Cosmic Acceleration

ISYA2018, Socorro, Colombia

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1990′s: Contradictions in our understanding of the Universe!

Cosmic Age < Globular Clusters Age
Too much small scale structure
Measured Average Density not 1 but close, why?

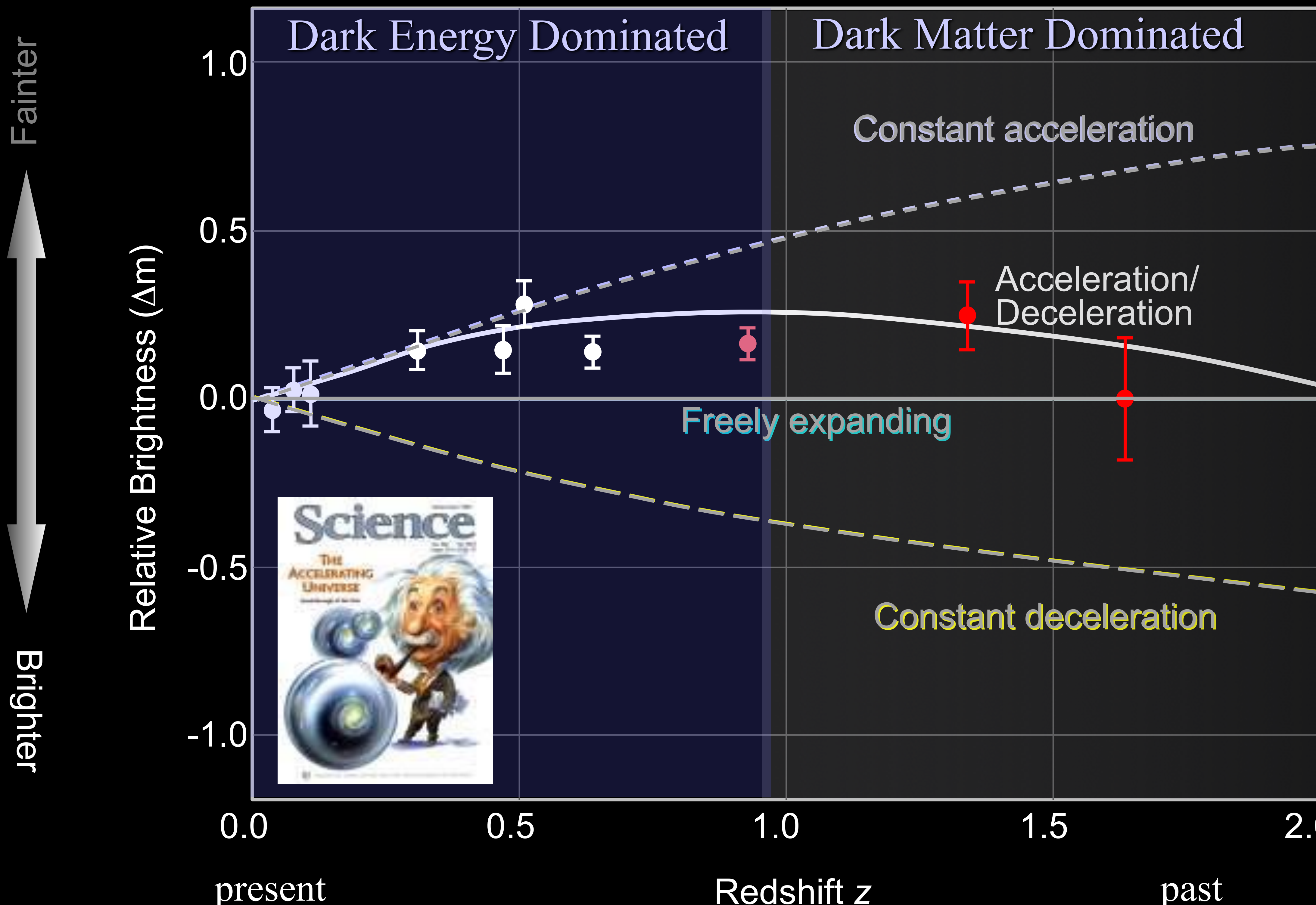
Theoretical Bias suggested mostly by theoretical simplicity:
Flat Universe $\Omega = 1$, matter dominated (baryonic + cold dark), scale invariant initial perturbations.

The model needed to be modified or extended!
at least modify one of the following hypothesis--
"flat," "cold DM," "scale invariant," perhaps "made only of matter"

High Redshift SN and Expansion History: Acceleration Just recently

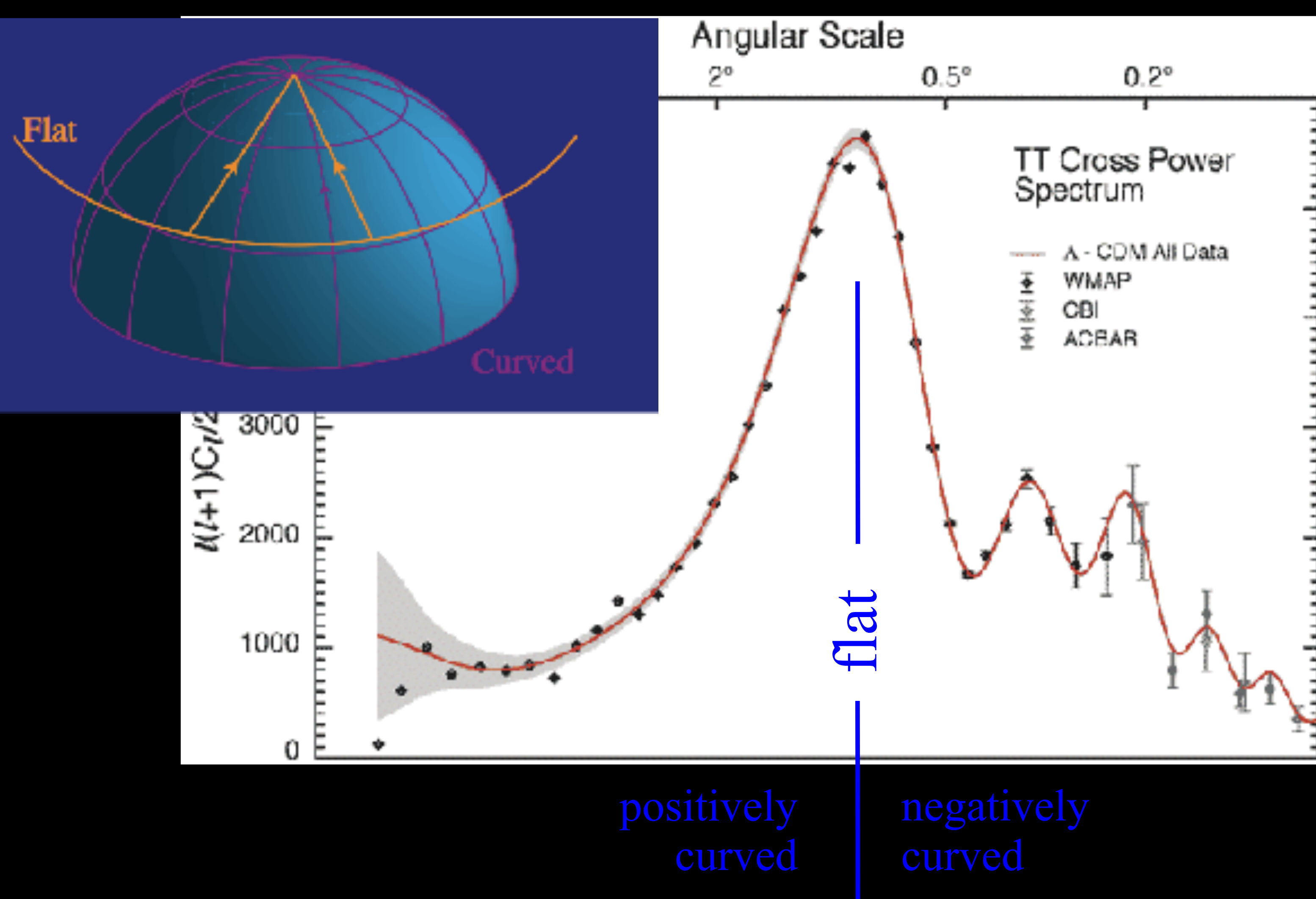
Found: Ground,
Followed: Hubble

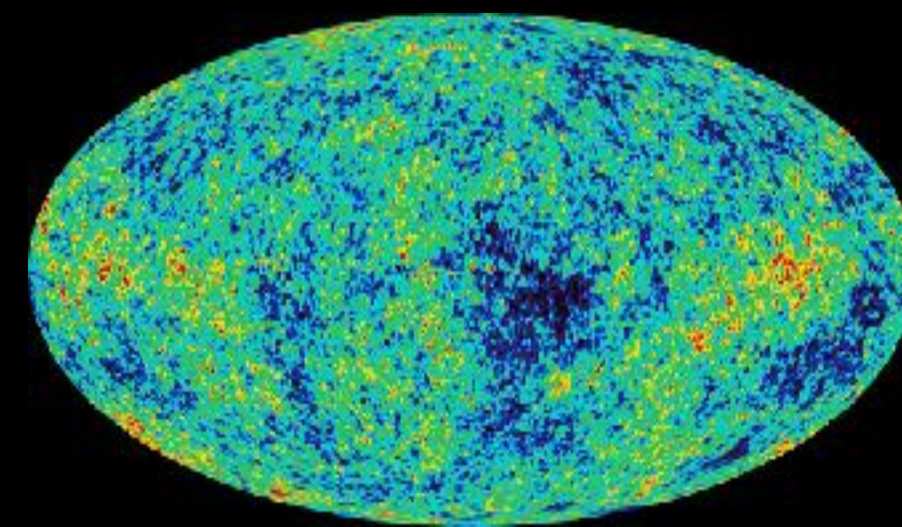
Found: Hubble,
Followed: Hubble



Cosmic Background Radiation (Sound speed plasma photons+baryons)

400,000 yrs after Big Bang
400,000 lyrs. Acustic Horizon
from cosmology, baryons, photons





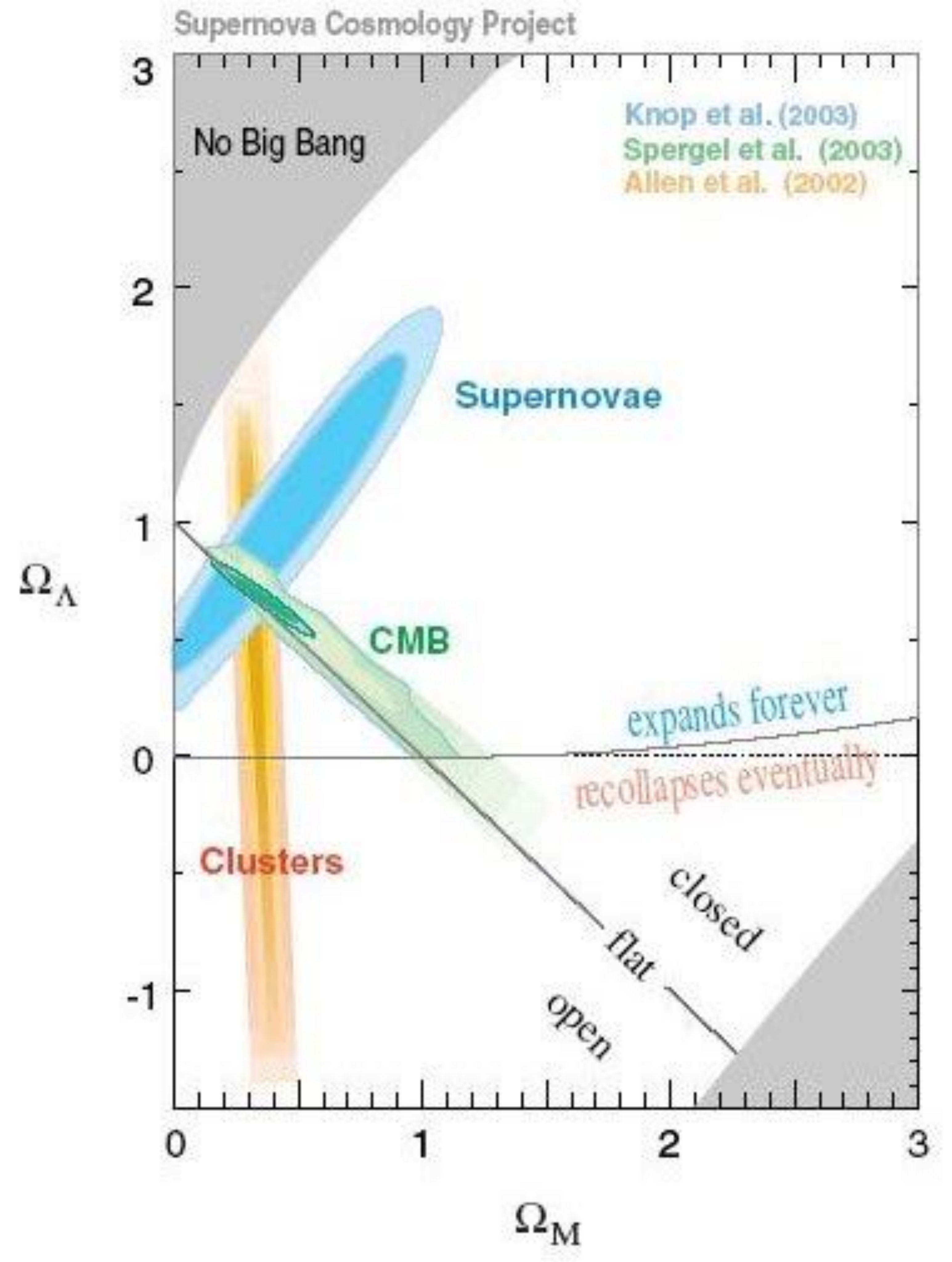
$\Omega_{Tot} = [\theta_{peak}(deg)]^{-1/2}$.

Observation: $\theta_{peak} = 1^o$.

<u>Universe is flat</u>:
then we need an extra component

$\Omega_{Tot} = 1$.

[Miller et al.; de Bernardis et al; WMAP]



Concordance:

$\Omega_M = 0.3,$

$\Omega_\Lambda = 0.7\ .$

Acceleration constrains the Dark Energy equation of state (pressure to density ratio)

What is Dark Energy: Constant? Scalar Field?

what if we change G instead?

$$H^2(a) + \frac{1}{a^2 R^2} = \frac{8\pi G}{3}\rho$$

$$\frac{1}{a}\frac{d^2 a}{dt^2} = -\frac{4\pi G}{3}(\rho + 3p)$$

$w = p / \rho$ $\quad w < -1/3$ para que haya aceleración

¿Is w, constant? We must accurately measure the expansion history?

¿What is the DE Nature?

