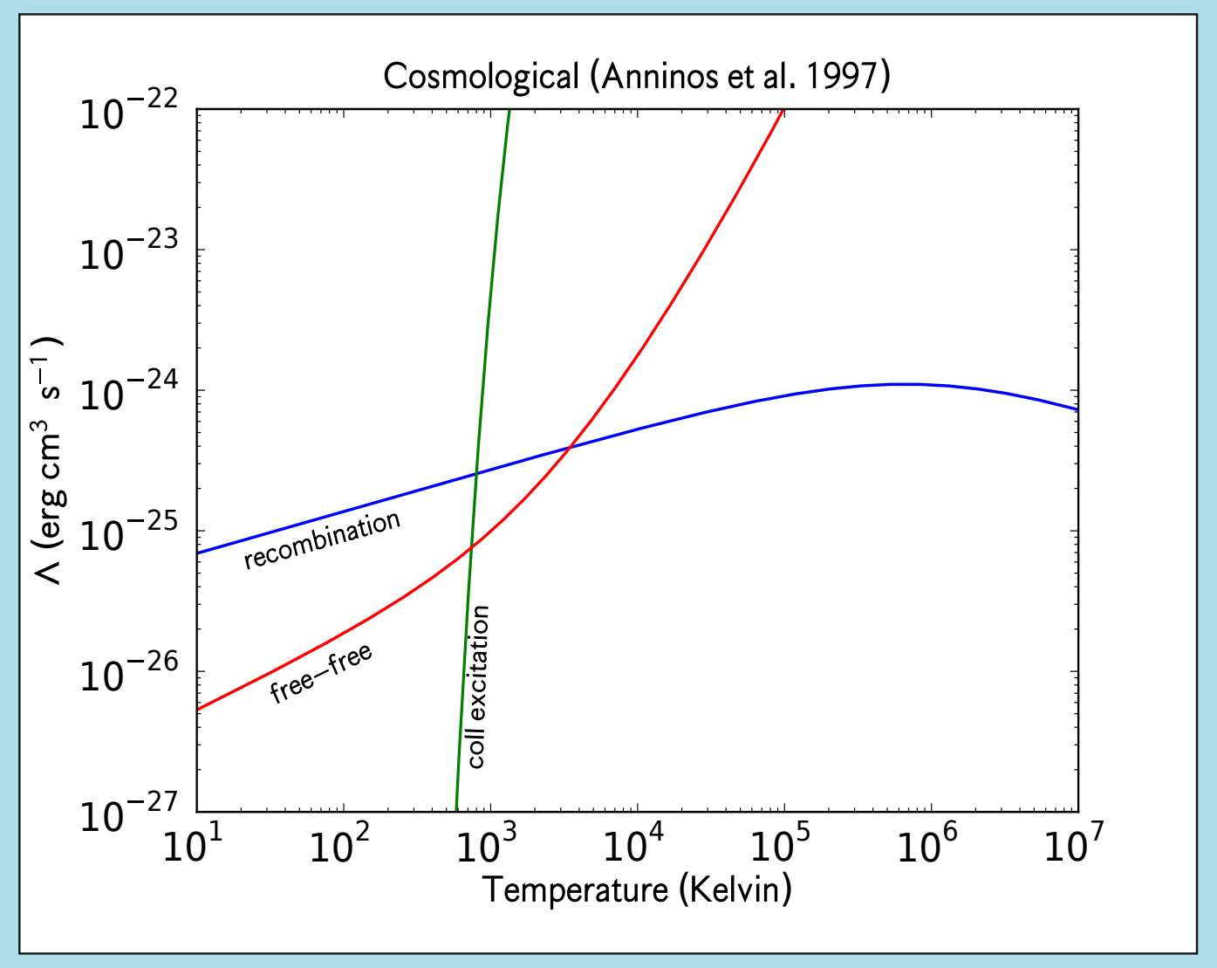
Numerical Methods for Radiative Feedback from the First Stars: Ionization in Adaptive Mesh Refinement Simulations

