Phantom Workshop 2023

Star formation / Software development

Going up the tree –

Introducing new algorithm to optimize the Radiation Hydrodynamics (RHD) scheme for simulating Stellar Photoionization Feedback

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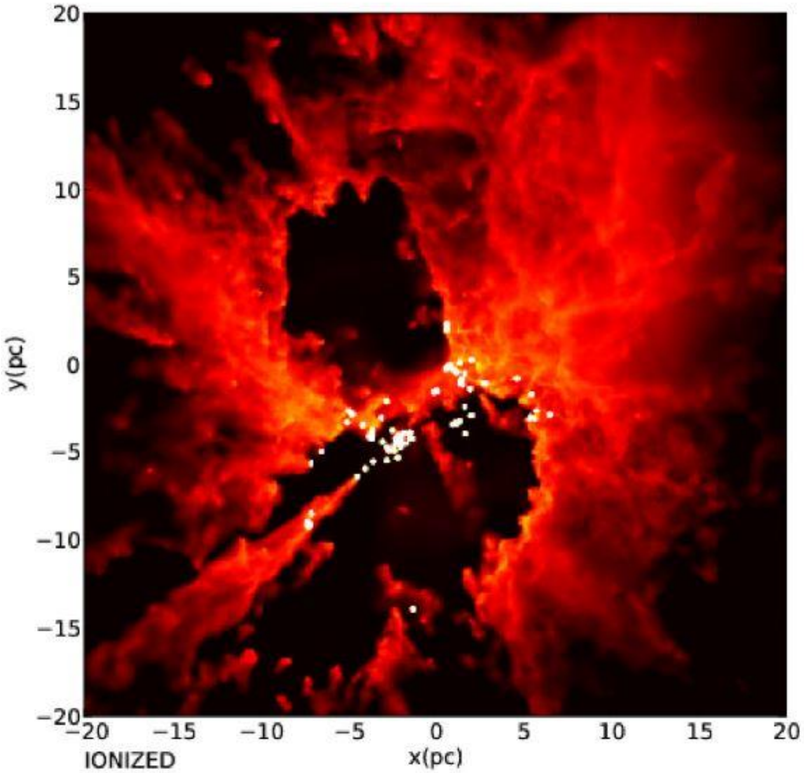
UKRI Science and Technology Facilities Council

Ionizing radiation feedback



Dale et al. 2014

Massive stars emit radiation which ionizes the surrounding and creates HII regions.

Expansion of HII regions can sweep gas and trigger star formation,

or hinder the process by destroying their natal cloud.

Monte Carlo Radiative Transfer (MCRT) simulation

Operates on **grids**

Simulates radiation by repetitively shooting photon packets on the grid until the cells' ionic fractions converge.

Good at modelling scattering and re-emission

Easier to include extra physics / chemistry

CMacIonize
(Vandenbroucke & Wood 2018)

The RHD scheme

Petkova et al. 2021

timestep i

Particles xyzhm

Map particle densities onto Voronoi grids

MCRT simulation

Map ionic fractions of grid cells back onto particles

Heat particles (update u)

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CMacIonize

Particle ⟺ **Grid cell**

The RHD scheme

Petkova et al. 2021

timestep i

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Exact density-mapping method

CMacIonize

Particle ⟷ **Grid cell**

The RHD scheme

Petkova et al. 2021

The Exact density-mapping method:

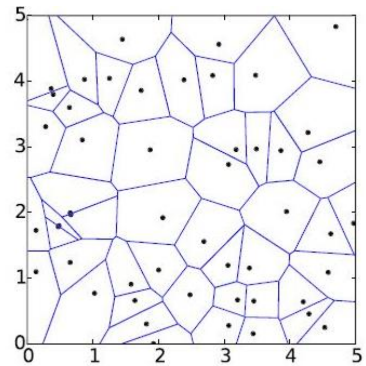
At an arbitrary point, $\rho(\boldsymbol{r}) = \sum_{a=1}^{N} m_a W(|\boldsymbol{r} - \boldsymbol{r}_a|, h_a)$

Integrate $\rho(\boldsymbol{r})$ over volume of a Voronoi cell,

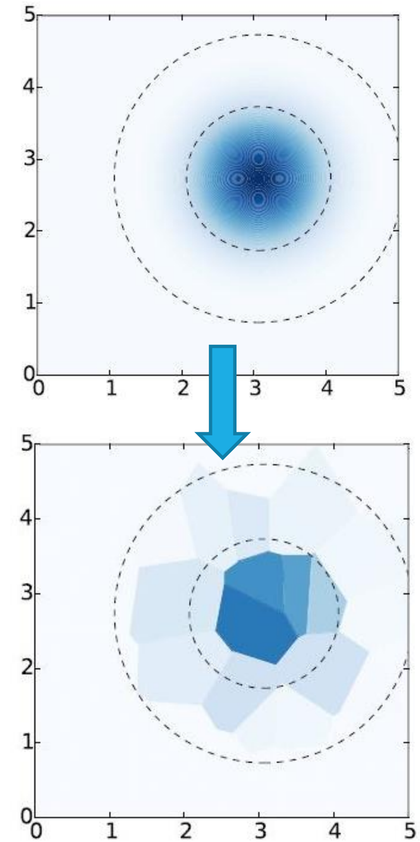
$$\langle \rho_{cell} \rangle = \frac{1}{V_{cell}} \int_{V_{cell}} \rho(\boldsymbol{r}')\, \mathrm{d}V'$$

[requires xyzhm of particles]

