Underdense stellar jets propagating into the ISM: radiation-hydrodynamics effects

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Outline

Introduction to radiation hydrodynamics

I. Moments models : FLD vs M1

II. The HERACLES code

III. Simulations of a jet impacting the ISM

Conclusions and perspectives

The radiation hydrodynamics

Radiative transfer treatment: 2 solutions

1. diagnostic and interpretation tool

→ no feedback with hydrodynamics

fine transfer (atomic data, lines….)

2. dynamic effects of the radiation

→ global budget (energy – impulsion)

This is **radiation hydrodynamics**

Relevant applications for radiation hydrodynamics:

- In astrophysics
  - accretion shocks on massive object or in formation
  - stellar jets and flows
  - radiative winds of pulsating stars
  - supernovae explosions…
- In laboratory plasmas
  - physics of Inertial Confinement Fusion
  - radiative shocks

How to solve the transfer equation ?

$$\left(\frac{1}{c}\frac{\partial}{\partial t} + \mathbf{n}.\nabla\right) I(\mathbf{x},t,\mathbf{n},\nu) = \eta(\mathbf{x},t,\mathbf{n},\nu) - \chi(\mathbf{x},t,\mathbf{n},\nu) I(\mathbf{x},t,\mathbf{n},\nu)$$

- **Direct integration**
  - ✓ high cost (time – memory)
- **Monte-Carlo methods**
  - ✓ coupling with hydrodynamics not natural
  - ✓ high cost in optically thick regions
- **Moments models**
  - ✓ approximations of the physical model

$$\left\{\begin{array}{lclll} E_r(\mathbf{x},t,\nu) & = & \frac{1}{c} & \oint I(\mathbf{x},t;\mathbf{n},\nu) & d\omega \\ \mathbf{F}_r(\mathbf{x},t,\nu) & = & & \oint I(\mathbf{x},t;\mathbf{n},\nu)\mathbf{n} & d\omega \\ \mathbf{P}_r(\mathbf{x},t,\nu) & = & \frac{1}{c} & \oint I(\mathbf{x},t;\mathbf{n},\nu)\mathbf{n}\otimes\mathbf{n} & d\omega \end{array}\right.$$

Radiative energy
Radiative flux
Radiative pressure

The moments models

If LTE and no scattering:

$$\partial_t E_r^\nu + \nabla.F_r^\nu = \sigma^\nu c(4\pi B(\nu,T) - E_r^\nu)$$
$$\partial_t F_r^\nu + c^2 \nabla.P_r^\nu = -\sigma^\nu c F_r^\nu$$

If grey assumption:

$$\partial_t E_r + \nabla.F_r = \sigma c(a_r T^4 - E_r)$$
$$\partial_t F_r + c^2 \nabla.\mathbf{P}_r = -\sigma c F_r$$

Needs then a closure relation to the system:

$$\mathbf{P_r = f(E_r, F_r)}$$

e.g. Diffusion : $F_r = -\frac{c}{\sigma}\nabla.P_r$ + $\mathbb{P}_r = \frac{1}{3}E_r\mathbb{I}$

$$\partial_t E_r + \nabla \cdot \lambda \frac{c}{3\sigma} \nabla E_r = \sigma c(a_r T^4 - E_r)$$

rapid BUT - flux always colinear and proportional with the energy gradient

- ad-hoc flux limiter λ

The M1 model

(Levermore 1984 ; Dubroca & Feugeas 1999)

Planck function:

$$B(\nu,T)=\frac{2h\nu^3}{c^2}[\exp(\frac{h\nu}{kT})-1]^{-1}$$

M1 distribution function:

$$B(\nu,\vec{\Omega},T^*)=\frac{2h\nu^3}{c^2}[\exp(\frac{h\nu}{kT^*}(1-\frac{2-\sqrt{4-3f^2}}{f^2}\vec{f}.\vec{\Omega}))-1]^{-1}$$

with $T^*=\frac{2}{f}\left(-1+\sqrt{4-3f^2}\right)^{\frac{1}{4}}\sqrt{f^2-2+\sqrt{4-3f^2}}T_R$

and $f=\frac{F_r}{cE_r}$

- **Minimization of radiation entropy**
- **Lorentz transformation of a Planck function**

The M1 model

The closure relation for M1 model is:

$$\mathbf{P}_r = \mathbf{D} E_r$$

$$\mathbf{D} = \frac{1-\chi}{2}\mathbf{I} + \frac{3\chi-1}{2}\mathbf{n}\otimes\mathbf{n}$$

General form assuming a privileged direction n

$$\chi = \frac{3+4f^2}{5+2\sqrt{4-3f^3}}$$ with $$f = \frac{F_r}{cE_r}$$

Advantages

- low cost
- take radiation anisotropies into account
- exact in both diffusive and free streaming limits
- can take (anisotropic) diffusion into account
- allow "proper" means over opacities

The radiation hydrodynamics

$$
\begin{aligned}
\partial_t \rho + \quad & \nabla.[\rho u] &= \quad & 0 \\
\partial_t \rho u + \quad & \nabla.[\rho u \otimes u + P\mathbf{I}] &= \quad & \frac{\sigma}{c} F_r + F \\
\partial_t E + \quad & \nabla.[u(E+P)] &= & -\sigma c(a_r T^4 - E_r) + (\frac{\sigma}{c} F_r + F).u \\
\partial_t E_r + \nabla.[E_r u] + \nabla.F_r + \mathbf{P}_r : \nabla u & &= \quad & \sigma c(a_r T^4 - E_r) \\
\partial_t F_r + \nabla.[F_r u] + c^2 \nabla.\mathbf{P}_r + (F_r.\nabla)u & &= & -\sigma c F_r
\end{aligned}
$$

comoving frame… at O(v/c)

