DARK ENERGY MODELS TOWARDS OBSERVATIONAL TESTS AND DATA

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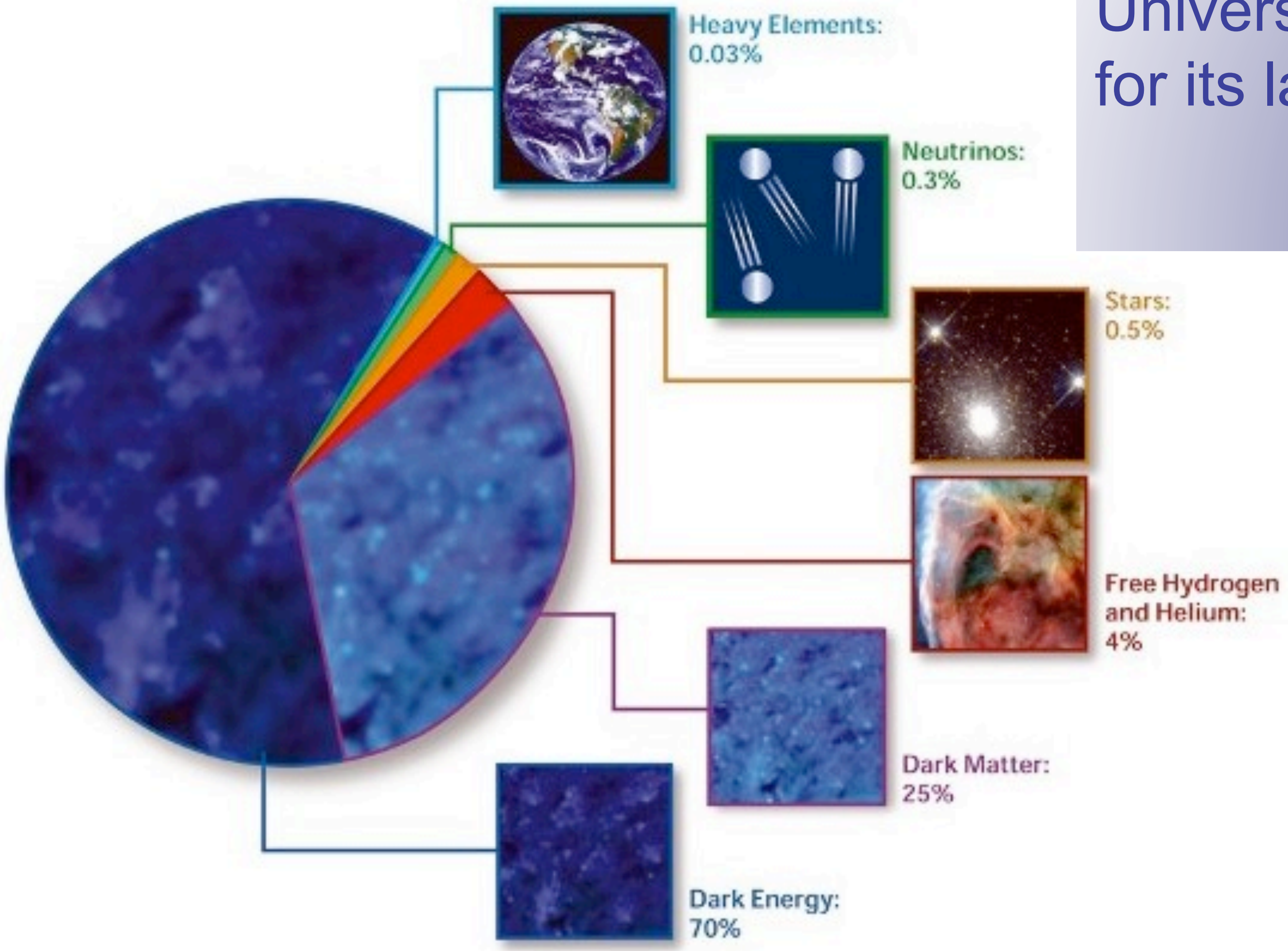
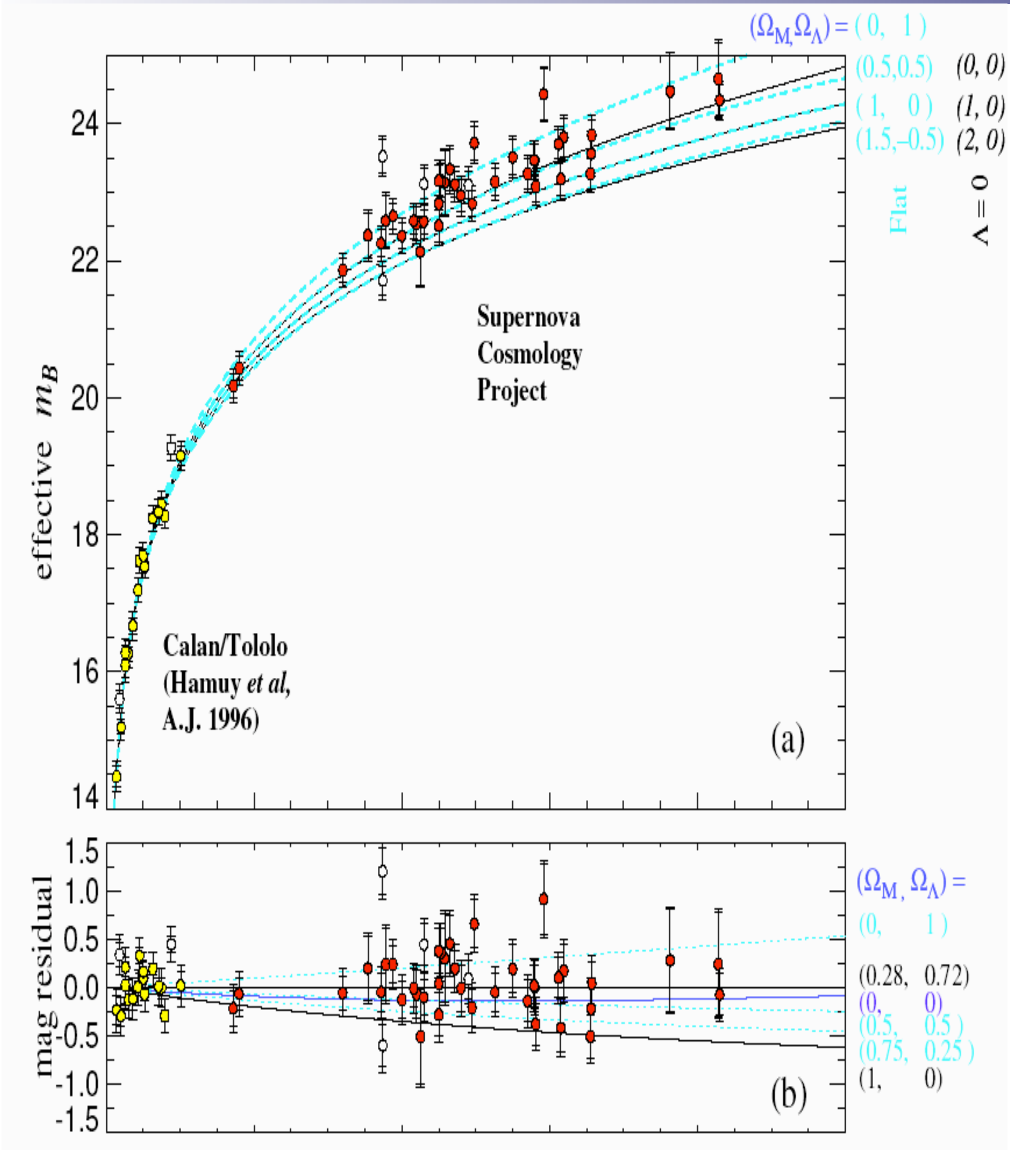
Theoretical situation is very “DARK” while observations are extremely good!

The matter-energy content of the Universe is unknown for its largest part

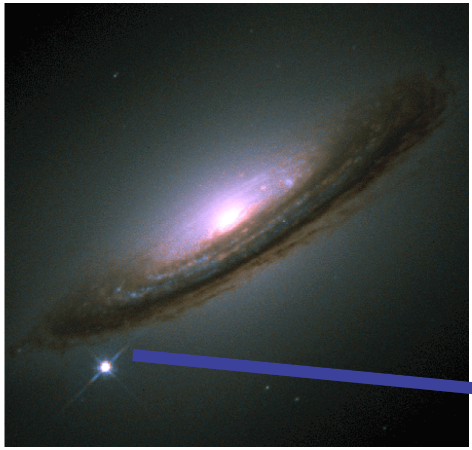


The Dark Energy sector



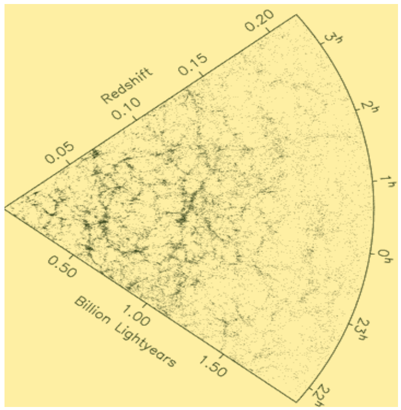
The presence of a Dark Energy component has been proposed after the results of SNeIa observations (HZT [Riess A.G. et al. Ap.J. 116, 1009 (1998)]- SCP [Perlmutter S. et al. Nature 391, 58 (1998)] collaborations)

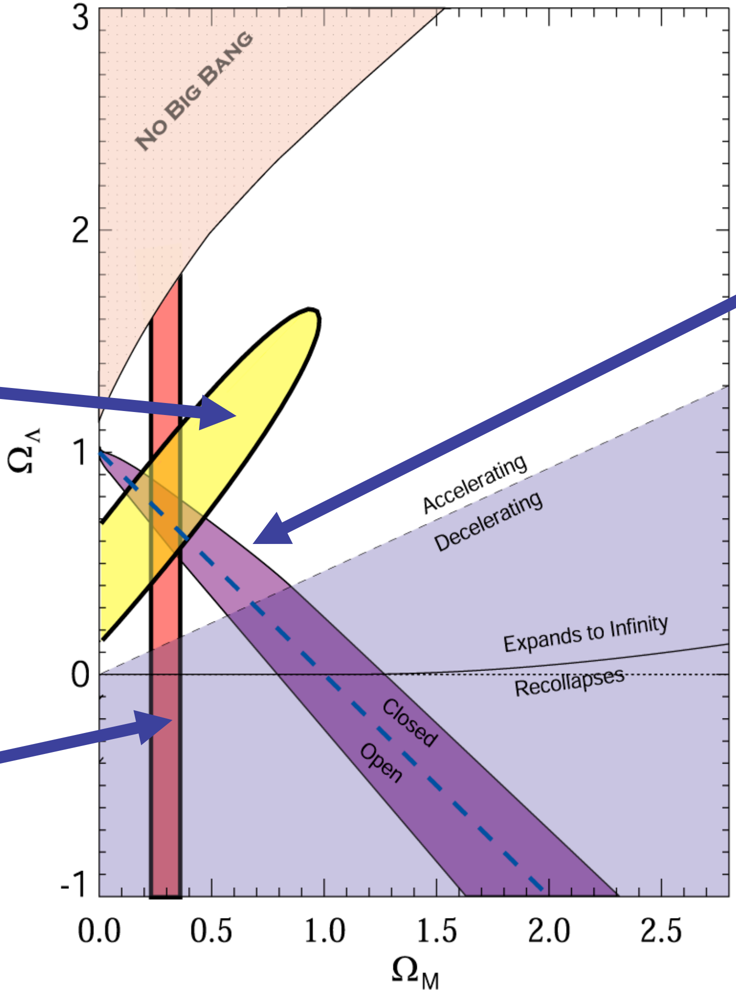
Dark Energy is here to stay…



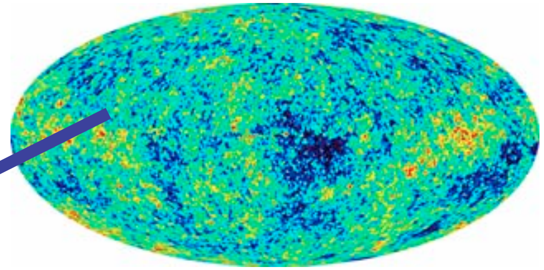
SNe Ia

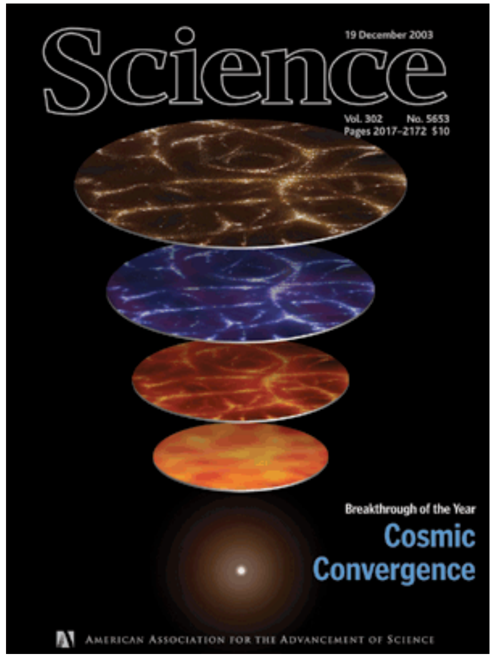
LSS



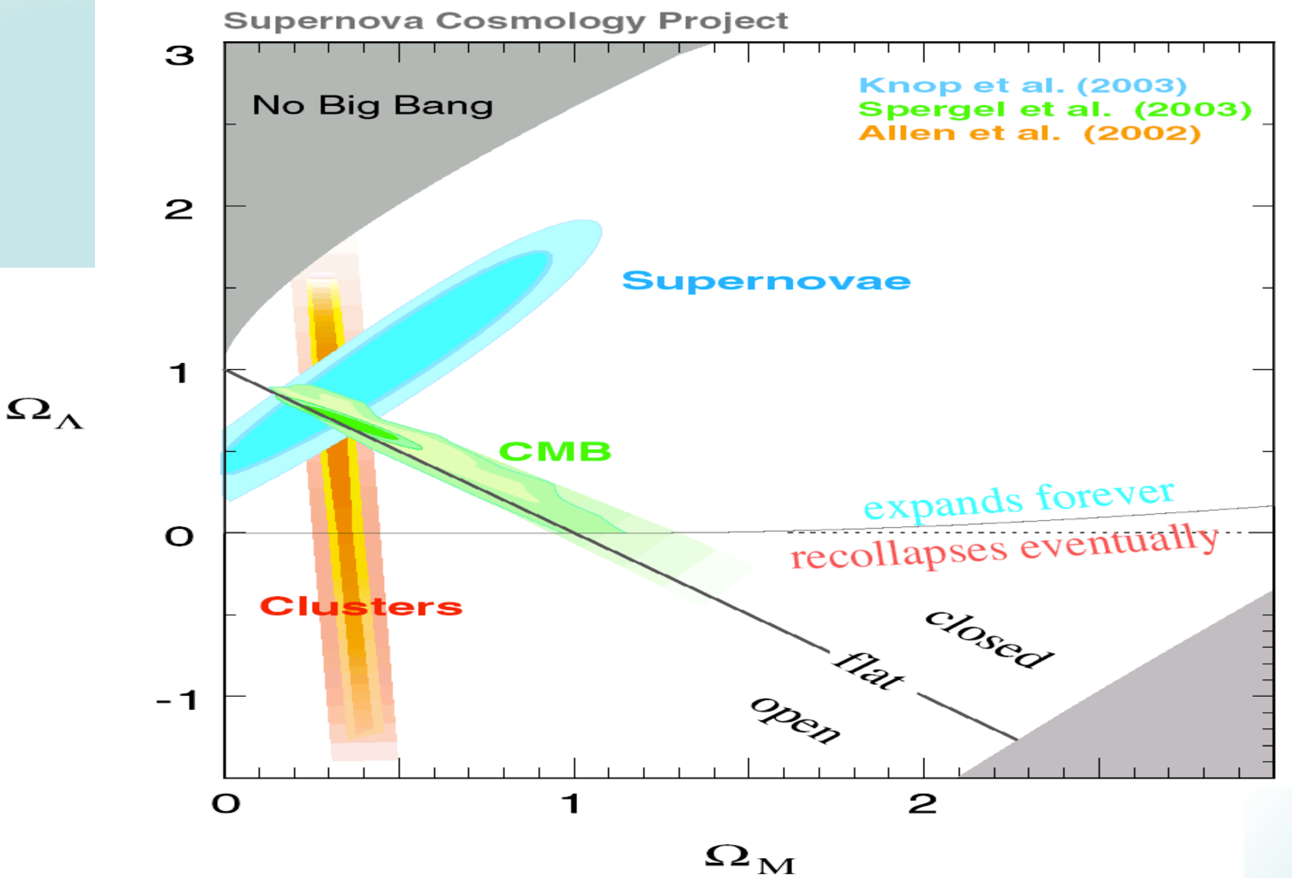


CMB(WMAP)





