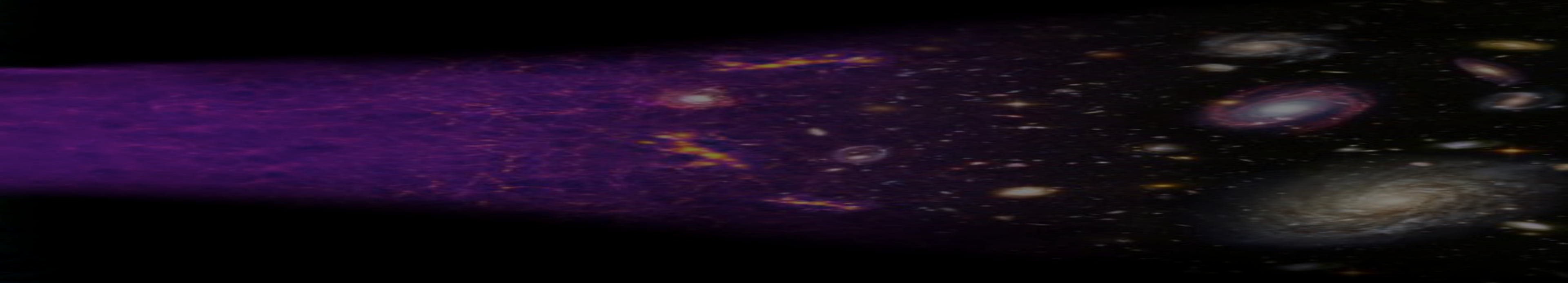


Observing the dark:
Cosmological constraints on theories of gravity

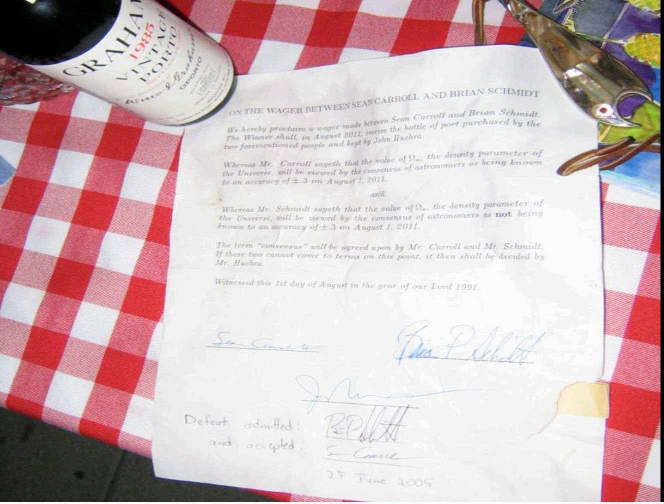
For more detail please see the review article I wrote, which covers most of the content of this talk:
http://adsabs.harvard.edu/abs/2014GReGr..46.1731D

Tamara Davis

University of Queensland, Brisbane, Australia

ARC Centre of Excellence in All-sky Astrophysics


Artist's Concept



ON THE WAGER BETWEEN SEAN CARROLL AND BRIAN SCHMIDT

We hereby proclaim a wager made between Sean Carroll and Brian Schmidt. The Winner shall, in August 2011, receive the bottle of port purchased by the two forementioned people and kept by John Huchra.

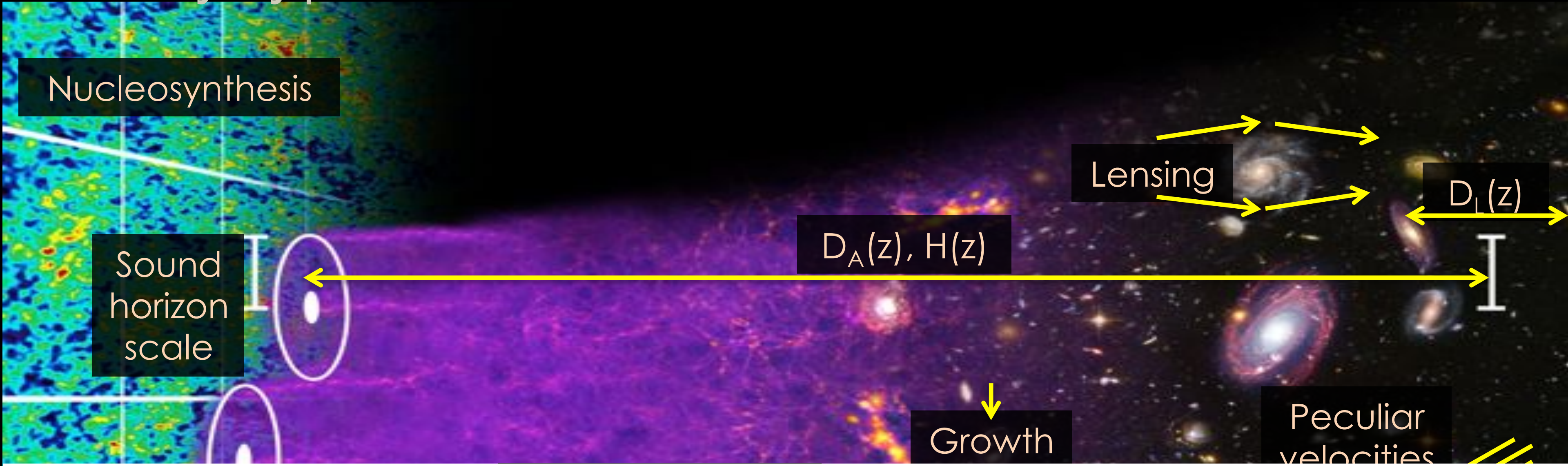
Whereas Mr. Carroll sayeth that the value of Ω_0, the density parameter of the Universe, will be viewed by the consensus of astronomers as being known to an accuracy of ±0.3 on August 1, 2011.

Whereas Mr. Schmidt sayeth that the value of Ω_0, the density parameter of the Universe, will be viewed by the consensus of astronomers as **not** being known to an accuracy of ±0.3 on August 1, 2011.

The term “consensus” will be agreed upon by Mr. Carroll and Mr. Schmidt. If these two cannot come to terms on this point, it then shall be decided by Mr. Huchra.

Witnessed this 1st day of August in the year of our Lord 1991.

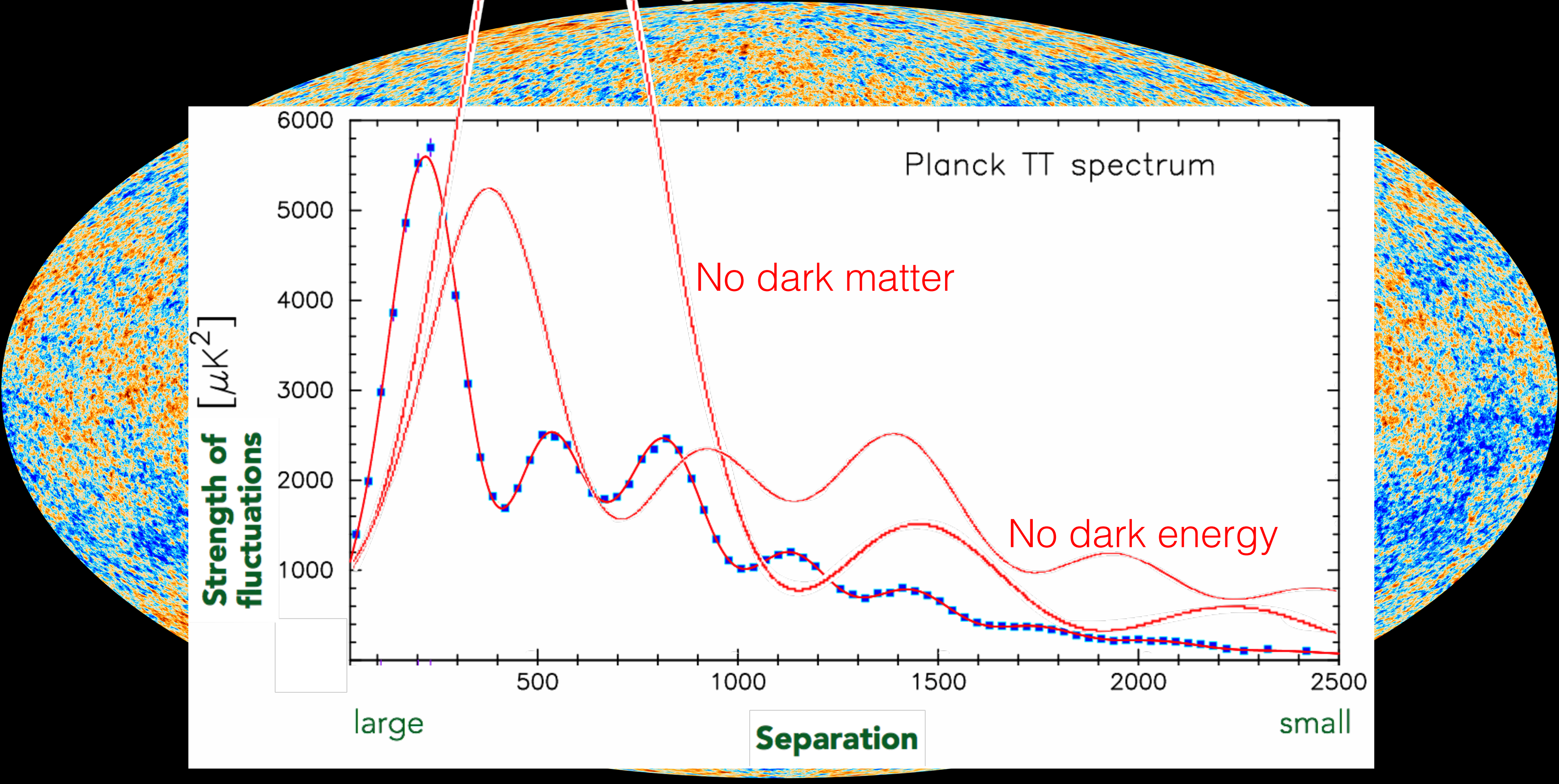
Many types of observations = concordance



Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010 (0.9% precision)
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.967		0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040

Planck collaboration, 2015

Planck - Cosmic Microwave Background



Overview

Review evidence for acceleration

Review methods by which we can distinguish dark energy models

1. Supernovae + lensing thereof
1a. Time dilation
2. Cosmic Microwave Background
2a. Fluctuations
2b. Sunyaev-Zeldovich Cluster Counts
2c. Integrated Sachs Wolfe Effect
3. Large Scale Structure
3a. Baryon Acoustic Oscillations
3b. Growth of Structure
3c. Alcock-Paczynski effect, H(z)
3d. Homogeneity
3e. Peculiar velocities
4. Gravitational Lensing
4a. Strong Gravitational Lensing
4b. Weak Gravitational Lensing

etc...

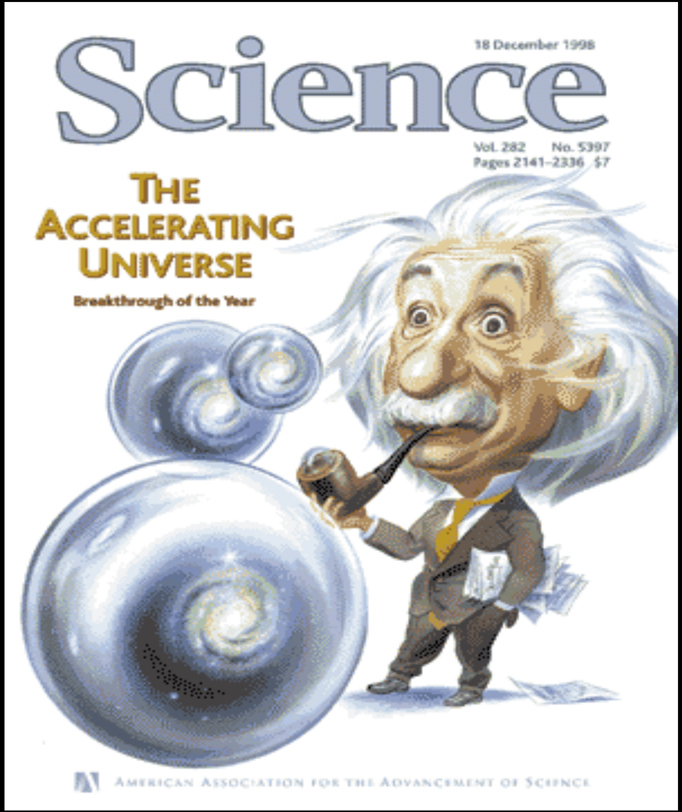
- X-ray clusters
- Baryogenesis
- Solar System Tests
- Galaxy ages vs redshift....

Evidence for dark energy

1. SUPERNOVAE

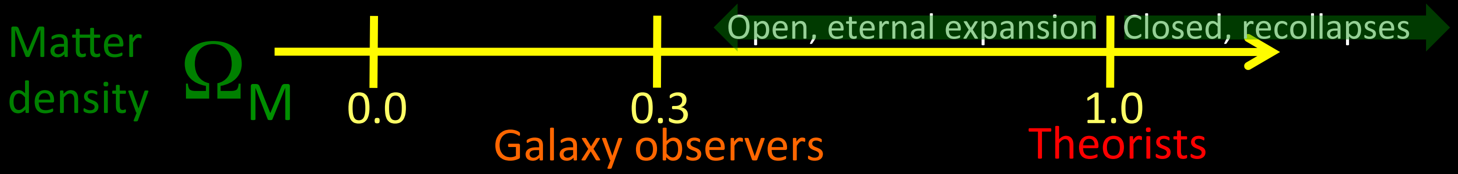
Acceleration was accepted very quickly

- Science's breakthrough of the year in 1998
  - (Riess et al. 1998, Perlmutter et al. 1999)
- How was such an astonishing discovery accepted so quickly?
- TWO TEAMS helped. But there was more…

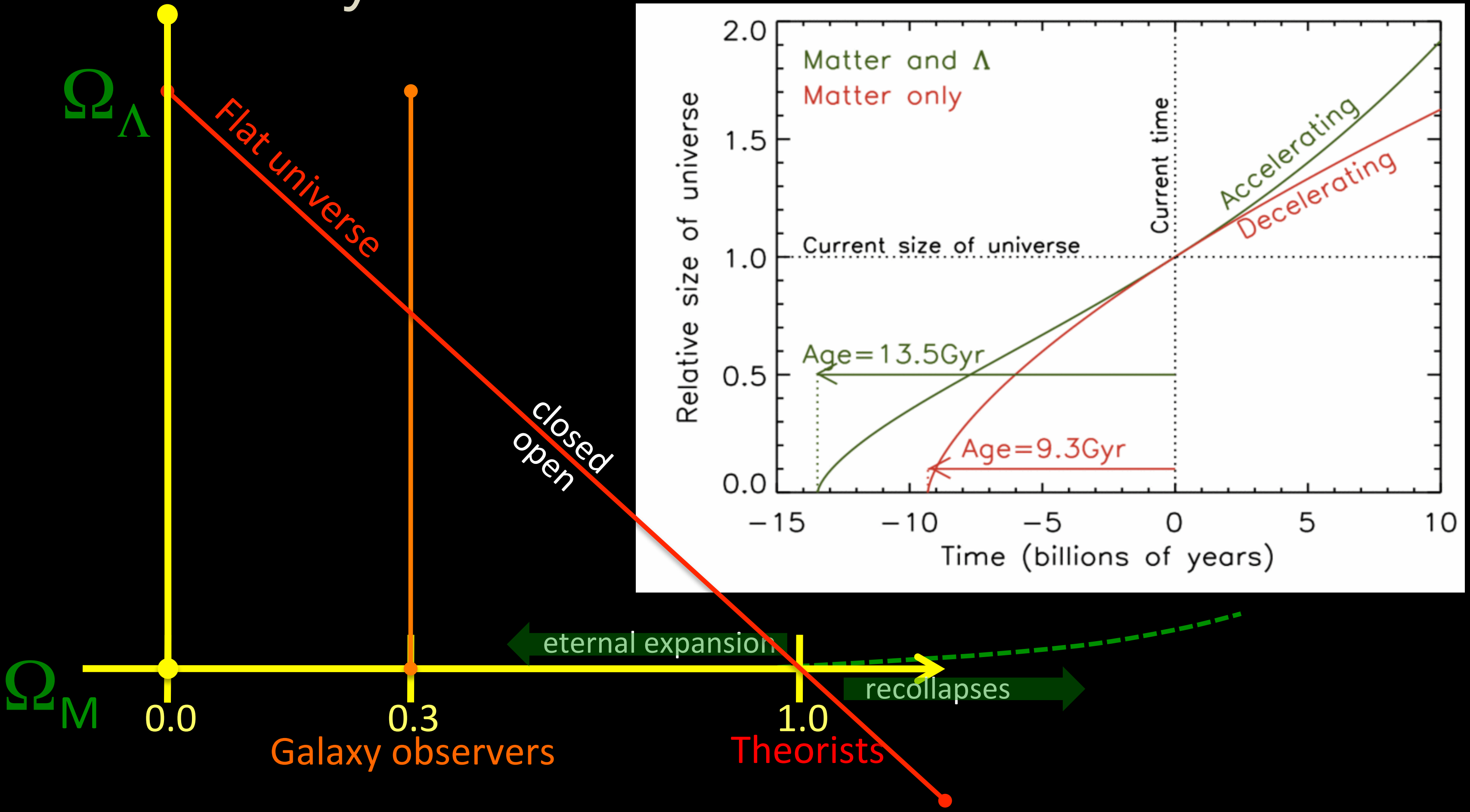


Think back 20 years….

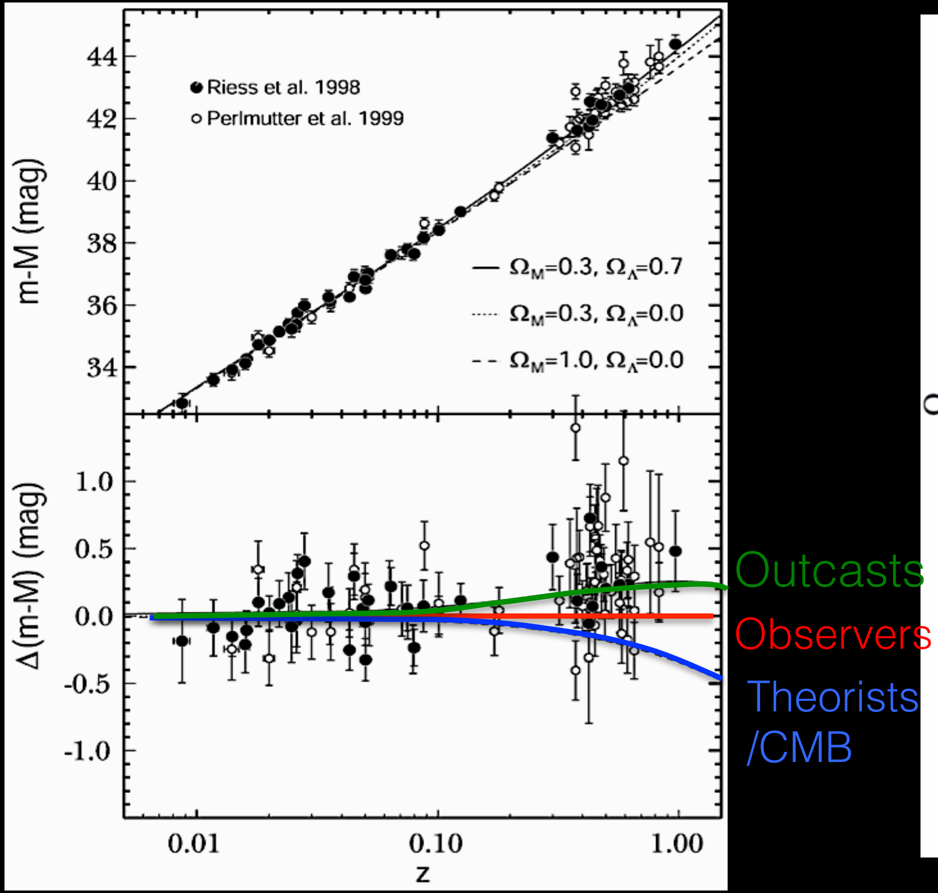
- Several problems with cosmology:
  - The universe was younger than the oldest stars
  - The number of galaxies at high redshift was too large
  - The amount of matter in the universe didn't add up
    - Theorists had good reason to believe $\Omega_{tot}=1$ (a prediction of inflation)
    - But galaxy observers could only find $\Omega_M=0.3$ (including dark matter)

