Massive star formation A tale of accretion, ejection and multiplicity

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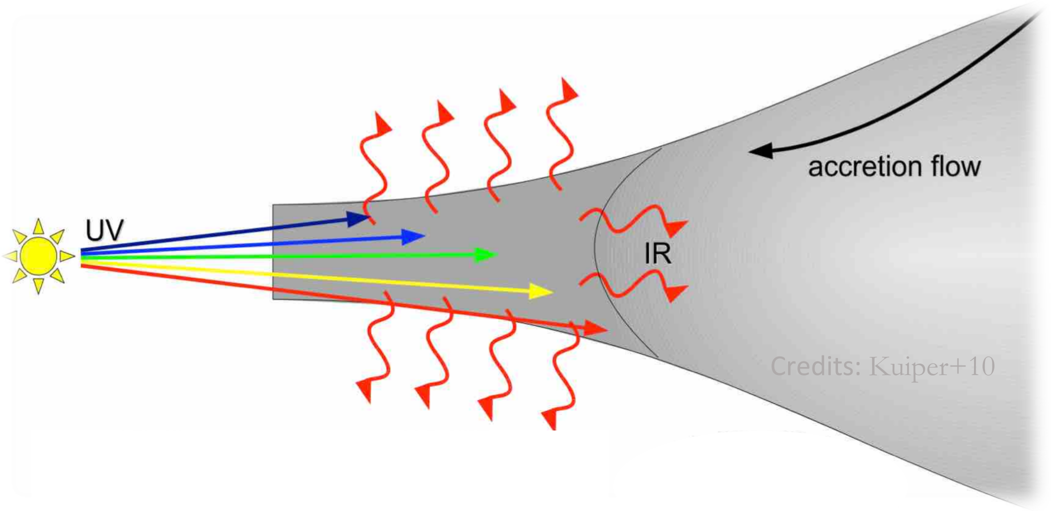
State of the art

- 1D : **radiative barrier**

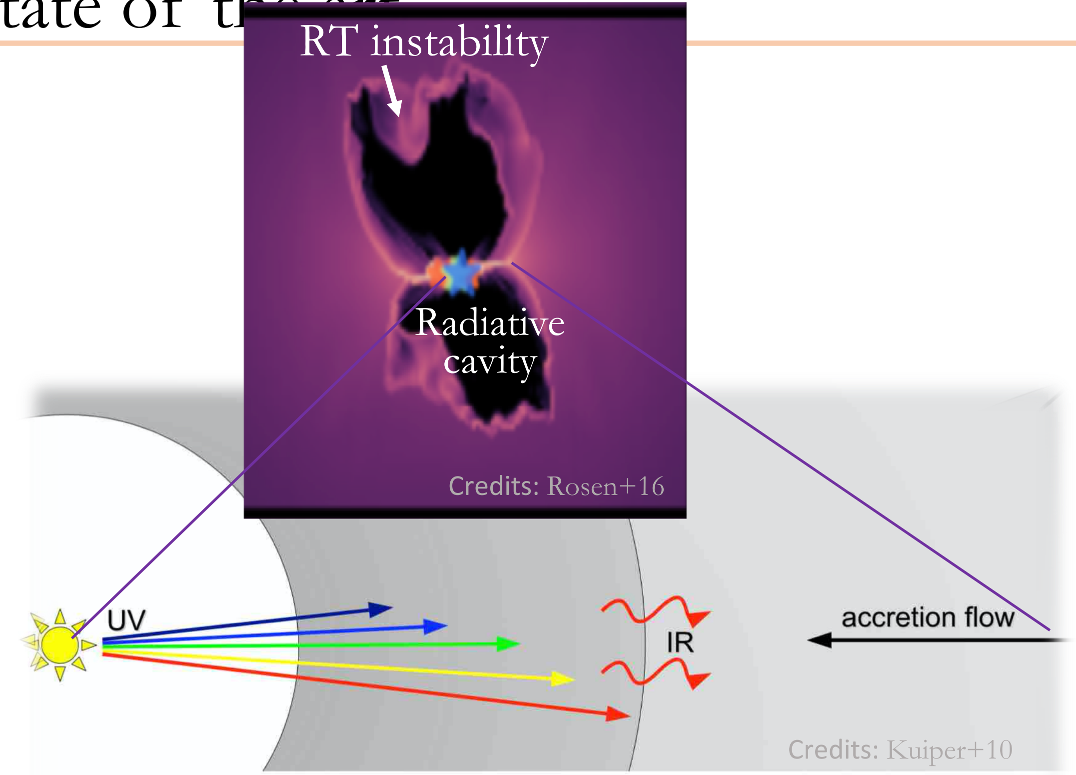
$$F_{rad} > F_g \, ?$$

(Larson, 1971, Kuiper+10a)

Maximal mass: 40 $M_\odot$



State of the art



- 2D, 3D

Accretion disk (Yorke+02)

Maximal mass > 100 $M_\odot$

(Kuiper+10a, FLD, Hybrid)

Rayleigh-Taylor instabilities ?

