DARK ENERGY MODELS TOWARD OBSERVATIONAL TESTS AND DATA

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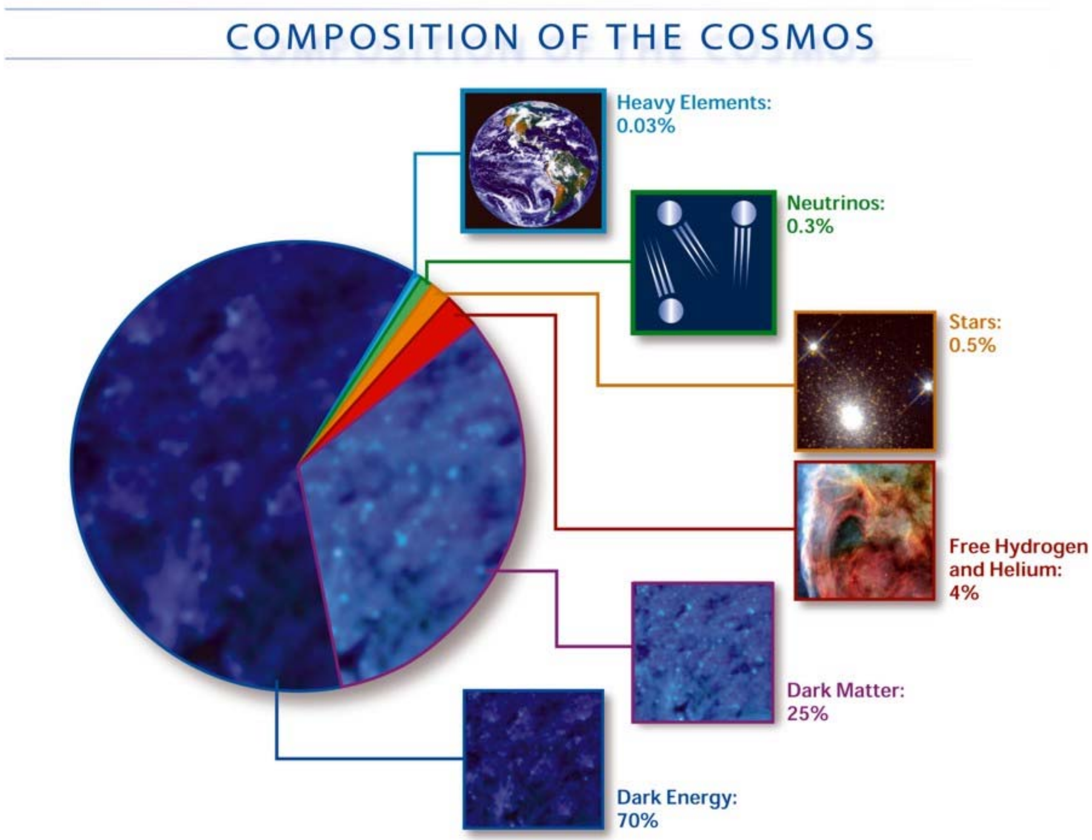
- The content of the universe is, up today, absolutely unknown for its largest part. The situation is very "DARK" while the observations are extremely good!



Status of Art: DE and DM come out from the Observations!

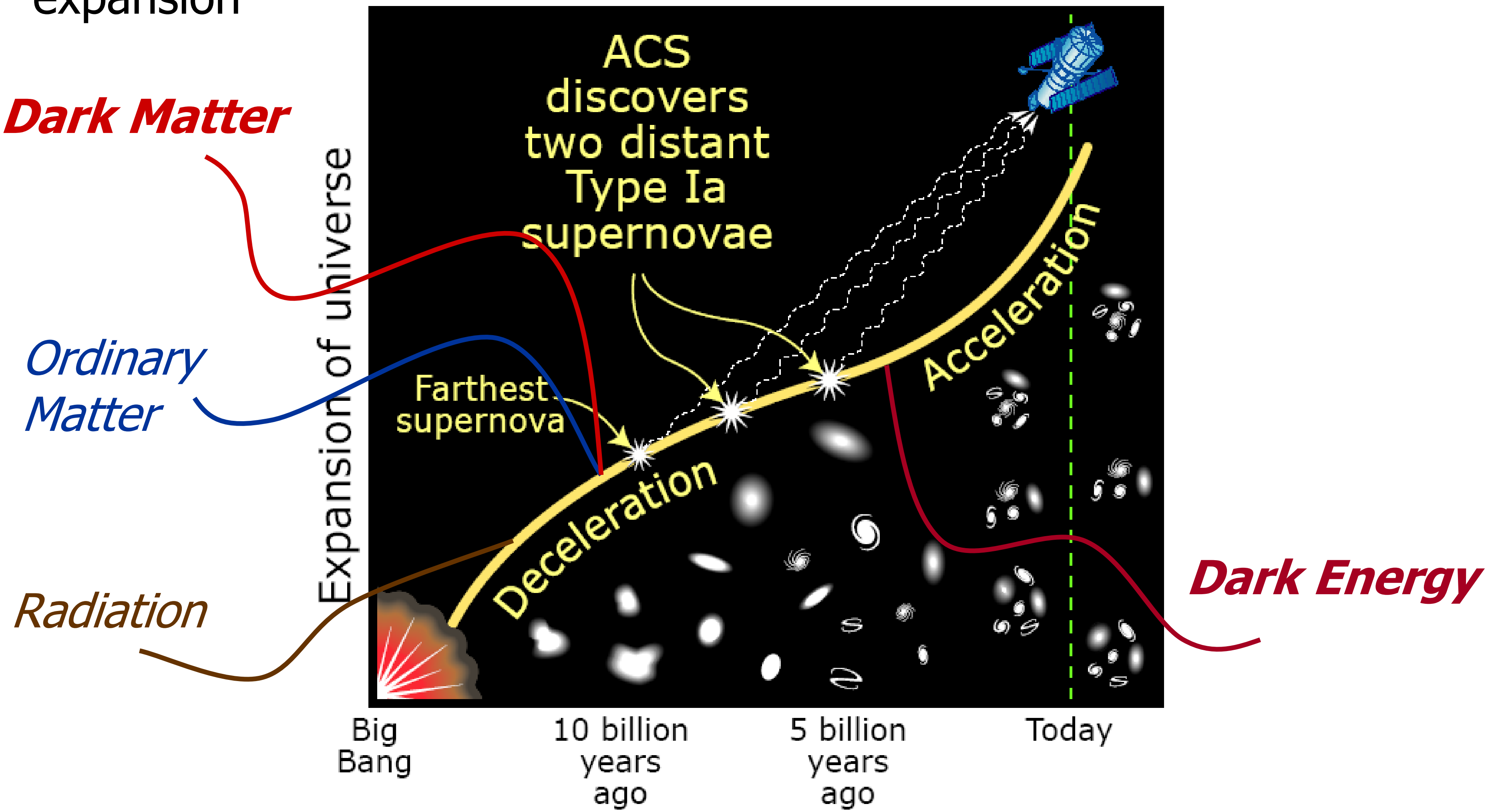
COMPOSITION OF THE UNIVERSE					
MATERIAL	REPRESENTATIVE PARTICLES	TYPICAL PARTICLE MASS OR ENERGY (ELECTRON VOLTS)	NUMBER OF PARTICLES IN OBSERVED UNIVERSE	PROBABLE CONTRIBUTION TO MASS OF UNIVERSE	SAMPLE EVIDENCE
Ordinary ("baryonic") matter	Protons, electrons	10^6 to 10^9	10^{78}	5%	Direct observation, inference from element abundances
Radiation	Cosmic microwave background photons	10^{-4}	10^{87}	0.005%	Microwave telescope observations
Hot dark matter	Neutrinos	≤ 1	10^{87}	0.3%	Neutrino measurements, inference from cosmic structure
Cold dark matter	Supersymmetric particles?	10^{11}	10[illegible]	25%	Inference from galaxy dynamics
Dark energy	"Scalar" particles?	10^{-33} (assuming dark energy comprises particles)	10^{118}	70%	Supernova observations of accelerated cosmic expansion

