Observational Probes

of

Dark Energy

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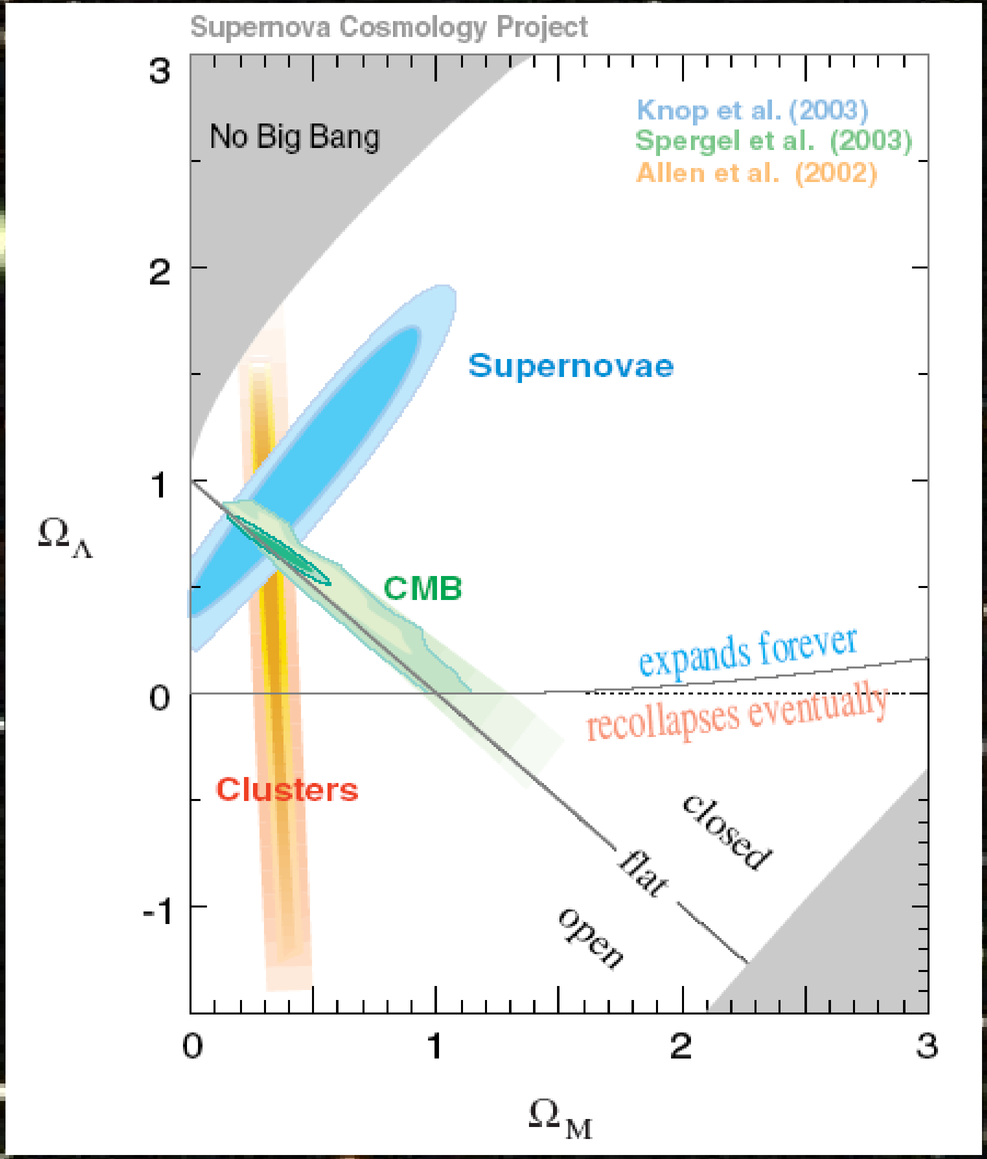
‘Space: Here Darkness Rules

Is there Dark Energy?

Multiple Observations show that Dark + Visible matter is NOT enough.

Cosmic Complimetarity →



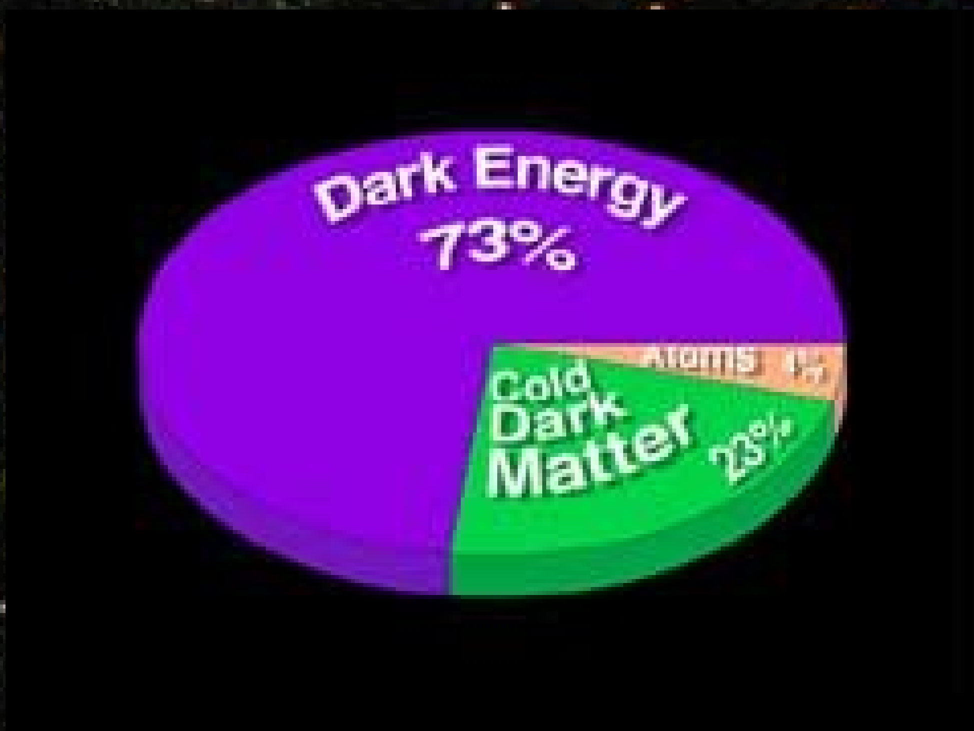
Conclusive evidence: recent accelerated expansion of the Universe instead of slowing down due to gravity.

There is 'SOMETHING ELSE'

Within standard cosmological framework, this must be due to substance that behaves as if it has negative pressure.

This has been termed

‘the dark side is strong…



So what are the possibilties?

Multiple talks in the Workshop session!!

Possibility 1: **Universe permeated by energy density, constant in time and uniform in space (Einstein's Λ).**

Possibility 2: **DE some kind of '*unknown*' dynamical fluid. Its eqn of state varies with time (or redshift z or $a = (1+z)^{-1}$).**

Impact of DE (or different theories) can be expressed in terms of different "evolution of equation of state"

$$w(a) = p(a) / \rho(a) \text{ with } w(a) = -1 \text{ for } \Lambda.$$

Possibility 3: GR or standard cosmological model incorrect

Motivation ☺

"Dark Energy appears to be the dominant component of the physical Universe, yet there is no persuasive theoretical explanation for its existence or magnitude……..Most experts believe that nothing short of a revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration. For these reasons, the nature of DE ranks among the very most compelling of all outstanding problems in physical science. These circumstances demand an ambitious observational program to determine the DE properties as well as possible."

-- From the Dark Energy Task Force Report

Observational Probes of Dark Energy

How does DE come into play in observations:
(A Hasty Primer)

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

In GR, scale factor a(t) describes growth of Universe. We know the time evolutio of a(t) → H(a)

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2(a) = \frac{8\pi G_N \rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\dot{\rho} = -3H(\rho + P)$$

← This holds for each component

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right]$$

xpansion history H(z) : written in terms of energy density of each compo

$$a^{-3(1+w)} \rightarrow \exp\left(3\int_a^1 \frac{da'}{a'}[1 + w(a')]\right)$$

Standard measures :

$$D(z)=\int_0^r \frac{dr'}{\sqrt{1-kr'^2}}=\int_t^{t_0}\frac{dt'}{a(t')}=\int_0^z \frac{dz'}{H(z')}$$

Distance (or co-ordinate) to source at z

$$r(z)=|k|^{-1/2}\,S_k\left[|k|^{1/2}\int_0^z \frac{dz'}{H(z')}\right]=|k|^{-1/2}\,S_k\left[|k|^{1/2}D(z)\right]$$

$$S_k[x]=\begin{cases}\sin x & k>0\\ x & k=0\\ \sinh x & k<0\end{cases}$$

r(z) can be connected to observables

Standard Candle : apparent flux to standard flux

$$d_L(z)=r(z)(1+z)$$

Standard Ruler: apparent angular size to real physical size

$$d_A(z)=r(z)/(1+z)$$

Standard density:

$$dV=\frac{r^2(z)}{\sqrt{1-kr^2(z)}}\,dr\,d\Omega$$

Growth of structures...

Static Universe – exponential growth of structures!
Expanding Universe – struggle between gravitational collapse and expansion. (DE → more recent expansion)

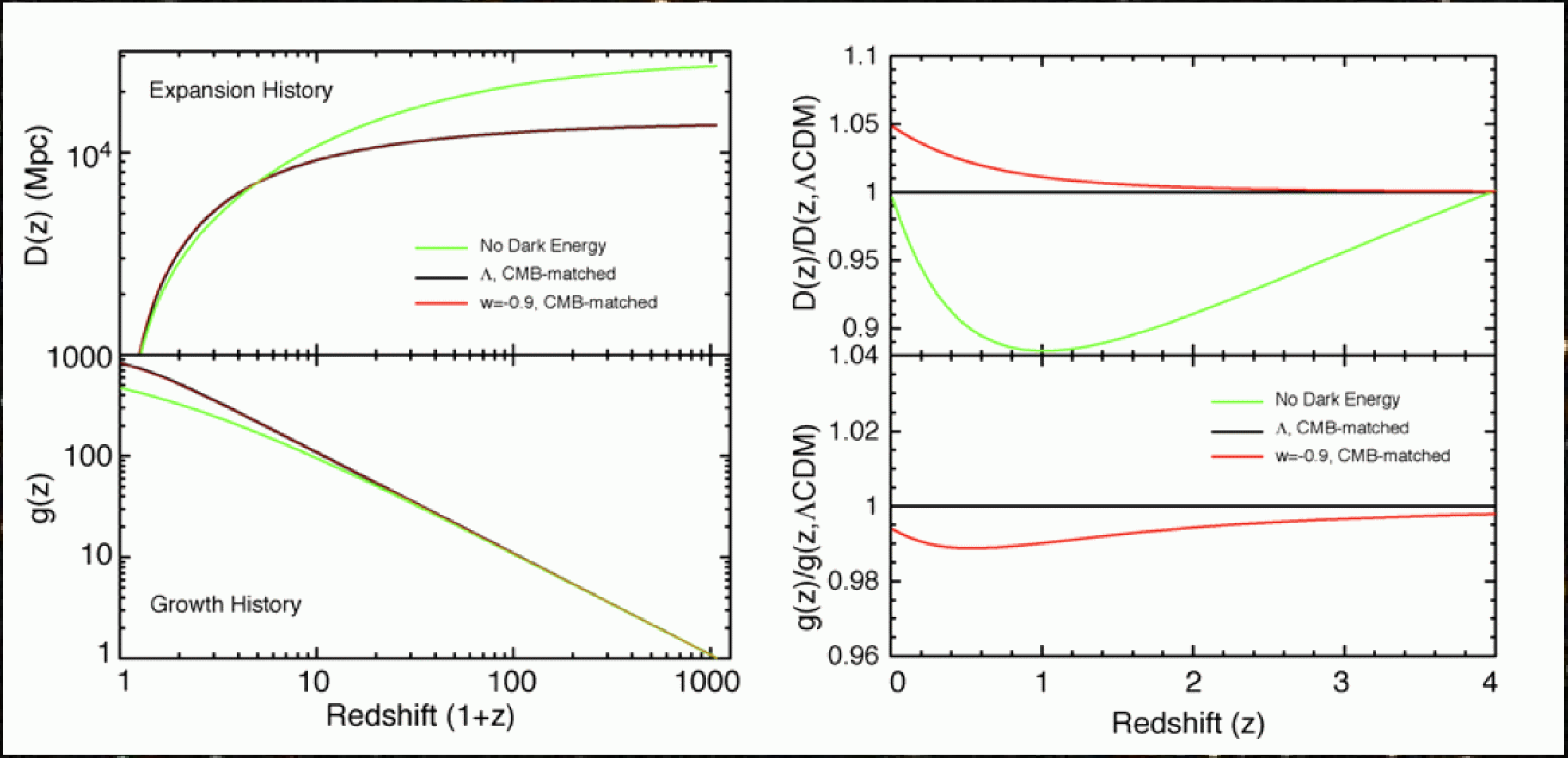
$$\ddot{g} + 2H\dot{g} = 4\pi G\rho_m g = \frac{3\Omega_m H_0^2}{2a^3} g$$

reln between expansion and growth factor g(z)

CMB fixes amplitude of matter fluctuations at z~1100. This is seen at low redshift coupled to g(z).

Within GR, the above diffn reln provides ‘one-to-one’ reln between two observables : D(z) & g(z). Any inconsistency would mean either GR is failing at largest scales.

Effect of DE on D(z) and g(z)



Formation of the 'Jedi Council' and their strategy...

OE; NASA; NSF appointed the Jedi Council a.k.a. Dark Energy Task Force

2 member team  Master Yoda a.k.a. Chairman Rocky Kolb

White Papers (36 Observational, 14 theoretical).

Four observational techniques :

Supernovae Surveys

measure flux and redshift of Type Ia SNe.

Baryon Acoustic Oscillations:

measure features in distribution of galaxies.

Cluster Surveys

measure spatial distribution of galaxy clusters.

