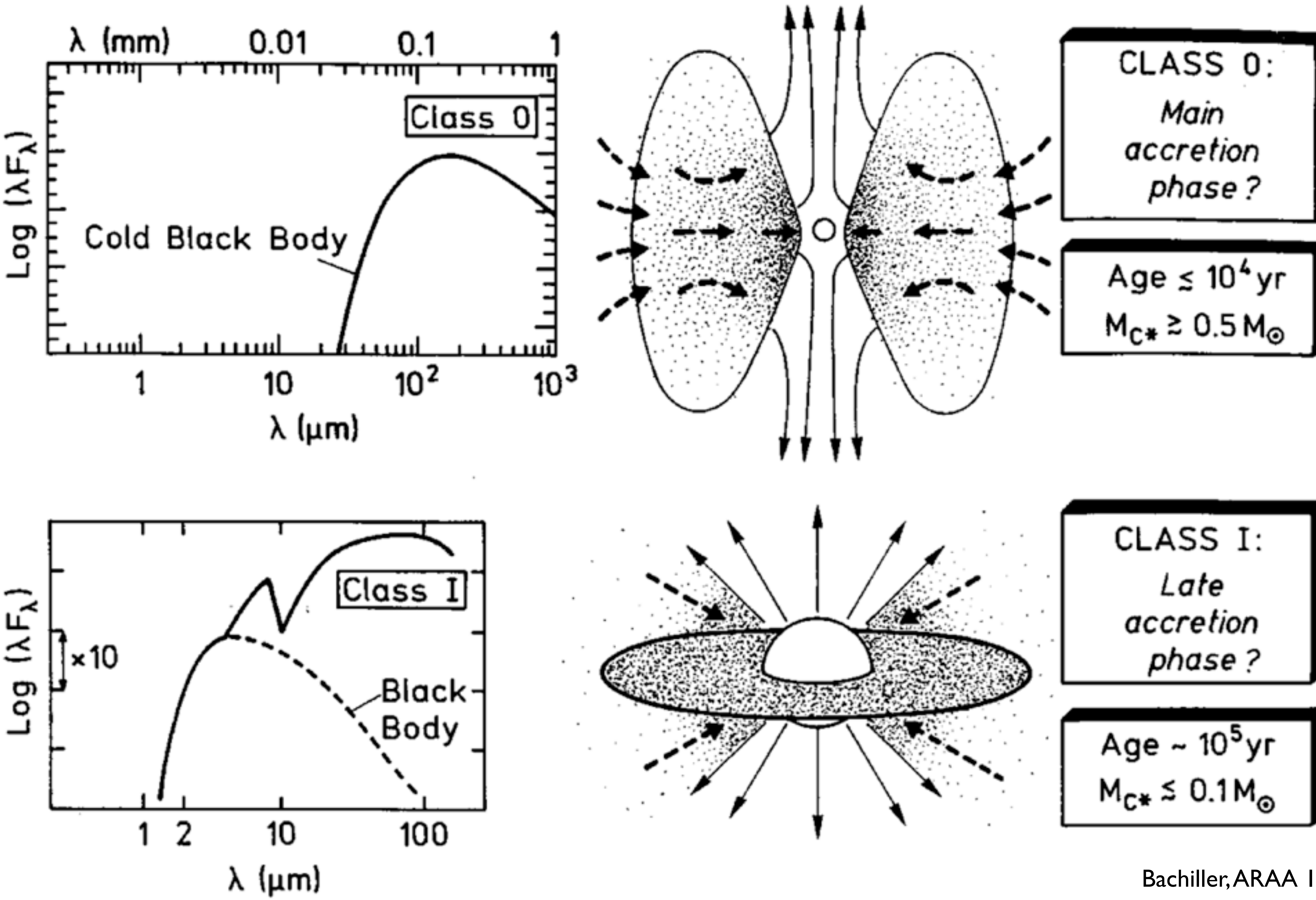


Seifried et al., 2011

$\Longrightarrow$ weak turbulence sufficient to seed fragmentation

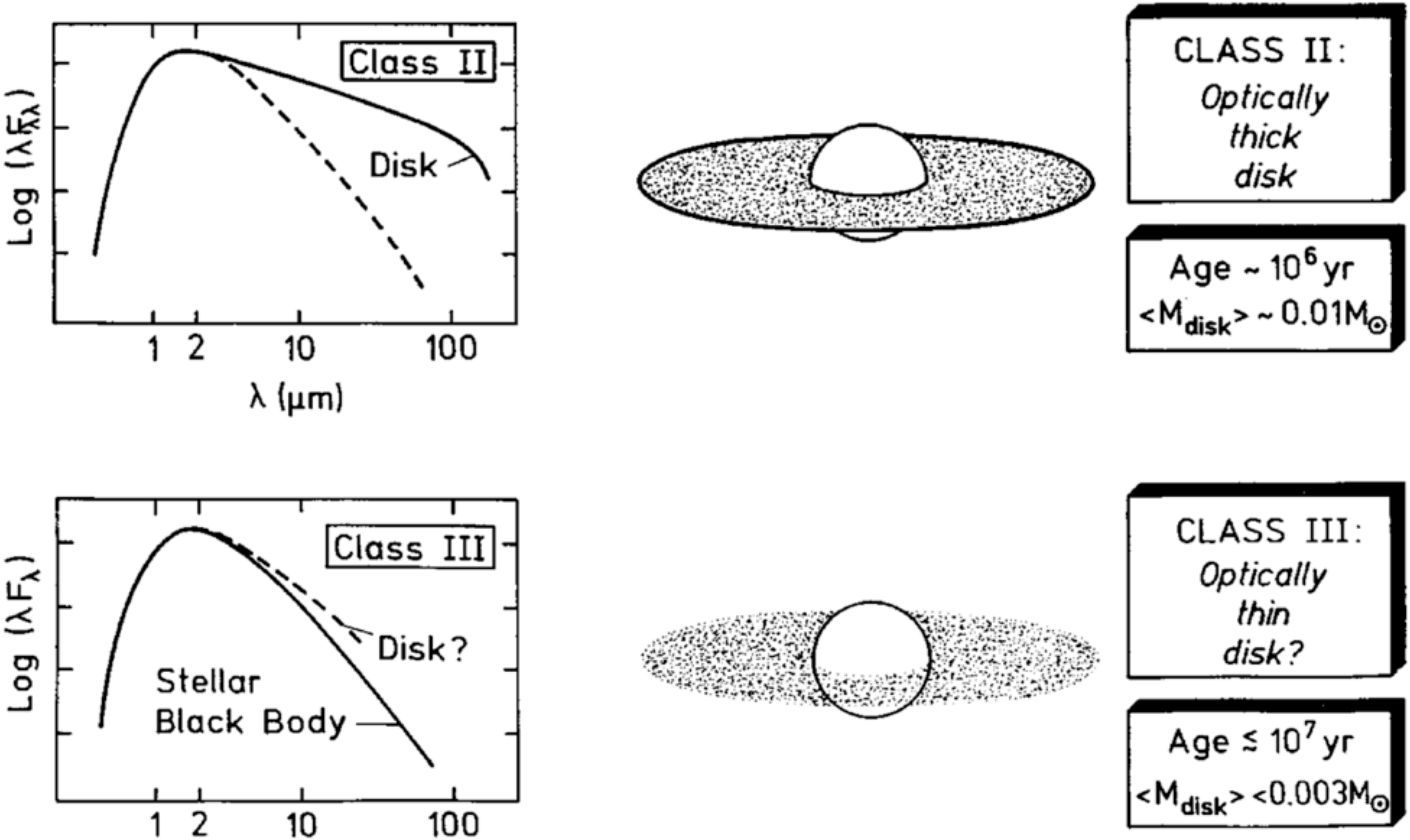
Disc evolution

Disc evolution



Bachiller, ARAA 1996

Disc evolution



Bachiller, ARAA 1996

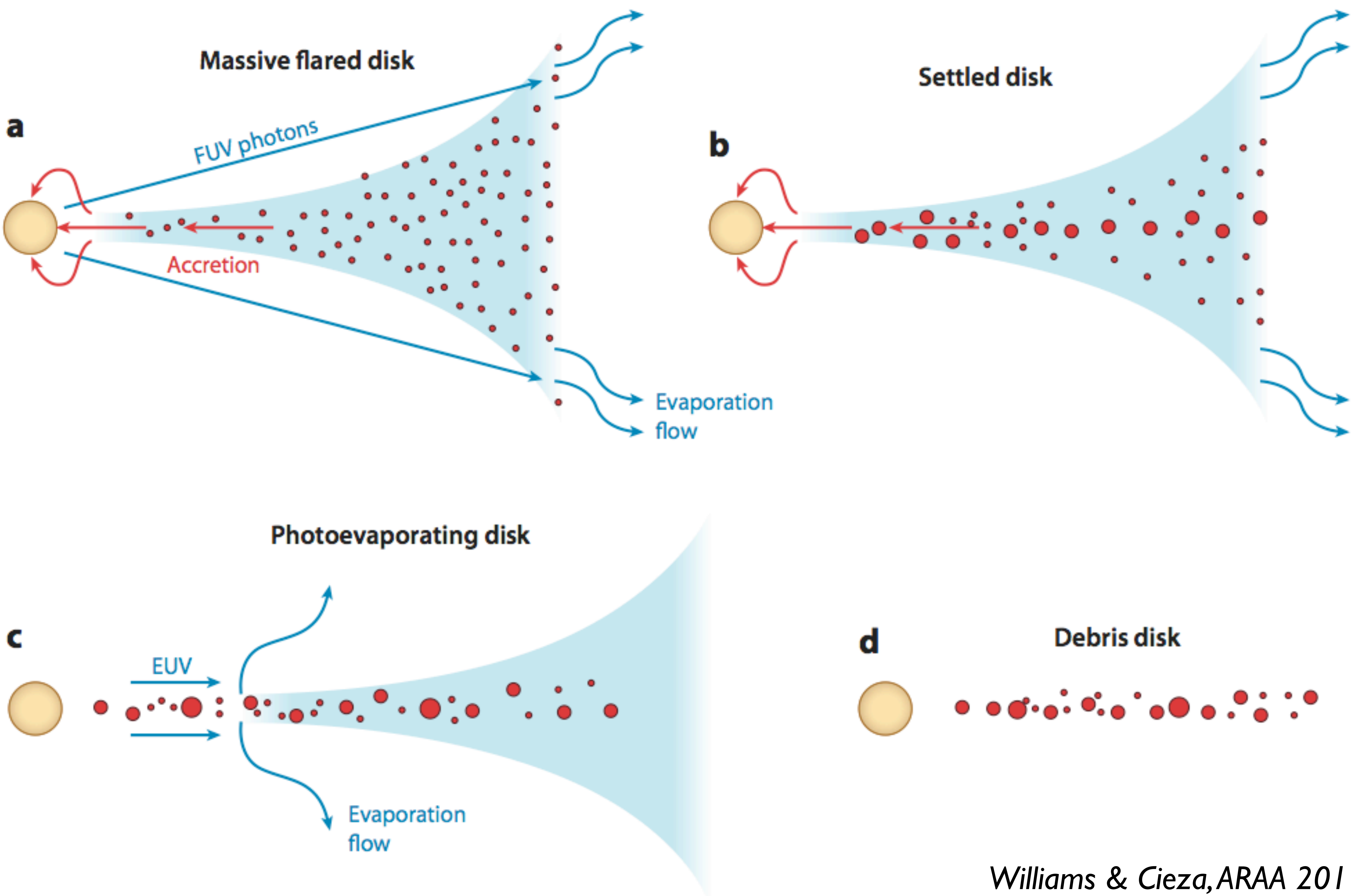
Disc evolution

Table 1 Classification of young stellar objects

