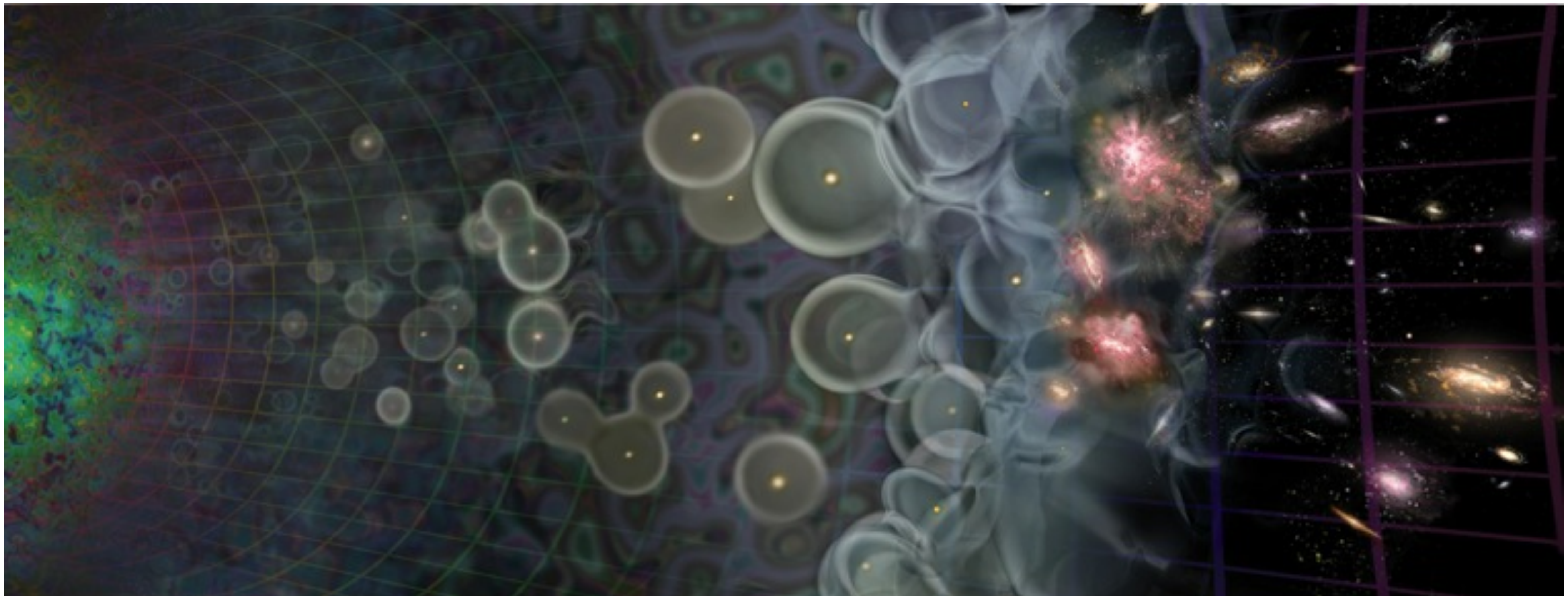


Known Unknown:
Dark Energy Review

Mariana Vargas-Magana
Instituto de Fisica,UNAM
(BOSS,eBOSS,DESI)

Instituto de Física

5 Nov, XV MEXICAN WORKSHOP ON PARTICLES AND FIELDS, Mazatlan

Outline

- Current Status of Cosmology
- DE Observables:
  - SUPERNOVAS
  - BAO
  - RSD
  - CLUSTERS
  - WEAK LENSING
- Present/Future Experiments DE:
  - Galaxy Surveys (eBOSS,DESI)
  - Others

Λ-Cold Dark Matter Model (Λ-CDM)

- Most simple model, $\{H_0, \Omega b, \Omega m, \Omega_{\Lambda}, \tau, As, ns\}$
- In agreement with all observations (supernovas, structure formation, CMB,BAO,etc…)
- Consider:
  - Dark Energy (cosmic acceleration)
  - Cold Dark Matter.
  - Baryonic Matter
- Inflation, power spectrum of initial perturbations scale invariant.

Observations in favor of Λ-CDM Model

General

- Cosmic Microwave Background Radiation , black body spectrum+ primordial fluctuations
- Universe Expansion, Hubble Law,

Primordial Universe

- Light elements abundances H, He, Li (Primordial Nucleosynthesis)
- Tensorial Fluctuations (gravitational waves) Modes B CMB (Inflation)

Dark Energy

- Supernovas
- BAO
- Cluster Number density
- Weak Lensing

Dark Matter

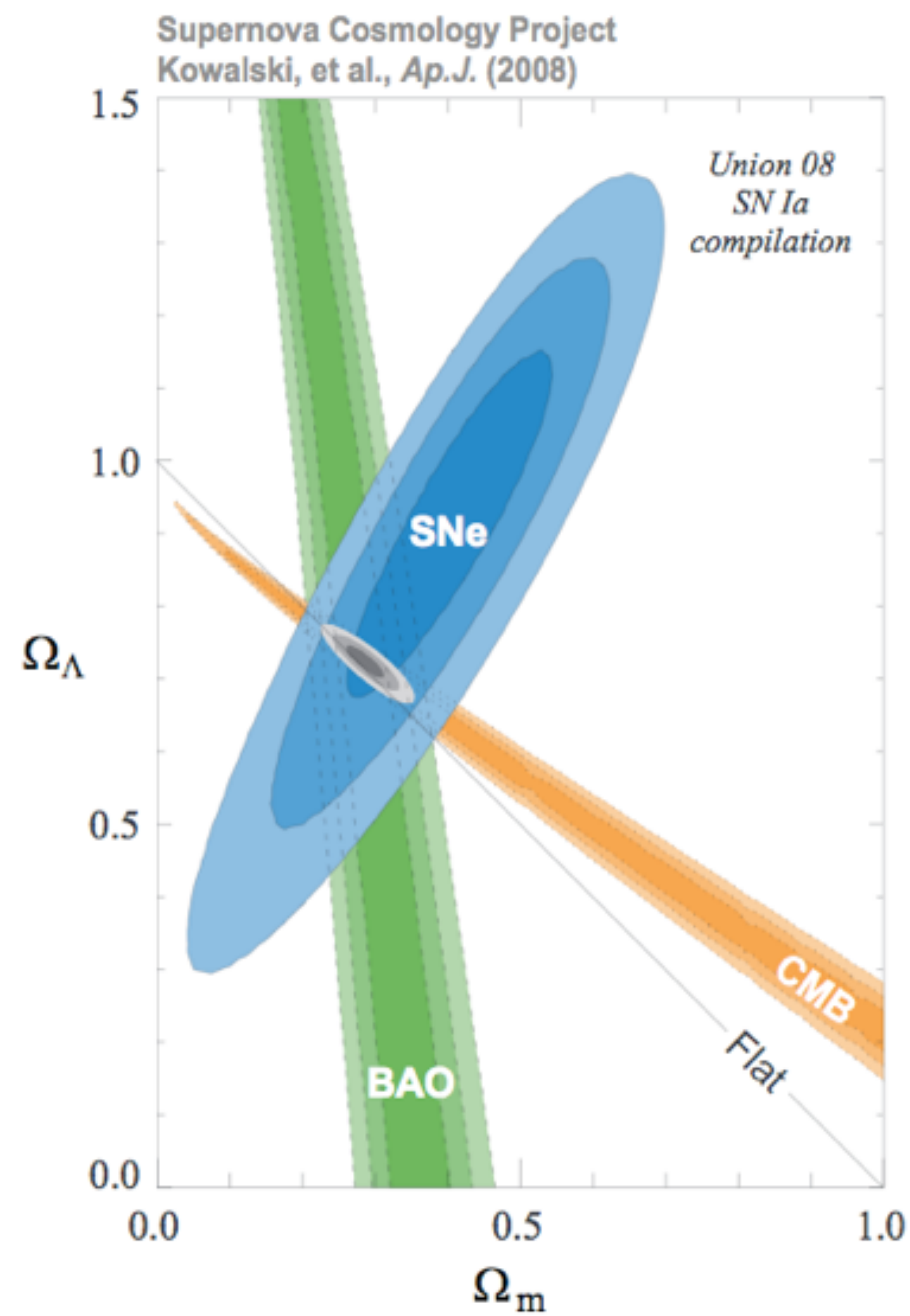
Galaxy Rotation curves

Gravitational Potential in clusters (Weak and Strong lensing)

Dynamics of clusters & X-ray Emission (hydrostatic equilibrium in the gravitational potential=> clusters mass)

Status de la Cosmology today

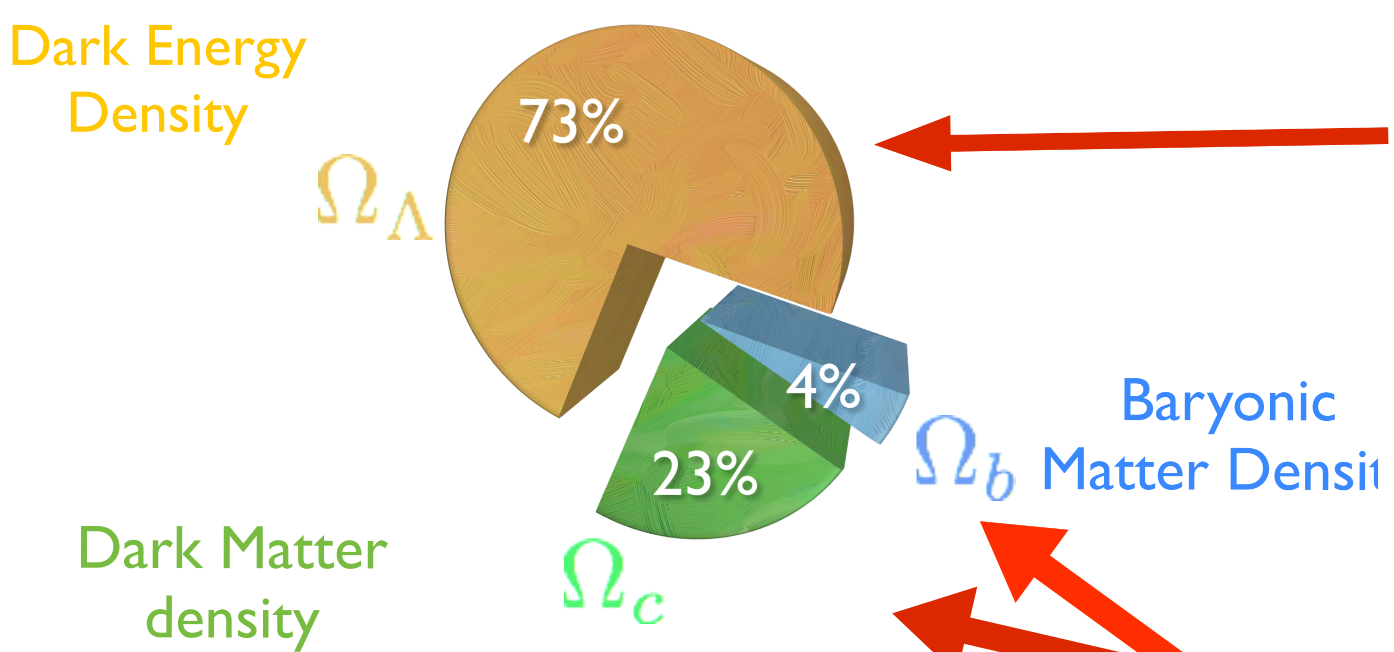
- We have a consensus in the community about what is the best model (we have) for describing our Universe, this model is called LCDM.
- LCDM model well stablished (observationally)!
  CMB,SNe,BAO,Lensing
- Remarkable convergence of different observables.

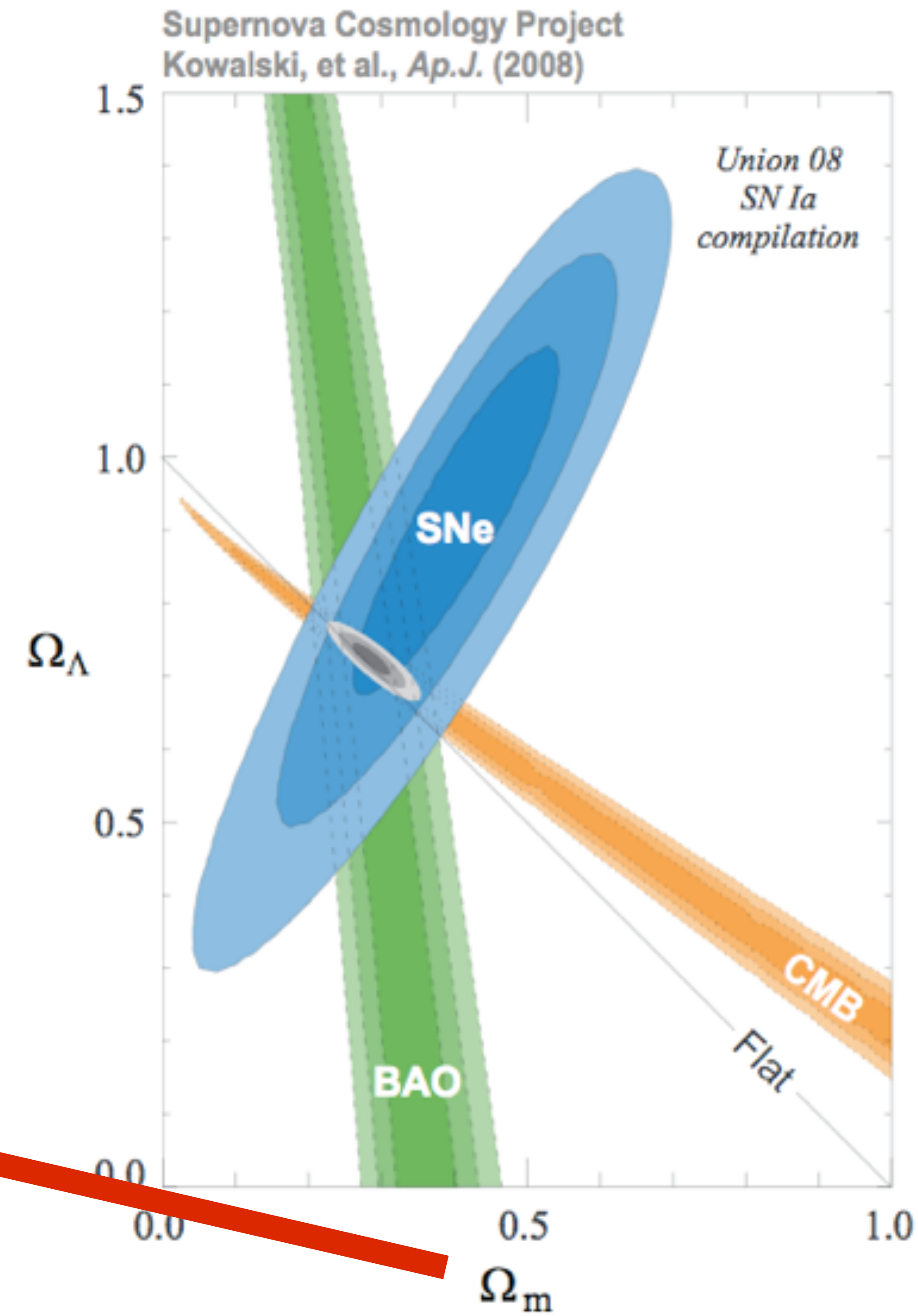


Status de la Cosmology today

Energetic budget today

$$\Omega_i = \frac{\rho}{\rho_c}$$ ← Density value for a flat universe





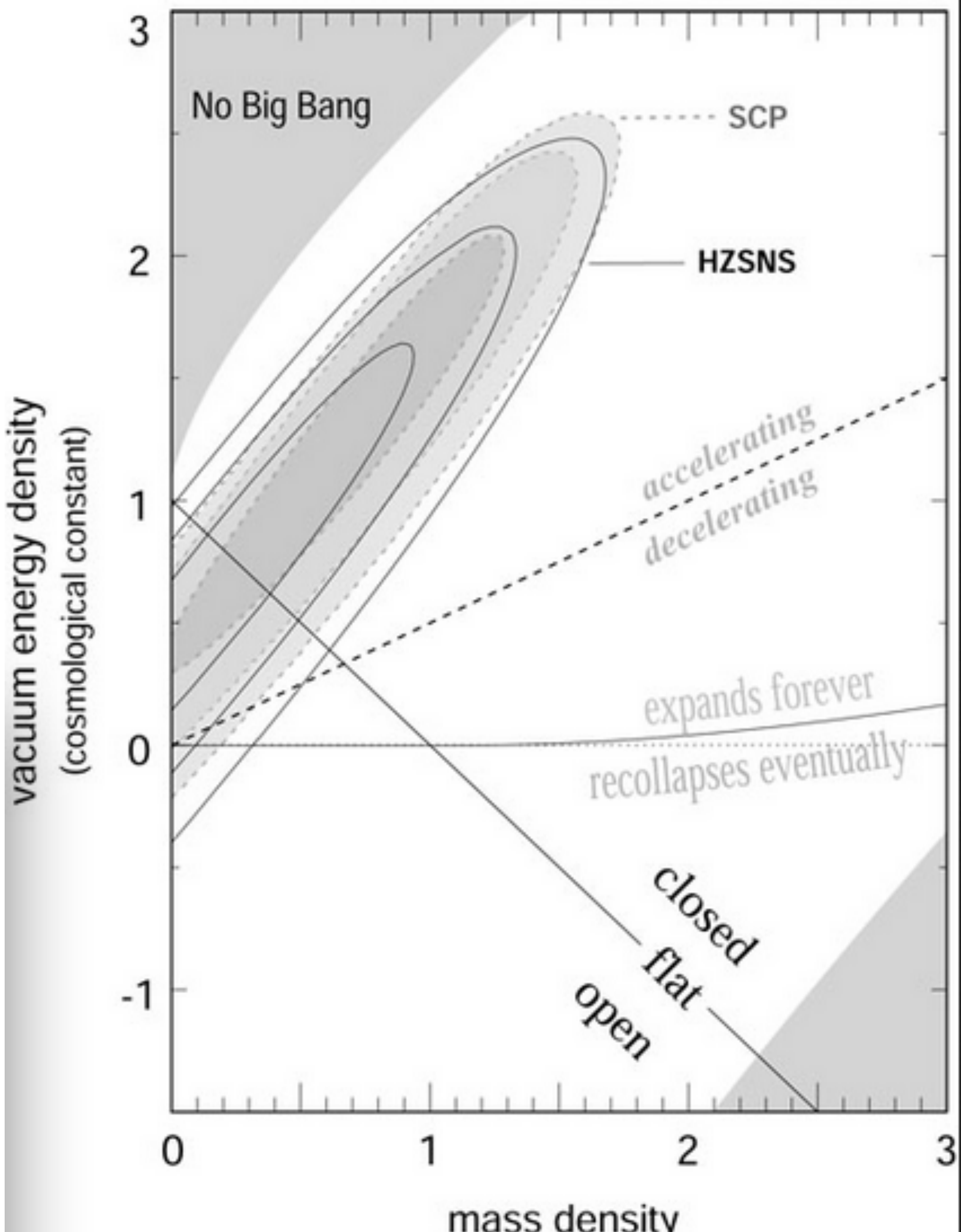
$$\Omega_m = \Omega_c + \Omega_b$$

- Still many questions to address:
  - Nature of dark matter….
  - **Nature of dark energy**
  - What happened in the early universe?

Nature of Dark Energy, the most upsetting question in cosmology…

Cosmic Acceleration

1998 Perlmutter & Riess measured 42 supernovae de type Ia at hight redshift (z~1).



Weak luminosities

=>Farther objects compared with predictions of a matter dominated model ($\Omega_m = 1.0, \Omega_\Lambda = 0$).

=>period of accelerated expansion.

Dark Energy (DE)

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

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

Geometry

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu} + T^{\Lambda}_{\mu\nu}$$

$$w = -1 \qquad T^{\Lambda}_{\mu\nu} = \frac{\Lambda}{8\pi G}$$

Energy Momentum Tensor new component

Cosmological Constant

- For explaining the observed accelerated expansion of the Universe, the **simplest solution** was to borrow Einstein's idea of **vacuum energy,** namely cosmological constant.

- Einstein was seeking **statistic solutions** ($\dot{a} = 0$), so he proposed a modification of his equation. Einstein's equation with the **constant Λ** is given by

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

Cosmological Constant

- The **small positive cosmological constant** has been supported by a number of observations. The cosmological constant is a **perfect fit** to the dark energy data, even if we cannot explain it.

- There are two cosmological constant problems.

  - **Fine-tuning problem**: why the vacuum energy is so small?

  - **Coincidence Problem**: why it is comparable to the present mass density? **why does cosmic acceleration happen to begin right** now and not at some point in the past or future

Dark Energy (DE)

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

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

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Energy Momentum Tensor new component

DE Models and Alternatives to DE.

- Cosmological constant
- Quintessence
- K-essence
- Coupled dark energy and matter
- Unified dark energy and matter

Dark Energy (DE)

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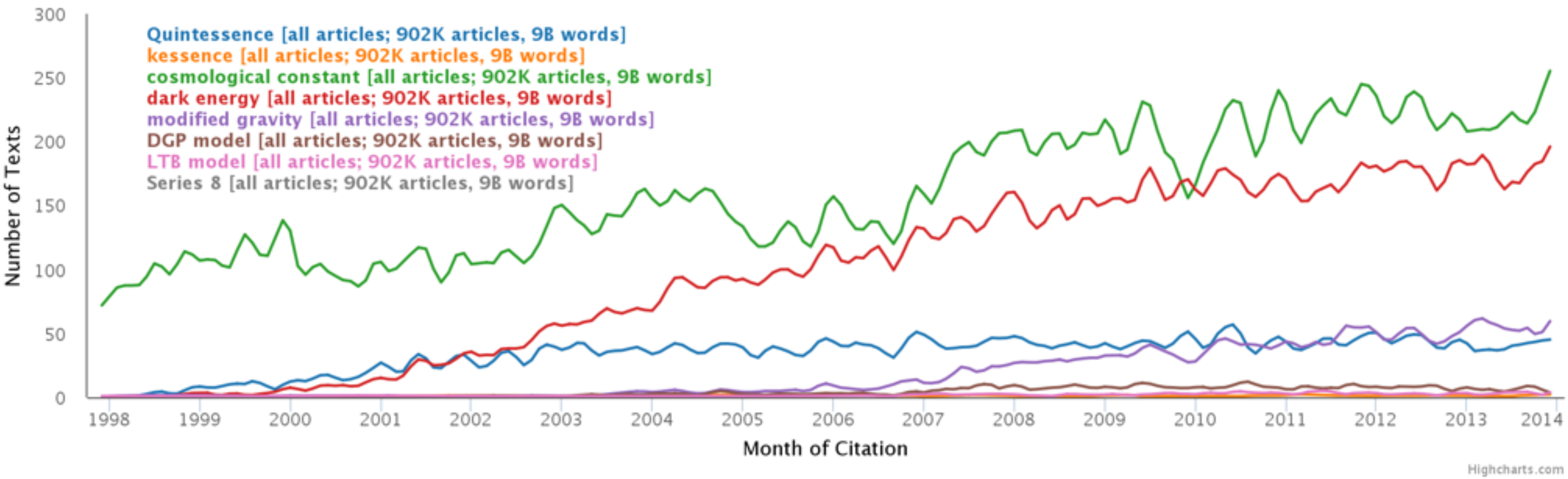
Energy Momentum Tensor new component

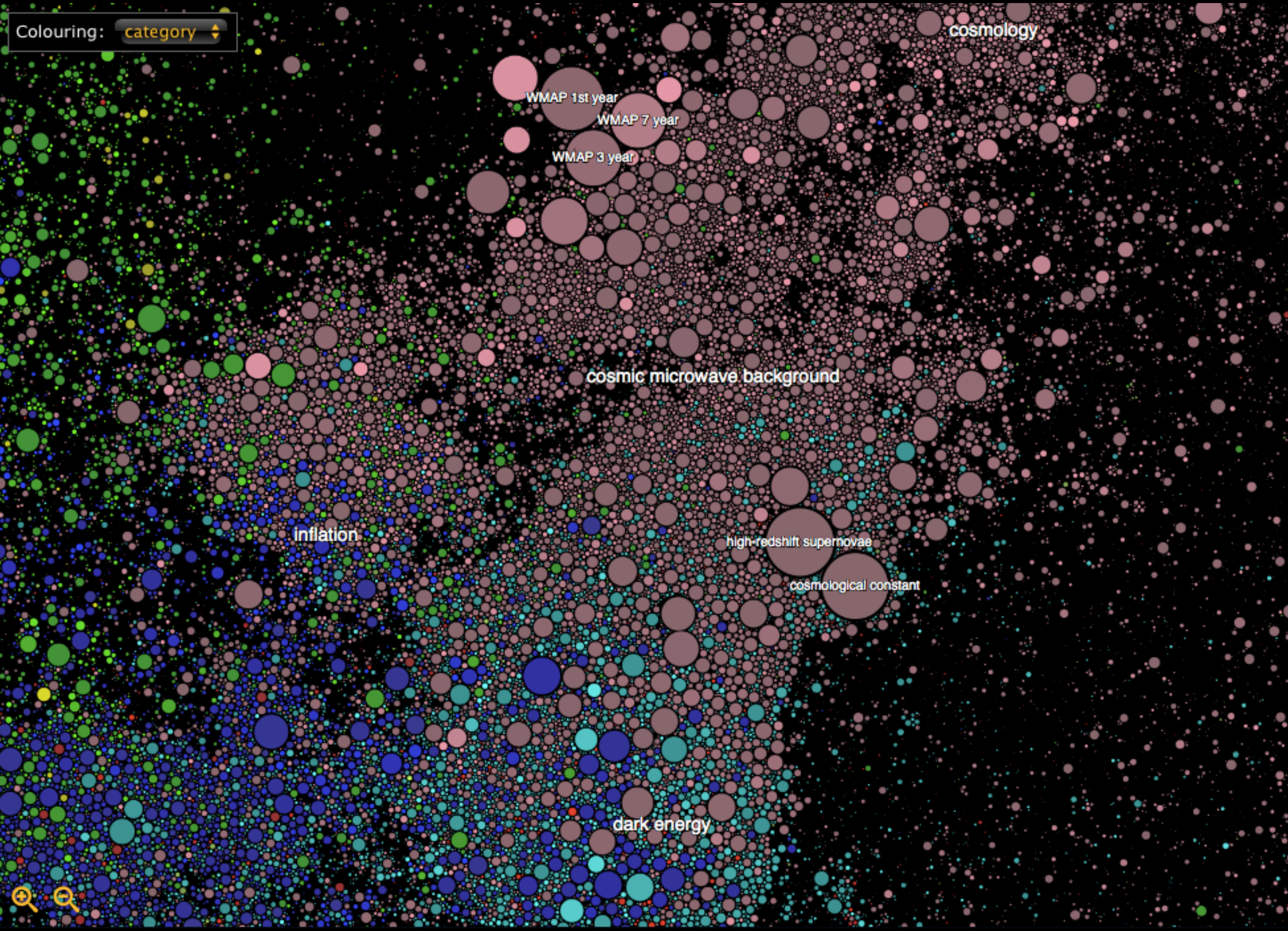
DE Models and Alternatives to DE.

- f(R) gravity
- DGP model
- Inhomogeneous LTB model

- Cosmological constant
- Quintessence
- K-essence
- Coupled dark energy and matter
- Unified dark energy and matter

Dark energy models





Colouring: category
cosmology
WMAP 1st year
WMAP 7 year
WMAP 3 year
cosmic microwave background
inflation
high-redshift supernovae
cosmological constant
dark energy

Phenomenological Approach

Perfect Fluid $\rho = \omega p$

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}(\rho_\Lambda + 3p_\Lambda)$$

$p_\Lambda < 0$

$\omega < -1/3$ → Accelerated expansion

Cosmological constant $\omega = -1$

$\rho_\Lambda = cte$

$p_\Lambda = -\rho_\Lambda$

$\Omega_\Lambda = cte$

Constant Energy Density

More general equation for DE $w(z)$

Energy Density evolves with time

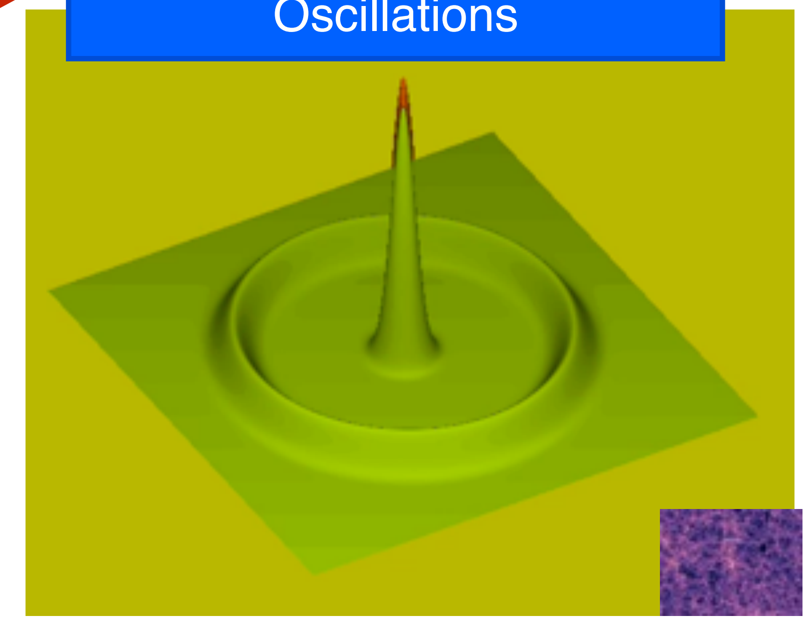
$$\Omega_X(z) = \Omega_{X_0} \times \exp\left(3\int_0^z \frac{1+\omega(z')}{1+z'}dz'\right) \qquad \omega(z) = \omega_0 + \omega_a\left(\frac{z}{1+z}\right)$$

How we can study DE?

Distances

Supernovas

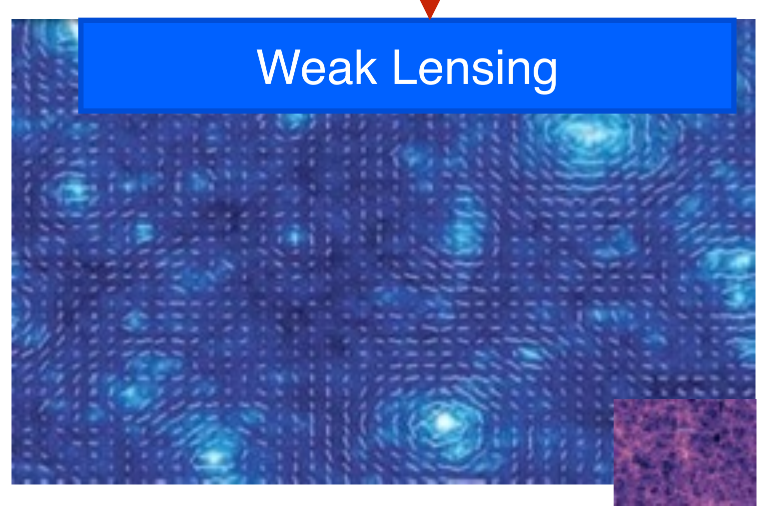
Baryon Acoustic Oscillations



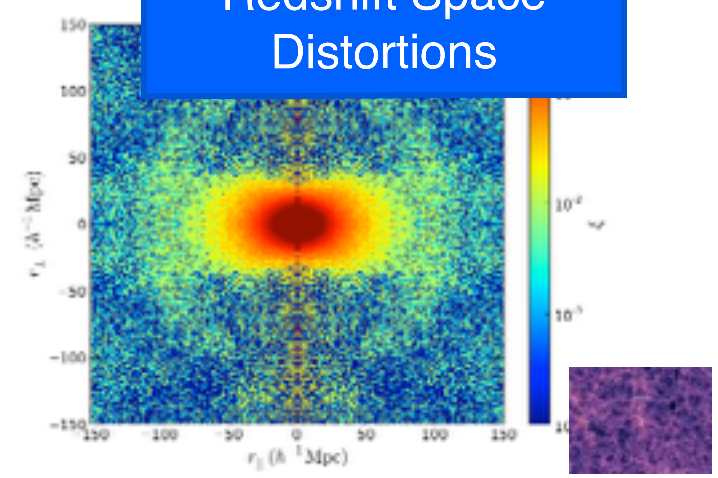
Growth Factor

Clusters

Weak Lensing



Redshift Space Distortions

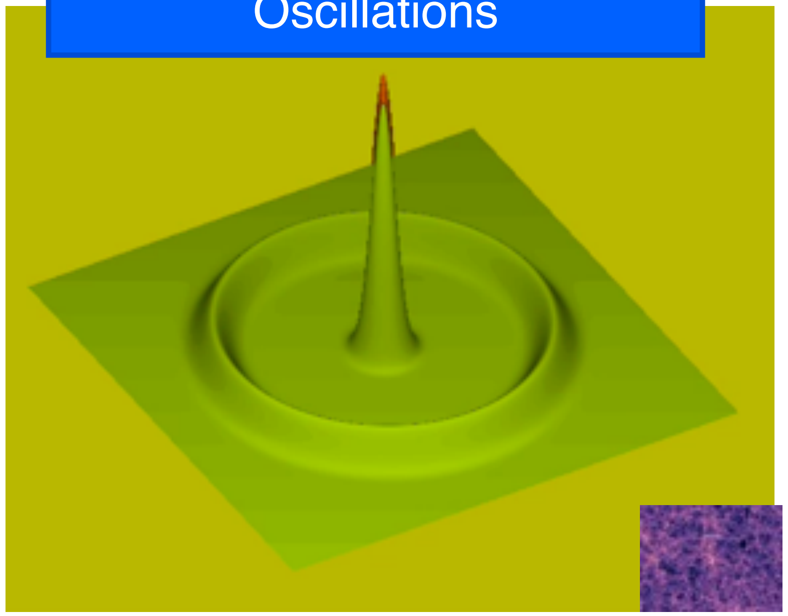


How we can study DE?

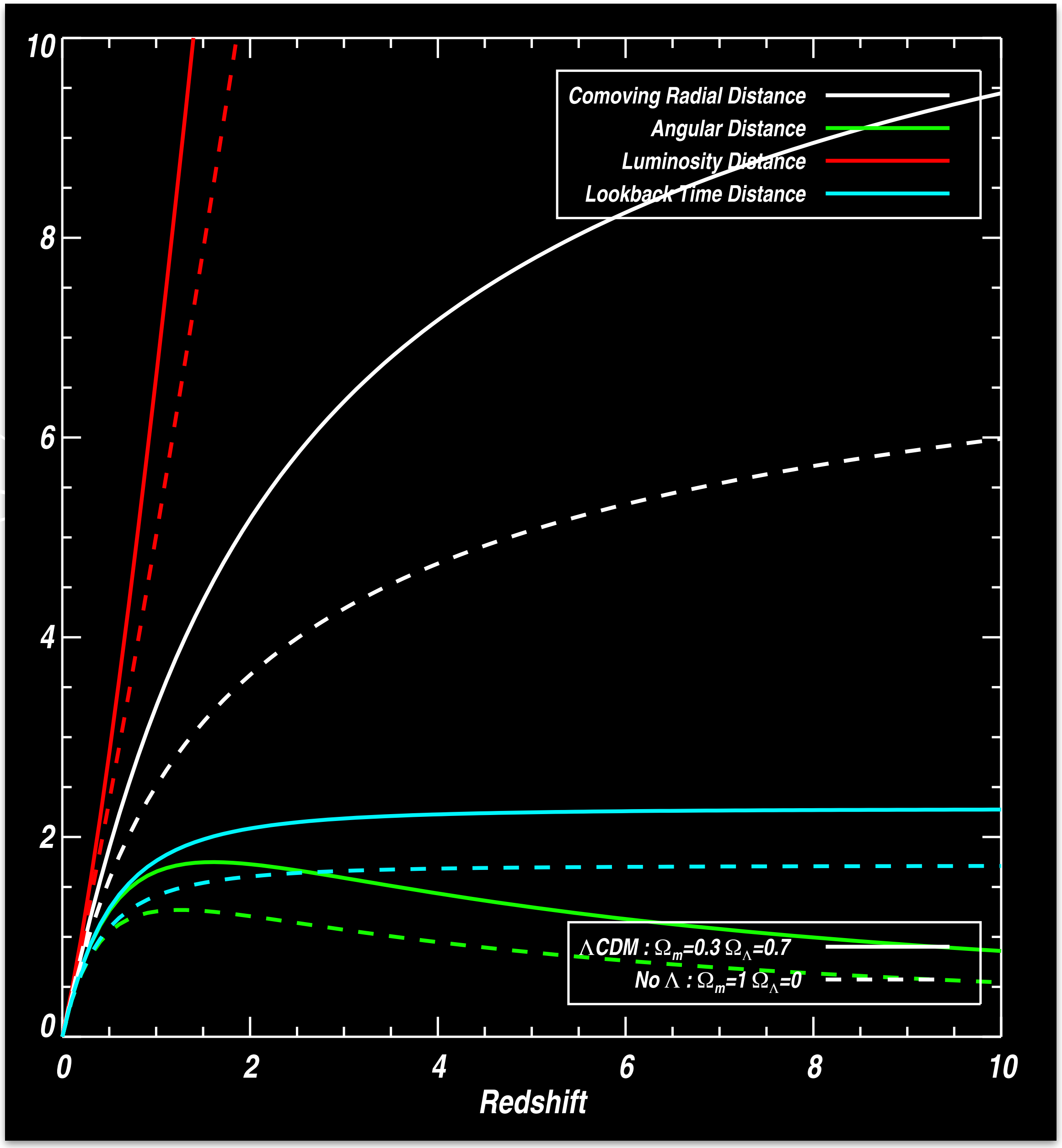
Distances

Supernovas

Baryon Acoustic Oscillations



Distances



$$D_A(z) = \chi/(1+z)$$

$$D_L = \chi(1+z)$$

$$\chi = a_0 r(z) = \int_0^z \frac{dz'}{H(z')}$$

Hubble parameter=expansion rate universe

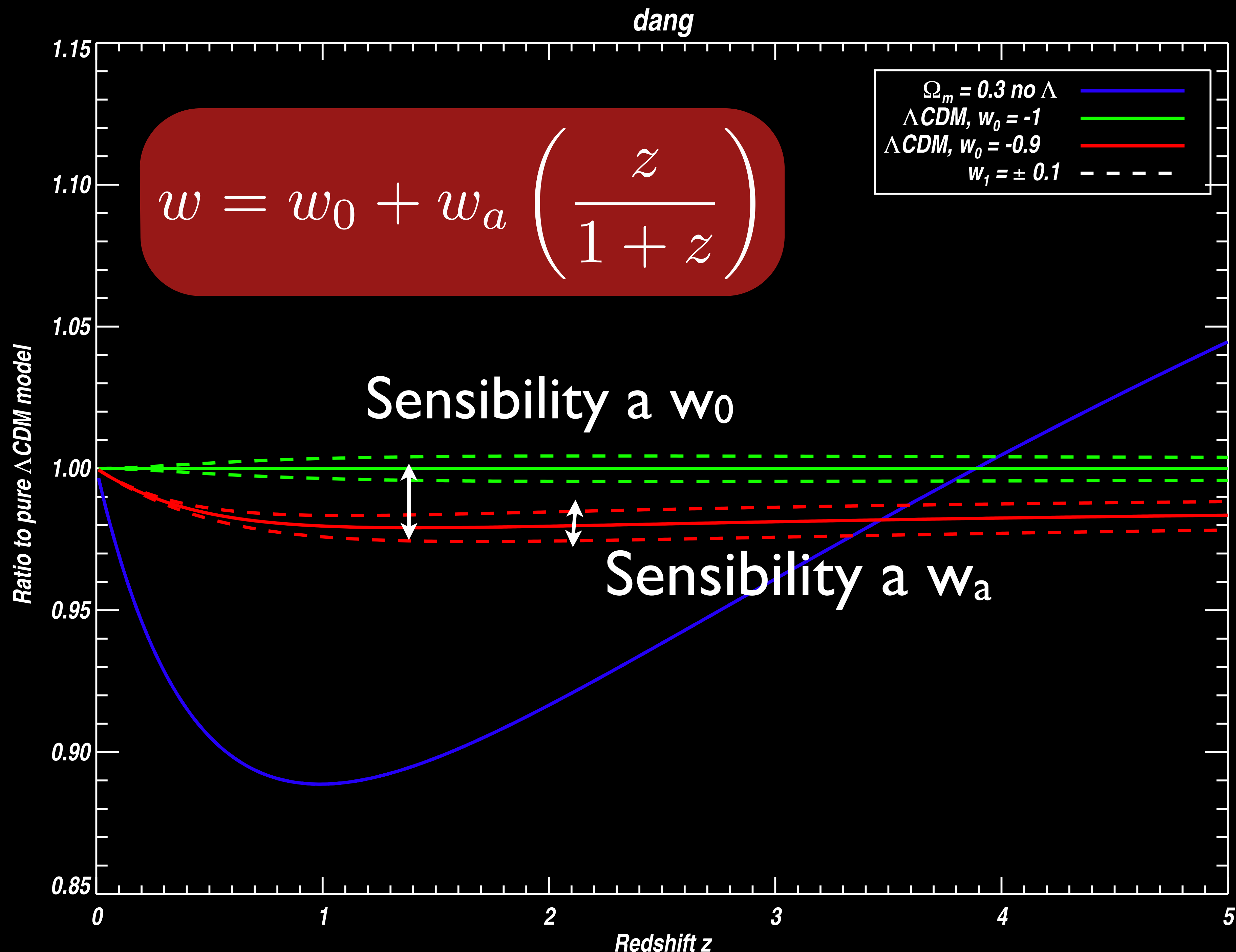
energetic content

$$H(z)^2 = \left(\frac{\dot{a}}{a}\right)^2 = H_0(\Omega_m + \Omega_k + \Omega_\Lambda)$$

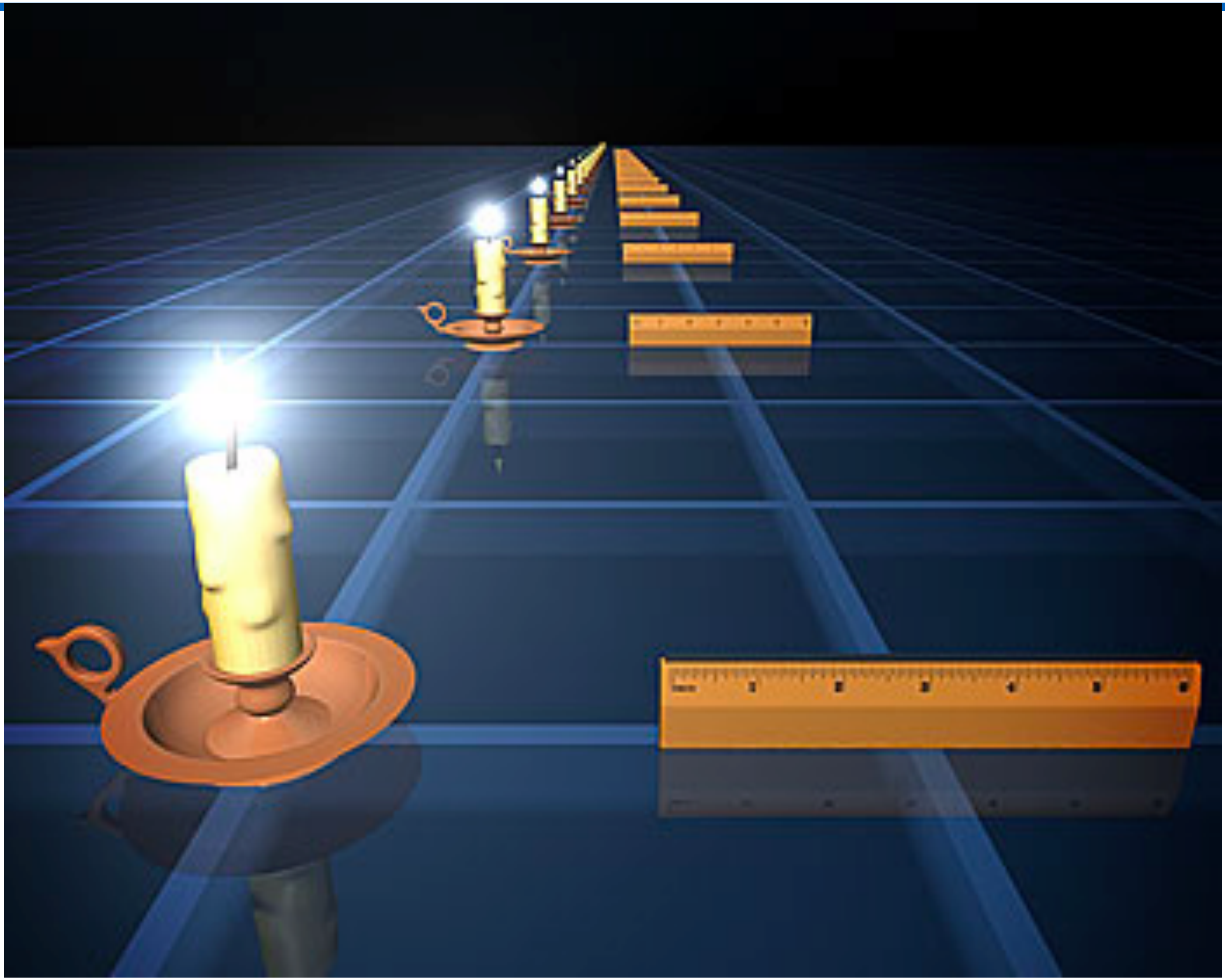
Dark Energy **matter** **curvature** **DE**

The relation between distance and redshift depends of cosmological parameters.

DA(Z) SENSITIVITY TO DARK ENERGY PARAMETERS



Standard Ruler



Outline

- Motivation: Dark Energy
- Observables:
    - SUPERNOVAS
    - BAO
    - RSD
    - CLUSTERS
    - WEAK LENSING
- Present/Future Experiments DE: Galaxy Surveys

Observables

SUPERNOVAS

SUPERNOVAS

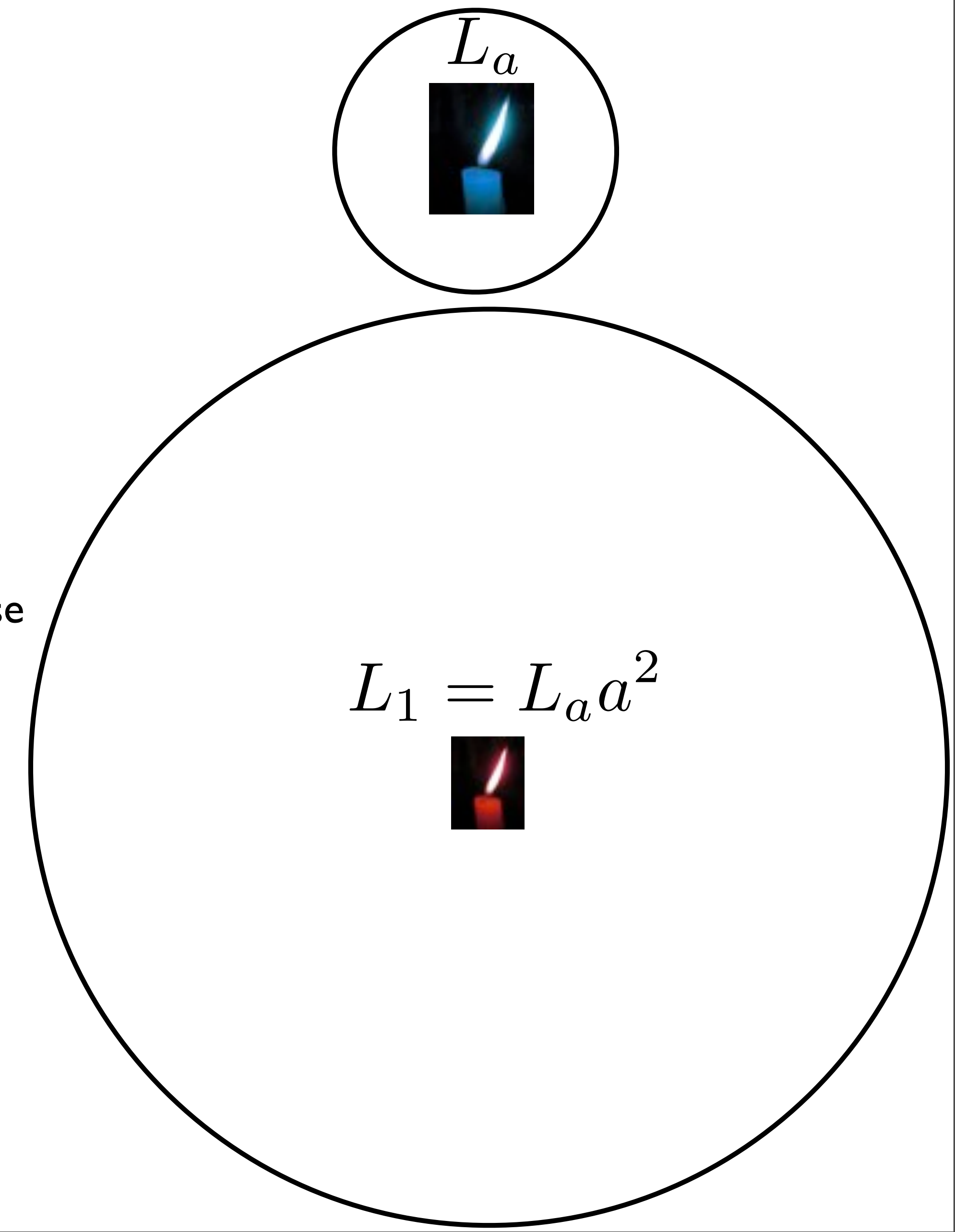
Supernova (SN) surveys use Type Ia supernovae as standard candles to determine the luminosity distance vs. redshift relation.

The SN technique is sensitive to dark energy through its effect on this relation luminosity distance vs. redshift relation.

SUPERNOVAS COSMOLOGY

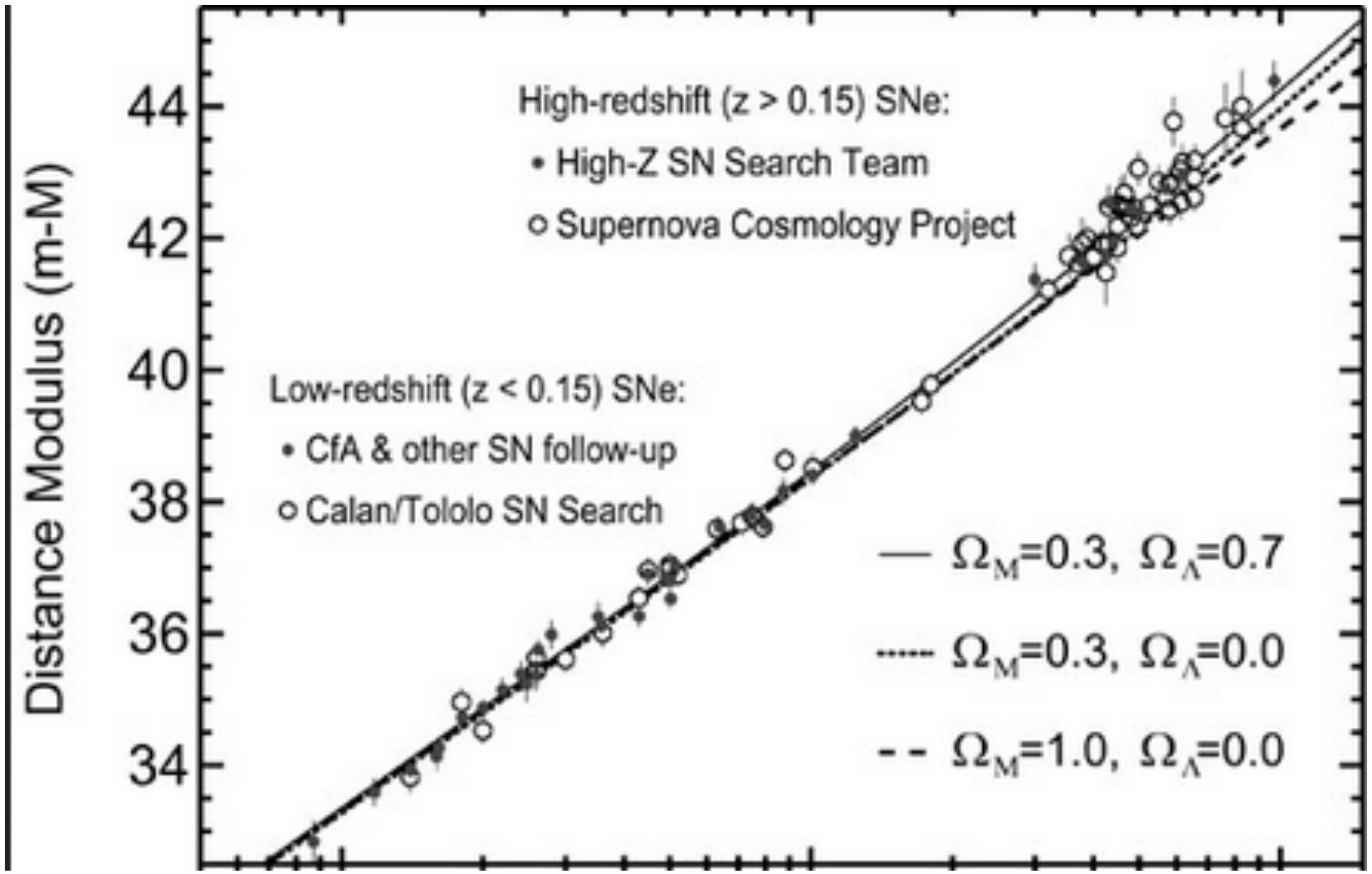
Standard Candle To Cosmology: Predicted Flux

- Piece 1 - Luminosity emitted (L_a) versus what that same energy looks like today (L_1)
  - In the FRW metric
    - a(t) is the scale factor that describes the size of the Universe
    - Photon energy proportional to a^{-1}
      - Redshift
    - Clocks appear to move as a^{-1}
      - Time Dilation
  - $L_1=L_a a^2$



Cosmic Acceleration

1998 Perlmutter & Riess measured 42 supernovae de type Ia at hight redshift (z~1).



Weak luminosities

=>Farther objects compared with predictions of a matter dominated model ($\Omega_m = 1.0, \Omega_\Lambda = 0$).