95%!

Unknown!!

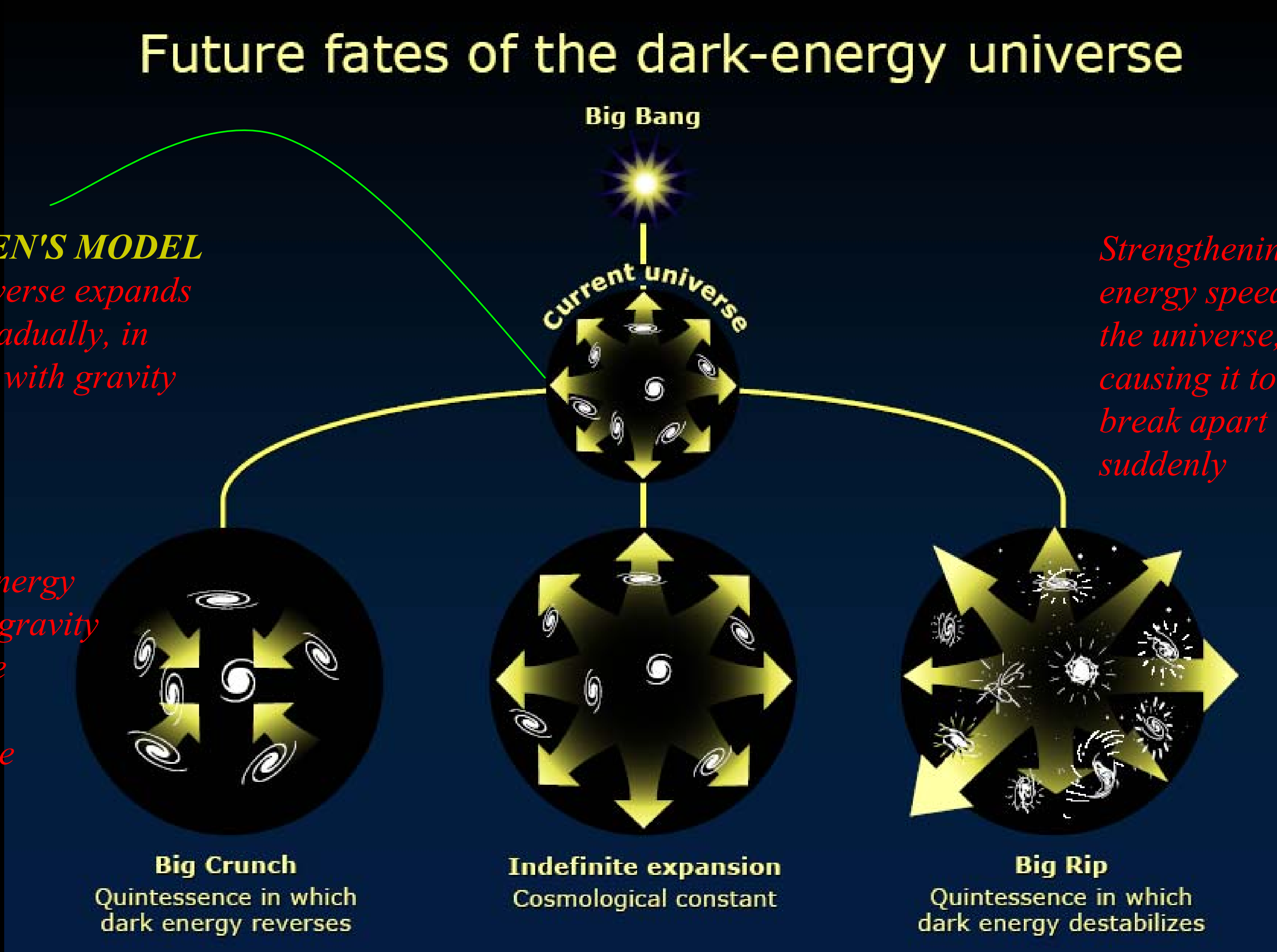
The Observed Universe Evolution

- Universe evolution seems characterized by different phases of expansion



EINSTEN'S MODEL

The universe expands more gradually, in balance with gravity



Strengthening dark energy speeds up the universe, causing it to break apart suddenly