(Yes: Krumholz+09, FLD, Rosen+17, Hybrid
No: Kuiper+13, Mignon-Risse+20)

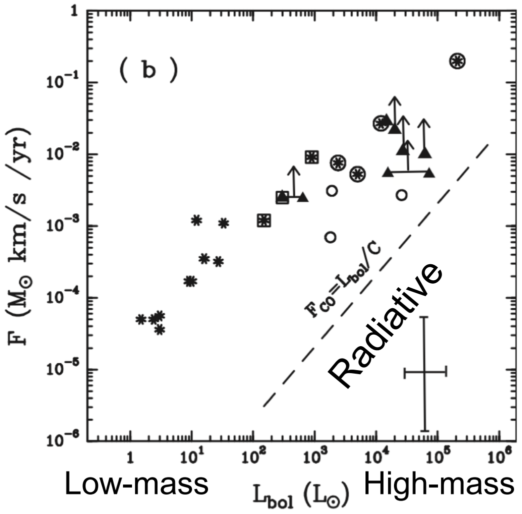
- Hybrid methods distinguish stellar radiation ⟹ accurate radiative force
  (Mignon-Risse et al, 2020)

Observational constraints

- Disks are present, relatively few constraints (ALMA)
  (see review by Beltrán+20)

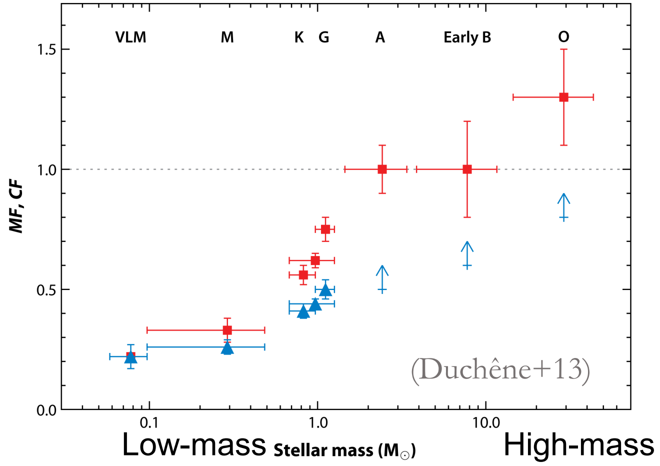
- Outflows: unlikely to be (only) radiative

  (e.g., Lada+85, Cabrit+92, Wu+05)



(Shepherd & Churchwell, 1996, Wu+05)

- Massive stars are often
  in multiple systems
  (Chini+12, Sanna+12)



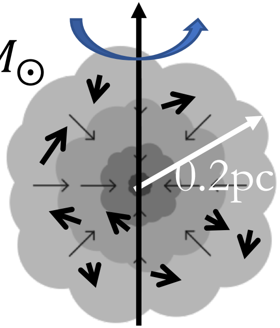
How do massive stars accrete/eject material?
What physics sets the stellar multiplicity?

Collapse of turbulent, magnetized core

Physics:

- Hybrid RT
- Non-ideal MHD (ambi. diffusion)
  (Masson+12,16, Marchand+16)

