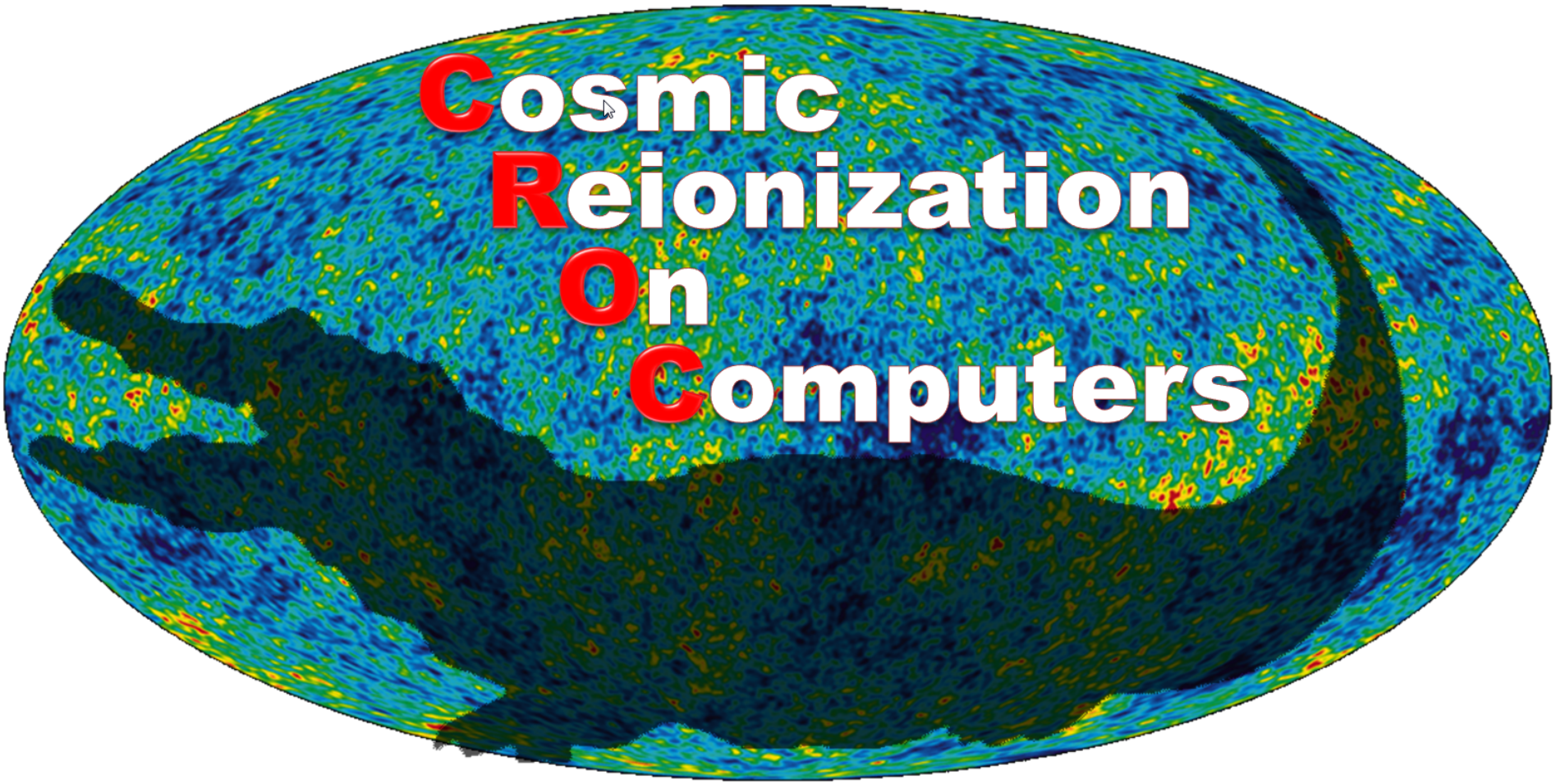


Nick Gnedin

Fermilab

THE UNIVERSITY OF CHICAGO

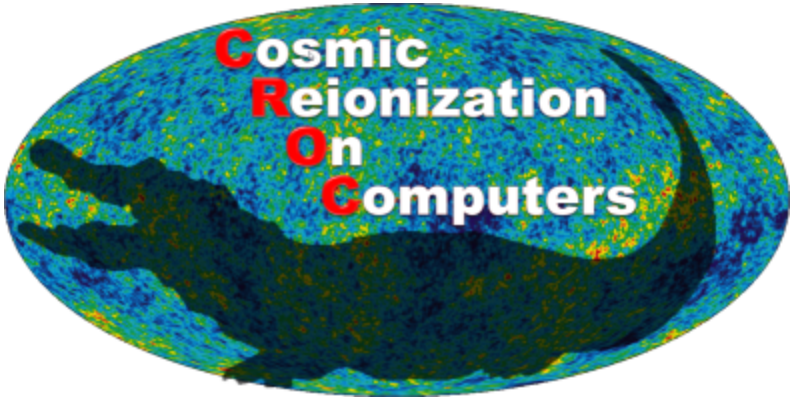
Epigraph

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.

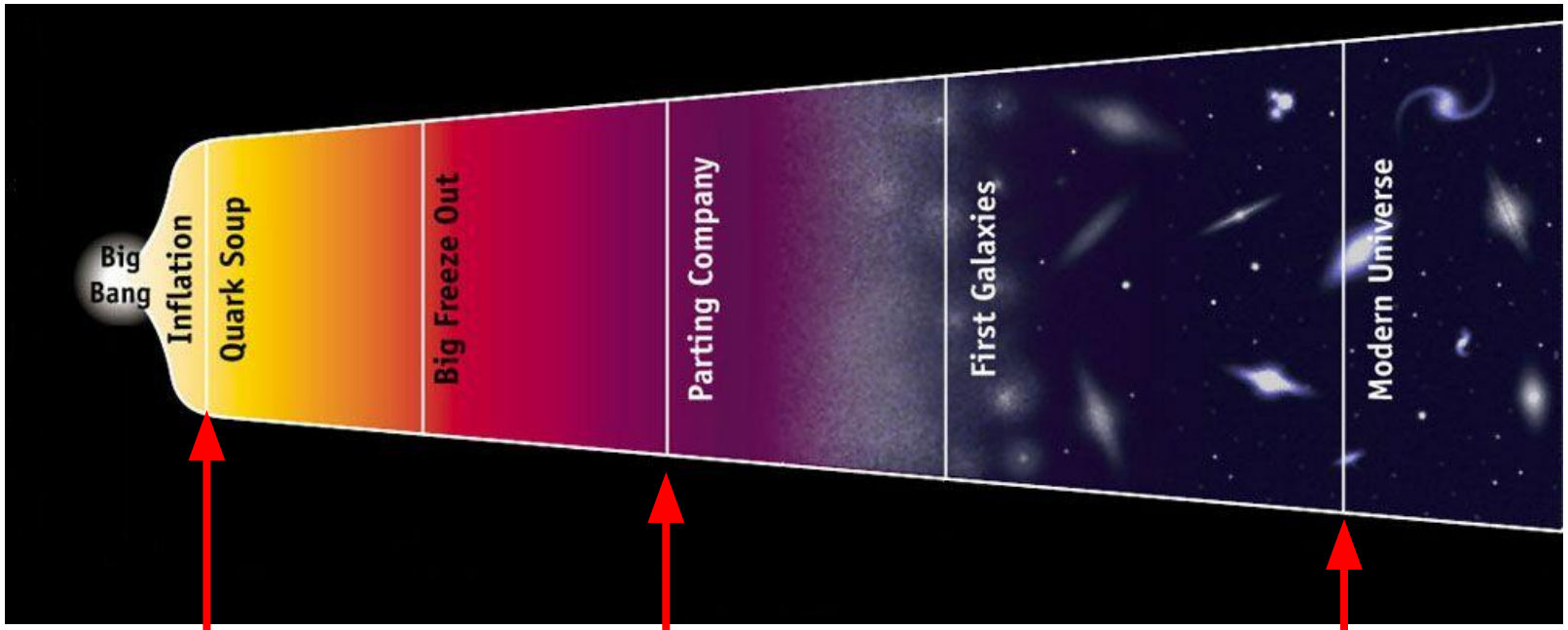
Peng Oh

Outline

- The brief history of time.
- How to reionize the universe.
- Simulations of yesterday: successes and limitations.
- CROC Project and everybody else: today we do things better.
- The Flood is coming.



The Brief History of Time

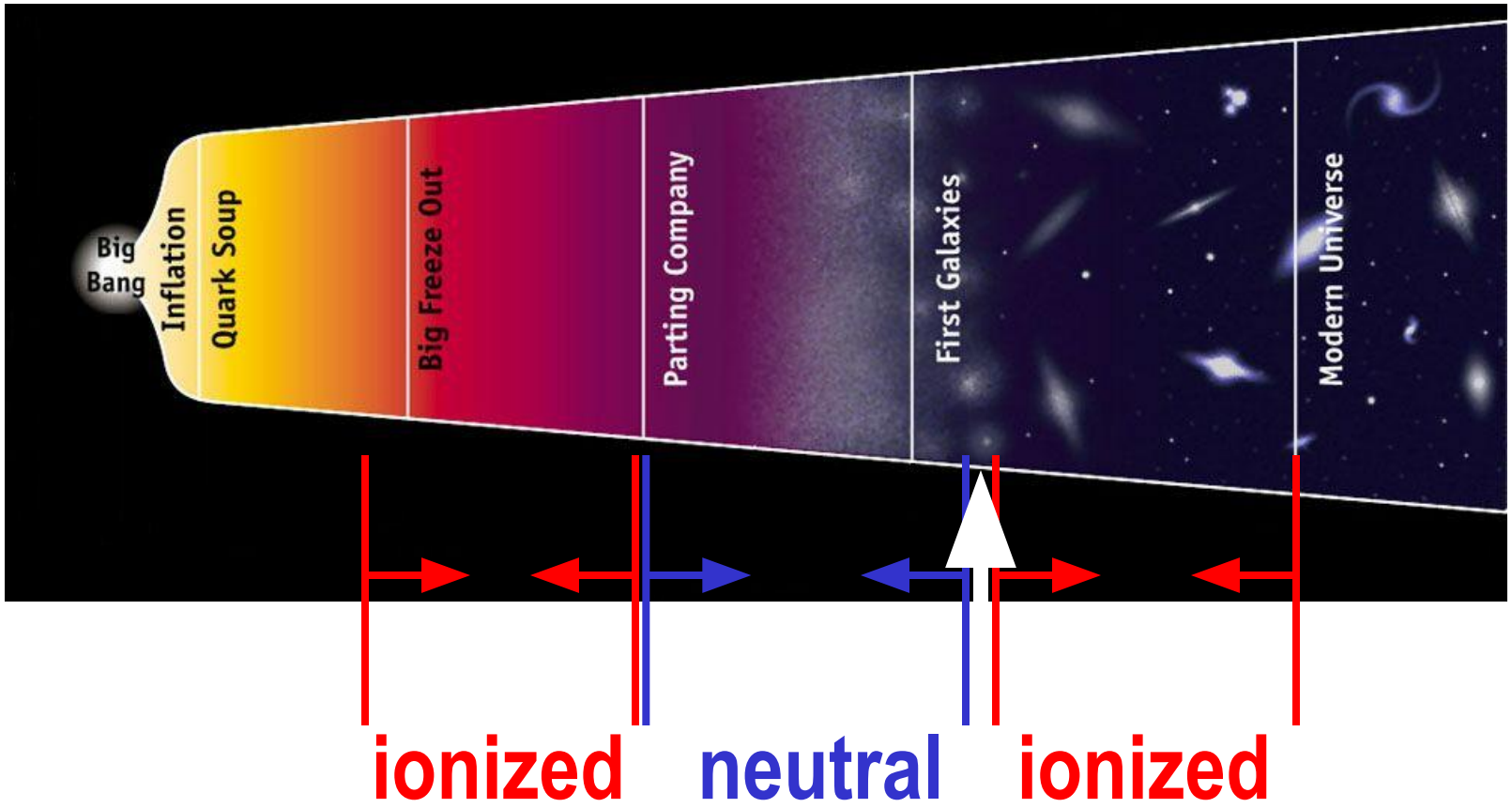


End of inflation
$z=10^{27}$
$t=10^{-36}$s

Recombination:
z=1089
t=379 kyr

Today:
z=0
t=13.7 Gyr

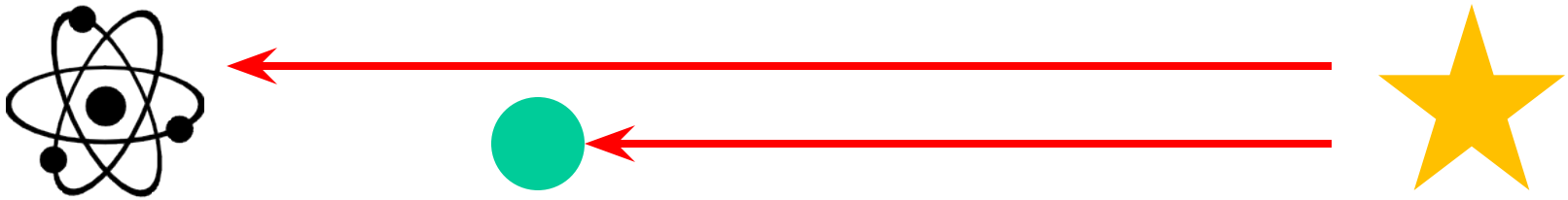
The Brief History of Time



RE-IONIZATION

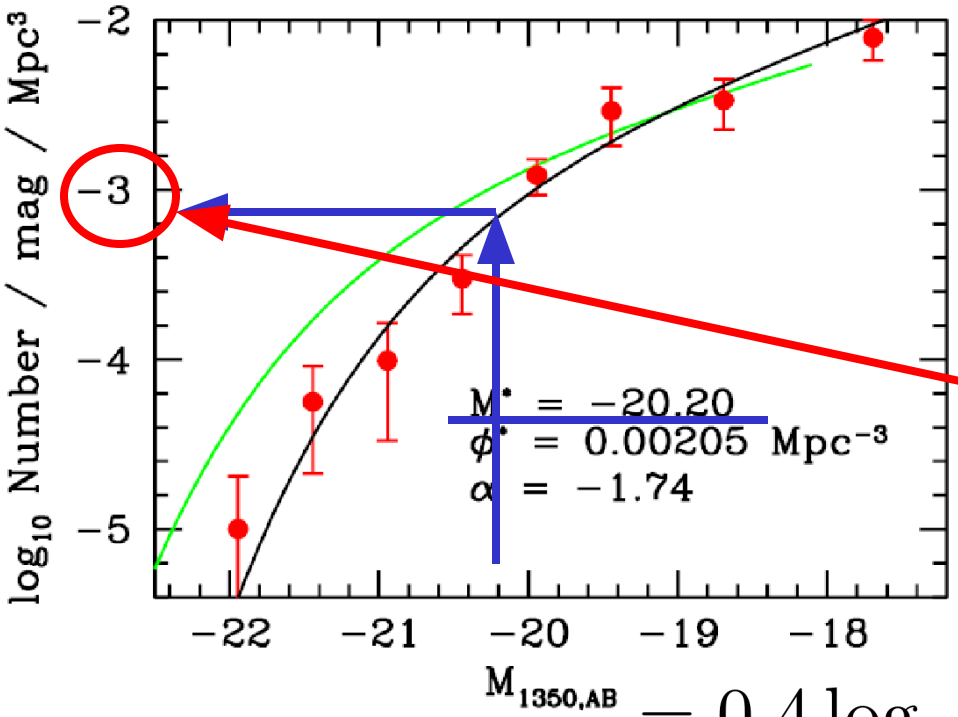
How To Reionize Universe

- Ionizing radiation must be produced by some sources (galaxies, quasars, gamma-ray bursts, dark matter annihilation, laser-armed alien spaceships).
- As ionizing photons propagate through space, they will be consumed in ionizing neutral atoms.
- They can also be absorbed by other sinks – hence, wasted from the point of view of reionization.



Sources: Galaxies

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



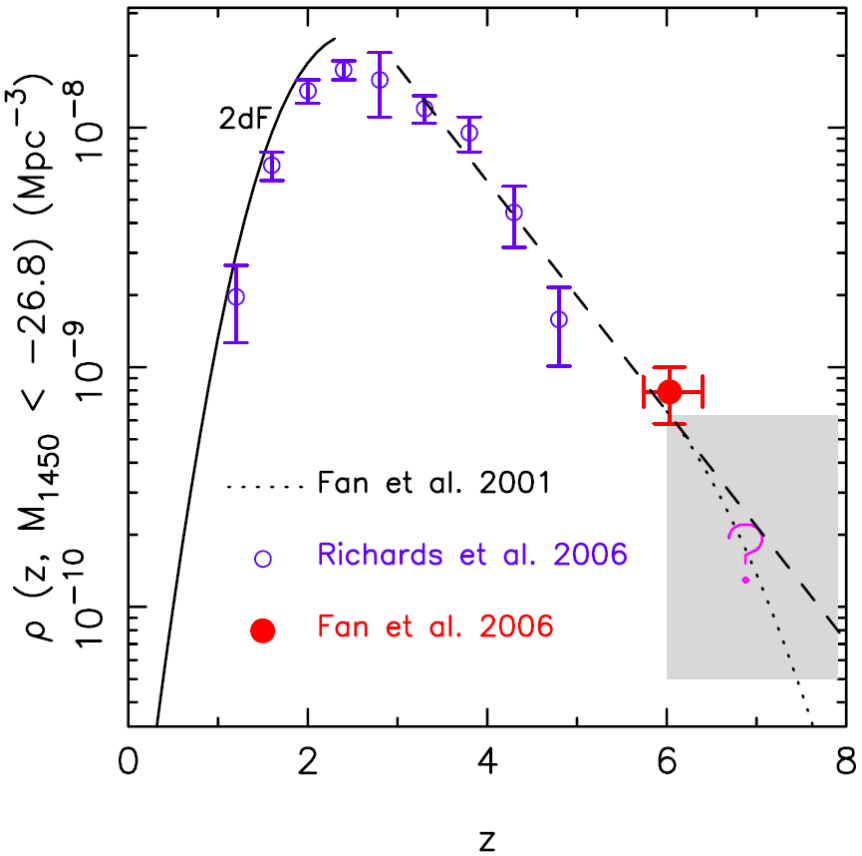
Galaxy LF at z=6
(Bouwens et al. 2006)

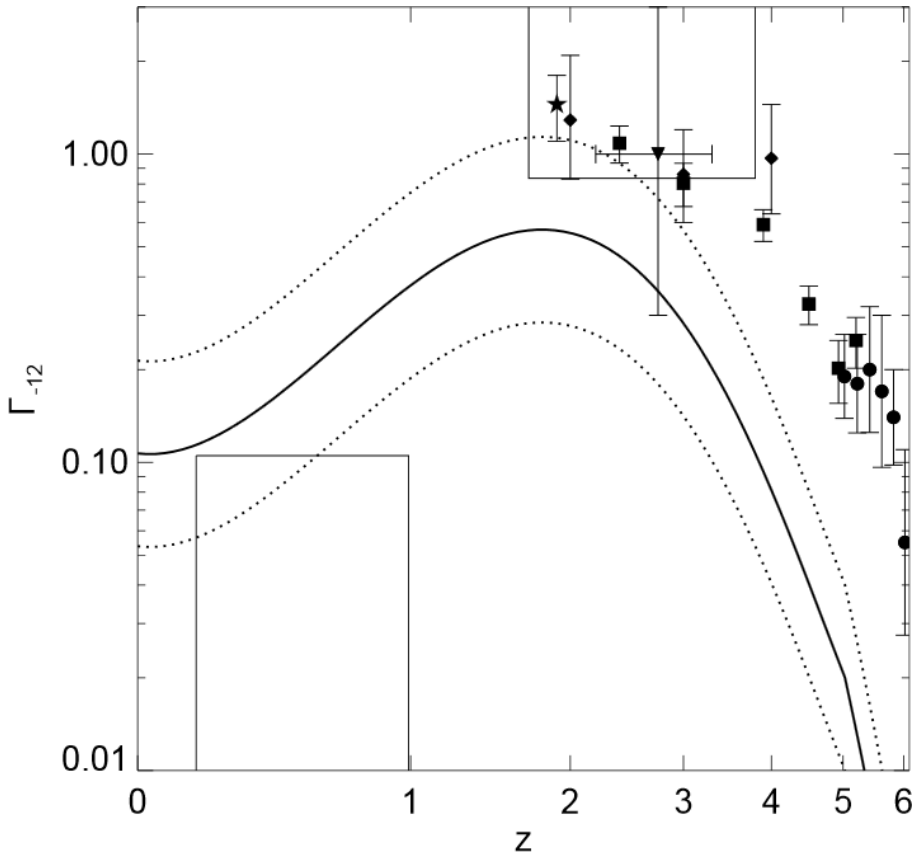
Need ~50 Mpc box

$$= 0.4 \log_{10} L_*$$

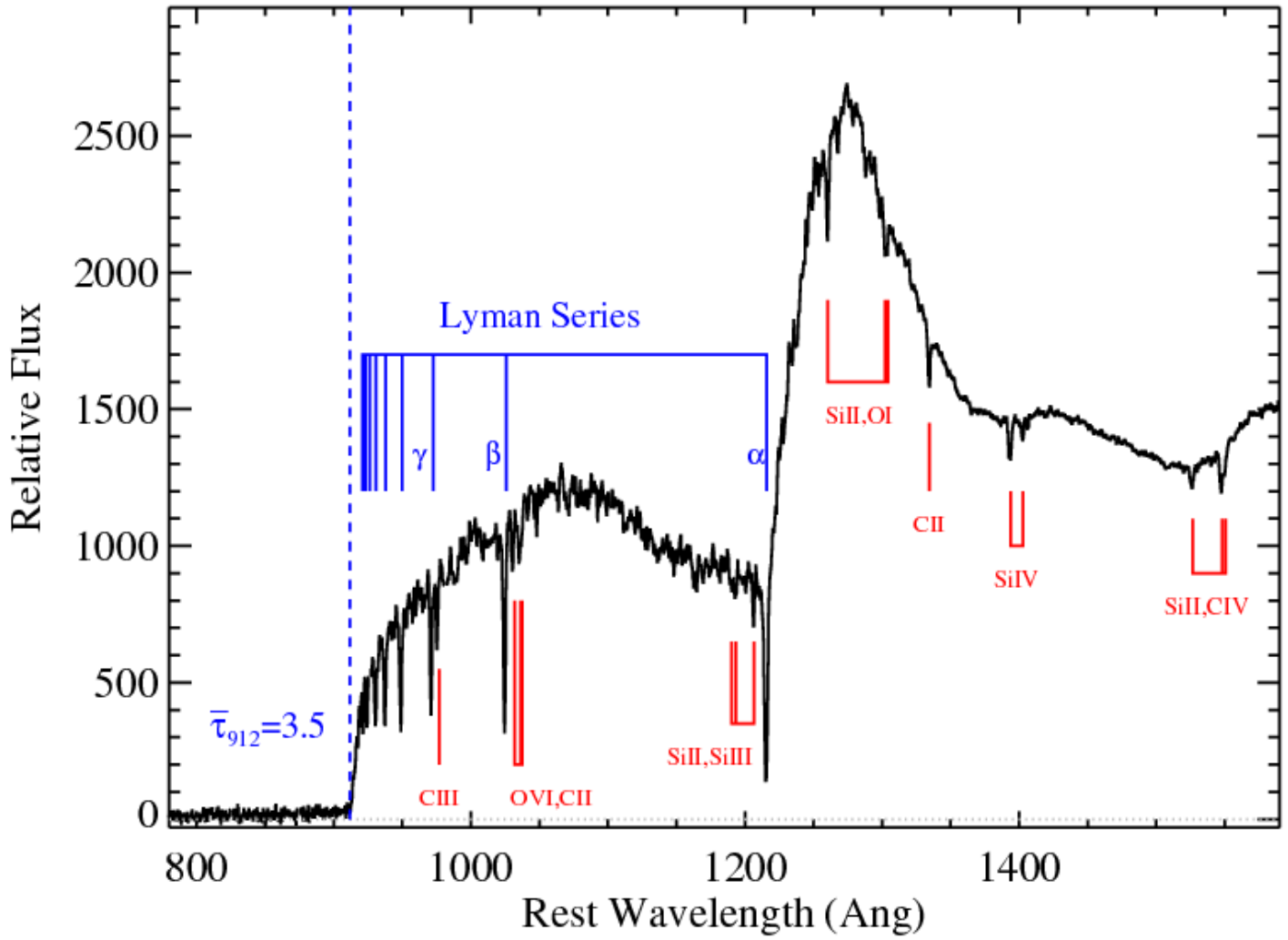
Sources: Quasars

- QSOs are efficient producers of ionizing radiation.
- The only problem – they are too rare at z>3.



