Cosmological Radiative Transfer Comparison Project

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Project website:
http://www.cita.utoronto.ca/~iliev/rtwiki/doku.php
Data available at:
http://www.phys.susx.ac.uk/~iti20/RT_comparison_project

Motivation and Basic Strategy

- *The full RT problem is very expensive, multy-dimensional problem, so approximations are inevitably required.*
- *Our aim is to validate our codes and evaluate their reliability and limitations, on the way creating a development testbed for future codes.*
- *Very few, simplified problems have exact analytical solutions to check RT codes against.*
- *Next best approach – compare results from independent codes on common problems.*
- *Problems: simple and clean, of increasing difficulty, involving astrophysically-interesting situations.*
- *Everybody is welcomed to join. Regular workshops (this is 4th one). Results published in series of papers and at a community website:*
  http://www.cita.utoronto.ca/~iliev/rtwiki/doku.php and

  http://www.phys.susx.ac.uk/~iti20/RT_comparison_project/

Organization

- *Open project: everybody free to join.*
- *Open-ended project – continually updated and new tests/new physics added.*
- *Any problem could be considered, but for inclusion minimum 3 codes should do it.*
- *Regular workshops (4 to date).*
- *Papers on results published after each stage of the project is completed.*
- *Project and analysis coordinated by me, with help from volunteers.*

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Cosmological Radiative Transfer Codes Comparison Project I: The Static Density Field Tests

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26 June 2006

11 codes (new ones joining), including ray-tracing (long and short char.), Monte-Carlo, moment; fixed, AMR, unstructured grids, and no grid (particle-based): cover most of the spectrum of possible approaches.

Paper has 100+ citations to date, standard set of tests for all new codes.

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Cosmological radiative transfer comparison project – II. The radiation-hydrodynamic tests

Ilian T. Iliev,[1,2,3★] Daniel Whalen,[4] Garrelt Mellema,[5] Kyungjin Ahn,[6,7] Sunghye Baek,[8] Nickolay Y. Gnedin,[9] Andrey V. Kravtsov,[10] Michael Norman,[11] Milan Raicevic,[12] Daniel R. Reynolds,[13] Daisuke Sato,[14] Paul R. Shapiro,[7] Benoit Semelin,[8] Joseph Smidt,[15] Hajime Susa,[16] Tom Theuns[12,17] and Masayuki Umemura[14]

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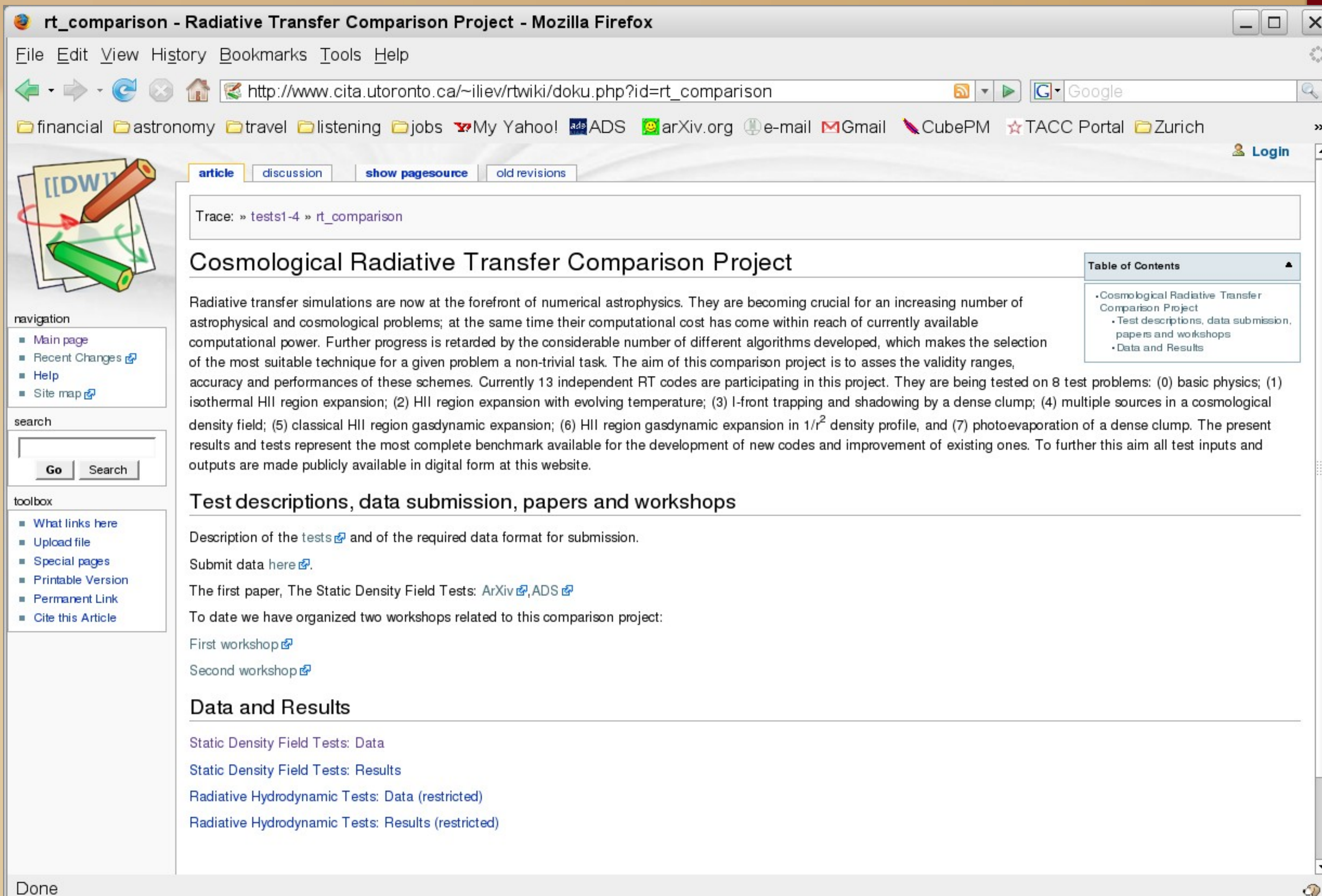
[17]*Department of Physics, University of Antwerp, Campus Groenenborger, Groenenborgerlaan B-171, B2020 Antwerp, Belgium*

10 codes: varieties of ray-tracing, Monte-Carlo, moments, particles; hydro: Eulerian, Lagrangean, SPH, AMR, Riemann solver; many codes parallel.

Paper: 33 citations, standard set of radiative-hydro tests for all new codes.

Radiative Transfer Comparison Project Wiki



Site (specifically the data) now being moved to Sussex. Will not be a wiki anymore. File submission method is being worked on.

Radiative Transfer Comparison Project Wiki: Results & Errata

tests1-4res - Radiative Transfer Comparison Project - Mozilla Firefox

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Results: Static Density Field Tests

Here we would publish results which were not included in Paper I of our Comparison Project, as well as any errata and corrections to the published results.

Corrections

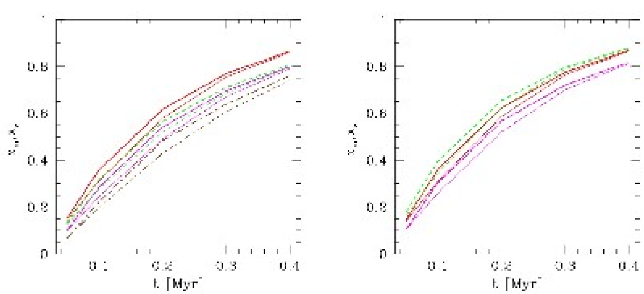

Figure 35 in Paper I had incorrect time axis, the corrected version of the figure is shown here. We thank Dominique Aubert for pointing this out.

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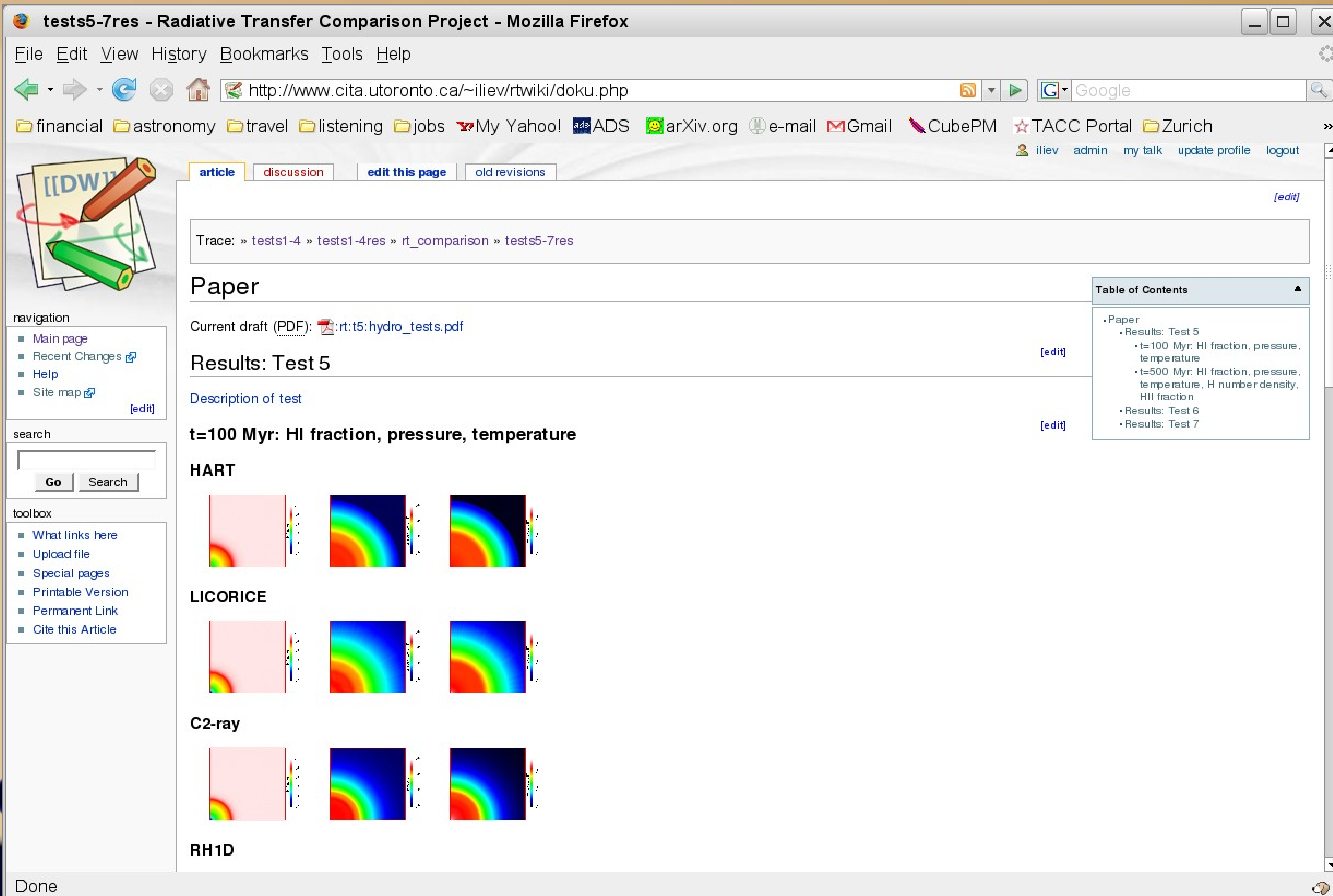
tests1-4res.txt · Last modified: 2007/01/27 18:40 by iliev

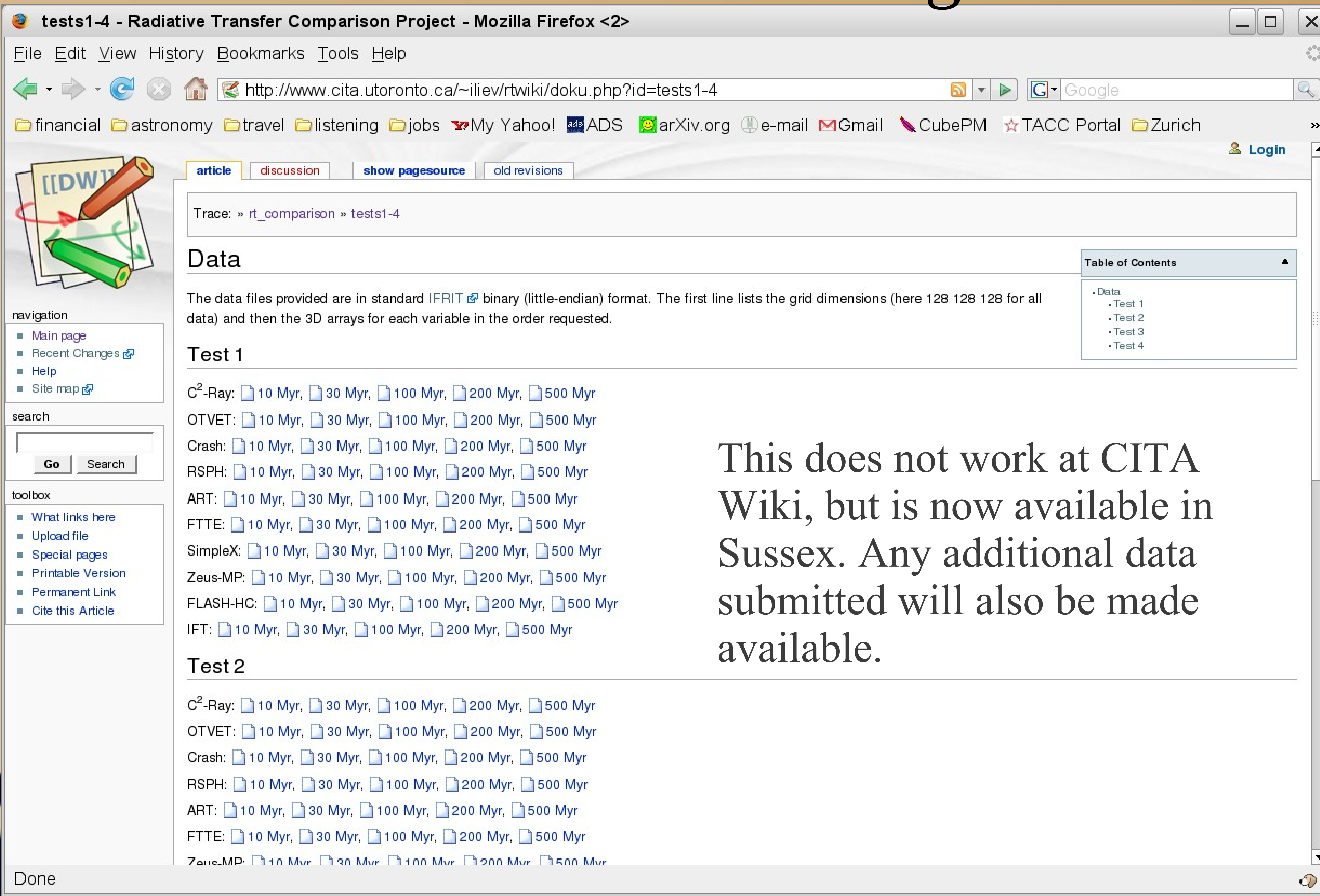
Results are mostly in the published papers. However, any additional data submitted, as well as further results, errata, etc. will be available at site. We also put the published images and data for comparison with new codes.