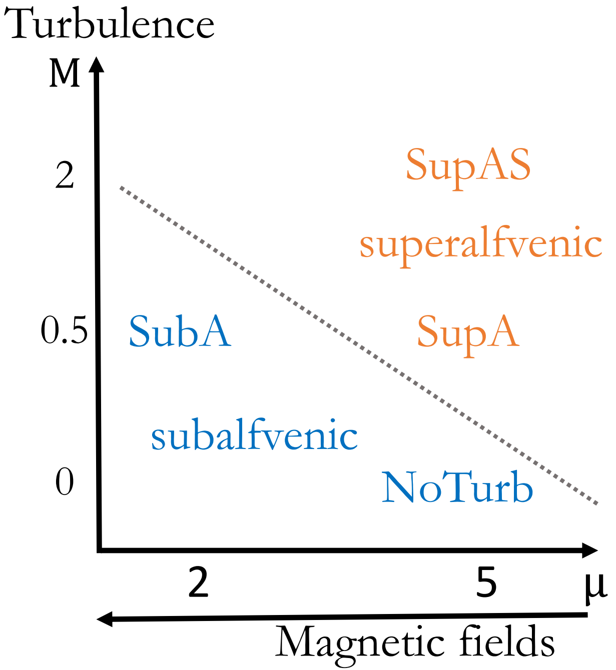
$100\ M_{\odot}$



$\frac{E_{rot}}{E_{grav}} = 1\%$ solid-body rotation

Initial conditions:

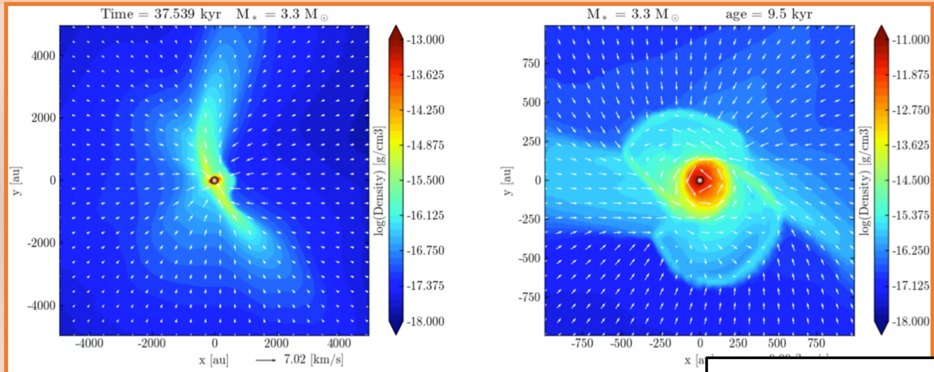
- Density profile $\rho(r)\ \alpha \frac{1}{1+r^2}$
- Magnetic field $B \approx 7 - 18\ 10^{-5}$G
- Initial turbulence
  $0 \leq \text{Mach} \leq 2$
  $0 \leq \text{Mach}_{\text{alfvénic}} \leq 5.7$