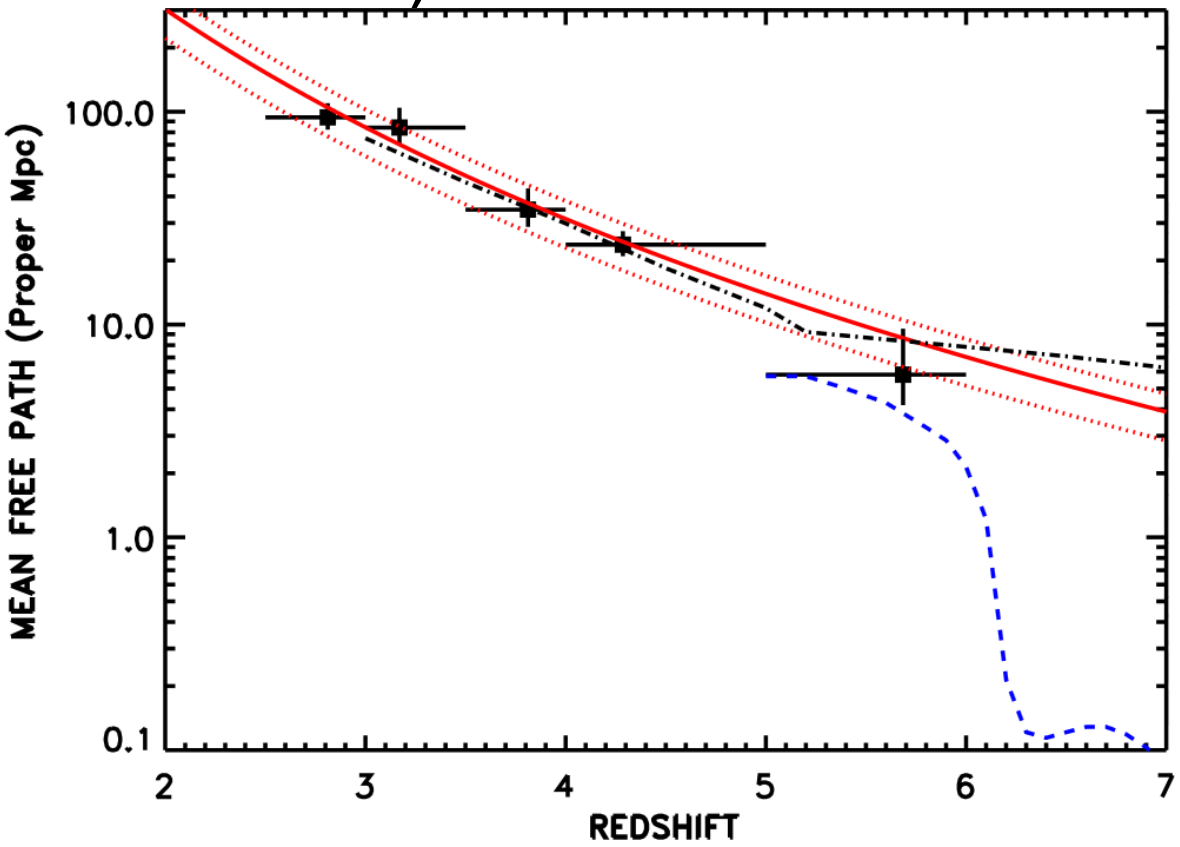


Sinks: Lyman-Limit Systems

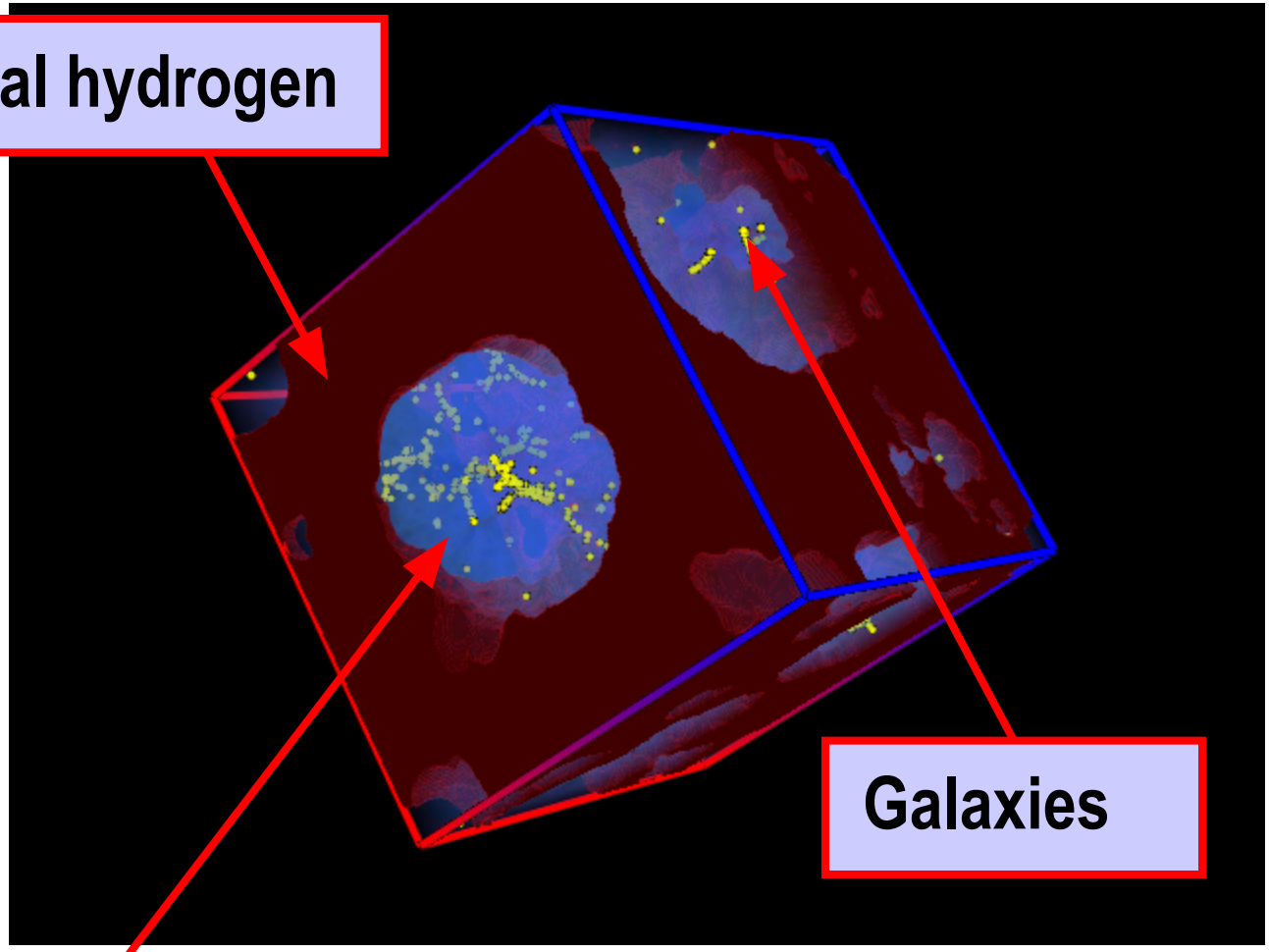


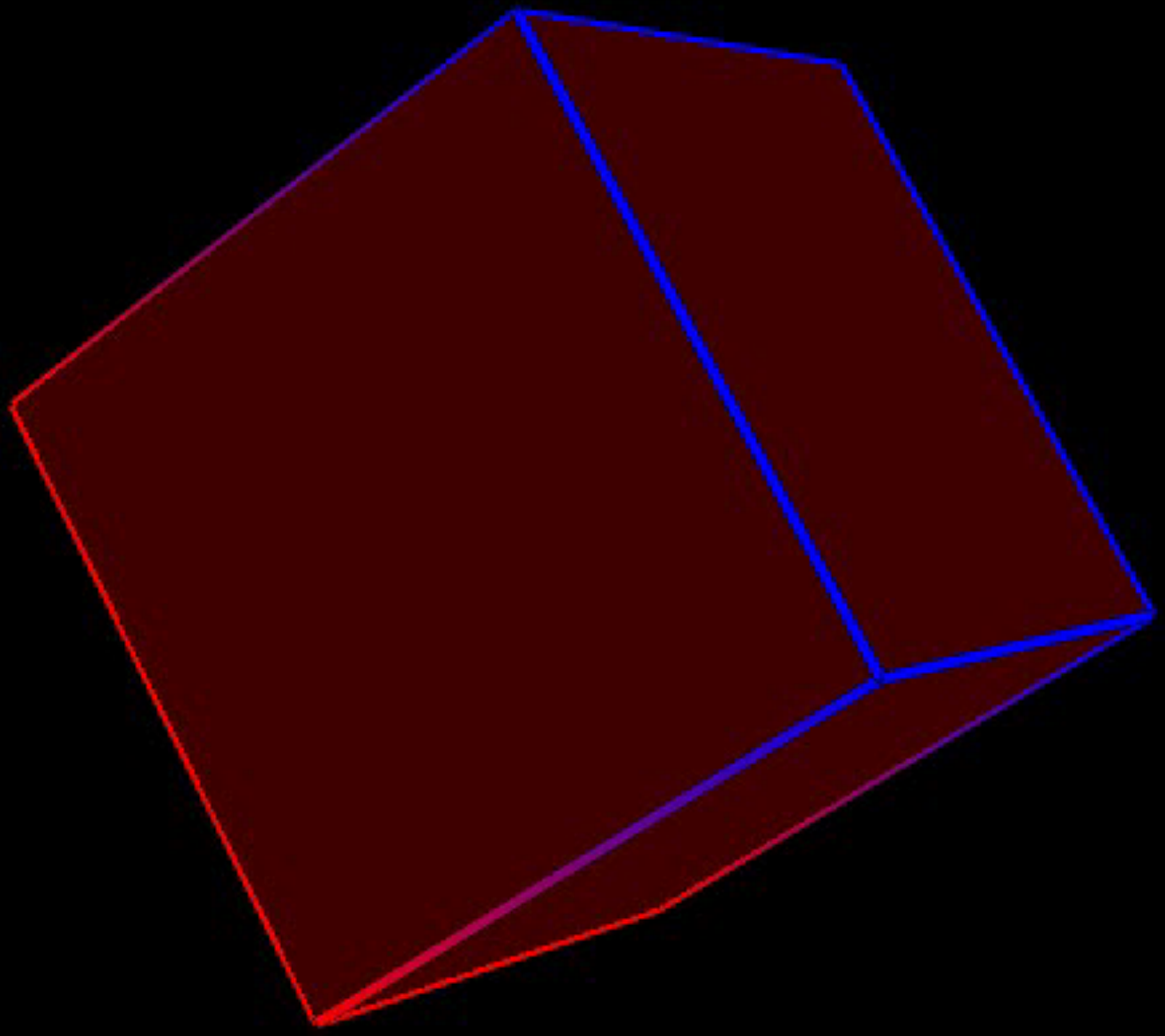
Sinks: Lyman-Limit Systems

- LL systems limit the Mean Free Path of an ionizing photon (a source cannot ionize a very distant atom).

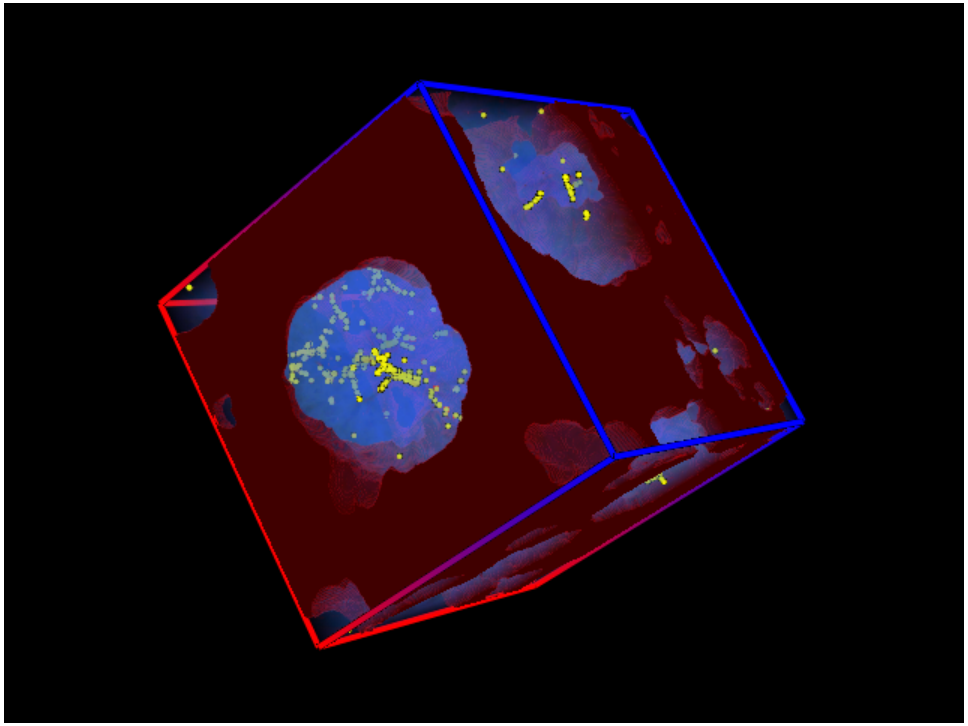


How It All Happens...





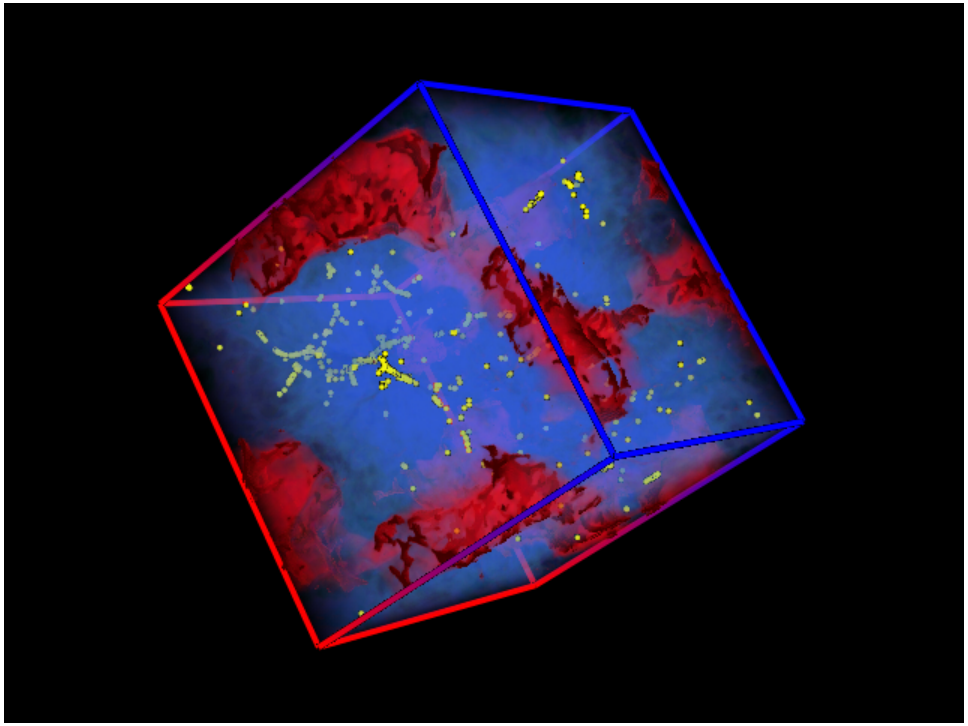
How It All Happens



Pre-overlap:

- Ionized bubbles expand in the low density gas.
- Most of ionizing photons are expended on ionizing IGM.

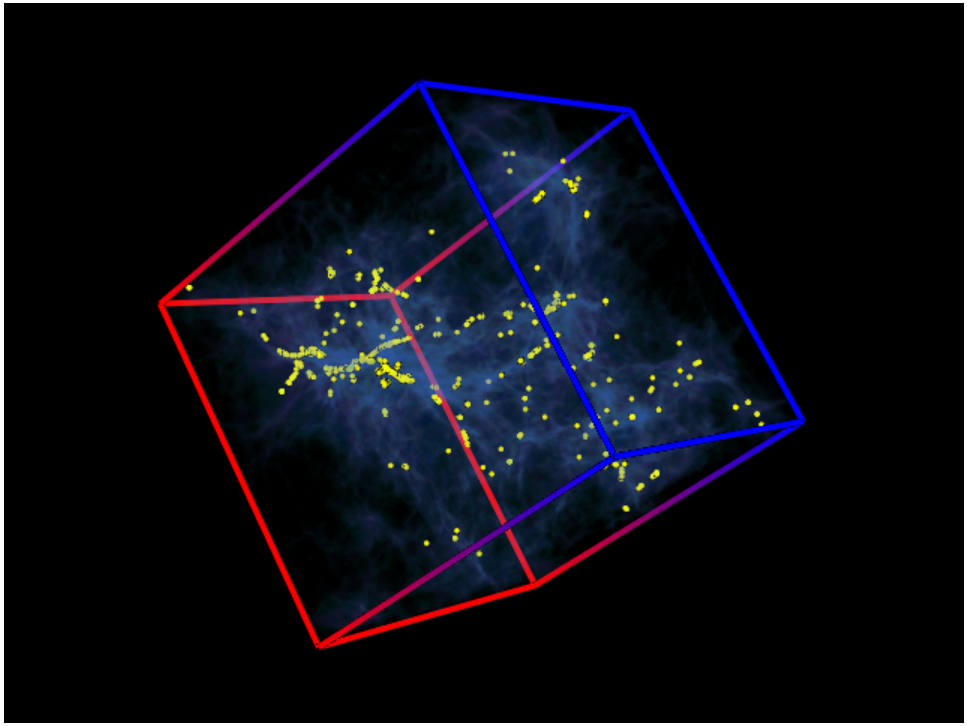
How It All Happens



Overlap:

- Ionized bubbles merge – the moment of *reionization*.
- Some ionizing photons are absorbed in LL systems.

How It All Happens



Post-overlap:

- Most of gas in the universe is highly ionized.
- All ionizing photons are absorpbed in LL systems.

Simulating Reionization: Scales

- Capturing most of star-forming galaxies requires boxes > 50 Mpc (comoving).
- Resolving LL system requires resolution ~ 1 kpc.
- Resolving star formation requires resolution ~100-200 pc (depends on your sub-grid model).
- Resolving all star-forming galaxies requires mass resolution of about 10^6 $M_\bullet$.
- Conclusion: we need simulations with
  - spatial dynamic range $L/\Delta x > 100{,}000$
  - mass dynamic range $M_{box}/M_{cell} >$ 10 billion

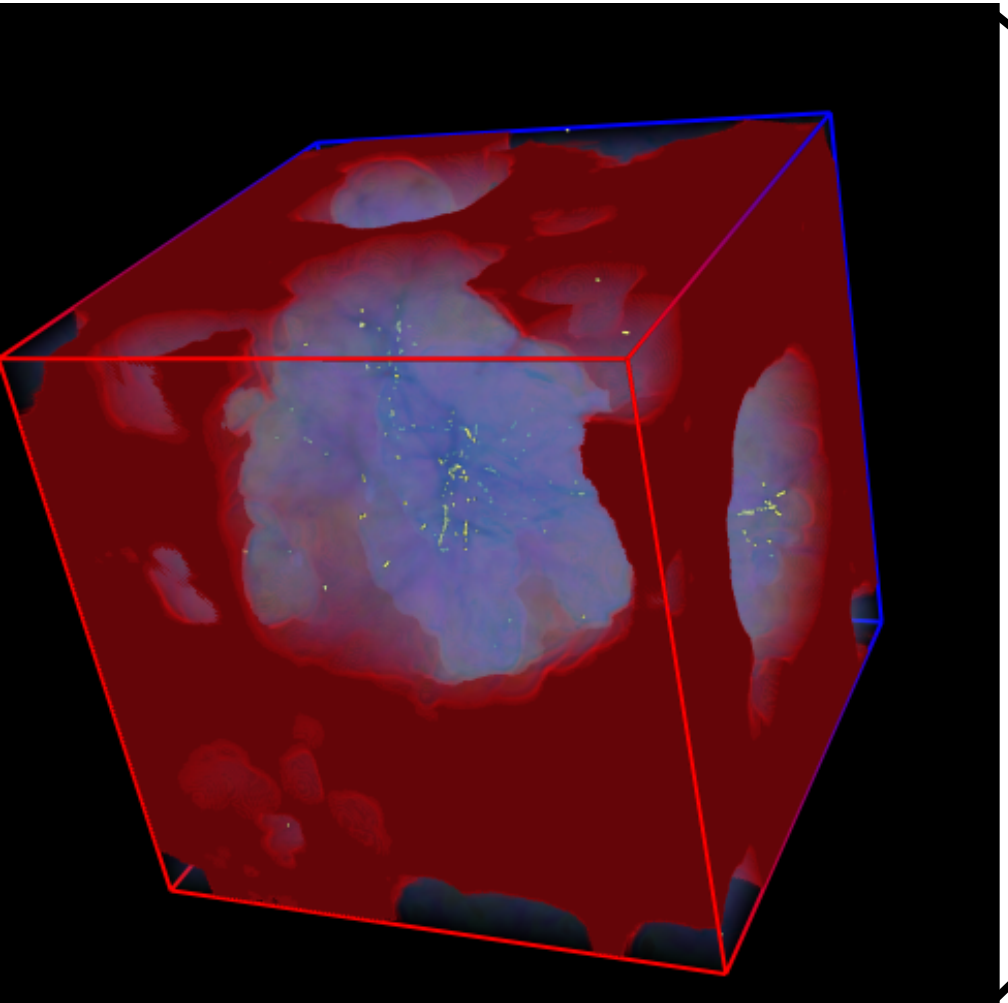
Simulating Reionization: Physics

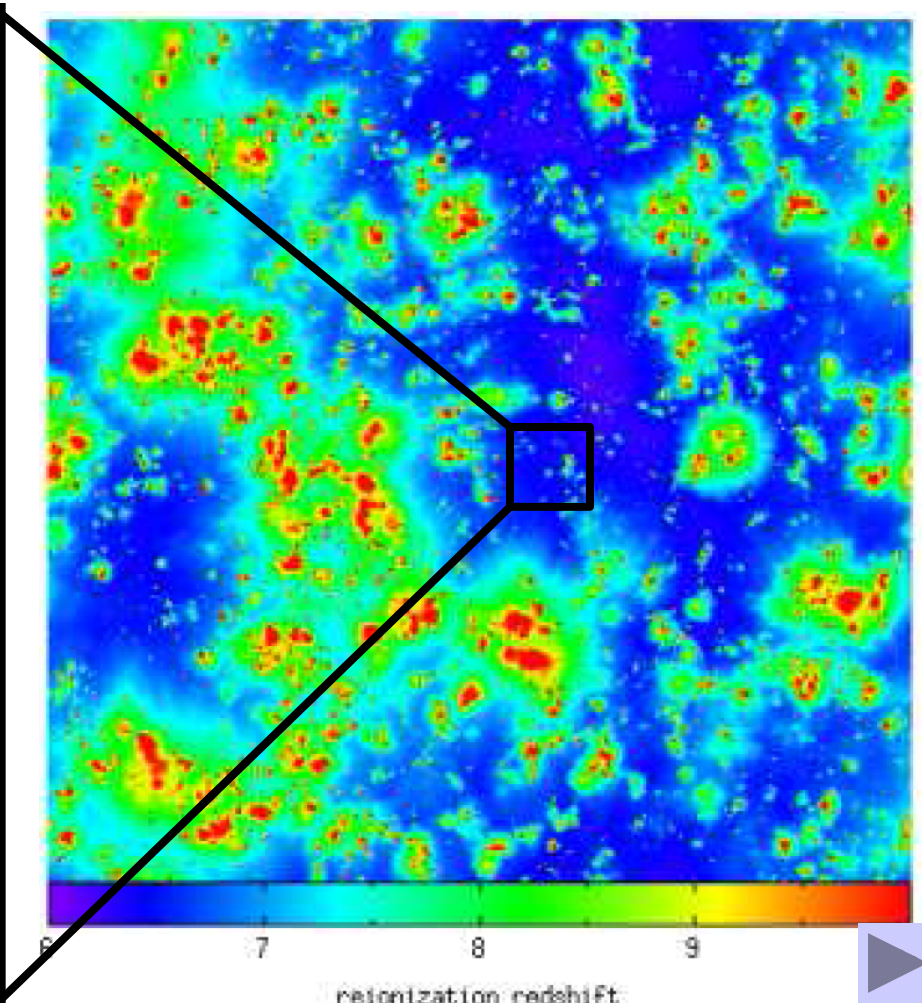
- Dark matter
- Gas dynamics
- Atomic processes (cooling, H_2 chemistry)
- Radiative transfer of ionizing+UV radiation
- ***Star formation and stellar feedback***
  - Problem is not only in the lack of complete understanding, but also in the huge spatial dynamic range that needs to be modeled.
  - Star formation today can only be modeled as a *sub-grid* model.

