Cosmological Probes of LSST

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Credit:
Thanks to Martin White and Rachel Mandelbaum to provide some of lecture notes!

Outlines

- BAO
- Supernova
- Lensing
- Others we won't have time to cover:
  - Cluster counts
  - Cross-probes
  - ....

Probing DE via cosmology

- We "see" dark energy through its effects on the expansion of the universe:

$$H^2(z) = \frac{8\pi G}{3} \sum_i \rho_i(z)$$

- Three (3) main approaches
  - Standard candles
    - measure d_L (integral of H^{-1})
  - Standard rulers
    - measure d_A (integral of H^{-1}) and $H(z)$
  - Growth of fluctuations.
    - Crucial for testing extra ρ components vs modified gravity.

Standard rulers

- Suppose we had an object whose length (in *meters*) we knew as a function of cosmic epoch.
- By measuring the angle ($\Delta\theta$) subtended by this ruler ($\Delta\chi$) as a function of redshift we map out the angular diameter distance d_A

$$\Delta\theta = \frac{\Delta\chi}{d_A(z)} \qquad\qquad d_A(z) = \frac{d_L(z)}{(1+z)^2} \propto \int_0^z \frac{dz'}{H(z')}$$

- By measuring the redshift interval (Δz) associated with this distance we map out the Hubble parameter H(z)

$$\boxed{c\Delta z} = H(z) \boxed{\Delta\chi}$$

Ref: David Hogg's "Distance Measures in Cosmology"

Ideal Properties of Standard Ruler

- To get competitive constraints on Dark Energy, we need to see changes in H(z) at ~1 % level, this would give us statistical errors in DE equation of State to ~10%
- We need to be able to calibrate the ruler accurately over most of the age of the Universe.
- We need to be able to measure the ruler over much of the volume of the Universe
- We need to be able to make extra precise measurements of the ruler

Where do we find such a ruler?

- Individual Cosmological objects will probably never be uniform enough.
- Use Statistics of large scale structure of matter and radiation. (aka. if we stick with early times and large scale, perturbative treatment of the Universe will still be valid, and the calculations will be under control.)
- Preferred length scales arise from Physics of early Universe and imprinted on the distribution of matter and radiation
- Sunyaev & Zel'dovich (1970); Peebles & Yu (1970); Doroshkevitch, Sunyaev & Zel'dovich (1978); Cooray, Hu, Huterer & Joffre (2001); **Eisenstein** (2003); Seo & Eisenstein (2003); Blake & Glazebrook (2003); Hu & Haiman (2003)

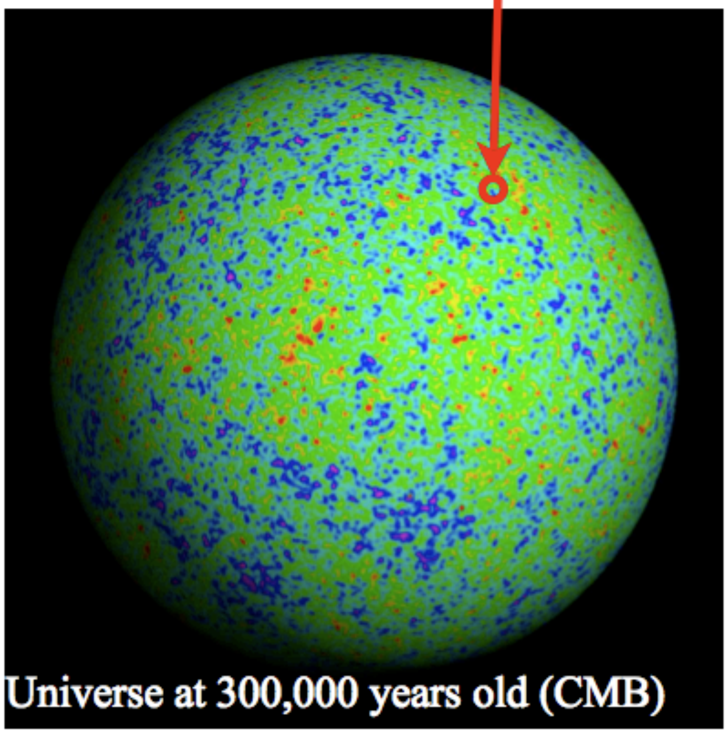
So, what is this standard ruler?

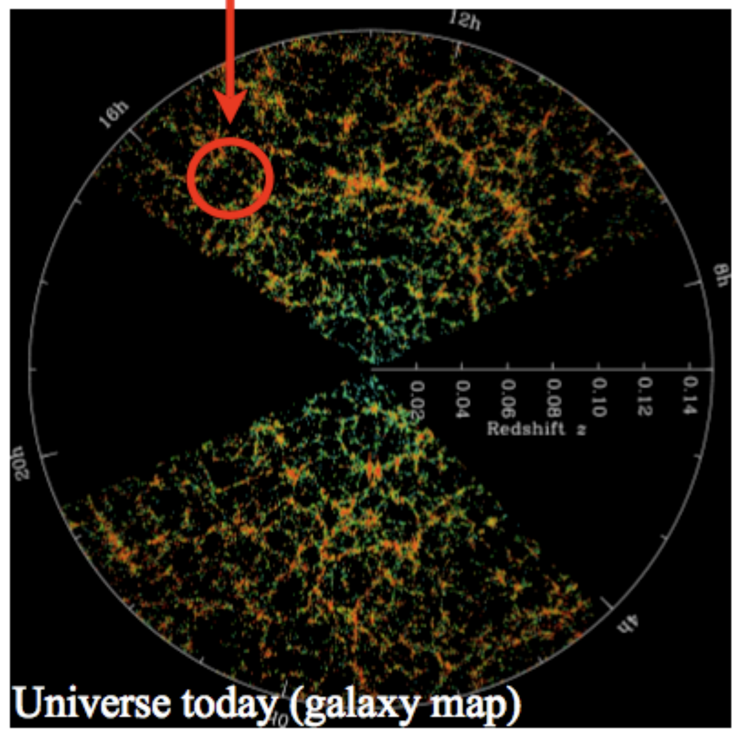
Baryon Acoustic Oscillations?!

What are baryon acoustic oscillations (BAO)?

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

...these ~unity fluctuations today





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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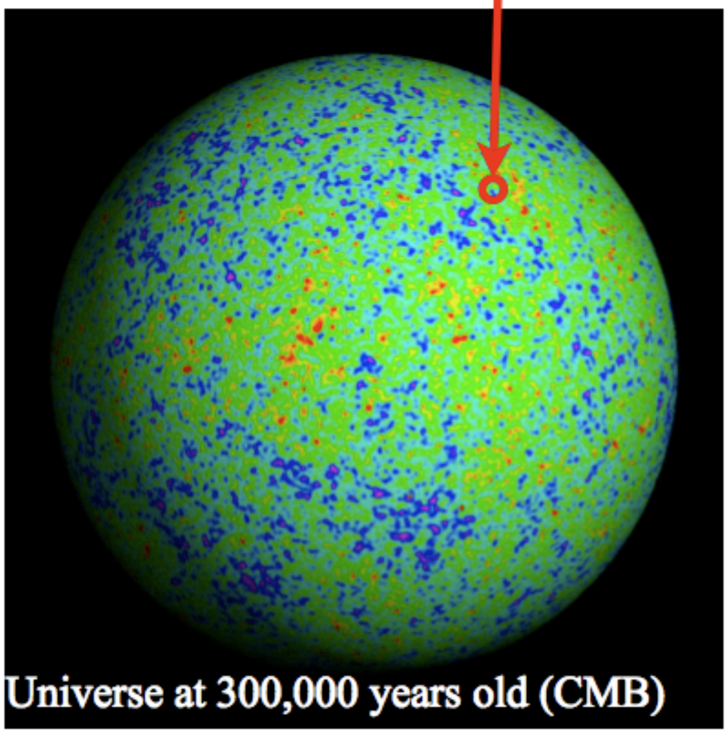

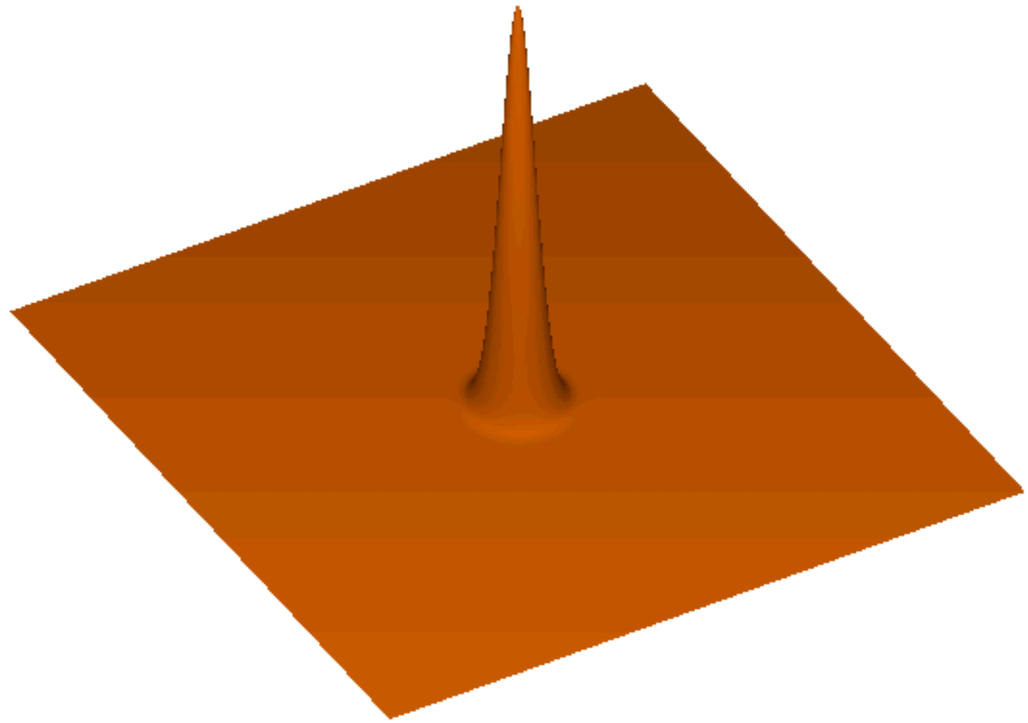

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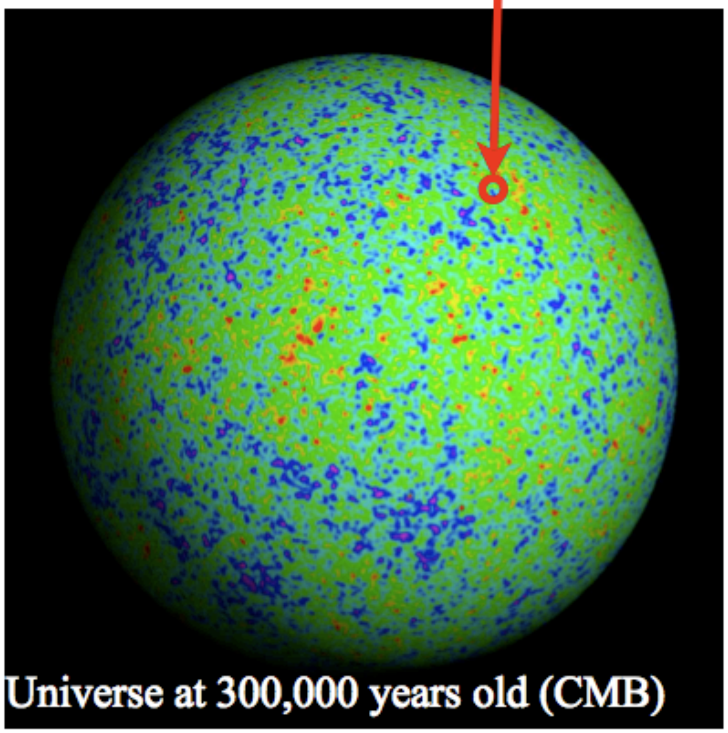

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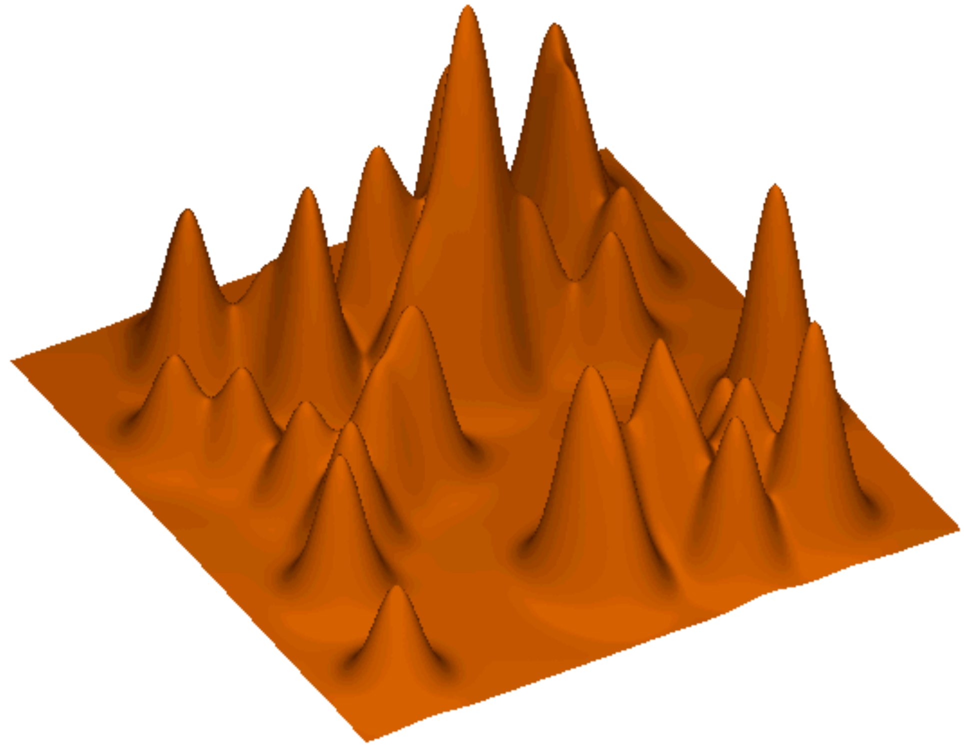

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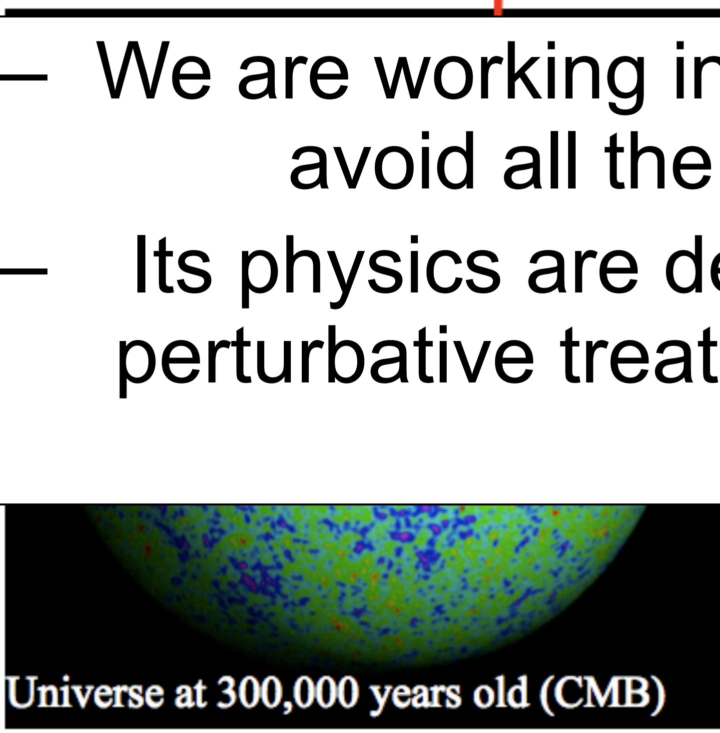
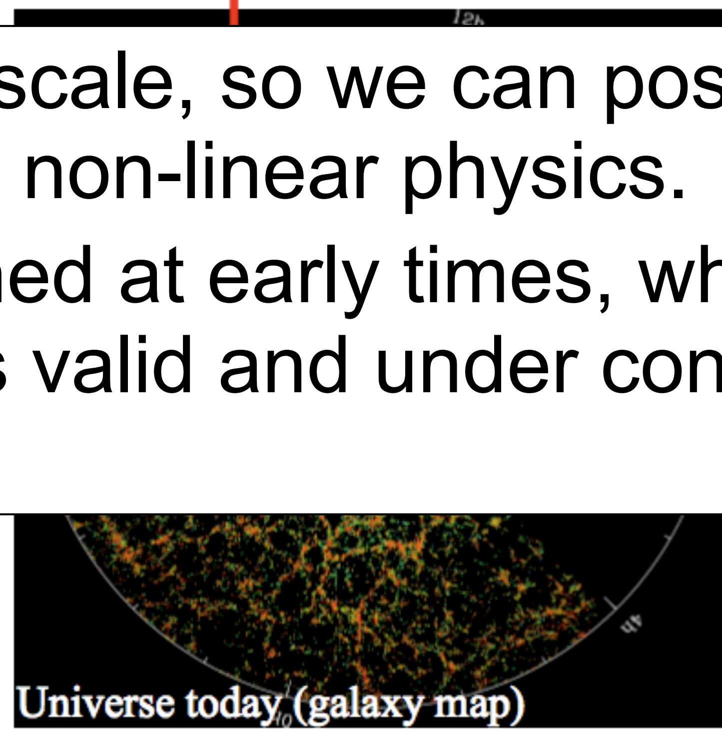


Universe at 300,000 years old (CMB)



Universe today (galaxy map)

— 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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Dark energy changes this apparent ruler size

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BAO as a Standard Ruler

- Nature has supplied us with a distinctive feature of well-known intrinsic size!
- We can measure the distance to a sample by measuring the angular size of this feature.