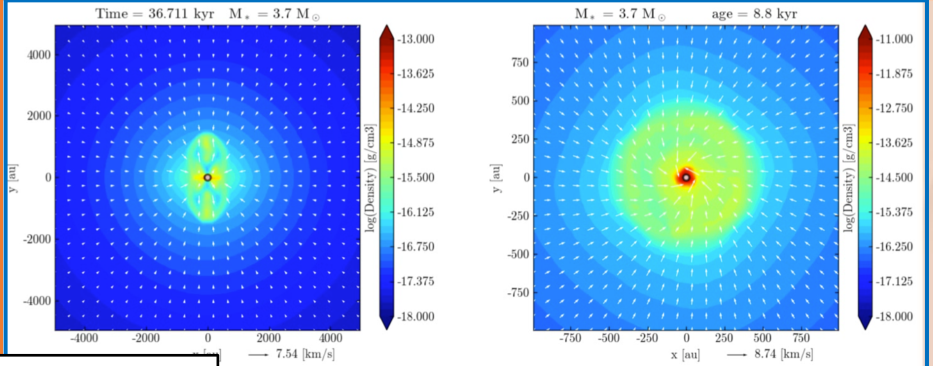
2 subalfvenic runs
2 superalfvenic runs

- AMR refinement criteria: Jeans length (12), sink; Max. resolution : 5 AU

Overview: density slices



M = 0.5 μ = 5 Run SupA



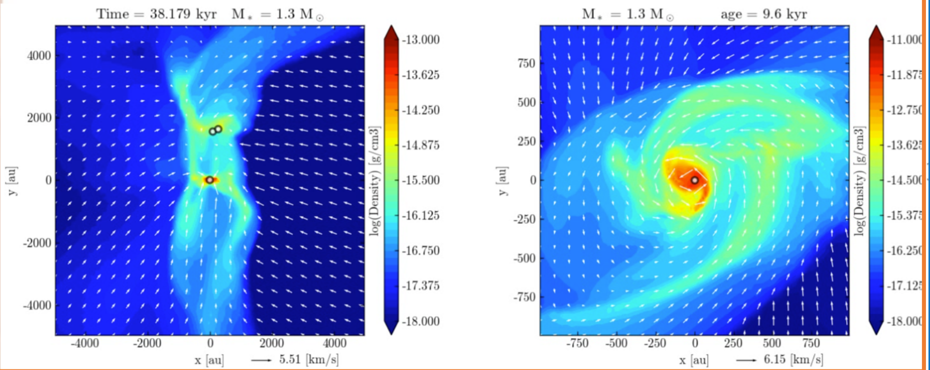
M = 0 μ = 5 Run NoTurb

Binary system

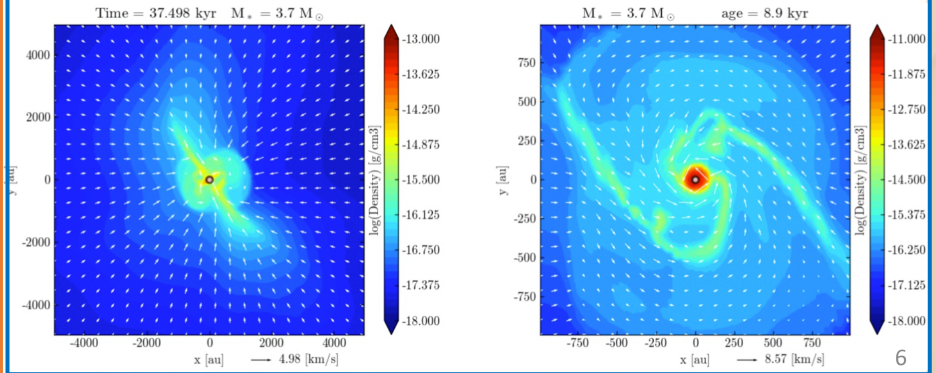
Disk-mediated accretion
Outflows

Unitary system

M = 2 μ = 5 Run SupAS

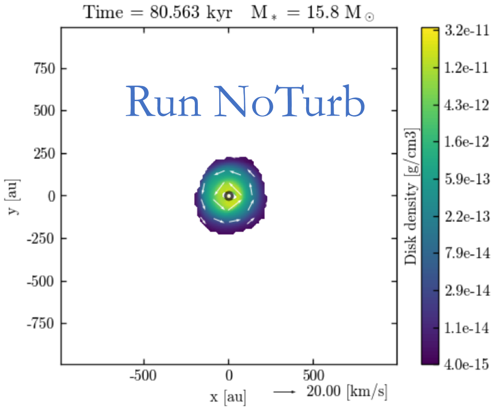


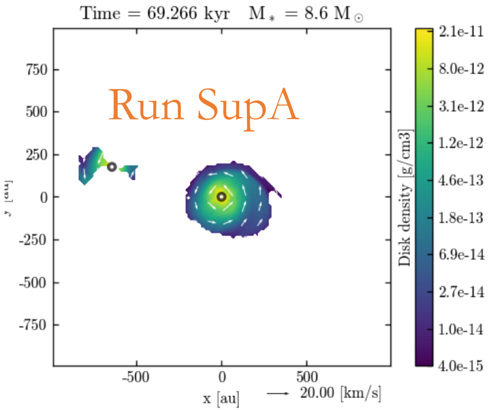
M = 0.5 μ = 2 Run SubA



Accretion disks

- Individual disks have similar properties :





$R_{disk} = \ 100 - 200 \text{ AU} < R_{disk,RHD} \sim 1000 \text{ AU}$ (MR+21a, A&A)

