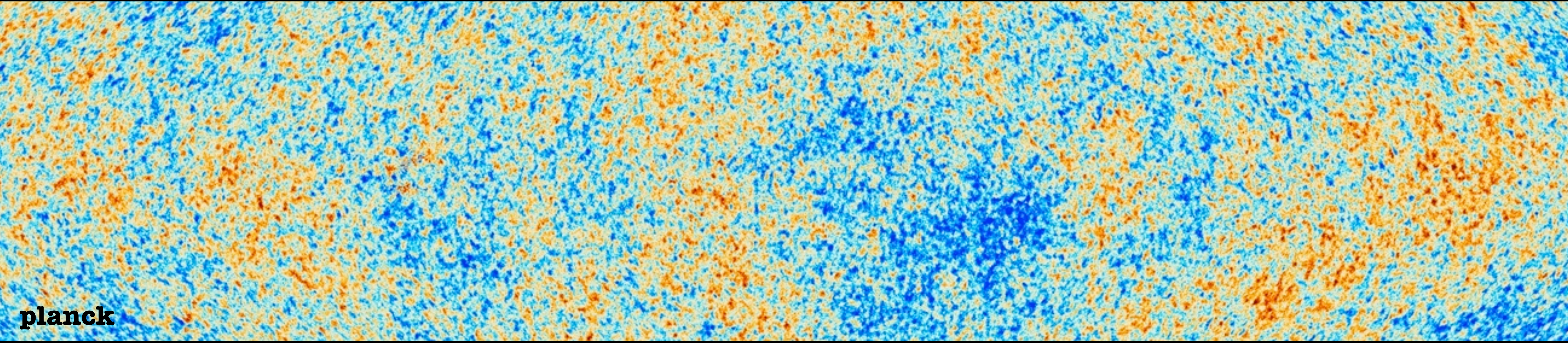
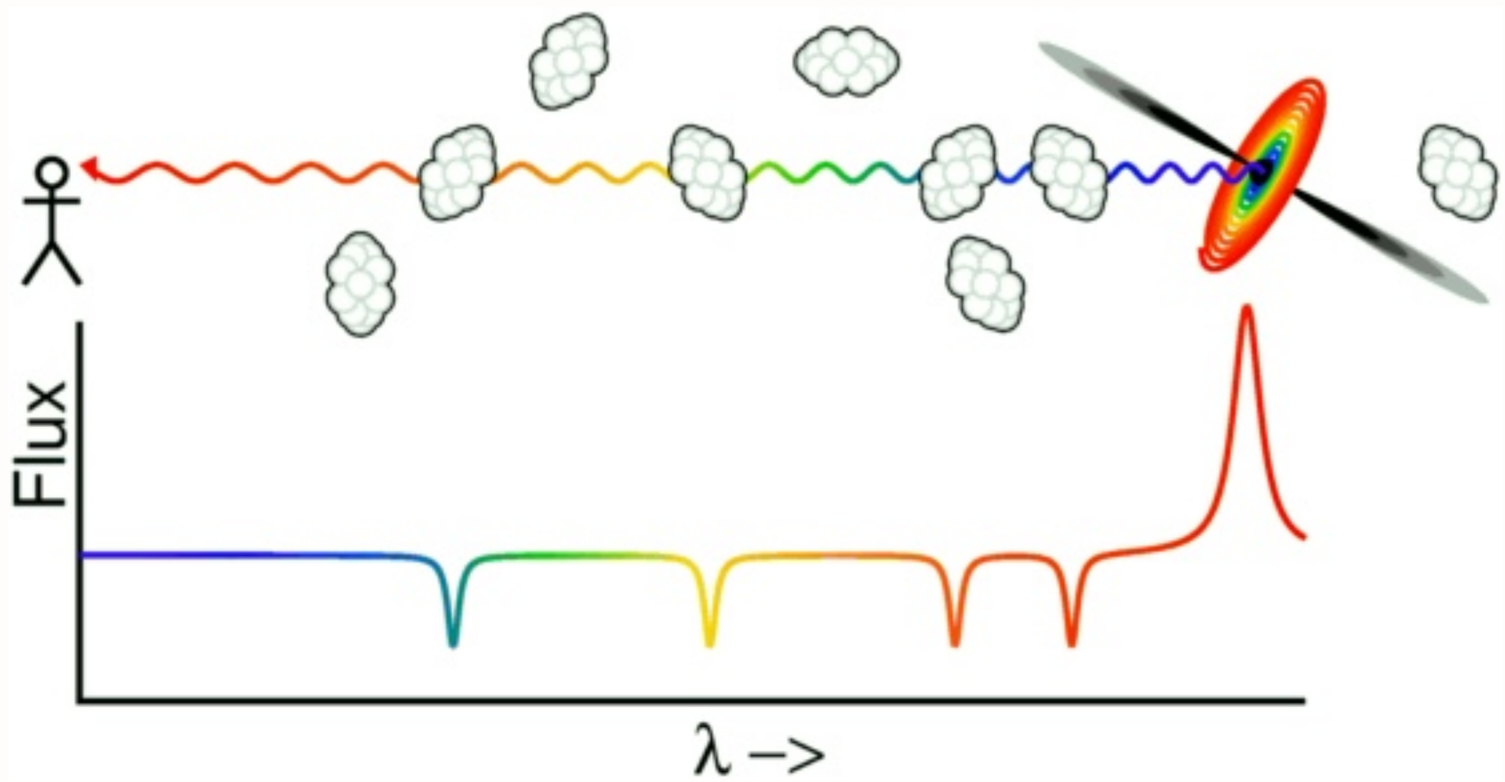
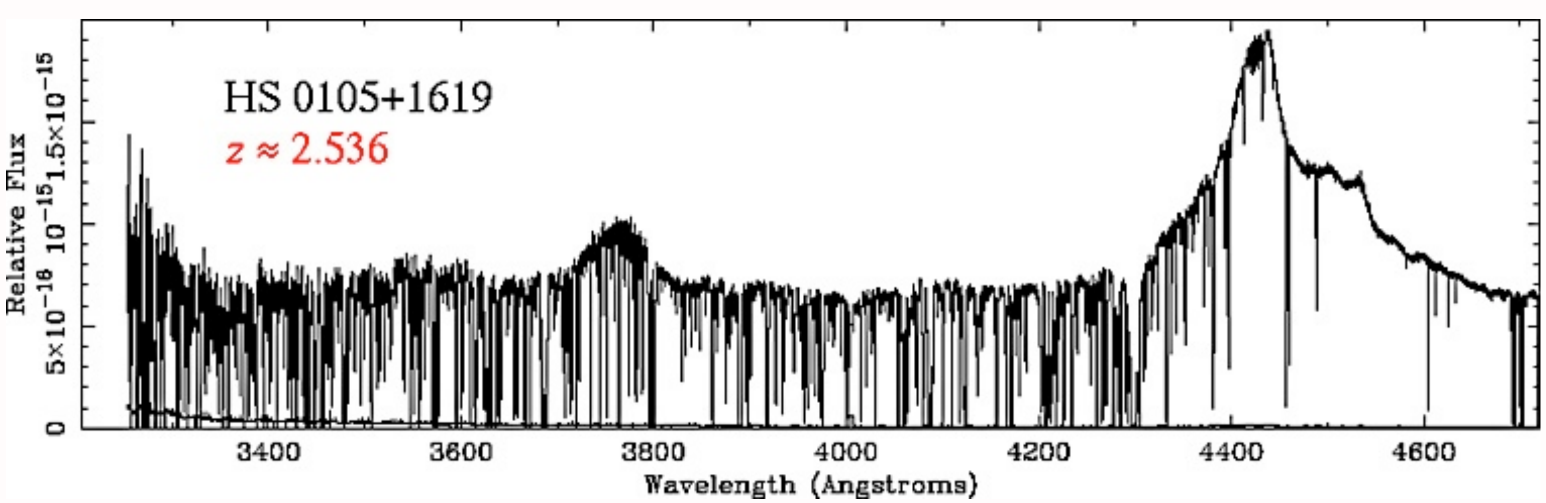


Quasar spectra and Cosmology

Zarija Lukić
Lawrence Berkeley National Laboratory

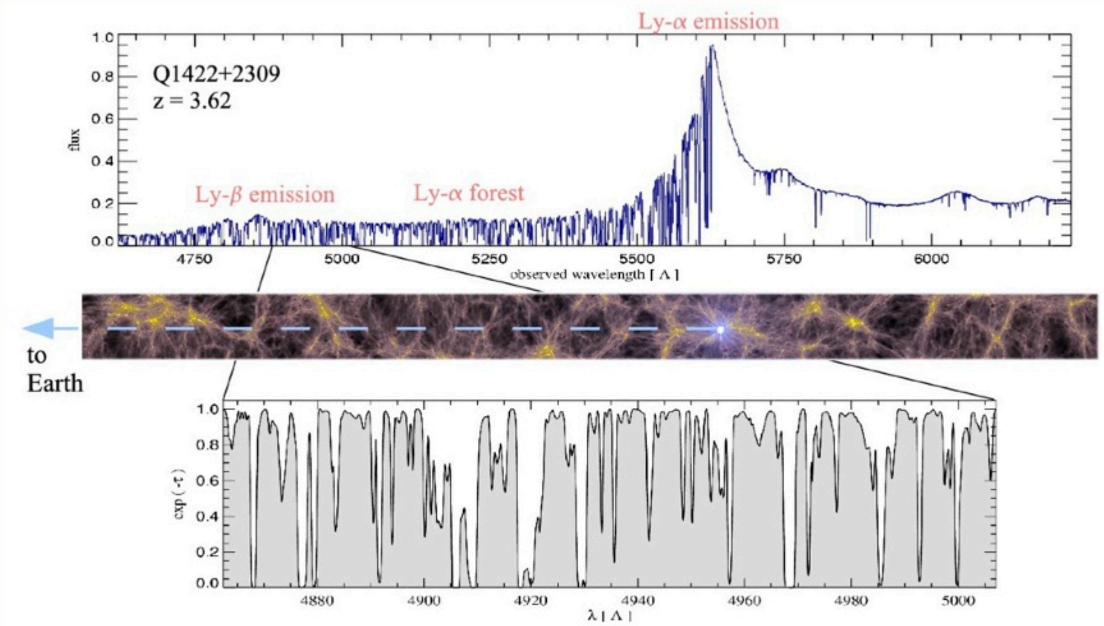
Lyman alpha forest

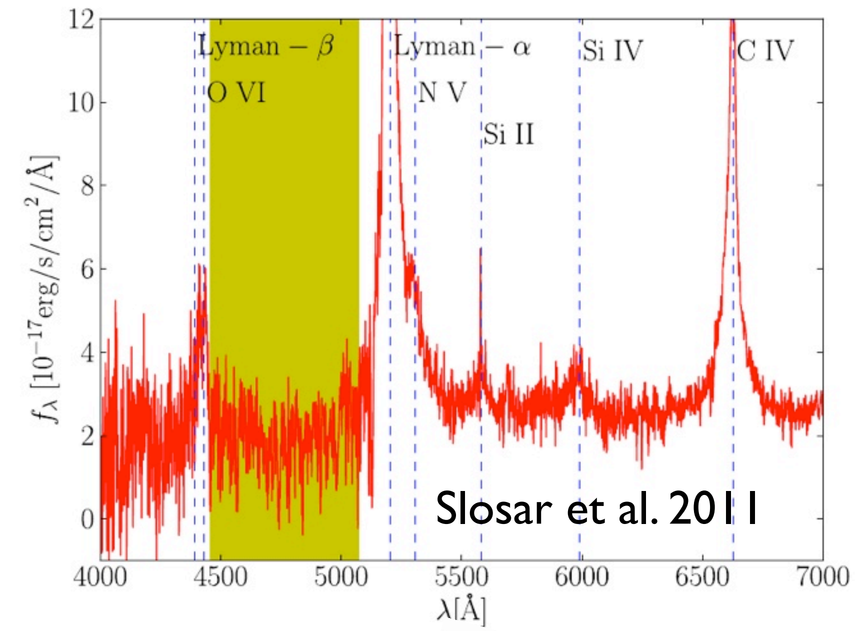




- Quasars emit featureless spectrum with a few broad emissions
- Neutral hydrogen absorbs light at its rest-frame Ly-A
- HI traces gas, which traces dark matter...
- Each "skewer" is a 1-D map of density