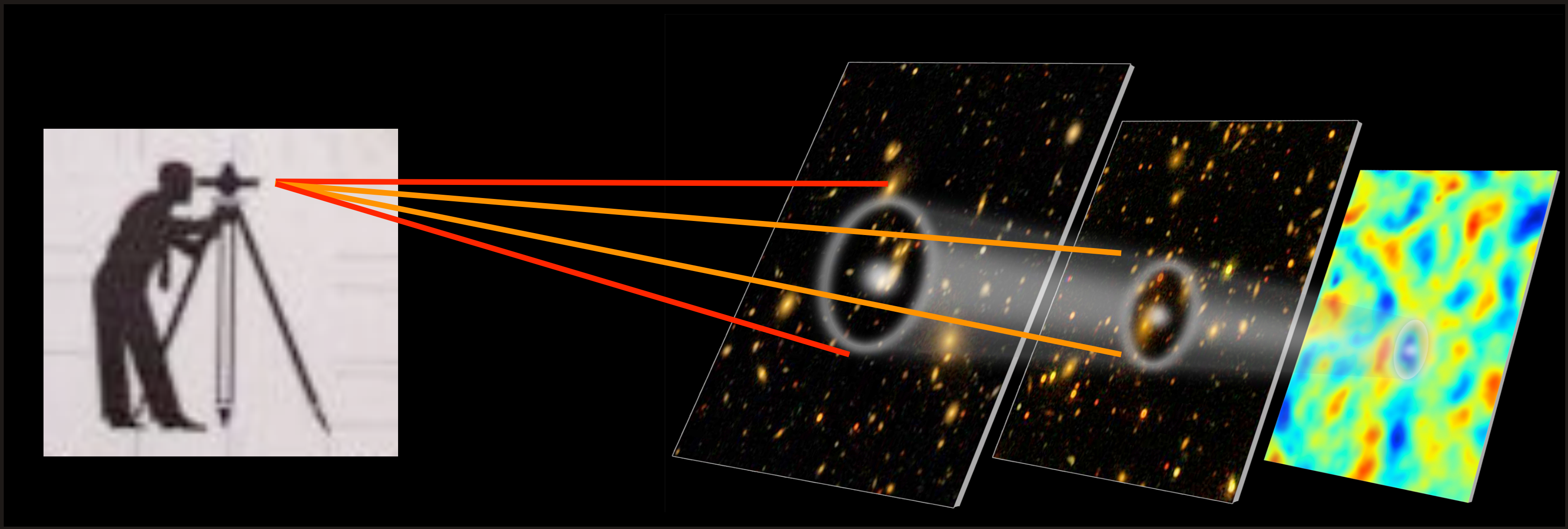


Image Credit: E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian

SDSSIII

The cartoon

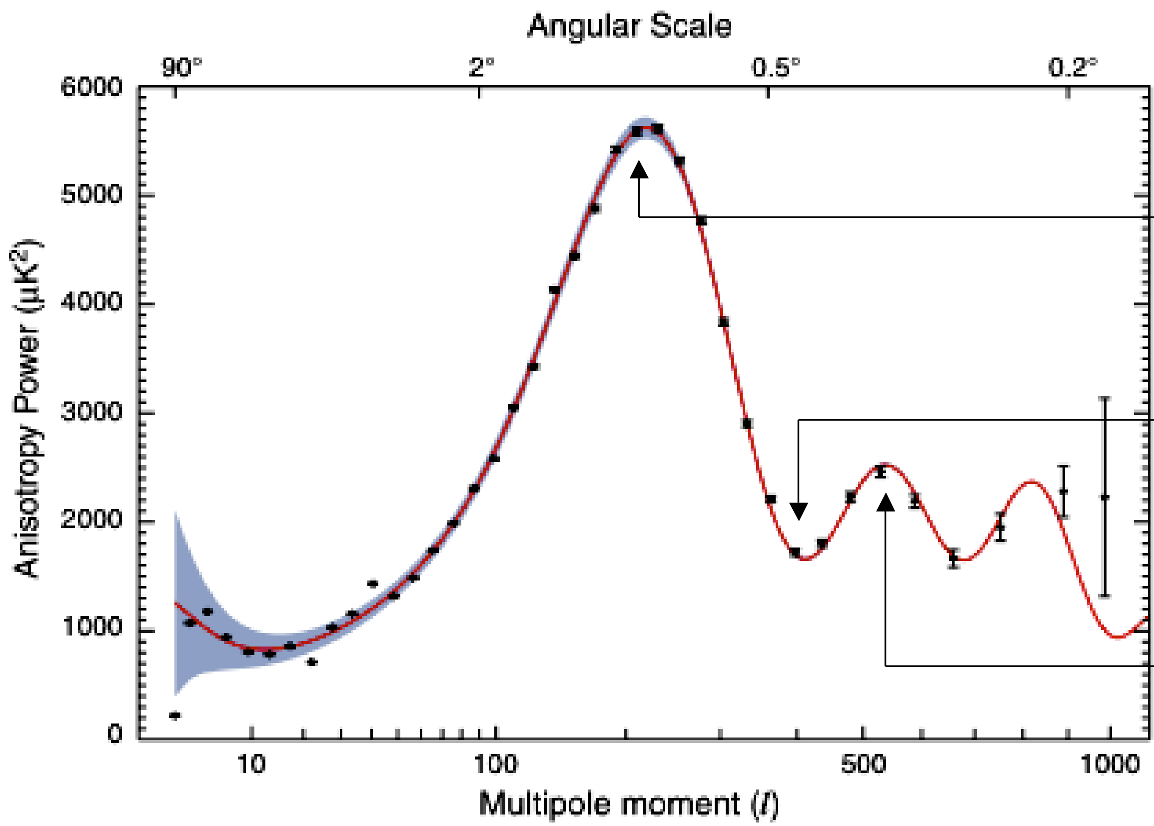
- At early times the universe was hot, dense and ionized. Photons and matter were tightly coupled by Thomson scattering.
  - Short m.f.p. allows fluid approximation.
- Initial fluctuations in density and gravitational potential drive acoustic waves in the fluid: compressions and rarefactions.

$$\frac{d}{d\tau}\left[m_{\rm eff}\frac{d\delta_b}{d\tau}\right]+\frac{k^2}{3}\delta_b=F[\Psi] \qquad m_{\rm eff}=1+3\rho_b/4\rho_\gamma$$

- These show up as temperature fluctuations in the CMB

$$\Delta T\sim\delta\rho_\gamma^{1/4}\sim A(k)\cos(kc_s t) \qquad \text{[harmonic wave]}$$

Acoustic oscillations seen!



First "compression", at $kc_s t_{ls}=\pi$. Density maxm, velocity null.

Velocity maximum

First "rarefaction" peak at $kc_s t_{ls}=2\pi$

Acoustic scale is set by the *sound horizon* at last scattering: $s = c_s t_{ls}$

Sound horizon more carefully

$$s = \int_0^{t_{\rm rec}} c_s\,(1+z)dt = \int_{z_{\rm rec}}^{\infty} \frac{c_s\,dz}{H(z)}$$

- Depends on
  - Epoch of recombination
  - Expansion of universe
  - Baryon-to-photon ratio (through c_s)

$$c_s = [3(1+3\rho_b/4\rho_\gamma)]^{-1/2}$$

Photon density is known exquisitely well
from CMB spectrum.

CMB calibration

- Not coincidentally the sound horizon is extremely well determined by the structure of the acoustic peaks in the CMB.

$$
\begin{aligned}
s &= 147.8 \pm 2.6 \text{ Mpc} \\
&= (4.56 \pm 0.08) \times 10^{24}\text{m}
\end{aligned}
$$

WMAP 3rd yr data

Dominated by uncertainty in ρ_m from poor constraints near 3rd peak in CMB spectrum.

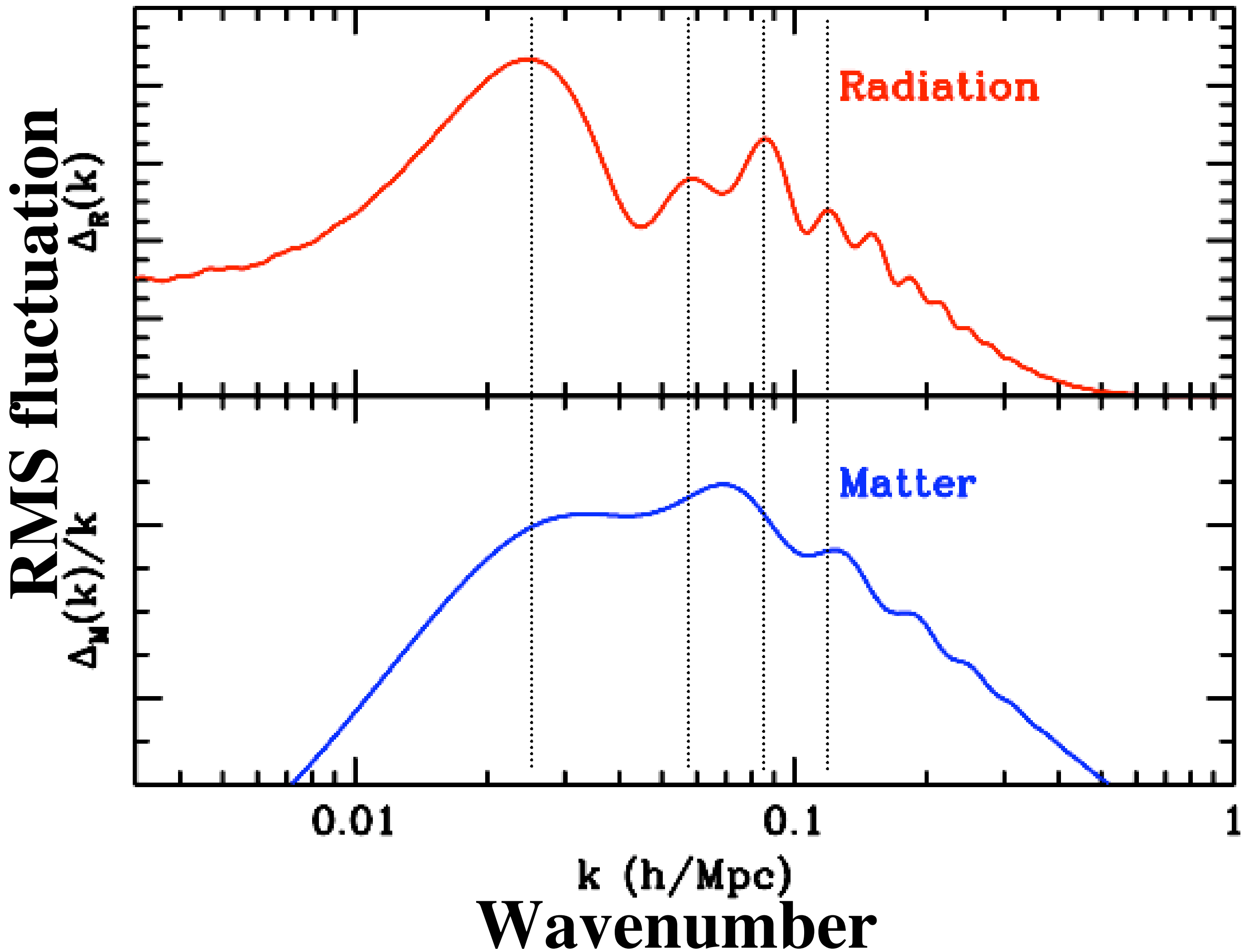
Planck has nailed this now

Baryon oscillations in $P(k)$

- Since the baryons contribute ~15% of the total matter density, the total gravitational potential is affected by the acoustic oscillations with scale set by *s*.
- This leads to small oscillations in the matter power spectrum $P(k)$.

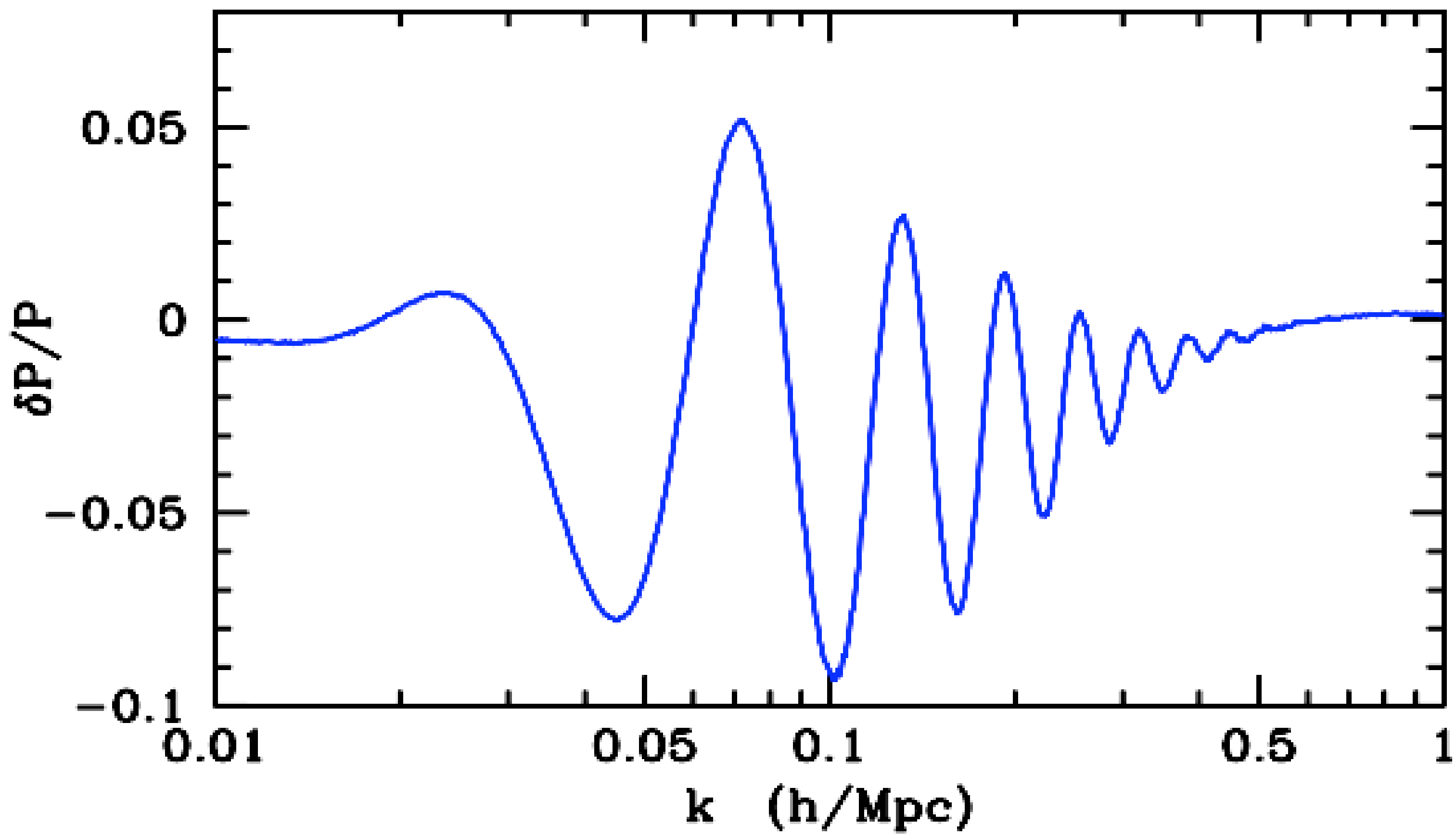
However, this is suppressed by the baryon to total matter fraction

Baryon (acoustic) oscillations



Divide out the gross trend …

A damped, almost harmonic sequence of "wiggles" in the power spectrum of the mass perturbations of amplitude $O(10\%)$.



