Title: Tree-Based Cosmological Radiative Transfer

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Abstract: One of the most challenging problems in computational galaxy formation is modeling distant heating and ionization by locally produced radiation. Most Radiative Transfer (RT) techniques are very computationally expensive and limit users to poor resolution or post-processing thus decoupling the radiation from the dynamics of the simulation. We present a new efficient method for RT implemented in the SPH code GASOLINE aimed at full cosmological simulations. The method is tree-based (similar to a gravity solver) scaling as N$_sinklogN_source$ in the optically thin case and as N$_sinklogN_sourcelogN_tot$ in the optically thick case. Applications range from the reionization of the Universe to H$_2$ formation and destruction. First applications focus on FUV and EUV emission from Milky Way-type galaxies and how these affect satellites galaxies.

Tree-Based Cosmological Radiative Transfer

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May 7, 2014

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1. Why is Radiation Important?
2. Gasoline & Gravity
3. Our Algorithm
4. Stromgren Sphere Test
5. Future Work

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Radiative Transfer

Radiation is *very* important in astrophysics:

Rosette Nebula, image from Wikimedia Commons

Radiative Transfer (RT)

- It's what we see!
- Cools and heats gas
- Can drive chemical evolution of gas
- Can disrupt molecular clouds, regulate star formation?

NGC 604 in Triangulum Galaxy, image from Wikimedia Commons

Modeling Radiative Transfer

Radiation very difficult to model - 7D (x,y,z,θ,ϕ,t,ν)

- Accurate schemes are *very* computationally expensive
- Ray Tracing
  - Good for optically thick + thin mediums
  - Good angular information
  - Bad scaling with number of sources
  - Scattering impossibly expensive
- Flux Limited Diffusion (FLD)
  - Good for optically thick mediums, scattering
  - Bad angular information
  - Good scaling with number of sources
- Other approximations
  - Simply diminish flux at source and/or sink, ignore everything in between
  - A little *too* simplified for many cases

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Many codes don't bother...

Due to large computational expense....

- Many codes ignore radiation or just set constant background field
- Others simply add thermal or kinetic energy to gas

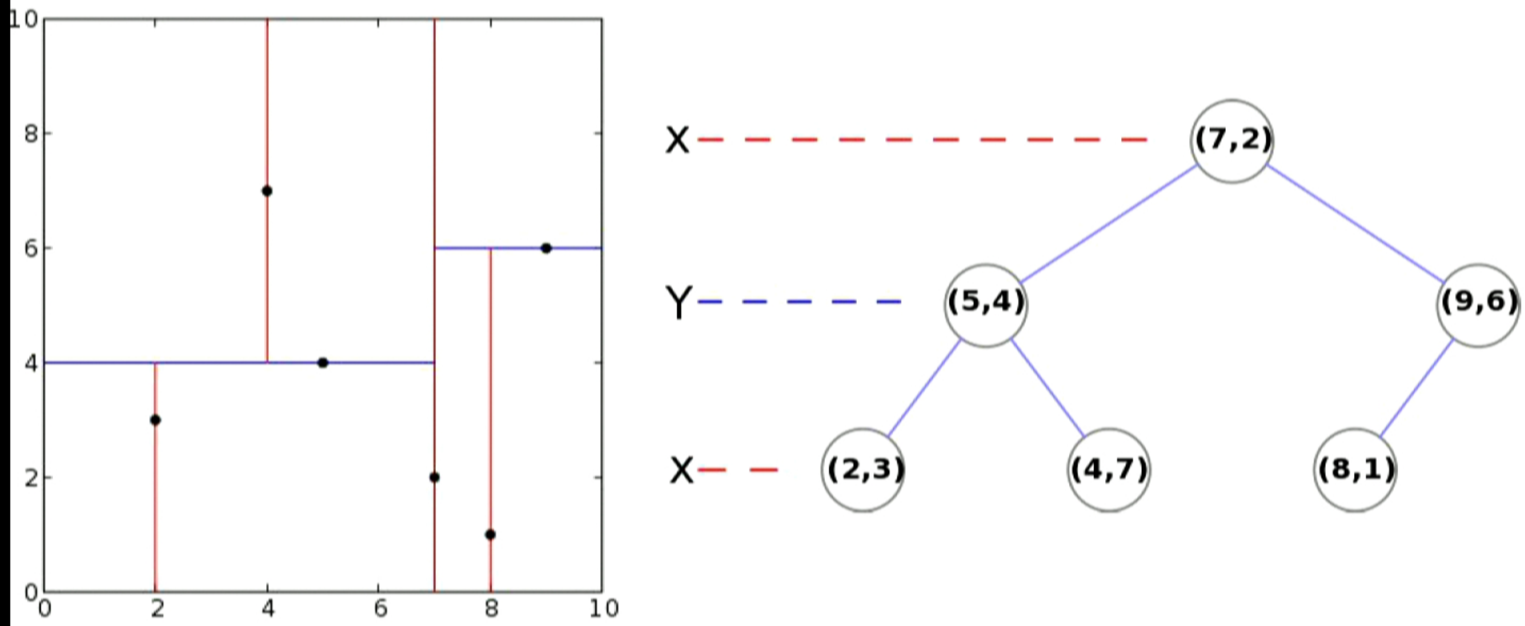
$\rightarrow$ Big market for cheap RT approximation.

Some Numerical Background

- GASOLINE is a TreeSPH code
- Can do gravity, hydrodynamics, star formation, and many more physical processes
- Borrow from (efficient) gravity tree - scales as $\mathcal{O}(n \log n)$
- Algorithm implemented in GASOLINE, but is code independent.

Radiative Transfer Algorithm

Our idea: Make use of kd-tree (like gravity) to calculate radiation field.



Images from wikimedia commons

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Radiative Transfer Algorithm

Particles within specific radius (called r_{open}) calculated directly. Otherwise use moment of cell.