Simulations: The First Decade (2000-2010)

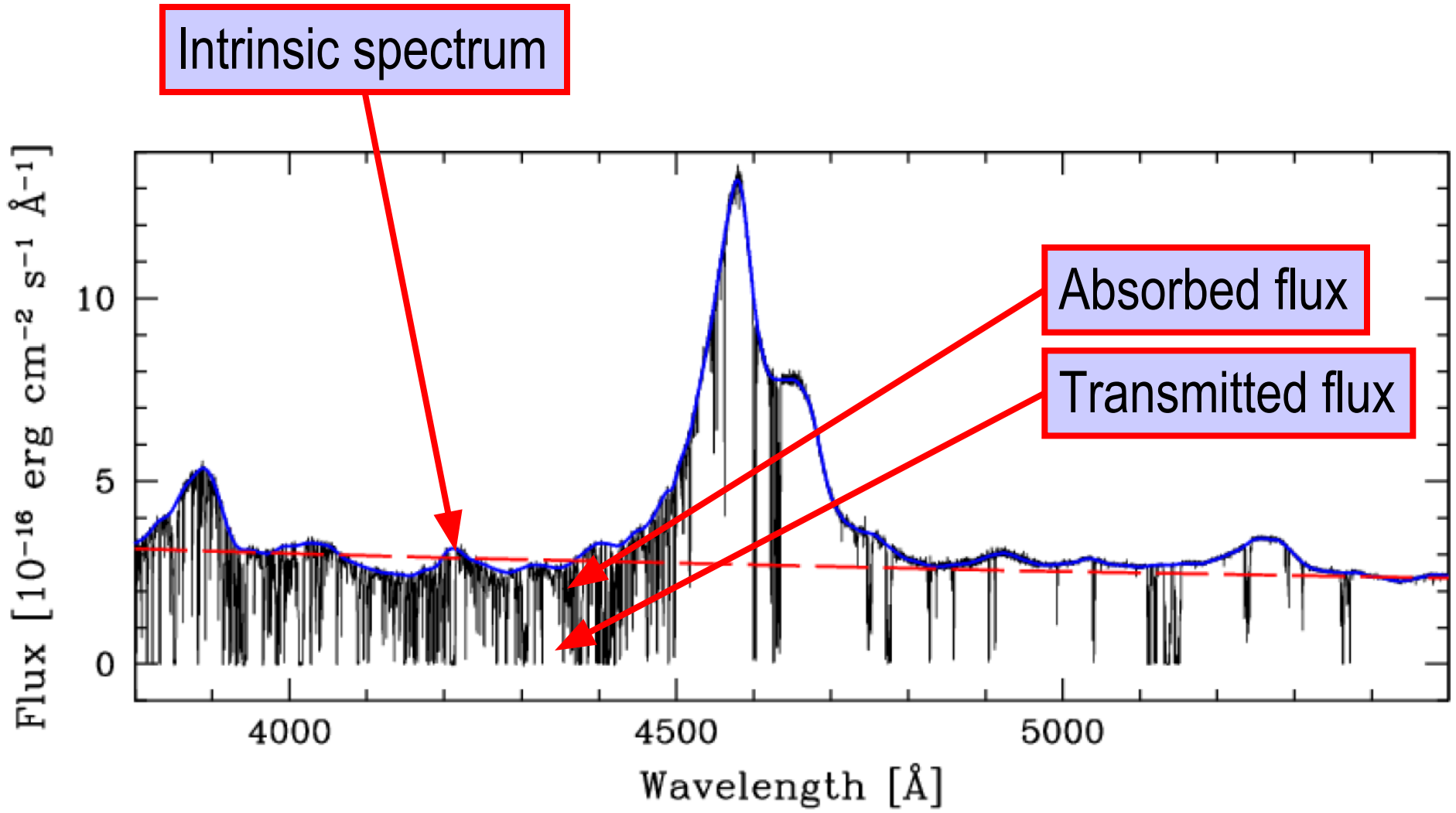
	Small box	Large box
physics	full	incomplete
spatial resolution	high	low
mass resolution	high	high
dynamic range	low	high
volume	small	large

Simulations: The First Decade (2000-2010)

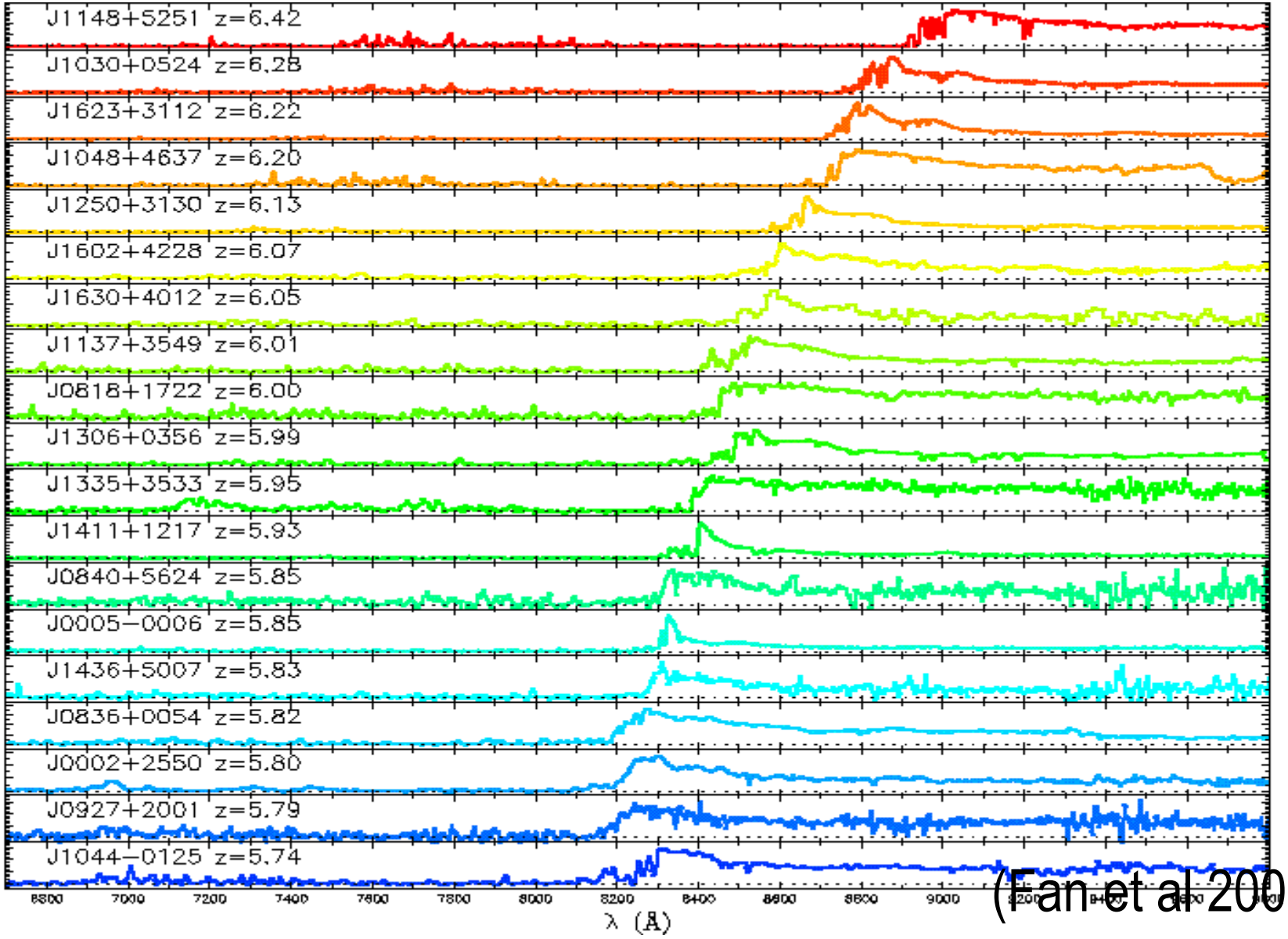




Refresher: Ly-α Forest

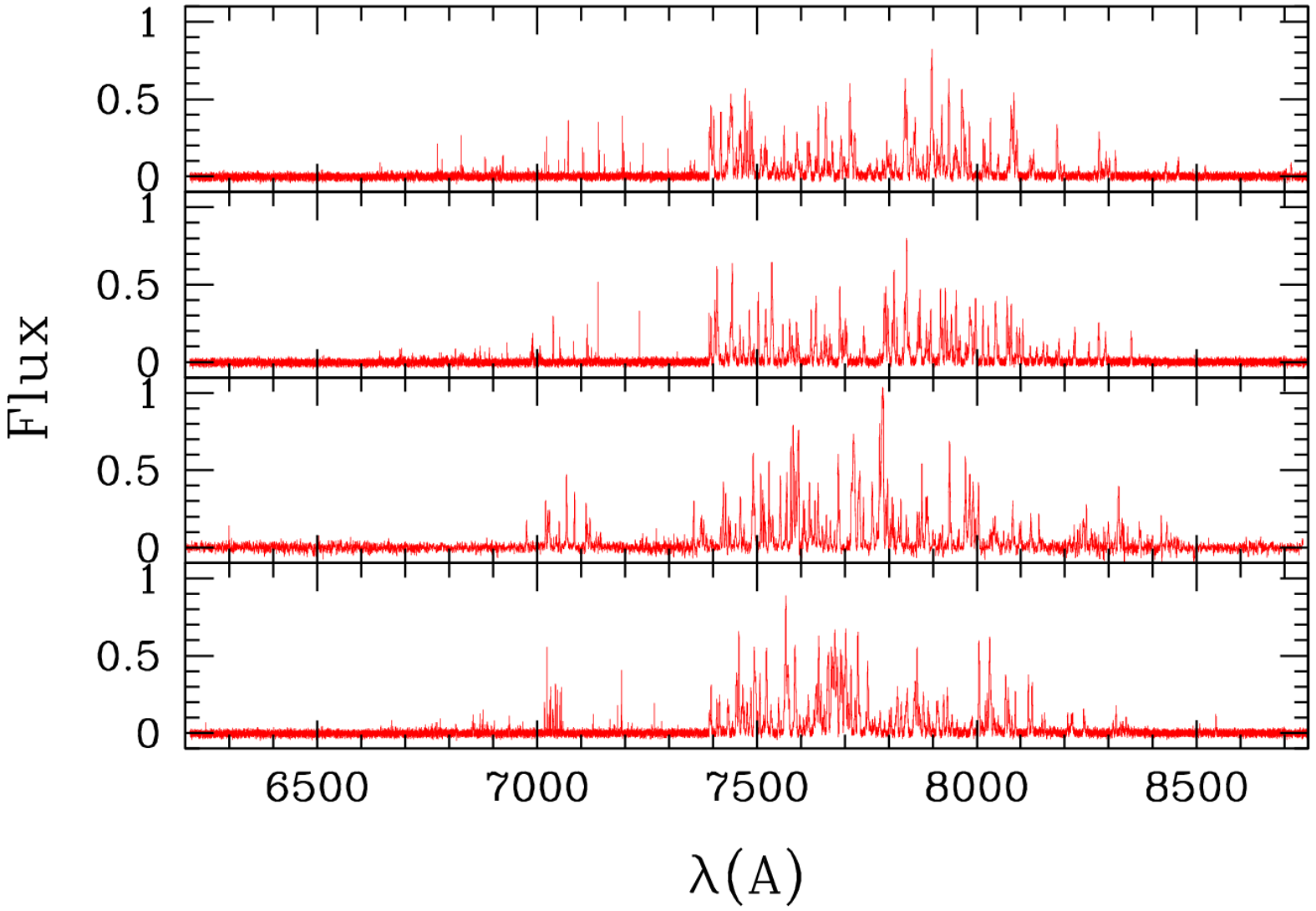


SDSS Quasars ~ 2005

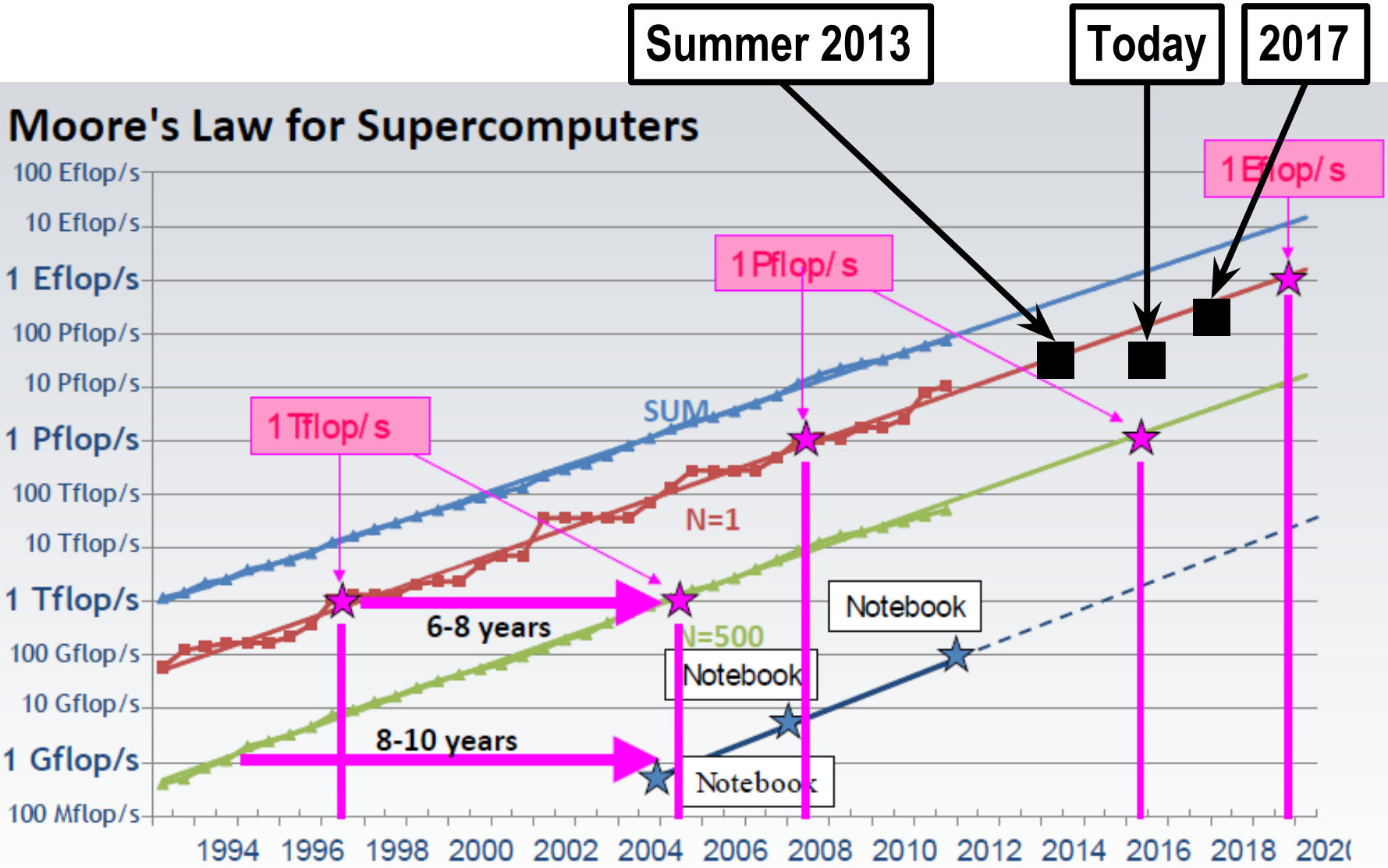


(Fan et al 2005)

Quiz: find the SDSS Quasar

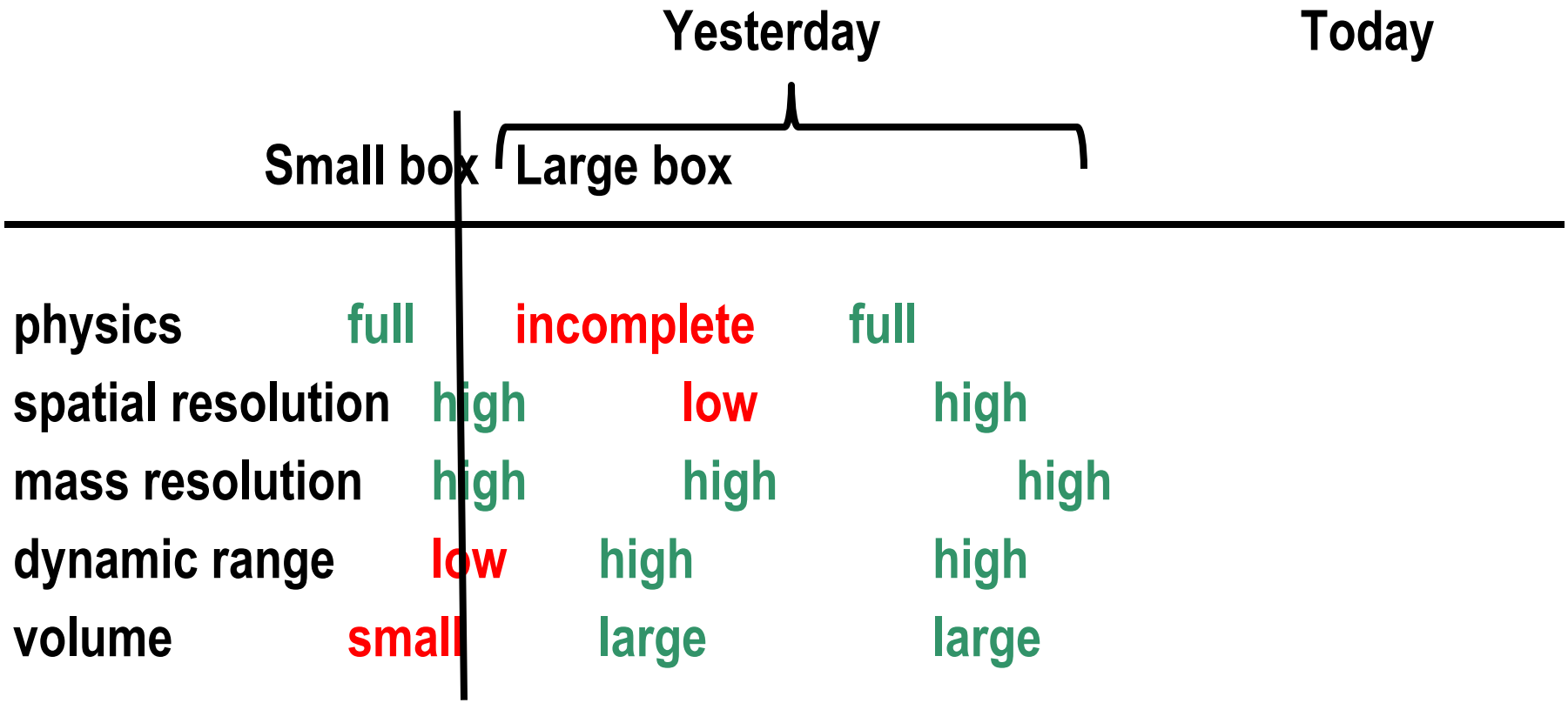


Moore's Law

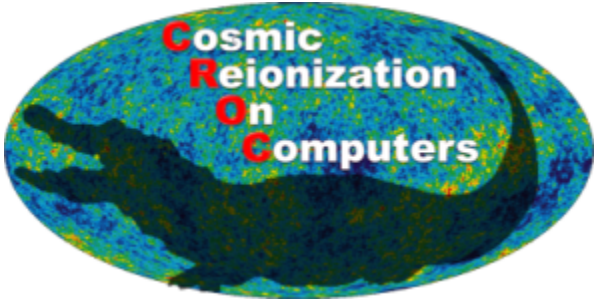

Summer 2013
Today
2017
Moore's Law for Supercomputers
100 Eflop/s
10 Eflop/s
1 Eflop/s
100 Pflop/s
10 Pflop/s
1 Pflop/s
100 Tflop/s
10 Tflop/s
1 Tflop/s
100 Gflop/s
10 Gflop/s
1 Gflop/s
100 Mflop/s
1 Eflop/s
1 Pflop/s
1 Tflop/s
SUM
N=1
N=500
6-8 years
8-10 years
Notebook
Notebook
Notebook
1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016 2018 202

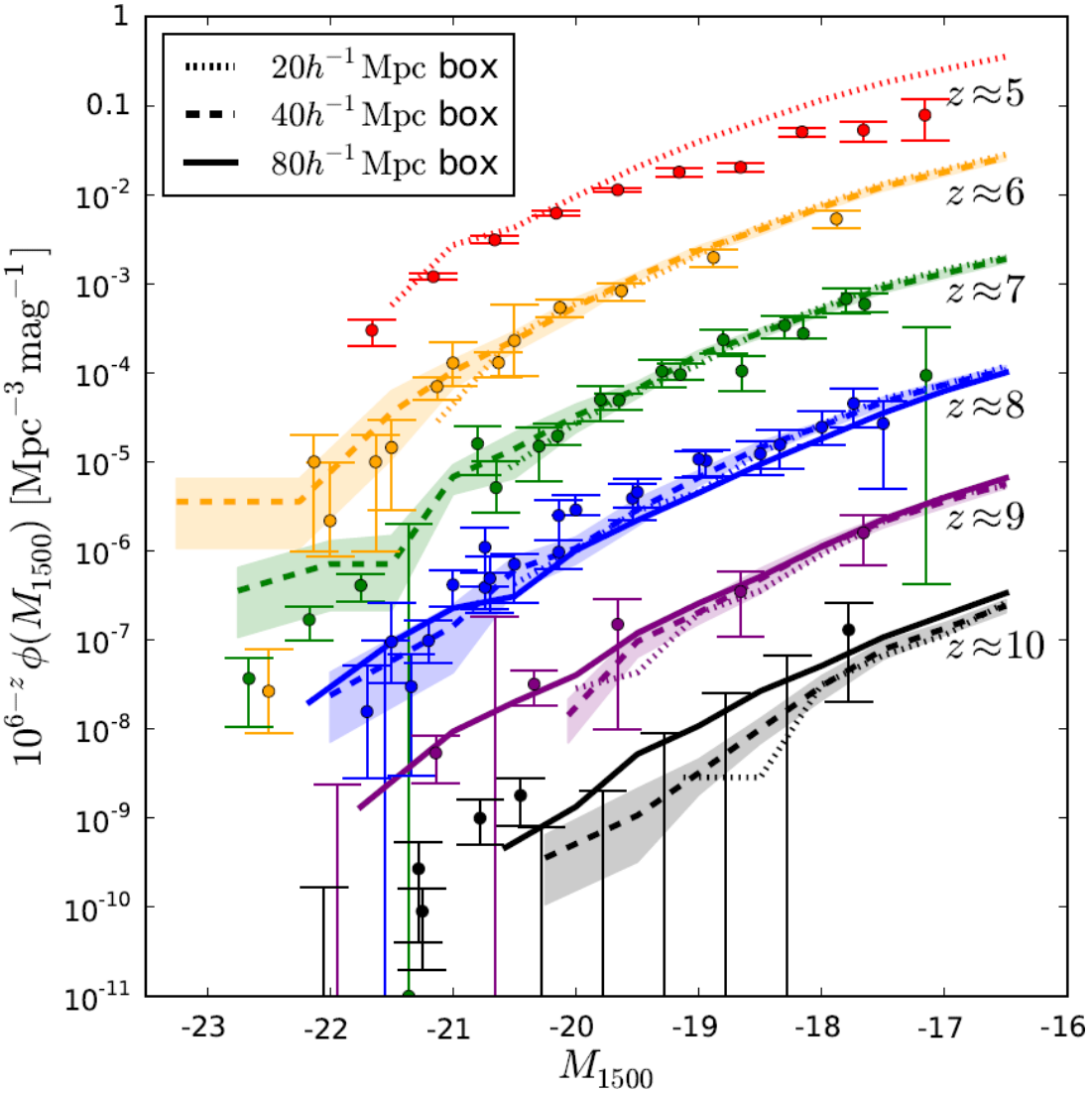
Covering The Gap

- With peta-scale computing power we can run large-box simulations with full physics.



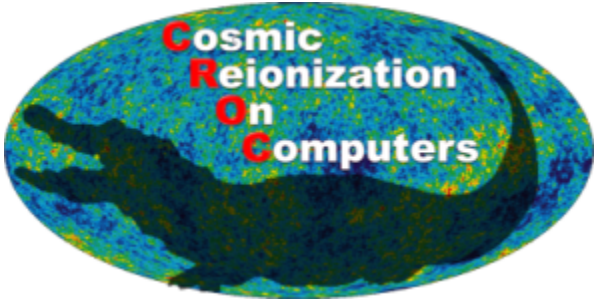
The CROC Project: Validation



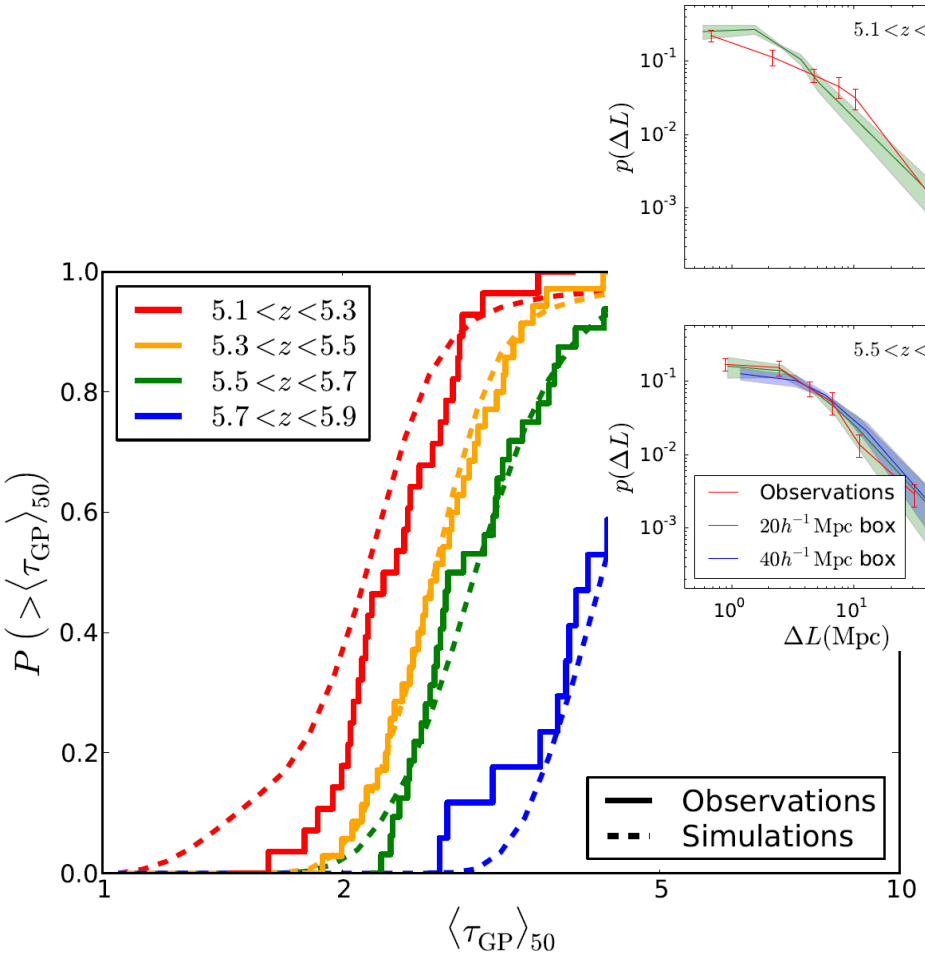


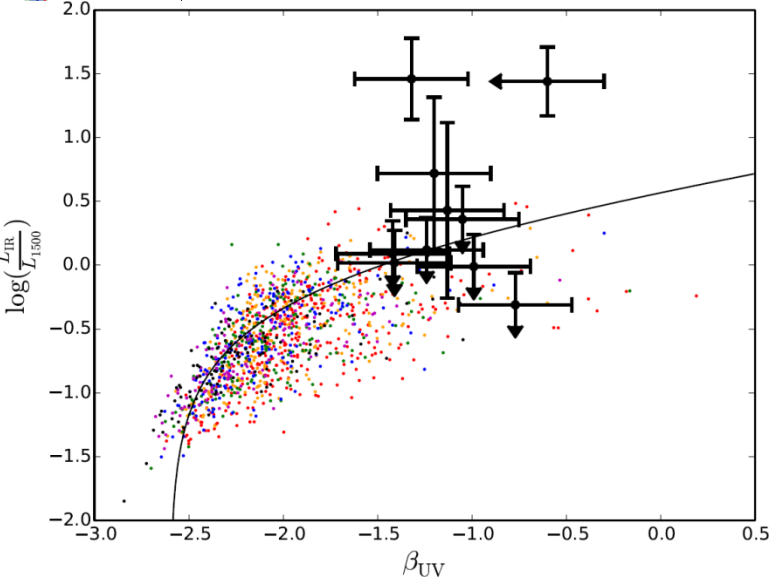
- Galaxies in right halos ***all the time***!