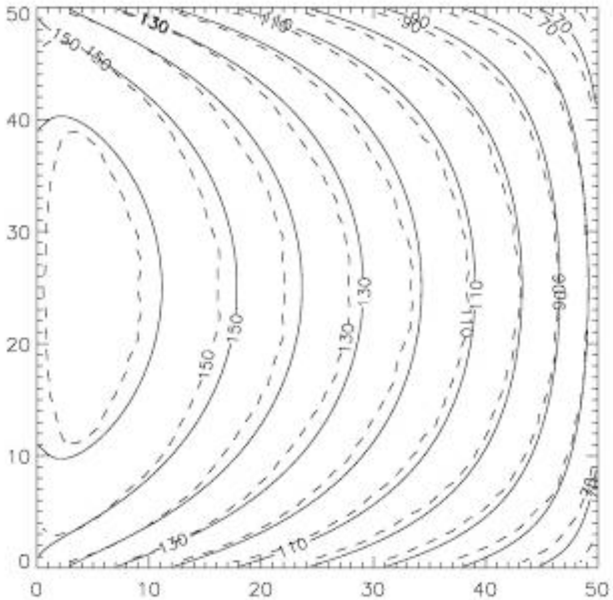
interaction terms

The HERACLES code

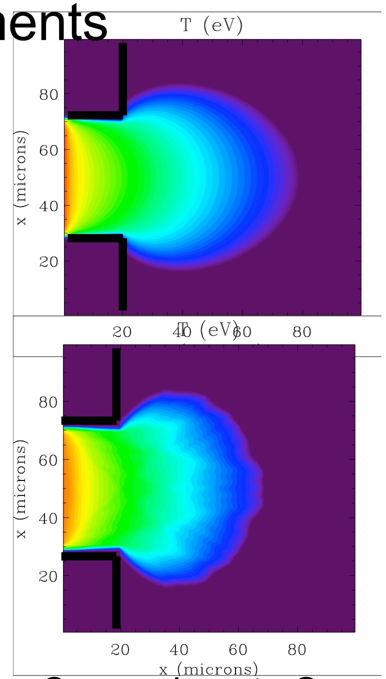
González & Audit ApSS 2005
González *et al.* A&A 2007
Fromang *et al.* A&A 2006 (MHD)

- An Eulerian 3D RMHD code
- Hydrodynamics: explicit, MUSCL-Hancock
- Radiative transfer:
  - grey M1 model
  - MPI implicit solver
- Cross-validation with numerical tests and laboratory experiments

Conserves the radiation anisotropy



Comparison to a Monte Carlo code



Comparison to Sn
(González *et al.* ASPCS 2008, ANE 2009)