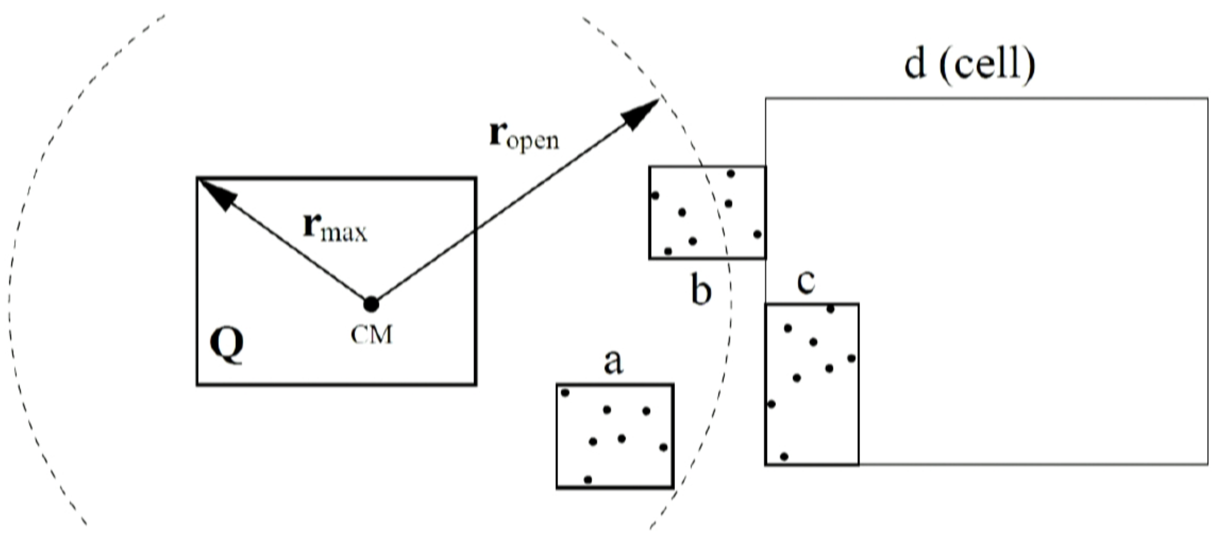
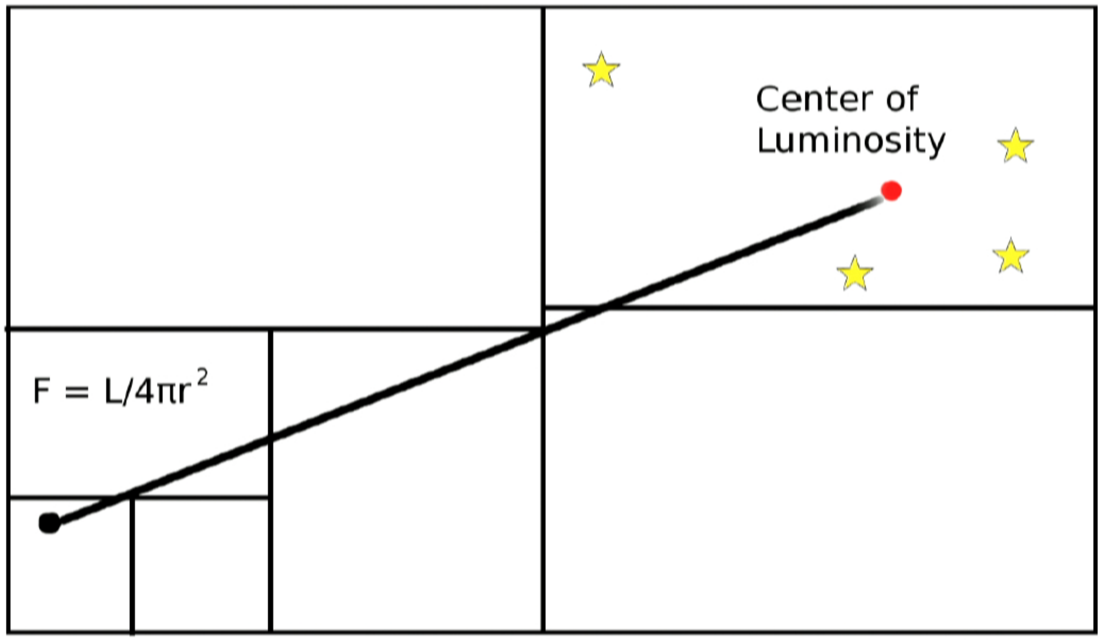


Image from Stadel (2001)

Radiative Transfer Base Algorithm

By exchanging radiation during a tree walk, algorithm scales as $\mathcal{O}(n_{\text{sink}} \log n_{\text{source}})$. Instead of mass moments, we use center of radiation from cells:



But how do we account for absorption?

The Physics of Absorption

To calculate absorption, we need to calculate "optical depth" - integral of absorption along path of photon

$$\tau = \int_0^r \rho \kappa ds$$

Flux is then just diminished by $F = F_o e^{-\tau}$.

