

Simulating Reionization: Yesterday, Today, Tomorrow



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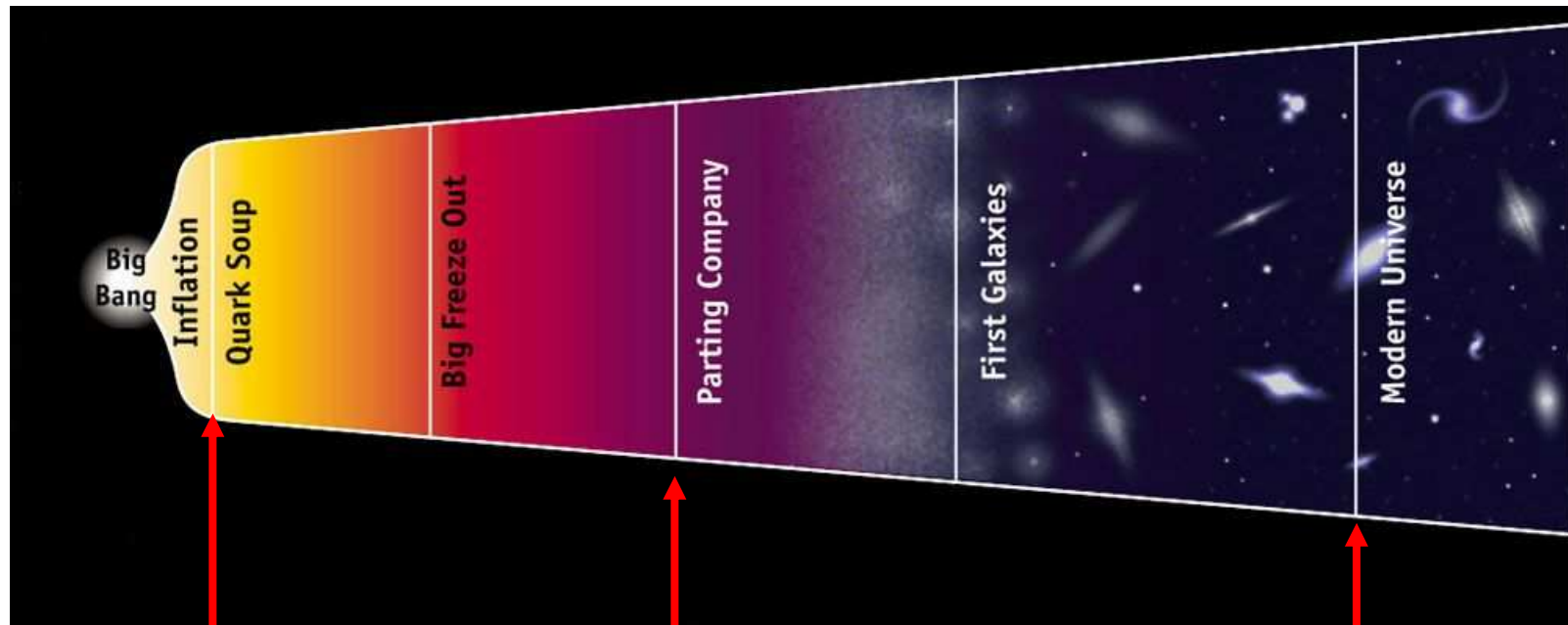


Outline

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



The Brief History of Time



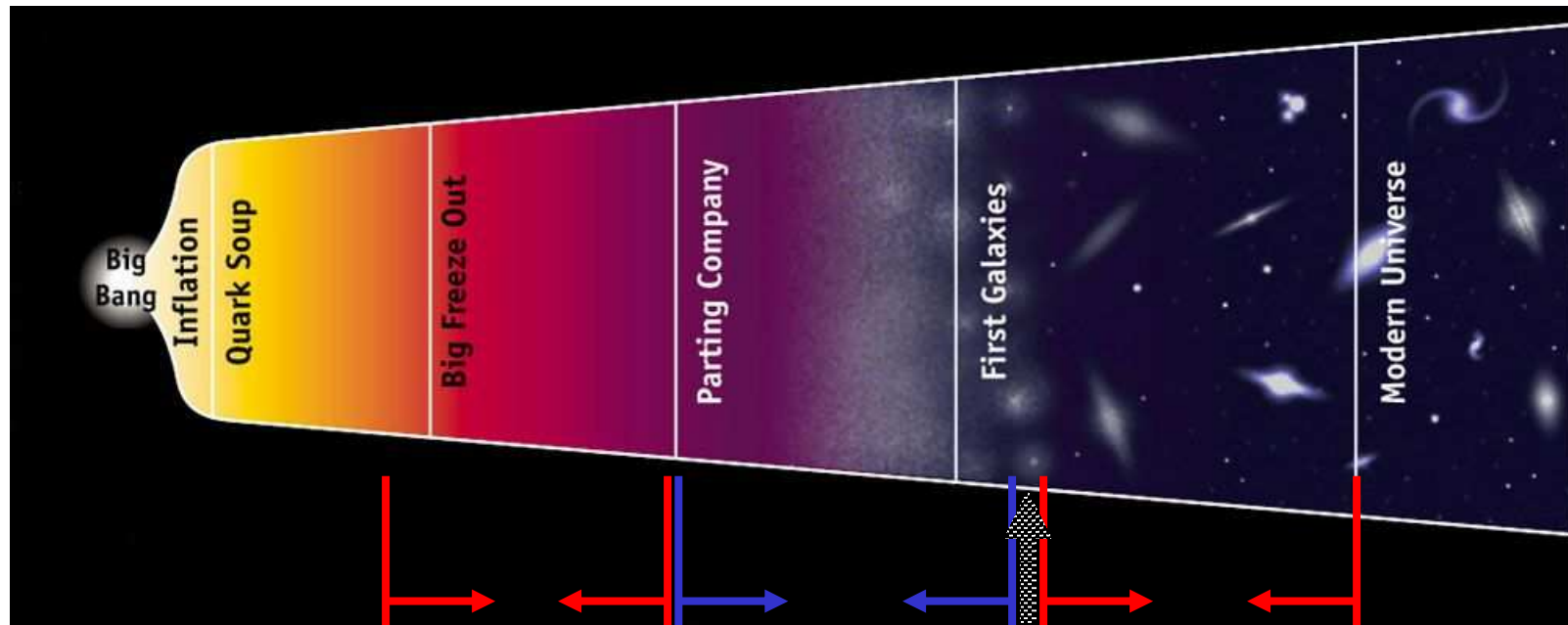
End of inflation
 $z=10^{27}$
 $t=10^{-36}$ s

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

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



The Brief History of Time



ionized neutral ionized

RE-IONIZATION

Cooking Reionizable Universe



- dark matter dynamics
- gas dynamics
- star formation ← the only phenomenology!
- metal cooling
- exact physics of primeval plasma
- fine print (secondary electrons, Ly- α pumping, ...)
- radiative transfer

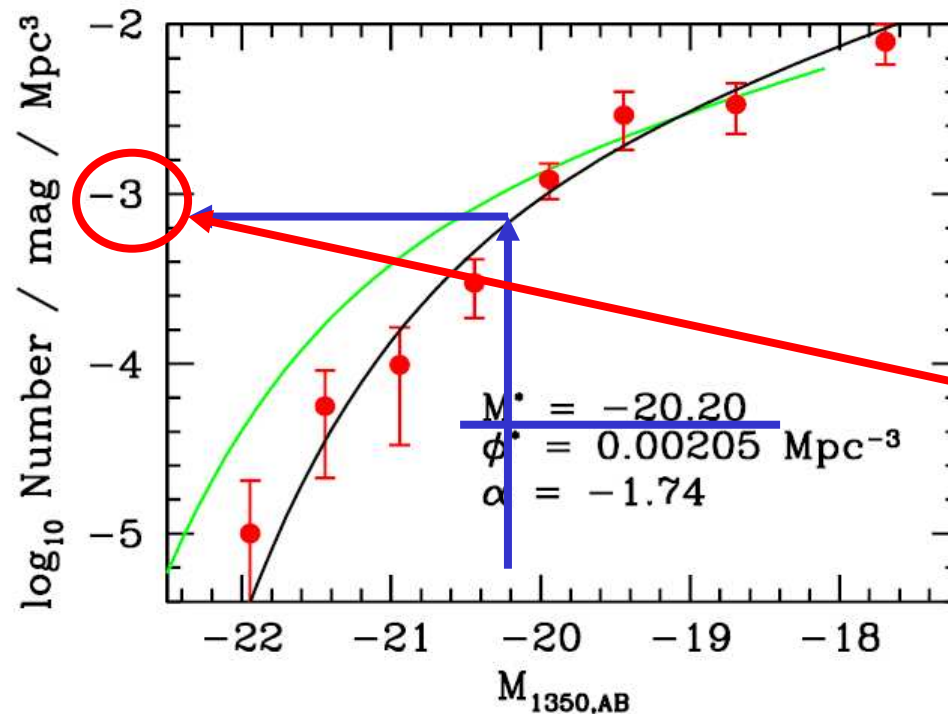
That's the key!

