First Light

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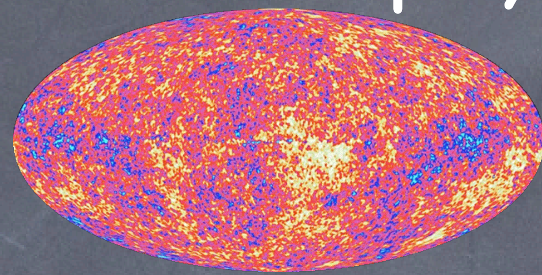
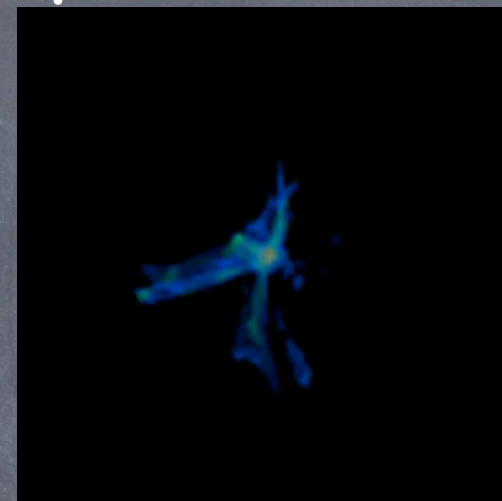
Outline

- First Stars are massive and isolated
- Why it is difficult predicting their exact initial masses and what's needed to fix that
- Some things they do to their environment?

Given LCDM, First Structure Formation is a straightforward physics problem:





Ralf Kähler & Tom Abel for PBS

- Initial conditions statistically specified
- Simple but non-linear physics
  - Gravity, hydrodynamics, non-equilibrium chemistry, optically thin radiative processes
- Complex because of large range of scales required

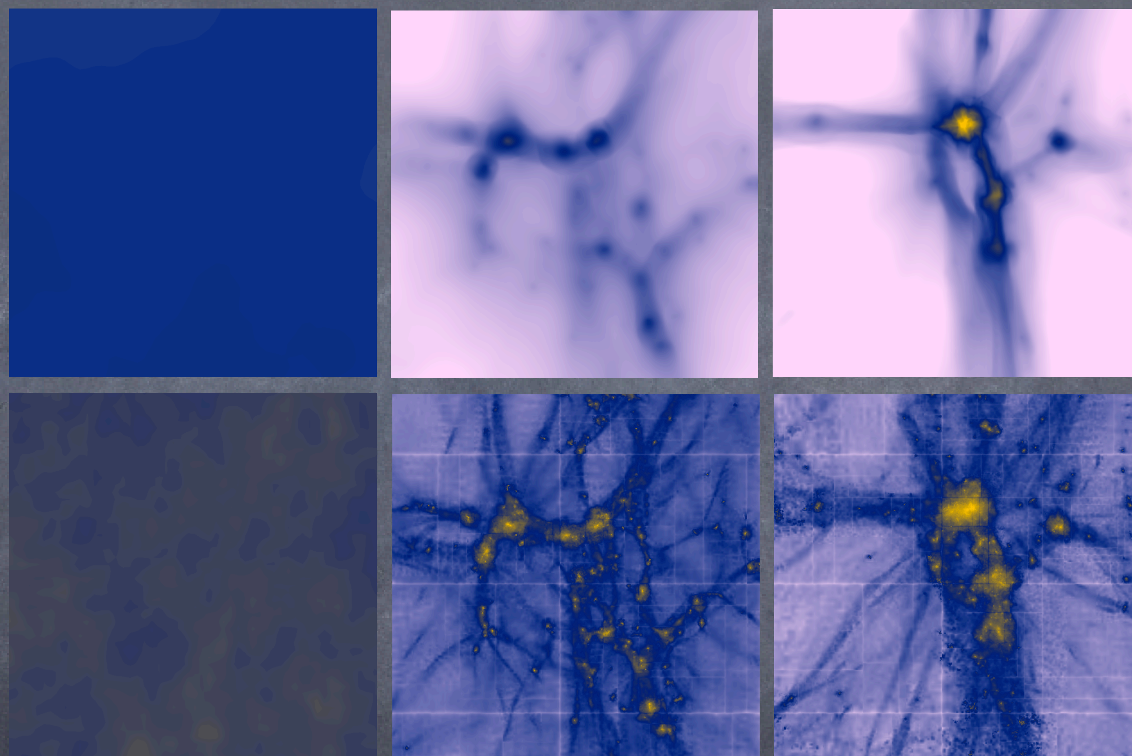
$$\frac{R_{\odot}}{R_{\mathrm{Milky Way}}} \approx 10^{-12} \qquad \frac{P_{\odot,\mathrm{Kepler}}}{t_{\mathrm{Hubble}}(z=30)} \approx 10^{-12}$$

Equation Summary

- Collision-less N-body system
- Self-gravity: gas & DM
- continuity
- momentum
- energy
- 9 coupled ODEs for non-equ. chemistry

