Hybrid Radiative Transfer for Massive Star Formation

Zooming in on Star Formation

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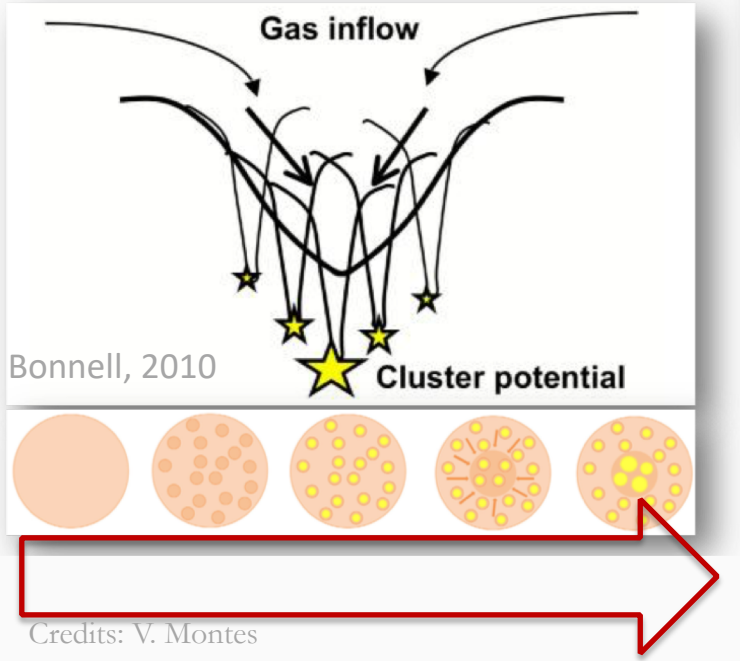
Context

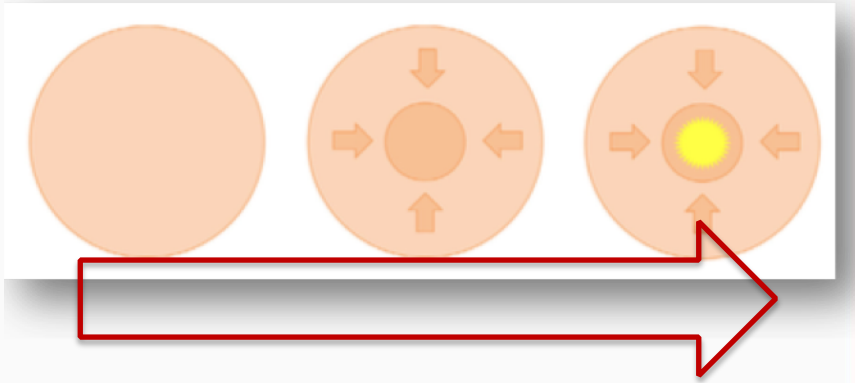
« Competitive Accretion » (Bonnell+04)

vs (?)

« Turbulent Core Accretion » (Mckee+03)

