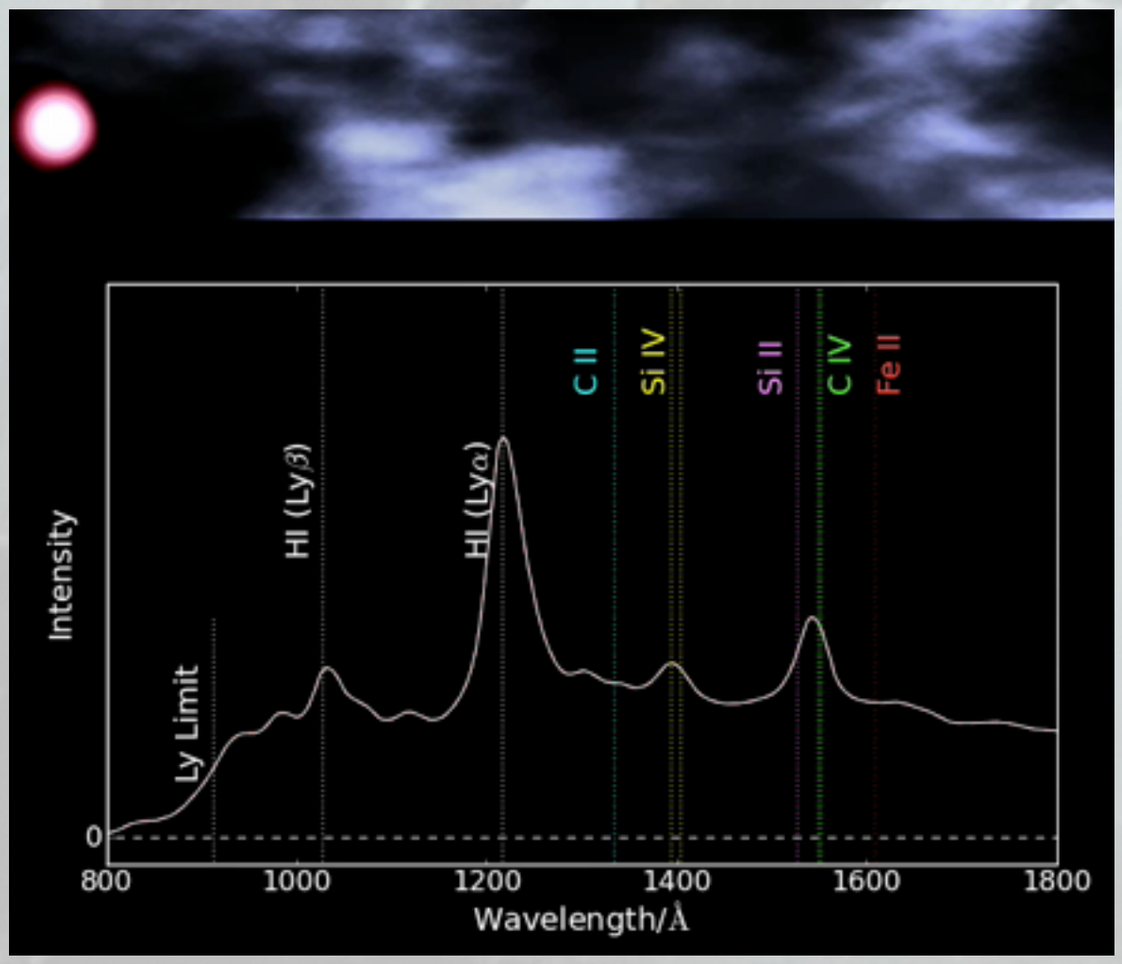
Multi-Object Spectroscopy in the Next Decade, La Palma, 5th March 2015

Cosmology with Massive Intergalactic Medium Surveys: Past, Present and Future

Mat Pieri

with the BOSS, eBOSS, DESI and WEAVE

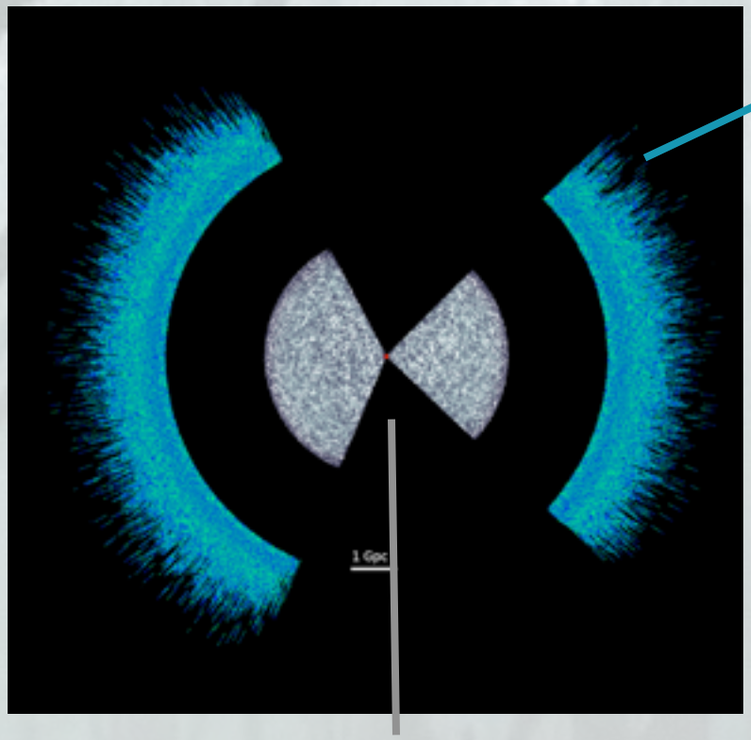
Quasar Spectra and Lyman α Forest

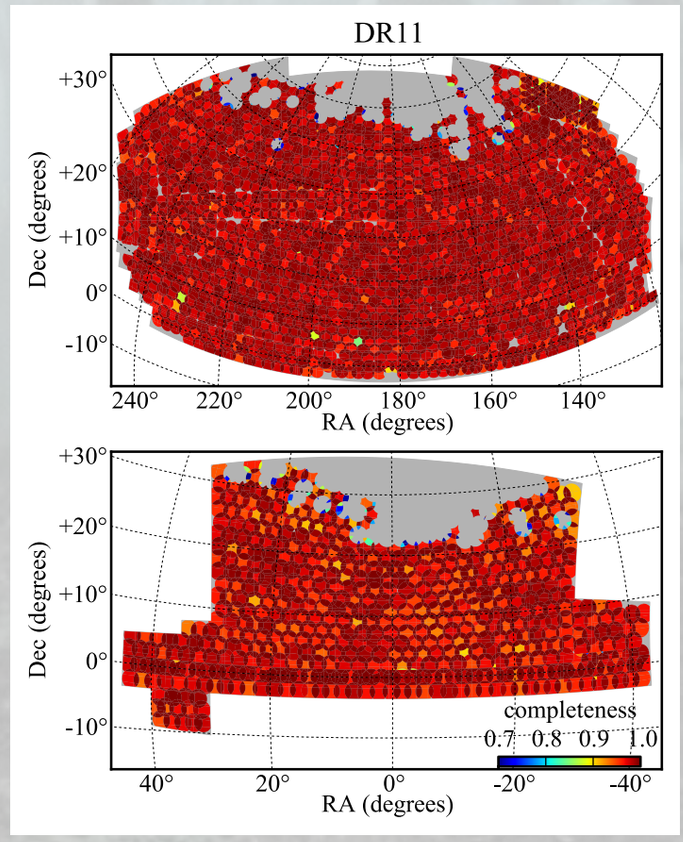


- Line-of-sight probe
- Gas with $1 \lesssim \frac{\rho}{\bar{\rho}} \lesssim 10$
  - traces dark matter on large scales
  - Largely photoionized
    - $\tau_{\rm HI} \propto \rho_{\rm H}^{0.4}$ and $F = Ce^{-\tau_{\rm HI}}$ and $F = CF = Ce^{-\tau_{\rm HI}}$
  - Departures from this
    - UV background modulation
    - Strong lines
    - Small scale physics
    - Metal lines

Baryon Oscillation Spectroscopic Survey (BOSS)

- 1 of 4 in SDSS-III 2009-2014
- 10k deg^2
- Goal: 1.6M galaxies and >150k forest quasars
- Resolution R = 2000



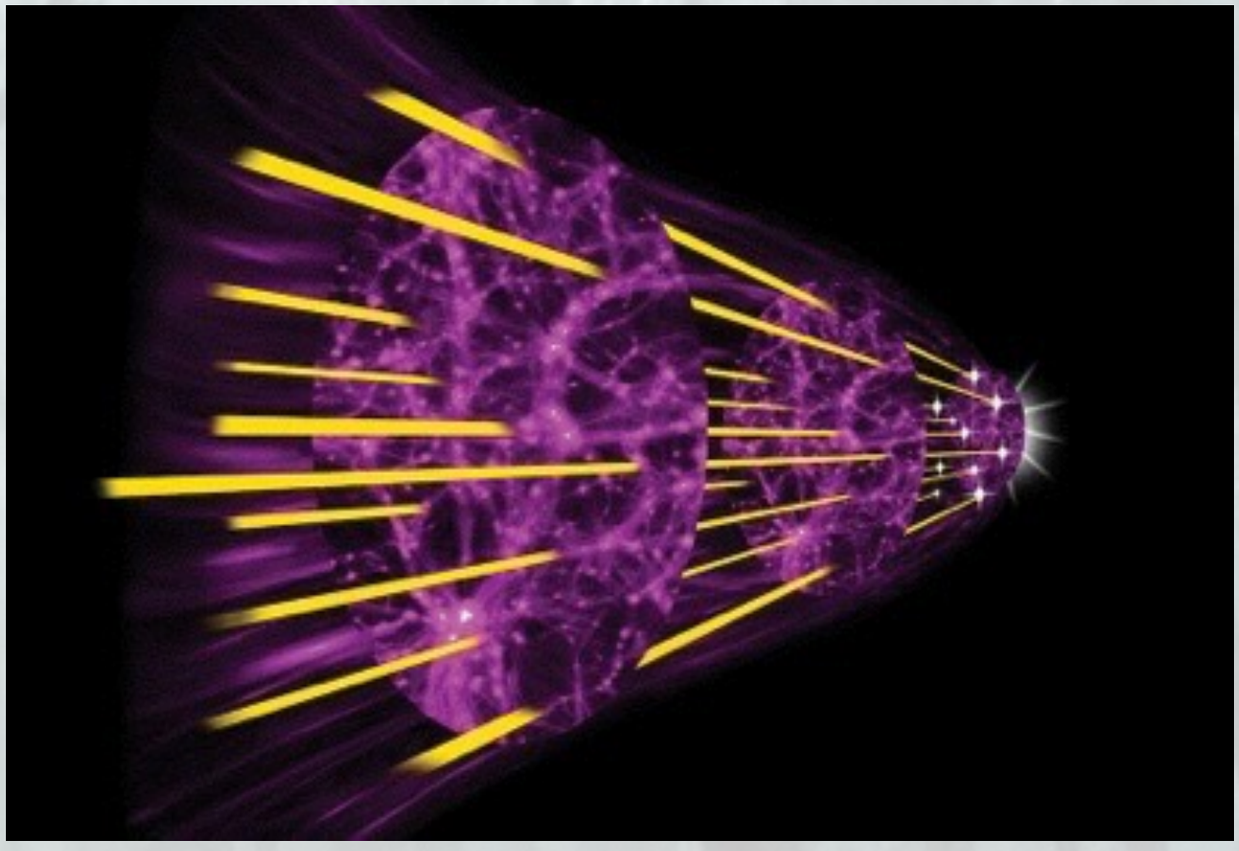


Final BOSS Lyα forest survey (DR12):

- 158k quasars with z > 2.15
- Final analysis on the way

Measuring Structure in BOSS-LyαF

- Along LOS - only small-scales (e.g. *Palanque-Delabrouille et al 2013*)
- Measure correlation between lines of sight (*Slosar et al. 2011*)
- BAO 1st measurement last year *Busca et al. (2013) and Slosar et al. (2013)*



Updated DR11 results in *Delubac et al (2014)*

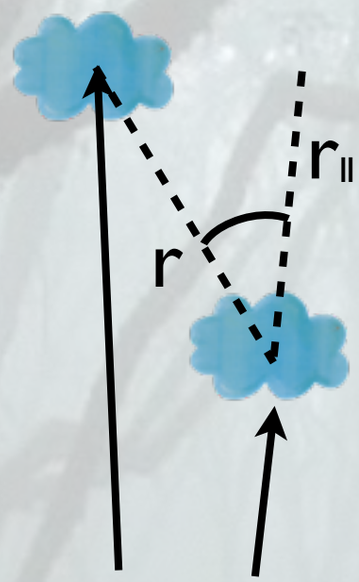
- Measure $\xi(r) =< \delta\delta >$ where $\delta(z) = \frac{f}{C\bar{F}} - 1$
- Compared with mocks (*Bautista et al 2014, Font-Ribera et al. 2012*)

Correlation Function Measurement

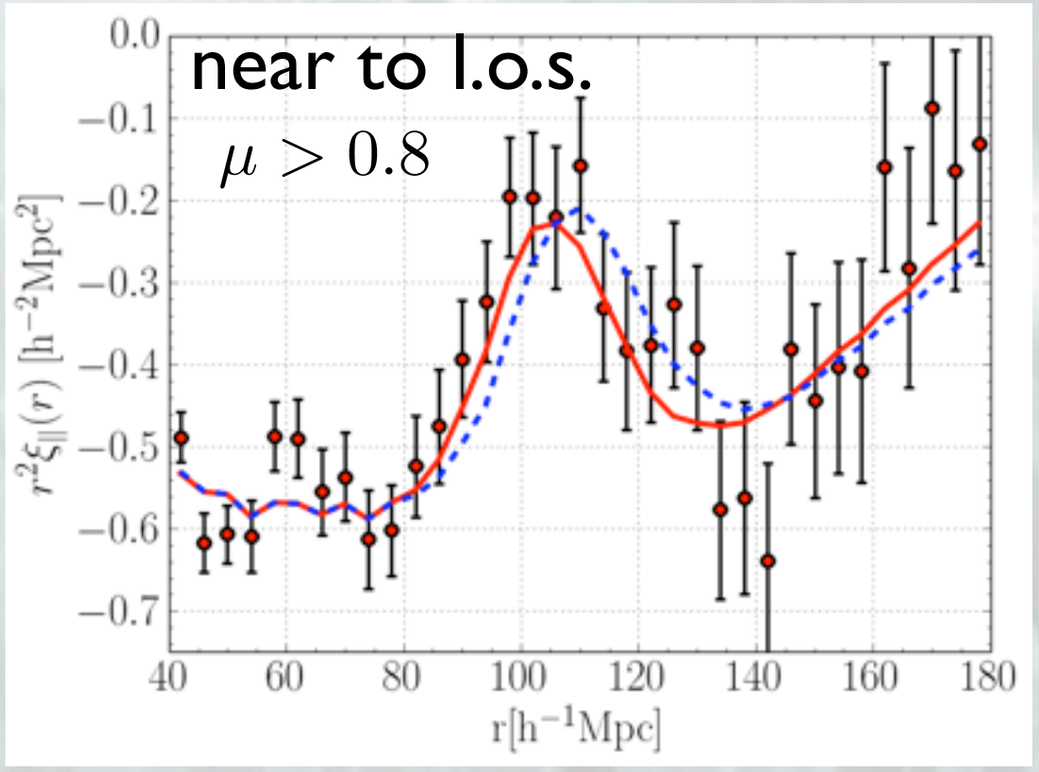
Sum over all pairs of deltas

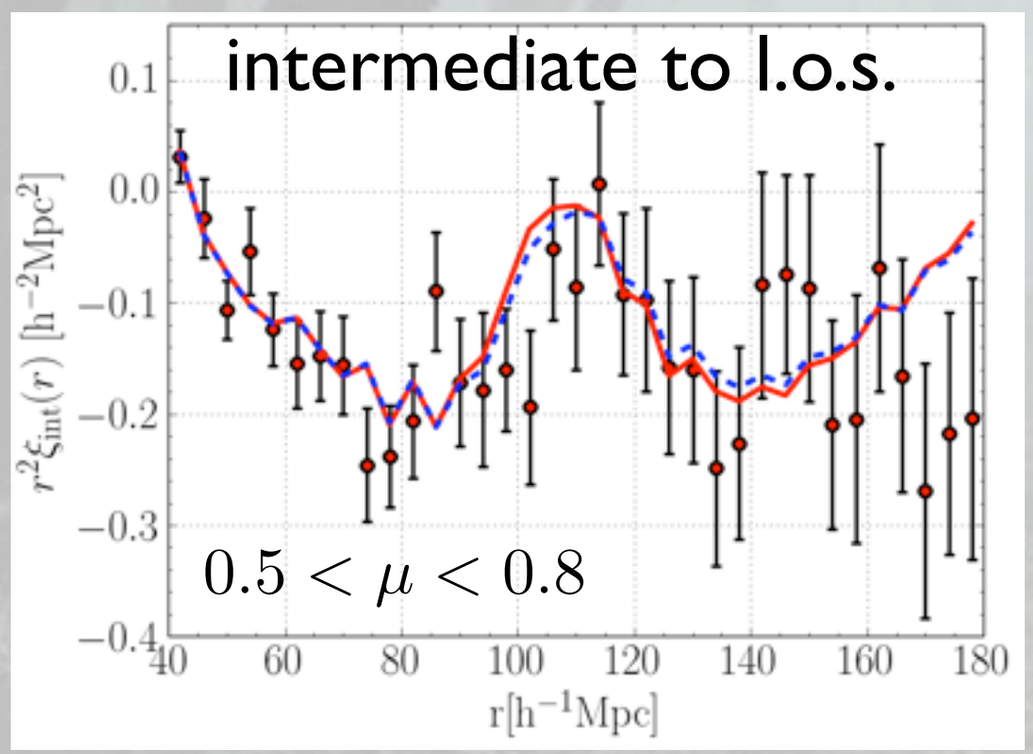
$$\xi(A) = \sum_{i,j \in A} w_{ij} \delta_i \delta_j$$

