Student seminar

Baryon Acoustic Oscillation

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Content

I. Basic facts of cosmology

II. What is Baryon Acoustic Oscillation(BAO)?

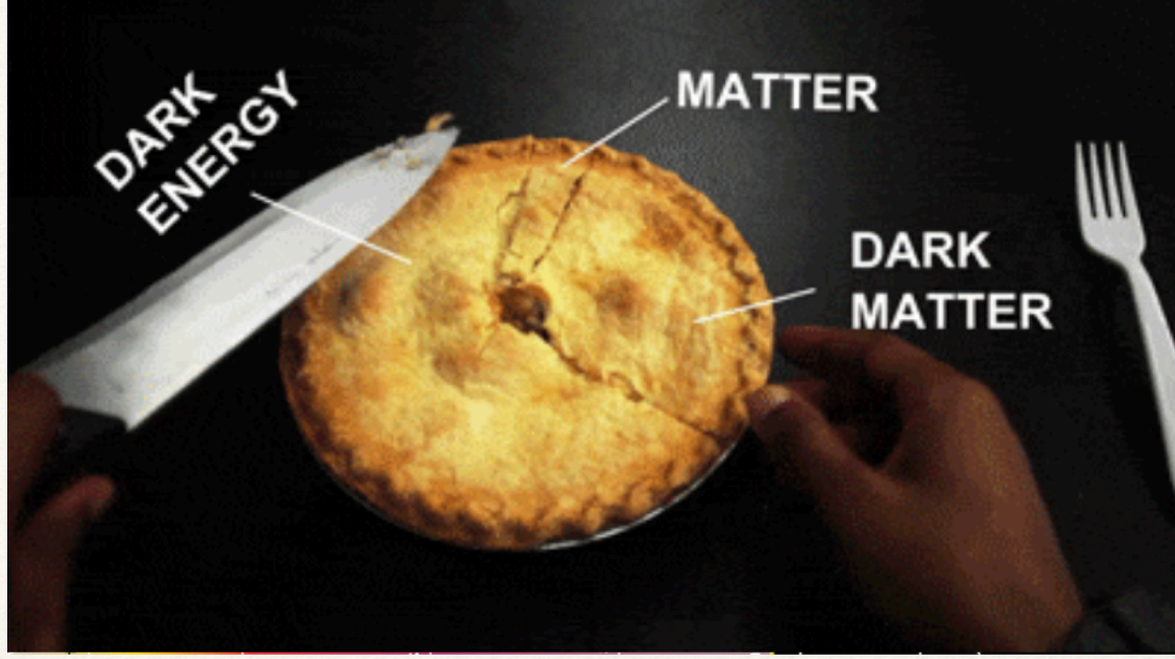
III. How to measure BAO?