Done

Radiative Transfer Comparison Project Wiki: Results & Errata II



Radiative Transfer Comparison Project Wiki: Data Sharing



This does not work at CITA Wiki, but is now available in Sussex. Any additional data submitted will also be made available.

Data Formats

- *Maximally simple and machine independent.*
- *Submission: ASCI data, defined loops and variables order, evolution times at which data is required (typically 5 timeslices, to limit total data amount).*
- *(Relatively) Low resolution requested (128^3 grid) in interests of inclusivity.*
- *For standartization data required on a regular grid – not optimal for all codes (e.g. AMR, Lagrangean, unstructured grids).*
- *Reduced (public) data: binaries - lower bandwidth requirements.*

Issues and problems

- *People need regular pushing along, or nothing will happen.*
- *A number of issues with the data submissions (inevitable when a number of busy people involved?) – significant amount of time and efforts to fix:*
  - *incorrect data format of submissions (e.g. multiple files instead of one).*
  - *incorrect variable (e.g. HII instead of HI fraction).*
  - *different units (e.g. cm vs. kpc, sec vs. Myr).*
  - *more subtle – in some cases slightly incorrect/different problem ran (e.g. different ionizing spectrum used).*
  - *not all data requested is submitted (e.g. missing a variable).*

Cosmological Radiative Transfer: specifics

- *Main problem: Reionization of the Universe by the first sources.*
- *Large scales (from kpc to hundreds of Mpc), up to hundreds of thousands of sources.*
- *Low densities → fast I-fronts (R-type), converting to D-type in denser regions (halos).*
- *3D, inhomogeneous density fields.*
- *Very high optical depths.*
- *H+He are most important, but metal cooling also matters at later times.*
- *Generally non-equilibrium chemistry.*

Tests: 0-4

- *Test 0 : Basic physics, rates used + single zone evolution in ionizing up and then recombining*

Pure radiative transfer tests:

- *Test 1: Pure hydrogen isothermal HII region expansion*
- *Test 2: HII region expansion: the temperature state (H+He or pure H)*
- *Test 3: I-front trapping in a dense clump and formation of a shadow (w/point source and plane-parallel flux)*
- *Test 4: Multiple sources in a (fixed) cosmological density field.*

Tests: 5-7

Radiative hydrodynamics tests:

- *Test 5: Classical HII region expansion and R-type to D-type transition*
- *Test 6: HII region expansion in $1/r^2$ profile: (re-)acceleration down a steep density profile and inside-out dwarf galaxy photoevaporation*
- *Test 7: Photoevaporation of a dense clump (w/point source and plane-parallel flux)*

Chemistry and Cooling Rates (Test 0)

Chemistry and cooling rates vary significantly between sources in literature – this can introduce noticeable variations in the results.

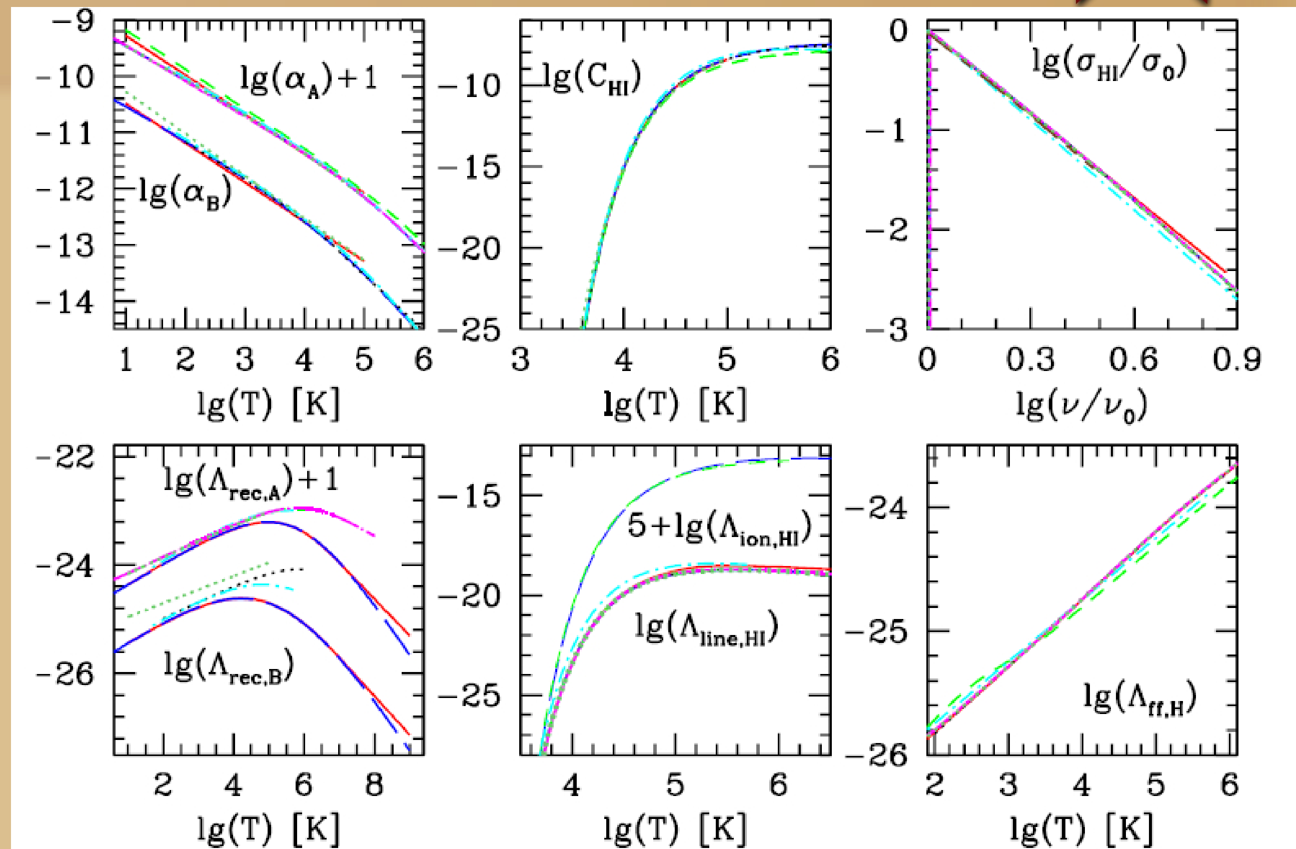
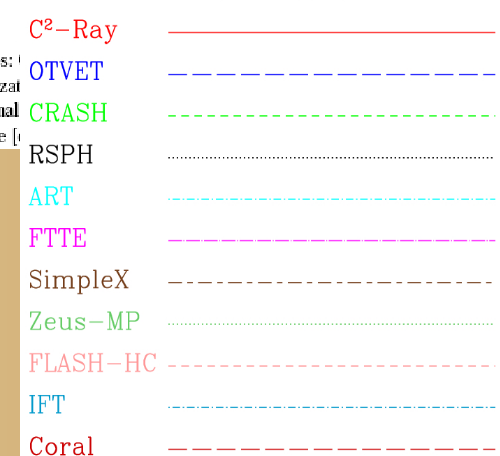
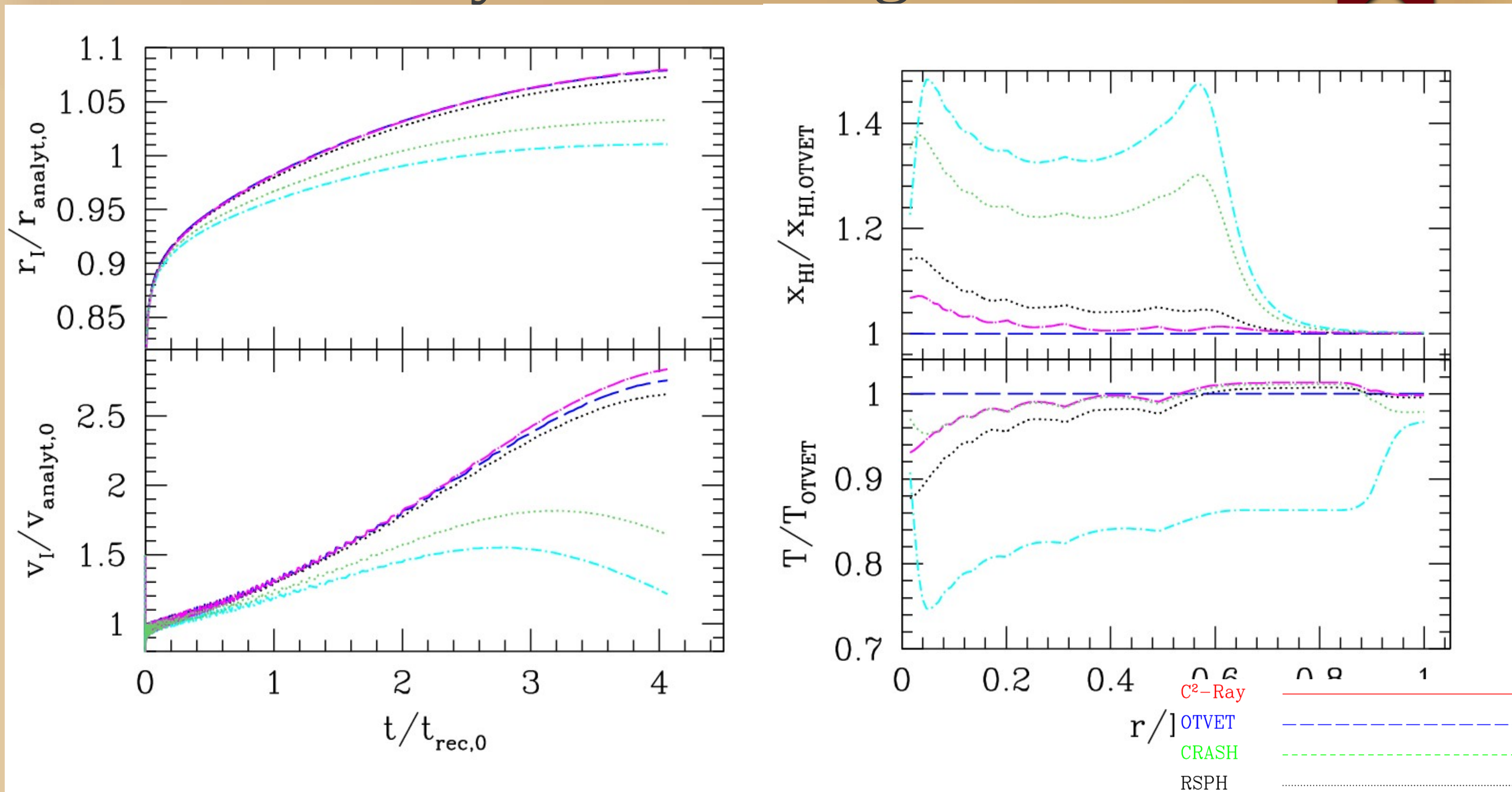
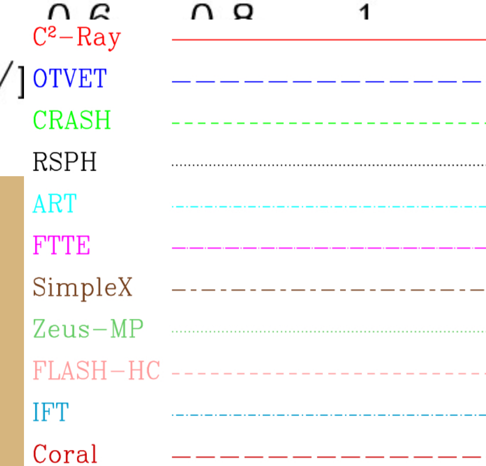


Figure 2. Test 0, part 1: Hydrogen rates, cooling and cross-sections used by the participating codes: (α_B; collisional ionization rate, C_{HI}; cross-section, σ_{HI}/σ_0, normalized to the value at the ionizat case A recombination cooling rate, $\Lambda_{rec,A}$; case B recombination cooling rate, $\Lambda_{rec,B}$; collisional rate for hydrogen, $\Lambda_{ff,H}$. Units of α_A, α_B, and C_{HI} are [cm^{3}s^{-1}], units of the cooling rates are [



