Pillars, Jets and Dynamical Features (Ionization in SPH-simulations)

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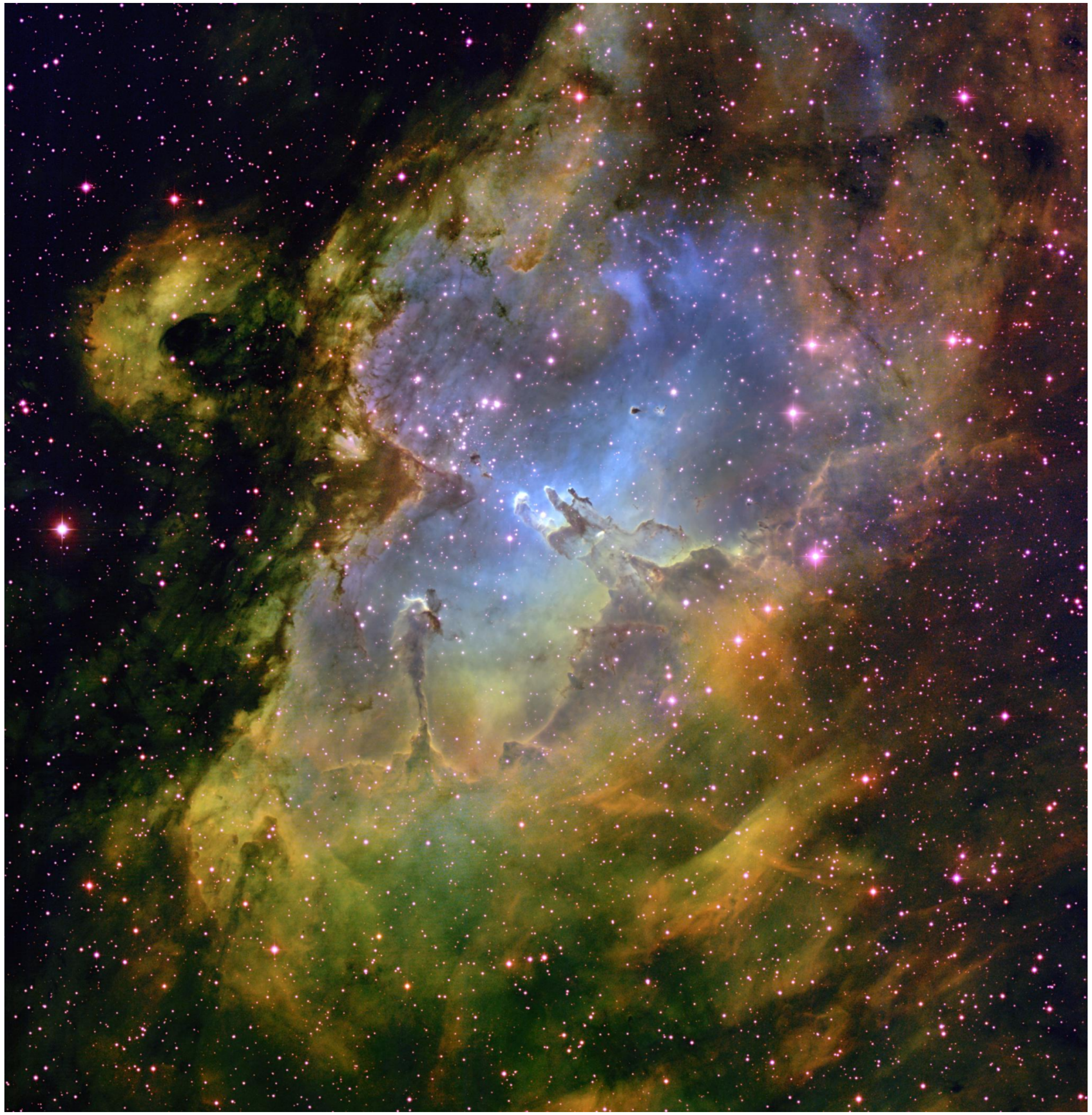
ISIMA Santa Cruz, July 2010

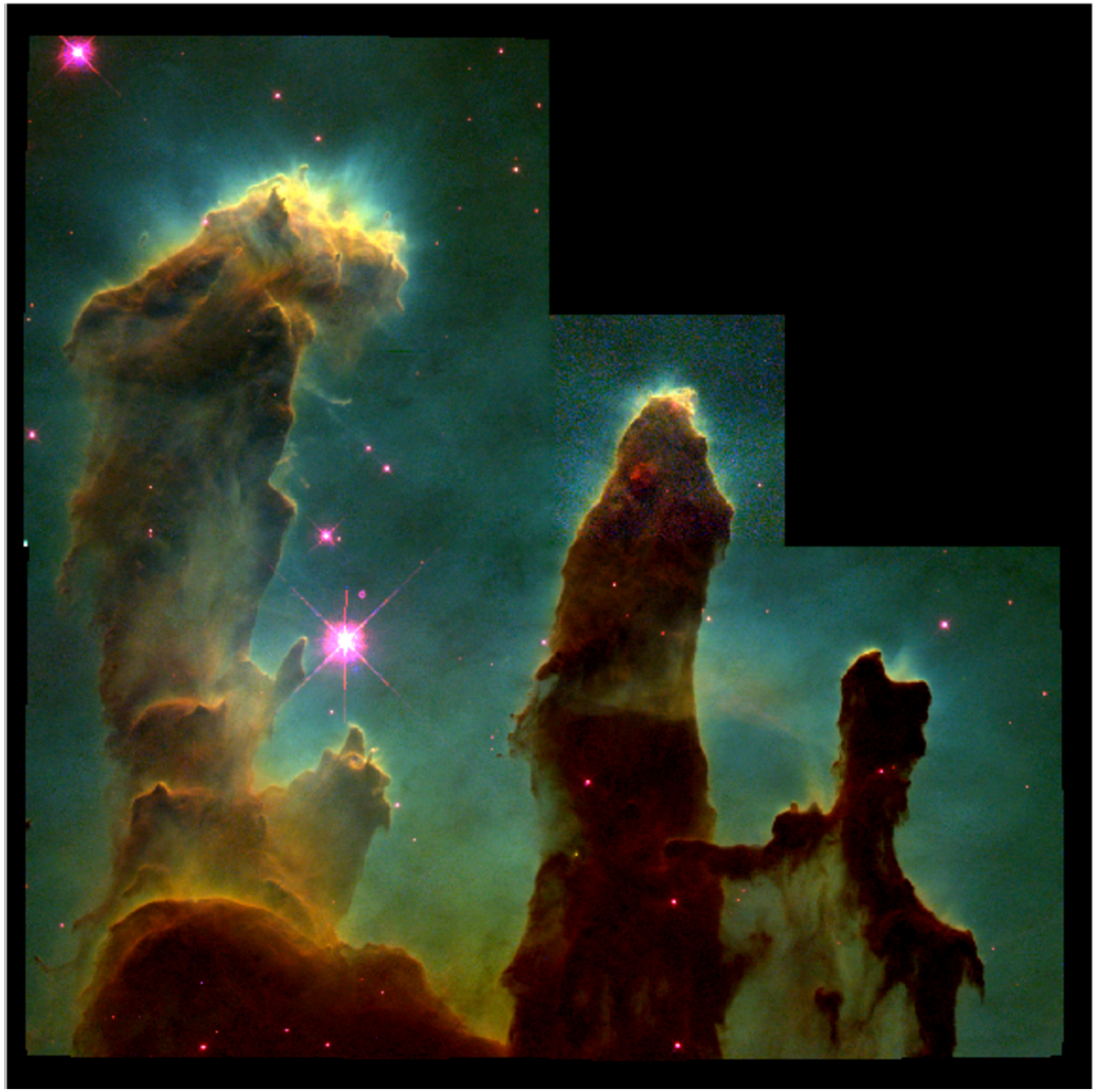
www.kiaa.pku.edu.cn

The Eagle Nebula (M16)



T. A. Rector & B. A. Wolpa, NOAO, AURA

The Pillars of Creation in M16



J. Hester, P. Scowen (ASU), HST, NASA


Pillar and Jets HH 901/902
Hubble Space Telescope ▪ WFC3/UVIS
NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI)
STScI-PRC10-13a

How do these structures form?