=>period of accelerated expansion.

$$D_L = \chi(1+z)$$

$$\chi = a_0 r(z) = \int_0^z \frac{dz'}{H(z')}$$

Dark Energy

energetic content

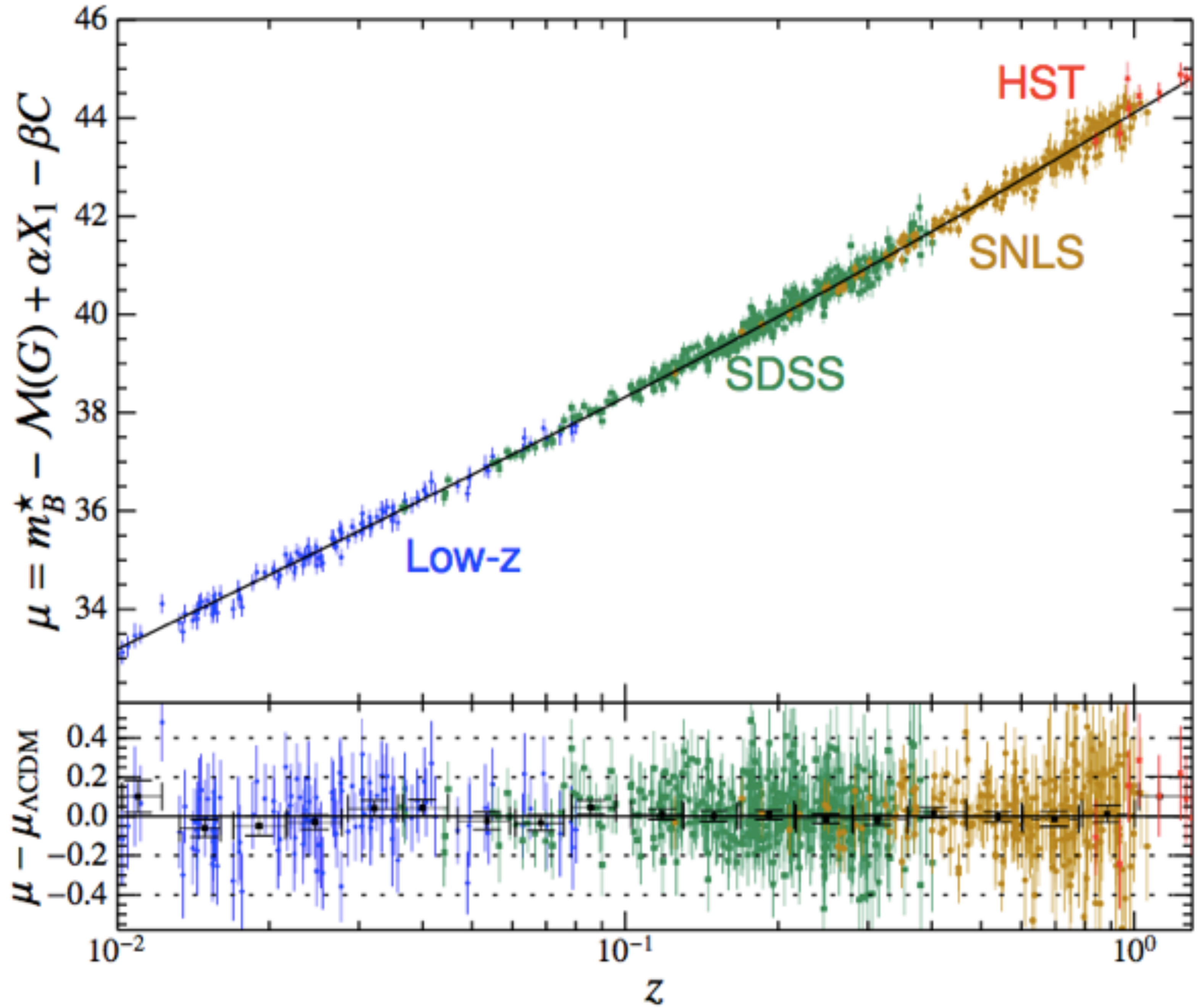
$$H(z)^2 = \left(\frac{\dot{a}}{a}\right)^2 = H_0(\Omega_m + \Omega_k + \Omega_\Lambda)$$

Expansion Rate

Matter

curvature

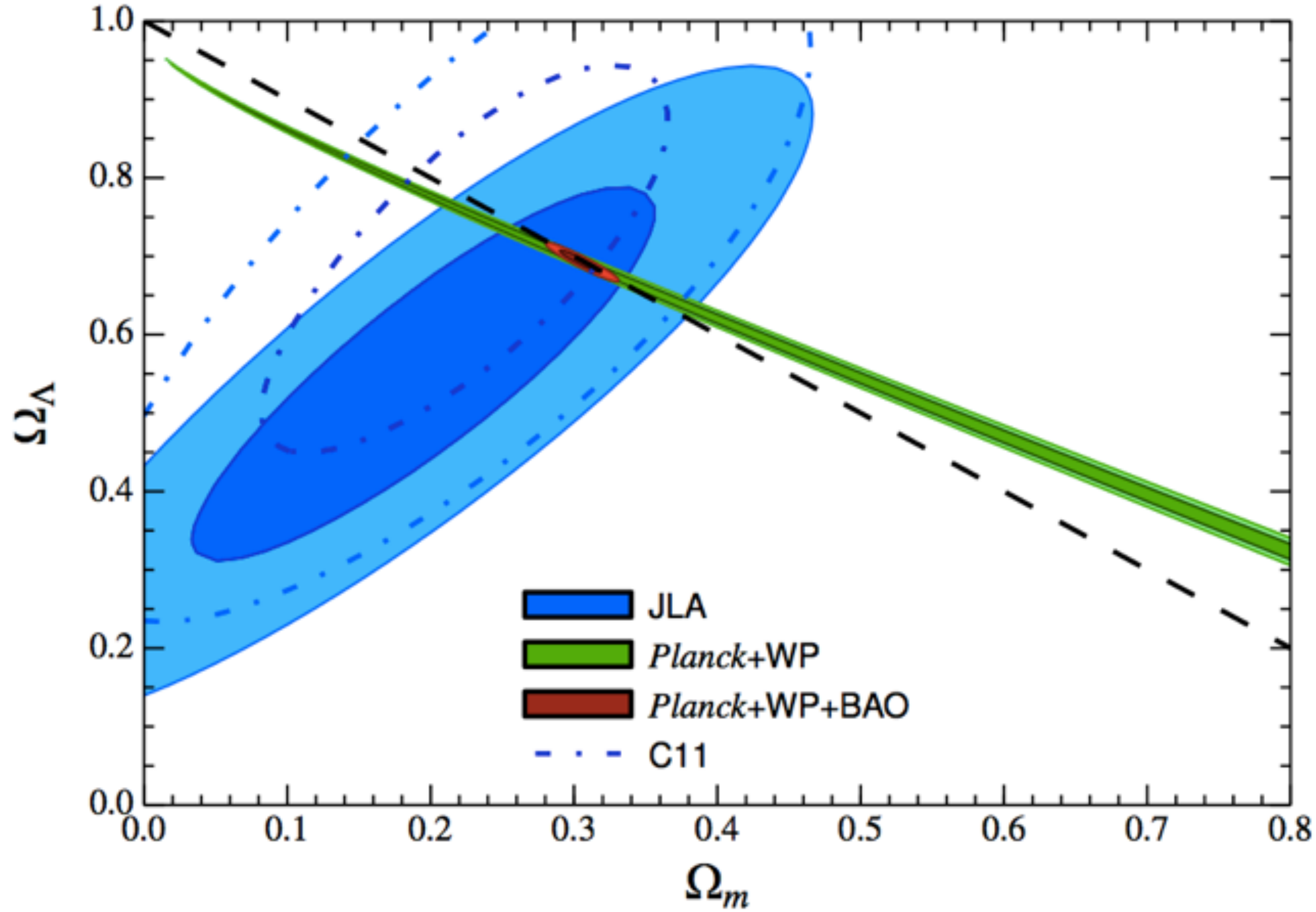
SN COSMOLOGY NOW (BETAULE ET AL 2014)



Combined analysis of 740 Type 1A from multiple projects

Photometric calibration is the largest uncertainty

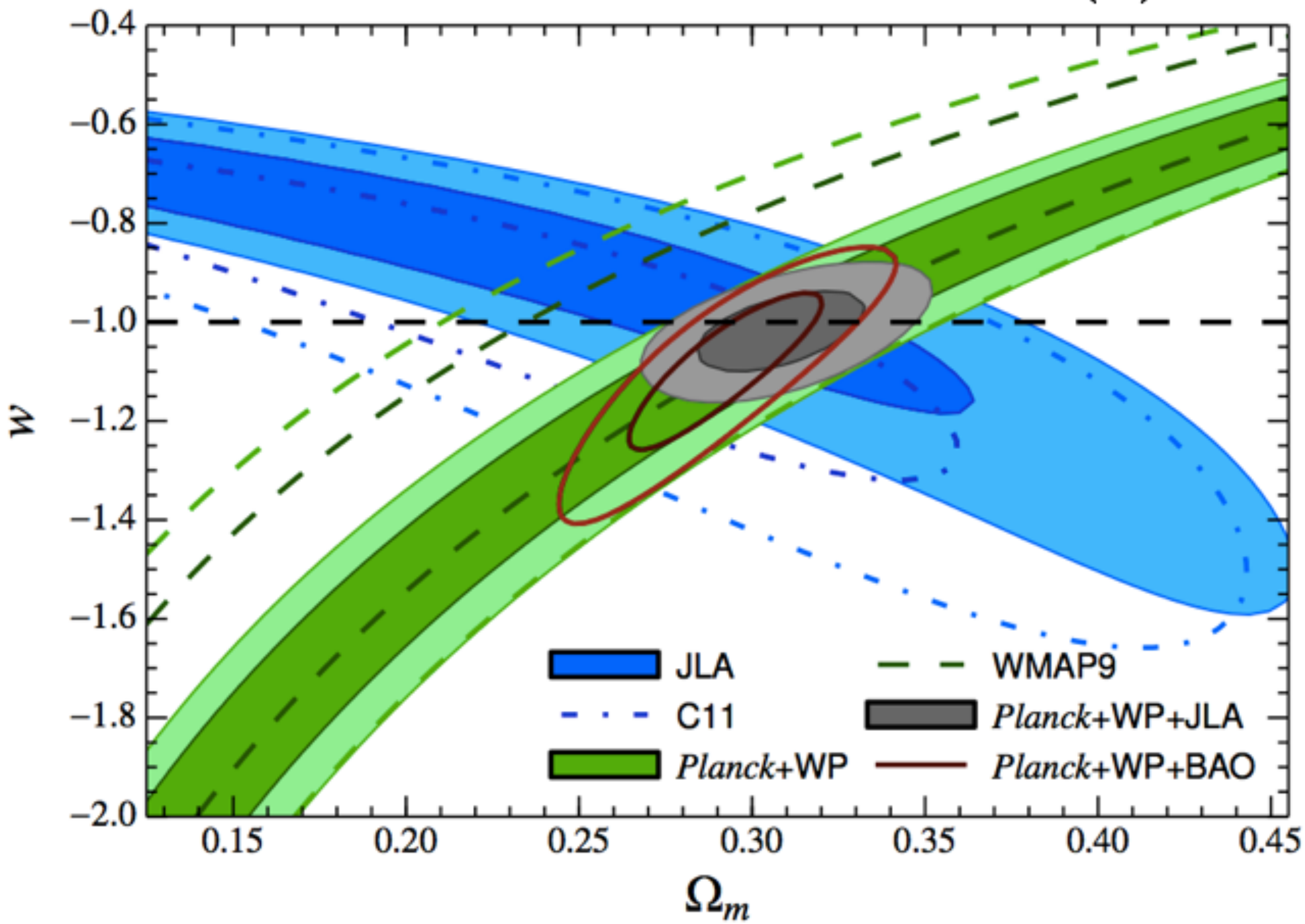
SN COSMOLOGY NOW (BETAULE ET AL 2014)



CMB (PLANK)+ SN+BAO:

SN COSMOLOGY NOW (BETAULE ET AL 2014)

$$\omega(z) = \omega_0 + \omega_a\left(\frac{z}{1+z}\right)$$

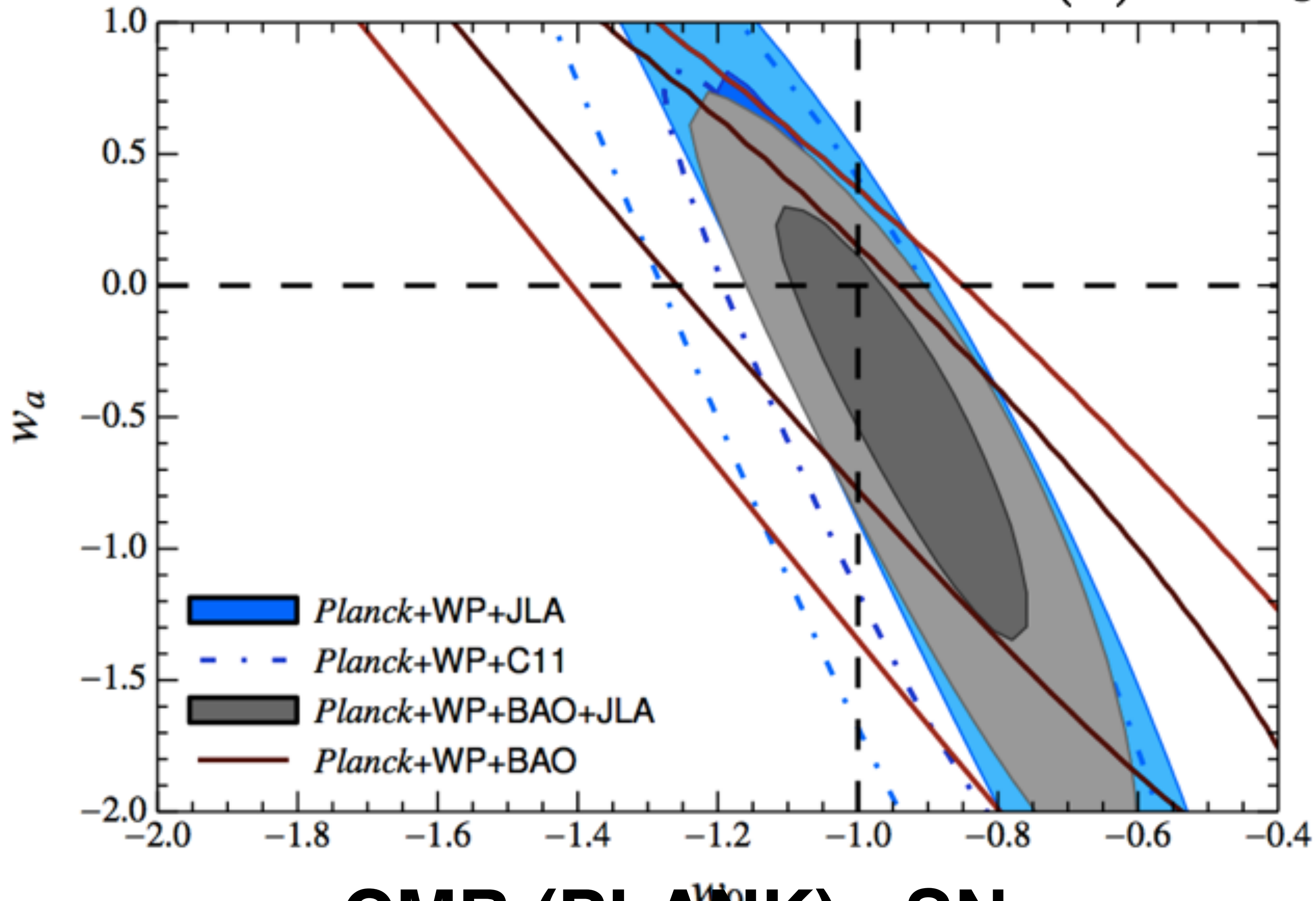


CMB (PLANK)+ SN:

w=-1.018 +/- 0.057 (flat Universe and wa=0)

SN COSMOLOGY NOW (BETAULE ET AL 2014)

$$\omega(z) = \omega_0 + \omega_a\left(\frac{z}{1+z}\right)$$



CMB (PLANK)+ SN:
w0=-0.957 +/- 0.124 (flat Universe)
wa=–0.336 ± 0.552(flat Universe)

Conclusions from Supernova Cosmology

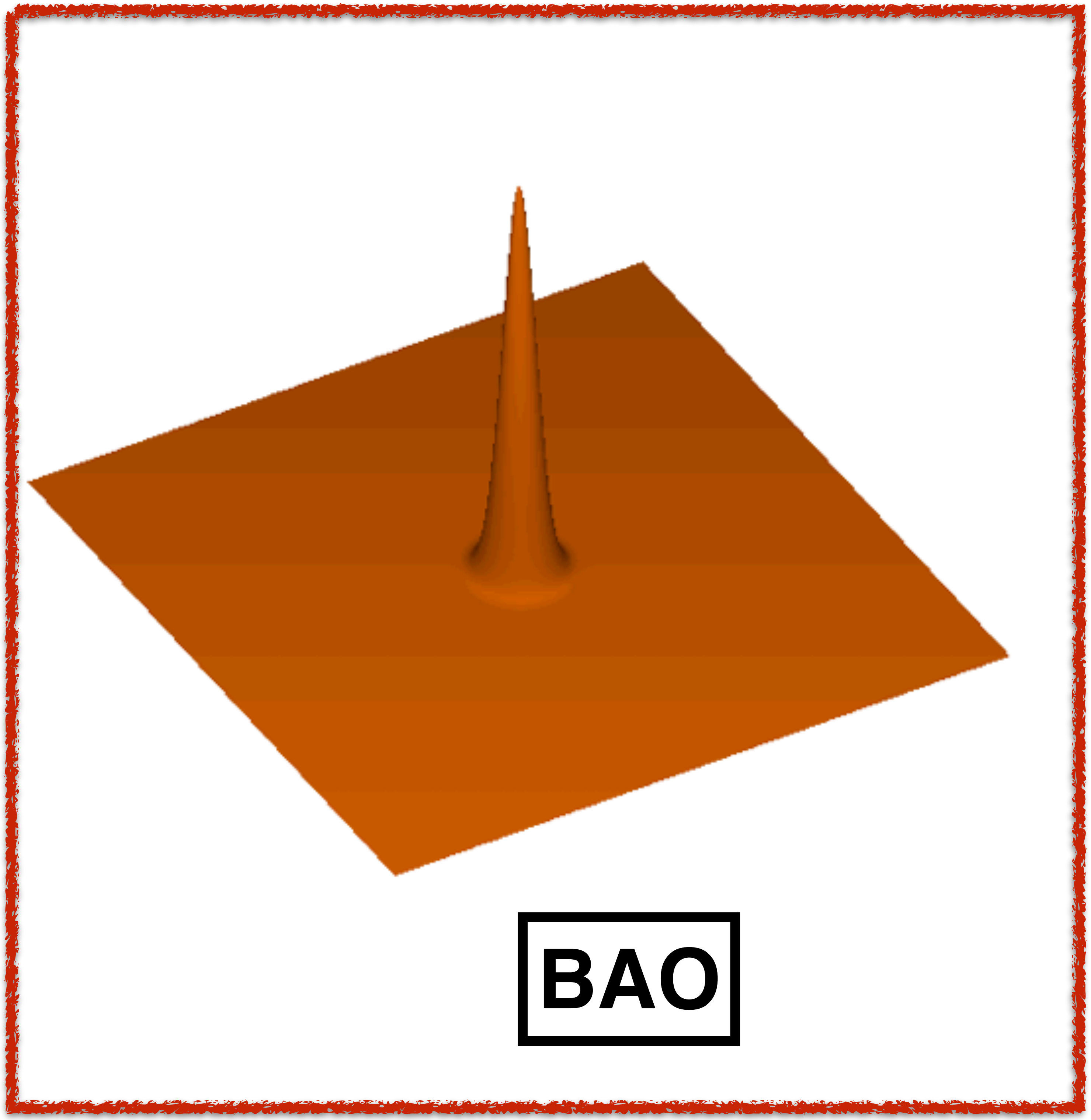
- The SN technique is at present the most powerful and best proven technique for studying dark energy.

- **calibration systematics. the accuracy of the photometric calibration remains (by far) the limiting systematic uncertainty.**

- However, there is no known reason why this situation can not be improved in future surveys.

- Better wavelength coverage would alleviate the partial **degeneracy between the cosmology, the calibration and the SNe Ia model,** the degeneracy that is responsible for a large part of the sensitivity of cosmology to calibration uncertainties.

Observables

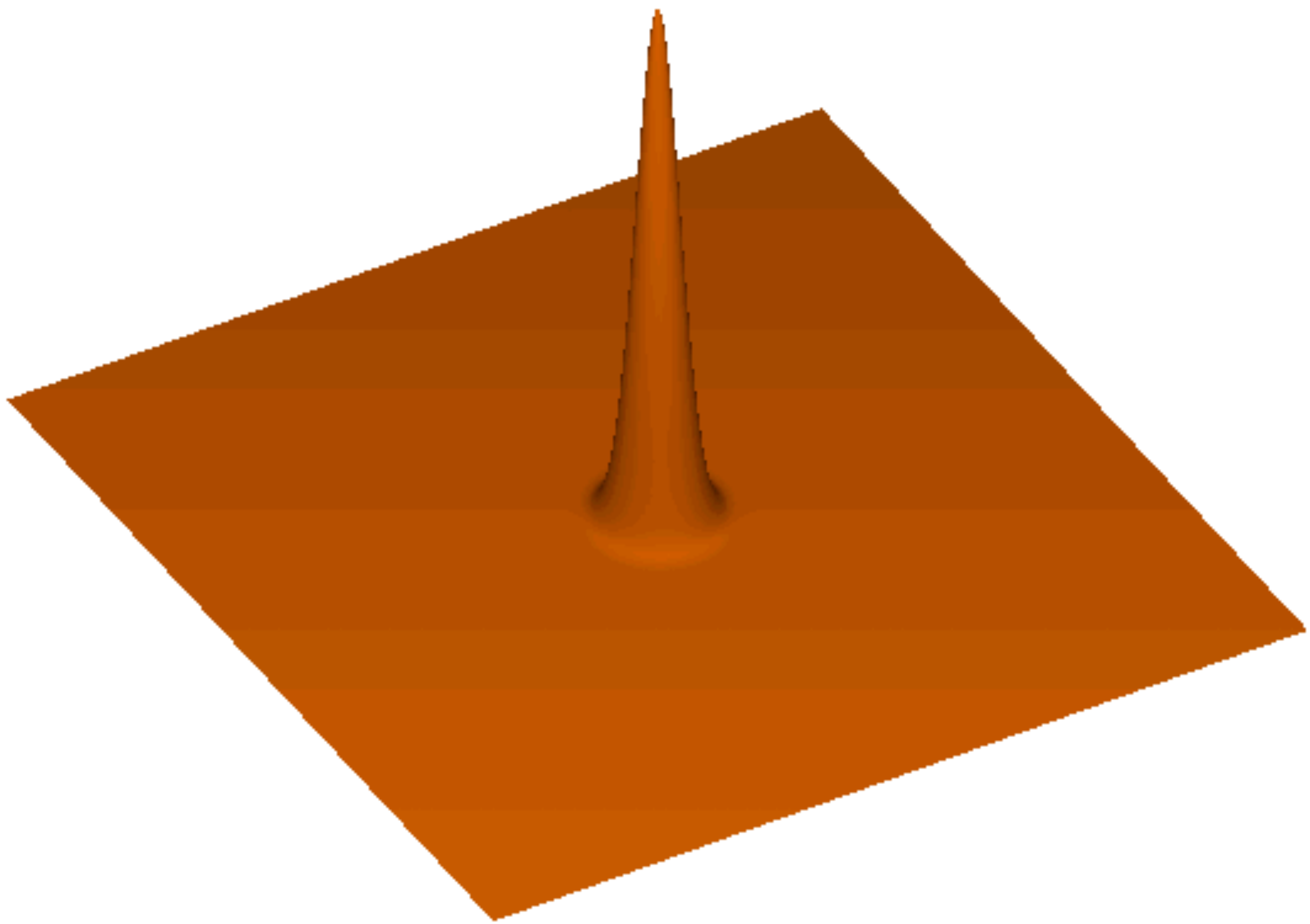


Baryonic Acoustic Oscillations

Baryon Acoustic Oscillations (BAO) are observed in large-scale surveys of the spatial distribution of galaxies.

The BAO technique is sensitive to dark energy through its effect on the angular-diameter distance vs. redshift relation and through its effect on the time evolution of the expansion rate.

Baryonic Acoustic Oscillations (BAO)



Eisenstein(2005)

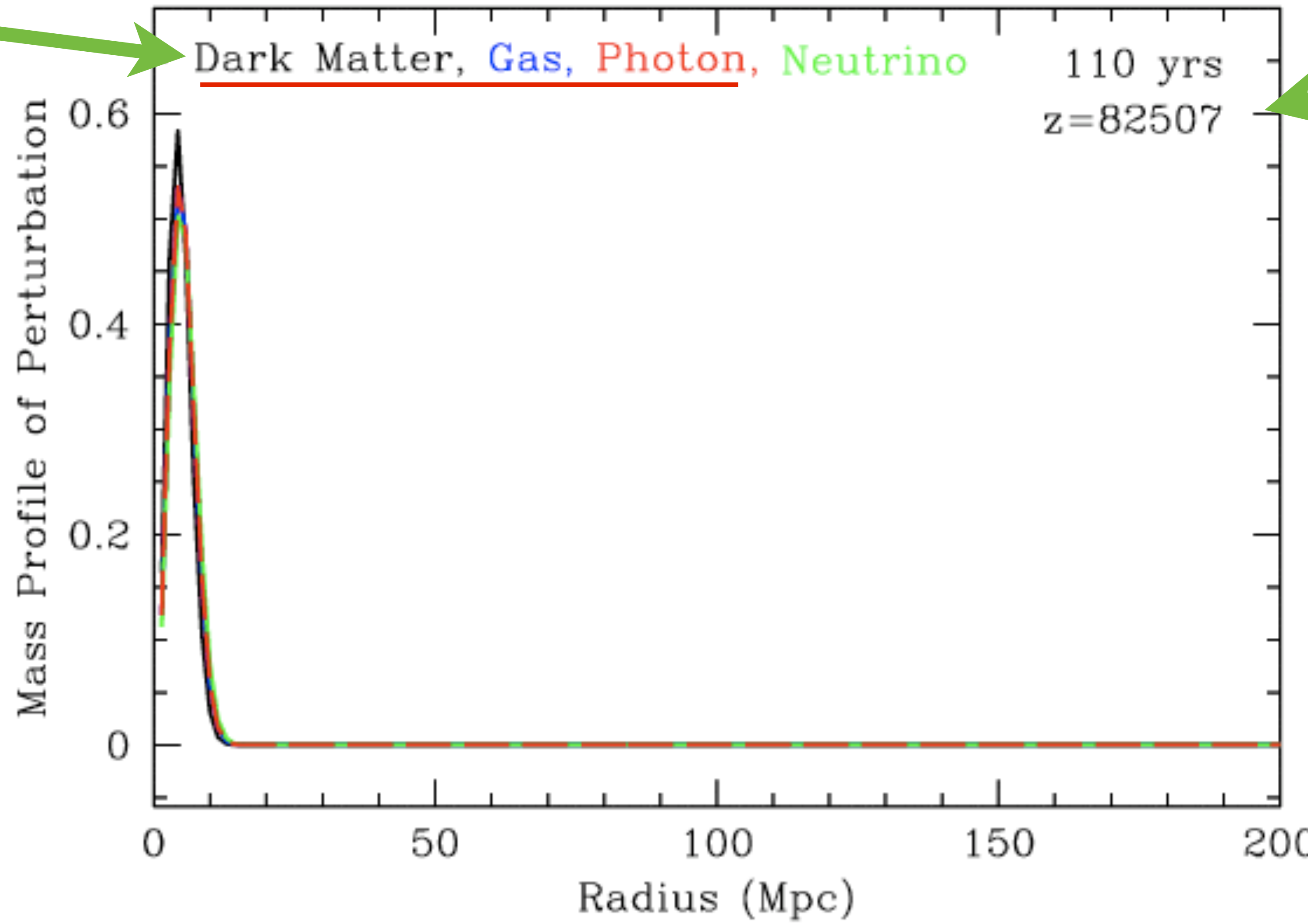
Baryonic Acoustic Oscillations

- Plasma over-density at the center, rest of the universe is homogeneous
- Perturbations **adiabatic** , all species are equally perturbed.

Different species

Early Universe

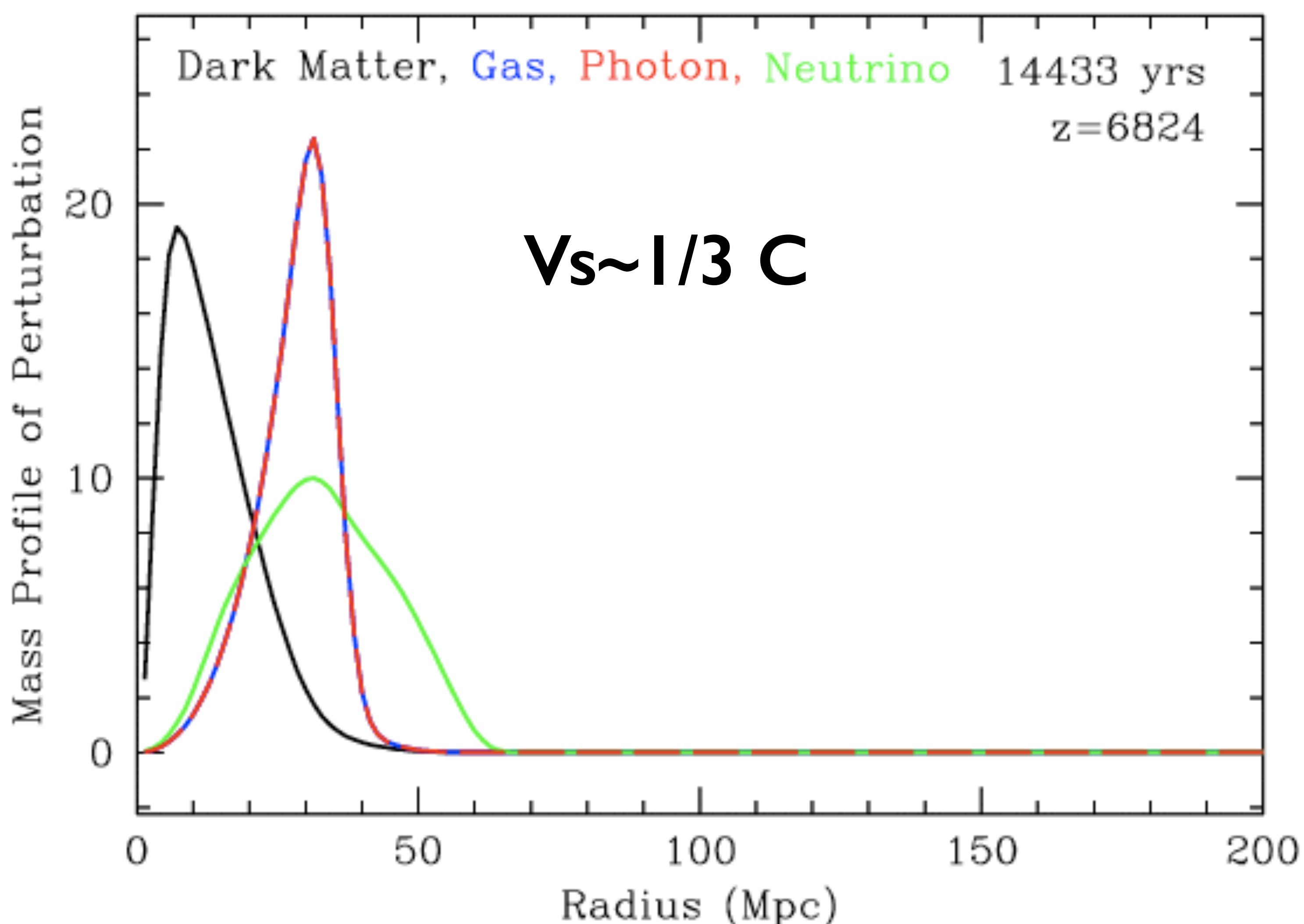
mass profile



Eisenstein(2005)

Baryonic Acoustic Oscillations

Baryons are coupled with photons, radiation pressure produce **spherical waves** that start propagating.

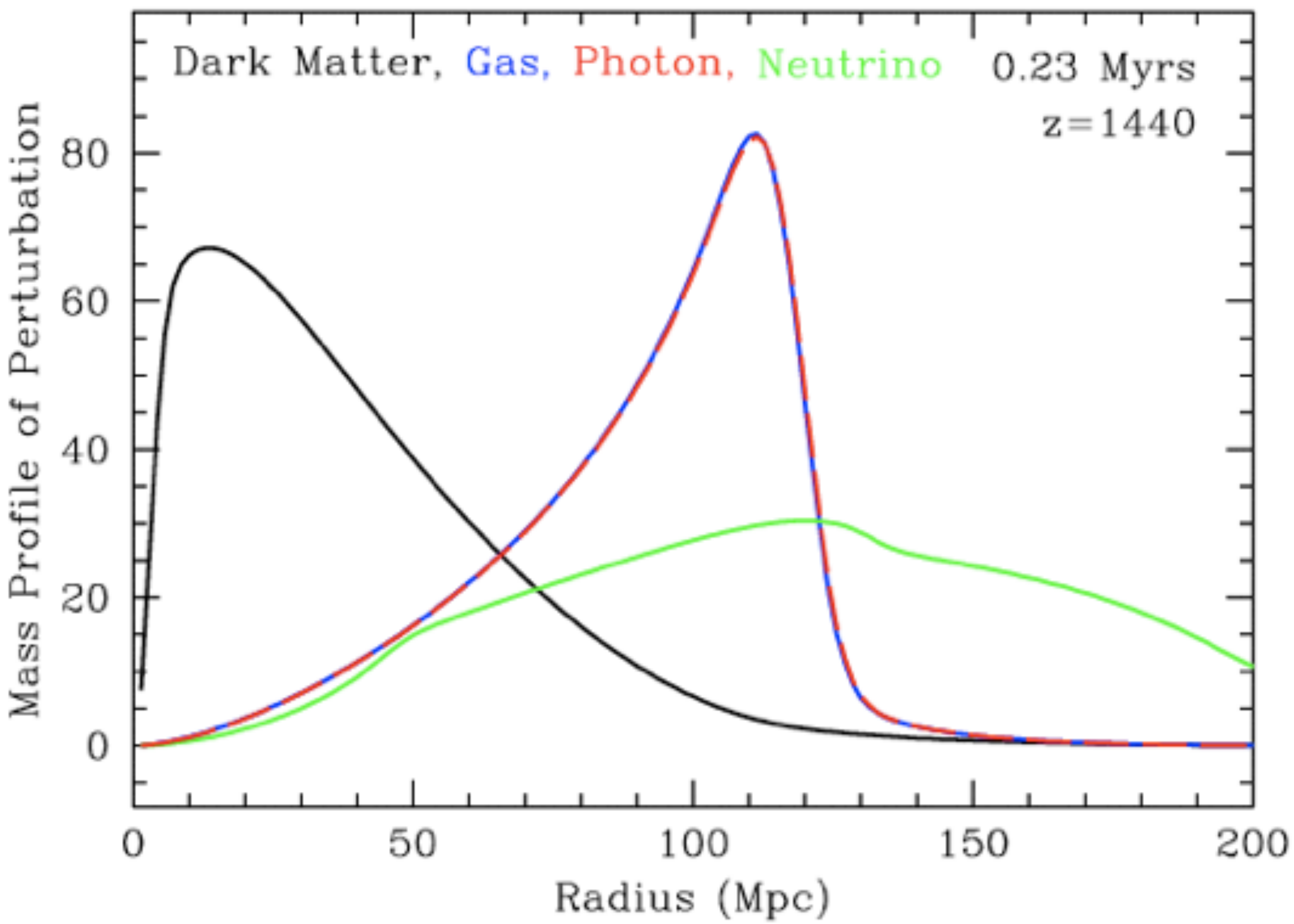


Eisenstein(2005)

Baryonic Acoustic Oscillations

Dark Matter only interacts gravitationally and **stays** at the center, neutrinos do not interact gravitationally and dilute with time.

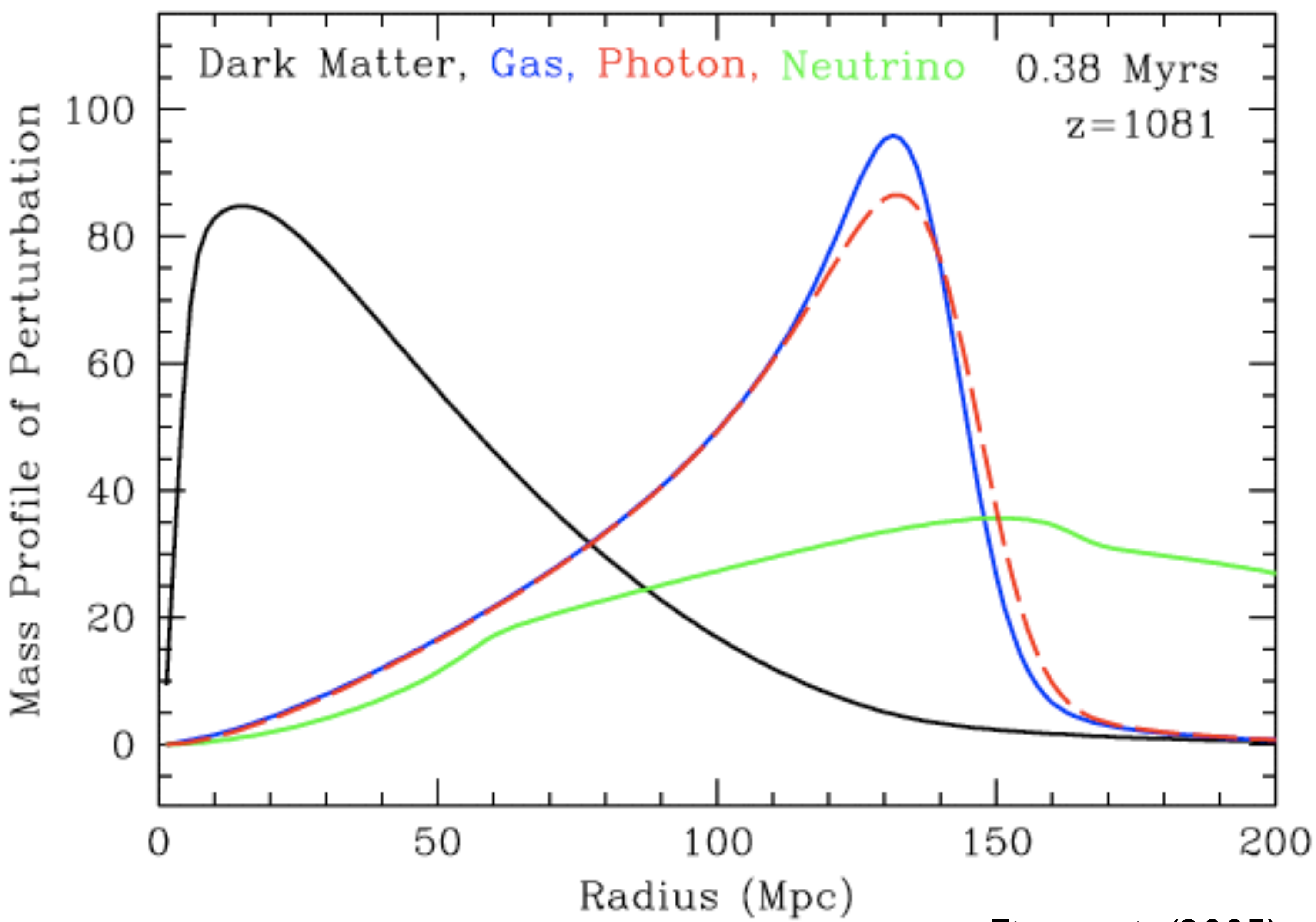
Neutrinos decouple from the cosmic plasma when the temperature of the Universe is about 1 MeV



Eisenstein(2005)

Baryonic Acoustic Oscillations

Photons decouple (last scattering surface), with radiation pressure, baryons remain frizzed and the matter accretion becomes faster.

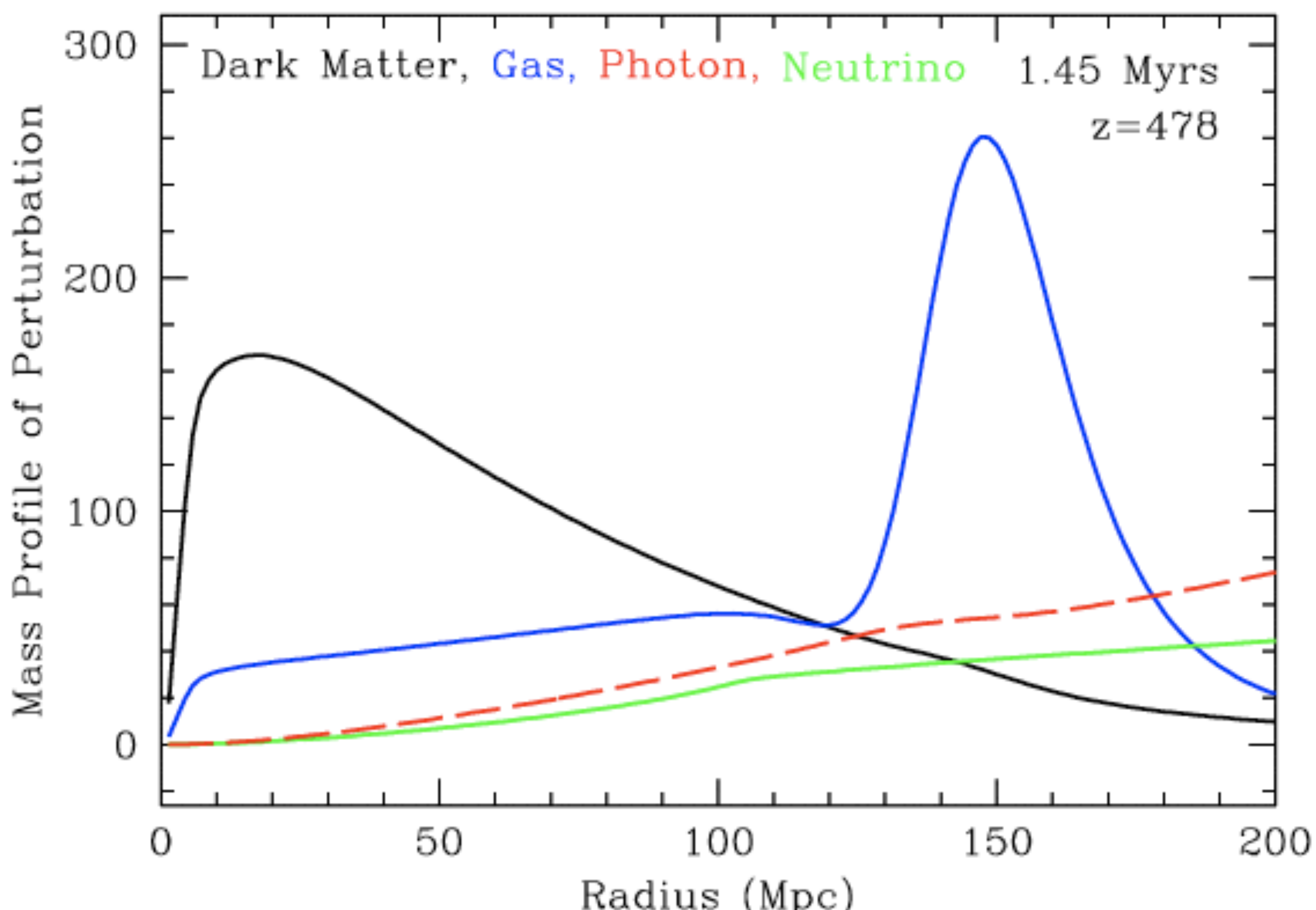


Eisenstein(2005)

Eisenstein(2005)

Baryonic Acoustic Oscillations

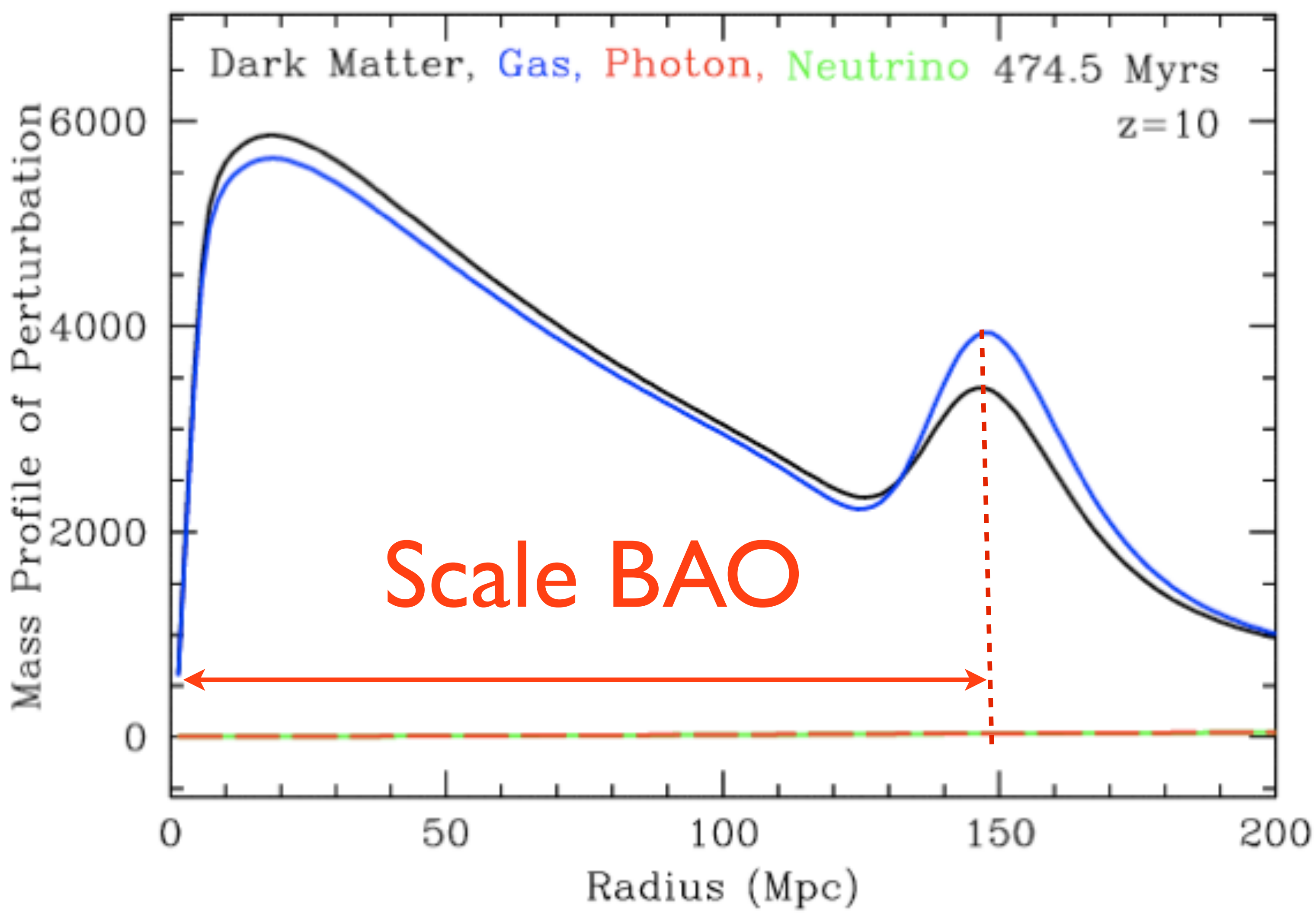
Dark matter pertubartion at the center interacts **gravitationally** with the shell of **baryons**.