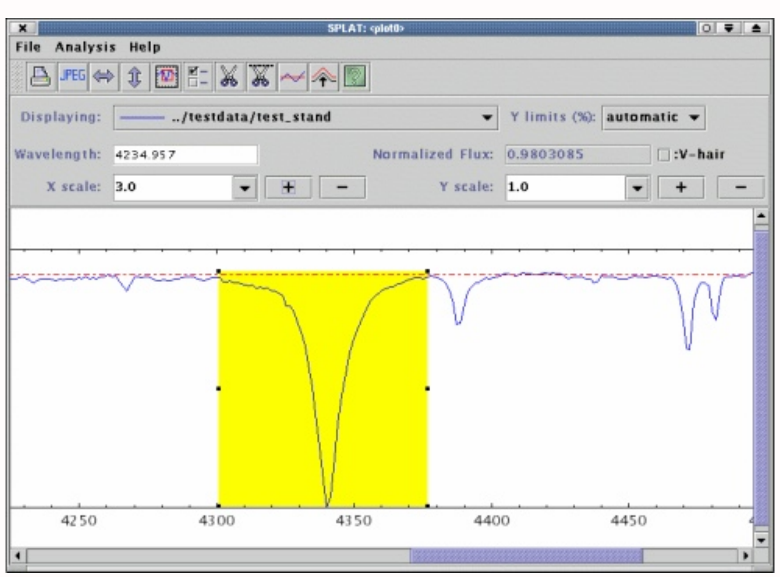
Lines ➠ Physics

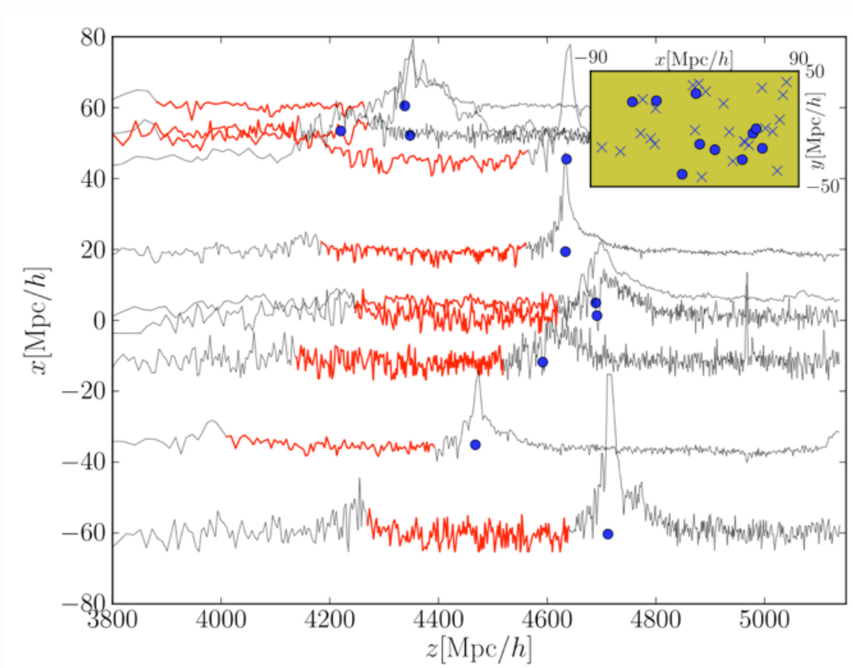


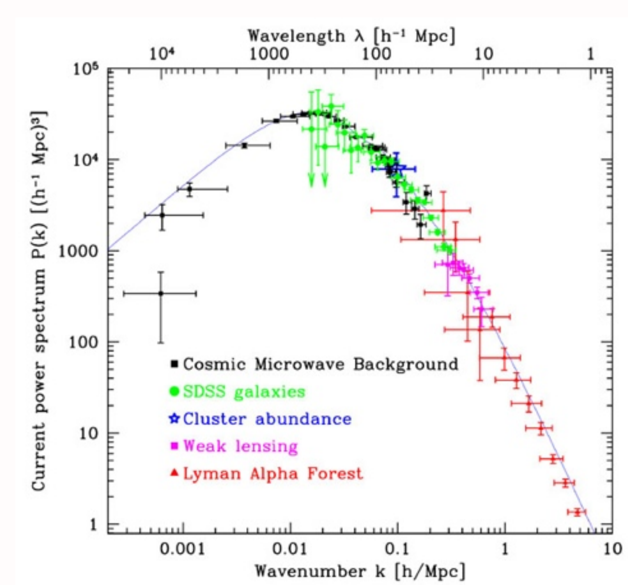


line fitting

n-point distribution

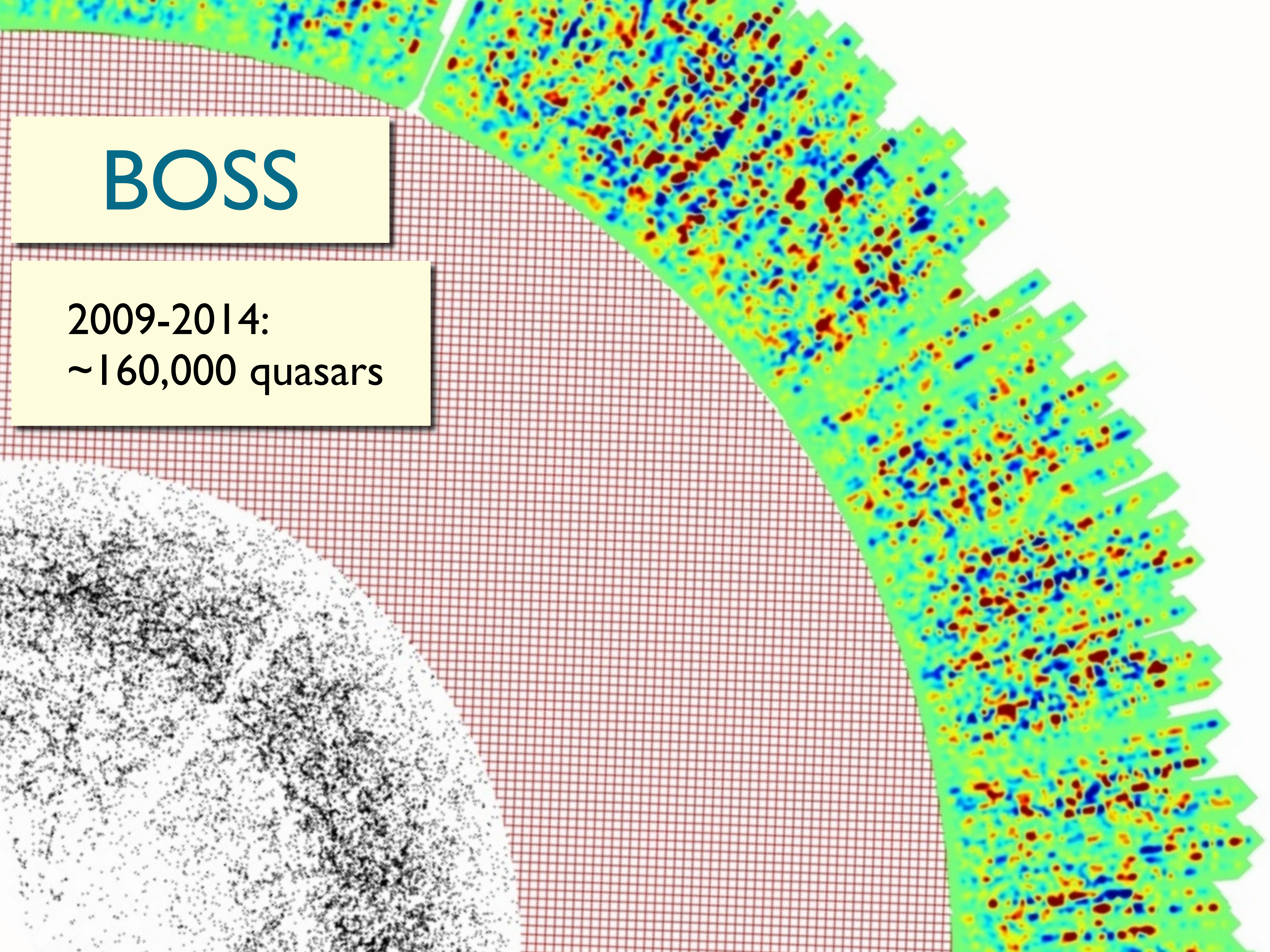






Observables

Statistic	Symbol	Measurements
Mean flux	$\langle F \rangle$	Bernardi et al. 2003, Faucher-Giguere et al. 2008, Becker et al. 2013, ...
Flux PDF	$P(F)$	Rauch et al. 1997, McDonald et al. 2000, Becker et al. 2007, Lee+ 2014...
Flux 1D power	$P_{F,1D}(k_{\parallel})$	Croft et al. 2002, McDonald et al. 2006,Palanque-Delabrouille et al. 2013
Flux 3D power	$P_F(k, \mu)$	Slosar et al. 2011, 2013, Busca et al. 2013, Delubac et al. 2014
Column density distribution	$f(N_{\rm HI})$	Tytler 1987, Janknecht et al. 2011, ...
Doppler parameter distribution	$f(b)$	Carswell et al. 1991, Lu et al. 1996, Kirkman and Tytler 1997, ...


BOSS
2009-2014:
~160,000 quasars

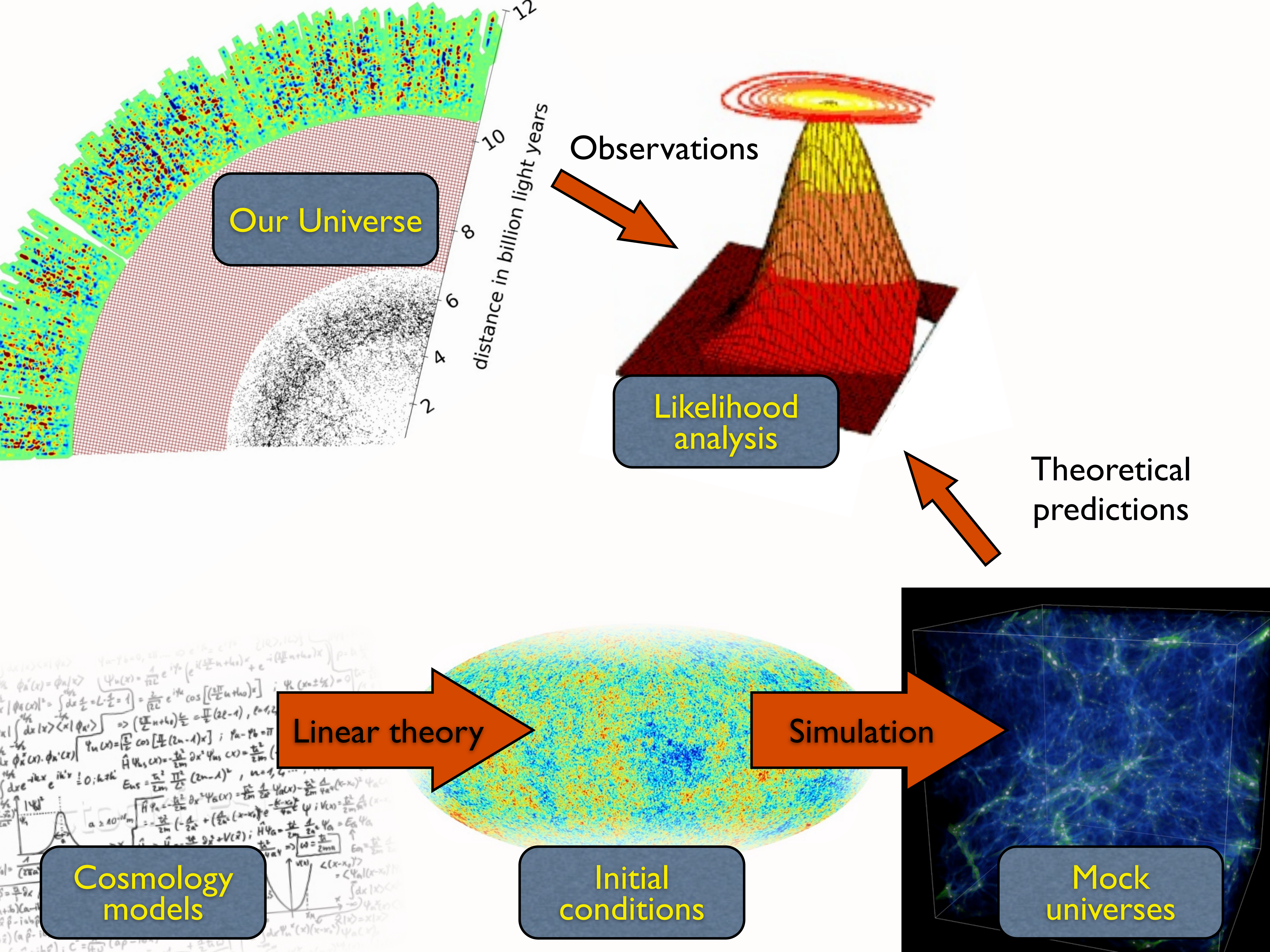
Beyond BOSS

eBOSS (SDSS-IV): 2014 - 2020

- adds ~50k new quasars
- re-observes ~60k faint quasars

DESI: 2018+

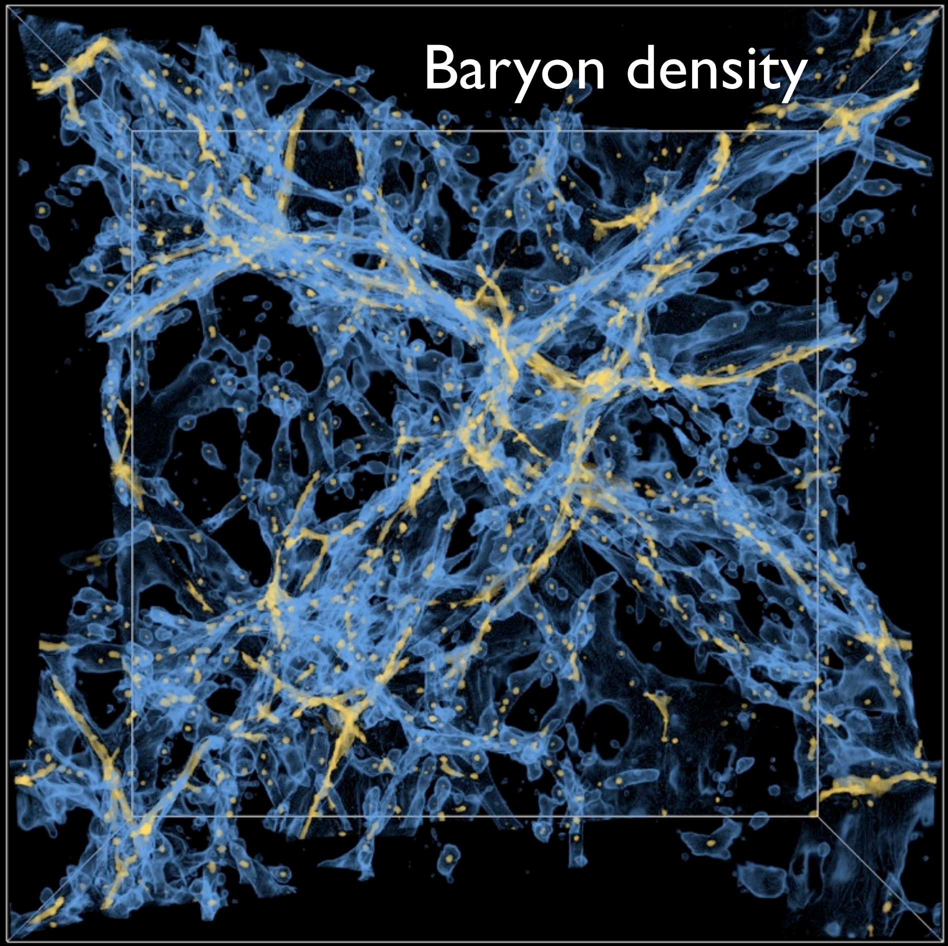
- 4m Mayal telescope
- total ~600,000 quasars at $z>2$

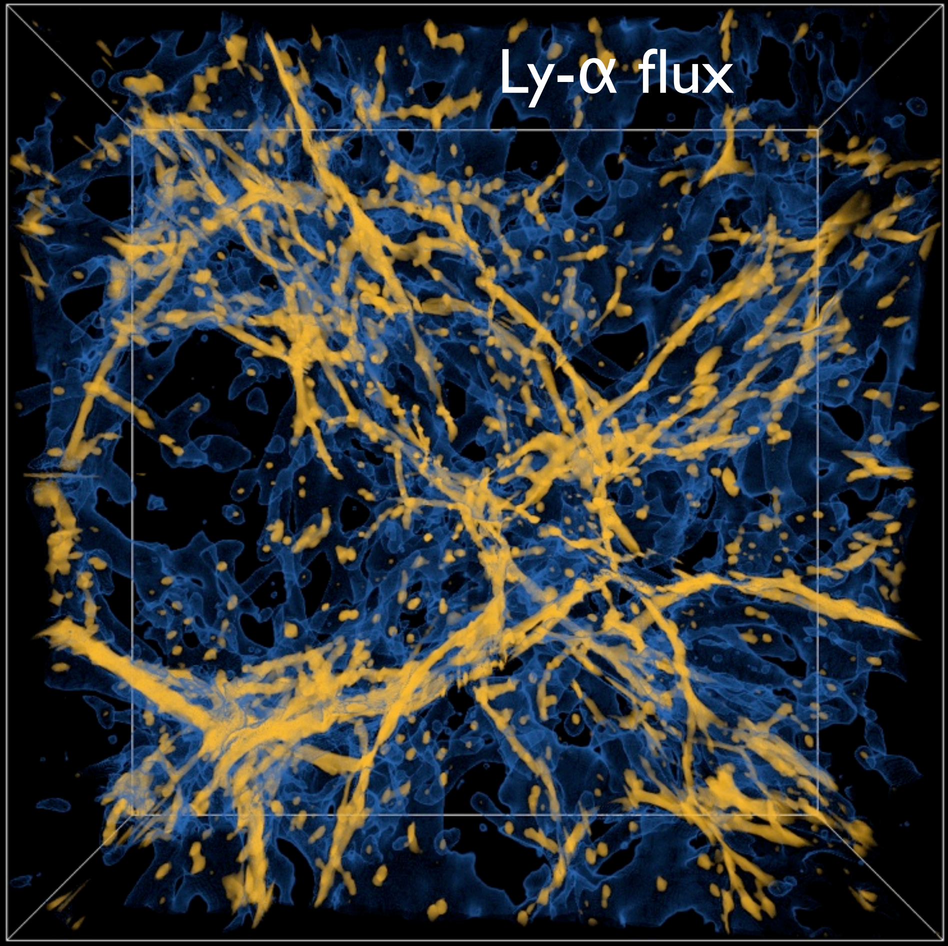


Our Universe
distance in billion light years
2
4
6
8
10
12
Observations
Likelihood analysis
Theoretical predictions
Cosmology models
Linear theory
Initial conditions
Simulation
Mock universes

Nyx

- 3-D Cartesian grid, finite volume representation
- Evolve dark matter as collisionless Lagrangian fluid
- Evolve baryons as ideal gas using unsplit, Godunov-type methodology
- Adaptive mesh refinement (AMR) to extend dynamic range
- Uses BoxLib software framework developed at LBL
- Code paper: ApJ, 765, 39 (2013)





