Simulating Reionization: Yesterday, Today, Tomorrow

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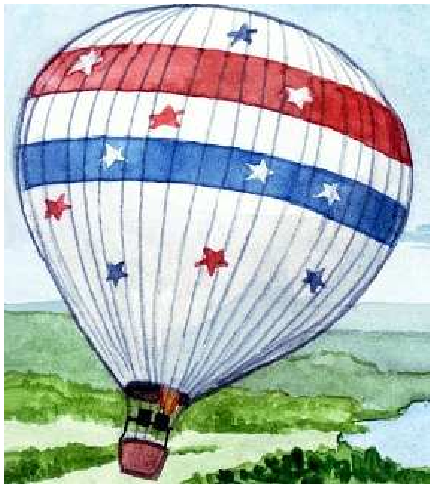


Epigraph

Why is reionization interesting?
I think the way to think about it is that
it was the last time when most baryons got together
and did something together.
After that they kind of did their own thing.

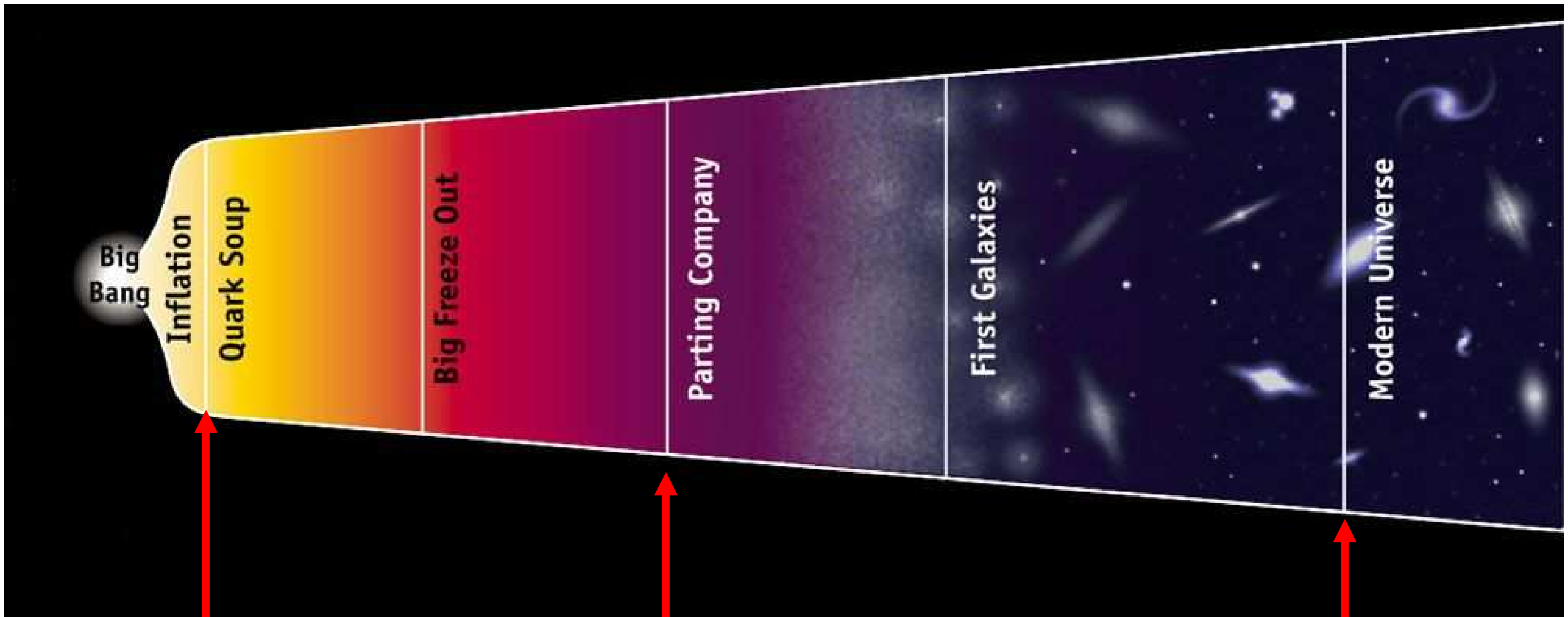
Peng Oh

Co-starring

Outline

- The brief history of time on one slide
- Cooking *reionizable* universe
- Yesterday (z = 3×10^{-10})
- Today (z = 0)
- Tomorrow (z = -3×10^{-10})

The Brief History of Time

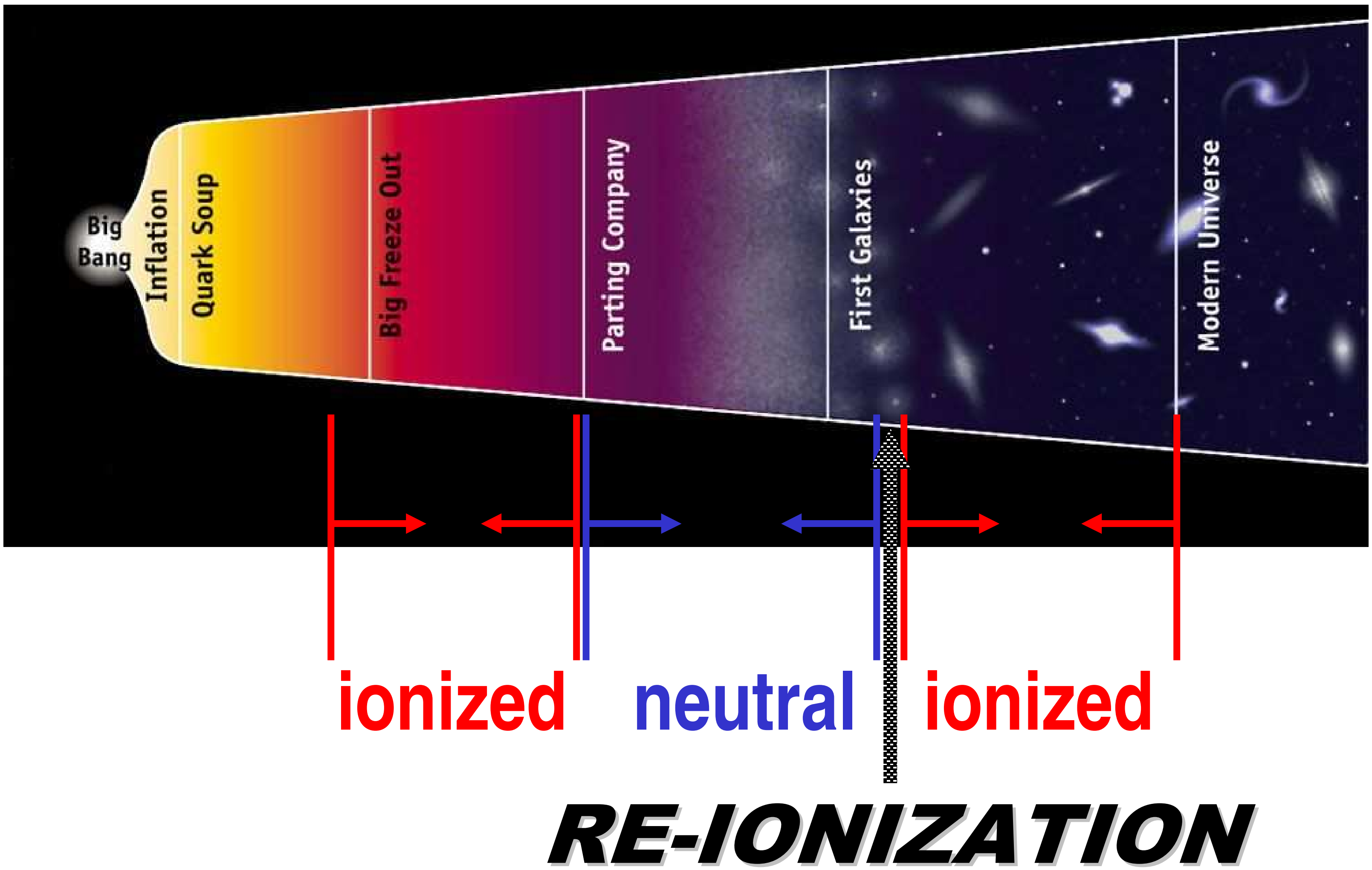


End of inflation
$z=10^{27}$
$t=10^{-36}s$

Recombination:
$z=1089$
$t=379$ kyr

Today:
$z=0$
$t=13.7$ Gyr

The Brief History of Time



Cooking Reionizable Universe

- dark matter dynamics
- gas dynamics
- star formation ⇦ the <u>only</u> phenomenology!
- metal cooling
- exact physics of primeval plasma
- fine print (secondary electrons, Ly-α pumping, …)
- radiative transfer

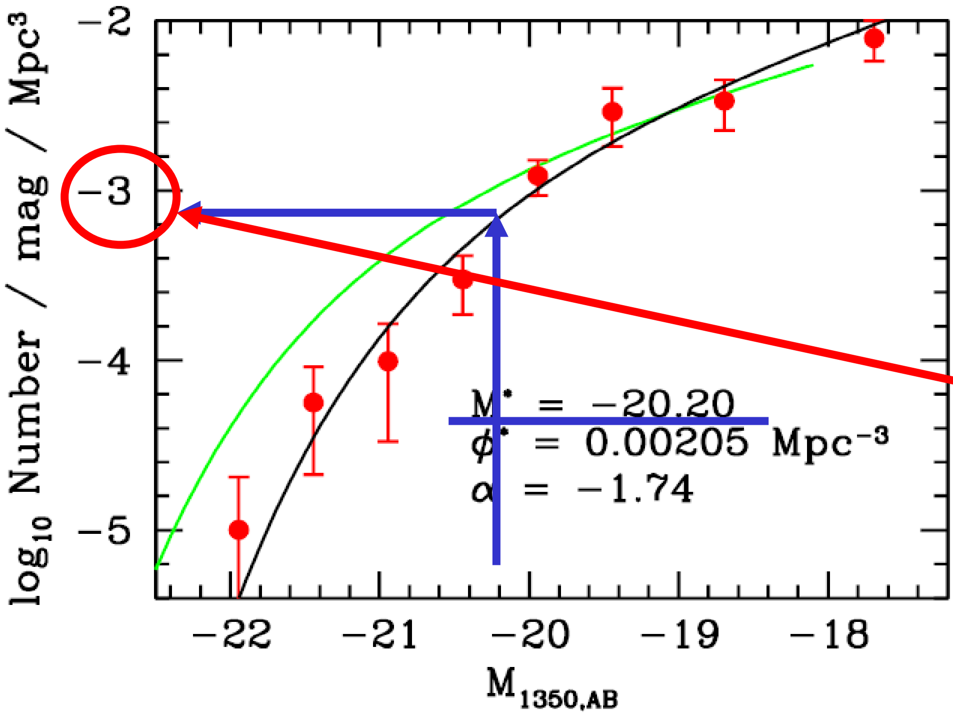
That's the key!

Note: non-existing things are not included

Sources & Sinks: Galaxies at z=6

• To the best of our knowledge today, reionization is produced by stars.

• Stars only form inside galaxies.

