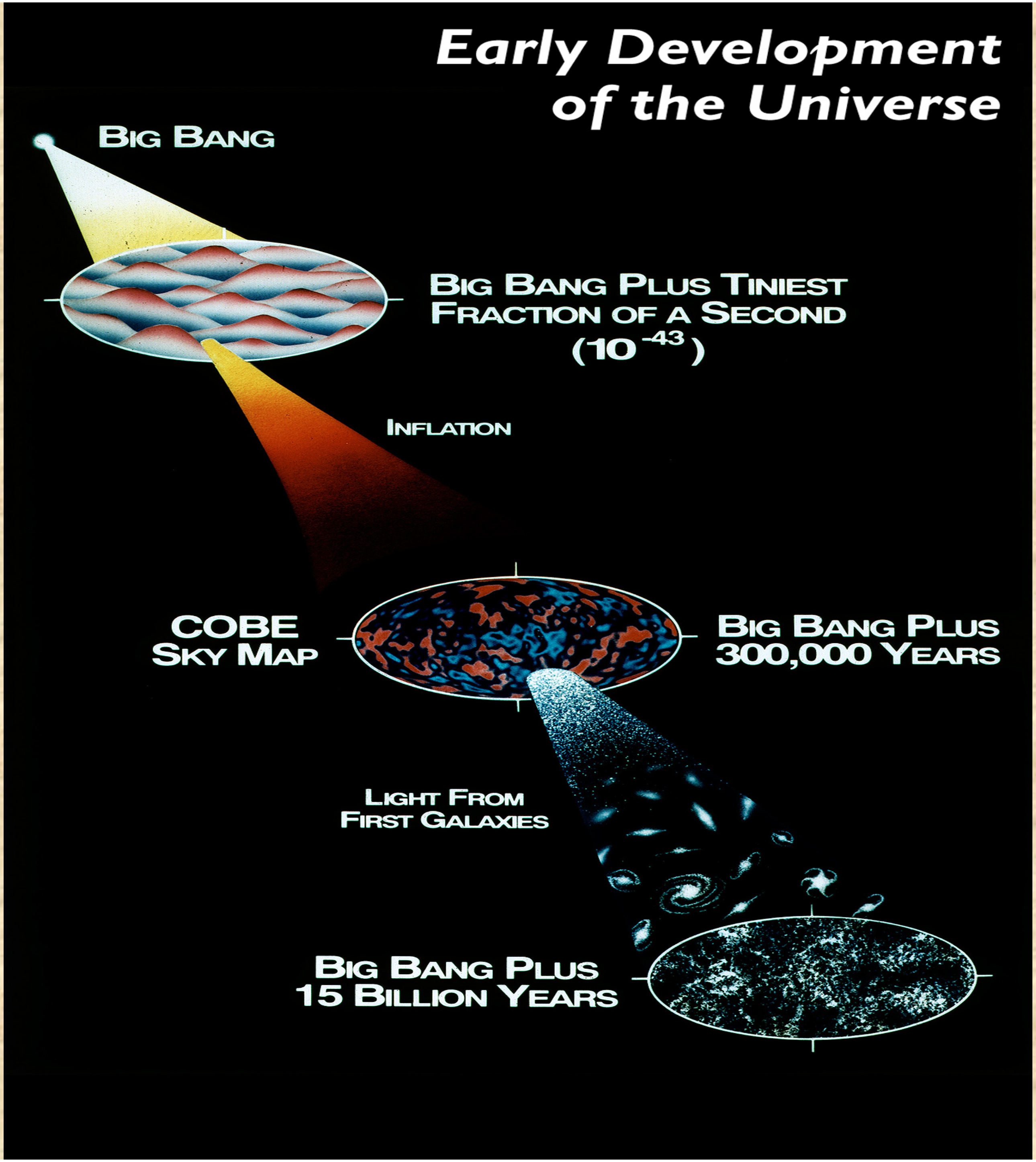
Testing the Dark Energy Paradigm with DES

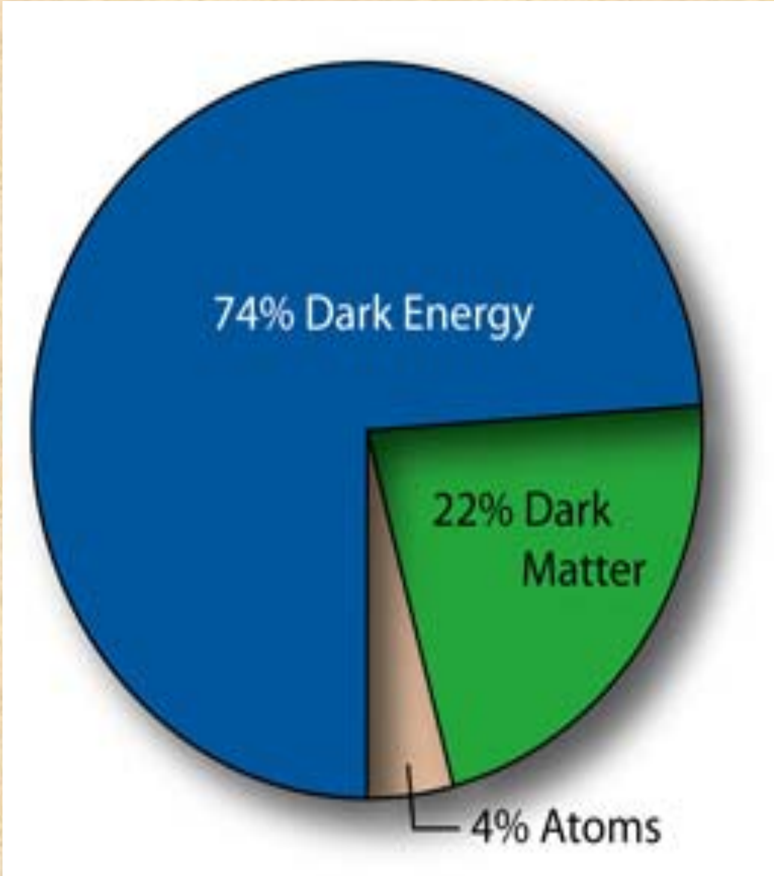
- Brief History of Dark Energy and Modified Gravity
- Galaxy Surveys
- The Dark Energy Survey
- Neutrino Mass

UCL

Ofer Lahav
University College London


Early Development of the Universe
Big Bang
Big Bang Plus Tiniest Fraction of a Second (10 -43)
Inflation
COBE Sky Map
Big Bang Plus 300,000 Years
Light From First Galaxies
Big Bang Plus 15 Billion Years

Probes of Darkness



Observational data

- Type Ia Supernovae
- Galaxy Clusters
- Cosmic Microwave Background
- Large Scale Structure
- Gravitational Lensing
- Integrated Sachs-Wolfe

Physical effects:

- Geometry
- Growth of Structure

Both depend on the Hubble expansion rate:

$$H^2(z) = H^2_0 \; [\Omega_M (1+z)^{3} + \Omega_{DE} (1+z)^{3(1+w)}] \qquad \text{(flat)}$$

Can we rule out w = pressure/density = -1?

WMAP 7-year Cosmological Interpretation

TABLE 4

SUMMARY OF THE 68% LIMITS ON DARK ENERGY PROPERTIES FROM *WMAP* COMBINED WITH OTHER DATA SETS

Section	Curvature	Parameter	+BAO+H_0	+BAO+H_0+$D_{\Delta t}$[a]	+BAO+SN[b]
Section 5.1	$\Omega_k = 0$	Constant w	-1.10 ± 0.14	-1.08 ± 0.13	-0.980 ± 0.053
Section 5.2	$\Omega_k \neq 0$	Constant w	-1.44 ± 0.27	-1.39 ± 0.25	$-0.999^{+0.057}_{-0.056}$
		Ω_k	$-0.0125^{+0.0064}_{-0.0067}$	$-0.0111^{+0.0060}_{-0.0063}$	$-0.0057^{+0.0067}_{-0.0068}$
			+H_0+SN	+BAO+H_0+SN	+BAO+H_0+$D_{\Delta t}$+SN
Section 5.3	$\Omega_k = 0$	w_0	-0.83 ± 0.16	-0.93 ± 0.13	-0.93 ± 0.12
		w_a	$-0.80^{+0.84}_{-0.83}$	$-0.41^{+0.72}_{-0.71}$	$-0.38^{+0.66}_{-0.65}$

Scientific Paradigm

In his book *The Structure of Scientific Revolutions* Thomas Kuhn argued:

- Science undergoes periodic "paradigm shifts", instead of progressing in a linear and continuous way
- These paradigm shifts open up new approaches to understanding that scientists would never have considered valid before
- Scientists can never divorce their subjective perspective from their work; thus, our comprehension of science can never rely on full "objectivity" - we must account for subjective perspectives as well

The Chequered History of the Cosmological Constant Λ

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

* The old CC problem:
Theory exceeds observational limits on Λ by 10^{120} !

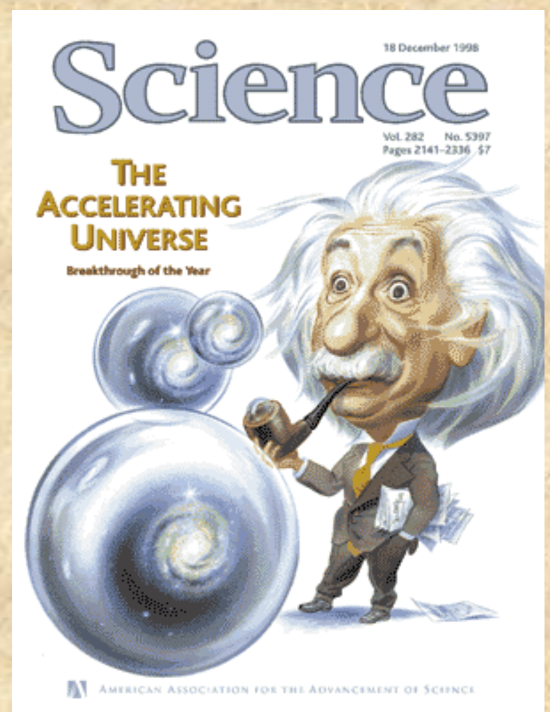
* The new CC problem:
Why are the amounts of Dark Matter and Dark Energy so similar? What is W (the ratio of pressure to density)?

Pre-Supernovae paradigm shift

- Peebles (1984) advocated Lambda
- APM result for low matter density (Efstathiou et al. 1990)
- Baryonic fraction in clusters (White et al. 1993)
- The case for adding Lambda (Ostriker & Steinhardt 1995)
- Cf. linear Lambda-like force (Newton 1687 !)

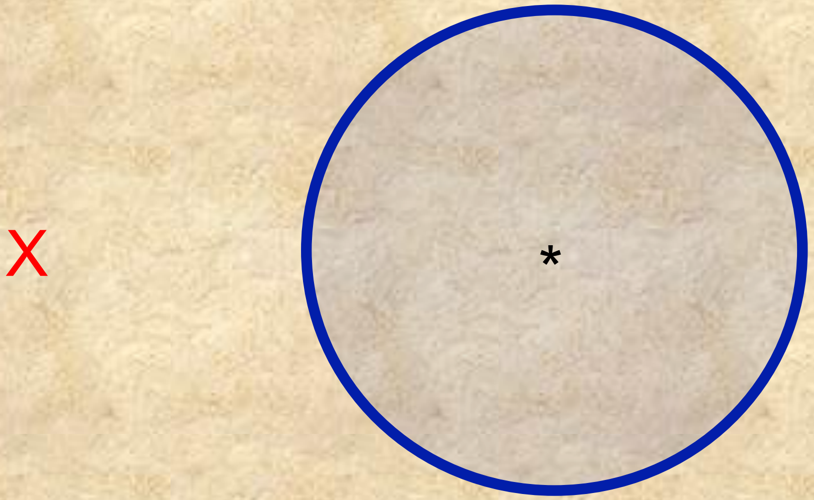
Calder & Lahav (2008, 2010)

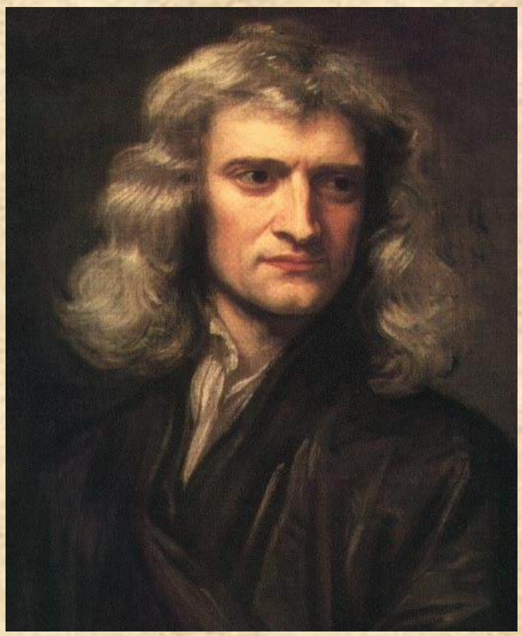
The Dark Energy problem: 10, 90 or 320 years old?



The weak field limit of GR:

$F = -GM/r^2 + \Lambda/3\ r$





"I have now explained the TWO principle cases of attraction… which is very remarkable"

Isaac Newton, Principia (1687)

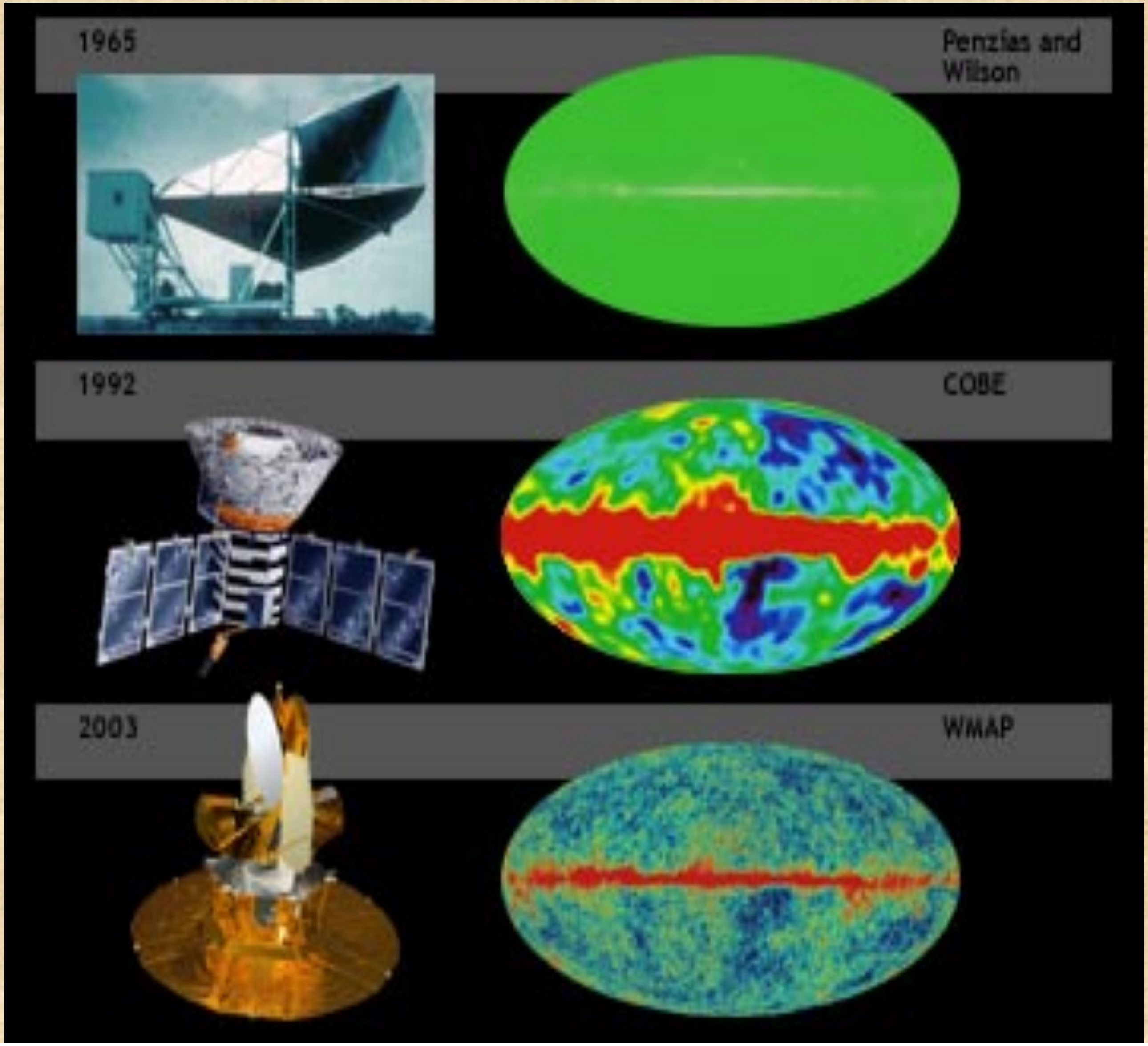
Lucy Calder & OL
A&G Feb 08 issue
http://www.star.ucl.ac.uk/~lahav/CLrev.pdf (revised)