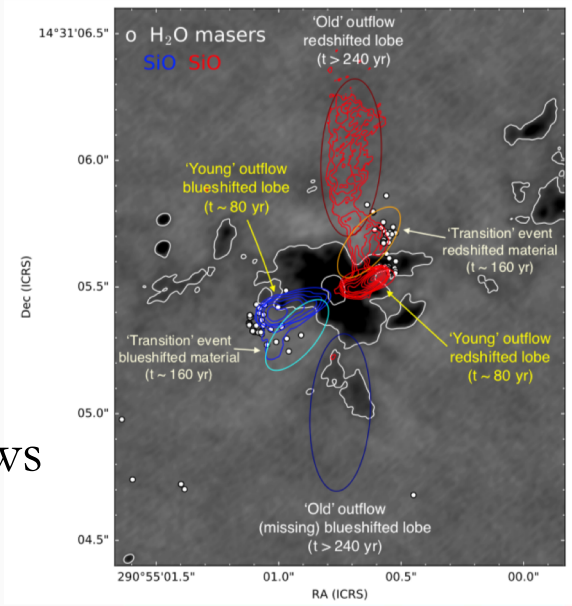


Credits: V. Montes

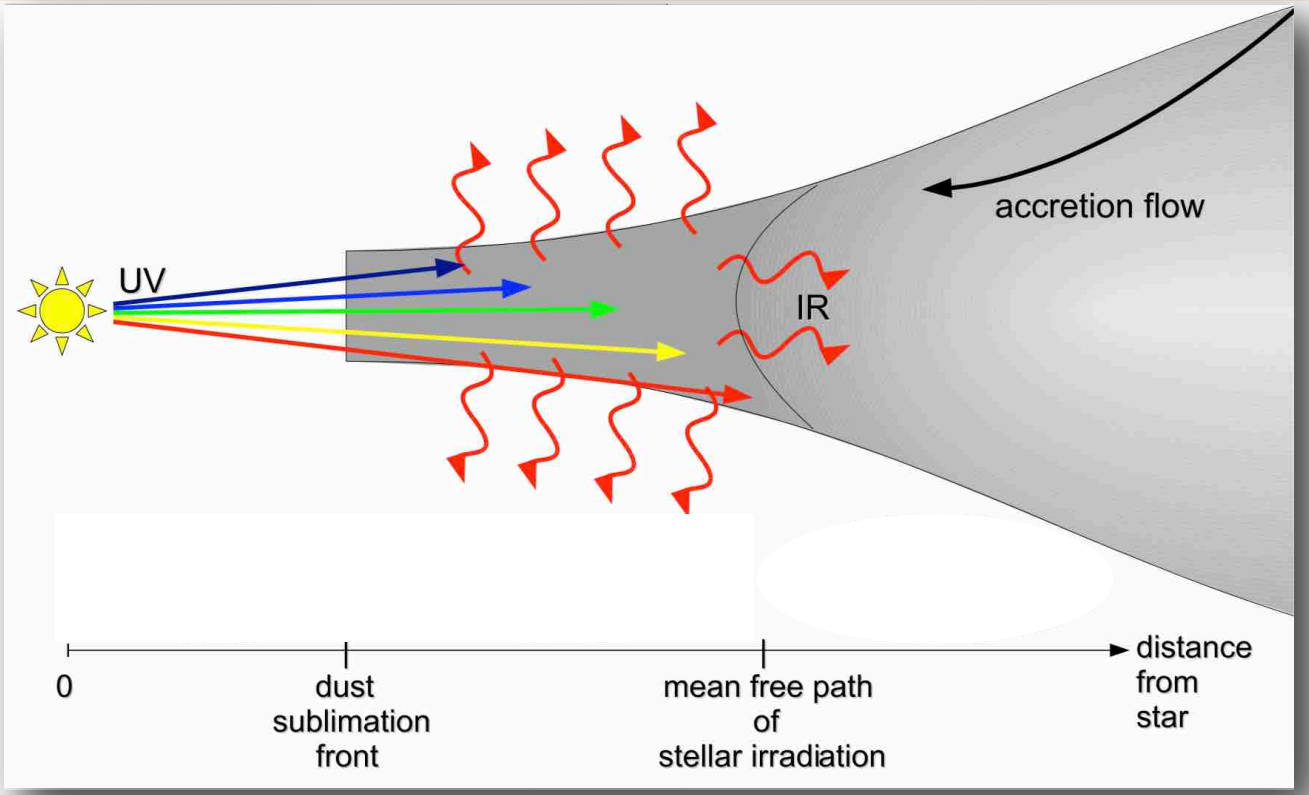


Explained by J. Molet & A. Rosen

Multi-directional outflows (Goddi+18)



Radiation pressure barrier problem



Credits:
Kuiper+10a

Explained
by R. Kuiper
& A. Rosen

- 1D

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

(Larson+1971, Kuiper+10a)

Maximal mass : 40 $M_\odot$

(Kuiper+10a ray-tracing+FLD)

- 2D

Disk accretion (Yorke & Sonnhalter, 02)

« Flashlight effect »

Maximal mass : 130 $M_\odot$

(Kuiper+10a ray-tracing+FLD,
Yorke & Sonnhalter 02 FLD)

- 3D

(Kuiper+10a ray-tracing+FLD,
Commerçon+11b FLD,
Rosen+17 HARM2,
Harries+17 MC)

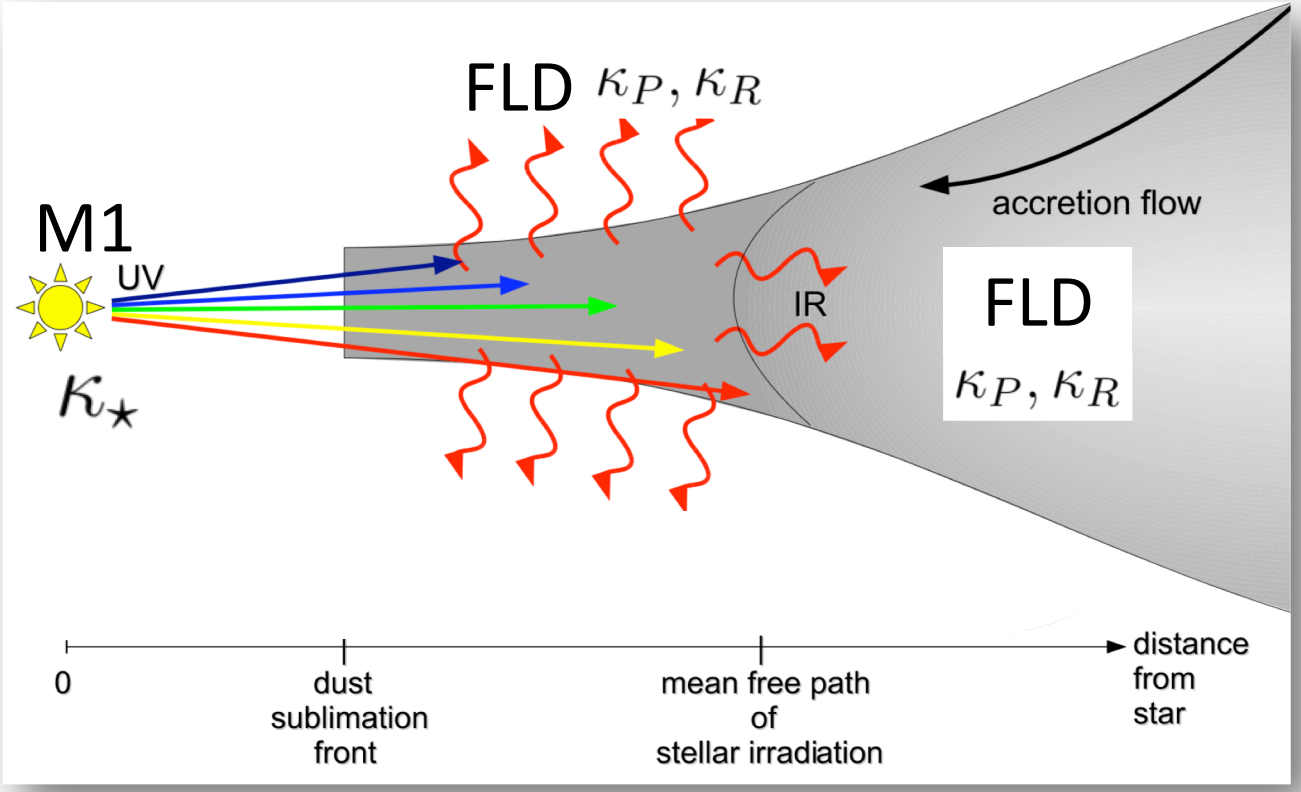
Flux-Limited Diffusion and M1

• Flux-Limited Diffusion (FLD) 1. Radiative energy ▪ Hyp : Optically-thick medium ▪ Does not conserve shadows	• M1 method 1. Radiative energy 2. Radiative flux ▪ More advanced ▪ More computationally expensive

Shadow test, González+07

The Hybrid (M1+FLD) approach

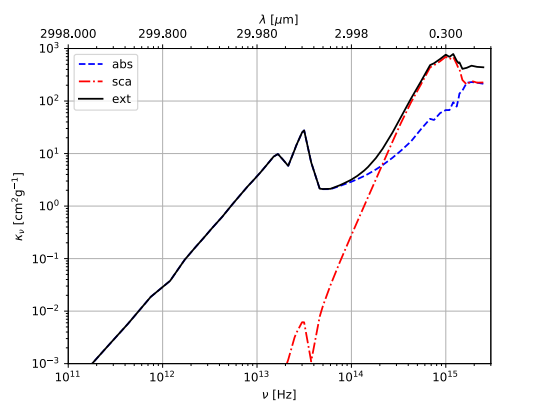
Flux-Limited Diffusion (FLD)	M1 : RAMSES-RT
(Commerçon+11, González+15)	(Rosdahl+13)
Implicit	Explicit (RSLA)
Star-formation	Reionization simulations