Weak Lensing Surveys

measure distortion of background images due to gravitational lensing

Why these 4 methods?

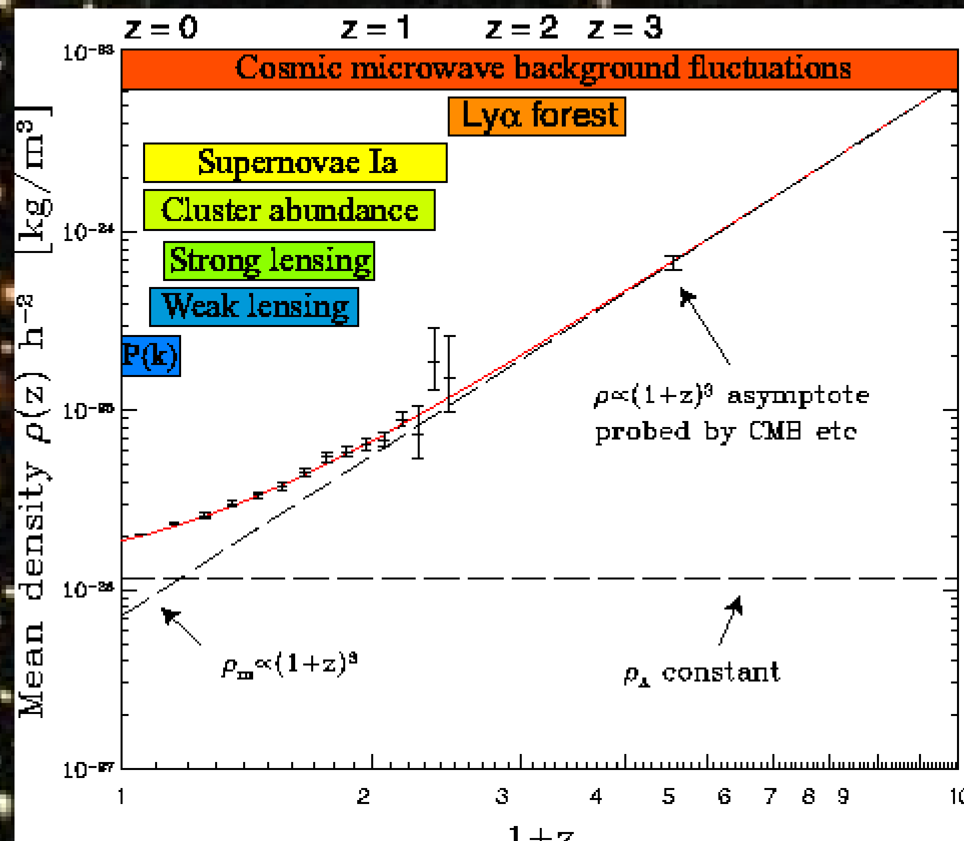
- Different techniques have different strengths and weaknesses and sensitive in different ways to dark energy and other cosmological parameters. Cross check to see is failure of GR.

- Each of the four techniques can be pursued by multiple observational approaches (radio, visible, NIR, x-ray observations), and a single experiment can study dark energy with multiple techniques.

- Moreover constraints on *Hubble* Const measurements and constraints on other cosmological parameters expected to come from measurement of CMB temperature and polarization anisotropies.
  – These data, though insensitive to $w(a)$ on their own but help in breaking degeneracies.

At what redshifts should we probe?

- Effect of dark energy becomes apparent at late times
- Expansion passes from decelerating to accelerating
- Effective density asymptotes to vacuum contribution
- DE is apparent at z < 3



Tegmark astroph/0101354

Probe 1

SUPERNOVAE

Supernovae as Standard Candles..

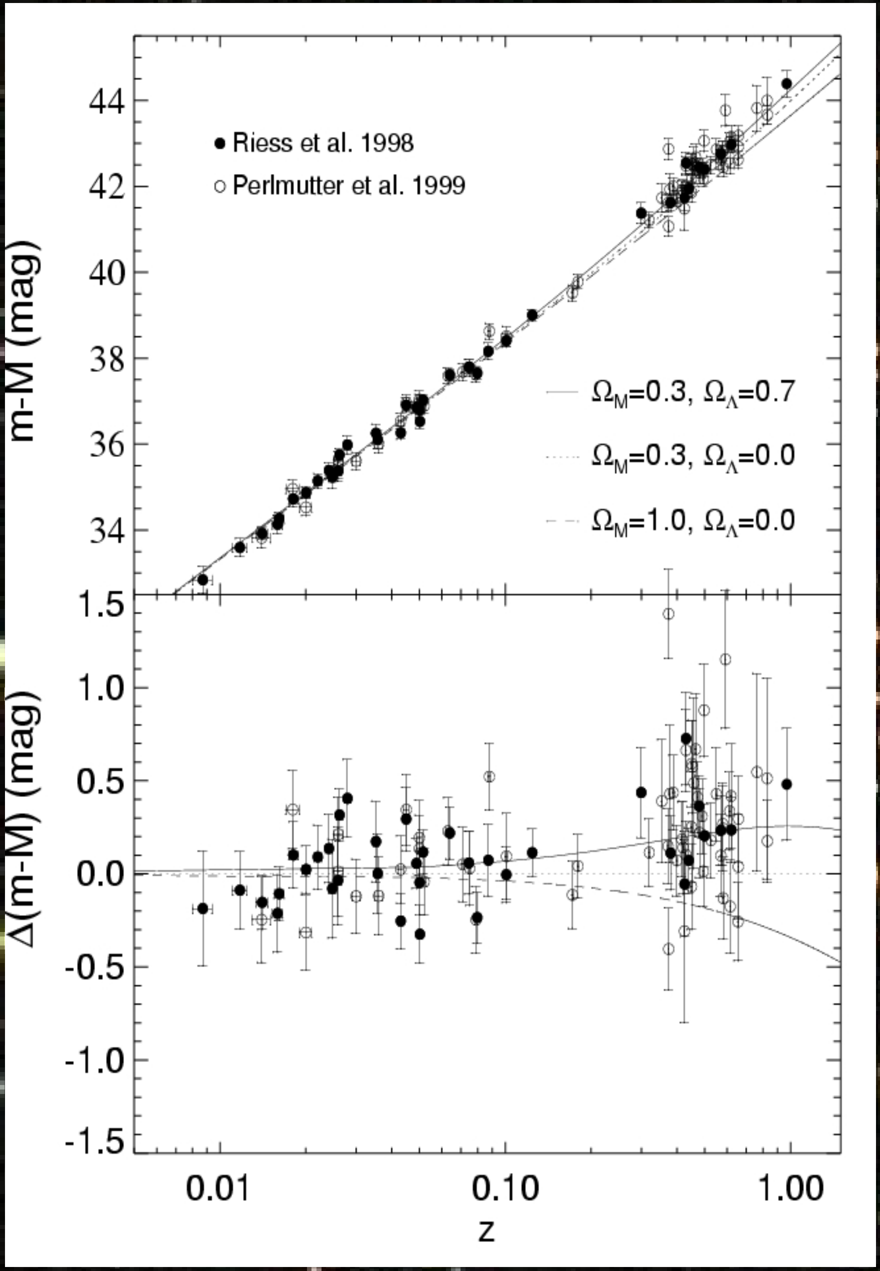
- **Standard candles – Their intrinsic luminosity known.**

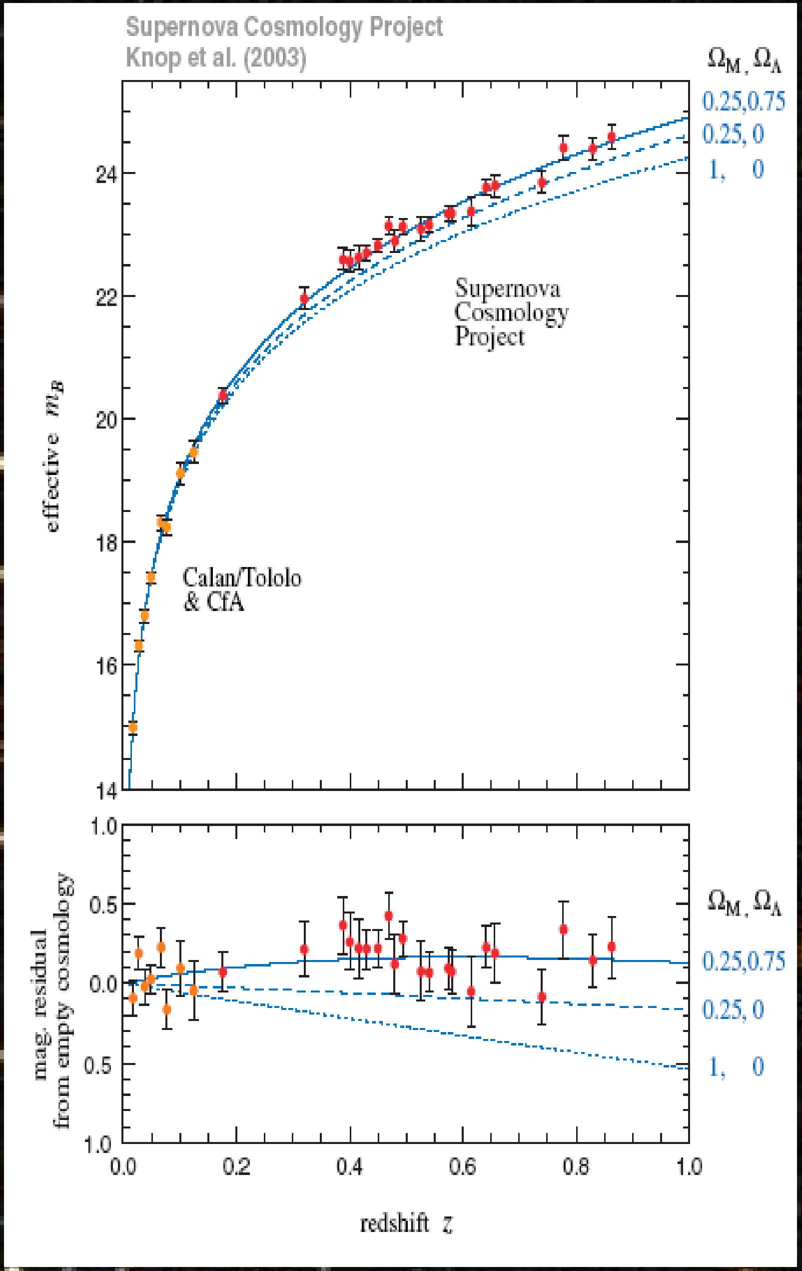
- **Their apparent luminosity can be measured.**

- **The ratio of the two can provide the luminosity-distance (d_L) of the supernova**

- **The red shift z can be measured independently from spectroscopy**

- **Finally, one can obtain d_L (z) or equivalently the magnitude(z) and draw a Hubble diagram**





IAGRG-24, Jamia Milia Islamia, Feb 5-8, 2007

Supernova Surveys…

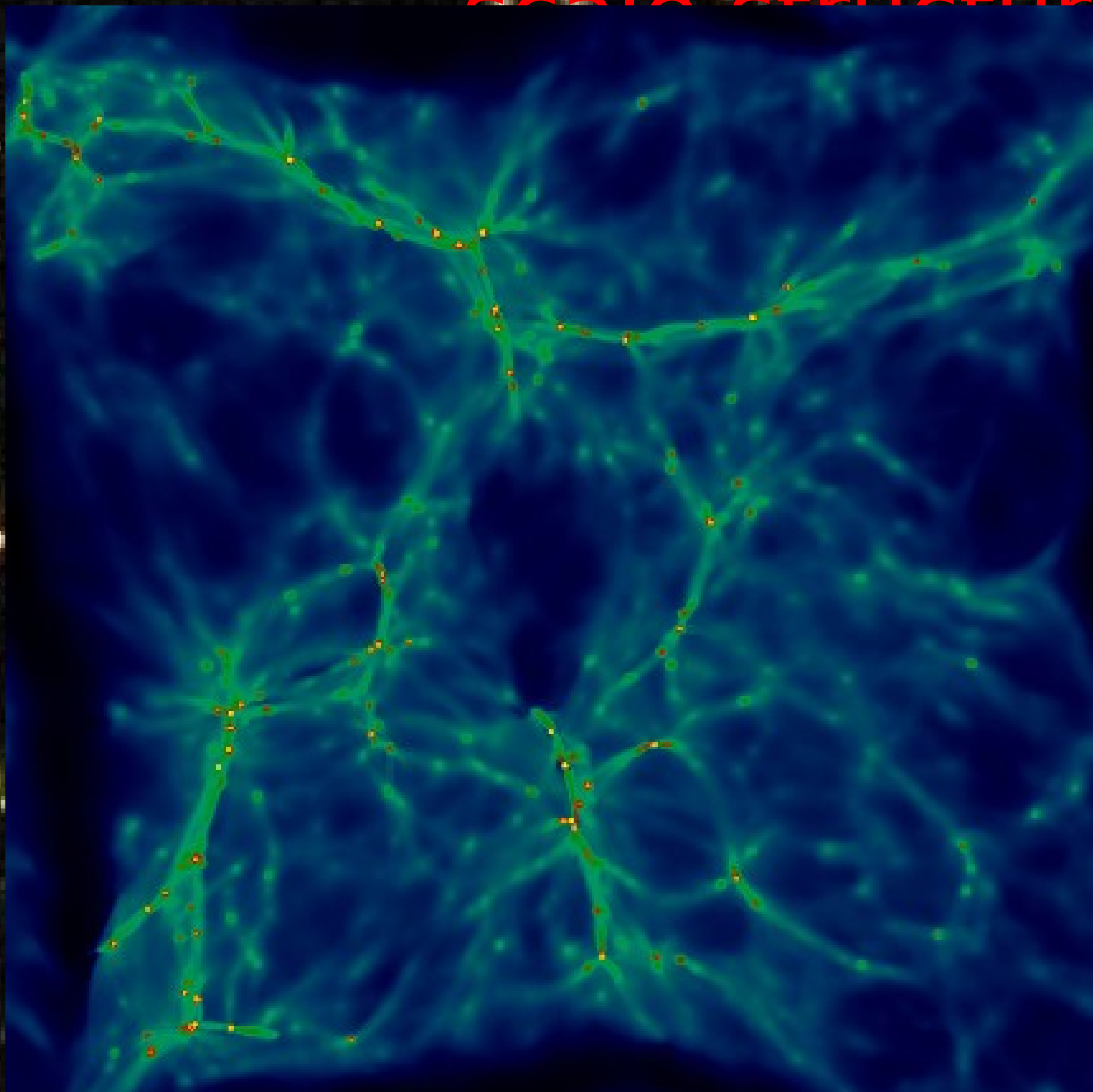
For SNe to be good cosmological standard candles → need to nail the systematic

uncertainties (*luminosity evolution, gravitational lensing, dust etc*).