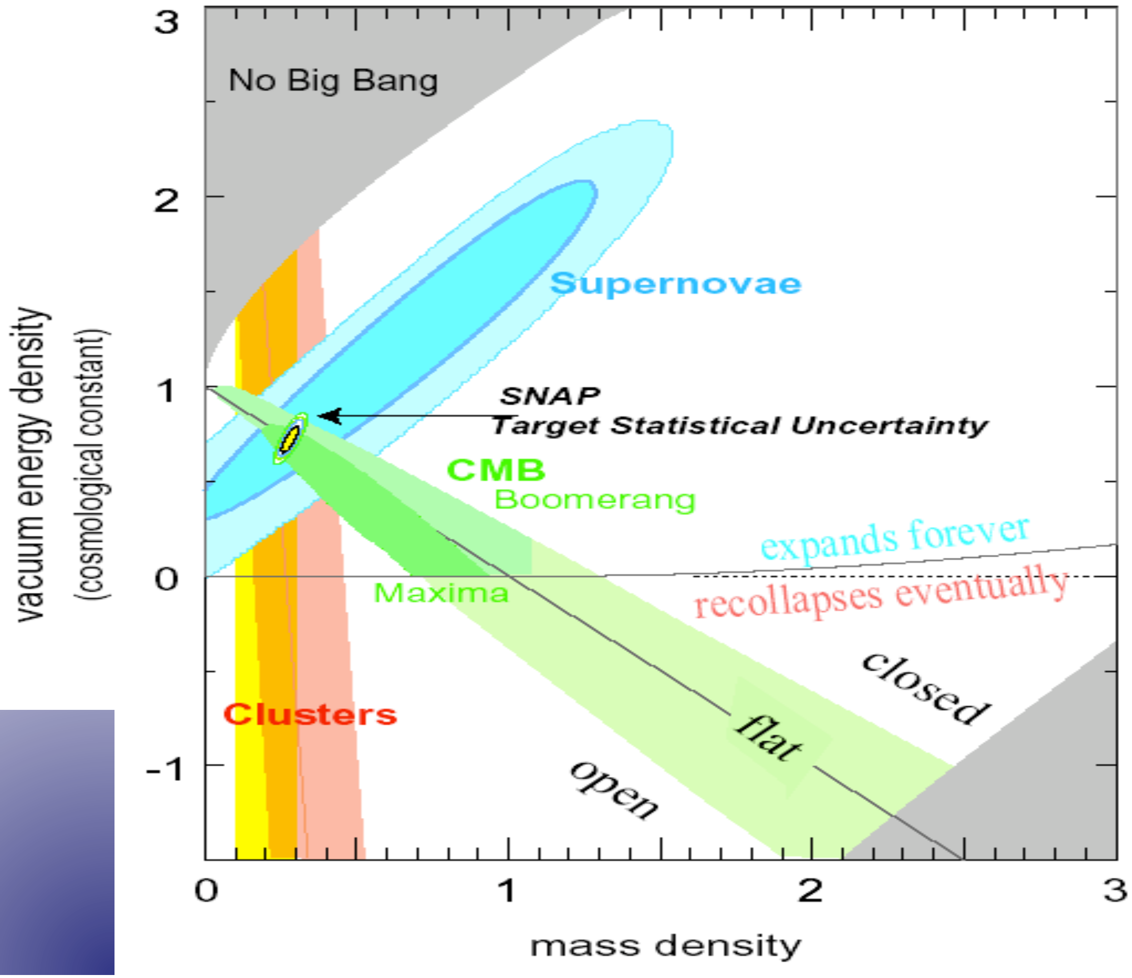
The energy density parameter space (today)



Cosmic Triangle Equation:

$$\Omega_M + \Omega_\Lambda + \Omega_k \cong 1$$

The incoming observations (We hope!)



Cosmic Triangle Equation: $$\Omega_M + \Omega_\Lambda + \Omega_k \equiv 1$$

Physical Effects of Dark Energy

Dark Energy affects expansion rate of the Universe:

$$H^2 = \frac{8\pi G}{3}\left(\rho_M + \rho_X\right)$$

$$H(z)^2 = H_0^2\left[\Omega_M(1+z)^3 + \Omega_X \exp\left[3\int_0^z (1+w(x))\, d\ln(1+x)\right]\right]$$

Dark Energy may also interact: long-range forces, new laws of gravity?

Key Issues

- Is there Dark Energy?

  Will the SNeIa and other results hold up?

- What is the nature of the Dark Energy?

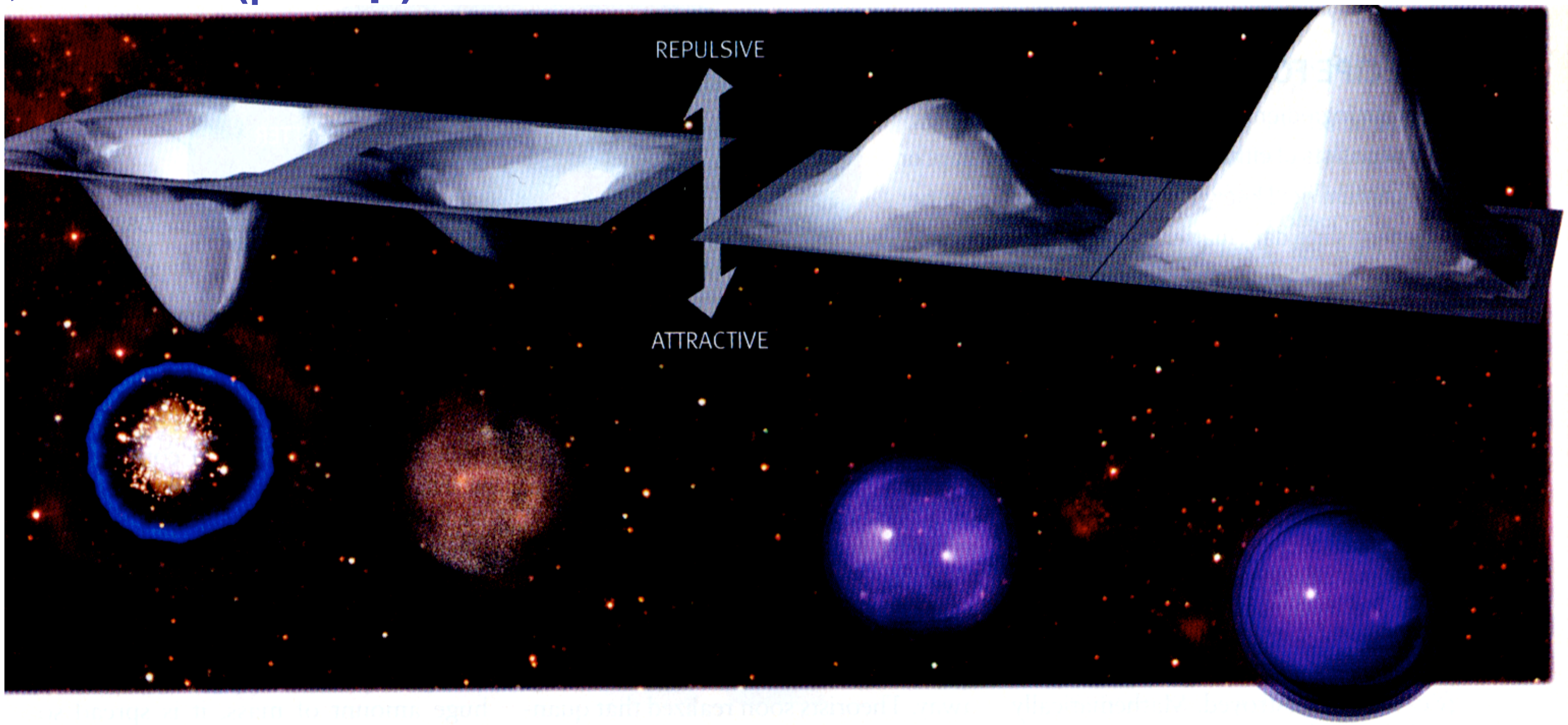
  Is Λ or something else?

- How does $w = p_X/\rho_X$ evolve?

  Dark Energy dynamics → Final Theory!

Dark Energy and *w* (the EoS viewpoint)

In GR, force ∝ (ρ + 3p)



RADIATION	ORDINARY MATTER	QUINTESSENCE (MODERATELY NEGATIVE PRESSURE)	Cosmological Constant (vacuum)

$w = p/\rho =$ $+1/3$ $\quad 0 \quad$ $-1 < w < -1/3$ $\quad -1$

If $w < -1/3$ the Universe accelerates, $w < -1$, phantom fields

What is the target?

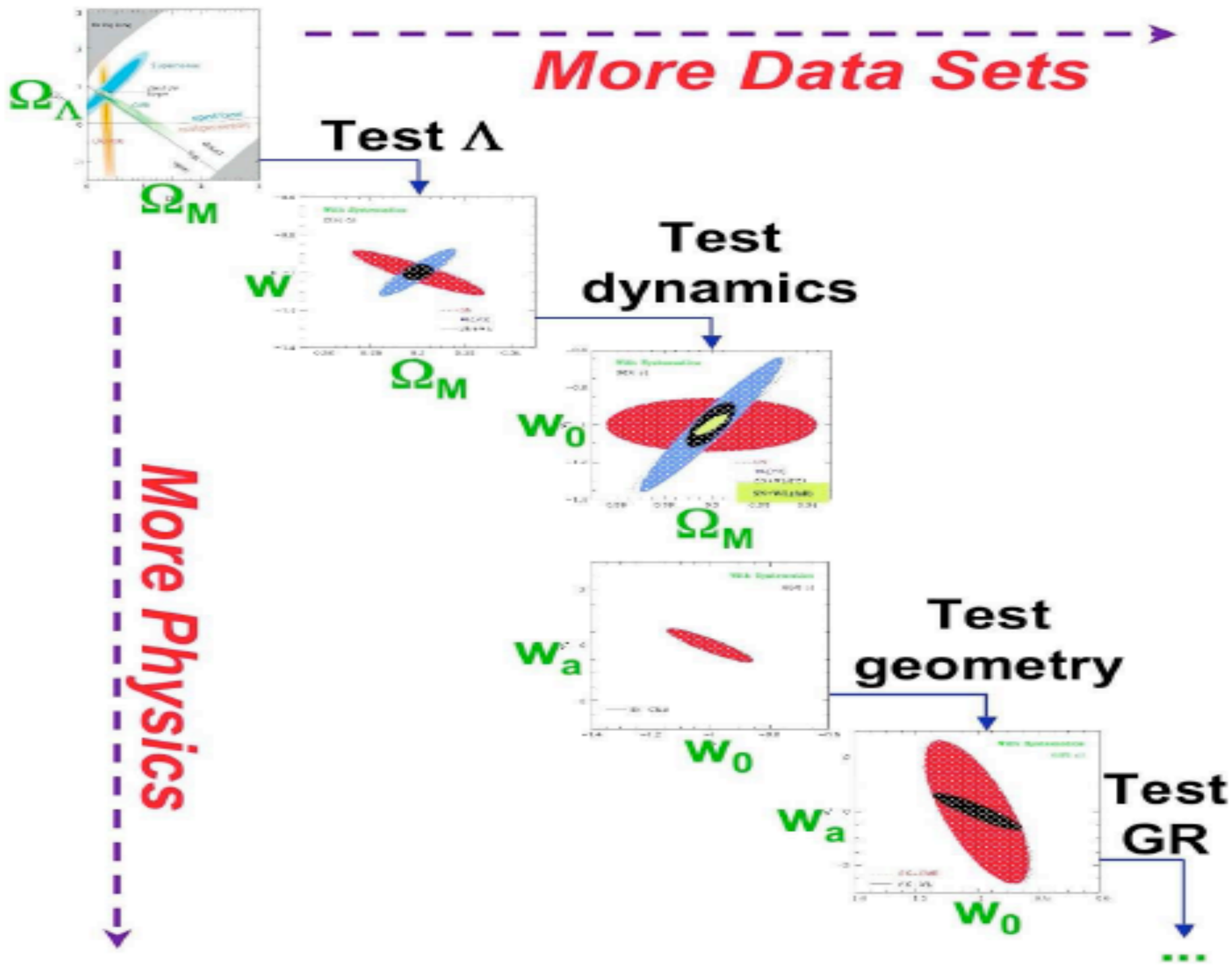
- Dark energy has no agreed physical basis

constant $\Lambda \rightarrow$ static $w \rightarrow$ dynamics ($w = w_0 + w_1 z$)
$w(z)$ has no naturally-predicted form

- Wrong parameterization can lead to incorrect deductions: models are degenerate!