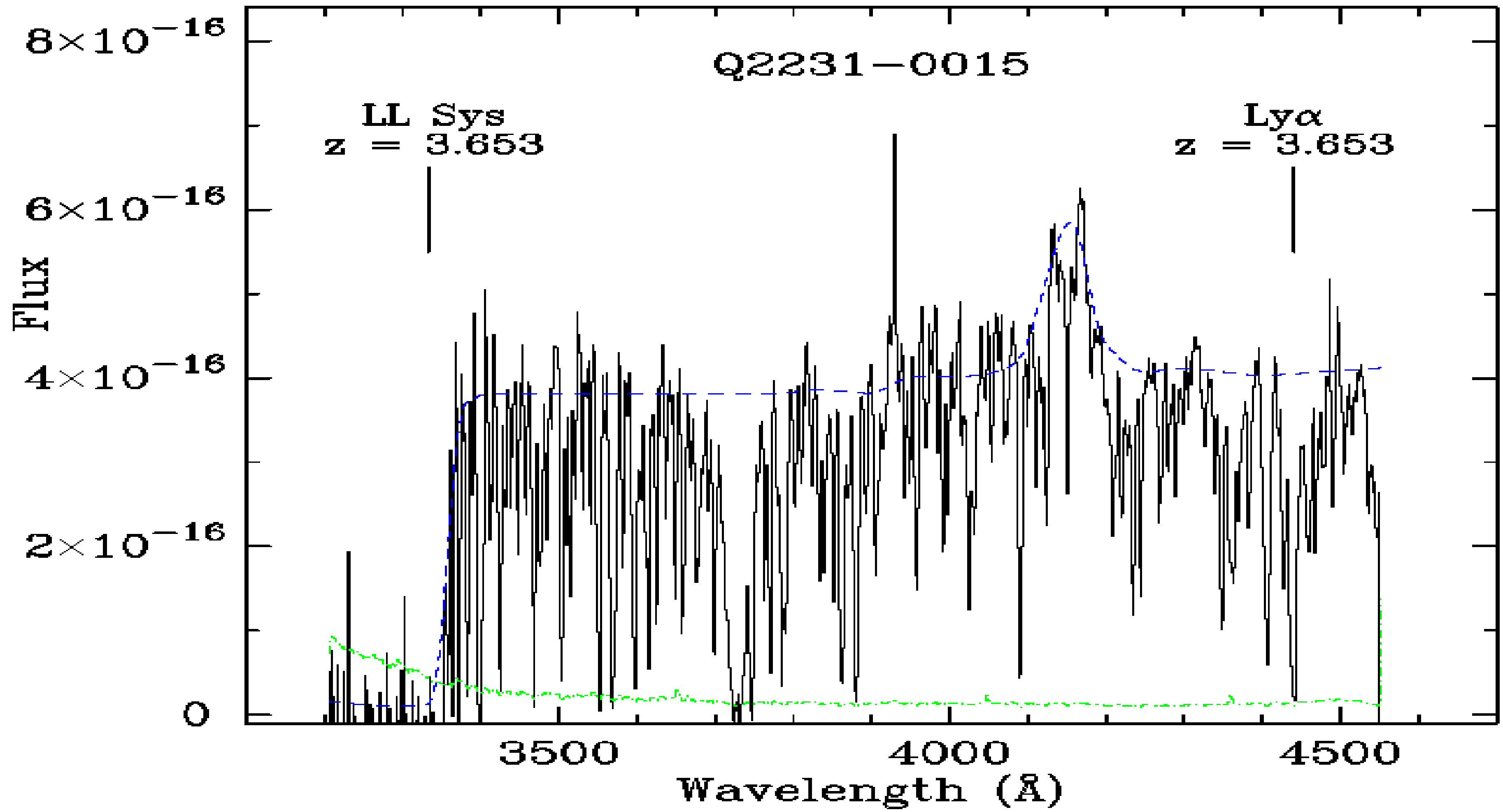


Galaxy LF at z=6

(Bouwens et al. 2006)

Need ~50 Mpc box (do not forget bias!)

Sources & Sinks II: Lyman-Limit Systems



Sources & Sinks III:

- LL systems determine the Mean Free Path (MFP) of an ionizing photon at z=4
(mfp = 0.034 c/H = 17 h^{-1} Mpc proper = 85 CHIMP). But it will be smaller at z>6.
- You need at least 1 kpc (proper) spatial resolution to resolve LL systems (0.5 kpc is even better).

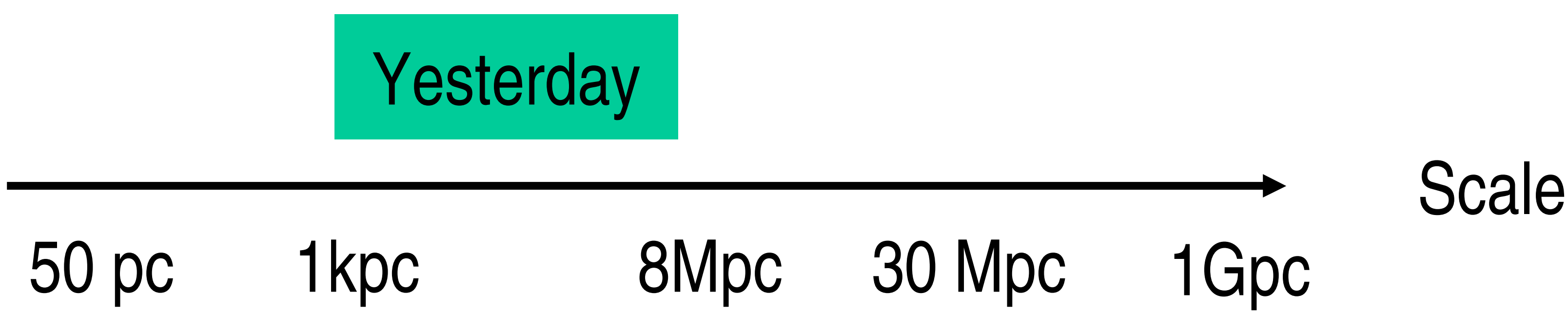
Ideal reionization simulation:

- Spatial resolution: 2 h^{-1} kpc
- Box size: 50 h^{-1} Mpc

That's tough!

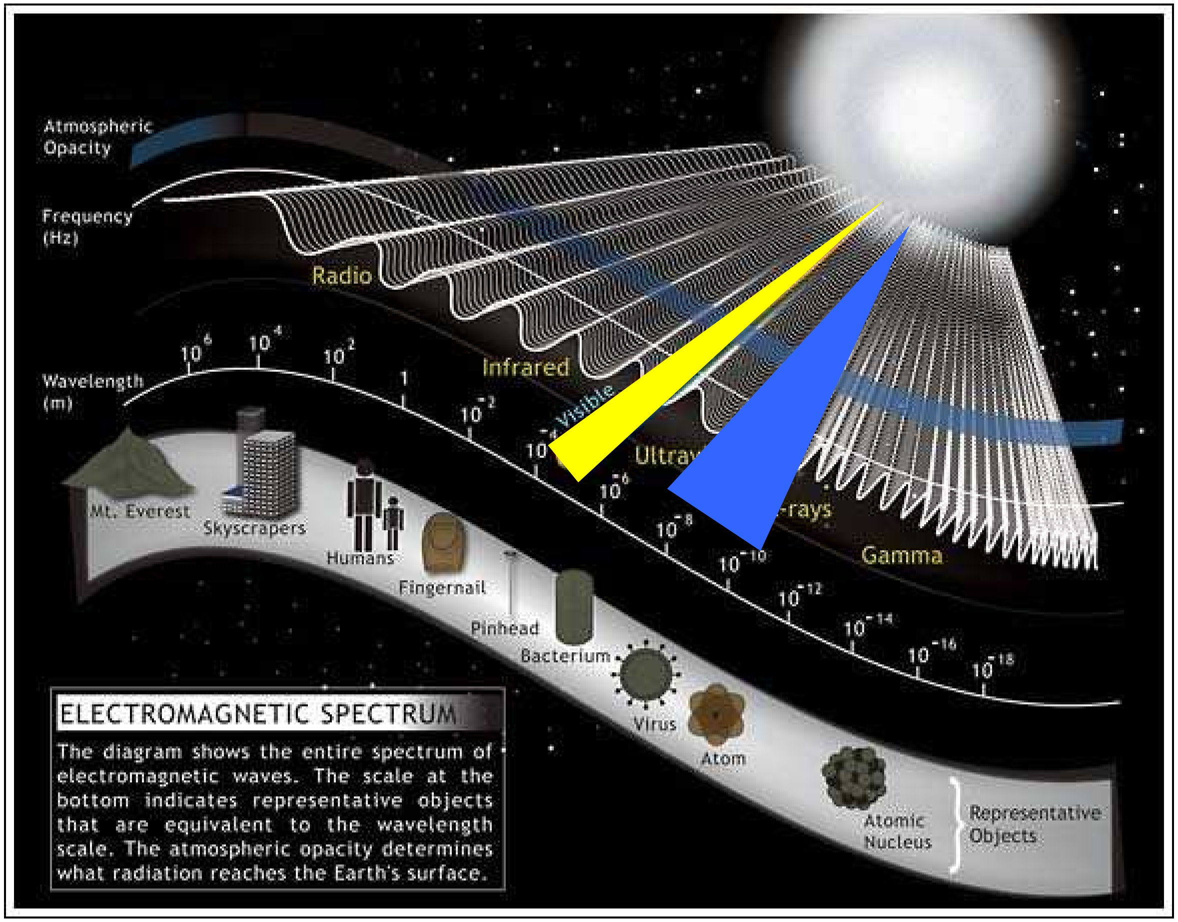
Yesterday's Simulations
(a brute force approach)

- Only galaxies as sources
- Mostly mean properties
- ISM is not resolved

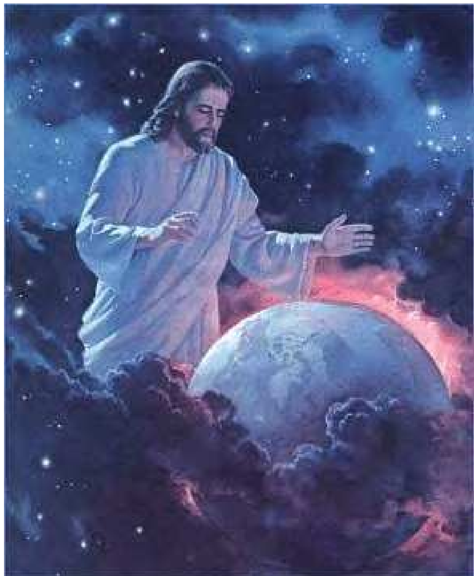


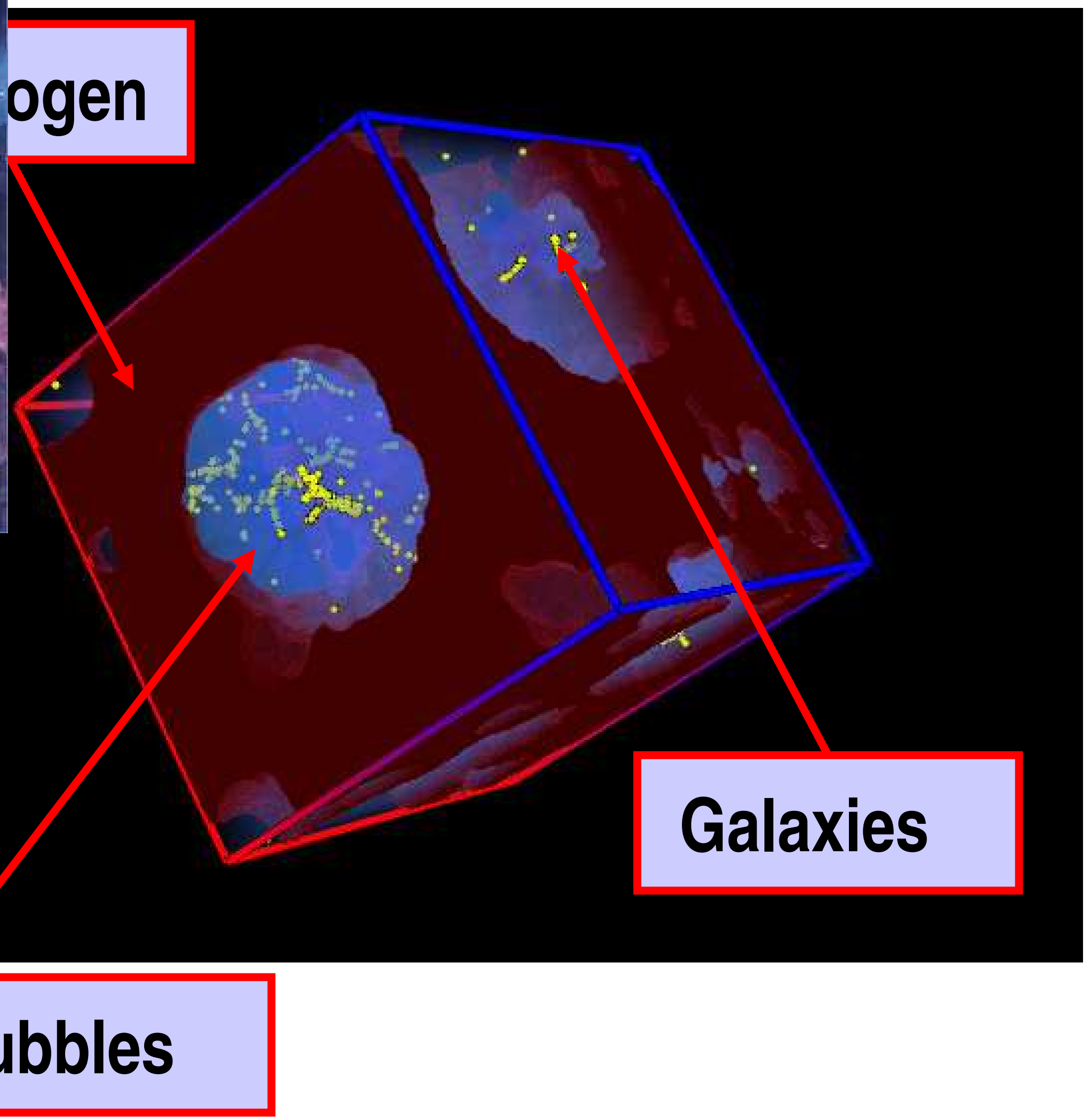
How It All Happens...