As dark energy weakens, gravity causes the universe to collapse

Possible theoretical answers

DARK MATTER

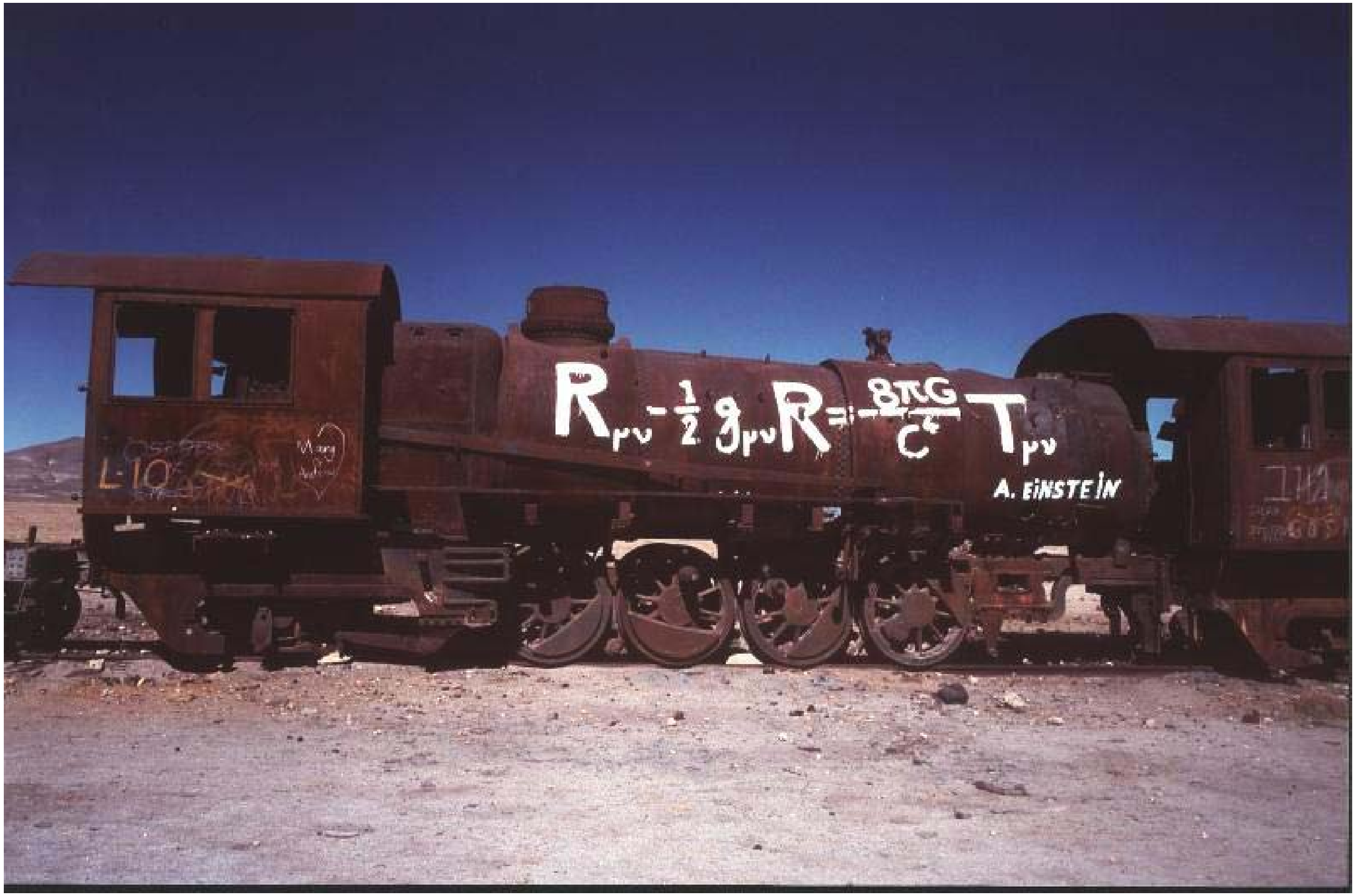
- ✓ Neutrinos
- ✓ WIMPs
- ✓ Wimpzillas, Axions, the "particle forest".....
- ✓ MOND
- ✓ MACHOs
- ✓ Black Holes
- ✓ ......

DARK ENERGY

- ✓ Cosmological constant
- ✓ Scalar field Quintessence
- ✓ Phantom fields
- ✓ String-Dilaton scalar field
- ✓ Braneworlds
- ✓ Unified theories
- ✓ New Law of Gravity
- ✓ ....

Alternatively:

Are extragalactic observations and cosmology probing the breakdown of General Relativity at large (IR) scales?