Instabilities in a shocked shell:

Rayleigh-Taylor instability:

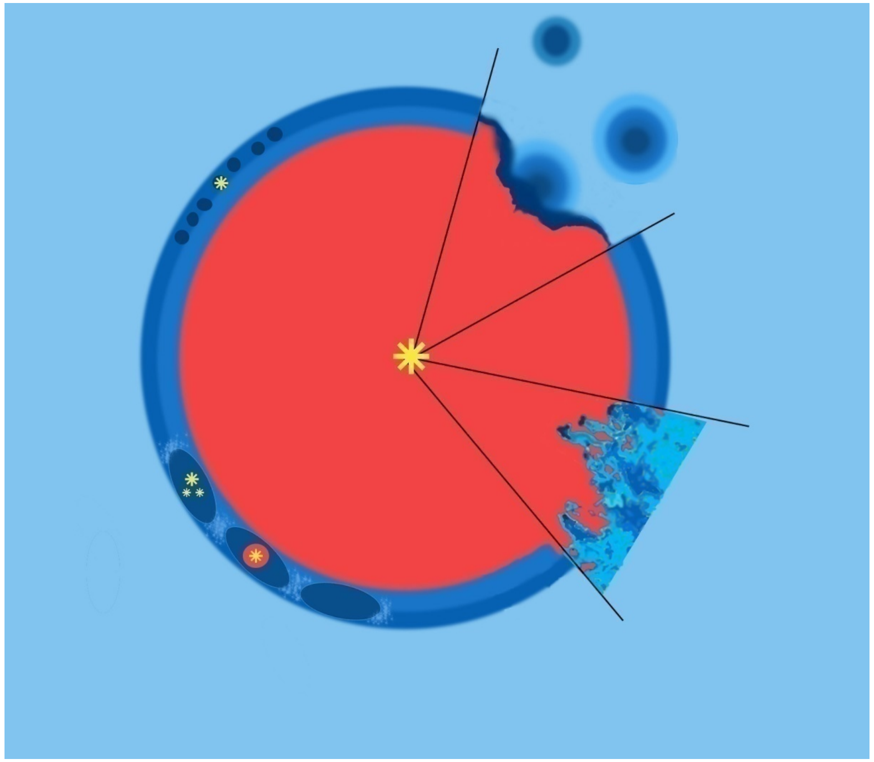
•Structures to smooth, no complex density structure

Gravitational instability: (Collect and Collapse)

•Timescale and masses to large, more likely in supernova-shells

Radiation Driven Implosion of pre-existing clumps

Ionization of the turbulent parental cloud 'Radiative Round-Up'



(figure by courtesy of Lise Deharveng)

Radiative Transfer

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \vec{n}\cdot\vec{\nabla} I_\nu = \varepsilon_\nu - \kappa_\nu \rho I_\nu$$

$I_\nu = I_\nu(\vec{r},\vec{n},t)$: intensity at a given monochromatic frequency ν

$\varepsilon_\nu = \varepsilon_\nu(\vec{r},\vec{n},t)$: emissivity

$\kappa_\nu = \kappa_\nu(\vec{r},\vec{n},t)$: mass absorption coefficient

⇨ 7-dimensional partial differential equation

Assumptions: •Intensity is not time dependent

•Only one source emitting / no scattering => ε=0

$$\vec{n}\cdot\vec{\nabla} I_\nu = -\kappa_\nu \rho I_\nu \qquad \Rightarrow I_\nu(\vec{r}) = I_0 e^{-\tau(\vec{r})} \text{ with } \tau(\vec{r}) = \int_{\vec{r}_0}^{\vec{r}} \kappa_\nu(r)\rho(r)dr$$

Ionization

Ionizing Radiation:

$$J(x) = \int_{\nu_{Ly}}^{\infty} I_\nu(x)\, d\nu = J_0 e^{-\tau(x)}$$

Mass absorption:

$$\kappa_\nu = \frac{\sigma_\nu n_H}{\rho} \approx \frac{\bar{\sigma} n_H}{\rho} \quad \text{with } \bar{\sigma} = \frac{\int_{\nu_{Ly}}^{\infty} I_\nu \sigma_\nu d\nu}{\int_{\nu_{Ly}}^{\infty} I_\nu d\nu}$$

Optical Depth:

$$\Rightarrow \tau(\vec{r}) = \int_{\vec{r}_0}^{\vec{r}} \frac{\bar{\sigma} n_H}{\rho} \rho\, dr = \int_{\vec{r}_0}^{\vec{r}} \bar{\sigma} n_H(r)\, dr$$

Ionization Degree:

$$\eta \equiv \frac{n_e}{n} \quad , \quad \frac{d\eta}{dt} = \frac{1}{n}\frac{dn_e}{dt} = \frac{1}{n}(I - R)$$

$$and \quad I = -\nabla J \ , \ R = n_e^2 \alpha_B = n^2 \eta^2 \alpha_B$$

Recombination:

$$\alpha_B = \sum_{i=2}^{\infty} \alpha_k \ \ \textit{(on the spot approximation)}$$

The Strömgren-Sphere

•Ionization degree: $\eta \equiv \frac{n_e}{n}$, $\frac{d\eta}{dt} = \frac{1}{n}\frac{dn_e}{dt} = \frac{1}{n}(I - R)$

•Recombination: $R = n_e^2 \alpha_B = n^2 \eta^2 \alpha_B$ $\alpha_B = \sum_{i=2}^{\infty} \alpha_k$

•Equilibrium: $\frac{d\eta}{dt} \overset{!}{=} 0 \Leftrightarrow I = R \Leftrightarrow -\nabla J_{Ly} = n^2 \eta^2 \alpha_B$

