Centre de Physique des Particules de Marseille, 9th February 2015

In the Deep, Dark Lyman-α Forest: Exploring Dark Energy and Galaxy Formation using the Intergalactic Medium

Mat Pieri

with the BOSS LyαF Working Group

Outline

- What is the Intergalactic Medium and how is it observed?
- Using the IGM to measure cosmology
- Surveys present and future

Space is not a vacuum

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- You all knew that though

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  - There is the interstellar medium

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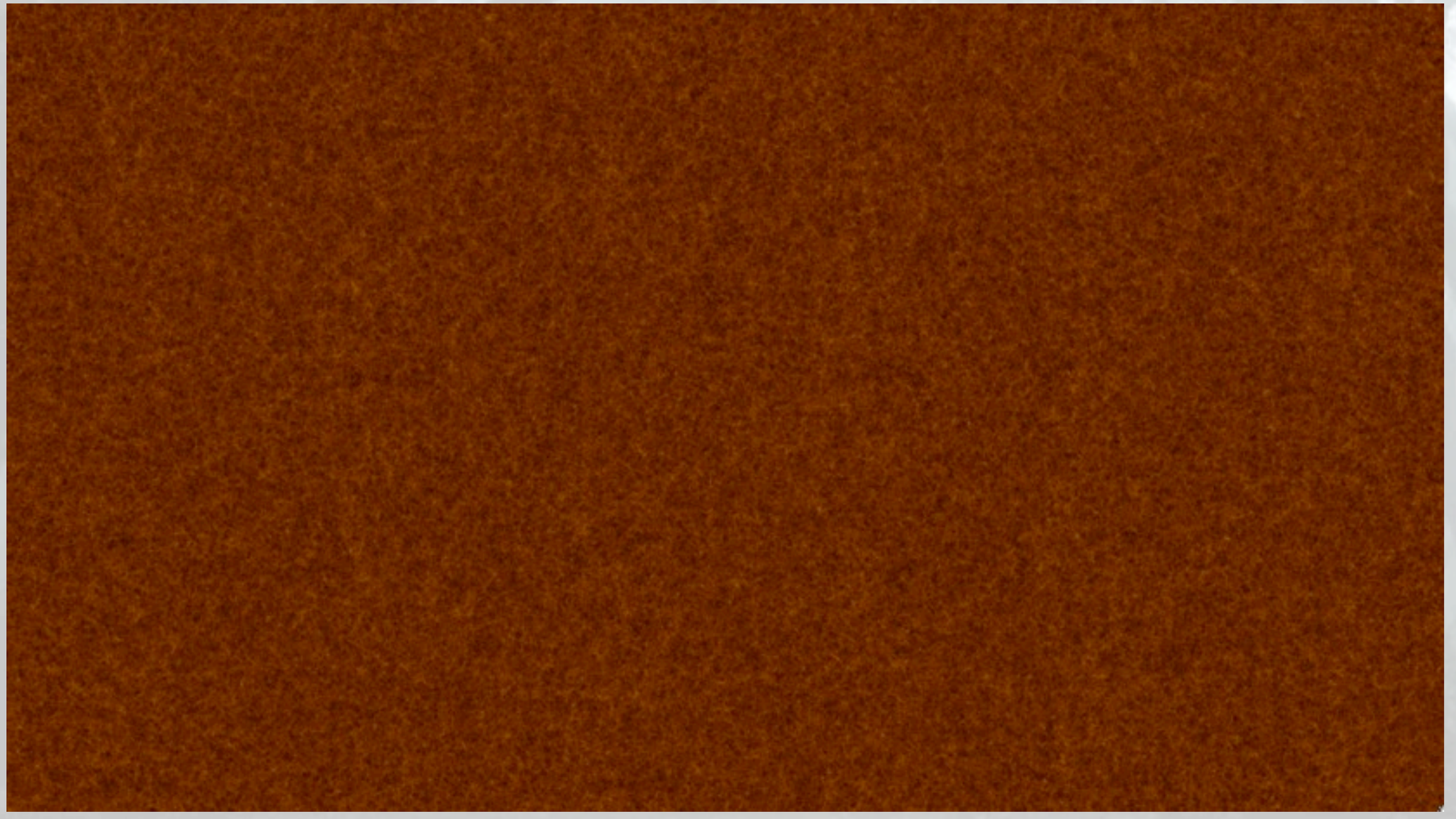
  - ... oh and the gas in filaments
- No part of the universe is empty!

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)

Monday, 9 February 15

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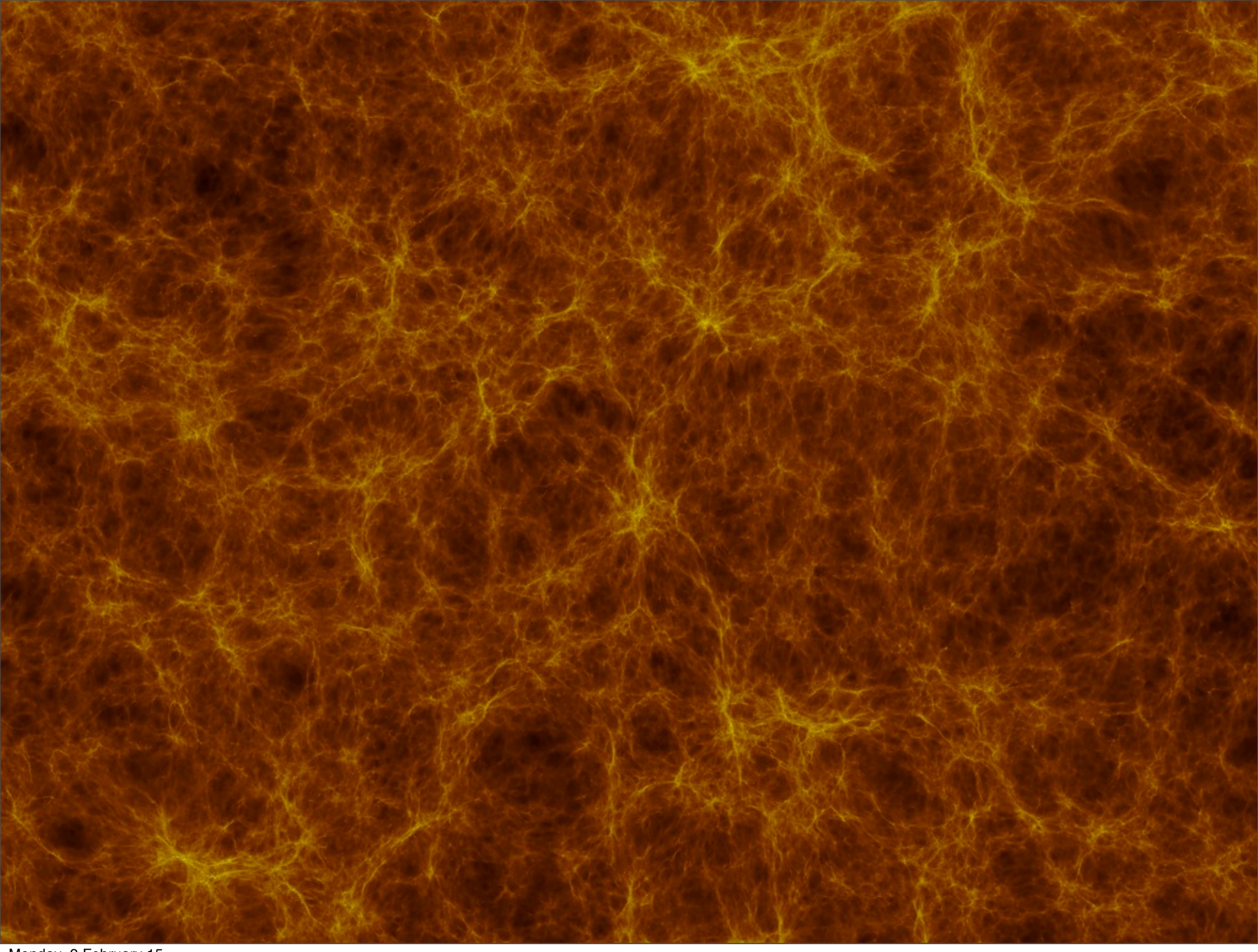
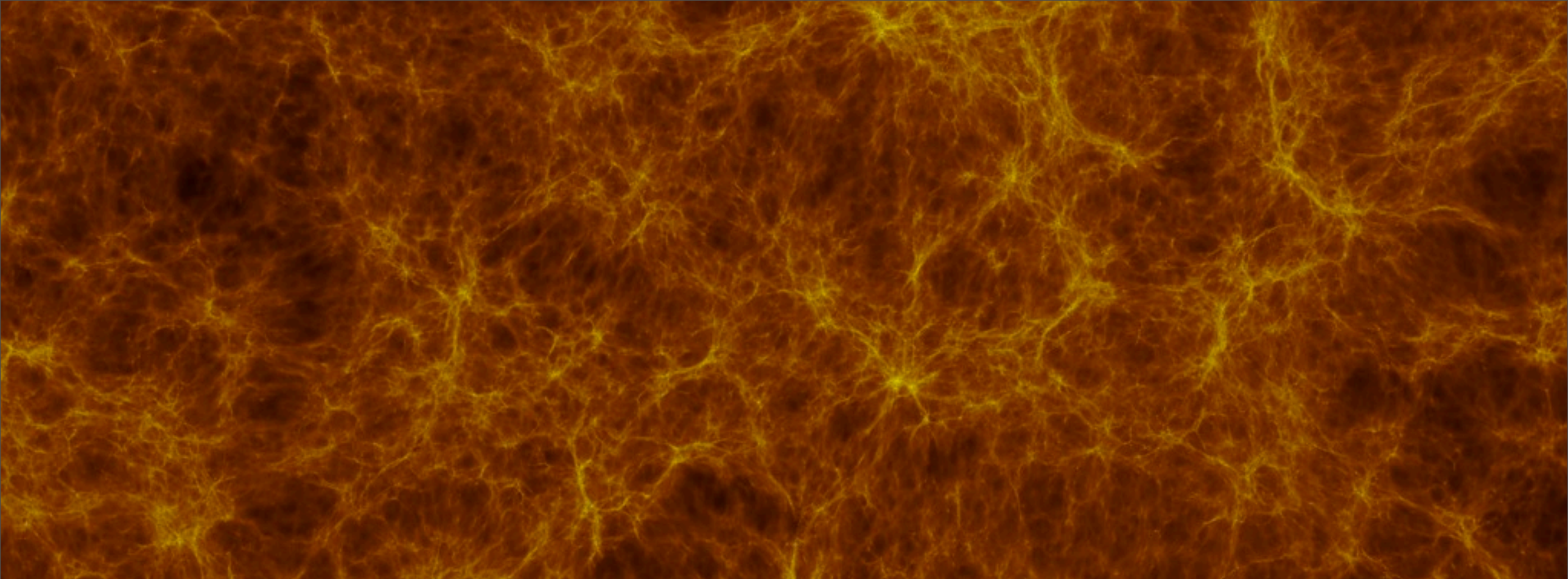
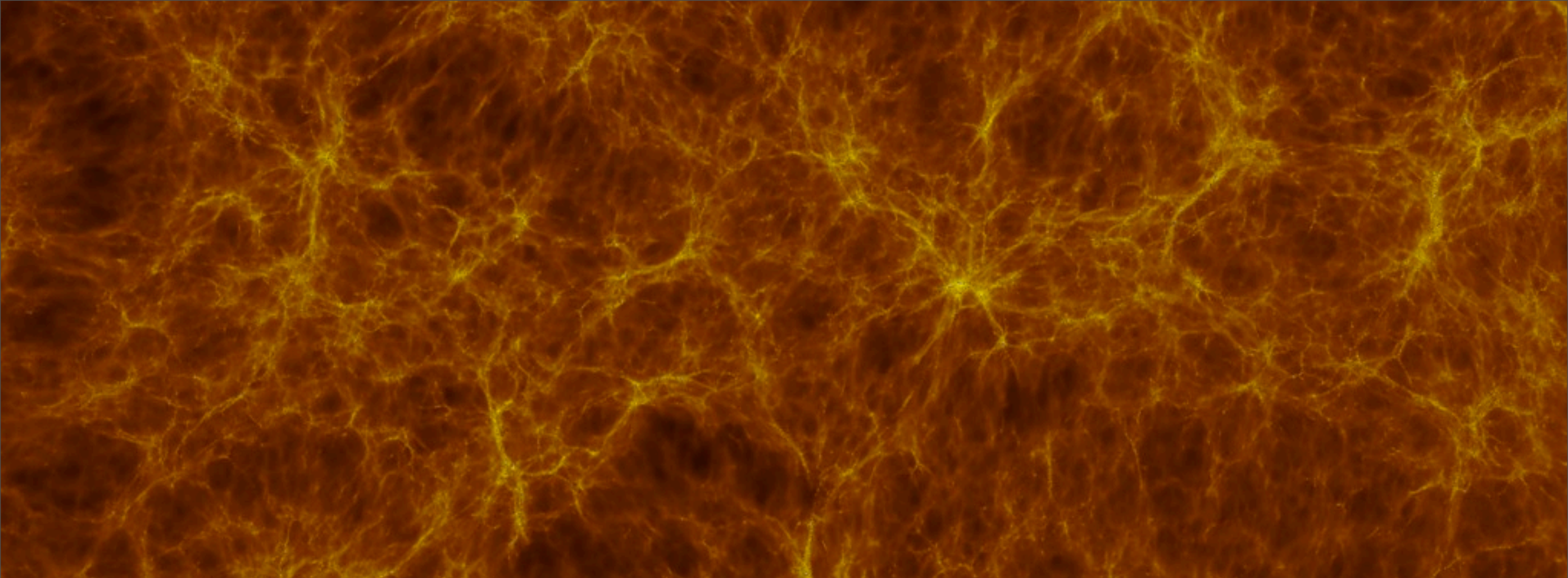
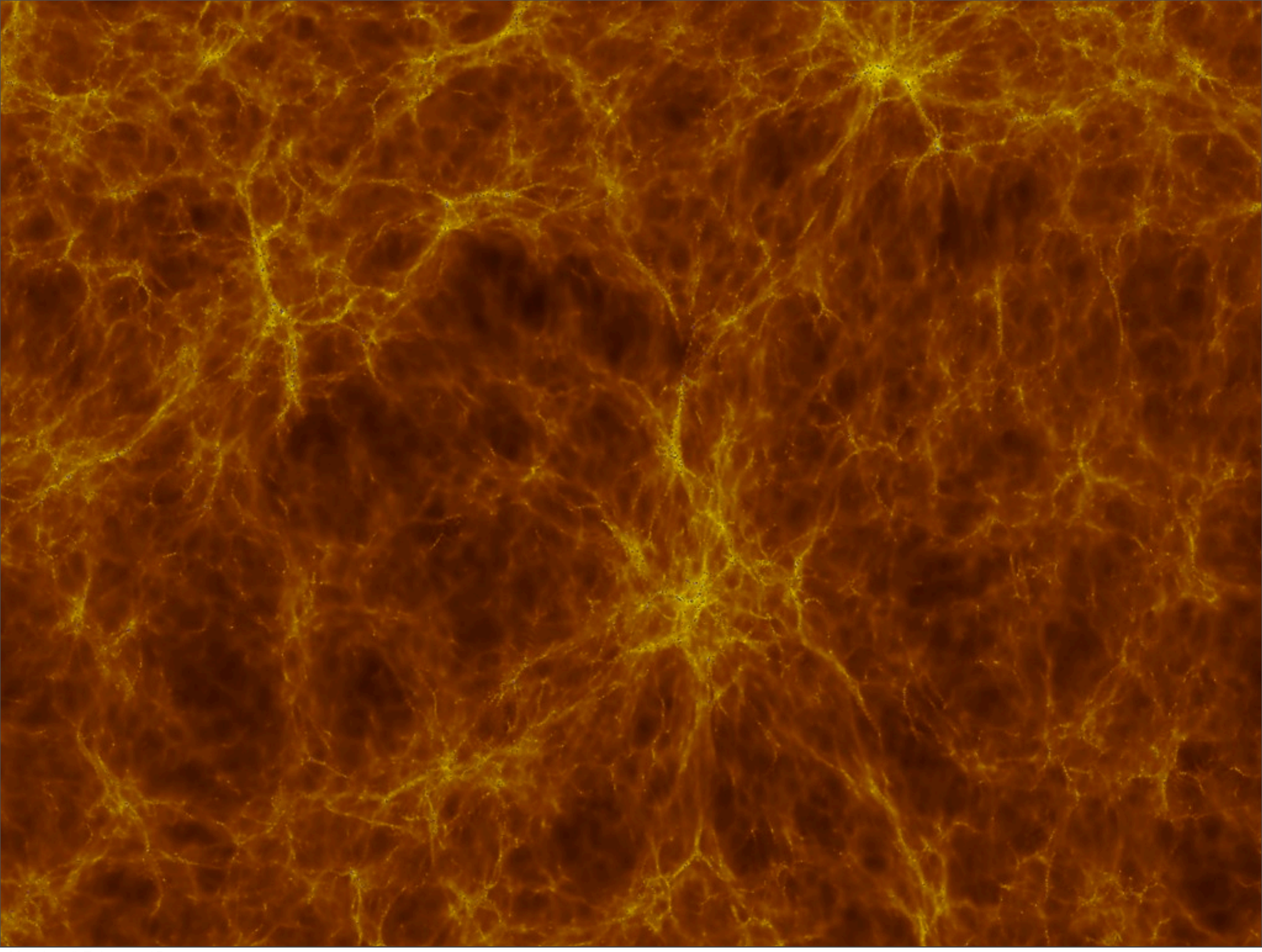
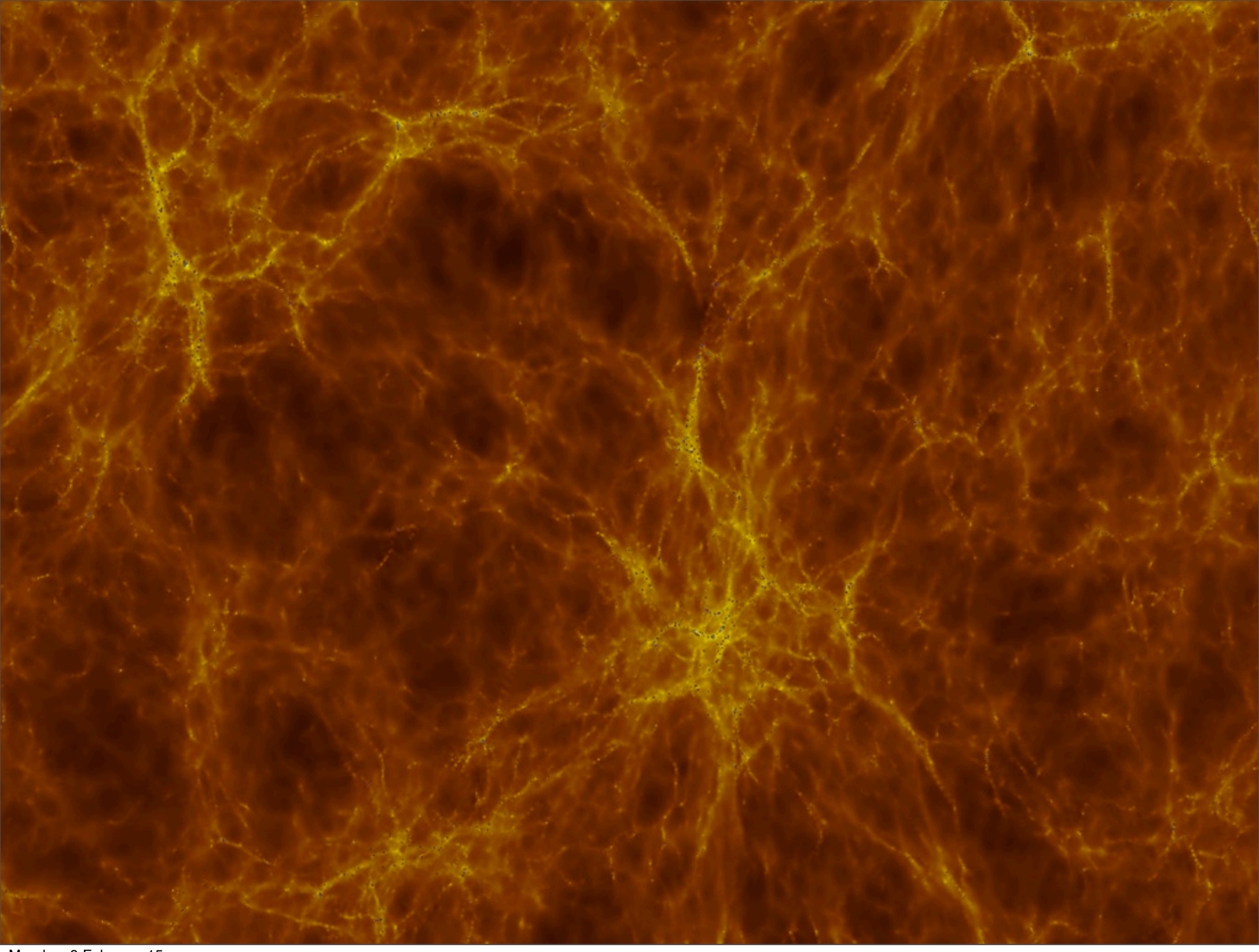
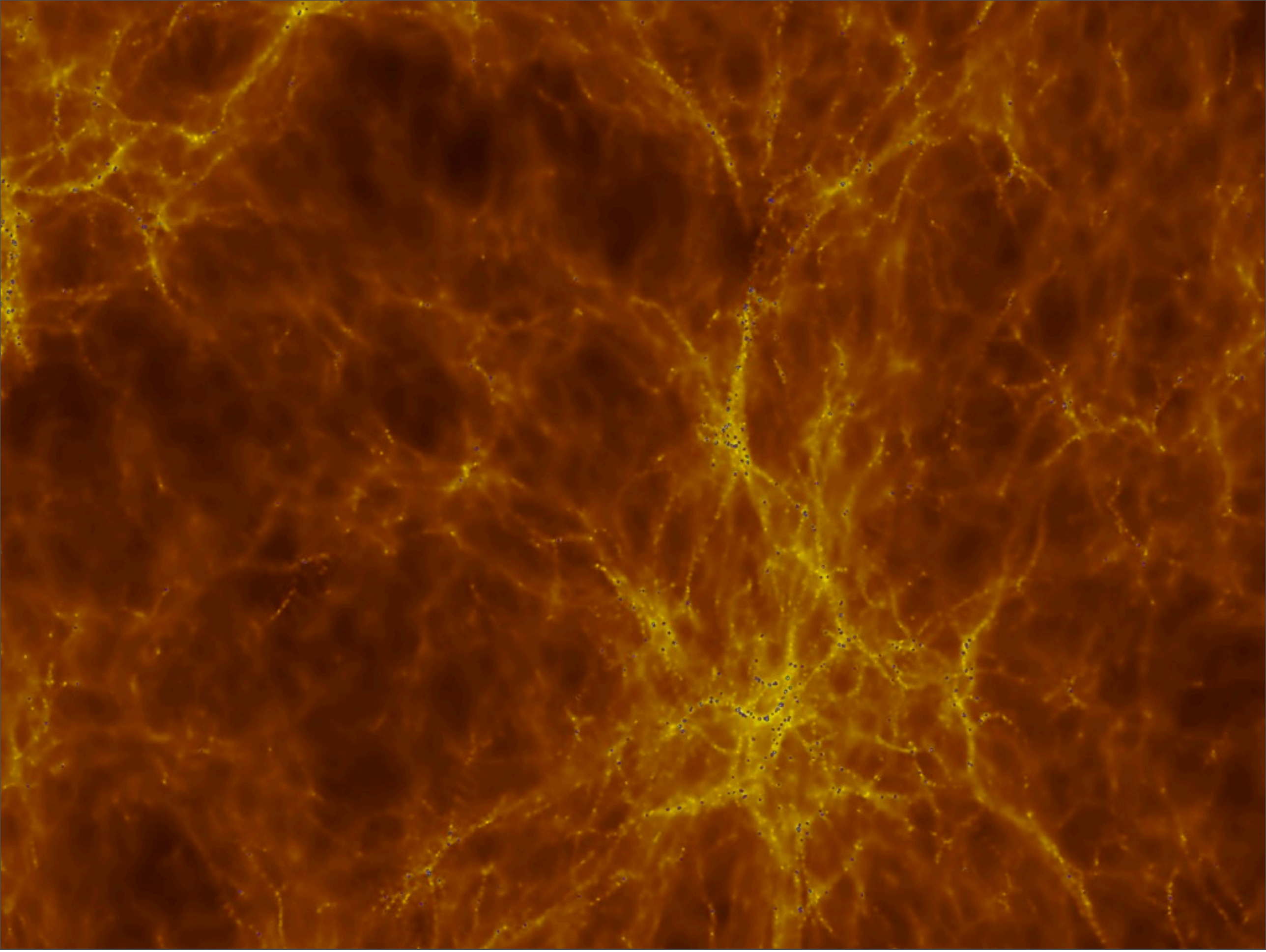