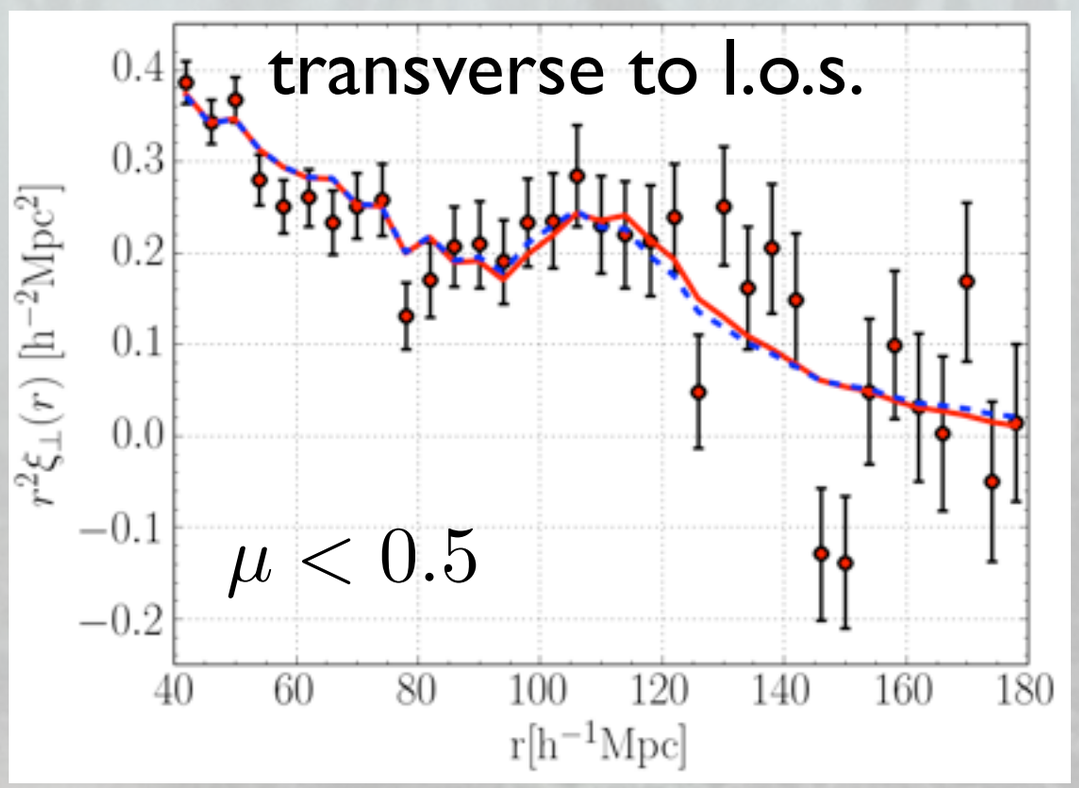
note that $\mu = \frac{r_\parallel}{r}$



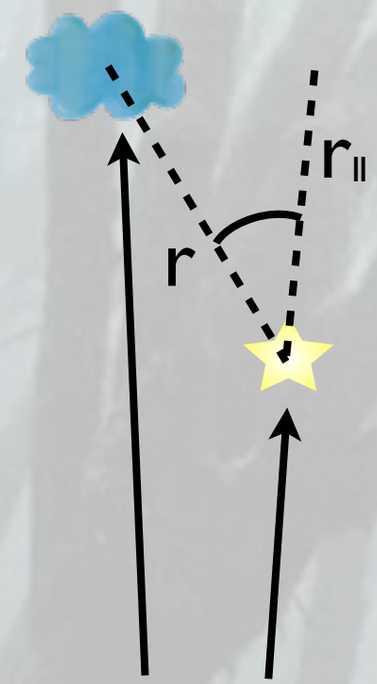
Delubac et al (2014)

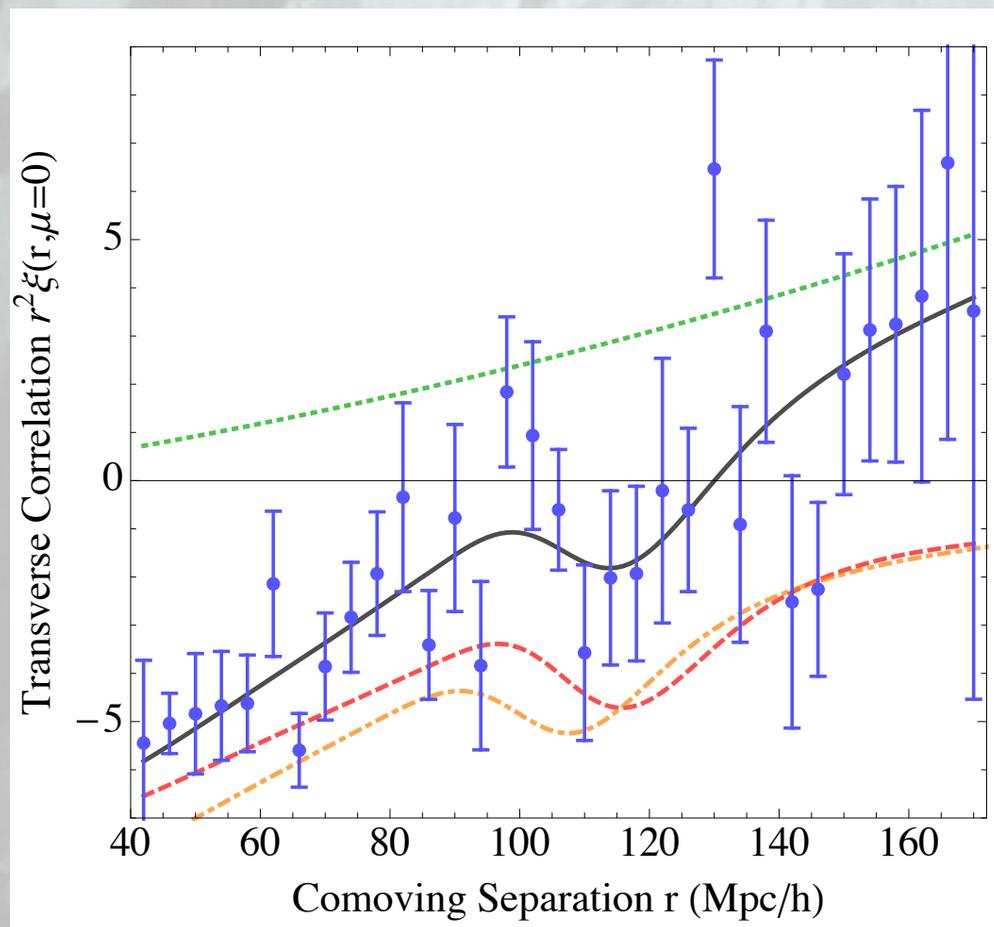


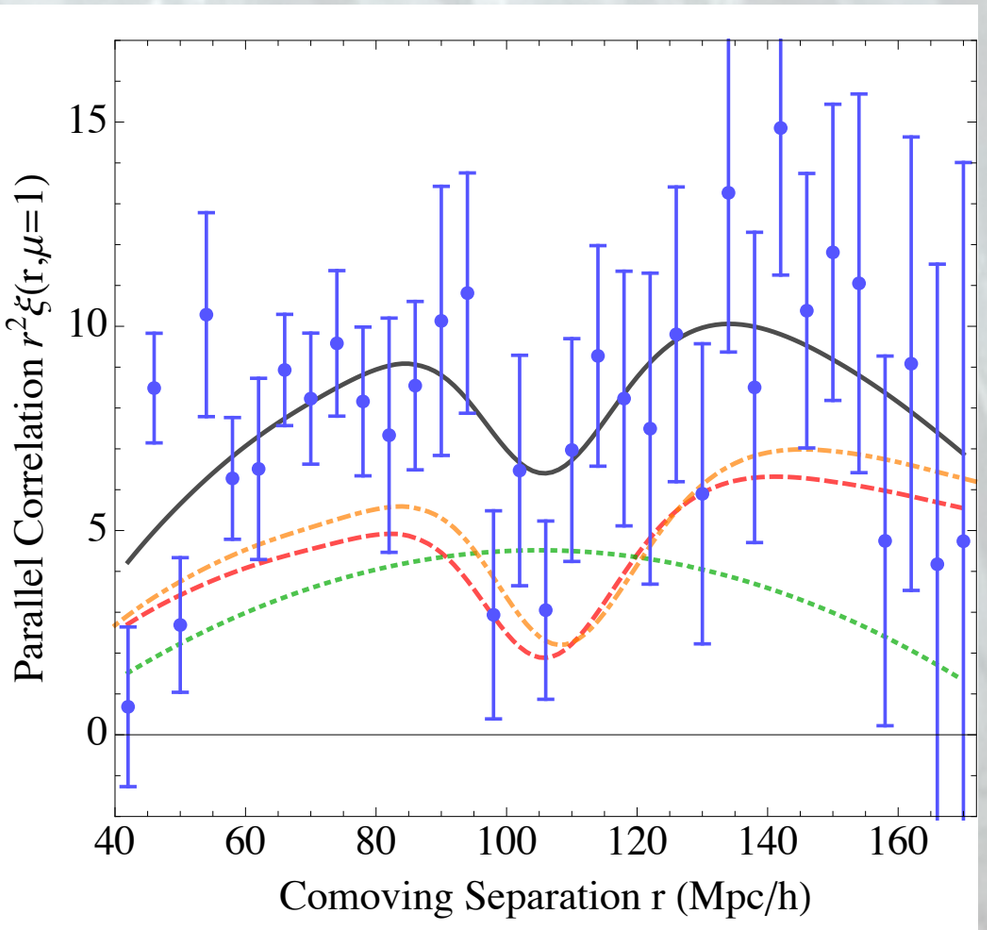




Cross-correlation Quasars-LyαF



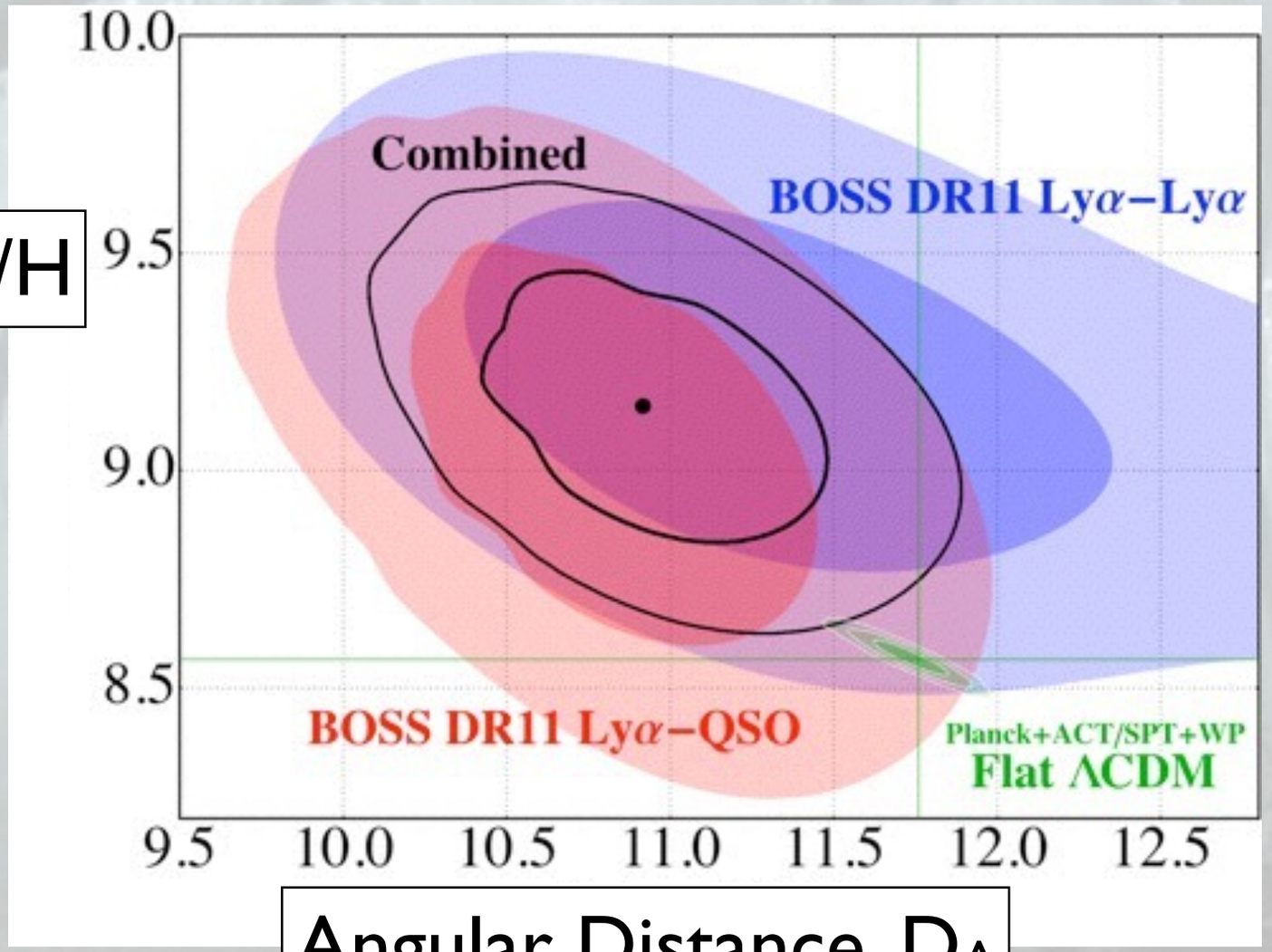




Font-Ribera et al (2013)

BAO Cosmology

2.5σ tension with concordance models based on Planck ...

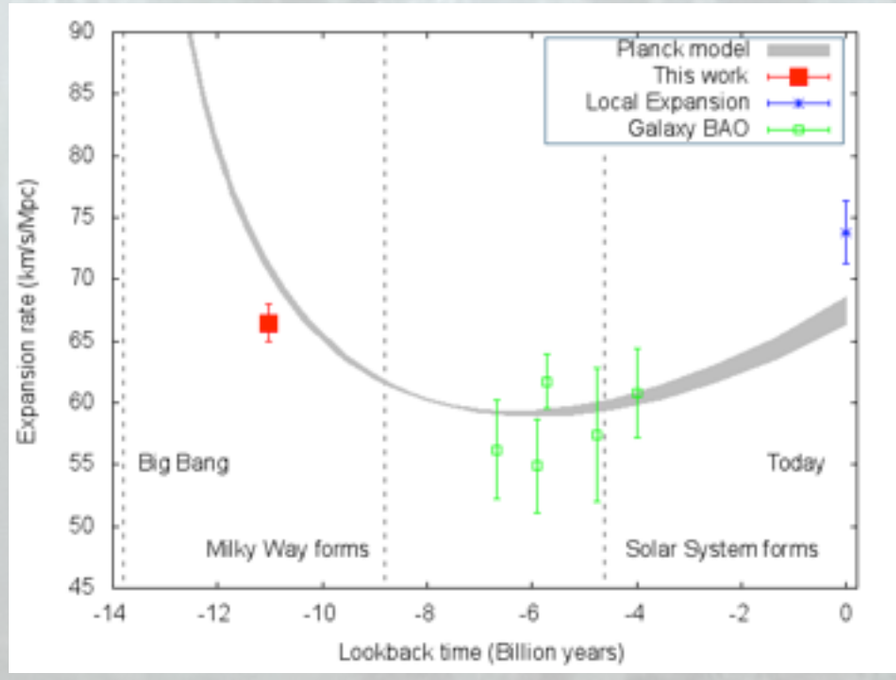


Delubac et al (2014)

Current Cosmology Results

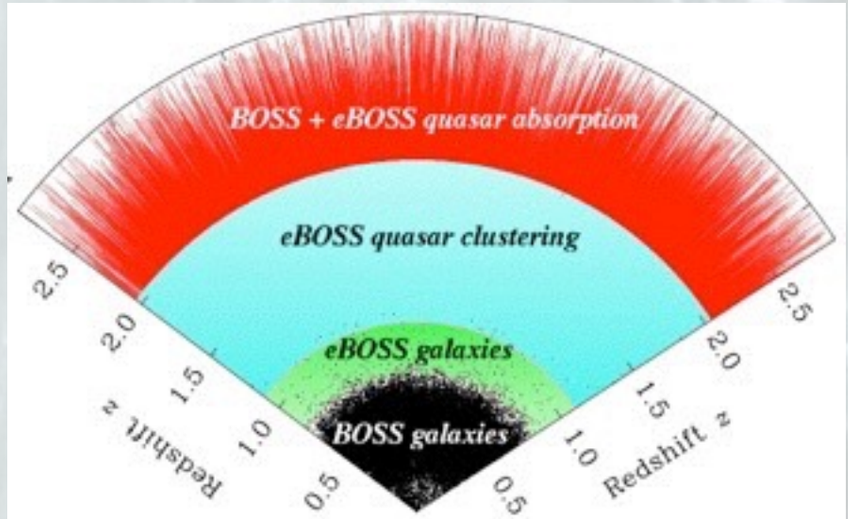
Dark energy from the Lyα forest works!