The CROC Project: Validation

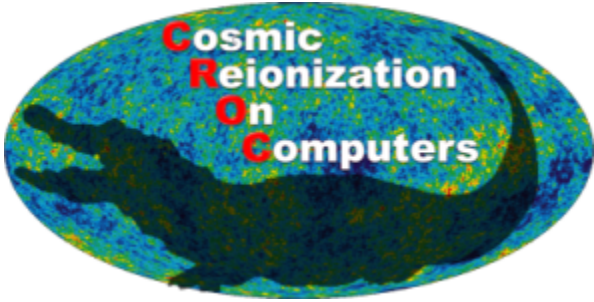


- Many other observations are reproduced too…

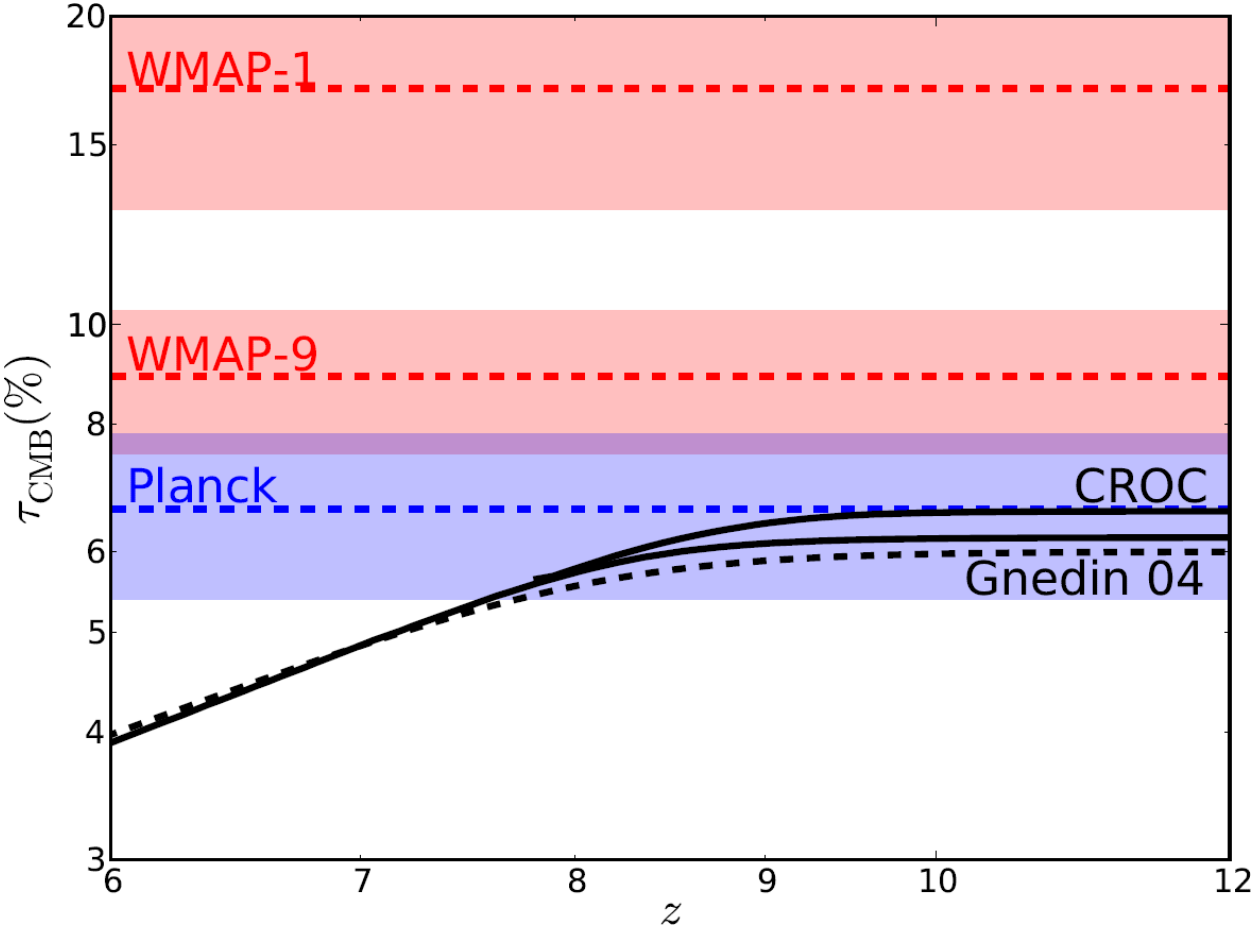




The CROC Project: Validation



- Finally, CMB observations succeeded in matching theoretical predictions.



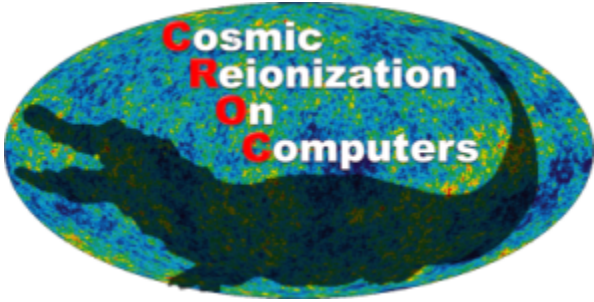
Example: Backreaction of Reionization on Galaxies

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

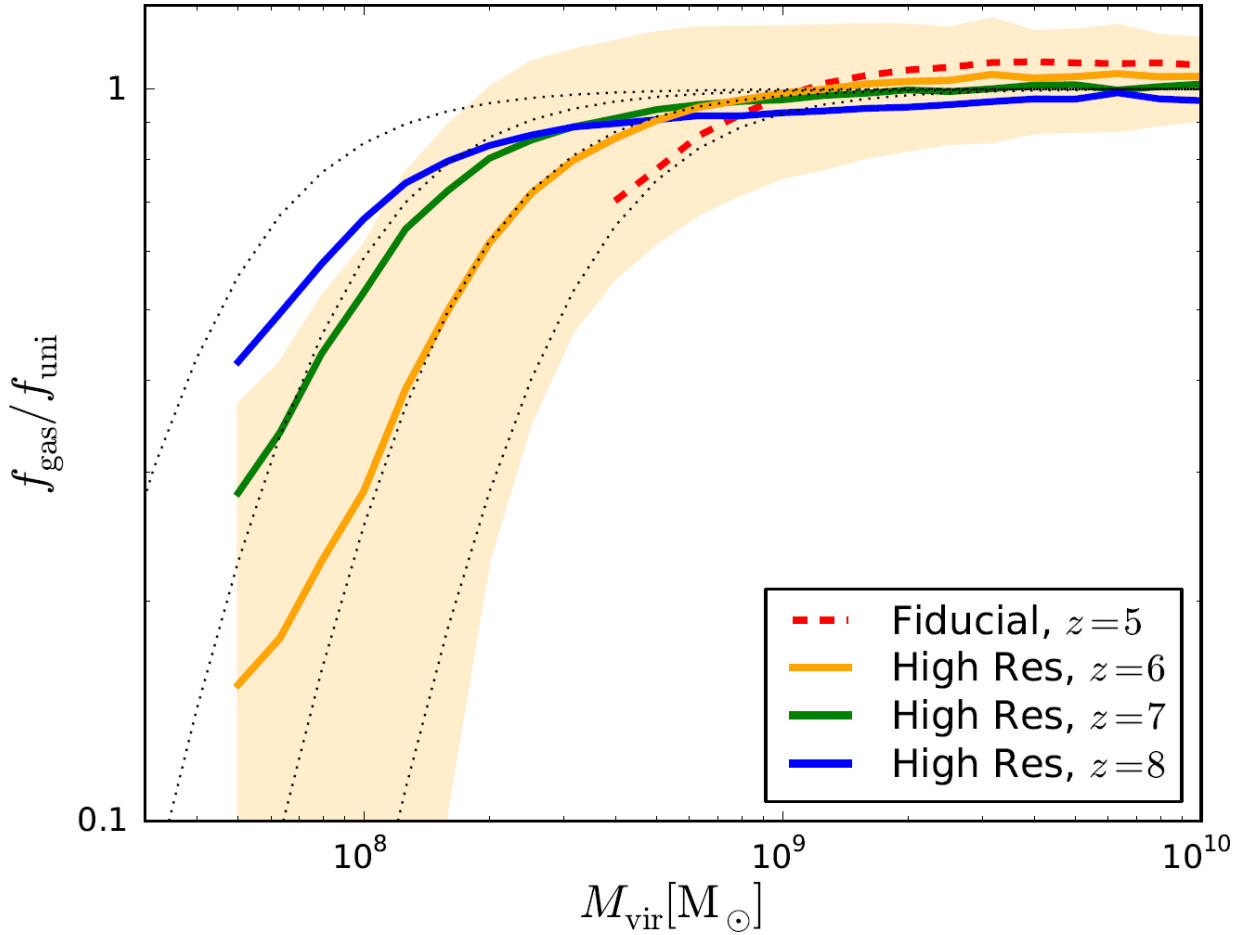
- One of JWST science goals.

(Barkana & Loeb 2000)

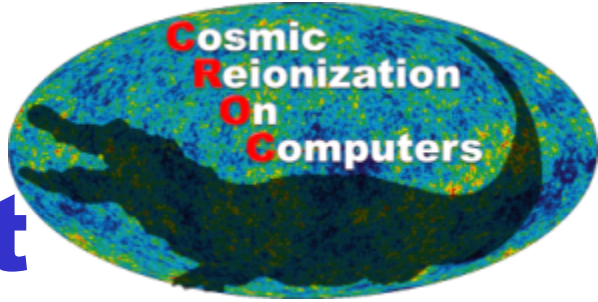
Backreaction: Gas Fractions



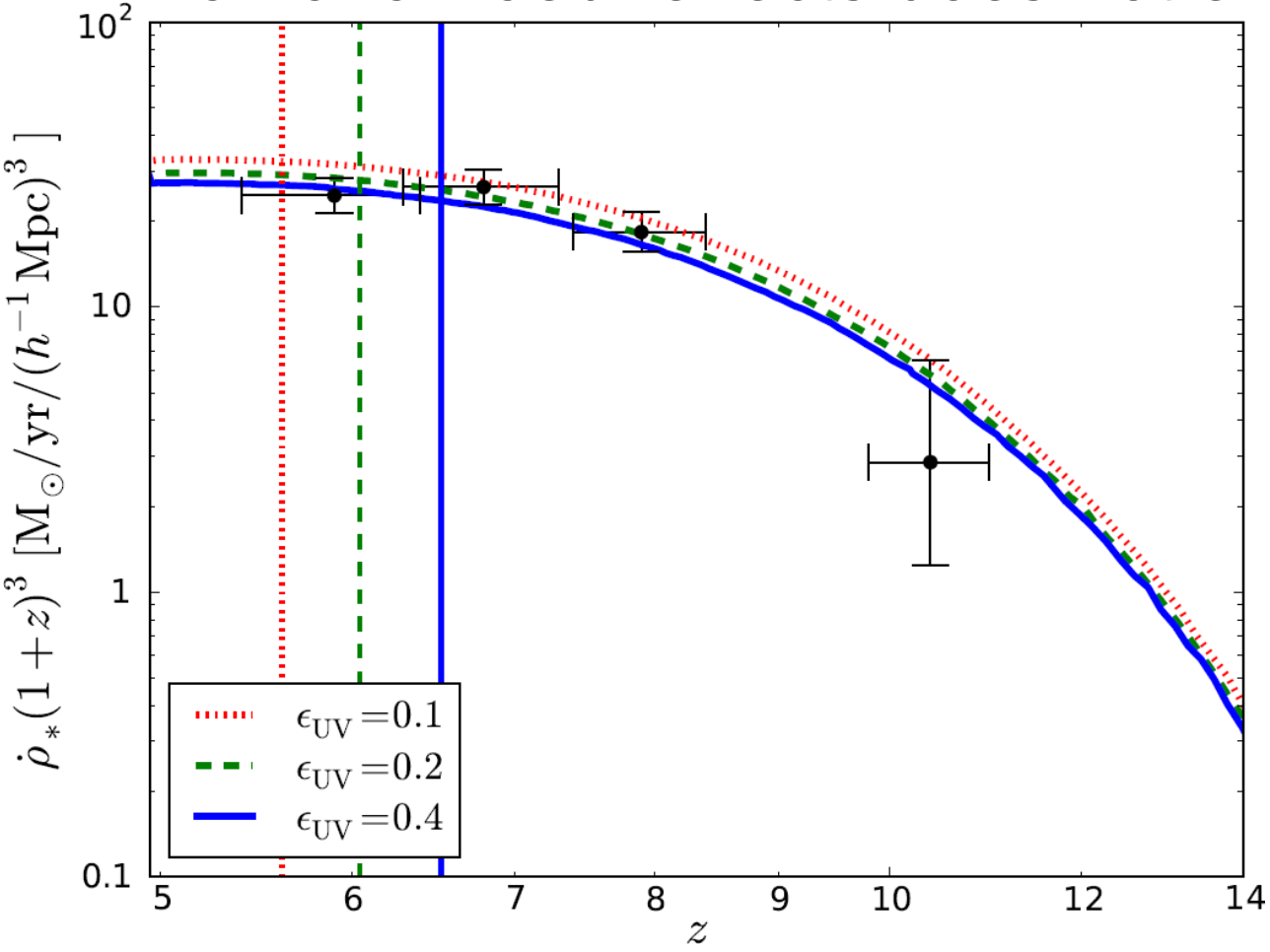
- Match Okamoto et al (2008) results *exactly* (after reionization, of course).



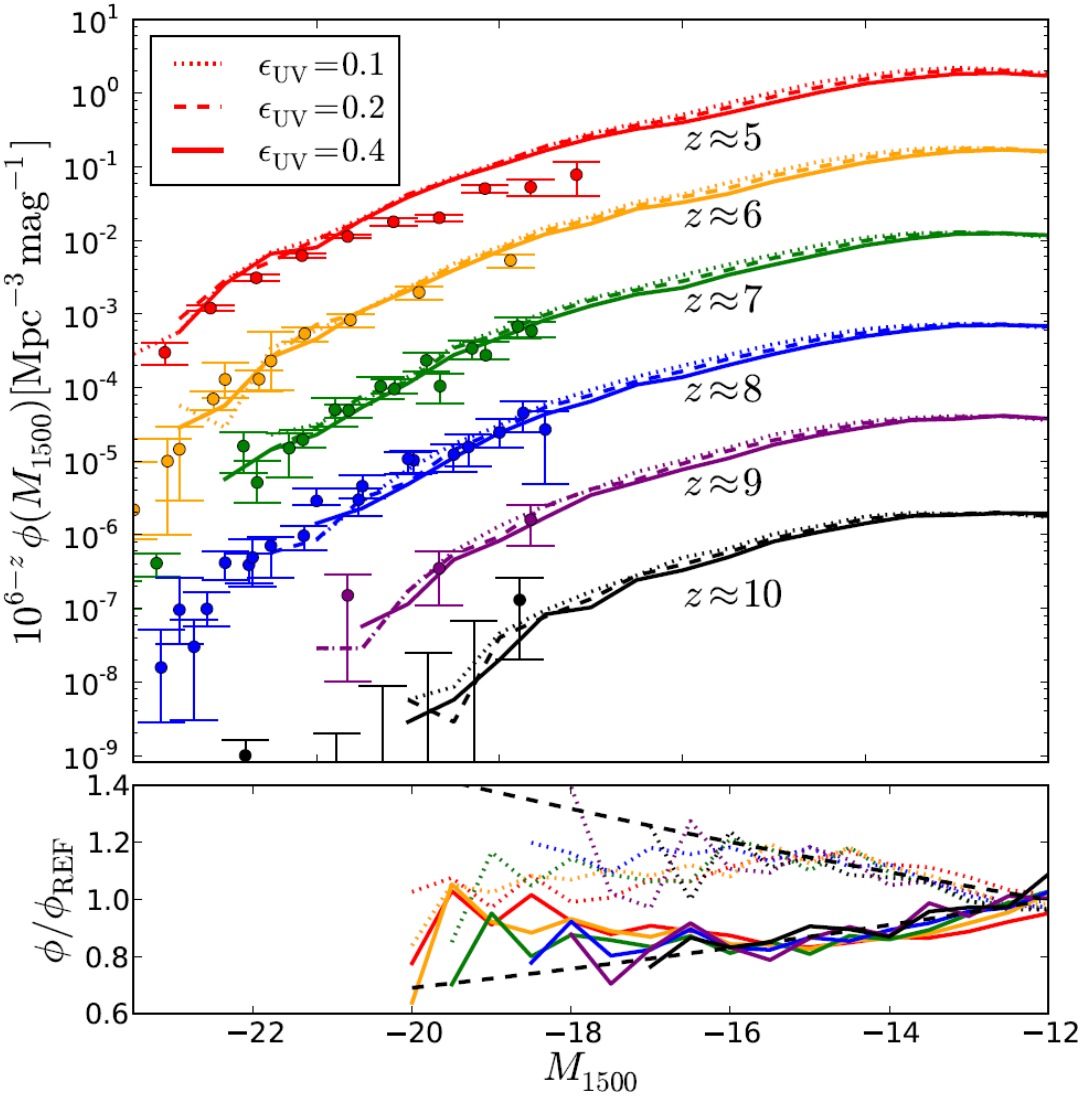
Backreaction: Barkana-Loeb Effect



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



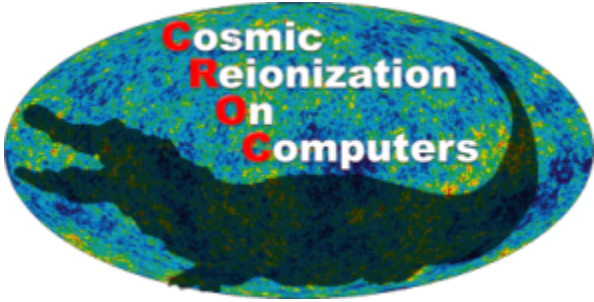
Backreaction: Faint-End Slope



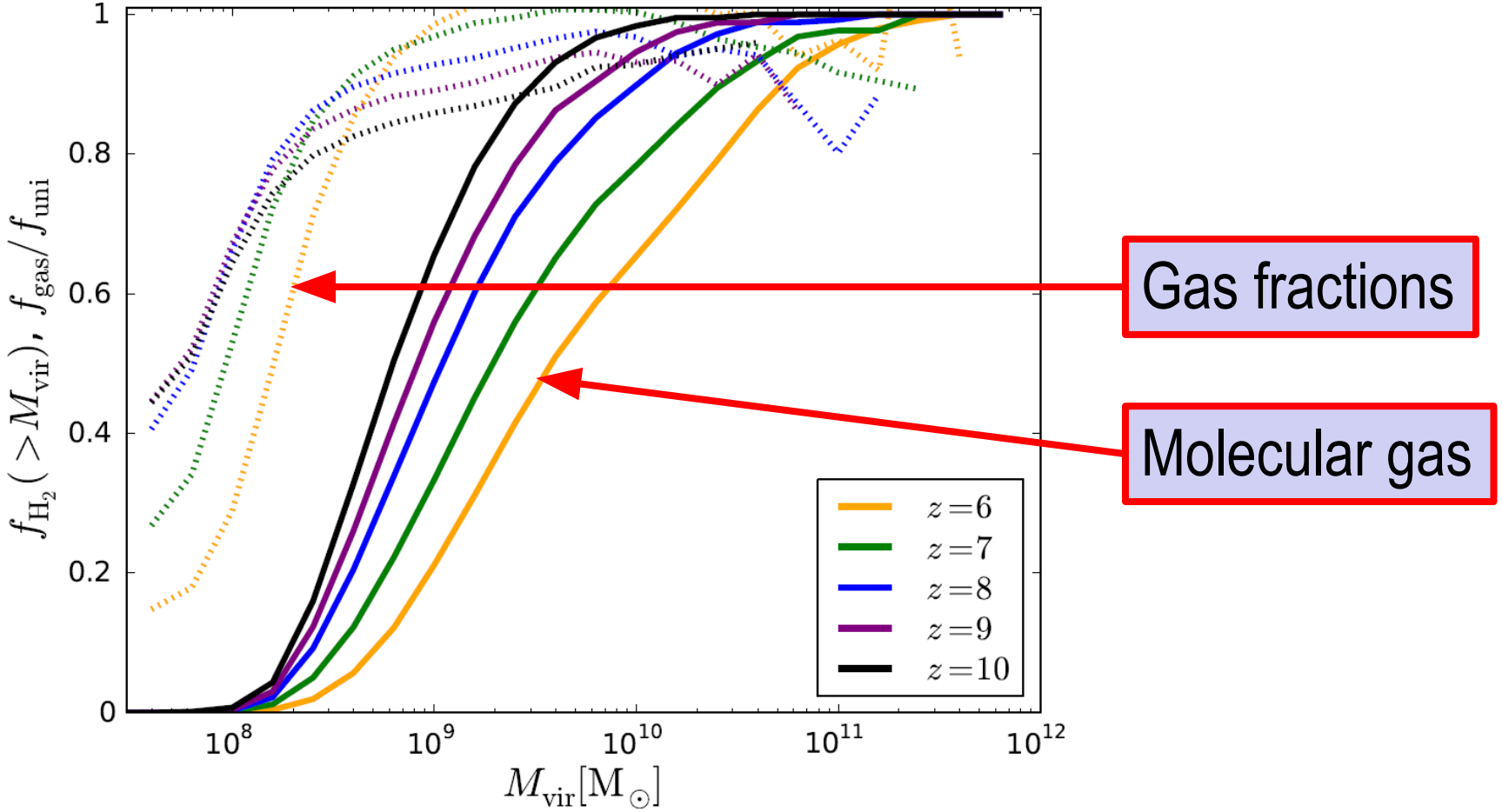
- Faint-end slope of UV luminosity function varies

$$\sim 0.1 \qquad \Delta z = 1$$

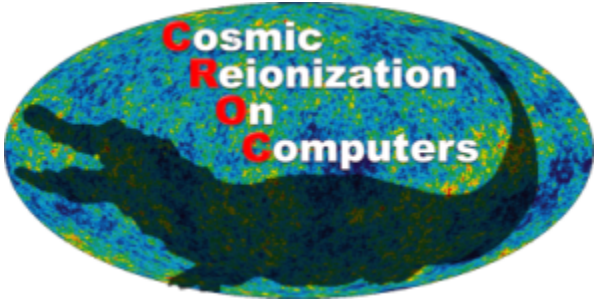
Backreaction: Why?



- Galaxies affected by photoionization contain no molecular gas.



And Many More...



- The quintessential question: does reionization proceed inside-out or outside-in? Answer: both (first inside-out, later outside-in).
- Modeling radiative transfer self-consistently (i.e. with the same spatial and temporal resolution as hydro) is crucial for getting z>5 IGM right.
- Cosmic dust may not follow metals at z>7 (formation and destruction time-scales are not negligibly short).
- Lyman-α emitters are not a useful probe of reionization.