(or what we would see if the Sun was much hotter)

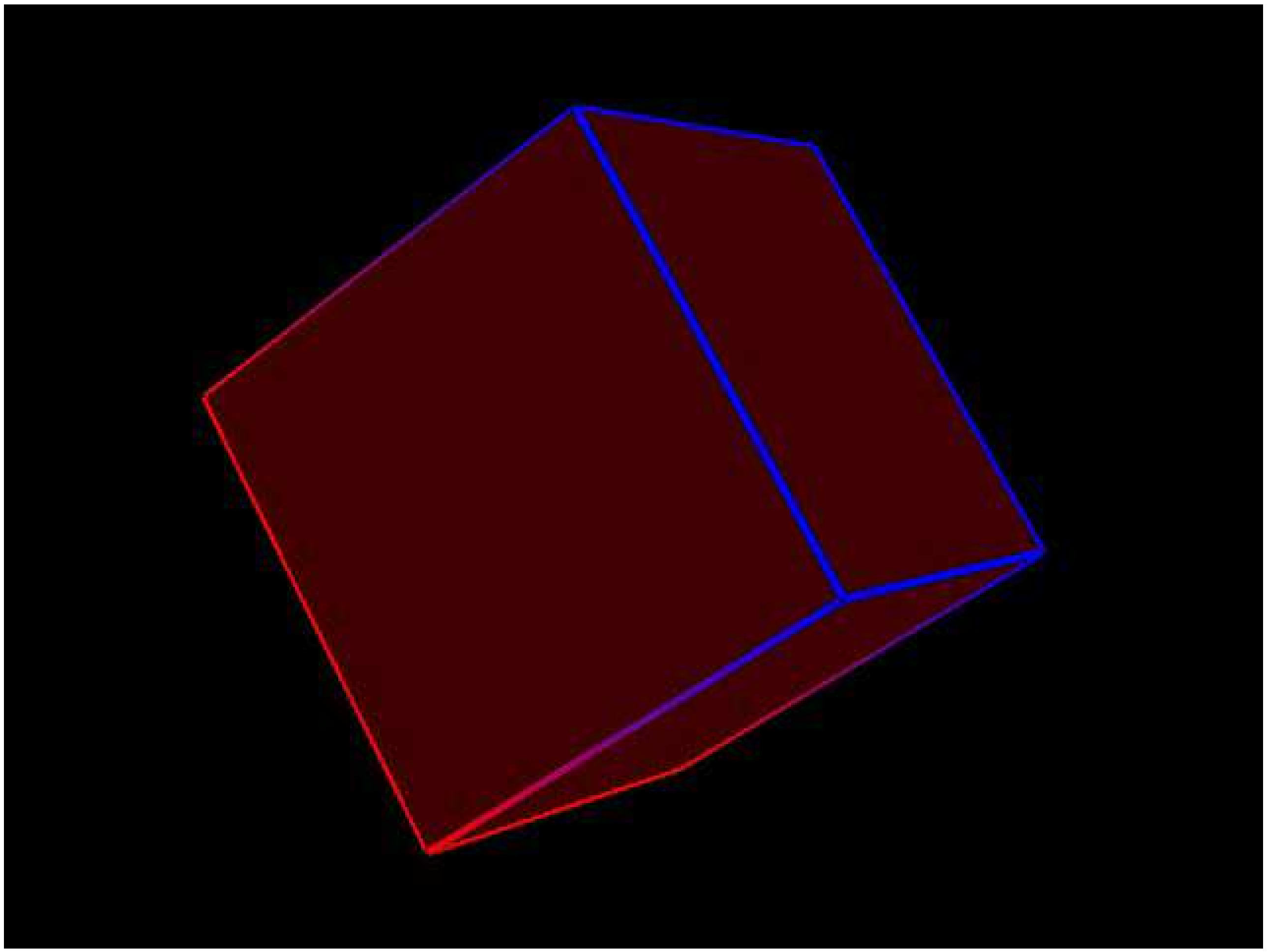


Let Us Be Gods...

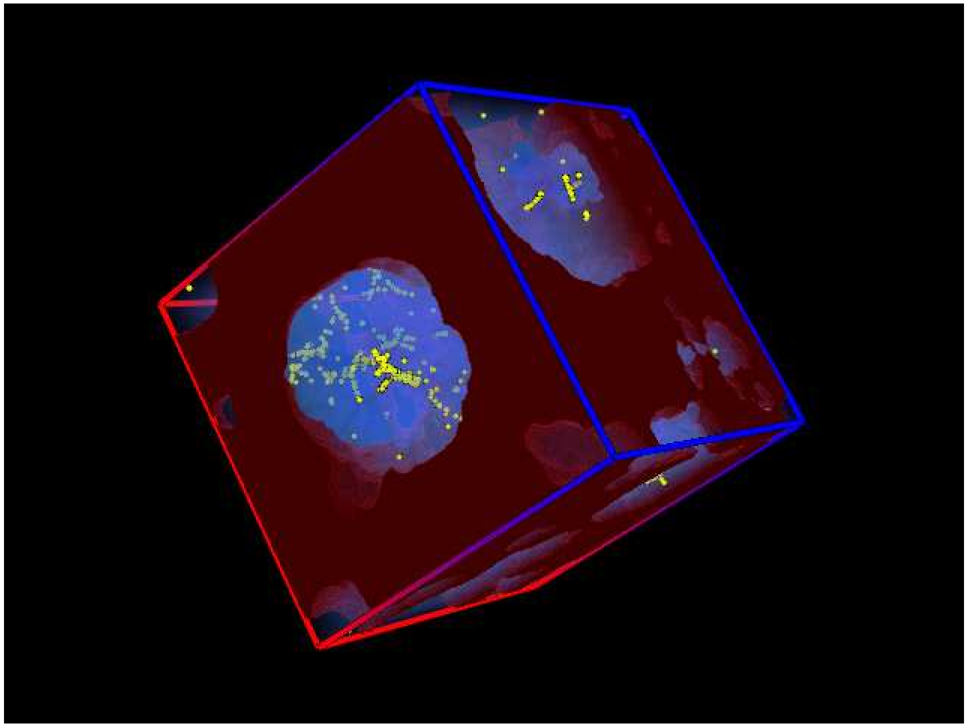




How It All Happens...

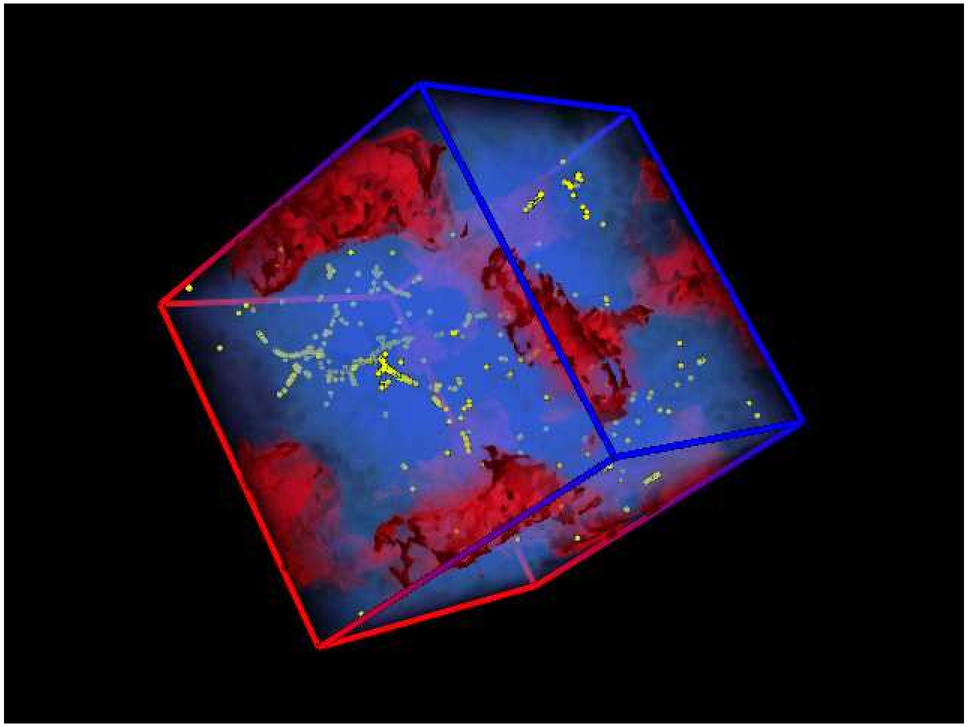


How It All Happens



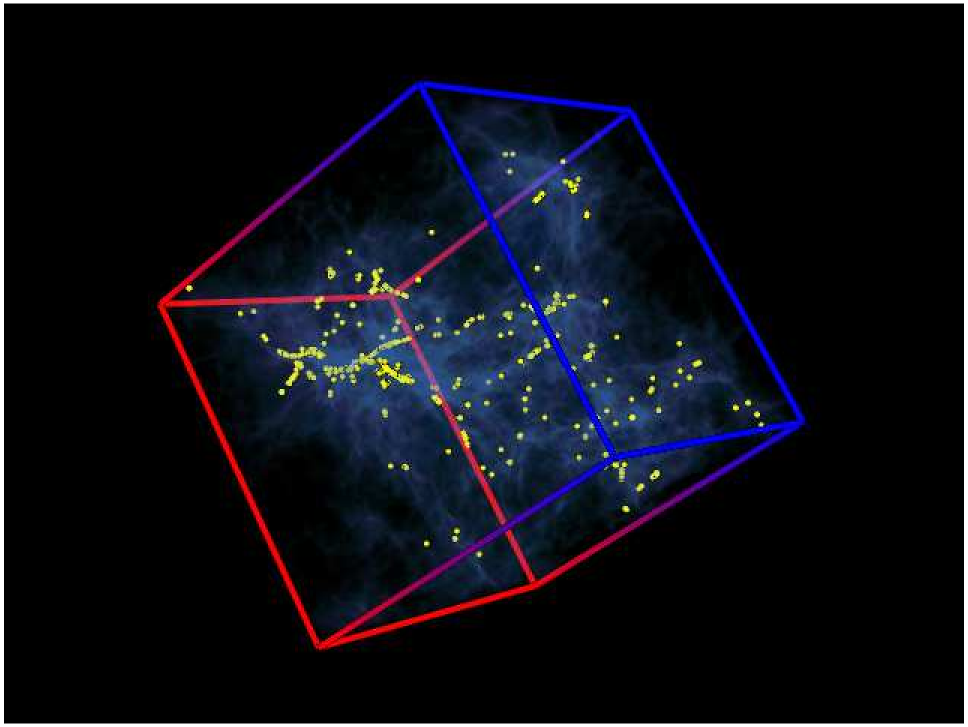
Pre-overlap: **Ionized bubbles expand in the low density gas.**