Chemistry and Cooling Rates: effects





same RT method, different rates

Few examples: Test 2: initial expansion

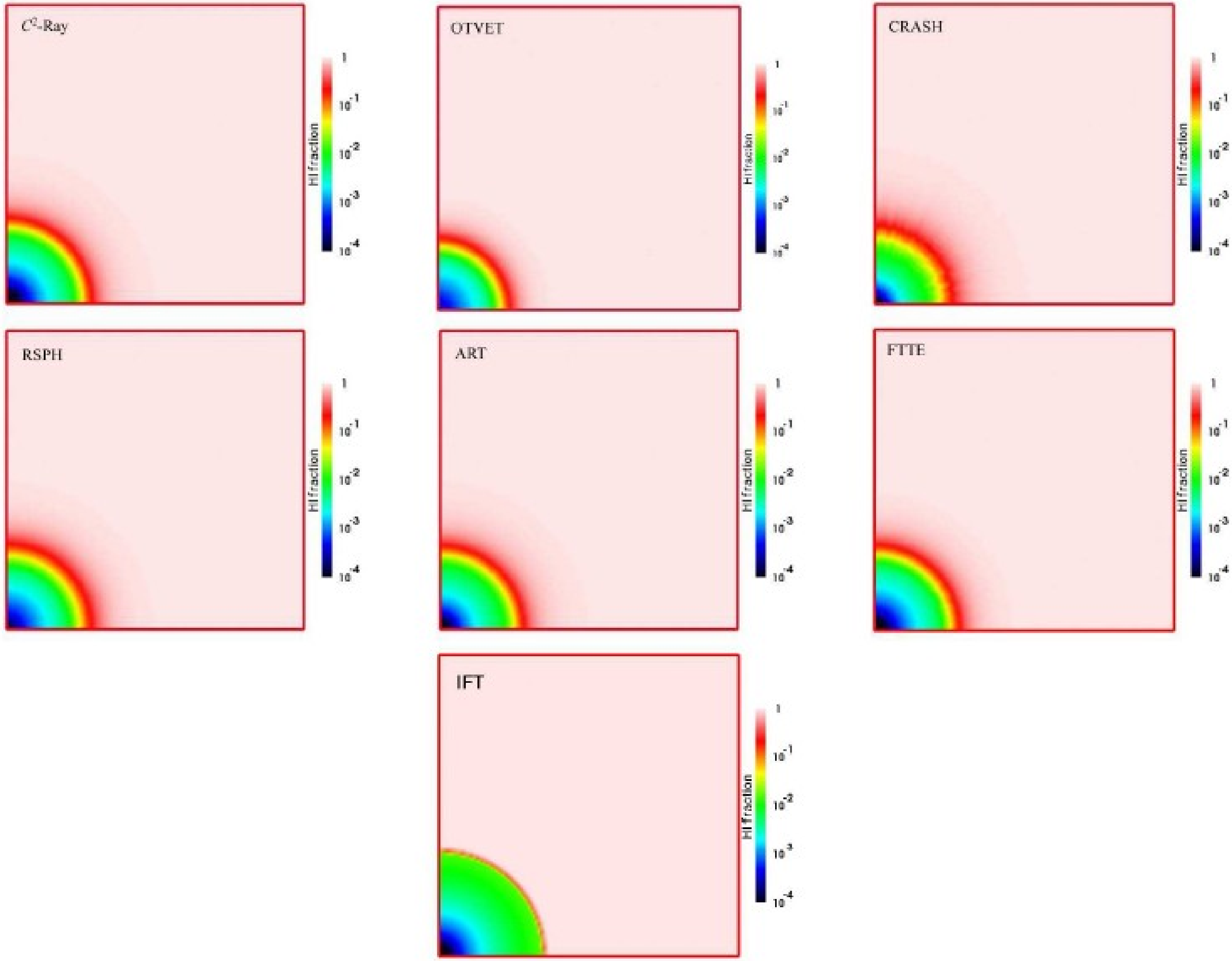


Figure 11. Test 2 (H II region expansion in an uniform gas with varying temperature): Images of the H I fraction, cut through the simulation volume at coordinate $z = 0$ at time $t = 10$ Myr for (left to right and top to bottom) C^2-Ray, OTVET, CRASH, RSPH, ART, FTTE, and IFT.

Test 2: T during initial expansion

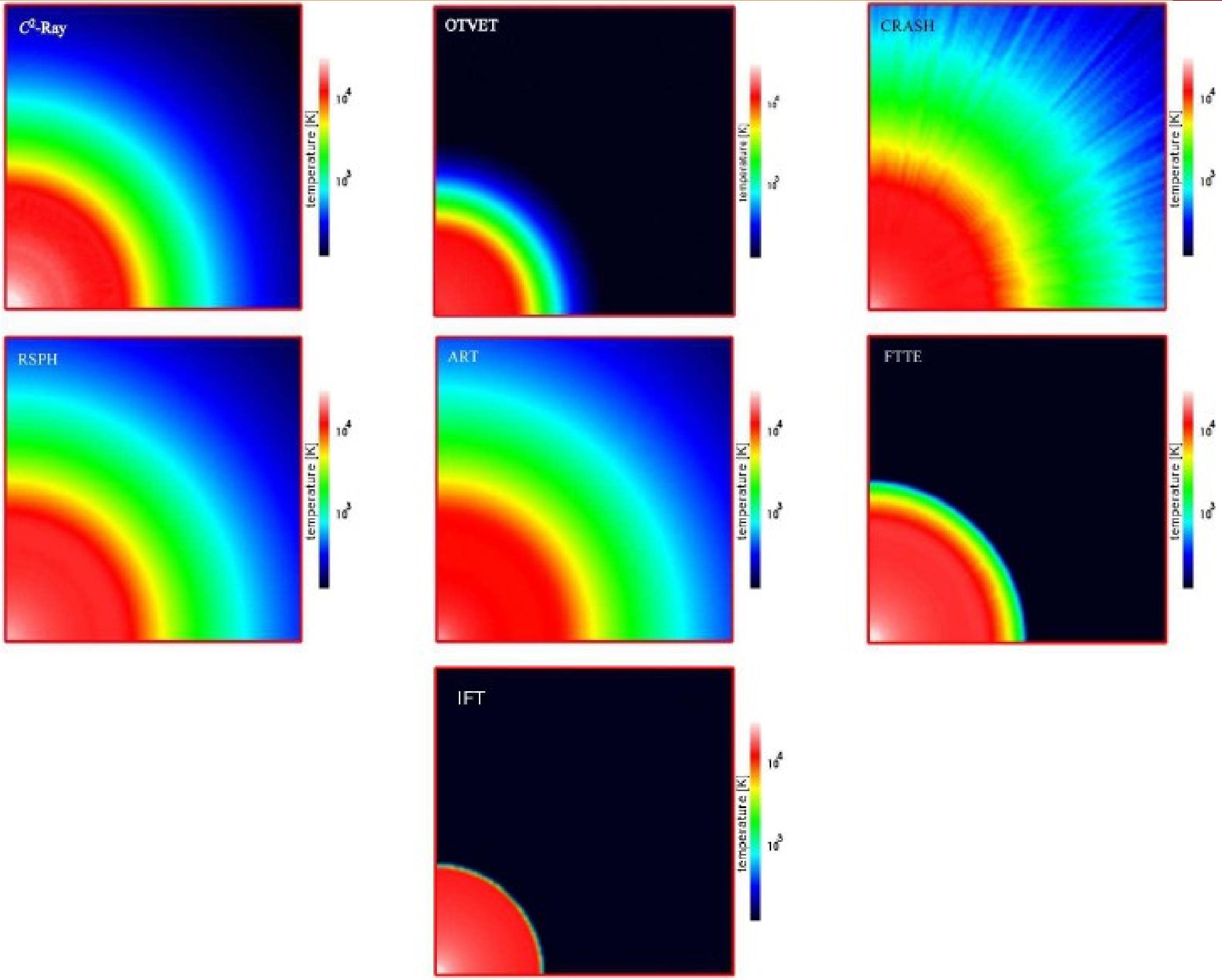


Figure 12. Test 2 (H II region expansion in an uniform gas with varying temperature): Images of the temperature, cut through the simulation volume at coordinate $z = 0$ at time $t = 10$ Myr for (left to right and top to bottom) C^2-Ray, OTVET, CRASH, RSPH, ART, FTTE, and IFT.

Test 2: Stromgren sphere

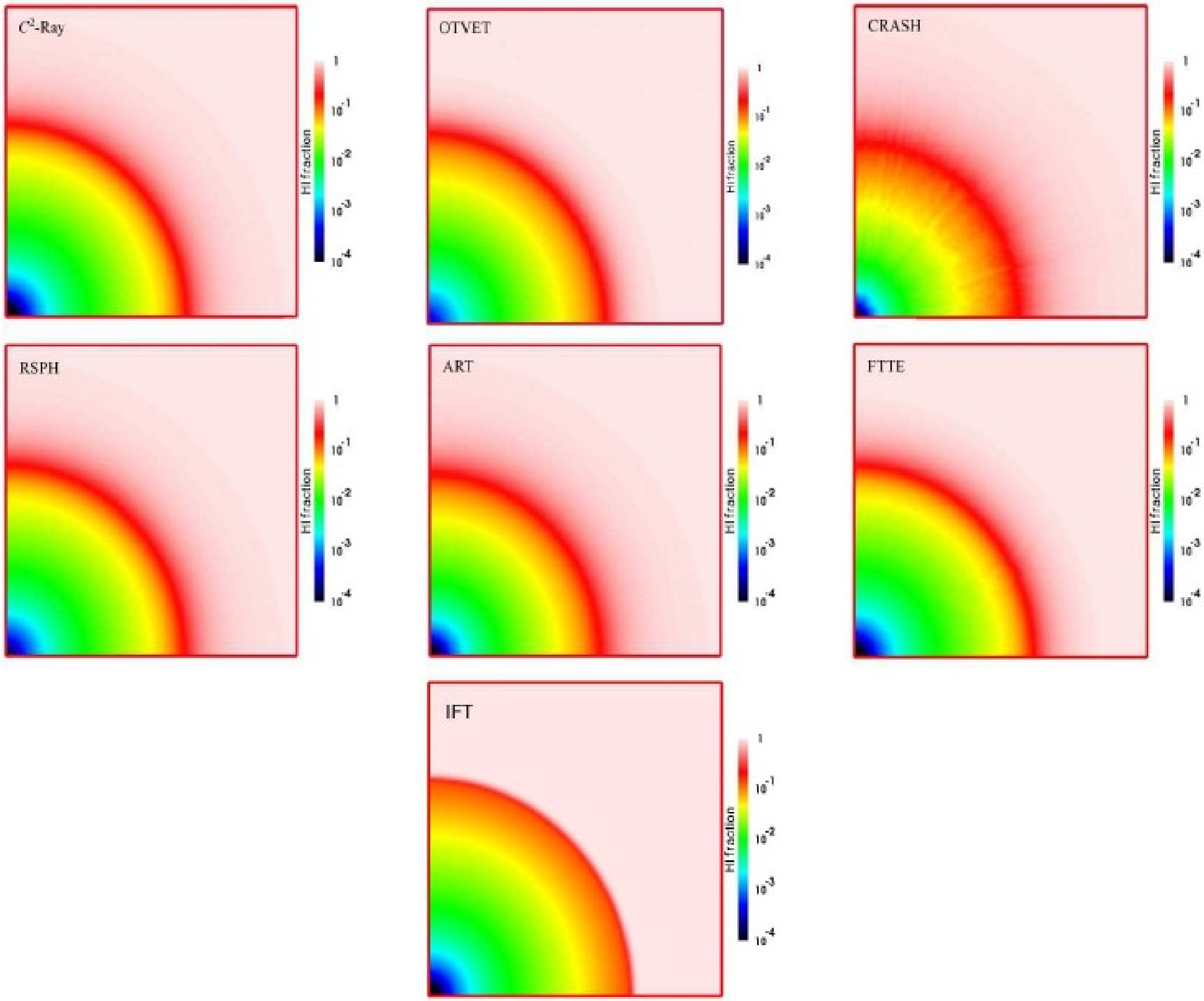


Figure 13. Test 2 (H II region expansion in an uniform gas with varying temperature): Images of the H I fraction, cut through the simulation volume at coordinate $z = 0$ at time $t = 100$ Myr for (left to right and top to bottom) C^2-Ray, OTVET, CRASH, RSPH, ART, FTTE, and IFT.