Higher order effects

- The matter and radiation oscillations are not in phase, and the phase shift depends on k.
- There is a subtle shift in the oscillations with k due to the fact that the universe is expanding and becoming more matter dominated.
- The finite duration of decoupling means photons can diffuse out of over-densities smaller than a certain scale, leading to damping of the oscillations on small scales.
- But regardless, the spectrum is calculable and s can be inferred!

These features are frozen into the mass power spectrum, providing a known length scale that can be measured as a function of z.

DE or early universe weirdness?

- Key to computing ***s*** is our ability to model CMB anisotropies.
- Want to be sure that we don't mistake an error in our understanding of $z \sim 10^3$ for a property of the DE!
- What could go wrong in the early universe?
  - Recombination.
  - Misestimating c_s or ρ_B/ρ_γ.
  - Misestimating H(z>>1) (e.g. missing radiation).
  - Strange thermal history (e.g. decaying ν).
  - Isocurvature perturbations.
  - ….
- It seems that future measurements of CMB anisotropies (e.g. with Planck) constrain ***s*** well enough for this measurement even in the presence of odd high-*z* physics.

Eisenstein & White (2004); White (2006)
Planck Blue Book

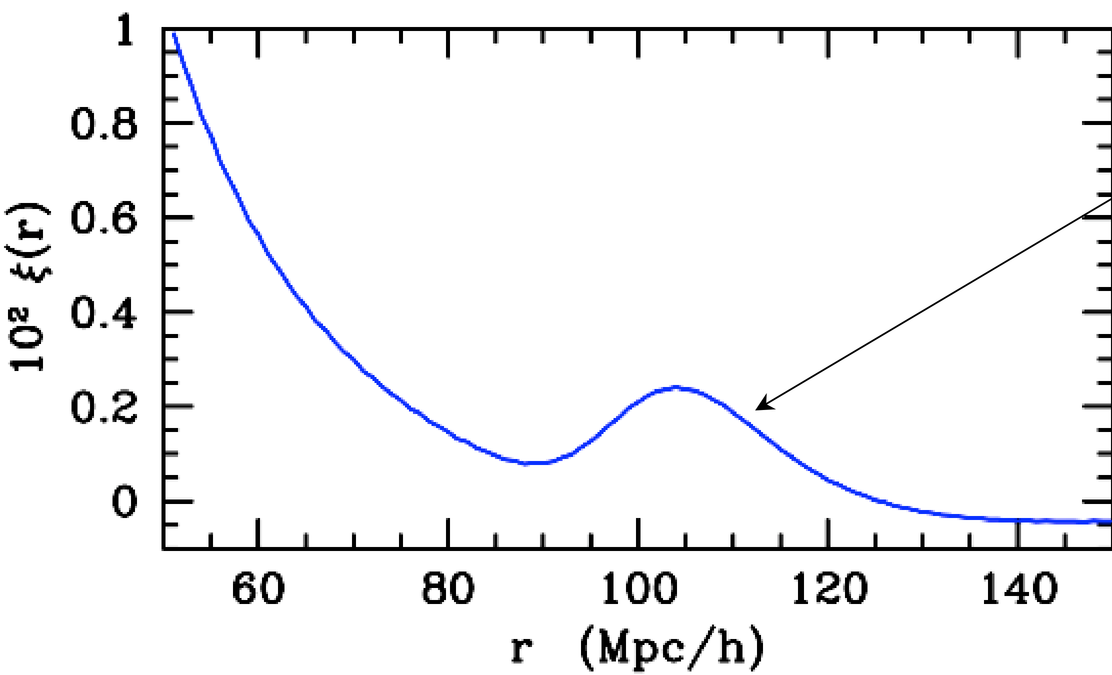
Ask/Discuss with your neighbor for next 2 mins:

What are the possible problems of BAO?

BAO in configuration space

In configuration space

- The configuration space picture offers some important insights,and will be useful when we consider non-linearities and bias.
- In configuration space we measure not power spectra but correlation functions
- A harmonic sequence would be a δ-function in *r*, the shift in frequency and diffusion damping broaden the feature.



Acoustic feature at ~100 Mpc/*h* with width ~10 Mpc/*h* (Silk scale)

So what are we waiting for?

- Find a tracer of the mass density field and compute its 2-point function.
- Locate the features in the above corresponding to the sound horizon, *s*.
- Measure the $\Delta\theta$ and Δz subtended by the sound horizon, *s*, at a variety of redshifts, *z*.
- Compare to the value at $z \sim 10^3$ to get d_A and $H(z)$
- Infer expansion history, DE properties, modified gravity.

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Those pesky details …

- Unfortunately we don't measure the linear theory matter power spectrum in real space.
- We measure:
  - the non-linear
  - galaxy power spectrum
  - in redshift space
- How do we handle this?
- We don't have a "turn-key" method for reliably going from measured galaxy positions to sound horizon constraints.
  - Hard to propagate systematics
  - Hard to do trade-off studies
  - Hard to investigate sample selection effects

BAO surveys are *always* in the sample variance dominated regime.
Cannot afford to take a large "hit" due to theoretical uncertainties!

Numerical simulations

- Our ability to simulate structure formation has increased tremendously in the last decade.
- Simulating the dark matter for BAO:
  - Meiksin, White & Peacock (1999)
    - 10^6 particles, 10^2 dynamic range, ~1Gpc^3
  - Springel et al. (2005)
    - 10^{10} particles, 10^4 dynamic range, 0.1Gpc^3
- Our understanding of galaxy formation has also increased dramatically.

Numbers vs Insight

- Trying to learn from these simulations

  What range of behaviors do we see?
  Which kind of galaxy prescription works best?
  How do we parameterize the effects?
- Can we gain an analytic understanding of the issues?
- Are there shortcuts for describing the complexities?
  - e.g. the Lagrangian displacement distribution (ES&W '07)
- Can we push further into the non-linear regime?
  - Reconstruction (Eisenstein et al. 2007).

Effects of non-linearity

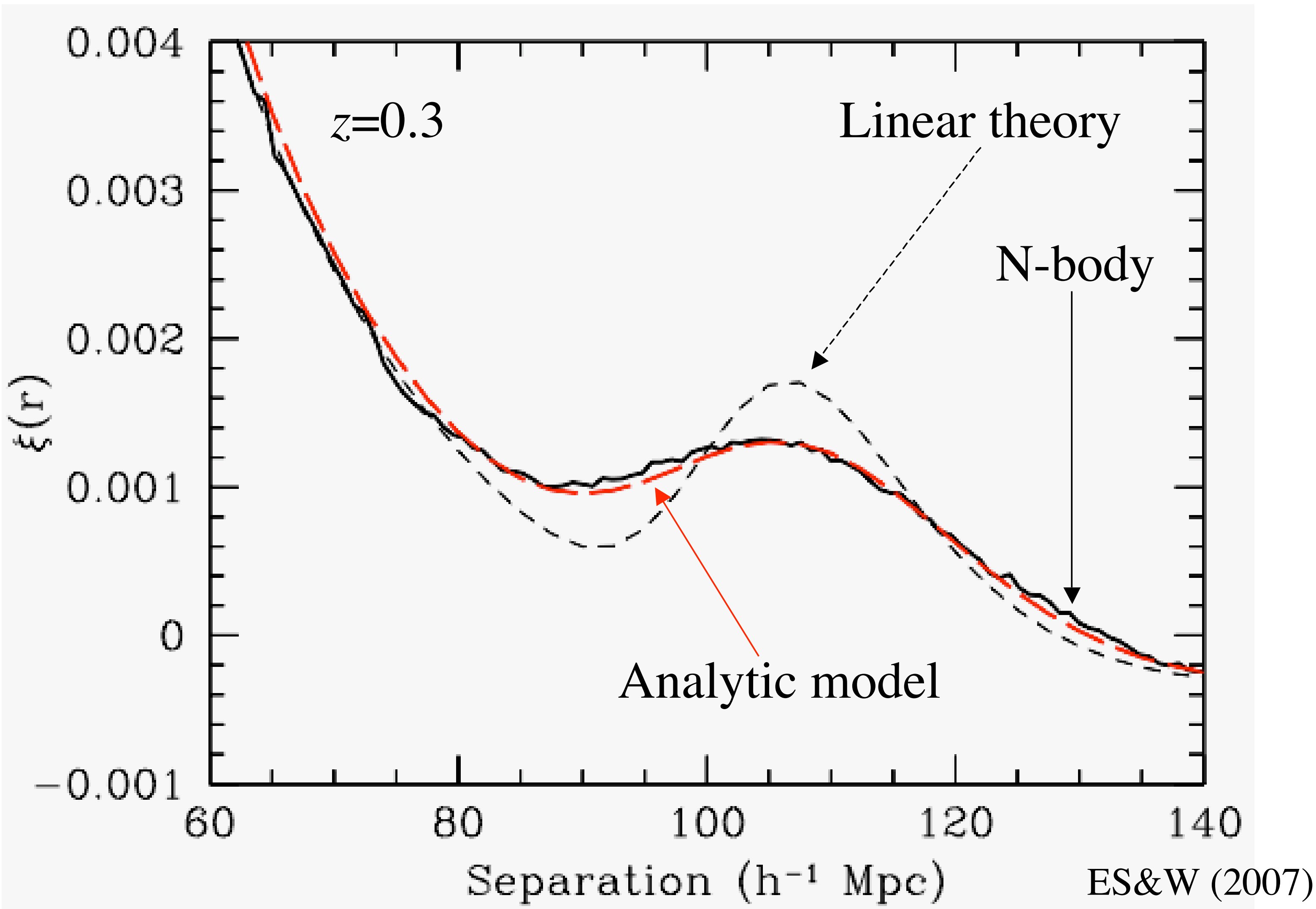
As large-scale structure grows, neighboring objects "pull" on the baryon shell around any point. This super-clustering causes a broadening of the peak [and additional non-linear power on small scales]. From simulations or PT find:

$$\Delta^2(k) = \Delta^2_{\rm lin}(k)\exp\left[-k_{||}^2\Sigma_{||}^2 + k_\perp^2\Sigma_\perp^2\right] + \cdots$$

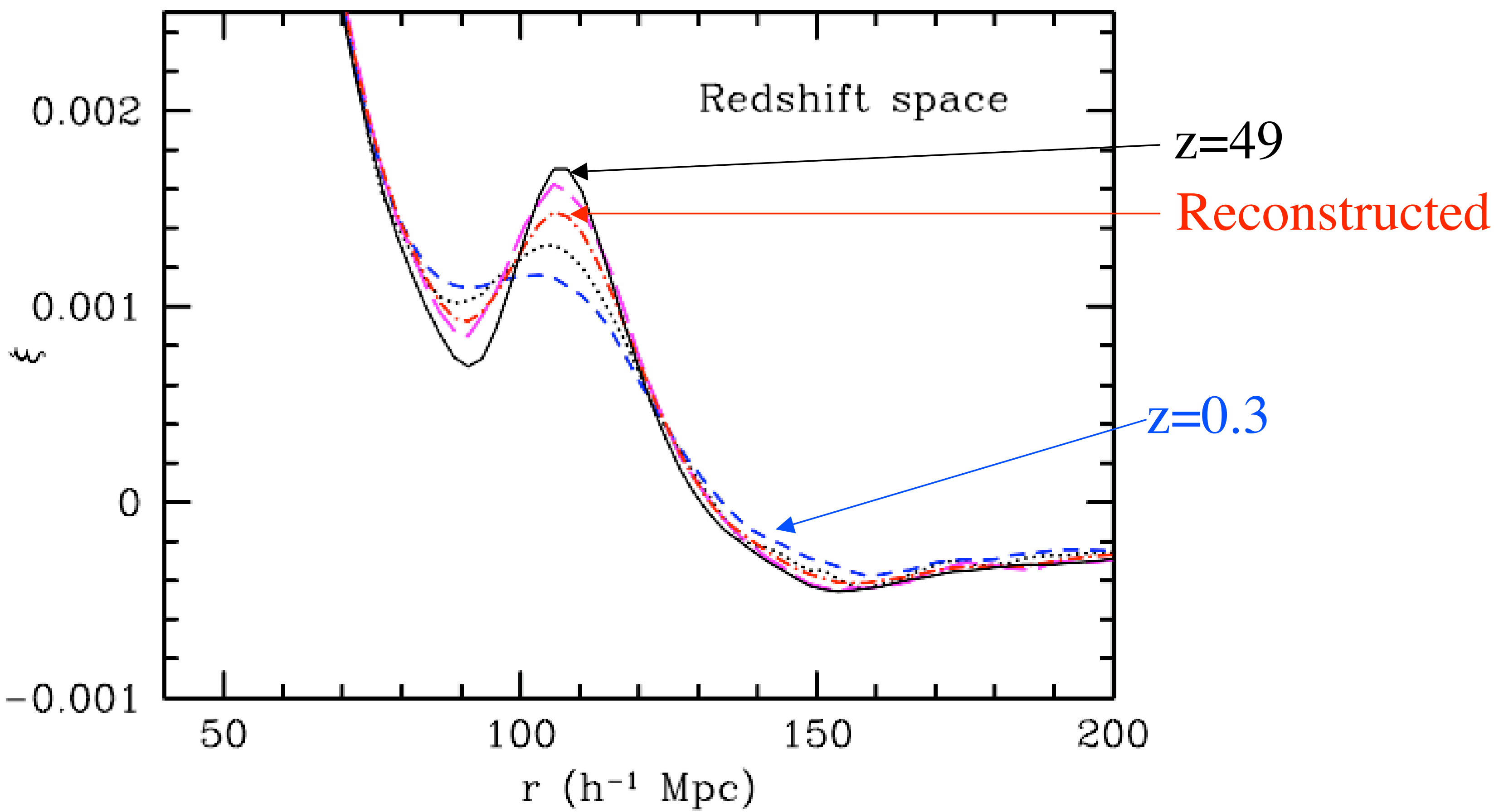
This does a reasonable job of providing a "template" low-z spectrum, and it allows us to understand where the information lives in Fourier space.