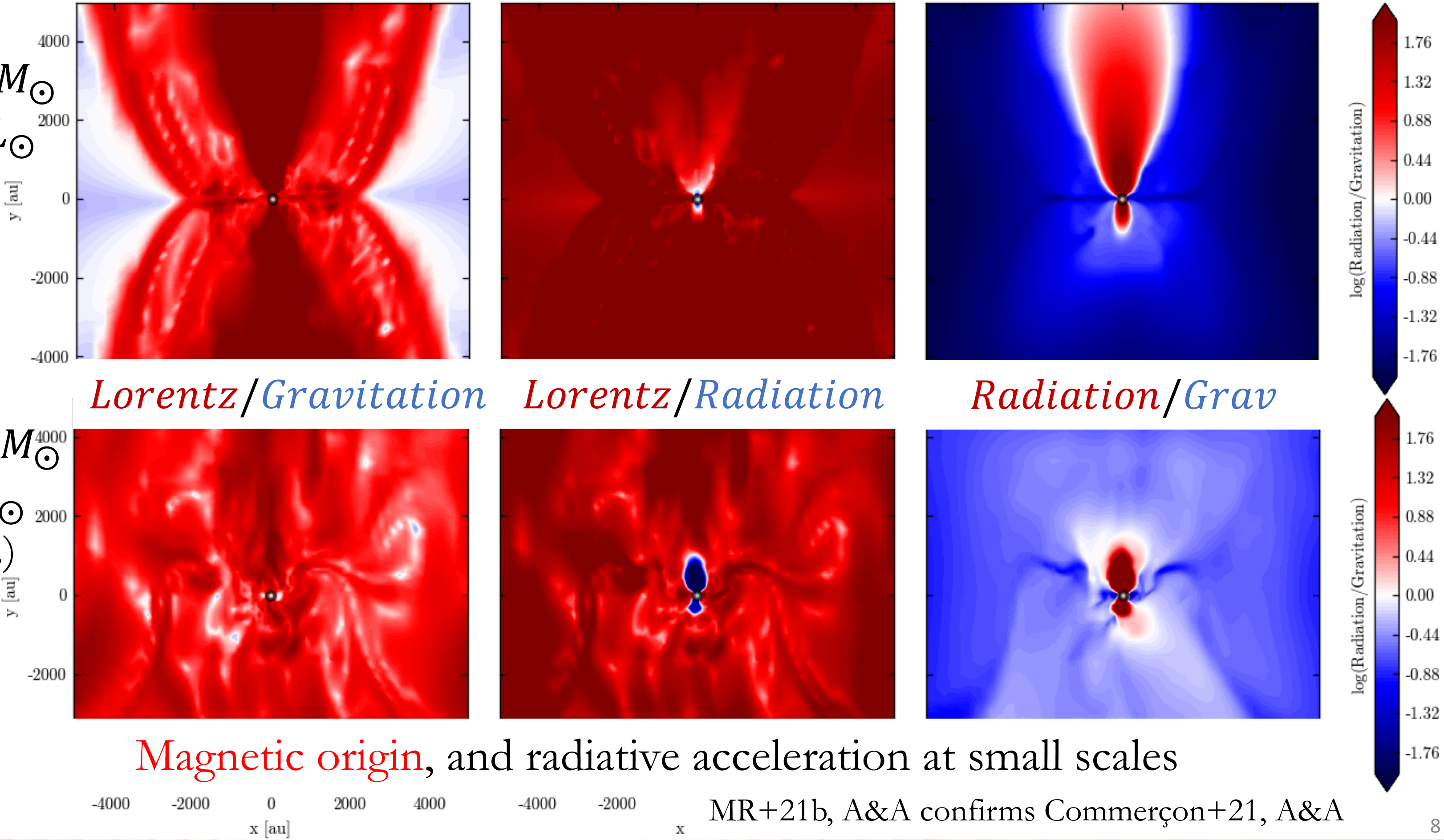
vs observations: 20-2000AU (Kraus+10, Johnson+15)

Radius consistent with magnetic regulation (Hennebelle+16)

Outflows origin: run NoTurb

$M = 10 M_\odot$
$L \sim 10^4 L_\odot$

$M = 23.8\ M_\odot$
$L \sim 10^5 L_\odot$
(Low-resol.)