IV. Alternative method to measure BAO

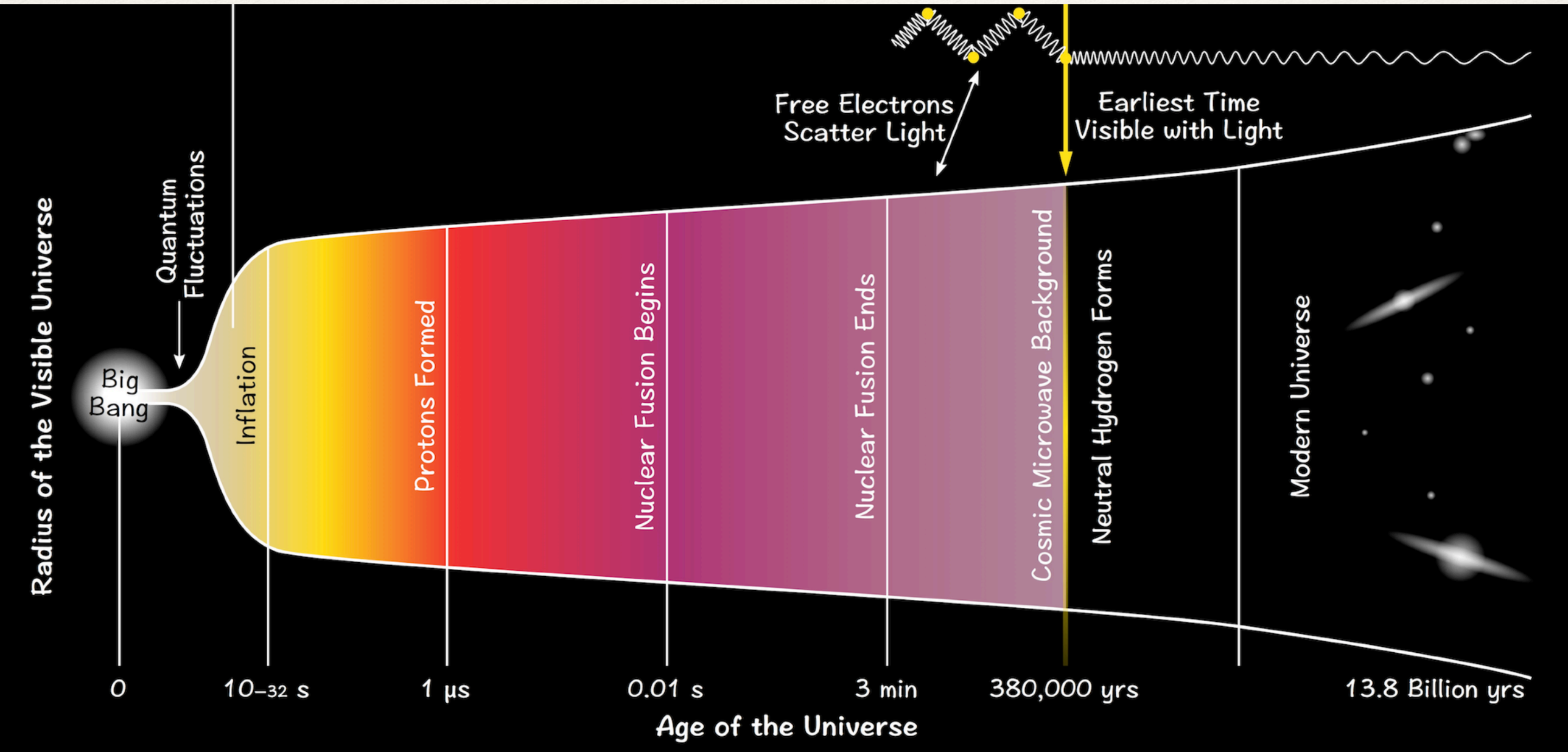
Basic facts of cosmology

Level-1: Background

Cosmic Pie

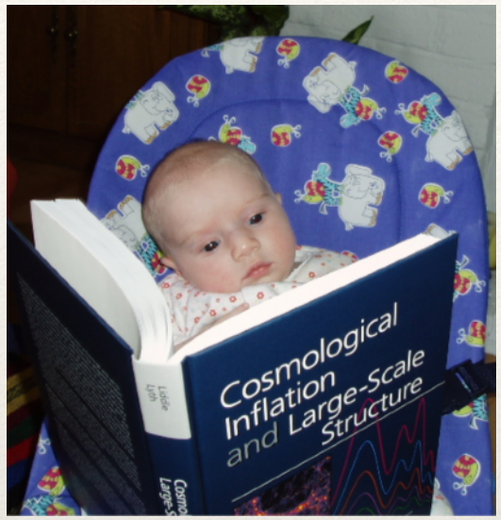


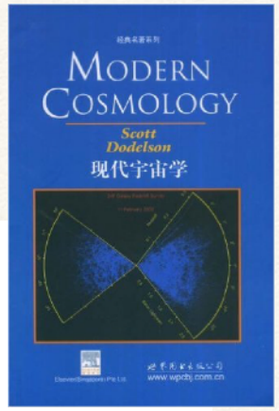
Cosmic Thermal History

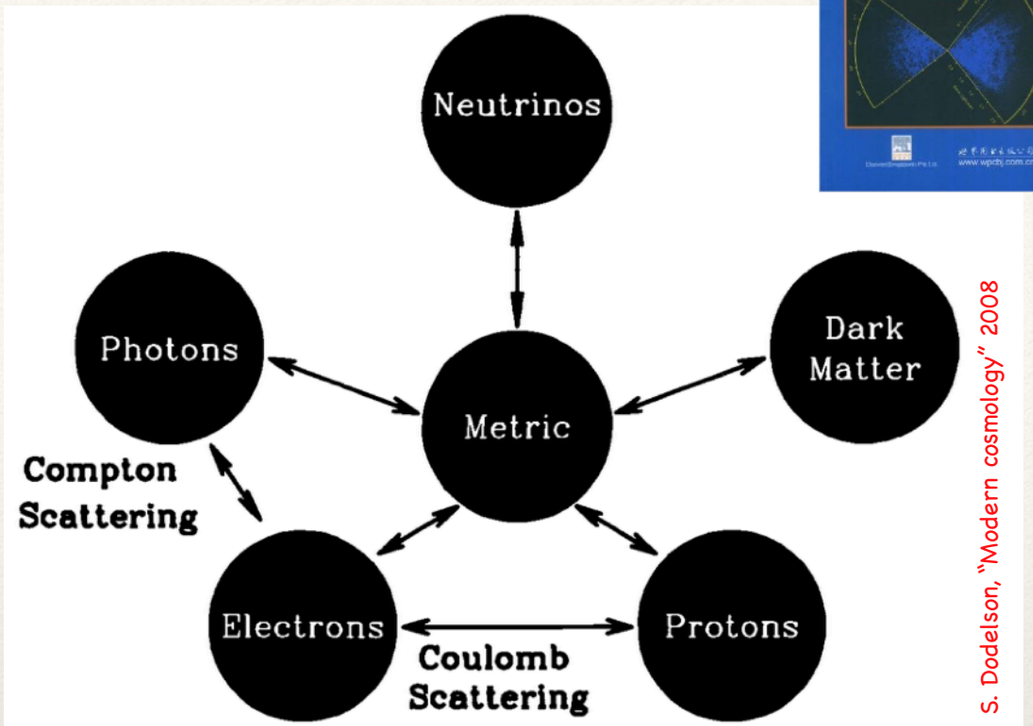


Level-2: Perturbations

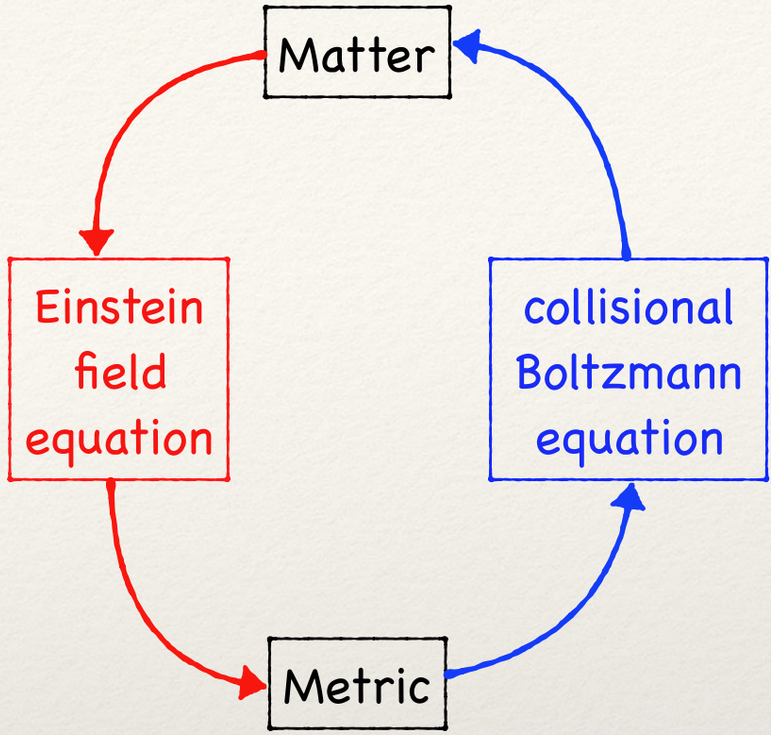
Initial condition
from inflation