- Incremental approaches:
  - reject null hypothesis of Λ (w=-1)
  - prove via more than one method $w \neq$ const
  - derive empirical evolution for a(t), G(t), $d_A(z)$

Incremental Exploration of the Unknown



Physical Observables: probing DE

- Luminosity Distance vs redshift:
  Standard candles: SNe Ia

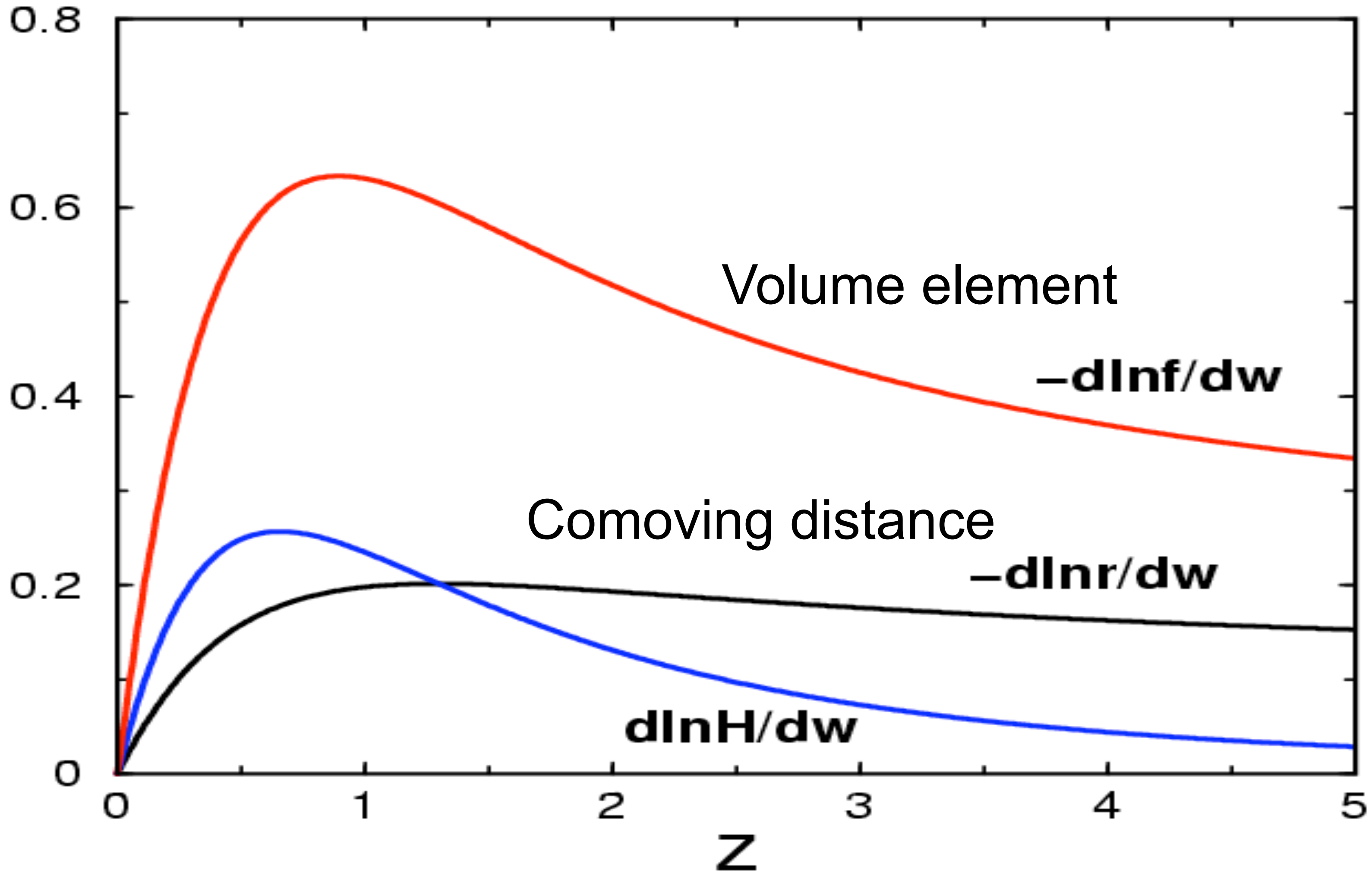
- Angular diameter distance vs. z:
  Alcock-Paczynski test: Ly-alpha forest;
  redshift correlations

- Number counts vs. redshift:
  probes: * Comoving Volume element
  * Growth rate of density Pertubations
  Counts of galaxy halos and of clusters;
  QSO lensing
- GRBs as distance indicators
- Lookback time vs. clusters and galaxies
- Exteded Radio Source Surveys (SKA!)

Which method is most promising for measuring *w*?

- **Type Ia Supernovae: H(t) to z ≈ 2**
  - Ongoing with various ground-based/HST surveys
  - Proposed for both ground and space projects
  - Key issue is systematics: *do we understand SNe Ia?*
- **Weak lensing: G(t) to z ≈ 1.5**
  - Less well-developed; requires photo-z's
  - Proposed for both ground and space projects
  - Key issues are *fidelity, calibration etc..*
- **Baryon "wiggles": $d_A(z)$ to z=3**
  - Late developer: clean but *requires huge surveys*
- **Others:** lookback time, cluster gas/counts, GRBs, Radio Sources

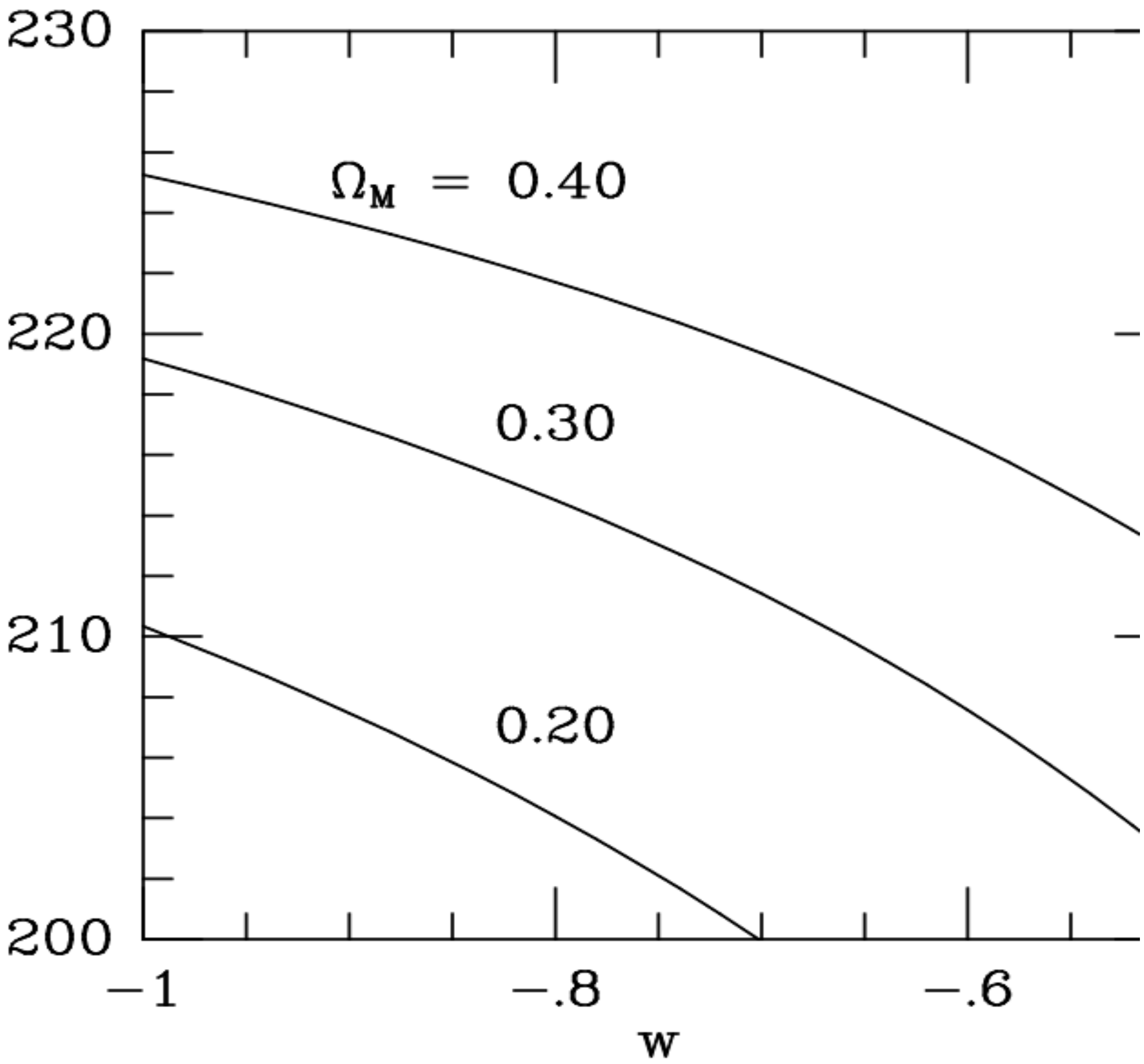
Sensitivity to Dark Energy equation of state



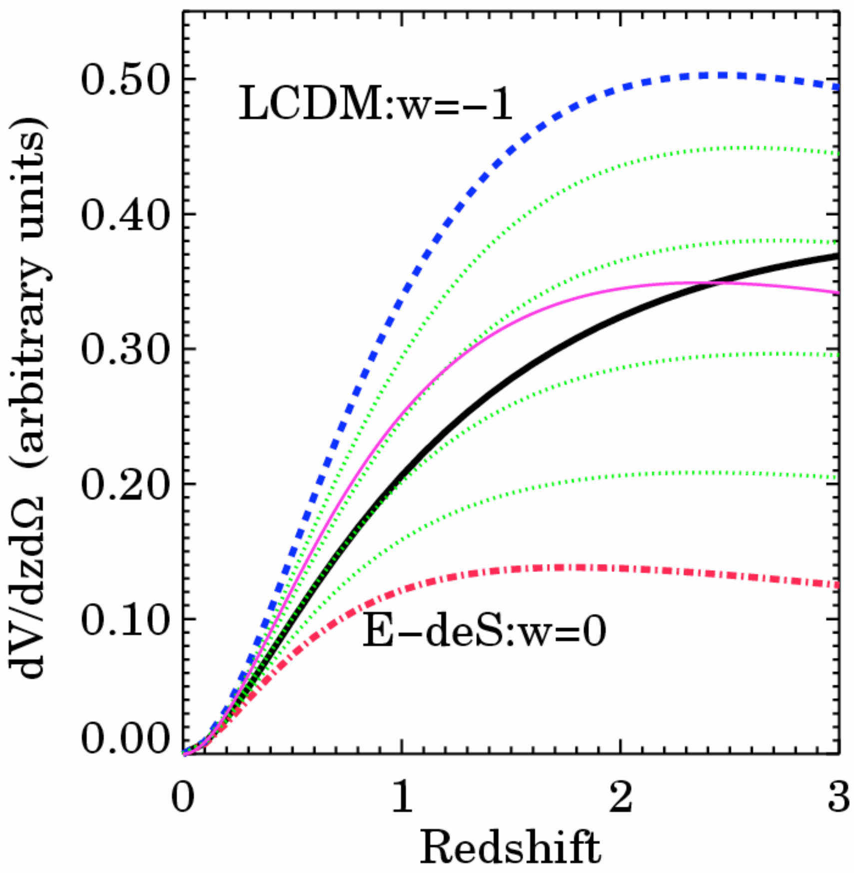
CMB Anisotropy:

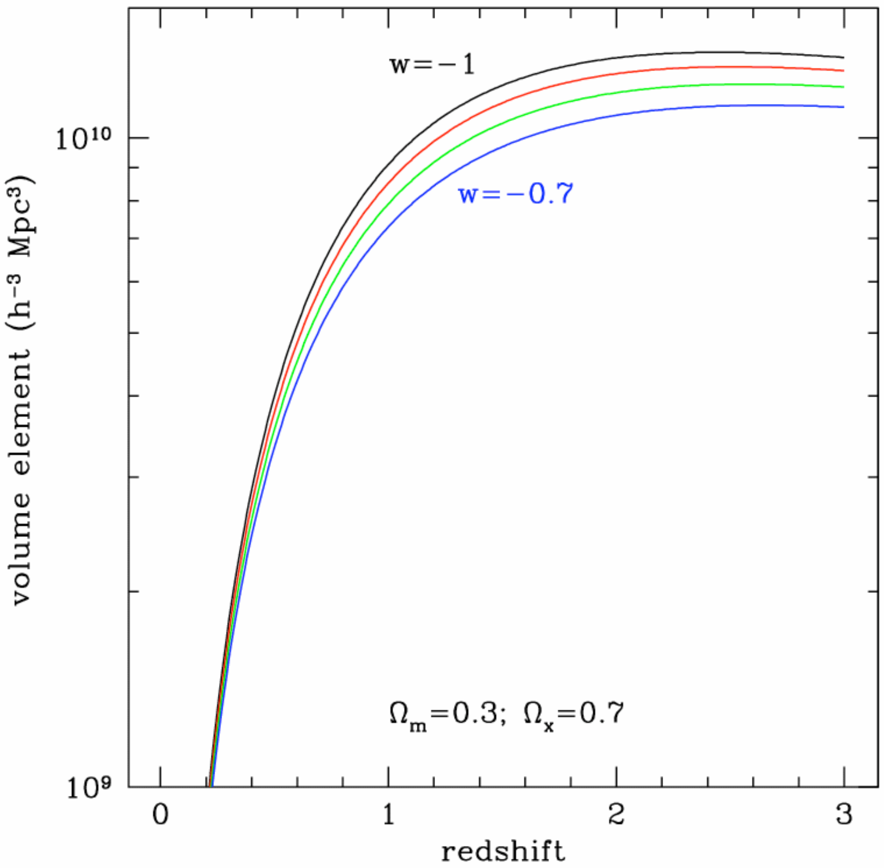
Angular diameter
Distance to last
Scattering surface