Eisenstein(2005)

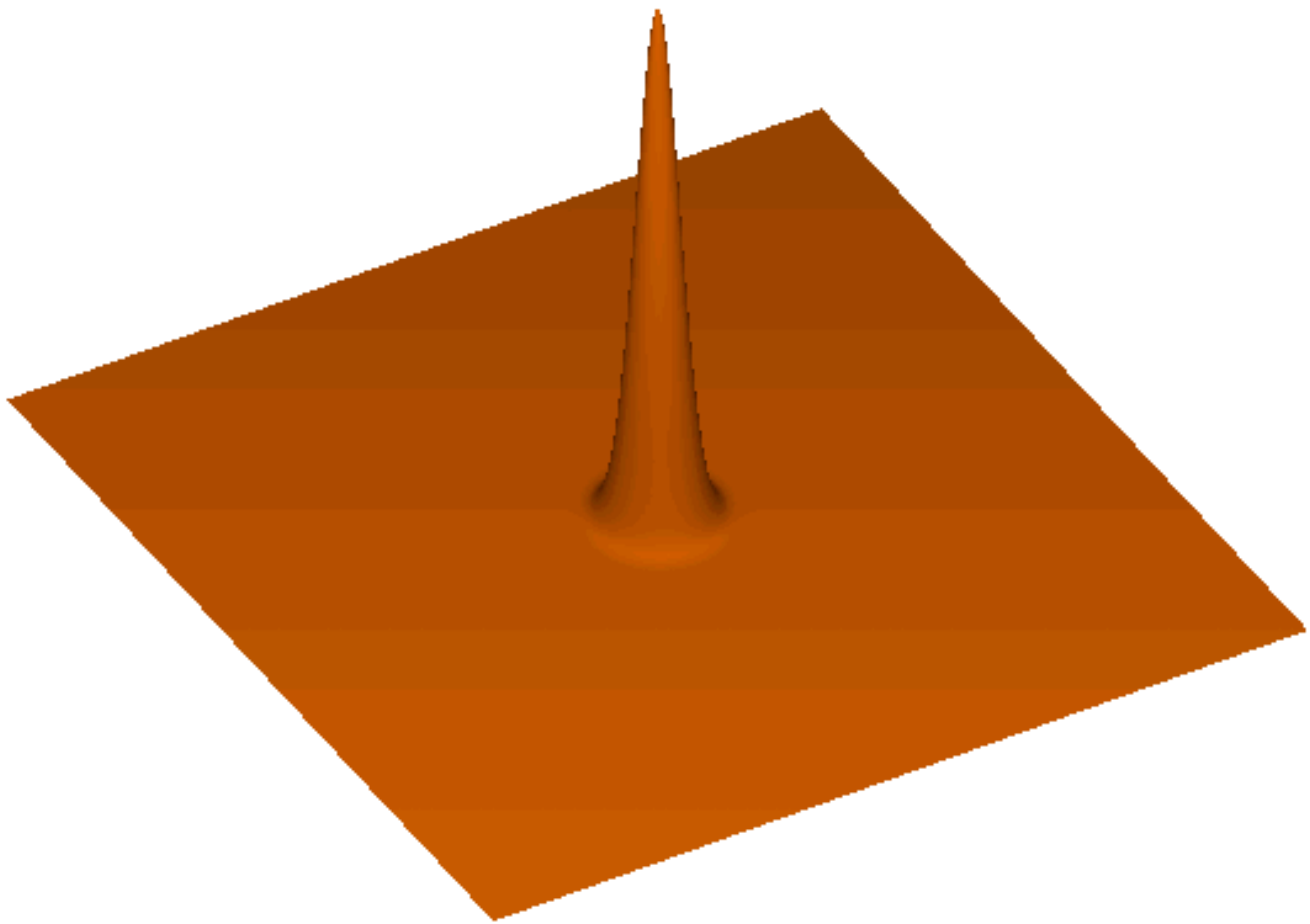
Baryonic Acoustic Oscillations

Final Configuration: a pic at the center surrounded by an spherical shell at 150 Mpc



Eisenstein(2005)

Baryonic Acoustic Oscillations (BAO)



Eisenstein(2005)

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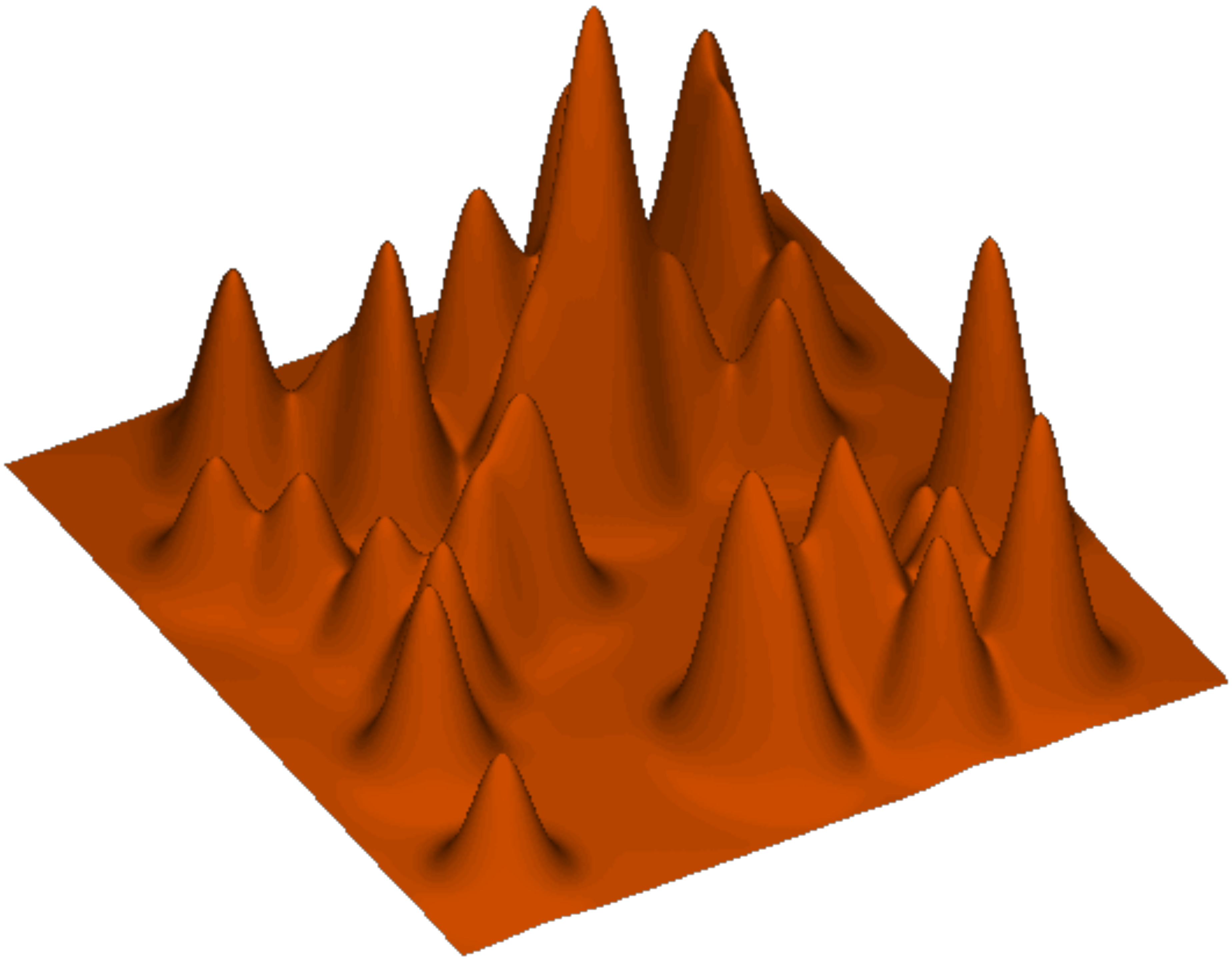
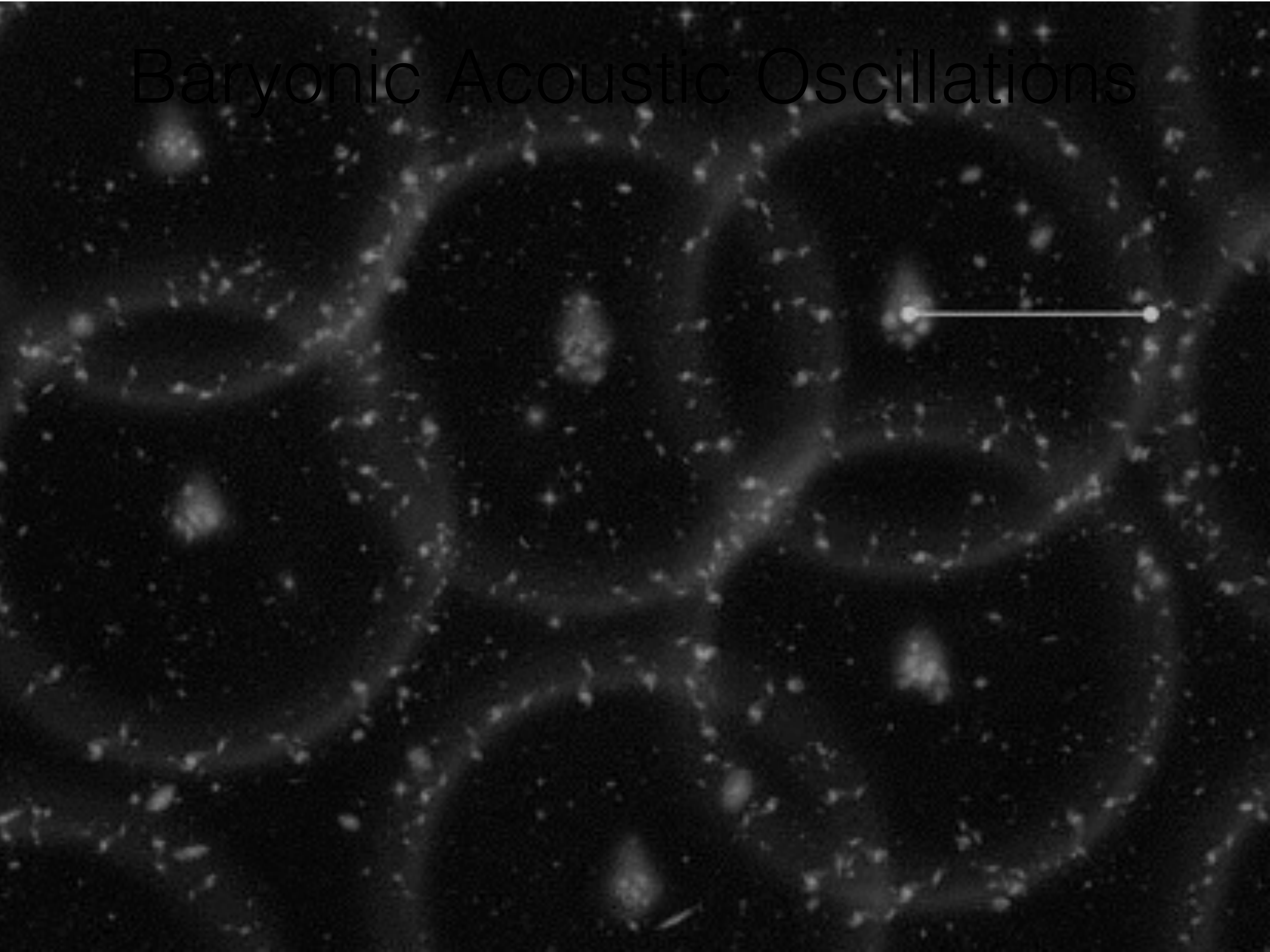


Eisenstein(2005)

Baryonic Acoustic Oscillations



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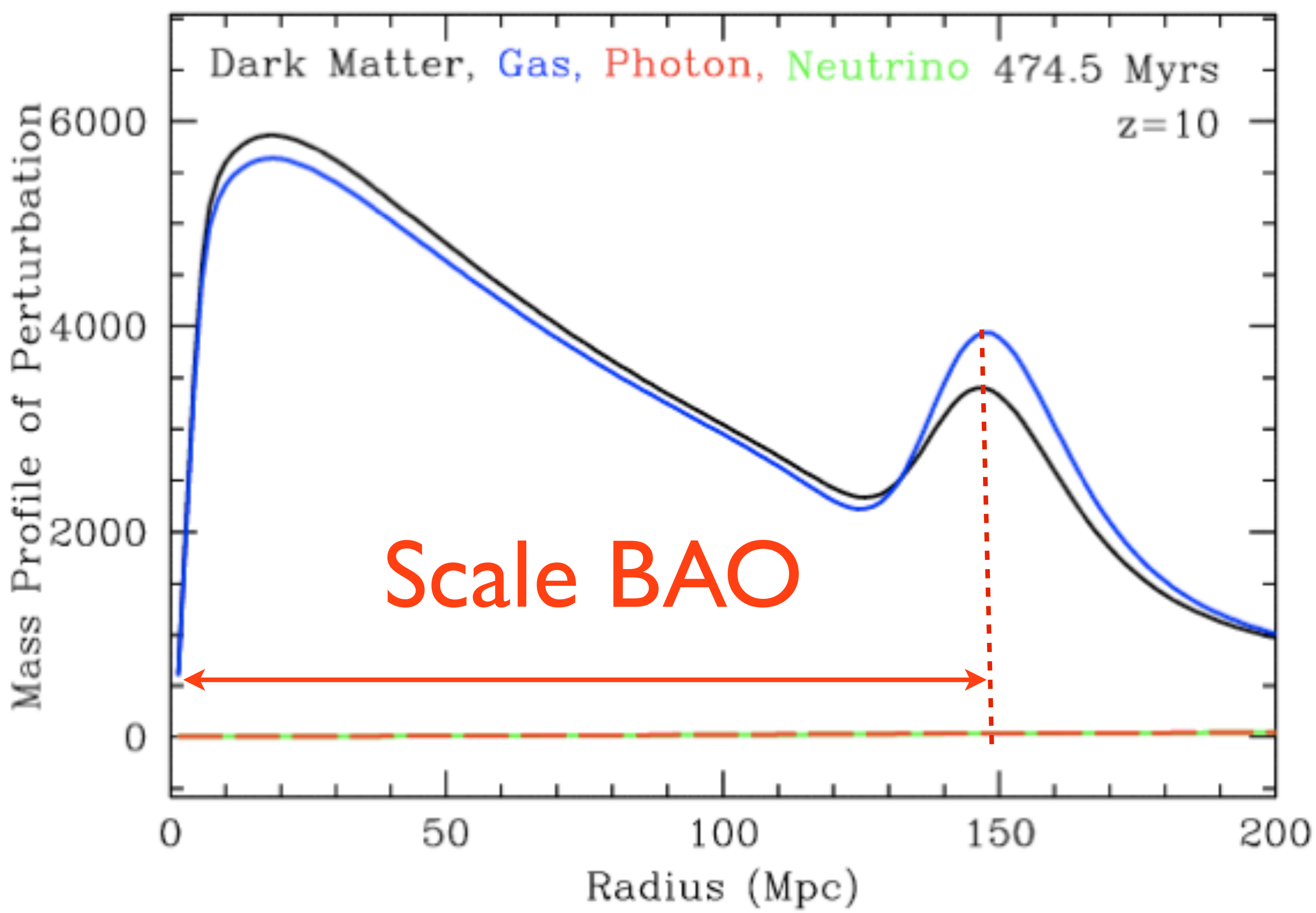
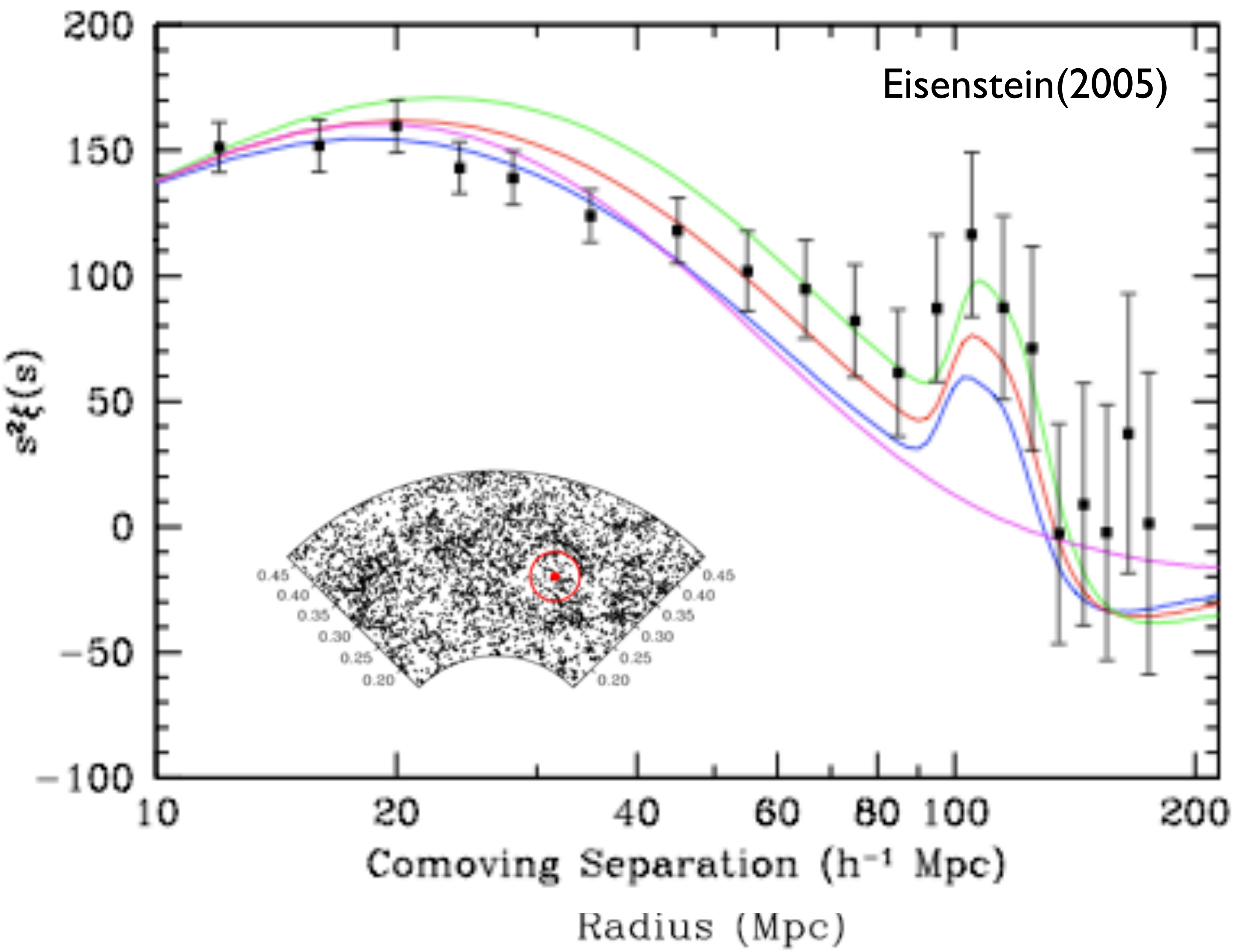


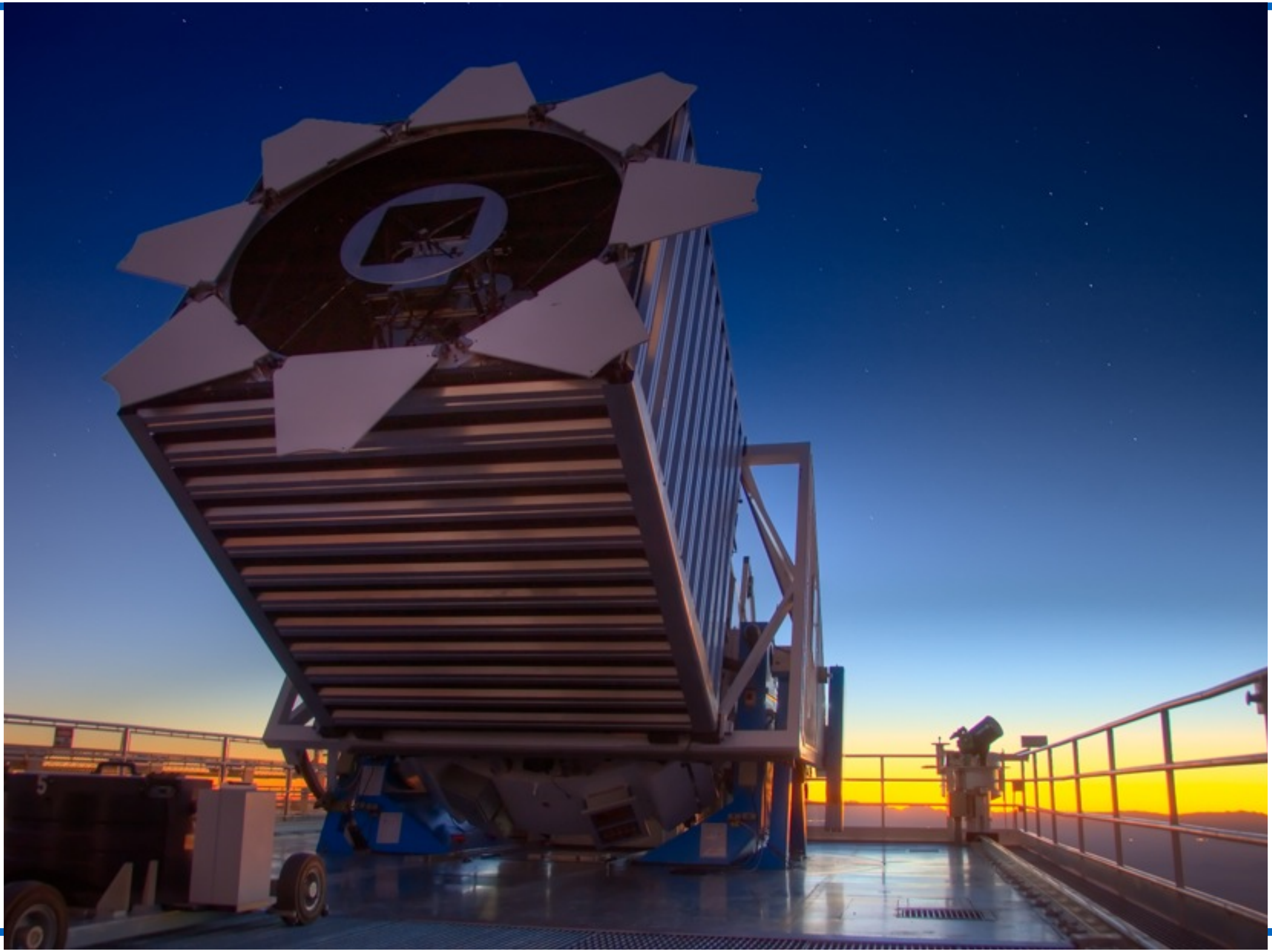
Eisenstein(2005)

Baryonic Acoustic Oscillations

BAO Detection in the correlation function of LRG Luminous Red Galaxies(2005)



Baryonic Oscillations Spectroscopic Survey (BOSS)



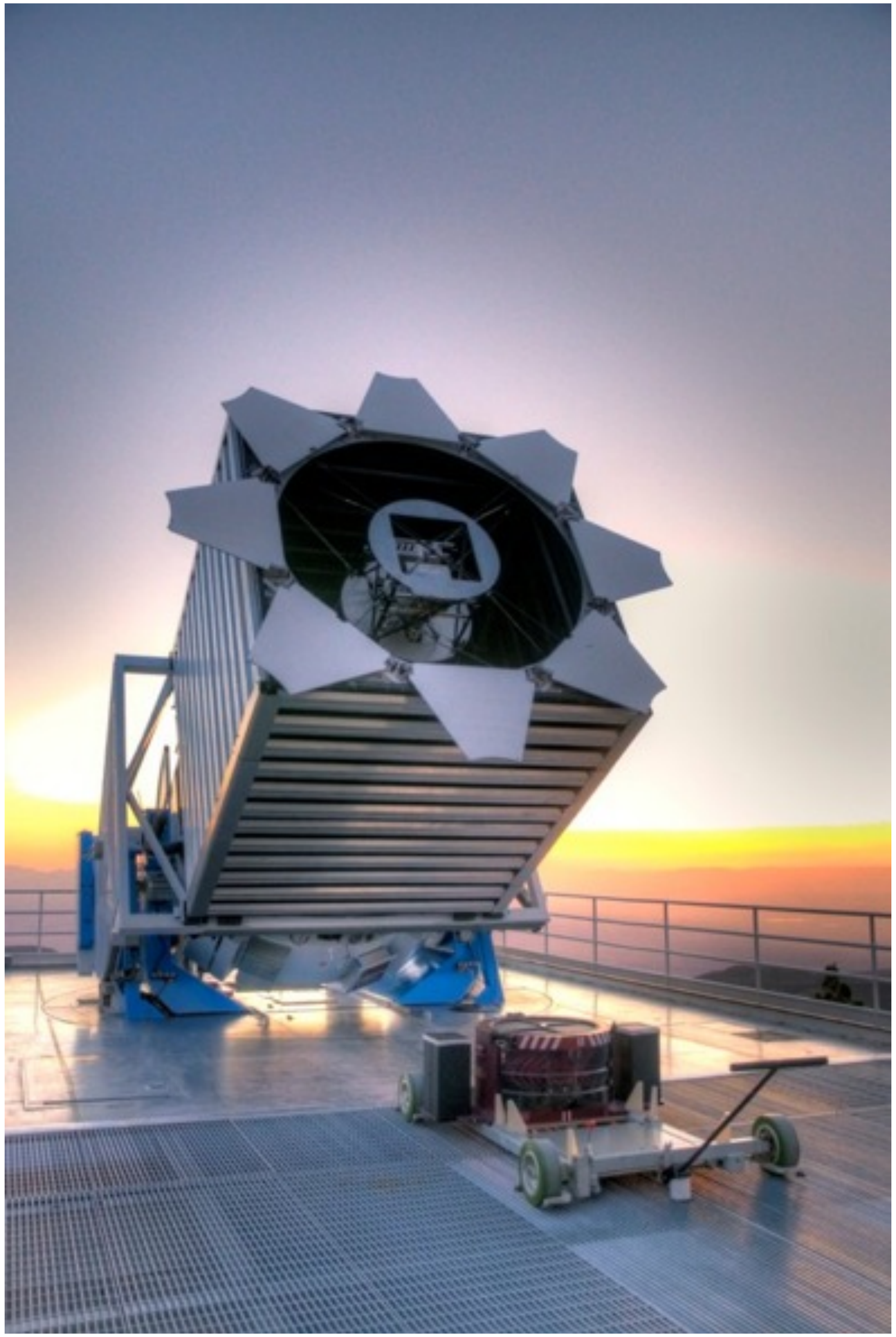
What is BOSS?

Description:

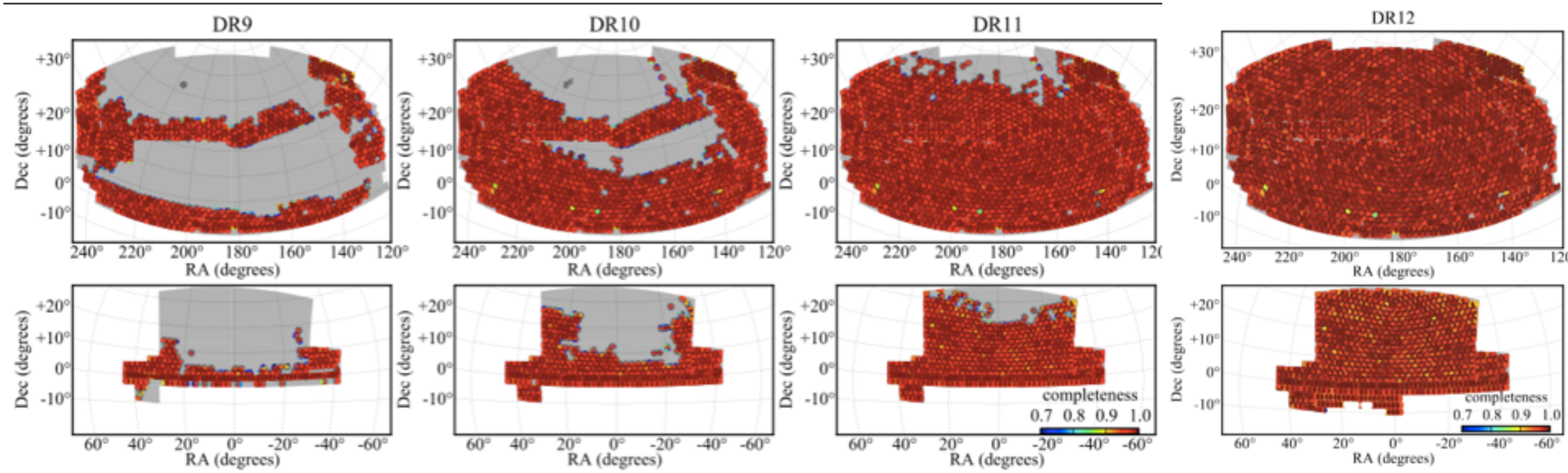
- Main SDSS-III project (2008-2014)
- APO telescope (New Mexico, USA), 2.5 m diameter
- Spectroscopic survey with SDSS-II photometry.
- 2 two-arms spectrographs: 1000 fibers
- 3600 Å < l < 10000 Å, $\lambda/\Delta\lambda \sim 3000$
- **1.5 Millions Luminous Red Galaxies at <z> ~ 0.6**
- **150 000 Quasars with Ly-α forests at <z> ~ 2.3**

Objectives:

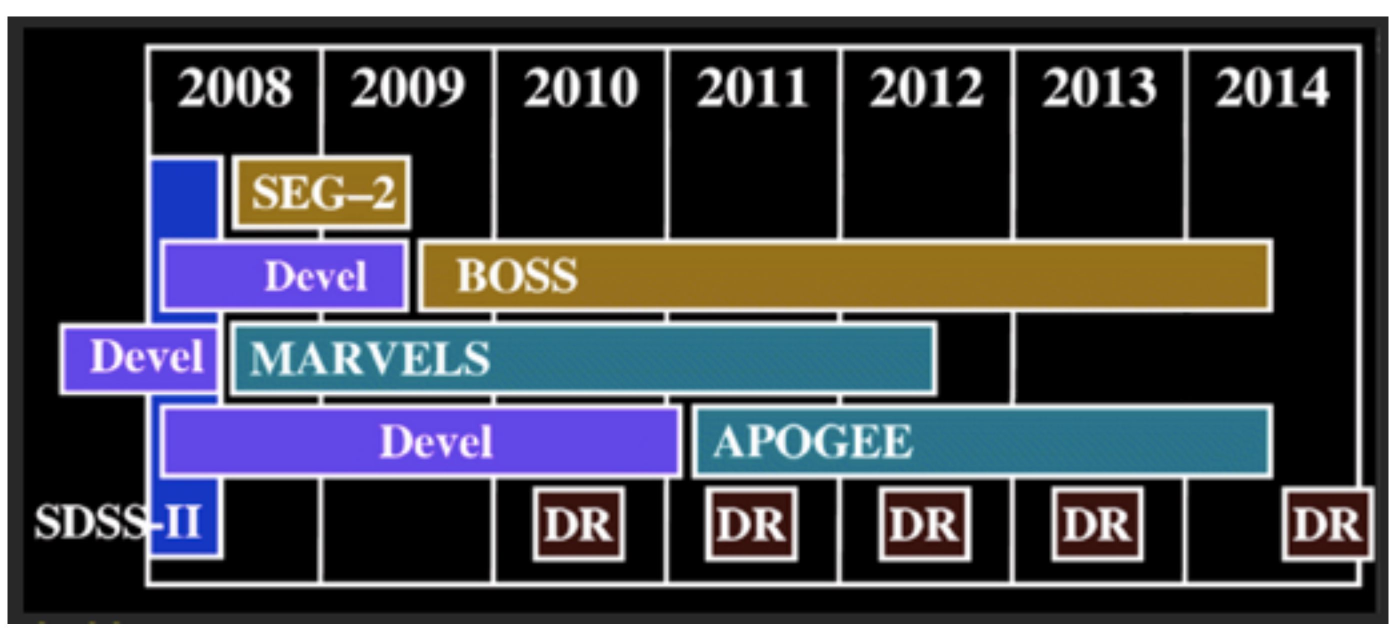
- BAO peak position 1% at z=0.6 and 1.5% at z=2.3
- Best constraints on the Dark Energy equation of state before next generation



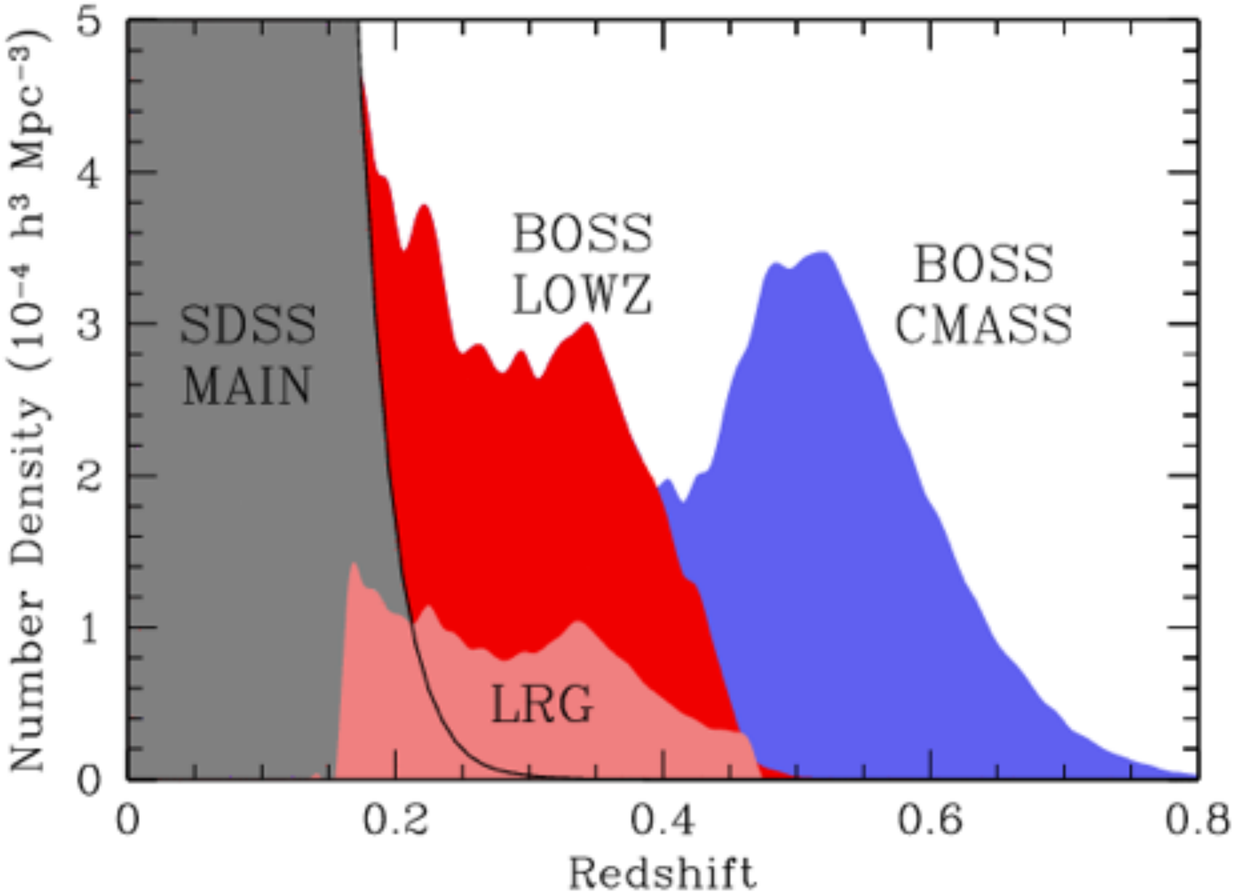
BOSS is done !!

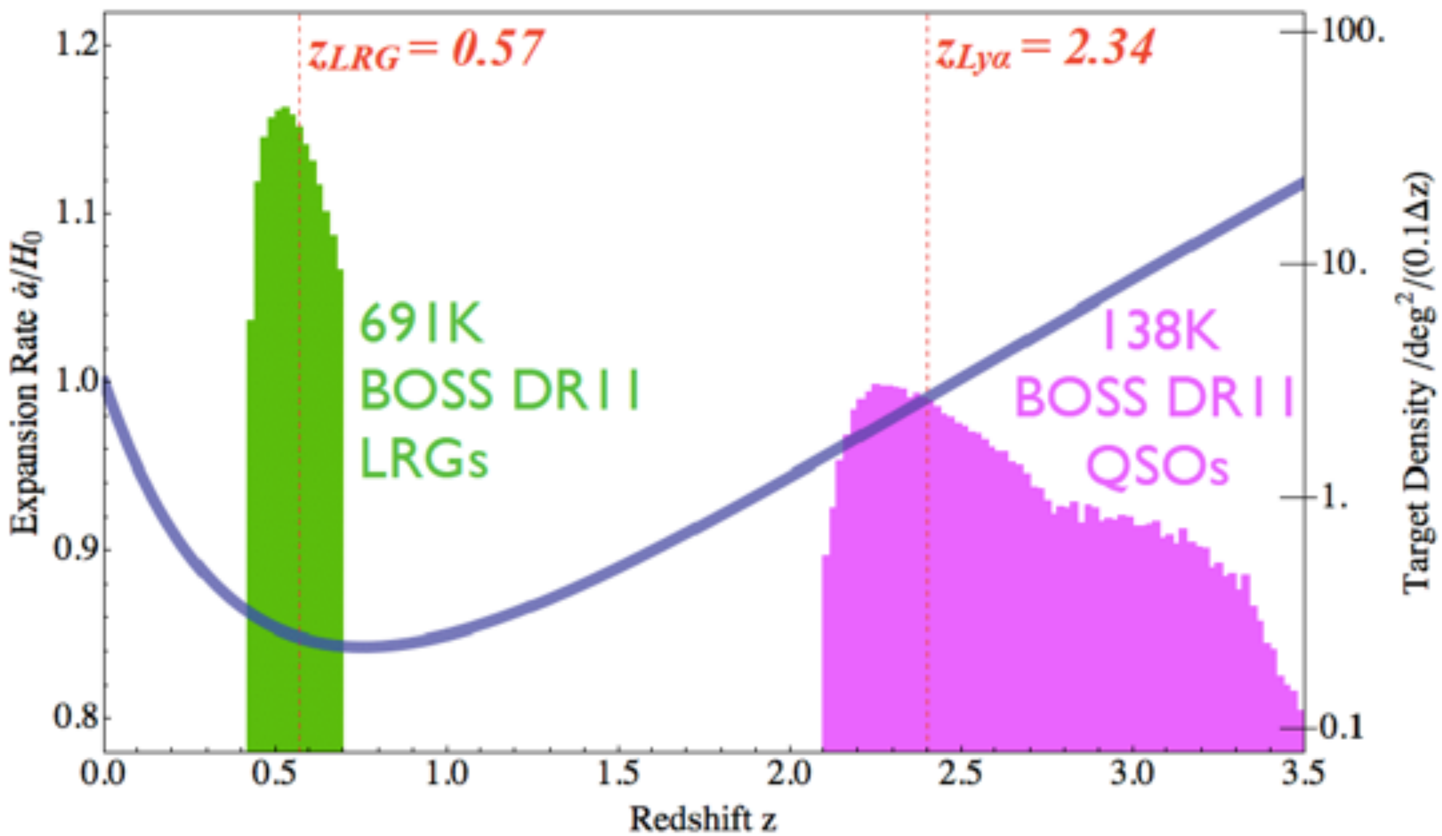


2011 **2012** **2013** **2014**

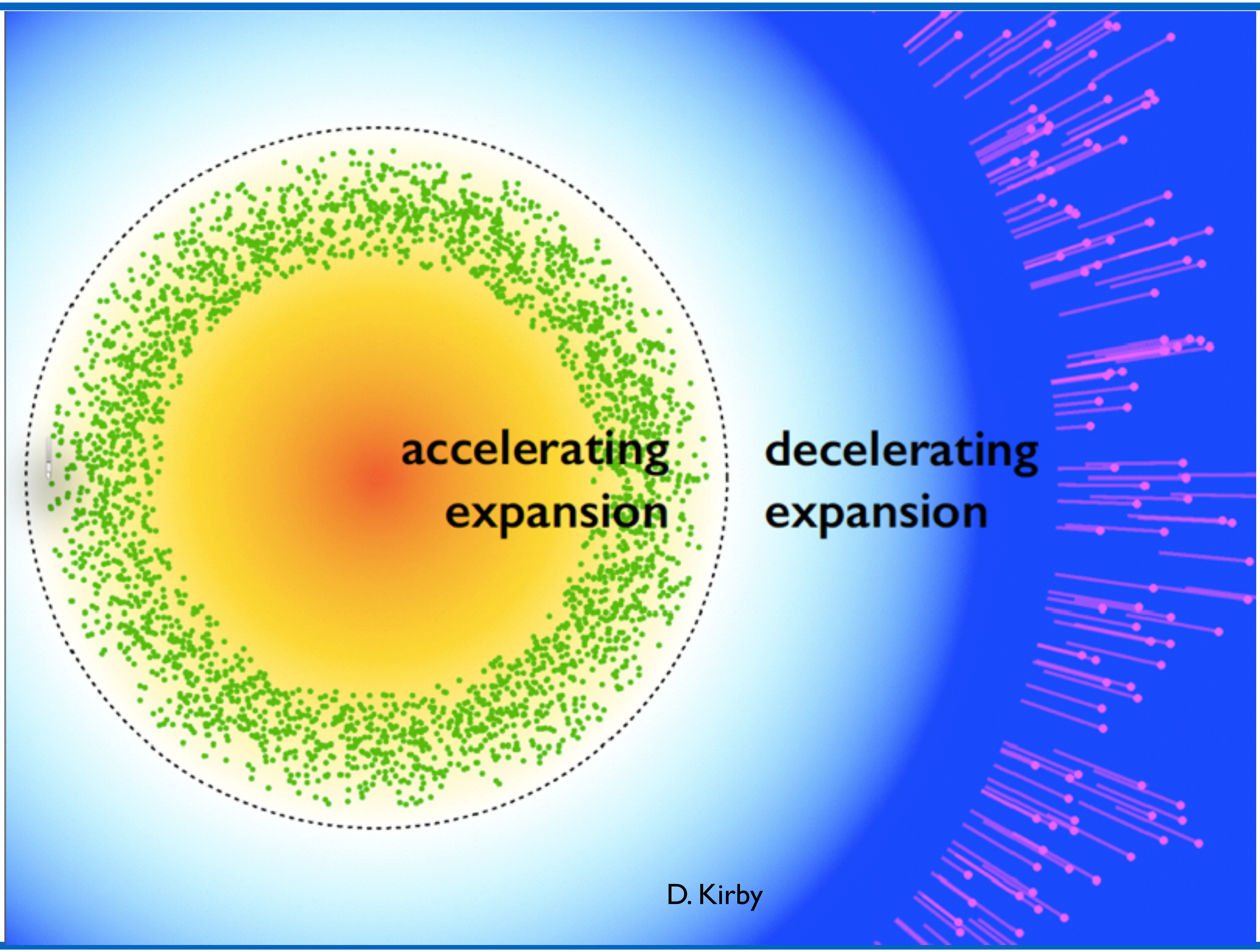


Galaxy/Quasar Samples



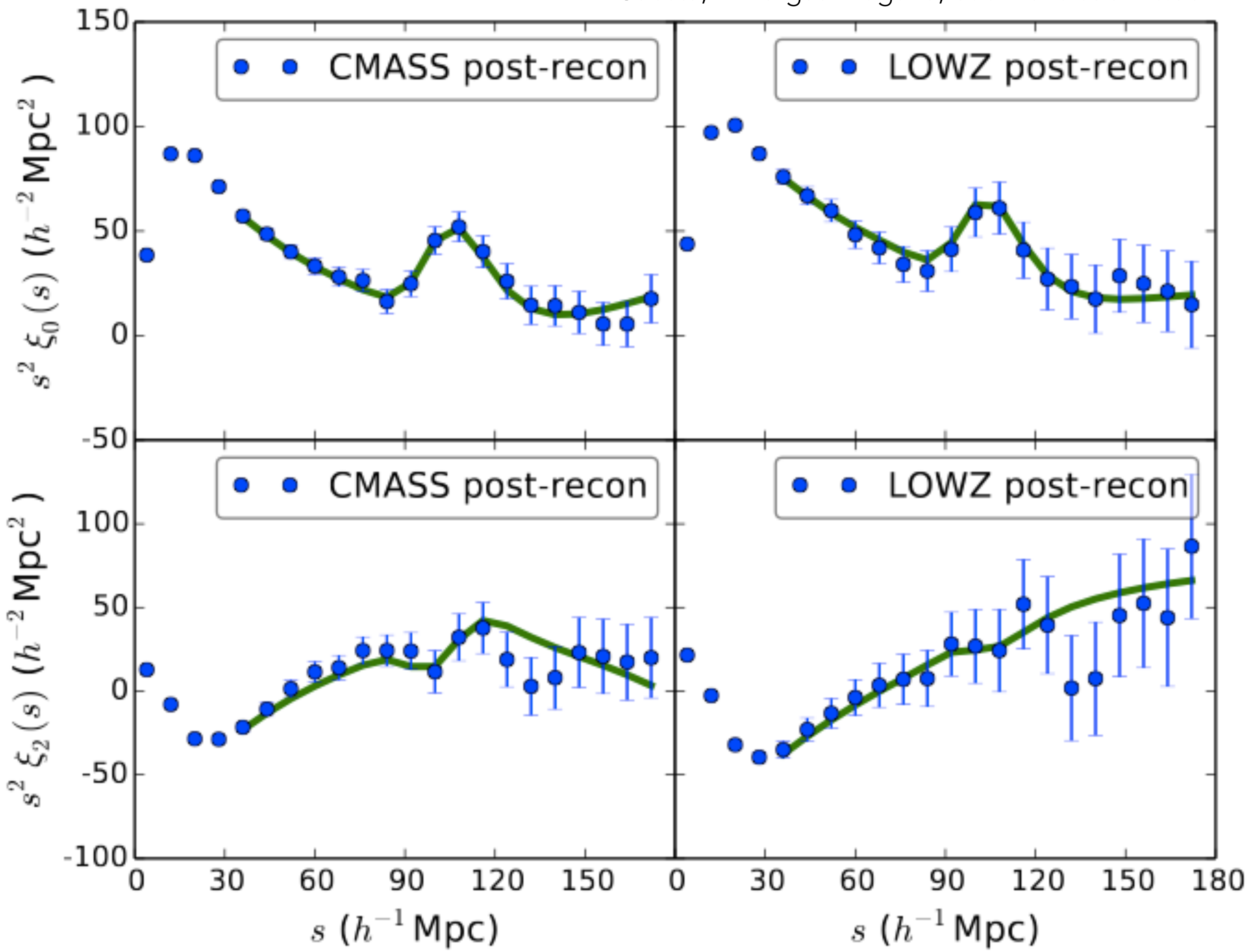


Redshift ranges



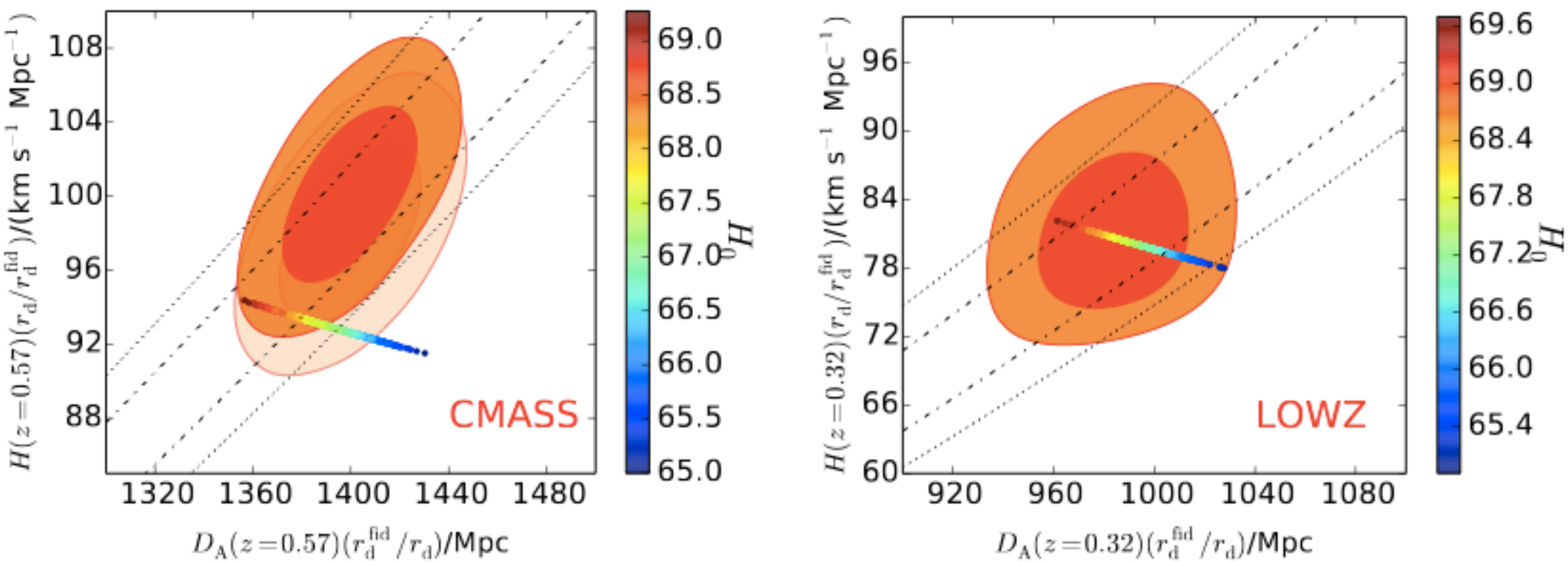
Best Fits

A. Cuesta, M.Vargas-Magana, et al 2015 submitted



Results Mocks and Data

Sample	$D_V(z)r_d^{fid}/r_d$ (Mpc)	$D_A(z)r_d^{fid}/r_d$ (Mpc)	$H(z)r_d/r_d^{fid}$ (km $s^{-1}Mpc^{-1}$)	$\rho_{D_A,H}$
LOWZ Pre-Recon	1246 ± 35	941 ± 53	77.8 ± 5.0	0.35
LOWZ Post-Recon	1263 ± 21	981 ± 20	79.2 ± 5.5	0.29
CMASS Pre-Recon	2040 ± 27	1399 ± 66	96.1 ± 4.6	0.52
CMASS Post-Recon	2028 ± 19	1401 ± 19	100.3 ± 3.4	0.57



A. Cuesta, M.Vargas-Magana, et al 2015 submitted

Cosmology Lessons from BOSS

Cosmological Model	Data Sets	$\Omega_m h^2$	Ω_m	H_0 km s^{-1} Mpc^{-1}	Ω_K	w_0	w_a
ΛCDM	Planck + CMASS-iso + LOWZ	0.1411 (14)	0.306 (8)	67.9 (6)			
ΛCDM	Planck + CMASS + LOWZ	0.1412 (13)	0.307 (7)	67.9 (5)			
ΛCDM	Planck + BAO	0.1415 (12)	0.308 (7)	67.7 (5)			
ΛCDM	Planck + CMASS + LOWZ + SN	0.1412 (12)	0.306 (7)	67.9 (5)			
ΛCDM	Planck + BAO + SN	0.1414 (12)	0.308 (7)	67.8 (5)			
ΛCDM	WMAP + BAO + SN	0.1397 (22)	0.301 (8)	68.2 (7)			
ΛCDM	eWMAP + BAO + SN	0.1410 (15)	0.301 (7)	68.5 (6)			
oCDM	Planck + CMASS-iso + LOWZ	0.1418 (25)	0.306 (8)	68.1 (7)	+0.0010 (30)		
oCDM	Planck + CMASS + LOWZ	0.1421 (25)	0.308 (7)	68.0 (7)	+0.0011 (29)		
oCDM	Planck + BAO	0.1424 (25)	0.309 (7)	67.9 (6)	+0.0012 (29)		
oCDM	Planck + CMASS + LOWZ + SN	0.1418 (24)	0.307 (7)	68.0 (6)	+0.0009 (29)		
oCDM	Planck + BAO + SN	0.1420 (24)	0.308 (7)	67.9 (6)	+0.0009 (28)		
oCDM	WMAP + BAO + SN	0.1388 (41)	0.299 (9)	68.1 (7)	-0.0013 (40)		
oCDM	eWMAP + BAO + SN	0.1367 (34)	0.296 (8)	68.0 (7)	-0.0049 (34)		
wCDM	Planck + CMASS-iso + LOWZ	0.1428 (22)	0.288 (19)	70.5 (26)		-1.12 (11)	
wCDM	Planck + CMASS + LOWZ	0.1419 (21)	0.301 (14)	68.7 (19)		-1.04 (9)	
wCDM	Planck + BAO	0.1413 (20)	0.309 (13)	67.7 (17)		-1.00 (7)	
wCDM	Planck + CMASS + LOWZ + SN	0.1421 (19)	0.300 (12)	68.9 (15)		-1.05 (7)	
wCDM	Planck + BAO + SN	0.1418 (19)	0.305 (11)	68.2 (14)		-1.02 (6)	
wCDM	WMAP + BAO + SN	0.1370 (34)	0.309 (11)	66.6 (16)		-0.91 (8)	
wCDM	eWMAP + BAO + SN	0.1372 (28)	0.314 (11)	66.2 (15)		-0.88 (7)	
owCDM	Planck + CMASS-iso + LOWZ	0.1419 (25)	0.282 (28)	71.2 (36)	-0.0015 (40)	-1.16 (18)	
owCDM	Planck + CMASS + LOWZ	0.1422 (25)	0.309 (22)	68.0 (24)	+0.0020 (49)	-1.00 (13)	
owCDM	Planck + BAO	0.1423 (25)	0.321 (18)	66.7 (18)	+0.0038 (46)	-0.93 (10)	
owCDM	Planck + CMASS + LOWZ + SN	0.1421 (25)	0.301 (14)	68.7 (16)	+0.0004 (34)	-1.04 (8)	
owCDM	Planck + BAO + SN	0.1423 (25)	0.309 (13)	67.9 (14)	+0.0013 (34)	-1.00 (7)	
owCDM	WMAP + BAO + SN	0.1372 (43)	0.309 (13)	66.7 (16)	+0.0001 (46)	-0.91 (8)	
owCDM	eWMAP + BAO + SN	0.1356 (35)	0.308 (13)	66.4 (14)	-0.0027 (41)	-0.90 (7)	
$w_0 w_a$CDM	Planck + CMASS-iso + LOWZ	0.1431 (22)	0.333 (49)	66.2 (52)		-0.67 (46)	-1.15 (112)
$w_0 w_a$CDM	Planck + CMASS + LOWZ	0.1424 (21)	0.373 (36)	62.1 (33)		-0.32 (33)	-1.86 (83)
$w_0 w_a$CDM	Planck + BAO	0.1423 (20)	0.375 (29)	61.7 (25)		-0.30 (27)	-1.91 (73)
$w_0 w_a$CDM	Planck + CMASS + LOWZ + SN	0.1429 (22)	0.308 (17)	68.2 (19)		-0.93 (18)	-0.43 (62)
$w_0 w_a$CDM	Planck + BAO + SN	0.1427 (22)	0.315 (16)	67.4 (17)		-0.89 (18)	-0.50 (59)
$w_0 w_a$CDM	WMAP + BAO + SN	0.1366 (42)	0.304 (16)	67.1 (17)		-0.96 (16)	0.11 (56)
$w_0 w_a$CDM	eWMAP + BAO + SN	0.1363 (31)	0.303 (15)	67.1 (16)		-1.00 (14)	0.32 (40)
o$w_0 w_a$CDM	Planck + CMASS-iso + LOWZ	0.1418 (25)	0.328 (46)	66.3 (49)	-0.0040 (45)	-0.63 (40)	-1.62 (102)
o$w_0 w_a$CDM	Planck + CMASS + LOWZ	0.1417 (24)	0.371 (36)	62.0 (32)	-0.0015 (51)	-0.31 (30)	-1.99 (79)
o$w_0 w_a$CDM	Planck + BAO	0.1419 (24)	0.376 (29)	61.6 (25)	-0.0003 (48)	-0.28 (26)	-1.95 (74)
o$w_0 w_a$CDM	Planck + CMASS + LOWZ + SN	0.1420 (25)	0.309 (17)	67.9 (18)	-0.0027 (45)	-0.86 (20)	-0.83 (85)
o$w_0 w_a$CDM	Planck + BAO + SN	0.1422 (25)	0.315 (16)	67.2 (17)	-0.0011 (43)	-0.86 (19)	-0.65 (77)
o$w_0 w_a$CDM	WMAP + BAO + SN	0.1368 (44)	0.304 (16)	67.1 (18)	+0.0035 (71)	-0.98 (17)	0.27 (67)
o$w_0 w_a$CDM	eWMAP + BAO + SN	0.1357 (35)	0.304 (15)	66.8 (17)	-0.0011 (56)	-0.96 (16)	0.18 (55)

flat Universe with DE described by a cosmological constant

non-flat Universe with DE described by a cosmological constant

flat Universe with DE with constant but arbitrary equation of state

non flat Universe DE with constant but arbitrary equation of state

flat Universe with a time-dependent equation of state

non-flat Universe with a time-dependent equation of state

DR12 (“Almost Final”) Results

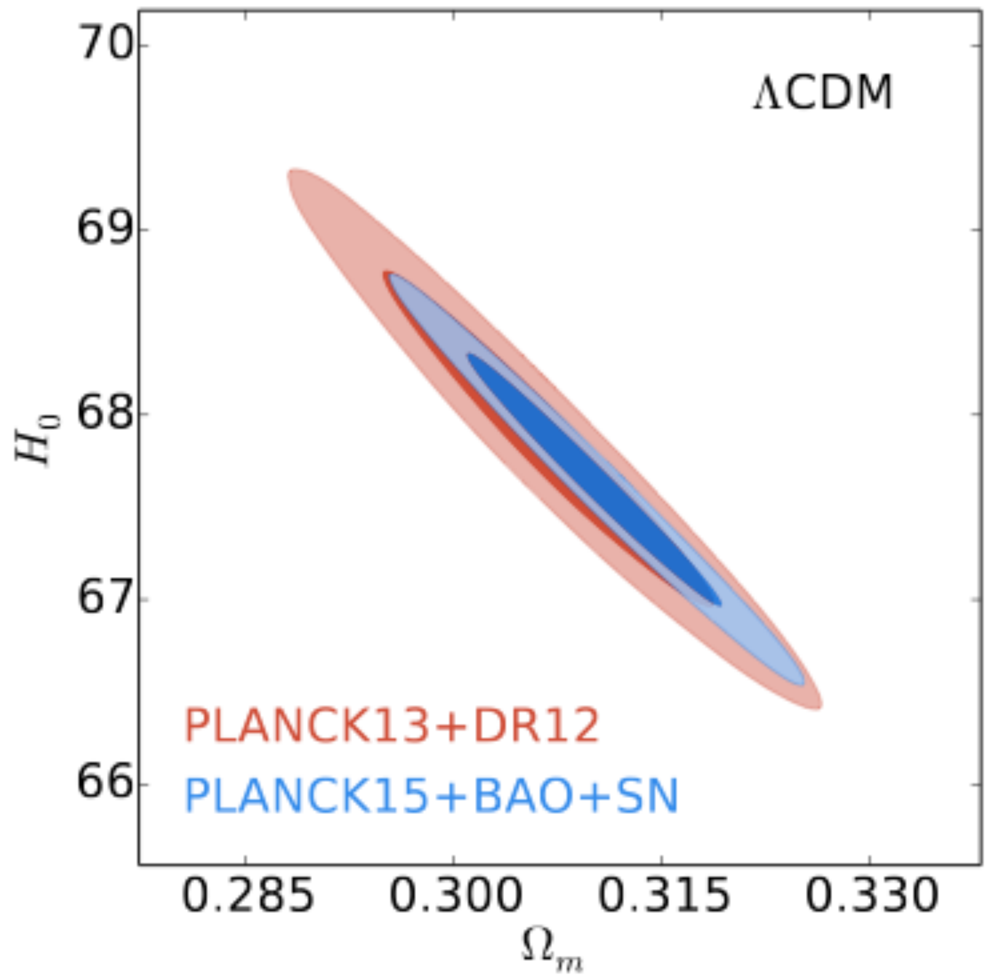
Table 13. Cosmological constraints from Planck15+LOWZ+CMASS and from Planck15+LOWZ+CMASS+MGS+6DF+JLA. 'CMASS' indicates the anisotropic measurement from the CMASS sample, whereas 'LOWZ' is the isotropic measurement from the LOWZ sample. 'BAO' stands for the combination LOWZ + CMASS + MGS + 6DF. Numbers in parenthesis represent the uncertainty in the accompanying value, e.g. 0.123 (45) should be read as 0.123 ± 0.045.

