SIRIUS: A new semi-numerical method for simulating cosmic reionization and IGM heating

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June 23, 2023 Suzhou

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We hope we can observe images of reionization in the near future.

Ionization and Gas temperature are coupled.

$$\frac{dn_{\rm HII}}{dt} = \Gamma(I, n_{\rm HI}, SED) - \alpha(T_{gas}) n_e n_{\rm HII} + \dots$$

Ionization

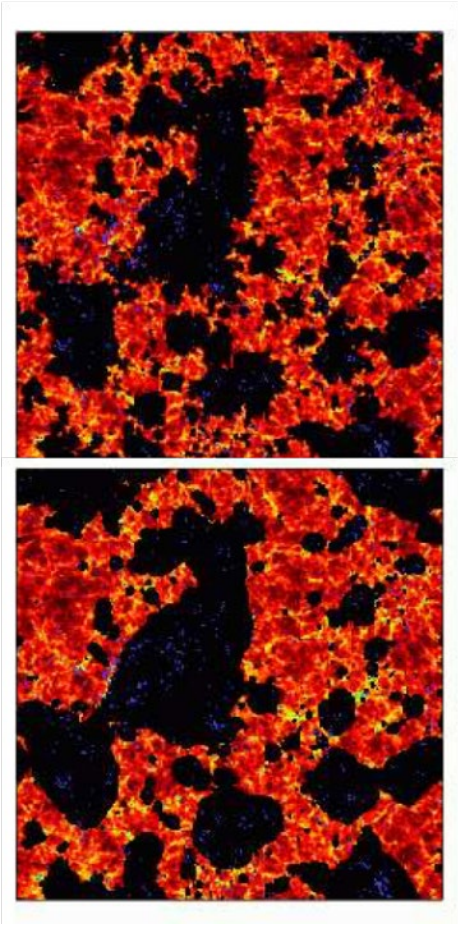
Photoionization

Recombination (Gas Temperature)

Radiative Transfer

Full numerical:
C²-Ray
(Mellema et al),
RAMESES-RT
(Rosdahl et al)…

Semi-numerical:
21cmFAST
(Mesinger et al),
SimFAST
(Santos et al)…



Zahn et al 2007

Gas Temperature

Heating

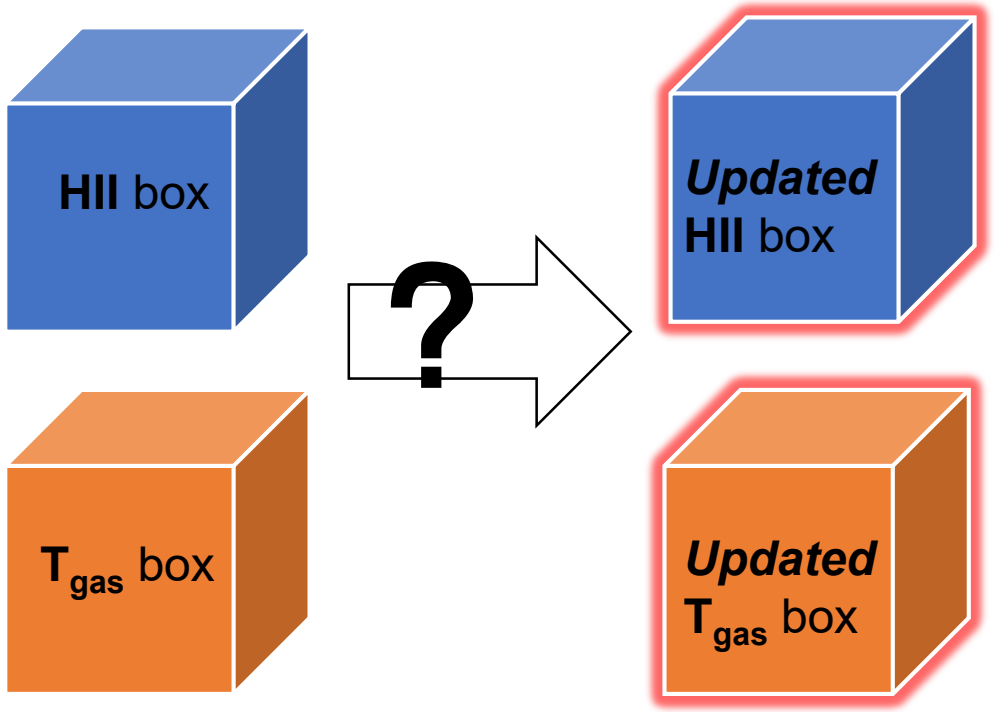
Cooling (Atomic…)