Note: non-existing things are not included

Sources & Sinks: Galaxies at $z=6$



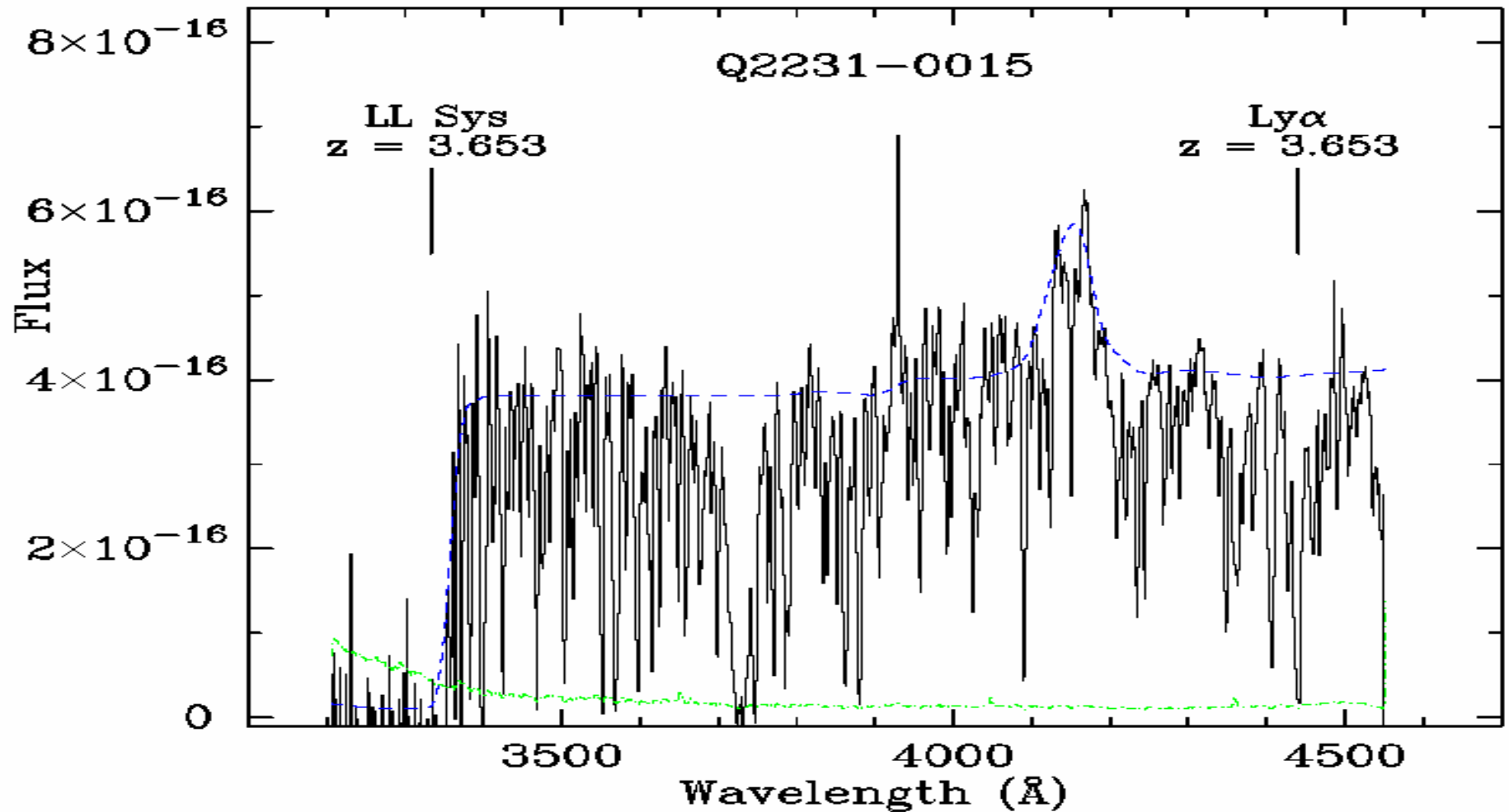
- To the best of our knowledge today, reionization is produced by stars.
- Stars only form inside galaxies.



Galaxy LF at $z=6$
(Bouwens et al. 2006)

Need ~ 30 Mpc box

Sources & Sinks II: Lyman-Limit Systems





Sources & Sinks III:

- LL systems determine the Mean Free Path (MFP) of an ionizing photon at $z=4$
($mfp = 0.034 c/H = 17 h^{-1} \text{ Mpc proper} = 85 \text{ CHIMP}$). 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:

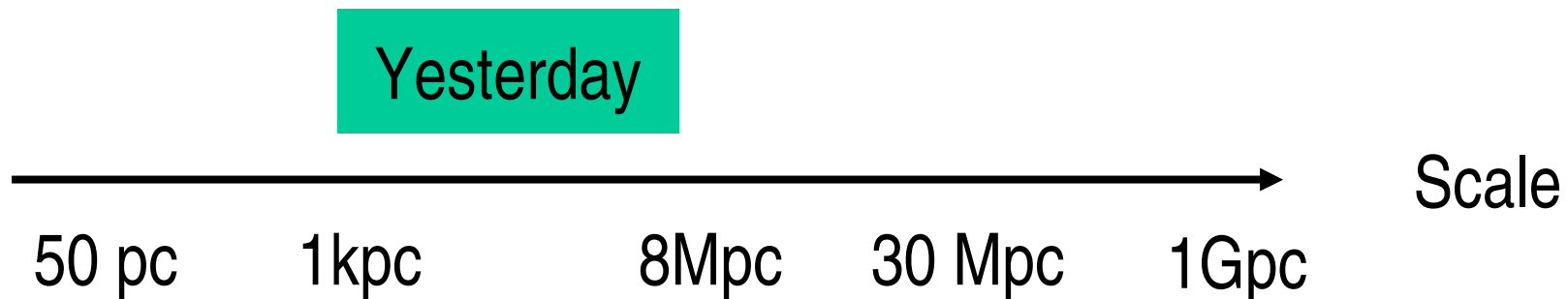
- Spatial resolution: $2 h^{-1} \text{ kpc}$
- Box size: $40 h^{-1} \text{ Mpc}$

That's tough!

Yesterday's Simulations (a brute force approach)



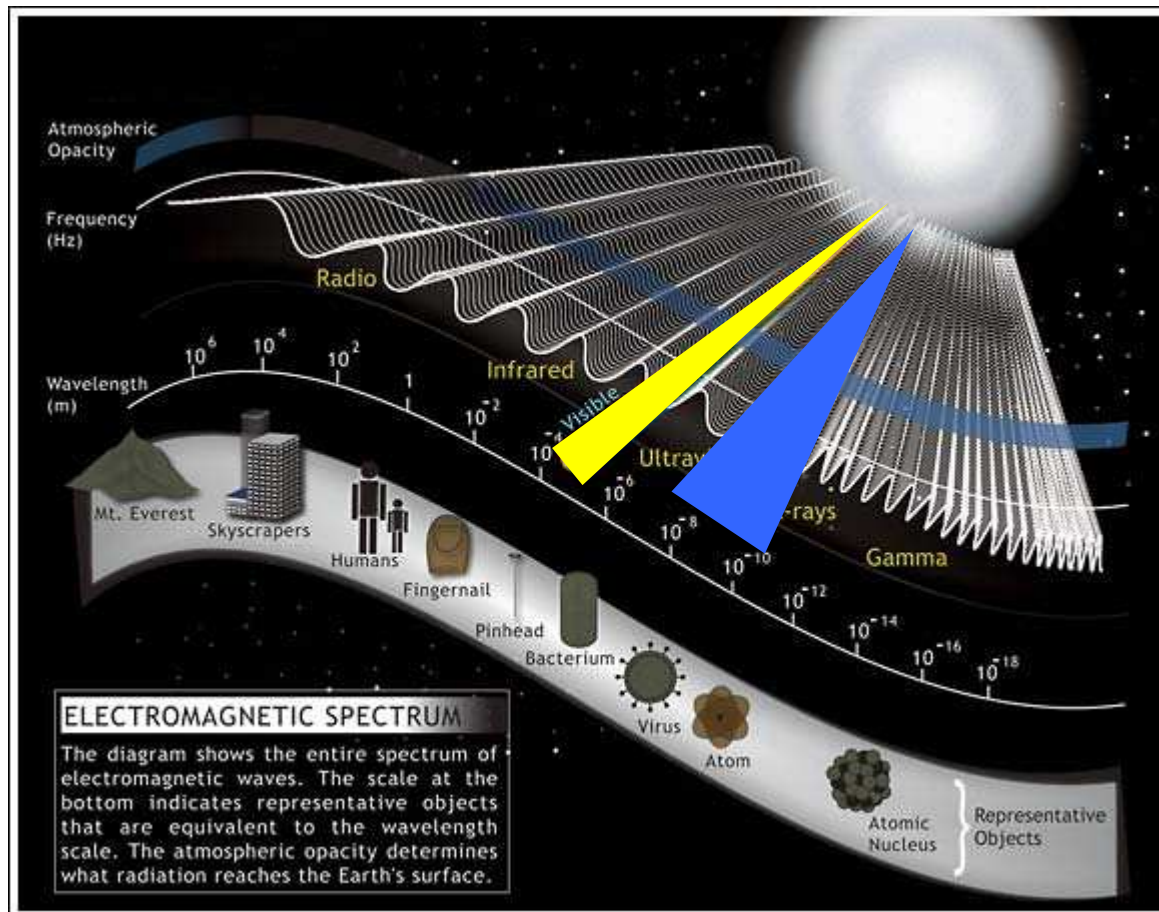
- Only galaxies as sources
- Mostly mean properties
- ISM is not resolved





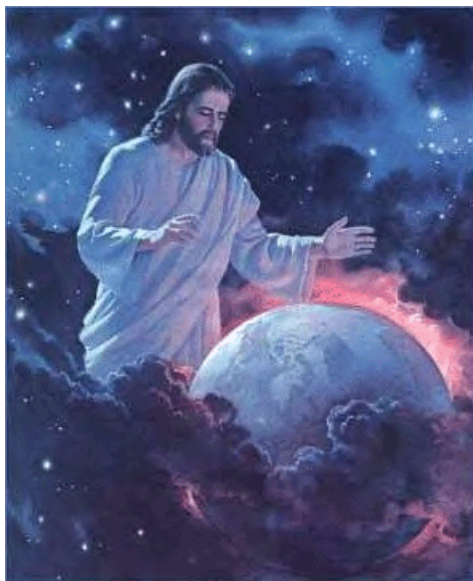
How It All Happens...