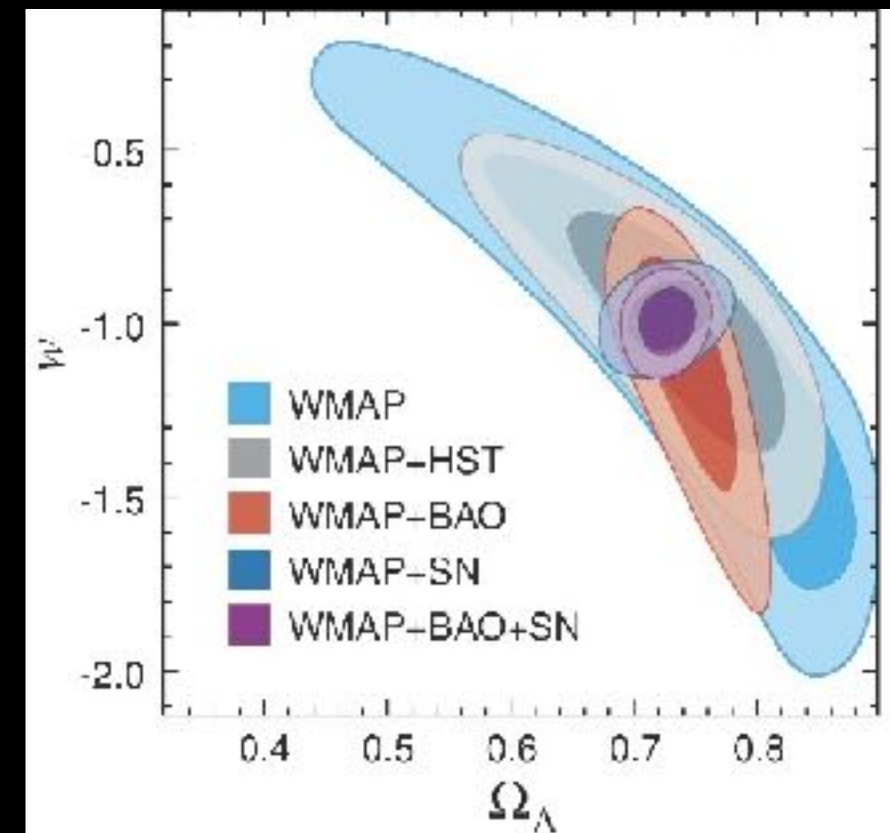
- Cosmological Constant?
- Dynamical Dark Energy: Scalar field: Quintesence, k-esence
- Gravity Theory
- How can I distinguish between them??
-

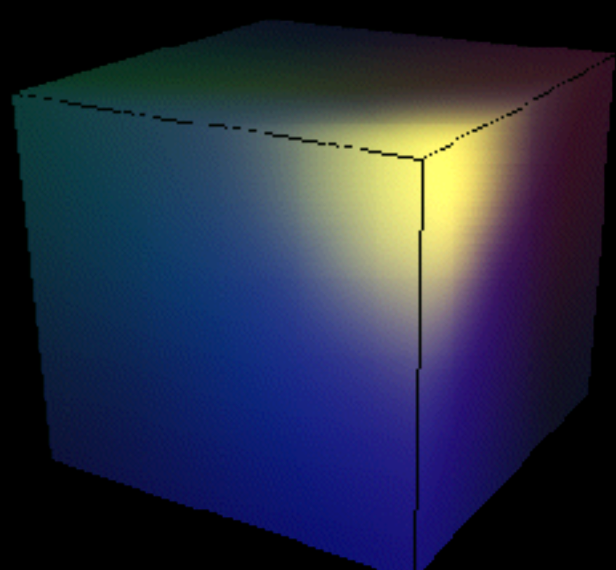
1. Vacuum Energy (the Cosmological Constant)

What we know about dark energy:

- <u>smoothly distributed</u> through space?
- <u>varies slowly</u> (if at all) with time

  $\rho \approx$ constant $(w \approx -1)$





(artist's impression of vacuum energy)

Dark energy could be <u>exactly</u> constant through space and time: vacuum energy (i.e. the cosmological constant Λ).

Energy of empty space.
Minimum Energy Level of Fields

Could we just be lucky?

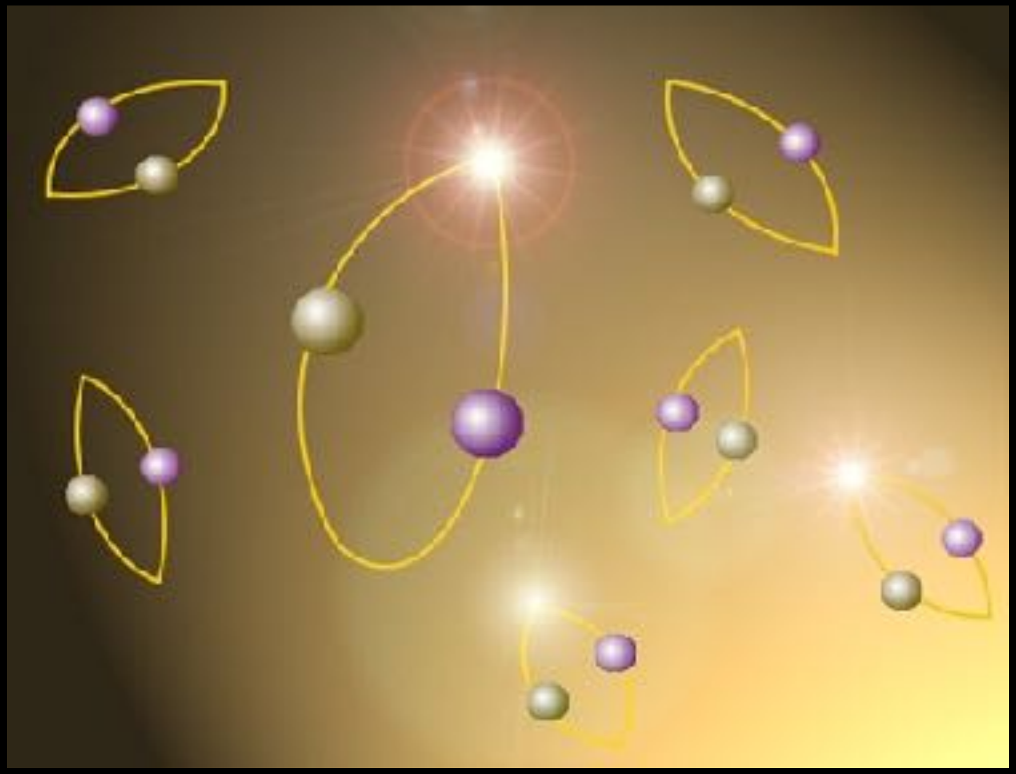
The Gravitational Physics Data Book:

Newton's constant:

$G = (6.67 \pm 0.01) \times 10^{-8}$ cm^3 g^{-1} sec^{-2}

Cosmological constant:

$\Lambda = (1.2 \pm 0.2) \times 10^{-55}$ cm^{-2}



If we set $h = c = 1$, we can write $G = E_{\rm Planck}^{-2}$ and $\rho_{\rm vac} = E_{\rm vac}^{4}$, and

$E_{\rm Planck} = 10^{27}$ eV , $E_{\rm vac} = 10^{-3}$ eV .

Different by 10^{30}.

Supersymmetry can squelch the vacuum energy; unfortunately, in the real world it must be broken at $E_{SUSY} \sim 10^{12}$ eV.

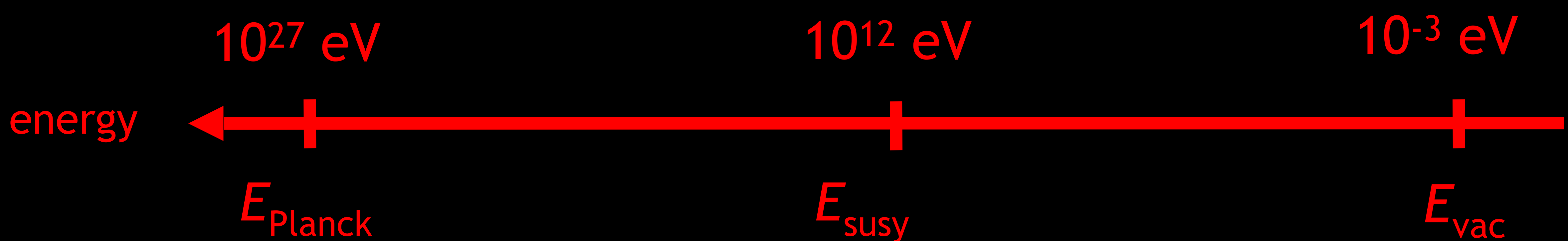
Typically we would then expect

$$E_{\rm vac} = E_{\rm susy}$$

which is off by 10^{15}. But if instead we were able to predict

$$E_{\rm vac} = \left(\frac{E_{\rm susy}}{E_{\rm Planck}}\right) E_{\rm susy}$$

it would agree with experiment. (All we need is a theory that predicts this relation!)



For simulations you solve the s field or fluid simultaneously with DM particles, expensive

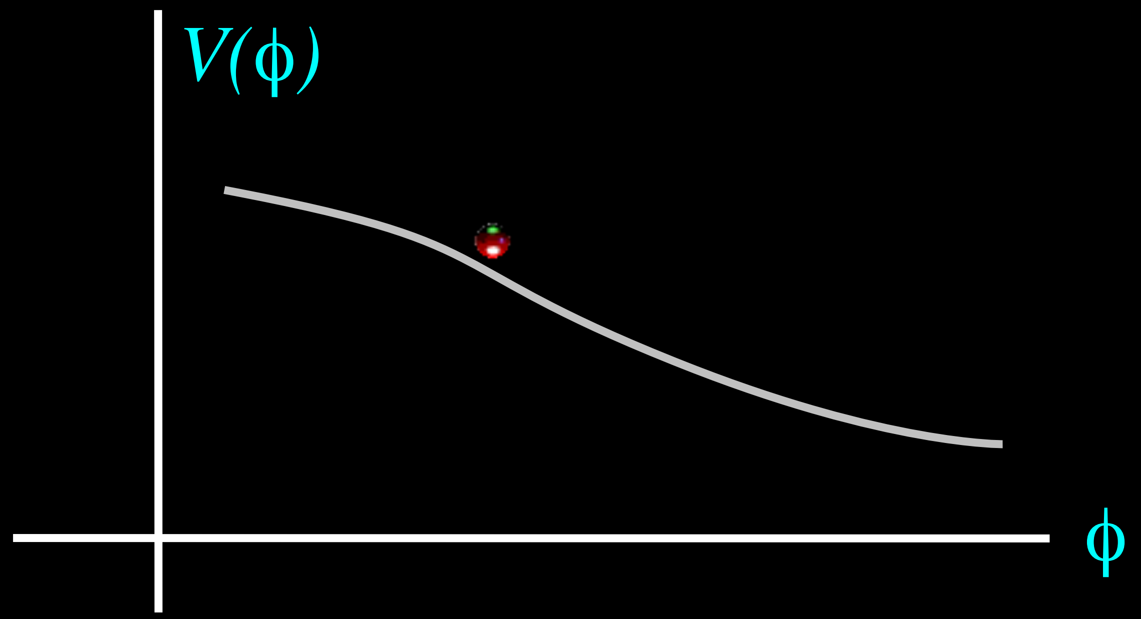
2. Dynamical Dark Energy (Quintessence: Scalar Field)

Dark energy doesn't vary quickly, but maybe slowly.

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V(\phi)$$

kinetic energy — gradient energy — potential energy

$$w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \geq -1$$



[Wetterich; Peebles & Ratra; Caldwell, Dave & Steinhardt; etc.]

- This is an observationally interesting possibility.
- Might be relevant to the cosmological constant problem or the coincidence scandal -- somehow.

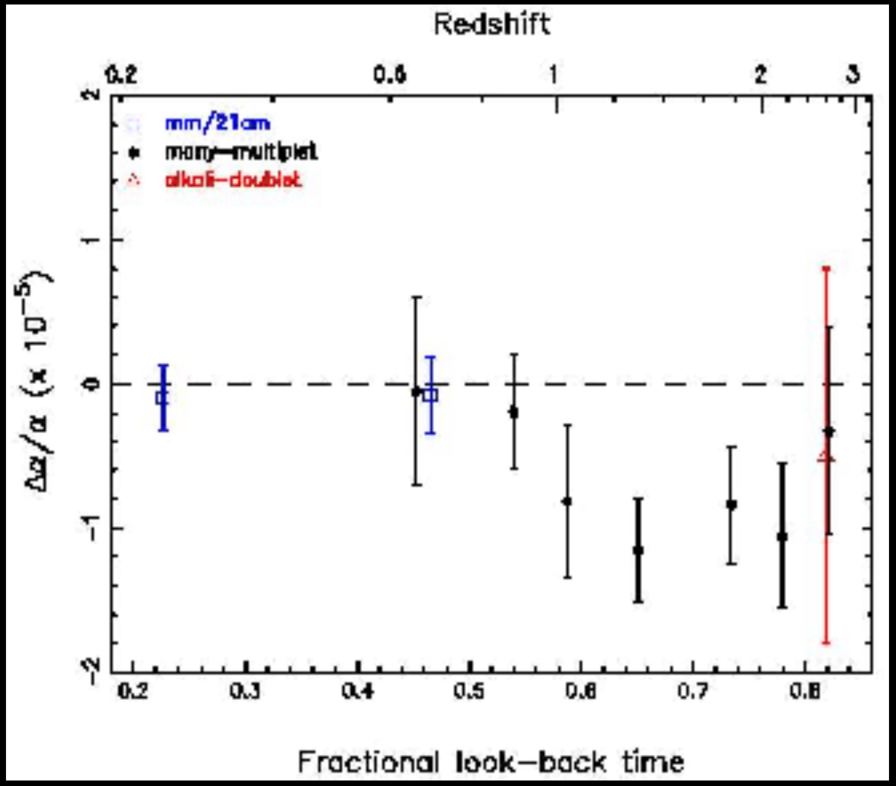
Coupling to a low-mass (long-range) field implies a fifth force of nature, which can be searched for in laboratory experiments.

torsion-balance experiment

[Adelberger et al.]

Also: gradual evolution of physical constants as the field evolves.

Emission Lines separation at different Redshift



[Webb et al.]

Limit: couplings must be suppressed by ~ $10^5 M_P$.

Gravity Constrains

- As an alternative to Dark Energy, General Relativity can be modified.
- **GR has been te**
- **Cosmic Acceler** may be modified at large scales
- **Modifying GR c**, but **structure growth depend** ng growth rate breaks the dege
- Challenges at m gravitational wa

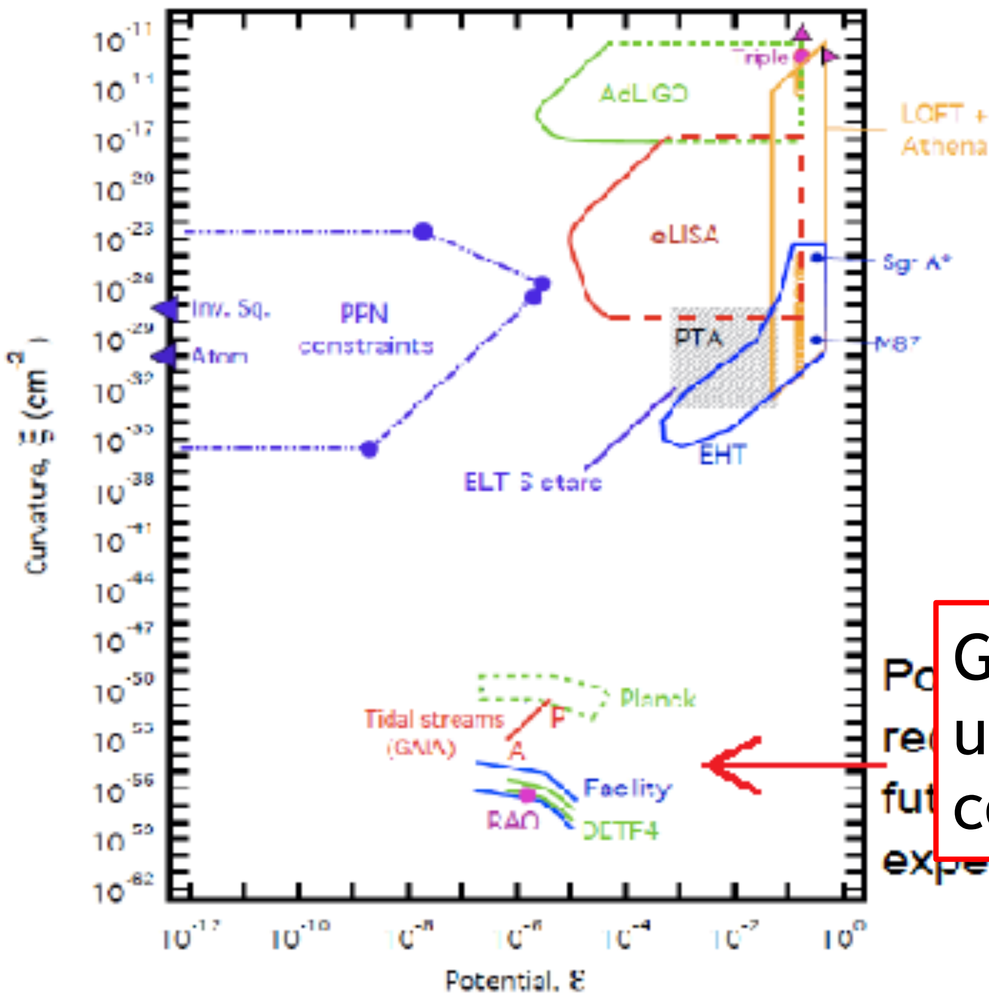


Figure 2. The experimental version of the parameter space. PPN= Parameterised Post-Newtonian regime, Inv.Sq.=laboratory tests of the inverse square law of the gravitational force, Atom=atom interferometry experiments, EHT=Event Horizon Telescope,

