# Dark Matter with the Euclid Satellite

## Baryonic Acoustic Oscillations and Redshift Space Distortion


Renata Kopečná

Physikalisches Institut
University of Heidelberg


Physics teams
Summer term 2017

# Introduction

- Universe expansion is accelerating: 2 options

$\Rightarrow$ GR is wrong

$\Rightarrow$ The universe is dominated by a material violating the strong energy condition

# Introduction

- Universe expansion is accelerating: 2 options

⇒ GR is wrong

⇒ **The universe is dominated by a material violating the strong energy condition**

# Introduction

- Universe expansion is accelerating: 2 options

$\Rightarrow$ GR is wrong

$\Rightarrow$ **The universe is dominated by a material violating the strong energy condition**

  - Not *any* fluid, but *Dark Energy*
  - Density of DE well constrained by the data: $\rho_{DE} = 1.42 \pm (0.09) \times 10^{-29}$ g/cm$^3$
  - The difference between the models is the *time-evolution* of $\rho_{DE}$
  - Described by EOS: $w \equiv \frac{p}{\rho} = \frac{\rho_m RT}{\rho_m c^2} = \frac{C^2}{c^2}$
    - Nonrelativistic matter: $w = 0$
    - Ultrarelativistic matter: $w = \frac{1}{3}$
    - Vacuum: $w = -1$
    - Phantom energy $w < -1$
    - DE models $w > -1$ $\quad\Rightarrow$ goal is to show $w \neq -1$ at *any* time

# How to get *w*?

- Studied via Universe expansion:

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

- In order to get an error in DE EOS $w = p/\rho$ of $\sim 10\%$ we need to measure changes in $H(z)$ at the level of 1%

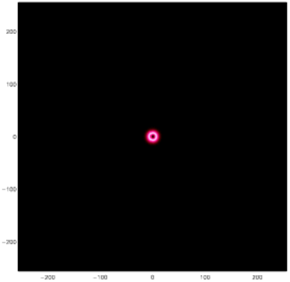
$\Rightarrow$ We need a precise ruler
$\Rightarrow$ We need to calibrate the ruler over most of the **age** of the Universe
$\Rightarrow$ We need to calibrate the ruler over most of the **volume** of the Universe

  - Cosmological objects not uniform enough
  - Assuming the laws of physics are constant over time one can use early Universe processes
  - Using large objects allows to use statistics of the distribution of matter and radiation

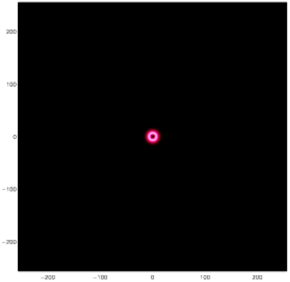
# An example of such a ruler?

An example of such a ruler?

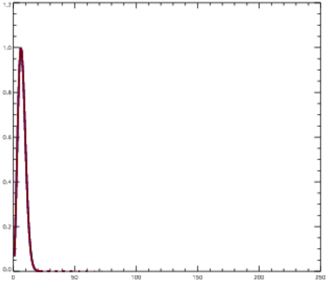
Baryonic acoustic oscillations!



Baryons

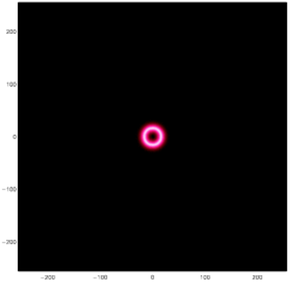


Photons

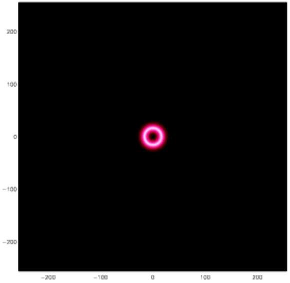


Mass profile
baryons, photons

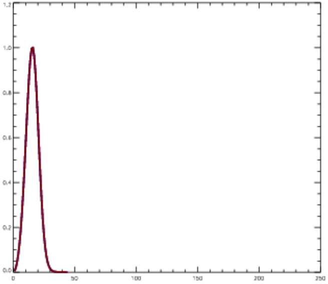
- Start with a single perturbation
- The plasma is uniform except for an excess of matter at the origin
- High pressure drives the gas+photon fluid outward at $\approx c$




