A General Hybrid Radiation Transport Scheme for Star Formation Simulations on an AMR grid

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KITP Santa Barbara, May 2014

Context

- Star formation proceeds inside of turbulent, magnetized, and highly filamentary clouds (André et al. 2013)
- Radiation feedback is connected to a wide range of physical problems on a wide range of scales: from protoplanetary disks (Williams & Cieza 2011) to galaxies and the circumgalactic medium (e.g. Ceverino & Klypin 2009, Hopkins et al. 2013)

STScI-PRC2011-38

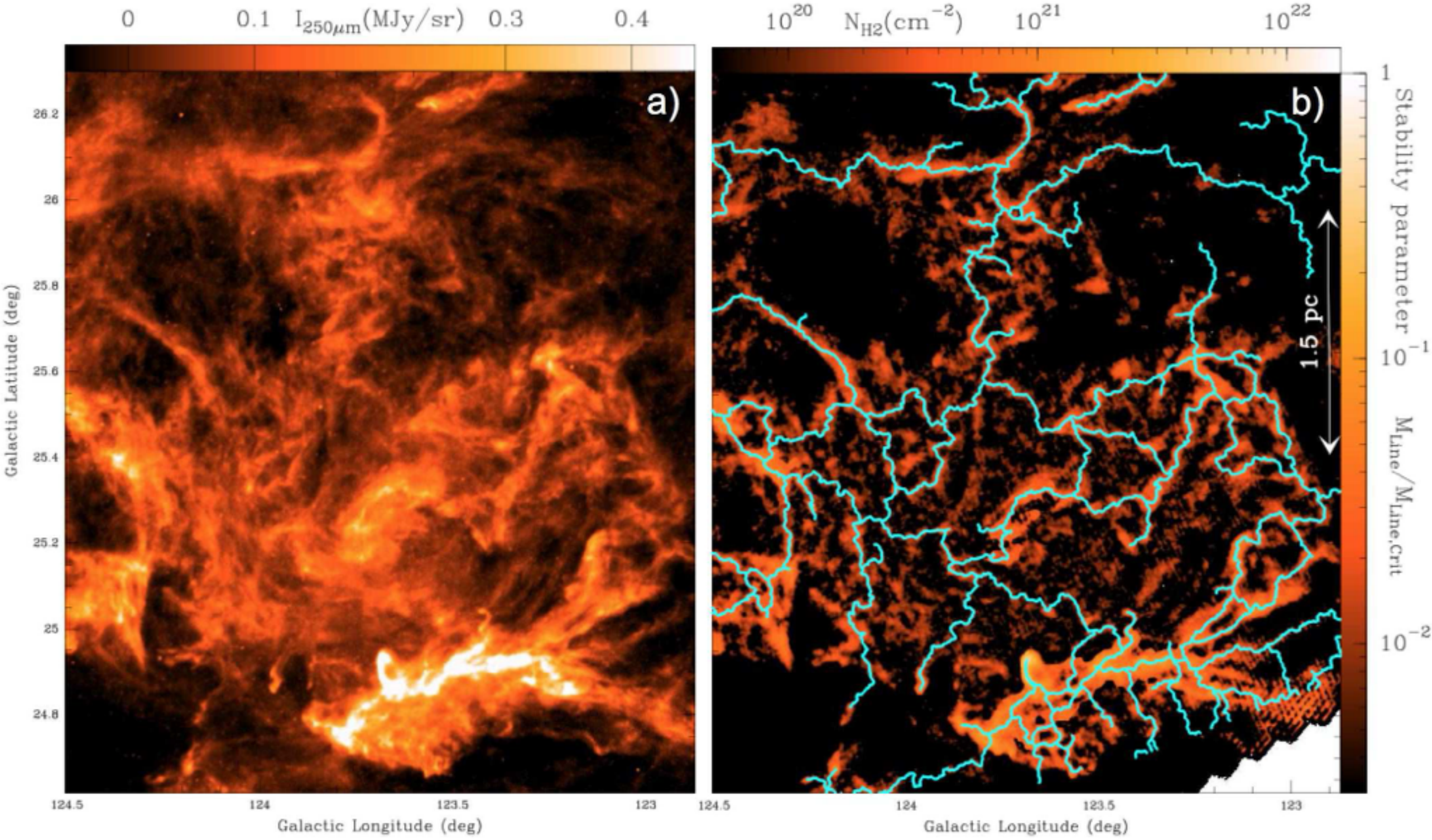
S106 Star-forming region containing IRS4.

NASA / ESA / Hubble Heritage Team (STScI/AURA)

Motivation

- We also want to study the impact of radiation feedback on these environments: **suppression of fragmentation**, creation of **outflows**, **radiation pressure**

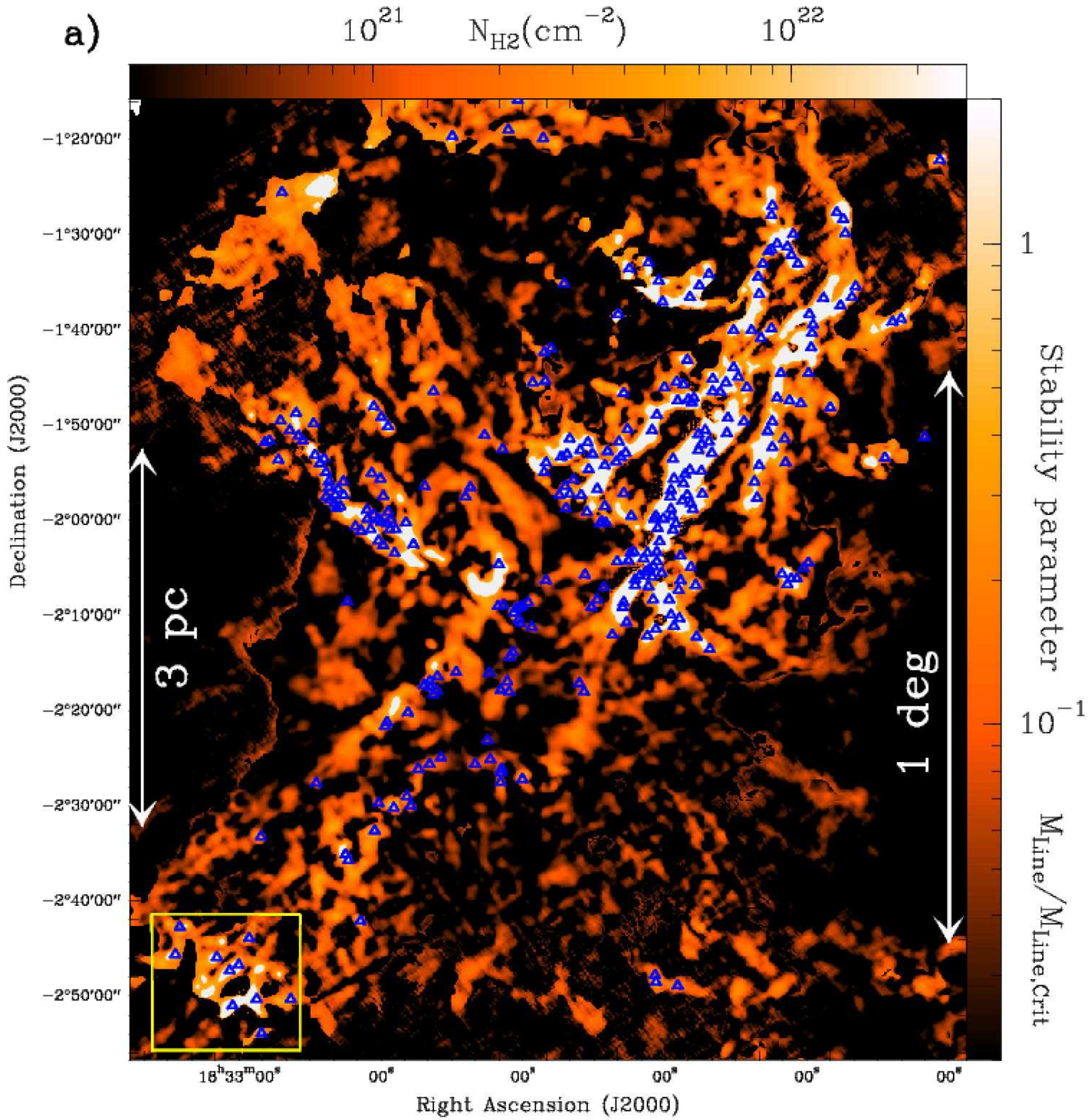
- We are interested in correctly modelling the environments of star formation, including all of the effects of **supersonic turbulence** and **magnetic fields**



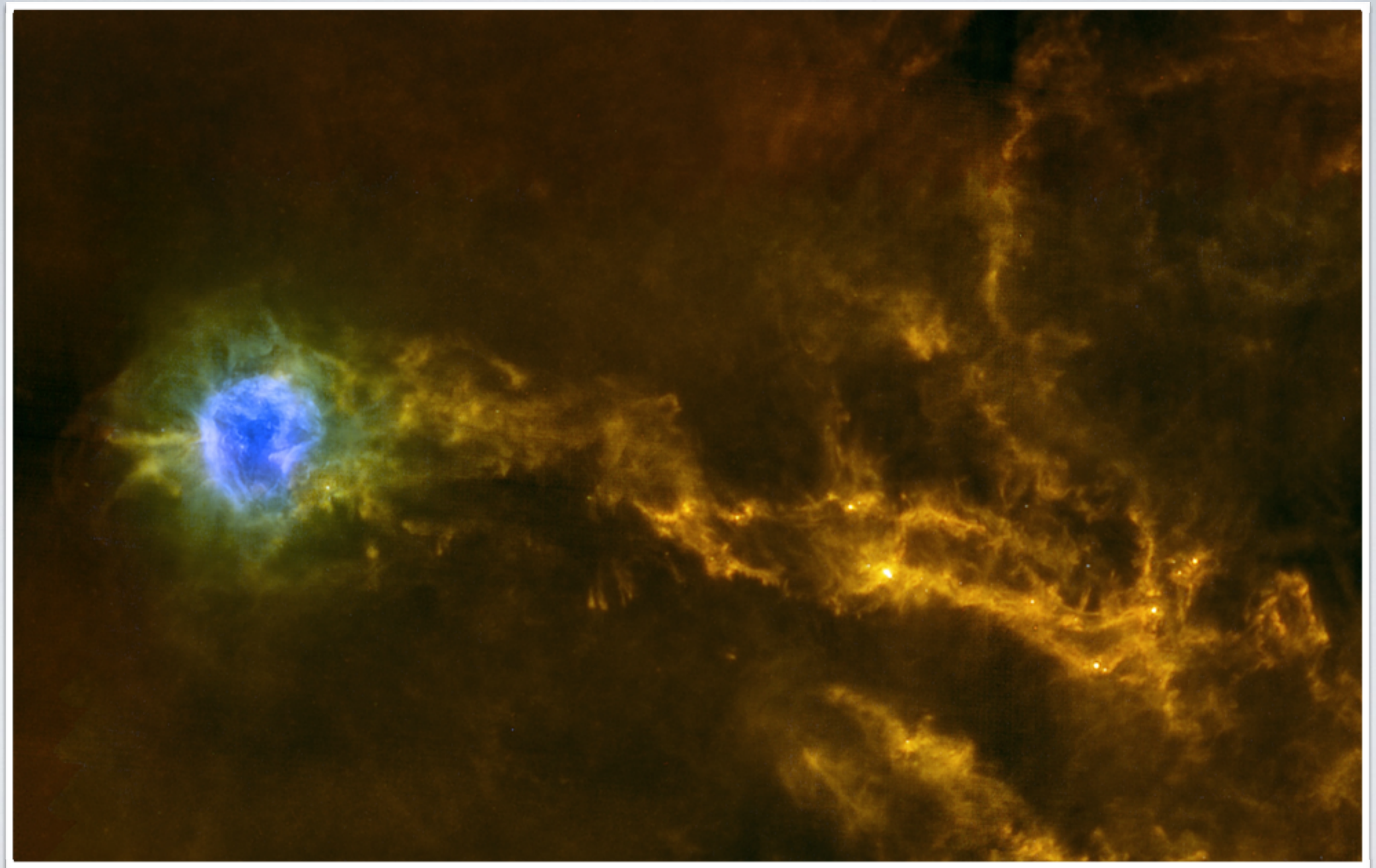
Herschel/SPIRE 250μm dust map of the Polaris flare (Miville-Deschênes et al. 2010), processed by André et al (2010) to map the filaments

