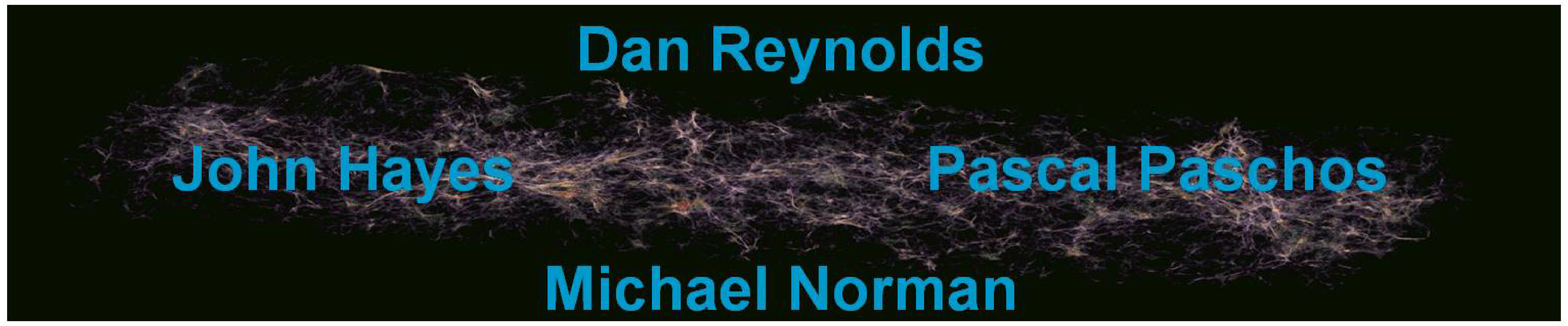
EnzoRad: FLD Radiation Transfer in Enzo



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Enzo is a multi-physics fluid dynamics code designed for simulations of structure formation in the early universe. We are implementing a fully implicit flux limited radiation diffusion module in Enzo in order to study a wide range of radiation transfer in astrophysical problems such as reionization of the universe. We present results of verification problems used to test the diffusion module and assess its accuracy.

Equations/Method:

Coupled Matter-Radiation System

Combining the original, cosmological hydrodynamic system with the chemical and radiation equations, we consider the coupled system,

$$
\begin{aligned}
\partial_t \rho_b + \tfrac{1}{a}\mathbf{v}_b \cdot \nabla \rho_b &= -\tfrac{1}{a}\rho_b \nabla \cdot \mathbf{v}_b, \\
\partial_t \mathbf{v}_b + \tfrac{1}{a}(\mathbf{v}_b \cdot \nabla)\mathbf{v}_b &= -\tfrac{\dot a}{a}\mathbf{v}_b - \tfrac{1}{a\rho_b}\nabla p - \tfrac{1}{a}\nabla\phi, \\
\partial_t e + \frac{1}{a}\mathbf{v}_b \cdot \nabla e &= -\tfrac{2\dot a}{a}e - \tfrac{1}{a\rho_b}\nabla\cdot(p\mathbf{v}_b) - \tfrac{1}{a}\mathbf{v}_b\cdot\nabla\phi + G - \Lambda, \\
\partial_t \mathbf{n}_i + \nabla\cdot(\mathbf{n}_i\mathbf{v}_b) &= -3\tfrac{\dot a}{a}\mathbf{n}_i - \mathbf{n}_i\Gamma_i^{ph} + \alpha_{i,j}^{rec}\mathbf{n}_e\mathbf{n}_j, \\
\partial_t E + \tfrac{1}{a}\nabla\cdot(E\mathbf{v}_b) - \tfrac{1}{a^2}\nabla\cdot(D\nabla E) - \tfrac{1}{ca^3}(\nabla(D\nabla E)) &: (\nabla\mathbf{v}_b) \\
&= -4\tfrac{\dot a}{a}E + 4\pi\eta - ckE.
\end{aligned}
$$

In the fluid energy equation, G is the heating rate and Λ is the combined cooling rate, corresponding to energy sources and sinks due to radiation and chemical couplings.

- ▸ **Split the radiation, ionization and energy feedback (red) from hydrodynamics**
- ▸ **Solve resulting system with fully implicit scheme with time stepping based on accuracy not on stability**
- ▸ **Solution can be obtained for either grey or monochromatic cases**

For real world applications we reconstruct the absorption spectrum to compute realistic ionization and heating rates.