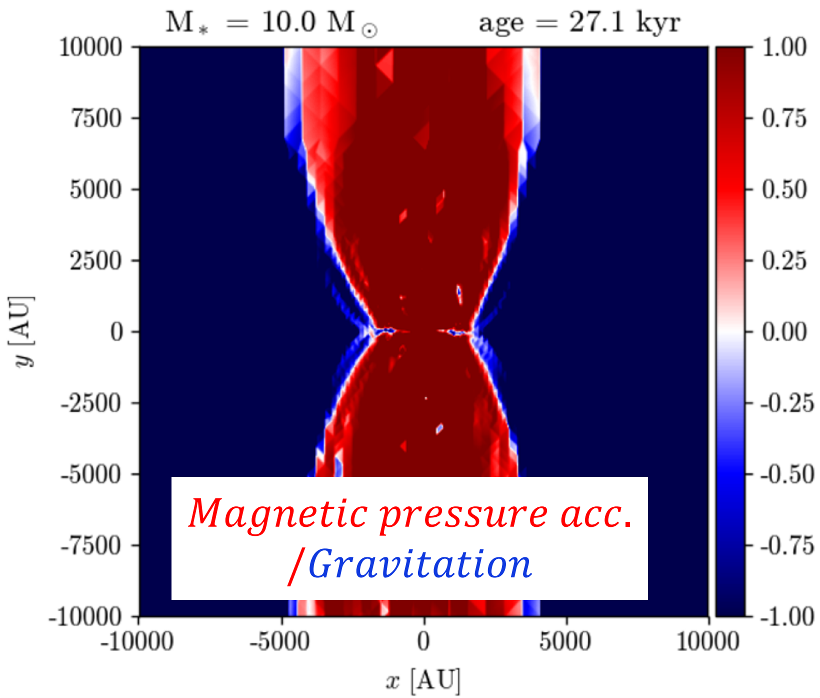


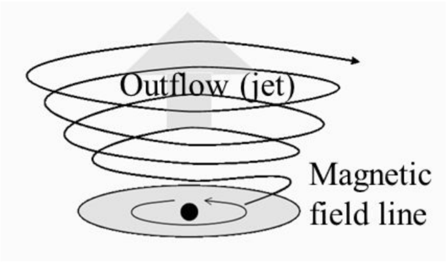
Magnetic origin, and radiative acceleration at small scales

MR+21b, A&A confirms Commerçon+21, A&A

Lorentz force decomposition

Lorentz acceleration = magnetic pressure gradient + magnetic tension





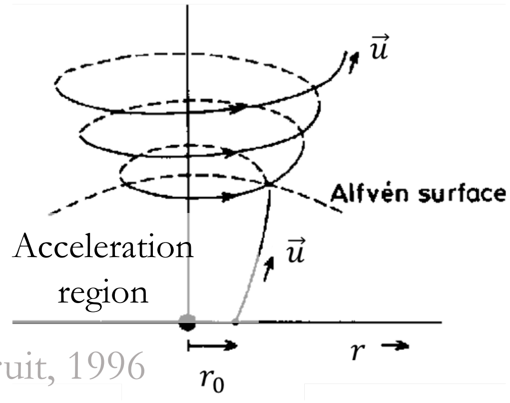
Credits: Spruit, 1996

- Magnetic tower flow

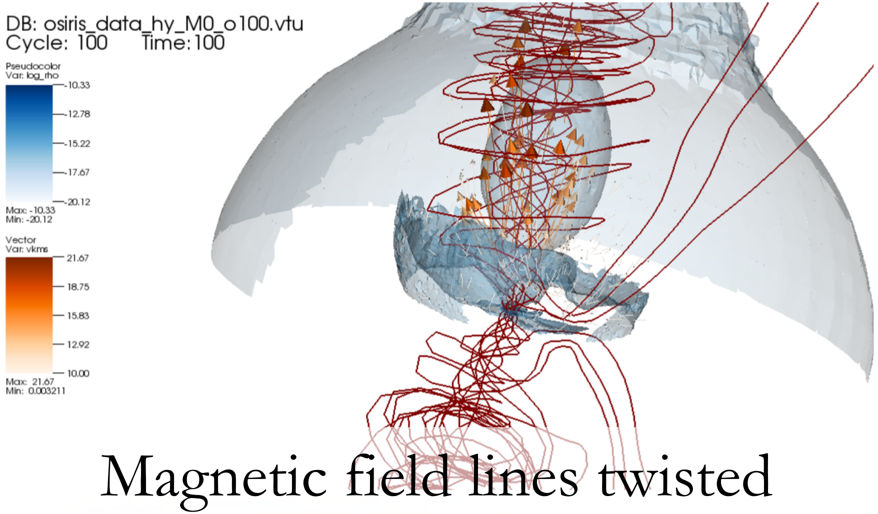
  Toroidal magnetic pressure

  (Lynden-Bell, 1997, 2003)