Po re fut experimentos

GR is almost unconstrained at cosmological scales

3. Modified Gravity

Simplest possibility: replace

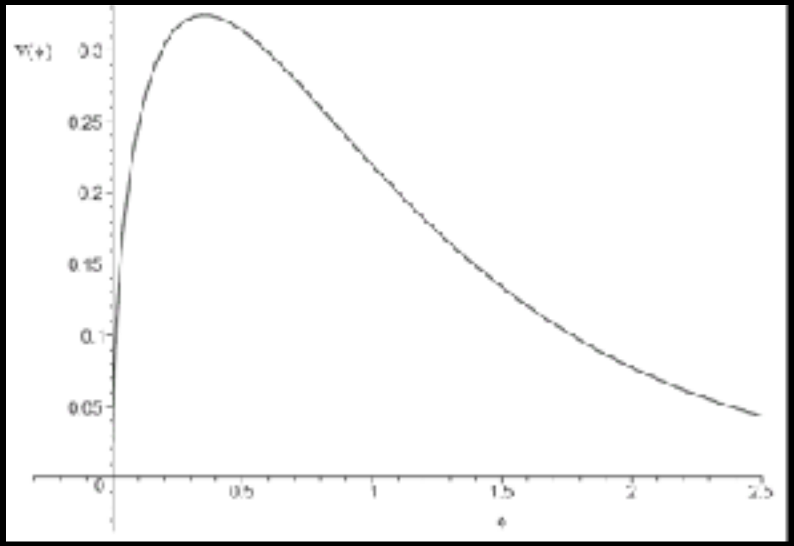
$$S = \int R \, d^4x$$

with

$$S = \int \left(R - \frac{\mu^4}{R} \right) d^4x$$

[Carroll, Duvvuri, Trodden & Turner 2003]

The vacuum in this theory is not flat space, but an accelerating universe!



But: the modified action brings a new tachyonic scalar degree of freedom to life. A scalar-tensor theory of gravity.

For simulations you solve the s field or fluid simultaneously with particles and also change poisson equation, expensive

Scalar-Tensor Gravity

Introduce a scalar field $\phi(x)$ that determines the strength of gravity. Einstein's equation

$$G_{\mu\nu} = 8\pi G T^{(\mathrm{m})}_{\mu\nu}$$

is replaced by

$$G_{\mu\nu} = f(\phi)\left[T^{(\mathrm{m})}_{\mu\nu} + T^{(\phi)}_{\mu\nu}\right]$$

variable "Newton's constant"

extra energy-momentum from ϕ

The new field $\phi(x)$ is an extra degree of freedom; an independently-propagating scalar particle.

Loophole: the Chameleon Effect or Screening

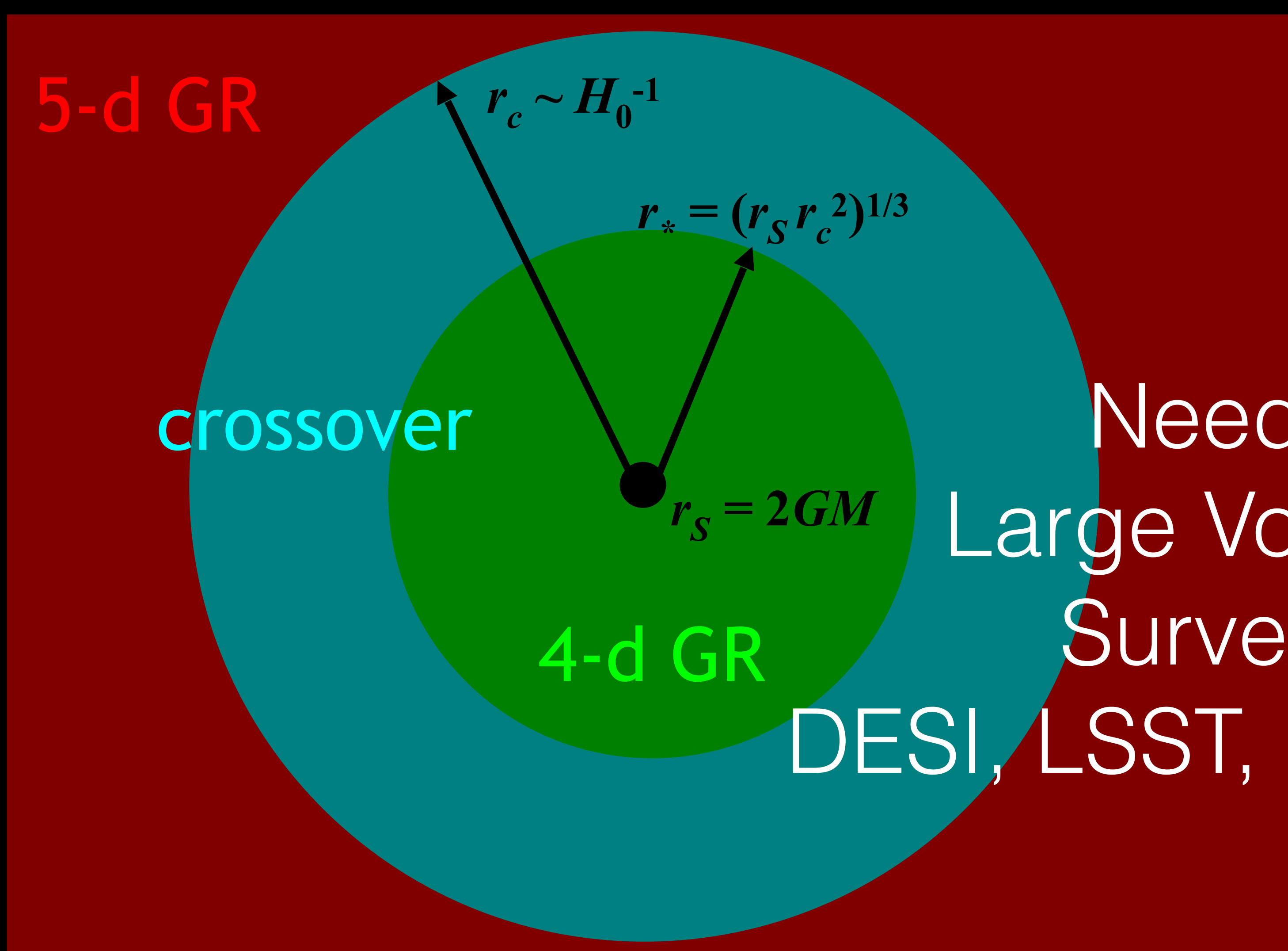
Curvature contributes to the effective potential for ϕ. With the right bare potential, the field can be normalized (with large mass) in dense regions, e.g. the galaxy, pulsars, solar system.

Deviations from GR can be hidden on sub-galactic scales. How? Field properties

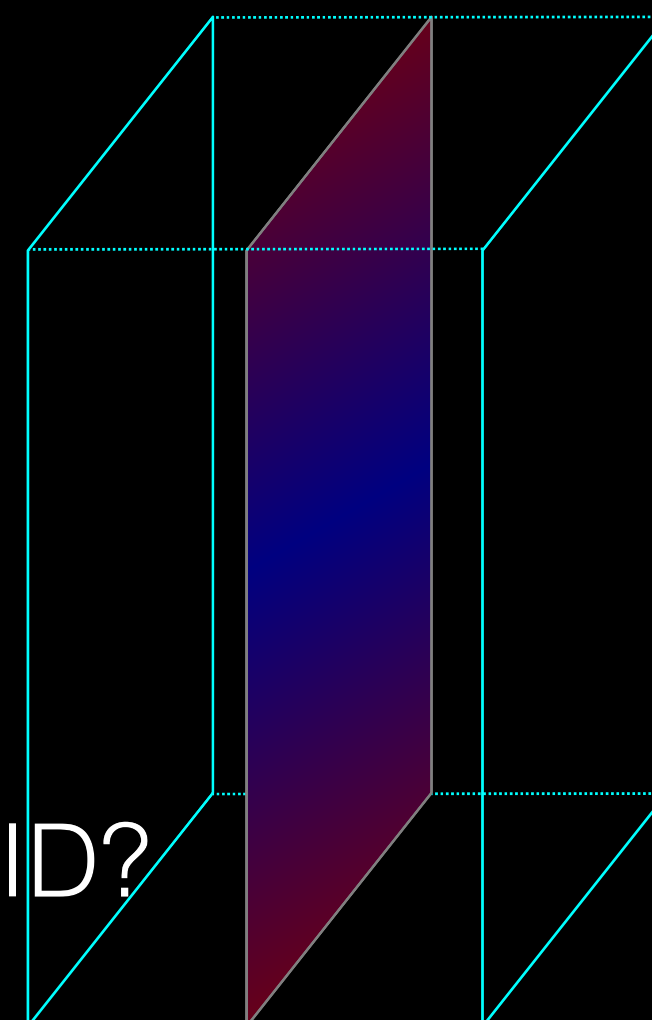
Dvali, Gabadadze, & Porrati (DGP) gravity: an infinite extra dimension, with gravity stronger in the bulk; 5-d kicks in at large distances.

$$S = \frac{M^2}{2} \int R_4 \, d^4x + \frac{M^2}{2r_c} \int R_5 \, d^5x$$

4-d gravity   5-d gravity suppressed by $r_c \sim H_0^{-1}$



Needs
Large Volume
Surveys
DESI, LSST, EUCLID?



[Dvali, Gabadadze & Porrati 2000]

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 ! components vs modified gravity.

Standard Ruler

- Suppose we have an object whose length we know as a function of cosmic epoch.

- By measuring the angle (θ) subtended by this ruler (χ) as a function of redshift we map out the angular diameter distance d_A

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

$$\Delta\theta = \frac{\Delta\chi}{d_A(z)}$$

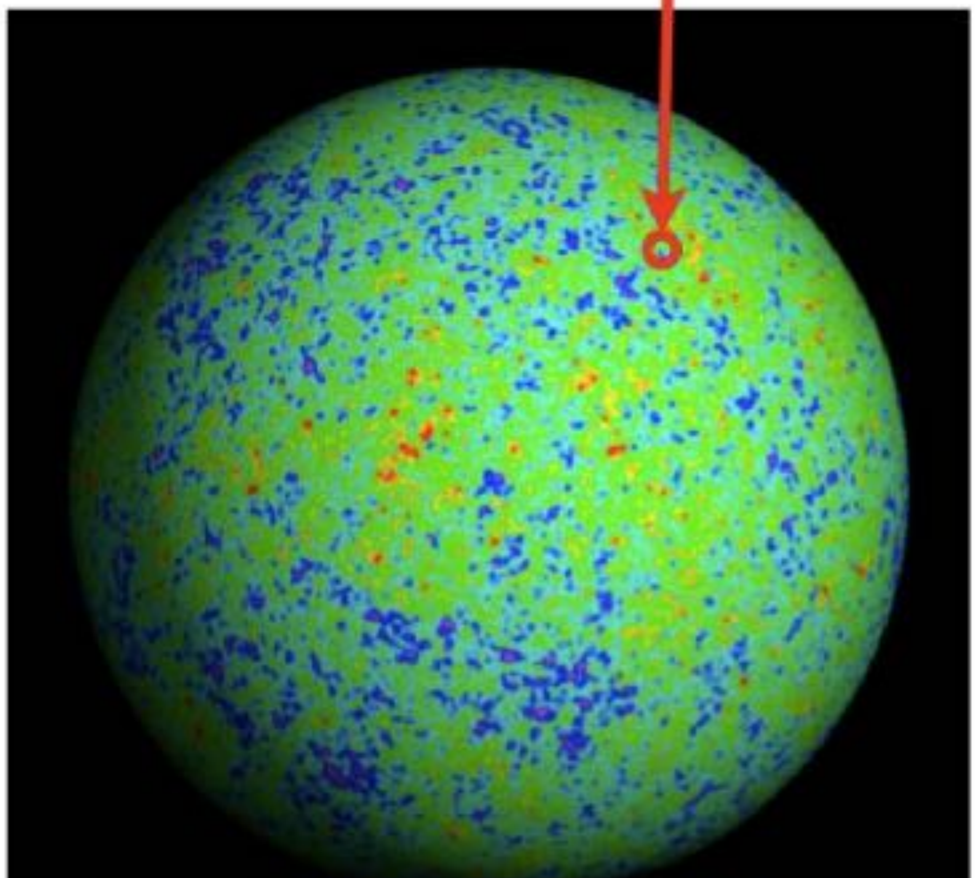
- By measuring the redshift interval (△z) associated with this distance we map out the Hubble parameter H(*z*)

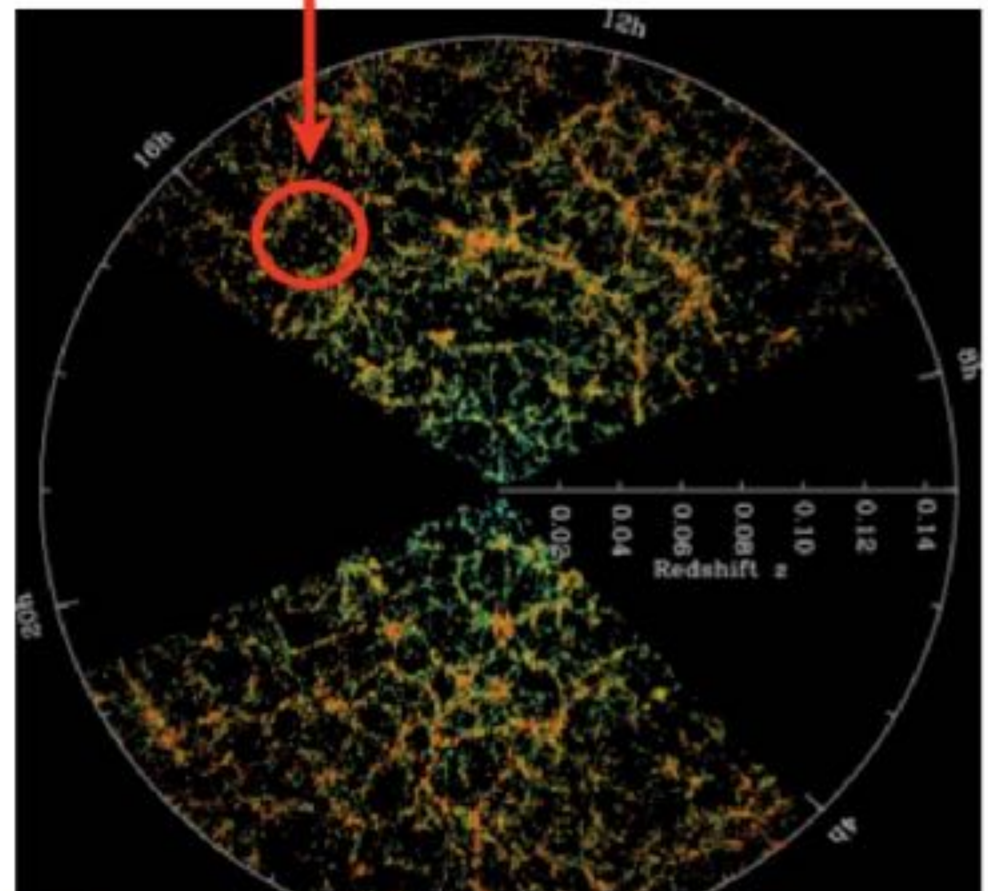
$$c\Delta z = H(z)\,\Delta\chi$$

What are baryon acoustic oscillations (BAO)?