Baryons

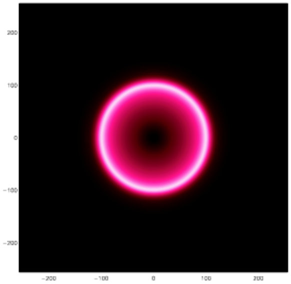



Photons

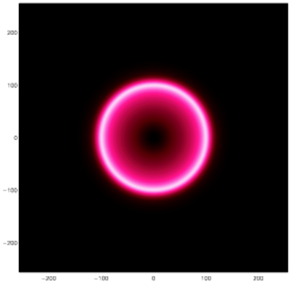



Mass profile
baryons, photons

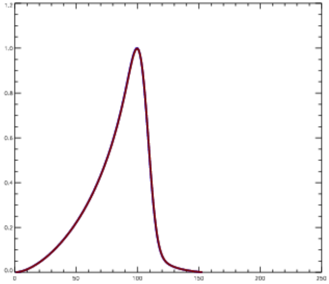
- Initially both the photons and the baryons move outward together
- The radius of the shell moving at $> c/2$



Baryons

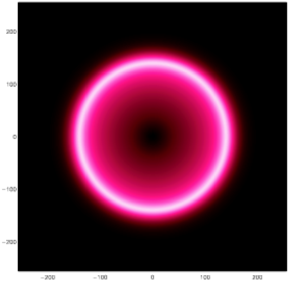


Photons

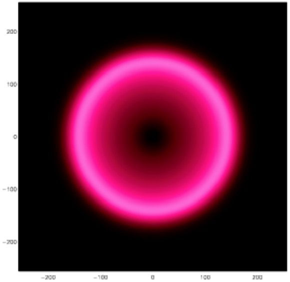


Mass profile
baryons, photons

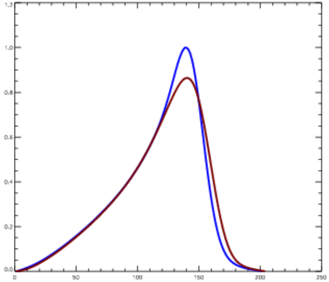
- This expansion continues for $10^5$ years




Baryons

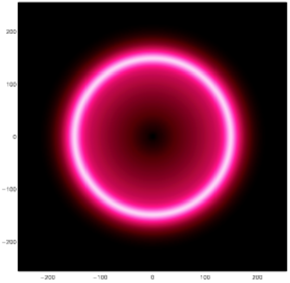



Photons

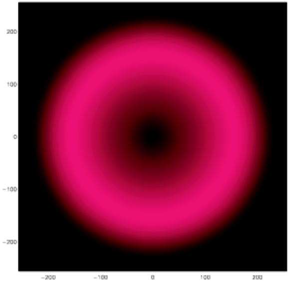



Mass profile
baryons, photons

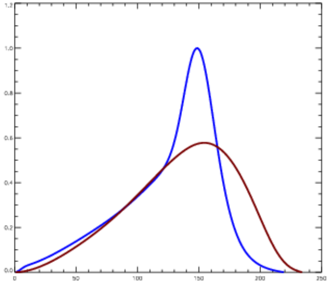
- After $10^5$ years the universe is cool enough the protons capture the electrons to form neutral H
- This decouples the photons from the baryons
- The former quickly stream away, leaving the baryon peak stalled




Baryons

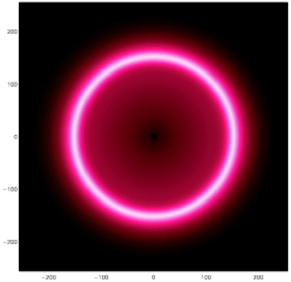



Photons

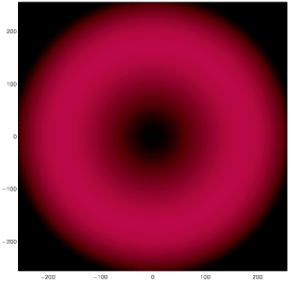



Mass profile
baryons, photons

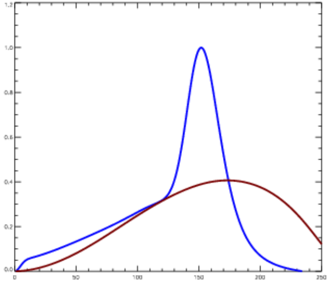
- The photons continue to stream away while the baryons, having lost their motive pressure, remain in place