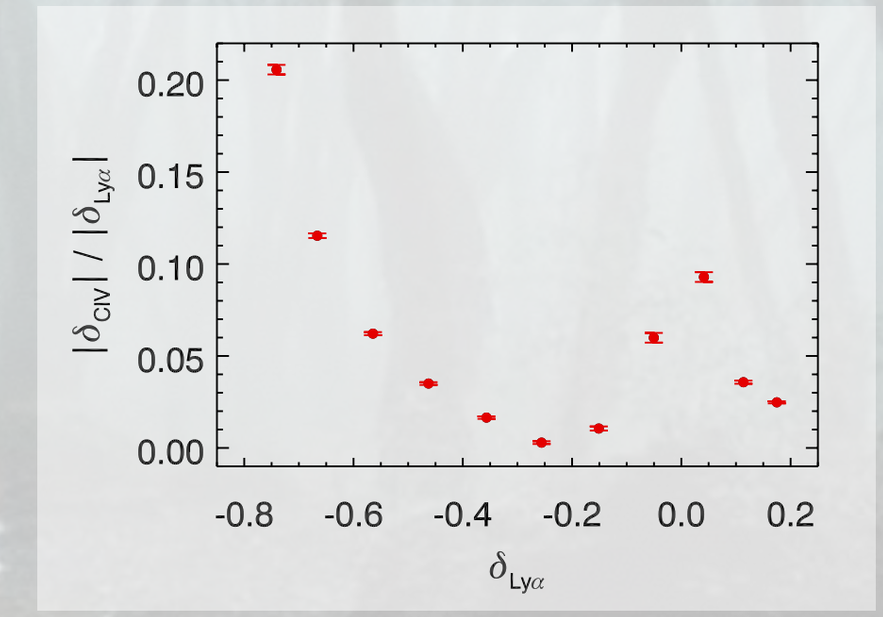
- 2% precision on line of sight BAO
- Highest precision on expansion rate since CMB
- Highest z observation of BAO peak (at z ~ 2.3)
- Matter domination epoch, so high-z deceleration
- Novel
  - New redshift
  - New type of probe
  - Surprises?
- Perhaps seeing this in our 2.5σ tension with Planck
- Final BOSS results to come in 2015



Growth of Massive IGM Surveys 2014-2019: SDSS-IV/eBOSS

- Improved Lyα forest BAO
  - 60k new spectra and 60k reobserved
- Fill redshift gap between galaxy and LyαF BAO with clustering of ~600k 1<z<2 quasars
- No Lyα forest but can use the carbon forest to trace BAO (MP 2014)
- Weaker signal than LyαF offset by x4 more quasars compared to BOSS
- If 2% precision on each tracer, x-corr is 1%
- Effectively turns 1 survey into 3 surveys
- Also metal BAO is a potential contaminant of LyαF BAO





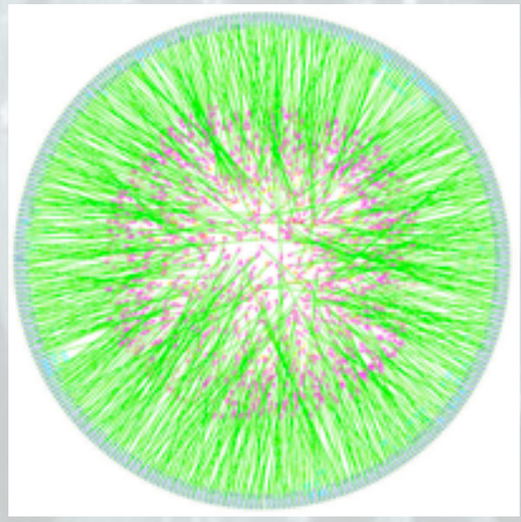
MP (2014)

Growth of Massive IGM Surveys 2019-2024: DESI

- Takes over the Mayall 4m at Kitt Peak Arizona, USA
- Not SDSS - Cosmology sole focus, 14k sq deg
- Resolution R=2000

- 600k high-z (Lyα forest) quasar spectra
- 1.4M intermediate-z quasar spectra
- 20M+ galaxies with z<1.6
- ~0.5% precision on high-z BAO
- Potential to cross-correlate quasars, galaxies and carbon absorption at intermediate-z
  - Effectively ~6 BAO measurements

Growth of Massive IGM Surveys 2018-2023: WEAVE



- 400k Lyα (z_Q>2.1) quasar spectra
- Resolution R=20000 (4040-4650 Ang) or 5000
  - 250k high res QSO spectra (2.3<z_F<2.8)
    - resolve the forest
  - 150k "low" res quasar spectra
- BAO with more precise continuum estimation
- Probe smaller scale effects
  - e.g. 1D power, warm dark matter, varying fine structure constant, deuterium abundance, IGM heating
- Combing DESI and WEAVE

Fin

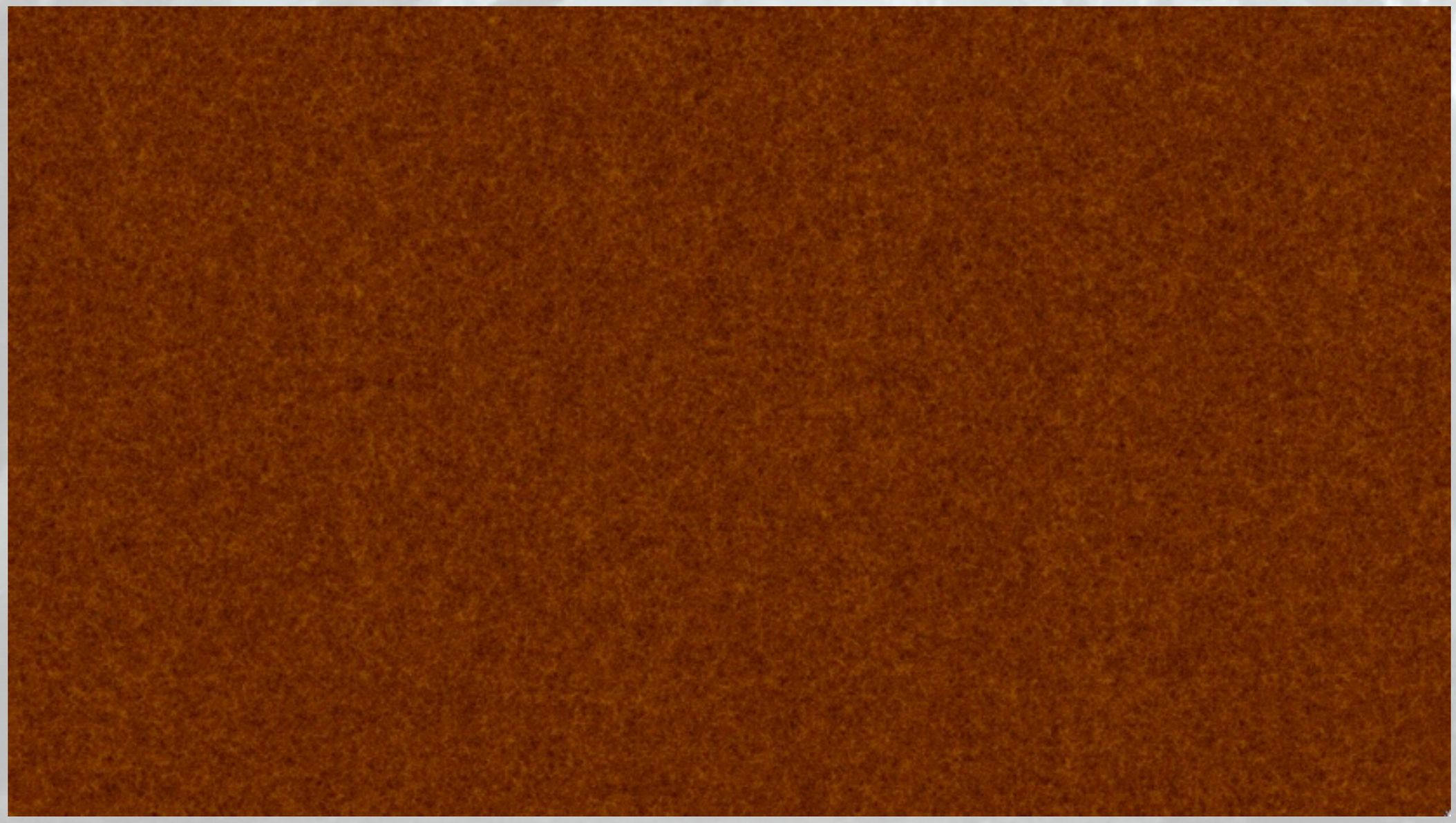
Mat Pieri - MOS ING, La Palma, 5th March 2015

Space is not a vacuum

- You all knew that though
  - There is the interstellar medium
  - ... oh and the gas around galaxies
    - ... oh and the gas in filaments
- No part of the universe is empty!
- All that gas matters

