Large Scale Clustering from SDSS III Now and Beyond

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With collaborators:

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Sloan Digital Sky Survey III Collaboration

The Return of de Sitter, Stockholm, March 2011

Outline

- Motivations
- Introduction
  - —What are Baryon Acoustic Oscillations?
- Baryon Acoustic Oscillations: Now and Beyond
  - —Now: With Luminous Red Galaxies
  - —Beyond: With Lyman Alpha Forest
- Conclusions

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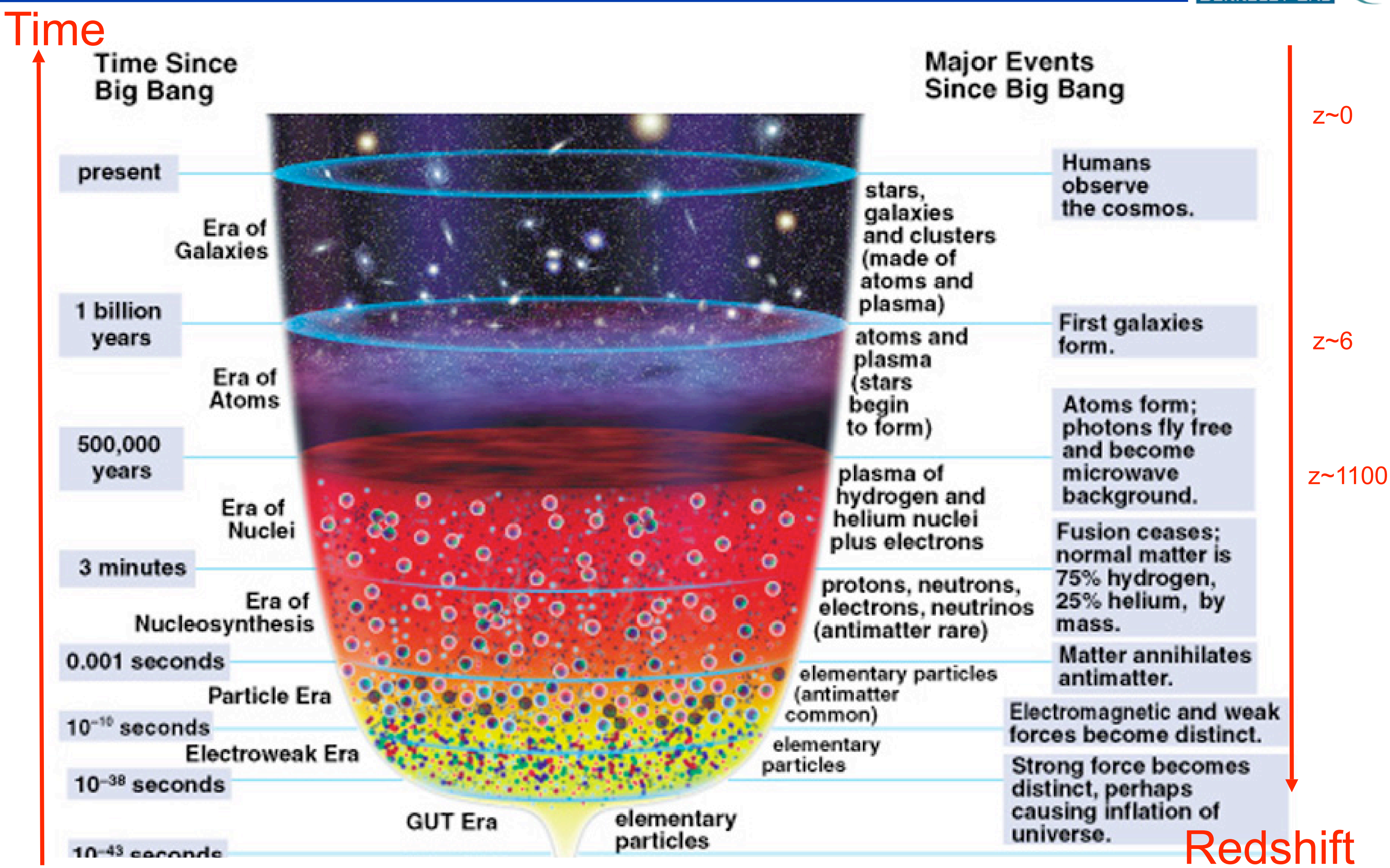
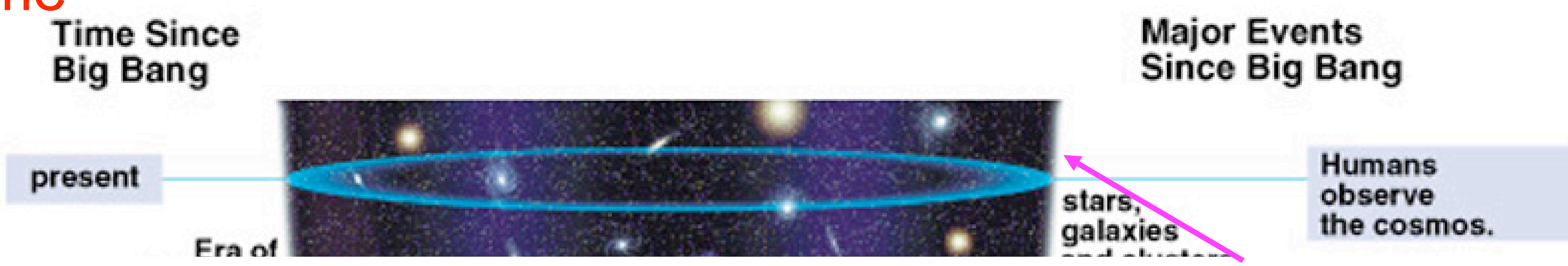
Motivations



Motivations

Time



Gravity +
observing movement of
local galaxies ->
"Dark Matter"

z~0

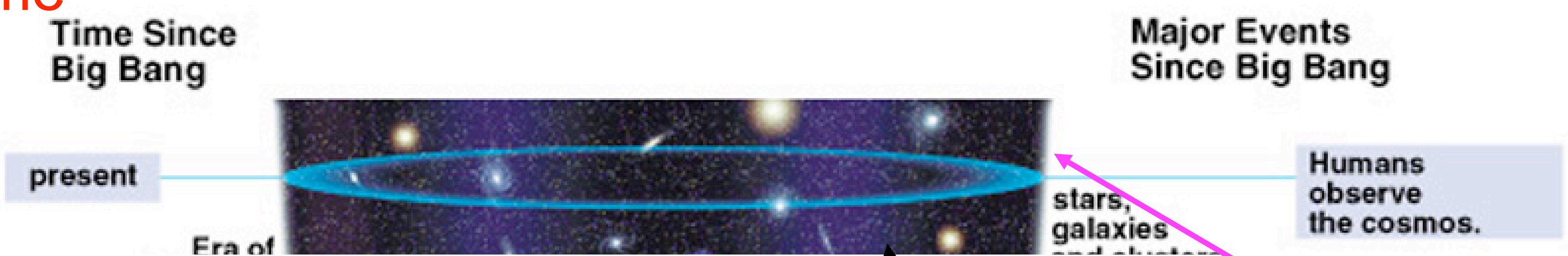
z~6

z~1100

Redshift

Motivations

Time



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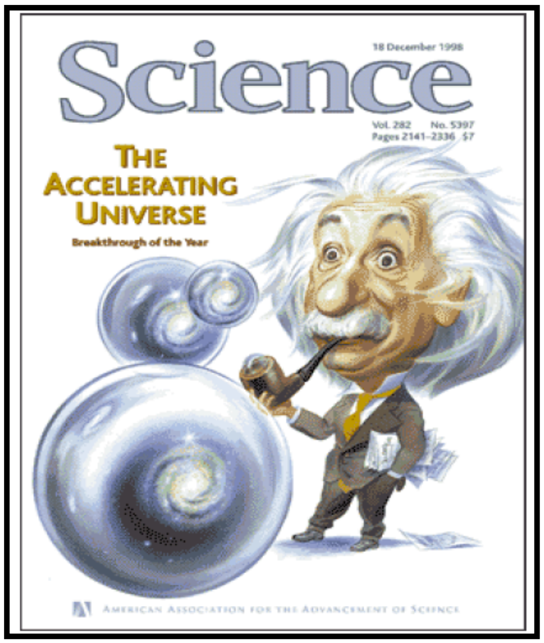


Distant supernovas appear fainter than expected (1998)->
Universe is accelerating ->
Cosmological Constant?
Dark Energy?

z~0

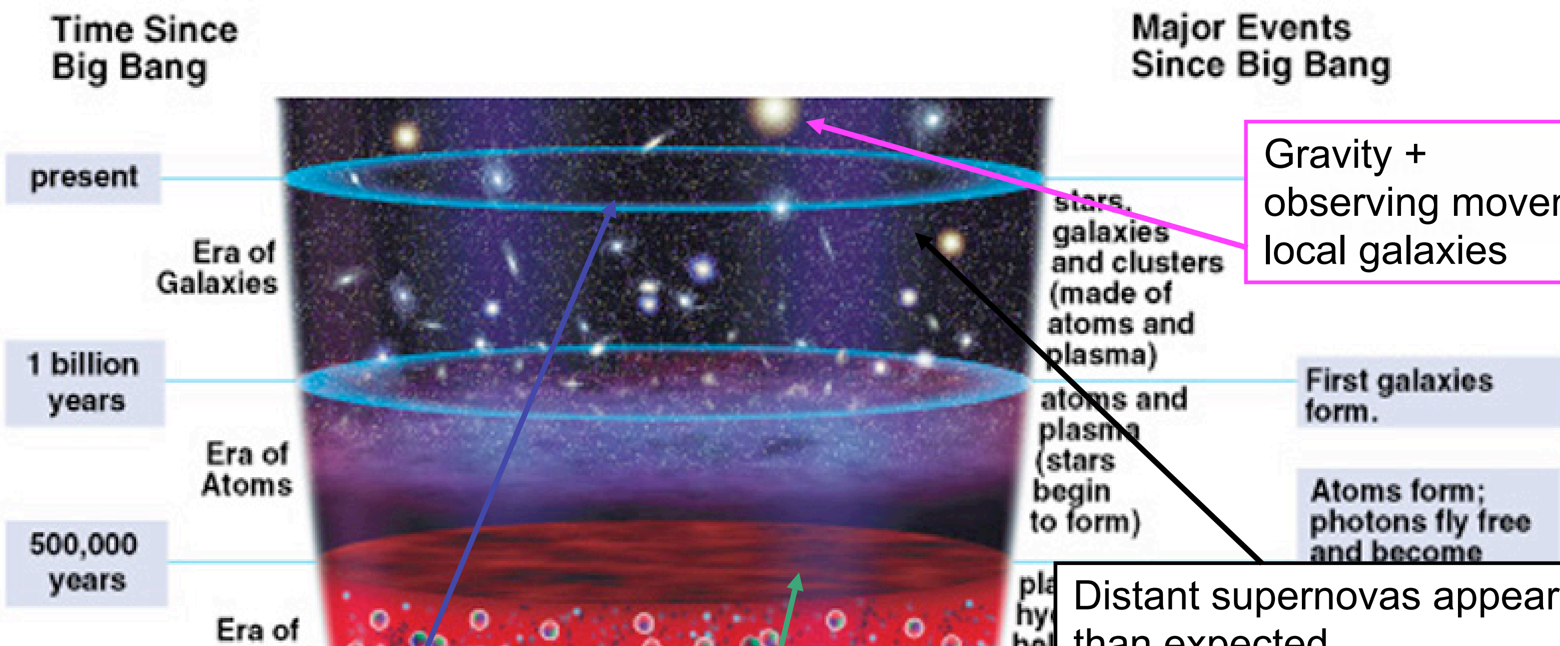
z~6

z~1100

Redshift

Motivations

Time



z~0

Gravity +
observing movement of
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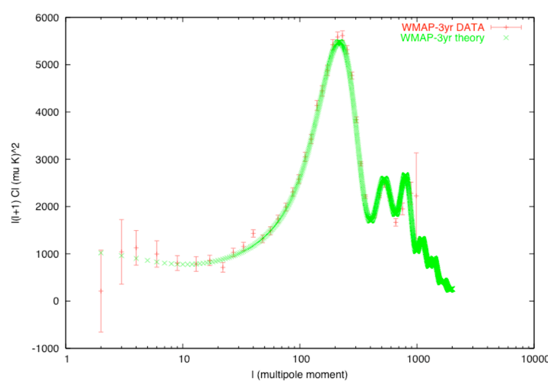
z~6

~1100

Distant supernovas appear fainter than expected

Observations of how galaxies cluster



Observations of
Cosmic Microwave Background (CMB)
-> angular powerspectrum of
temperature anisotropies

Redshift

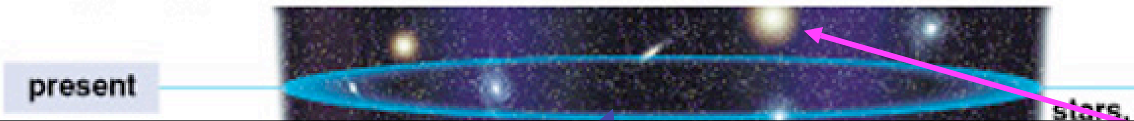
Motivations

Berkeley Lab

Time

Time Since Big Bang

Major Events Since Big Bang



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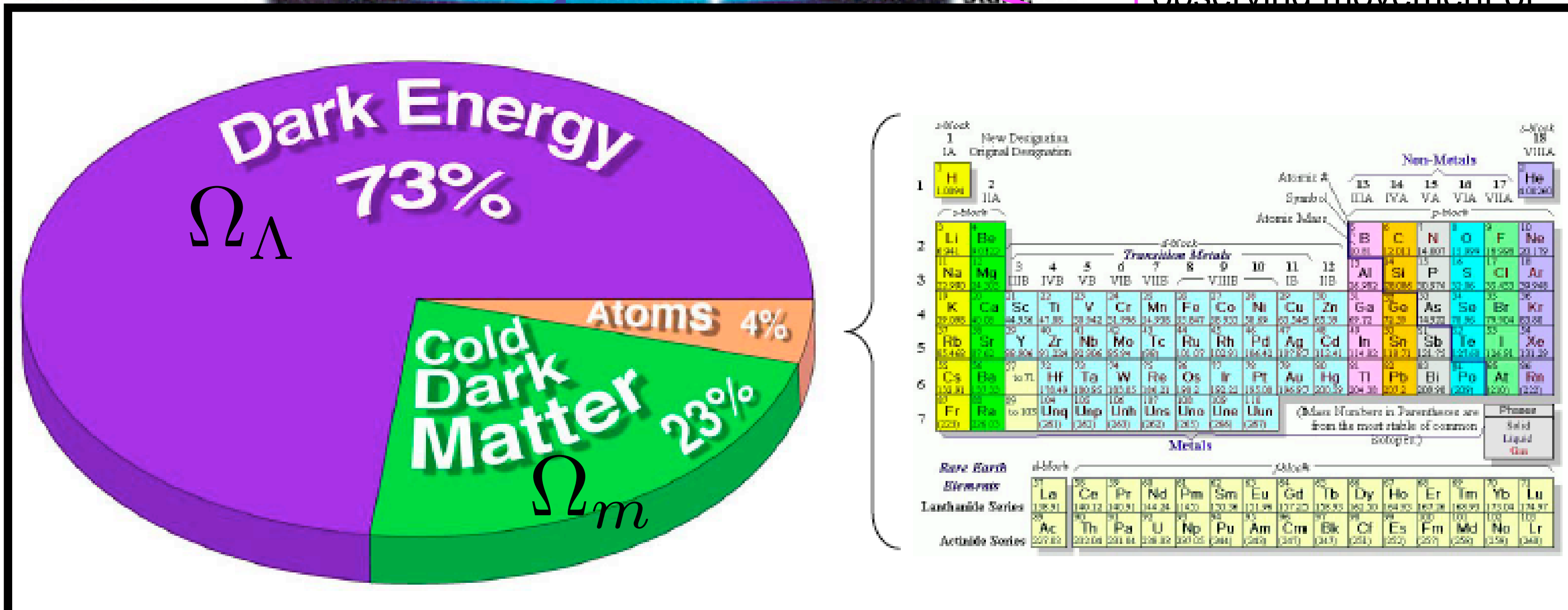
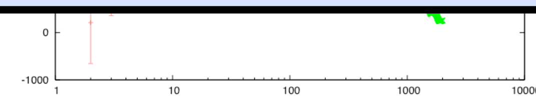


100

What happened at the Very Beginning of the Universe?

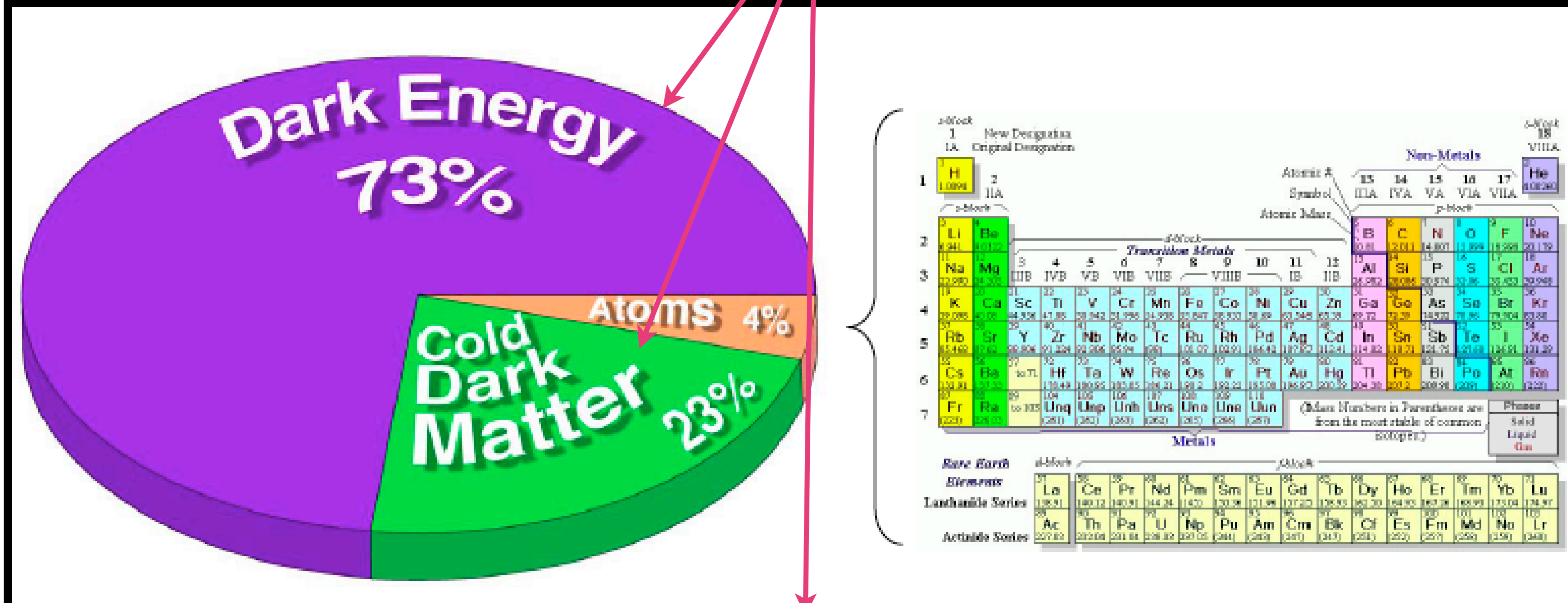
-> angular powerspectrum of temperature anisotropies



Redshift

Motivations

??



What happened at the Very Beginning of the Universe?

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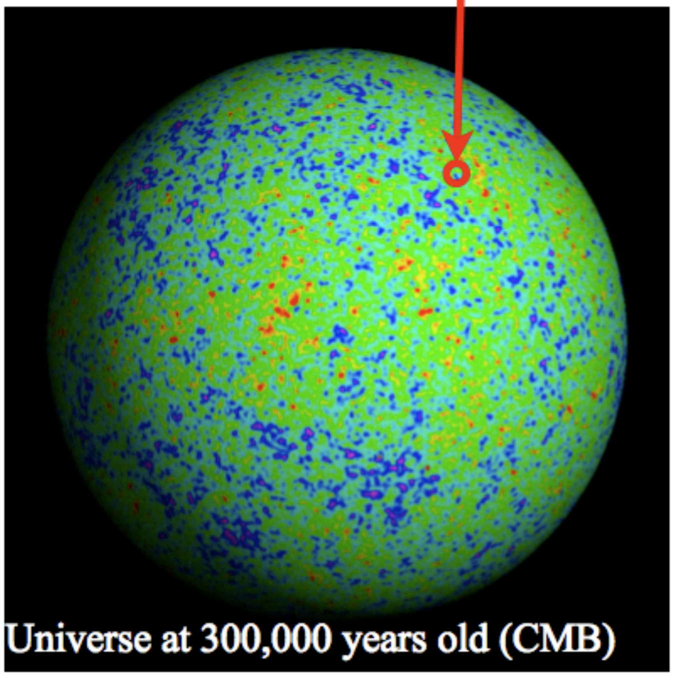
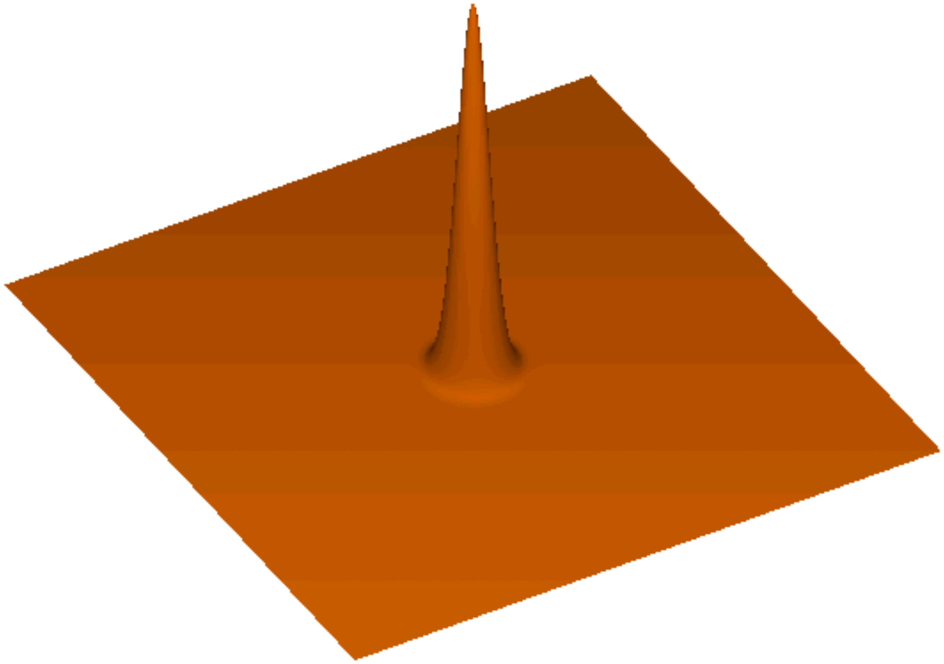
What are the Baryon Acoustic Oscillations?

What are baryon acoustic oscillations (BAO)?

These fluctuations of 1 part in 10^5 gravitationally grow into...





This sound wave can be used as a "standard ruler"

Dark energy changes this apparent ruler size

Courtesy slide from David Schlegel and animation from Daniel Eisenstein

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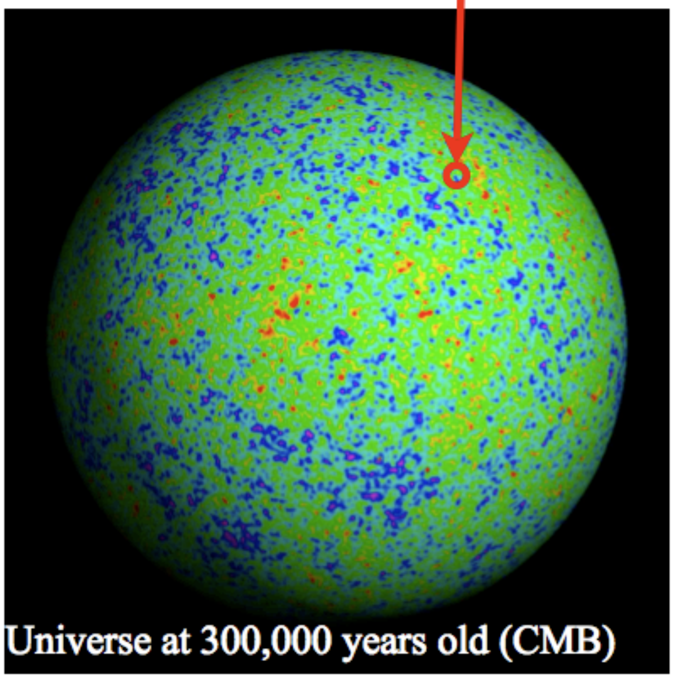

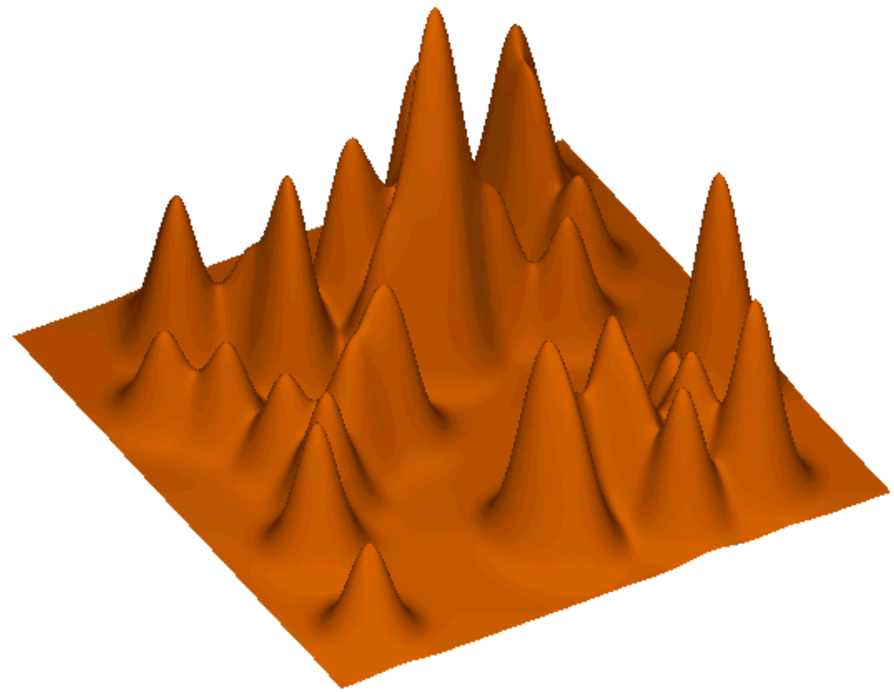

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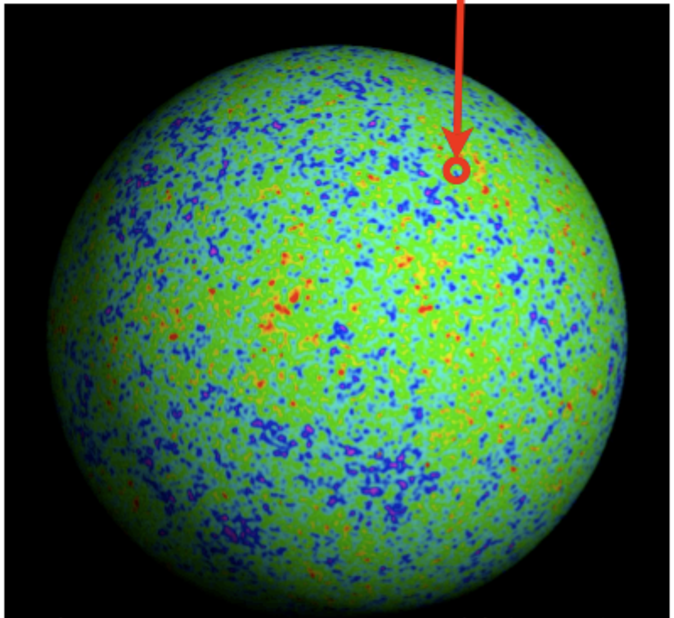
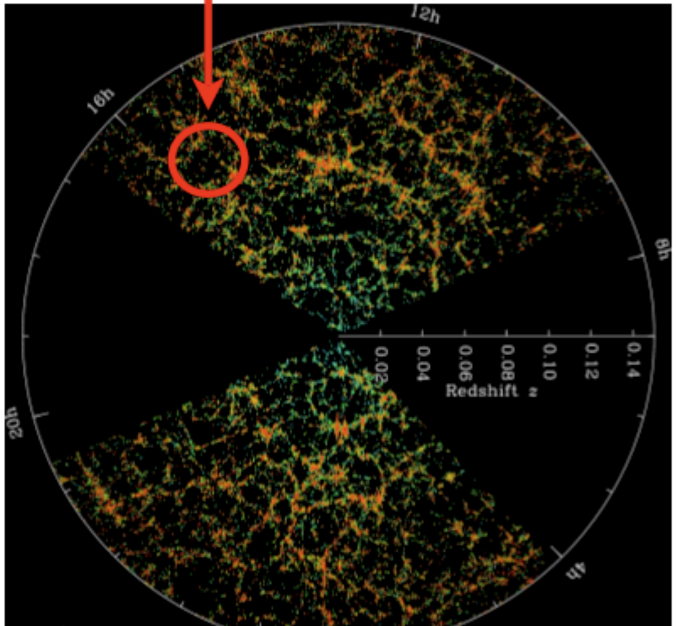


Universe at 300,000 years old (CMB)



Universe today (galaxy map)

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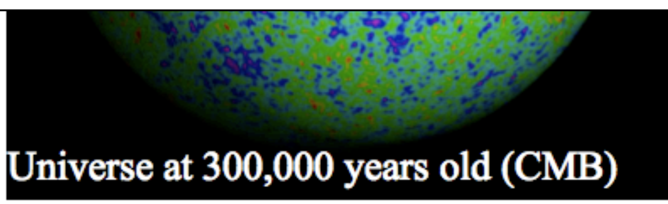
- BAO is possibly the cleanest probe of Dark Energy:
  - —We are working in large scale, so we can possibly avoid all the messy non-linear physics.
  - —Its physics are determined at early times, where perturbative treatment is valid and under control.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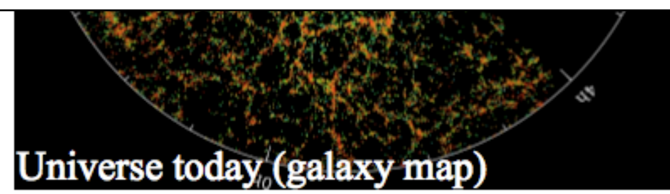
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We calculate the correlation function or its Fourier Transform: power-spectrum

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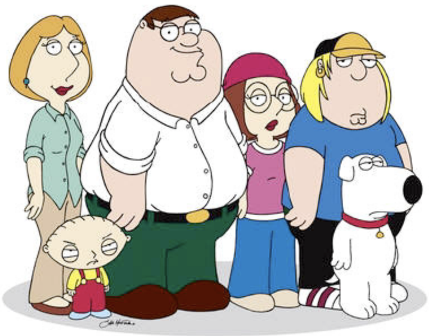

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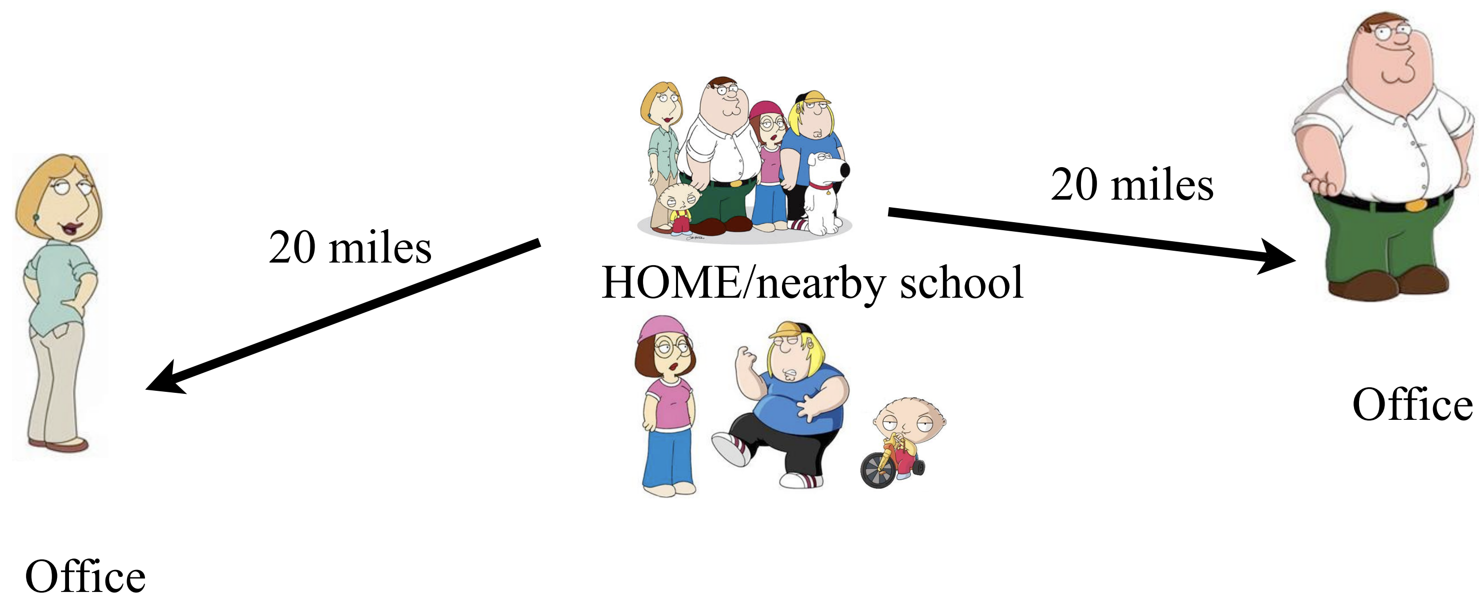

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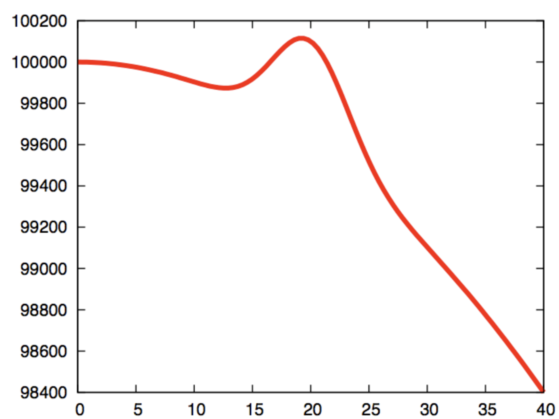
Population correlation function during the day

20 miles



Office

Office

The bump will be at 20 miles!

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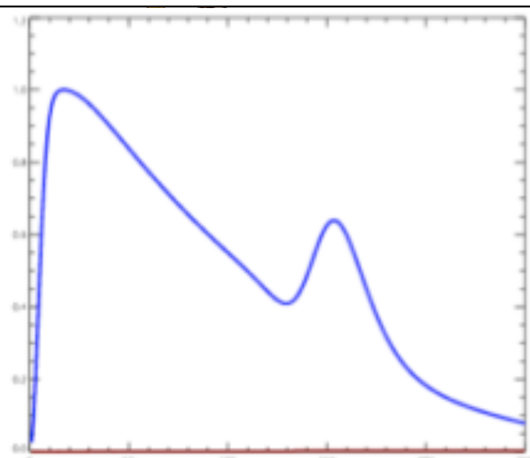
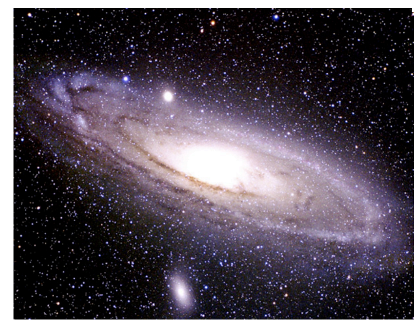
Galaxy correlation function

100 Mpc





The bump will be at ~100 Mpc

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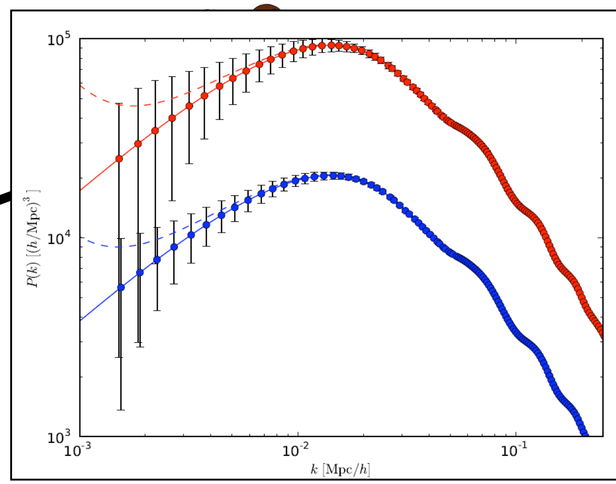
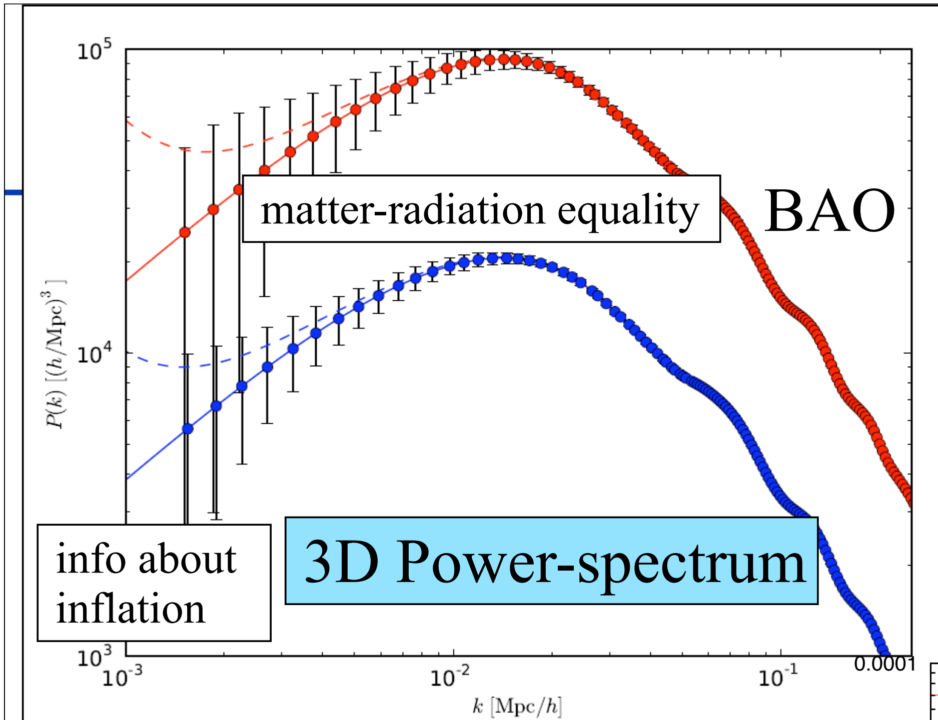
Fourier Transform: correlation function-> **power-spectrum**

100 Mpc

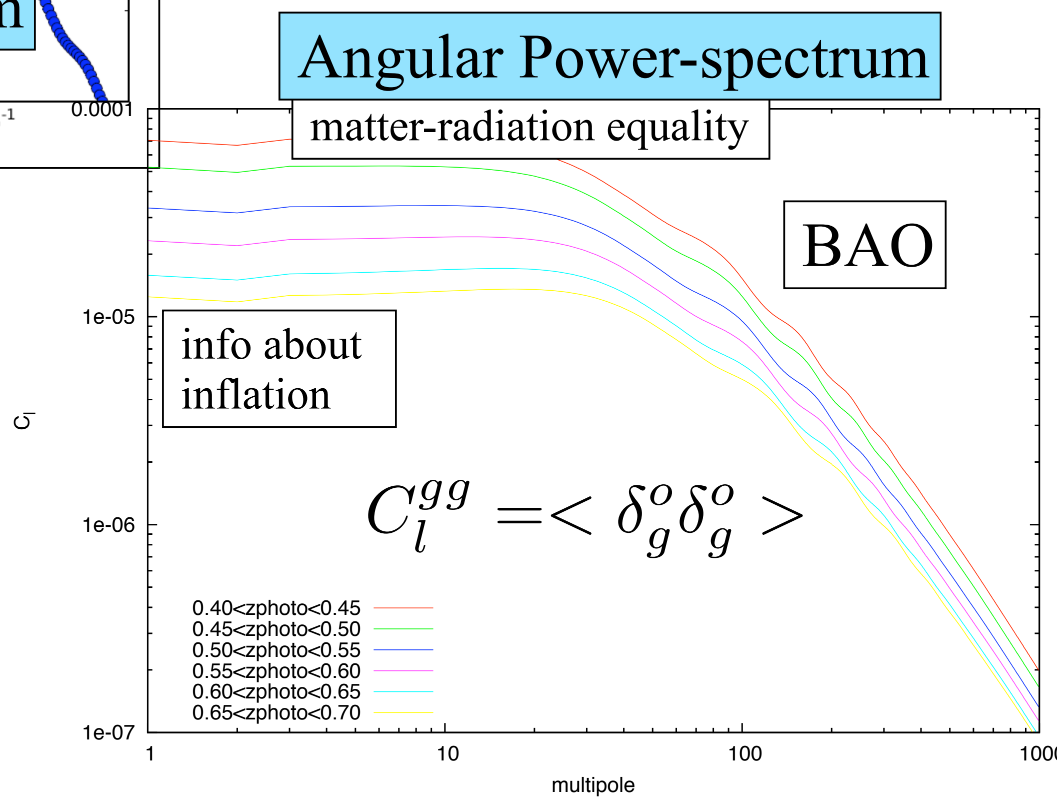


There will be wiggles



plot borrowed from Anze Slosar

Recall: Eisenstein et al.(2005), Percival & Reid et al. (2010)



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BAO: with Luminous Red Galaxies
Physics of Angular Clustering

$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

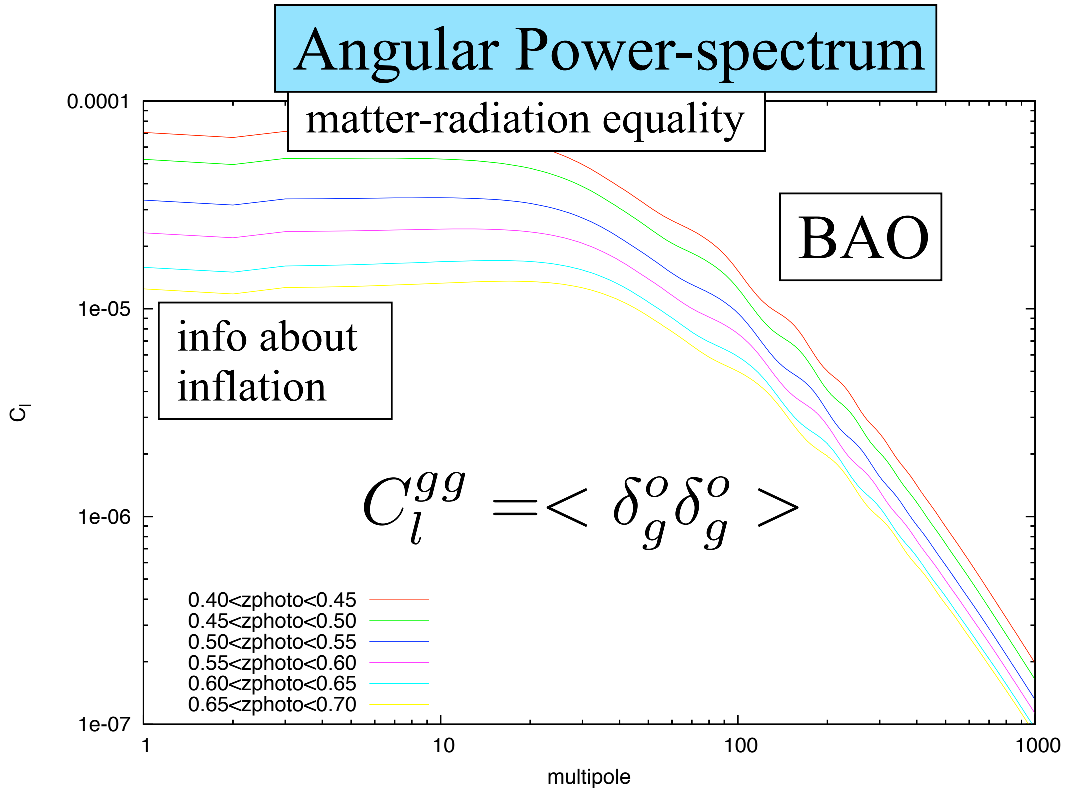
$P(\frac{l+\frac{1}{2}}{\chi})$ describe how matter cluster (matter powerspectrum, describes the rms fluctuations)

Galaxy angular power-spectrum

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

Angular power-spectrum

- BAO
- Overall shape of the spectrum
- inflationary parameters affect the largest scale



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Galaxy Angular power-spectrum contains a wealth of cosmological information ranging from

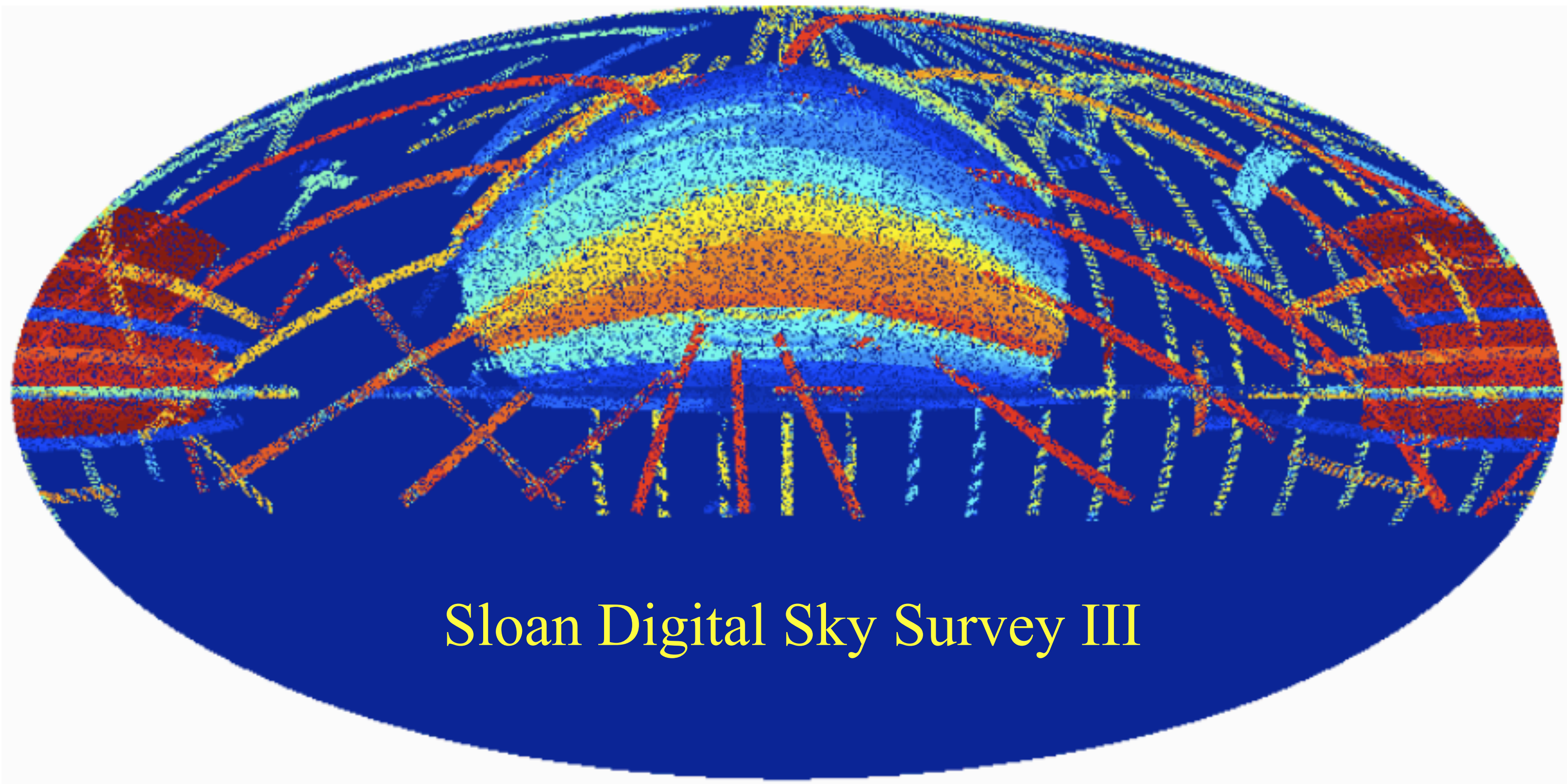
a) What is **dark energy**? to

b) What happened at the very early Universe? Inflation? What kind?

BAO: with Luminous Red Galaxies
The Data

Total Area: 14,555 sq deg

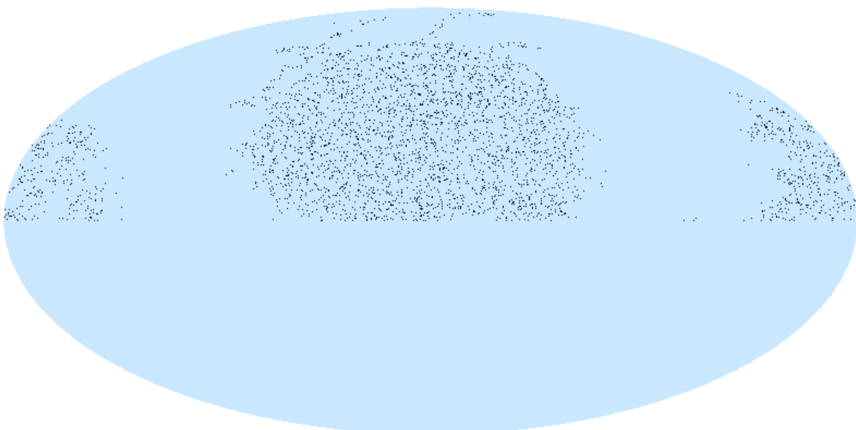
1.5 million LRGs: 0.4<z<0.7



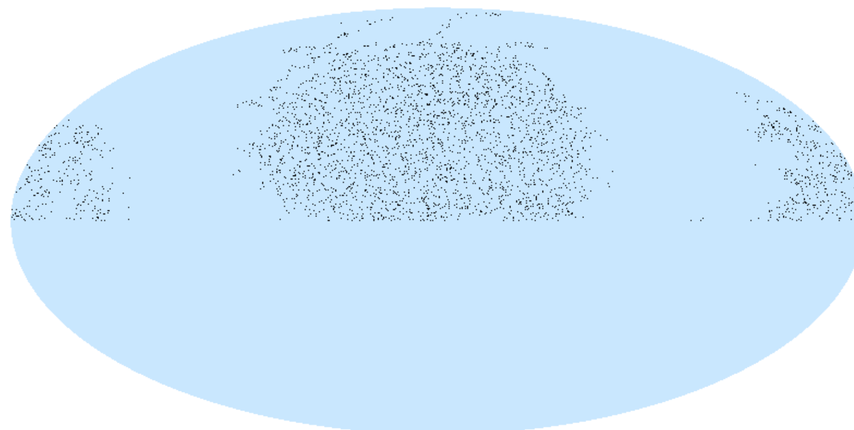
note: Colors only indicates the when a certain area of the sky is surveyed.

BAO: with Luminous Red Galaxies
The Data: Splitting them into redshift bins

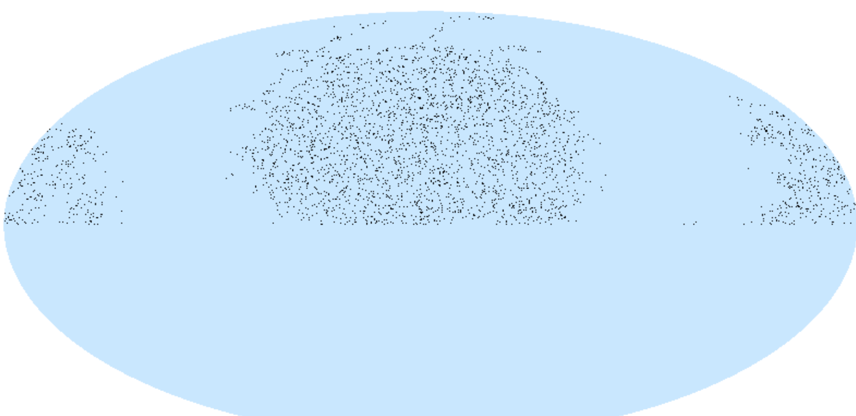
z=0.45-0.5



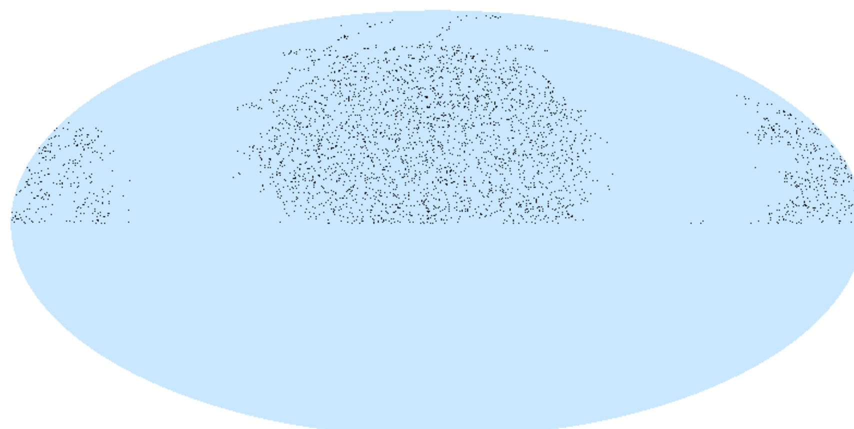
z=0.5-0.55



z=0.55-0.6



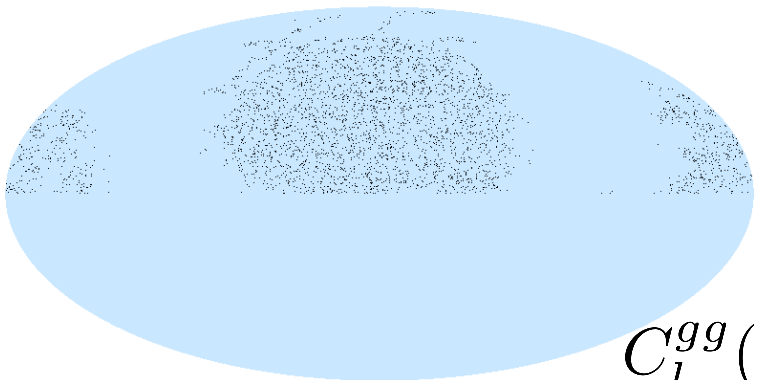
z=0.6-0.65



Ho, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.



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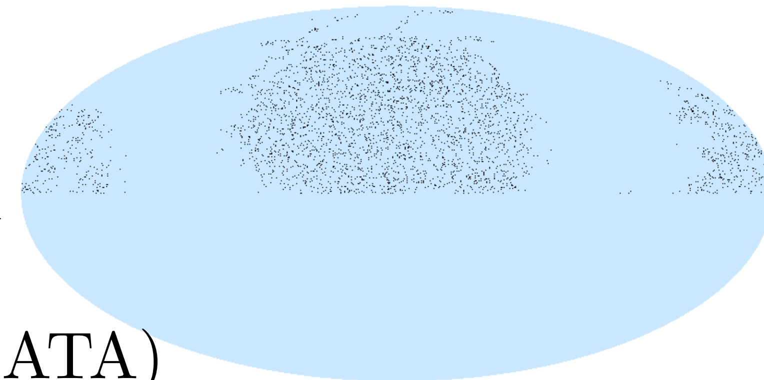

$$C_l^{gg}(\mathrm{DATA})$$

- We want the best measurement of the angular power-spectra possible, from the stand point of not only statistical error, but also systematic errors.
- To get the best statistical errorbar, we apply “Quadratic Estimator”, which are proven to provide:
  - — Unbiased Minimum variance measurement of the parameters that are being estimated if the field is gaussian.
  - — Many people have worked on this Quadratic Estimators: Hamilton, Tegmark, Bond, Jaffe and Knox, White, Padmanabhan, Hirata, Blake, et al.