Cosmological Model	Data Sets	$\Omega_m h^2$	Ω_m	H_0 km s^{-1} Mpc^{-1}	Ω_K	w_0	w_a
ΛCDM	Planck15 + LOWZ + CMASS	0.1418 (9)	0.310 (6)	67.7 (4)			
ΛCDM	Planck15 + BAO + SN	0.1419 (9)	0.310 (6)	67.6 (4)			
oCDM	Planck15 + LOWZ + CMASS	0.1424 (13)	0.308 (6)	68.0 (6)	+0.0012 (19)		
oCDM	Planck15 + BAO + SN	0.1424 (13)	0.309 (6)	67.9 (6)	+0.0009 (19)		
wCDM	Planck15 + LOWZ + CMASS	0.1426 (12)	0.298 (14)	69.2 (17)		-1.06 (7)	
wCDM	Planck15 + BAO + SN	0.1423 (11)	0.307 (8)	68.1 (10)		-1.02 (4)	
owCDM	Planck15 + LOWZ + CMASS	0.1425 (14)	0.297 (21)	69.4 (26)	+0.0000 (37)	-1.08 (13)	
owCDM	Planck15 + BAO + SN	0.1425 (13)	0.308 (9)	68.1 (10)	+0.0008 (25)	-1.01 (5)	
$w_0 w_a$CDM	Planck15 + LOWZ + CMASS	0.1427 (13)	0.370 (36)	62.4 (32)		-0.33 (33)	-1.88 (83)
$w_0 w_a$CDM	Planck15 + BAO + SN	0.1430 (13)	0.312 (10)	67.8 (11)		-0.91 (10)	-0.45 (38)
o$w_0 w_a$CDM	Planck15 + LOWZ + CMASS	0.1422 (14)	0.364 (36)	62.8 (32)	-0.0023 (40)	-0.35 (30)	-2.04 (76)
o$w_0 w_a$CDM	Planck15 + BAO + SN	0.1422 (14)	0.312 (10)	67.5 (11)	-0.0033 (35)	-0.84 (13)	-0.92 (66)

LCDM Model

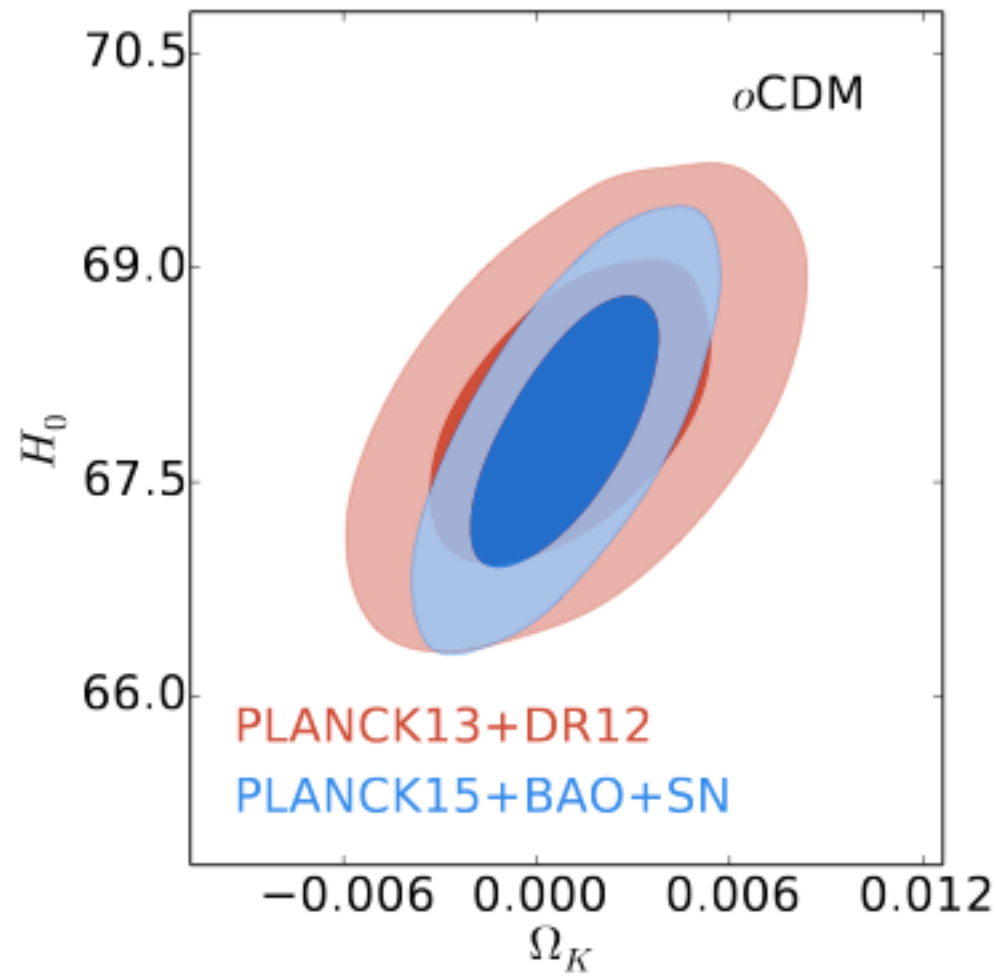
H0=67.7 +/- 0.4

Ωm=0.310 +/-0.006



H0=67.9 +/- 0.6

Ωk=0.0009 +/-0.0019

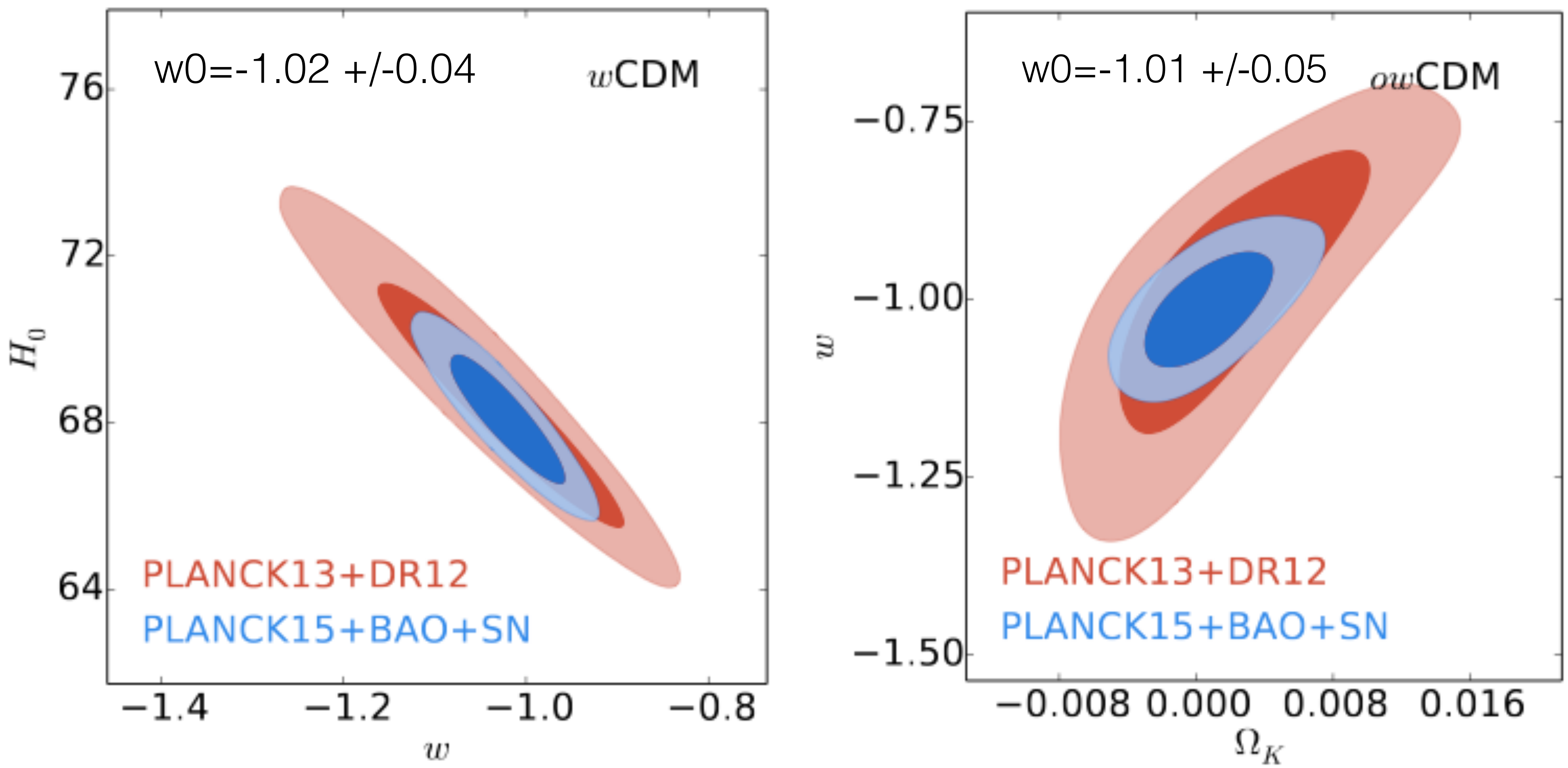


The constraint on the Hubble constant has an error bar half its size for the CMB only case in Planck Collaboration et al. (2015b).

The LCDM model is an excellent fitting to the combination of CMB, BAO, and SN datasets. The values we derive for the cosmological parameters include a **curvature parameter of k= +0.0009 0.0019**, consistent with a at geometry of the Universe.

Contant DE models

The equation of state of dark energy is also reported with **an error bar half its size** in Planck Collaboration et al. (2015b) for the CMB+BAO+Supernovas and is consistent with a cosmological constant Anderson et al (2015).



The curvature is also reported here **with an error bar half its size** in Planck Collaboration et al. (2015b) for the CMB+BAO+supenovas dataset combination (K= 0.0008 +/- 0.0040) and is consistent with flatness.

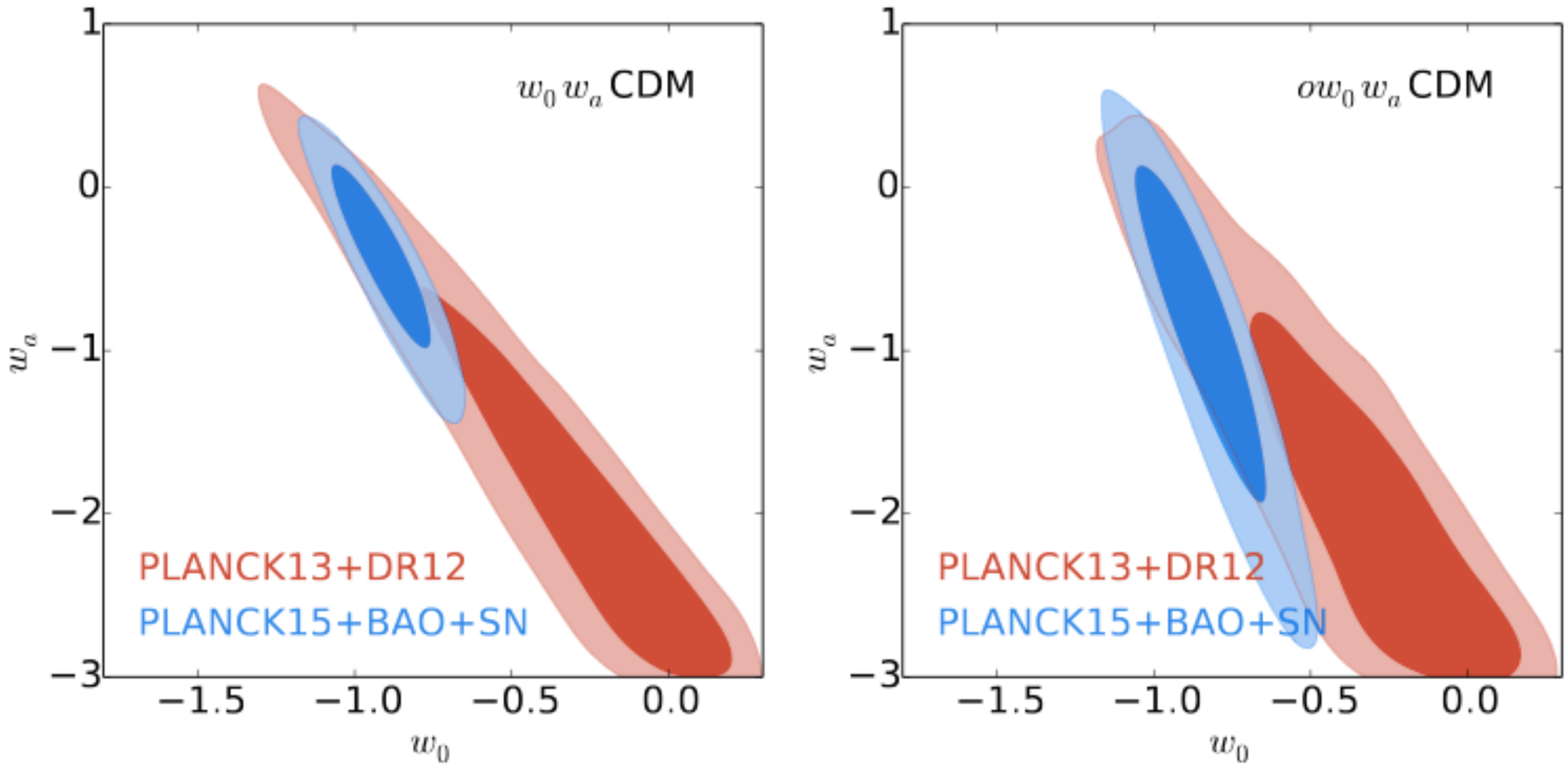
Dynamic DE models

w0=-0.91 +/-0.10

wa=-0.45 +/-0.38

w0=-0.84+/-0.13

wa=-0.92 +/-0.66

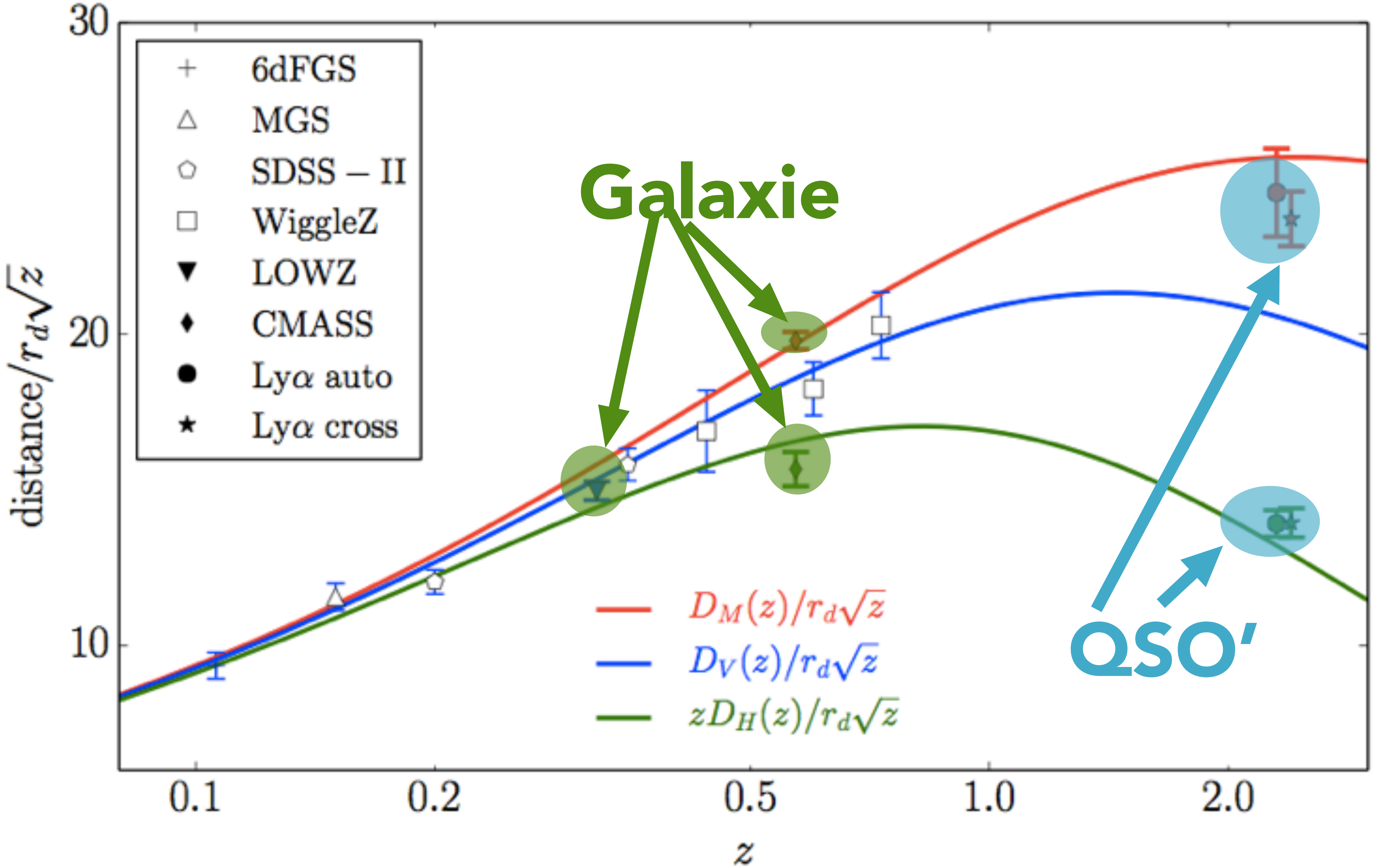


A. Cuesta, M.Vargas-Magana, et al 2015 submitted

$$\omega(z) = \omega_0 + \omega_a\left(\frac{z}{1+z}\right)$$

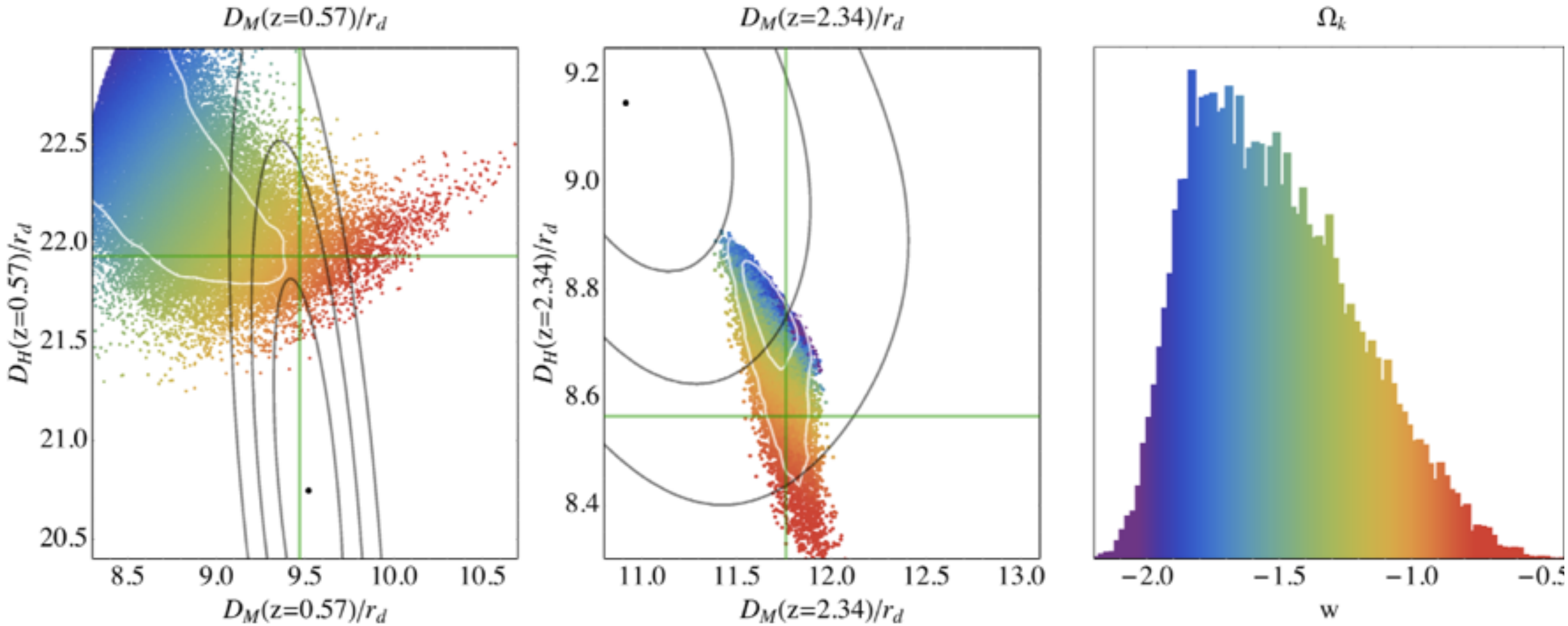
Join Analysis

Aubourg, E, Mariana Vargas-Magana et al **Cosmological implications of baryon acoustic oscillation (BAO) measurements.** [arXiv:1411.1074].



Join Analysis

Aubourg, E, Mariana Vargas-Magana et al **Cosmological implications of baryon acoustic oscillation (BAO) measurements.** [arXiv:1411.1074].



The CMB data alone are consistent with a wide range of w values, and they are generally better fit with w < - 1. The combination with CMASS BAO data sharply limits the acceptable range of w , favoring values close to -1. The fit to the LyaF BAO results could be significantly improved by going to w <-1.3.

$$\omega(z) = \omega_0 + \omega_a\left(\frac{z}{1+z}\right)$$

BAO final comments

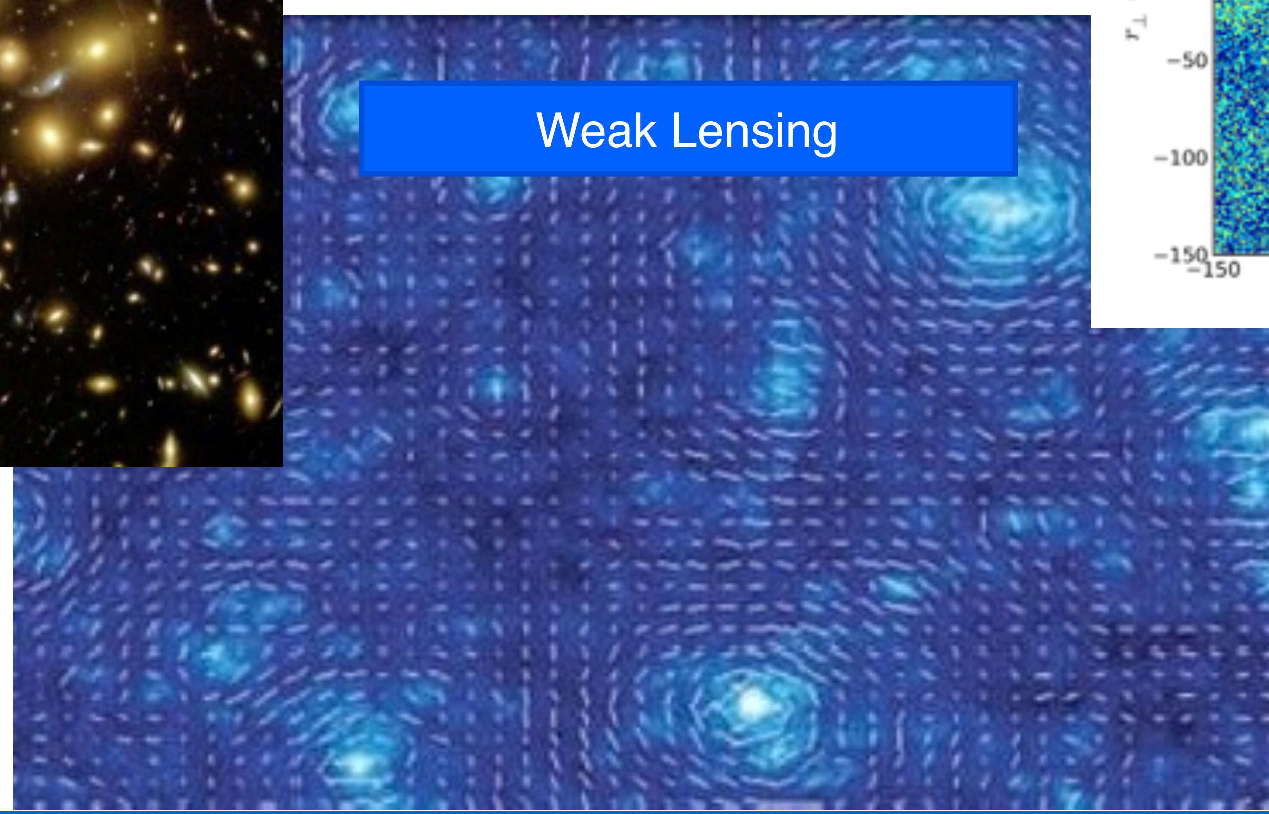
- **BAO are a powerful tool for cosmology.**
- **BAO, a well established method.**
- **In combination with CMB and SN data, these measurements yield impressively tight constraints on the cosmic expansion history and correspondingly stringent tests of dark energy theories.**
- **BOSS results are consistent with Planck ΛCDM,but there are interesting hints of tension.**

How we can study DE?

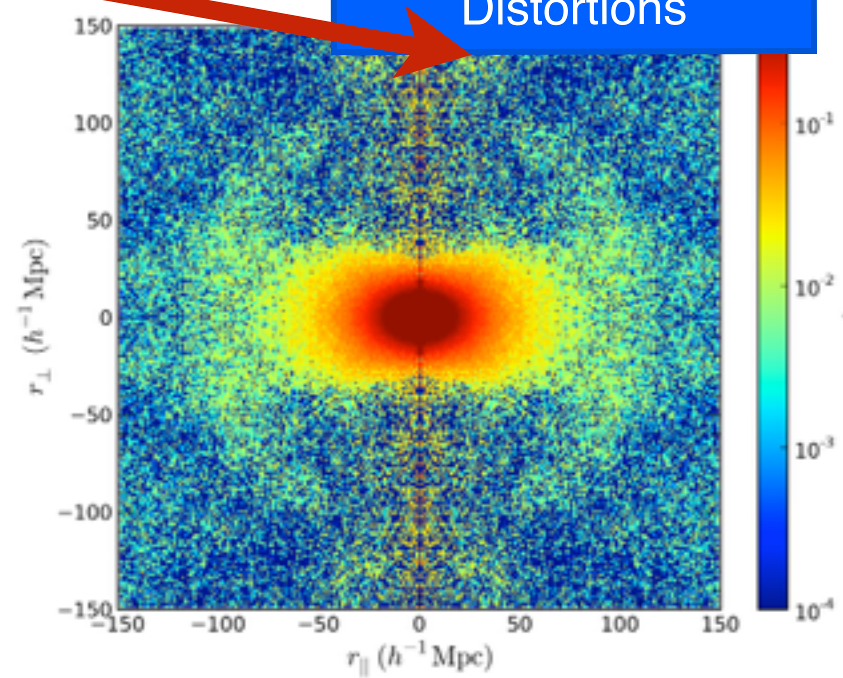
Growth Factor

Clusters

Weak Lensing

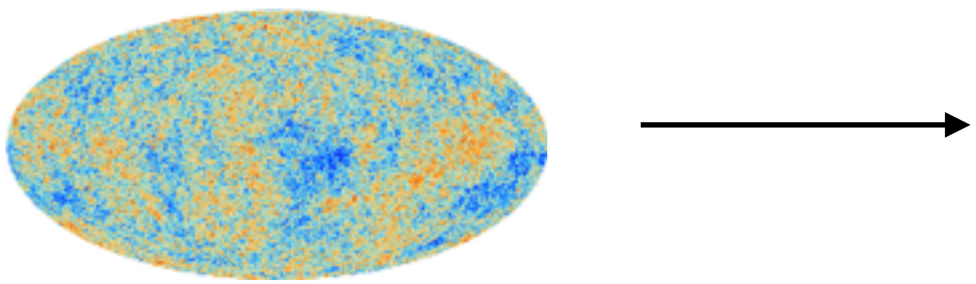


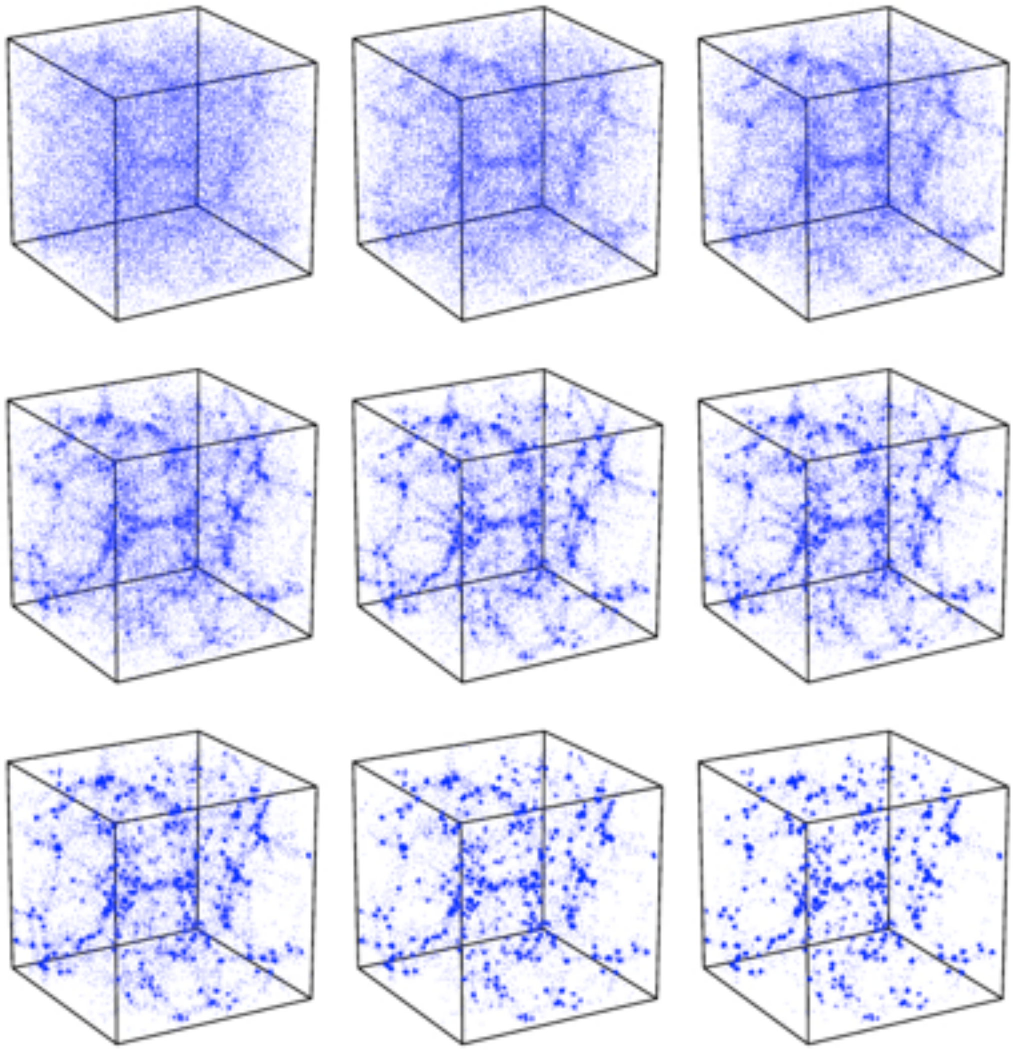
Redshift Space Distortions



Perturbations Evolution

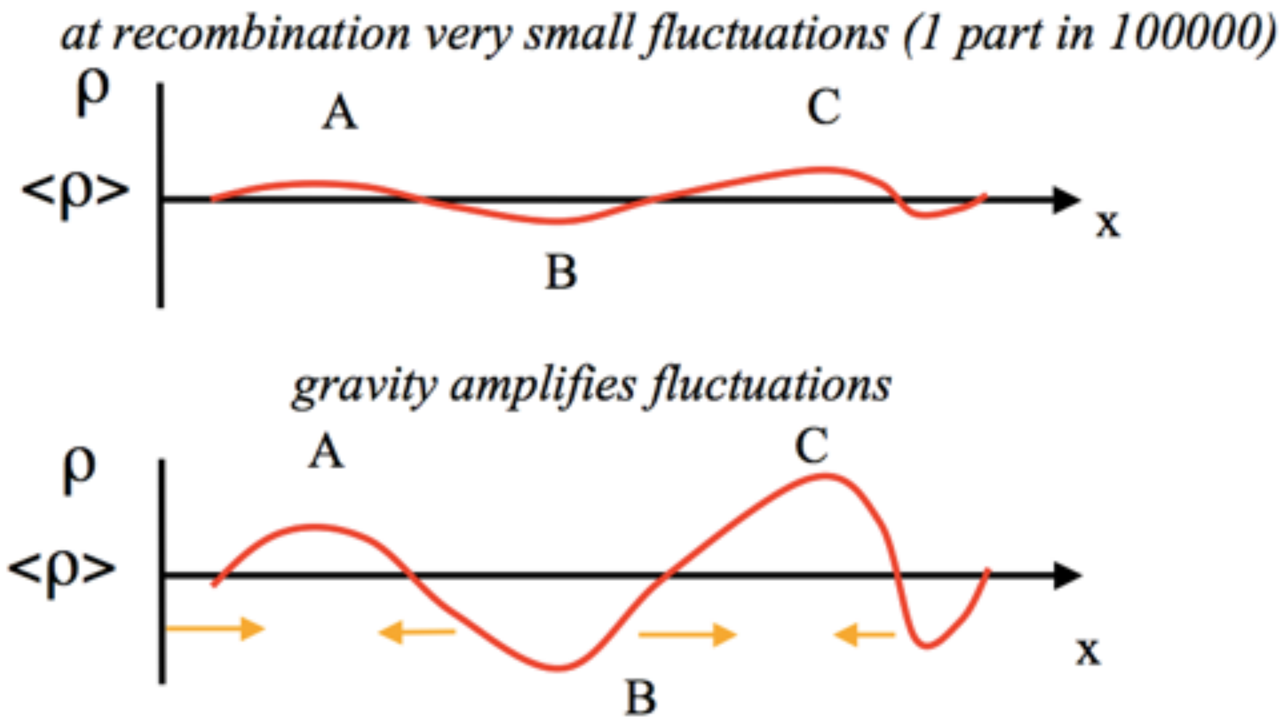
- Small initial deviations from homogeneous FLRW model
- Inhomogenities grew by gravitacional instability.





Review: Linear Perturbation Theory

- Small initial deviations from homogeneous FLRW model
- Inhomogenities grew by gravitacional instability.



$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}} << 1$$

linearity condition

Dynamics: Growth Factor

Evolution of perturbations in a expanding Universe is given by

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = 4\pi G \rho_b \delta .$$

which has the general solution

$$\delta(t,k) = \delta_+(k) D_+(t) + \delta_-(k) D_-(t)$$

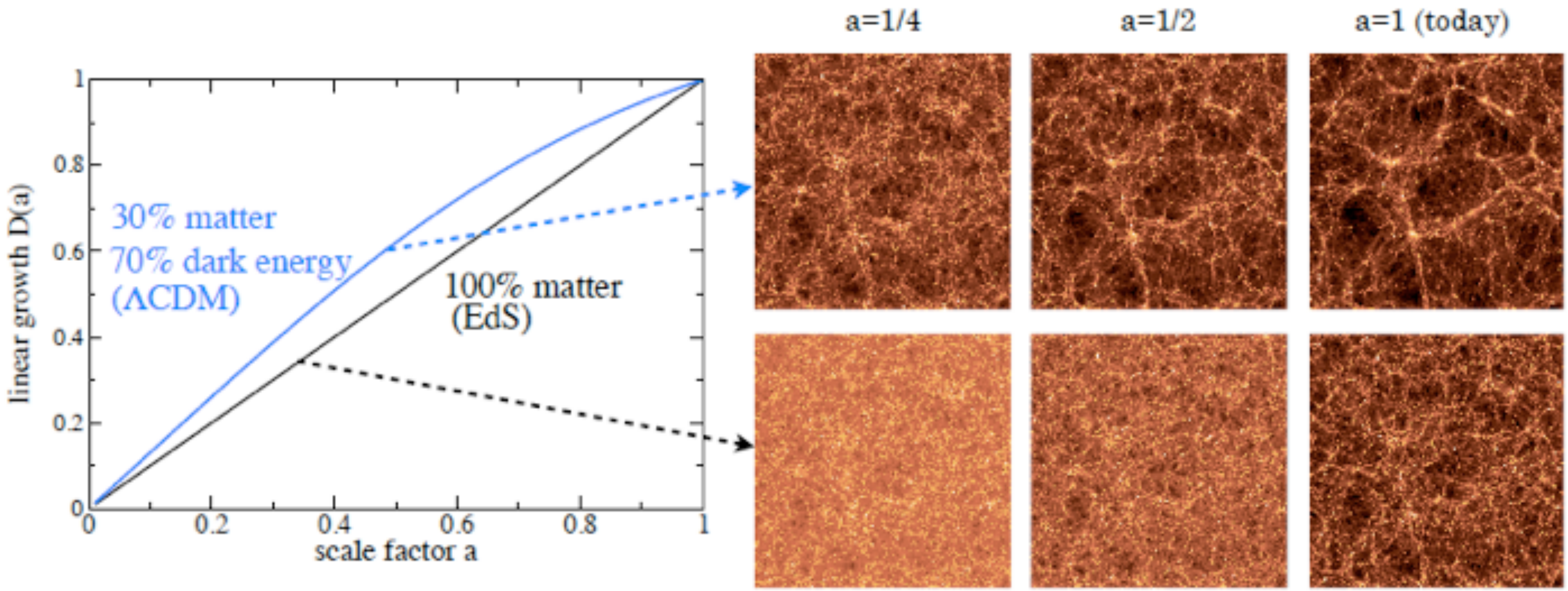
The growing solution D+(t) is called **linear growth function** and is normalized such that D+(t0) = 1.

The **growth factor** is defined as:

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

Dynamics: Growth Factor

Structure formation at large scales



Community Planning Study: Snowmass 2013 ARXIV:1309.5385

Linear Growth D(a), D(a=1)=1

Snapshots de 2 N-body simulaciones a diferentes tiempos, muestra fluctuaciones de densidad mayores en un modelo **LCDM** comparado con un **universo dominado por materia (EdS).**

Growth factor

The growth factor can be right with a good approximation as:

$$f(a) \approx \Omega_m^\gamma(a)$$

γ is named « growth index »and can be calculated for different models (Linder 2005)

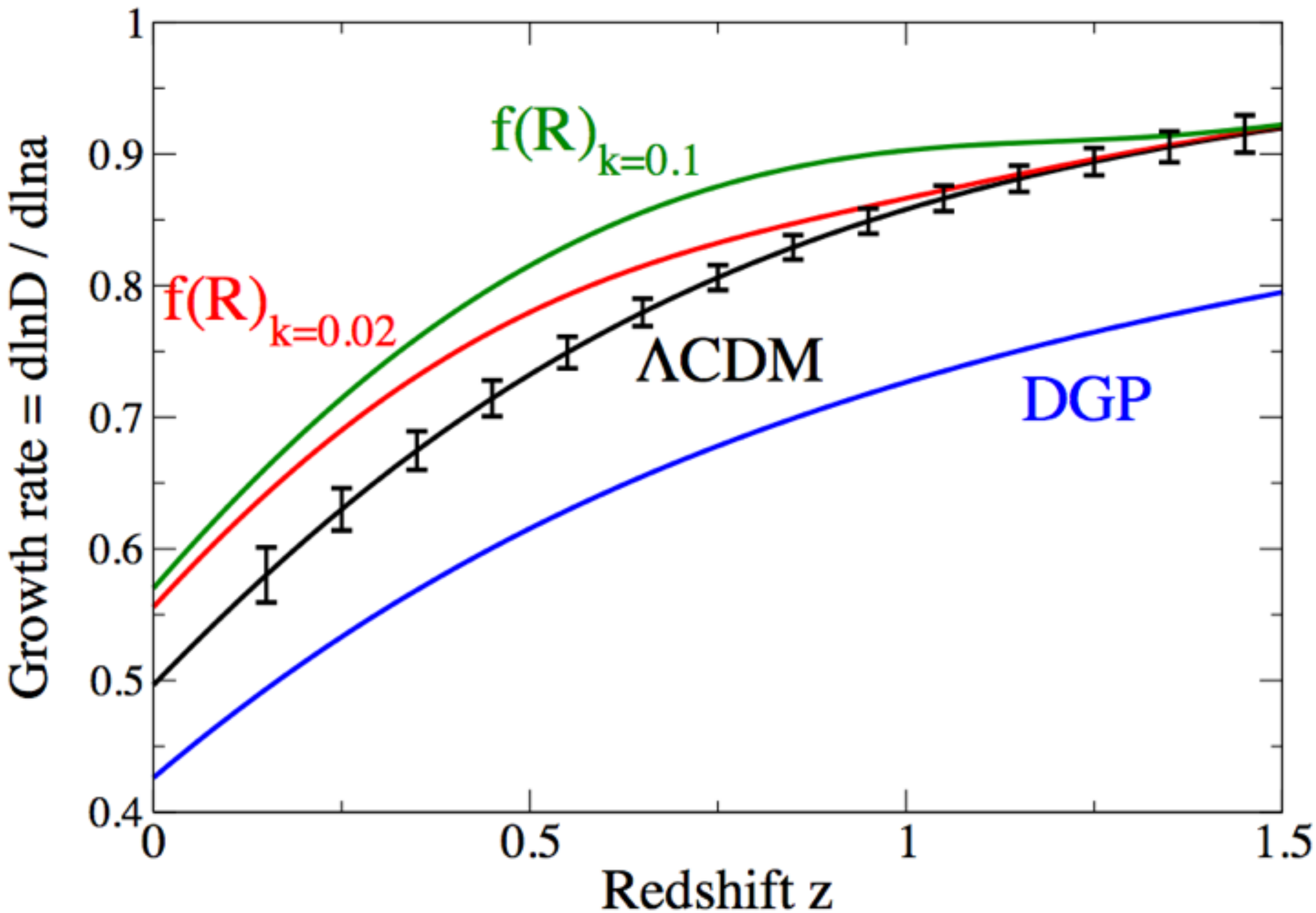
$$CDM \Rightarrow \gamma = 0.6$$

$$\Lambda CDM \Rightarrow \gamma = 0.55$$

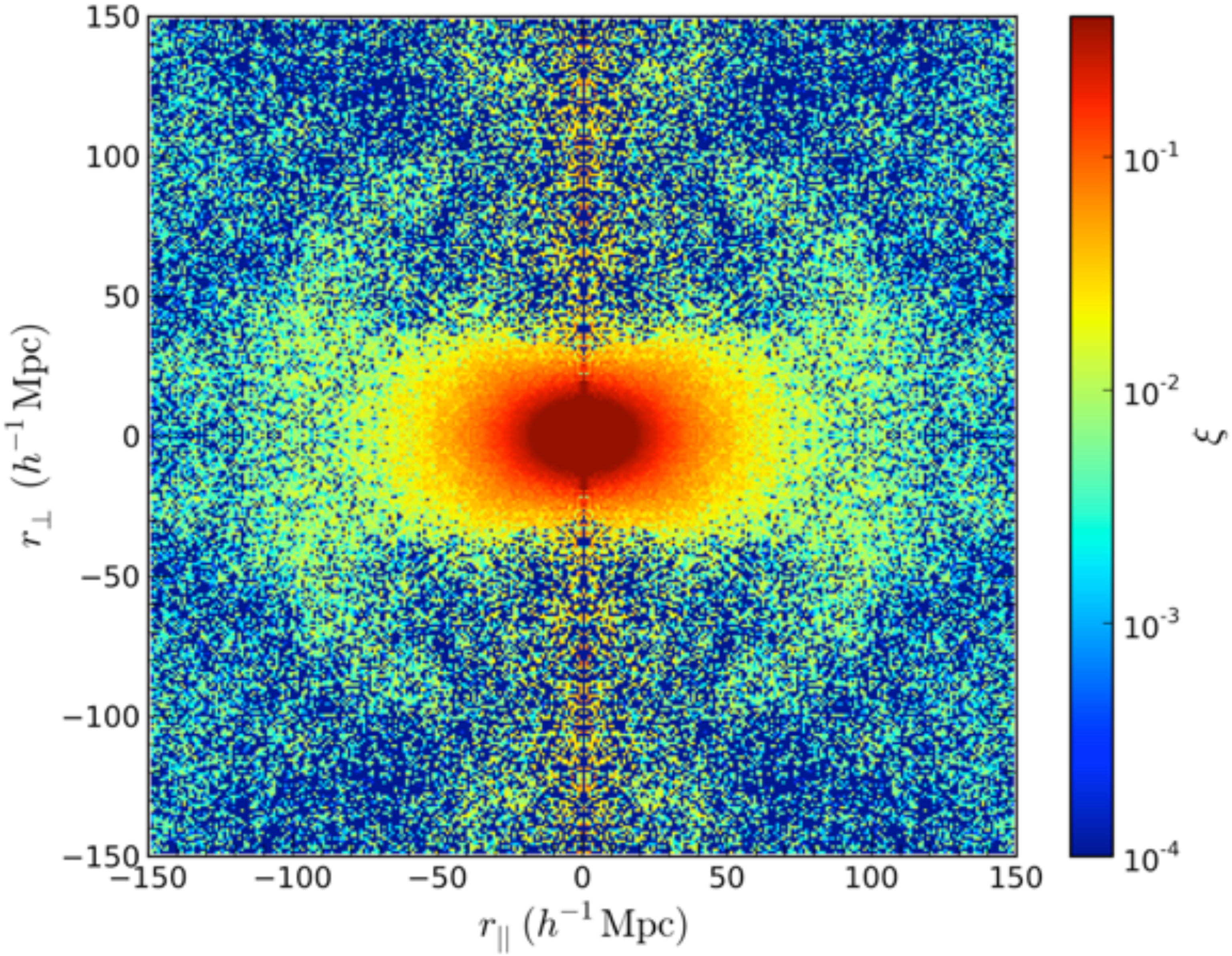
$$\omega CDM \Rightarrow \gamma = 0.55 + 0.05[1+\omega]$$

$$DGP \Rightarrow \gamma \approx 0.68$$

Growth Factor



How we can study DE?



RSD

Redshift Space Distortions use the spacial distortions in the correlation function generated from the peculiar velocities.