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

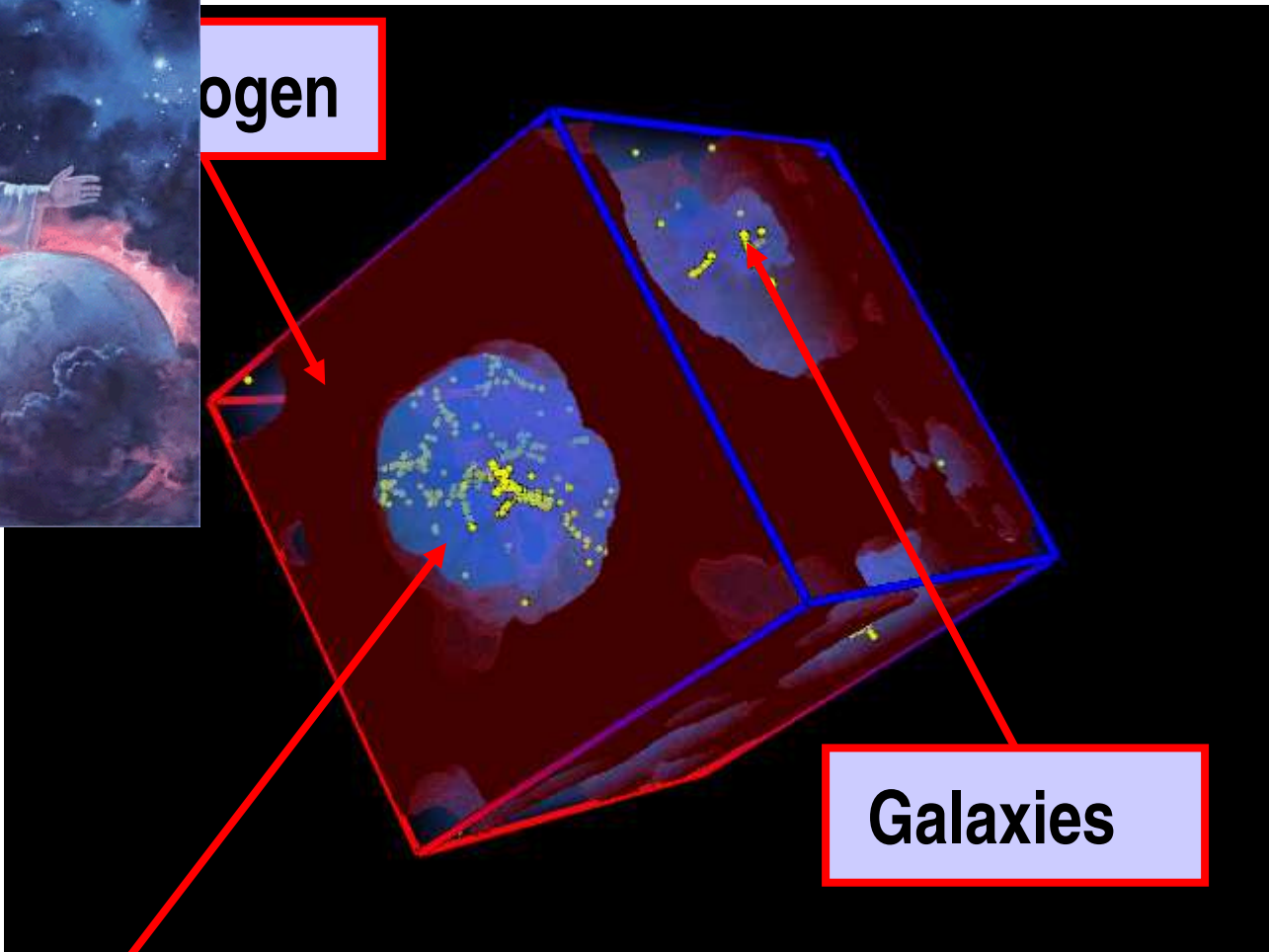




Let Us Be Gods...



ogen

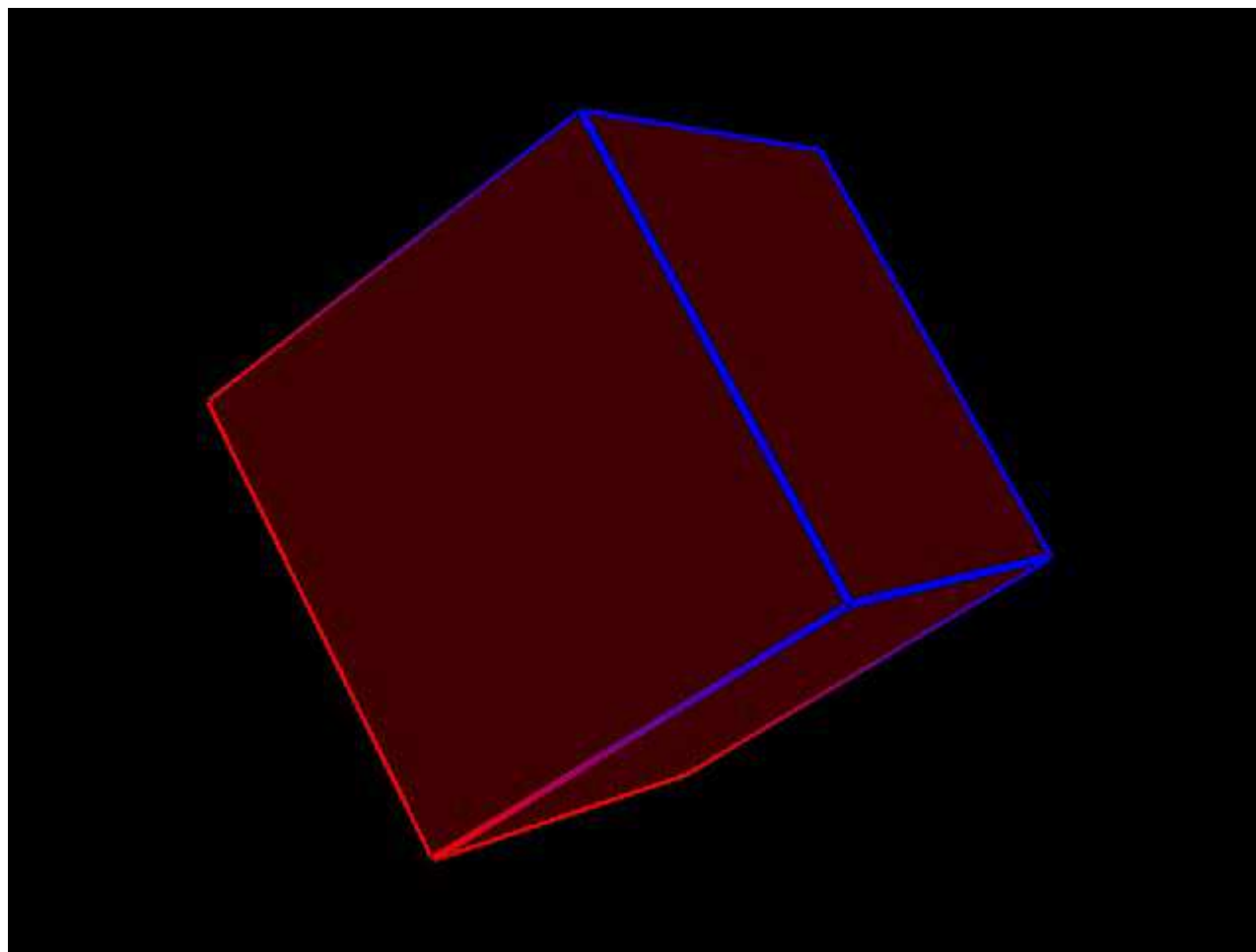


Galaxies

Ionized bubbles

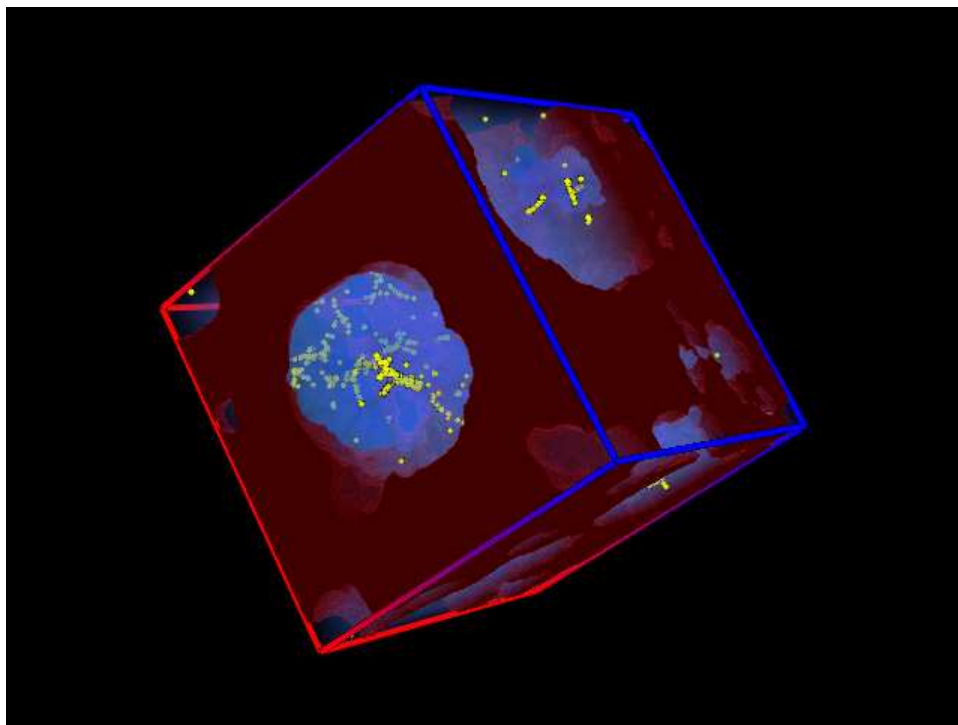


How It All Happens...