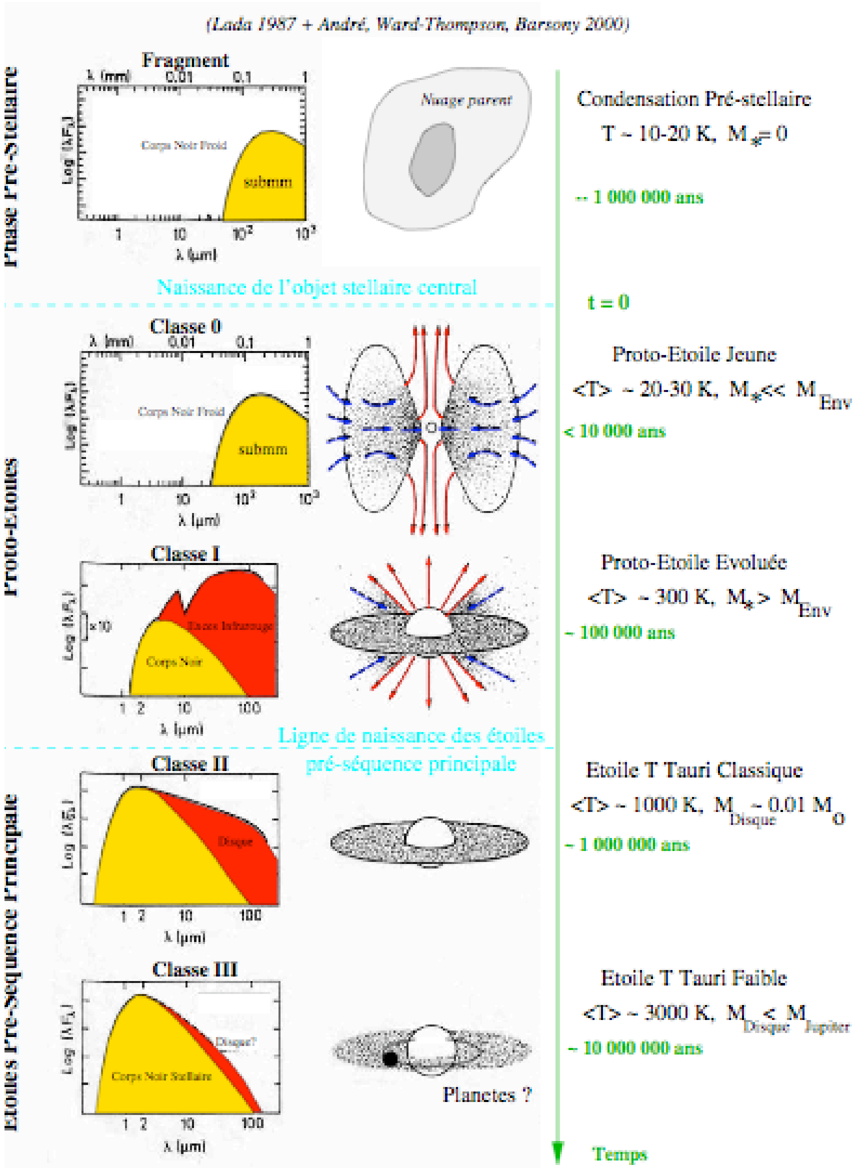
The HERACLES code

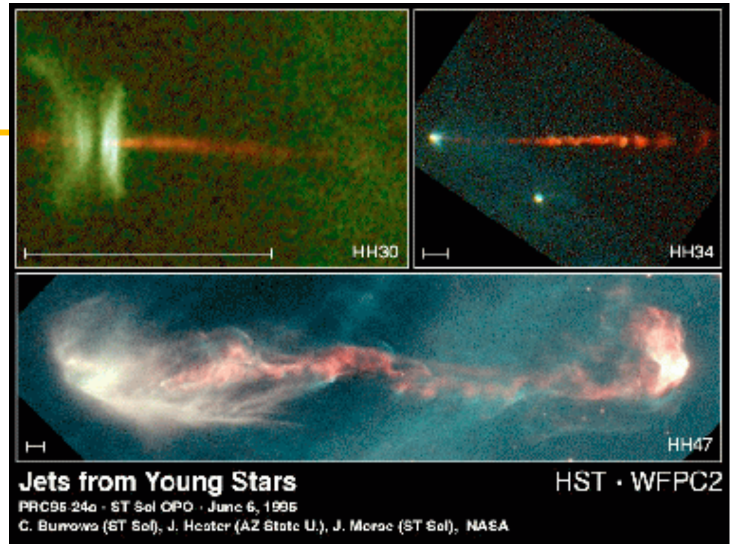
- Advantages
  - ✓ natural coupling to the hydrodynamics (3D)
  - ✓ modelling of transport and diffusion
  - ✓ low cost => can model complex situations

- Disadvantages
  - ✓ physical approximations inherent to the M1 model
  - ✓ grey model (on-going multigroup development)

- Applications
  - ✓ modelling of radiative shocks experiments (cross-validation)
  - ✓ stellar jets
  - ✓ interstellar turbulence (cf. E. Audit’s talk)
  - ✓ physics of ICF

Context of protostars jets



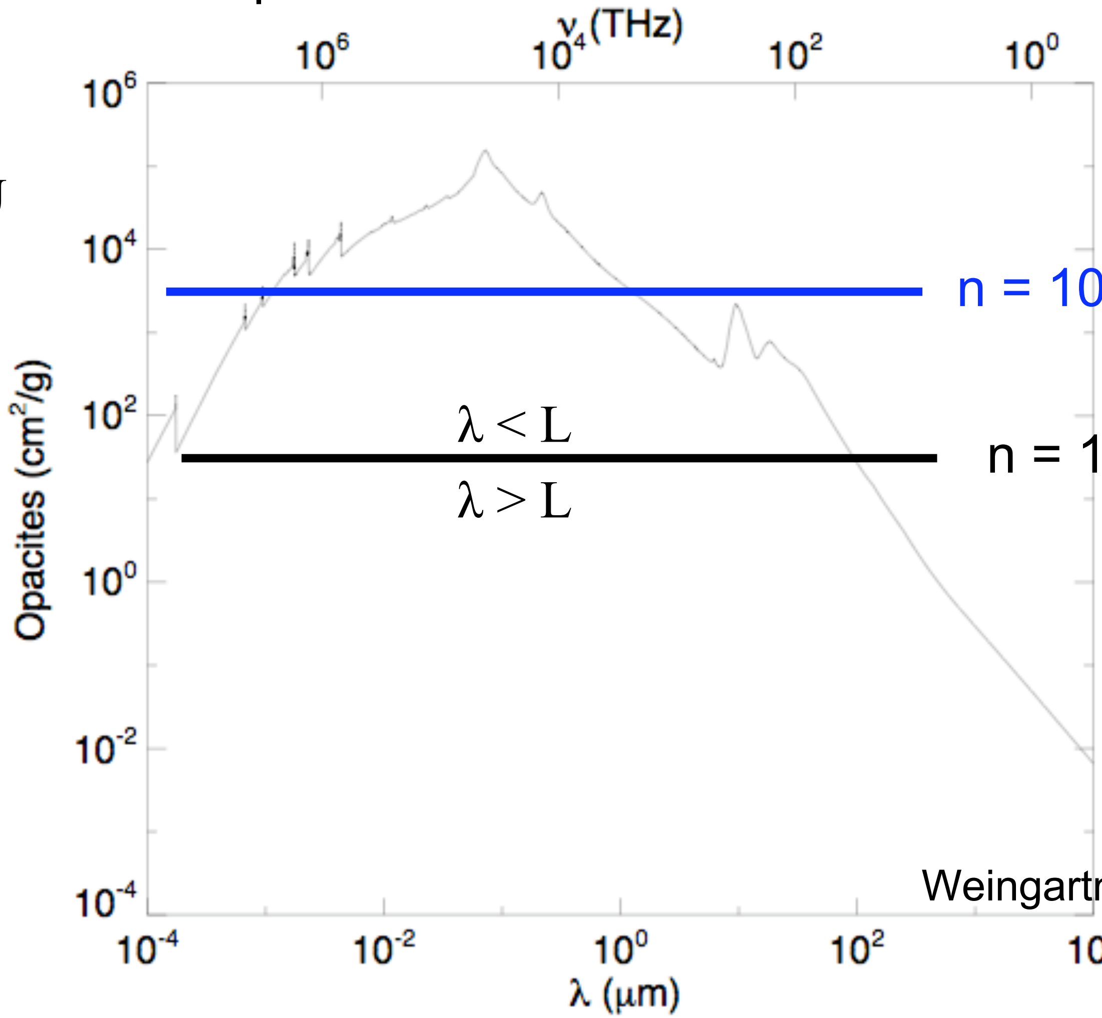


- Their formation
  - ✓ Accretion discs + bipolar jets
  - ✓ Magnetic field influence
- Their propagation
  - ✓ Kinetic regime
  - ✓ Very dense ambient medium (molecular cloud)
- The ISM properties (André *et al.* PPIV 2000)
  - ✓ $n \sim R^{-1.5}$ with $n \sim 10^6$ cm^{-3} at $R \sim 1000$ AU

Why including radiative transfer ?