Peak Multipole



Volume Element as a function of *w*

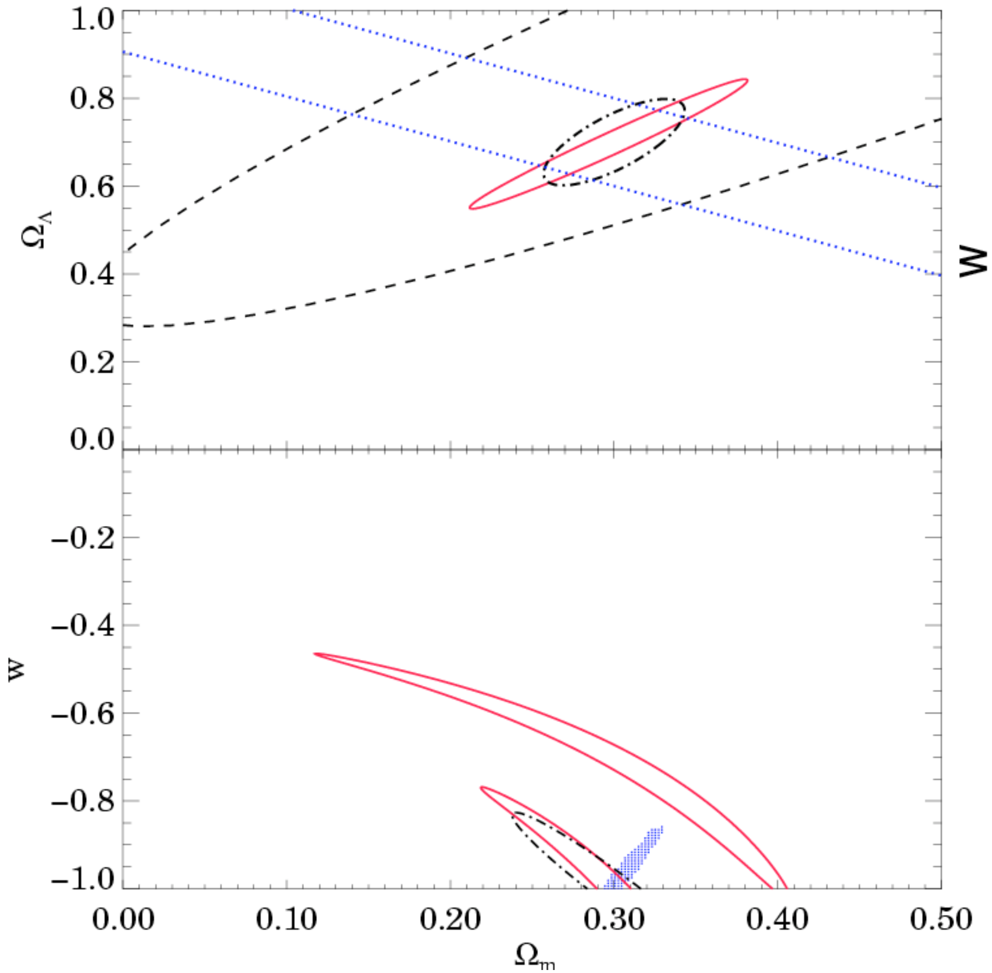


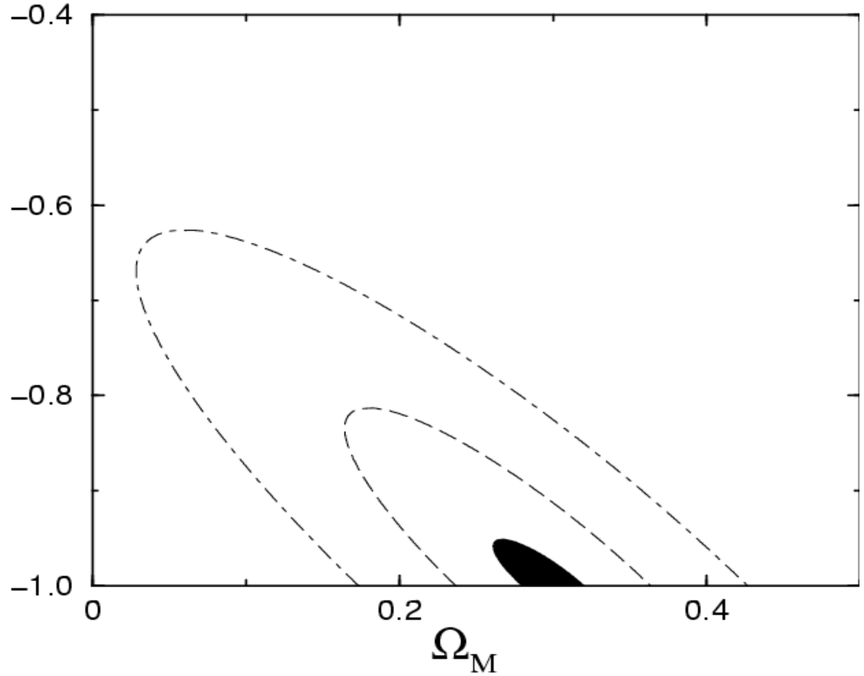


Dark Energy More volume → at moderate redshift

Counting Galaxy Dark Matter Halos with the DEEP Redshift Survey

10,000 galaxies at z ~ 1 with measured linewidths
(rotation speeds)

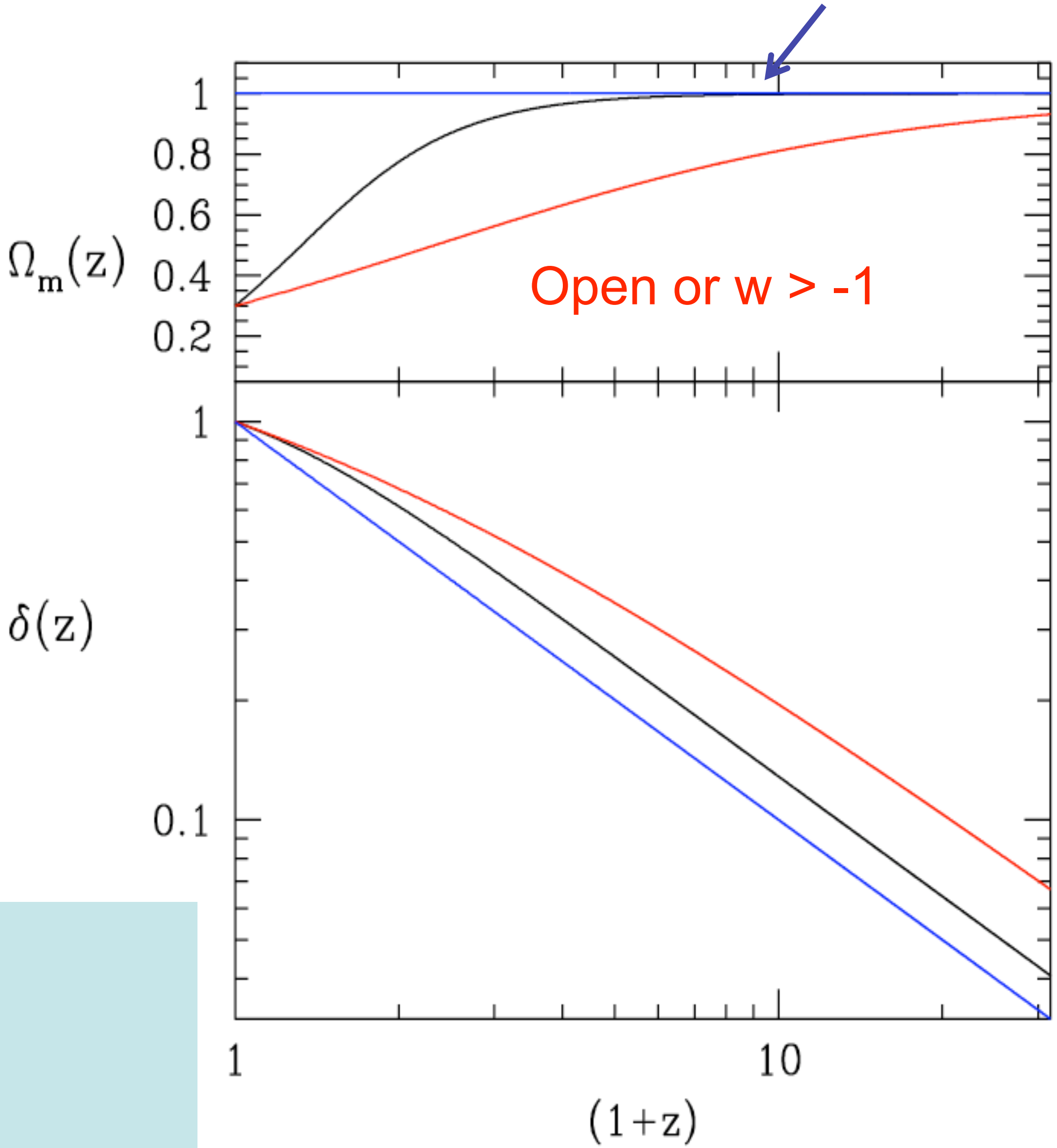




NB: must probe Dark Matter-dominated regions

Growth of Density Perturbations

Flat, matter-dominated



Holder 2005

Counting Clusters of Galaxies

- Sunyaev Zel'dovich effect
- X-ray emission from cluster gas
- Weak Lensing

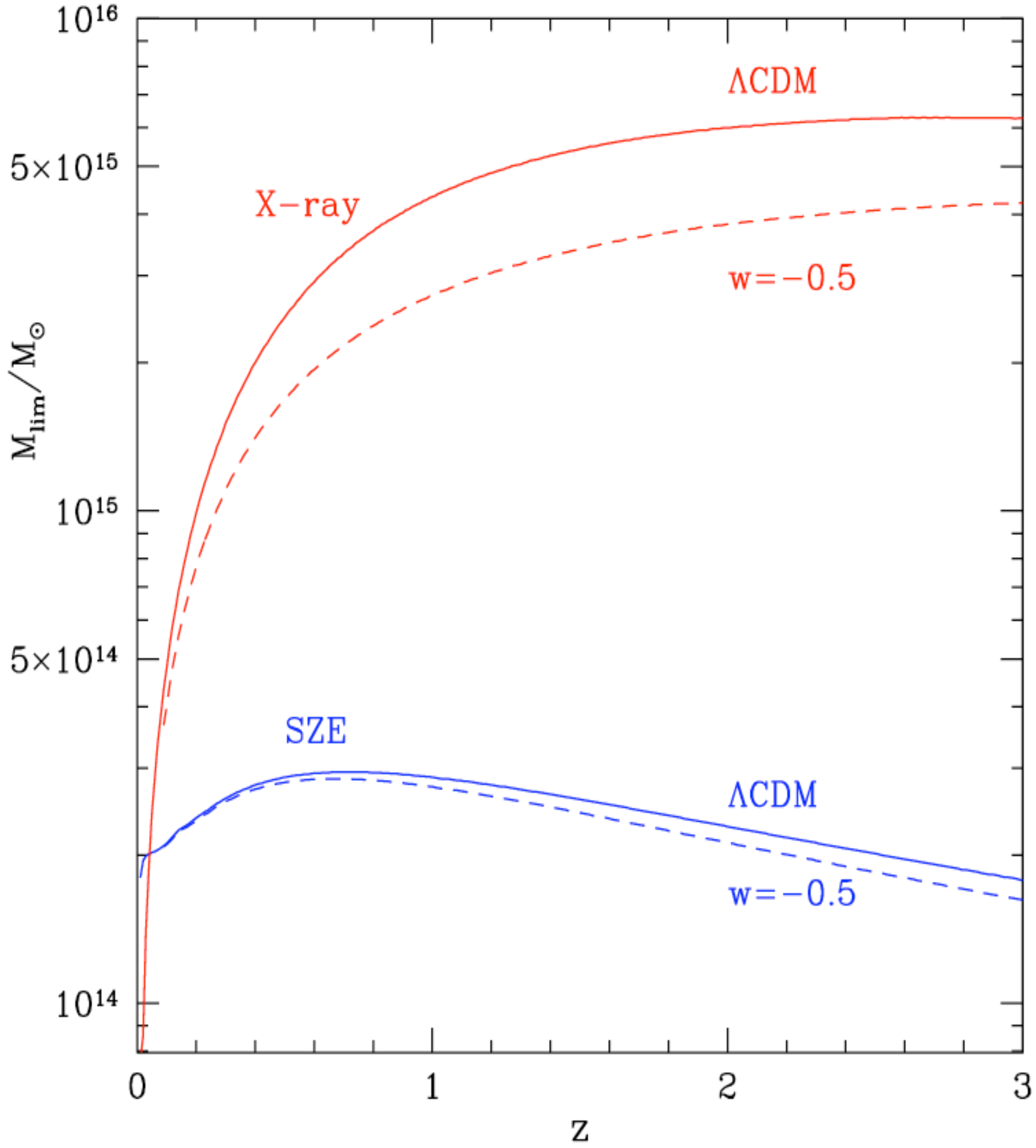
$$\frac{dN}{dz d\Omega}(z) = \frac{dV}{dz d\Omega}(z) \int_{M_{\min}(z)}^{\infty} dM \frac{dn}{dM}$$

Simulations:

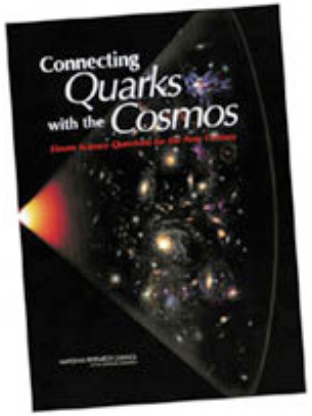
$$\frac{dn}{dM}(z,M) = 0.315 \frac{\rho_0}{M} \frac{1}{\sigma_M} \frac{d\sigma_M}{dM} \exp\left[-\left| 0.61 - \log(D_z \sigma_M) \right|^{3.8} \right]$$

growth factor

Detection Mass thresholds



Haiman,
Holder, Mohr 2008, 2011



Proposals for Tracking Dark Energy

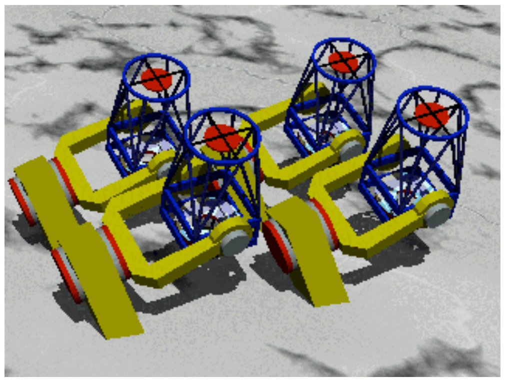
DoE/NASA initiated studies for a Joint Dark Energy space mission (JDEM, 2015+), also ESA is at work…

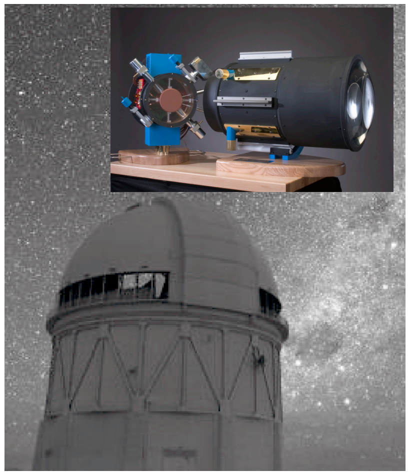
Contenders: SNAP, Destiny, JEDI, EUCLID, PLANCK, (SKA?)..

Shorter term initiatives on the ground (DoD/DoE/NSF):

Pan-STARRS (2008) Dark Energy Survey (2009), VISTA-Dark Camera (2011), WFMOS (2011), LSST (2012)..