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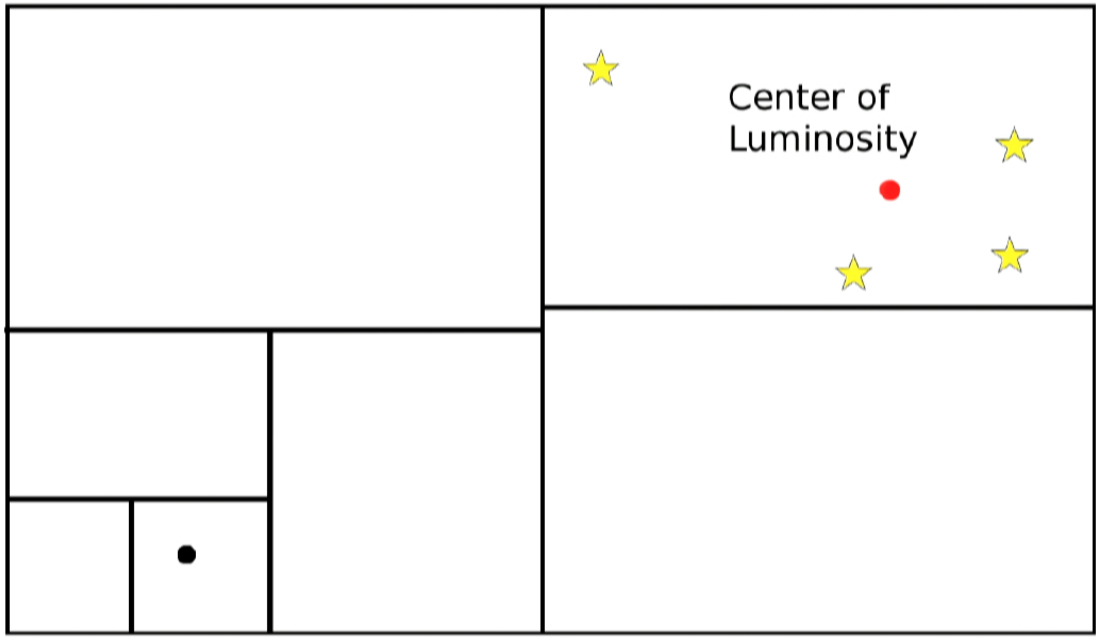
Radiative Transfer Algorithm With Absorption

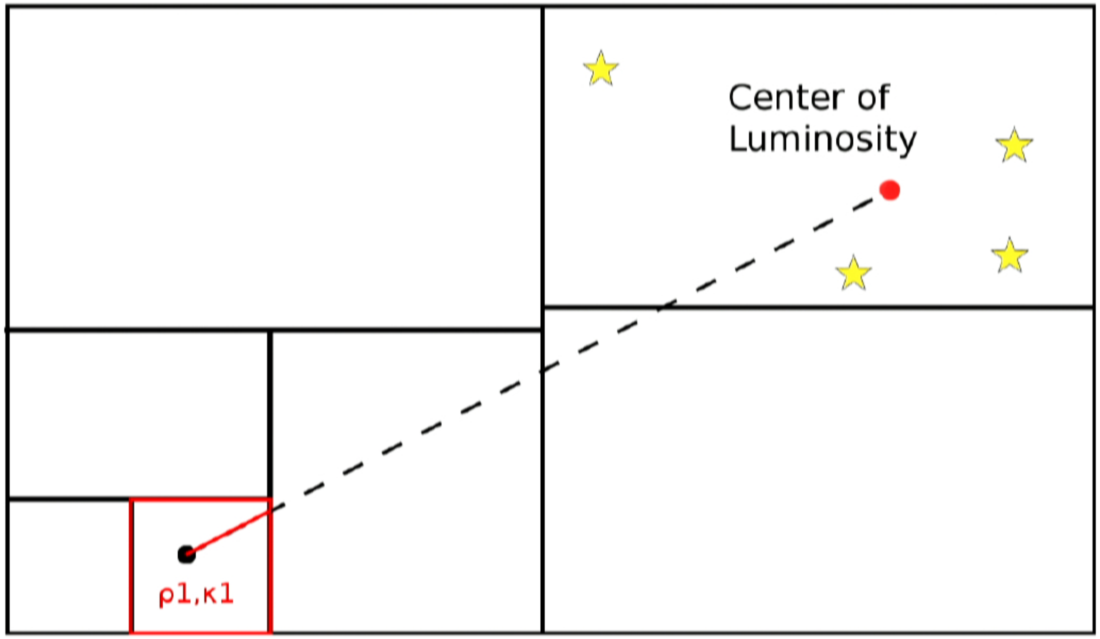
We walk up tree, accumulating optical depth as we go. See animation...



ds	ρ	κ

Radiative Transfer Algorithm With Absorption

We walk up tree, accumulating optical depth as we go. See animation...



ds | ρ | κ
ds1, ρ1, κ1

Radiative Transfer Algorithm With Absorption

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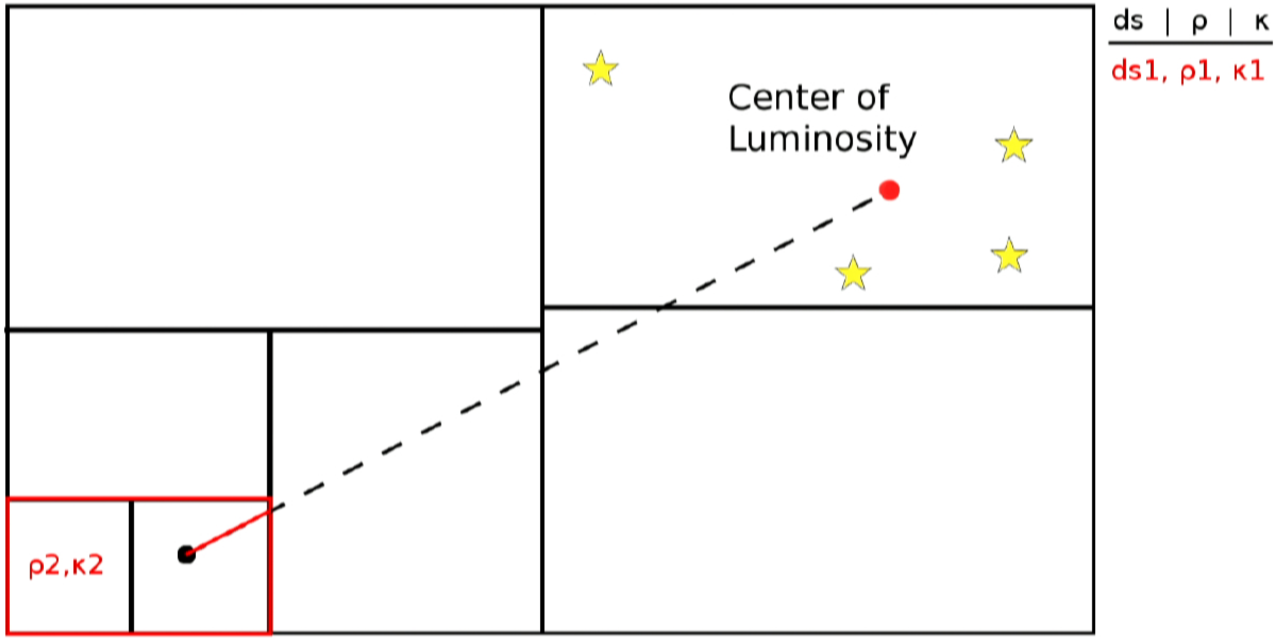