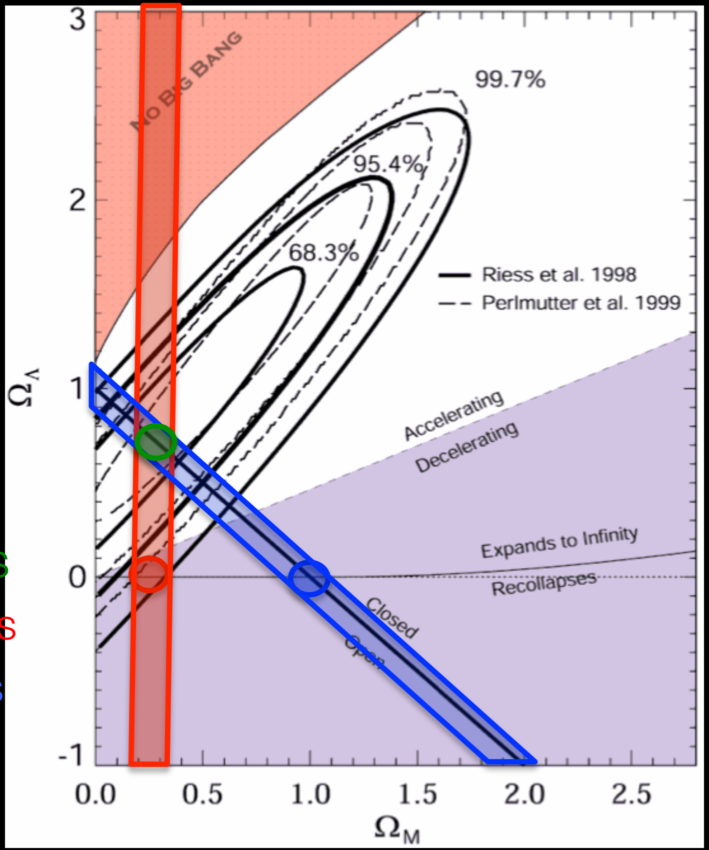


All solved by acceleration



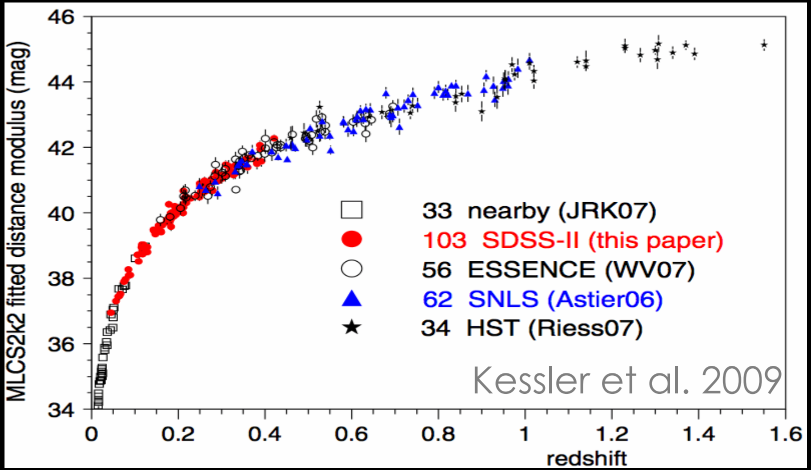
First supernova results

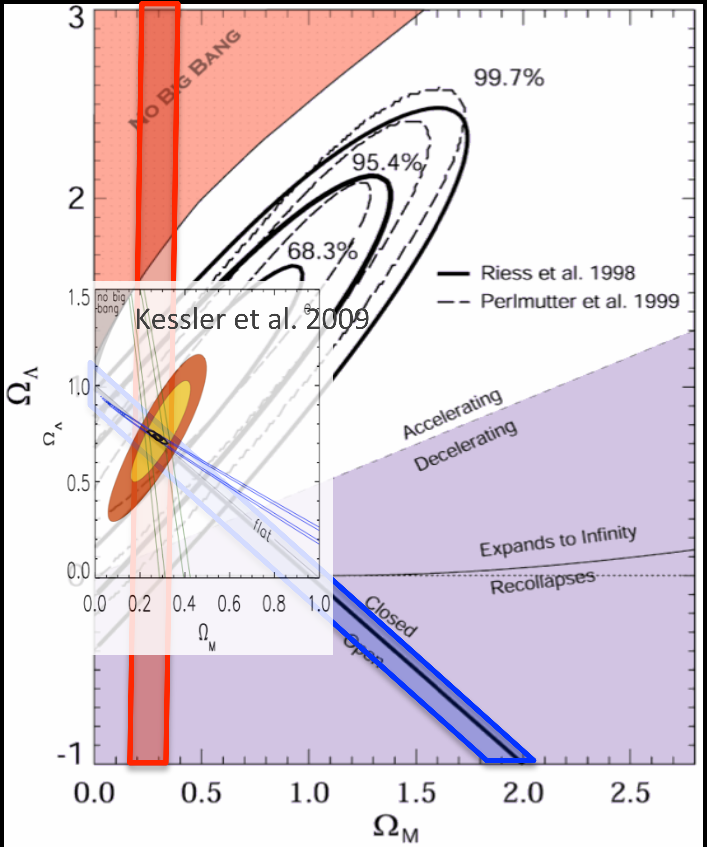




Perlmutter and Schmidt 2003

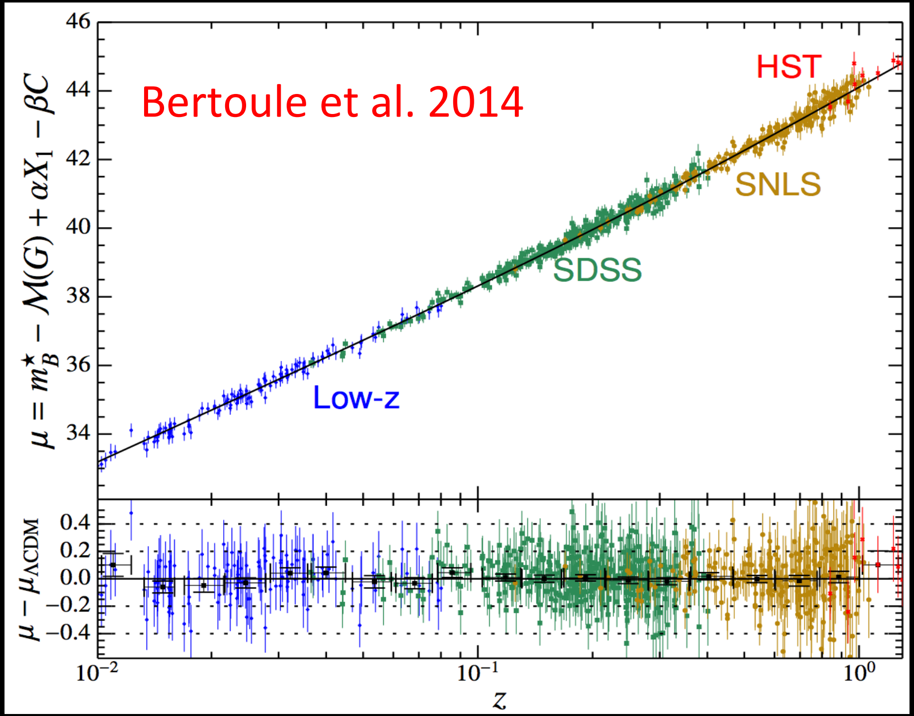
Newer supernova results

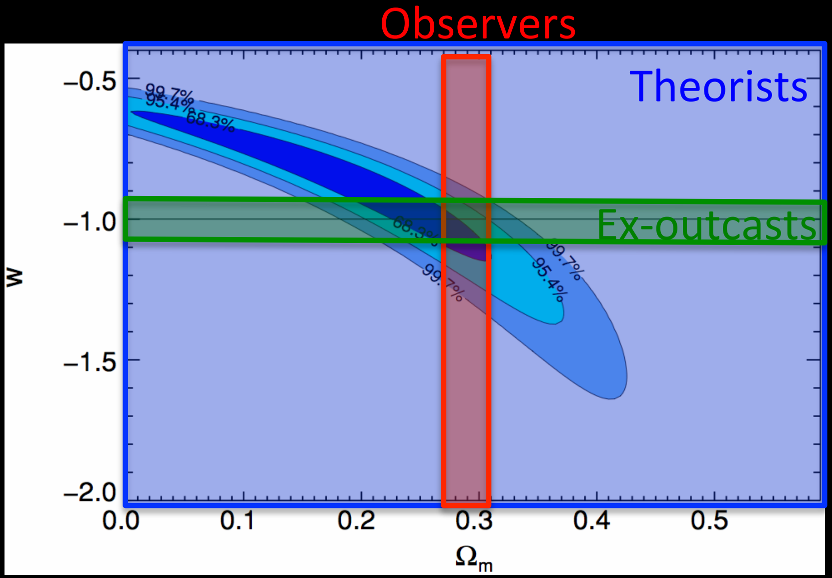




Perlmutter and Schmidt 2003

Even newer supernova results





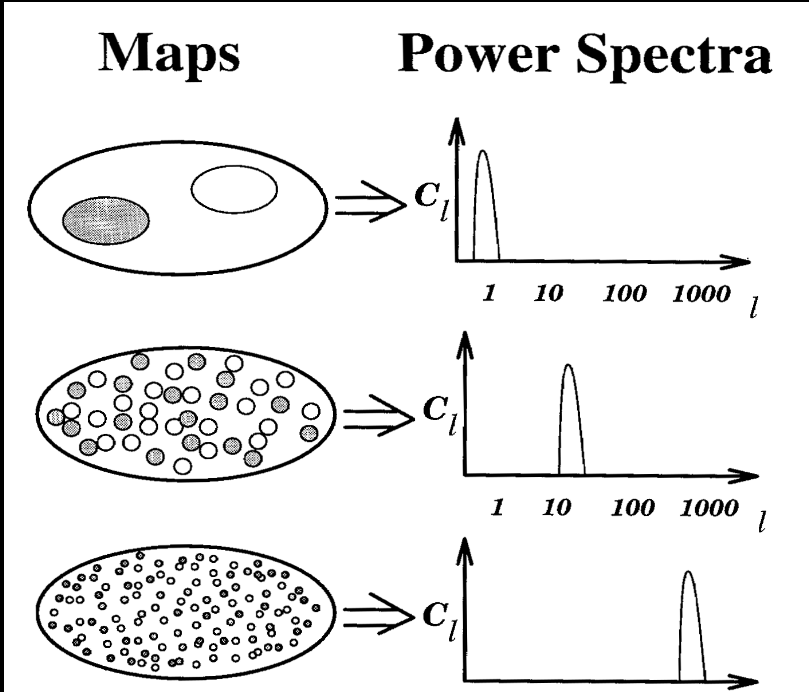
Equation of state of dark energy

w = pressure / density
w = -1 for Λ
(cosmological constant)
(vacuum energy)

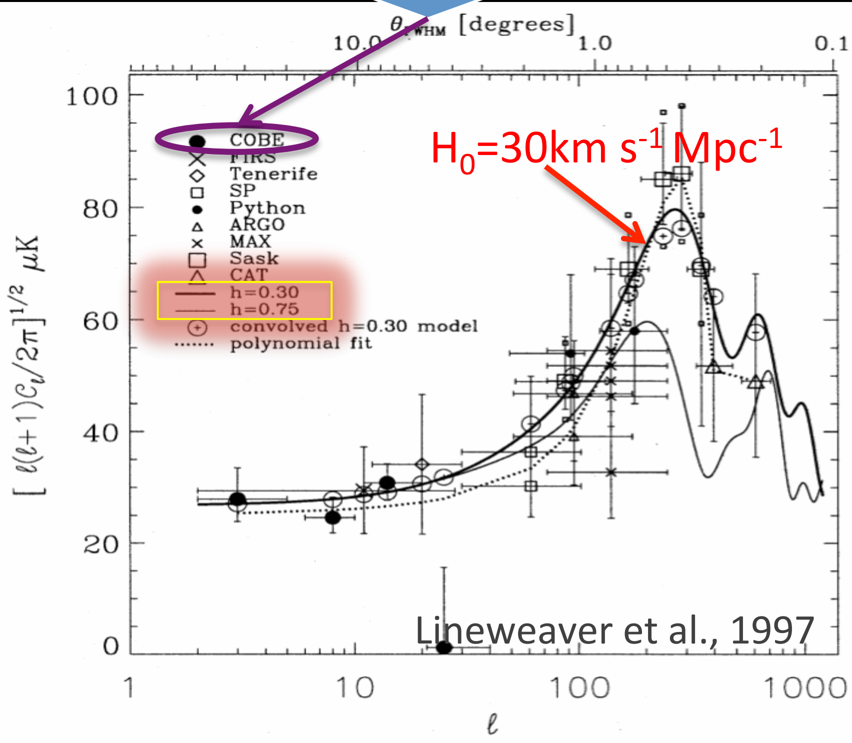
Constraining parameters of our cosmological model

2A. COSMIC MICROWAVE BACKGROUND - POWER SPECTRUM

Early CMB results

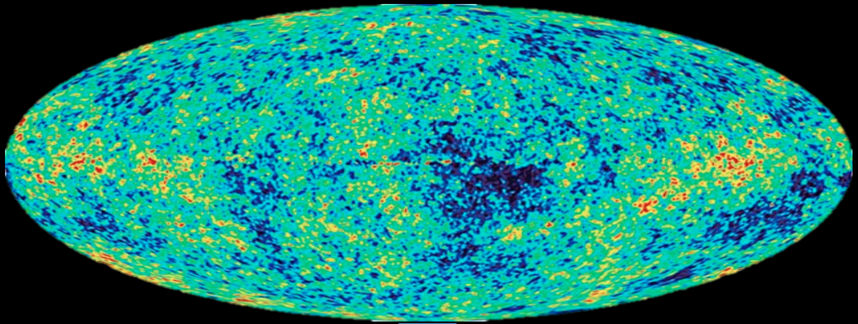


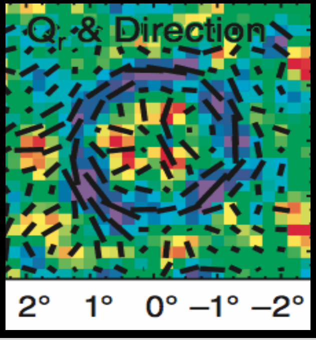
Lineweaver et al., 1997



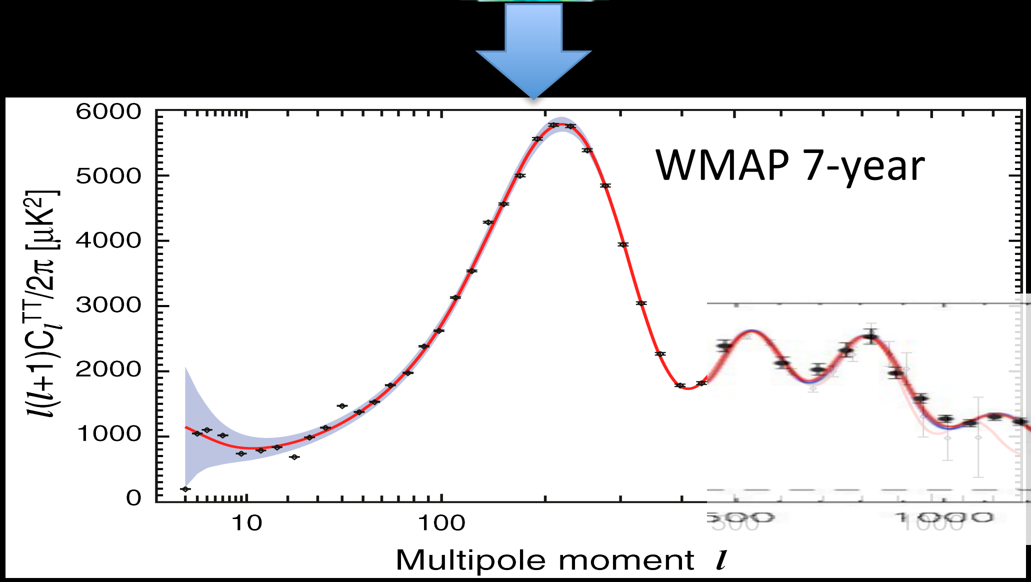
Lineweaver et al., 1997

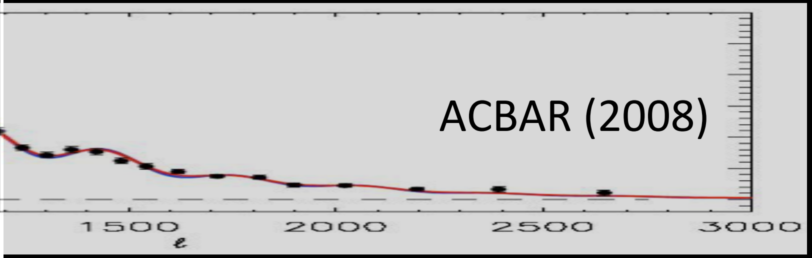
Intermediate CMB results – WMAP++



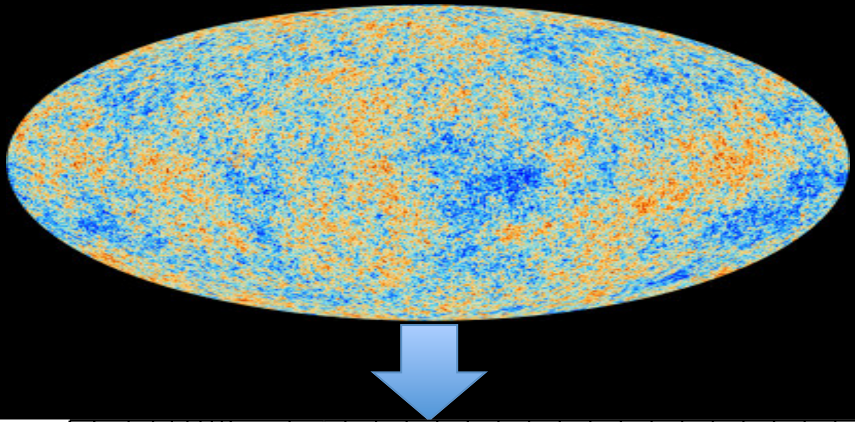


Polarisation detected

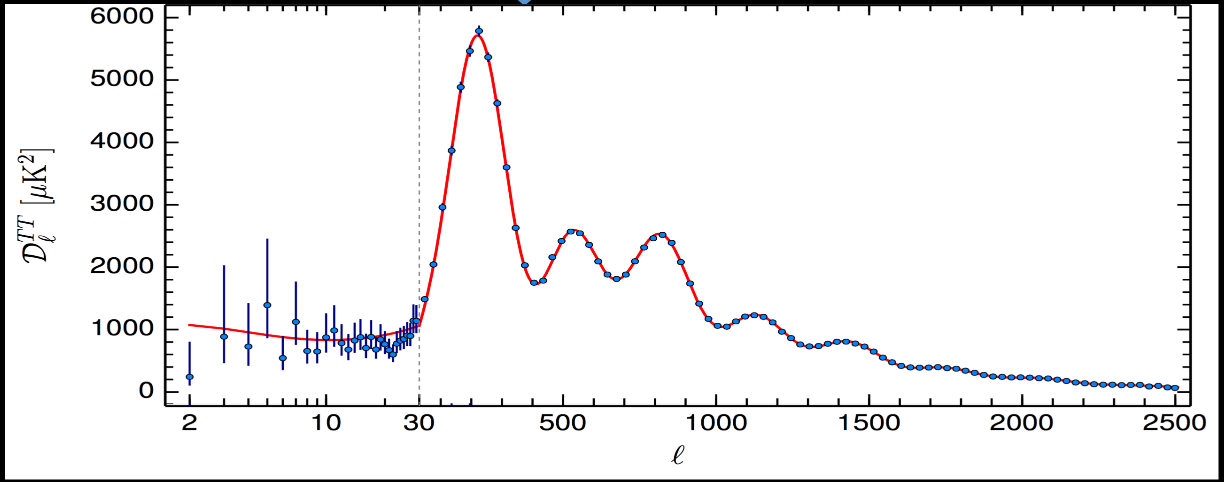




Latest CMB results – Planck ++ (SPT and ACT)



Temperature fluctuations
+ Lensing
+ Polarization



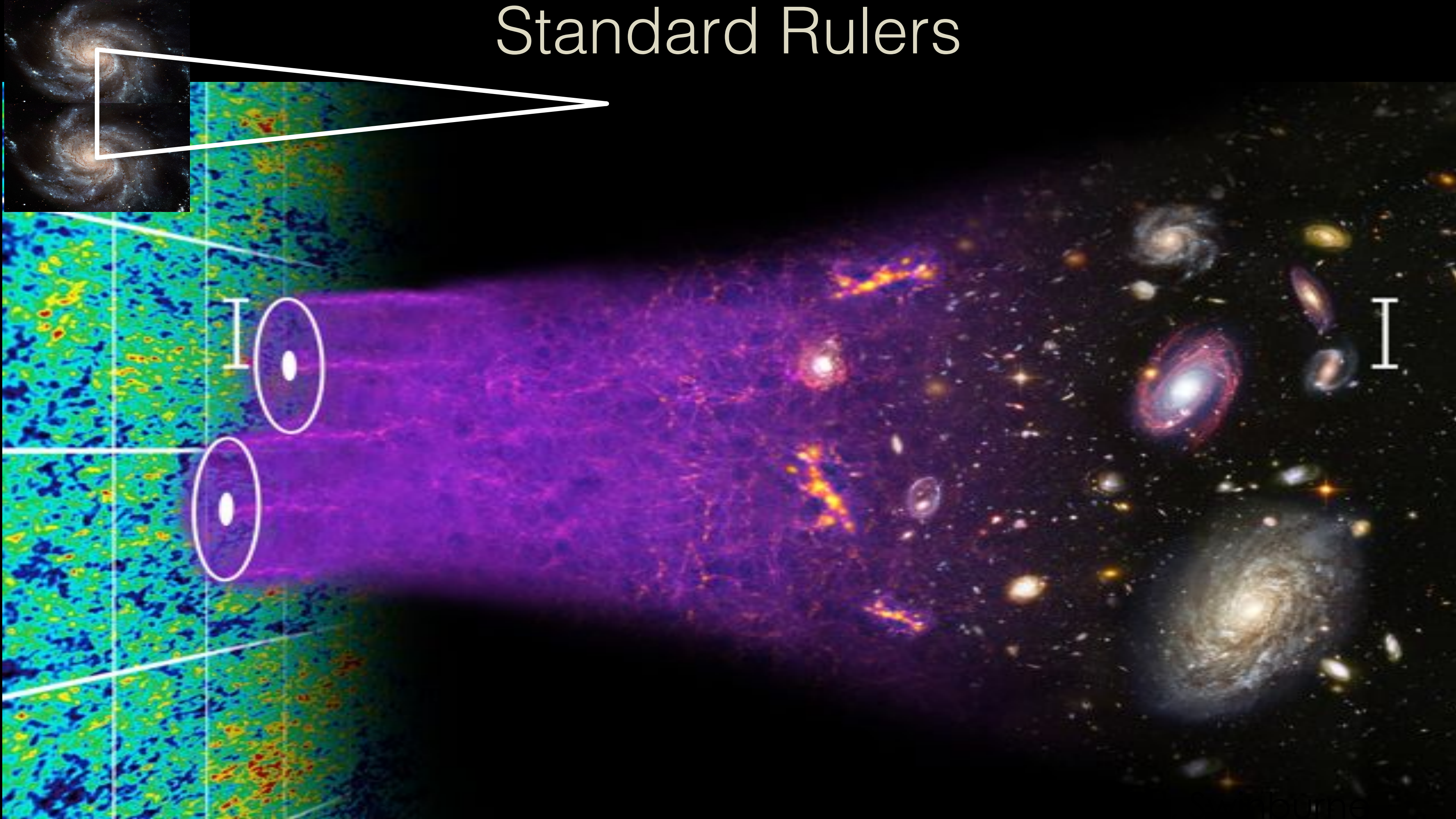
$\Omega_m = 0.308 \pm 0.012$ (4%)
$w = -1.006 \pm 0.045$ (incl. SNe)

Measuring dark energy

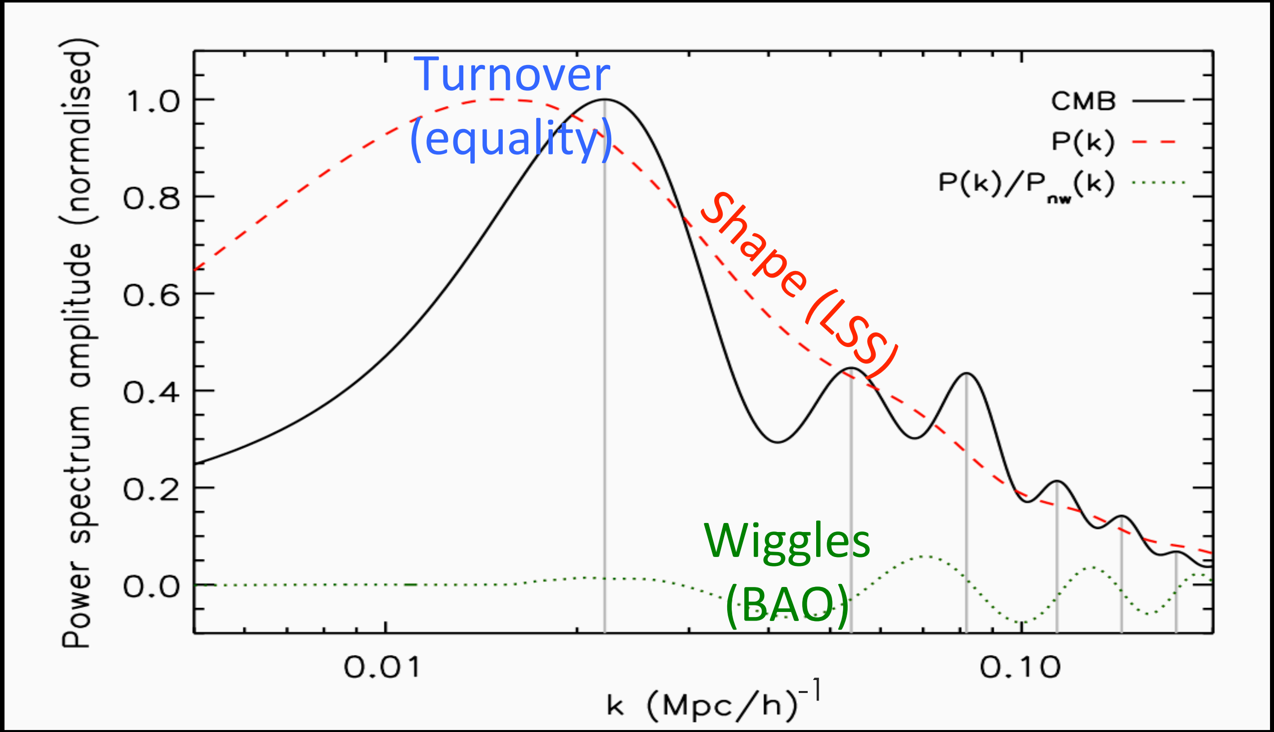
3A. LARGE SCALE STRUCTURE

- BARYON ACOUSTIC OSC.

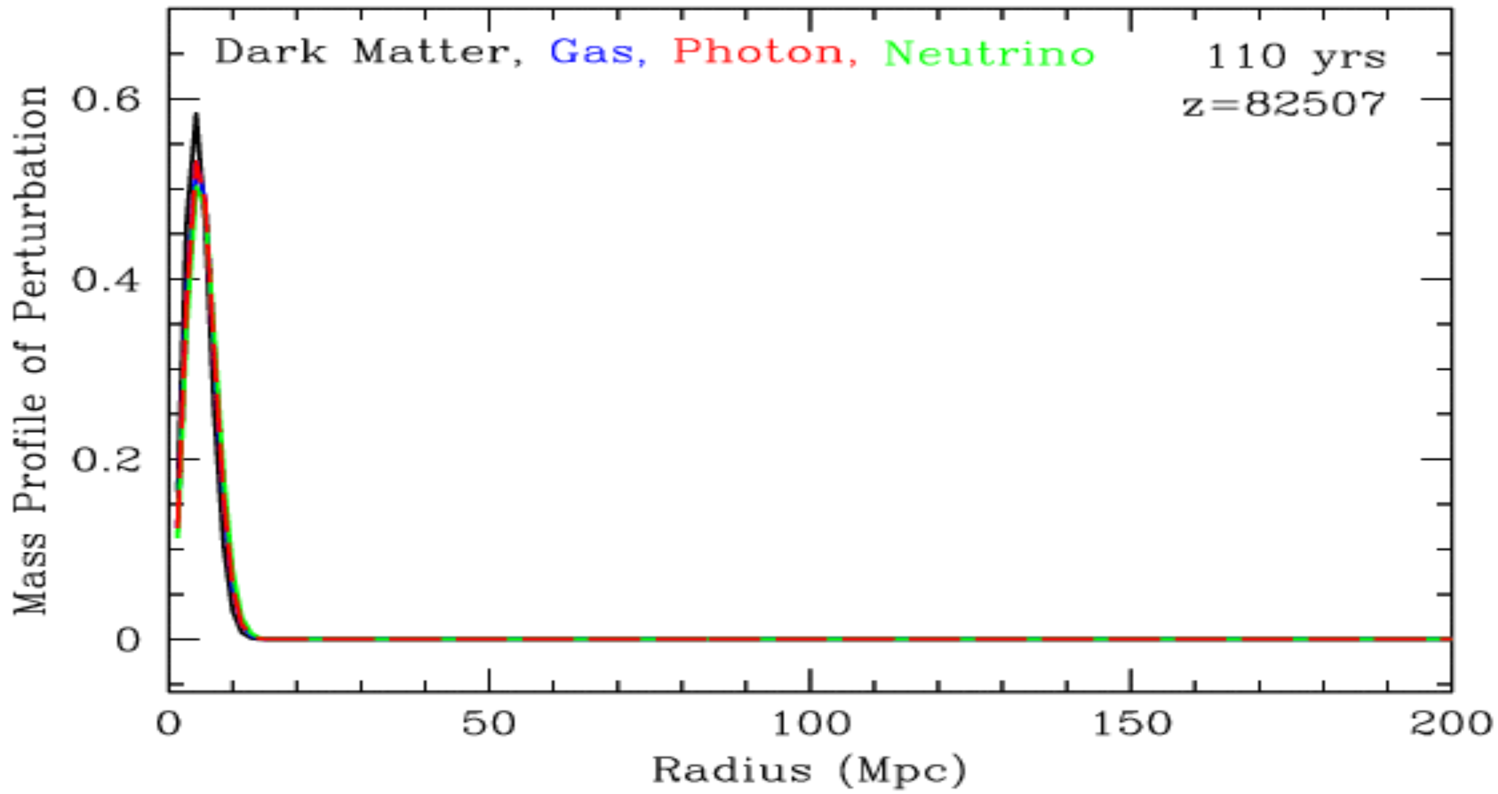
Standard Rulers



Features of power spectrum (compared to CMB)