Time Evolution

Z=100 Z=24 Z=20.4



10 comoving kpc

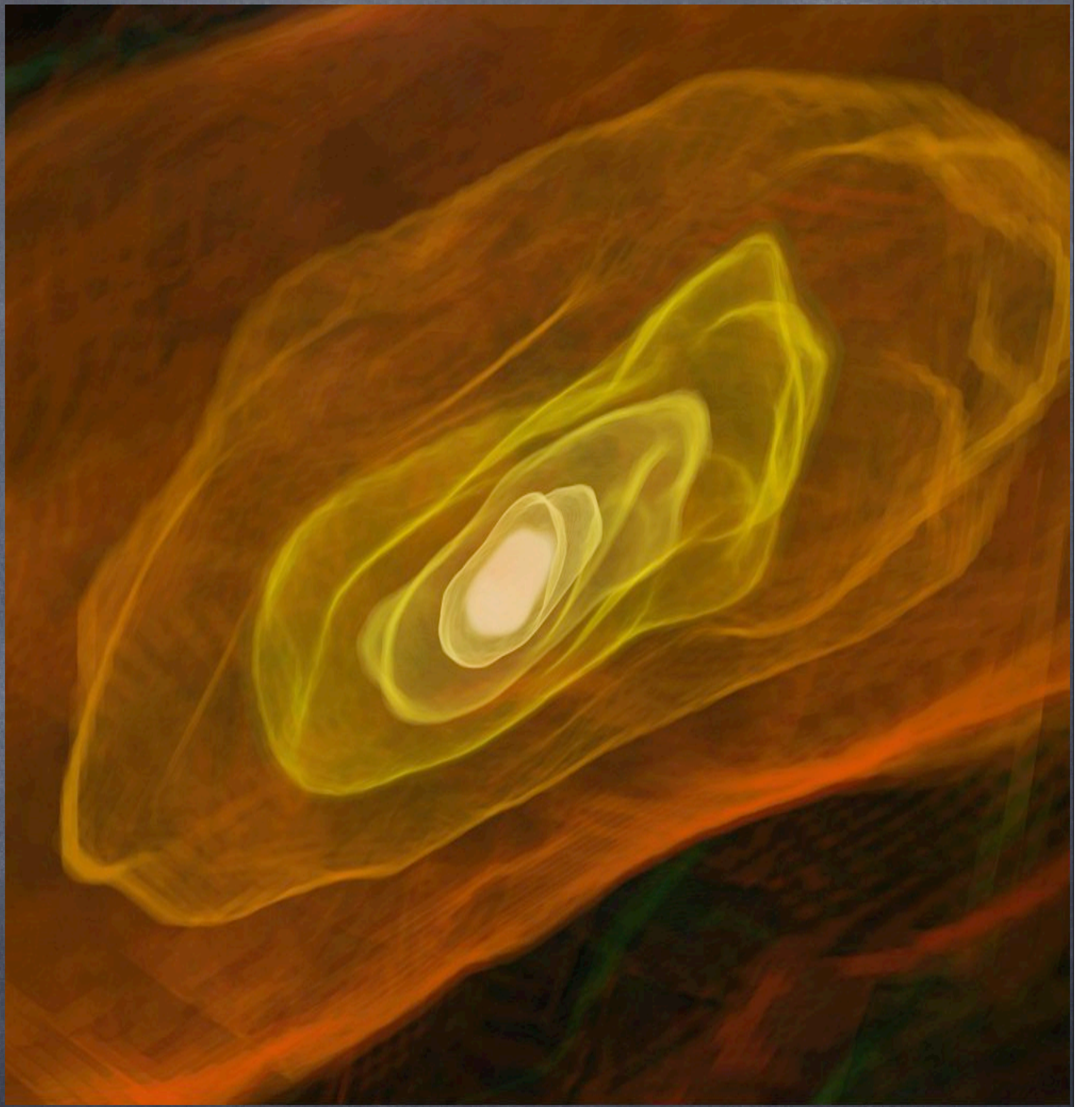
Cosmological Jeans mass ~ 1e4 M

12 comoving kpc on a side, projection of 0.001 of the simulation volume

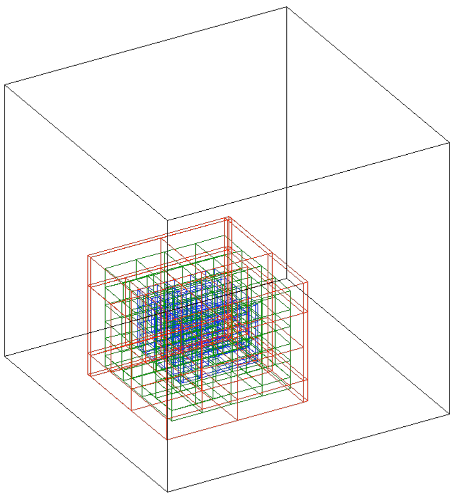
Protostar

Even at a scale
~ 40 AU
no other fragments

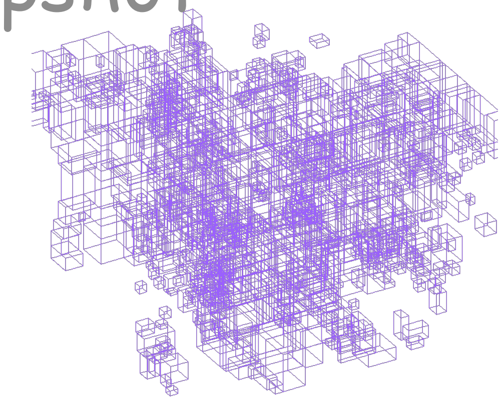
proto-star with "disk"
~ 1 $M_\odot$
fH2 ~ 1
no fragmentation



