Cosmic Reionization On Computers

Part 2. How To Build A Virtual Universe

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The Flood Is Coming

- Astro2010:

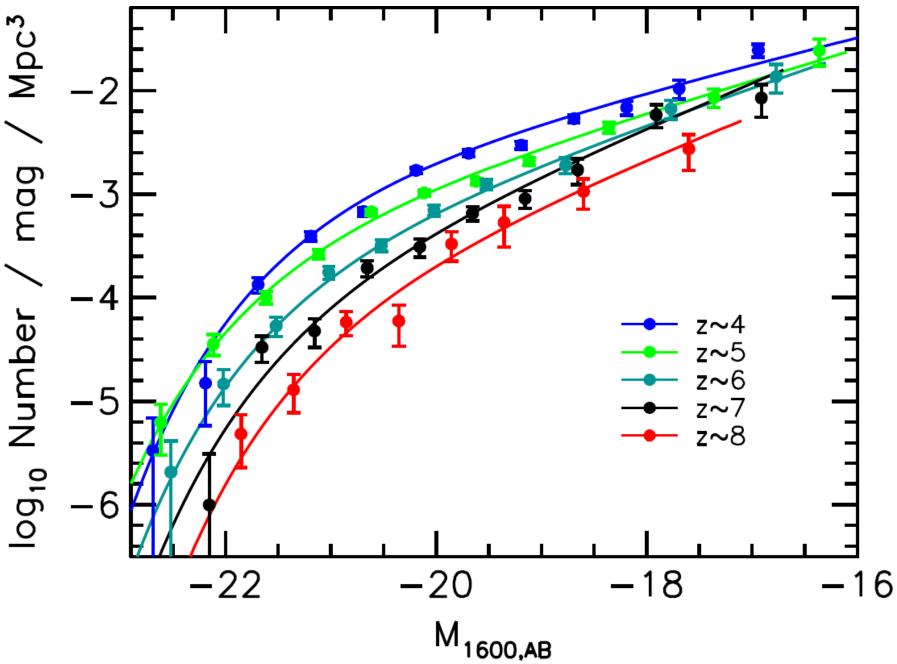
The priority science objectives chosen by the survey committee for the decade 2012-2021 are searching for the first stars, galaxies, and black holes;

- ALMA: 2014+
- HSC: 2017-2018
- JWST: 2018
- HERA: 2015-2020
- NGOT: 2021-2025 (GMT, TMT, E-ELT)

The Flood Is Coming

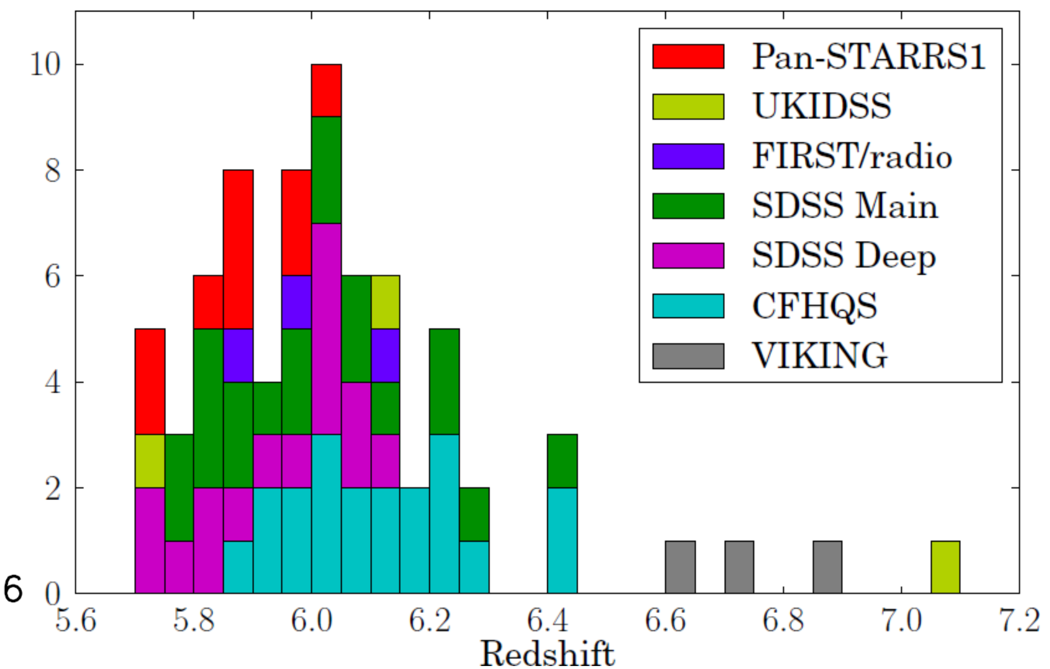
- Actually, it is already rather wet…

UV Luminosity Functions



Bouwens+2015

Quasars at z>5.7



Banados+2014

The Flood Is Coming

- It is clear that forthcoming observations will make all existing theoretical models obsolete.
- We are preparing for the flood:

Cosmic
Reionization
On
Computers

Cosmic Dawn

Em
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Renaissan
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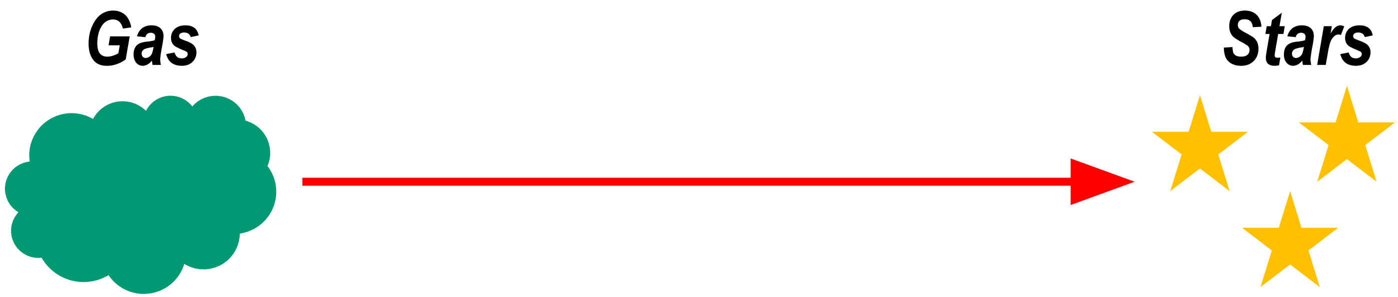
Where Do We Go Next?

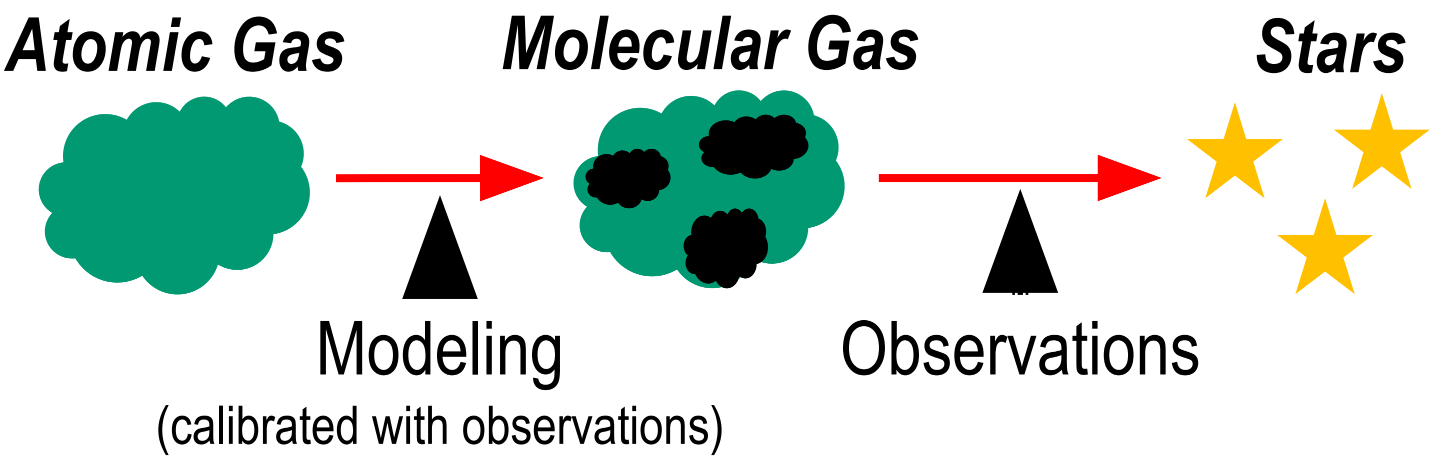
- One can run bigger simulations today than yesterday, but what's the point if we do not model physics right?
- We have homework!
  - #1: Figure out how to model star formation (sufficiently accurately for our purposes).
  - #2: Figure out how to model stellar feedback.

Homework #1: Star Formation

- 2000s SF:

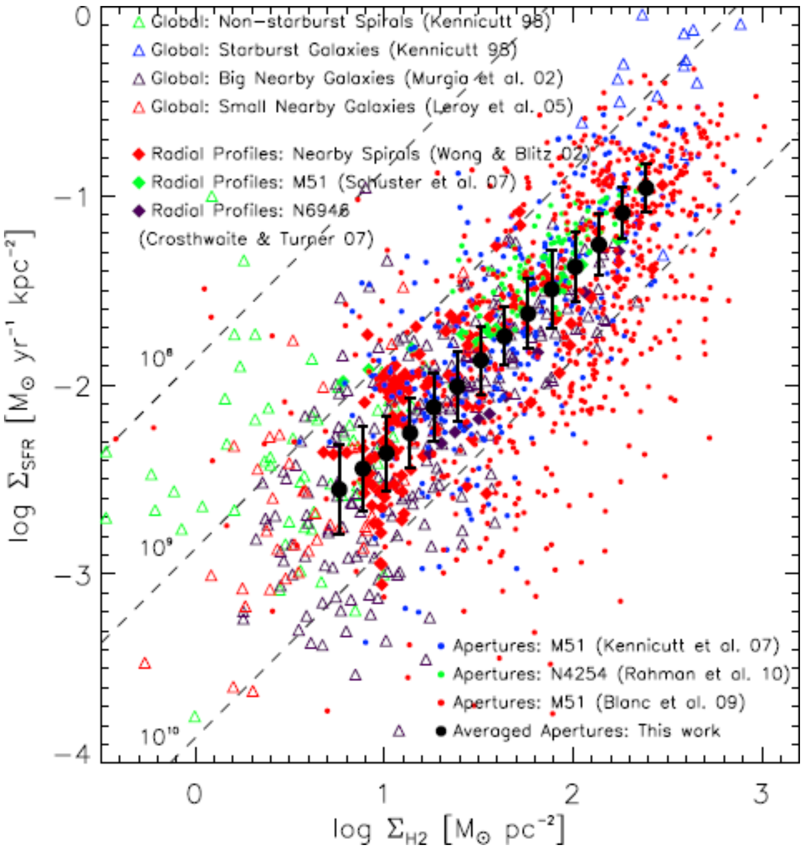


- 2010s SF:

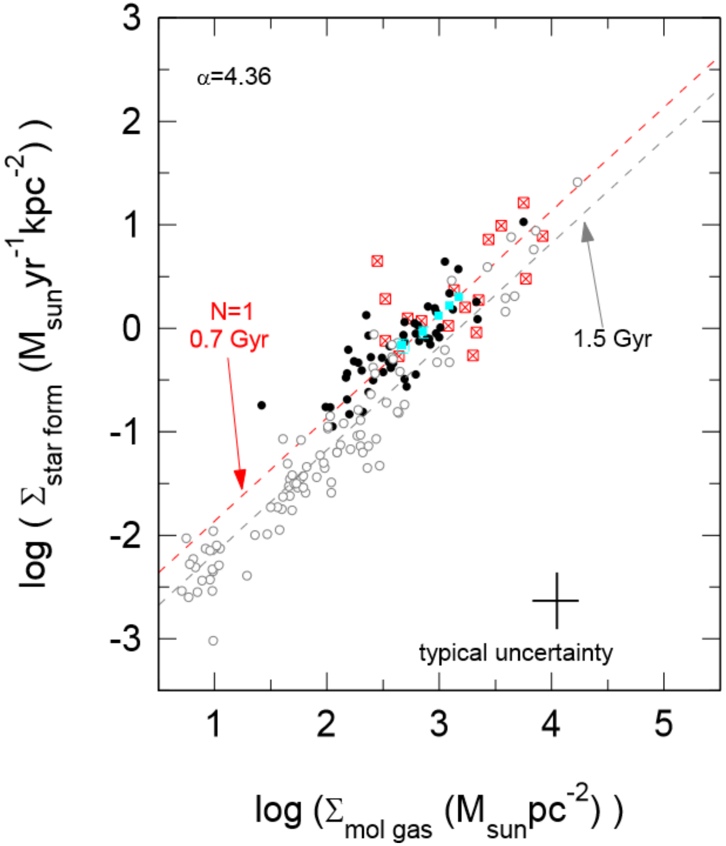


Homework #1: Star Formation

Star formation correlates well with molecular gas…



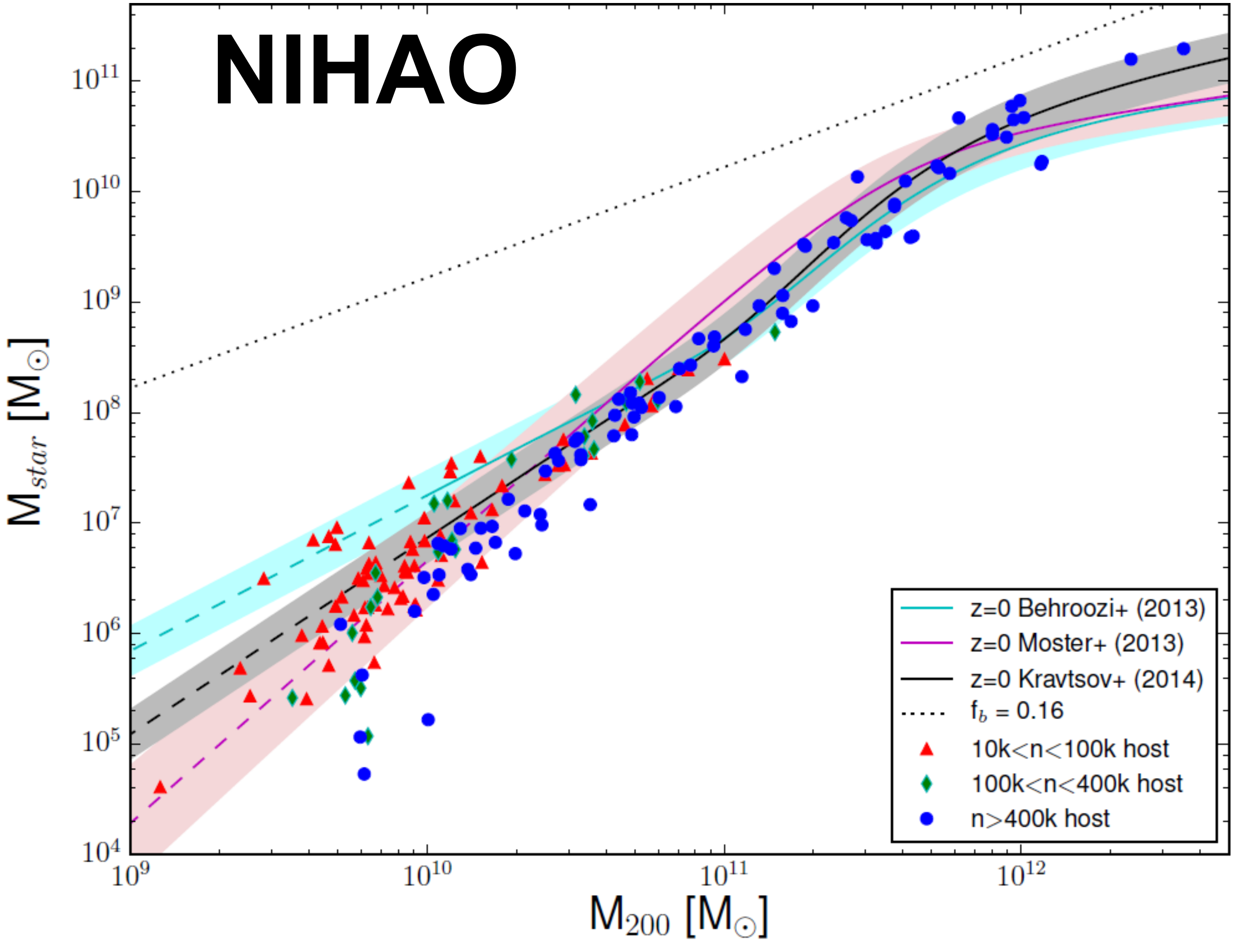
z=0 (Bigiel et al 2011)

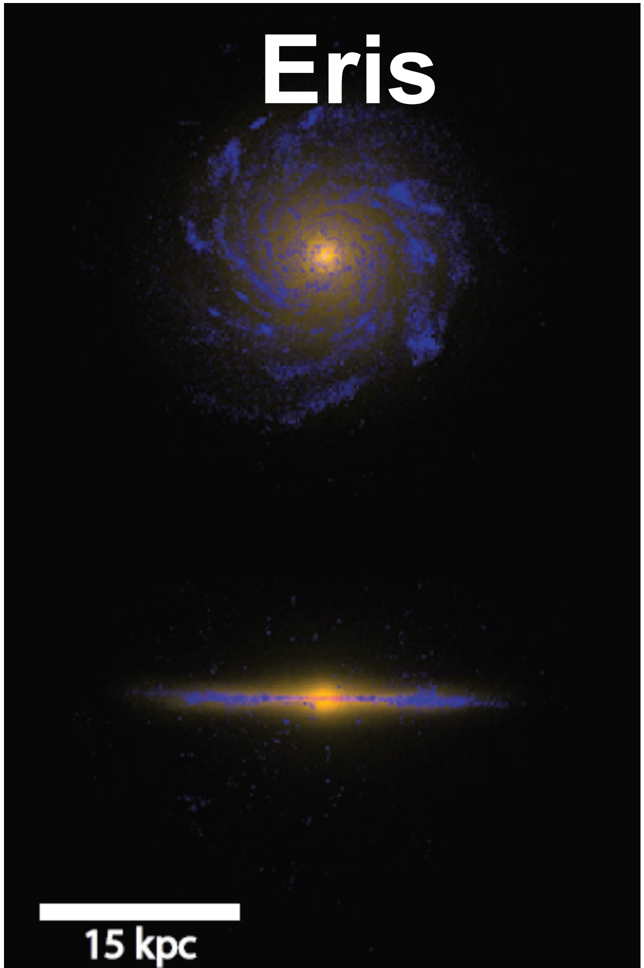


High z (Tacconi et al 2013)

Homework #2:
Stellar Feedback

"Delayed cooling" is now "industry standard".





Simulator's Bane: Numerical Convergence

- One can have the best subgrid models for star formation and feedback, but if the simulation results are not numerically converged, one is studying truncation errors…

$$\frac{df}{dx} = \frac{\Delta f}{\Delta x}[\Delta x] + \mathrm{T.E.}$$

- If T.E. is small, then

$$\frac{\Delta f}{\Delta x}[\Delta x_1] \approx \frac{df}{dx} \approx \frac{\Delta f}{\Delta x}[\Delta x_2]$$

Simulator's Bane: Numerical Convergence

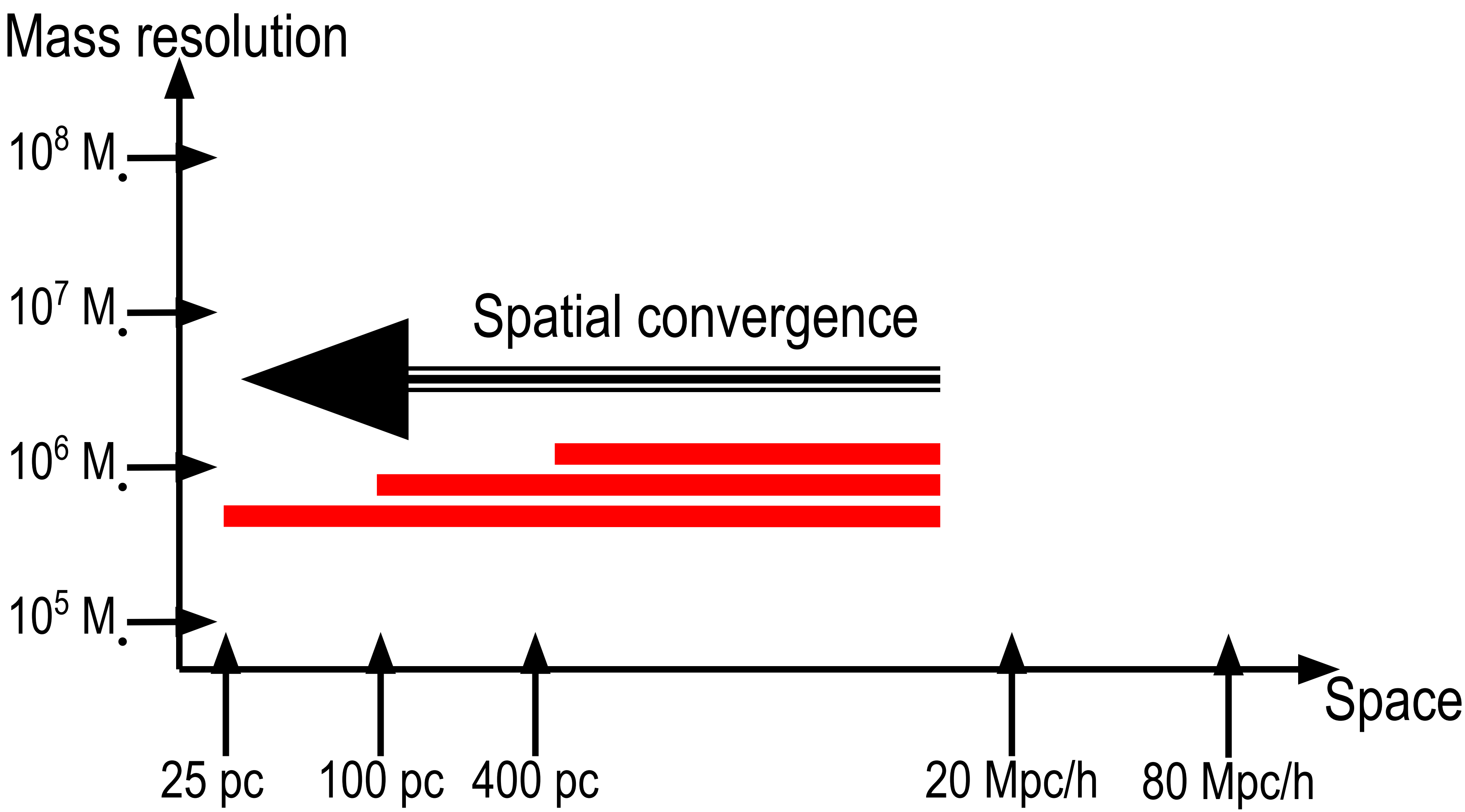
- Individual simulations have fixed spatial Δr and mass M_1 resolution.
- Any quantity measured in a simulation depends on resolution:

$$Q = Q(\Delta r, M_1)$$

- But only a converged value has physical meaning.

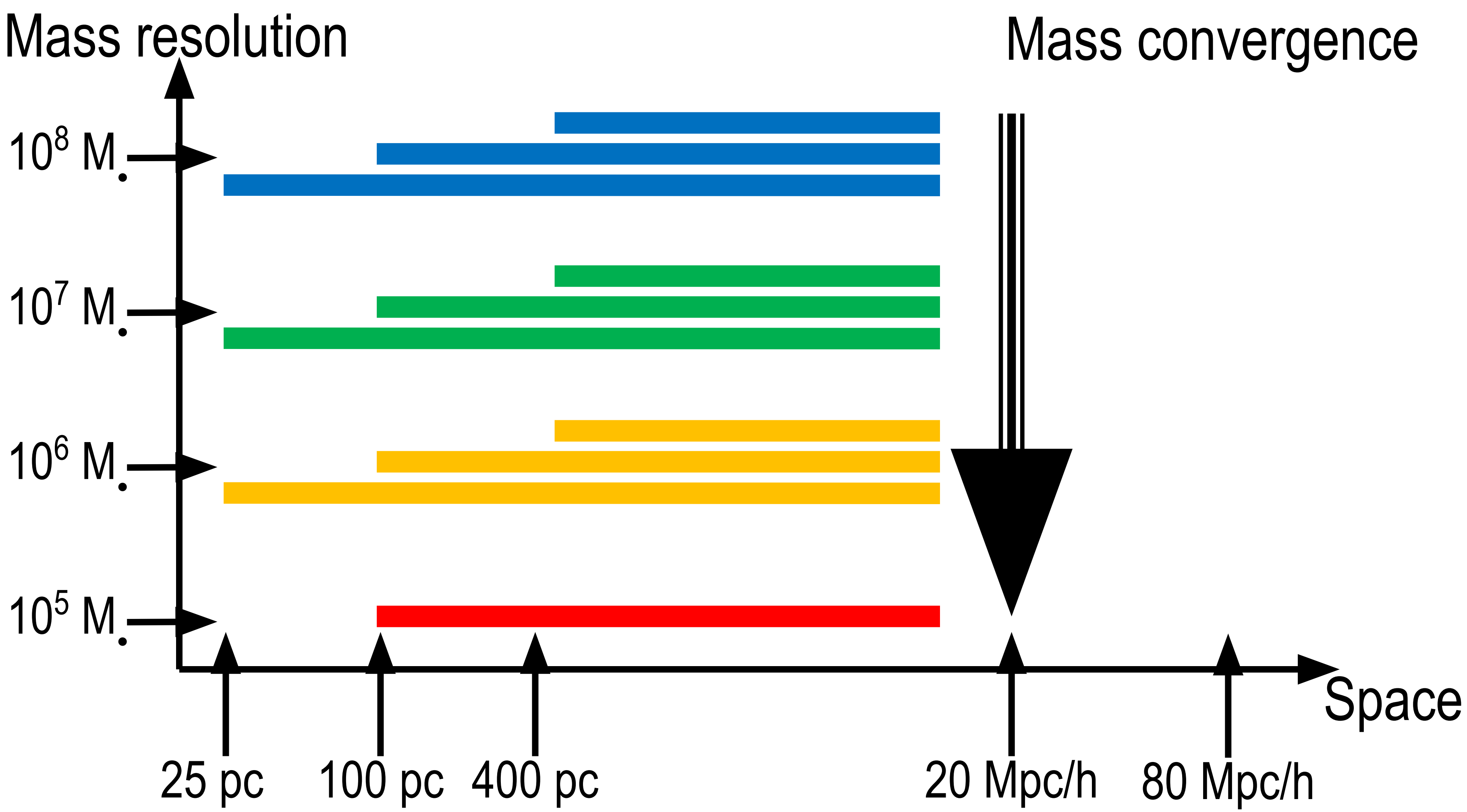
$$\hat{Q} = \lim_{\Delta r \to 0} \lim_{M_1 \to 0} Q(\Delta r, M_1)$$