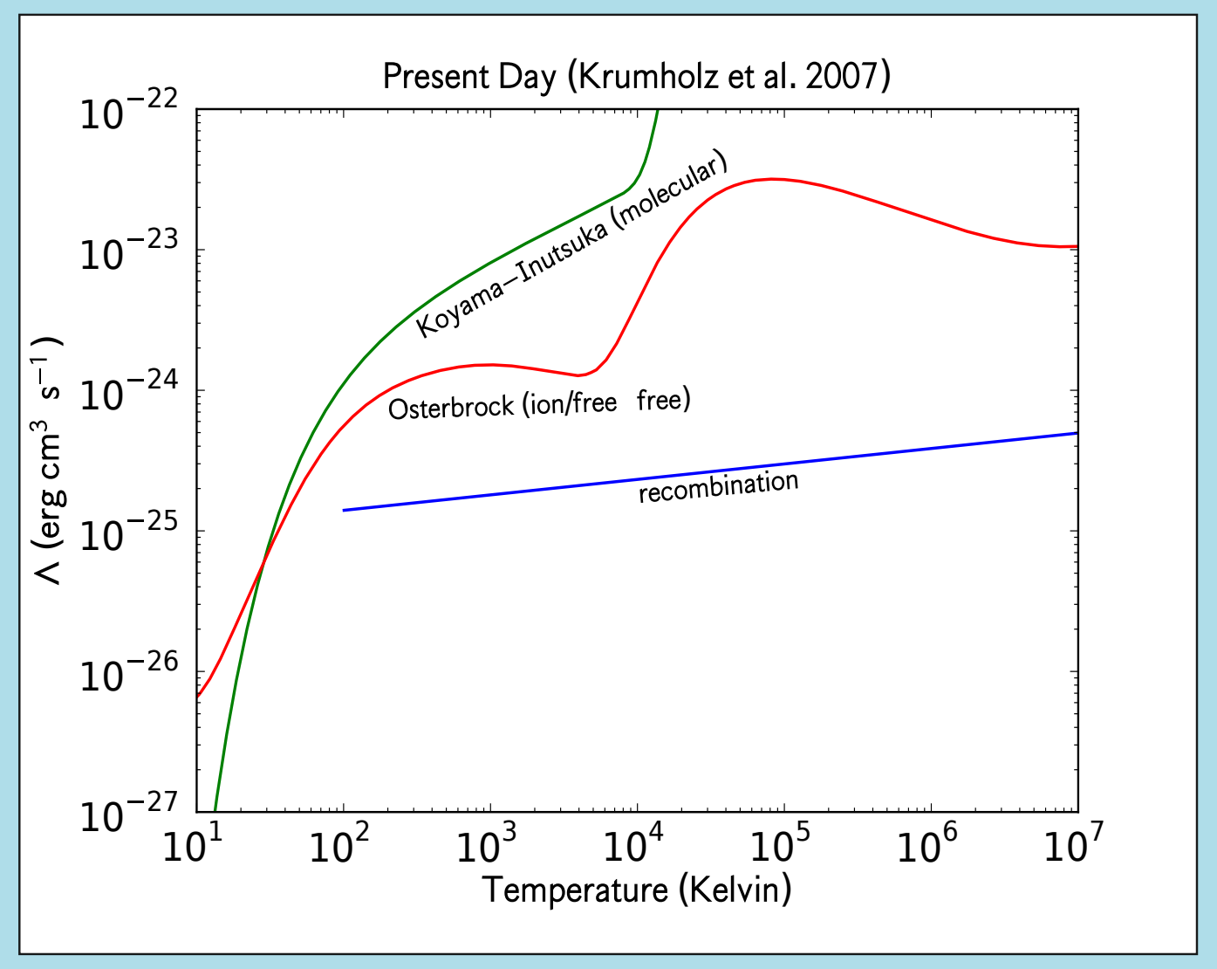
J. S. Oishi, C. McKee (Berkeley), R. Klein (LLNL/Berkeley)

Overview & motivation

In order to ascertain the final masses of Population III stars, which are belived to be order 30-300 $M_\odot$, we must follow the prolonged period of accretion during which these stars are believed to gain the majority of their masses. The key question in such a study, essentially, is *what terminates accretion, and at what mass?* In order to answer this question, we turn to 3D simulations including ionizing radiative feedback capable of following the flow for many accretion timescales. As following ab-initio simulations including a fully hydrostatic core for such a long time will remain computationally infeasable for the forseeable future, we use a sink particle approach to remove the highest density ($n \gtrsim 10^{12} \mathrm{cm}^{3}$) material. **We here describe our implementation of a ray tracing approach to ionizing radiation transport in our Orion AMR radiation hydrodynamics framework.**