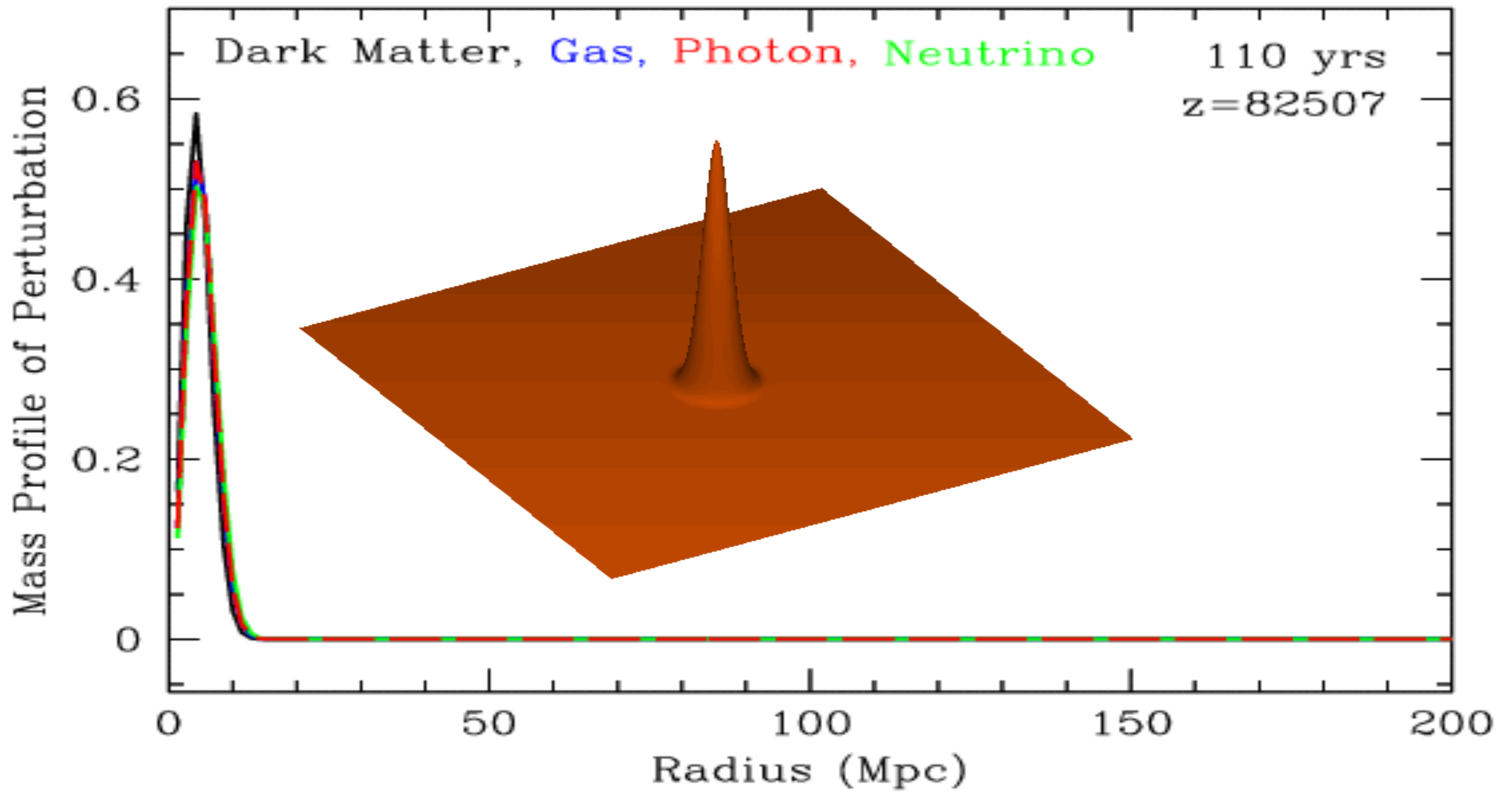


Formation of acoustic peak



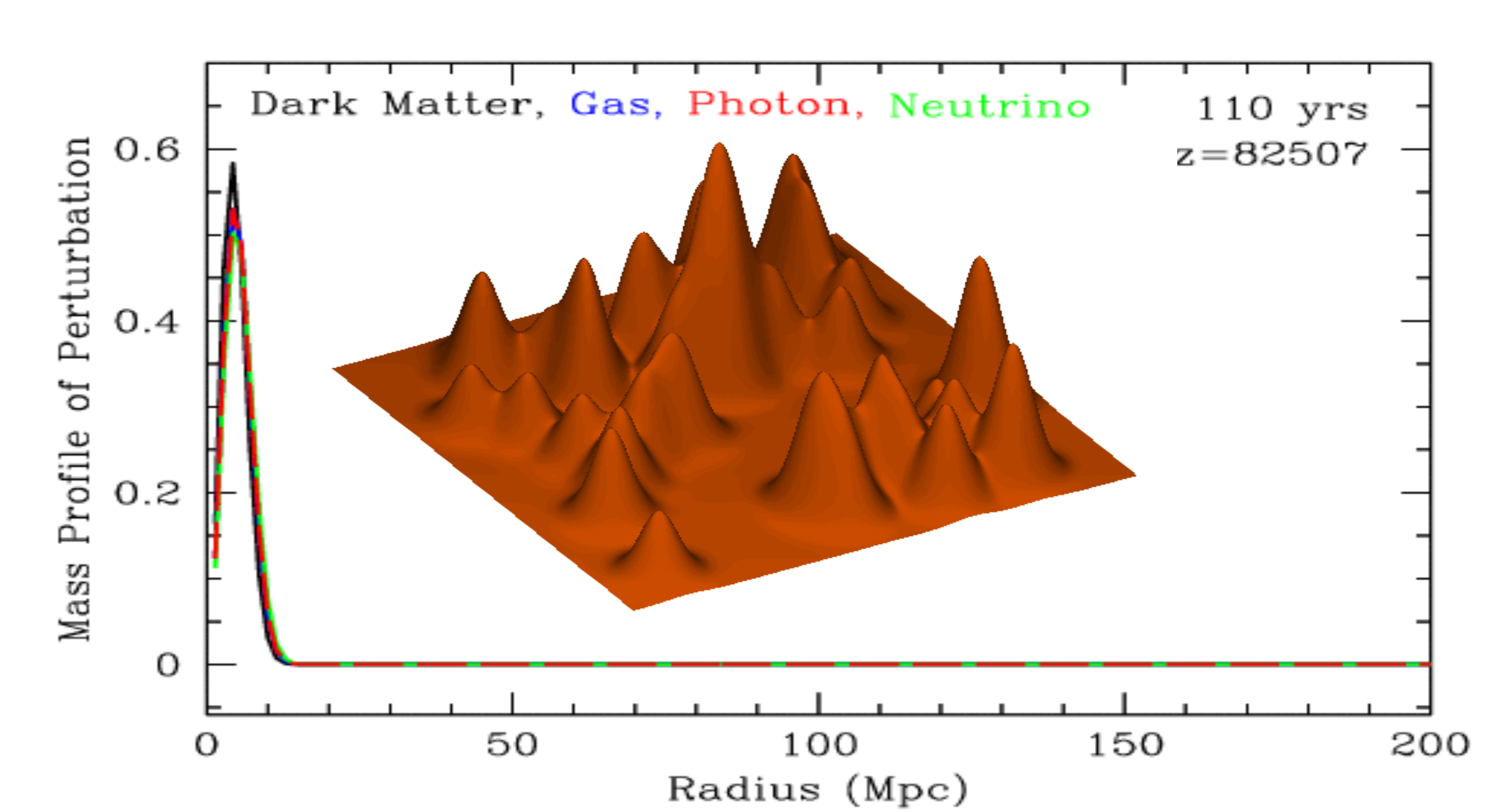
Animation by Daniel Eisenstein: http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

Formation of acoustic peak



Animation by Daniel Eisenstein: http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

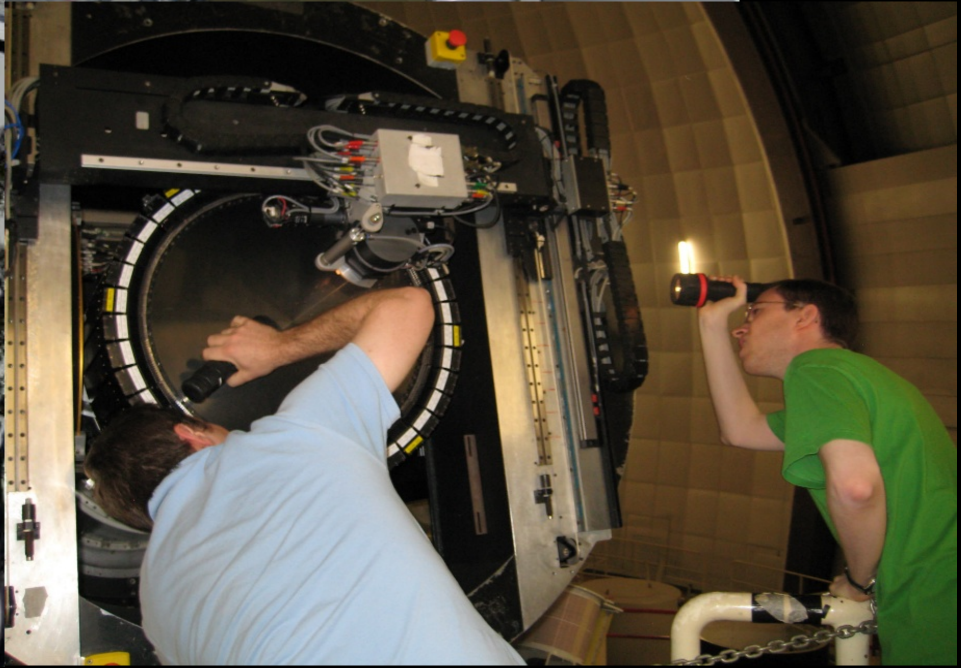
Formation of acoustic peak



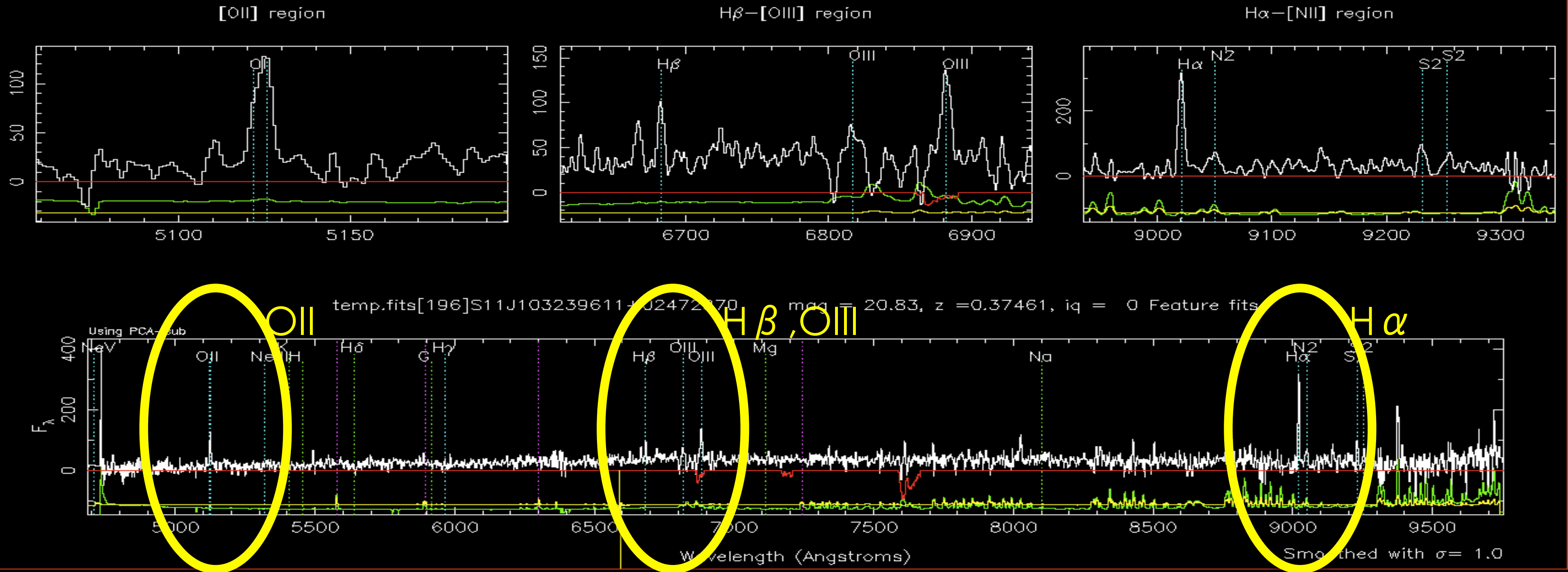
Animation by Daniel Eisenstein: http://cmb.as.arizona.edu/~eisenste/acousticpeak/acoustic_physics.html

Gregory Poole
The GiggleZ Simulation Suite
Swinburne
Centre for Astrophysics and Supercomputing

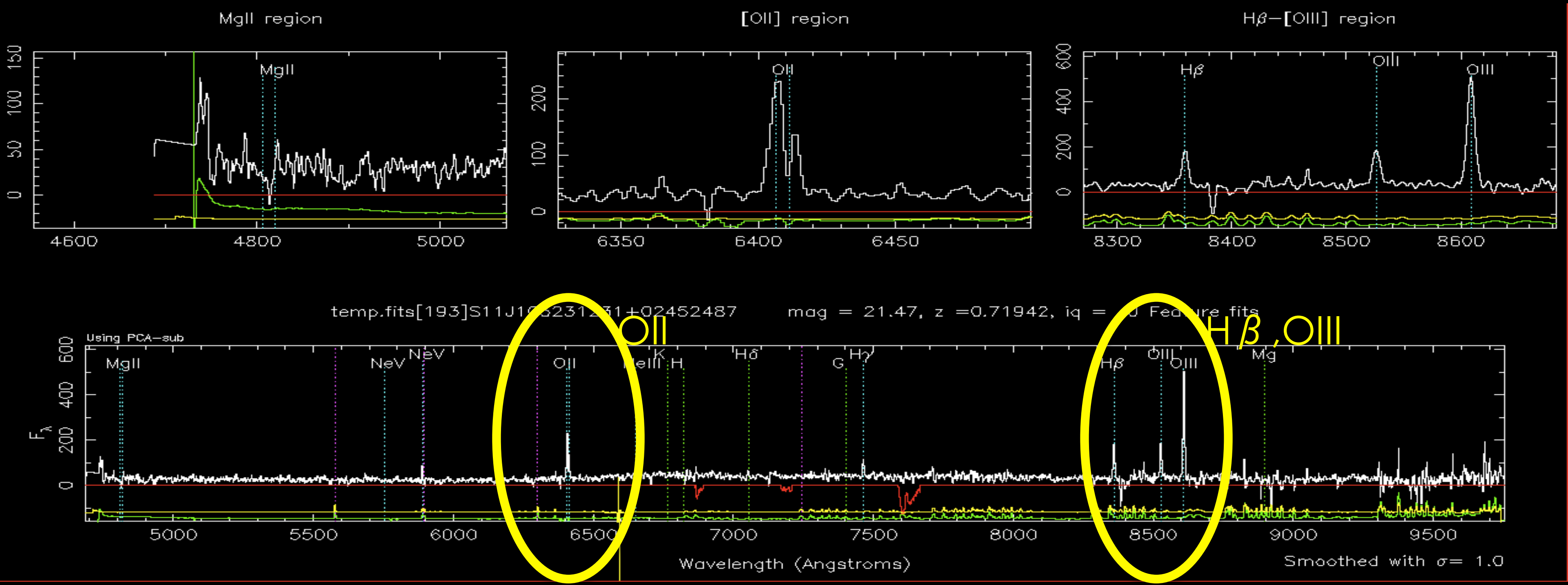




Example spectrum: z=0.37



Example spectrum: z=0.72



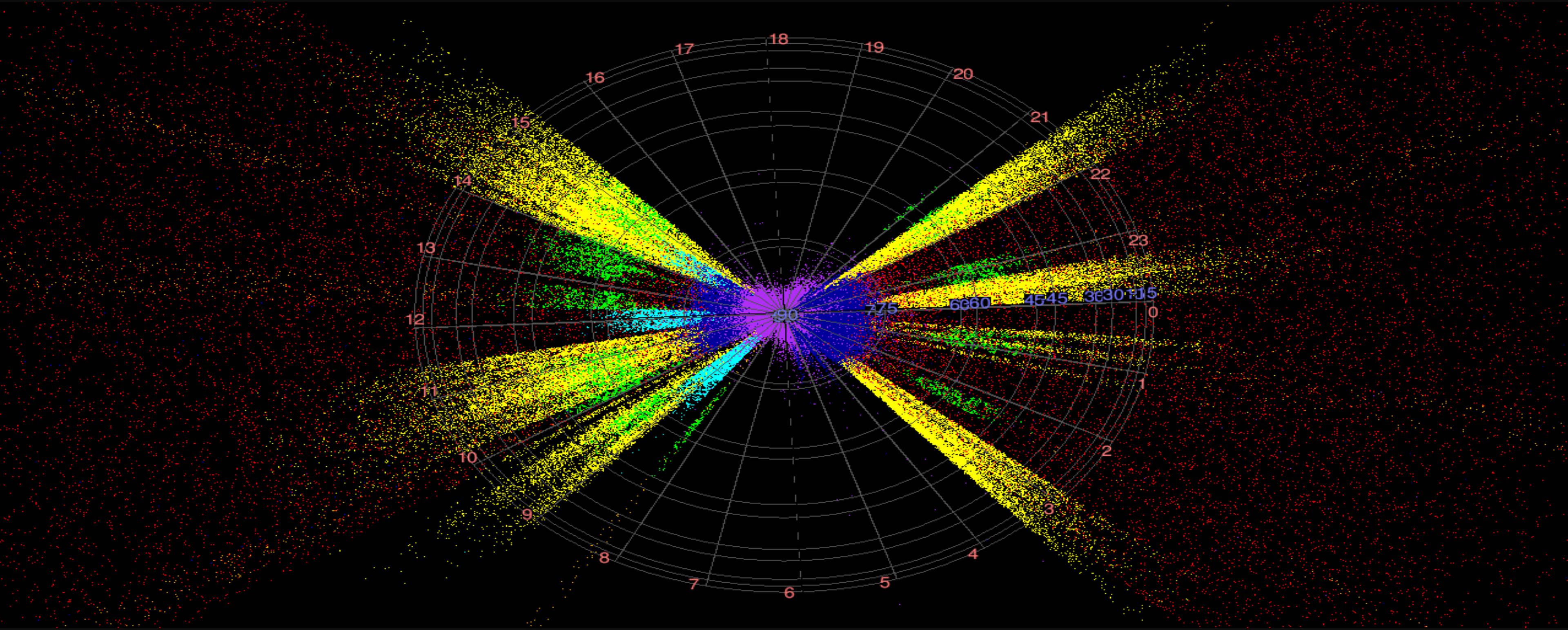
Redshifts become less certain above $z \sim 1$ because we lose $H\beta$

Redshift surveys
(e.g. WiggleZ)

7 equatorial fields, each 100-200 deg^2

>9° on side, ~3 x BAO scale at $z > 0.5$

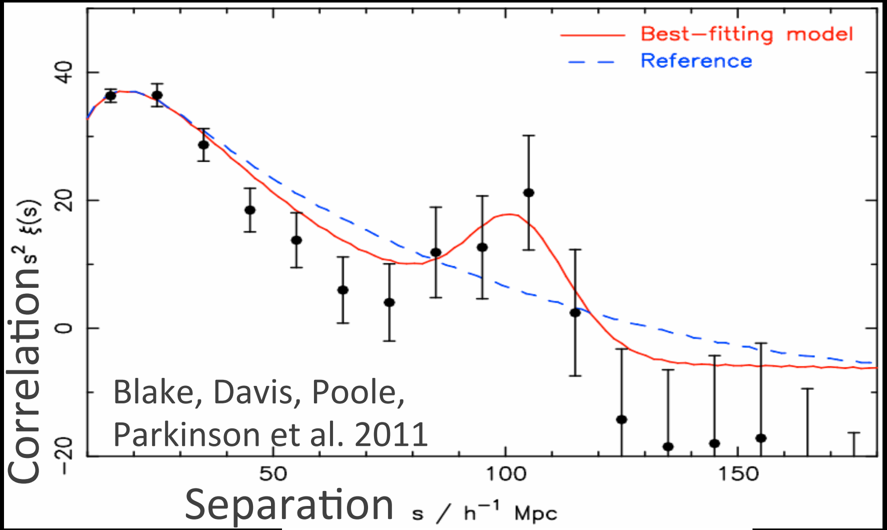
Physical size ~ 1300 x 500 x 500 Mpc/h

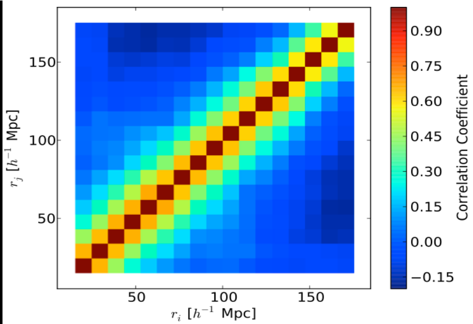


6dFGS (purple), 2dFGRS (blue), MGC (navy), GAMA (cyan), 2SLAQ-LRG (green), WiggleZ (yellow), 2SLAQ-QSO (orange), 2QZ (red); the celestial sphere is at z=1.