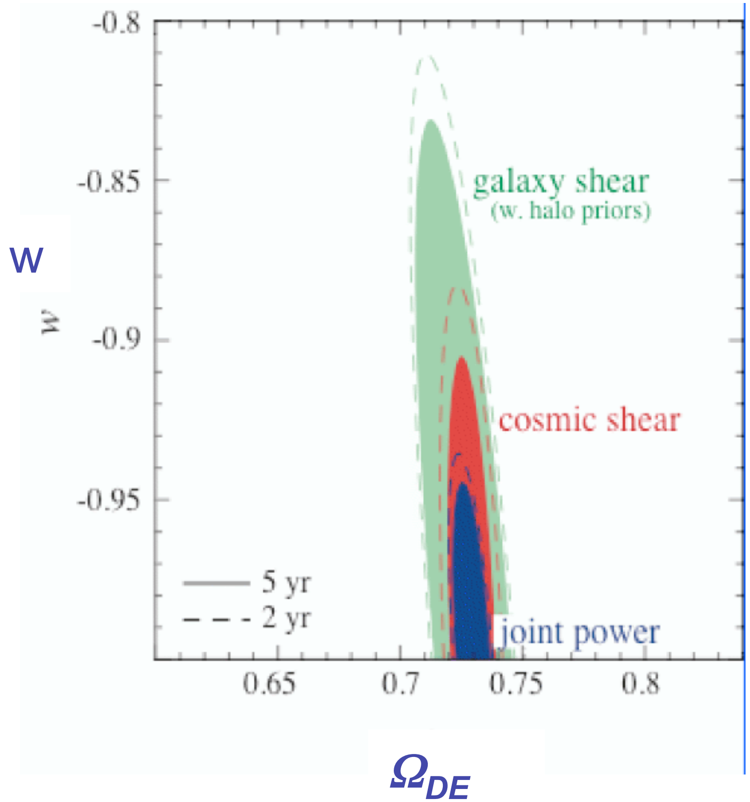
SKA
SQUARE KILOMETRE ARRAY



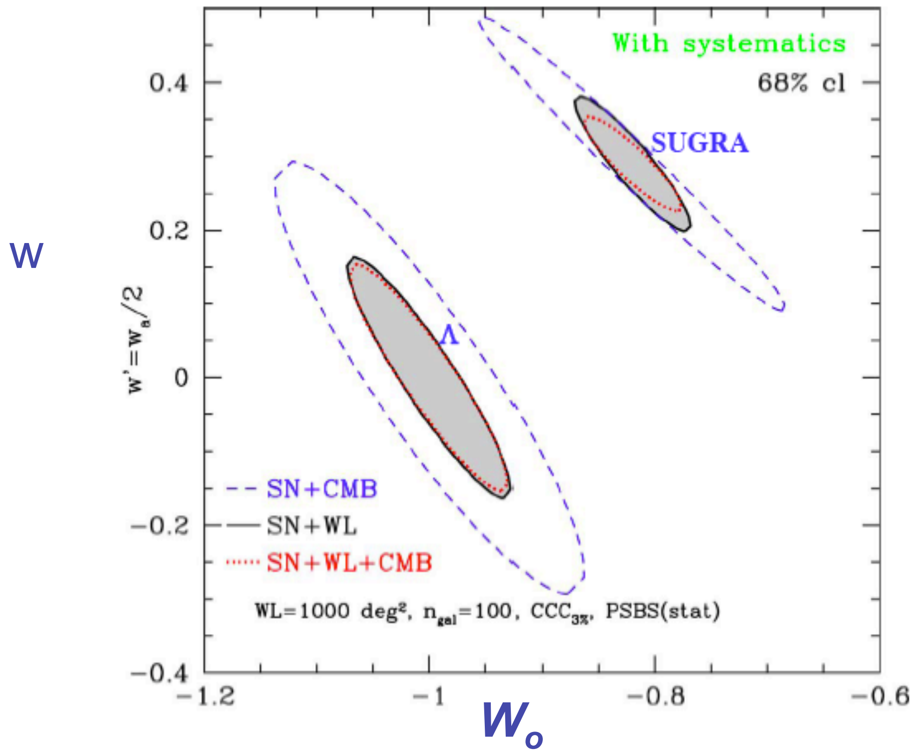


Dark Energy Strategy

- Initial goal: verify whether *w* = -1 (NB: precision depends on value)
- Next goal: combine measures at different z: is w ≠const
- Long term goal: track *w(z)* empirically



Dark Energy Survey (2009-13)



SNAP satellite (2015-2018)

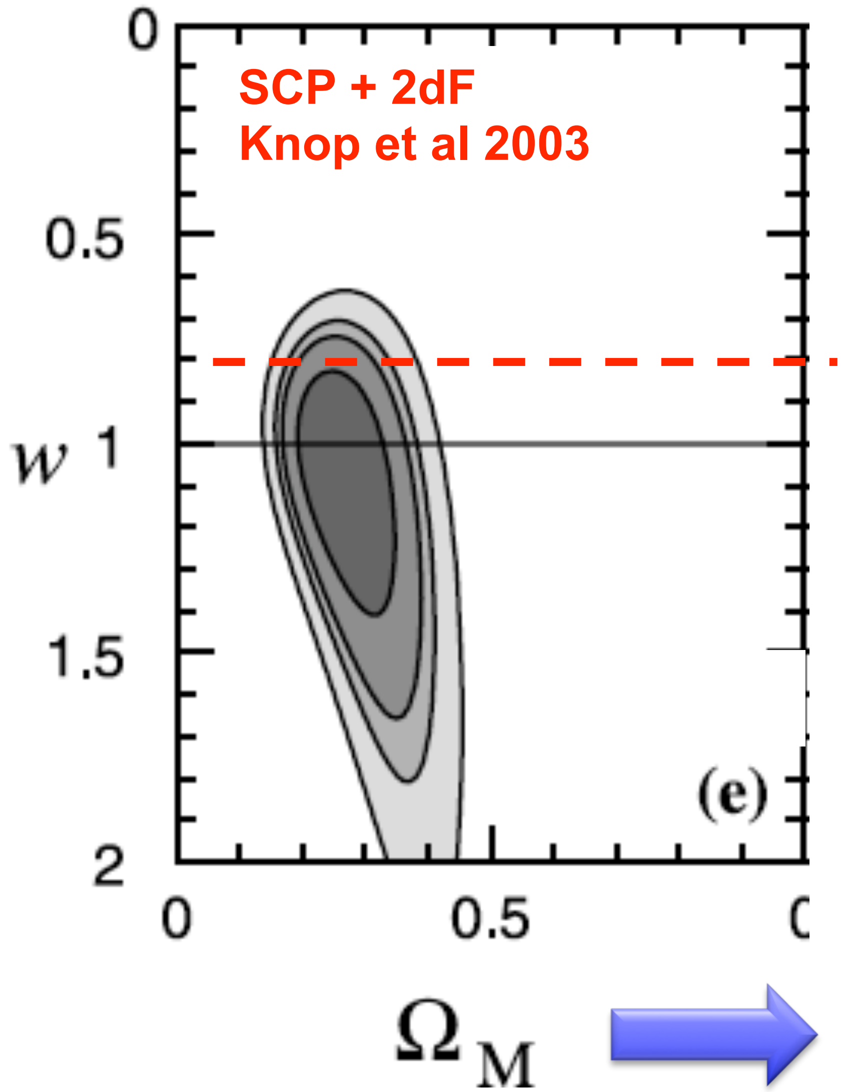
Dark Energy Equation of State from the SNeIa Hubble Diagram

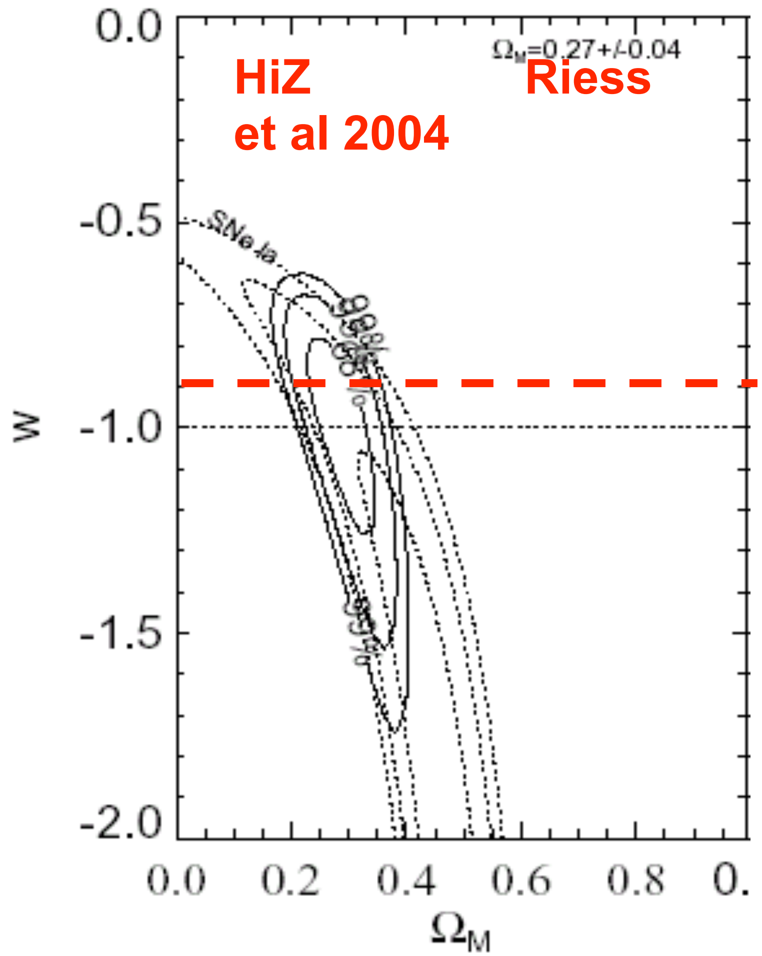
- A two fluid scenario : dark matter + dark energy
- Unknown equation of state (EoS) w(z)
- Assume a functional form for the EoS (motivated or not)
- Compute the luminosity function $d_L(z)$ as

$$d_L = \frac{1+z}{H_0} \sqrt{1+g} \int_1^{1+z} \left\{ g + \exp\left[3 \int_1^x w_Q(y) \frac{dy}{y} \right] \right\}^{-\frac{1}{2}} \frac{dx}{x^{\frac{3}{2}}}$$

- Fit to the SNeIa Hubble diagram
  - *Double integration over $w_Q(z)$*
  - *Similar degeneracy problem for other tests*

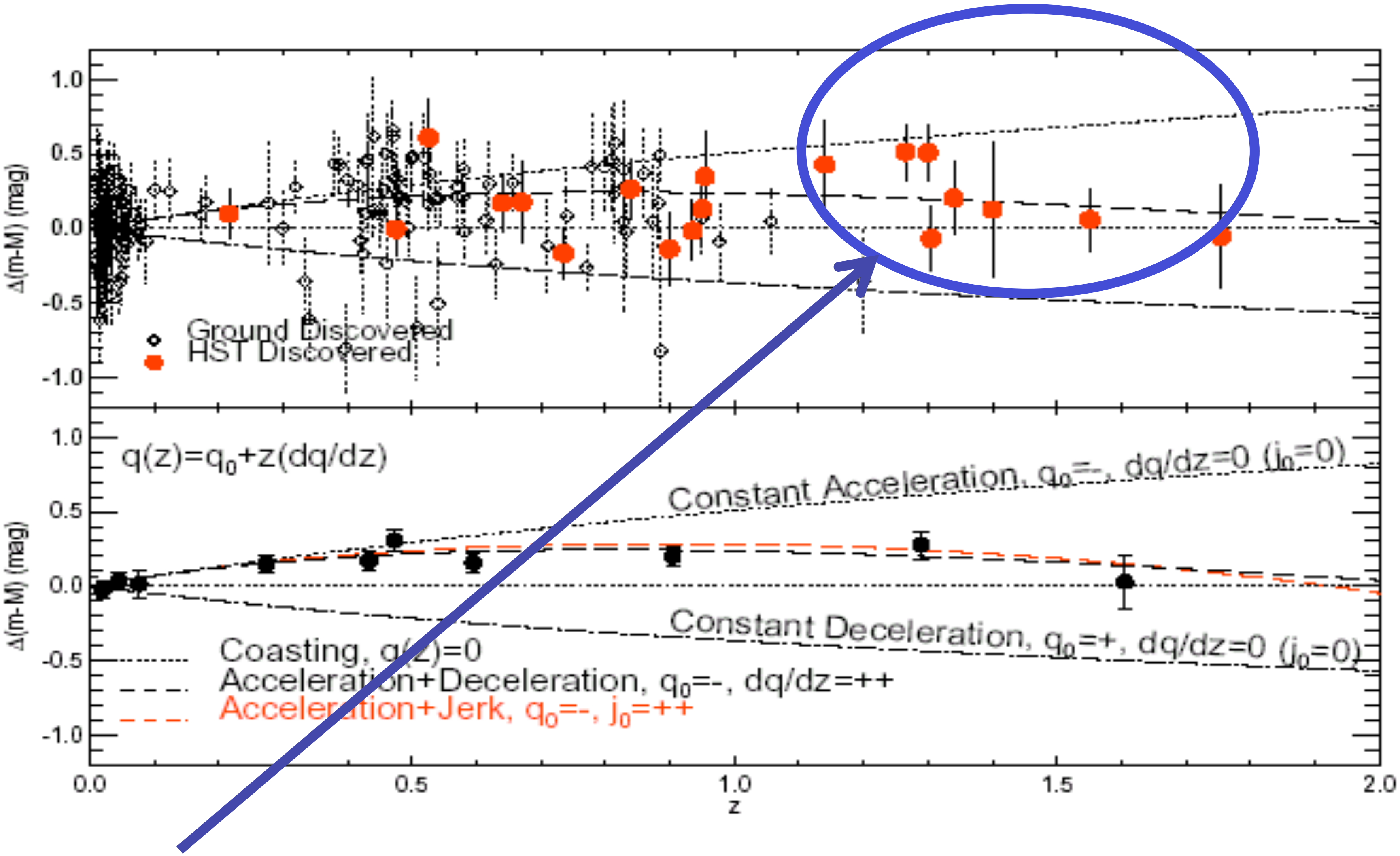
SNe Ia: early constraints on *w* + LSS data