The Cosmic Microwave Background

1965

1992

2003

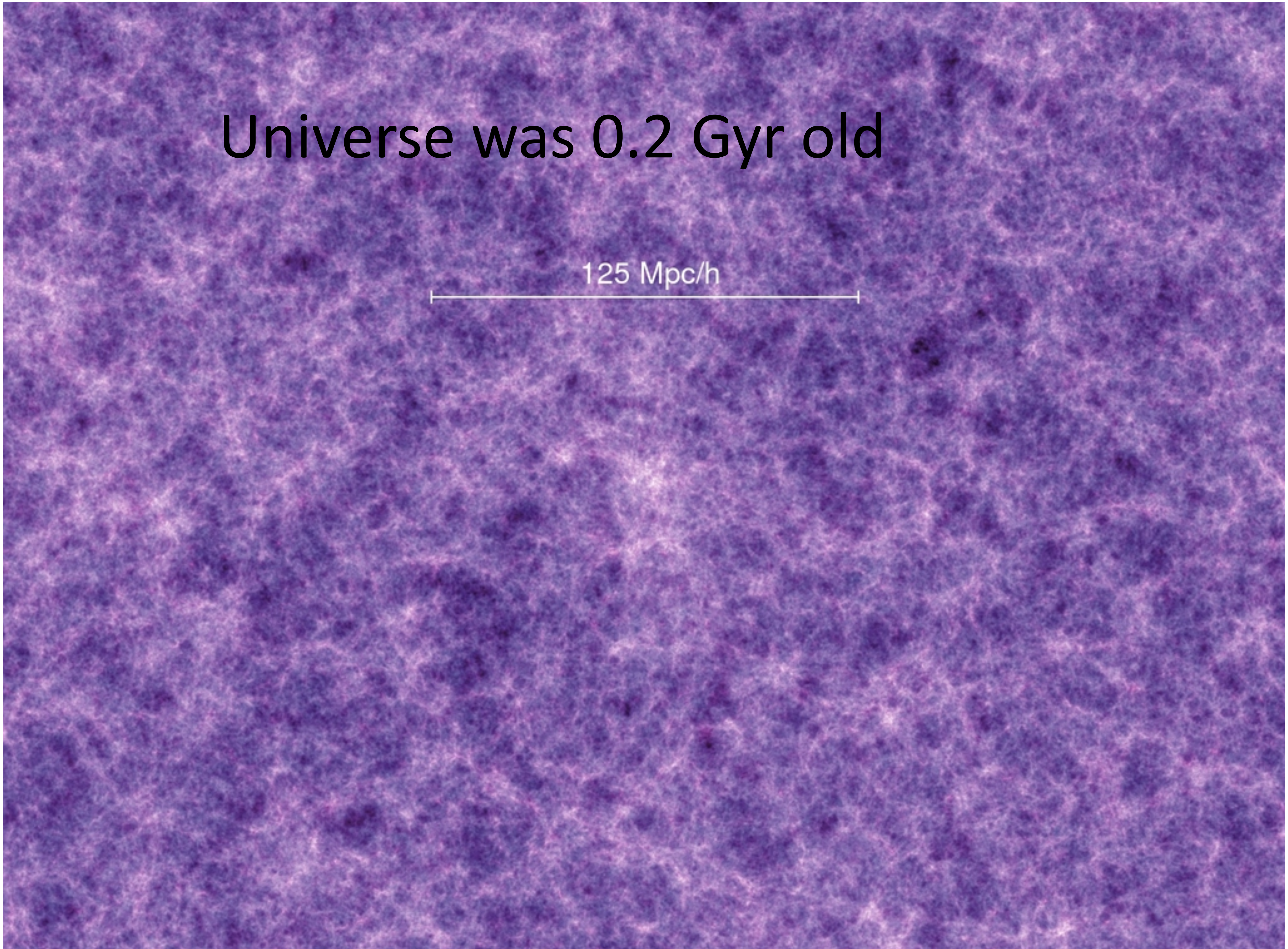


Discovery

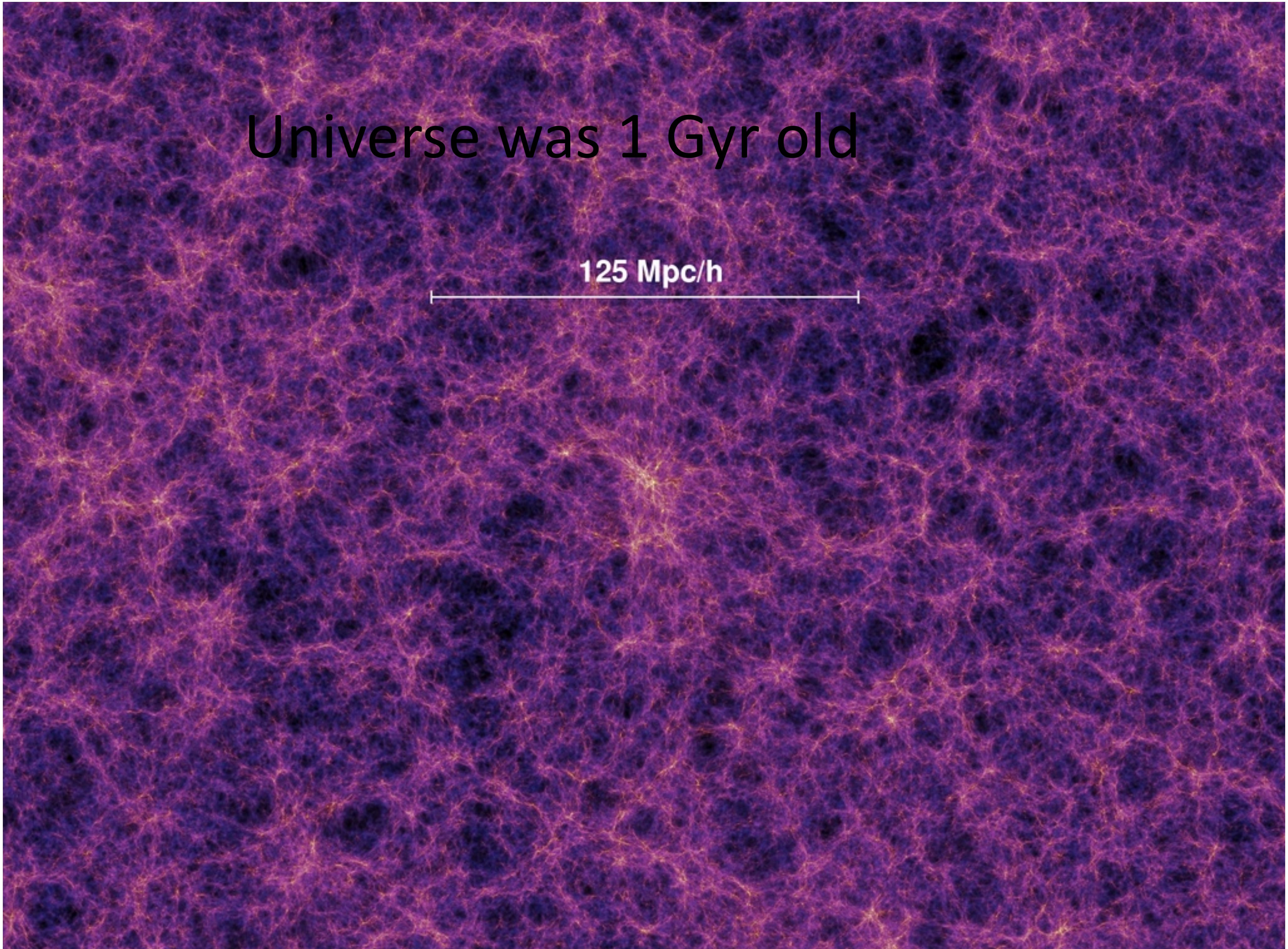
COBE

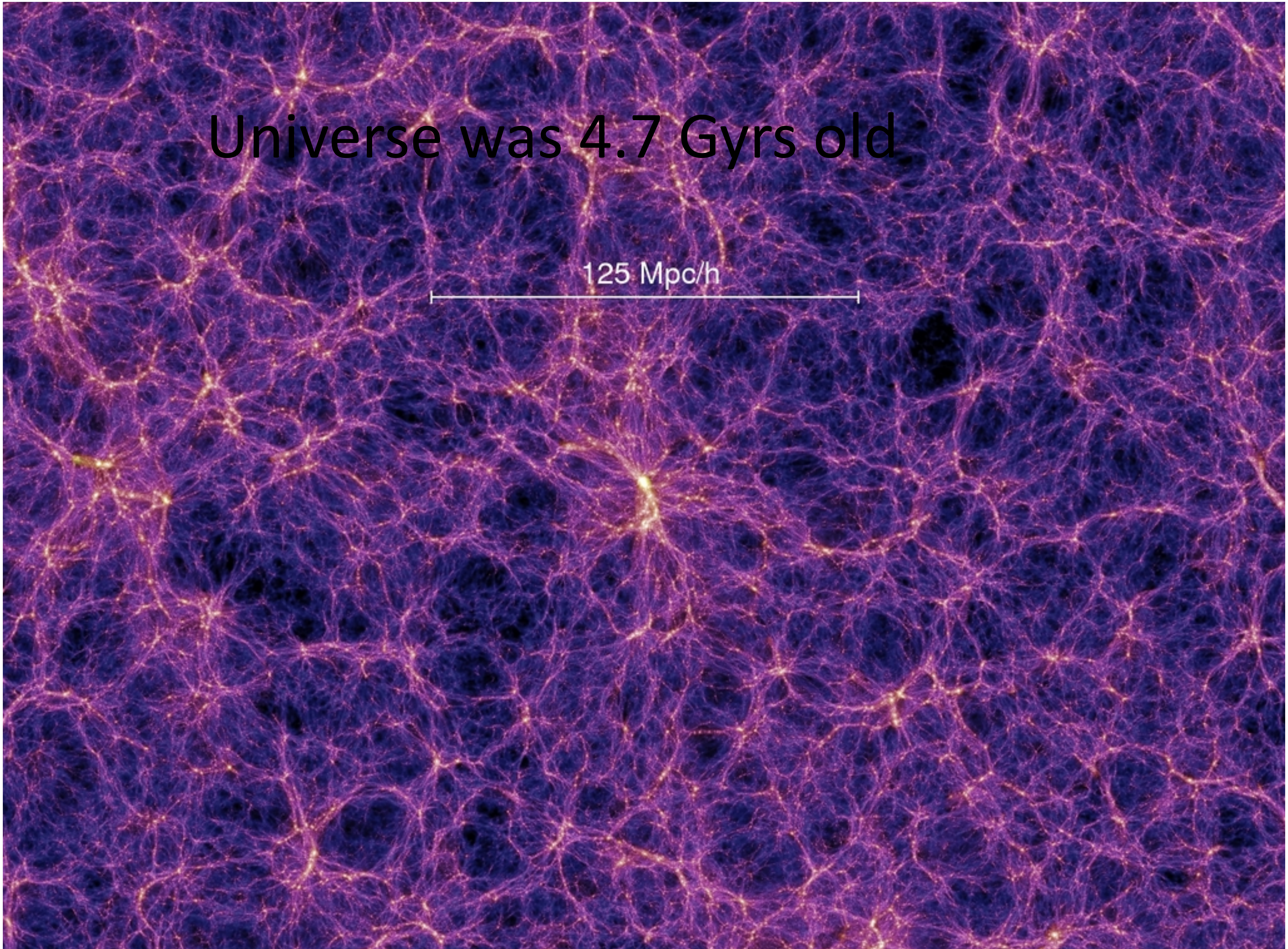
WMAP

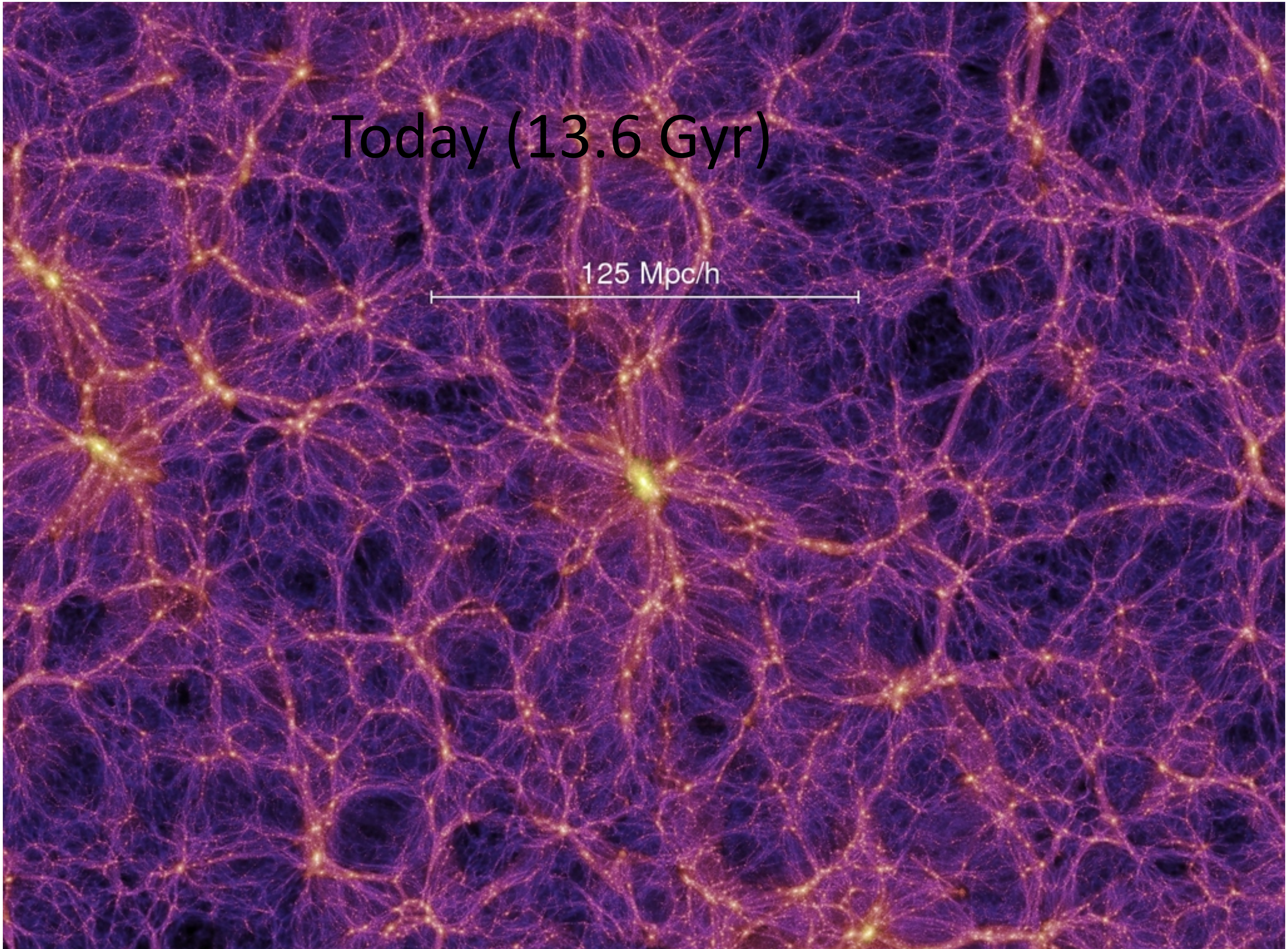
Universe was 0.2 Gyr old



Universe was 1 Gyr old

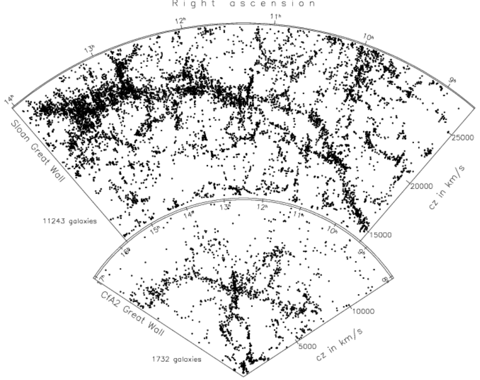



Universe was 4.7 Gyrs old
125 Mpc/h


Today (13.6 Gyr)
125 Mpc/h