Eisenstein, Seo & White (2007)
Smith, Scoccimarro & Sheth (2007)
Eisenstein et al. (2007)

Non-linearities smear the peak



Reconstruction: simplest idea



Eisenstein, Seo, Sirko, Spergel. 2007,
Xu, Padmanbhan et al. 2012, Padmanbahn,Xu et al. 2012,
Vargas, Ho +SDSS3 2014, Anderson (SDSS3) et al. 2014

Reconstruction

- The broadening of the peak comes from the “tugging” of large-scale structure on the baryon “shell”.
- We measure the large-scale structure, and hence the gravity that “tugged”.
- Half of the displacement in the shell comes from “tugs” on scales > 100 Mpc/h
- Use the observations to “undo” non-linearity
  - Measure $\delta(x)$, infer $\phi(x)$, hence displacement.
  - Move the galaxies back to their original positions.
- Putting information from the phases back into $P(k)$.
- There were many ideas about this for measuring velocities in the 80’s and 90’s; but not much of it has been revisited for reconstruction (yet).

Musings on non-linearity

- Fourier space
  - Excess power on small-scales.
  - Mode coupling erases oscillations at high *k*
  - Non-linearities appear to encroach on signal.
  - Unclear whether acoustic scale is shifted.
- Configuration space
  - Non-linearities “smear” initial peak by ~10Mpc
  - Smearing decreases contrast (lower S/N).
  - Existence of collapsed halos increases ξ variance even at 100Mpc -- decreasing S/N.
  - A bias/shift in peak position can be estimated.

Galaxy bias

- The hardest issue is galaxy bias.
  - Galaxies don't faithfully trace the mass
- ... but galaxy formation "scale" is << 100Mpc so effects are "smooth".
  - In *P*(*k*) effect of bias can be approximated as a smooth multiplicative function and a smooth additive function.
- Work is on-going to investigate these effects:
  - Seo & Eisenstein (2005)
  - White (2005)
  - Schulz & White (2006)
  - Eisenstein, Seo & White (2007)
  - Huff et al. (2007)
  - Angulo et al. (2007)
  - Smith et al. (2007)
  - Padmanabhan et al. (20XX)

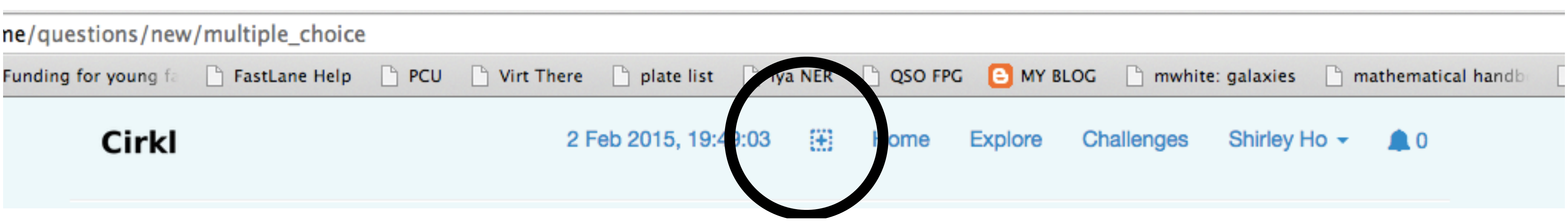
$$\Delta^2_g(k) = B^2(k)\,\Delta^2(k) + C(k)$$

Rational functions
or polynomials

Break Time:

Please Sign in at
template.cirkl.me
and answer the challenges I have sent you all!
for next 10 mins.

If you finish early, please consider making your own challenge and Challenge me or your fellow classmates.
Simply Click the “plus within box” sign next to “Home”



SUPERNOVA COSMOLOGY

Additional refs on SNe:

http://supernova.lbl.gov/PDFs/PhysicsTodayArticle.pdf

http://www.astro.ucla.edu/~wright/sne_cosmology.html

http://adsabs.harvard.edu/abs/2012arXiv1201.2434W

Type Ia supernova properties

- Spectral properties as a function of time are consistent for different supernovae
- "Light curves" have the same general shape for each one
- Variations in shape correlate with luminosity
  - Depends on wavelength
  - Relates to varying amounts of radioactive Ni from progenitor explosion

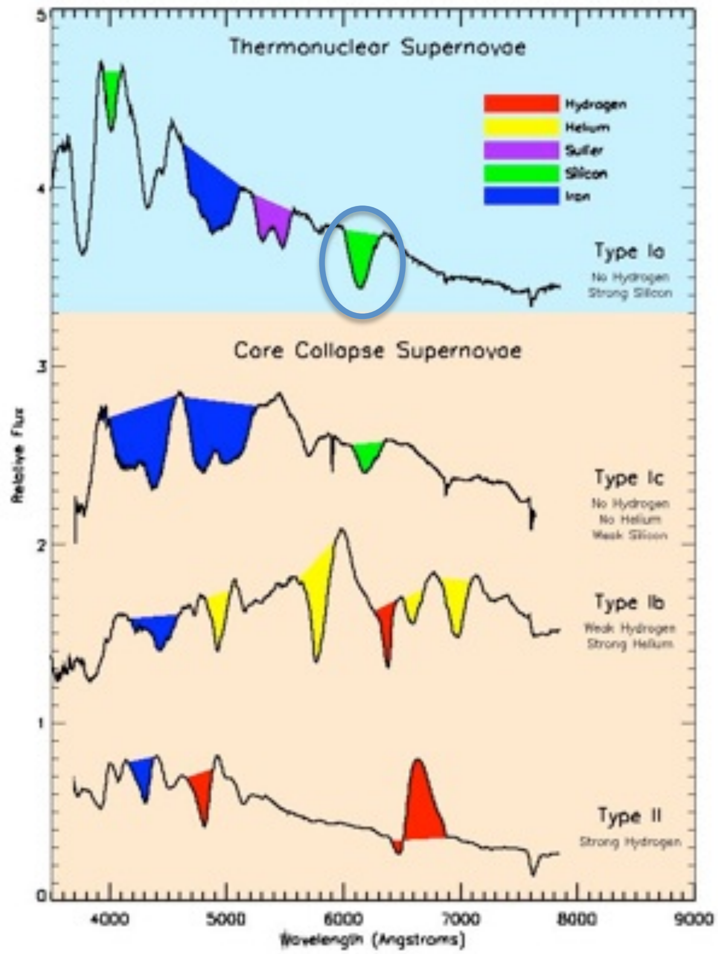
What is a supernova?

- Visual impression:
  - Suddenly there's a very bright star where there wasn't one before, often on a faint galaxy
  - Its light fades on time scales of a few weeks
- Gut reaction: something blew up!
  - A supernova can emit radiation in ~1 month that exceeds the total amount that the sun will radiate in its lifetime!

Different types

First question:
Hydrogen?

Second question:
Silicon?



This type is 2x as common as Type I.

What observations are needed?

- Detection, with automated monitoring
- Flux measurement (calibrated) vs. time, at least every few days in rest frame
- At least two bands of monitoring, to get color
- Spectrum / redshift

Challenge

- Depends on chance
- Rare: ~1/galaxy/century
- Limited time to make many observations

Need to make sure it is the right type!

- Spectra: compare spectral features against templates
- Can be low-resolution spectroscopy (R~250)
- Still takes ~10x the time of the imaging
- Other options are available but not adequately explored
- Or cheat: use only those from non-star-forming hosts

Some key equations

$$D_L = (L_{bol} / 4\pi f_{bol})^{1/2}$$

$$D_L = (1+z)^2 D_A = (1+z) D_C \text{ [flat]}$$

$$D_C = c \int dz' / H(z')$$

$$[H(z')/H_0]^2 = \Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \Omega_\Lambda \text{ [flat]}$$

These tell us about dependence on expansion history. Dependence on curvature also comes in several places.

Tough systematics

- Dust: dims and reddens the light that is observed
  - *Question: why?*
  - *Less important in NIR*
- K-correction, and the limits of optical imaging
- Evolution in SNe properties with redshift
- Contamination by non-Ia
- Flux calibration

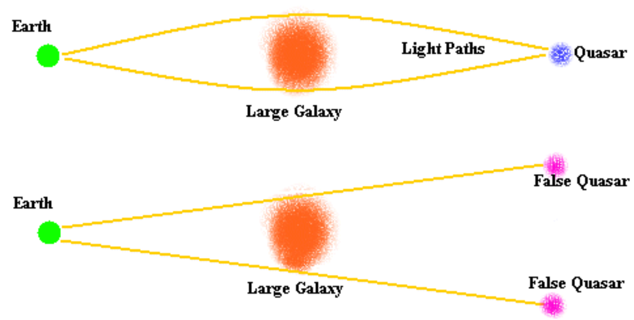
"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

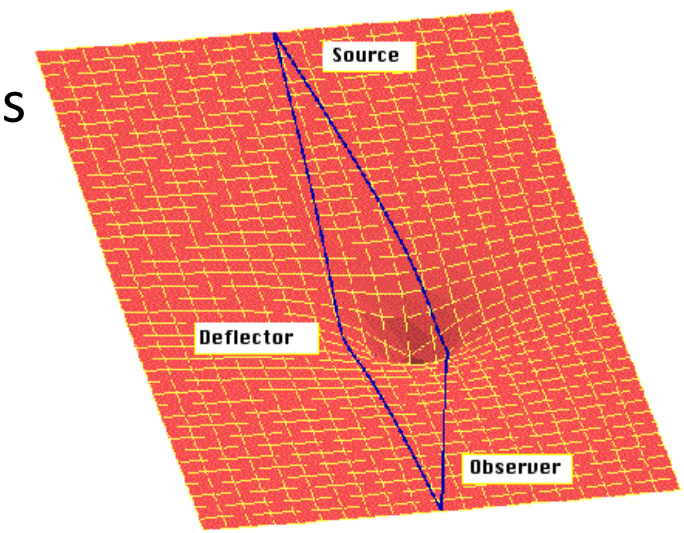
Ask/Discuss with your neighboring physicists for next 5 mins.
1) Can you come up with other types of standard candles?
2) Suggestions of possible systematics of standard candles you just came up with?

Gravitational Lensing

Some history

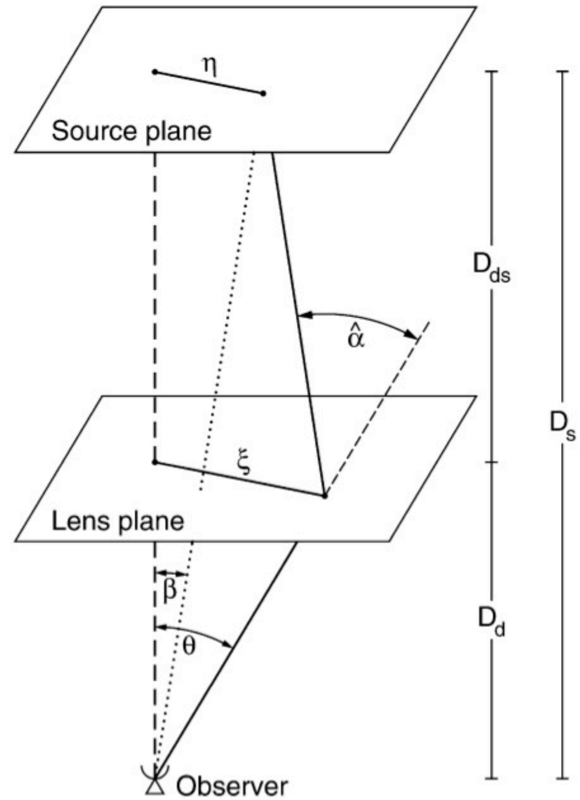
- Basic principles in General Relativity
  - Matter (any) causes space-time curvature
  - Light follows geodesics
  - With curvature, the least-time path might not be straight!
  - Initially stars; later galaxies





- Thin lens approximation
- Projected mass
- Exaggerated scales! (angles are small)
- Actual deflection angle: integrate over density of lens
- Note: achromatic effect

$$\hat{\alpha} = \frac{4G}{c^2}\frac{M(<\xi)}{\xi}$$



Weak lensing

- Strong lensing occurred when

$$\kappa = \Sigma / \Sigma_{crit} \sim 1$$

- Weak lensing: $\kappa \ll 1$
  - Good news: ubiquitous
  - Bad news: small effects on images
- To understand, need to consider the gravitational potential

What is ψ?

- 2d analogy of the Newtonian gravitational potential:

$$\psi(\vec{\theta}) = \frac{1}{\pi} \int_{\mathbb{R}^2} d^2\theta' \, \kappa(\vec{\theta}') \ln |\vec{\theta} - \vec{\theta}'|$$

- Can relate κ and γ to its second derivatives

Mapping from source plane to

- 1-to-1 in the weak lensing regime
- Can (locally) linearize in most realistic situations

$$I(\vec{\theta}) = I^{(s)}[\vec{\beta}(\vec{\theta})]$$

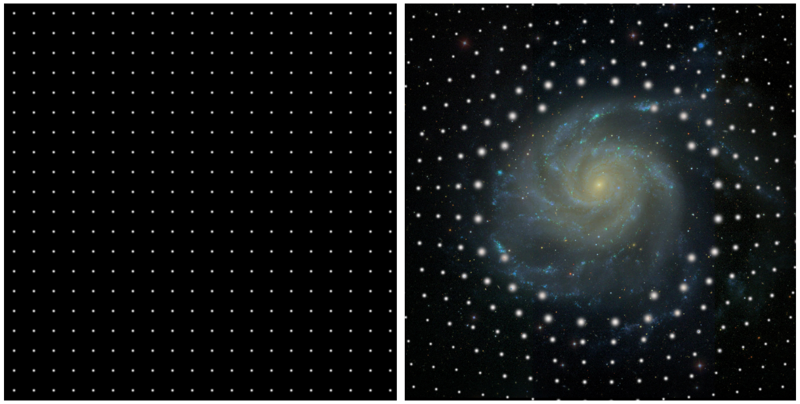
$$\mathcal{A}(\vec{\theta}) = \frac{\partial\vec{\beta}}{\partial\vec{\theta}} = \left(\delta_{ij} - \frac{\partial^2\psi(\vec{\theta})}{\partial\theta_i\partial\theta_j}\right) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

- Given some image position θ_0 which corresponds to source position β_0,

$$I(\vec{\theta}) = I^{(s)}\left[\vec{\beta}_0 + \mathcal{A}(\vec{\theta}_0)\cdot(\vec{\theta}-\vec{\theta}_0)\right]$$

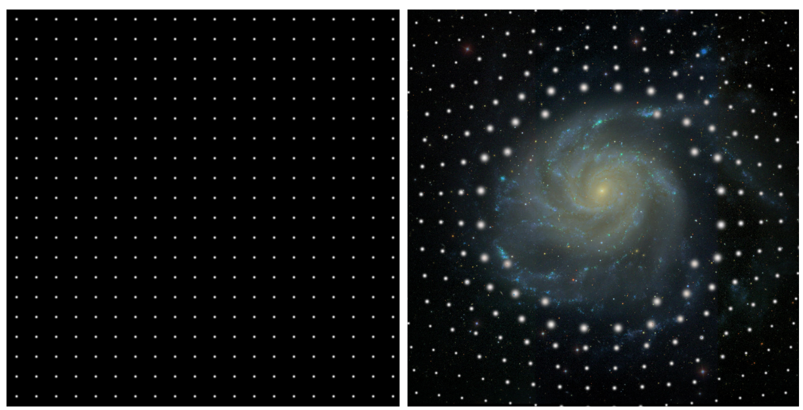
What does convergence do?

What does convergence do?



What does convergence do?

- Magnification of size
  - We don't have any null test for this.



What does convergence do?

