Radiative Transfer and Star Formation

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Programme PhD Track

2019 B.Sc. 2023 **M1** 2024 **M2** 2025

Bachelor of Science

- Spécialisation en Physique
- Mineure en mathématiques appliquées et en philosophie
- Stage en astrophysique théorique (1.5 an) a NYUAD – Andrea MACCIO

M1: Parcours Physique

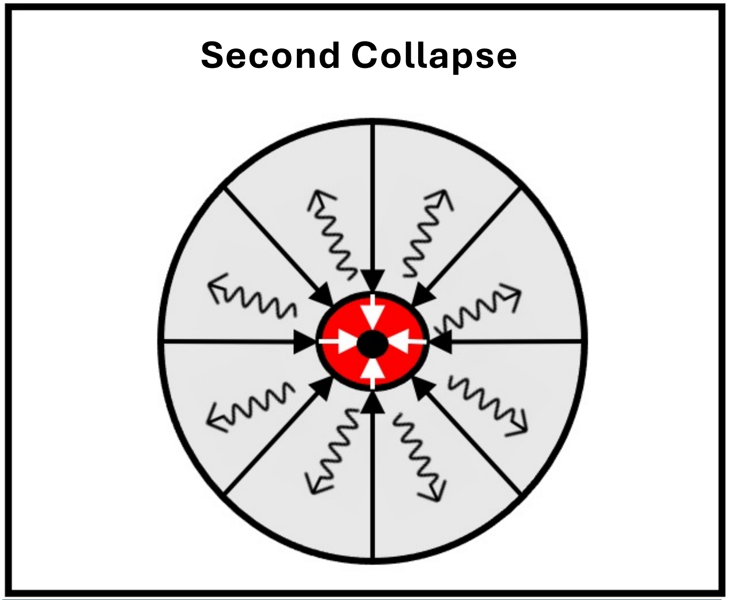
- Cours du master High Energy Physics (HEP)
- Stage 4 mois AIM/LMPA – Patrick HENNEBELLE

M2: Physique des Plasmas et de la Fusion

- Spécialisation Plasmas Astrophysiques
- Stage 5.5 mois AIM/LMPA – Matthias GONZÁLEZ

The collapse of dense molecular clouds

RT is important for:
- Realistic temperature gradients
- Dust enrichment
- Formation of planets



Optically Thin Fluid
- H_2 dissociates
- Quasi-isothermal contraction

Modeling complicated by:
-Scale dynamics
-Variety of processes

Need approximations!

Pillars of Creation — JWST. Credit : NASA / ESA / CSA / STScI – 2022

RAMSES branches

	RAMSES ISM	RAMSES TINE
Photon Wavelengths:	…	…
Moment Model:	…	…
Solver Type:	…	…
Flux Limiting Scheme:	…	…

- Let’s quickly walk through the differences in RT treatment:

The radiative transfer equation

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \boldsymbol{n} \cdot \nabla I_\nu = -\chi_\nu I_\nu + \eta_\nu,$$

where $I_\nu(\boldsymbol{x}, \boldsymbol{n}, t)$ is the radiation specific intensity, $\chi_\nu(\boldsymbol{x}, \boldsymbol{n}, t)$ is the absorption coefficient and $\eta_\nu(\boldsymbol{x}, \boldsymbol{n}, \boldsymbol{t})$ is the emission coefficient.

ISM – Gray photons

Difference 1: Photon wavelength

TINE – Multigroup photons

Moment models

$$E_r(\mathbf{x}, t) = \frac{1}{c} \int_0^\infty \int_{S^2} I_\nu(\mathbf{x}, \mathbf{n}, t)\, d\Omega\, d\nu,$$

$$\mathbf{F}_r(\mathbf{x}, t) = \int_0^\infty \int_{S^2} I_\nu(\mathbf{x}, \mathbf{n}, t)\, \hat{\mathbf{n}}\, d\Omega\, d\nu,$$

$$\mathbb{P}_r(\mathbf{x}, t) = \frac{1}{c} \int_0^\infty \int_{S^2} I_\nu(\mathbf{x}, \mathbf{n}, t)\, \hat{\mathbf{n}} \otimes \hat{\mathbf{n}}\, d\Omega\, d\nu.$$

$$\frac{\partial E_\nu}{\partial t} + \nabla \cdot \mathbf{F}_\nu = -\rho \kappa_\nu c E_\nu + S_\nu,$$

$$\frac{\partial \mathbf{F}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = -\rho \kappa_\nu c \mathbf{F}_\nu.$$

Difference 2: Moment model

Algorithm

Timestepping with the Courant–Friedrichs–Lewy condition:

$$C = \frac{u\Delta t}{\Delta x} < C_{max},$$

Implicit solver + large number of iterations.