The CROC Project: Convergence Study



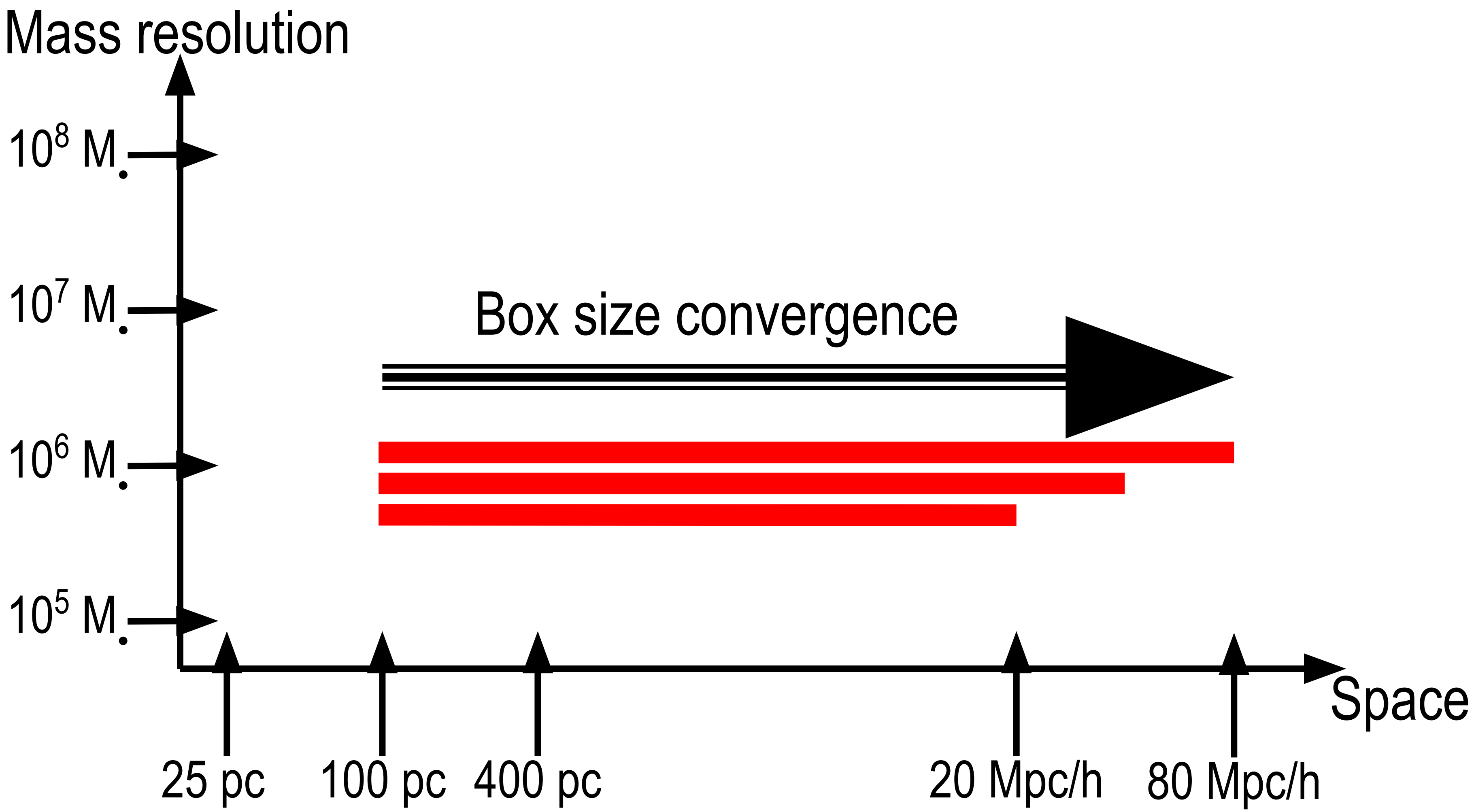
The CROC Project: Convergence Study

Cosmic Reionization On Computers



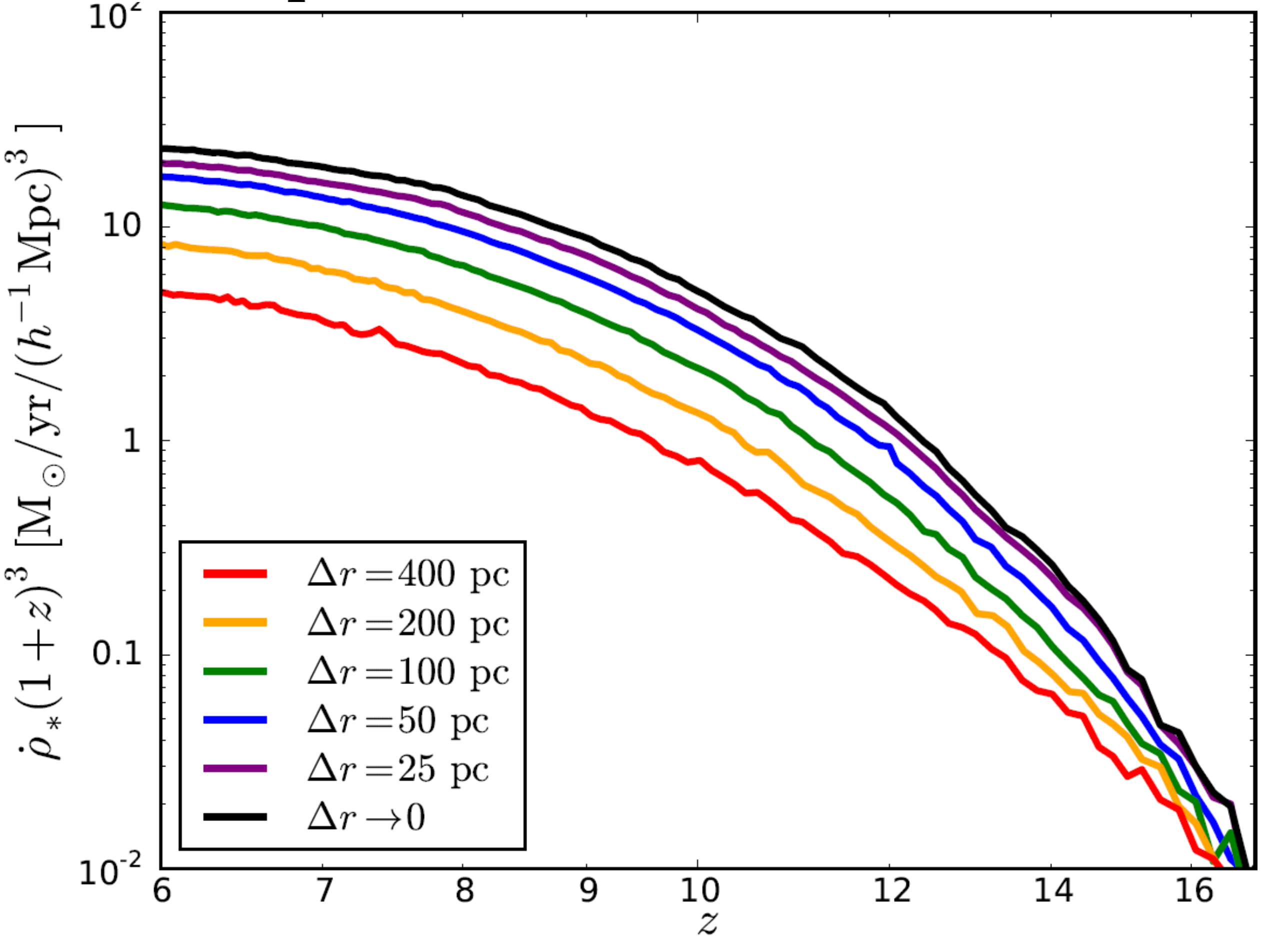
The CROC Project: Convergence Study

Cosmic Reionization On Computers



Global SFR

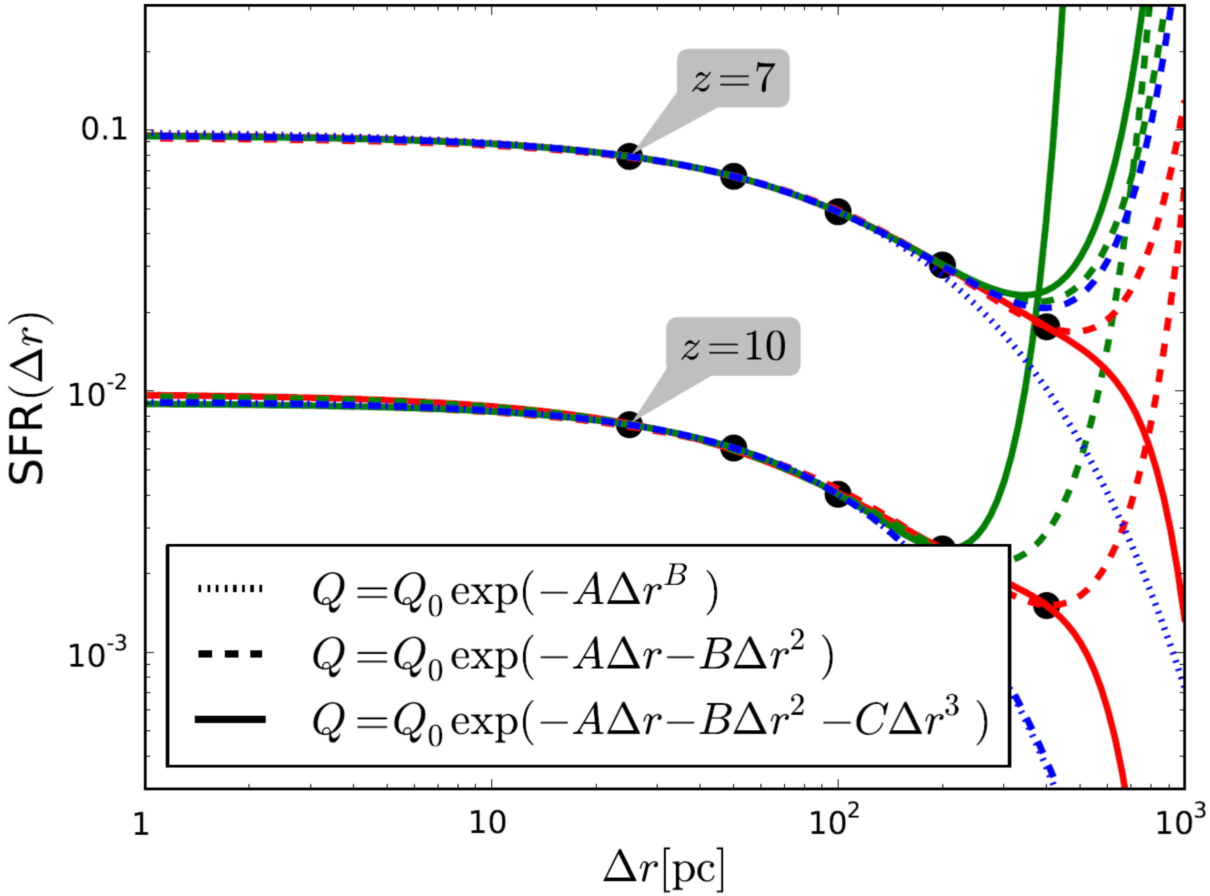
- Spatial convergence is slow – only reached $\Delta r < 50\text{pc}$.



Global SFR

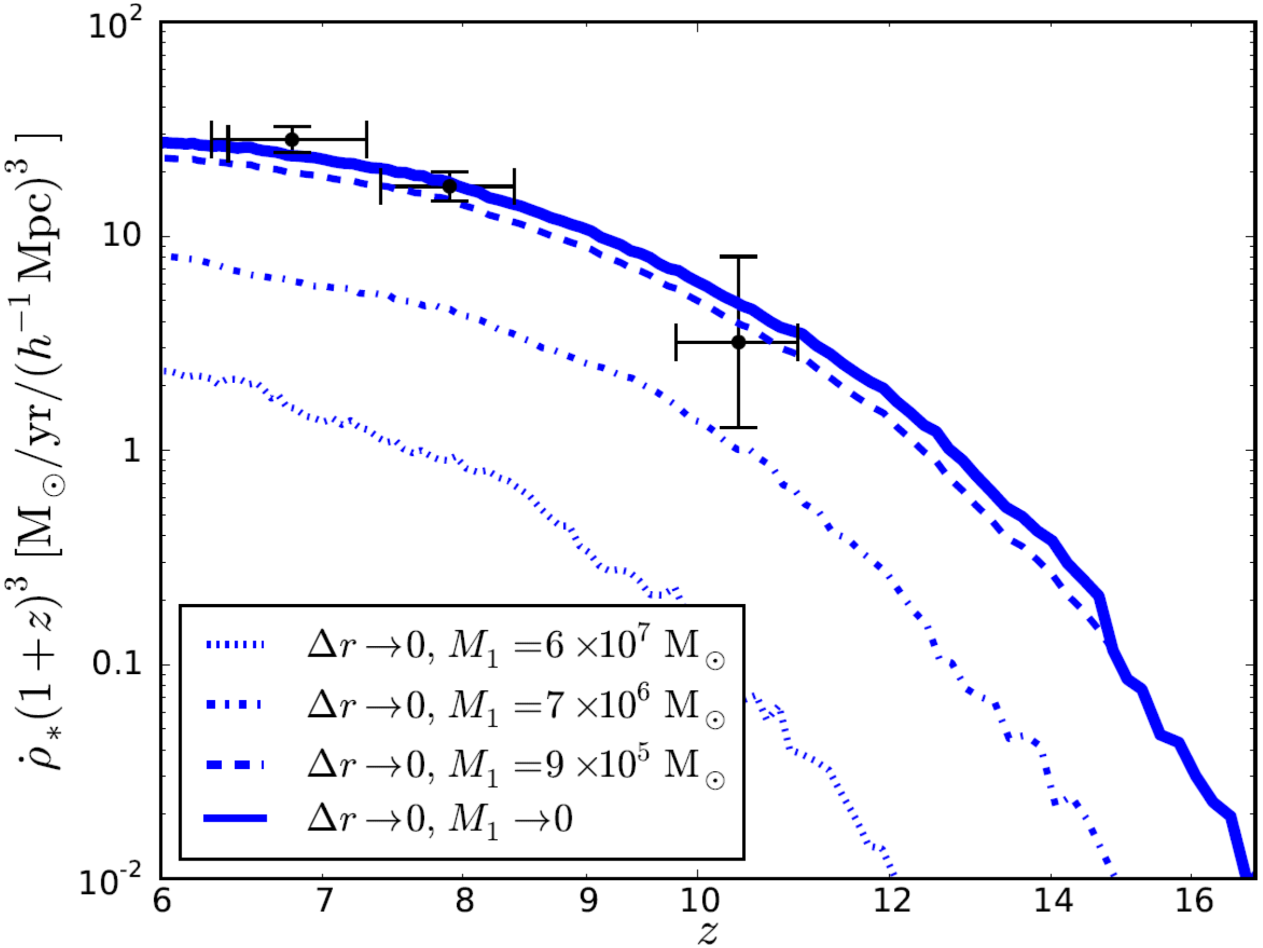
Cosmic Reionization On Computers

- When convergence is close, extrapolation $\Delta r \to 0$ is robust.