Characterizing filaments

- Apparent characteristic width of 0.1pc (Arzoumanian et al. 2011)
- Velocity-coherent structures (Hacar et al. 2013)
- Stability (Ostriker 1964)
- Magnetic field alignment (Chapman et al. 2011)
- Clustered star formation at intersections (Schneider et al. 2012)
- Formation of HII regions (e.g. Dale & Bonnell 2011)

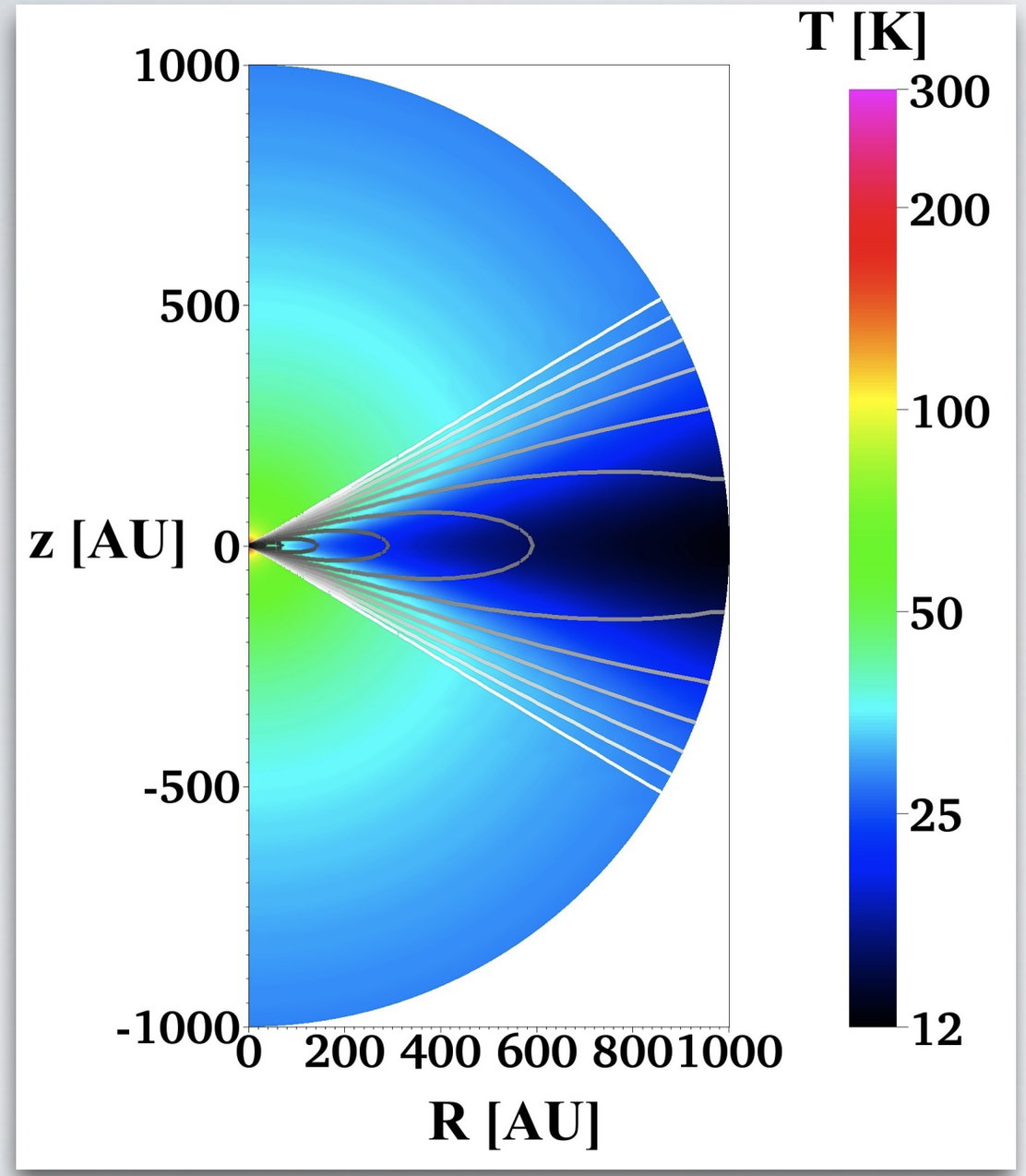


Herschel column density map of part of Aquila star-forming region by André et al (2010). Blue triangles show bound prestellar (Könyves et al. 2010)

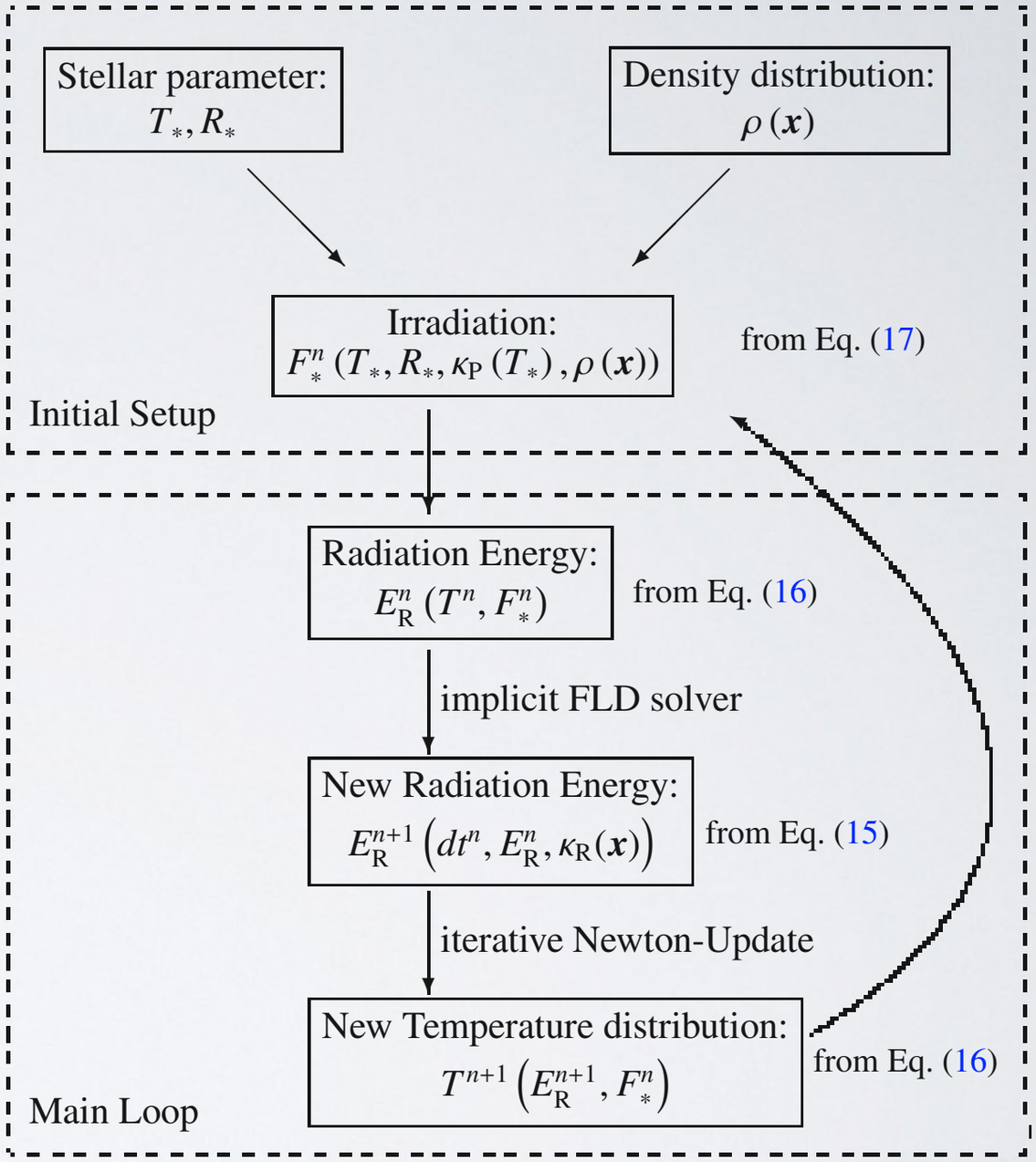


IC5146. *ESA / Herschel / PACS / Gould Belt Survey*

Hybrid radiation transport



Kuiper & Klessen (2013)



Kuiper et al. (2010)

$$\frac{1}{c}\frac{\partial I}{\partial t}+\Omega\cdot\nabla I+\sigma I=\frac{c}{4\pi}\left(\sigma_a B+\sigma_s E\right),$$

$$E(\boldsymbol{r},t)=\frac{1}{c}\int_{4\pi} d\Omega I(\boldsymbol{r},\Omega,t).$$

$$\frac{\partial E}{\partial t}+\nabla\cdot\boldsymbol{F}=c\sigma_a\left(B-E\right),$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \boldsymbol{F} = c\sigma_a (B - E),$$

$$\boldsymbol{F}_{\mathbf{rad}} = -D\nabla E_R,$$

$$D = \frac{\lambda c}{\kappa_R \rho}$$

c.f. Levermore & Pomraning (1981)

$$\partial_t \rho\epsilon = -\kappa_P \rho c \left(a_R T^4 - E_R\right) + Q_{\text{sources}}$$
$$\partial_t E_R - \boldsymbol{\nabla} \cdot F = +\kappa_P \rho c \left(a_R T^4 - E_R\right)$$

Radiation from stars typically added one of two ways:

$$E = \frac{L}{4\pi r^2 c},$$

e.g. Krumholz et al. (2007)

$$\sum_i L_i W(\boldsymbol{x} - \boldsymbol{x}_i),$$

e.g. A. Myers et al. (2011)

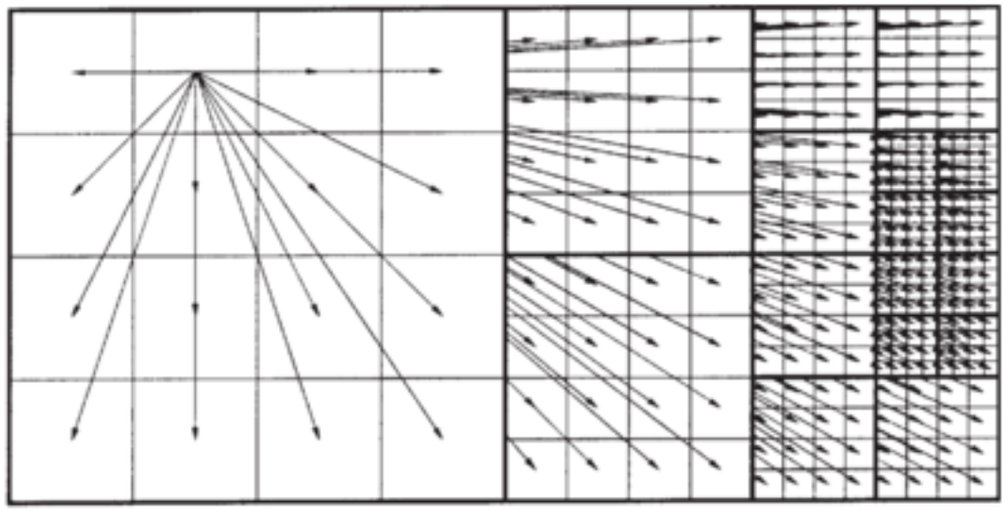
$$\partial_t \rho\epsilon = -\kappa_P \rho c \left(a_R T^4 - E_R\right) + Q_{\text{sources}}$$

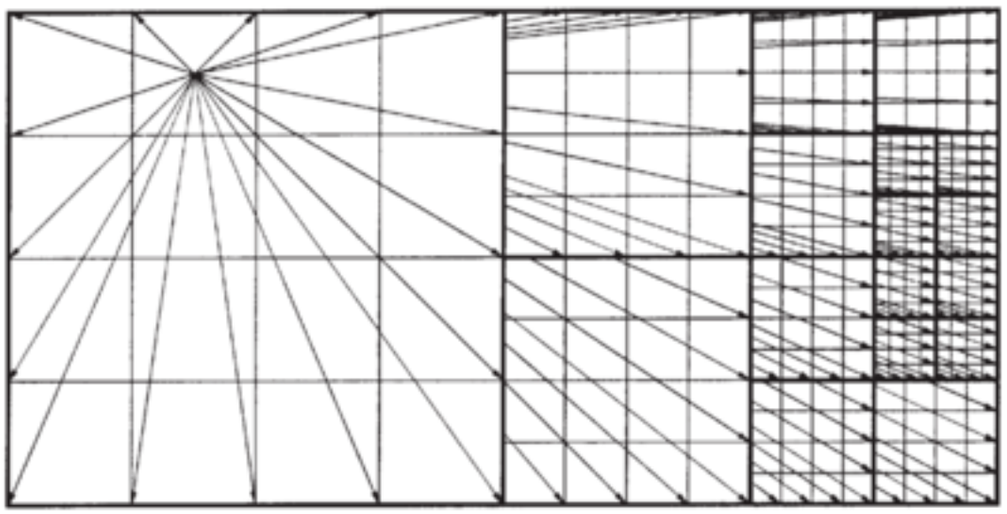
$$\partial_t E_R - \boldsymbol{\nabla} \cdot F = +\kappa_P \rho c \left(a_R T^4 - E_R\right)$$