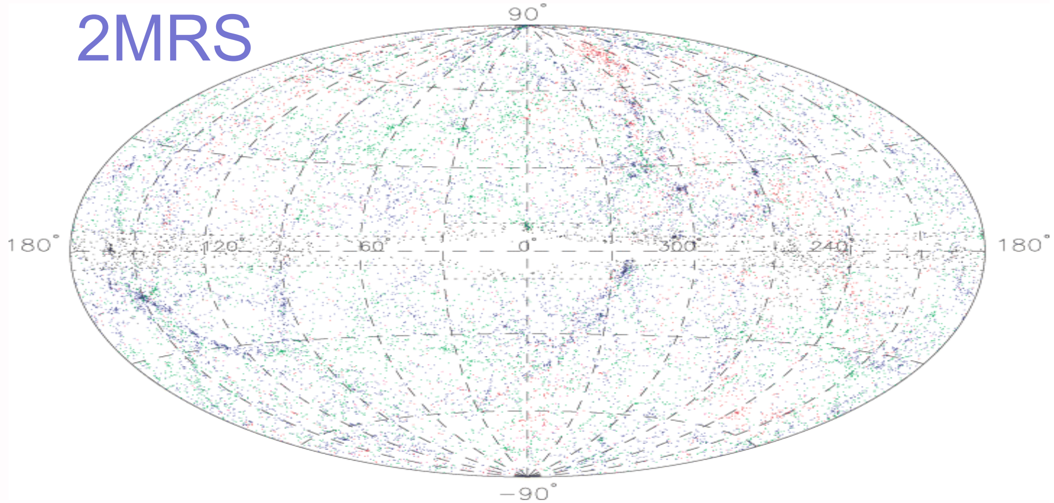
Spectroscopic Surveys

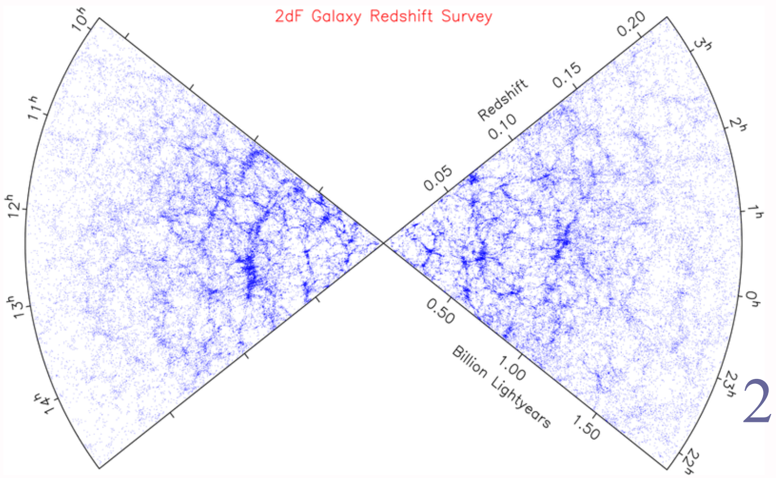
SDSS



CfA

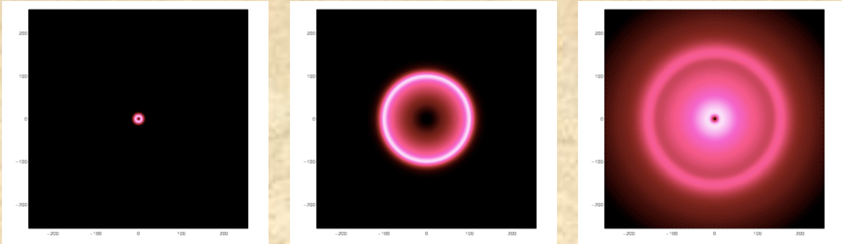
2MRS



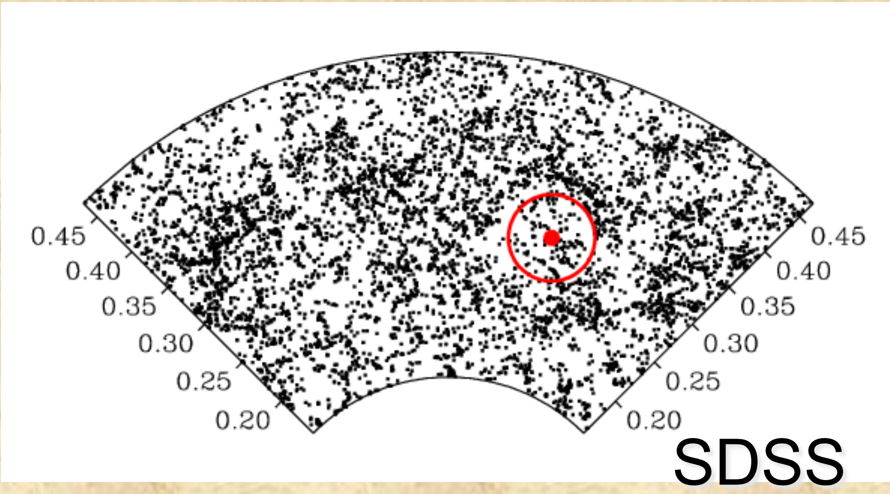


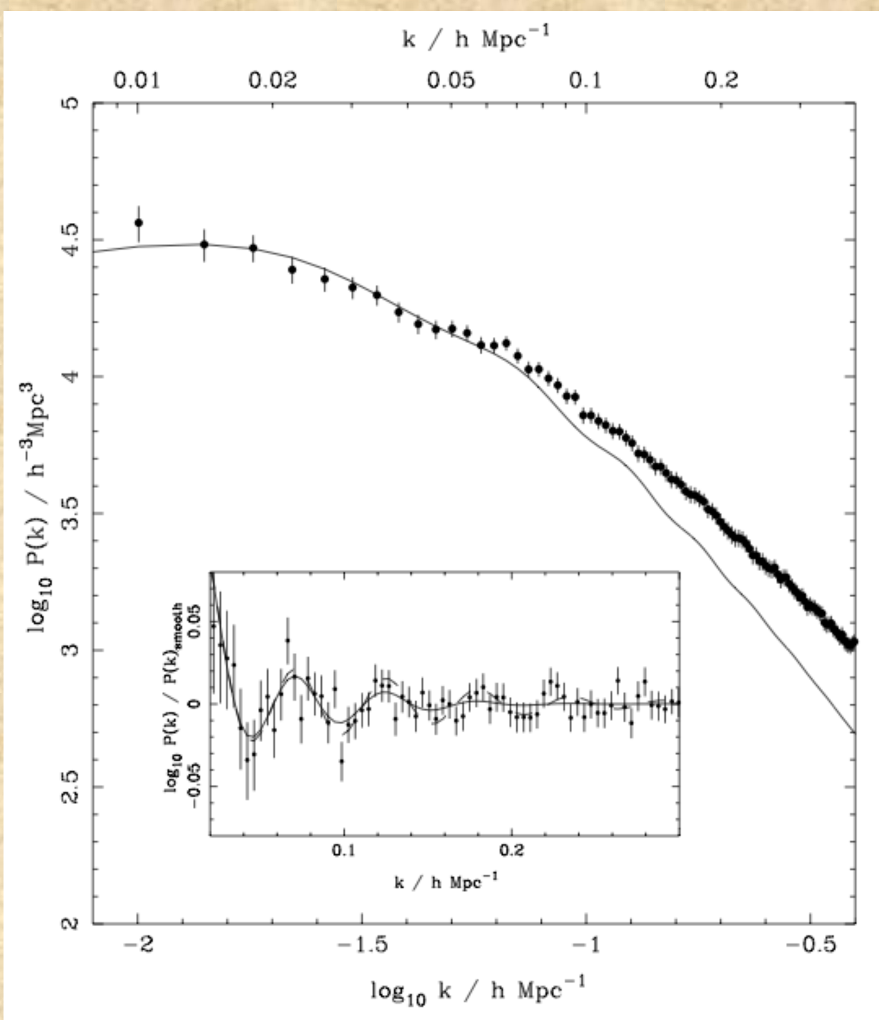
2dFGRS

Baryon Acoustic Oscillations (BAO)



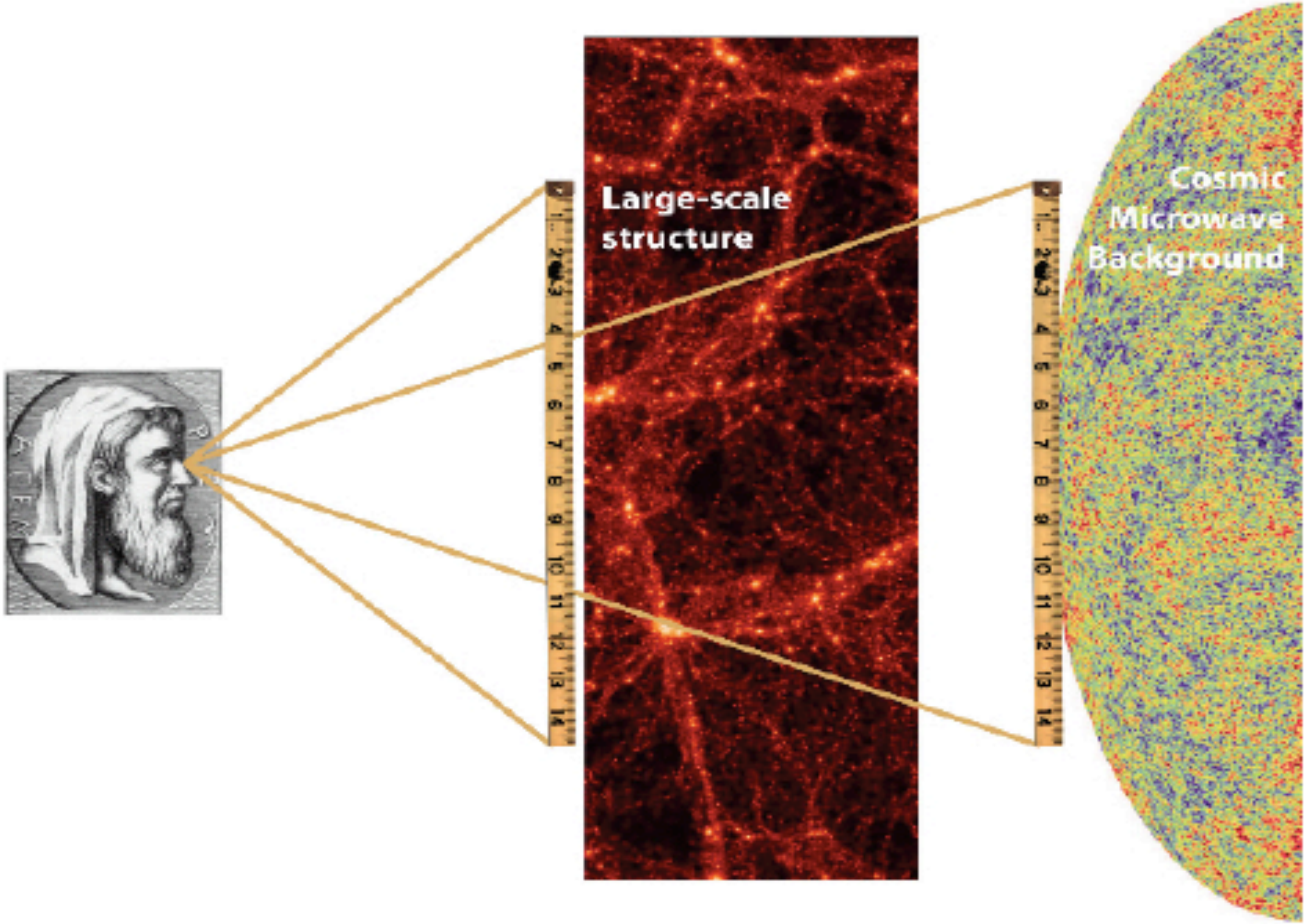
(images from Martin White)



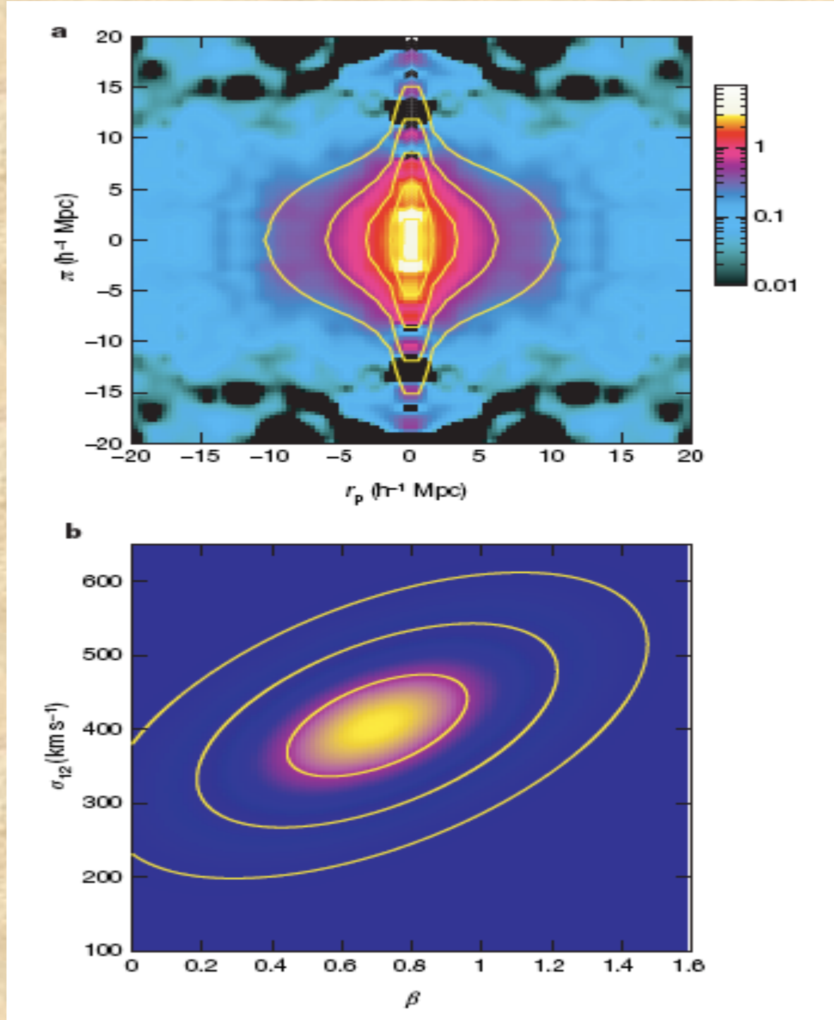


Percival et al. (2007)