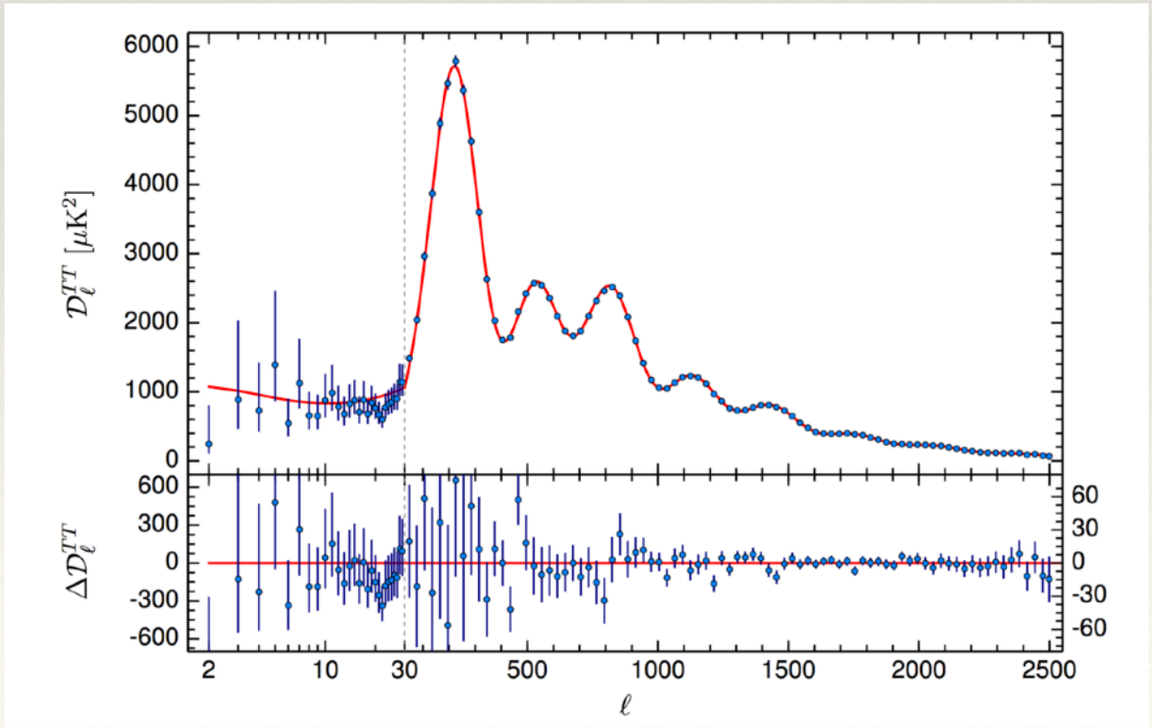




S. Dodelson, "Modern cosmology" 2008

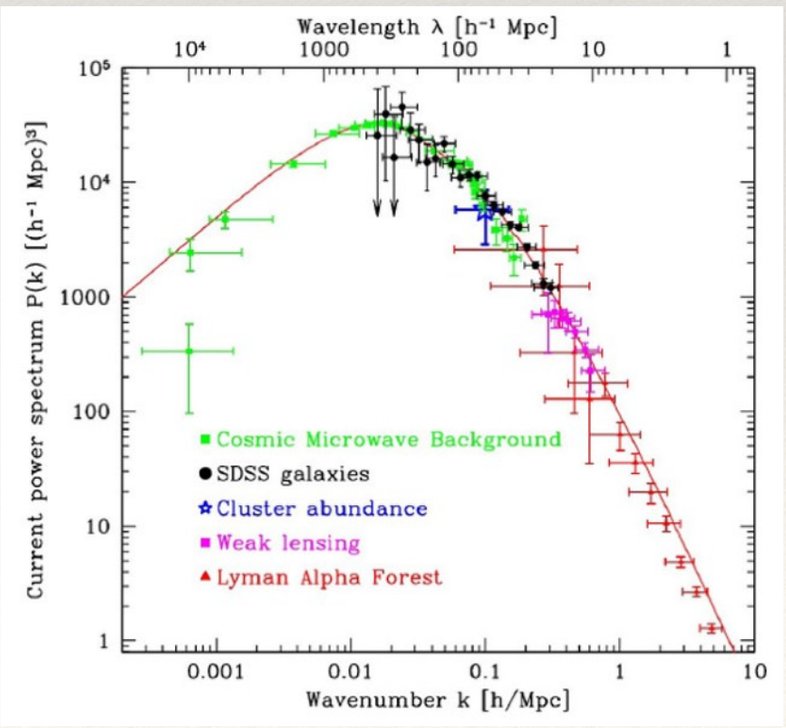


BAO in photon distribution



Planck Collaboration A&A 594, A11 (2016)

BAO in matter distribution

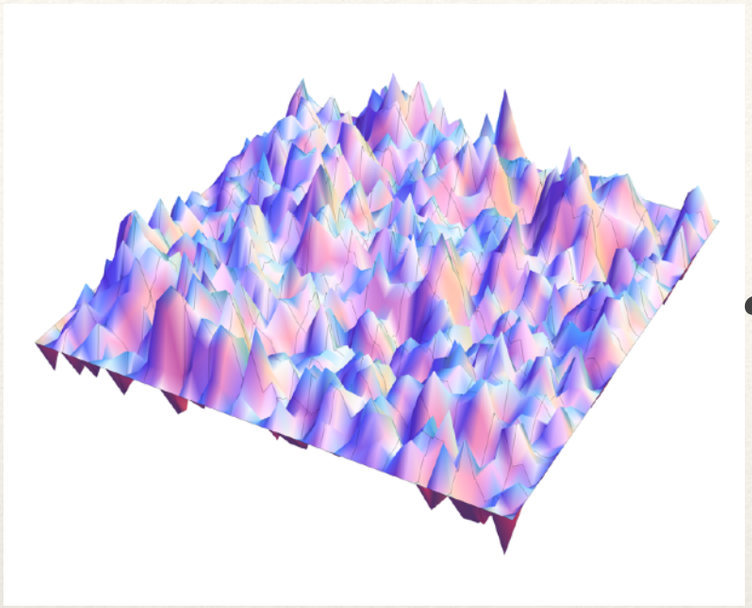


M. Tagmark et al. ApJ 606:702–740, (2004)

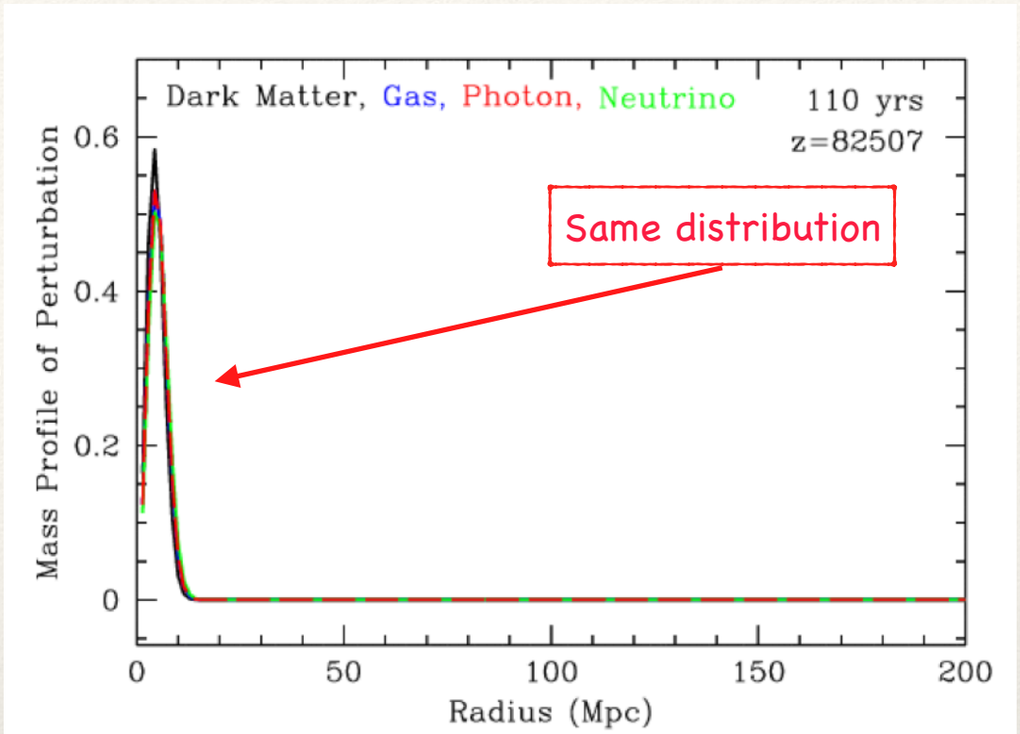
What is Baryonic Acoustic Oscillation(BAO)?