Atomic species

- 2 primordial elements: H and He
- 6 ionic species: H_0, H_+, He_0, He_+, He_{++}, e^-

$$\frac{\mathrm{d}n_{\mathrm{H}_0}}{\mathrm{d}t} = \alpha_{\mathrm{H}_+}(T)n_{\mathrm{H}_+}n_{\mathrm{e}} - \Gamma_{\mathrm{eH}_0}(T)n_{\mathrm{e}}n_{\mathrm{H}_0} - \Gamma_{\gamma\mathrm{H}_0}n_{\mathrm{H}_0}$$

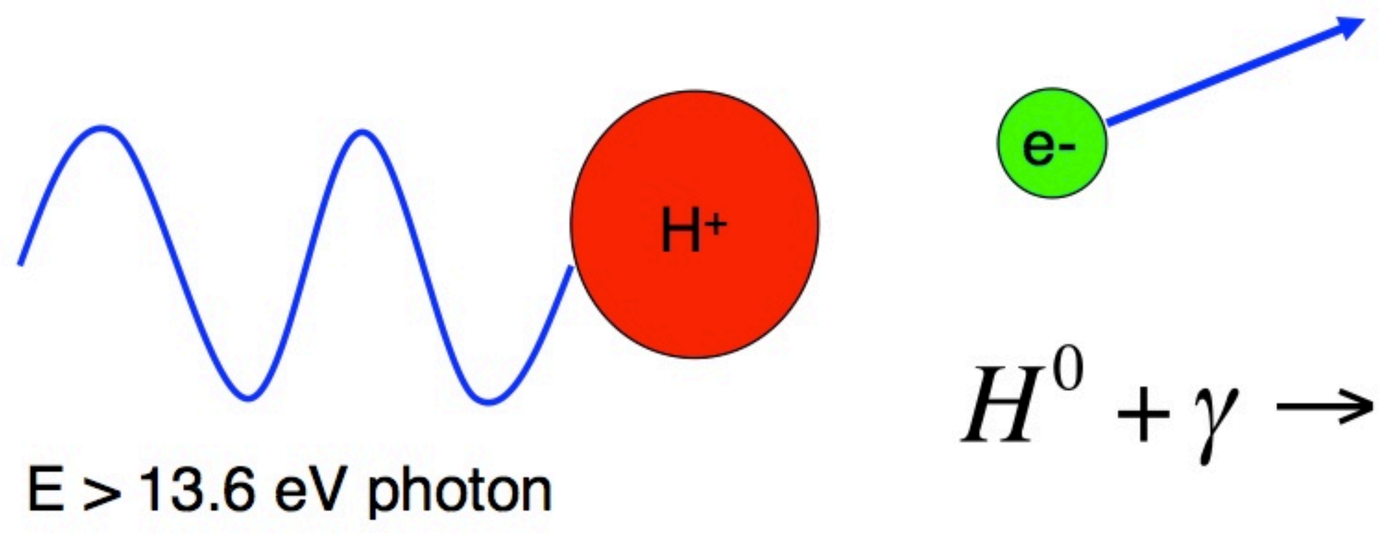
- Timescale on which species evolve:

$$t \sim \left| n \left(\frac{\mathrm{d}n}{\mathrm{d}t} \right)^{-1} \right| \sim \left| n_{\mathrm{e}}(\alpha_{\mathrm{H}_+}(T) - \Gamma_{\mathrm{eH}_0}(T)) - \Gamma_{\gamma\mathrm{H}_0} \right|^{-1}$$

For $z \sim 2,\ J(\nu) \sim \mathrm{few} \times 10^{-22} \mathrm{erg\,s^{-1}\,cm^{-2}\,sr^{-1}\,Hz^{-1}}$

$t \sim$ few x 10^4 years

Photo-heating



$$H^0 + \gamma \rightarrow H^+ + e^-$$

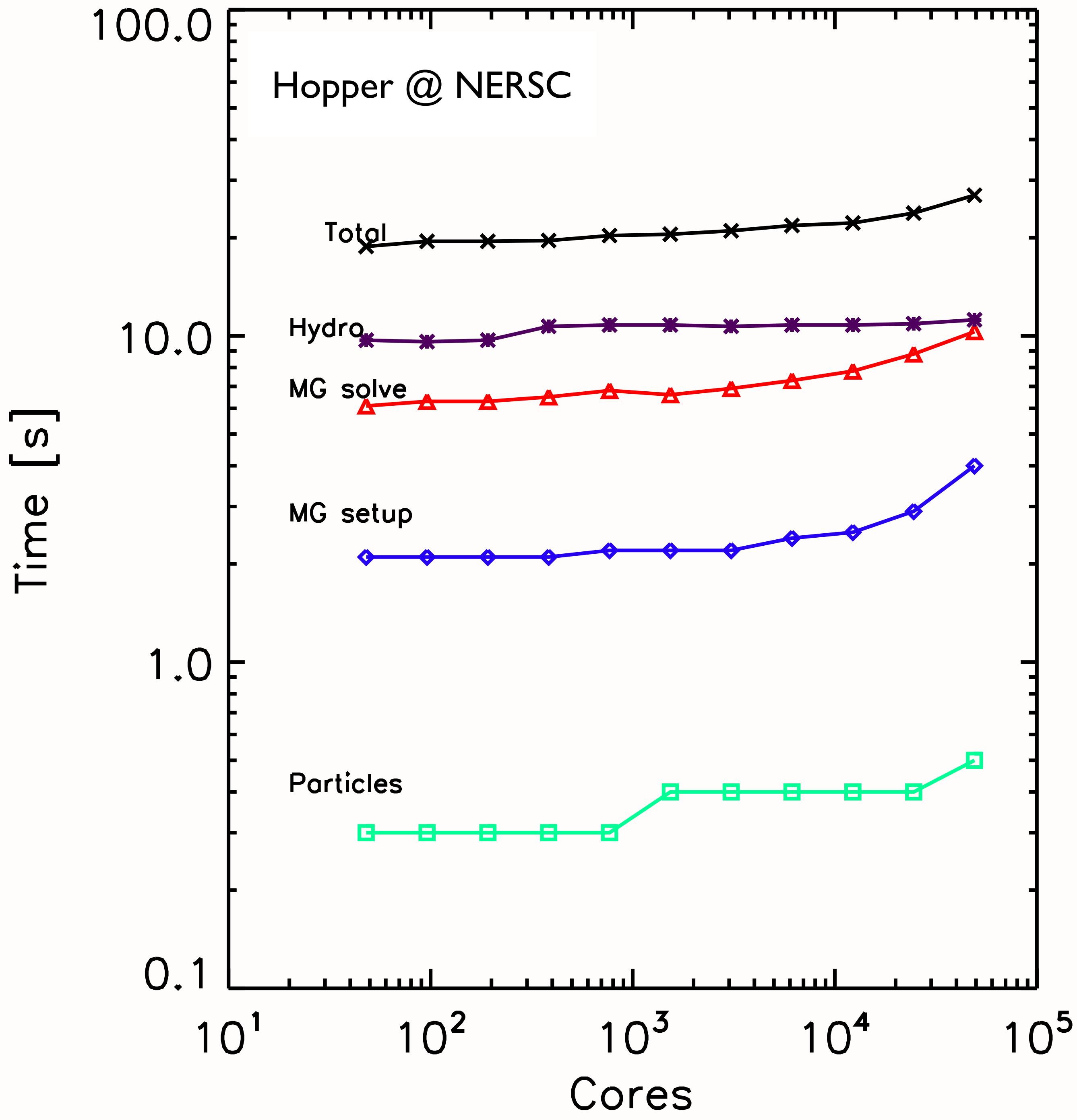
- Mean excess energy of ionizing photon for $J_\nu \propto \nu^{-\beta}$ (Abel & Haehnelt 1999):

$$\langle E \rangle = \frac{h\nu_i}{\beta + 2}$$

- Low density IGM in ionization equilibrium (Miralda-Escudé & Rees 1994):

$$\frac{dT}{dt} = \frac{2}{3k_B} \langle E \rangle \alpha(T) n - 2HT$$

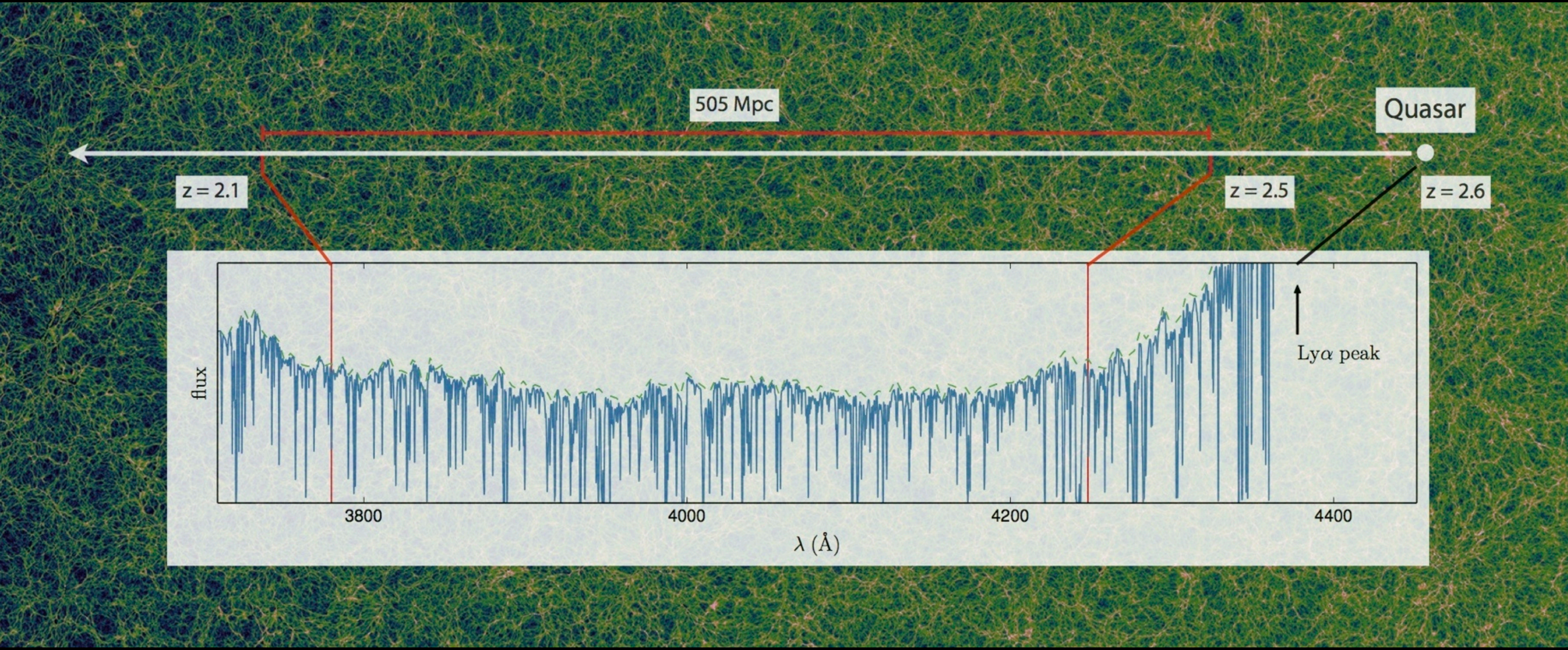
Excellent scaling

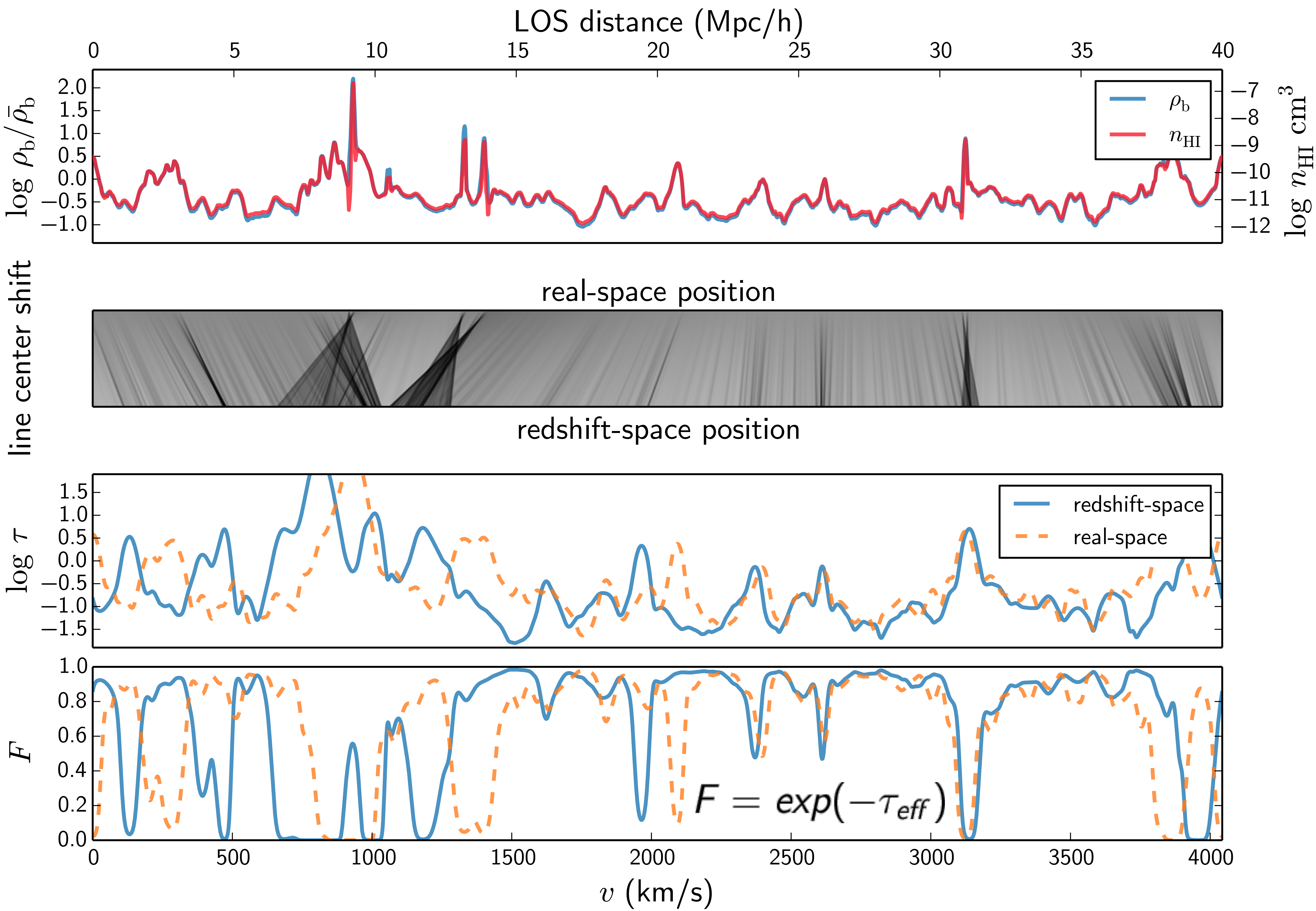


- Currently we are using NERSC resources under ALCC allocation.
- Mostly running 4096^3 simulations now.
- Hopper/Edison: standard cluster architecture, 24 cores on a node, 32/64GB per node, ~5,000 nodes.
- Analysis pipeline on par with simulations.