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

...these ~unity fluctuations today


Universe at 300,000 years old (CMB)



Universe today (galaxy map)

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

Slide from Shirley Ho

Linearizing the Fluid Equations

The next step is to linearize the fluid equations: Using that both ρ and v are small, we can neglect all higher order terms (those with ρ^2, v^2, or $\rho\, v$).

If we write $T = \bar{T} + \delta T$ and also igore higher-order terms containing the small temperature perturbation δT , the fluid equations simplify to

continuity equation
$$\frac{\partial \delta}{\partial t} + \frac{1}{a}\nabla \vec{v} = 0$$

Euler equations
$$\frac{\partial \vec{v}}{\partial t} + \frac{\dot{a}}{a}\vec{v} = -\frac{\nabla \Phi}{a} - \frac{c_{\rm s}^2}{a}\nabla \delta - \frac{2\bar{T}}{3a}\nabla S$$

Differentiating the continuity eq. wrt t and using the Euler & Poisson eqs yields:

$$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = 4\pi G \bar{\rho} \delta + \frac{c_{\rm s}^2}{a^2}\nabla^2 \delta + \frac{2}{3}\frac{\bar{T}}{a^2}\nabla^2 S$$

This \`master equation' describes the evolution of the density perturbations in the linear regime ($|\delta| \ll 1$), but only for a non-relativistic fluid !!!

Baryon Acoustic Oscillations!!

Consider adiabatic evolution of isentropic perturbations ➡ $\delta_S = 0$ at all times.

Go to fourier space laplacian implies a k^2 factor

If we ignore for the moment the expansion of the Universe ($\dot{a} = 0$), then our linearized equation in Fourier space reduces to a wave equation:

$$\frac{\mathrm{d}^2\delta_{\vec{k}}}{\mathrm{d}t^2} = -\omega^2 \delta_{\vec{k}} \qquad \text{where} \quad \omega^2 = \frac{k^2 c_s^2}{a^2} - 4\pi G\bar{\rho}$$

pressure vs selfgravity

The special case $\omega = 0$ defines a characteristic mode, k_J, which translates into a characteristic scale

the Jeans length

$$\lambda_J^{\mathrm{prop}} = a(t)\lambda_J^{\mathrm{com}} = a(t)\frac{2\pi}{k_J} = c_s\sqrt{\frac{\pi}{G\bar{\rho}}}$$

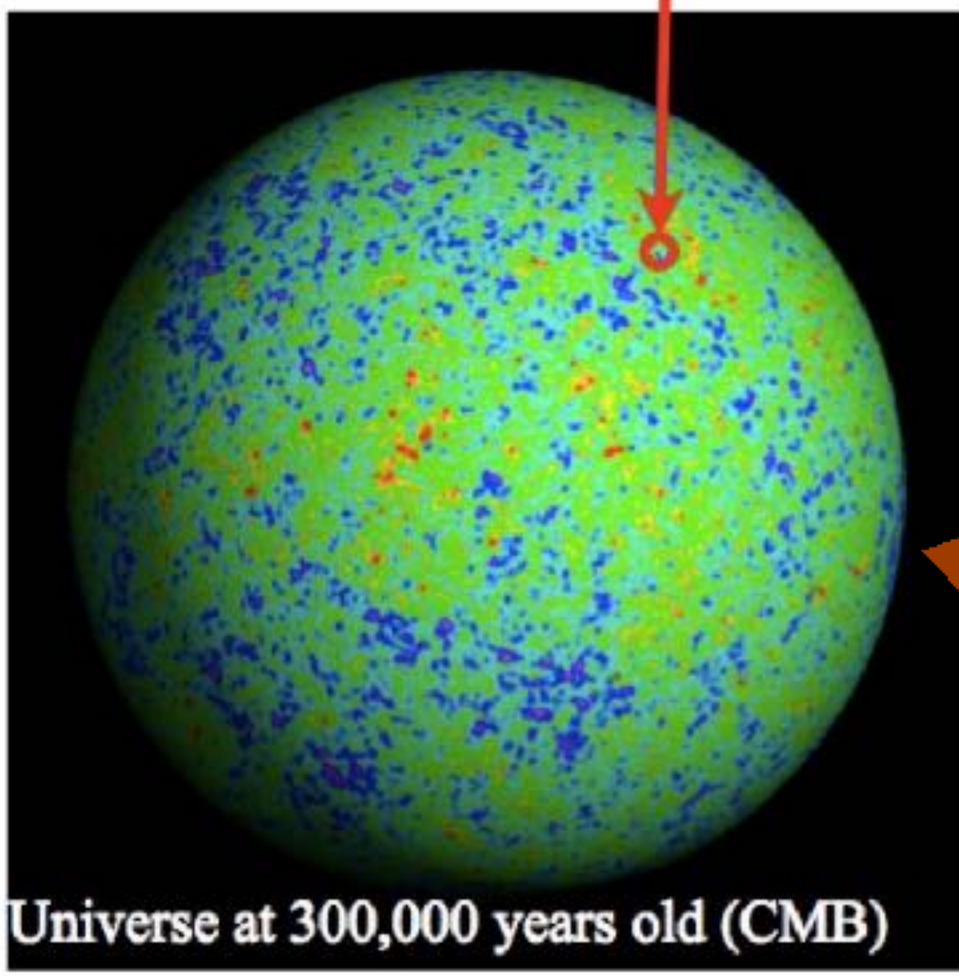
Hence, we have the following Jeans criterion:

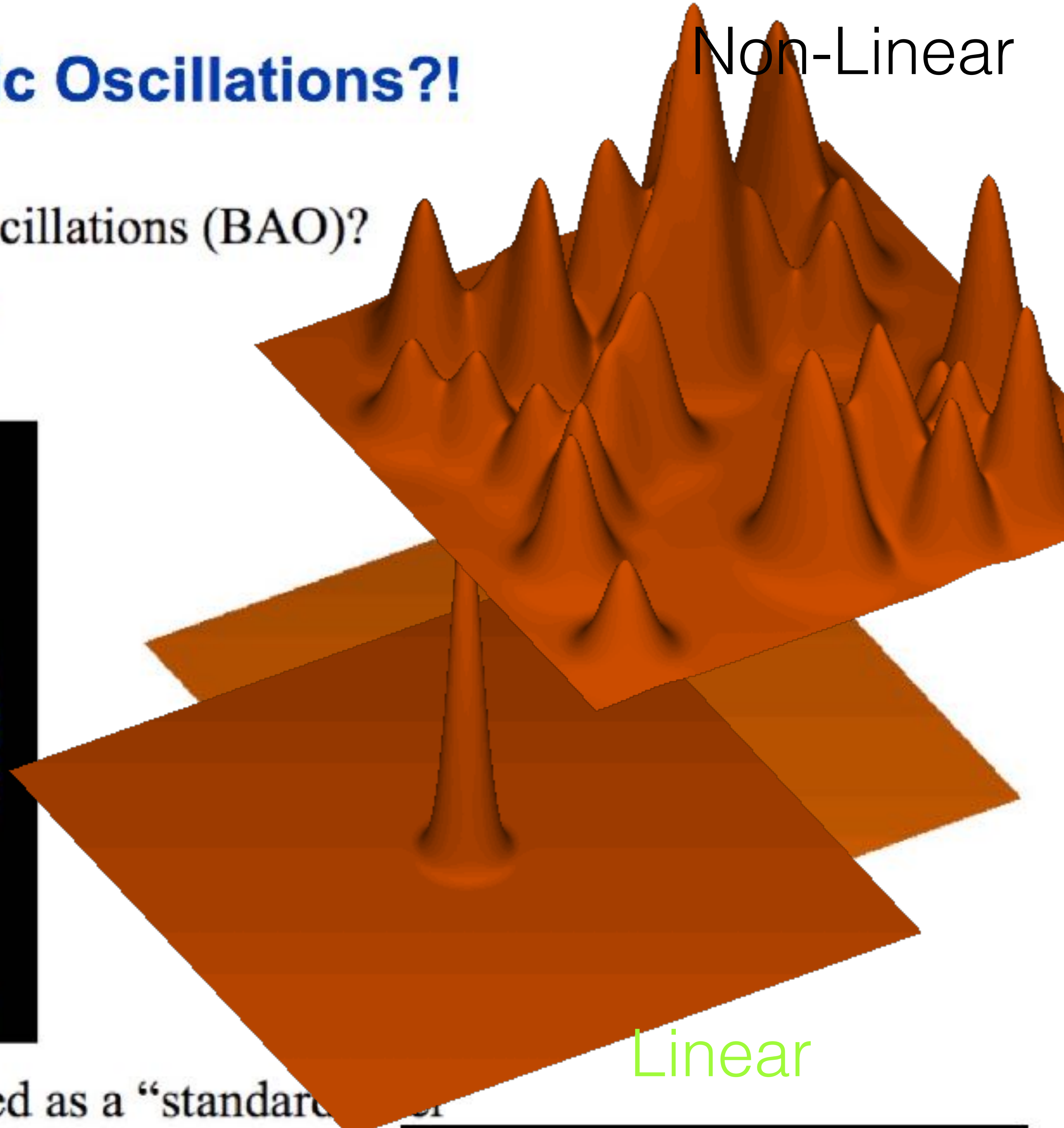
$\lambda < \lambda_J$ ➡	$\omega^2 > 0$ ➡	$\delta_{\vec{k}}(t) \propto e^{\pm i\omega t}$	sound wave, propagating w. sound speed
$\lambda > \lambda_J$ ➡	$\omega^2 < 0$ ➡	$\delta_{\vec{k}}(t) \propto e^{\pm i\omega t}$	static mode, growing or decaying exponentially with time

Baryon Acoustic Oscillations?!

What are baryon acoustic oscillations (BAO)?

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



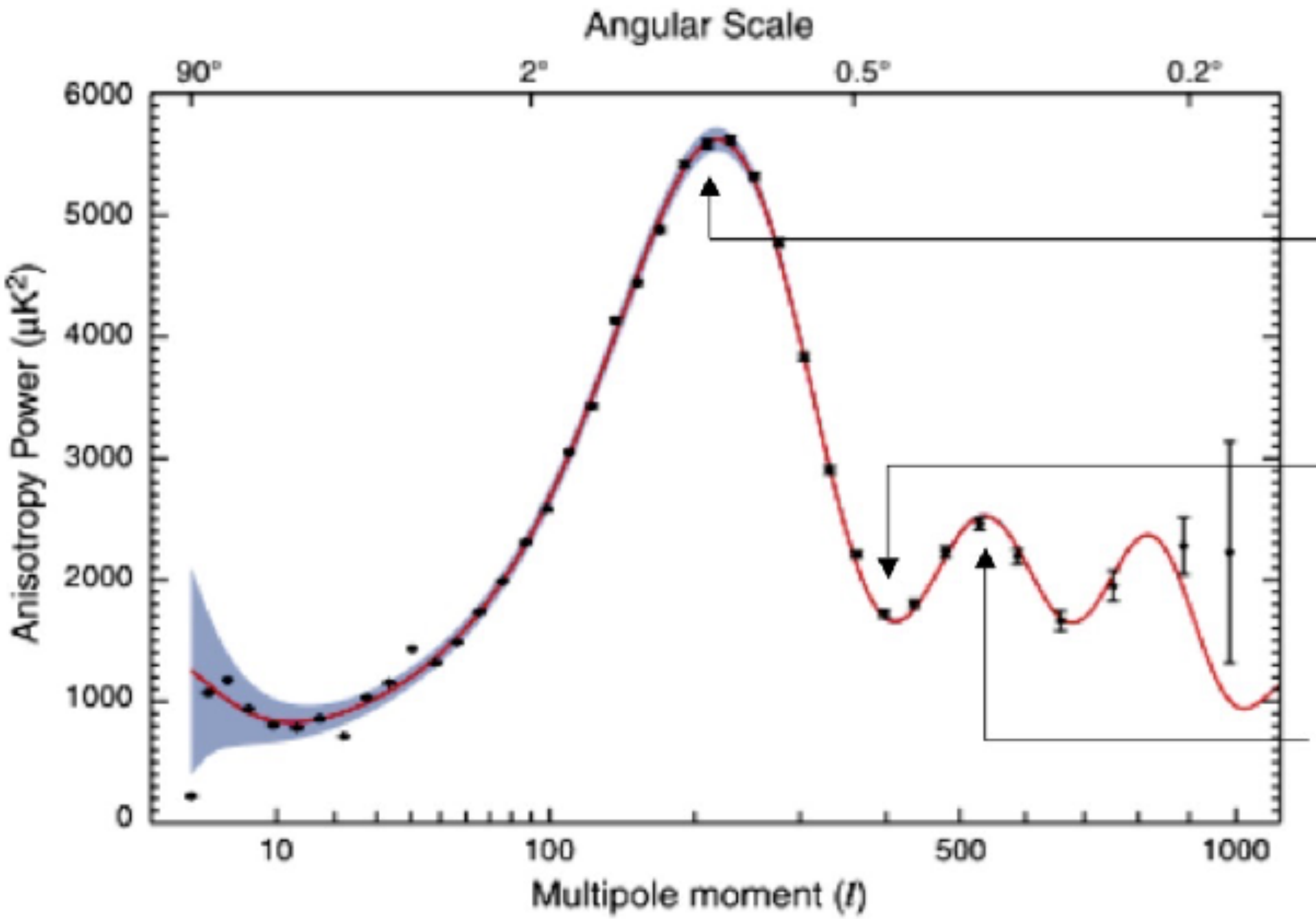


This sound wave can be used as a “standar

Dark energy changes this apparent ruler size

Courtesy slide from David Schlegel
and animation from Daniel Eisenstein

Acoustic oscillations seen!