The RSD technique is sensitive to dark energy through the growth factor rate measurement

Distorsiones de Corrimiento al rojo

$$s = cz$$

distancia por corrimiento al rojo

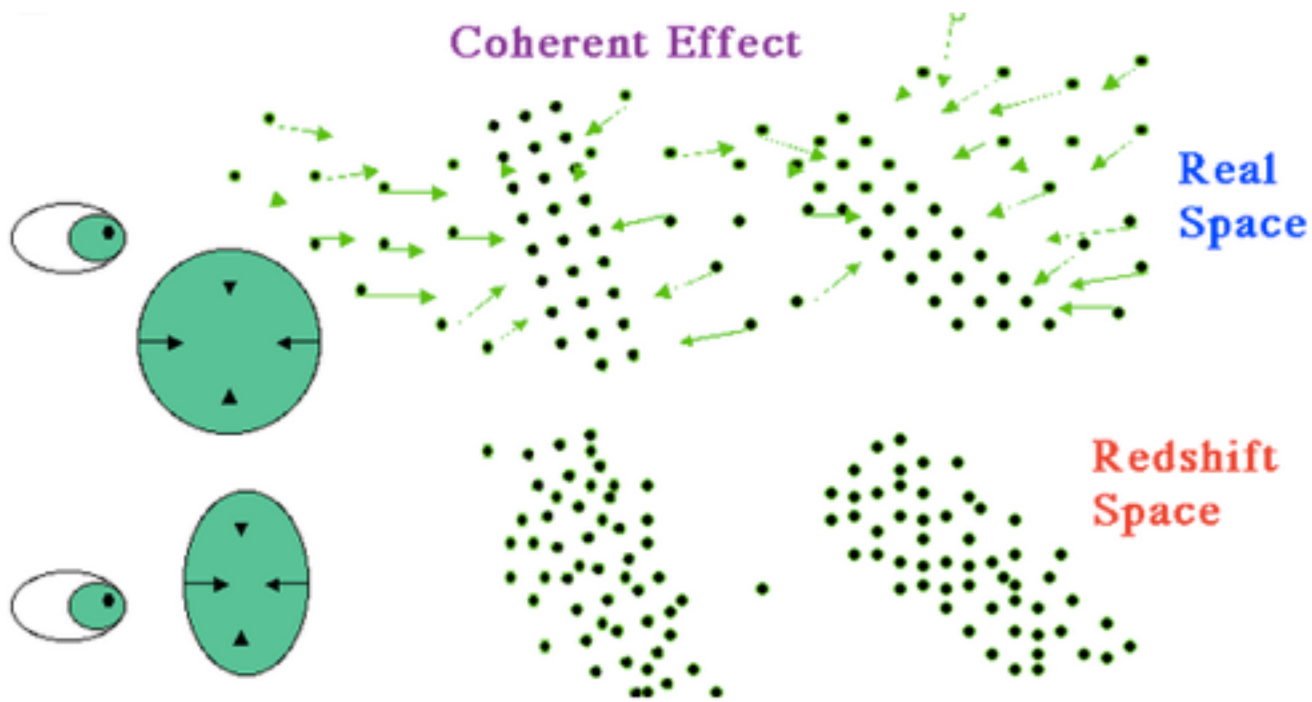
$$s = r + v$$

Verdadera distancia

$$r = H_0 d$$

velocidad peculiar

$$v = \hat{r} \cdot \vec{v}$$



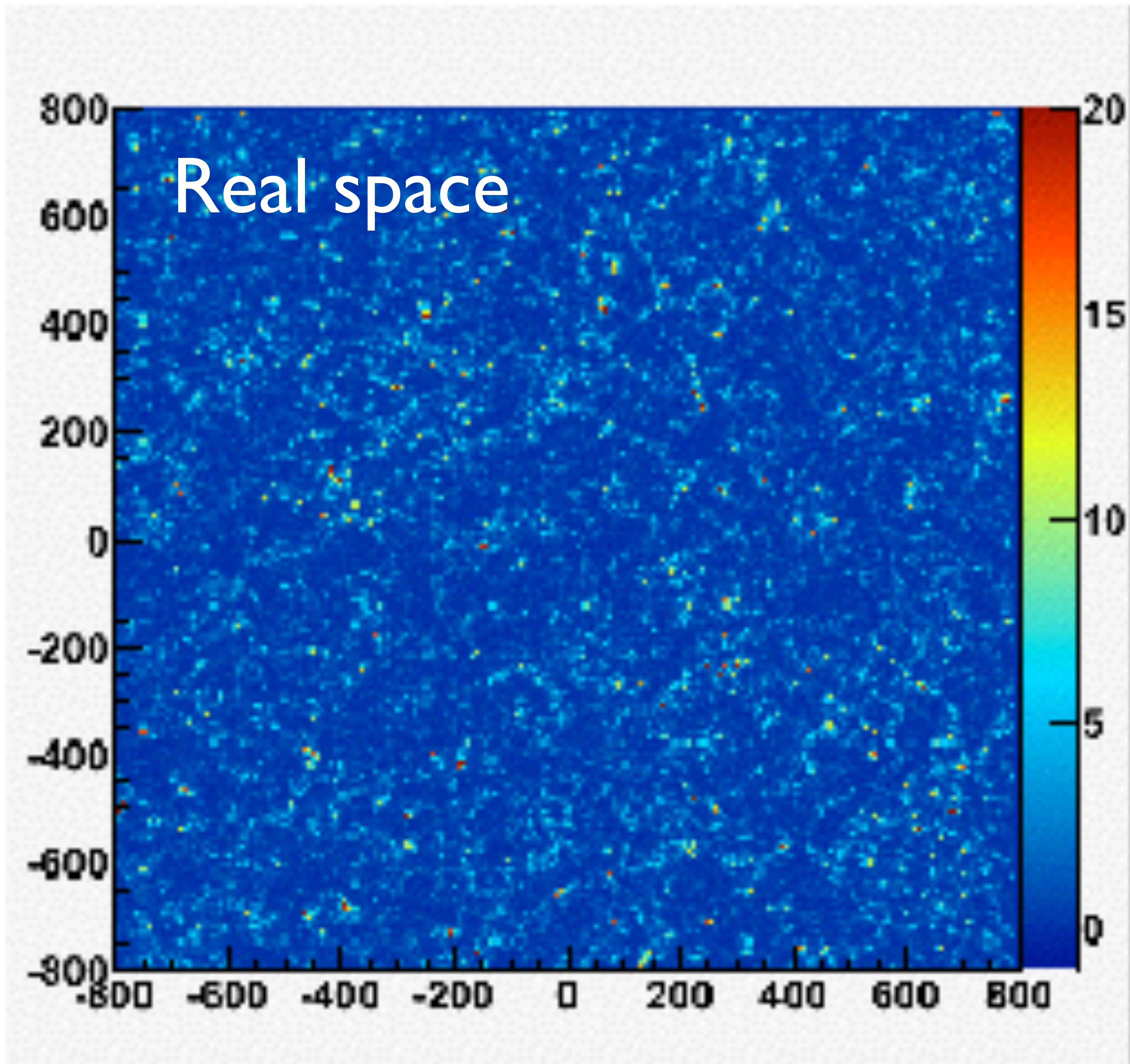
Estas distorsiones generan un incremento del agrupamiento a lo largo de la linea de visión en comparación con la dirección perpendicular.

Distorsiones de Corrimiento al rojo

$s = r + v$

$s = cz$

$r = H_0 d$

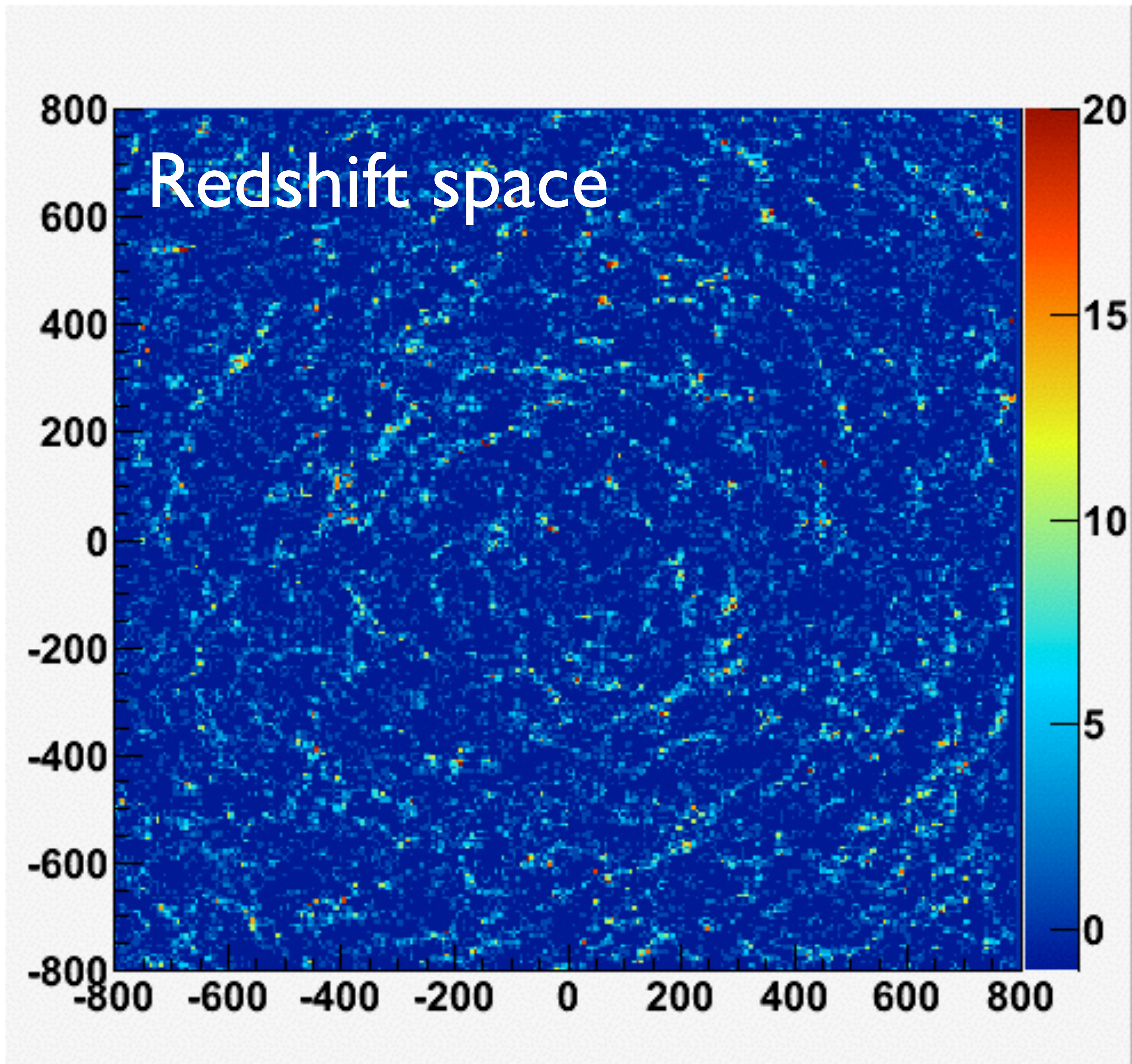


Distorsiones de Corrimiento al rojo

$s = r + v$

$$s = cz$$

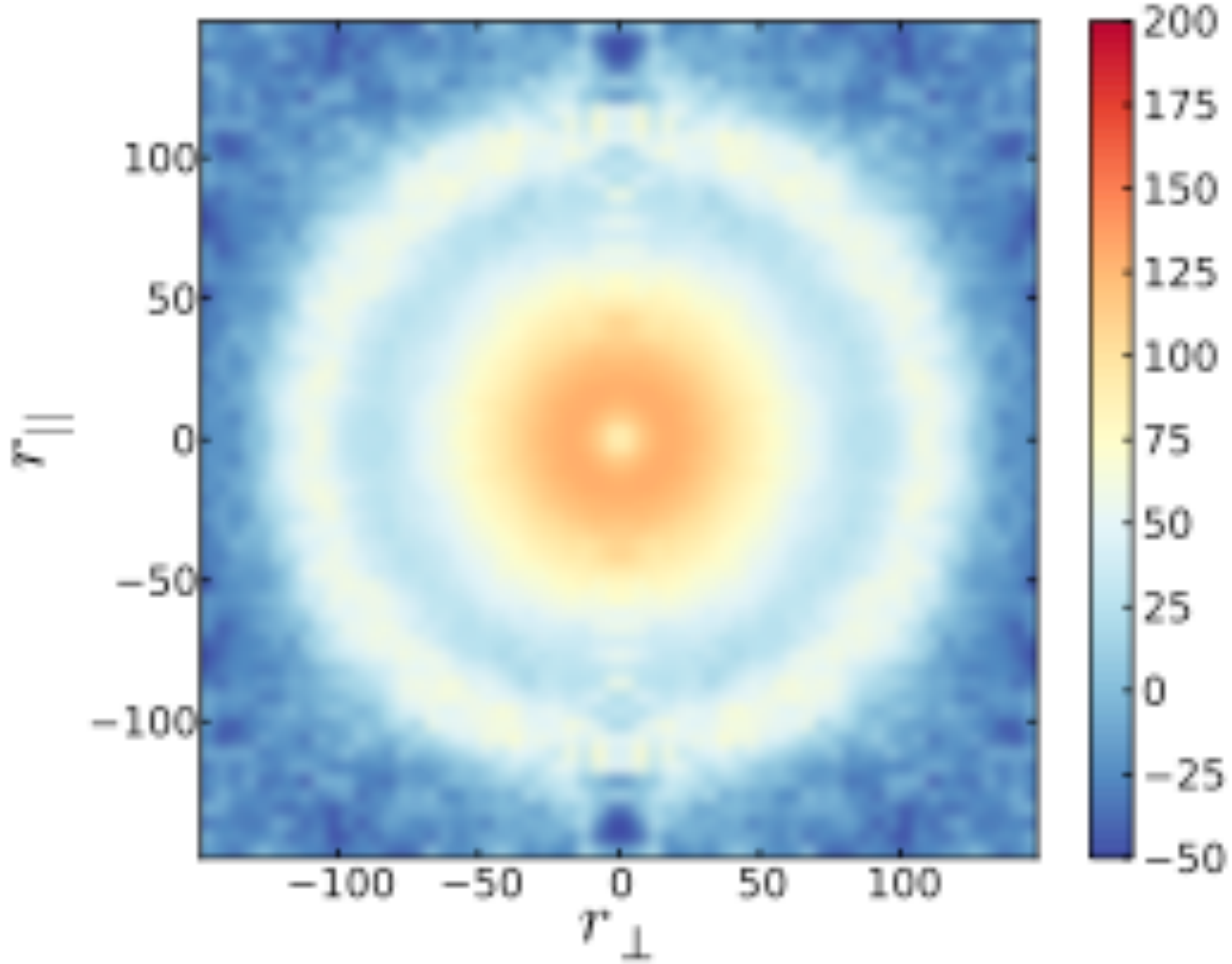
$r = H_0 d$



Real Space Correlation Function

$$r = H_0 d$$

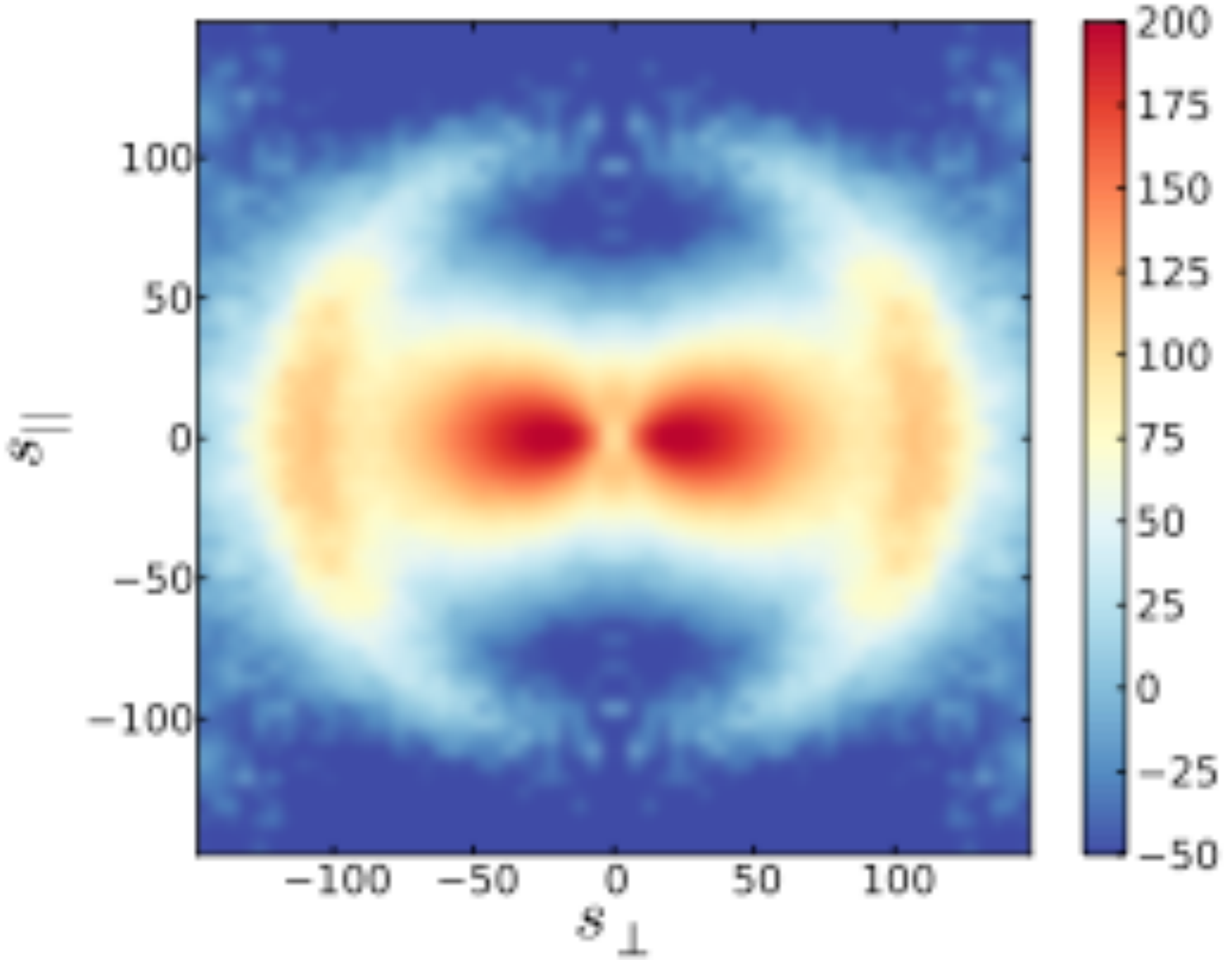
Padmanabham et al 2012



Redshift Space Correlation function

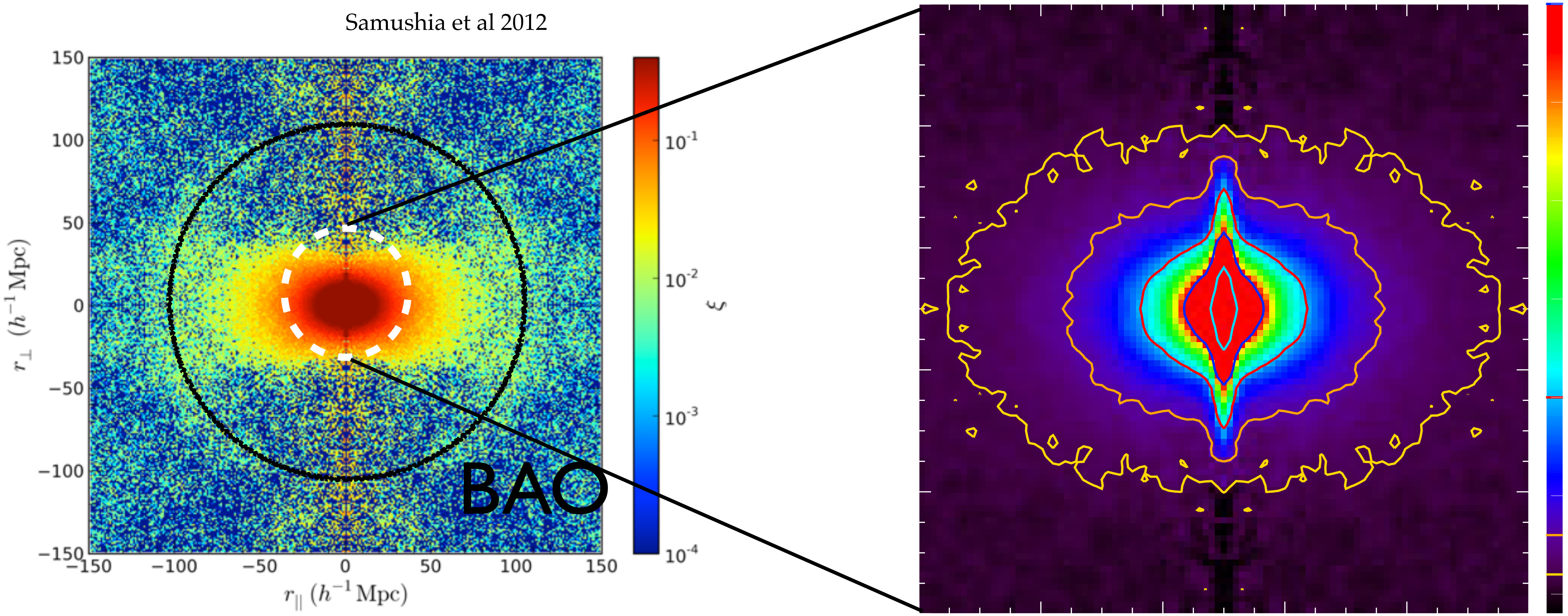
$$s = cz$$

Padmanabham et al 2012



Distorsiones de Corrimiento al rojo

grandes escalas | escalas pequeñas



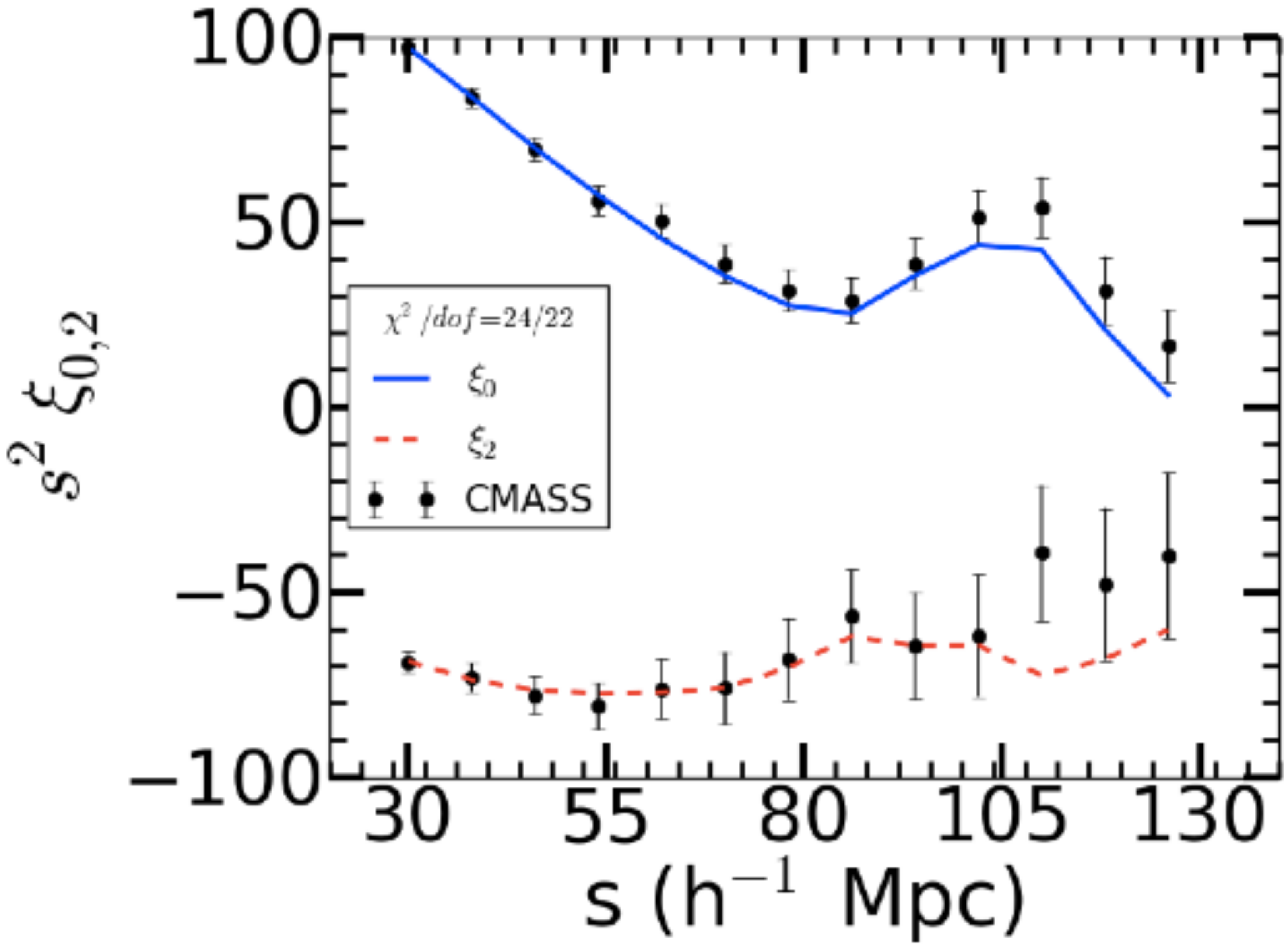
Efecto Kaiser

Fingers of God
(Dedos de dios)

Instituto de Física

Resultados cosmológicos de RSD con BOSS

Alam, Ho & M.Vargas-Magana 2014

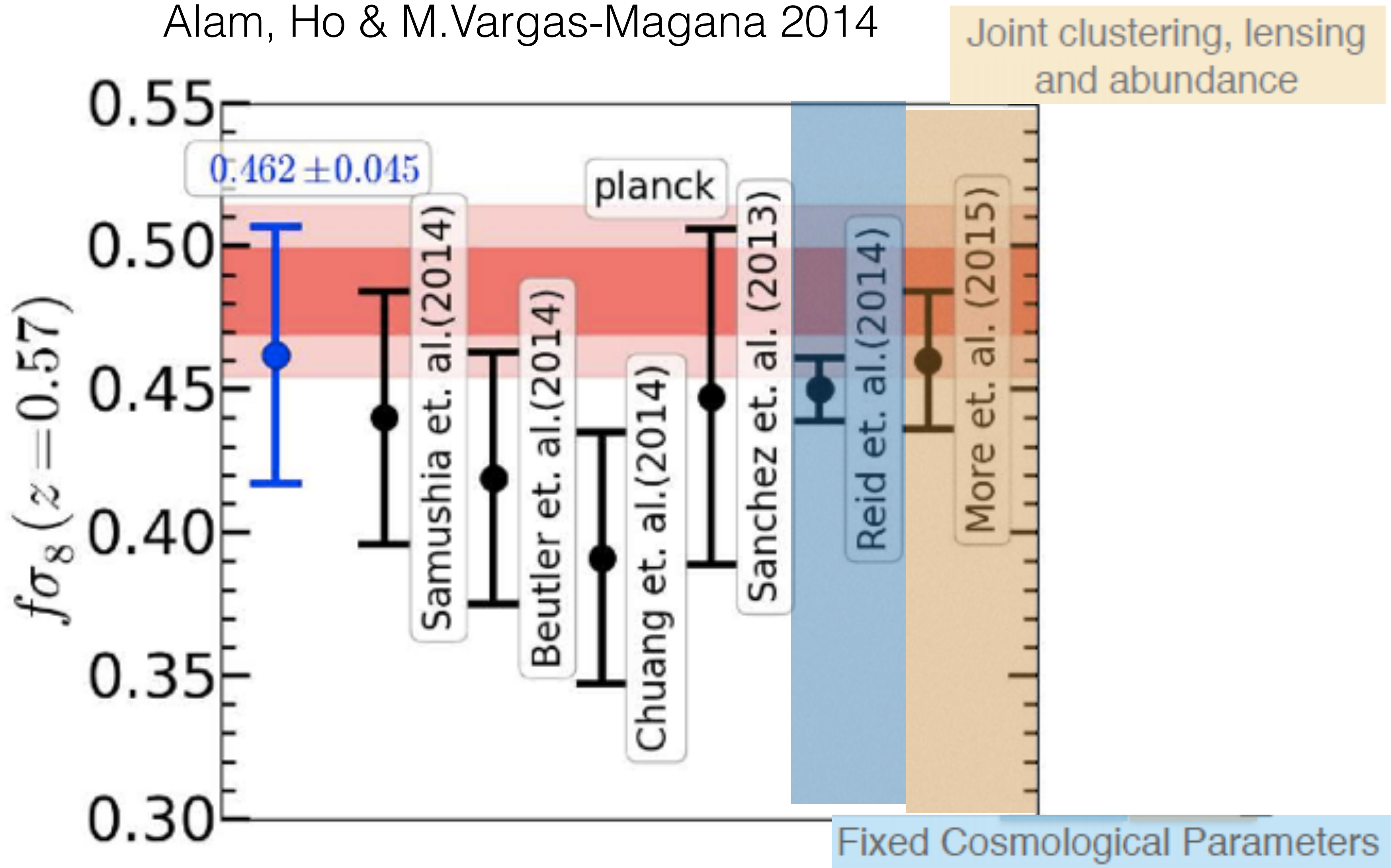


Medotodologia

Parameter	prior range	Peak background split		First and Second order bias
		with WMAP prior	with Planck prior	with Planck prior
Sampling Parameters				
$\Omega_b h^2 \ldots$	[0.02042 , 0.02372]	0.02267 ± 0.00036	0.02206 ± 0.00026	0.02206 ± 0.00026
$\Omega_c h^2 \ldots$	[0.1041 , 0.1351]	0.1141 ± 0.0021	0.11956 ± 0.00086	0.11956 ± 0.00086
$n_s \ldots$	[0.914 , 1.008]	0.9741 ± 0.0085	0.9614 ± 0.0058	0.9613 ± 0.0058
$\ln(10^{10} A_s) \ldots$	[2.67 , 3.535]	3.178 ± 0.029	3.093 ± 0.066	3.103 ± 0.070
$\alpha_{\parallel}$	[0.8 ,1.2]	1.003 ± 0.039	1.051 ± 0.043	1.058 ± 0.047
$\alpha_{\perp}$	[0.8 ,1.2]	0.997 ± 0.018	1.03 ± 0.016	1.032 ± 0.016
$f = dlnD/dlna$	[0.3 , 1.2]	0.739 ± 0.067	0.747 ± 0.072	0.729 ± 0.073
σ_{FOG}	[0 , 10]	2.26 ± 1.46	1.91 ± 1.28	2.70 ± 1.69
v_{RSD}	[1.5 , 2.0]	1.83 ± 0.038	1.80 ± 0.05	
$F1$	[0.5 , 1.5]			0.93 ± 0.07
$F2$	[0.5 , 1.5]			1.0 ± 1.78
Derived Parameters				
$f\sigma_8$	...	0.454 ± 0.041	0.462 ± 0.041	0.453 ± 0.041
$b\sigma_8$	...	1.21 ± 0.030	1.194 ± 0.032	1.20 ± 0.032
$D_A(z = 0.57)$	...	1356.0 ± 24.0	1400.9 ± 22.7	1403 ± 21.9
$H(z = 0.57)$	...	93.4 ± 3.6	89.2 ± 3.6	88.5 ± 3.9
F_{AP}	...	0.663 ± 0.033	0.654 ± 0.033	0.651 ± 0.034
$D_V(z = 0.57)$	...	2024.5 ± 27.2	2101.4 ± 25.6	2108 ± 29.4

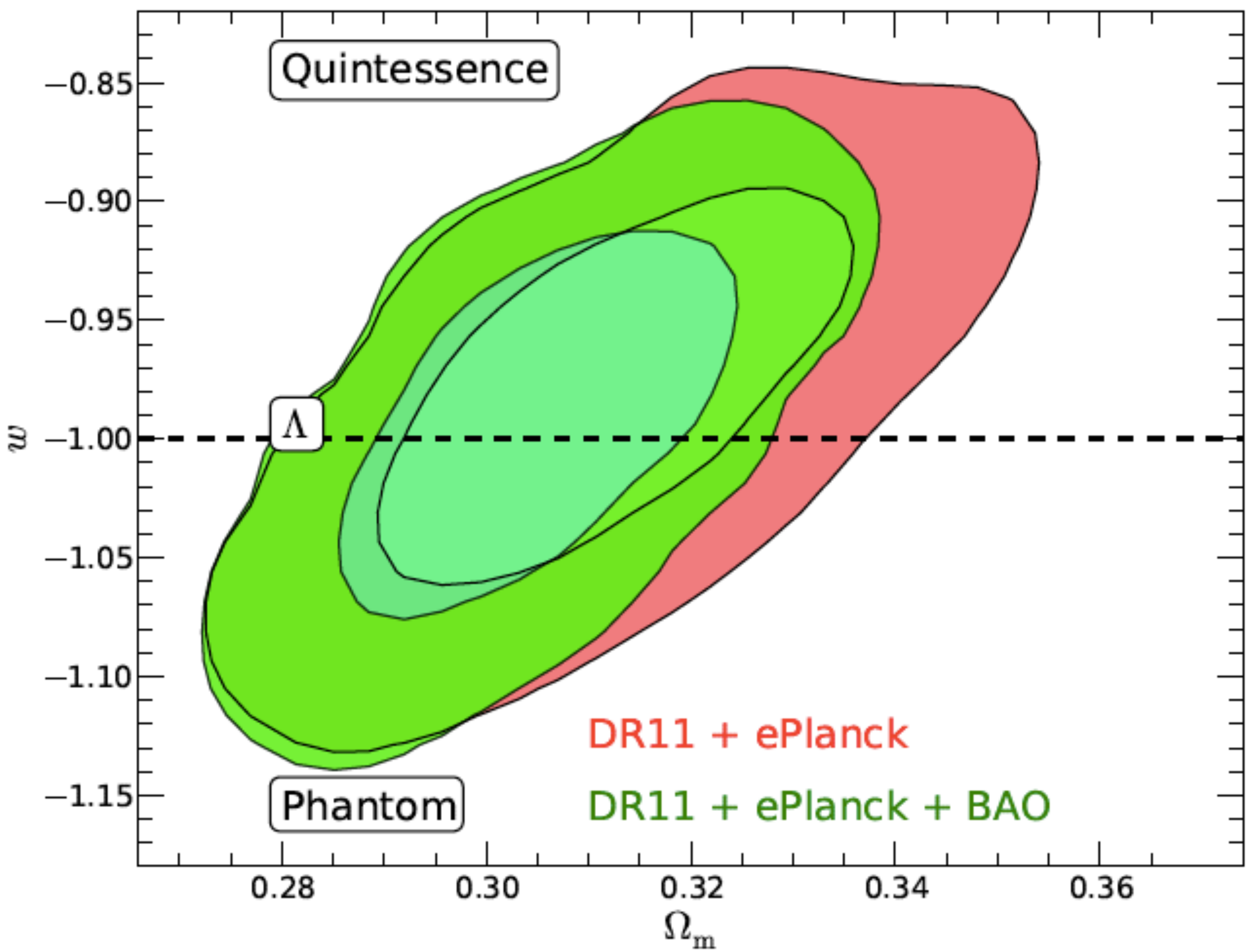
Resultados cosmológicos de RSD con BOSS

Alam, Ho & M.Vargas-Magana 2014



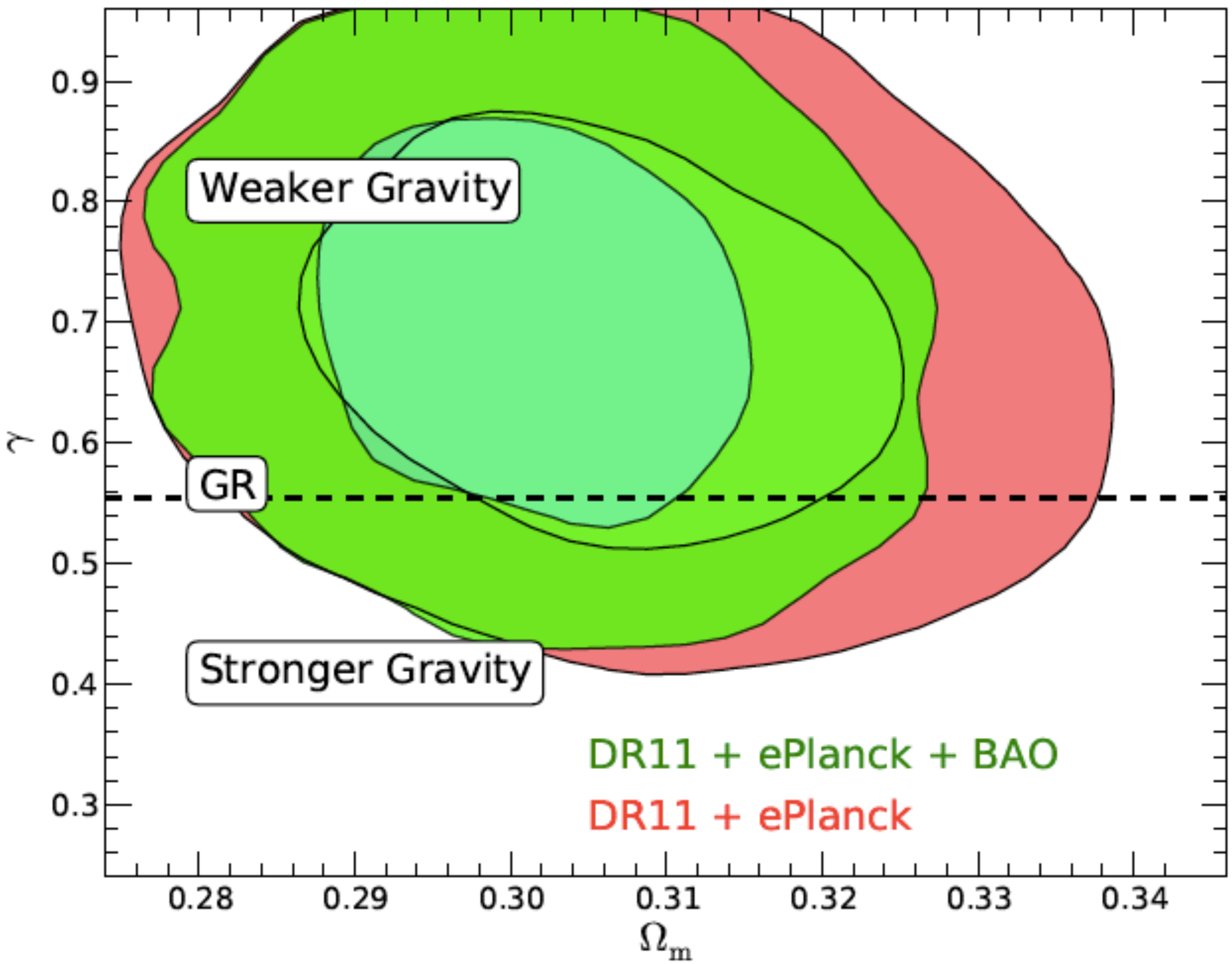
In linear theory, b and f are completely degenerate with σ_8, and observed clustering is only sensitive to their combination $b\sigma_8$ and $f\sigma_8$

RSD Cosmological Results

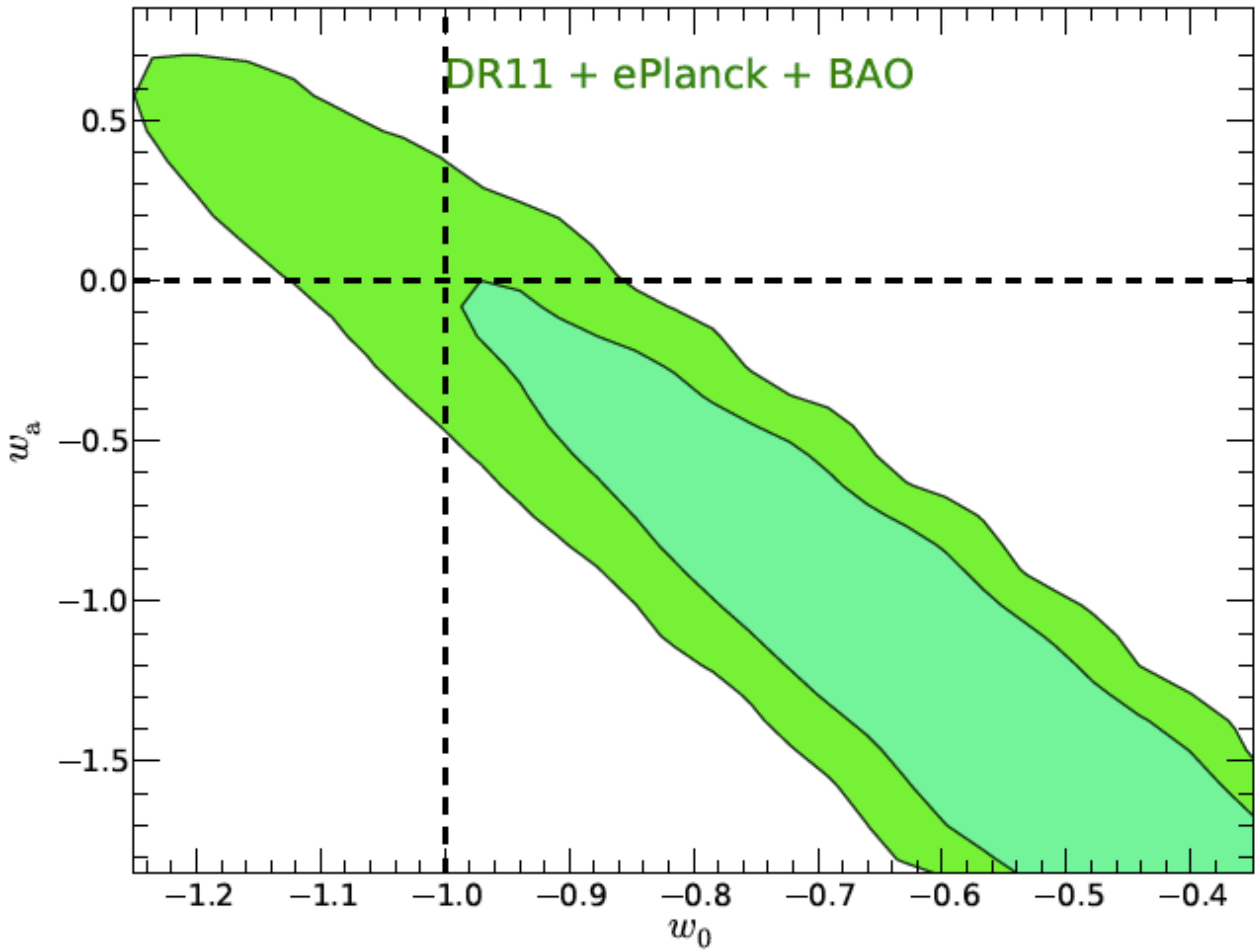


RSD Cosmological Results

$$f(a) \approx \Omega_m^\gamma(a)$$



RSD Cosmological Results



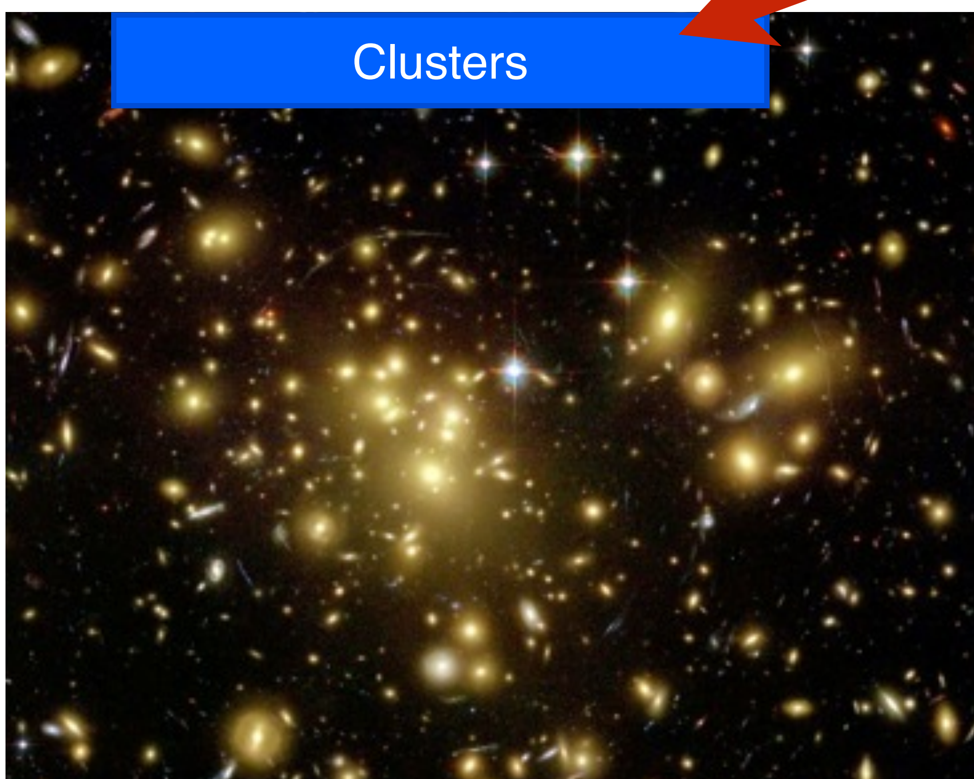
RSD final comments

- RSD uses the anisotropic clustering of galaxies in to simultaneously constrain the growth rate, the redshift-distance relationship and the expansion rate.
- RSD, one of the most promising tools to investigate modified gravity.
- Overall, the measurements are in good agreement with the results of the Planck satellite propagated to low redshifts assuming ΛCDM-GR.

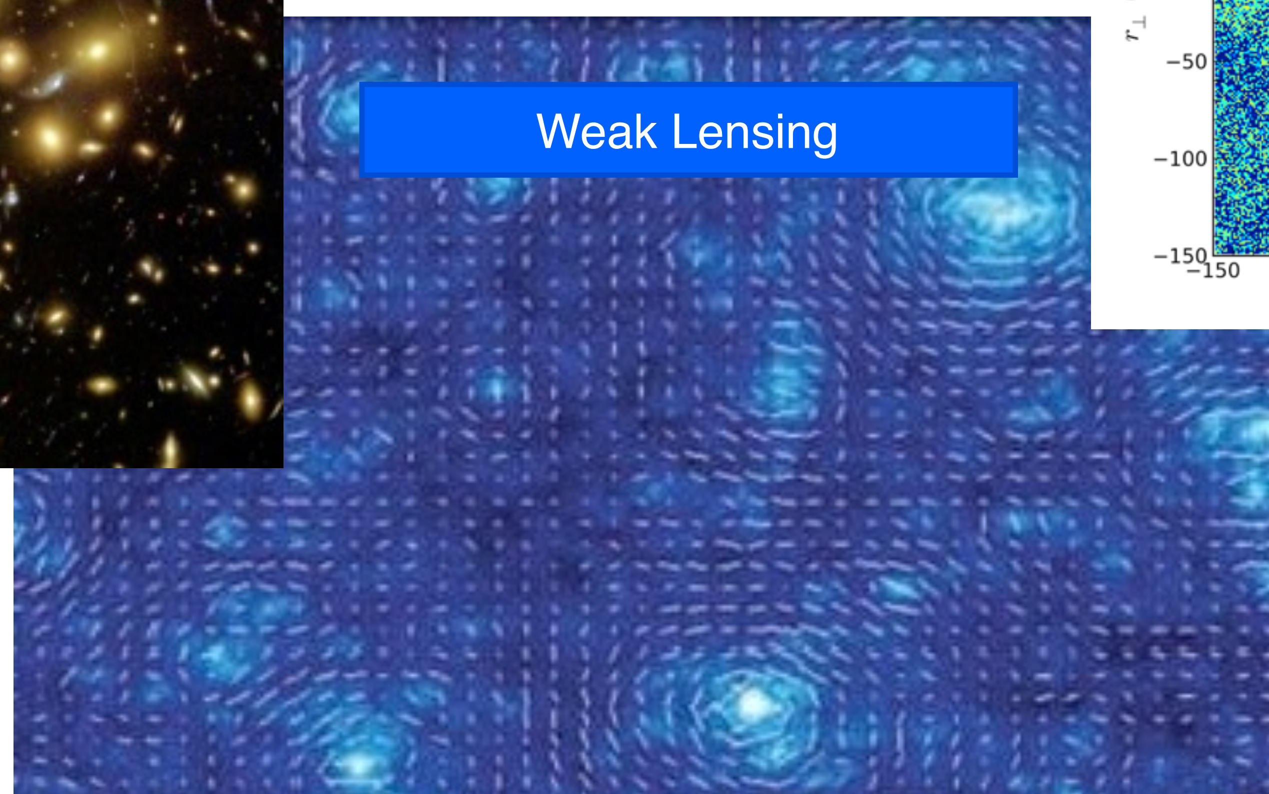
How we can study DE?

Growth Factor

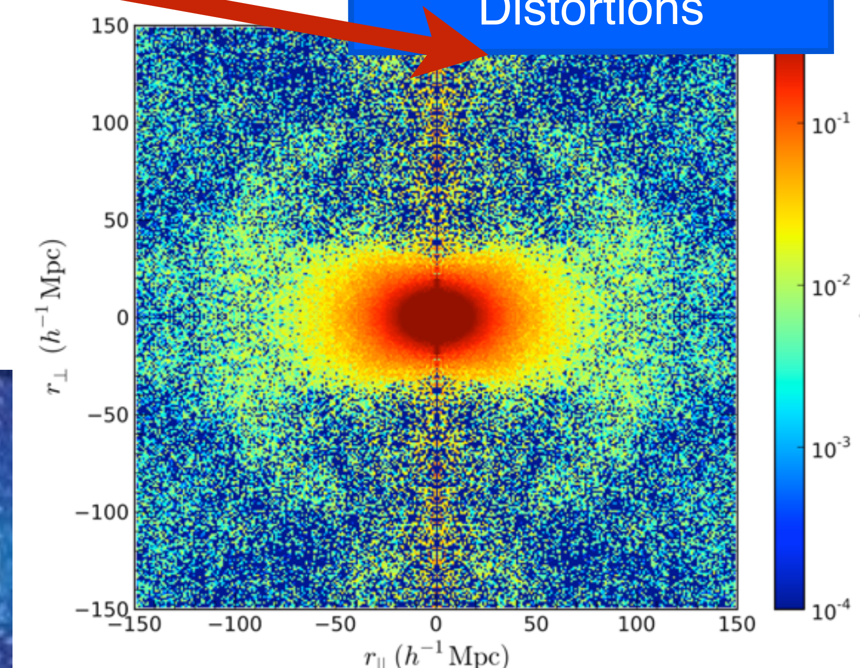
Clusters



Weak Lensing



Redshift Space Distortions



How we can study DE?

CLUSTERS

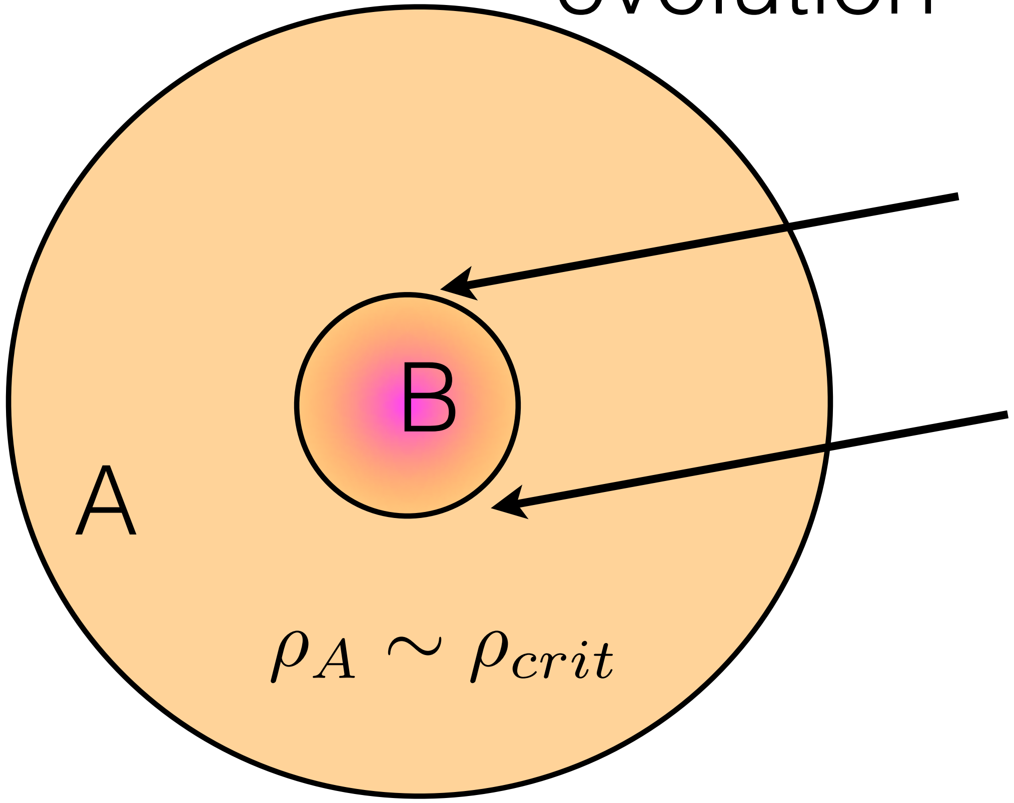
Galaxy Cluster (CL) surveys measure the spatial density and distribution of galaxy clusters.