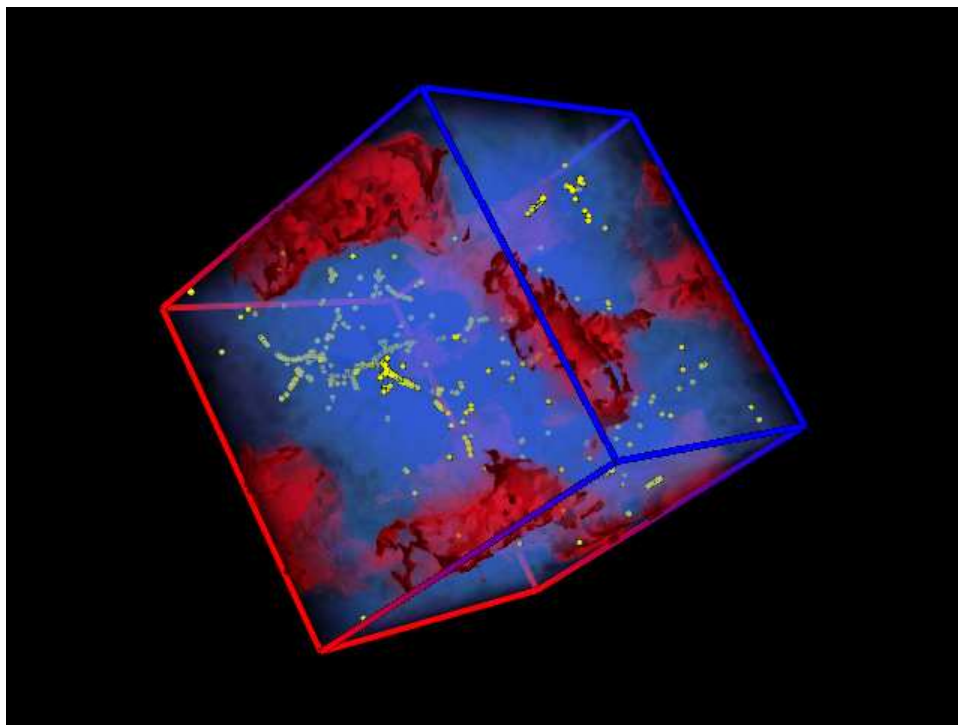
How It All Happens



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



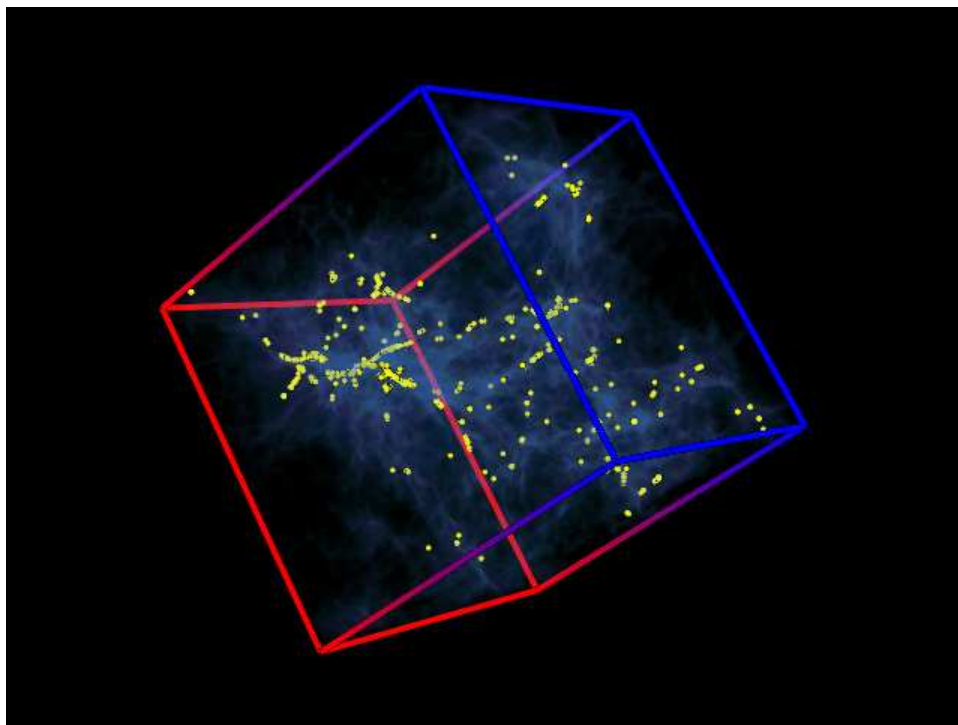
How It All Happens



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

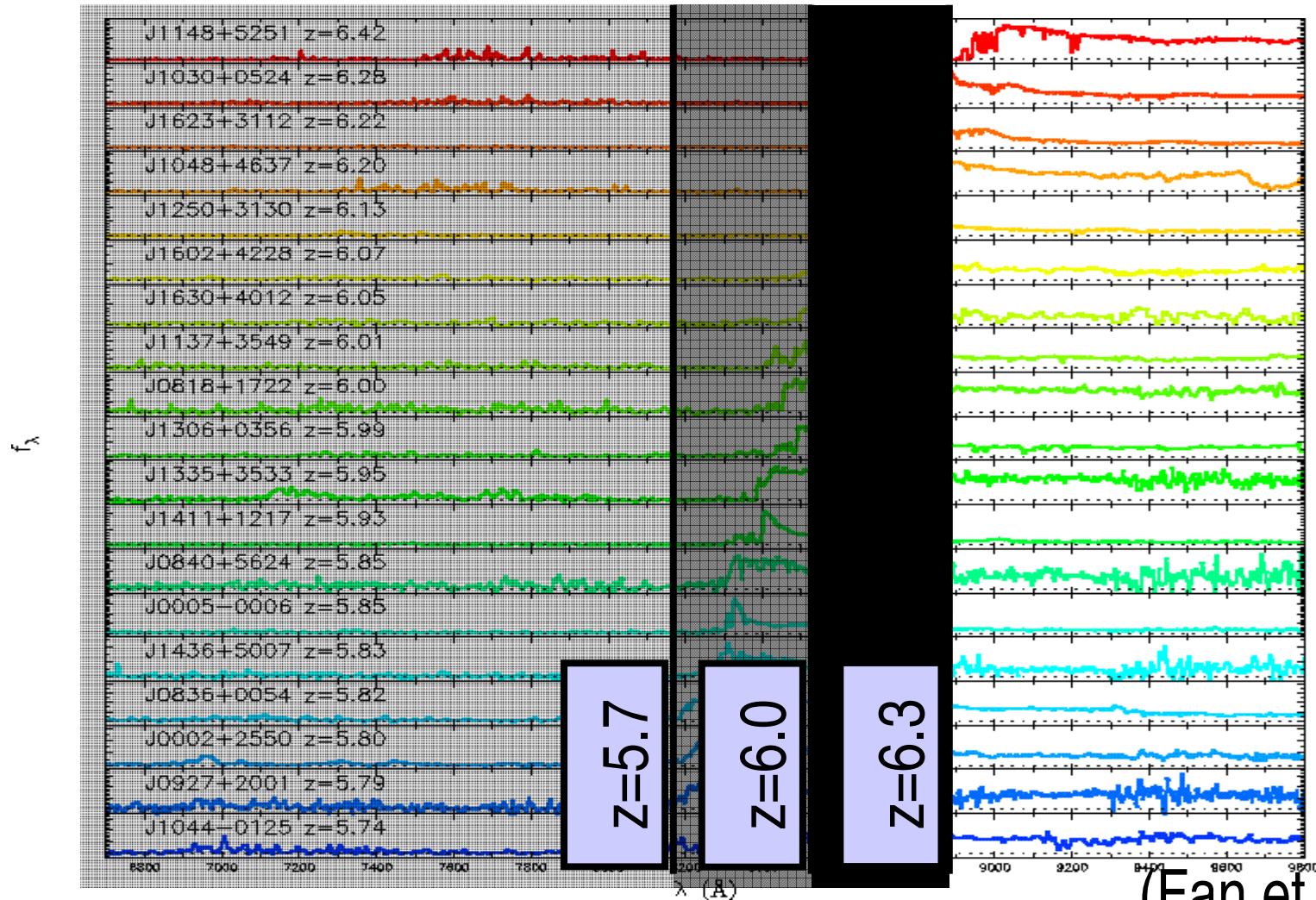


How It All Happens



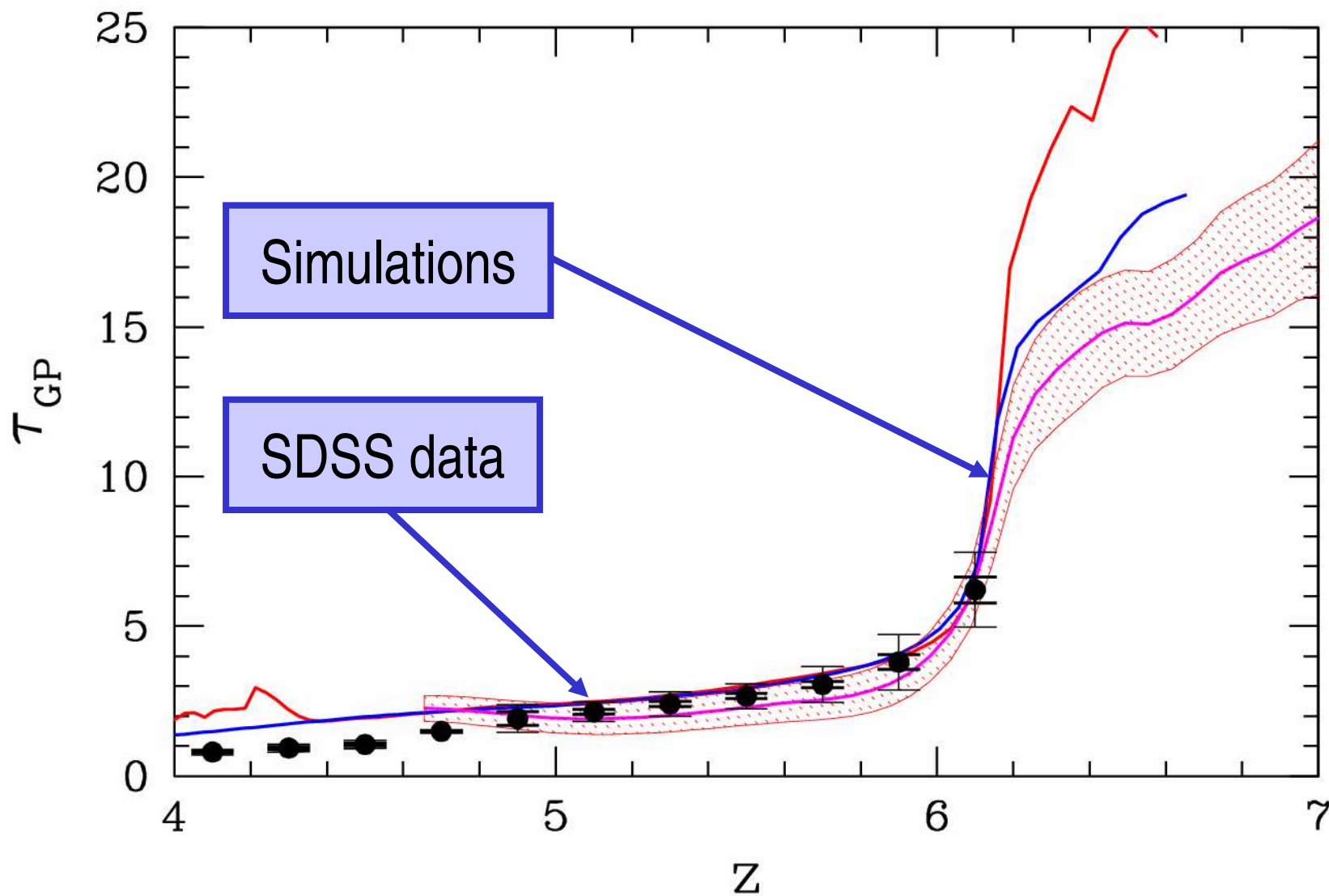
Post-overlap: Most of gas in the universe is highly ionized.