Baryons

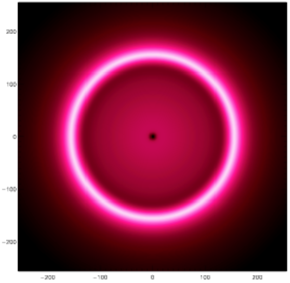


Photons

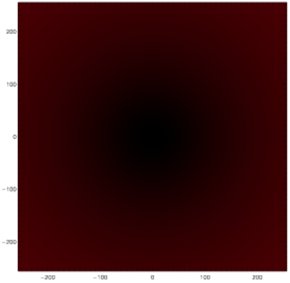


Mass profile
baryons, photons

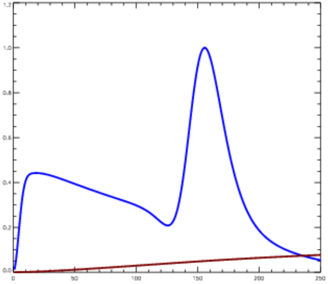
- The photons continue to stream away while the baryons, having lost their motive pressure, remain in place. . .




Baryons

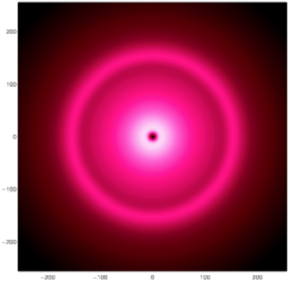



Photons

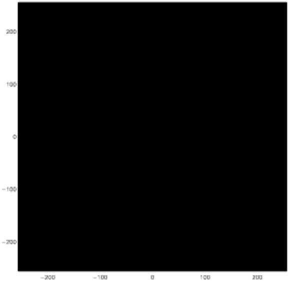



Mass profile
baryons, photons

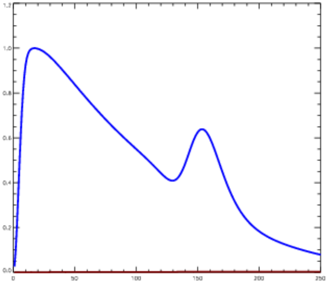
- The photons have become almost completely uniform
- The baryons remain overdense in a shell 100Mpc in radius
- The large gravitational potential well which we started with starts to draw material back into it



Baryons



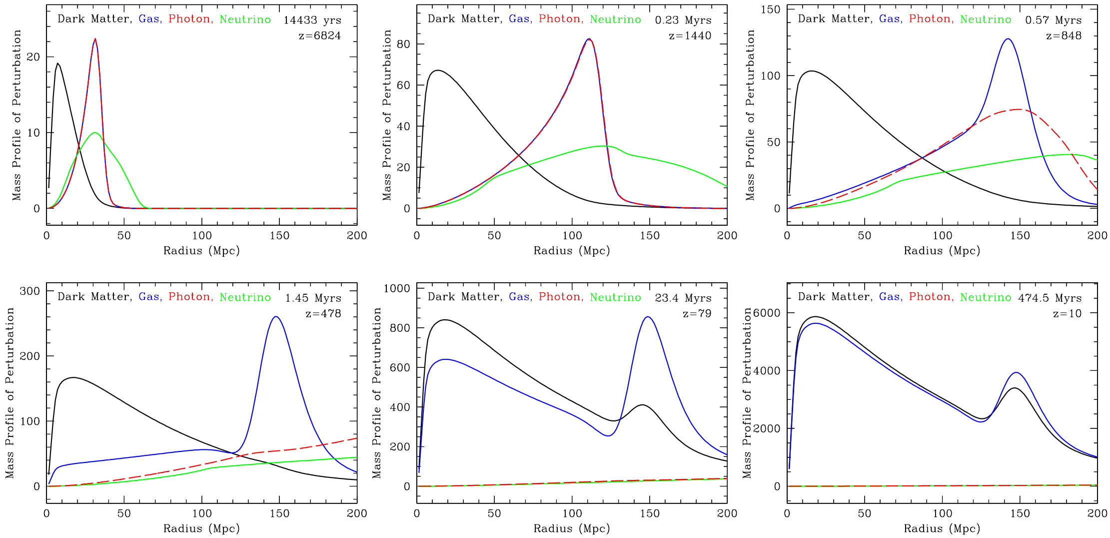
Photons



Mass profile
baryons, photons

- The perturbation grows by $O(1000)$
  $\rightarrow$ The baryons and DM reach equilibrium densities
- The final configuration is our original peak at the center and an 'echo' in a shell $\sim$ 100Mpc in radius.
- The radius of this shell is known as the *sound horizon*