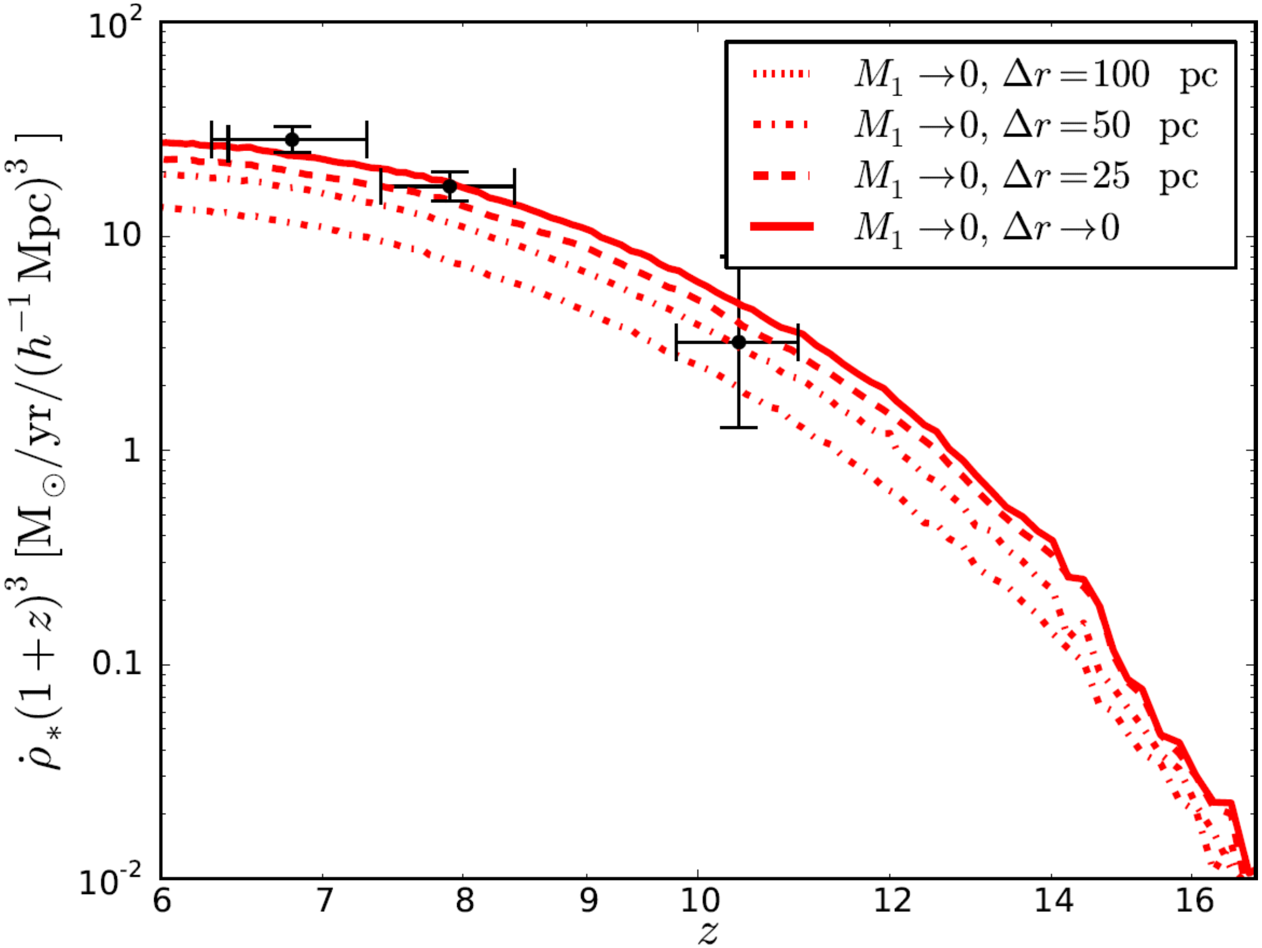
Global SFR

- Extrapolate first in space, then in mass…



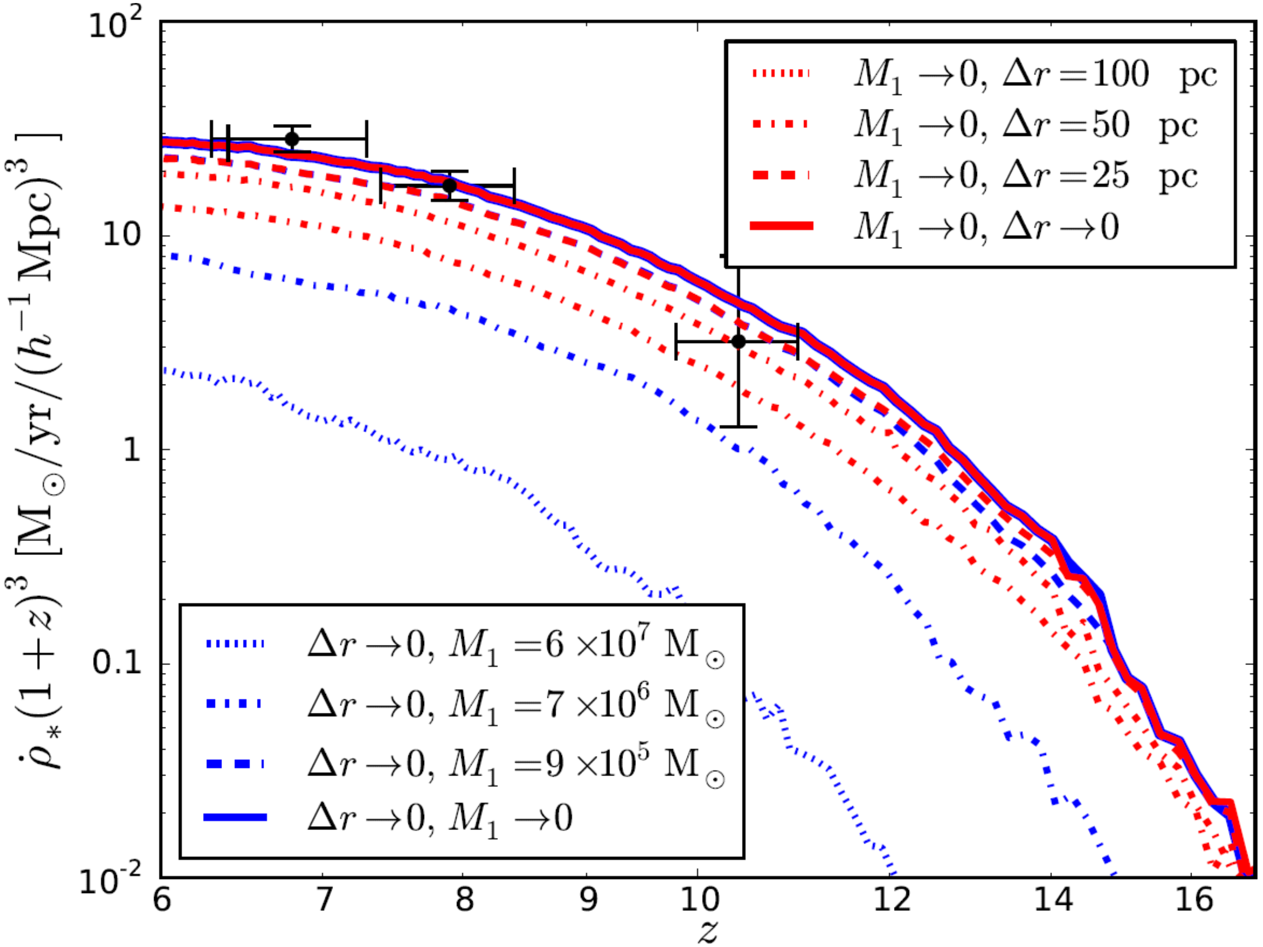
Global SFR

- Extrapolate first in mass, then in space…



Global SFR

- …and both together.



Weak Convergence

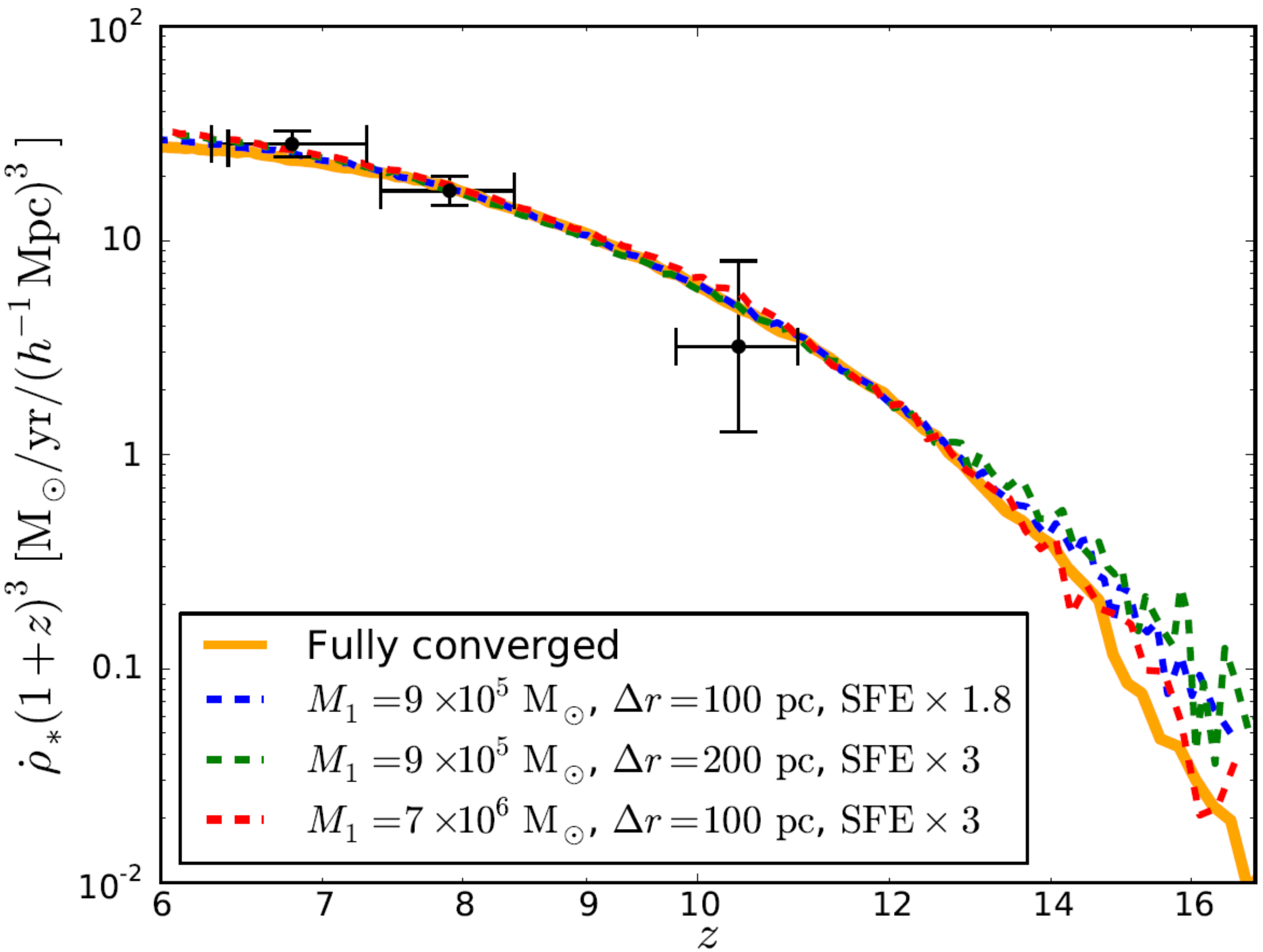
- At production scale, we cannot run the whole convergence ladder – have to reply on “weak convergence”.

$$\hat{Q} = \lim_{\Delta r, M_1 \to 0} Q(\Delta r, M_1 | p_j) \approx Q(\Delta r, M_1 | \hat{p}_j)$$

- As we change the resolution, we adjust the parameters of the model to keep the solution fixed.
- WARNING: if quantity Q is weakly converged, it does not guarantee that some other H quantity is weakly converged too!

Weak Convergence

- To weakly converge on global SFR is easy.



The CROC Project: Simulations

Cosmic Reionization On Computers

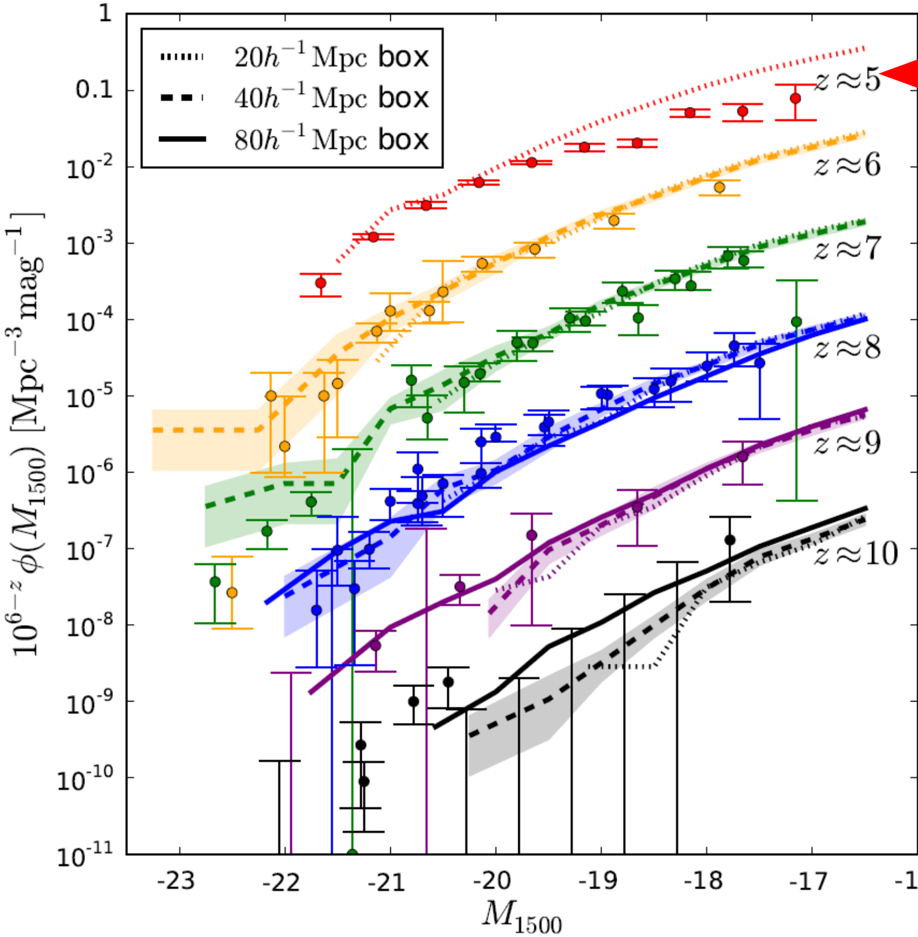
- Δx = 100/200 pc with AMR (Deep/Shallow)
- $M_1 = 9\text{x}10^5 M_\odot$, $7\text{x}10^6 M_\odot$ (High/Medium)