The problem could be reversed

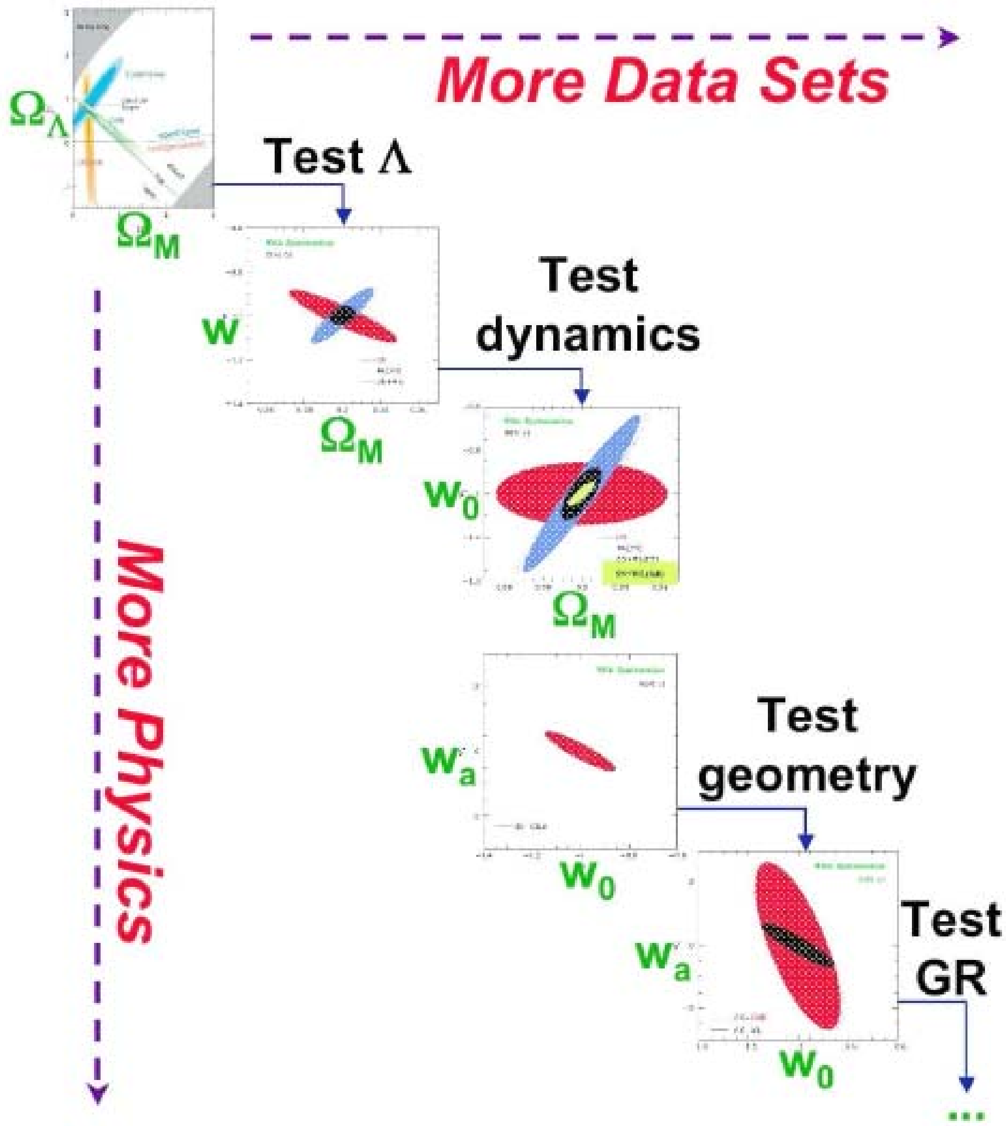
Up to now, we are able to observe and test only baryons, radiation, neutrinos and gravity

Dark Energy and Dark Matter as “shortcomings” of GR. *Results of flawed physics?*

The “correct” theory could be derived by matching the largest number of observations at ALL SCALES!

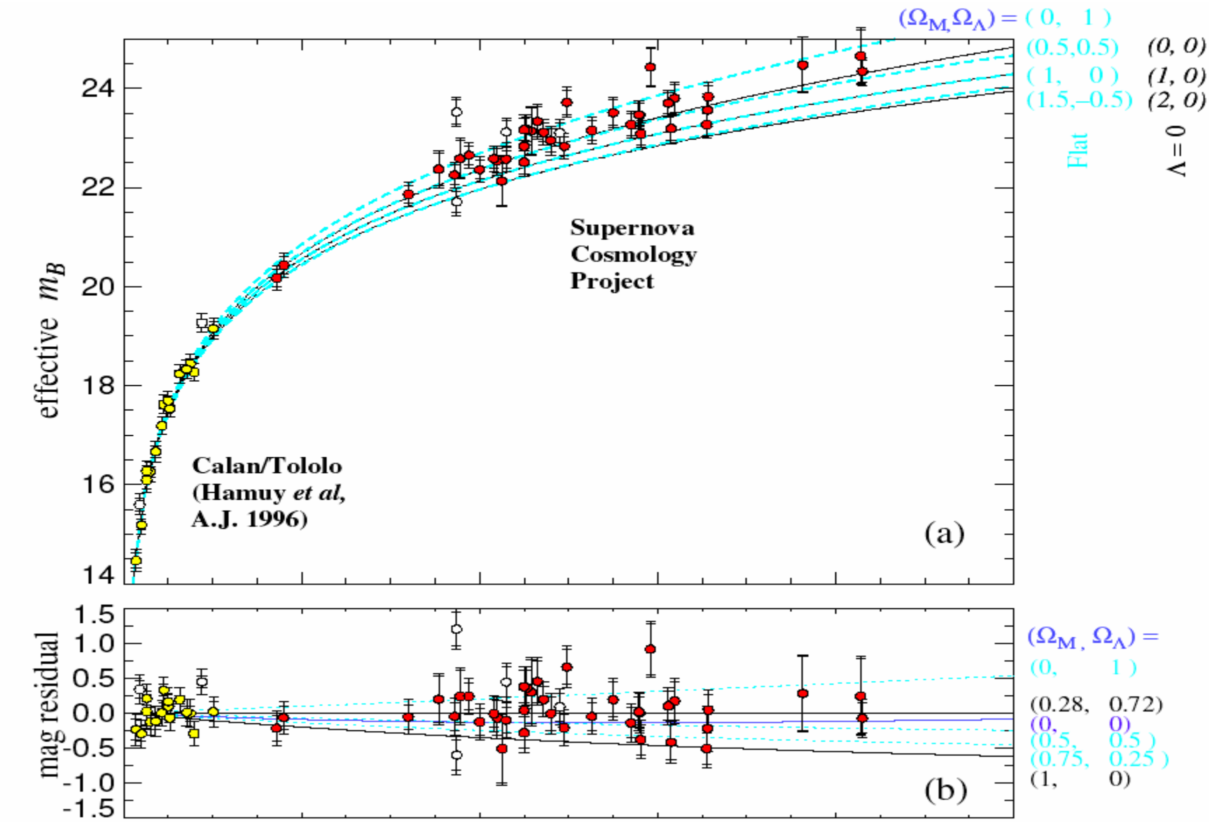
*Accelerating behaviour (DE) and dynamical phenomena (DM) as the **EFFECTS** of a new theory?*

Incremental Exploration of the Unknown



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).