# The acoustic wave

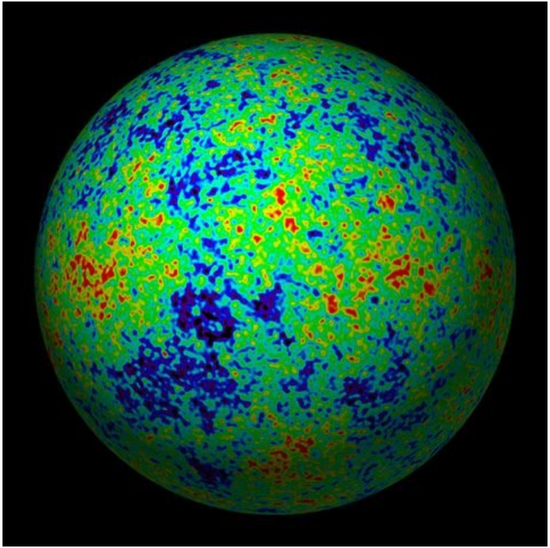


# The acoustic wave: useful links

- http://adh-sj.info/bao_cmb.php
- https://youtu.be/GPiQVRS8kCg

# How do we measure it?

# How do we measure it?



# Spherical harmonics transform

- Let's take Fourier transform

$$f(x) = \sum_k \left[b_k \cos(kx) + c_k \sin(kx)\right] = \sum_k a_k e^{ikx} \quad (1)$$

$$a_k = \int f(x) e^{-ikx} dx \,. \quad (2)$$

- For ”noise-like” phenomena, we are only interested the amplitude of the fluctuations as a function of scale (CMB *IS* a noise)
- Quantified by the power spectrum, $P(k) = |a_k|^2$

# Spherical harmonics transform

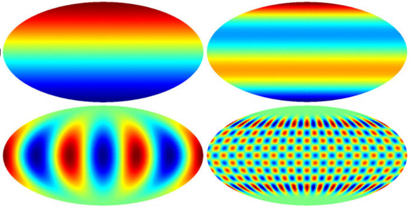
- Let's start with Laplace: $\nabla^2 \Psi = 0$
- CMB defined on a sphere: $\Psi(\theta, \phi) = \Theta(\theta)\Phi(\phi)$

$$\Rightarrow \Psi = \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}} P_{lm}(\cos\theta)e^{im\phi} \equiv Y_{lm}(\theta, \phi)$$

$\Rightarrow$ Analogous to complex exponential in flat space $Y_{lm}$

- Instead of wave number $k$, described via $l$ and $m$
  - $l$: number of waves along a meridian
  - $m$: number of modes along equator
- Any function can be expanded into spherical harmonics:

$$T(\theta, \phi) = \sum_{l=0}^{l_{max}} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \phi)$$



TL: $Y_{1,0}$, TR: $Y_{3,0}$
BL: $Y_{0,3}$, BR: $Y_{20,12}$,

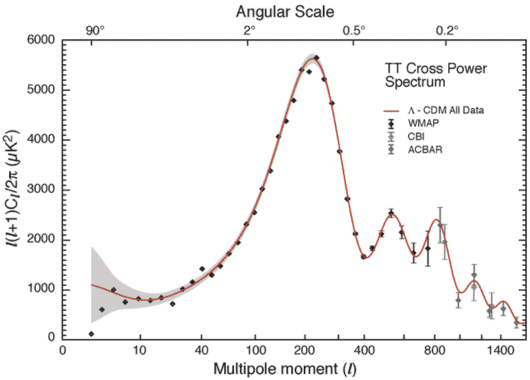
# Angular power spectrum

- Spherical transform of CMB $\rightarrow$ amplitudes
- Defined as $C_l = \frac{1}{2l+1}\sum_{m=-l}^{l} |a_{lm}|^2$
- Observed spectrum: specific map, we get

$$\hat{C}_l = \frac{1}{2l+1}\sum_{m=-l}^{l} |a_{lm}|^2$$

- Theoretical spectrum: Ensemble of maps, we get

$$C_l = \langle \frac{1}{2l+1}\sum_{m=-l}^{l} |a_{lm}|^2 \rangle_{ensemble}$$




Great agreement!