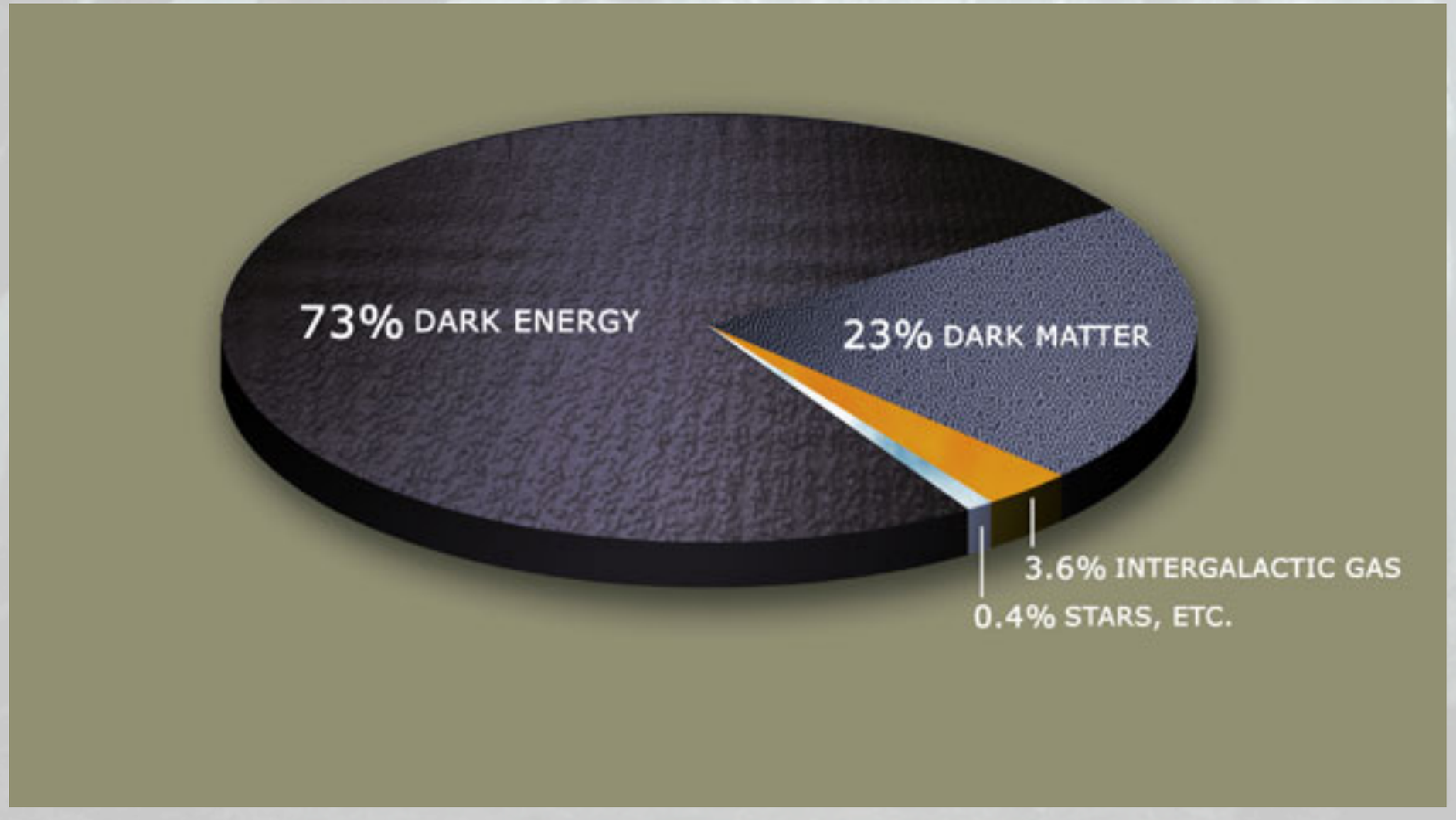






Google: “gigapan Massive Black” to explore this

Mass density of Intergalactic Medium



Gas collapses to form galaxies and accretes to grow them

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

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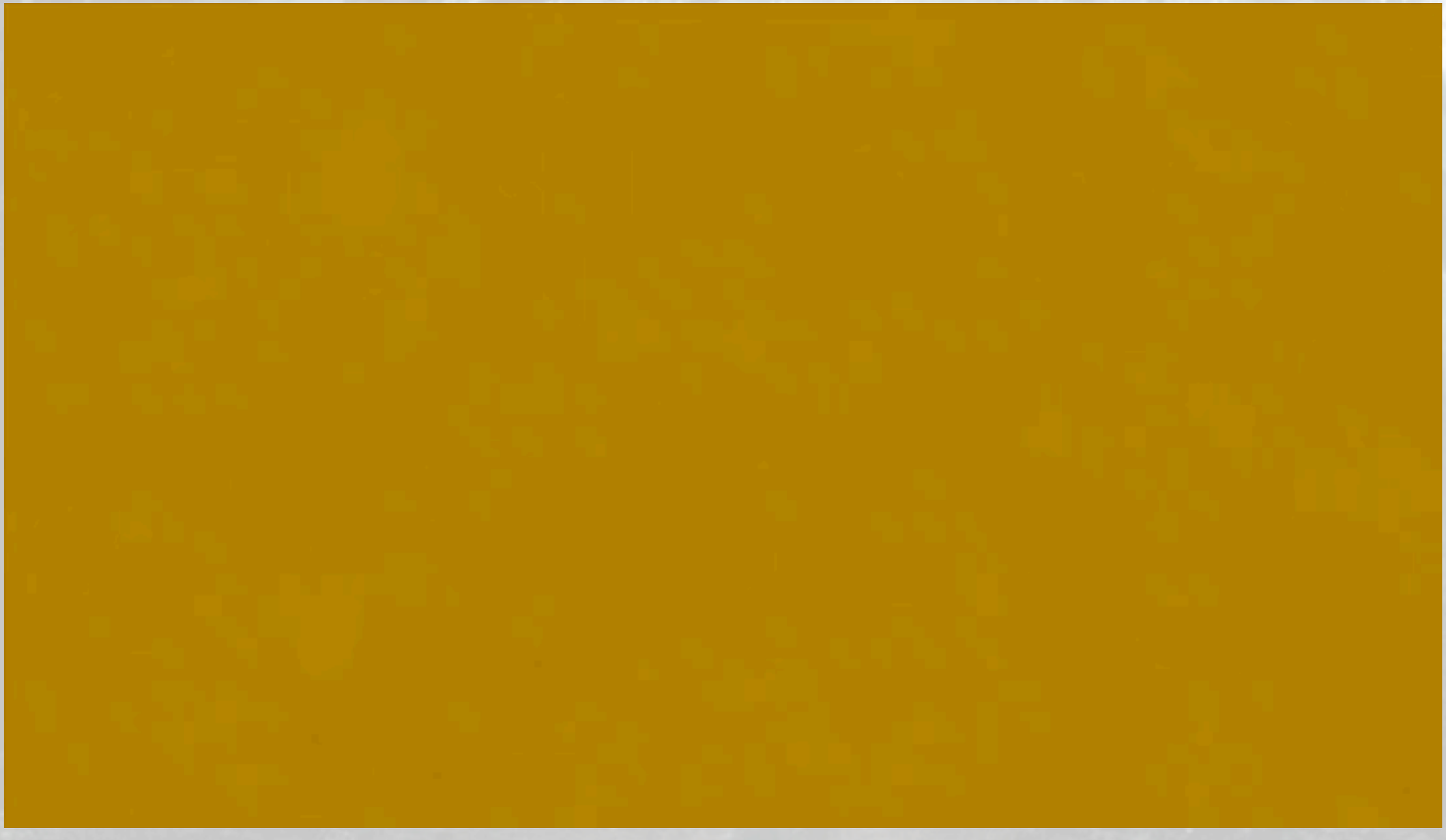
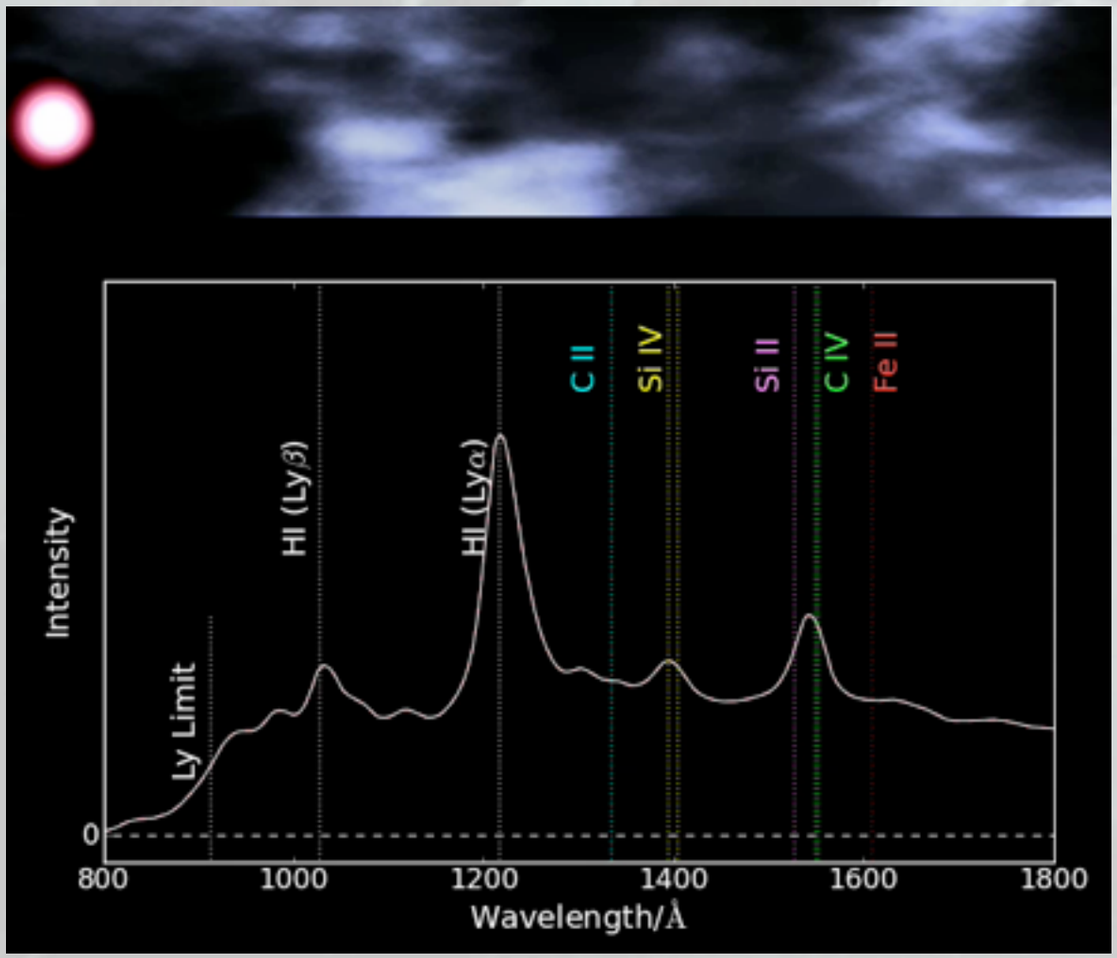


Di Matteo et al. (2011), Feng et al (2011)

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 $f = CF = Ce^{-\tau_{\rm HI}}$
- Departures from this
  - UV background modulation
  - Strong lines
  - Small scale physics

Quasar Spectra and Lyman α Forest



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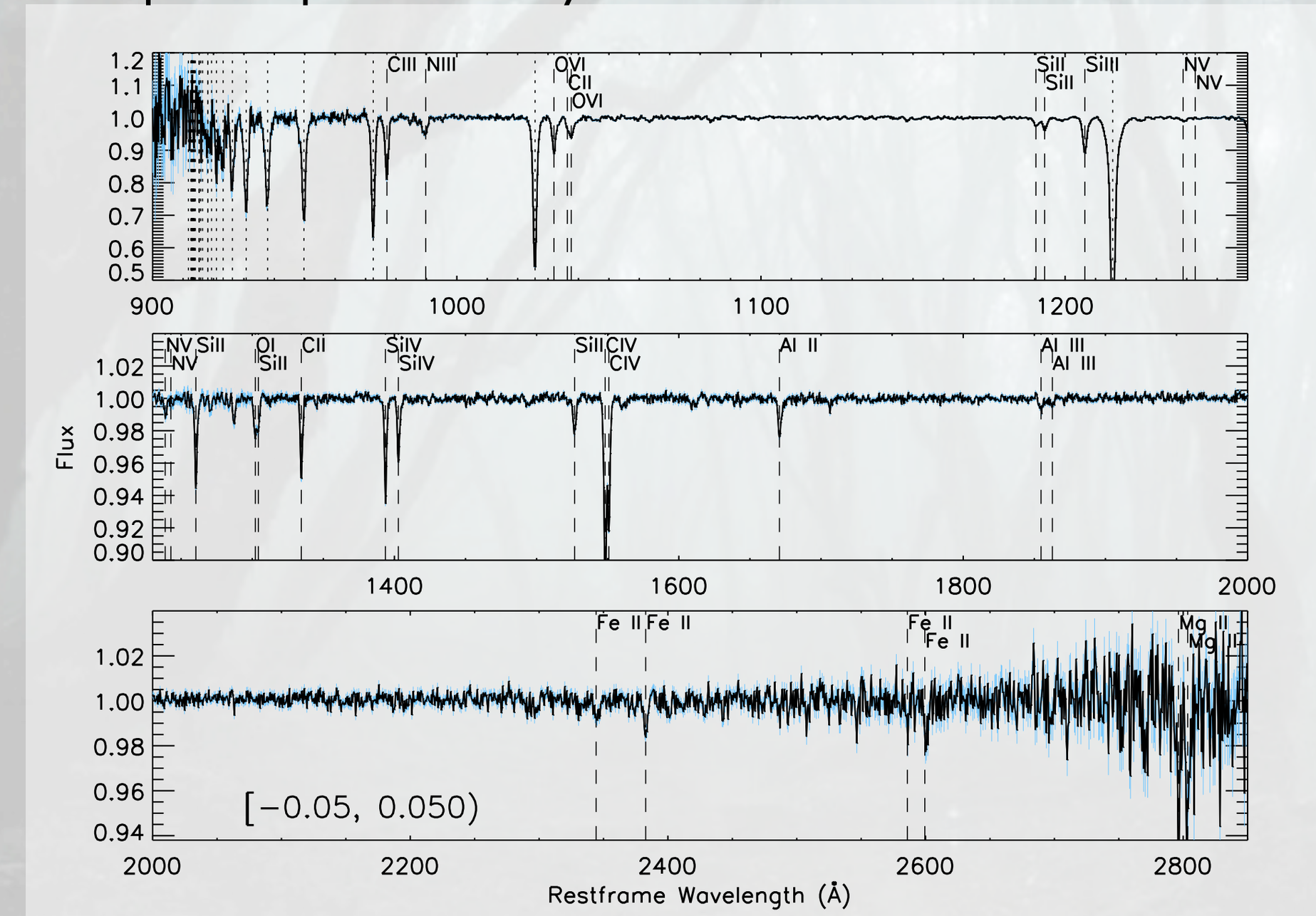
Other Absorption in the Forest

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



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

Outline

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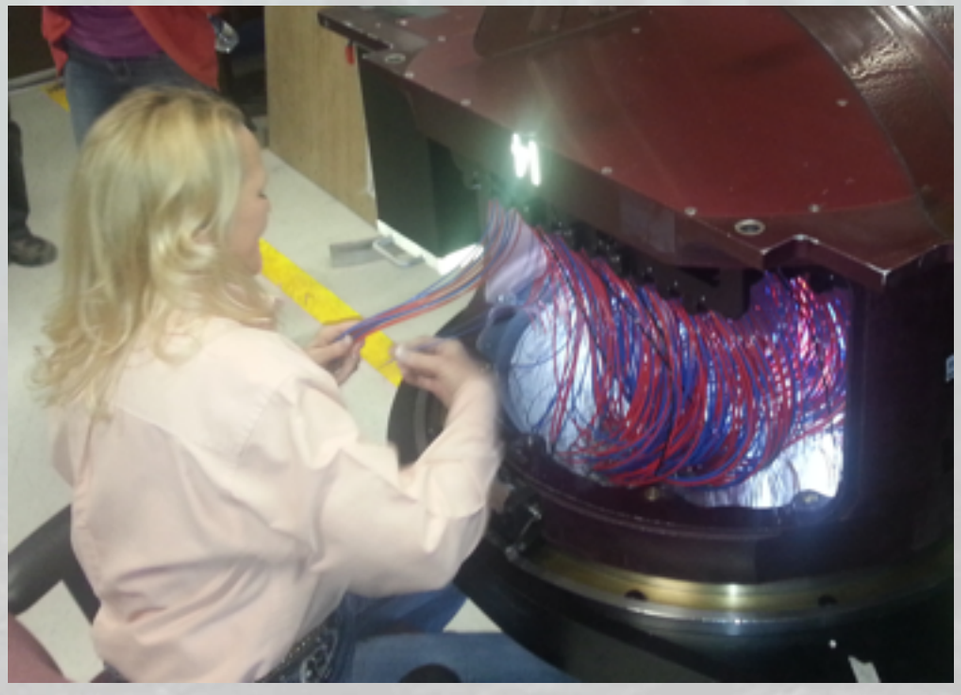
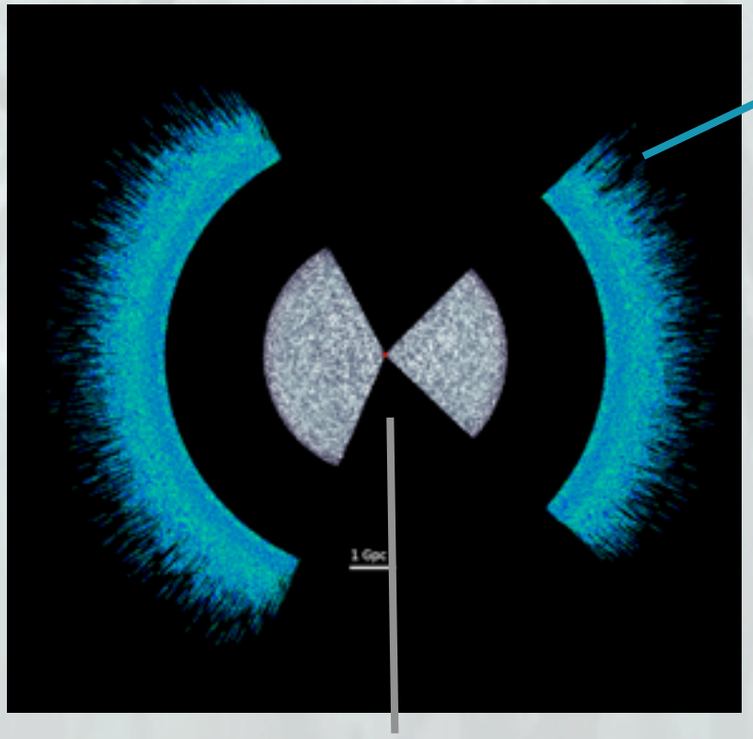
The Sloan Digital Sky Survey (SDSS)

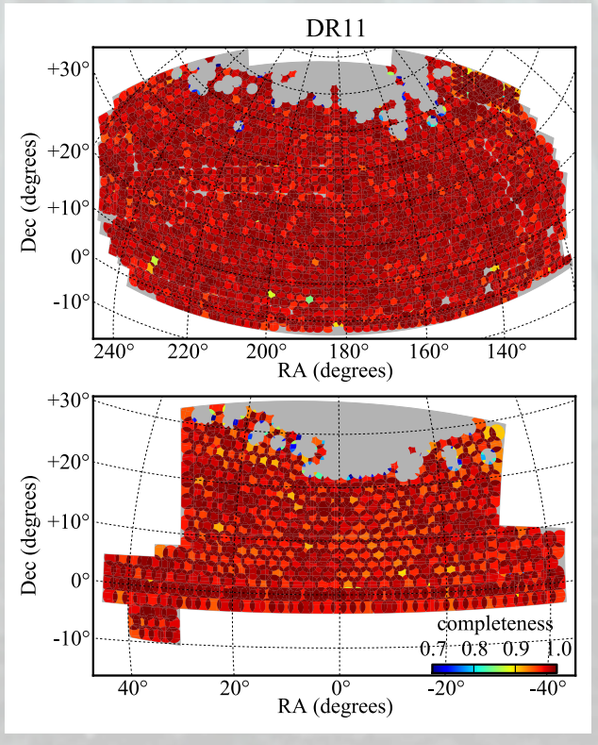
- Began in 2000
- Dedicated 2.5m SDSS telescope at Apache Point, New Mexico, USA
- On of the most highly cited endeavors in the history of astronomy
- Imaging and spectra across ~1/3 the sky
- Spectra of many million stars, galaxies and quasars
- 1000 fibres per “field”
- Resolution R = 2000
- Began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