How It All Happens



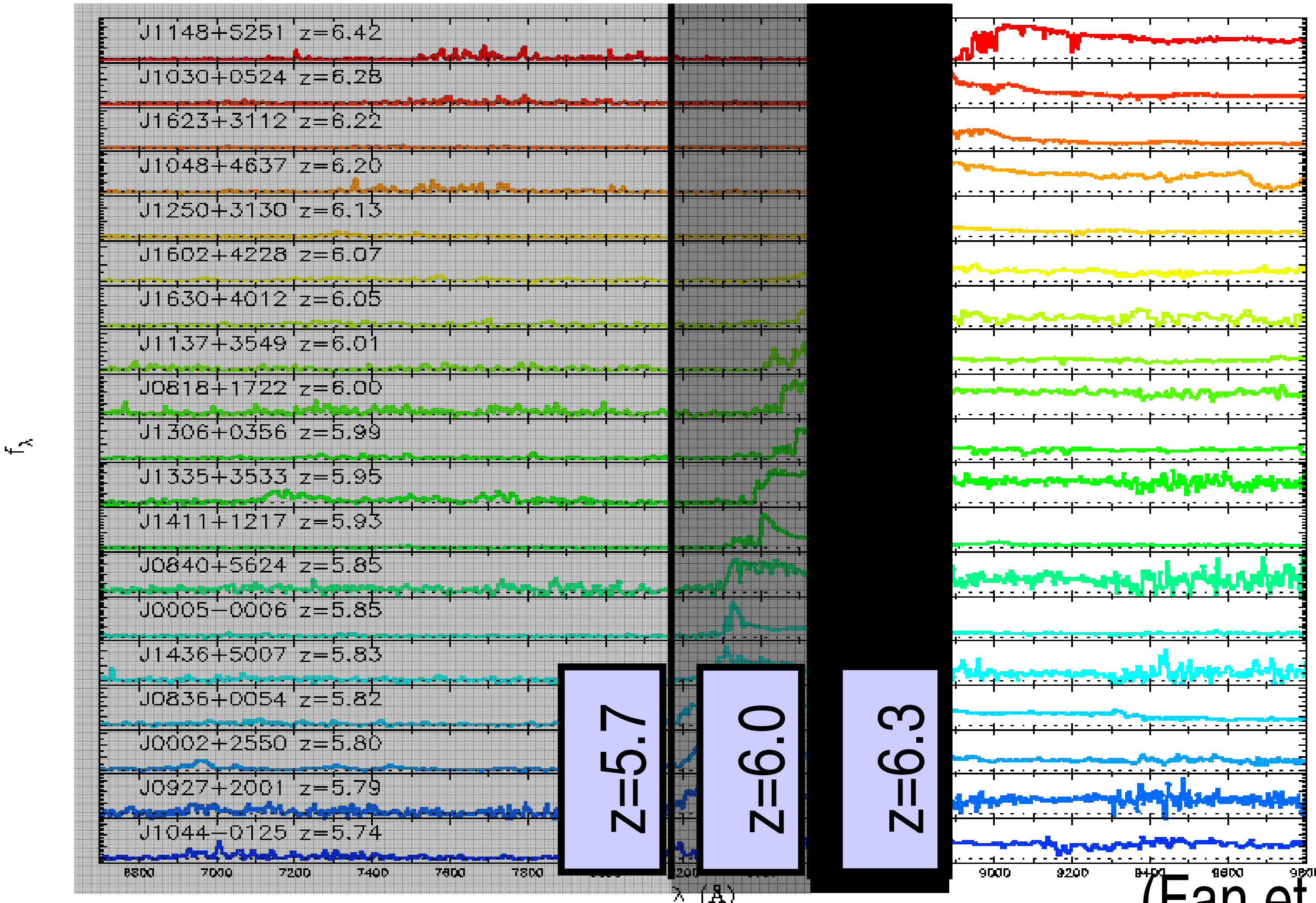
Overlap: **Ionized bubbles merge – the moment of *reionization*.**

How It All Happens



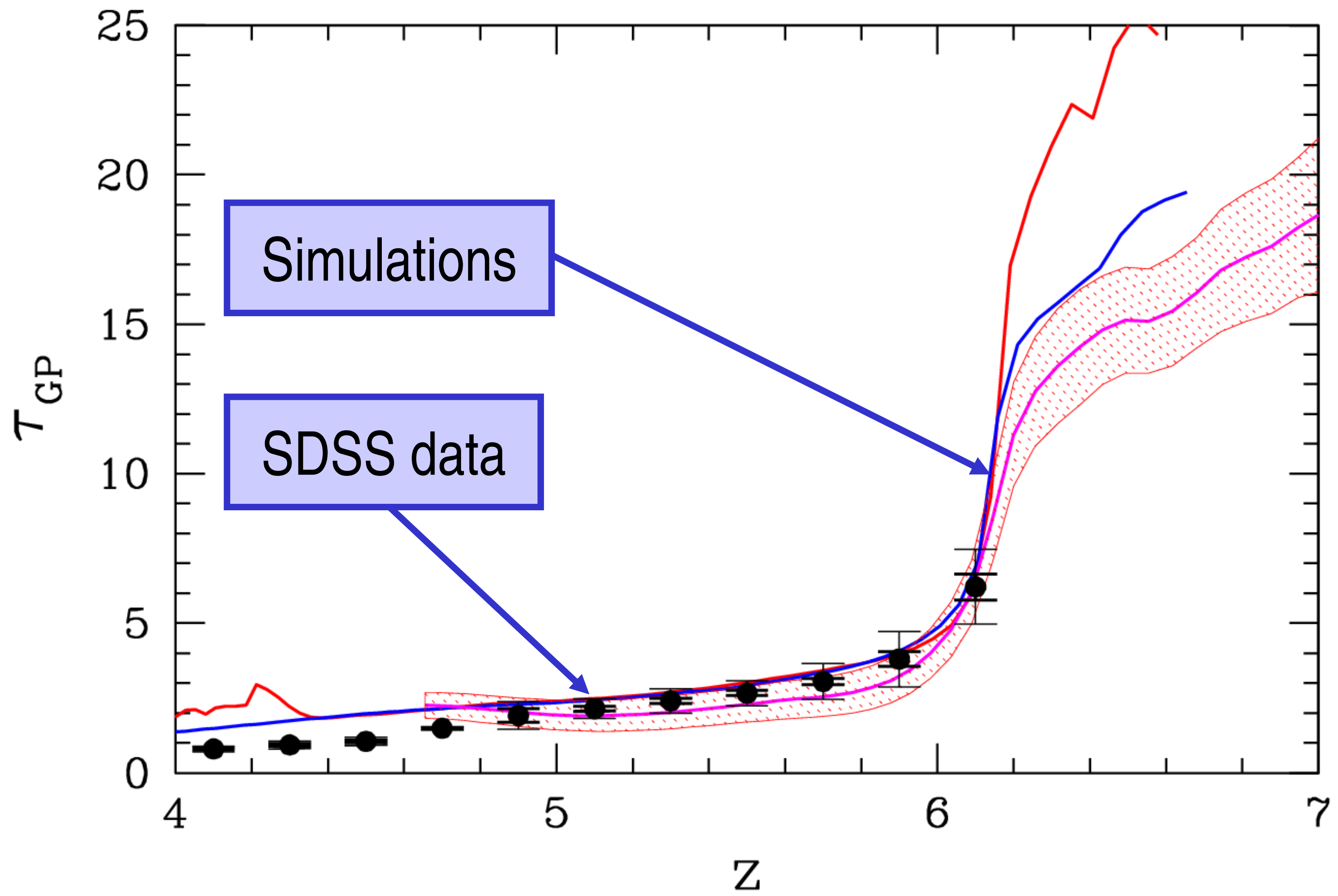
Post-overlap: Most of gas in the universe is highly ionized.

What We Know About Reionization



(Fan et al 2005)

The Power of Sloan



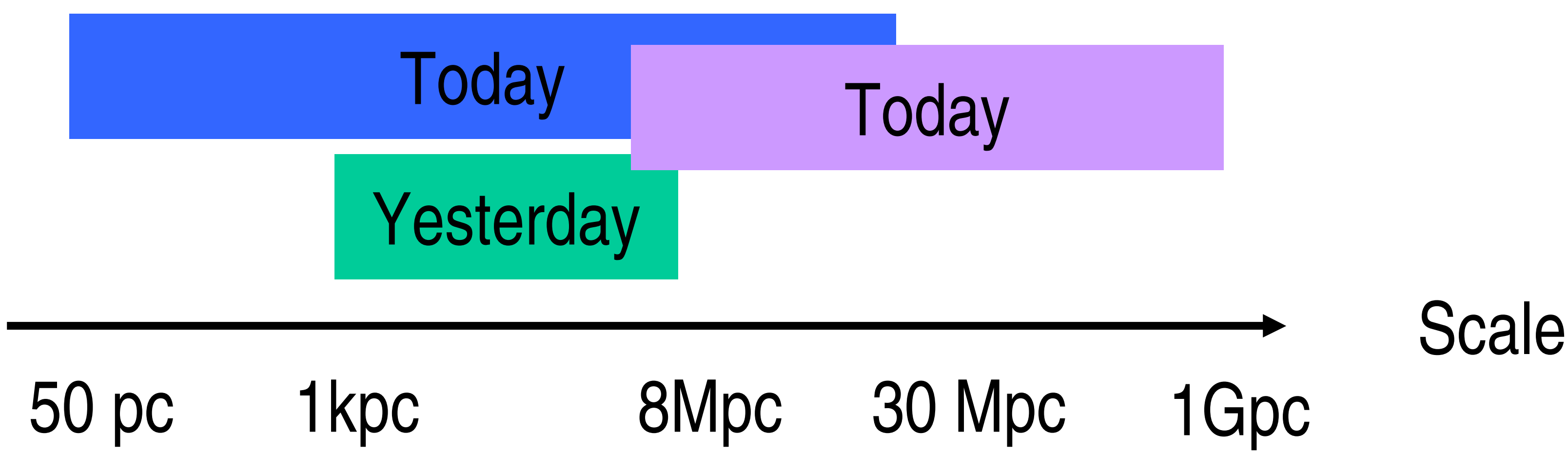
Yesterday's Simulations

- Helped to understand the process of reionization.
- Reached close to numerical convergence.
- Helped to measure the redshift of overlap from the data.
- Provided some assurance that we are on the right way.

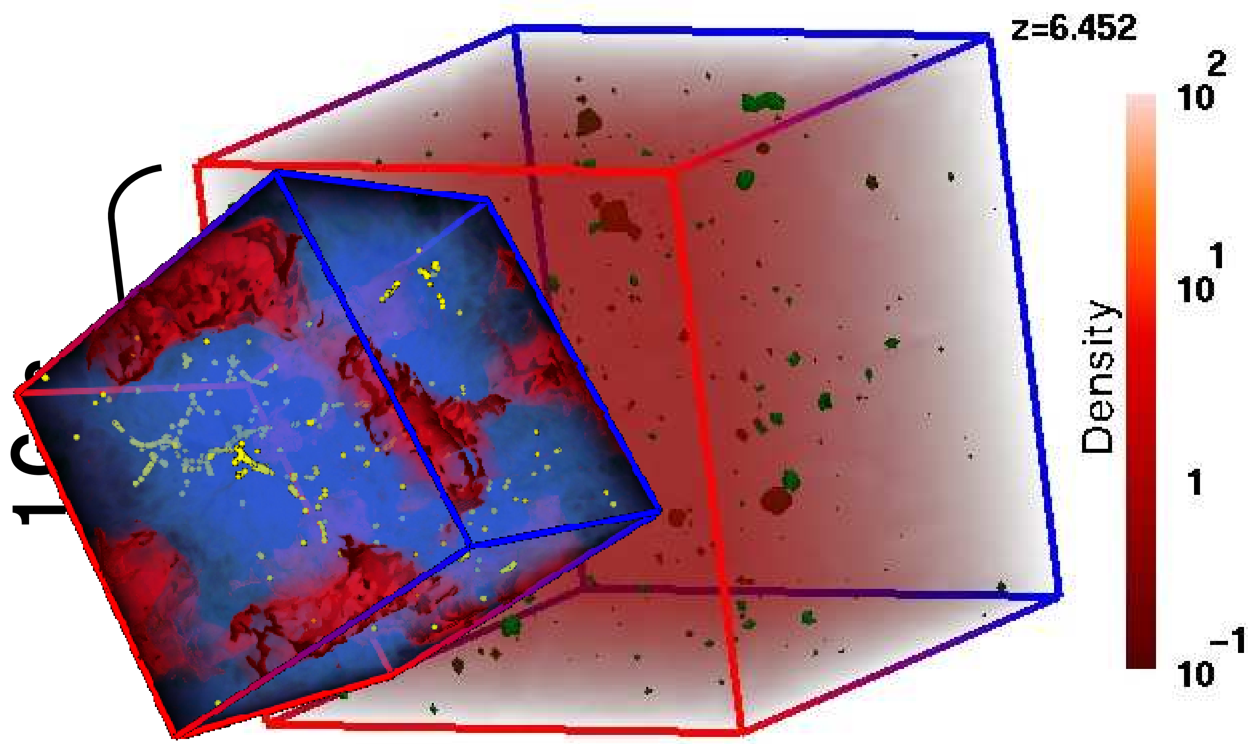
[illegible]

Today's Simulations
(a smart approach)

- Include bright quasars and large volumes
- Detailed morphology of HII regions on all scales
- Escape of ionizing radiation from the ISM is resolved



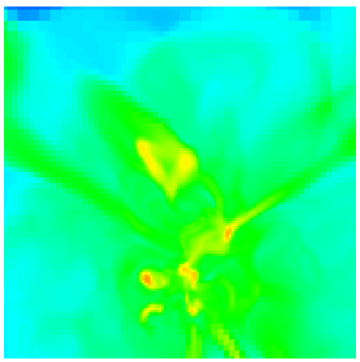
Large Scales



Small box → sub-cell model for the large box
(clumping factors)

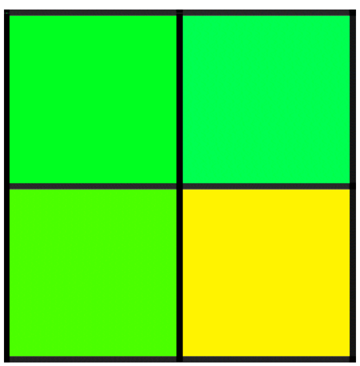
Clumping Factors

$$\frac{dn_{\mathrm{H\,I}}}{dt} = -n_{\mathrm{H\,I}}\Gamma + R(T)n_e n_{\mathrm{H\,II}}$$



Real universe:

- Gas has structure on all scales



Simulation:

- Resolution is finite.
- It can only deal with quantities defined over 1 cell.