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

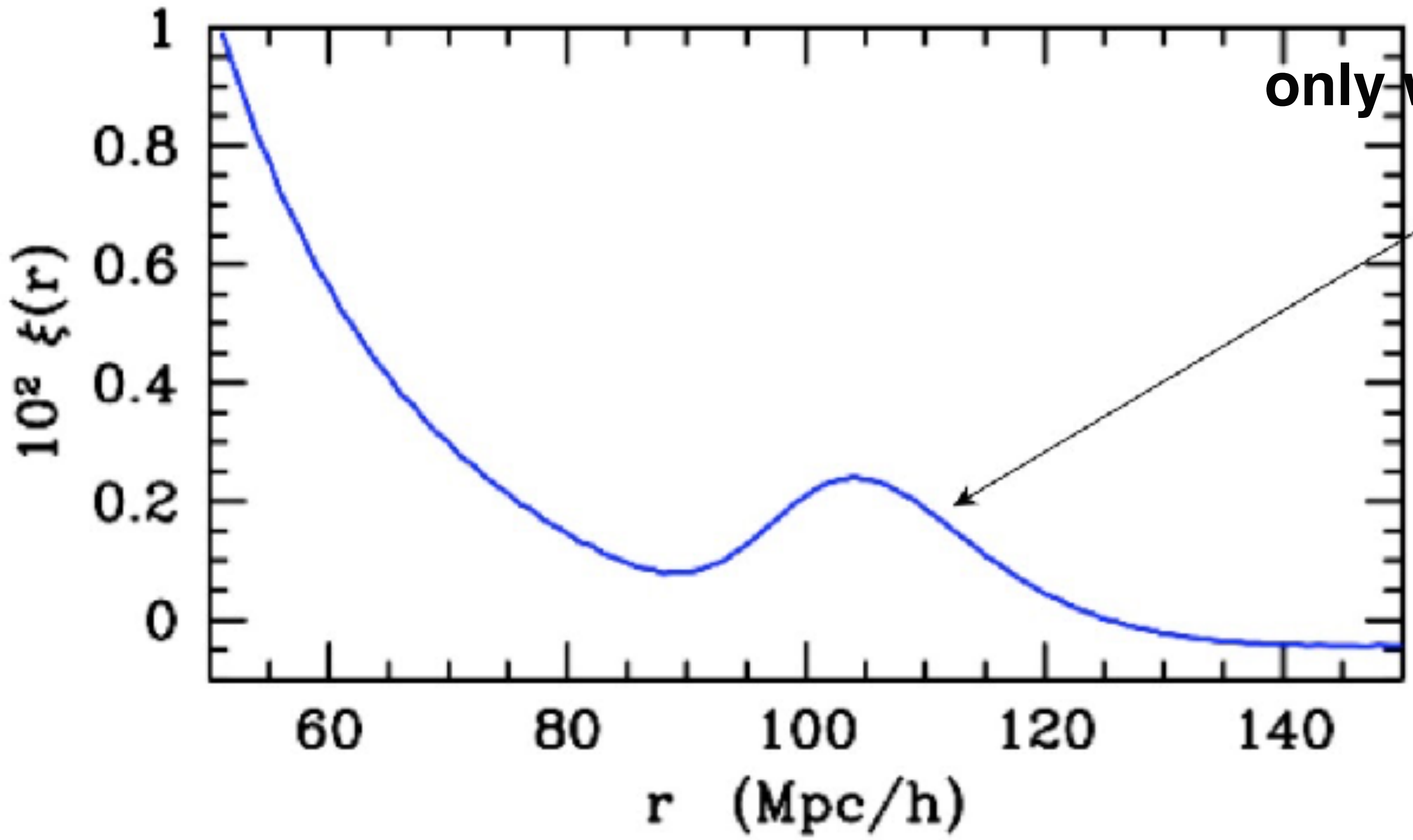
Velocity maximum

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

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

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.



It happens only with baryons presence

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

Is this our Universe? Do you believe it?

BAO and Galaxies

- Pairs of galaxies are slightly more likely to be separated by 150 Mpc than 120 Mpc or 170 Mpc.

NOTE: BAO effects highly exaggerated here

Credit: Zosia Rostomian, LBNL

Carnegie Mellon University

SDSS III

Finally technically possible

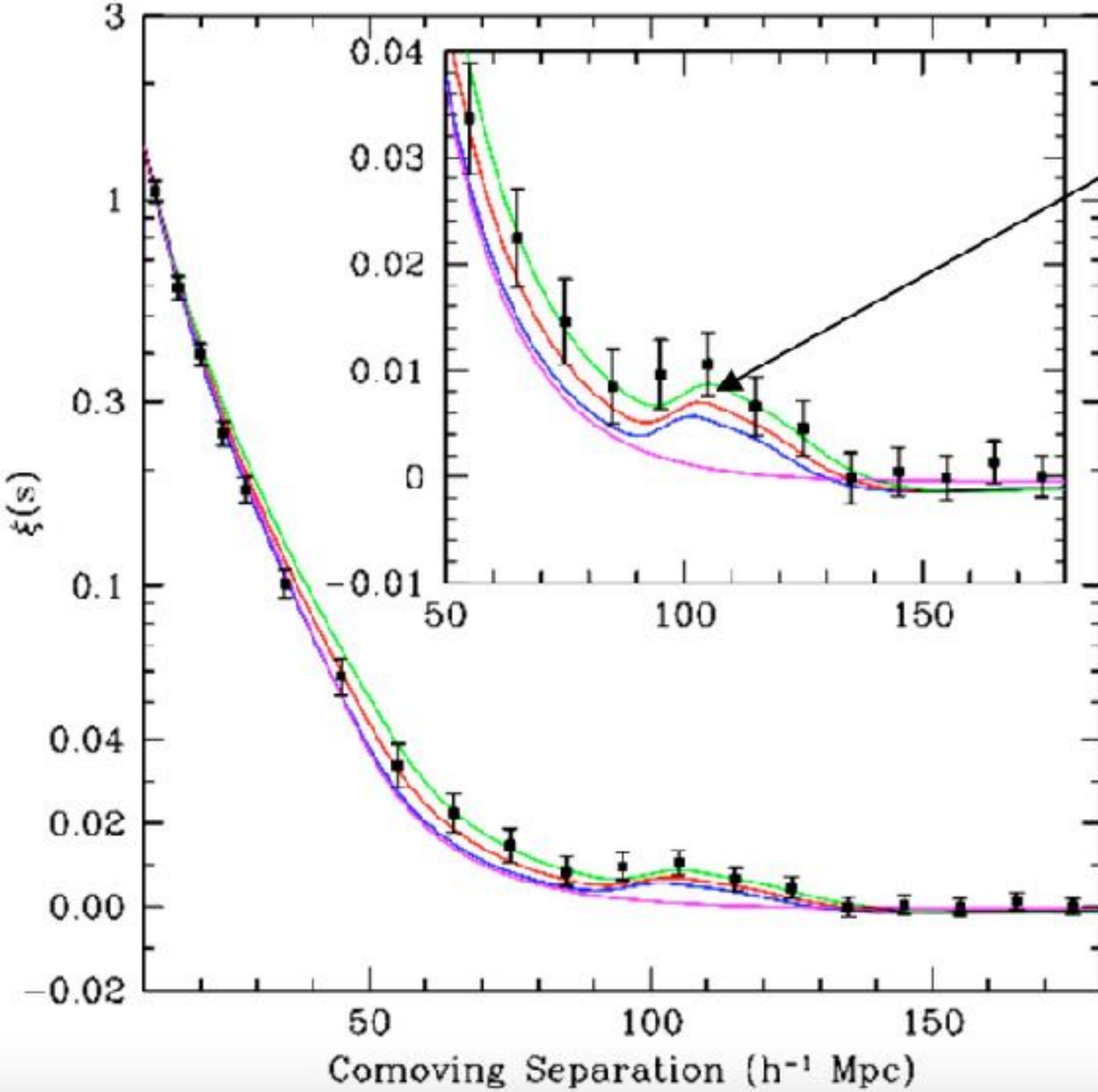
SDSS and 2dF surveys allow detection of BAO signal …

Mayall Telescope interior.

Many New Surveys: SDSS III, SUMIRE-PFS, **DESI**
WFIRST?

BAO signal

Another prediction verified!!



Eisenstein et al. (2005) detect oscillations in the SDSS LRG ξ(r) at z~0.35! Knowing ***s*** determines D(*z*=0.35).

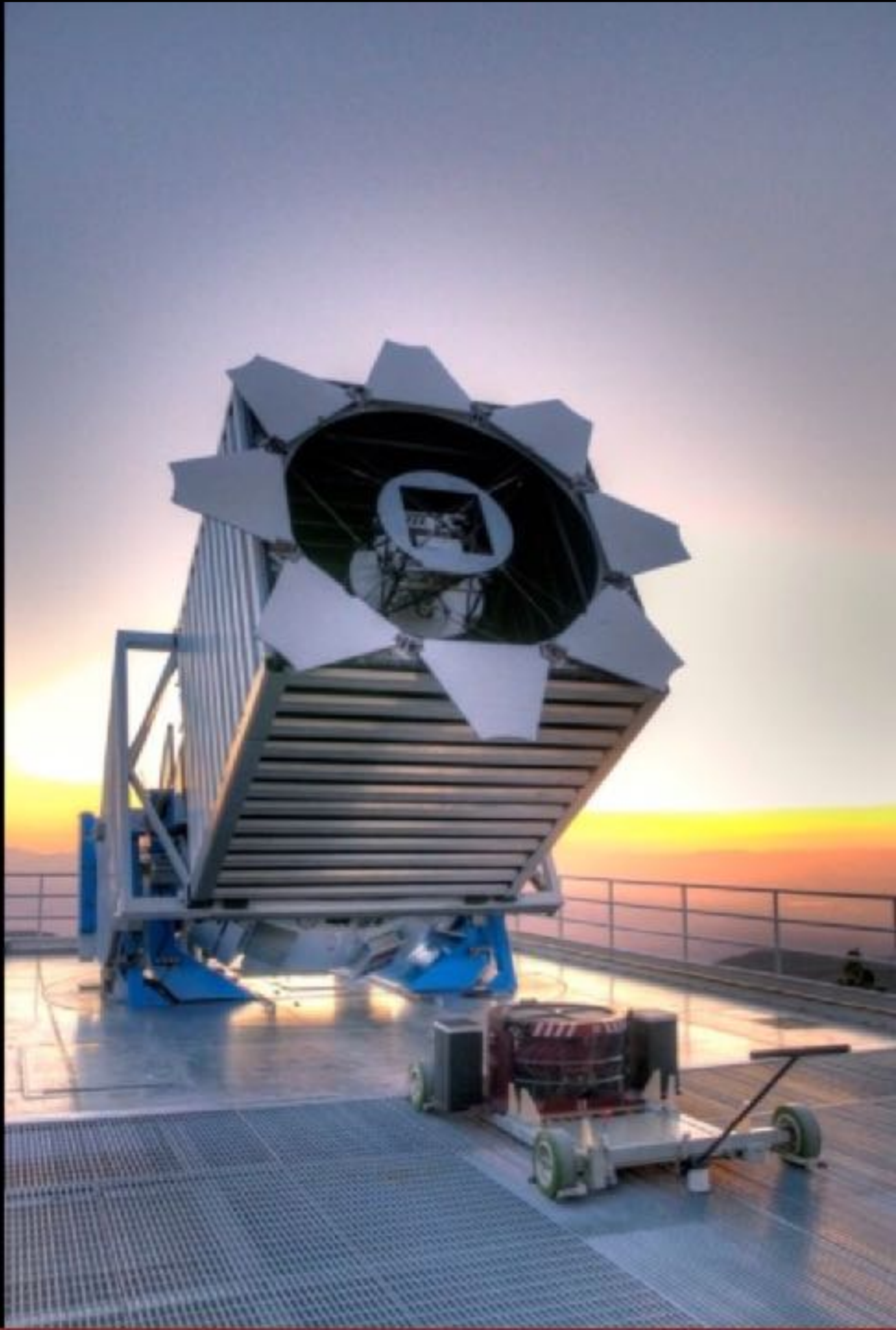
About 10% of the way to the surface of last scattering!

Constraints argue for the existence of DE, but do not strongly constrain its properties.

independently of SNIa

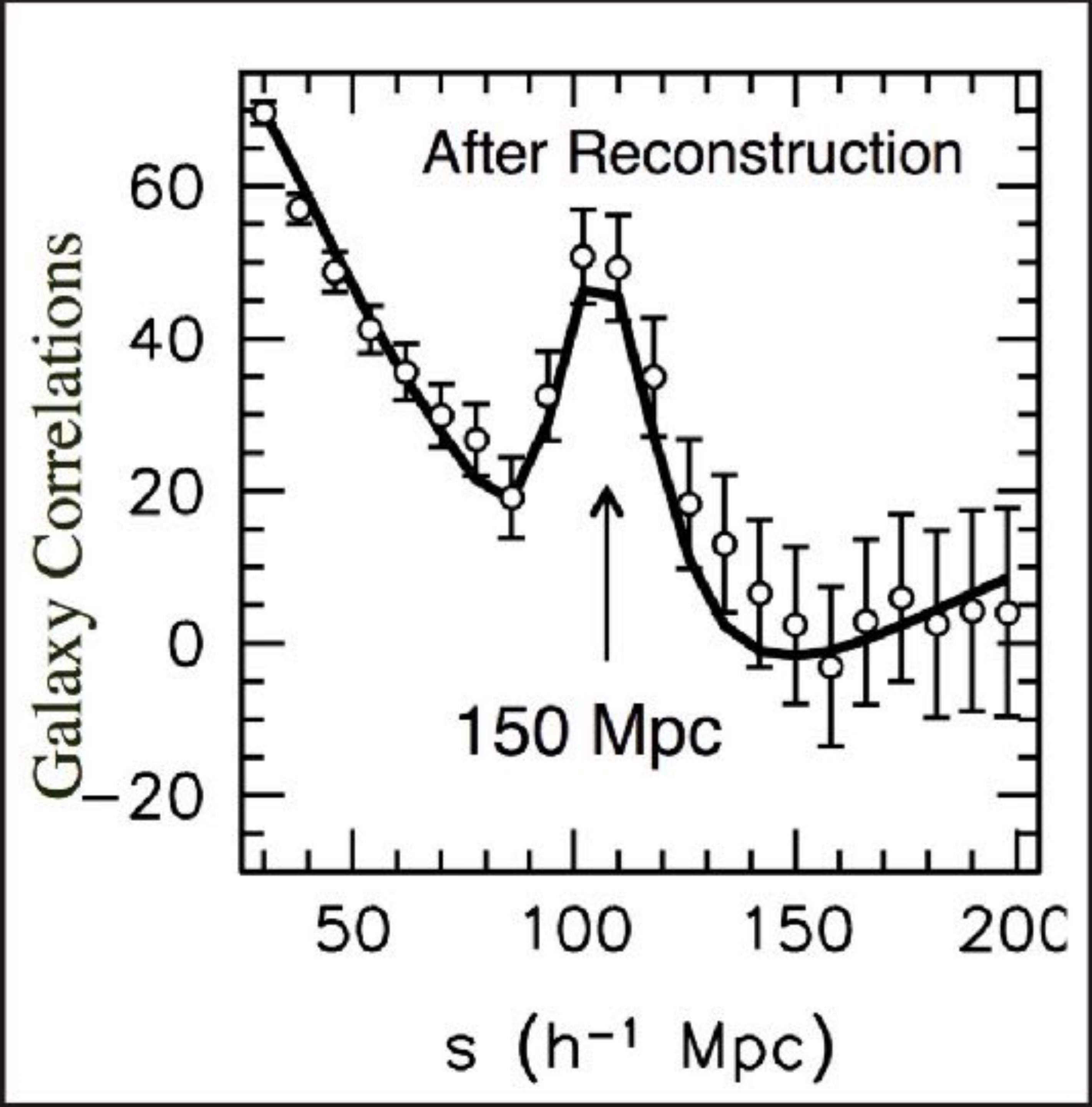
SDSS-III/BOSS

- Main SDSS-III project
- APO telescope (New Mexico, USA), 2.5 m diameter
- Spectroscopic survey with SDSS-II photometry.
- 2 two-arms spectrographs: 1000 fibers
- 3600 Å < l < 10000 Å, $\lambda/\Delta\lambda \sim 3000$
- **1.5 Millions Luminous Red Galaxies at $\langle z \rangle \sim 0.6$**
- **150 000 Quasars with Ly-α forests at $\langle z \rangle \sim 2.3$**
- Objectives:
- **BAO peak position 1% at z=0.6 and 1.5% at z=2.3**
- **Best constraints on the Dark Energy equation of state before next generation** DESI, LSST, EUCLID