Standard rulers

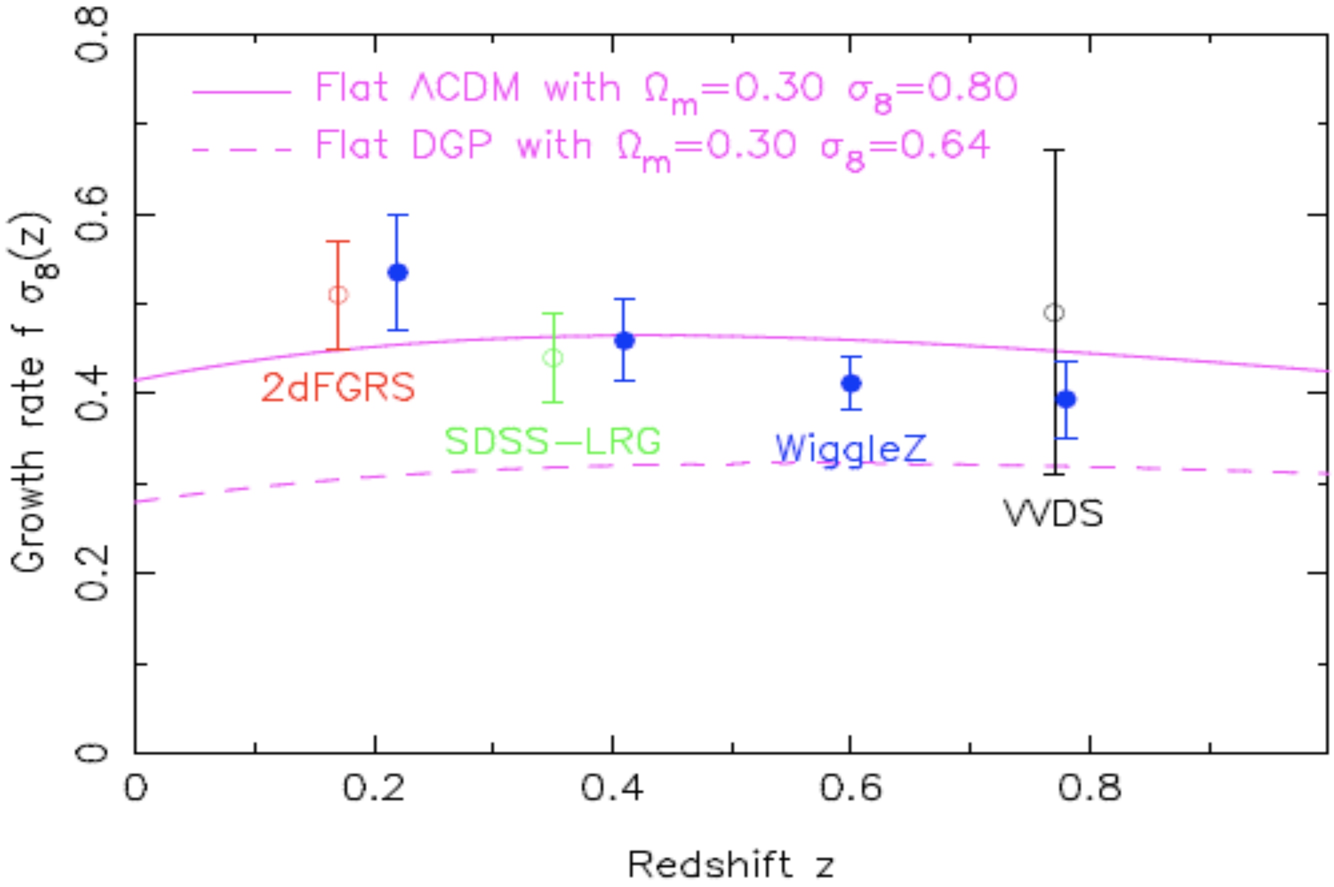


Redshift Distortion as a test of Modified Gravity



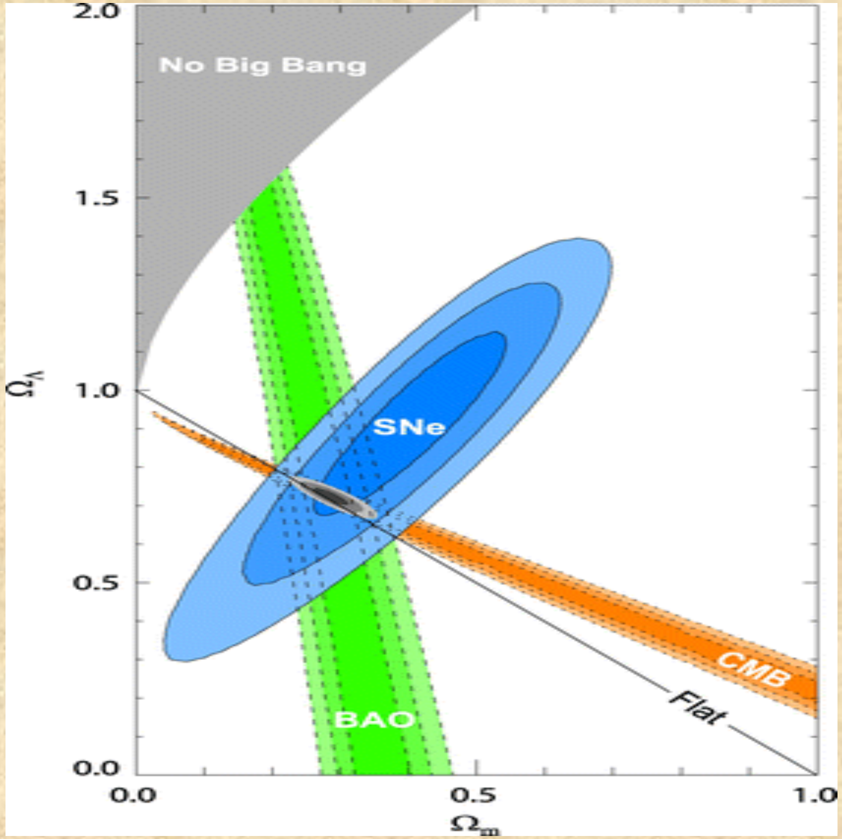
Guzzo et al. 2008

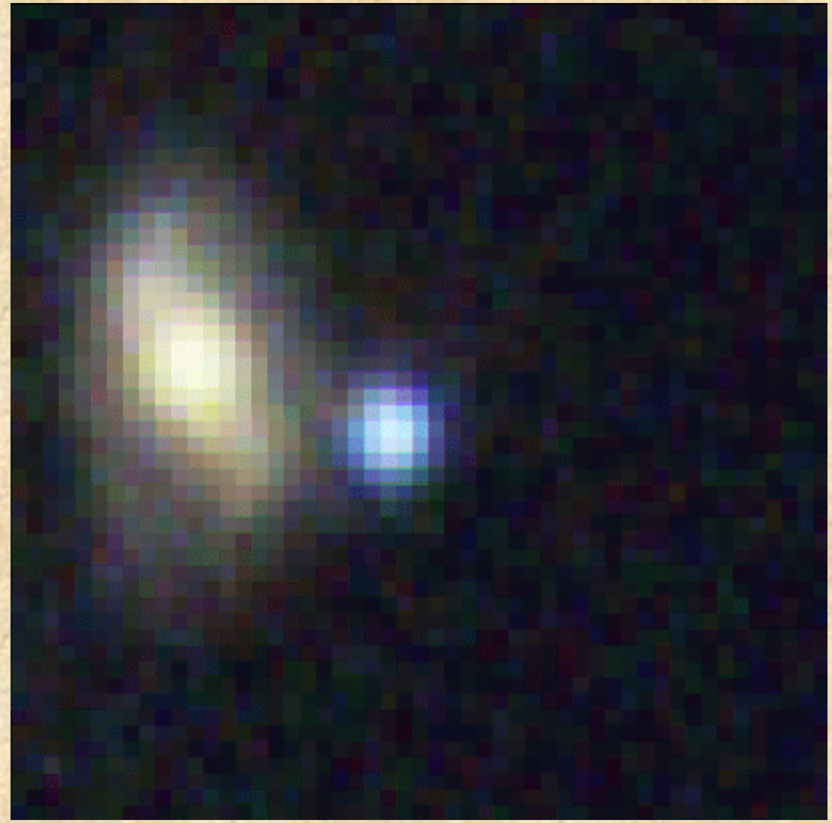
Growth of structure results



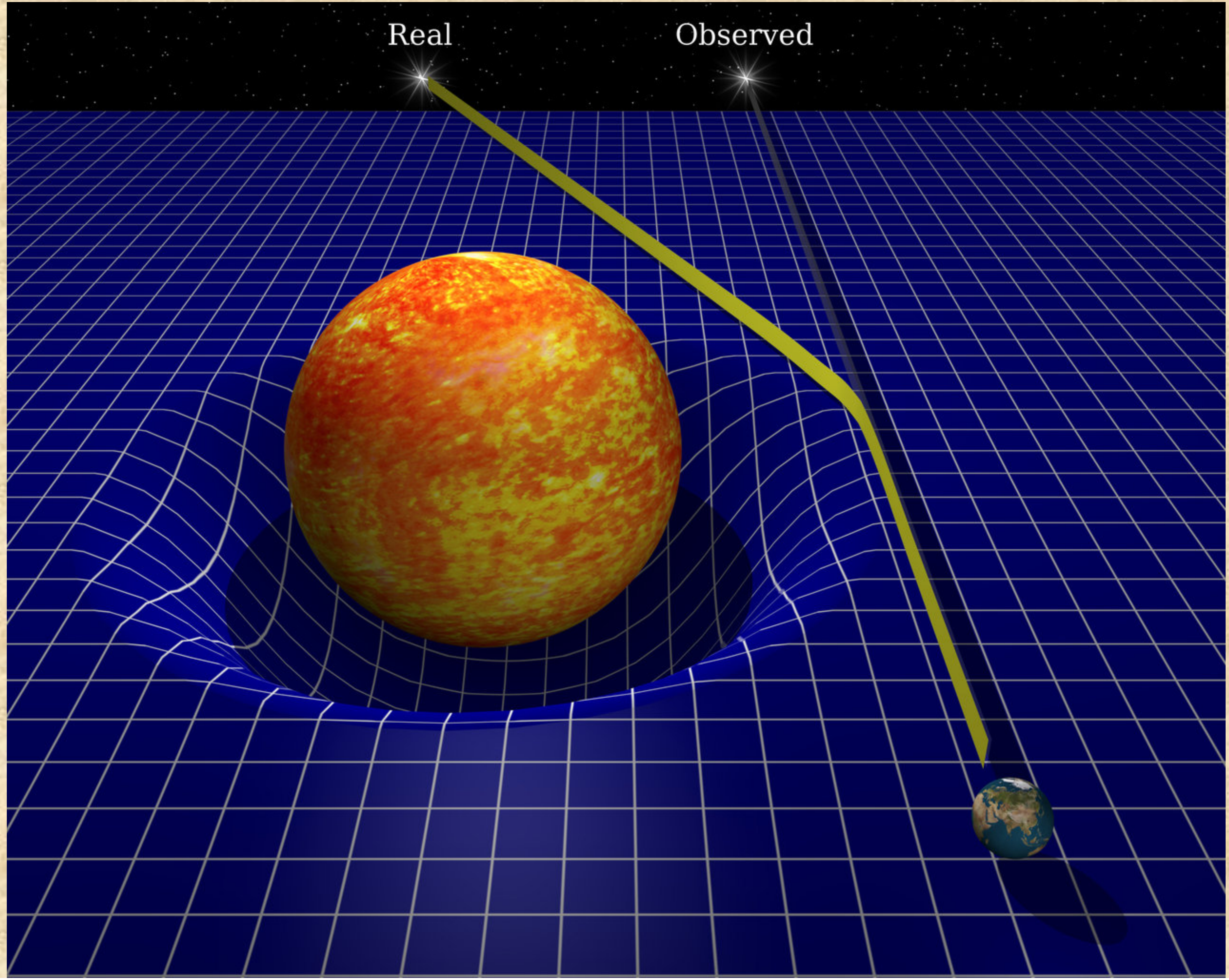
Credit: Chris Blake

Probing the Geometry of the Universe with Supernovae Ia





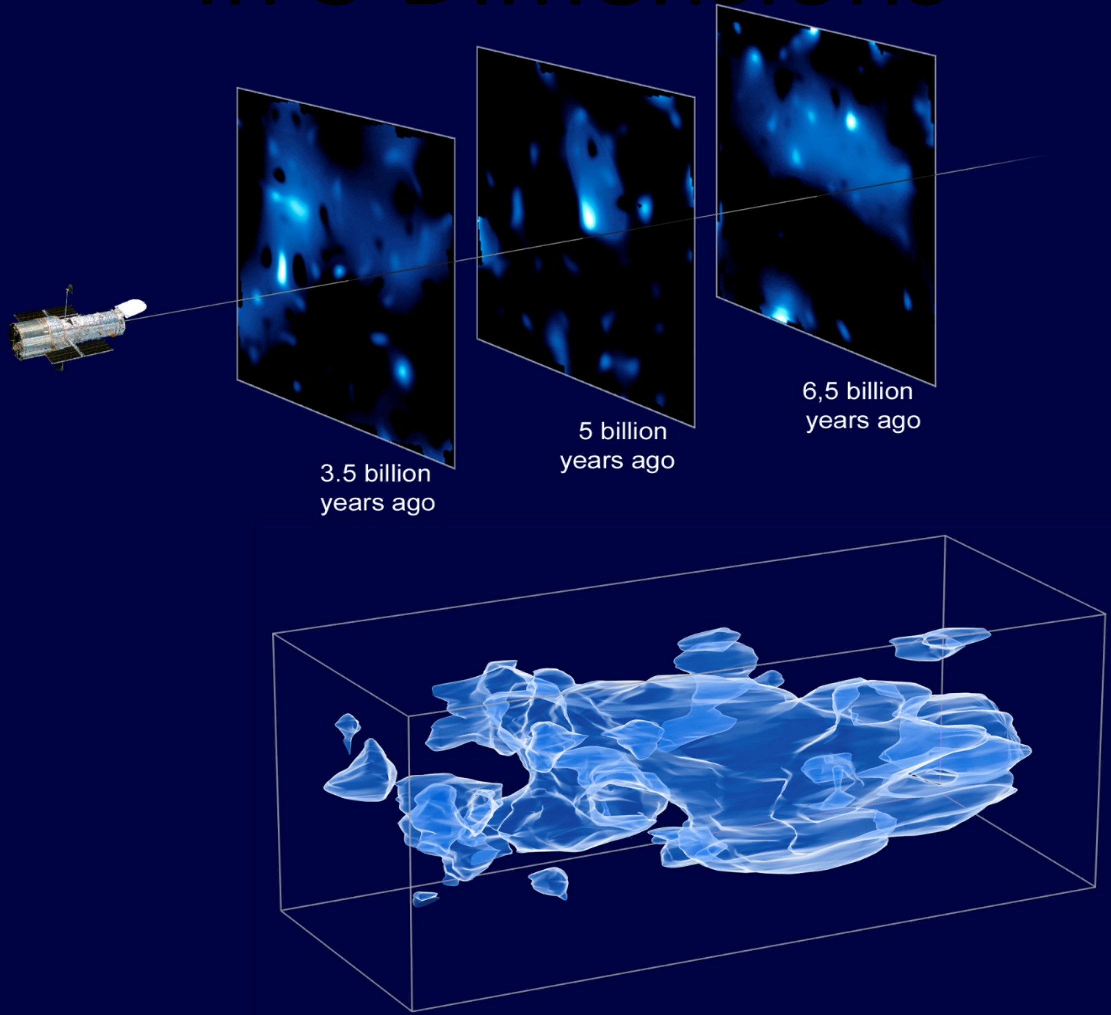
'Union' SN Ia sample (Kowalski et al. 2008)