Integration

•The Strömgren-Sphere: $J_{Ly} = V_S n^2 \eta^2 \alpha_B$

Evolution of a Strömgren-Sphere

$t < t_{crit}$

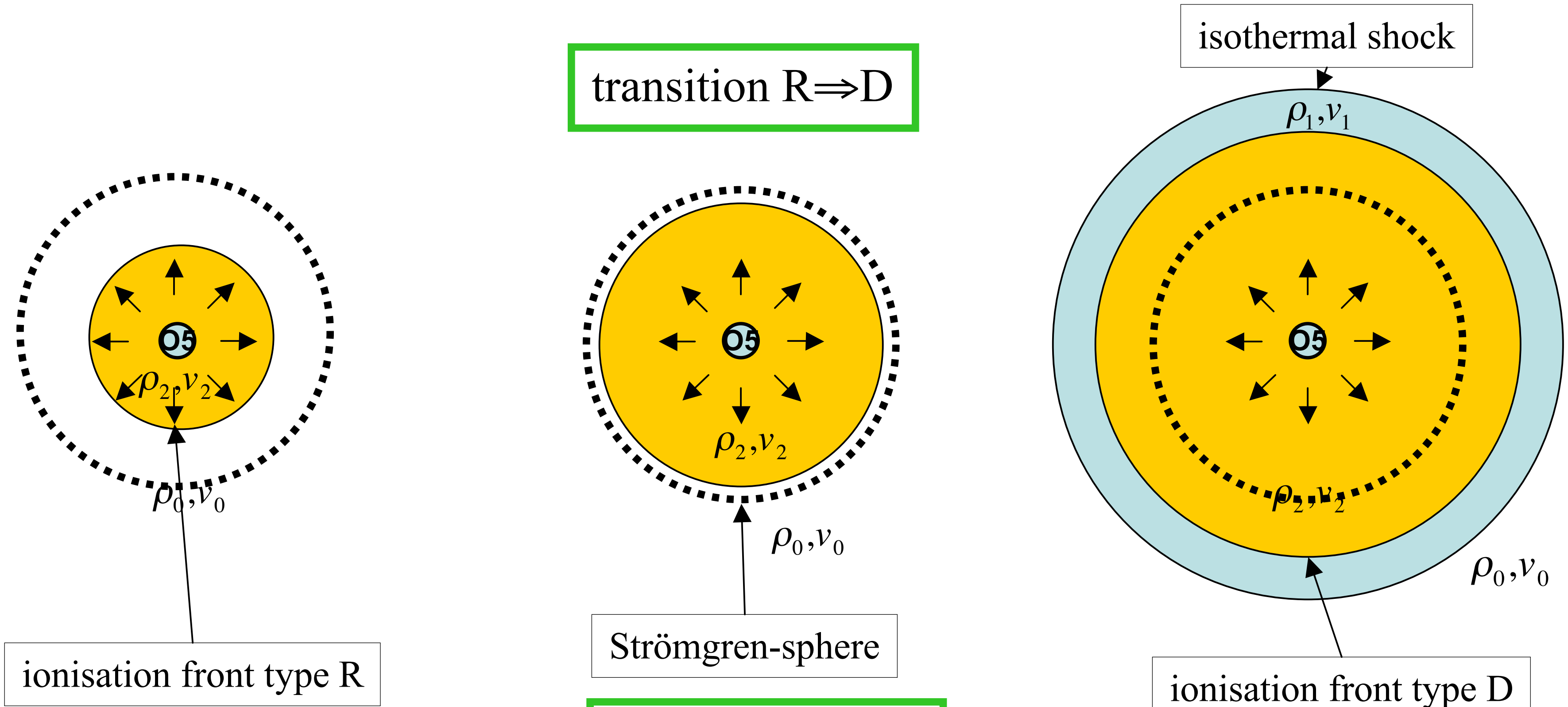
$\rho_2 \approx \rho_0$

$t = t_{crit} \approx 5kyr$

$\rho_2 < \rho_0$

$t > t_{crit}$

$\rho_2 < \rho_1 > \rho_0$



$v_{ion} = v_0 > c_2$

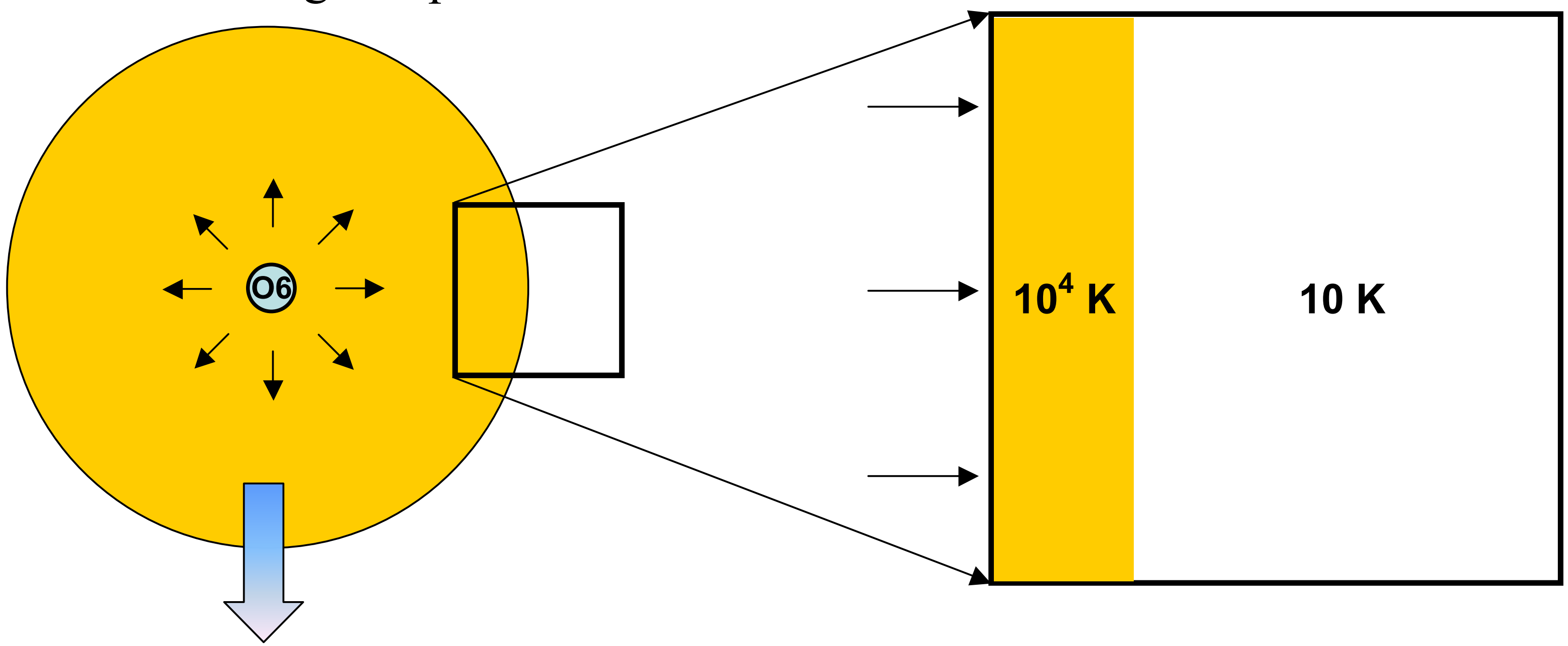
$$R_S = \left(\frac{3F_{Ly}}{4\pi\alpha_B n_0^{\ 2}} \right)^{1/3}$$

$v_{ion} = v_1 < c_2$

Simplified Prescription

•Heating by UV radiation via $T = T_{cold} \cdot (1 - \eta) + T_{ion} \cdot \eta$

Ionised Strömgren sphere



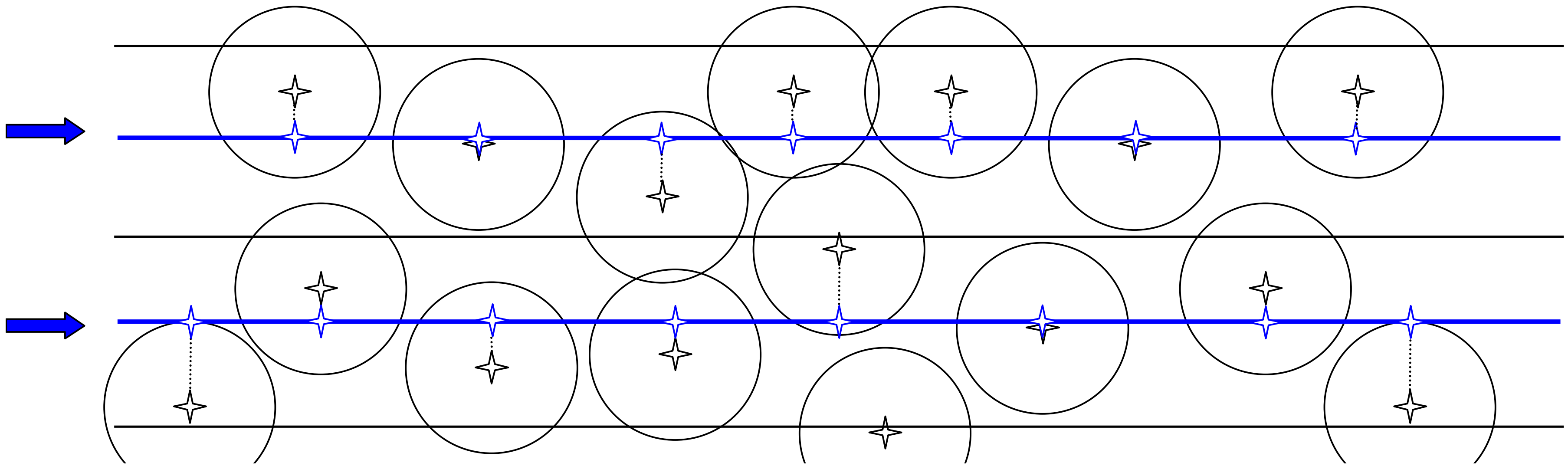
Every UV-photon ionises one hydrogen atom

Shock front is driven into the cold medium

Average temperature $T_{ion} = 10^4$ K

Numerical Method I: iVINE

- OMP-parallel tree/SPH-Code: iVINE: Ionization + VINE
  (Gritschneder et al. 2009, MNRAS, 393, 21 ; Wetzstein et al. 2009, ApJS, 184, 298)
- Following the radiation along a grid of line-of-sights (ray shooting)
- The size Δy of the rays is determined by the smoothing length close to the area of infall
- As soon as the ray size gets twice as large as the local smoothing length, the ray is refined.
- On the ray the ionization is calculated (photon conserving)
- The particles get assigned a temperature $T = \eta\, T_{hot} + (1-\eta)\, T_{cold}$



Physical Timescales

- Gravity: $t_{ff} = \sqrt{\dfrac{3T}{32\pi\rho}}$
- Hydrodynamics: $t_{hydro} = l/c_s$ with $c_s = \sqrt{\dfrac{kT}{\mu m_H}}$
- Ionisation: $t_{rec} = \dfrac{1}{n\alpha_B}$
- Cooling $t_{cool} = \dfrac{nkT}{\Lambda_{cool}}$

$$n = 100cm^{-3},\ T_{cold} = 10K,\ T_{hot} = 10^4 K,\ \alpha_B = 2.7 \cdot 10^{-13} cm^3 s^{-1}$$

$$\Downarrow$$

$$t_{ff} > t_{cold} > t_{hot} > t_{rec} > t_{cool}$$

$$5Myr > 4Myr > 76kyr > 1kyr > 0.3kyr$$

Numerical Timesteps

- Gravity: $t_{ff} \approx 5\,Myr$ => Timestep criterion via acceleration
- Cold Gas: $t_{cold} \approx 4\,Myr$ => Timestep criterion (CFL)
- Hot Gas: $t_{hot} \approx 75\,kyr$ => Boost in energy, no criterion

  Solution: new timestep as soon as x>10^{-3}

$$\Delta t_{new} = \Delta t_{old} \cdot c_{cold} / c_{hot}$$

- D-front: $v_D < c_{cold}$ => Timestep criterion of hot gas sufficient
- R-front: $v_R > c_{cold}$ => No timestep criterion

  Solution: small initial timestep to avoid $\Delta x > 0.1$
- Cooling: $t_{cooling} \approx 0.3\,kyr$ => Isothermal Equation of State