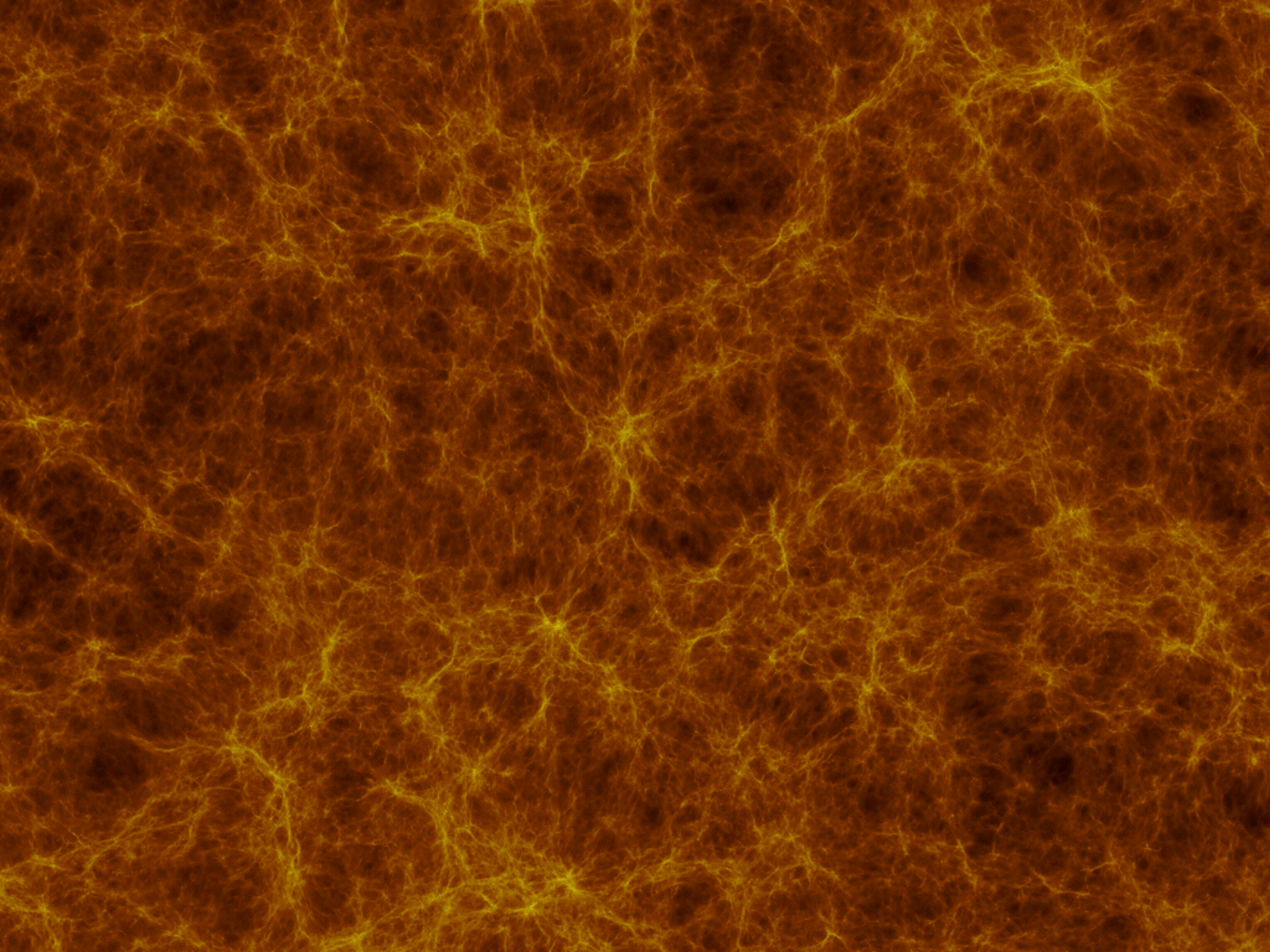
The Universe on the Largest Scales

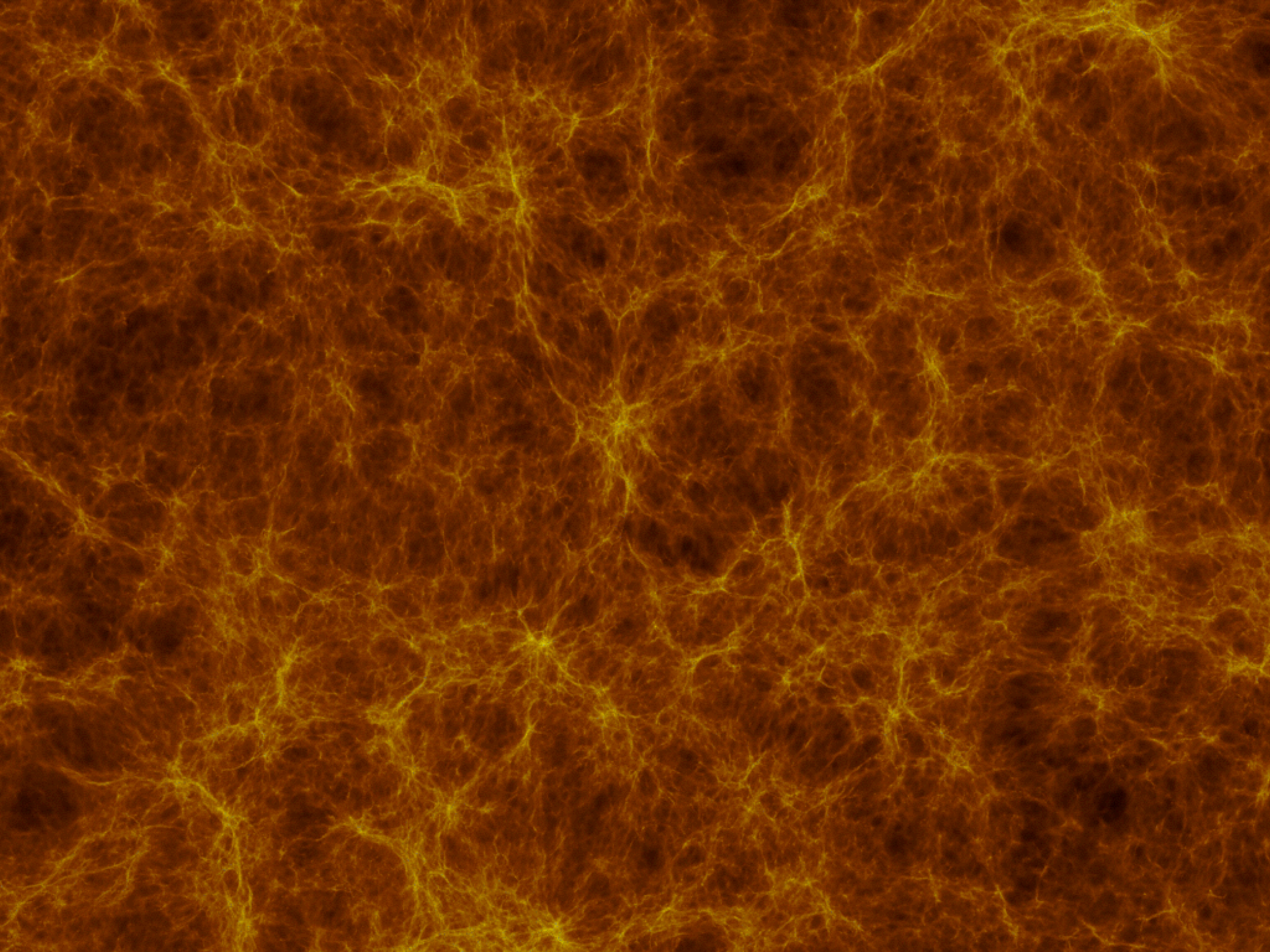
1.5 Gigaparsecs

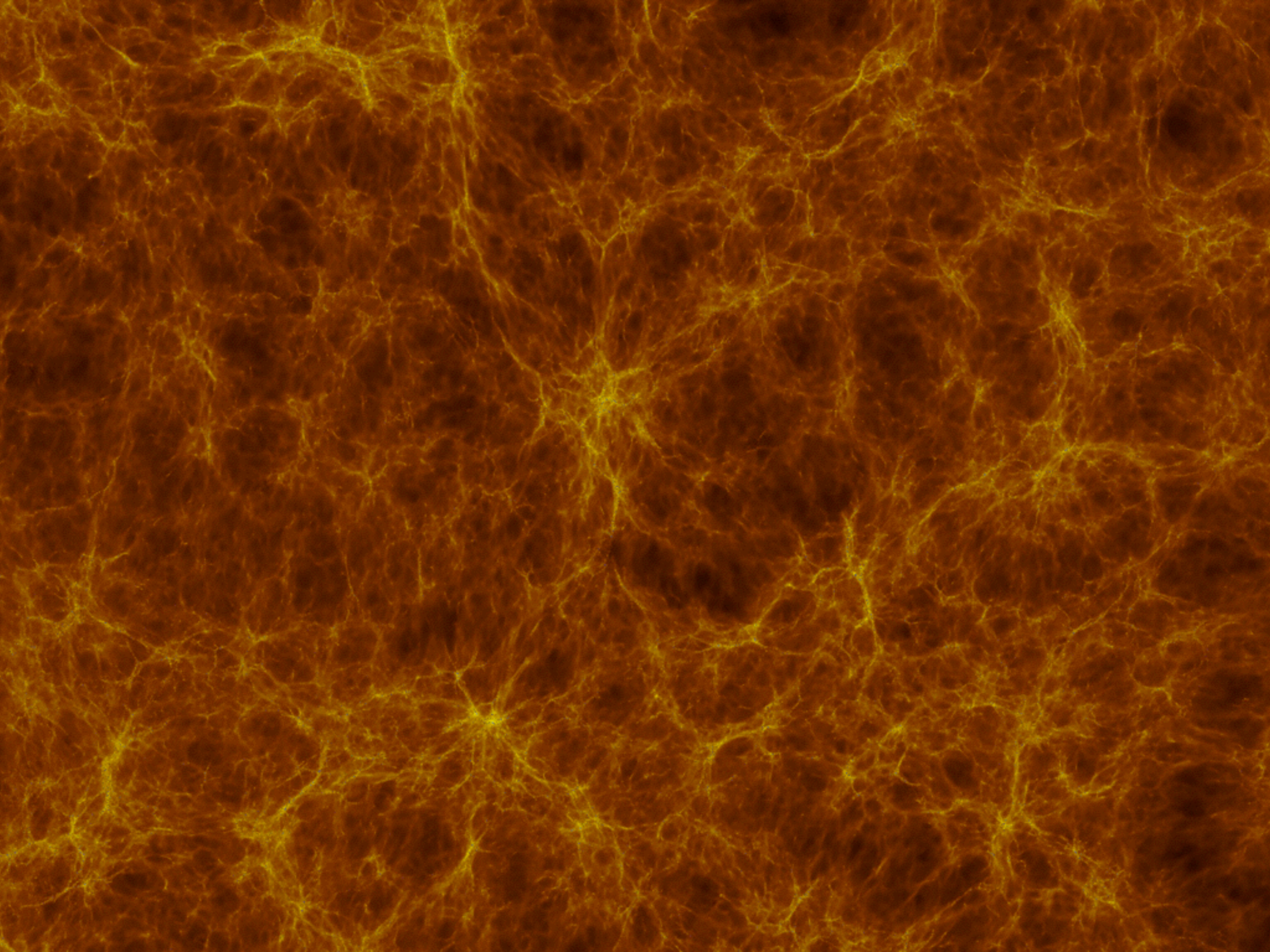


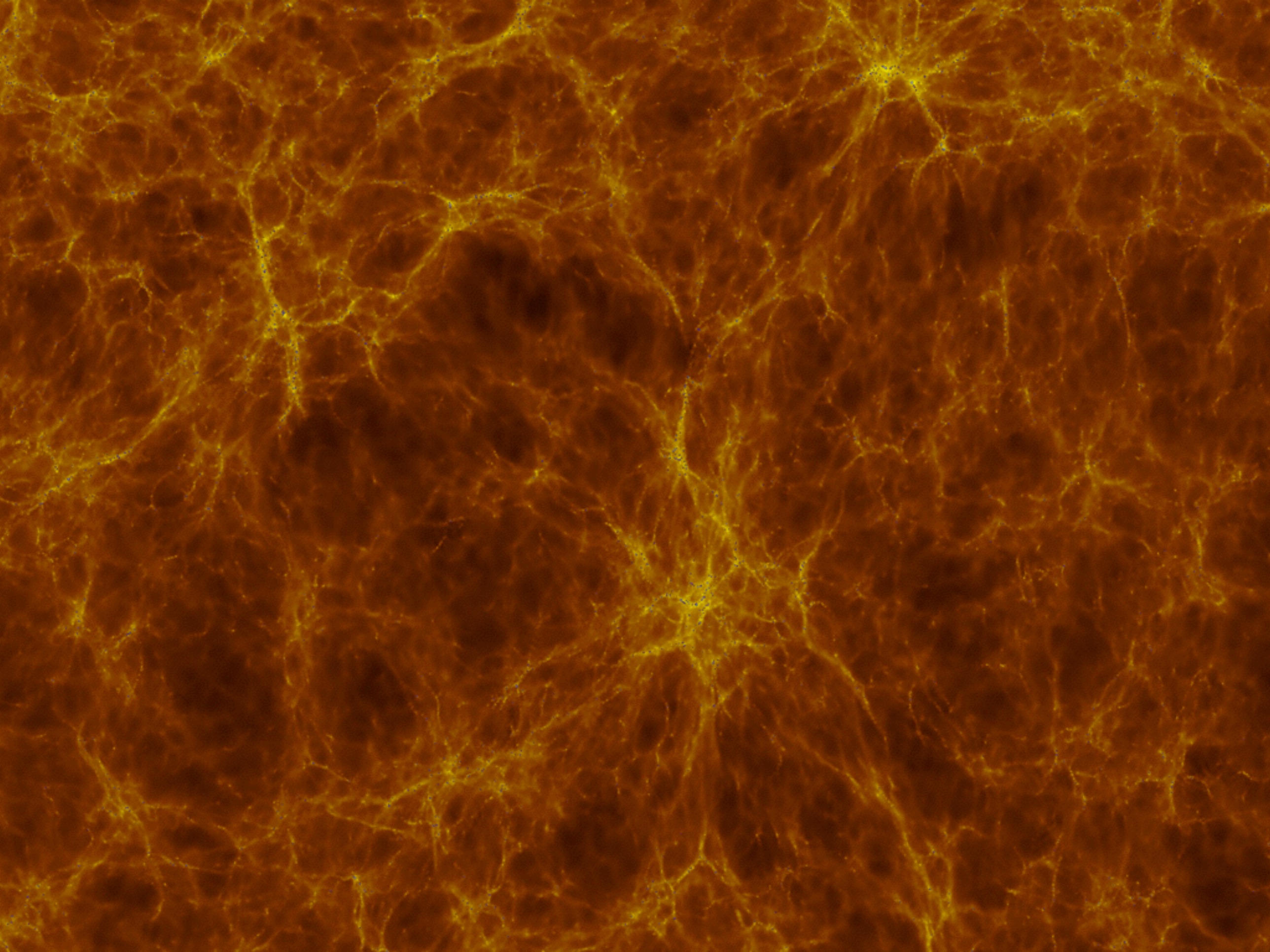
Yellow/red shows gas between galaxies. Blue shows the galaxies!

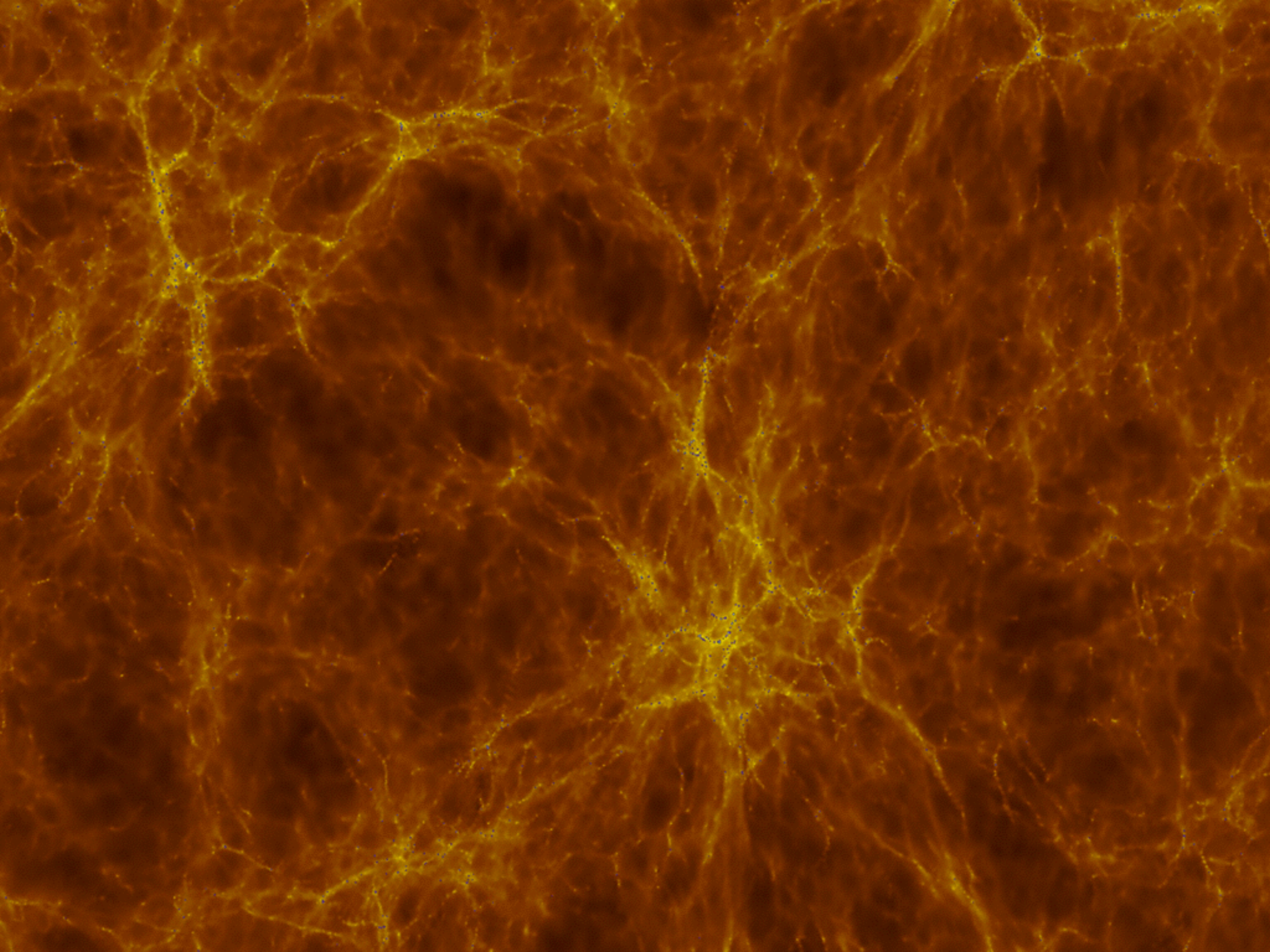
Di Matteo et al. (2011), Feng et al (2011)