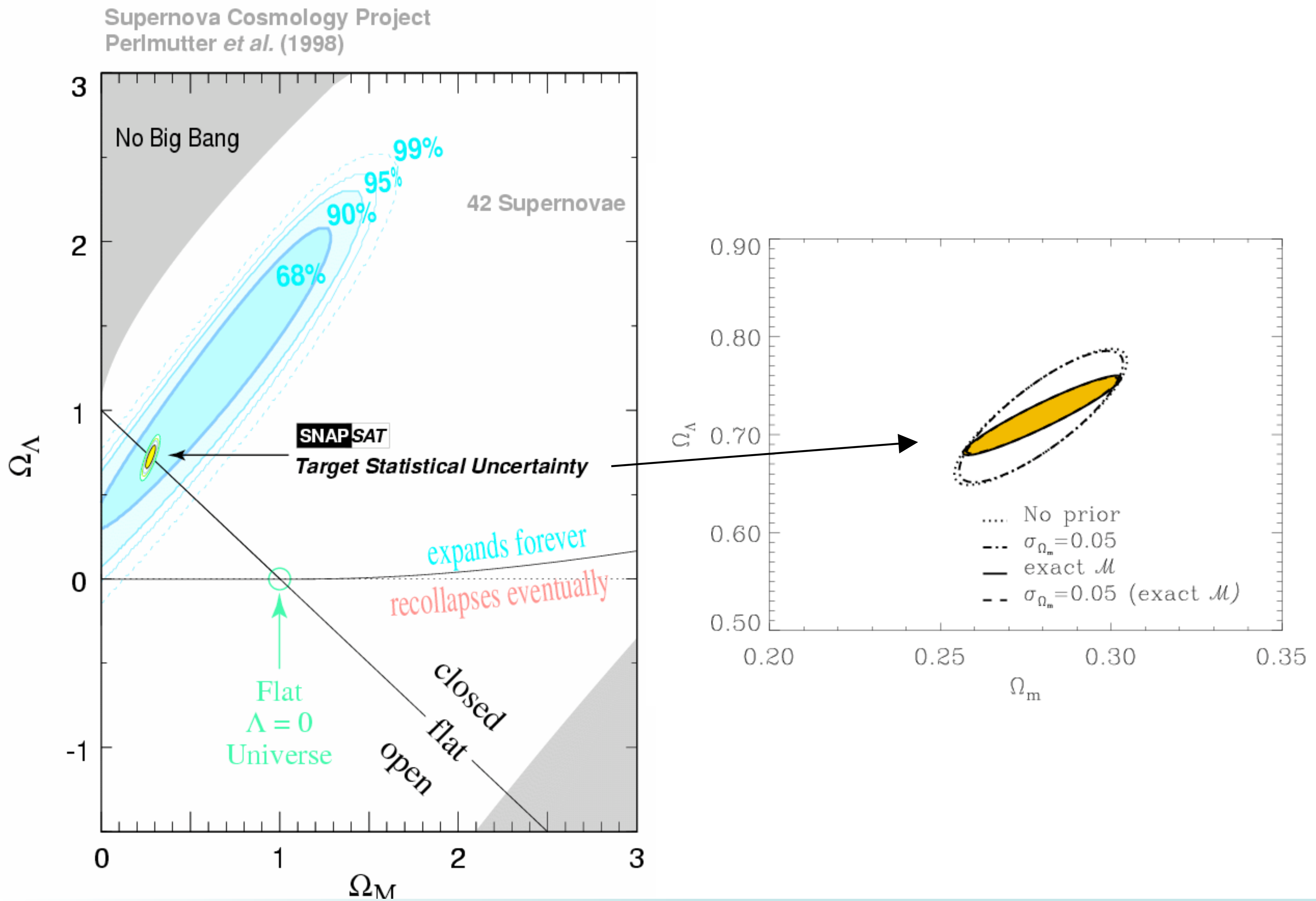


consistent with Einstein's Λ

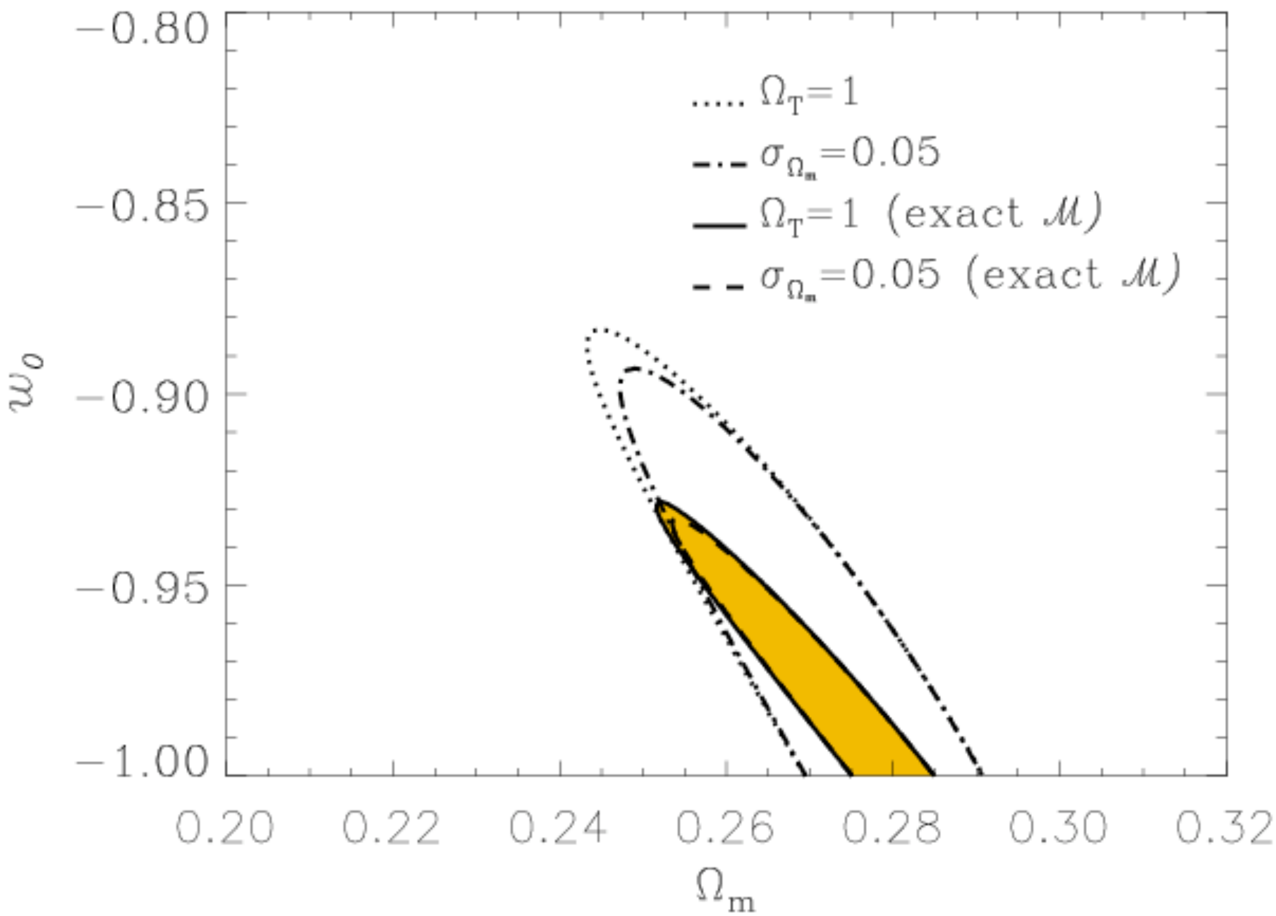
GOODS sample of z > 1 SNe (Riess et al 2010)



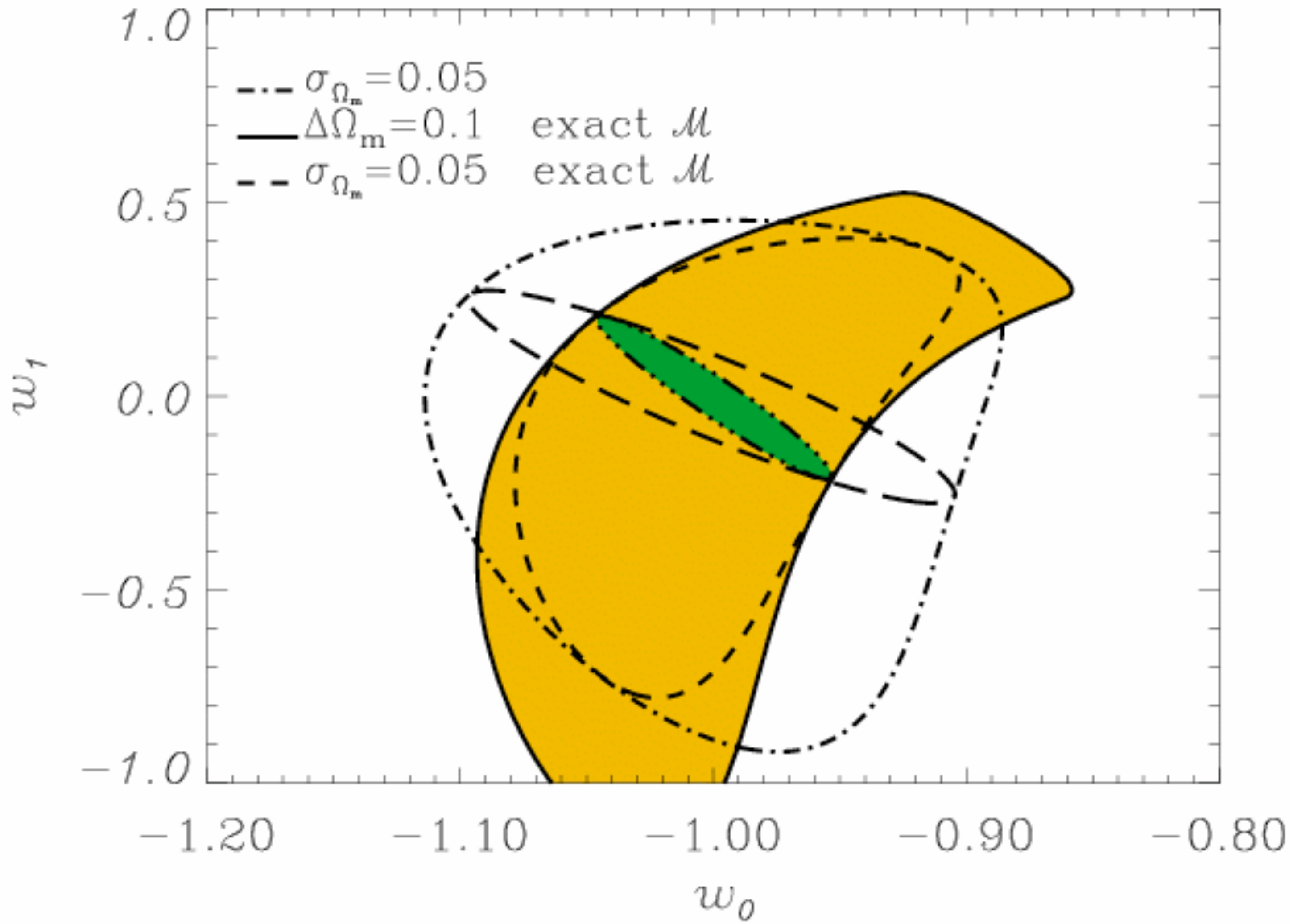
Interpretation depends crucially on UV spectrum


Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAP SAT
Target Statistical Uncertainty
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
ΩΛ
ΩM
No prior
σΩm=0.05
exact M
σΩm=0.05 (exact M)
Ωm

Projected SNAP Sensitivity to DE Equation of State

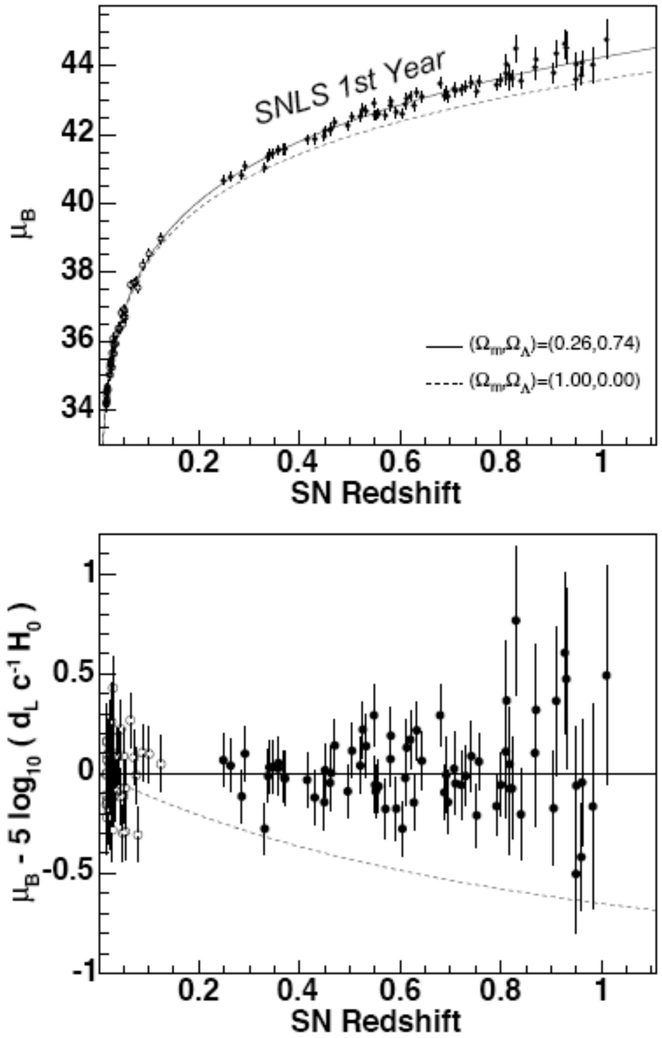


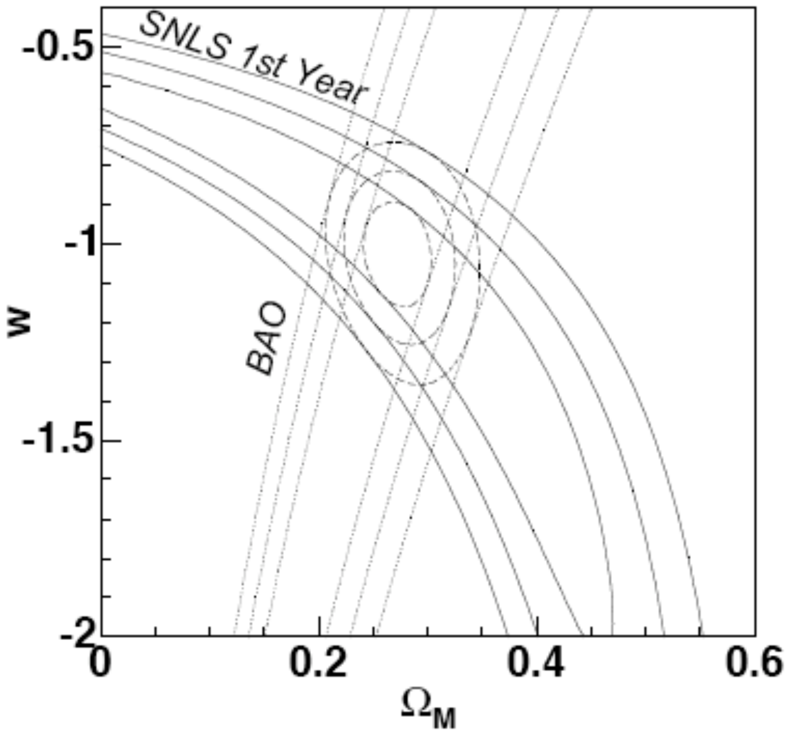
SNAP Sensitivity to Varying DE Equation of State