What We Know About Reionization



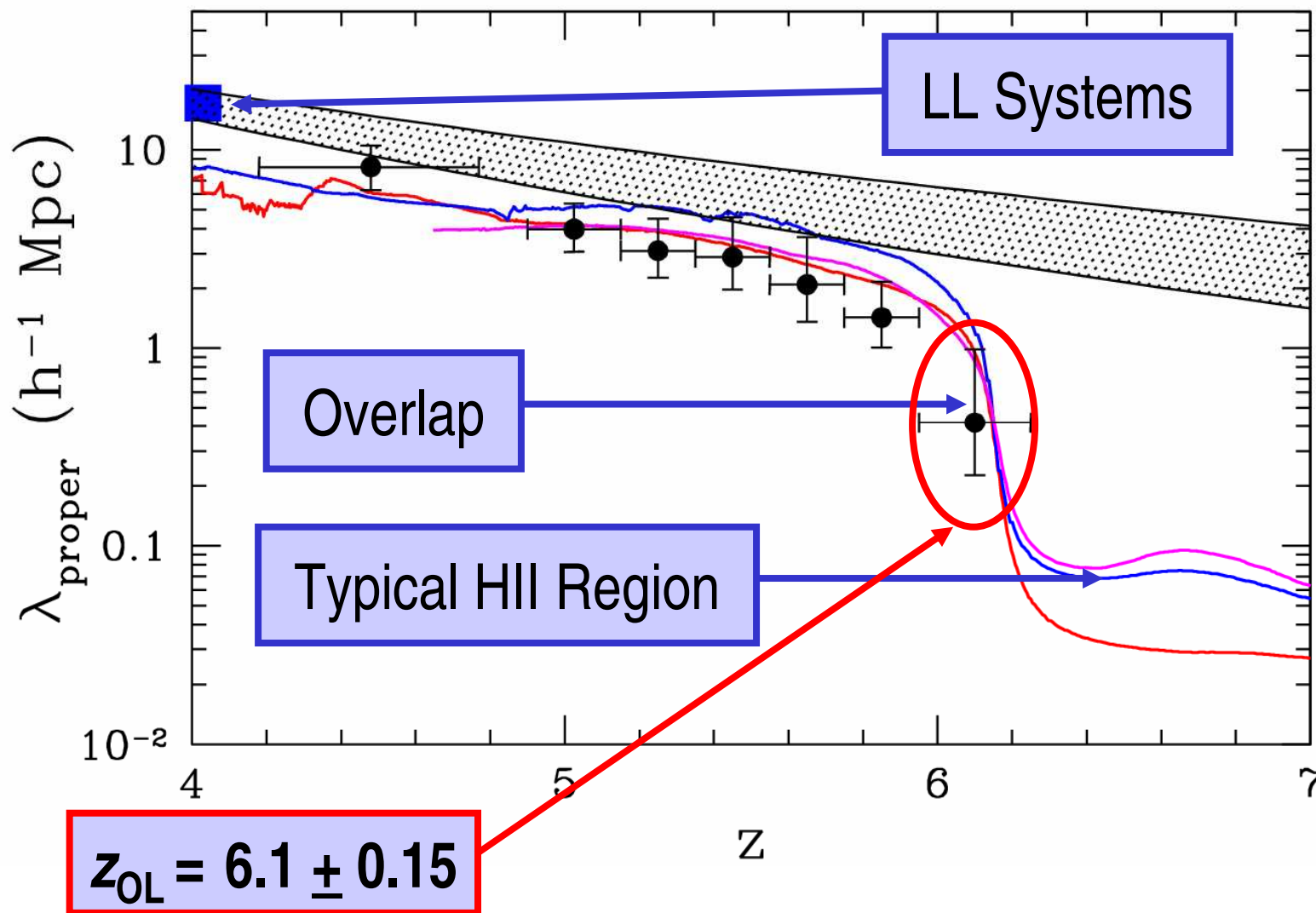
(Fan et al 2005)