- ✓ Status of Art: After 1998, more and more data have been obtained confirming this result. Combining SNeIa data with other observations and in particular with data coming from CMBR experiments (COBE, MAXIMA, BOOMERANG, WMAP) we have, up today, a ***"best fit"*** universe which is filled with about 30% of matter (dark and baryonic) and about 70% of dark energy, a component, in principle, different from the standard dark matter. Dark Energy is always characterized by a negative pressure and does not give rise to clustered structures.
- ✓ The most important consequence of this result is that our universe is in a phase of accelerating expansion

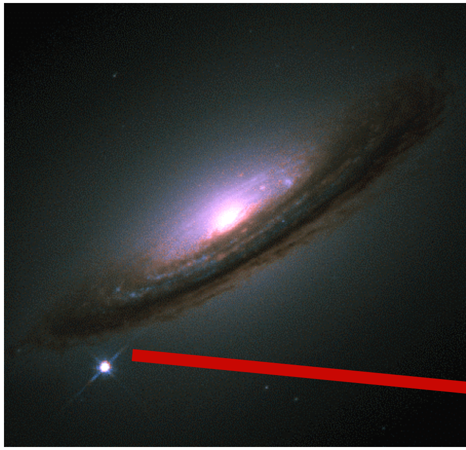
$$\boxed{q_0 = -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}(3\gamma + 1)\Omega_M - \Omega_\Lambda}$$

$$\Omega = \frac{\rho}{\rho_C}$$

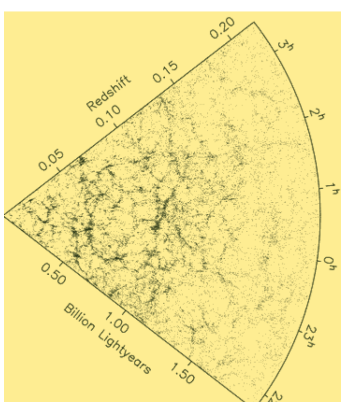
$$\rho_C = \frac{3H^2}{8\pi G}$$

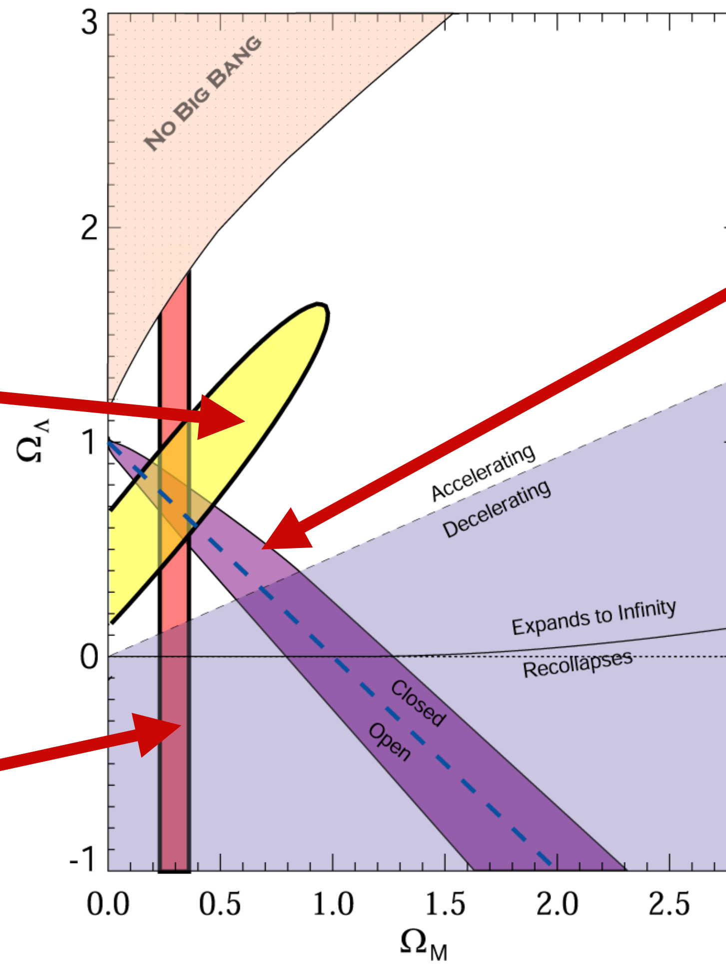
Dark Energy is here to stay…

SNe Ia

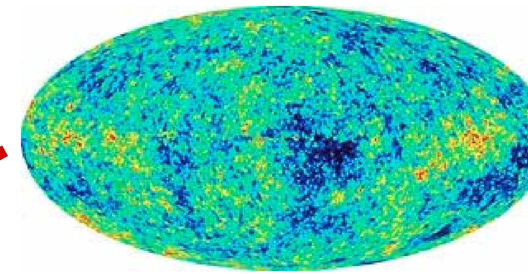


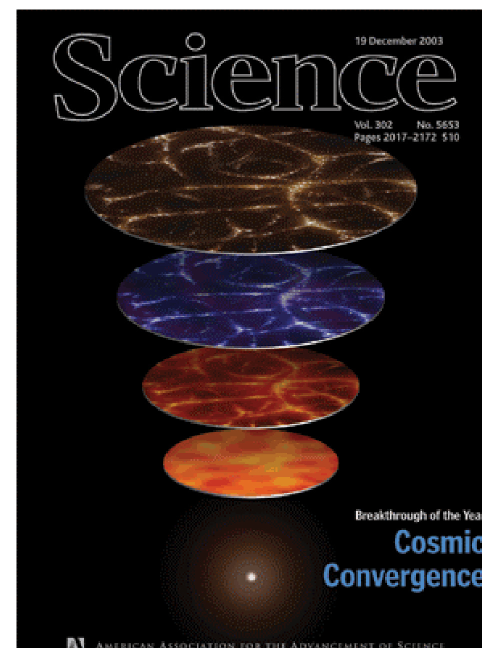
LSS





CMB(WMAP)