The Flood Is Coming

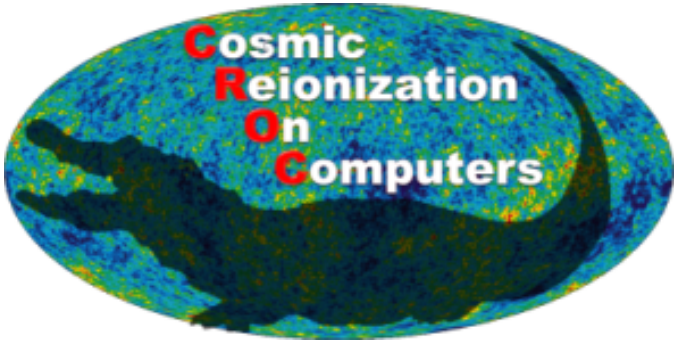
- Astro2010:

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

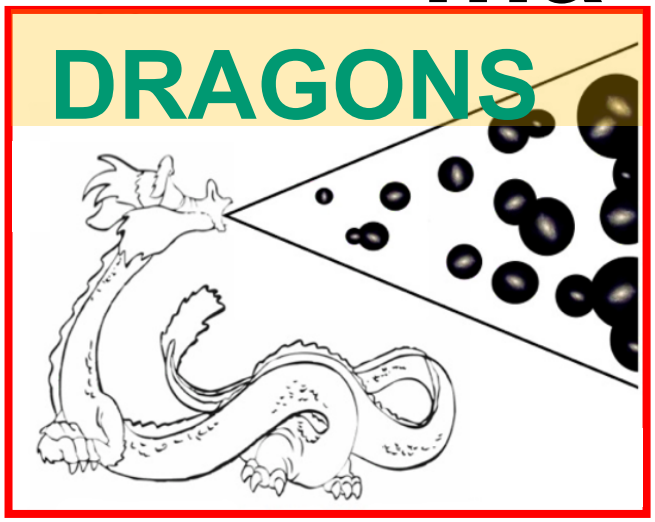
- It is clear that forthcoming observations will make all existing theoretical models obsolete.
- We are preparing for the flood:



Cosmic Dawn

Em
ma

Renaissan
ce



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.

---

* ALMA, HSC, JWST, 30m telescopes, 21cm

The End

Reionization

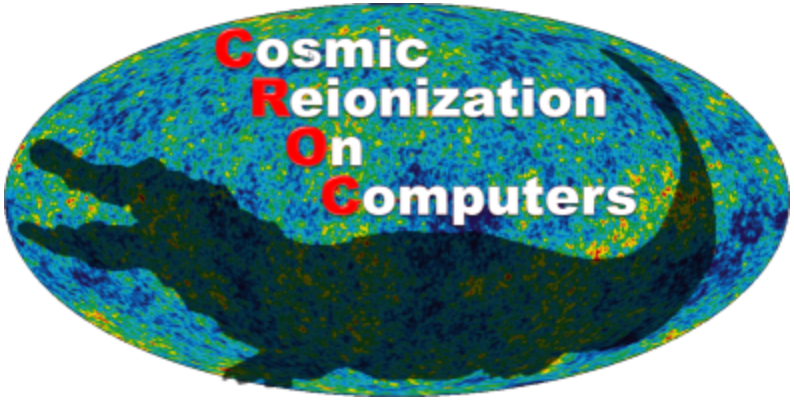
Epigraph

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.

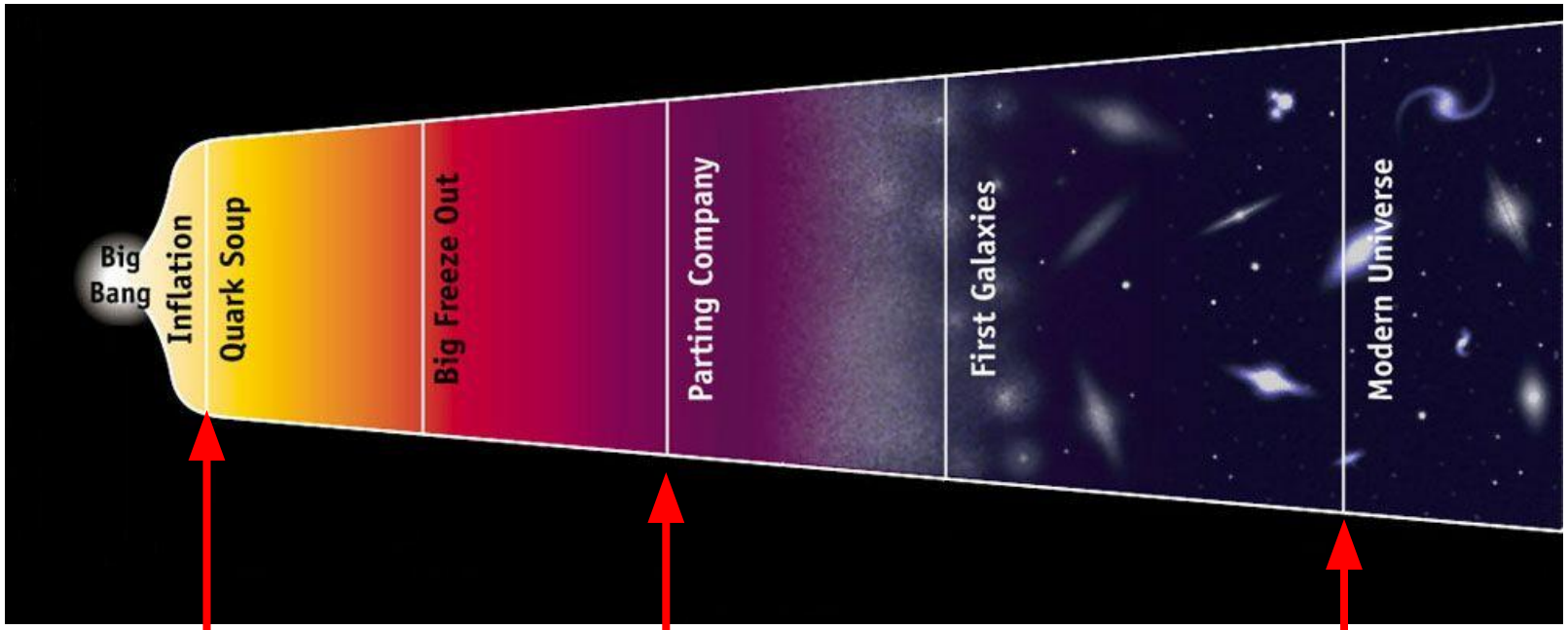
Peng Oh

Outline

- The brief history of time.
- How to reionize the universe.
- Simulations of yesterday: successes and limitations.
- CROC Project and everybody else: today we do things better.
- The Flood is coming.



The Brief History of Time

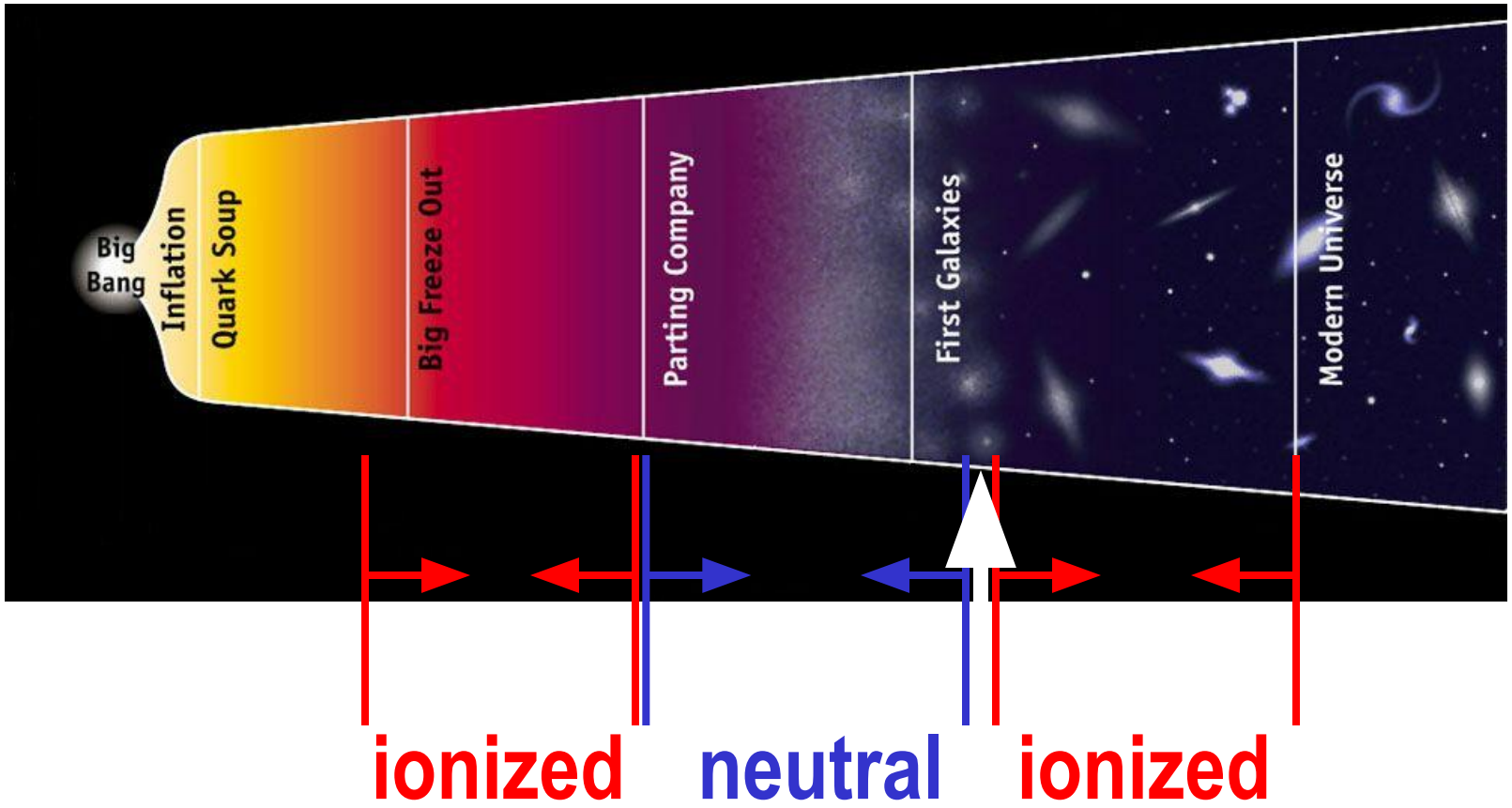


End of inflation
$z=10^{27}$
$t=10^{-36}$s

Recombination:
z=1089
t=379 kyr

Today:
z=0
t=13.7 Gyr

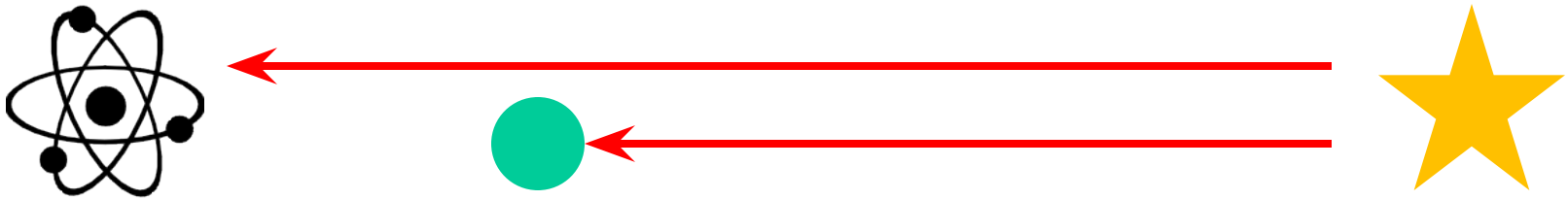
The Brief History of Time



RE-IONIZATION

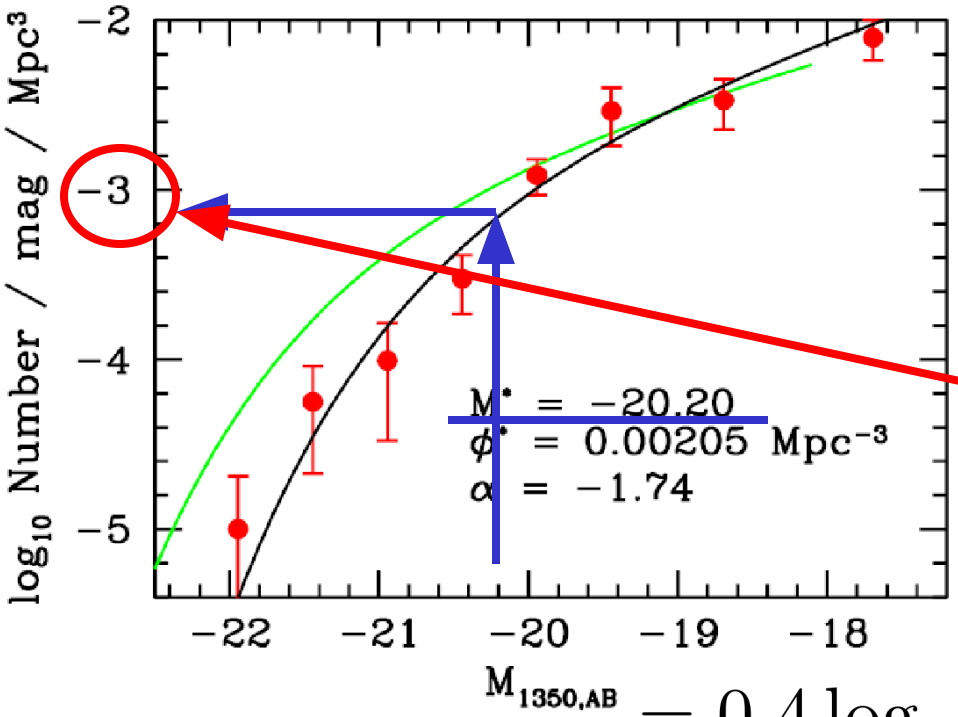
How To Reionize Universe

- Ionizing radiation must be produced by some sources (galaxies, quasars, gamma-ray bursts, dark matter annihilation, laser-armed alien spaceships).
- As ionizing photons propagate through space, they will be consumed in ionizing neutral atoms.
- They can also be absorbed by other sinks – hence, wasted from the point of view of reionization.



Sources: Galaxies

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



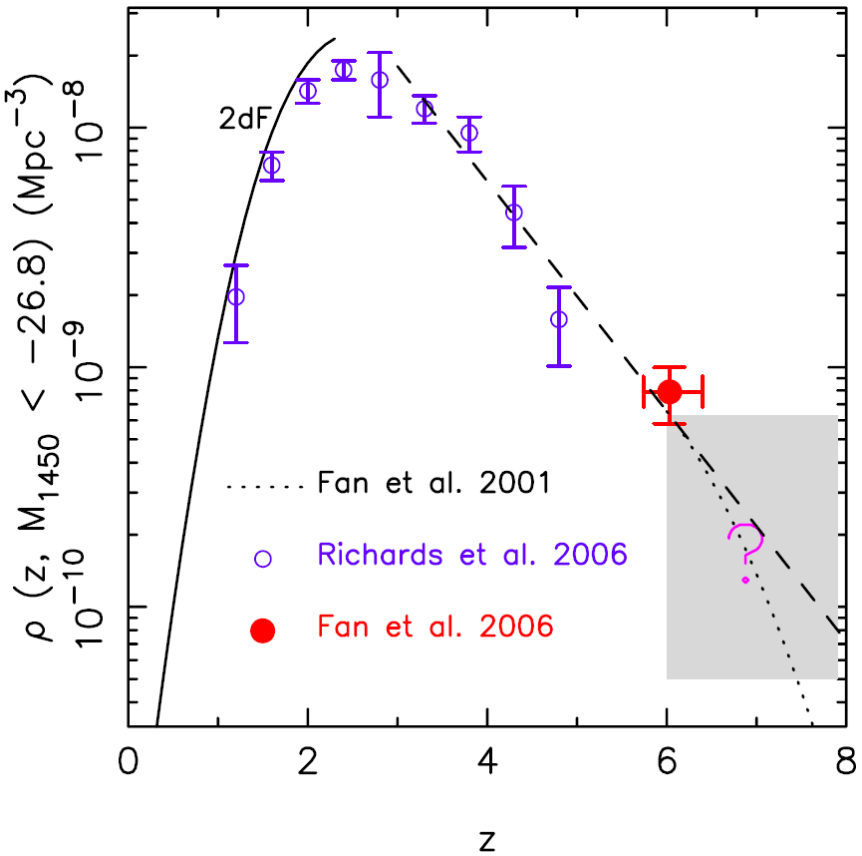
Galaxy LF at z=6
(Bouwens et al. 2006)

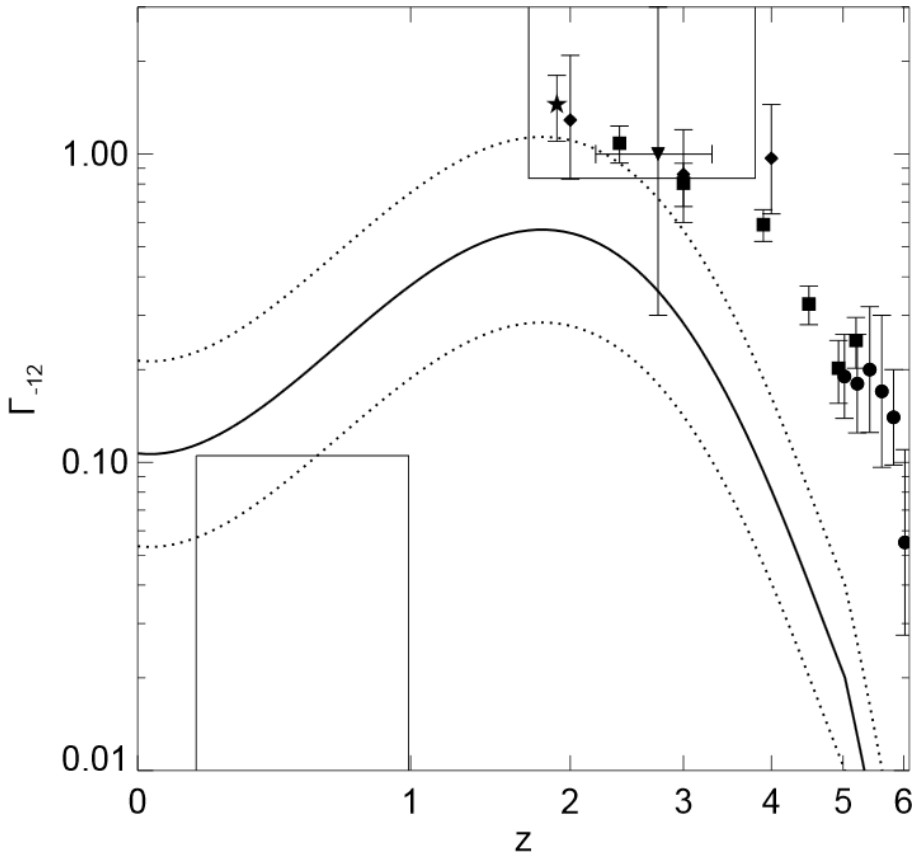
Need ~50 Mpc box

$$= 0.4 \log_{10} L_*$$

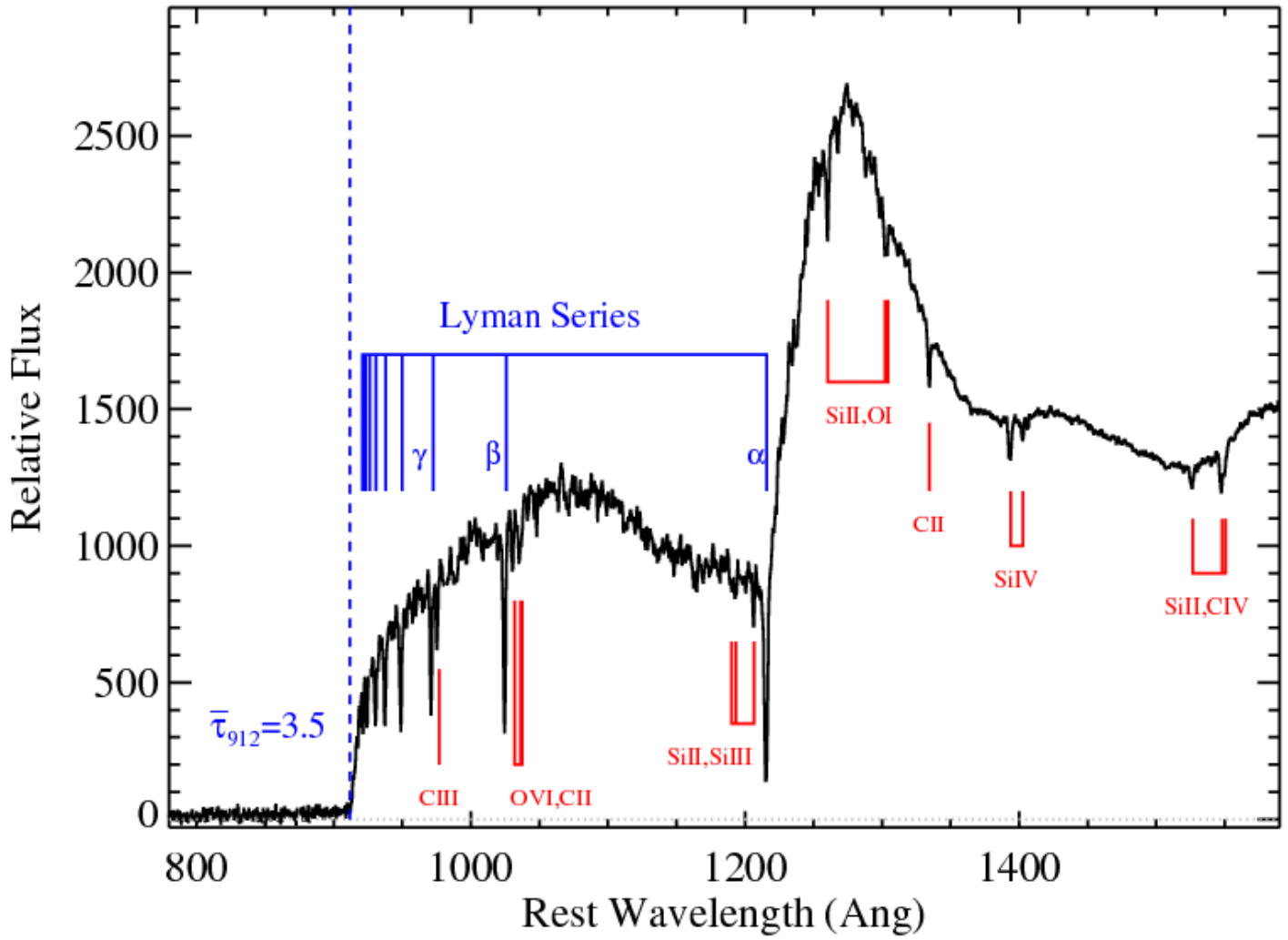
Sources: Quasars

- QSOs are efficient producers of ionizing radiation.
- The only problem – they are too rare at z>3.