Flexible chemistry

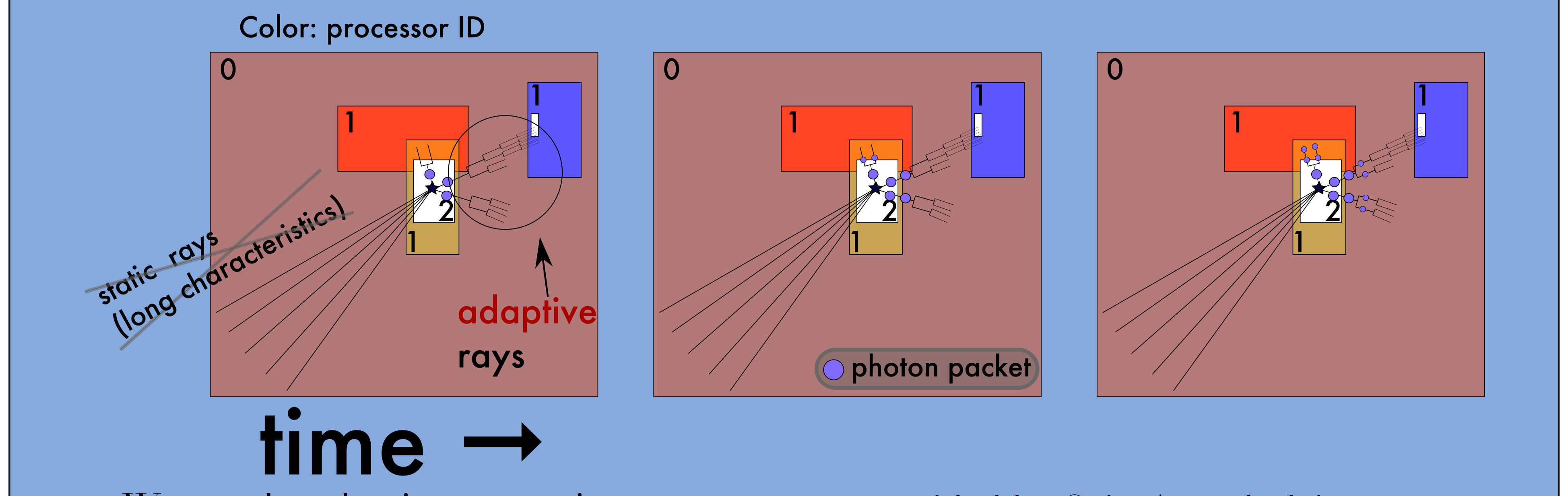




Our interests lie not only in ionization feedback from Pop III stars, but also present day Pop I star formation, which occurs in gas with vastly different chemical composition. A design goal of our code is therefore to easily switch between full 9 or 12 species primordial chemistry solvers (e. g. Anninos et al. 1997) and parameterized heating/cool functions for the more complex present day gas chemistry (e. g. Krumholz, Stone, & Gardiner 2007). In the former case, the temperature is evaluated self-consistently with the multiple species; in the latter, a mean mass per hydrogen nucleus approach allows temperature calculation from two density fields (neutral and total).