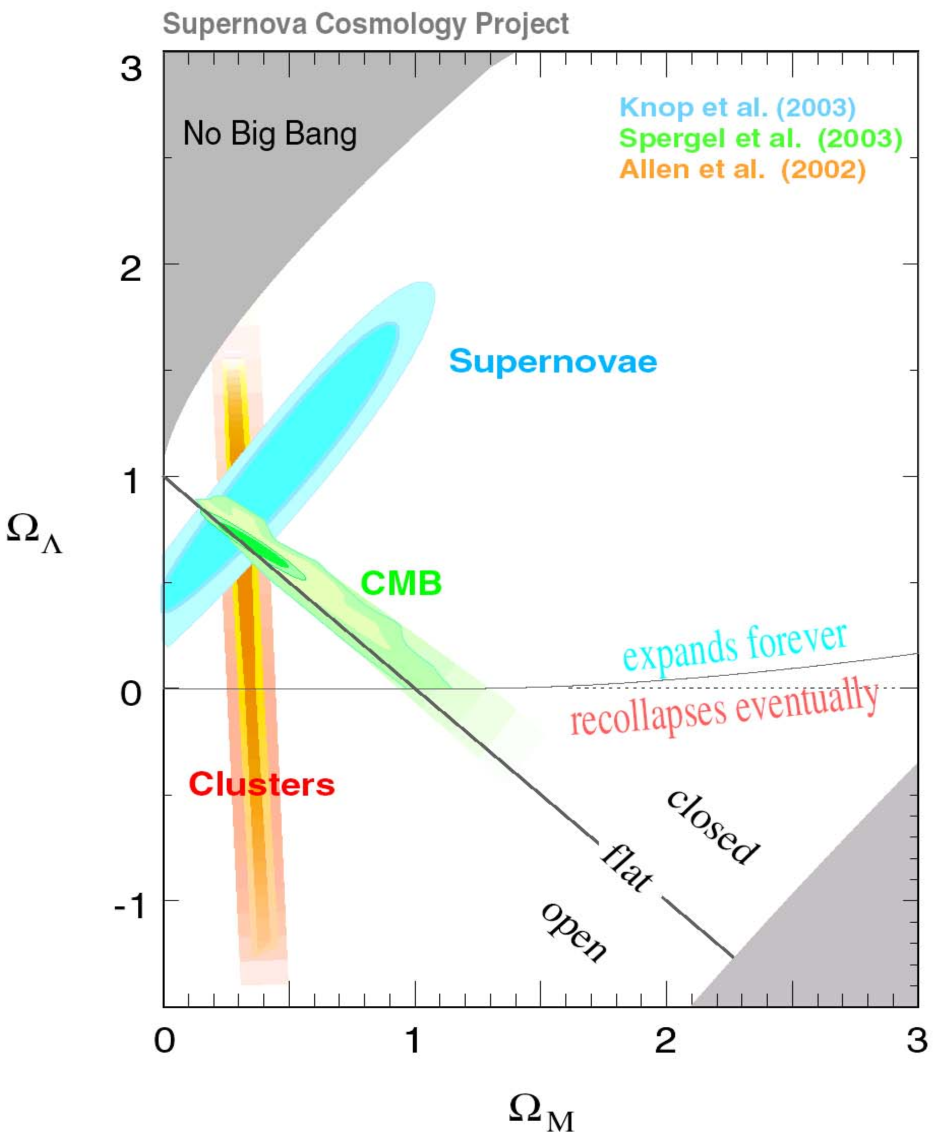




- The energy density parameter space (today)

Cosmic Triangle Equation:

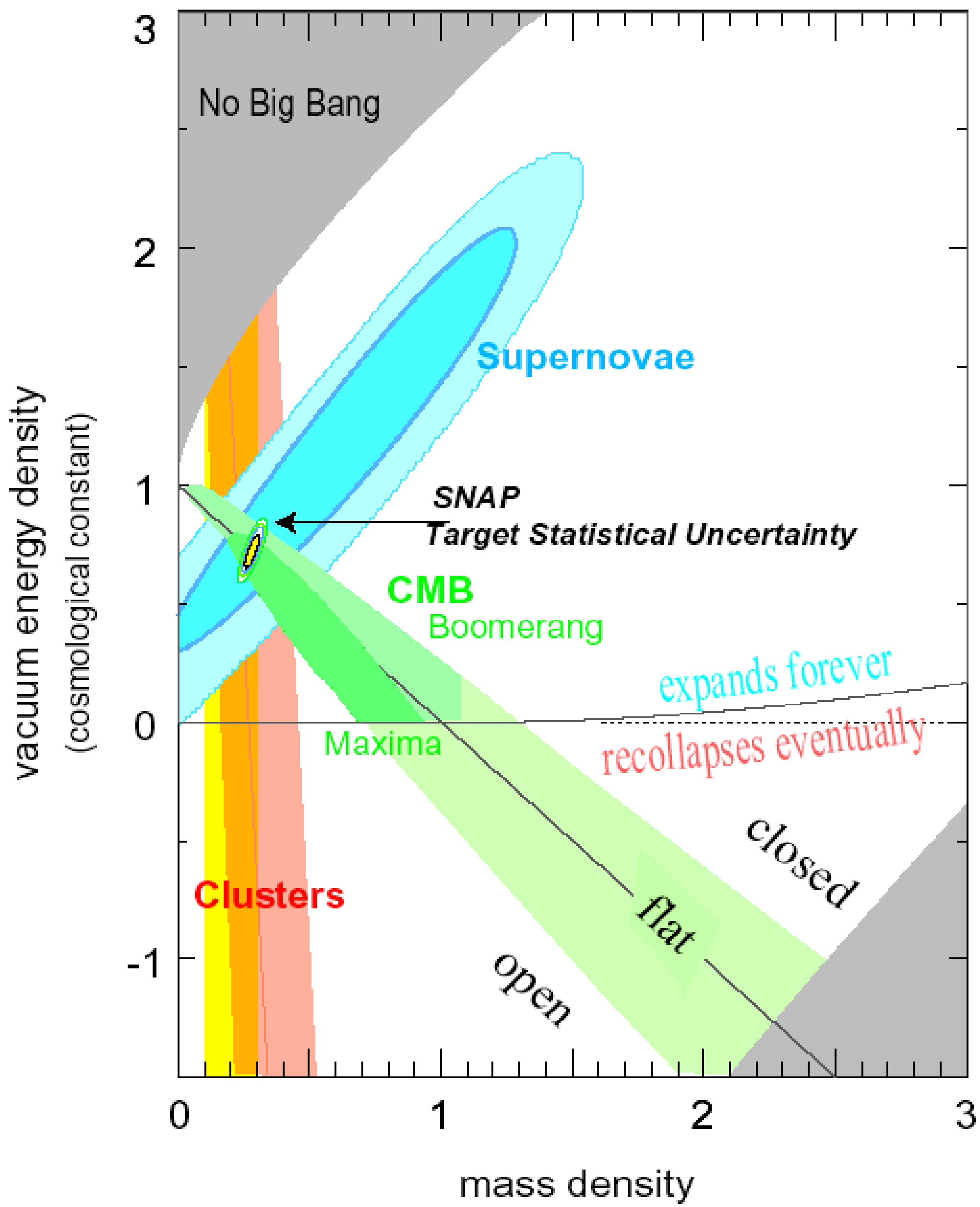
$$\boxed{\Omega_M + \Omega_\Lambda + \Omega_k \cong 1}$$



The incoming observations
(We hope!)

Cosmic Triangle Equation:

$$\boxed{\Omega_M + \Omega_\Lambda + \Omega_k \equiv 1}$$



Physical Effects of Dark Energy

Dark Energy affects expansion rate of the Universe:

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

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

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

Key Issues

1. Is there Dark Energy?

   Will the SNe and other results hold up?

1. What is the nature of the Dark Energy?

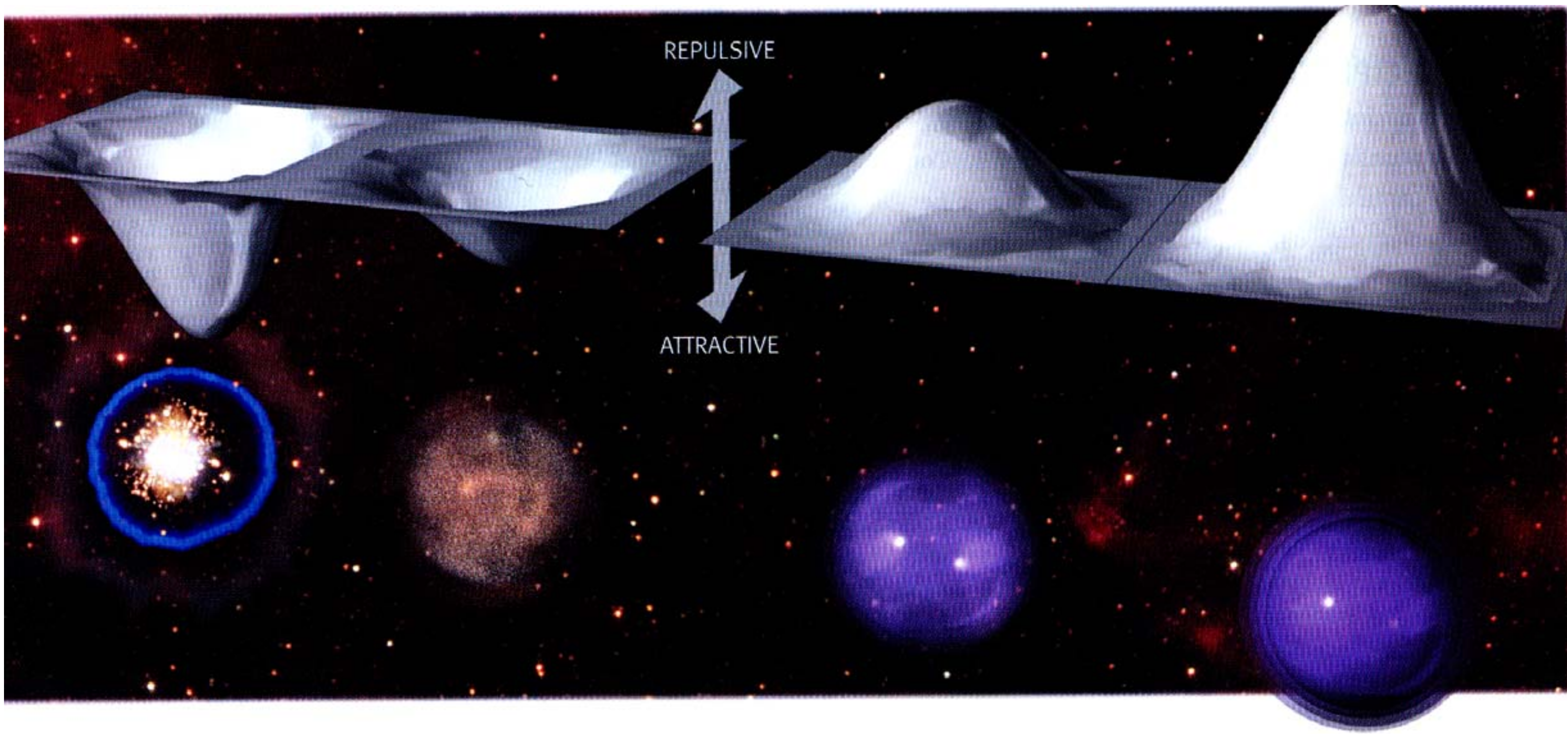
   Is Λ or something else?