Perfect but computationally expensive



Voronoi grid

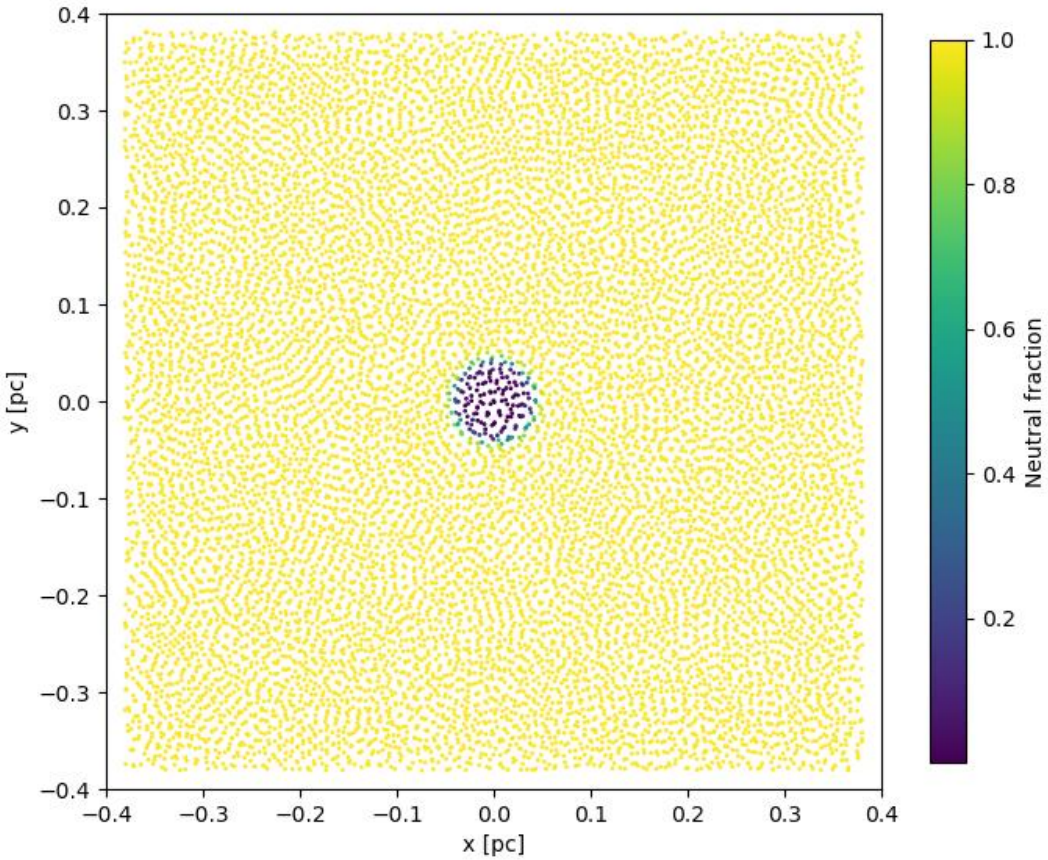


Petkova et al. 2018

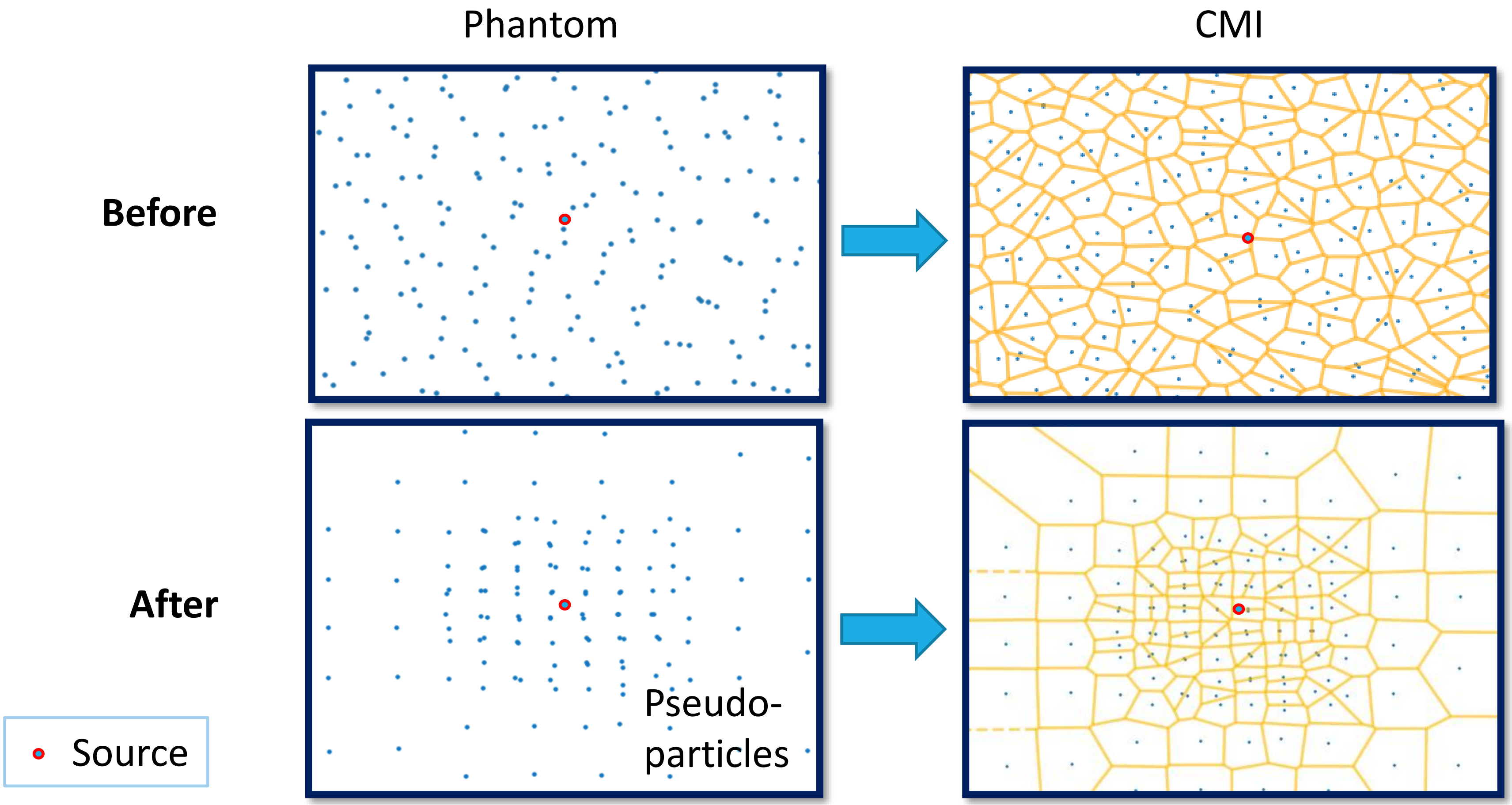
The RHD scheme

Uniform box

Ionizing source at (0,0)