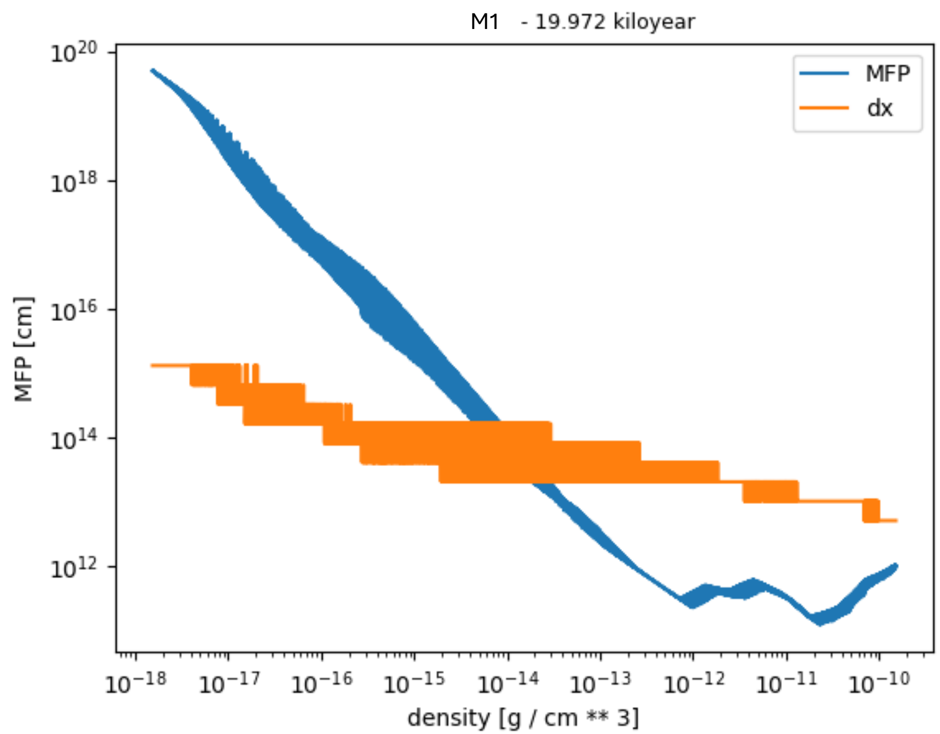
Explicit solver + reduced speed of light.

$$\tilde{c} = 10^{-4}c.$$

Difference 3: Algorithm

Flux limiting scheme

Difference 4: Flux Limiting Scheme



Problem - Overdiffusivity
Bouchut et al. (2004)

Trapped photons
Rosdhal et al. (2015)
RAMSES Tine

$$E_s = \frac{2}{2+3\tau_c} E_r, \quad \mathbf{F}_s = \mathbf{F}_r,$$

$$E_t = \frac{3\tau_c}{2+3\tau_c} E_r, \quad \mathbf{F}_t = \mathbf{0},$$

Flux limiter
Minerbo (1978)
RAMSES ISM

$$\mathbf{F}_\mathrm{r} = -\frac{c\lambda}{\sigma_\mathrm{R}} \nabla E_\mathrm{r}, \qquad R = |\nabla E_\mathrm{r}|/(\sigma_\mathrm{R} E_\mathrm{r})$$