- $\lambda > L$: the photons freely escape => cooling
- $\lambda < L$: the photons are absorbed => radiative transfer

L=1000 AU



n = 10^4 cm^{-3}

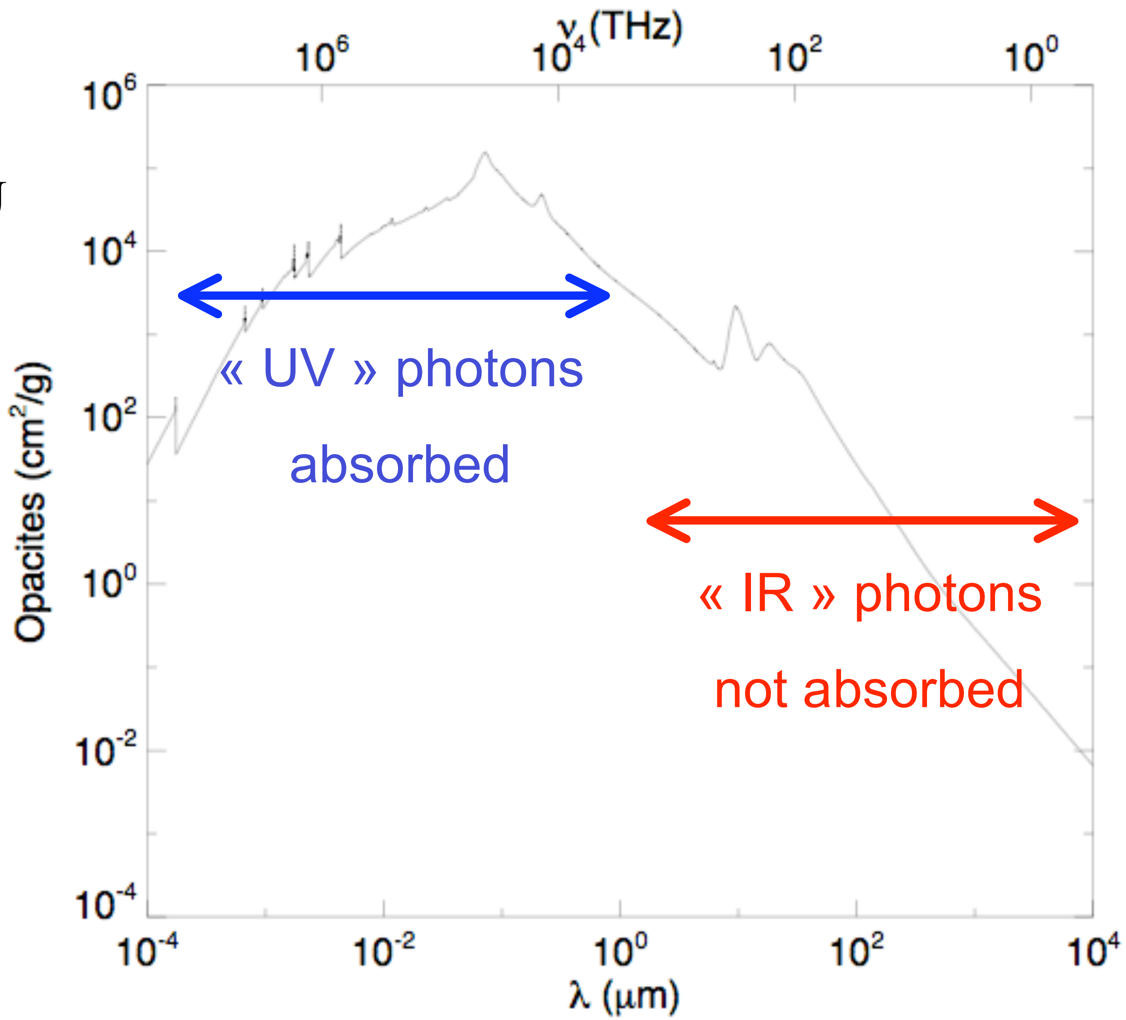
n = 10^6 cm^{-3}

dust opacities
Weingartner&Draine 2001, Draine 2003

Why including radiative transfer ?

- 2 groups of photons

L=1000 AU



The physics included

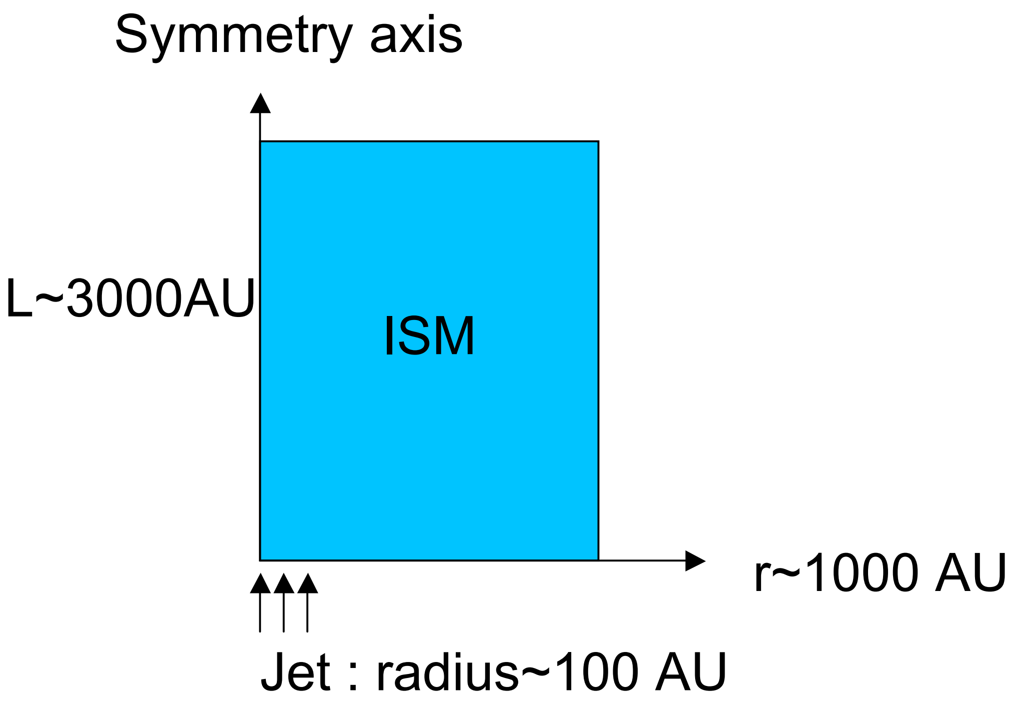
- ✓ Opacities: Draine et al. 2003 (dust) + Huré 2000 (gas)
  dust sublimation for T>2000K