$w = w_0 + w_1 z + \ldots$

Results from CFHT SNLS





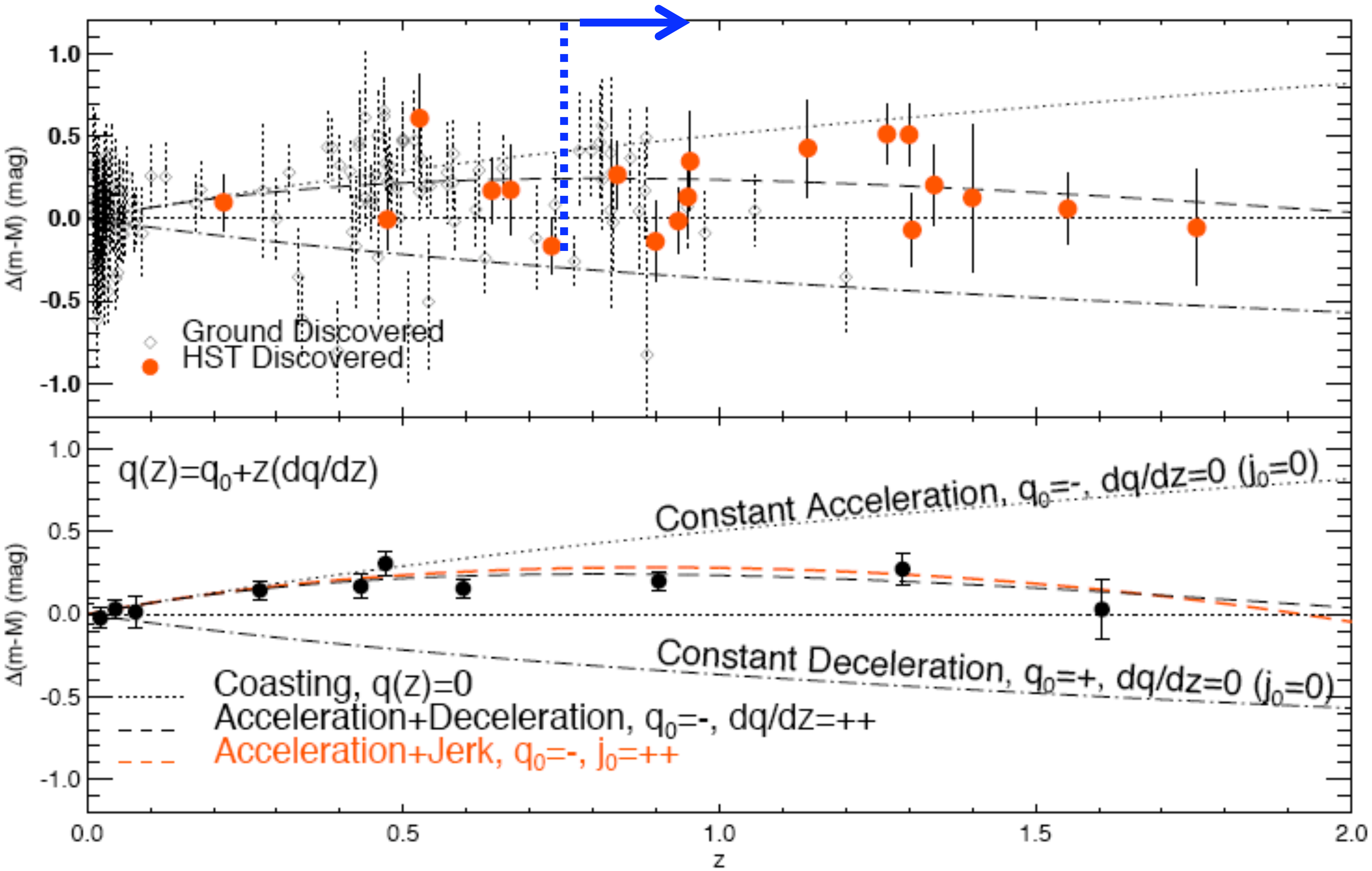
71 homogenously studied SNe Ia

$w = -1.023 \pm 0.090$

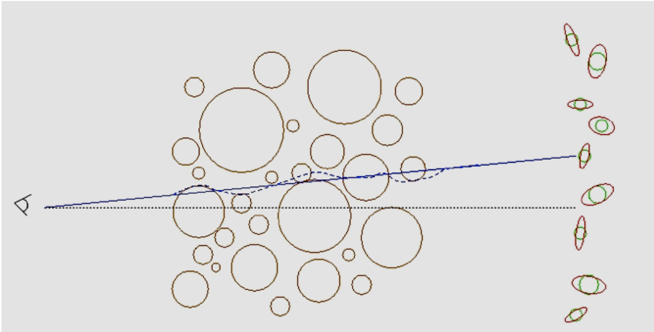
Astier et al 2007

What does this mean for precision work beyond z~1?

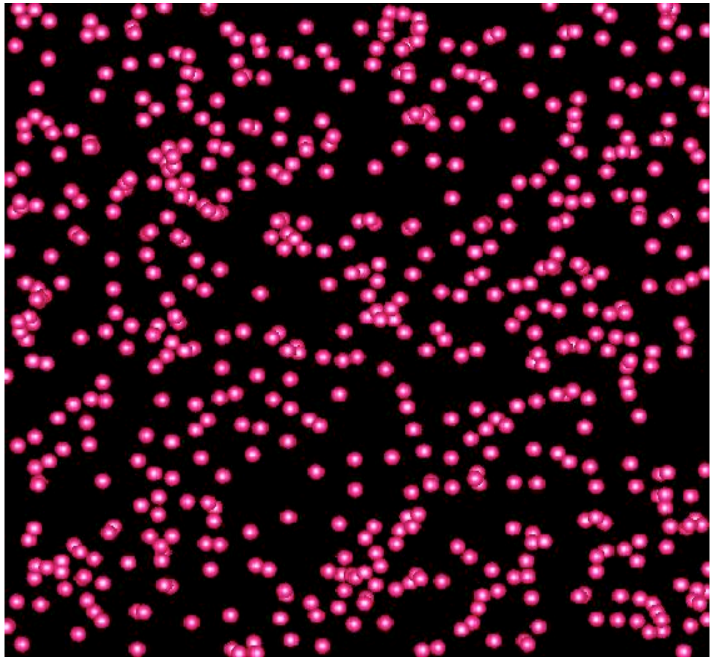
Beyond z~1, UV dispersion affects color k-correction



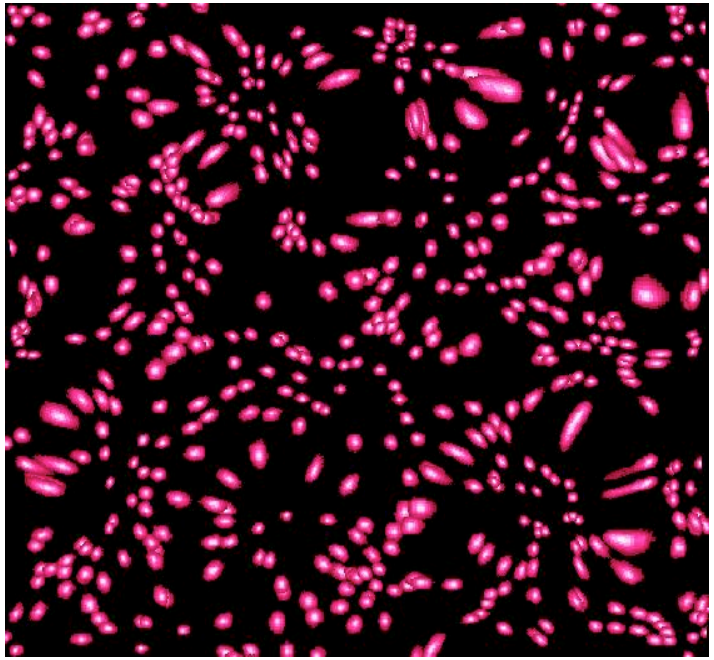
Weak Gravitational Lensing



Intervening dark matter distorts the pattern: various probes: shear-shear, g-shear etc



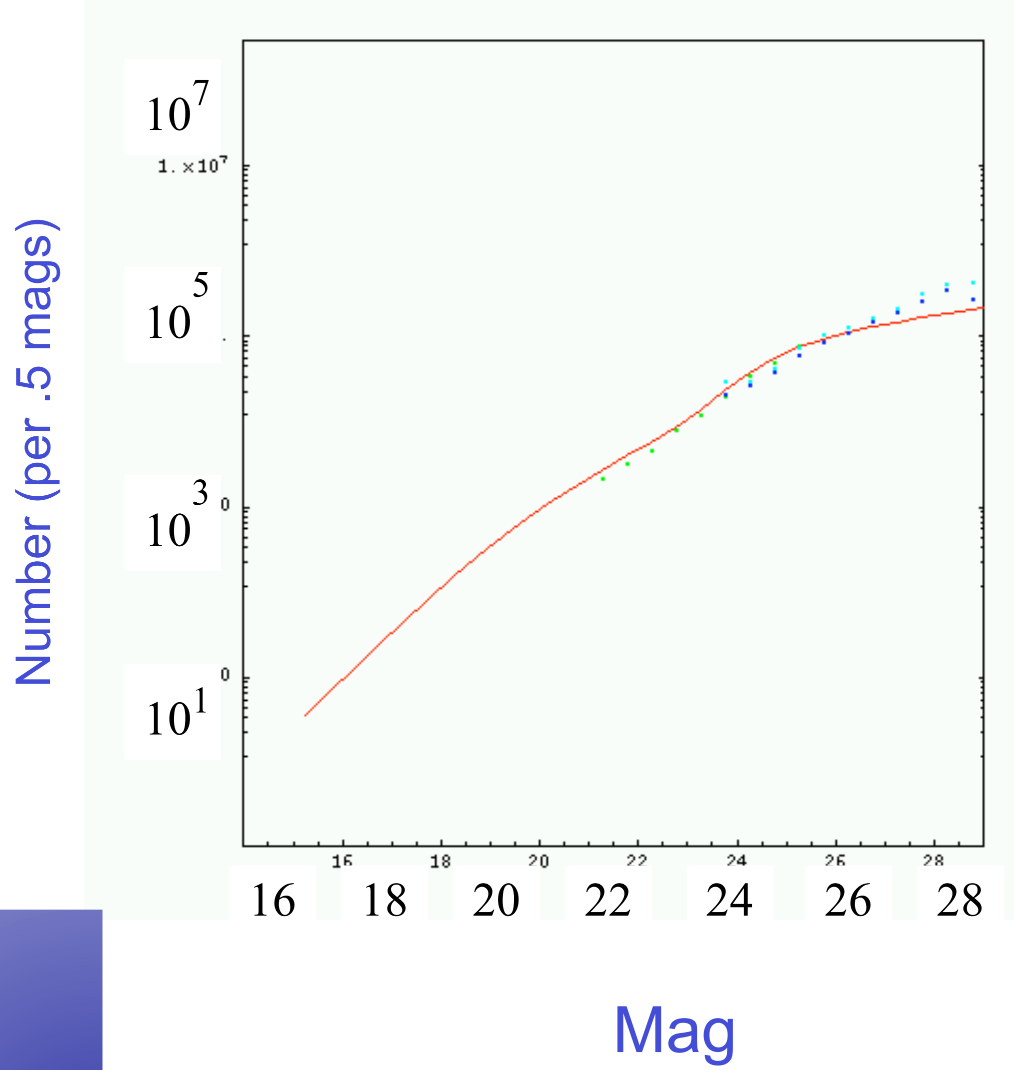
Unlensed



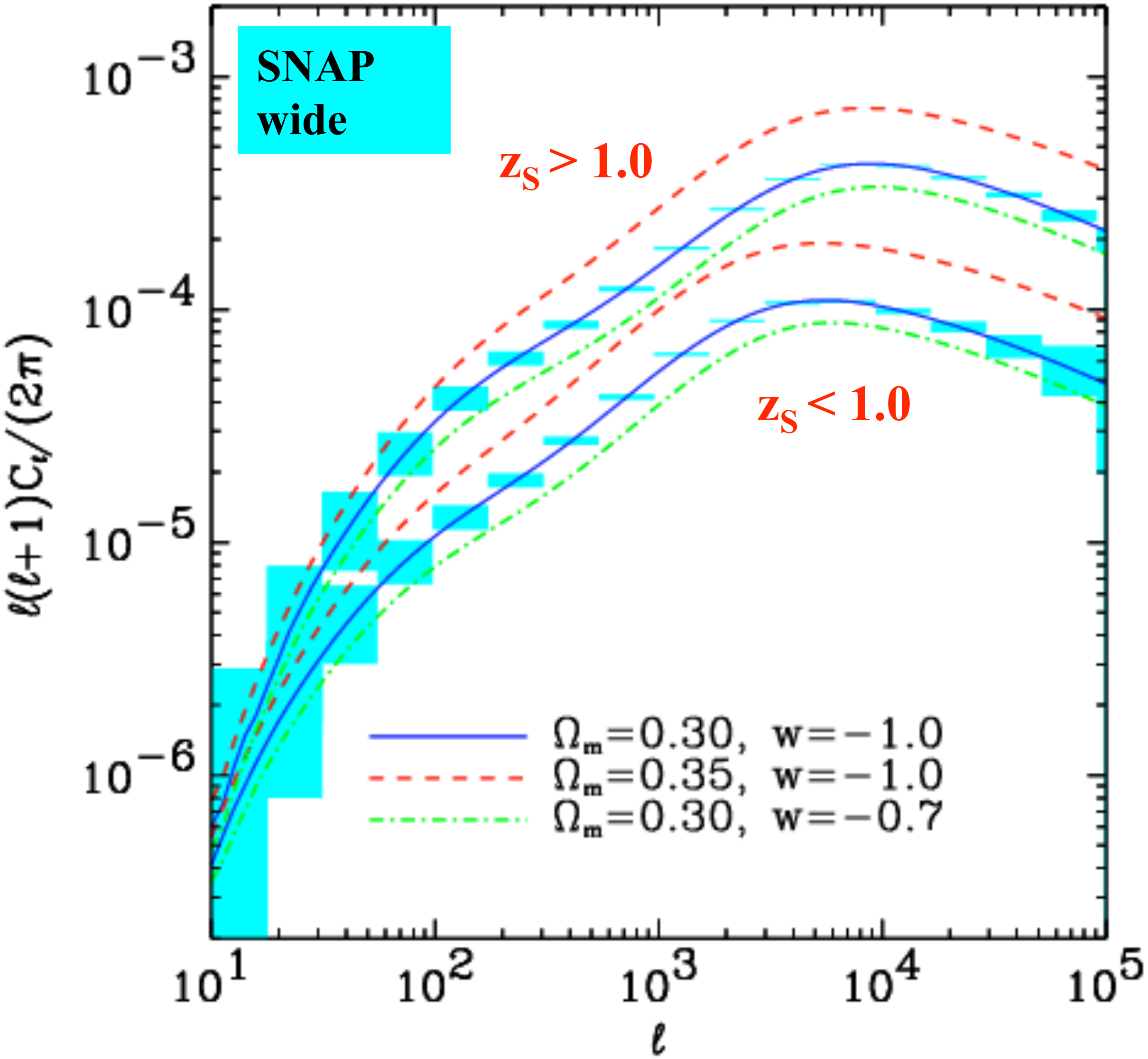
Lensed

Weak Lensing: Number Cts of Background Galaxies

Points: HubbleDeep Field
Curve: extrapolation
From SDSS luminosity
Function w/o mergers



Evolution of the DM Power Spectrum



Growth of DM power spectrum is particularly sensitive to dark energy and *w*.