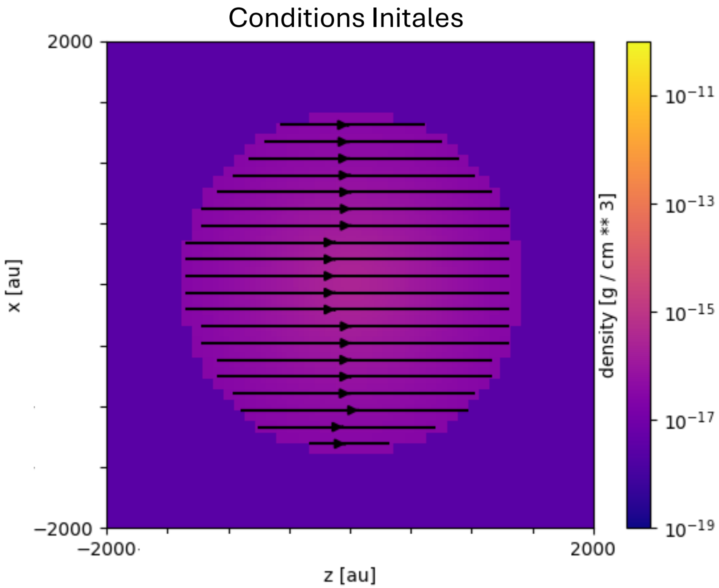
$$\lambda = \begin{cases} 2/(3+\sqrt{9+12R^2}) & \text{if } 0 \le R \le 3/2, \\ (1+R+\sqrt{1+2R})^{-1} & \text{if } 3/2 < R \le \infty. \end{cases}$$

RAMSES branches: Summary

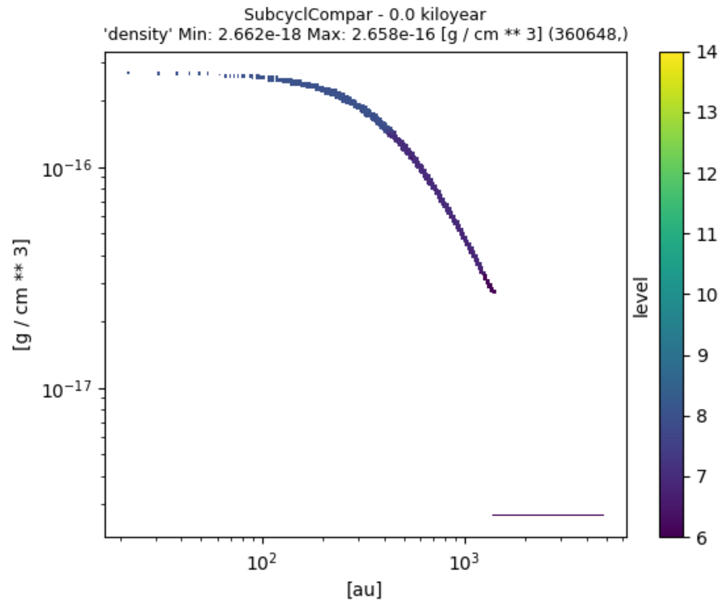
	RAMSES ISM (FLD)	RAMSES TINE (M1)
Photon Wavelengths:	Gray	Multigroup
Moment Model:	Flux Limited Diffusion	M1
Solver Type:	Implicit	Explicit
Flux Limiting Scheme:	Minerbo Limiter	Trapped Photons

- Protostellar collapses have historically been studied in RAMSES ISM
- RAMSES TINE has an advantageous treatment of RT, but is not made with smaller scales in mind
- My main contribution so far: Adapting RAMSES Tine to the scales of the ism, and implementing matching opacity computations from Vaytet et al. (2013)