Example 2: Redshift of Overlap





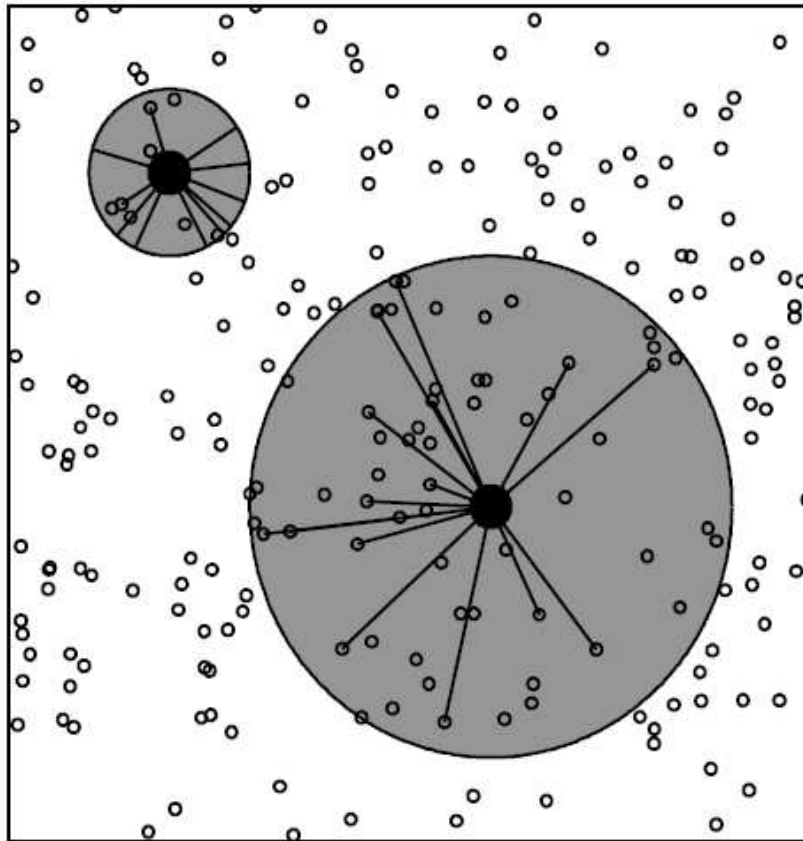
Example 2: Redshift of Overlap



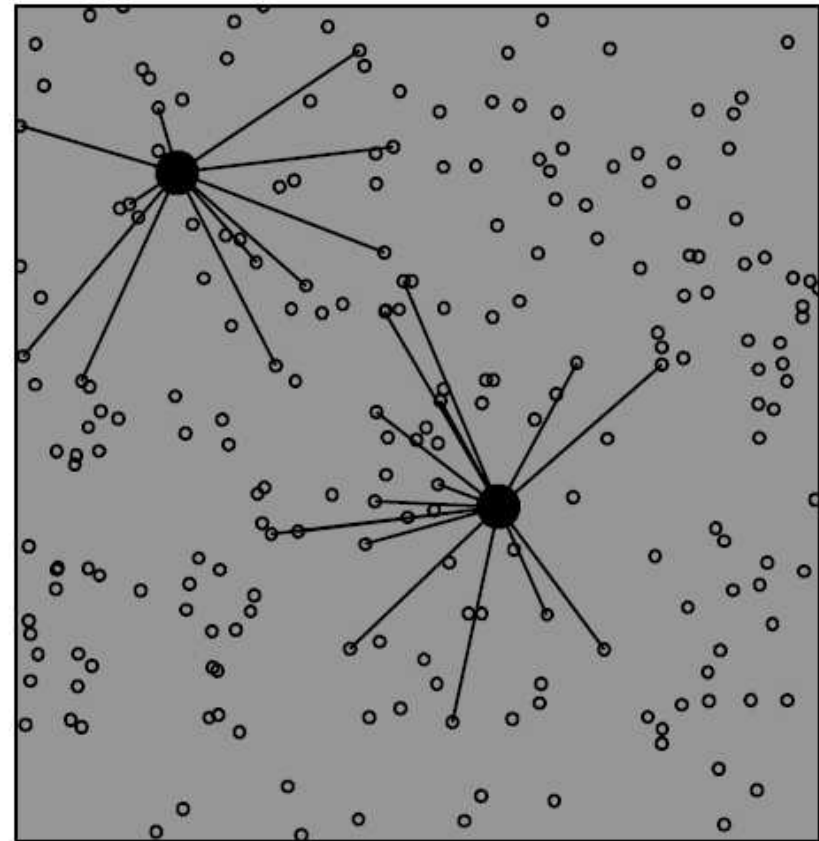
Reminder: MFP & LL



Before overlap



After overlap





Yesterday's Simulations

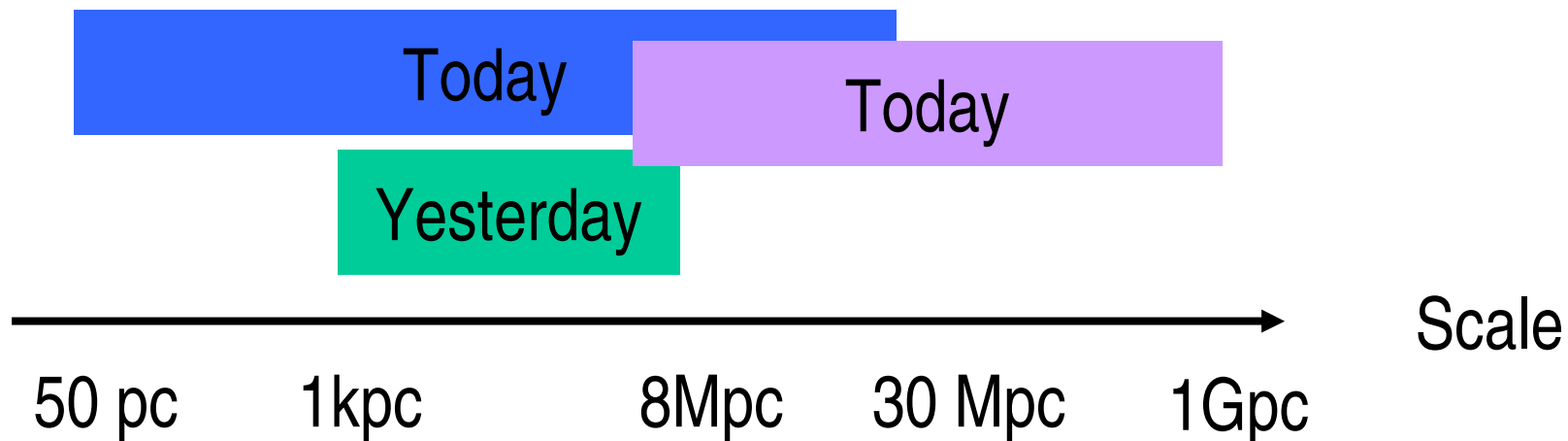
- Helped to understand the process of reionization.
- Reached close to numerical convergence.
- Helped to measure the redshift of overlap from the data.
- Provided some assurance that we are on the right way.

Small spheroidal galaxies (in the simulation) as a population of galaxies is spheroidal in the present epoch. Their abundance.



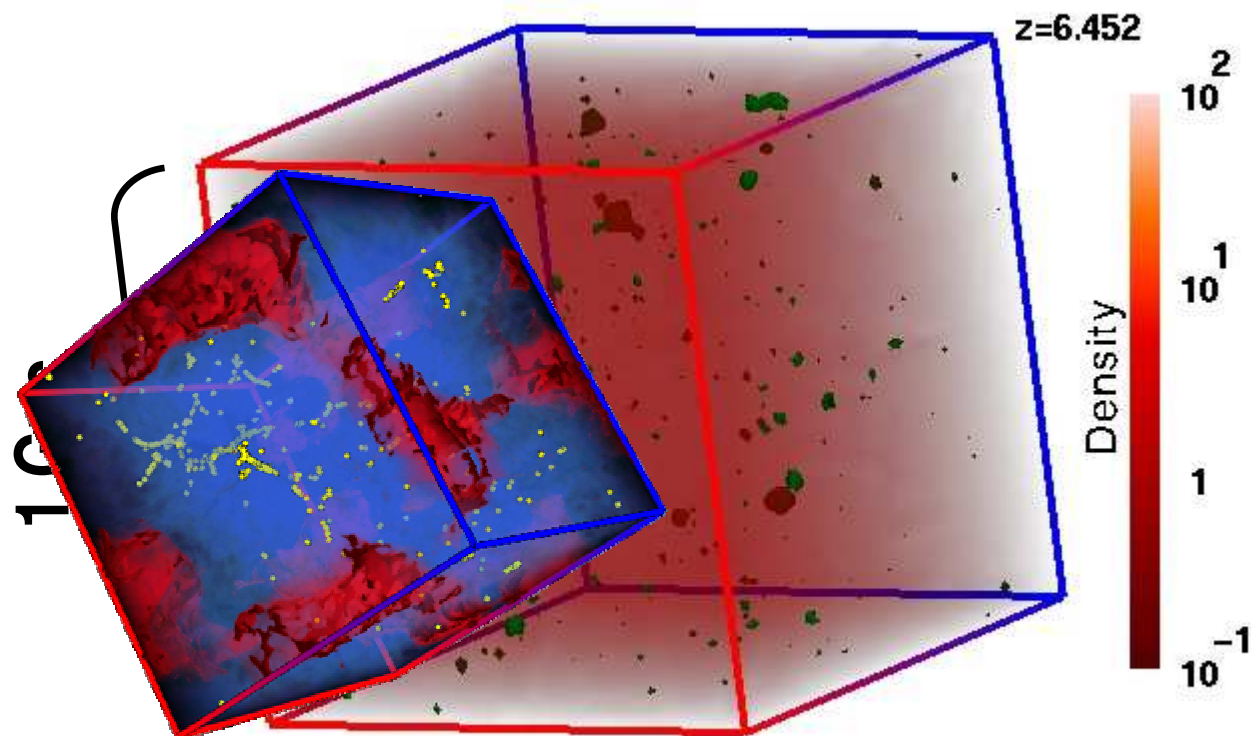
Today's Simulations (a smart approach)

- 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

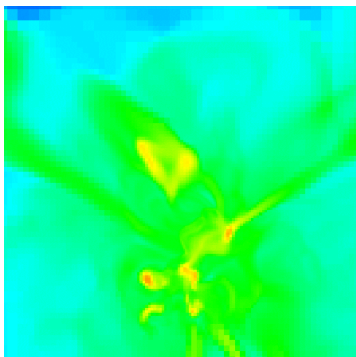


Small box \rightarrow sub-cell model for the large box
(clumping factors)



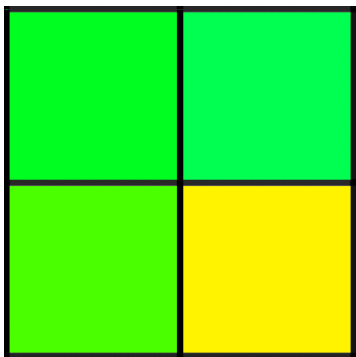
Clumping Factors

$$\frac{dn_{\text{HI}}}{dt} = -n_{\text{HI}}\Gamma + R(T)n_en_{\text{HII}}$$



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

$$\left\langle \frac{dn_{\text{HI}}}{dt} \right\rangle_{\text{cell}} = -\langle n_{\text{HI}}\Gamma \rangle_{\text{cell}} + \langle R(T)n_e n_{\text{H II}} \rangle_{\text{cell}}$$

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

“Clumping factors”



Clumping Factors III

Recombination clumping factor:

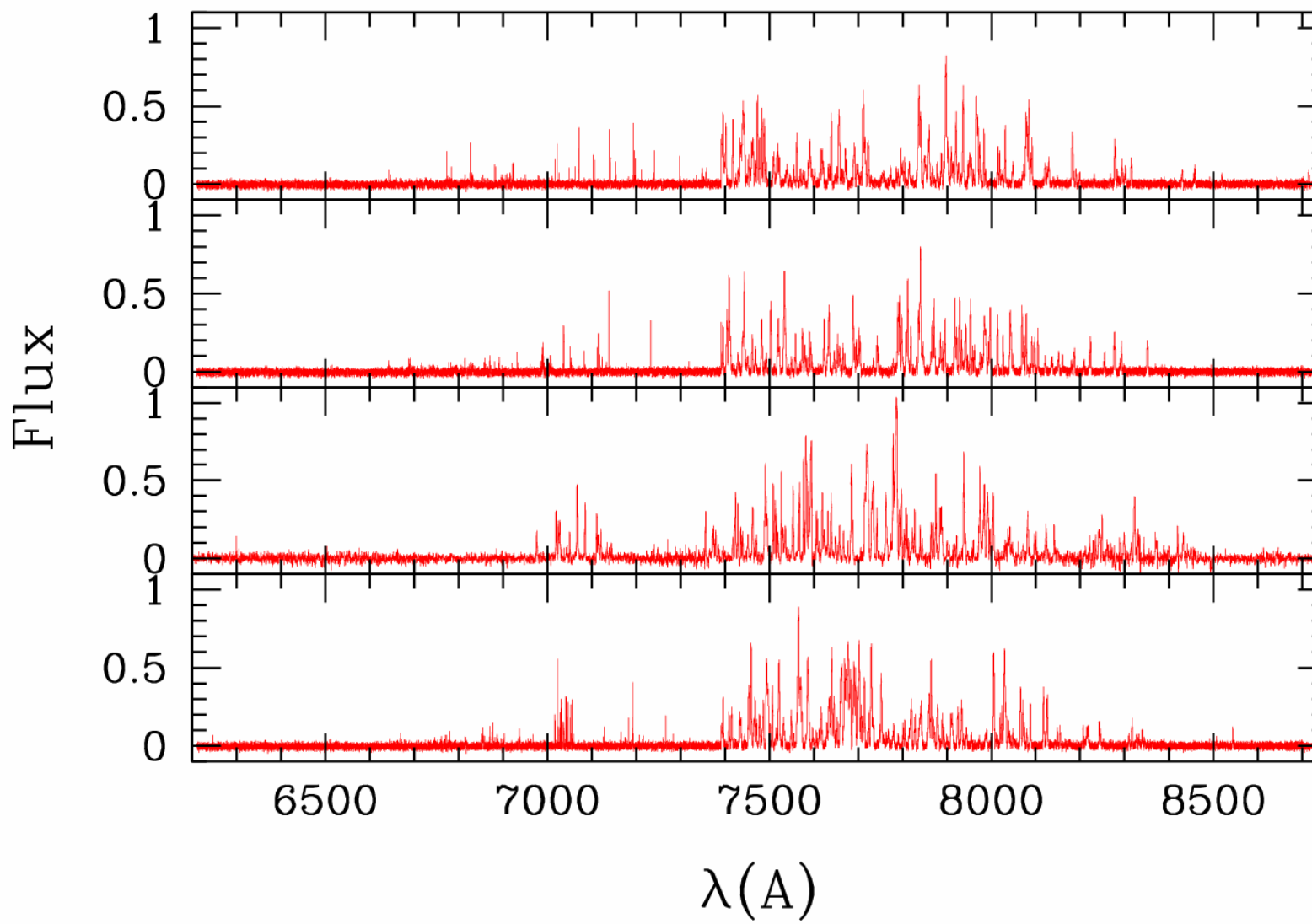
$$C_R = \frac{\langle R(T) n_e n_{\text{H II}} \rangle_{\text{cell}}}{\langle R(T) \rangle_{\text{cell}} \langle n_e \rangle_{\text{cell}} \langle n_{\text{H II}} \rangle_{\text{cell}}}$$