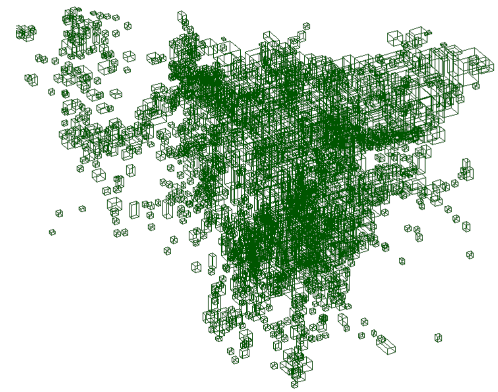
Grids in one intermediate snapshot



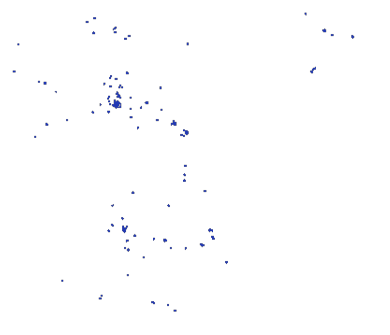
Level 5, 1924



Level 6, 1423

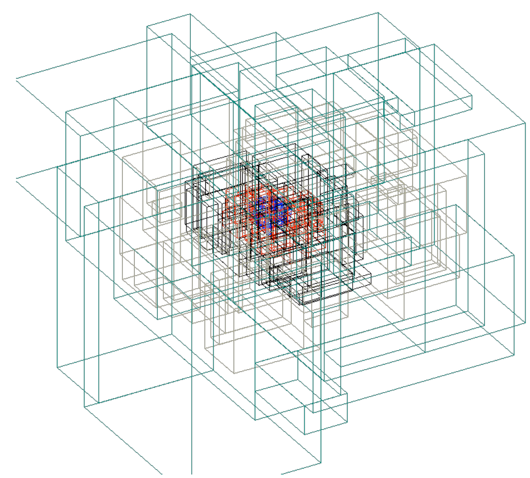


Level 8, 123

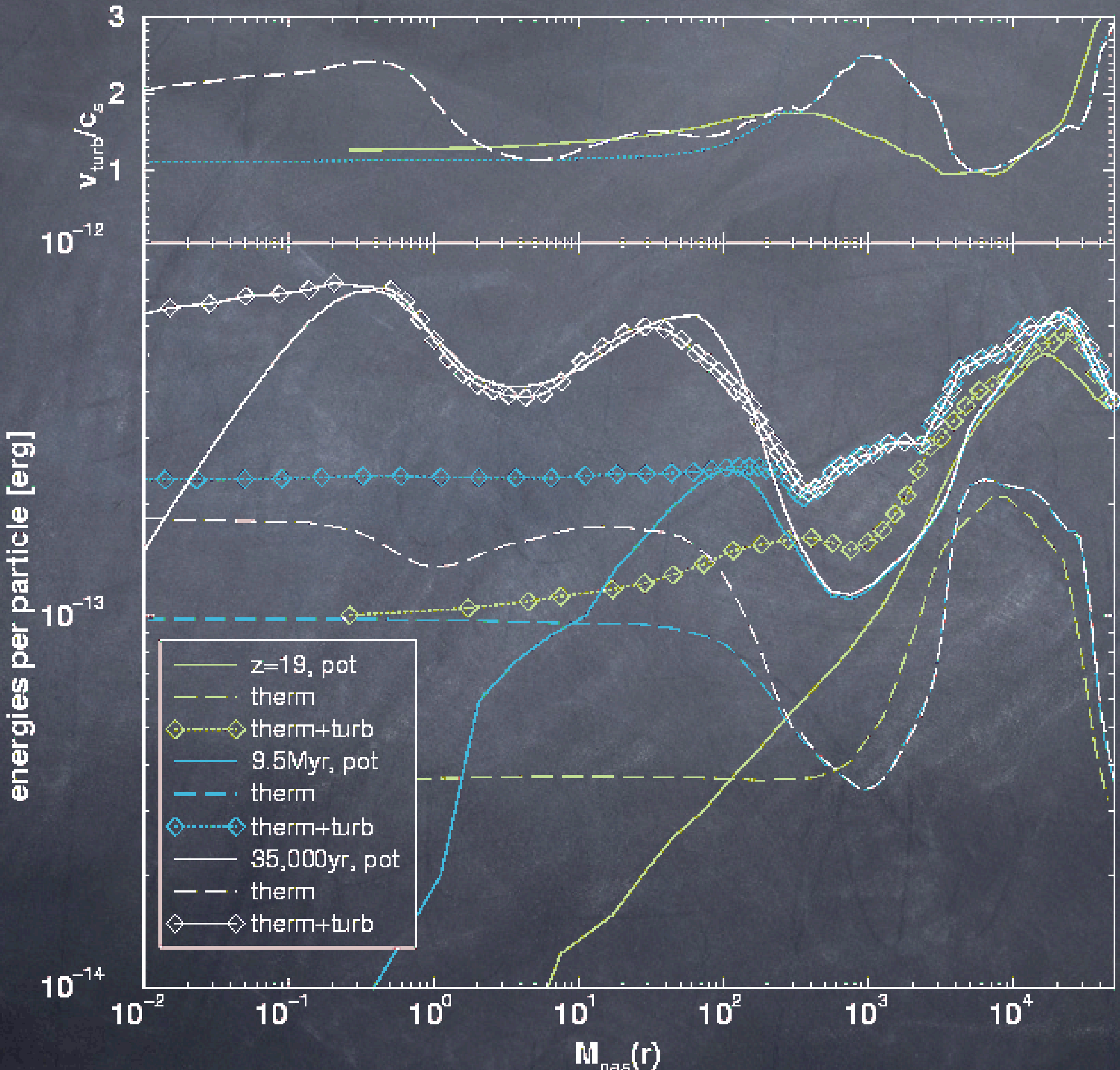


Level 9, only one has child grids!

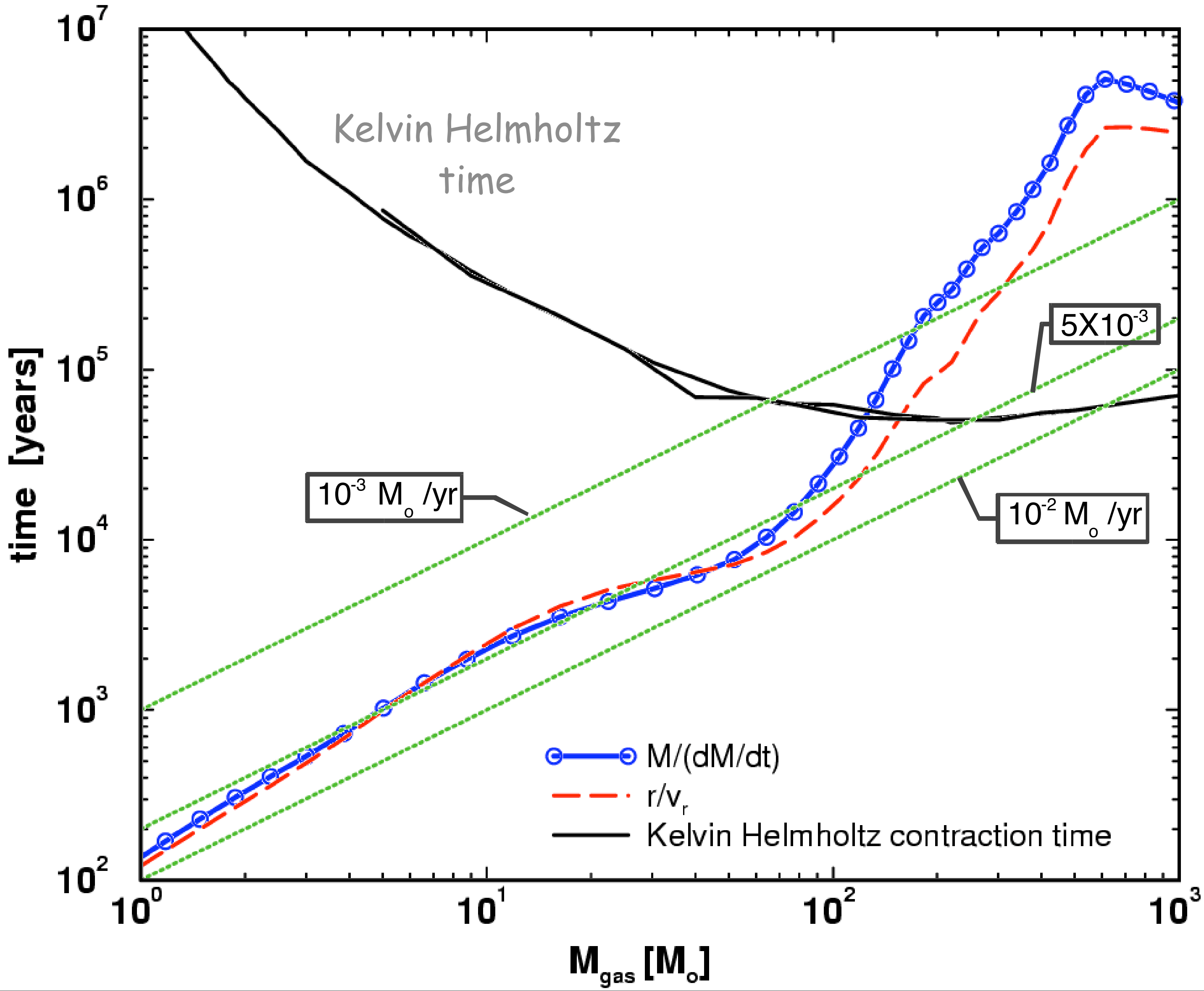
Level 20-23 1e-7 of box size.