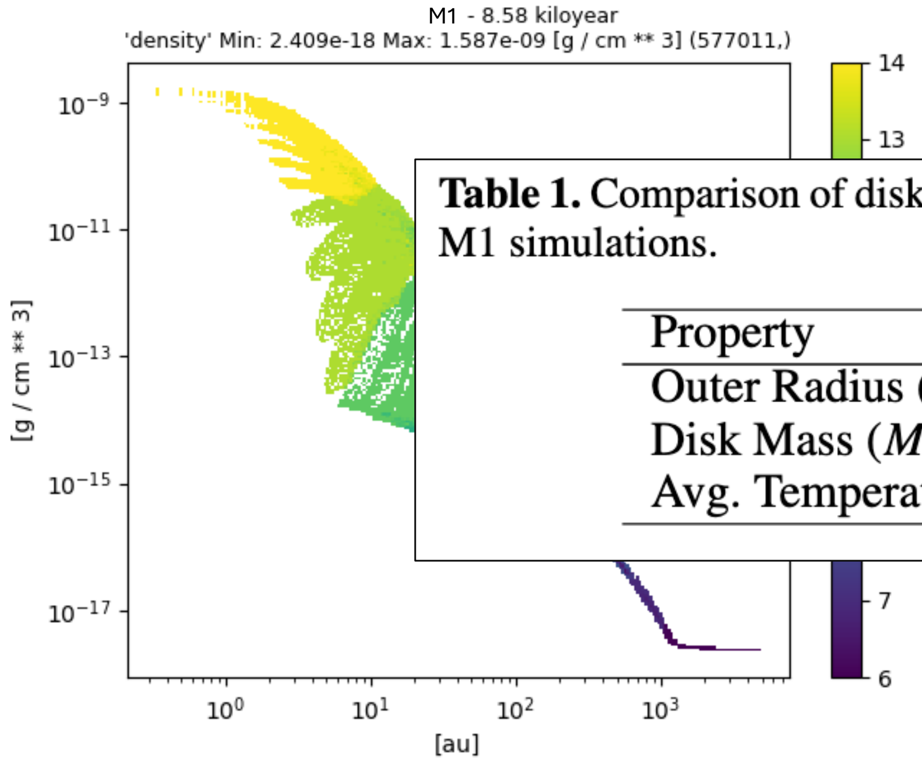
Initial conditions



$M_{core} = 1\ M_\odot$
$R_{core} \approx 1400$ AU
H_2 and He in solar proportion
$Z = Z_\odot$
$\tau_{ff} \approx$ 8,5 Kiloyears
T = 10 K
$L_{box} \approx 5600$ AU
Dust to gas ratio = 1/100