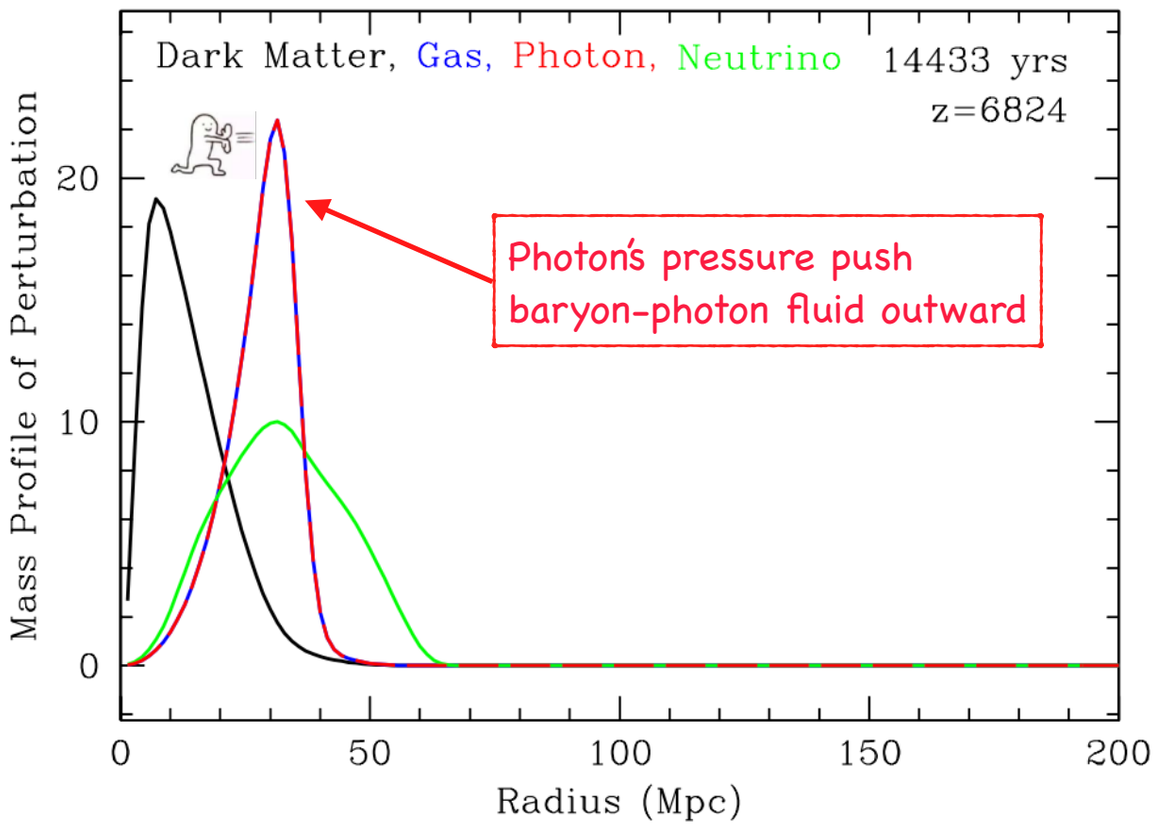
Phase-1. baryon coupled with photon

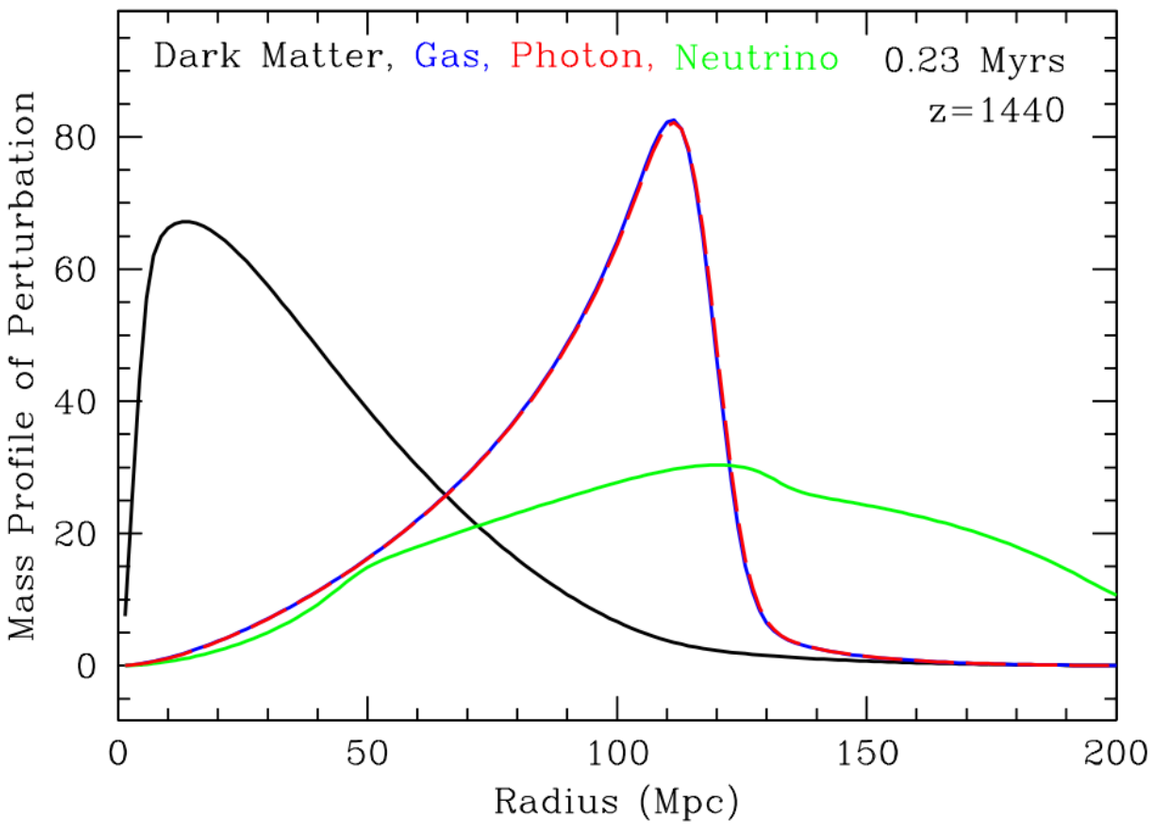
Quantum fluctuations from inflation



Select one overdensity peak

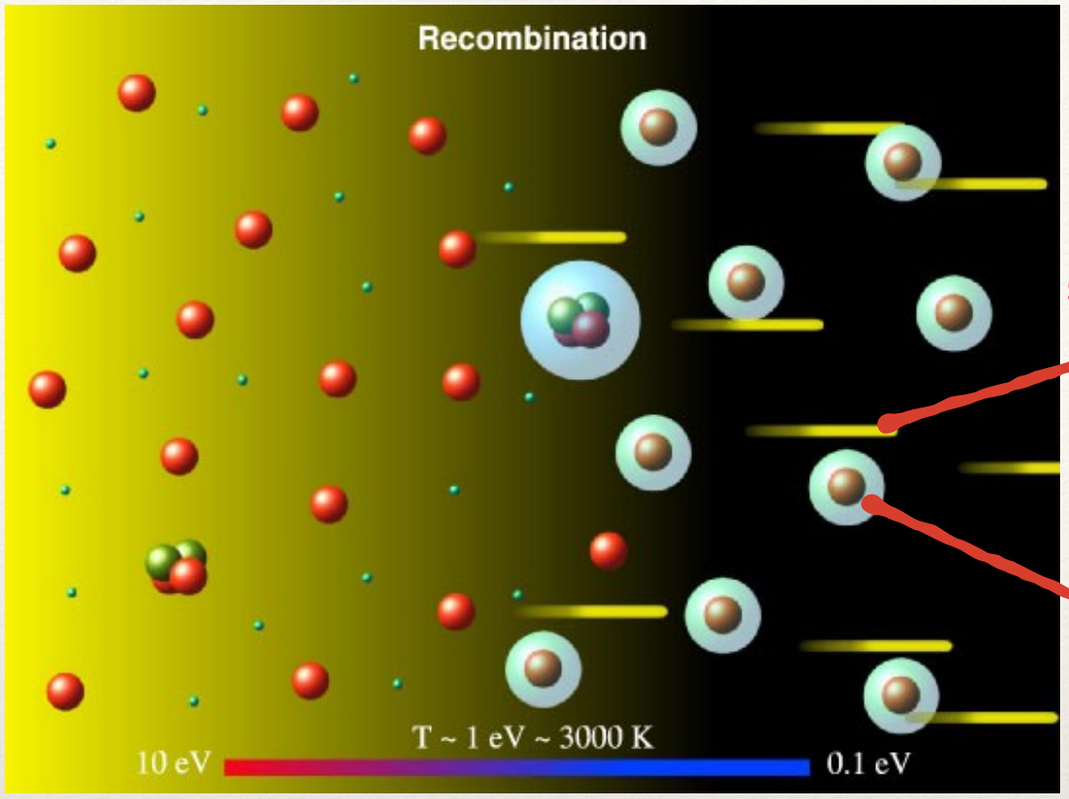




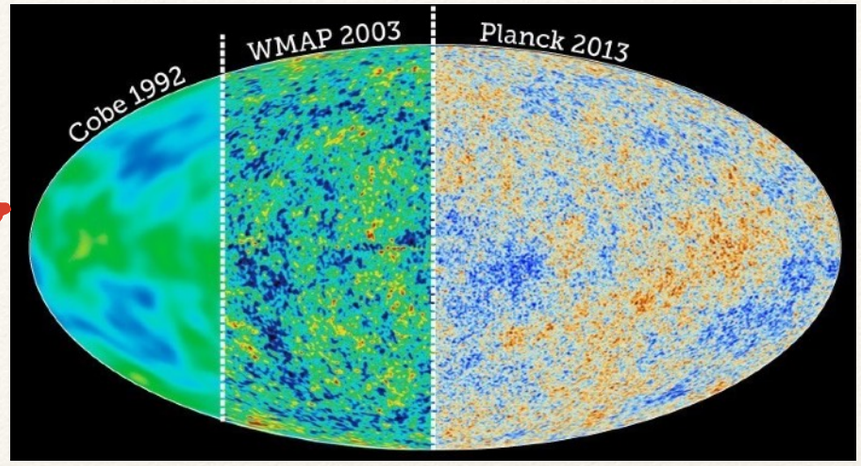


Eisenstein, D. J., Seo, H.-J., and White, M. ApJ, 664: 660-674 (2007)

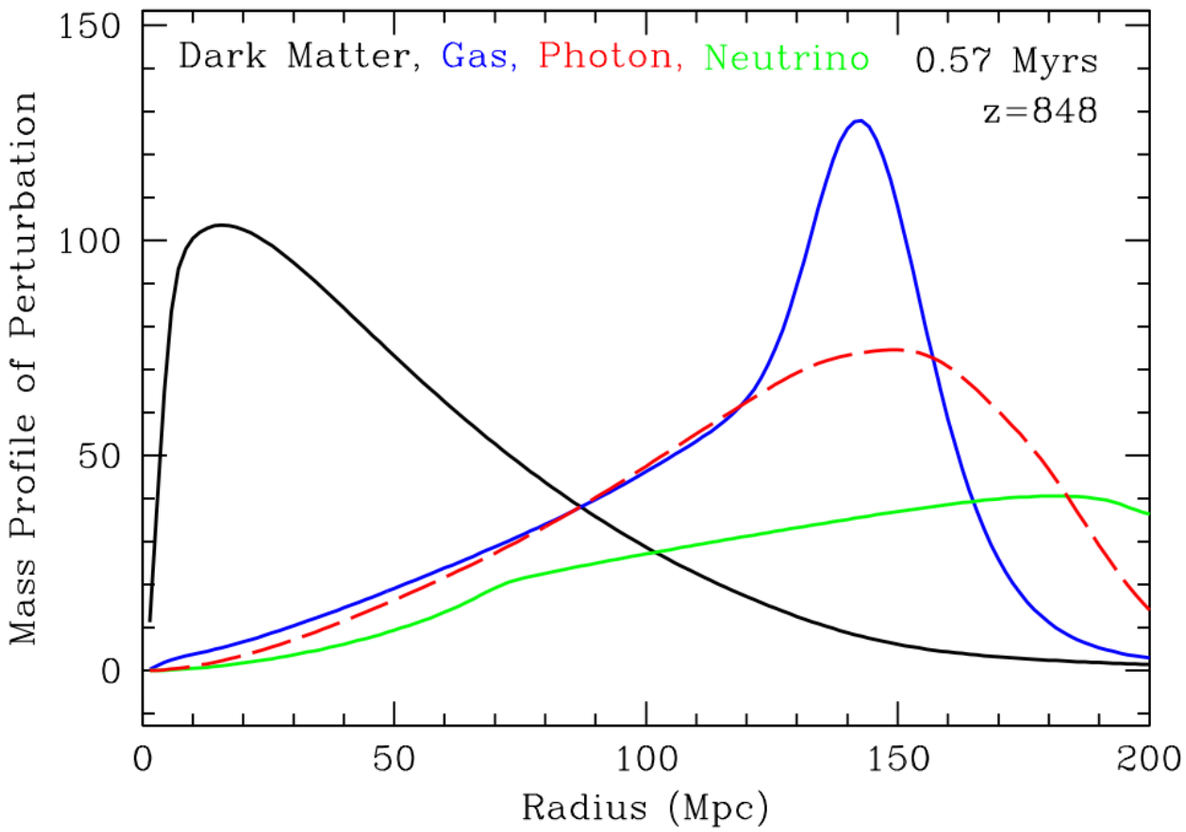
Phase-2. baryon and photon are decoupled