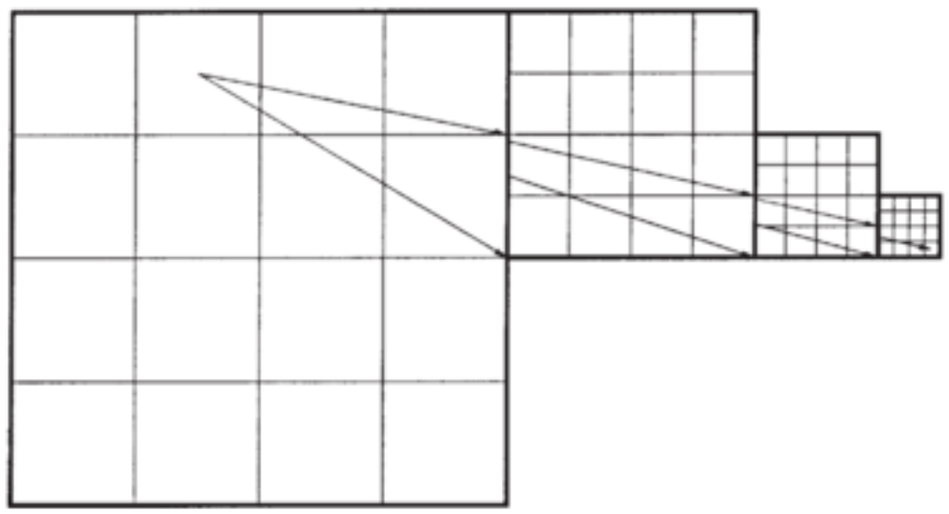
Alternatively, we use a raytracer to compute the source term and its coupling to the matter internal energy

$$Q_{\text{sources}} = -\nabla \cdot F_*$$

$$F_*(r) = \sigma T_*^4 \left(\frac{R_*}{r}\right)^2 \exp(-\tau)$$



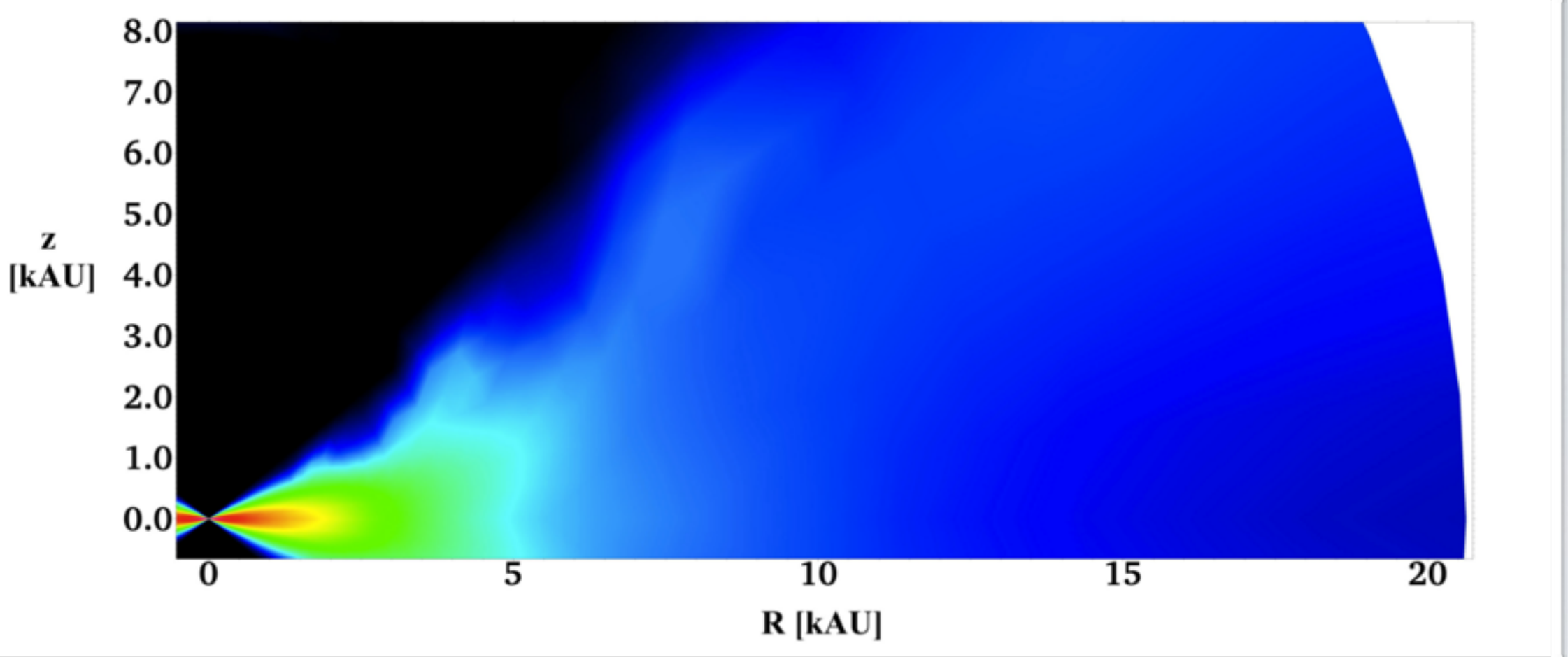




"Hybrid-Characteristics" raytracing (Rijkhorst et al. 2006)

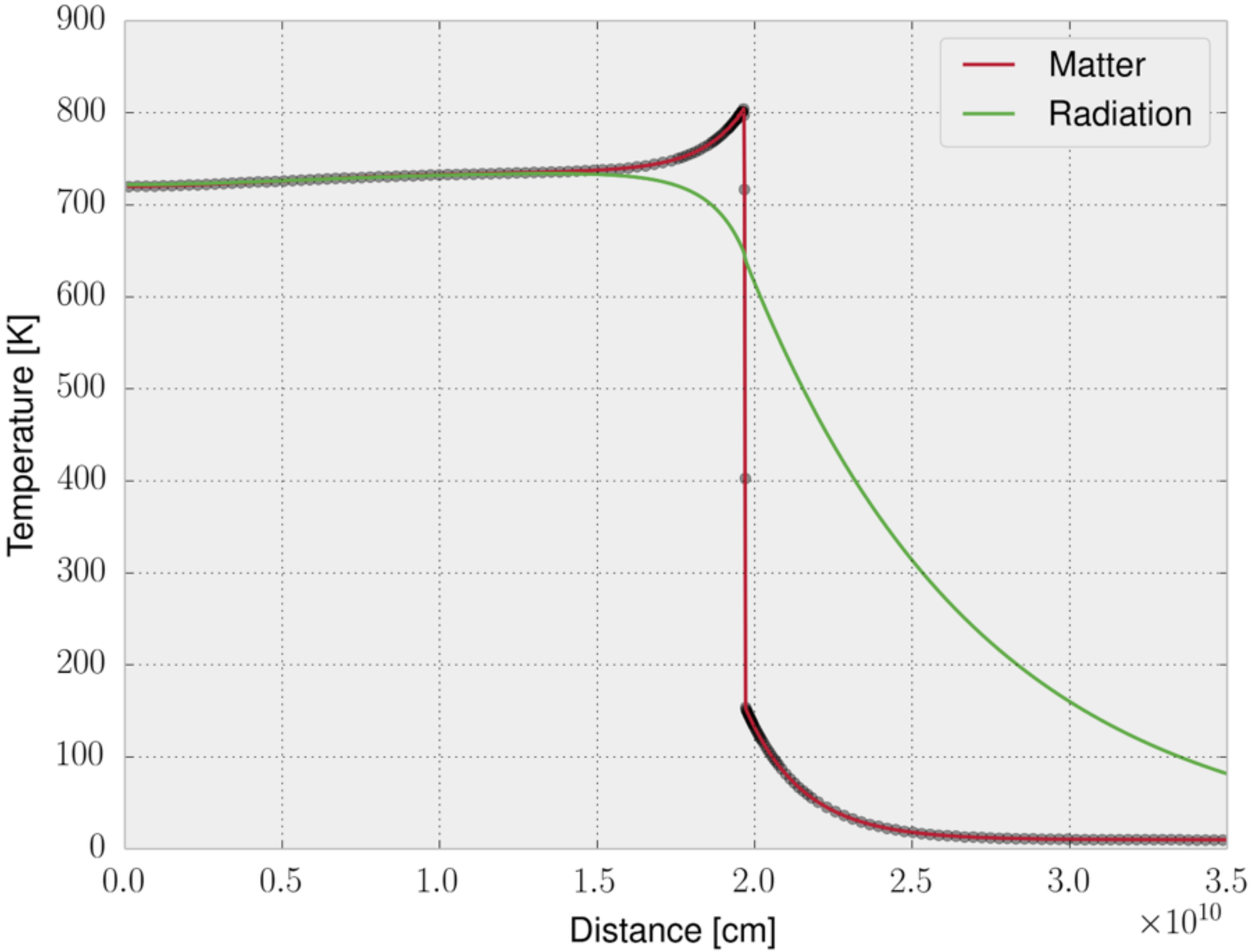
$$\nabla \cdot F_*(r) \approx -\frac{(1 - e^{\tau_{\rm local}})}{\Delta x} F_*(r),$$

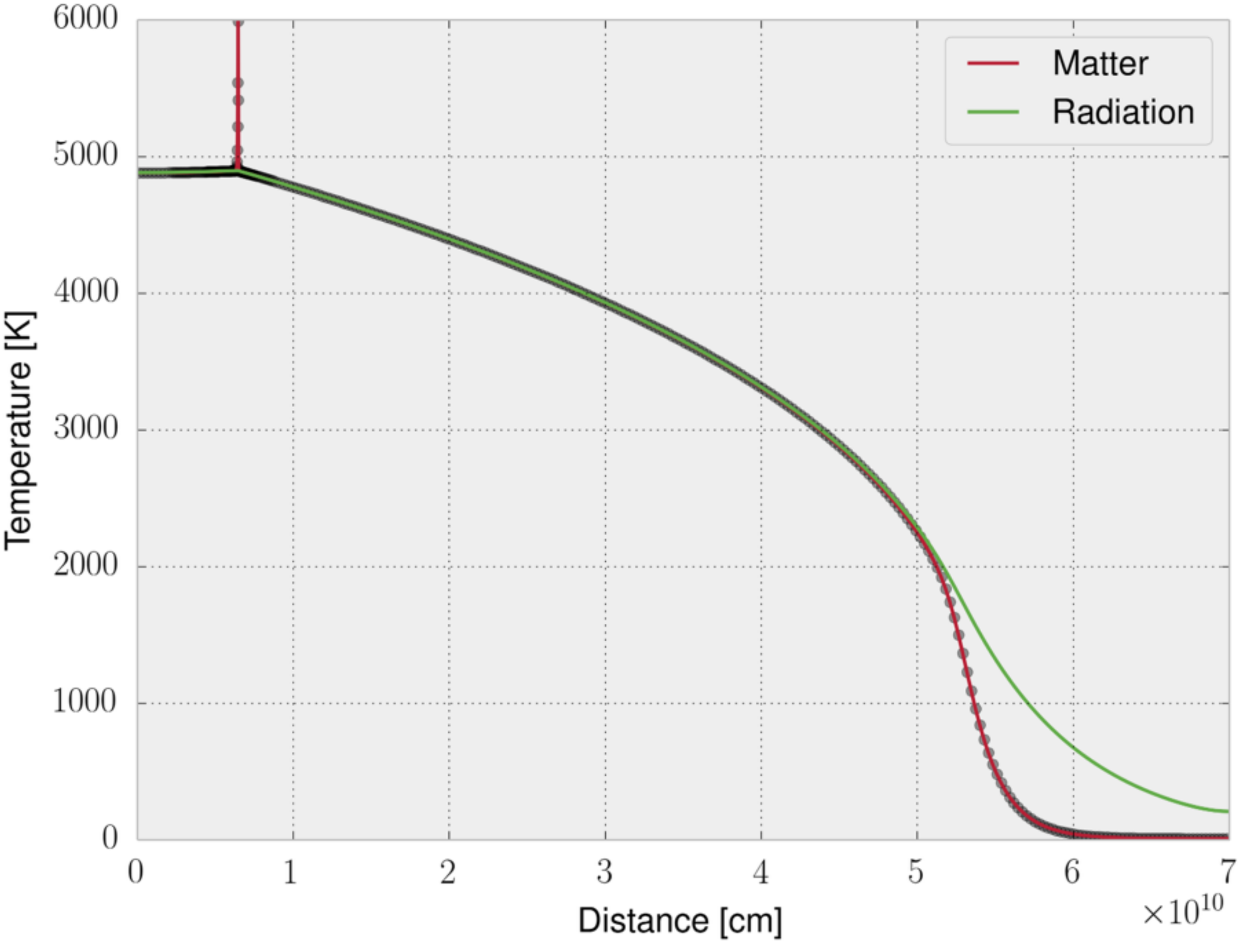
We compute the specific "irradiation" for each cell in the simulation grid.