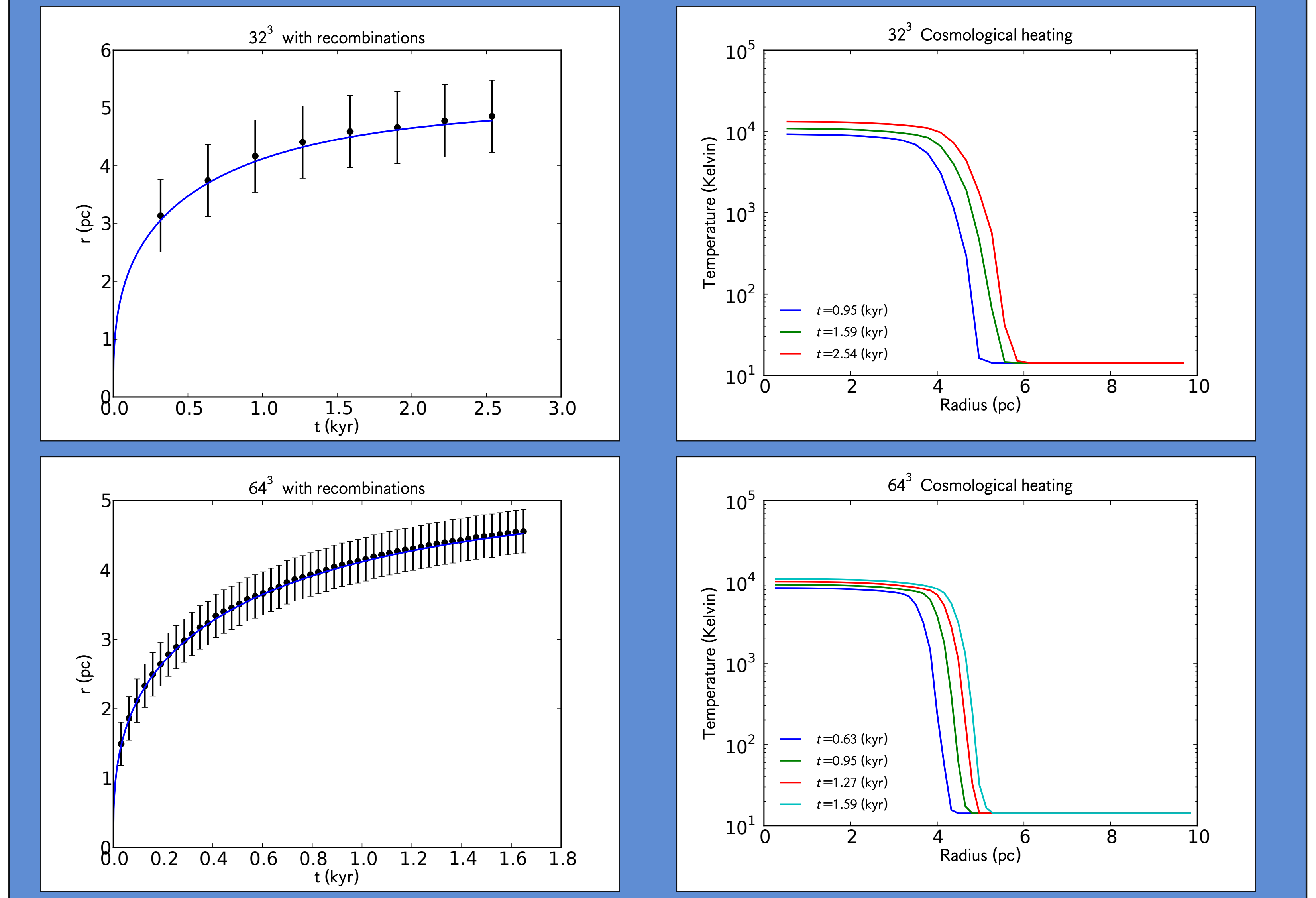
Method

adaptive ray tracing + photon packet tracing



We use the adaptive ray tracing method developed by Abel & Wandelt (2002) and Abel, Wise & Bryan (2007). In this method, we solve the radiative transfer equation along rays which split when the area they subtend exceeds a threshold, usually set to one-fifth of a cell area. This allows excellent angular resolution everywhere on the grid without an extraneous number of rays near the source. In order to couple the scheme to Orion, we follow Whalen & Norman (2006) and Krumholz et al. (2007): at the beginning of each update cycle, each source launches photon packets, travling until they reach a grid edge or 99% of the initial photon flux has been absorbed. At grid edges, the photon packet uses the information provided by Orion's underlying AmrLib framework to find its next grid. Grids are distributed across multiple processors to balance the hydrodynamic load. During the ionization step, each processor loops over all of its grids, and each grid processes all photon packets in its work queue. Grids then exchange photons, and finish any incoming packets. After the photoionization rates are computed, we calculate ionization and cooling timesteps based on the condition that no more than 10% of each timescale be covered in a single step. Then, the FLD solver computes a new solution for the non-ionizing radiation, hydrodynamics is updated via a PPM scheme, and the update is complete.

Test results



Results of a static ionization test from Kruholz et al. (2007) showing the expansion of an R-type ionization front into a uniform density medium including recombinations. The heating and cooling is provided by the Anninos et al. (1997) cooling function. As noted by Abel et al (2007) and Krumholz et al (2007), the scheme provides subgrid accuracy (grid dx is given by the error bars in the left hand figures).

Status and future

The ray tracing/photon packet solver is complete and fully tested on static ionization problems. The solver works on a single level distributed over multiple processors with nearly ideal scaling. We have completed the AMR code, and it is also in the testing phase.

Future

- finish AMR testing
- optimization
- integration tests with flux-limited diffusion solver
- integration tests with 12-species chemistry solver

References

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