MIRA
45
CRAY
CRAY
CRAY
CRAY
NERSC
EDISON

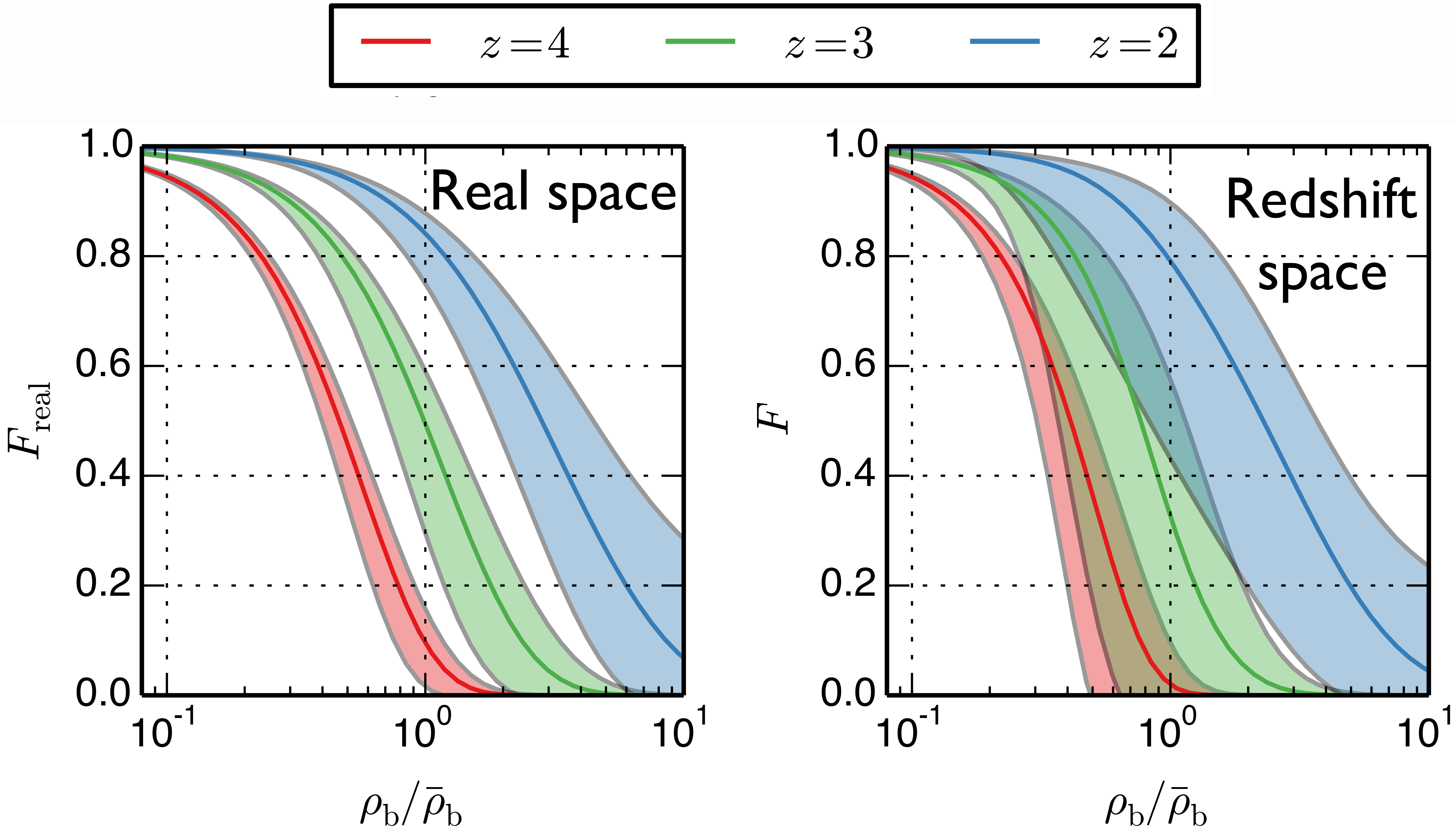
The Lyman-α forest in optically-thin hydro simulations





LOS distance (Mpc/h)
$\log \rho_b/\bar{\rho}_b$
$\log n_{HI}$ cm^3
ρ_b
n_{HI}
line center shift
real-space position
redshift-space position
$\log \tau$
redshift-space
real-space
F
$F = exp(-\tau_{eff})$
v (km/s)

Where the flux comes from



Lukić et al. 2015

Density - temperature

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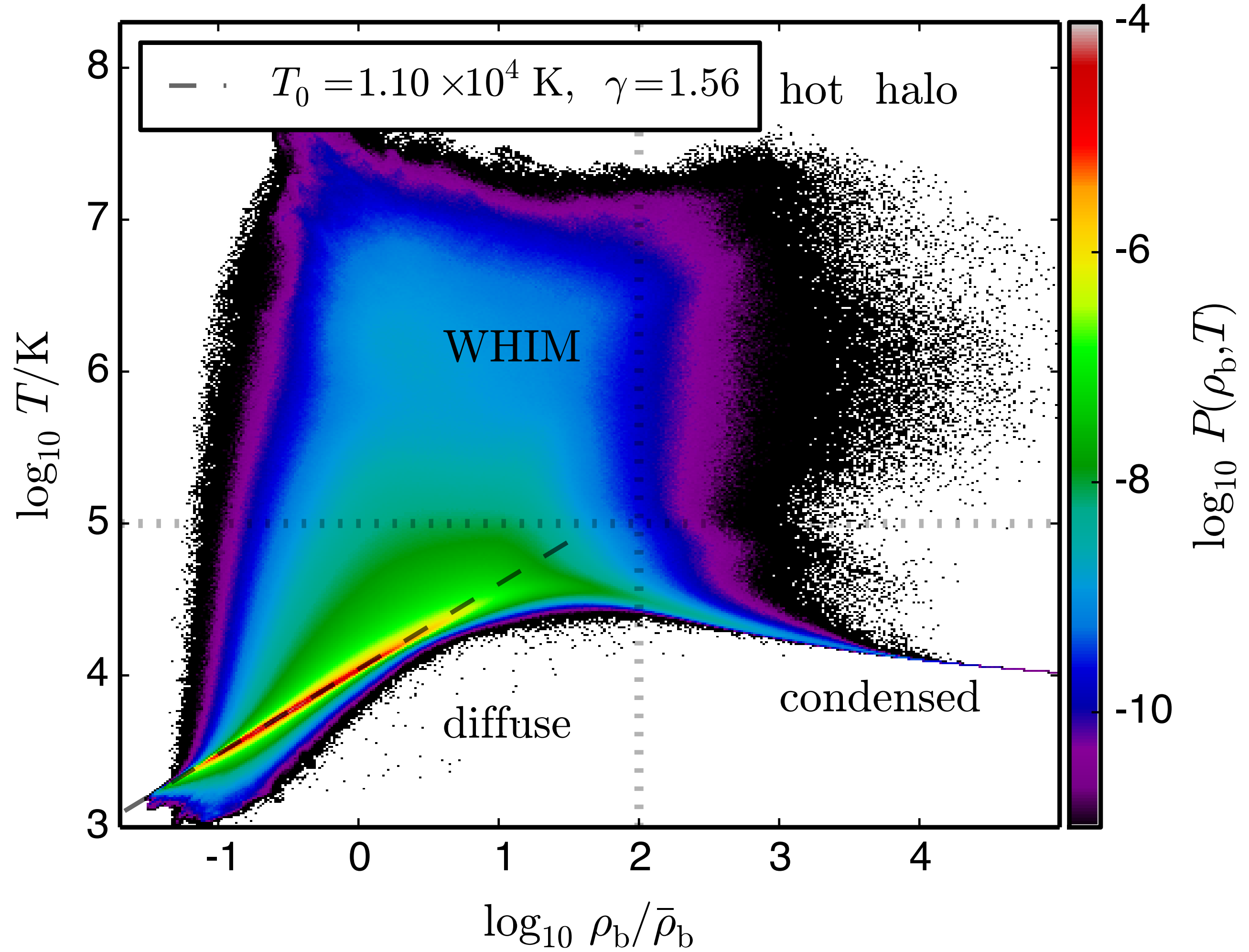
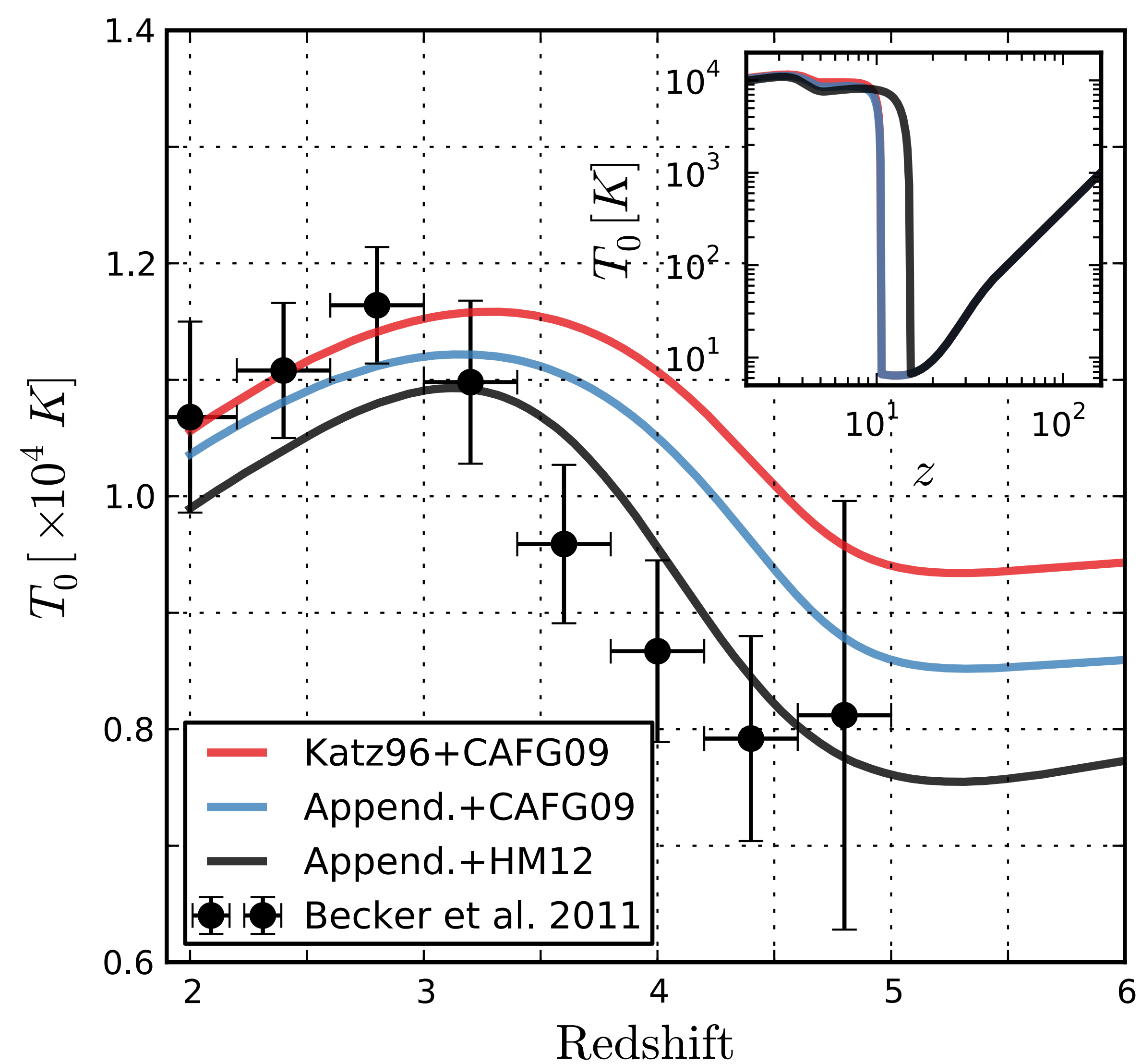


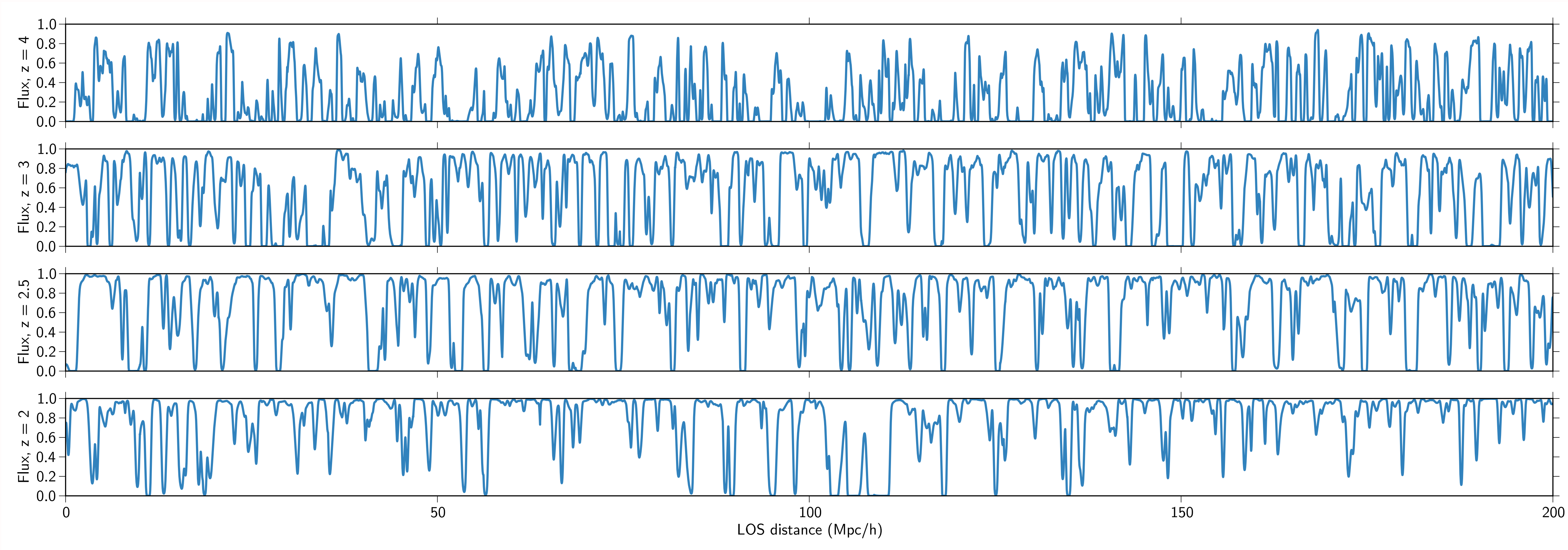
- Optically thin simulations recover basic properties of diffuse IGM



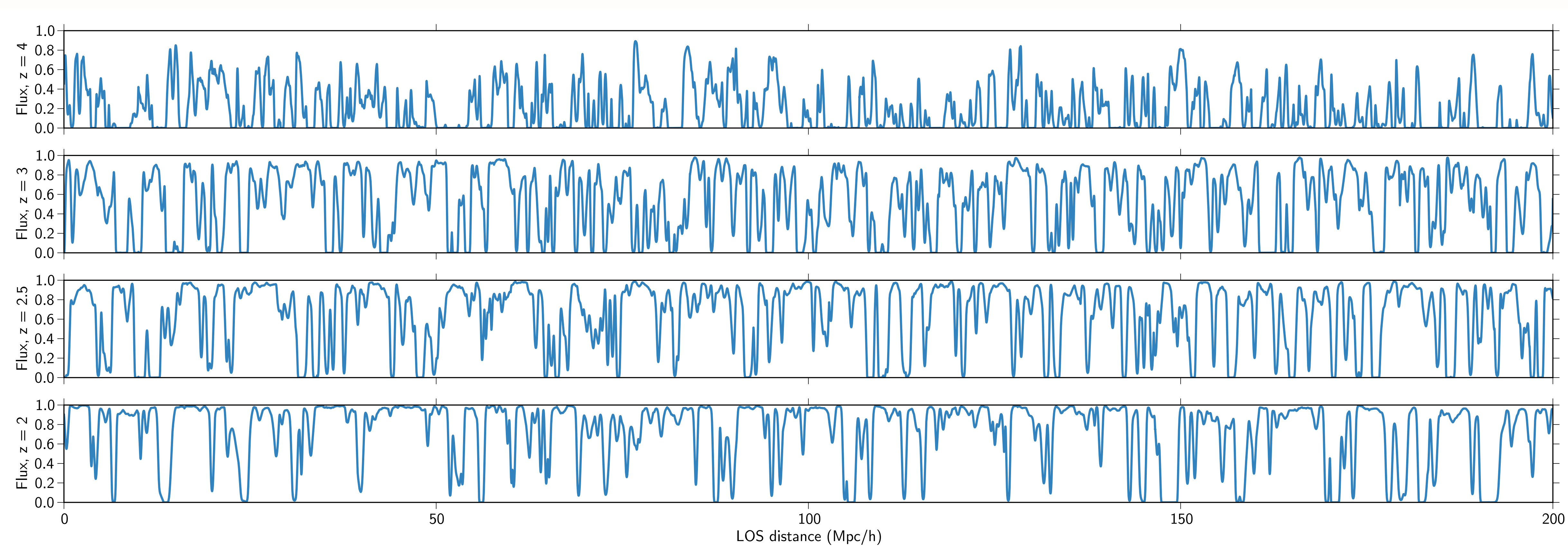
$$T = T_0 \left(\frac{\rho}{\rho_0} \right)^{\gamma - 1}$$