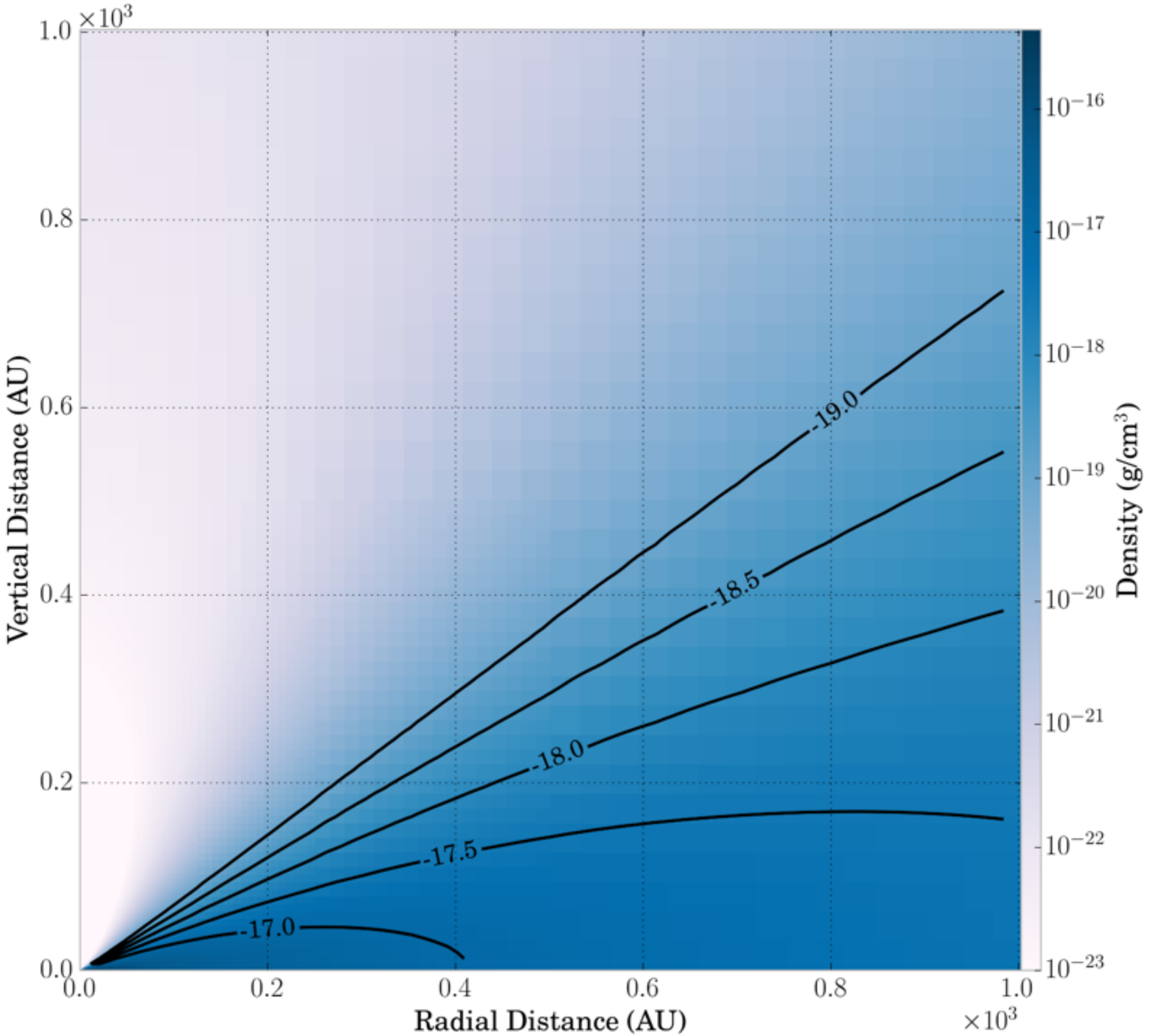


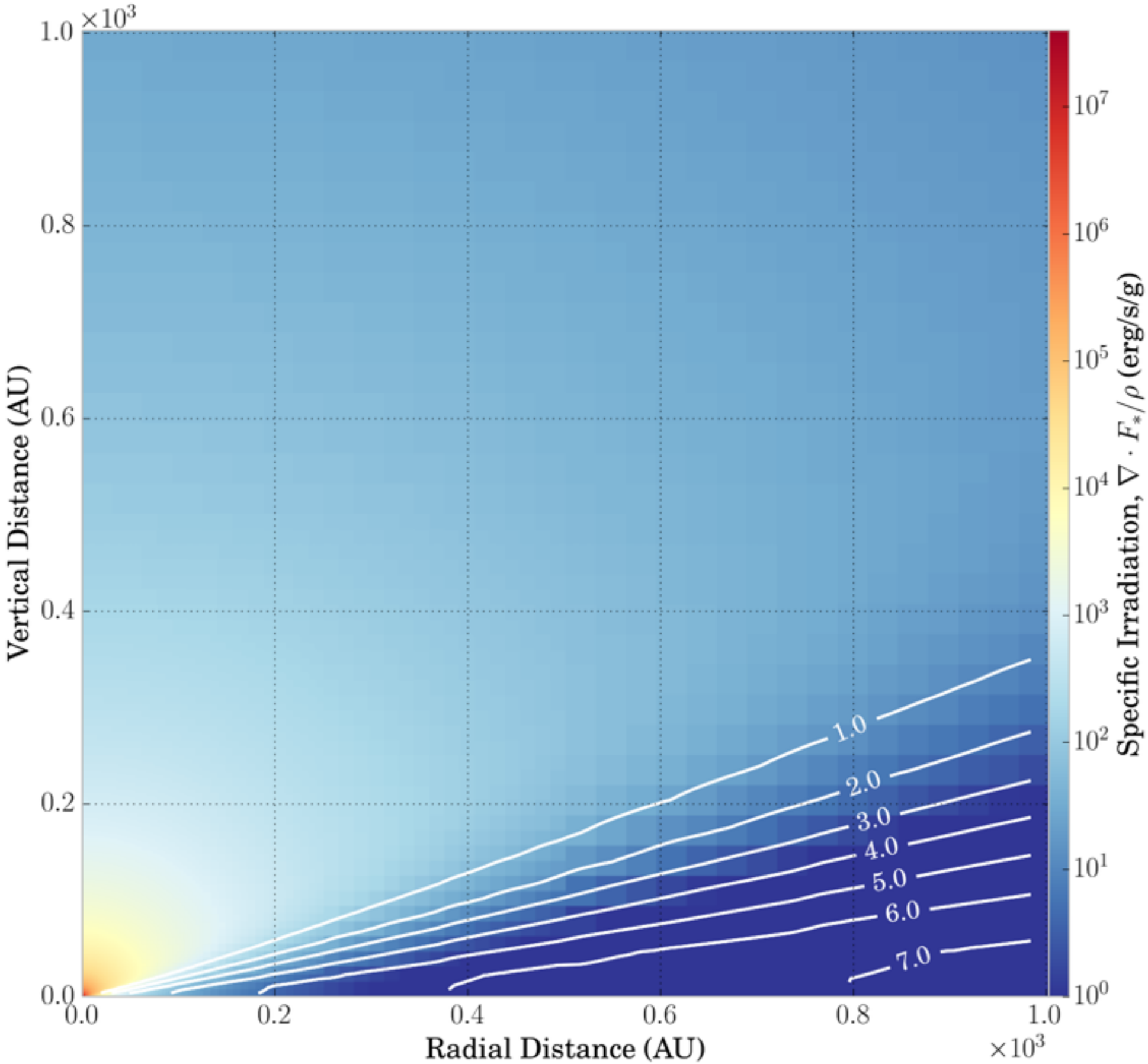
- Update the energies/temperatures including new source terms and continue the evolution.
- 2T method on a Cartesian AMR grid that can handle multiple sources: i.e. clustered star formation on GMC scale