The CL technique is sensitive to dark energy through its effect on a combination of the angular-diameter distance vs. redshift relation, the time evolution of the expansion rate, and the growth rate of structure.

Spherical halo model

The 2 areas A & B are considered as local universe with proper scale factor evolution

(Gunn & Gott 1972)

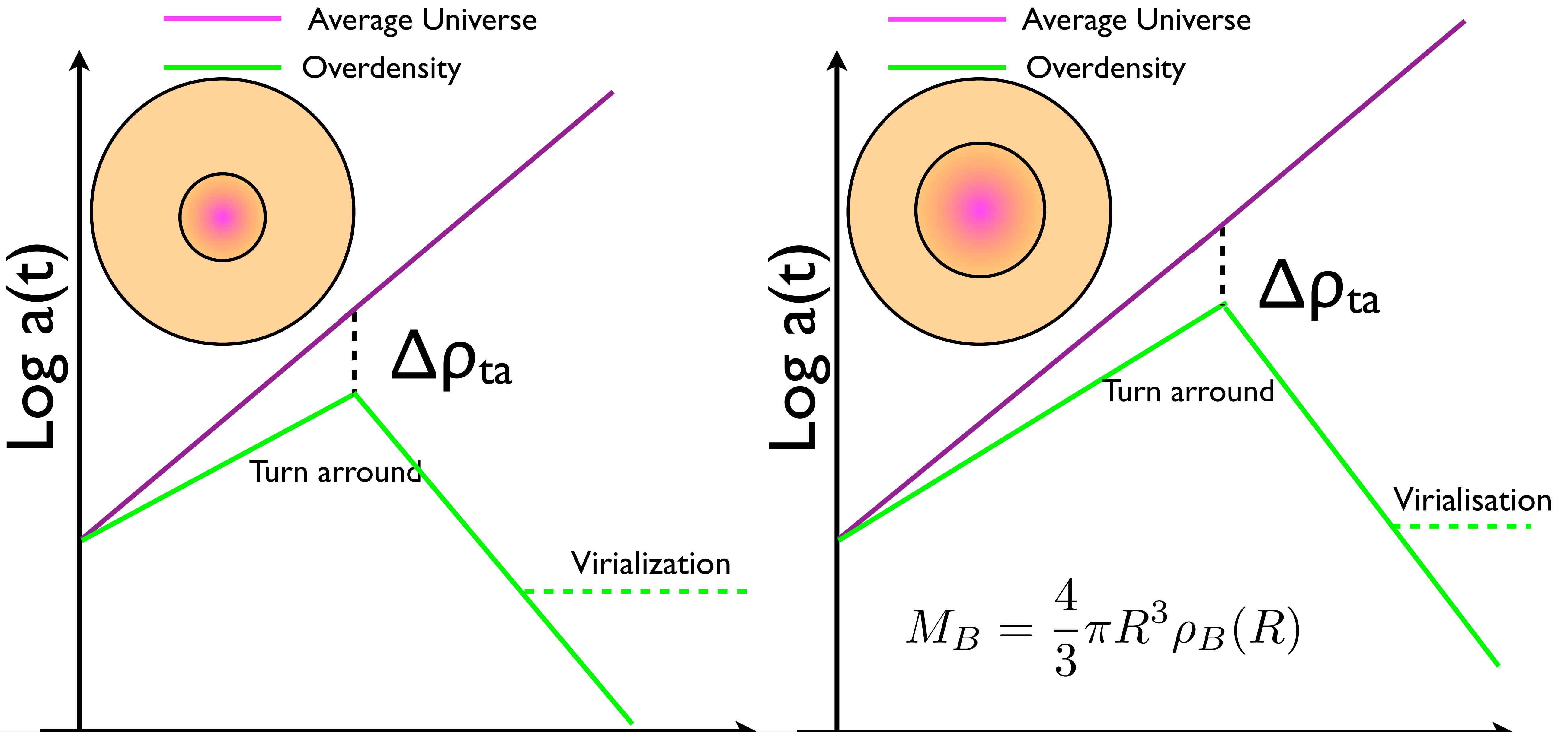


Curvature

$$H_B^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_B + \frac{\Lambda}{3} - \frac{k}{a^2}$$

$$H_A^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_A + \frac{\Lambda}{3}$$

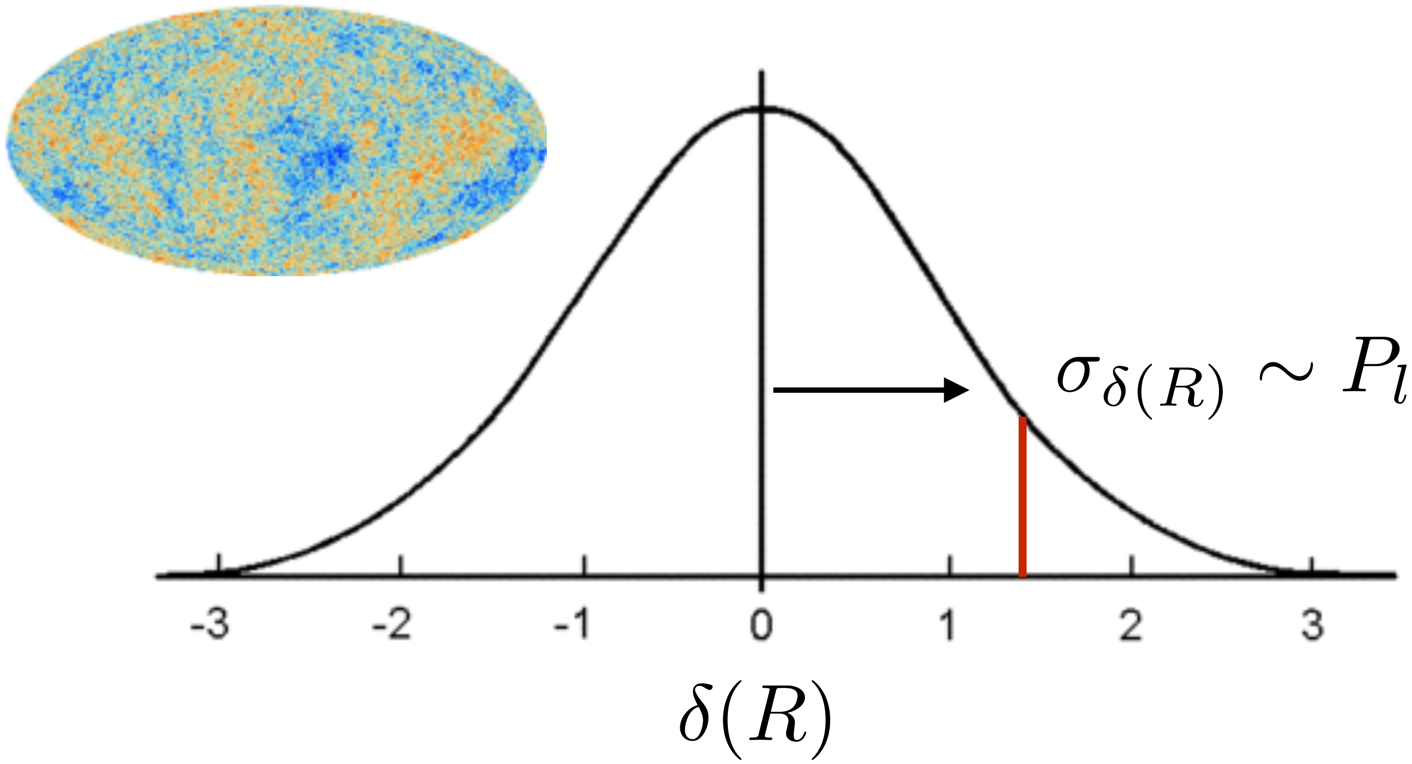
Galaxy clusters



$$M_B = \frac{4}{3}\pi R^3 \rho_B(R)$$

The number of virialized halos of a given mass at a given redshift

Press-Schechter function

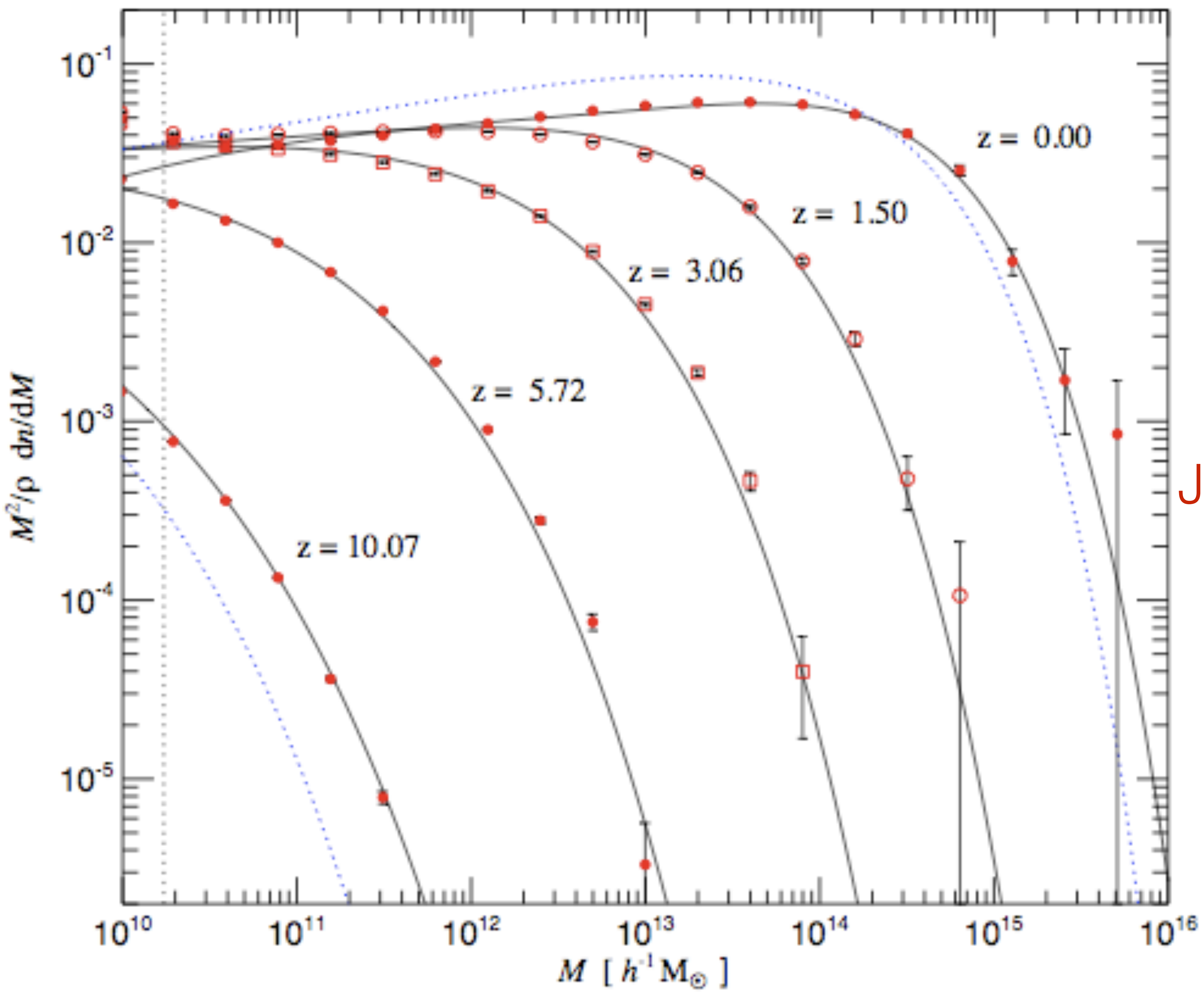


$$\sigma_{\delta(R)} \sim P_{lin}(k = 2\pi/R) \approx function(\sigma_8, R)$$

Express the probability at each scales
to rich the Turn Around at a given redshift

Depends on $\sigma_8, \boxed{H(z)} \longrightarrow \Omega_m, \omega_{DE}$

Cluster Mass Function



Points

Millenium simulation

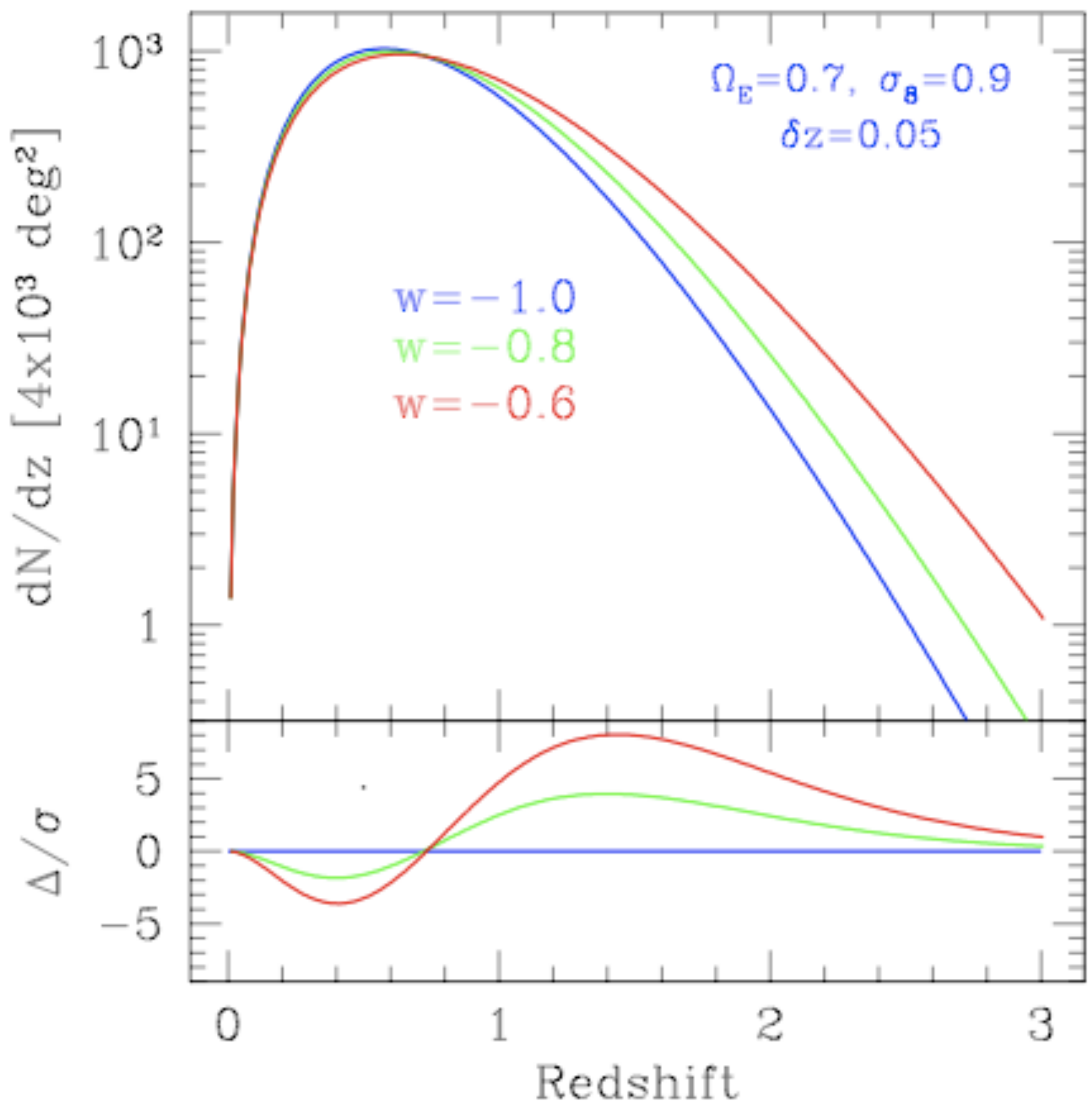
Red lines

Jenkins Mass Function

Blue lines

Press-Schechter MF

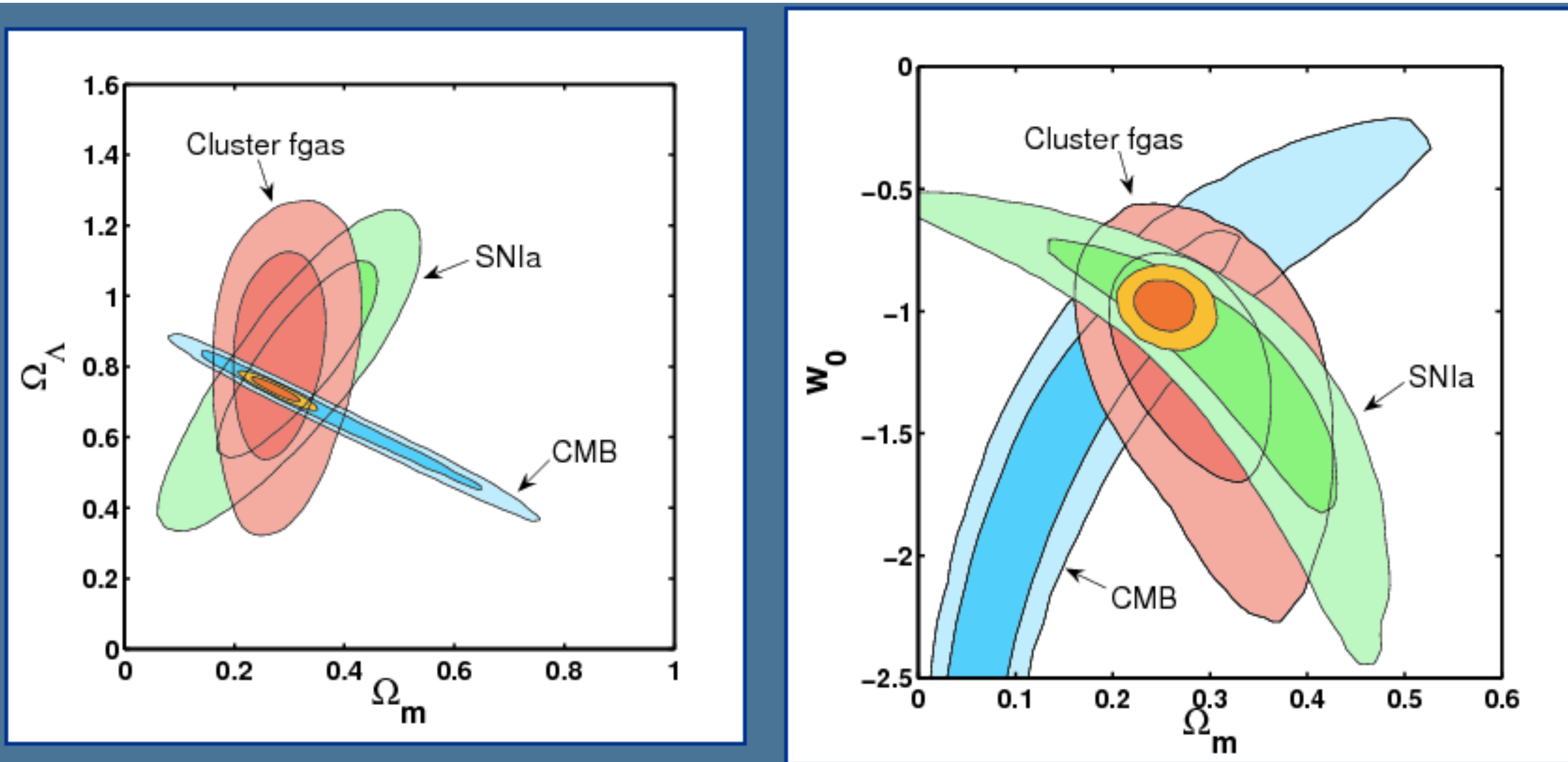
Cluster Mass Function



Mohr 2002

Clusters constraints today

Allen et al. 2008 (MNRAS, 383, 879)



(l) A LCDM model is assumed, with the curvature included as a free parameter.

(r) A flat cosmology with a constant dark energy equation of state parameter w is assumed.

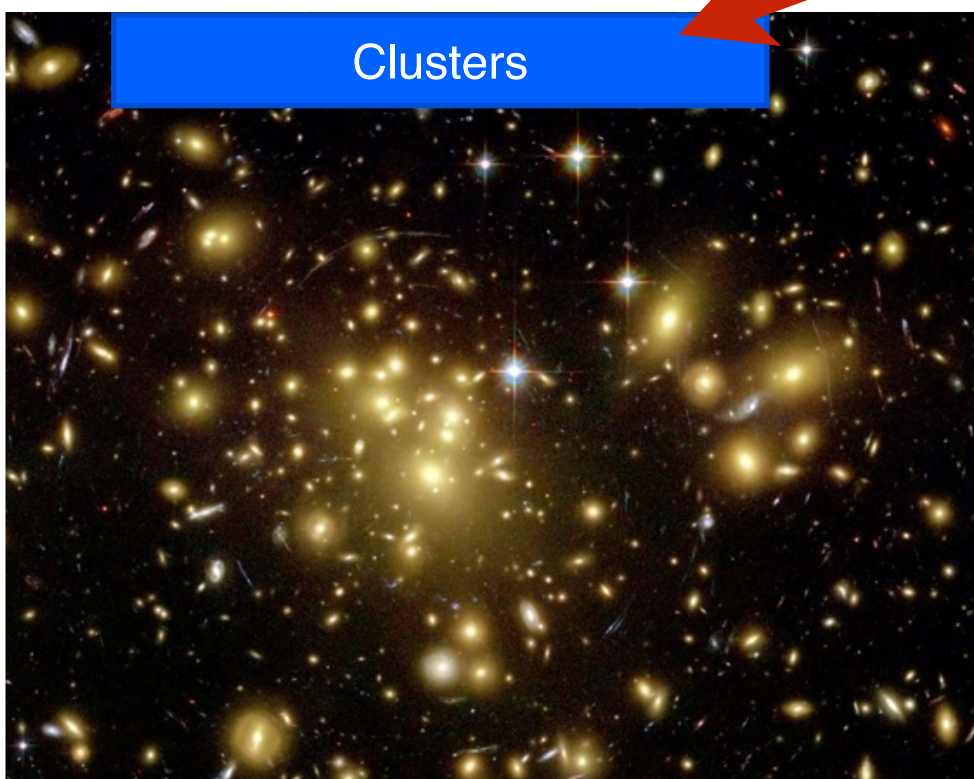
Cluster final comments

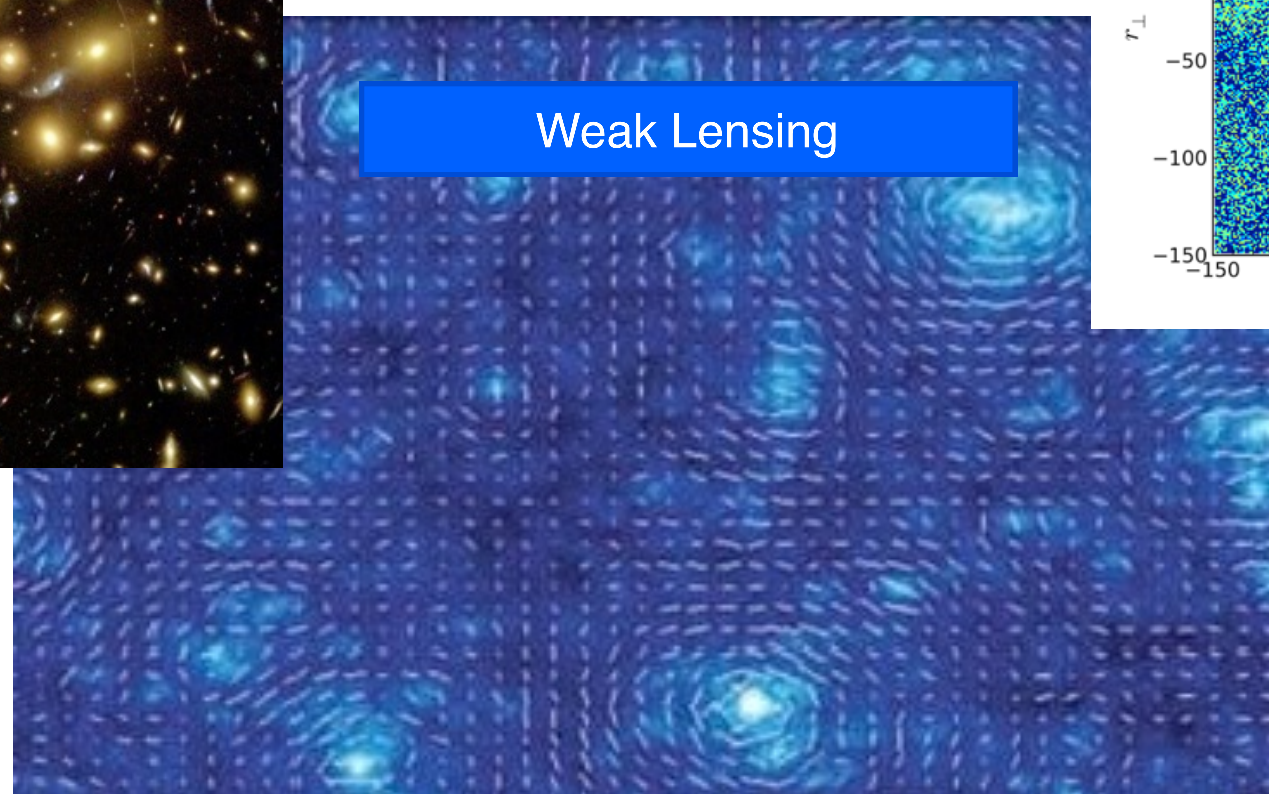
- The clusters technique has **the statistical potential to exceed the BAO and SN** techniques but at present has the largest systematic errors.

- Its eventual accuracy is currently very difficult to predict and its ultimate utility as a dark energy technique can only be determined through the *development of techniques* that **control systematics due to non-linear astrophysicalprocesses**.

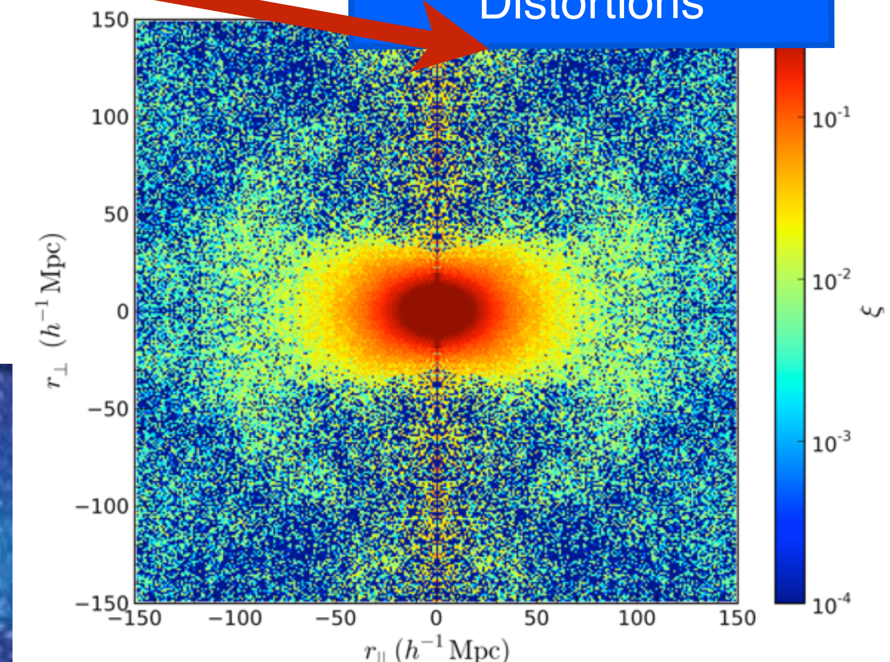
How we can study DE?

Growth Factor

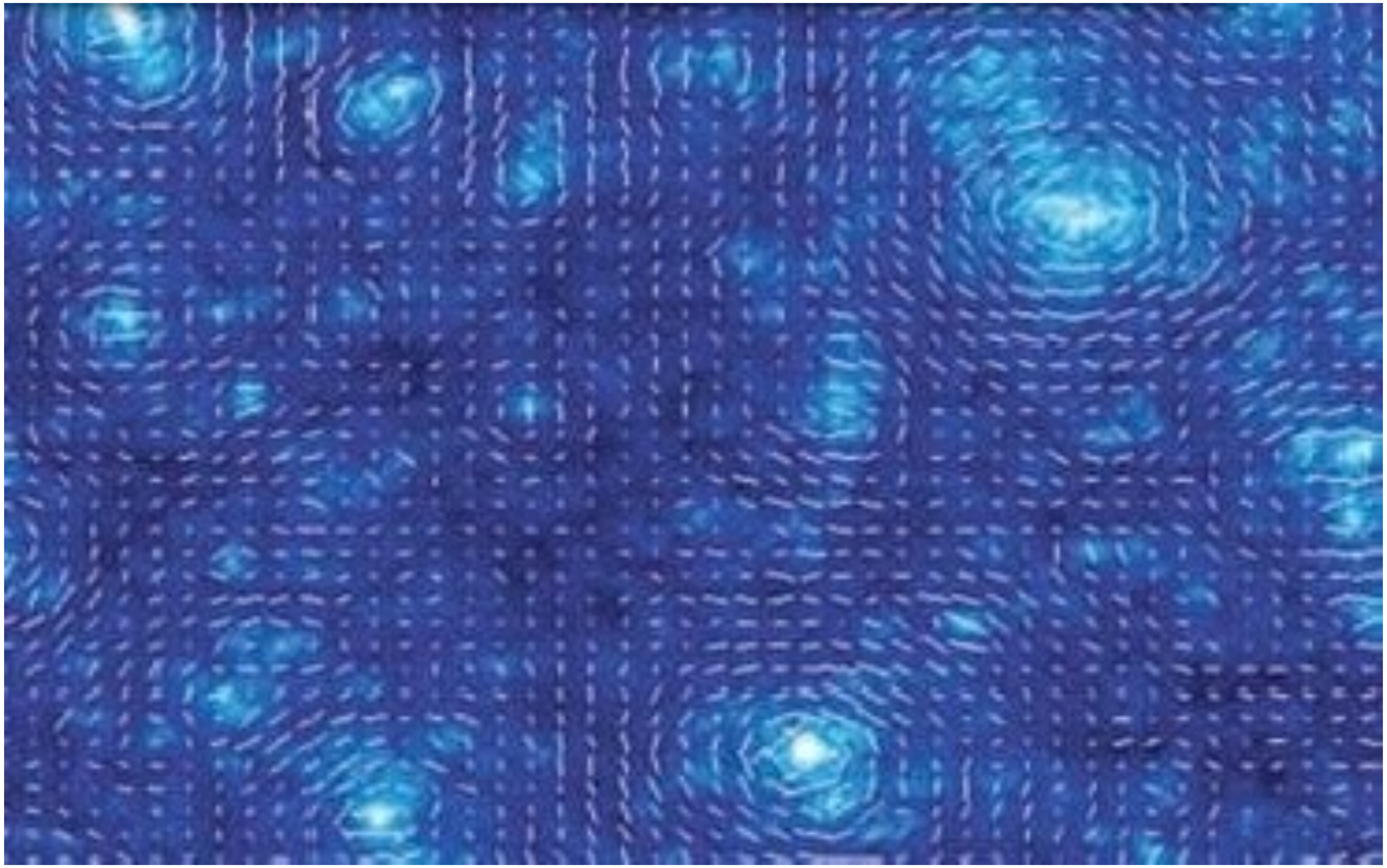




Redshift Space Distortions



How we can study DE?

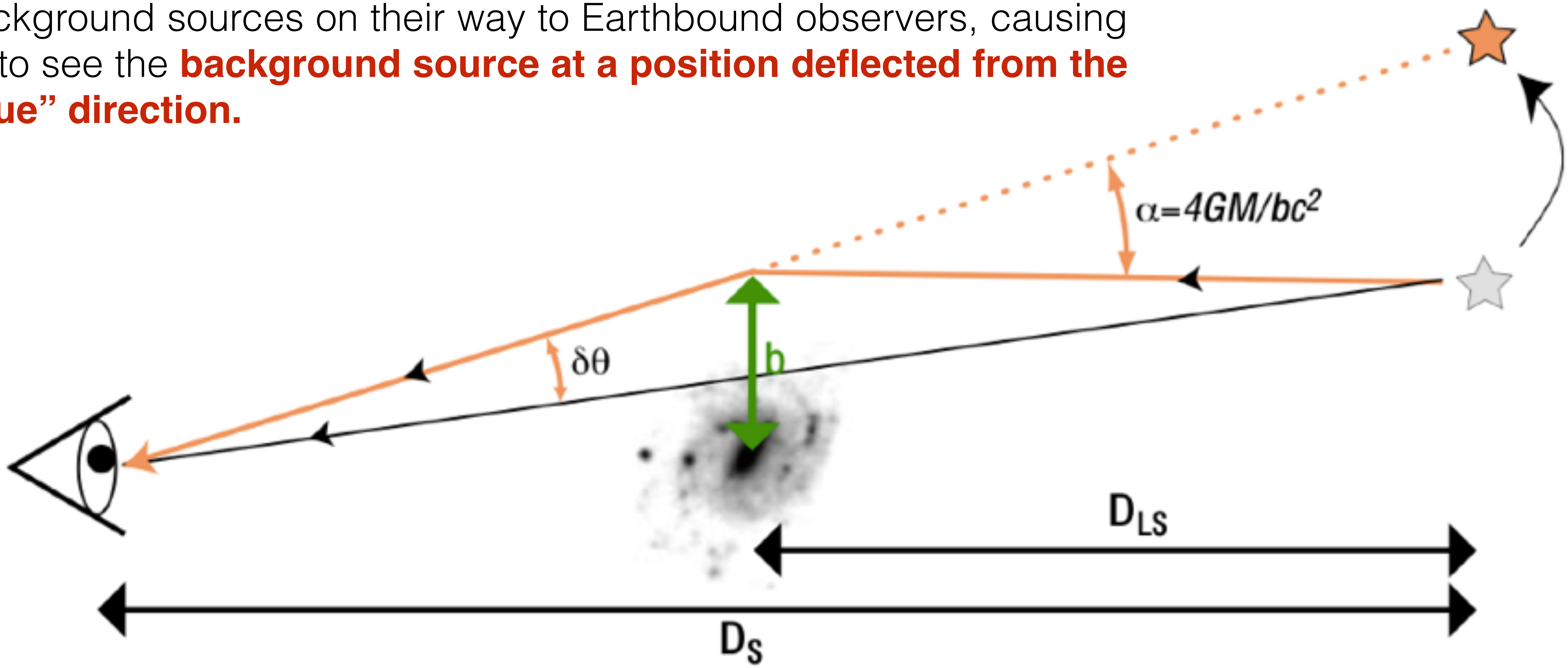


WEAK LENSING

Weak Lensing (WL) surveys measure the distortion of background images due to the bending of light as it passes by galaxies or clusters of galaxies.

Weak Lensing

Foreground mass concentrations deflect the photons from background sources on their way to Earthbound observers, causing us to see the **background source at a position deflected from the "true" direction.**



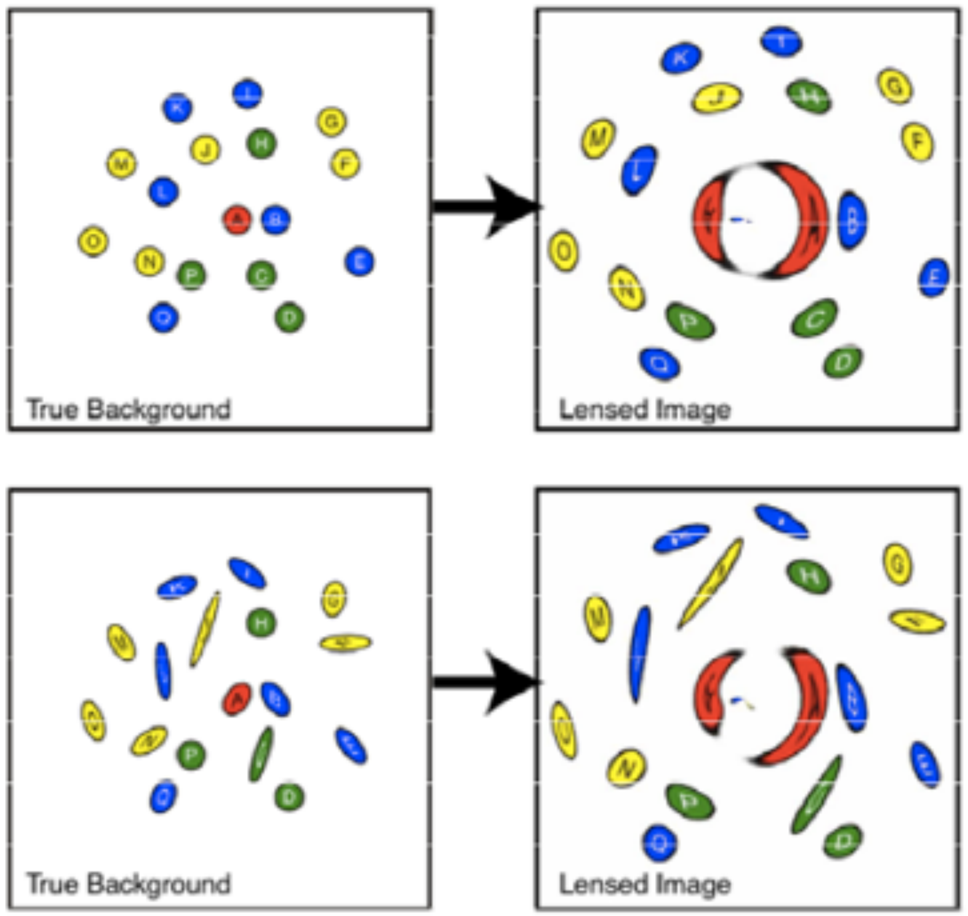
- The size of the deflection angle depends both on the **mass of the foreground deflector** and upon the **ratios of distances between observer, lens, and source.**

Weak Lensing (WL) surveys measure the distortion of background images due to the bending of light as it passes by galaxies or clusters of galaxies.

The WL technique is sensitive to dark energy through its effect on the angular-diameter distance vs. redshift relation and the growth rate of structure.

Weak Lensing

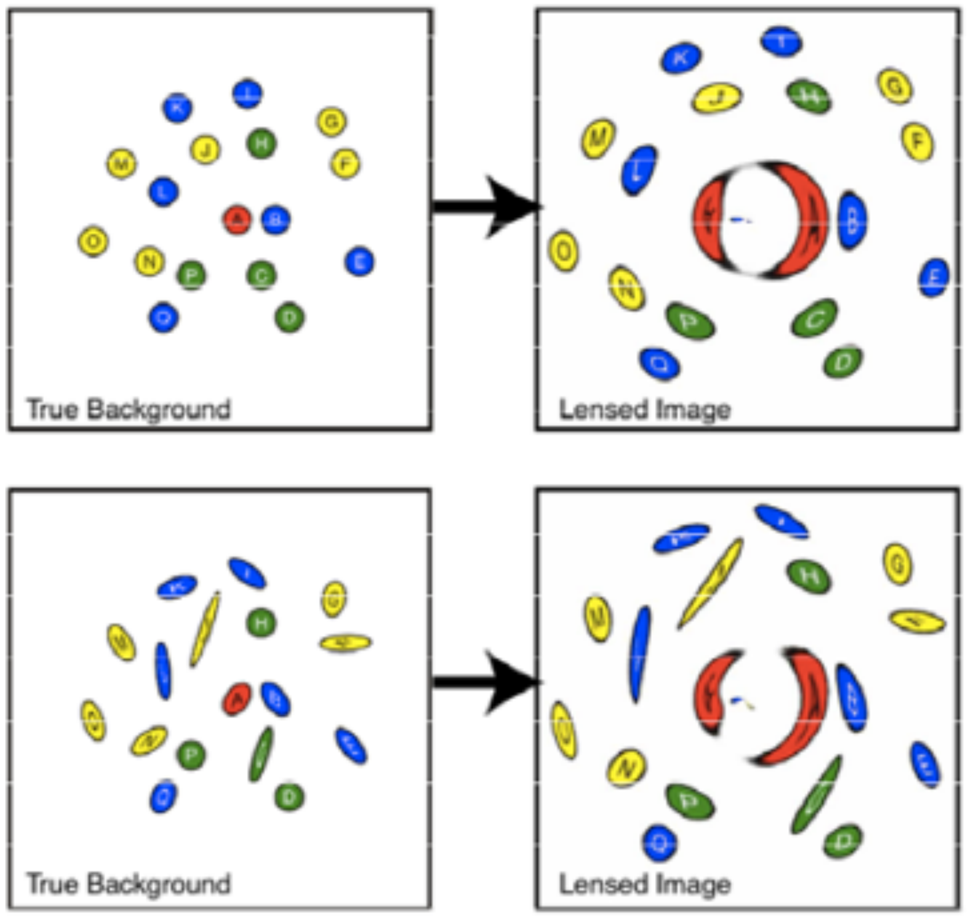
Weak lensing, we can measure the **gradient of the deflection angle** because any **anisotropy in this gradient makes circular source galaxies look slightly elliptical.**



Weak Lensing

Weak lensing, we can measure the **gradient of the deflection angle** because any anisotropy in this gradient makes **circular source galaxies look slightly elliptical.**

Since most **galaxies are far from circular** even in an unlensed view, it is not possible to deduce the lensing signal from a single background galaxy image.

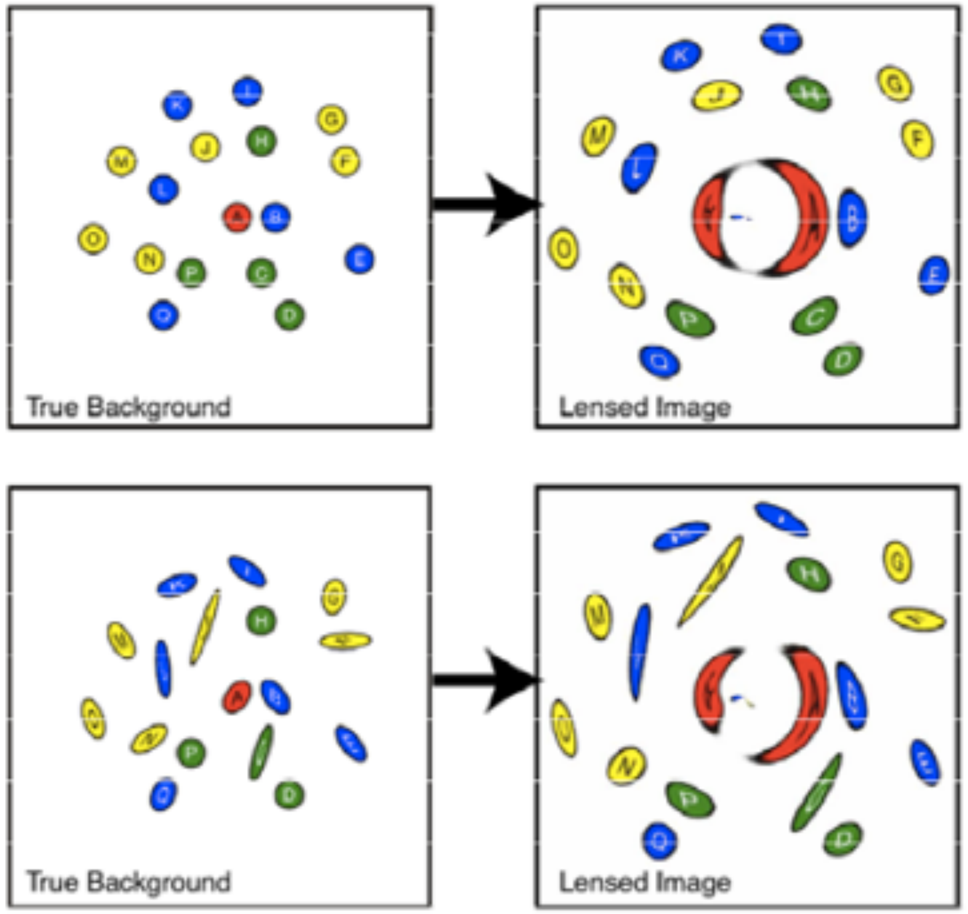


Weak Lensing

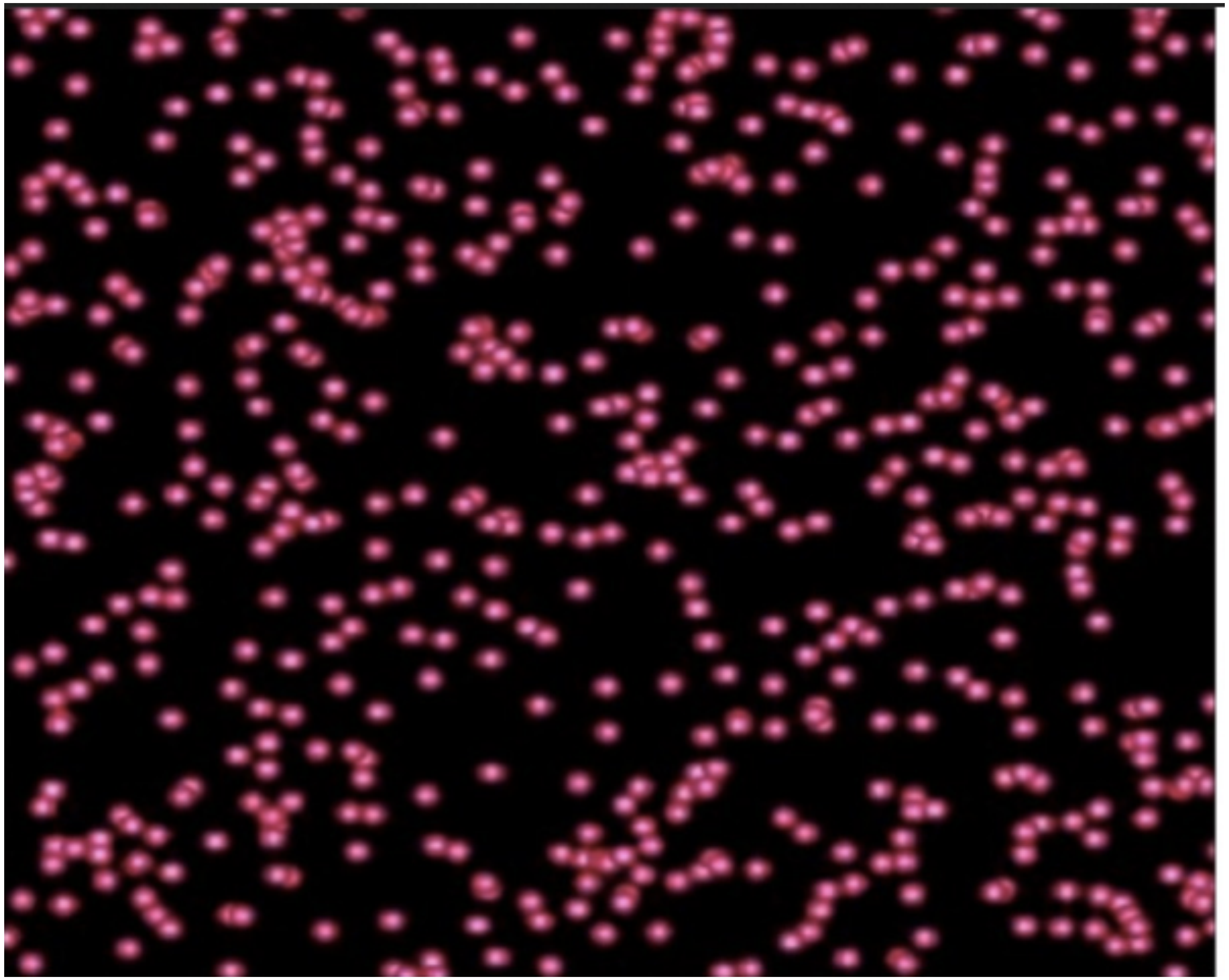
Weak lensing, we can measure the **gradient of the deflection angle** because any anisotropy in this gradient makes **circular source galaxies look slightly elliptical.**

Since most **galaxies are far from circular** even in an unlensed view, it is not possible to deduce the lensing signal from a single background galaxy image.

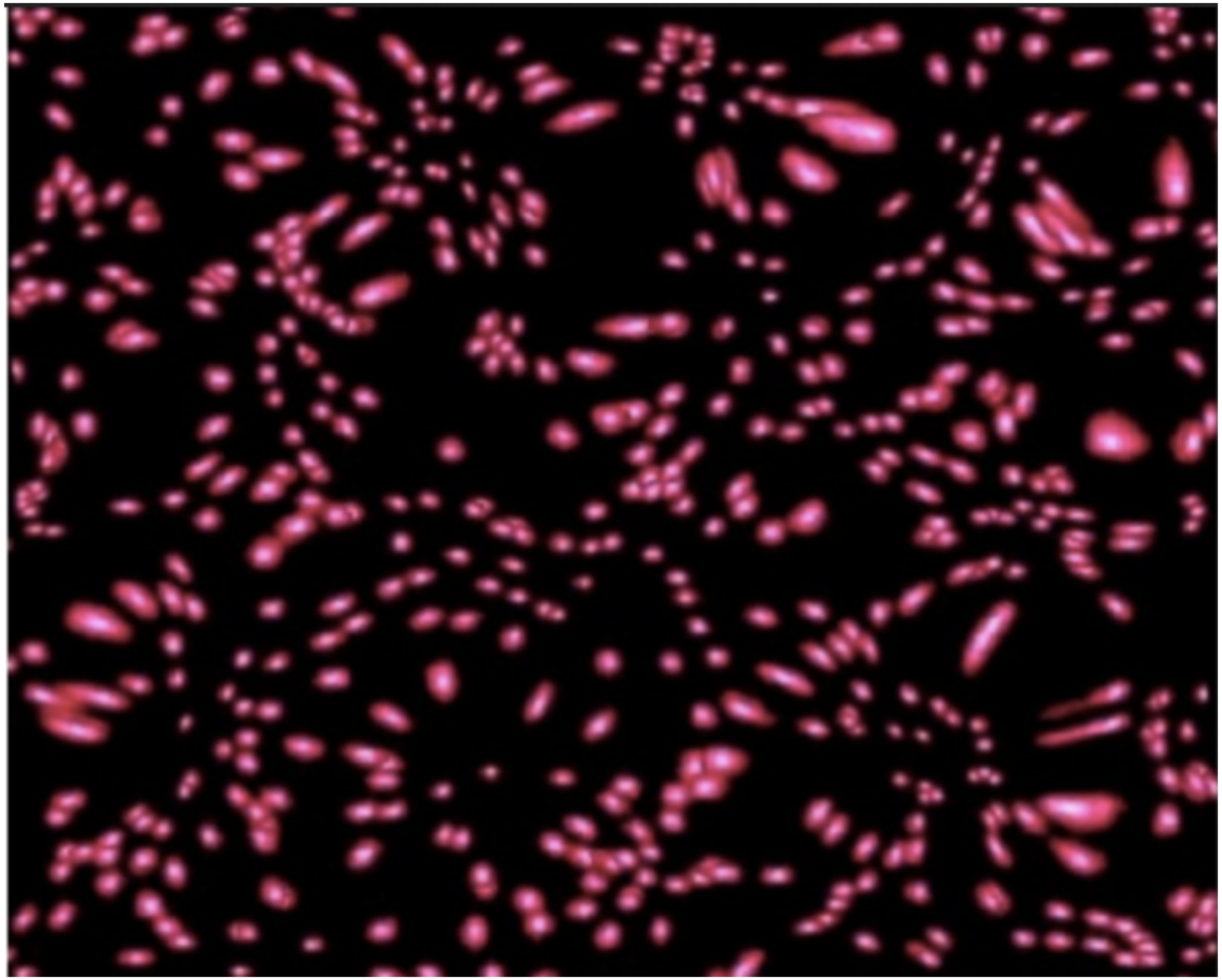
However when **large numbers of galaxies are observed**, the lensing signal can be discerned as a slight tendency for **nearby galaxies to have aligned shapes**.