Lukić et al. 2015

σ_8=1.0



σ_8=0.8



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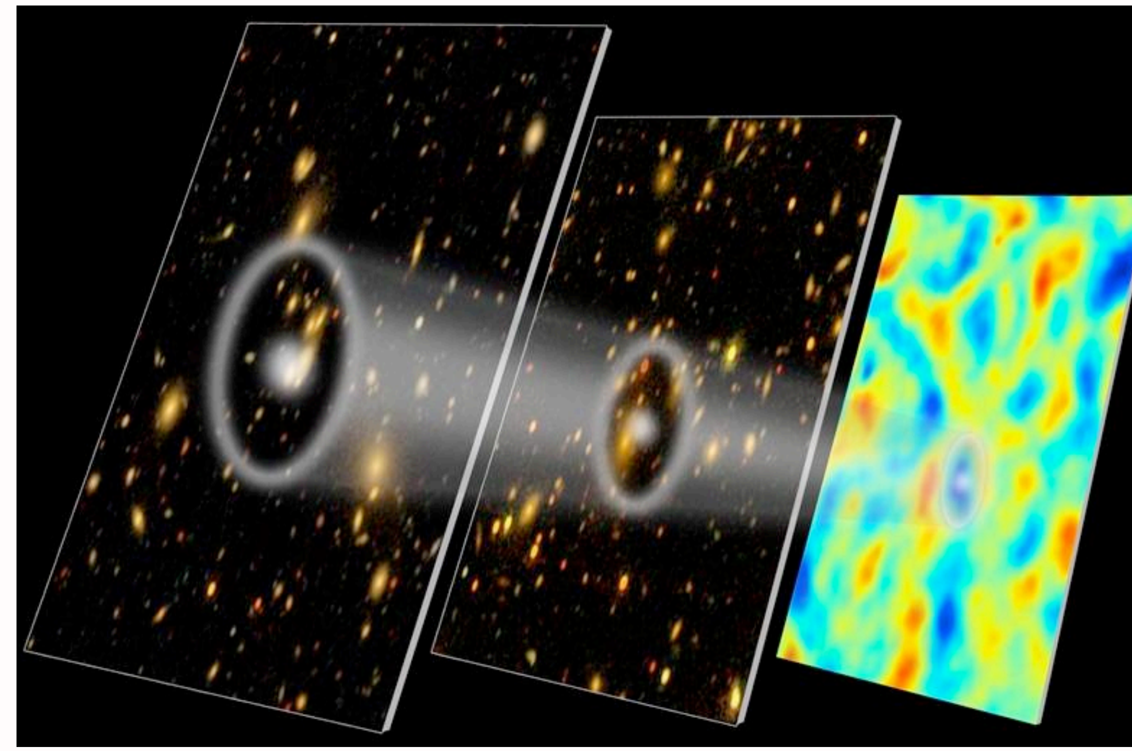
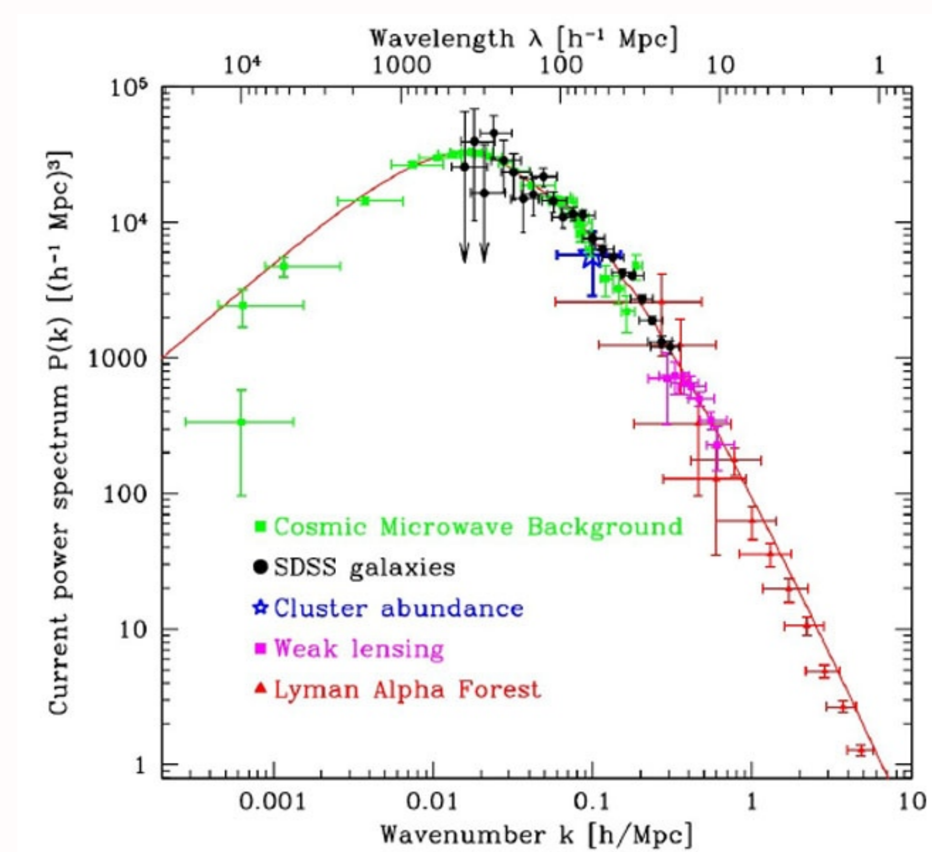
Flux P(k)

- On large scales, Lya flux is a biased tracer of matter. Use BAO to constrain cosmological parameters. Simulations of limited value.



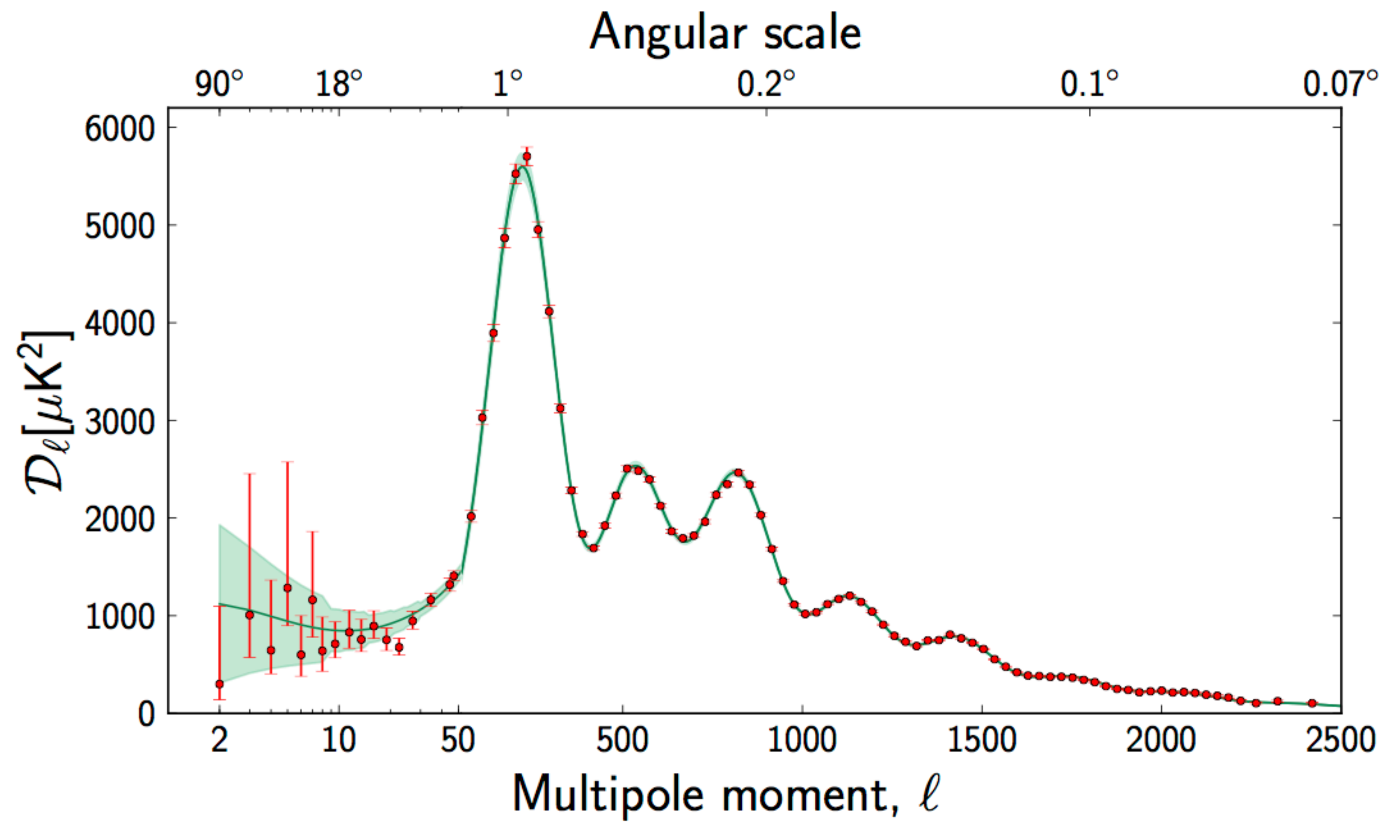
- On small scales, Lya flux P(k) can be modeled from first principles. Handle on neutrino mass, warm dark matter, inflation... Simulations essential.



Large scales: BAO

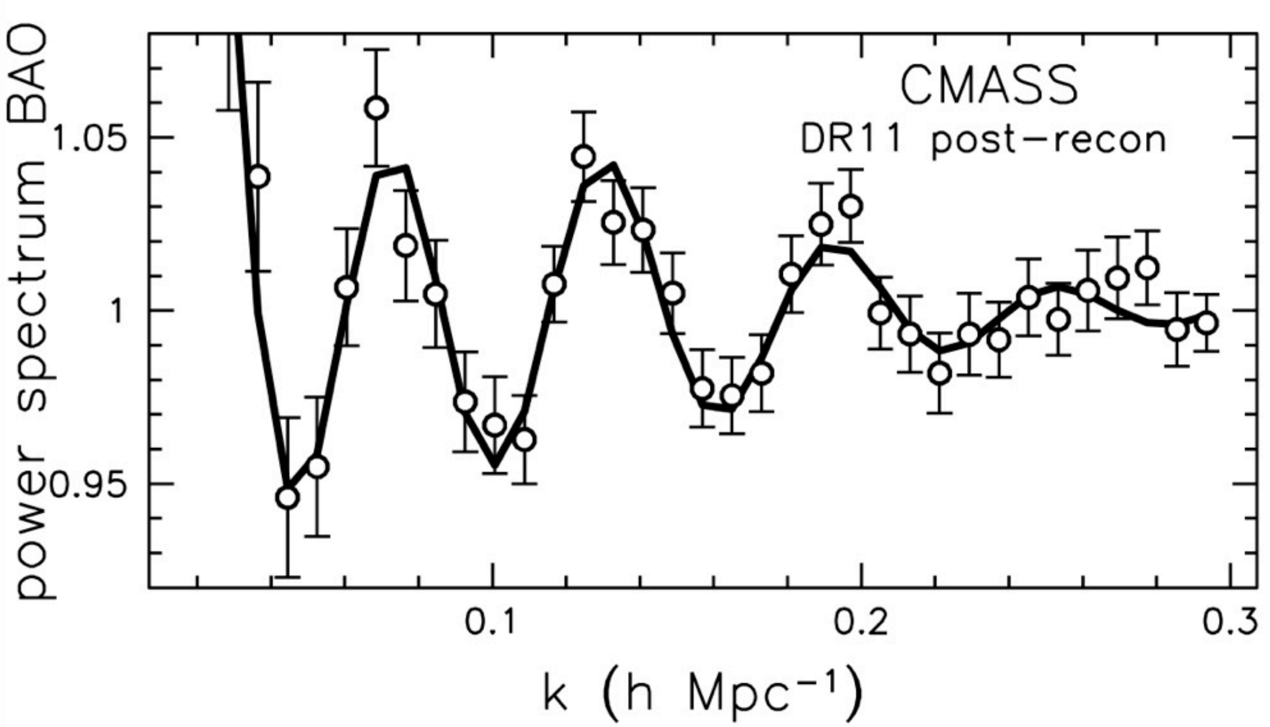
- CMB, z~1000

(Planck collaboration)



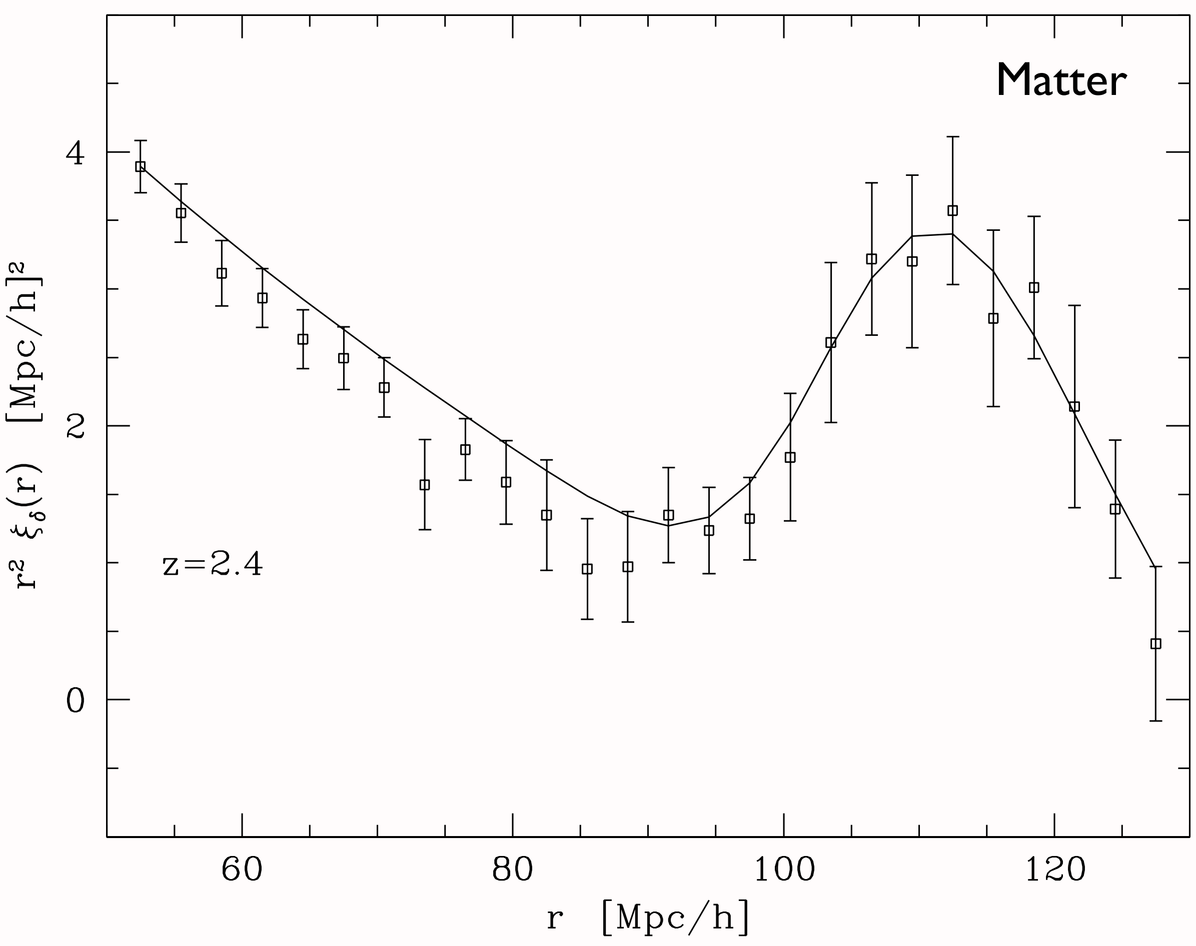
- Galaxies, z~0.5

(BOSS, Anderson et al. 2014)