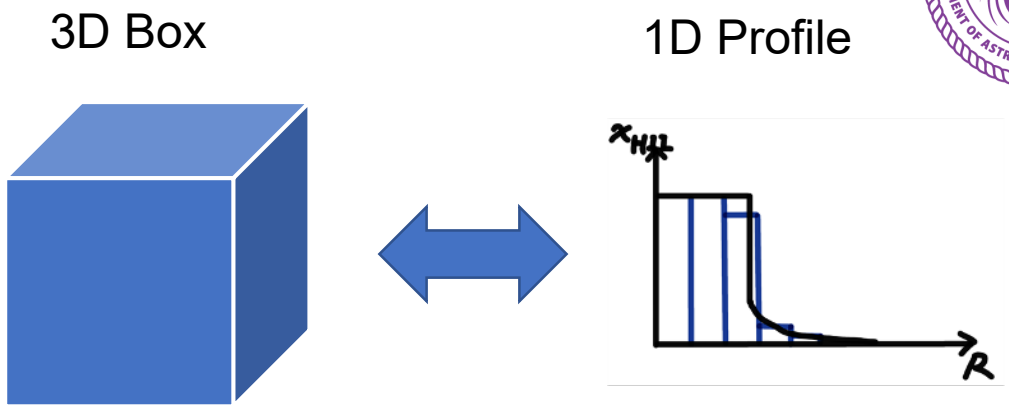
Cooling (Ionization)

$$\frac{dT}{dt} = \frac{2}{3nk_B(1+x_e)}(H - \Lambda) - \frac{T}{1+x_e}\frac{dx_e}{dt} + \frac{2T}{3n}\frac{dn}{dt} + \dots$$

Brainstorm!

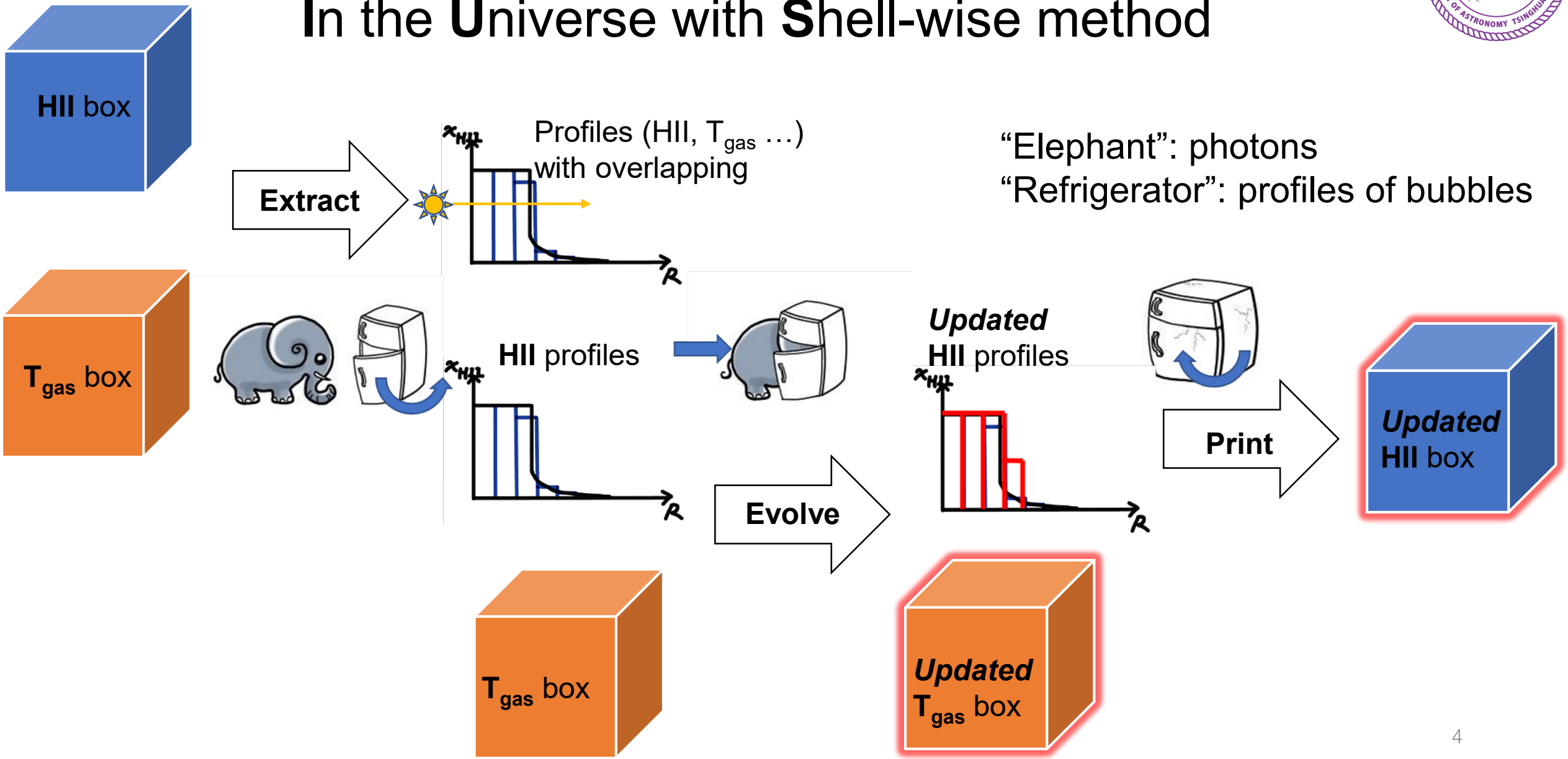
- As fewest approximations as possible
- Flexible to any kind of source model
- Fast





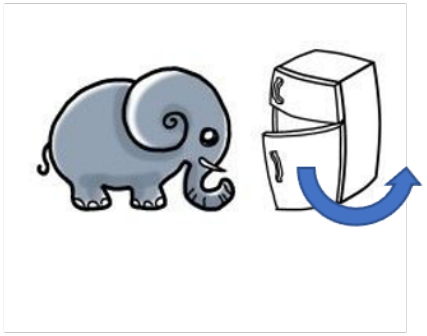
- Reduce the number of quantities to be updated per time step;
- Include overlapping effect in RT;
- Apply another method for temperature evolution.