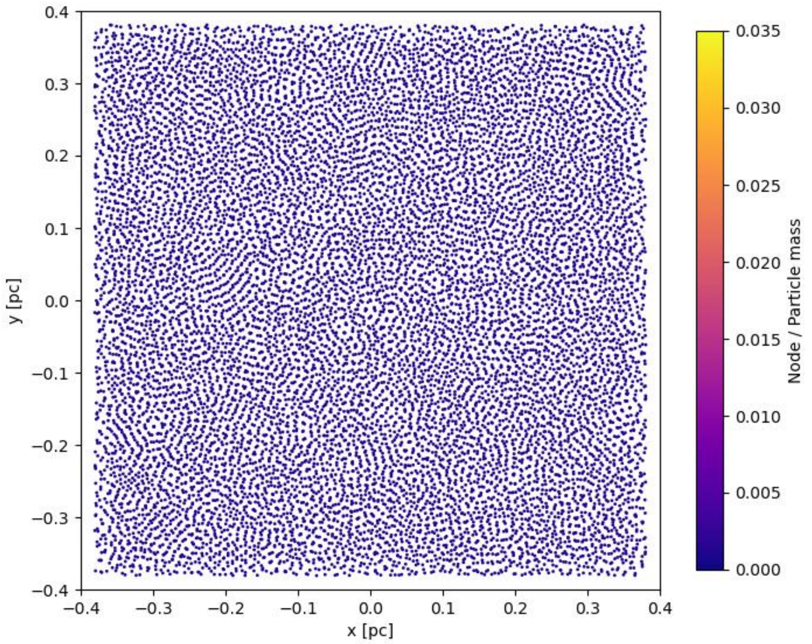


Moving it up the tree

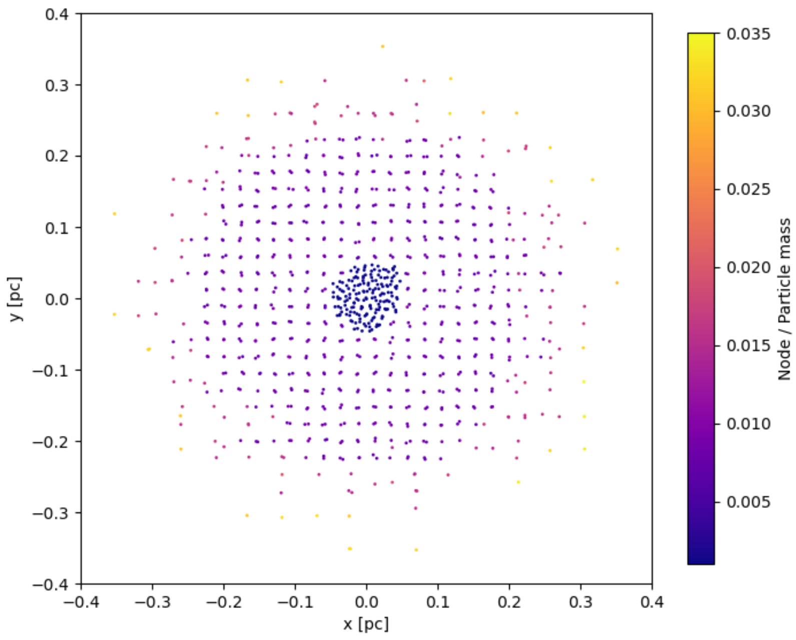


Moving it up the tree

Mass of particles

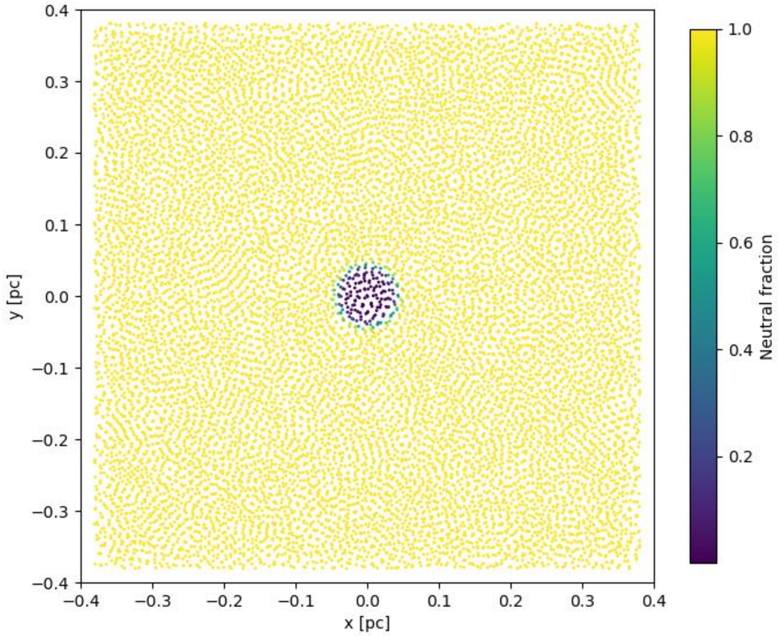


Mass of particles & nodes

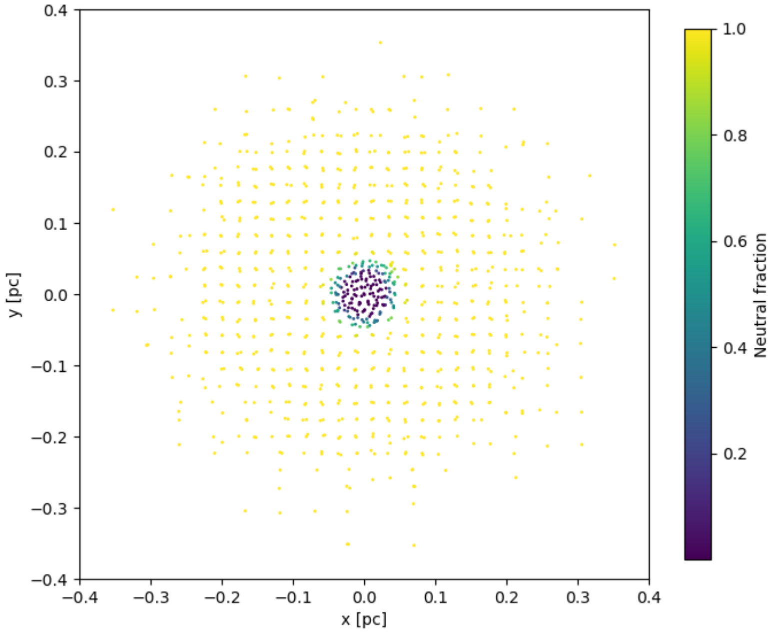


Moving it up the tree

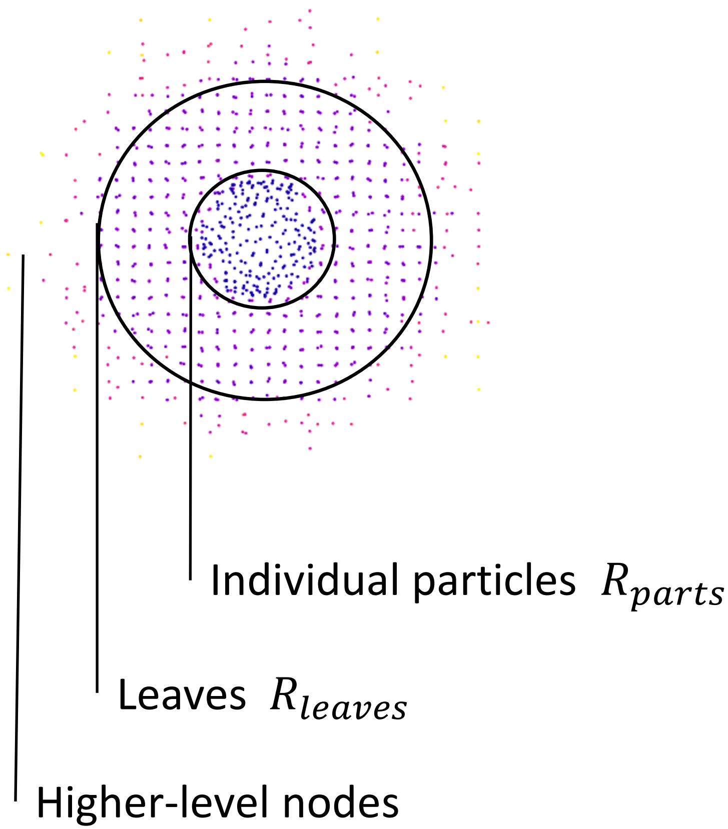
Neutral fraction of particles



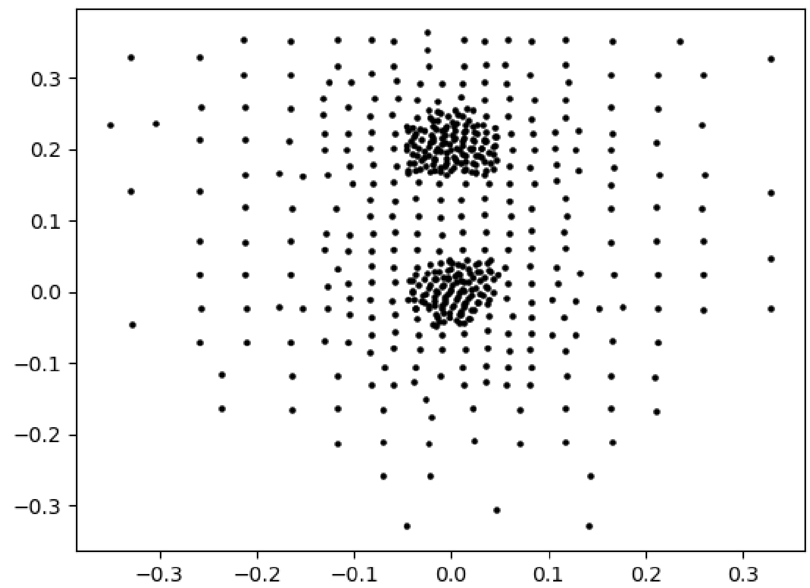
Neutral fraction of particles & nodes



Moving it up the tree