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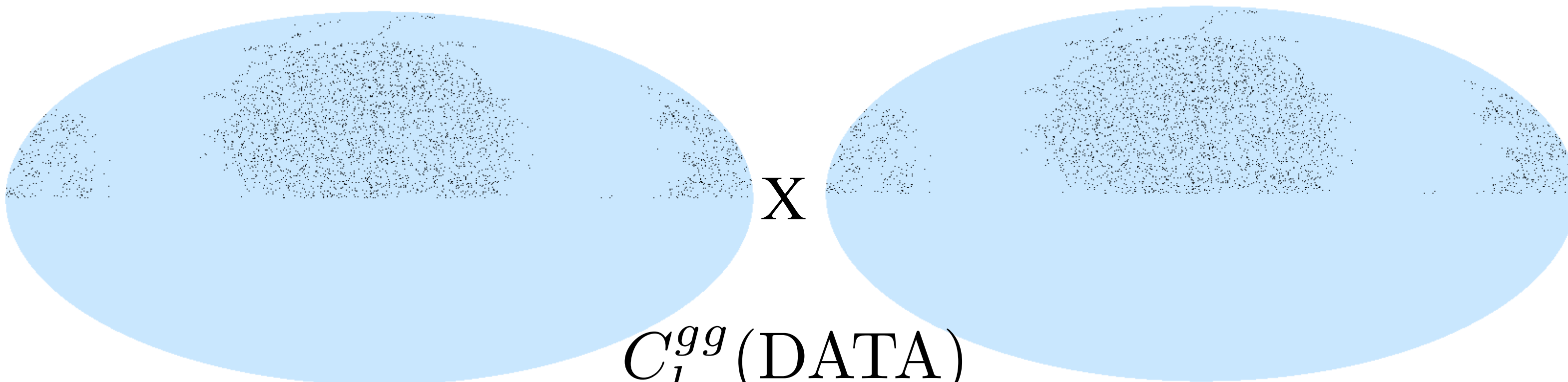

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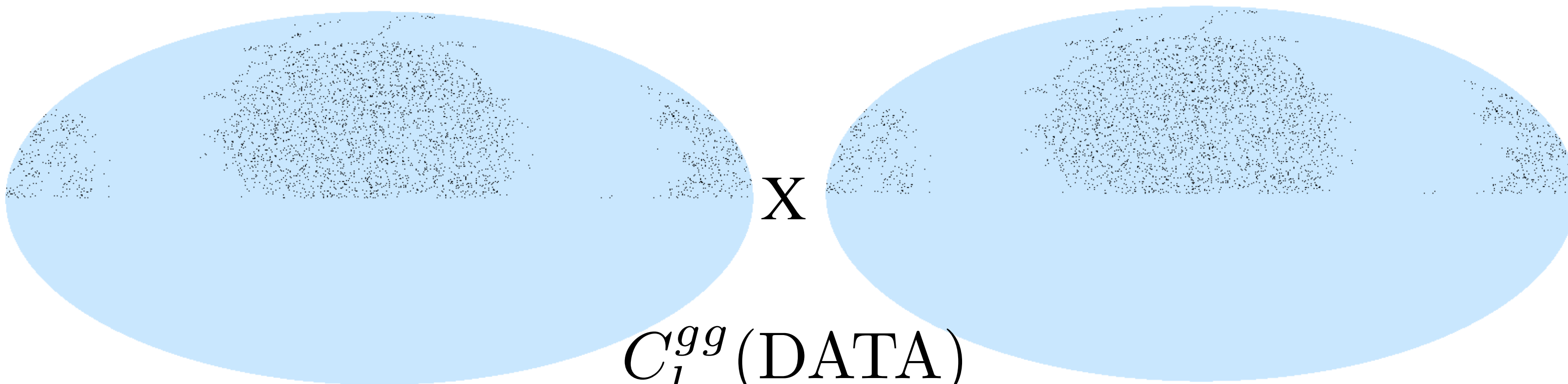

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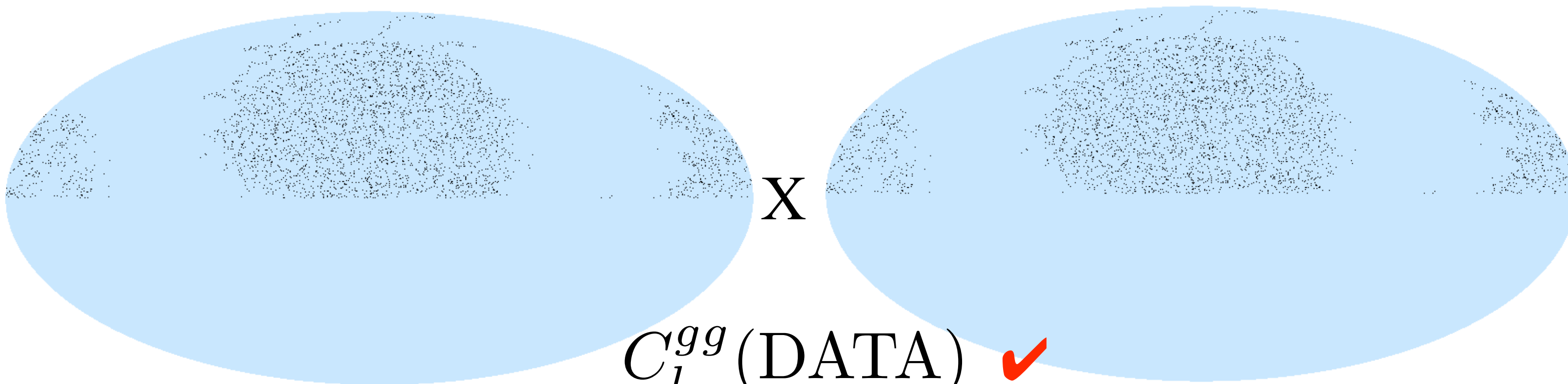

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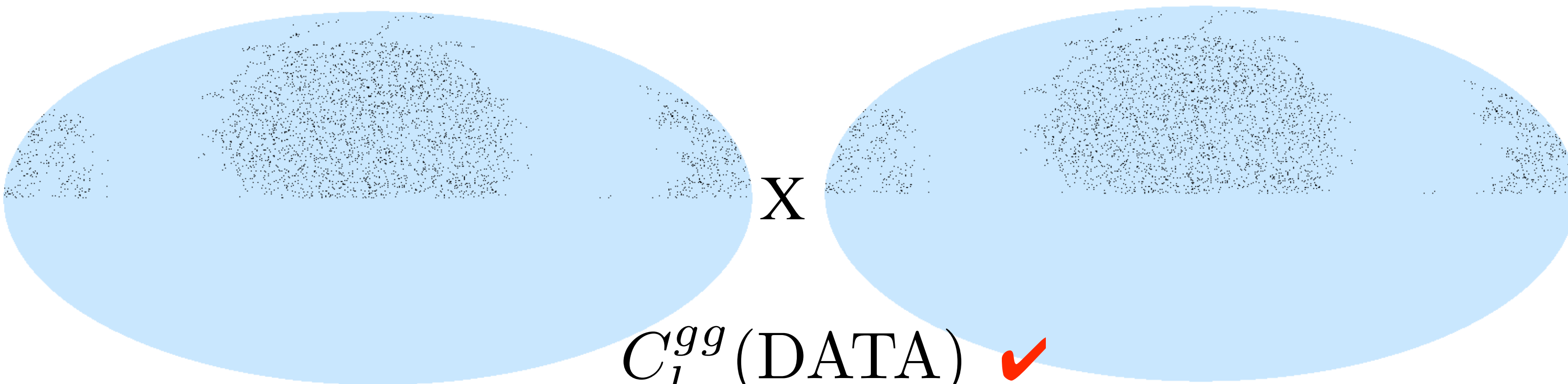

$C_l^{gg}(\mathrm{DATA})$ ✔

- But in order to derive cosmological constraints, we need to be able to predict the angular power-spectra given any cosmological models.
- That's why: we need the **theory**:

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

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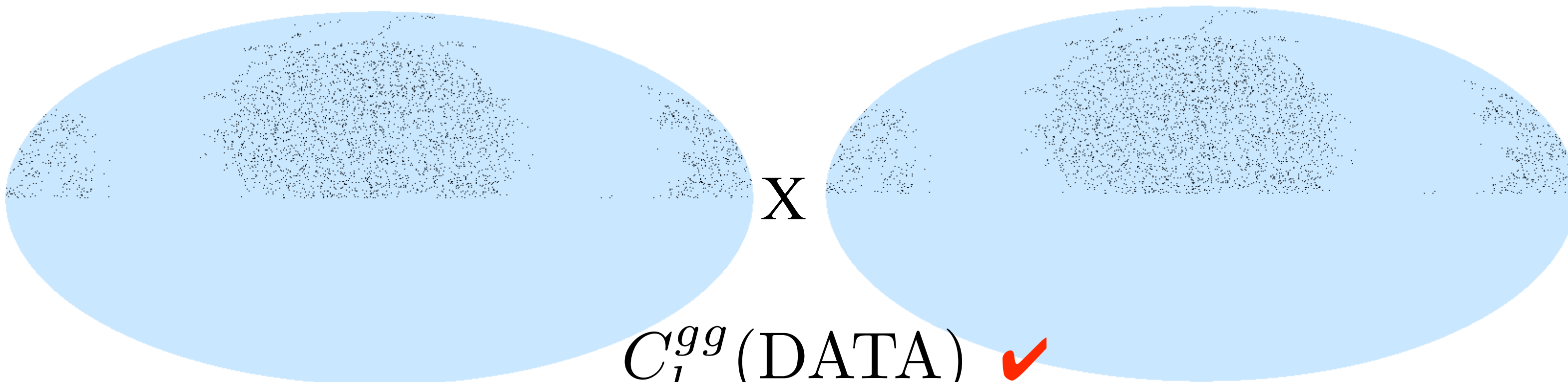

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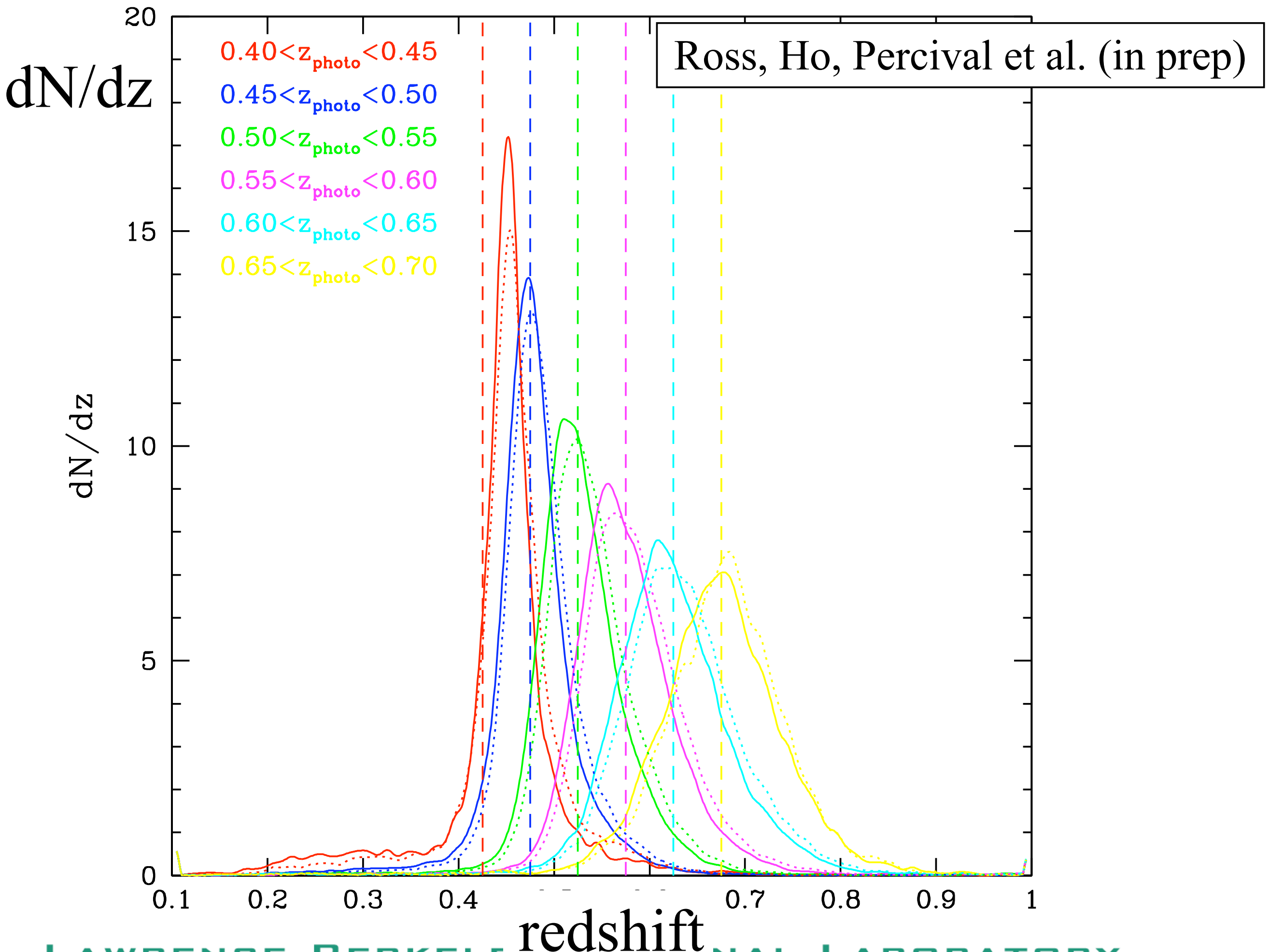
- Given a cosmological model, we can predict the theory, except we need two inputs: bias b(z) and redshift distribution dN/dz.

BAO: with Luminous Red Galaxies
The Data: Redshift distribution

SDSS III has been taking spectra of all of these photometric LRGs, therefore, we have an unbiased spectroscopic confirmation of the photometric redshifts for ~10% of the sample, therefore, we have very good understanding of the redshift distribution of the sample.



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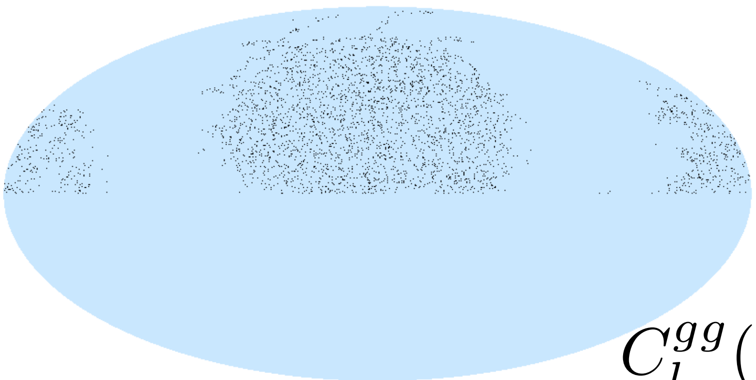

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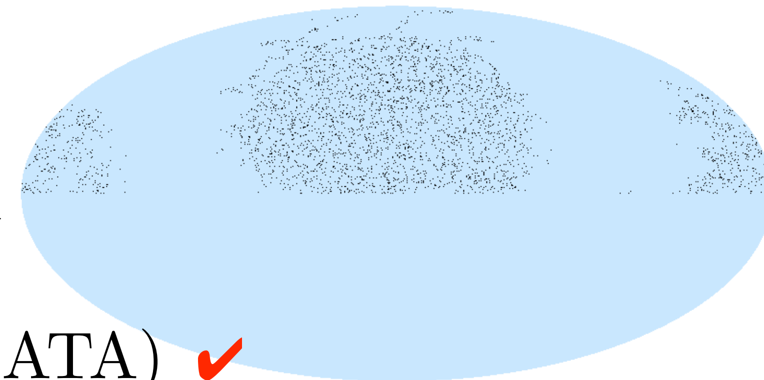

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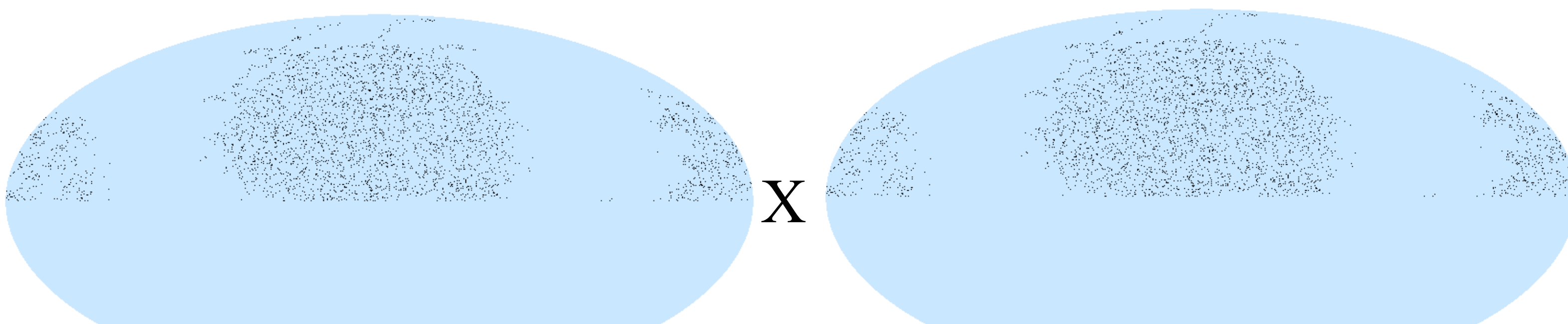
$$C_l^{gg} = \int dz \frac{H_0}{c} \boxed{b^2(z)} (dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

- We then only need to know bias, but since it only changes the overall amplitude of the angular power-spectrum.
- We don't need to worry about this for BAO

BAO: with Luminous Red Galaxies
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.



$$C_l^{gg}(\mathrm{DATA}) \checkmark$$

- But in order to derive cosmological constraints, we need to be able to predict the angular power-spectra given any cosmological models.
- That’s why: we need the theory:

$$C_l^{gg} = \int dz \frac{H_0}{c} \boxed{b^2(z)} (dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

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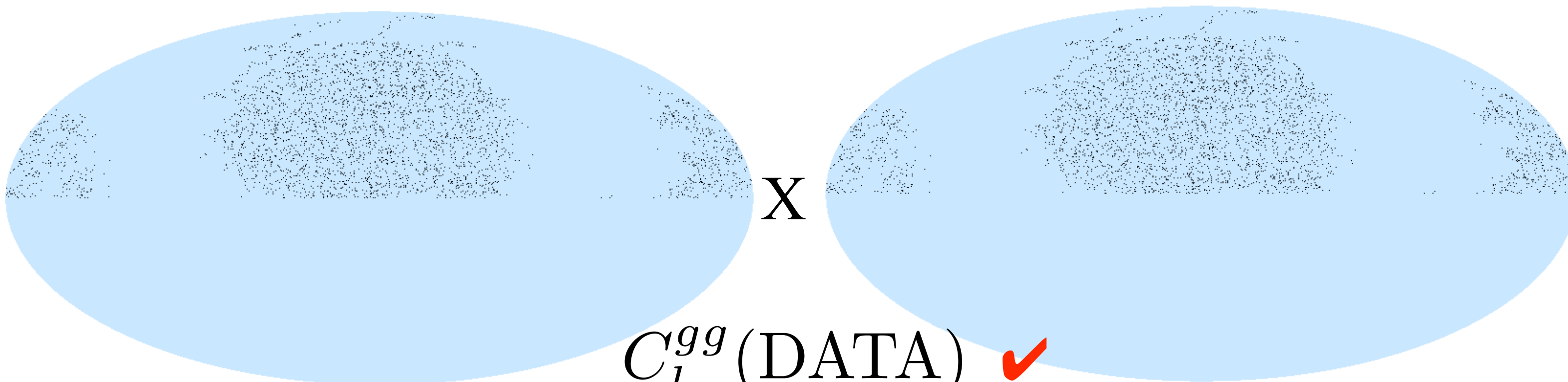

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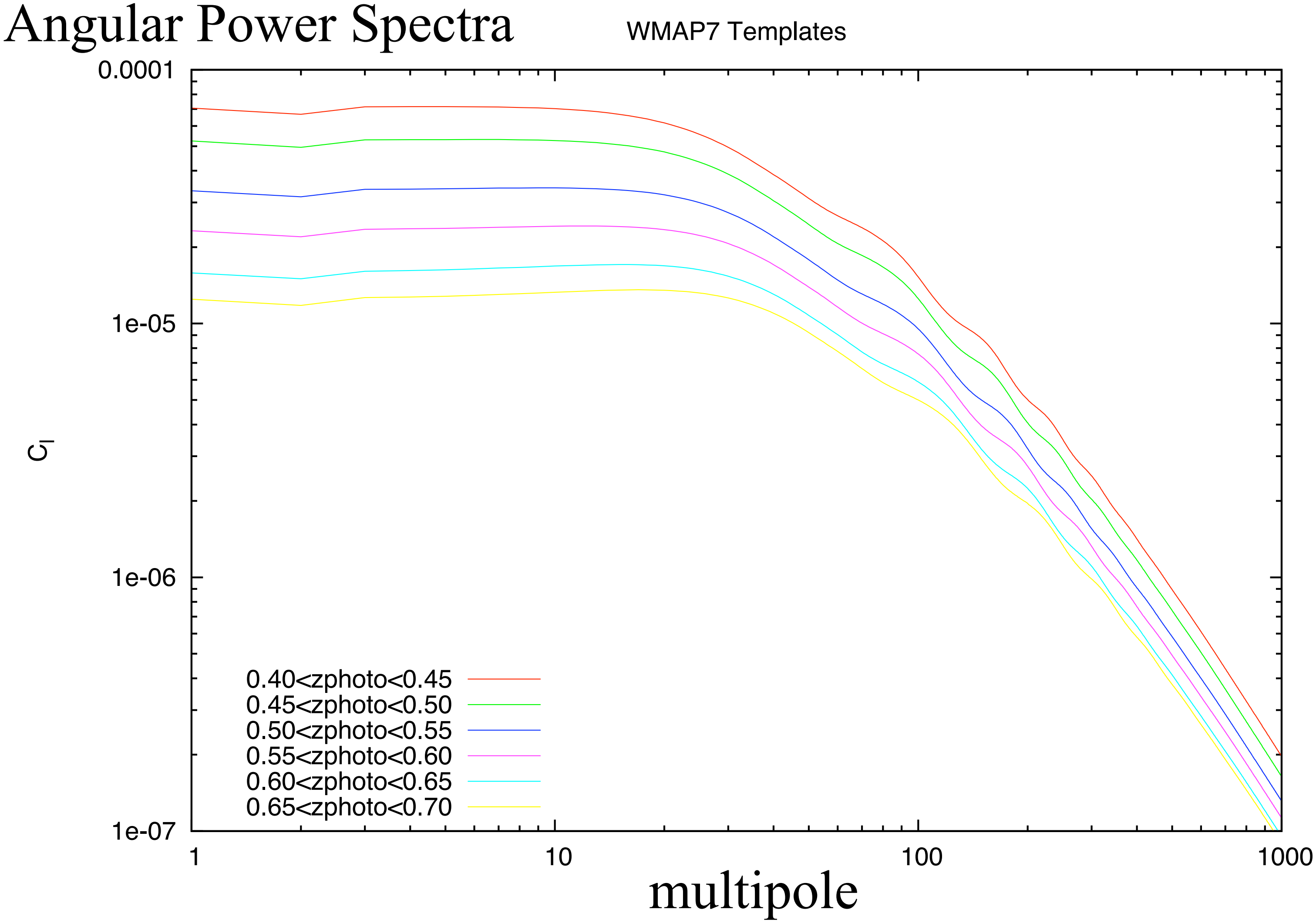
What we expect to see

Angular Power Spectra



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Dust Extinction

Stellar Contamination

Galaxies from next photometric slice

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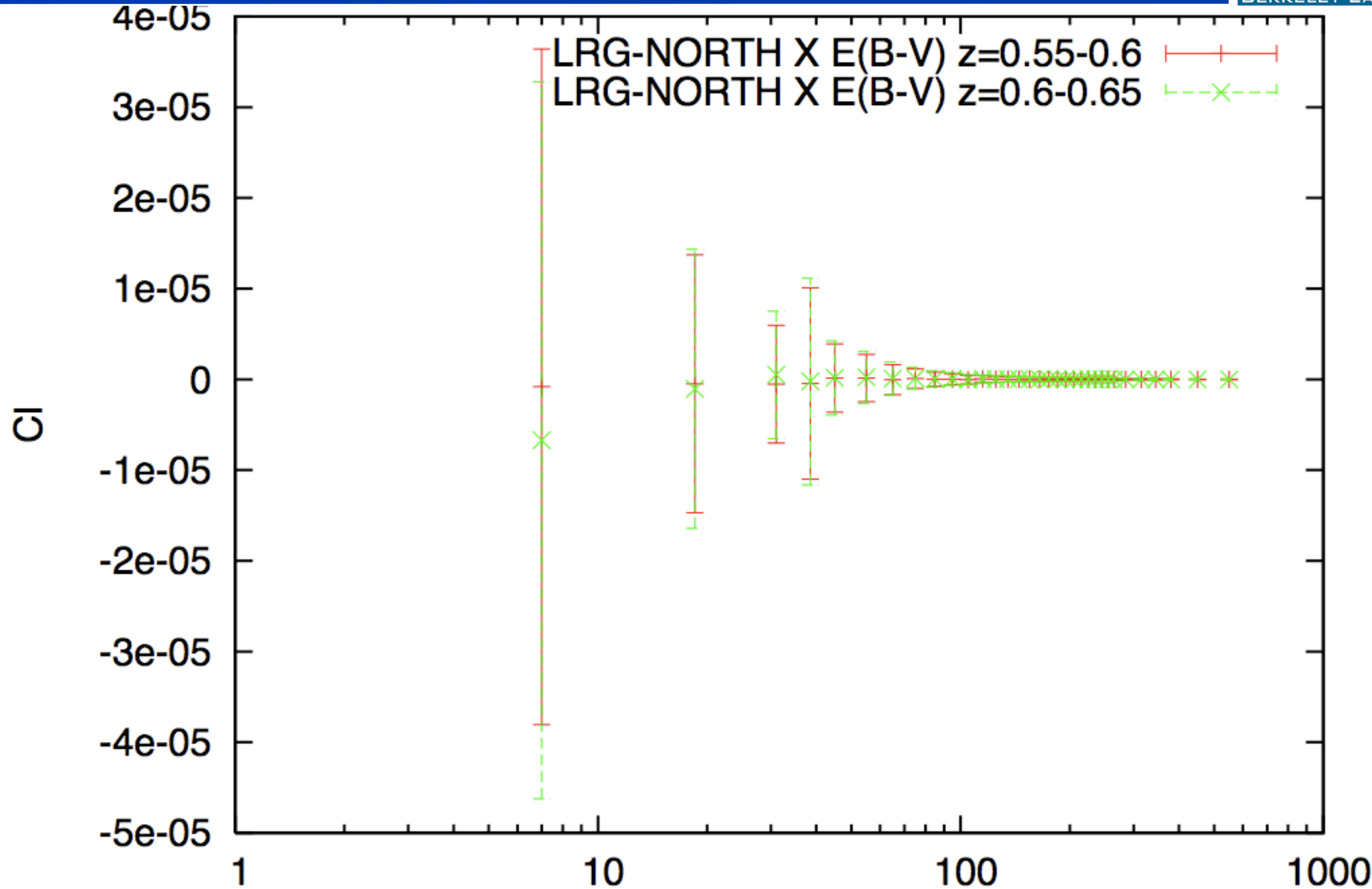
The effect of dust extinction



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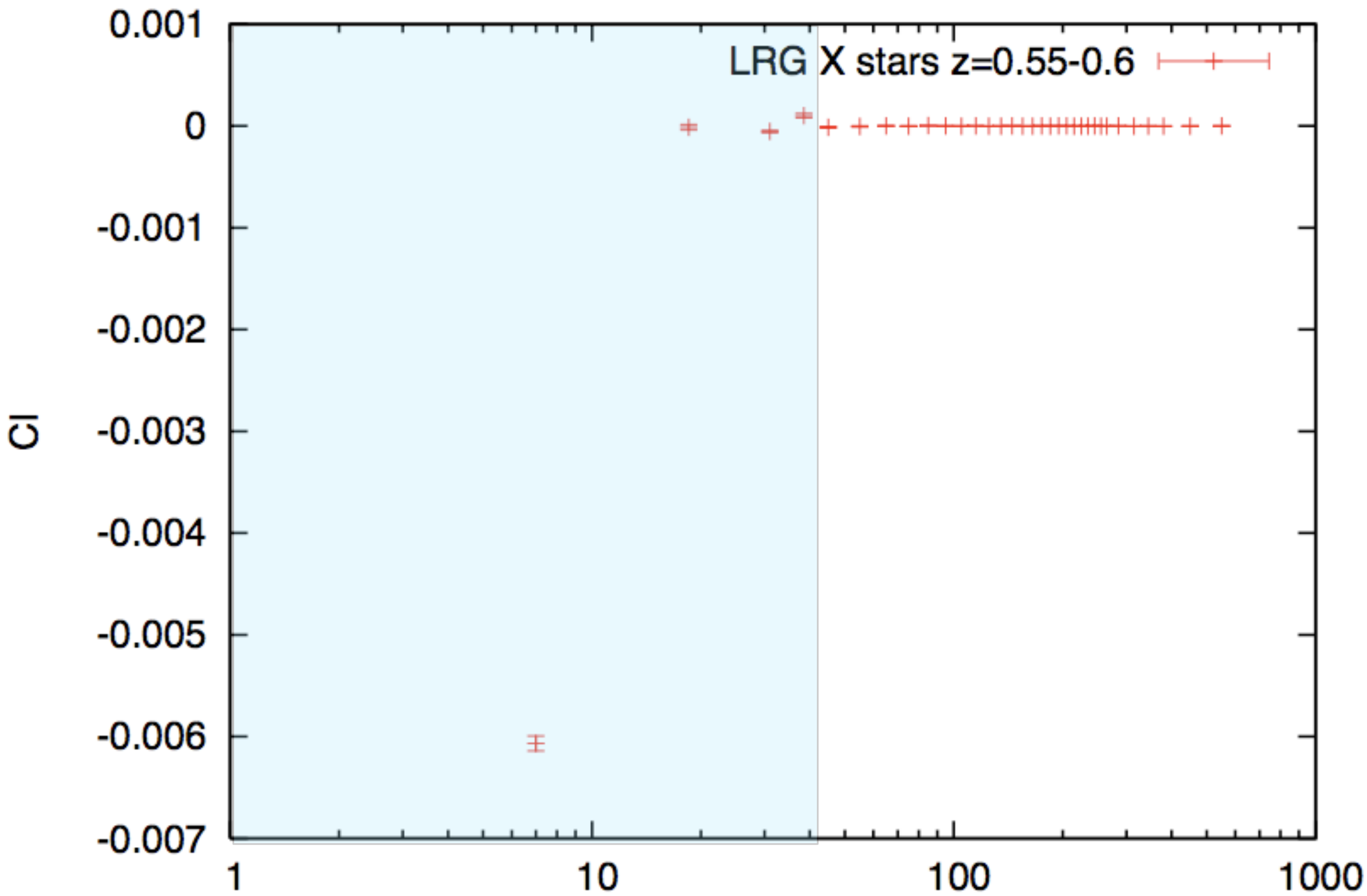

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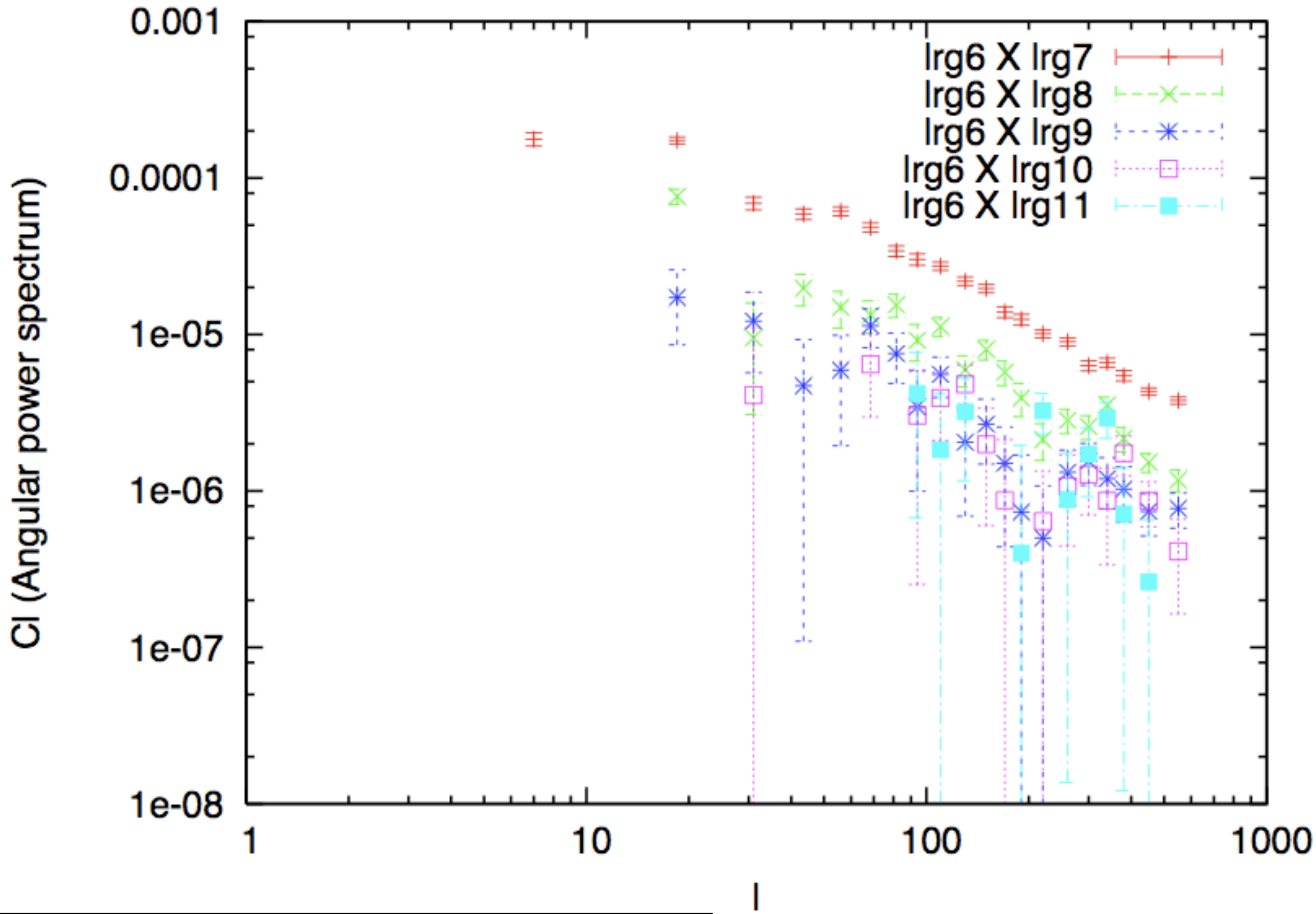
Overlap of the redshift bins



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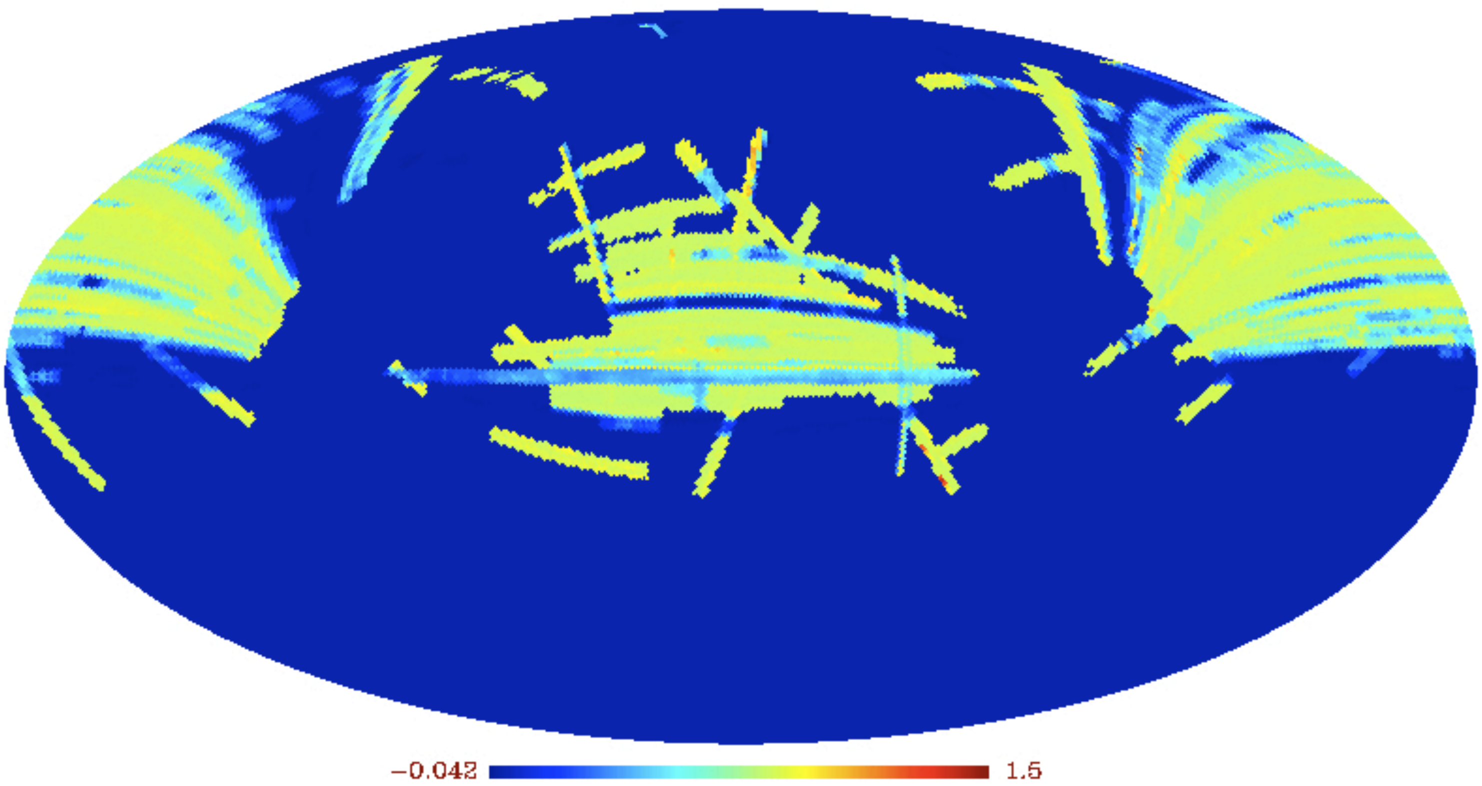
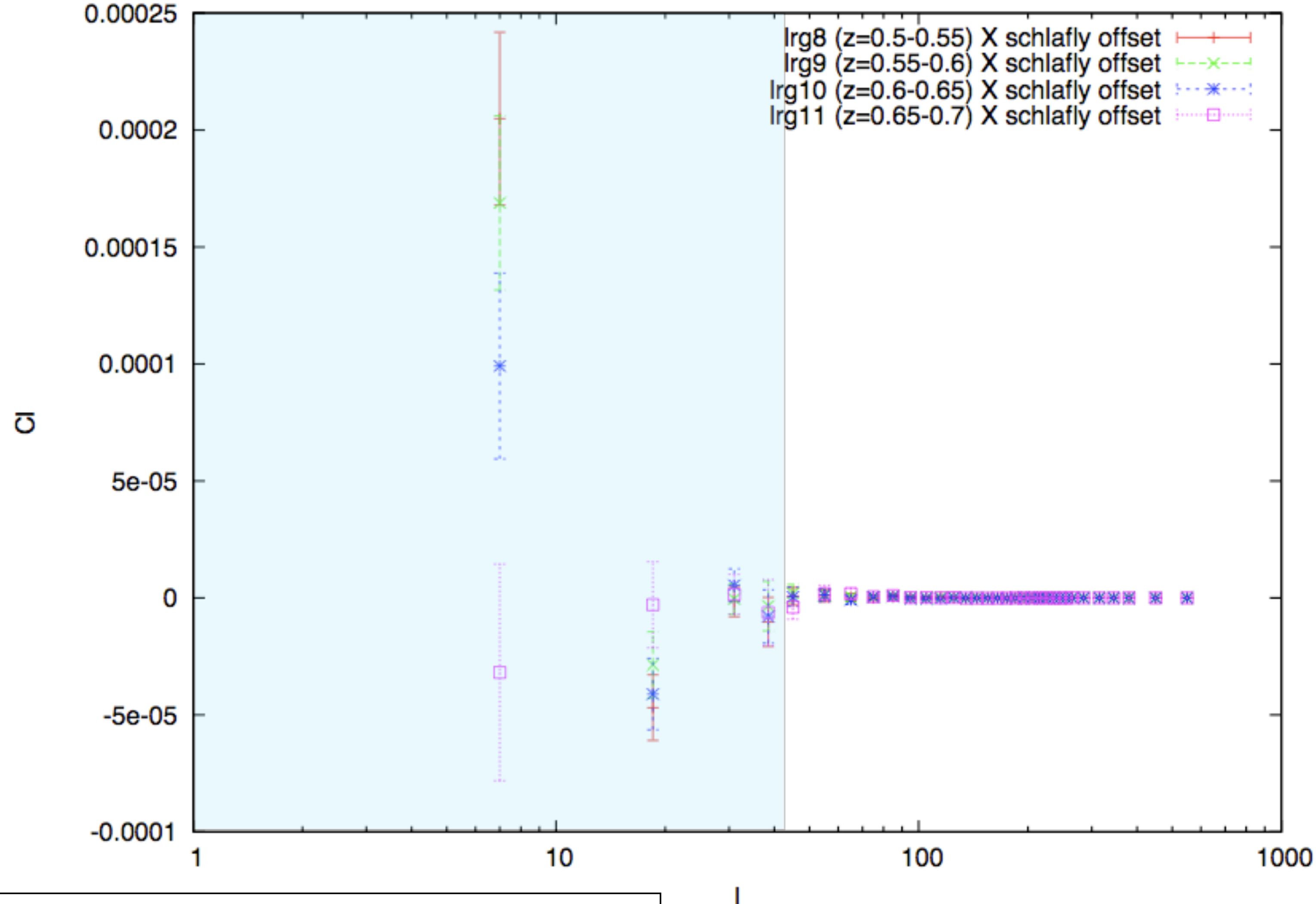
What are the photometric offsets?



Color offsets as discussed in Schlafly et al. 2010

The effect of the photometric offsets



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Dust Extinction

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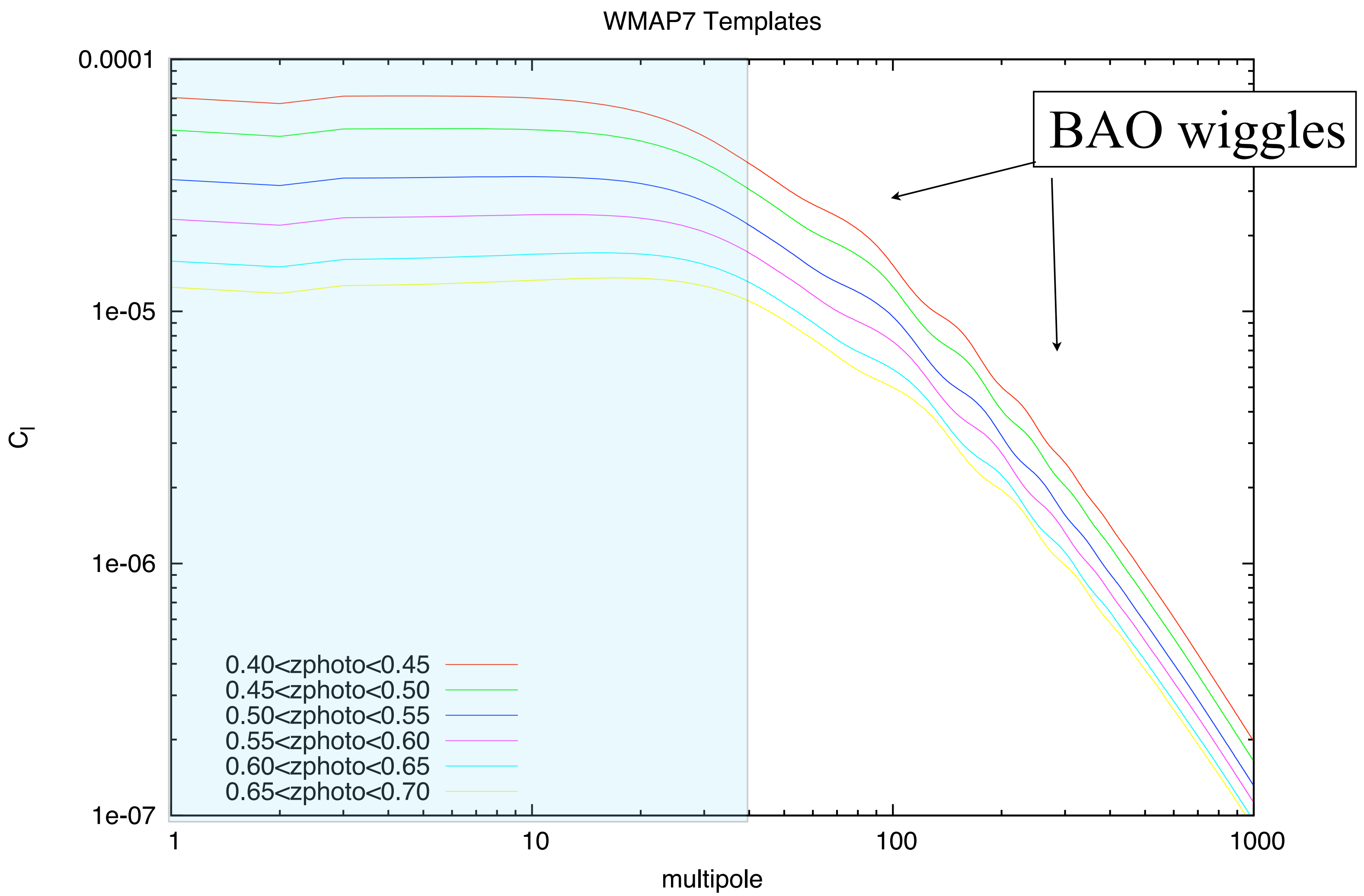
Galaxies from next photometric slice

If we don't take out the systematics, we won't be able to trust the power-spectra until at least **l> 40**

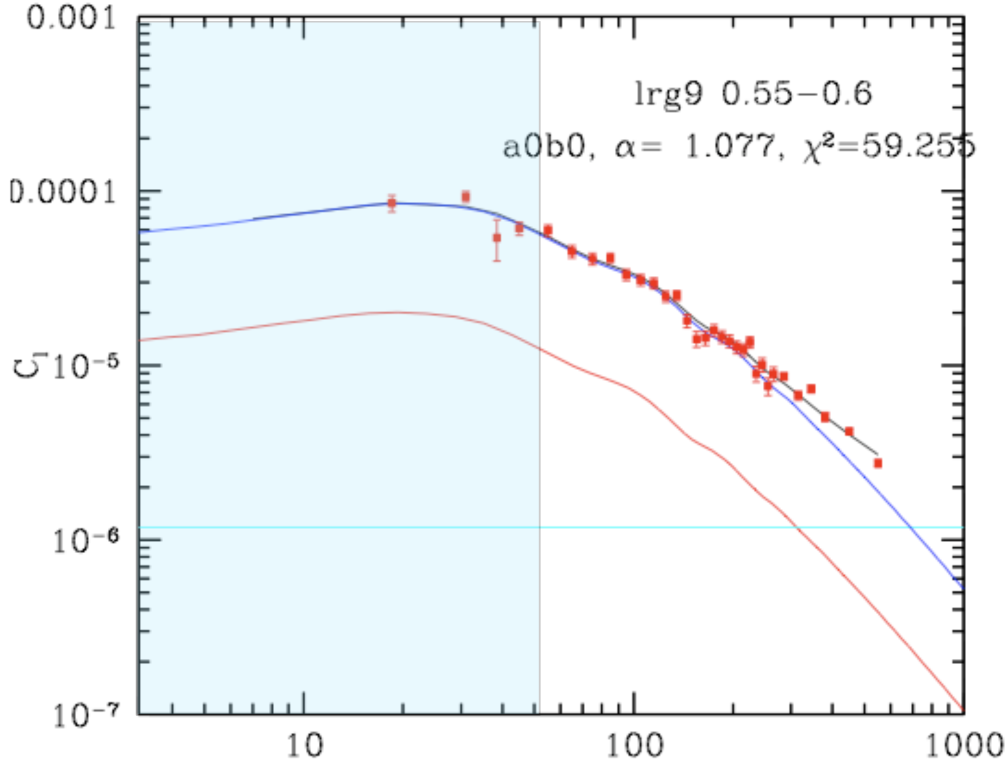
Remember? What we expect to see



BAO: with Luminous Red Galaxies
Preliminary Results before taking out systematics

Angular Power-spectrum

z=0.55-0.6



l (as in spherical harmonics)

It is really hard to see the BAO feature, but one can divide out the smooth part of the spectrum

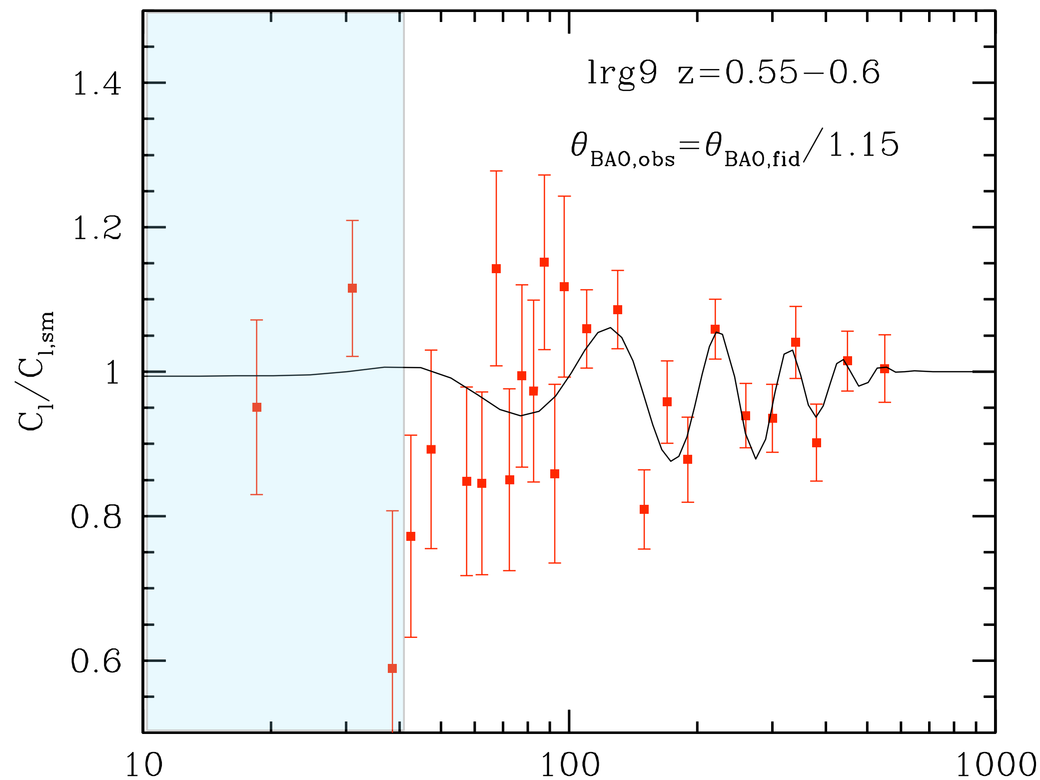
Ho, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies

Preliminary BAO before taking out systematics

$C_l / C^{smoothed}(l)$

z=0.55-0.6



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BAO: with Luminous Red Galaxies

Preliminary BAO before taking out systematics

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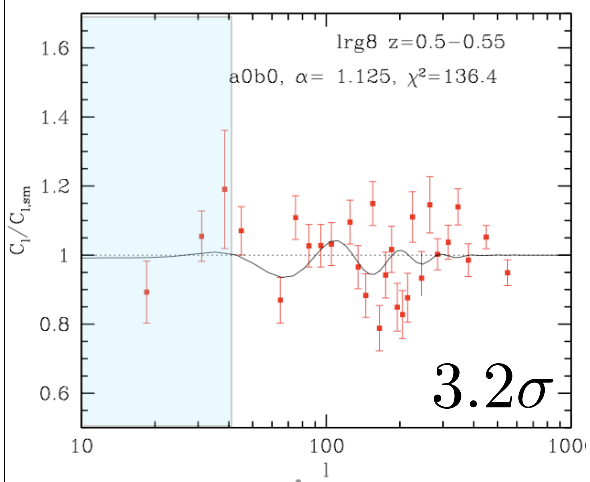
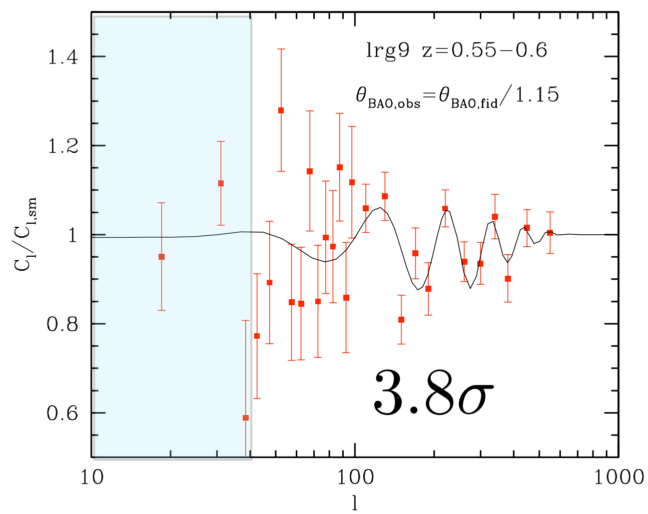
z=0.5-0.55



z=0.55-0.6



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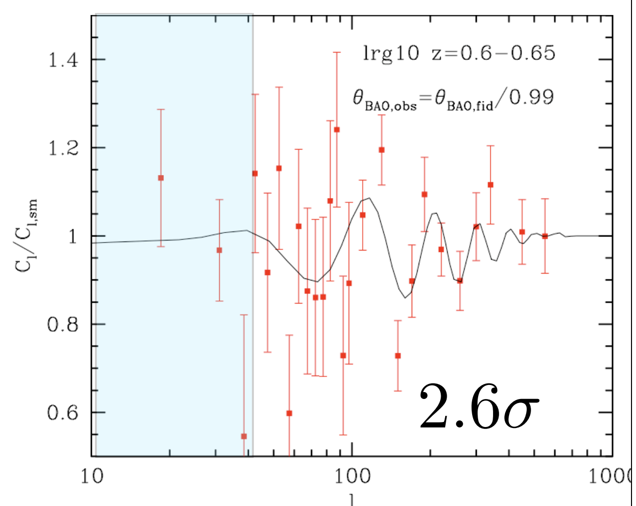

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Ho, Seo, Ross, White, Schlegel et al. (in prep)

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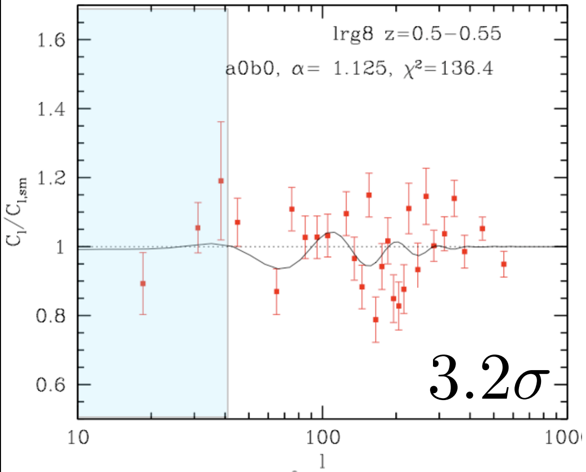

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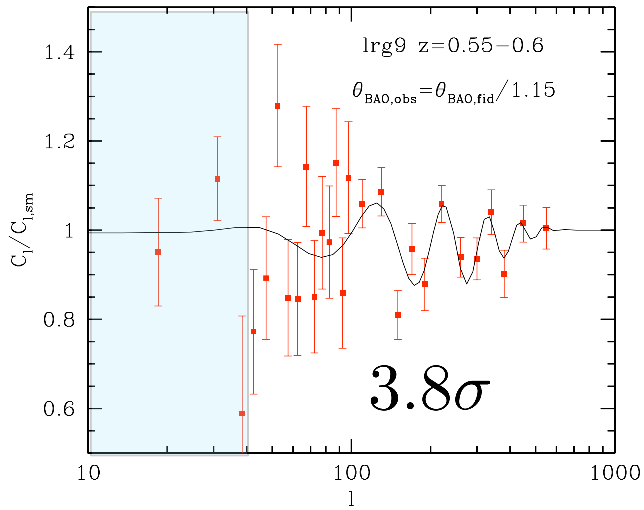

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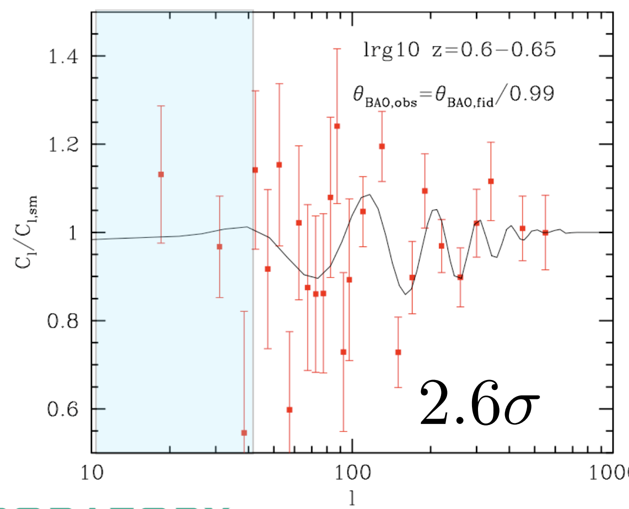


However, there may still be small remaining systematics in higher l...

BAO: with Luminous Red Galaxies

Systematics: Taking them out of the equation

True galaxy overdensity

Observed galaxy overdensity $$\delta_g^o = \delta_g^t + \sum_{i=0}^{N} \epsilon_i \delta_{s_i}$$ Various systematics

For example, if i=2 only:

$$< \delta_g^o \delta_{s_1} >=< \delta_g^t \delta_g^t > + \epsilon_1 < \delta_{s_1} \delta_{s_1} > + \epsilon_2 < \delta_{s_2} \delta_{s_1} >$$

$$< \delta_g^o \delta_{s_2} >=< \delta_g^t \delta_g^t > + \epsilon_1 < \delta_{s_1} \delta_{s_2} > + \epsilon_2 < \delta_{s_2} \delta_{s_2} >$$

$$< \delta_g^o \delta_g^o >=< \delta_g^t \delta_g^t > + \epsilon_1^2 < \delta_{s_1} \delta_{s_1} > + 2\epsilon_1 \epsilon_2 < \delta_{s_2} \delta_{s_1} > + \epsilon_2^2 < \delta_{s_2} \delta_{s_2} >$$

We also need to take into account of all the covariances between systematics and across different band power

Awaiting for the new answers ...

Ho, Seo, Ross, White, Schlegel et al. (in prep)

Preliminary results
without taking out all of the systematics

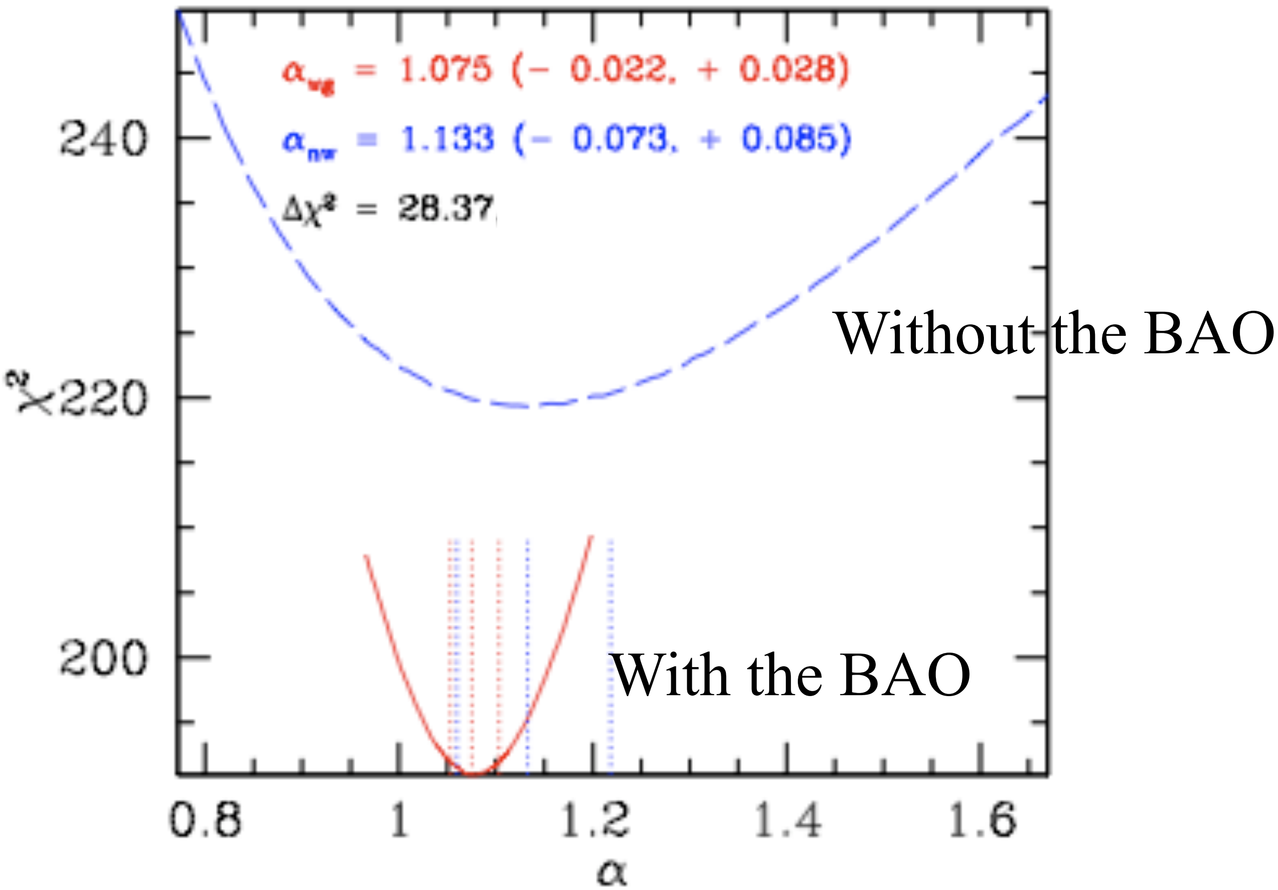
(if you really want to know)

The following results are derived:

by taking into account of angular power-spectra from l >40 from z=0.45-0.65.

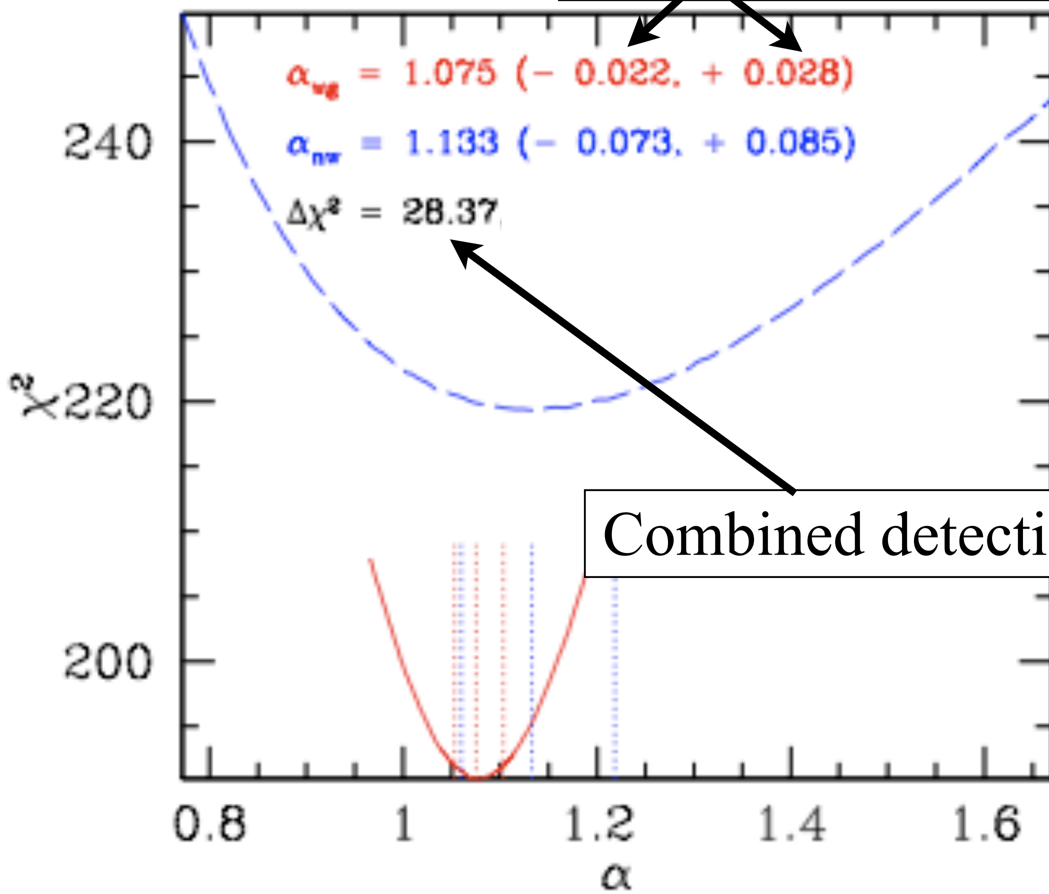
It should be quite clean of systematics, but there are probably some residuals which we are going to take out with our new method.

Preliminary results
without taking out all of the systematics



Preliminary results
without taking out all of the systematics

~2.5% measurement of the angular diameter distance



Combined detection of ~5.3 sigmas

BAO: with Luminous Red Galaxies
What is new?