Class	SED slope	Physical properties	Observational characteristics
0	–	$M_{env} > M_{star} > M_{disk}$	No optical or near-IR emission
I	$\alpha_{IR} > 0.3$	$M_{star} > M_{env} \sim M_{disk}$	Generally optically obscured
FS	$-0.3 < \alpha_{IR} < 0.3$		Intermediate between Class I and II
II	$-1.6 < \alpha_{IR} < -0.3$	$M_{disk}/M_{star} \sim 1\%$, $M_{env} \sim 0$	Accreting disk; strong Hα and UV
III	$\alpha_{IR} < -1.6$	$M_{disk}/M_{star} \ll 1\%$, $M_{env} \sim 0$	Passive disk; no or very weak accretion

Williams & Cieza, ARAA 2011

Disc evolution



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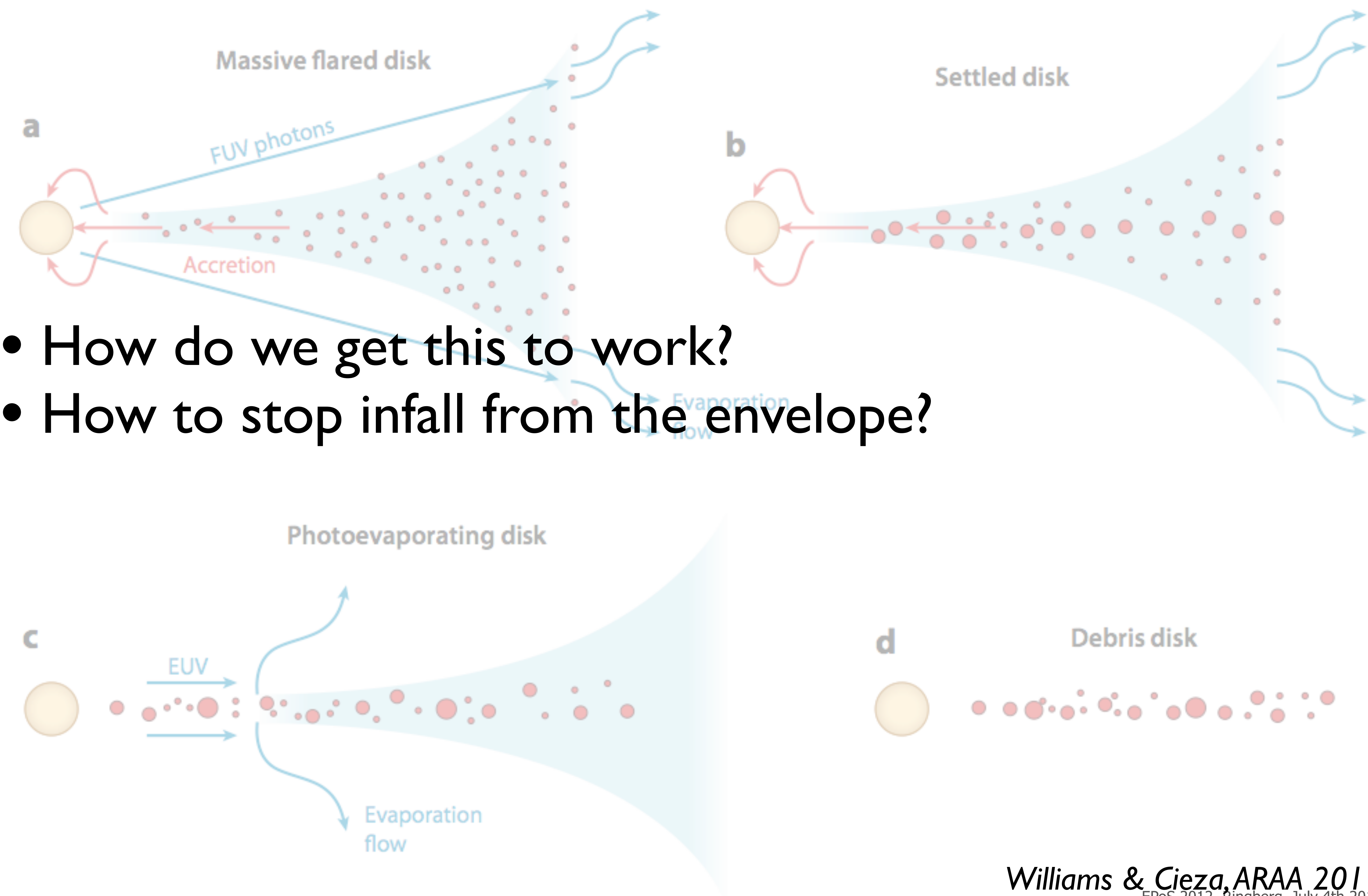
Disc evolution



- How do we get this to work?
- How to stop infall from the envelope?