Clumping Factors II

$$\langle \frac{dn_{\mathrm{H\,I}}}{dt} \rangle_{\mathrm{cell}} = -\langle n_{\mathrm{H\,I}} \Gamma \rangle_{\mathrm{cell}} + \langle R(T) n_e n_{\mathrm{H\,II}} \rangle_{\mathrm{cell}}$$

$$\frac{d\tilde{n}_{\mathrm{H\,I}}}{dt} = -C_I \tilde{n}_{\mathrm{H\,I}} \tilde{\Gamma} + C_R \tilde{R} \tilde{n}_e \tilde{n}_{\mathrm{H\,II}}$$

“Clumping factors”

Clumping Factors III

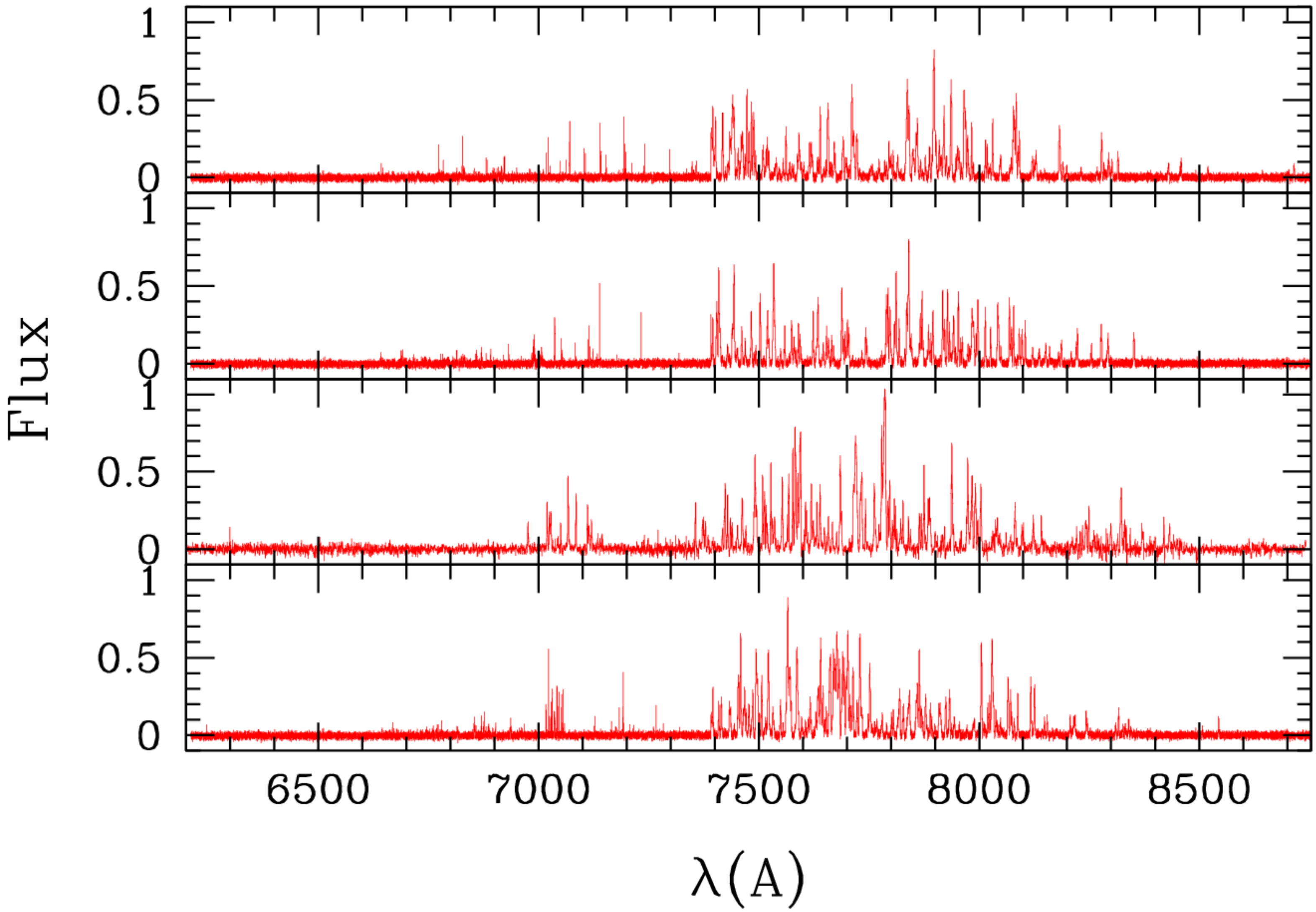
Recombination clumping factor:

$$C_R = \frac{\langle R(T) n_e n_{\mathrm{H\,II}} \rangle_{\mathrm{cell}}}{\langle R(T) \rangle_{\mathrm{cell}} \langle n_e \rangle_{\mathrm{cell}} \langle n_{\mathrm{H\,II}} \rangle_{\mathrm{cell}}}$$

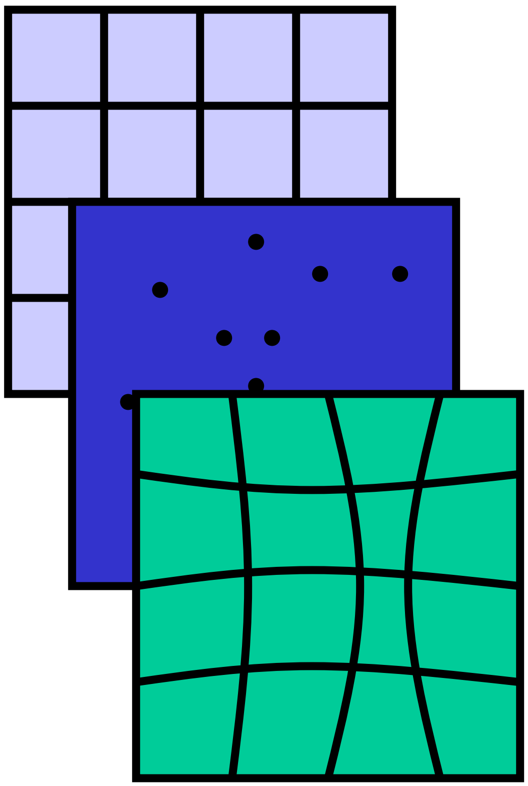
Ionization clumping factor

$$C_I = \frac{\langle n_{\mathrm{H\,I}} \Gamma \rangle_{\mathrm{cell}}}{\langle n_{\mathrm{H\,I}} \rangle_{\mathrm{cell}} \langle \Gamma \rangle_{\mathrm{cell}}}$$

Find the SDSS Quasar

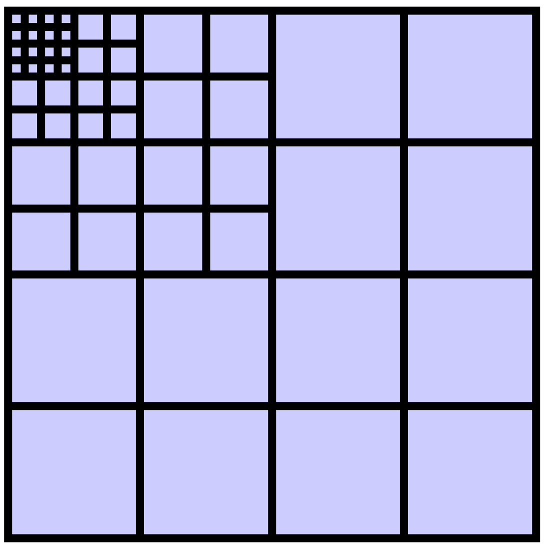


A Quiet Revolution:
XX Century



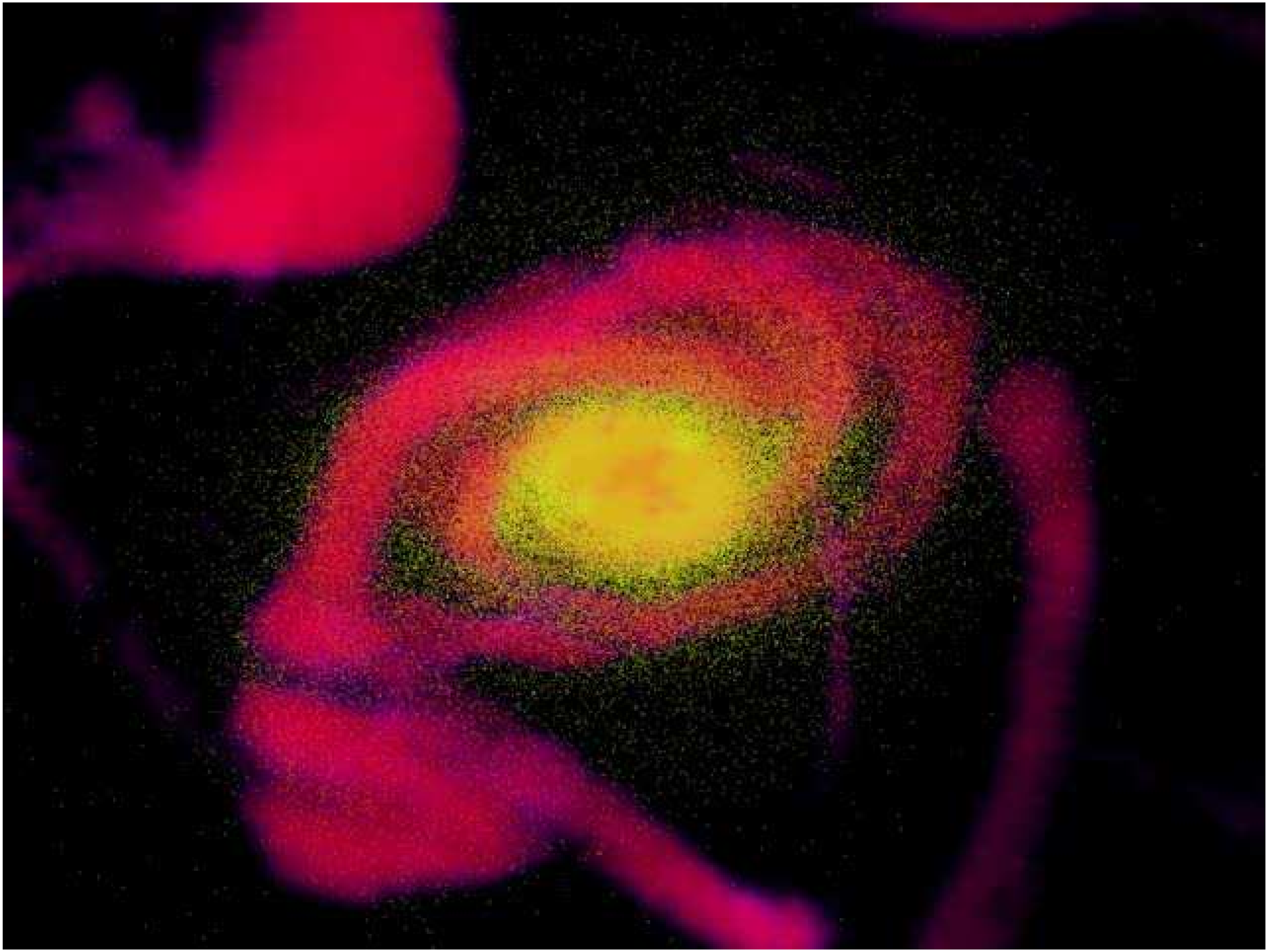
- Eulerian schemes
- Smooth Particle “Hydrodynamics” (SPH)
- Arbitrary Lagrangian-Eulerian (ALE)