Ionization of a Turbulent Cloud

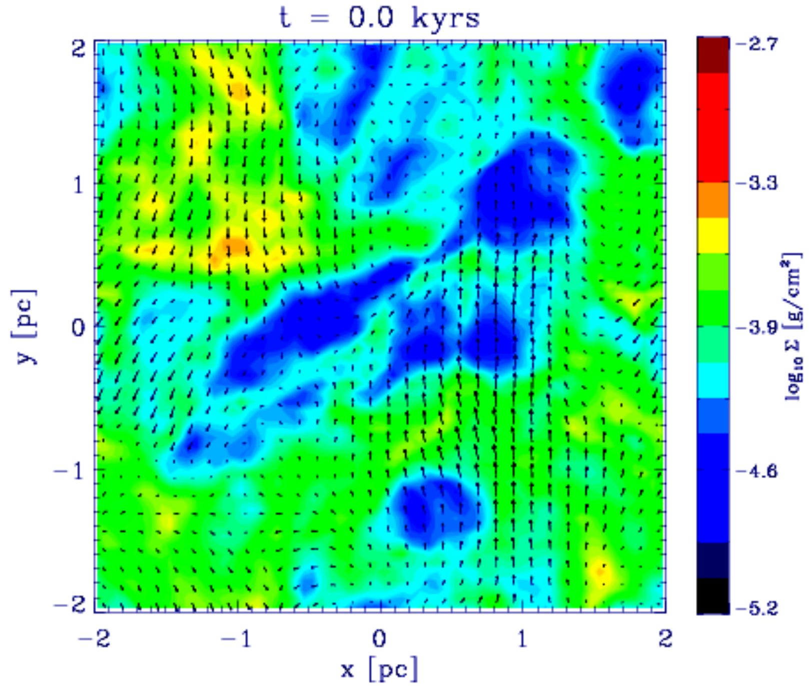
- the radiation sweeps up hydrogen and triggers it into collapse
  (Gritschneder et al. 2009, MNRAS, 393, 21 , Gritschneder et al. 2009, APJ, 694, L26)

Turbulent box (Mach 5):

Particles	T	n_{mean}
>2 Mio	10 K	300 cm^{-3}

Source of ionization:

F_0=5•10^9 photons cm^{-2}



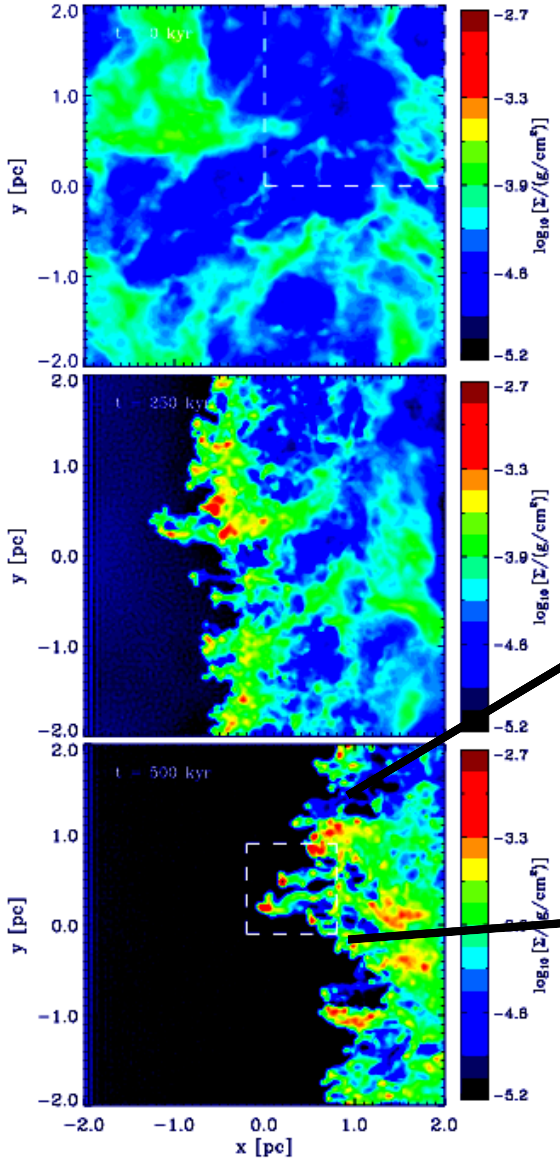
⇨ spatial resolution as high as 0.03 pc

⇨ $M_{part} \sim 10^{-4}$ M_{sun}

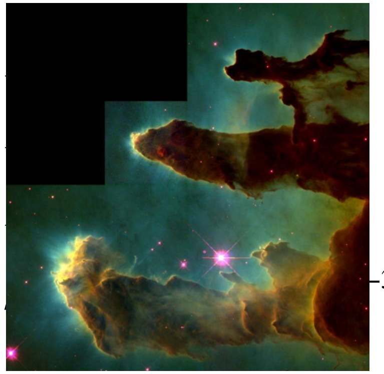
⇨ with self-gravity (open boundaries)

⇨ hydrodynamics: periodic boundaries

'Radiative Round-Up'

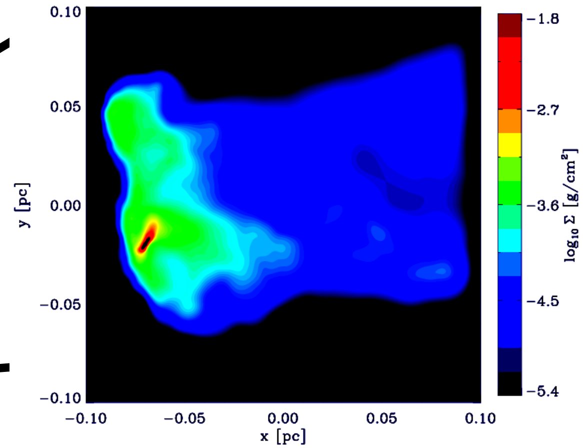


~10% of the mass is ionized

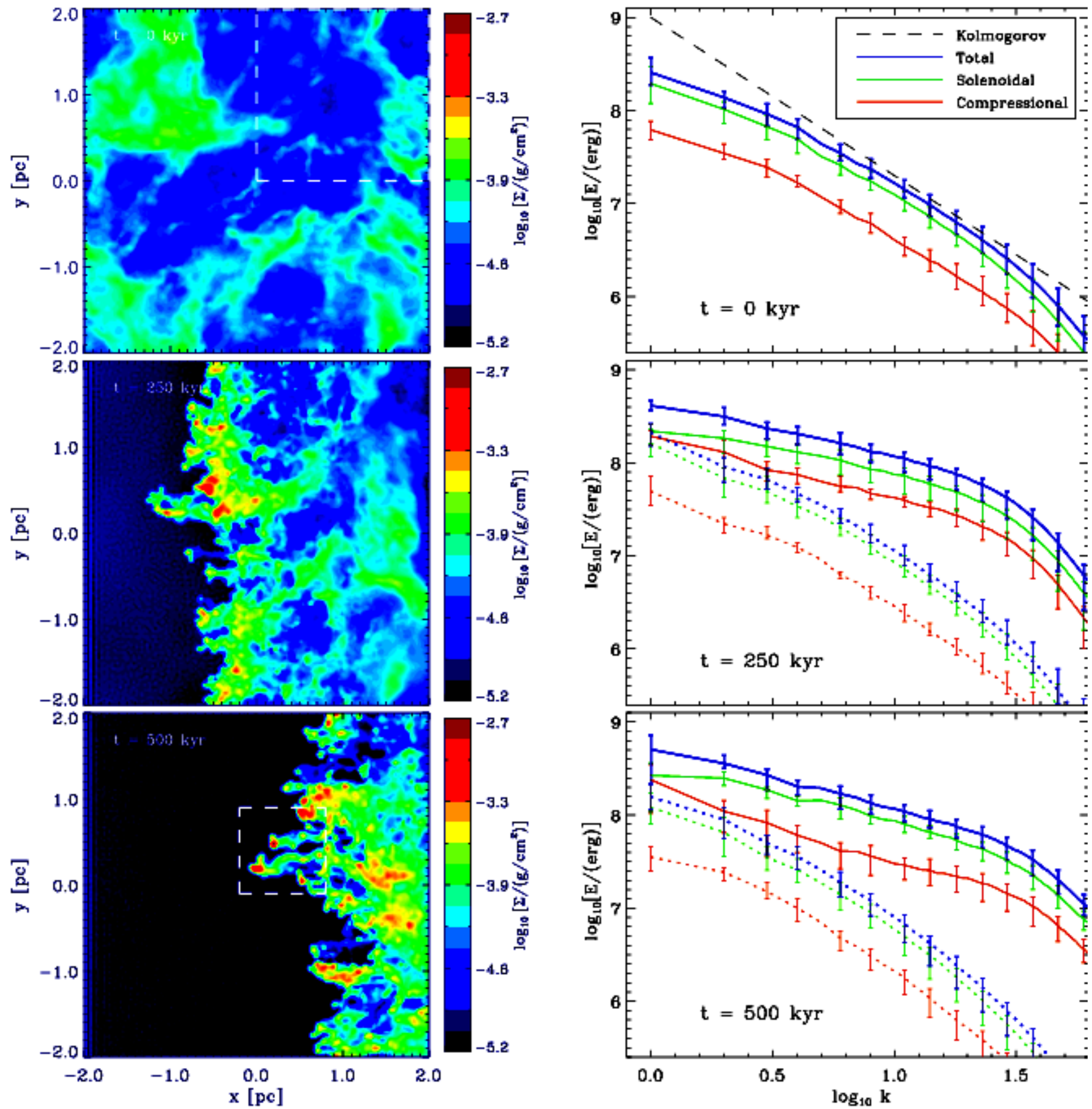


–3

t=550 kyr



Driving Turbulence



$$v' = \rho^{1/2} v$$

$$10^2 cm^{-3} < \rho < 10^4 cm^{-3}$$

Conversion efficiency:

(Gritschneder et al. 2009, APJ, 694, L26)

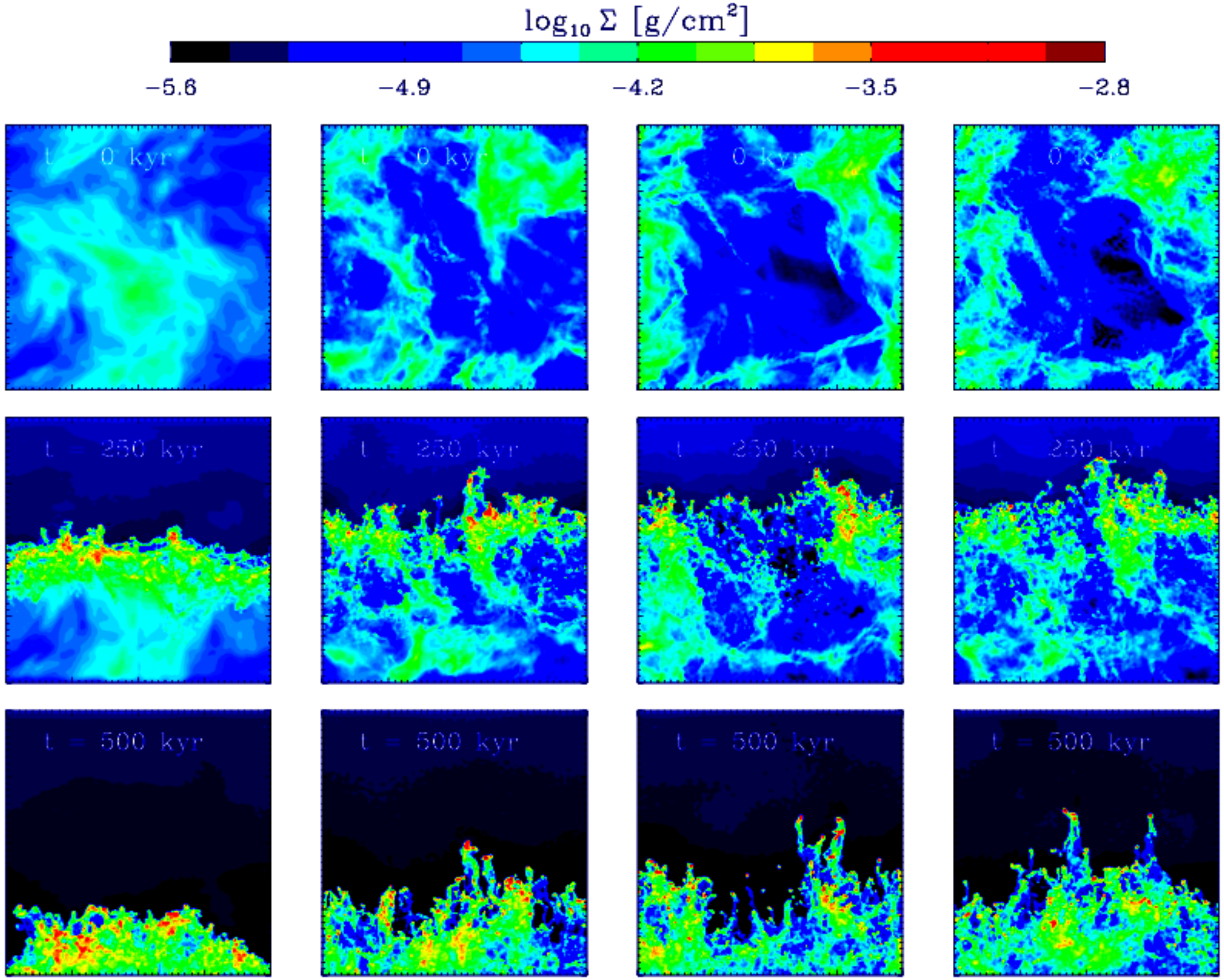
$$\sigma = \frac{e_{turb}}{e_{Ly}} \approx 2 \cdot 10^{-5}$$

Previous estimates:

$$\sigma \approx 2 \cdot 10^{-6}$$

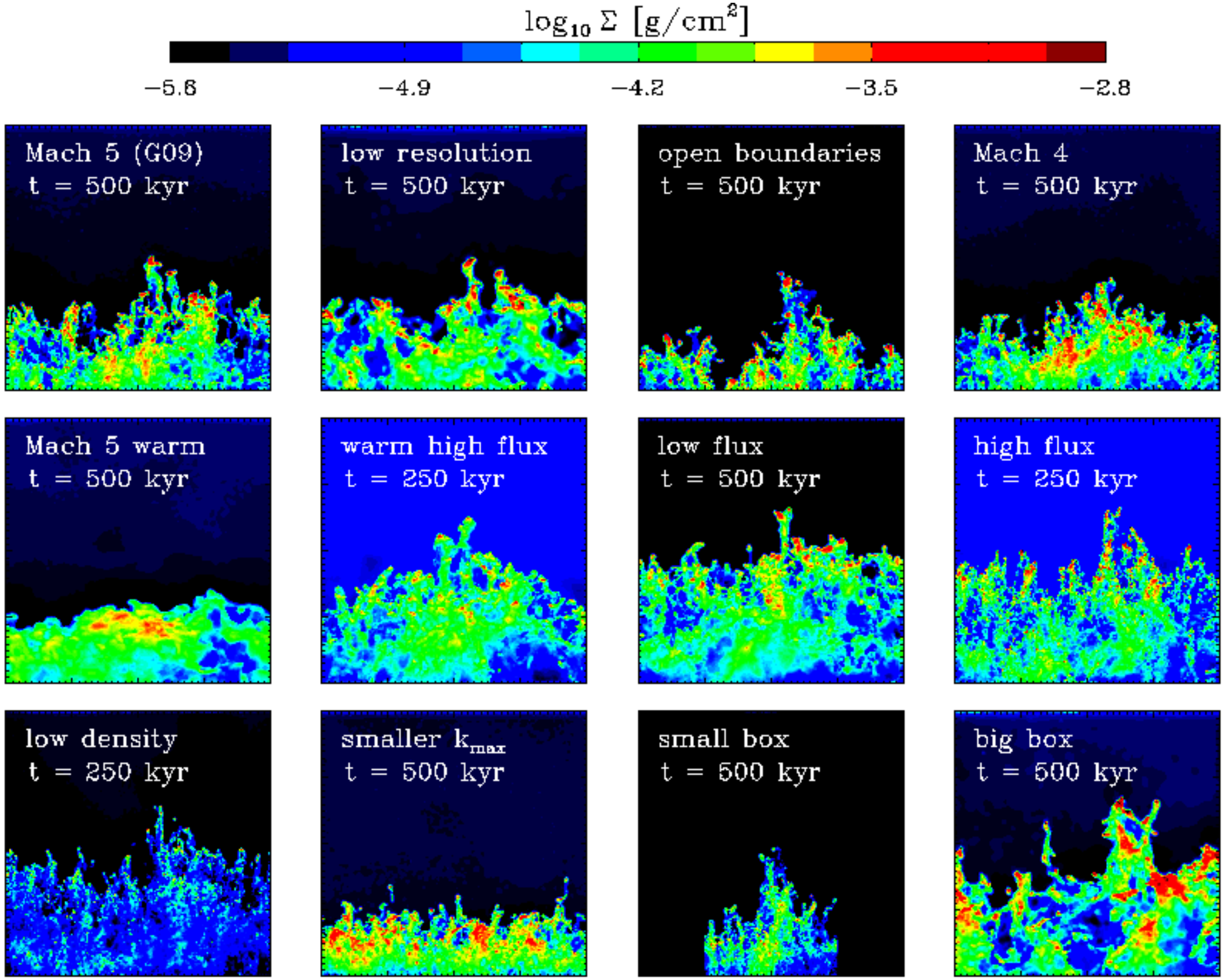
(e.g MacLow & Klessen, 2004)