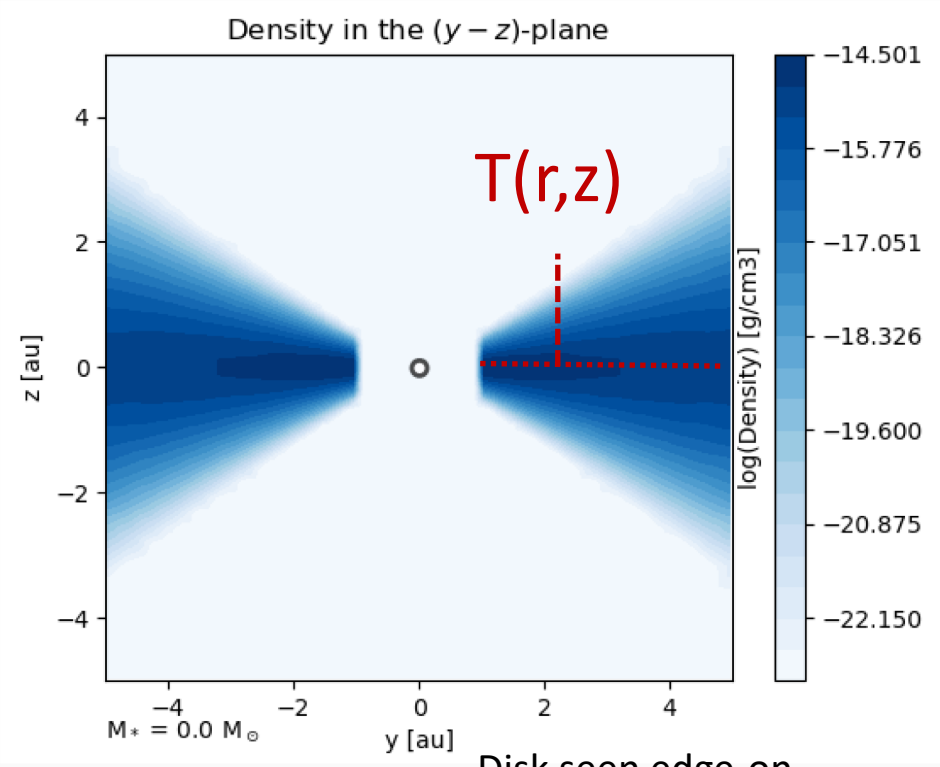


Static test : pure radiative transfer

- A central star $T_\star$ $R_\star$

- Opacity (d/g = 1%)



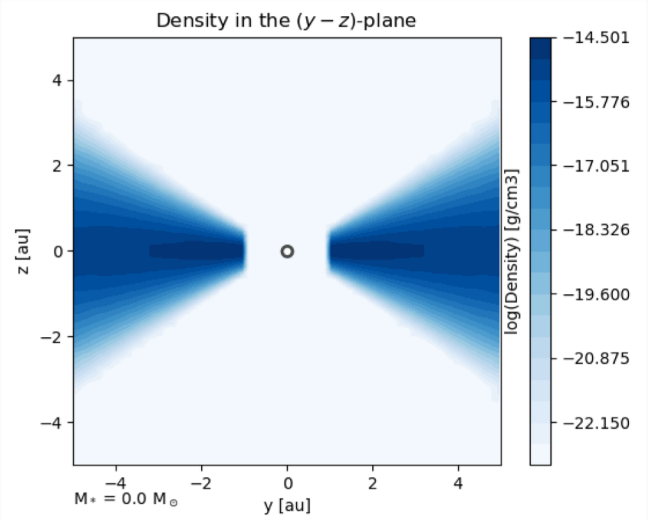


Disk seen edge-on

- Free parameter : optical-depth $\boldsymbol{\tau}$

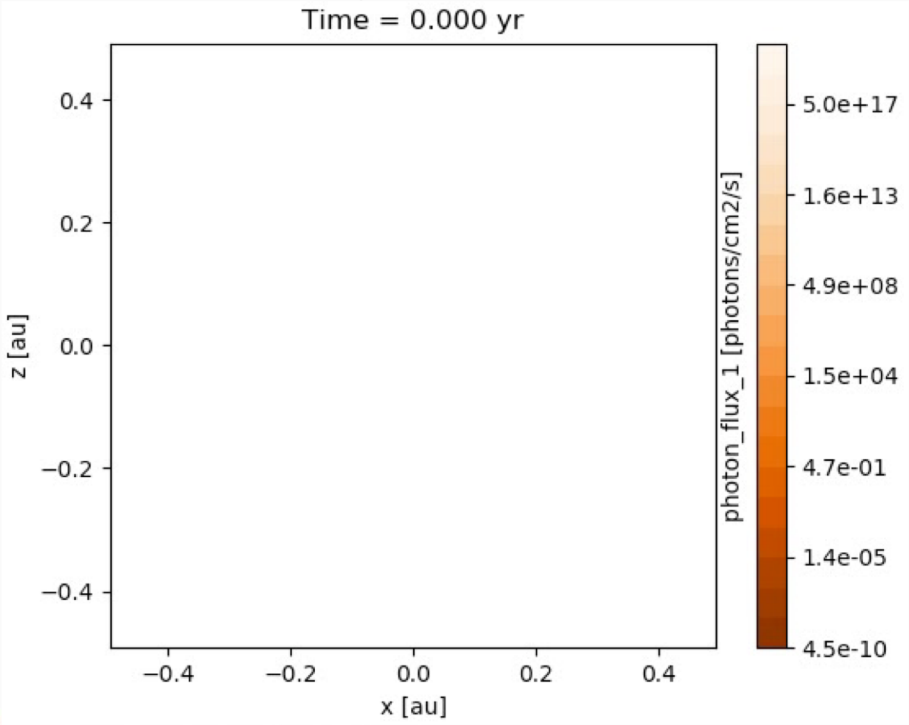
➢ Temperature comparison after stationarity with RT codes : MCFOST (Pinte+06), RADMC-3D (Dullemond+12)