Turbulence plays a significant role



Accretion Time



Why there can be only one

- Small DM potential drives cold gas to center, cooling flow rather than molecular cloud formation
- Cooling time longer than dynamical time
- Inefficient H_2 cooling allows pressure to smooth out density perturbations
- $3H \rightarrow H_2$ does not lead to fragmentation, initial isobaric contraction is weak because of the same cut off temperature, no independent Jeans unstable fragments form.
- Feedback from first star gives others no chance

Can be understood analytically:
Ripamonti & Abel 2004 MNRAS

Uncertain mass of the First Stars between 30 and 300 solar mass

- Still progress! Before we did not know whether it is stars, star clusters, super-massive black holes, Jupiter size objects, etc.
- Remaining uncertainties come from the complicated accretion physics.
- However, within this range these are ~200,000K hot and approximately radiate about a million times the energy of the sun.
- Copious UV production will lead to $H + \gamma \rightarrow p + e$

Whats stopping us?

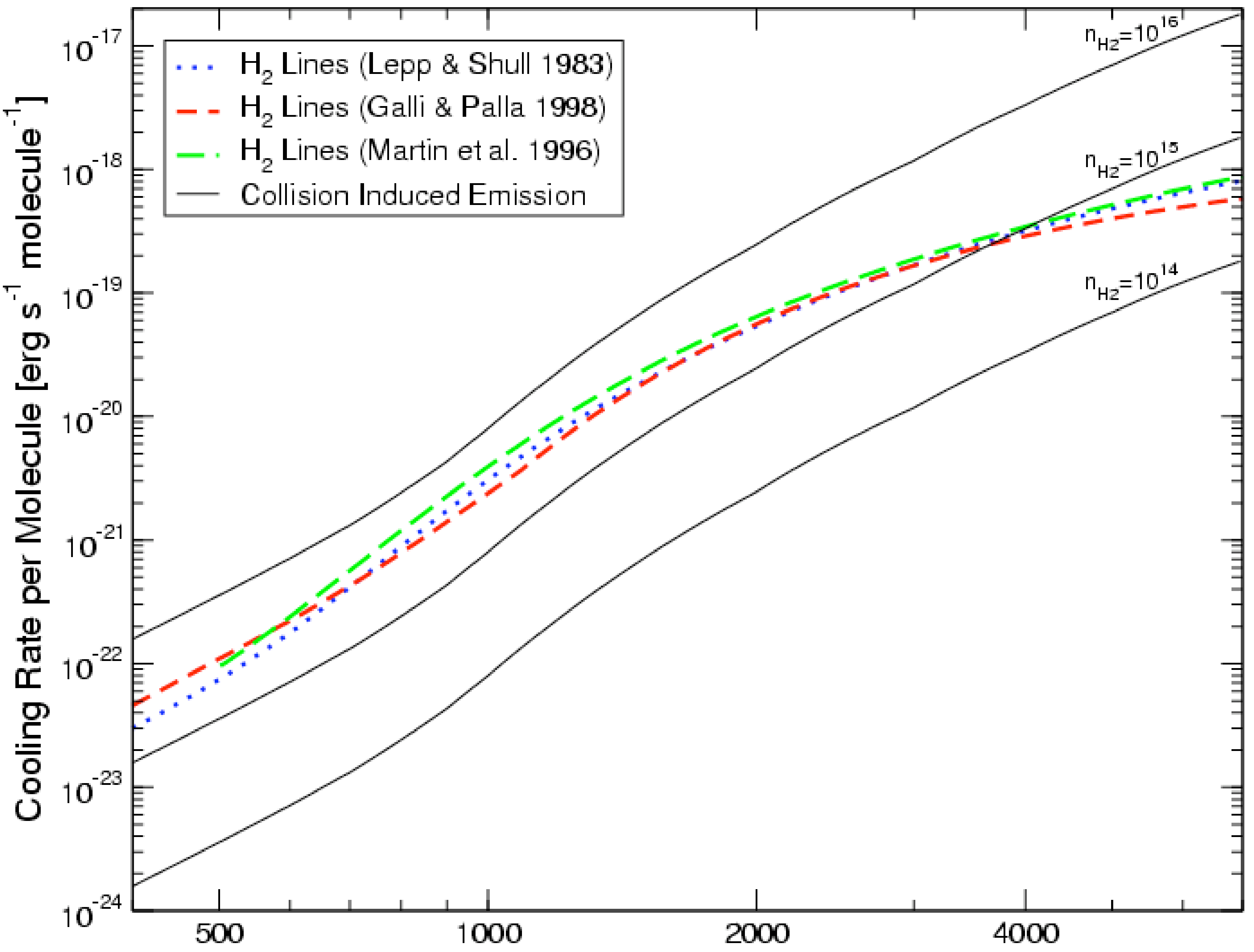
- Luminosity Evolution of the proto-star

$$\tau_{m,n} \simeq 0.53\,\xi \left(\frac{\nu_{m,n}}{10^{12}\ \mathrm{Hz}}\right)^{-3} \left(\frac{A_{m,n}}{10^{-9}\ \mathrm{s}^{-1}}\right) \left[\left(e^{\frac{h\nu_{m,n}}{k_{\mathrm{B}}T_c}} - 1\right) \frac{2J_m+1}{U(T_c)} e^{\frac{E_m}{k_{\mathrm{B}}T_c}}\right] (X f_{\mathrm{H}_2,c}) n_c^{1/2} \left(\frac{\gamma_c}{\mu_c}\right)^{2/3}$$

- Radiative Transfer of molecular hydrogen cooling lines

$$L_{\mathrm{lines,thin}}(T) = \frac{X f_{\mathrm{H}_2}}{2m_H} \sum_{m,n} h\nu_{m,n} A_{m,n} \left[\frac{2J_n+1}{U(T)} e^{\frac{E_n}{k_{\mathrm{B}}T}}\right]$$