SIRIUS: Simulation of **I**GM **R**eionization In the **U**niverse with **S**hell-wise method

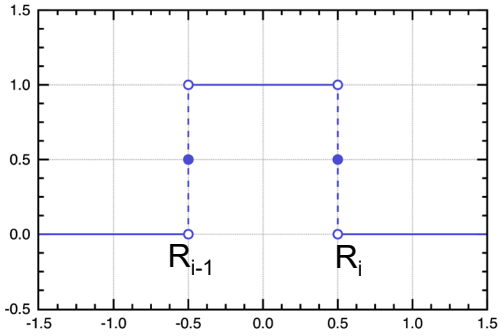


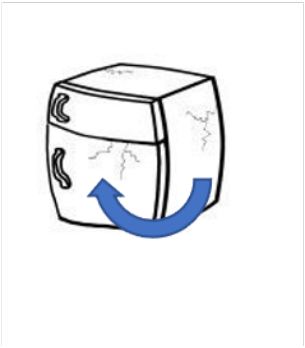
"Elephant": photons
"Refrigerator": profiles of bubbles

We use **Shell** window functions to print/extract profiles.



Extract:





Print:

$$W_{un}(|\vec{x}-\vec{x}_s|;R_i) = \begin{cases} 1 & R_{i-1} < |\vec{x}-\vec{x}_s| < R_i \\ 0 & \text{Otherwise} \end{cases}$$

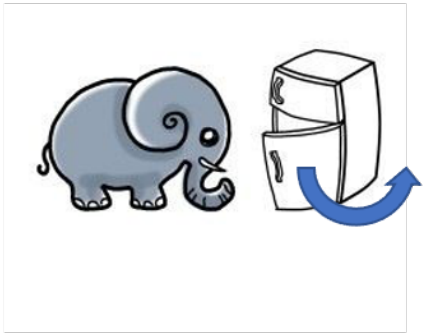
Unnormalized

$$W_{Vn}(|\vec{x}-\vec{x}_s|;R_i) = W_{un}/V_{shell}(R_i)$$

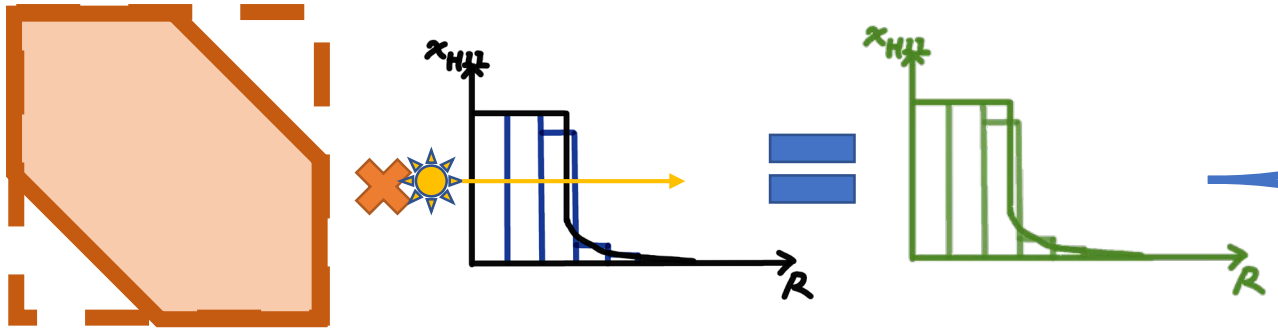
Volume-normalized

- Similar to “Top-hat”
- FFT convolution

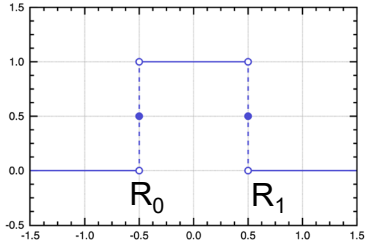
We use **Shell** window functions to extract/print profiles.

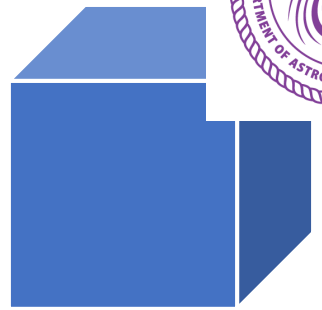


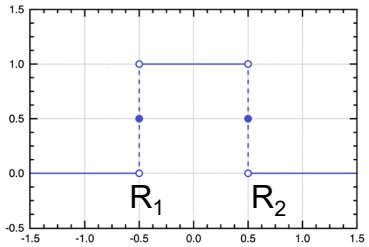
Extract:

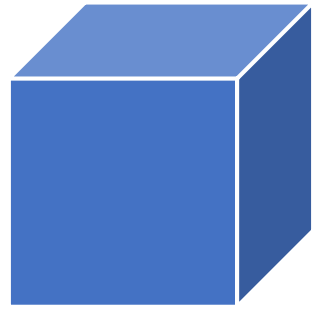


De-Correlation Matrix

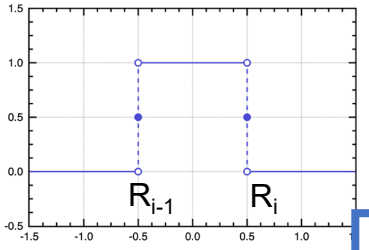




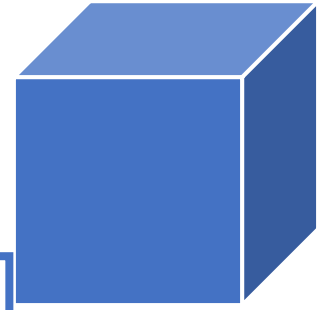




Volume-Normalized ……

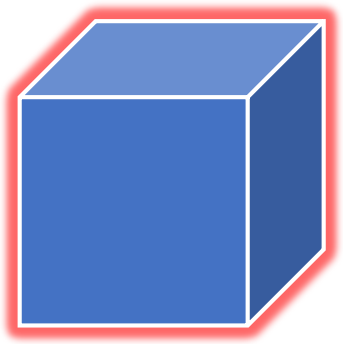


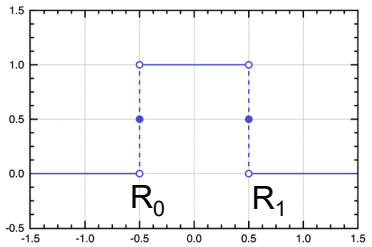
Convolution

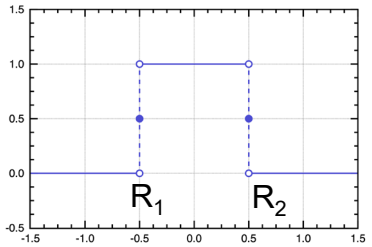


We use **Shell** window functions to print/extract profiles.

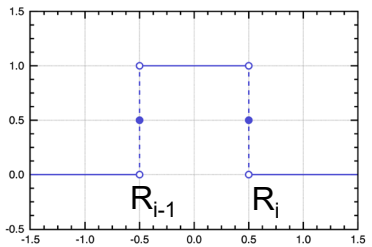
Print:



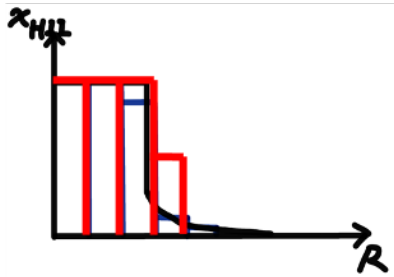


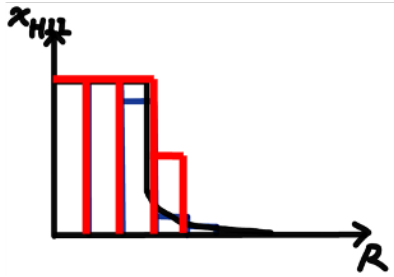


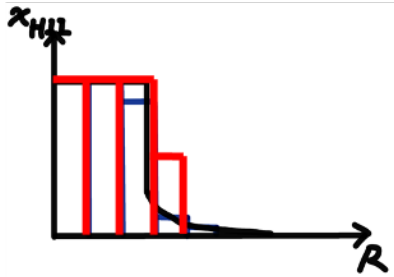
Unnormalized



Convolution







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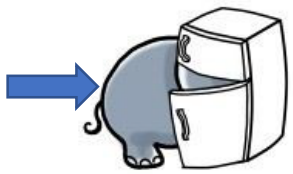
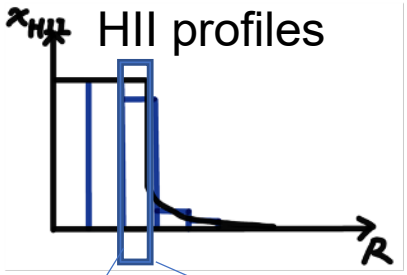
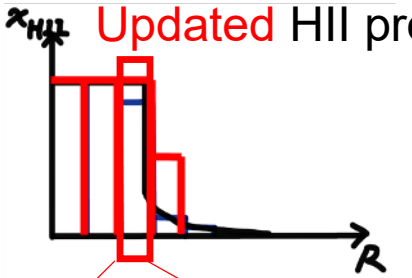
We use approximations of RT to evolve profiles.



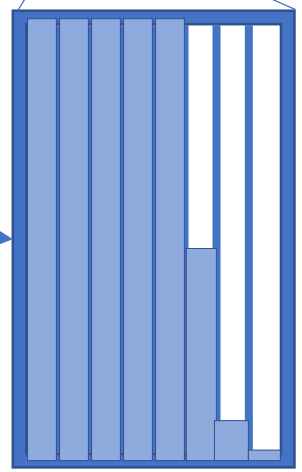
Evolve:



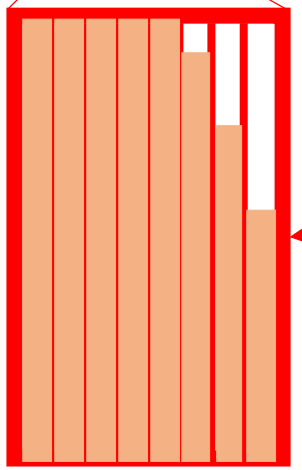


$t = t_0$

1. Central Emissivity
2. HI Column Density
3. Ionized fraction
4. Density
5. Recombination (T_{gas})



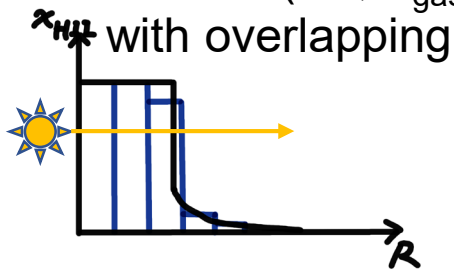
Evolve



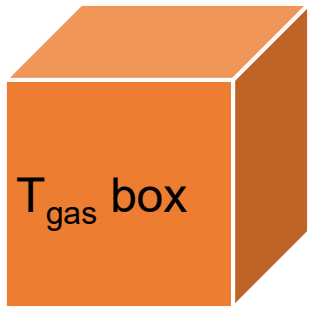
$t = t_0 + dT$

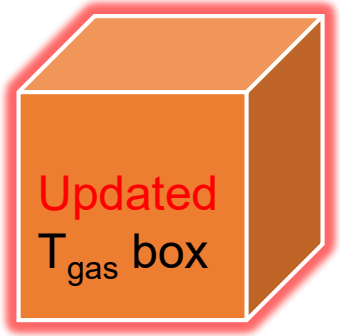
1. Updated ionized fraction

Profiles (HII, T_{gas} …) with overlapping



Approximation of Radiative Transfer





Approximations of Radiative Transfer

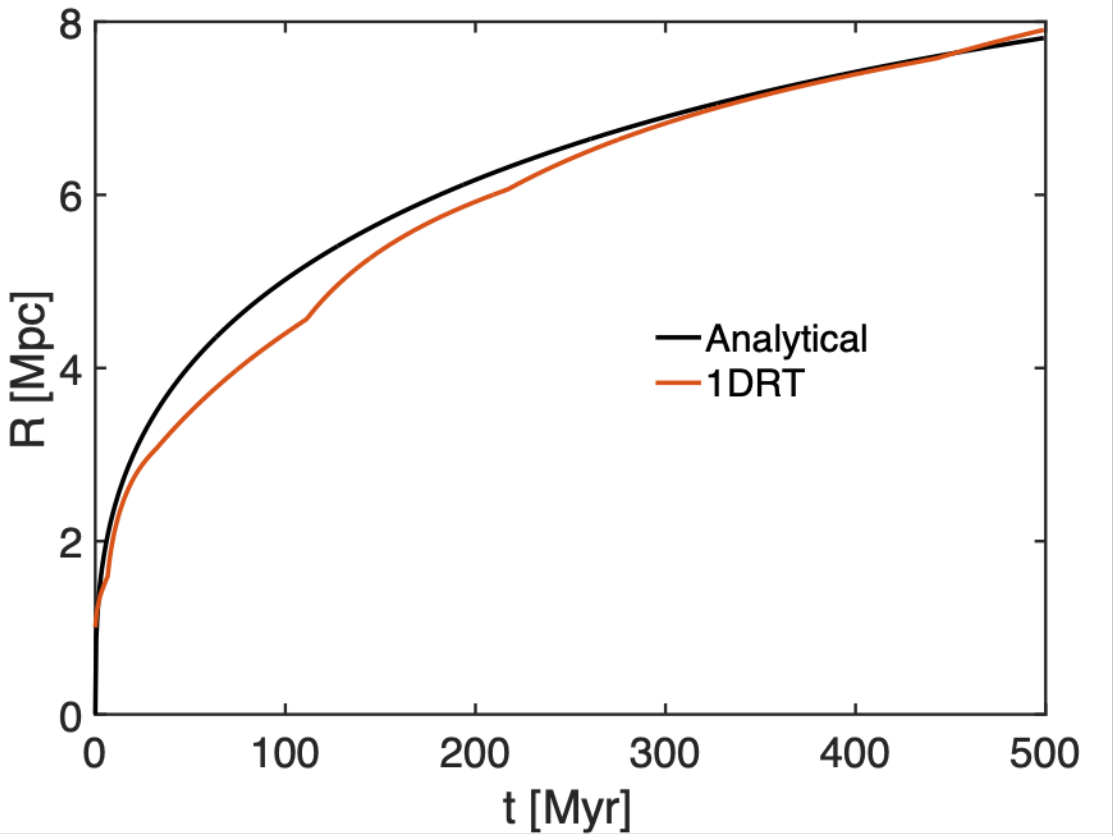
	UV	X-ray
Method	1D Radiative Transfer (Thomas et al 2008, Ghara et al 2015, Krause et al 2018…)	Linear Perturbation Theory of Reionization (Zhang et al 2007, Mao et al 2015)
Used in	Photoionization	Photoionization, Heating, Lyα background
Assumptions	Spherically symmetric propagation;	Spatial average and linear perturbation; Attenuated by mean optical depth;
Modification	Include overlapping in radiative transfer; Shell-Wise instead of full bubbles.	Remove other approximations on source models.

Both methods do not have any assumptions on source models!

Single Source Test: Roughly consistent with strong source.