Simulation properties at free fall time



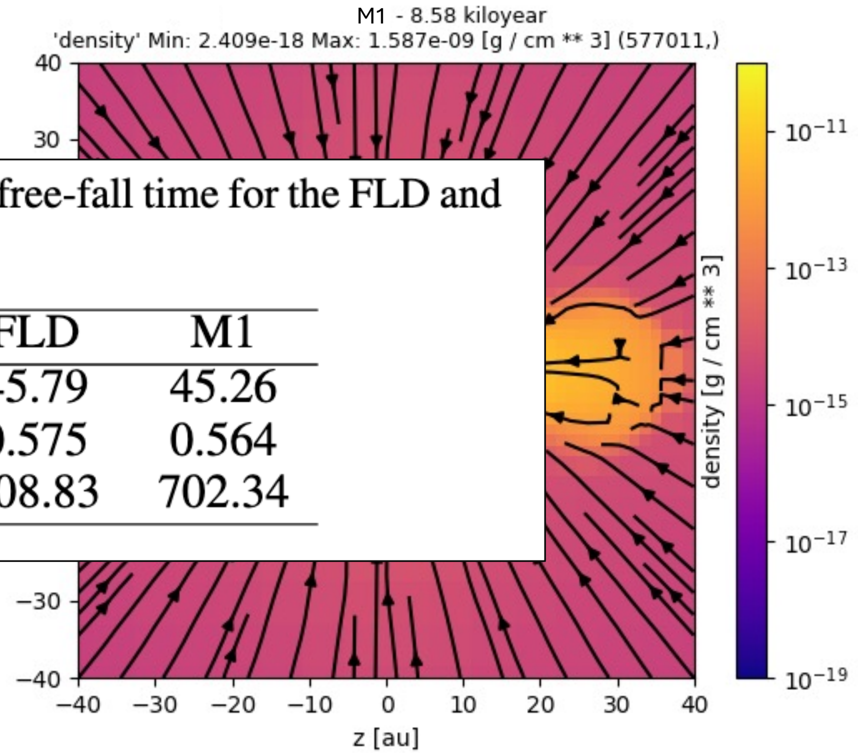
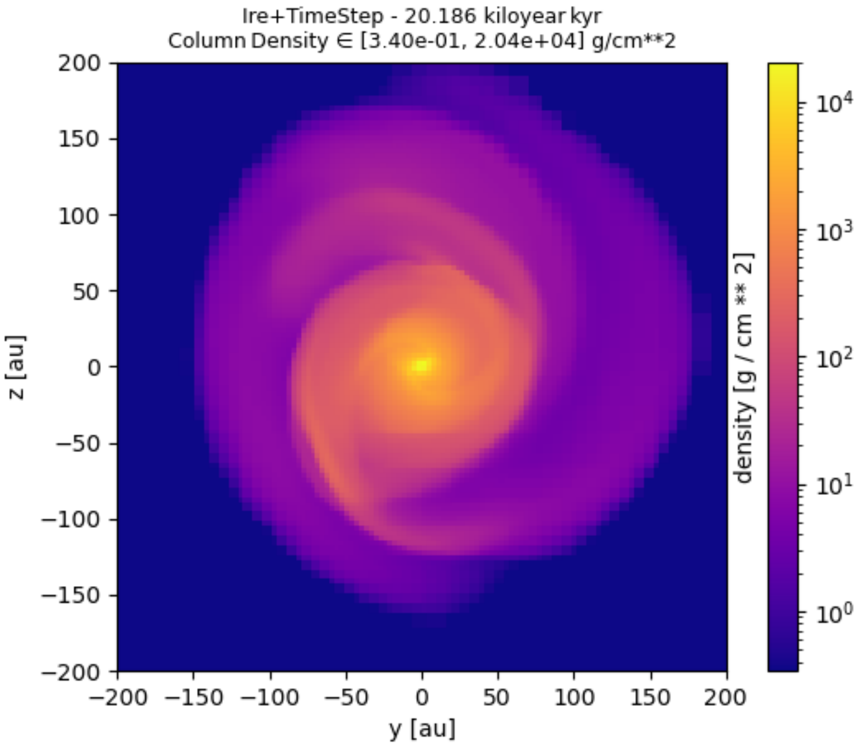
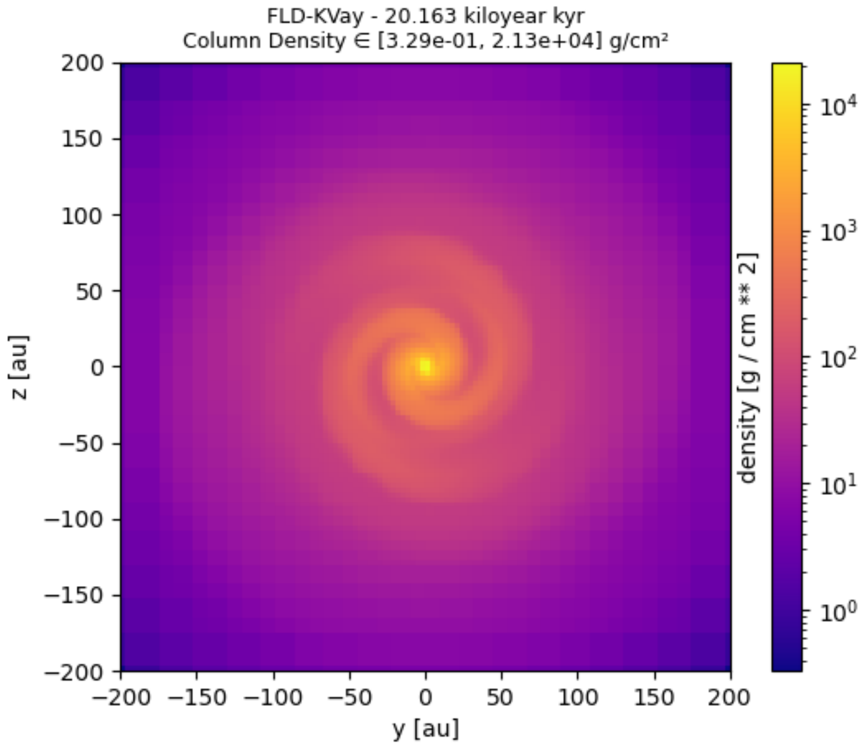


Table 1. Comparison of disk properties at free-fall time for the FLD and M1 simulations.