- ✓ « UV » photons group treated by M1 model
  « IR » photons group treated by a cooling function

- ✓ Cooling/Heating function (J.P. Chièze):
  OI, CI, C^+, H_2, H_20, ^{13}CO lines
  cosmic rays + grains photoelectric effect

Configuration of the 1D/2D simulations

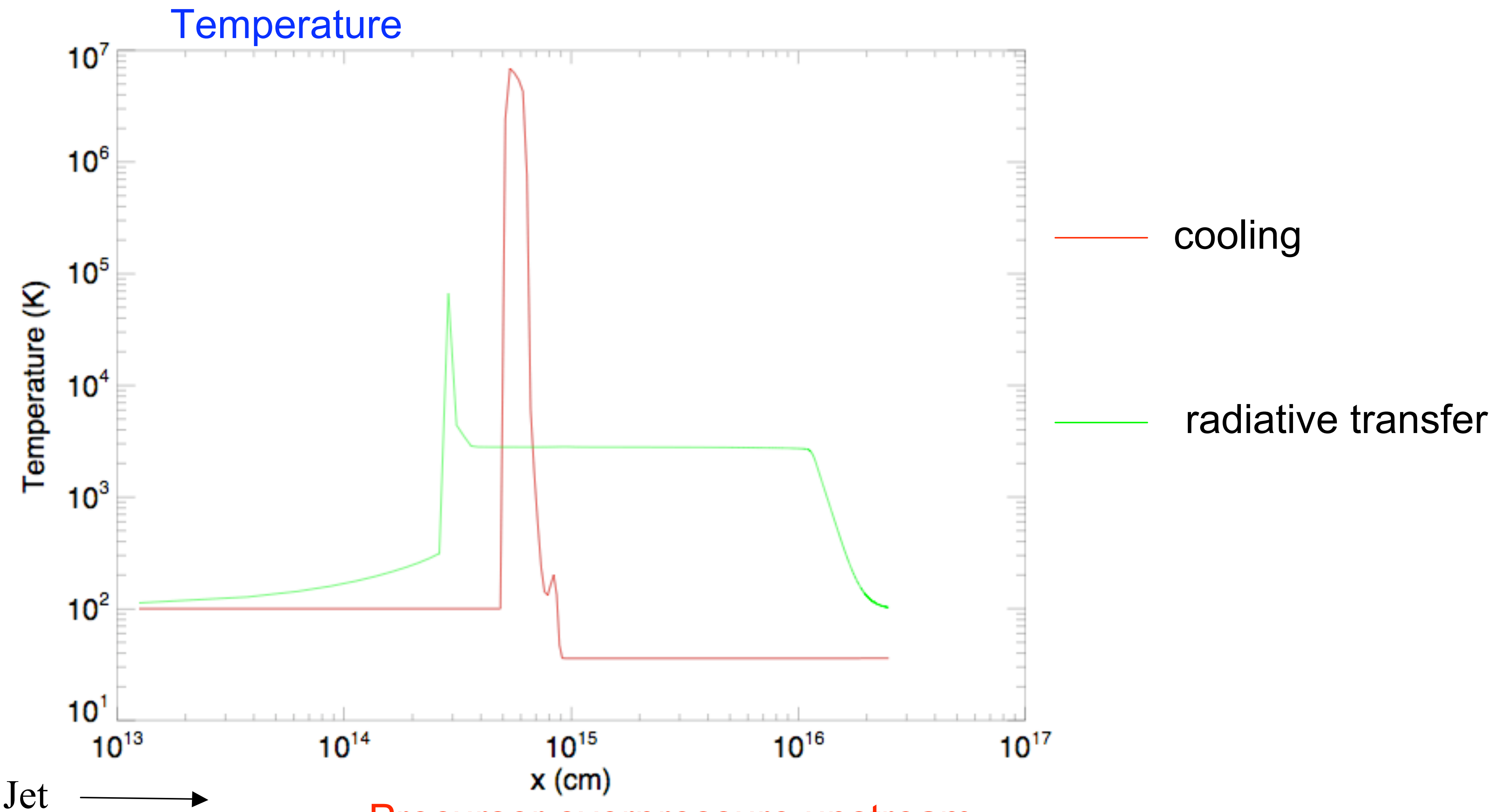
- ISM
  - ✓ n ~ 1e6 cm^{-3}
  - ✓ T ~ 100 K
  - ✓ u ~ 0 km/s



- Jet
  - ✓ n ~ 100 cm^{-3}
  - ✓ T ~ 100 K
  - ✓ u ~ 500 km/s

- Different simulations
  - ✓ hydrodynamics with cooling
  - ✓ hydrodynamics with radiative transfer
  - ✓ jet apodisation
  - ✓ jet pulsation: 25% over 60yrs (Cabrit 2002, Smith&Rosen 2005)
  - ✓ ISM density gradient