Test 2: Stromgren sphere T

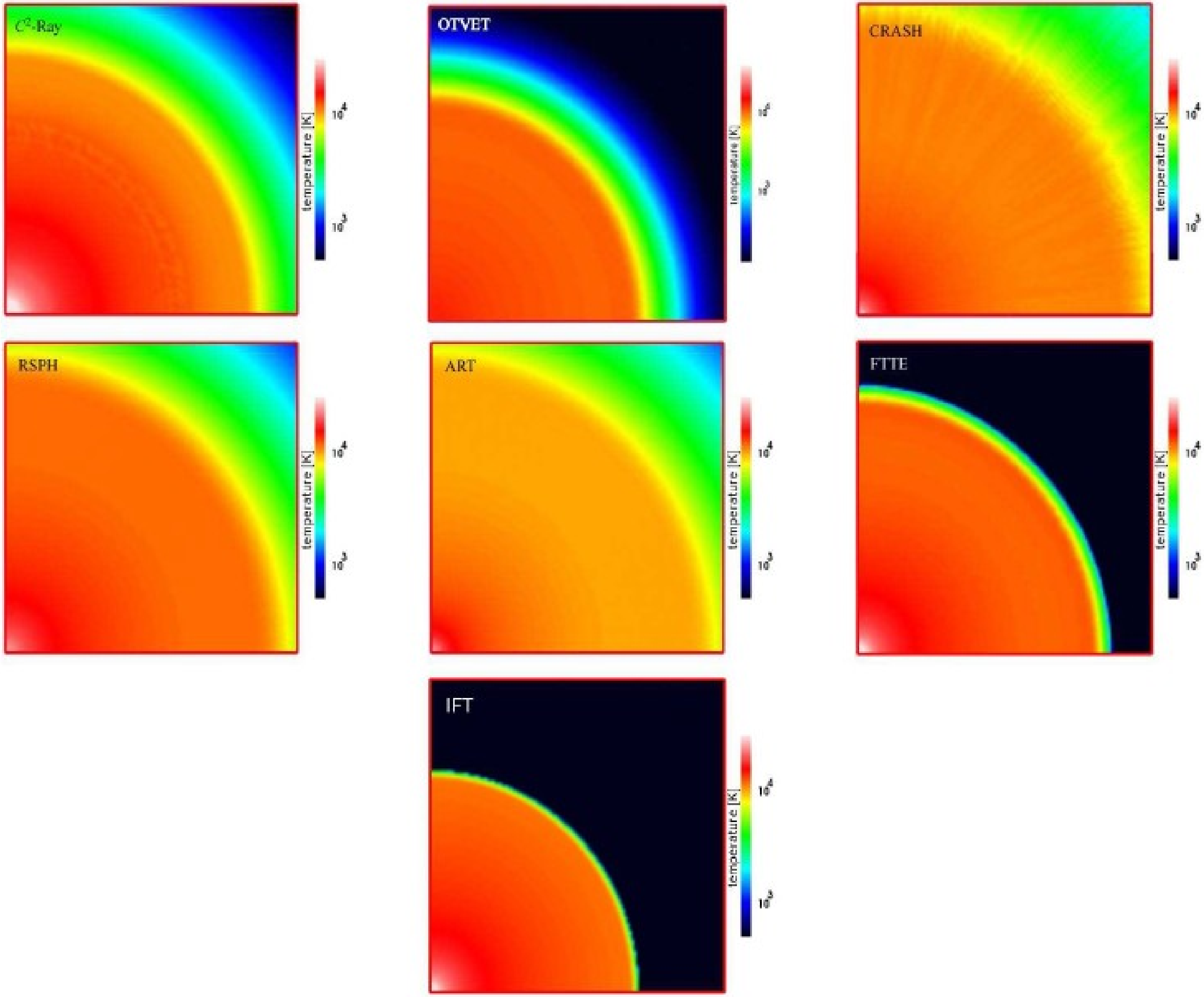
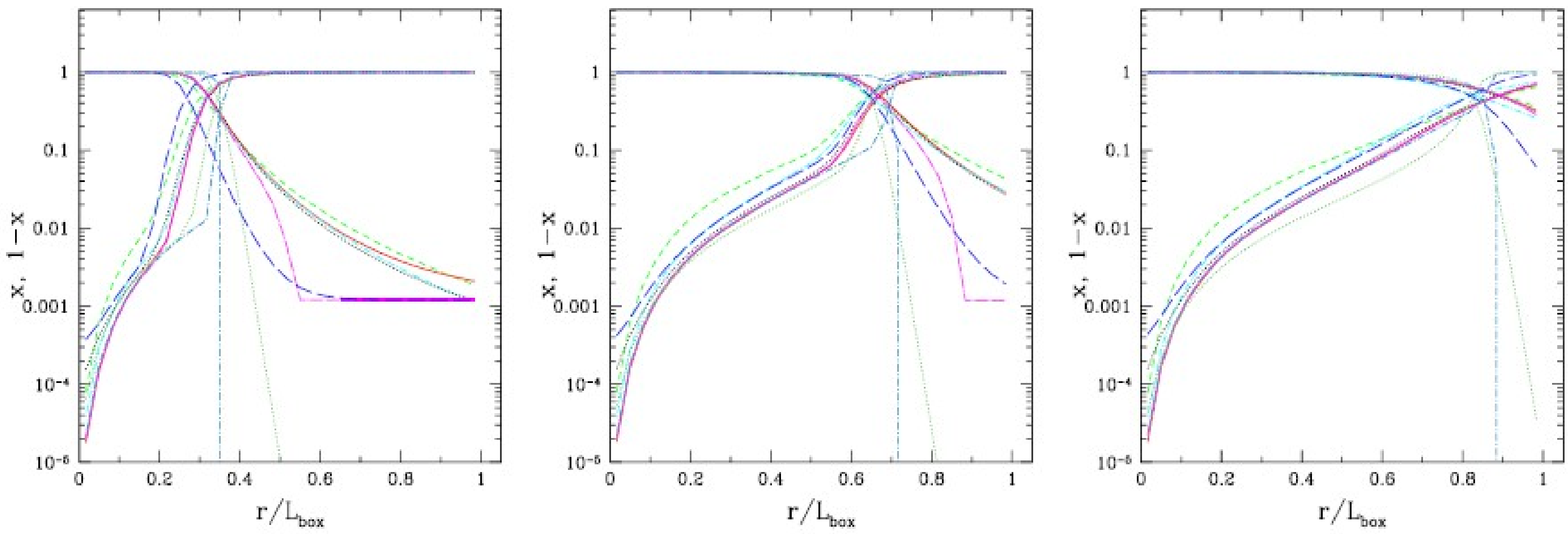
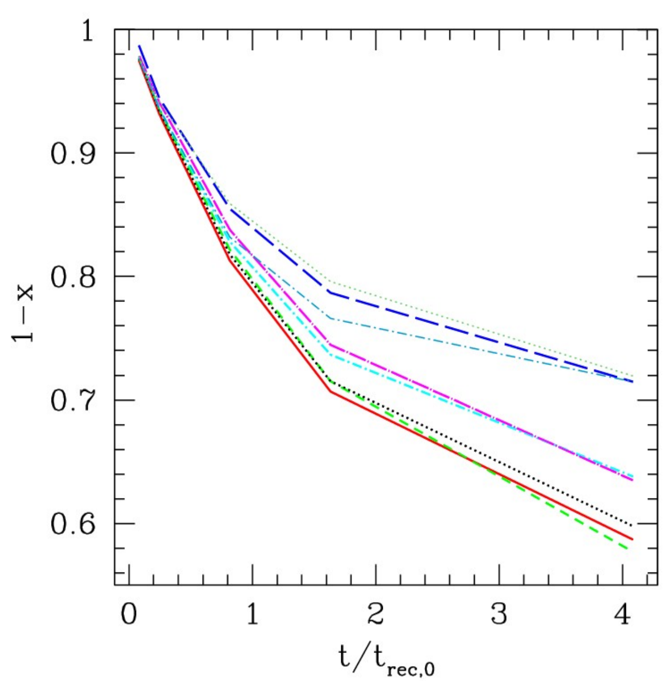


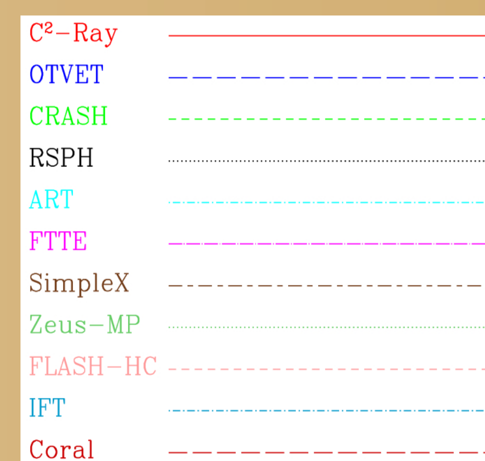
Figure 14. Test 2 (H II region expansion in an uniform gas with varying temperature): Images of the temperature, cut through the simulation volume at coordinate $z = 0$ at time $t = 100$ Myr for (left to right and top to bottom) C^2-Ray, OTVET, CRASH, RSPH, ART, FTTE, and IFT.

Test 2: ionization structure



ı gas with varying temperature): Spherically-averaged ionized fraction x and neutral fraction $1-x$





Test 2: temperature structure

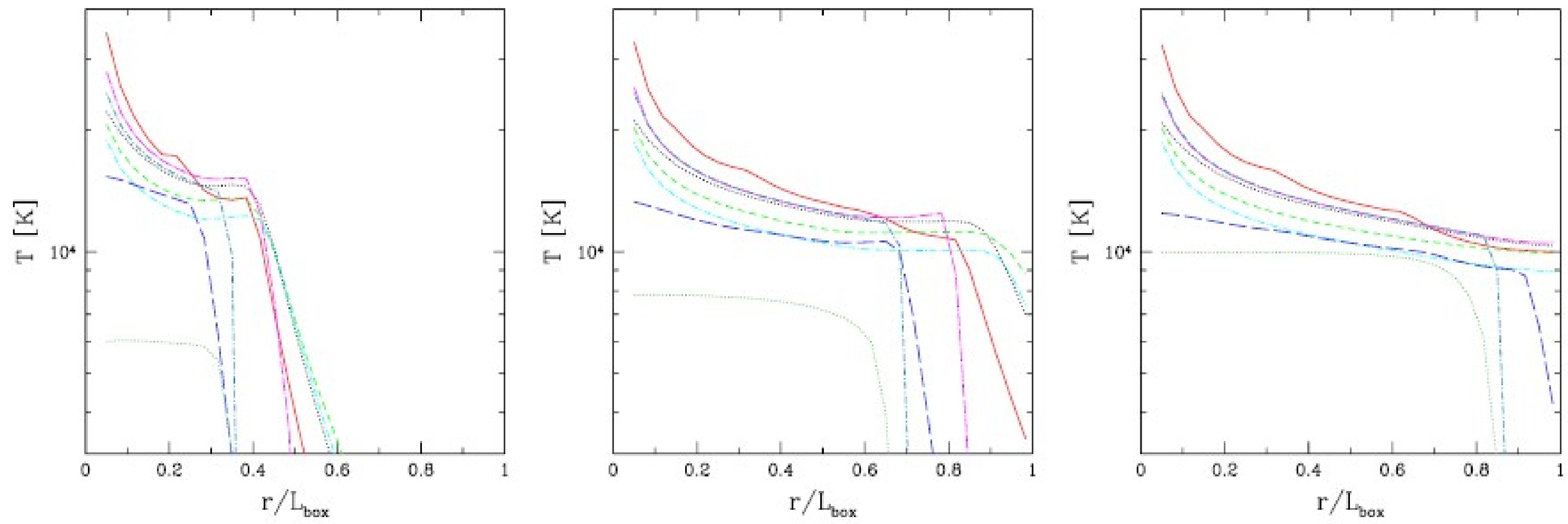
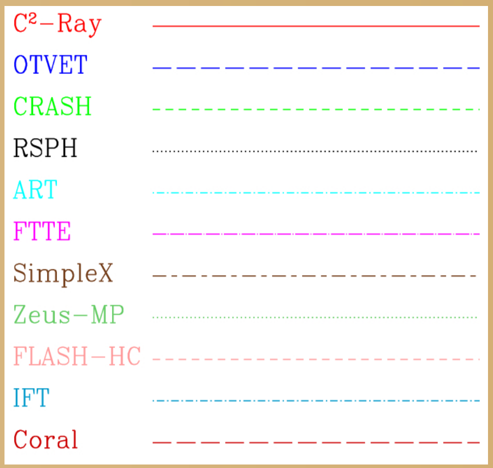


Figure 17. Test 2 (H II region expansion in an uniform gas with varying temperature): Spherically-averaged temperature profiles at times $t = 10$ Myr, 100 Myr and 500 Myr (from left to right).



Test 2: x and T histograms

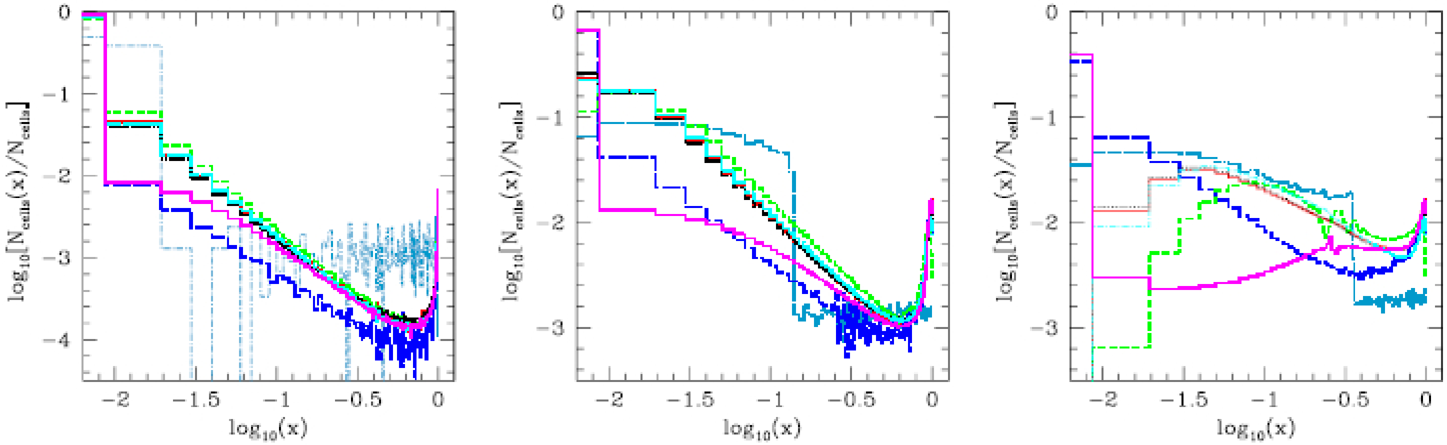


Figure 18. Test 2 (H II region expansion in an uniform gas with varying temperature): Fraction of cells with a given ionized fraction, x, at times (left) $t = 10$ Myr, (middle) 100 Myr and (right) 500 Myr.