Pascucci+04, Pinte+09

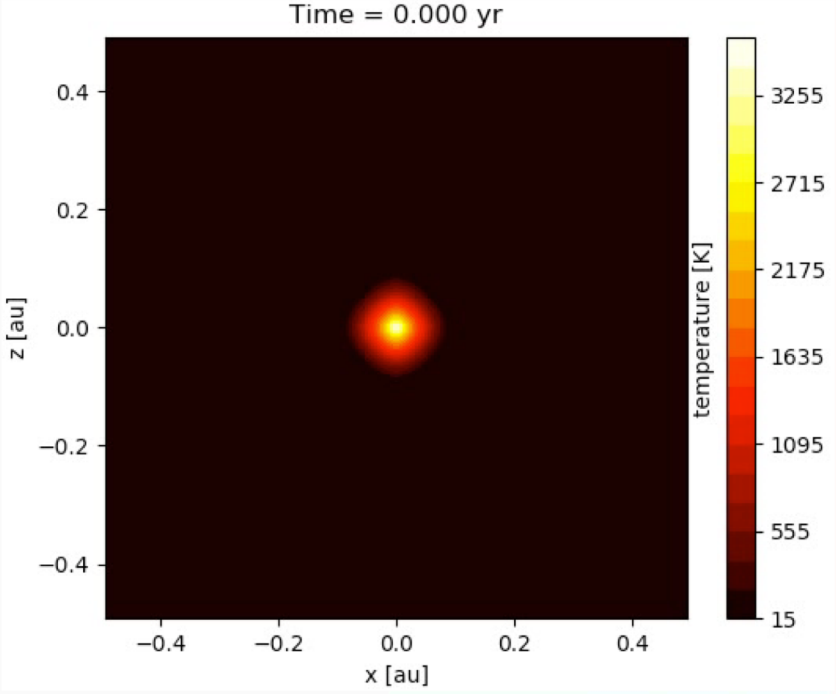


Density

M1 photons



Temperature

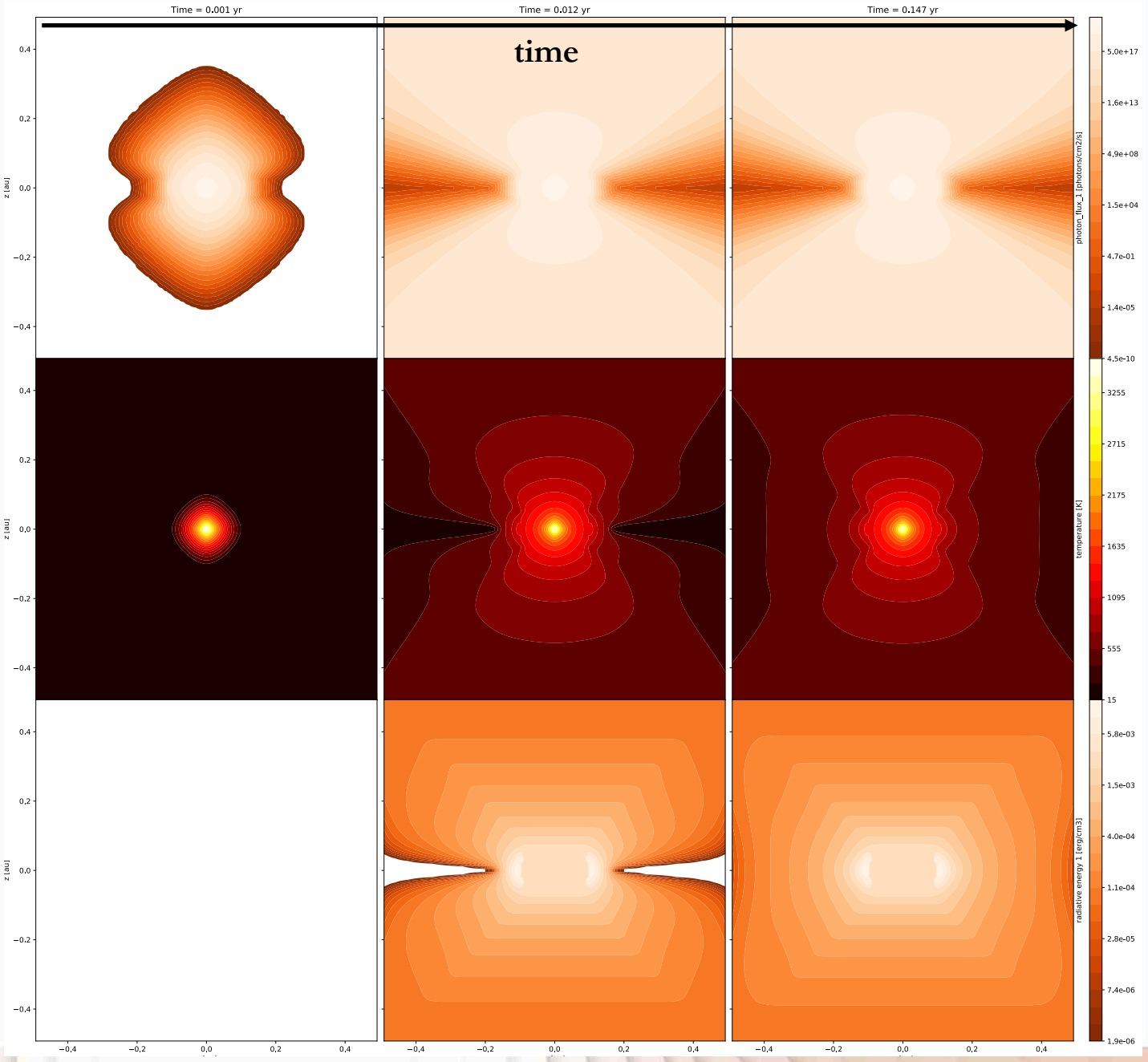


M1 + FLD

M1 photons

Temperature

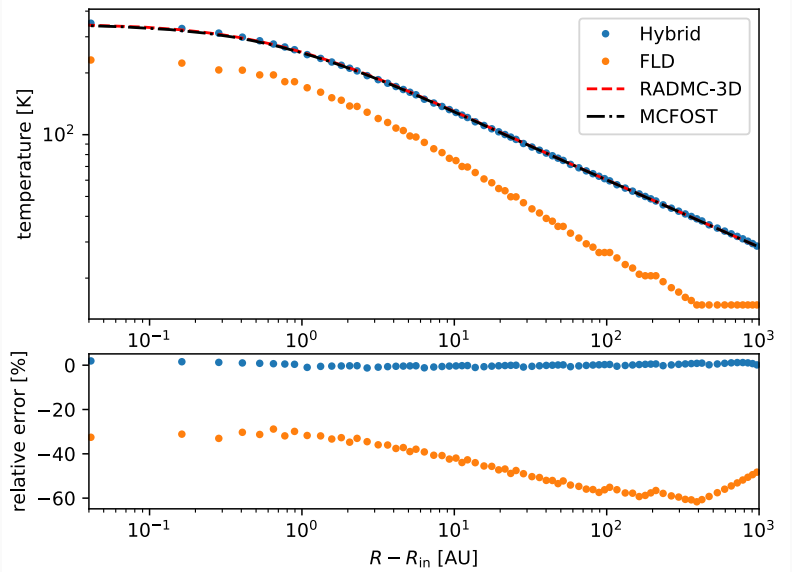
FLD photons



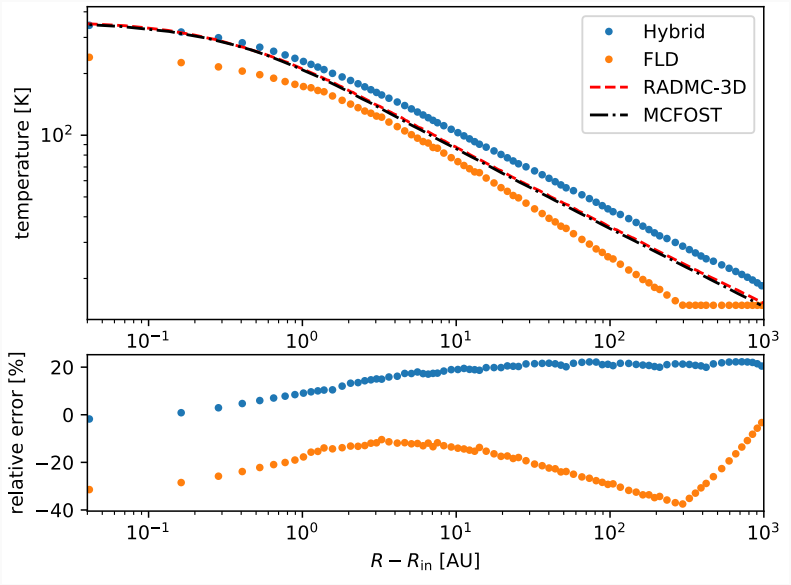
Raphaël Mignon-Risse

Temperature profile

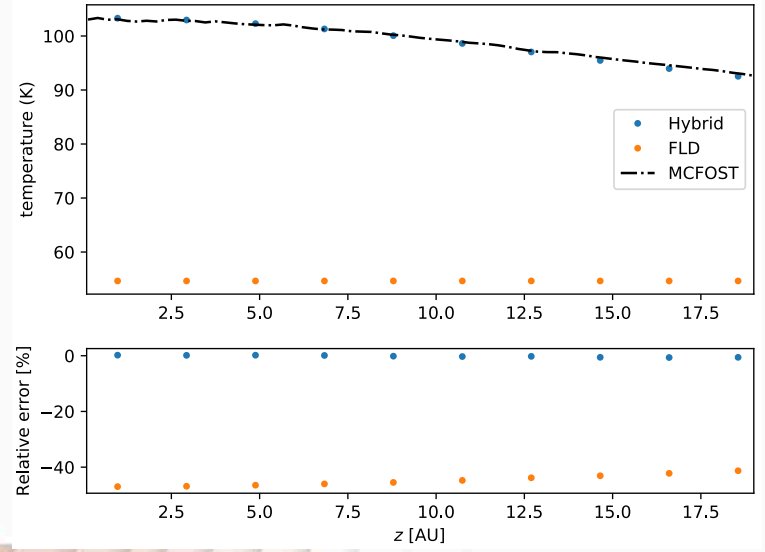
$\tau = 0.1$ Error max: ~2%



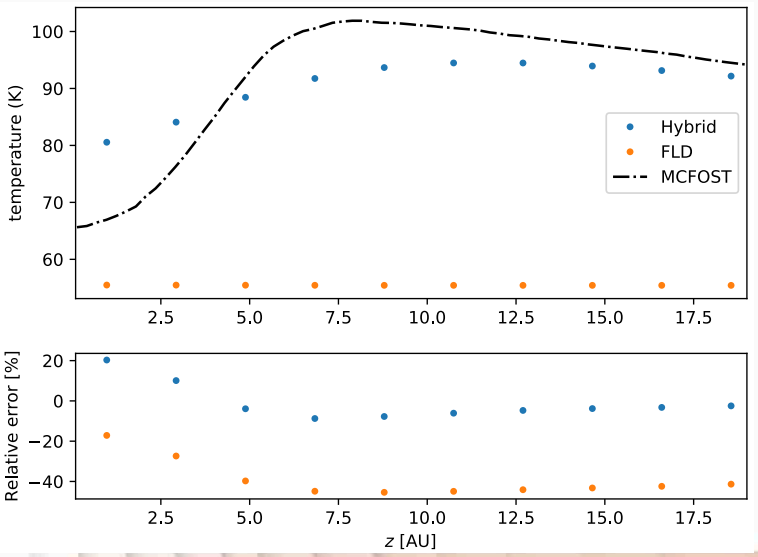
$\tau = 100$ Error max: ~25%