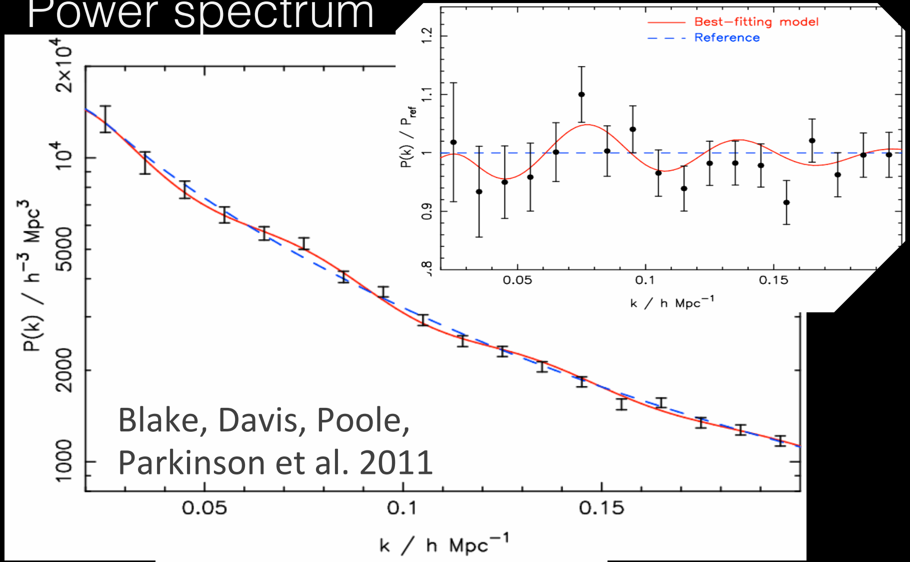
Correlation function vs Power spectrum

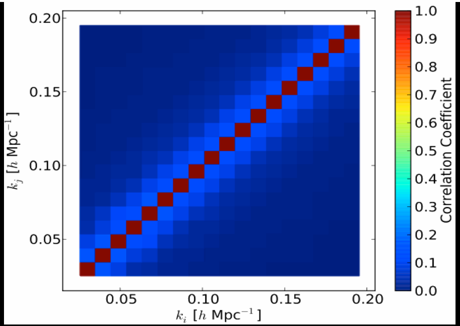
Correlation Function





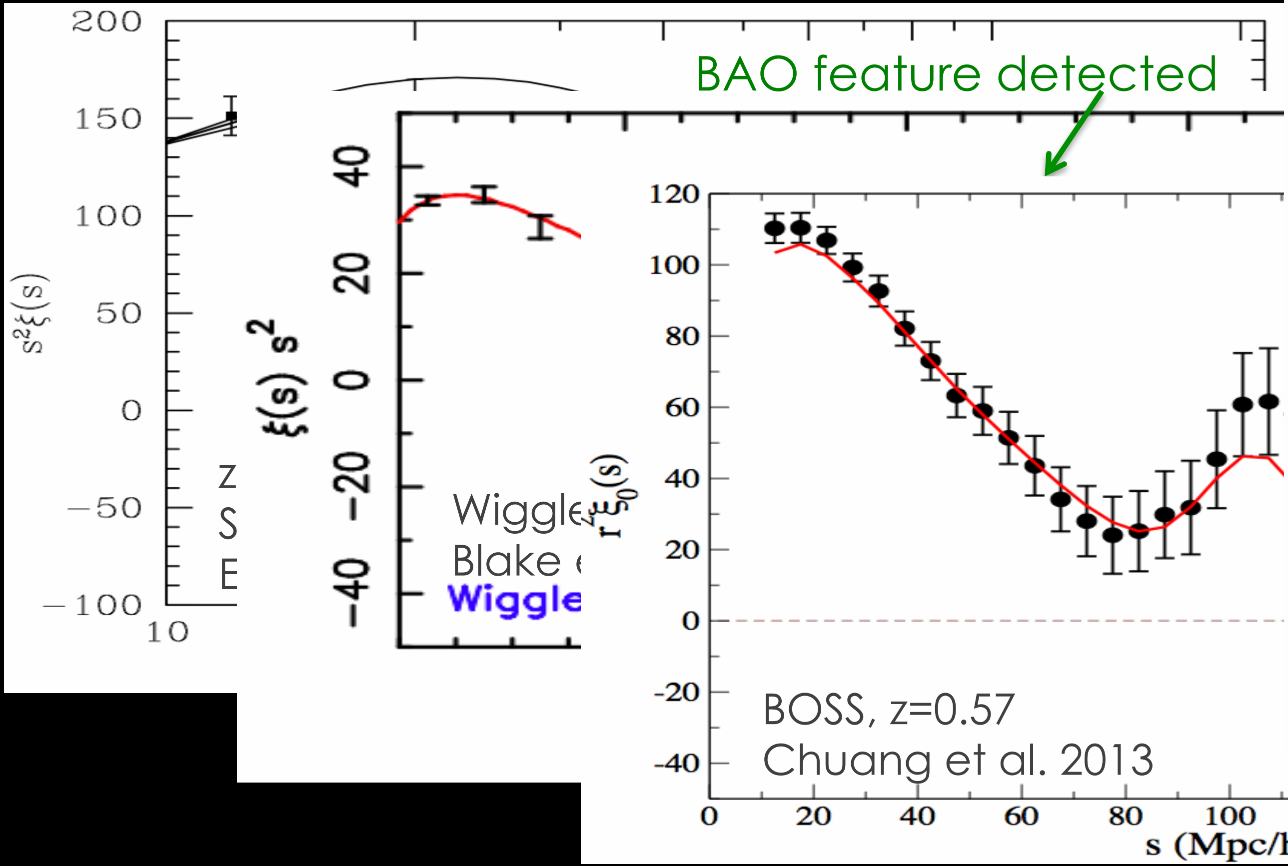
Power spectrum

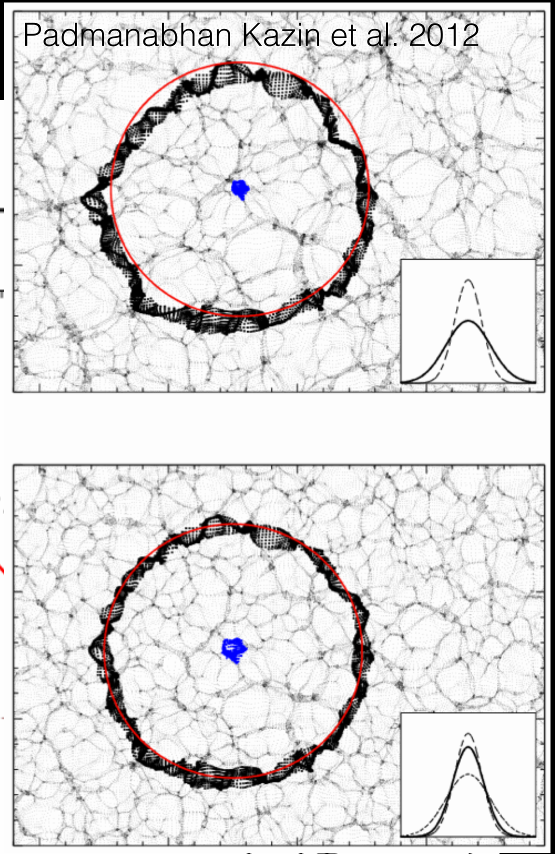




Acoustic peak detections

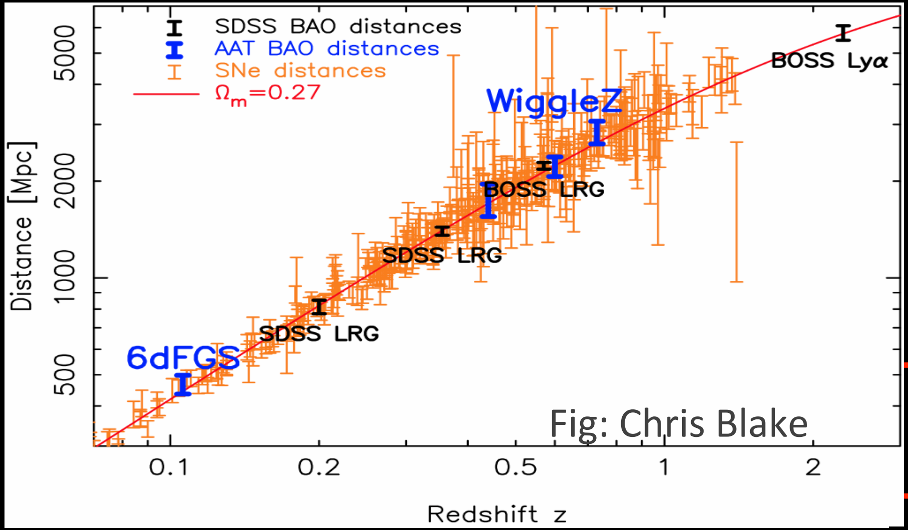
Reconstruction





Baryon Acoustic Oscillations

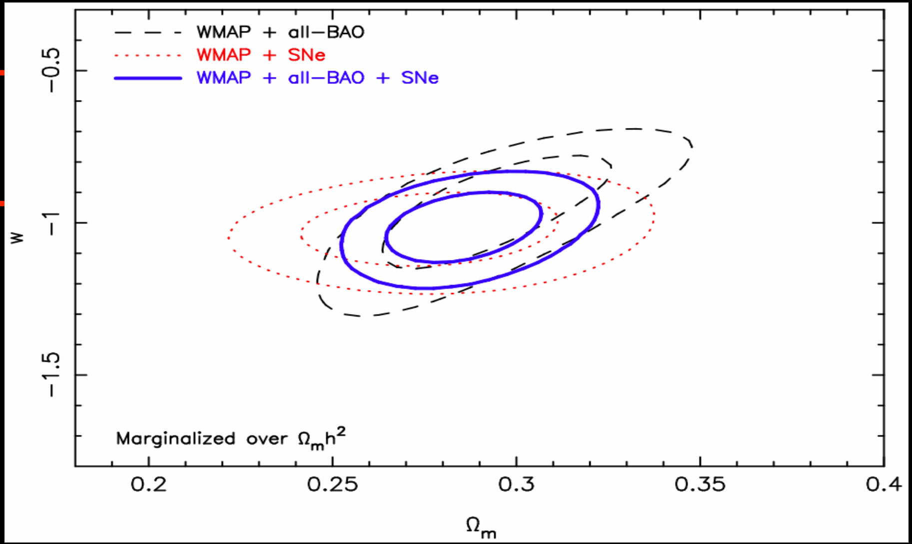
Compared to supernovae



No longer need SNe!

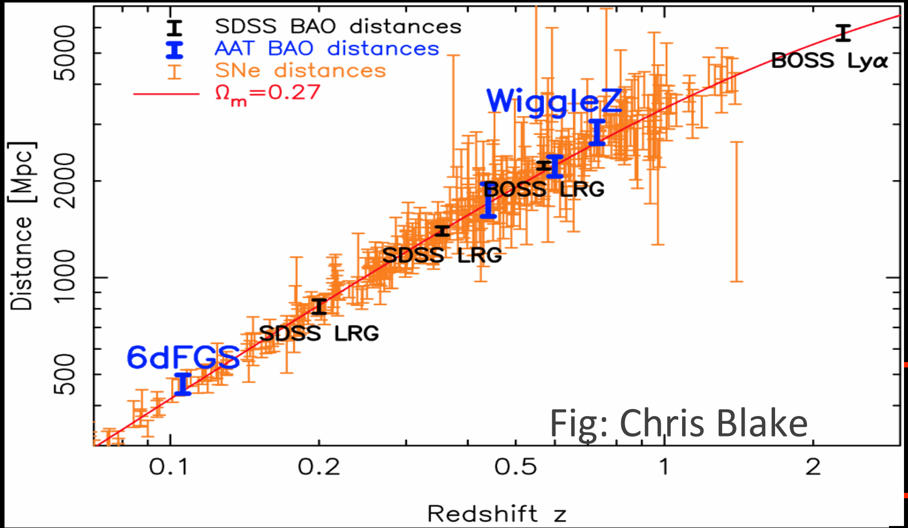
BAO distances alone now require acceleration!

BAO and SNe Combined with CMB



Baryon Acoustic Oscillations

Compared to supernovae



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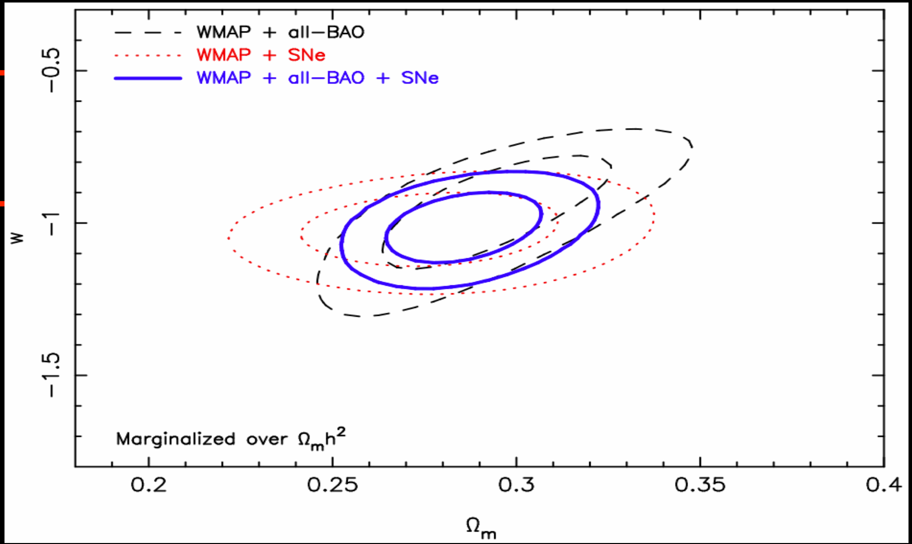
BAO and SNe Combined with CMB



We don't know what is causing the acceleration

(And the leading candidate, vacuum energy, is way too large)

Model testing vs parameter fitting

INTERLUDE…

- A CAUTIONARY TALE

What is the value of [parameter]?

[Matter density; equation of state of dark energy; Hubble's parameter]

Data combination

Model | Parameters

Model	Parameter	CMB + WiggleZ	+ H_0	+ SN-Ia	+ BAO	+ H_0 + BAO
Flat ΛCDM	$100\Omega_b h^2$	2.238 ± 0.052	2.255 ± 0.050	2.240 ± 0.053	2.239 ± 0.050	2.253 ± 0.050
	$\Omega_{\rm CDM} h^2$	0.1153 ± 0.0027	0.1145 ± 0.0026	0.1150 ± 0.0028	0.1152 ± 0.0024	0.1146 ± 0.0024
	100θ	1.039 ± 0.002	1.040 ± 0.002	1.039 ± 0.003	1.039 ± 0.002	1.039 ± 0.002
	τ	0.083 ± 0.014	0.084 ± 0.014	0.083 ± 0.014	0.083 ± 0.014	0.084 ± 0.014
	n_s	0.964 ± 0.012	0.968 ± 0.012	0.965 ± 0.013	0.964 ± 0.012	0.968 ± 0.011
	$\log(10^{10} A_s)$	3.084 ± 0.029	3.086 ± 0.029	3.085 ± 0.030	3.083 ± 0.029	3.086 ± 0.029
	Ω_m	0.290 ± 0.016	0.283 ± 0.014	0.288 ± 0.017	0.289 ± 0.013	0.284 ± 0.012
	$H_0 [\rm km\, s^{-1}\, Mpc^{-1}]$	68.9 ± 1.4	69.6 ± 1.3	69.1 ± 1.6	69.0 ± 1.2	69.5 ± 1.2
	σ_8	0.825 ± 0.017	0.825 ± 0.017	0.825 ± 0.017	0.825 ± 0.017	0.825 ± 0.017
Flat wCDM	$100\Omega_b h^2$	2.265 ± 0.062	2.253 ± 0.057	2.228 ± 0.055	2.247 ± 0.056	2.253 ± 0.056
	$\Omega_{DM} h^2$	0.1164 ± 0.0036	0.1146 ± 0.0030	0.1157 ± 0.0030	0.1147 ± 0.0029	0.1148 ± 0.0030
	100θ	1.039 ± 0.003	1.039 ± 0.003	1.038 ± 0.003	1.039 ± 0.003	1.039 ± 0.003
	τ	0.084 ± 0.015	0.084 ± 0.014	0.082 ± 0.014	0.084 ± 0.014	0.084 ± 0.014
	n_s	0.975 ± 0.019	0.968 ± 0.014	0.962 ± 0.014	0.967 ± 0.014	0.968 ± 0.014
	$log[10^{10}$	3.096 ± 0.031	3.086 ± 0.030	3.082 ± 0.029	3.085 ± 0.030	3.086 ± 0.030
	w	-0.525 ± 0.293	-1.007 ± 0.084	-1.062 ± 0.072	-0.973 ± 0.086	-1.008 ± 0.085
	Ω_m	0.487 ± 0.132	0.283 ± 0.018	0.844 ± 0.028	0.294 ± 0.018	0.284 ± 0.018
	H_0	55.2 ± 8.4	69.7 ± 2.1	70.5 ± 2.3	68.4 ± 2.0	69.7 ± 2.1
	σ_8	0.664 ± 0.110	0.826 ± 0.032	0.844 ± 0.028	0.815 ± 0.033	0.827 ± 0.032
ΛCDM	$100\Omega_b h^2$	2.215 ± 0.055	2.263 ± 0.054	2.256 ± 0.054	2.252 ± 0.054	2.262 ± 0.052
	$\Omega_{\rm CDM} h^2$	0.1118 ± 0.0039	0.1162 ± 0.0039	0.114 ± 0.0042	0.1150 ± 0.0038	0.1161 ± 0.0038
	100θ	1.038 ± 0.003	1.040 ± 0.003	1.040 ± 0.003	1.040 ± 0.003	1.040 ± 0.003
	τ	0.086 ± 0.014	0.088 ± 0.015	0.089 ± 0.014	0.088 ± 0.015	0.088 ± 0.014
	n_s	0.958 ± 0.013	0.970 ± 0.013	0.969 ± 0.013	0.968 ± 0.013	0.969 ± 0.013
	$\log(10^{10} A_s)$	3.072 ± 0.031	3.101 ± 0.031	3.096 ± 0.031	3.096 ± 0.031	3.101 ± 0.030
	Ω_m	0.454 ± 0.058	0.287 ± 0.029	0.303 ± 0.038	0.302 ± 0.020	0.288 ± 0.016
	Ω_k	-0.046 ± 0.017	0.001 ± 0.008	-0.005 ± 0.012	-0.004 ± 0.006	0.000 ± 0.005
	$H_0\ [\rm km\, s^{-1}\, Mpc^{-1}]$	54.65 ± 3.8	69.86 ± 3.6	67.7 ± 4.7	67.6 ± 2.3	69.9 ± 3.6
	σ_8	0.782 ± 0.024	0.838 ± 0.023	0.825 ± 0.026	0.829 ± 0.022	0.838 ± 0.023

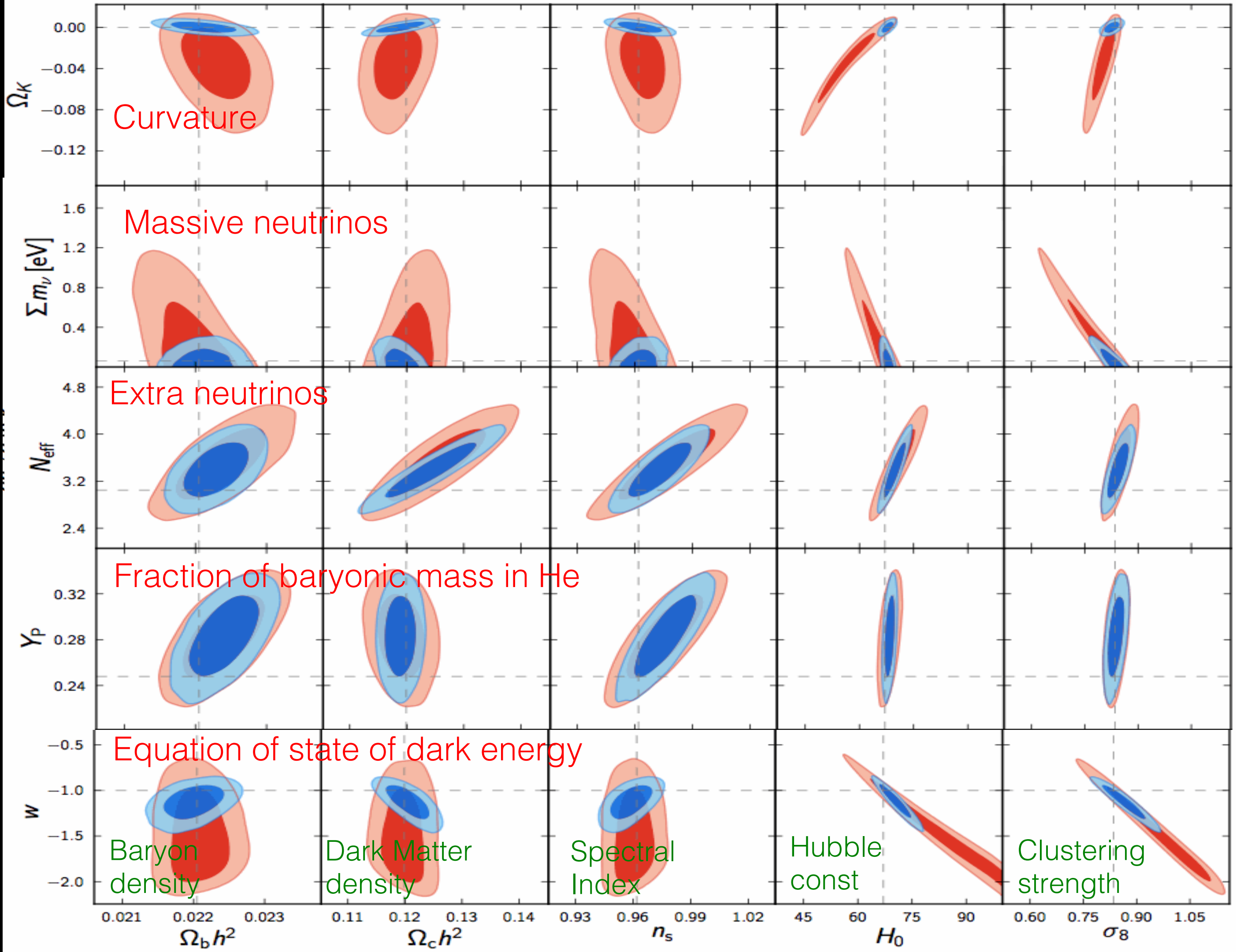
Model

Model

Parkinson et al. 2013

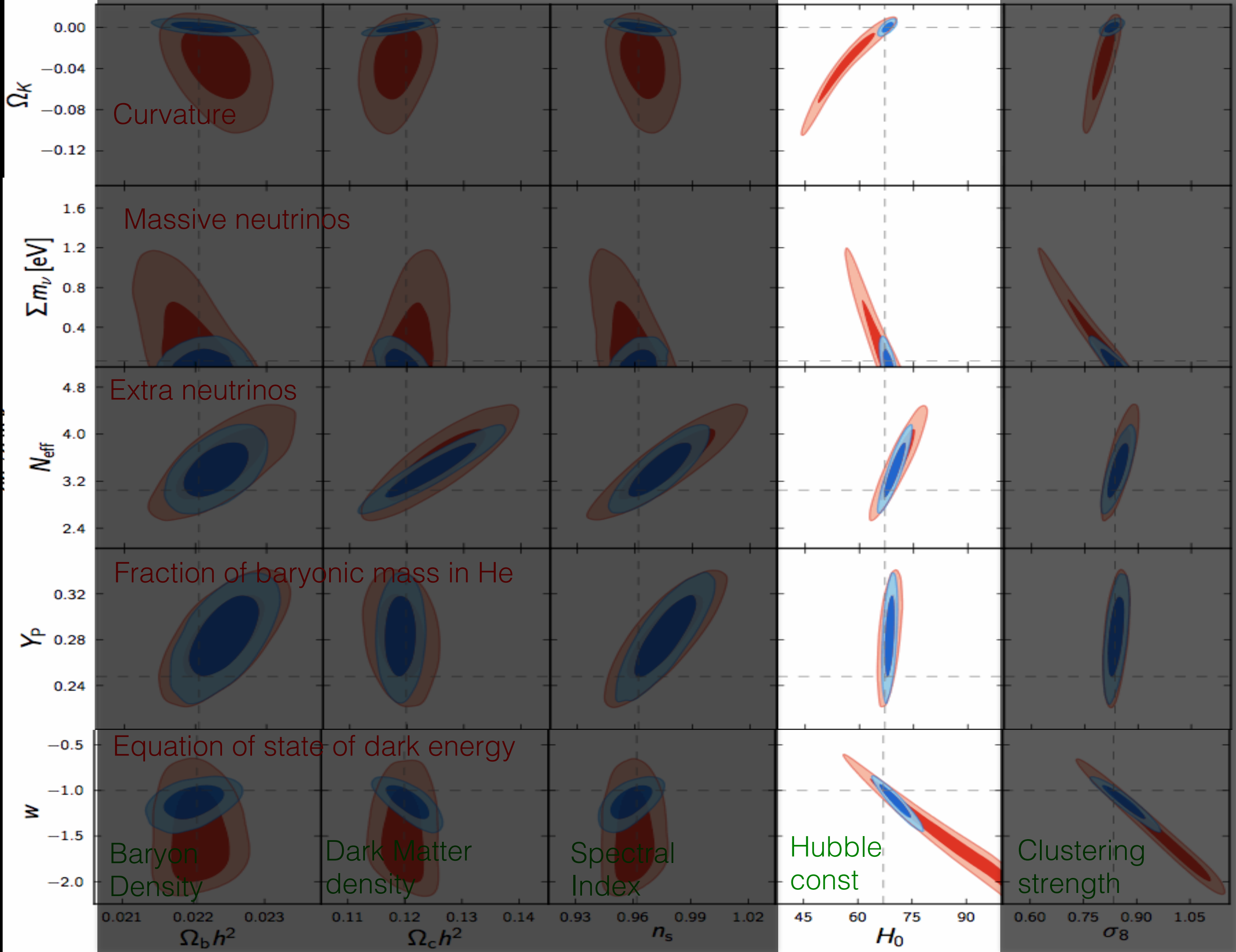
CMB: Model extensions

Planck XVI, 2013
+BAO (blue)



CMB: Model extensions

Planck XVI, 2013
+BAO (blue)



CMB: Model extensions

Best fit in standard model (ΛCDM)

Best fit in extended model (wCDM)

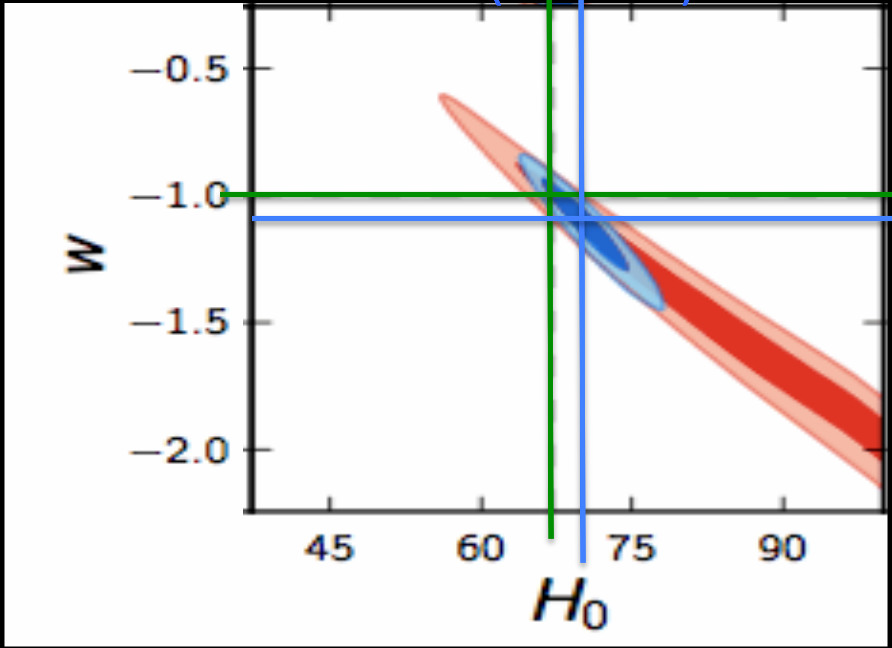
Planck+WP+highL +BAO

$H_0 = 67.80 \pm 0.77$

Planck+WP+highL +BAO

$H_0 = 71 \pm 4$ (?)

Dark energy equation of state



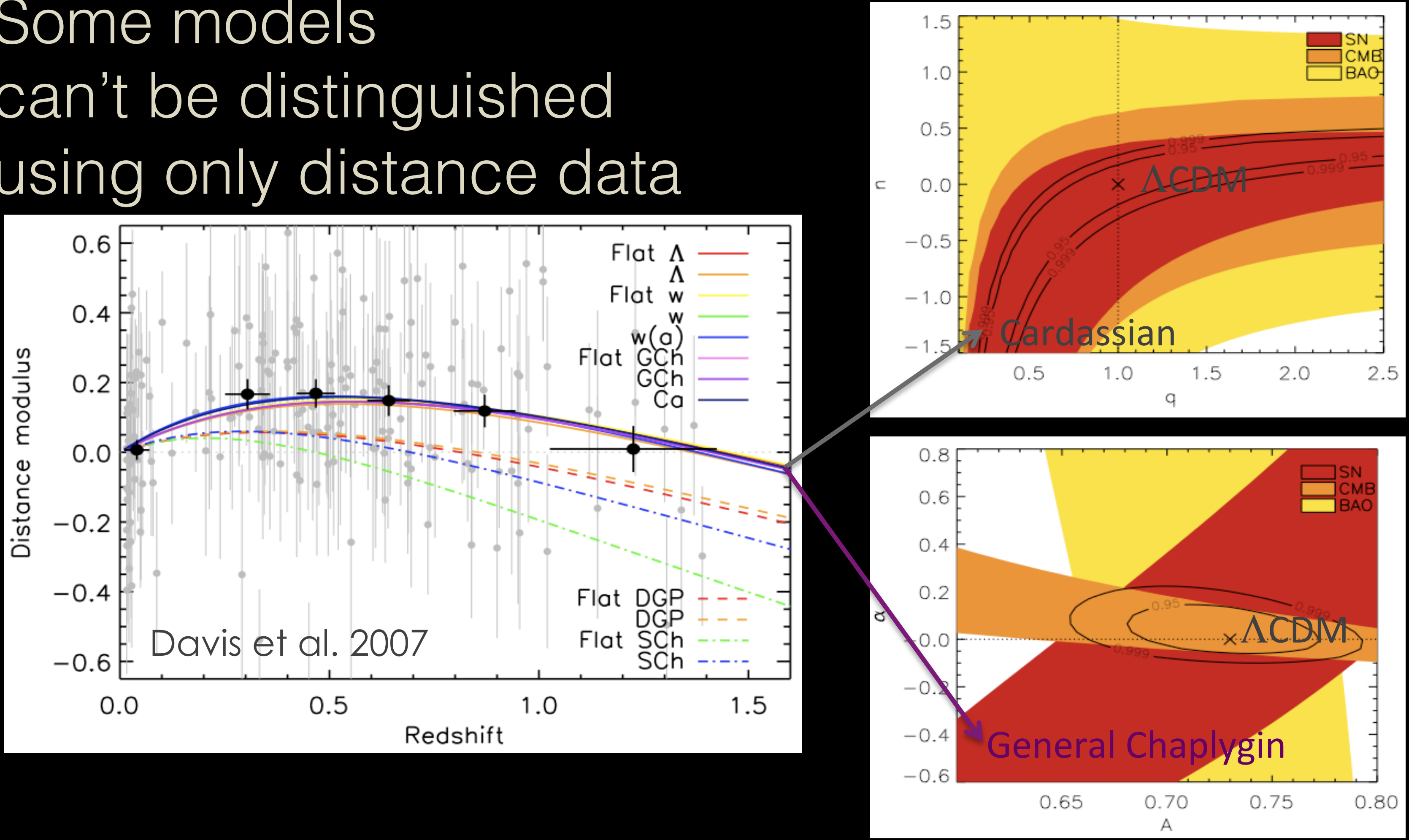
Hubble's constant

Back on track

WHAT IS DARK ENERGY?