- Sets of boxes: Med/High
  - Small 20 CHIMP, $512^3/1024^3$
  - Medium 40 CHIMP, 1024^3/**2048^3**
  - Large 80 CHIMP, **2048^3**/4096^3

"Ultimate" simulation (300Mh)

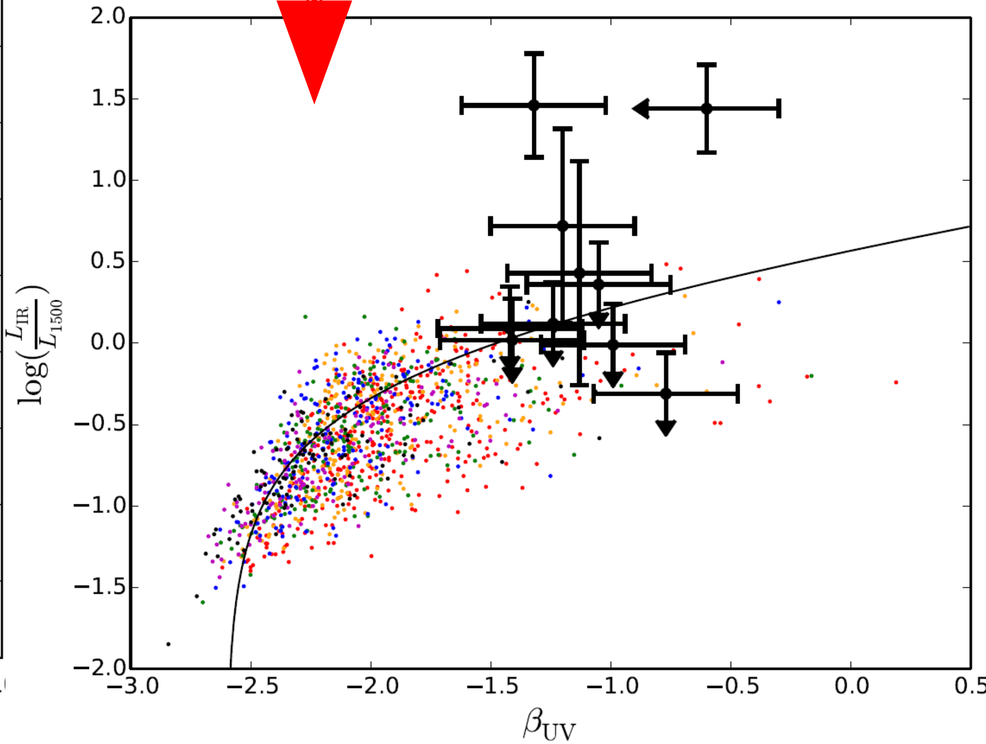
The CROC Project: Validation Test #1

- **Sources** are modeled correctly (at least at $z>5$).



Luminosity functions

UV slopes, IR excess

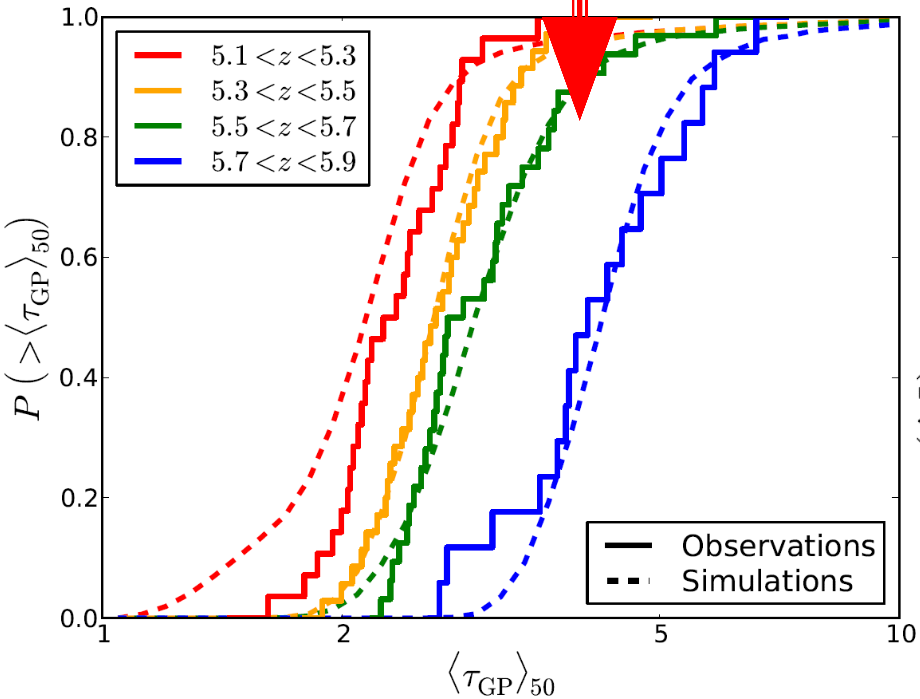


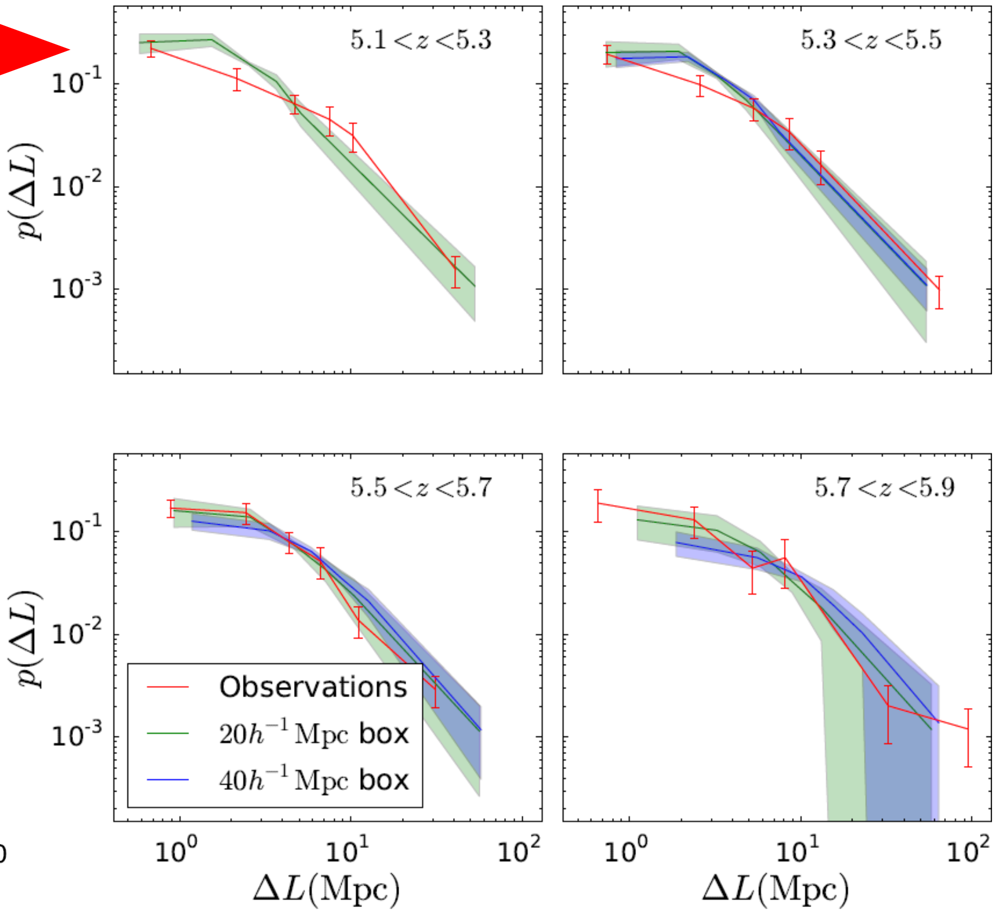
The CROC Project: Validation Test #2

- **Sinks** are modeled correctly (at least at z>5).

Gap statistics (2 point)

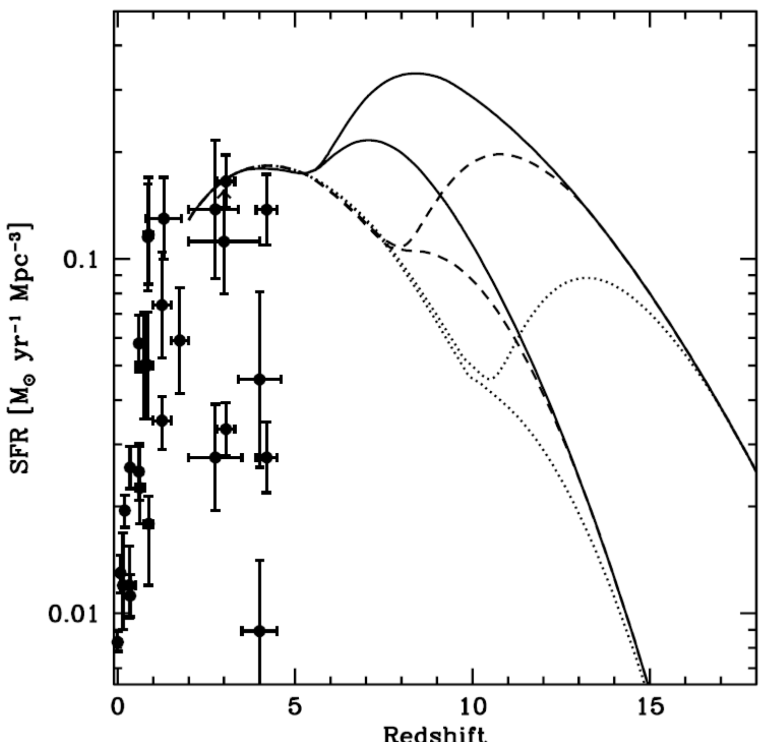
PDF (1 point)





Backreaction of Reionization on Galaxies

- Reionization suppresses gas accretion on low mass halos ("photoevaporation").
- Reionization may affect global star formation rate ("Barkana & Loeb effect").

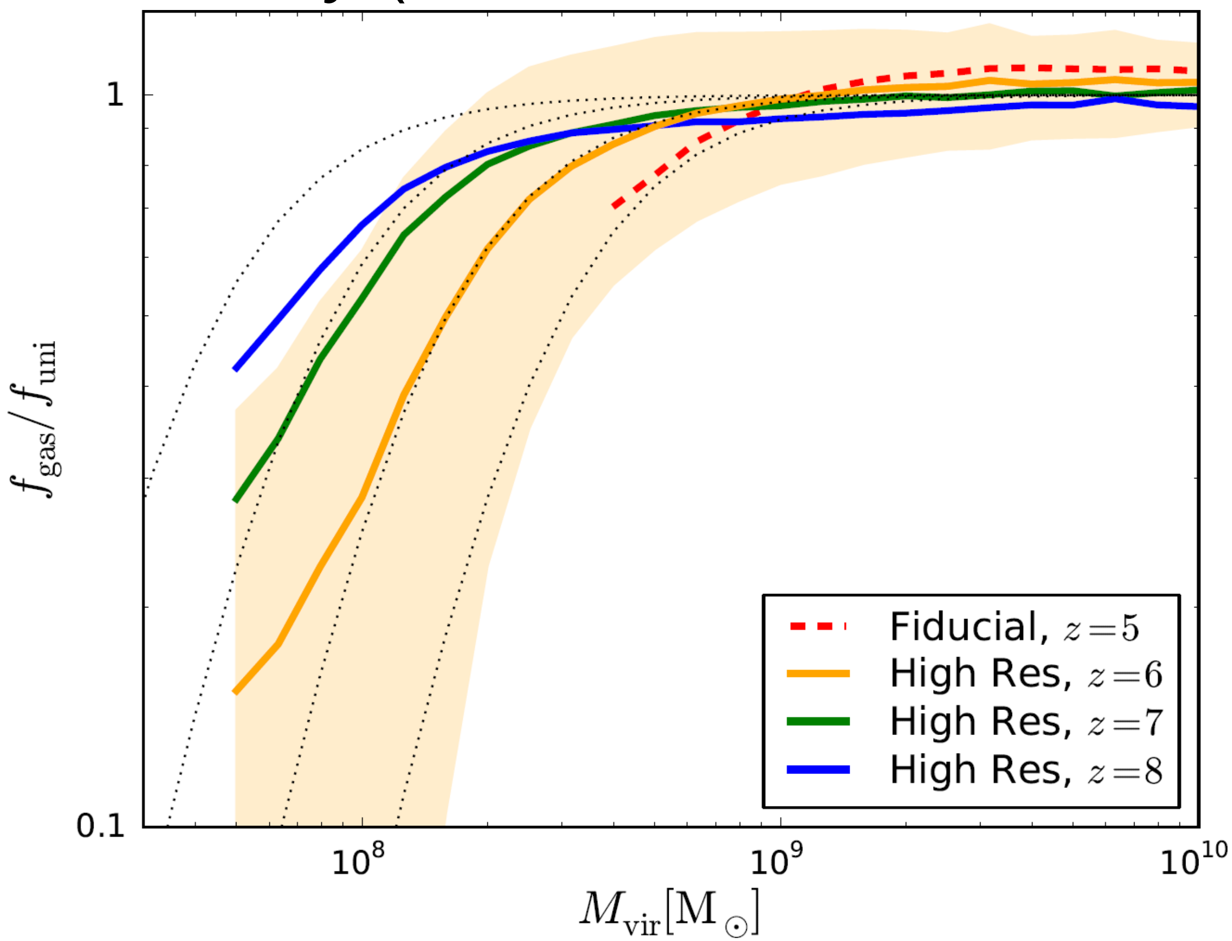


- One of JWST science goals.