Vertical profile at 20AU Error max: ~4%



Error max: ~20%

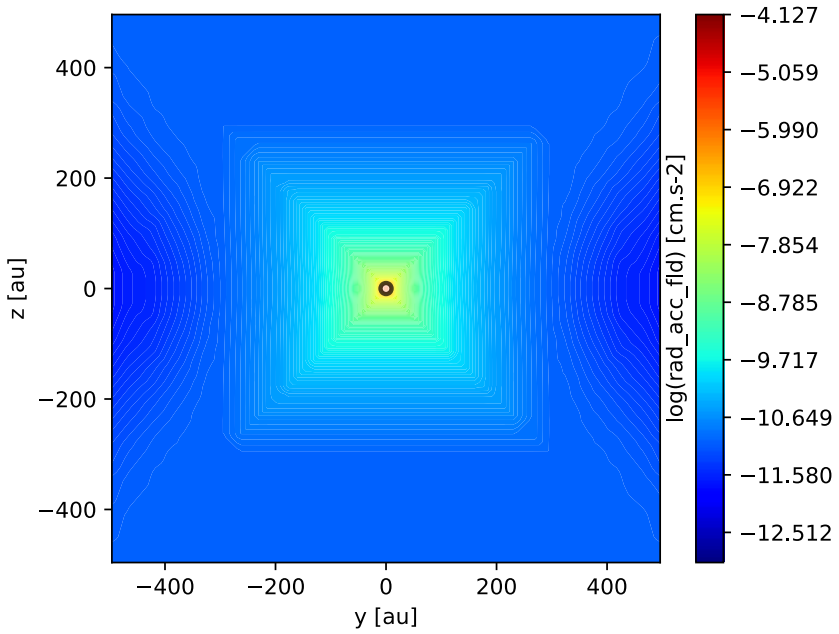


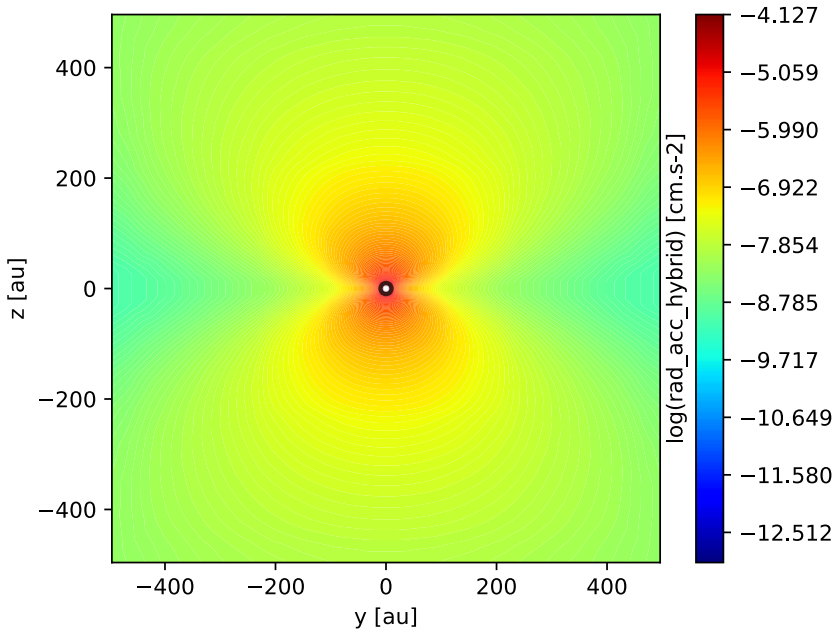
Radiative Force

FLD

Hybrid

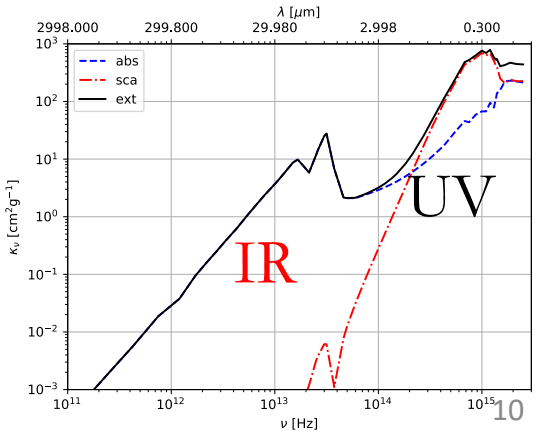
$\tau = 100$
T=5800K





~100 times greater with the Hybrid

$$F_{rad} \propto \kappa_\nu$$



R. Kuiper's
& A. Rosen's talks

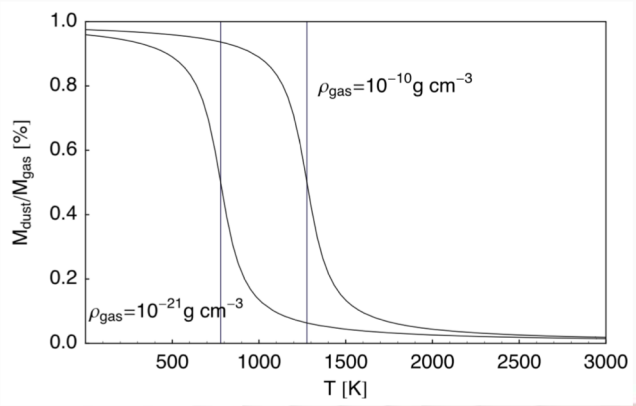
Collapse of a massive pre-stellar core

Initial conditions (Rosen+16):