Ionization clumping factor

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

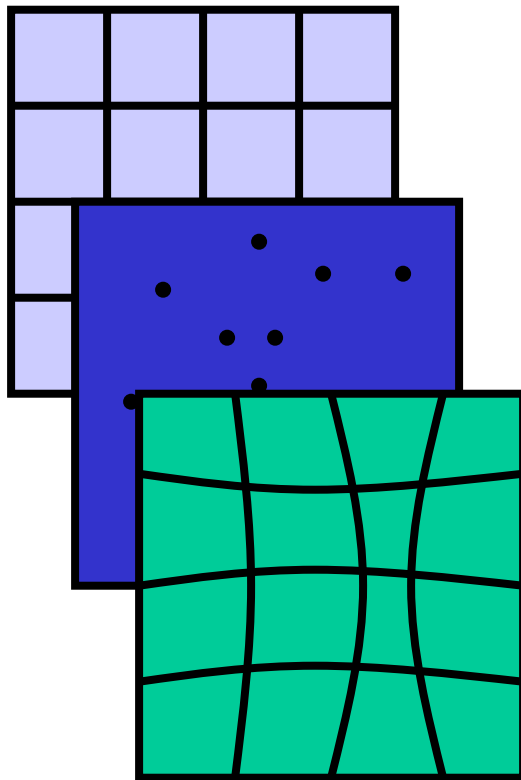


Find the SDSS Quasar



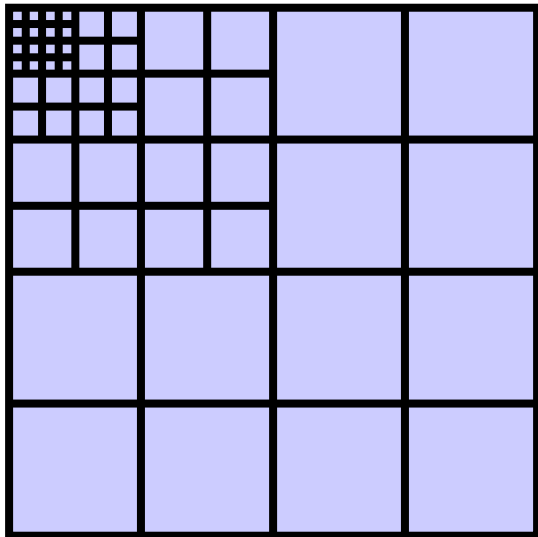
(Figure courtesy Katharina Kohler)

A Quiet Revolution: XX Century



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

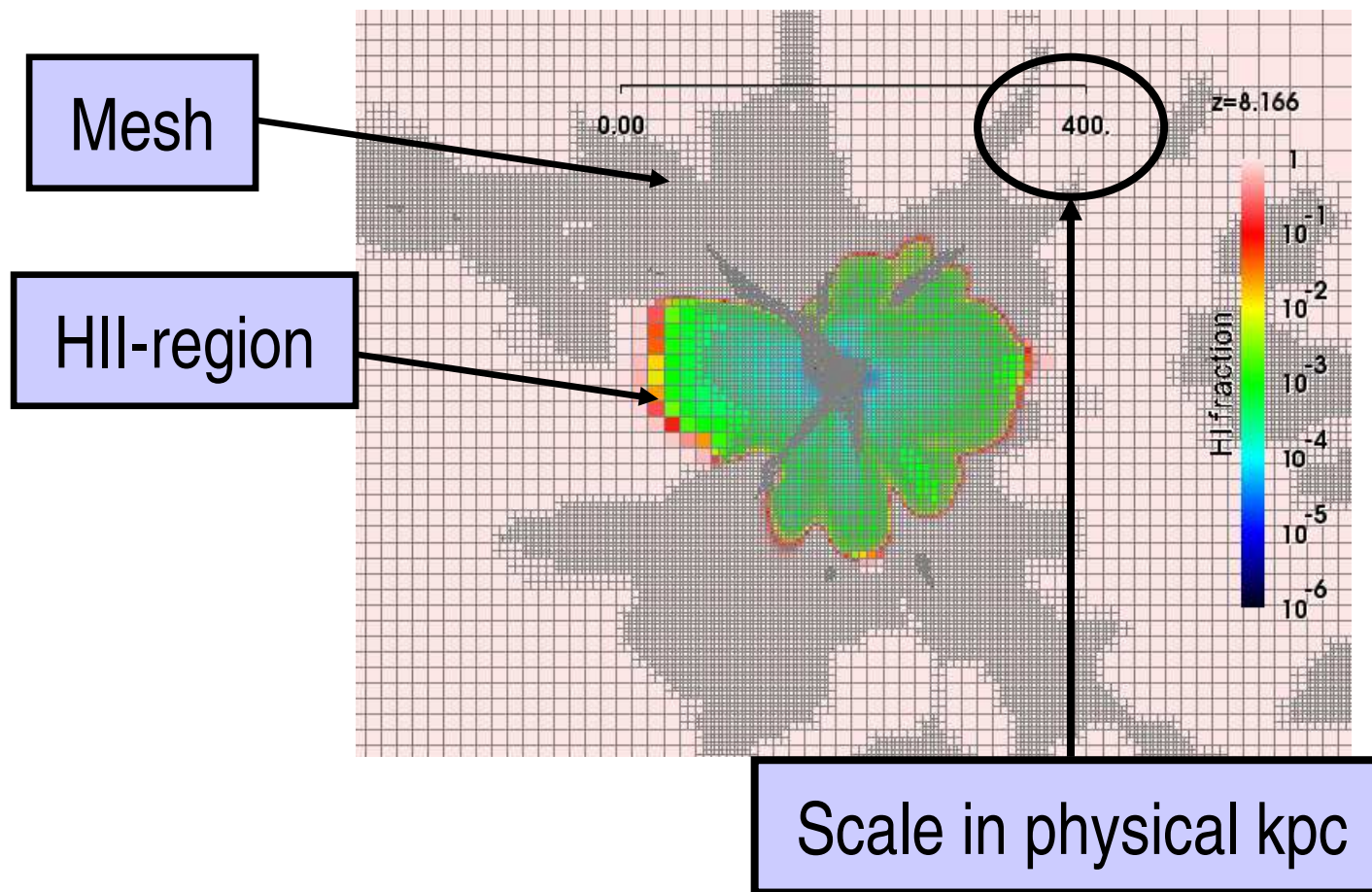
A Quiet Revolution: XXI Century



- Adaptive Mesh Refinement (AMR)
 - ✓ *can follow fragmentation*
 - ✓ *non-uniform initial conditions*
 - ✓ *spatially variable resolution*
 - ✓ *faster-than-Lagrangian*