Baryon Oscillation Spectroscopic Survey (BOSS)

- 1 of 4 surveys in SDSS-III between 2009-2014
- 1/4 of the sky (10,000 deg^2)
- The goal: 1.6M galaxies and >160k forest quasars
- Resolution R = 2000





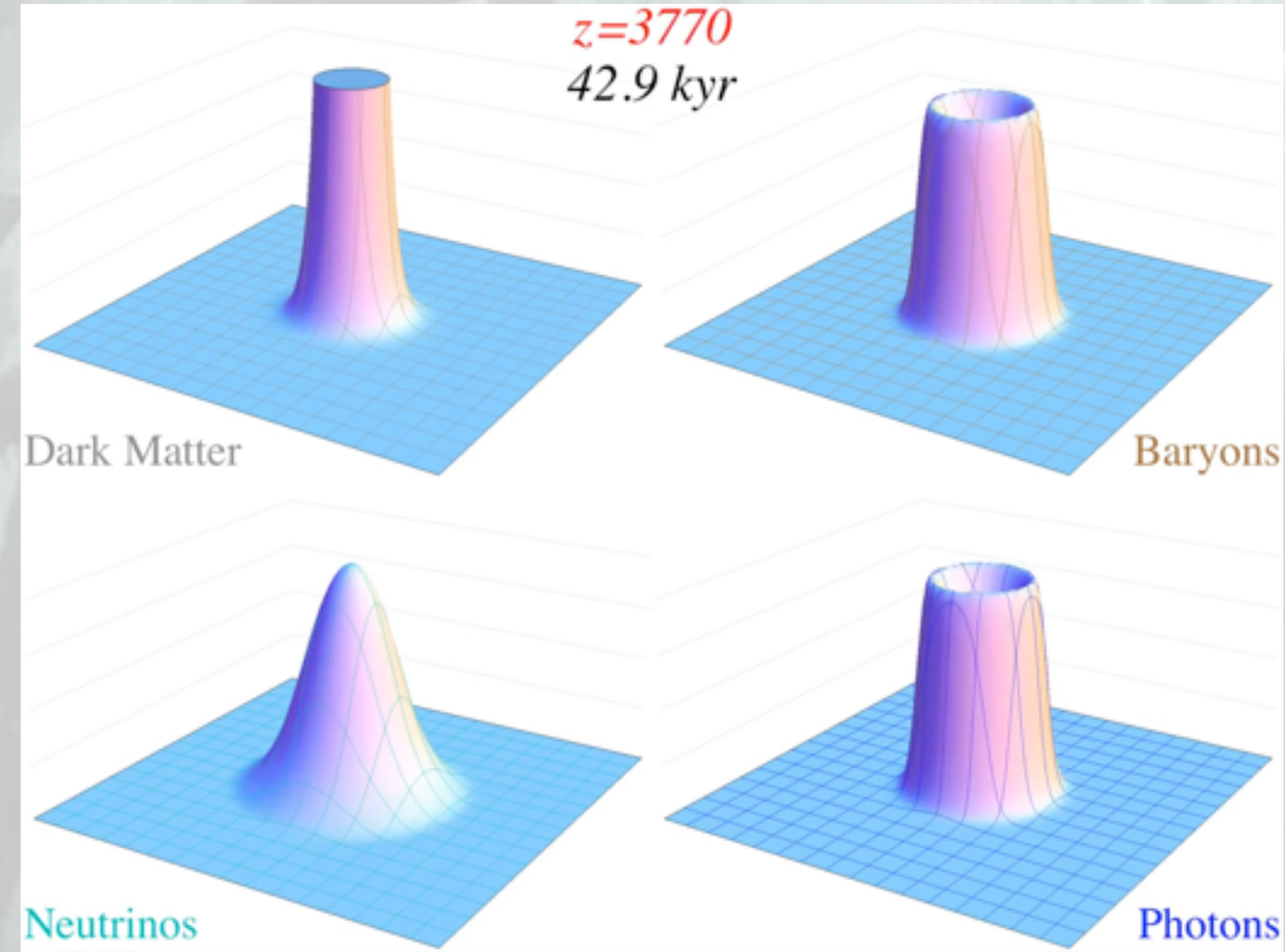
The final BOSS Lyα forest survey (DR12):

- 158k quasars with z > 2.15
  - ~550k visually inspected (Paris et al. 2014)
- > 30k DLAs (Noterdaeme et al. 2012)
- DR9 forest sample public (*Lee et al. 2013*)

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

Baryon Acoustic Oscillations



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- BIG ~100 Mpc/h comoving
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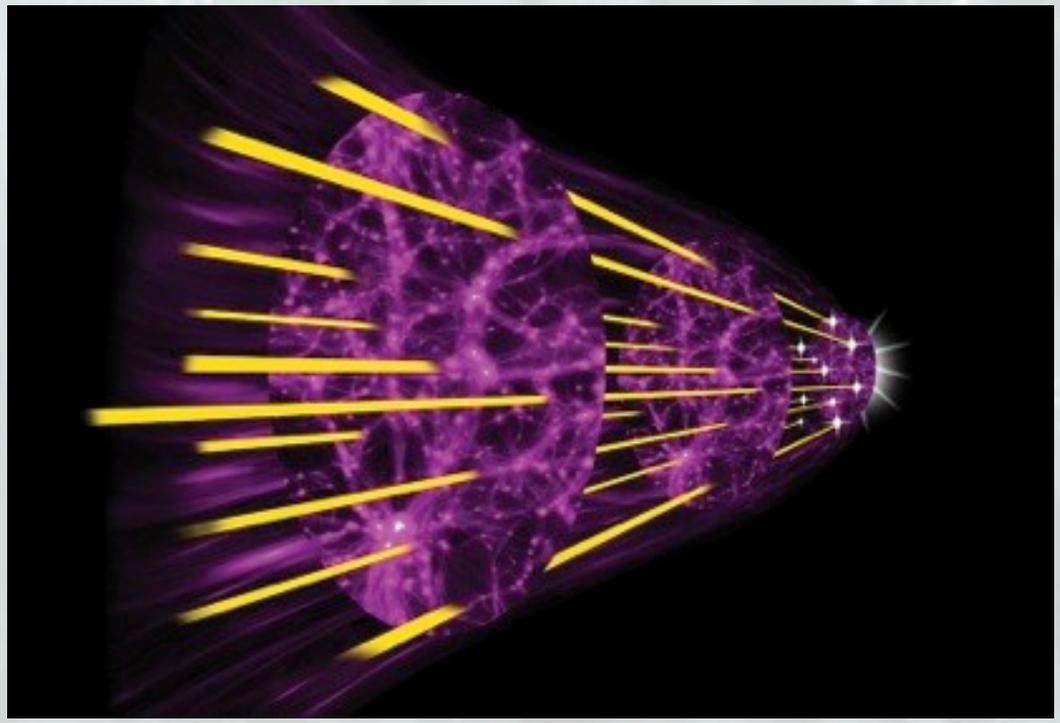
Measuring BAO in BOSS-LyαF

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



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

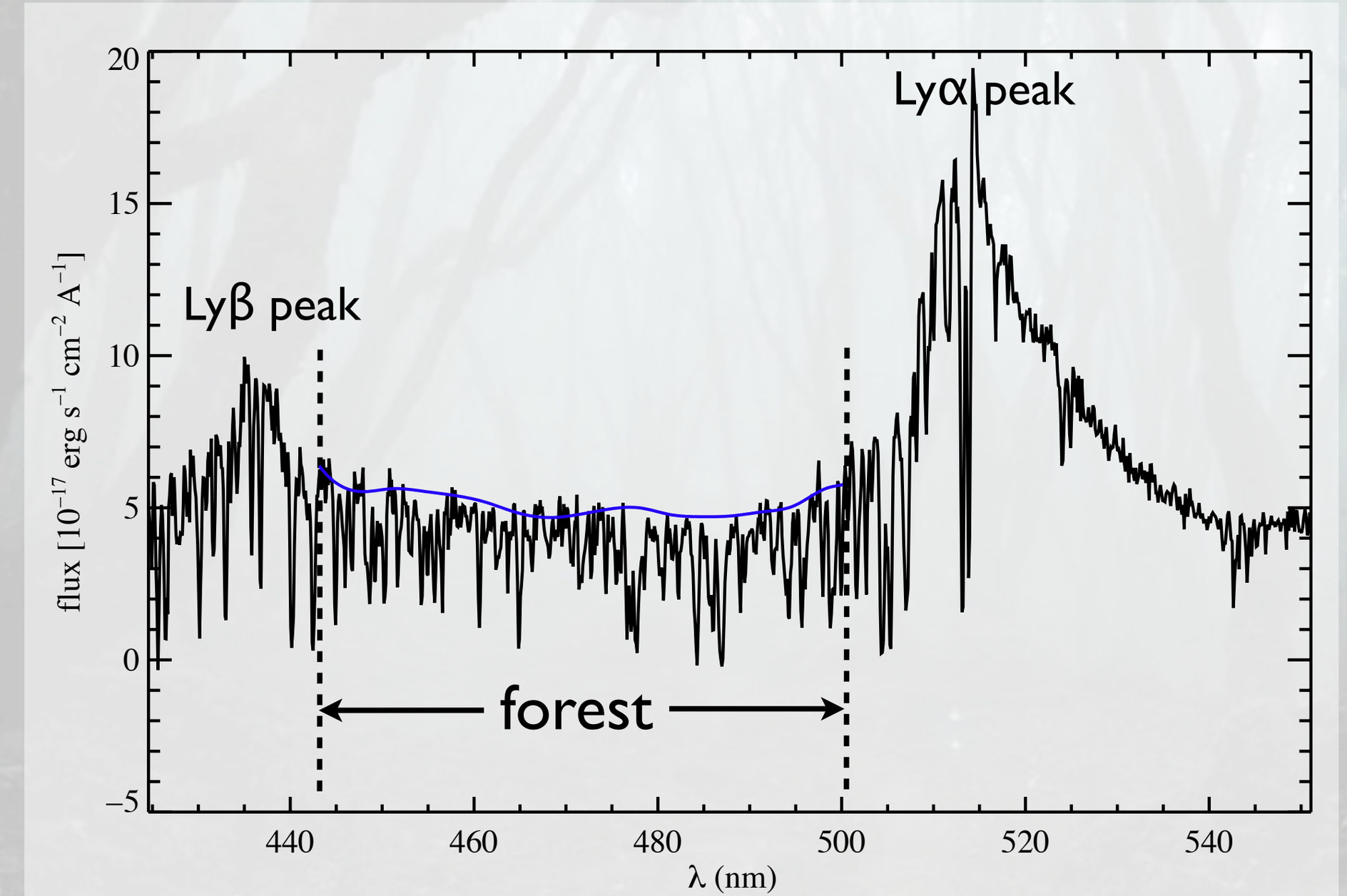
- Measure $\xi(r) =< \delta\delta >$ where $\delta(z) = \frac{f}{C\bar{F}} - 1$
- Compared with mocks (*Bautista et al 2014, Font-Ribera et al. 2012*)

Can also measure BAO using metal absorption *(MP 2014)*

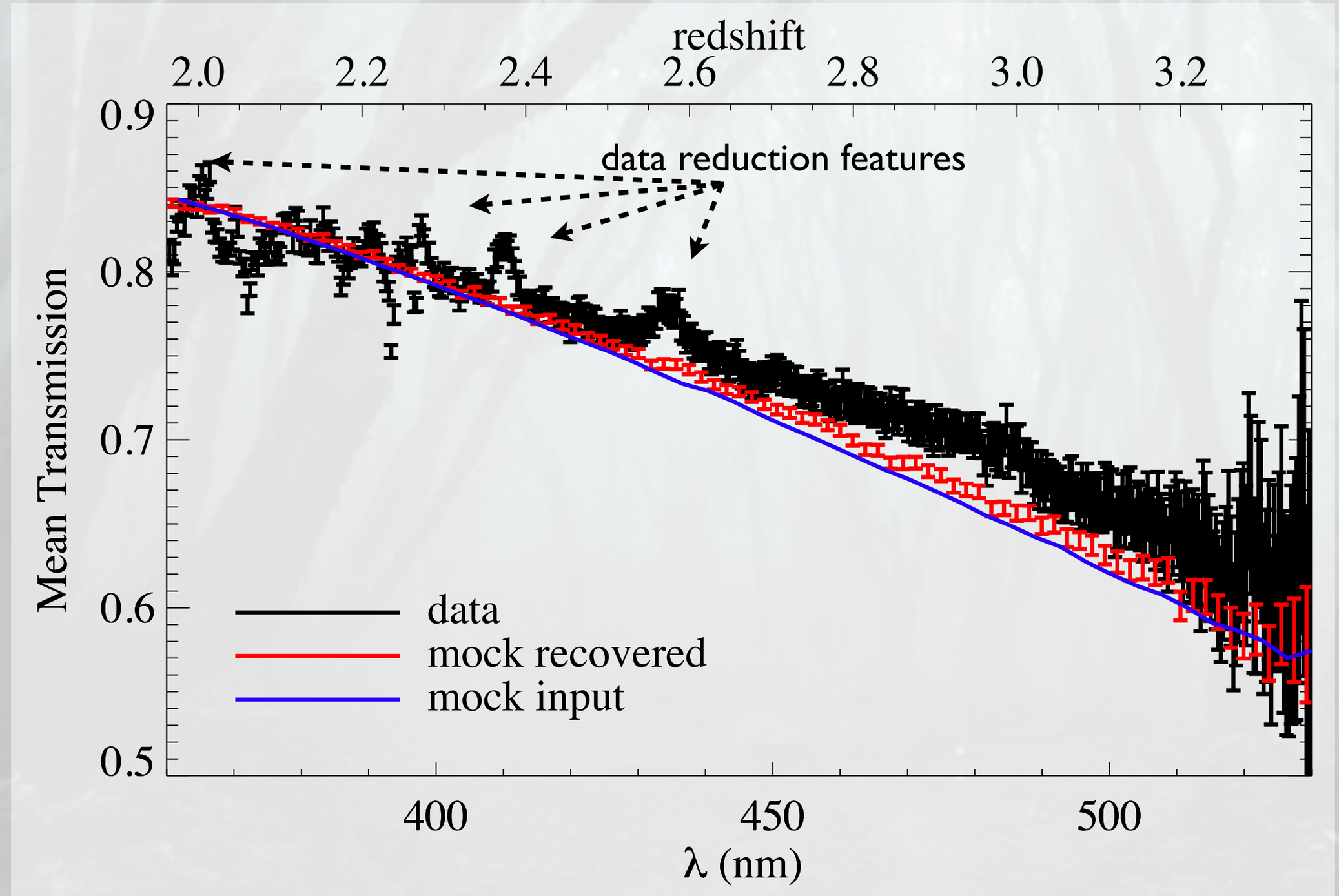
Calculating $\delta(z) = \frac{f}{C\bar{F}} - 1$