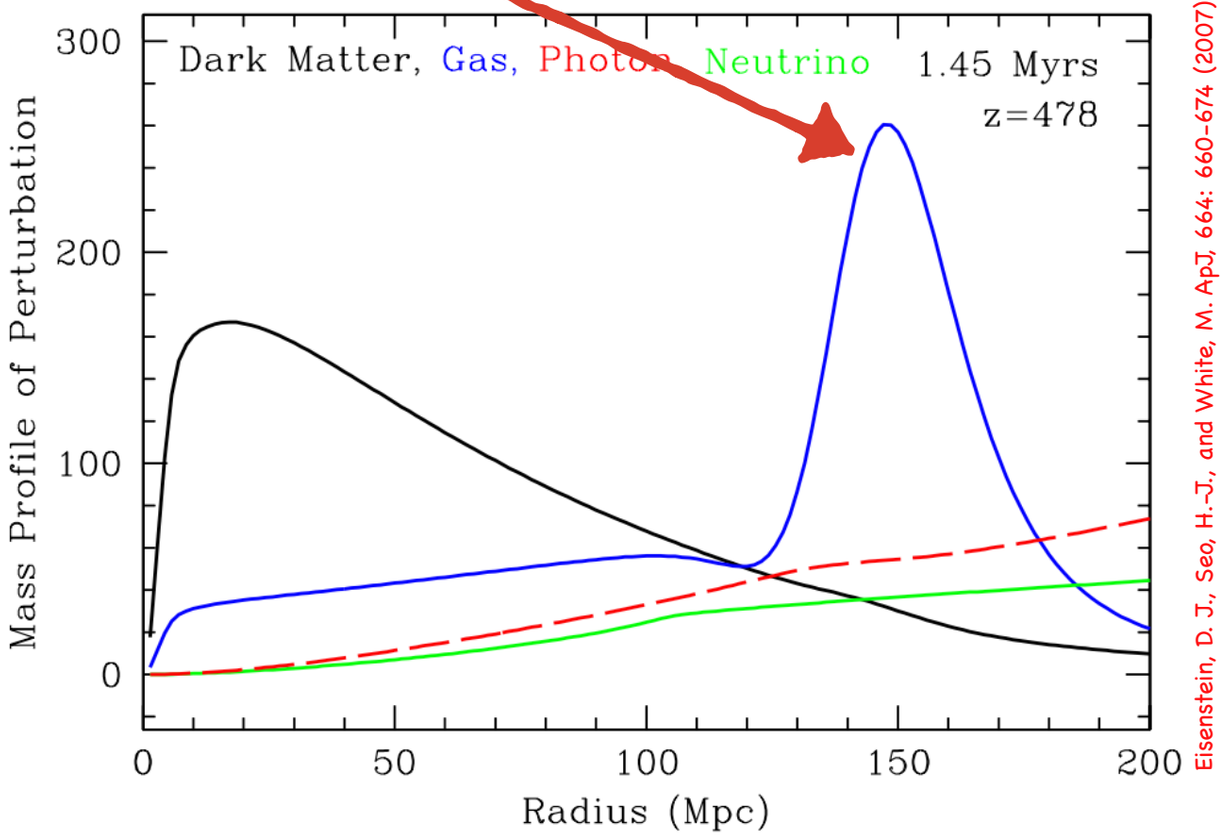


free-streaming photon



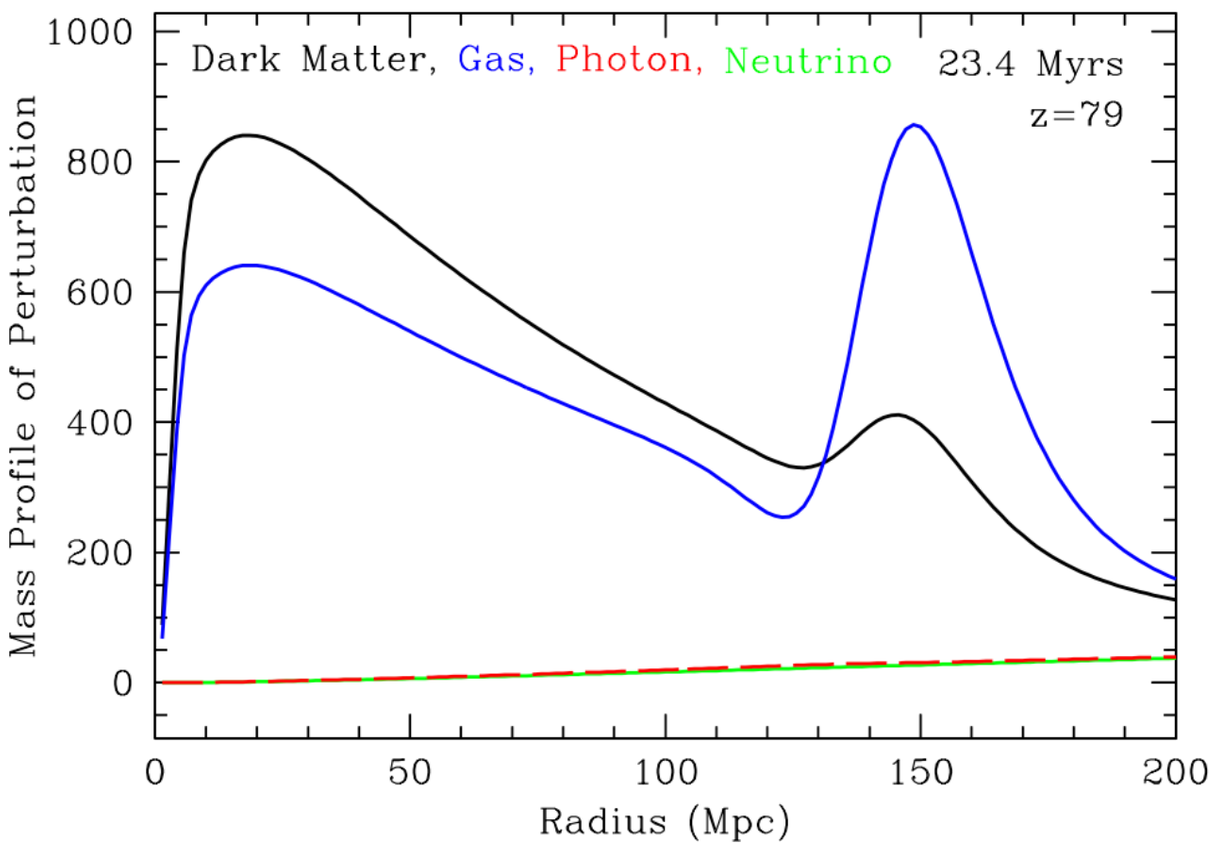
leave baryons alone

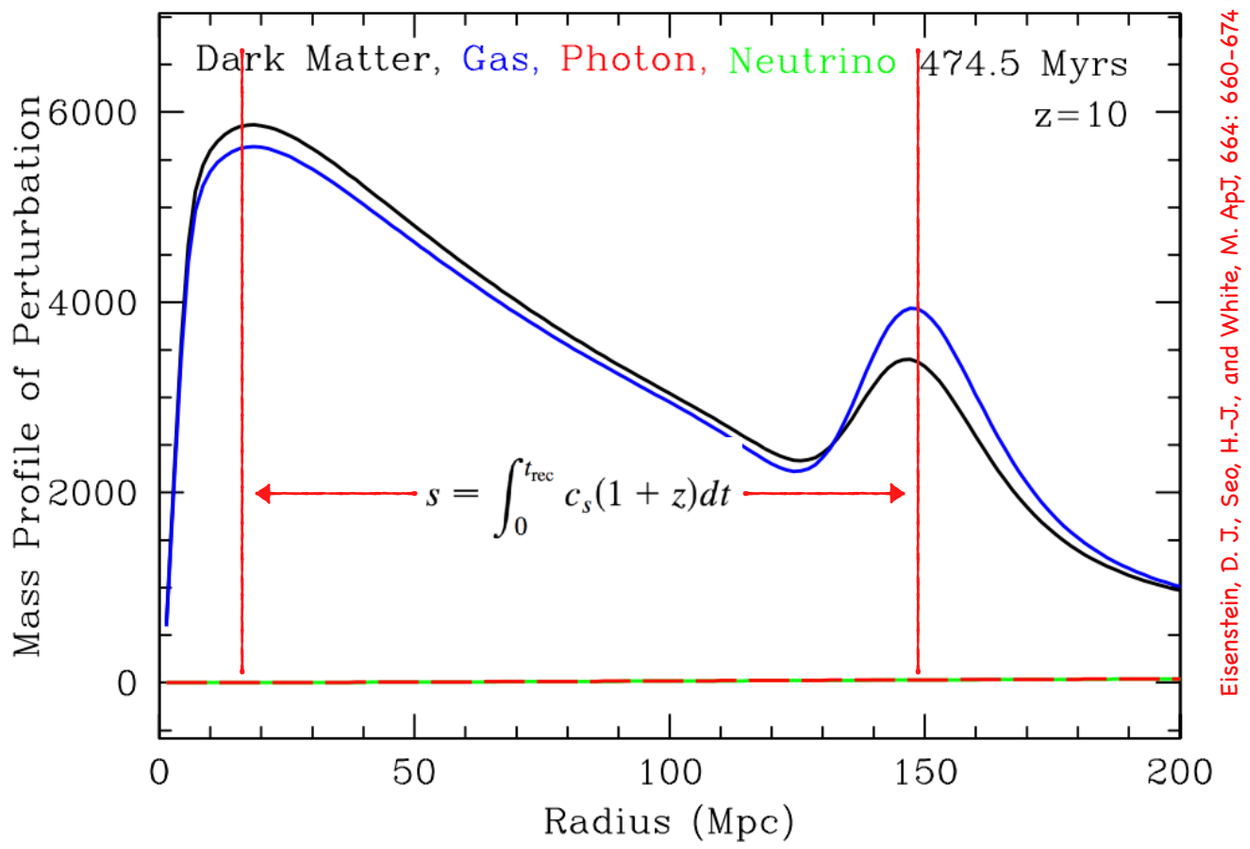




Eisenstein, D. J., Seo, H.-J., and White, M. ApJ, 664: 660-674 (2007)

Phase-3. baryon and dark matter attract each other



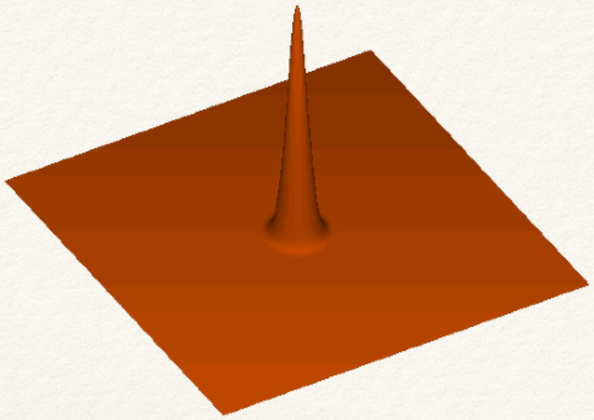


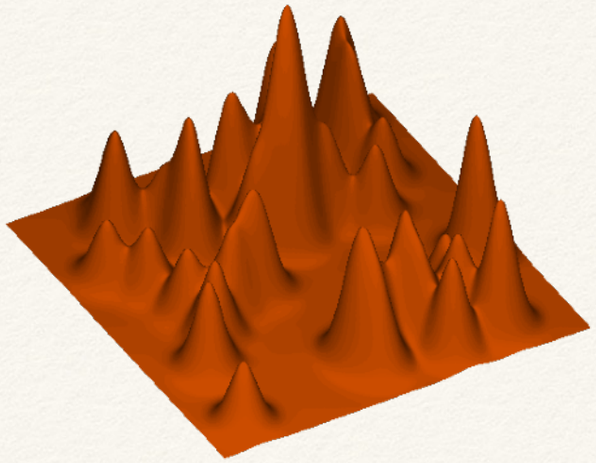
Eisenstein, D. J., Seo, H.-J., and White, M. ApJ, 664: 660-674 (2007)

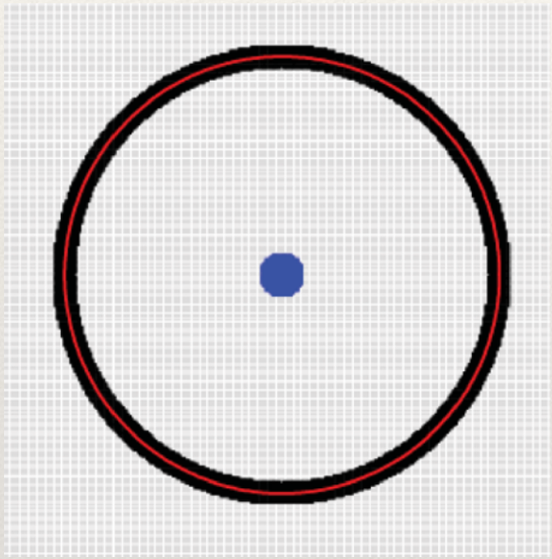
Next: Nonlinear evolution & Galaxy formation —> another topic

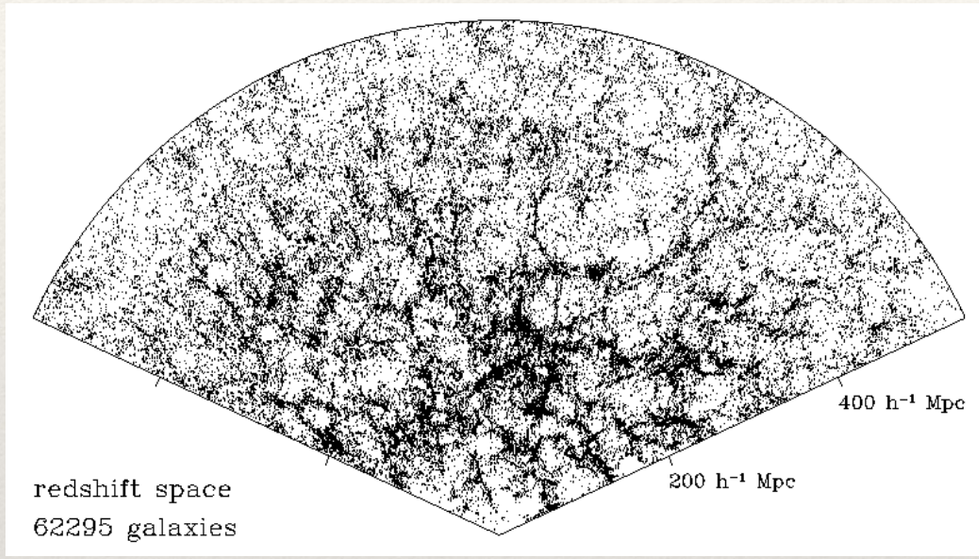
Why we choose BAO to probe our Universe?

1. Large scale —> more linear —> possible to calculate analytically
2. There is a bump —> prominent feature
3. Both radial and tangential information —> better than CMB, which is just a 2D map









You may need a special eye to help you see the truth.