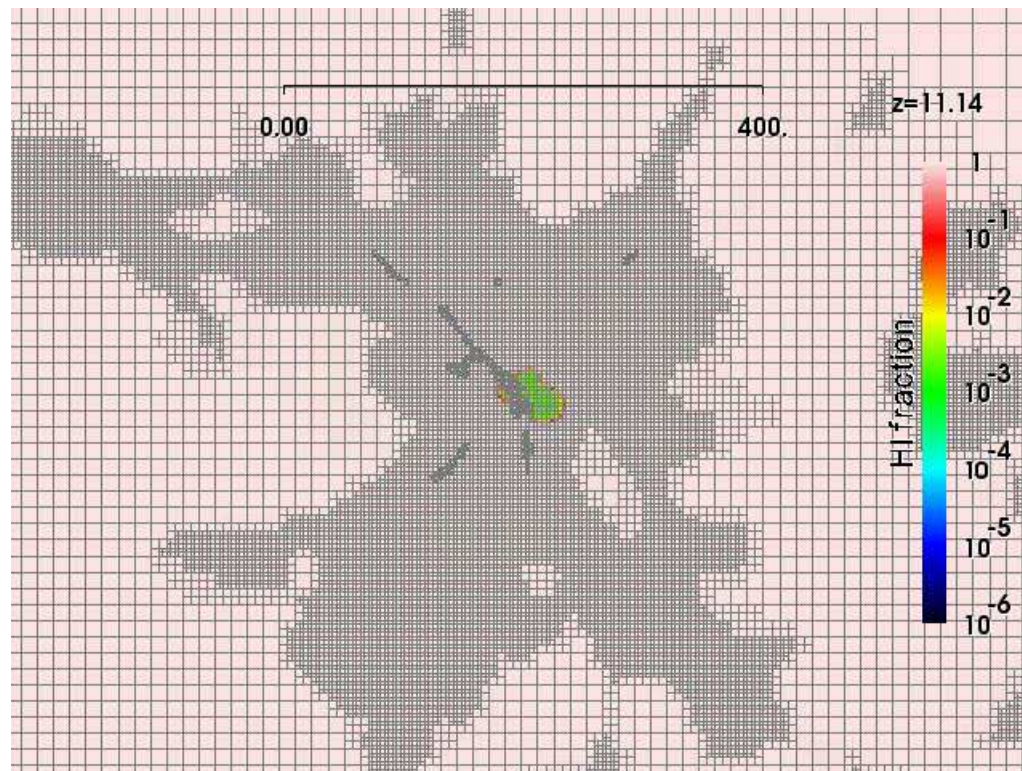


Cosmic Butterfly





Cosmic Butterfly





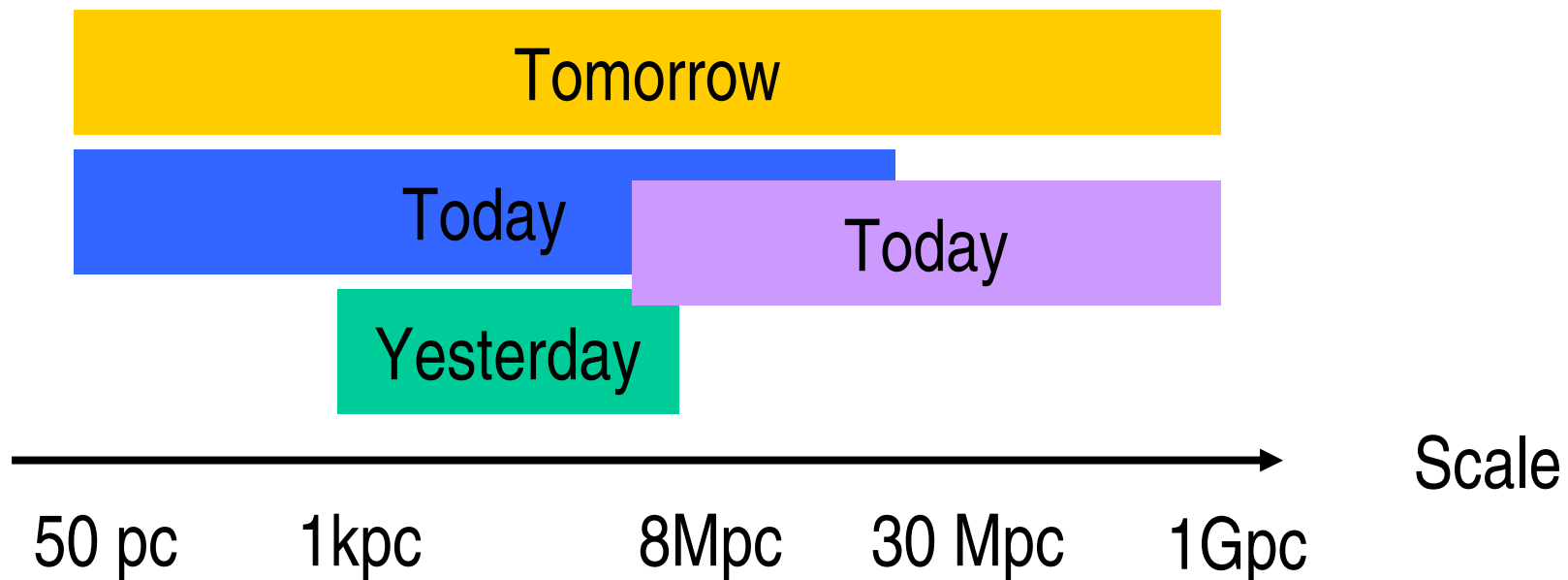
Today's Simulations

- 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.



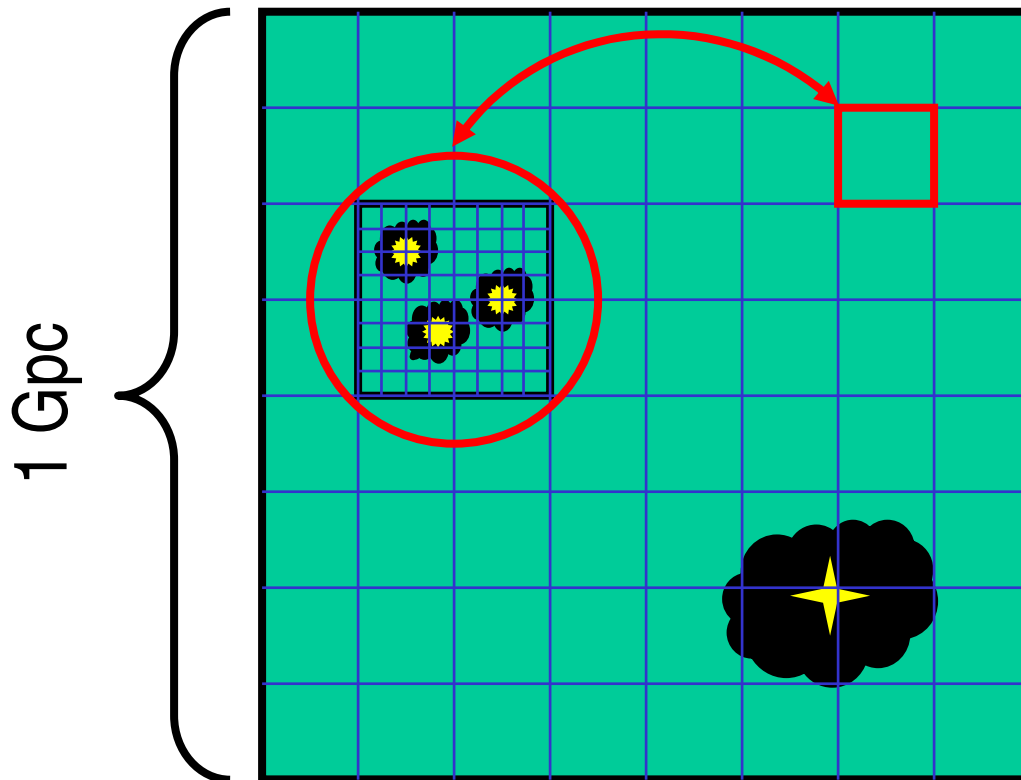
Tomorrow's Simulations (a smart brute force approach)

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





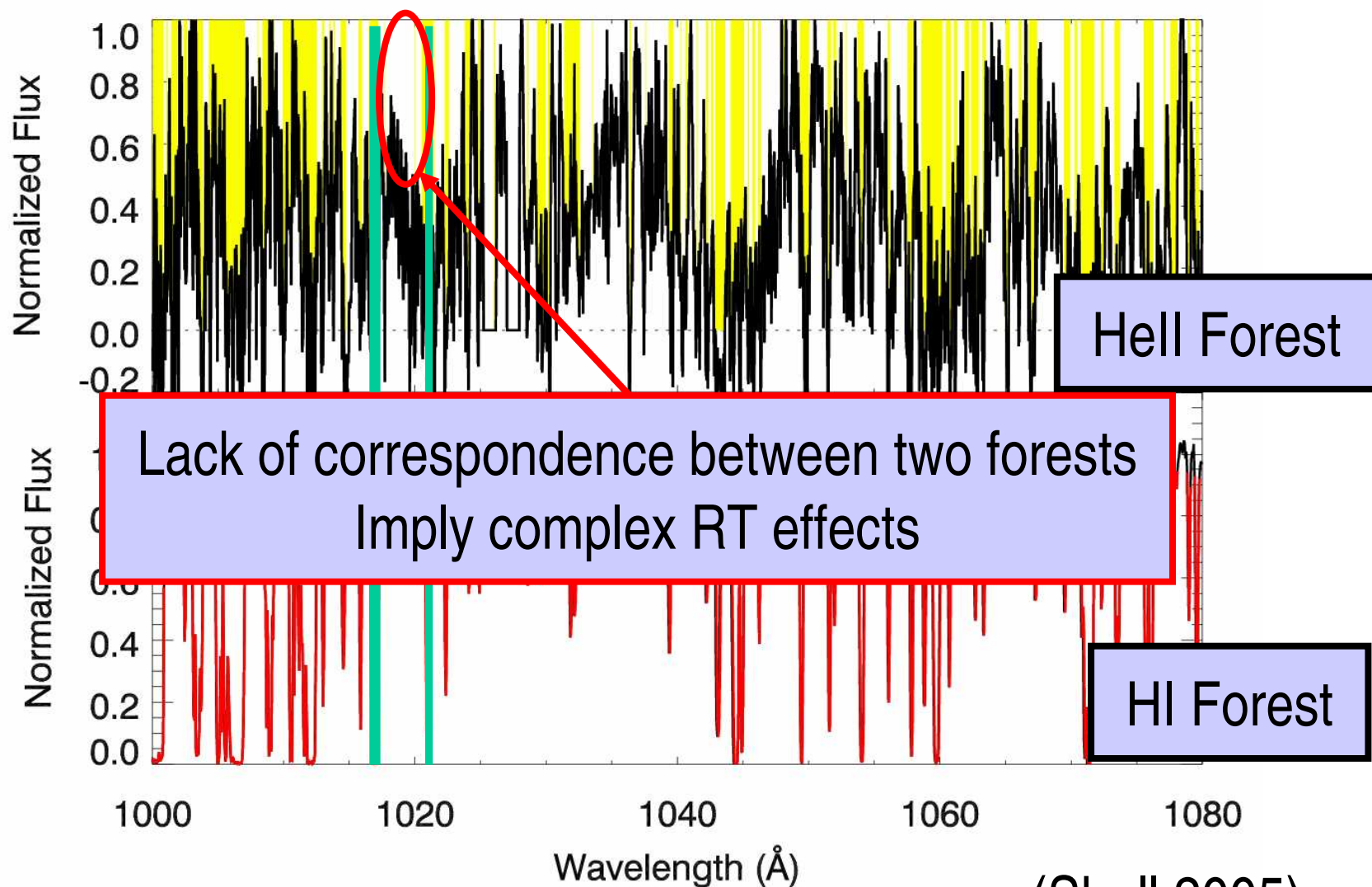
Simulation Royal



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 $z \sim 2$ (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 $z \sim 6$ 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