maximum likelihood of mean quasar + absorption PDF + noise PDF

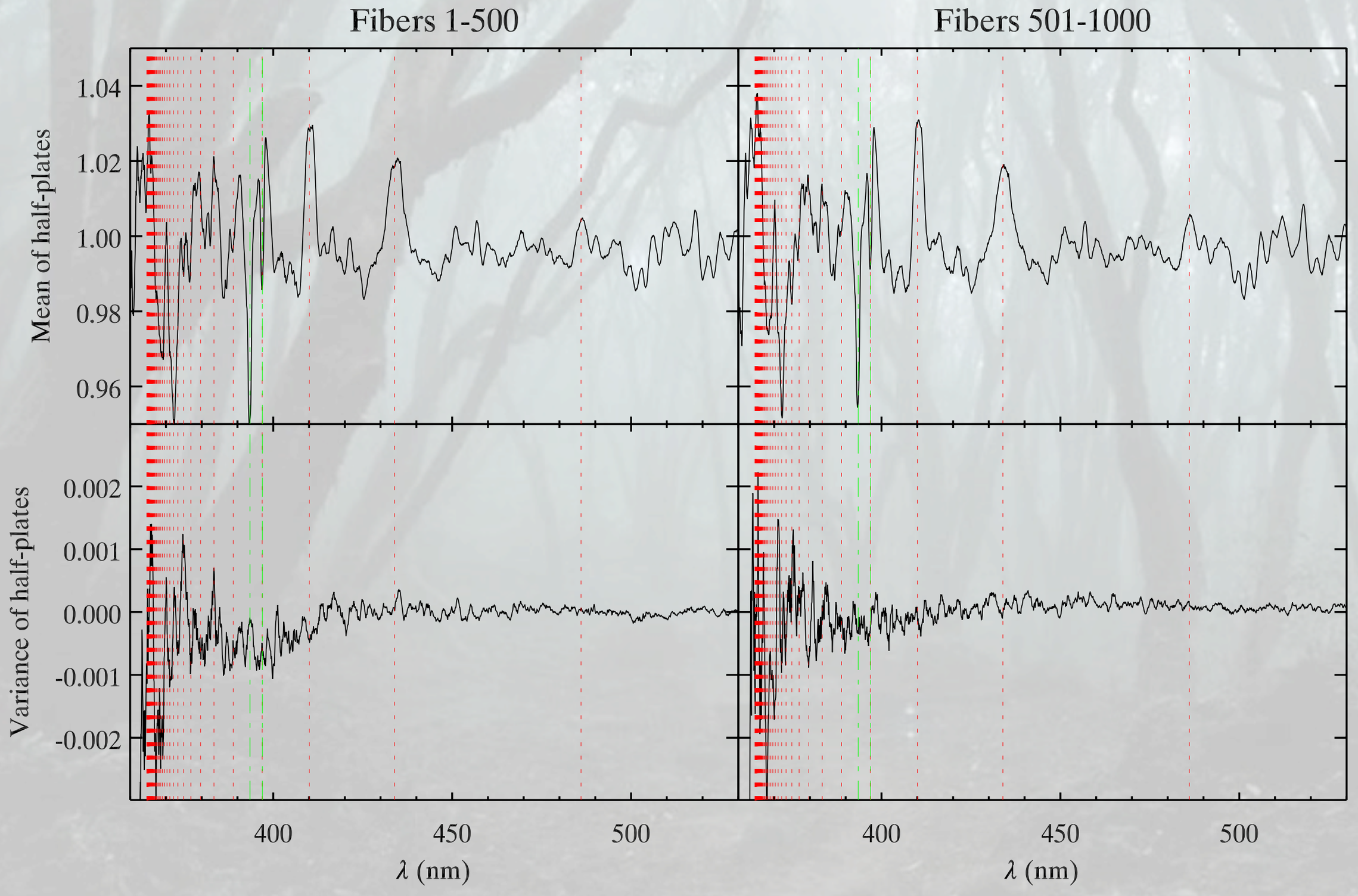
→ continuum



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

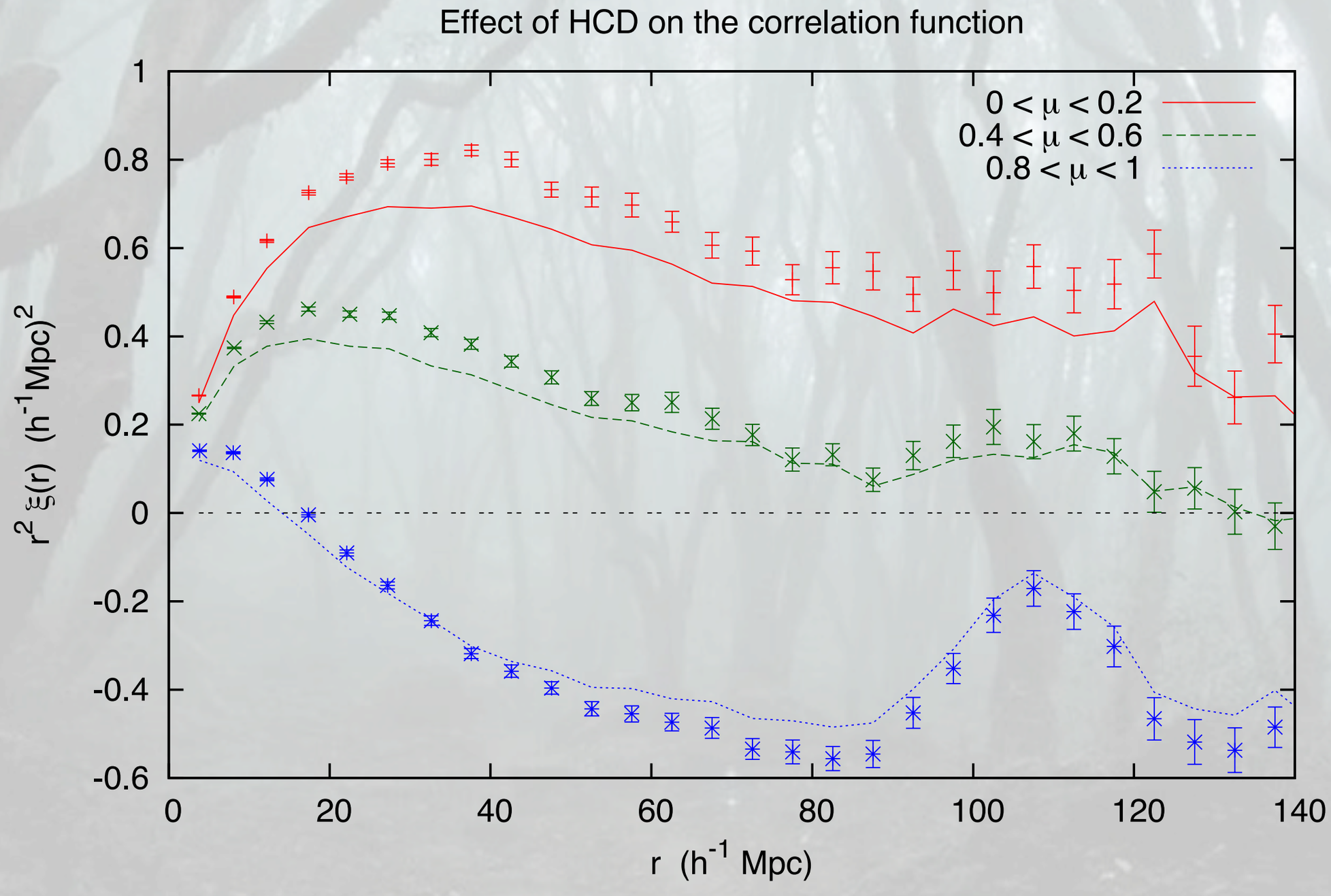


Spectral Artifacts



Impact of Lyα Strong Lines

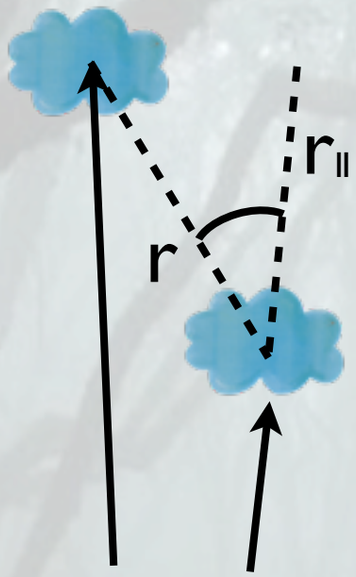
Font-Ribera & Miralda-Escudé (2012)



Correlation Function Measurement

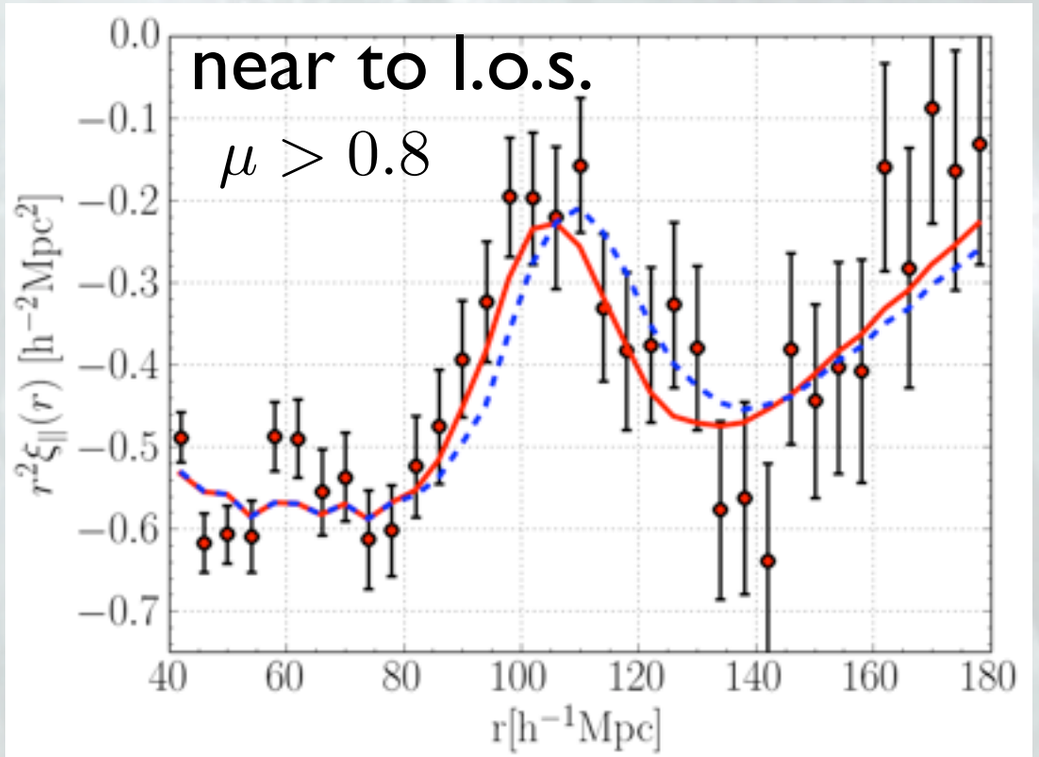
Sum over all pairs of deltas

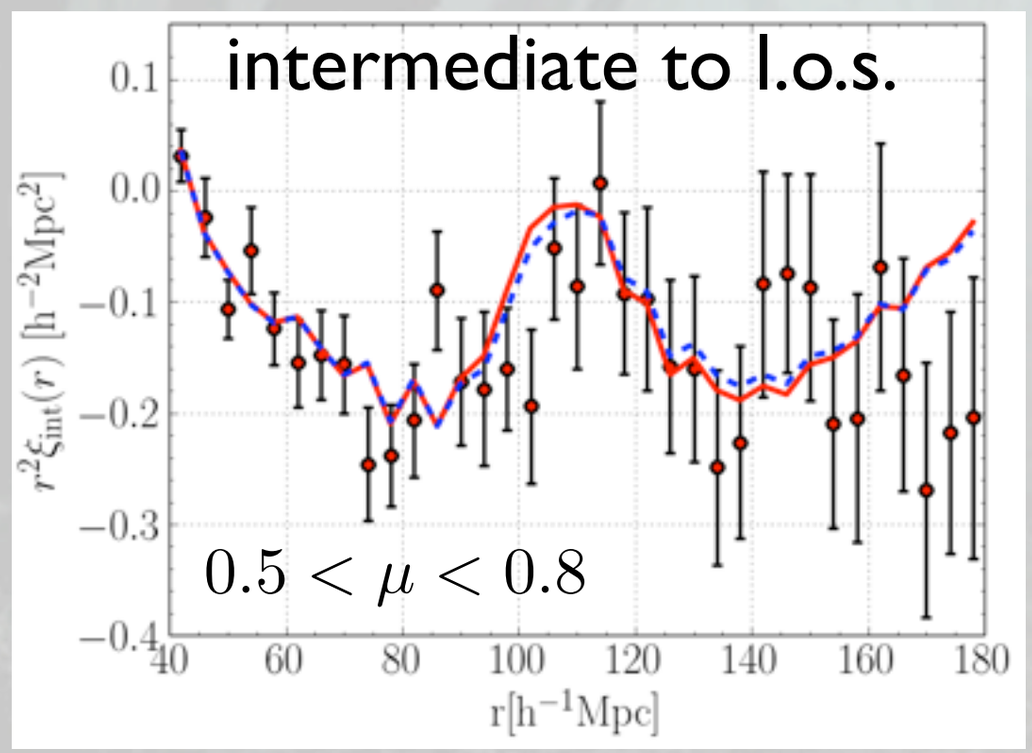
$$\xi(A) = \sum_{i,j \in A} w_{ij} \delta_i \delta_j$$