Real
Observed

Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

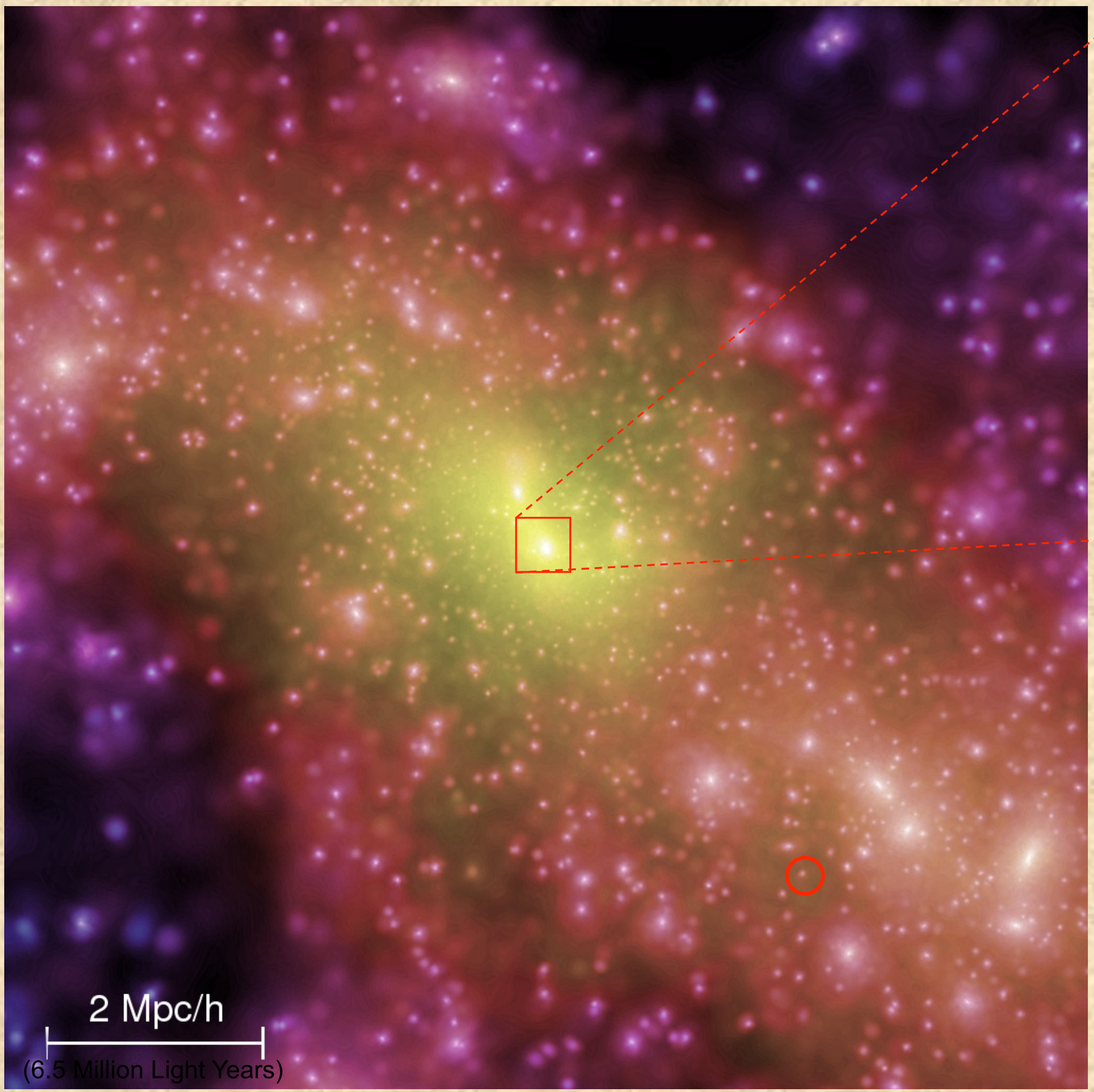
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

In 3 Dimensions

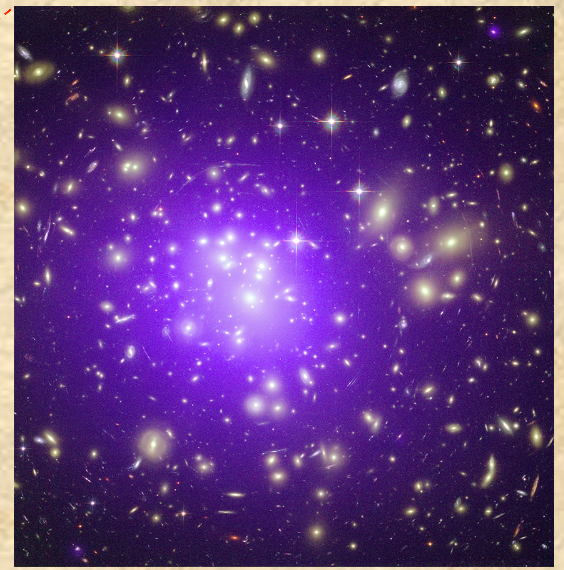


Massey et al. 2007

CLASH: An HST Multi-Cycle Treasury Program



Simulation of dark matter around a forming cluster (Springel et al. 2005)



Deep HST image of massive cluster

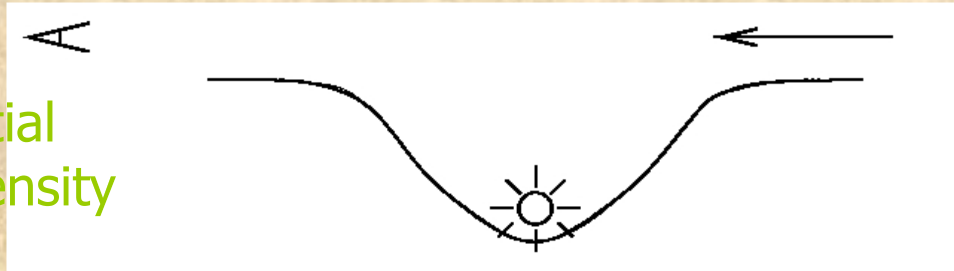
25 clusters

PI:Postman

from UCL: Lahav, Host, Jouvel

The Integrated Sachs-Wolfe Effect

gravitational potential traced by galaxy density



potential depth changes as cmb photons pass through

$$\frac{\delta T}{T} = -2 \int \dot{\Phi}(\tau) d\tau$$

In EdS the potential is constant with time, hence no ISW effect.

An effect is expected in a universe with DE, and it can be detected by cross-correlating the CMB with galaxy maps (Crittenden et al).

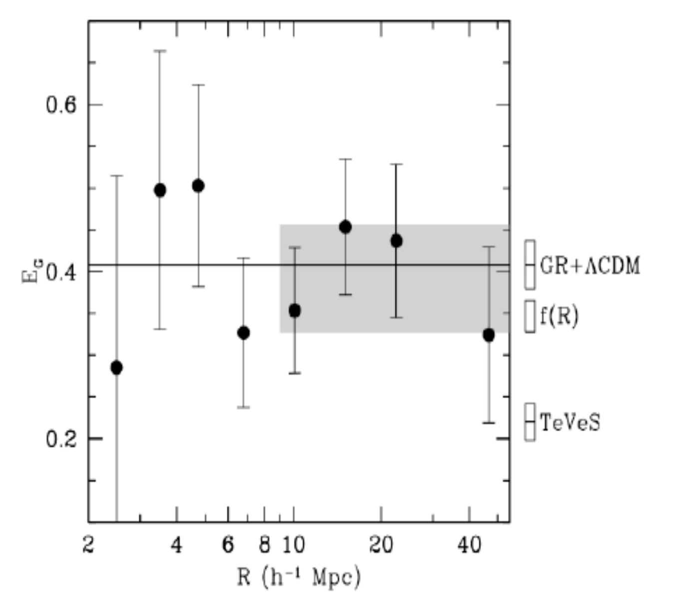
Deviations from standard GR?

$$ds^2 = -a^2(\tau)\{d\tau^2[1+2\psi(\mathrm{x},\tau)] + d\mathrm{x}^2[1-2\phi(\mathrm{x},t)]\}$$

Lensing is sensitive to the sum of potentials,
while velocities respond to the temporal potential

$$\gamma(k,a) \equiv \frac{\ln(\dot{\delta}_c/\mathcal{H}\delta_c)}{\ln\Omega_m(a)}, \quad \eta(k,a) \equiv \frac{\phi(k,a)}{\psi(k,a)},$$

Reyes et al. (Nature, 2010)
'confirm' GR from
weak lensing and galaxy velocities



Also B. Jain et al. (2009)

LCDM - ‘problems on the small scales’

- The MW satellites – too many in simulations?
- Cluster mass profiles – concentration too low in simulations?
- Hierachical clustering – the wrong order?
- Galaxies in voids- too many in simulations?
- Superclusters – too few in simulatons?
- Are we near a centre of a void?

Sources of uncertainties in measuring Dark Energy

- Theoretical (e.g. the cosmological model)
- Astrophysical (e.g. galaxy and cluster properties)
- Instrumental (e.g. image quality)

Galaxy Surveys 2010-2020

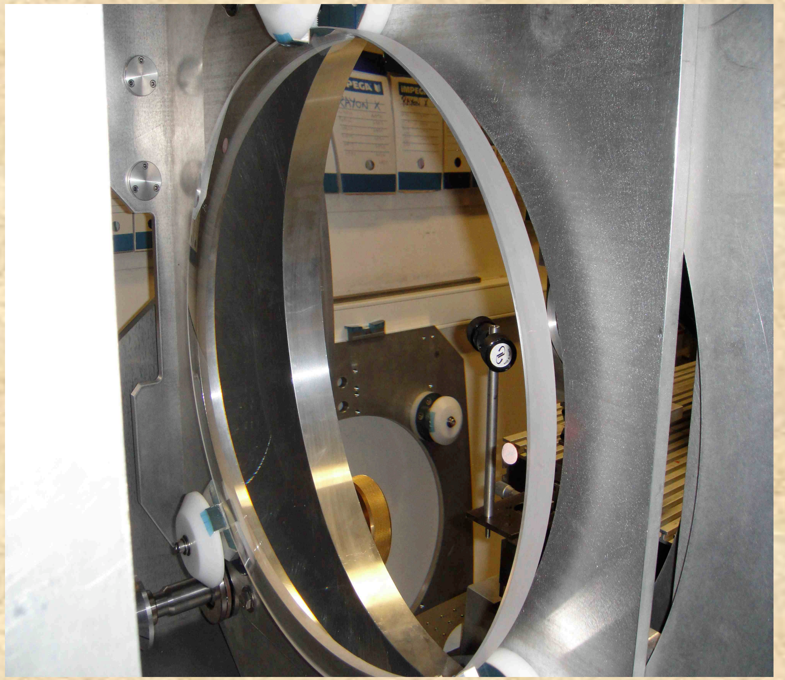
Photometric surveys: DES, Pan-STARRS, HSC, Skymapper, PAU, LSST, …

Spetroscopic surveys: WiggleZ, BOSS, BigBOSS, DESpec, hetdex, WFMOS/Sumire, SKA, …

Space Missions: Euclid vs. WFIRST

The Dark Energy

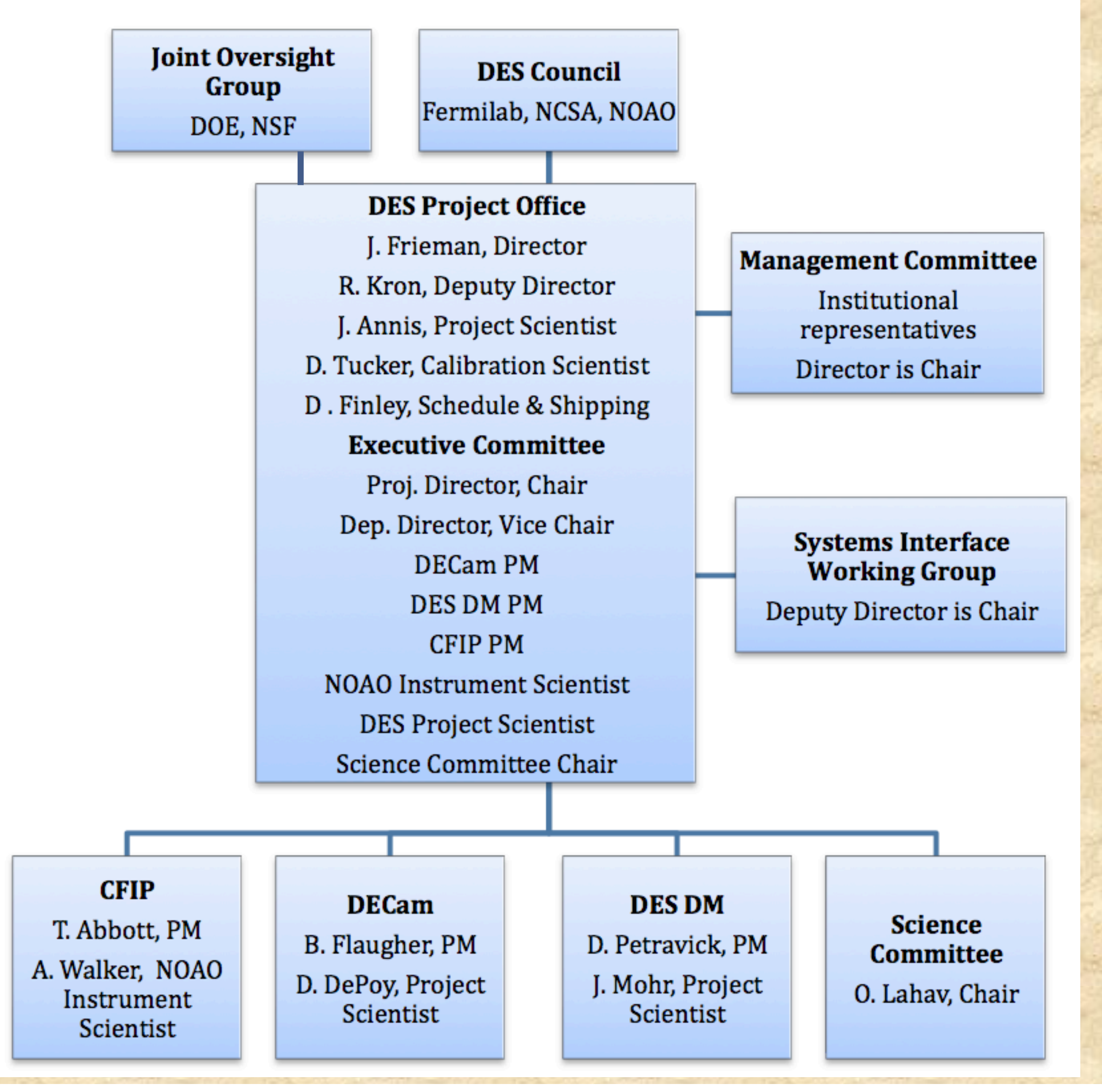
http://www.darkenergysurvey.org



The DES Collaboration

Fermilab
University of Illinois at Urbana-Champaign/NCSA
University of Chicago
Lawrence Berkeley National Lab
NOAO/CTIO
DES Spain Consortium
DES United Kingdom Consortium
University of Michigan
Ohio State University
University of Pennsylvania
DES Brazil Consortium
Argonne National Laboratory
SLAC-Stanford-Santa Cruz Consortium
Universitats-Sternwarte Munchen
Texas A&M University
plus Associate members at: Brookhaven National Lab,
U. North Dakota, Paris, Taiwan

Over 120 members plus students & postdocs


Joint Oversight Group
DOE, NSF
DES Council
Fermilab, NCSA, NOAO
DES Project Office
J. Frieman, Director
R. Kron, Deputy Director
J. Annis, Project Scientist
D. Tucker, Calibration Scientist
D . Finley, Schedule & Shipping
Executive Committee
Proj. Director, Chair
Dep. Director, Vice Chair
DECam PM
DES DM PM
CFIP PM
NOAO Instrument Scientist
DES Project Scientist
Science Committee Chair
Management Committee
Institutional representatives
Director is Chair
Systems Interface Working Group
Deputy Director is Chair
CFIP
T. Abbott, PM
A. Walker, NOAO Instrument Scientist
DECam
B. Flaugher, PM
D. DePoy, Project Scientist
DES DM
D. Petravick, PM
J. Mohr, Project Scientist
Science Committee
O. Lahav, Chair

DES Science Committee

- SC Chair: O. Lahav
- Large Scale Structure: E. Gaztanaga & W. Percival
- Weak Lensing: S. Bridle & B. Jain
- Clusters: T. McKay & J. Mohr
- SN Ia: J. Marriner & B. Nichol
- Photo-z: F. Castander & H. Lin
- Simulations: G. Evrard & A. Kravtsov
- Galaxy Evolution: D. Thomas & R. Wechsler
- QSO: P. Martini & R. McMahon
- Strong Lensing: L. Buckley-Geer & M. Makler
- Milky Way: B. Santiago & B. Yanny
- Theory & Combined Probes: W. Hu & J. Weller