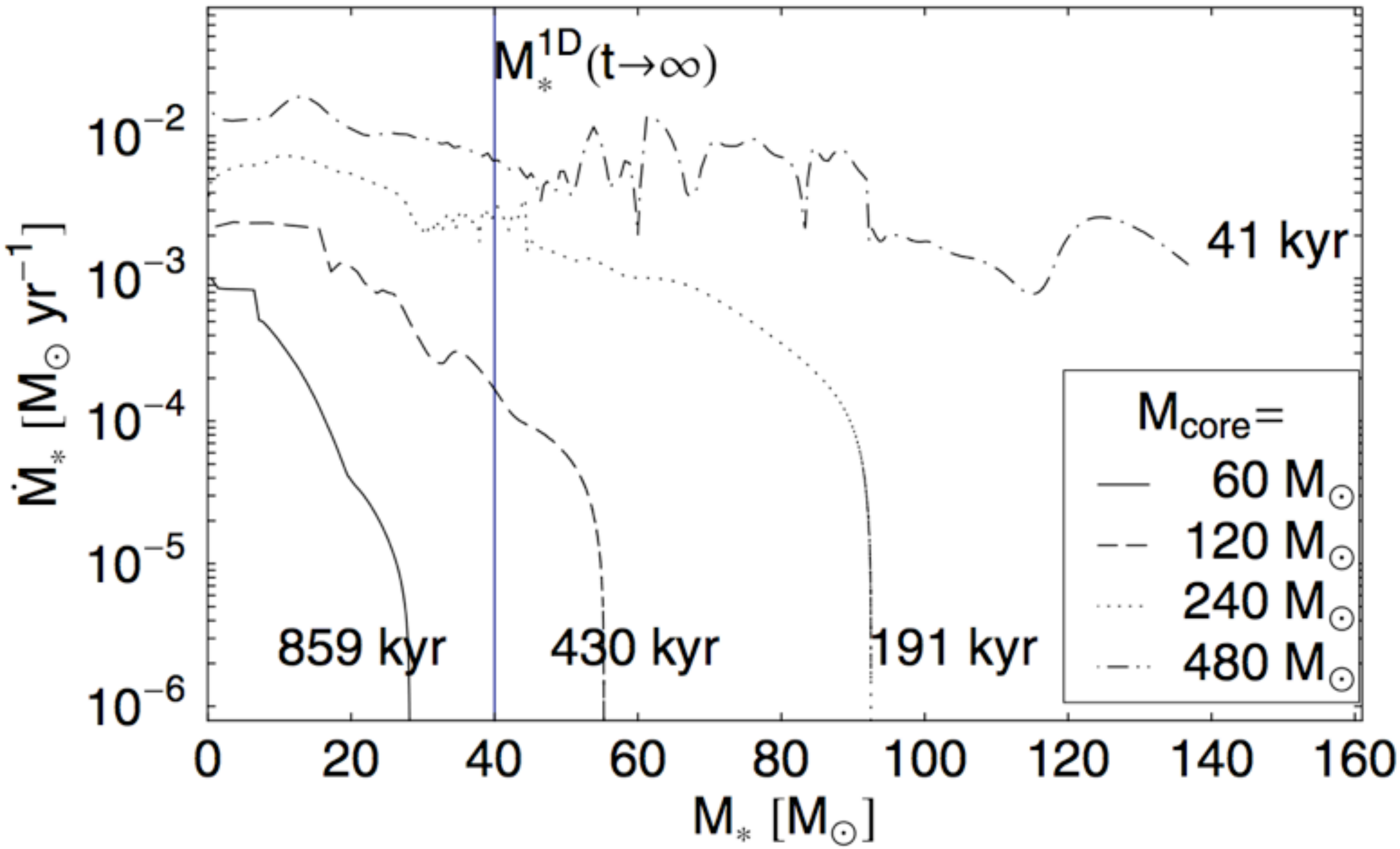
Williams & Cieza, ARAA 2011

Disc evolution

- so far no complete 3D simulation:
  from collapsing cloud cores
  $\Longrightarrow$ transition to class I and later phases