This will require thousands of SNe with at least hundreds of SNe Ia at $z>1$.

Ultra deep supernova survey using dedicated telescope (SNAP, JDEM, Essence etc)

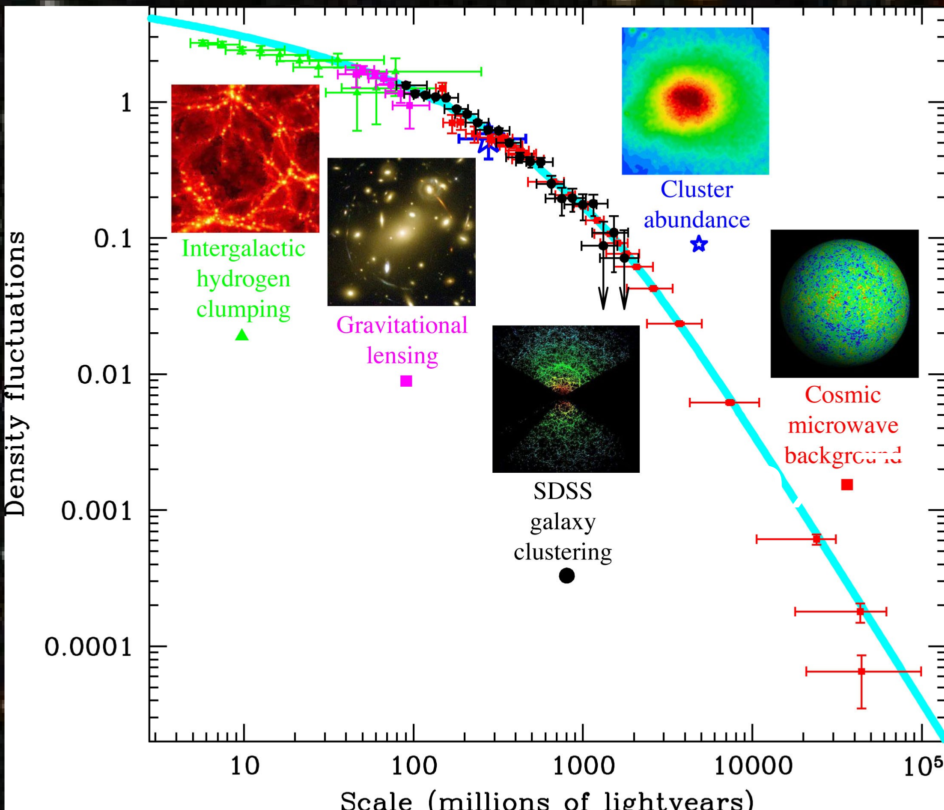
The 3 other probes all deal with galaxies, cluster of galaxies and large scale structure

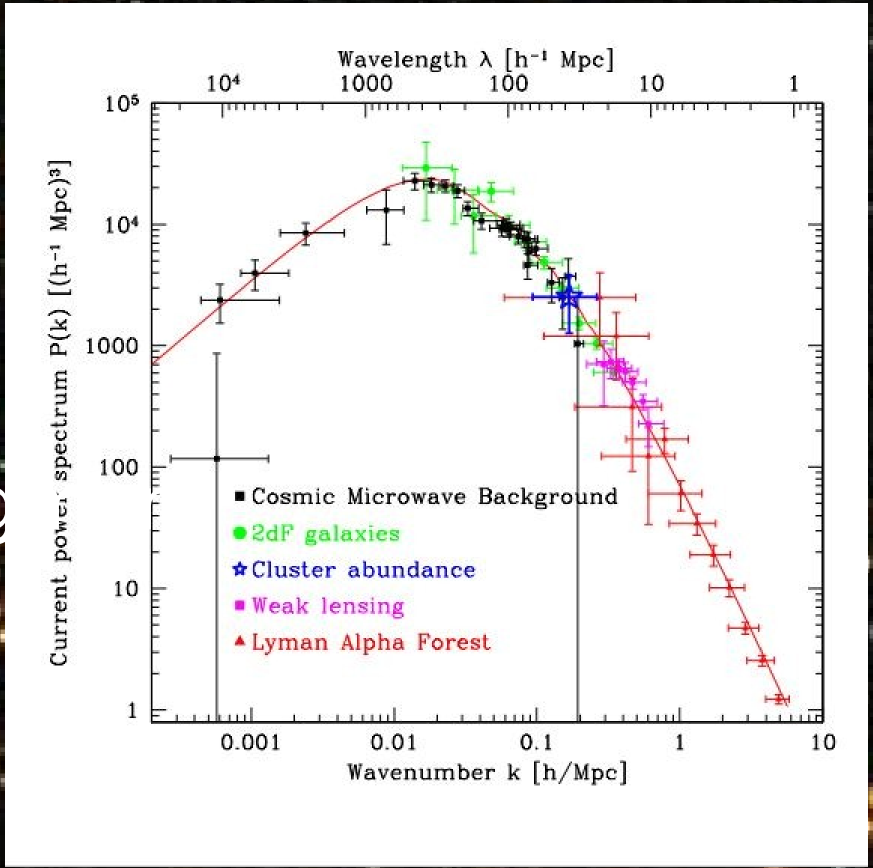


Hierarchical Structure Formation

Spingel et al. (2005)

Different methods probe different scales...





Max Tegmark

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$

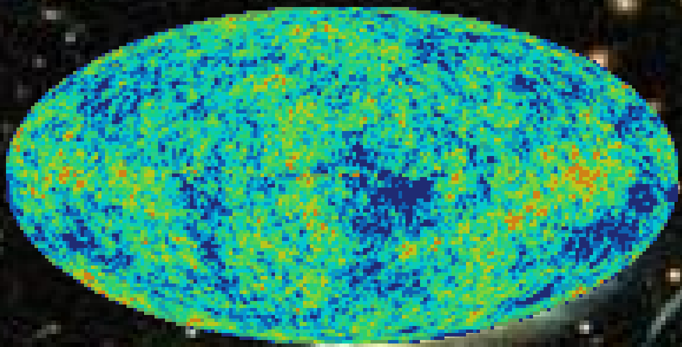
$$\tilde{\delta}(\mathbf{k}) = \frac{1}{(2\pi)^{3/2}} \int \mathrm{d}\mathbf{x}\, \delta(\mathbf{x}) \mathrm{e}^{\mathrm{i}\mathbf{k}\cdot\mathbf{x}}$$

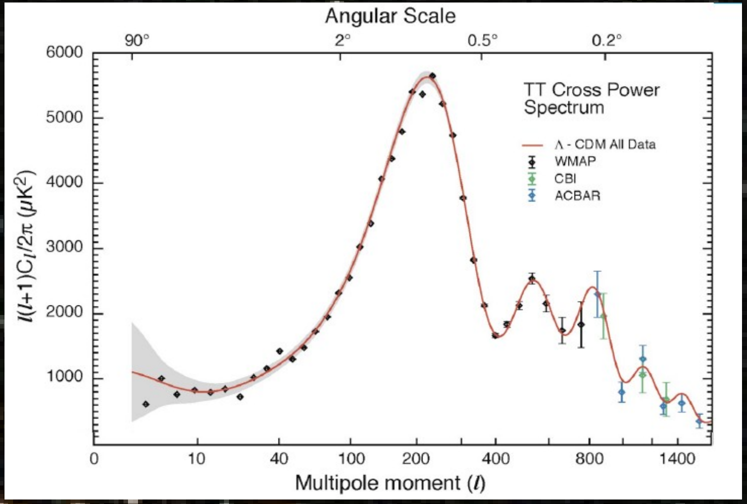
$$P(k) = \langle |\tilde{\delta}(\mathbf{k})|^2 \rangle = \frac{1}{2\pi^2} \int \mathrm{d}r\, r^2 \xi(r) \frac{\sin kr}{kr}$$

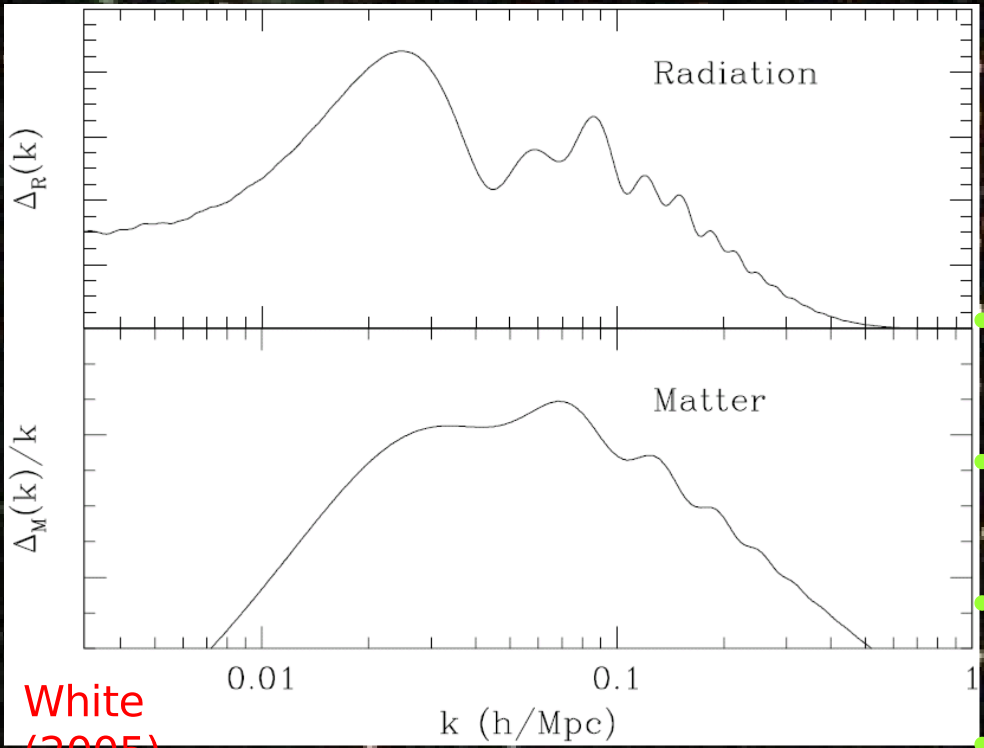
Probe 2

Baryon Accoustic Oscillations (BAO)