Property	FLD	M1
Outer Radius (AU)	45.79	45.26
Disk Mass ($M_\odot$)	0.575	0.564
Avg. Temperature (K)	608.83	702.34

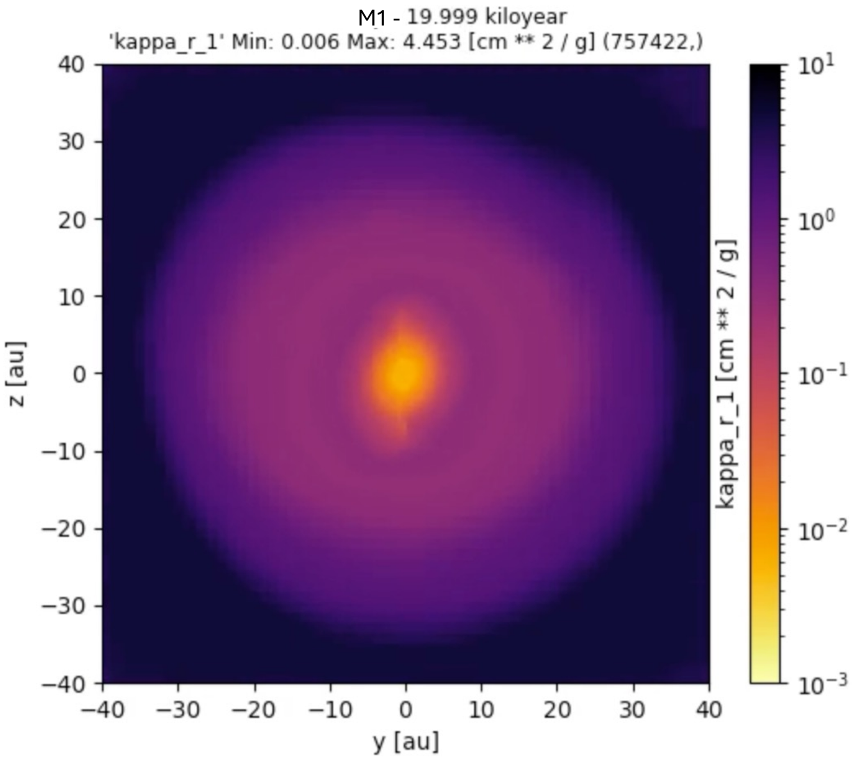