Via redshift binning of background galaxies, it is possible to constrain *w* independently of SNe

As SNe probe a(t) directly, so power spectrum of DM probes evolution of structure G(t)

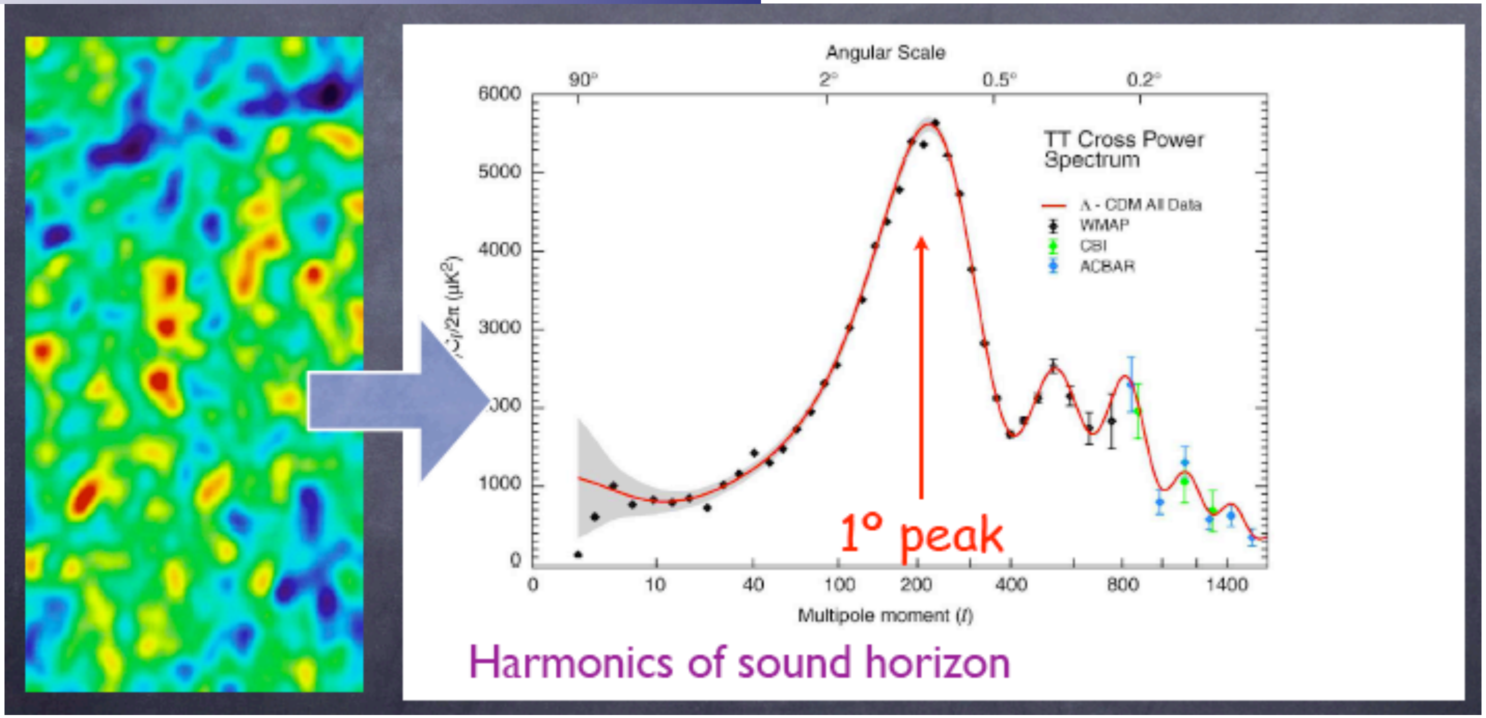
Is Weak Lensing Going to Cut It..?

- Everyone agrees: WL is a promising probe
- Many believe it is more fundamentally reliable than SNeIa
- Need calibration of shear to 10^{-3}; systematics to $10^{-3.5}$
- Currently best methods 10 x worse
- OK if we *understand* limitations - not clear we do, so much work is needed in next few years

Baryonic Features in the Large Scale

Peebles & Yu 1970;

Sunyaev & Zel'dovich 1970

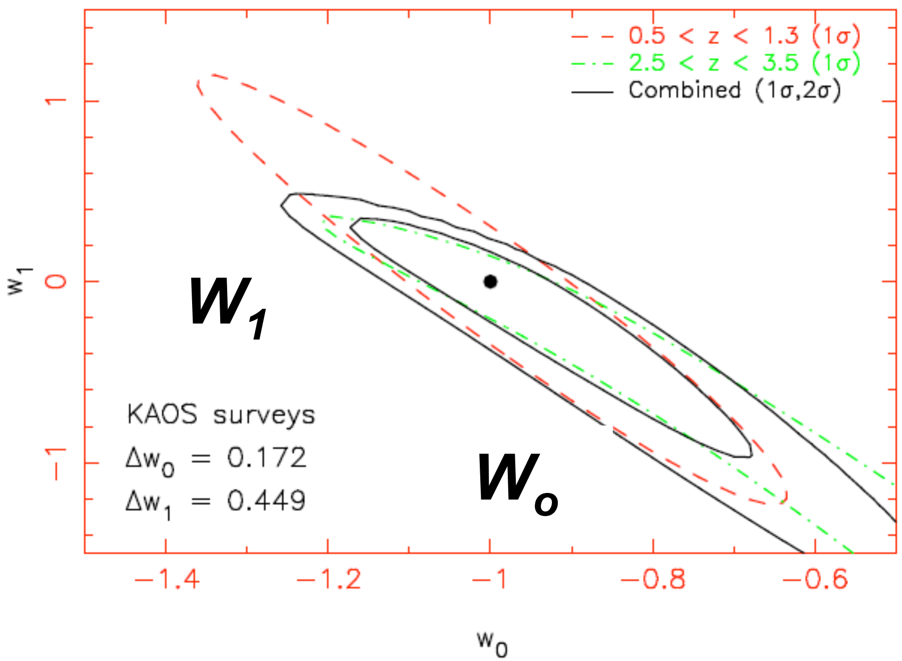


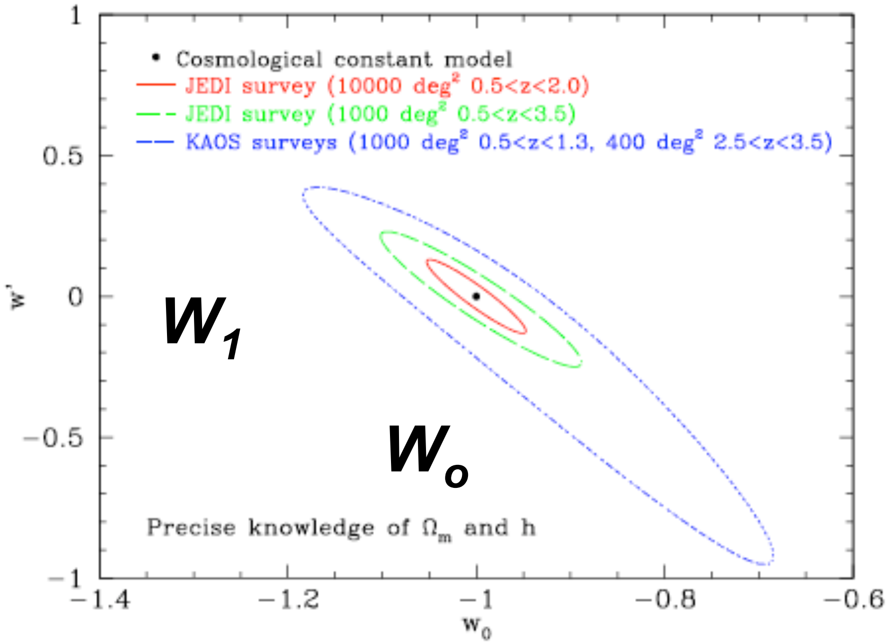
Weak residual of acoustic peaks will be seen in galaxy distribution. Today, for flat geometry it should be at:

$$\lambda_s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_r} \frac{c_s}{(a + a_{eq})^{1/2}} da \quad = 150 \text{ Mpc}$$

Confirmed at 3-4σ by 2dF (Cole et al 2004) and SDSS (Eisenstein 2005

Baryon Oscillation Probes





WFMOS being considered for Subaru 8m telescope

JEDI: contender for JDEM

Cryogenic 2m + 1deg^2 field + microshutters placed at L2

Hα survey of 10^4deg2 z~2; 10^3deg, z~4

1000 deg^2 N=10^6g 0.5<z<1.3

400 deg^2 N=6.10^5g 2.5<z<3.5

4000 fibers, 200 clear nights

Furthermore we can use time-based measurements using the LOOKBACK TIME

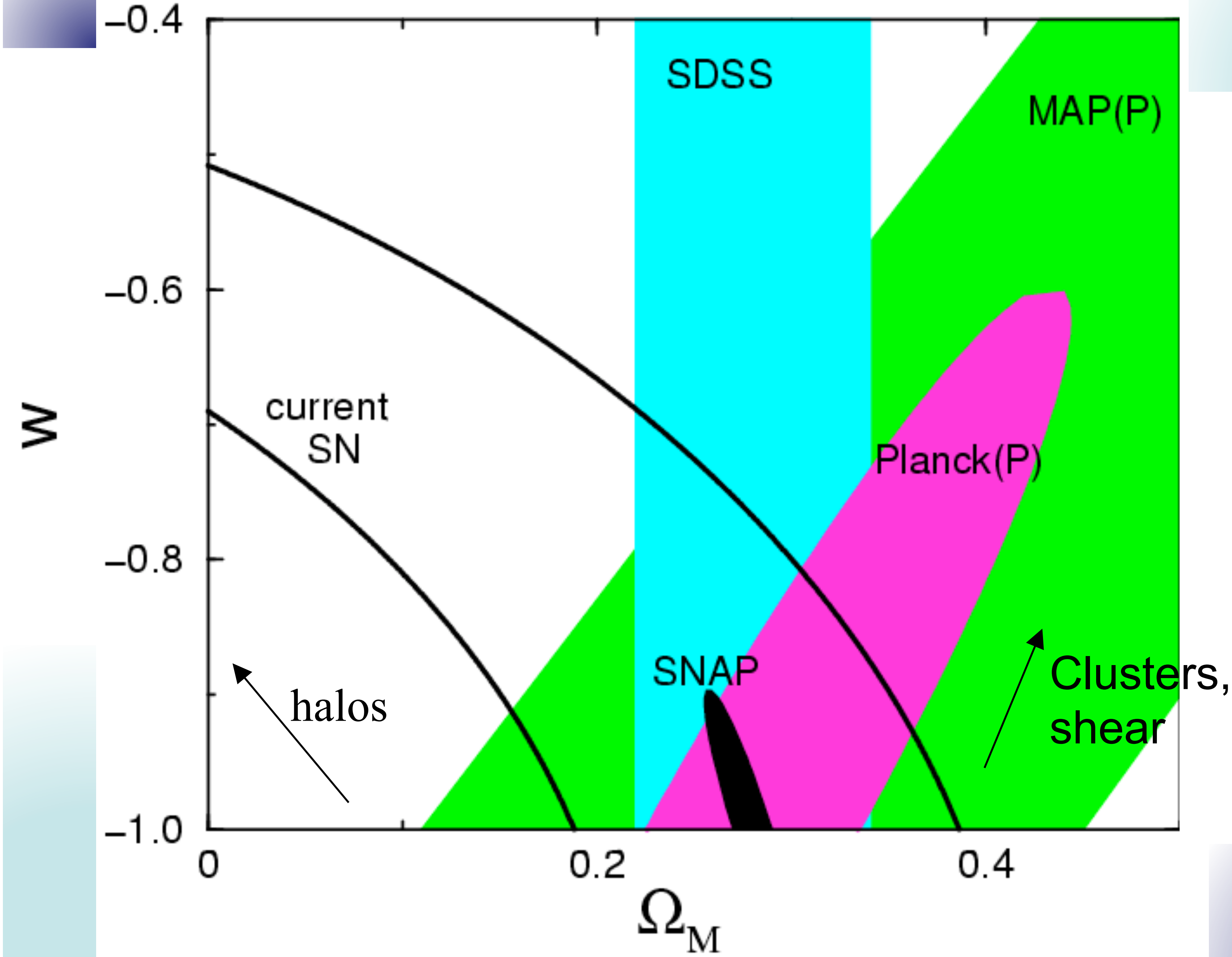
$$t_{lb} = \frac{1}{H_0}\int_0^z \frac{dz}{(1+z)^2(1+2q_0 z)^{1/2}}$$

Light travel time from an object at redshift z

$$df = t_0^{obs} - t_{lb}(z_F)$$

The estimated age of the Universe today minus the lb-time gives the delay factor related to the ignorance on the formation redshift z_F of the object.
We used galaxy clusters, radio-galaxies and quasars.

S.C., V. Cardone, M. Funaro, S. Andreon PRD 70 (2004) 123501
S.C., P. Dunsby, E. Piedipalumbo, C. Rubano A&A 472 (2007) 51



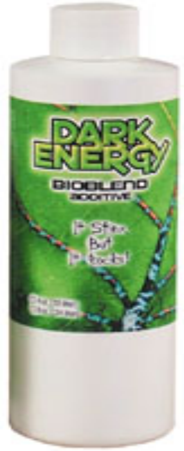
−0.4
−0.6
−0.8
−1.0
w
0
0.2
0.4
Ω_M
SDSS
MAP(P)
current
SN
Planck(P)
SNAP
halos
Clusters,
shear

Warning !!!

Constraint contours depend on priors assumed for other cosmological parameters!

Conclusions depend on the projected state of knowledge/ignorance !

Conclusions



- Dark energy is here to stay:

  Does it represent the new cosmological frontier?'

- Its characterization is largely the province of the z<3 universe.
- CMBR measures will not be sufficient
- There is a sound incremental approach: $w \neq -1 \rightarrow w \neq const \rightarrow w(z)$
- Observers are promoting 3 probes:

  SNe,WL & BAO; probably need > 1 method spanning $0<z<3$

- Observationally there are formidable challenges (GRBs?)
- SKA could play a major role as **SURVEY RADIO TELESCOPE**
- It is going to take a long long time - but we will eventually get there!

In conclusions …we need…

- Knowledge of DE at fundamental level (Casimir?)
- Versatile and precise physical models
- Removing degeneracies in the parameter space
- Good fit with existing observations (Universe Age, SNeIa, Angular Size-redshift, CMBR,…)
- Large bulk of data (SKA is particularly WELCOME!)

further developments…suggest…

- to explore the full parameter space (a, b, z_s, H_0, $q_{0....}$)
- proposals for new distance and time indicators (GRBs?)
- investigations at low and high redshifts

WORK IN PROGRESS!!