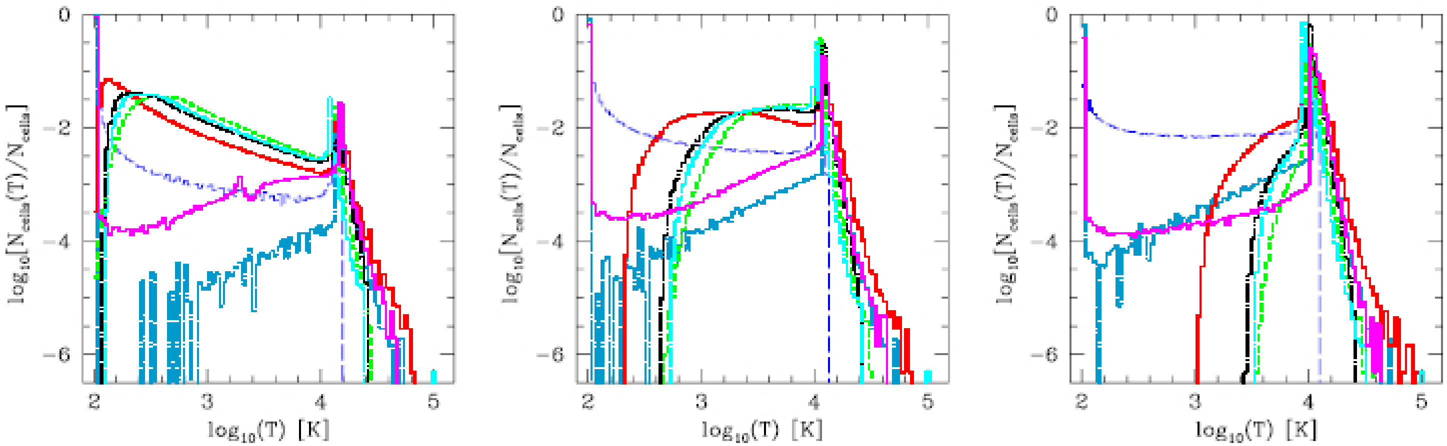
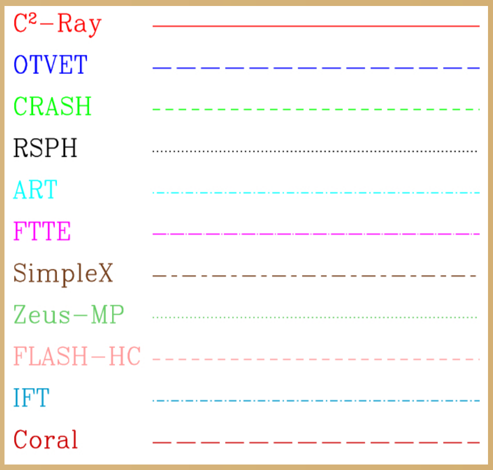


Figure 19. Test 2 (H II region expansion in an uniform gas with varying temperature): Fraction of cells with a given temperature T at times (left) $t = 10$ Myr, (middle) 100 Myr and (right) 500 Myr.



Test 5: the R-type phase

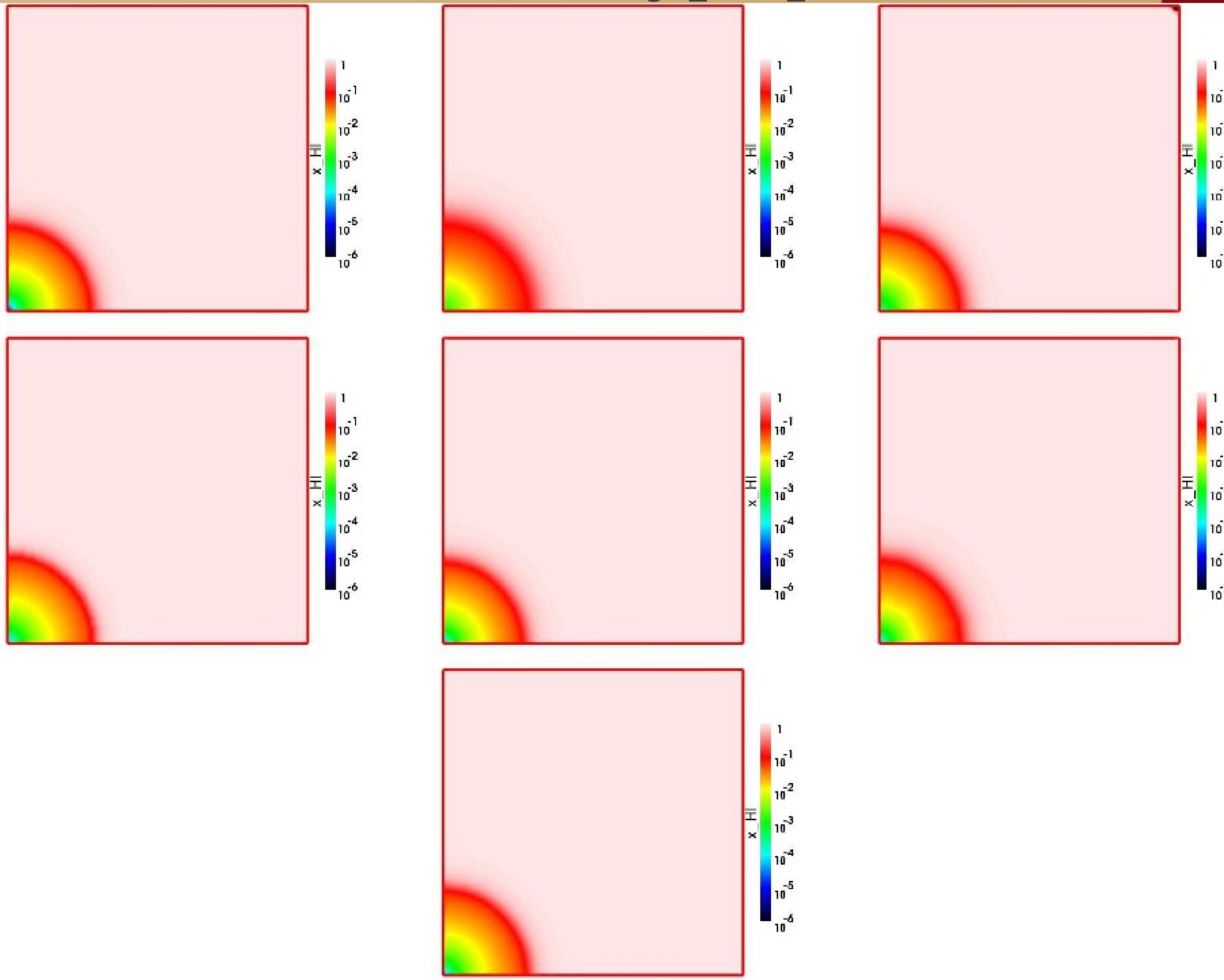


Figure 2. Test 5 (H II region expansion in an initially-uniform gas): Images of the H I fraction, cut through the simulation volume at coordinate $z = 0$ at time $t = 100$ Myr for (left to right and top to bottom) C^2-Ray, HART, RSPH, ZEUS-MP, RH1D, LICORICE, and FLASH.

Test 5: the R-type phase, the pressure

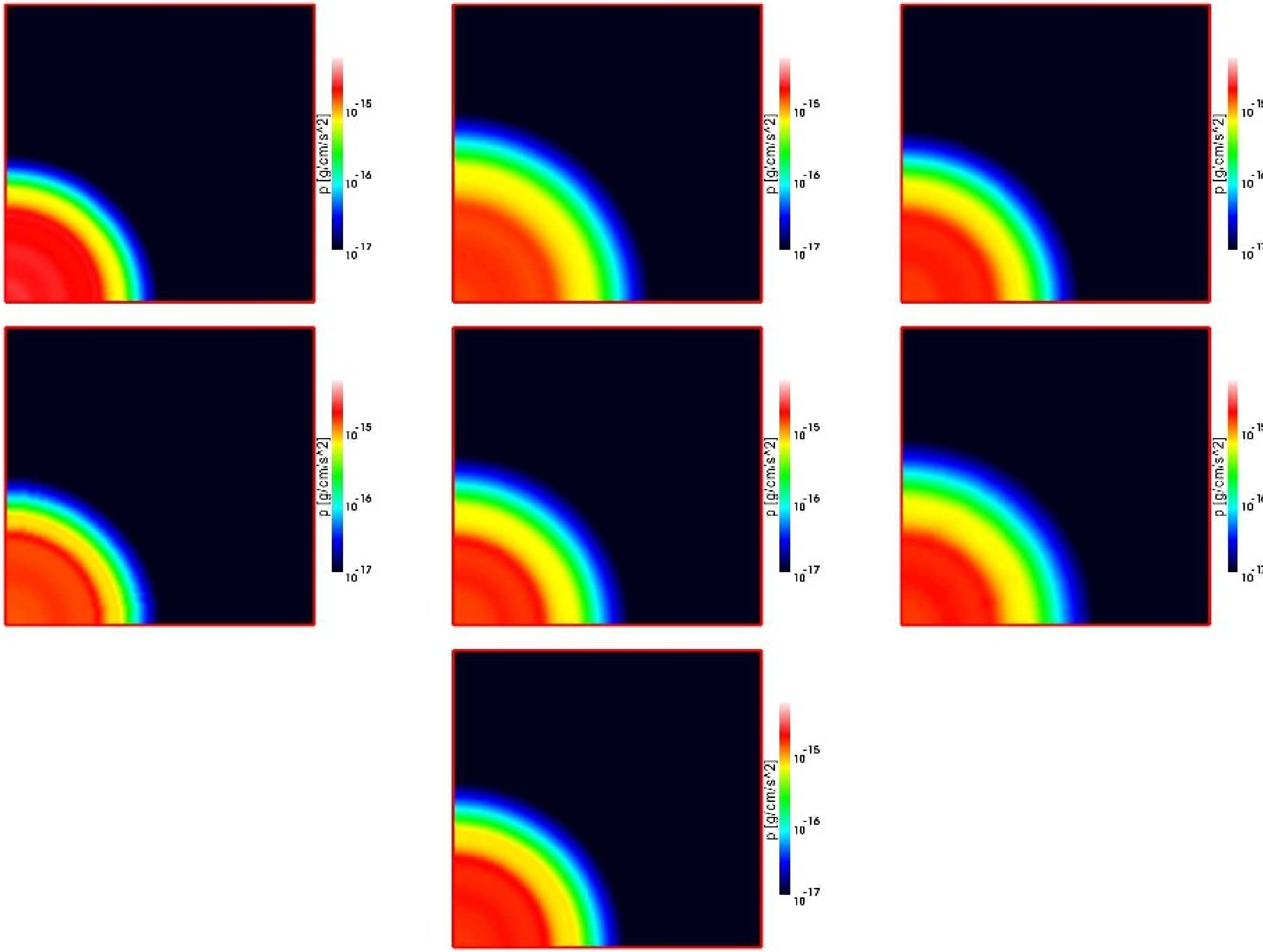


Figure 3. Test 5 (H II region expansion in an initially-uniform gas): Images of the pressure, cut through the simulation volume at coordinate $z = 0$ at time $t = 100$ Myr for (left to right and top to bottom) C^2-Ray, HART, RSPH, ZEUS-MP, RH1D, LICORICE, and FLASH.

Test 5: the R-type phase, the temperature

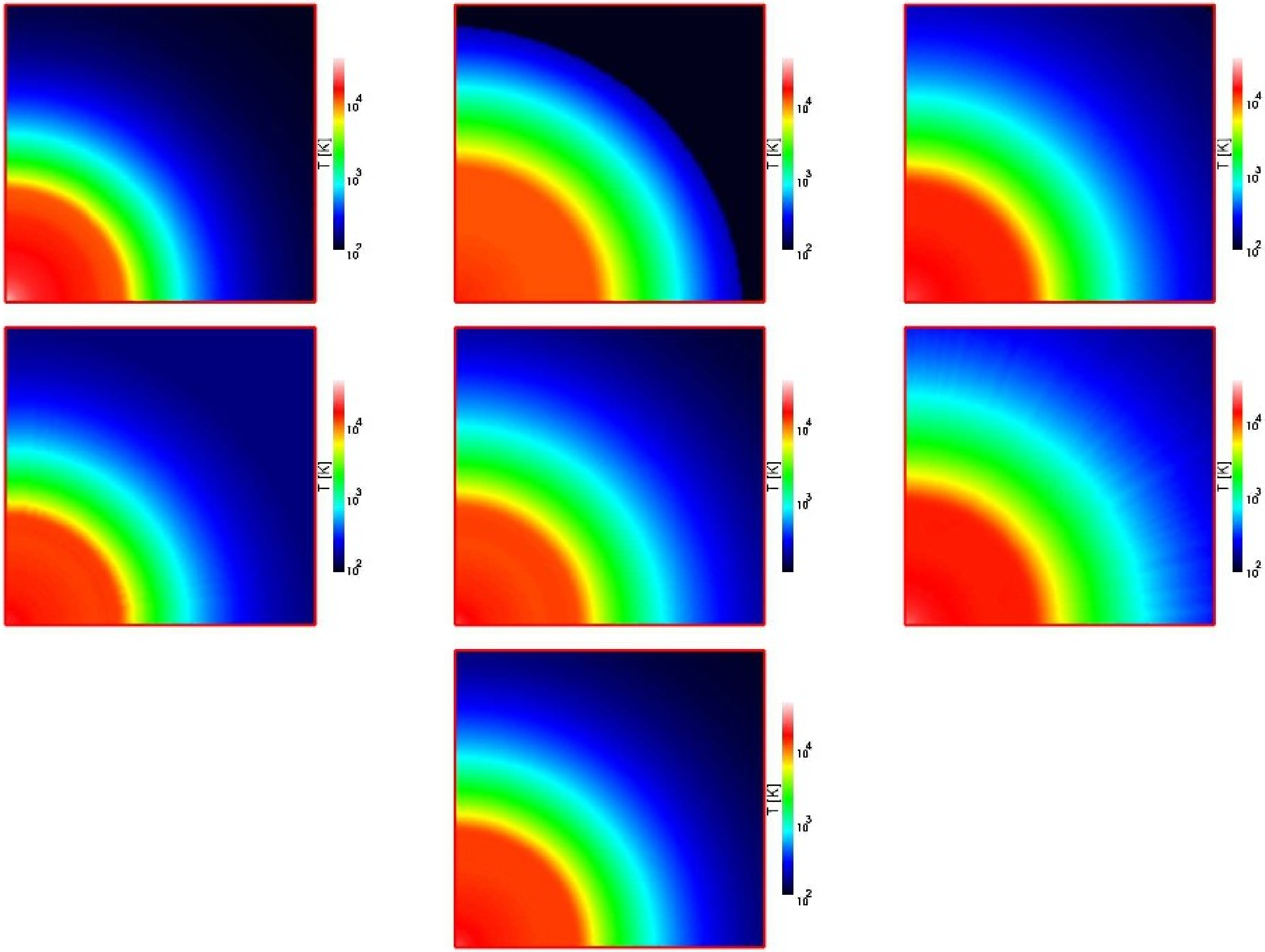


Figure 4. Test 5 (H II region expansion in an initially-uniform gas): Images of the temperature, cut through the simulation volume at coordinate $z = 0$ at time $t = 100$ Myr for (left to right and top to bottom) C^2-Ray, HART, RSPH, ZEUS-MP, RH1D, LICORICE, and FLASH.