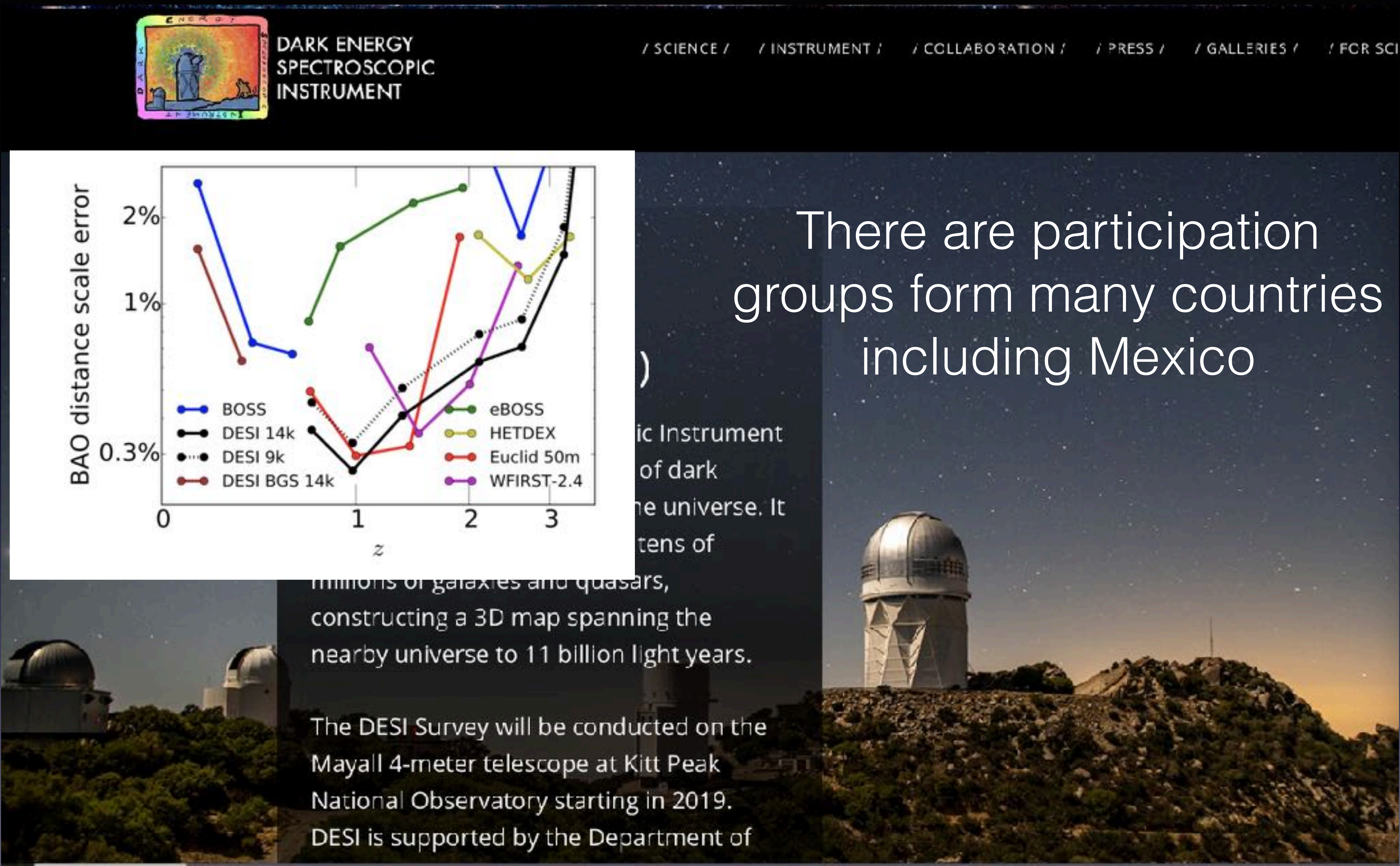
BAO in BOSS Galaxies

- The peak location is measured to 1.0% in our $z = 0.57$ sample and 2.1% in our $z = 0.32$ sample



Anderson et al. 2014;
Vargas, Ho et al. 2014;
Tojeiro et al. 2014

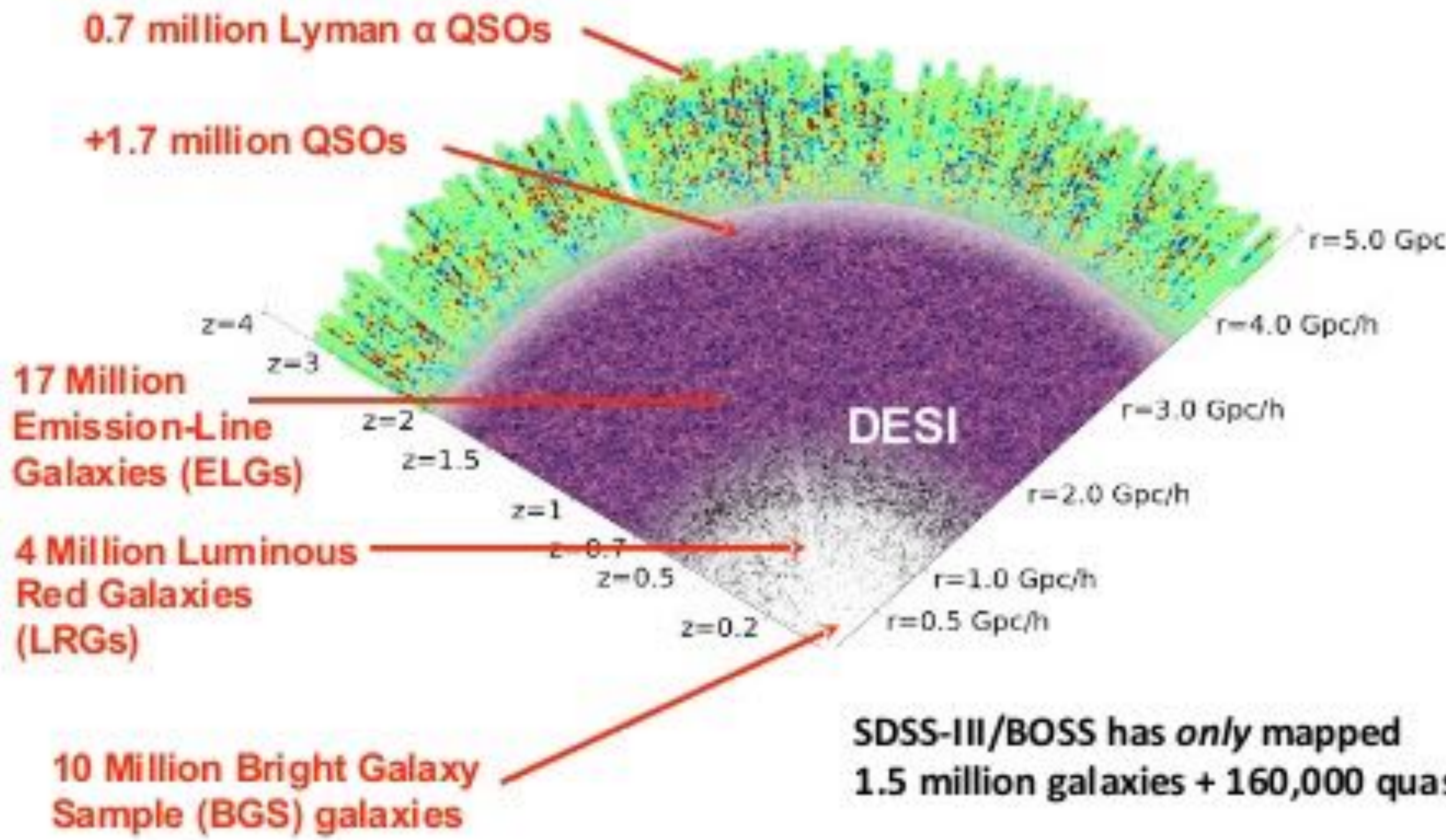
There are participation groups form many countries including Mexico



The largest spectroscopic survey for dark energy

SDSS ~$2h^{-3}Gpc^3$ ⇨ BOSS ~$6h^{-3}Gpc^3$ ⇨ DESI $50h^{-3}$

DESI Goals:
35 Million Galaxy + Quasar Redshift Survey

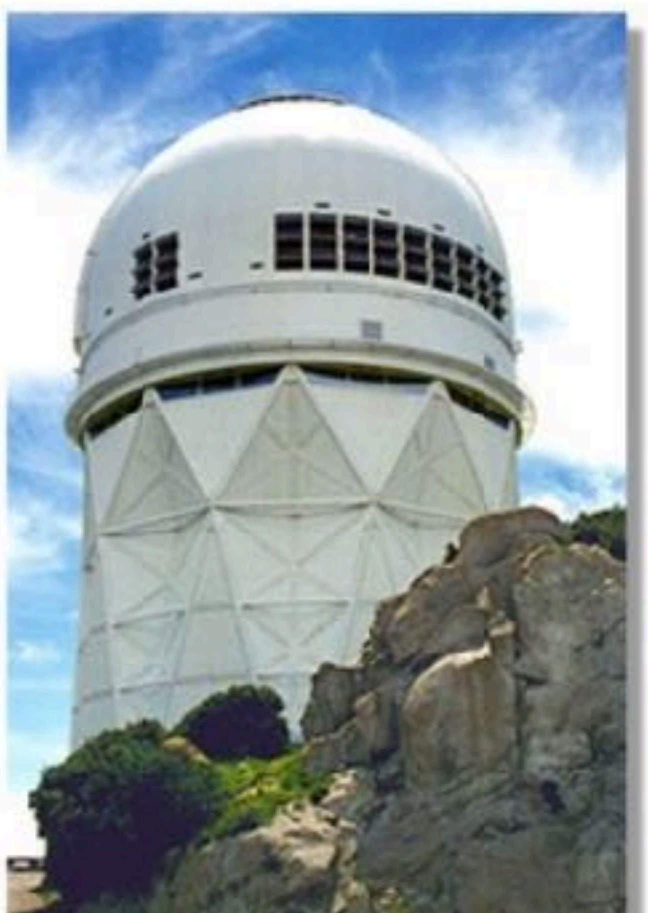


SDSS-III/BOSS has *only* mapped
1.5 million galaxies + 160,000 quasars

DESI

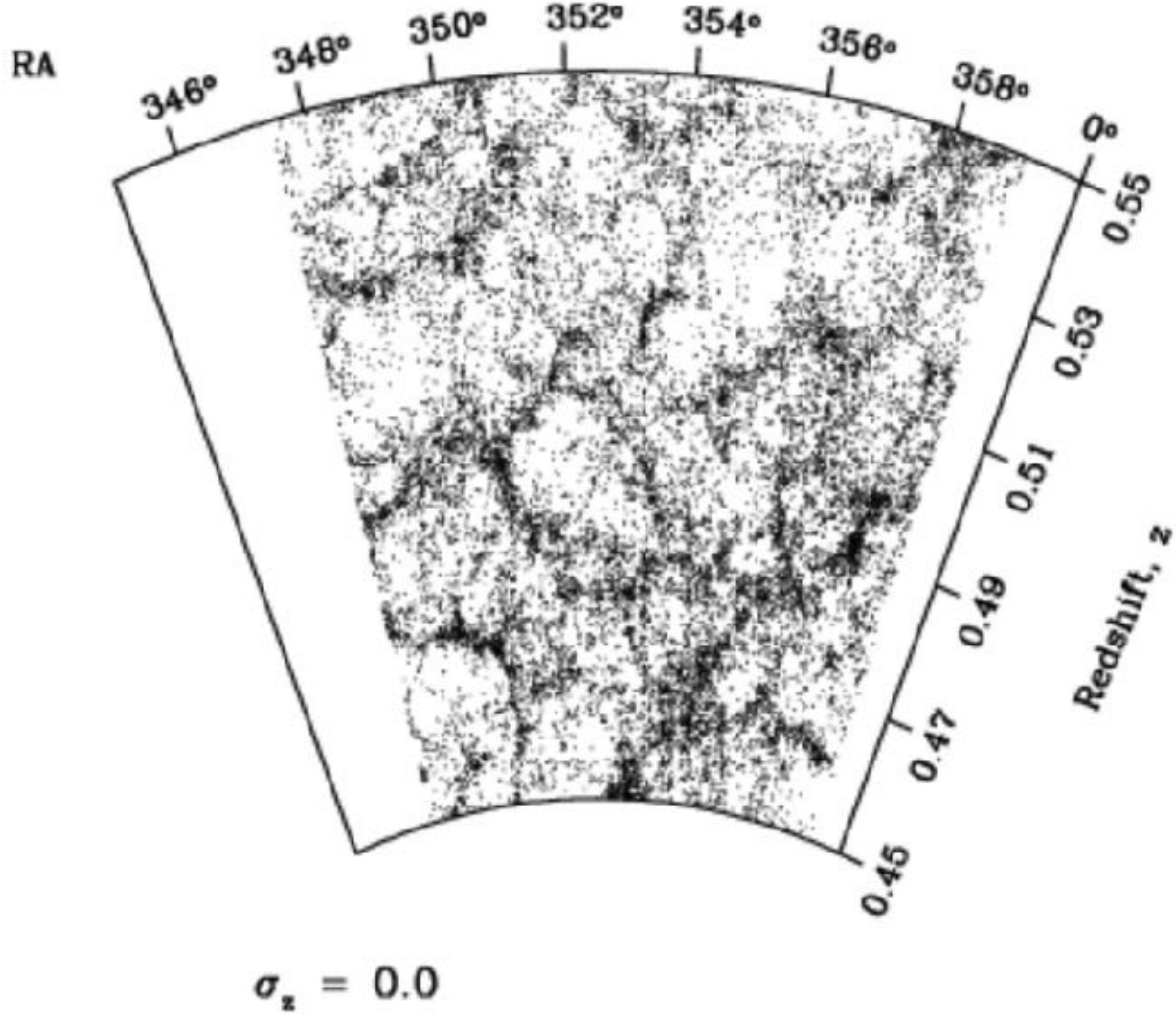
(Dark Energy Spectroscopic Instrument)

The US entry in the next generation of massively multiplexed, wide-field spectrographs on 4m telescopes

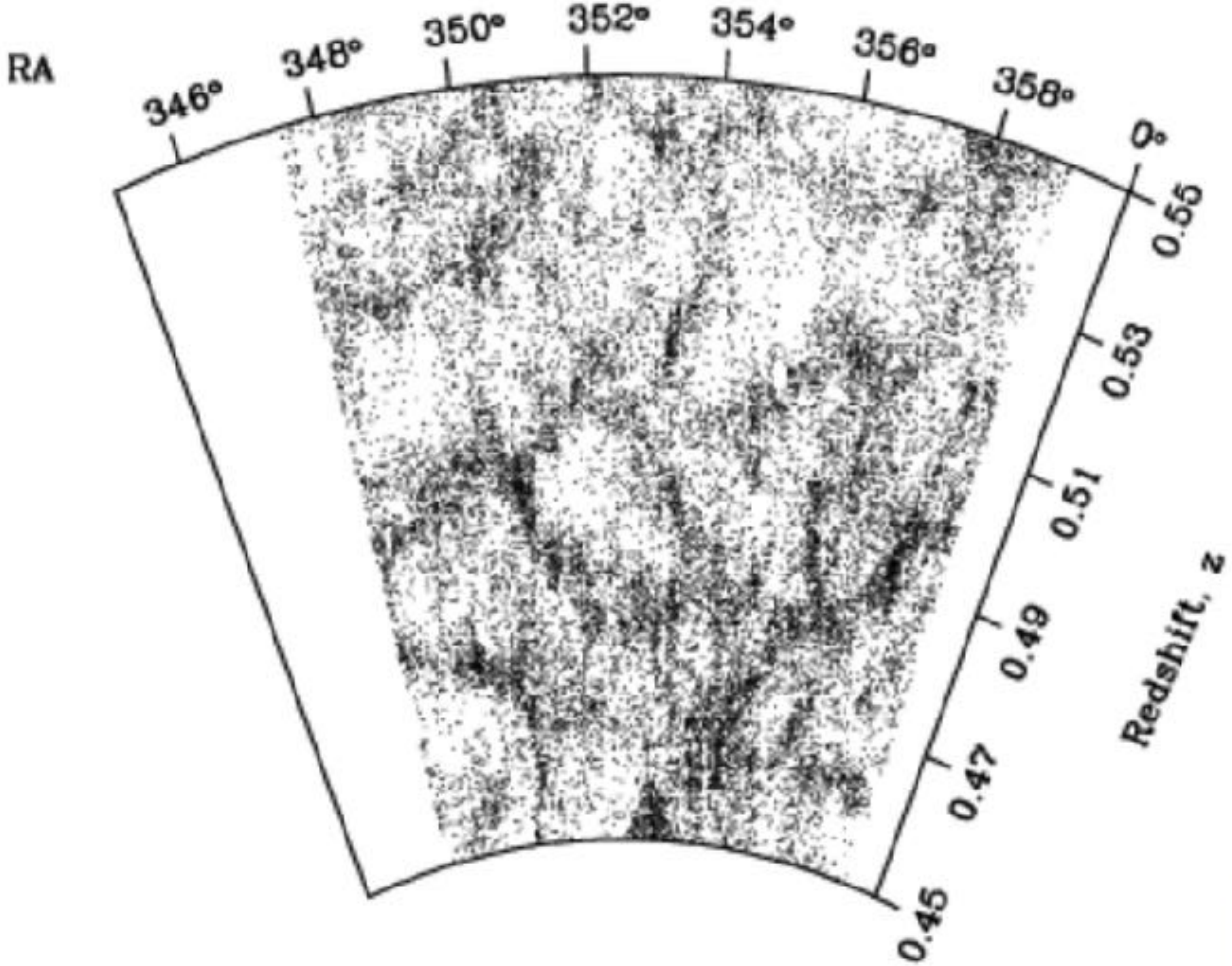


DESI MW Survey: basic parameters (v0.1)

- 14,000 square degrees
- 1 million+ stars
- expect S/N 25 per $\Delta\lambda$ at $r = 17$
- RVs to $r \sim 20$ @ the Gaia limit
- Should be an exciting facility for MW science



Using Hubble Law to map galaxy 3D distribution



$\sigma_z = 0.001(1+z)$

Gravitationally induced peculiar motions on top of Hubble flow

Observational Systematic?