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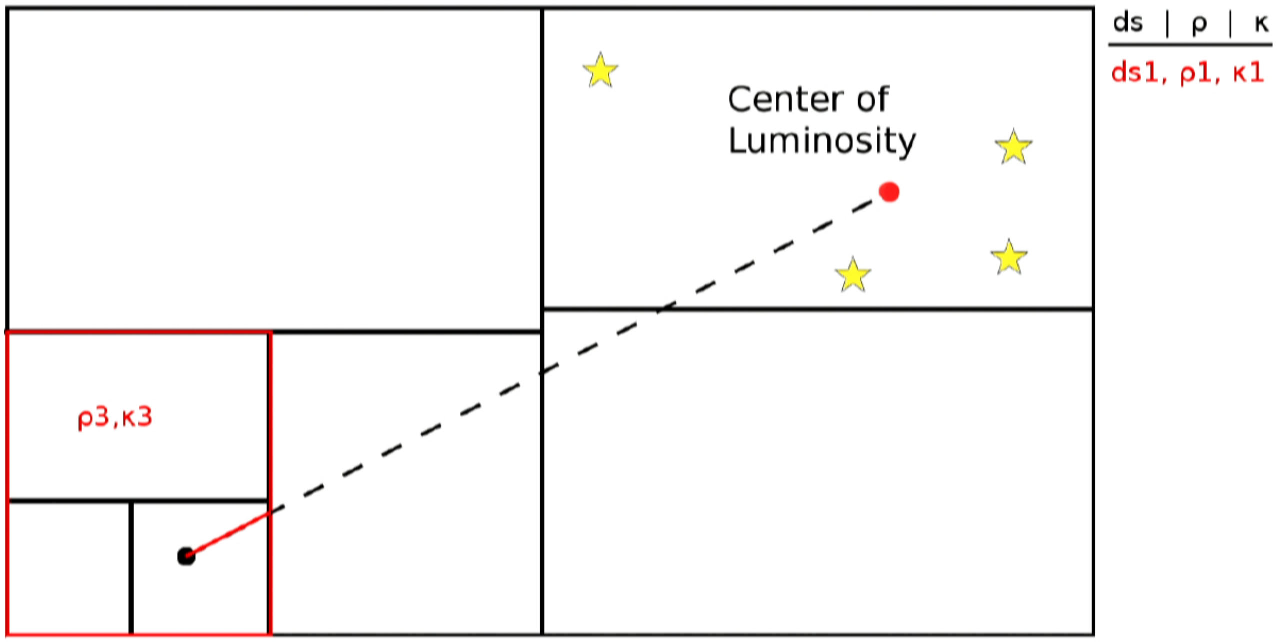

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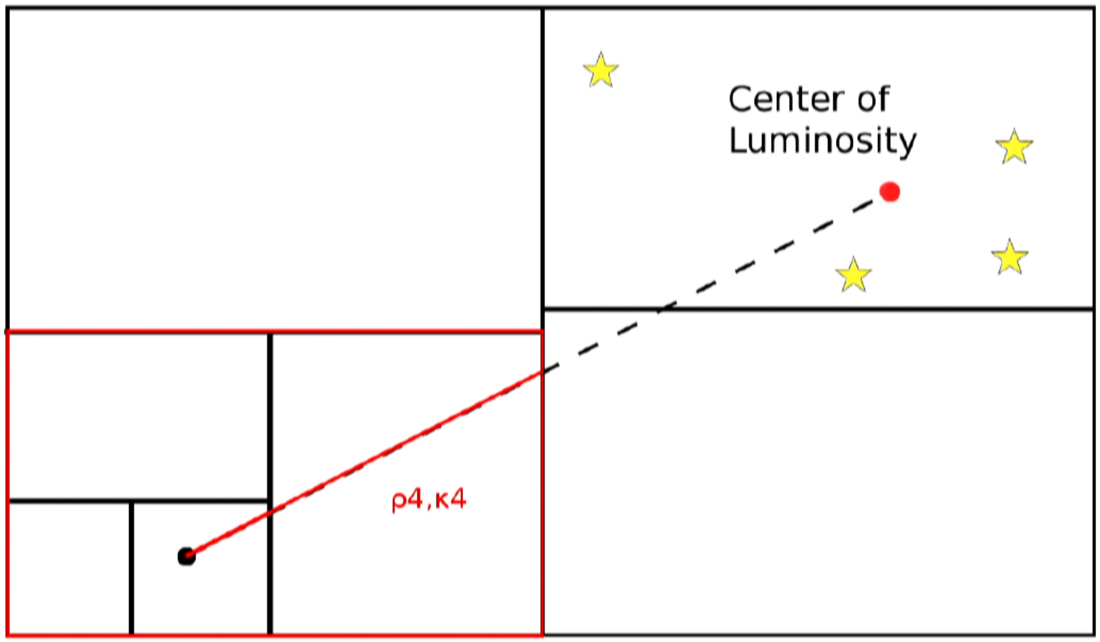

ds	ρ	κ
ds1,	ρ1,	κ1
ds4,	ρ4,	κ4

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Radiative Transfer Algorithm With Absorption