Or you can use a statistical tool called "Two Point Correlation Function".

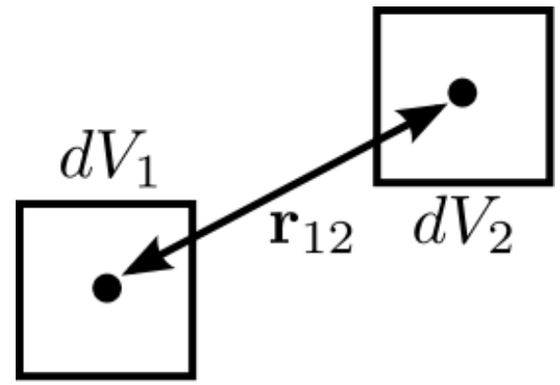
How to measure BAO?

Step-1. Measure the 2PCF

2PCF:

$$P_{12} = [1 + \xi(r)] dV_1 dV_2$$

$$\xi(r) = \frac{DD(r)}{RR(r)} - 1$$



Given a galaxy, the probability to find another galaxy with distance r to it.

BAO calculation is linear, but non-linearity enters though...

1. Redshift-Space Distortion(RSD)
   The peculiar velocity of galaxies will contaminate the conversion from redshift to distance
2. Galaxy bias
   We use galaxies to trace matter distribution & galaxies are biased tracers
3. Non-linear evolution
   After forming the BAO peaks, matter will further experience non-linear evolution to form halos and galaxies

……

Reconstruction technique can partly correct these non-linearities...

Reconstruction technique

Zel'dovich approximation:

Displacement field → $\boldsymbol{\Psi} = \nabla\phi$ ← Gravitational potential

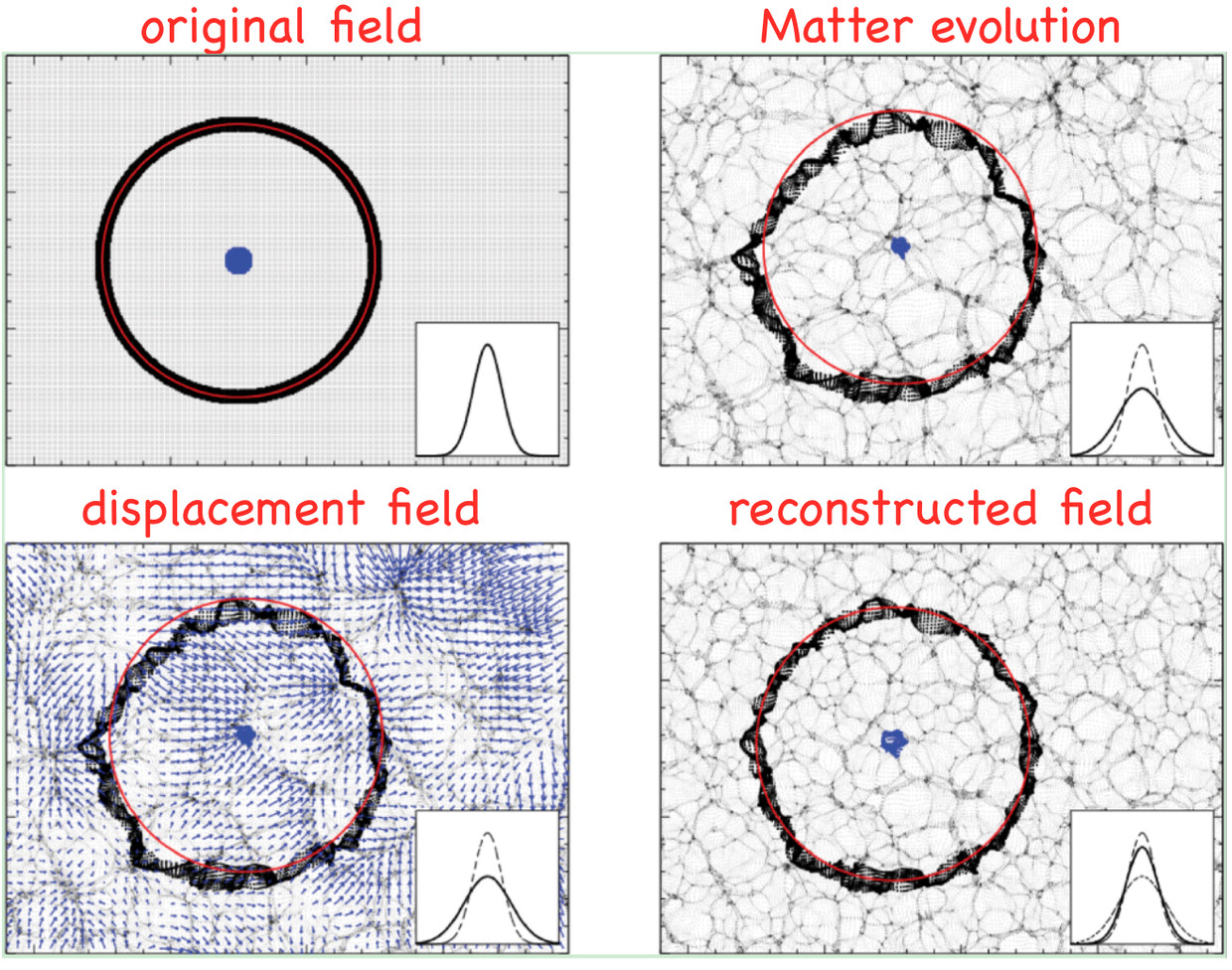
Poisson equation:

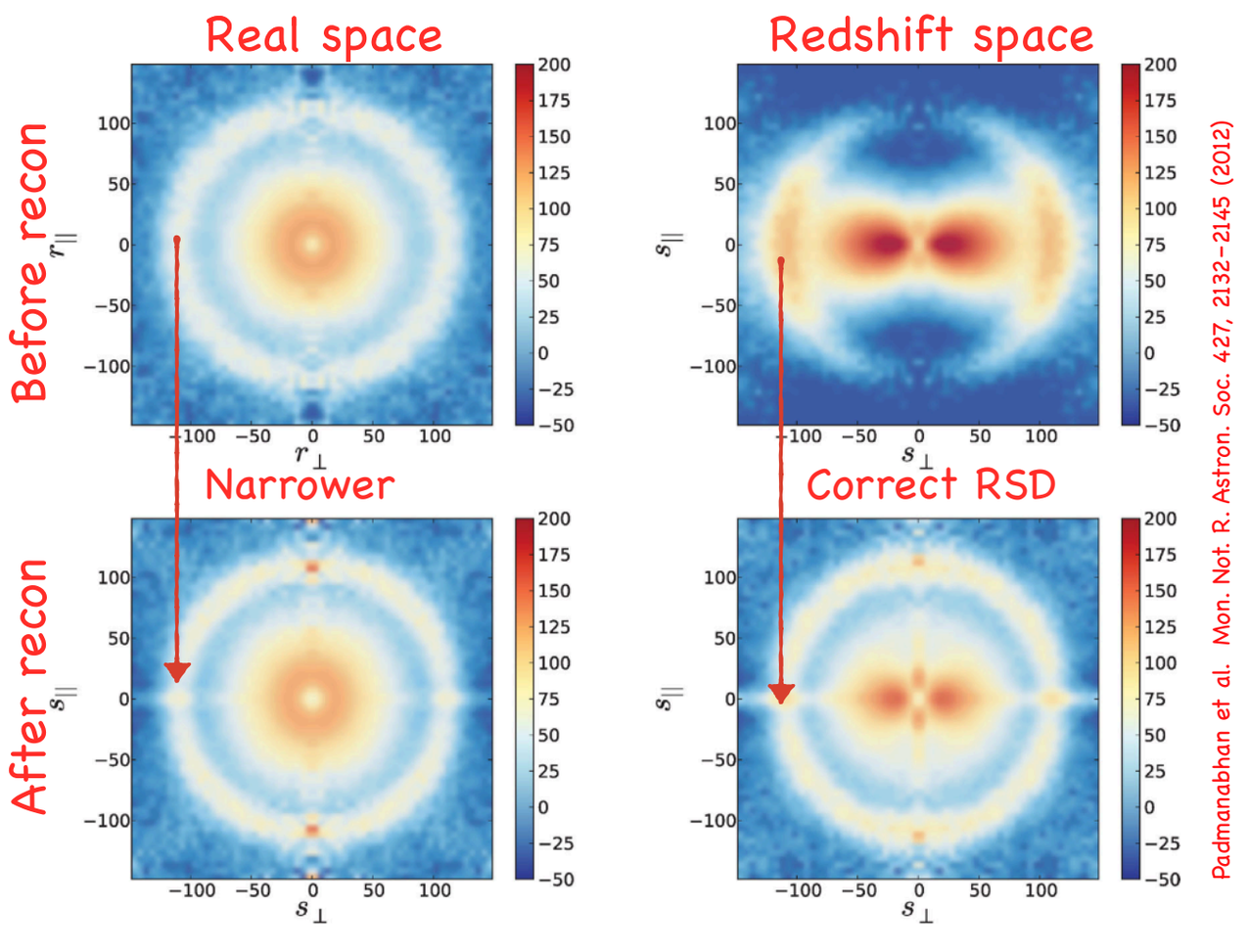
RSD

$$\nabla \cdot \boldsymbol{\Psi} + f\nabla \cdot (\Psi_s \hat{\boldsymbol{s}}) = -\frac{\delta_{\rm gal}}{b}$$