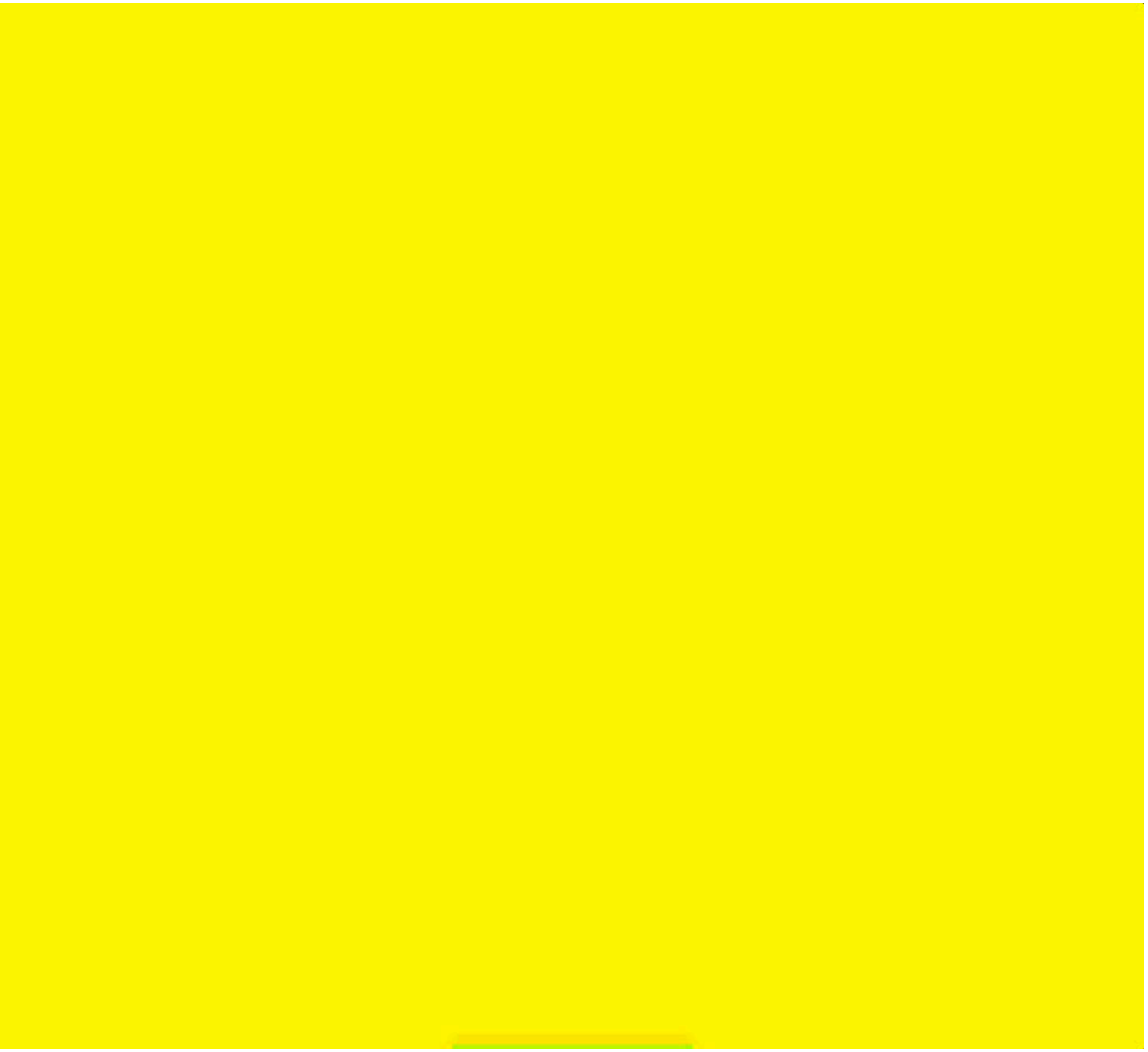
1D jet



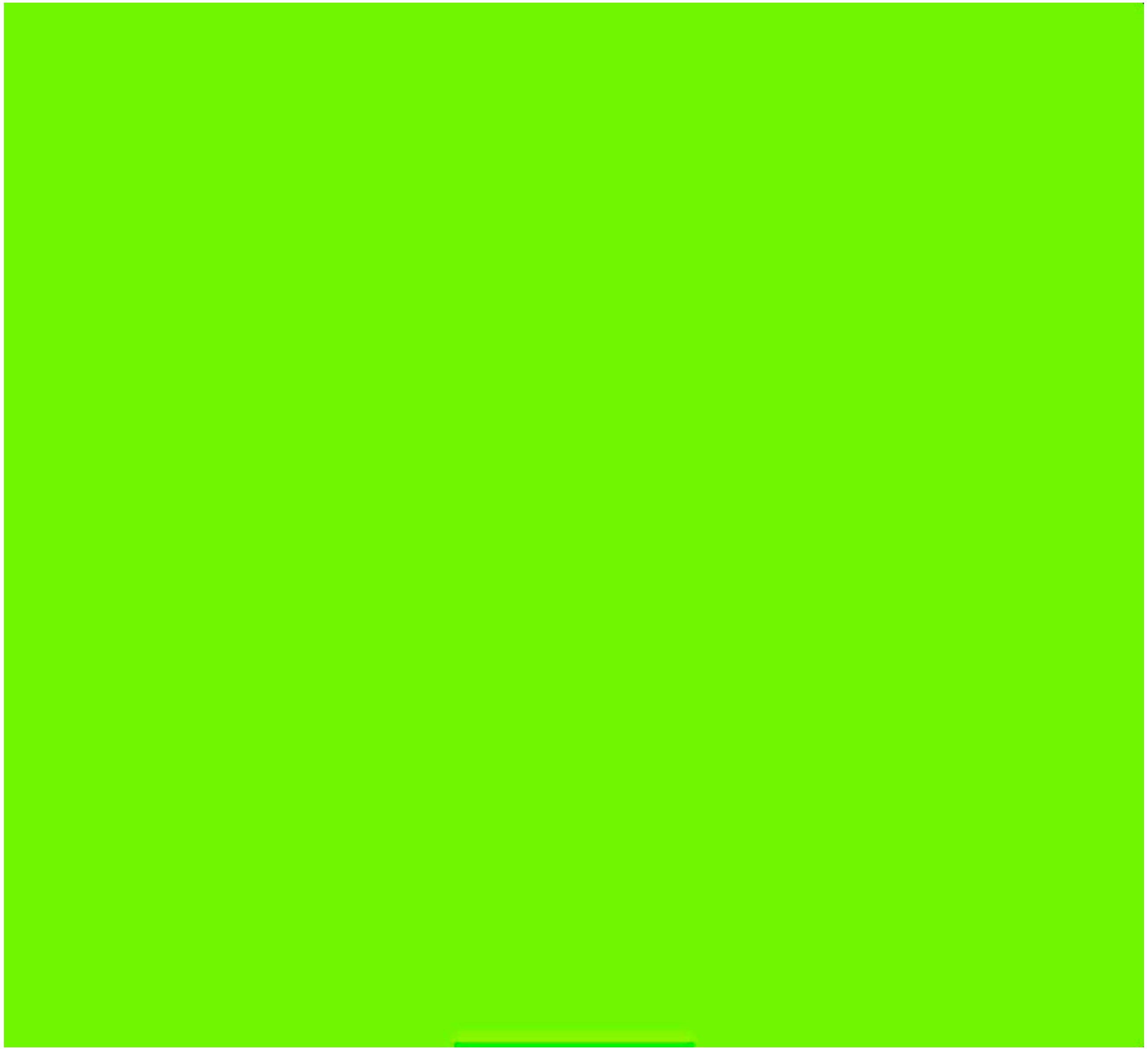
Precursor overpressure upstream

Different temperature peaks -> different observational footprints

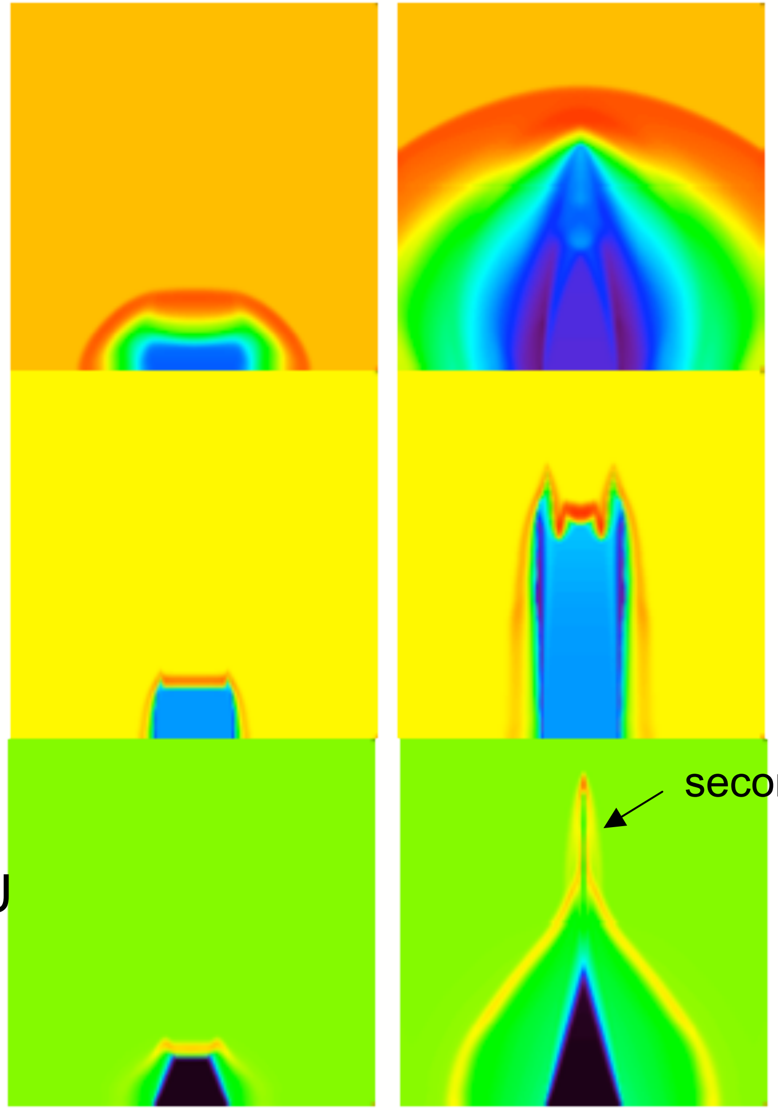
2D simulation with cooling



2D simulation with radiative transfer



Snapshots



3000 AU

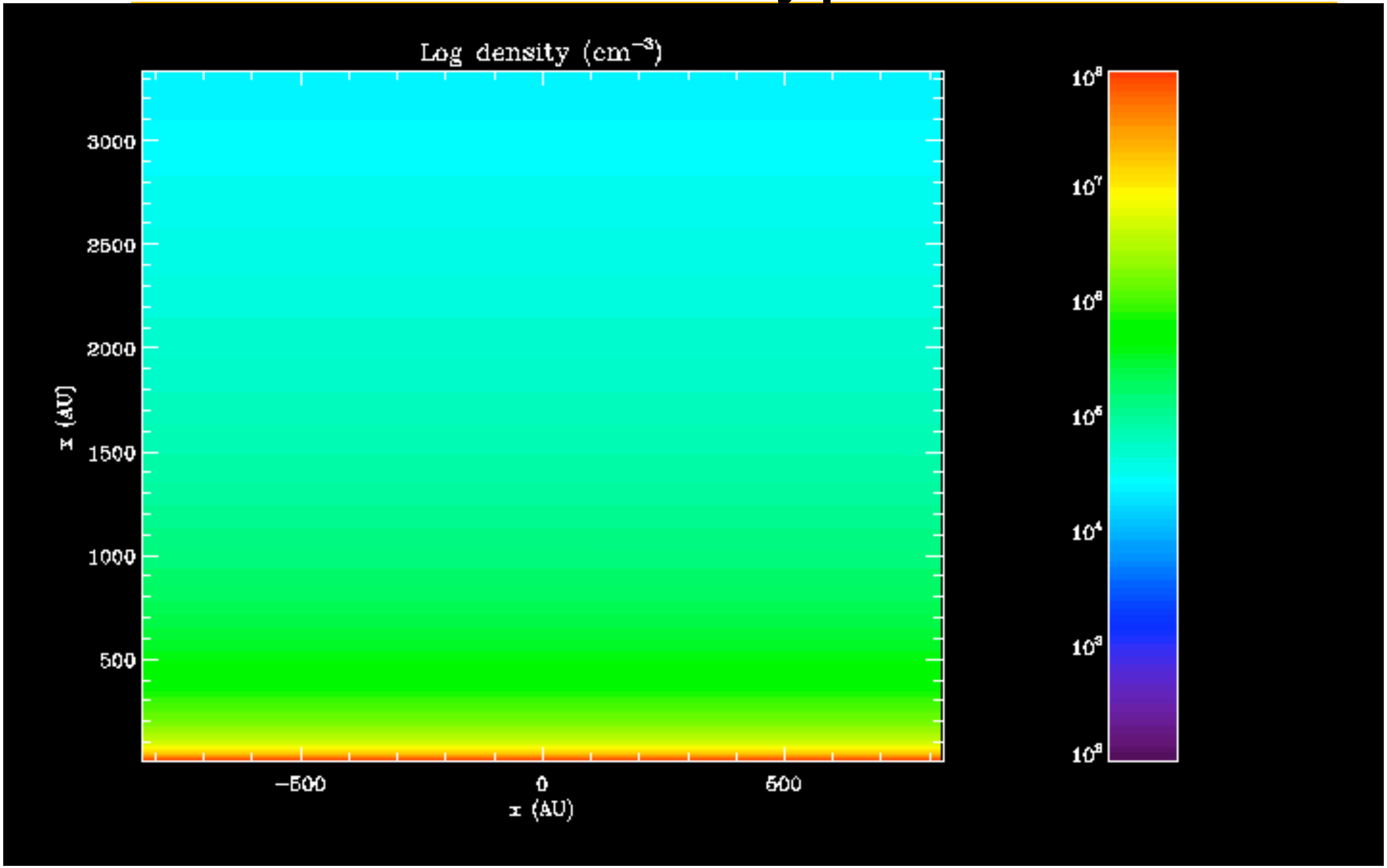
500 yrs   2 000 yrs