- Magnification of size
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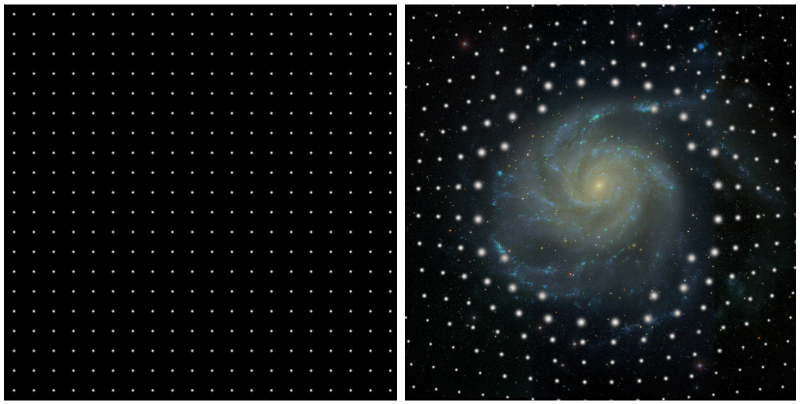
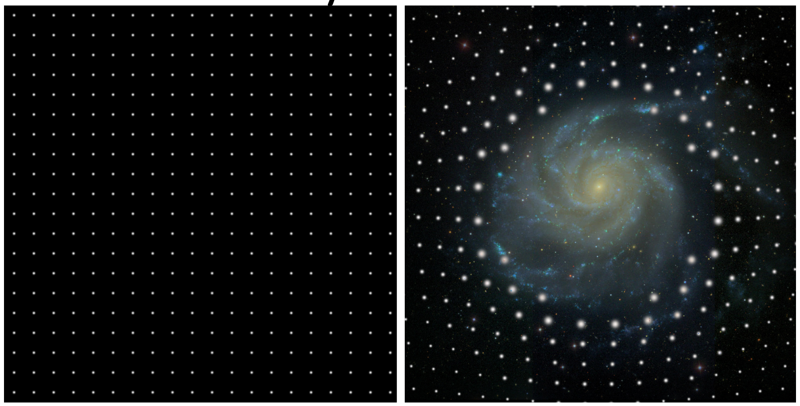
- Decrease of number density



What does convergence do?

- Magnification of size
  - We don't have any null test for this.
- Decrease of number density
- Increase brightness so more objects are visible
  - Both of these are easy to confuse with clustering.



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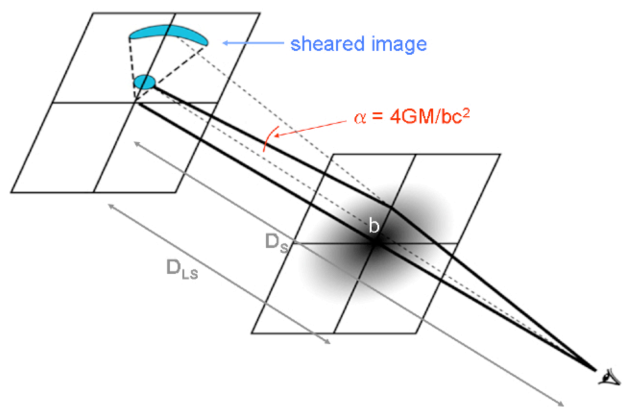
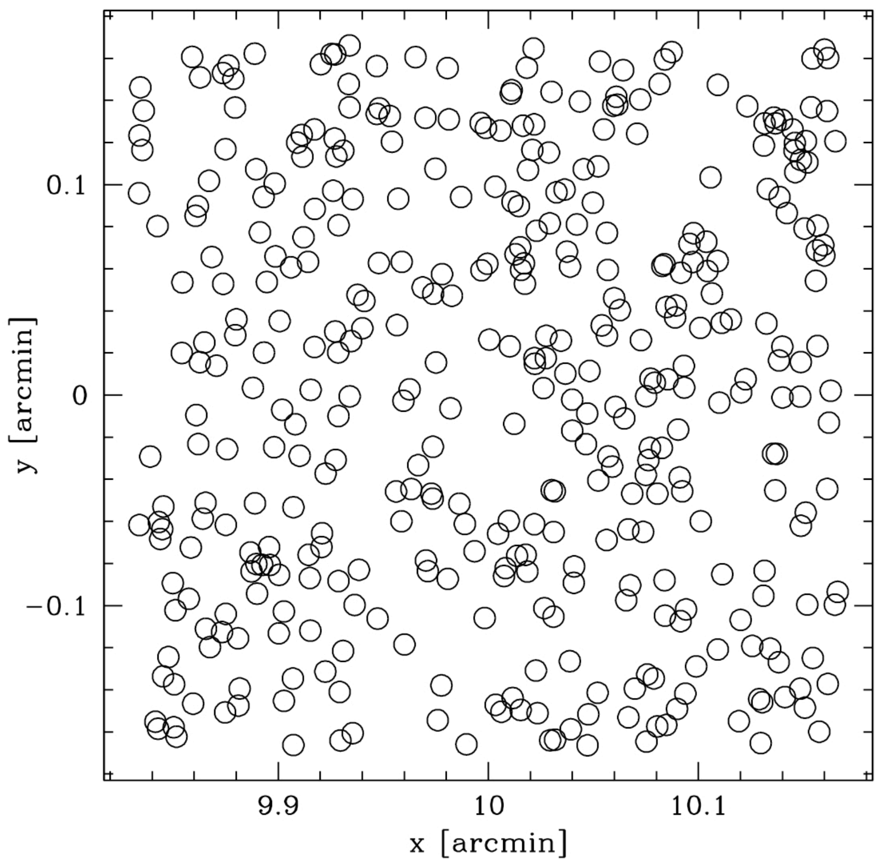


Weak lensing illustration



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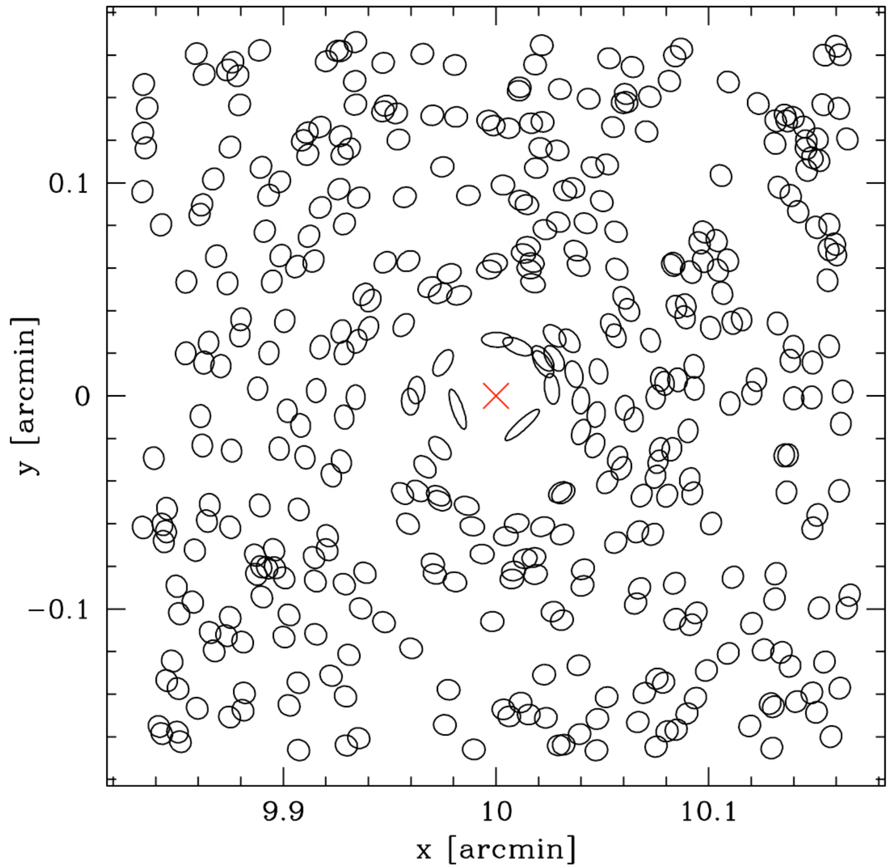

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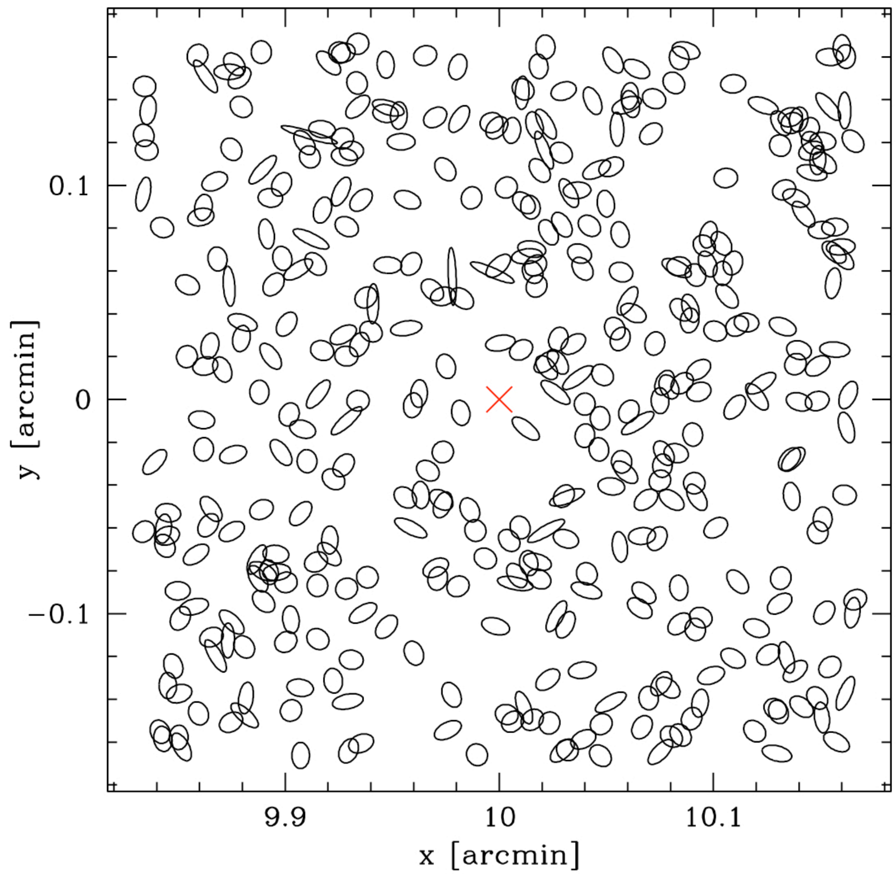

Why might this be hard?

3 mins: Discuss with your neighbor why this may be hard?

What we want to measure: statistics of

Correlation function:
probability in excess of random
$dM = \bar{\rho}\,[1+\xi_{mm}(r)]\,dV$

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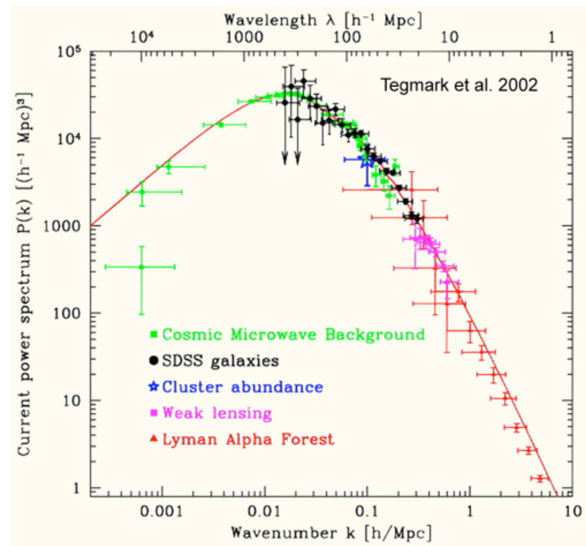

Tegmark & Zaldarriaga (2002)

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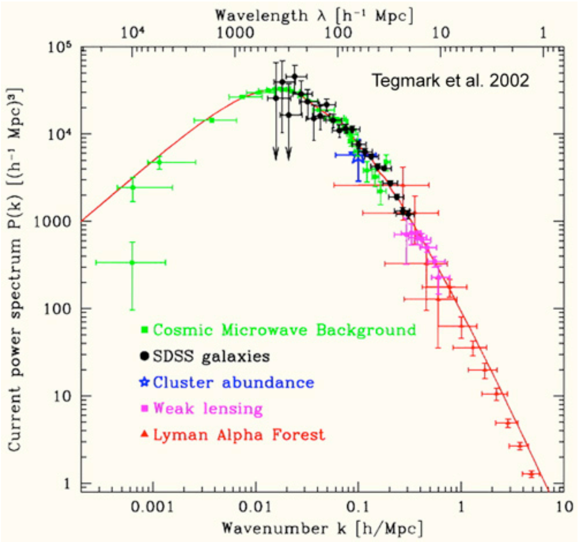

Tegmark & Zaldarriaga (2002)

Measure at one redshift:
- amplitude of fluctuations $\boldsymbol{\sigma_8}$,
- matter density compared to critical, $\boldsymbol{\Omega_m}$

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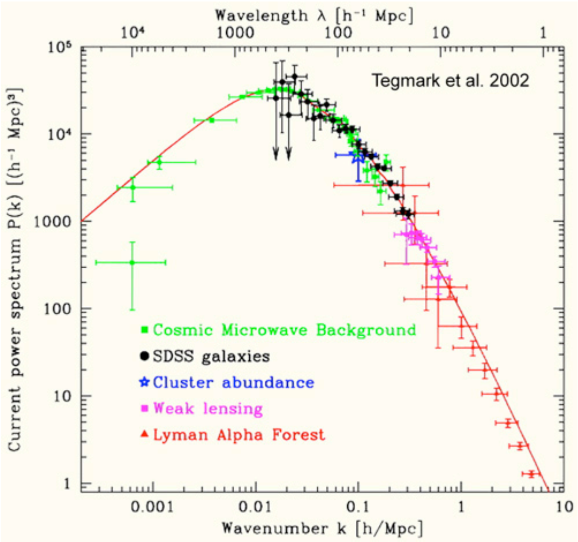

Tegmark & Zaldarriaga (2002)

Measure at several redshifts:
- growth of structure
- **nature of dark energy! (w)**

Houston, we have a problem

We most easily see **galaxies**, not dark matter!!

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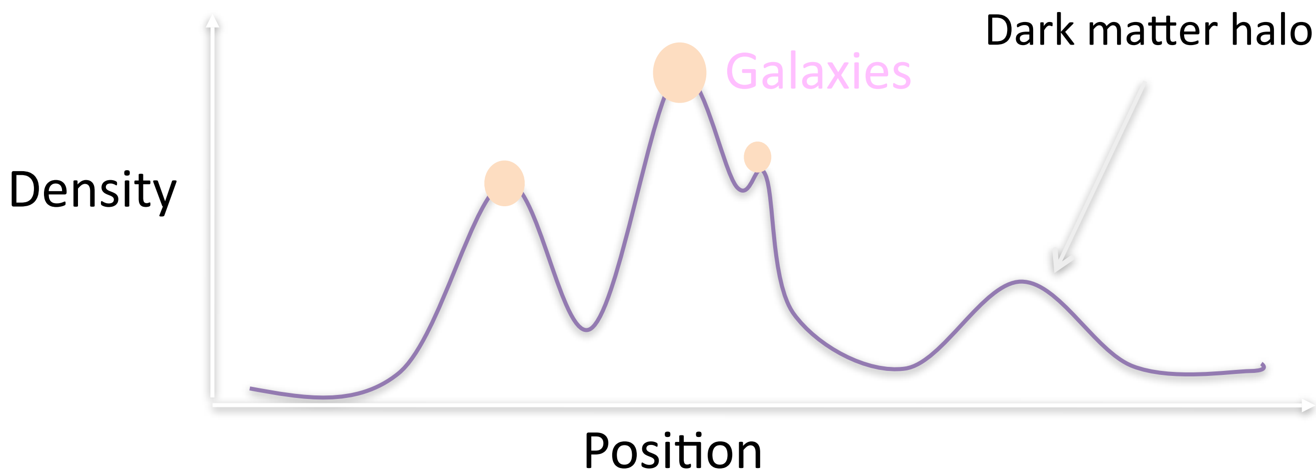

Implications for clustering

Can we use galaxy clustering $P_{gg}(k)$ to constrain matter clustering $P_{mm}(k)$?