New theory?
New stuff?
Whoops?

Some models can't be distinguished using only distance data



Distinguishing dark energy models

3B. LARGE SCALE STRUCTURE

- GROWTH

(dynamic)

Other types of measurements needed

- Growth

overdensity

$$f = \frac{d(\ln \delta)}{d(\ln a)} \sim \Omega_{\mathrm{M}}(z)^{\gamma}$$

scalefactor

γ = 6/11 in ΛCDM
γ = 6/10 in CDM
γ = 11/16 in DGP

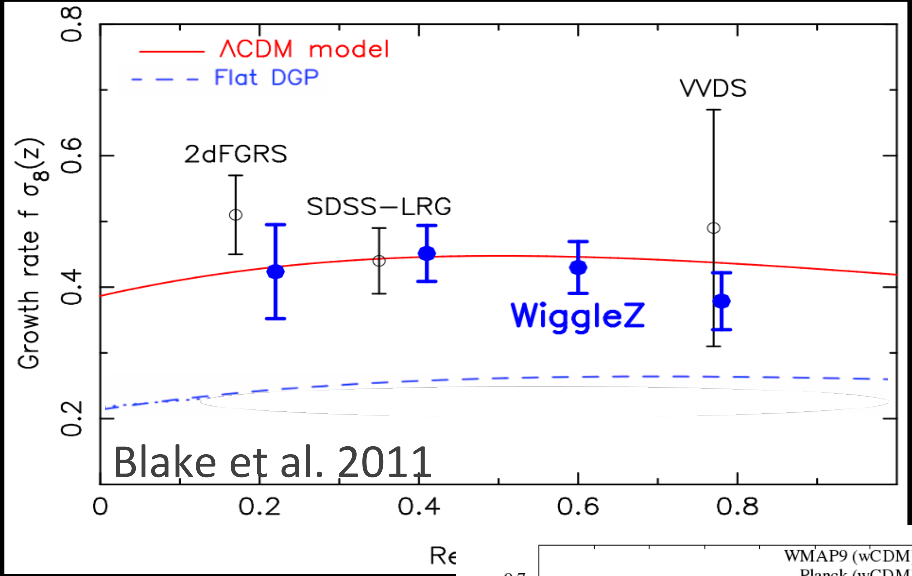
γ is different in different models

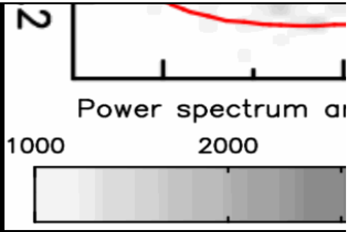
- Amplitude of density fluctuations at present day

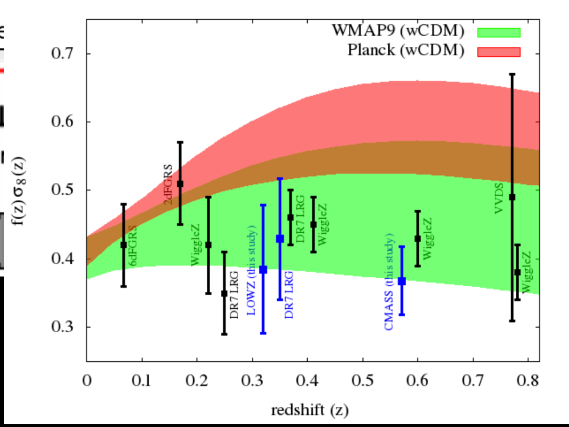
$$\sigma_8$$

1. measure density in spheres 8 Mpc in radius
2. calculate the dispersion

Growth


ΛCDM model
Flat DGP
VVDS
2dFGRS
SDSS−LRG
WiggleZ
Growth rate f $\sigma_8(z)$
0.2
0.4
0.6
0.8
0
0.2
0.4
0.6
0.8
Blake et al. 2011


Power spectrum
1000
2000

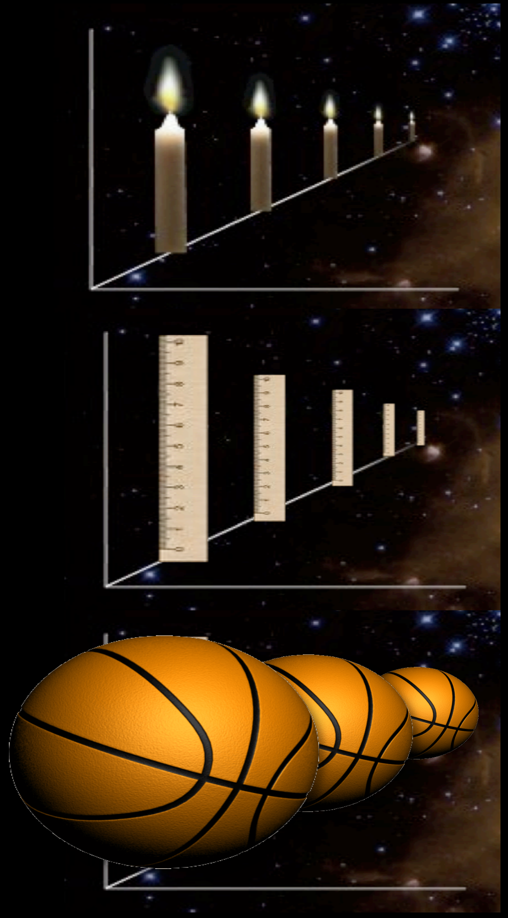

WMAP9 (wCDM)
Planck (wCDM)
$f(z)\sigma_8(z)$
0.3
0.4
0.5
0.6
0.7
6dFGRS
2dFGRS
WiggleZ
DR7 LRG
LOWZ (this study)
DR7 LRG
DR7 LRG
WiggleZ
CMASS (this study)
WiggleZ
VVDS
WiggleZ
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
redshift (z)

Measuring acceleration more directly

3C. LARGE SCALE STRUCTURE

- H(Z) ALCOCK-PACZYNSKI

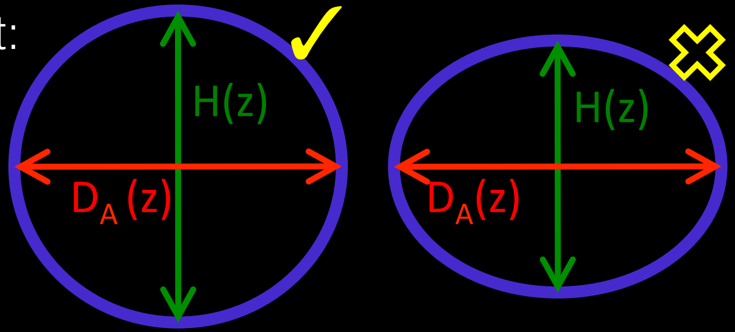
BAO – a standard sphere



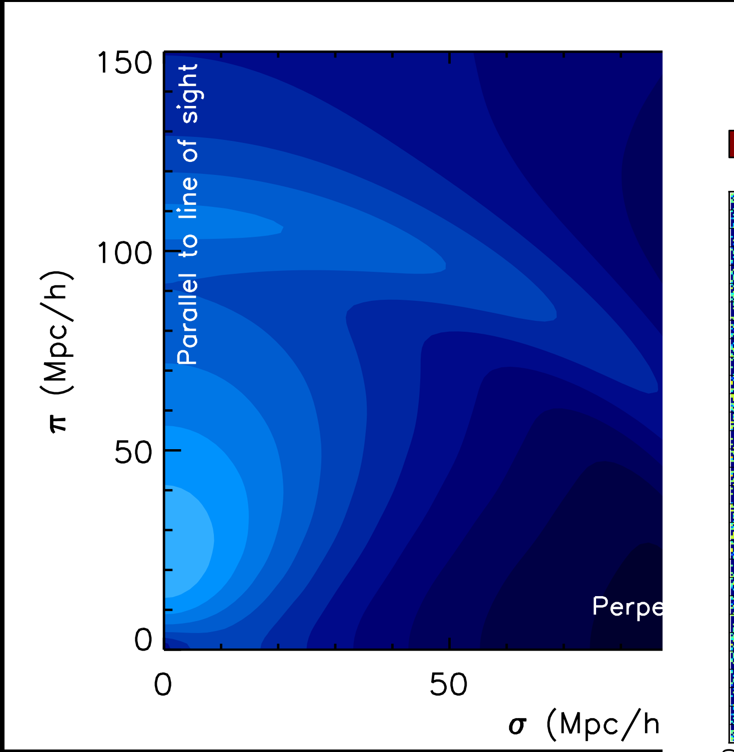
- SNe = radial info (line of sight)
- CMB = tangential info (surface of sphere)

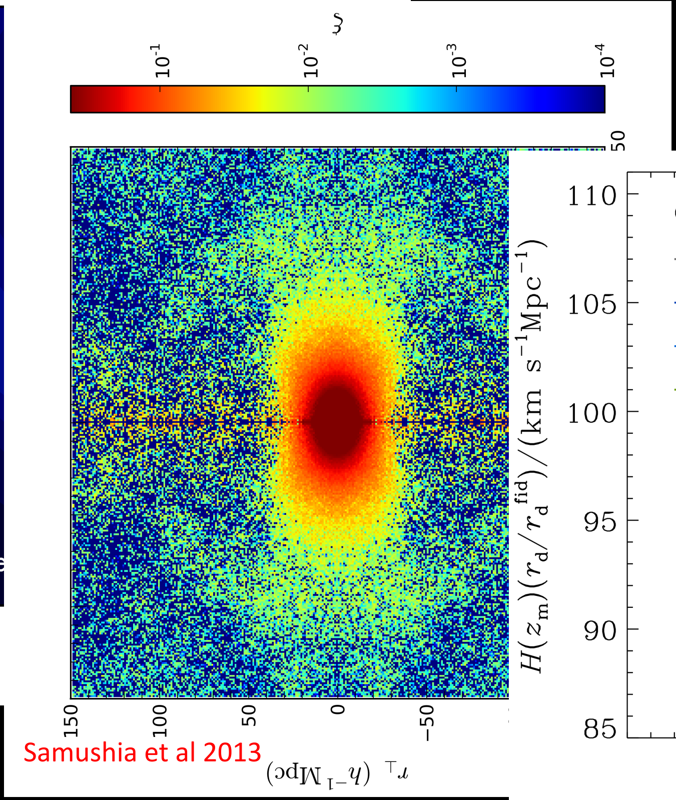
- BAO can be applied radially to give H(z) AND tangentially to give $D_A(z)$

Alcock-Paczynski test:

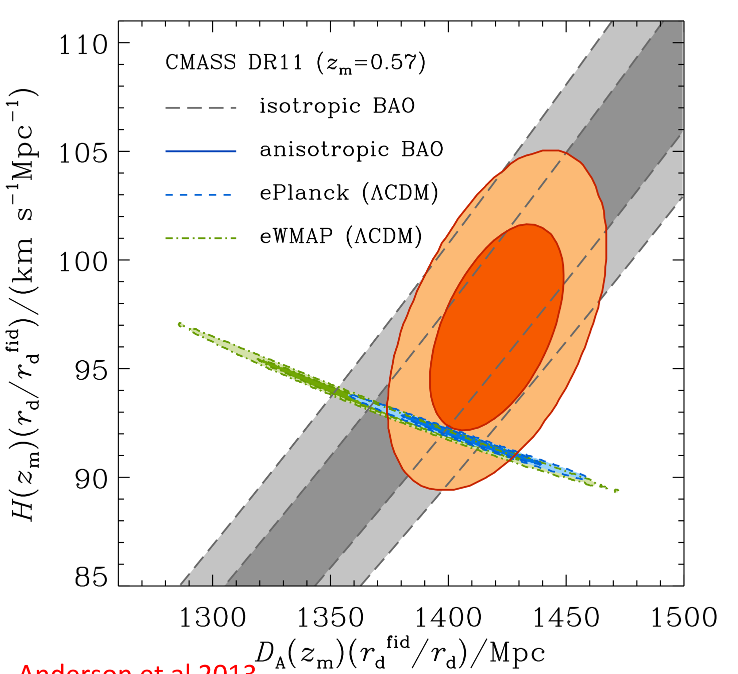


2D BAO





Samushia et al 2013



Anderson et al 2013

Measurement of H(z)

AP measures

$$(1+z)D_A(z)H(z)/c$$

Supernovae measure

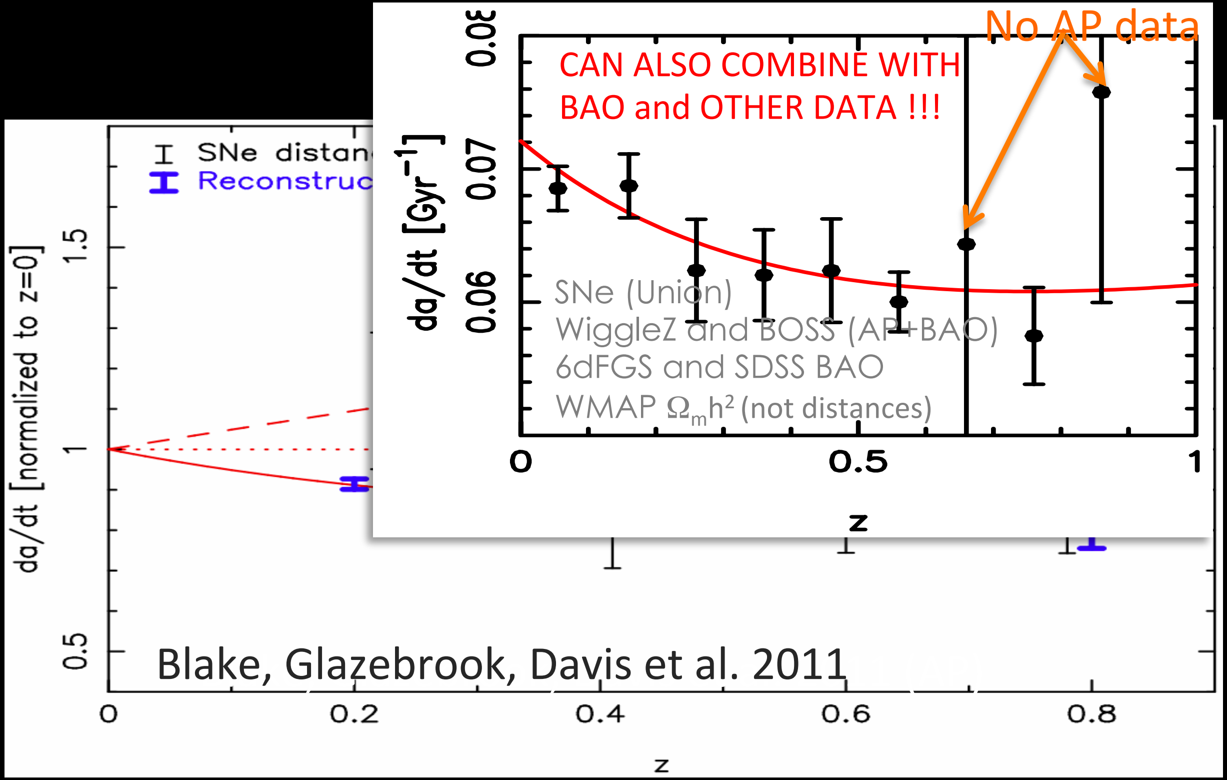
$$D_L(z)\,H_0/c$$

Distances are related by

$$D_L(z) = D_A(z)\,(1+z)^2$$

So the ratio gives

$$H(z)/H_0$$



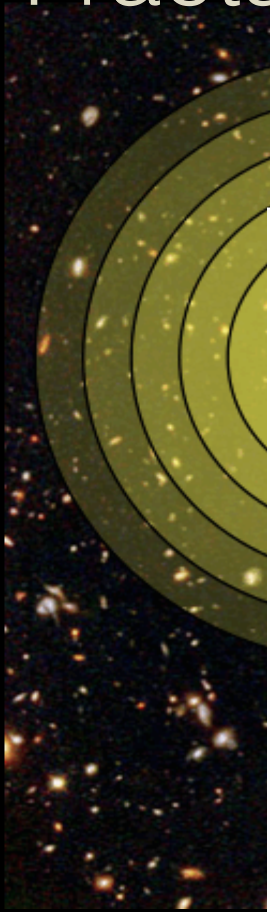
Testing the cosmological principle

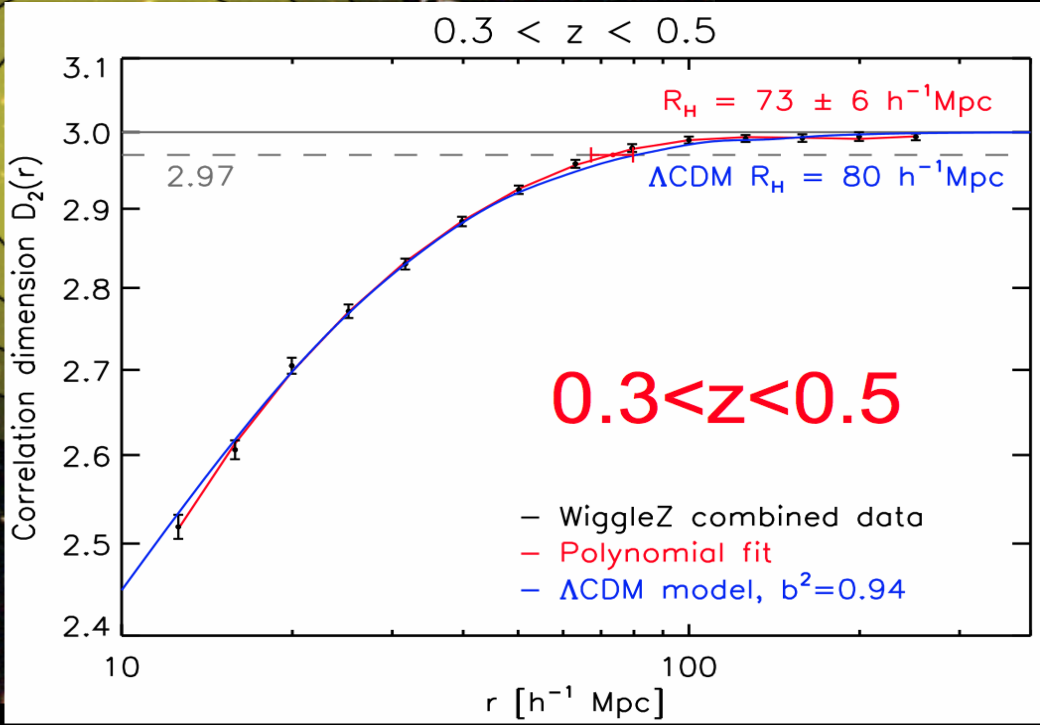
3D. LARGE SCALE STRUCTURE

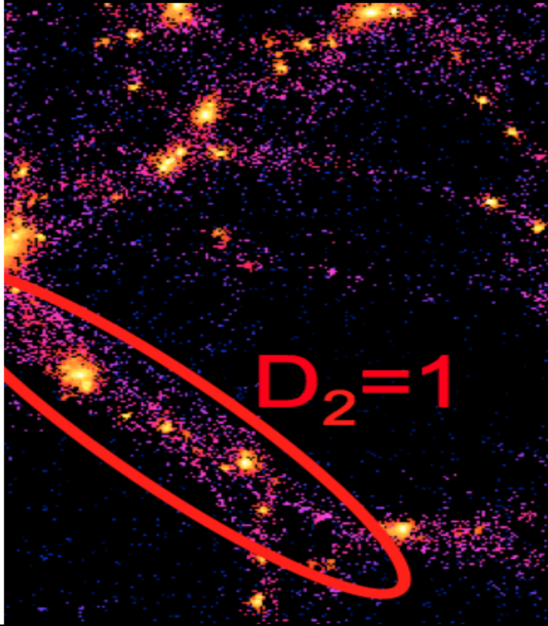
- HOMOGENEITY

Fractal dimension (Morag Scrimgeour, ICRAR)

$$N(<r) \propto r^{D_2}$$





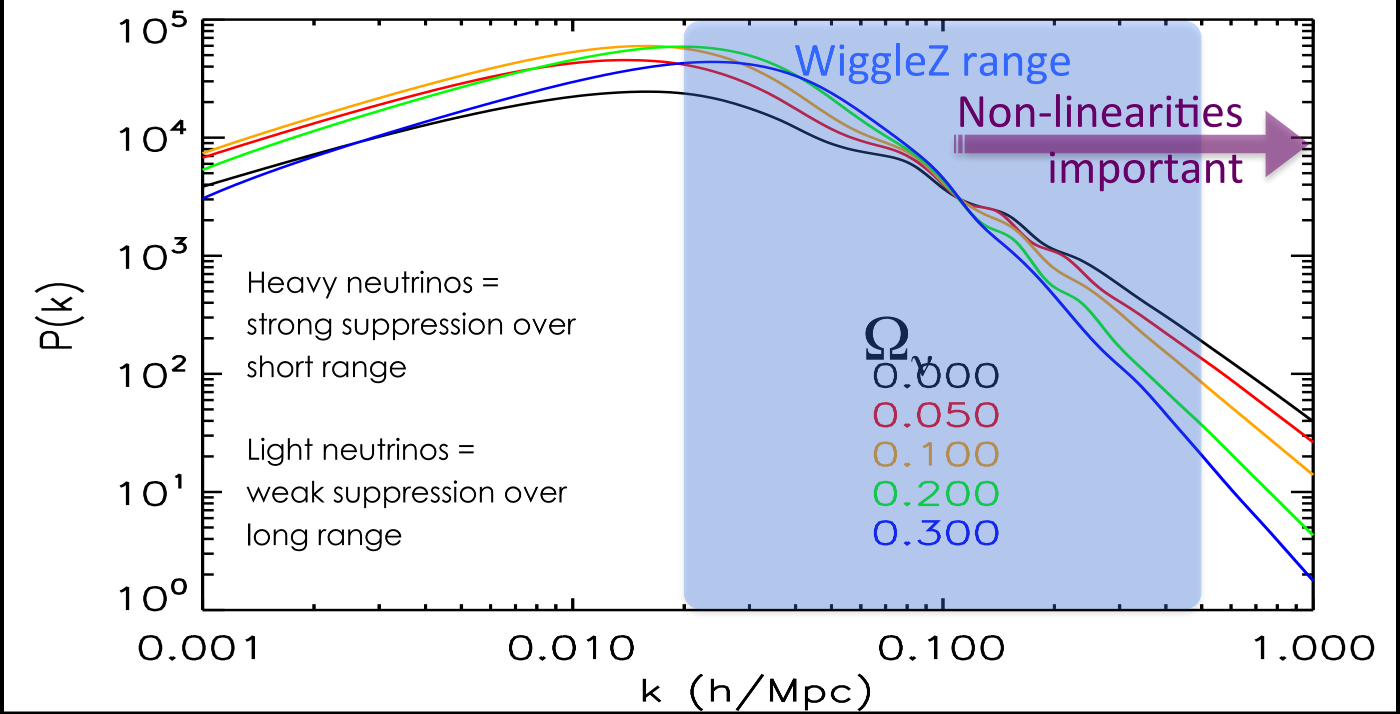


Particle physics

3E. LARGE SCALE STRUCTURE

- NEUTRINO MASS

Neutrino mass and number

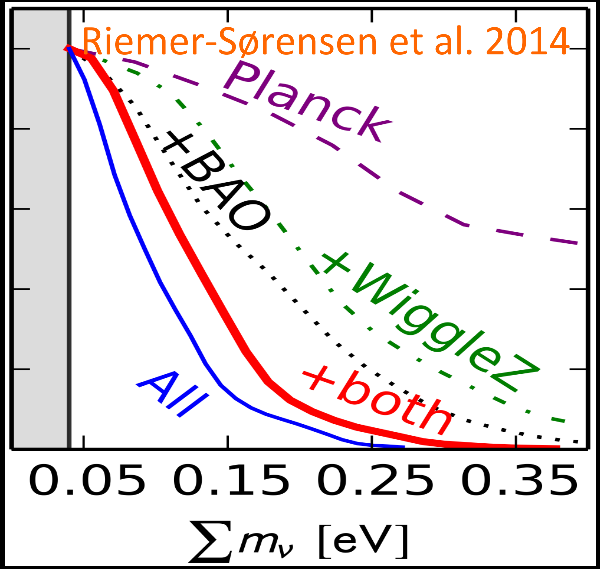


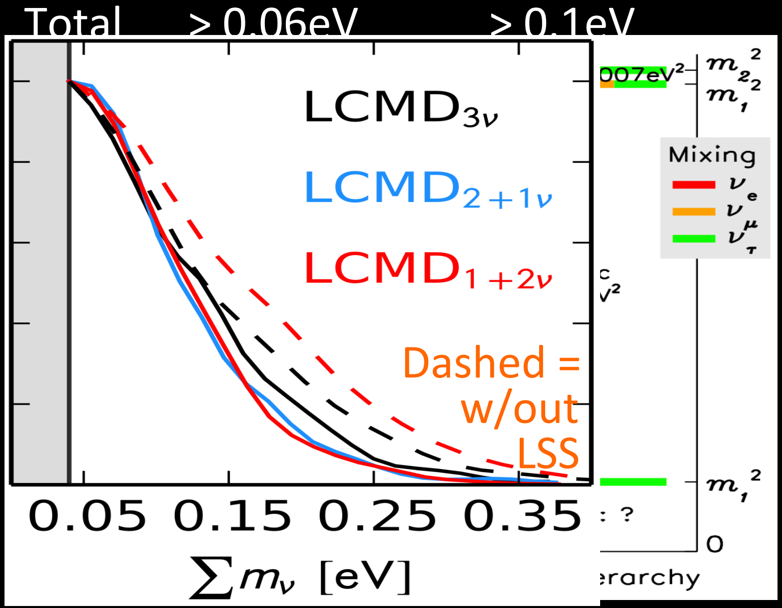
Changes balance of radiation to dust

$\Rightarrow$ changes expansion rate vs time

$\Rightarrow$ changes horizon size at matter radiation equality

Neutrino mass constraint





Allowed range for the sum of neutrino masses is now:

$0.05 \text{ eV} < \Sigma m_\nu < 0.18 \text{ eV}$

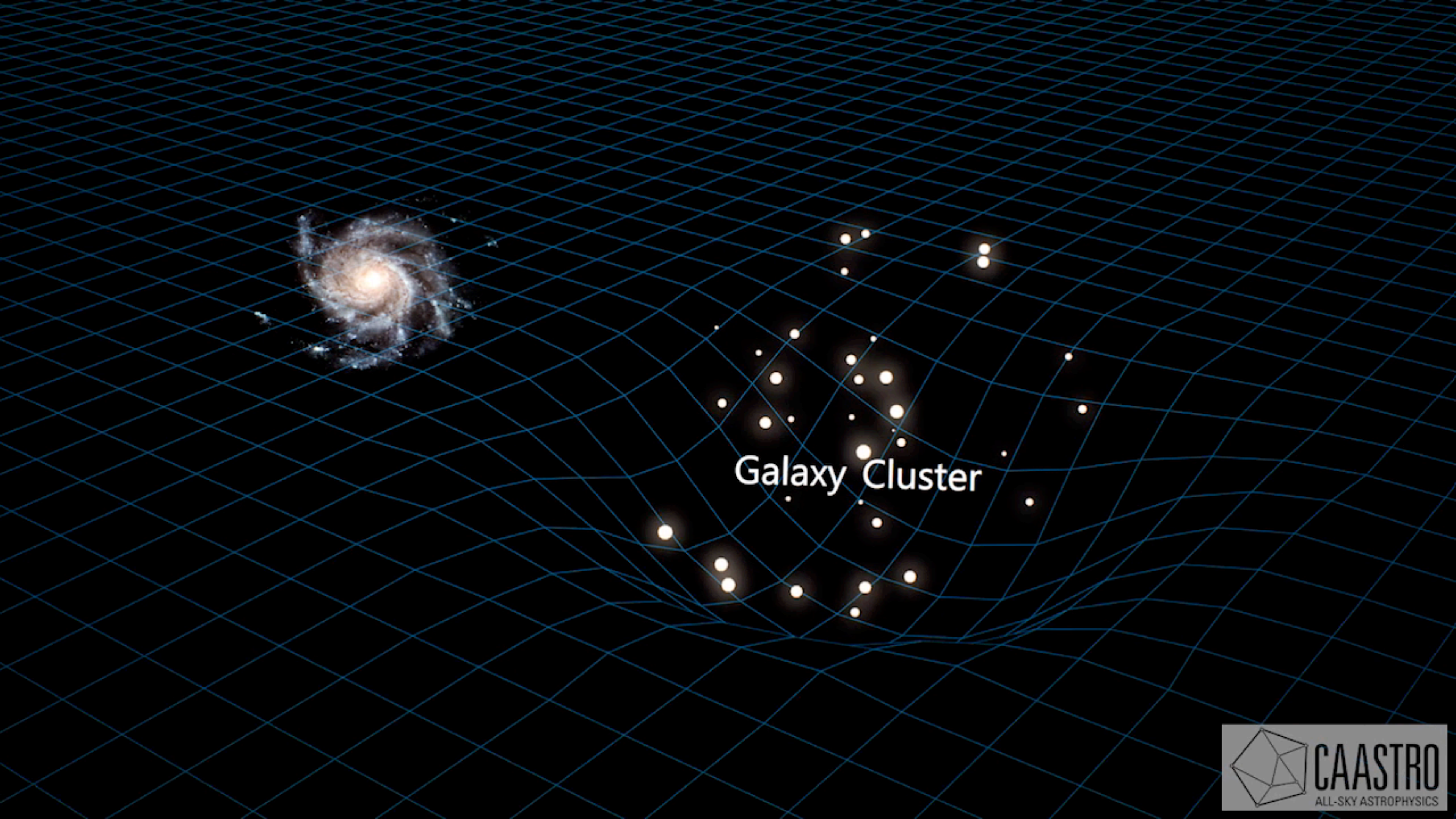
(lab oscillation expts)

(cosmology, 95% confidence, FlatΛCDM model)

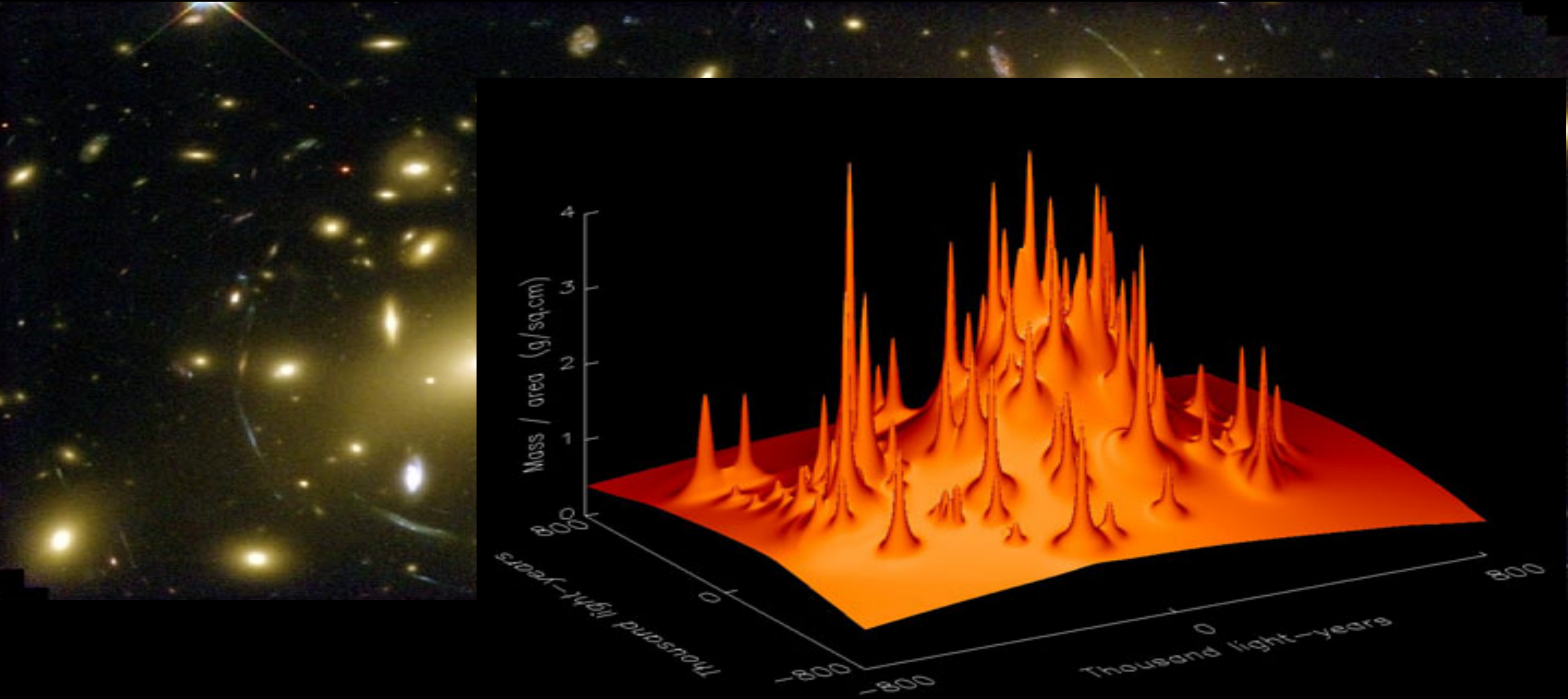
Measuring dark matter

4A. LENSING

- STRONG LENSING


Galaxy Cluster
CAASTRO
ALL-SKY ASTROPHYSICS

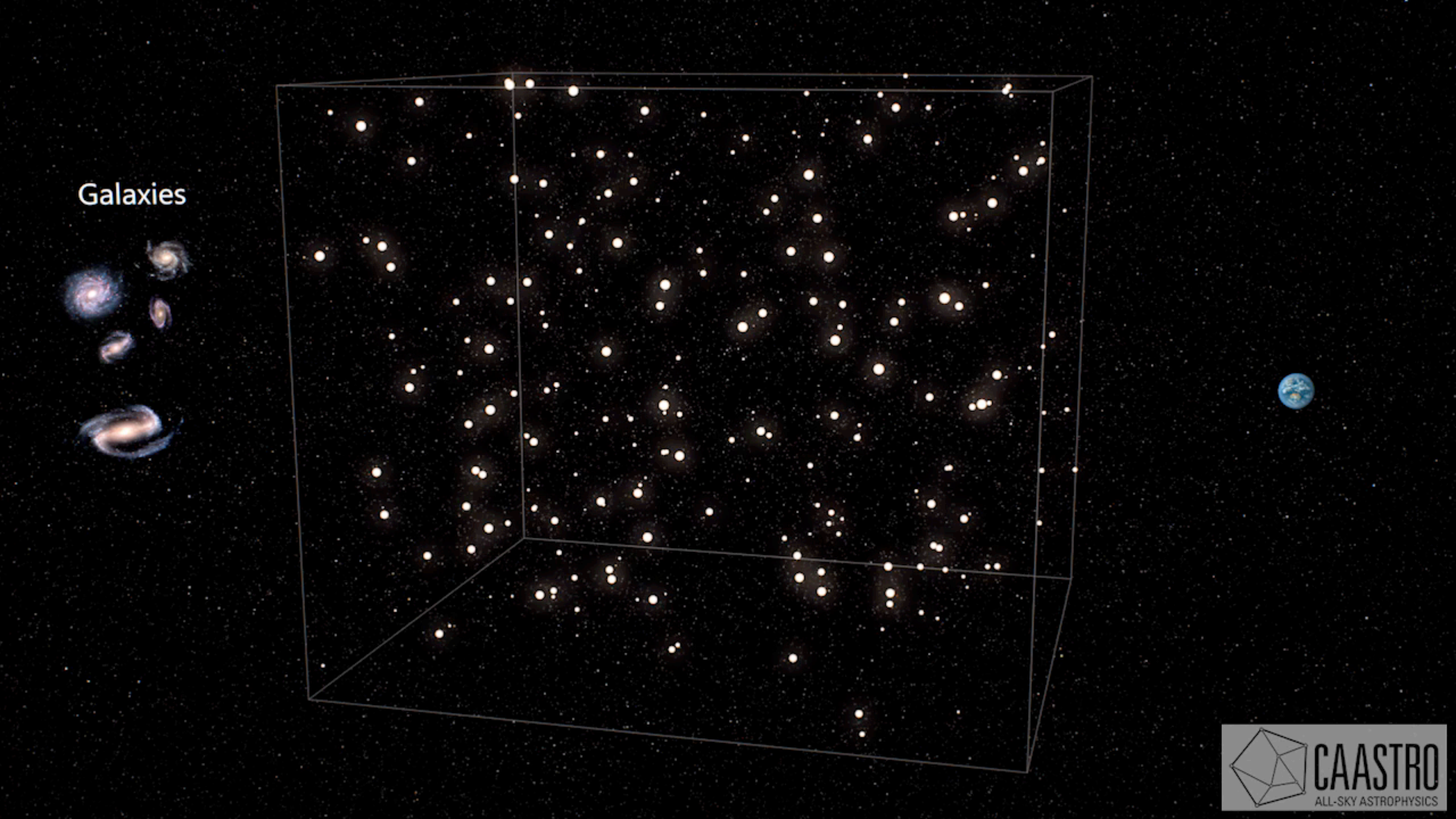
Strong Lensing

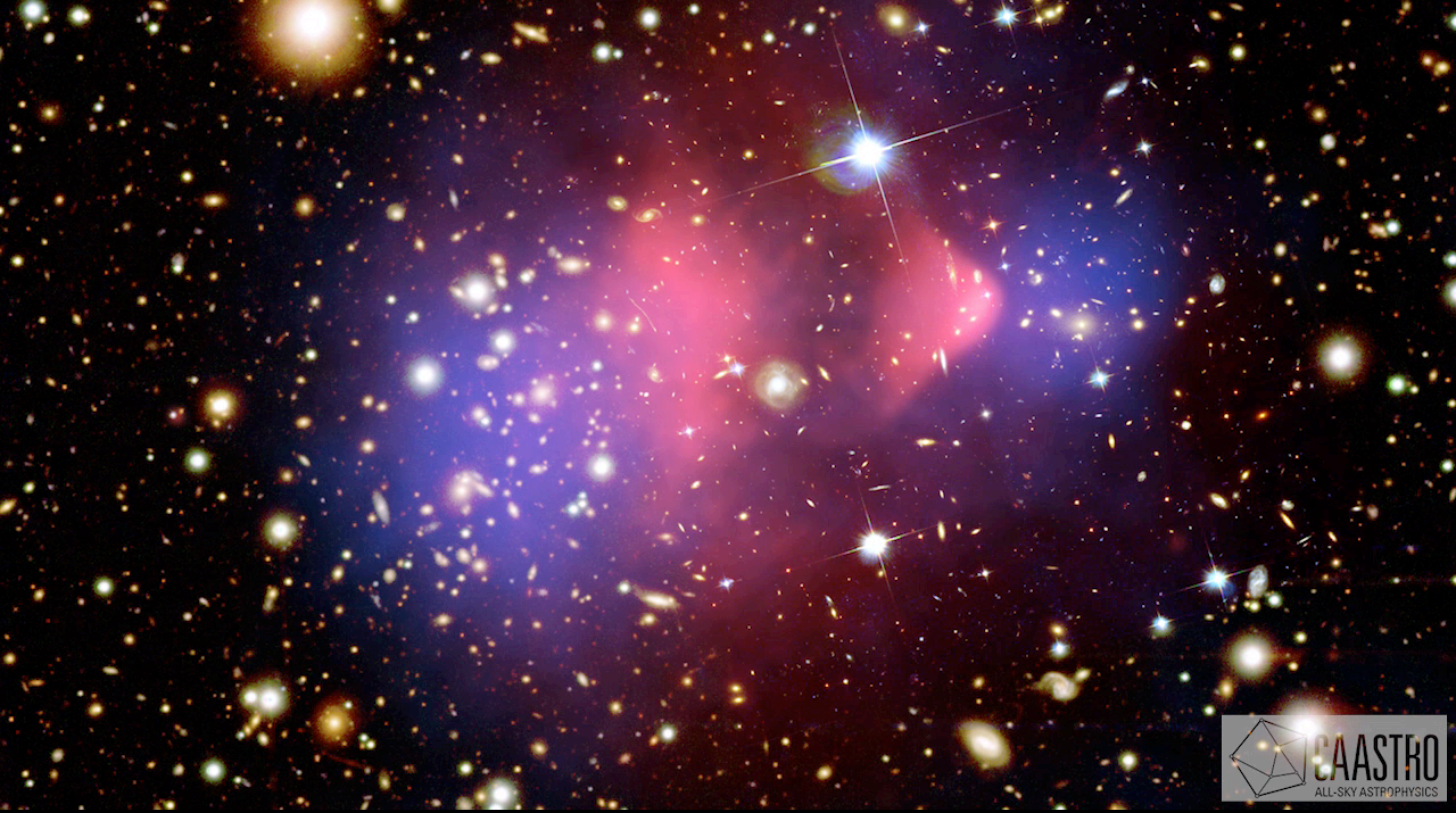


Measuring cosmological parameters

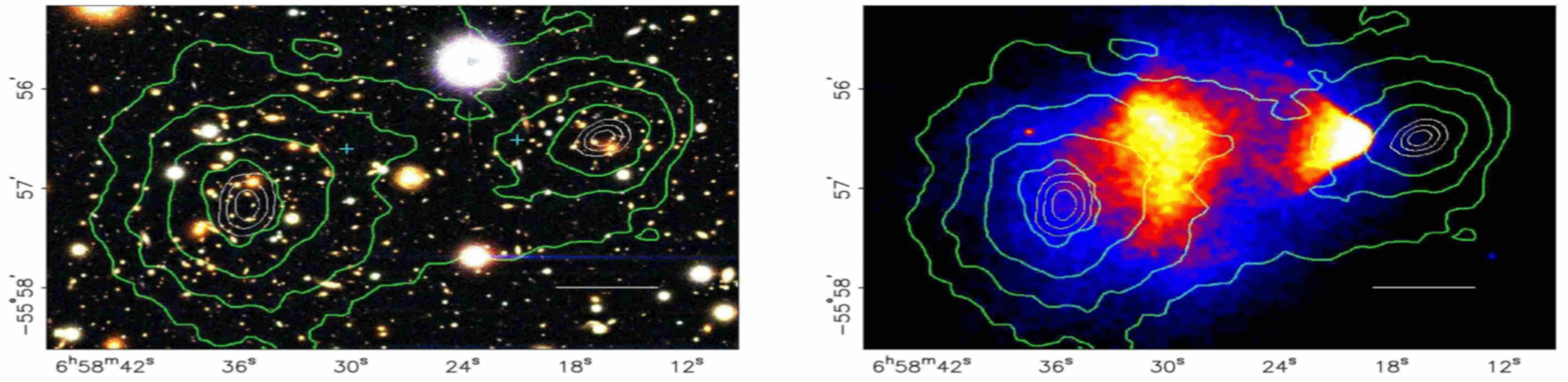
4B. LENSING

- WEAK LENSING


Galaxies
CAASTRO
ALL-SKY ASTROPHYSICS


CAASTRO
ALL-SKY ASTROPHYSICS

Weak Lensing



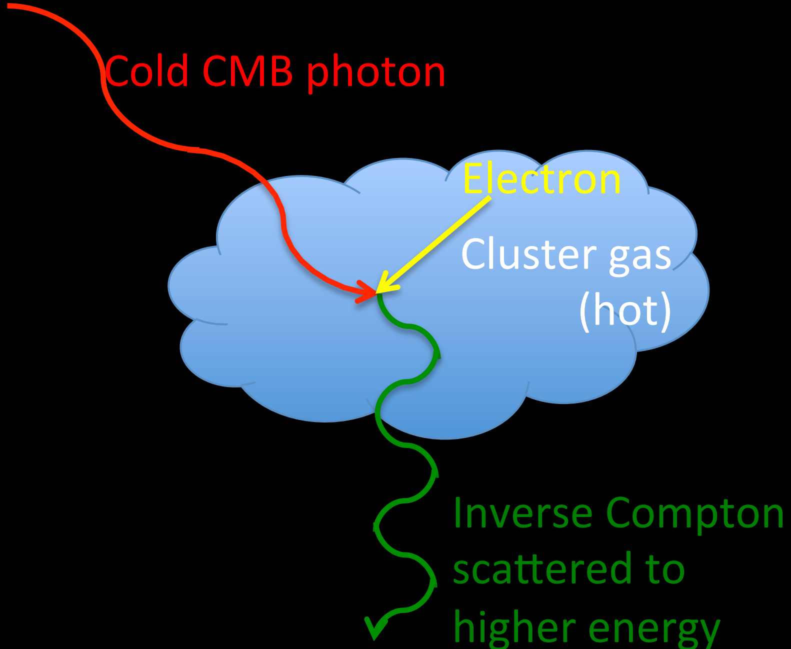
NOTE: Dark matter has to explain a lot more than galaxy rotation curves!!

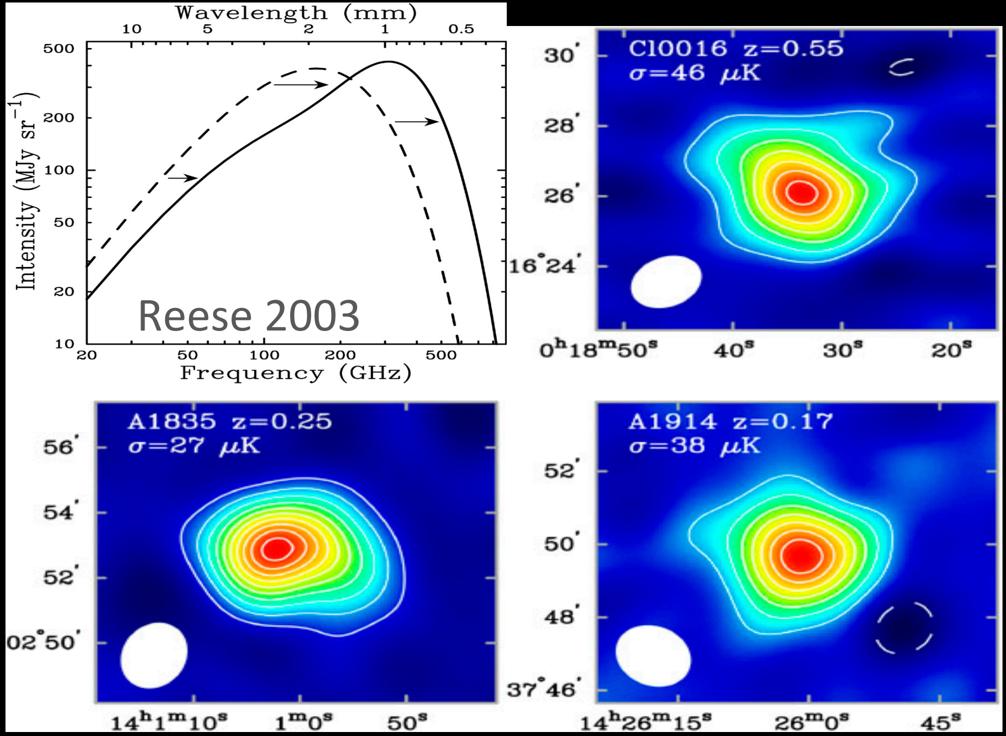
- All CMB + Galaxy P(k) + other methods already mentioned
- Timing of structure formation
- Lensing around ellipticals and clusters

Constraining parameters

2B. COSMIC MICROWAVE BACKGROUND - SUNYAEV ZELDOVICH

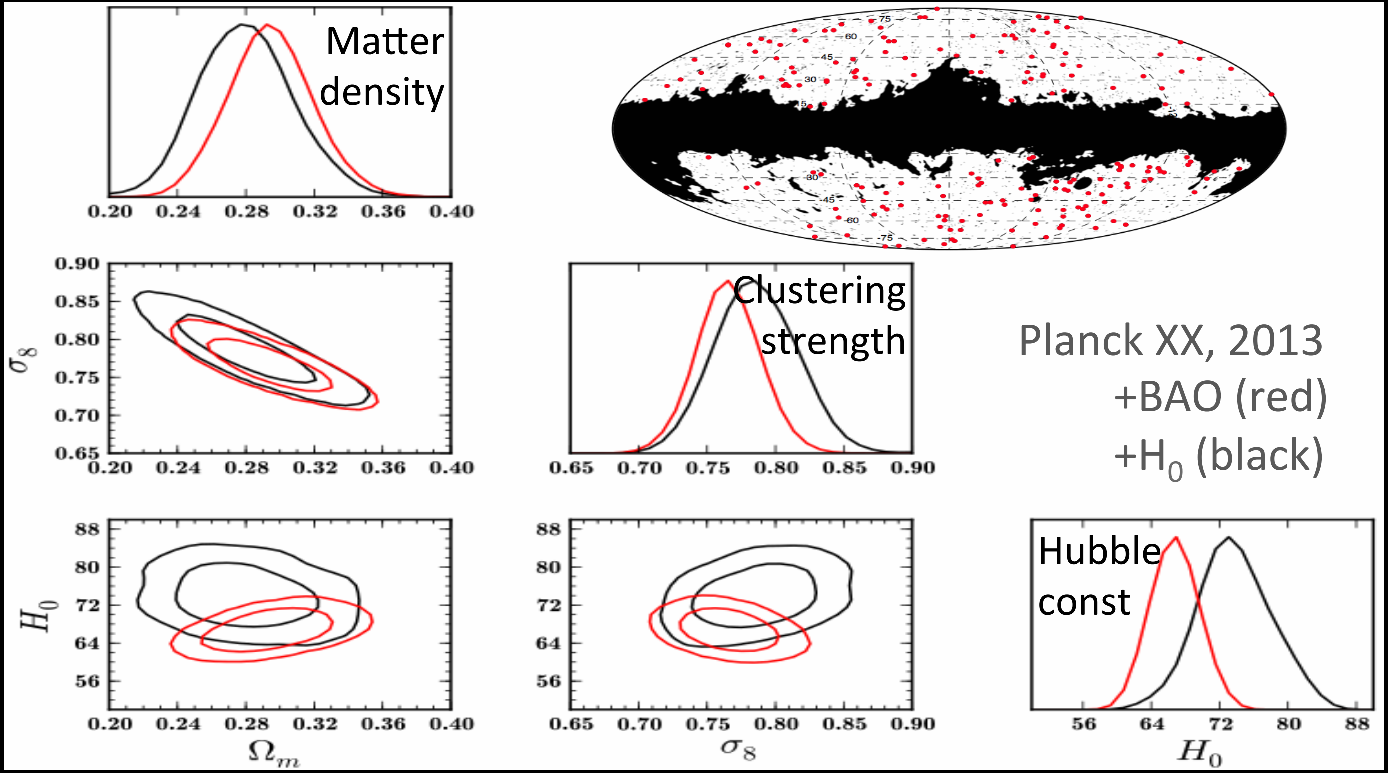
Sunyaev-Zeldovich (SZ) effect



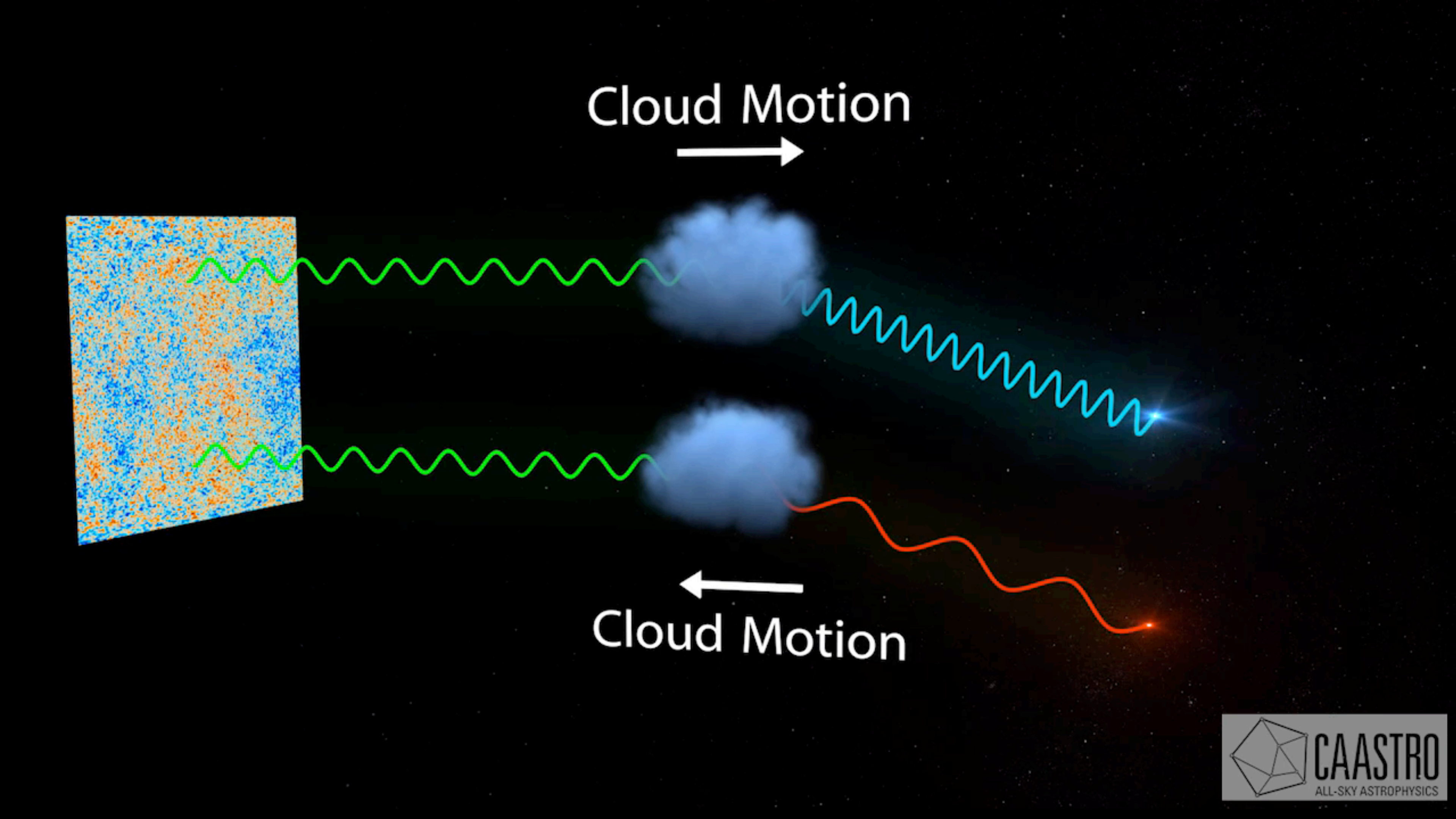


Independent of redshift !