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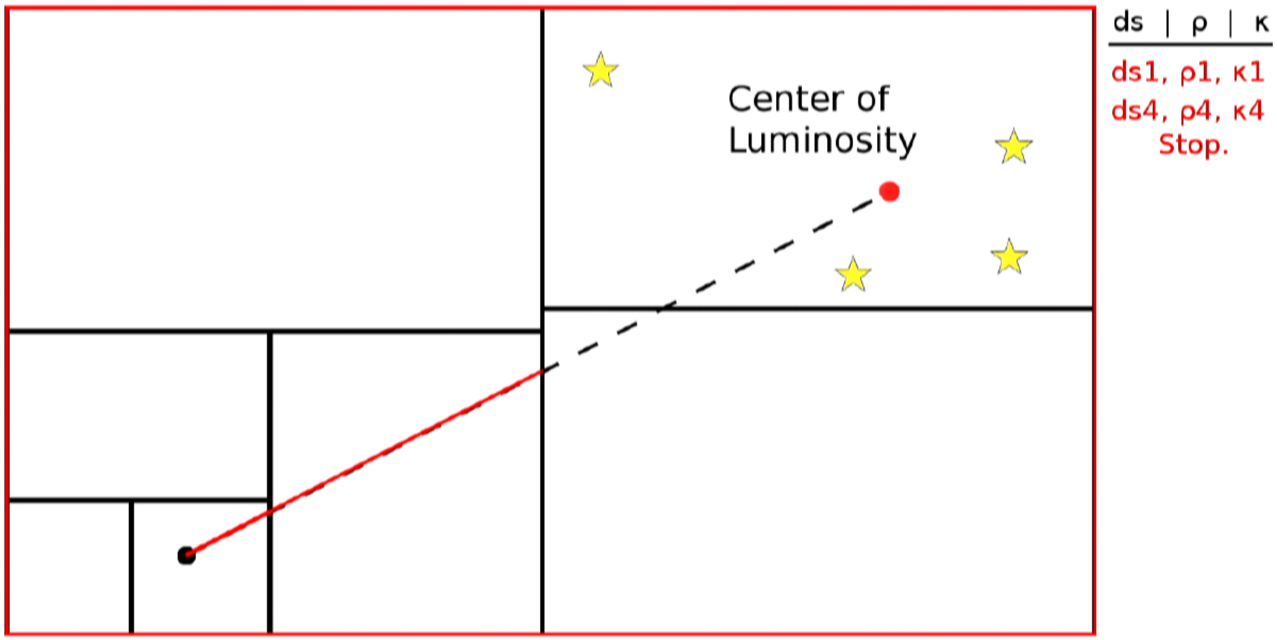

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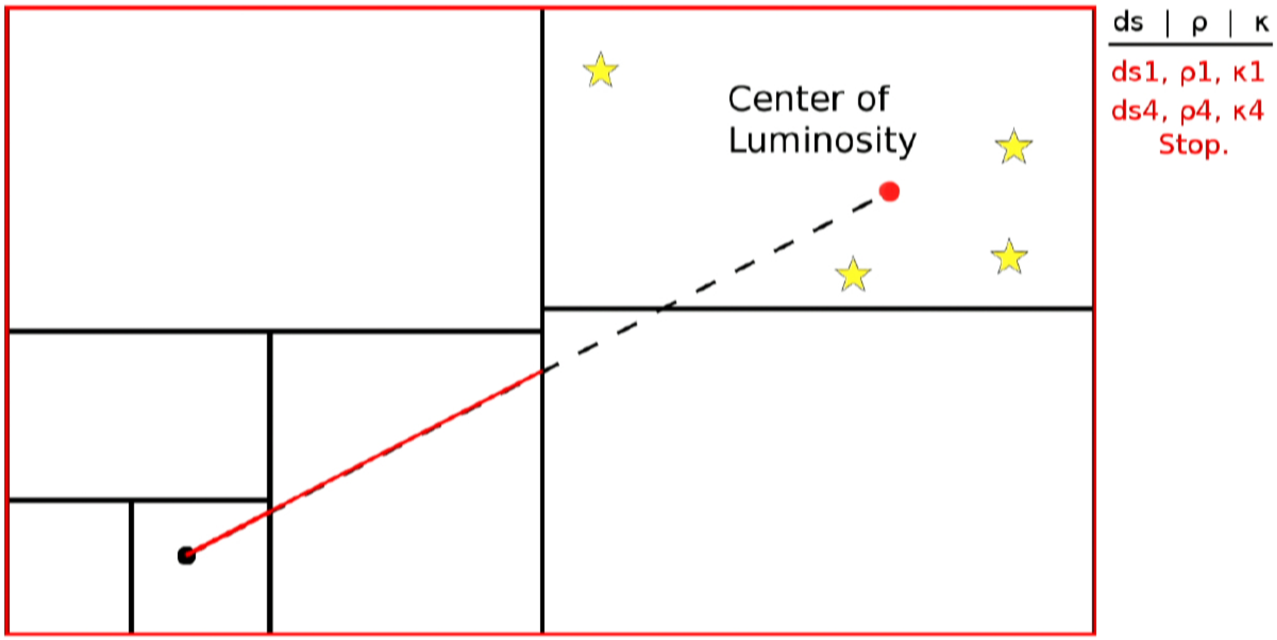