A Quiet Revolution: XXI Century

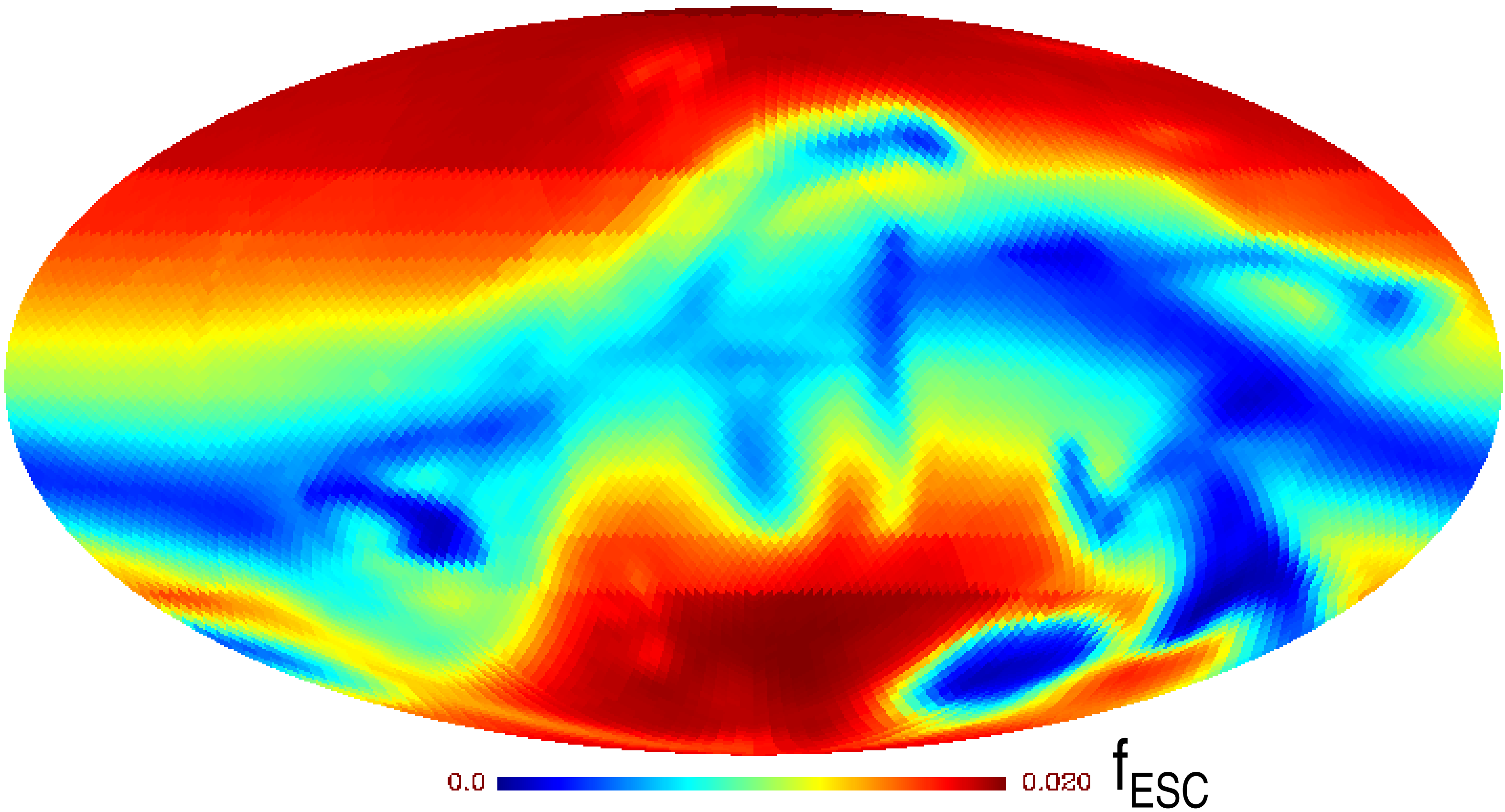


- Adaptive Mesh Refinement (AMR)

  ✓ *can follow fragmentation*
  ✓ *non-uniform initial conditions*
  ✓ *spatially variable resolution*
  ✓ *faster-than-Lagrangian*

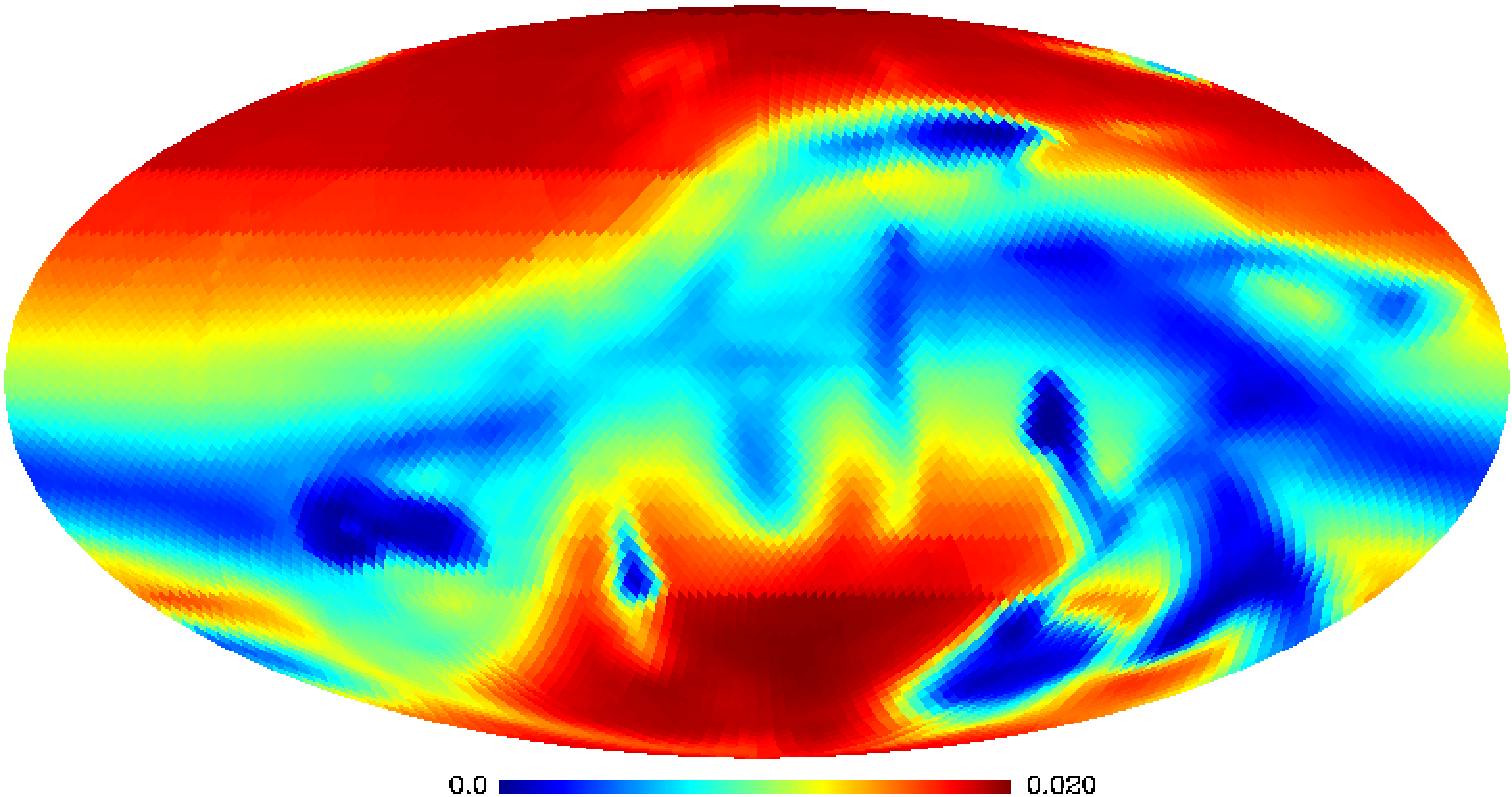


A View from the Source



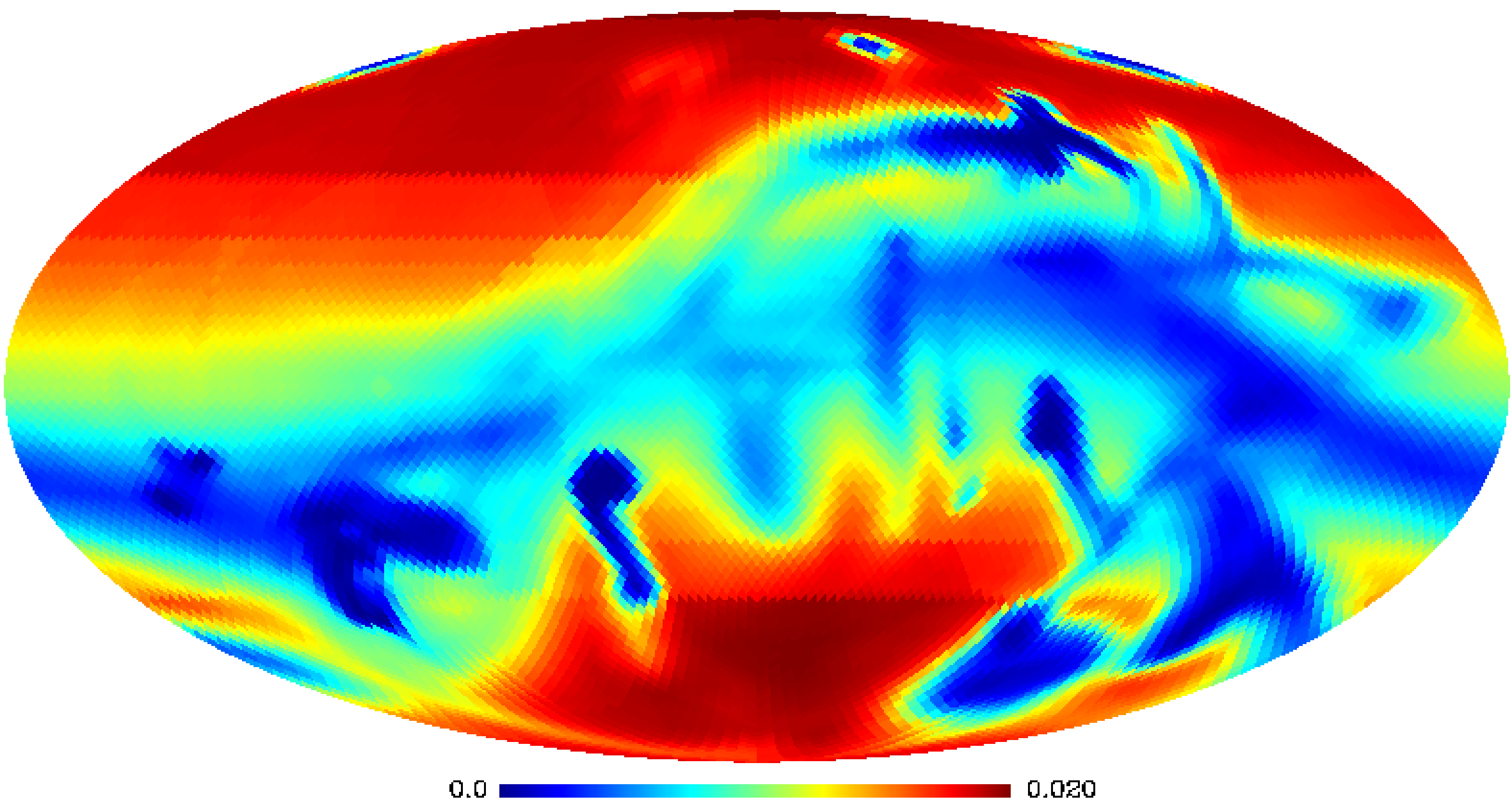
@ D = 0.5 R_{VIR} (50 h^{-1} kpc, 0.0006 λ_{LL})