(Barkana & Loeb 2000)

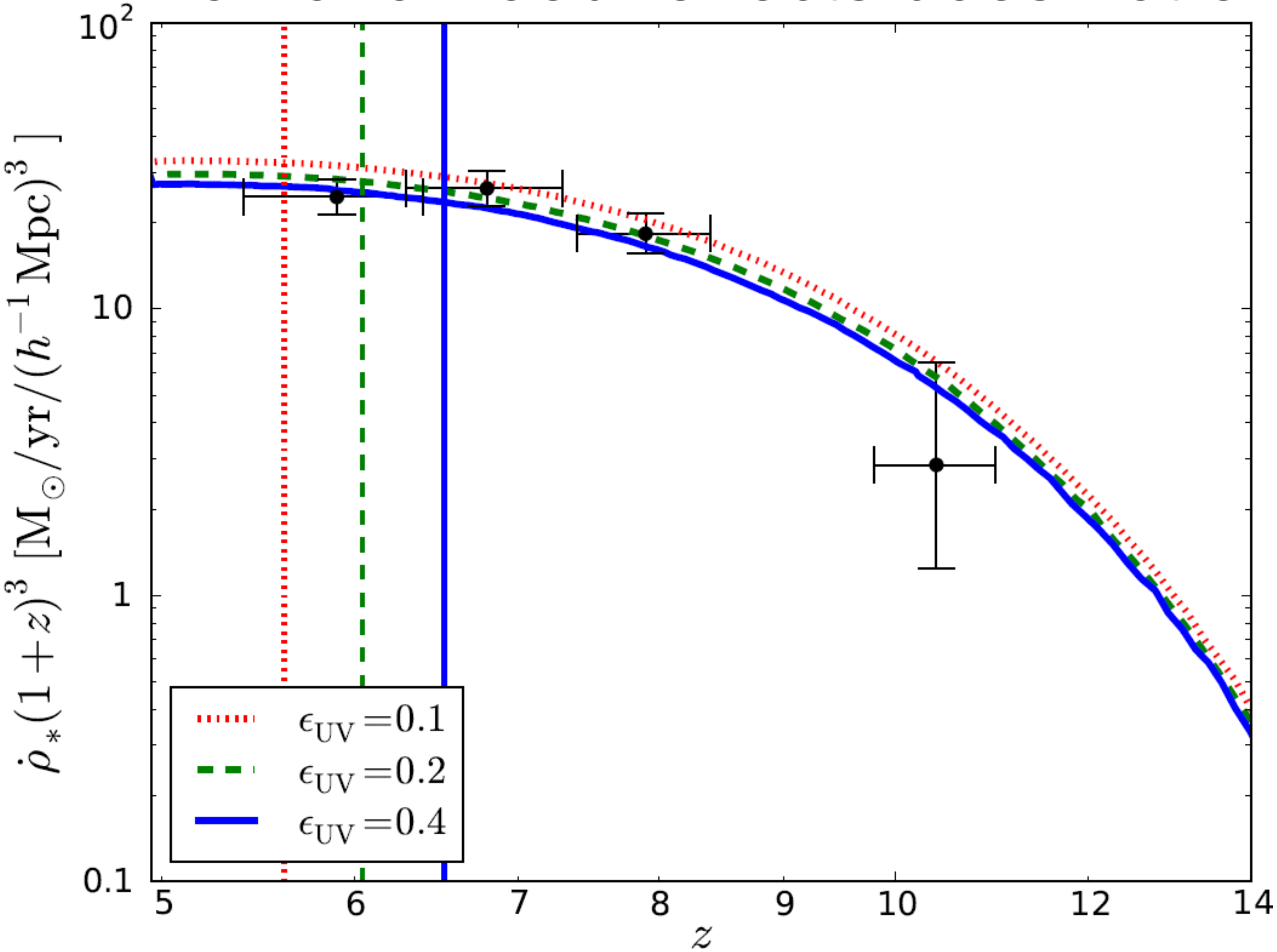
Backreaction: Gas Fractions

- Match Okamoto et al (2008) results *exactly* (after reionization, of course).

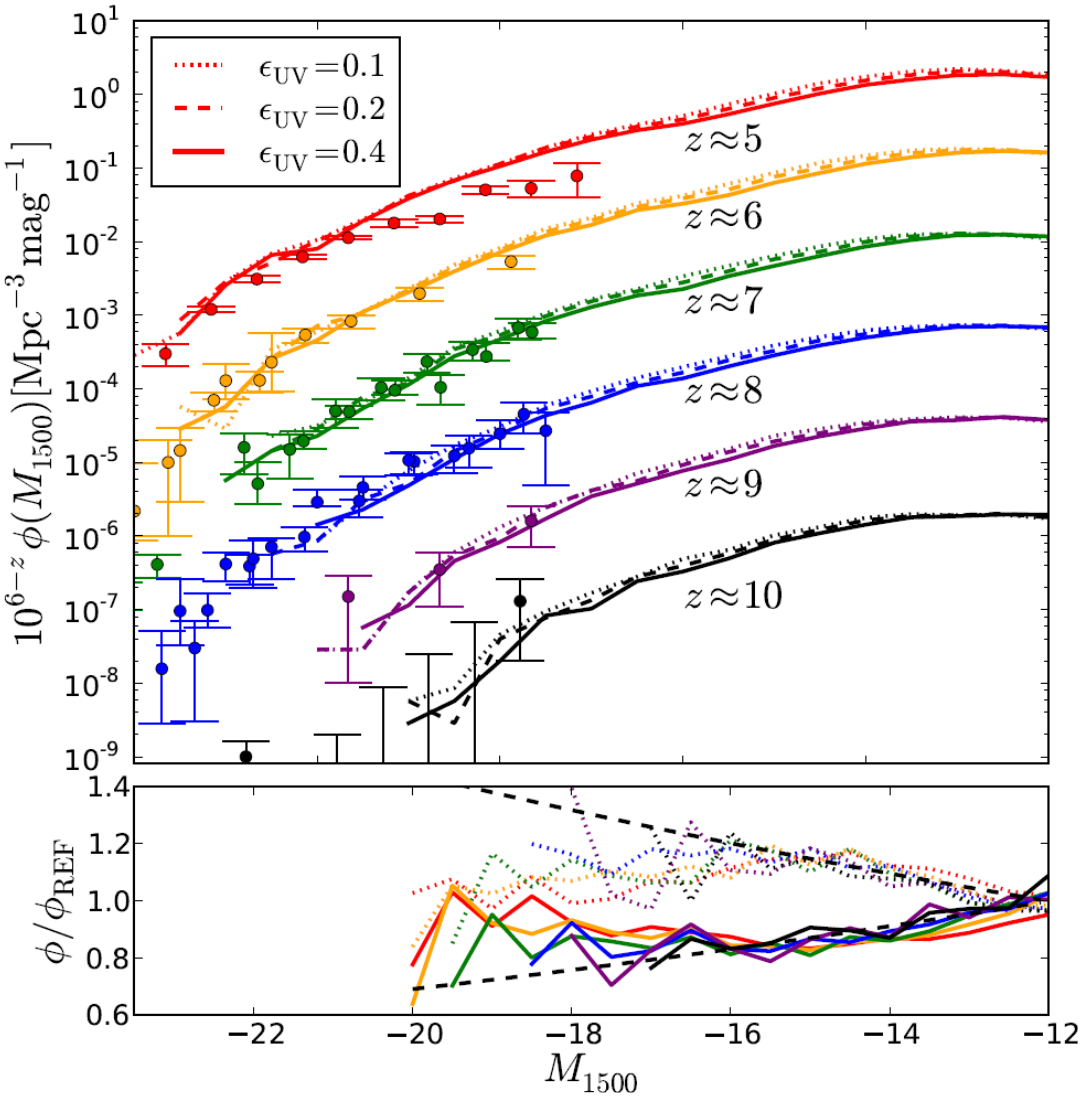


Backreaction: Barkana-Loeb Effect

- There is no feature at reionization: "Barkana-Loeb" effects does not exist.



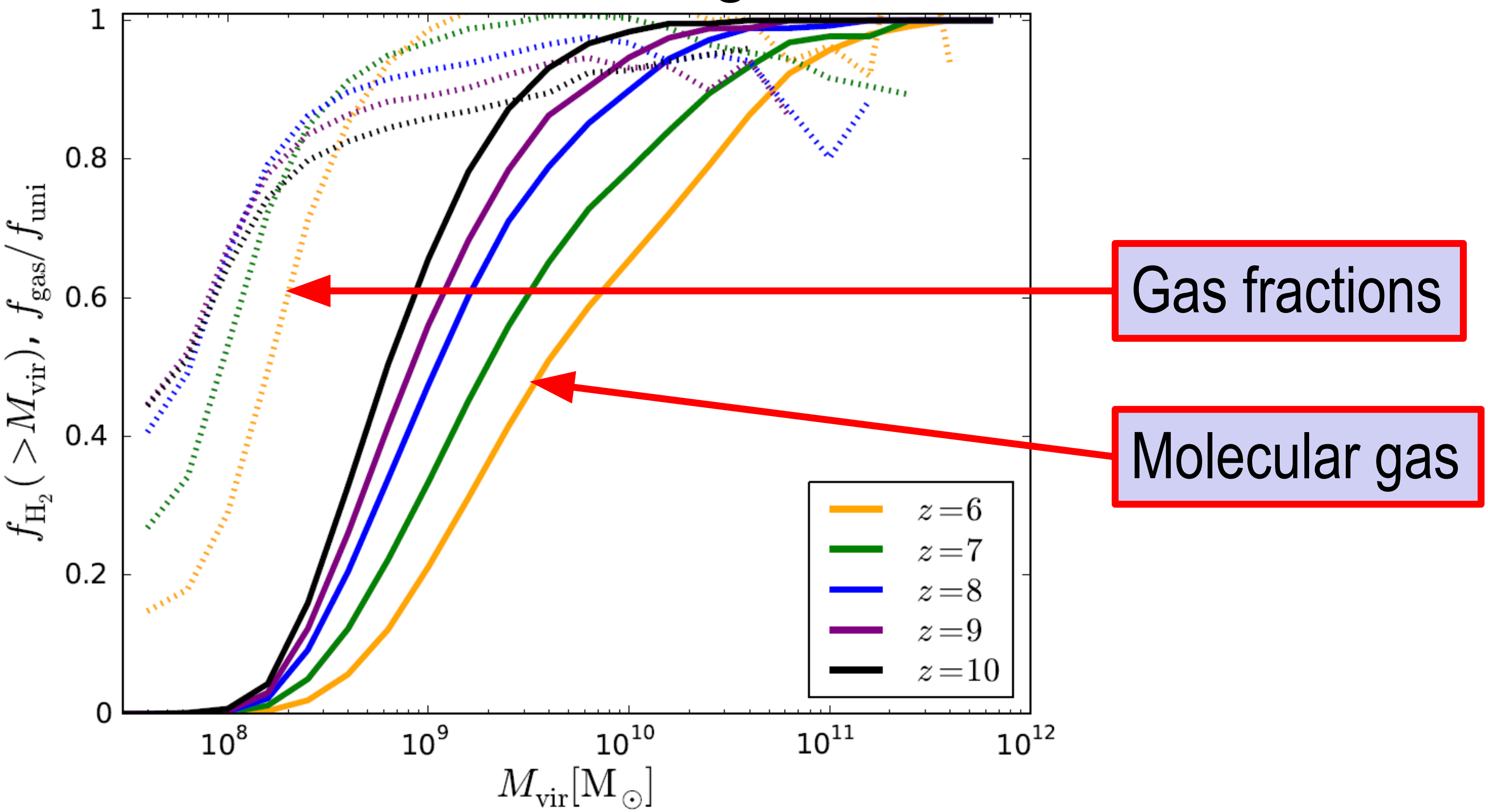
Backreaction: Faint-End Slope



- Faint-end slope of UV luminosity function varies $\lesssim 0.1$ $\Delta z = 1$

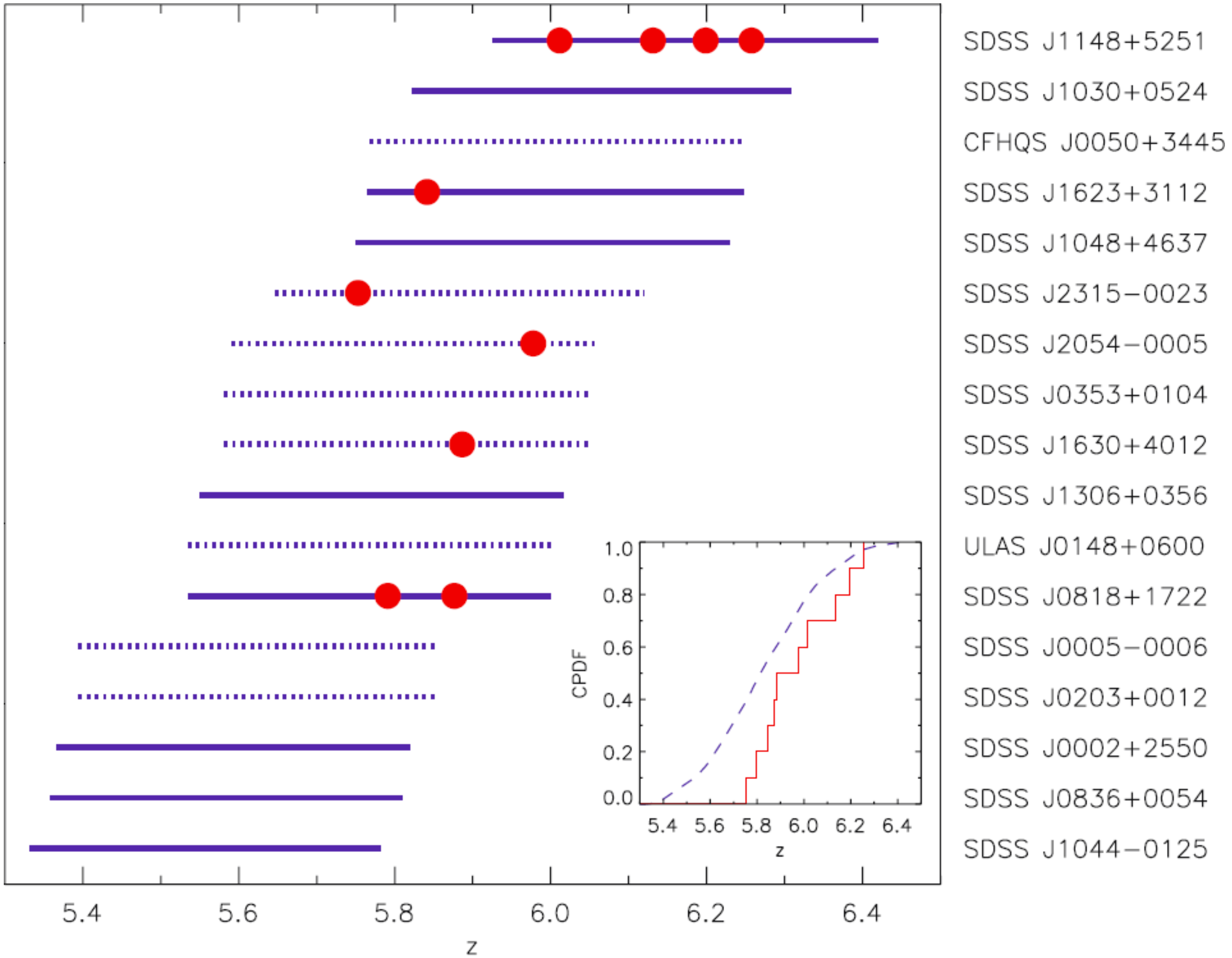
Backreaction: Why?