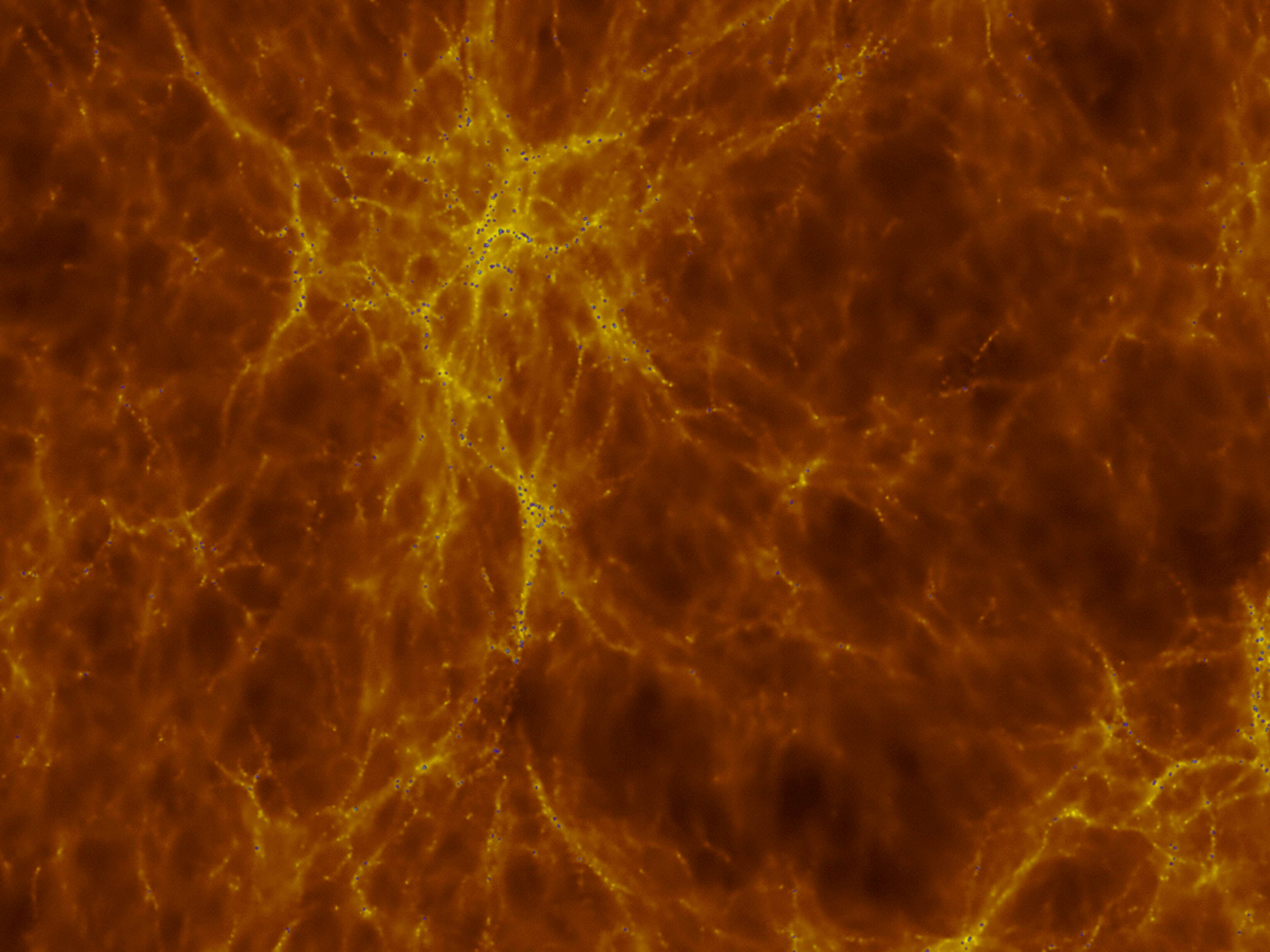


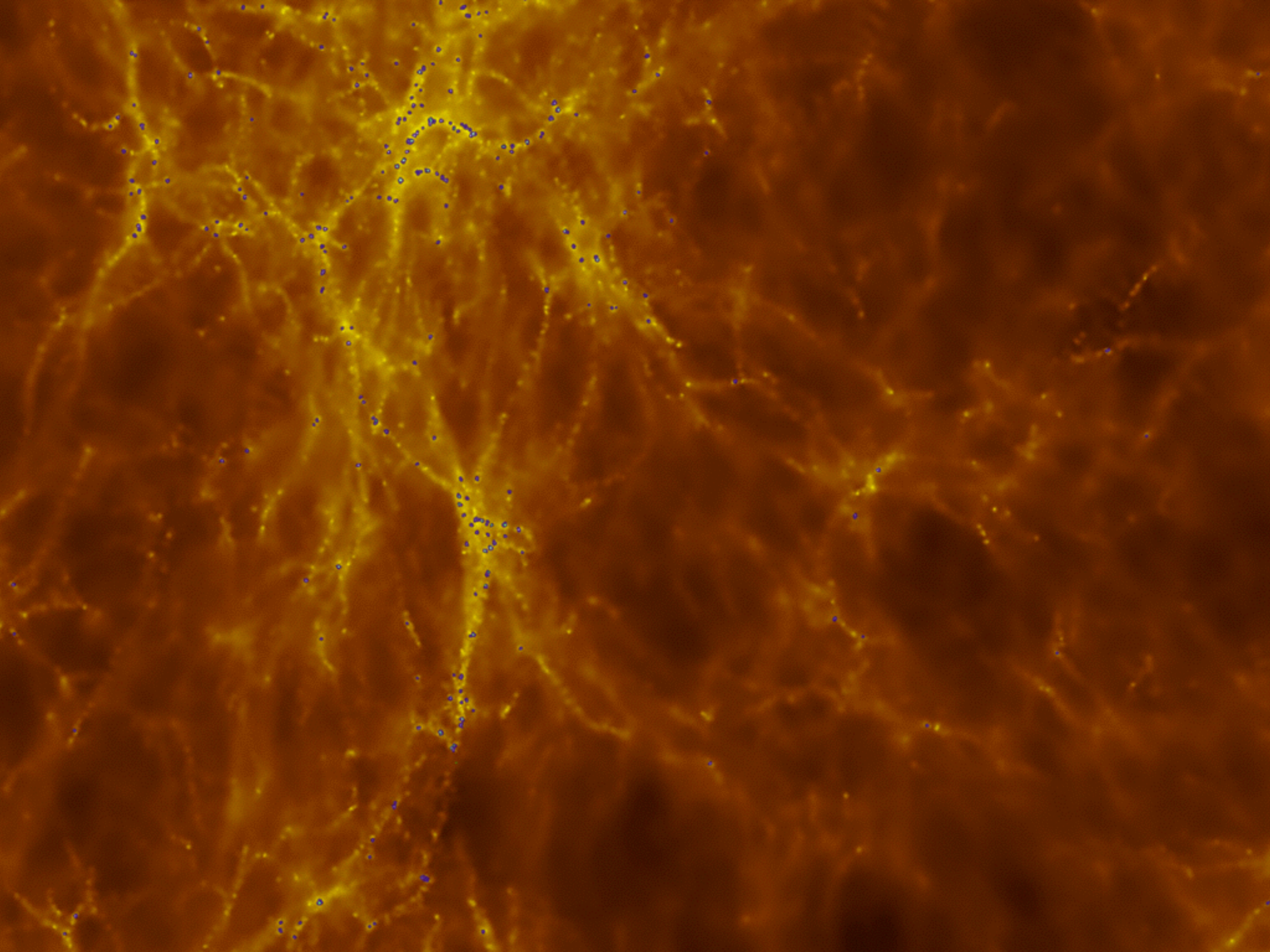




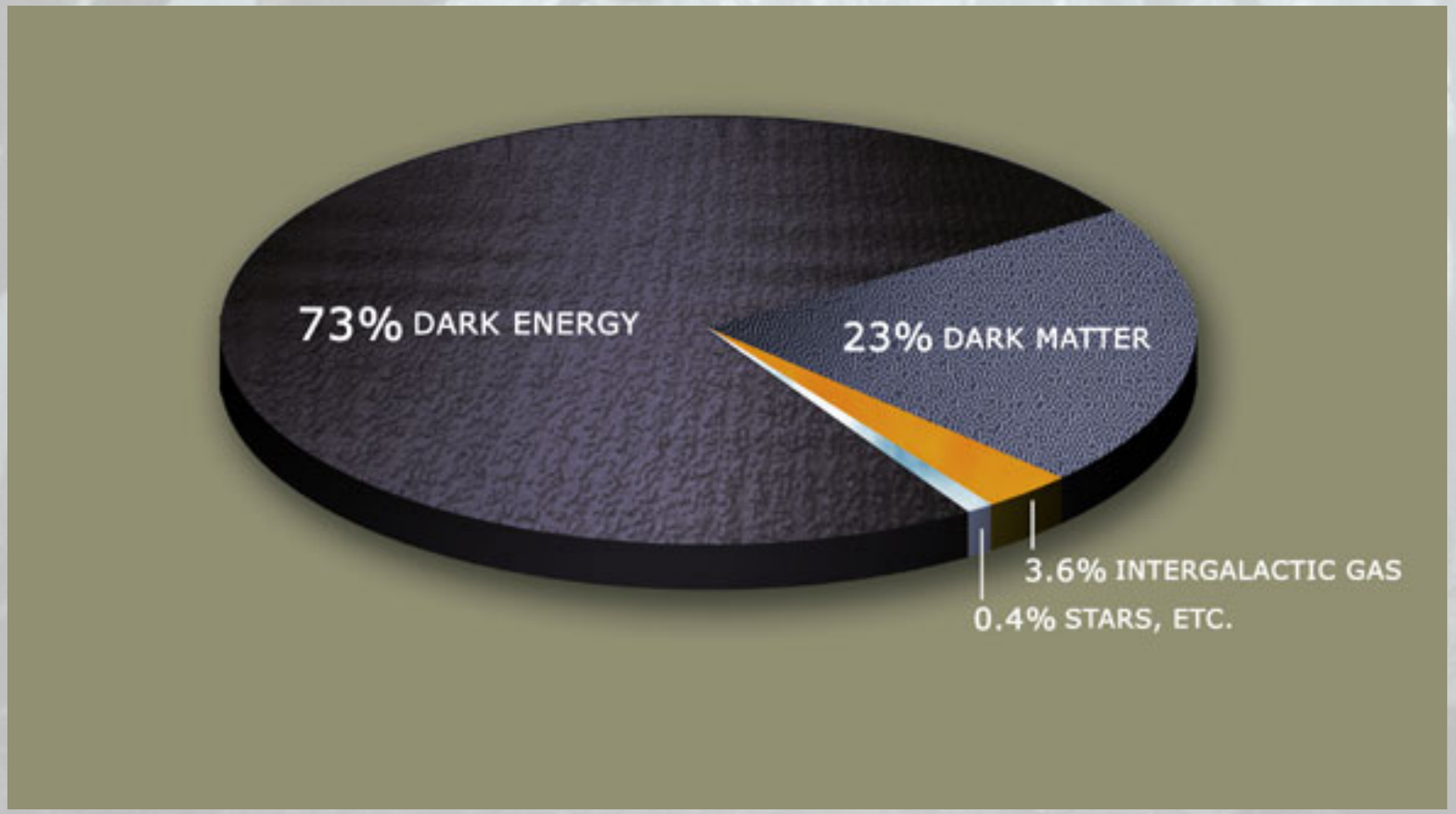








Mass density of Intergalactic Medium

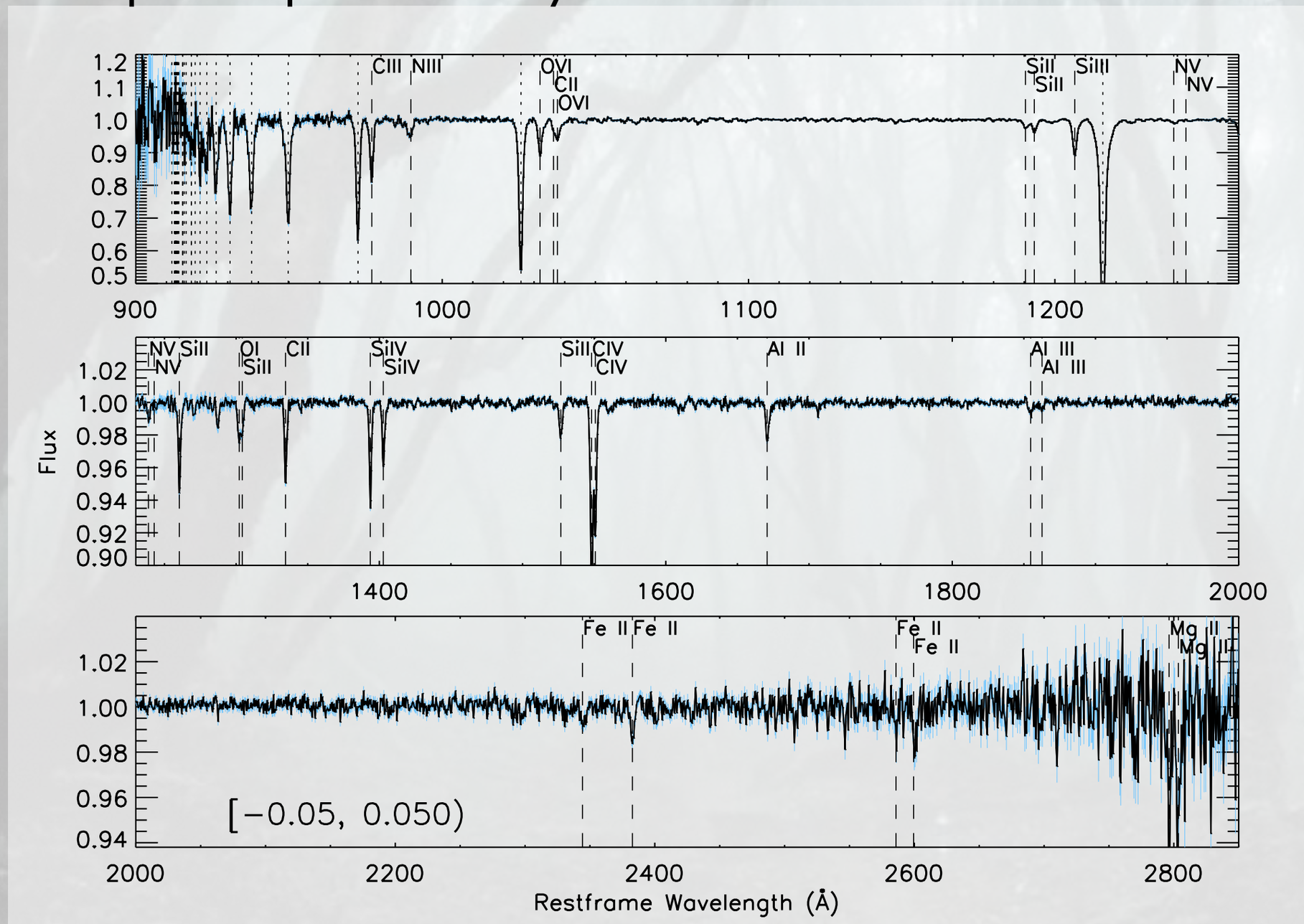


Gas collapses to form galaxies and accretes to grow them

Di Matteo et al. (2011), Feng et al (2011)

Other Absorption in the Forest

The composite spectrum of Lyα forest absorbers measured in SDSS ...



MP et al. (2010) and *MP et al. (2014)*

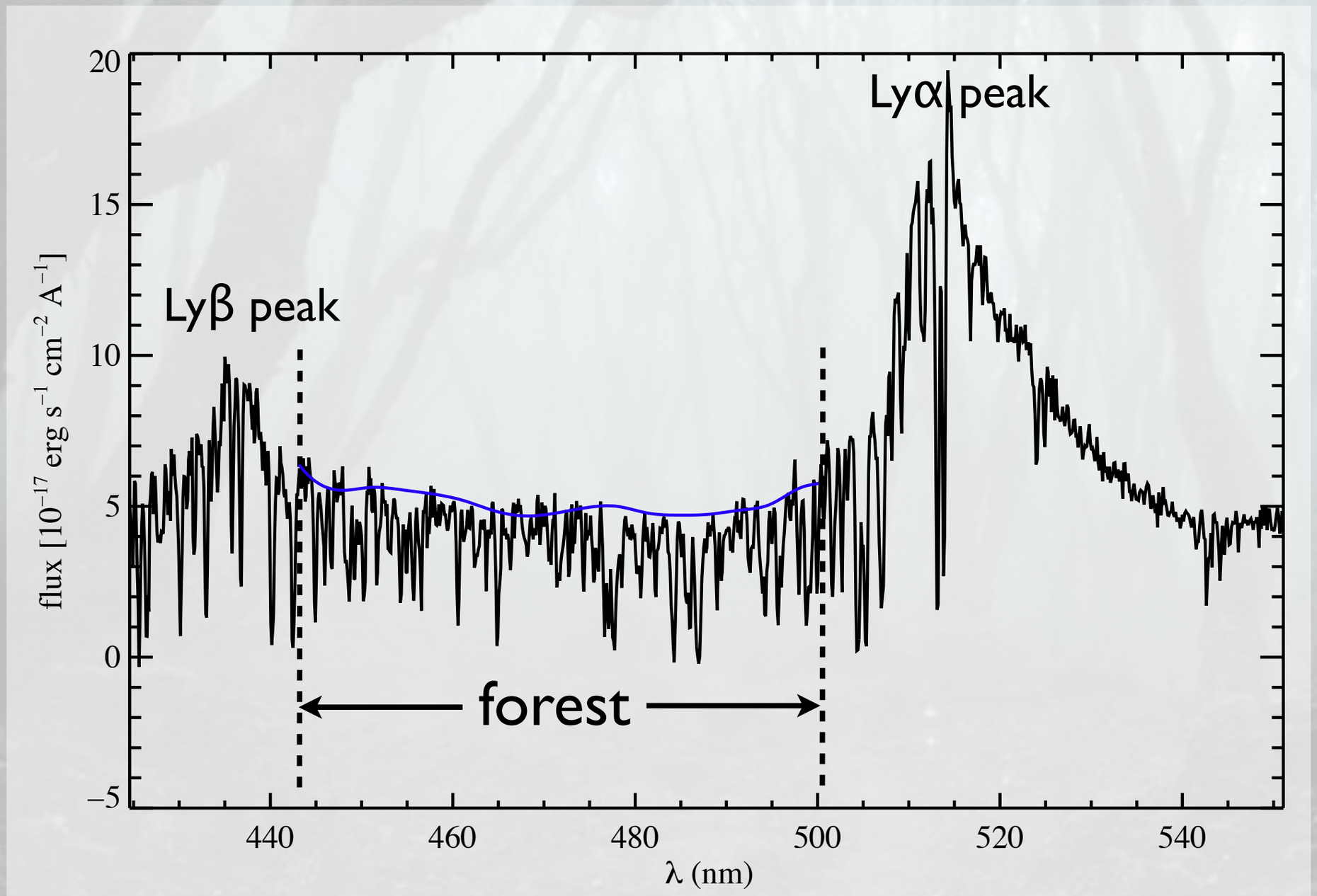
The Sloan Digital Sky Survey (SDSS)

- Began in 2000
- Dedicated 2.5m SDSS telescope at Apache Point, New Mexico, USA
- On of the most highly cited endeavors in the history of astronomy
- Imaging and spectra across ~1/3 the sky
- Spectra of many million stars, galaxies and quasars
- 1000 fibres per "field"
- Resolution R = 2000
- Began SDSS-III in 2009

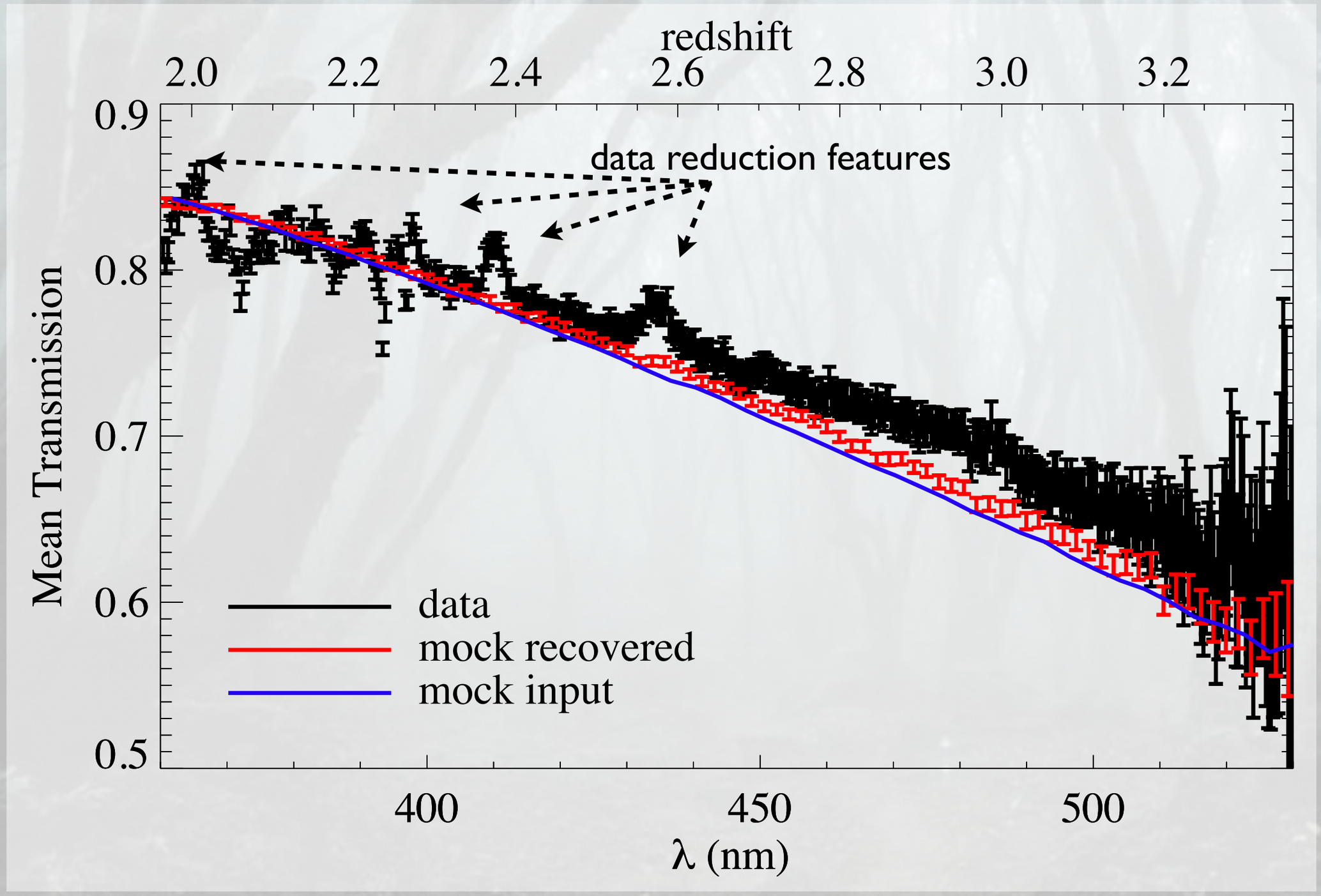
Calculating $\delta(z) = \frac{f}{C\bar{F}} - 1$