- Data: **Largest volume** ever used for galaxy clustering: 14,000 sq deg up to z=0.7, this is equivalent to $15\mathrm{Gpc}^3$

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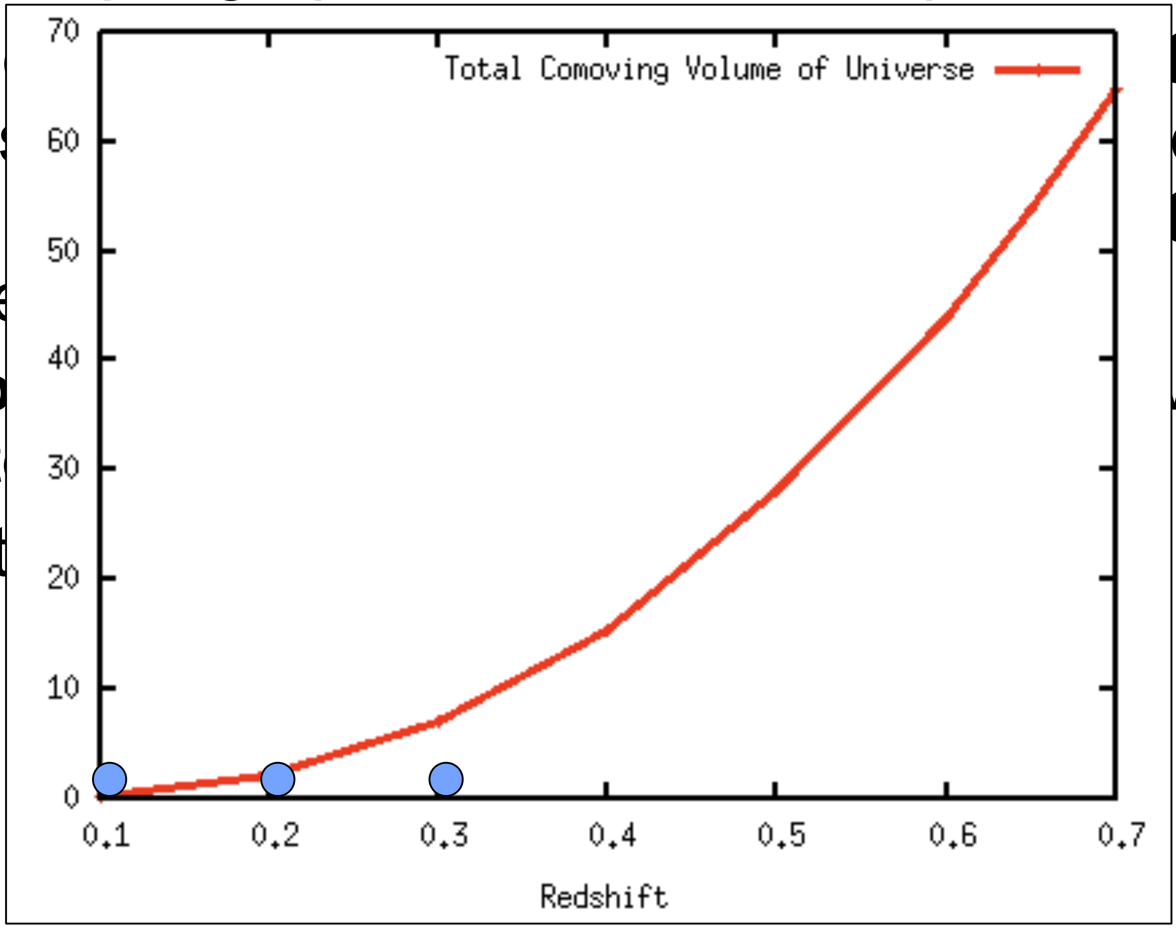

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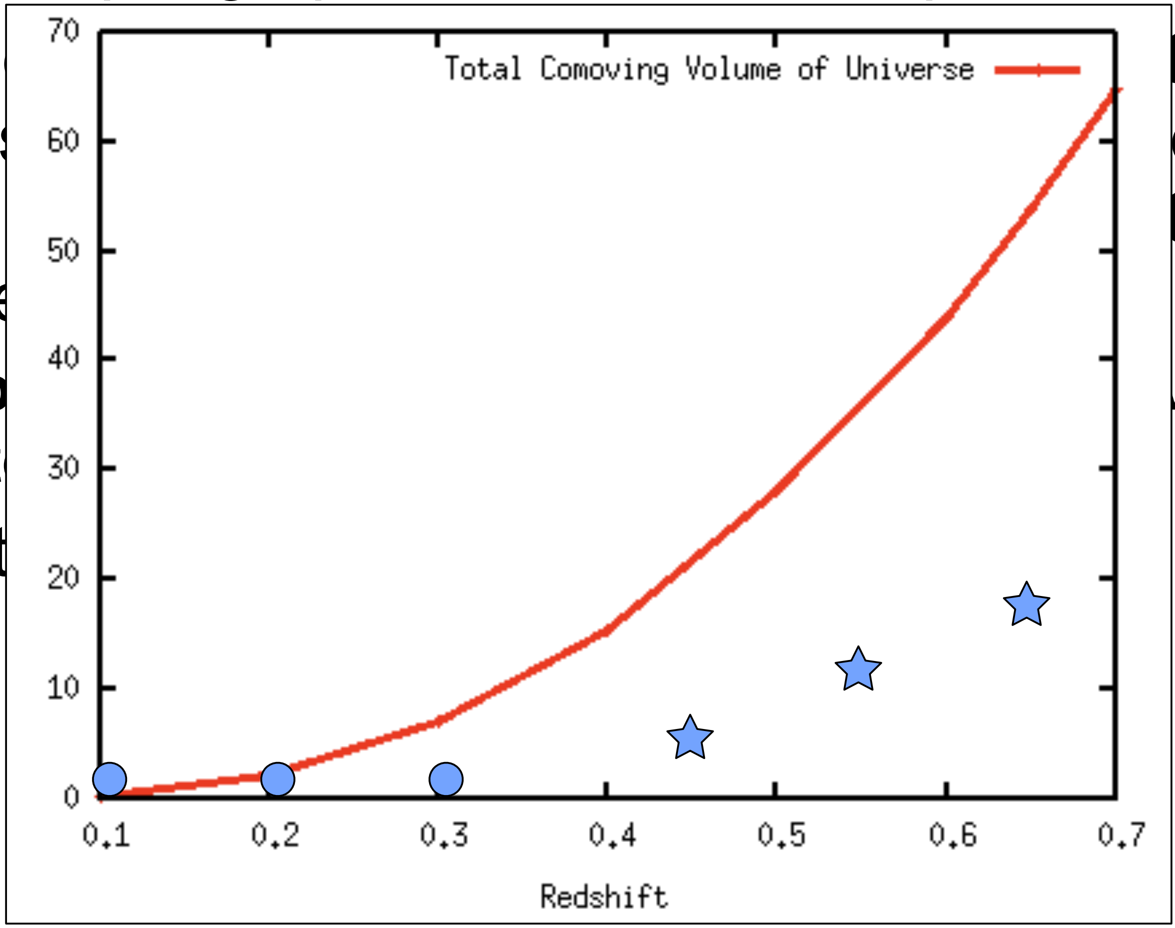

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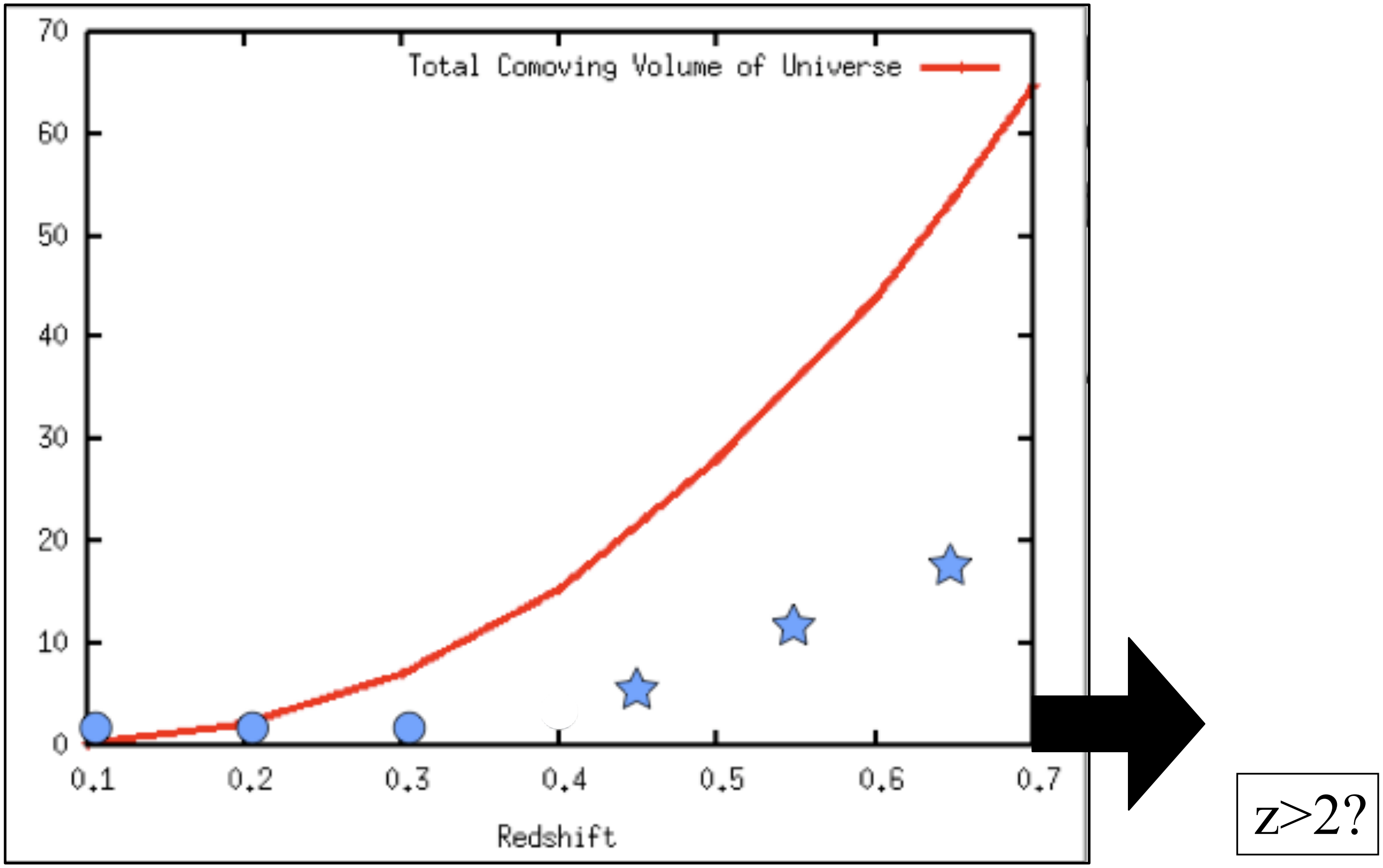
  - Before this work, the highest redshift with any significant BAO detection is at z=0.275
  - This work: Significant Detections at **highest redshift** range: 0.45<z<0.65

BAO: with Luminous Red Galaxies
Looking forward

- Cosmological Constraints from BAO will be coming soon.
- More detailed systematic tests have to be carried out.
- Photometric LRGs can be used for BAO in upcoming surveys such as DES, PanStarrs and LSST.
- A variant of the Quadratic Estimator can be applied to any Spectroscopic LRGs (in BOSS and maybe in BigBOSS) will provide ~10% level constraint on equation of state of Dark Energy.

BAO: Beyond Galaxies

- How can we learn about cosmology at much higher redshift ?

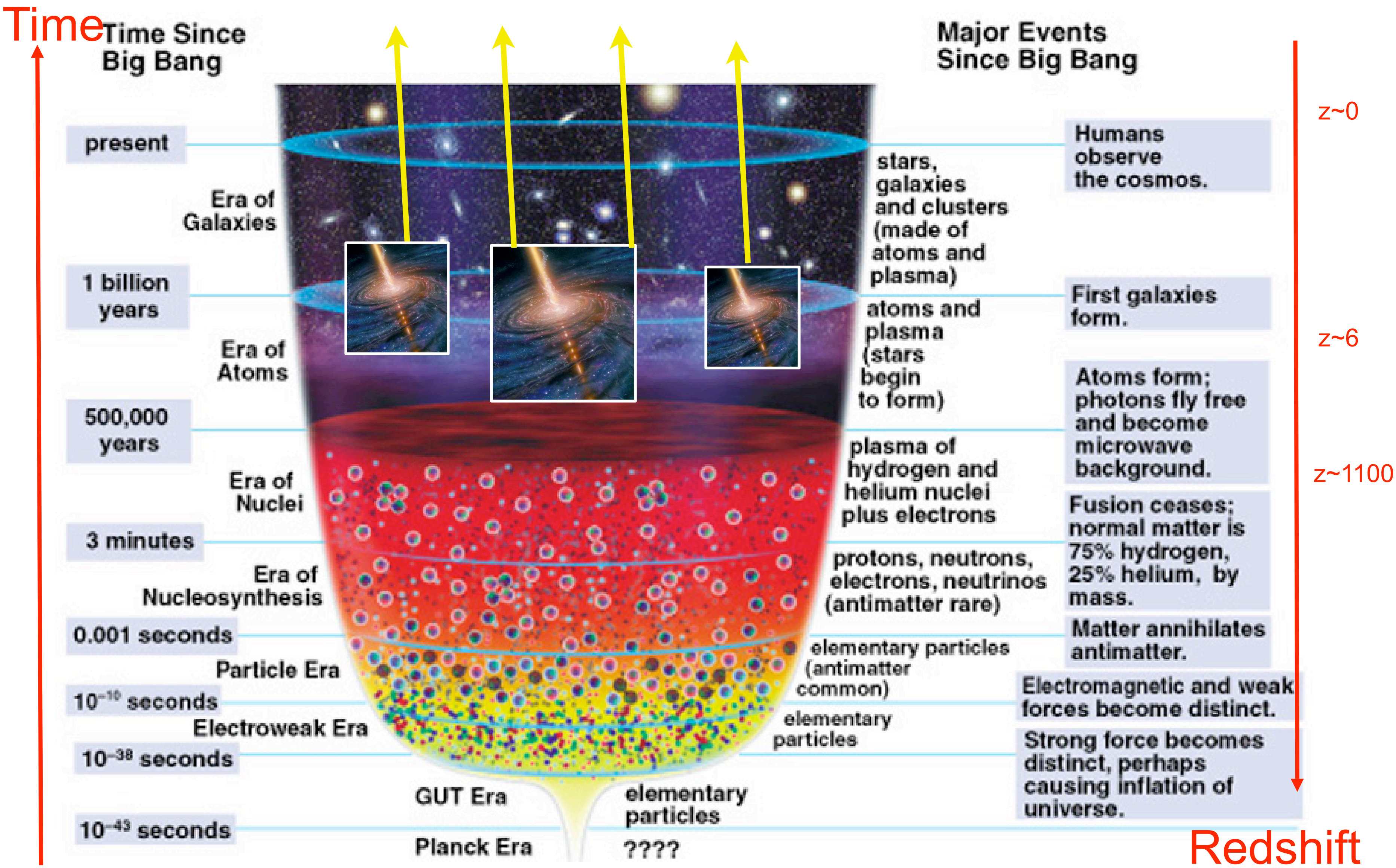


Outline

- Motivations
- Introduction
  - —What are Baryon Acoustic Oscillations?
- Baryon Acoustic Oscillations: Now and Beyond
  - —Now: With Luminous Red Galaxies
  - —Beyond: With Lyman Alpha Forest
- Conclusions

Beyond: With Lyman Alpha Forest

What is it?



Beyond: With Lyman Alpha Forest
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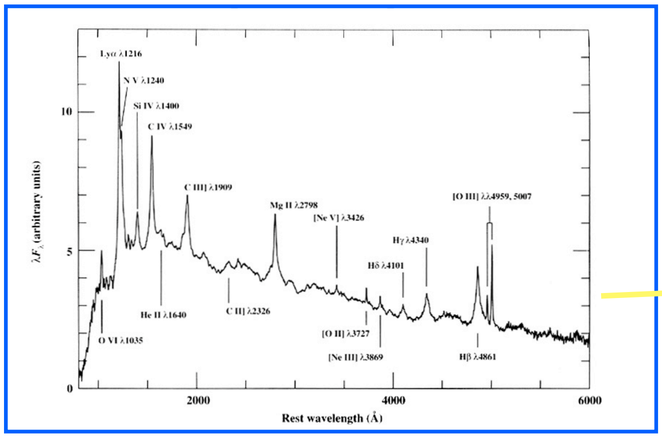
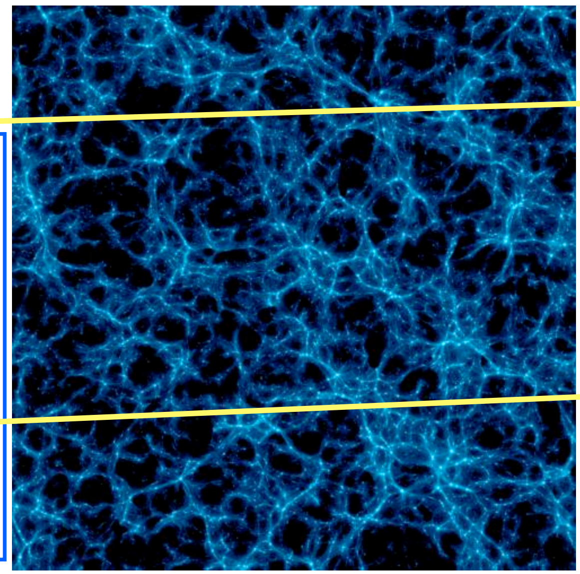
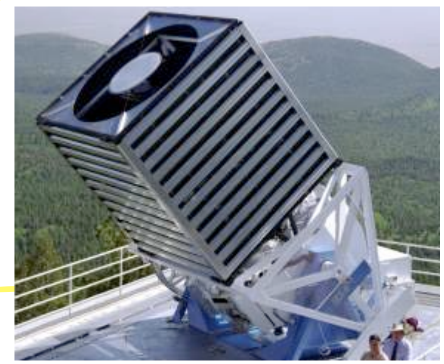
Quasar Spectra







Courtesy simulation of gas from
Renyue Cen and Jerry Ostriker

Beyond: With Lyman Alpha Forest
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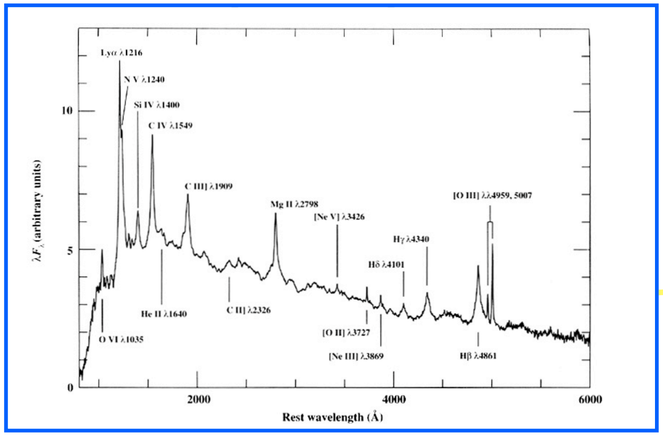

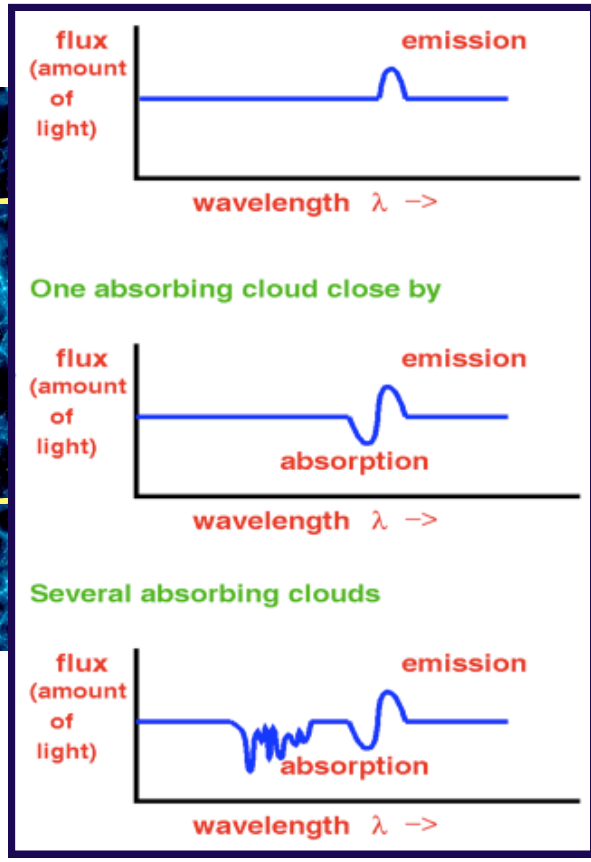

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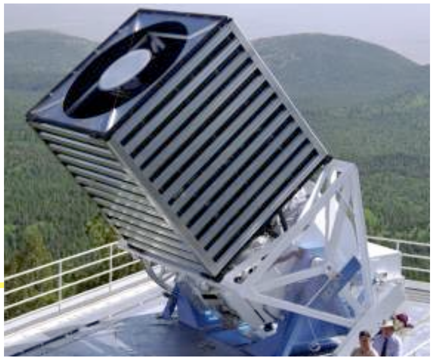
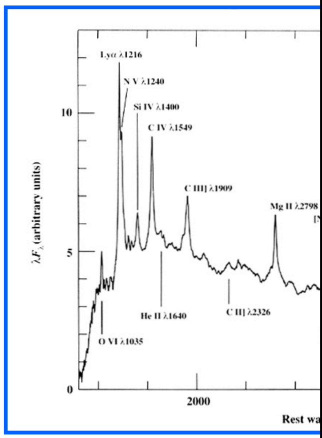


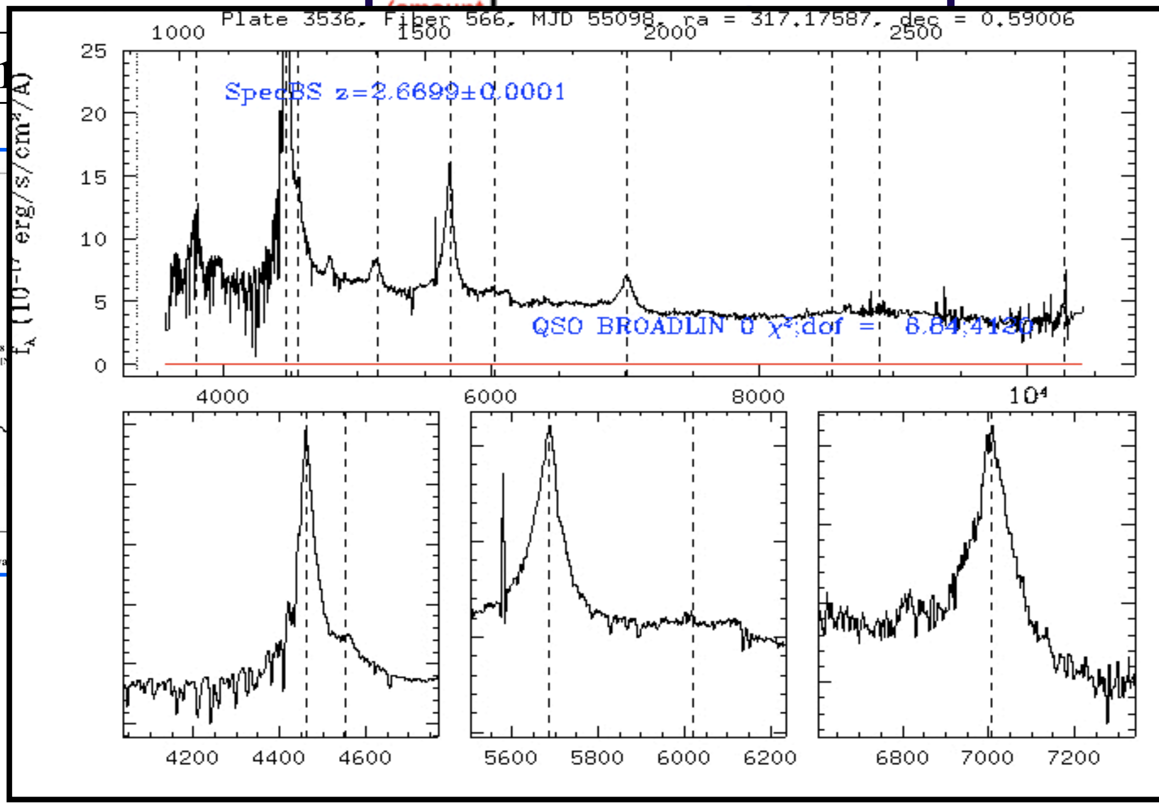
From Joanne Cohn's website

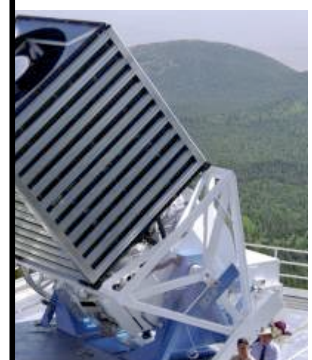
Beyond: With Lyman Alpha Forest
What is it?

Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe

Quasar







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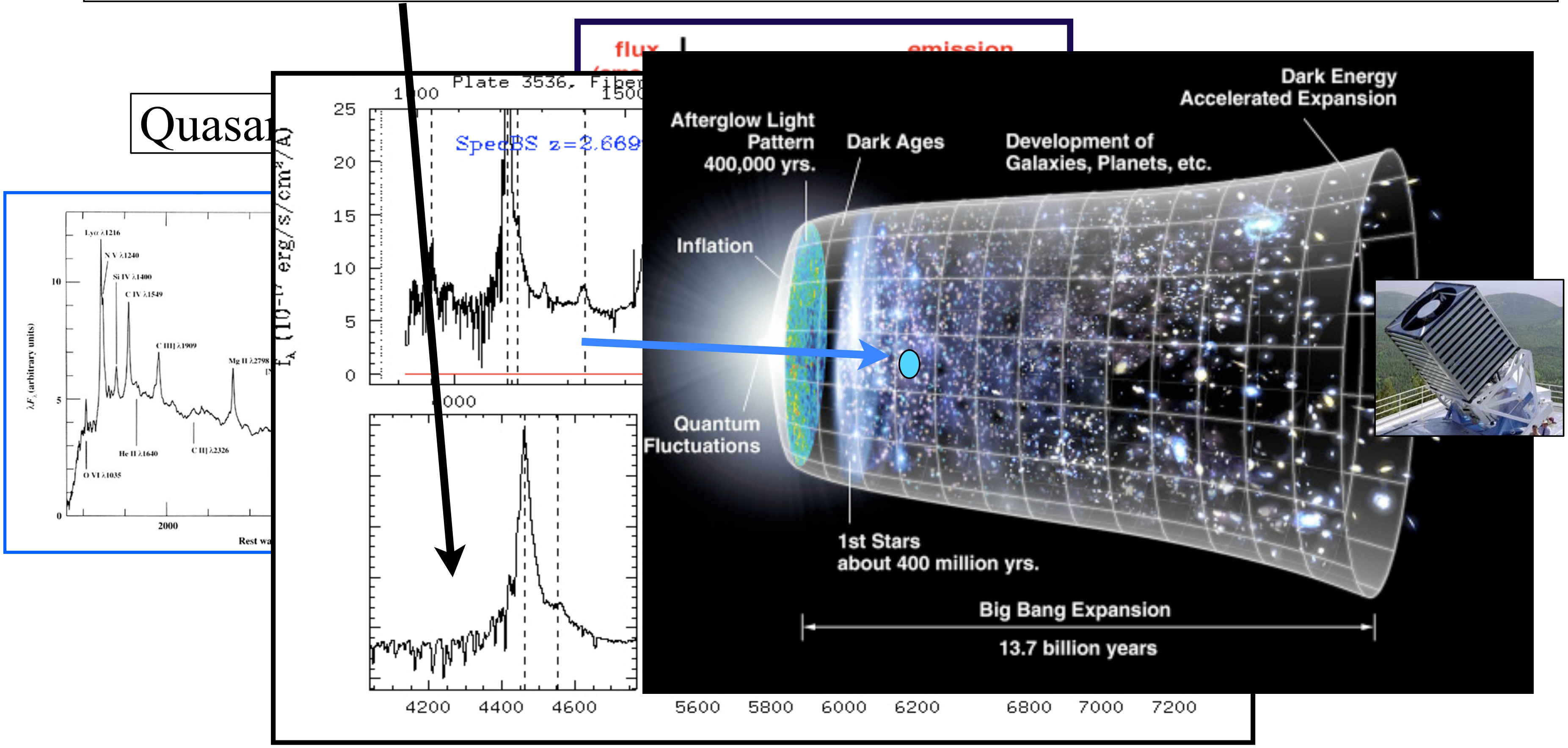

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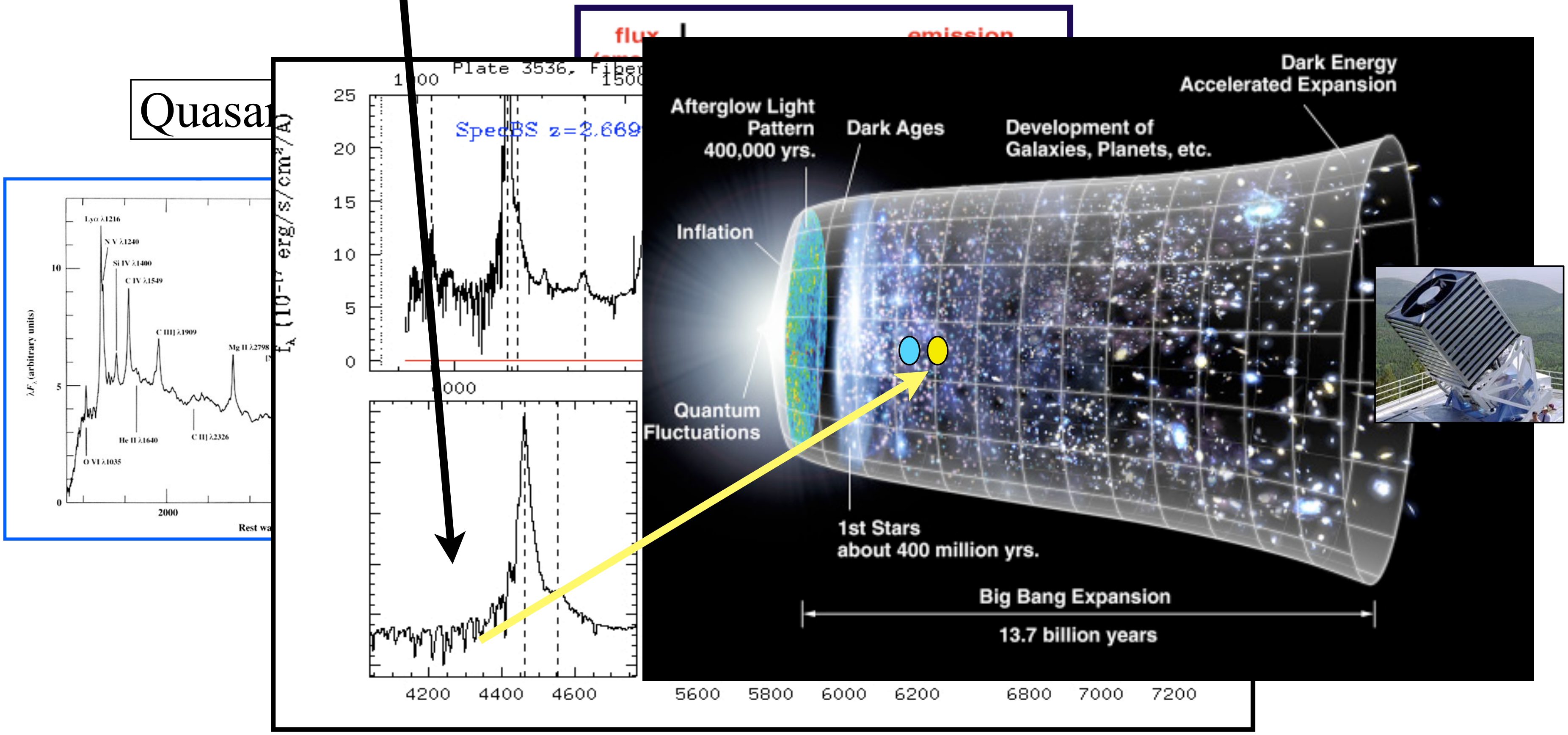
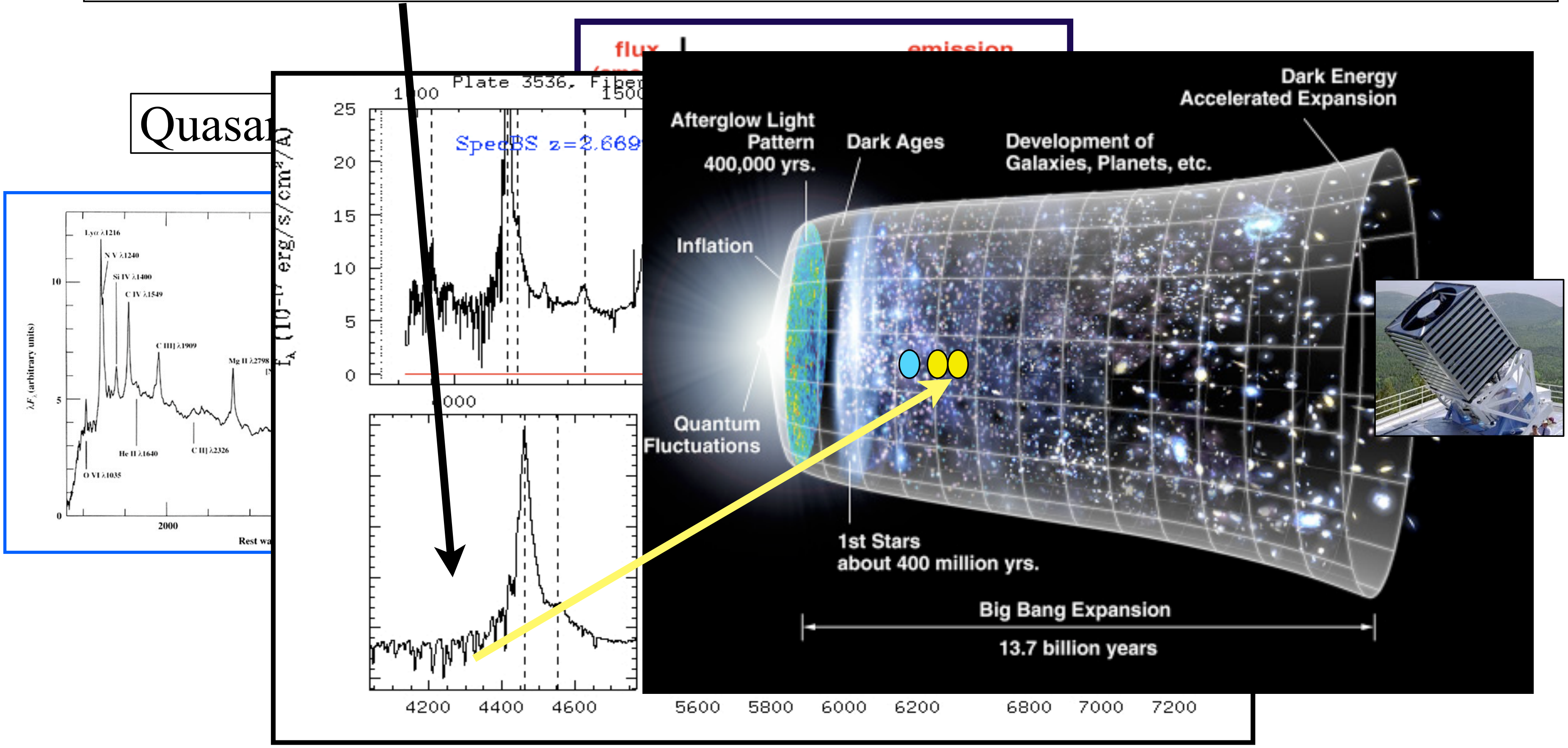


Beyond: With Lyman Alpha Forest
What is it?

Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe



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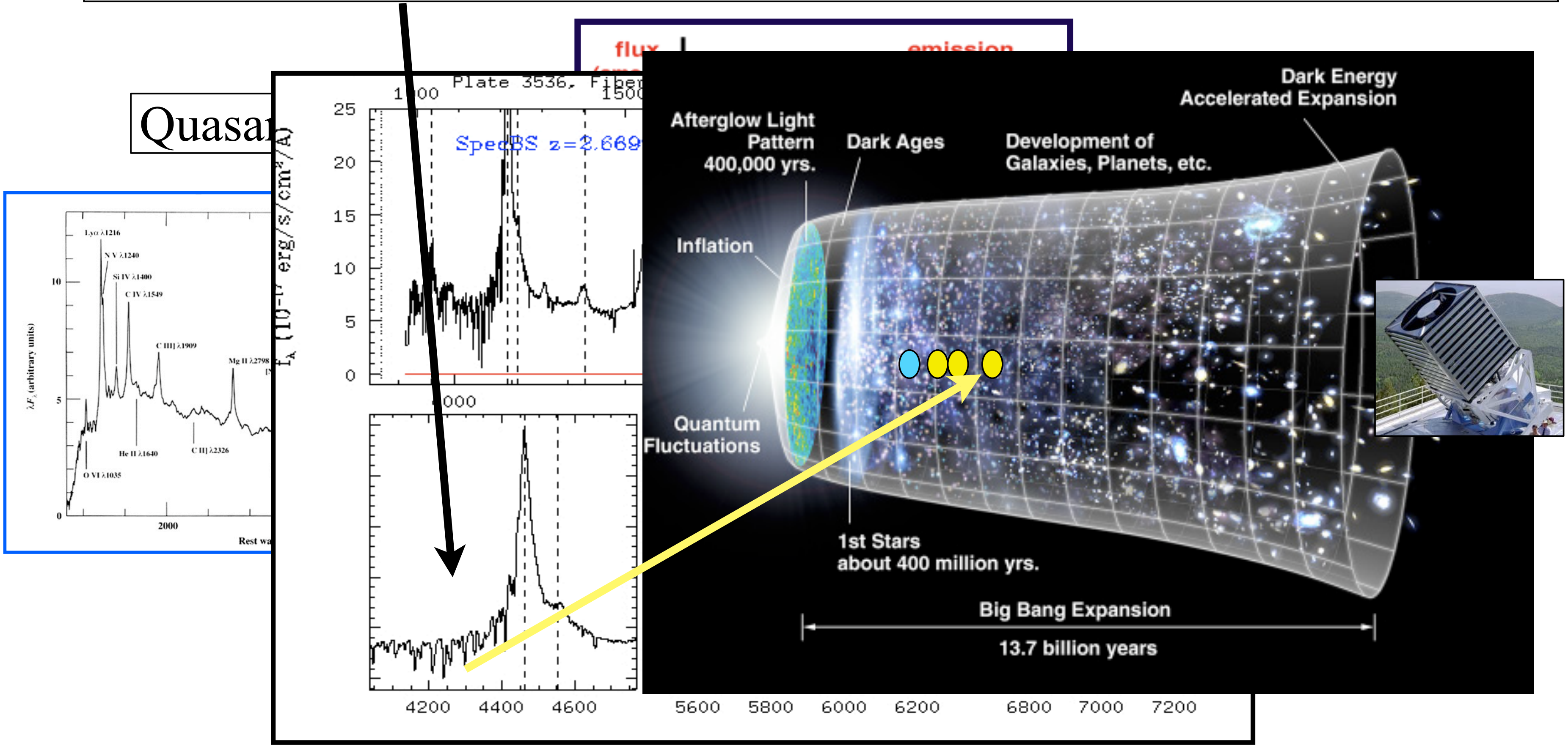

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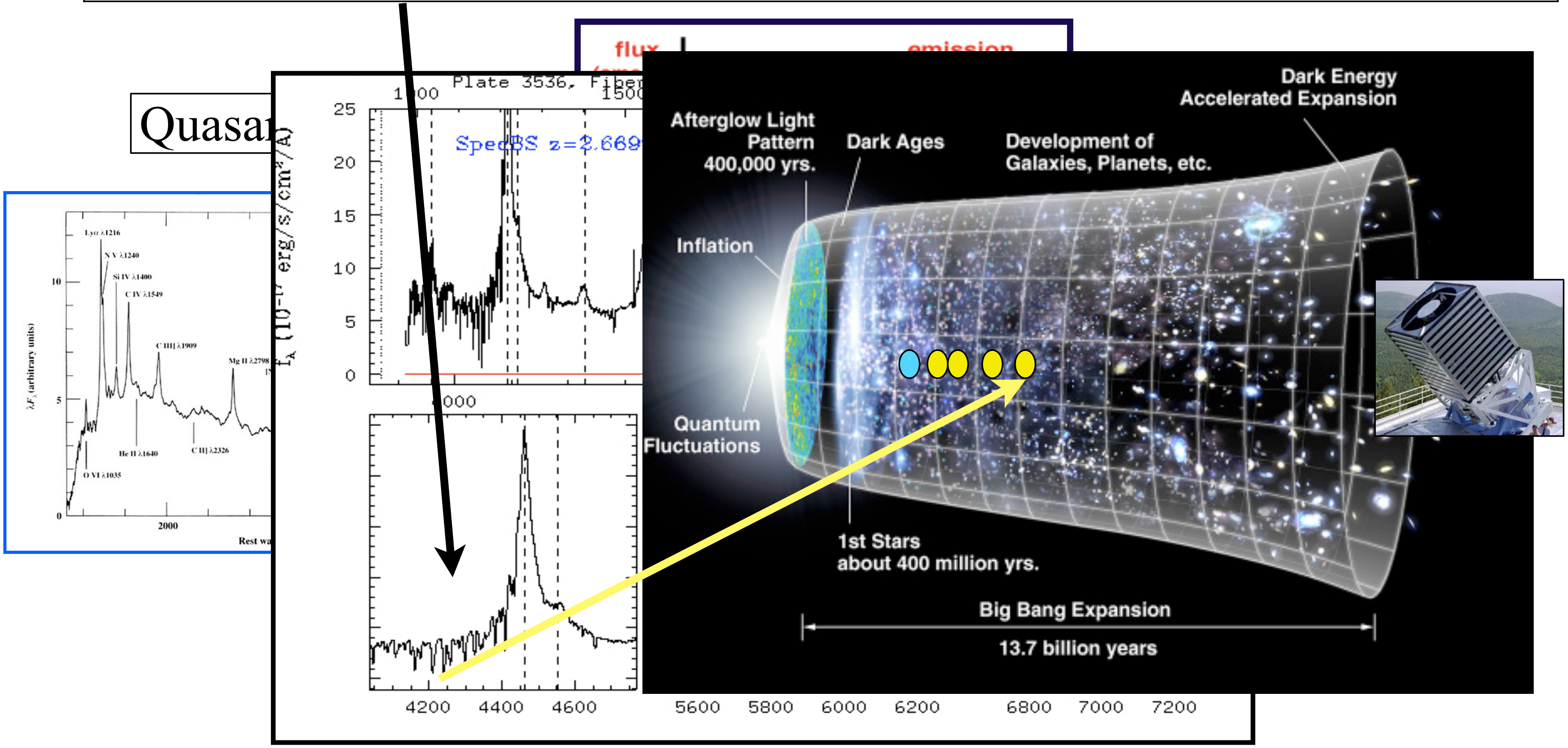

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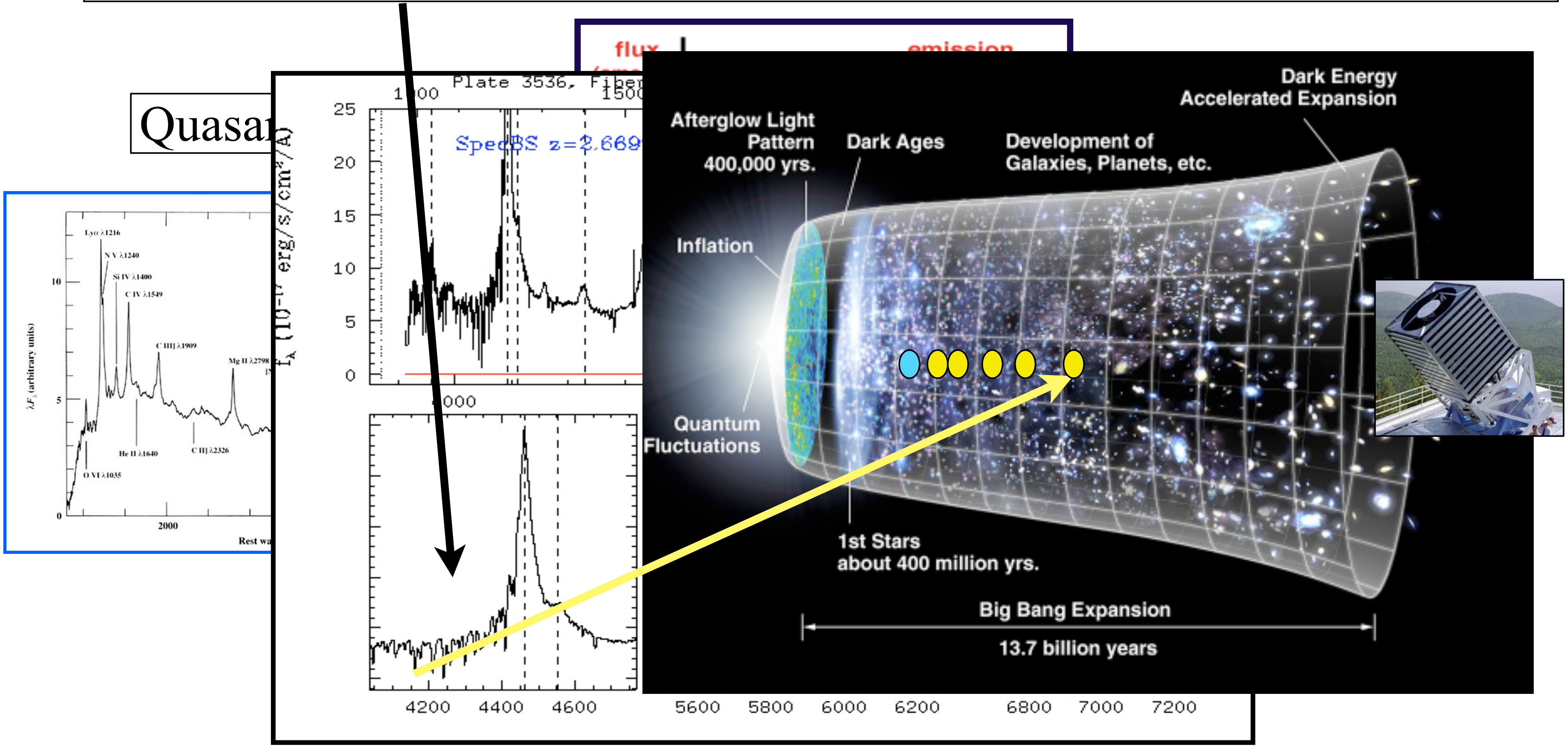

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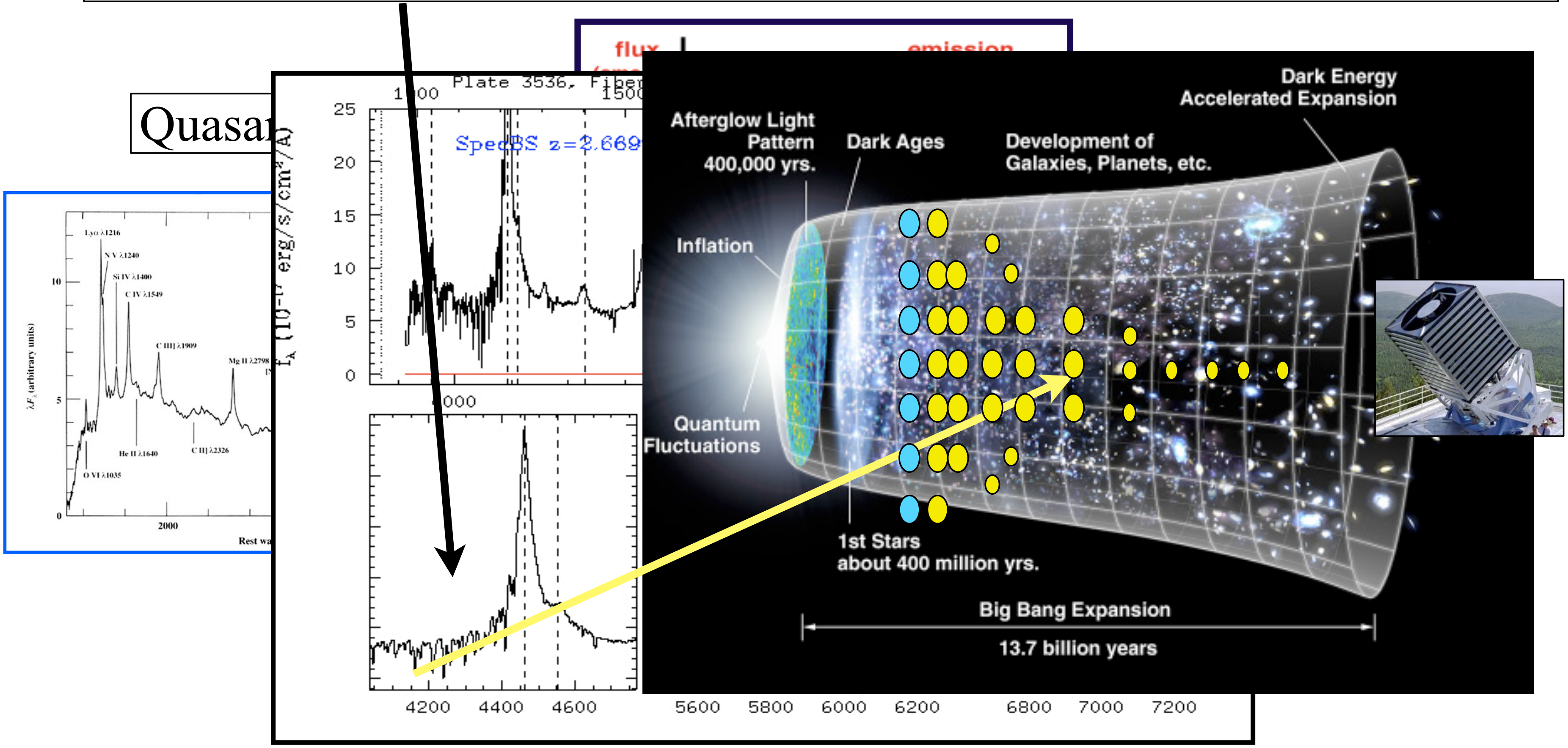

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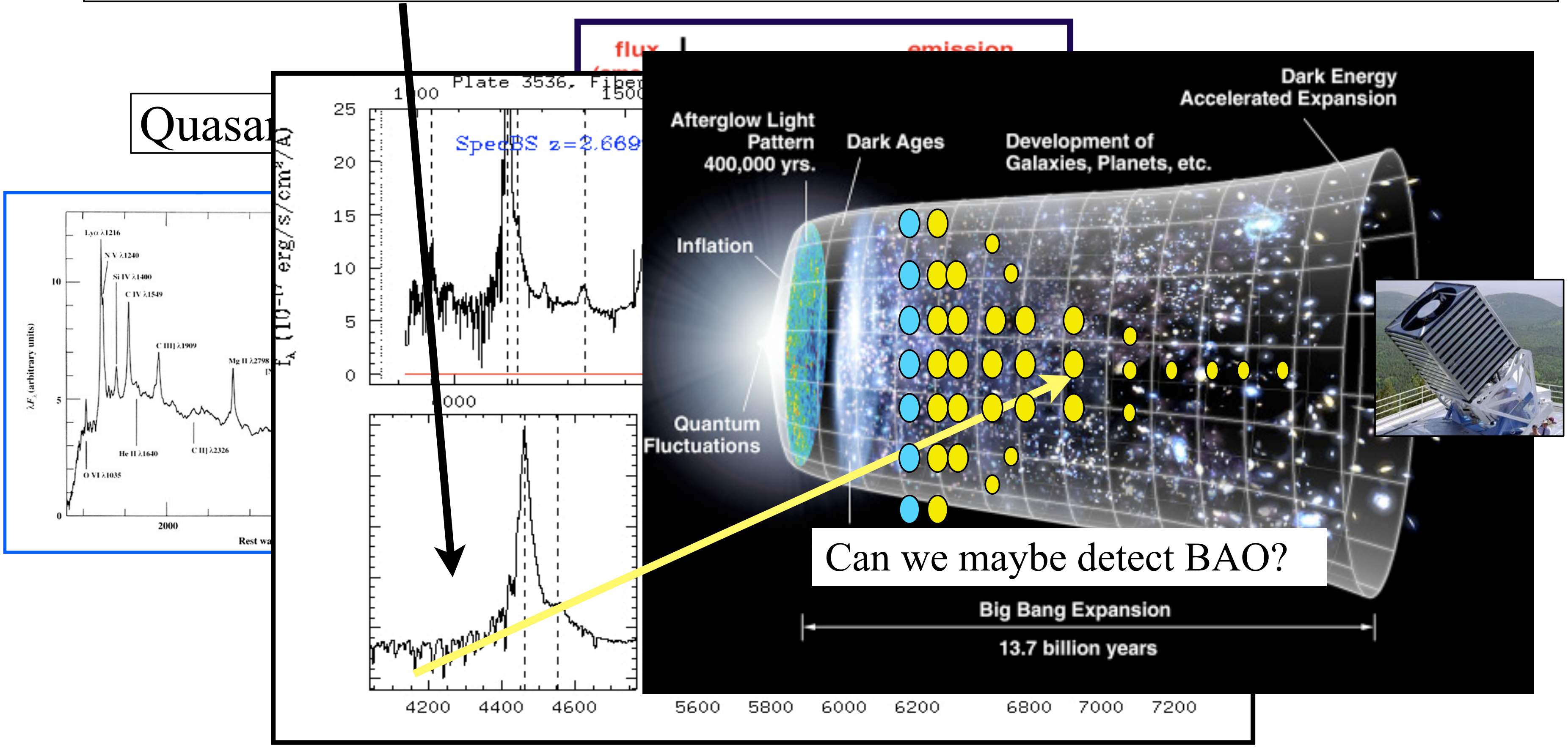
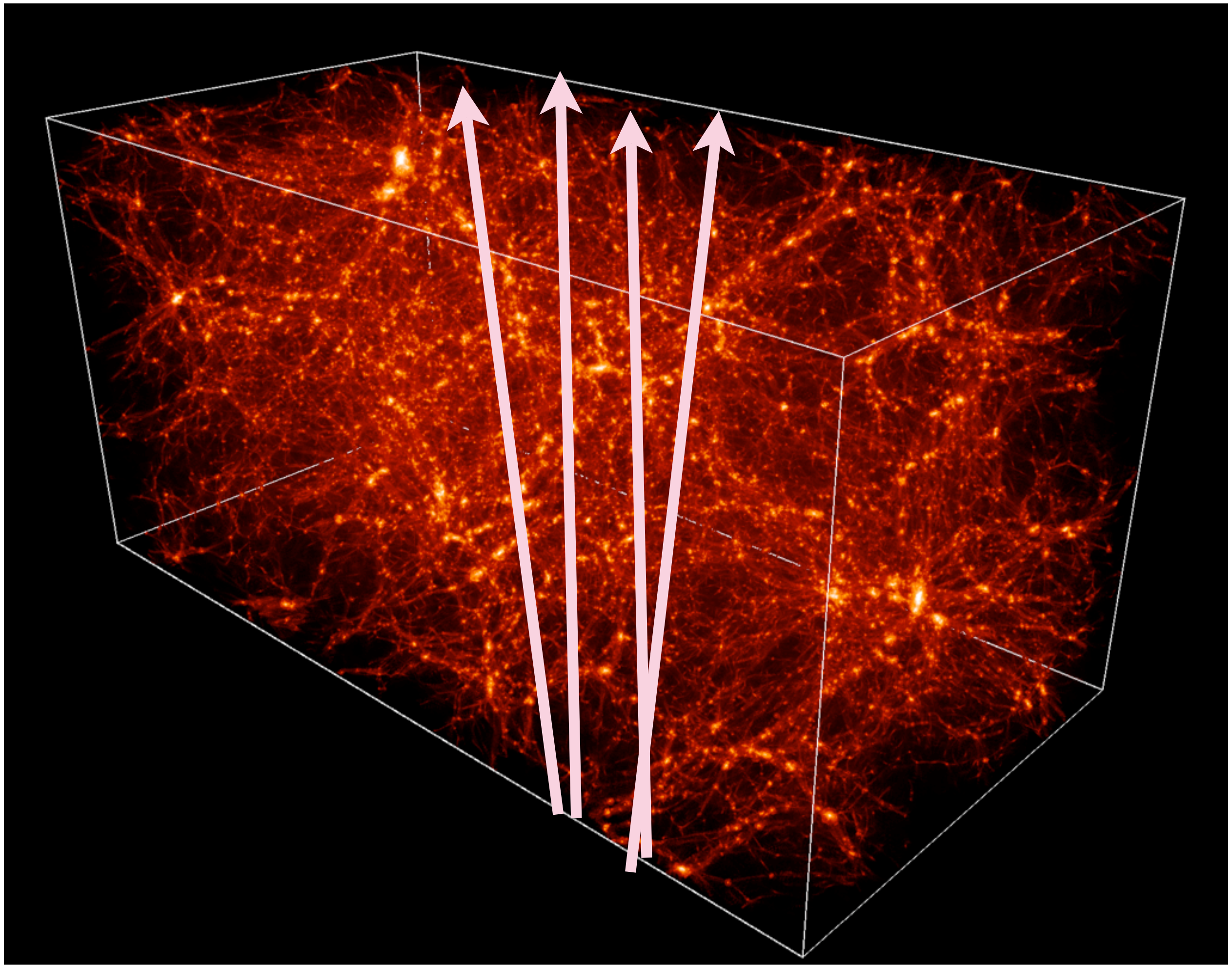


Beyond: With Lyman Alpha Forest
Simulations



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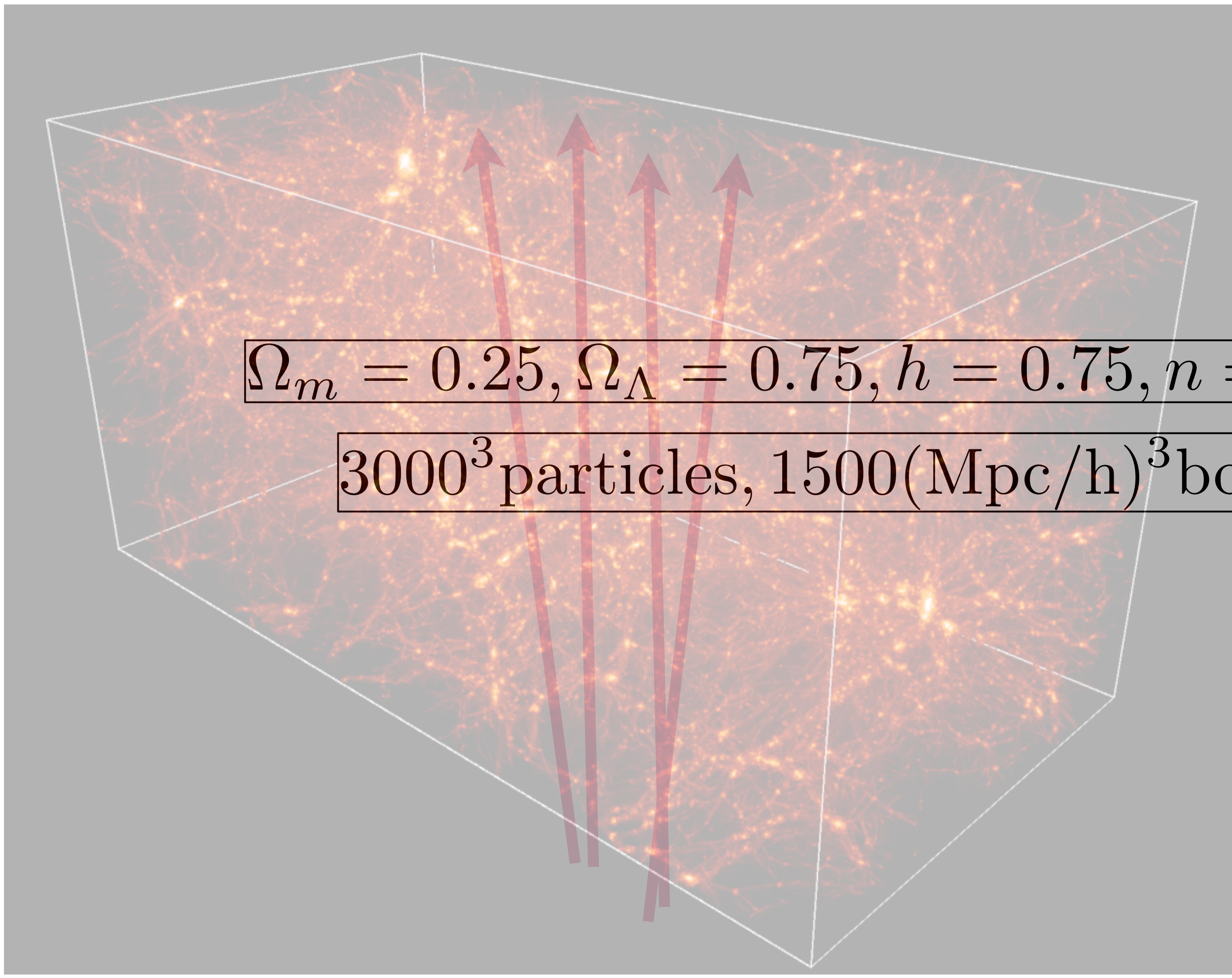

$$\boxed{\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8}$$

$$\boxed{3000^3 \text{particles}, 1500(\text{Mpc/h})^3 \text{box}, 3000^3 \text{grid}}$$