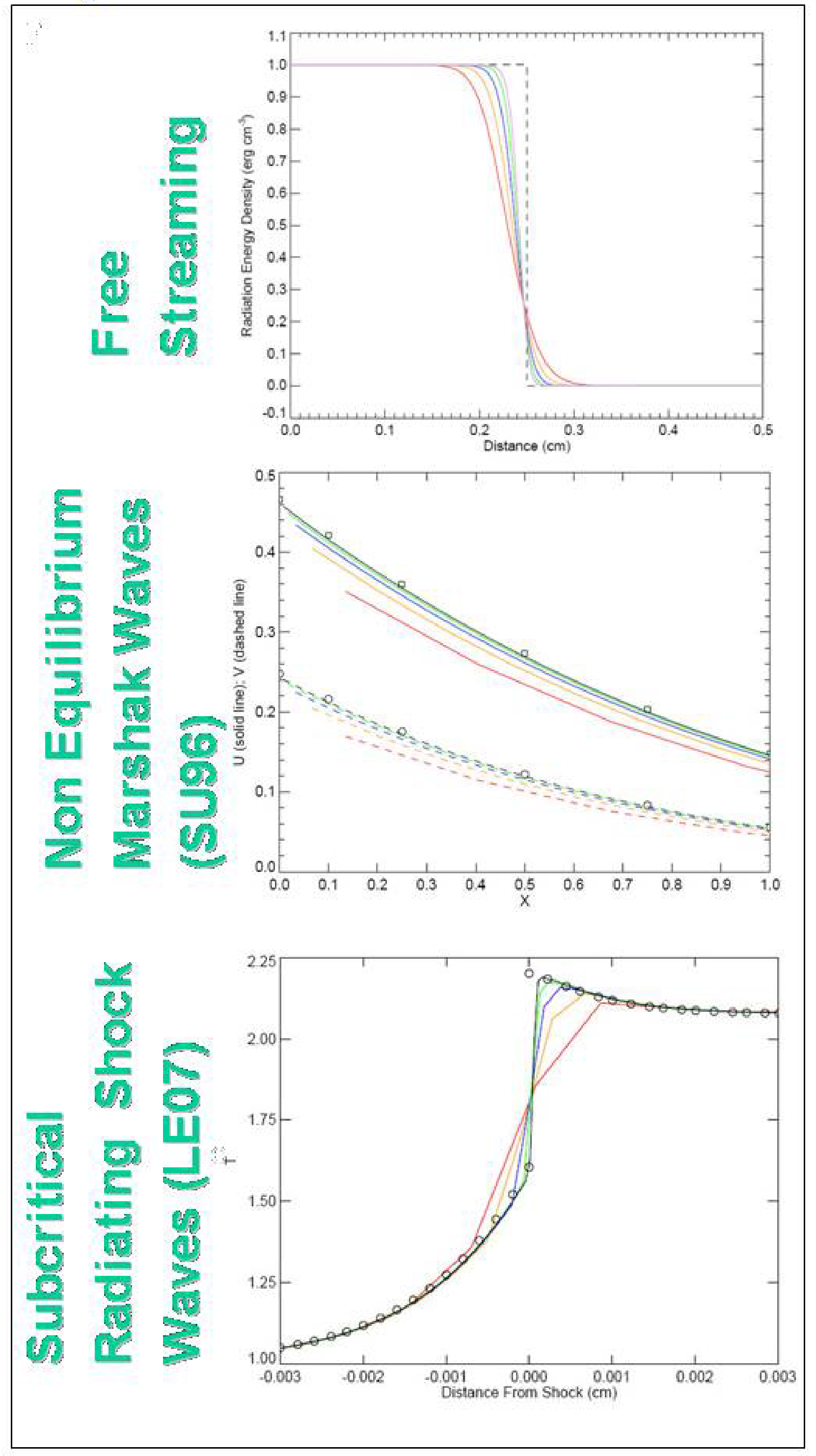
- ▸ **Obtain solutions at a limited number of photon energies ε_i and a solution at the free streaming limit $E_{fs}(\varepsilon) = f(x,t)\ \varphi(\varepsilon)$ which has a spatial distribution modulated by an input radiation spectrum**