Sunyaev-Zeldovich (SZ) effect

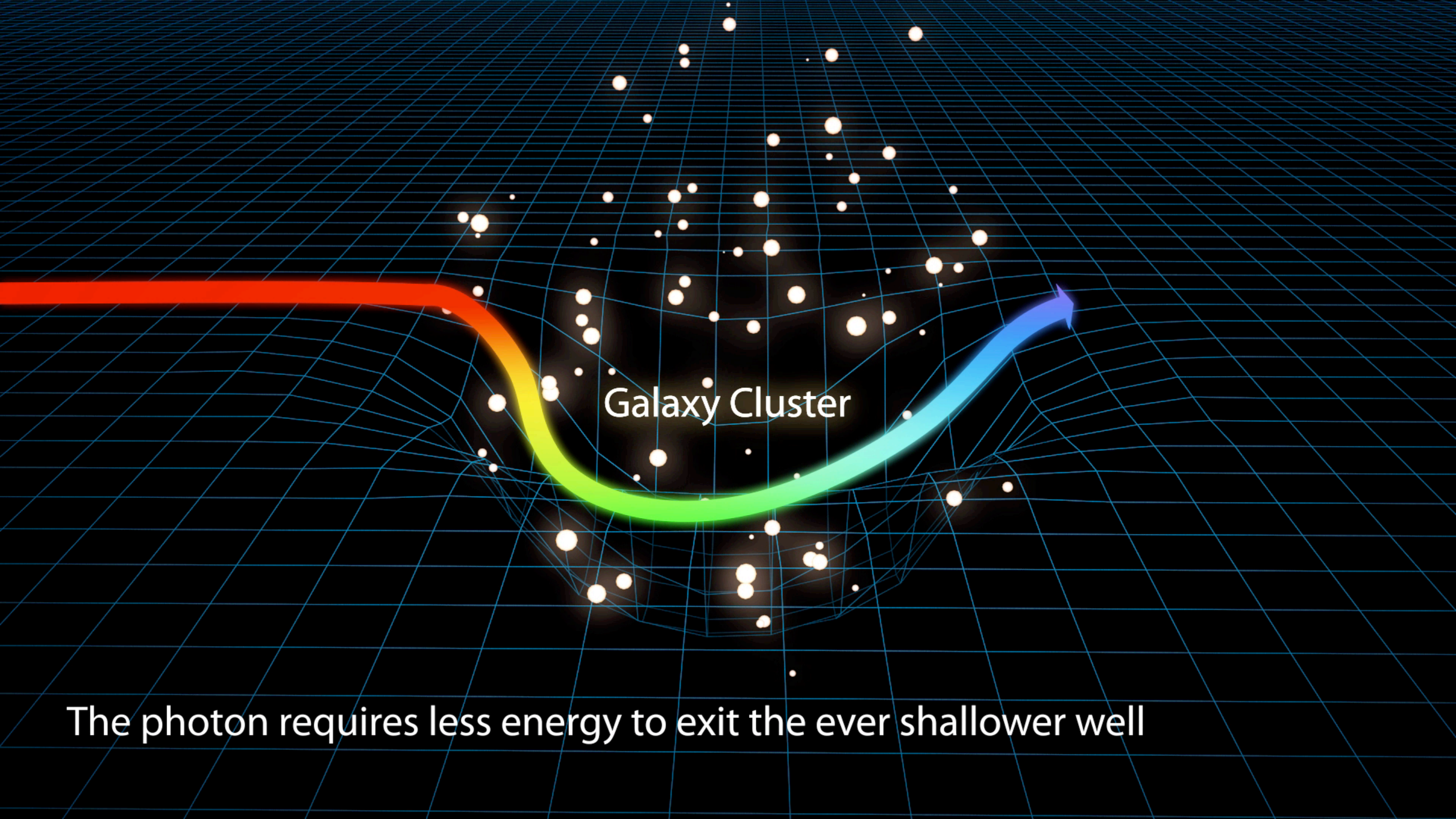


Constraints from dN/dz of clusters from SZ catalogue

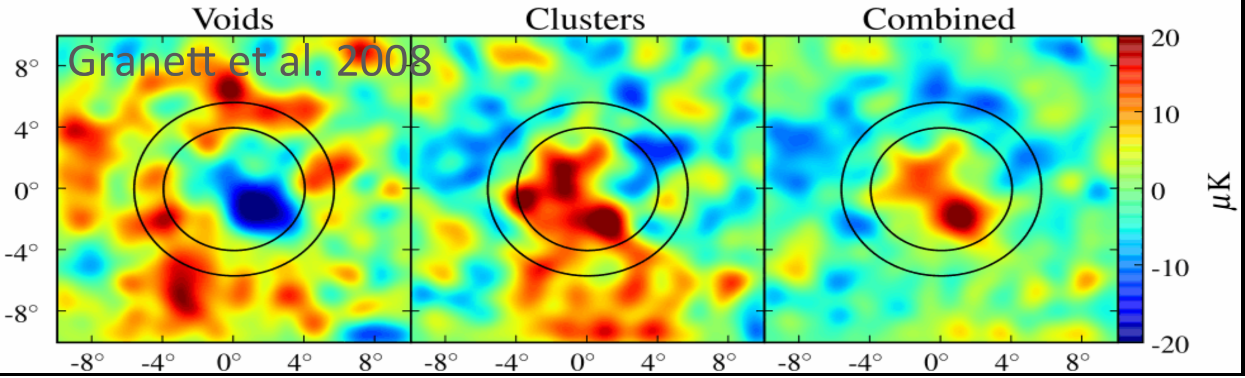

Cloud Motion
Cloud Motion
CAASTRO
ALL-SKY ASTROPHYSICS

Detecting dark energy

2C. COSMIC MICROWAVE BACKGROUND - INTEGRATED SACHS WOLFE

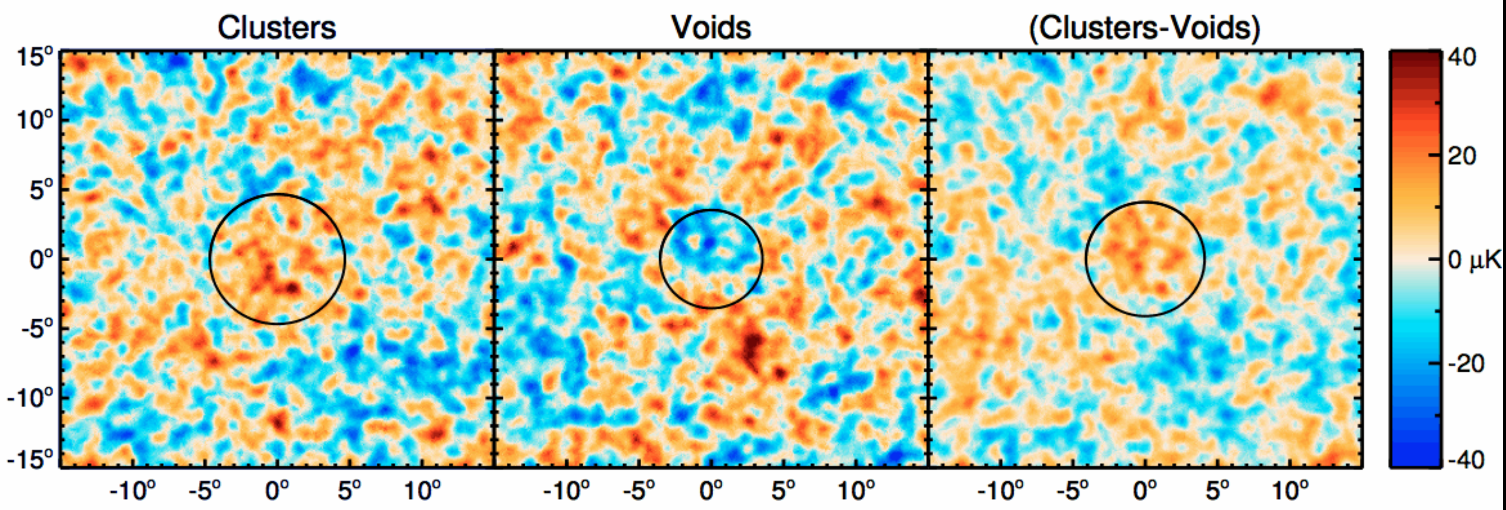

Galaxy Cluster
The photon requires less energy to exit the ever shallower well

Integrated Sachs-Wolfe (ISW) effect



Can cross-correlate with
-galaxy surveys
-lensing maps

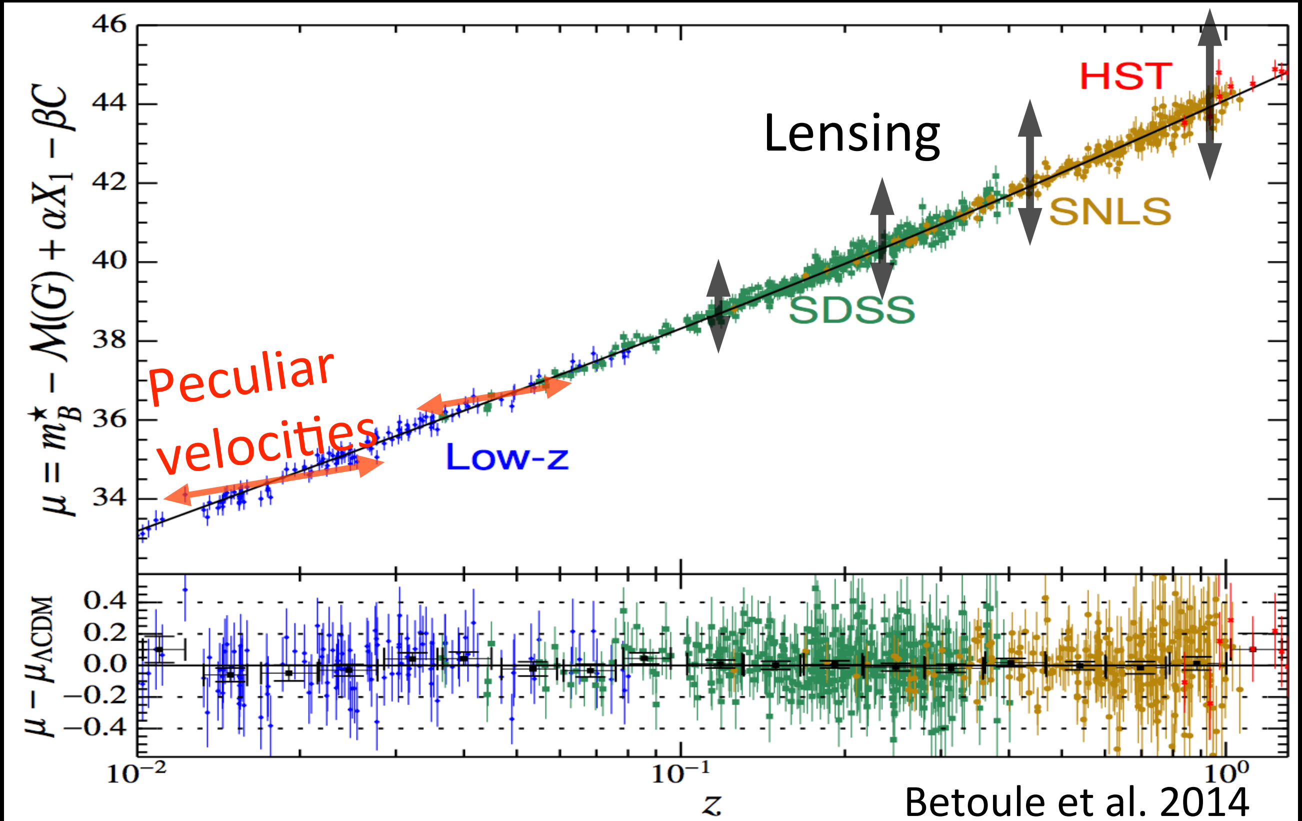
Magnitude matches
ΛCDM



4C LENSING

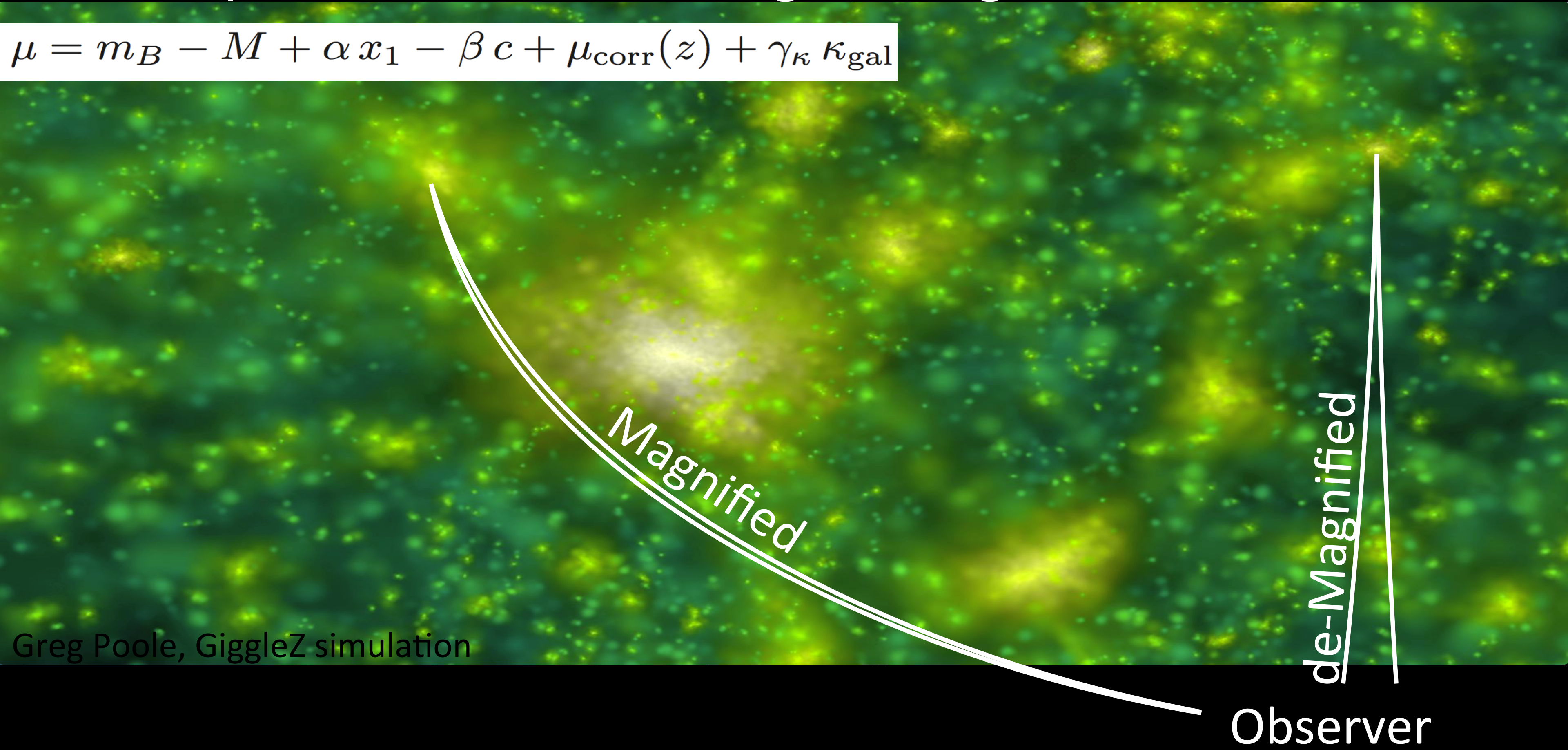
- MAGNIFICATION

Not all scatter is random



Supernova Lensing (magnification)

$$\mu = m_B - M + \alpha\, x_1 - \beta\, c + \mu_{\rm corr}(z) + \gamma_\kappa\, \kappa_{\rm gal}$$



Distribution of magnifications is asymmetric

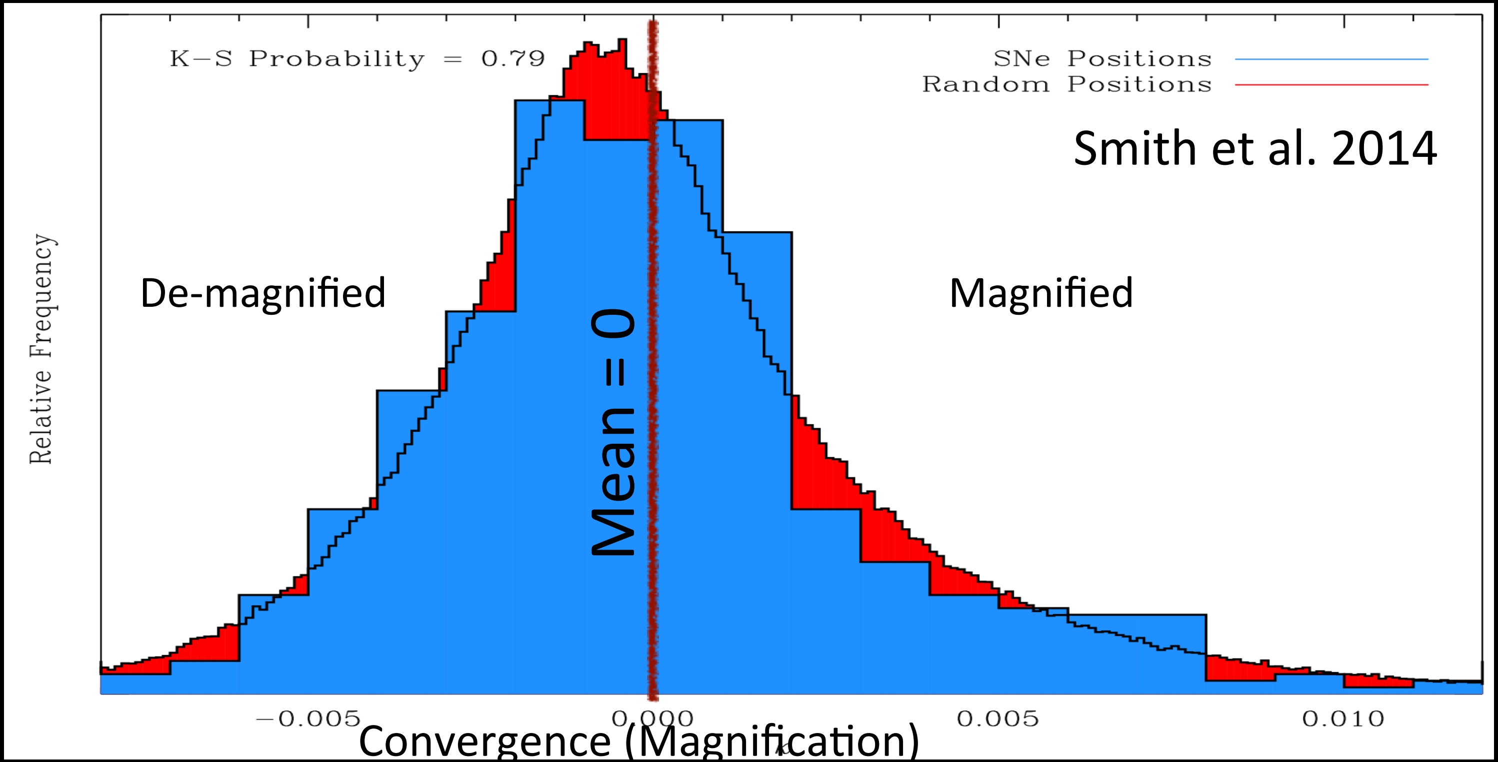


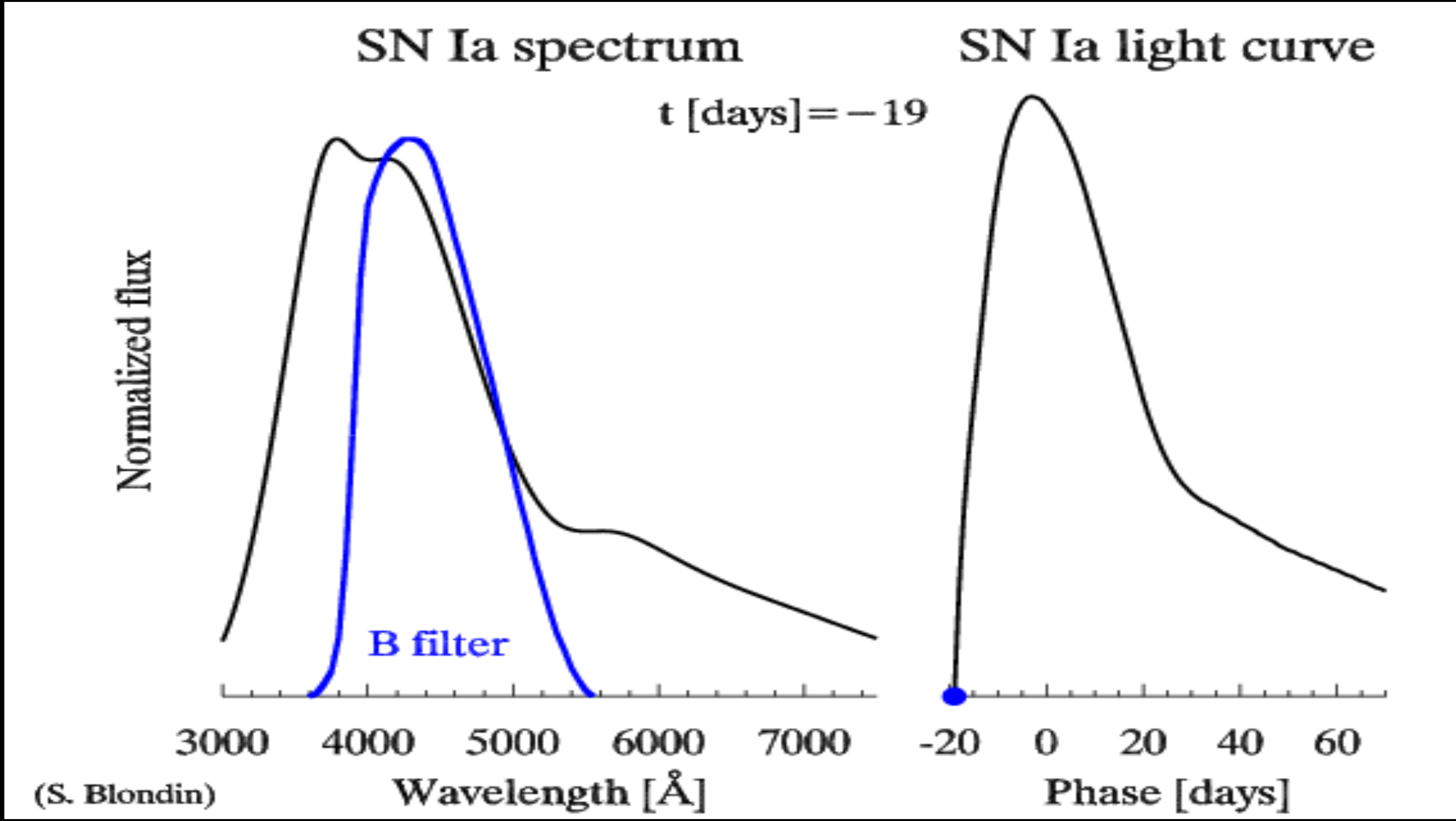
FIG. 5.— Normalized histogram of the distribution of $\kappa_{\rm gal}$ for the sample of 749 SDSS SNe (in blue), compared to a sample produced from 1000 realizations of 749 random positions within the "Stripe82" footprint (shown in red), when a fixed aperture of 12 arcminutes is considered. The probability obtained from a K-S test is also shown.