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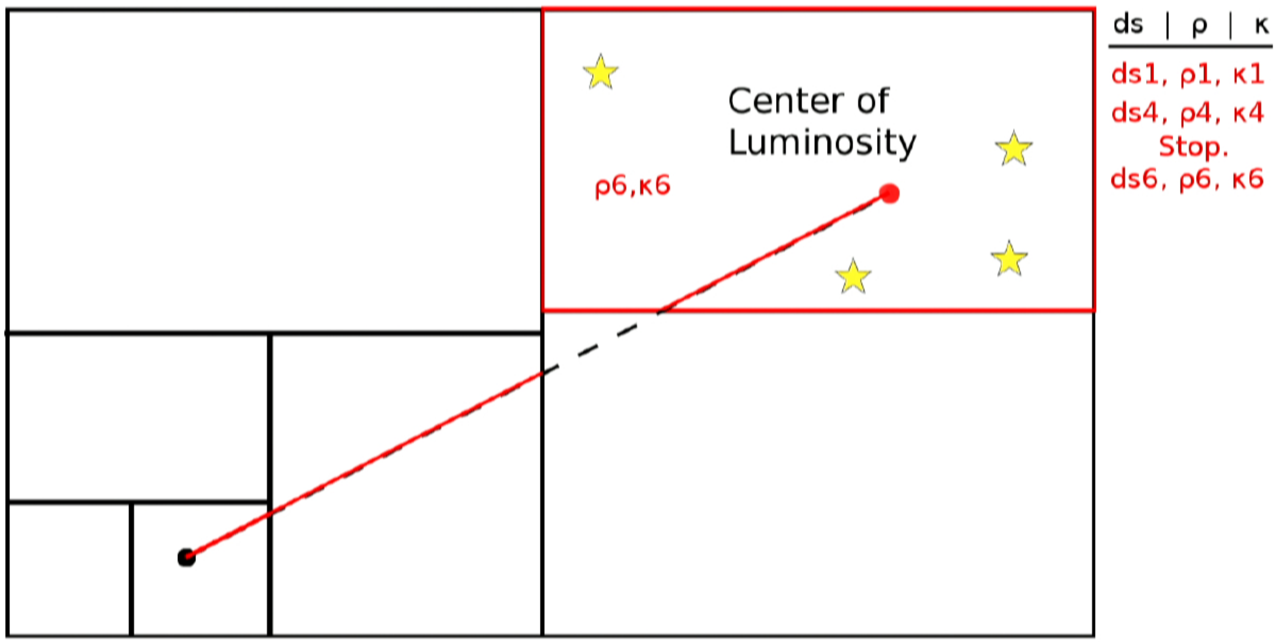

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Radiative Transfer Algorithm With Absorption

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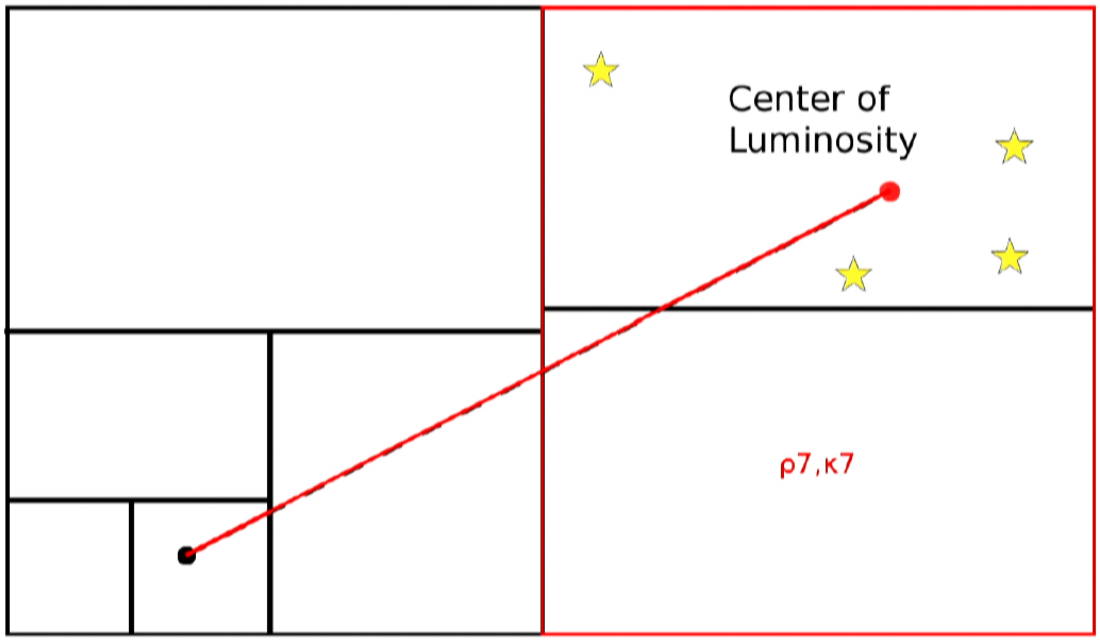