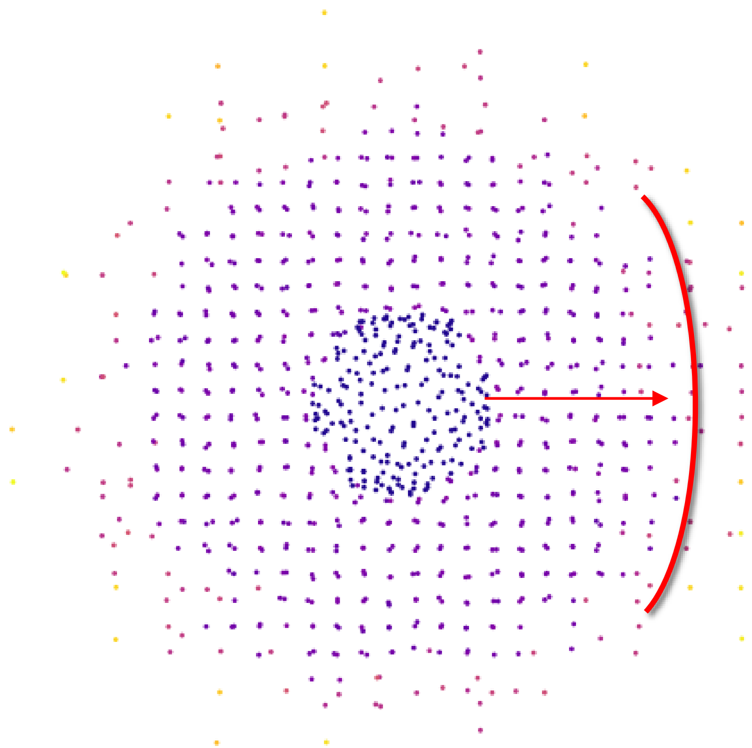


Multiple ionizing sources:



Moving it up the tree

What if the ionization front went to lower resolution regions?



Adaptive tree-walk

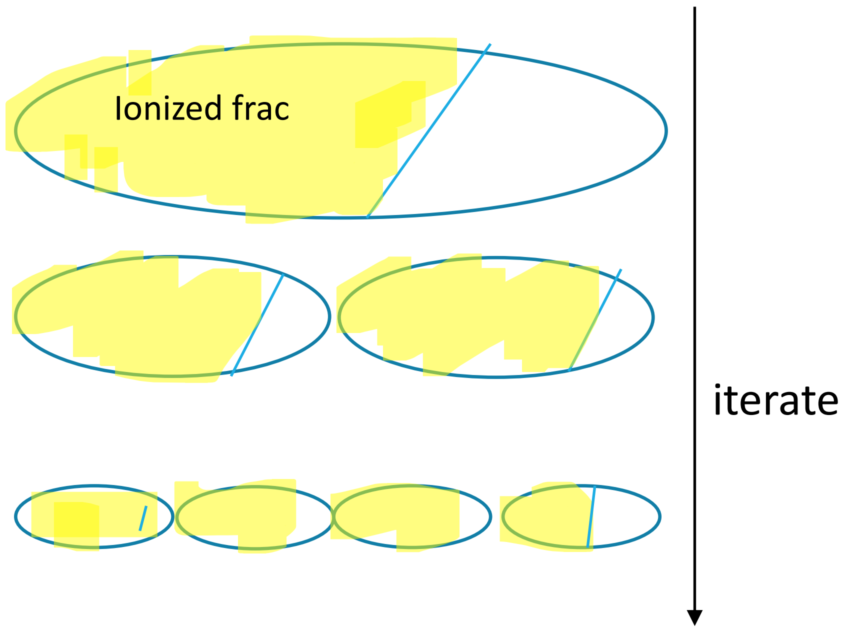
Using the ionic fractions returned from CMI to adjust tree-walk:

If a big node is ionized, open node.

Call CMI to try again.

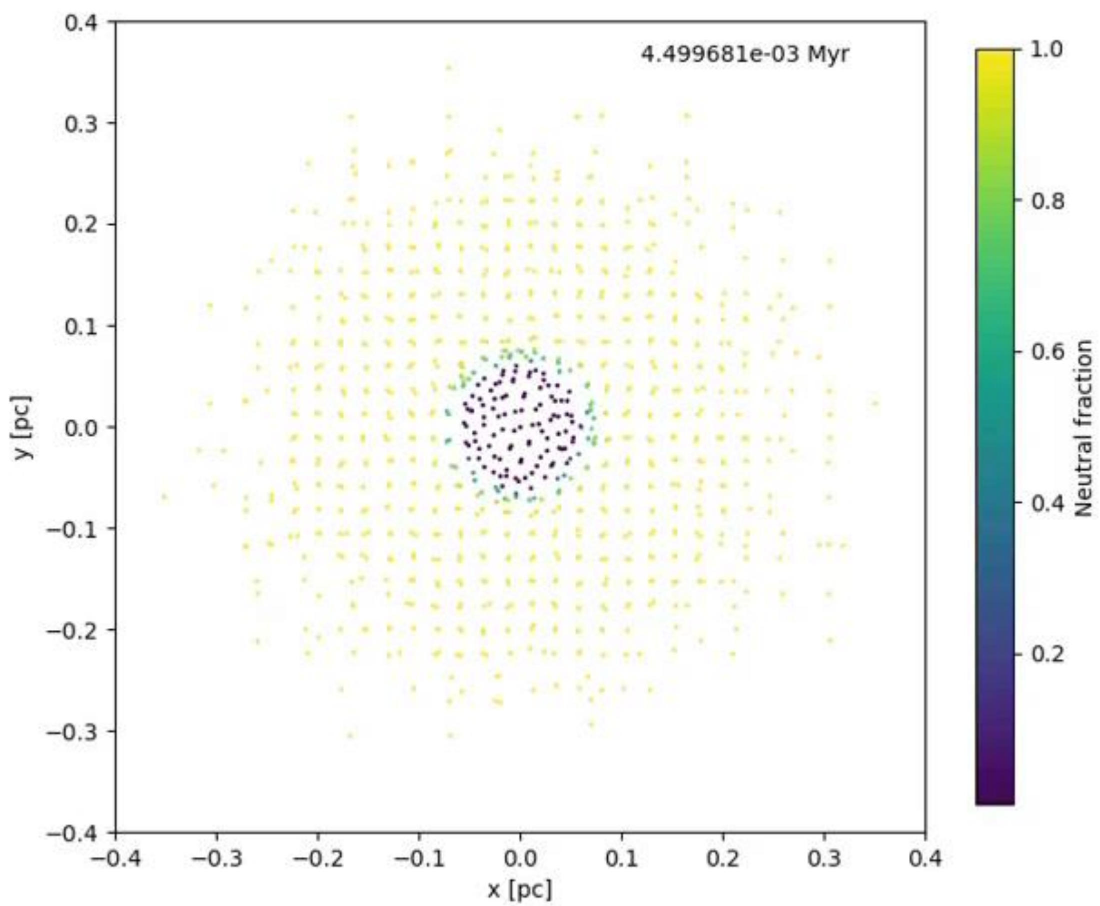
Repeat until the ionized nodes are all sufficiently small*.