mprints on the Matter Power Spectrum





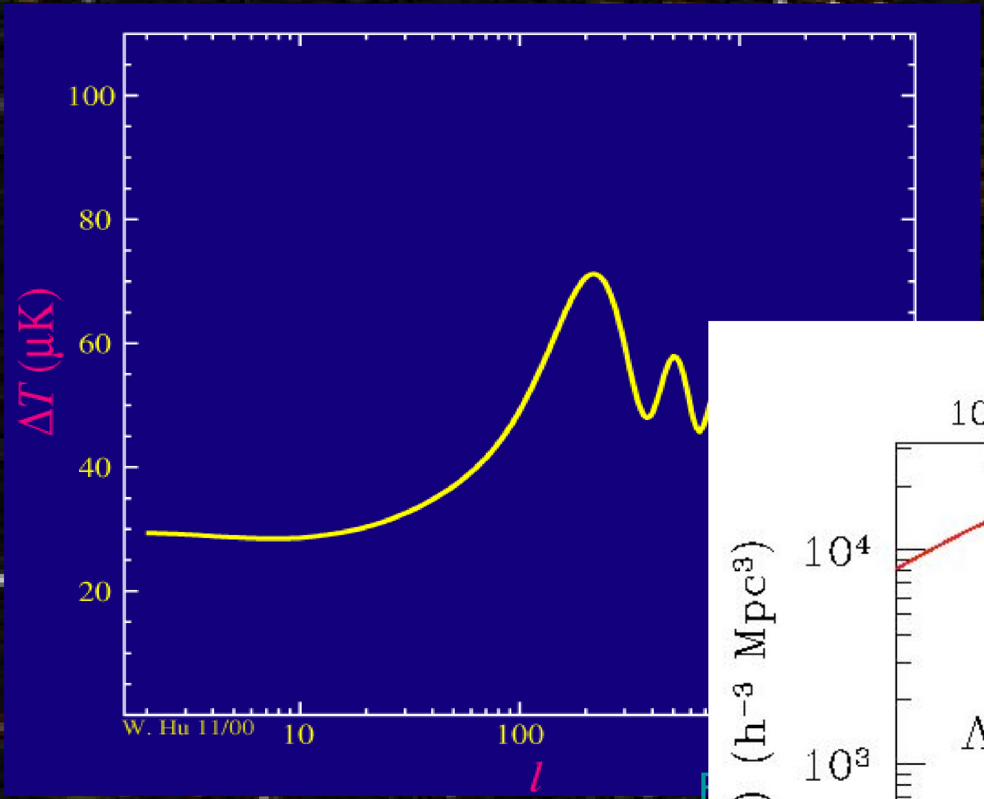


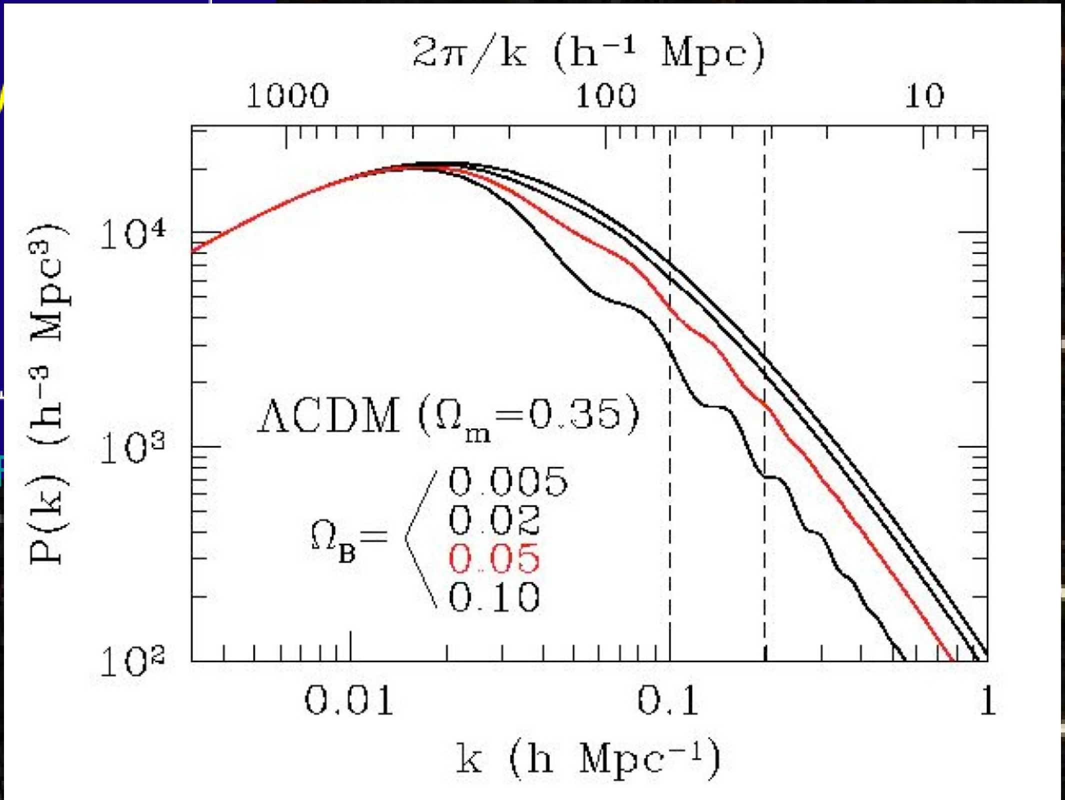
White (2005)

The same physical processes affect both the CMB and the matter power spectrum.

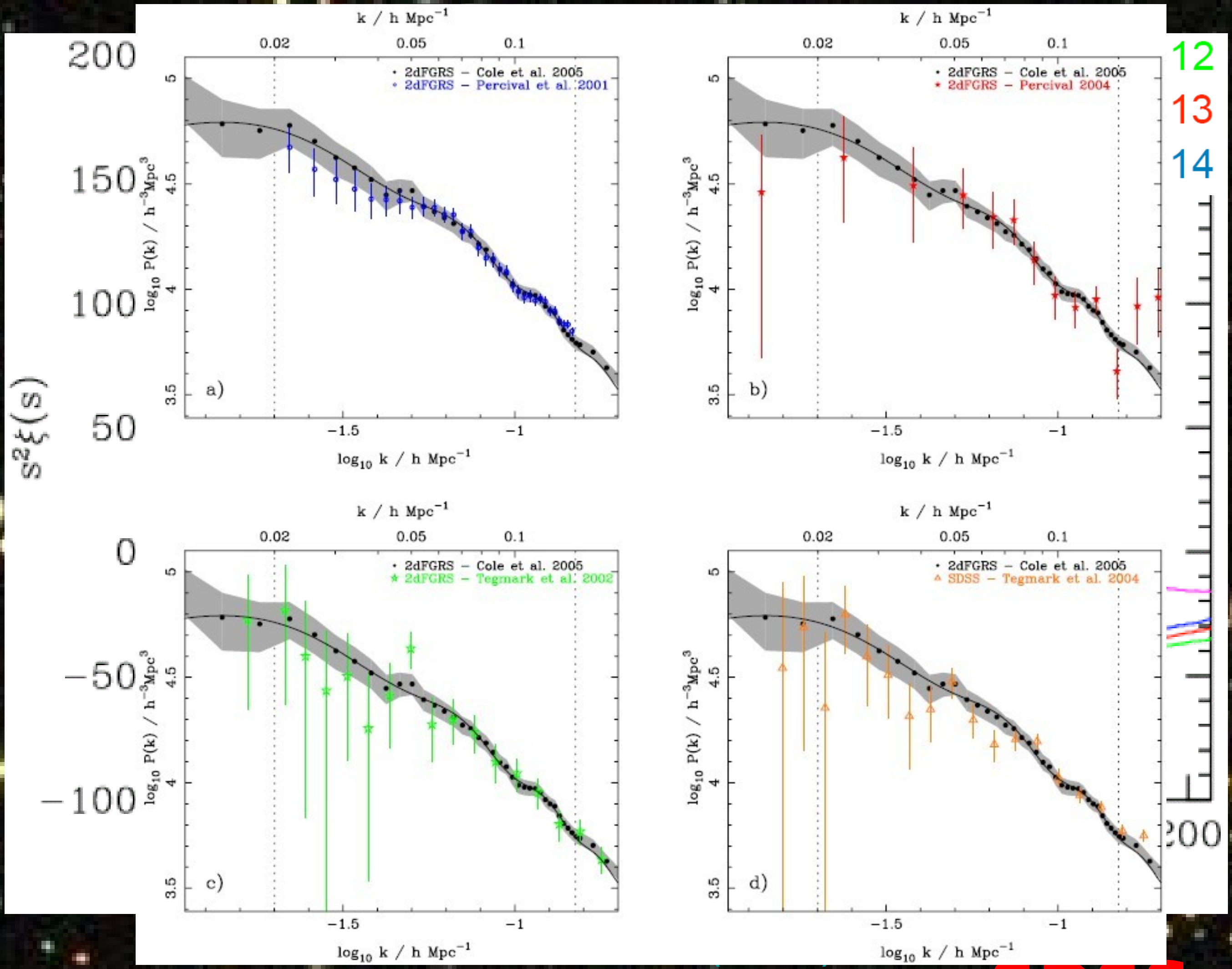
- Plane-waves interfere with each other
- Phases frozen at recombination
- Gravity+hydro on small scale evolves perturbations
- Small-scale silk damping

CMB Acoustic Peaks and BAO





BAO has been detected:

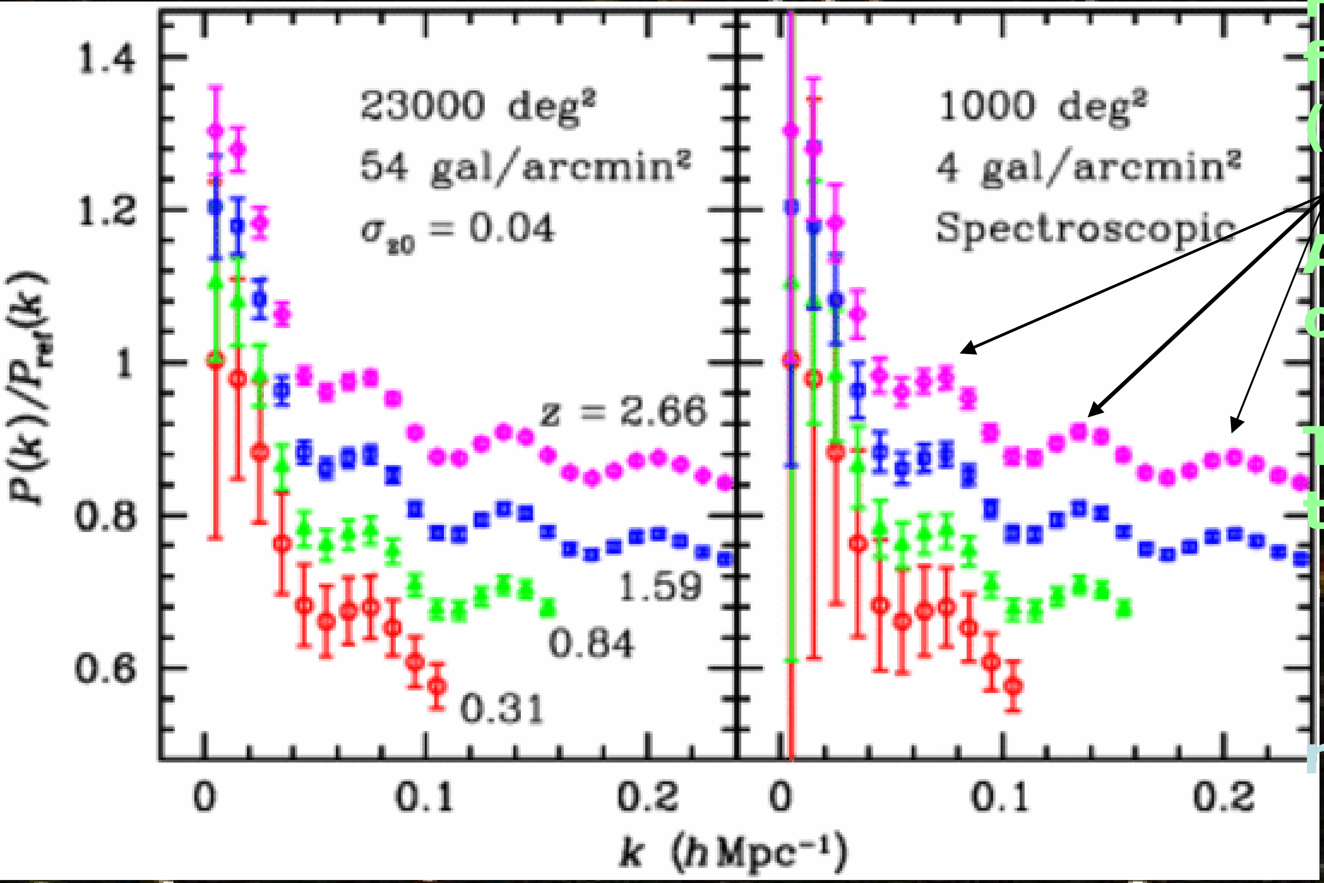


Cole et al. (2005)

SDSS

2DFGRS

Prospects for BAO



Physical scale known from primary CMB. (Standard ruler).

Angular scale is observed.

The ratio along transverse

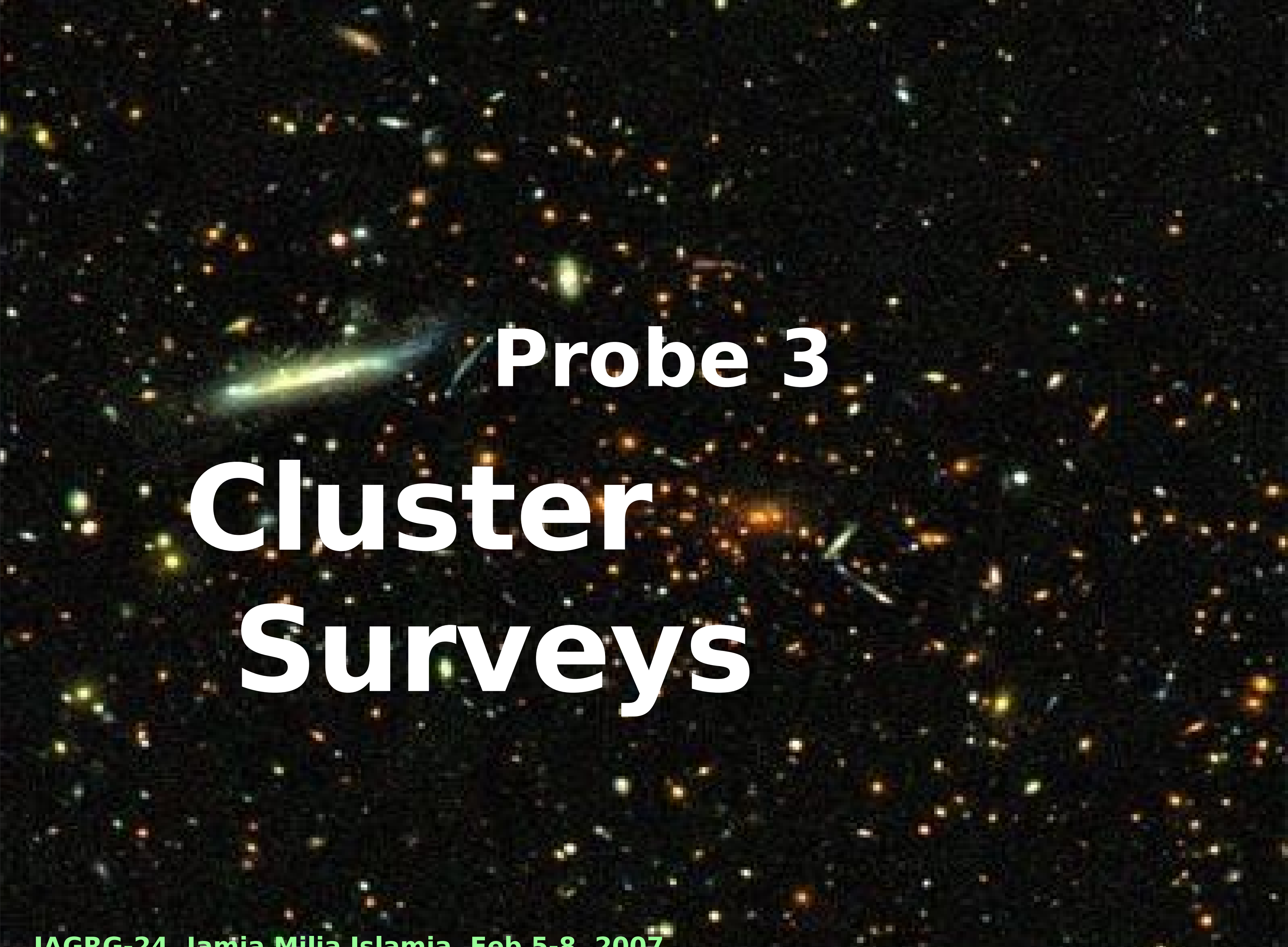
$d_A \rightarrow w(a)$

radial

$cH/z \rightarrow w(a)$

Errors are dominated by sample variance (volume) at low-z and shot noise (number density) at high-z. For photo-z surveys, σ_z reduces the number of modes.