- Mass: 150 M_{sol}, radius 0.1pc, $\tau_{ff} = 42.6$kyr
- Density profile $\rho(r)\ \alpha \frac{1}{r^{1.5}}$
- $0.001 < \frac{E_{rot}}{E_{grav}} = 0.04 < 0.1$ (Goodman+93) solid-body rotation

RAMSES (Teyssier 2002) 3D simulations including:

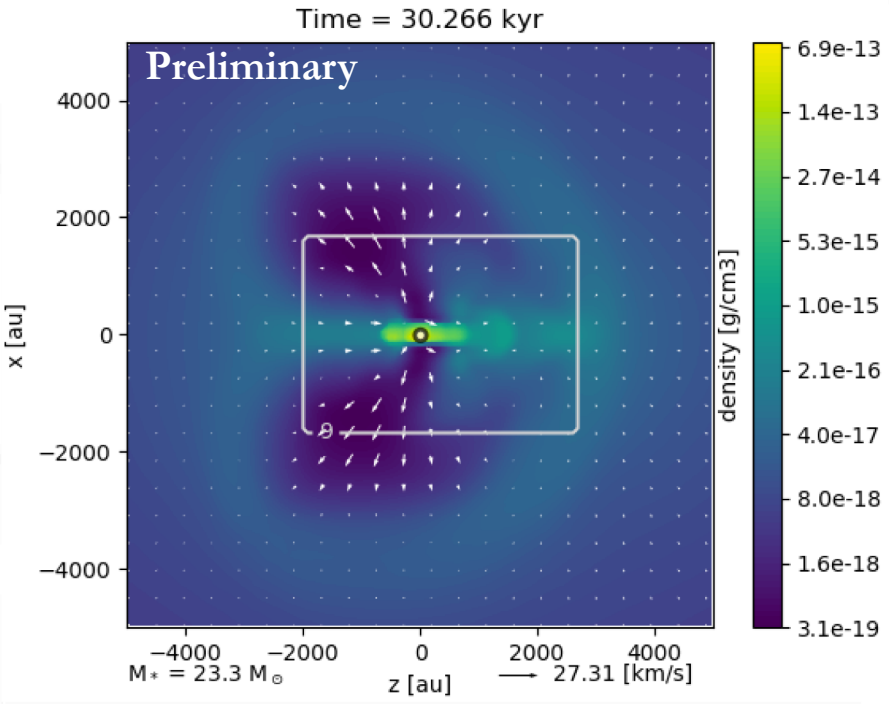
- Hydrodynamics
- Radiative Transfer (Commerçon+11, González+15, Rosdahl+13)
- Sink particles (Bleuler & Teyssier 2014) + NO outflow model
- AMR refinement criteria: Jeans length (12), sink
- Dust sublimation