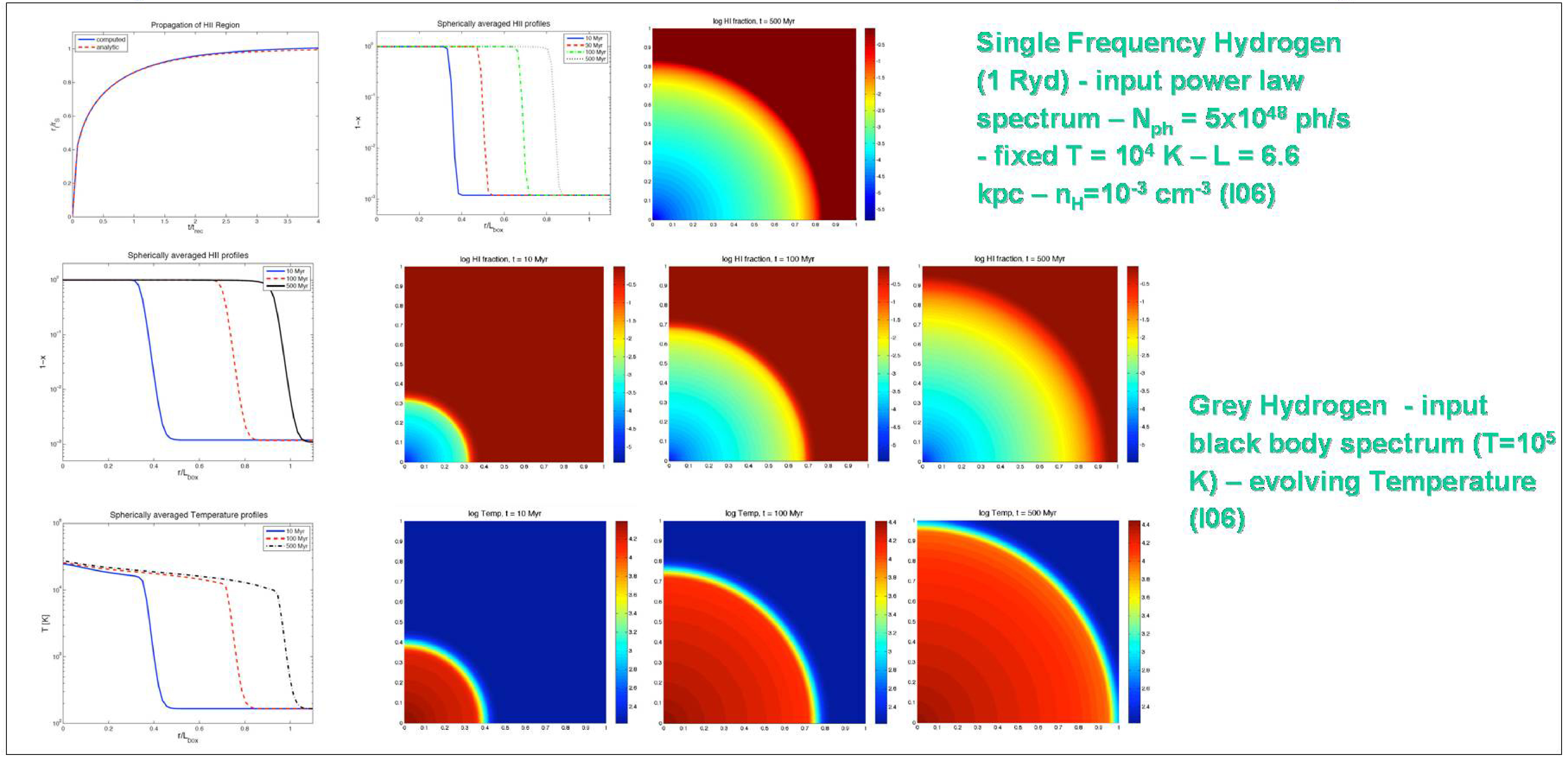
The radiative spectrum is approximated by:

$E(\varepsilon) = E_{fs}(\varepsilon)\ \Pi[E_i\ /\ E_{fs}(\varepsilon_i)]^{S_i(\varepsilon)}$

where $S_i(\varepsilon)$ are functions of the species cross sections.