Disc evolution

- Kuiper et al 2010: 2D Simulations of massive cores

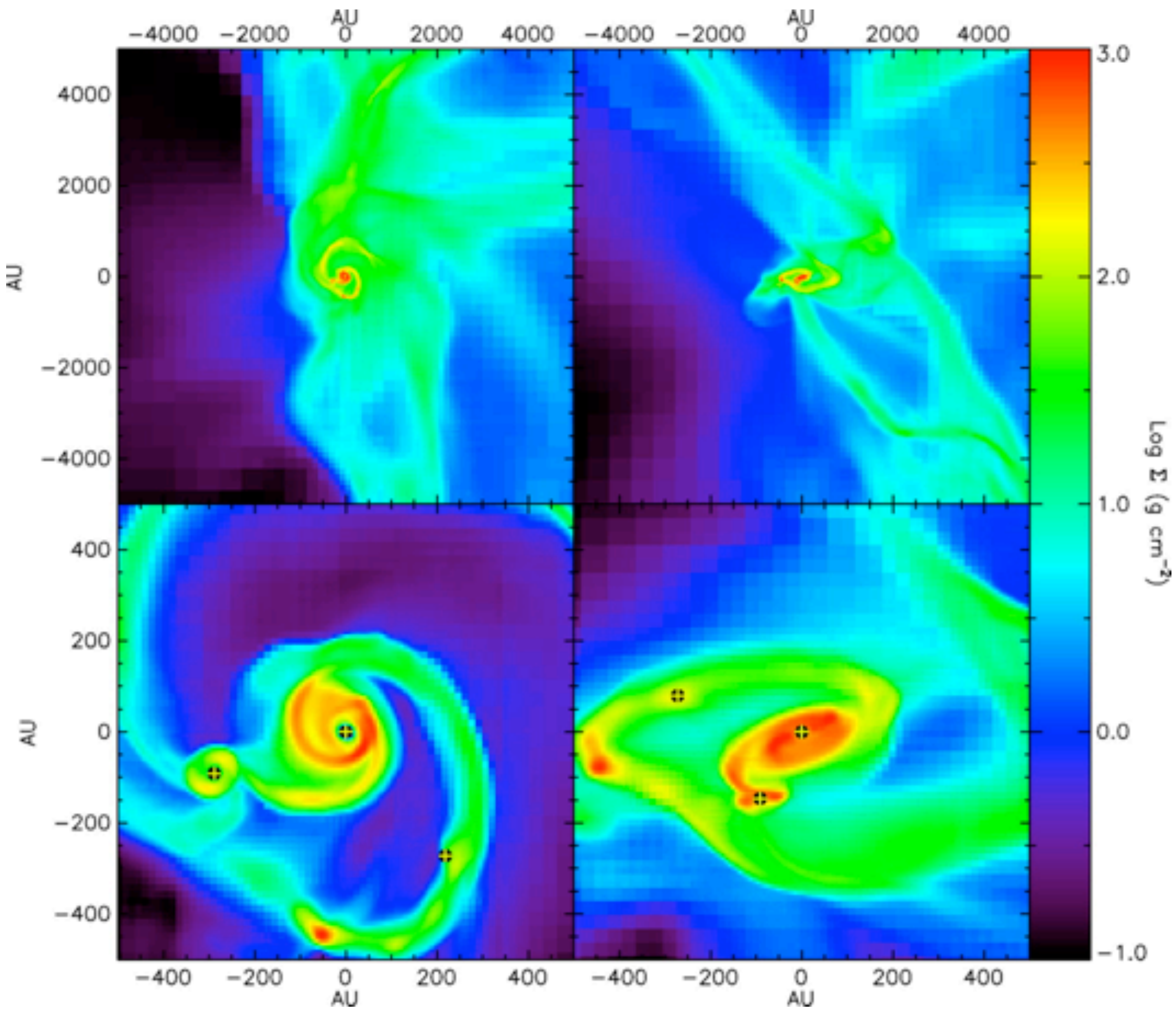


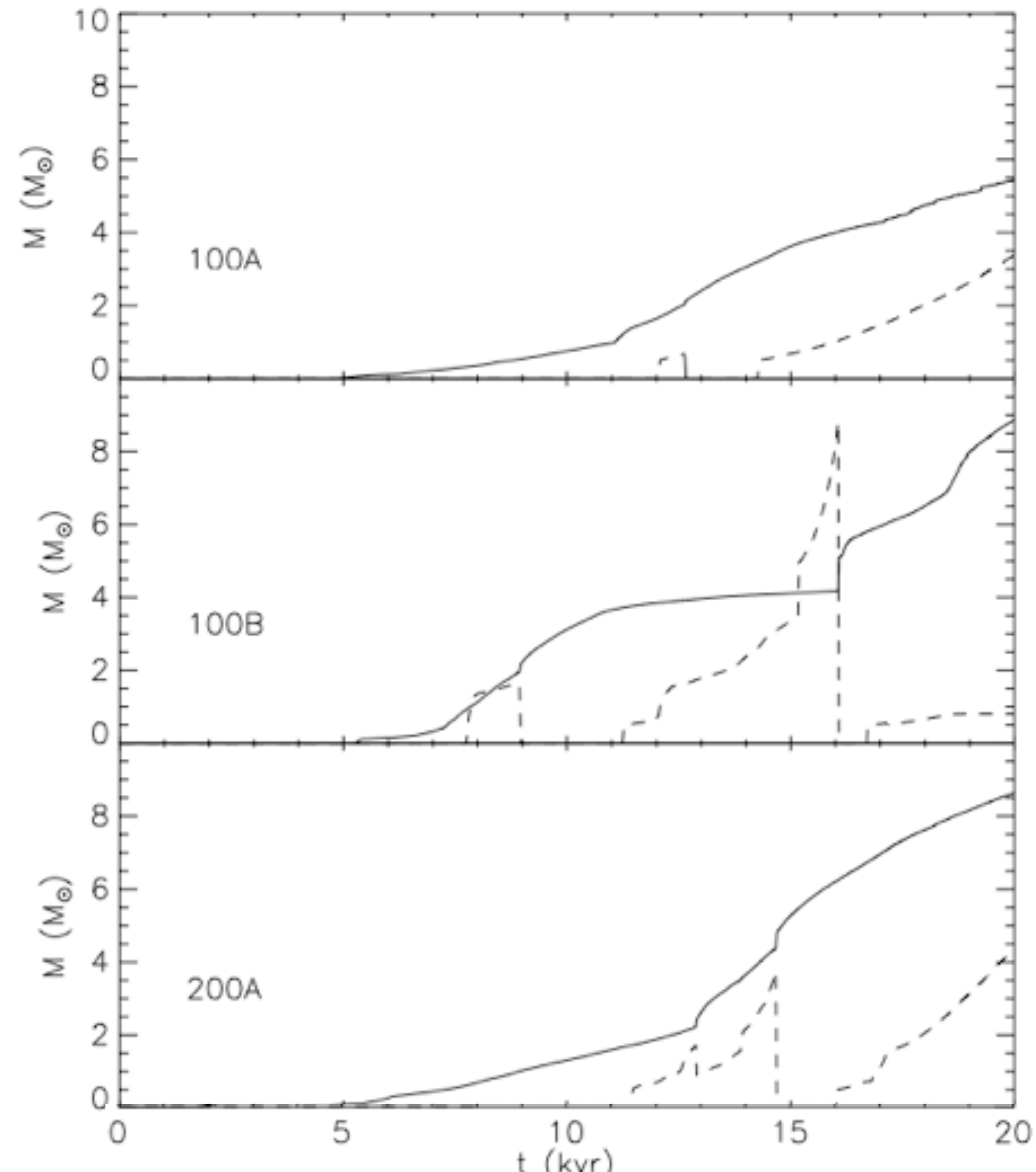
disc accretion ceased