Measuring expansion

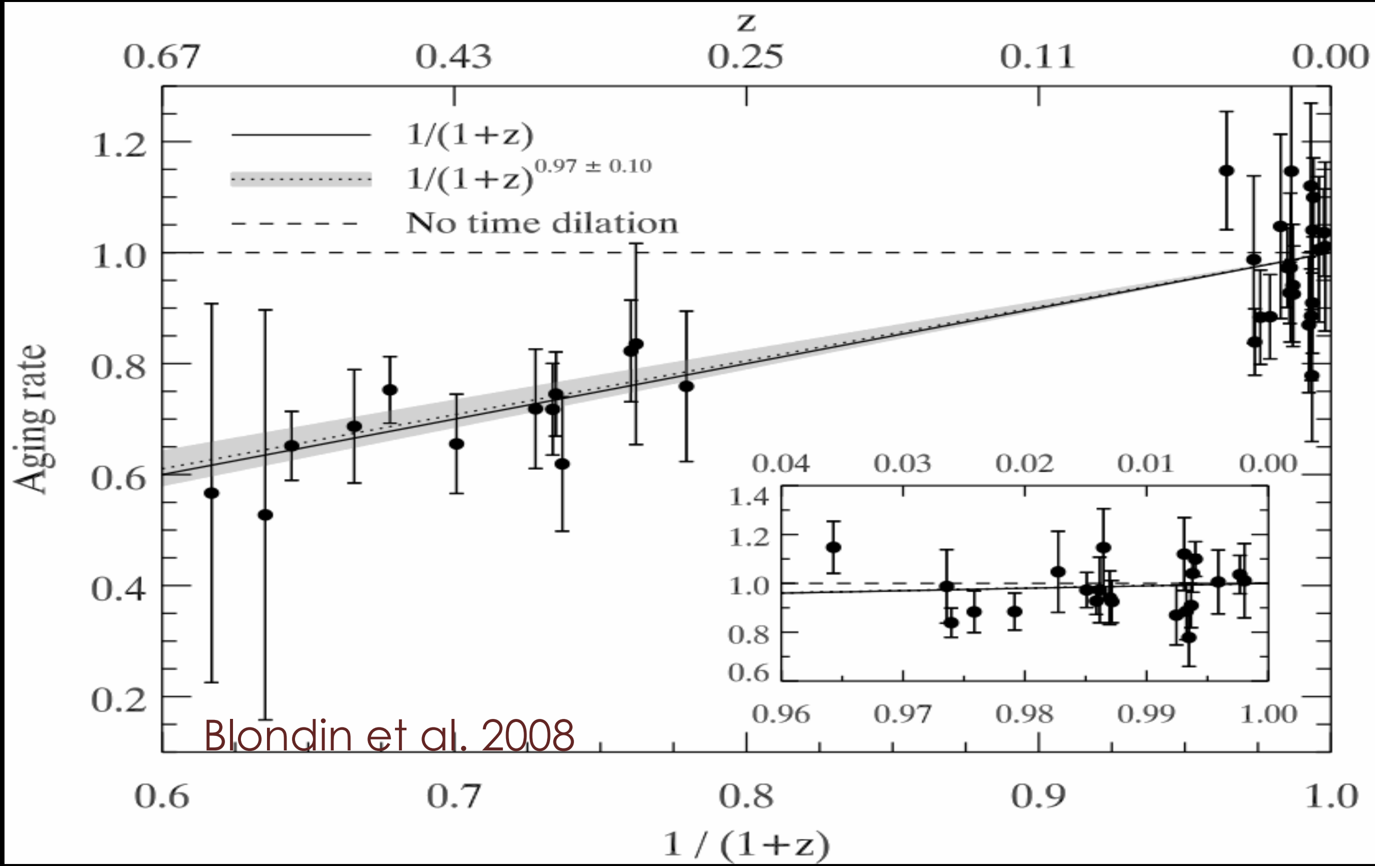
1C. SUPERNOVAE

- TIME DILATION

Supernovae as clocks

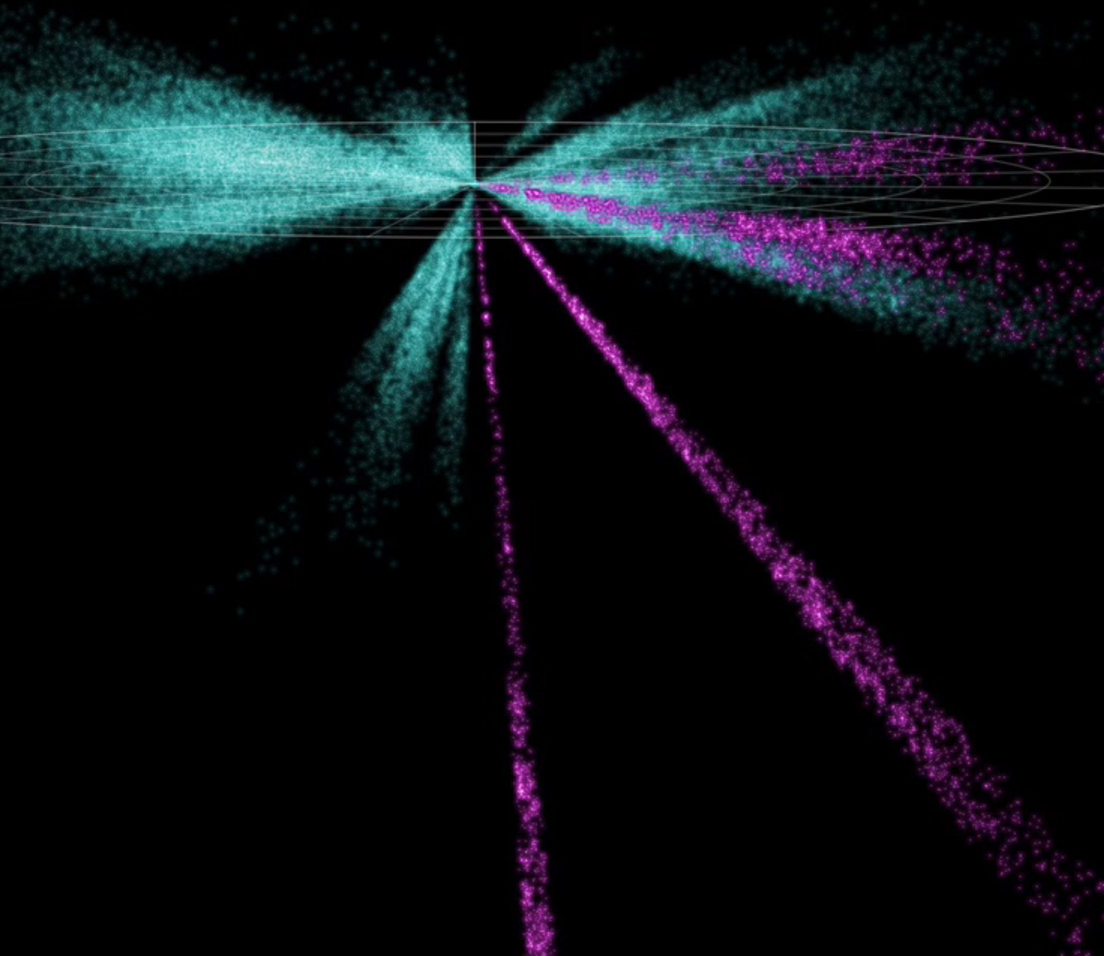


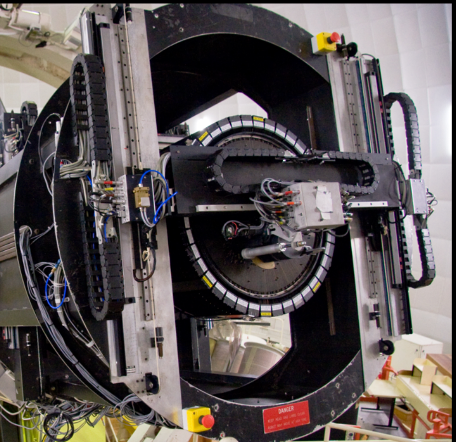
Supernovae as clocks

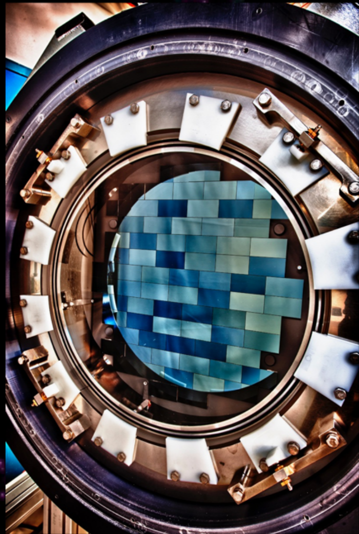


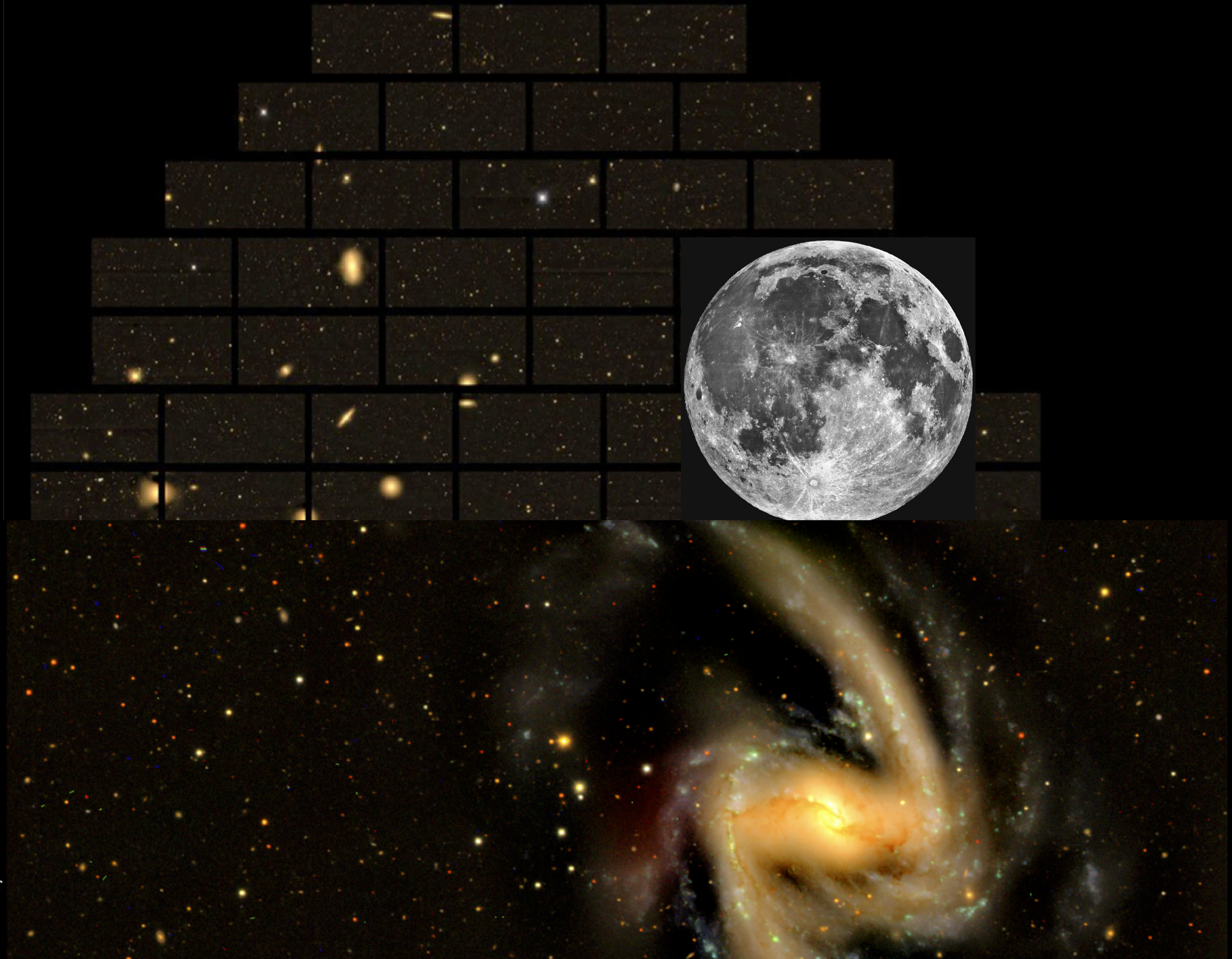
The Dark Energy Survey (DES)

Animation: Edward Macaulay
(University of Queensland)





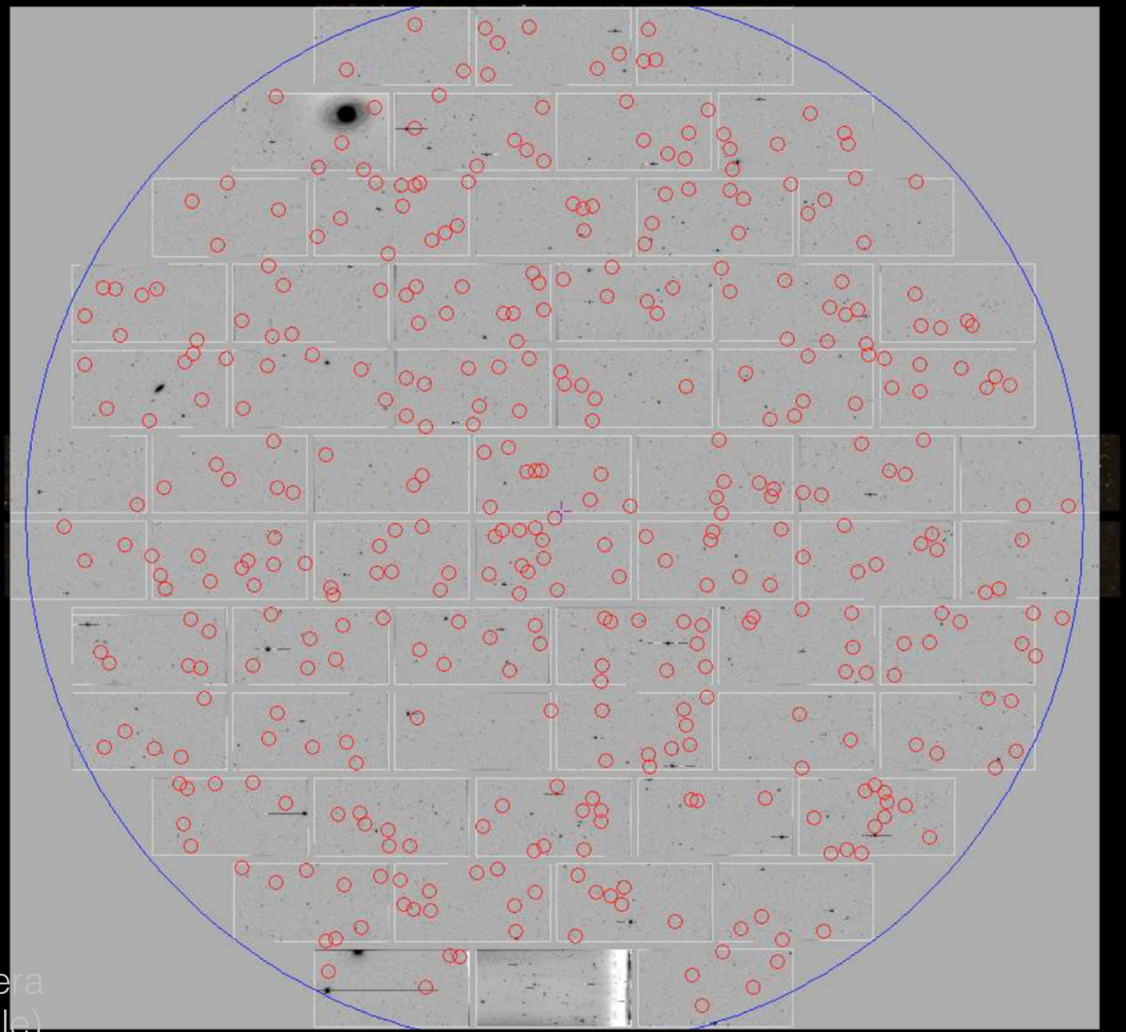




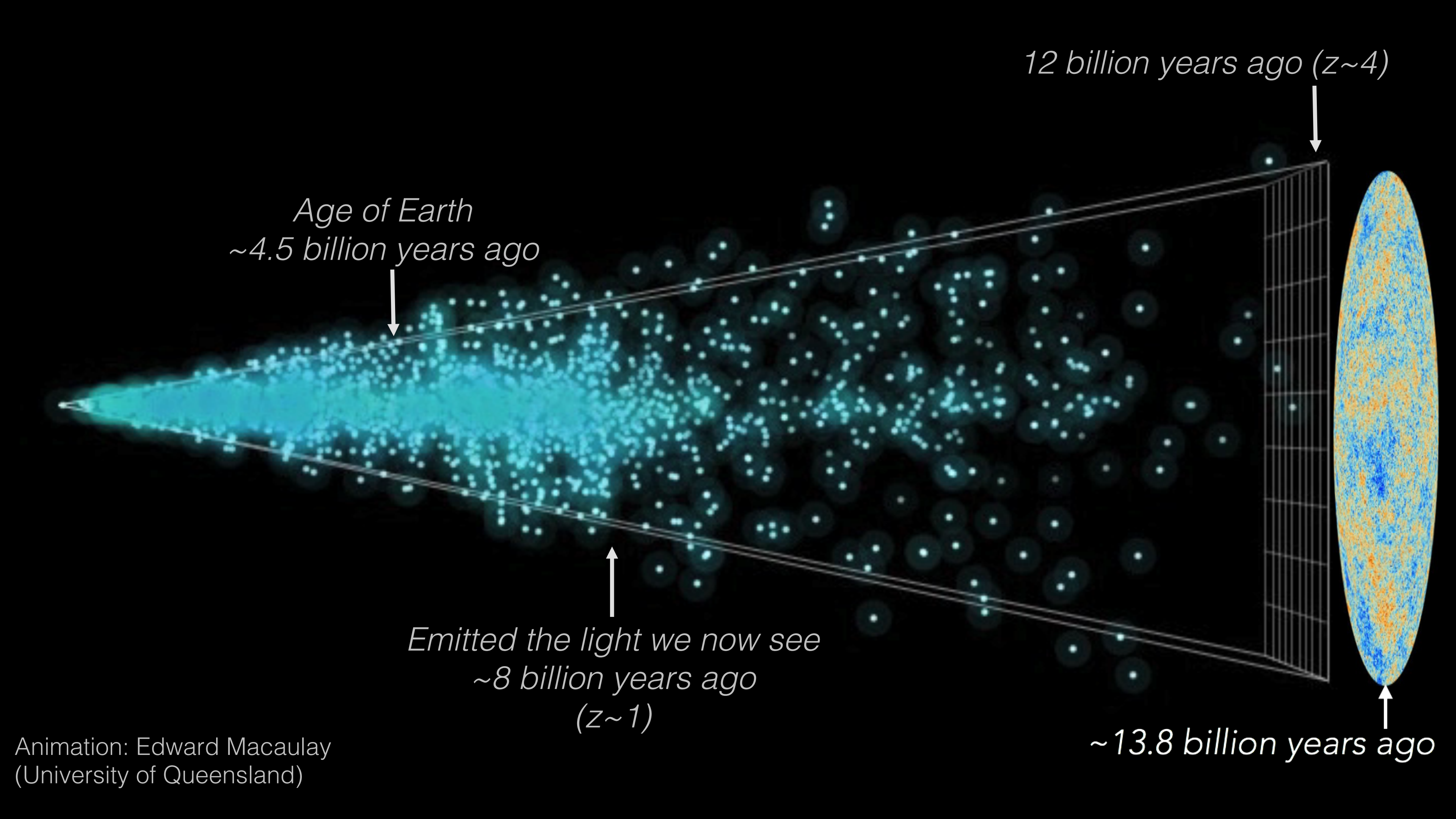
The Dark Energy Car
(Blanco telescope, C

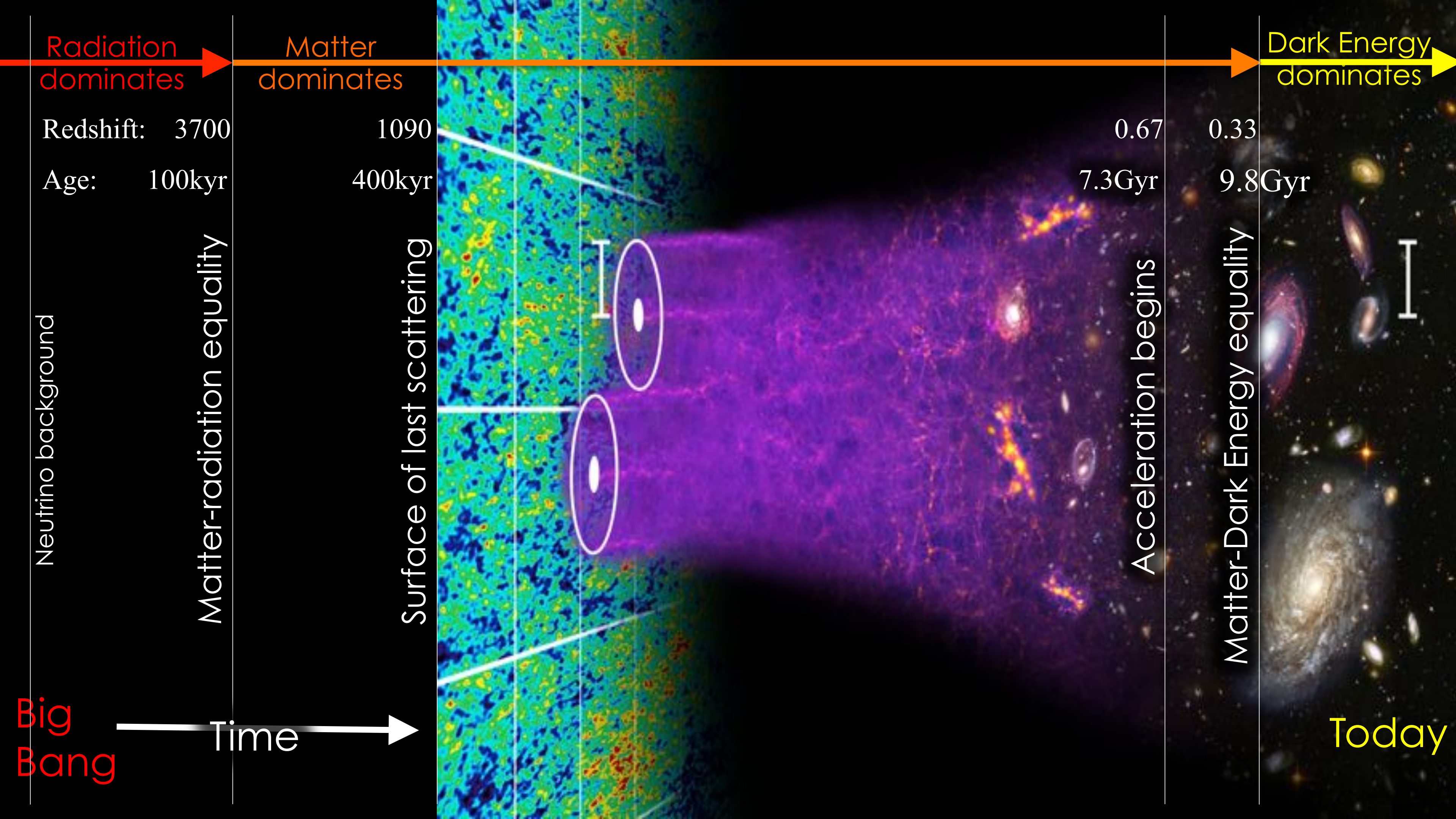
2 degree field spectrograph (Anglo-Australian Telescope)

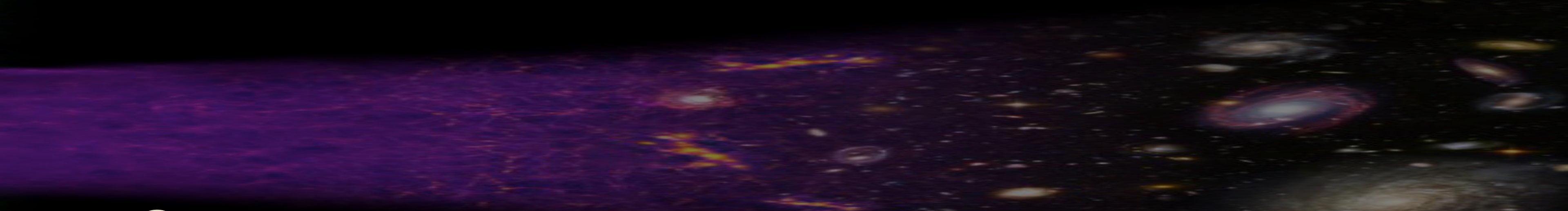
superimposed on



The Dark Energy Camera (Blanco telescope, Chile)


12 billion years ago (z~4)
Age of Earth
~4.5 billion years ago
Emitted the light we now see
~8 billion years ago
(z~1)
~13.8 billion years ago
Animation: Edward Macaulay
(University of Queensland)


Radiation dominates
Matter dominates
Dark Energy dominates
Redshift: 3700
1090
0.67
0.33
Age: 100kyr
400kyr
7.3Gyr
9.8Gyr
Neutrino background
Matter-radiation equality
Surface of last scattering
Acceleration begins
Matter-Dark Energy equality
Big Bang
Time
Today



Summary

Evidence for dark energy:
Supernovae
Cosmic Microwave Background
Baryon Acoustic Oscillations
Large Scale Structure,
Growth
Alcock-Paczynski
Strong Gravitational Lensing
Weak Gravitational Lensing
Sunyaev-Zeldovich
Integrated Sachs-Wolfe
Time dilation
Galaxy ages vs redshift
Big bang nucleosynthesis
Solar system tests
X-ray galaxies

Cosmology has advanced in leaps and bounds over the last two decades

Any model that wants to explain dark energy needs to explain a very wide range of observational tests

(ΛCDM is winning)

Better theories needed!!

(Both for dark energy,

and for structure formation)