Need to connect galaxies to DM haloes i.e halo bias. Also,

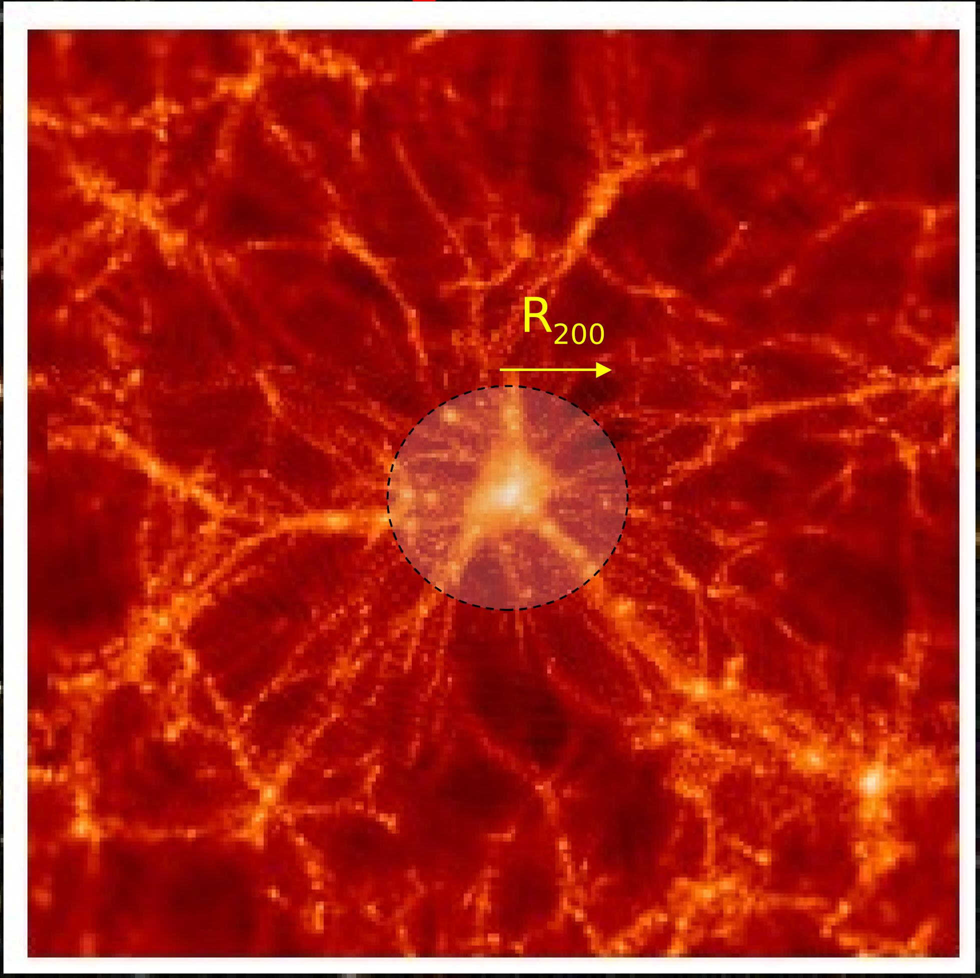


Probe 3

Cluster Surveys

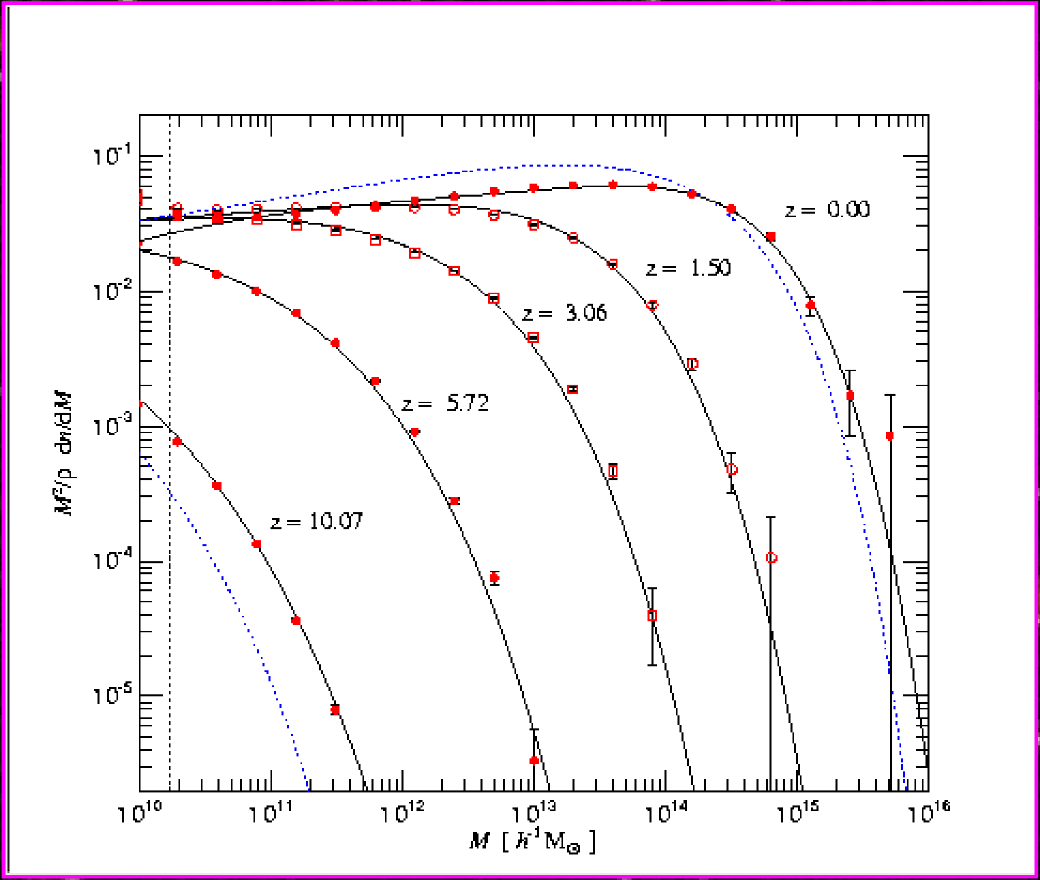
Clusters in simulations/theory?

- A large peak in the dark matter density
- Mass defined (for example) as total mass within R_{200}, where mean overdensity is 200 times the critical density => M_{200}



Springel et al. 2001

Ensemble of clusters from Simulations:



Universality when written in terms σ_M

$$f(\sigma_M, z) = \frac{M}{\bar{\rho}} \frac{dn(M,z)}{d\ln \sigma_M^{-1}}$$

$$f(\sigma_M, z) = \sqrt{\frac{2}{\pi}} \frac{\delta_c}{\sigma_M} \exp\left(-\frac{\delta_c^2}{2\sigma_M^2}\right)$$

Press-Schecter form, theoretical (since 1976)

$$f(\sigma_M, z) = \sqrt{\frac{2a}{\pi}} C \left[1 + \left(\frac{\sigma_M^2}{a\delta_c^2}\right)^q\right] \frac{\delta_c}{\sigma_M} \exp\left(-\frac{a\delta_c^2}{2\sigma_M^2}\right)$$

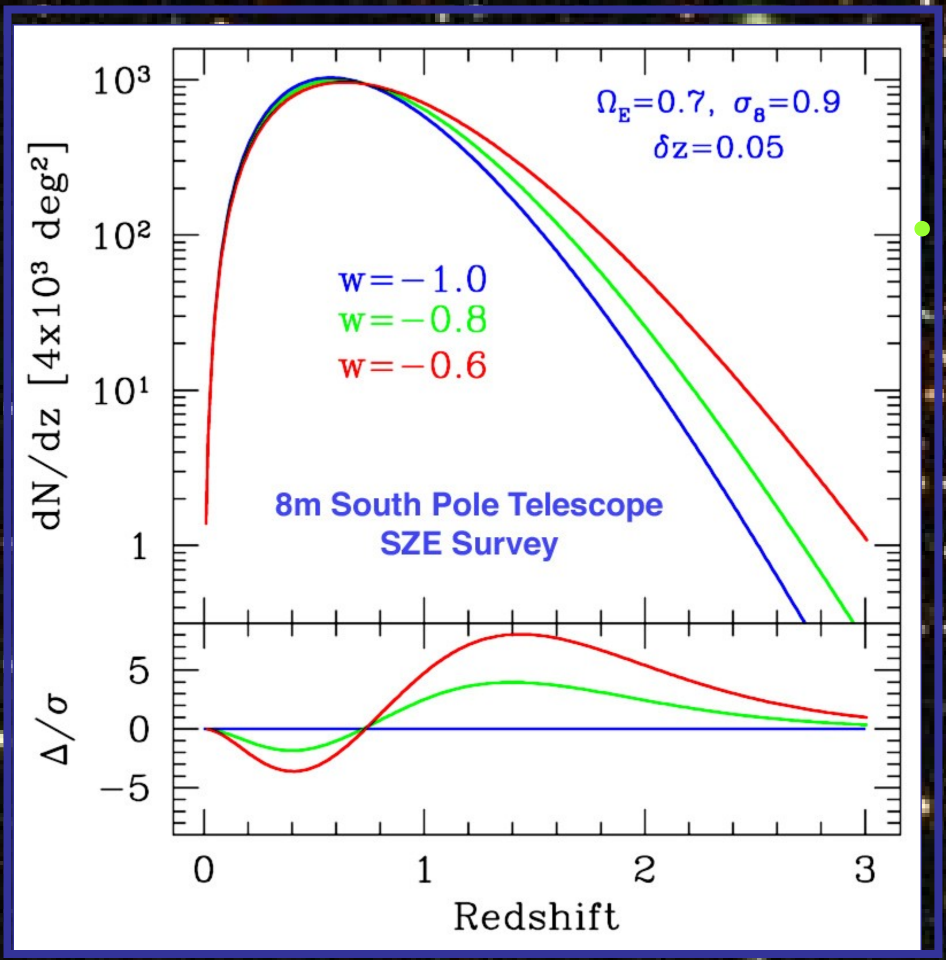
Seth-Tormen: ellipsoidal collapse & Nbo

$$f(\sigma_M, z) = 0.315 \exp(-|\ln \sigma_M^{-1} + 0.61|^{3.8})$$

Jenkins etal, bestfit to simulations
Also Warren etal, Lukic etal latest.

DE affects cluster redshift distribution…

$$\frac{dn}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_{M_{lim}}^{\infty} dM \frac{dn(M,z)}{dM}$$

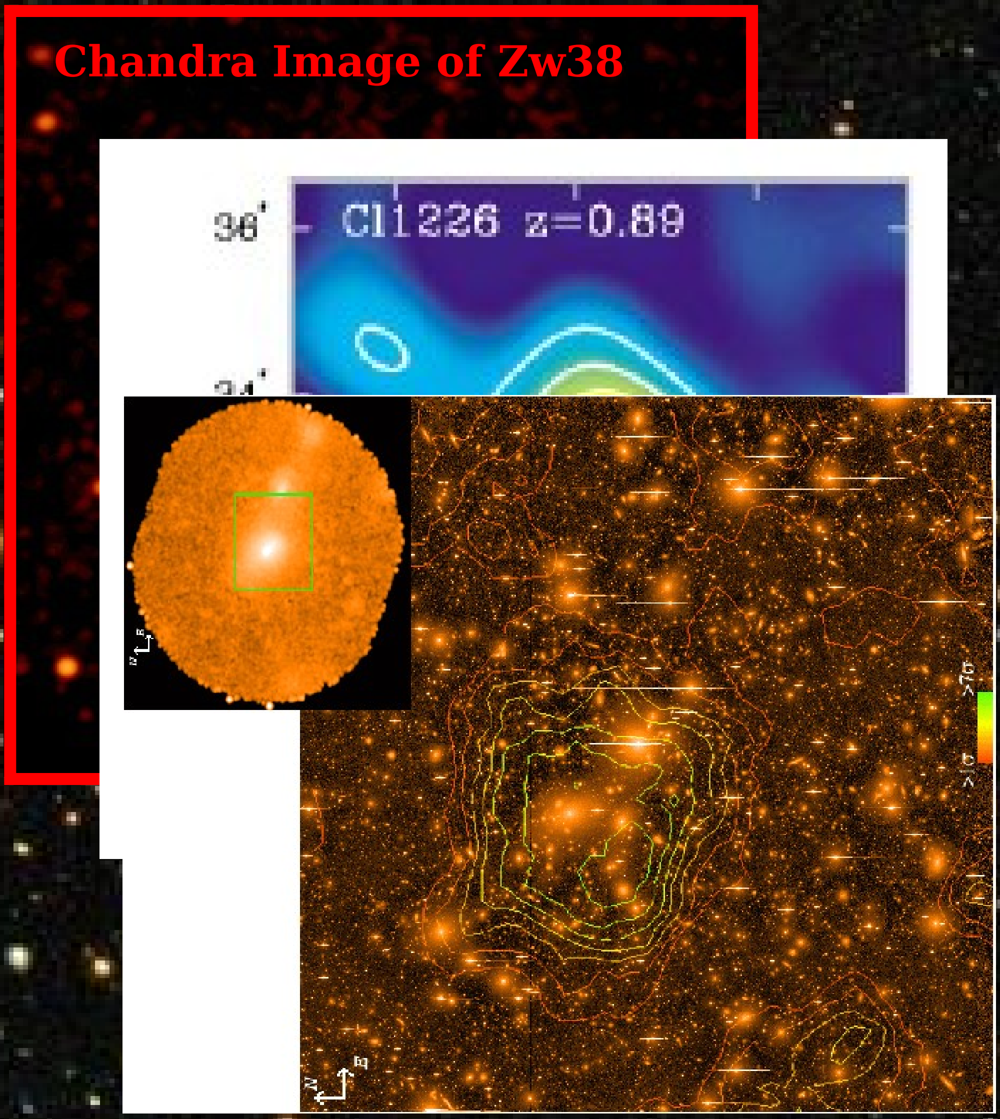


- Increasing **w** keeping **WE** fixed has following effects:
  - It decreases volume.
  - It decreases growth rate of density perturbations.