Test 5: the D-type phase ion. structure

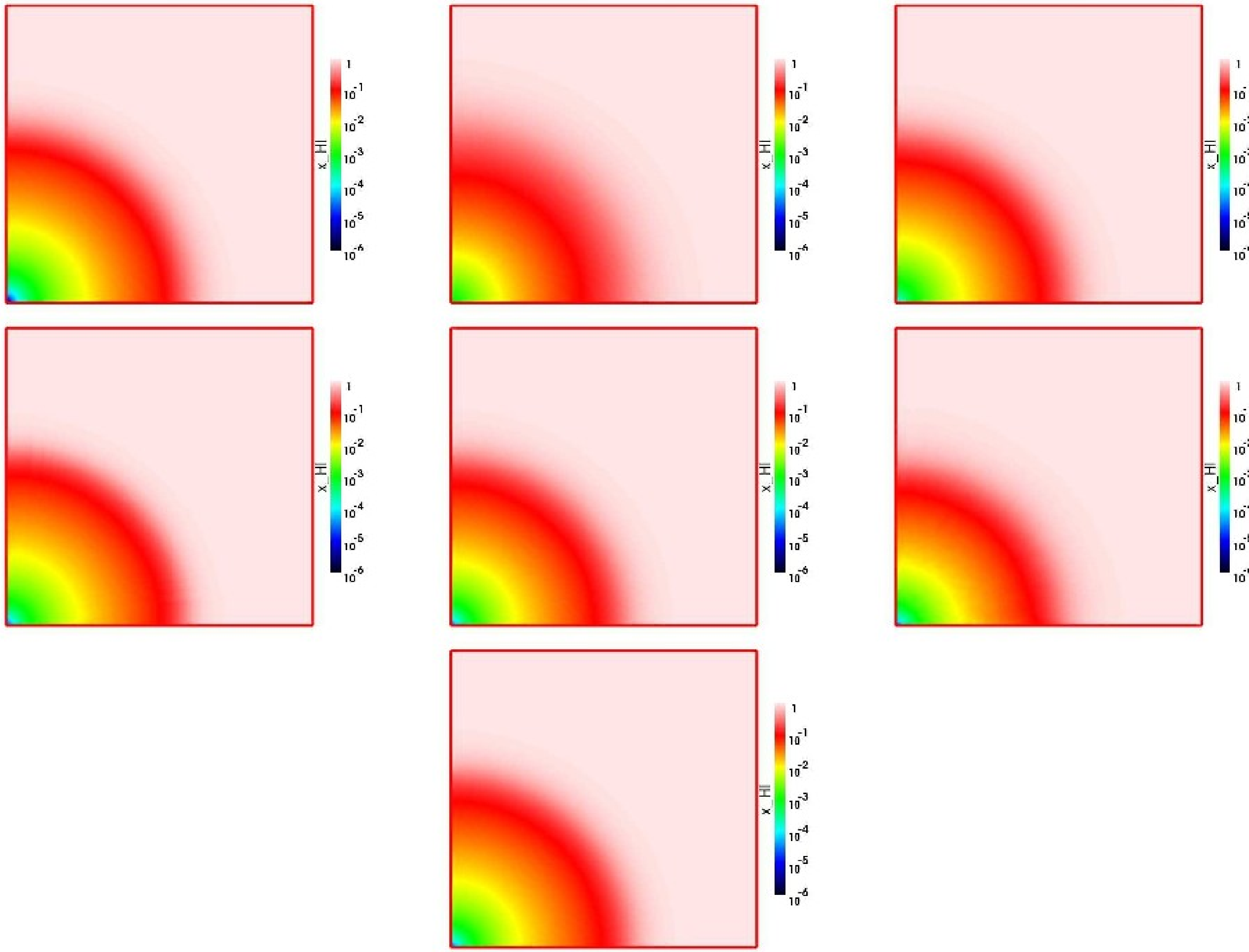


Figure 5. Test 5 (H II region expansion in an initially-uniform gas): Images of the H I fraction, cut through the simulation volume at coordinate $z = 0$ at time $t = 500$ Myr for (left to right and top to bottom) C^2-Ray, HART, RSPH, ZEUS-MP, RH1D, LICORICE, and FLASH.

Test 5: the D-type phase, pressure

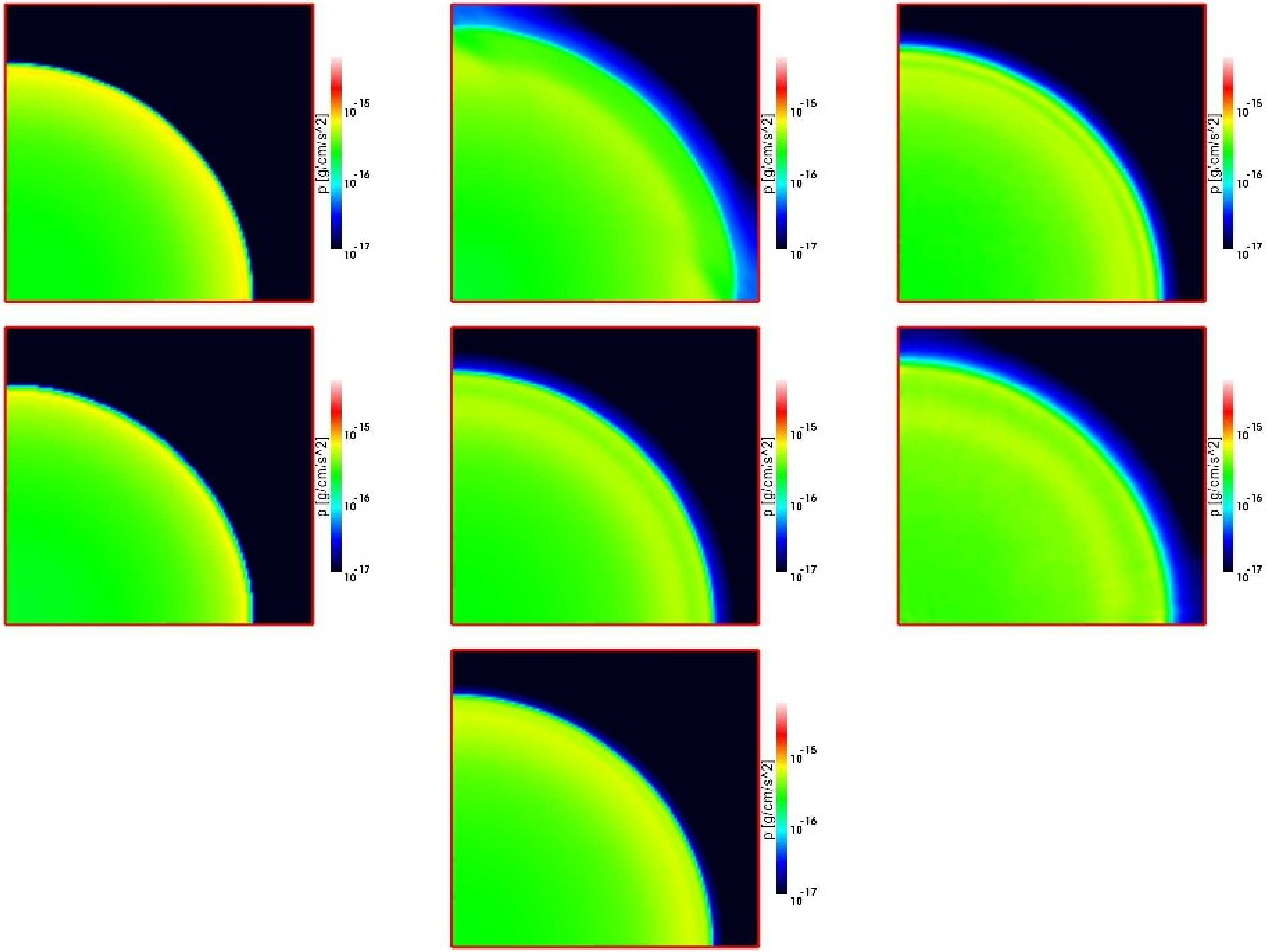


Figure 6. Test 5 (H II region expansion in an initially-uniform gas): Images of the pressure, cut through the simulation volume at coordinate $z = 0$ at time $t = 500$ Myr for (left to right and top to bottom) C^2-Ray, HART, RSPH, ZEUS-MP, RH1D, LICORICE, and FLASH.

Test 5: the D-type phase ion. structure

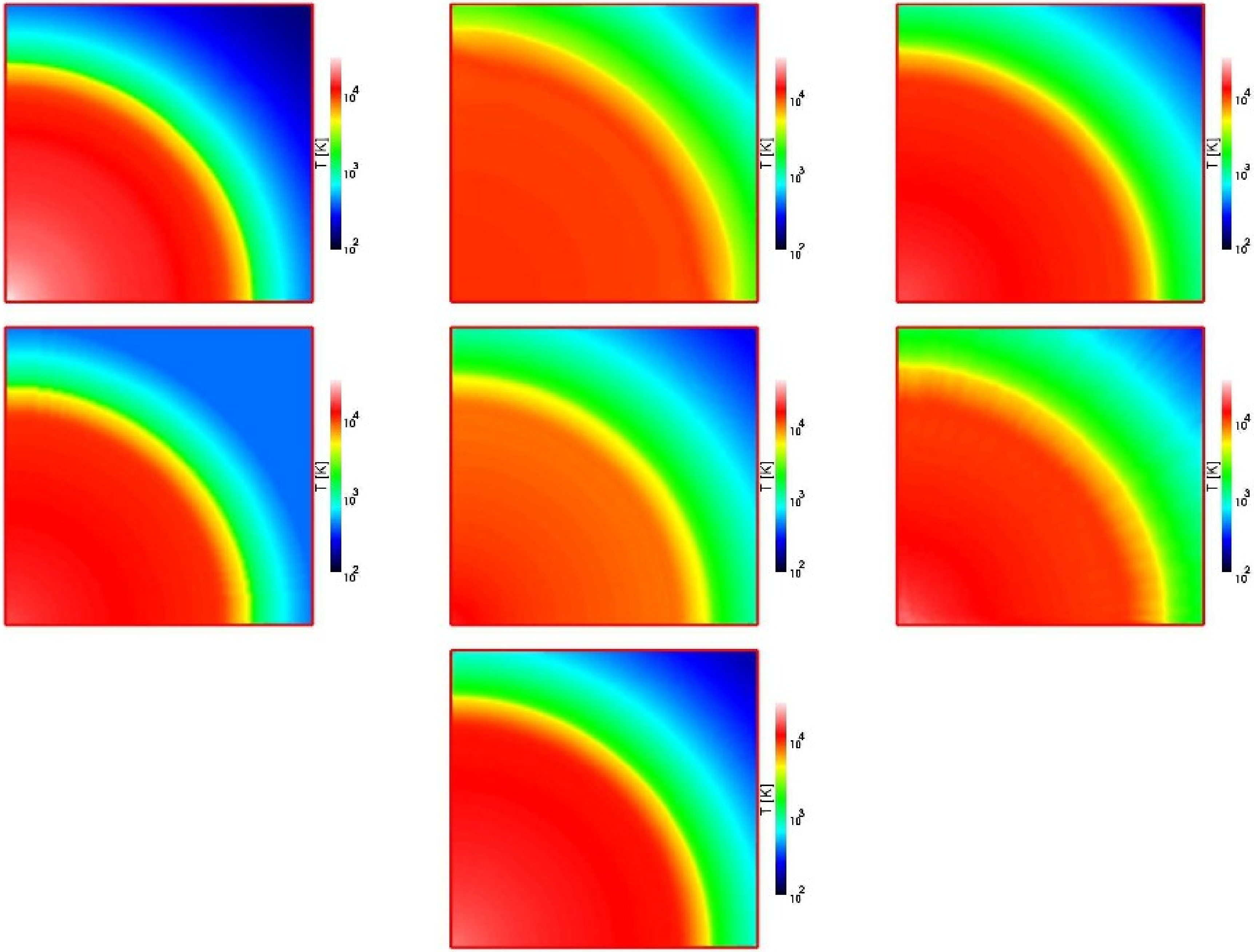


Figure 7. Test 5 (H II region expansion in an initially-uniform gas): Images of the temperature, cut through the simulation volume at coordinate $z = 0$ at time $t = 500$ Myr for (left to right and top to bottom) C^2-Ray, HART, RSPH, ZEUS-MP, RH1D, LICORICE, and FLASH.