If leaves are still not okay, increase R_{parts}
- back onto particle level

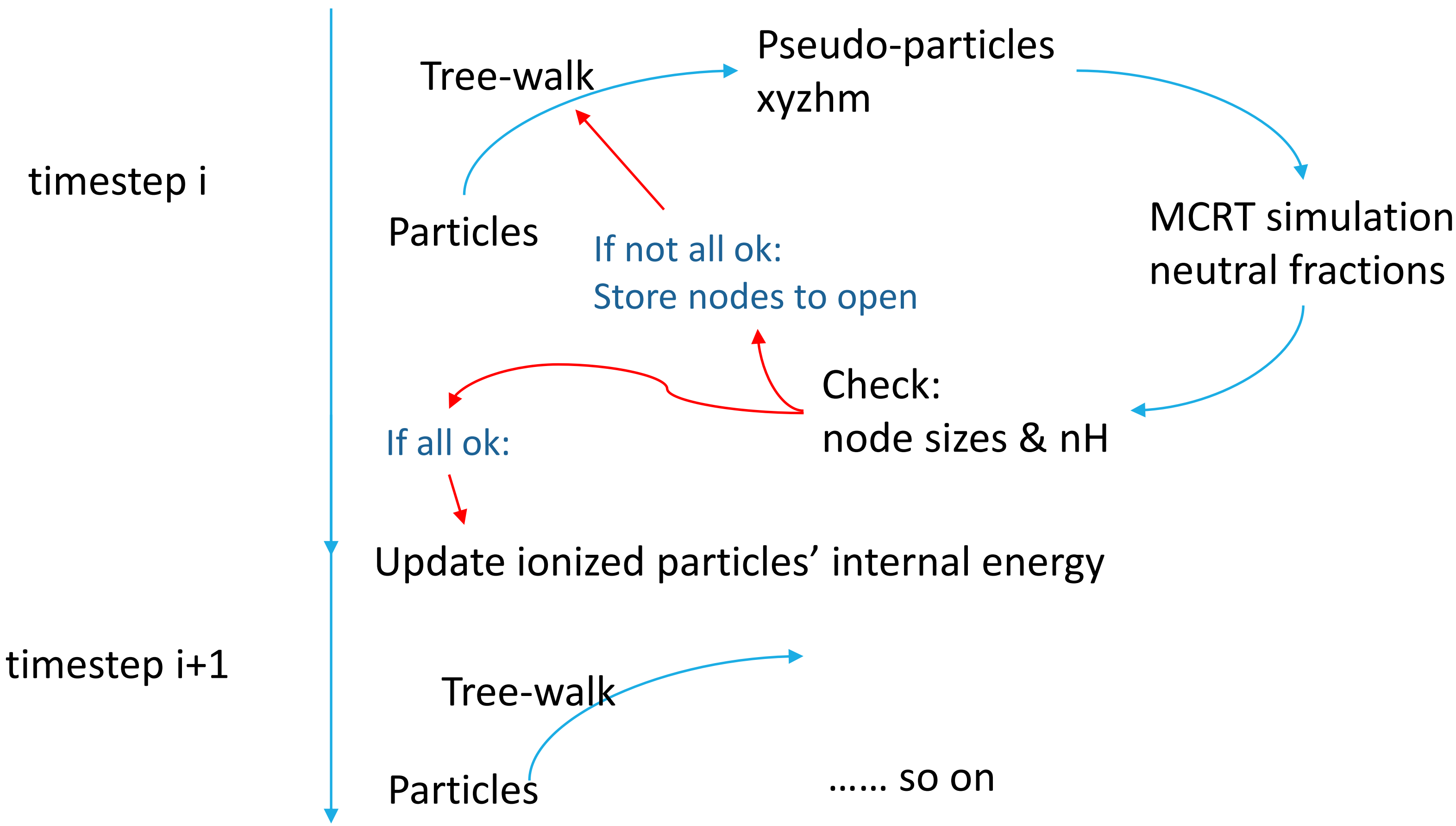


* Parametrized in the code - adjustable by the user

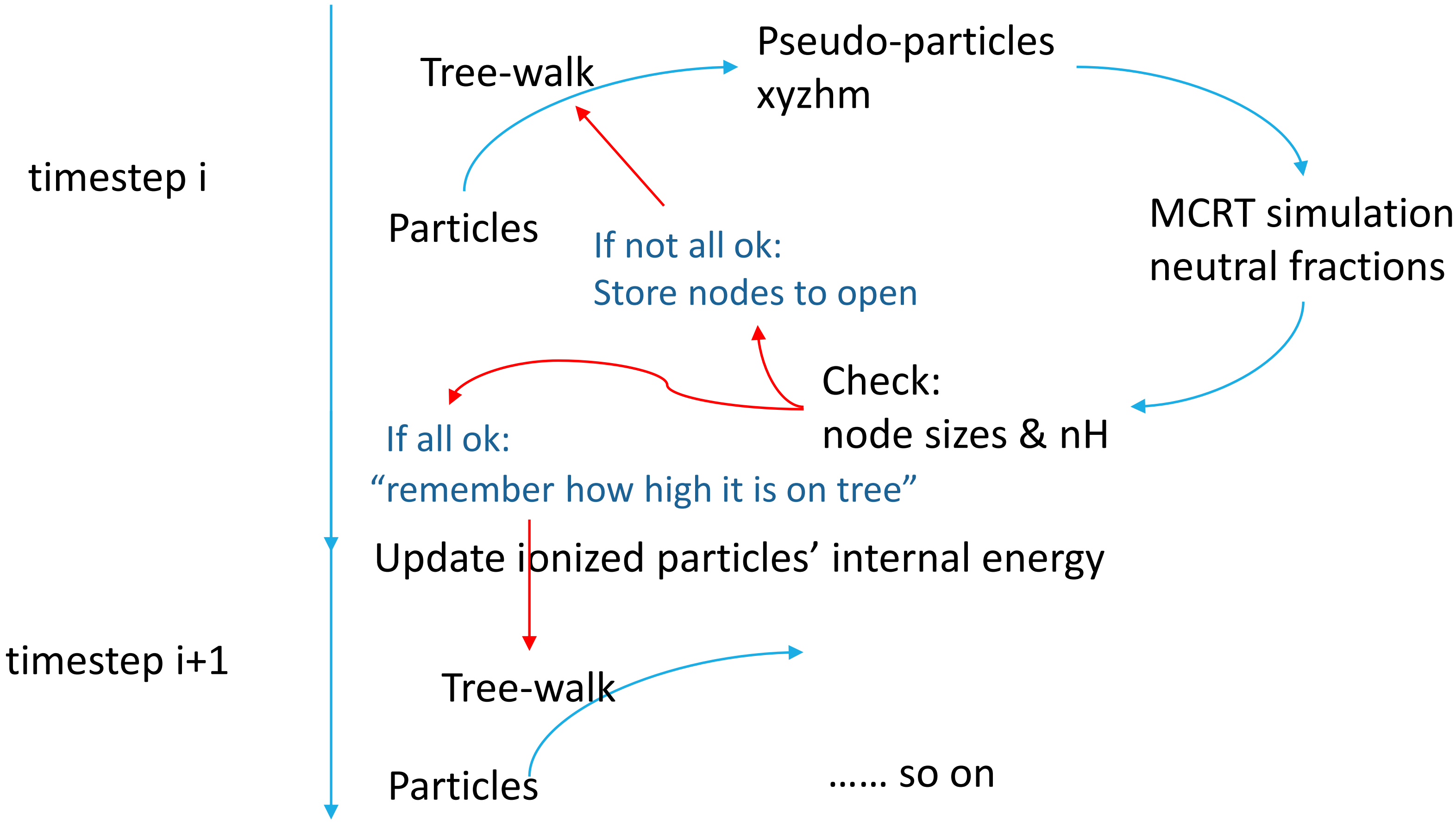
Adaptive tree-walk



Adaptive tree-walk



Adaptive tree-walk



Smoothing length of nodes

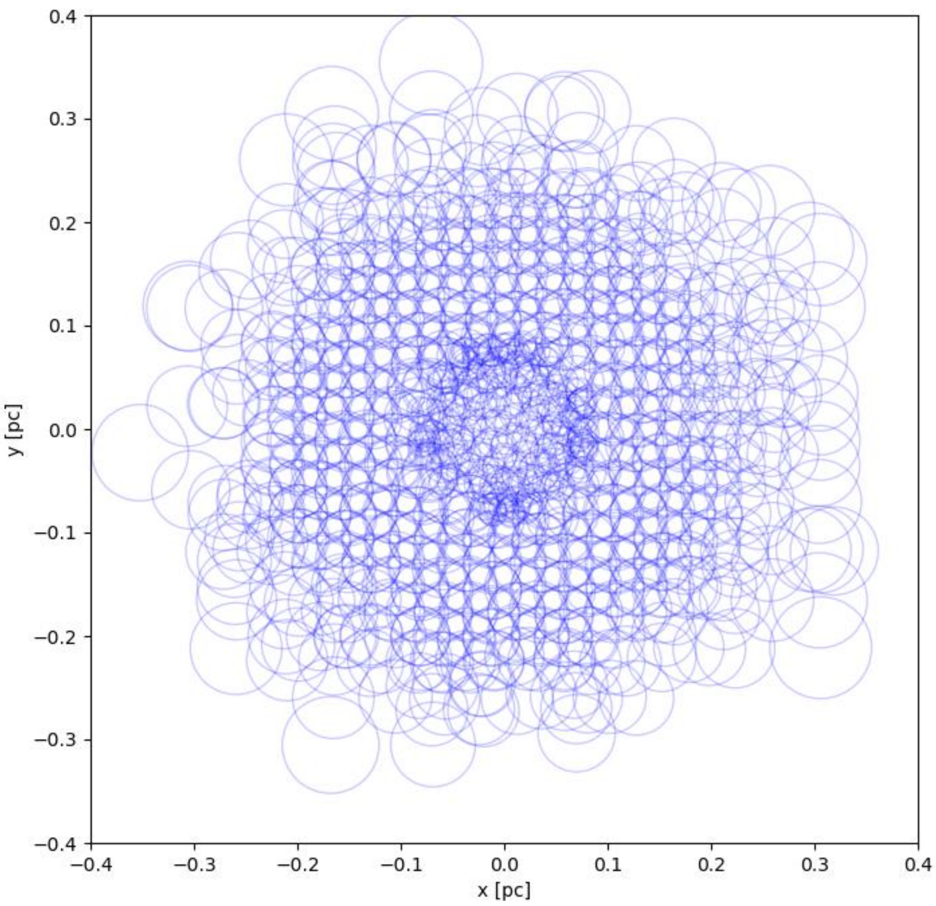
$h_a \neq h_{fact} \left(\frac{m_a}{\rho_a}\right)^{\frac{1}{3}}$ if masses are unequal.

Using $h_a = h_{fact} n_a^{-\frac{1}{3}}$ where number density $n_a = \sum_{b=1}^{N} W(|\boldsymbol{r}_a - \boldsymbol{r}_b|, h_a)$

[no longer dependent on density ρ]

Apply Newton-Raphson (with Bisection as backup) to solve for the nodes' smoothing lengths.