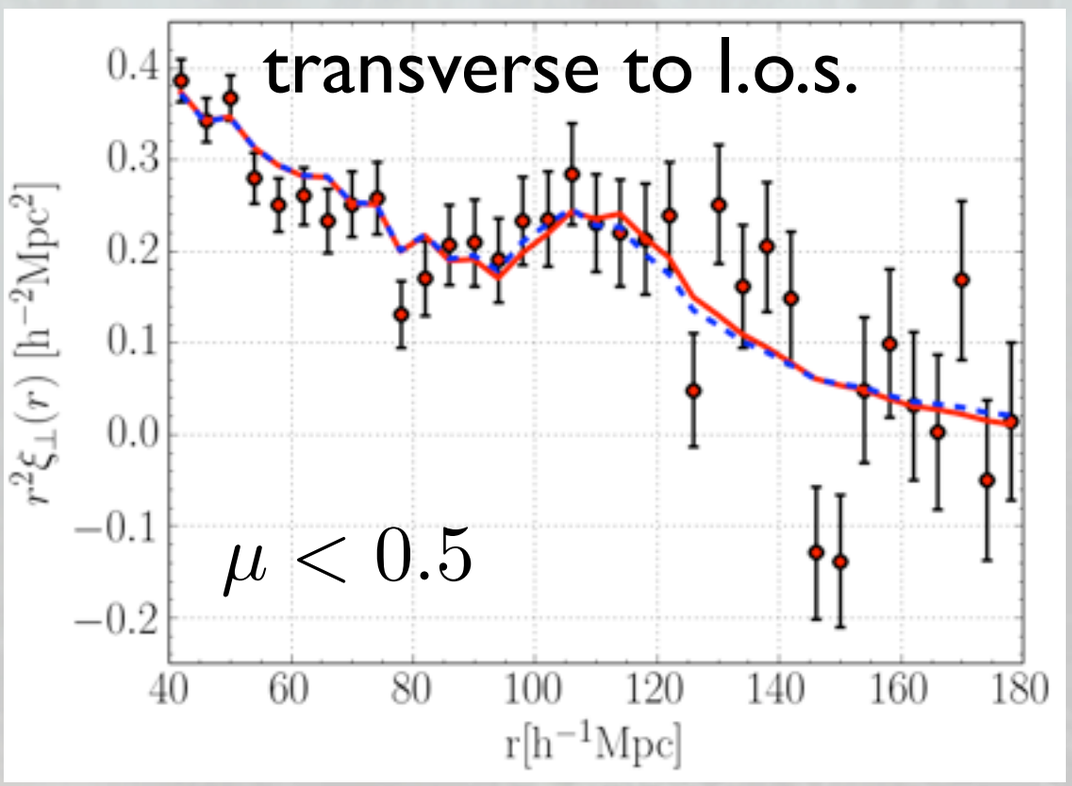


note that $\mu = \frac{r_\parallel}{r}$

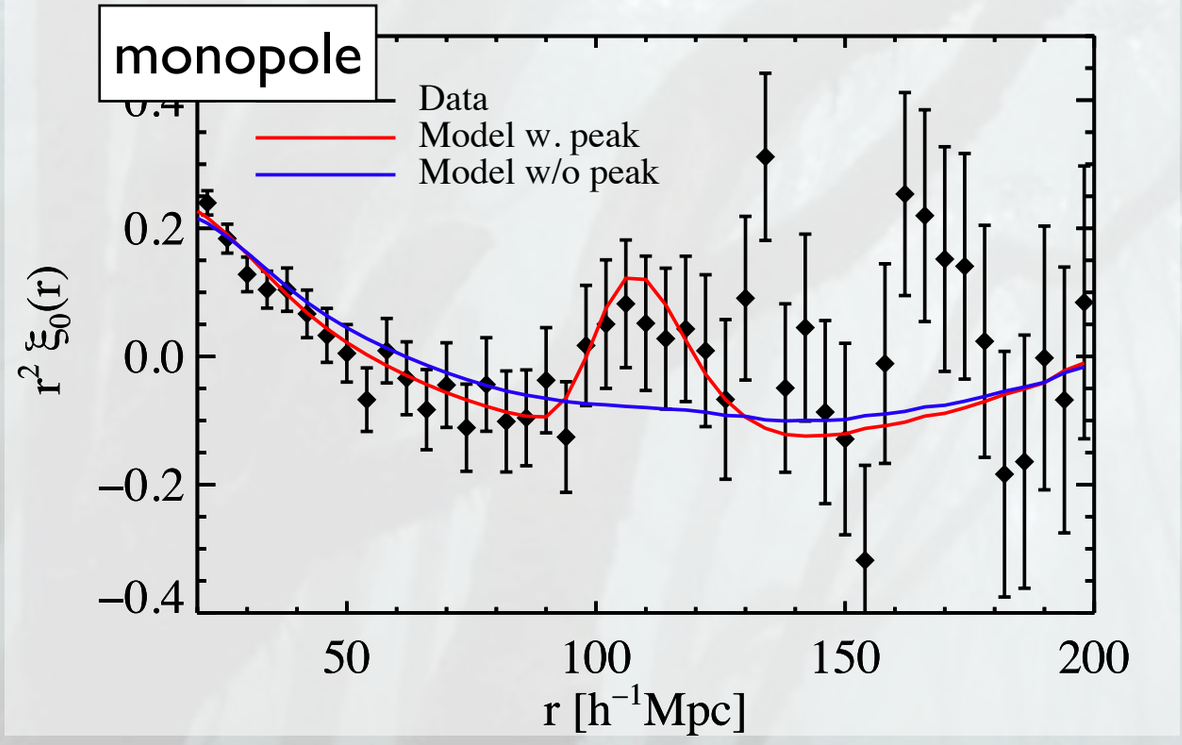
Delubac et al (2014)

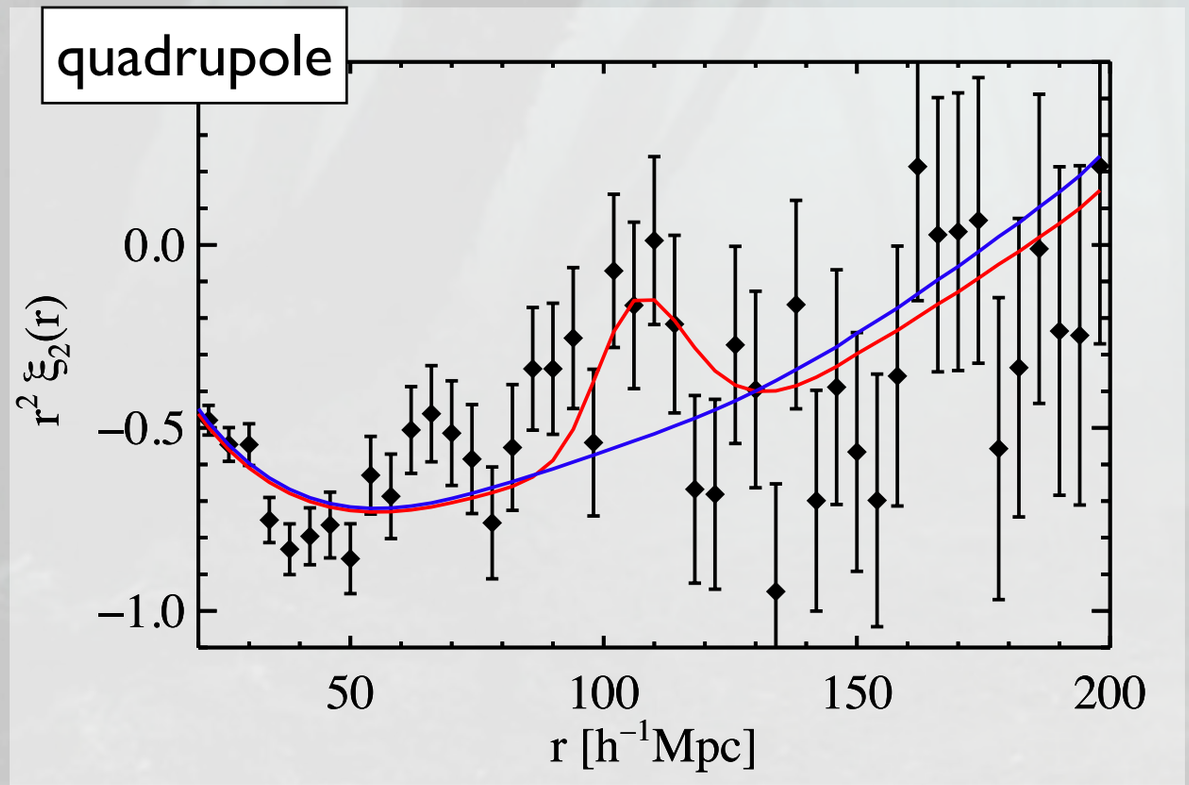






Correlation Function Measurement





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:

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

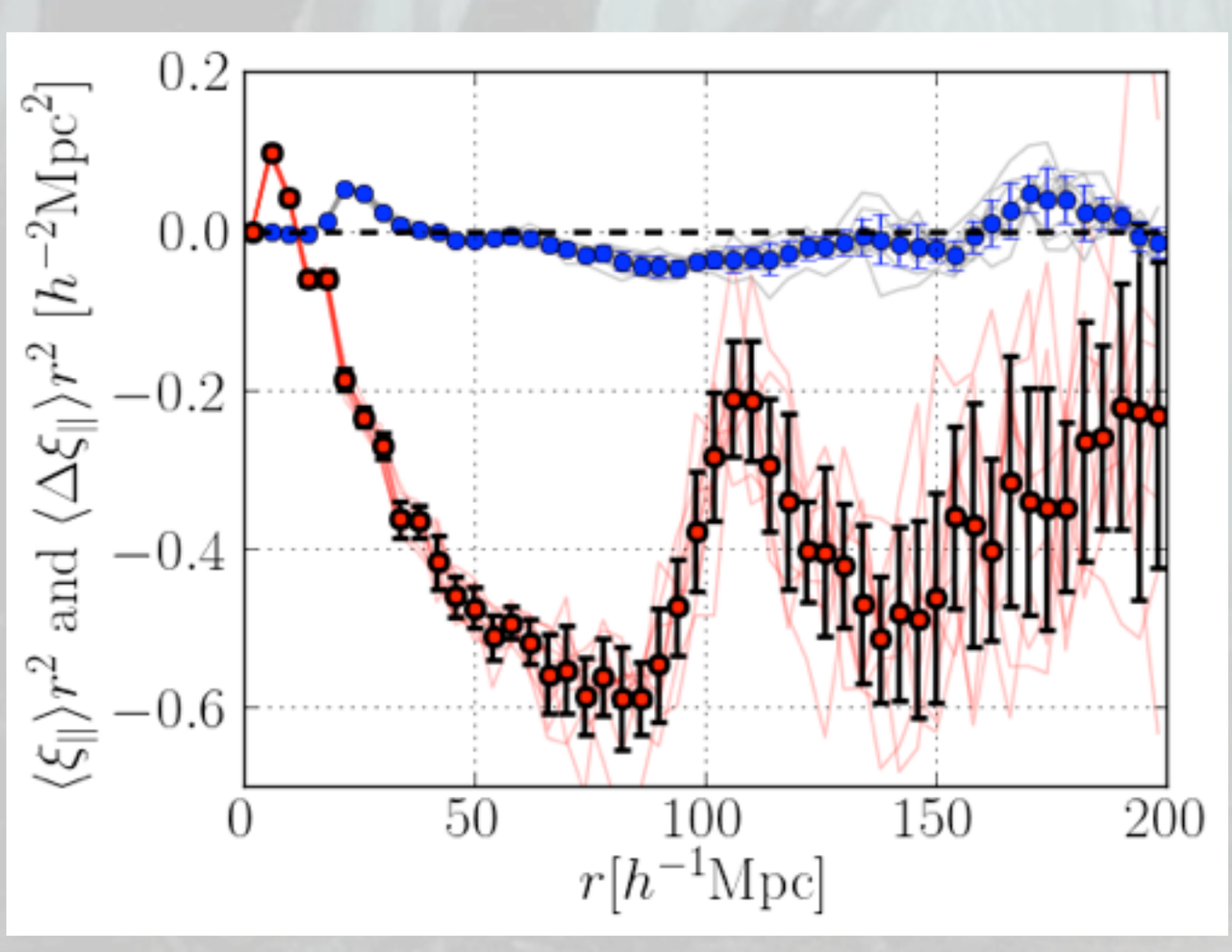
$$\alpha_{\rm d_A} \equiv \frac{(d_A/r_s)_{\rm fid}}{(d_A/r_s)}$$

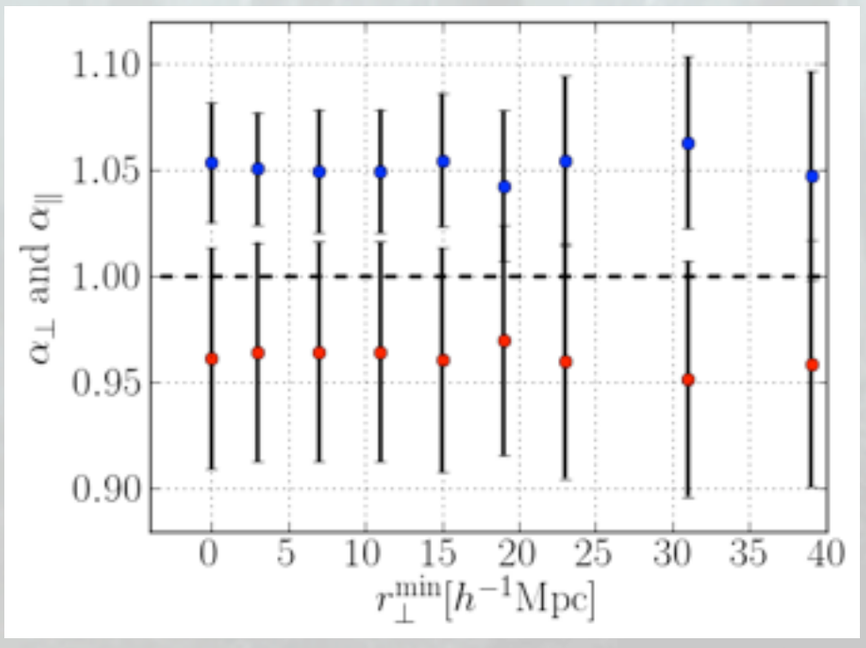
where r_s is the WMAP BAO scale

Constrained at 2% level

Metal Absorption Contaminating BAO

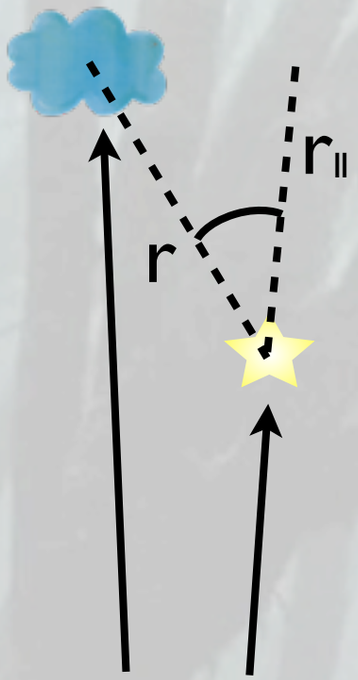
- Multiple metal lines add correlations in the data in 1D
  - Carries into 3D correlation function
- Tests adding metals from stacking to mock data