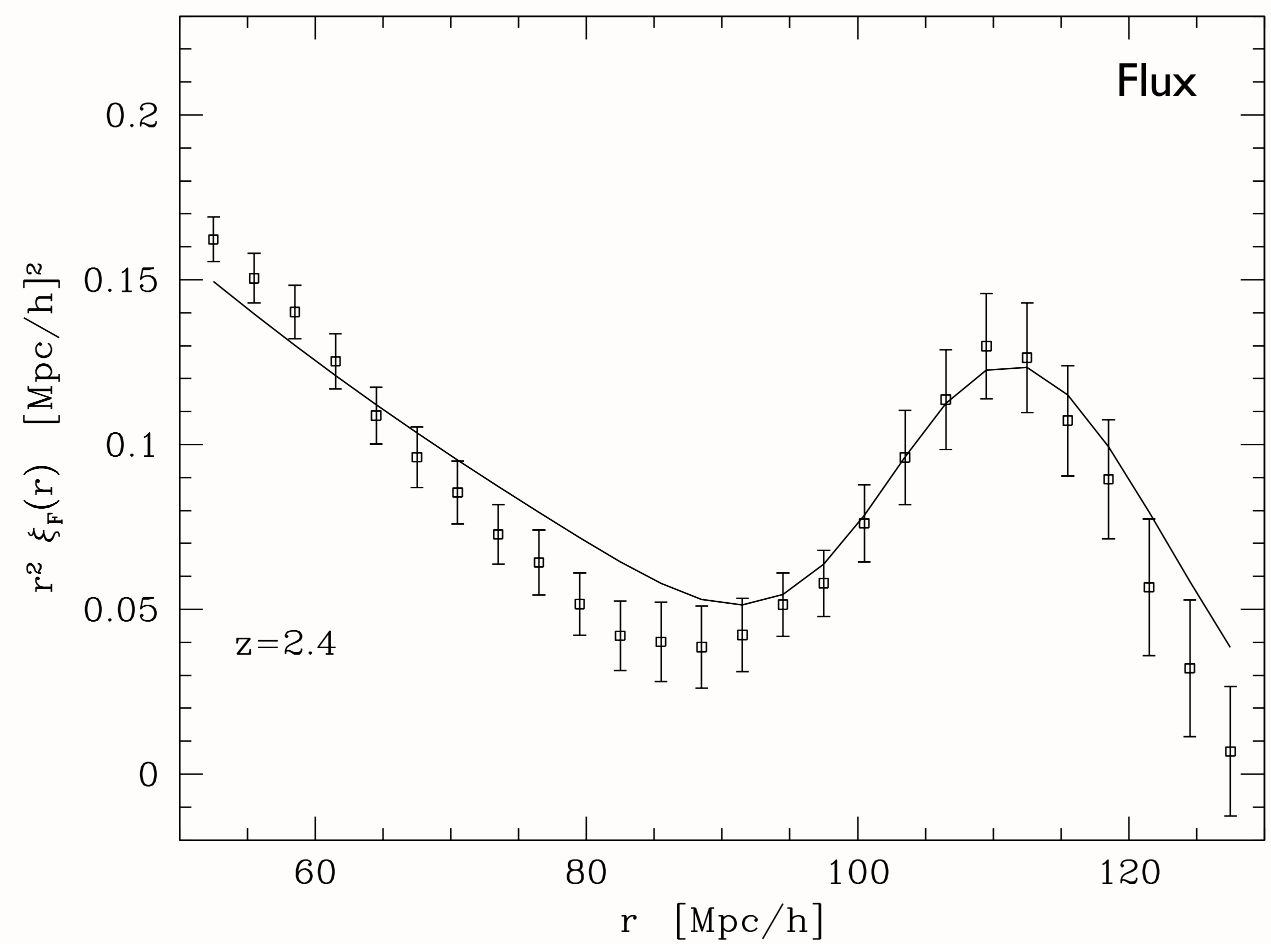


BAO

- Different redshift range with Ly-a: 2<z<5
- Roadrunner, gravity only simulations: 750 Mpc/h box, 4000^3 particles/grid



White et al. (2010)



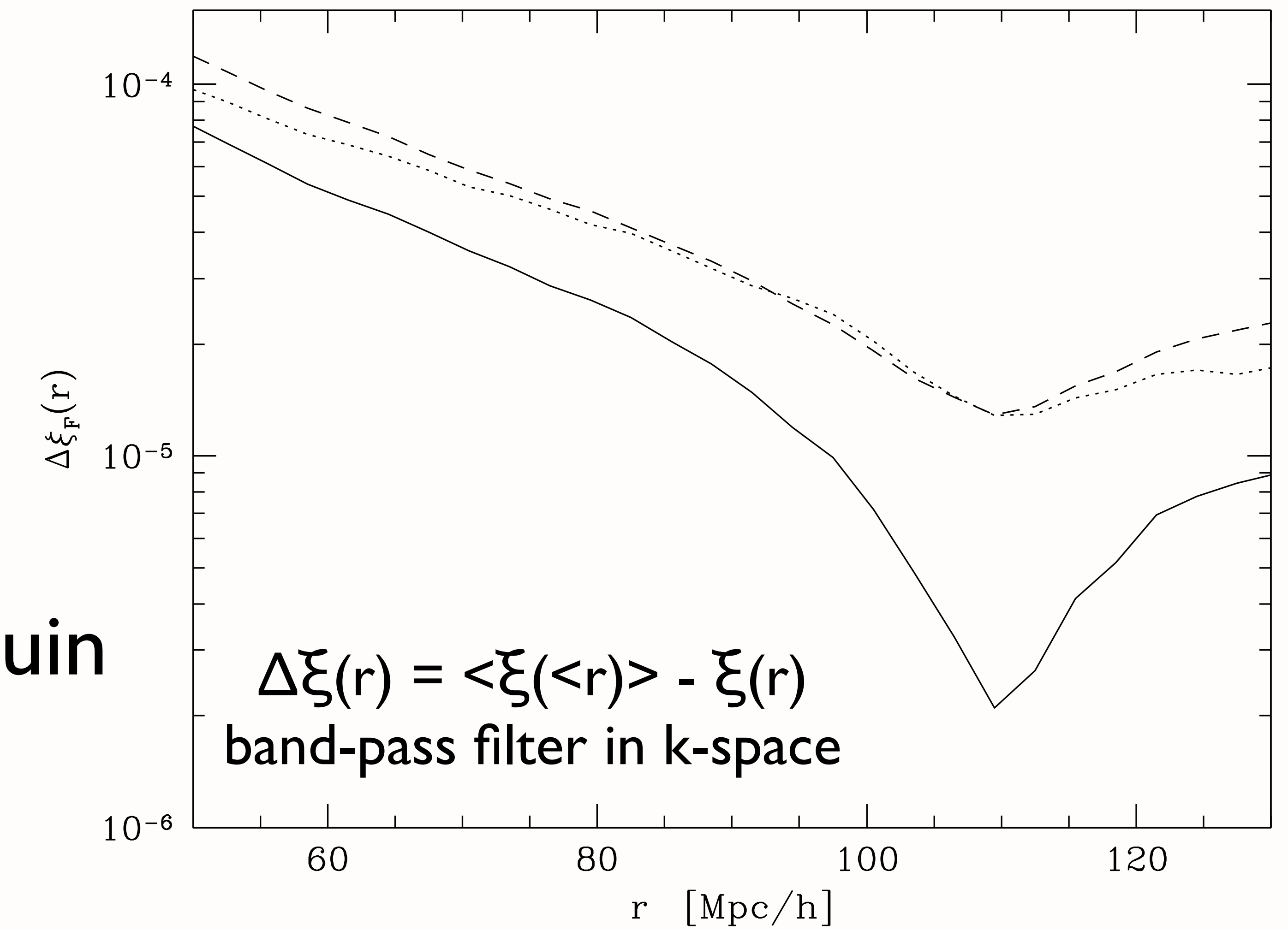
Non-grav. contribution

1. Fluctuations in ionizing radiation:

   Place quasars at random, assign luminosities, assume isotropic emission.

$$\Phi \propto \frac{1}{(L/L_*)^{-\alpha} + (L/L_*)^{-\beta}}$$ (Croom et al. 2004)

$$\Gamma_i \propto L_i \frac{e^{-r_i/r_0}}{4\pi r_i^2}$$ (Meiksin & White 2004)

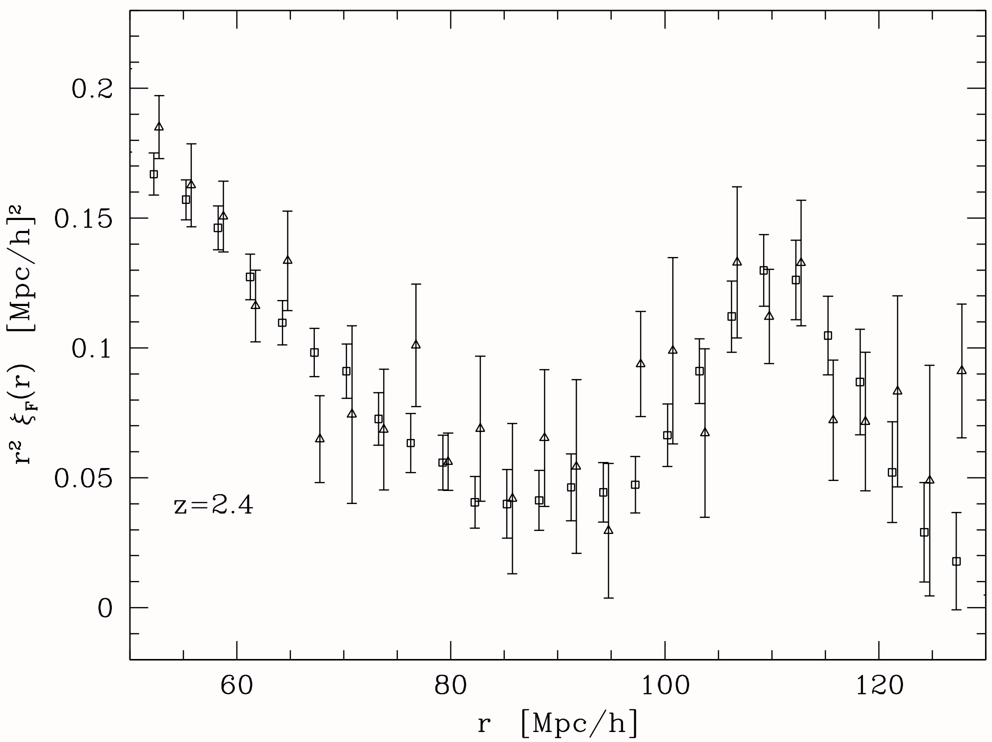


2. IGM temperature

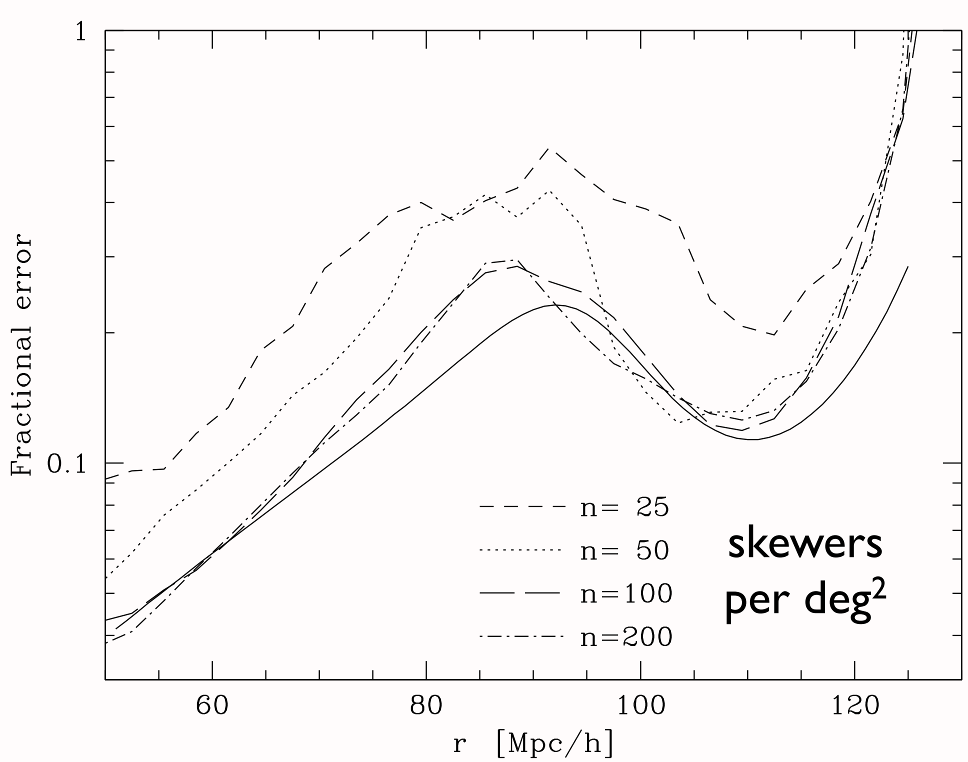
   HeII reionization at z~3 (McQuin et al. 2009...)

   T_0 from log-normal dist.