Smoothing length of nodes



With $h_{fact,node} = 1.1$,
avg. neigh: 55

Smoothing length of nodes

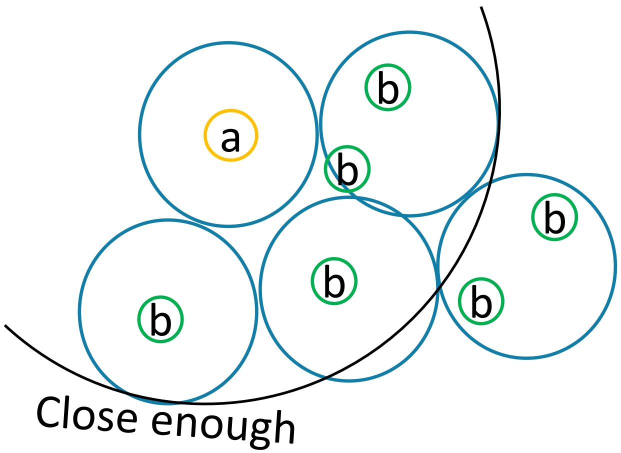
Simple neighbour-find:

[requires node indices]

1. Select a level somewhere midway on tree – level k_{mid}

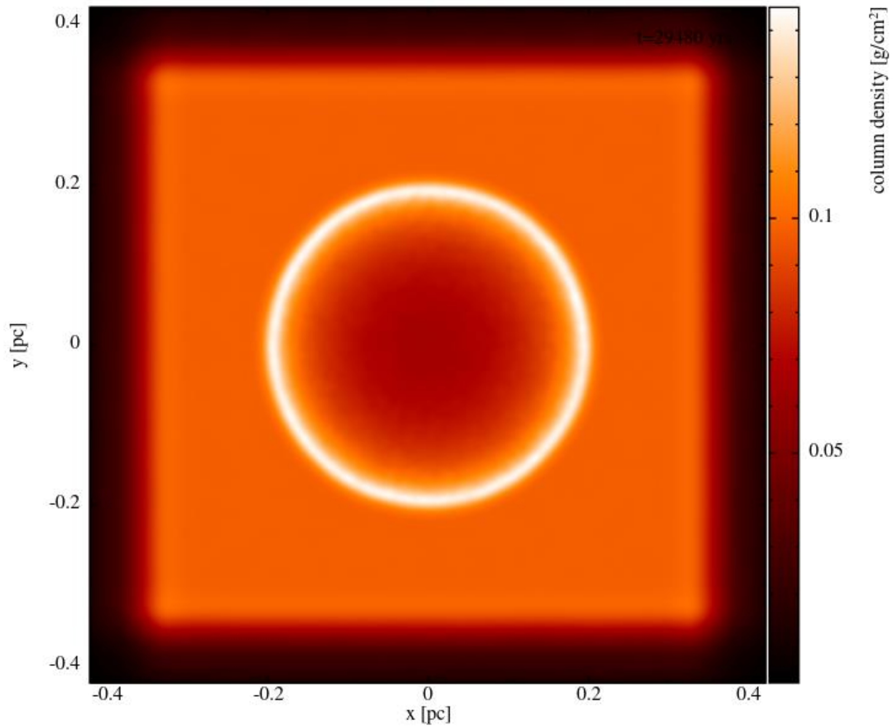
2. Find *a*'s ancestor on k_{mid}, evaluate its distance to other nodes on k_{mid}

3. Loop through list of pseudo-particles (nodes) *b*; if its ancestor on k_{mid} is sufficiently close to that of *a*, add *b* to trial-neighbour list



Normally brute-force method is sufficient if total number of nodes is not very large.