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$$P_{gg}(k) = b^2(k)\, P_{mm}(k)$$

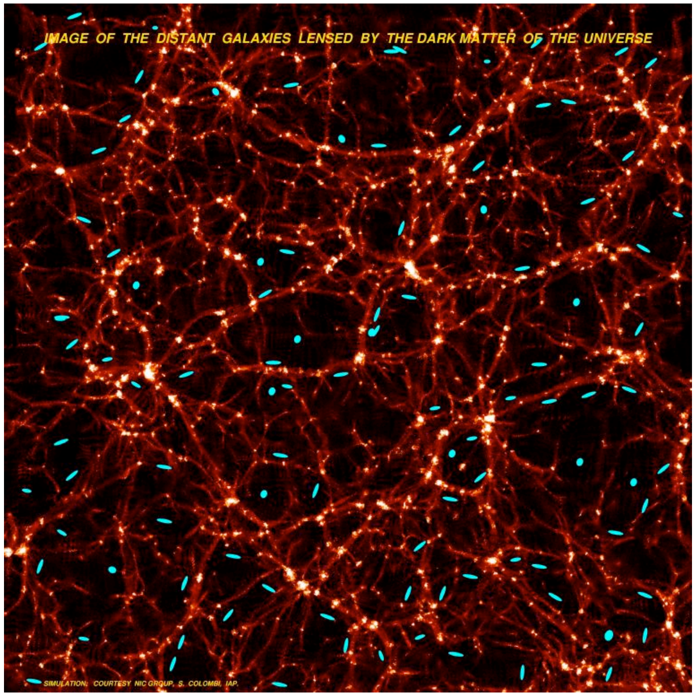
Galaxy bias:

- Depends on galaxy mass, color
- Depends on physical scale
- **Degeneracy between galaxy bias and matter power spectrum!**

Lensing to the rescue?

- We can measure statistics of the matter distribution now!
- Easiest theoretically: ξ_{mm} – measure directly?
- Or, combine ξ_{gg} with ξ_{gm} to infer ξ_{mm}?
- There are two types of lensing measurements, one for each of these

Cosmic shear



- Galaxy shape auto-correlation
- Measures matter power spectrum (a statistical map of large-scale structure)
- If measured at several redshifts ➔ an especially powerful probe of the ***growth*** of structure, which depends on ***dark energy***

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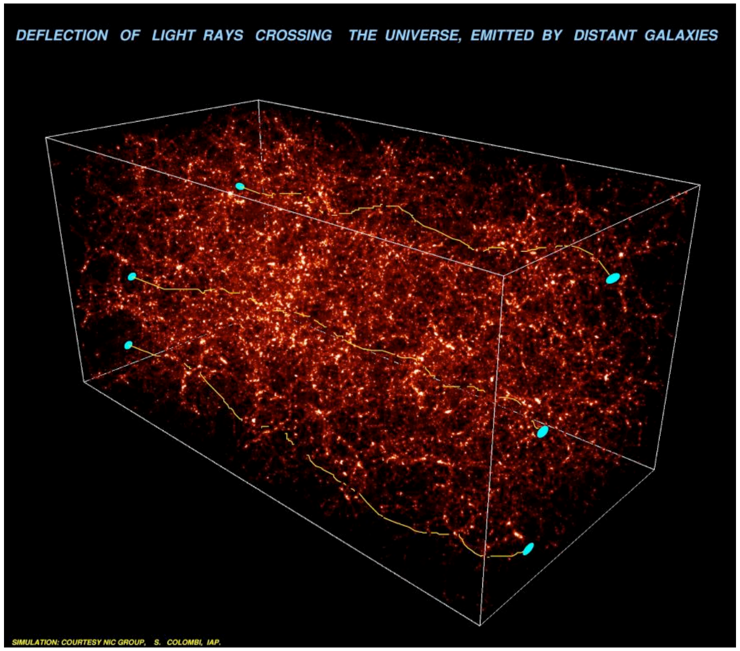

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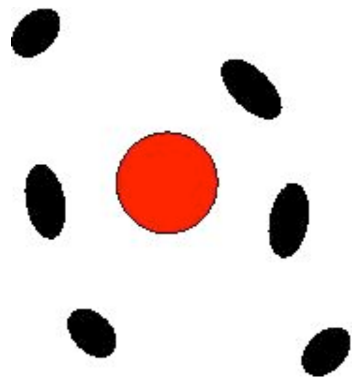
Galaxy-galaxy lensing

- ***Cross***-correlation: Lens galaxy positions versus source galaxy shapes



- Reveals ***total*** matter distribution around lens galaxies or clusters (galaxy-mass correlation):

Matter surface density Σ

(a projection of 3d cross-correlation ξ_{gm})

Main sources of noise

- Statistical uncertainty in shears
- “Cosmic variance”

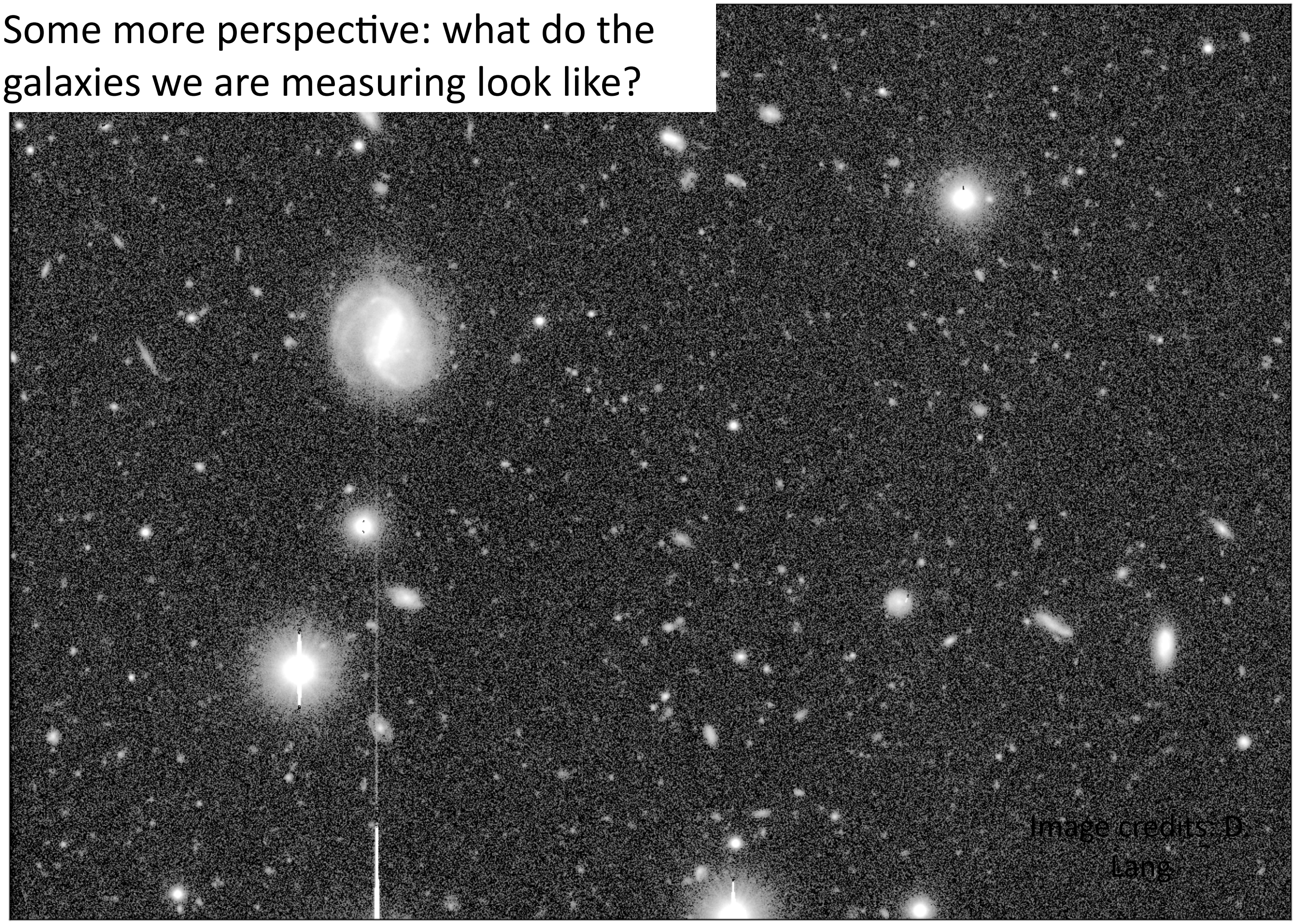
“Shape noise”: random ellipticities

- Typical shear ~ 0.01
- Typical galaxy ellipticity ~ 0.35
- *Question: how many galaxies do you need to measure shear to 10%? What is typical sky area?*
- *What if you want to measure it to 0.1%?*

Shape measurement error

- Effects of pixel noise: typical scatter in ellipticity ~ 4/(S/N)
- Adds in quadrature with shape noise
- *Question: at what S/N is this comparable to shape noise?*
- *What can we conclude about galaxy populations to use*?

Some more perspective: what do the galaxies we are measuring look like?



Other Probes!

- Time Delays with strong lenses
- Cluster Abundances
- Joint Probes
- ...Your creation?

Cosmic Distances

- Measuring extragalactic distance is hard.
  - Need intrinsic size or luminosity.
- Distances tell us the age and size of the Universe.
- Measuring distance vs. redshift helps us infer the composition of the Universe.

Image: Robert Lupton & SDSS

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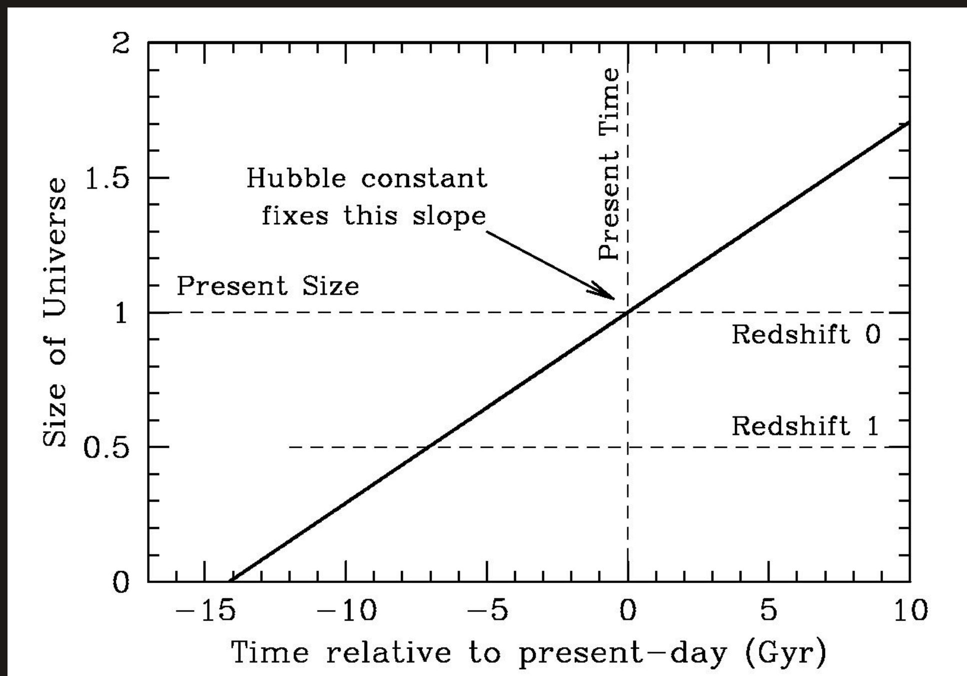