Tests:





Single Frequency Hydrogen (1 Ryd) - input power law spectrum – N_{ph} = 5x10^{48} ph/s - fixed T = 10^4 K – L = 6.6 kpc – n_H=10^{-3} cm^{-3} (I06)

Grey Hydrogen - input black body spectrum (T=10^5 K) – evolving Temperature (I06)

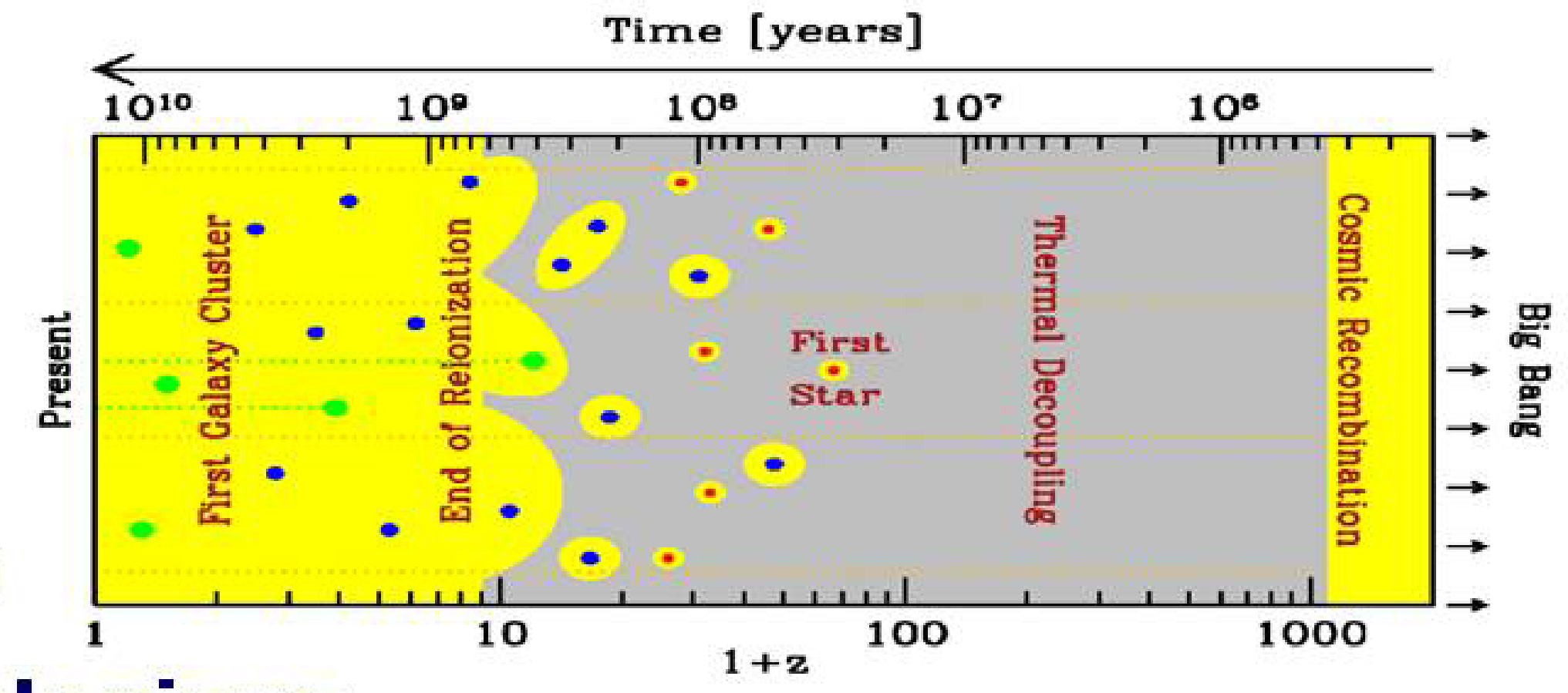
Target Simulations

***HI/HeII reionization**

***Cosmic Evolution of the UVB**

***Radiative Shocks in high redshift SN explosions**

***Radiative Feedback on Early Star Formation and the Lyman-Werner background**



Conclusions

***Solver is accurate & stable from laboratory to cosmic scales**

***Solver is scalable**

***Solver is extensible to additional physics**

***Solver is extensible to alternate spatial discretizations (AMR)**

References

***Reynolds et al Journal for Computational Physics (2008)**

•Su and Olson Journal for Quantitative Spectroscopy and Radiative Transfer 56 (1996) (SU96)

•Lowrie and Edwards LANL preprint LA-UR-07-6879 (LE07)

***Iliev et al, MNRAS 371 2006 (I06)**

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