Dependence on Mach Number



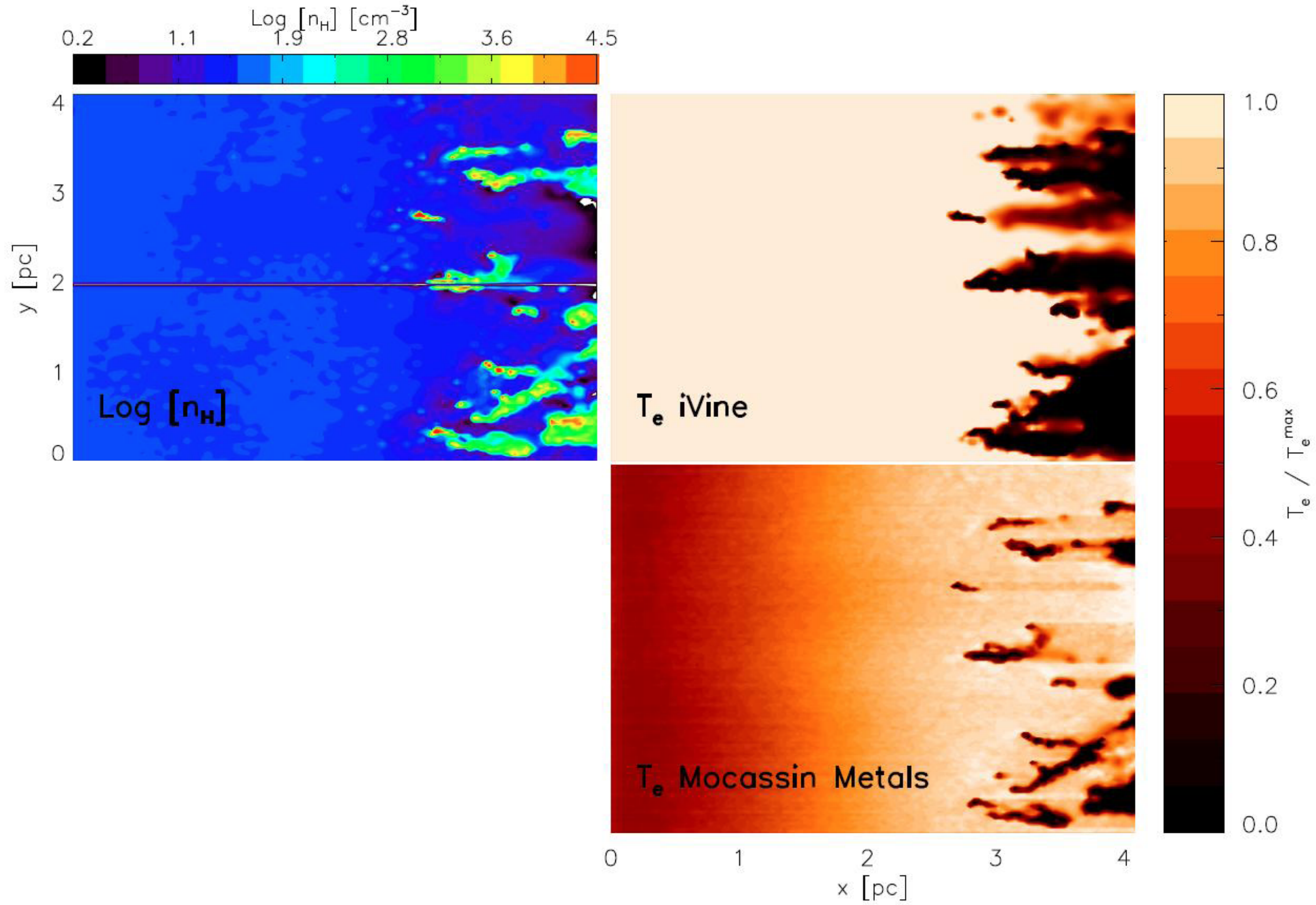
Mach 1.5 Mach 5 Mach 7 Mach 12.5

Further Parameter Study

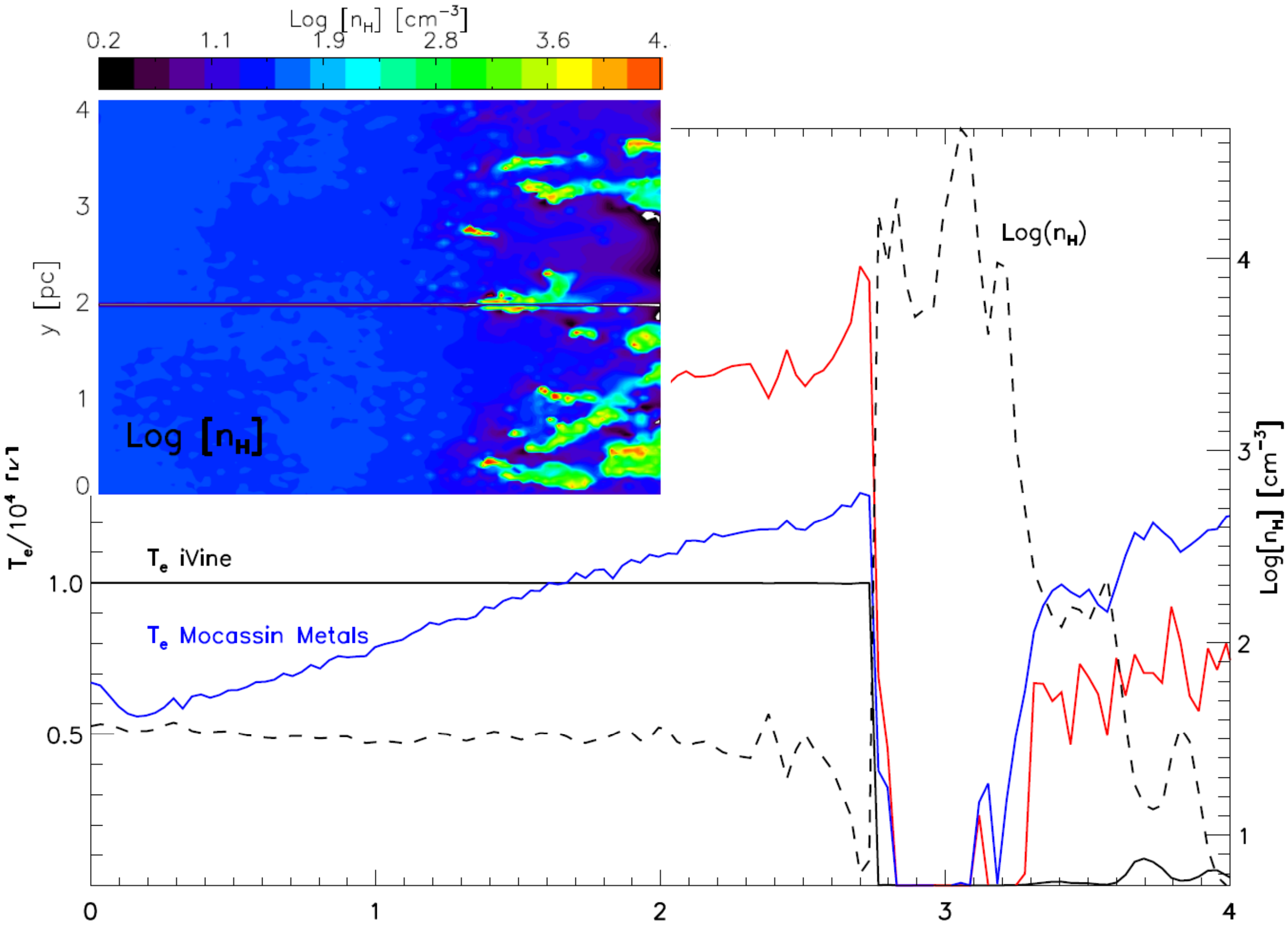


Gritschneder et al., submitted

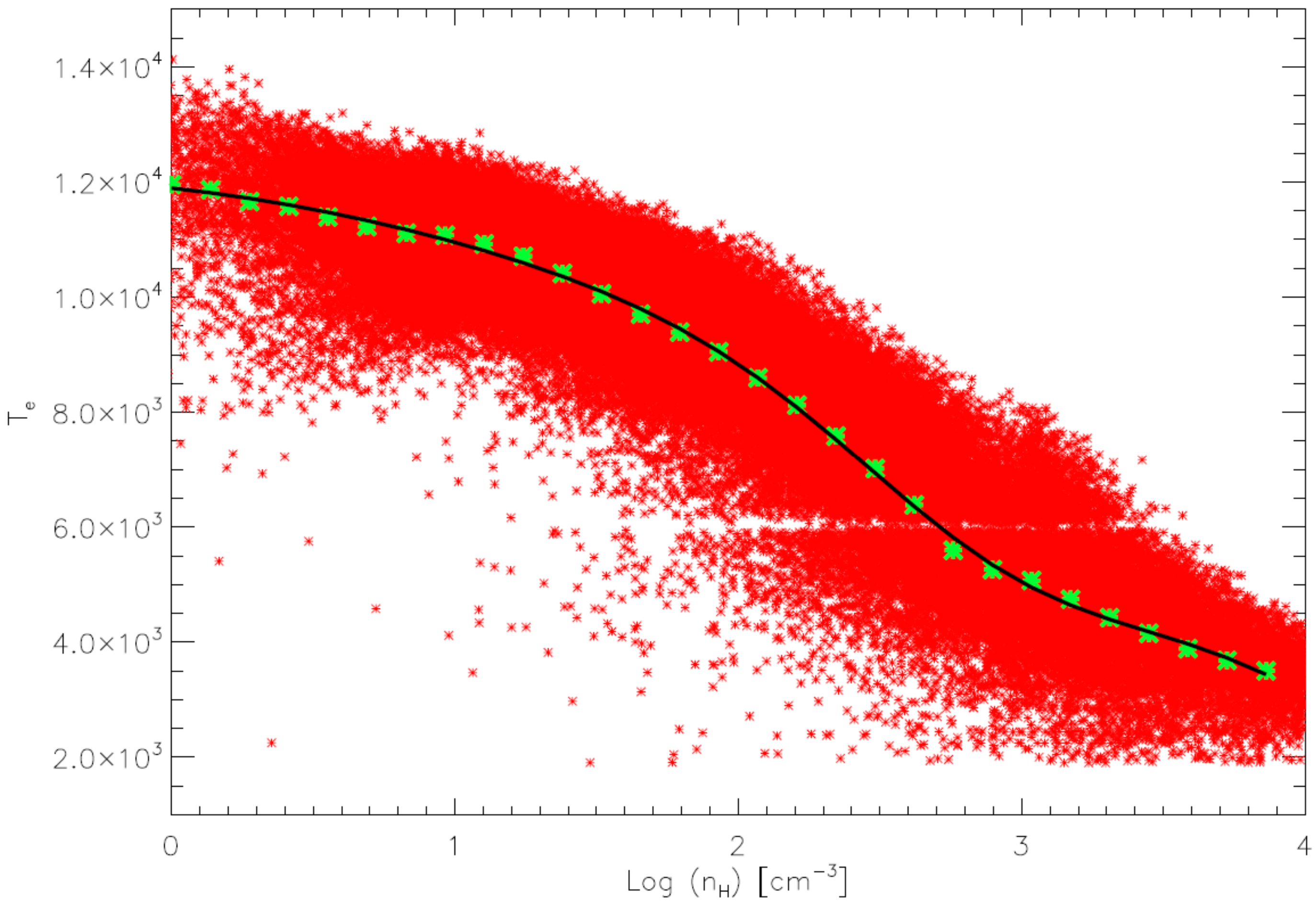
VINE vs MOCASSIN

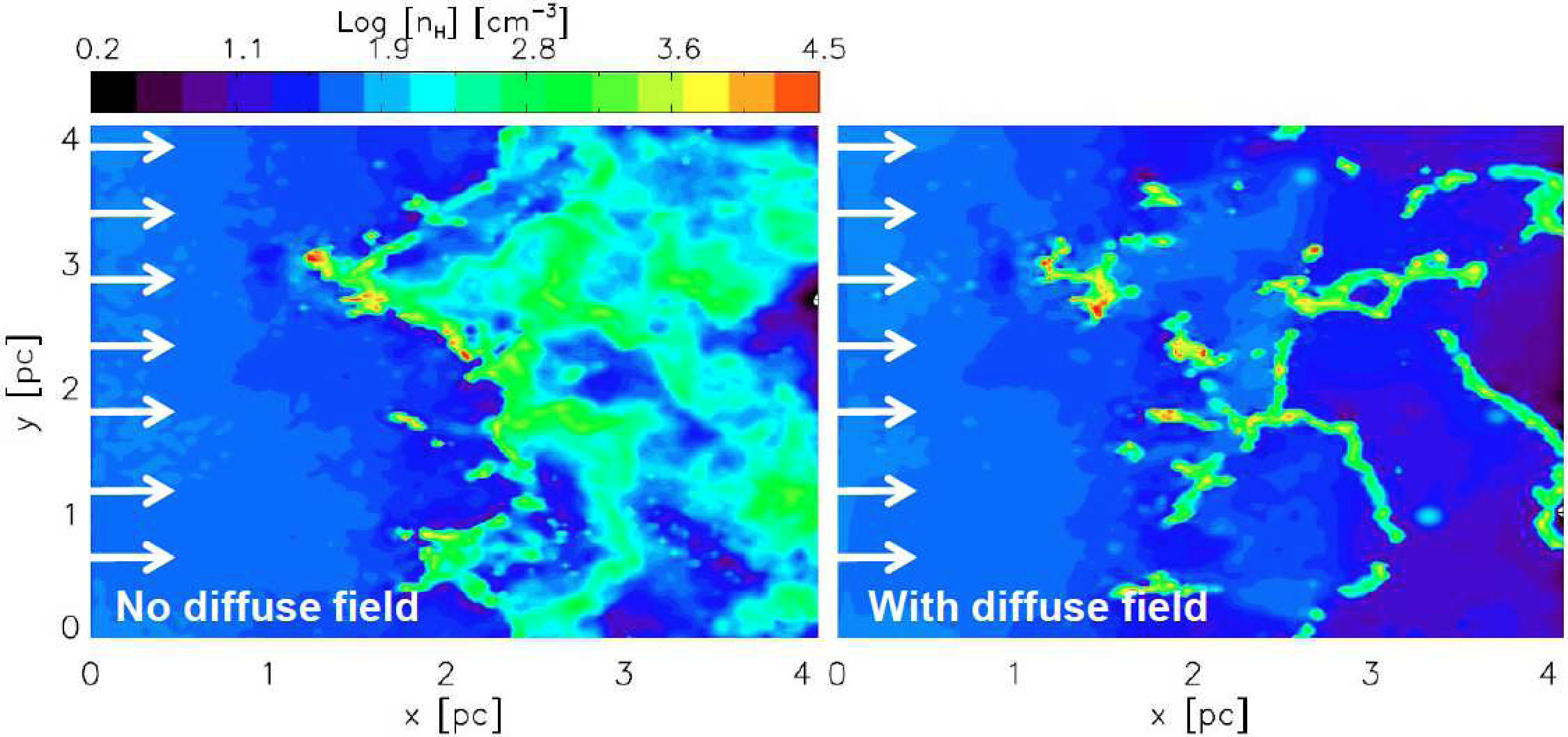


Ercolano & Gritschneder, 2010, in prep