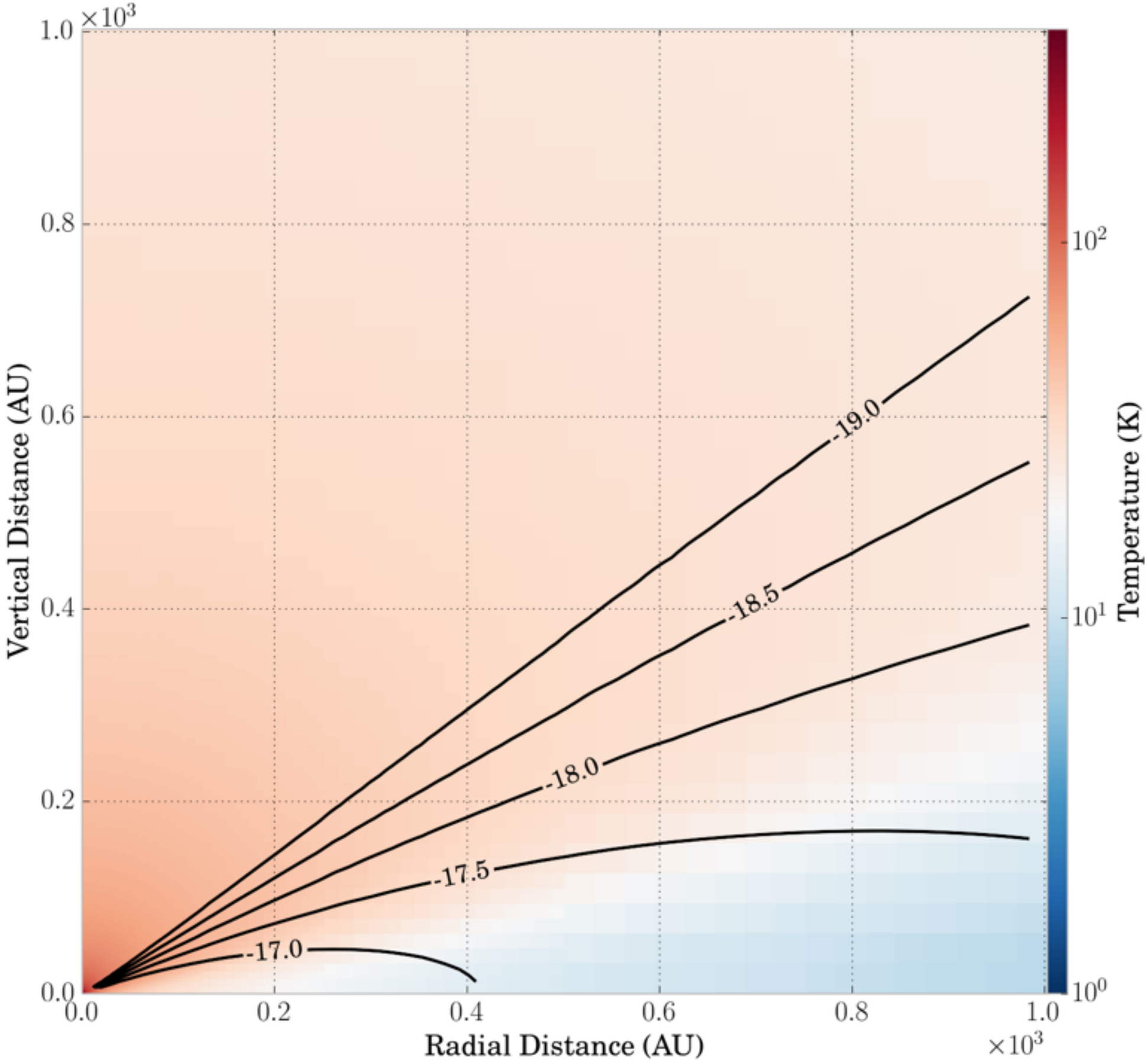
Testing the method

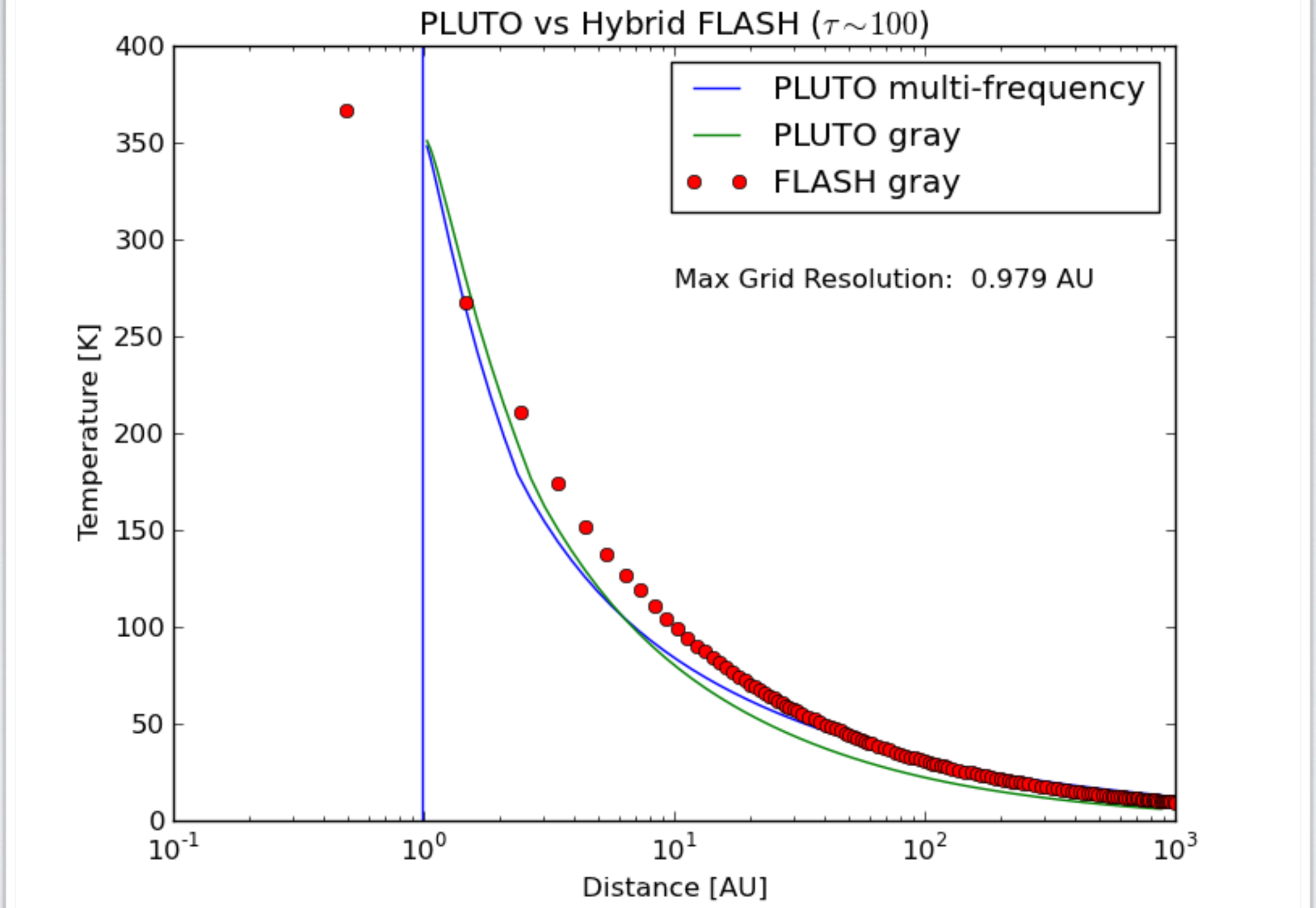

Matter
Radiation
Temperature [K]
900
800
700
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Distance [cm]
×10^10


Matter
Radiation
Temperature [K]
6000
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
×10^10
Distance [cm]


1.0
×10^3
0.8
0.6
0.4
0.2
0.0
Vertical Distance (AU)
-19.0
-18.5
-18.0
-17.5
-17.0
0.0
0.2
0.4
0.6
0.8
1.0
Radial Distance (AU)
×10^3
10^−16
10^−17
10^−18
10^−19
10^−20
10^−21
10^−22
10^−23
Density (g/cm^3)


1.0
0.8
0.6
0.4
0.2
0.0
×10^3
Vertical Distance (AU)
0.0
0.2
0.4
0.6
0.8
1.0
×10^3
Radial Distance (AU)
1.0
2.0
3.0
4.0
5.0
6.0
7.0
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Specific Irradiation, ∇ · F_*/ρ (erg/s/g)


1.0
×10^3
0.8
0.6
0.4
0.2
0.0
Vertical Distance (AU)
0.0
0.2
0.4
0.6
0.8
1.0
×10^3
Radial Distance (AU)
-19.0
-18.5
-18.0
-17.5
-17.0
10^2
10^1
10^0
Temperature (K)


PLUTO vs Hybrid FLASH ($\tau \sim 100$)
PLUTO multi-frequency
PLUTO gray
FLASH gray
Max Grid Resolution: 0.979 AU
Temperature [K]
Distance [AU]
400
350
300
250
200
150
100
50
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

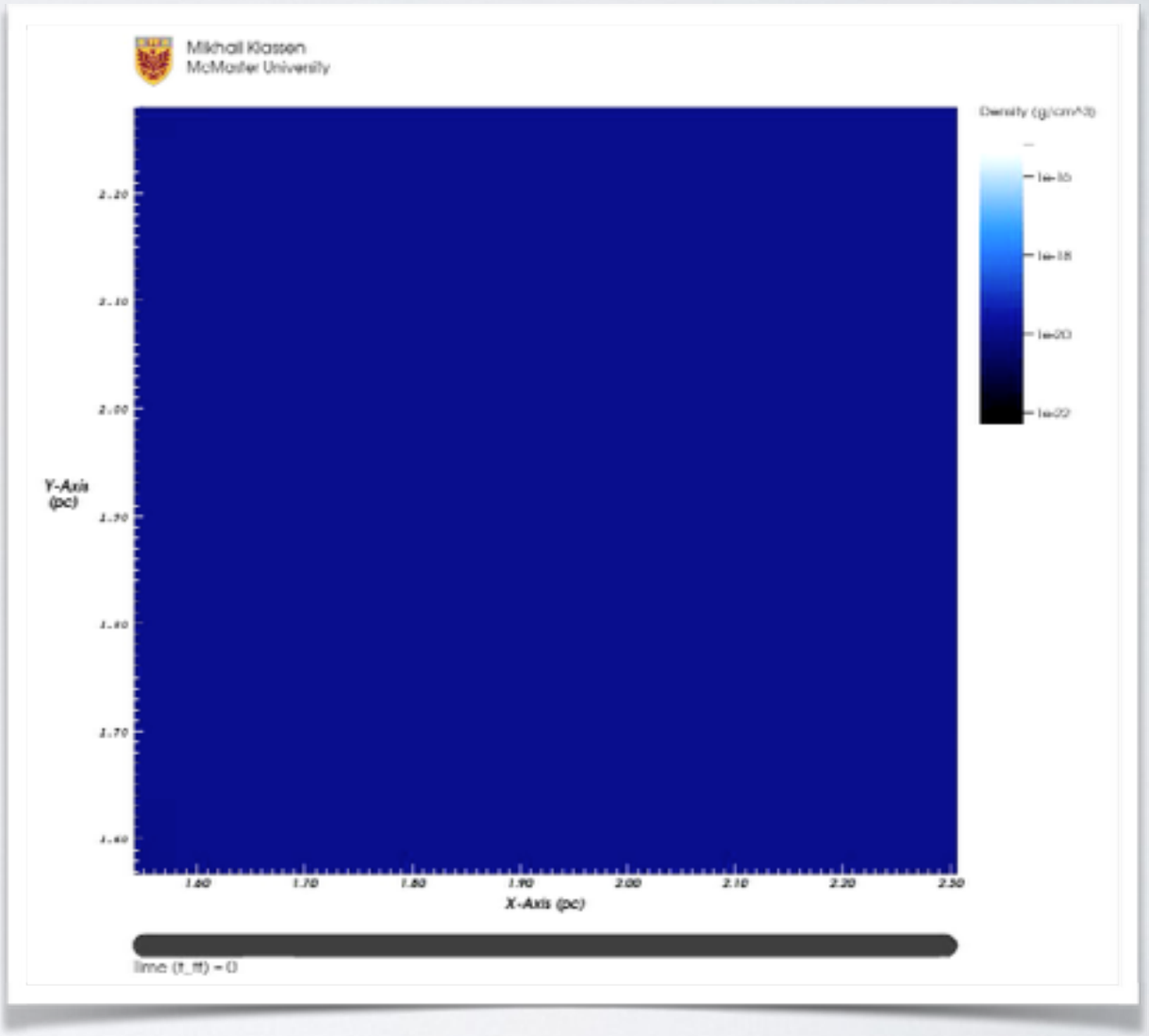
Under development

Currently in testing/development

- Radiation feedback from evolving sink particles, using protostellar evolution subgrid model, in a turbulent, magnetized medium (Klassen et al. 2012a,b)

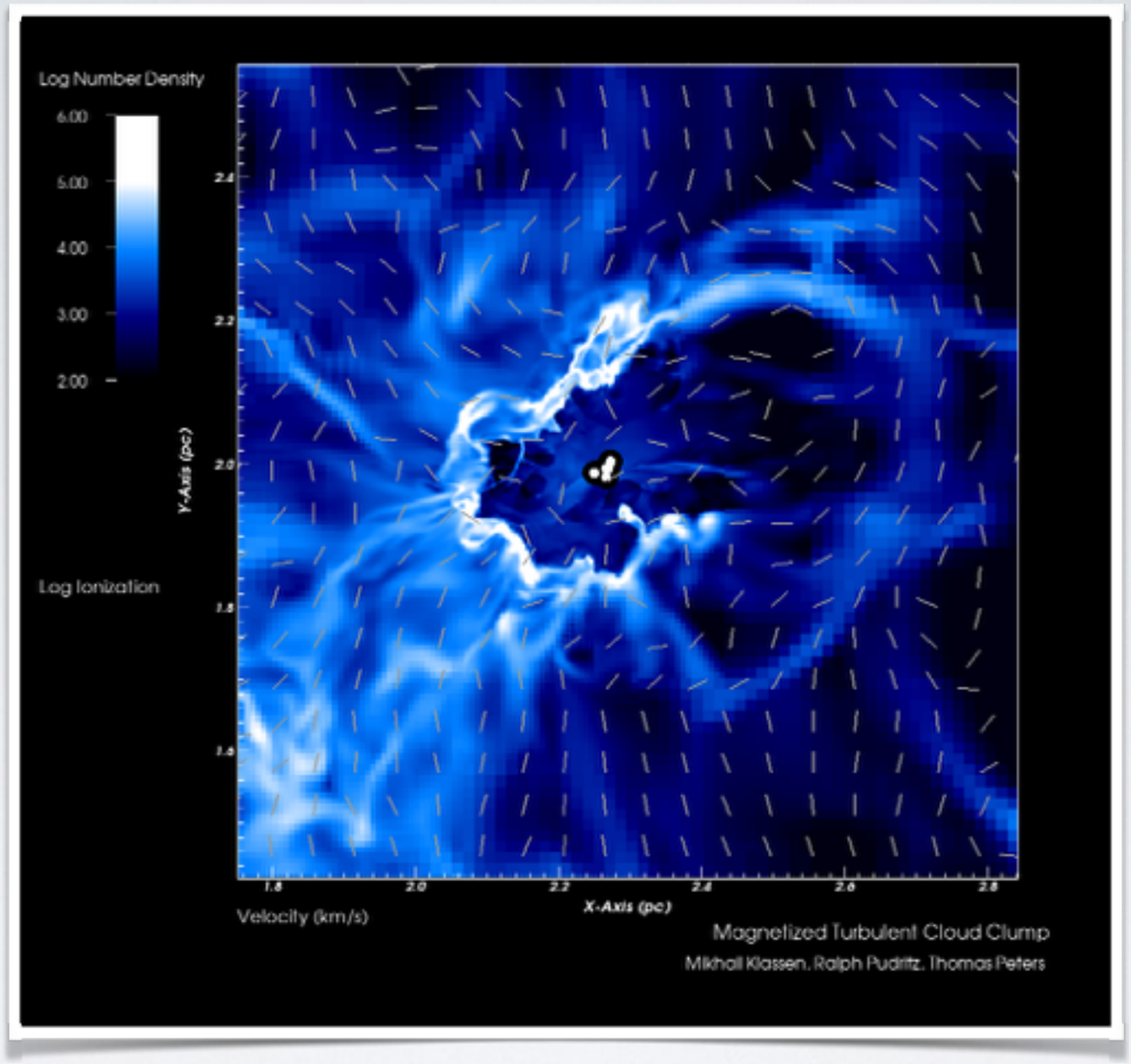
- Updating FLASH4 with ionizing radiation (Peters et al. 2010)