Dark Energy Science Program

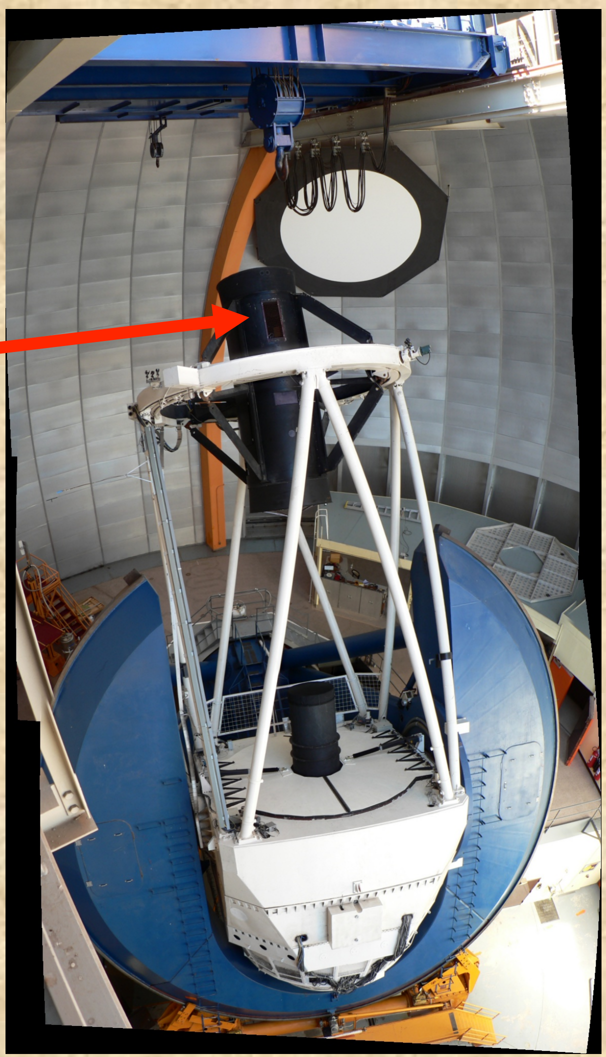
Four Probes of Dark Energy

- **Galaxy Clusters**
  - clusters to z>1
  - SZ measurements from SPT
  - Sensitive to growth of structure and geometry
- **Weak Lensing**
  - Shape measurements of 300 million galaxies
  - Sensitive to growth of structure and geometry
- **Large-scale Structure**
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- **Supernovae**
  - 15 sq deg time-domain survey
  - ~3000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

Plus QSOs, Strong Lensing, Milky Way, Galaxy Evolution

The Dark Energy Survey (DES)

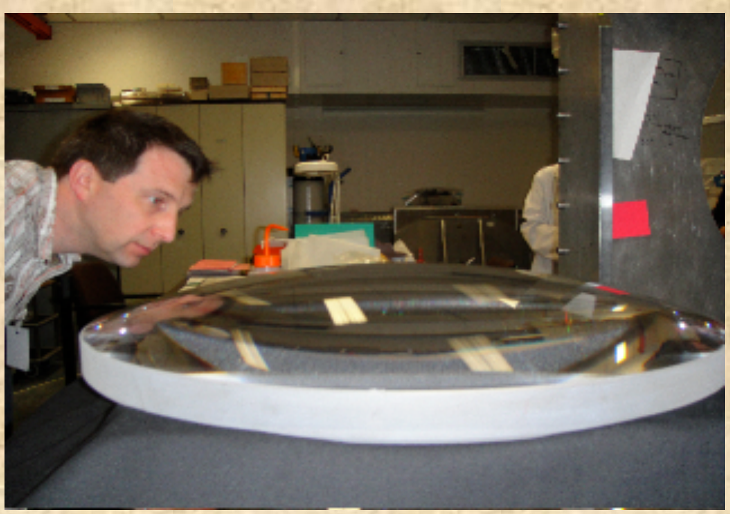
- Proposal:
  - Perform a 5000 sq. deg. survey of the southern galactic cap
  - Measure dark energy with 4 complementary techniques
- New Instrument:
  - Replace the PF cage with a new 2.2 FOV, 520 Mega pixel optical CCD camera + corrector
- Time scale:
  - Instrument Construction 2008-2011
- Survey:
  - 525 nights during Oct.–Feb. 2011-2016
  - Area overlap with SPT SZ survey and VISTA VHS

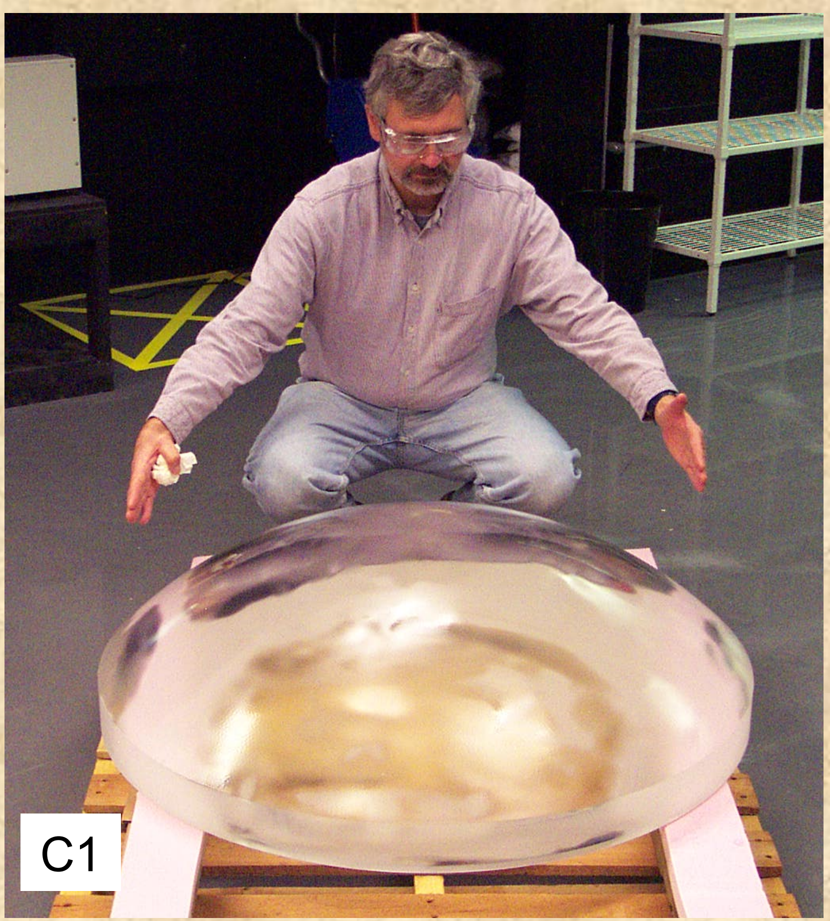


Use the Blanco 4m Telescope at the Cerro Tololo Inter-American Observatory (CTIO)

The 5 lenses are nearly ready

C3

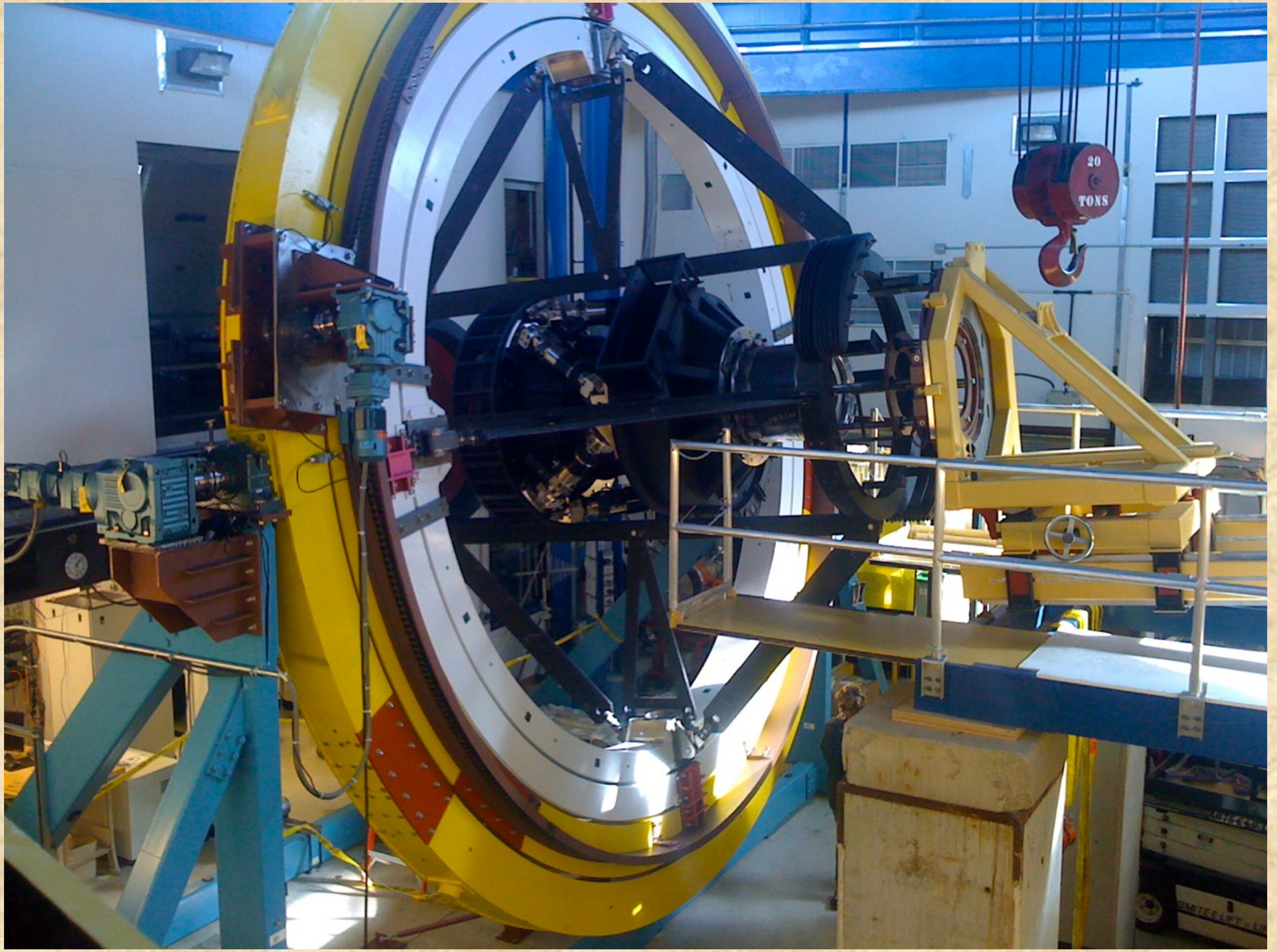




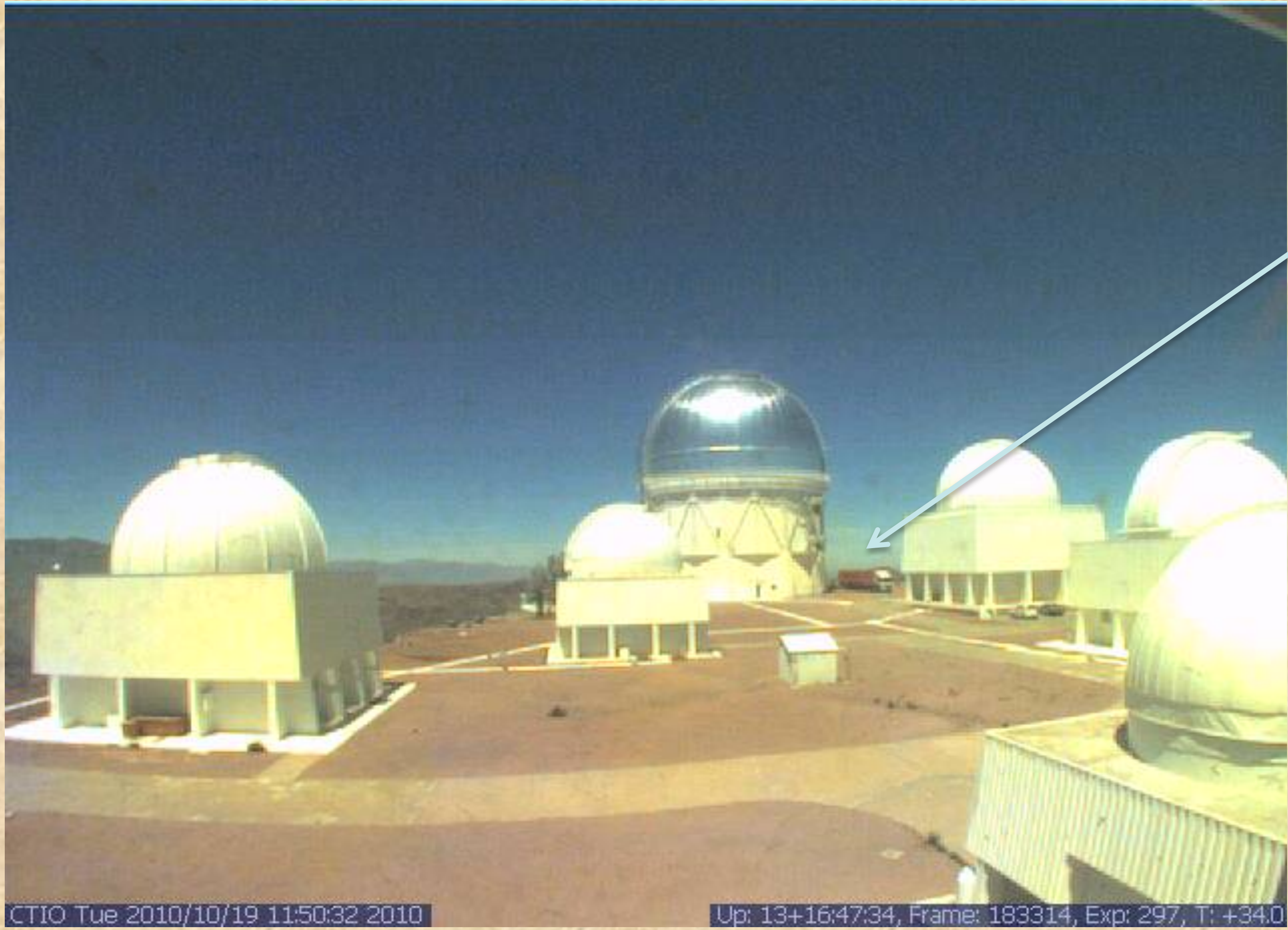
C1

Polishing & coating coordinated
by UCL (with 1.7M STFC funding)

Telescope Simulator

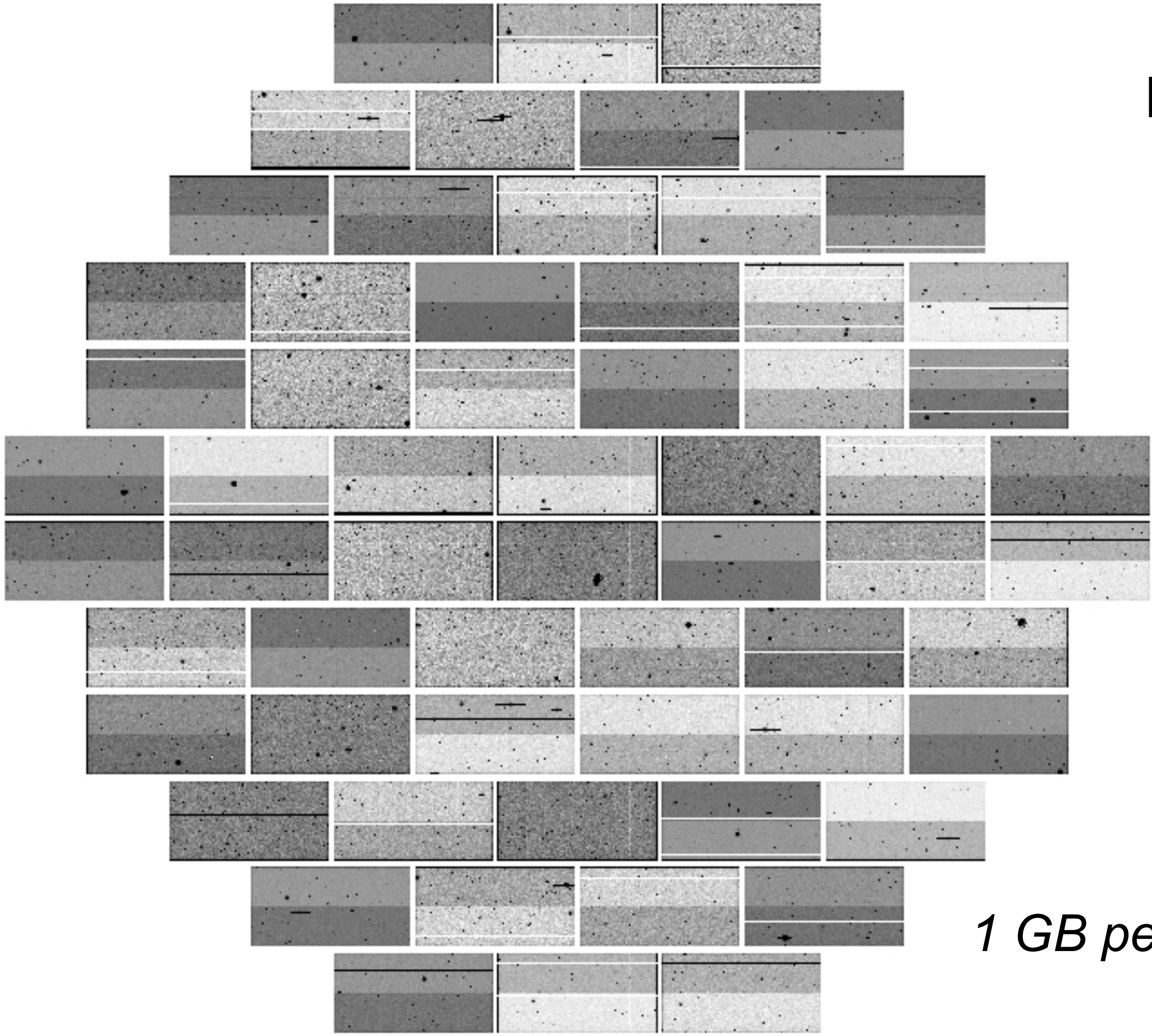


CTIO



F/8 handling system just arrived at CTIO

Image Level Simulations – Data Challenges, Brazil Portal



DECam Focal Plane

62 2kx4k Science CCDs (520 Mpix)