maximum likelihood of mean quasar + absorption PDF + noise PDF

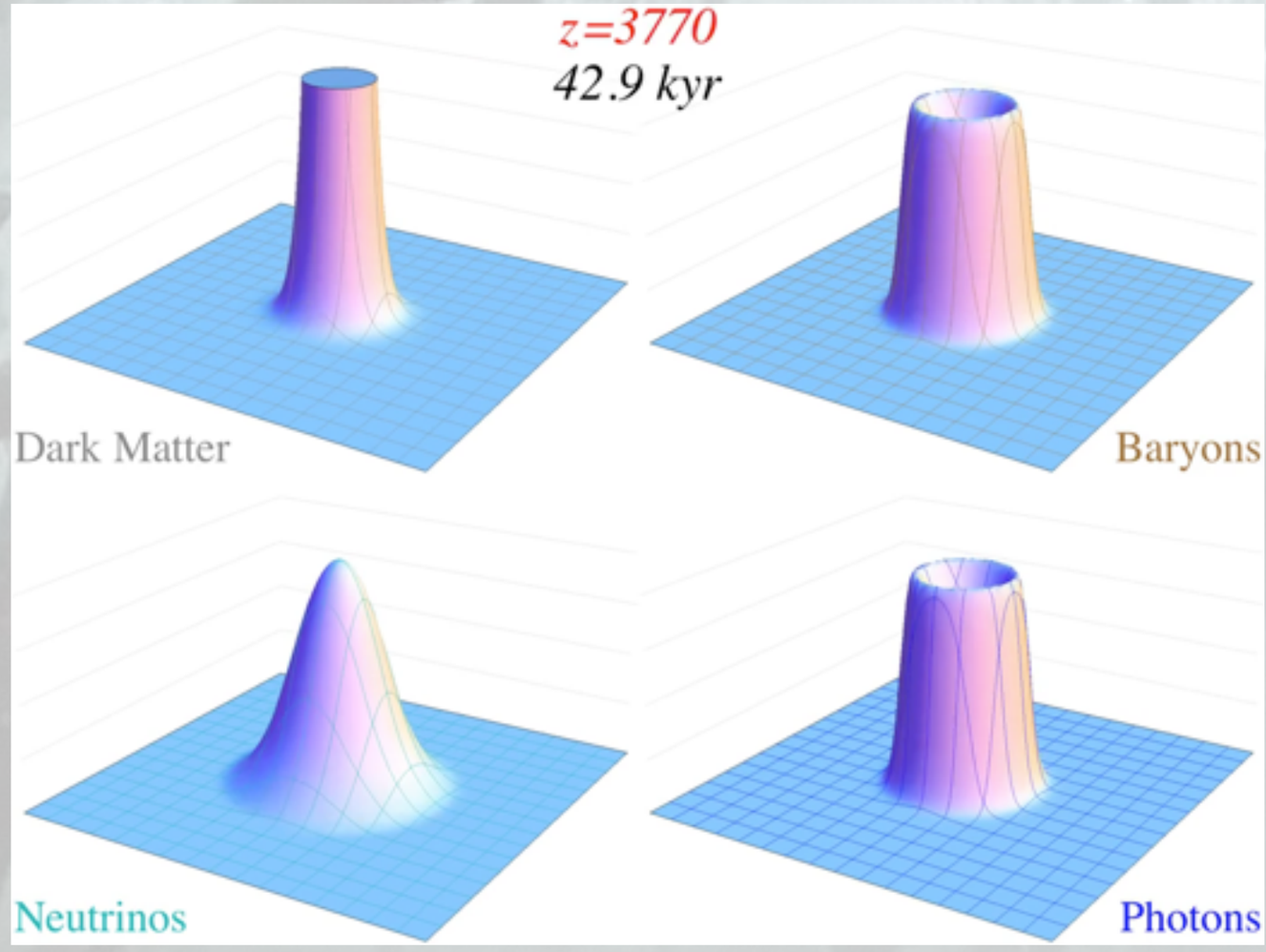
→ continuum



Calculating $\delta(z) = \frac{f}{C\bar{F}} - 1$

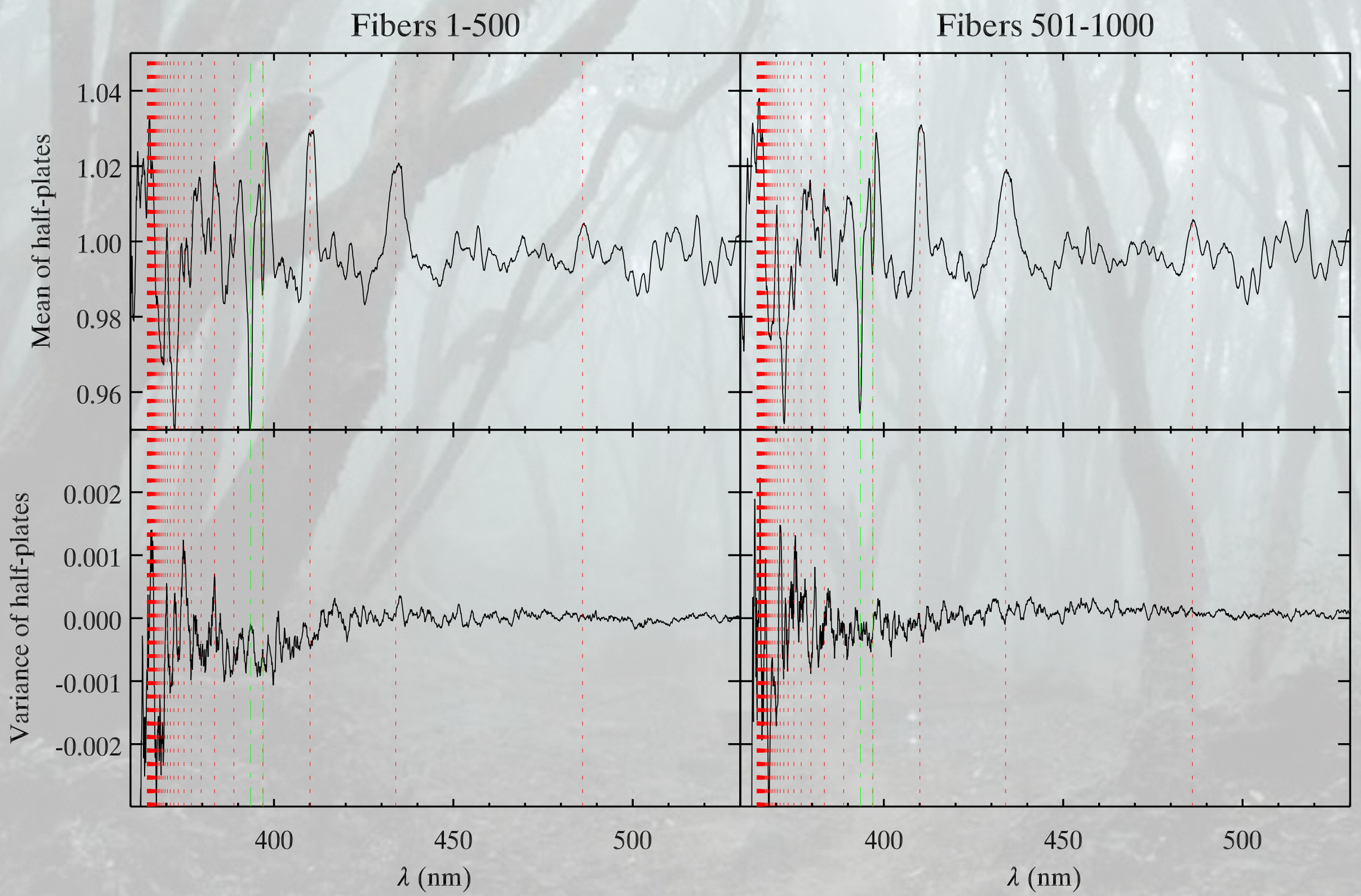


Baryon Acoustic Oscillations



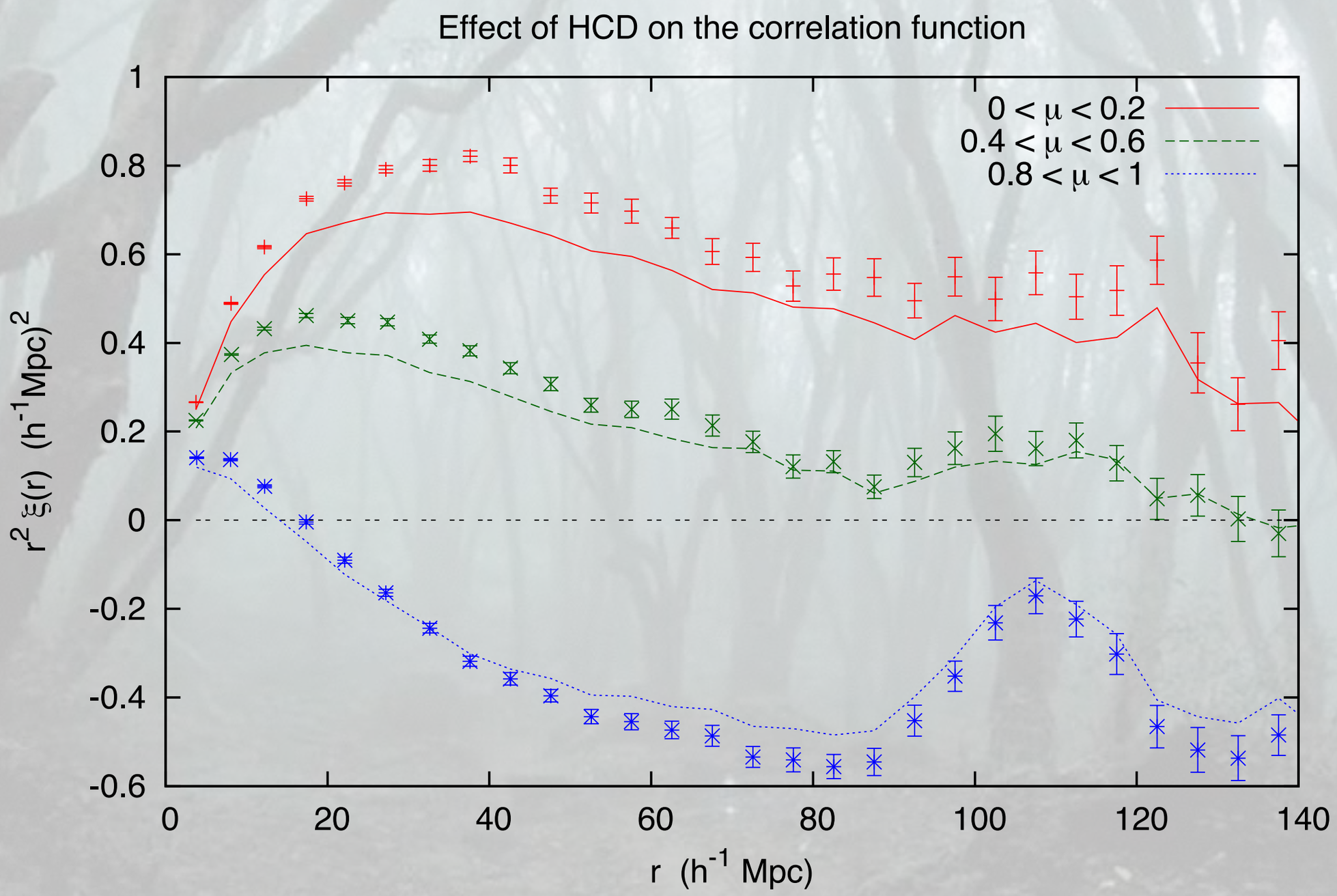
- A useful ruler on the sky measured in the CMB (Eisenstein et al 2005, Cole et al. 2005)
- BIG ~100 Mpc/h comoving
- Trace expansion over time

Spectral Artifacts



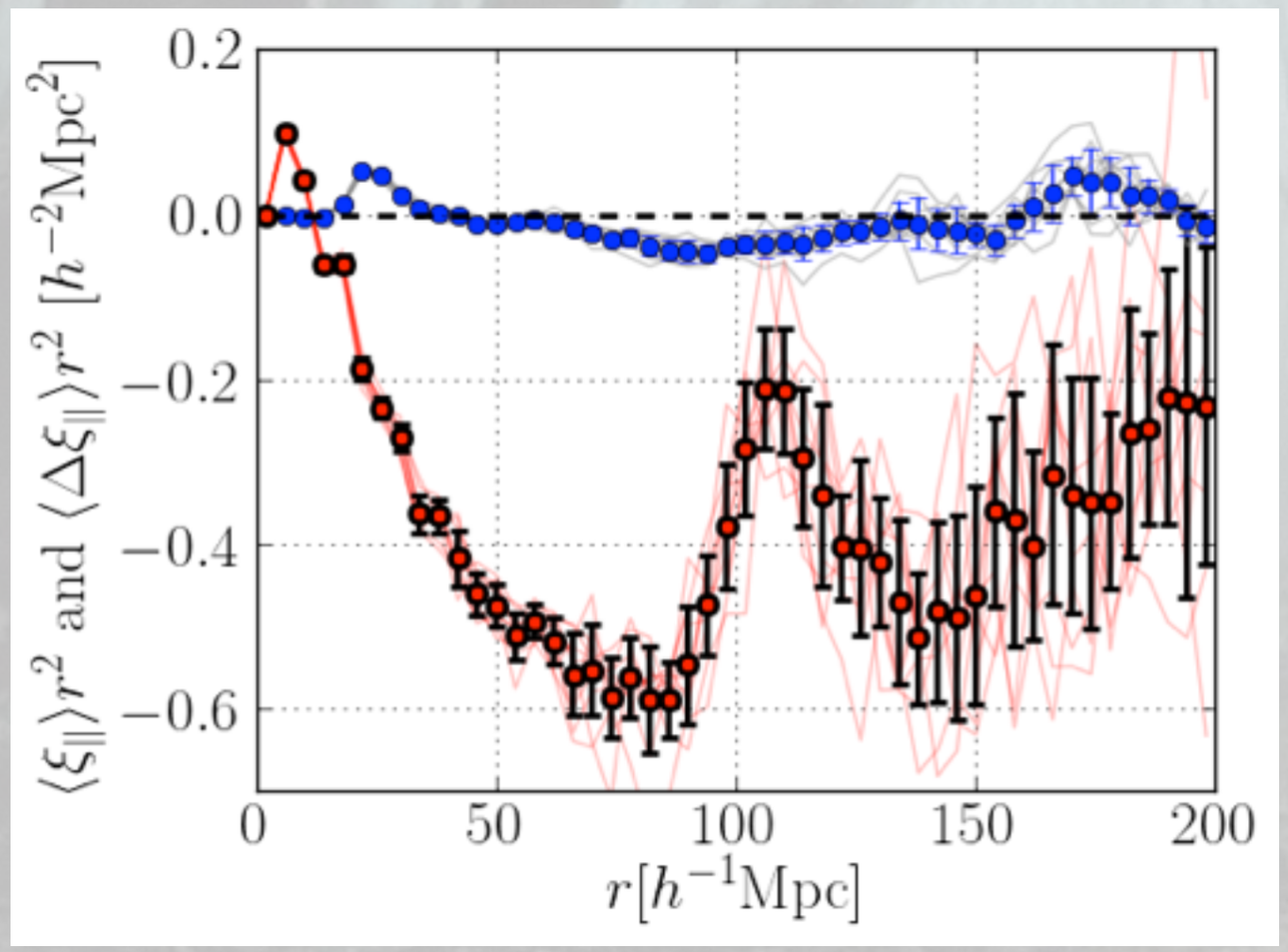
Impact of Lyα Strong Lines

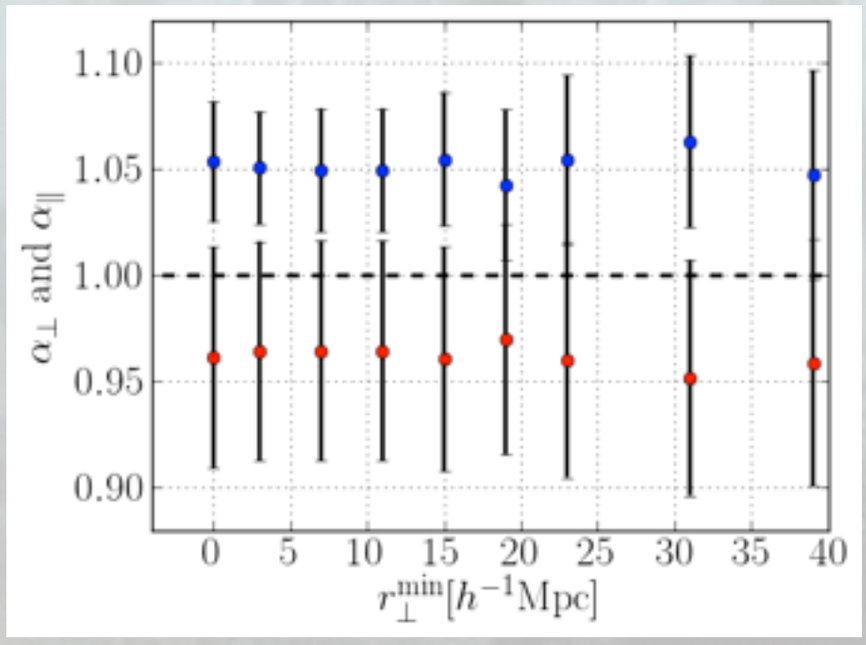
Font-Ribera & Miralda-Escudé (2012)



Metal Absorption Contaminating BAO

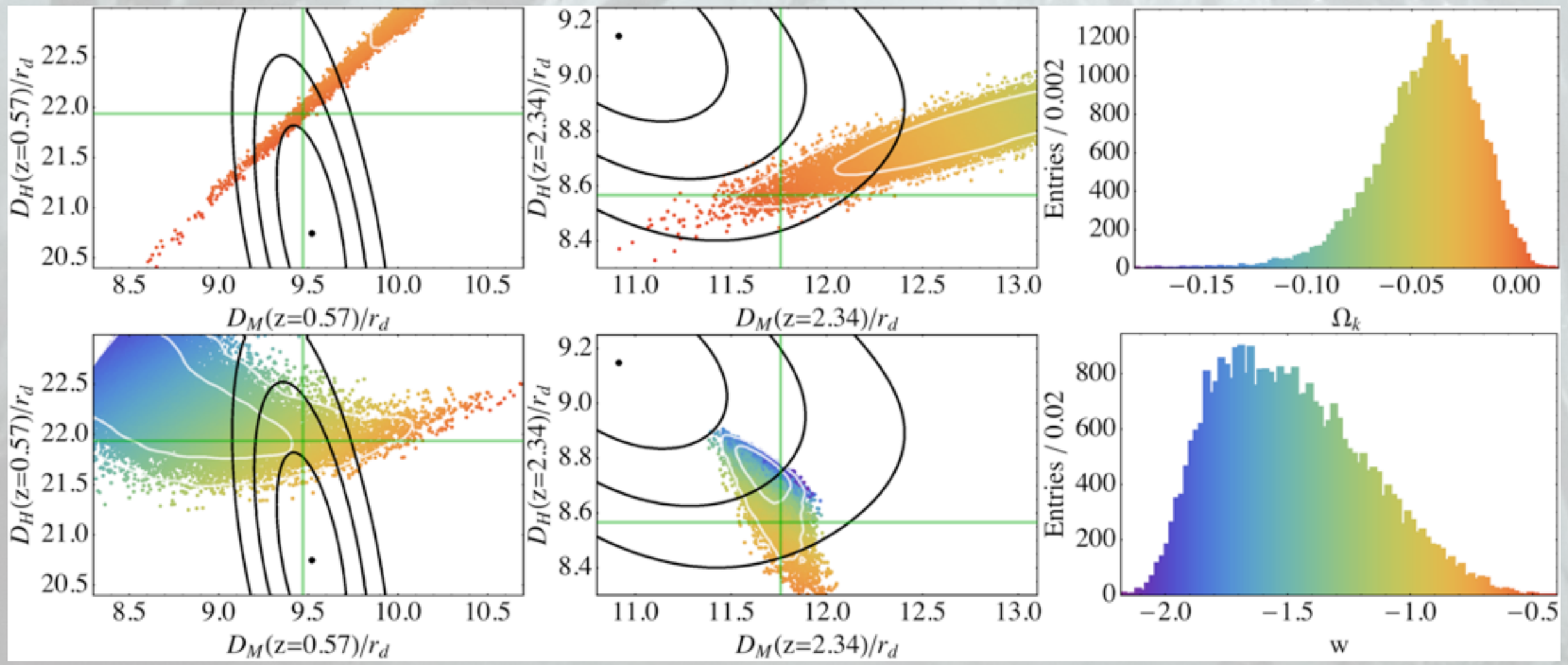
- Multiple metal lines add correlations in the data in 1D
  - Carries into 3D correlation function
- Tests adding metals from stacking to mock data





Delubac et al. (2014)
Bautista et al (2014)

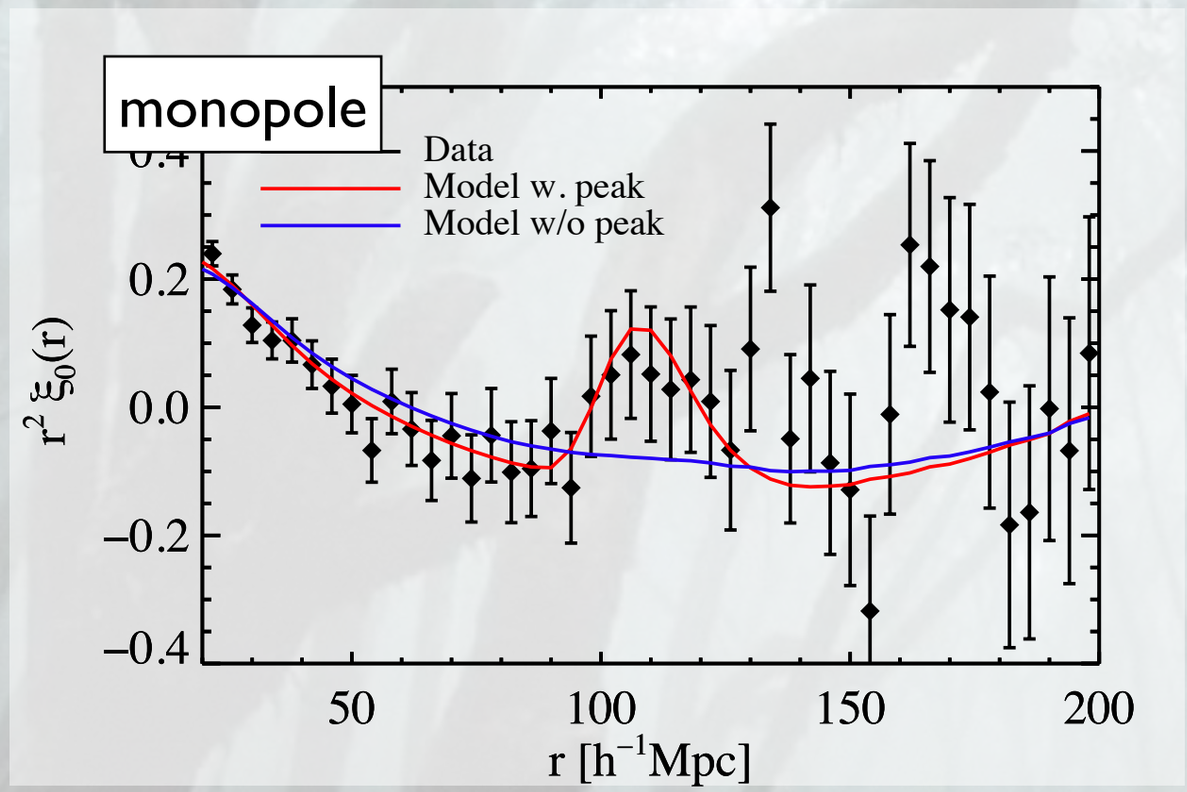
Modifications to Cosmology?