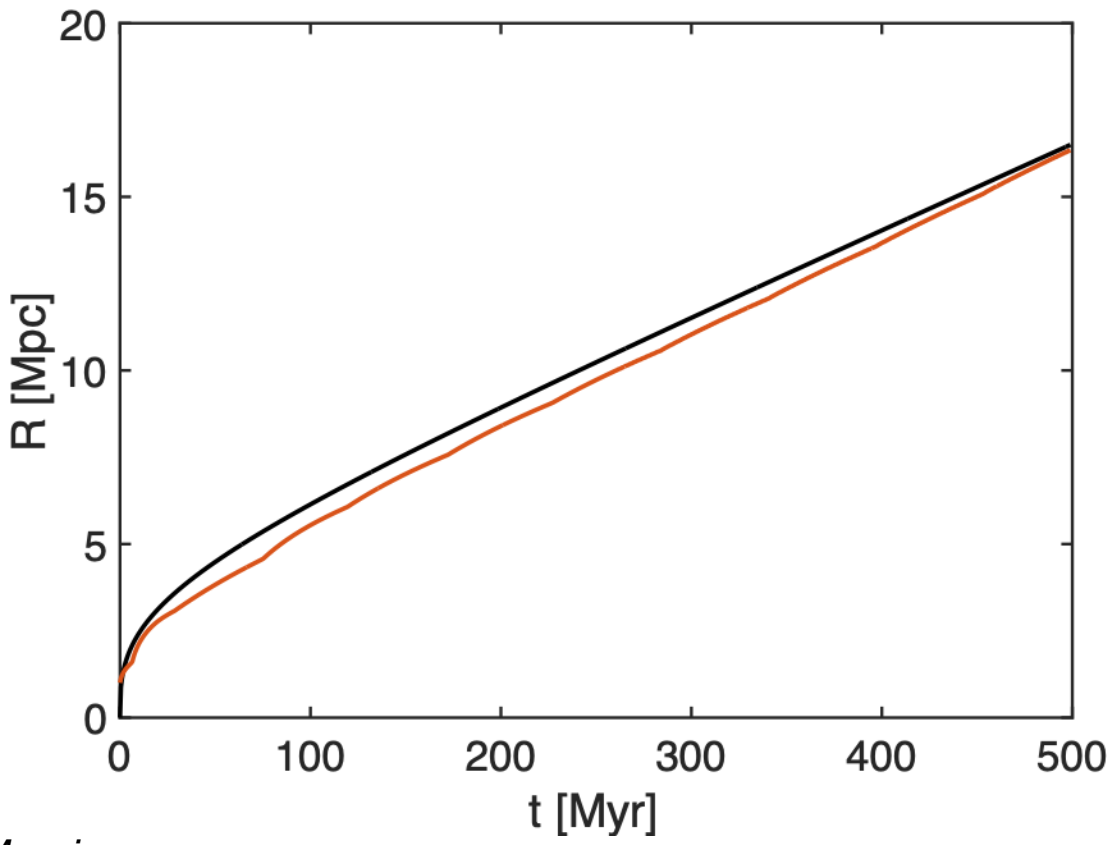
$$r_s = r_0[1 - \mathrm{Exp}(-t/t_{\mathrm{rec}})]^{1/3}$$

$$r_e = r_0\{\lambda e^{\lambda t_i/t}[t/t_i E_2(\lambda t_i/t) - E_2(\lambda)]\}^{1/3}$$