Kuiper+10a

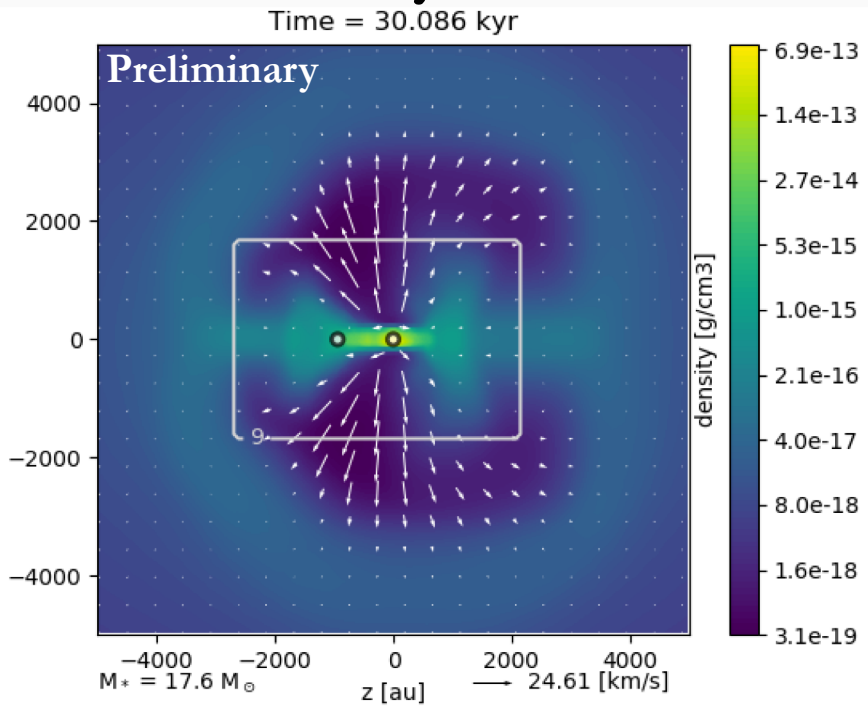
Disk edge-on views

FLD



- 1 (or few) sink(s)
- M = 23.3 $M_\odot$
- Polar outflows > 2000 AU launching for M >15 $M_\odot$

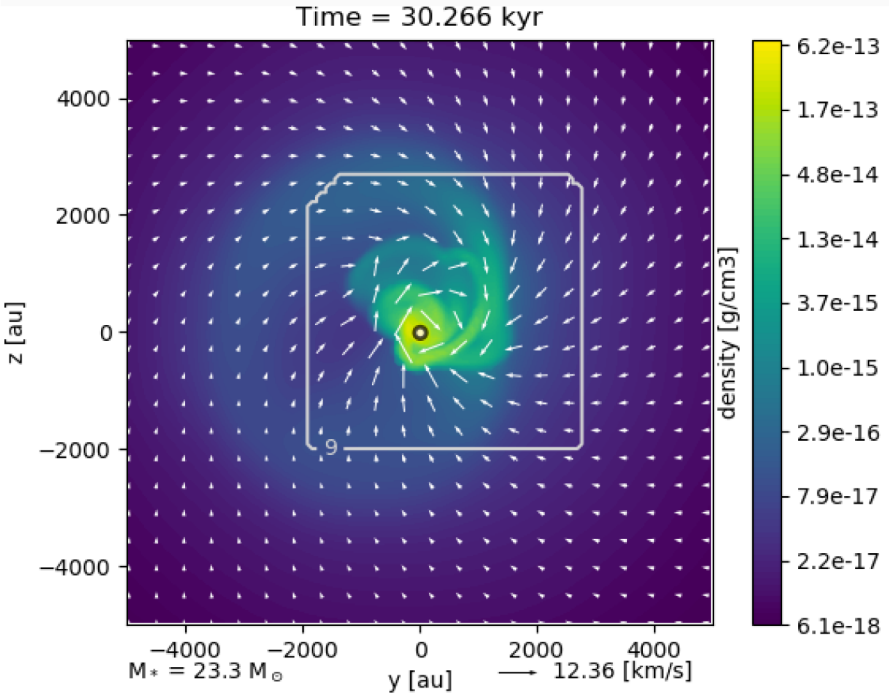
Hybrid



- 1 (or few) sinks
- M = 17.6, 0.03 $M_\odot$
- Polar outflows > 3000 AU launching for M >12 $M_\odot$

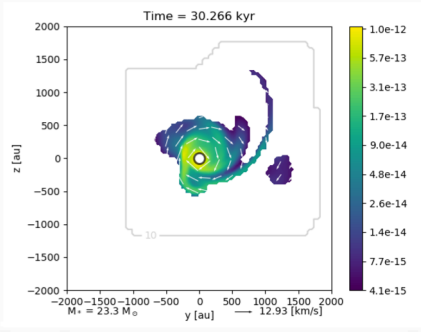
Disk face-on views

FLD

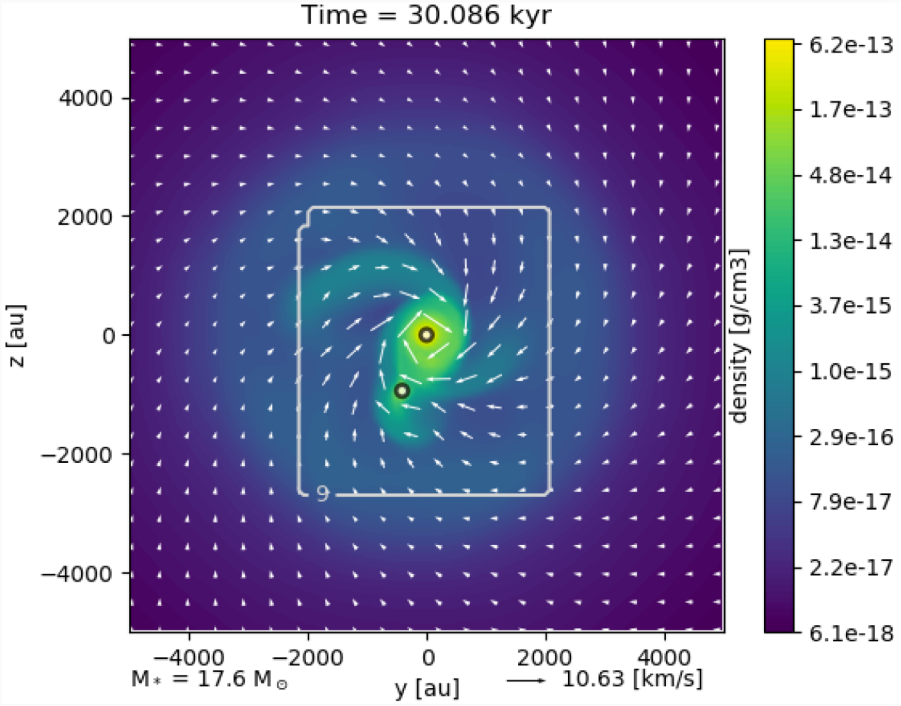


- 1 (or few) sink(s)
- M = 23.3 $M_\odot$
- Disk M_{disk}= 18.8 $M_\odot$;
  $R_{disk,90\%}$~ 840 AU