ds	ρ	κ
ds1,	ρ1,	κ1
ds4,	ρ4,	κ4
Stop.		
ds6,	ρ6,	κ6
ds7,	ρ7,	κ7

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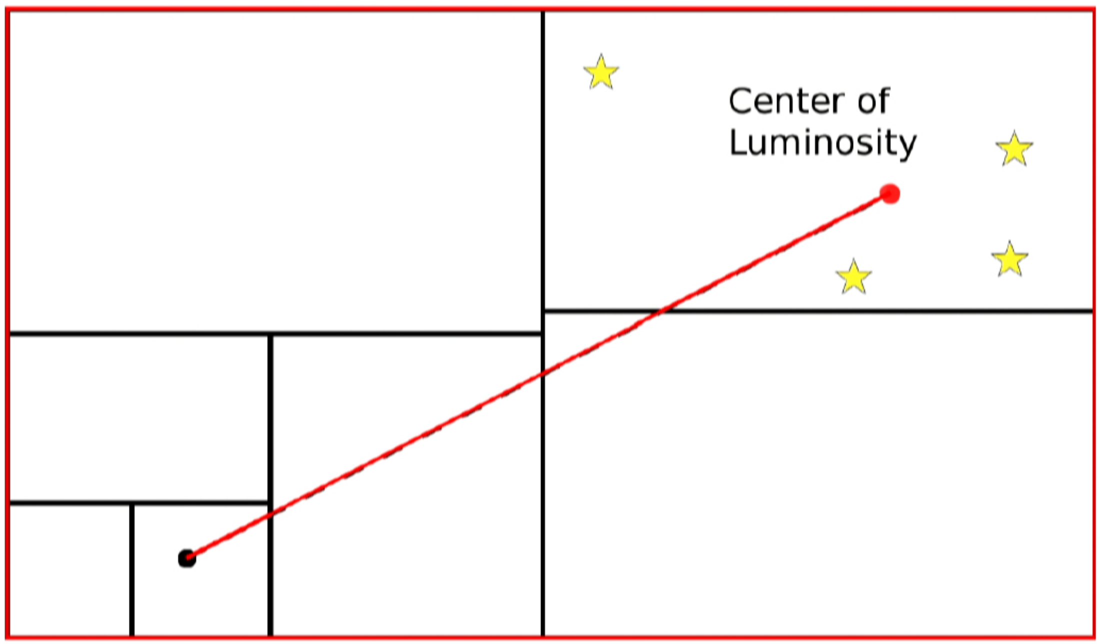
Radiative Transfer Algorithm With Absorption

We walk up tree, accumulating optical depth as we go. See animation...



ds | ρ | κ
ds1, ρ1, κ1
ds4, ρ4, κ4
Stop.
ds6, ρ6, κ6
ds7, ρ7, κ7
Stop.

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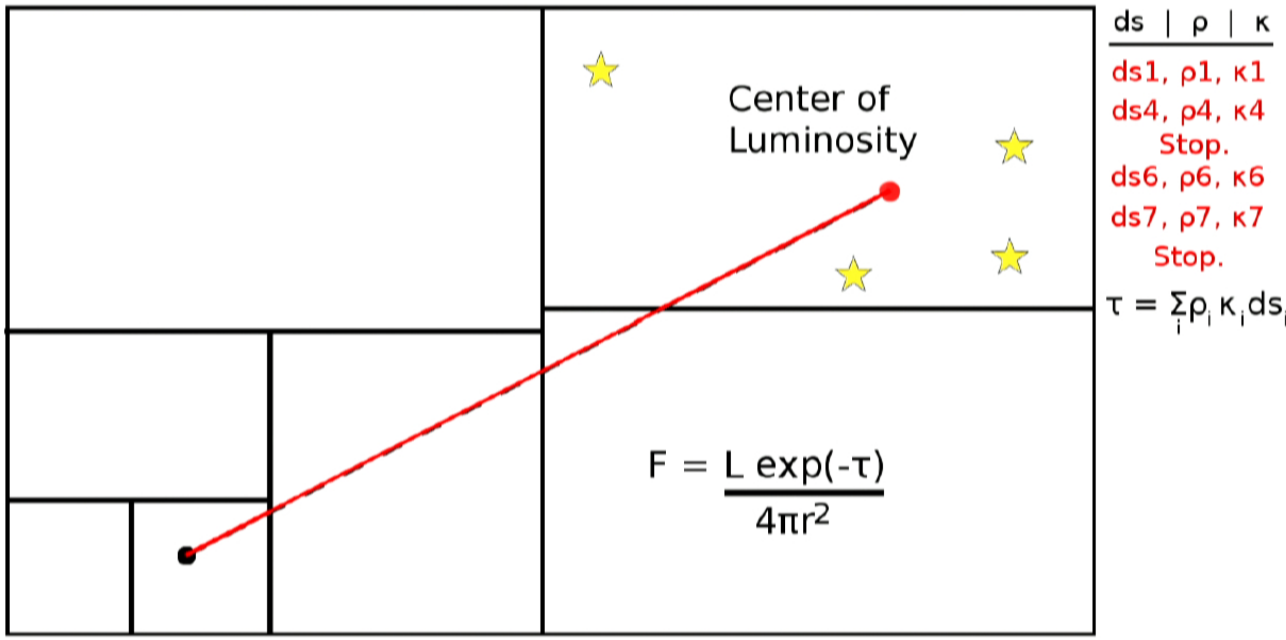
Radiative Transfer Algorithm With Absorption

We walk up tree, accumulating optical depth as we go. See animation...



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Algorithm Properties

- Runs in $\mathcal{O}(n_{\text{sink}} \log n_{\text{source}} \log n_{\text{total}})$ time
- Can adjust accuracy with opening angle criteria
- Better absorption "resolution" near sink and source
- Can handle many sources due to source aggregation

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Strongren Sphere Test

By coupling radiation to ionization, can test accuracy of radiation.

- Hydrogen gas at uniform temperature and density
- Single source at center emitting ionizing photons
- Turn hydrodynamics, gravity off
- Ionization front should move out at specific rate to specific radius