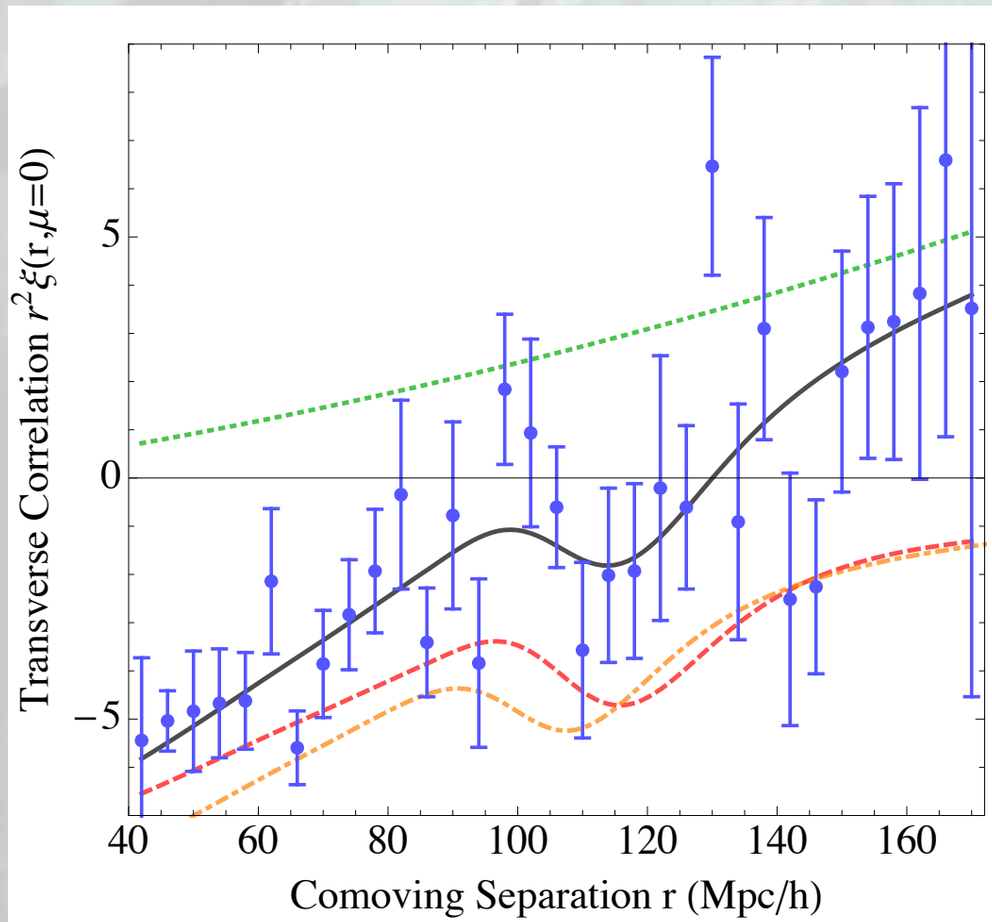


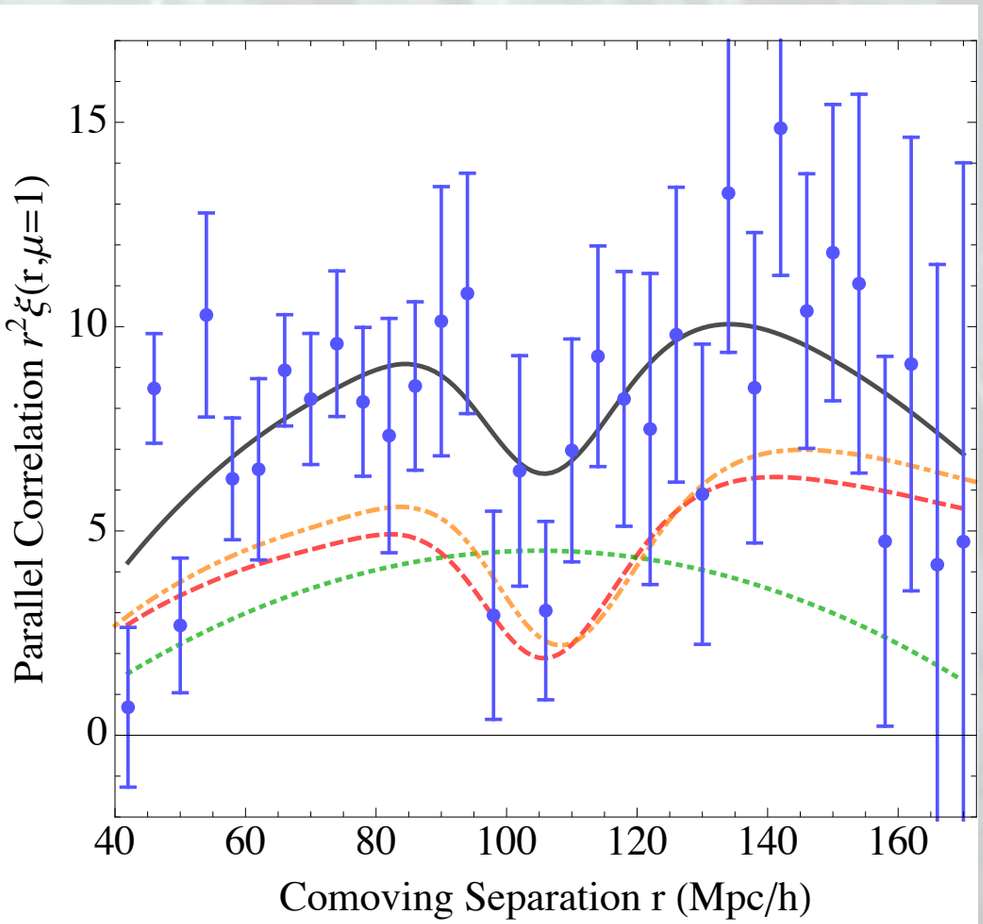


Delubac et al. (2014)
Bautista et al (2014)

Also Cross-correlation Quasars-LyαF

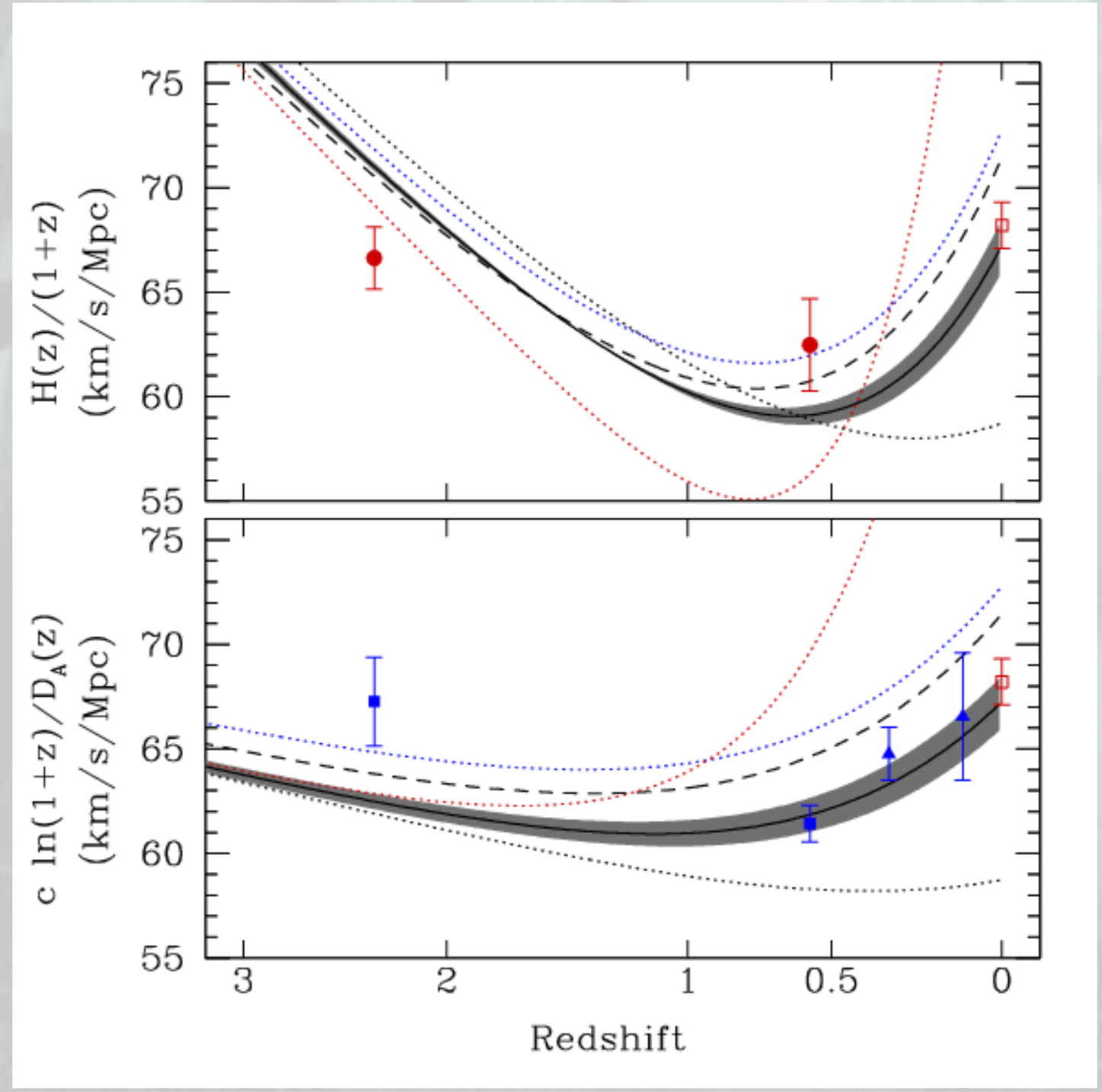






Font-Ribera et al (2013)

Tension with Standard Models

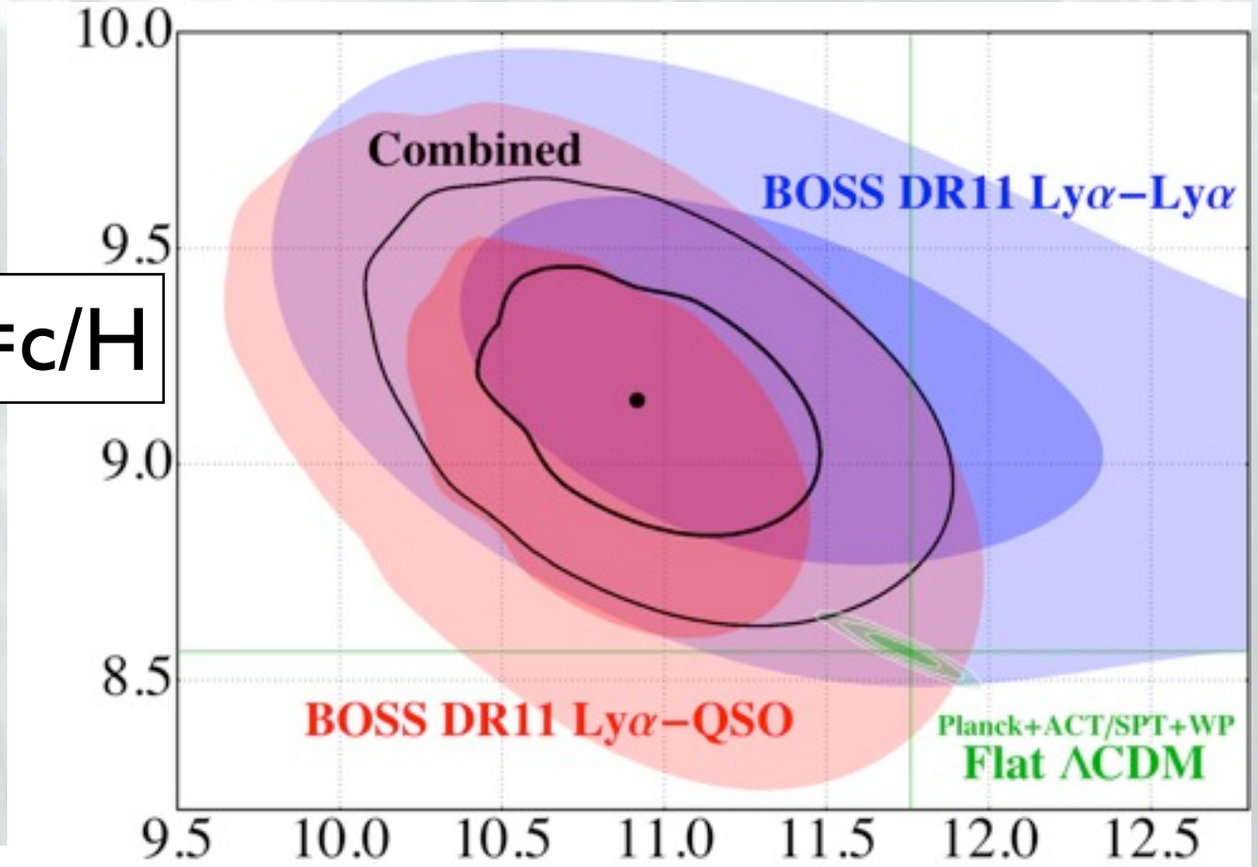


Aubourg et al (2014)