$\Longrightarrow$ but: **isolated** core

Disc evolution

- Krumholz et al. 2007: 3D sims + RT





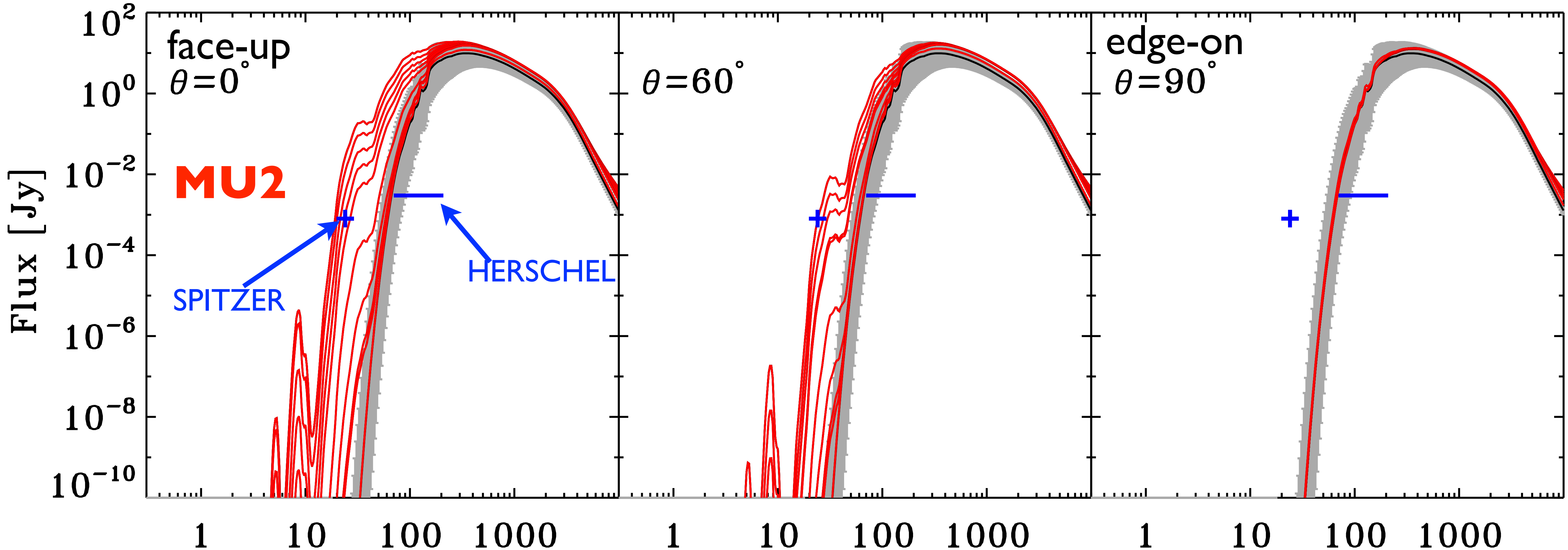
Krumholz et al. 2007

⟹ disc is still massive/thick:

⟹ accretion onto the disc didn't stop so far

Observational predictions

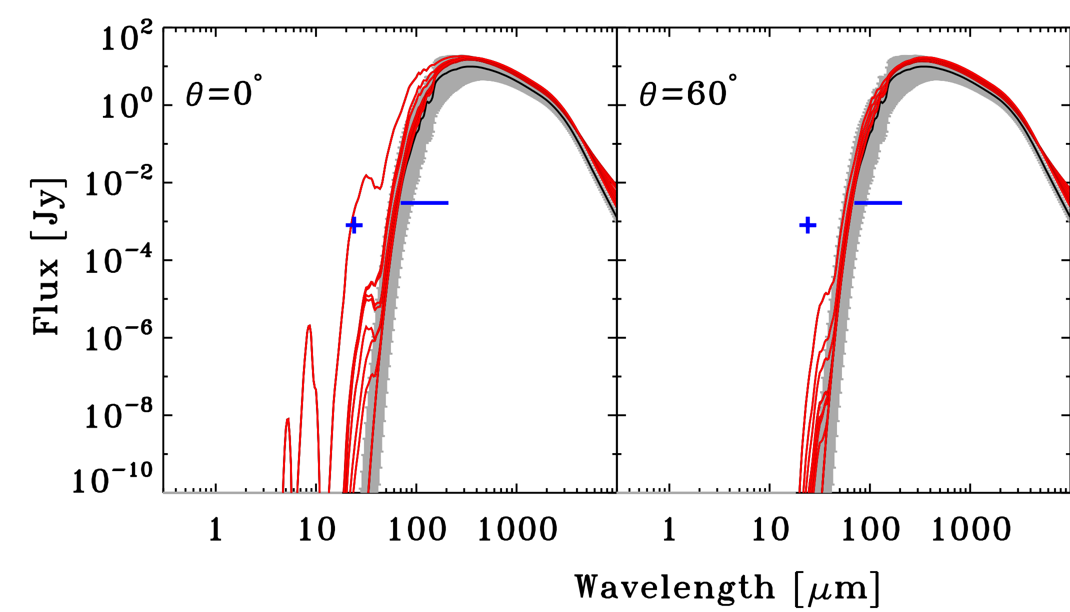
Observational predictions



Commerçon, Levrier et al. in prep

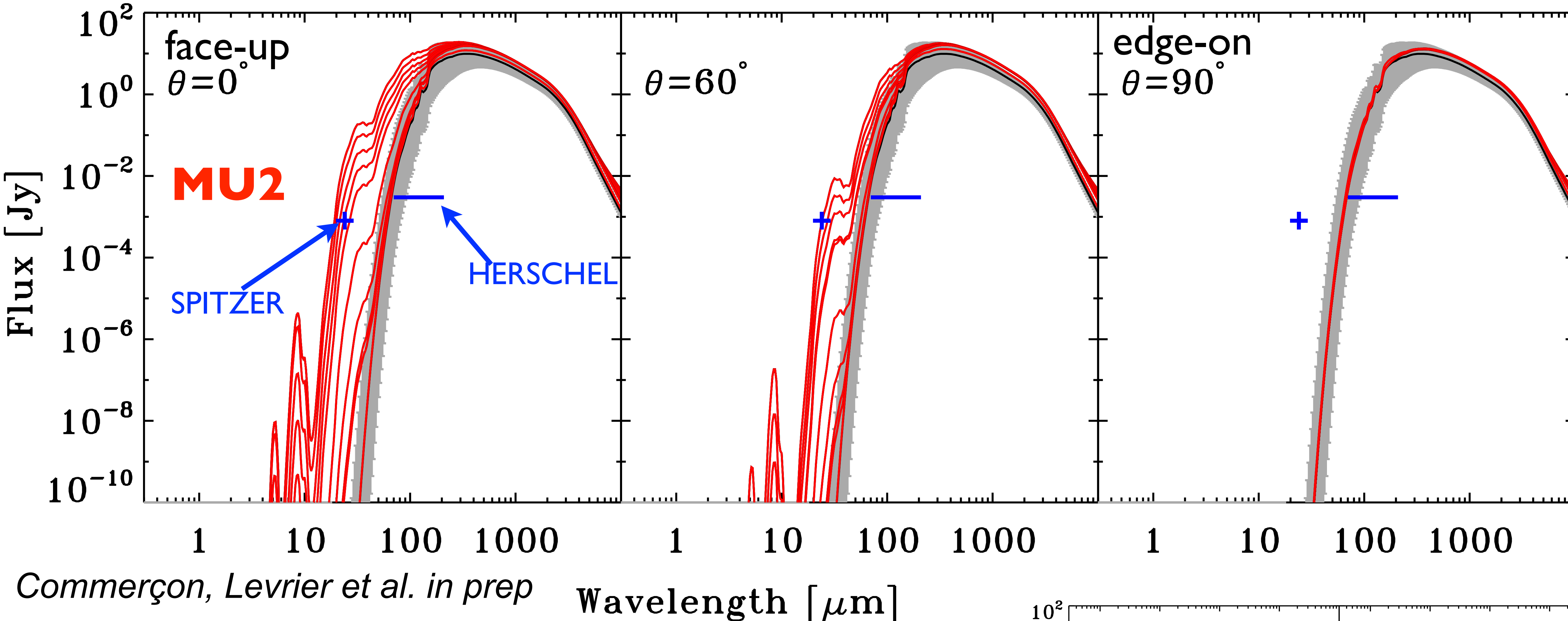
- *Objects at 150 pc, 3000 AU x 3000 AU region*
- *Prestellar core = initial conditions (black line)*
- Emission in the FIR => **HERSCHEL, SPITZER**
- But similar SEDs in the MU200 model, i.e. **with a disk**!