A single simulated DECam pointing (= tile = hex)

1 GB per single 3 deg^2 pointing

Lin

Photometric redshifts

- Probe strong spectral features (e.g. 4000 break)
- Template vs. Training methods

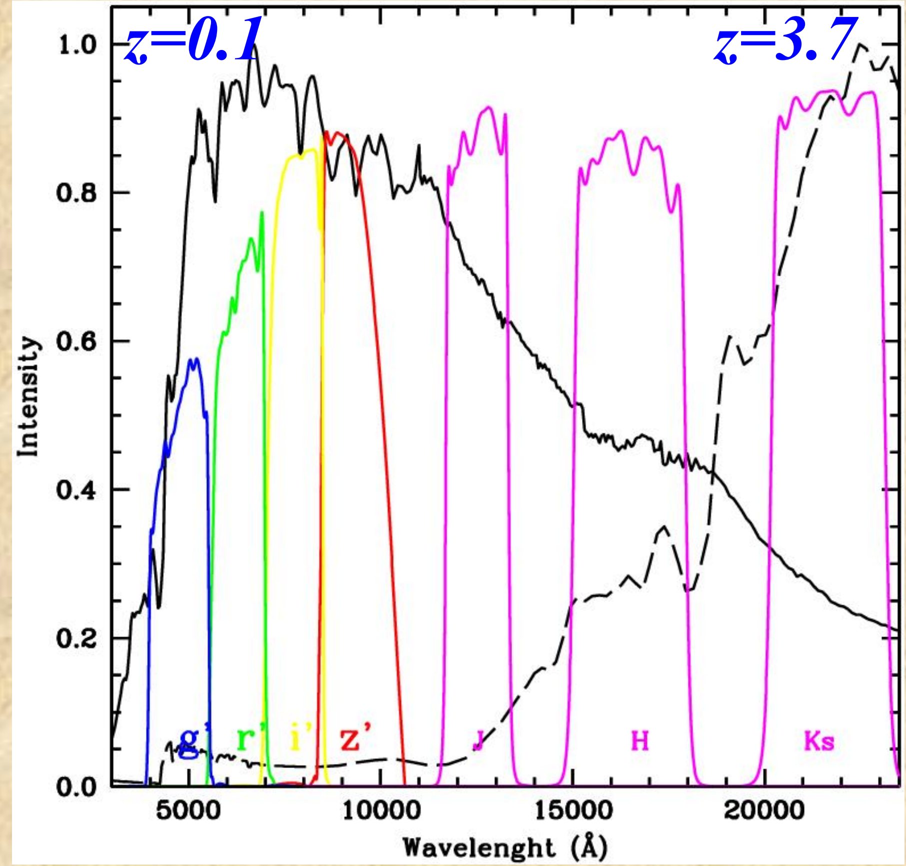


Photo-z –Dark Energy cross talk

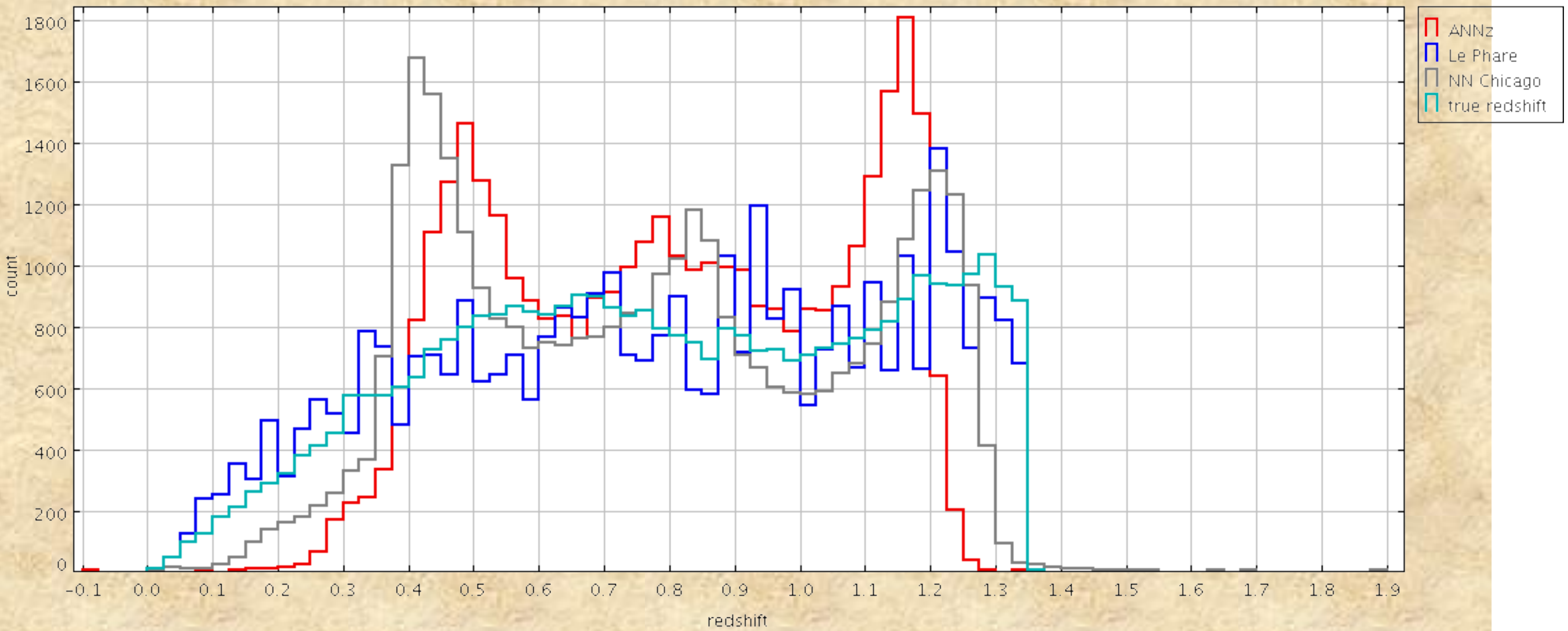
- Approximately, for a photo-z slice:

$$(\delta w/ w) = 5 (\delta z/ z) = 5 (\sigma_z/z) N_s^{-1/2}$$

=> the target accuracy in w and photo-z scatter σ_z dictate the number of required spectroscopic redshifts

$$N_s = 10^5 - 10^6$$

Comparison of photo-z codes on DC5B

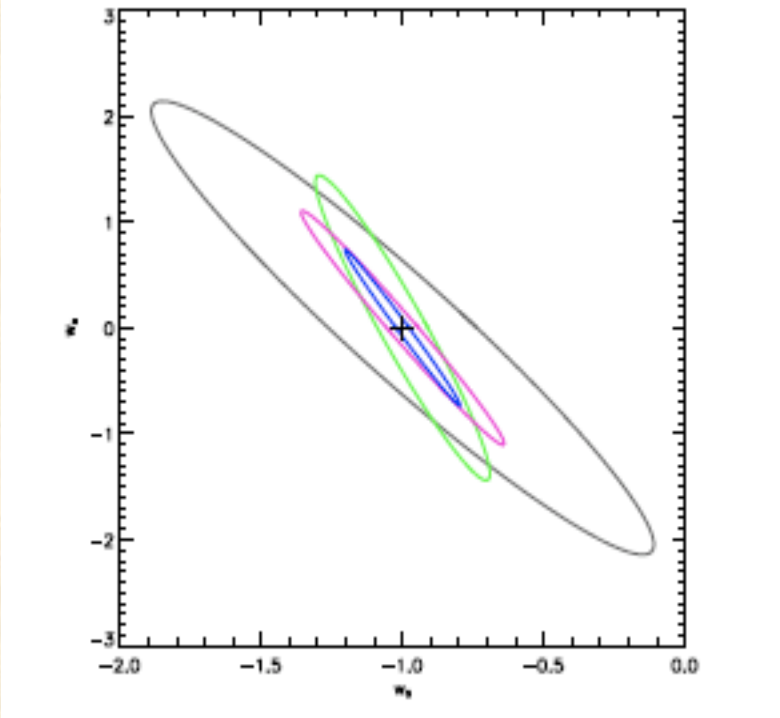


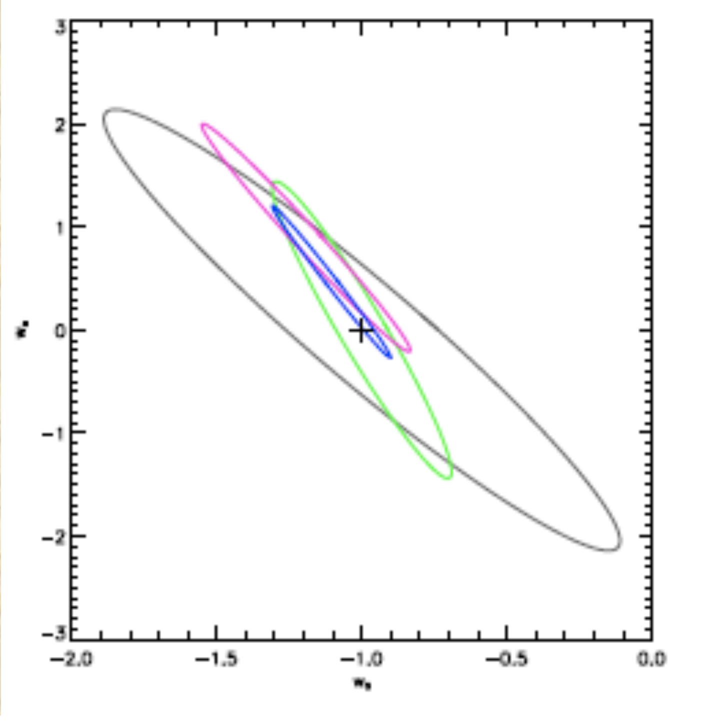
Jouvel, Abdalla, OL

DES Timeline

- Camera construction currently ~80% complete
- Final construction, testing, integration now on-going
- Ship components to Chile: Sept. 2010-July 2011
- Installation: Jan.-Oct./Nov. 2011 (imager Aug./Sept.-Oct./Nov.)
- First light on telescope: Oct./Nov. 2011
- Commissioning: Nov. 2011-Jan. 2012 (FY12)
- Survey begins: 2012

Dark energy vs Modifed Gravity
DES-like (WL, clusters, SN, BAO)





$$w = w_0 + (1 - a) w_a$$

Assumed DE

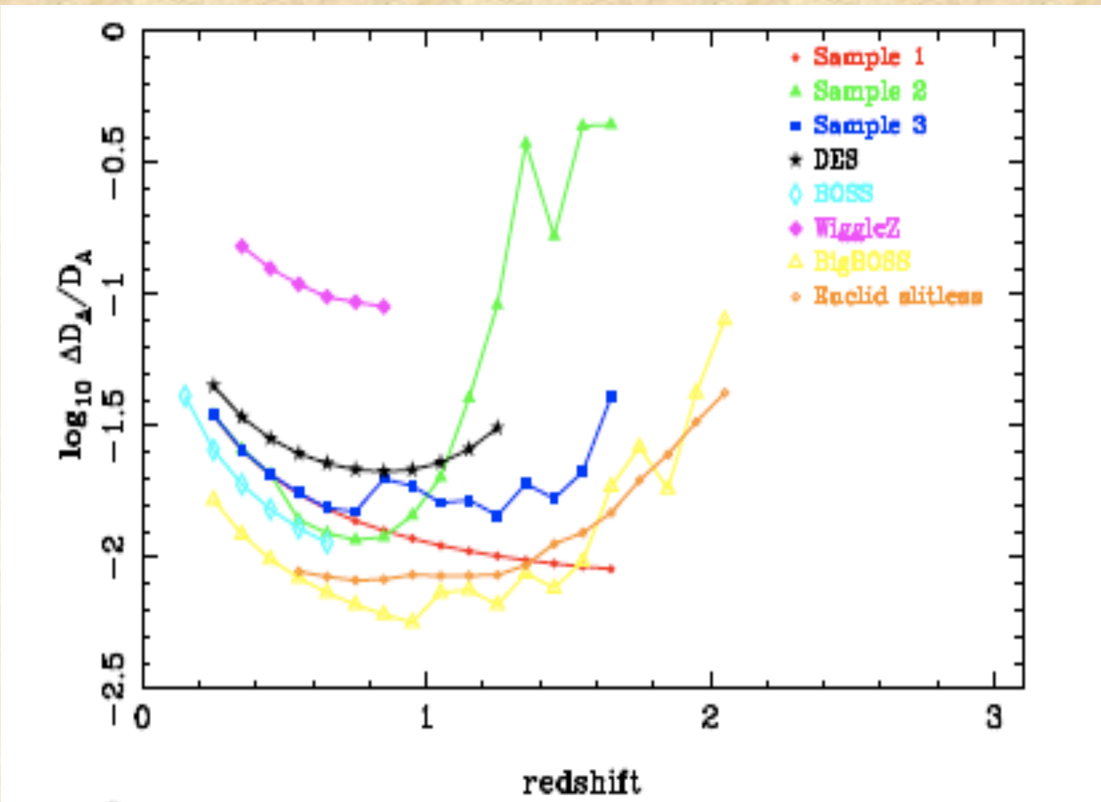
Assumed Mod Grav

Shapiro et al. (2010)

Spectroscopy follow up: DESpec

Assume for 10^7 spectra over 0.2<z<1.7
(sample 1)

FoM (DESpec+DES4+II + Planck) / FoM(DES4+II+Planck) = 3 - 6



Percival & Samushia

DES Synergy with VISTA
(8 filters together)

500 sq deg of the DES footprint (Stripe 82 and SPT region) already observed

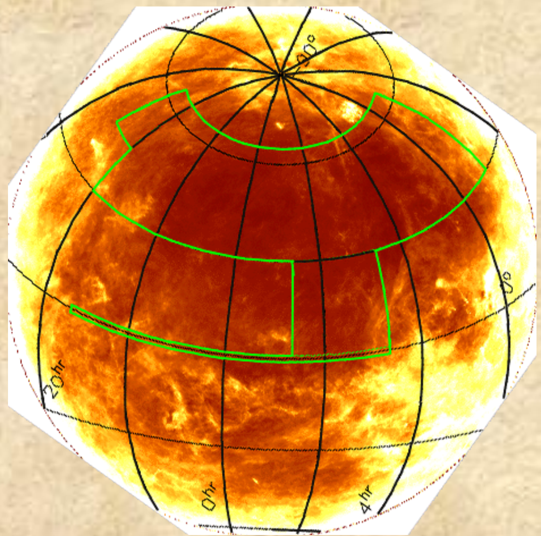
in J, H, K (median depth 21.0, 20.8, 20.4)