Log [n$_H$] [cm^{-3}]
0.2
1.1
1.9
2.8
3.6
4.
y [pc]
0
1
2
3
4
Log [n$_H$]
Log(n$_H$)
Log[n$_H$] [cm^{-3}]
T$_e$ iVine
T$_e$ Mocassin Metals
1.0
0.5
0
1
2
3
4

Diffuse Heating

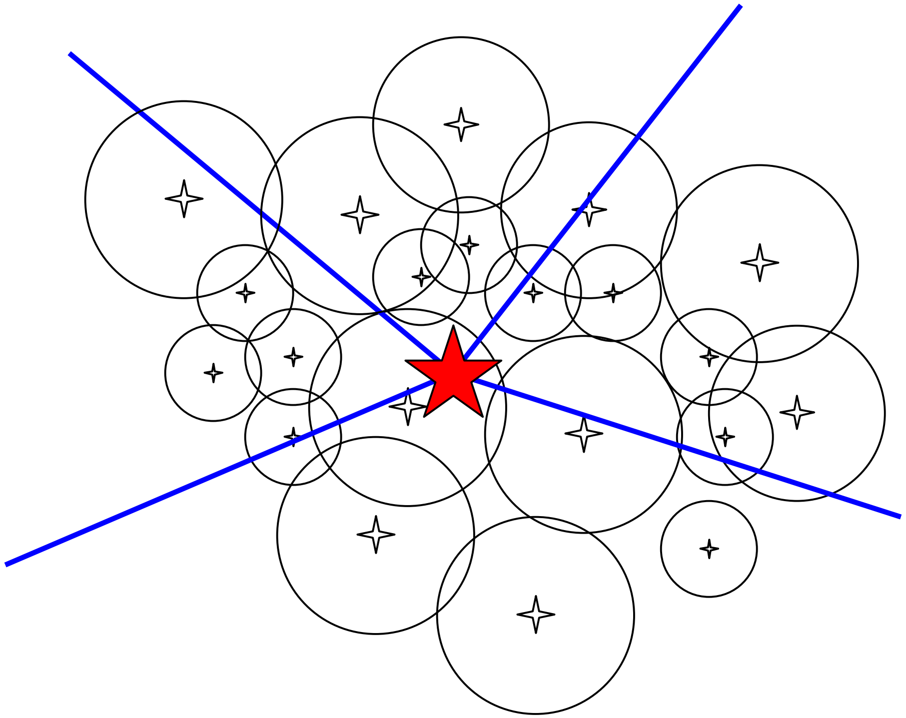


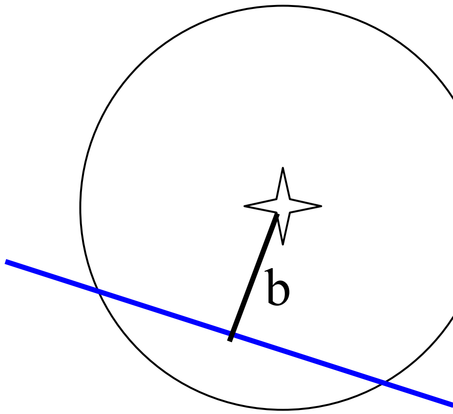


Log [n_H] [cm^-3]
0.2
1.1
1.9
2.8
3.6
4.5
y [pc]
x [pc]
No diffuse field
With diffuse field