A View from the Source



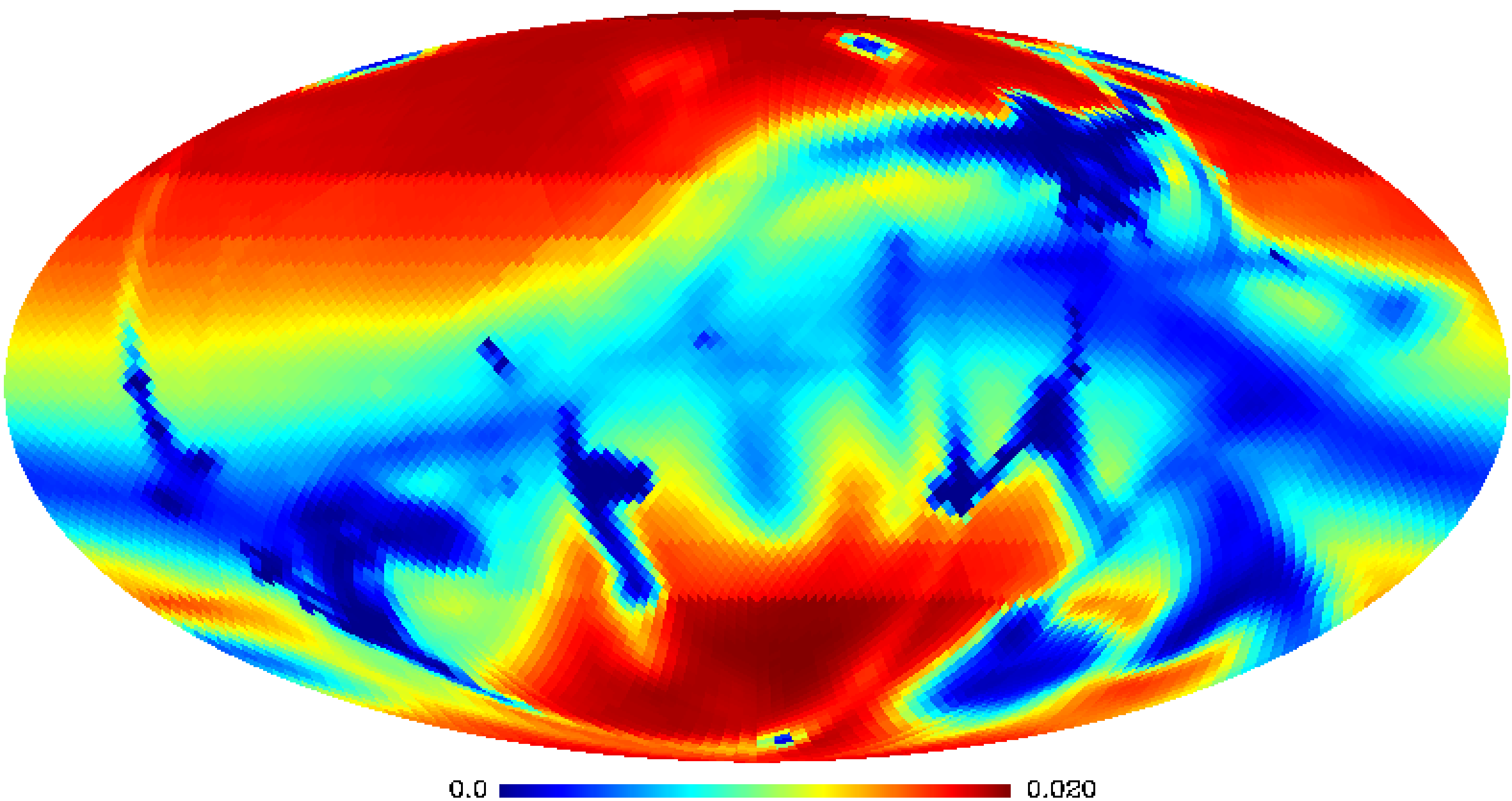
@ D = 1.0 R_{VIR} (100 h^{-1} kpc, 0.0012 λ_{LL})

A View from the Source



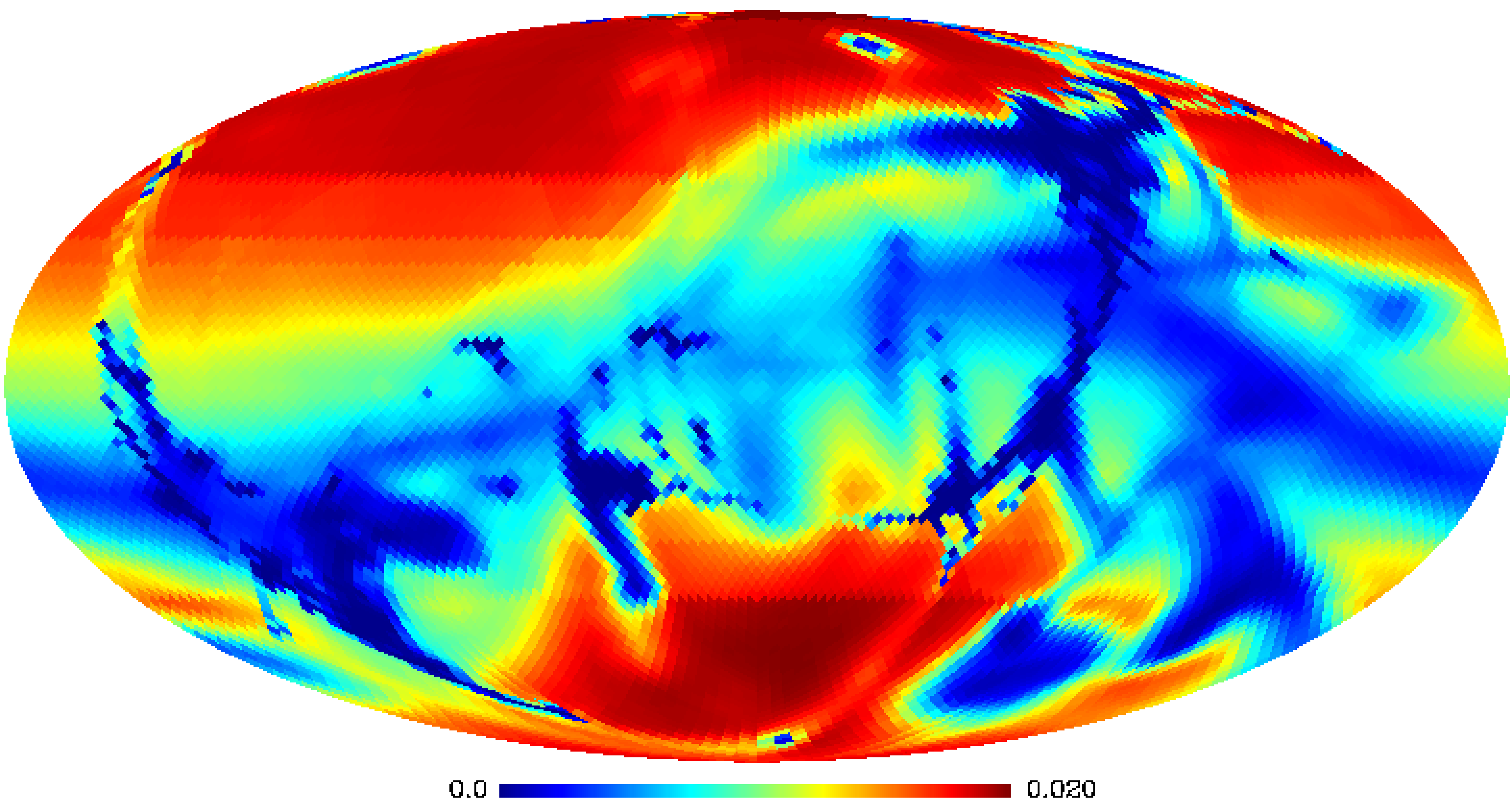
@ D = 2.0 R_{VIR} (200 h^{-1} kpc, 0.0025 λ_{LL})

A View from the Source



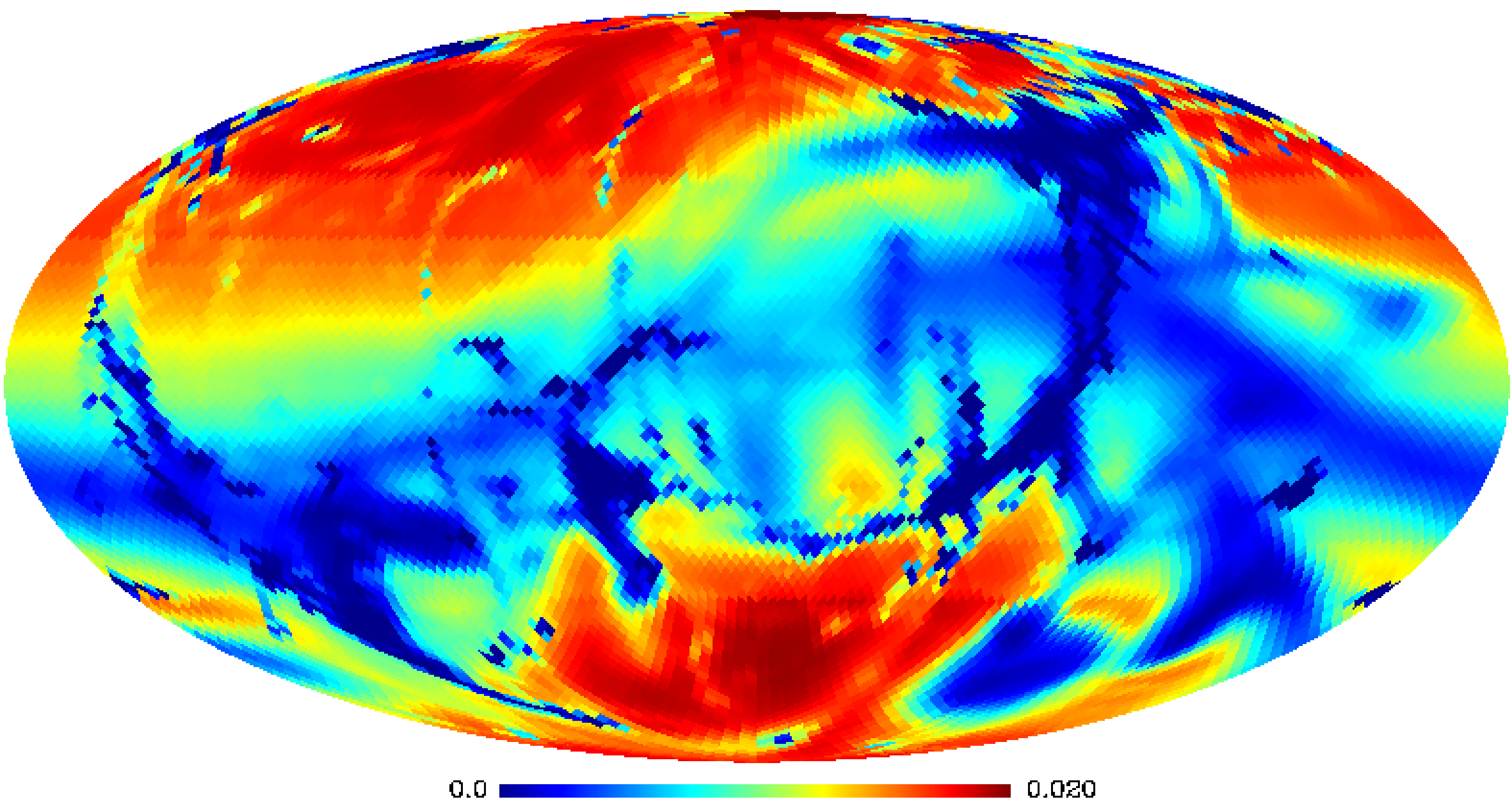
@ D = 5.0 R_{VIR} (500 h^{-1} kpc, 0.005 λ_{LL})

A View from the Source



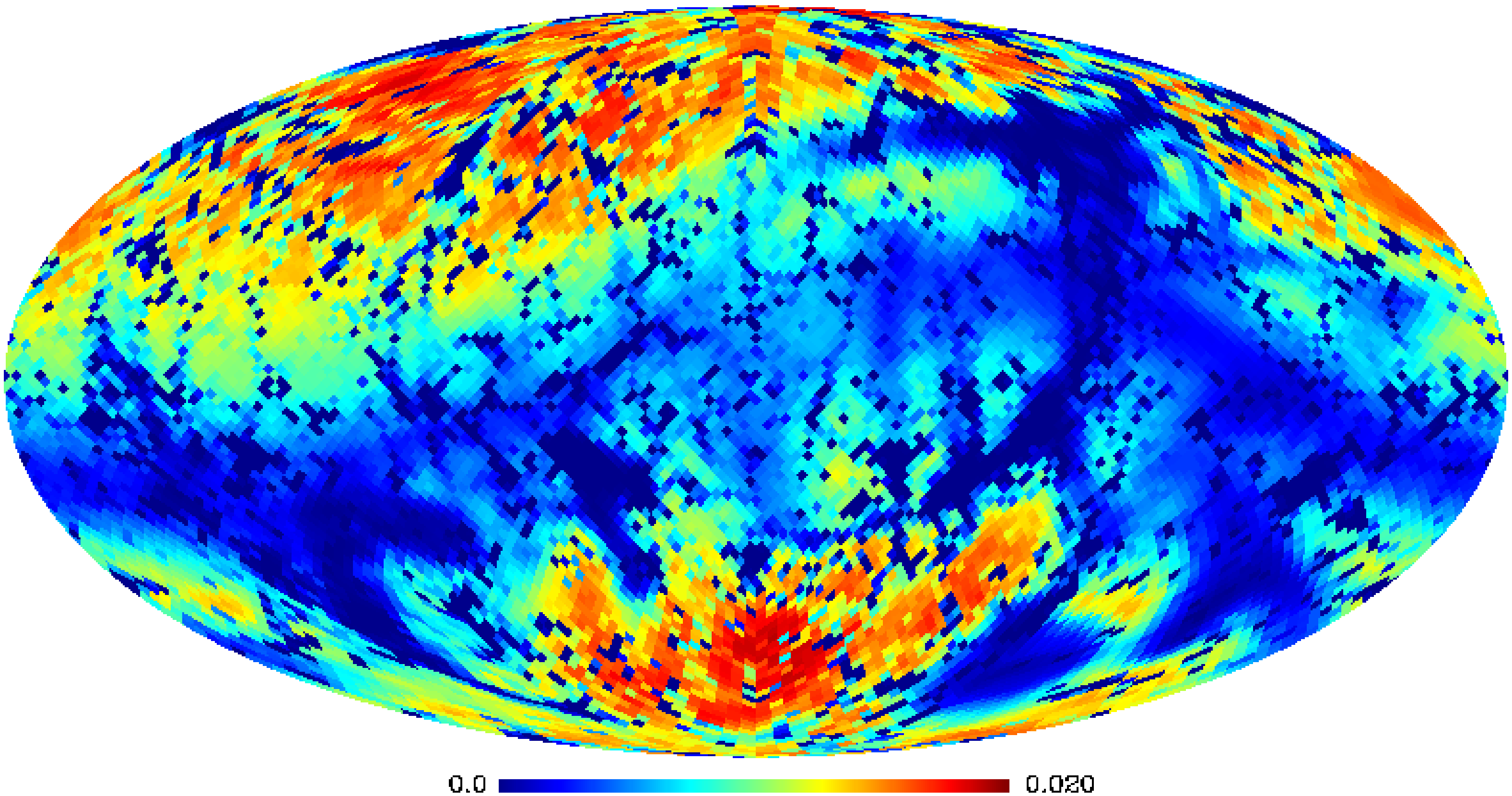
@ D = 10 R_{VIR} (1 h^{-1} Mpc, 0.01 λ_{LL})