- Galaxies affected by photoionization contain no molecular gas.



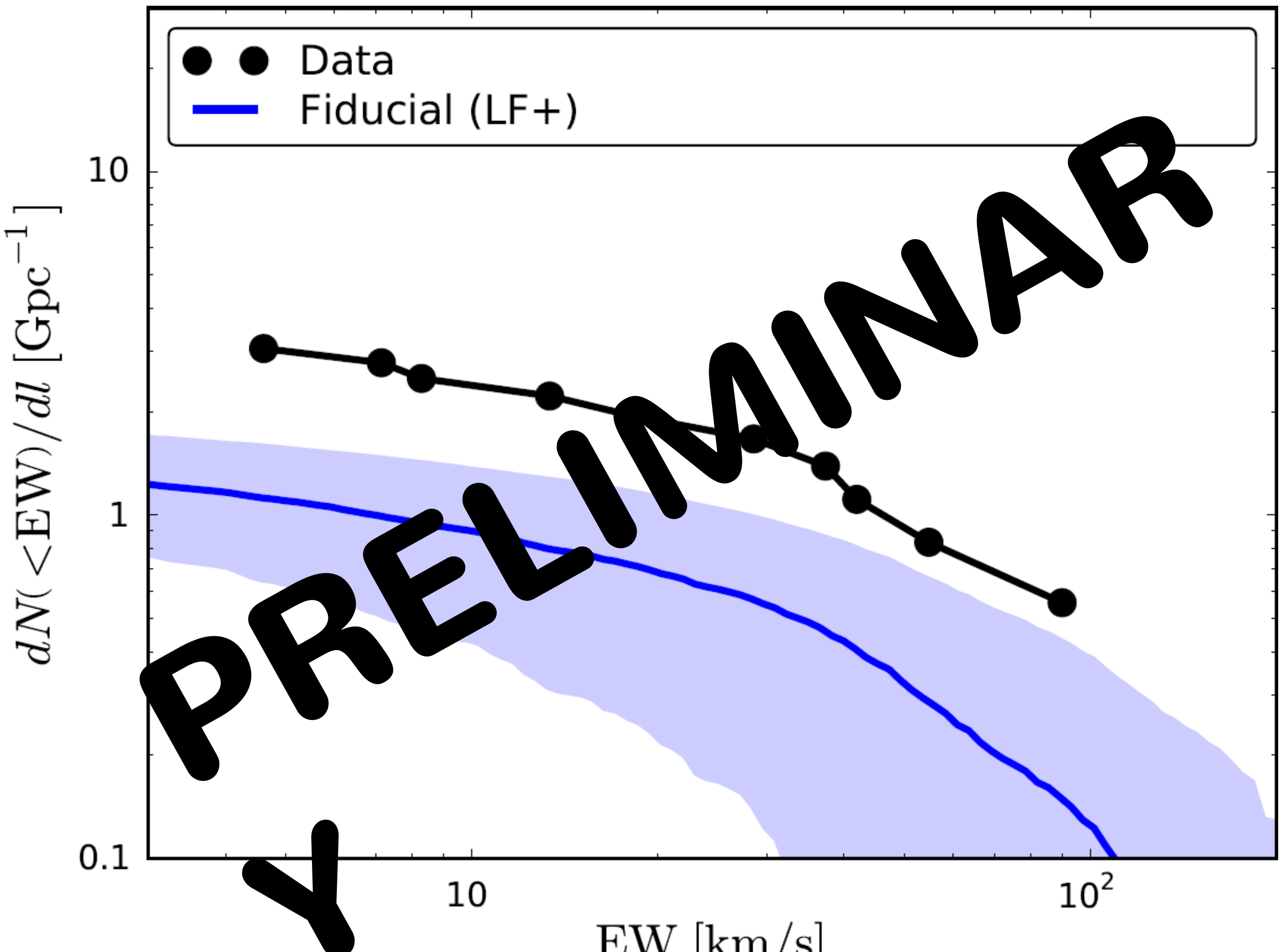
Failure #1: OI Absorption

- Neutral gas: Becker et al 2011



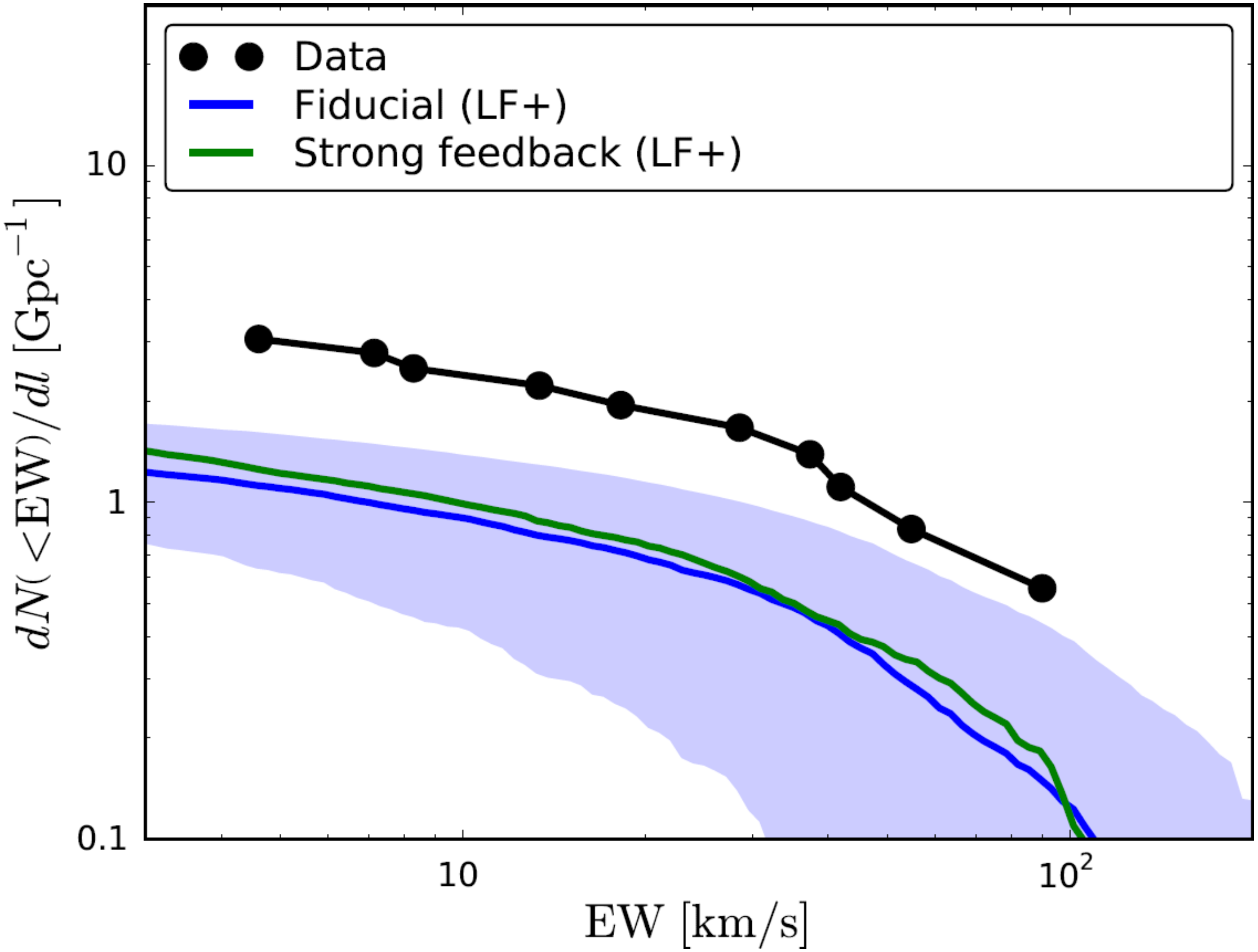
OI Absorption

- CROC vs George Becker & Co.



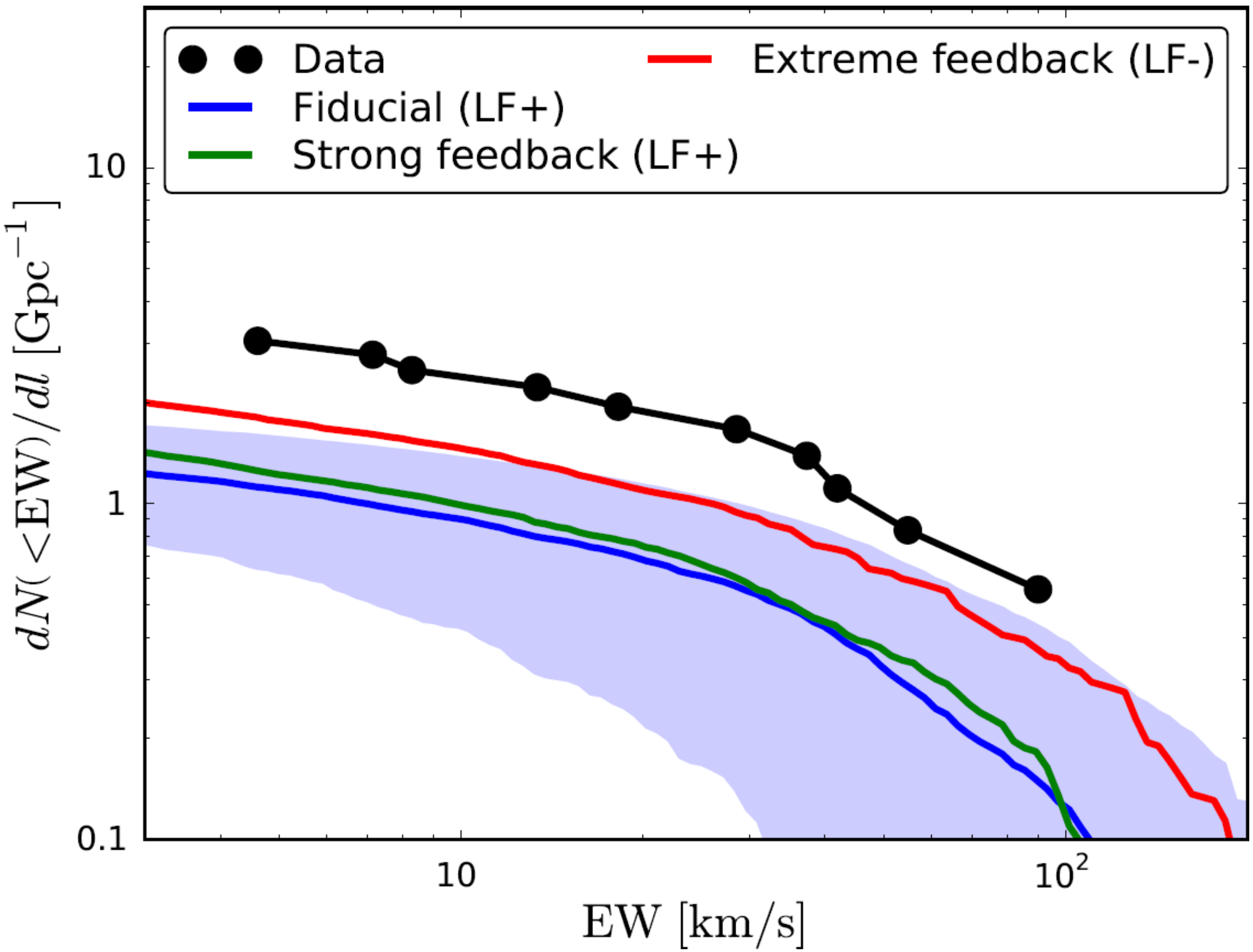
OI Absorption

- Direct probe of feedback…



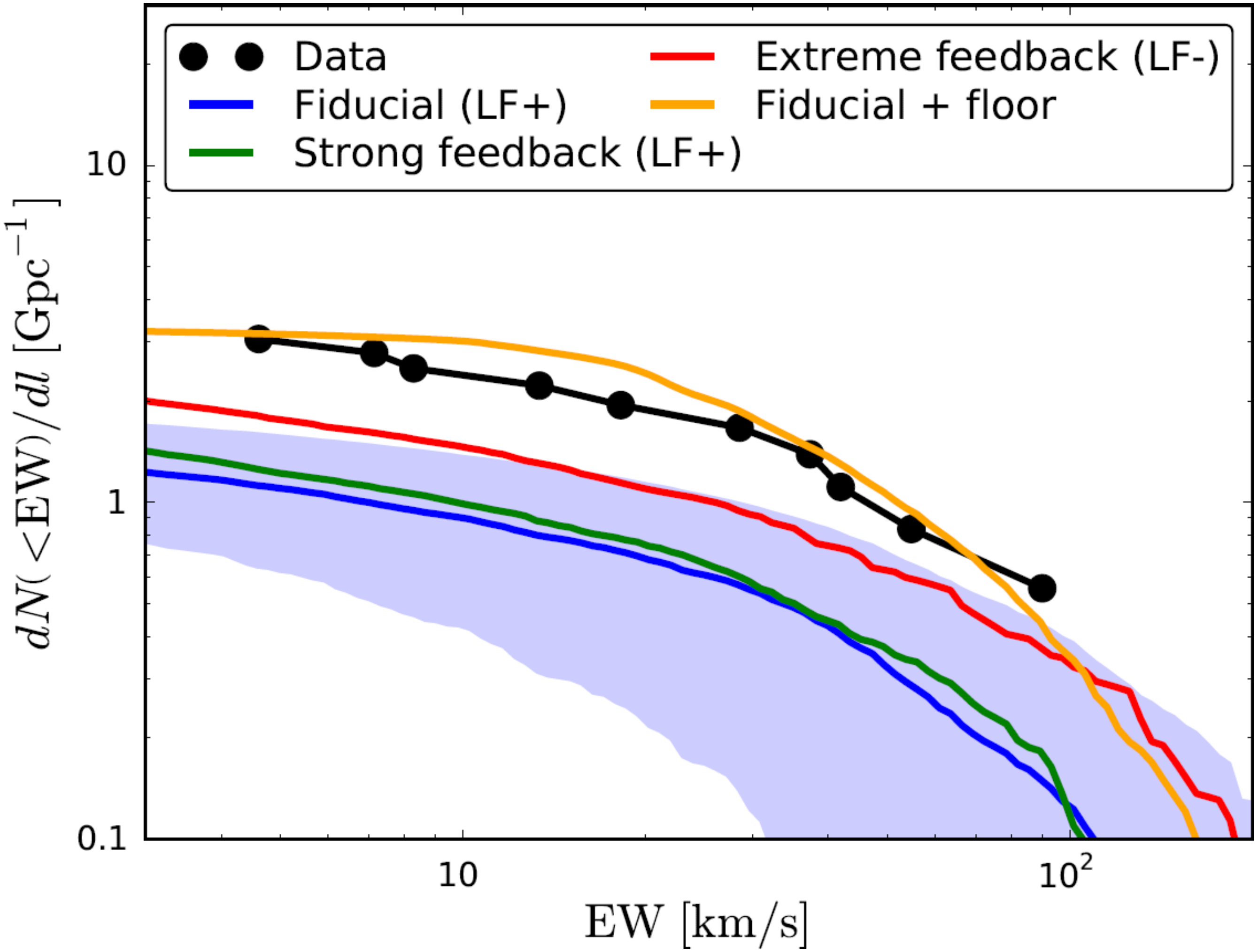
OI Absorption

- …but not a strong one.