- Non-lineal density evolution create distortions (widening and shift) BAO´s peak. *<u>That's why you need Simulations</u>*
- *<u>Because survey volumes are large and tracers</u>*
- *<u>small you need very expensive simulations</u>*
- *<u>Do I have to redo all again??</u>*
  - **Redshit Space Distortion: instantaneous grow rate of fluctuations, modifies BAO too**

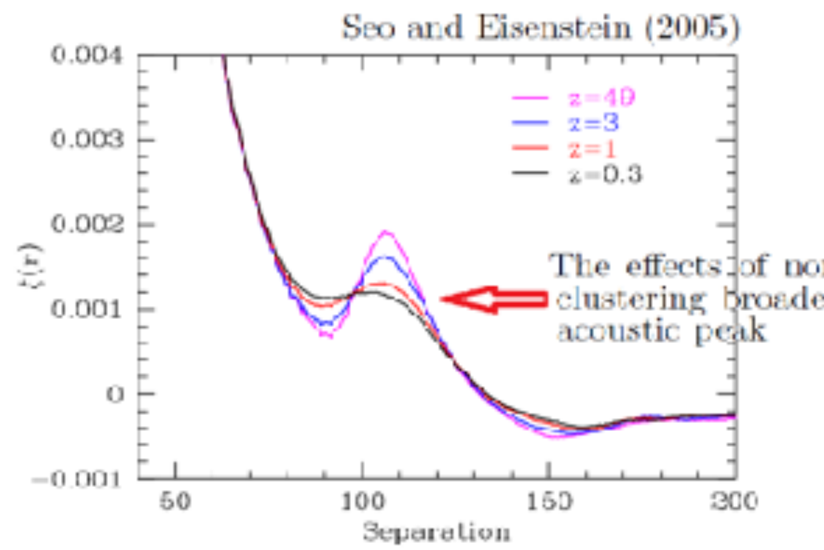
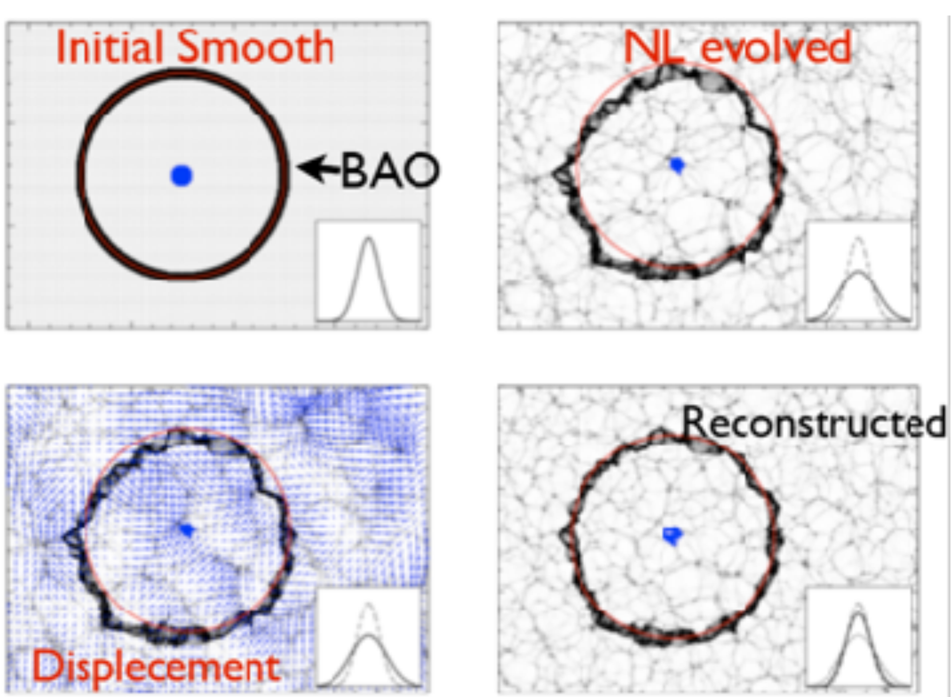
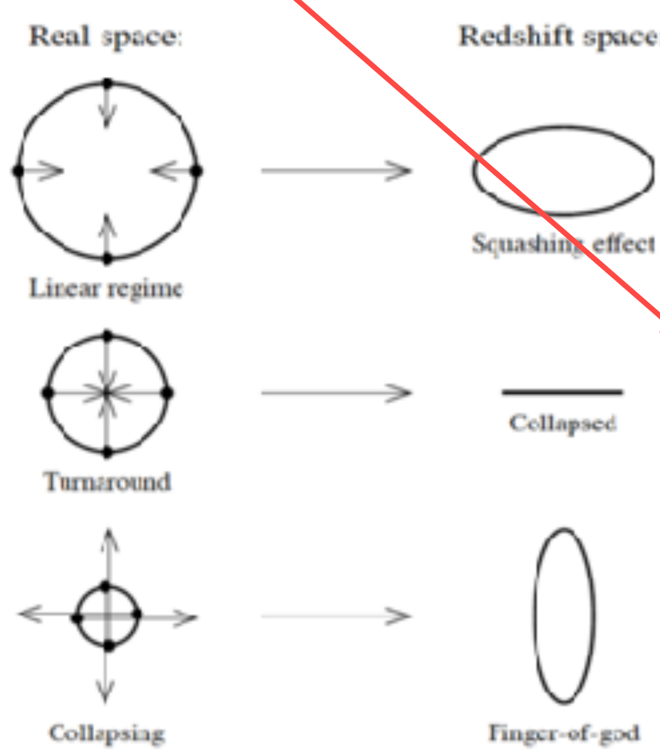
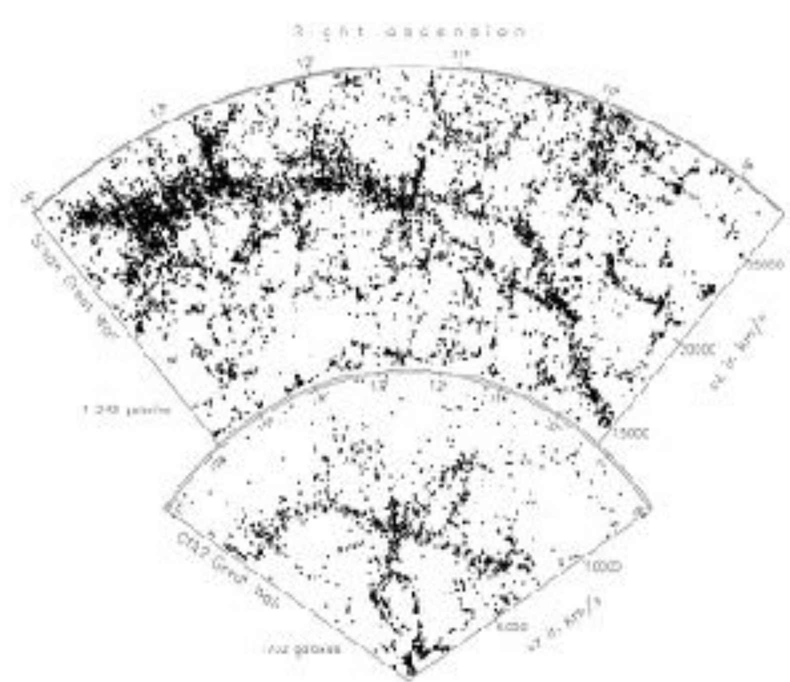


Figure 11 Redshift-space matter correlation function



Padmarabhan et al. 2012





RSD basics

- These velocities are driven by the matter distribution, according to gravitational physics

$$\dot{\delta} = -a^{-1}\nabla\cdot v$$
$$\delta \frac{d\ln\delta}{d\ln a} H = -a^{-1}\nabla\cdot v$$
$$f\delta = \theta = -\frac{\nabla\cdot v}{aH}$$

- For example in linear perturbation theory:

$$\theta = \vec{\nabla}.(\vec{v}/aH) = -f\,\delta_m$$

continuty eq

- in terms of the growth rate $f = d(\ln G)/d(\ln a)$

grow function

- where $\delta_m(a) = G(a)\,\delta_m(1)$

- The dependence of the growth rate on scale and time is a key discriminator between gravity models

The Linearized Fluid Equations

$$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = 4\pi G\bar{\rho}\delta + \frac{c_s^2}{a^2}\nabla^2\delta + \frac{2}{3}\frac{\bar{T}}{a^2}\nabla^2 S$$

`Hubble drag' term, expresses how expansion suppresses perturbation growth

gravitational term, expresses how gravity promotes perturbation growth

pressure terms, expressing how pressure gradients due to spatial gradients in density and/or entropy influence perturbation growth

Independent of expansion history

Linear RSD theory

$$P_g^s(k,\mu) = P_{gg}(k) - 2\mu^2\, P_{g\theta}(k) + \mu^4\, P_{\theta\theta}(k)$$

- Linear perturbation theory $\quad \tilde{\theta}(k) = -f\,\tilde{\delta}_m(k)$
- Linear galaxy bias $\quad \delta_g = b\,\delta_m$

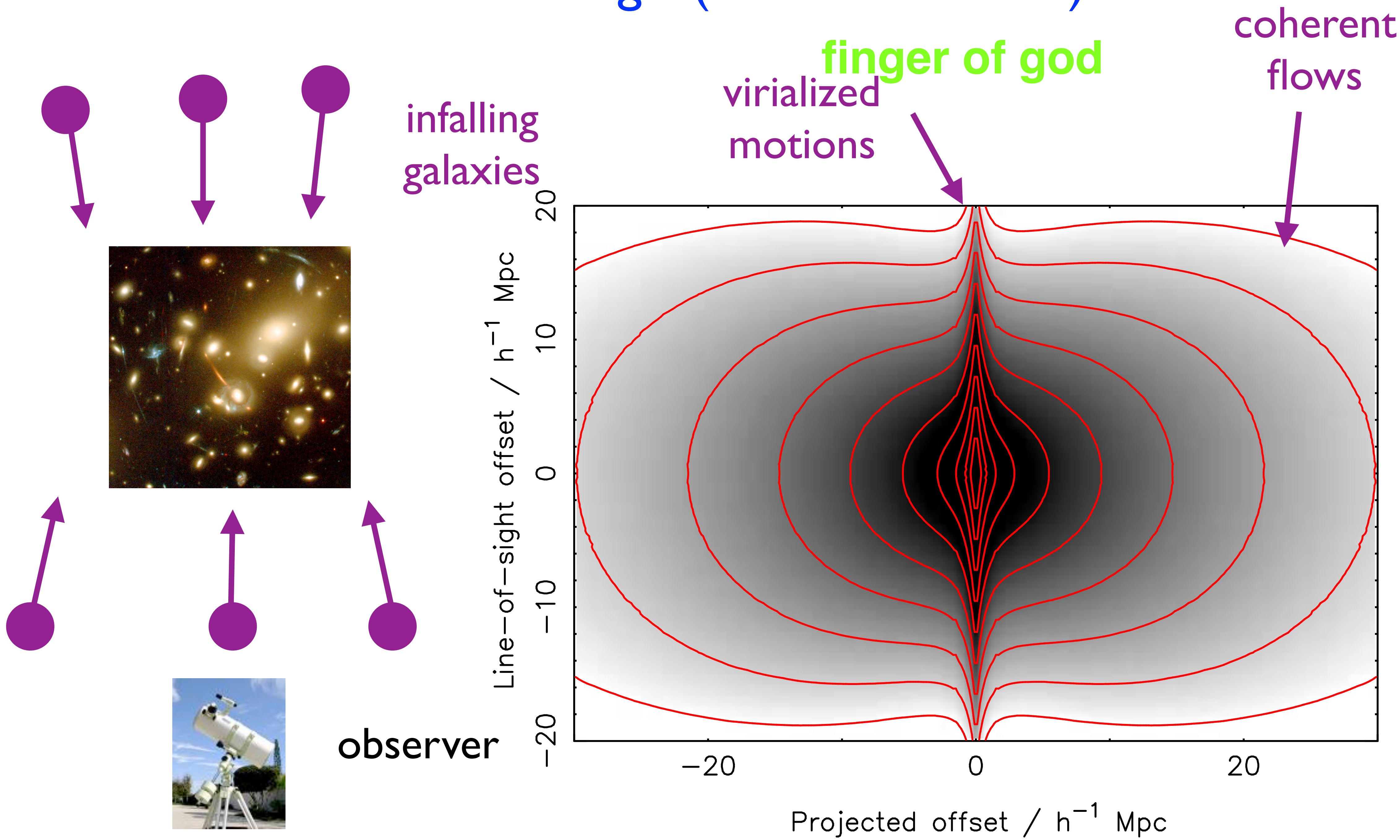
$$P_g^s(k,\mu) = P_m(k)\,(b + f\mu^2)^2$$

- Matter power spectrum $\quad P_m(k) \propto \sigma_8^2$

depends on sky position anisotropy in correlation function signal of RSD watch out Alcok-Pacinsky

RSD basics

- What are we measuring? (cartoon version)



RSD basics

- Can measure line-of-sight velocities because they add an extra Doppler shift to the galaxy redshift:

$$(1 + z_{\rm obs}) = (1 + z_{\rm cosmo})\,(1 + v_{\rm r}/c)$$

- Approach (1) : measure direct peculiar velocity v_r using standard-candle estimate of z_{cosmo}
- Approach (2) : measure redshift-space distortions in the clustering distribution of galaxies in “redshift space” (i.e. using positions based on z_{obs})
- The RSD approach has so far been the most accurate method of measuring cosmic growth