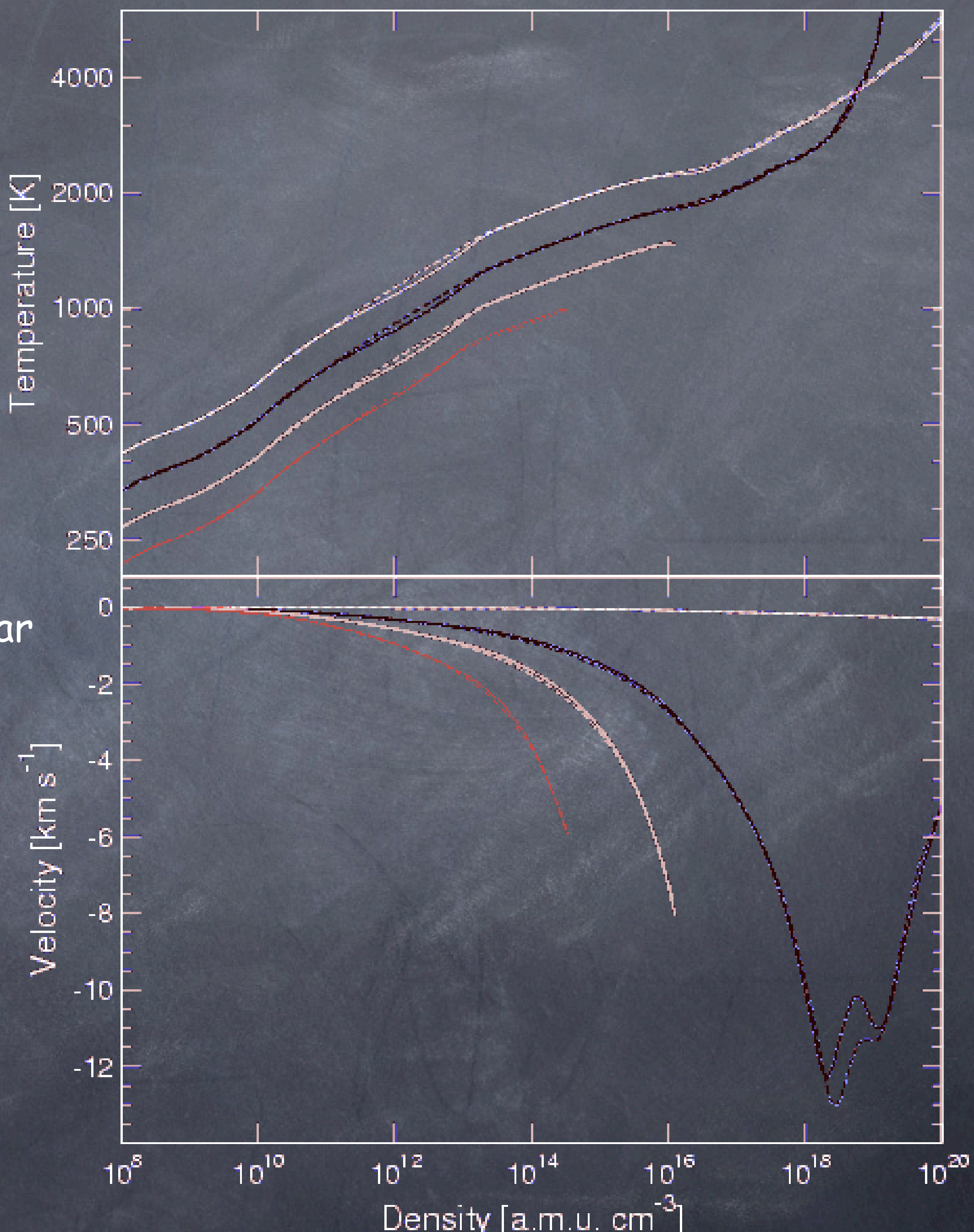
- Collision Induced Emission - Continuum - its radiative transfer
- Radiative Transfer of UV continuum
- Explicit Hydrodynamics not adequate eventually



Ripamonti & Abel

Results from 1D radiation-hydro calculation

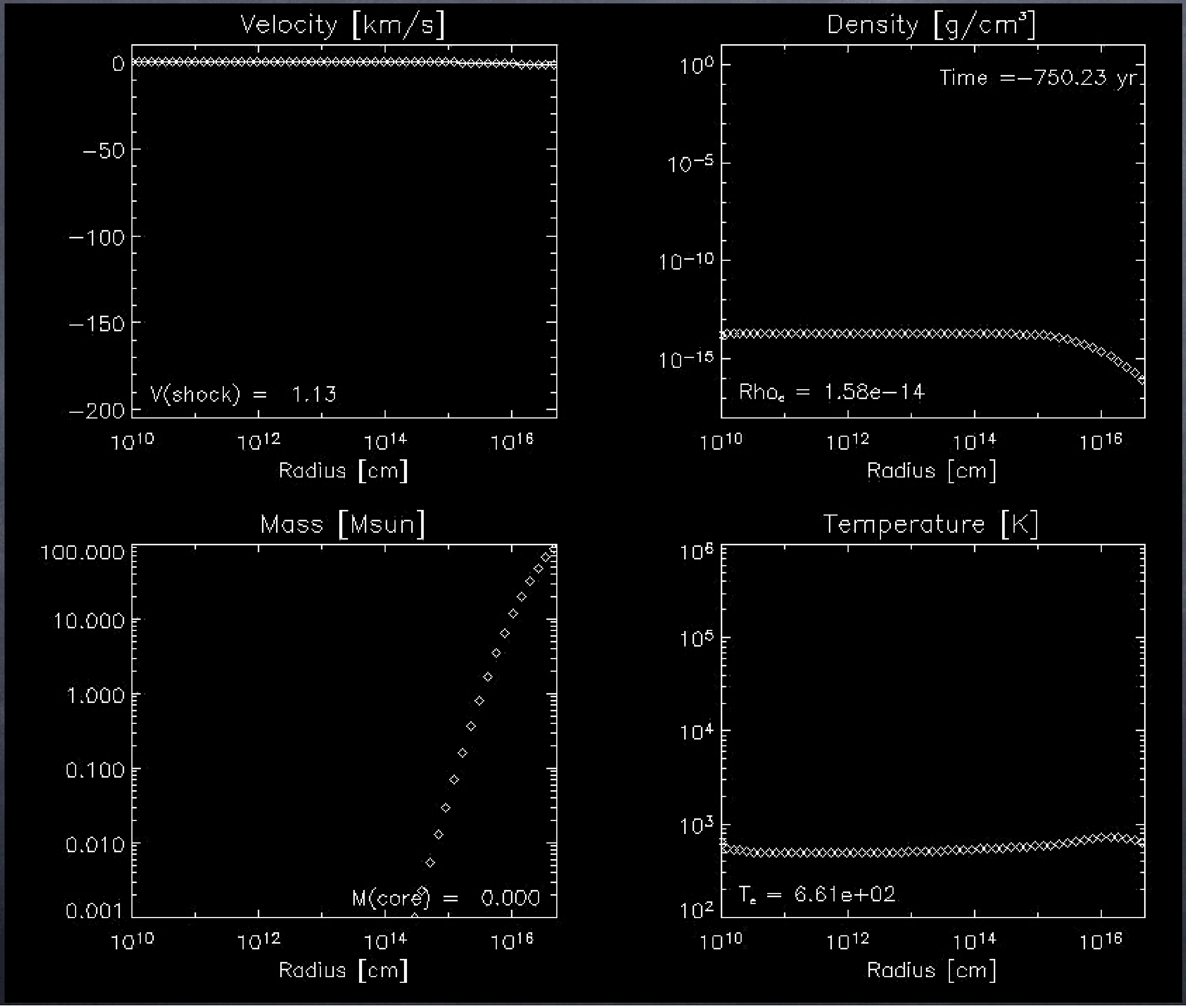
solid: ~ 6000 frequency bins
dashed: local approximation (≈ 100 times faster)



Now we can study early proto-stellar accretion in 3D!