- Multifrequency RT



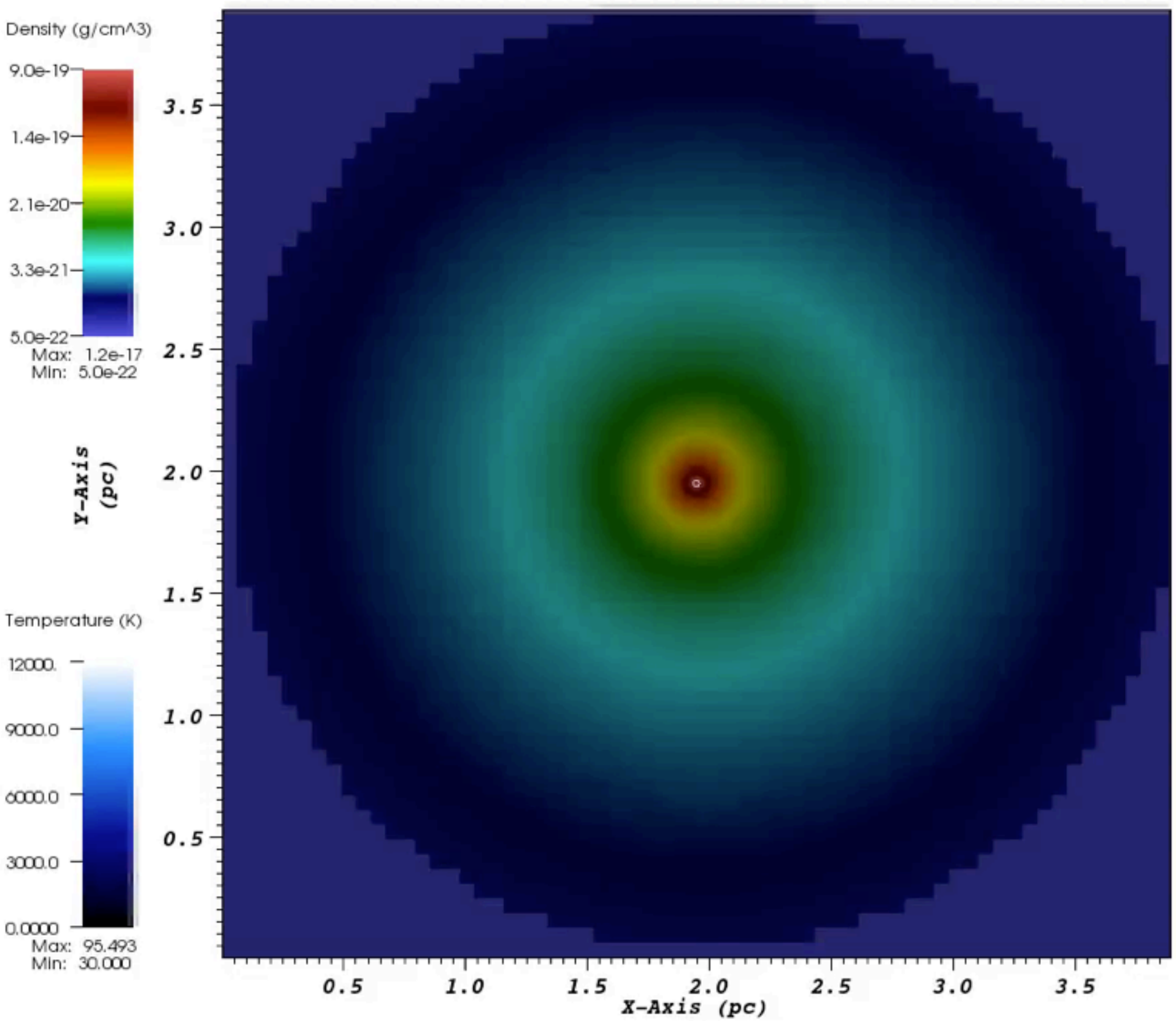
Science goals

- Simulate clustered star formation in the turbulent, magnetized, filamentary interstellar medium
- Study massive stars and their outflows
- Resolve the structure of protoplanetary disks and measure their properties