Numerical Implementation II: VINERY

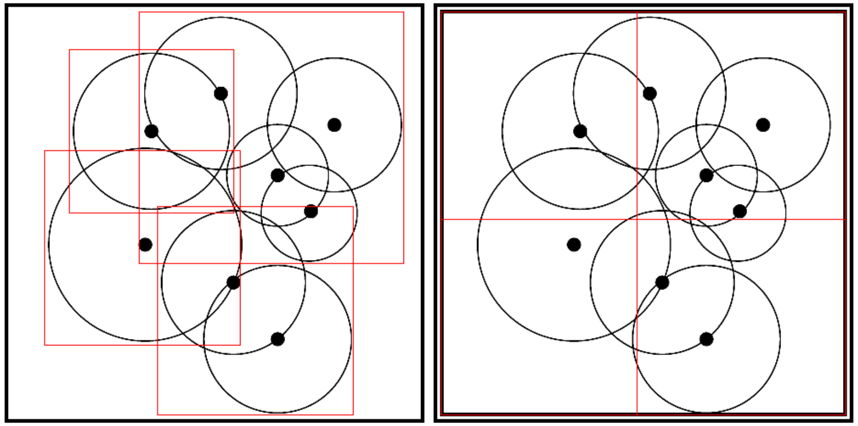
- VINE + SPHRAY (Altay et al. 2008, MNRAS 386)
- Monte Carlo approach
- Axis Aligned Bounding Box (AABB) test to calculate intersections
- Ray updates similar to CRASH



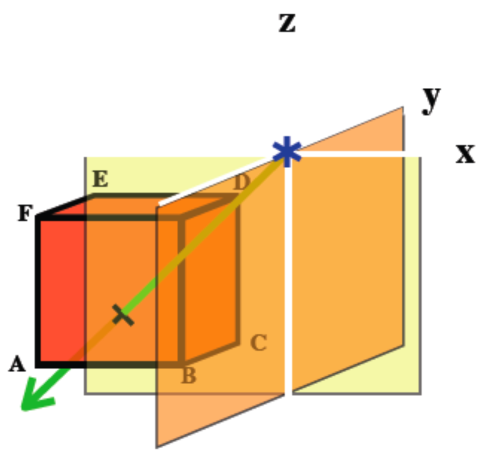


Ray - Particle Intersection

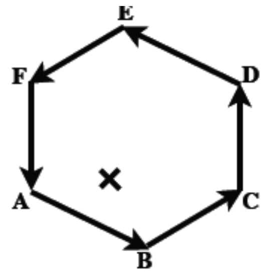
- Amend oct-tree with AABB (define leaves)



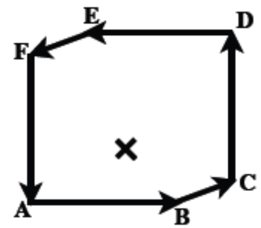
- Determine leaves hit by ray by using Plücker coordinates



AABB in the VI. octant (-,+,-), which the ray is pointing into



Silhouette as seen by green ray



Silhouette as seen by reader

- Determine particles hit by ray

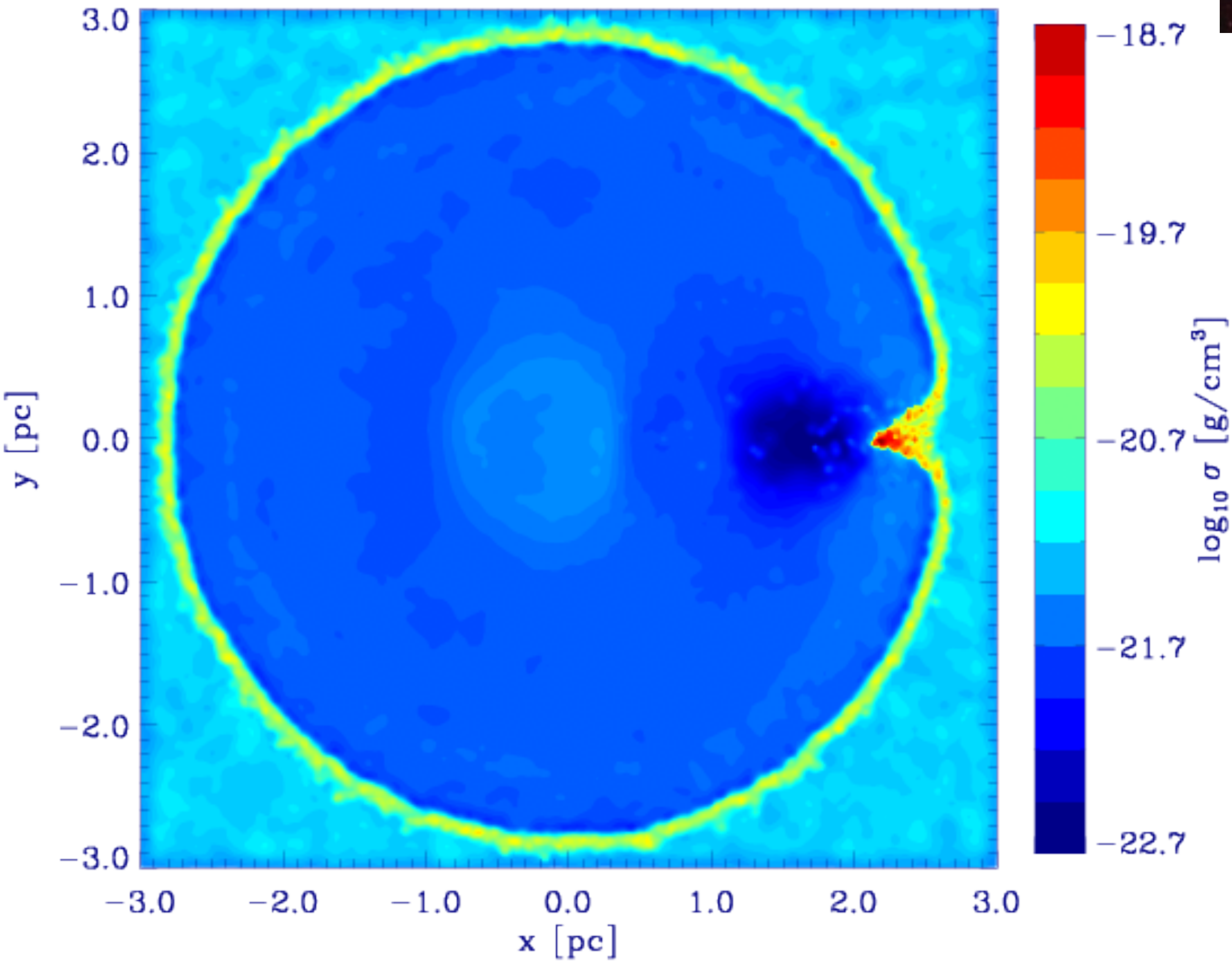
$$\left|\vec{p}-\vec{s}-l\vec{d}\right| < h \text{ and } l=\left(\vec{p}-\vec{s}\right)\cdot\vec{d} > 0$$

Calculation of the Ionisation Degree

- Photons are deposited according to the column density, calculated via W(b)
- Recombinations since the particle got last hit by a ray are taken into account
- Rate equations for 6 species (HI, HII, HeI, HeII, HeIII,e^-)
- Time integration using a RK or a BDF solver

$\Rightarrow$ New ionisation degree / abundances / temperature

$\Rightarrow$ New time-step (as in iVINE) t=160 kyr


3.0
2.0
1.0
0.0
−1.0
−2.0
−3.0
y [pc]
−3.0
−2.0
−1.0
0.0
1.0
2.0
3.0
x [pc]
−18.7
−19.7
−20.7
−21.7
−22.7
$\log_{10} \sigma$ [g/cm^3]

Conclusions

- 'Radiative Round-Up' leads naturally to the observed structures and morphology, density and kinematics are reproduced
  - Whether pillars form at all depends on the temperature and the Mach number (i.e. $\mathcal{M} > 2$ @ 10K, $\mathcal{M} > 10$ @ 100K)
  - The size of the pillars is depending on the turbulent driving mode (i.e. the extend of the initial largest structure)
  - The density of the pillars is determined by the initial flux, density and the time since the ignition of the source
  - Whether pillars or globules form depends on the initial tangential velocity ($v_c \sim 1 \mathrm{km\ s^{-1}}$), i.e. on the Mach number

- To treat the evolution of the entire HII region an implementation of point sources will be needed

- These implementation (and any other treating radiative transfer on a non-constant grid) will need very effective ray-sphere-intersection test

- There are open issues with respect to turbulence, turbulent driving, mixing, …