Ripamonti & Abel 2004

1D implicit adaptive radiation hydrodynamics Ripamonti & Abel



Approximate Radiative Transfer

Norman, Paschos, Abel 1998
Abel 1999, PhD thesis
Gnedin & Abel, 2001, NewA

OTVET:
Optically Thin Variable Eddington Tensor formalism
independent of $N_{sources}$
very fast moment solver
multi-frequency
all cosmological terms

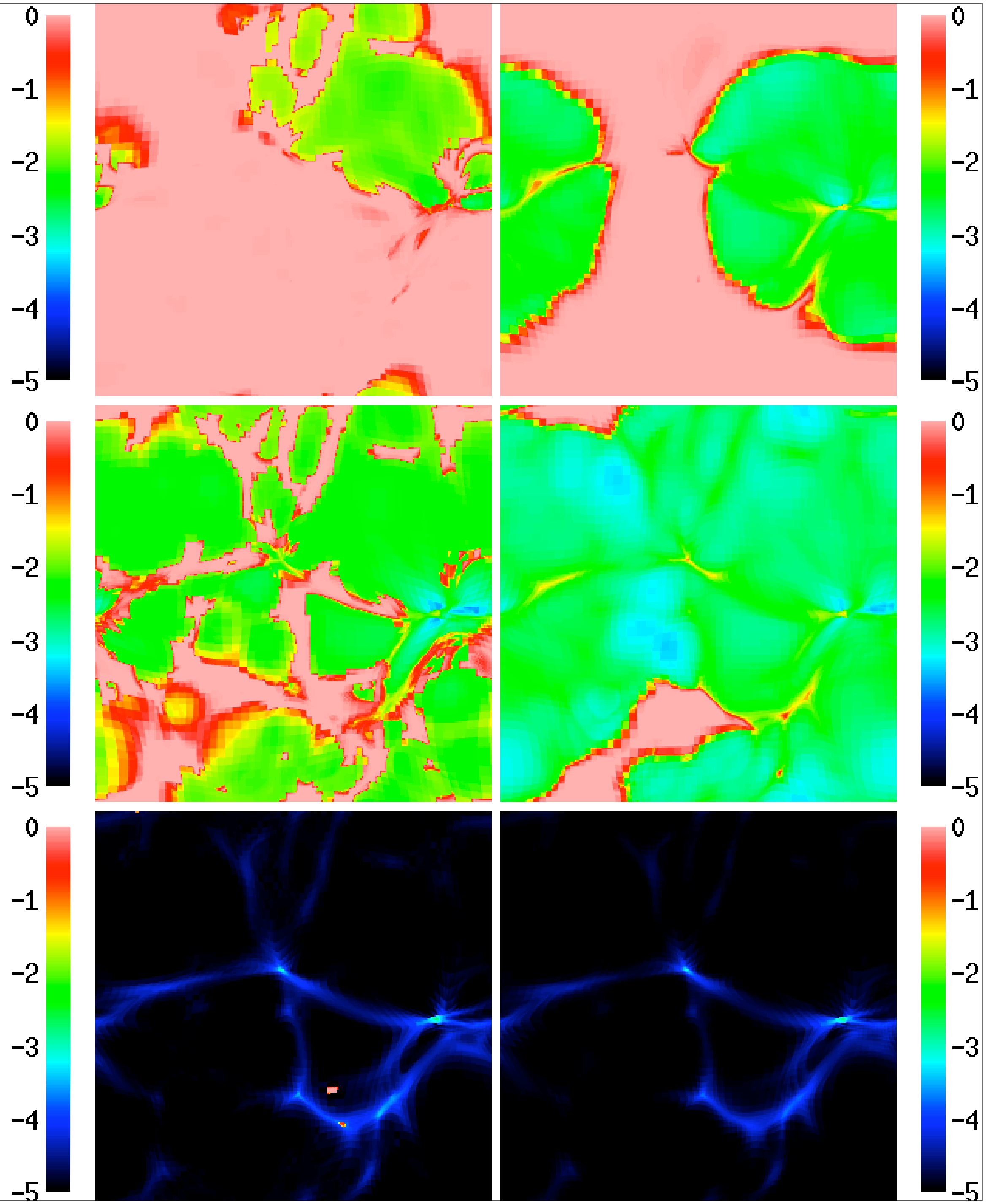
Adequate 3D-RT for apps. in
cosmology,
ISM physics,
star formation

$$\frac{a}{c}\frac{\partial E_\nu}{\partial t} + \frac{\partial F_\nu^i}{\partial x^i} = -\hat{\kappa}_\nu E_\nu + \psi_\nu$$

$$\frac{a}{c}\frac{\partial F_\nu^j}{\partial t} + \frac{\partial}{\partial x^i} E_\nu h_\nu^{ij} = -\hat{\kappa}_\nu F_\nu^j$$