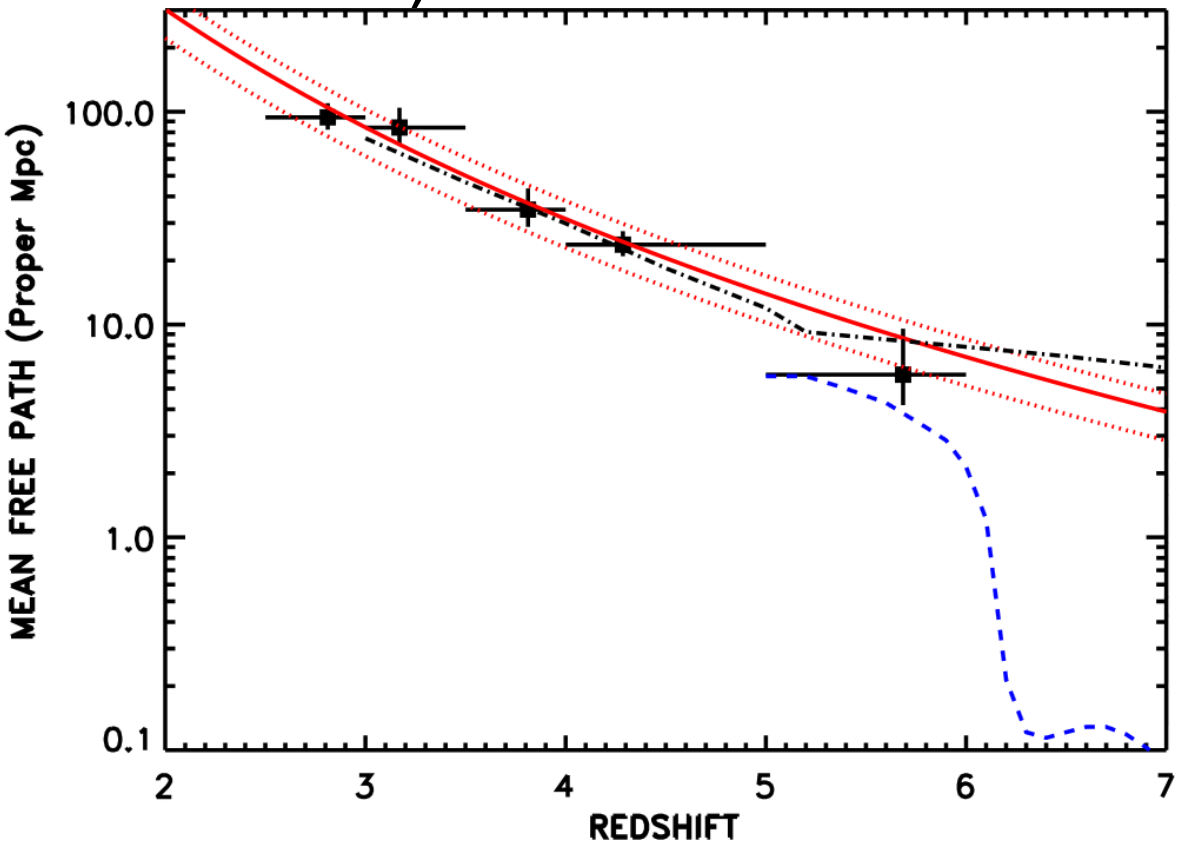


Sinks: Lyman-Limit Systems

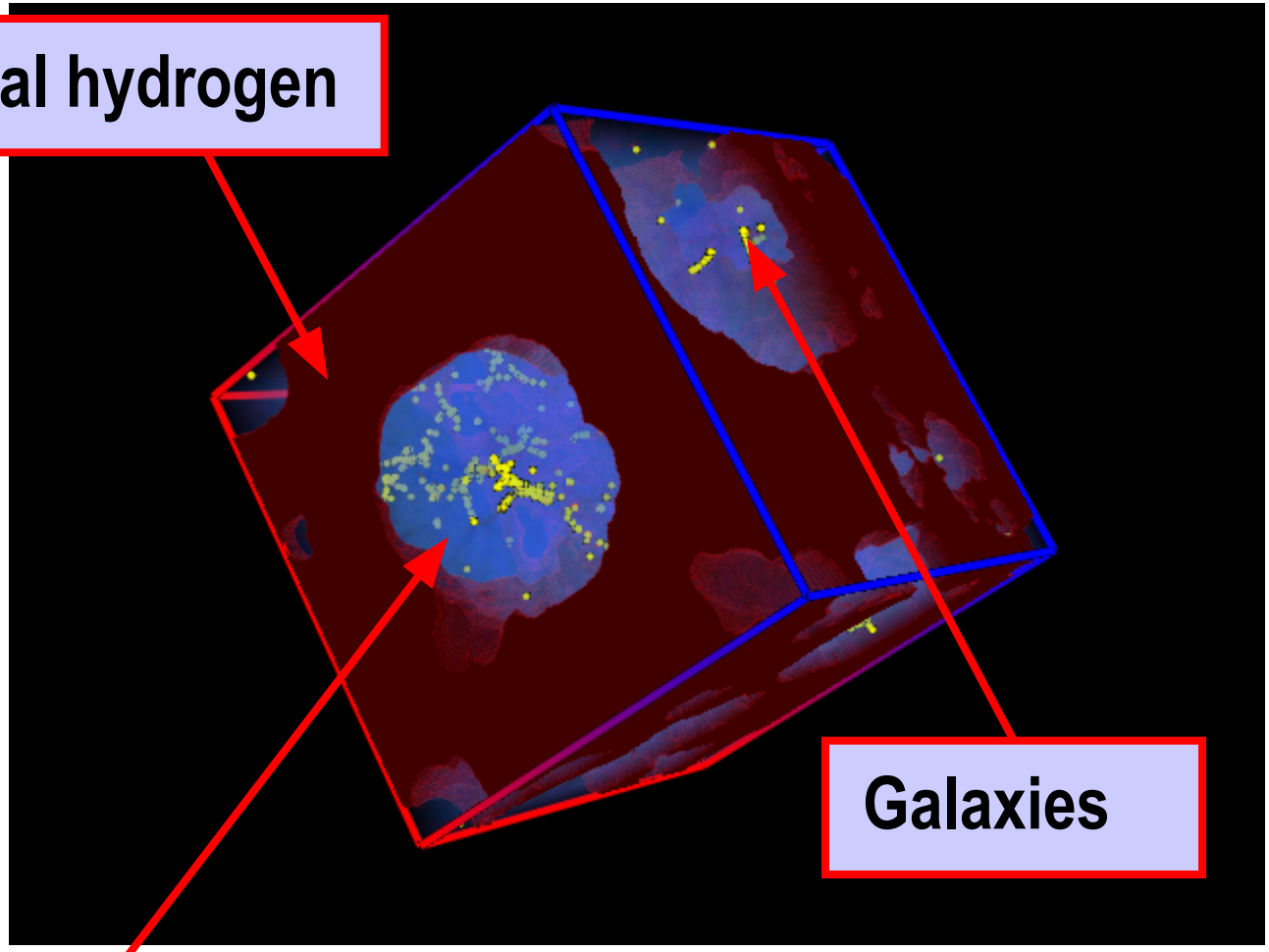


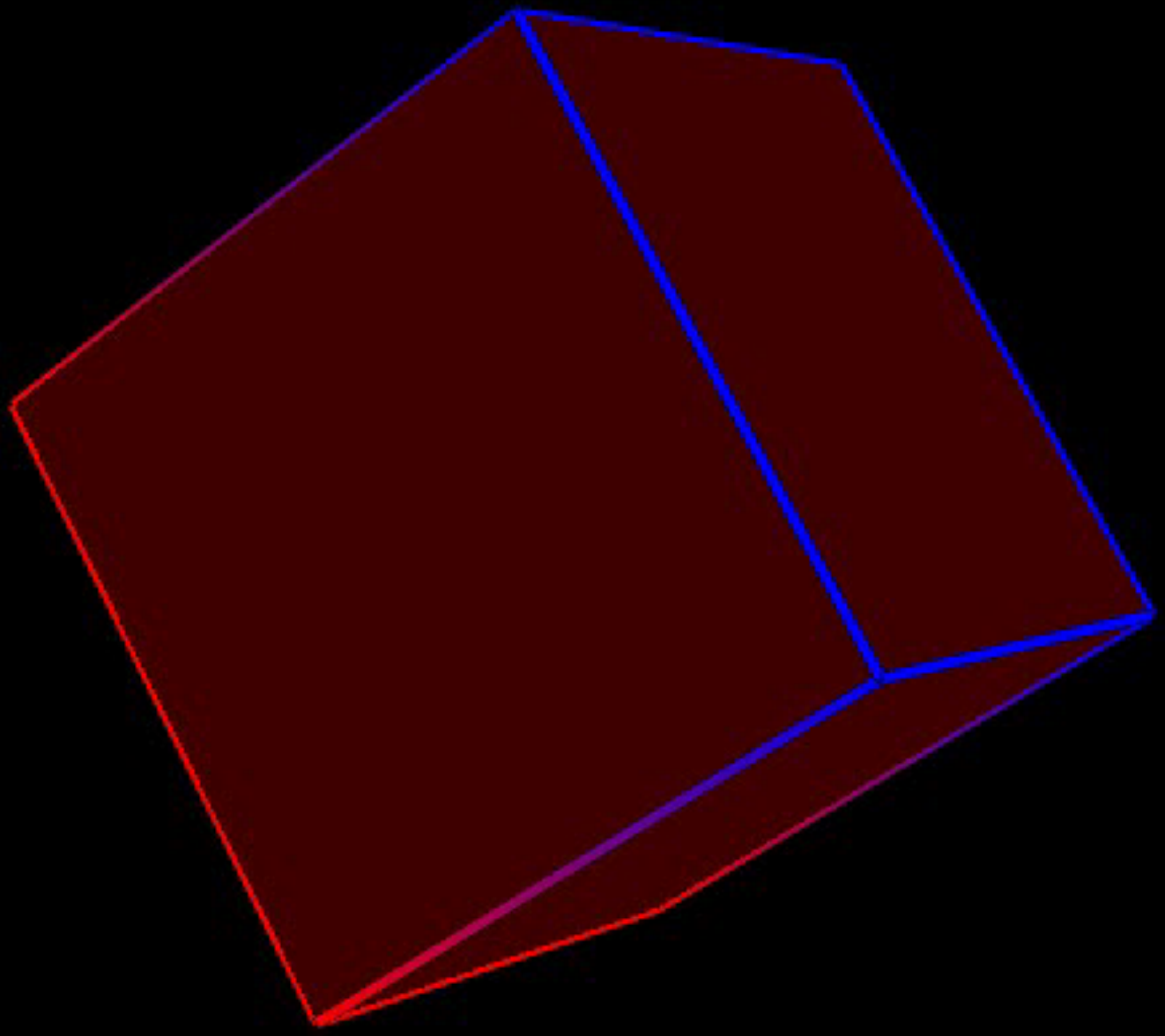
Sinks: Lyman-Limit Systems

- LL systems limit the Mean Free Path of an ionizing photon (a source cannot ionize a very distant atom).

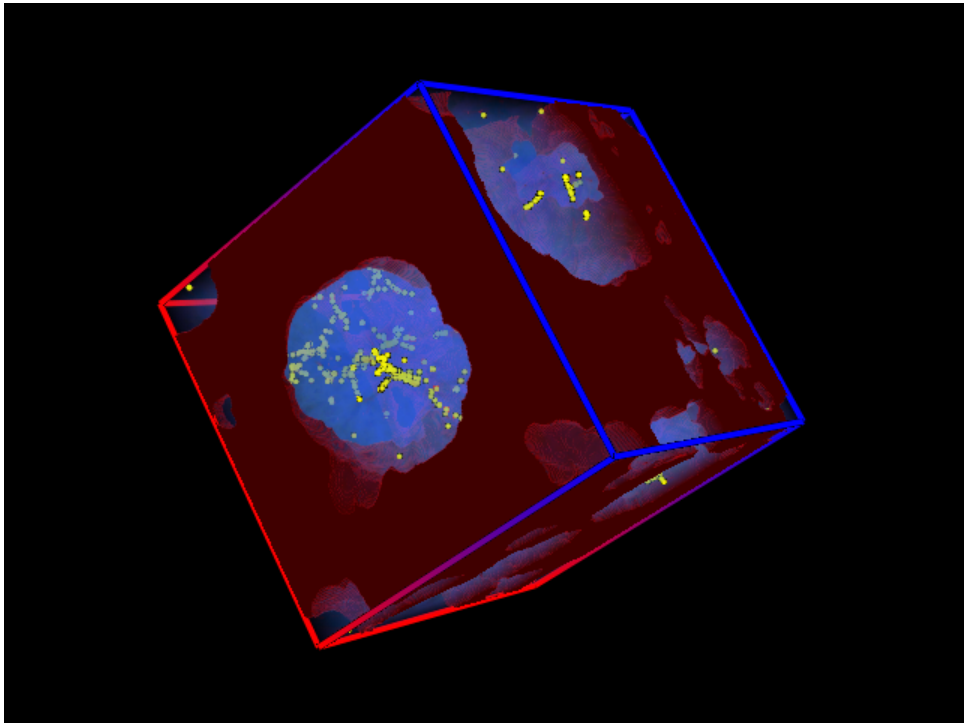


How It All Happens...





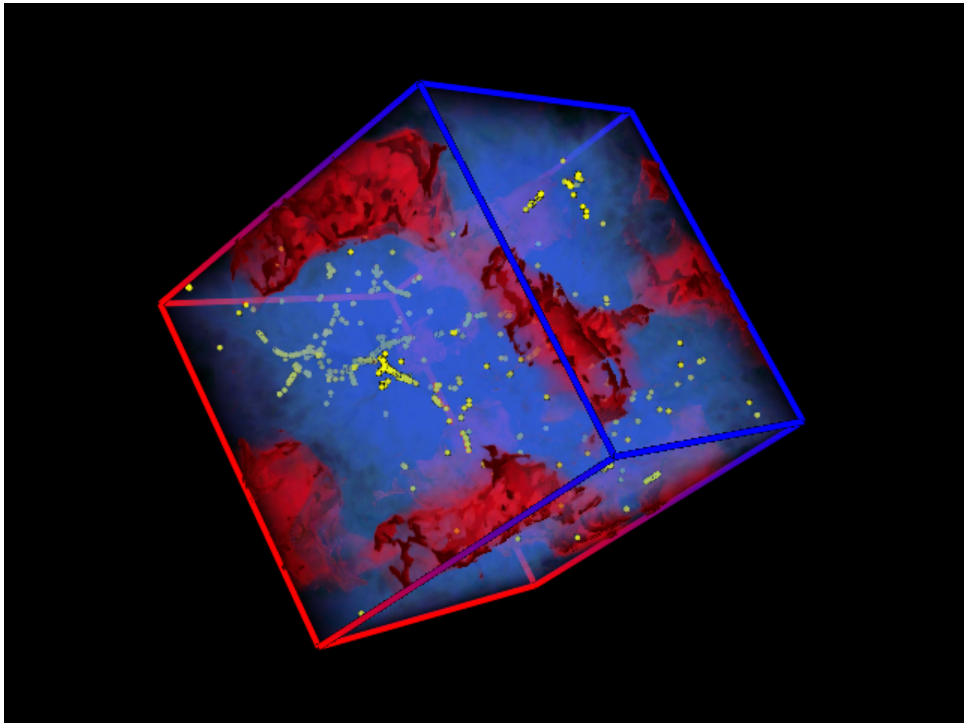
How It All Happens



Pre-overlap:

- Ionized bubbles expand in the low density gas.
- Most of ionizing photons are expended on ionizing IGM.

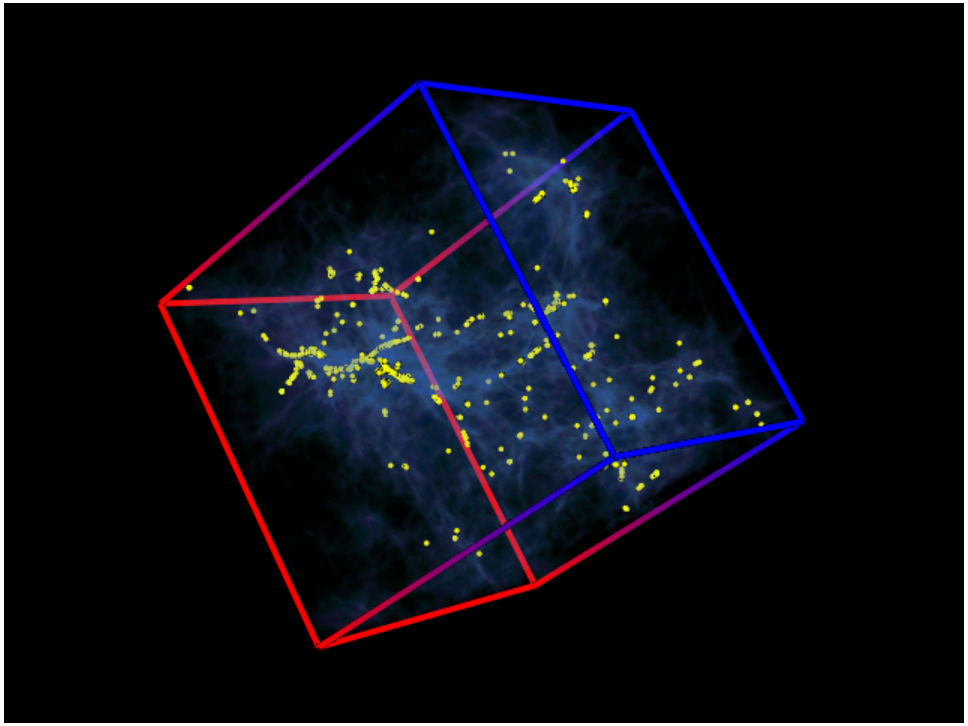
How It All Happens



Overlap:

- Ionized bubbles merge – the moment of *reionization*.
- Some ionizing photons are absorbed in LL systems.

How It All Happens



Post-overlap:

- Most of gas in the universe is highly ionized.
- All ionizing photons are absorpbed in LL systems.

Simulating Reionization: Scales

- Capturing most of star-forming galaxies requires boxes > 50 Mpc (comoving).
- Resolving LL system requires resolution ~ 1 kpc.
- Resolving star formation requires resolution ~100-200 pc (depends on your sub-grid model).
- Resolving all star-forming galaxies requires mass resolution of about 10^6 $M_\bullet$.
- Conclusion: we need simulations with
  - spatial dynamic range $L/\Delta x > 100{,}000$
  - mass dynamic range $M_{box}/M_{cell} >$ 10 billion

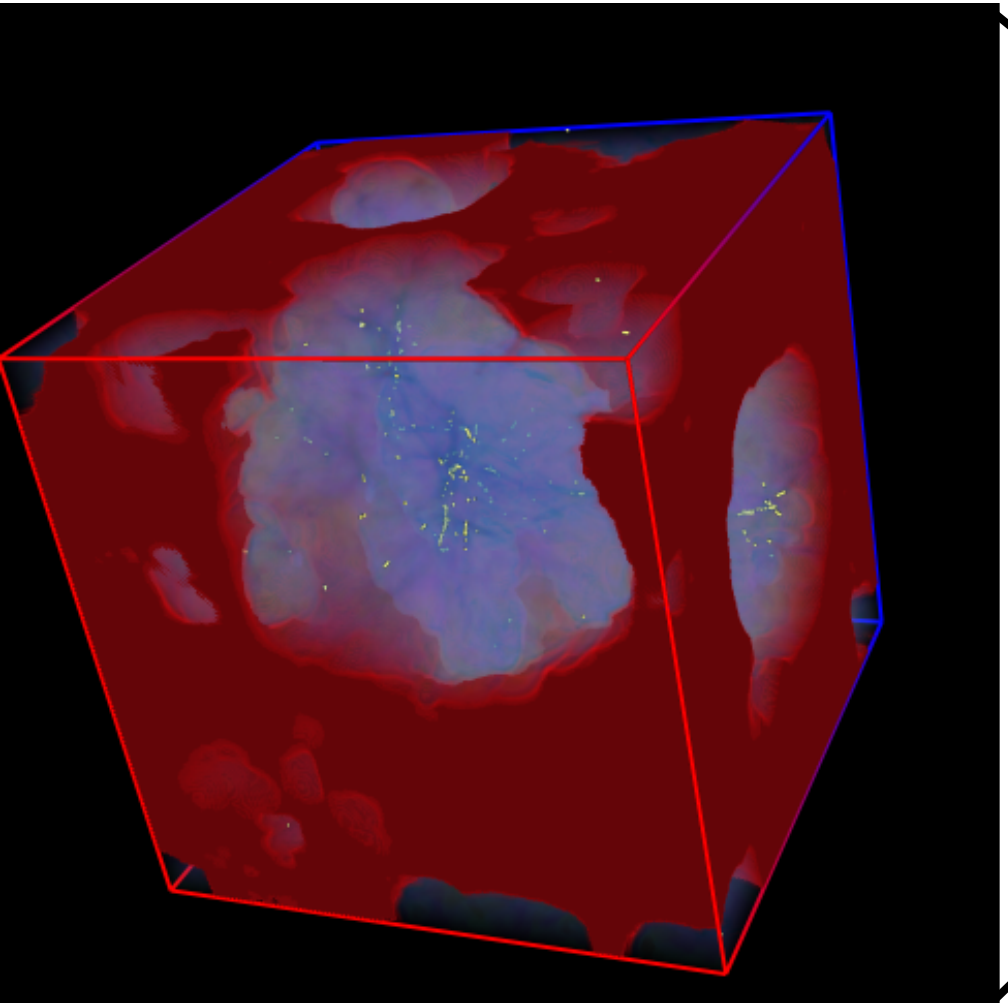
Simulating Reionization: Physics

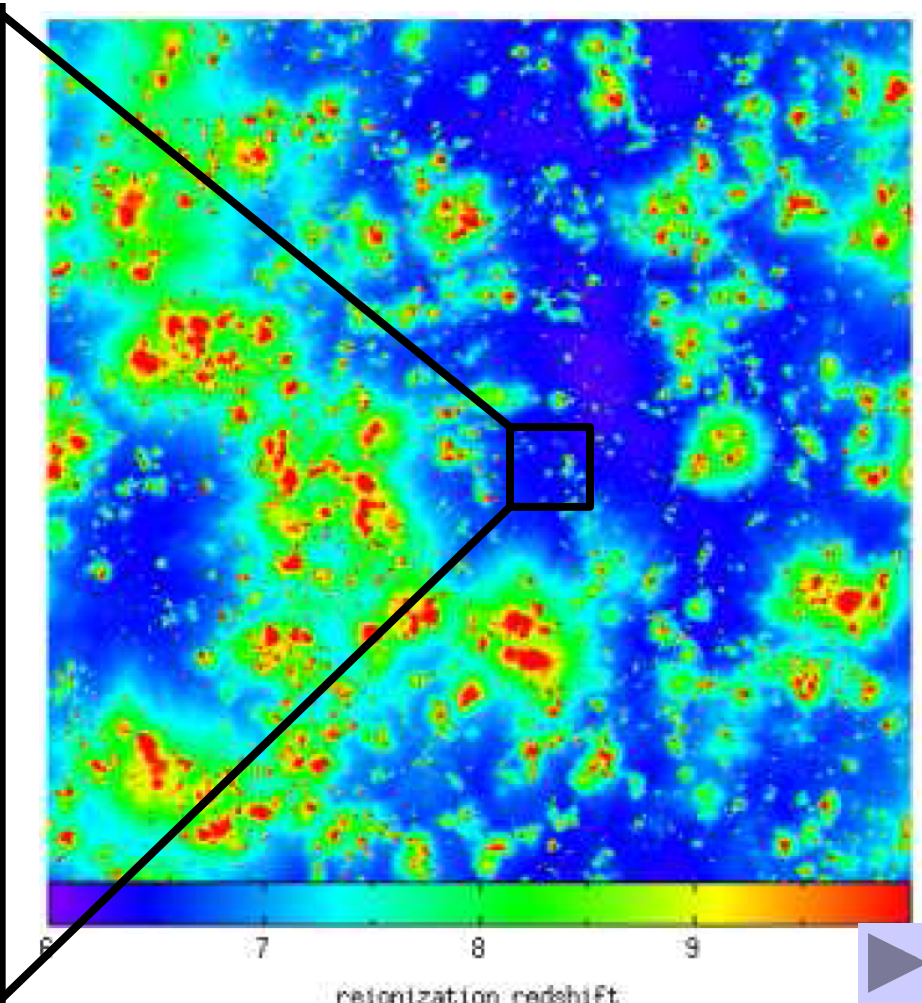
- Dark matter
- Gas dynamics
- Atomic processes (cooling, H_2 chemistry)
- Radiative transfer of ionizing+UV radiation
- ***Star formation and stellar feedback***
  - Problem is not only in the lack of complete understanding, but also in the huge spatial dynamic range that needs to be modeled.
  - Star formation today can only be modeled as a *sub-grid* model.