Later times – disk evolution

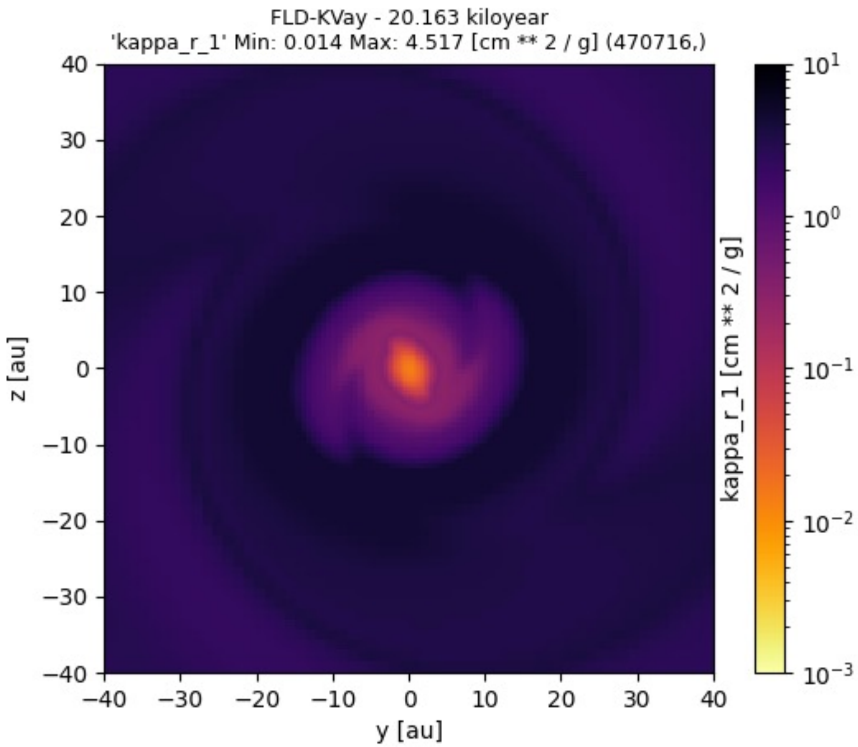




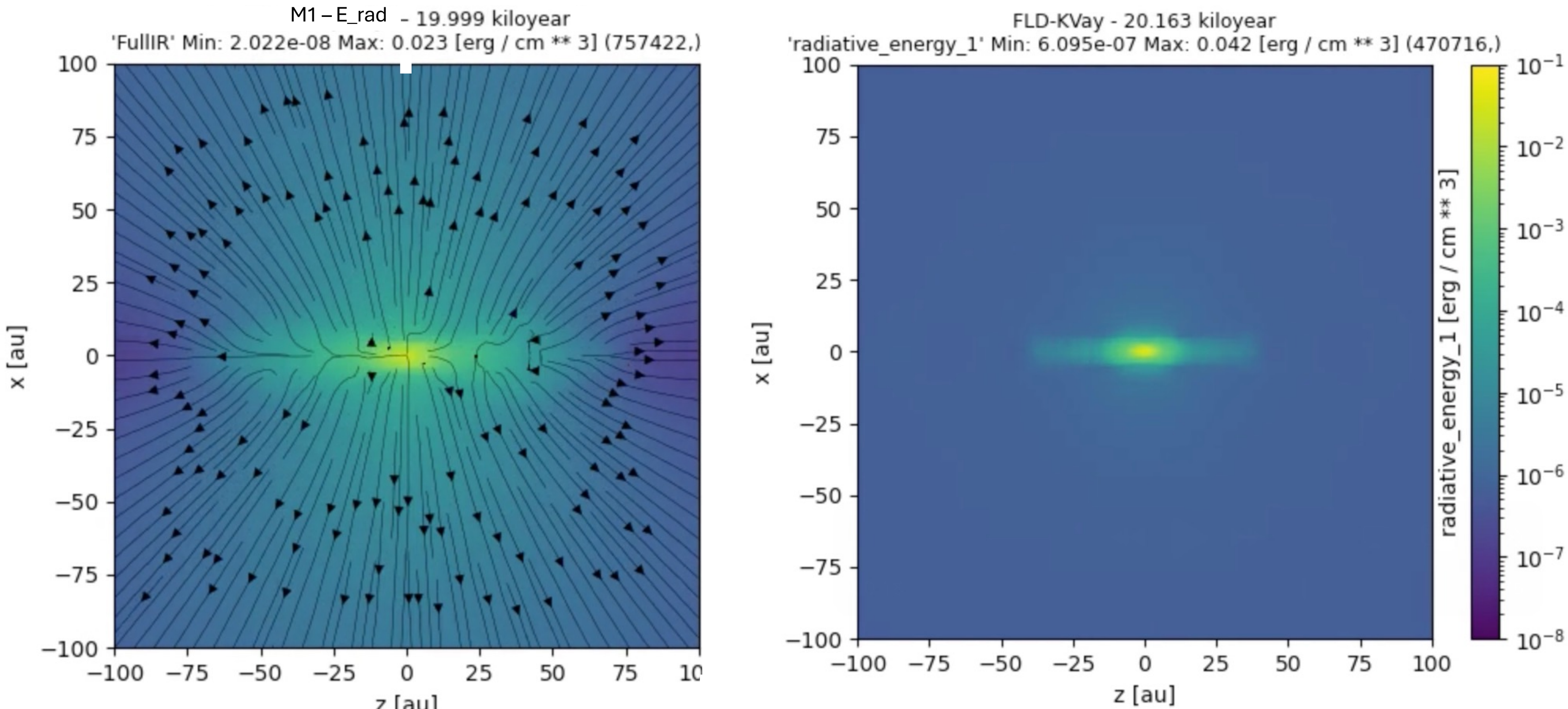
Disks look different: investigate optical properties