A View from the Source



@ $D = 30\ R_{VIR}$ ($3\ h^{-1}$ Mpc, $0.03\ \lambda_{LL}$)

A View from the Source



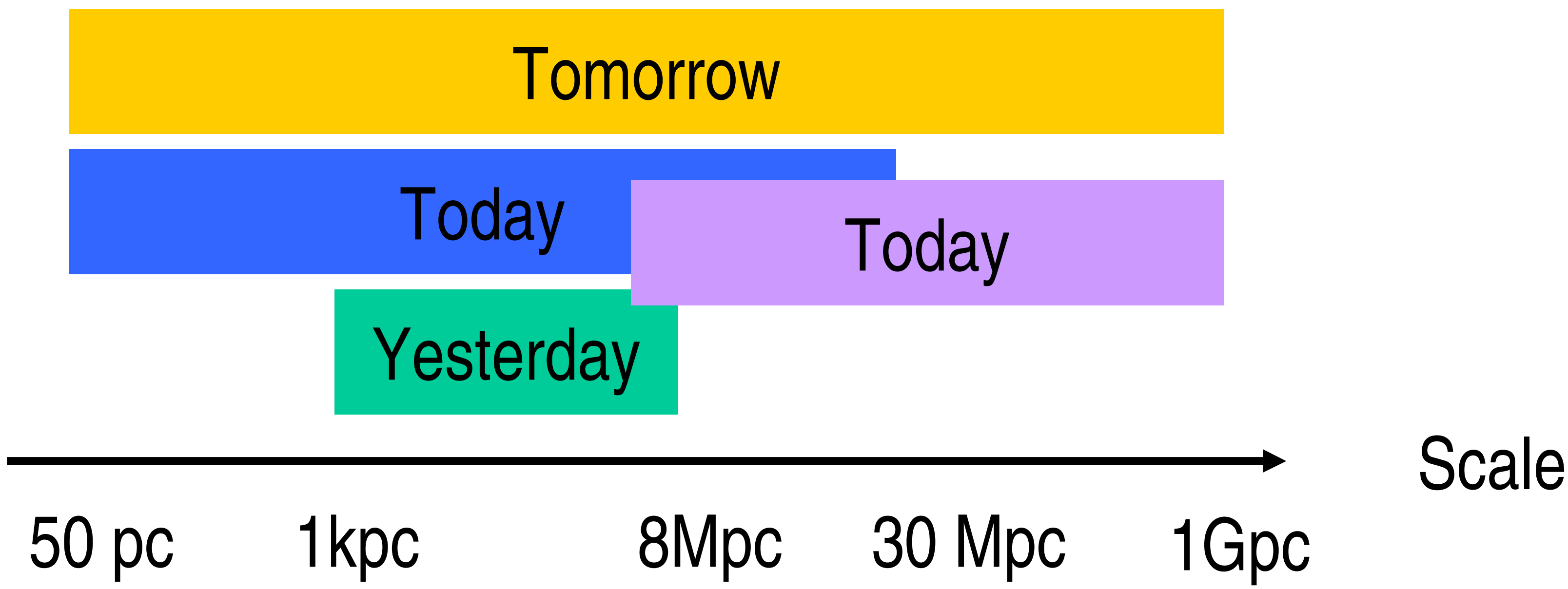
@ D = 100 R_{VIR} (10 h^{-1} Mpc, 0.1 λ_{LL})

Today's Simulations

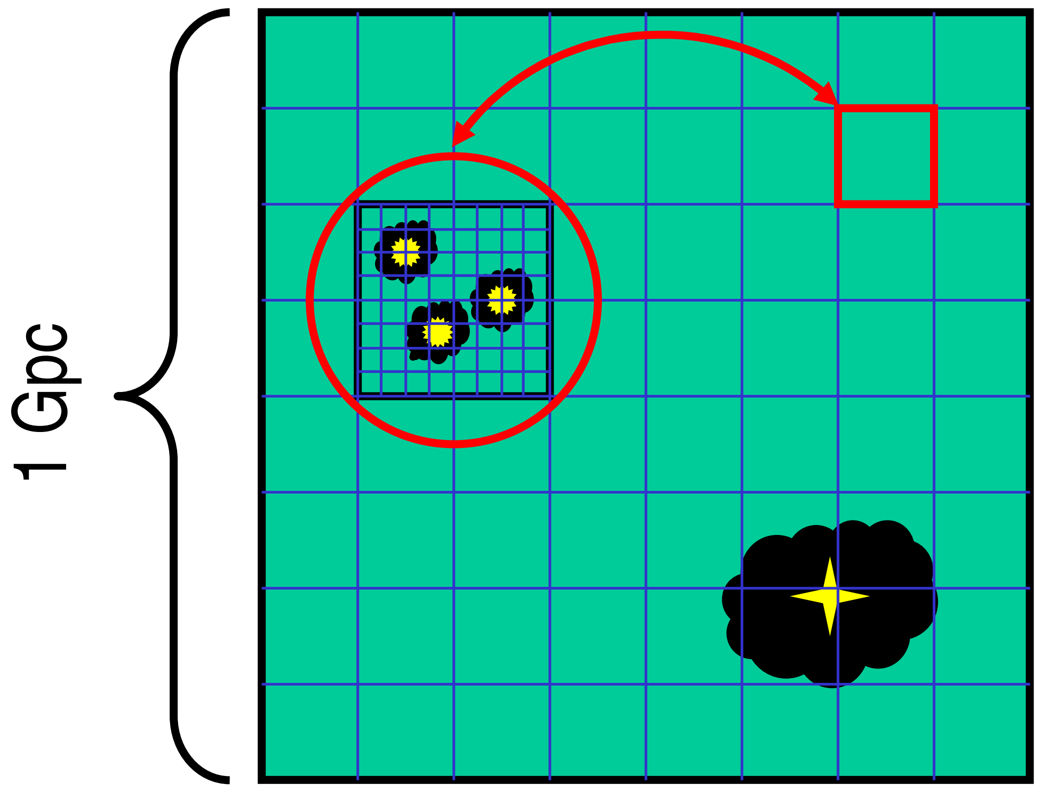
- Can be used to provide adequate theoretical predictions for all existing observations of $z>5$ universe.
- Serve as testing grounds for developing methods for analyzing $z>5$ Lyman-α forest data.
- Will give us deep insights in the detailed formation of early galaxies and supermassive black holes.

Tomorrow’s Simulations
(a smart brute force approach)

- Self-consistently treat clumping factors “on the fly”

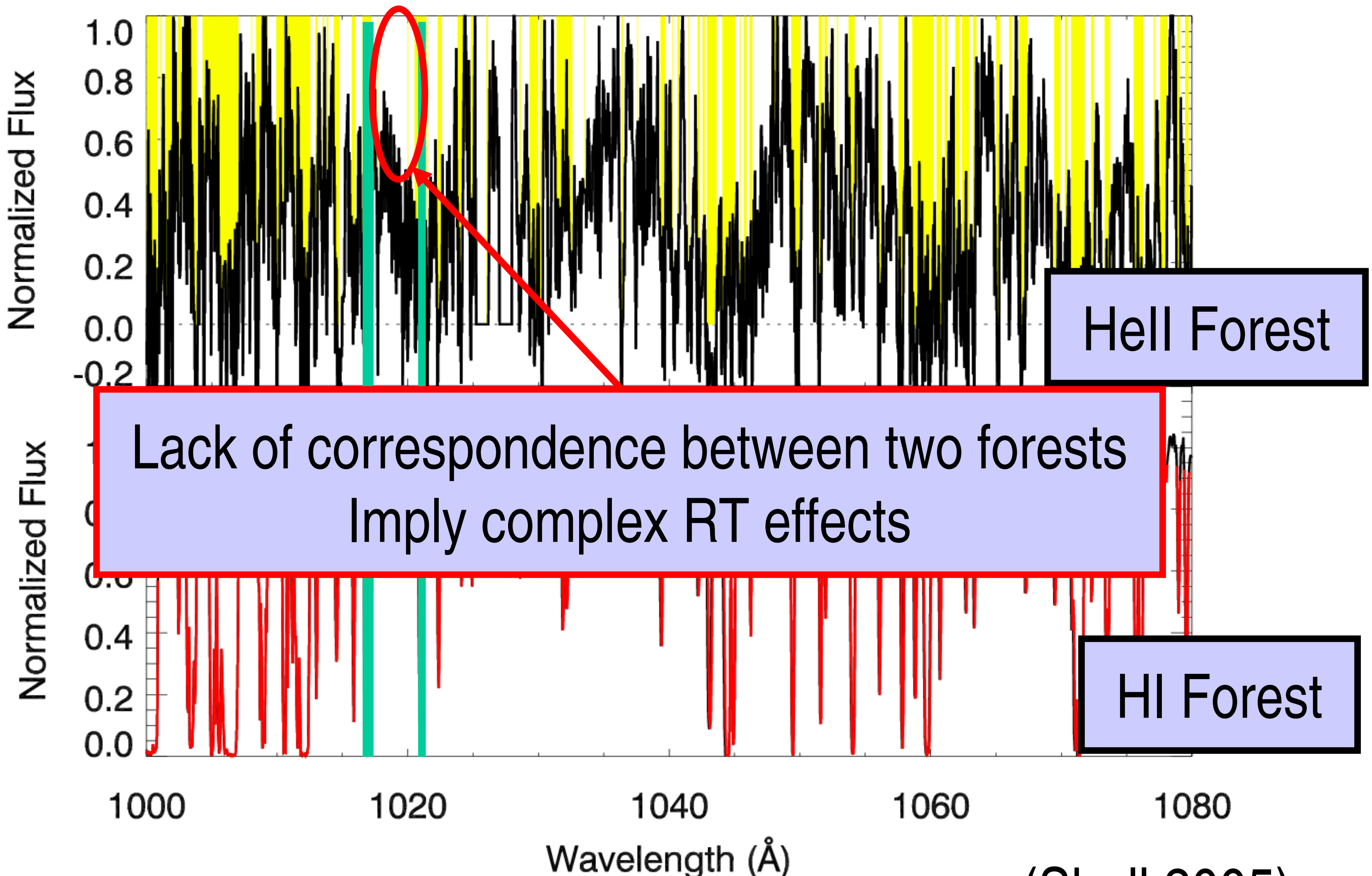


Simulation Royal



Use highly refined sub-volumes to compute the clumping factors "on the fly".

The Ultimate Prize



(Shull 2005)

Tomorrow's Simulations

- Will be able to model with reasonable quantitative precision the evolution of the IGM on a wide range of scales up to z~2 (beyond Helium reionization).
- Will be important for studying Helium reionization and the relationship between hydrogen and helium Lyman-α forests.
- Will be useful for understanding the details of escape of ionizing radiation from galaxies and quasars at high and intermediate redshifts.
- Something we haven't anticipated…

Conclusions

- Numerical simulations of reionization passed the infant stage: we can now model large enough boxes to obtain converged results on average properties of the IGM.
- Current simulations will be able to resolve the ISM in star forming galaxies at $z>6$ (in small boxes) and to model absorption spectra of individual $z\sim6$ quasars (in large boxes).
- Future simulations will be able to achieve a dynamic range of > 10,000,000 (in small fraction of the volume) and treat the rest of the IGM fully self-consistently via the clumping factors formalism.

The End