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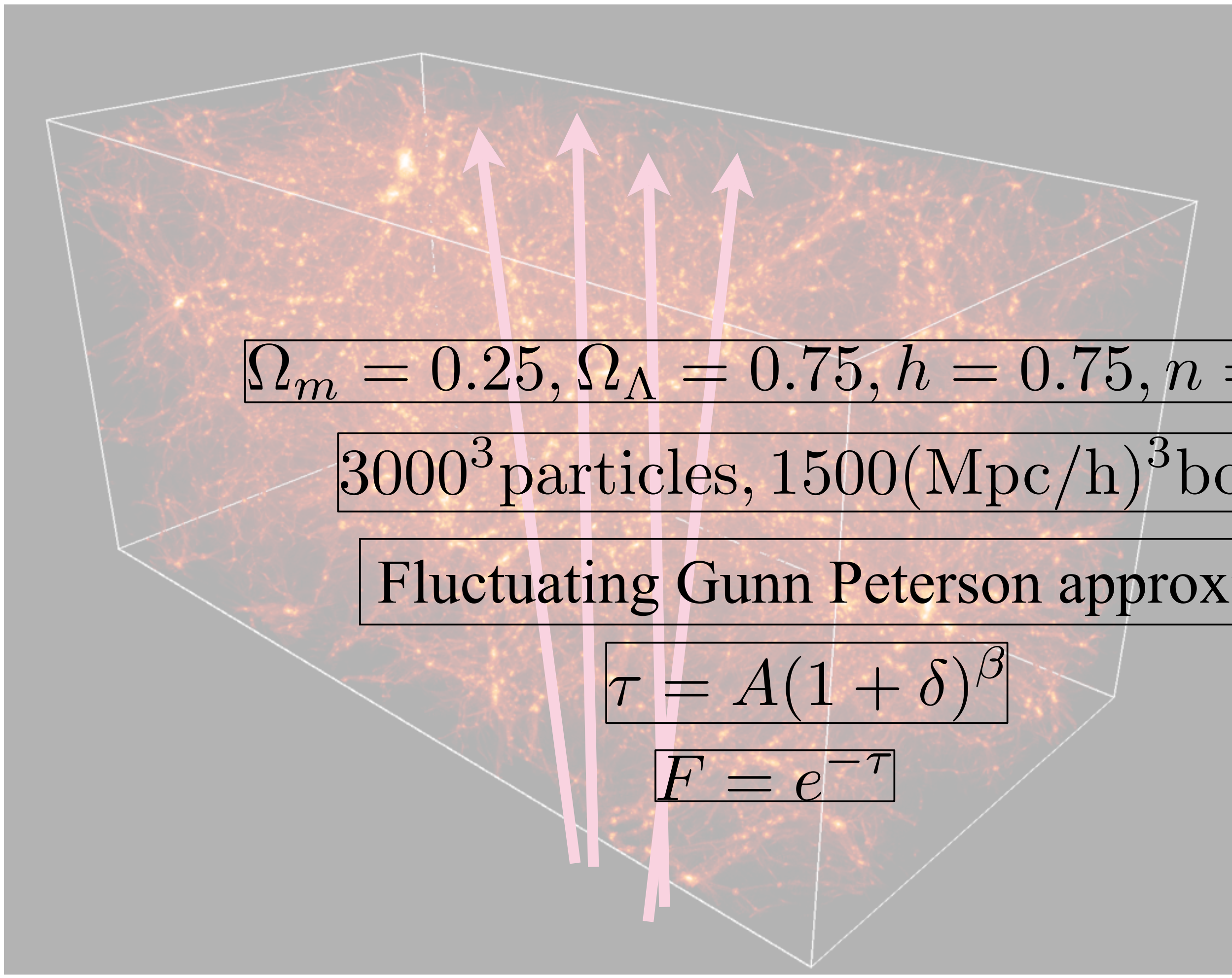
Simulations



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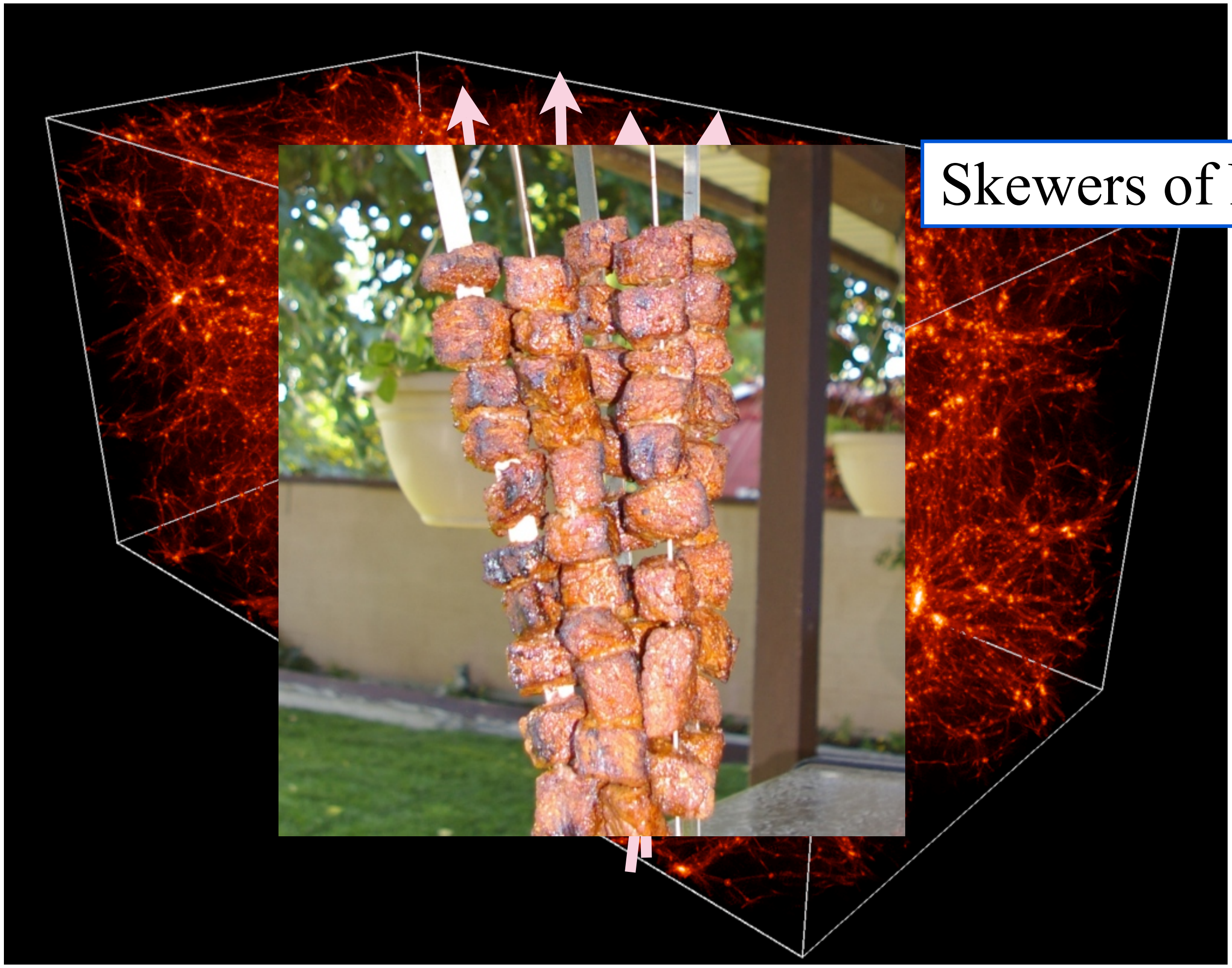
Fluctuating Gunn Peterson approximation

$$\tau = A(1+\delta)^\beta$$

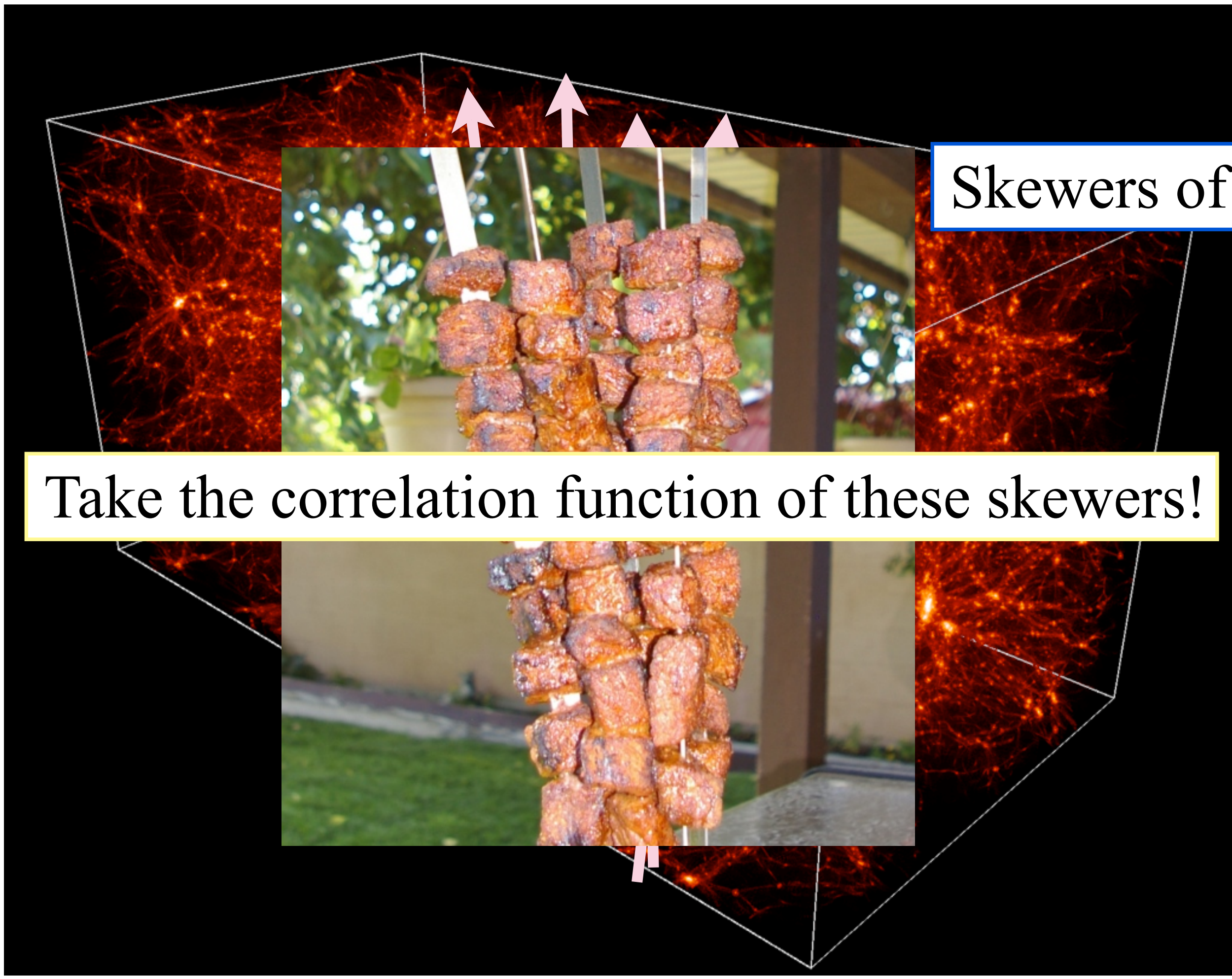
$$F = e^{-\tau}$$

Beyond: With Lyman Alpha Forest
Simulations



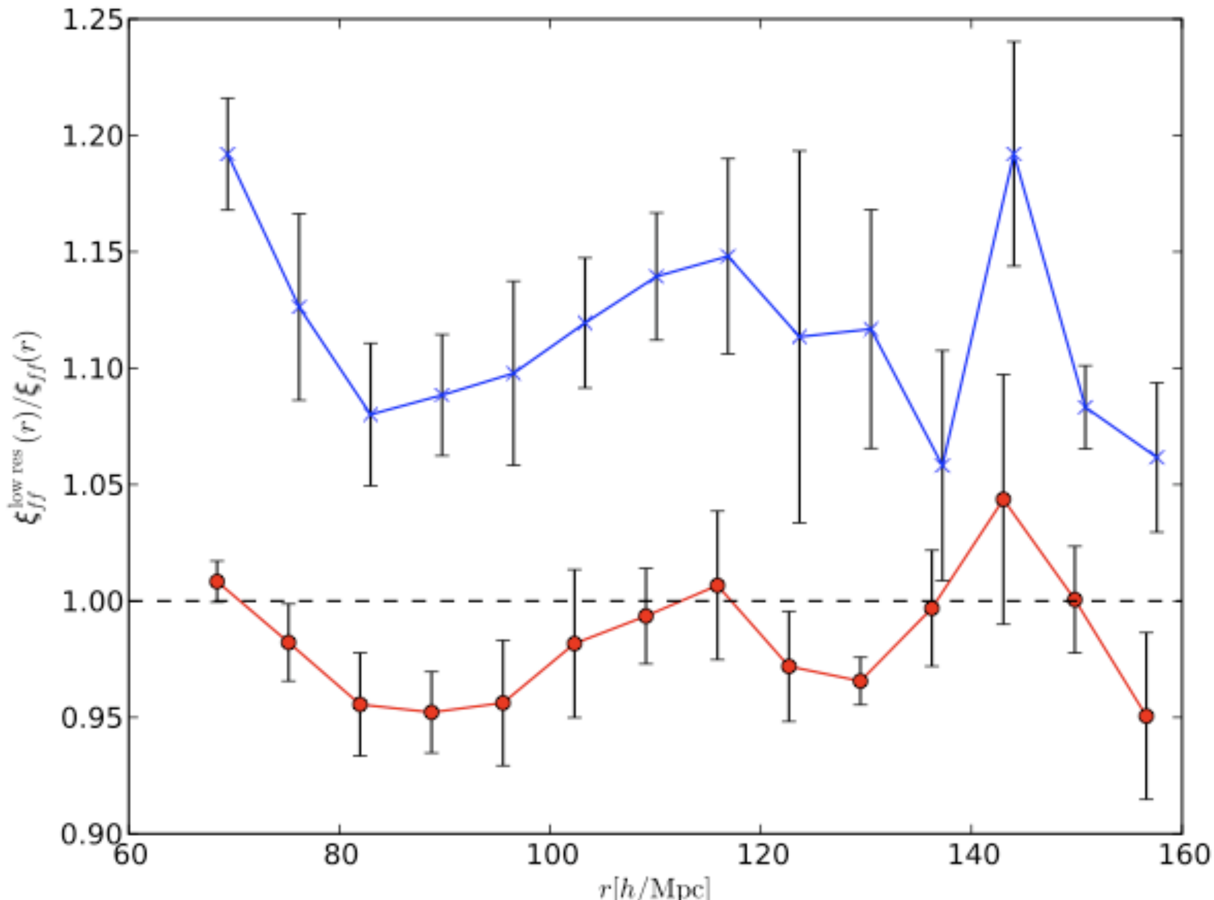
Skewers of Neutral Hydrogen

Beyond: With Lyman Alpha Forest
Simulations



Beyond: With Lyman Alpha Forest
Simulations: Resolution Effects?

$$\xi_{ff}^{\mathrm{lowres}}(r)/\xi_{ff}(r)$$



$r[h/Mpc]$

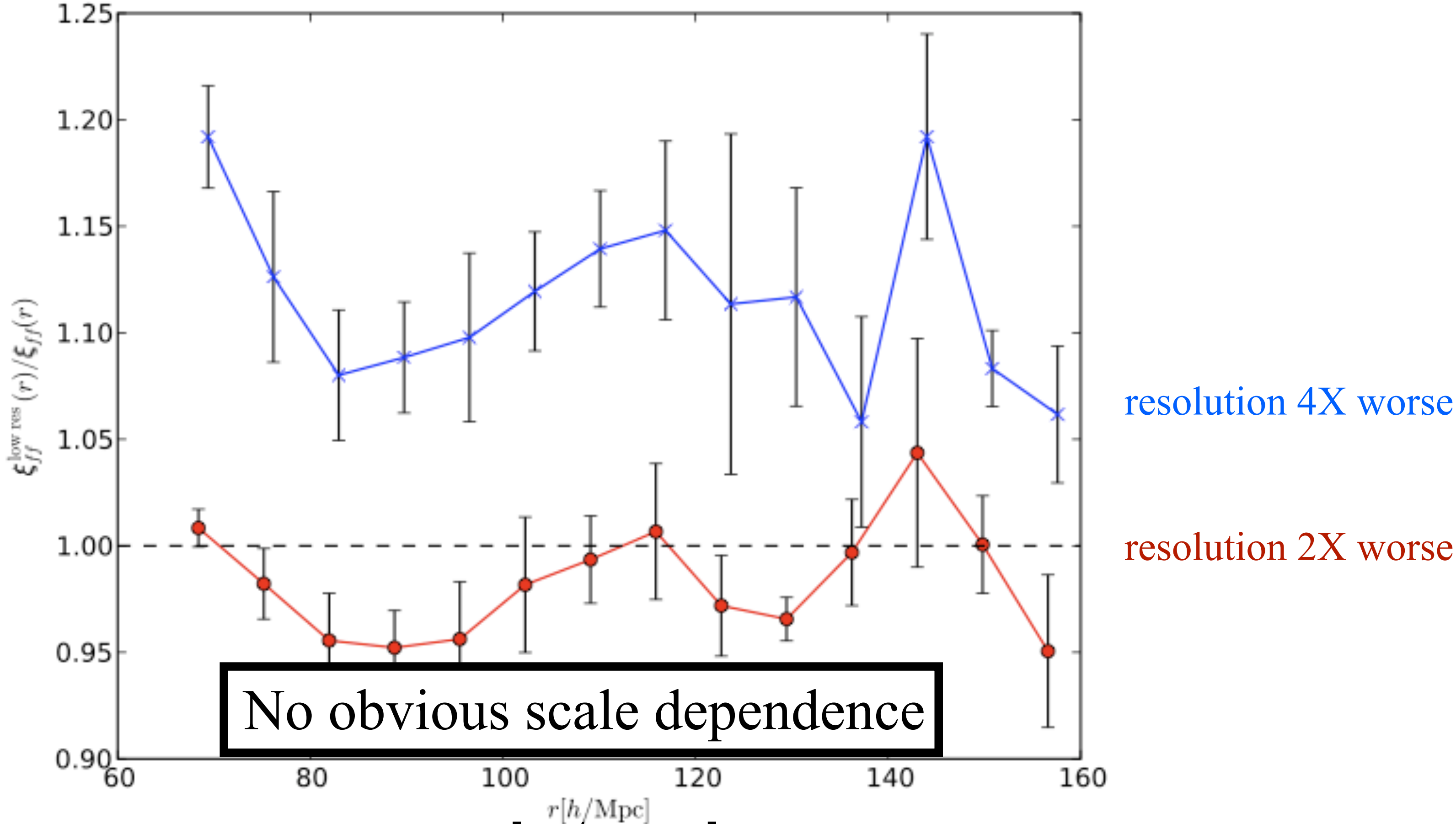
resolution 4X worse

resolution 2X worse

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest
Simulations: Resolution Effects?

$\xi_{ff}^{\rm lowres}(r)/\xi_{ff}(r)$



$r[h/Mpc]$

Slosar, SH, White & Louis (2009)

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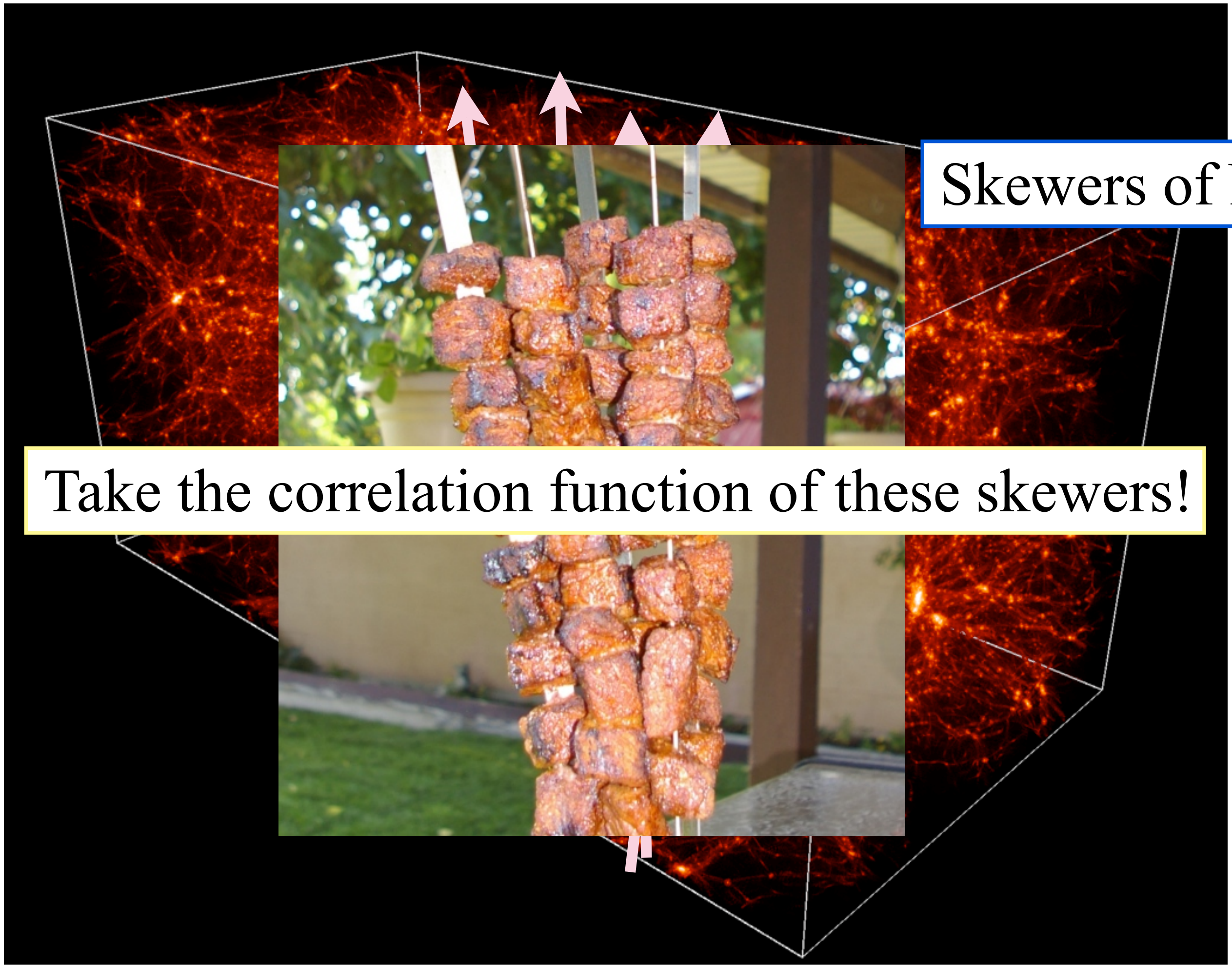
Simulations



Skewers of Neutral Hydrogen

Take the correlation function of these skewers!

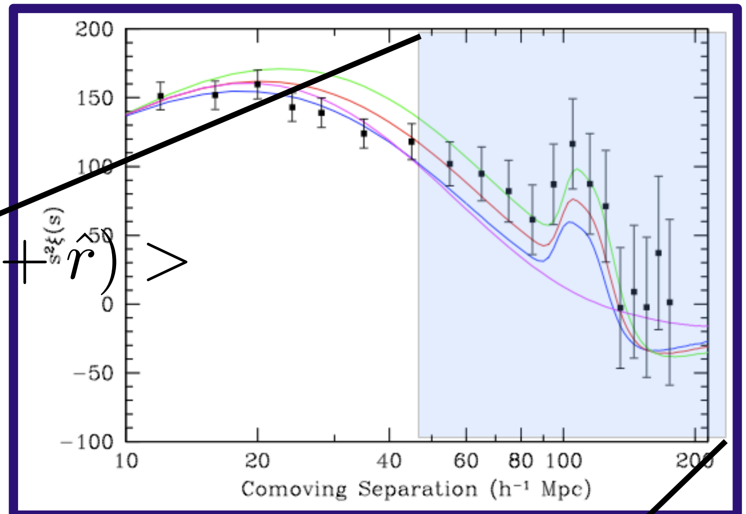
Beyond: With Lyman Alpha Forest
Correlation function (in configuration space)

$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

Beyond: With Lyman Alpha Forest

Correlation function (in configuration space)

$$\xi_f(r) = < \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$



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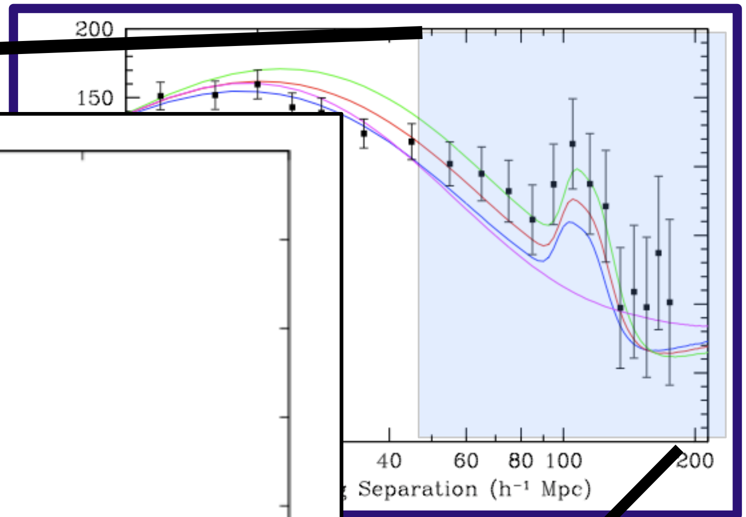
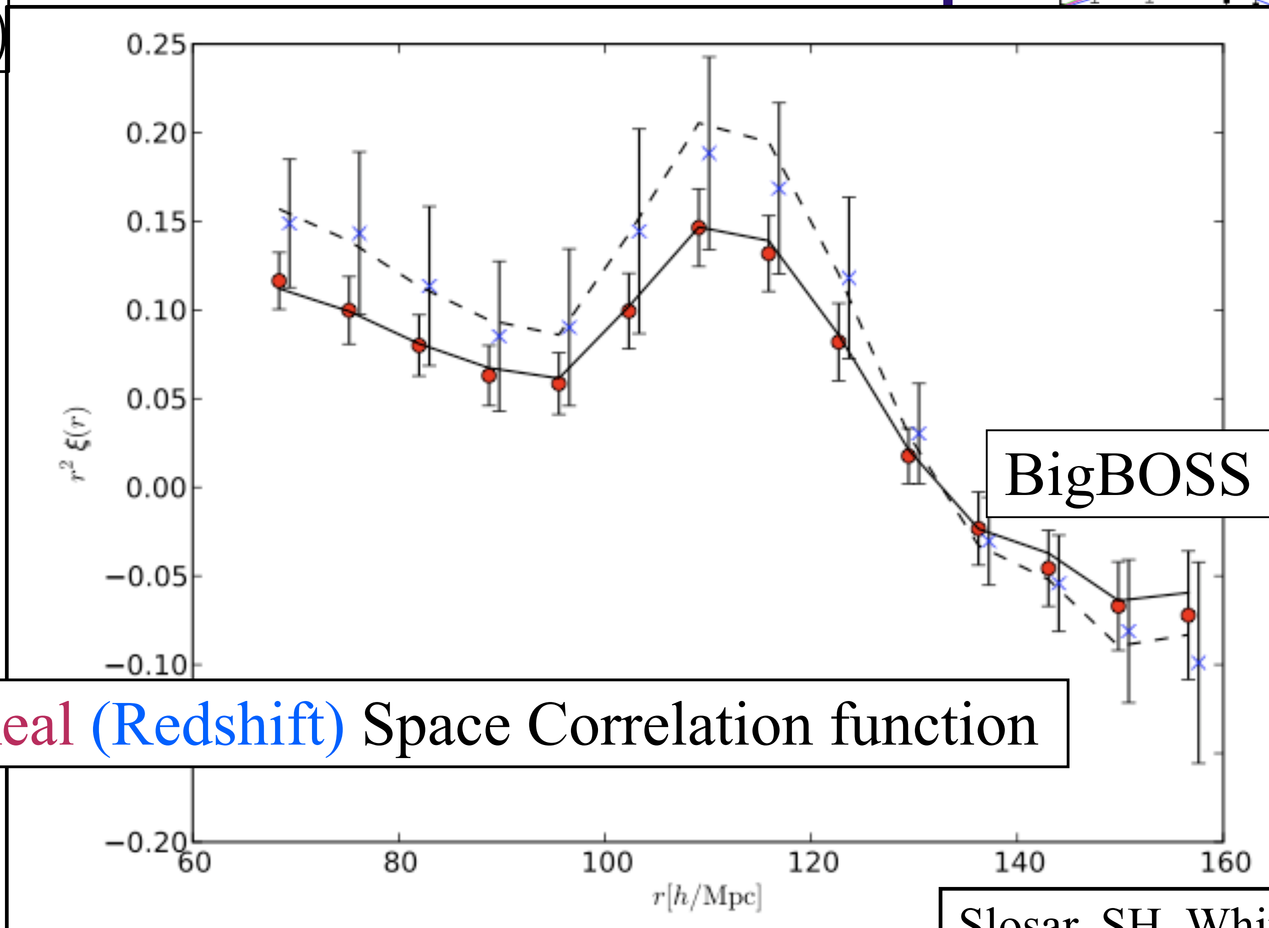




$r^2\xi(r)$

BigBOSS density of QSO

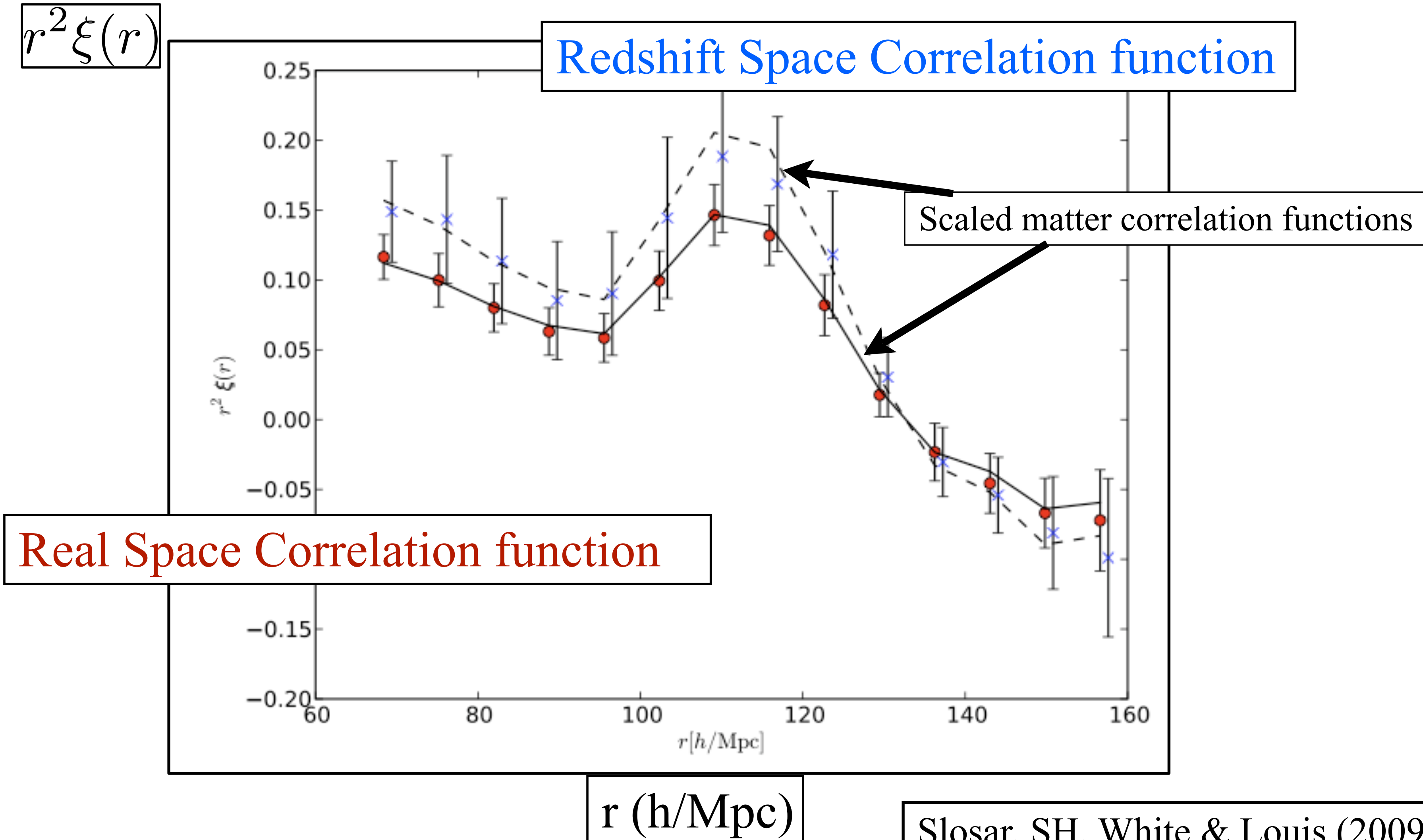
Flux Real (Redshift) Space Correlation function

r (h/Mpc)

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

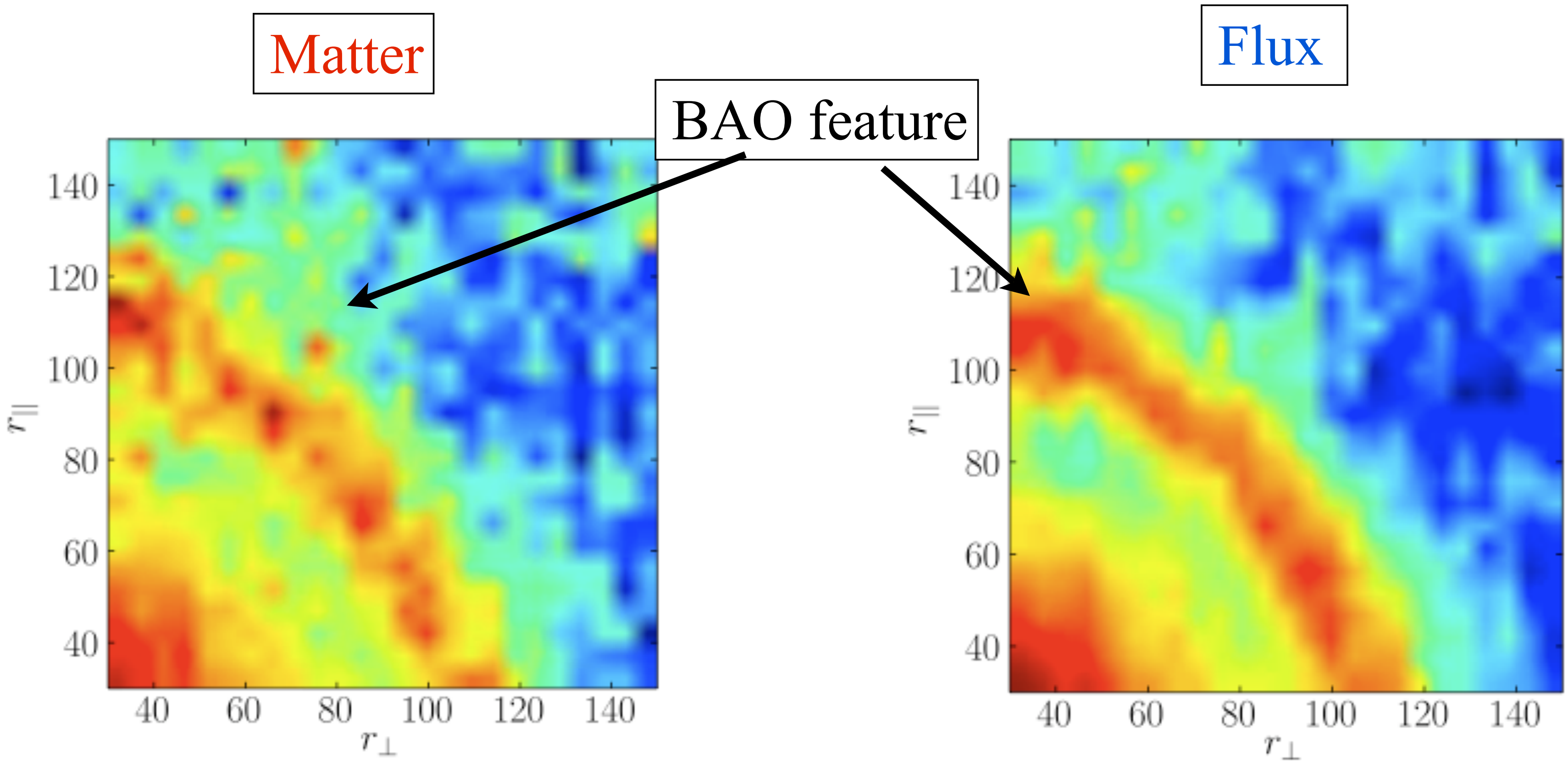
Correlation function (in configuration space)



Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest
Correlation function (in configuration space)

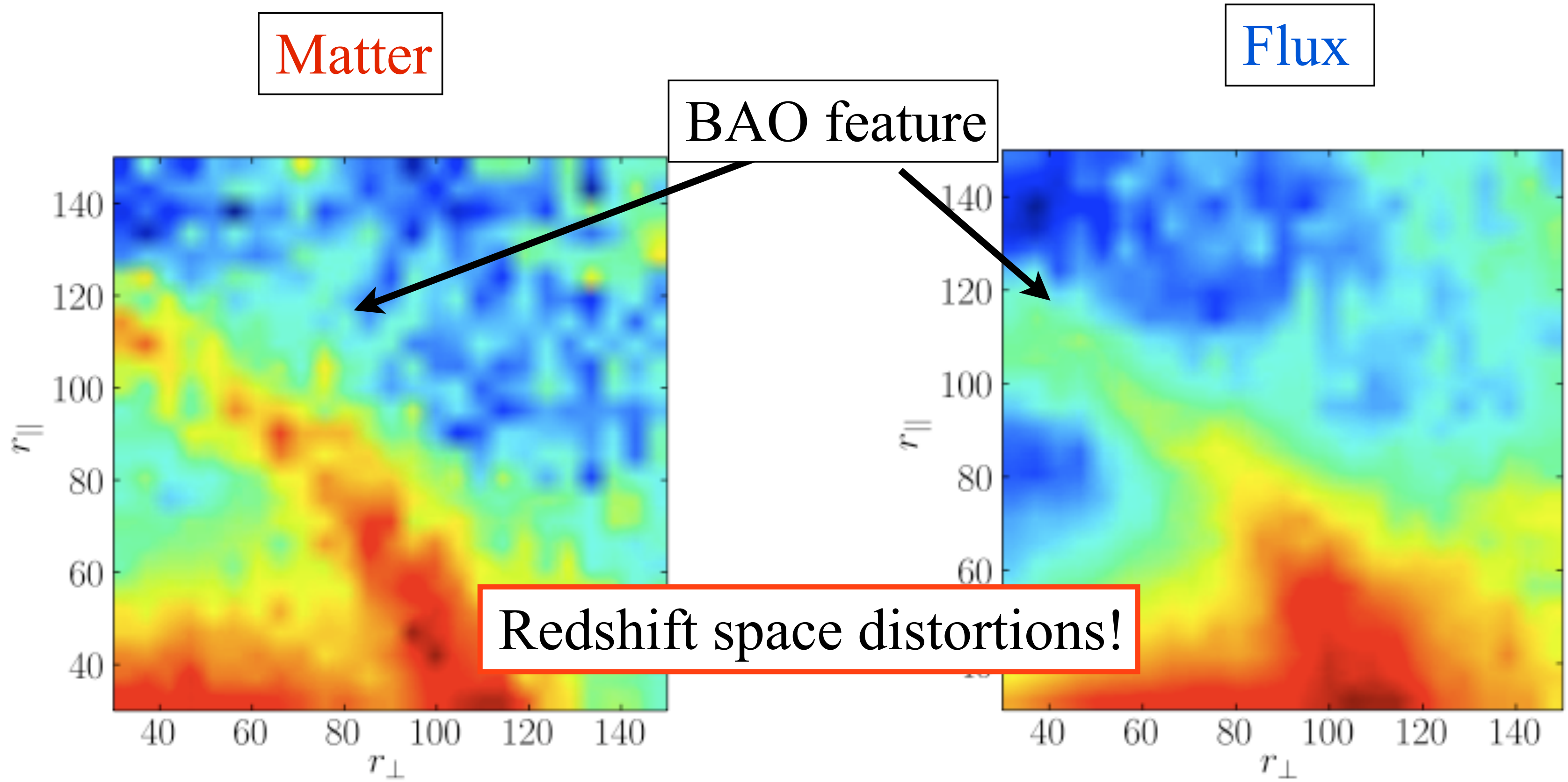
Real Space Correlation function



Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest
Correlation function (in configuration space)

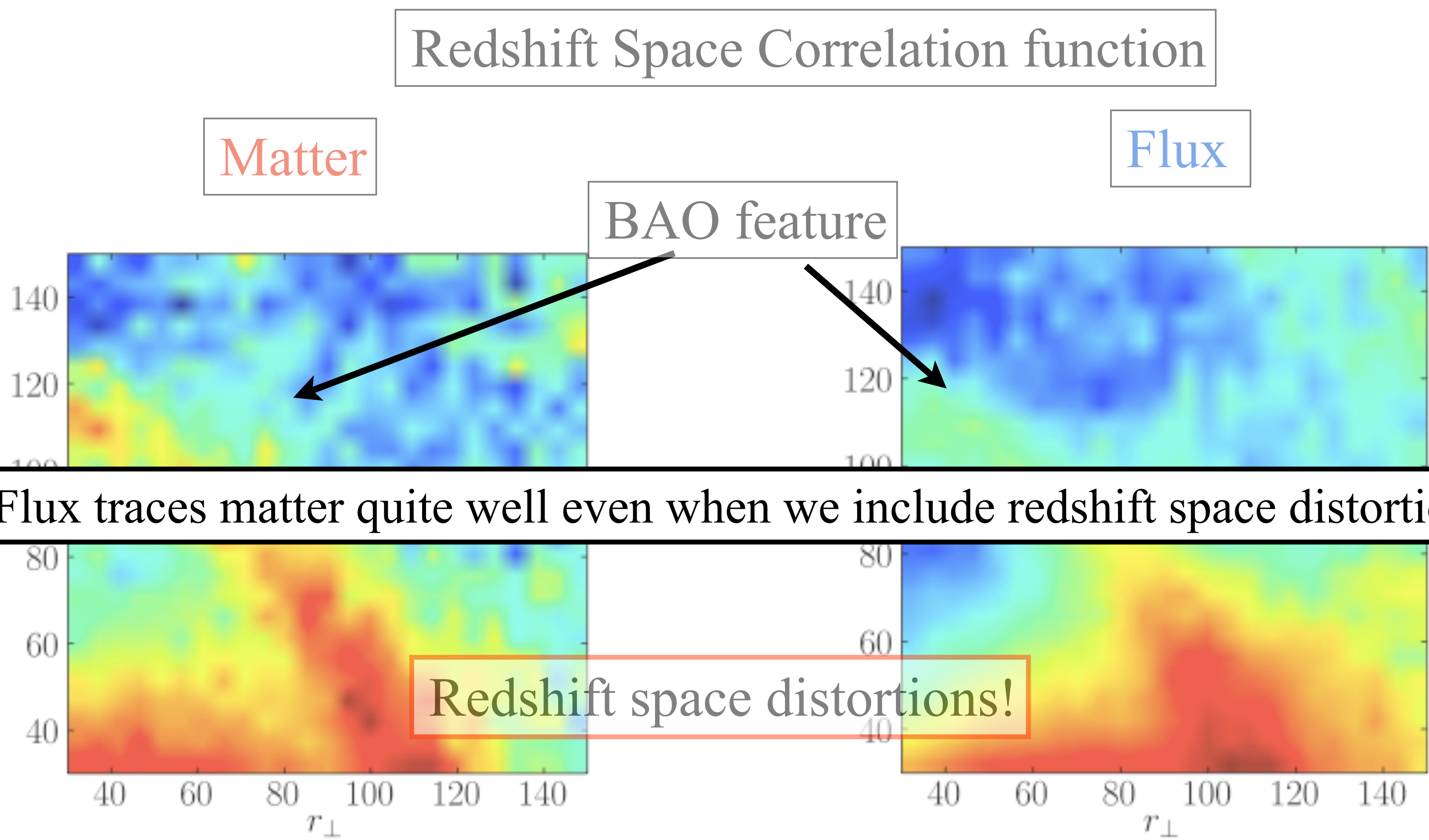
Redshift Space Correlation function



Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

Correlation function (in configuration space)



Flux traces matter quite well even when we include redshift space distortions!

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest
Correlation function (in configuration space)

Flux

distortions!

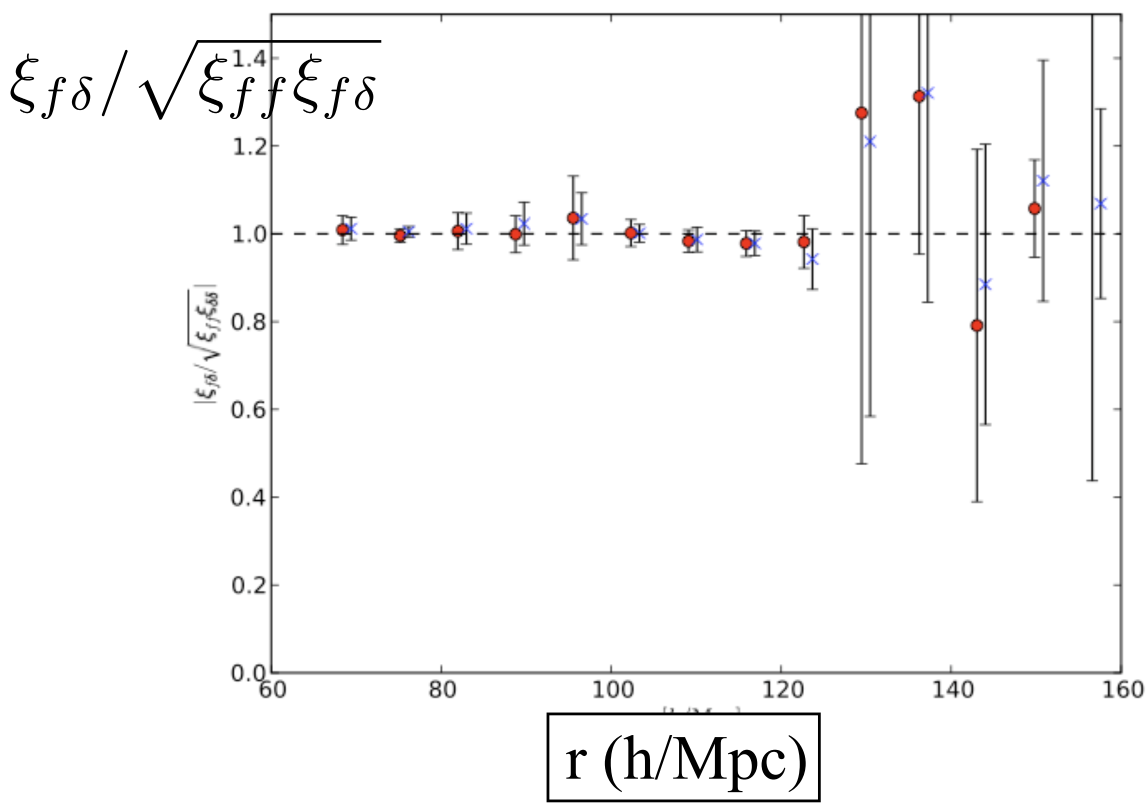


FIG. 7: The cross-correlation coefficient between flux and matter over-density in real (red) and redshift (blue) space.

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

Redshift space distortions

Redshift Space Correlation function

Matter

Flux

BAO feature

But what how should we deal with this redshift space distortion ?

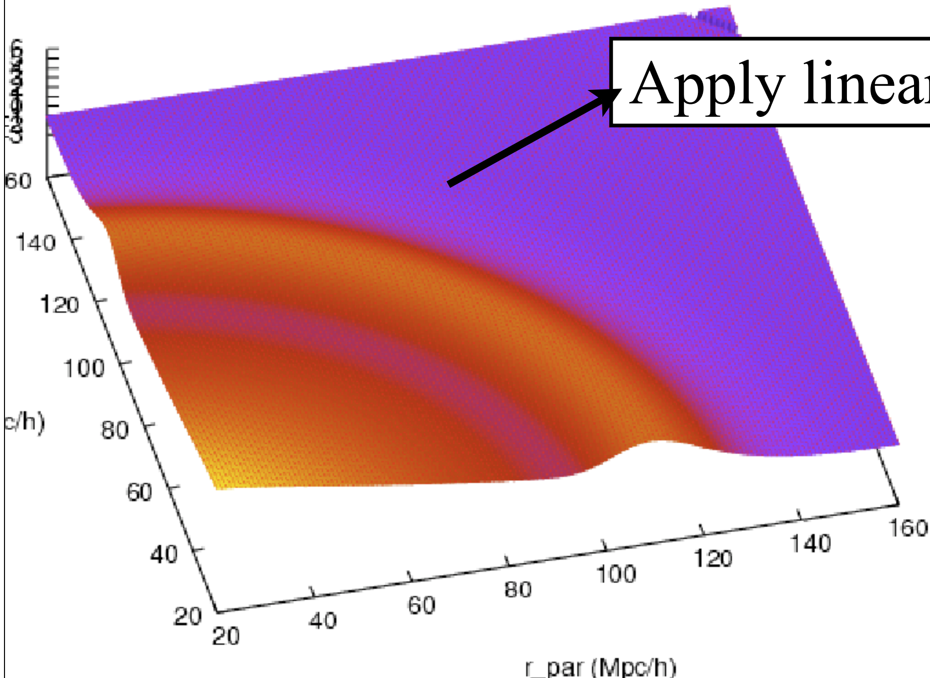
Flux traces matter quite well even when we redshift space distortions!

Redshift space distortions!

Beyond: With Lyman Alpha Forest
Redshift space distortions

No z-space distortion

z-space distortions



Apply linear Kaiser formula

$$\xi(r,\mu) = \sum_{\ell=0,2,4} L_\ell(\mu)\xi_l(r),$$

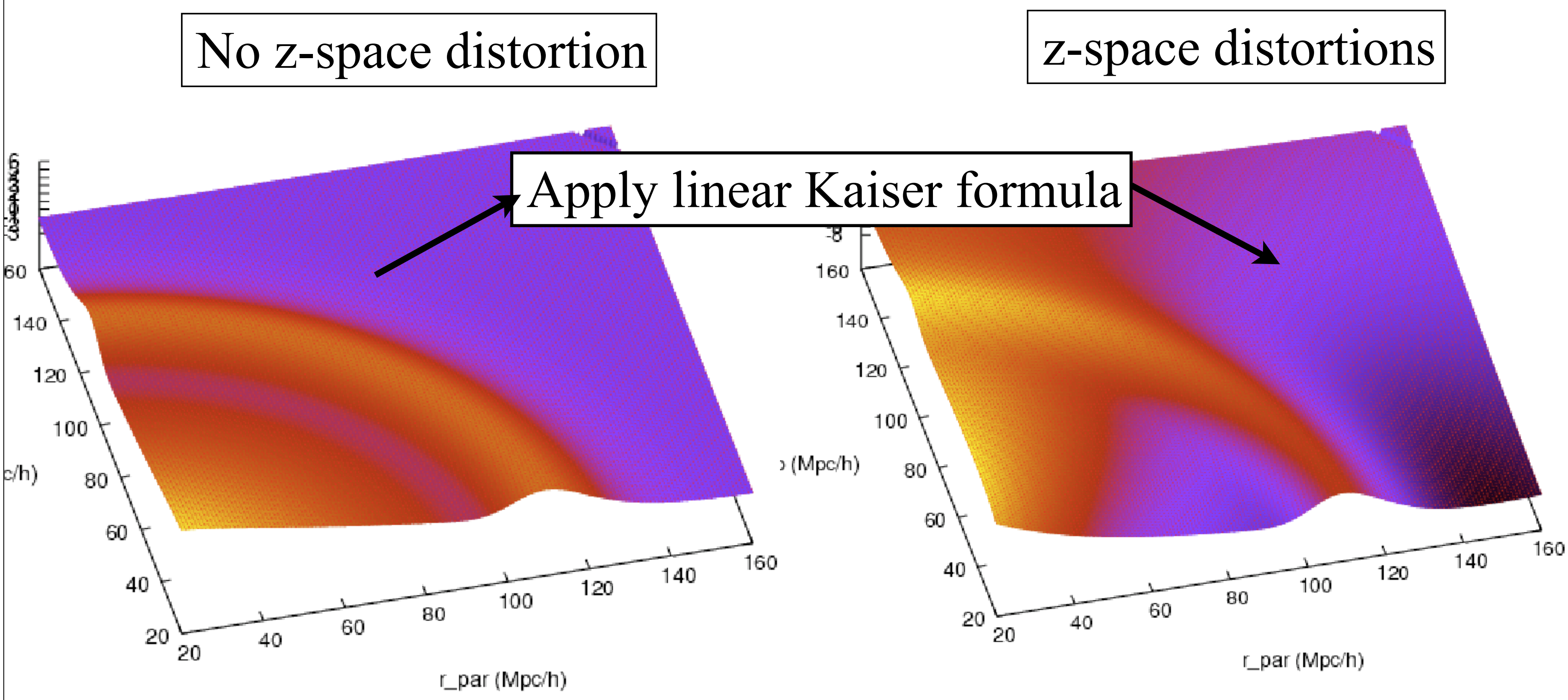
$$\xi_0(r) = C_0\xi_R(r),$$

$$\xi_2(r) = C_2\left(\xi_R(r) - \bar{\xi}(r)\right),$$

$$\xi_4(r) = C_4\left(\xi_R(r) + 2.5\bar{\xi}(r) - 3.5\bar{\bar{\xi}}(r)\right),$$

$$\mu = r_{par}/|\vec{r}|$$
$$C_i = f_i(\beta)$$
$$\beta = dln\delta/dlna = \Omega_m^{0.6}$$

Beyond: With Lyman Alpha Forest
Redshift space distortions



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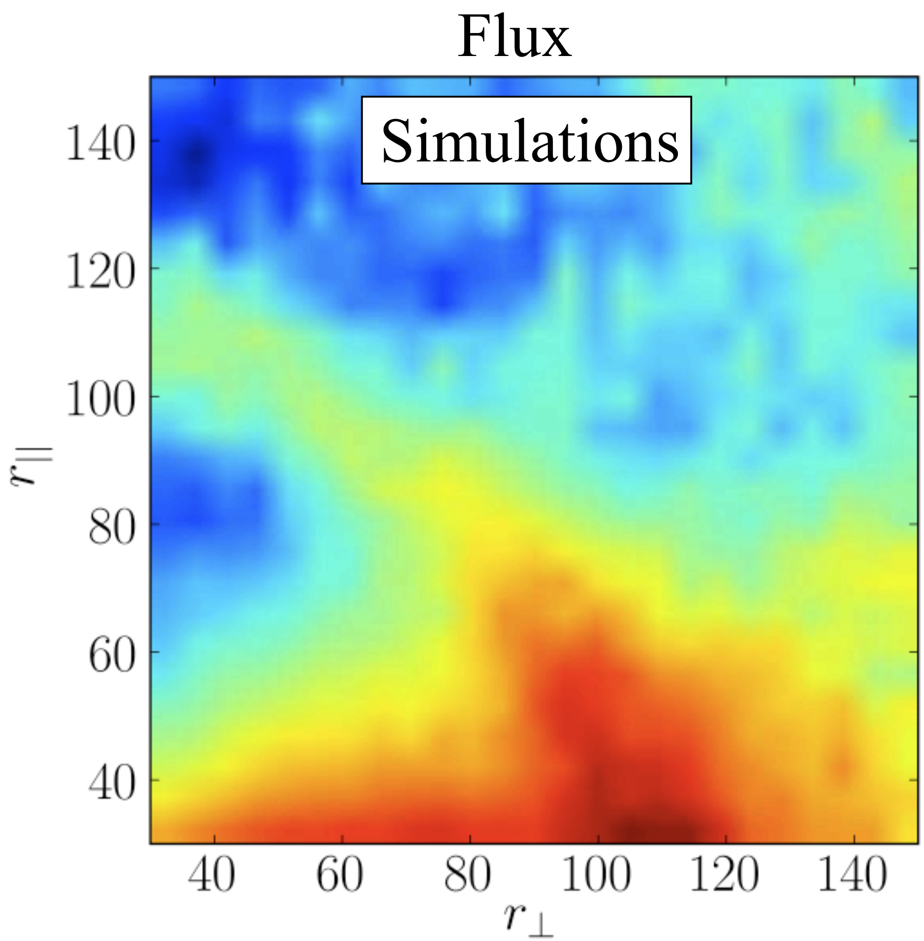

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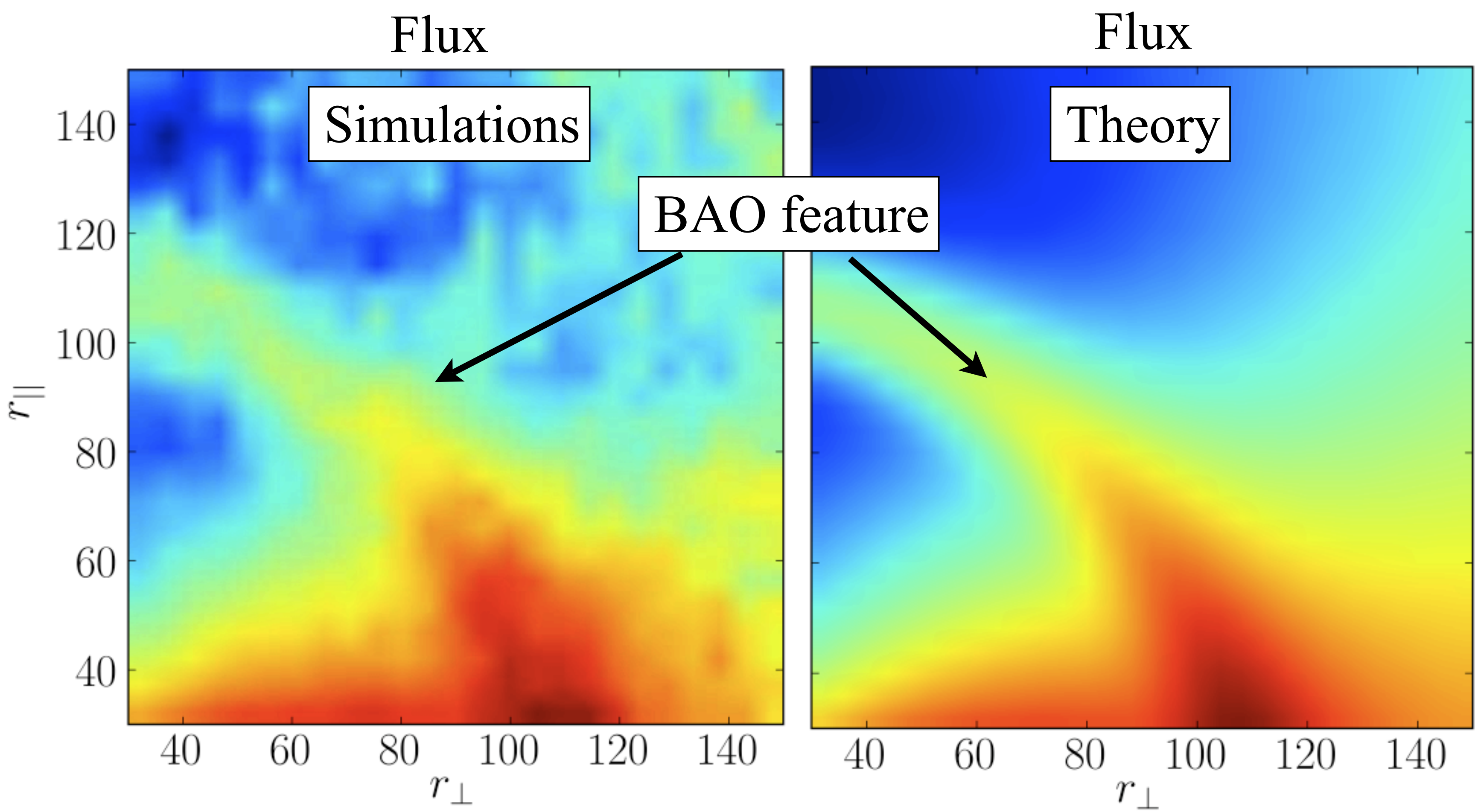
Redshift space distortions



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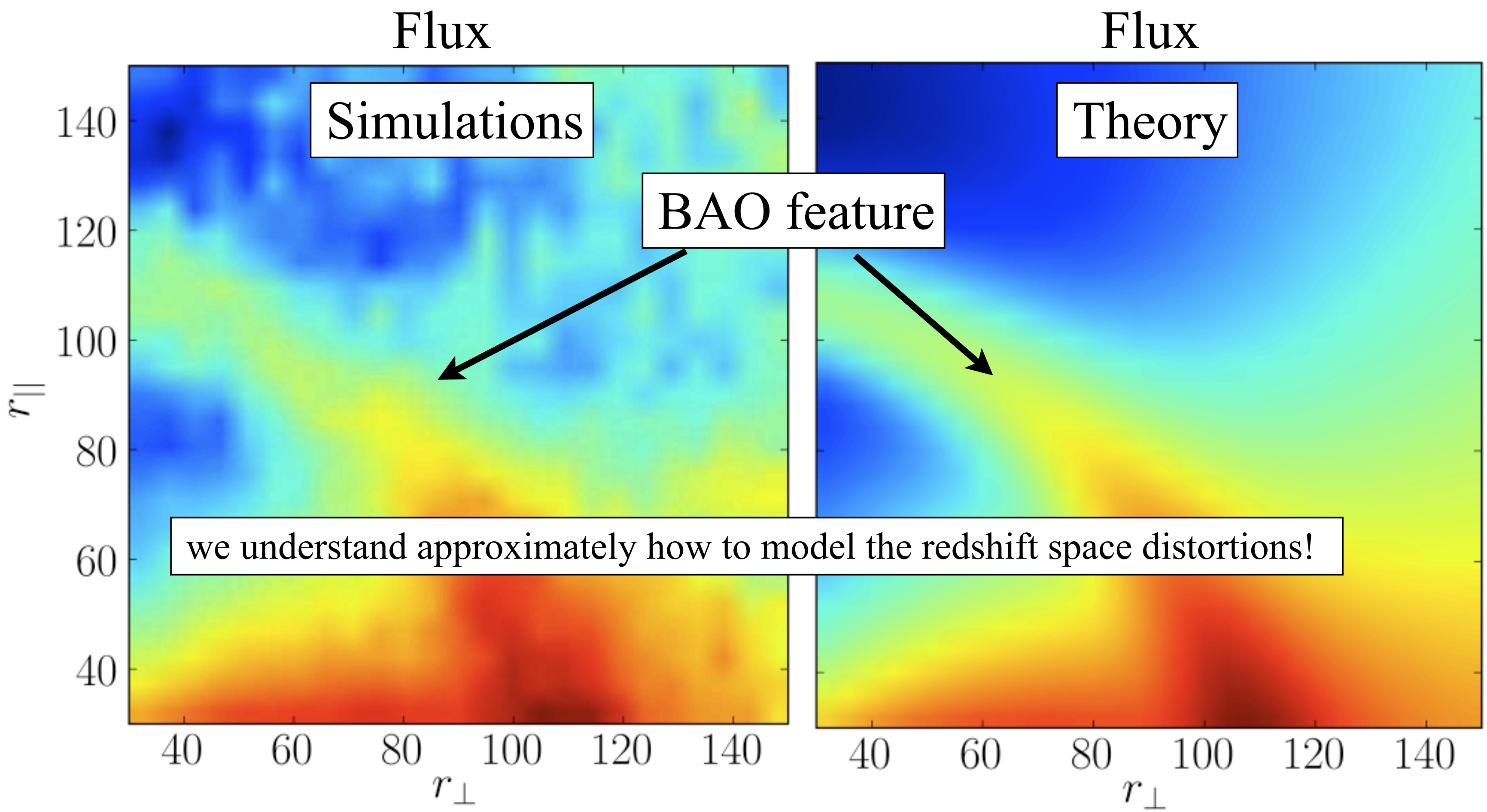
Redshift space distortions



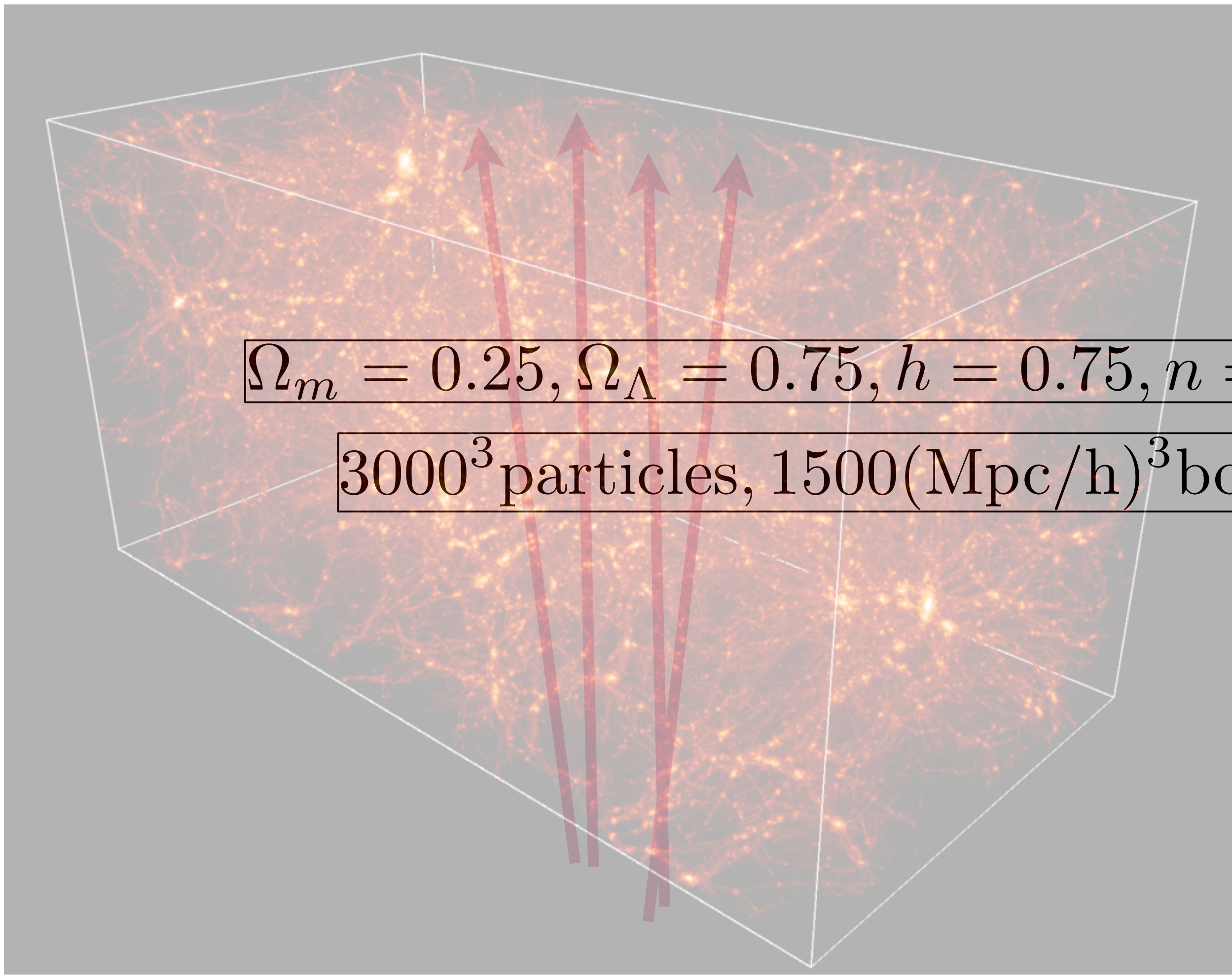
we understand approximately how to model the redshift space distortions!