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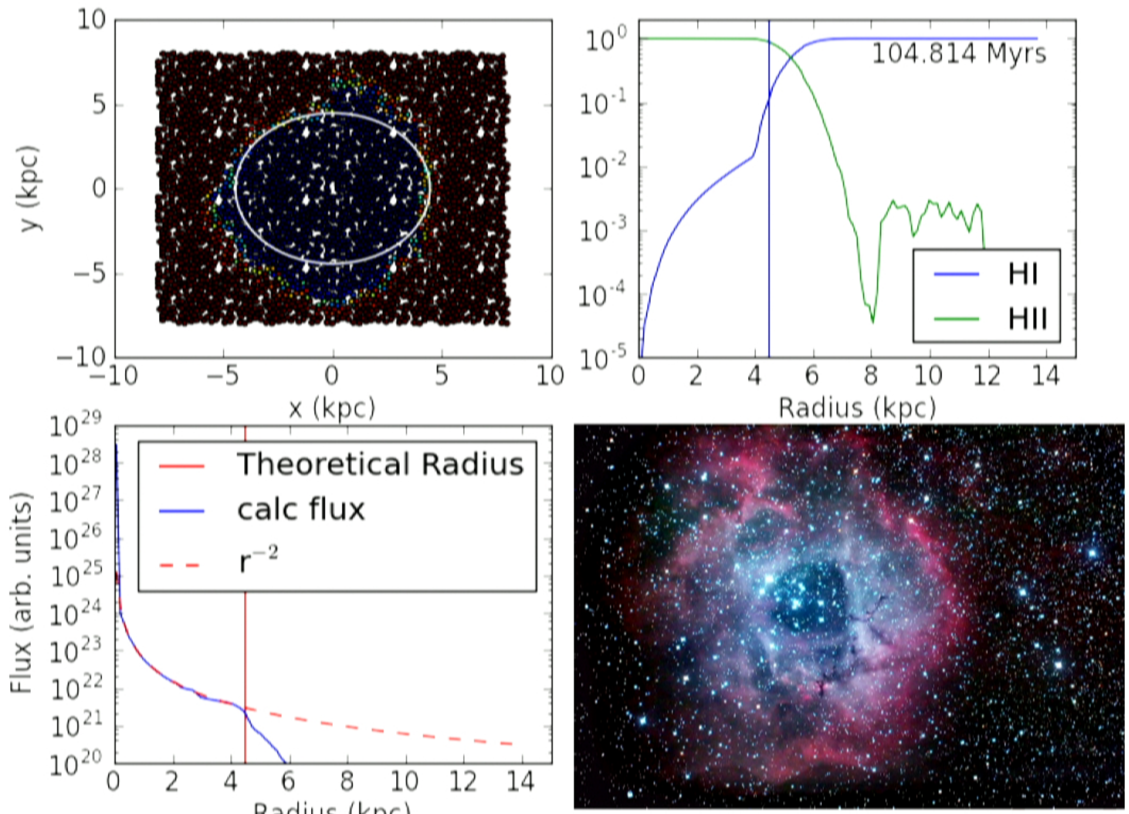
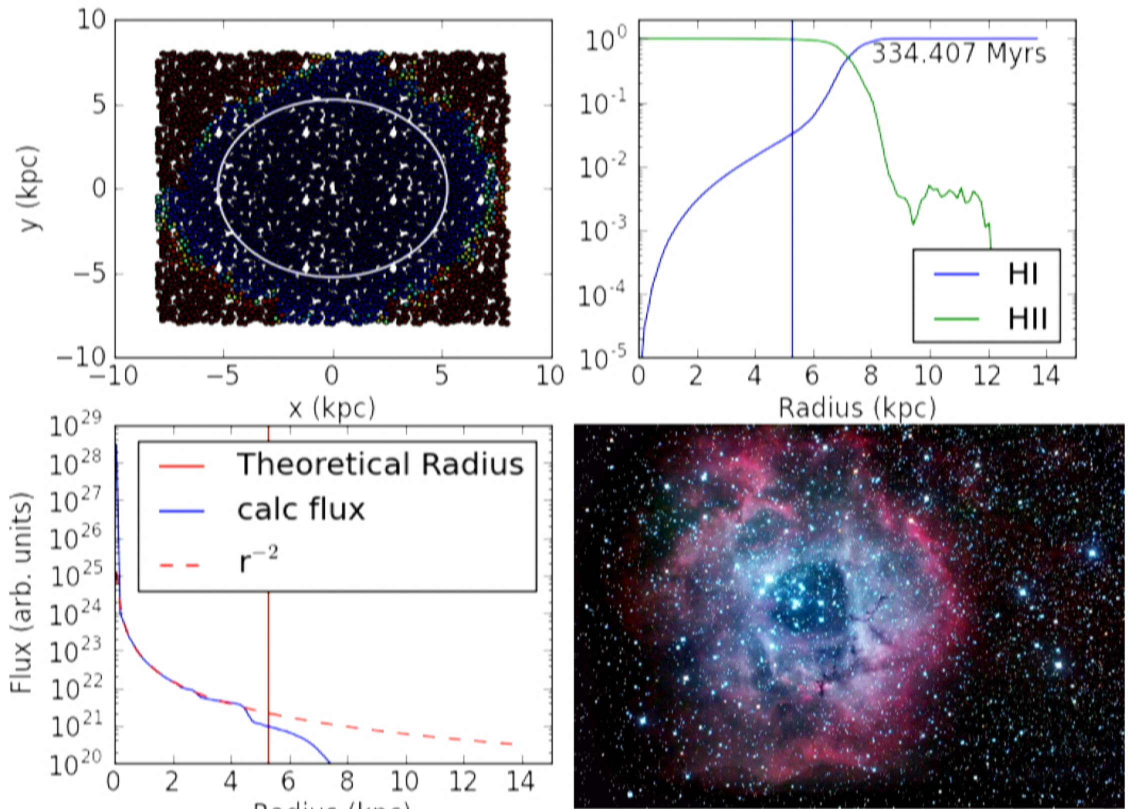
Stromgren Sphere Test



Strongren Sphere Test



Acknowledgements

Thanks to...

- James Wadsley, Hugh Couchman
- Charlotte Christensen
- Compute Ontario

Conclusions & Future Work

Summary

- Created tree-based algorithm for RT
- Added treatment to approximate absorption
- Coupled radiation to ionization to test Stromgren sphere

Future Work

1. Add generic "source function" (treat gas as sources)
2. Add multi-wavelength support
3. Add periodic functionality - deal with background radiation, hubble-shifted radiation
4. Couple radiation to force calculations (radiation pressure)

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