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



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

Observational predictions



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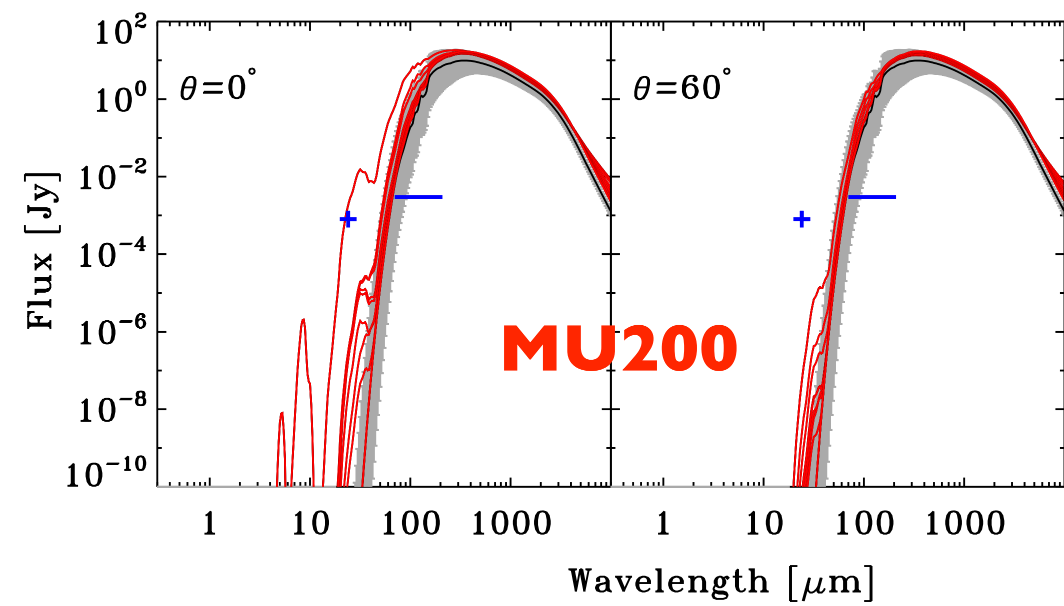


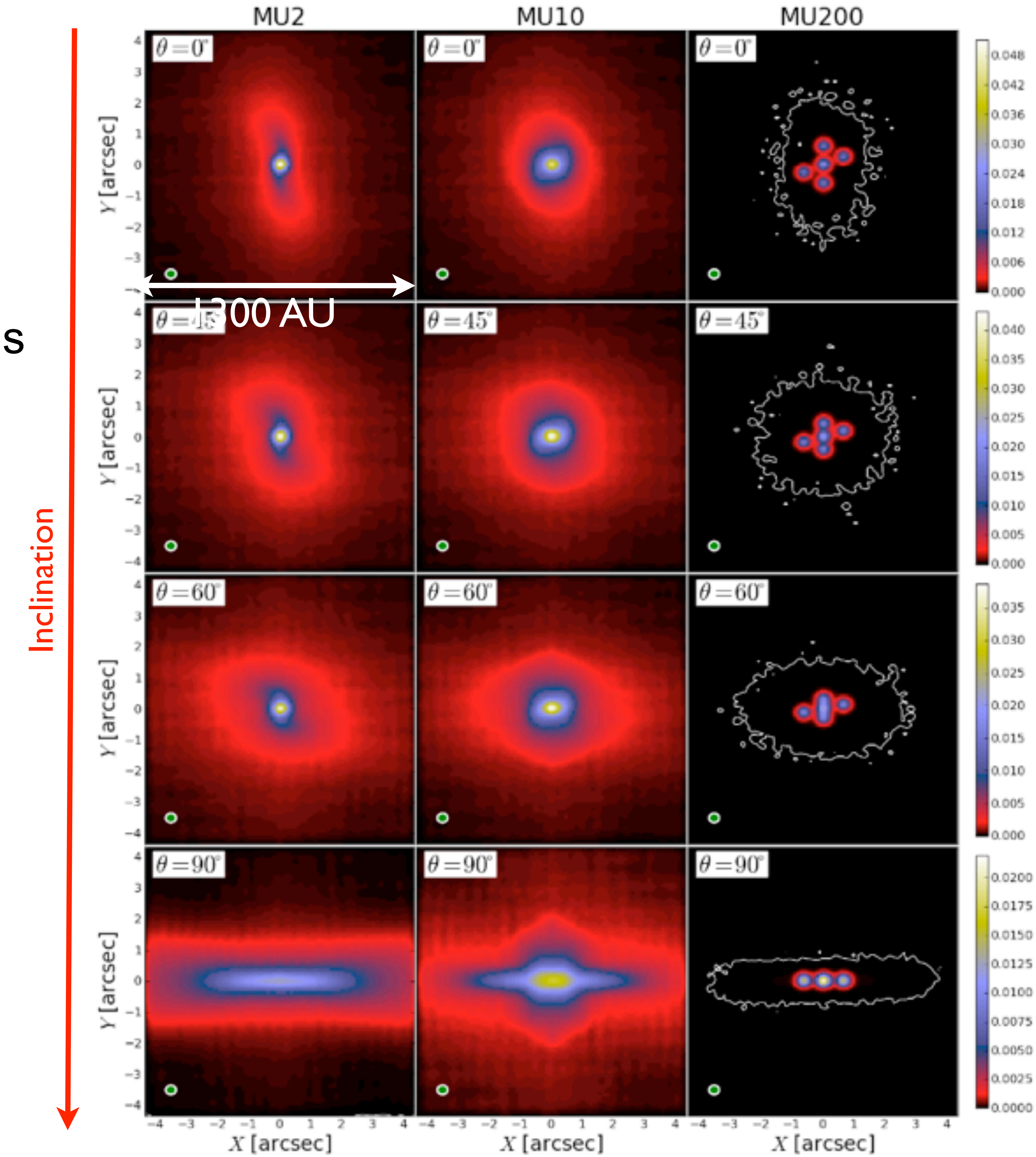
Help to select first core candidates & to distinguish starless cores and first cores

Observational predictions

- GILDAS ALMA simulator

- Different bands and configurations tested

ALMA Band 4 Config 15 @150 pc



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What we don't know

- what determines fragmentation/binary formation

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What we don't know

- what determines fragmentation/binary formation
- how do we get rid of the massive envelope?

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What we don't know

- what determines fragmentation/binary formation
- how do we get rid of the massive envelope?
- how do discs look like?