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest
Possible systematics

- UV background fluctuations
- Metal Line contaminations
- Continuum fitting errors
- Damped Lyman alpha systems
- Broad Absorption Line systems

Lyman Alpha Forest: what can it do?



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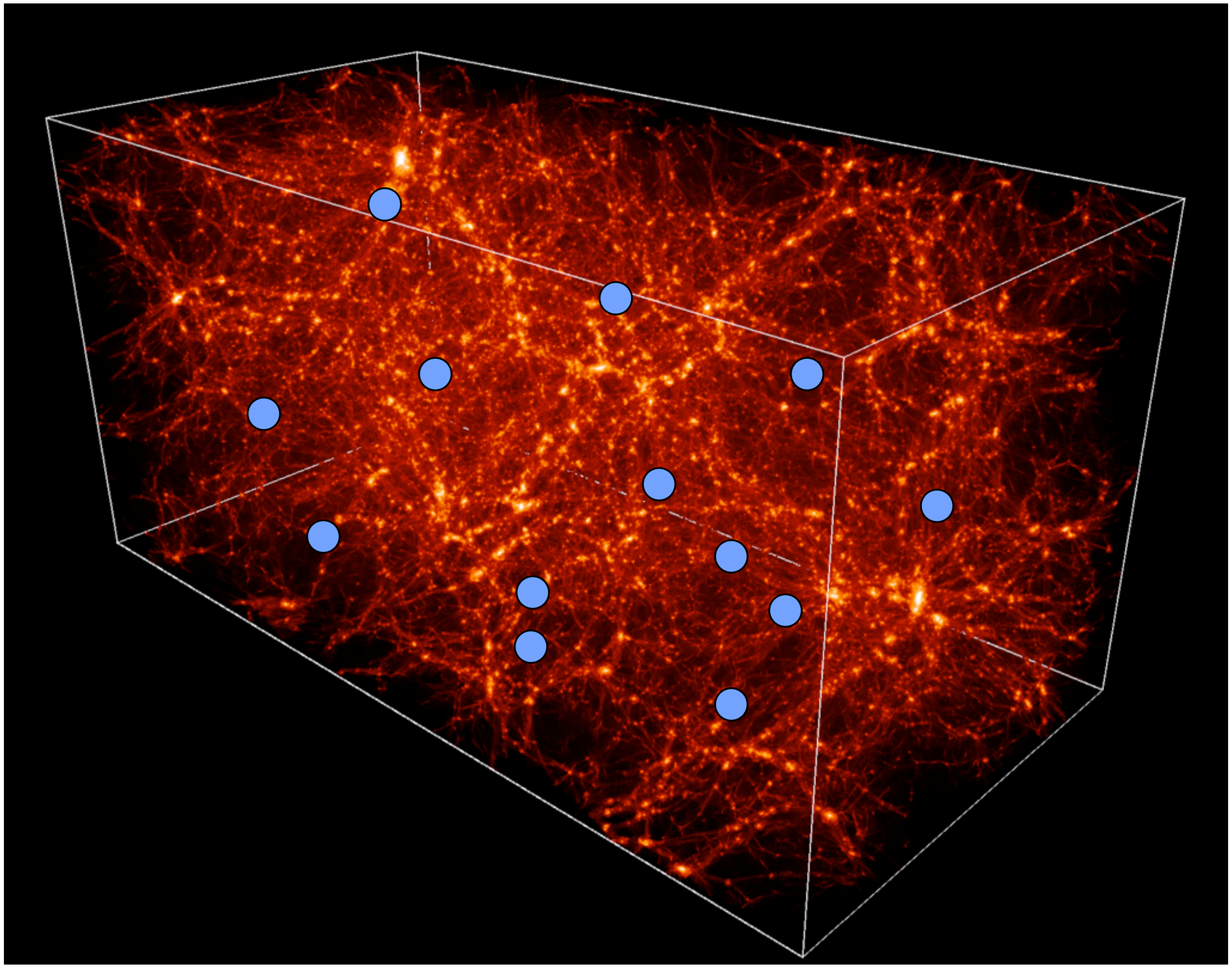
Beyond: With Lyman Alpha Forest

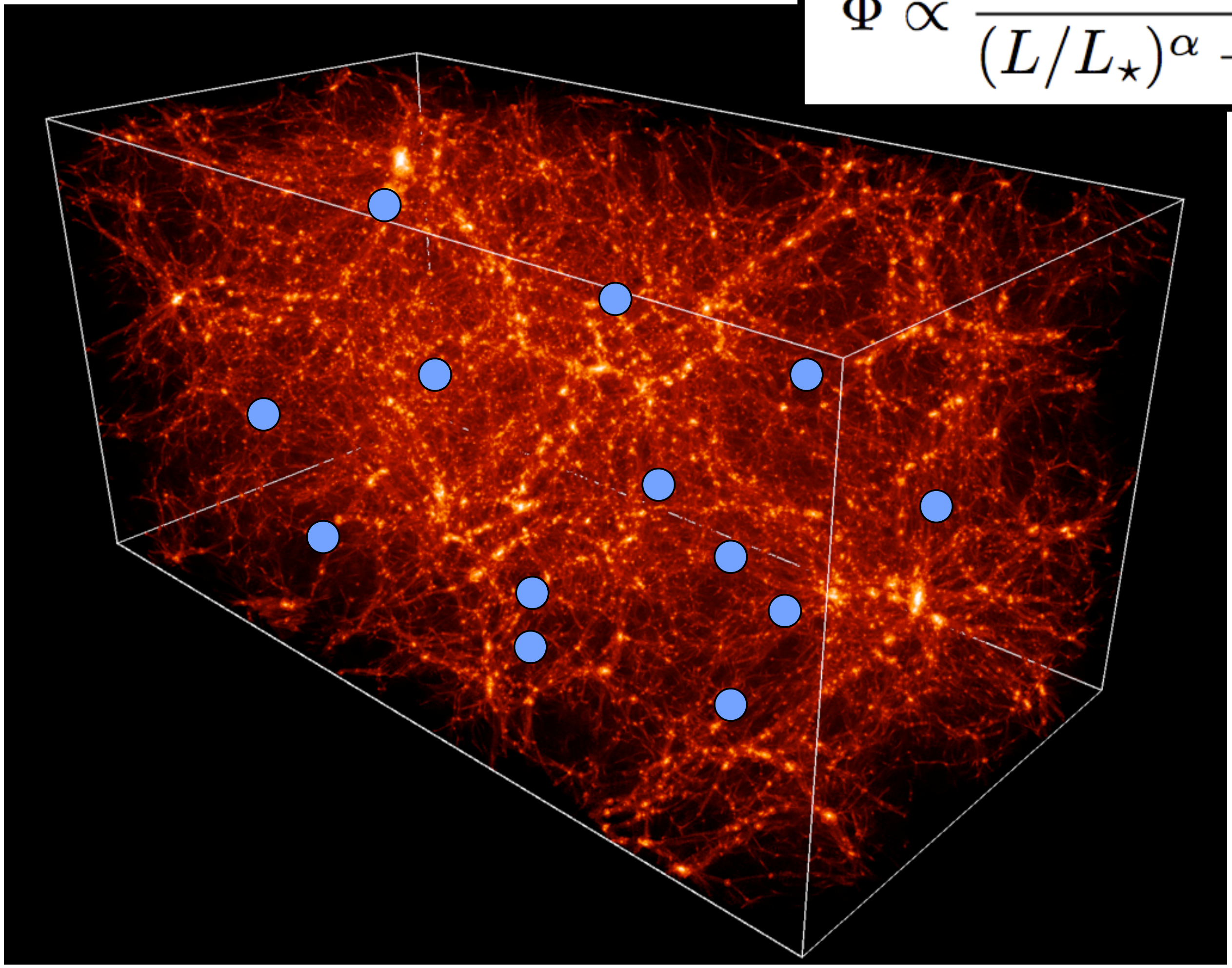
Possible systematics: UV background fluctuations



Beyond: With Lyman Alpha Forest

Possible systematics: UV background fluctuations

$$\Phi \propto \frac{1}{(L/L_\star)^\alpha + (L/L_\star)^\beta}$$



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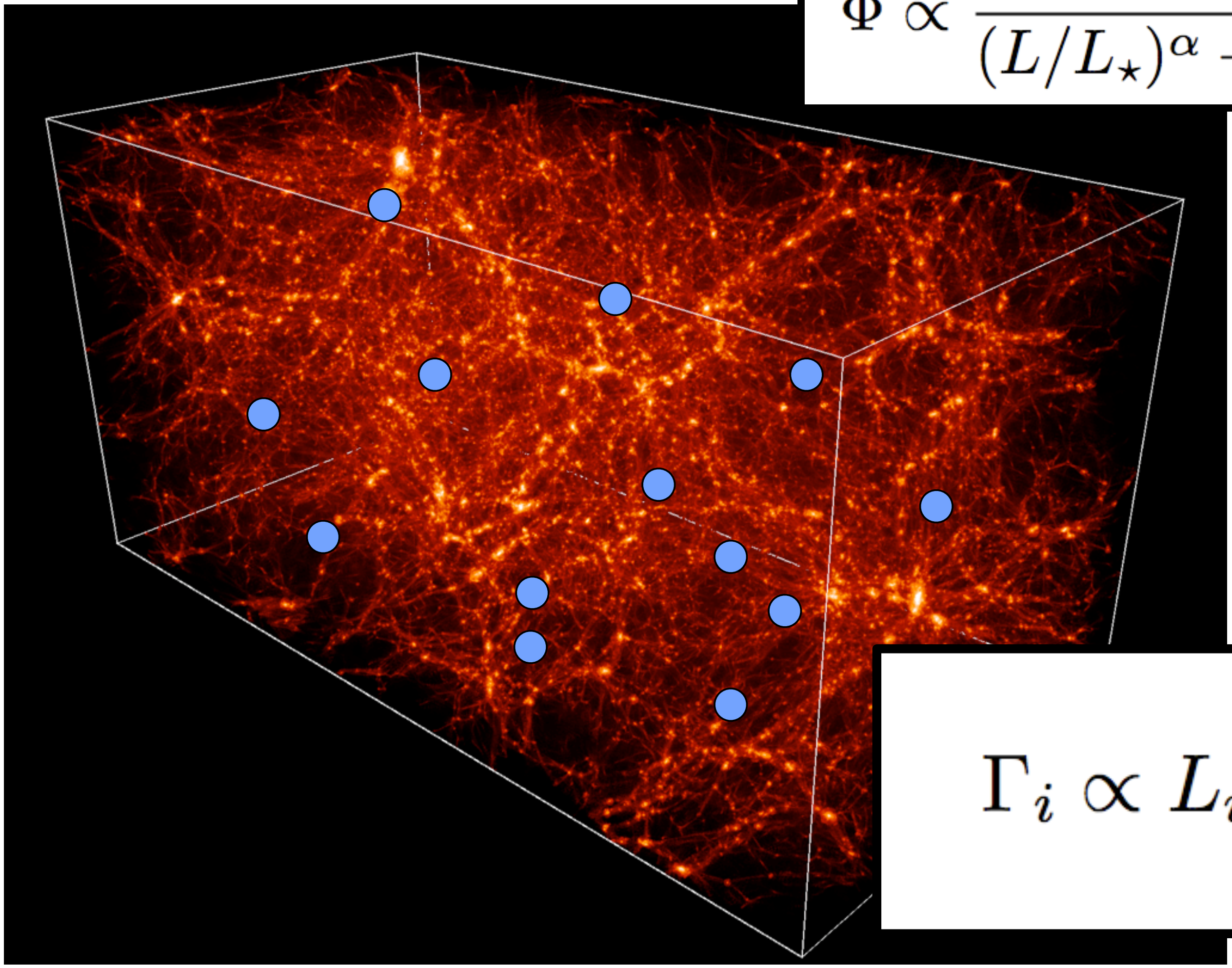
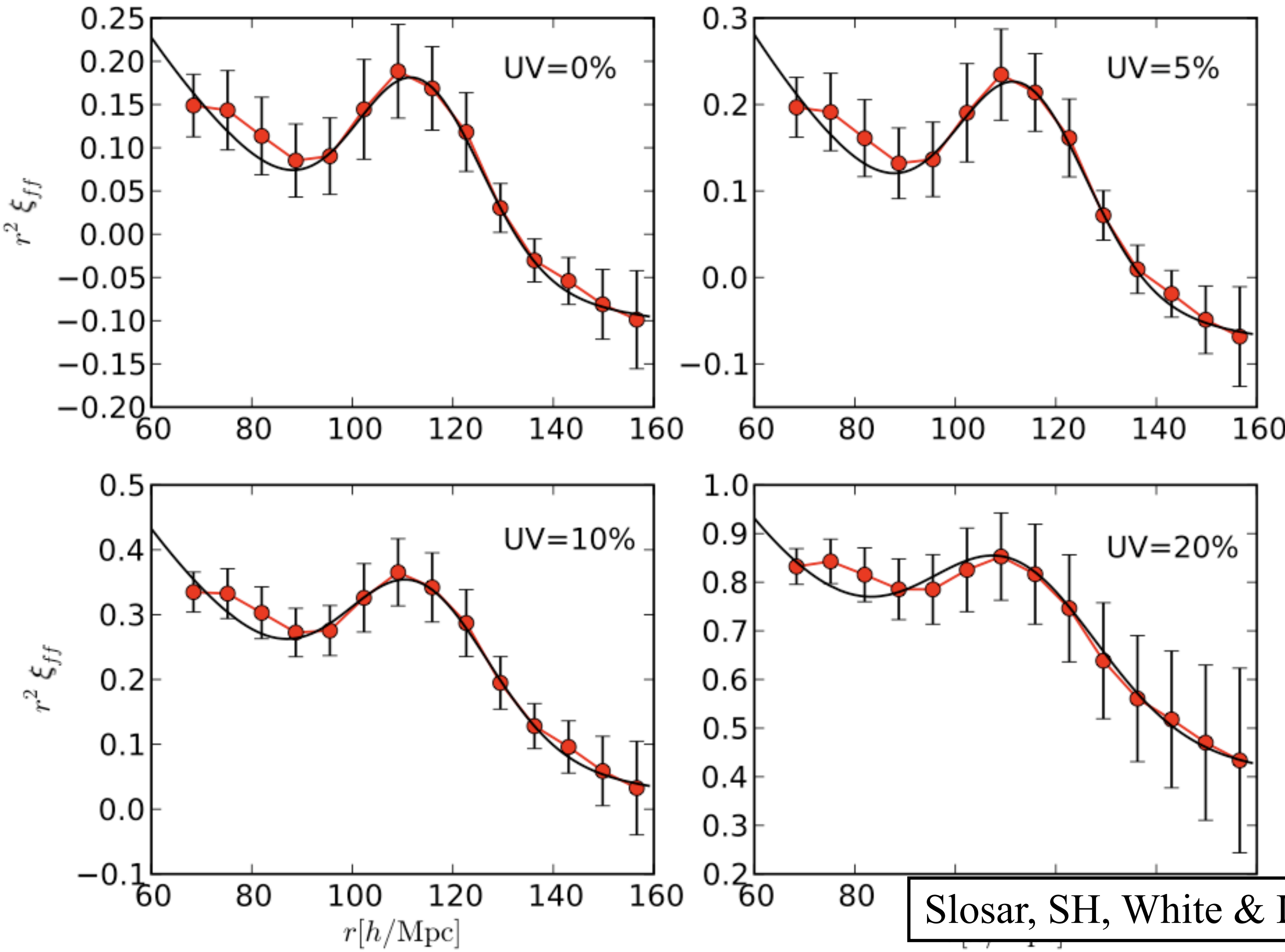


$$\Gamma_i \propto L_i \, \frac{e^{-r_i/r_0}}{4\pi r_i^2}$$

Beyond: With Lyman Alpha Forest

Possible systematics: UV background fluctuations



Slosar, SH, White & Louis (2009)

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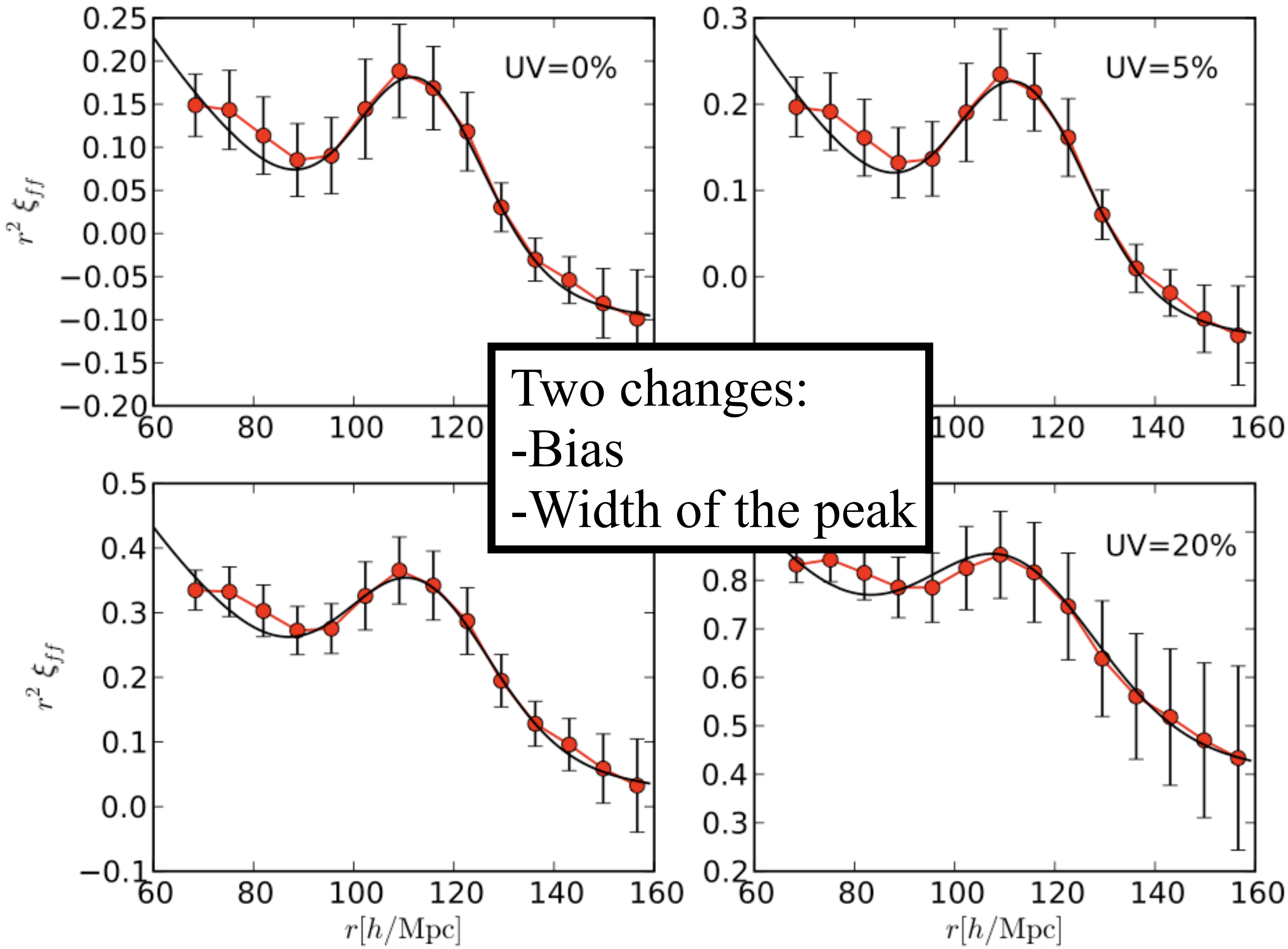
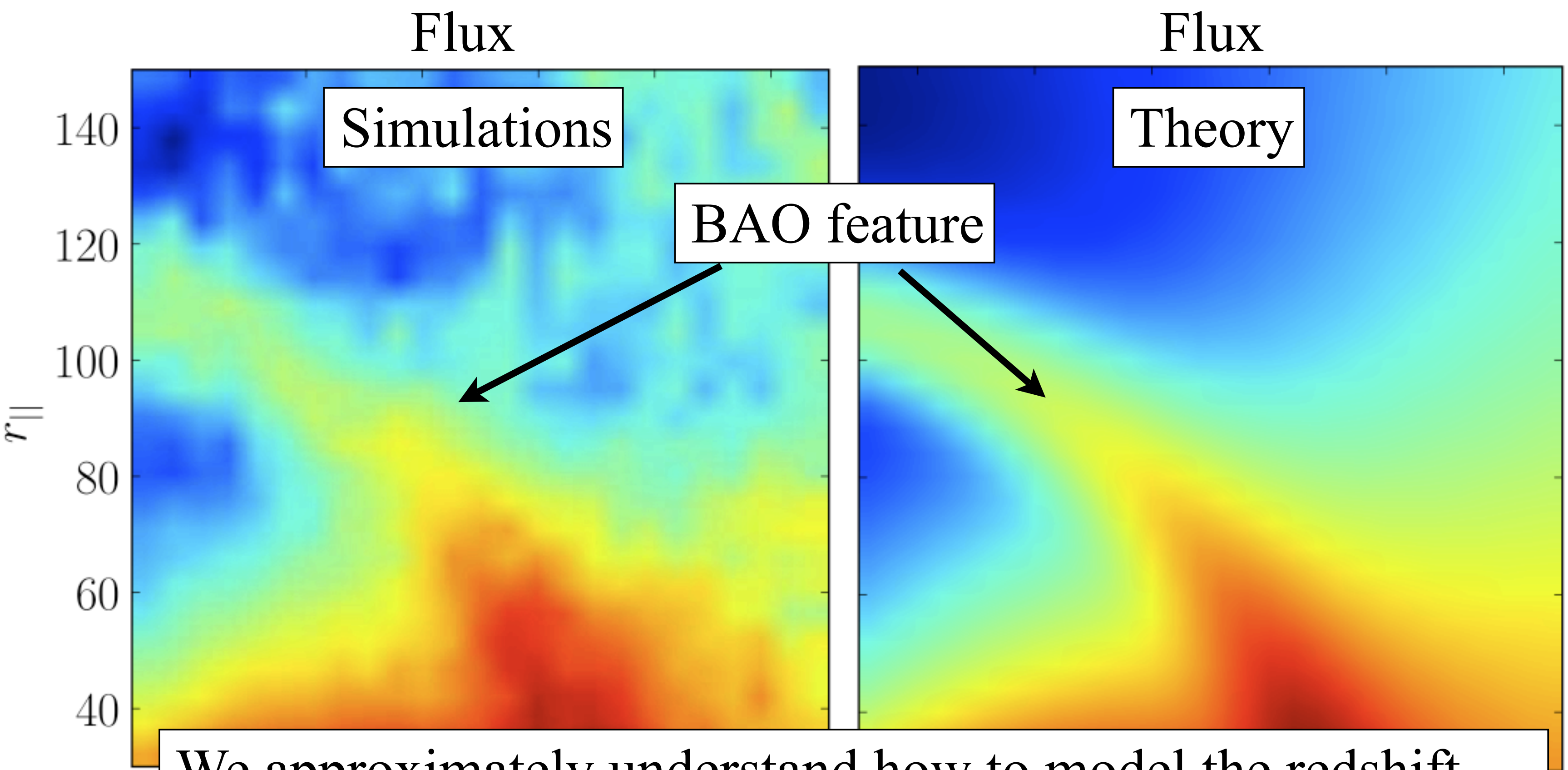
Possible systematics: UV background fluctuations



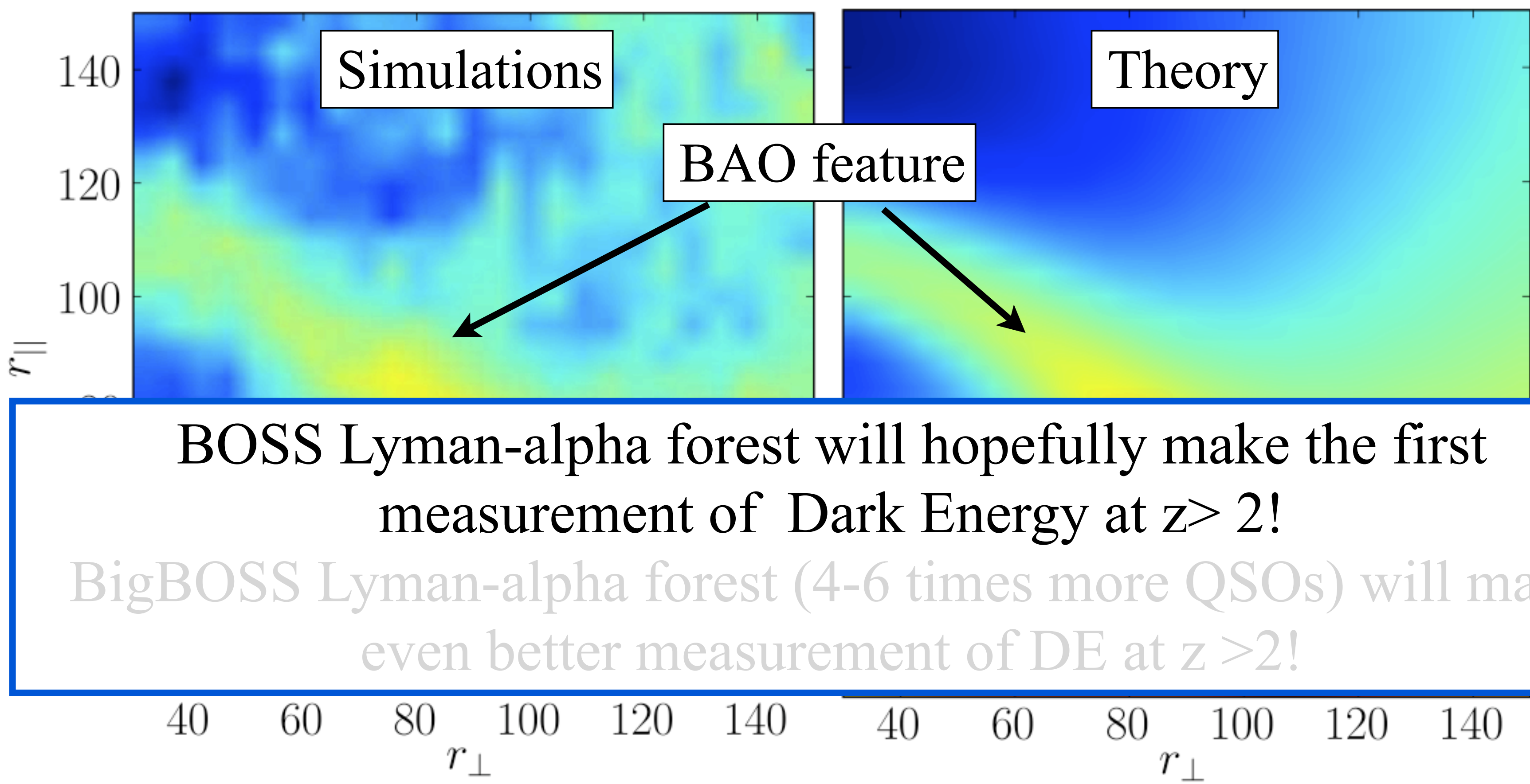
Two changes:
-Bias
-Width of the peak

Beyond: With Lyman Alpha Forest
Mini Conclusion



We approximately understand how to model the redshift space distortions, and what happens when we include systematics such as UV background fluctuations.

Beyond: With Lyman Alpha Forest
Mini Conclusion

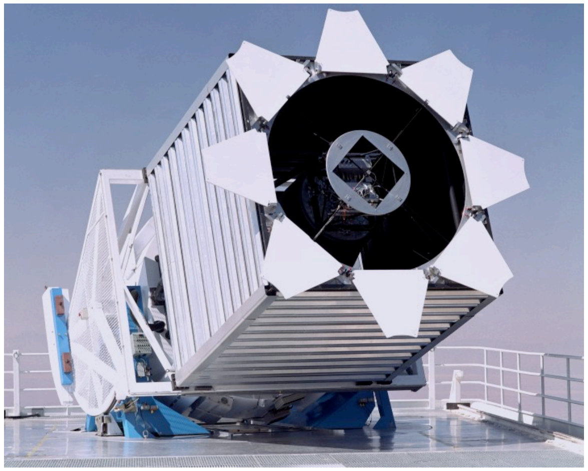


BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at z> 2!

BigBOSS Lyman-alpha forest (4-6 times more QSOs) will make even better measurement of DE at z >2!

SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

- New program for the SDSS telescope for 2008–2014 (already working and providing data!).
- Definitive study of the low-redshift acoustic oscillations. 10,000 deg^2 of new spectroscopy from SDSS imaging.
  — 1.5 million LRGs to z=0.8, including 4x more density at z<0.5.
  — 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at z=0.35 and z=0.6.
  — Easy extension of current program.
- Simultaneous project to discover the BAO in the Lyman α forest.
  — 160,000 quasars. 20% of fibers.
  — 1.5% measurement of distance to z=2.3.
  — Higher risk but opportunity to open the high-redshift distance scale.



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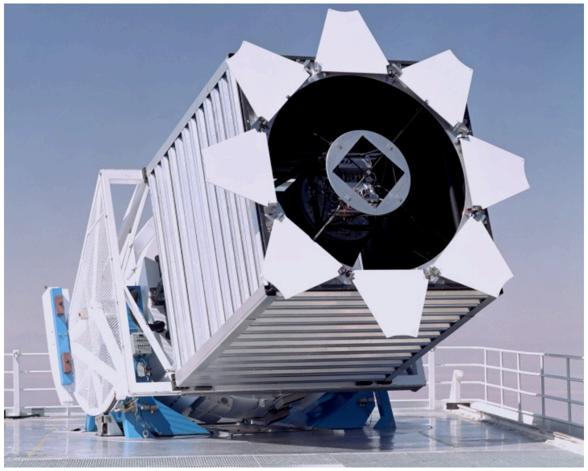

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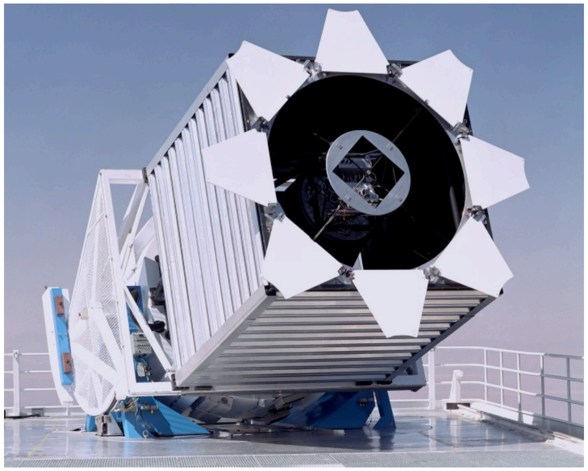
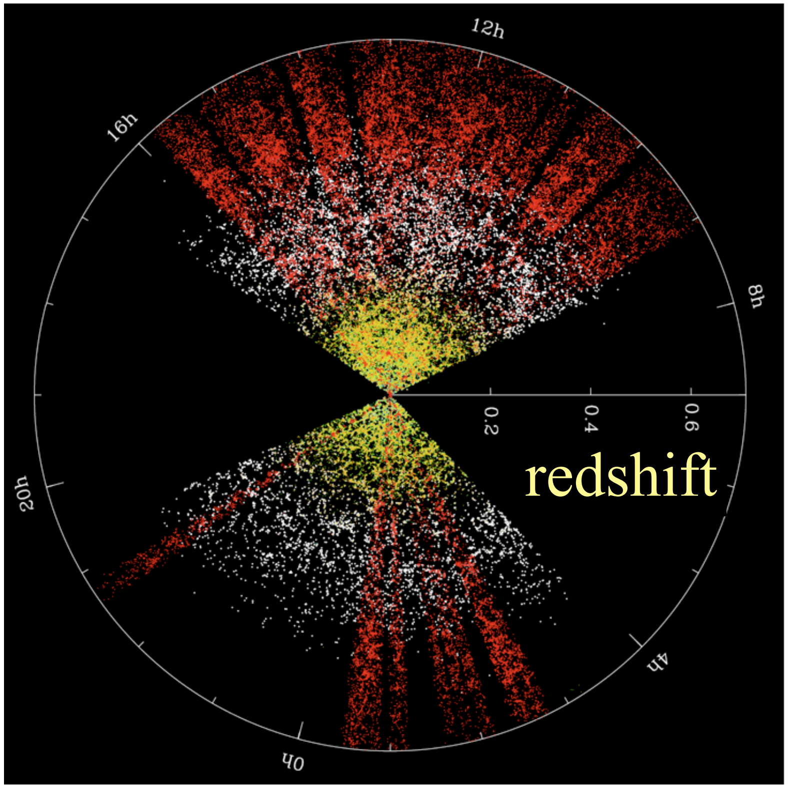


SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

Volume of the Universe probed by SDSS



Courtesy plots from Michael Blanton

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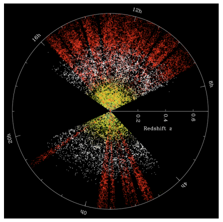
Baryon Oscillation Spectroscopic Survey

Volume of the Universe probed by SDSS

Volume of the Universe probed by BOSS



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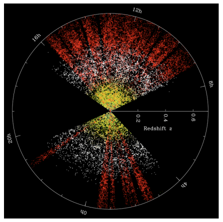

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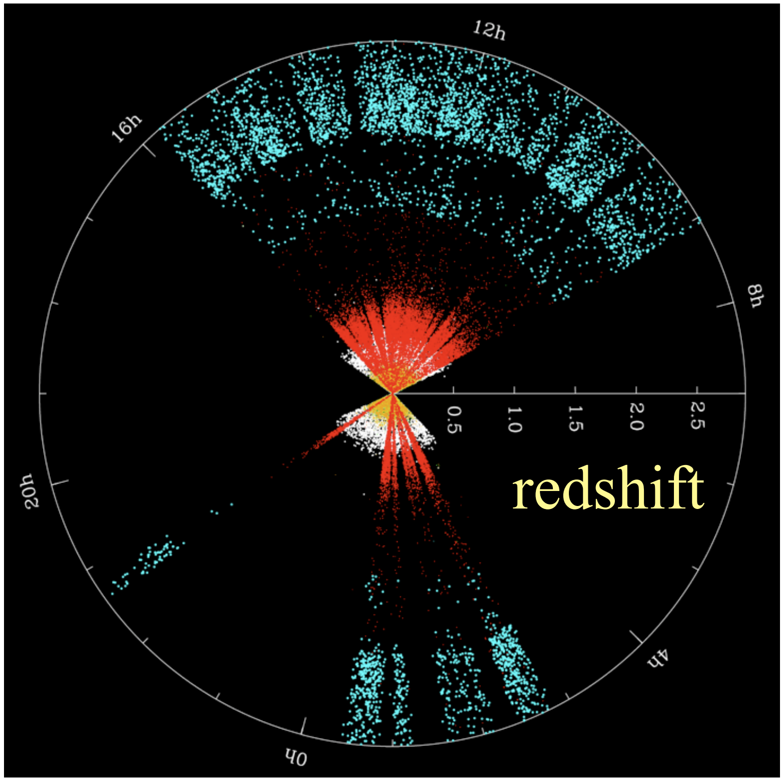

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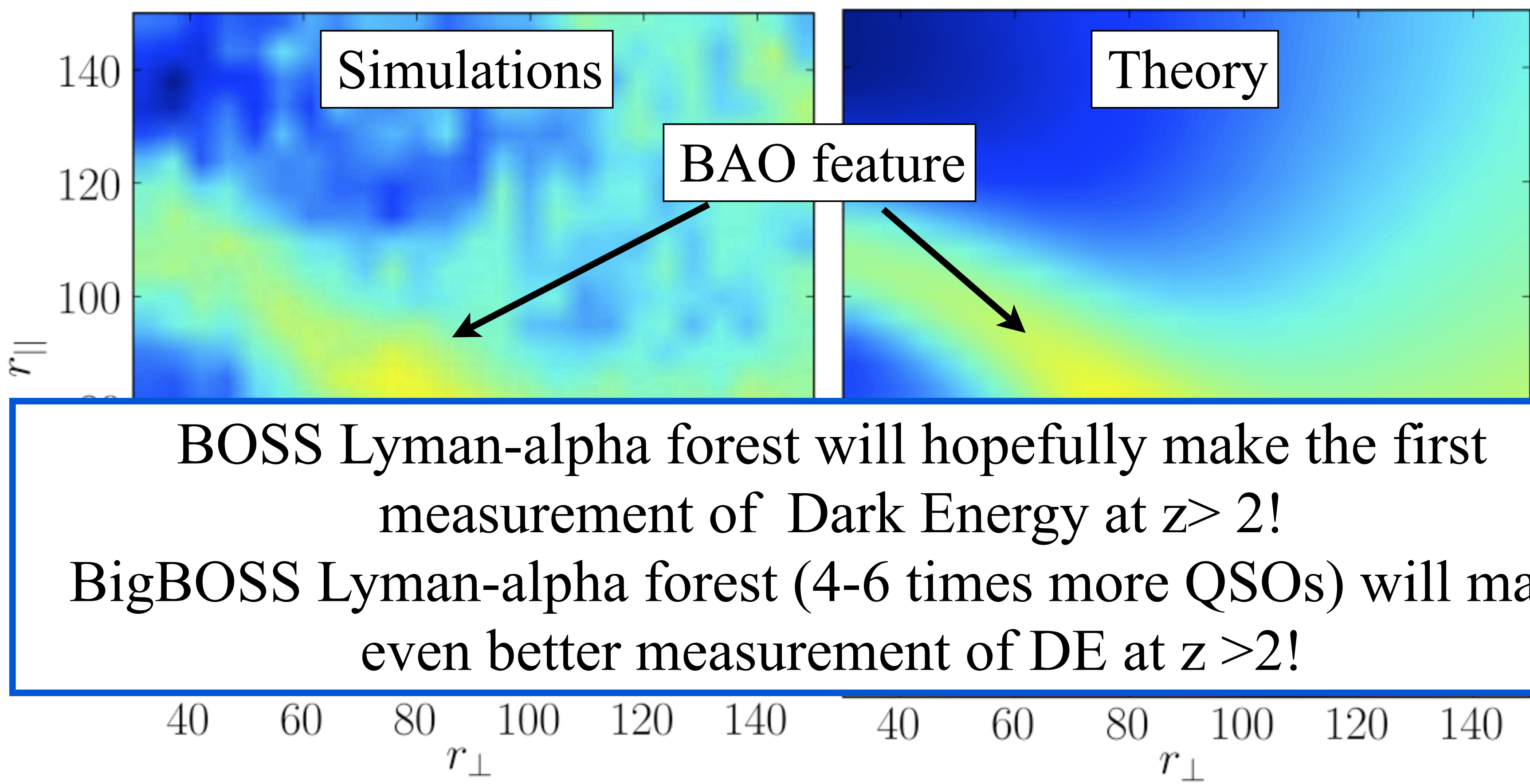
Beyond: With Lyman Alpha Forest
Mini Conclusion



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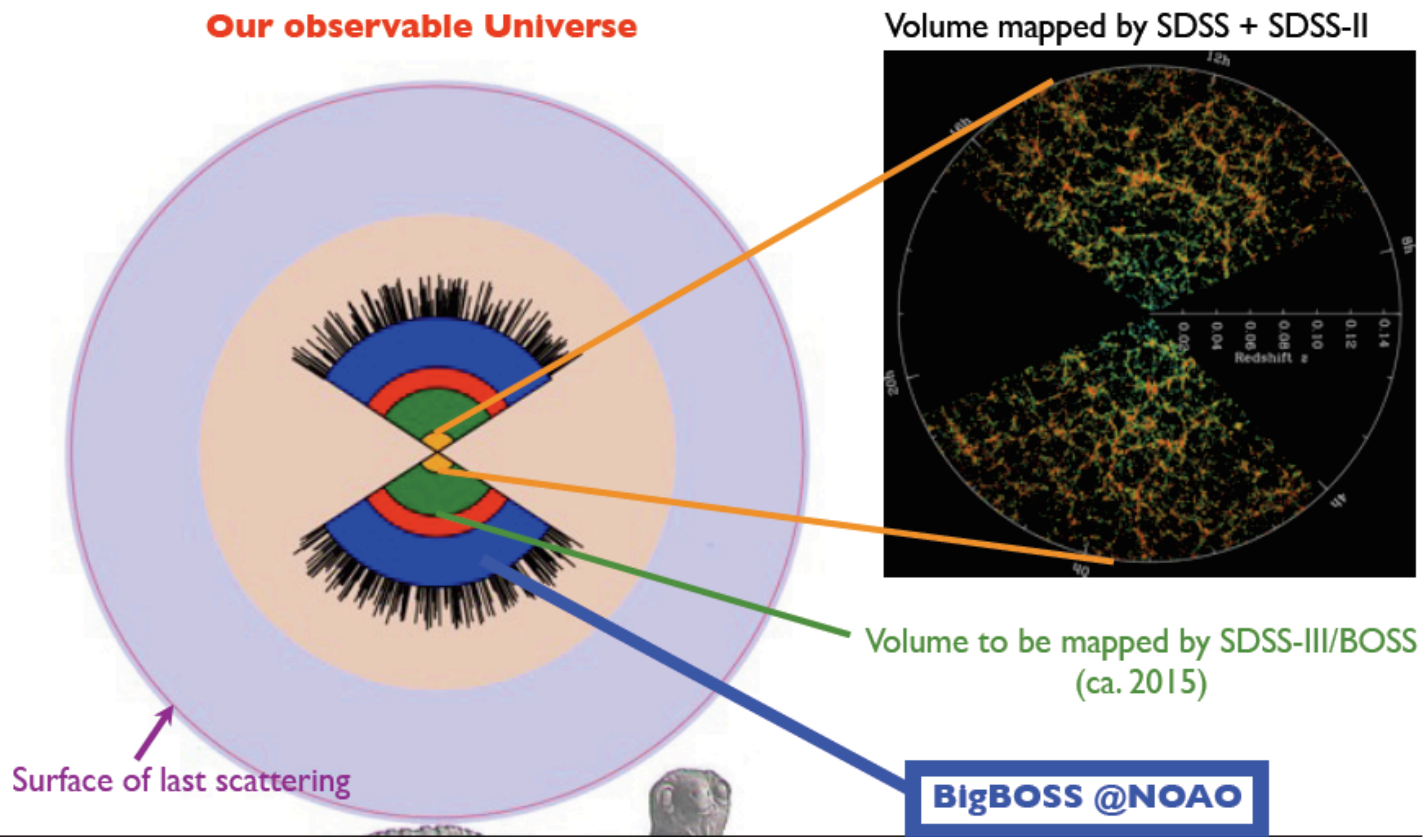
The Ground-Based Stage IV BAO Experiment

BigBOSS

Science Goals: 50 million redshifts

Sensitivity to new physics scales as volume surveys -- # of modes



Courtesy Slide from David Schlegel

Outline

- Motivations
- Introduction
  - What are Baryon Acoustic Oscillations?
- Baryon Acoustic Oscillations: Now and Beyond
  - Now: With Luminous Red Galaxies
  - Beyond: With Lyman Alpha Forest
- Conclusions

Conclusions

- Baryon Acoustic Oscillations is one of the cleanest probes of **Dark Energy**
- We made the **minimum variance measurement** of galaxy clustering for **largest volume** of galaxies ever used for clustering
- Allowing us to make **significant detection of BAO at z=0.45-0.65**, the **highest redshift** range BAO is ever detected significantly.
- Looking forward, we can apply the same optimal method to both photometric and spectroscopic surveys such as DES, LSST, BOSS and BigBOSS
- We can also push measurement of BAO to higher redshift via Lyman alpha forest.
- Our results of **first simulation** of Lya forest BAO signals indicate that Lyman alpha flux provides **a good tracer of the underlying dark matter field** on large scales, therefore making Lyman alpha forest a well-suited candidate for BAO measurement.

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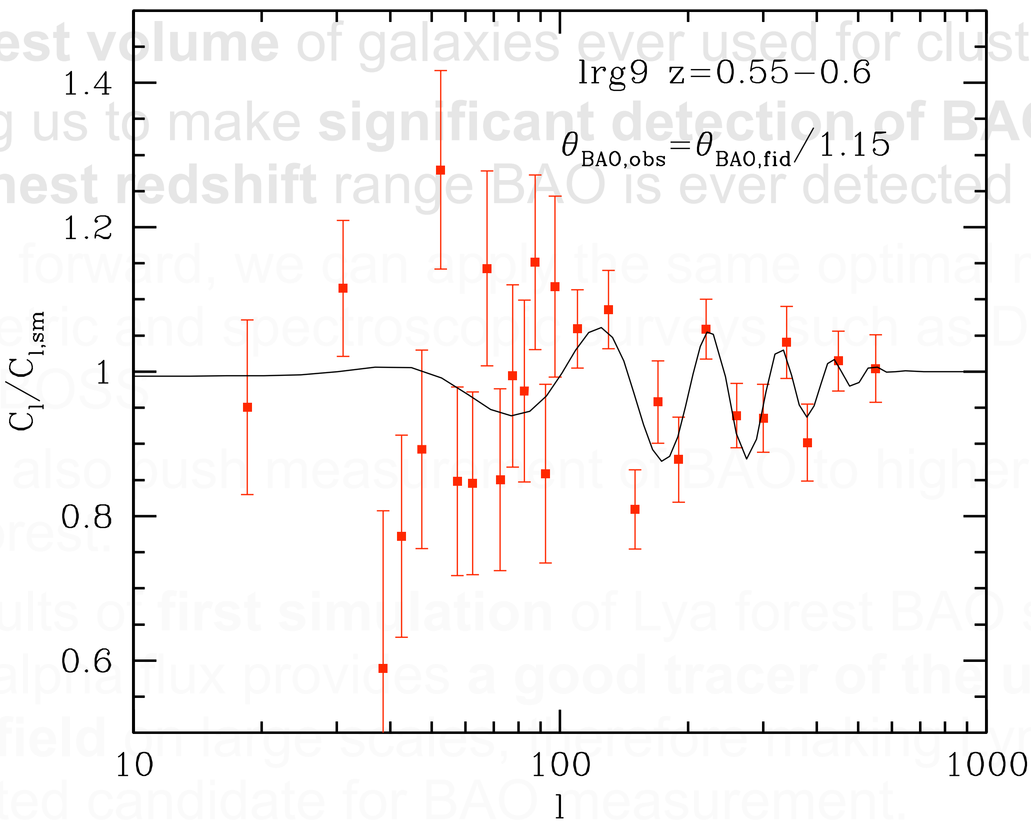
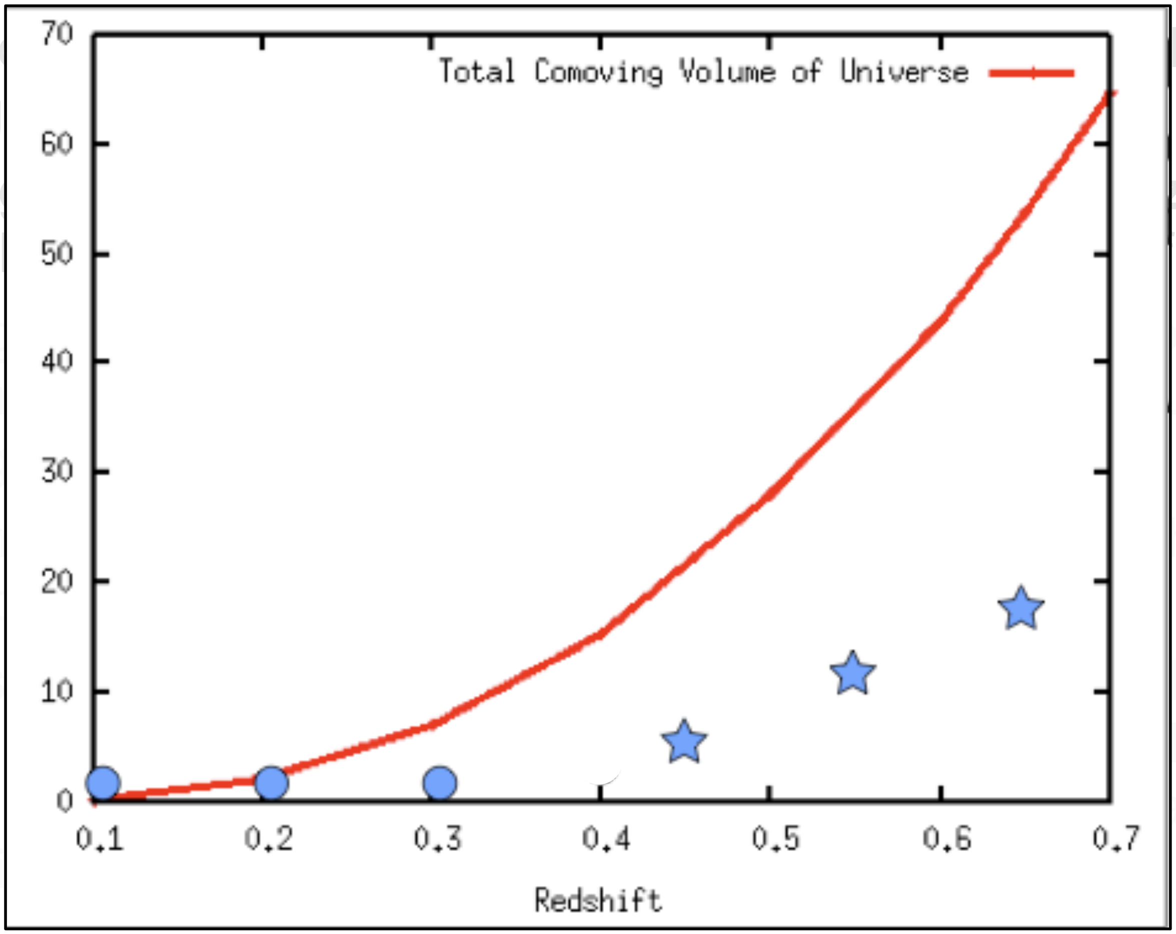


Conclusions

- Baryon Acoustic Oscillations is one of the cleanest probe of Dark Energy
- We ma… laxy clustering for larg…
- Allowin… z=0.45-0.65, the hig… icantly.
- Looking… d to both photom… SST, BOSS and Big…
- We can… hift via Lyman alpha fo…
- Our res… s indicate that Lyman… ying dark matter… lpha forest a well-su…



Conclusions

- Baryon Acoustic Oscillations is one of the cleanest probes of **Dark Energy**
- We made the **minimum variance measurement** of galaxy clustering for **largest volume** of galaxies ever used for clustering
- Allowing us to make **significant detection of BAO at z=0.45-0.65**, the **highest redshift** range BAO is ever detected significantly.
- Looking forward, we can apply the same optimal method to both photometric and spectroscopic surveys such as DES, LSST, BOSS and BigBOSS
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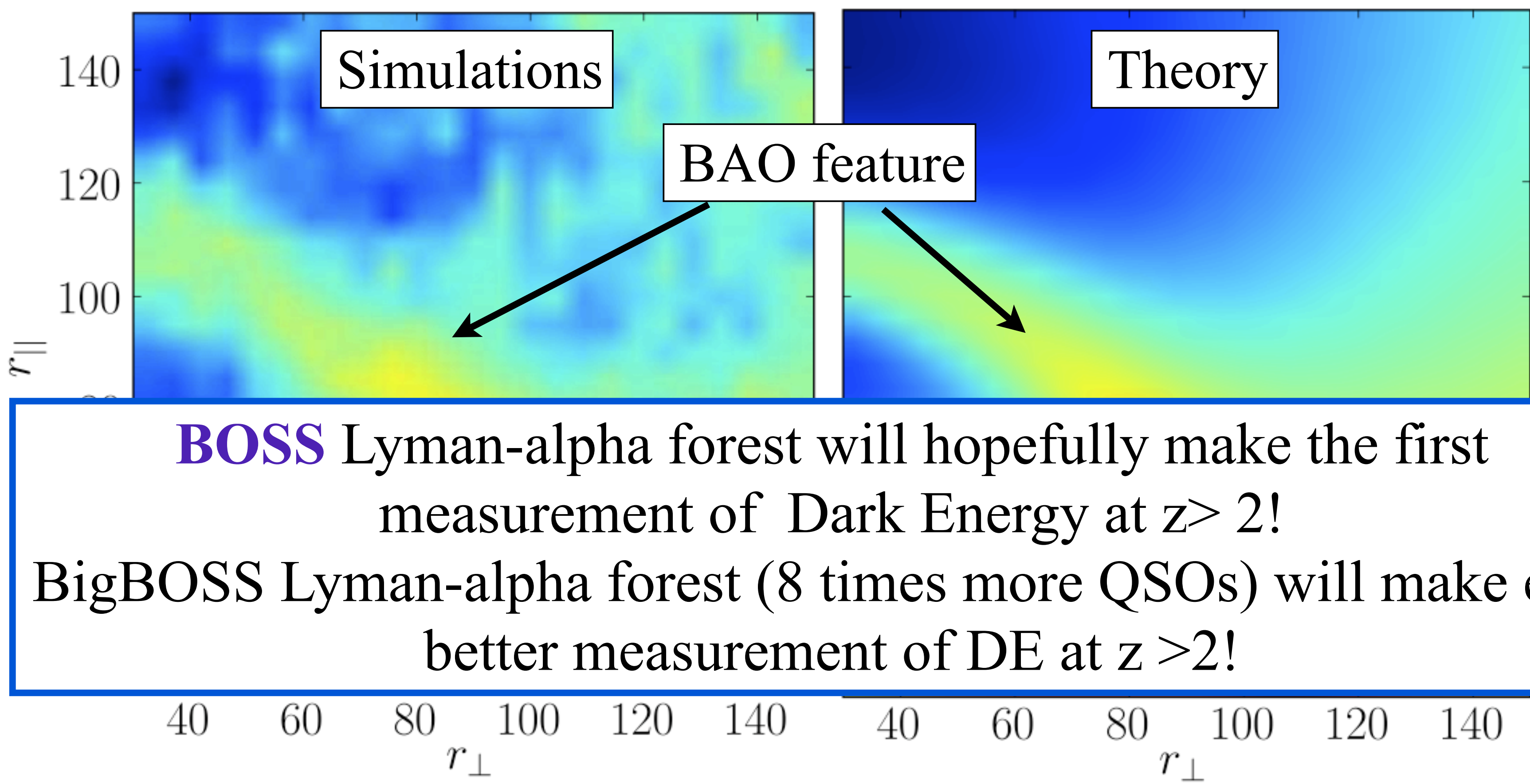
The End

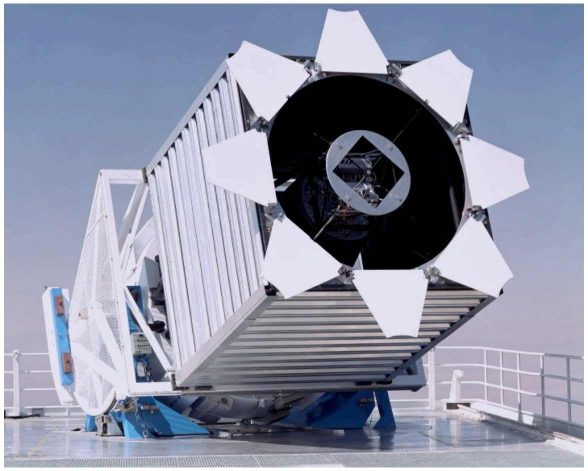
Beyond: With Lyman Alpha Forest
Mini Conclusion



BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at z> 2!
BigBOSS Lyman-alpha forest (8 times more QSOs) will make even better measurement of DE at z >2!

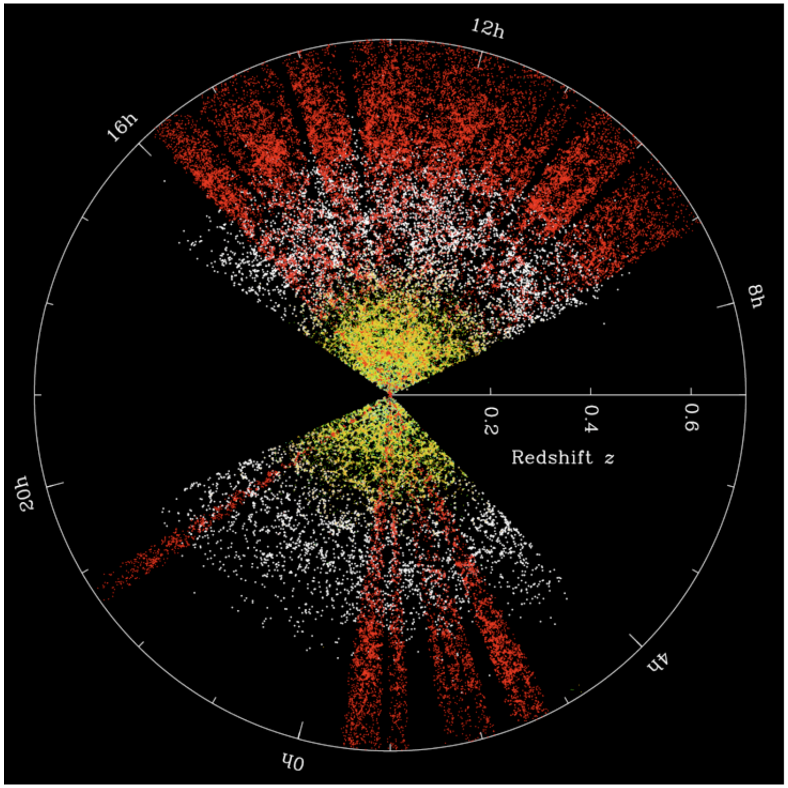
What is BOSS?
Baryon Oscillation Spectroscopic Survey

- New program for the SDSS telescope for 2008–2014 (already working and providing data!).
- Definitive study of the low-redshift acoustic oscillations. 10,000 deg^2 of new spectroscopy from SDSS imaging.
  - 1.5 million LRGs to $z=0.8$, including 4x more density at $z<0.5$.
  - 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at $z=0.35$ and $z=0.6$.
  - Easy extension of current program.
- Simultaneous project to discover the BAO in the Lyman α forest.
  - 160,000 quasars. 20% of fibers.
  - 1.5% measurement of distance to $z=2.3$.
  - Higher risk but opportunity to open the high-redshift distance scale.