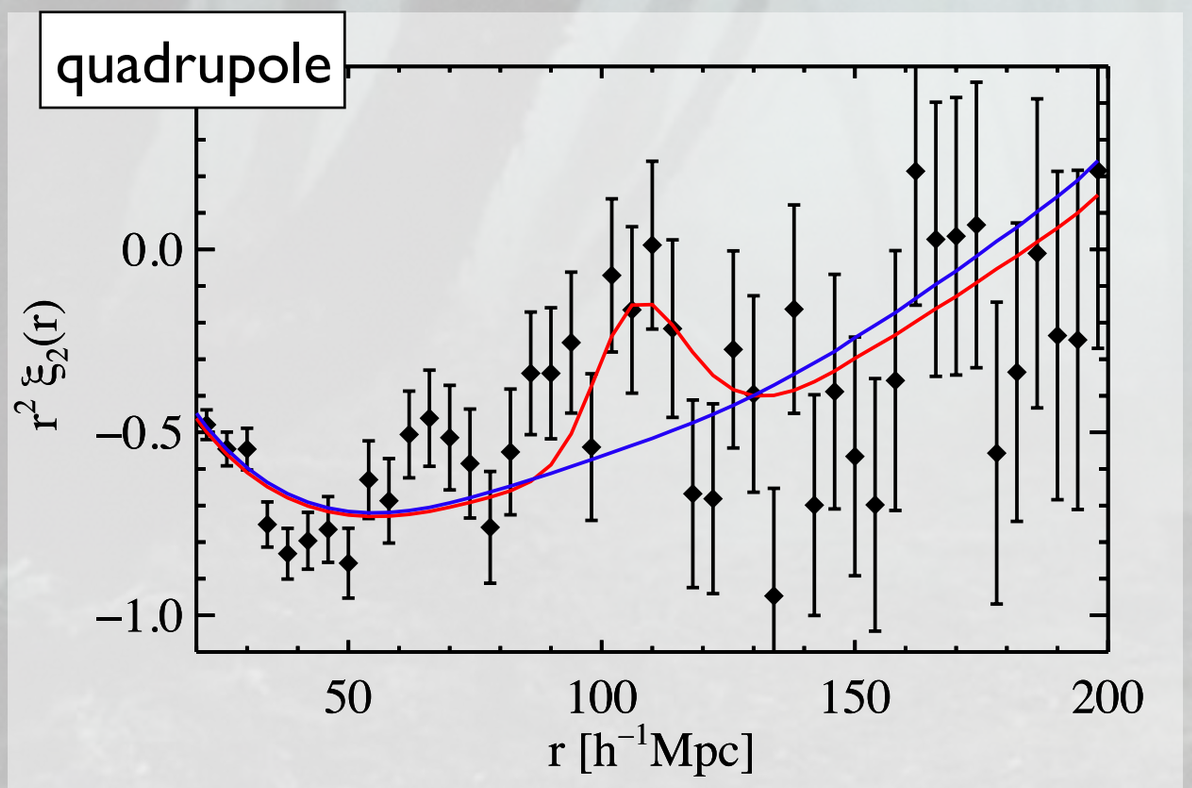


No known models that bring Lyα Forest results into line without harming BOSS galaxy agreement

Aubourg et al (2014)

Correlation Function Measurement





fit **peak model** and
no peak model
$\Delta\chi^2$ = 18.1 (significance ~ 4 sigma) in Busca et al. (2013)
now $\Delta\chi^2$ = 27.2 (significance ~ 5 sigma) in Delubac et al. (2014)

Then vary:

$$\alpha_H \equiv r_s H / (r_s H)_{\rm fid}$$

$$\alpha_{\rm d_A} \equiv \frac{(d_A/r_s)_{\rm fid}}{(d_A/r_s)}$$

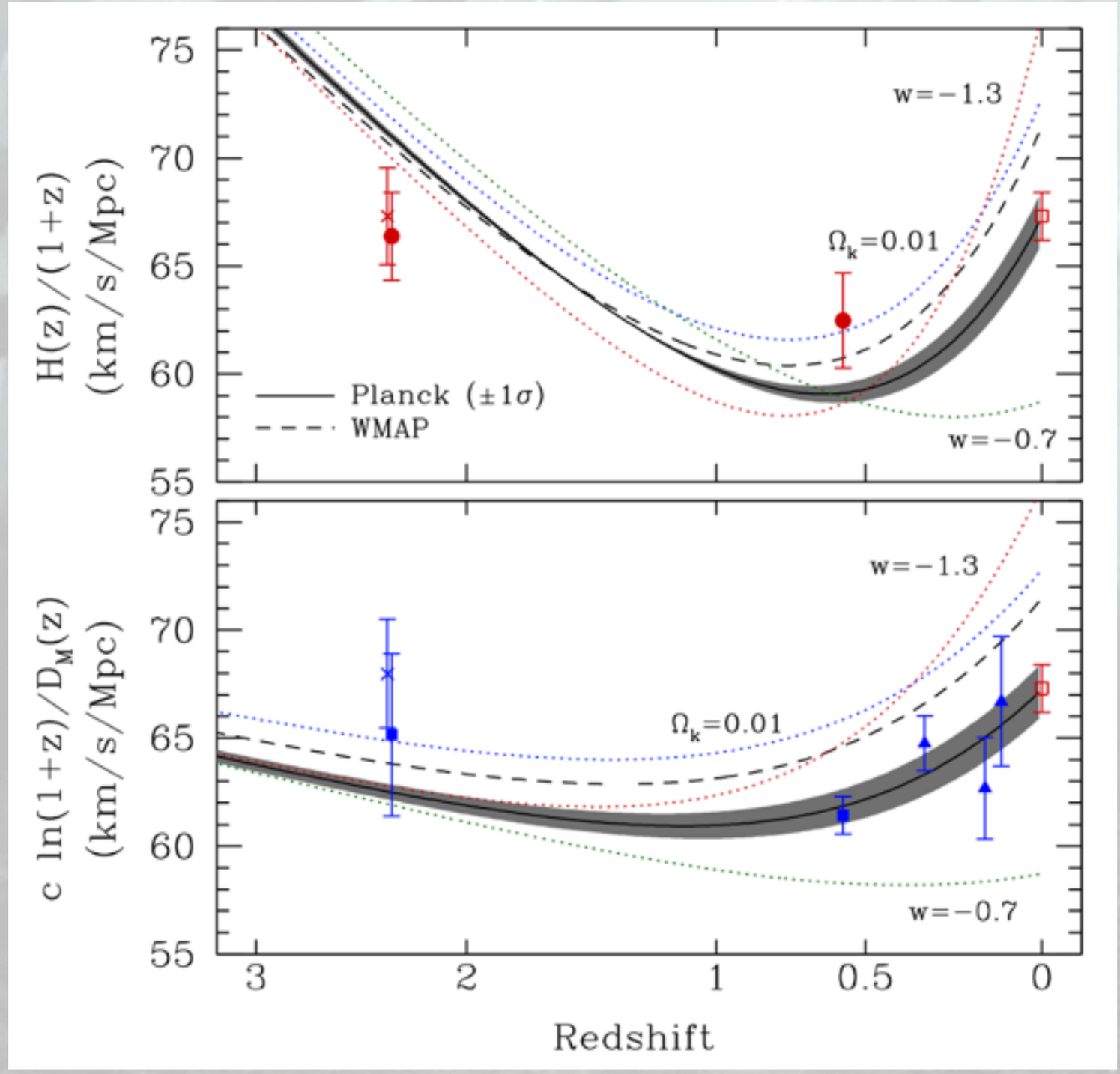
where r_s is the WMAP BAO scale

Constrained at 2% level

Current Limitations

- X-correlation measurement no mocks - nearly ready
- Metal forests BAO in Lyα forest are a currently untested systematic - eBOSS solves this
- Subtle spectroscopic and data reduction artifacts - latest reductions and tests show negligible impact
- Large scale UV background fluctuations tested in mocks
- Refinements of
  - Lyα-metal and metal-metal correlation tests
  - Addition of strong Lyα lines
- BAO fitting unphysical - new paper on the way

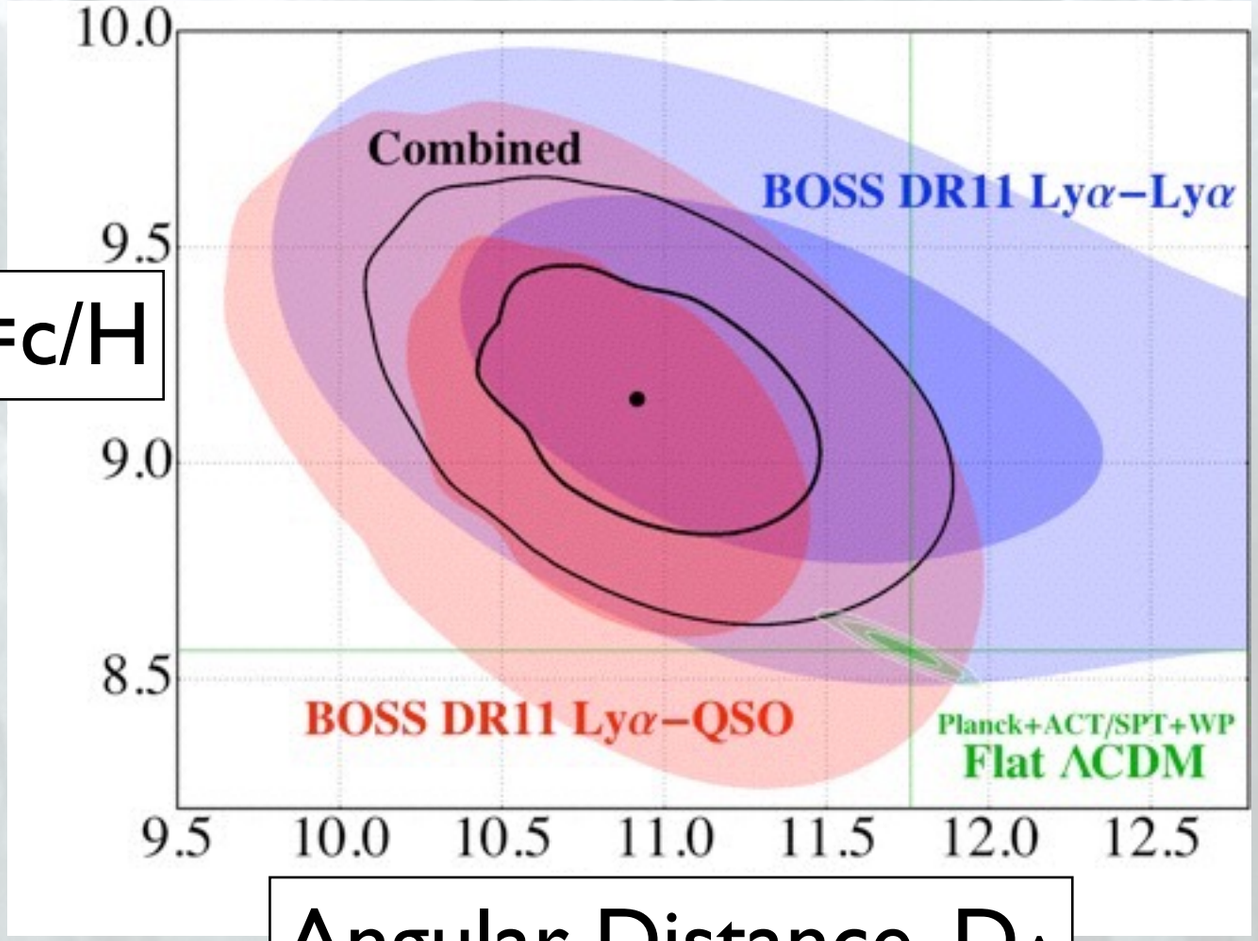
Tension with Standard Models

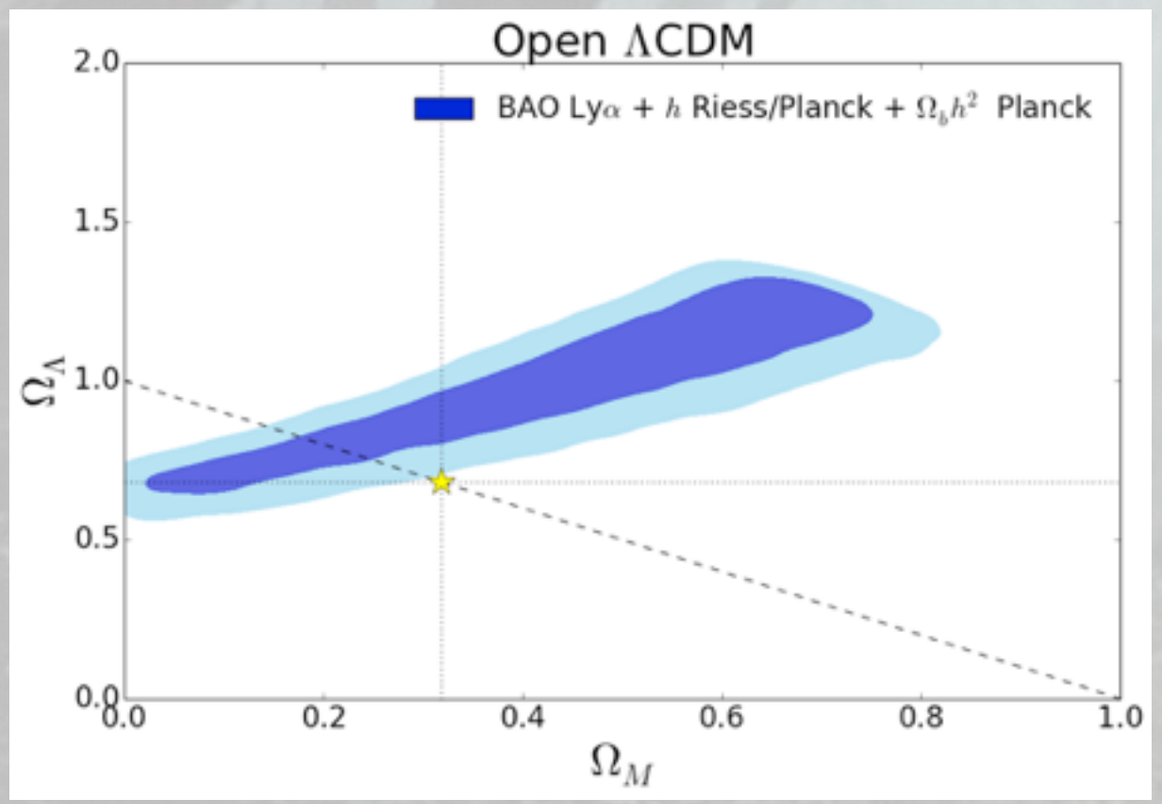


Aubourg et al (2014)

BAO Cosmology

2.5σ tension with concordance models based on Planck ...



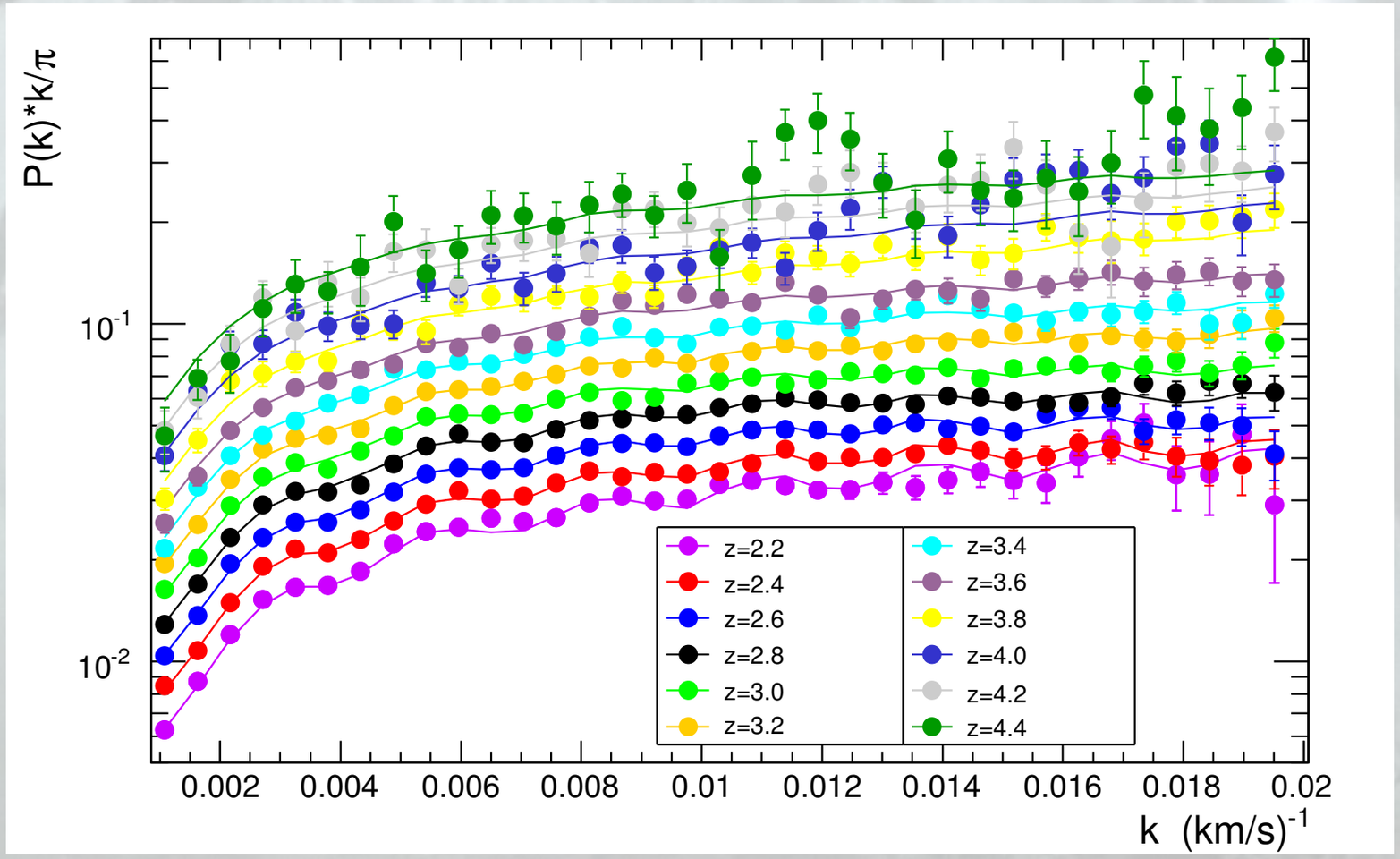


Delubac et al (2014)