Galaxy bias

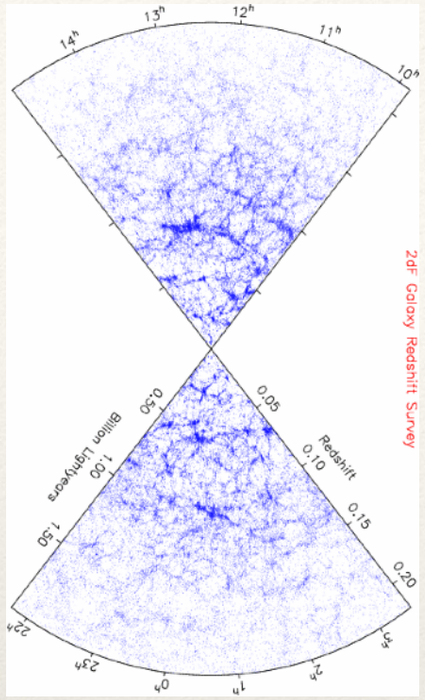
Give all the galaxies
a movement of $-\boldsymbol{\Psi}$. (to correct matter motion)
a movement of $-f(\boldsymbol{\Psi}\cdot\hat{\boldsymbol{s}})\hat{\boldsymbol{s}}$ (to correct RSD)



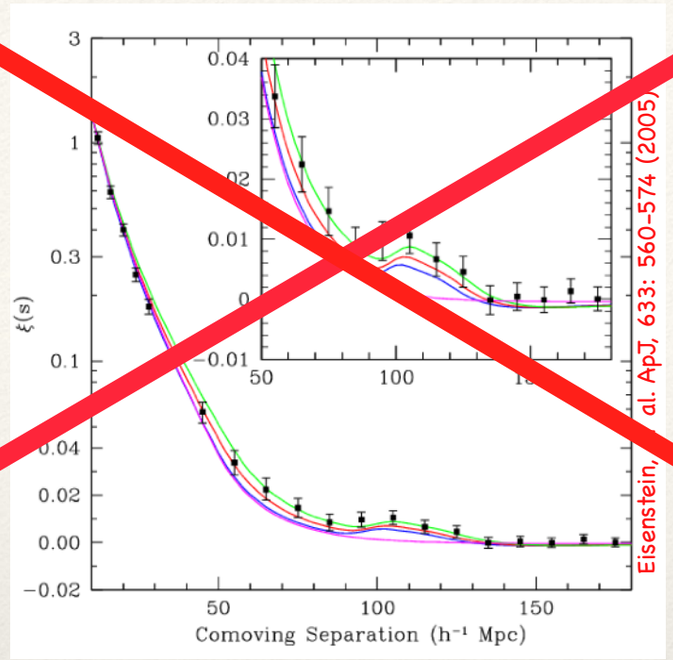


Padmanabhan et al. Mon. Not. R. Astron. Soc. 427, 2132–2145 (2012)

Tune the parameters & Draw a banana
End the story?

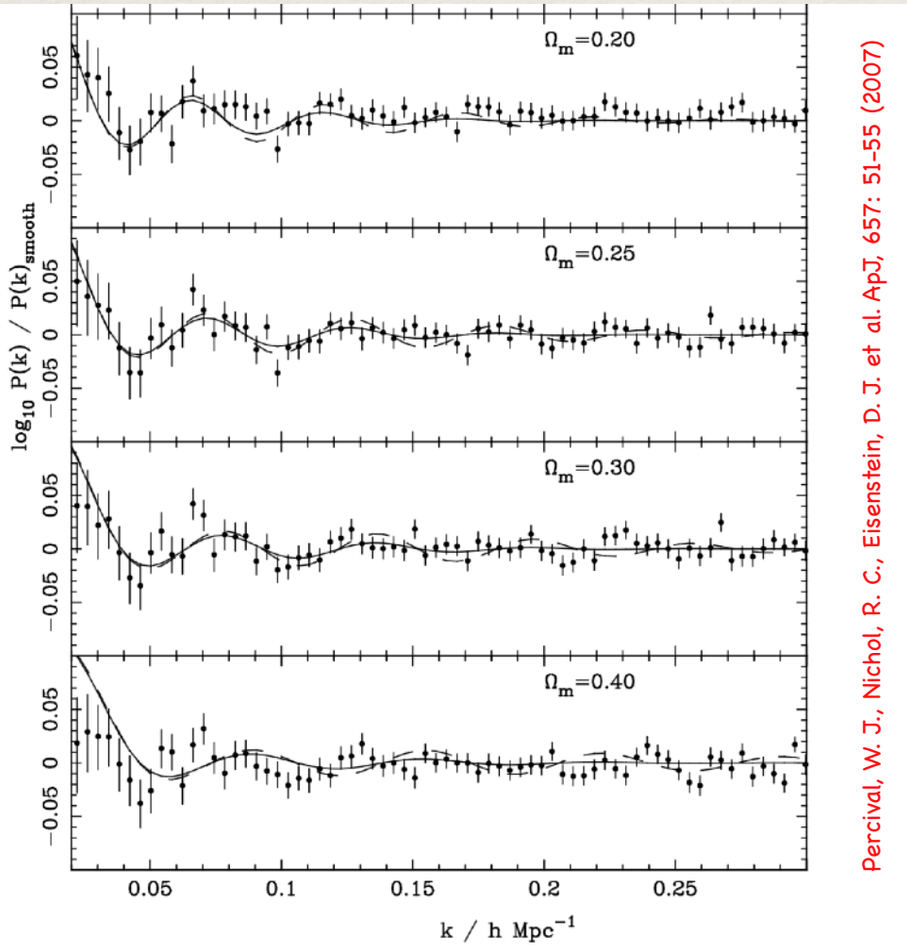


Observation



Theory

Cosmological parameters



Observed 2PCF varies with cosmological parameters!

$$d_0(z) = H_0^{-1} \int_{\frac{1}{1+z}}^{1} \frac{dx}{\sqrt{\Omega_0(x - x^2) - \Omega_\Lambda(x - x^4) + x^2}}$$

Step-2. Deal with the model

α : relative position of BAO peak w.r.t. fiducial cosmology

$$\alpha = \alpha_\perp^{2/3}\alpha_\parallel^{1/3} \quad \alpha_\perp = \frac{D_A(z)r_d^{fid}}{D_A^{fid}(z)r_d}, \quad \alpha_\parallel = \frac{H^{fid}(z)r_d^{fid}}{H(z)r_d}.$$

Solution:

First, assume a fiducial cosmology

Then, use α to tune the position of BAO peak

$$\xi^{fit}(r) = B^2\xi_m(\alpha r) + A(r)$$

modeling broad-band shape
(like scale-dependent bias, RSD)

$$A(r) = \frac{a_1}{r^2} + \frac{a_2}{r} + a_3$$

fiducial cosmology

Xu et al. Mon. Not. R. Astron. Soc. 427, 2146–2167 (2012)

Fourier transform the power spectrum

$$\xi_m(r) = \int \frac{k^2 dk}{2\pi^2} P_m(k) j_0(kr) e^{-k^2a^2} \qquad P_m(k) = b^2P_t(k)$$

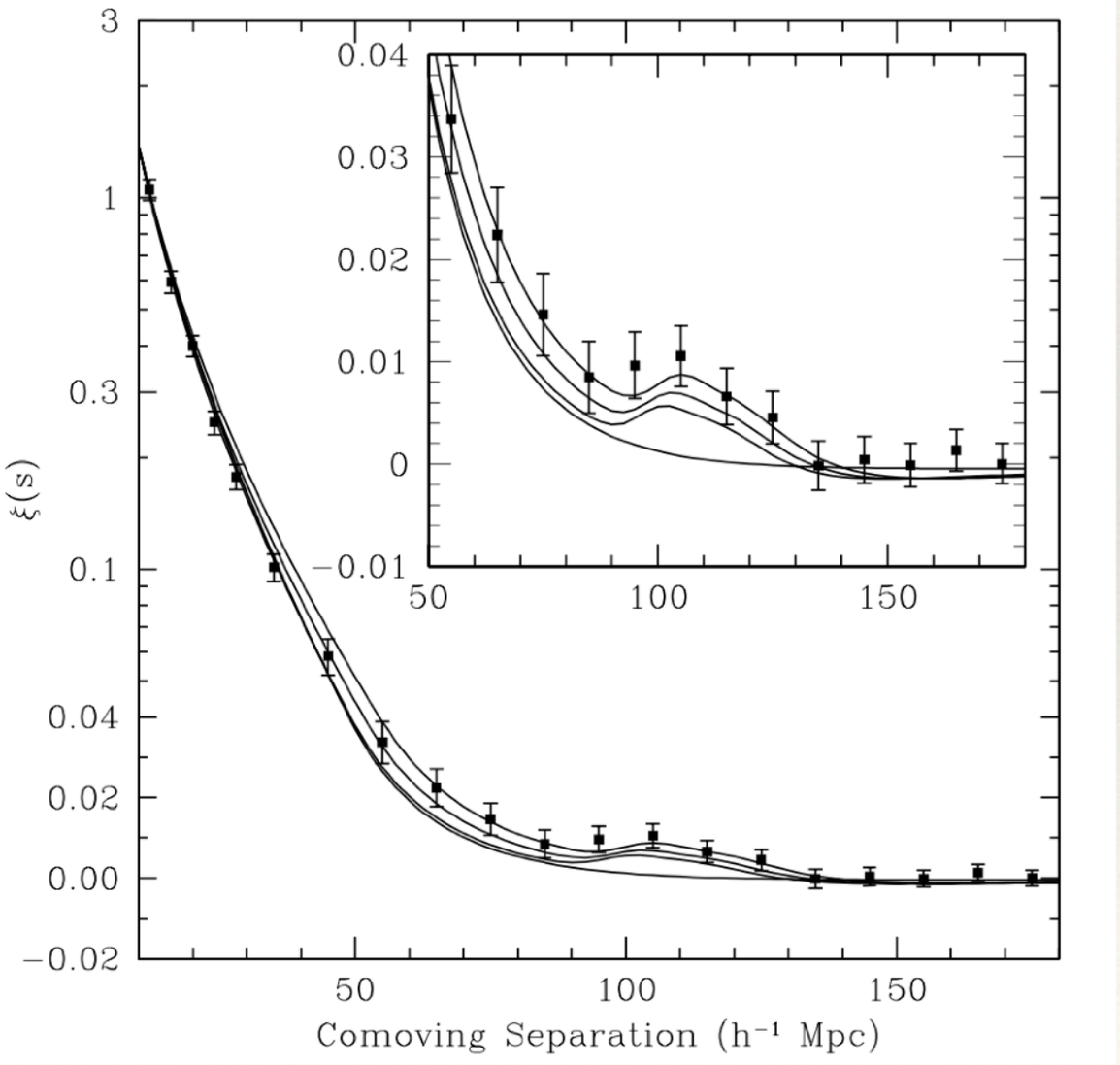
modeling degradation in the BAO peak due to non-linear evolution

$$P_t(k) = [P_{lin}(k) - P_{smooth}(k)]e^{-k^2\Sigma_{nl}^2/2} + P_{smooth}(k)$$

Results:

Eisenstein et al. 2005
First detection

sample: 46,000 LRGs
redshift: $0.16 < z < 0.47$
detection: 3.4σ



Padmanabhan et al. 2012
Xu et al. 2012
Reconstruction & Better model

sample: 46,000 LRGs
redshift: $0.16 < z < 0.47$
detection: 4.2σ

SDSS III BOSS 2013
LOWZ + CMASS

sample: 100,000 galaxies
redshift: $0.2 < z < 0.7$
detection: 7σ

SDSS IV eBOSS 2017

sample: 147,000 quasars
redshift: $0.8 < z < 2.2$
detection: 2.8σ

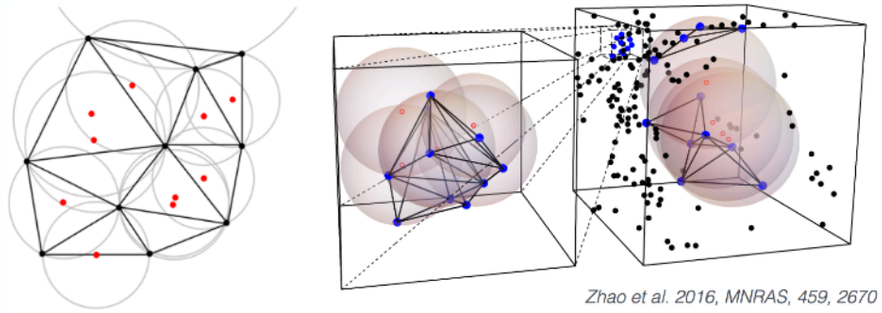
Alternative method to measure BAO

Combine galaxies and voids

C. Zhao, Y. Liang, C. Tao et al.

1. New technique to find voids

Delaunay Tr**I**angulation **V**oid Find**E**r



Zhao et al. 2016, MNRAS, 459, 2670

Delaunay Triangulation (DT)
Wikipedia

Dots: haloes
Open circles: centres of voids

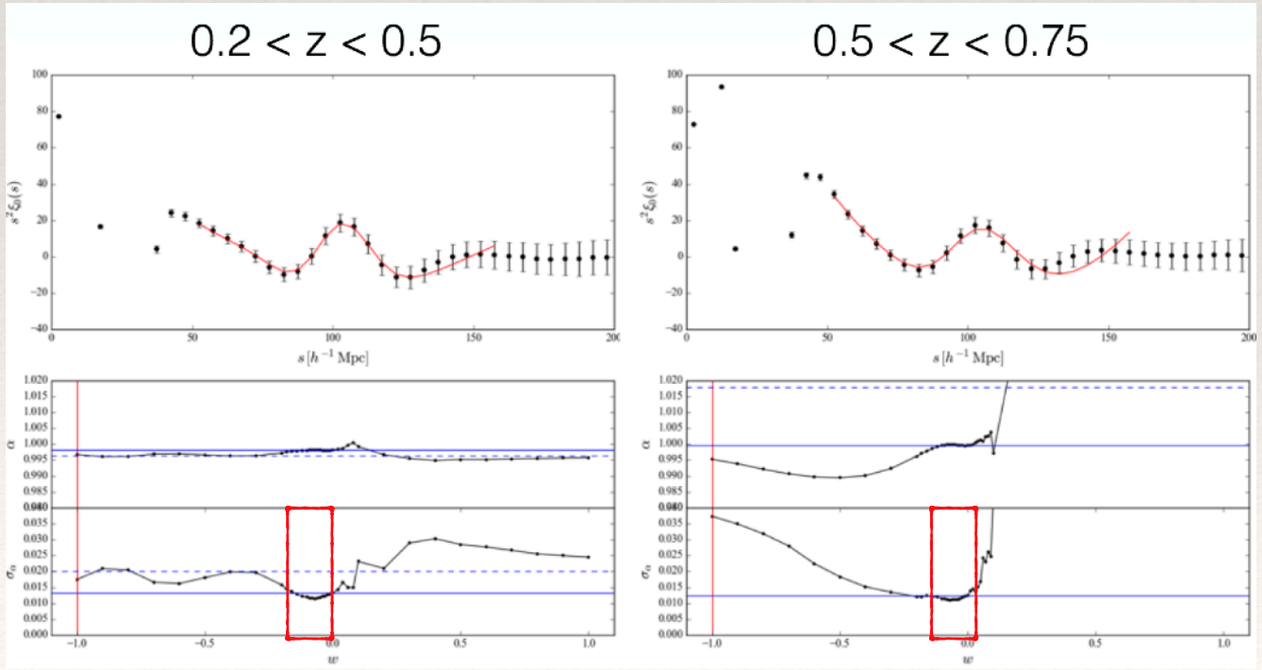
cosmology independent
~10 minutes for 5.5 million haloes with a single CPU core

2. Estimator combined galaxies and voids

$$\xi_{\rm comb} = \frac{\mathrm{DD_{comb}} - 2\mathrm{DR_{comb}} + \mathrm{RR_{comb}}}{\mathrm{RR_{comb}}}$$
$$= \frac{n_{\rm g}^2\xi_{\rm gg}\cdot \mathrm{R_gR_g} + n_{\rm v}^2 w^2 \xi_{\rm vv}\cdot \mathrm{R_vR_v} + n_{\rm g}n_{\rm v} w \xi_{\rm gv}\cdot \mathrm{R_gR_v}}{n_{\rm g}^2\cdot \mathrm{R_gR_g} + n_{\rm v}^2 w^2 \cdot \mathrm{R_vR_v} + n_{\rm g}n_{\rm v} w \cdot \mathrm{R_gR_v}}$$

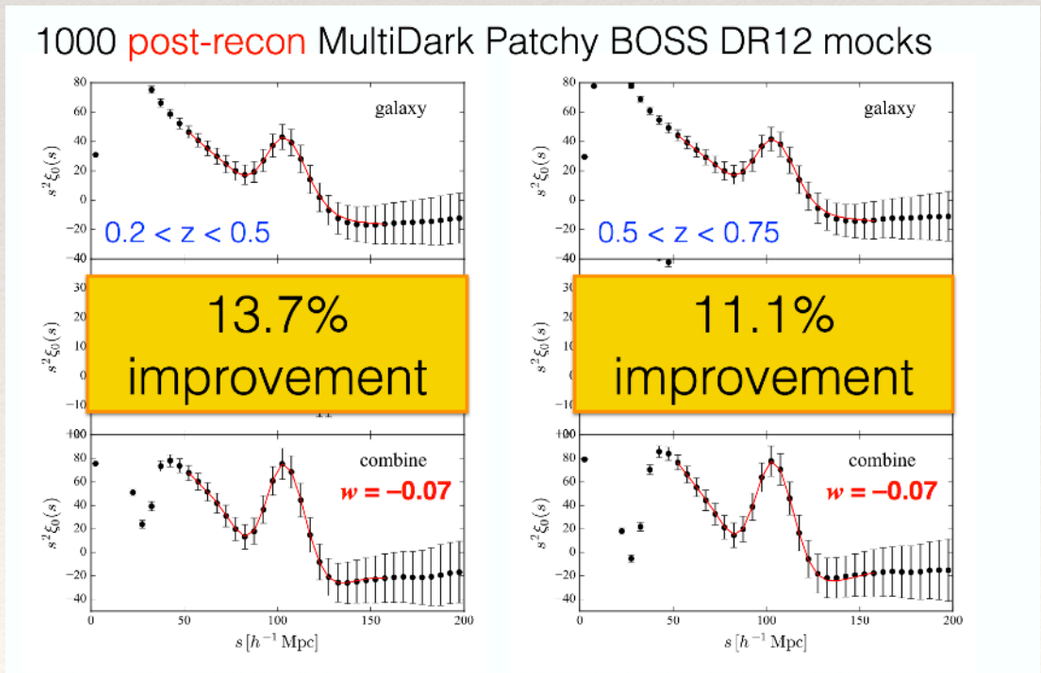
$$\xi_{\rm gg} = \frac{\mathrm{D_gD_g} - 2\mathrm{D_gR_g} + \mathrm{R_gR_g}}{\mathrm{R_gR_g}},$$
$$\xi_{\rm vv} = \frac{\mathrm{D_vD_v} - 2\mathrm{D_vR_v} + \mathrm{R_vR_v}}{\mathrm{R_vR_v}},$$
$$\xi_{\rm gv} = \frac{\mathrm{D_gD_v} - \mathrm{D_gR_v} - \mathrm{D_vR_g} + \mathrm{R_gR_v}}{\mathrm{R_gR_v}}.$$

3. Tune the weight to minimize the variance



σ α

4. Better result than just galaxies



C. Zhao, "constraining cosmology using large-scale structures" PhD thesis (2017)

Conclusion

1. Two levels of cosmology

- Background evolution
- Perturbation evolution

2. Three phases of BAO formation

- Photon and baryon coupled
- Photon and baryon decoupled
- Baryon and dark matter attract each other

3. Two steps to fit the data

- Reconstruct the galaxy distribution
- Using a fiducial cosmology, then modeling the broad-band shape and the degradation brought by non-linear evolution

thank you!

Acknowledgements: Thank Yi Mao and Cheng Zhao for helpful advises.