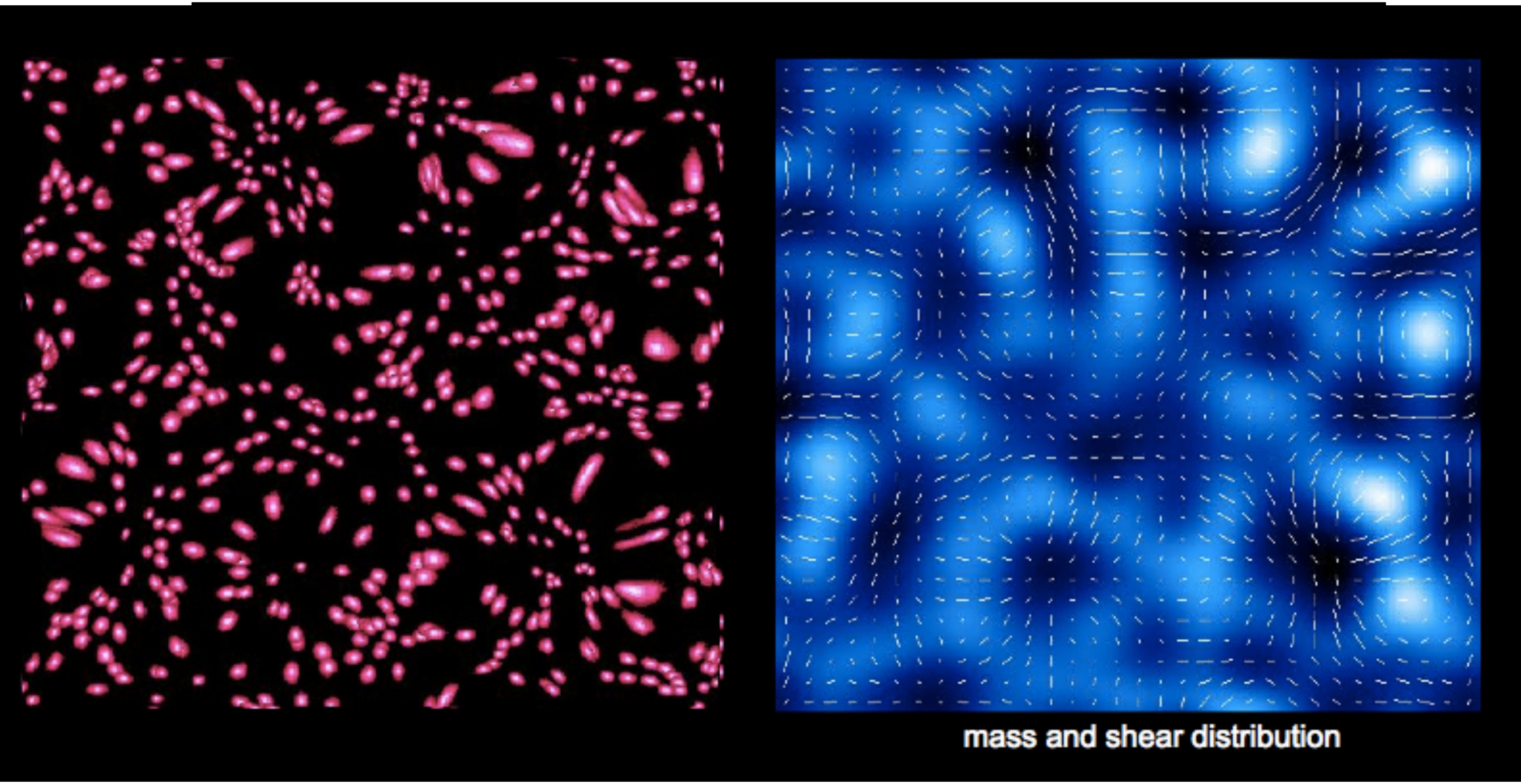
Shear Simulations



Shear Simulations



Shear Simulations



Weak Lensing

- Weak lensing (WL) is the **most direct probe of the mass distribution** in the Universe. It has been applied successfully on many different scales, from galaxy halos to large-scale structure.

- These measurements in turn allow us to constrain models of dark matter, dark energy, and cosmology. The primary **limitation** to date has been **statistical**:

  - Lensing causes a small perturbation to the initially random orientations of background galaxies, **so large numbers of background galaxies are required for high signal-to-noise ratio measurements.**

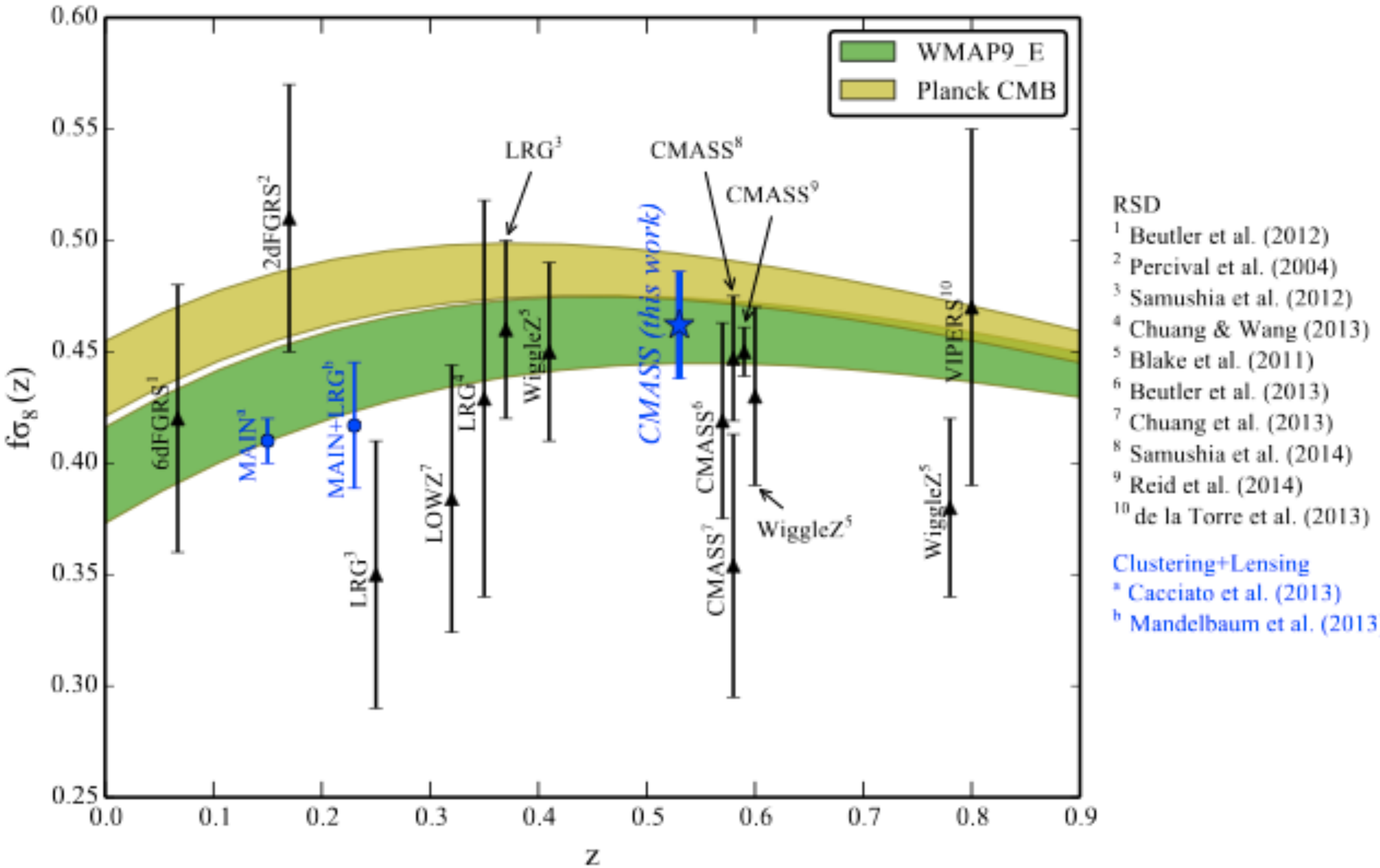
Weak Lensing Limitations

- Future surveys as LSST survey, encompassing **billions of galaxies**, will dramatically improve the statistical power of weak lensing observations.

  - At **large scales, cosmic variance is the limiting factor,** and the extremely **wide footprint** of the LSST survey will bring this limit down as well.

- At the same time, the greatly increased statistical power means that **systematic errors** must be carefully examined and **controlled**.

Constraints today using lensing & clustering



Weak Lensing final coments

- The WL technique is also an **emerging technique.** Its eventual accuracy will also be limited by **systematic errors** that are difficult to predict.

- If the systematic errors are at or below the level asserted by the proponents, it is **likely to be the most powerful individual Stage-IV** technique and also the most powerful component in a multi-technique program.

Outline

- Motivation: Dark Energy
- Observables:
    - SUPERNOVAS
    - BAO
    - RSD
    - CLUSTERS
    - WEAK LENSING
- Present/Future Experiments DE: Galaxy Surveys

How we are going to do: more DE Experiments

a. Stage III comprises near-term, medium-cost, currently proposed projects.

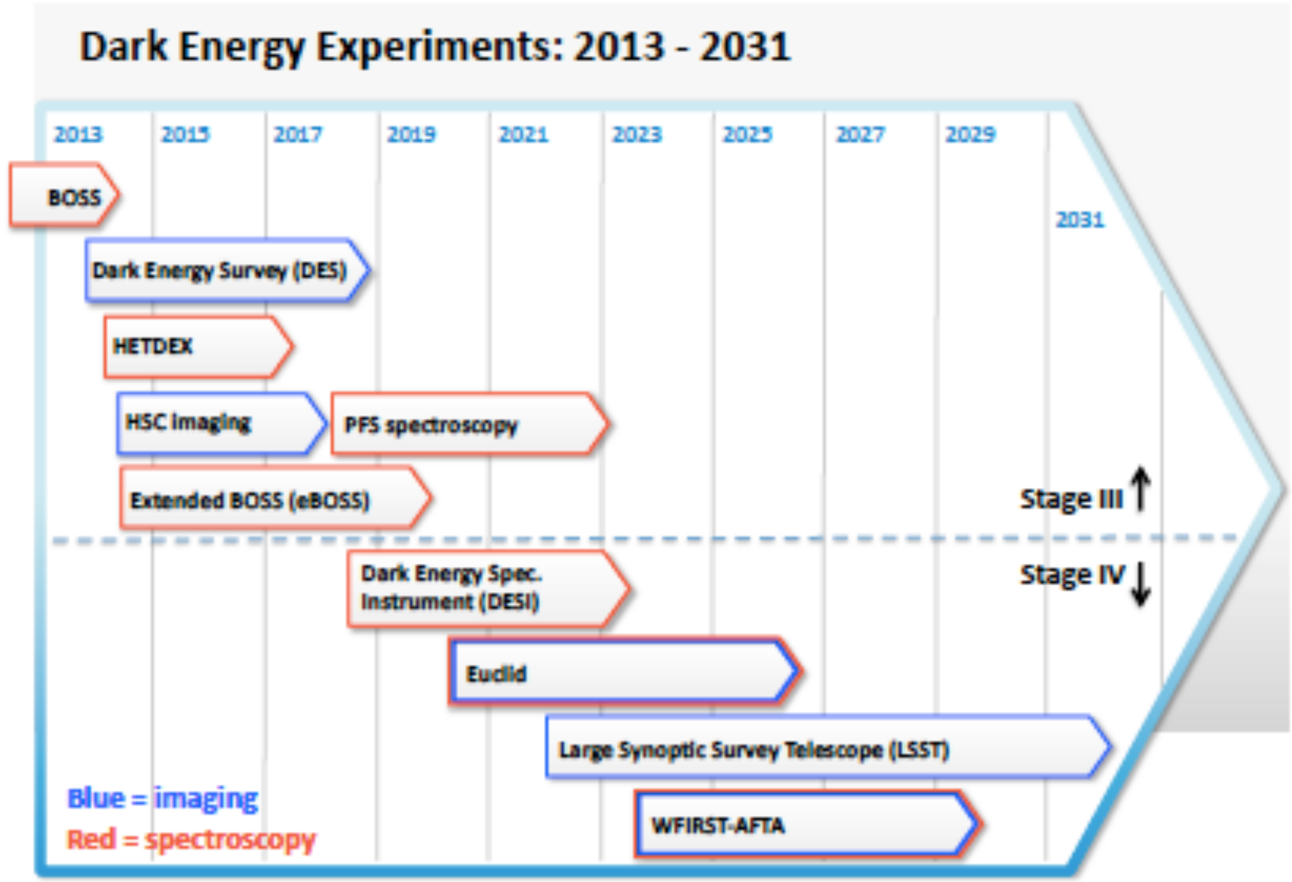
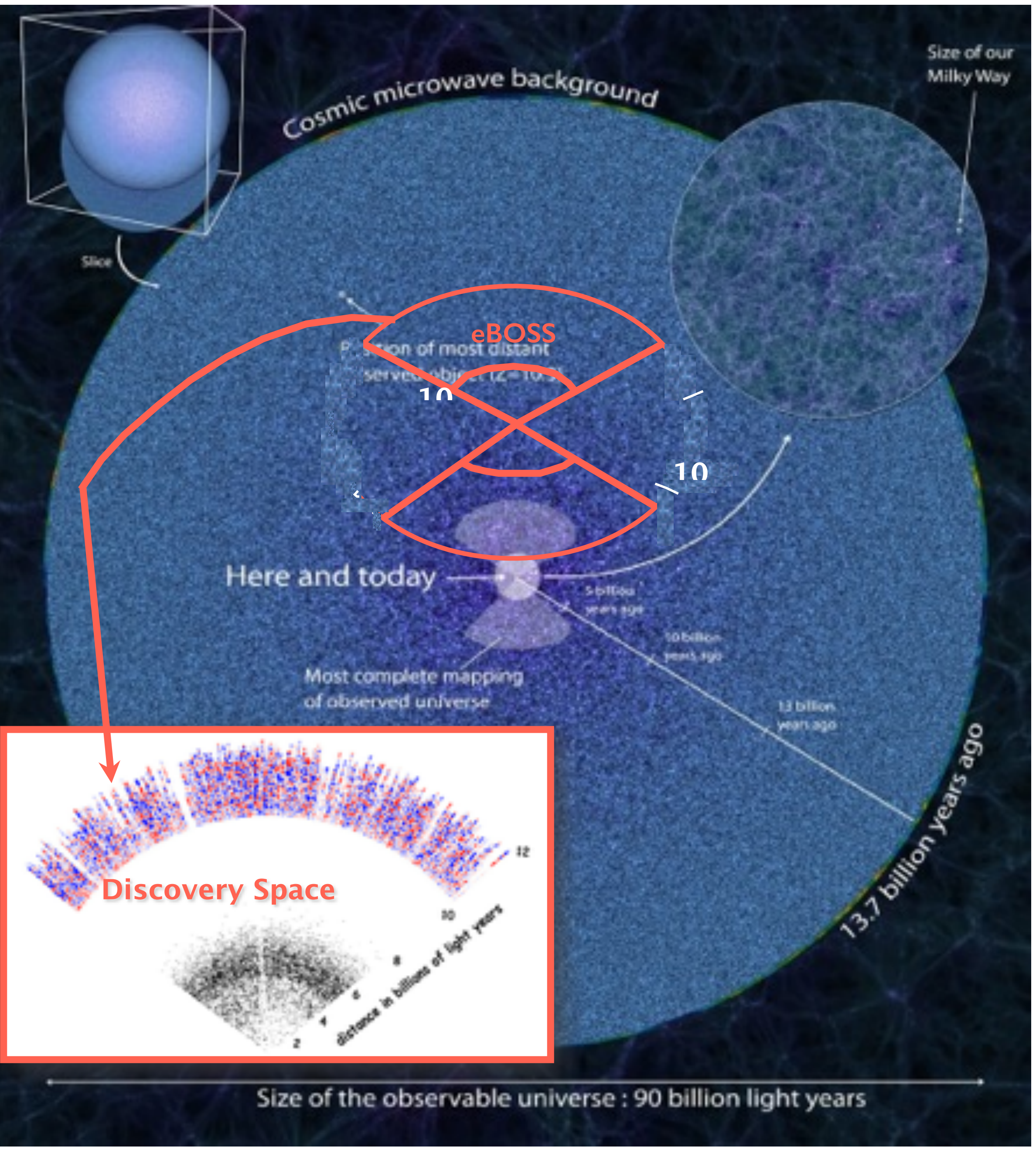


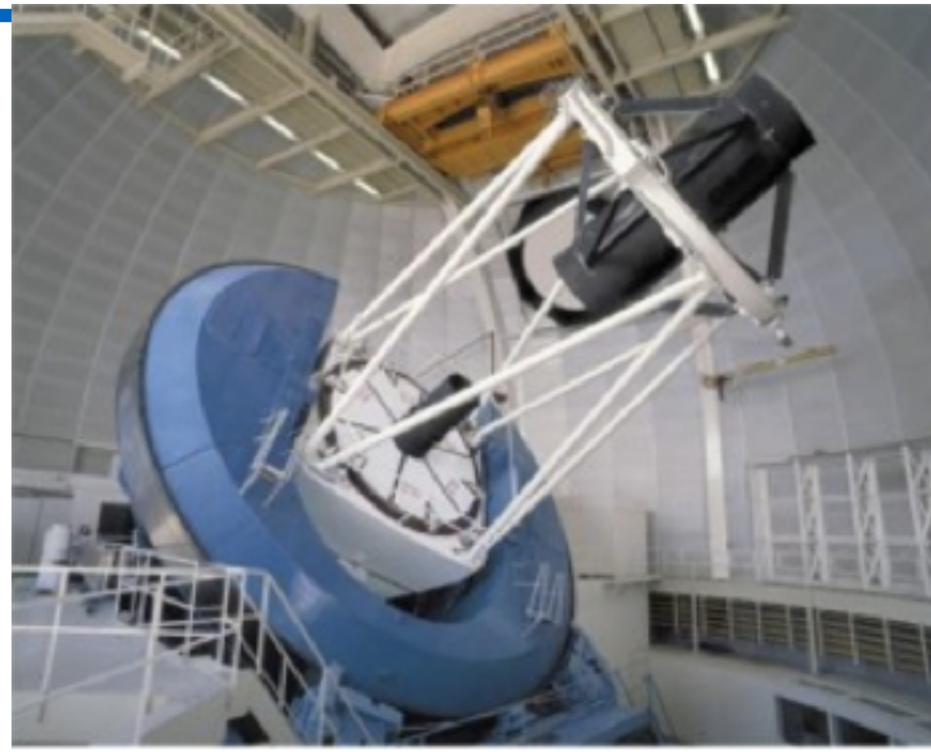
Figure 1. *A timeline of Stage III and Stage IV dark energy experiments – photometric and spectroscopic – in which US scientists are playing an important or leading role. Most of the projects are ground-based with either US leadership (BOSS, DES, HETDEX, eBOSS, DESI, LSST) or active participation (HSC, PFS). The two space missions are Euclid, led by the ESA with a NASA-sponsored team of US participants, and WFIRST, led by NASA.*

eBOSS

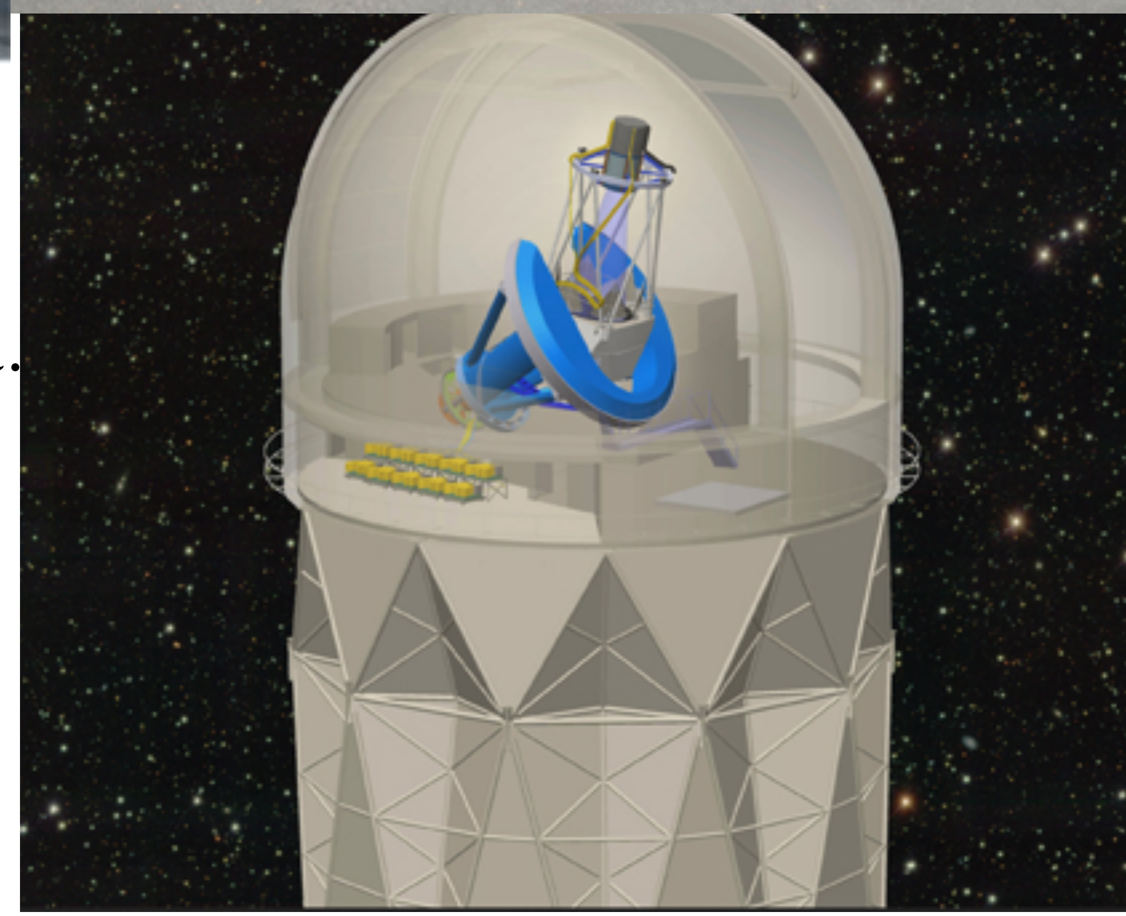


Fall **2014 - Spring 2020**
Telescope APO 2.5m
1000 fibers per 7 deg2 plate, 7000 square degrees
Wavelength: 360-1000 nm, resolution R~2000
4 different tracers of the underlying matter density field relatively unconstrained redshift range $0.6 < z < 2.2$.
250,000 **LRG** over 7500 deg2, $0.6 < z < 0.8$
195,000 **ELG** over 1500 deg2, $0.6 < z < 1.0$
500,000 **QSO** over 7500 deg2, $0.9 < z < 3.5$
1-2% distance measurements from baryon acoustic oscillations between $0.6 < z < 2.5$
LRG's dA(z) to an accuracy of 1.2% and measurements of H(z) to 2.1%
ELG's 3.1% and H(z) to 4.7% at an effective redshift of $z = 0.87$.
QSO 2.8% and 4.2% on dA(z) and H(z), respectively
Lyα forest measurements at redshifts $z > 2.1$,dA(z) and H(z) at $z > 2.1$ by a factor of 1.44 relative to BOSS.

DESI (2018-2022)



Mayall Telescope at Kitt Peak. Image: NOAO/AURA/NSF



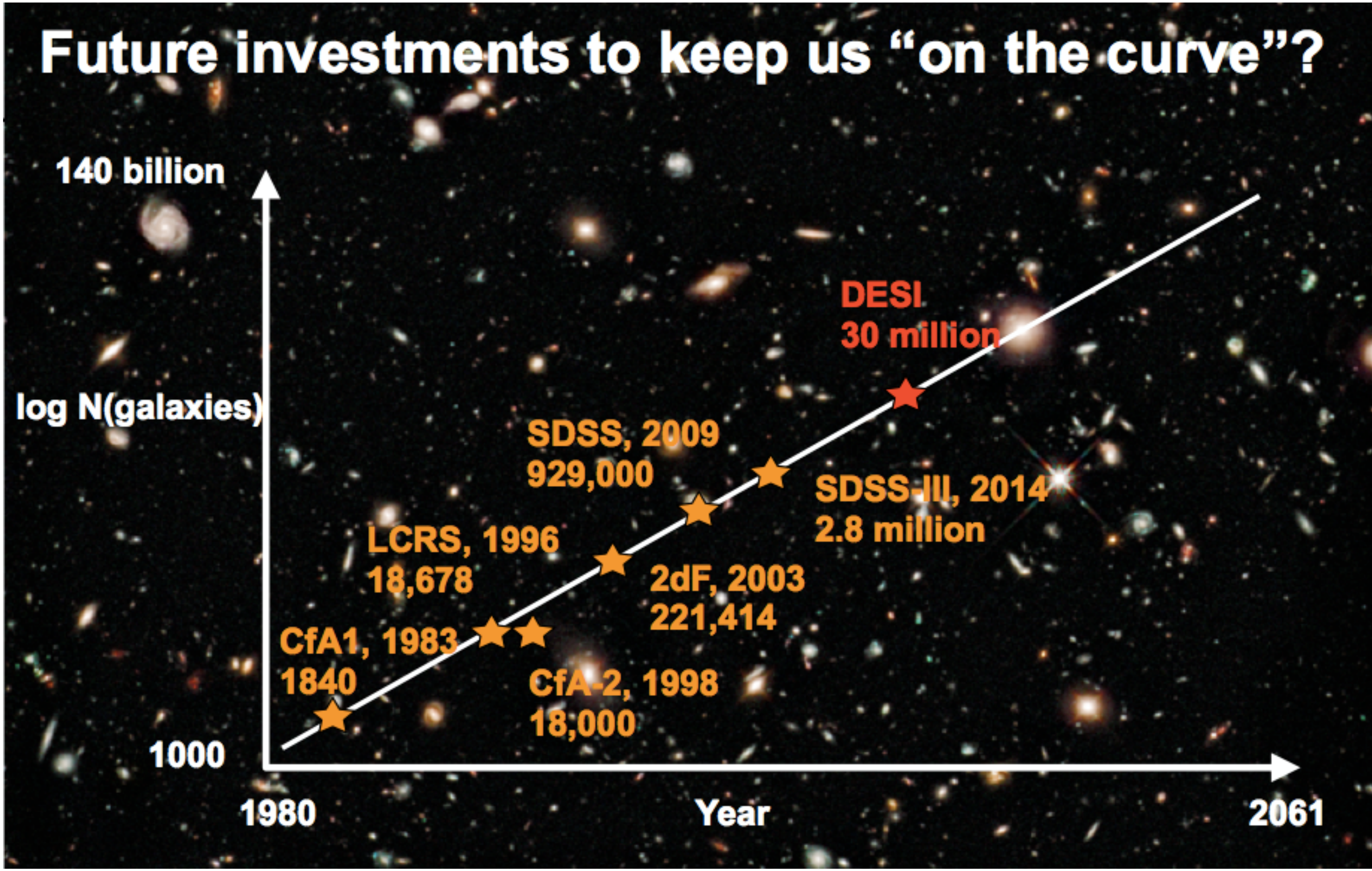
Stage-IV BAO experiment

4-m telescope Mayall Telescope,Tucson, Arizona.

14000 sq degrees.

1 meter diameter corrector
5000 fiber-robot army
200,000 meters fiber optics
10 spectrographs x 3 cameras

DESI



Future investments to keep us "on the curve"?
140 billion
log N(galaxies)
1000
1980
Year
2061
DESI
30 million
SDSS, 2009
929,000
SDSS-III, 2014
2.8 million
LCRS, 1996
18,678
2dF, 2003
221,414
CfA1, 1983
1840
CfA-2, 1998
18,000

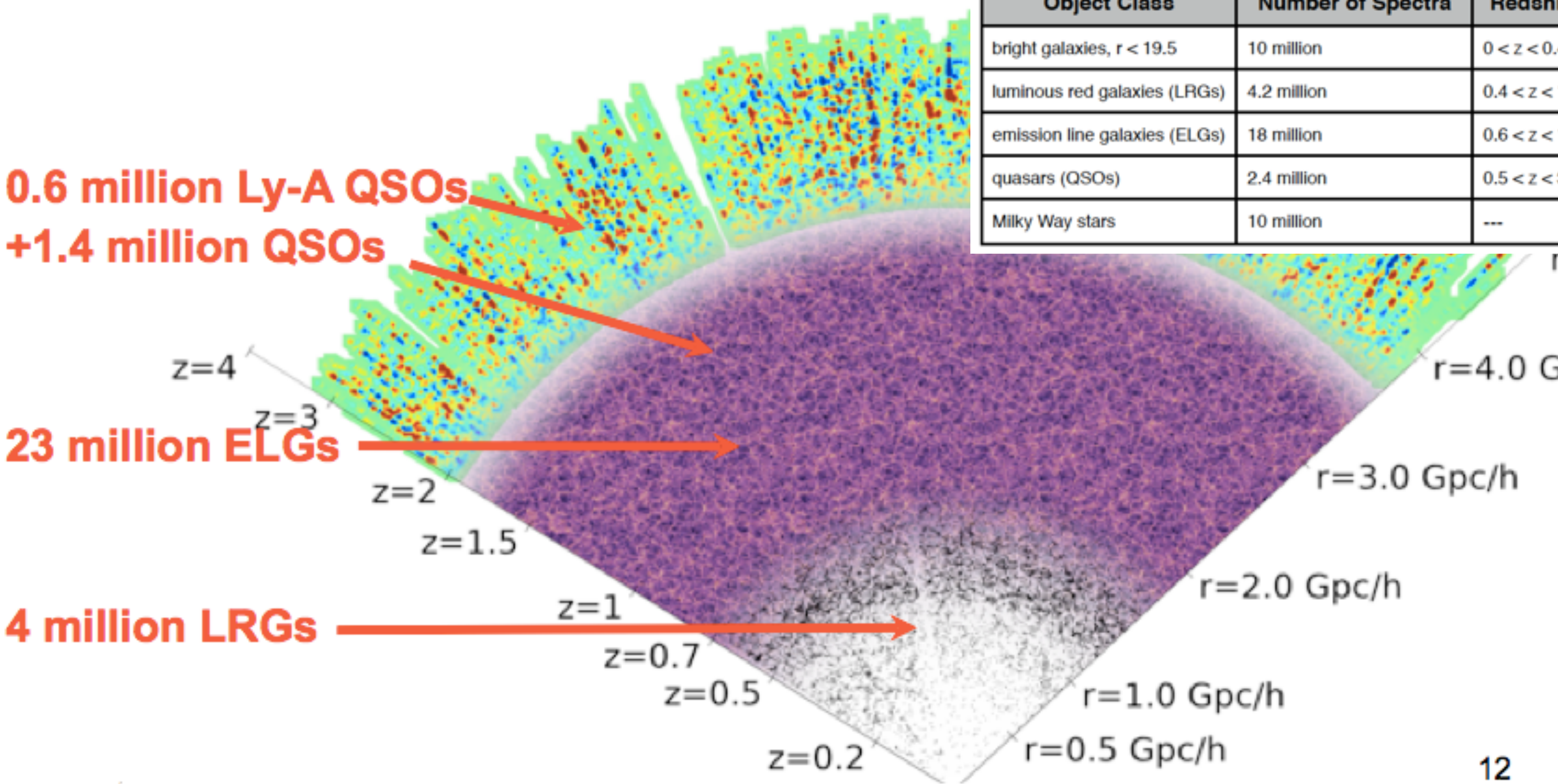
DESI tracers

Four target classes spanning redshifts z=0 → 3.5

Includes all the massive black holes in the Universe (LRGs + QSOs)

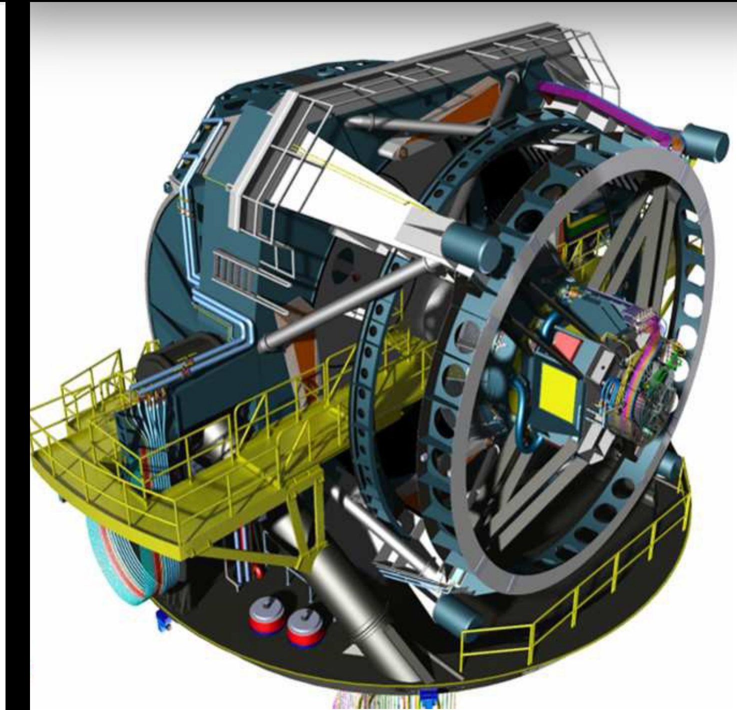
DESI, Conceptual Design Report (2014)

Object Class	Number of Spectra	Redshift Range
bright galaxies, $r < 19.5$	10 million	$0 < z < 0.4$
luminous red galaxies (LRGs)	4.2 million	$0.4 < z < 1.0$
emission line galaxies (ELGs)	18 million	$0.6 < z < 1.6$
quasars (QSOs)	2.4 million	$0.5 < z < 3.5$
Milky Way stars	10 million	---

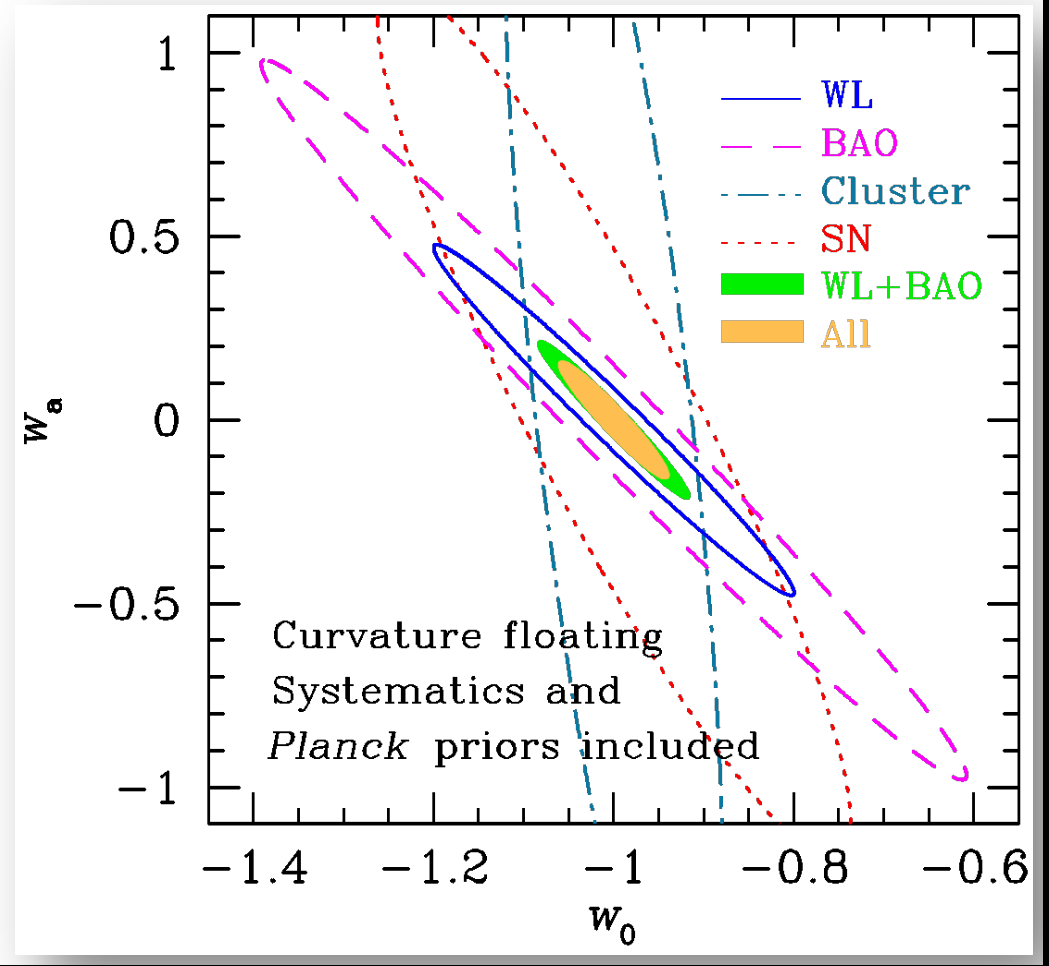


Future Dark Energy project: LSST

- The LSST is an integrated survey system designed to conduct a decade-long, deep, wide, fast time-domain survey of the optical sky. It consists of an 8-meter class wide-field ground based telescope, a 3.2 Gpix camera, and an automated data processing system.
- Over a decade of operations the LSST survey will acquire, process, and make available a collection of over 5 million images and catalogs with more than 37 billion objects and 7 trillion sources. Tens of billions of time-domain events will be detect and alerted on in real-time.
- NSF, DOE, Private Support, and International Partnerships
- LSST is under construction!
  - "Primera Piedra" event April 2015
  - DOE CD-2 Complete, CD-3 Summer 2015
  - Full Science Operations Start in 2022



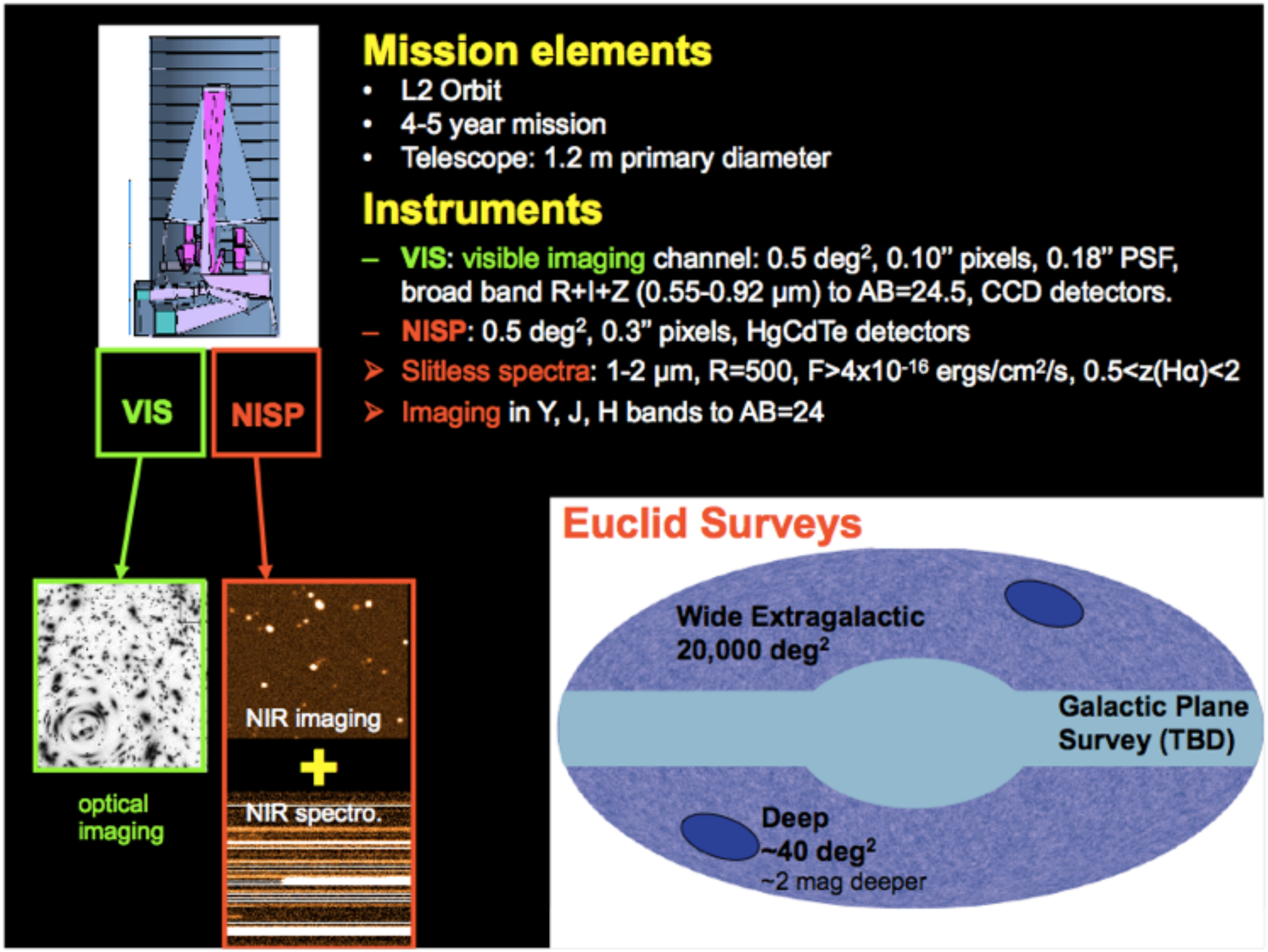
- Points to new positions in the sky every 39 seconds
- Tracks during exposures and slews 3.5° to adjacent fields in ~ 4 seconds
- 3.2 Gigapixel Camera
  - 0.2 arcsec/pixel
  - 6 filters (*ugrizy*)
- ~15TB per night



LSST will do much more than shrink the error ellipse! Measuring the growth of structure will test ΛCDM over wide range of distance scale and cosmic time

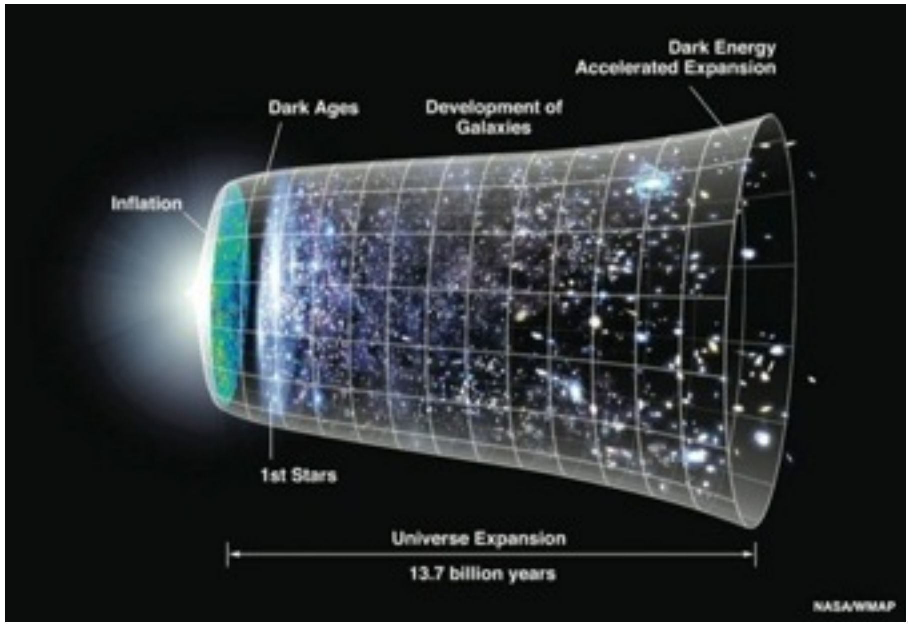
Slide from Steve Ritz, LSST Project Scientist

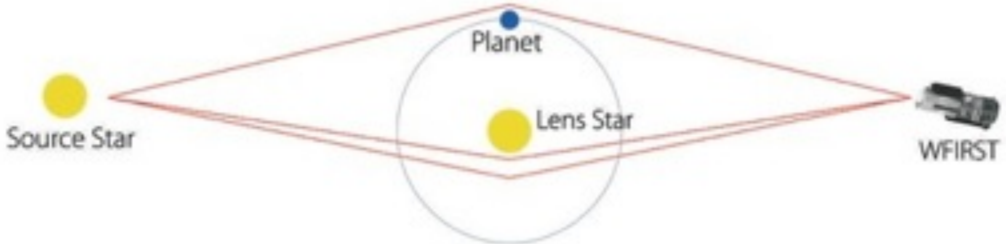
Euclid

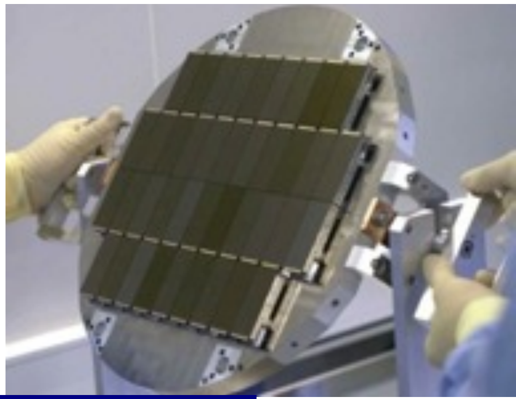

Mission elements
• L2 Orbit
• 4-5 year mission
• Telescope: 1.2 m primary diameter
Instruments
– VIS: visible imaging channel: 0.5 deg^2, 0.10" pixels, 0.18" PSF, broad band R+I+Z (0.55-0.92 μm) to AB=24.5, CCD detectors.
– NISP: 0.5 deg^2, 0.3" pixels, HgCdTe detectors
➢ Slitless spectra: 1-2 μm, R=500, F>4x10^{-16} ergs/cm^2/s, 0.5<z(Hα)<2
➢ Imaging in Y, J, H bands to AB=24
VIS
NISP
optical imaging
NIR imaging
+
NIR spectro.
Euclid Surveys
Wide Extragalactic 20,000 deg^2
Galactic Plane Survey (TBD)
Deep ~40 deg^2
~2 mag deeper

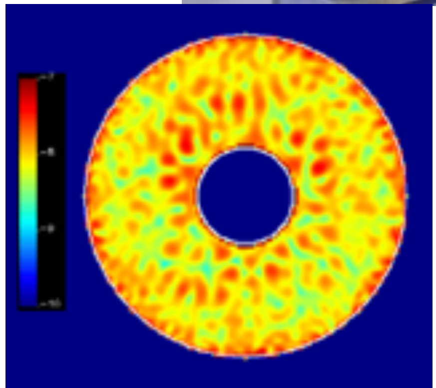
WFIRST-AFTA Summary

- WFIRST is the highest ranked NWNH large space mission.
  - Determine the nature of the dark energy that is driving the current accelerating expansion of the universe
  - Perform statistical census of planetary systems through microlensing survey
  - Survey the NIR sky
  - Provide the community with a wide field telescope for pointed wide observations
- Coronagraph characterizes planets and disks, broadens science program and brings humanity closer to imaging Earths.
- The WFIRST-AFTA Design Reference Mission has
  - 2.4 m telescope (already exists)
  - NIR instrument with 18 H4RG HgCdTe detectors
  - Baseline exoplanet coronagraph
  - 5 year lifetime, 10 year goal
- WFIRST-AFTA will perform Hubble quality and depth imaging over thousands of square degrees

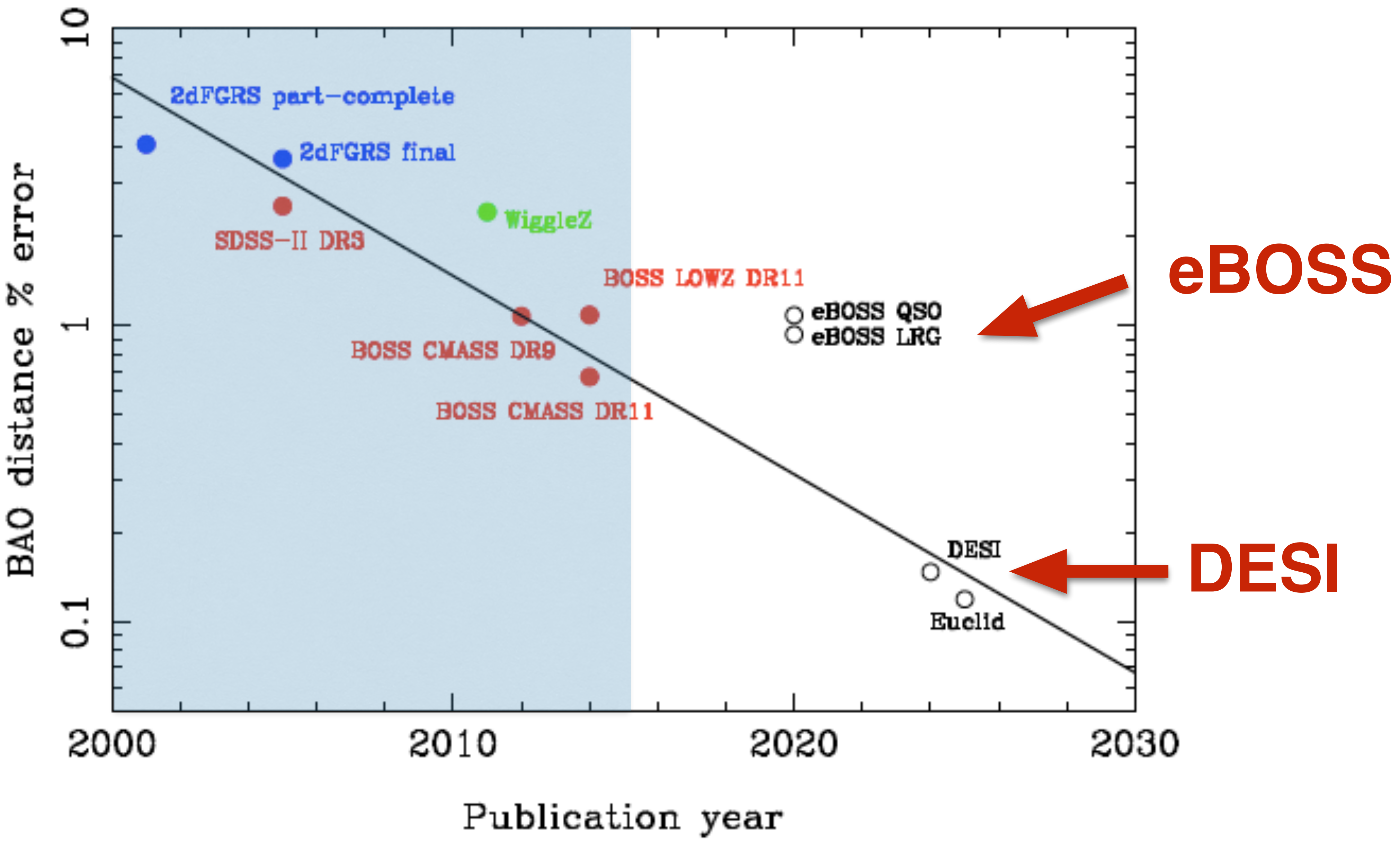








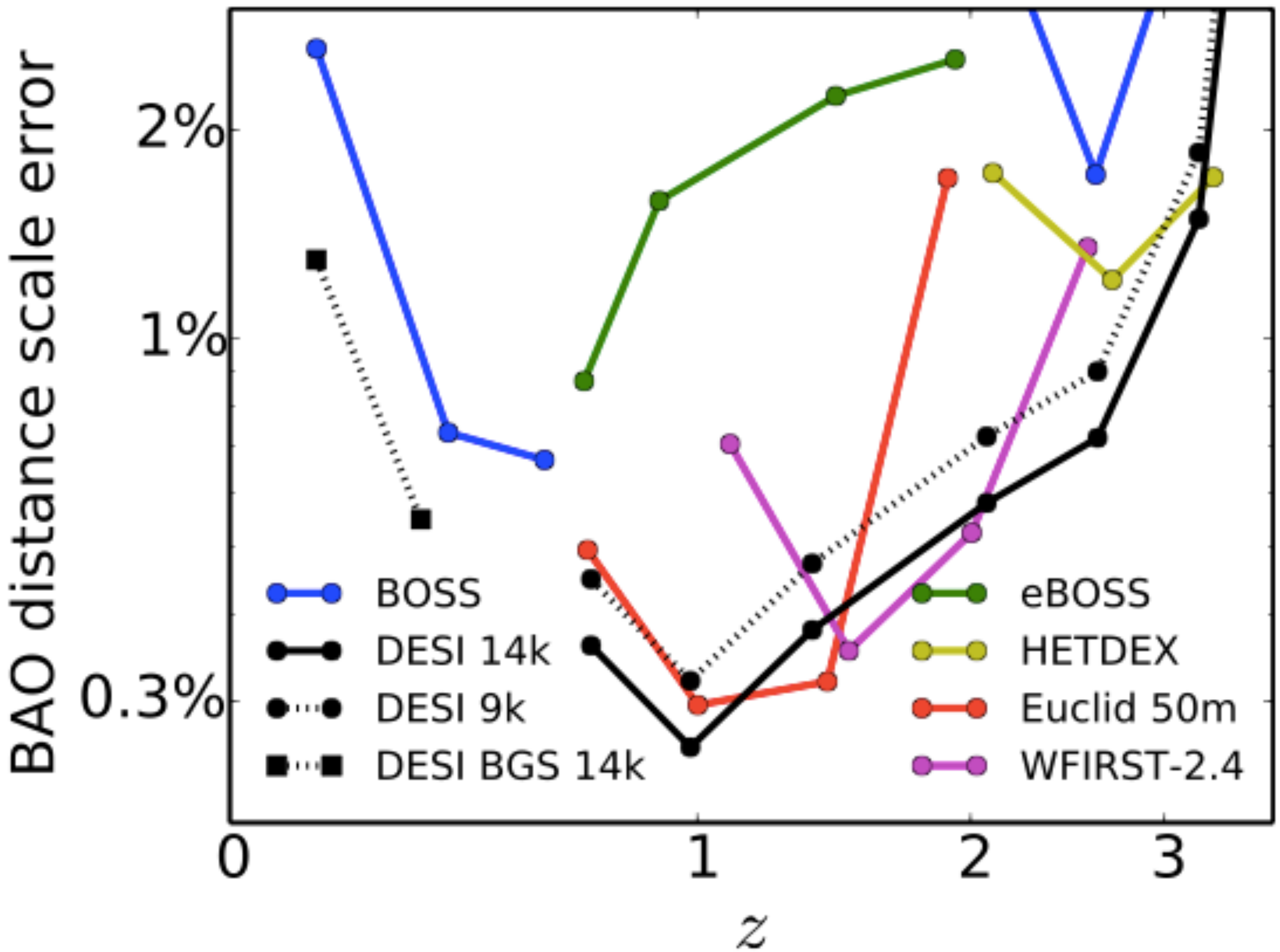
What is next?