Simulations: The First Decade (2000-2010)

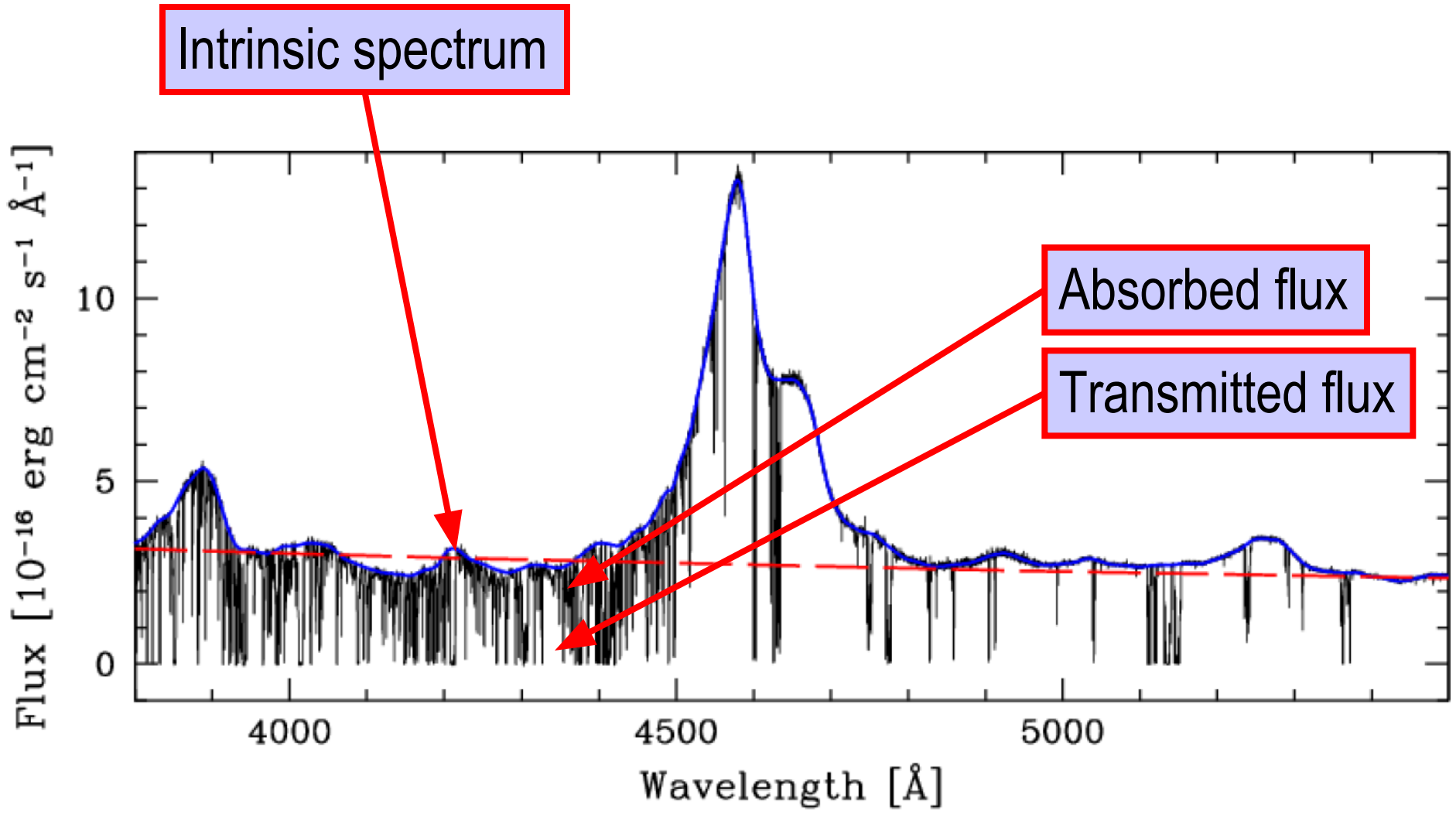
	Small box	Large box
physics	full	incomplete
spatial resolution	high	low
mass resolution	high	high
dynamic range	low	high
volume	small	large

Simulations: The First Decade (2000-2010)

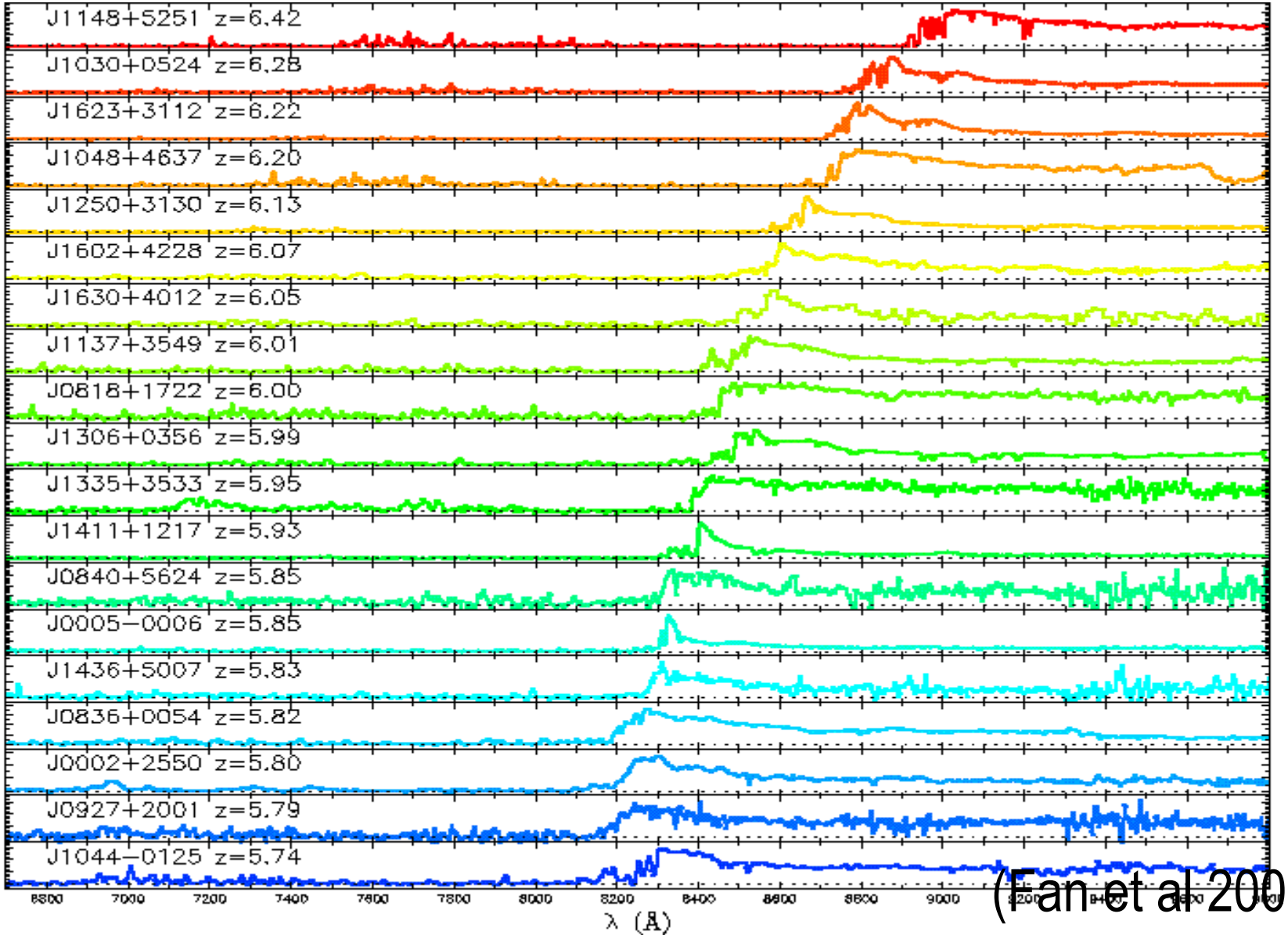




Refresher: Ly-α Forest

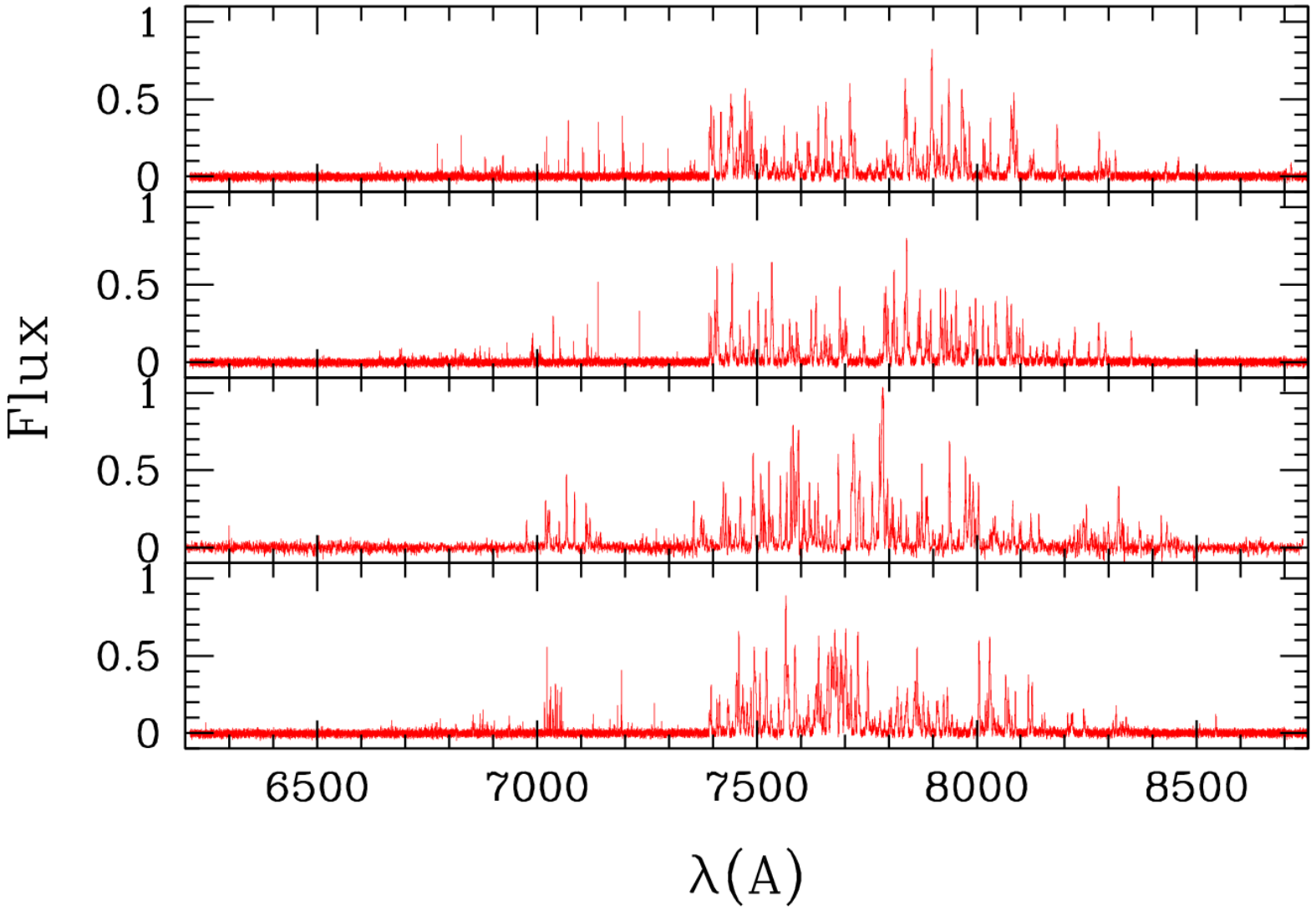


SDSS Quasars ~ 2005

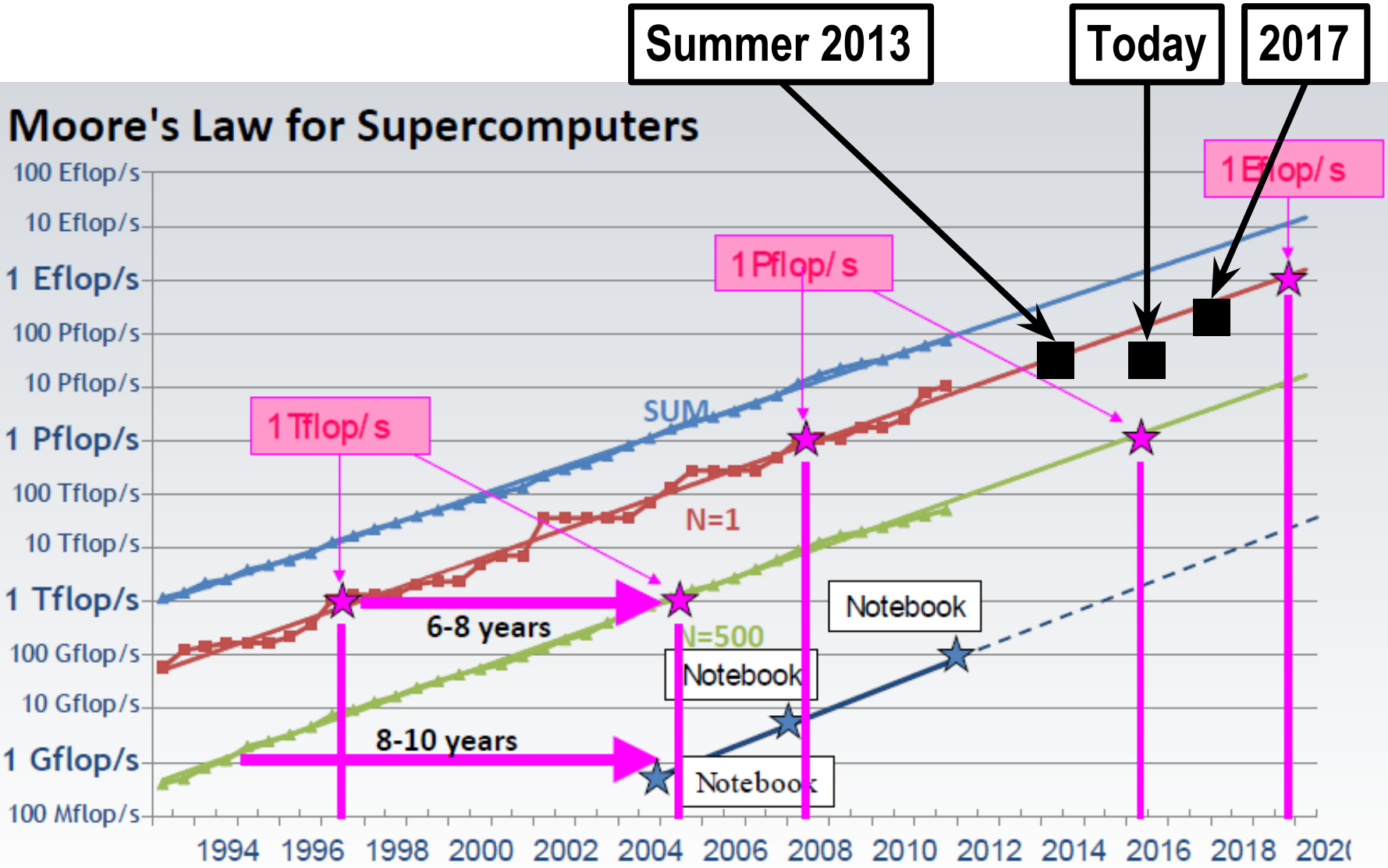


(Fan et al 2005)

Quiz: find the SDSS Quasar

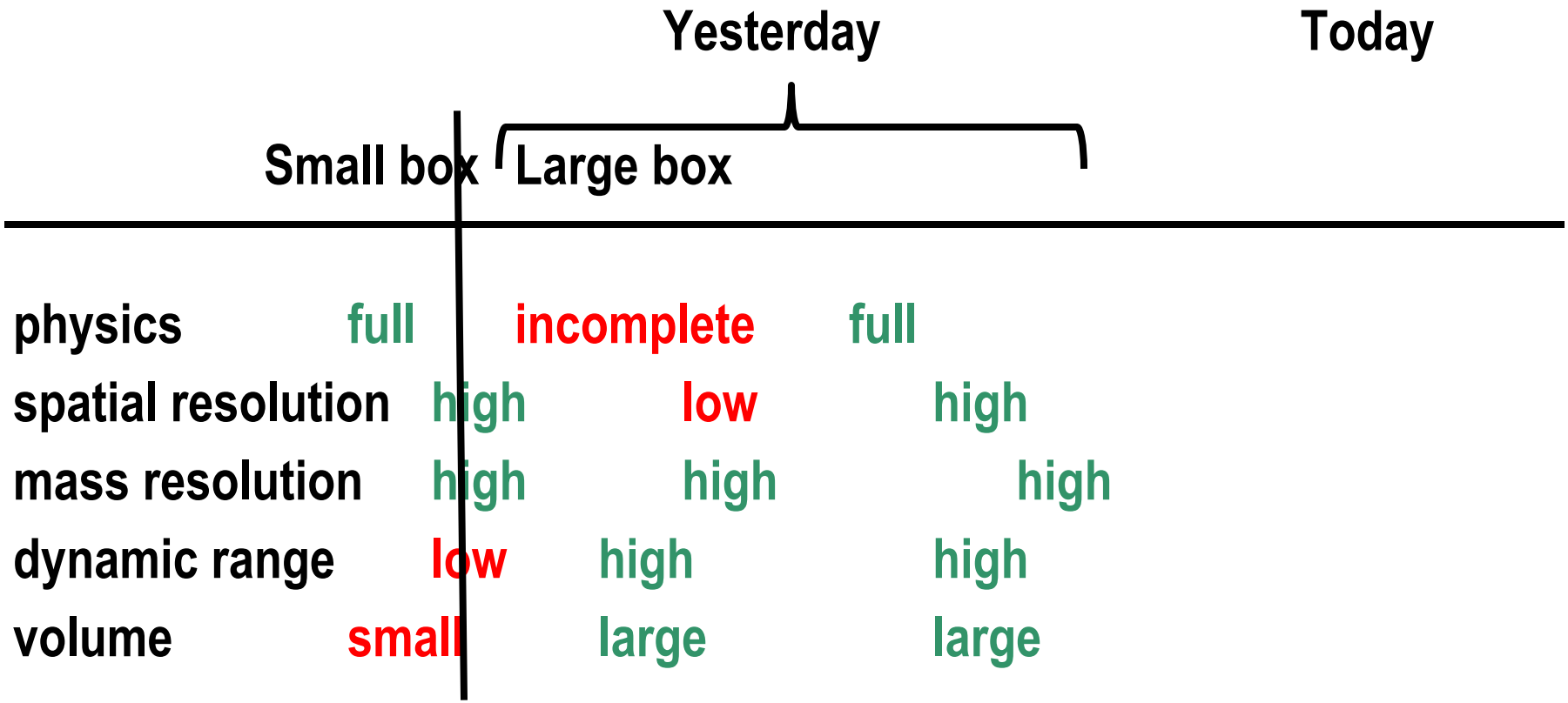


Moore's Law

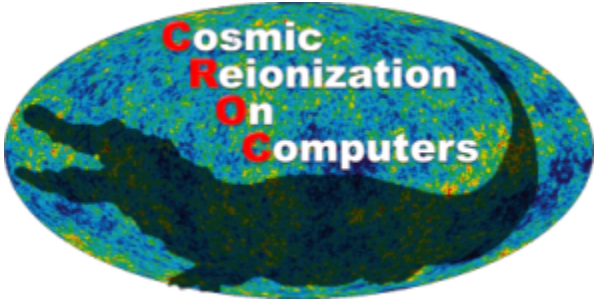

Summer 2013
Today
2017
Moore's Law for Supercomputers
100 Eflop/s
10 Eflop/s
1 Eflop/s
100 Pflop/s
10 Pflop/s
1 Pflop/s
100 Tflop/s
10 Tflop/s
1 Tflop/s
100 Gflop/s
10 Gflop/s
1 Gflop/s
100 Mflop/s
1 Eflop/s
1 Pflop/s
1 Tflop/s
SUM
N=1
N=500
6-8 years
8-10 years
Notebook
Notebook
Notebook
1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016 2018 202

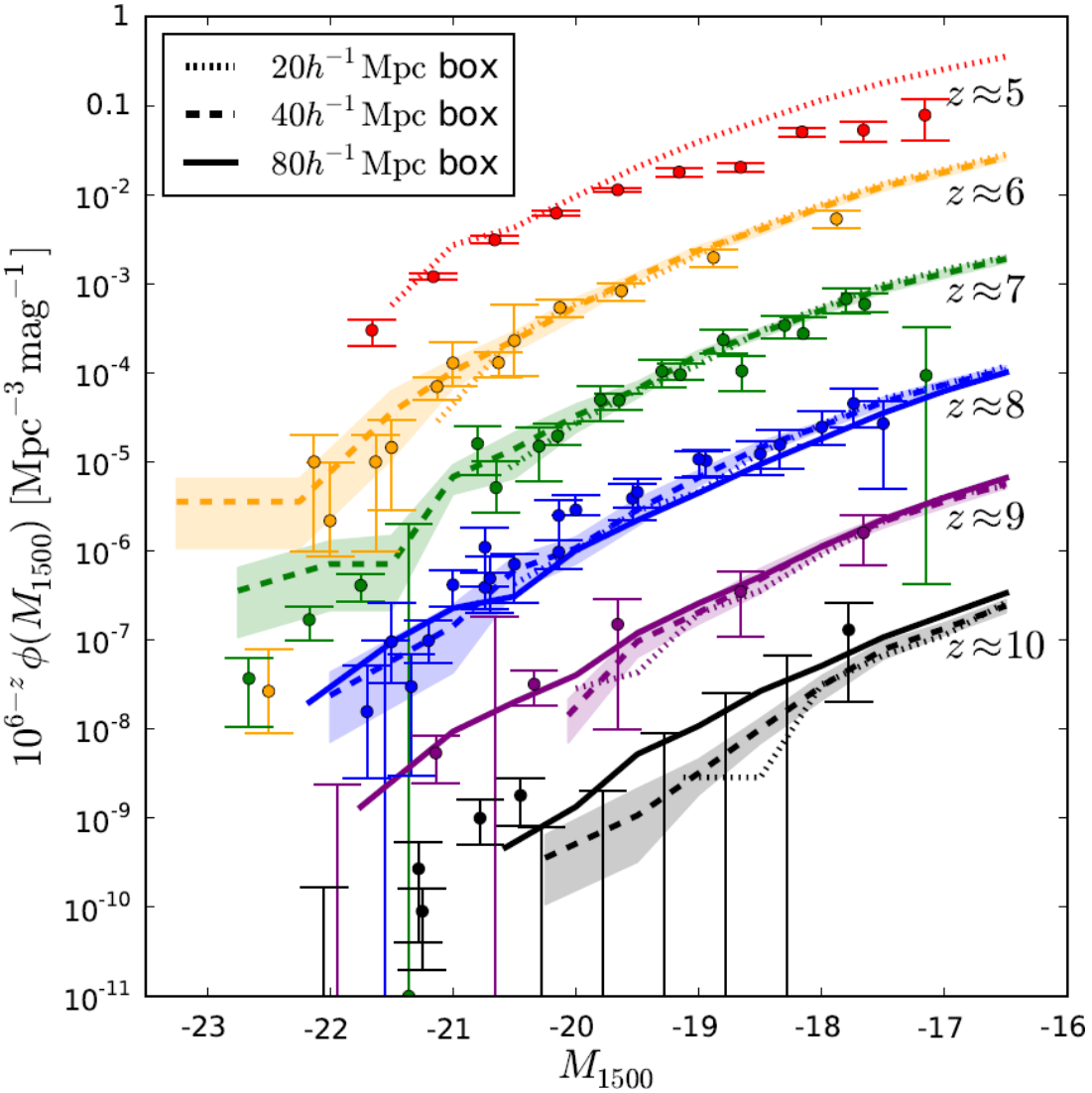
Covering The Gap

- With peta-scale computing power we can run large-box simulations with full physics.



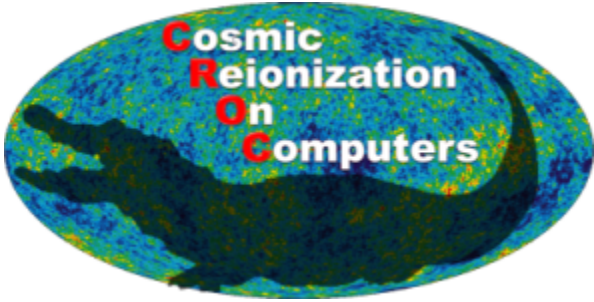
The CROC Project: Validation



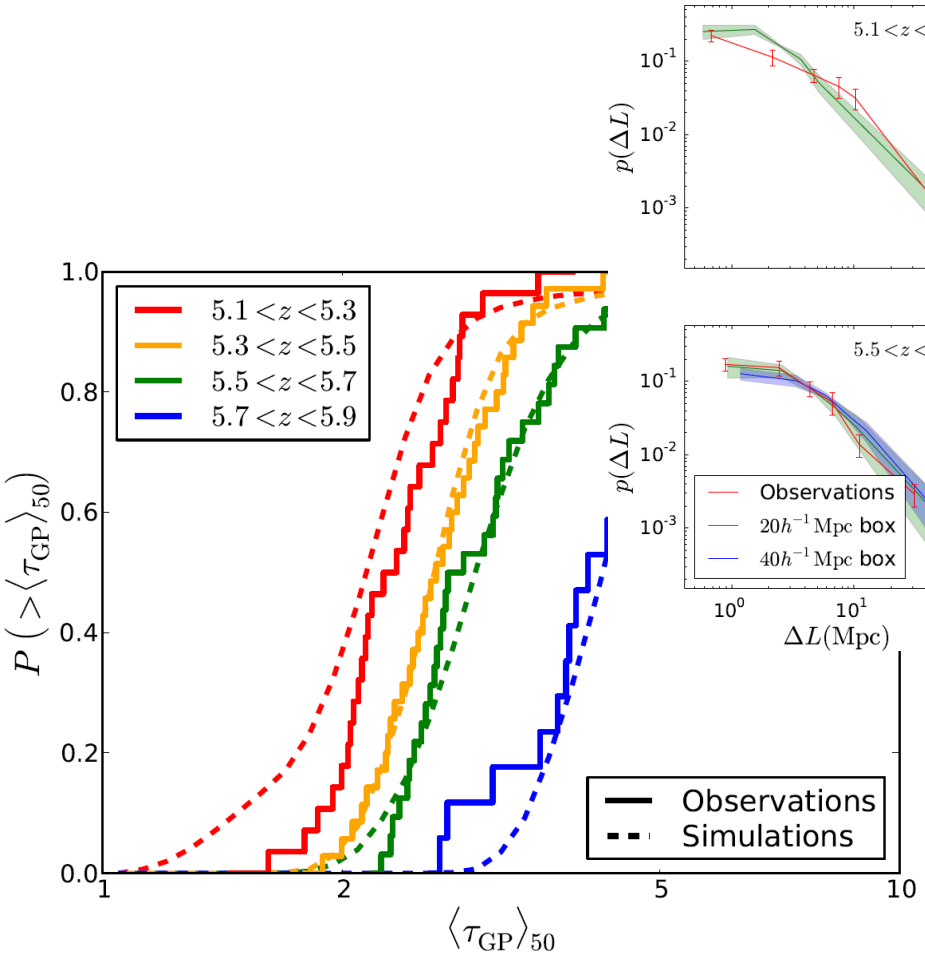


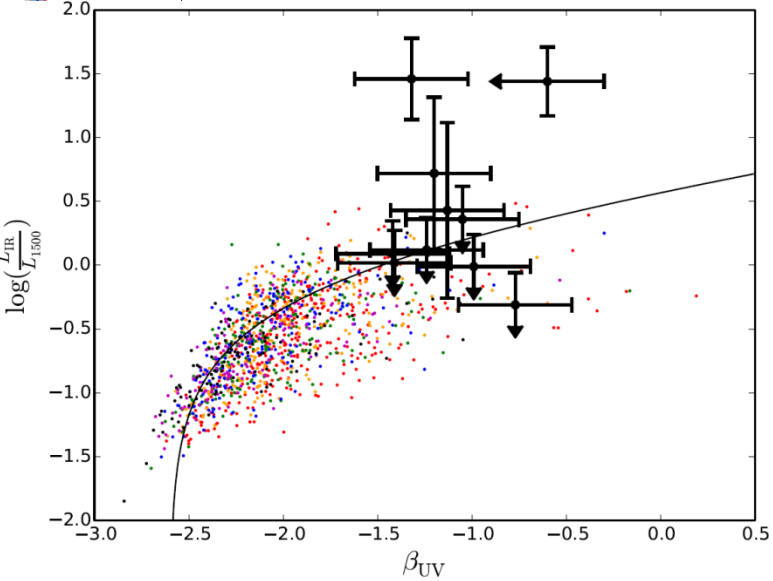
- Galaxies in right halos ***all the time***!