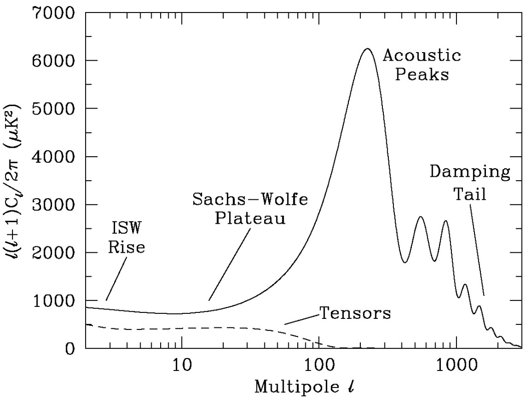
# Angular power spectrum

- Spherical transform of CMB $\rightarrow$ amplitudes
- Defined as $C_l = \frac{1}{2l+1}\sum_{m=-l}^{l}|a_{lm}|^2$
- Observed spectrum: specific map, we get

$$\hat{C}_l = \frac{1}{2l+1}\sum_{m=-l}^{l}|a_{lm}|^2$$

- Theoretical spectrum: Ensemble of maps, we get

$$C_l = \langle\frac{1}{2l+1}\sum_{m=-l}^{l}|a_{lm}|^2\rangle_{ensemble}$$



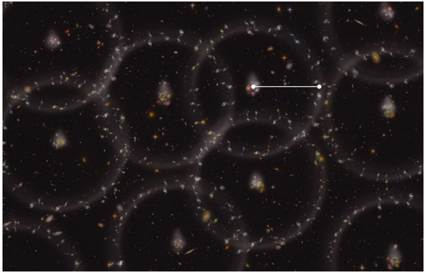
# Baryonic Acoustic Oscillations with Euclid

- Acoustic peak: zero velocity, maximum density, $kc_s t_{ls} = \pi\,, \quad l \sim kr_{ls}$
- Sound horizon: $s = c_s t_{ls}$ ls: last scattering

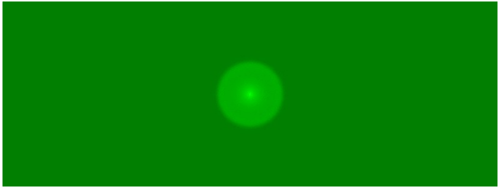
⇒ Acoustic scale: Scale at which galaxies are correlated set by sound horizon

⇒ Information about universe expansion at any redshift (hence at any time)

- Similarly to studying CMB, one can search for statistical imprint on galaxy distribution
- Take home message: BAO provide a precise ruler for studying DE EOS
- Note that all of the matter sees the acoustic oscillations, not just the baryons.



A cartoon produced by the BOSS project showing the spheres of baryons around the initial dark matter clumps.