Detect clusters + z

How are ‘real’ clusters ?

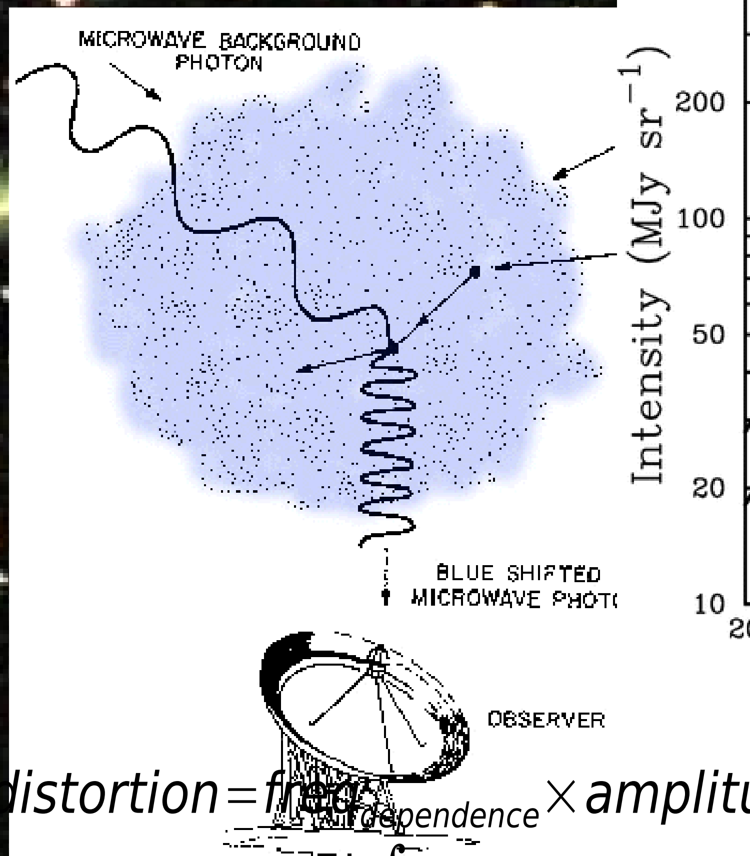
Large peak in matter density
- Dark matter clump (~80% of mass)
- Many luminous galaxies (~2%: 10% of baryons)
  - BCG and red sequence
  - Additional galaxies
  - Diffuse light
- Hot gas (~18%: 90% of baryons)
  - Emits X-rays
  - Causes SZ decrement in microwave background

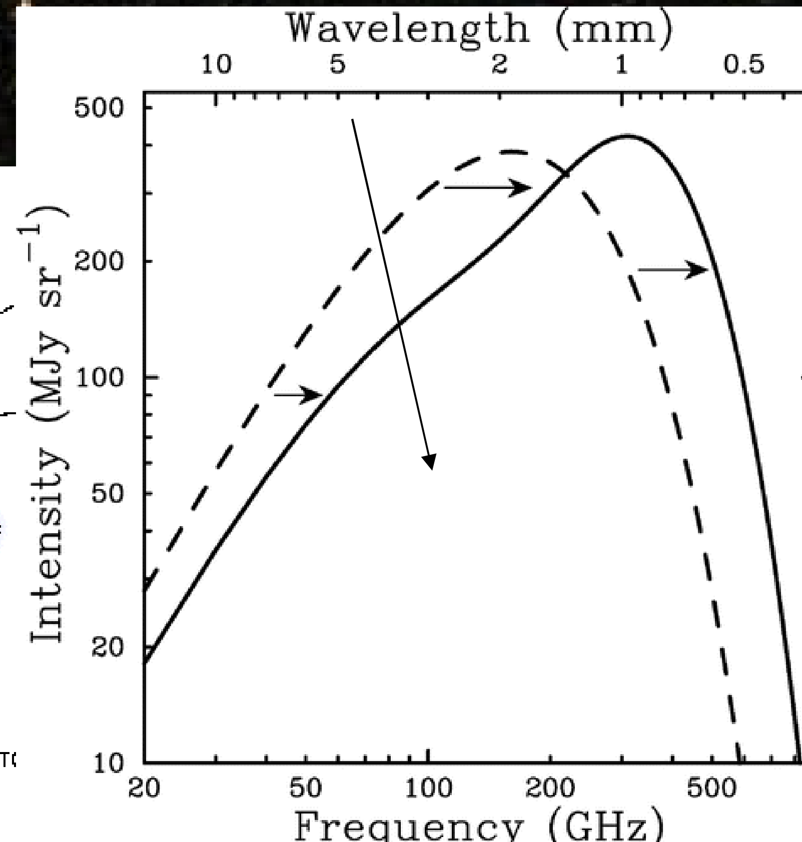


Carlstrom et al. 2002

The Sunyaev Zeldovich Effect...

Upscattering of photons





$$distortion = freq_{dependence} \times amplitude(cluster)$$

$$amplitude \propto \int_{line-of-sight} gas_{pressure}$$

When boon is your bane!

Mass function exponentially sensitive to mass

Observables translates to masses through simple observed/theoretical scaling relation

Error in translation can ruin use of clusters as DE probes.

'ay to go:

leed thousands of clusters to calibrate out uncertainties or nuisa arameters → ***Self-Calibration***

Many methods have now been suggested.

Recently demonstrated with RCS clusters.

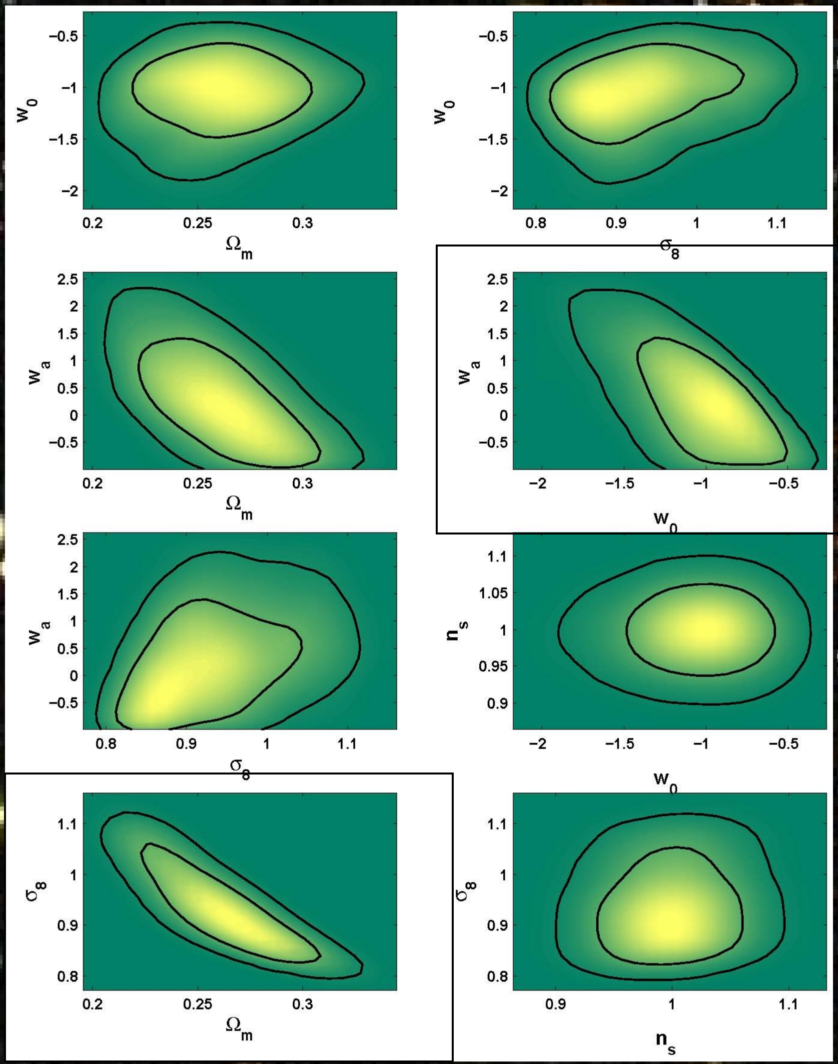
n general cosmology and gastrophysics degeneracies→

‘Self-Calibration’ Techniques...

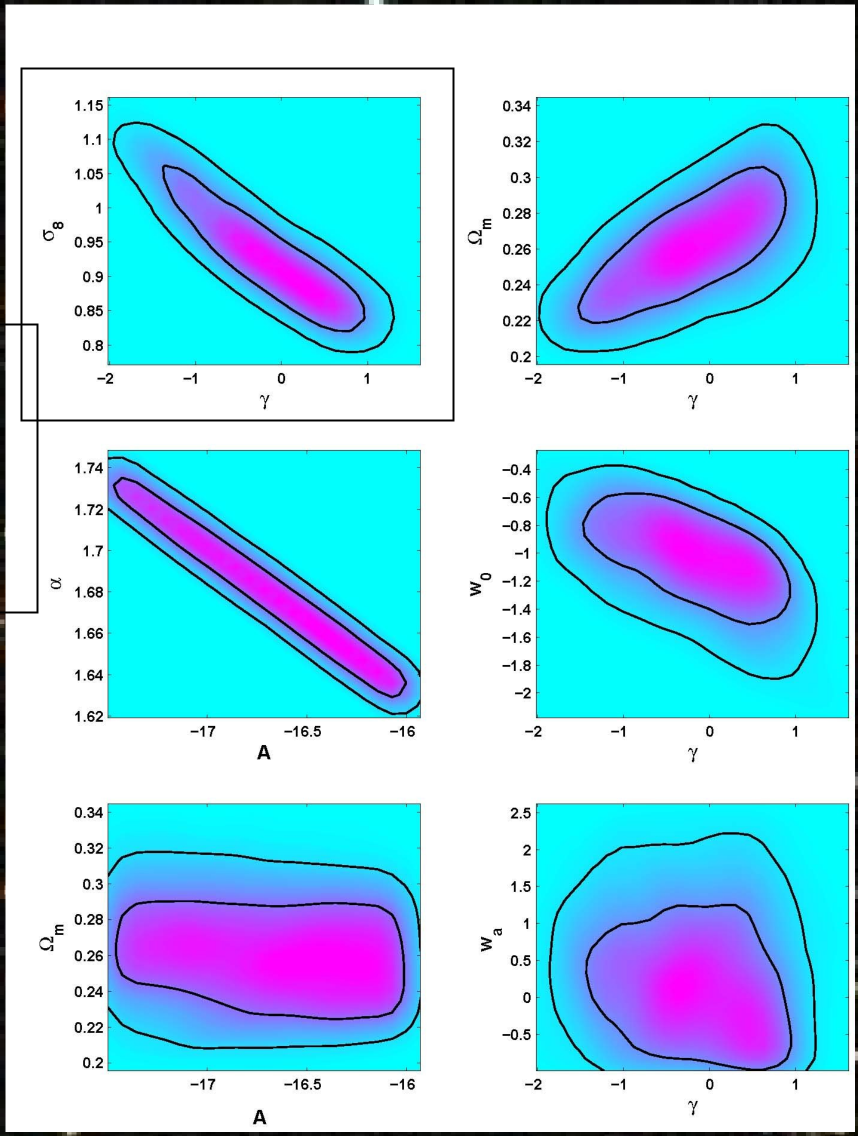
0. Just let dn/dz information self-calibrate the survey with simple scaling reln.
   But needs lots of clusters.
   Adding extra informations!