850 sq deg by March 2011

M. Banerji and R. McMahon

DES Area and Depth: Synergy with South Pole Telescope

- South Pole Telescope (10m, bolometer array, 150, 250, 270 GHz):
  - 2500 sq. deg. Survey (to end of 2011)
  - to detect ~1,000 clusters through Sunyaev-Zel'dovich effect
- Dark Energy Survey: measure *photometric* redshifts for these clusters to z ~ 1-1.3

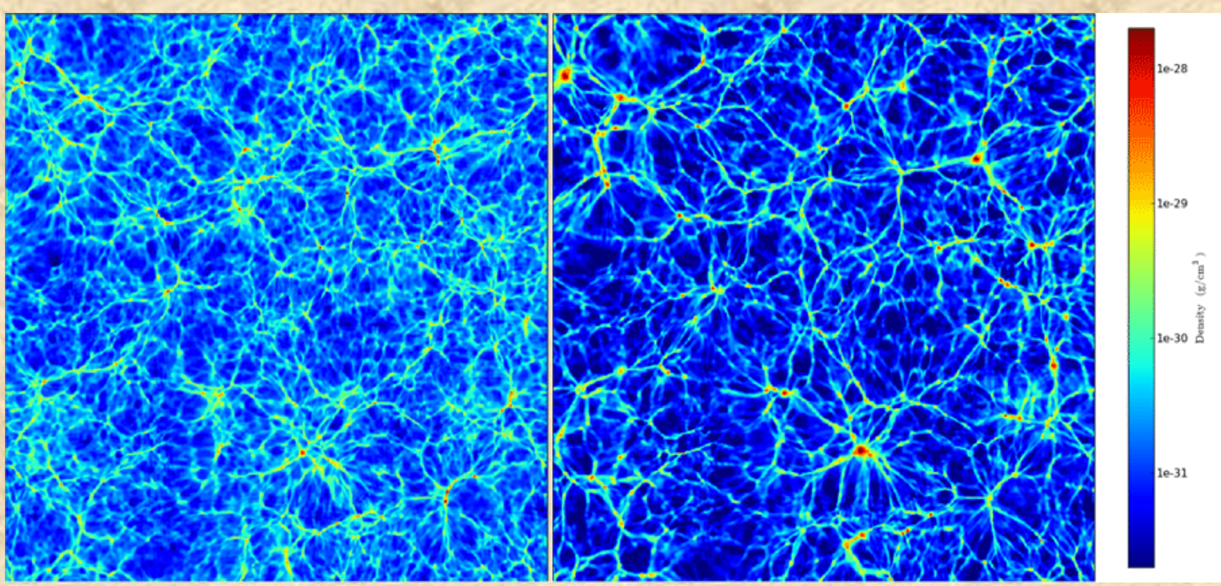


Galactic Dust Map

Neutrinos decoupled when they were still relativistic, hence they wiped out structure on small scales

$k > k_{nr} = 0.026\ (m_\nu / 1\ \mathrm{eV})^{1/2}\ \Omega_m^{1/2}\ h/\mathrm{Mpc}$

$\Omega_\nu h^2 = M_\nu/(94\ \mathrm{eV})$

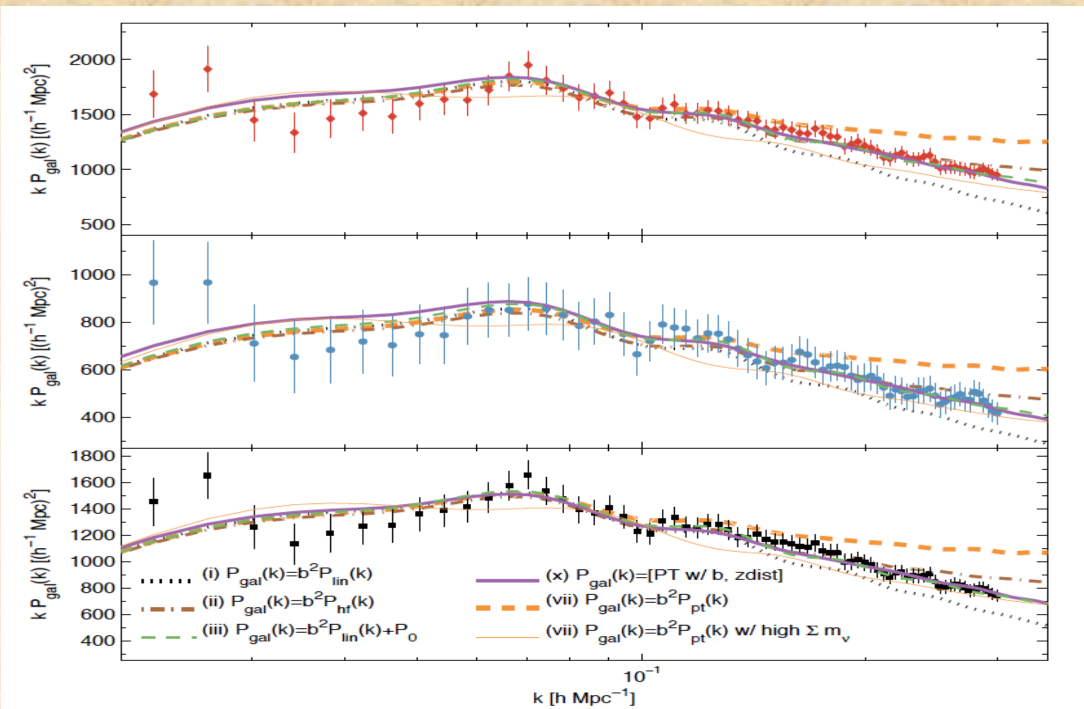


Agarwal & Feldman 2010

CDM+
1.9 eV neutrinos

CDM

Neutrino mass from red vs blue SDSS galaxies



red

blue

all

upper limit in the range 0.5-1.1 eV

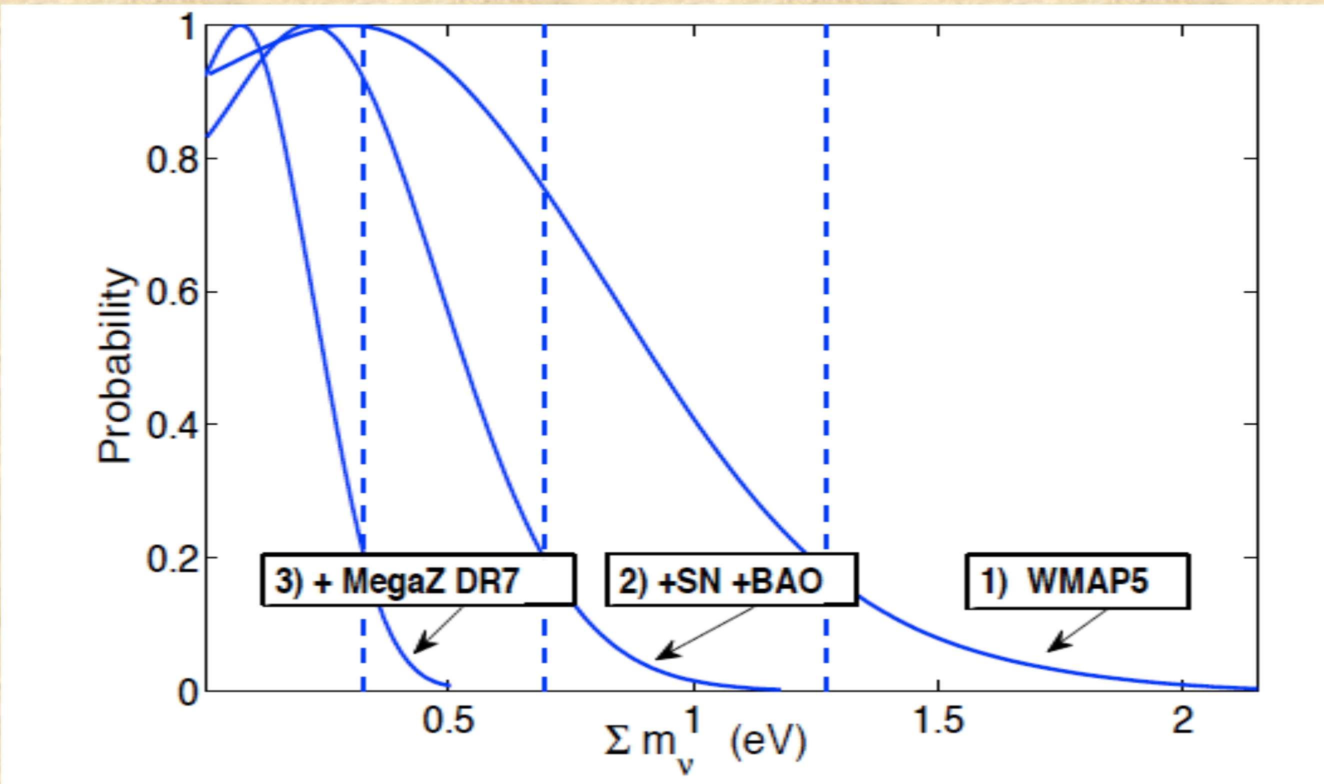
red and blue within 1–sigma

Swanson, Percival & OL 2010

Neutrino mass from MegaZ-LRG

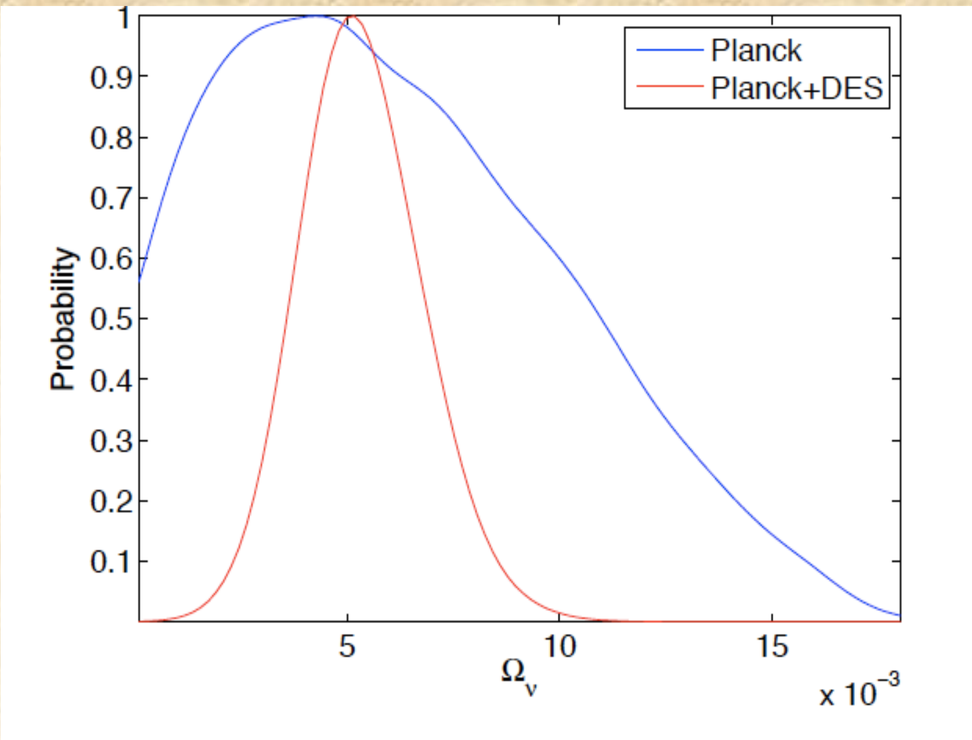
700,000 galaxies within 3.3 (Gpc/h)^3

Total mass < 0.28 eV (95% CL)



Thomas, Abdalla & Lahav, PRL (2010) 0911.5291

Neutrino mass from DES:LSS & Planck



Input:
M_ν =0.24 eV

Output:
M_ν =0.24 +- 0.12 eV (95% CL)

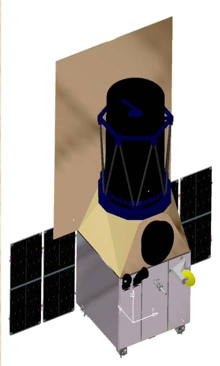
Lahav, Kiakotou, Abdalla & Blake 2010 (0910.4714)

Total Neutrino Mass

DES+Planck vs. KATRIN

$M_\nu < 0.1$ eV $M_\nu < 0.6$ eV

Lahav, Kiakotou, Abdalla and Blake (2010) 0910.4714

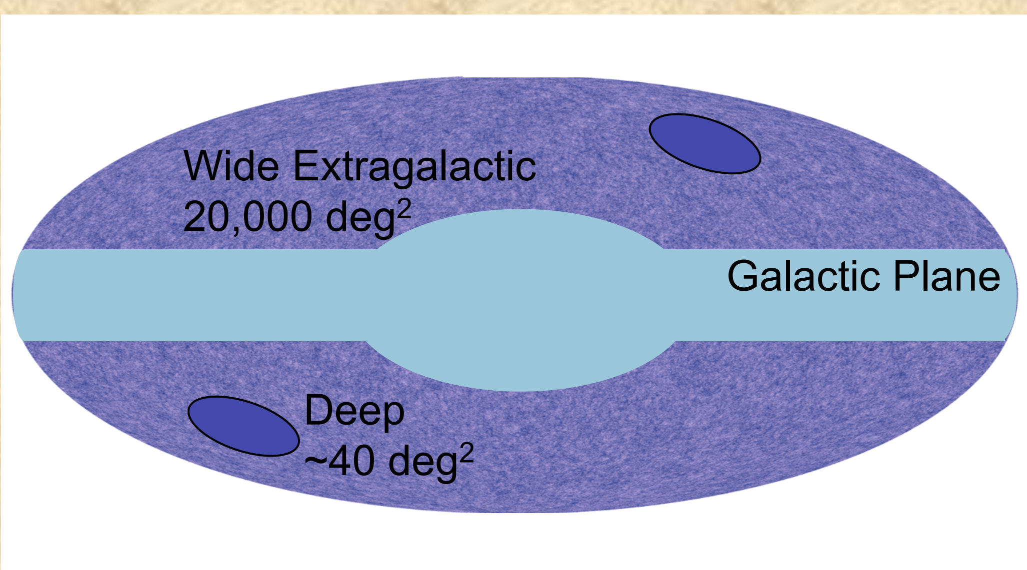


Euclid

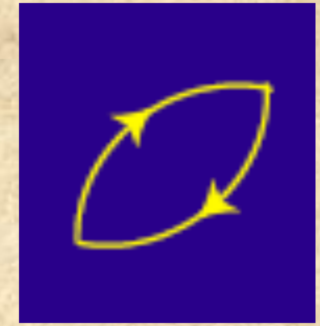
Wide Survey: Extragalactic sky (20,000 $deg^2 = 2\pi$ sr)

- Visible: Galaxy shape measurements to $RIZ_{AB} \leq 24.5$ (AB, 10σ) at 0.16” FWHM, yielding 30-40 resolved galaxies/$amin^2$, with a median redshift z~ 0.9
- NIR photometry: Y, J, H ≤ 24 (AB, 5σ PS), yielding photo-z’s errors of 0.03-0.05(1+z) with ground based complement (PanStarrs-2, DES. etc)
- Concurrent with spectroscopic survey for 50 million galaxies (0.5< z< 2.0)

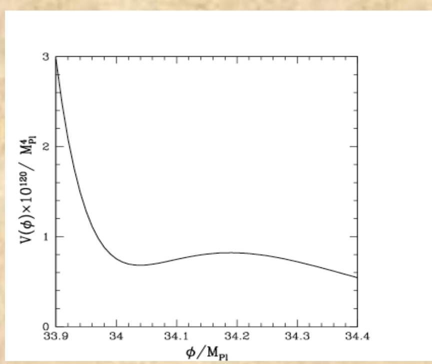
Deep Survey: 40 deg^2 at ecliptic poles



What will be the next paradigm shift?



- Vacuum energy (cosmological constant)?
- Dynamical scalar field?
  - $w=p/\rho$
  - for cosmological constant: $w = -1$
- Manifestation of modified gravity?
- Inhomogeneous Universe?



- What if cosmological constant after all?
- Multiverse - Landscape?
- The Anthropic Principle?

THE END