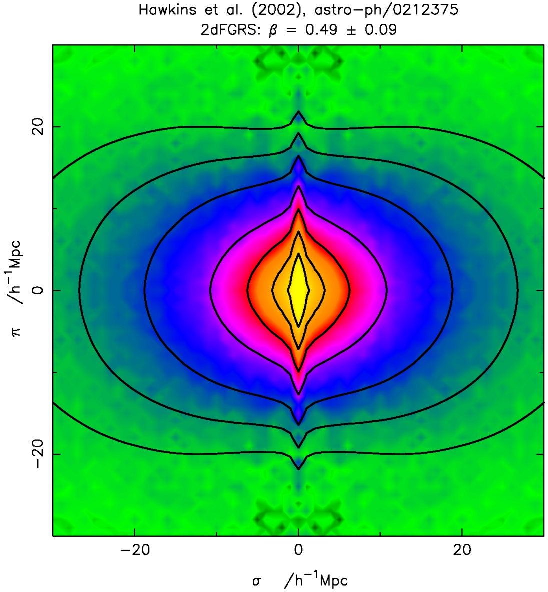


Redshift space distortions,

The Fingers of God,

Pancakes of God,

The growth of cosmic structure



# Redshift space distortions

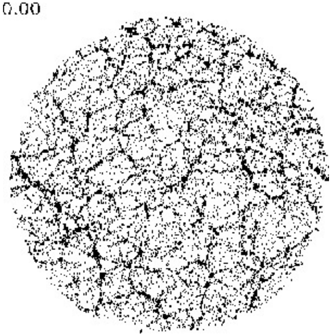
- Observation: Spatial distribution of galaxies appears to be distorted in the redshift space
- Small peculiar velocities not associated with the Hubble flow can cause distortions in redshift space
- 2 main 'background' manifestations: **Fingers of God** and **Kaiser effect**
- The distortions depend on non-linear density and velocity fields, which are correlated
- Wait, why do we need this?
  - Redshift is a measure of space and velocity
    $z_{obs} = Hr + v_{pec}\,, \qquad v_{pec} \sim at \sim (\nabla\nabla^{-2}\rho)t$
  - Using this $\Uparrow$ we can measure the growth of structure!
  - A key test of DE vs. modified GR models

# The Fingers of God

- Axis of elongation in redshift space points directly back at observer
- We are not the *chosen* observers
  $\Rightarrow$ the effect is unphysical
- This affects only redshift and not the position on the sky, the stretching occurs only radially

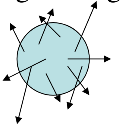
$\Rightarrow$ *Fingers* point back to observer

  - Important when creating 3D map of Universe: deviations from Hubble's law
- Caused by random velocity dispersions in galaxy clusters
  - Peculiar velocities come from the gravity of the clusters
  - Stretching out a cluster in redshift space



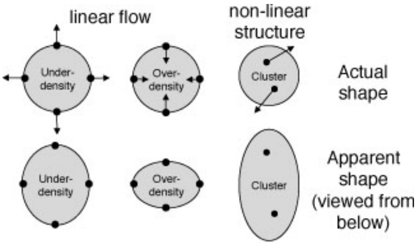

Random (thermal) motion

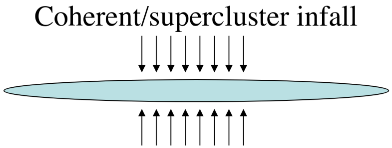
(fingers-of-god)



# Kaiser effect

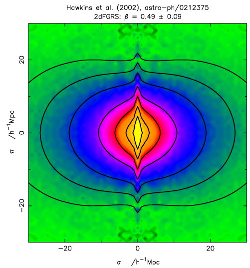
- Caused by peculiar velocities of galaxies bound to a central mass as they undergo in-fall
- Peculiar velocities are not random, but coherent towards the central mass
- This leads to elongation: *Pancakes of God*
- More difficult do quantify
- Large scales



# Redshift space distorstions 2.0

- Correlation function $\xi$ in redshift space is calculated
  - In $\pi$ and $\sigma$
  - $\pi$: Separation along the line of sight
  - $\sigma$: Separation across the line of sight
  - Central squish due to structure growth
- The distortions depend on non-linear density and velocity fields, which are correlated
- The correlation function depends on galaxy type:
  - ”Red”/early-type galaxies tend to cluster more heavily




The contours represent model predictions, with $\xi$ = 10,5,2,1,0.5,0.2, 0.1

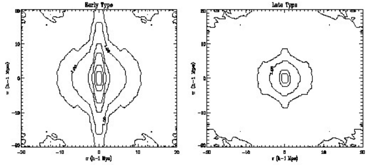
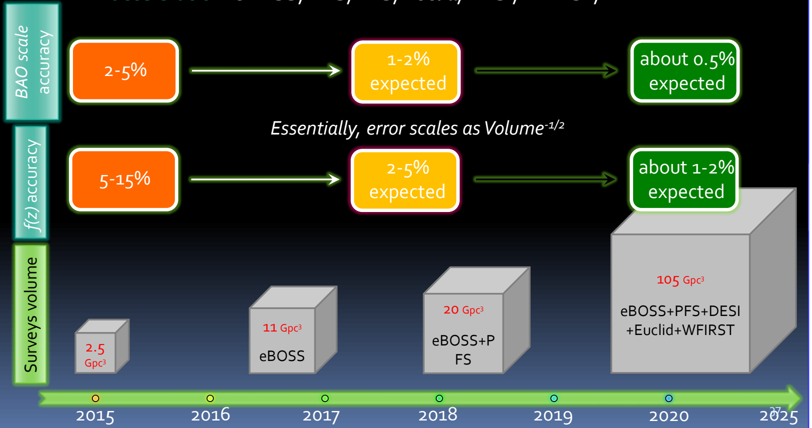