Simulating BAO peak



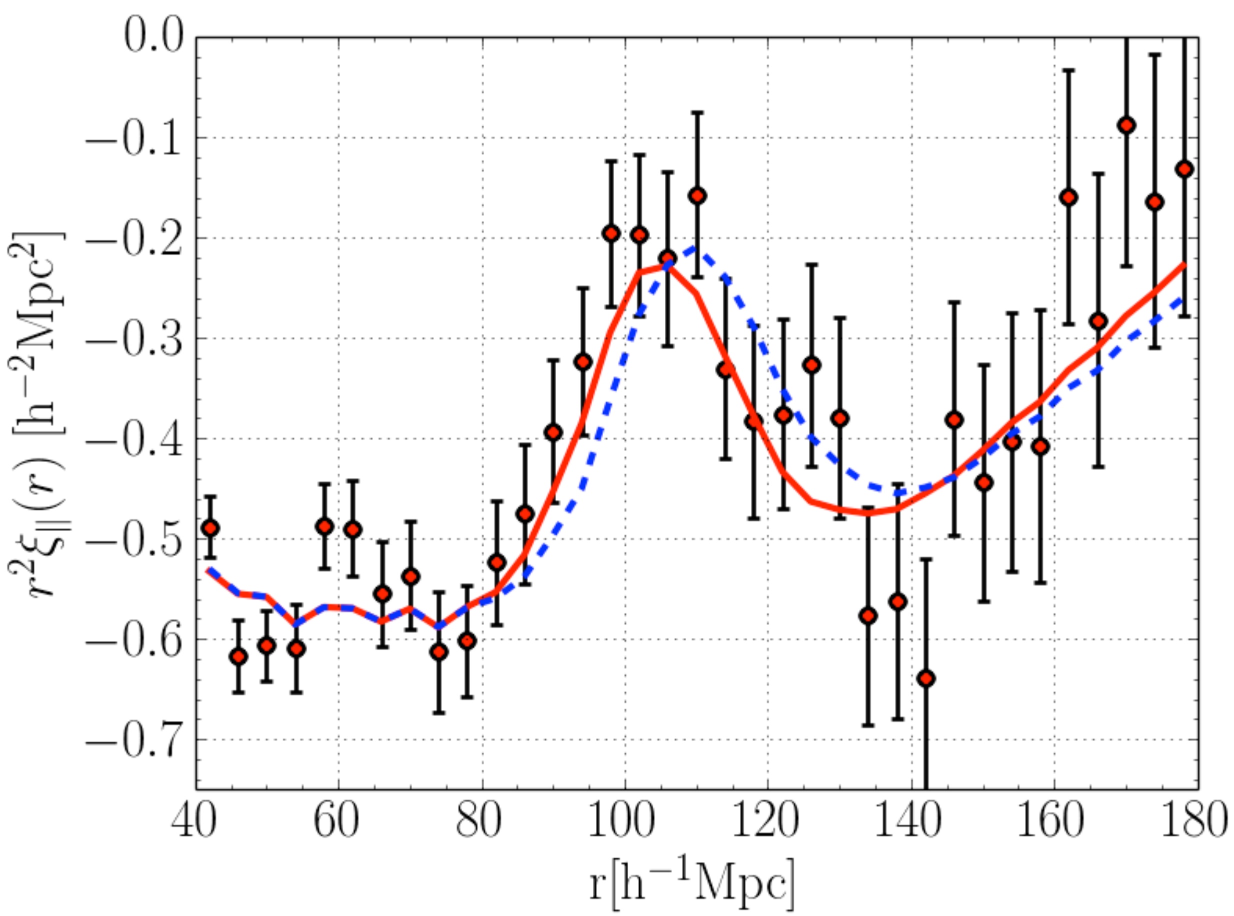
- Adding uncorrelated Gaussian noise



- Change in LOS areal density: saturation at 50-100 deg^{-2}; B-band m~23 cutoff

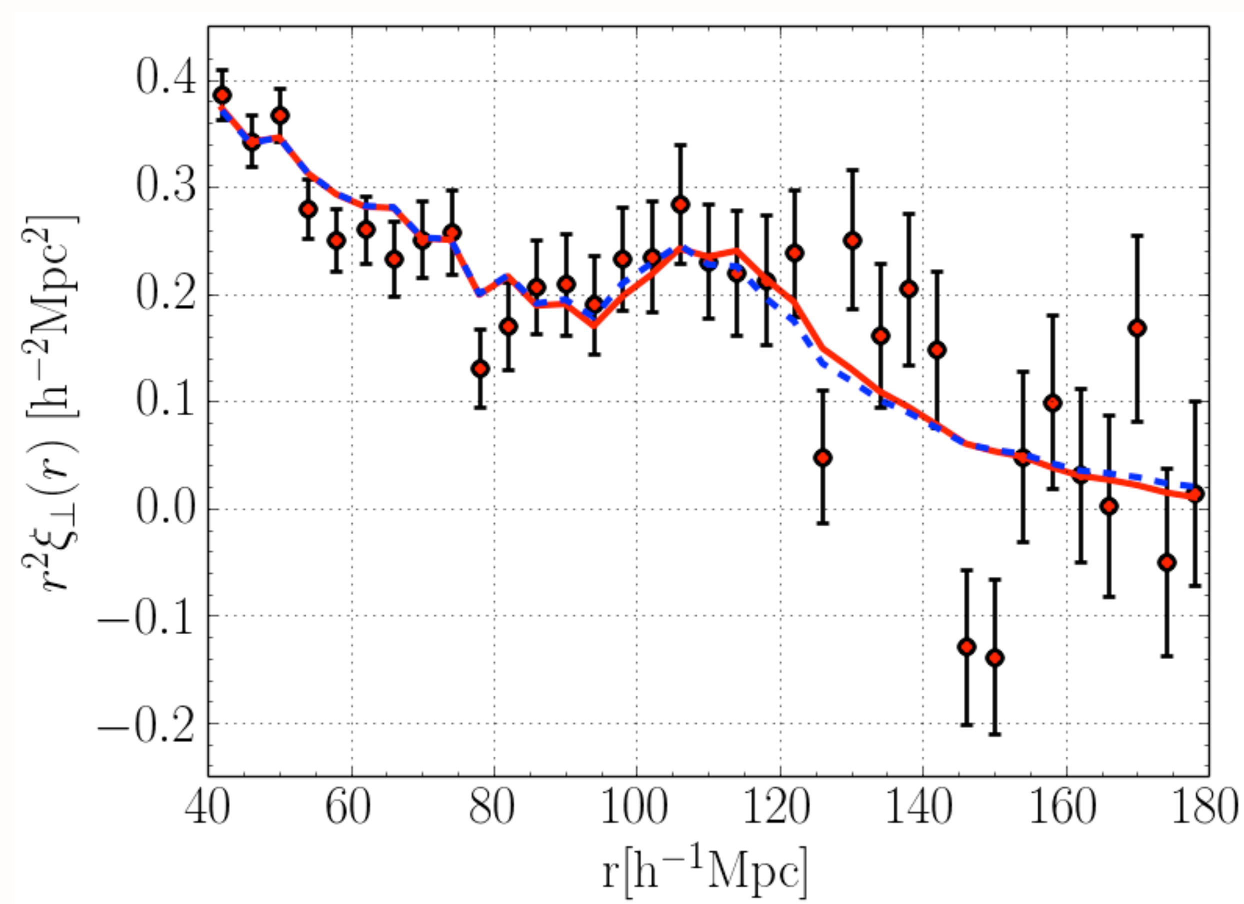
Matches MS-DESI

Measurement

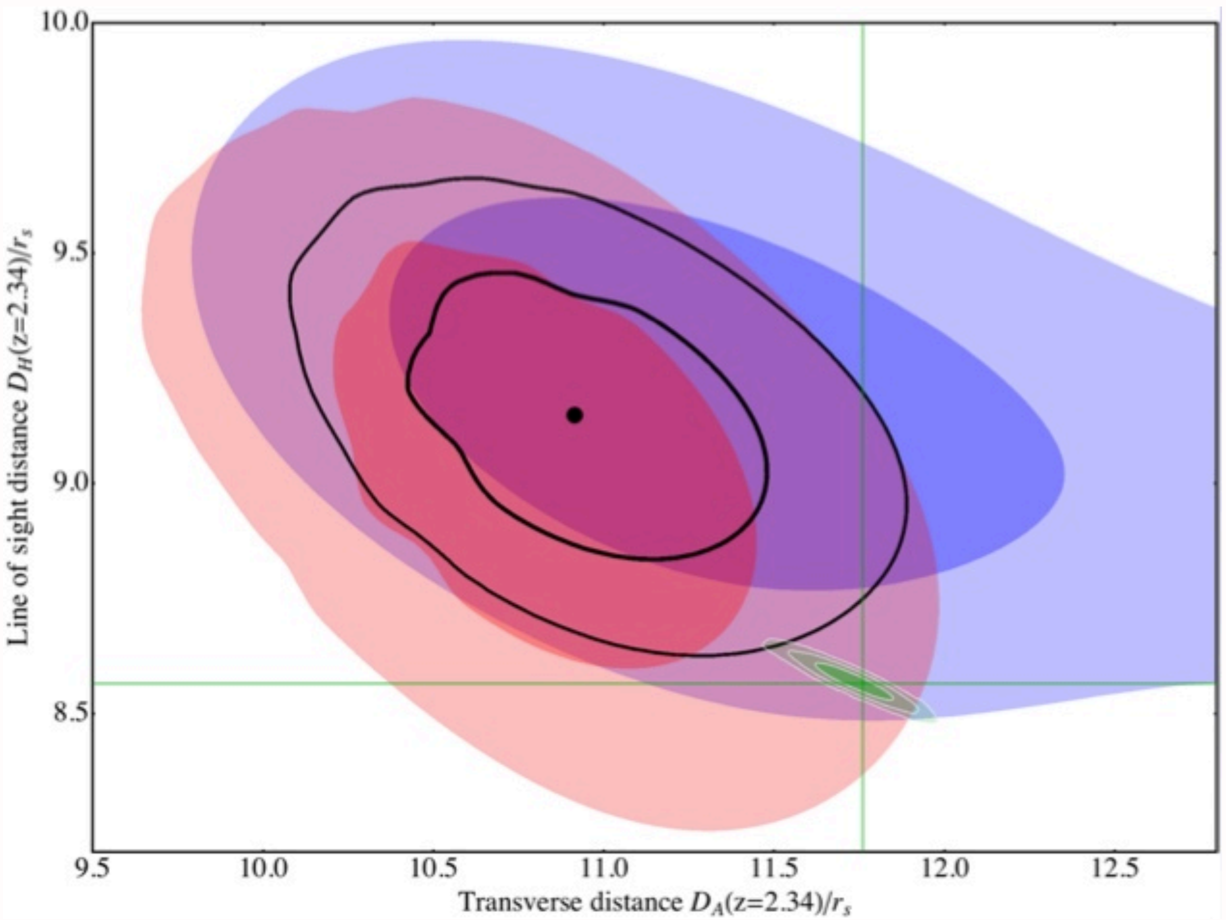


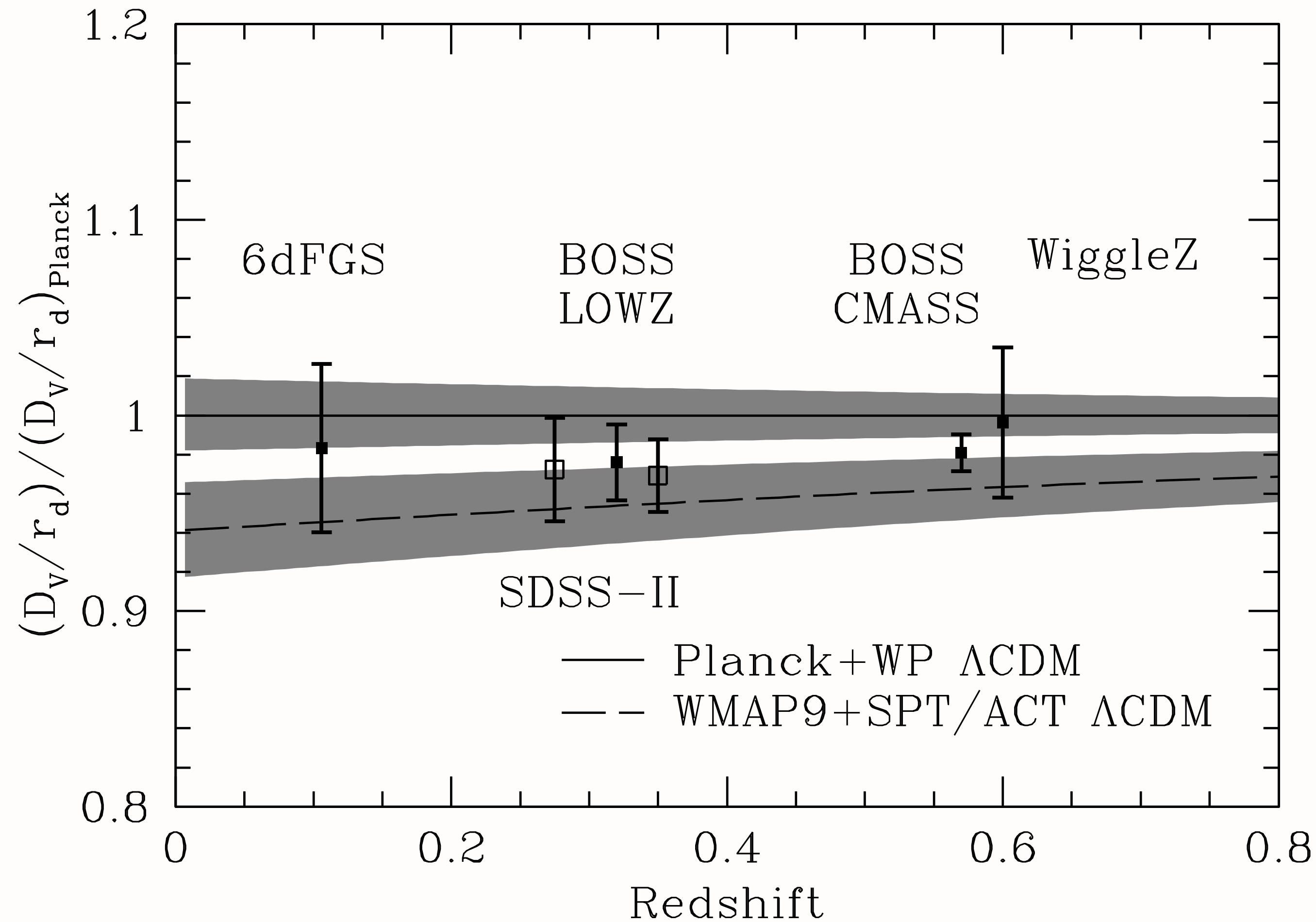
BOSS Ly-a BAO:

Delubac et al. 2014



Ly-a tension

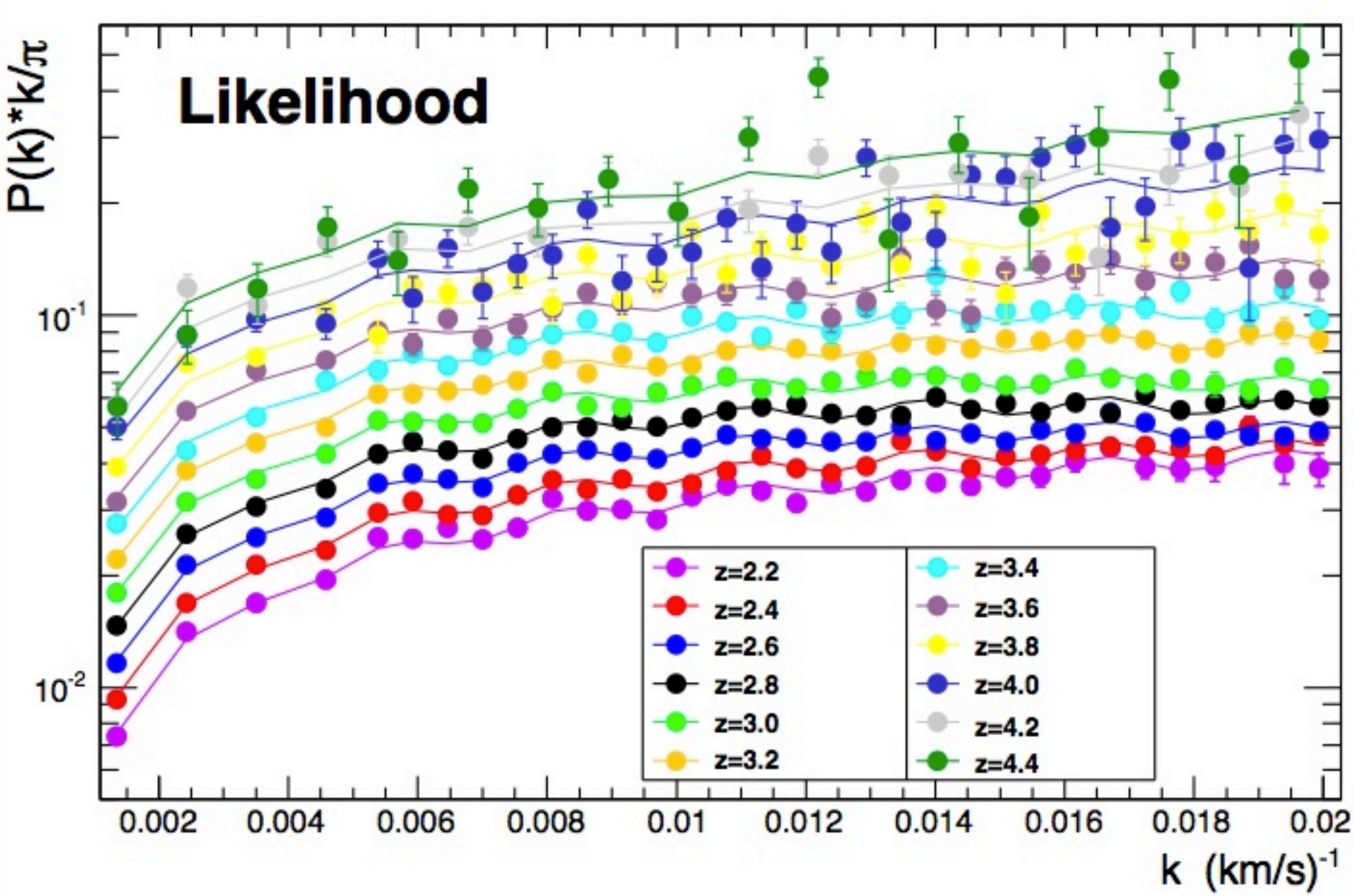




LyA: Delubac et al. 2014 + Font-Ribera et al. 2014

Galaxies: Anderson et al. 2014

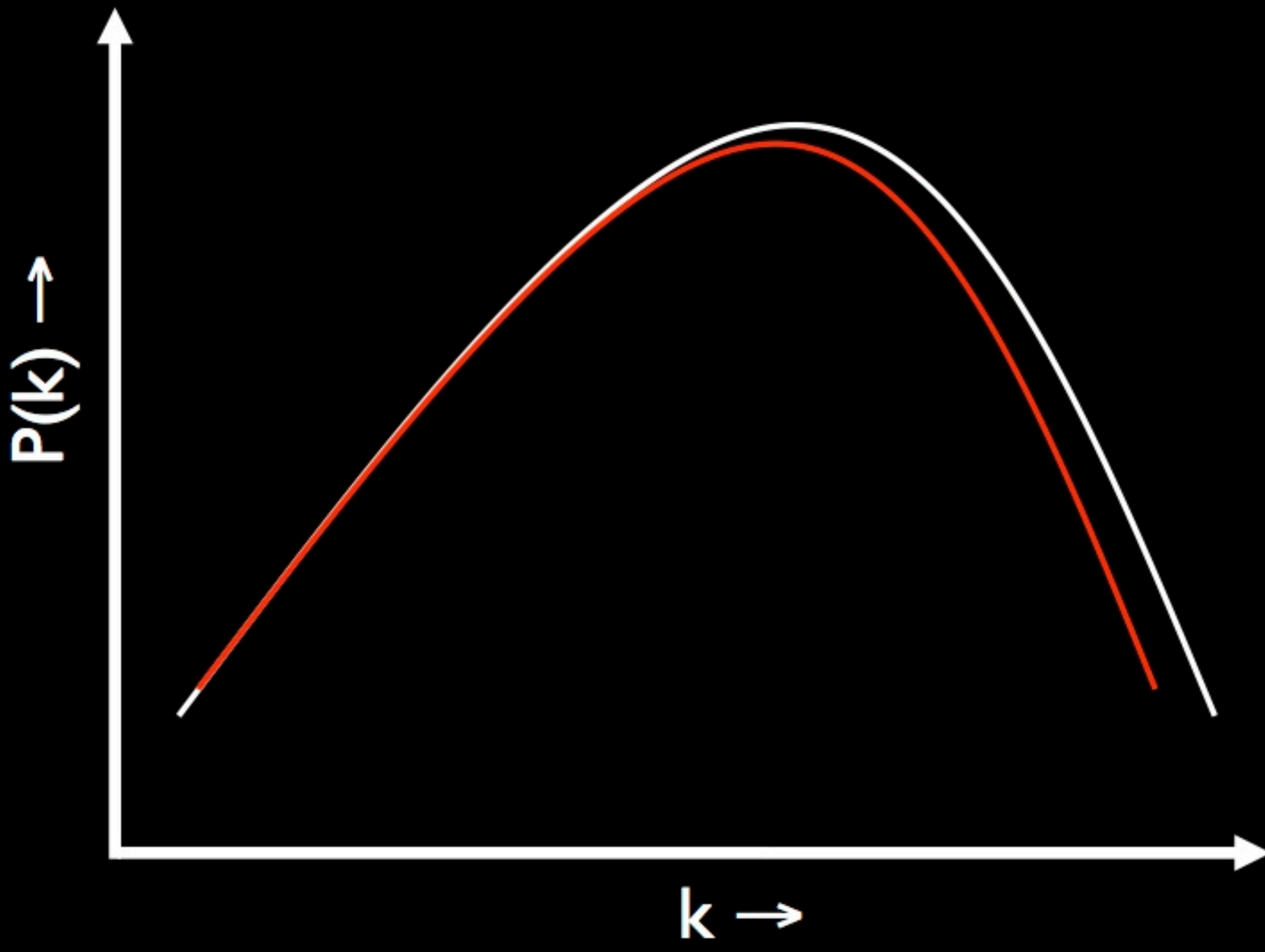
Small scales: 1D P(k)



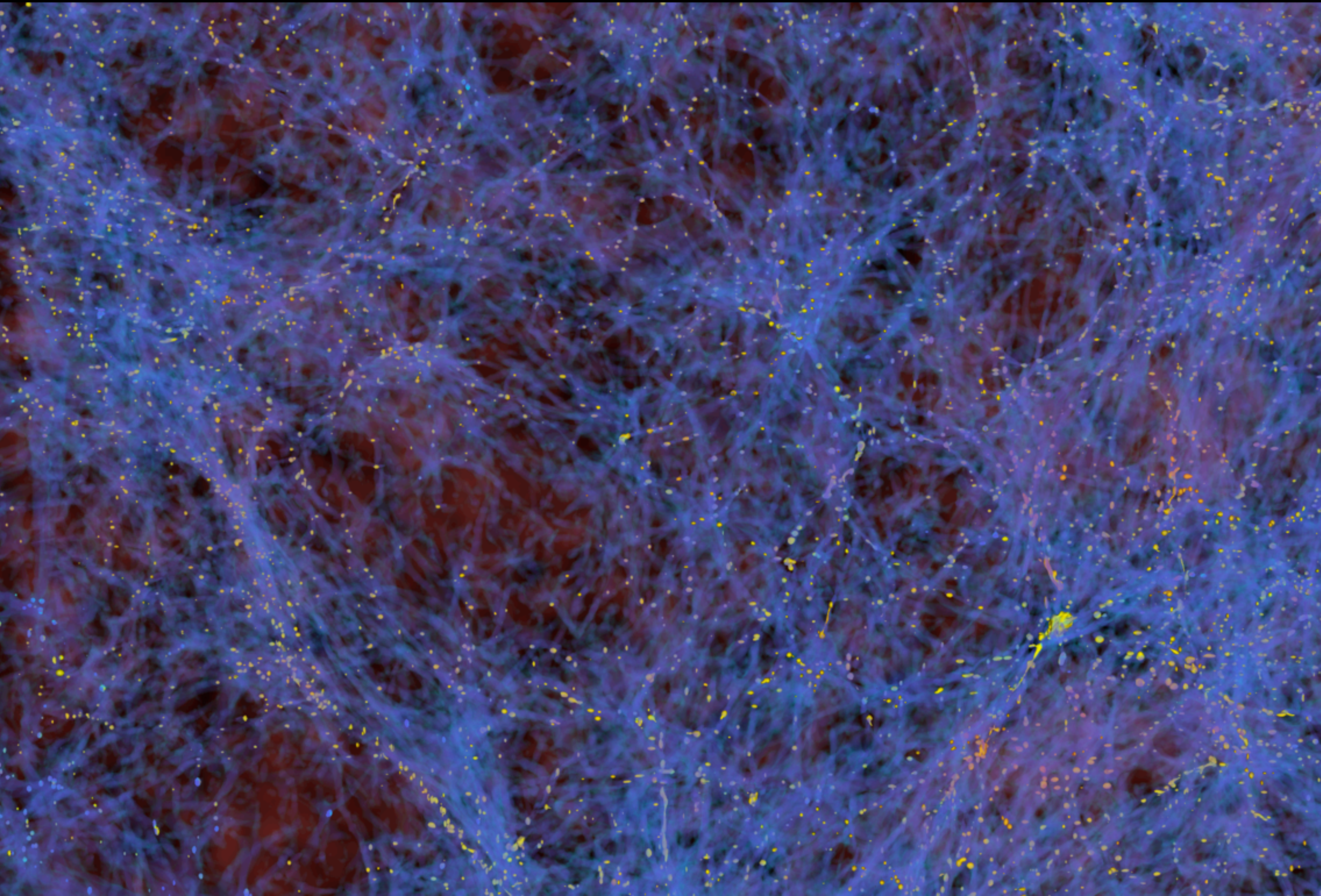
BOSS, Palanque-Delabrouille et al. 2013

the interesting things are

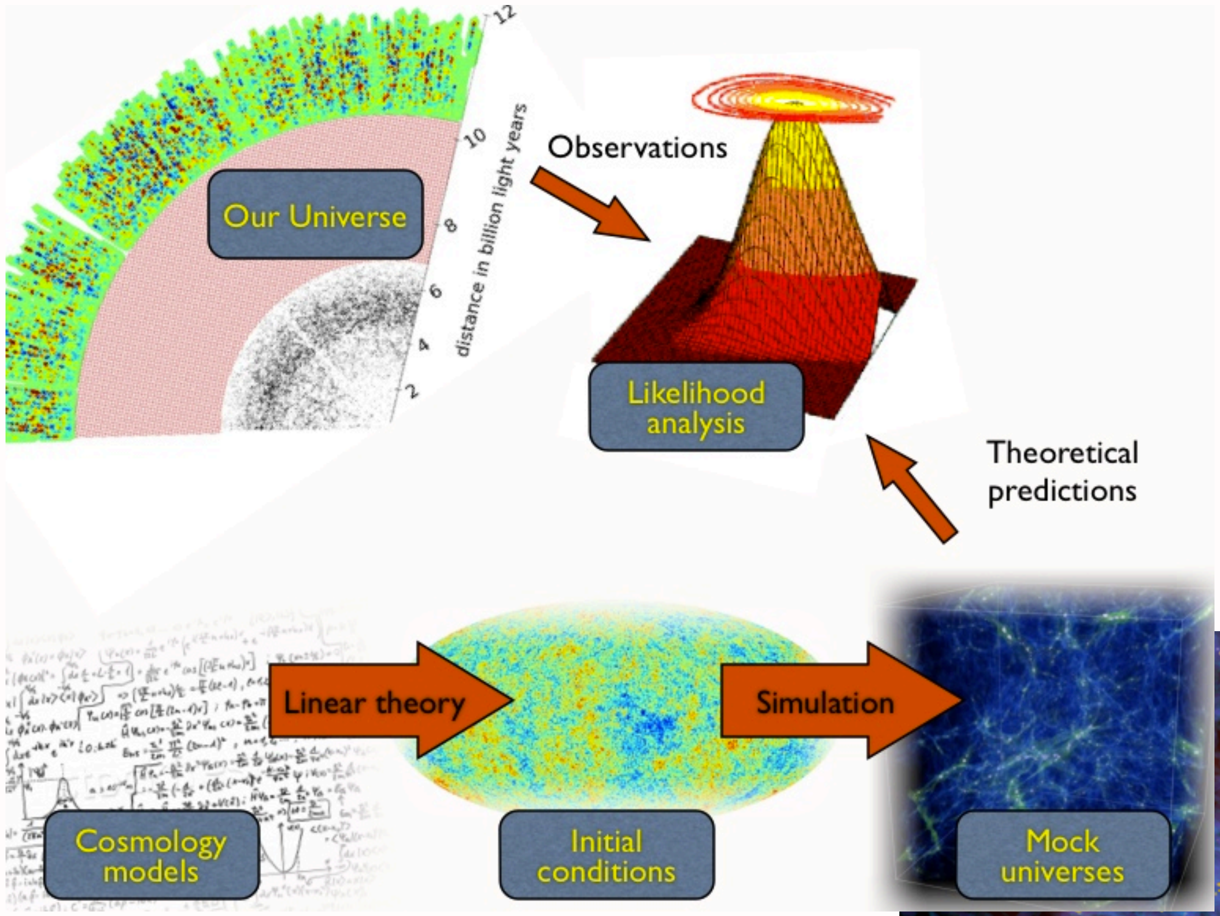
masses of neutrinos
warm dark matter
running of the spectral index...



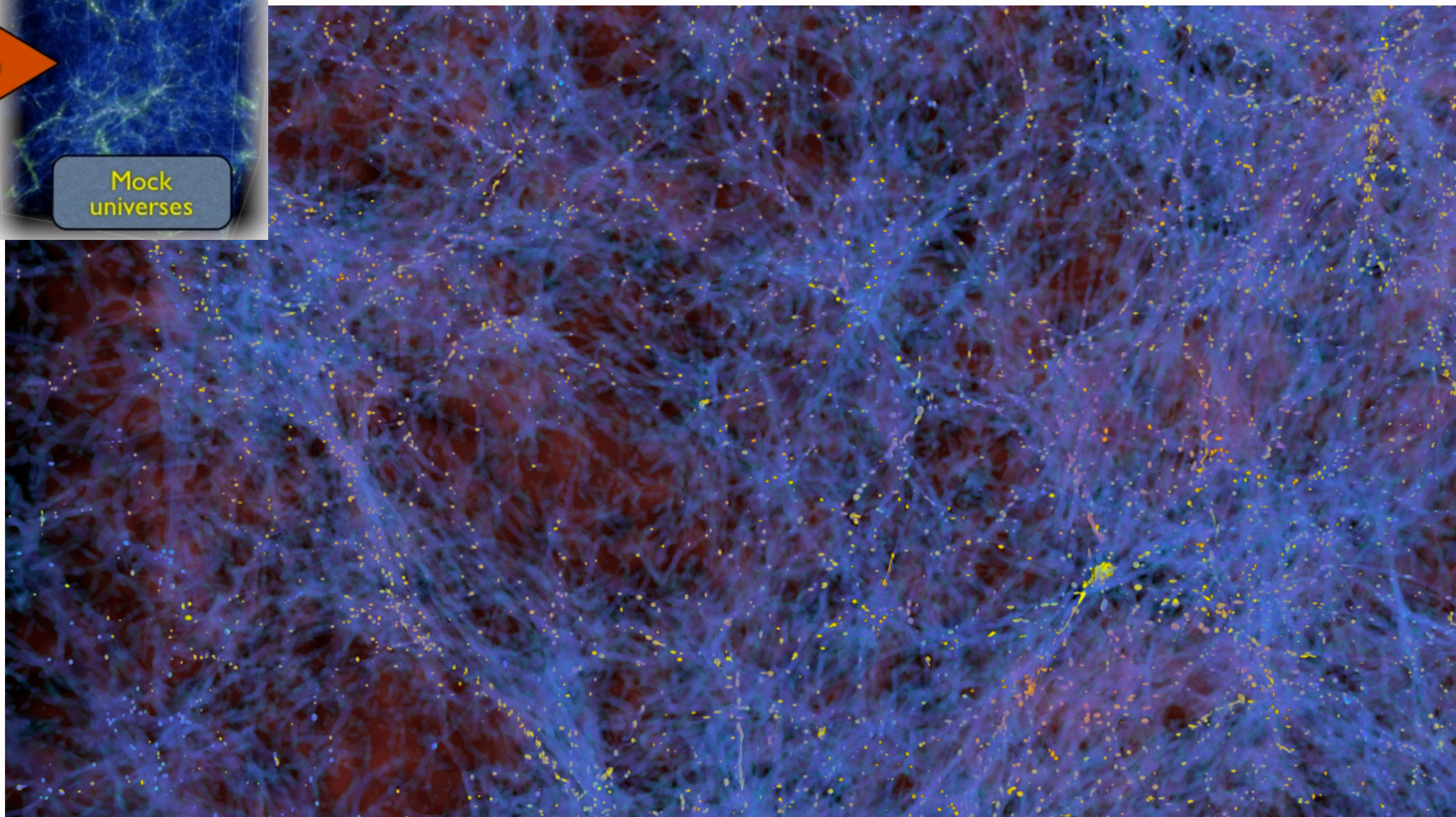
4096^3 hydro simulation (~100 Mpc/h) Blue: F~0; Red: F~1



Ongoing work



- Building an emulator with "gold standard" simulations.



Summary

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- Ly-α BAO better developed than high-end P(k), but arguably less interesting.
- Ly-α BAO exhibits some tension (~2.5 σ) with the "concordance" ΛCDM.
- 1D P(k) promise for constraining neutrino mass and running.
- We have developed Nyx code (improved applied math engine, good scaling wrt number of processors).
- Currently running 4096^3 hydro simulations.
- First cosmological constrains on the way.