Test 5: the D-type phase ion. structure

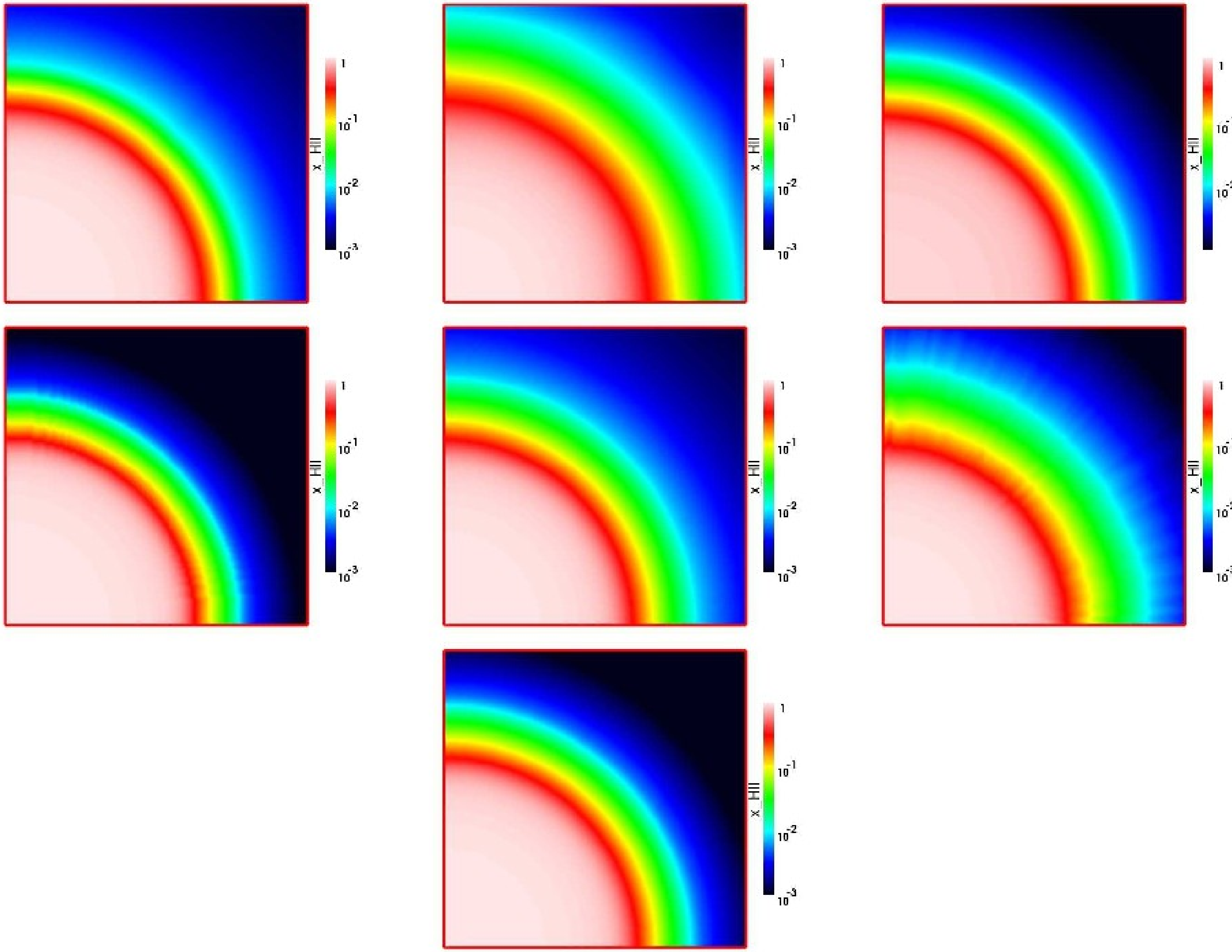


Figure 8. Test 5 (H II region expansion in an initially-uniform gas): Images of the H II fraction, cut through the simulation volume at coordinate $z = 0$ at time $t = 500$ Myr for (left to right and top to bottom) C^2-Ray, HART, RSPH, ZEUS-MP, RH1D, LICORICE, and FLASH.

Test 5: the D-type phase, density

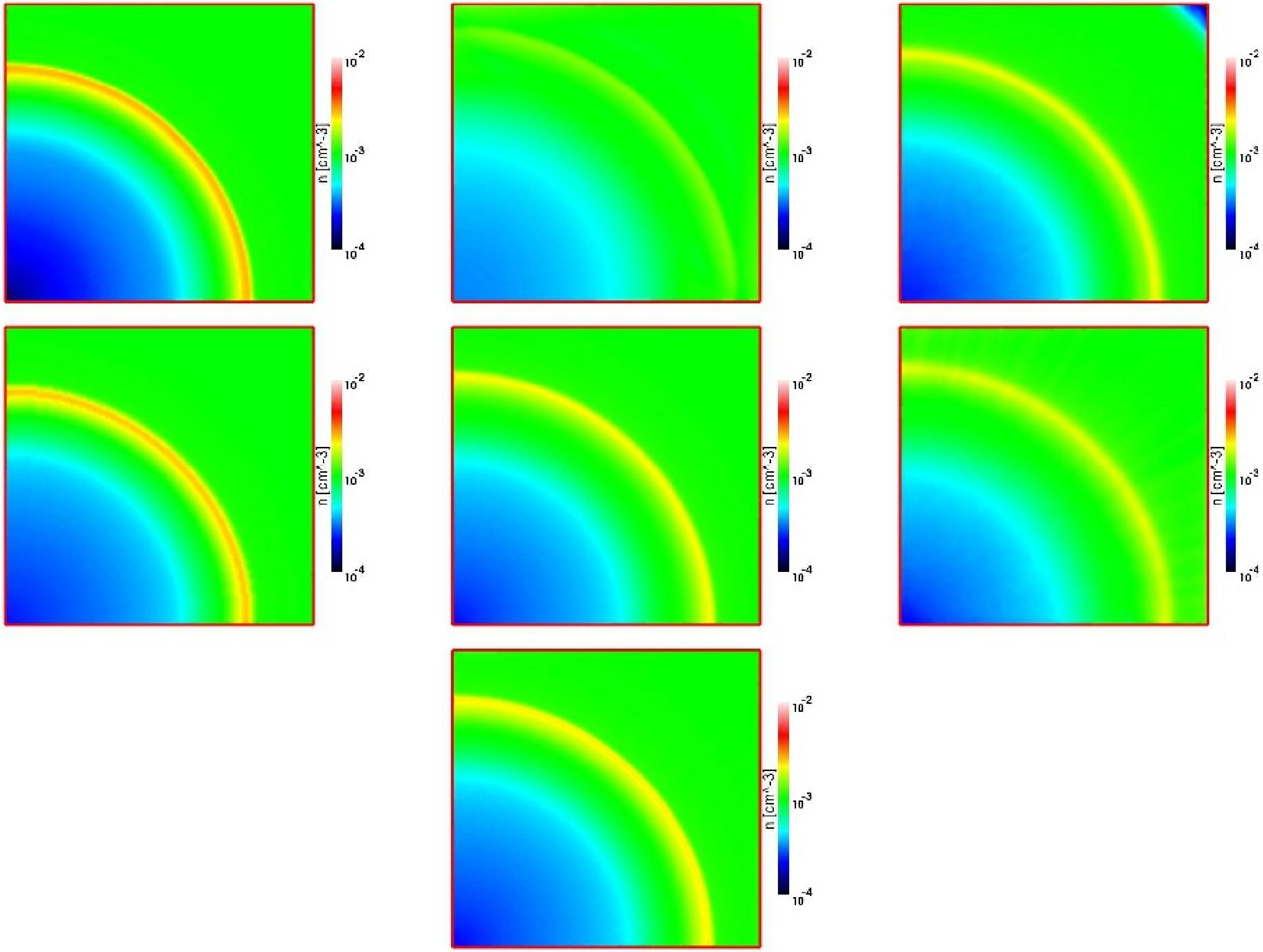


Figure 9. Test 5 (H II region expansion in an initially-uniform gas): Images of the gas number density, cut through the simulation volume at coordinate $z = 0$ at time $t = 500$ Myr for (left to right and top to bottom) C^2-Ray, HART, RSPH, ZEUS-MP, RH1D, LICORICE, and FLASH.

Test 5: the D-type phase, mach

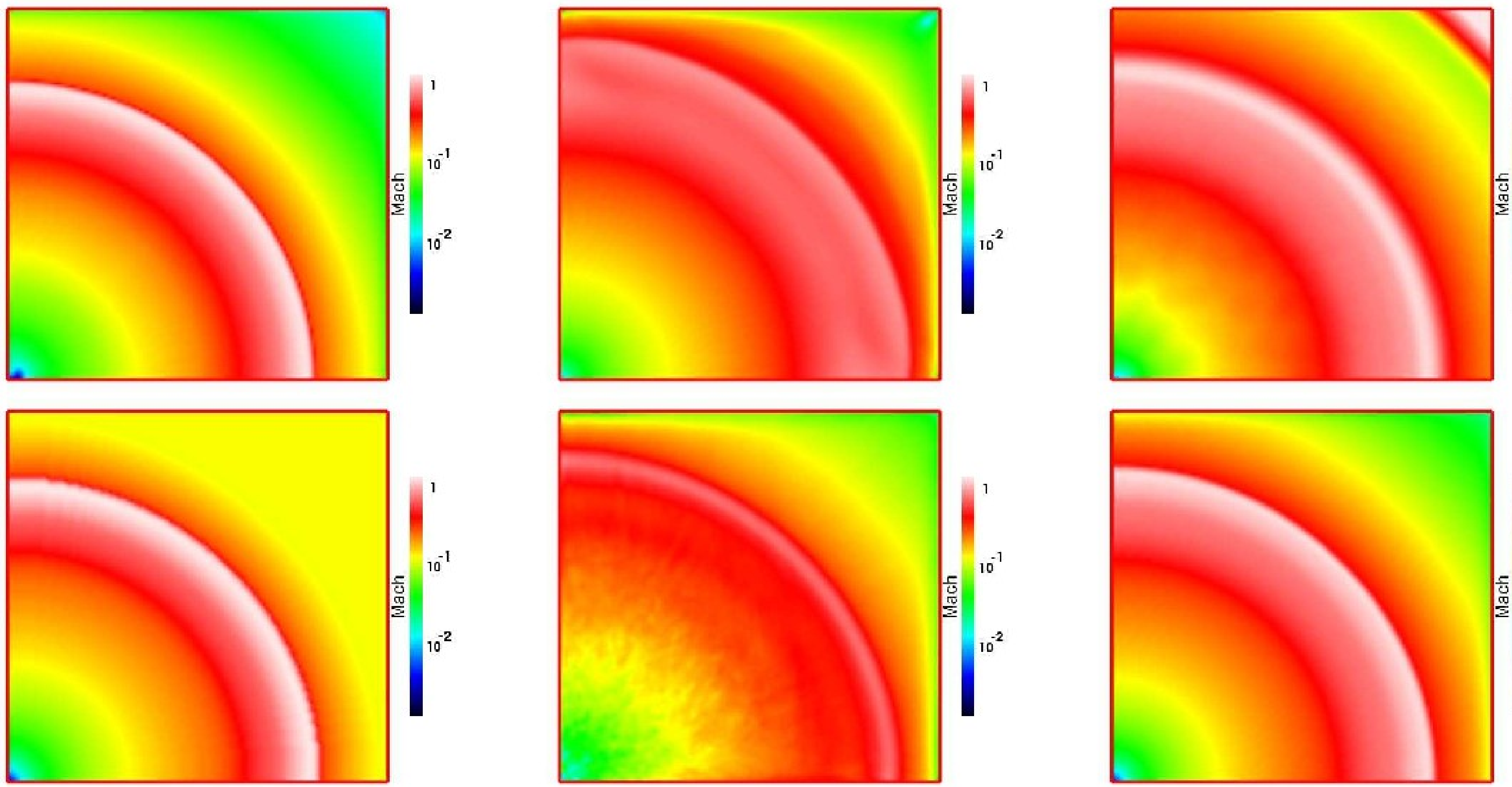
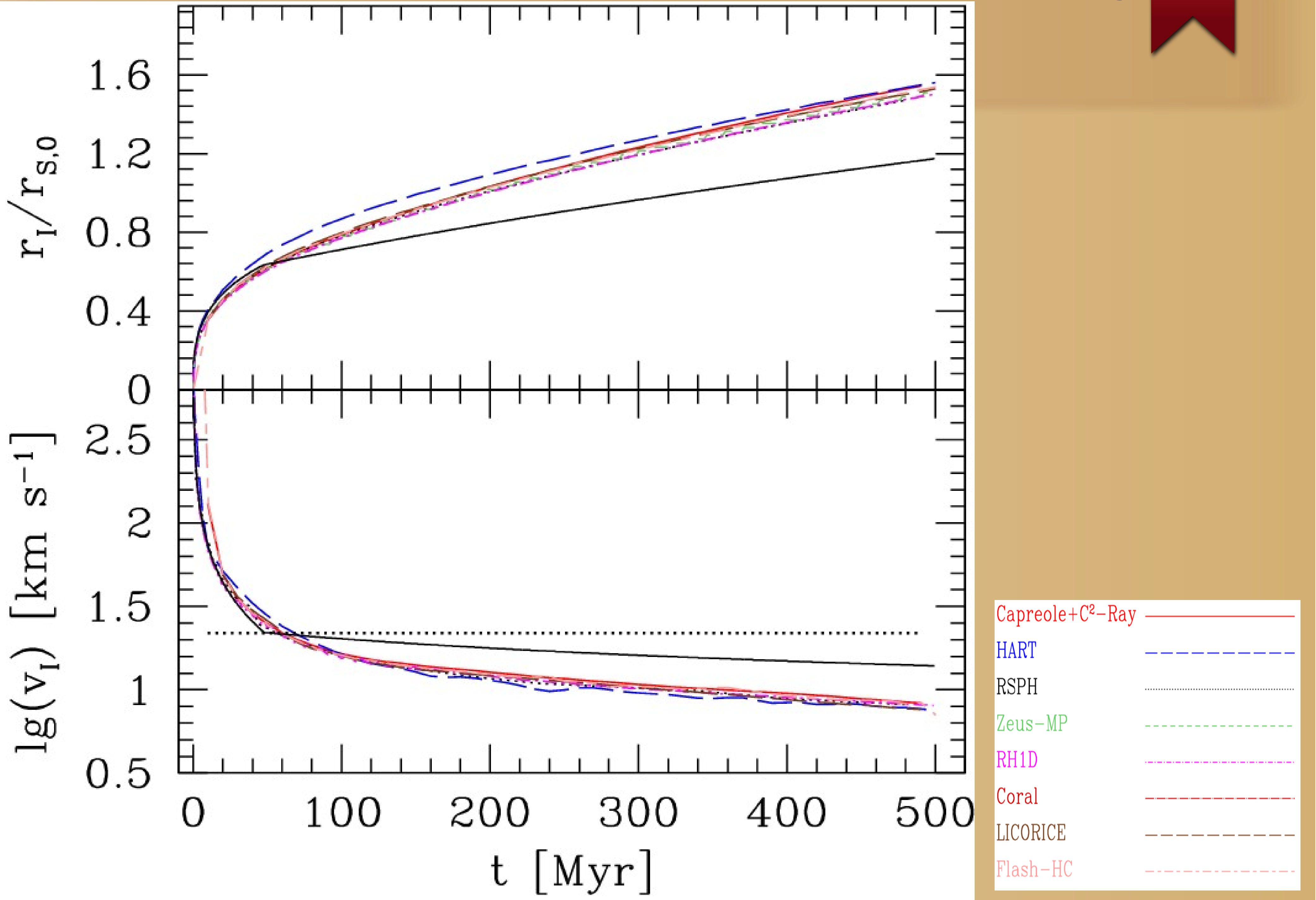


Figure 10. Test 5 (H II region expansion in an initially-uniform gas): Images of the Mach number, cut through the simulation volume at coordinate $z = 0$ at time $t = 500$ Myr for (left to right and top to bottom) C^2-Ray, HART, RSPH, ZEUS-MP, LICORICE, and FLASH.