Initial results



Starbench tests (Bisbas et al. 2015)

D-type expansion of HII region

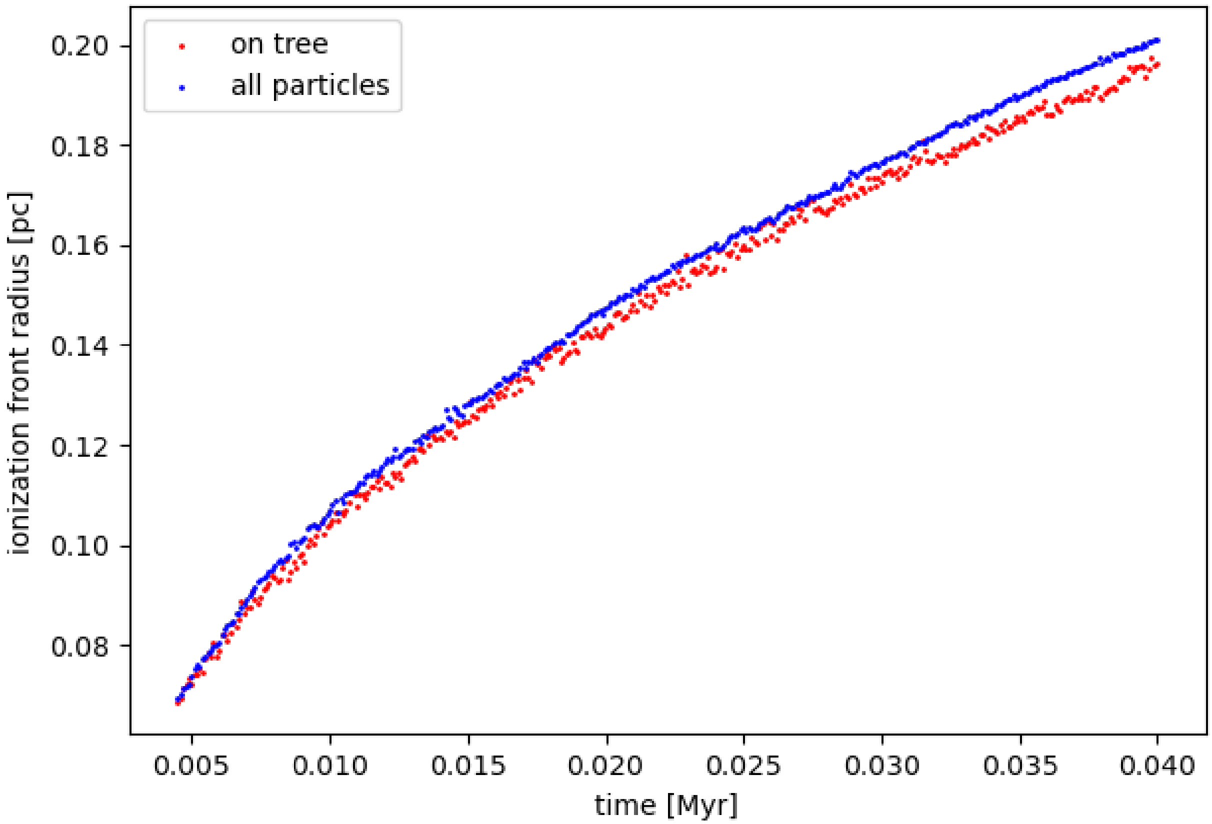
- Glass of 64^3 (=262144) particles
- Uniform box with no gravity

- $T_0 = 100$ K
- $T_i = 10^4$ K [when nH < 0.5]

- $\rho_0 = 5.21 \times 10^{-21}$ g cm^{-3}
- Particle mass 10^{-3} M$_\odot$
- Source $\dot{Q} = 1.4 \times 10^{48}$ s^{-1}

Initial results

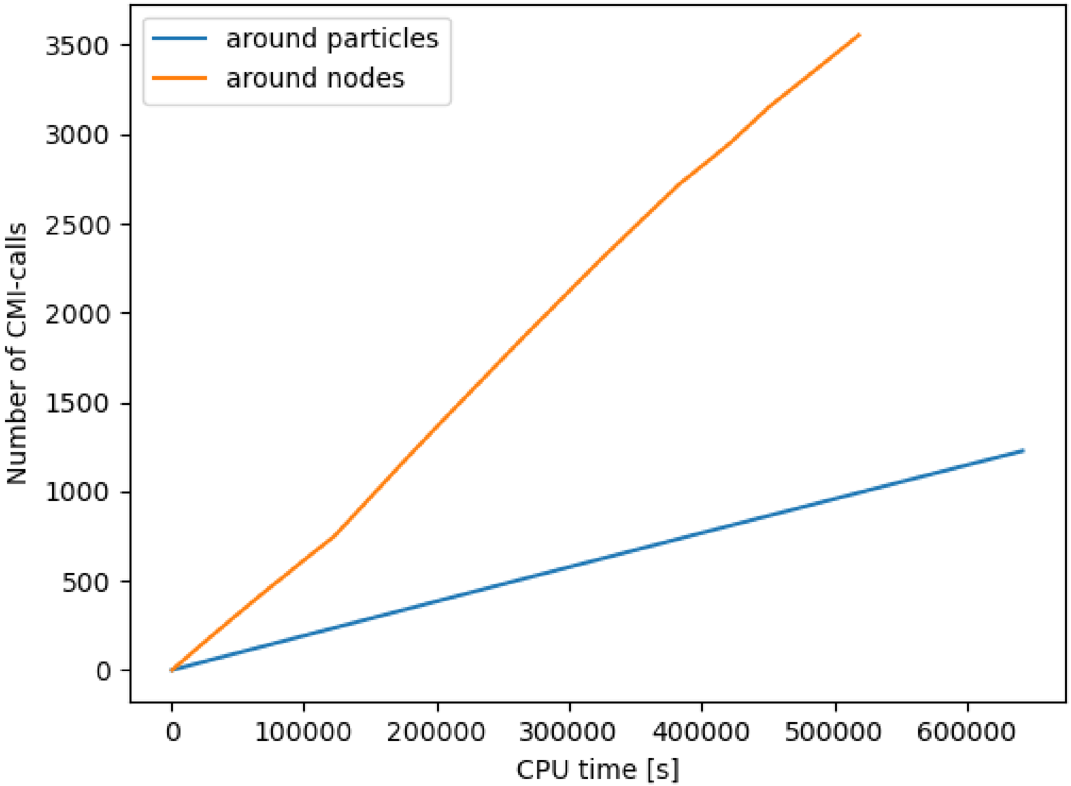
Evolution of Ionization front



2.6×10^5 particles → $\sim 10^4$ pseudo-particles

Initial results

Runtime comparison on a 6-core machine



Speed up by ~3-4 times

Dependent on:

Tree-opening angle

R_{parts} and R_{leaves}

Resolution of ionization front

Conclusion

- Optimization can be achieved by passing tree nodes as pseudo-particles to the MCRT code
- Adaptive tree-walks allow regions of interest (i.e. ionization fronts) to remain highly-resolved
- Computation time reduces by factor of 4 without detriment to the accuracy of simulation outputs