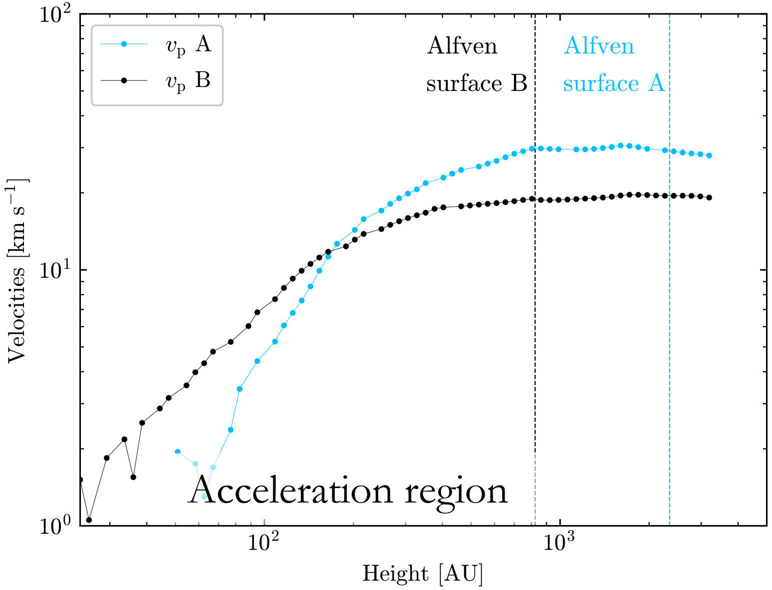
Magneto-centrifugal acceleration ? (Blandford & Payne, 1984)



Credits: Spruit, 1996



Magnetic field lines twisted



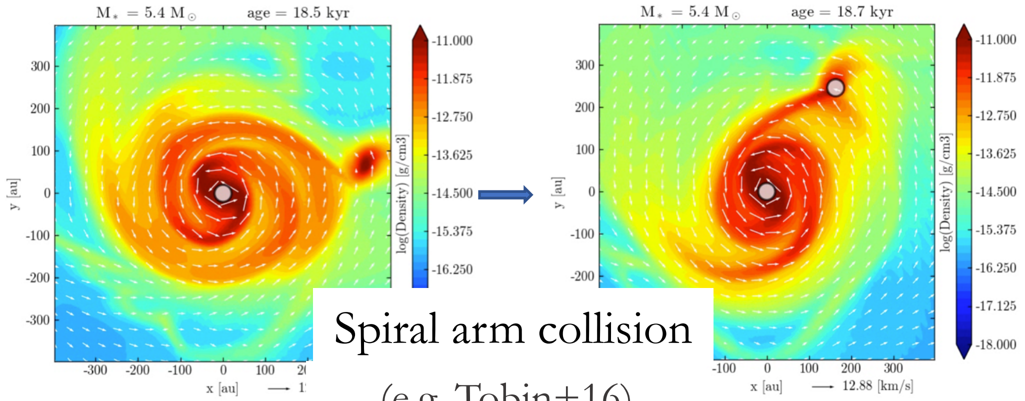
- ✓ Consistent with magneto-centrifugal acceleration
- ❖ dx<1 AU for numerical convergence (Kölligan & Kuiper, 2018)

Origin of multiplicity

- Fragments into sinks
- $1.1 < \mathit{Mass\ ratios} < 1.6$

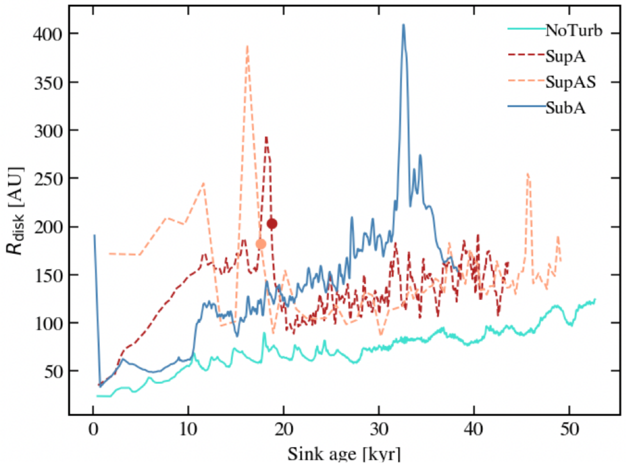
➤ What is the origin ?

➤ What is the impact of magnetic fields and turbulence ?