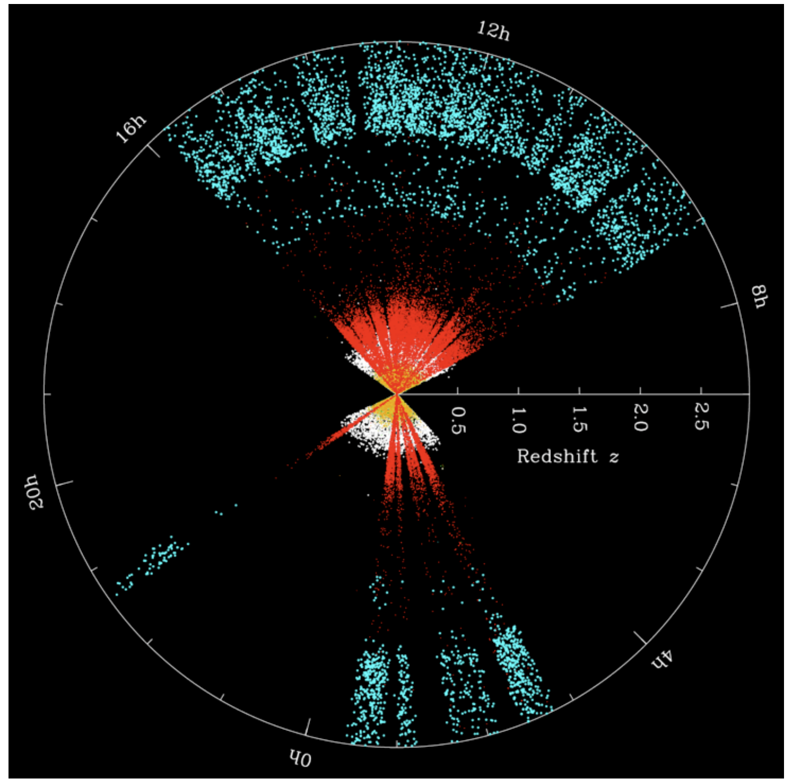


BOSS

Volume of the Universe probed by SDSS



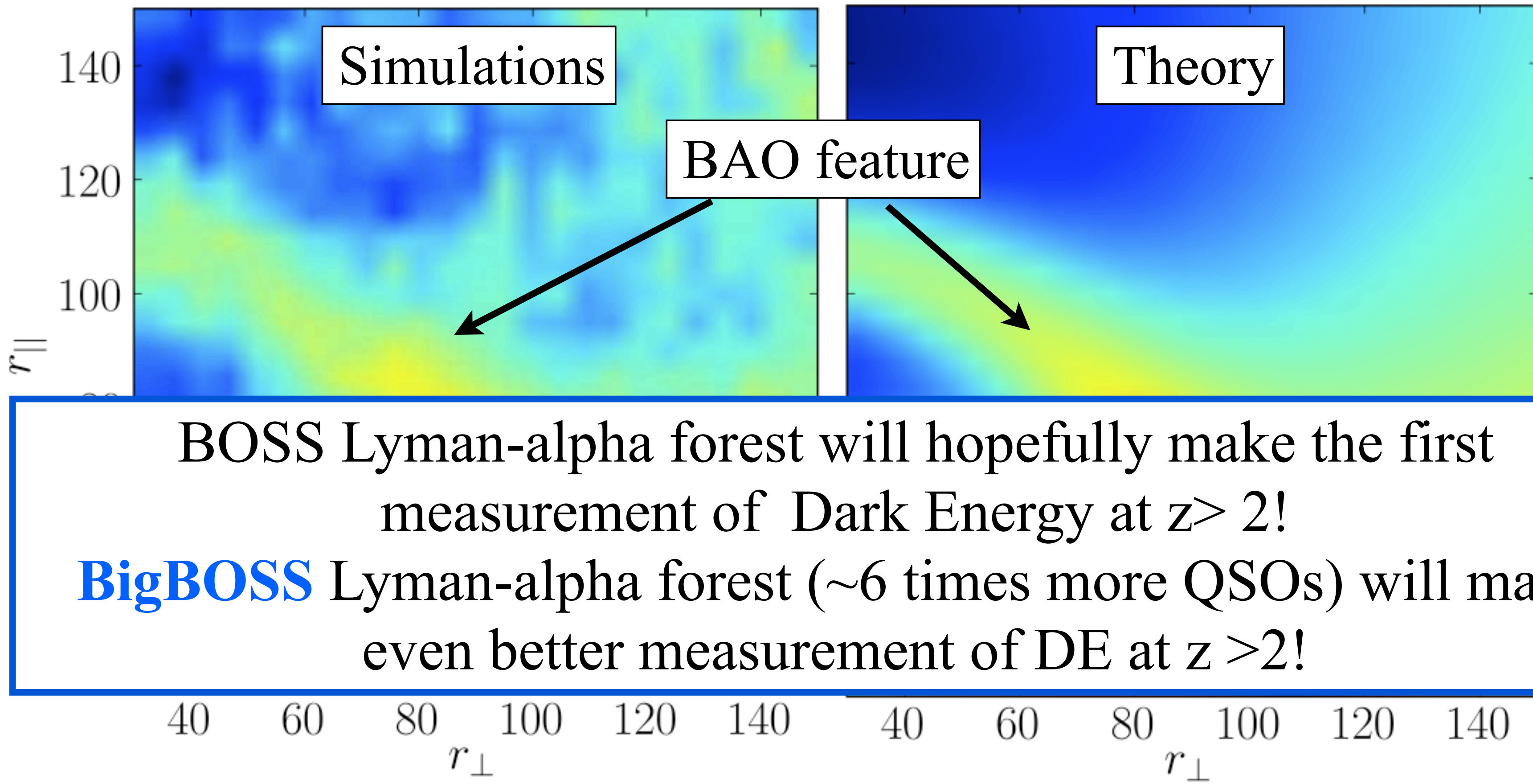
Volume of the Universe probed by BOSS



Courtesy plots from Michael Blanton

Beyond: With Lyman Alpha Forest
Mini Conclusion

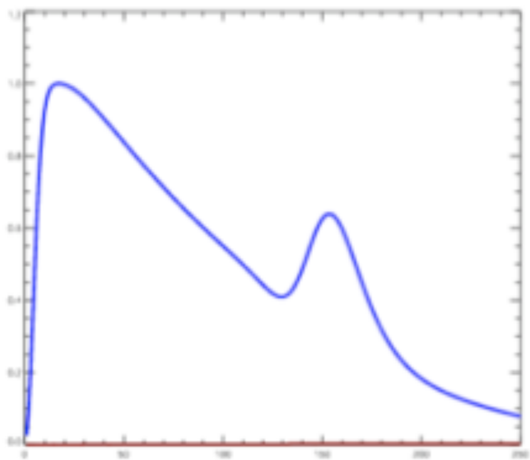
- **Dark Energy via Baryon Acoustic Oscillations**

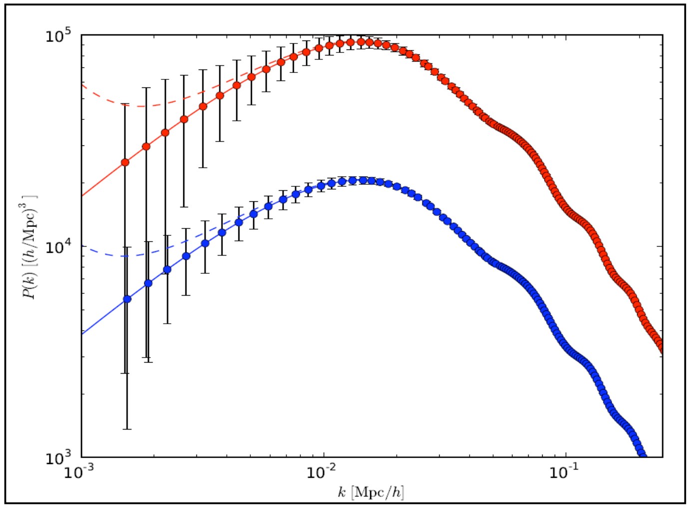


BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at z> 2!
BigBOSS Lyman-alpha forest (~6 times more QSOs) will make even better measurement of DE at z >2!

How do you go about measuring BAO?

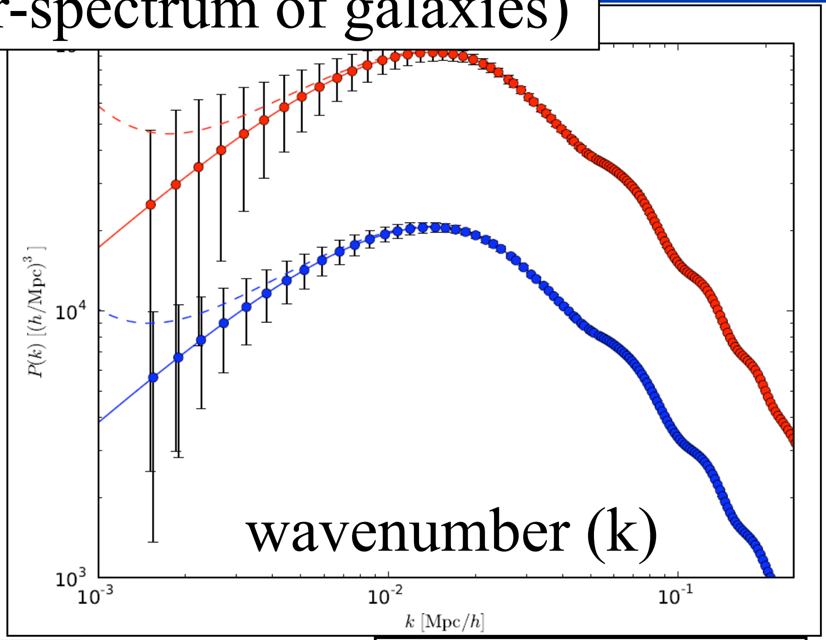
- Since there are many ripples, how do we actually measure the BAO?
- We measure the correlation function or its Fourier transform, called the power-spectrum.





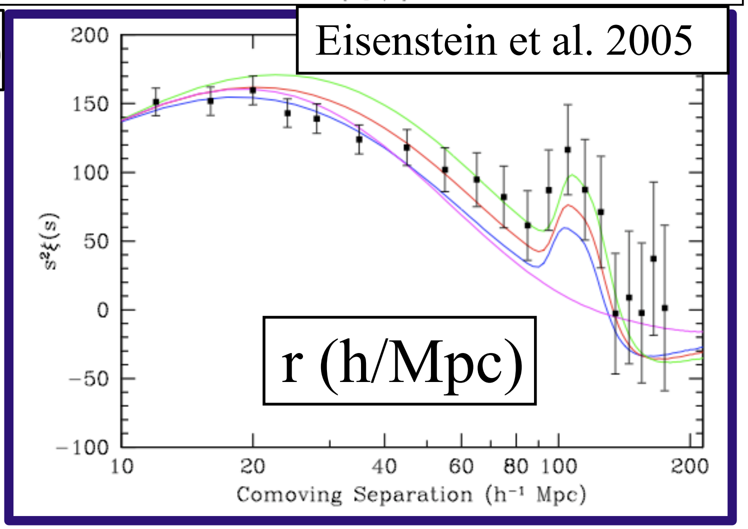
Predicted signals of BAO

P(k) (power-spectrum of galaxies)



Fourier space

$r^2\xi(r)$



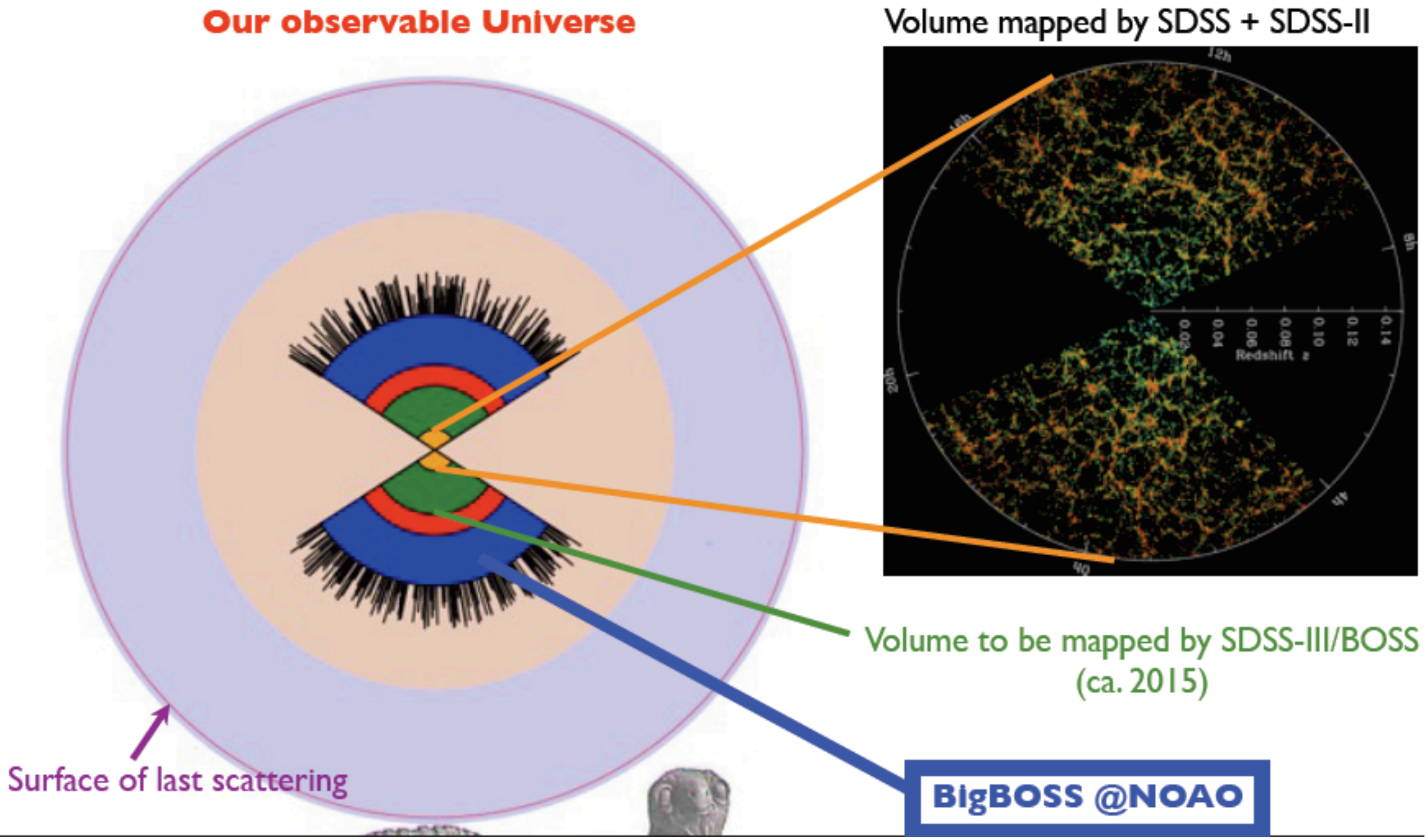
Configuration space

The Ground-Based Stage IV BAO Experiment

BigBOSS

Science Goals: 50 million redshifts

Sensitivity to new physics scales as volume surveys -- # of modes



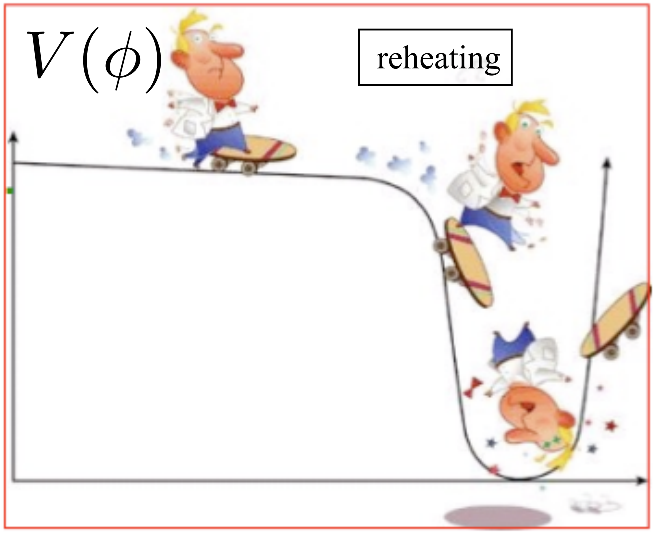
Courtesy Slide from David Schlegel

Lyman Alpha Forest: what can it do?
—Non-gaussianities in Early Universe

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)



Inflation

Lyman Alpha Forest: what can it do?
—Non-gaussianities in Early Universe

BERKELEY LAB

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)

Non-Gaussianity from Inflation

f_{NL} ~ 0.05 canonical inflation (single field, couple of derivatives) (Maldacena 2003, Acquaviva etal 2003)

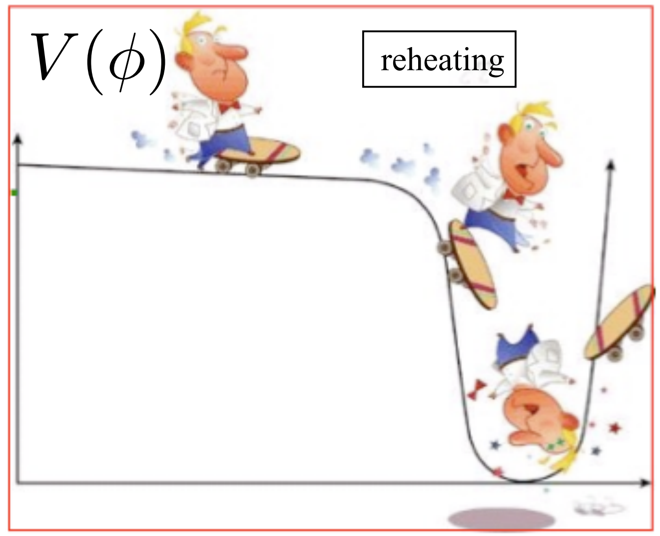
f_{NL} ~ 0.1--100 higher order derivatives

DBI inflation (Alishahiha, Silverstein and Tong 2004)

UV cutoff (Craminelli 2003)

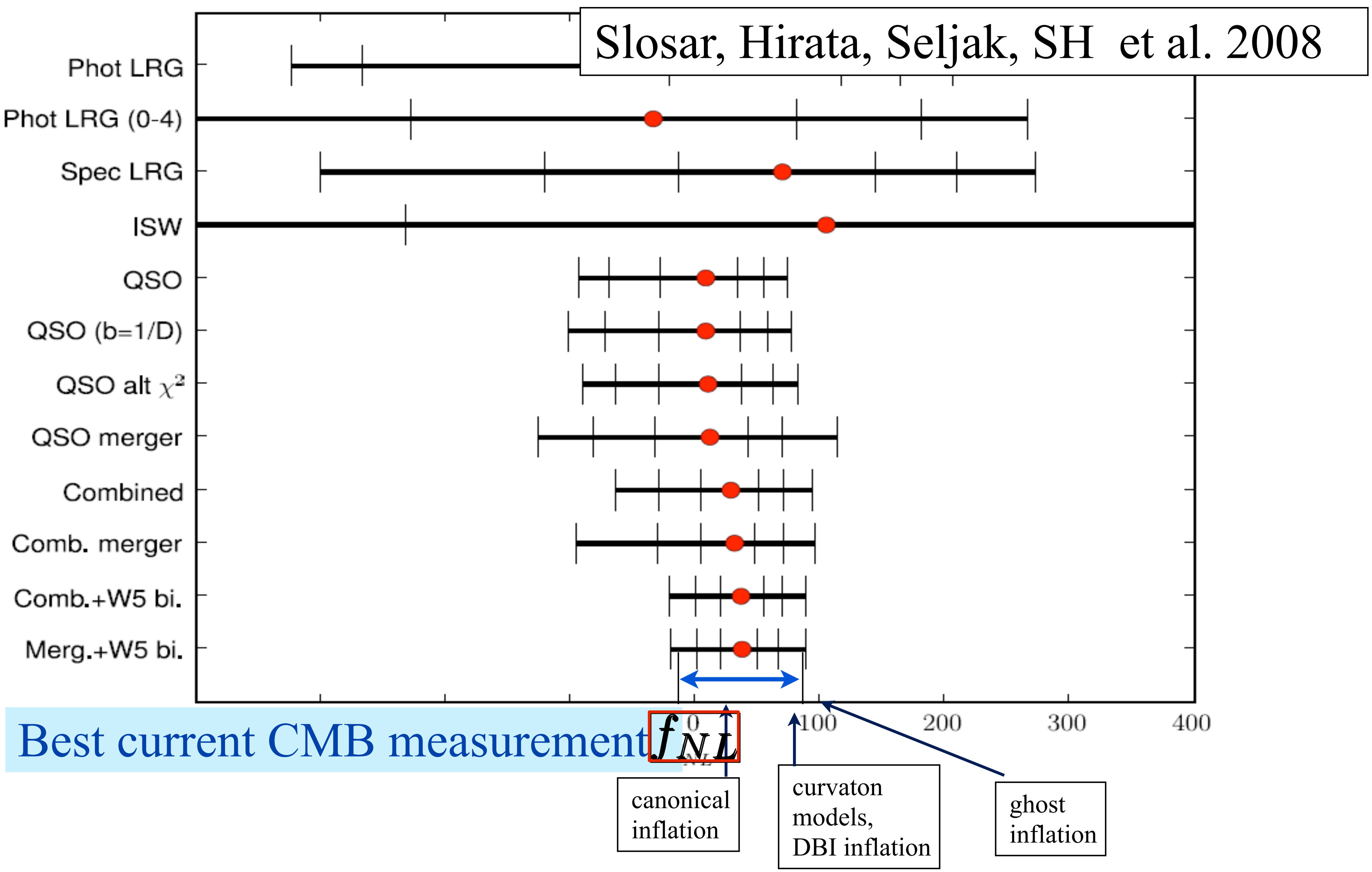
f_{NL} >10 curvaton models (Lyth, Ungarelli and Wands, 2003)

f_{NL} ~100 ghost inflation (Arkani-Hamed et al., 2004)

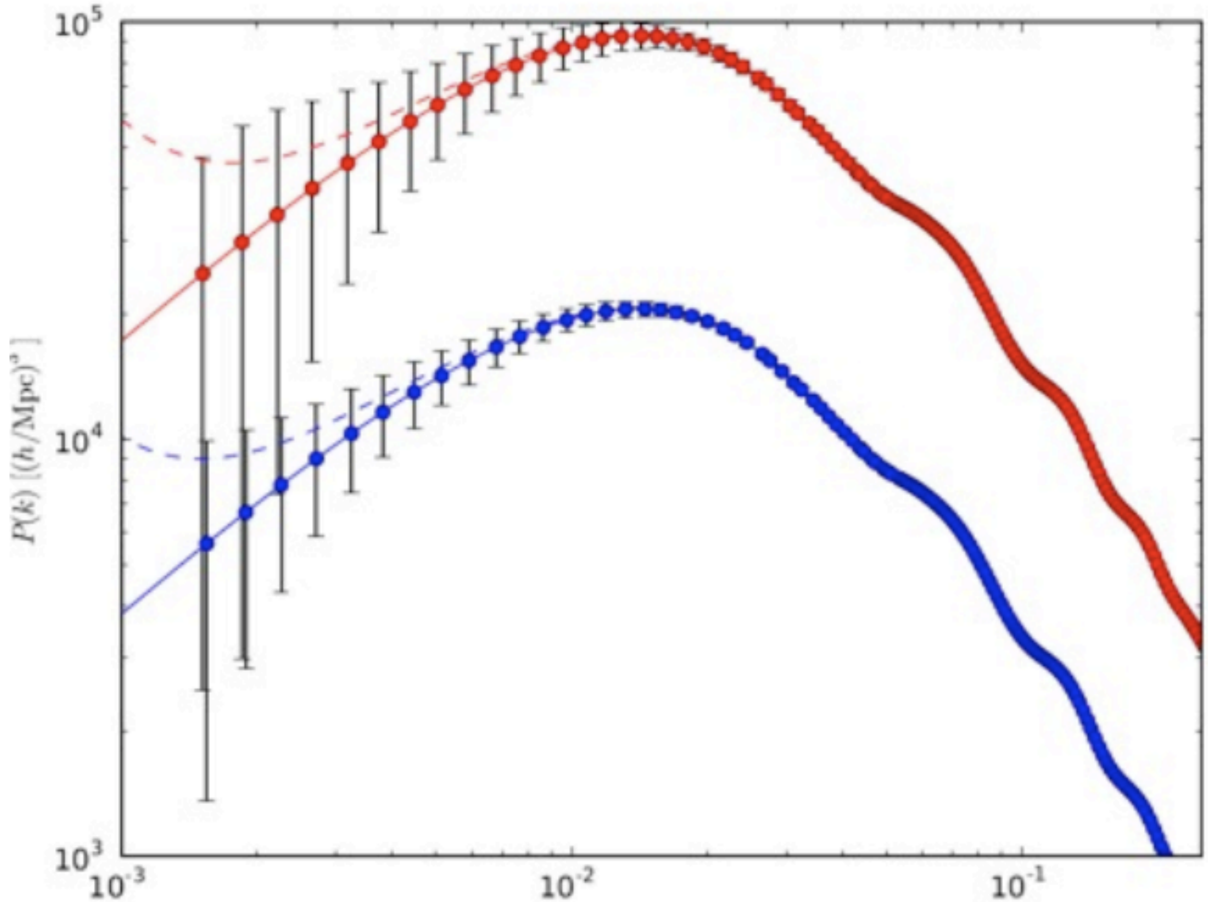


← Inflation →

Lyman Alpha Forest: what can it do?
—Non-gaussianities in Early Universe

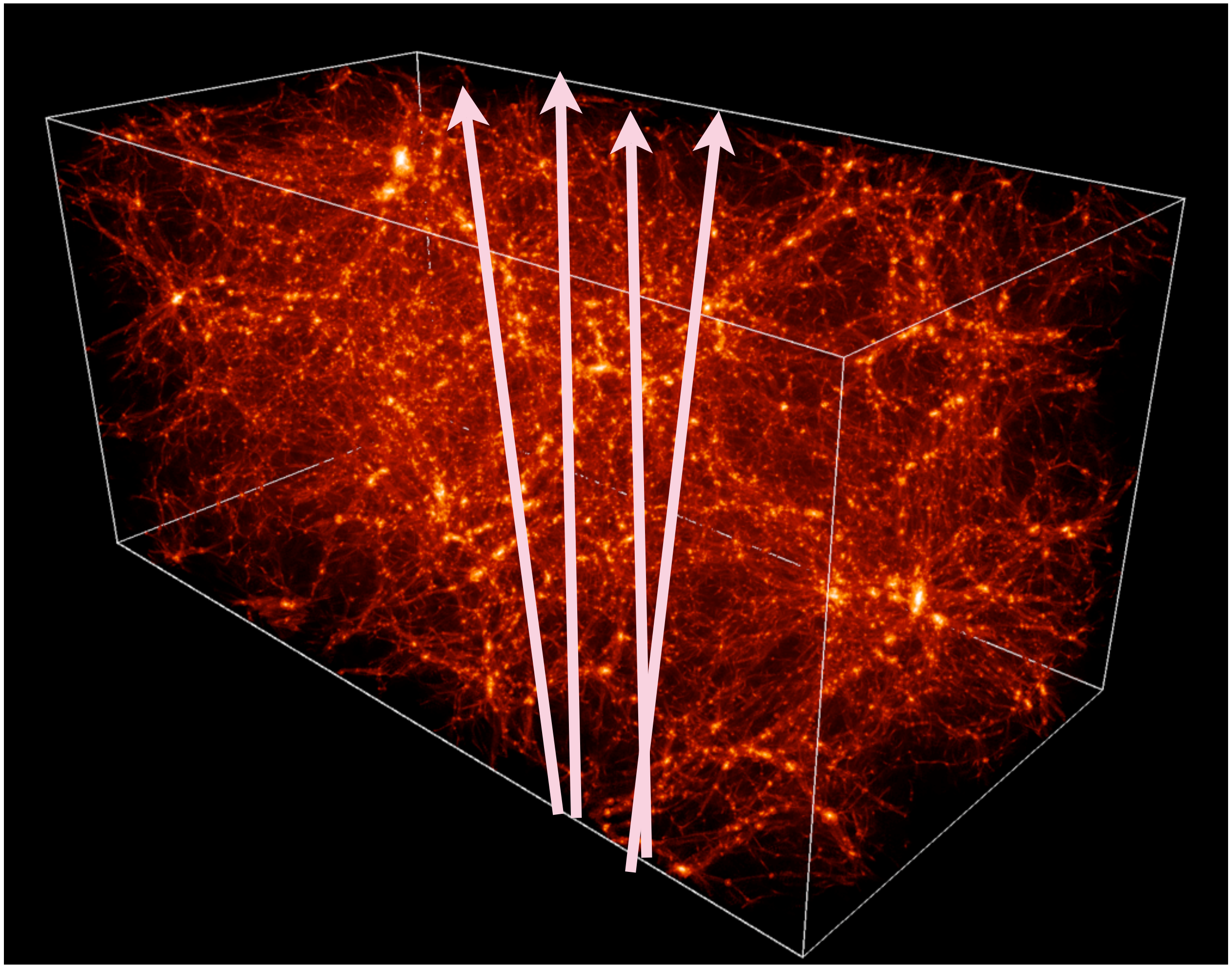


P(k) (Mpc/h)^3



k (h/Mpc)

Lyman Alpha Forest: what can it do?



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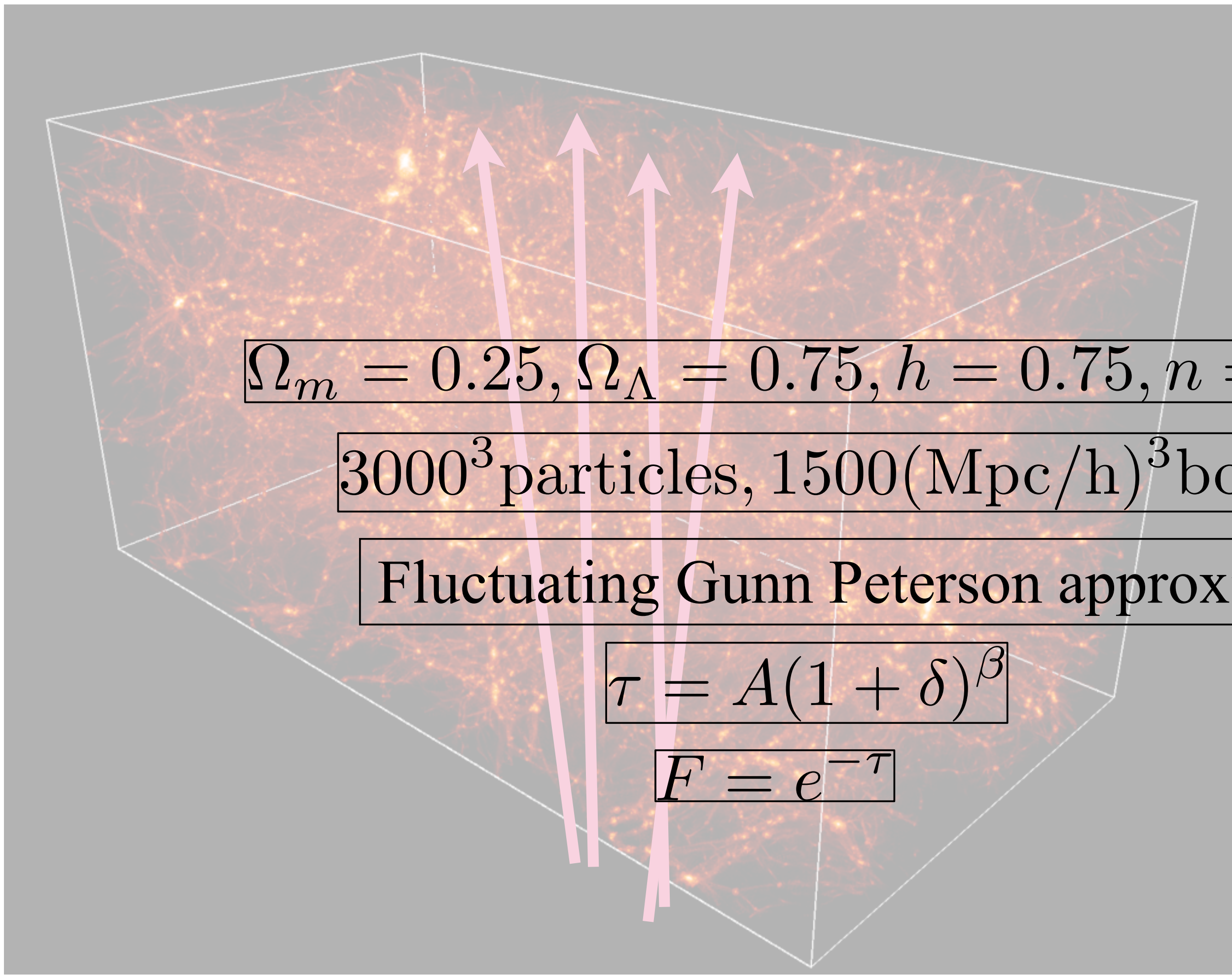


$\boxed{\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8}$

$\boxed{3000^3 \text{particles}, 1500(\text{Mpc/h})^3 \text{box}, 3000^3 \text{grid}}$

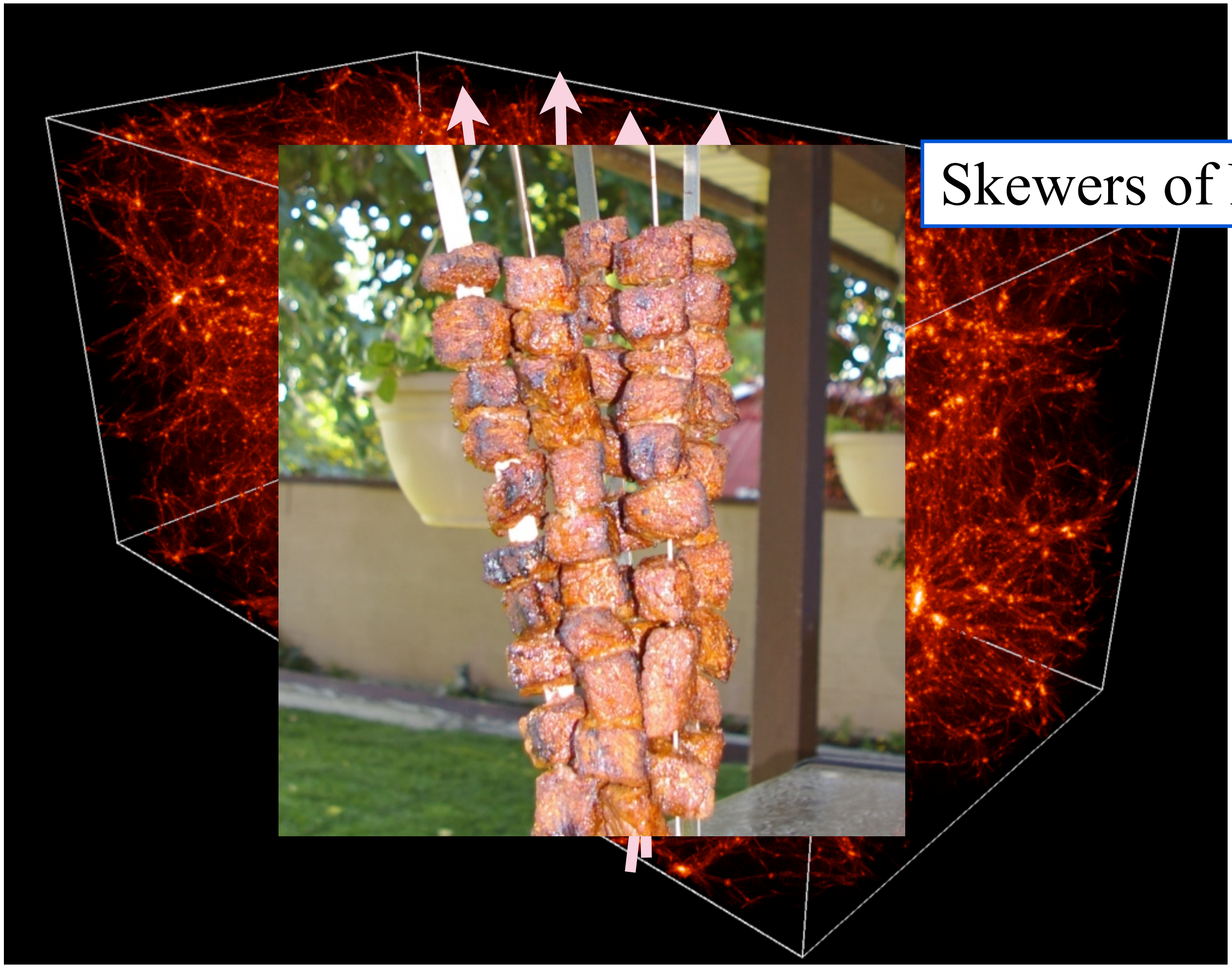
Fluctuating Gunn Peterson approximation

$$\boxed{\tau = A(1+\delta)^\beta}$$

$$\boxed{F = e^{-\tau}}$$

Lyman Alpha Forest: what can it do?

- **Dark Energy via Baryon Acoustic Oscillations**



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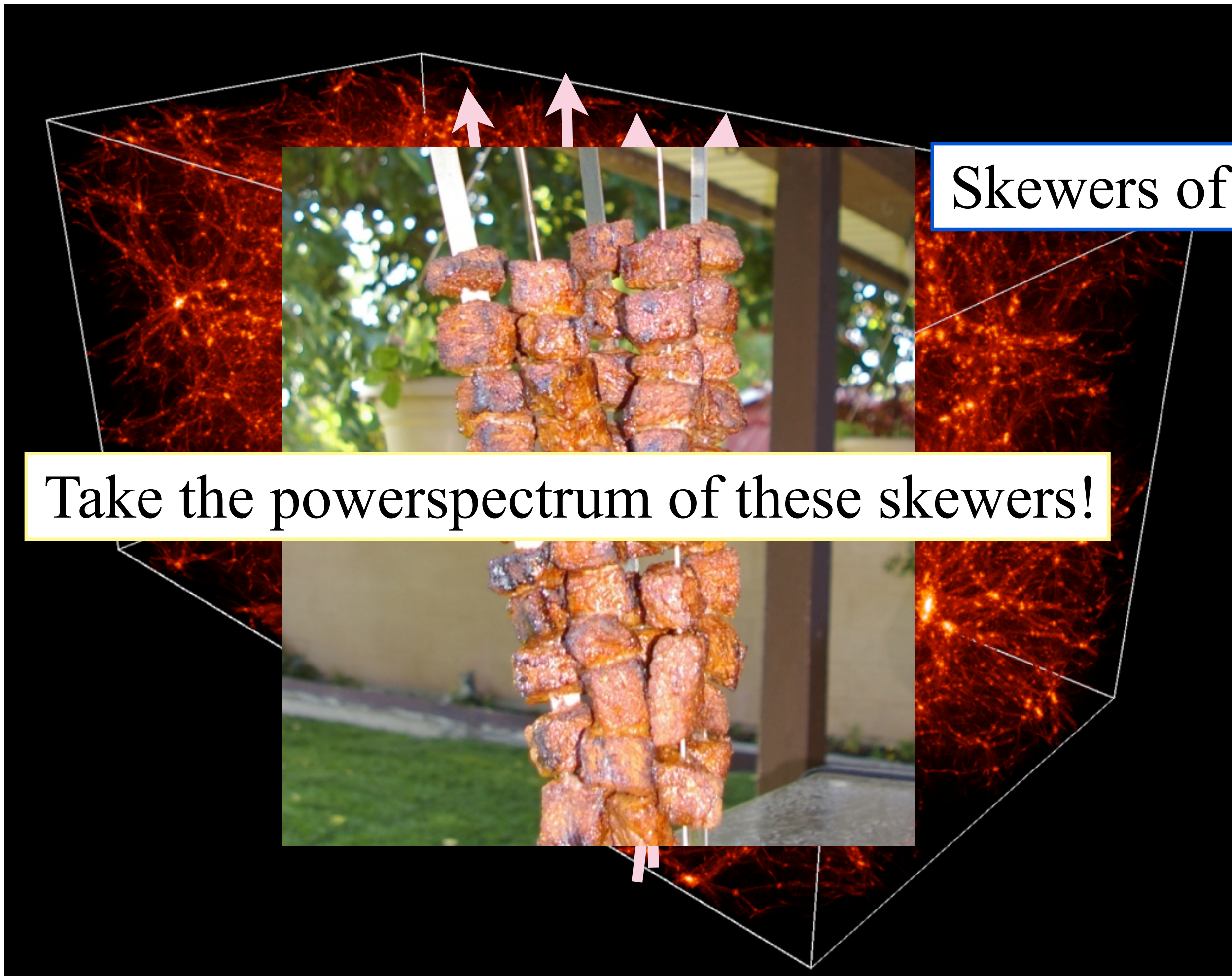
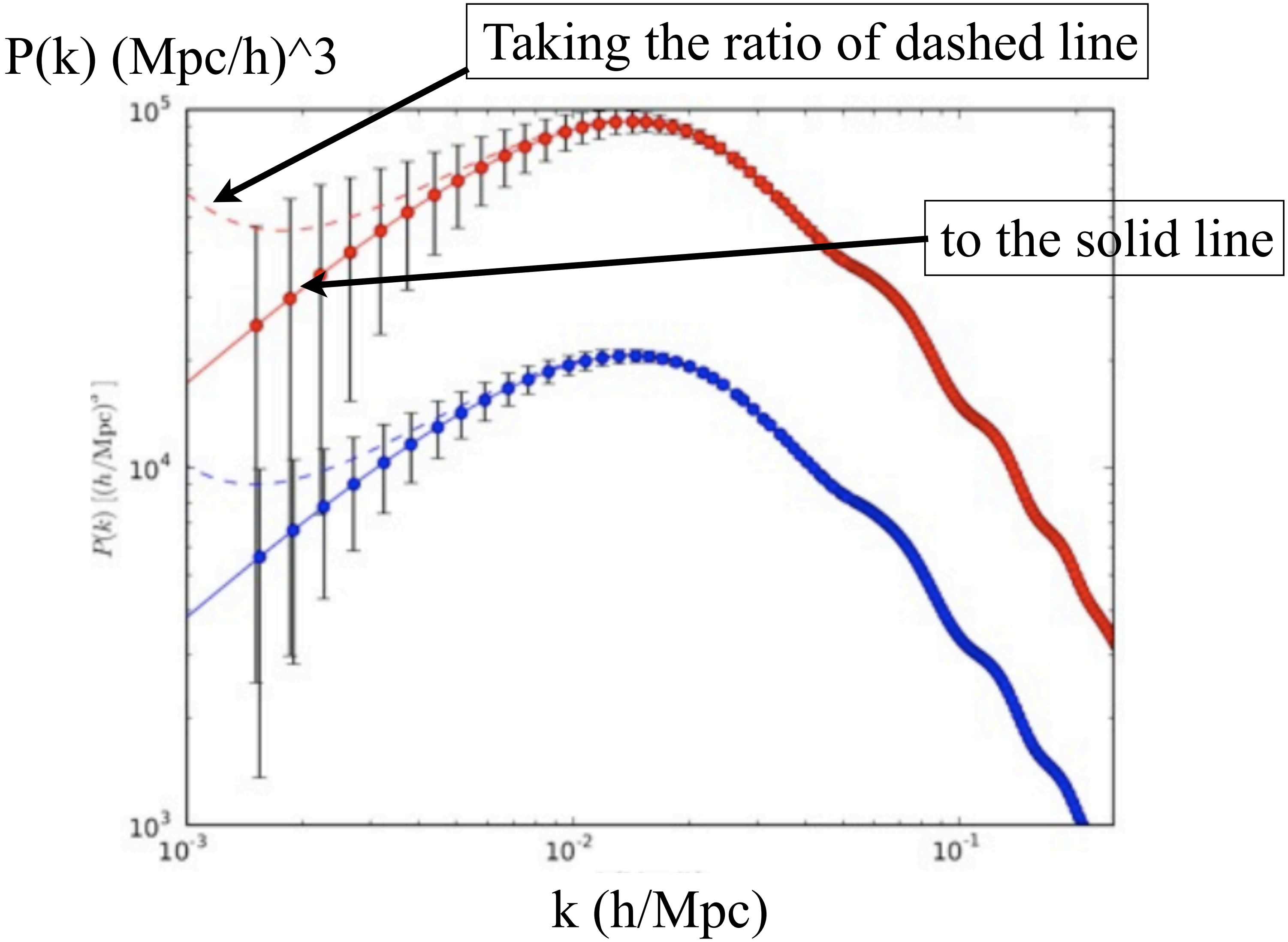
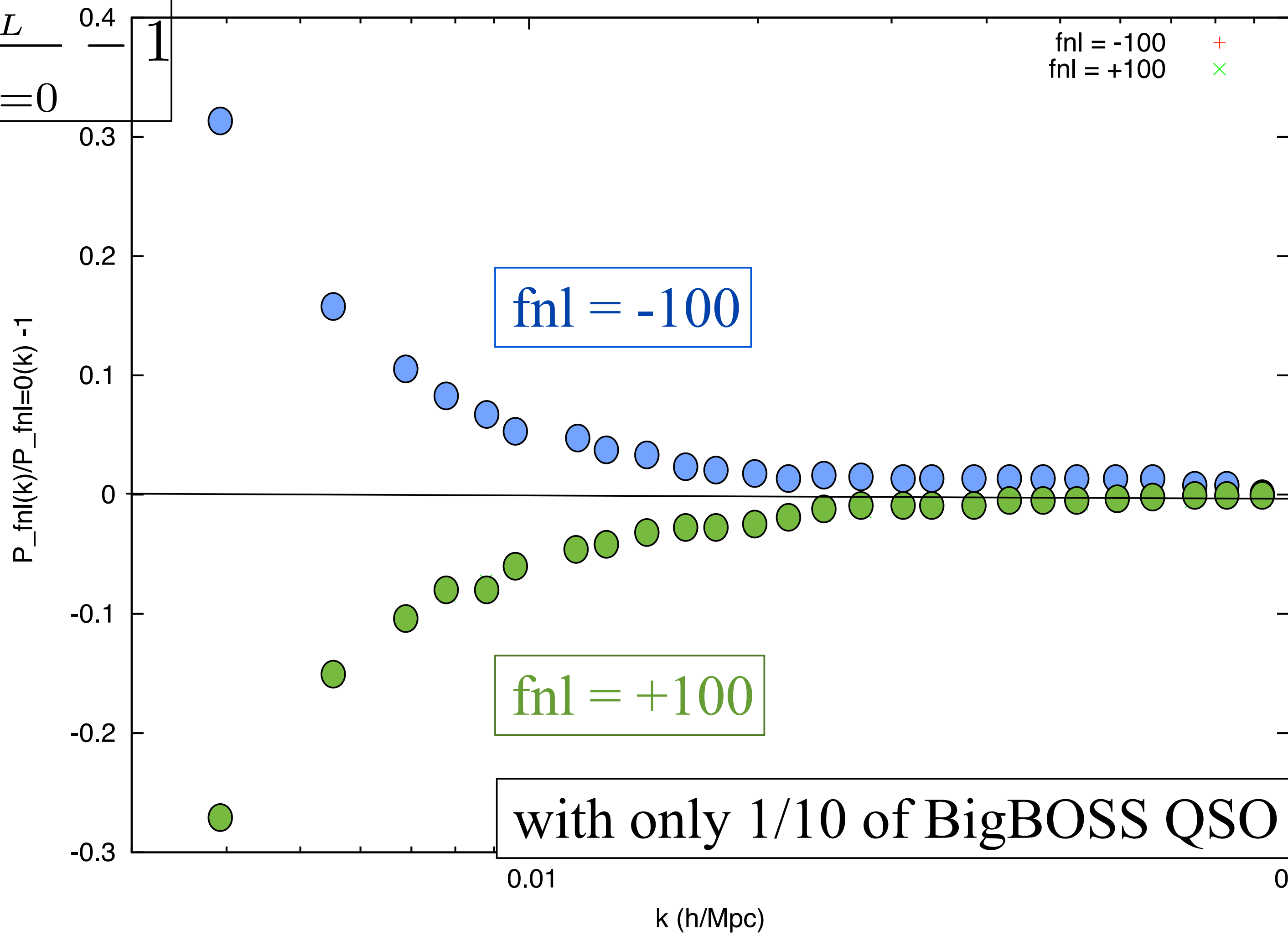



P(k) (Mpc/h)^3
Taking the ratio of dashed line
to the solid line
10^5
10^4
10^3
10^{-3}
10^{-2}
10^{-1}
$P(k)$ $[(h/\mathrm{Mpc})^3]$
k (h/Mpc)

What can we do with Lya and fnl?

$$\frac{P_{f_{NL}}}{P_{f_{NL}=0}} - 1$$



with only 1/10 of BigBOSS QSO density

Ho, Desjacques, Slosar & Seljak (in prep)

What can we do with Lya and fnl?

Preliminary theory predictions

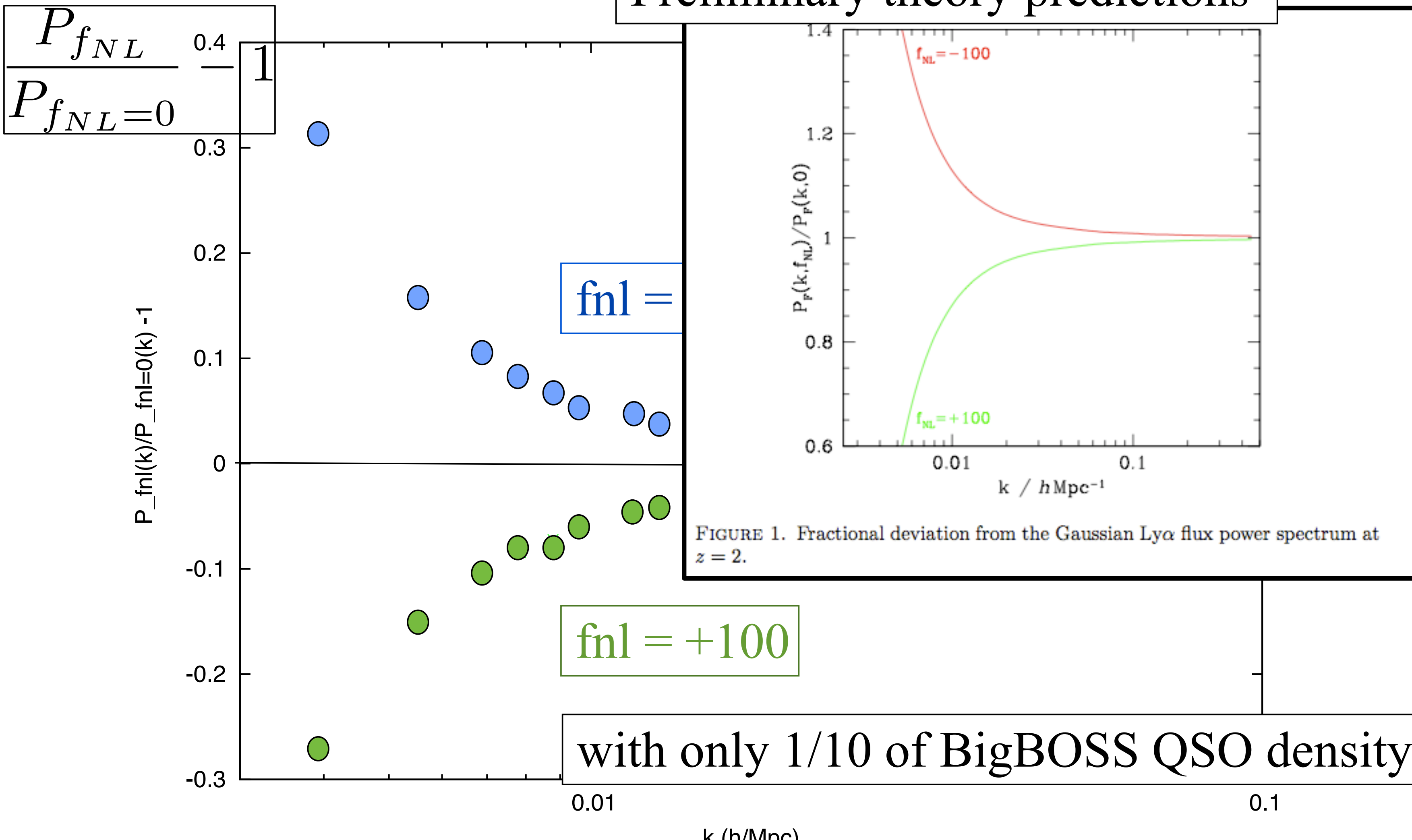
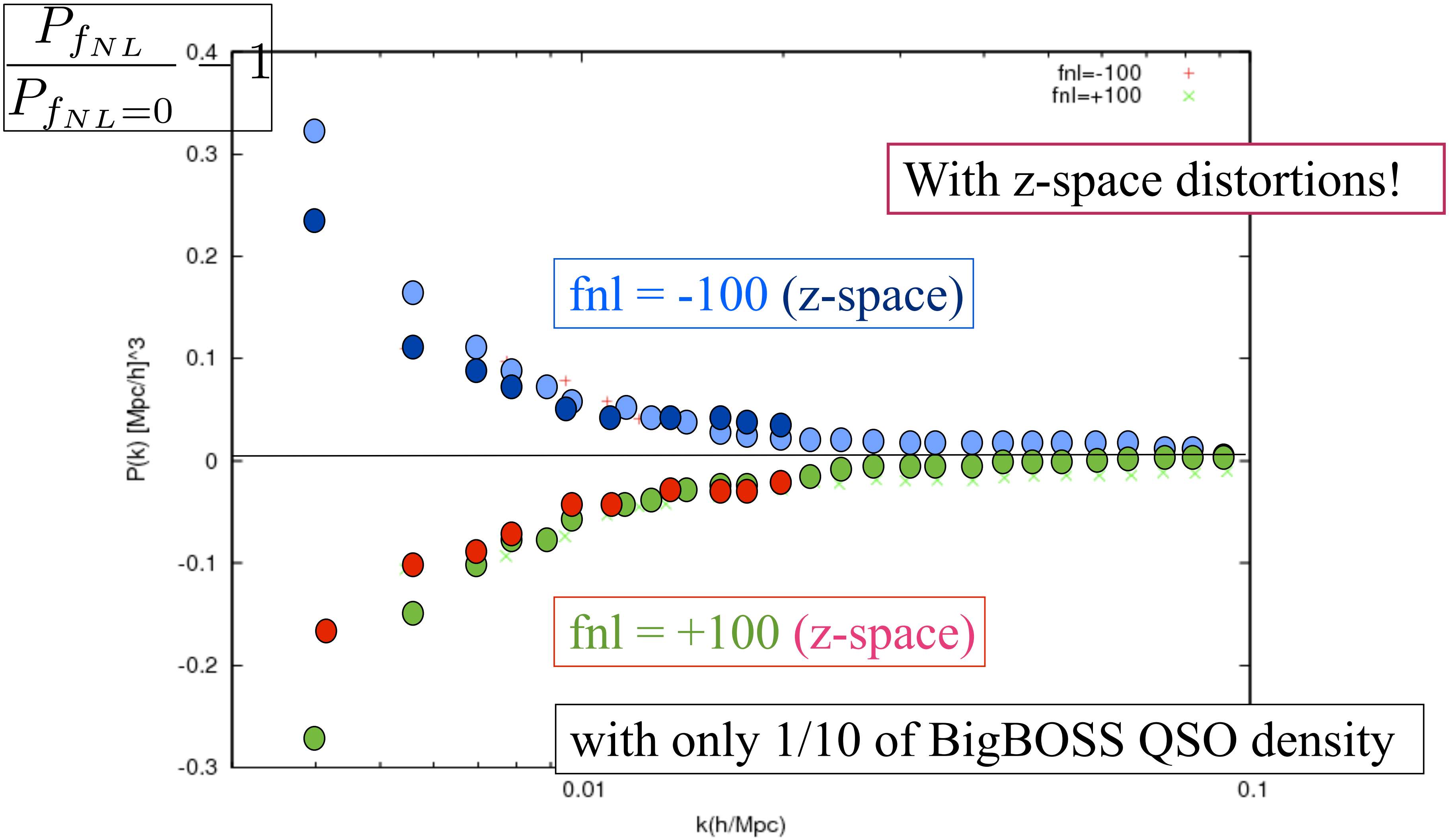


FIGURE 1. Fractional deviation from the Gaussian Lyα flux power spectrum at $z = 2$.

with only 1/10 of BigBOSS QSO density

Ho, Desjacques, Slosar & Seljak (in prep)

What can we do with Lya and fnl?



Ho, Desjacques, Slosar & Seljak (in prep)

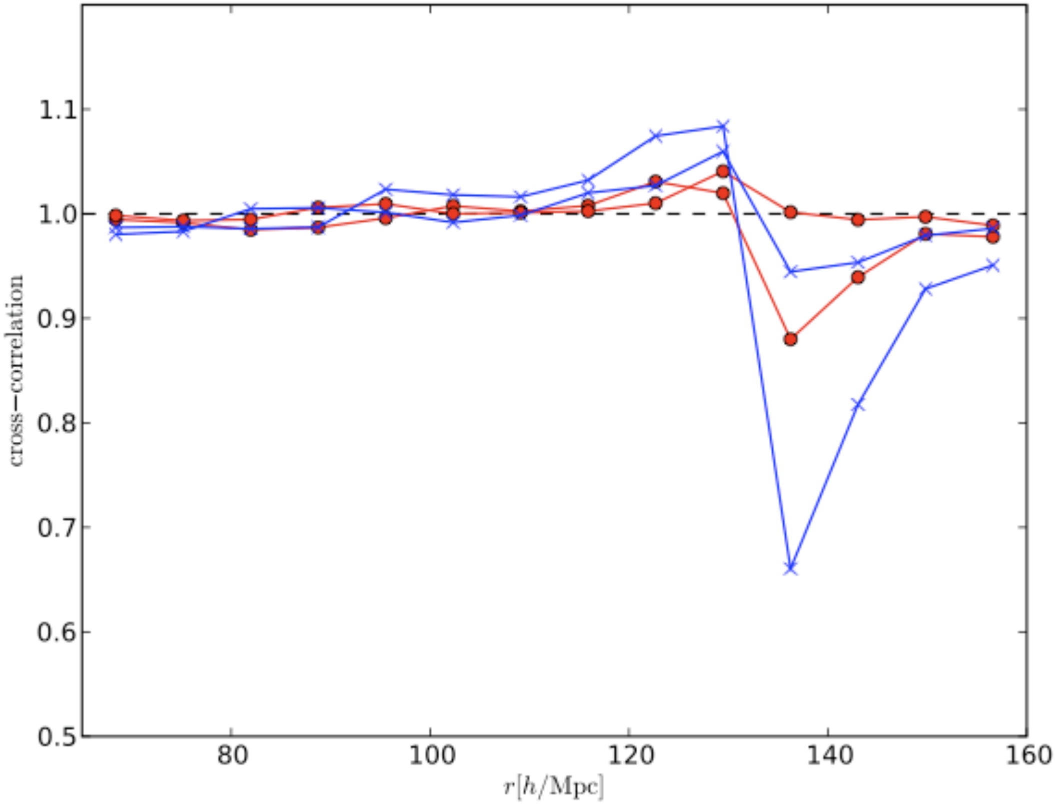
Things I can talk about, but won't...

- Redshift space distortions' effect
- Effects of DLAs (Damped Lya systems), BALs (Broad Absorption line systems), Metals
- Effect of incomplete continuum subtractions
- The other systematic error that will be coming from the experiment/analysis.