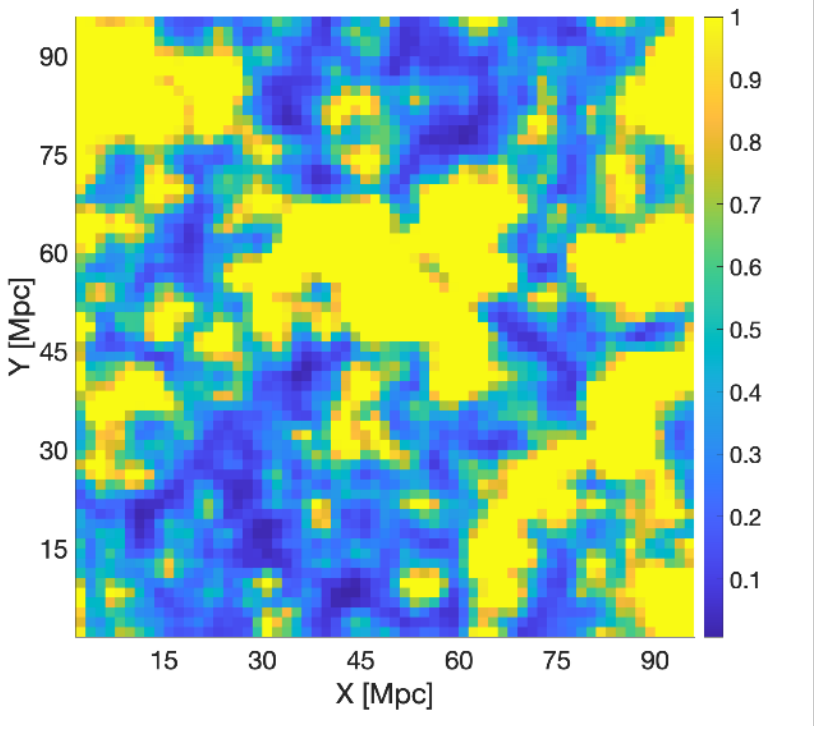
In Static Universe

Zhou and Mao in prep

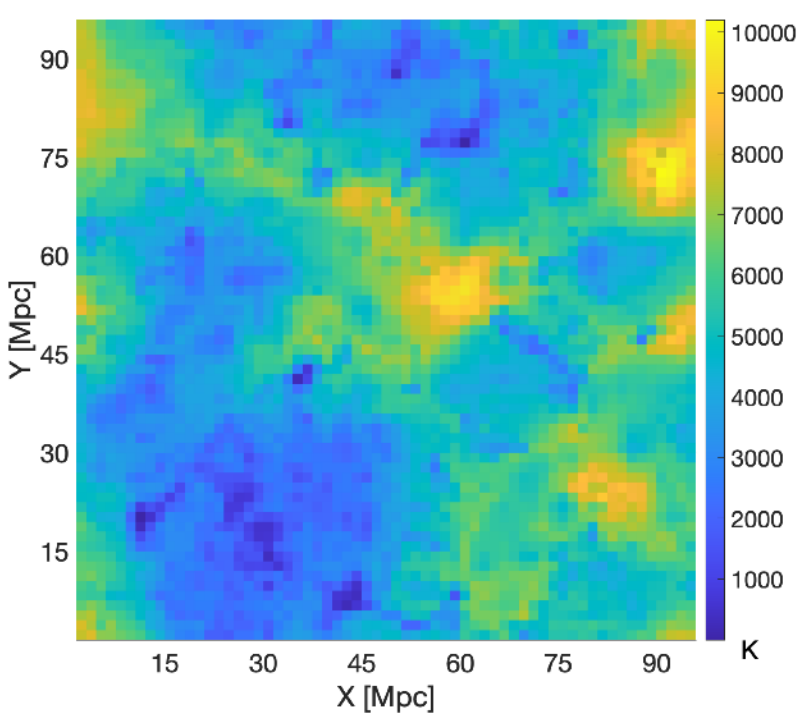


In Expanding Universe

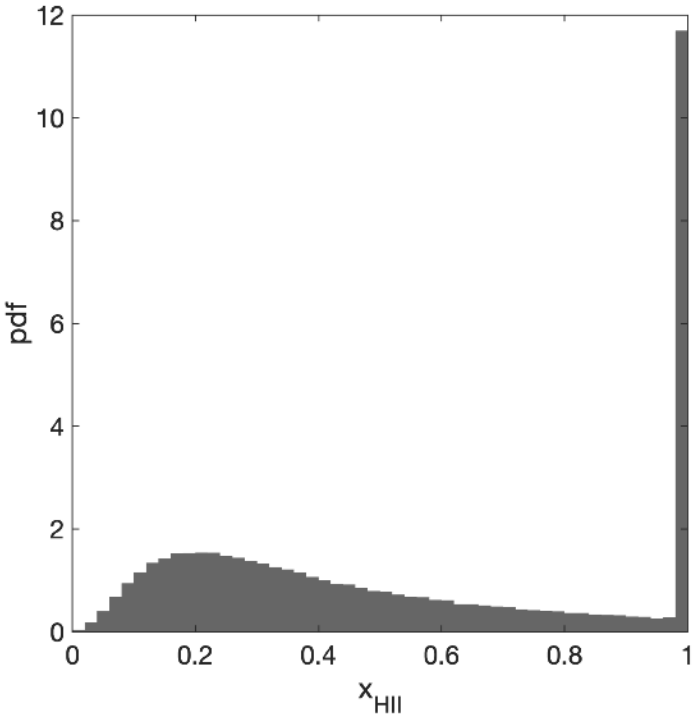
Cosmological density field test:



Ionization



Gas Temperature



Histogram of Ionization

Zhou and Mao in prep

Source Models

- Model 1
  - Density Field: 21cmFAST (Mesinger et al 2011)
  - Halo : Press-Schechter HMF

$$\epsilon_i \sim \gamma_i(\nu) f_{coll}(\eta, M_{min}, R, \delta_R) n_{\rm H}(\eta, \mathbf{x}, R)$$

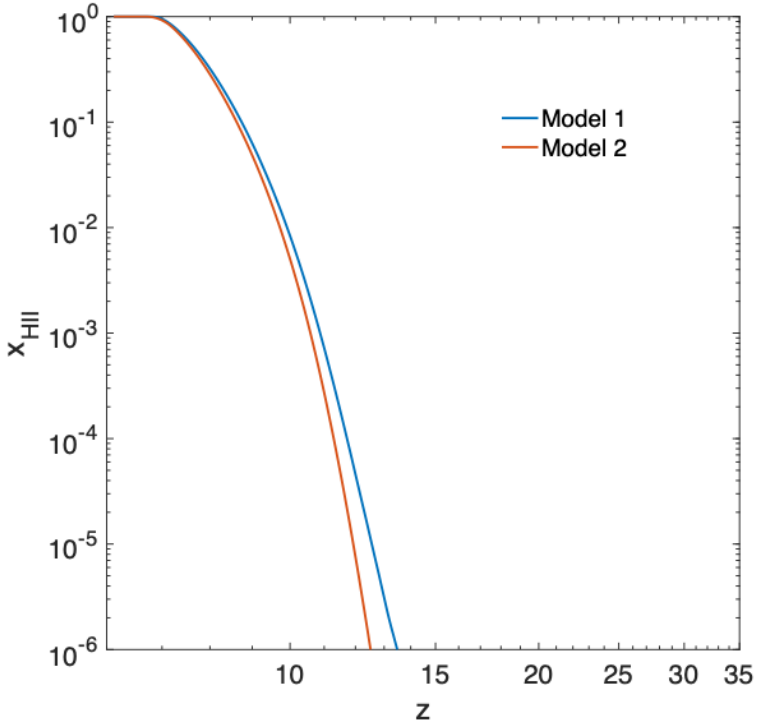
$$\gamma(\nu) = \zeta C_s (\nu/\nu_0)^{(1+s)}$$