Test 5: I-front position and velocity



Test 5: ionization & density structure

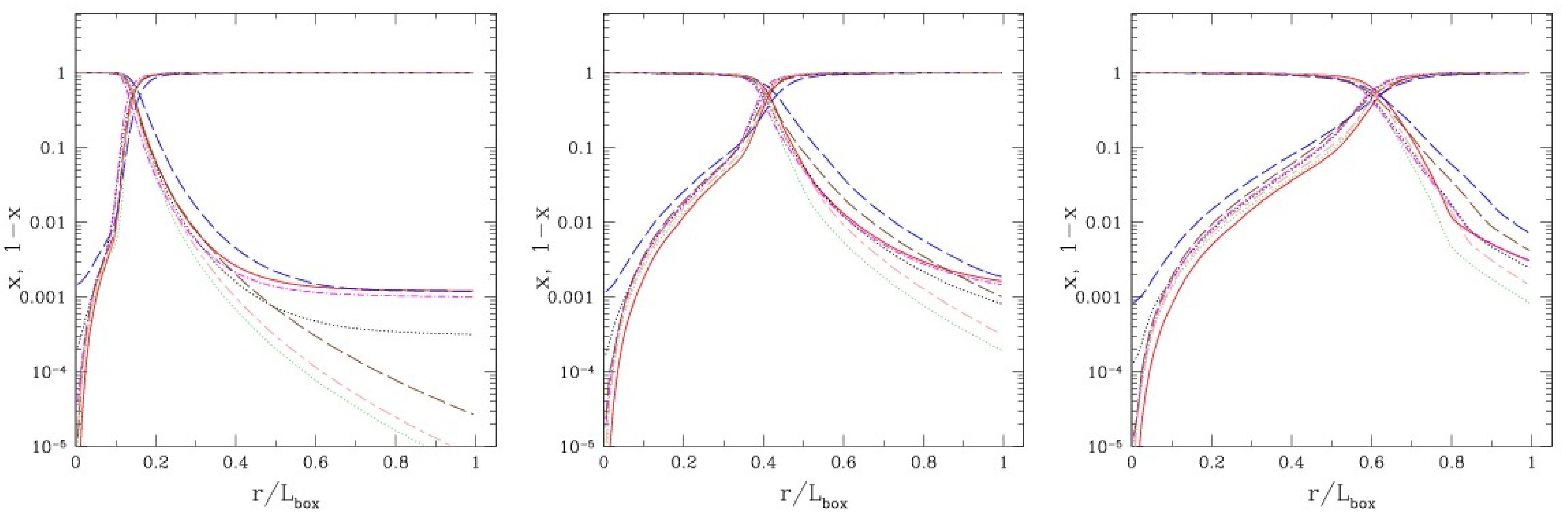
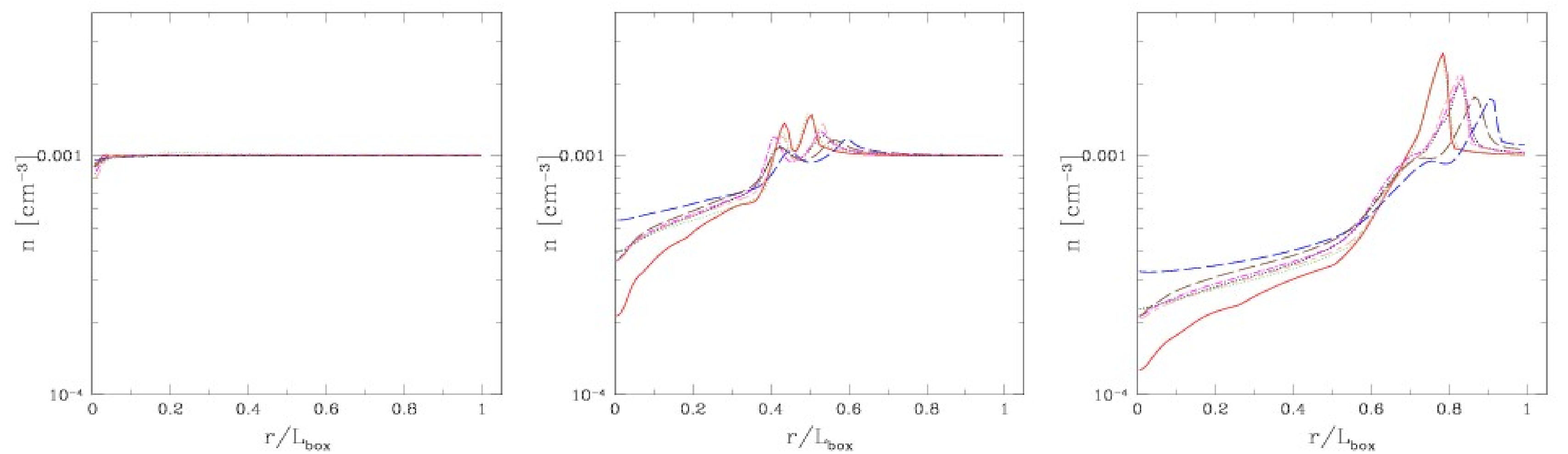


Figure 11. Test 5 (H II region expansion in an initially-uniform gas): Spherically-averaged profiles for ionized fractions x and neutral fractions $x_{xhi} = 1 - x$ at times $t = 10$ Myr, 200 Myr and 500 Myr vs. dimensionless radius (in units of the box size).



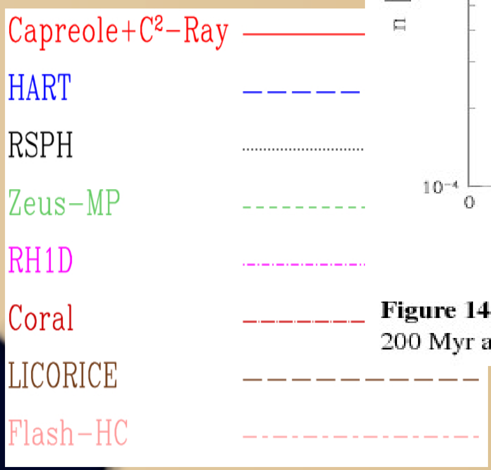


Figure 14. Test 5 (H II region expansion in an initially-uniform gas): Spherically-averaged profiles for the hydrogen number density, n, at times $t = 10$ Myr, 200 Myr and 500 Myr vs. dimensionless radius (in units of the box size).

Test 5: pressure & temp. structure

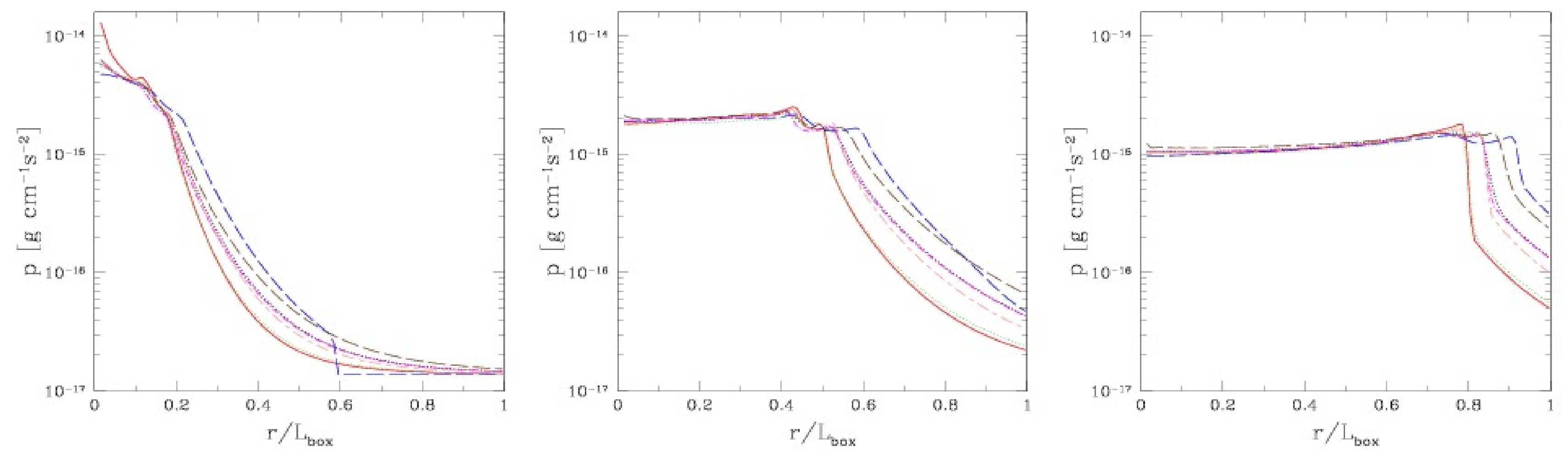


Figure 12. Test 5 (H II region expansion in an initially-uniform gas): Spherically-averaged profiles for pressure, p, at times t = 10 Myr, 200 Myr and 500 Myr vs. dimensionless radius (in units of the box size).

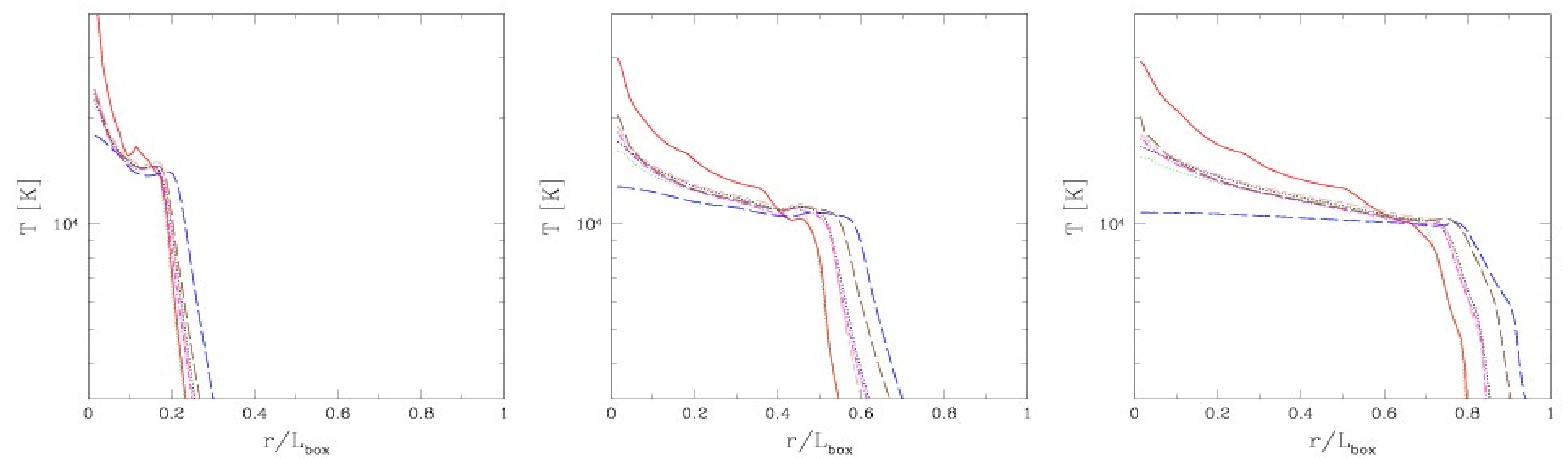
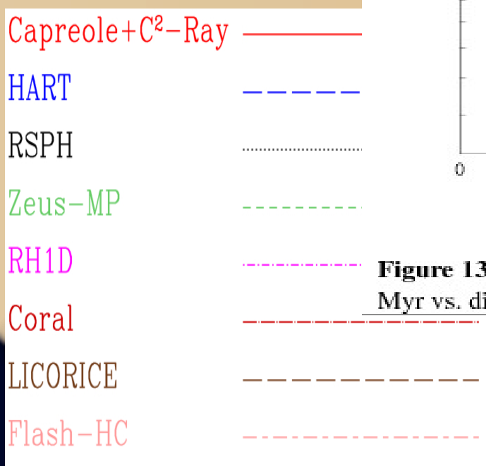


Figure 13. Test 5 (H II region expansion in an initially-uniform gas): Spherically-averaged profiles for temperature at times t = 10 Myr, 200 Myr and 500 Myr vs. dimensionless radius (in units of the box size).



Summary

- *Chemical reaction and cooling rates are still uncertain – can give up to 10-30% difference in outcome. Equilibrium chemistry is generally not a good approximation.*
- *All methods track I-fronts fairly well, yield reliable results. Some methods could introduce unphysical anisotropies, however.*
- *The largest discrepancies are due to imprecise treatments of the energy equation and the multi-frequency photons (hardening) – the best approach is very problem-dependent.*
- *Radiative-hydrodynamics direct coupling – inherently more complex. Results are relatively consistent for different methods, but there are also some significant variations.*
- *It is important to evaluate the limitations of each code, some methods could underperform or even fail in certain situations (e.g. R-type fronts, R- to D-type transition; instabilities).*
- *Spectral hardening and pre-heating are very important for the correct dynamics .*

Next steps: current tests

- *Where do we go from here?*
- *If you have a new code that is not at the wiki site please do the tests and submit the results.*
- *This is an important validation step and all future code developers will be grateful.*

Next steps: new projects

- *Cosmological post-processing simulations.*
- *Cosmological radiative-hydro simulations.*
- *X-rays and Helium treatment.*
- *Soft radiation: Lyman-Werner, Lyman-*α*?*
- *Other ideas?*