Spiral arm collision

(e.g. Tobin+16)



Turbulence ⟹ + Angular momentum ⟹ spiral arm growth ⟹ fragmentation

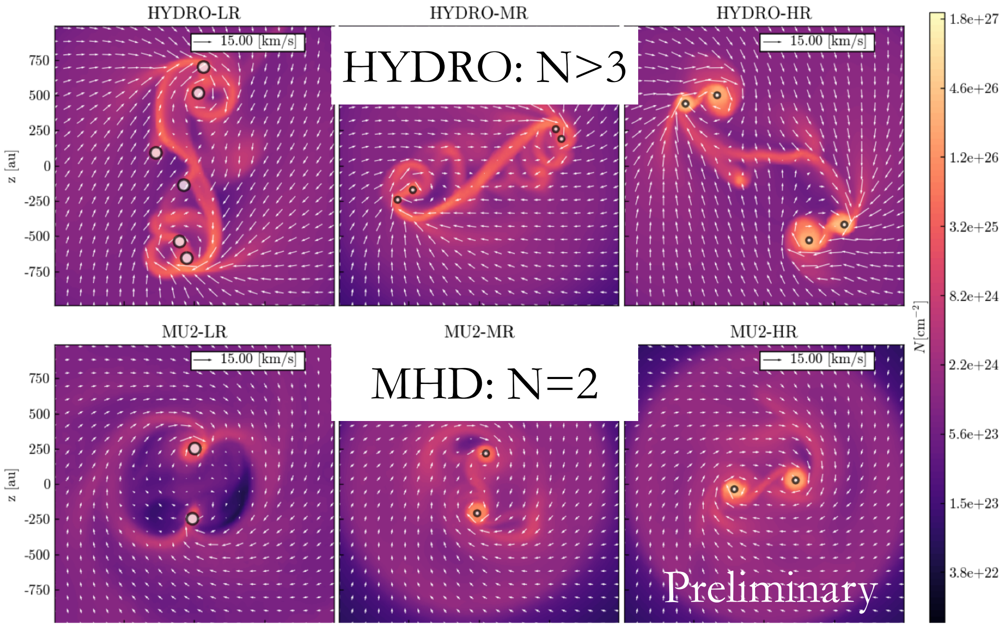
Magnetic braking ⟹ - Angular momentum ⟹ - spiral arm growth ⟹ fragmentation reduced

MR+21a, A&A

Does the multiplicity depend on the code ?

1. Capturing the fragmentation process
   - ➢ Spatial resolution

2. Capturing the evolution of fragments
   - ➢ Mergers or increasing orbital separation ?



vs

- ➢ Need to resolve the disks (more demanding in MHD), spiral arms, filaments…
- ➢ Need to go beyond symmetry assumptions ?

MR+21c, in prep

Conclusions

Accretion process?

- ✓ Disk-mediated accretion $R_{disk} = 100 - 200$ AU, smaller than in hydro
  HH80-81: $R \sim 170 - 300$ AU (Girart+18); Orion Src1: $R \sim 50$ AU (Ginsburg+18)
- ✓ No accretion by Rayleigh-Taylor instabilities (Mignon-Risse+20, A&A)

Multiplicity of massive stars?

- ✓ Interplay between turbulence and magnetic fields drives multiplicity (MR+21a, A&A)
- ✓ $1.1 < Mass\ ratios < 1.6$
- ❖ Need to resolve the fragmenting structures and /!\ with symmetries (MR+21c, in prep)

Origin of **outflows**?

- ✓ Magnetic origin (magnetic tower flow, Lynden-Bell, 1997) + radiative acceleration
  + hints of magneto-centrifugal acceleration
  (MR+21b, A&A)

The hybrid radiative transfer method (MR+20)

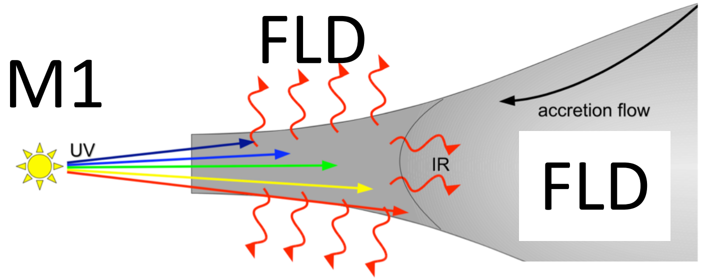
Flux-Limited Diffusion (FLD)
(Commerçon+11,14, González+15)
Implicit

M1 : RAMSES-RT (Rosdahl+13)
Explicit (reduced speed of light)

Why/when ?

- If radiative force important (factor ~100)
- Diskplane temperature (shielding effects)

only if mean free path resolved



How ?

Compile with FLD & M1
Namelist param: rt_protostar_m1