1. Limited mass follow-up (using full hydro equilibrium/weak lensing)
   (Majumdar & Mohr 2003,2004, Majumdar 2005)
2. Using shape of mass-function in redshift slices
   (Hu 2003)
3. Using the cluster power spectrum and P(k) oscillations
   (Majumdar & Mohr 2004, Hu & Haiman 2004, Huetsi 2005)
4. Adding information from counts-in-cell
   (Lima & Hu 2004, 2005)
5. Time or flux slicing of survey: using shape of dndz
   (Majumdar 2006, in prep)
6. For SZ surveys, adding SZ rms distortions to number counts
   (Diego & Majumdar, 2004)
7. Scatter is self-calibrated using both dndz and mass (flux) binning
   (Lima & Hu, 2005)
8. Having a subset of clusters observed in both SZ & Xray (assumption on cluster structure crucial)
   (Molnar etal, 2004, Majumdar 2006 in prep)

Systematics & degeneracies in 'w'-probes:
An example

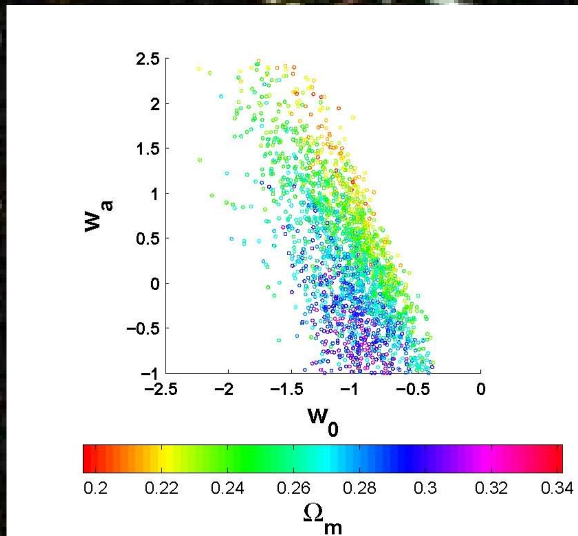


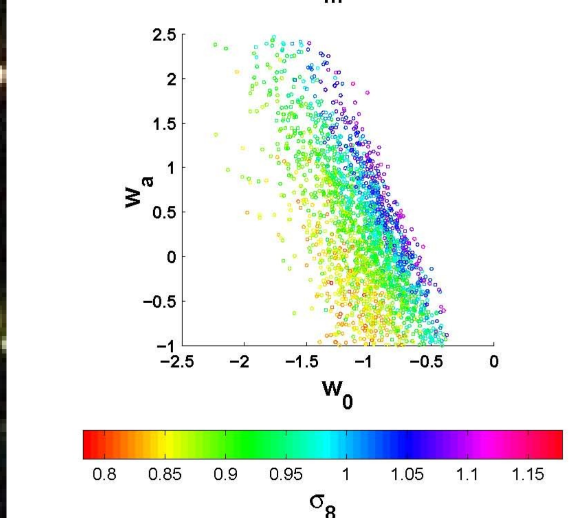
cosmological



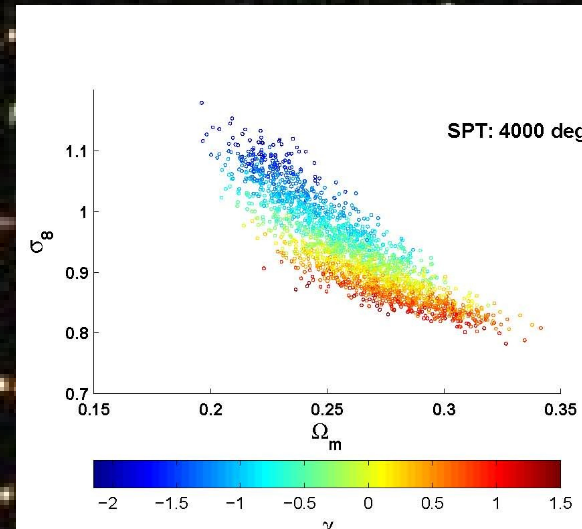
astrophysical

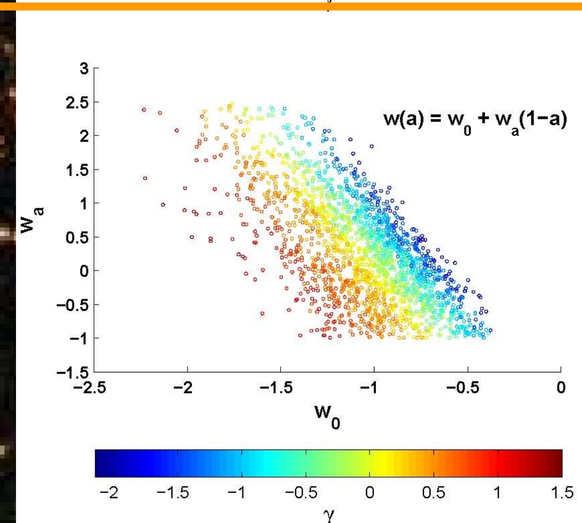
Need for extra information..





CMB is needed





High-z obs needed

Probe 4

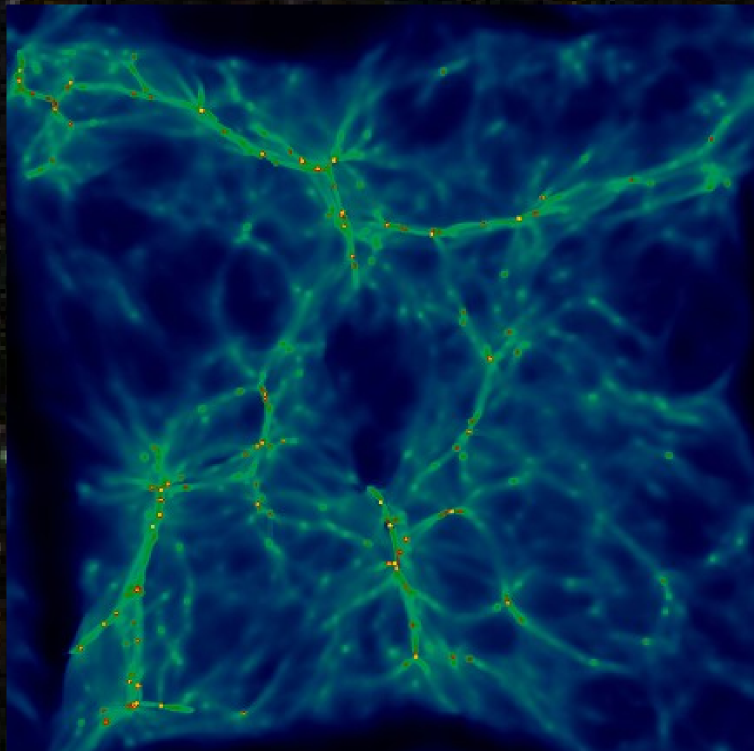
Weak Lensing Surveys

Foreground mass will lense background light...

Abell 2218: A Galaxy Cluster Lens, Andrew Fruchter et al.

(HST)

Weak Gravitational Lensing



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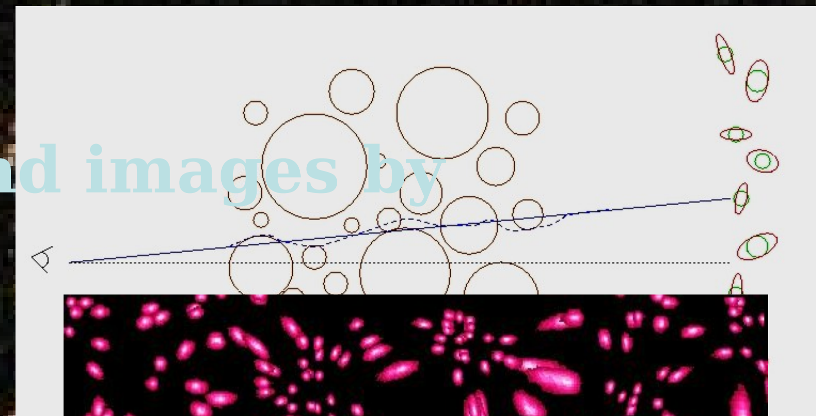
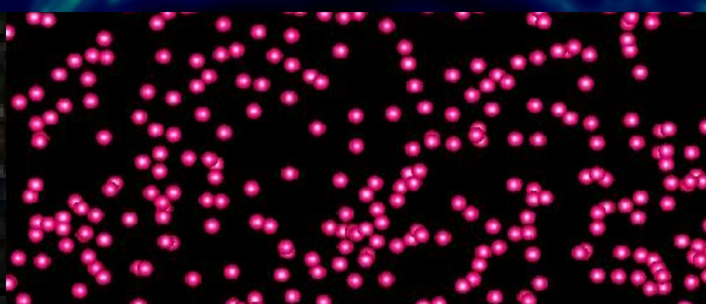
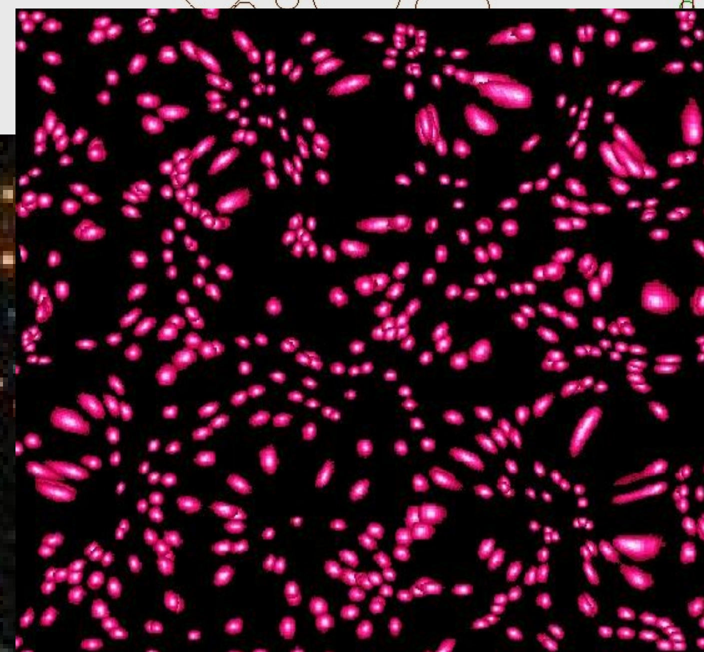






Unlensed **Lensed**

Credit: SNAP WL group

From shear maps to ‘w’ …

- **Weak Lensing Tomography:** compare observed cosmic shear correlations with theoretical/numerical predictions to measure g(z) *[Wittman et al. 2000]*

- **WL Cross-Correlation Cosmography** measure the relative shear signals of galaxies at different distances for the same foreground mass distribution: gives distance ratios that can be used to obtain H(z) *[Jain & Taylor 2003]*

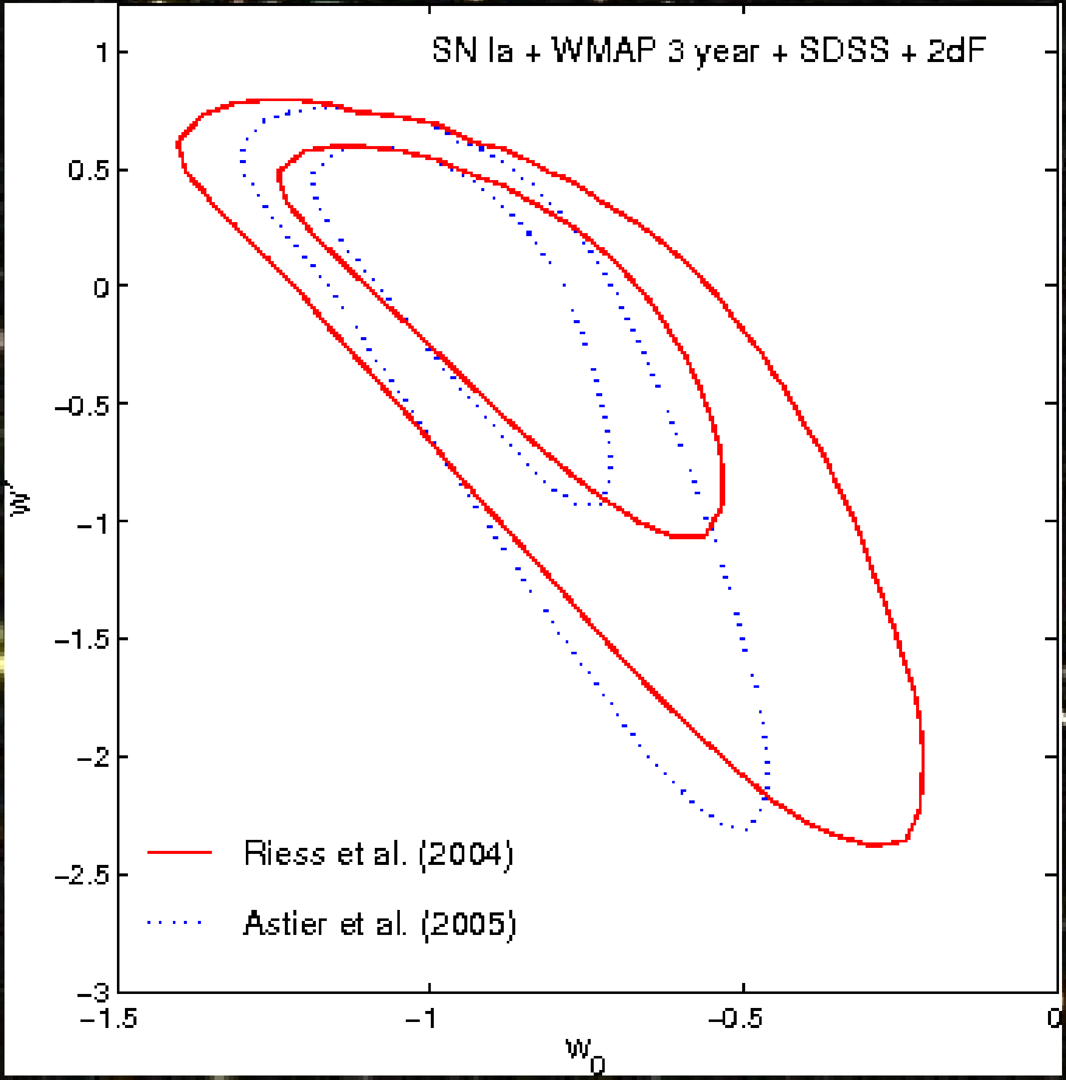
Systematics need to be overcome...

- Advantage: directly measures mass (unlike clusters)
- Disadvantages
  - Technically more difficult
  - Only measures projected mass-distribution
  - Intrinsic ellipticities
  - Need million plus galaxies
  - Depends crucially on background galaxy distribution modelling
  - Non-linearities and baryonic physics at 1-2% level

-- However, future surveys can still get great ‘w’ constraints ☺

Tereno et al 2004

What do current data tell us about DE?