hydrodynamics

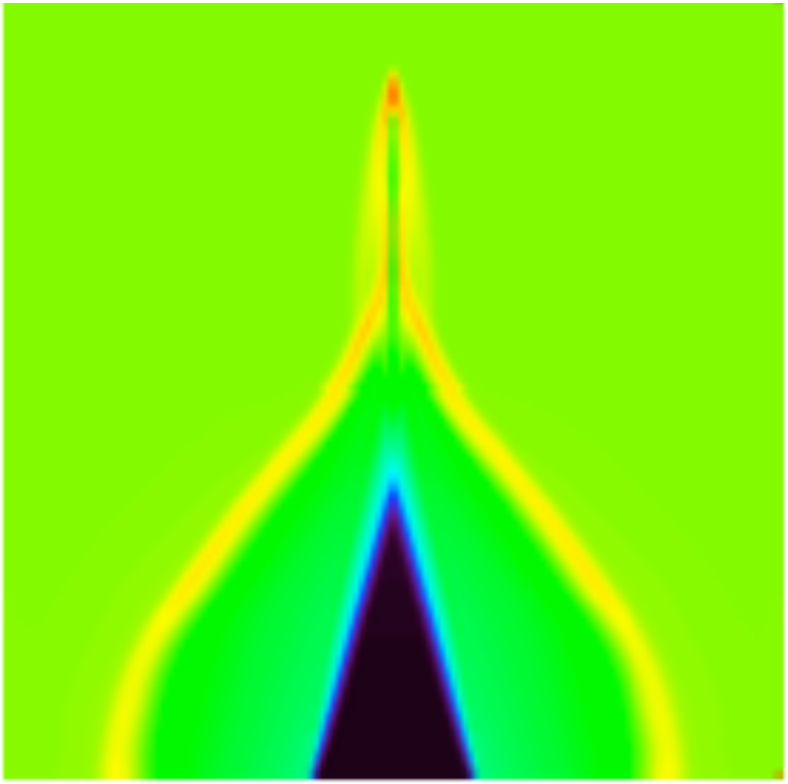
hydrodynamics with cooling
- jet head unstable
- jet width~constant

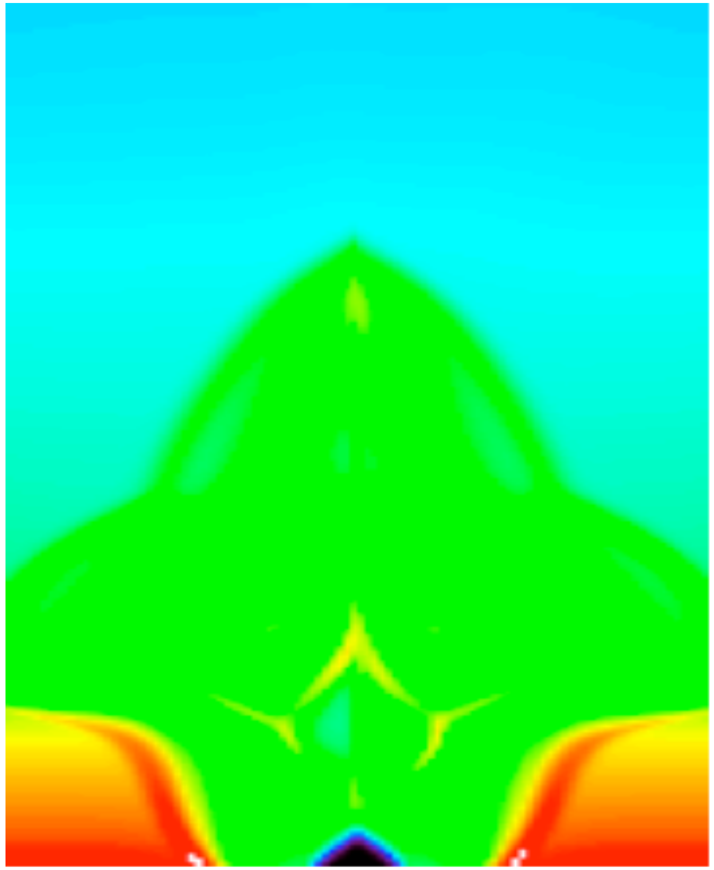
hydrodynamics with radiative transfer
- collimation
- secondary jet launched (few km/s)

Influence of an ISM density profile



Snapshots





Density profile (n ~ $R^{-1.5}$) influence:

jet no more collimated

sub-structures into the jet

Summary and perspectives

➢ Summary

- ✓ HERACLES is a 3D RMHD code based upon M1 model
- ✓ simulations of stellar jets: radiative collimation

➢ Perspectives

- ✓ 3D simulations (density and temperature ISM profiles, precession…)
- ✓ post-processing for synthetic maps emissivity (observations)
- ✓ real M1 multigroup treatment : cf. N. Vaytet's poster