Disk criteria : Joos+12

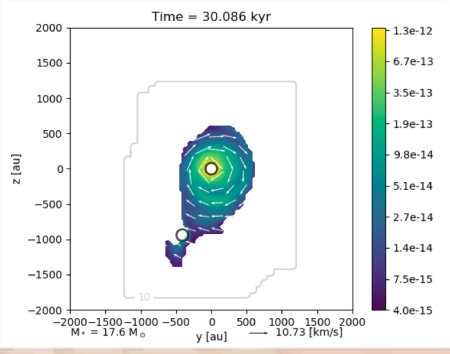


Hybrid

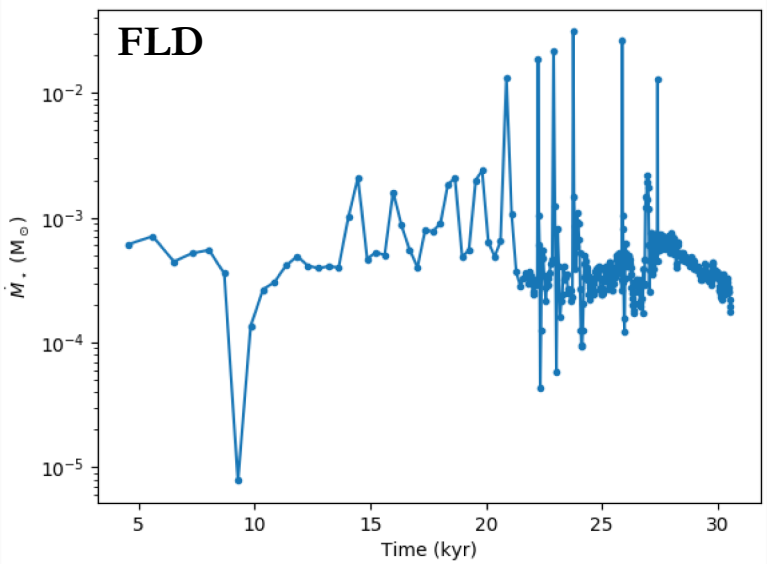


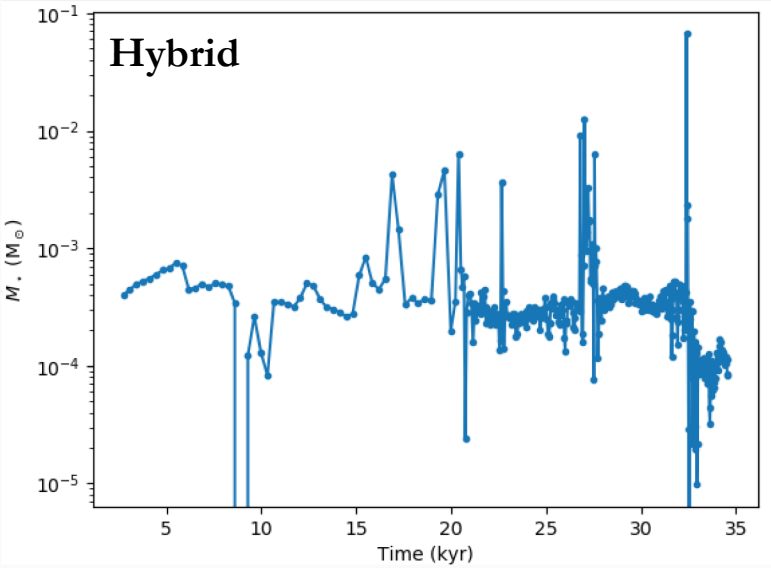
- 2 sinks
- M = 17.6, 0.03 $M_\odot$
- Disk M_{disk}= 16.9 $M_\odot$
  $R_{disk,90\%}$~ 630 AU

Disk sizes : Klassen+16



Accretion rates





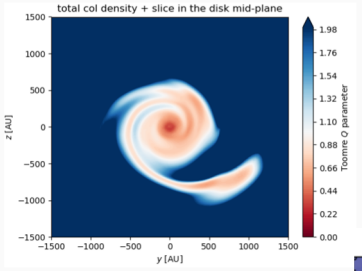
- Similar accretion rates at first order
- ✓ $10^{-4} < \dot{M} < 10^{-2} M_\odot.yr^{-1}$ **consistent with observations** (Motte+18 and ref. therein)
- peaks = accreted companion

Conclusions & Perspectives

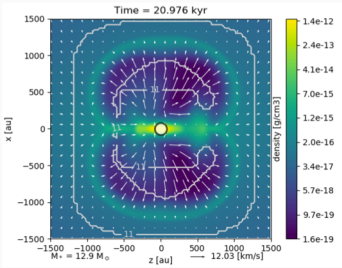
- ✓ Static validation test of the Hybrid method:
  - ➢ Valid in opt. thin and thick regimes + self-shielding
  - ➢ Hybrid radiative force ~100 times greater than FLD

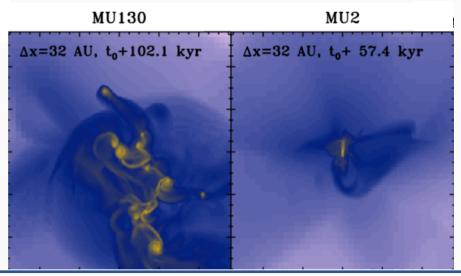
- ✓ Hybrid RT in the collapse of massive prestellar core (Mignon-Risse et al., in prep.)
  - ➢ Stronger radiative outflows (+50% in extent)
  - ➢ Less massive star
  - ➢ $\dot{M}$ and disk size consistent with previous studies (Klassen+16)

- Perspectives: Disk stability



Rayleigh-Taylor instabilities ?





- ❑ Collapse with Non-Ideal MHD (Commerçon+11, González+ in prep.)