SDSS III

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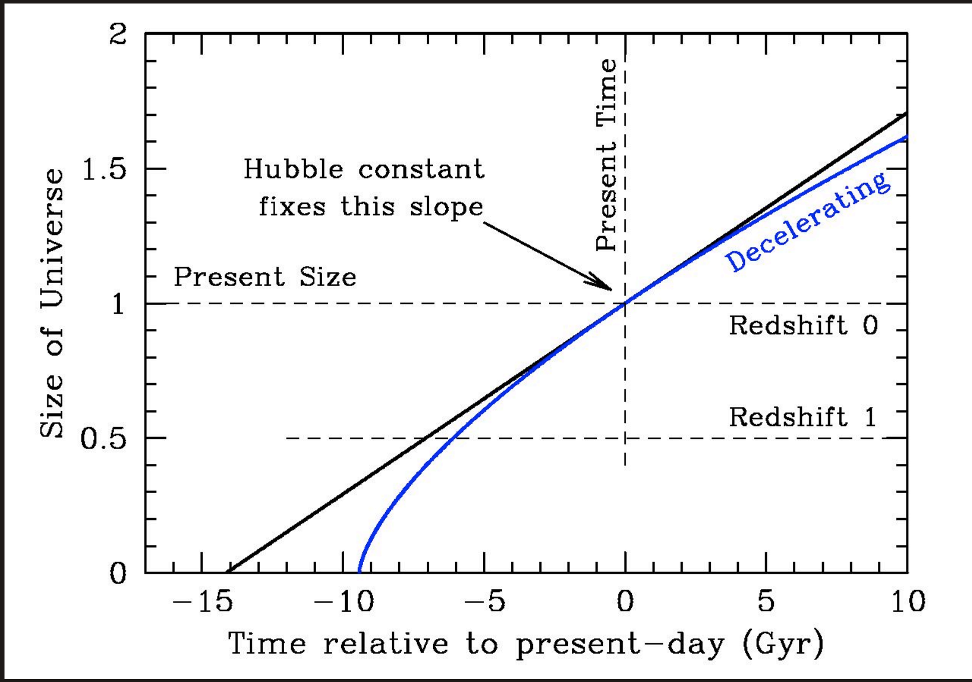
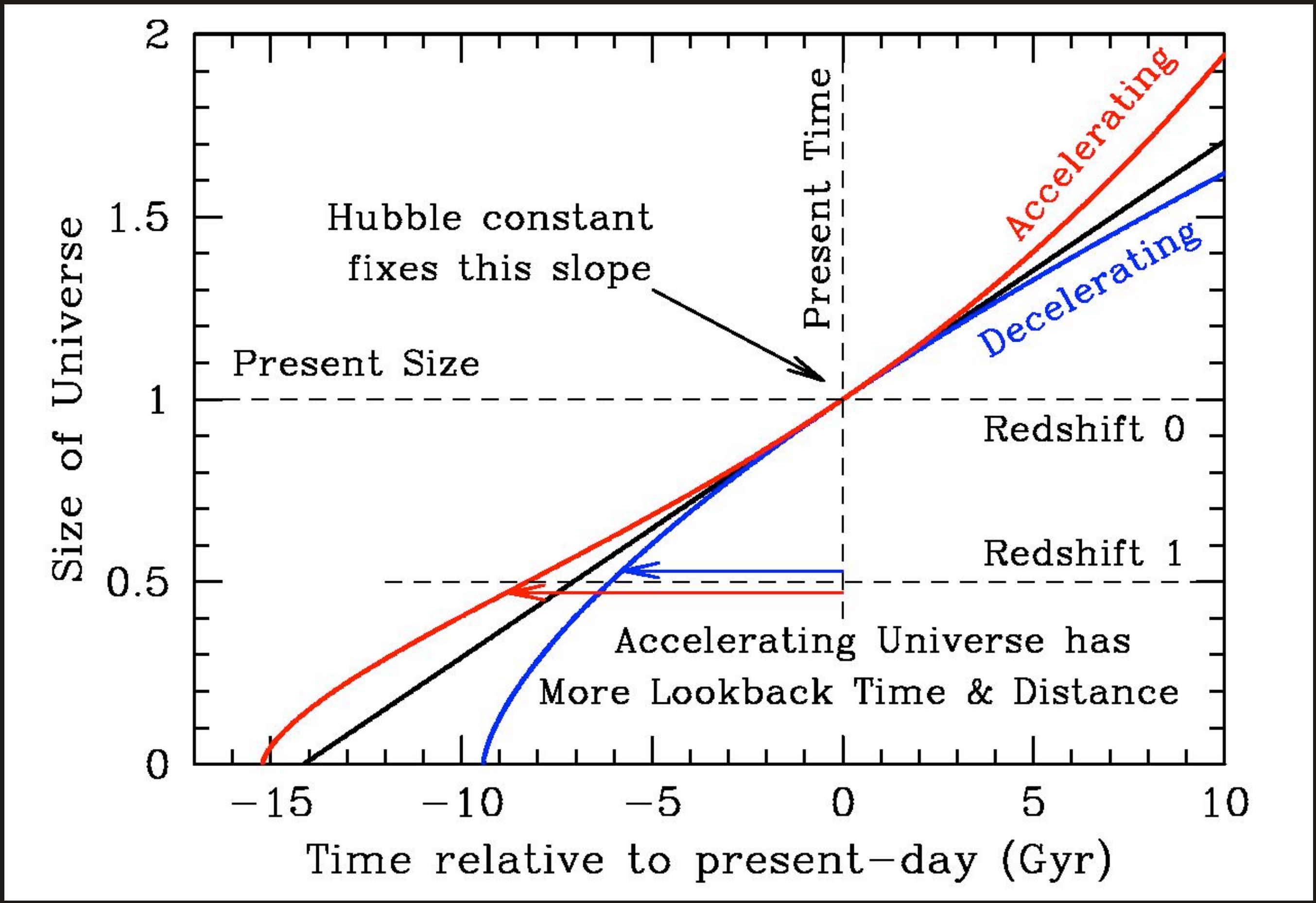
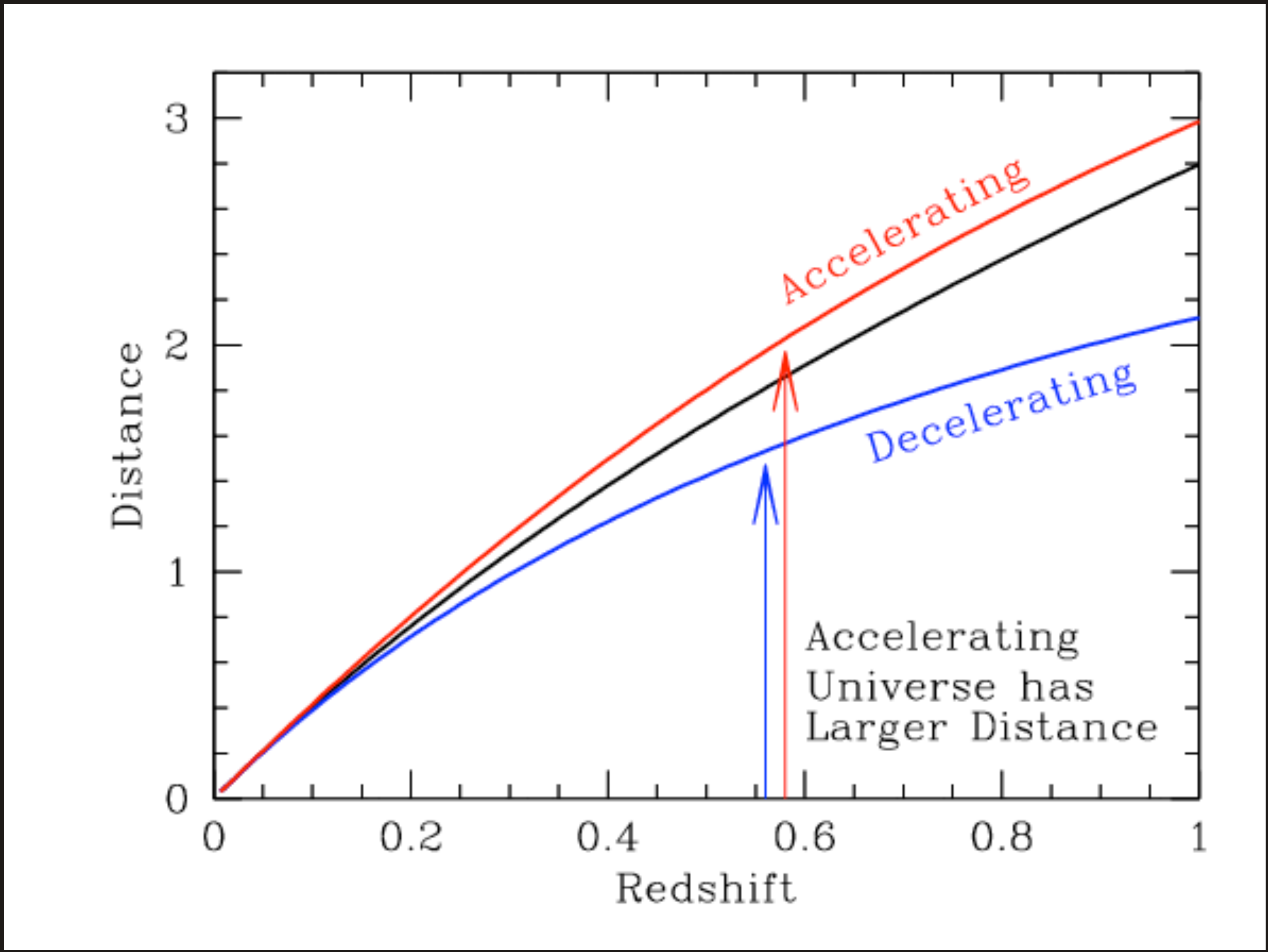


Cosmic Acceleration

- Discovered with precise distance measurements



Distance-Redshift Relation



Cosmic Sound

- Sound waves in the early Universe imprint a signature into the clustering of galaxies that encodes a known length scale.
- We can then measure this clustering feature and use it as a "standard ruler."
- This phenomenon is known as the "baryon acoustic oscillations."

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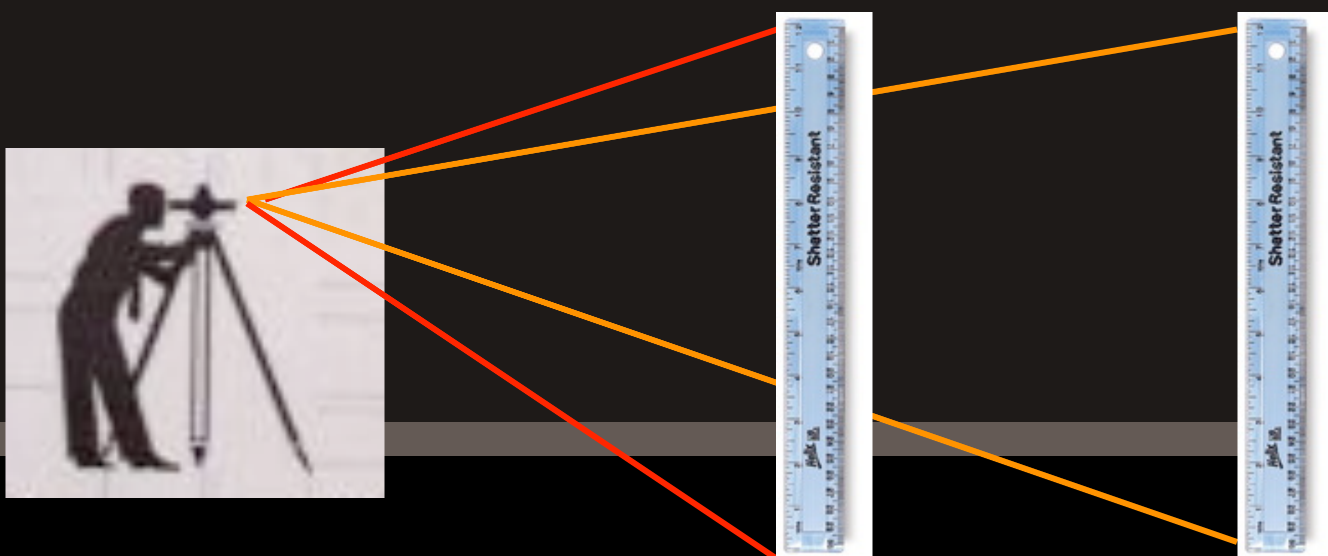


Cosmic Sound

- Early Universe was hot, dense, and nearly smooth.
  - All hydrogen ionized
- The pressure of the cosmic microwave background photons causes the density fluctuations seeded by inflation to oscillate as sound waves.

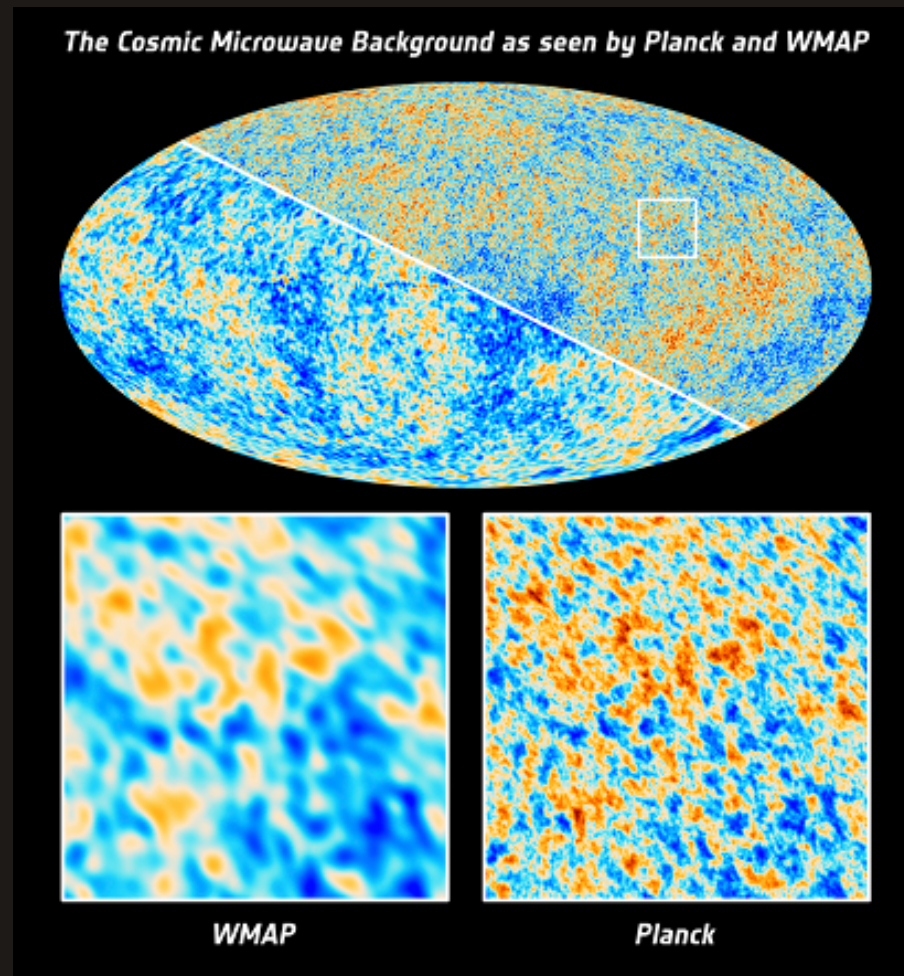


Image credit: ESA, Planck

Cosmic Sound

- Process ends after 400,000 years, when the Universe cools enough to become neutral atoms. This is known as the "recombination epoch."
- We see these waves in CMB temperature anisotropies.

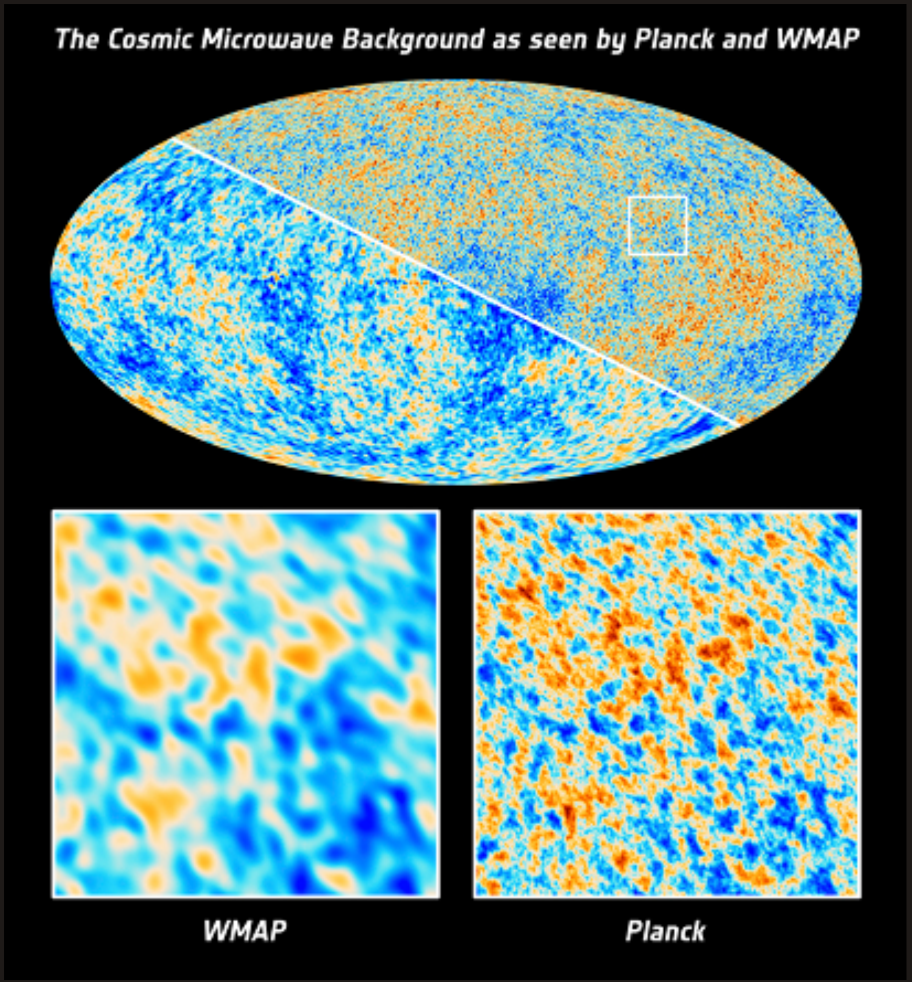
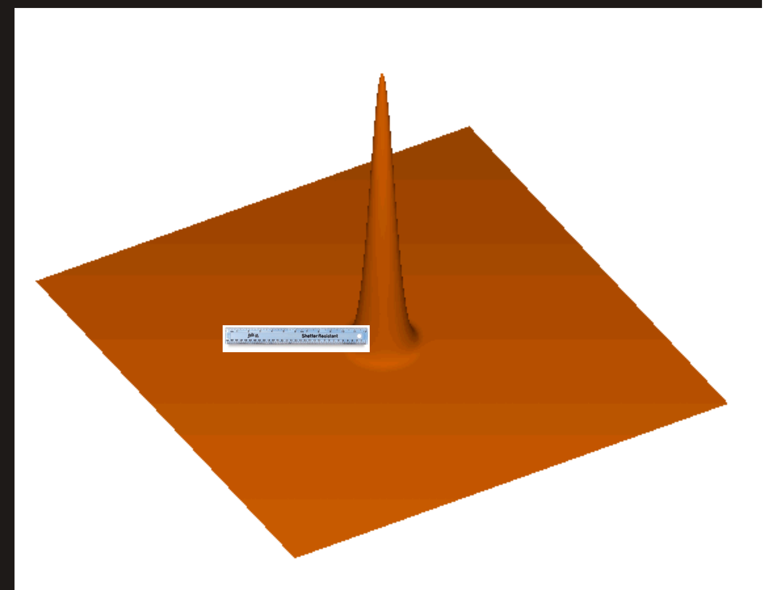


Image credit: ESA, Planck

Preserving Sound

- These sound waves create long-lasting changes in the large-scale structure of the Universe.
- Each initial overdensity has excess pressure, leading to an outward-going sound wave.
- At recombination, these sound waves halt, depositing their gas in a spherical shell 500 million light-years (150 Mpc) from the original location.
- An overdensity at one location implies a small increase in the density 500 million light-years away.