Conclusion

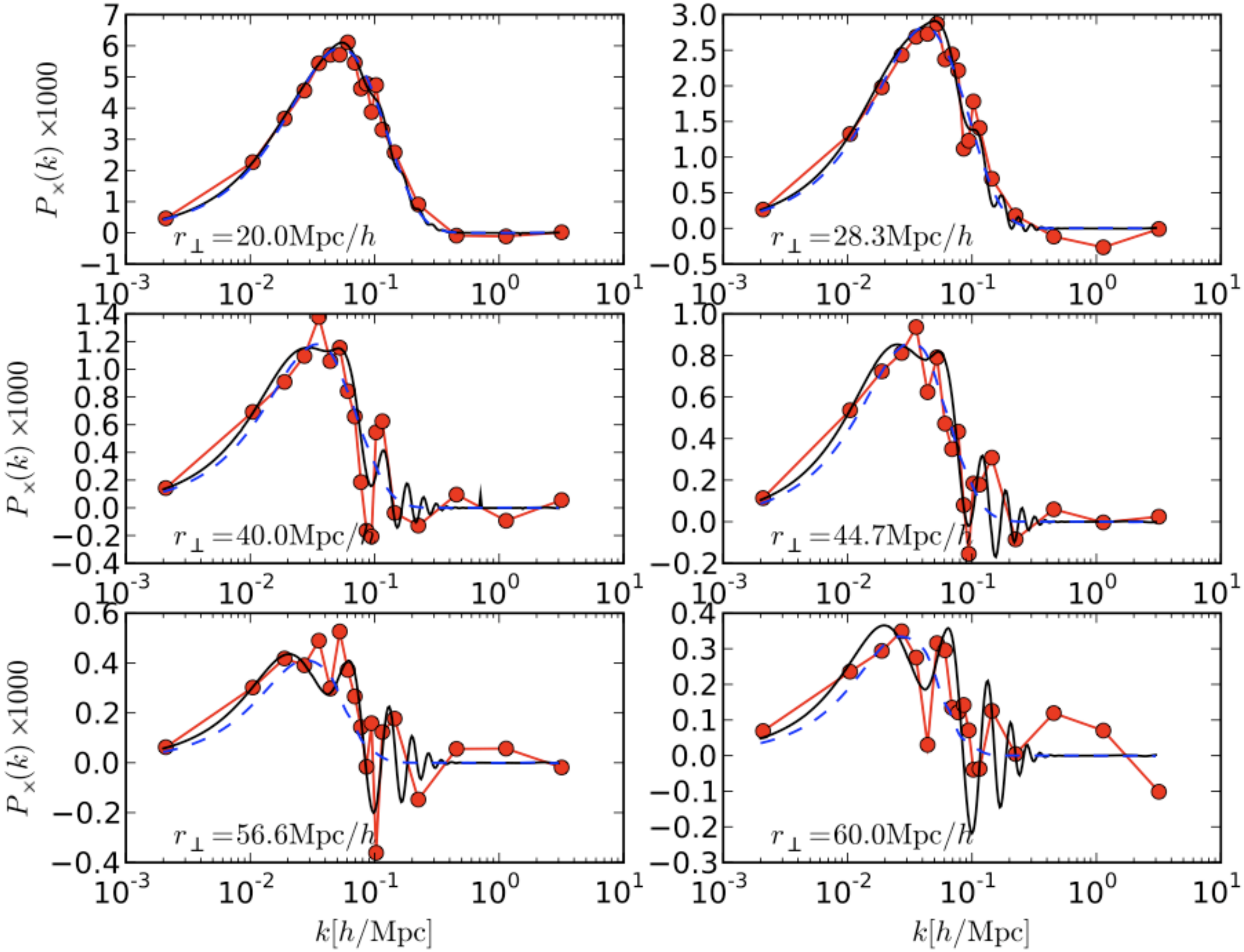
- Lyman-alpha forest in BOSS and BigBOSS will (hopefully) do the following:
  - —Lya BAO to measure Dark Energy at z>2
  - —Lya probes non-gaussianity of the Early Universe
  - —Other applications:
    - Lya P(k) tighten the cosmological constraints
    - temperature density relation in the IGM
    - finding missing baryons at higher z

$$\sqrt{\xi_{lh}^2/\xi_{ll}\xi_{hh}}$$



$$r[h/Mpc]$$

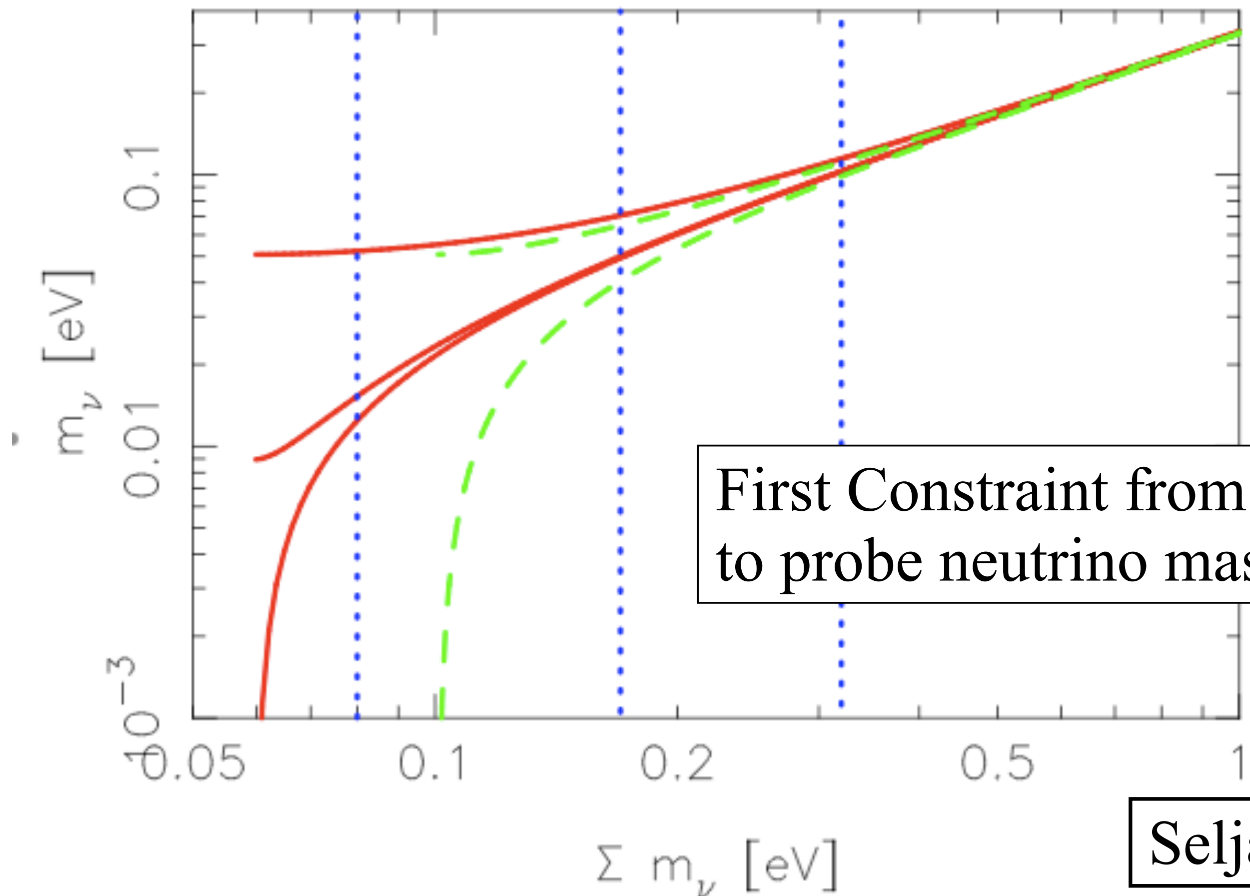
FIG. 2: The cross-correlation coefficient between the flux in our low and high resolution boxes, $\sqrt{\xi_{lh}^2/\xi_{ll}\xi_{hh}}$. Red points show the result for the two low resolution boxes having twice the smoothing length of the high resolution box, blue is the same for $4\times$ smoothing length.



$P_\times(k)\times1000$
$r_\perp = 20.0\mathrm{Mpc}/h$
$r_\perp = 28.3\mathrm{Mpc}/h$
$r_\perp = 40.0\mathrm{Mpc}/h$
$r_\perp = 44.7\mathrm{Mpc}/h$
$r_\perp = 56.6\mathrm{Mpc}/h$
$r_\perp = 60.0\mathrm{Mpc}/h$
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
$k[h/\mathrm{Mpc}]$

Lyman Alpha Forest: what can it do?

- **Cosmological Constraints from Lyman-alpha power spectrum**



First Constraint from Ly-alpha forest to probe neutrino masses

Seljak et al. 2006

Lyman Alpha Forest: what can it do?

- **Cosmological constraints from Lyman-alpha power spectrum (with no BAO)**

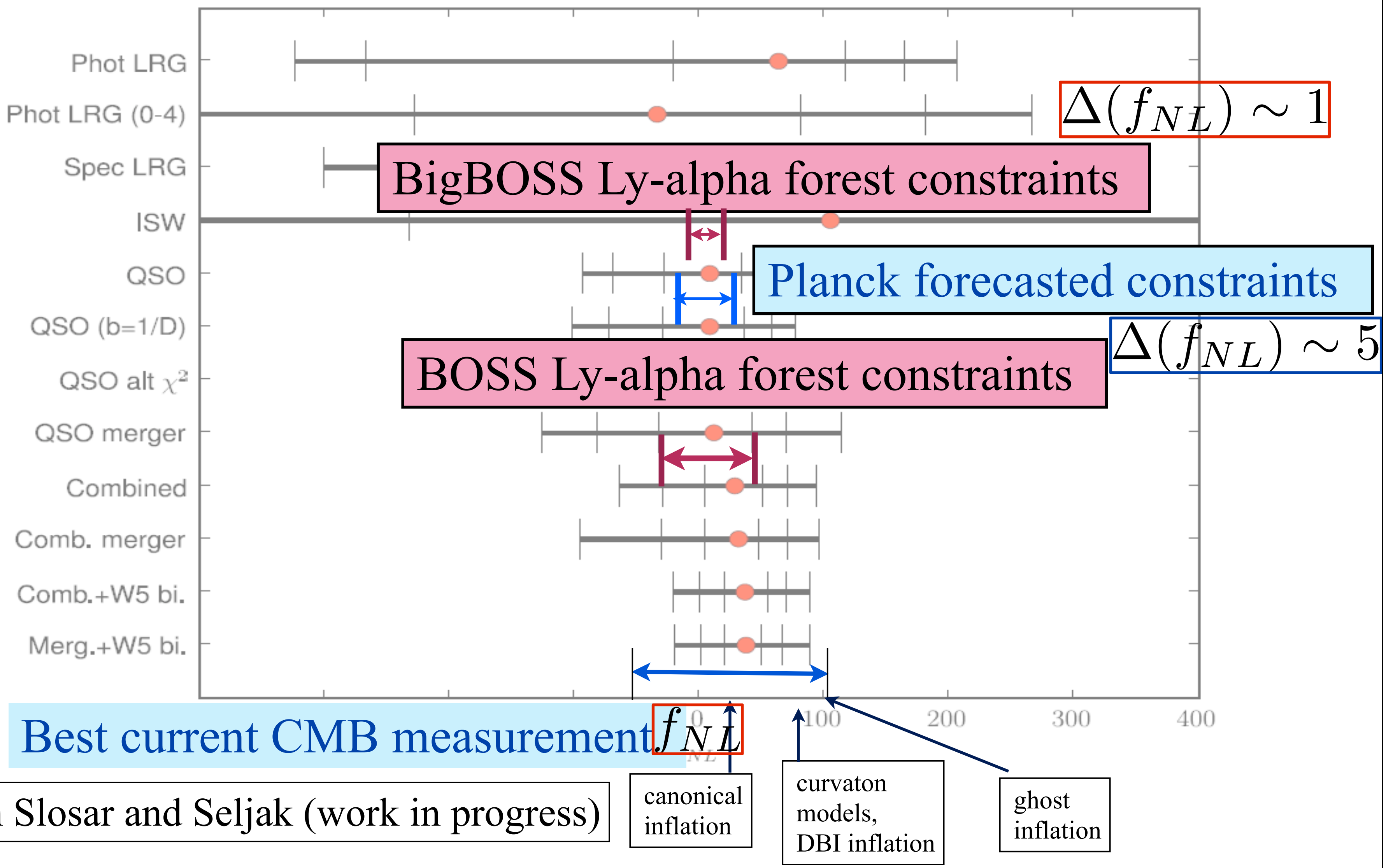
	Planck	Planck + BigBOSS Lya	Planck + BigBOSS Lya + Galaxies
$\sigma(\sum m_\nu)$	0.307	0.048	0.006
$\sigma(\Omega_K)$	0.011	0.0041	0.00038
$\sigma(n_s)$	0.0034	0.0023	0.001
$\sigma(dn_s/dln(k))$	0.003	0.0028	0.0005

Courtesy from Anze Slosar

Outline

- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - —Baryon Acoustic Oscillations -> Dark Energy
  - —Lyman-alpha power spectrum
  - —Non-gaussianities in Early Universe
- Conclusion

Lyman Alpha Forest: what can it do?
—Non-gaussianities in Early Universe



with Slosar and Seljak (work in progress)

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Lyman Alpha Forest: what can it do?

- **Simulation boxes of Dark matter**
- 3000^3 particles

  3000^3 mesh

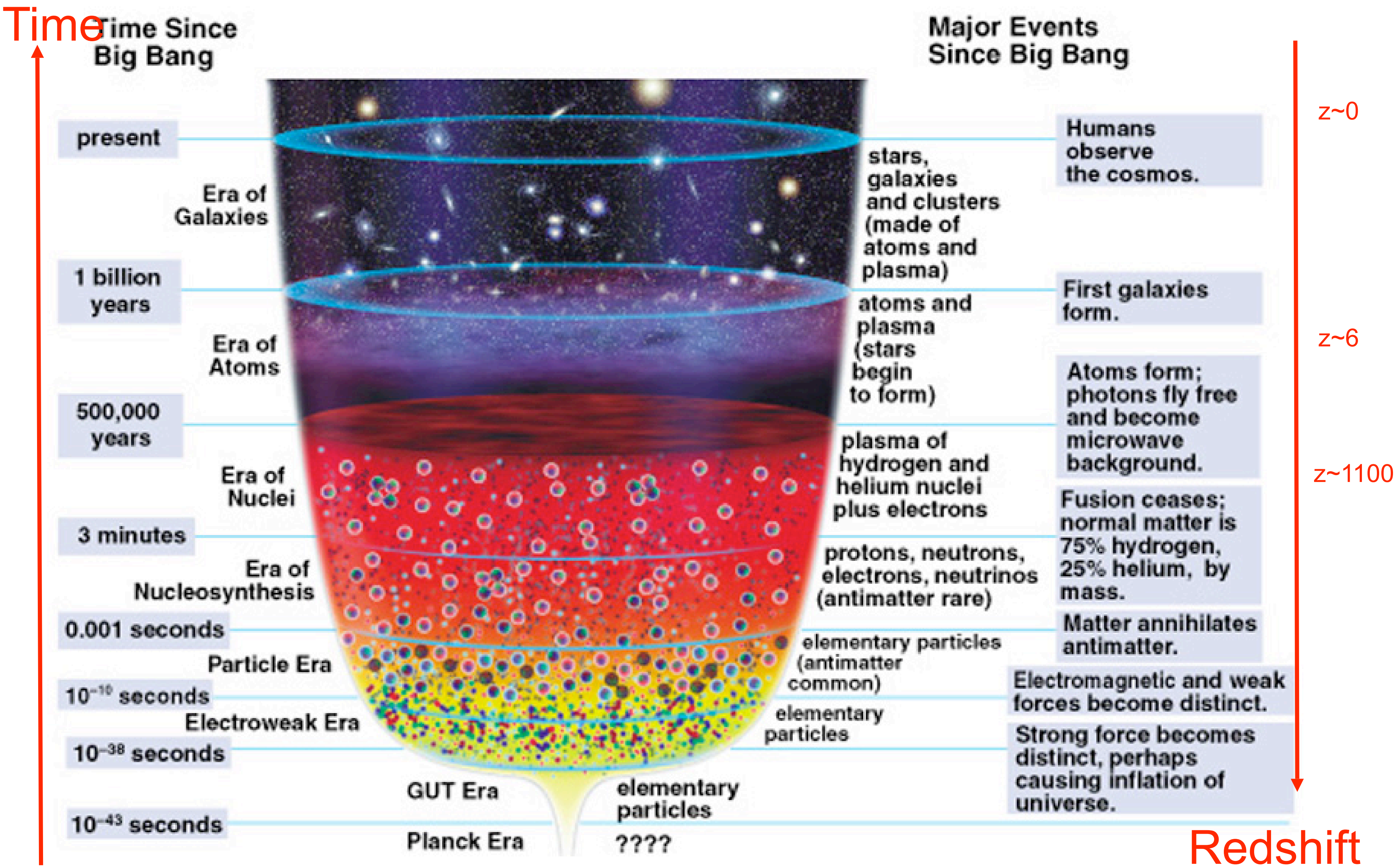
  $1500\ (h^{-1}Mpc)^3$ on the side

  $\Omega_m = 0.25,\ \Omega_\Lambda = 0.75,\ \mathrm{h} = 0.75,\ \mathrm{n} = 0.97,\ \sigma_8 = 0.8$

  Fluctuating Gunn Peterson approximation

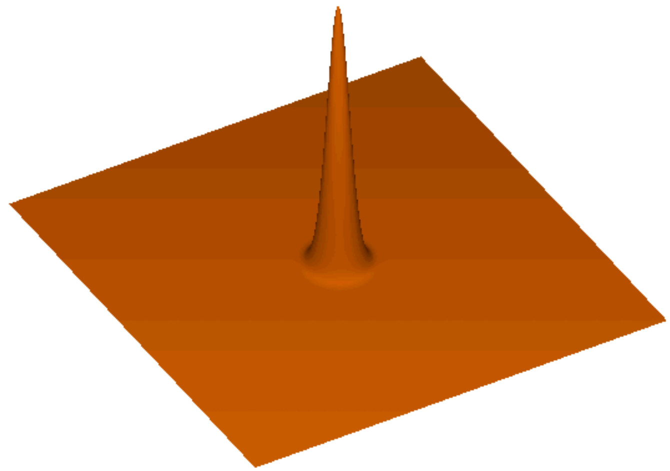
  Peculiar velocities included

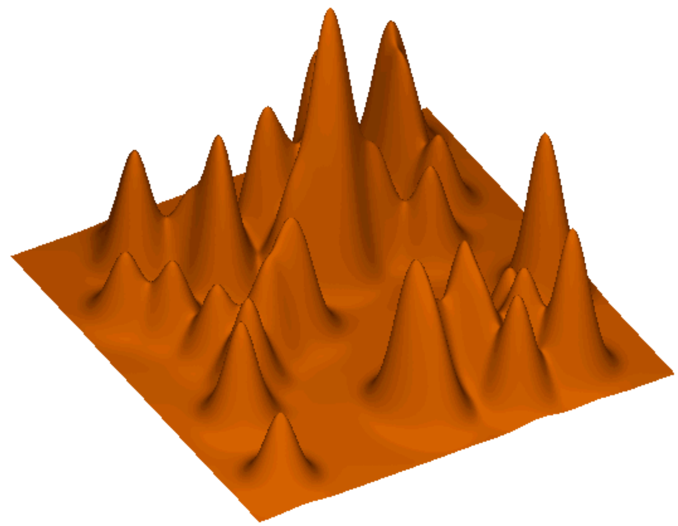
Motivations



What are these Sound Waves?

- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at ~half of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies.





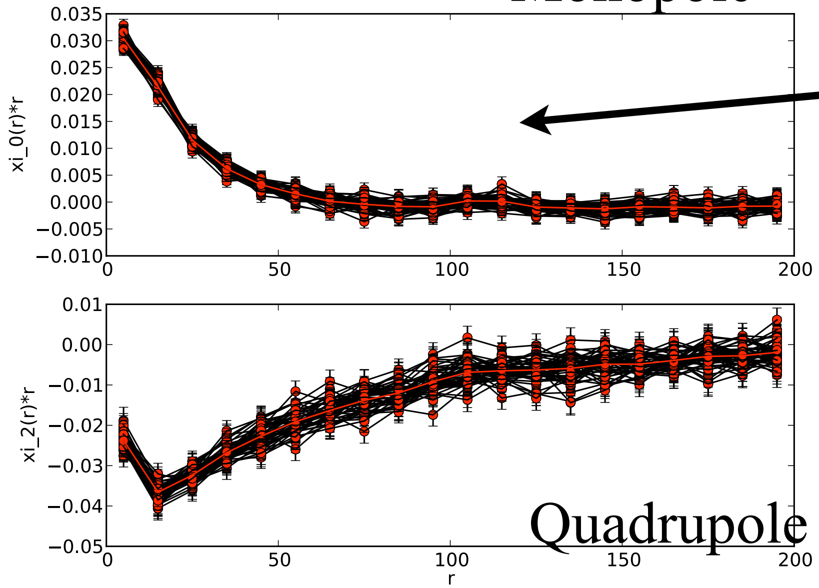
Courtesy slide from Daniel Eisenstein

Recall? Modeling z-space distortions

Simulations

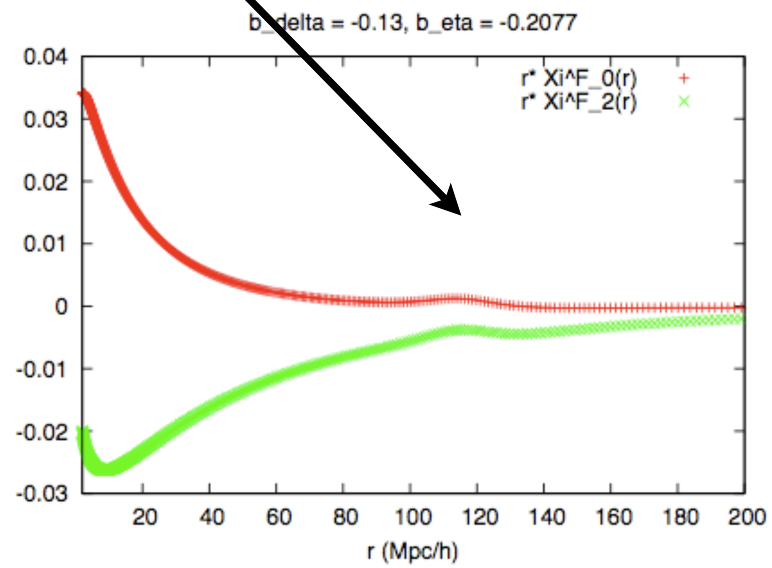
Recall that we are looking for an enhancement of power at ~110 Mpc/h?

Monopole



Quadrupole

Predictions



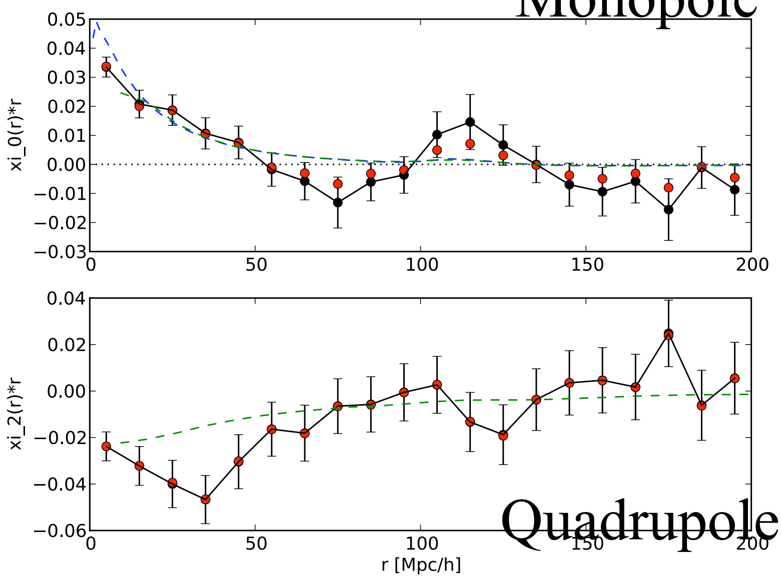
The large scale correlation functions from simulations of Lyman alpha fores

SH, Slosar & White (in prep)

Recall? Modeling z-space distortions

DATA

Monopole



Quadrupole

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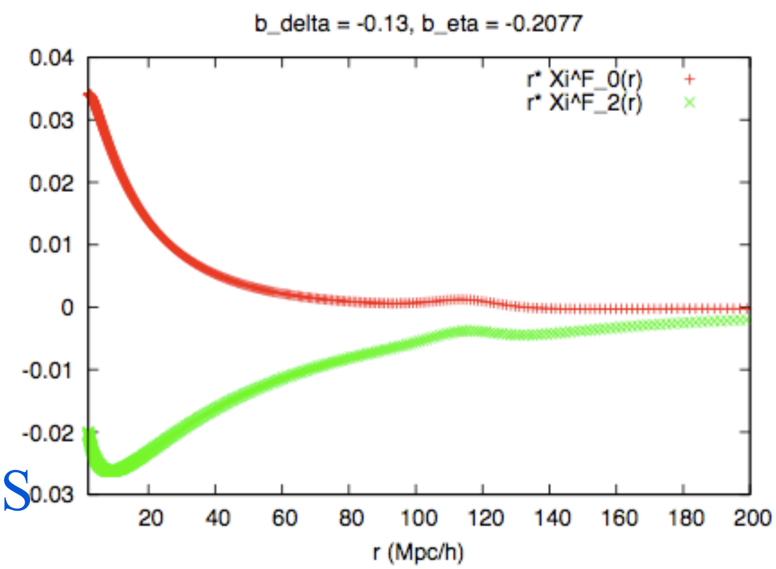
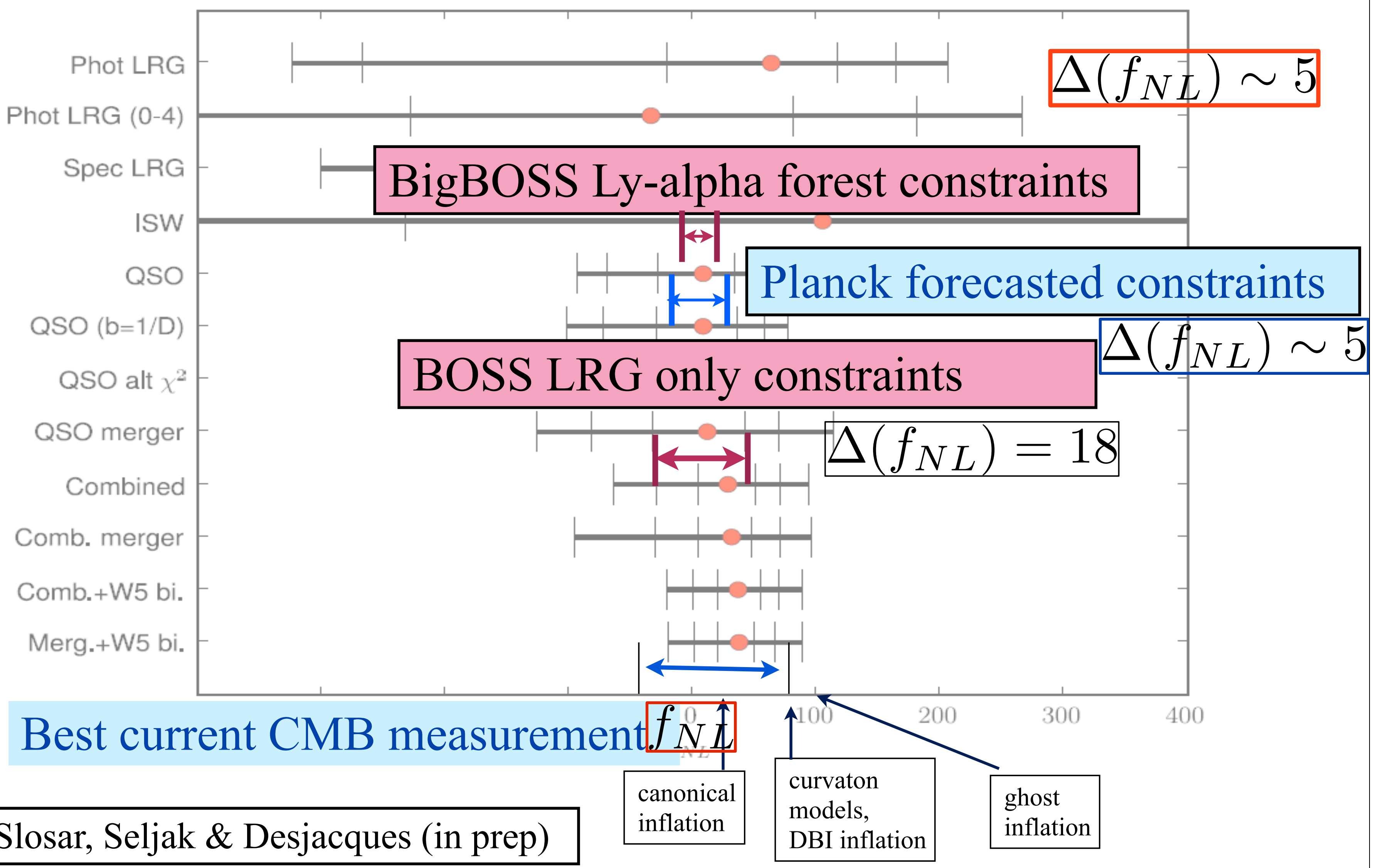
Predictions



The large scale correlation functions from 5% of Lyman alpha forest in BOSS

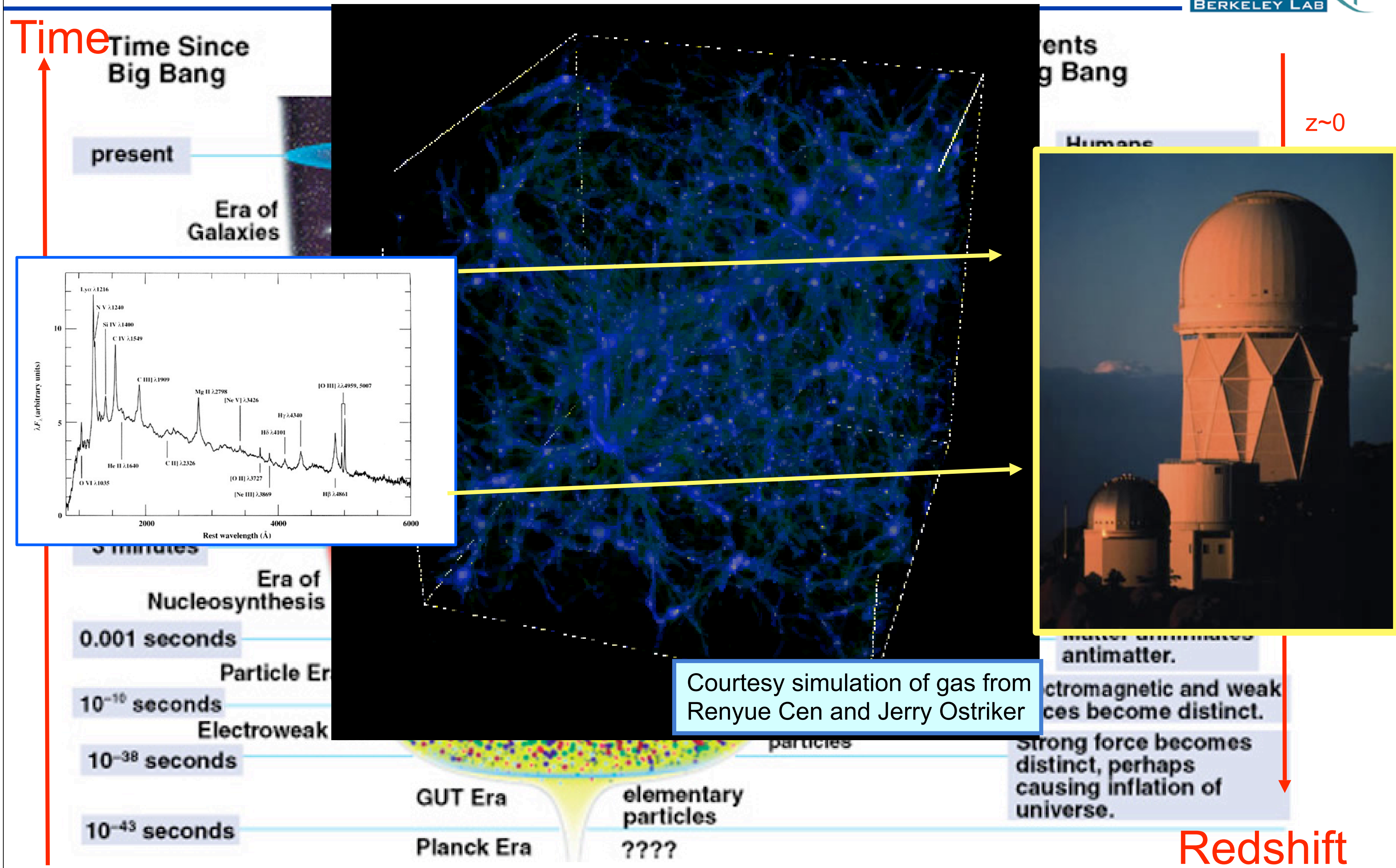
SH, Slosar & White (in prep)

What can we do with Lya and fnl?
—Non-gaussianities in Early Universe

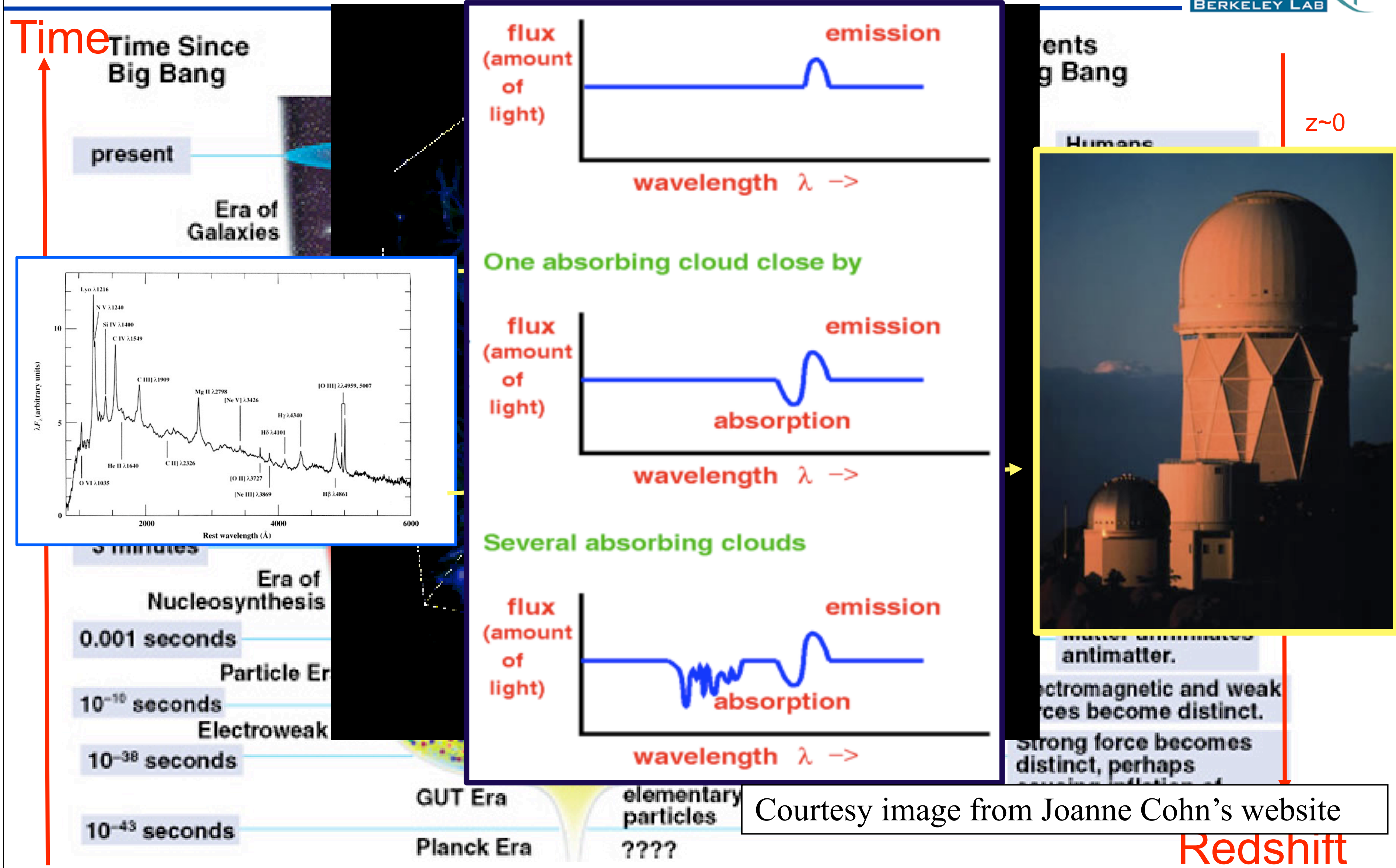


Ho, Slosar, Seljak & Desjacques (in prep)

Lyman Alpha Forest: what is it?



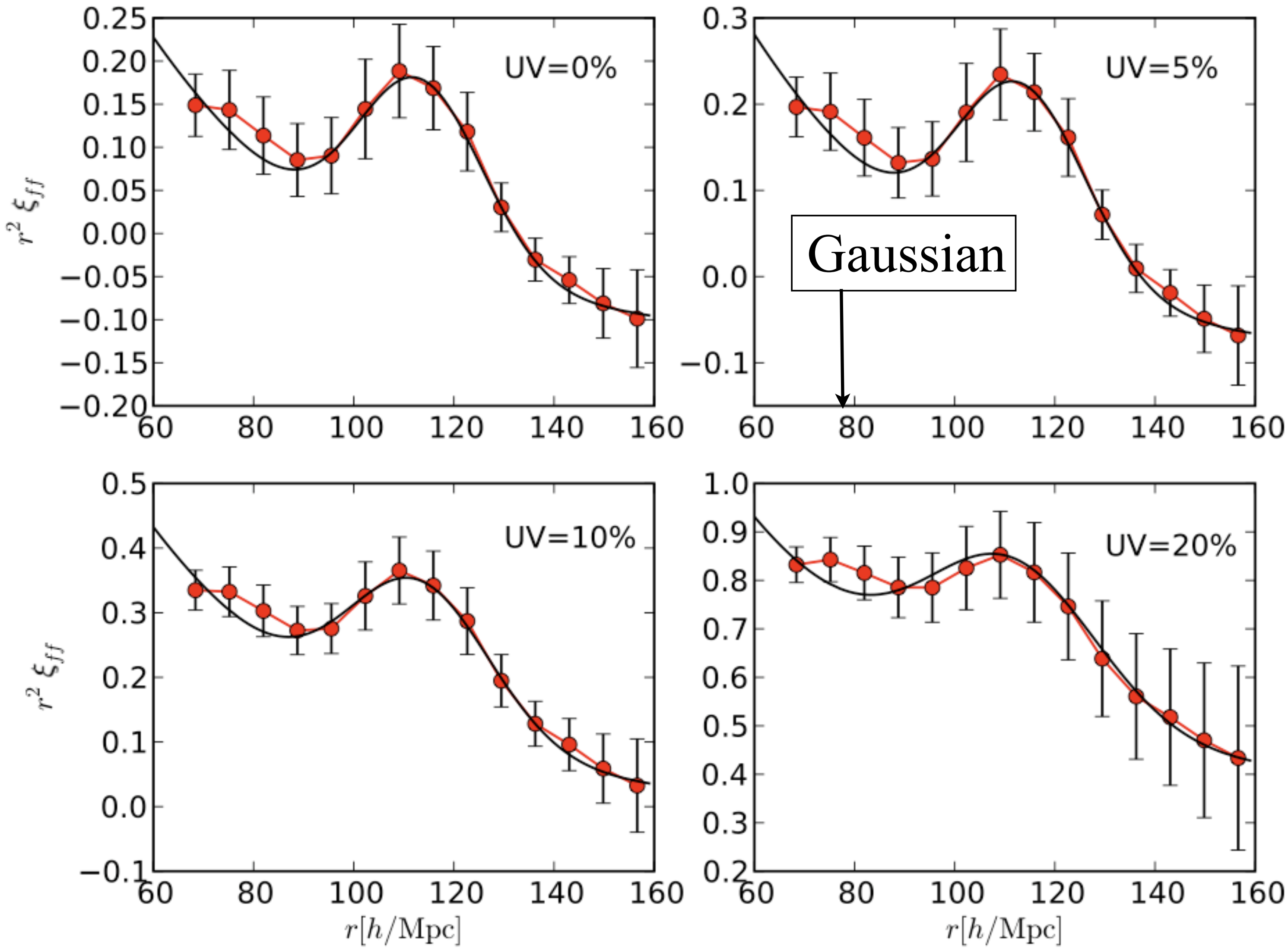
Lyman Alpha Forest: what is it?



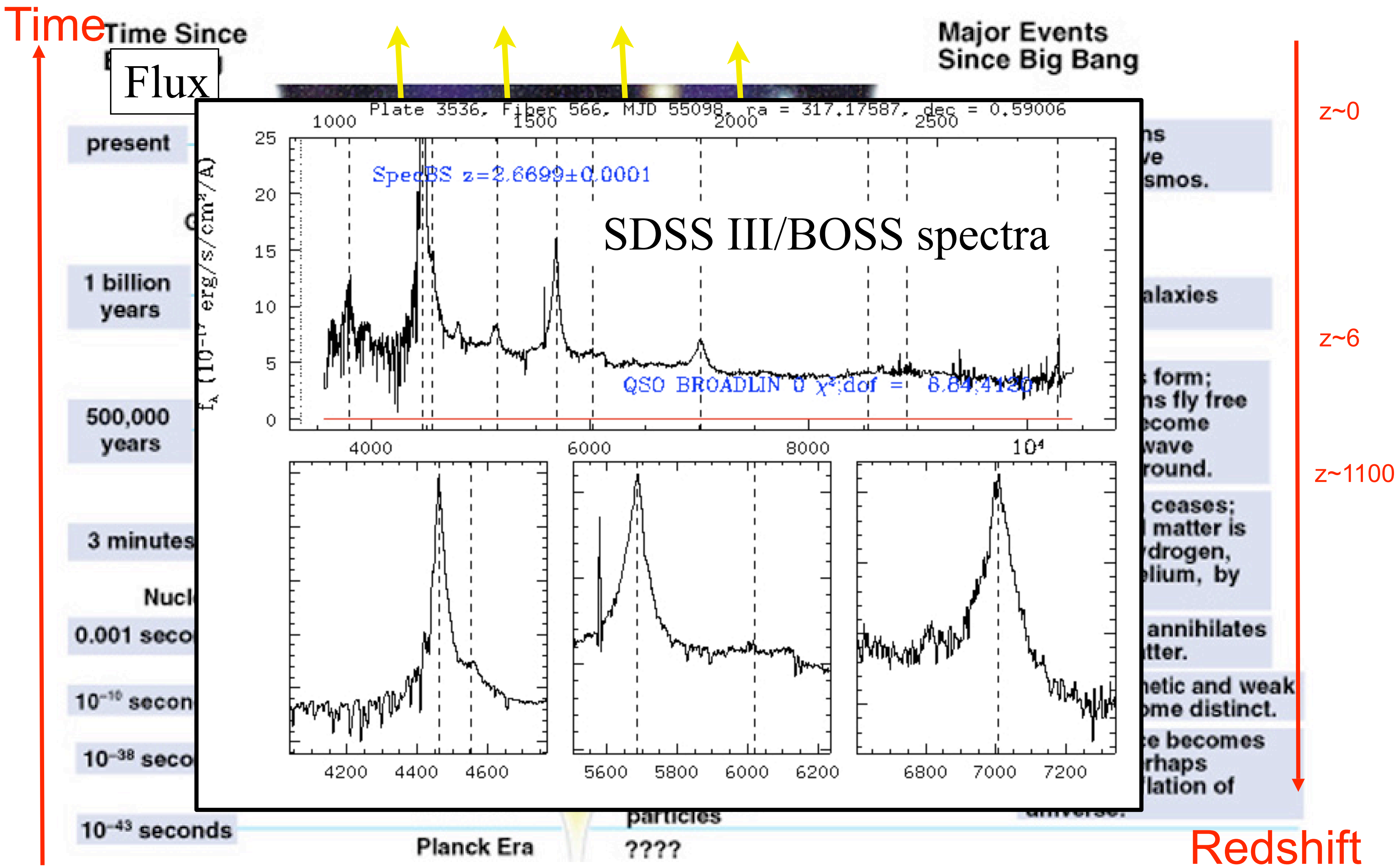
Courtesy image from Joanne Cohn's website

Beyond: With Lyman Alpha Forest

Possible systematics: UV background fluctuations

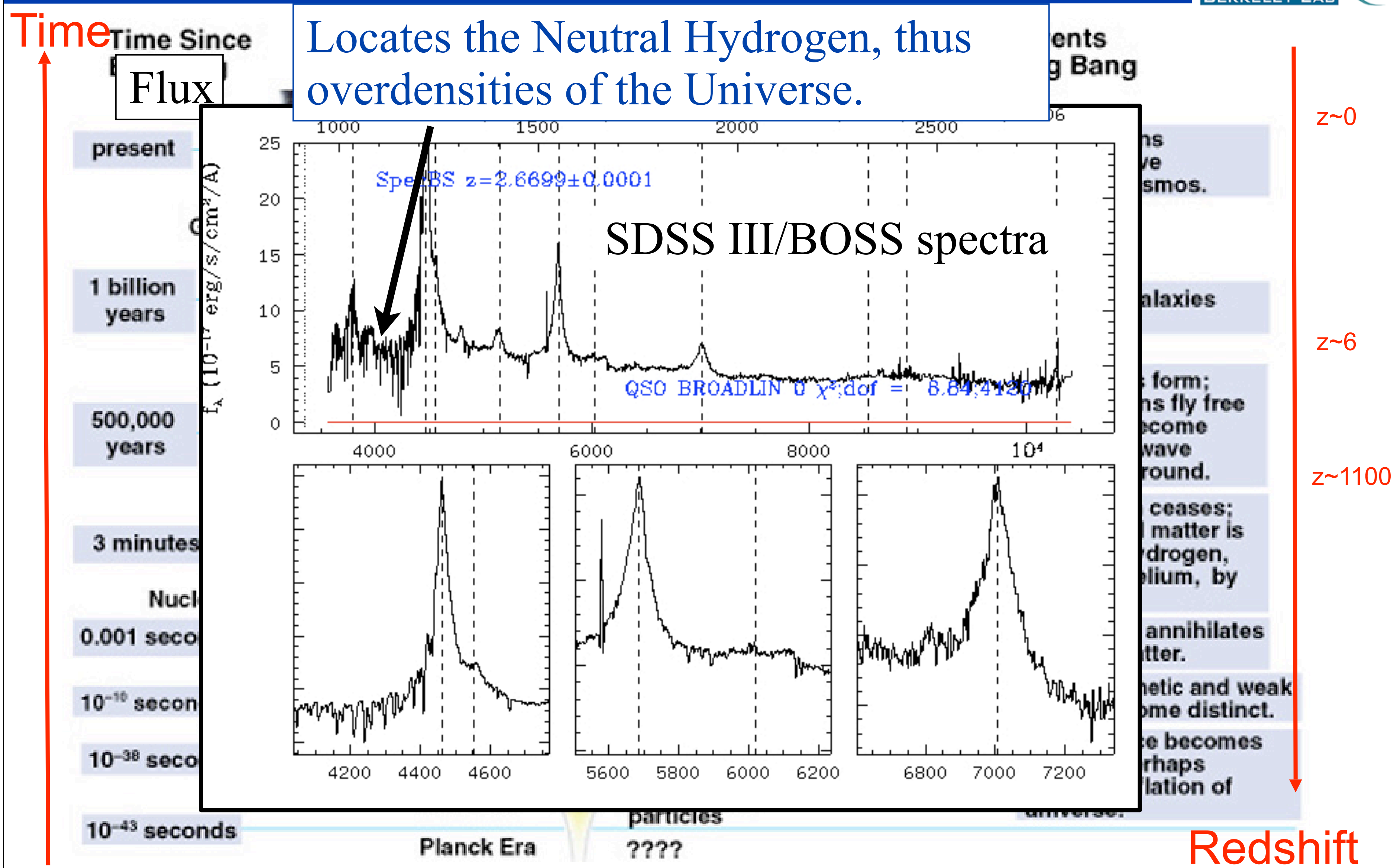


Lyman Alpha Forest: what is it?



Lyman Alpha Forest: what is it?

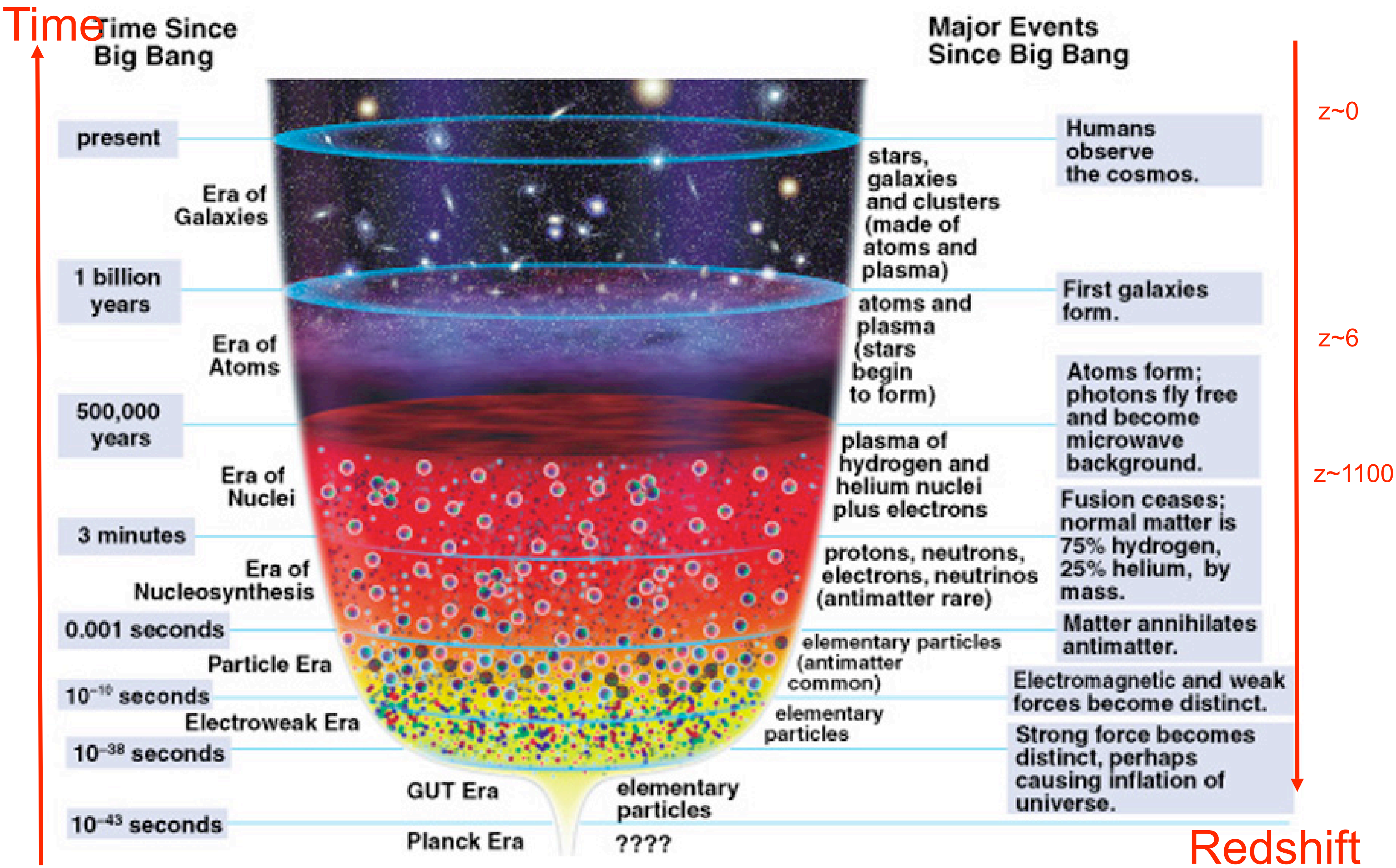
Locates the Neutral Hydrogen, thus overdensities of the Universe.



Outline

- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - —Baryon Acoustic Oscillations
    - Dark Energy
  - —Scale Dependent Bias
    - Primordial Non-gaussianities (f_nl)
- Conclusion

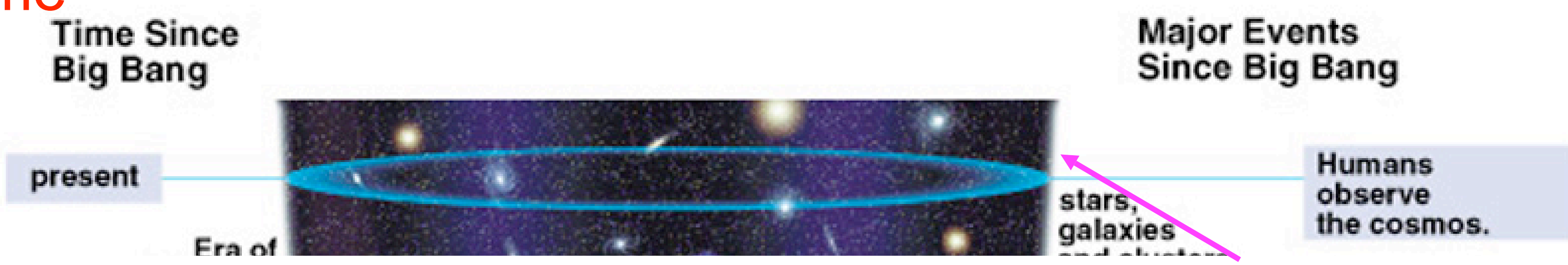
Motivations



Motivations

Berkeley Lab

Time



Gravity +
observing movement of
local galaxies ->
"Dark Matter"

z~0

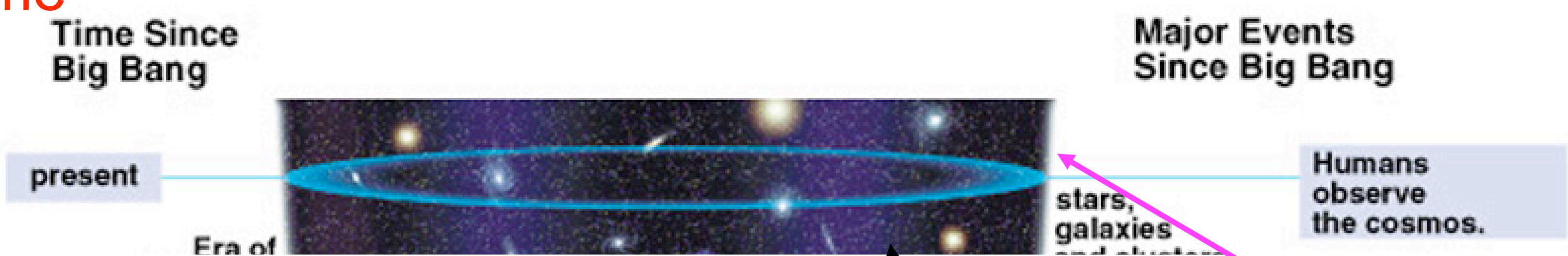
z~6

z~1100

Redshift

Motivations

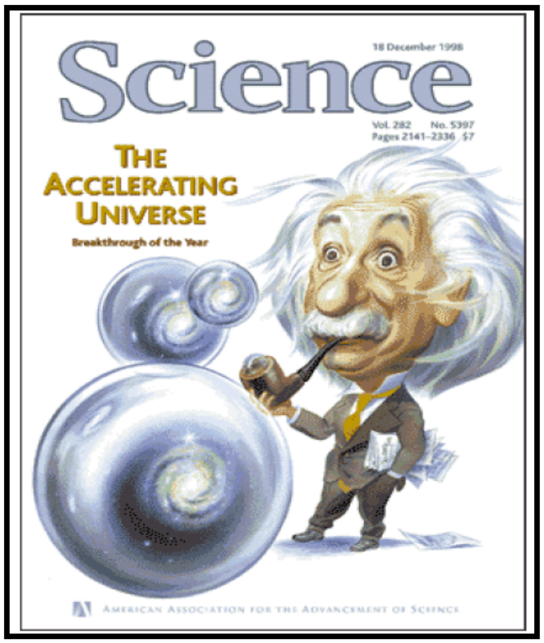
Time



z~0

Gravity +
observing movement of
local galaxies ->
"Dark Matter"

z~6



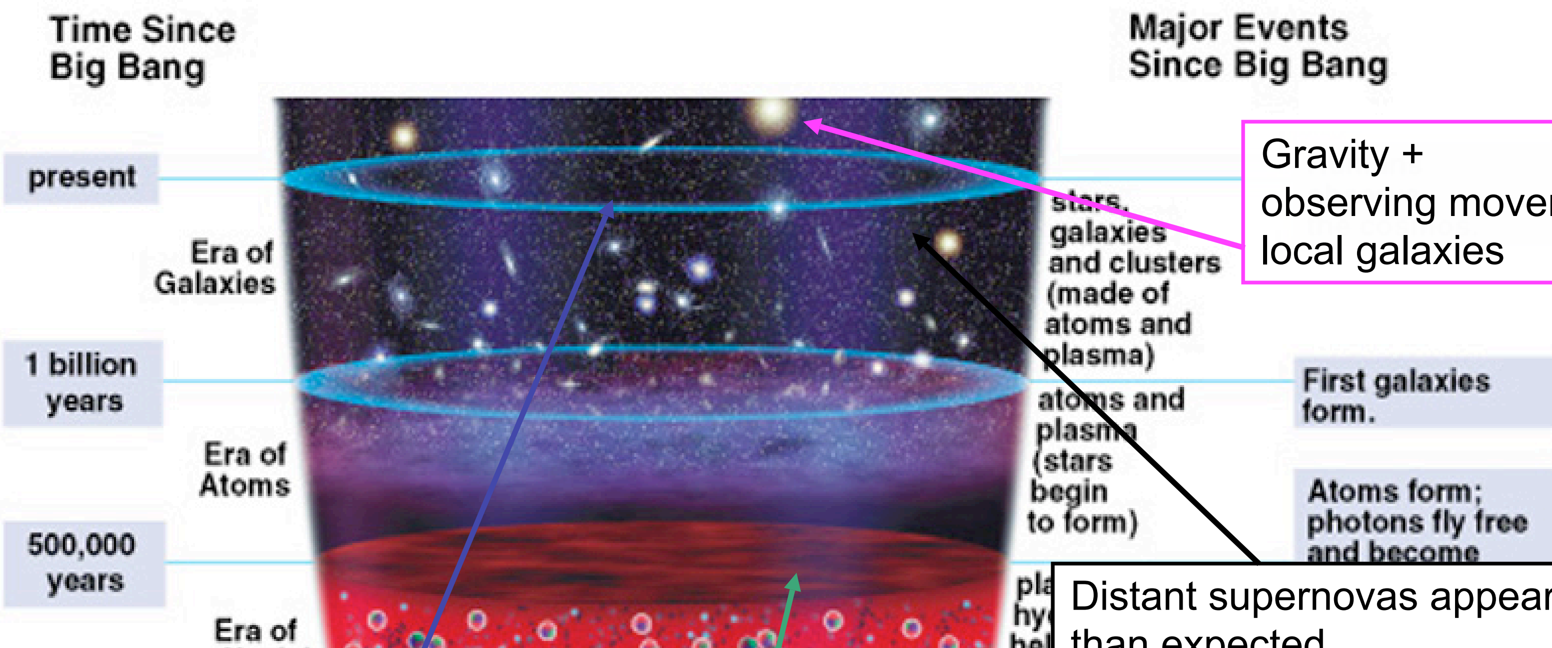
Distant supernovas appear fainter than expected (1998)->
Universe is accelerating ->
Cosmological Constant?
Dark Energy?

z~1100

Redshift

Motivations

Time



z~0

Gravity +
observing movement of
local galaxies

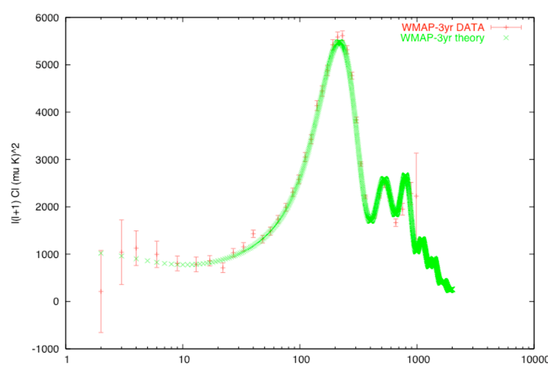
z~6

~1100

Distant supernovas appear fainter than expected

Observations of how galaxies cluster

Observations of
Cosmic Microwave Background (CMB)
-> angular powerspectrum of
temperature anisotropies



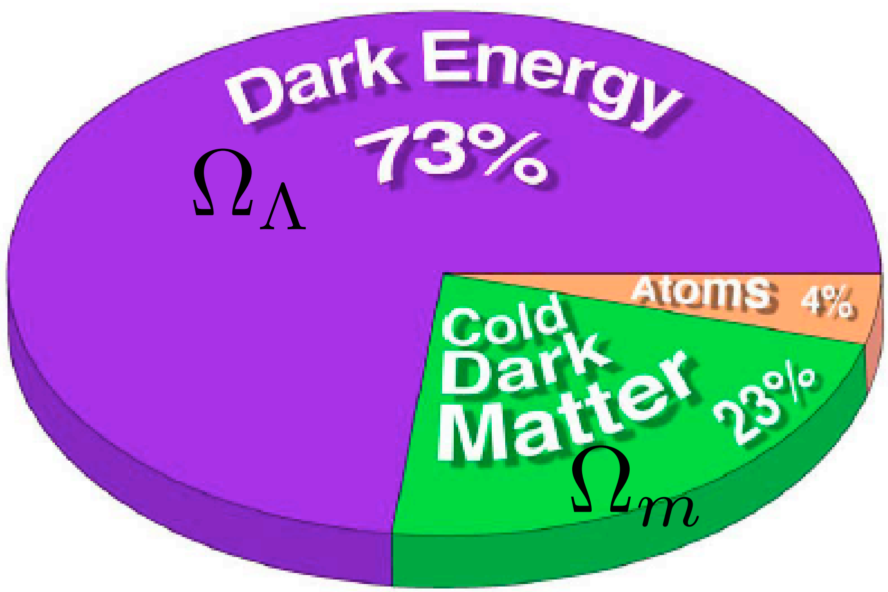
Redshift

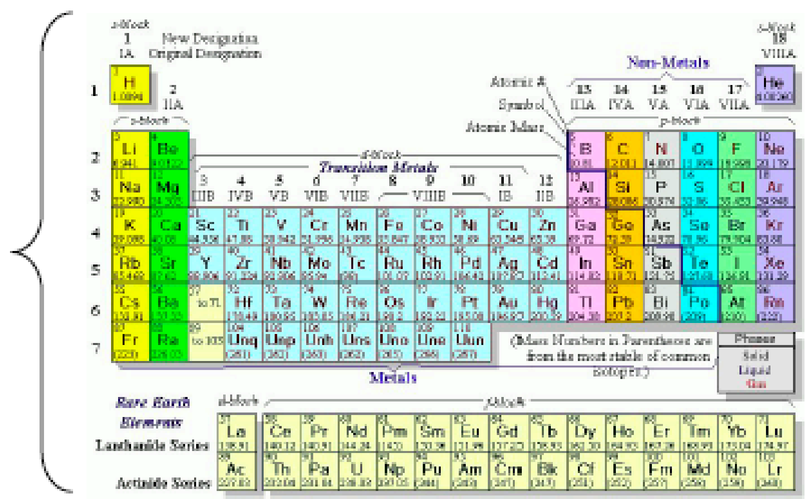
Motivations

Time

z~0

Gravity +
observing movement of

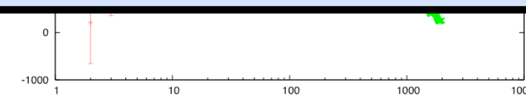




100

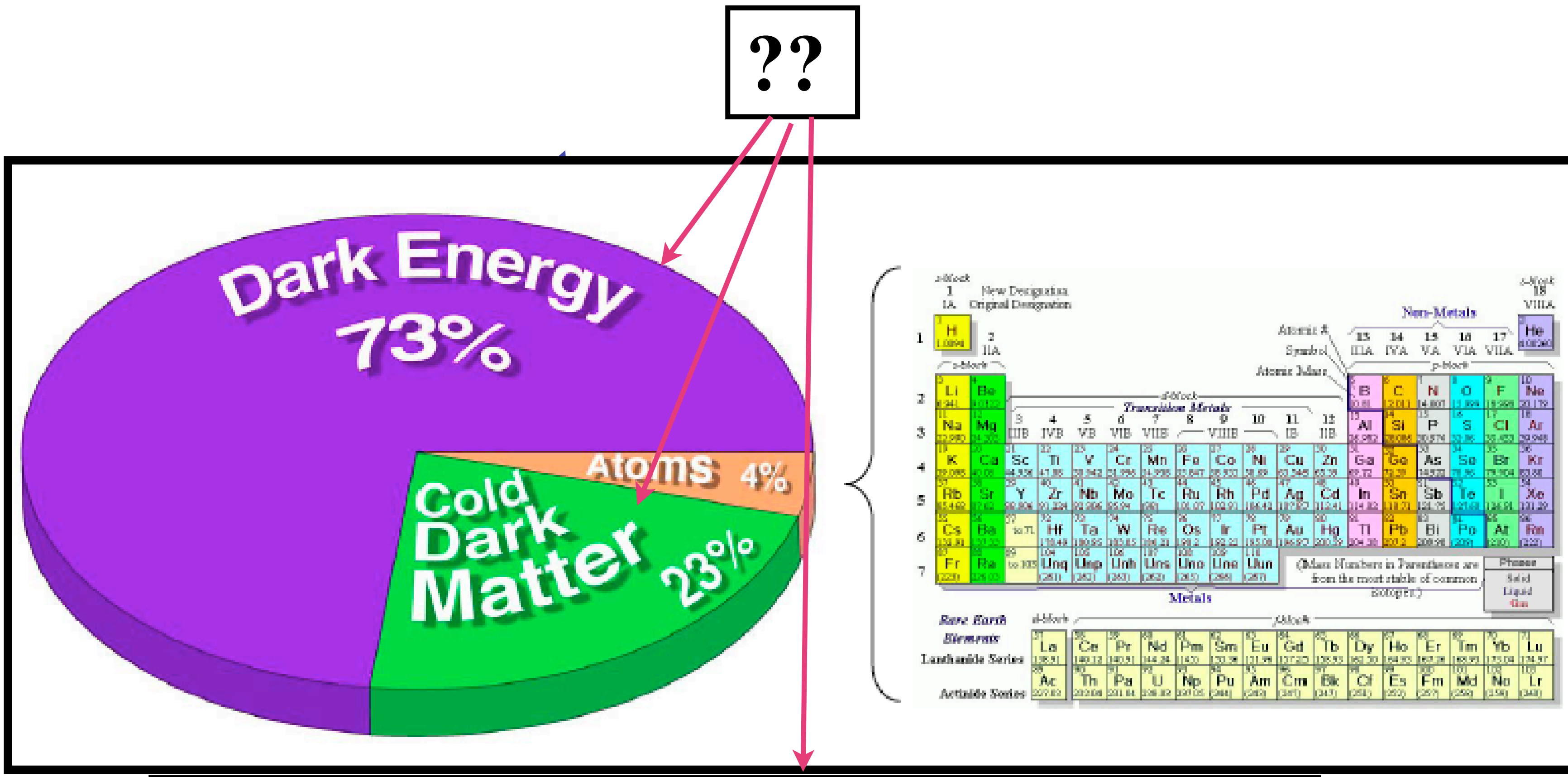
What happened at the Beginning of the Universe?