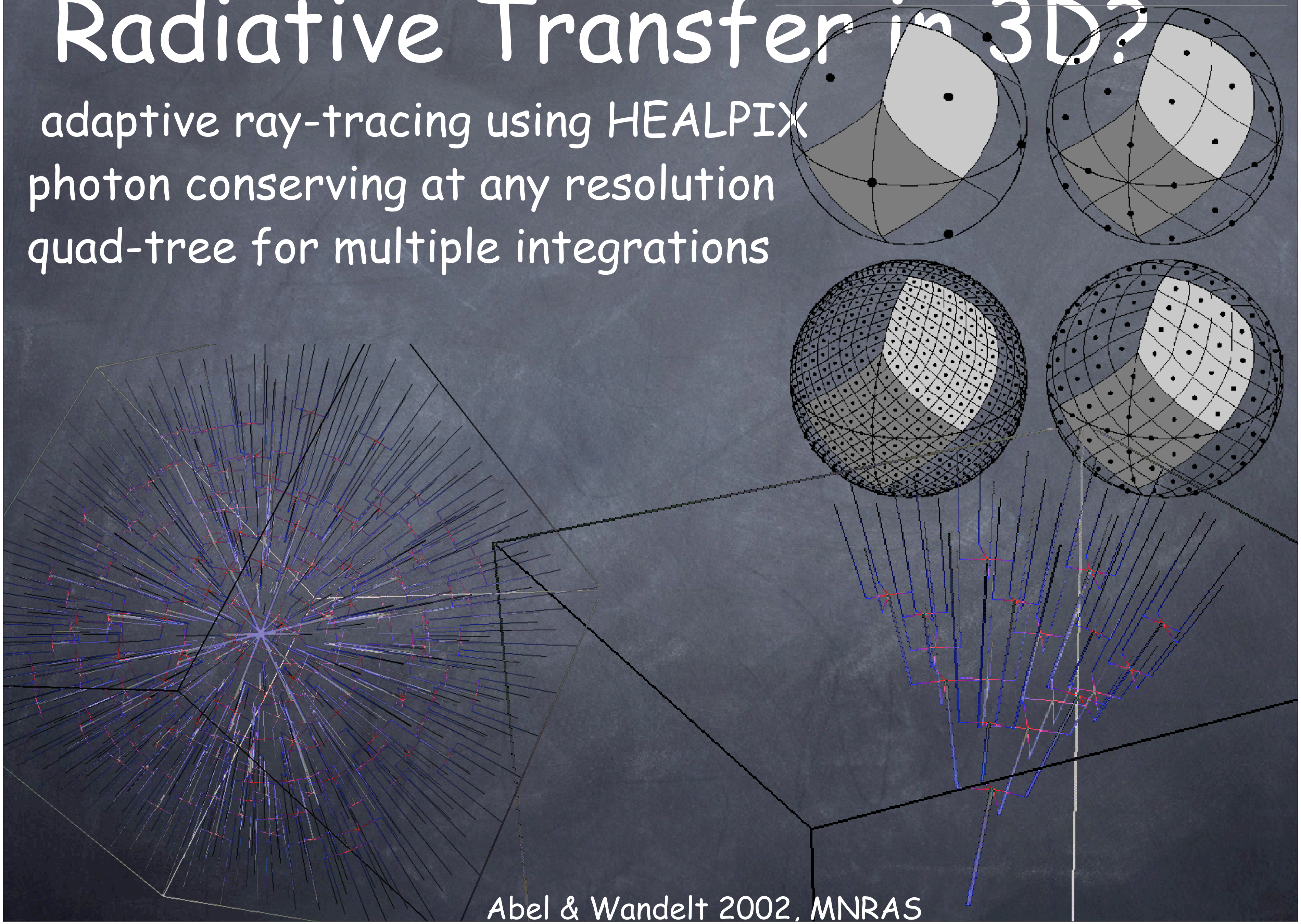
$$h_\nu^{ij} = \frac{P_\nu^{ij}}{\mathrm{Tr}\, P_\nu^{ij}},$$

$$P^{ij} = \int d^3x_1 \rho_*(\vec{x}_1) \frac{(x^i - x_1^i)(x^j - x_1^j)}{(\vec{x} - \vec{x}_1)^4}$$

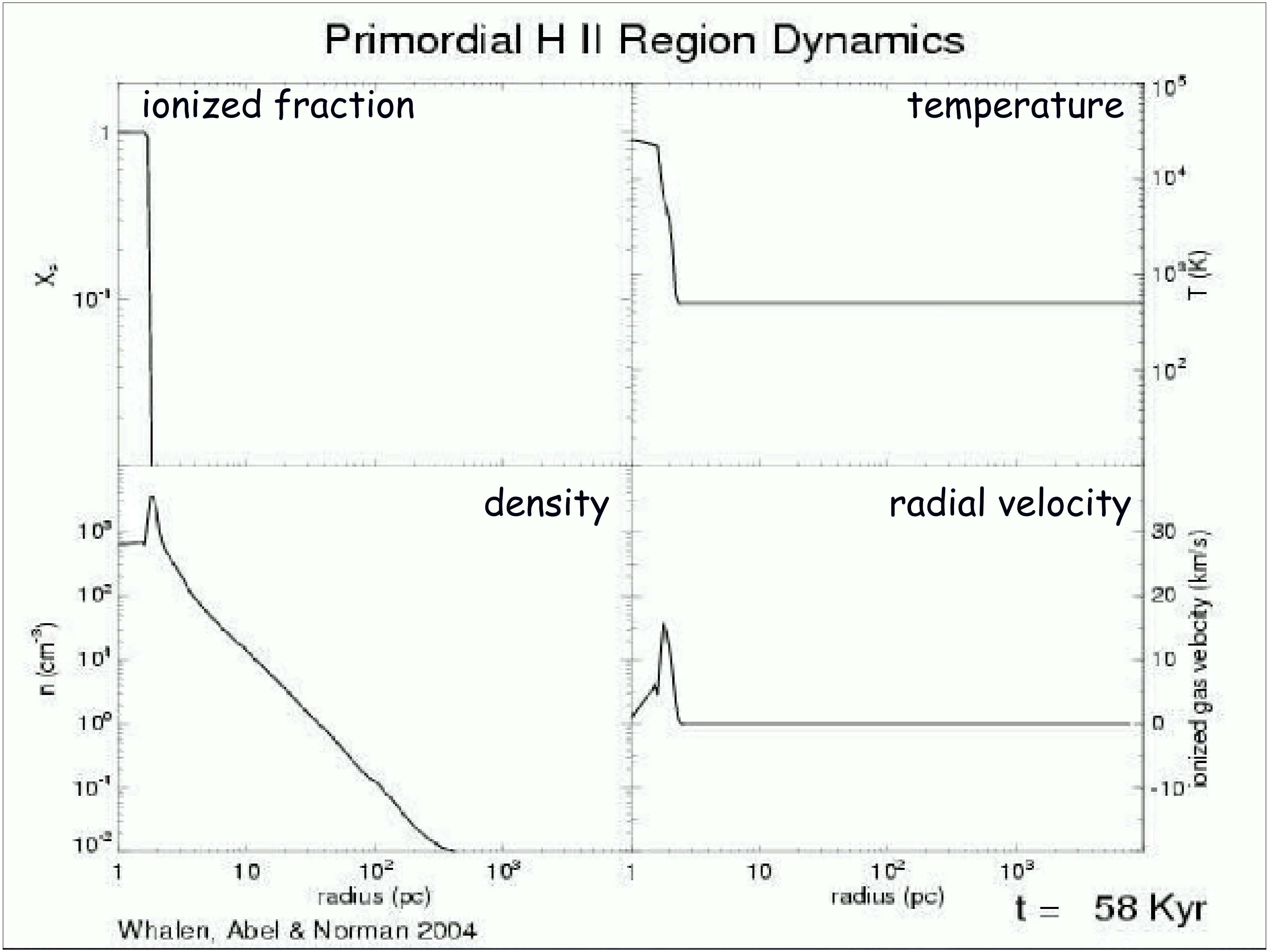


Radiative Transfer in 3D?

adaptive ray-tracing using HEALPIX
photon conserving at any resolution
quad-tree for multiple integrations