**Fig. 3.** The two point correlation function $\xi(\sigma, \pi)$ plotted for passively (left) and actively (right) star-forming galaxies. The contour levels are 15,10,5,3,1 (labelled),0.5,0. From Madgwick & Lahav (2001) and Madgwick, Hawkins et al. (in preparation).

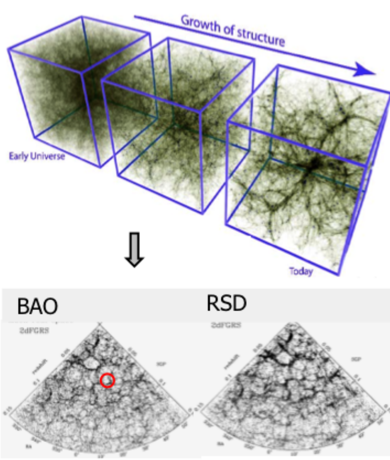
# Future Dark Energy surveys

- Massive effort today to prepare massive galaxy/quasar surveys to solve the problem of Dark Energy and the origin of late cosmic acceleration: *eBOSS, DES, PFS, Euclid, DESI, WFIRST, …*




**GC; BAO, RSD probes:** 3-D positions of galaxies over 0.7<z<1.8 :

35 million spectroscopic redshifts with 0.001 (1+z) accuracy over 15,000 deg$^2$



# Backup

# Definitions

$z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$

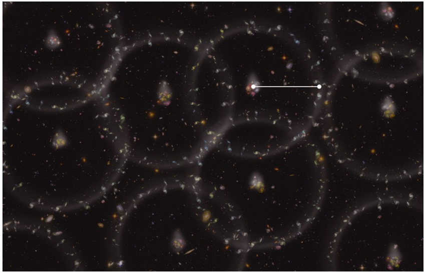
Angle $\Delta\theta$, subtended by the ruler $\Delta\chi$ $\Delta\theta = \frac{\Delta\chi}{d_a(z)}$

Einstein field equations (EFE)

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G T_{\mu\nu}$

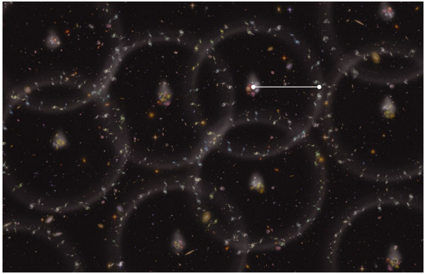
$\Rightarrow$ strong energy condition: $\rho + 3p > 0$

- Direct distance-redshift probe to explore the expansion rate of the Universe
- Provides an almost direct probe of dark matter
- Combined with angular distances
  $\rightarrow$ the expansion rate and the mass density contrast probe
    - $\rightarrow$ the growth rate of structure and gravity probe
- Every object has **intrinsic** properties: mass, size and luminosity/intrinsic brightness
- We can directly measure **apparent** size or brightness



A cartoon produced by the BOSS project showing the spheres of baryons around the initial dark matter clumps.

- **Standard candle**: Knowing intrinsic brightness + measuring apparent brightness → distance
- **Standard ruler**: Knowing intrinsic size + measuring apparent size → expansion
- **Acoustic scale**: Scale at which galaxies are correlated
  - if you collapse something too much when the Universe is young, the pressure from radiation will push it back out again
  - baryons are oscillating in-and-out of these overdense regions
    ⇒ baryon acoustic oscillations
    Information about universe expansion at any redshift (hence at any time)
- Note: all of the matter sees the acoustic oscillations, not just the baryons.



A cartoon produced by the BOSS project showing the spheres of baryons around the initial dark matter clumps.