Tracers

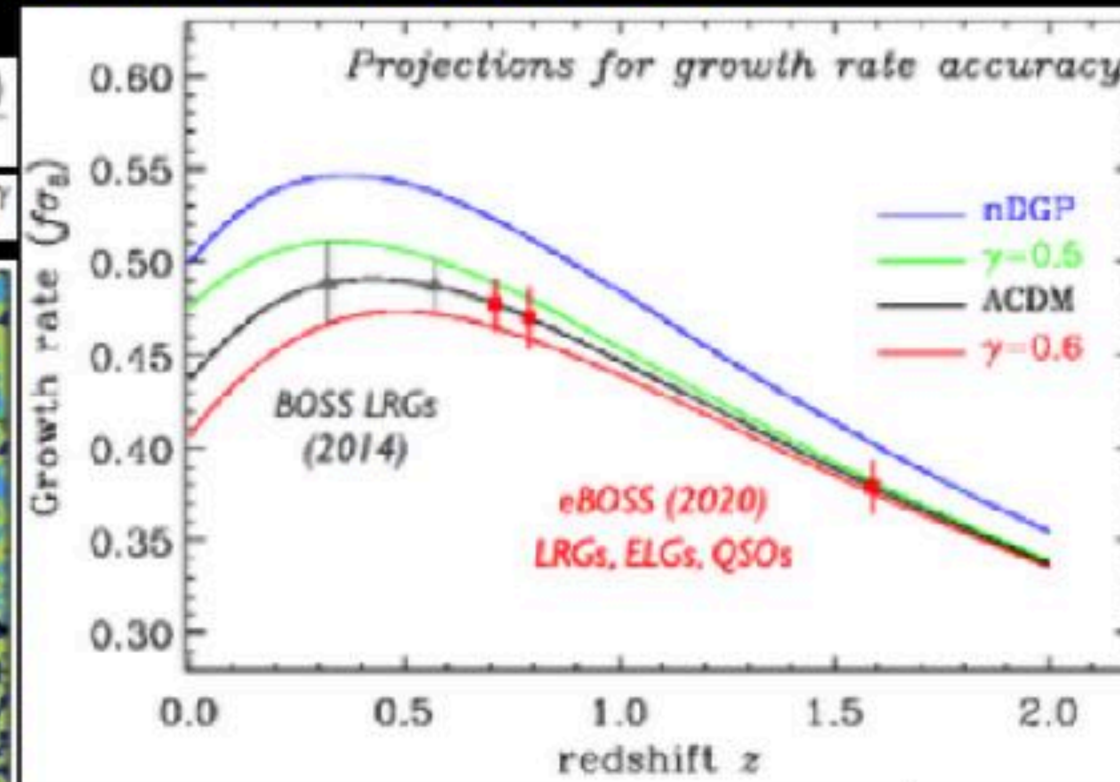
- Homogeneus and Bright
- Luminous Red Galaxies
- AGN´s
- Emission Line Galaxies

eBOSS: Science Goals

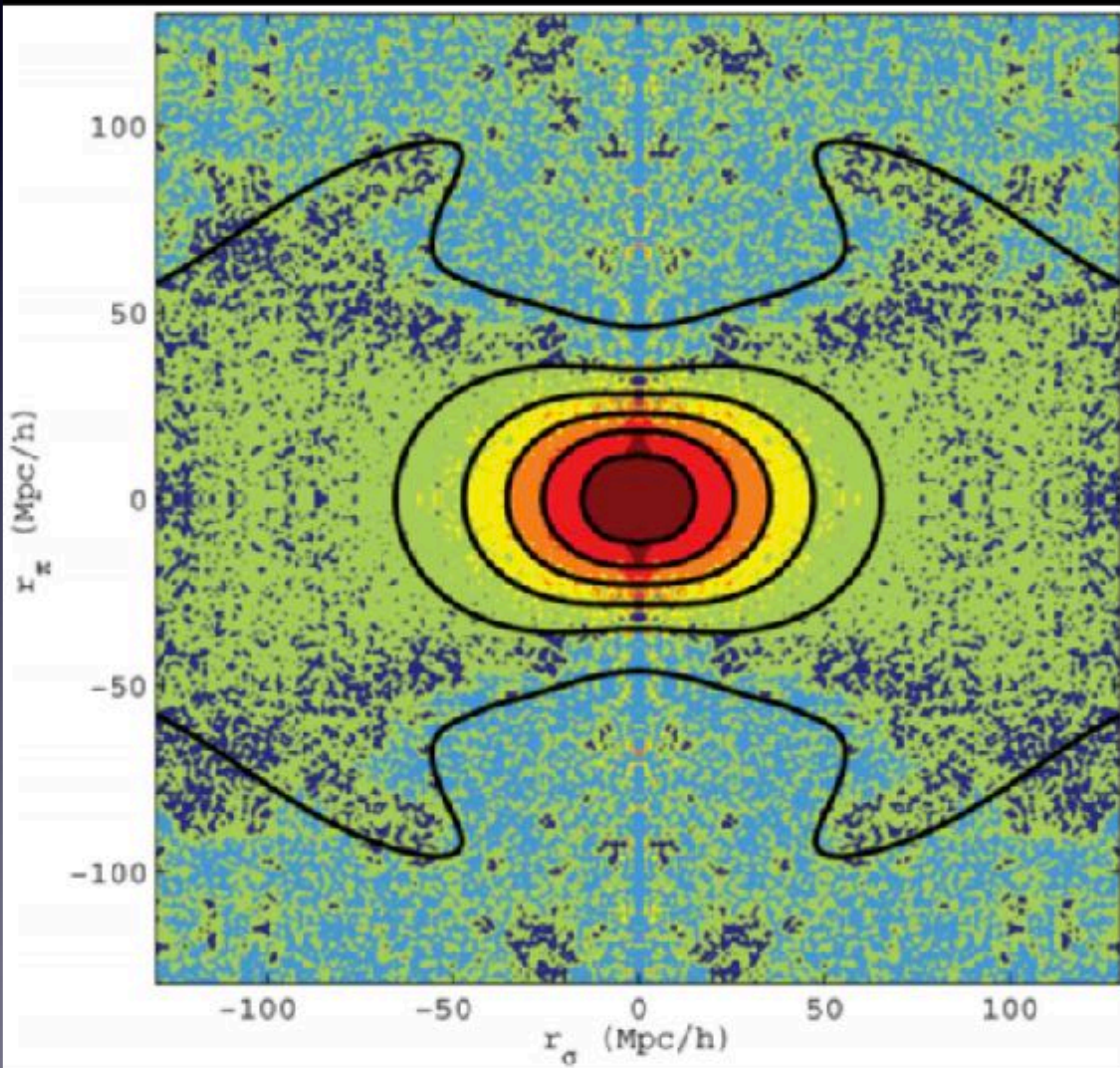
➢ **Redshift-Space Distortion (RSD): Growth of Structure**
→ **Test of General Relativity**

$$f = \frac{d\ln D(a)}{d\ln a}$$

$$f \simeq \Omega_m(z)^\gamma$$



SDSS WP



2D correlation function of DR9 CMASS (Reid+12)

The clustering of the SDSS-IV extended Baryon Oscillation Spectroscopic Surv
growth rate of stru
between redshift 0.

Pauline Zarrouk[1*], Etie ... ta
Tojeiro[6], Isabelle Pâris[7], ... a-

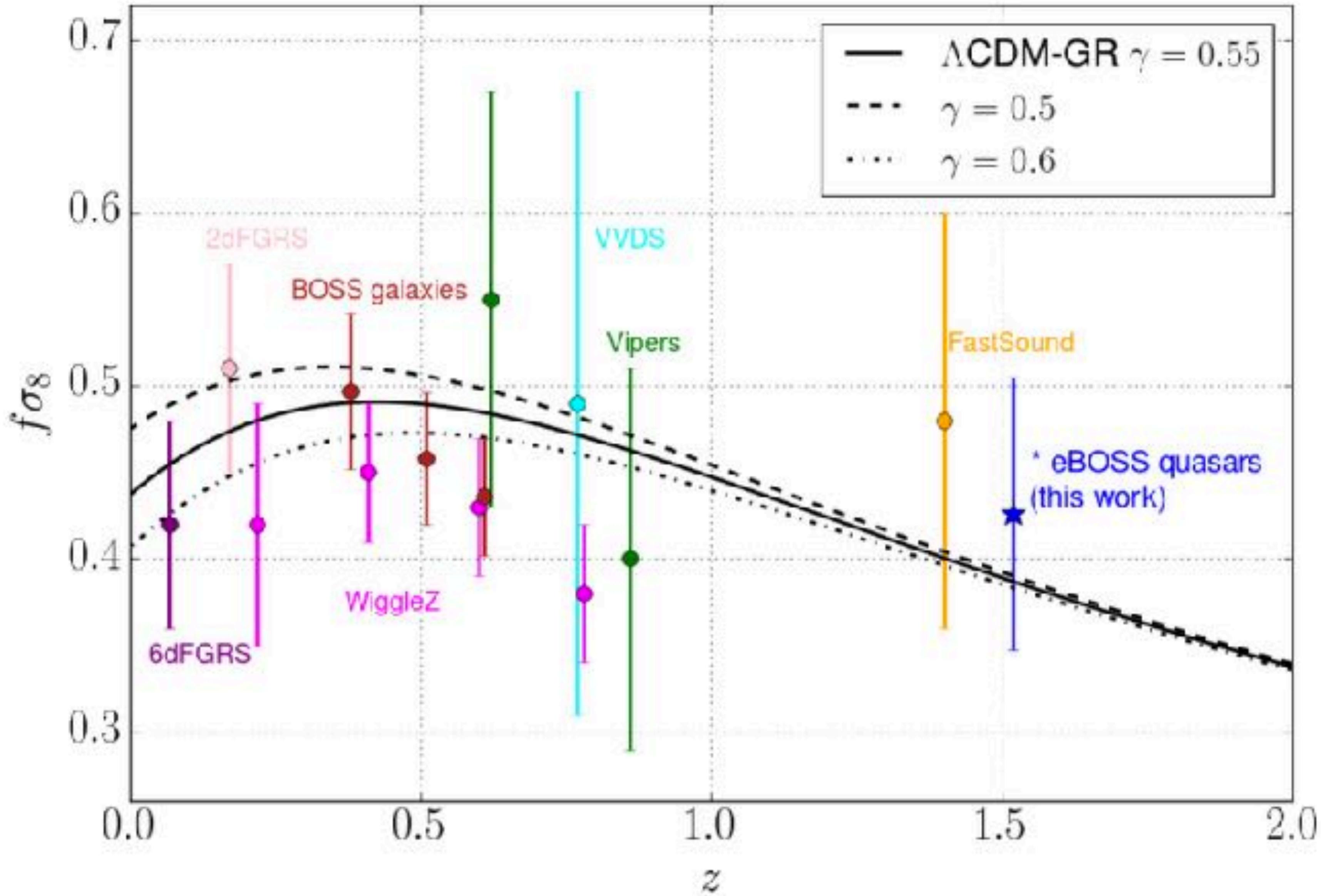
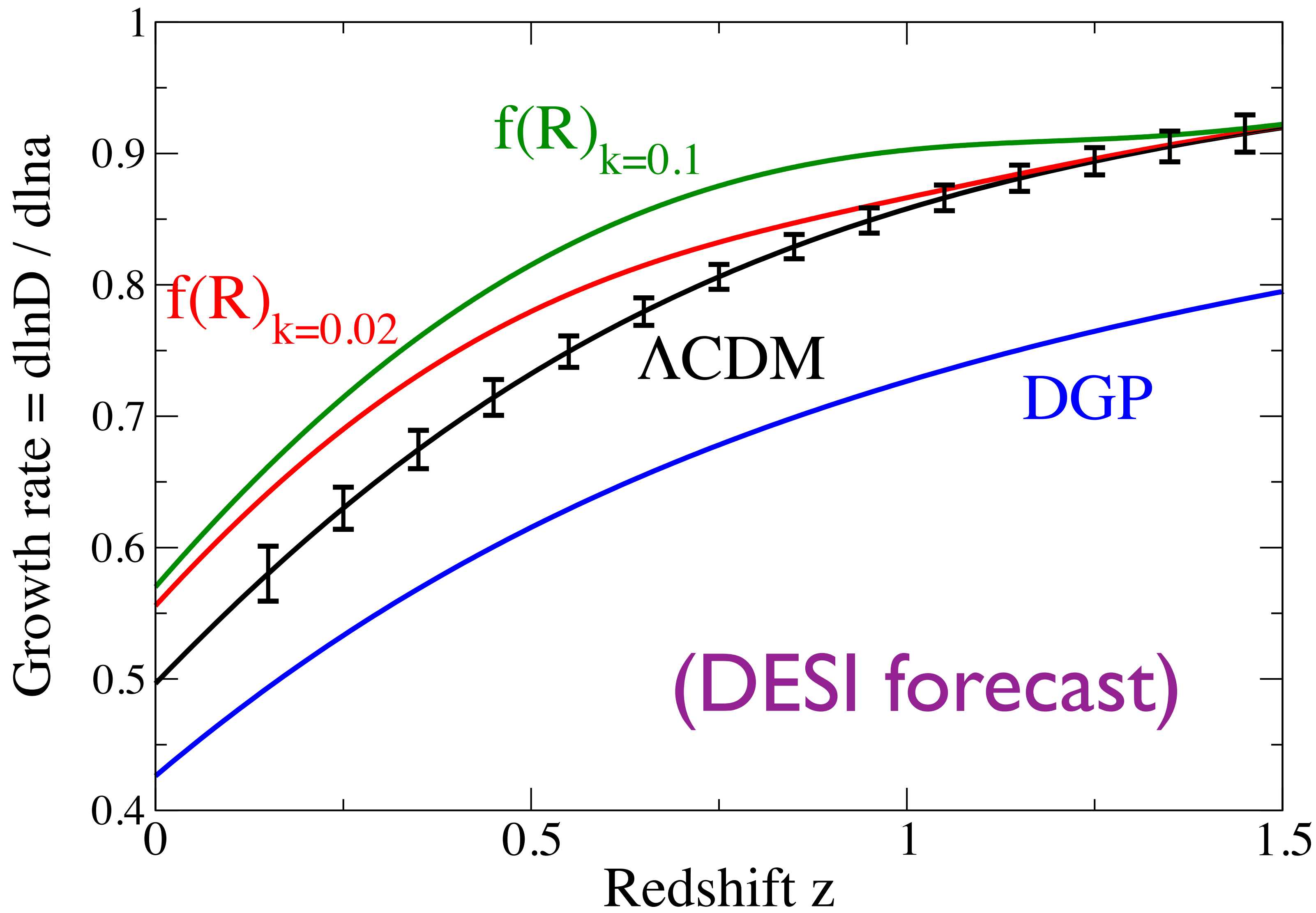


Figure 21. Measurements of $f\sigma_8(z)$ with redshift compared to the prediction from the flat Λ-CDM+GR model with Planck parameters. The $f\sigma_8(z)$ result presented in this work for the quasar sample is represented by the * marker and is obtained using 3-multipole fit. The error bar represents the total systematic error that includes the statistical precision and the systematic error related to the RSD modeling used in this analysis.

Future directions

- Future galaxy redshift surveys (e.g. DESI, Euclid, SKA) will allow per-cent level growth measurements



arXiv : 1309.5385

Conclusions

- Cosmic Acceleration Nature is a challenge
- Recent measurements suggest is a consistent with a constant (some tensions)
- A new gravity theory is a very attractive theory but there is a hughe challenge. Grab Waves kick out already some models (Galileons)
- A new field is a less dangerous model but if it clusters it may be also complex.
- Next decade galaxy surveys will strongly constrain our explanations for cosmic acceleration, trigger maybe new ones?
- Theoretical predictions need to be also very accurate (Tehory and simulations and mock observations)

Large Synoptic Survey Telesco

DESI Dark Energy Spectroscopic Instrument