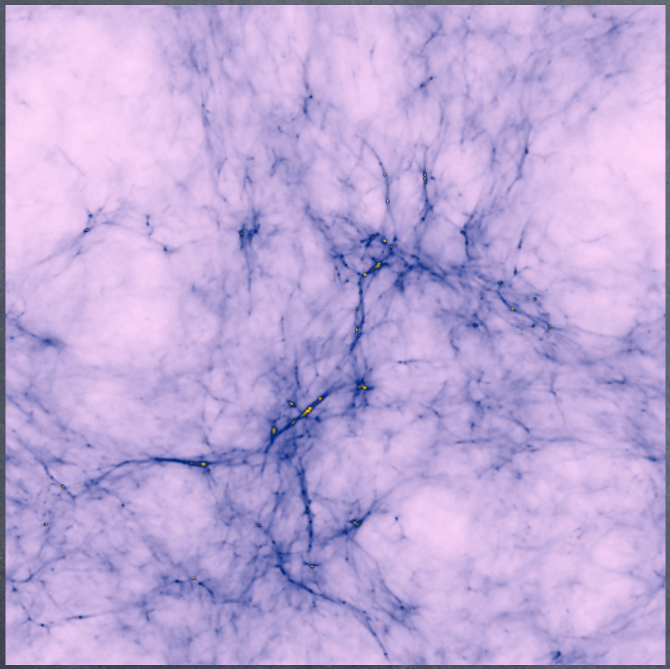
Abel & Wandelt 2002, MNRAS



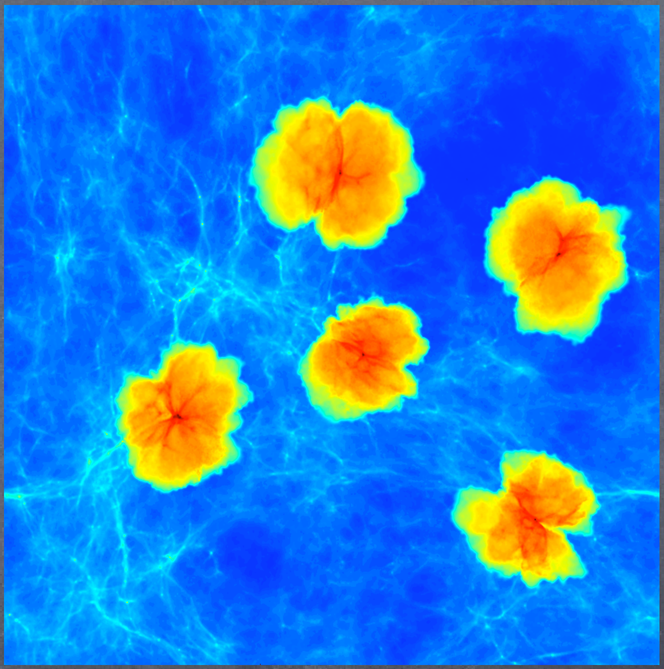
Primordial H II Region Dynamics
ionized fraction
temperature
density
radial velocity
X
T (K)
n (cm⁻³)
ionized gas velocity (km/s)
radius (pc)
radius (pc)
t = 58 Kyr
Whalen, Abel & Norman 2004

First Light

2x288^3 SPH particles
1/100 of Milky Way (600 kpc box)



Adaptive ray tracing a la
Abel & Wandelt 2002, MNRAS



~ 13.5 billion years ago

100 such cubes will eventually make up Milky Way

Yoshida, Abel, Hernquist & Sugiyama 2003 ApJ;   Yoshida, Abel, Hernquist in prep.

The First Supernovae

Yes and no question: Is one supernova enough to blow apart its host micro-galaxy? yes

-> Most metals produced end up in the IGM.

Where does the next generation of stars form?

Dust formation?

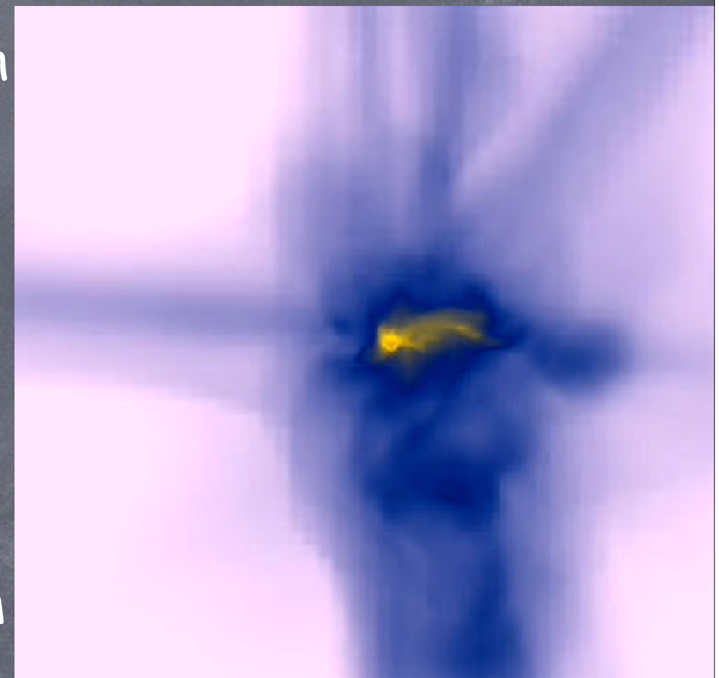
How much material will be enriched ?

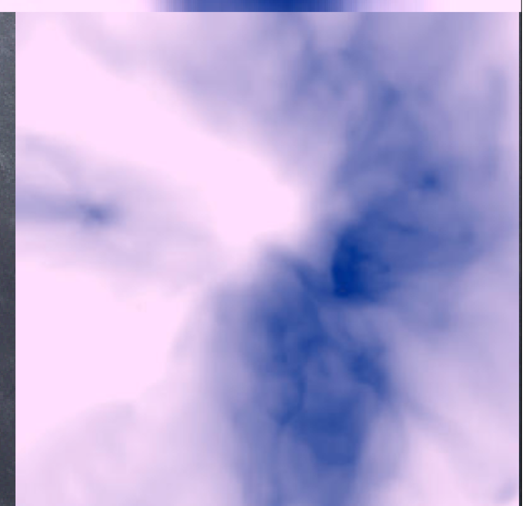
Requires radiative transfer, non-equilibrium metal chemistry and cooling, MHD and thermal conduction.

> 10^6 solar masses

Mixing in a shell driven from the first HII region.

In the stars? Rotation?





Abel, Bryan & Norman 2000

Collaborators

- Greg Bryan (Columbia)
- Emanuele Ripamonti
- Mike Norman, Dan Whalen, Brian O'Shea (LCA, UCSD)

3D visualizations from a collaboration with Ralf Kähler at the ZIB and AEI

Conclusions

- Formation of primordial proto-stars is now well understood. However, lots of new interesting open questions about the formation of the first stars arose.
- First stars are very massive and form in isolation without planets.
- Predicting the exact IMV (Initial Mass Value) of the first stars is relying on the development of practical 3d radiative transfer techniques and more physics.
- UV escape fraction from the very first objects are unity.
- The gas leaves halos just from photo-ionization alone.
- All metals of the first supernovae are ejected into the intergalactic medium.