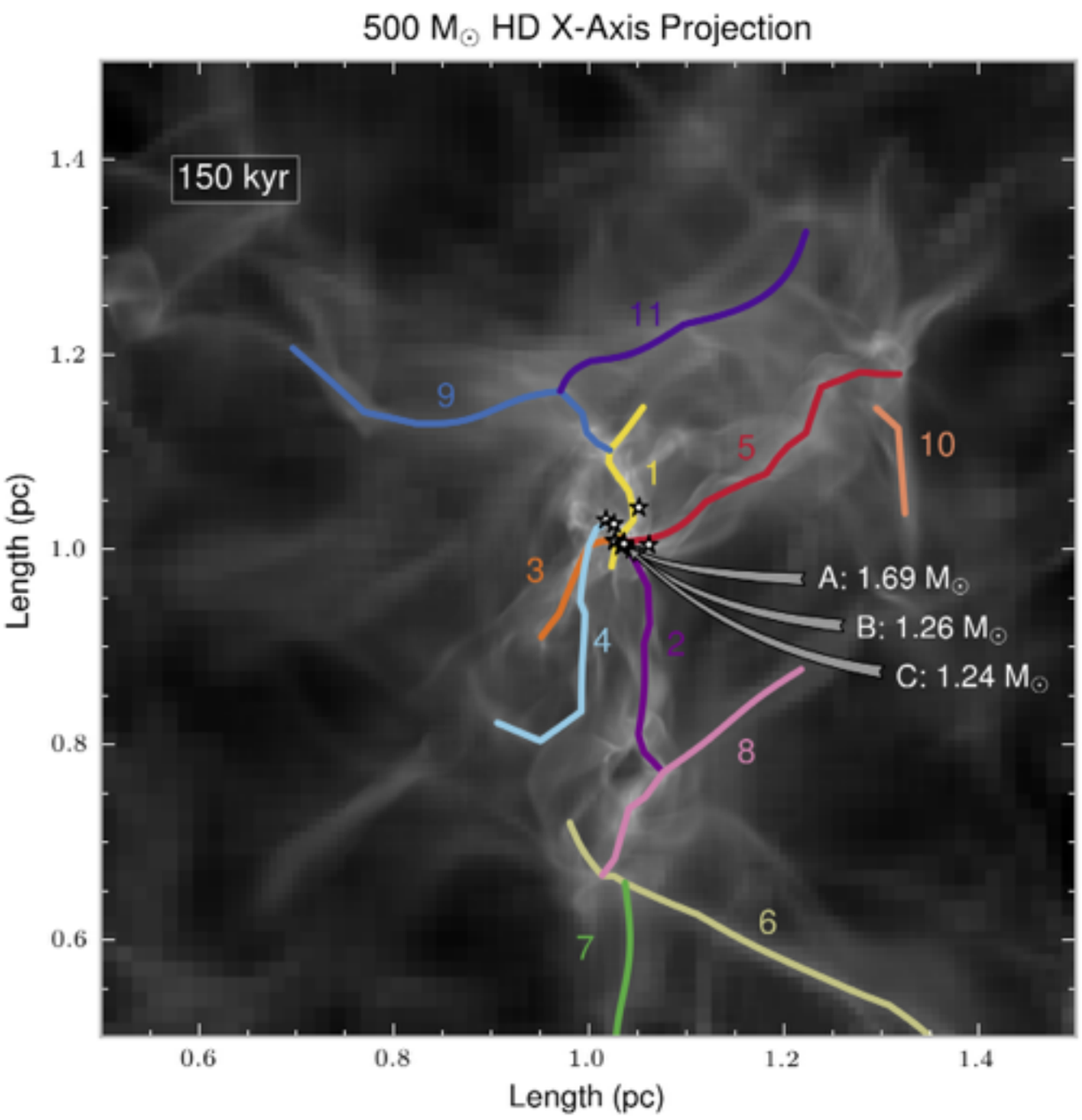
Studying filaments

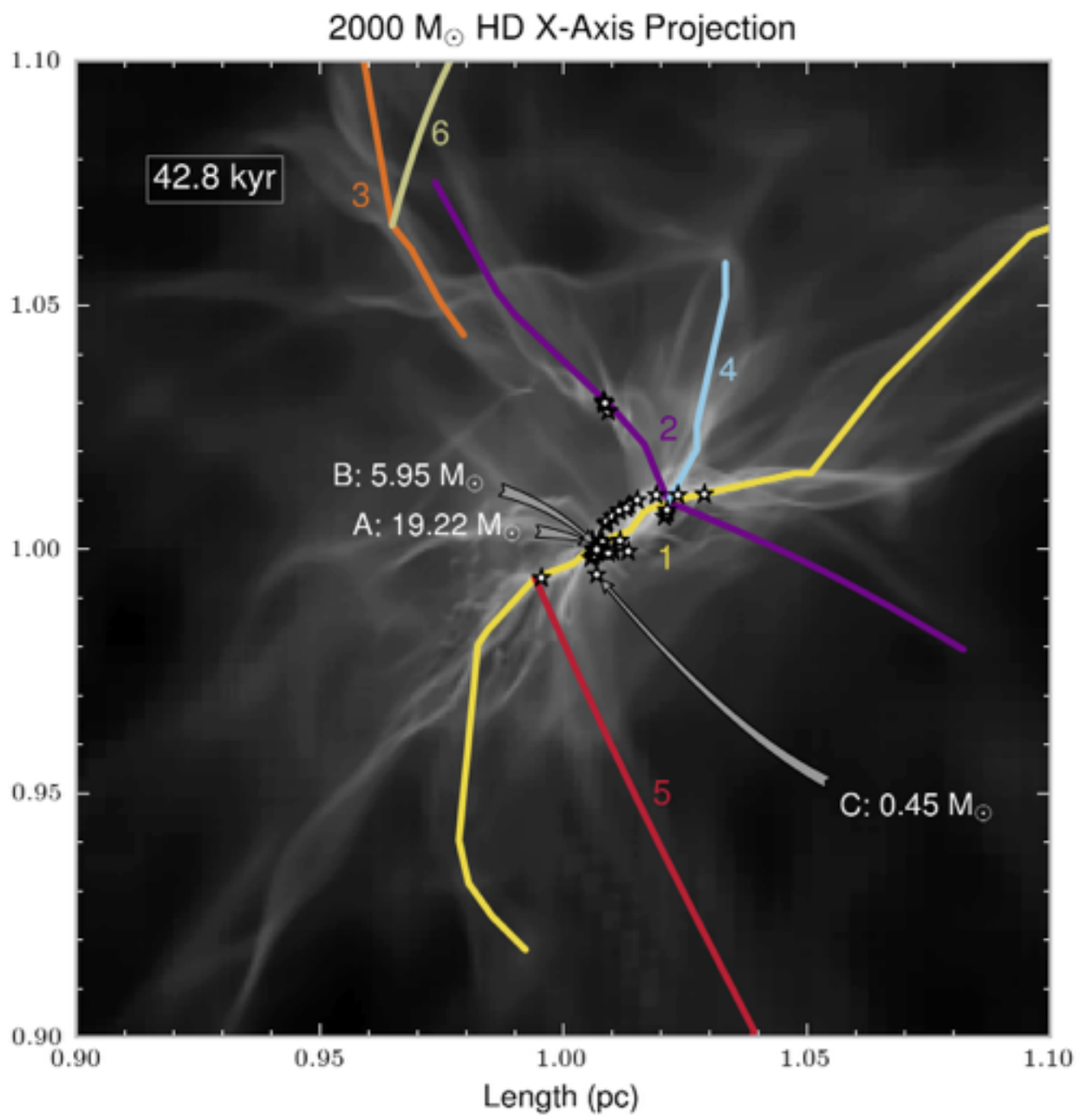
via hydrodynamic simulations

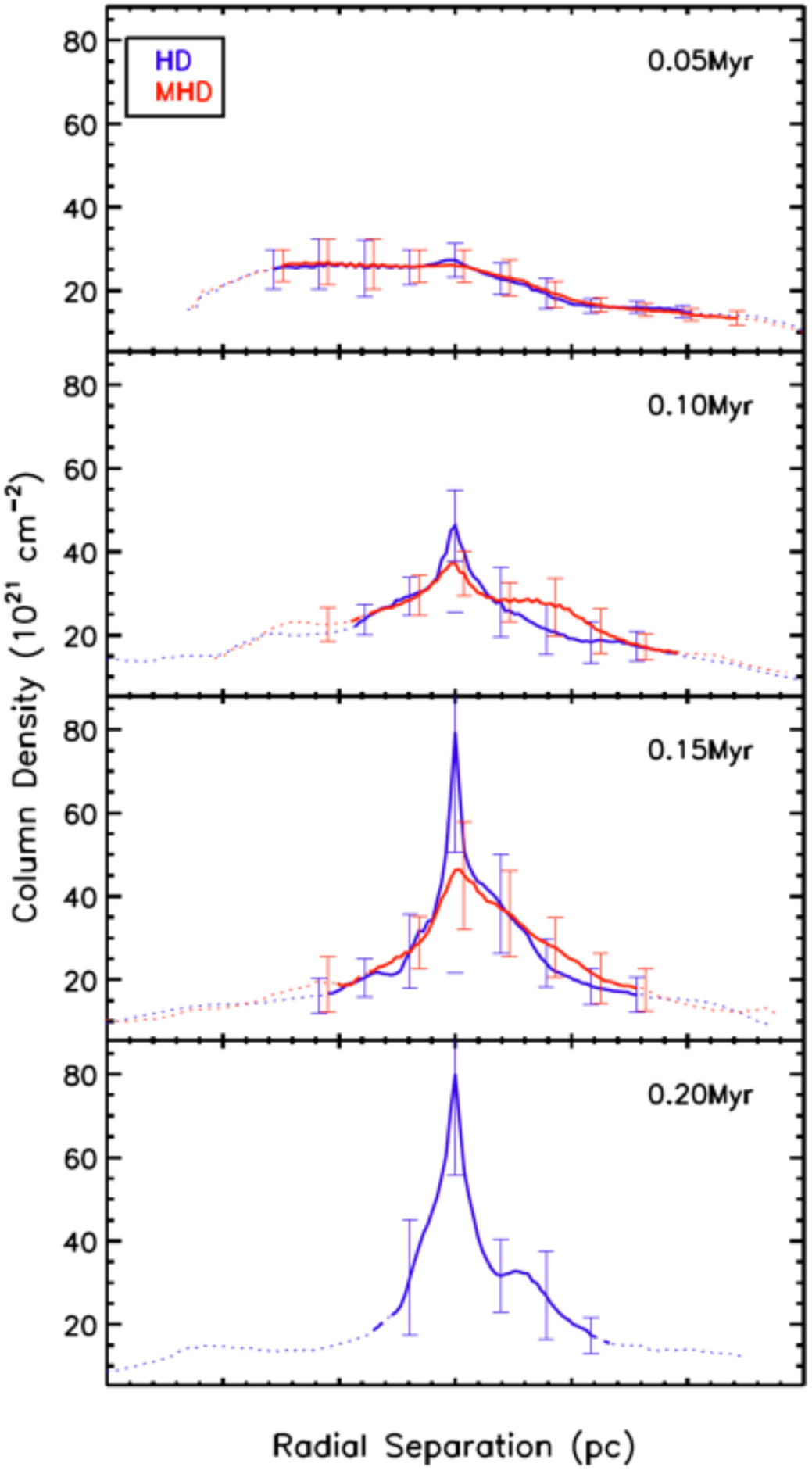

Density (g/cm^3)
9.0e-19
1.4e-19
2.1e-20
3.3e-21
5.0e-22
Max: 1.2e-17
Min: 5.0e-22
Temperature (K)
12000.
9000.0
6000.0
3000.0
0.0000
Max: 95.493
Min: 30.000
Y-Axis (pc)
0.5
1.0
1.5
2.0
2.5
3.0
3.5
X-Axis (pc)

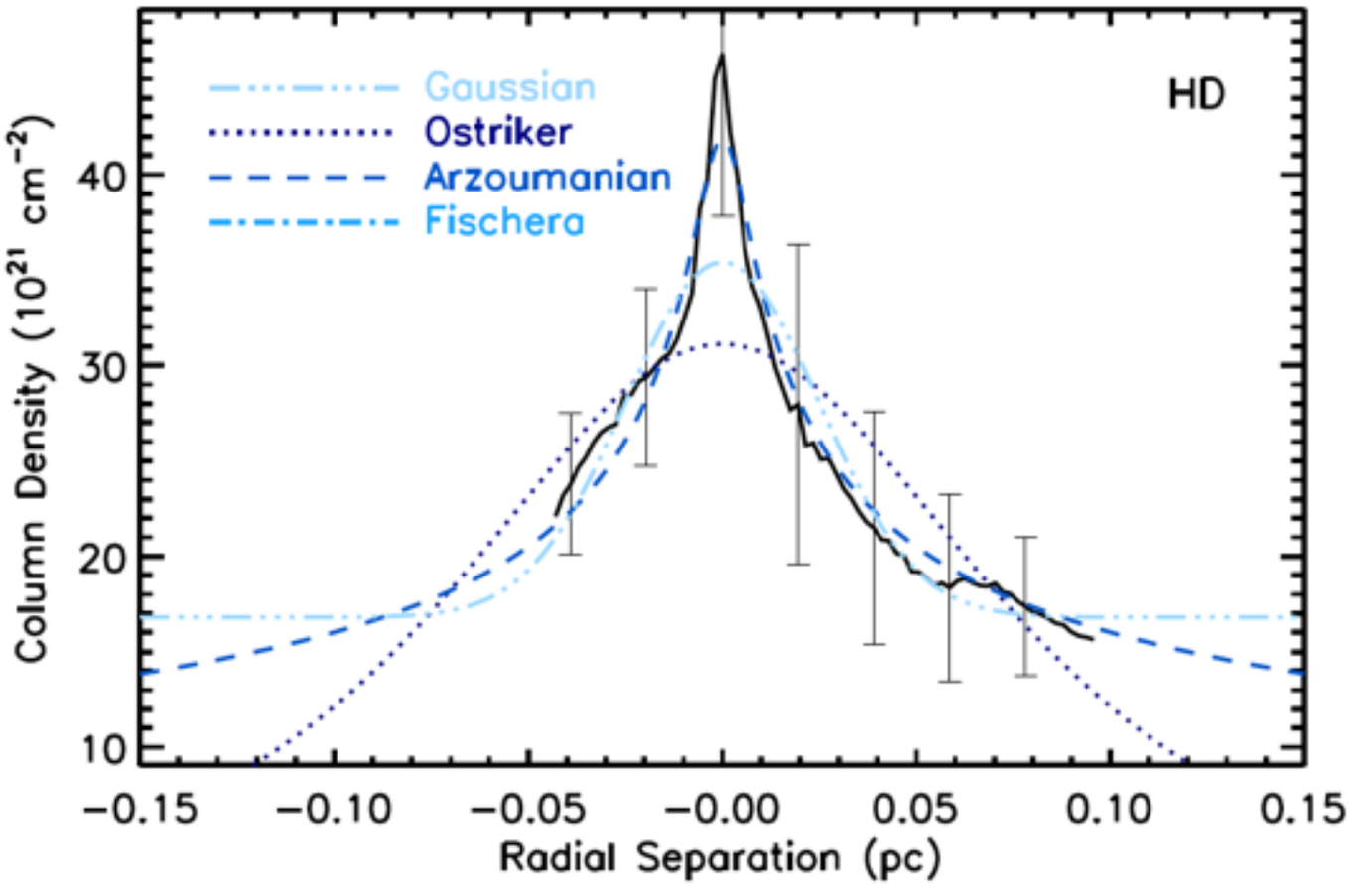
Star formation in filamentary molecular clouds

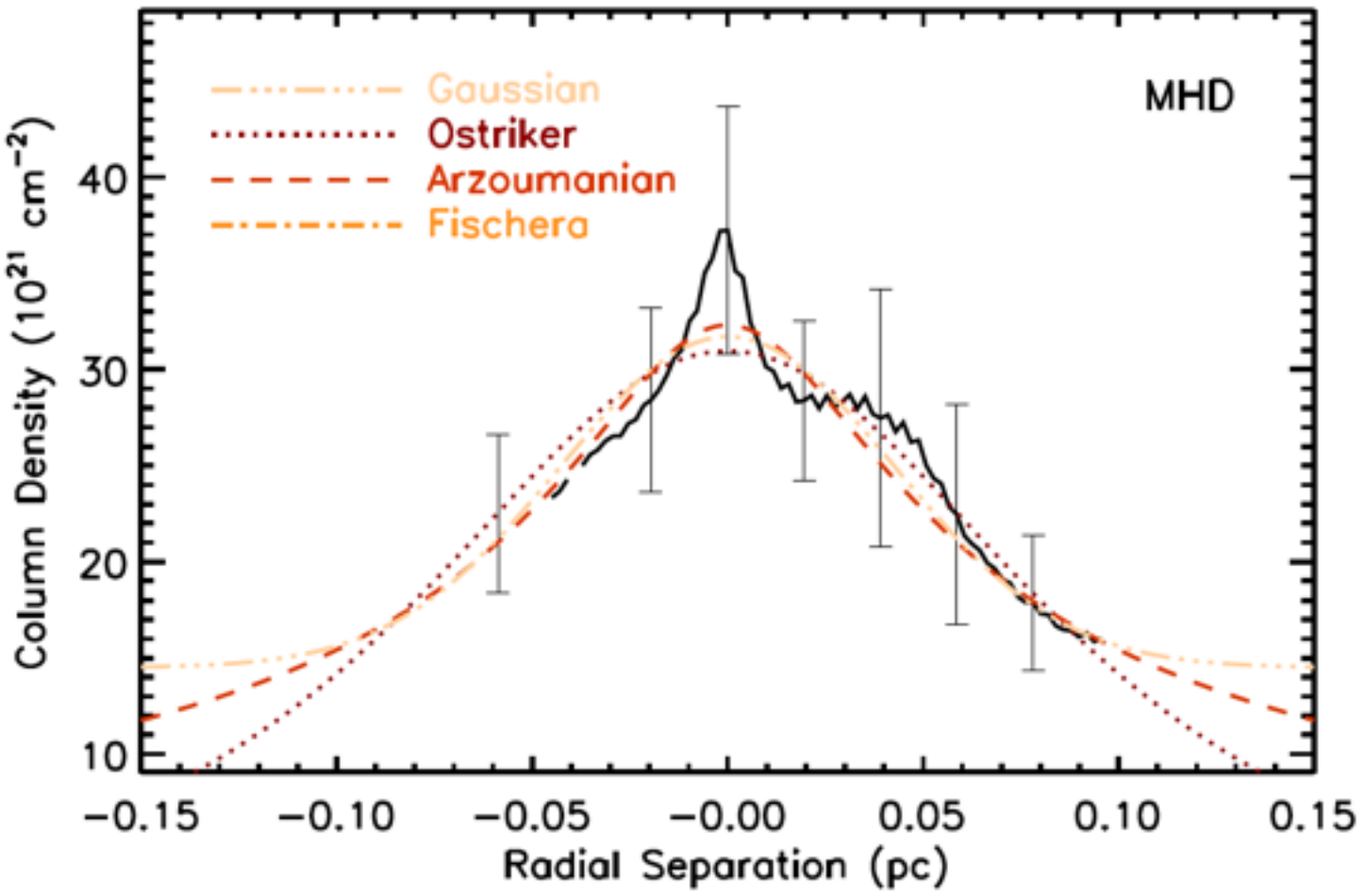
from *H. Kirk, Klassen, Pudritz, & Pillsworth* (2014, in prep.)