References

Bisbas T. G., et al., 2015, MNRAS, 453, 1324-1343

Dale, J. E., et al., 2014, MNRAS, 442, 694-712

Petkova, M. A., et al., 2018, J. Comp. Phys., 353, 300-315

Petkova, M. A., et al., 2021, MNRAS, 507, 858-878

Vandenbroucke, B., Wood, K., 2018, Astron. Comput., 23, 40-59

Acknowledgements

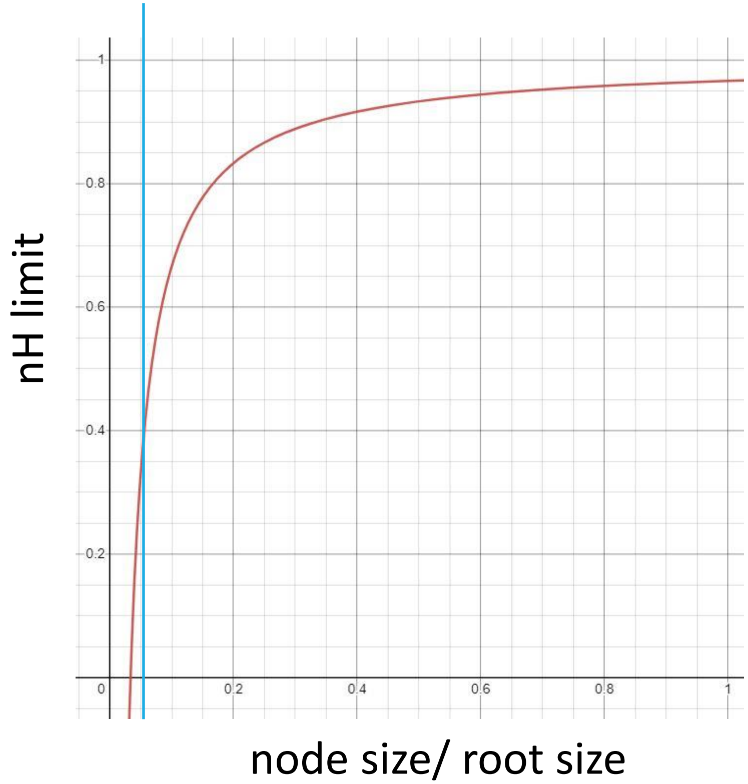
James Wurster for code advices

Maya Petkova for fixing issues in CMacIonize and algorithm advices

Bert Vandenbroucke for helping to couple the codes

Appendix

Defining the criterion to open node using nH:



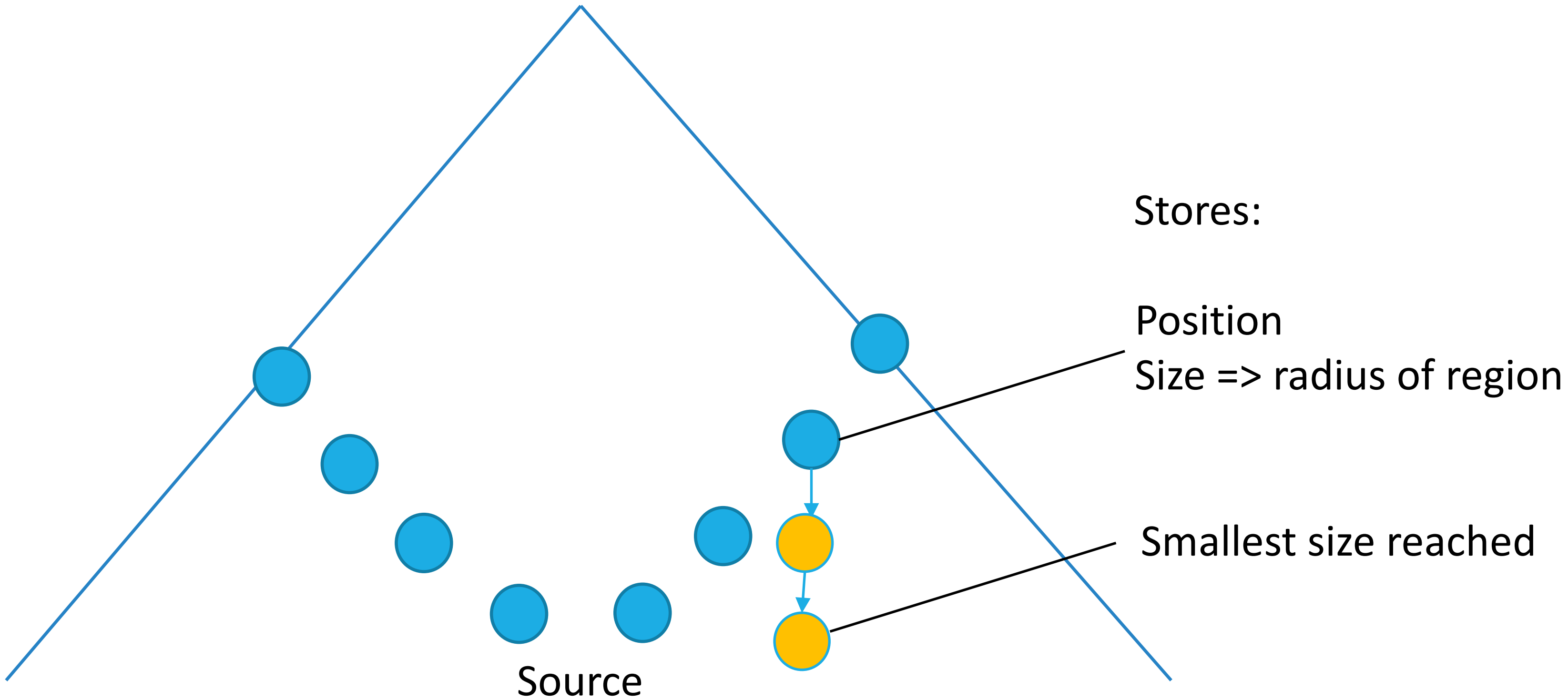
$$nH\ limit = \frac{1}{A}\left(-\frac{1}{size\ frac} + A\right)$$

where A is a parameter controlling the curvature of this function.

If nH < nH limit, open node.

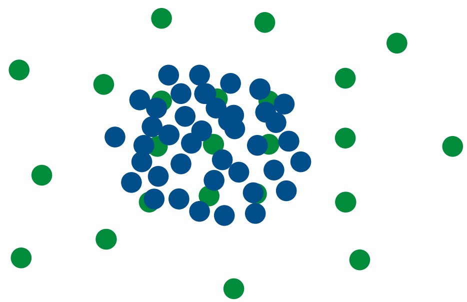
Appendix

Storing the tree to give to the next timestep:

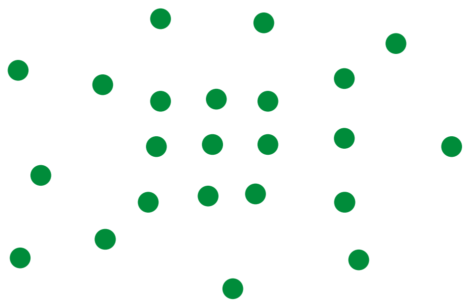


Appendix

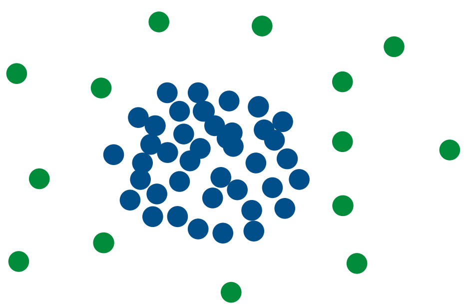
Combining nodes with ind. particles:



Get both particles and their leaves;
Mark the leaves



Solve for h with those leaves as well



Remove those leaves and put particles back in