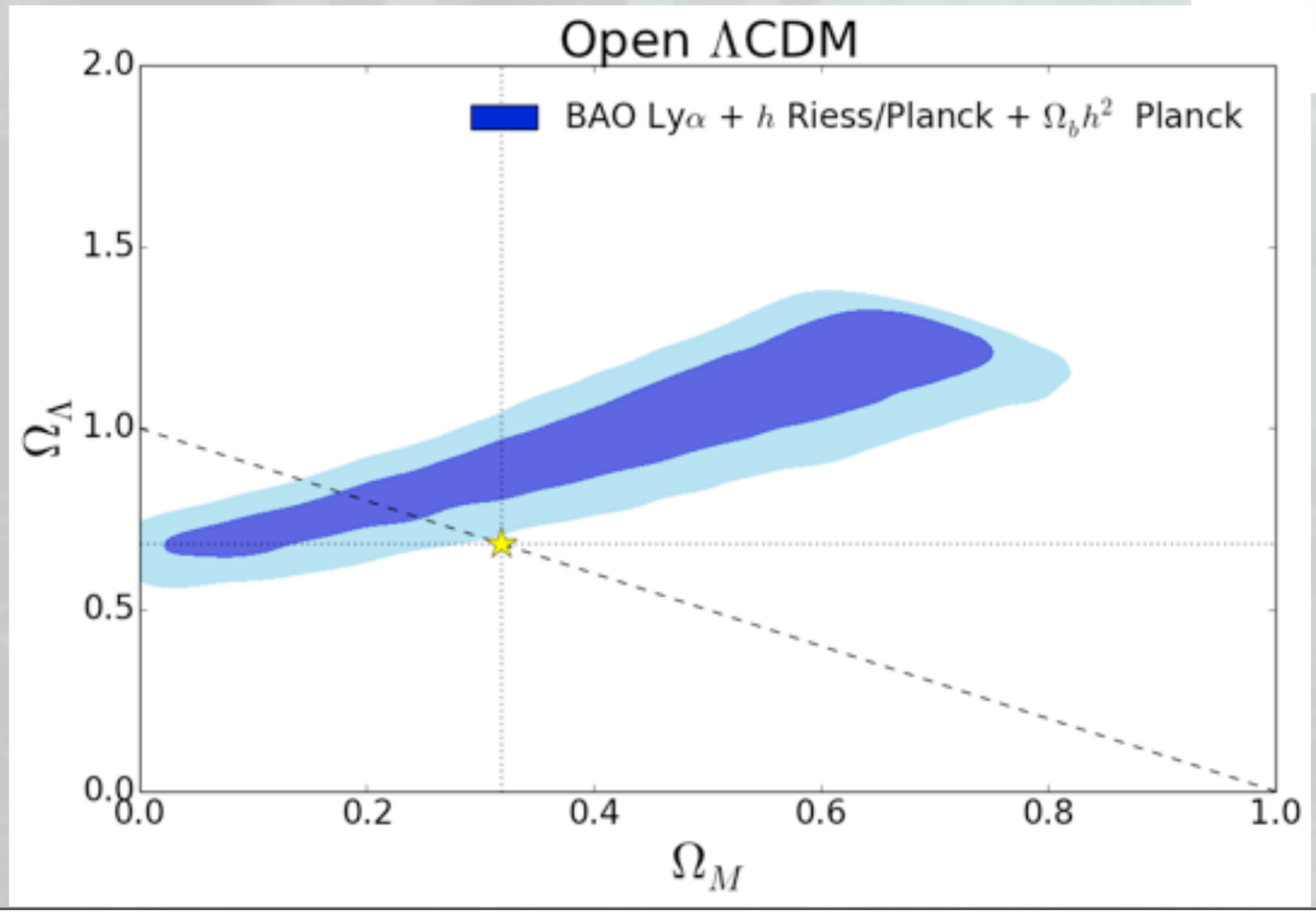
BAO Cosmology

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

$D_H = c/H$

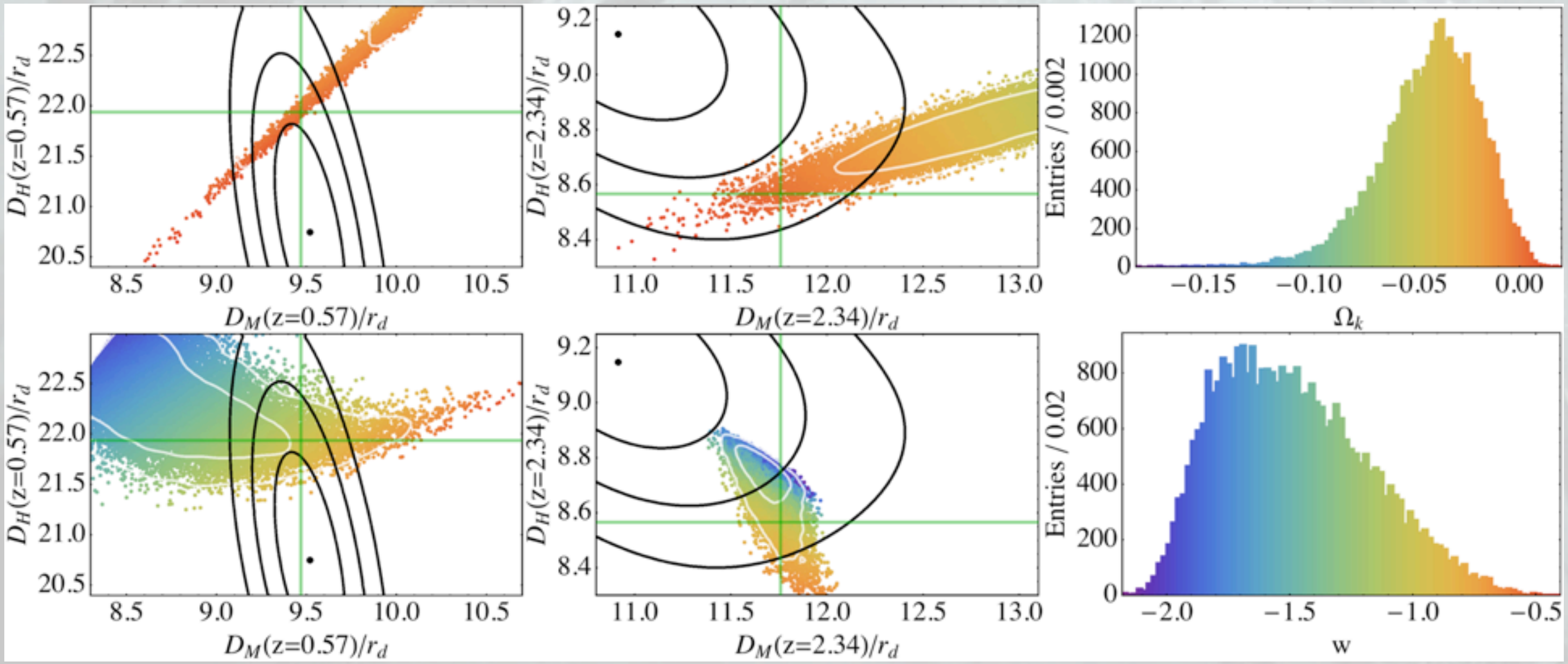


Angular Distance, D_A



Delubac 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)

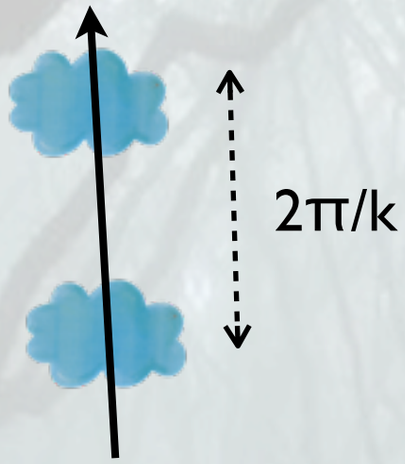
Current Limitations

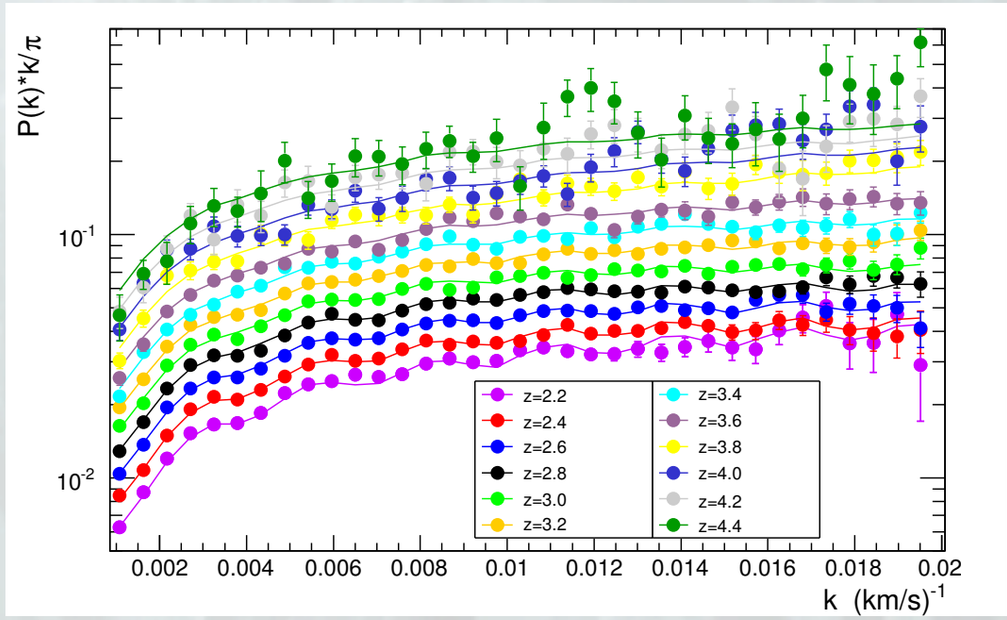
- X-correlation measurement no mocks - nearly ready
- Metal forests BAO in Lyα forest are a currently untested systematic - eBOSS solves this
- Subtle spectroscopic and data reduction artifacts - latest reductions and tests show negligible impact
- Large scale UV background fluctuations tested in mocks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

1D Power Spectrum

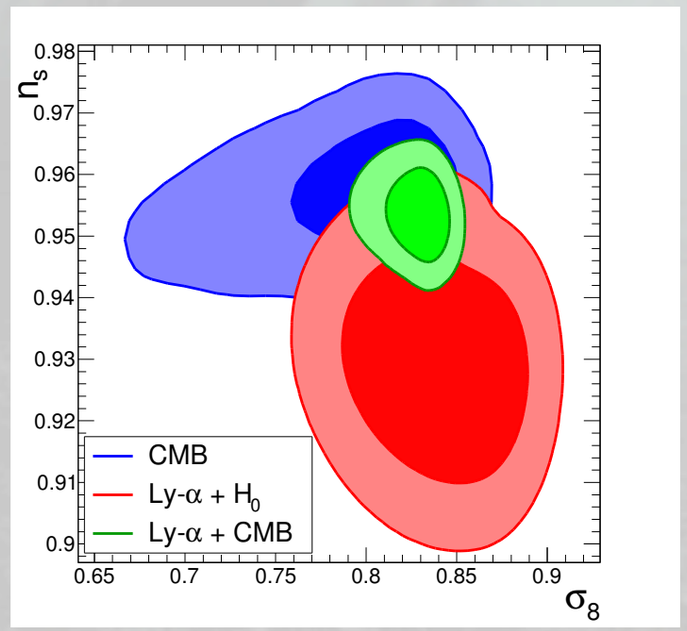
Power measured long line of sight

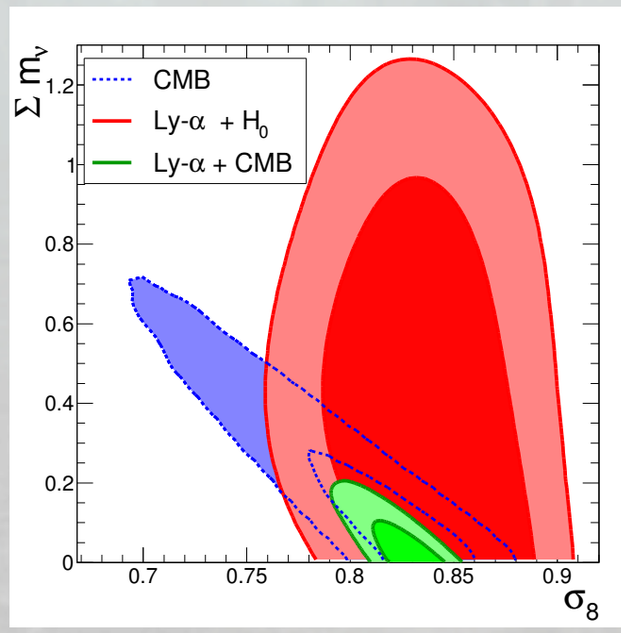
Palanque Delabrouille et al (2013)

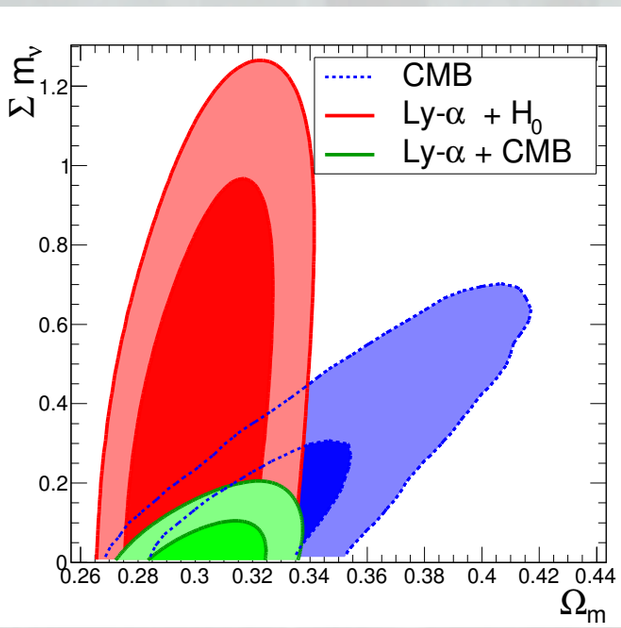




and constraint neutrino masses $\sum m_\nu < 0.15$ eV







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, measure H and so high-z deceleration
- Novel
  - New redshift
  - New type of probe
  - Surprises?
- Perhaps seeing this in our 2.5σ tension with Planck
- With CMB provide best upper limits on neutrino masses
- Final BOSS results to come in 2015

Outline

- What is the Intergalactic Medium and how is it observed?
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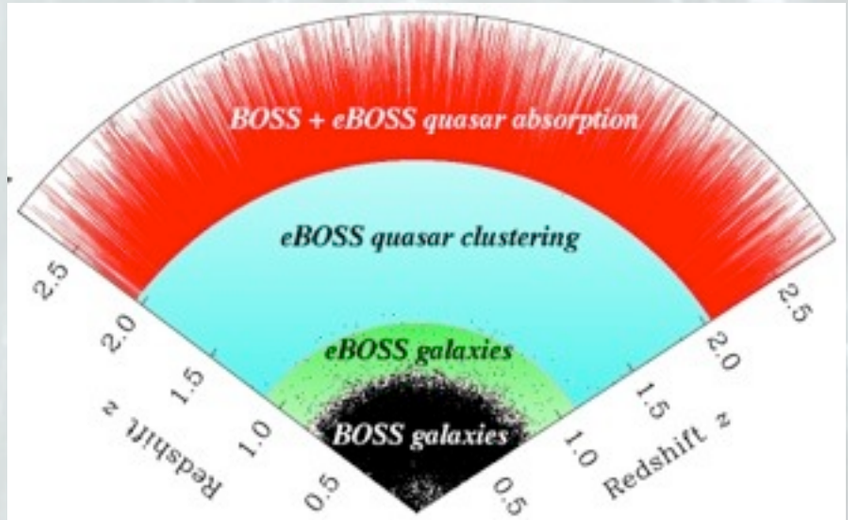
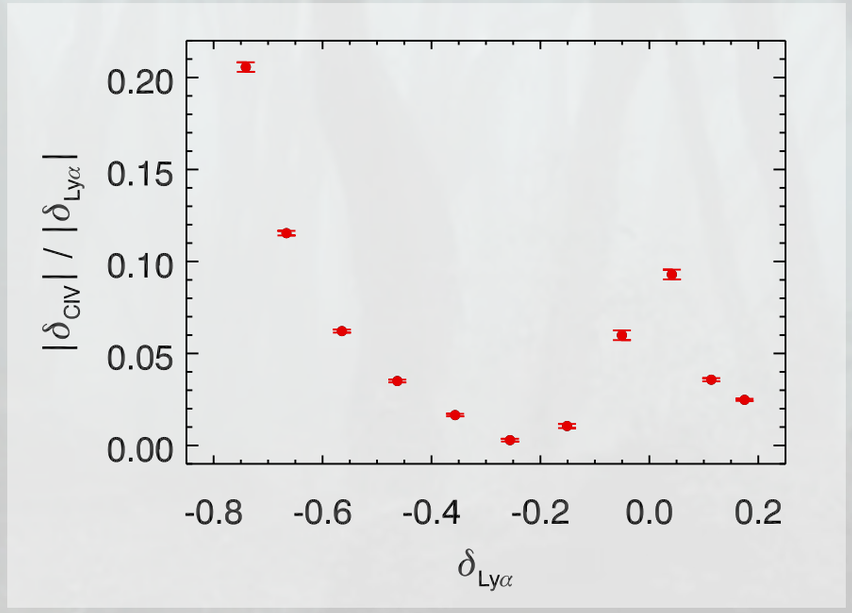
Growth of Massive IGM Surveys 2014-2019: SDSS-IV/eBOSS

- 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



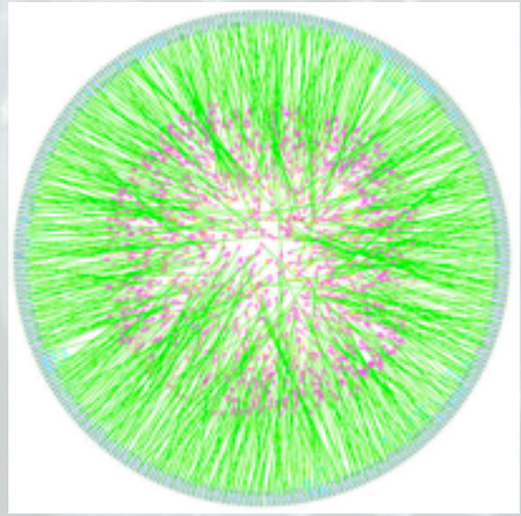


MP (2014)

Growth of Massive IGM Surveys 2019-2024: DESI

- Takes over the Mayall 4m at Kitt Peak Arizona, USA
- Not SDSS - Cosmology sole focus, 1/3 of the sky
- Resolution R=2000
- Quasar absorption survey co-chair
- 600k Lyα forest quasar spectra
- 1.4M intermediate redshift quasar spectra
- 20M+ galaxies with z<1.6
- Potential to cross-correlated quasars, galaxies and carbon absorption
  - Effectively ~6 surveys
  - X-corr powerful in the shot noise limit

Growth of Massive IGM Surveys 2018-2023: WEAVE



- Takes over 4m William Herschel Telescope
- 1000 robotically positioned fibres
- 500k Lyα quasar spectra.
- Resolution R=20000 (with limited wavelength) or 5000
- Quasar absorption survey lead
- BAO with more precise continuum estimation
- Probe of smaller scale effects
  - 1D power spectrum, warm dark matter, varying fine structure constant, deuterium abundance, IGM heating

Power of Cross-correlation

- Absorption and galaxy/quasar BAO both shot noise limited
- Systematics cancel
- Current quasar-forest results powerful
  - but quasars to 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
- Cross-correlate weak lensing and BAO?
- The future is bright for next generation LLS surveys

Fin