500 M⊙ HD X-Axis Projection
150 kyr
A: 1.69 M⊙
B: 1.26 M⊙
C: 1.24 M⊙
1
2
3
4
5
6
7
8
9
10
11
Length (pc)
Length (pc)
0.6
0.8
1.0
1.2
1.4

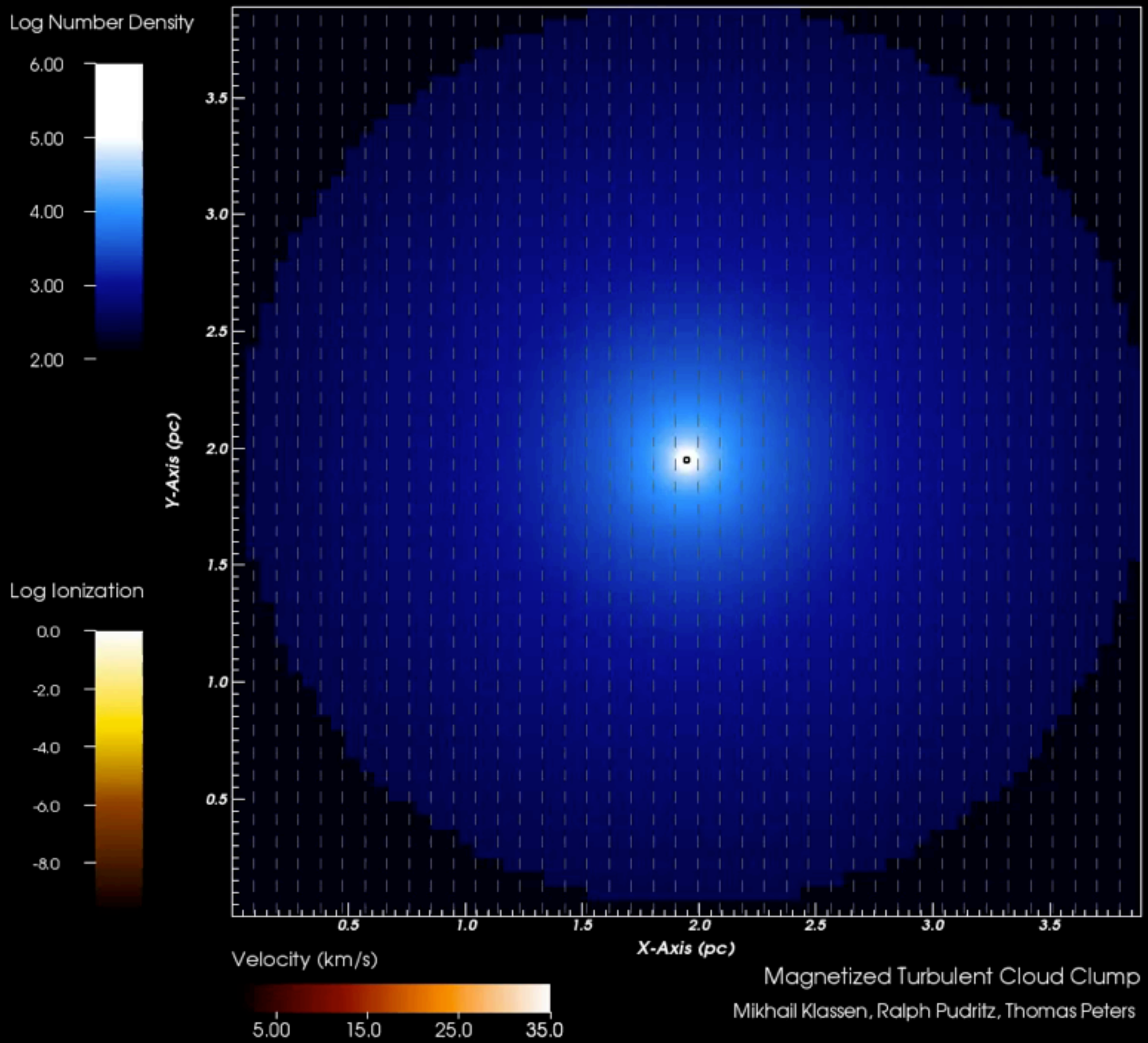

2000 M⊙ HD X-Axis Projection
42.8 kyr
B: 5.95 M⊙
A: 19.22 M⊙
C: 0.45 M⊙
1
2
3
4
5
6
Length (pc)
0.90
0.95
1.00
1.05
1.10


HD
MHD
0.05Myr
0.10Myr
0.15Myr
0.20Myr
80
60
40
20
Column Density (10^{21} cm^{-2})
Radial Separation (pc)


Gaussian
Ostriker
Arzoumanian
Fischera
HD
Column Density (10^{21} cm^{-2})
10
20
30
40
−0.15
−0.10
−0.05
−0.00
0.05
0.10
0.15
Radial Separation (pc)

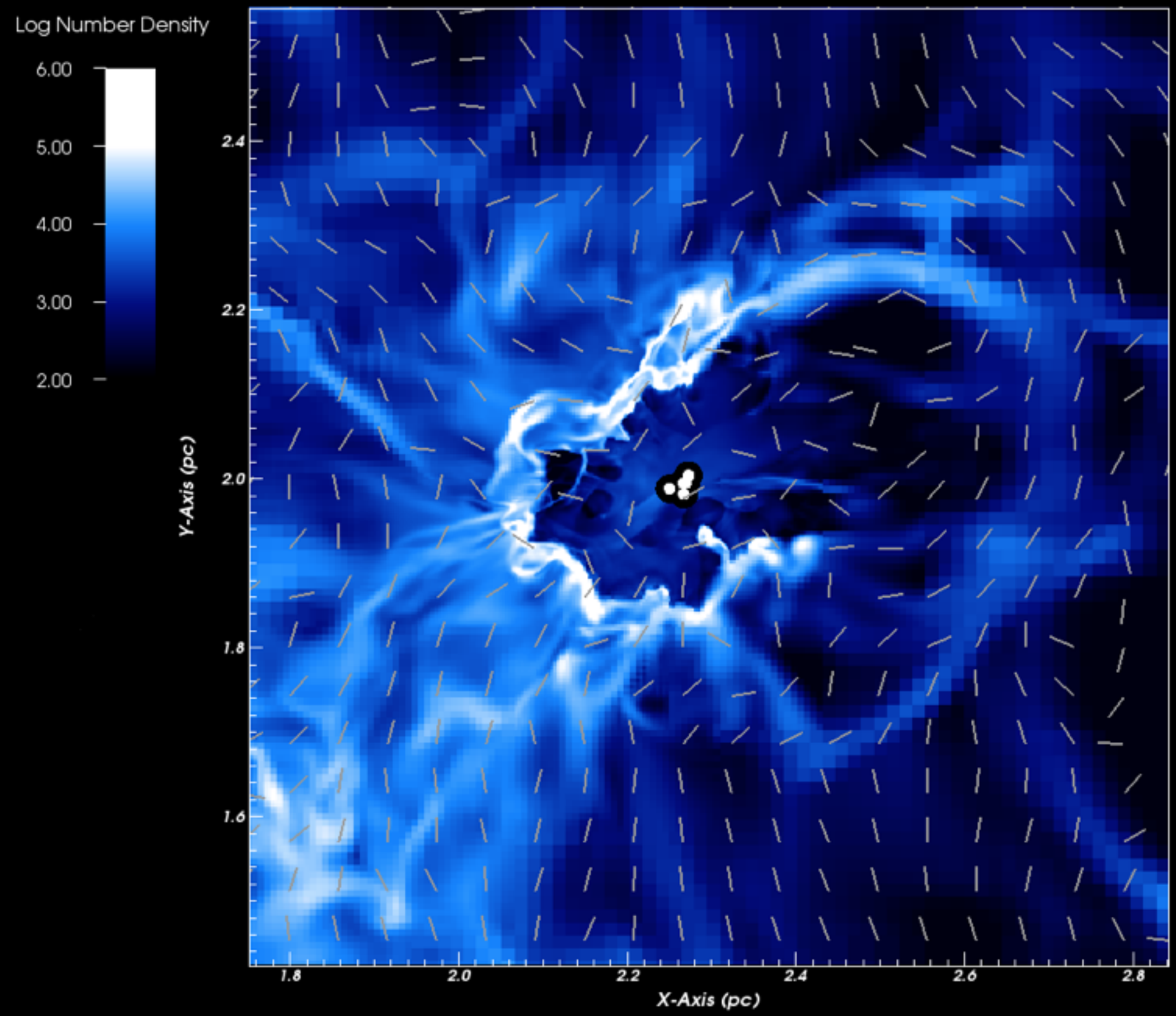

Gaussian
Ostriker
Arzoumanian
Fischera
MHD
Column Density (10^{21} cm^{-2})
10
20
30
40
−0.15
−0.10
−0.05
−0.00
0.05
0.10
0.15
Radial Separation (pc)

Magnetic fields in filaments



Magnetized Turbulent Cloud Clump

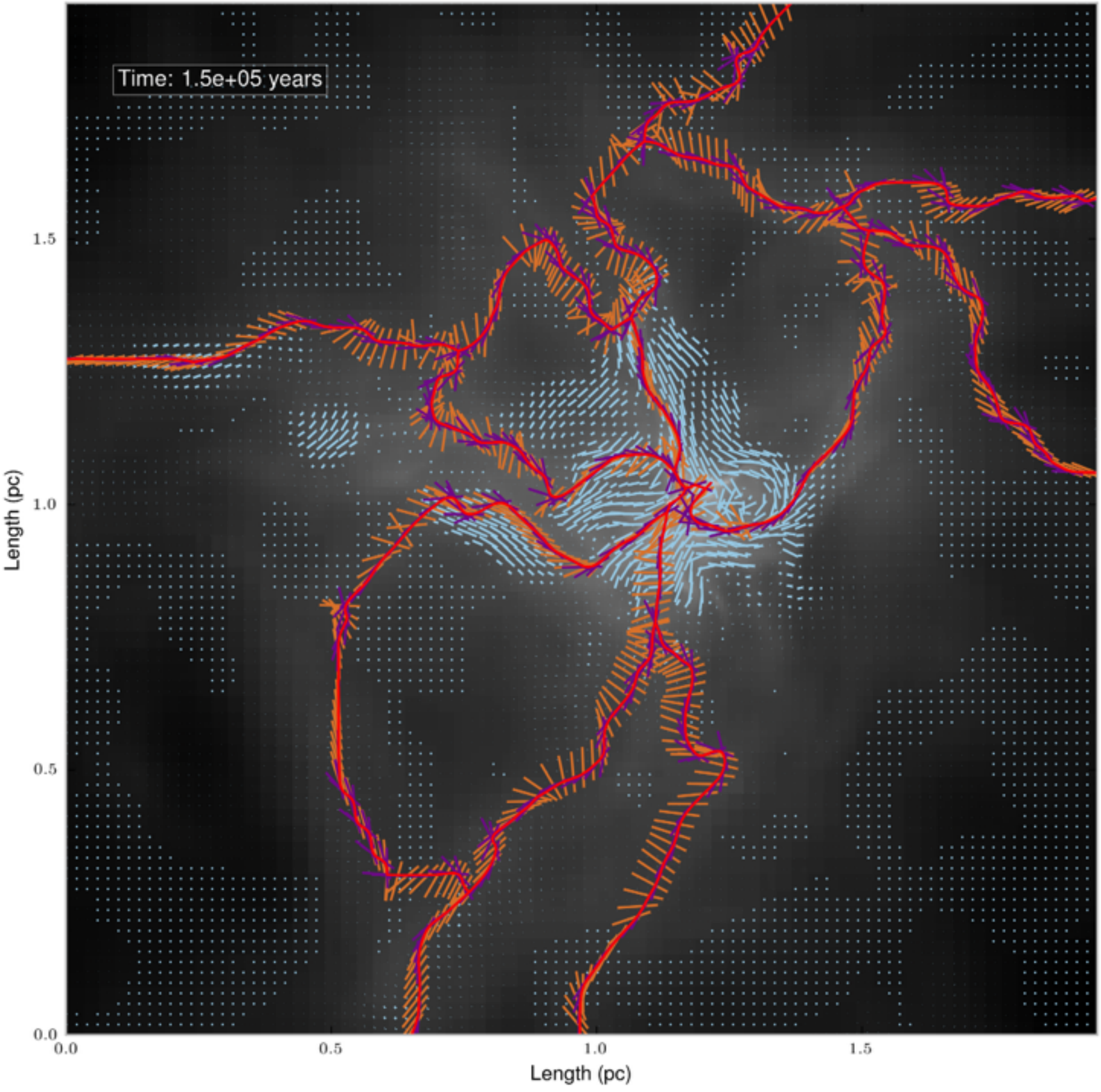
Mikhail Klassen, Ralph Pudritz, Thomas Peters



Magnetized Turbulent Cloud Clump

Mikhail Klassen, Ralph Pudritz, Thomas Peters

1200 $M_\odot$ Turbulent MHD Simulation
Z-Axis Projected Density and B-field Orientation



Summary

- Study of the ISM linked to star formation feedback — a challenging problem requiring detailed numerical simulation

- We are implementing a 2T hybrid radiation transport method in FLASH on AMR grids

  - Ionizing feedback and multifrequency treatment to come

- This method is ideally suited for studying star formation in the turbulent, magnetized, filamentary ISM and down to protoplanetary disk scales

Thank you