Wang & Mukherjee 2006

Consistent with Λ

However, doesn't constrain w(a)

McDonald etl 05

Future Dark Energy Surveys :

- Essence (2002-2007): 200 SNe Ia, $0.2 < z < 0.7$, 3 bands, $\Delta t \sim 2d$
- Supernova Legacy Survey (2003-2008): 2000 SNe Ia to $z=1$
- ESO VISTA (2005?-?): few hundred SNe, $z < 0.5$
- CFHT Legacy (2003-2008): 2000 SNe Ia, 100's high z SNe, 3 bands, $\Delta t \sim 15d$
- Pan-STARRS (2006-?): all sky WL, 100's SNe y[illegible], $z < 0.3$, 6 bands, $\Delta t = 10d$

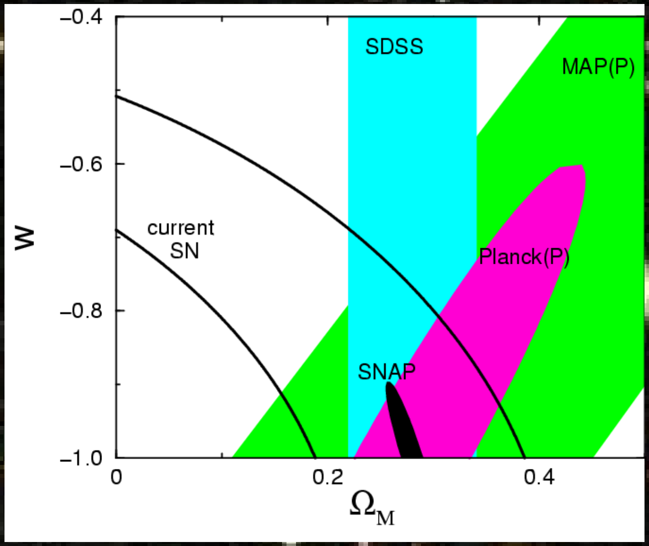
- HETDEX (?): 200 sq deg BAO, 1.8 [illegible]
- WFMOS on Subaru (?): 200[illegible] deg BAO, [illegible].5<z<1.3 and 2.5<z<3.5
- ALPACA (?): 50,000 SNe Ia [illegible] to [illegible]=0.8, $\Delta t = 1d$, 800 sq deg WL & BAO with photo-z's
- Dark Energy Su[illegible]ey [illegible]), clu[illegible]er at 0.1<z<1.3, 5000 sq deg WL, 2000 SNe at 0.3<z<[illegible]

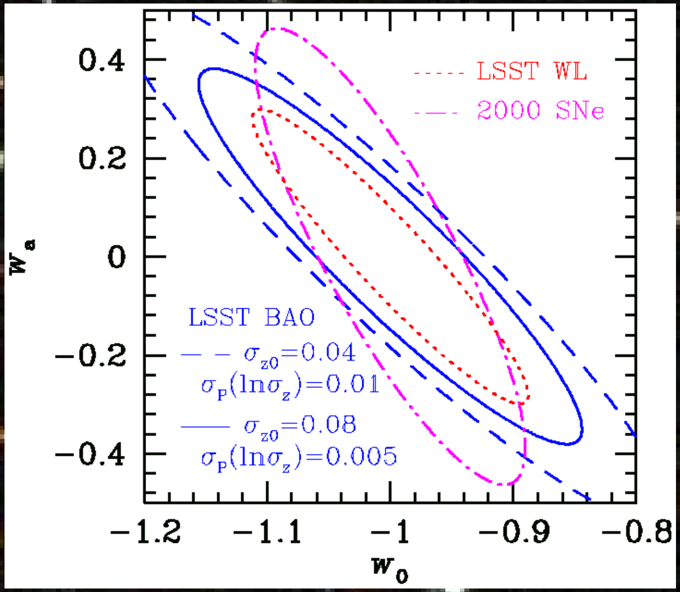
- LSST (2013-): 10^6 [illegible]Ne Ia y^{-1}, $z < 0.8$, 6 bands, $\Delta t = 4d$; 20,000 sq deg WL & BAO with photo-z's.
- JDEM (2015?): several competing mission concepts

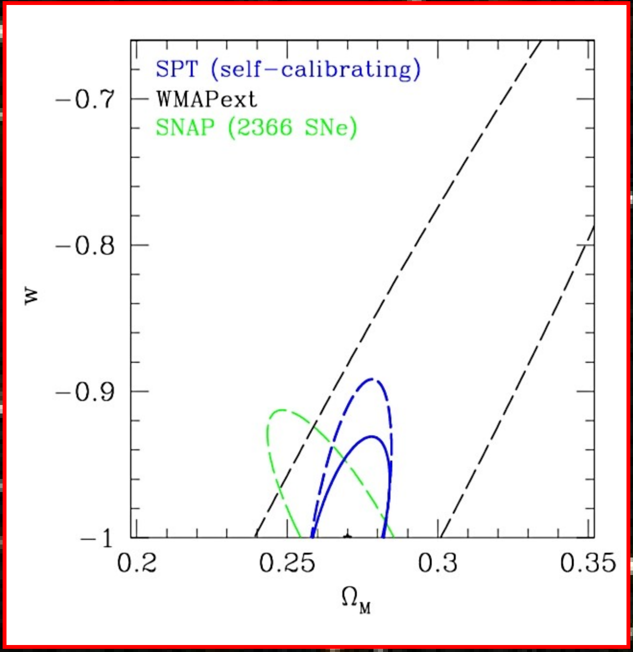
- SPT (2007), 4000 deg, CL , z< 1.3, 3+ bands
- RCS2, 2007, 10000 deg, optical,
- APEX, ACT, AMI, SZA, eROSITA, Planck etc

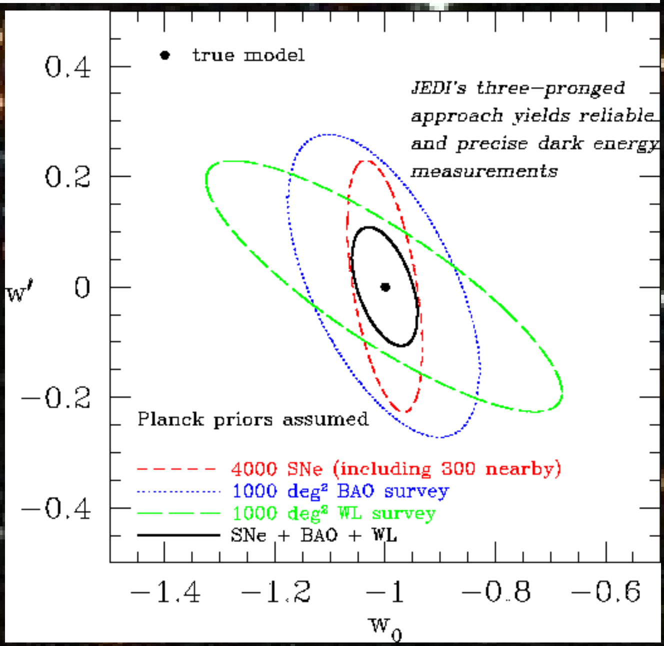
MANY

rom present 'w' contraints to future :

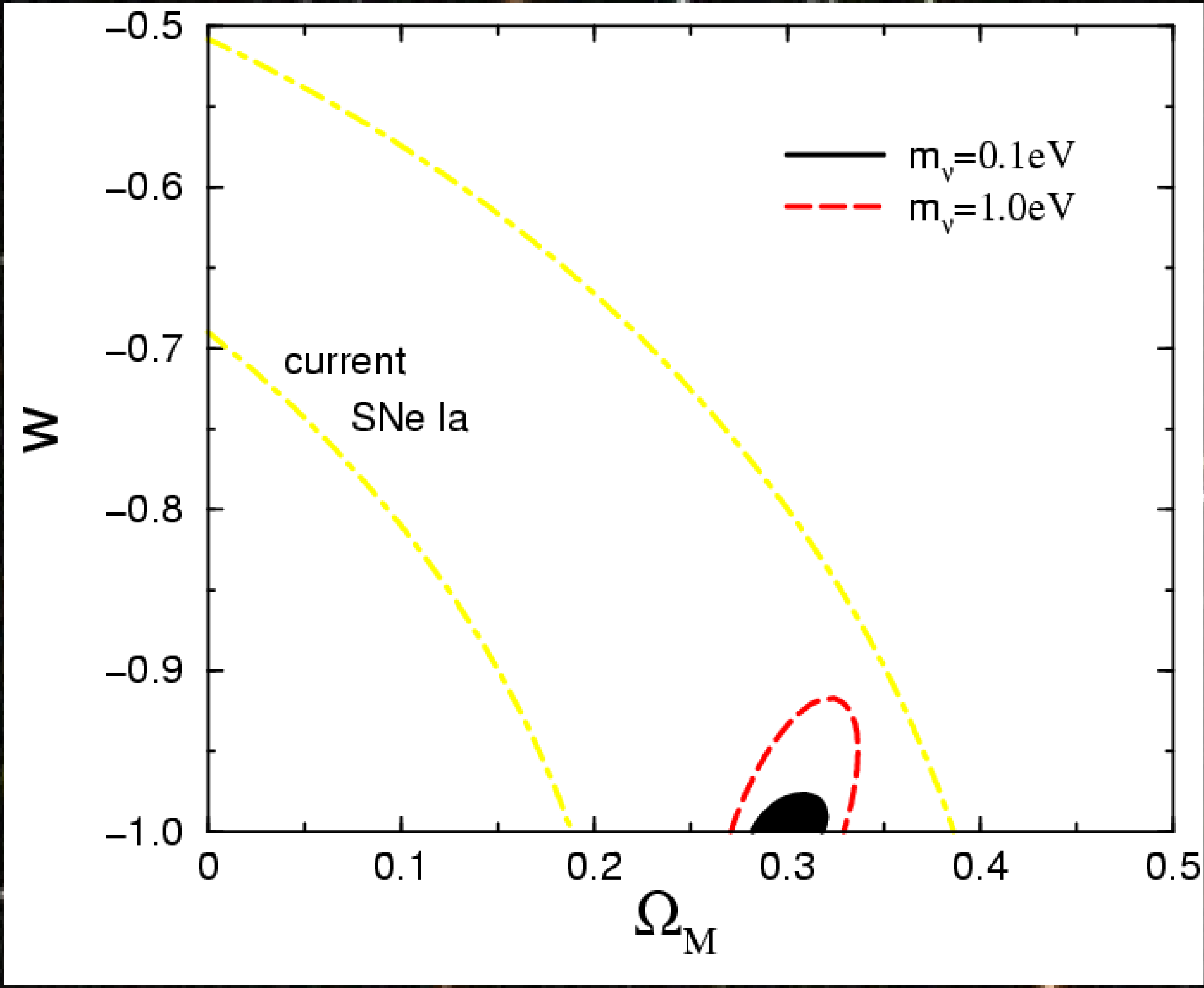








Just had to bring in neutrinos

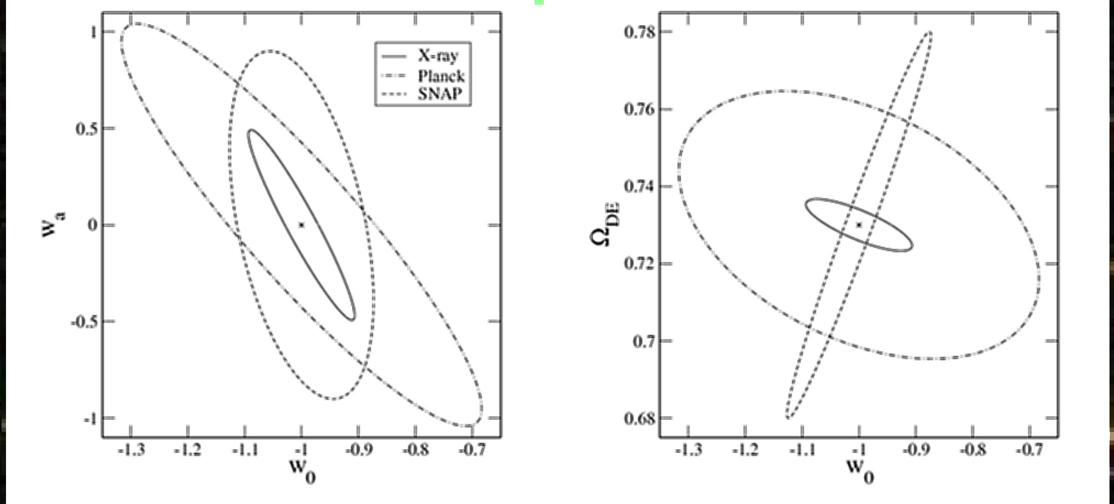


Lensing survey
1000 sq.deg,
R ~ 27

Finally some numbers – (An Example)...

One of the DETF white paper (Haiman etal, Subhabrata Majumdar)

100000 clusters upto z=1.3 in 20000 degs



eROSITA :

ESA, ESO, telescope

Russian rocket

Self–Calibrated Experiment(s)	$\sigma(w_0)$	$\sigma(w_a)$	$\sigma(\Omega_{DE})$
X-ray	0.093	0.490	0.0067
X-ray + Planck	0.054	0.170	0.0052
X-ray + Planck[a]	0.016	-	0.0045
Ideal Experiment[b]			
X-ray	0.021	0.120	0.0030
X-ray + Planck	0.013	0.066	0.0027
X-ray + Planck[a]	0.0087	-	0.0019

with systematics

without systematics

The picture looks promising… …. But its all about systematics:

SN– Detailed spectroscopic and photometric observations of about 500 nearby supernovae to study the variety of peak explosion magnitudes and any associated observational signatures of effects of evolution, metallicity, or reddening, as well as improvements in the system of photometric calibrations

BAO– Theoretical investigations of how far into the non-linear regime the data can be modeled with sufficient reliability and further understanding of galaxy bias on the galaxy power spectrum.

CL– Combined lensing and Sunyaev-Zeldovich and/or X-ray observations of large numbers of galaxy clusters to constrain the relationship between galaxy cluster mass and observables.

WL– Spectroscopic observations and narrow-band imaging of tens to hundreds of thousands of galaxies out to high redshifts and faint magnitudes in order to calibrate the photometric redshift technique and understand its limitations. It is also necessary to establish how well corrections can be made for the intrinsic shapes and alignments of galaxies, removal of the effects of optics (and from the ground) the atmosphere and to characterize the anisotropies in the point-spread function.

So what lies in the future ?