1D Power Spectrum

Power measured long line of sight

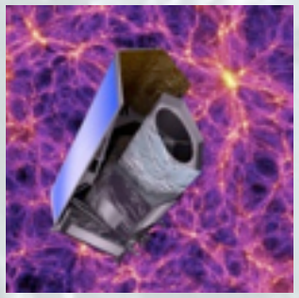
Palanque Delabrouille et al (2013)



and constraint neutrino masses $\sum m_\nu < 0.15$ eV

Prime Focus Spectrograph
SuMIRe

Power of Cross-correlation

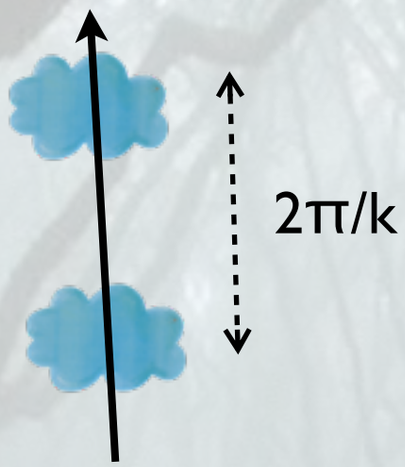


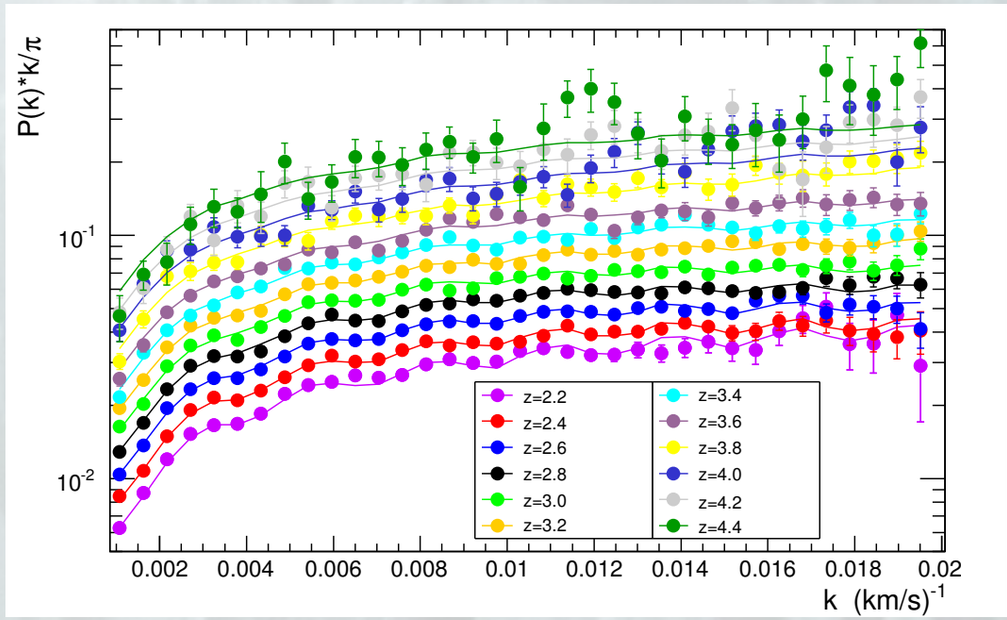
- Absorption and galaxy/quasar BAO both shot noise limited
- Systematics cancel
- Current quasar-forest results powerful
  - but quasars too sparse to be useful alone
- First attempt to probe two BAO tracers in same structure in eBOSS
  - but carbon is a weak tracer
- During DESI/WEAVE high-z galaxies surveys (PFS and Euclid) ⇒ wealth of IGM-galaxy data for cross-correlations

1D Power Spectrum

Power measured long line of sight

Palanque Delabrouille et al (2013)





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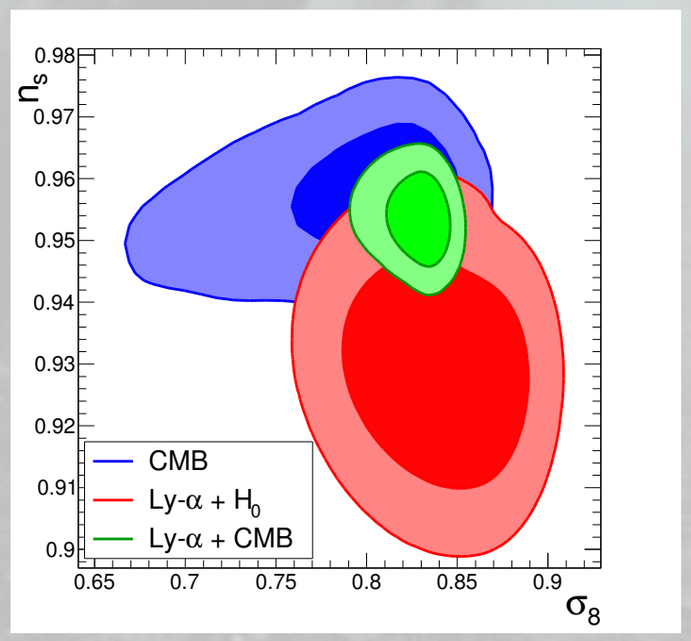
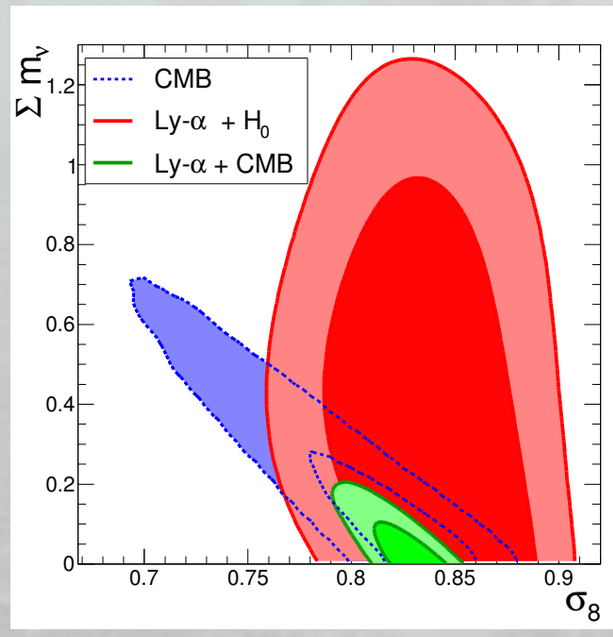
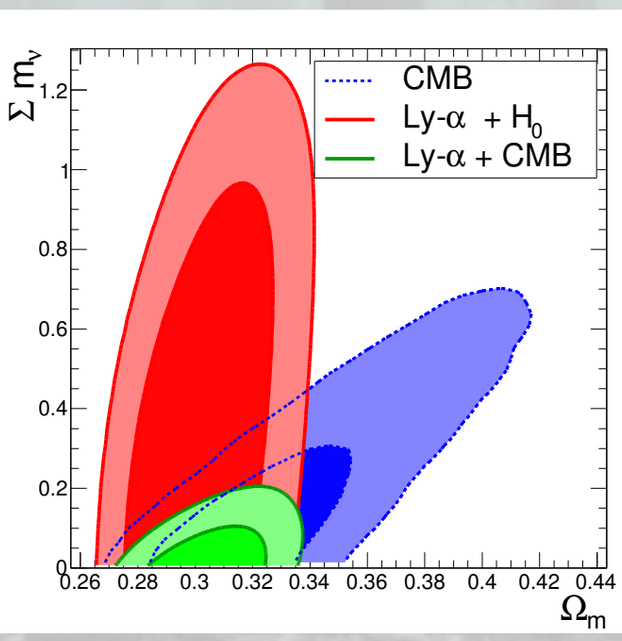
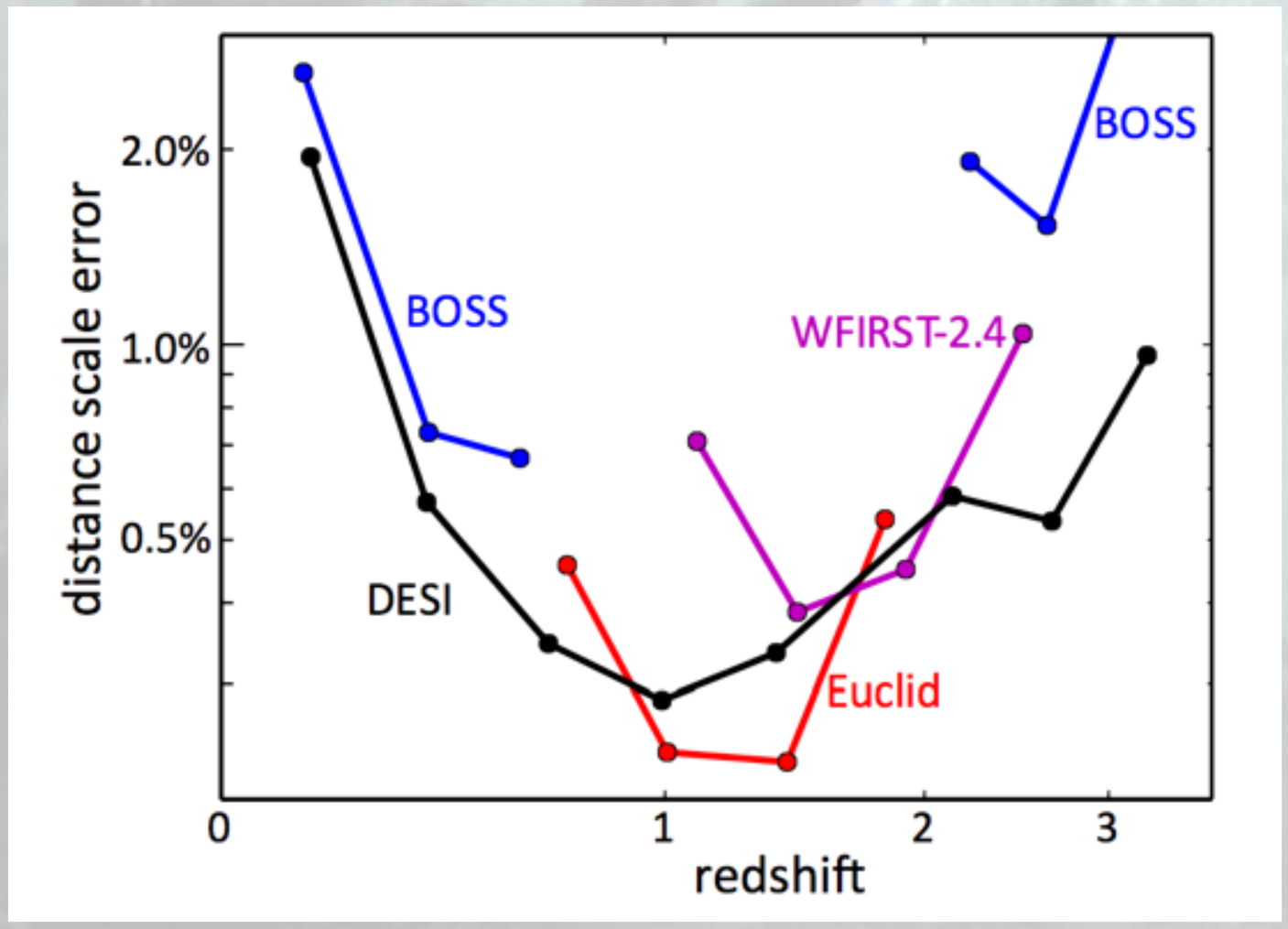
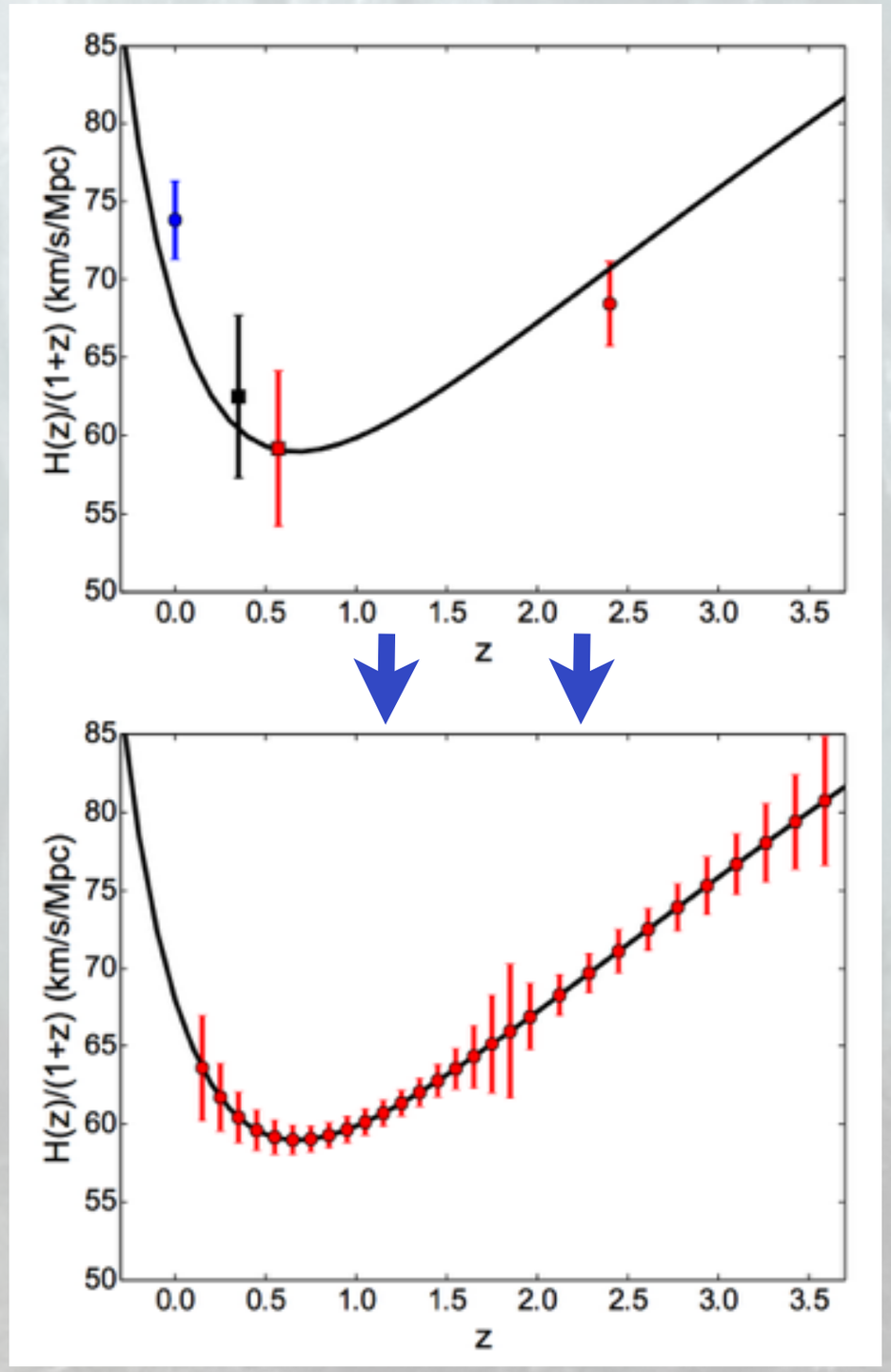






Next Generation BAO Precision



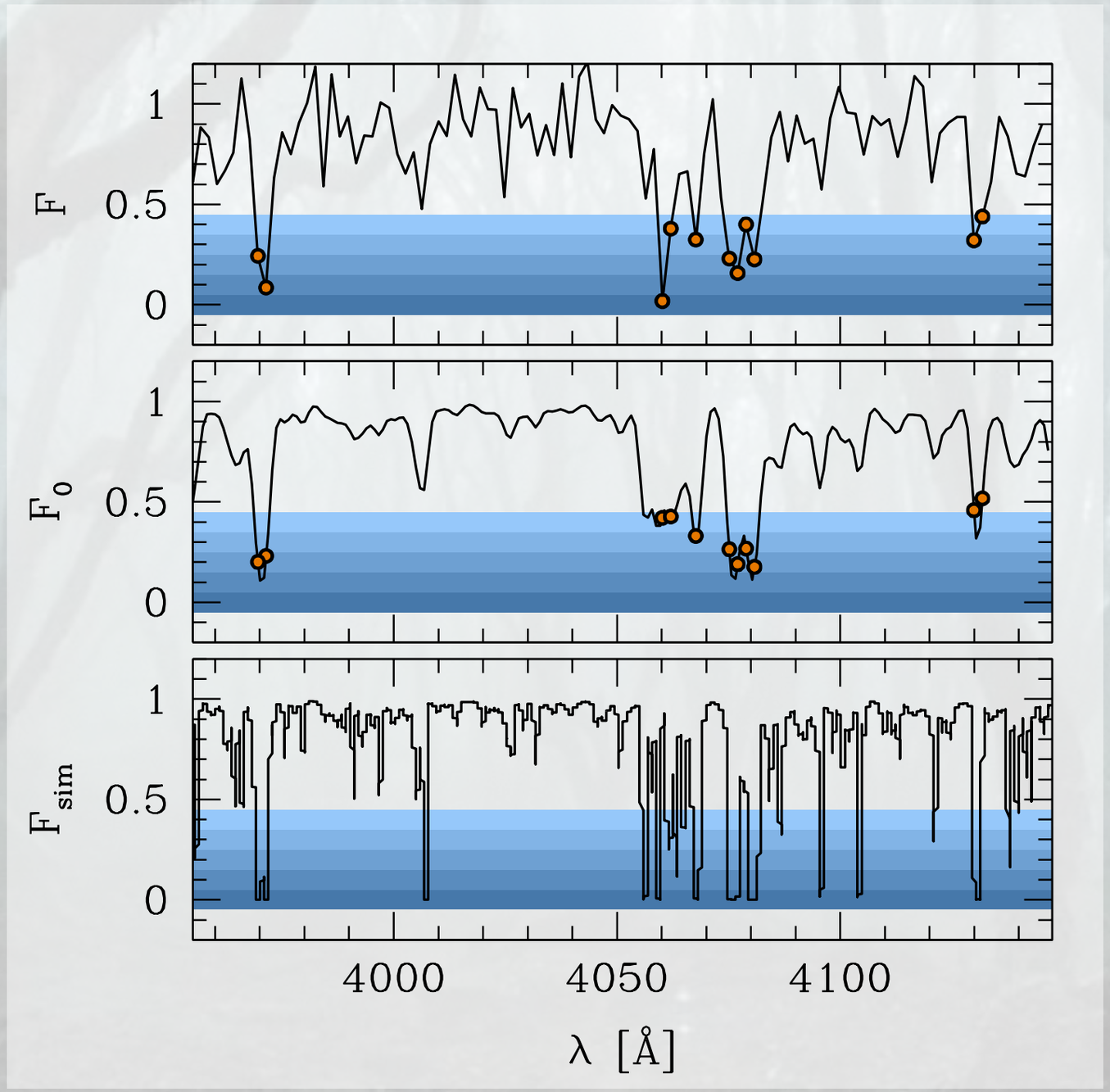


Lyman α Selection: Simulations

BOSS with noise

BOSS no noise

Perfect data



Probes blending at SDSS Resolution

MP et al. (2014)