- Model 2
  - Density Field: FASTPM (Feng et al 2016)
  - Halo : FoF + Press-Schechter HMF

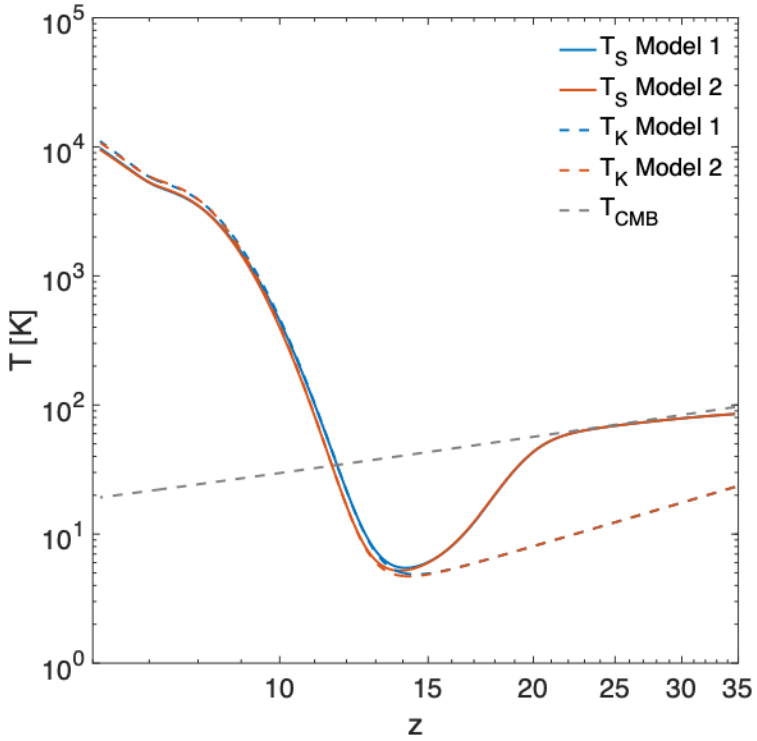
$$\epsilon_{resol} \sim \gamma_i(\nu) M_{halo}$$

$$\epsilon_{unresol} \sim \gamma_i(\nu) f_{coll}(\eta, M_{min}, R, \delta_R) n_{\rm H}(\eta, \mathbf{x}, R)$$

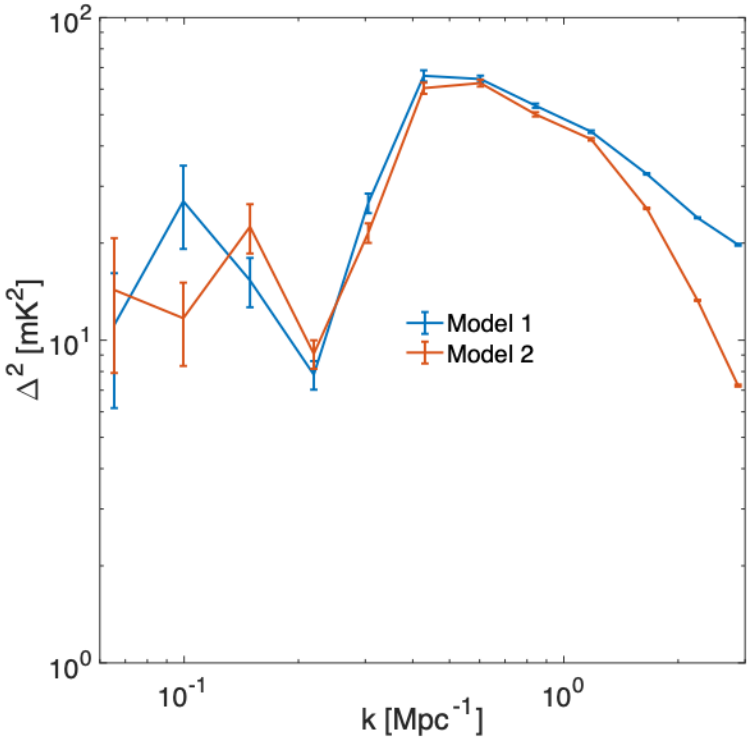
Source Model Comparisons



Reionization History



Heating History



21cm Power Spectrum
@ half ionized

Summary and future work

- We introduce SIRIUS, a new semi-numerical method for simulating cosmic reionization and IGM heating.
- Its uses shell window functions and approximations of radiative transfer.
- We perform single source test and cosmological density tests and obtain reasonable results.
- SIRIUS is flexible to any source model as long as you provide emissivity and density fields.