-> angular powerspectrum of
temperature anisotropies



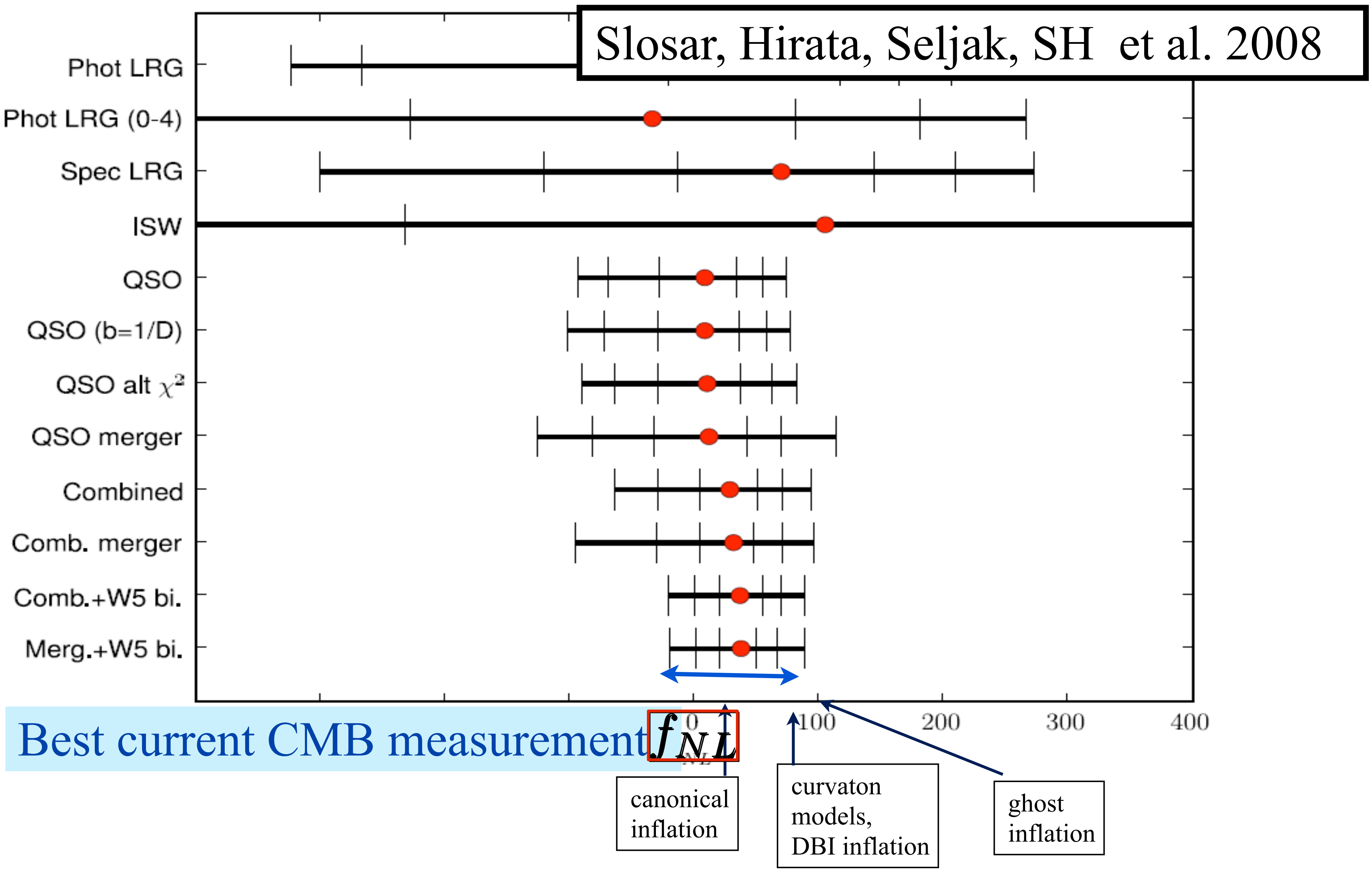
Redshift

Motivations



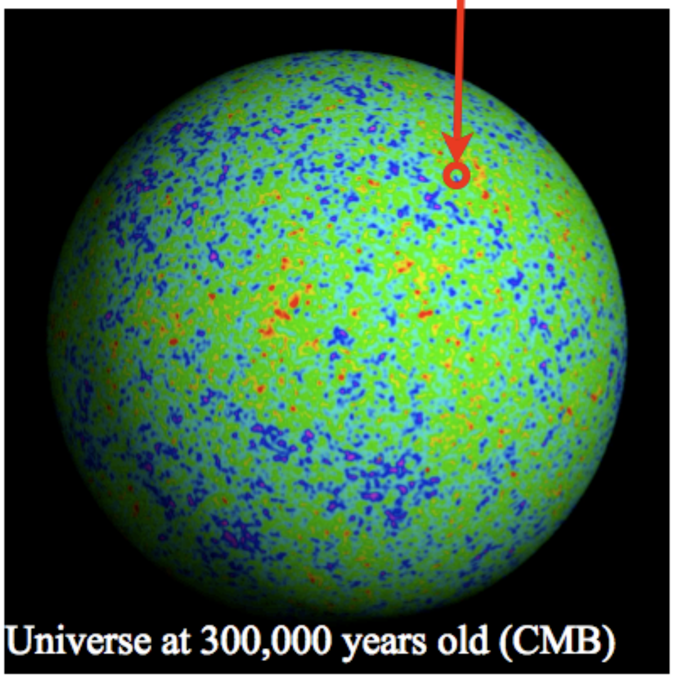
What happened at the Beginning of the Universe?

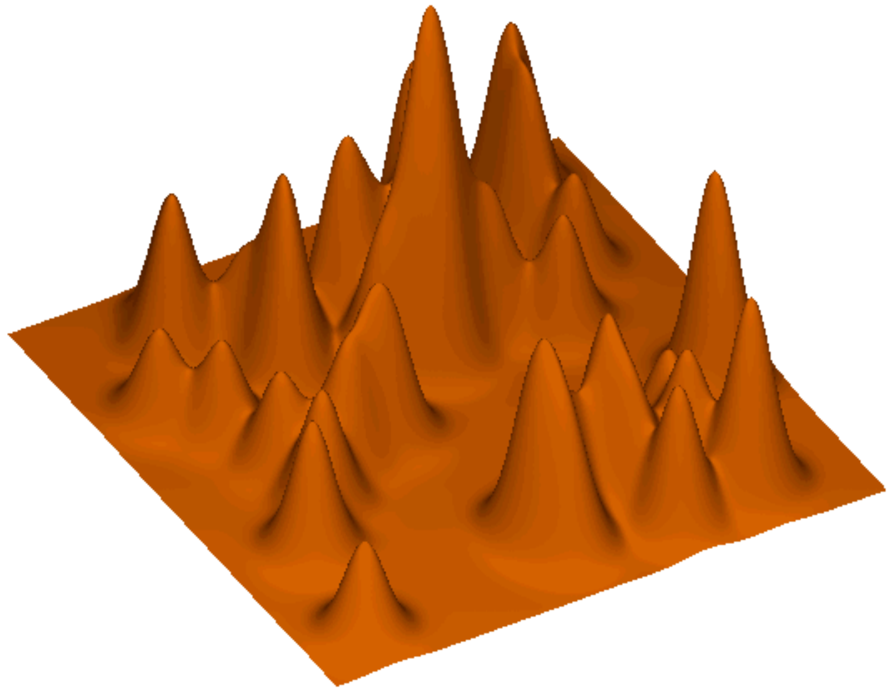
Lyman Alpha Forest: what can it do?
—Non-gaussianities in Early Universe



What are the Baryon Acoustic Oscillations?

What are baryon acoustic oscillations (BAO)?



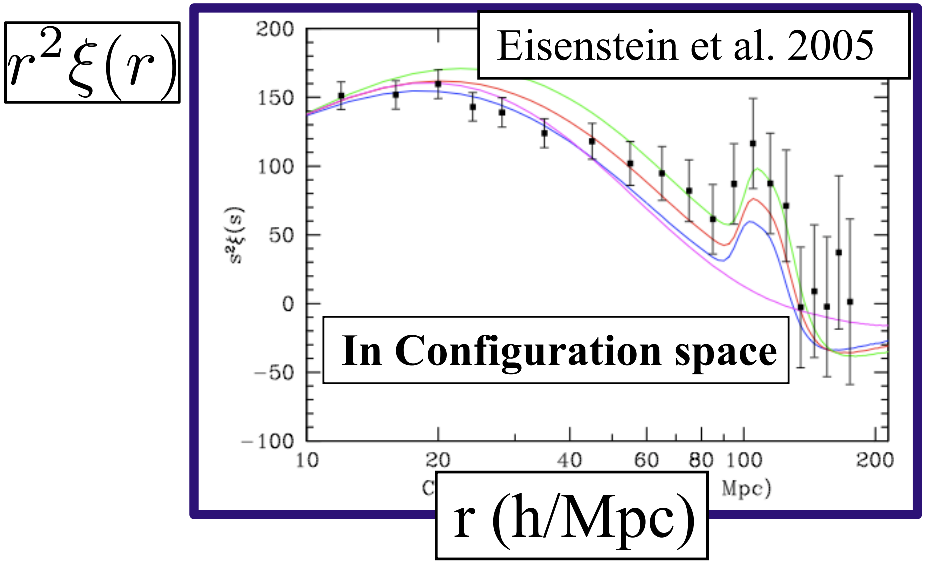


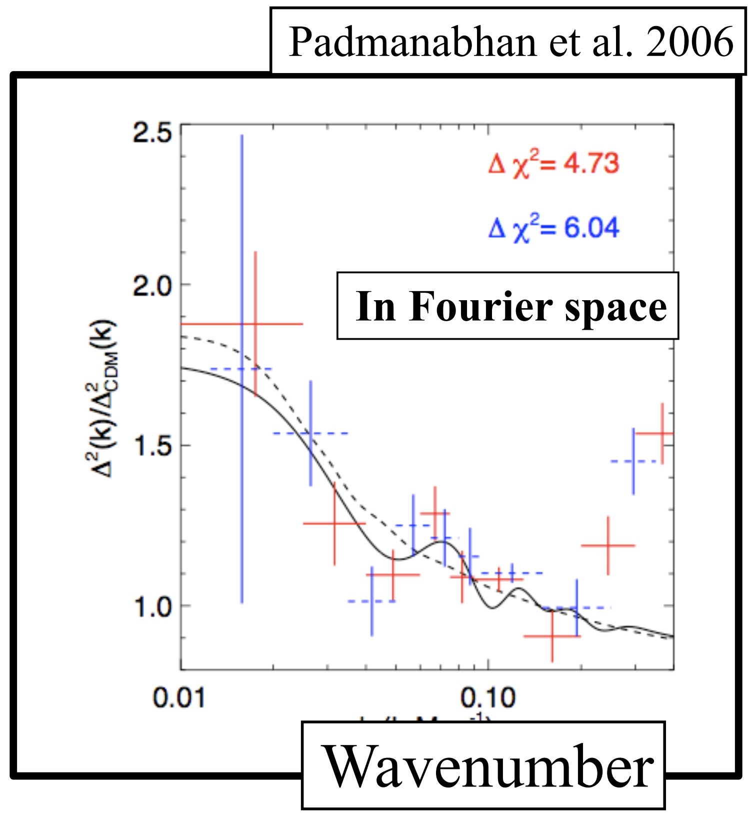
This sound wave can be used as a "standard ruler"

Dark energy changes this apparent ruler size

Courtesy slide from David Schlegel and animation from Daniel Eisenstein

First detections of BAO

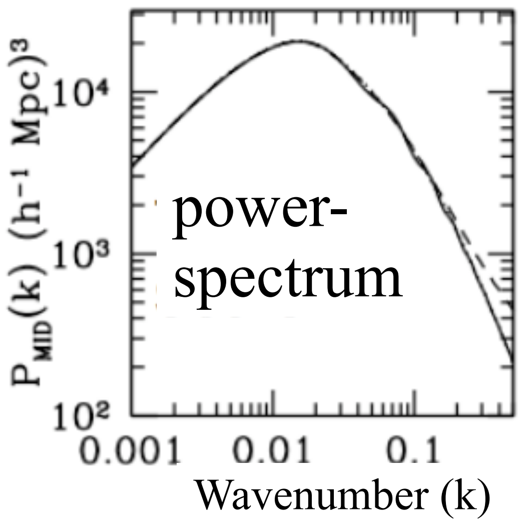




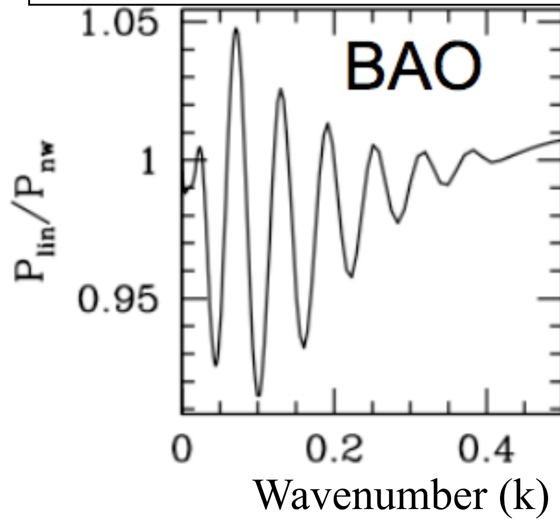
Outline

- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - —Baryon Acoustic Oscillations -> Dark Energy
  - —Lyman-alpha power spectrum
  - —Non-gaussianities in Early Universe
- Conclusion

Predicted signals of BAO

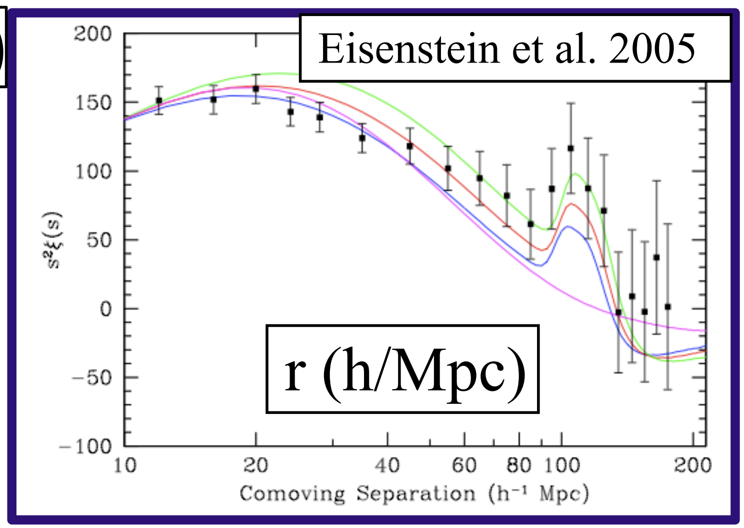


power-spectrum with smoothed part divided out



Fourier space

$r^2\xi(r)$



Configuration space

BAO: with Luminous Red Galaxies
Physics of Angular Clustering

$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$ describe how matter cluster (matter powerspectrum, describes the rms fluctuations)

Galaxy angular power-spectrum

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(dN/dz)^2 D^2(z) P(\frac{l+\frac{1}{2}}{\chi})$$

Galaxy Angular power-spectrum contains a wealth of cosmological information ranging from

a) What is **dark energy**? to

b) What happened at the very early Universe? Inflation? What kind?

BAO: with Luminous Red Galaxies
Systematics: Dust

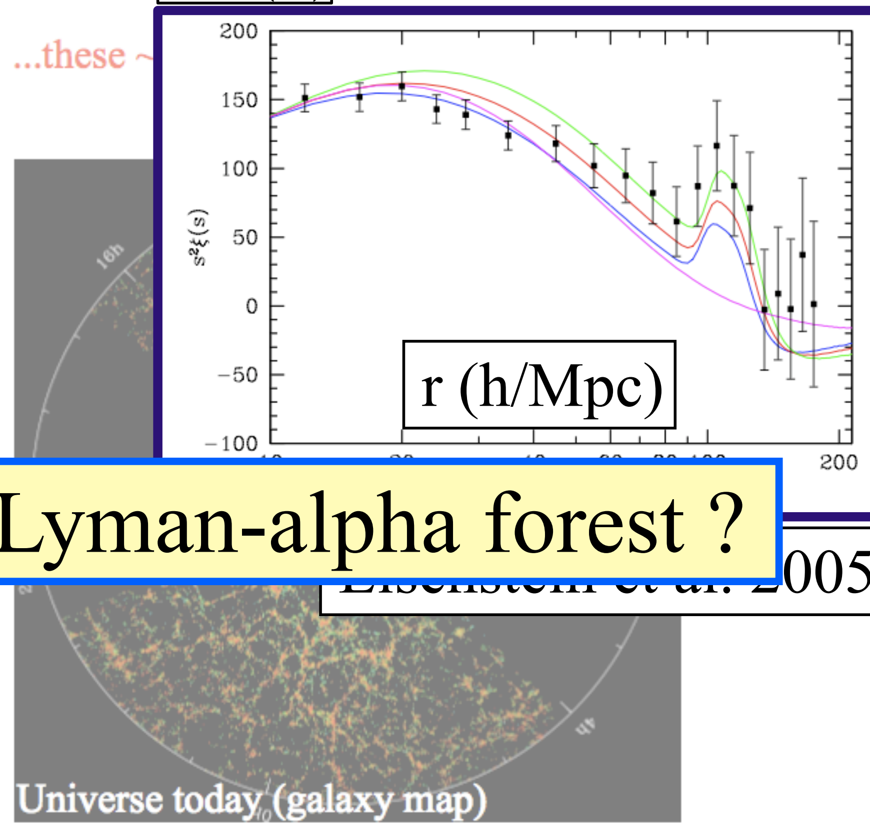
- As pointed out by Schlafly, Finkbeiner et al (2010), there is a normalization difference in galactic north and south of ~15%. There is also reddening factor overestimates by factor ~1.4.
- These all possibly contribute to extra power in galaxy power-spectra

Lyman Alpha Forest: what can it do?

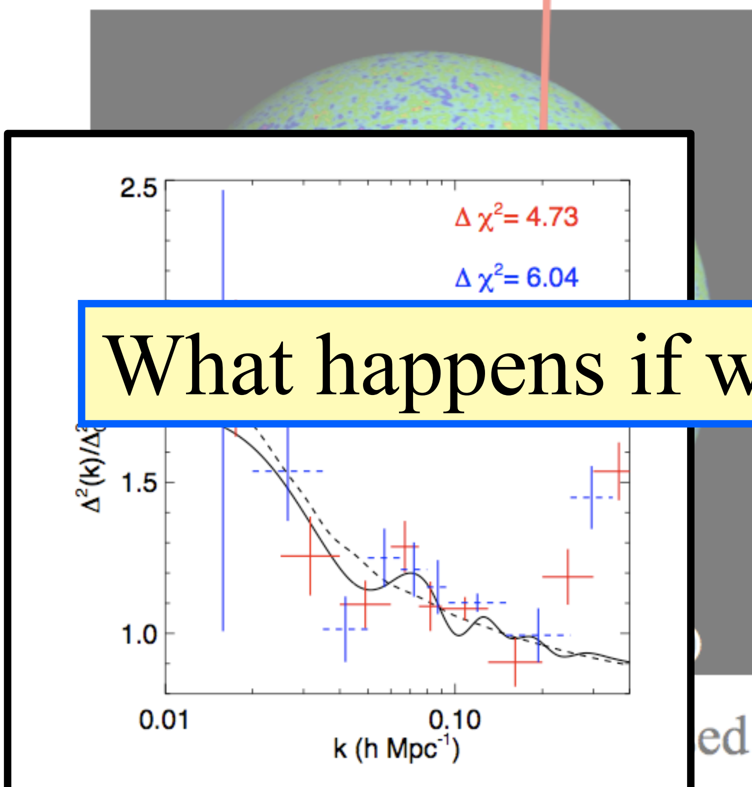
What are baryon acoustic oscillations (BAO)? $r^2\xi(r)$

These fluctuations of 1 part in 10^5 gravitationally grow into...

...these ~



Eisenstein et al. 2005



Padmanabhan et al. 2006

What happens if we use Lyman-alpha forest ?

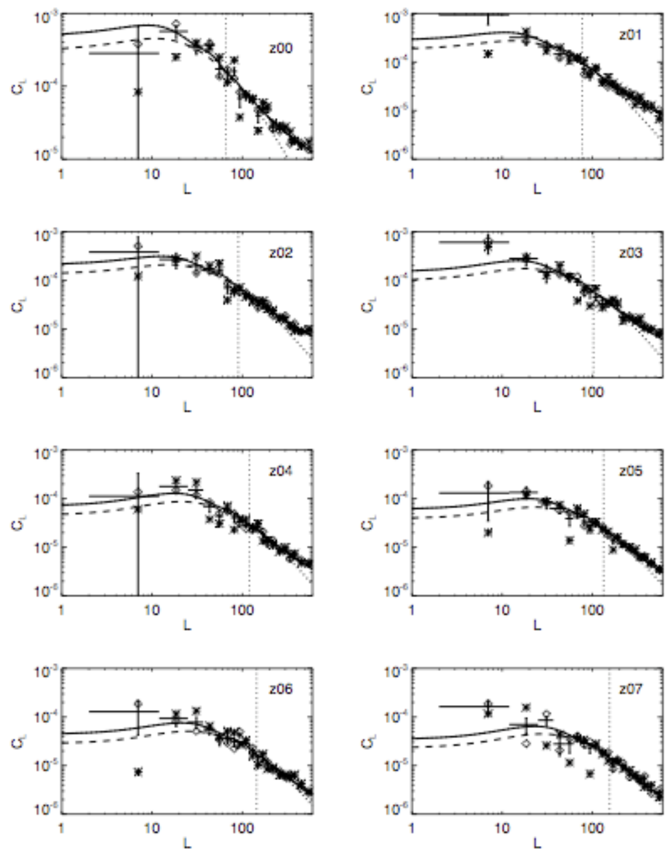
...ed as a "standard ruler"

...apparent ruler size

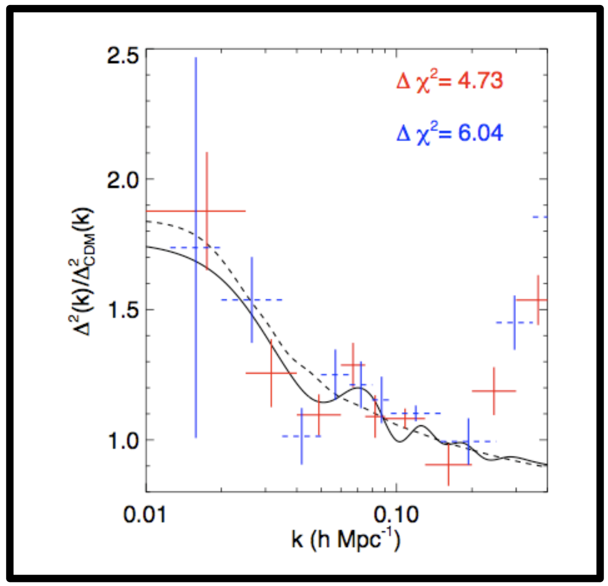
Courtesy slide from David Schlegel

How do you detect BAO with photometric data?

Angular power-spectrum
with 3500 sq deg of SDSS I/II imaging



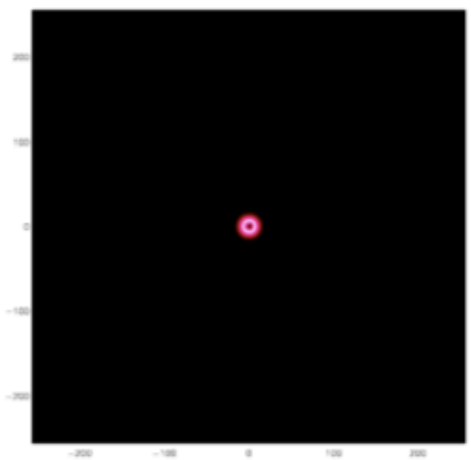
Reconstructed Galaxy power-spectrum
with ~2.6 sigma 'detection' of BAO



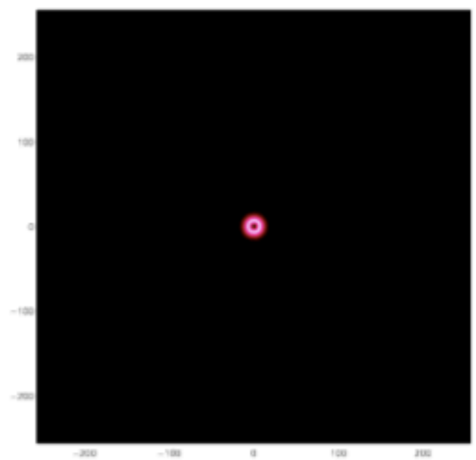
Padmanabhan et al. 2006

What are the Baryon Acoustic Oscillations?

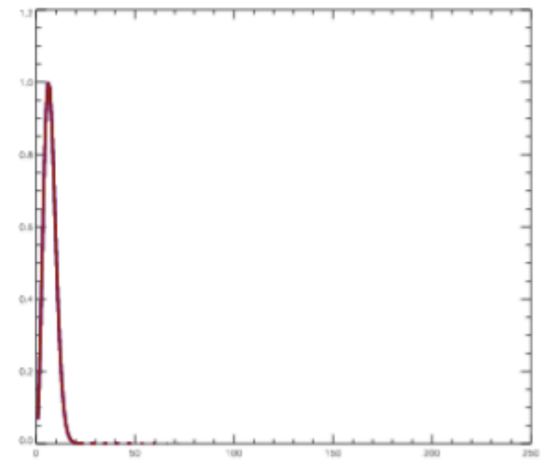
- We start with single perturbation and the plasma is totally uniform except for an excess of matter at the origin
- High pressure drives the gas+photon fluid outwards approaching speed of light.



Baryons



Photons

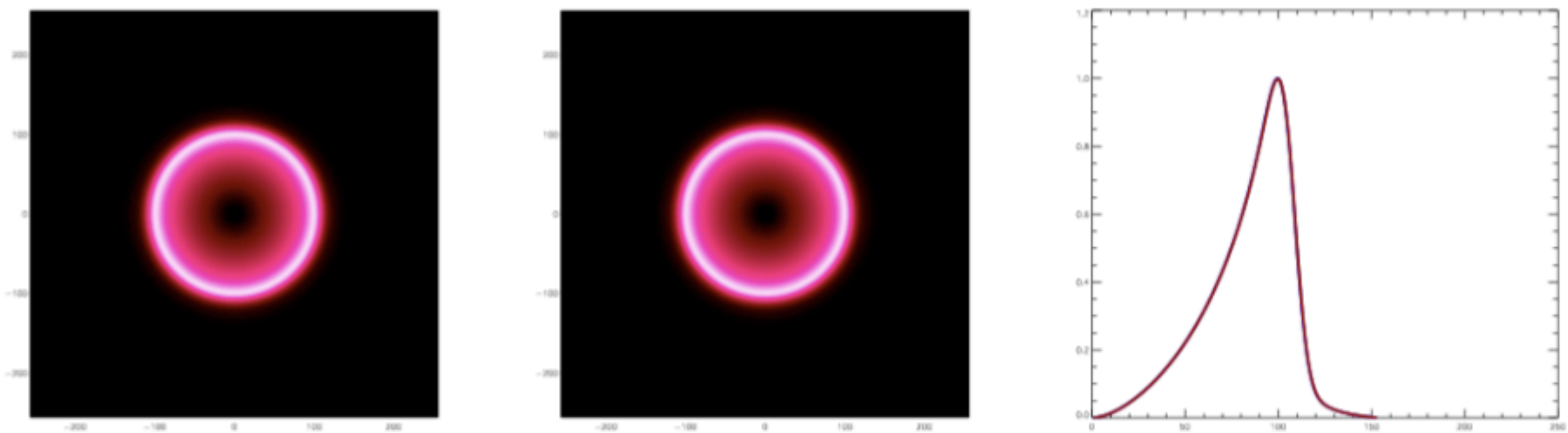


Mass profile

Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

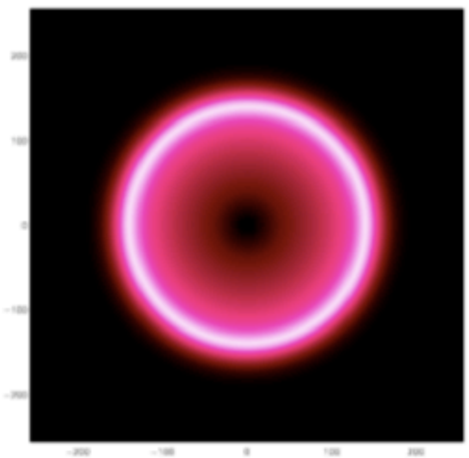
- **This expansion continues for 100,000 years.**

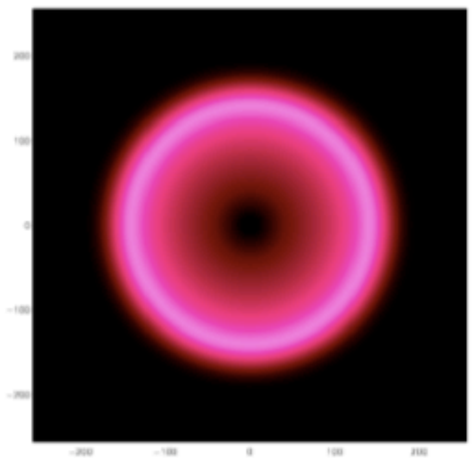


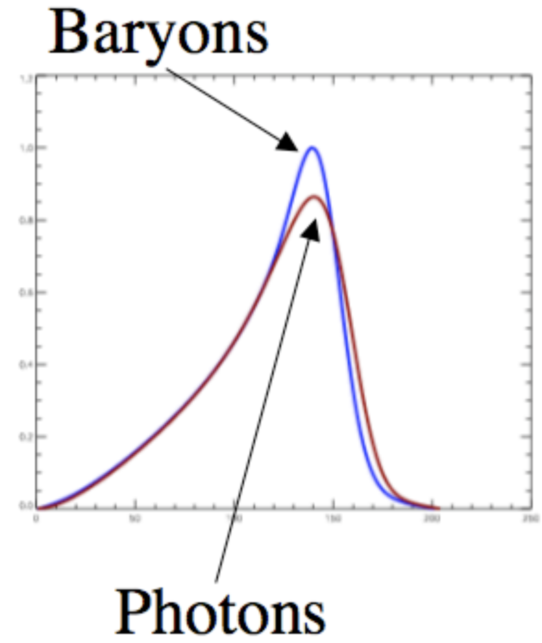
Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

- After 100,000 years, the Universe is cool enough that protons capture electrons to form neutral hydrogen
- This decouples the photons from the baryons. The photons quickly streamed away, leaving baryon peak stalled.



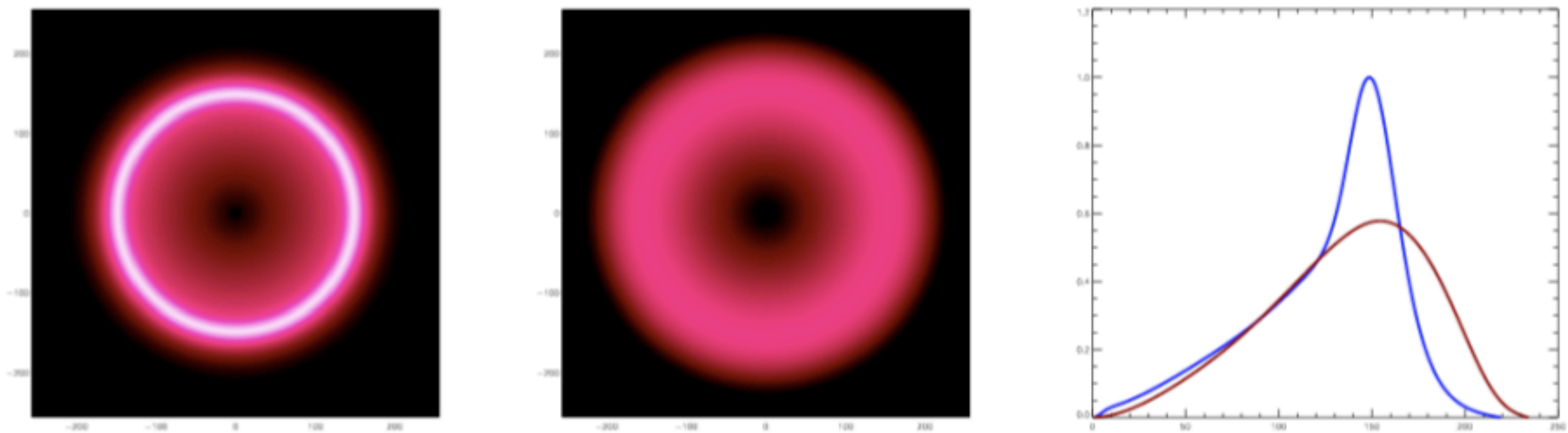




Eisenstein, Seo and White (2006)

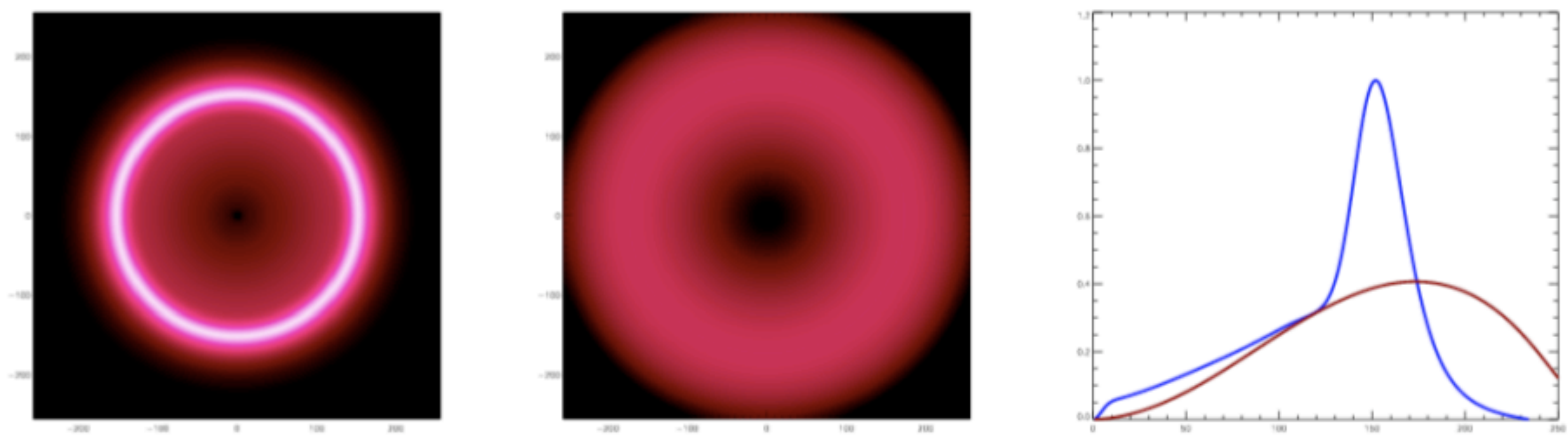
What are the Baryon Acoustic Oscillations?

- The photons continue to stream away, while baryons, having lost the motive pressure, remain in place.



Eisenstein, Seo and White (2006)

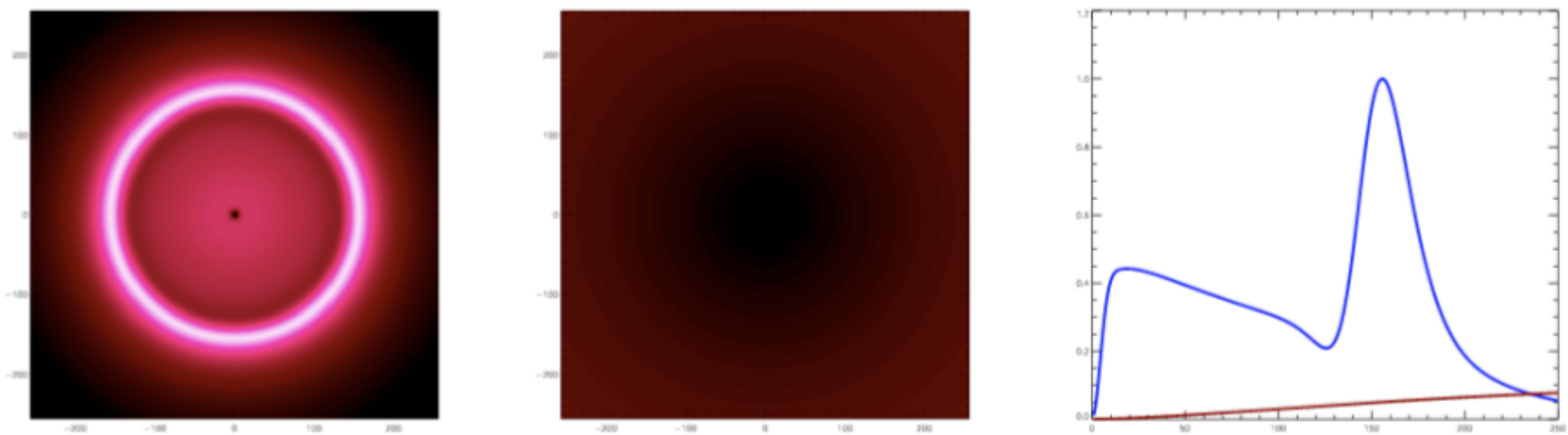
What are the Baryon Acoustic Oscillations?



Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

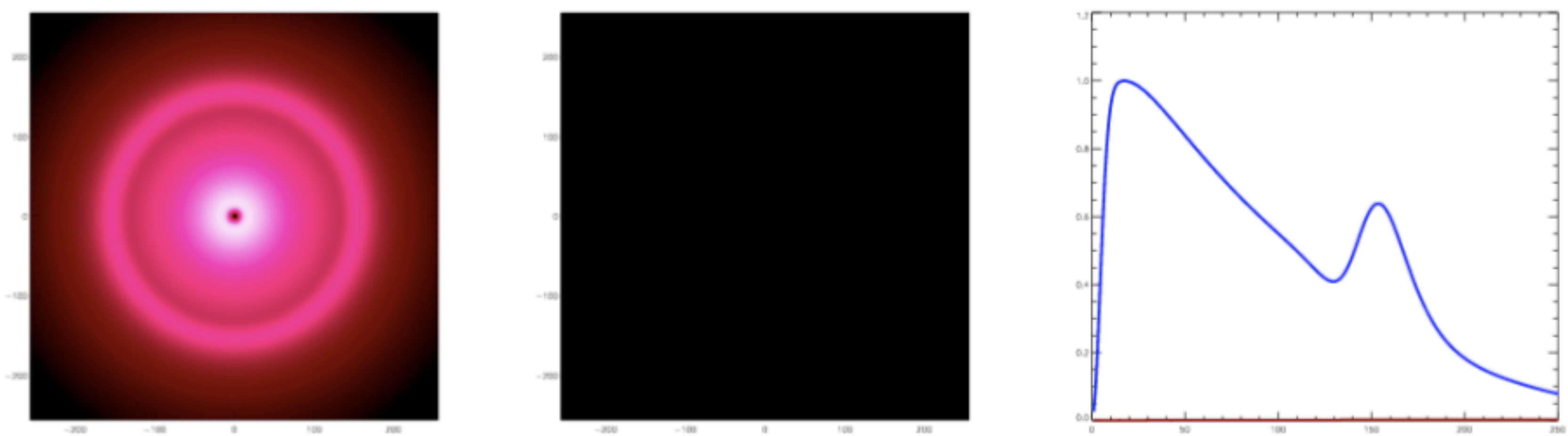
- The photons are nearly completely uniform now, but the baryons remain overdense in a shell of ~100 Mpc in radius
- In addition, the large gravitational potential well which we started with starts to draw the material back to it.



Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

- As the perturbation grows, the baryons and dark matter reach equilibrium densities in the ratio of global baryon-to-dark matter ratio.
- The final configuration is our original peak at the center and an ‘echo’ in a shell roughly 100 Mpc in radius with width ~10%



Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

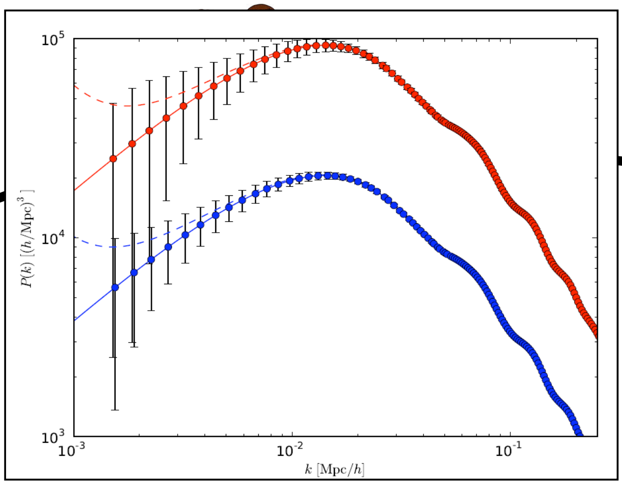
How do we detect Baryon Acoustic Oscillations?
We calculate the correlation functions or its Fourier Transform: power-spectrum

What is the correlation function ?

$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

Fourier Transform: correlation function-> **power-spectrum**

100 Mpc



There will be wiggles

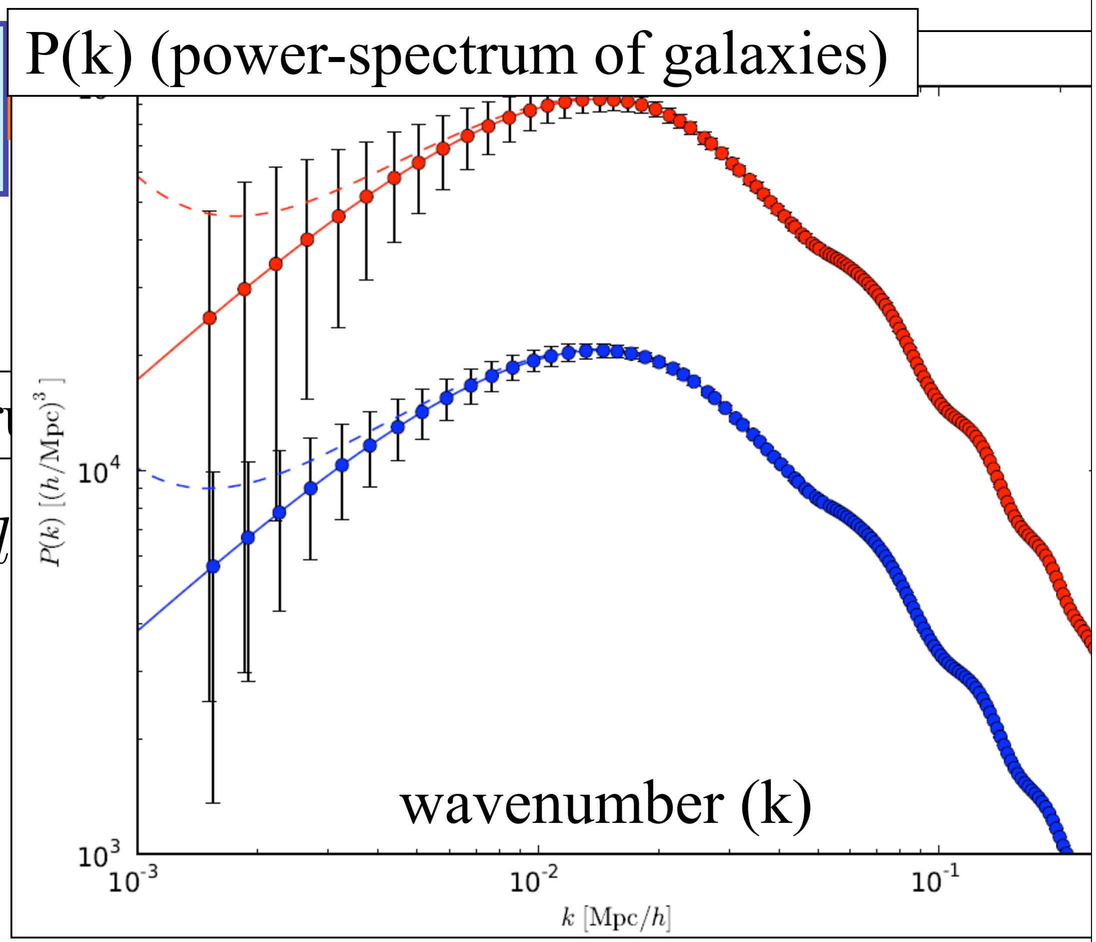
BAO: with Luminous Red Galaxies
Physics of Angular Clustering

$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$



Galaxy angular power-spectr

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(d$$

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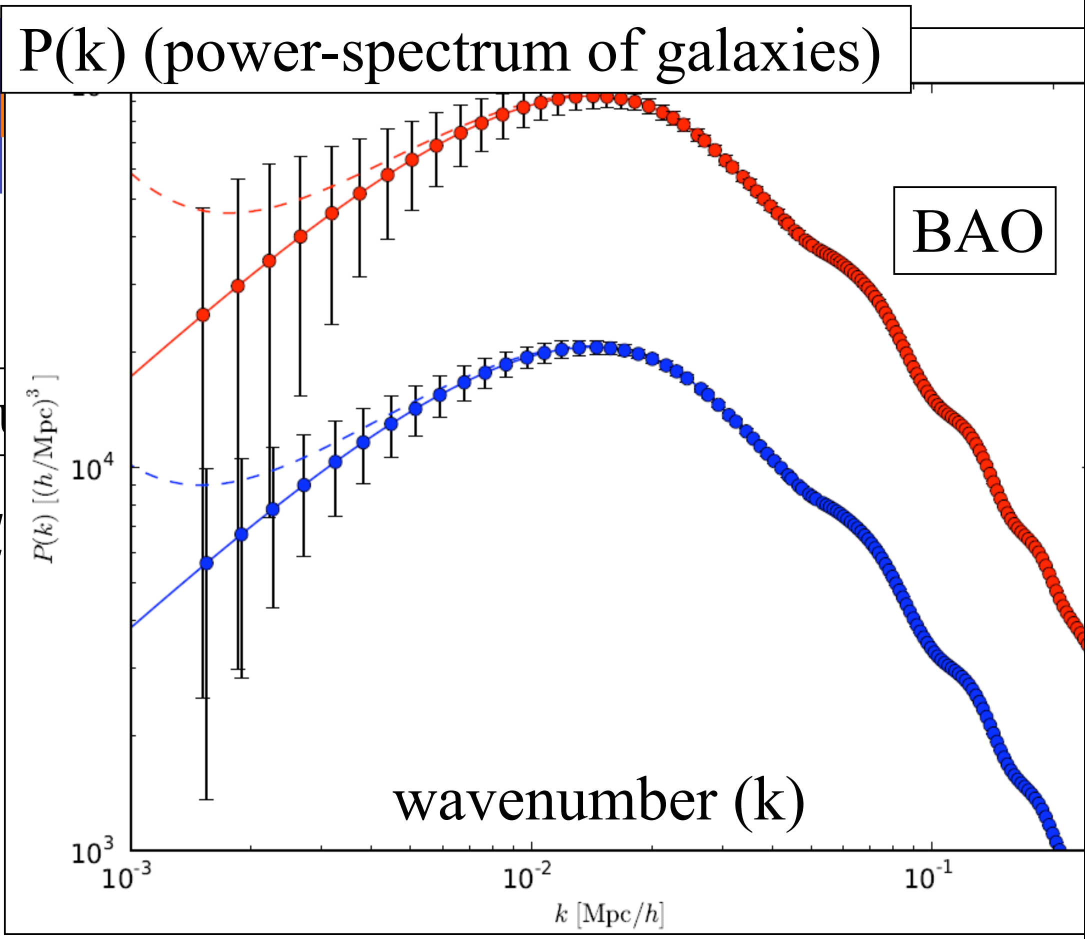

BAO: with Luminous Red Galaxies
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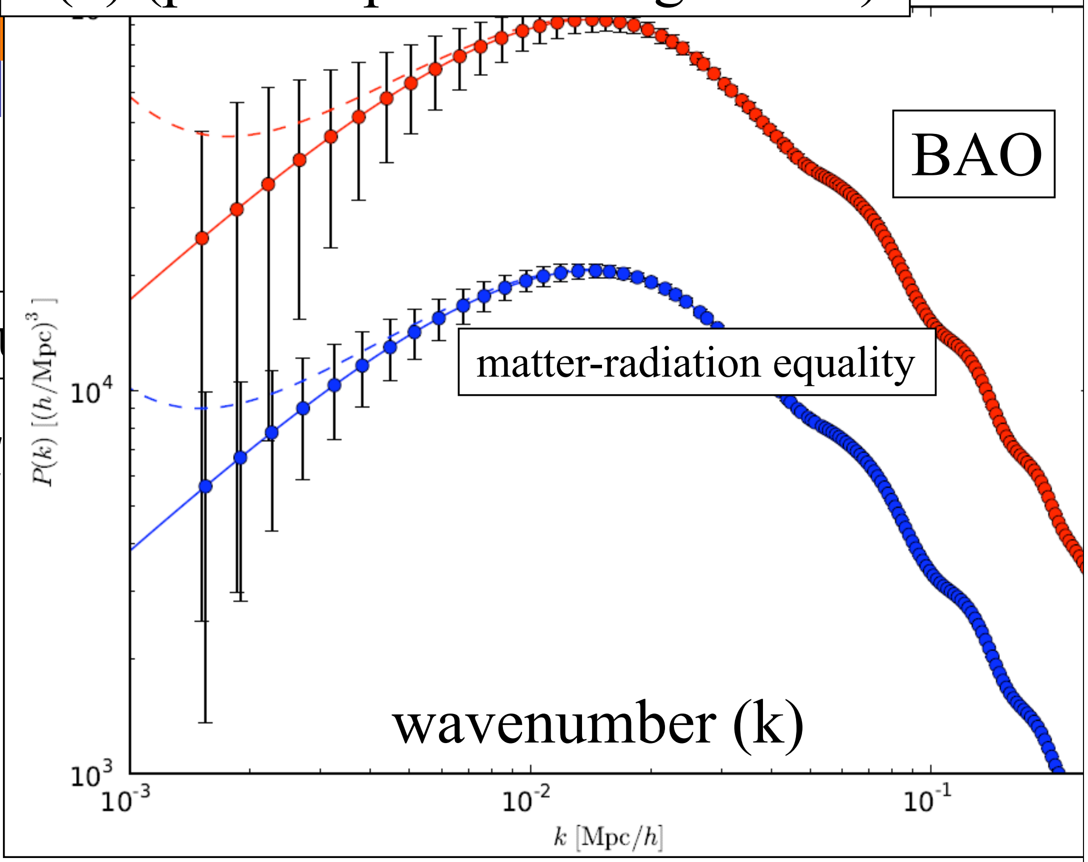
P(k) (power-spectrum of galaxies)



Galaxy angular power-spectr

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BAO: with Luminous Red Galaxies
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$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

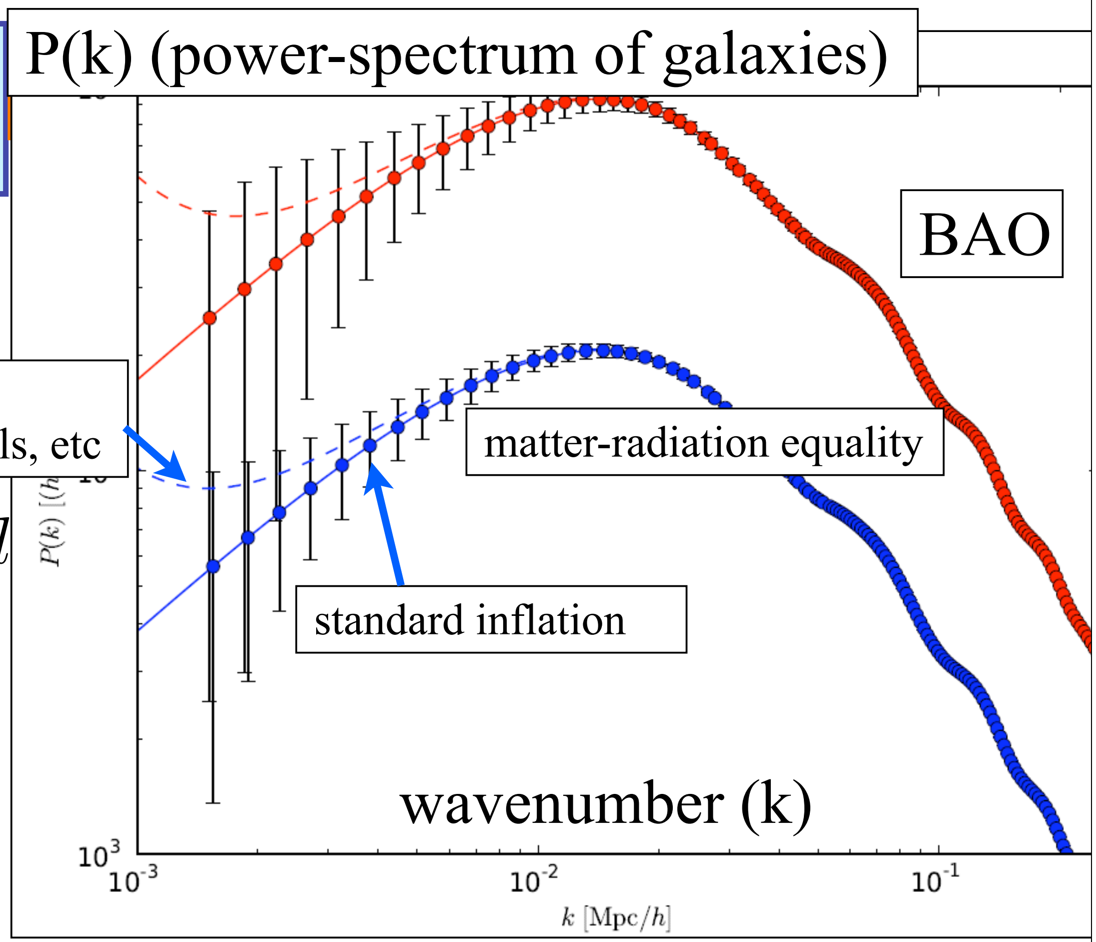
$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$

Galaxy angular p

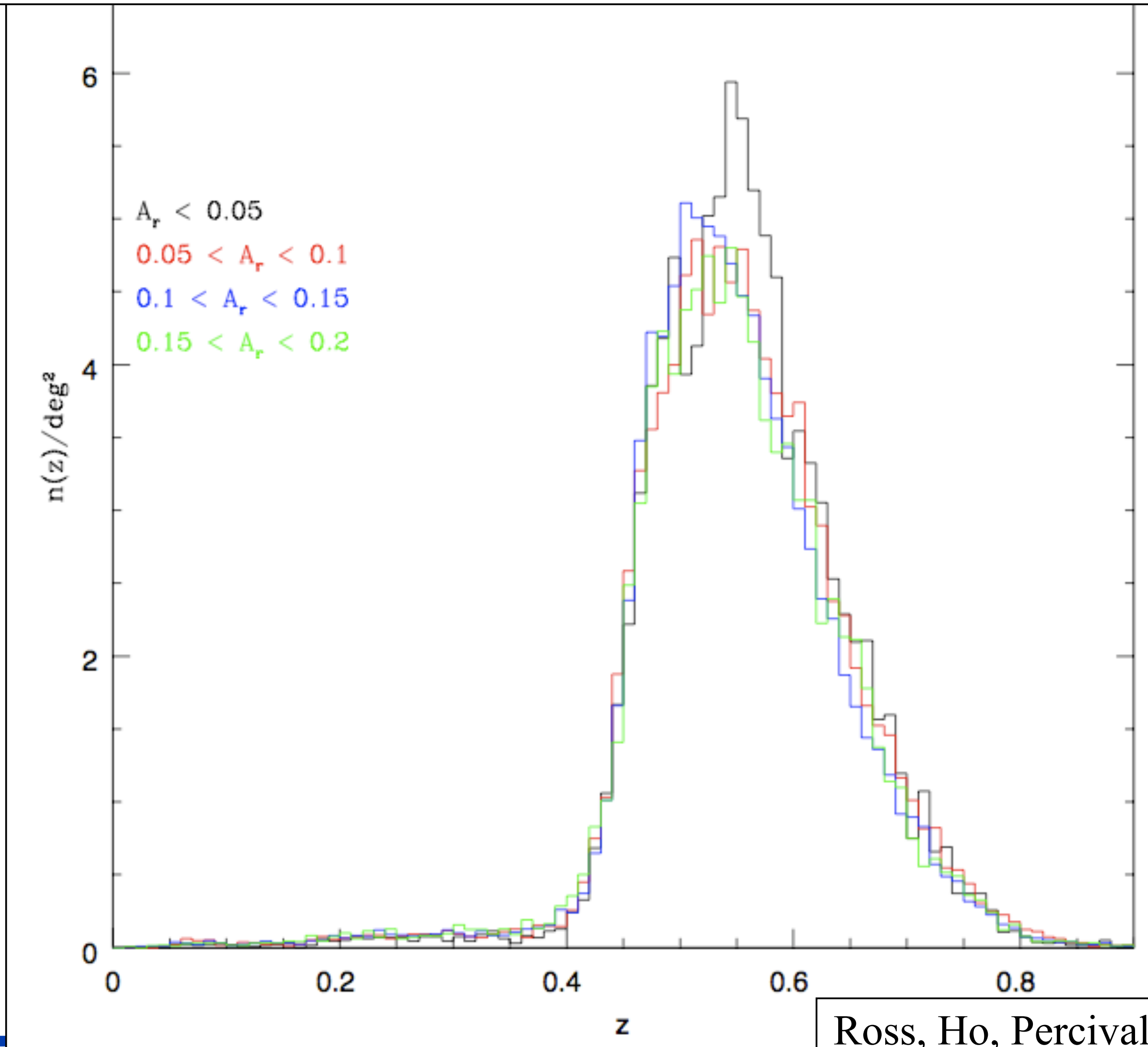
ghost inflation, curvaton models, etc

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(d$$



BAO: with Luminous Red Galaxies
Systematics: Dust

Dust extinction affects redshift distribution of the galaxies



Ross, Ho, Percival et al. (in prep)