Opacity Maps



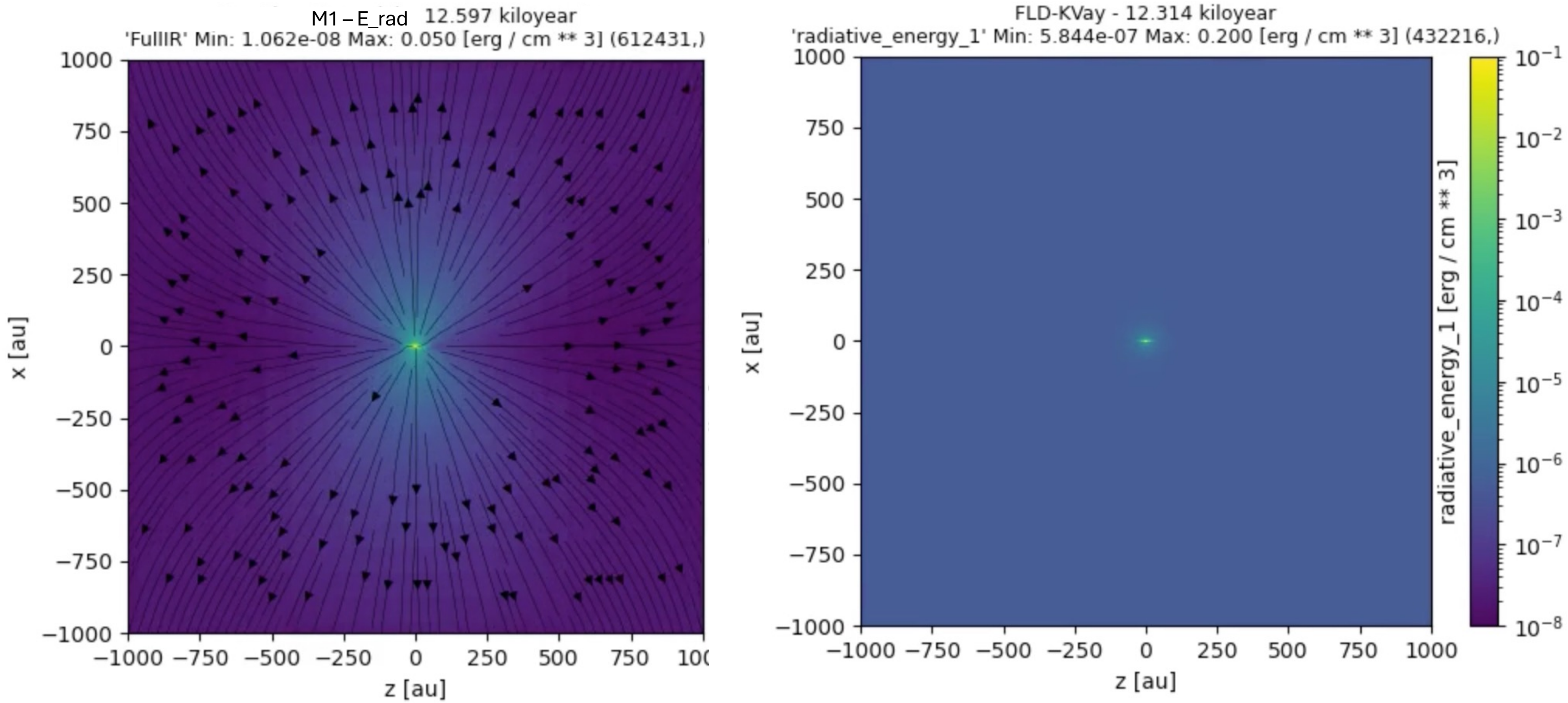


Radiative Energy Density



Main point: presence of shadows

Radiative Energy Density – Full box



Conclusion

- **At free fall time** FLD and M1 give similar disk radii (~45 AU) and masses (~0.57 $M_\odot$); M1 disks are hotter by ~15%.
- **After a few more kyrs** – disks present differences in size, temperature, susceptibility to fragmentation.

Next step – figure out if these results are physical:

1) Test the opacities: semi-analytic opacity-dependent polytrope (based on Matthew and Federath 2020)
2) Experiment with implementing a flux limiter in M1

Future project: realistic dust/gas temperature coupling -> retroaction of dust on opacity -> populations of disks -> solve planet formation ;)