The CROC Project: Validation

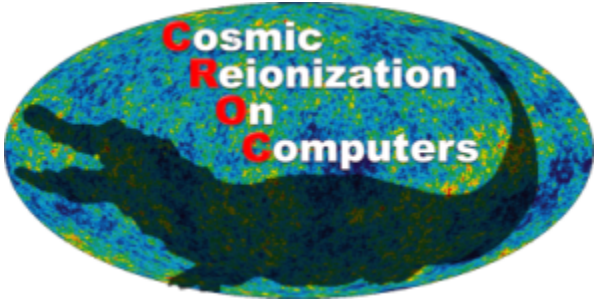


- Many other observations are reproduced too…

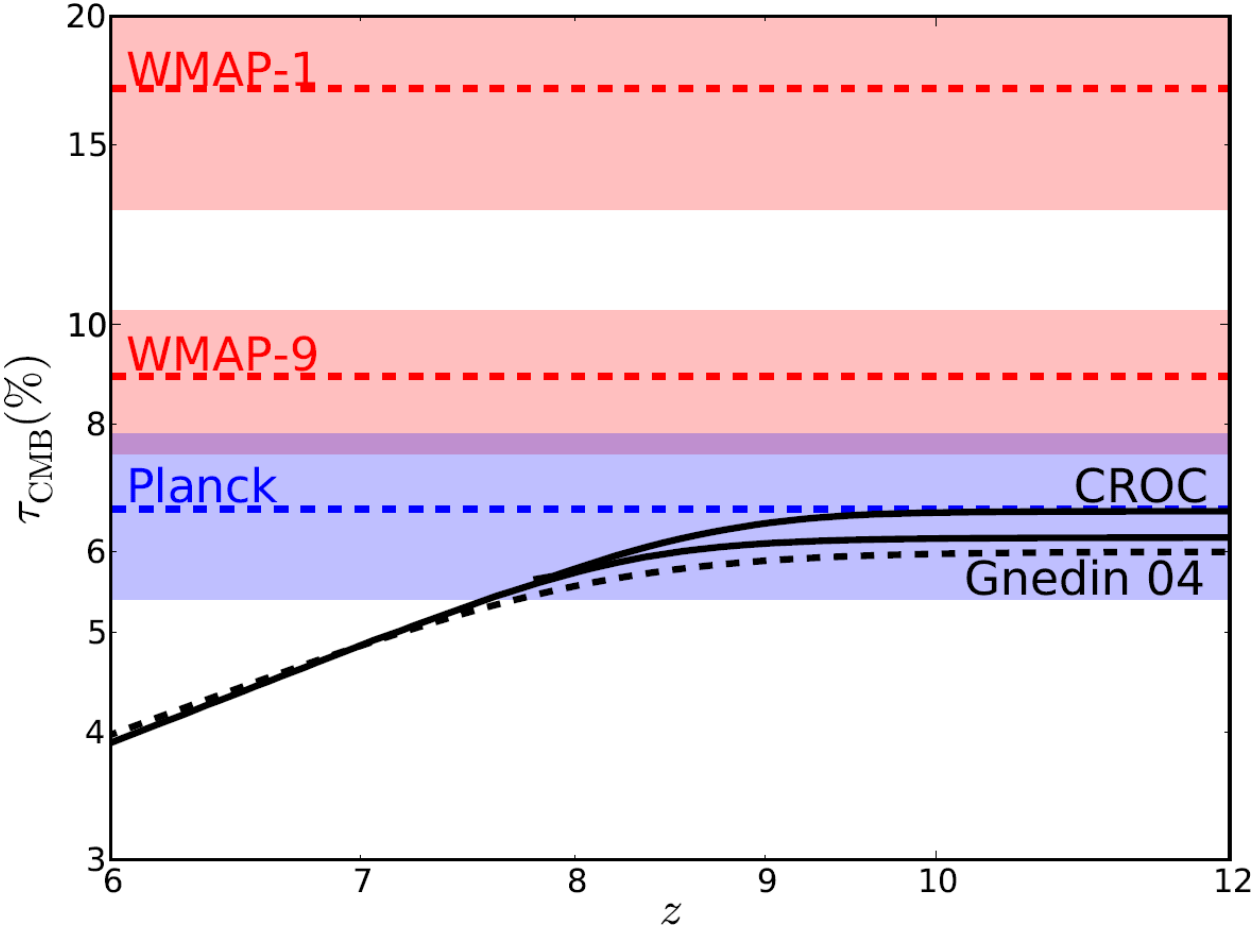




The CROC Project: Validation



- Finally, CMB observations succeeded in matching theoretical predictions.



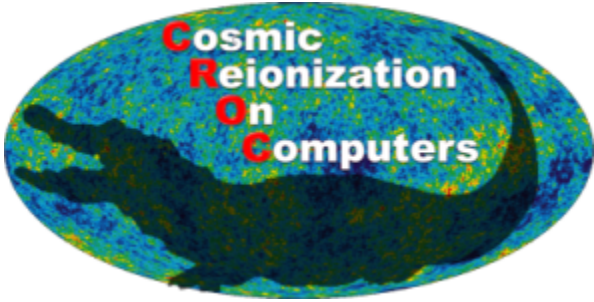
Example: Backreaction of Reionization on Galaxies

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

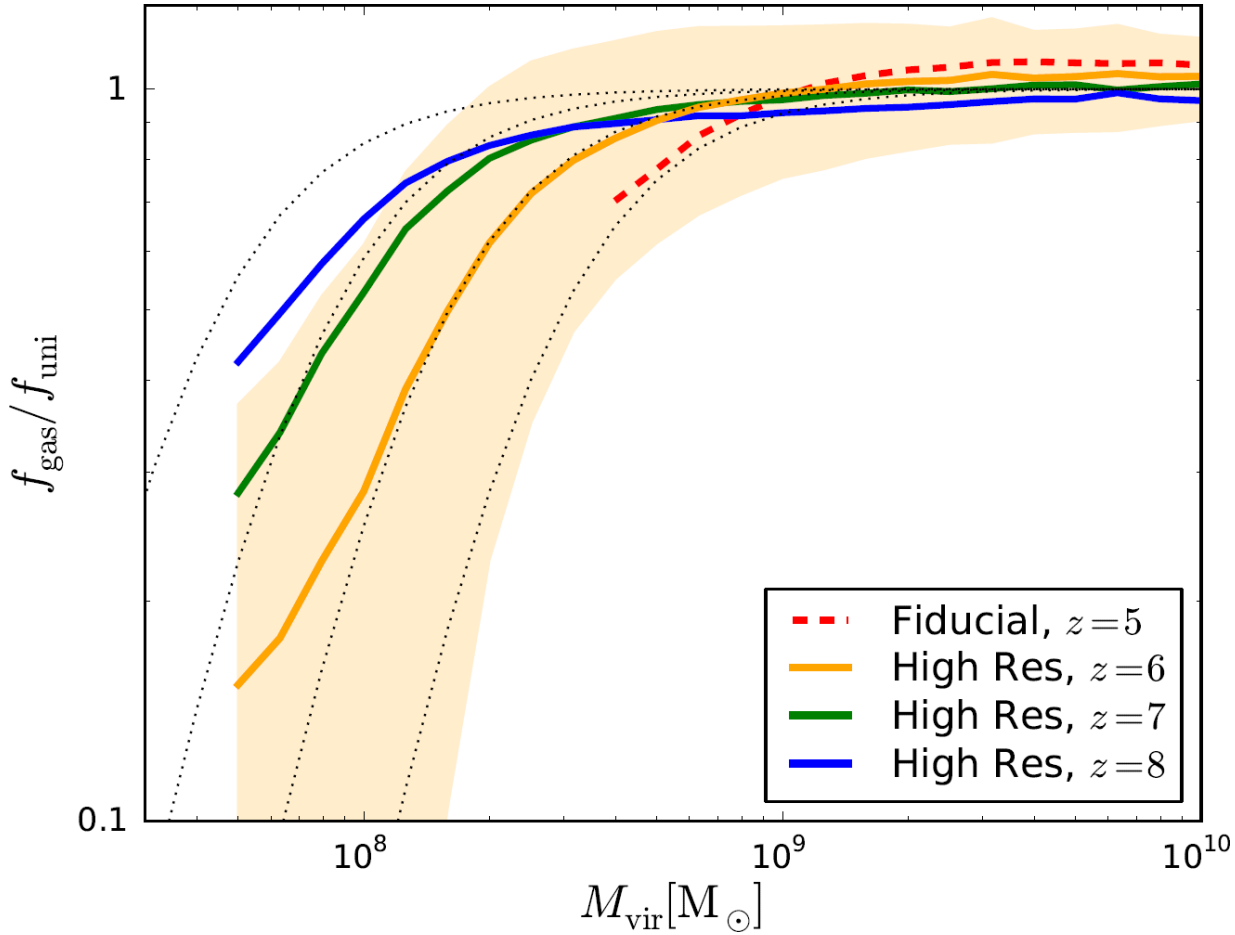
- One of JWST science goals.

(Barkana & Loeb 2000)

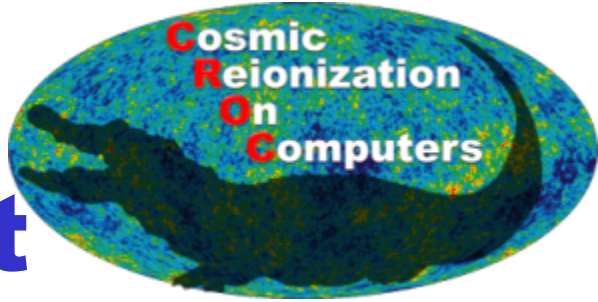
Backreaction: Gas Fractions



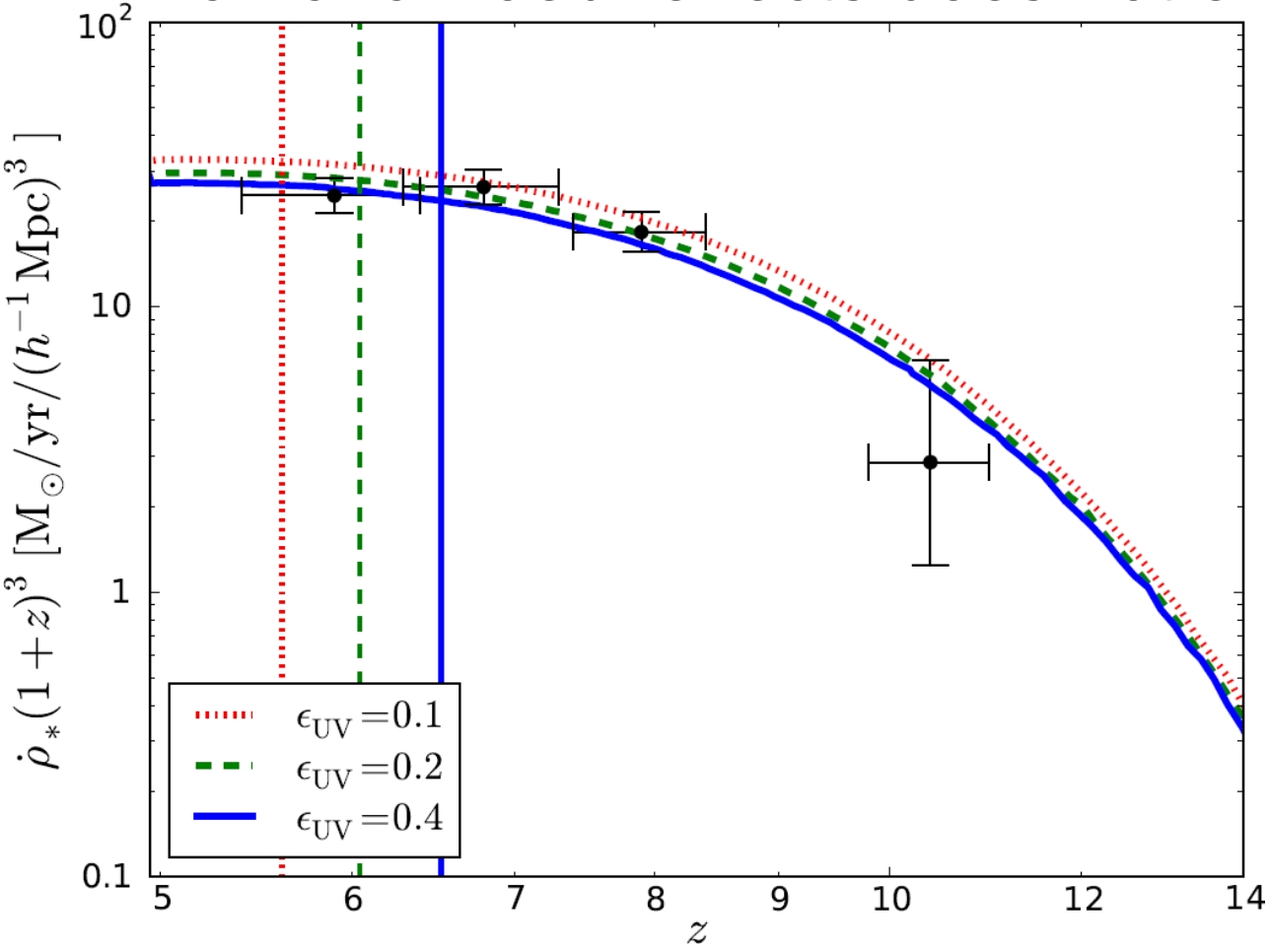
- Match Okamoto et al (2008) results *exactly* (after reionization, of course).



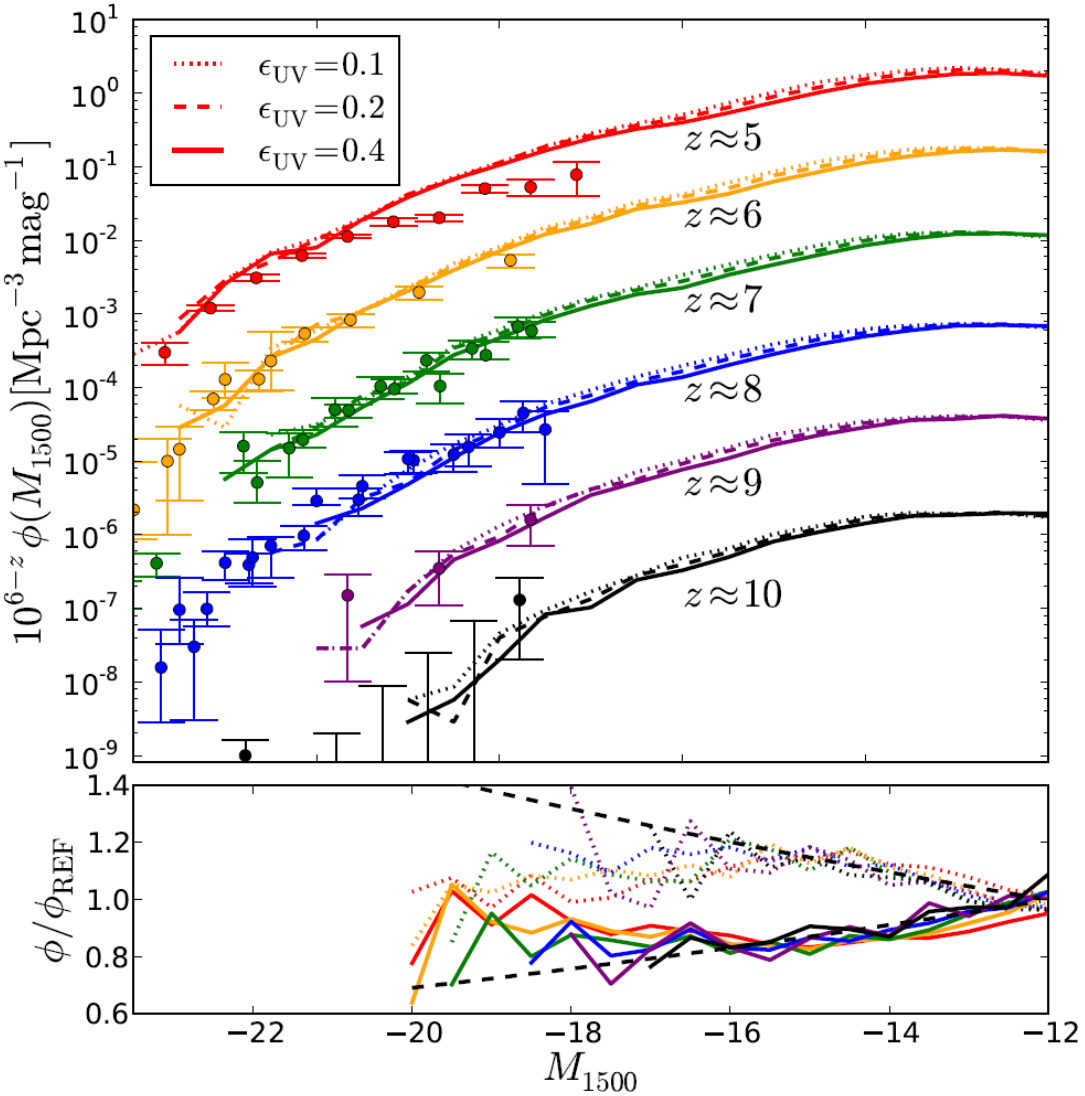
Backreaction: Barkana-Loeb Effect



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



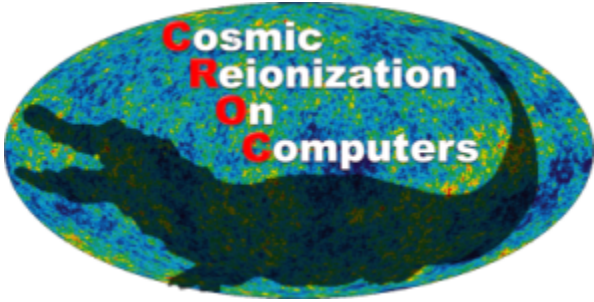
Backreaction: Faint-End Slope



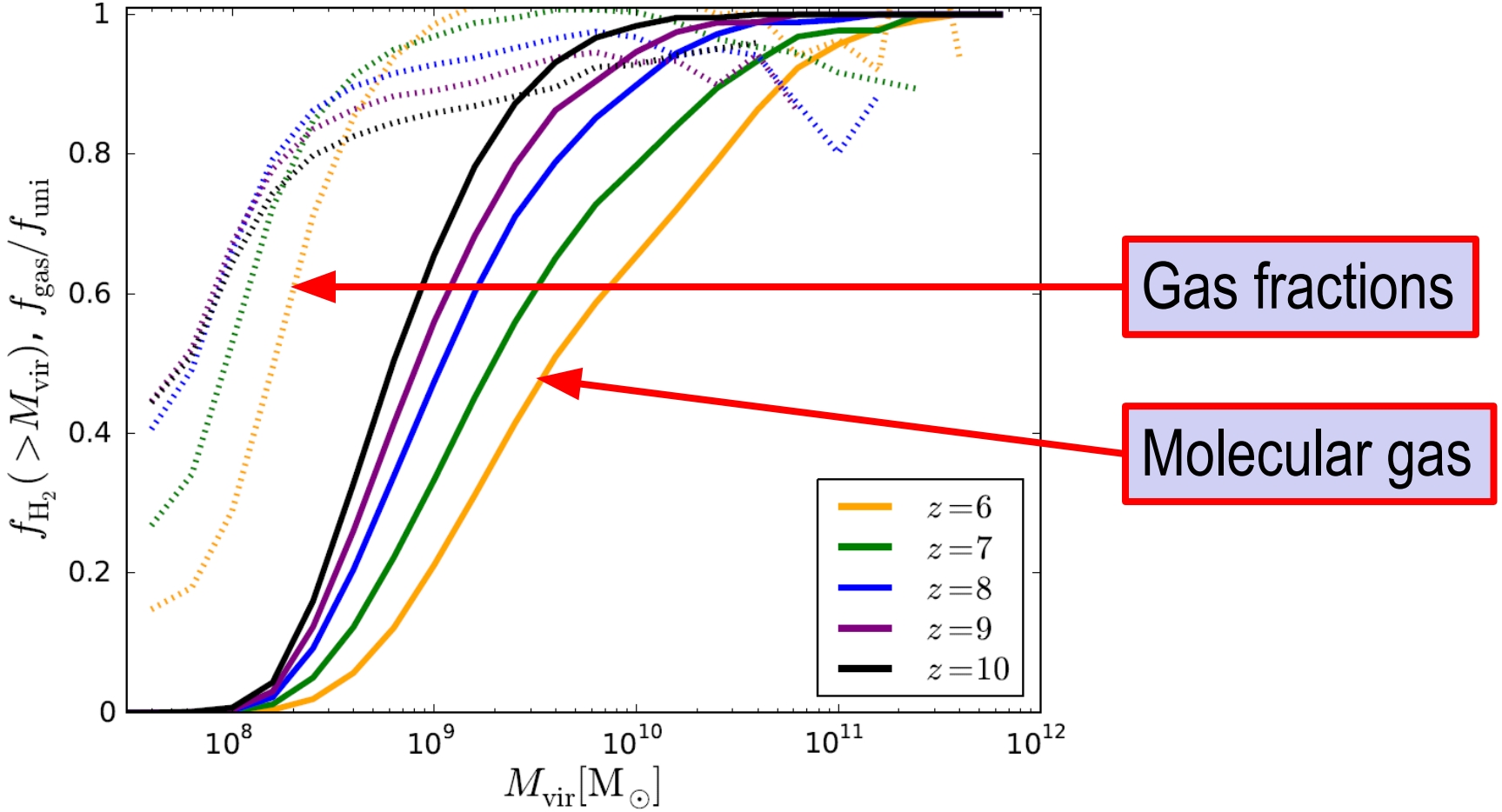
- Faint-end slope of UV luminosity function varies

$$\sim 0.1 \qquad \Delta z = 1$$

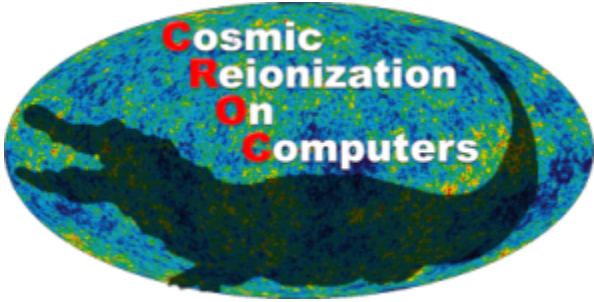
Backreaction: Why?



- Galaxies affected by photoionization contain no molecular gas.



And Many More...



- The quintessential question: does reionization proceed inside-out or outside-in? Answer: both (first inside-out, later outside-in).
- Modeling radiative transfer self-consistently (i.e. with the same spatial and temporal resolution as hydro) is crucial for getting z>5 IGM right.
- Cosmic dust may not follow metals at z>7 (formation and destruction time-scales are not negligibly short).
- Lyman-α emitters are not a useful probe of reionization.

The Flood Is Coming

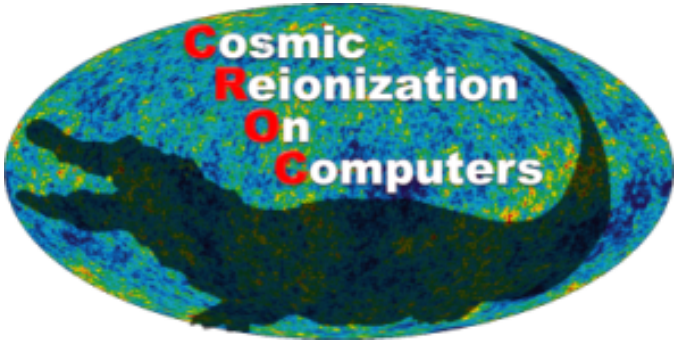
- Astro2010:

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

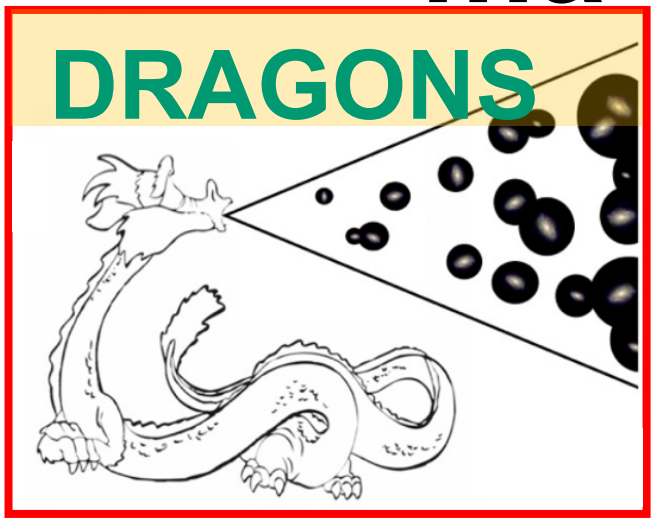
- It is clear that forthcoming observations will make all existing theoretical models obsolete.
- We are preparing for the flood:



Cosmic Dawn

Em
ma

Renaissan
ce



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.

---

* ALMA, HSC, JWST, 30m telescopes, 21cm

The End

Reionization