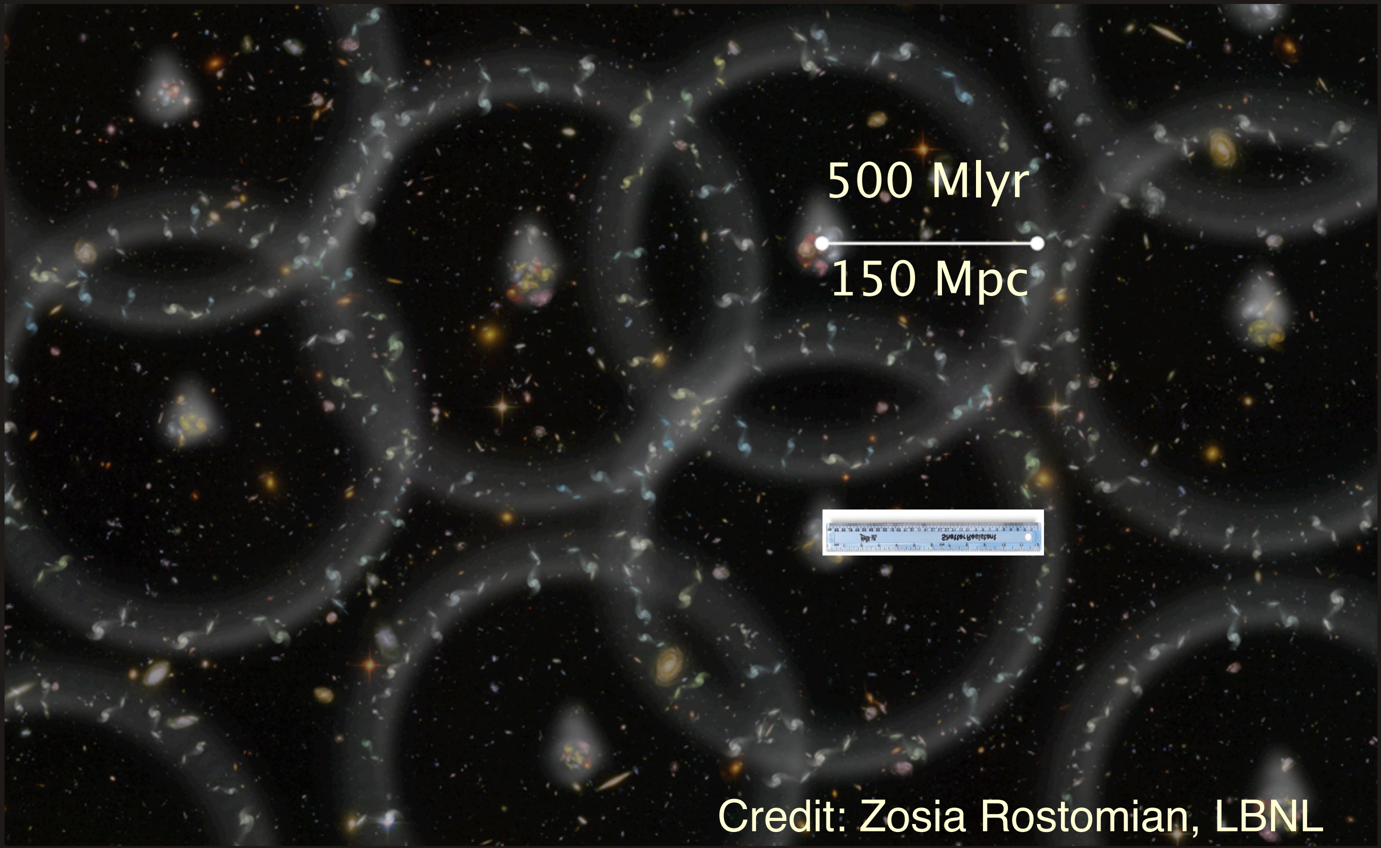


Credit: D. Eisenstein

SDSS III

BAO and Galaxies

- Pairs of galaxies are slightly more likely to be separated by 500 Mlyr than by 400 or 600.



Credit: Zosia Rostomian, LBNL

BAO as a Standard Ruler

- This distance of 150 Mpc is very accurately computed from the anisotropies of the CMB.
  - 0.4% calibration with current CMB.

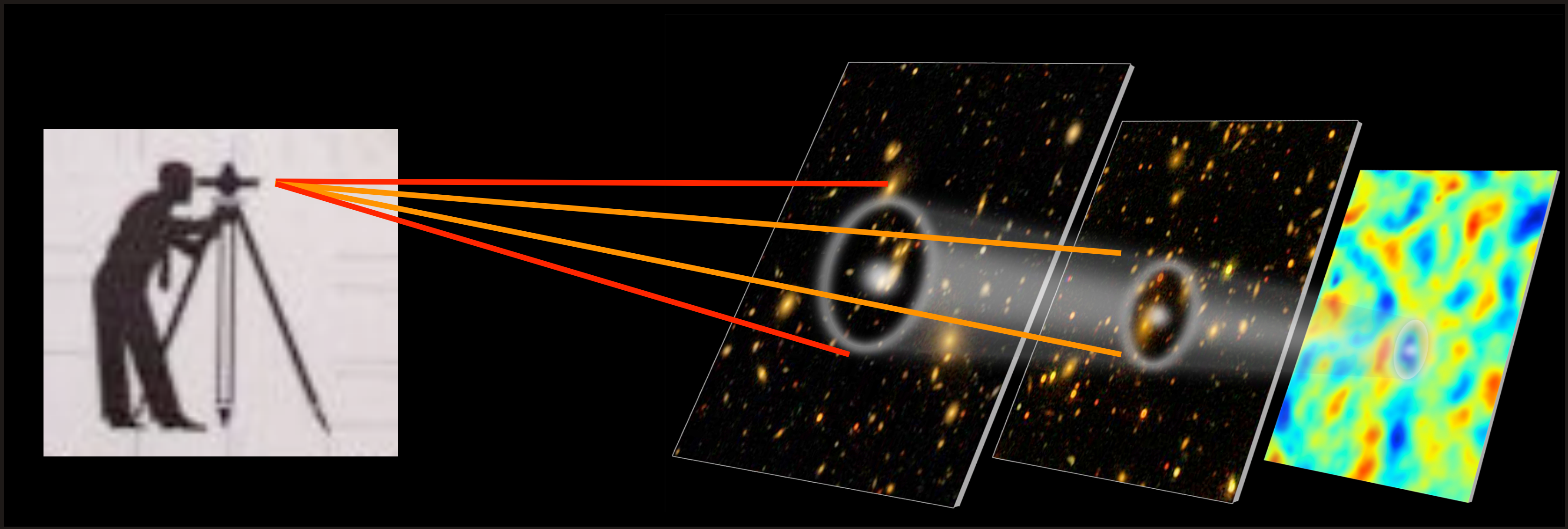
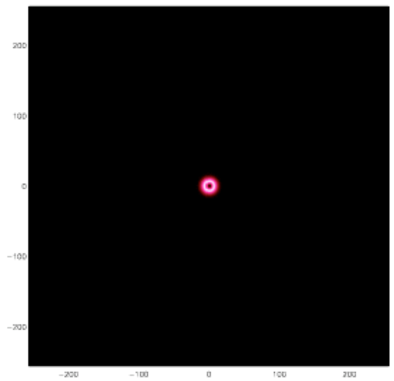


Image Credit: E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian

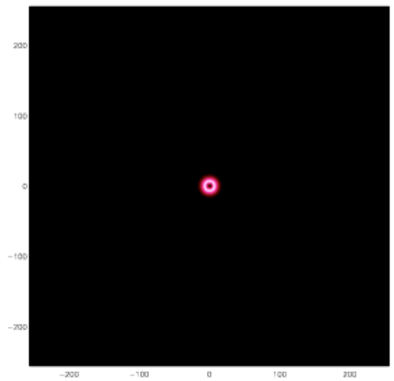
The acoustic wave

Start with a single perturbation. The plasma is totally uniform except for an excess of matter at the origin.

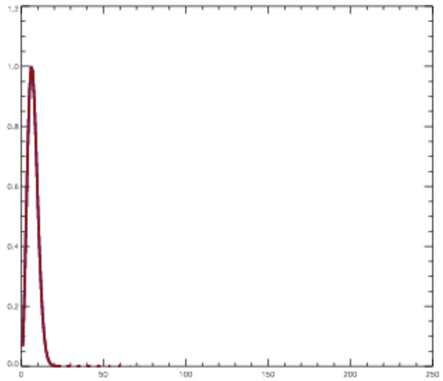
High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.



Baryons



Photons

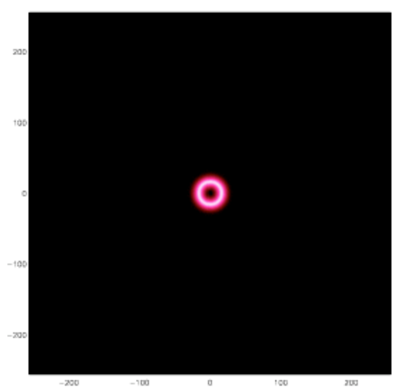


Mass profile

Eisenstein, Seo & White (2006)

The acoustic wave

Initially both the photons and the baryons move outward together, the radius of the shell moving at over half the speed of light.



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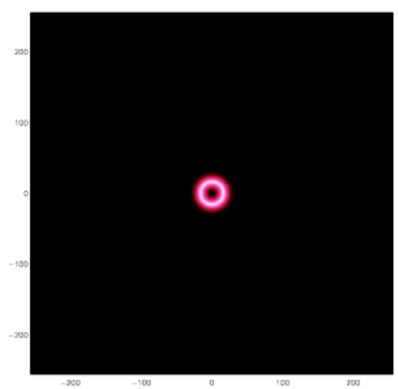

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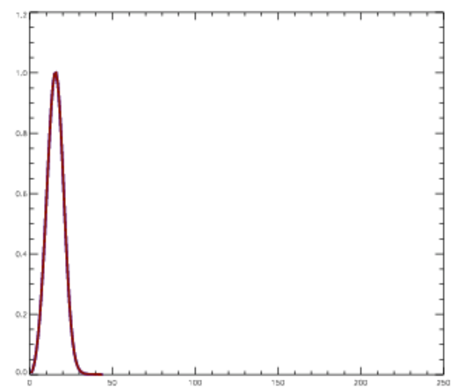
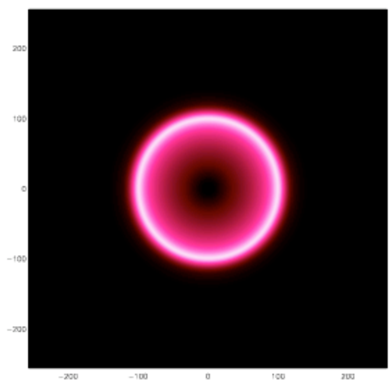
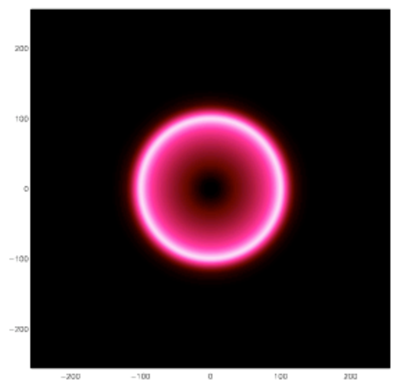
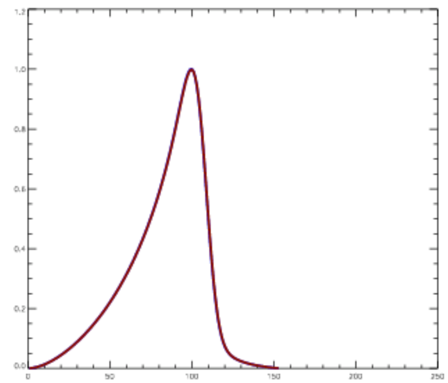


The acoustic wave

This expansion continues for 10^5 years

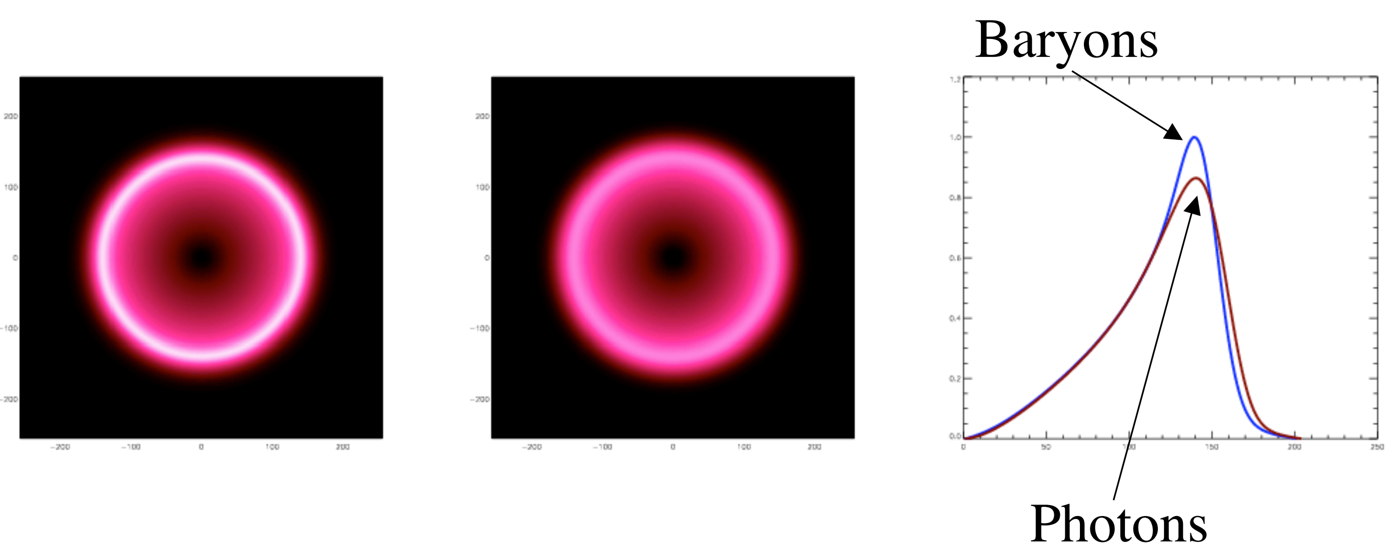






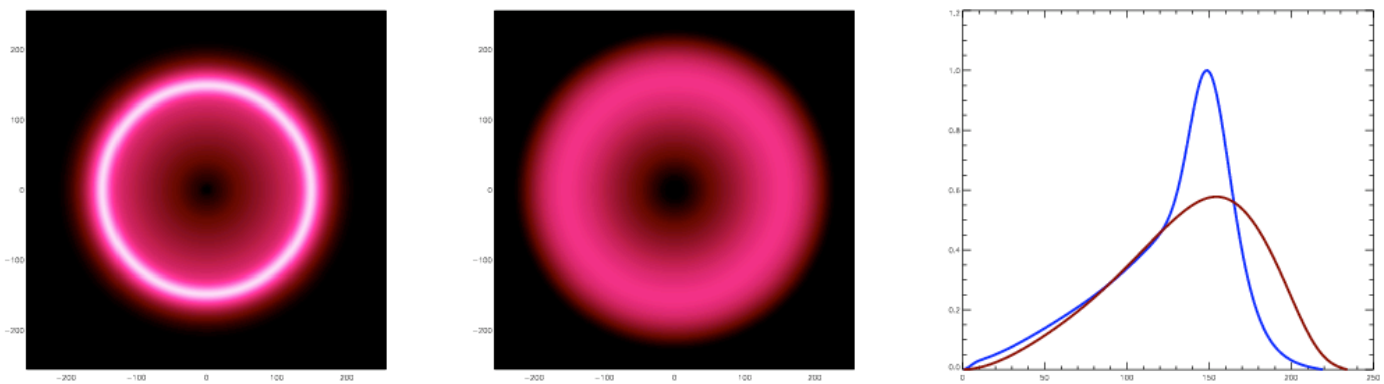
The acoustic wave

After 10^5 years the universe has cooled enough the protons capture the electrons to form neutral Hydrogen. This decouples the photons from the baryons. The former quickly stream away, leaving the baryon peak stalled.



The acoustic wave

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



The acoustic wave