OI Absorption

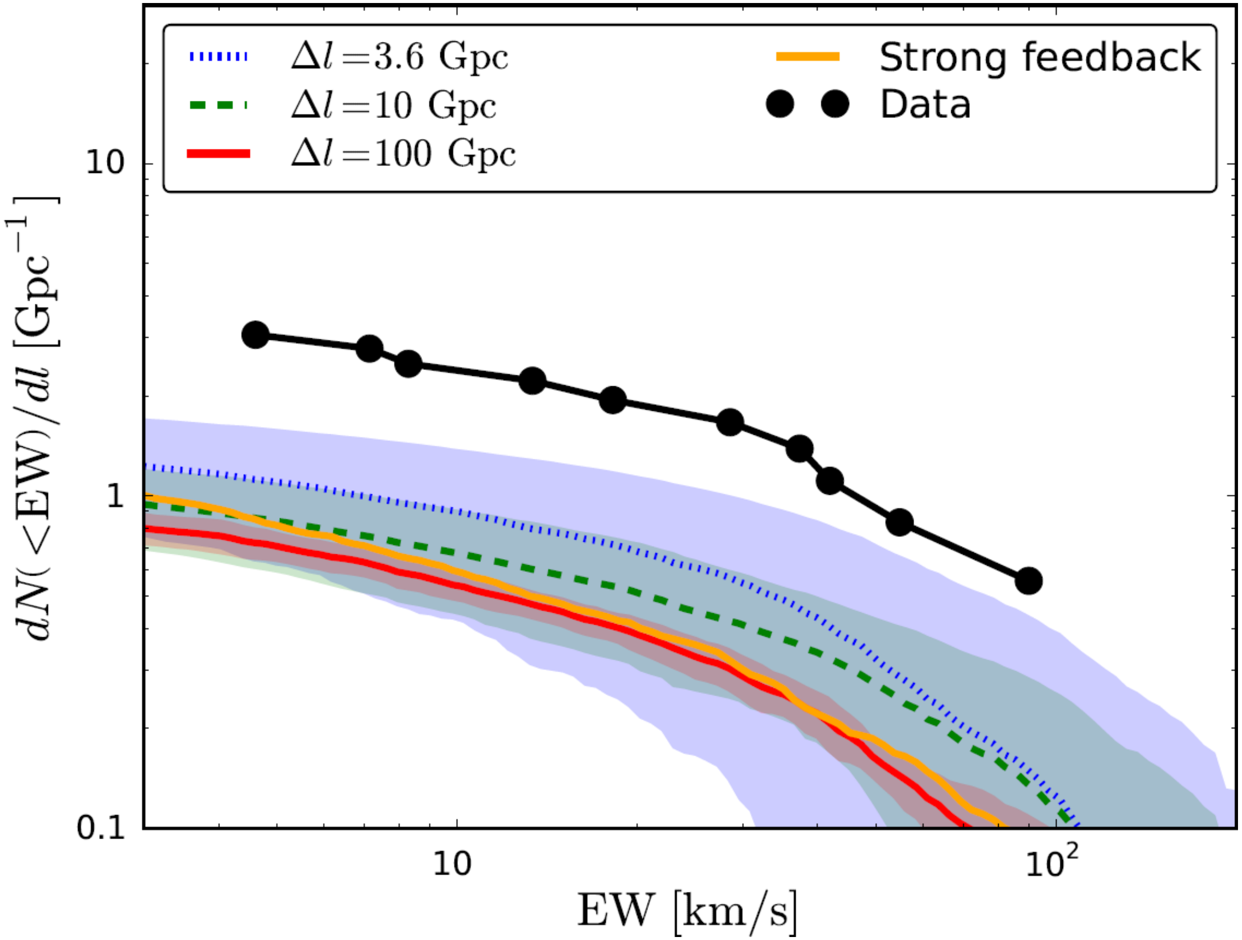
- There even may be sensitivity to the "floor".



OI Absorption

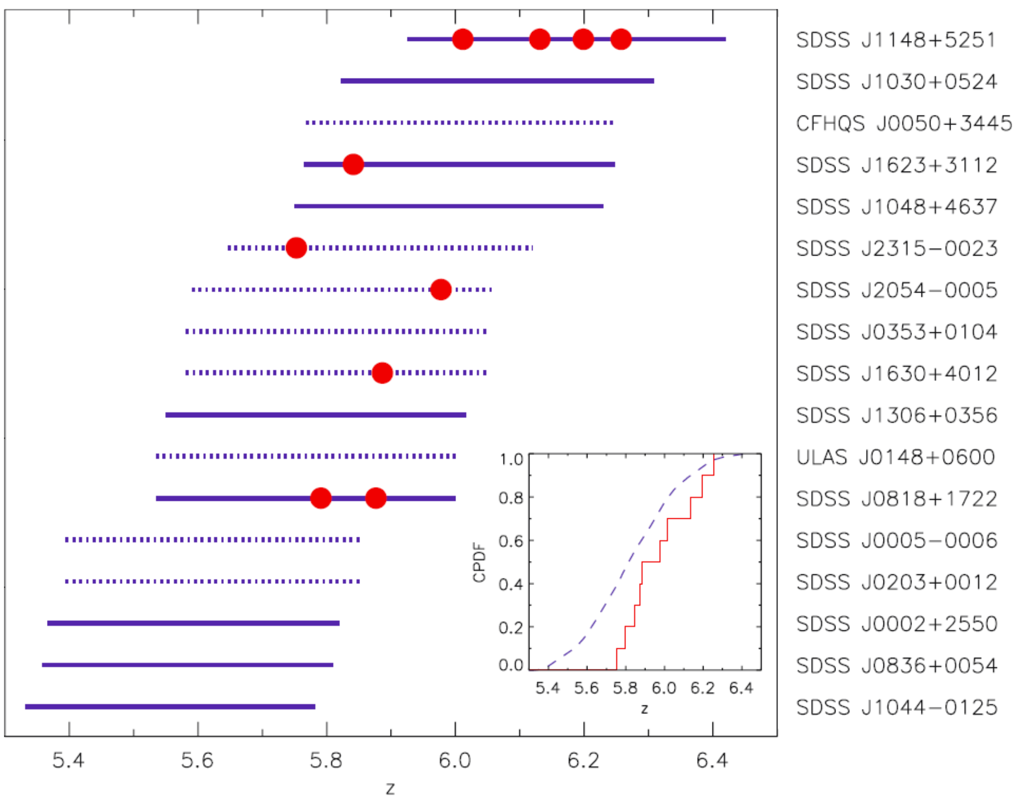
Cosmic Reionization On Computers

- How long a pathlength do we need to distinguish models?



OI Absorption

- We need 30 times more OI absorbers at z=6.
- 30-meter class optical telescopes will take us there by ~2025.



x 30

Failure #2: UV slopes

Cosmic Reionization On Computers

- In order to measure dust reddening in a simulated galaxy, we need to have dust.
- Two simple modes:

A. Dust follows metals (no sublimation)

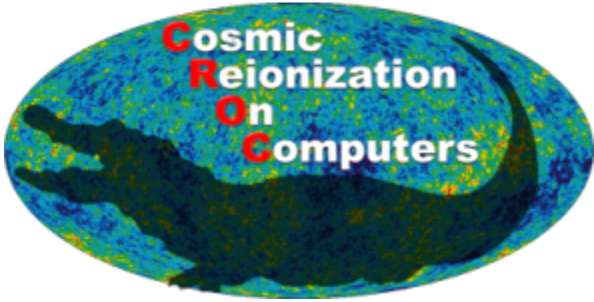
~~$\rho_D \propto \rho_Z$~~ Fails miserably

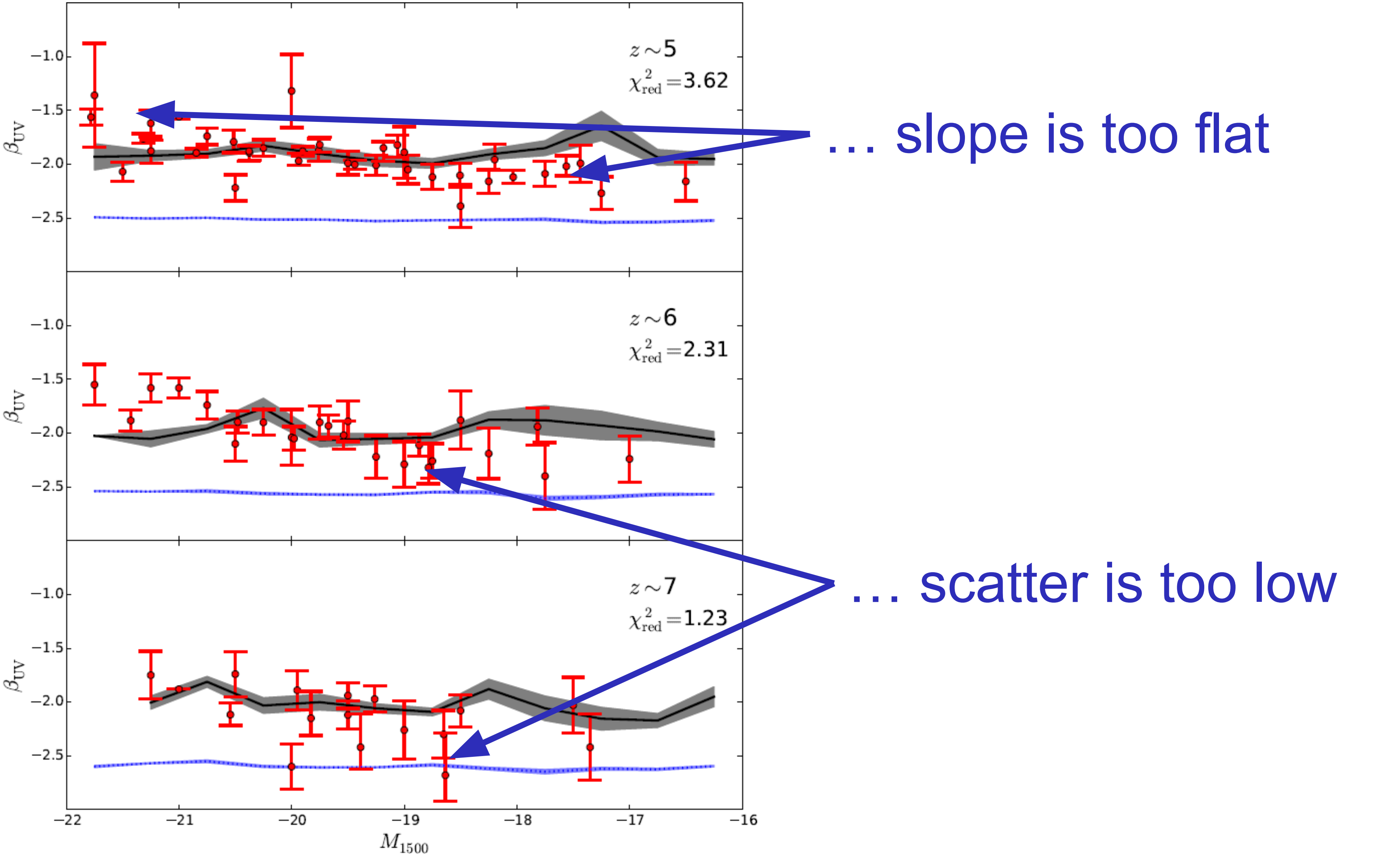
B. Instant sublimation in ionized gas

$$\rho_D \propto \rho_Z (1 - x_{\rm ion})$$

Works on average, but…

Are We Seeing The Birth of Dust?





(Examples of) What We Have Learned So Far:

- Modeling RT self-consistently (i.e. with the same spatial and temporal resolution as hydro) is crucial for getting z>5 IGM right.
- Reionization proceeds first inside-out, later outside-in.
- Reionization does **not** affect global star formation rate: galaxies that are affected by reionization have no molecular gas and, hence, form no stars.
- Cosmic dust may not follow metals at z>7 (formation and destruction time-scales are not negligibly short).

Conclusions

- Supercomputing power has passed the “peta-scale” mark. That power is just right for modeling cosmic reionization numerically.
- The first *realistic* (i.e. modeling both sources and sinks adequately) simulations of reionization are currently being worked on by several groups (CROC, DRAGONS, etc).
- By the time *The Flood** comes, theorists will be ready.

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* ALMA, JWST, 30m telescopes, 21cm

Title

- Text