2dFGRS part-complete
2dFGRS final
SDSS-II DR3
WiggleZ
BOSS LOWZ DR11
BOSS CMASS DR9
BOSS CMASS DR11
eBOSS QSO
eBOSS LRG
DESI
Euclid
eBOSS
DESI
BAO distance % error
10
1
0.1
2000
2010
2020
2030
Publication year

DESI Forecast

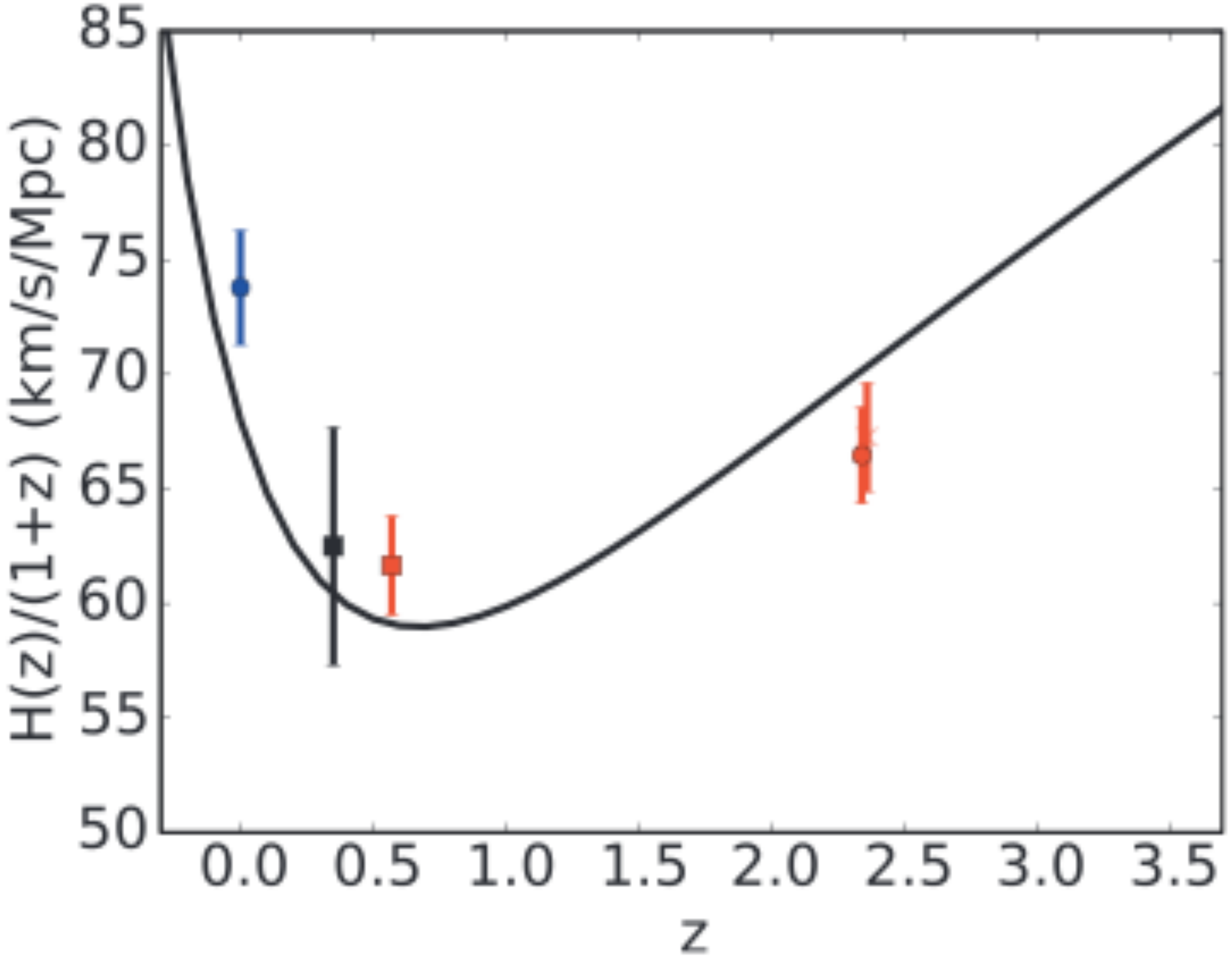
DESI, Conceptual Design Report (2014)



What is next?

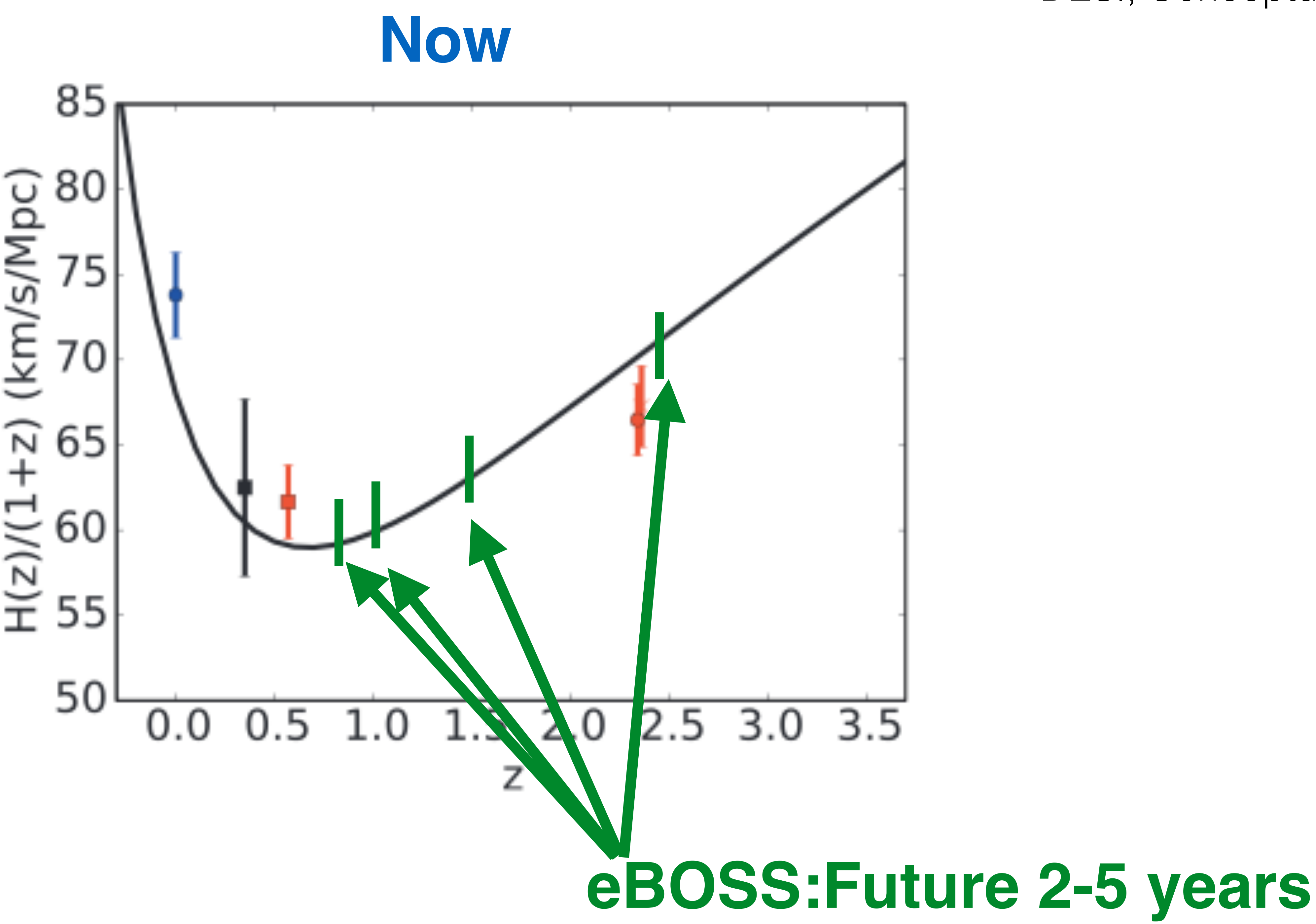
Now:BOSS Lyman Alpha+BOSS gal+SDSS

DESI, Conceptual Design Report (2014)



What is next?

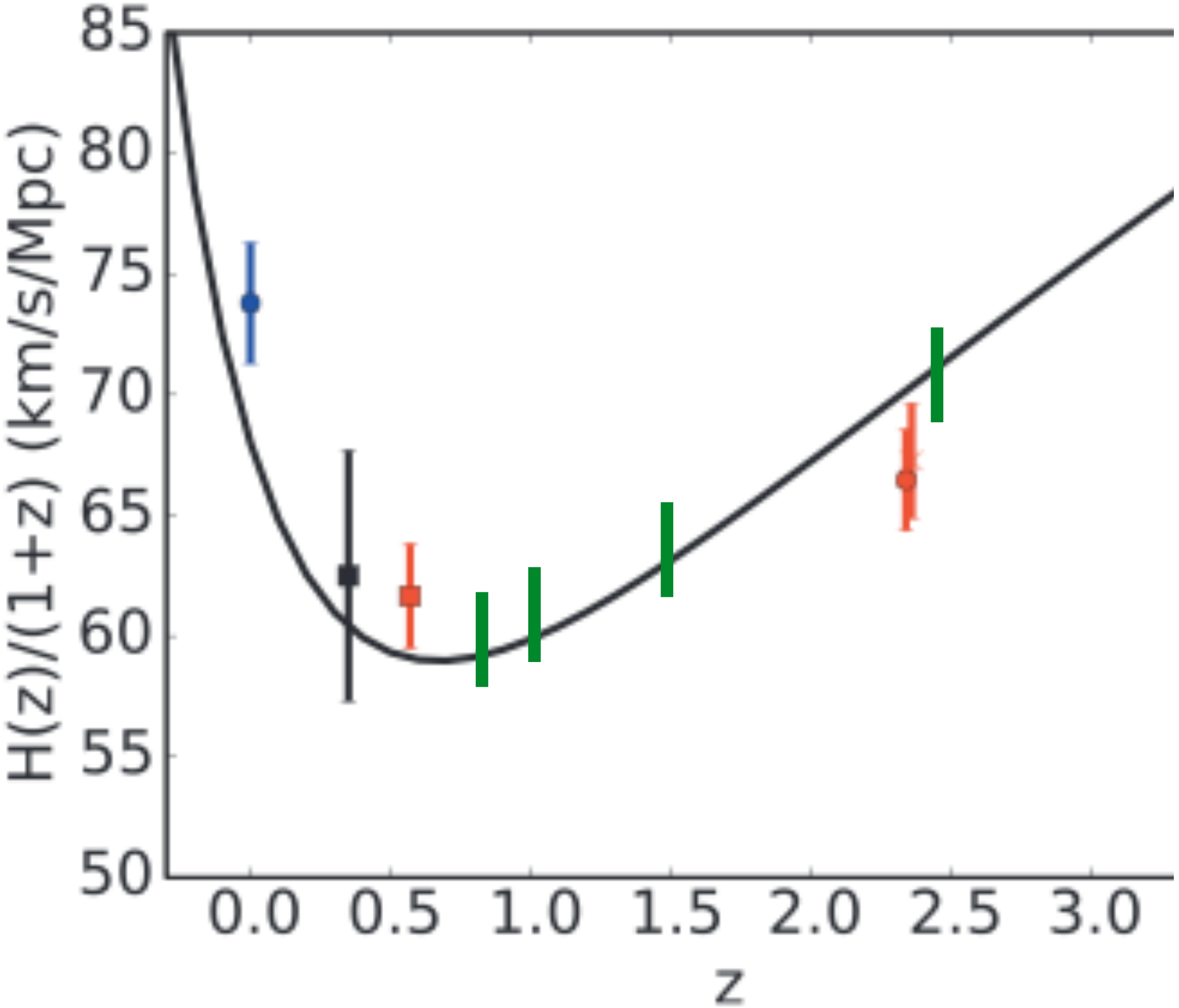
DESI, Conceptual Design Report (2014)



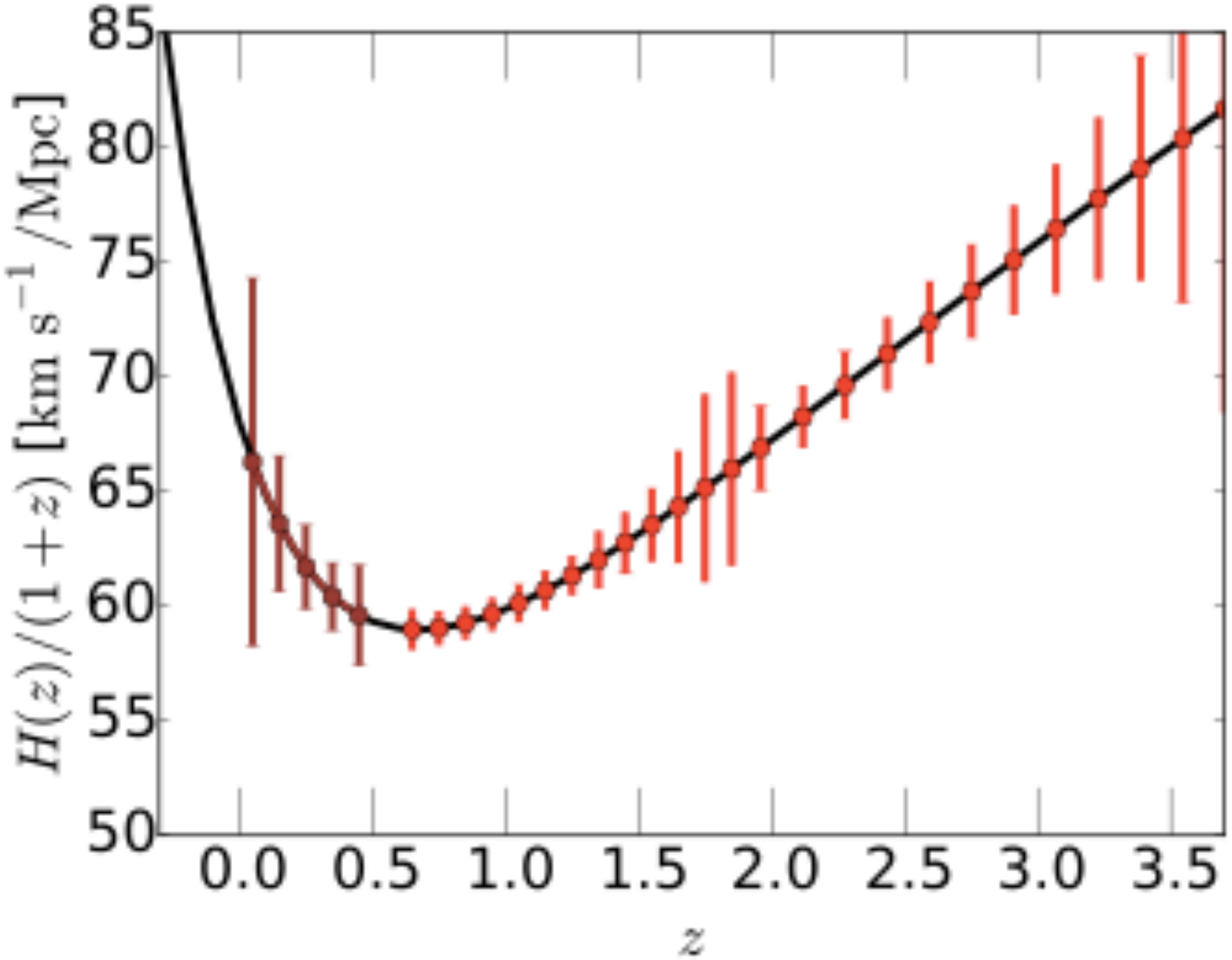
What is next?

DESI, Conceptual Design Report (2014)

Now



Future 8 years



Expansion rate of the Universe as a function of redshift.

More constrains on DE

DESI, Conceptual Design Report (2014)

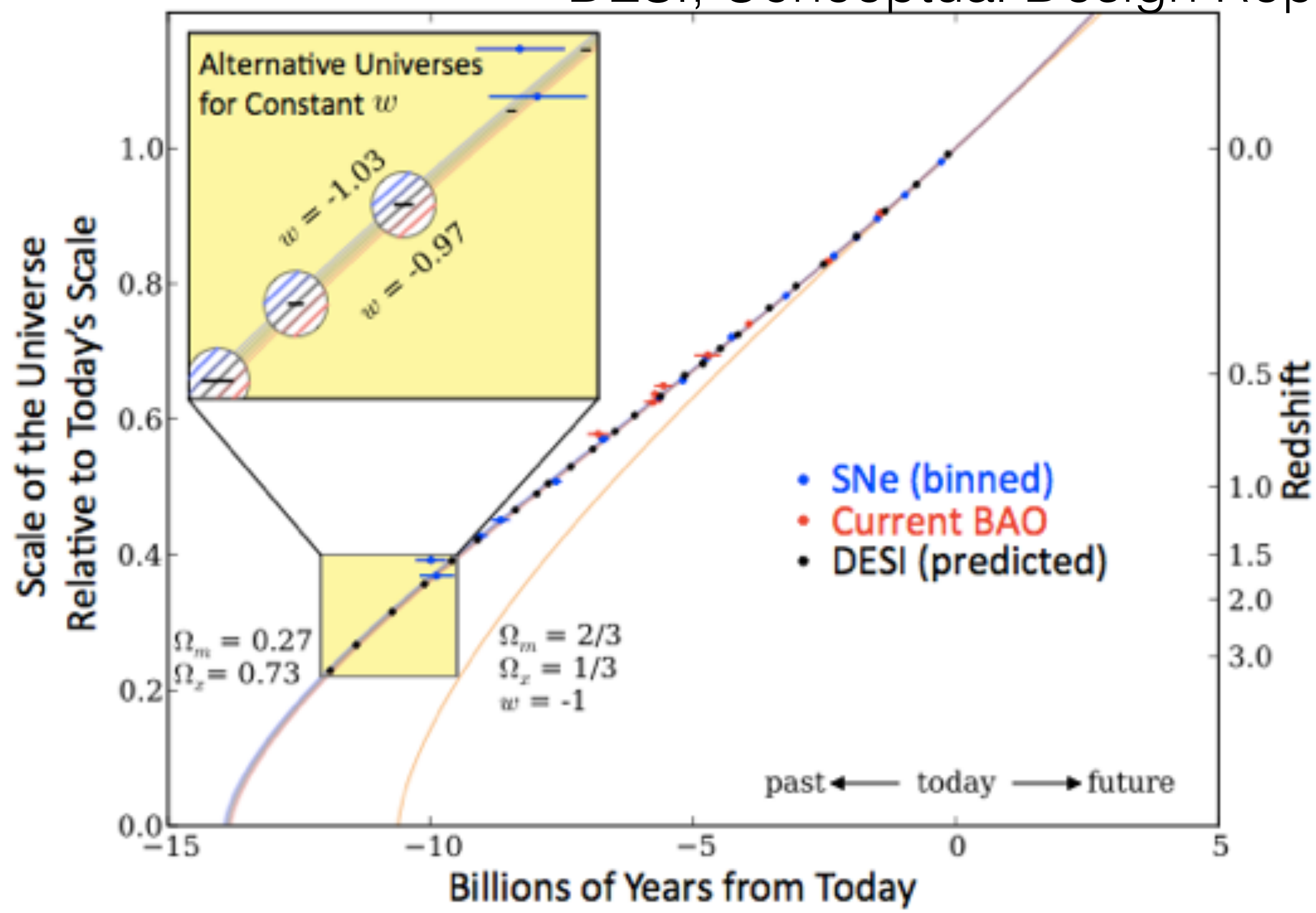
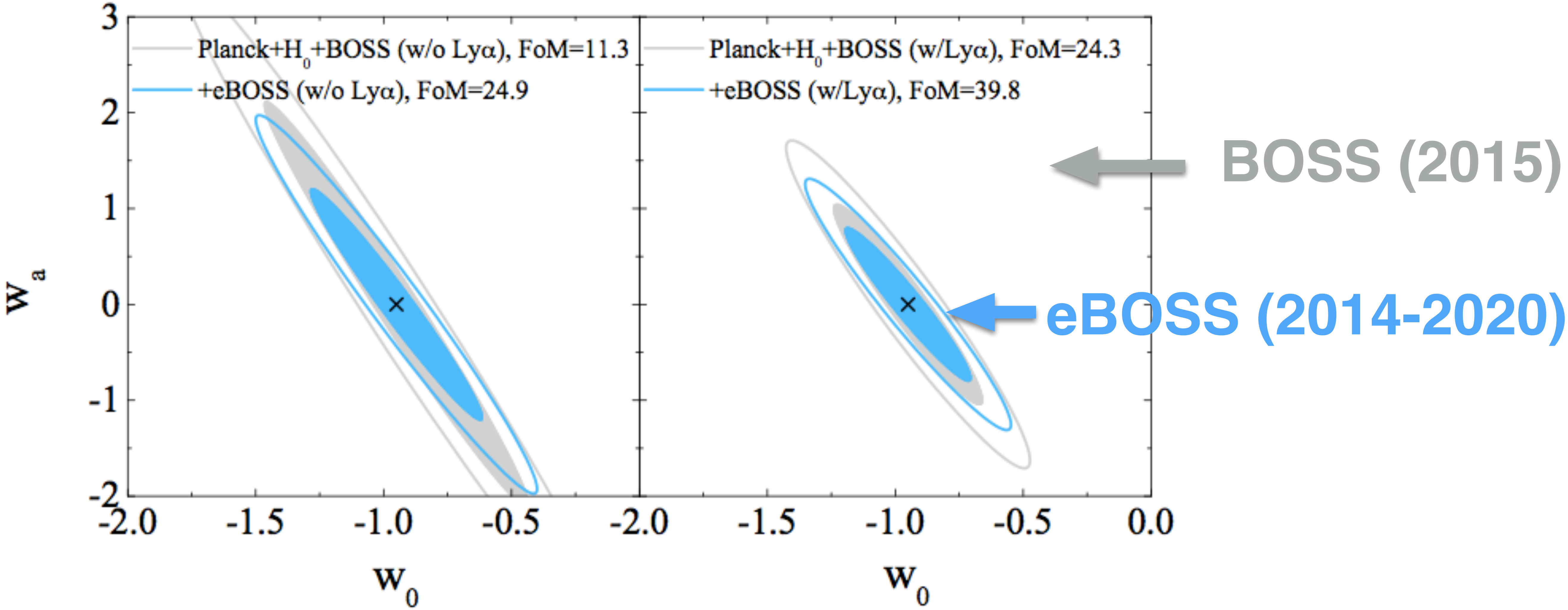


Figure 2.1: The expansion history of the Universe for different models of dark energy, holding the present-day Hubble constant fixed. The inset shows the spacing between five models with constant w ranging from −0.97 to −1.03, showing the exquisite precision required to distinguish these. Overlaid are measurements of the distance-redshift relation, translated into errors on lookback time at each redshift. Measurements from current supernovae, binned in redshift, are shown in blue; current BAO measurements from BOSS DR9, WiggleZ, and 6dF are shown in red; projections for DESI are shown in black. DESI measurements have the ability to make very tight constraints on dark energy, although we caution that this figure shows variations in only one cosmological parameter. Full forecasts, such as those presented in § 2.4.3, must marginalize over other cosmological parameters such as Ω_m and H_0.

Constraints on DE



K.Dawson et al 2015, eBOSS arXiv:1508.04473

Constraints on DE

DESI, Conceptual Design Report (2014)

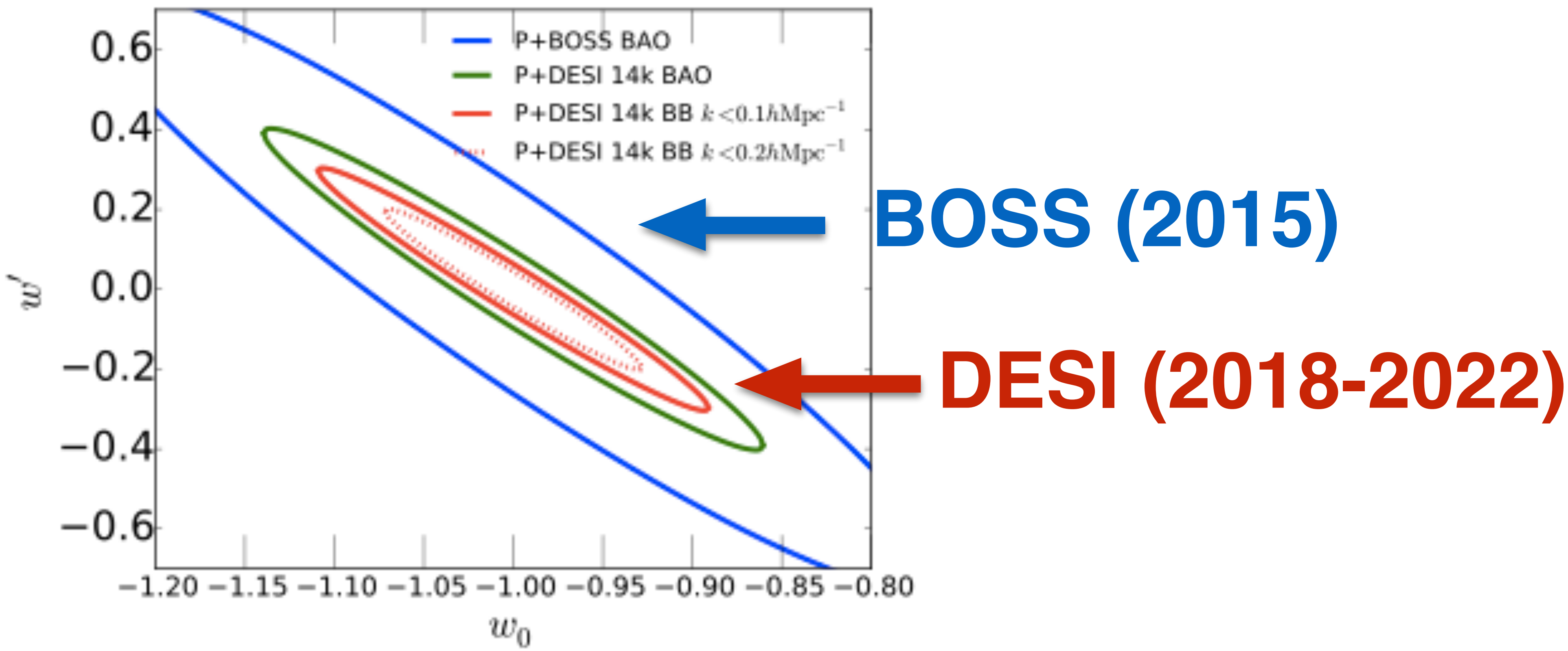
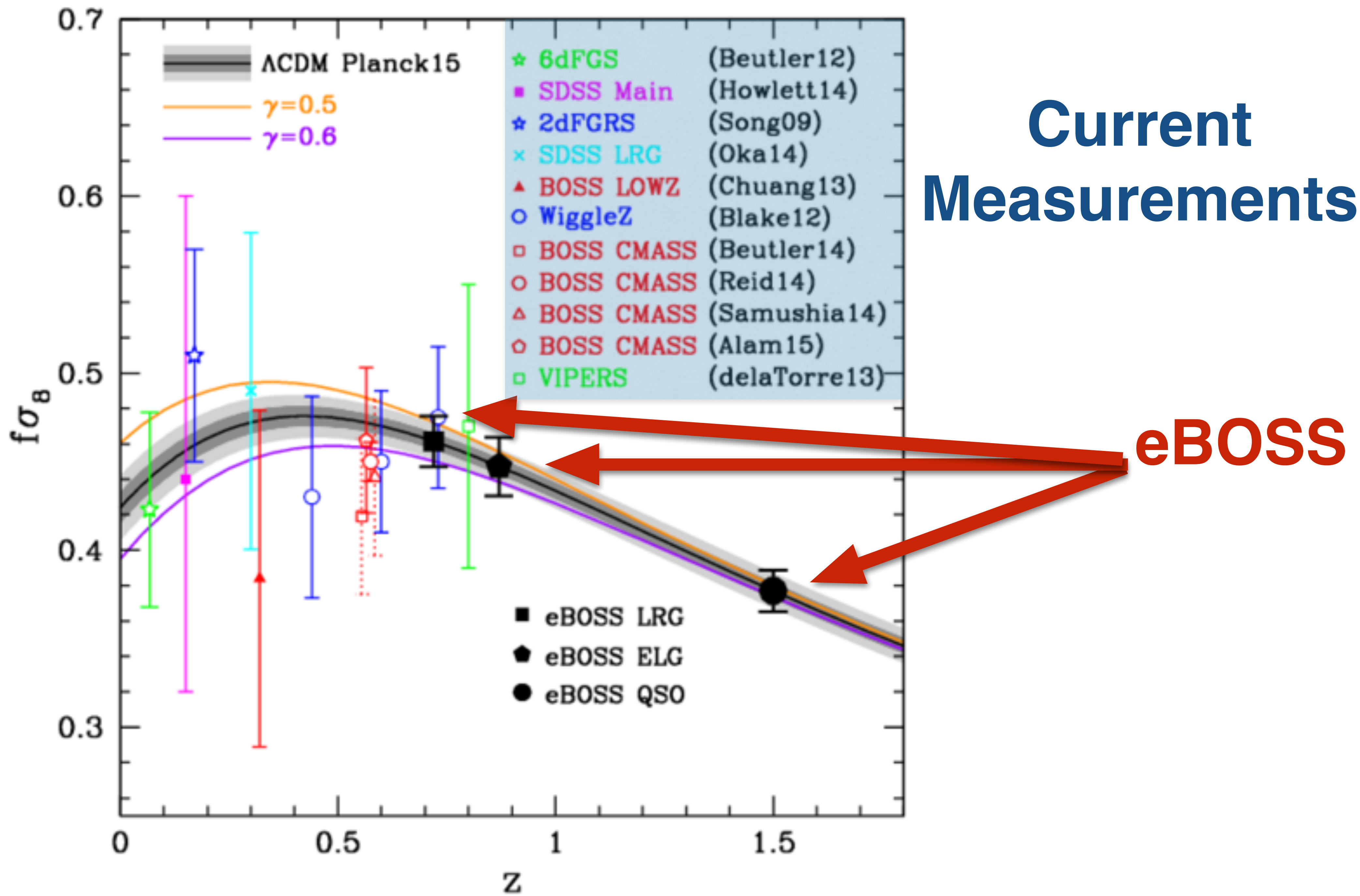


Figure 2.11: The $w_0 - w_a$ plane showing projected limits (68%) from DESI using just BAO and using the broadband (BB) power spectrum. Also shown is the limit from BOSS BAO. *Planck* priors are included in all cases, and DESI includes the BGS and non-redundant part of BOSS. The figure of merit of the surveys is inversely proportional to the areas of the error ellipses.

What is next?



K.Dawson et al 2015, eBOSS arXiv:1508.04473

Constraints in Gravity

DESI, Conceptual Design Report (2014)

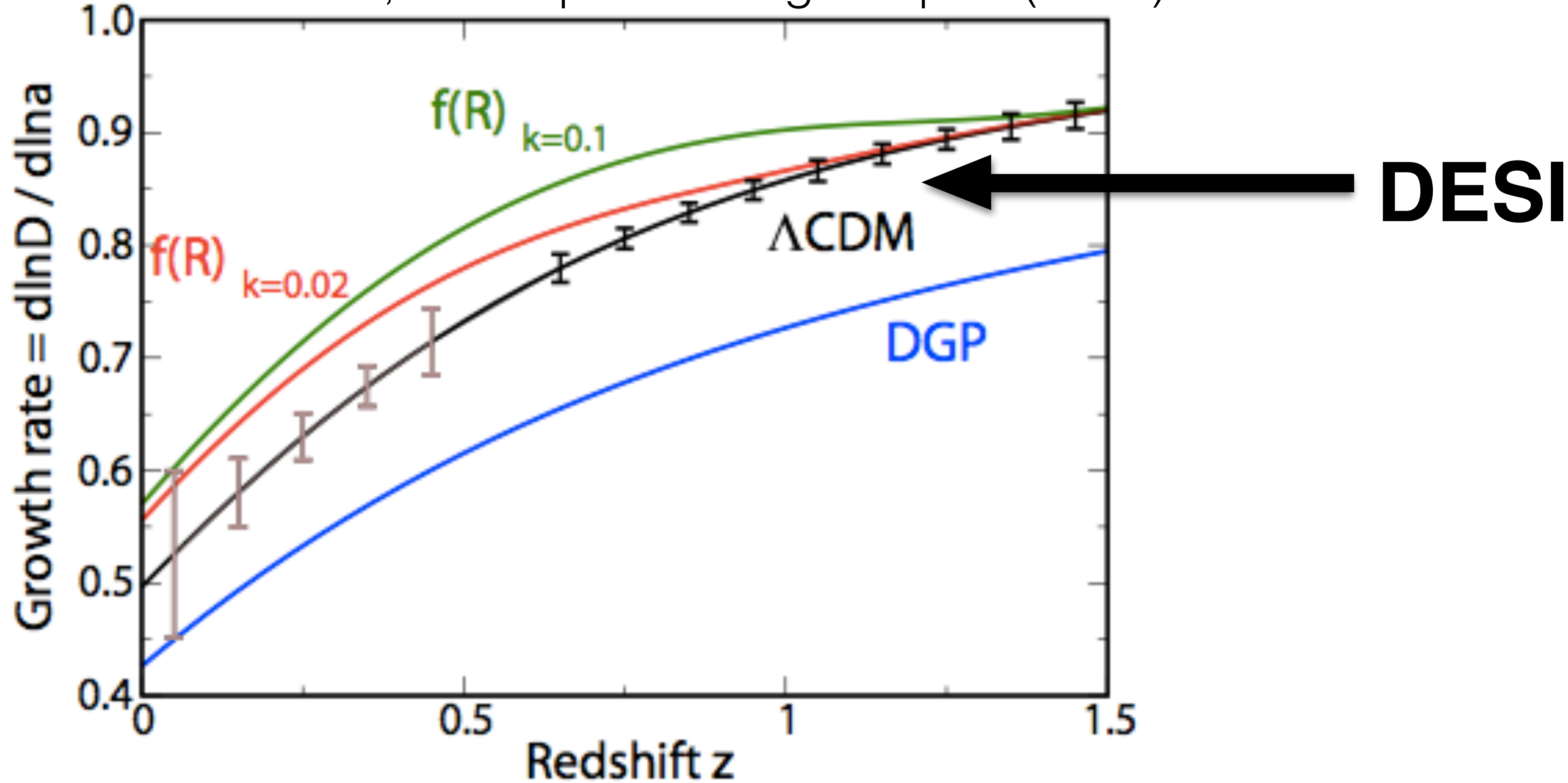


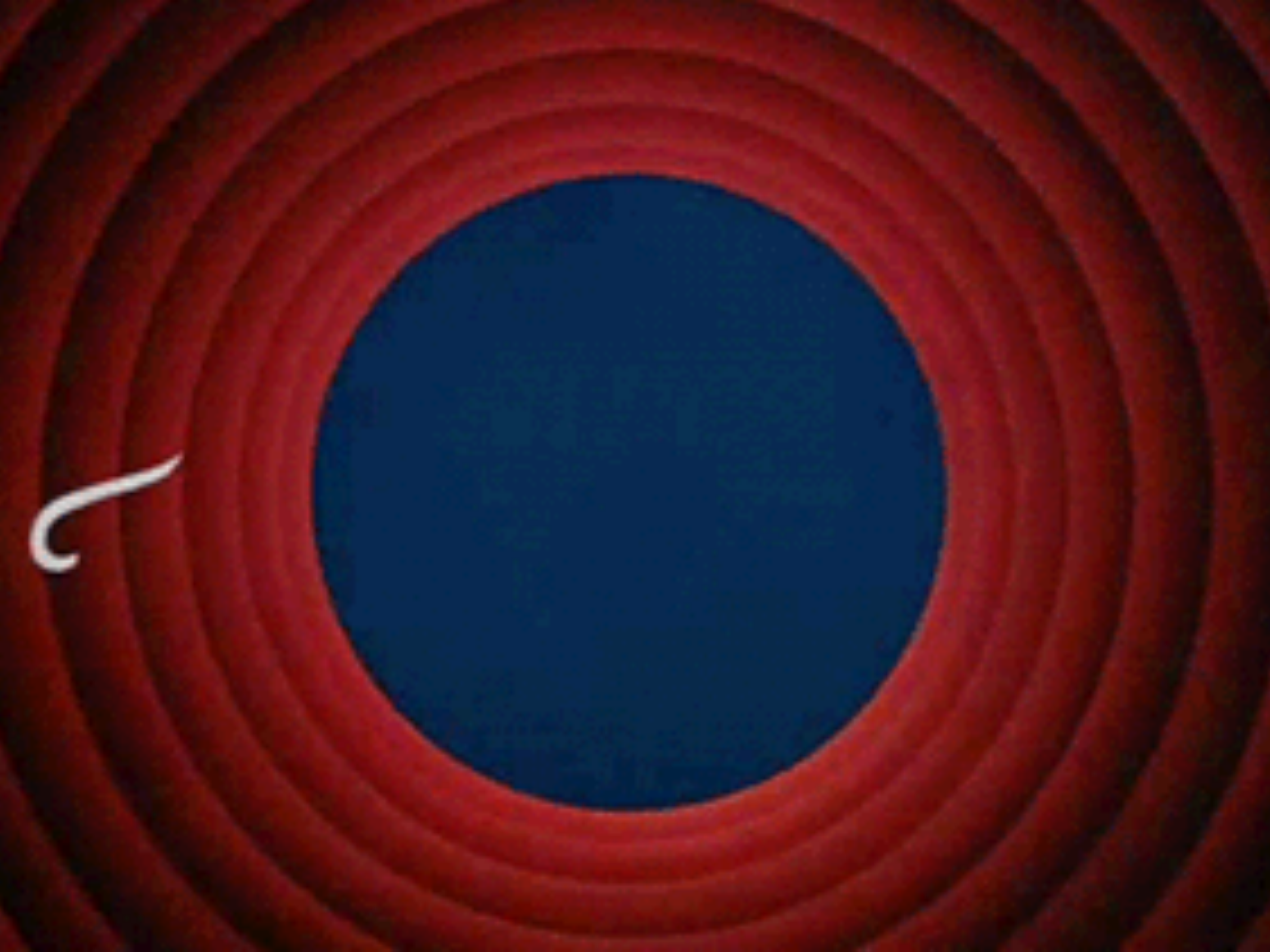
Figure 2.12: Growth of structure, f, as a function of redshift, showing projected DESI measurements and their ability to discriminate against alternative gravity models, $f(R)$ (whose scale-dependent growth we show evaluated at two different scales) and DGP. The brown (light) error bars at $z < 0.5$ correspond to DESI Bright Galaxy Survey; these are expected to improve when information from the multiple tracers in the BGS is included. Adopted from the Snowmass report on the growth of cosmic structure [59].

Conclusions

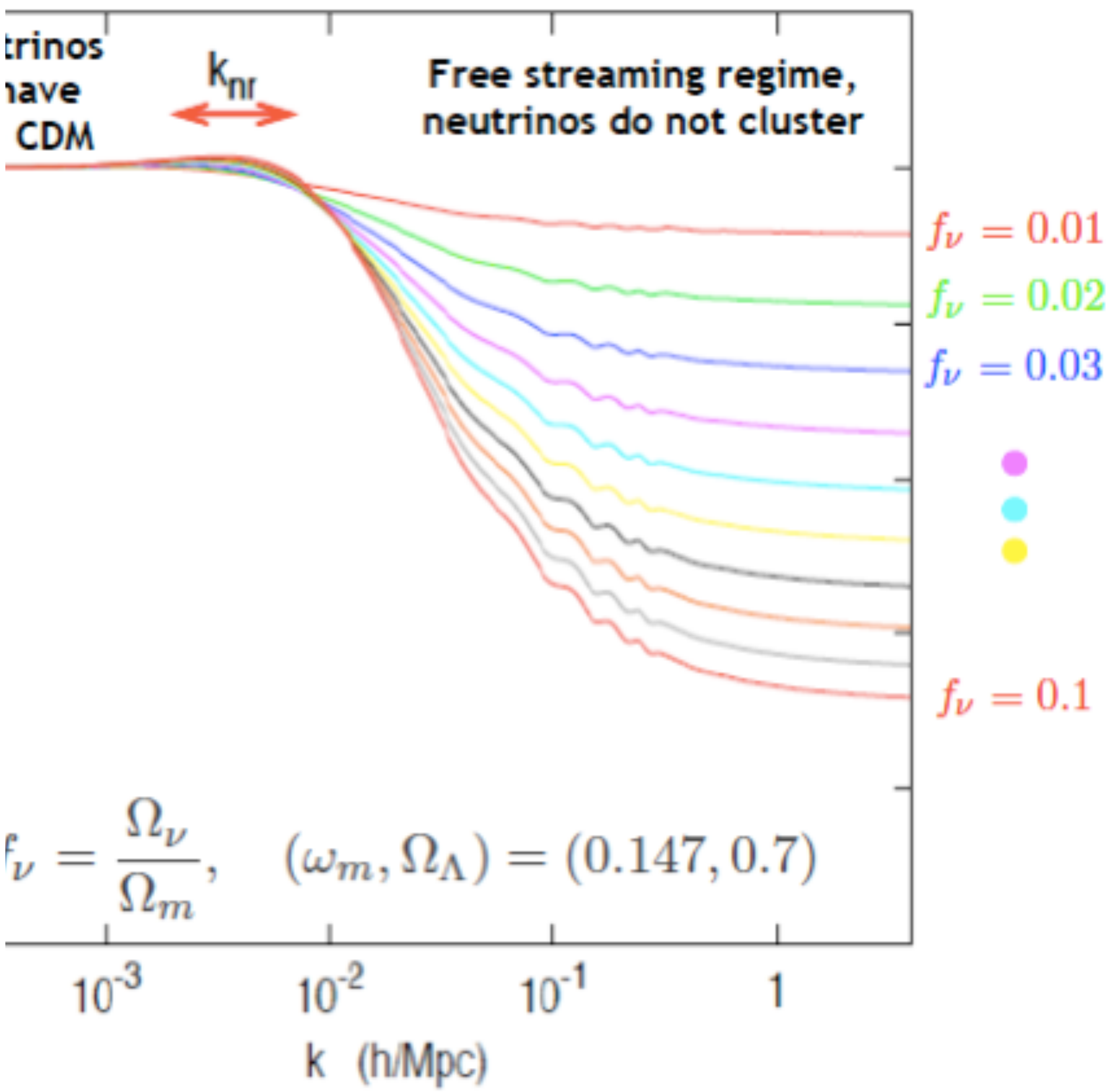
- We have entered the age of **precision cosmology** !
- **Constraints on the expansion rate** are at the **few %** level now and future projects will bring this to **sub percent level.**
- Measurements of the growth of structures provide complementary constraints. Comparison to the expansion rate may hold clues as to the nature of Dark Energy.
- **Everything is consistent with w=-1, cosmological constant**, but the data is just now getting good enough to seriously explore non-ΛCDM models (for example modified gravity, non-zero wa)
- **Strongest constraints come from combined probes, and wavelengths.**
- Many **experiments coming next decade**, an incredible amount of data !!
- Future projects such as DESI, LSST, EUCLID, WFIRST and stage 4 CMB will provide **new constraints on dark energy and neutrino mass in the next decade.**

"For the past 13 years, we've had a simple model of how dark energy works. But the truth is, we only have a little bit of data, and we're just beginning to explore the times when dark energy turned on. If there are surprises lurking out there, we expect to find them."

–DAVID SCHLEGEL



Neutrinos



ourgues & Pastor, Phys. Rept. 429, 307, 2006

Due to their large thermal velocities, $v_{\rm th}(z)$, neutrinos do not cluster at scales smaller than the free-streaming scale $k_{\rm FS}(z) \sim H(z)/v_{\rm th}(z)$. For neutrinos turning non-relativistic in the matter dominated regime, the comoving free-streaming scale has a maximum value at the time when the neutrinos become relativistic. Thus, at length scales larger than those set by this maximum, $k_{\rm nr}$, neutrinos cluster in the same way as dark matter, while at smaller scales their contribution to clustering is much smaller, leading to a suppression of the total matter power spectrum. In linear perturbation theory this suppression increases with increasing wave-number asymptoting to a value of $\sim 8\Omega_\nu/\Omega_{\rm m}$. Since this effect can be observed at length scales too small for linear perturbation theory to hold, it is essential to compute the nonlinear matter power spectrum [34].

Neutrinos

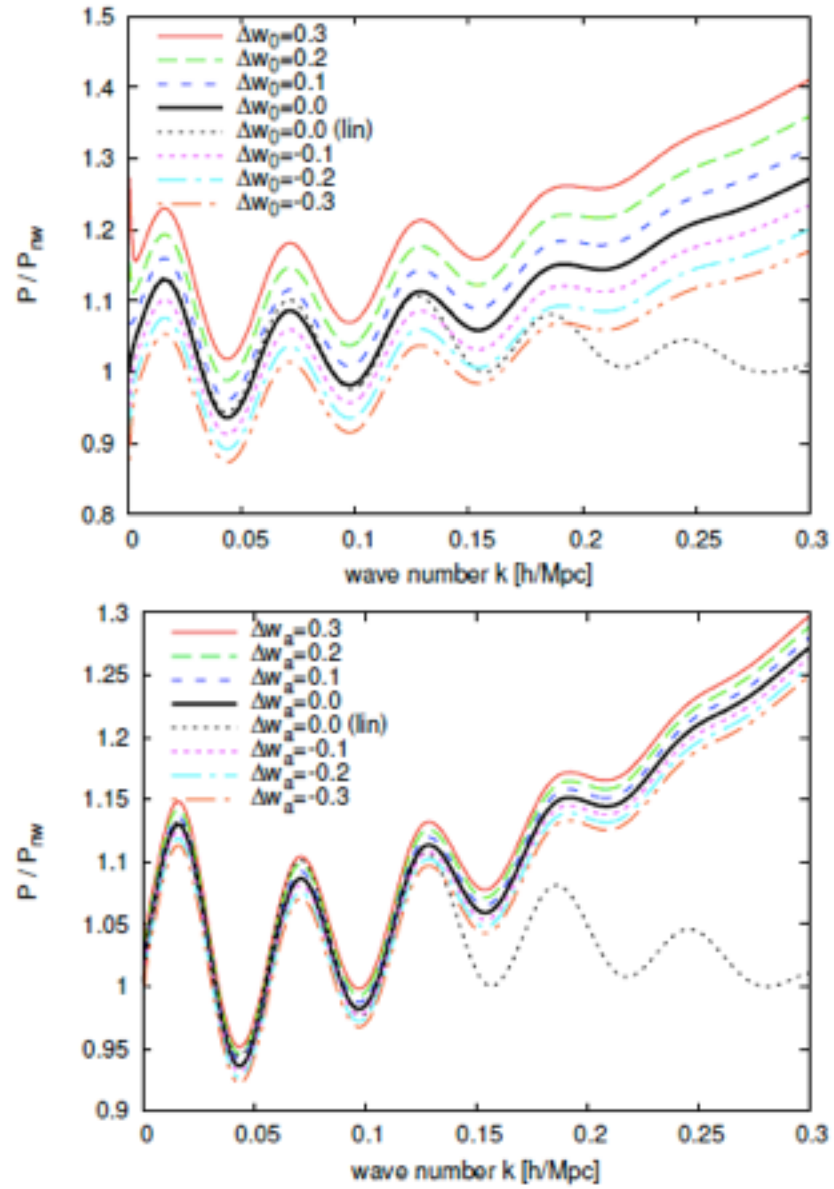


FIG. 6: Effects of varying w_0 (top) and w_a (bottom) on the Time-RG matter power spectrum $P(k)$ at $z = 1$. The fiducial model Δw_0, $\Delta w_a = 0$ is M000n0 in Table 1. $P(k)$ has been divided by the no-wiggle power spectrum (29) for clarity.

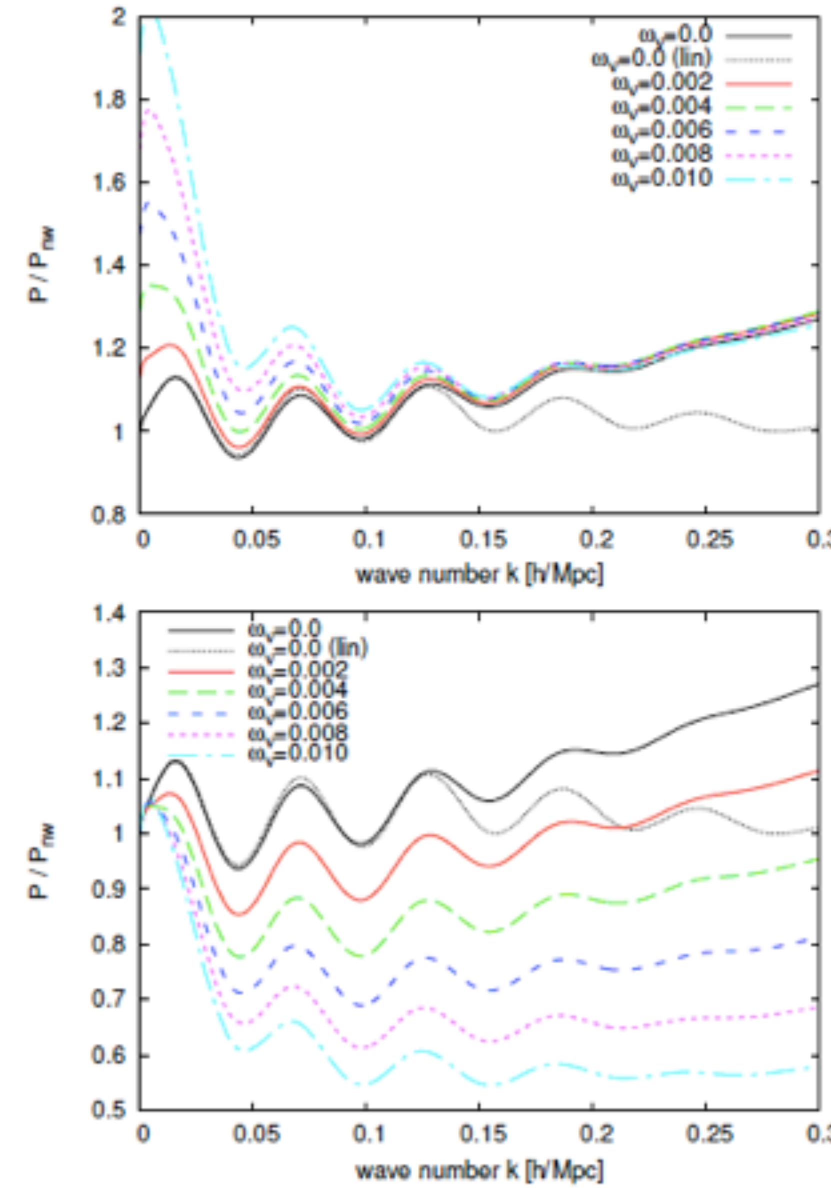


FIG. 7: Effects of varying ω_ν on the Time-RG matter power spectrum at $z = 1$. In each case the M000n0 values of ω_m, n_s, h, w_0, and w_a are assumed. Top: $\sigma_8 = 0.8$ is fixed for all of the models. Bottom: All models are normalized to the same low-k value.