1. How does $w = p_X/\rho_X$ evolve?

   Dark Energy dynamics → Theory

Dark Energy and *w*
(the EoS viewpoint)

In GR, force $\propto (\rho + 3p)$



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

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

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

Dark Energy as Λ

✓ Cosmological constant → Introduced by Einstein (1917) to get a static universe, has been recovered in the last years to interpret the cosmic acceleration evidenced by SNeIa data through the Einstein equations

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

The force law is

$$\mathcal{F} = -\frac{GM}{R^2} + \frac{\Lambda}{3} R, \quad (R \equiv a)$$

which shows that the cosmological constant gives rise to a repulsive force which could be responsible for the acceleration of the universe. Since 60's, cosmological constant has been related to vacuum energy of fields. ⇒ Cosmological constant problem (126 orders of magnitude of difference between the theoretical estimate and the observational one $\rho_\Lambda \simeq 10^{-47} \mathrm{GeV}^4$) & Coincidence problem (the today observed equivalence of dark energy and matter in order of magnitude).

Why not just a non-zero cosmological constant?

Two coincidences:

- ***Why so small?***

  Might expect $\frac{\Lambda}{8\pi G} \sim m^4_{\text{Planck}}$

  This is off by ~120 orders of magnitude!

- ***"Why now?"***

  $$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3p)$$

  MATTER: $p = 0 \longrightarrow \rho \propto R^{-3}$

  VACUUM ENERGY: $p = -\rho \longrightarrow \rho \propto constant$

What are the alternatives?

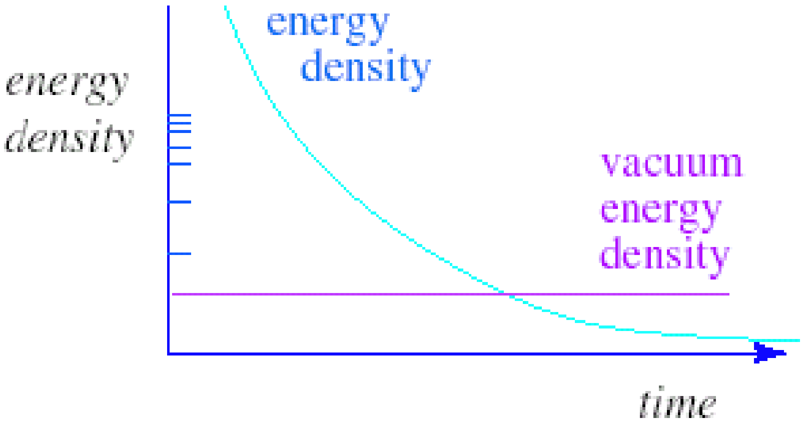
New Physics: "Dark energy":

Dynamical scalar fields, "quintessence",...

General Equation of State:

$$p = w\rho \longrightarrow \rho \propto R^{-3(1+w)}$$

and w can vary with time



✓ Dynamical dark energy (Quintessence) → Allows to overshoot the coincidence problem considering a dynamical negative pressure component. The standard scheme is to consider a scalar field Lagrangian.

$$\mathcal{L} = \frac{1}{2}\dot{\phi}^2 - V(\phi) \ ,$$

$$\rho \equiv T^0_0 = \frac{1}{2}\dot{\phi}^2 + V(\phi), \ p \equiv -T^\alpha_\alpha = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Potentials able to give interesting quintessential models:

Quintessence Potential	Reference
$V_0 \exp(-\lambda\phi)$	Ratra & Peebles (1988), Wetterich (1988), Ferreira & Joyce (1998)
$m^2\phi^2, \lambda\phi^4$	Frieman et al (1995)
$V_0/\phi^\alpha, \alpha > 0$	Ratra & Peebles (1988)
$V_0 \exp(\lambda\phi^2)/\phi^\alpha$	Brax & Martin (1999,2000)
$V_0(\cosh\lambda\phi - 1)^p$	Sahni & Wang (2000)
$V_0 \sinh^{-\alpha}(\lambda\phi)$	Sahni & Starobinsky (2000), Ureña-López & Matos (2000)
$V_0(e^{\alpha\kappa\phi} + e^{\beta\kappa\phi})$	Barreiro, Copeland & Nunes (2000)
$V_0(\exp M_p/\phi - 1)$	Zlatev, Wang & Steinhardt (1999)
$V_0[(\phi - B)^\alpha + A]e^{-\lambda\phi}$	Albrecht & Skordis (2000)

Do theorists really have a clue?

"A huge amount of proposals to constrain the data!"

Riess et al. 2004, ApJ, 607, 665
"Type Ia Supernova Discoveries…Constraints on Dark Energy Evolution"
w(z)=w(z,w0,w')
"Our constraints are consistent with the static nature of and value of w expected for a cosmological constant and inconsistent with very rapid dark energy evolution."

aastro-ph/0311622, revised Apr 2004
"Cosmological parameters from supernova observations"
Choudhury and Padmanabhan
w(z)=w(z,w0,w1)
"The key issue regarding dark energy is to determine the evolution of its equation of state...the supernova data mildly favours a dark energy equation of state with its present best-fit value less than -1 [evolving]...however, the data is still consistent with the standard cosmological constant at 99 per cent confidence level"

aastro-ph/0405446
Gong
"Model independent analysis of dark energy I: Supernova fitting result"
w(z)=tried many different forms
Tried various parameterizations, no firm conclusions.

astro-ph/0403292
"New dark energy constraints from supernovae, microwave background and galaxy clustering"
Wang and Tegmark
w(z)=w(z,w1,wa,etc)
"We have reported the most accurate measurements to date of the dark energy density as a function of time, assuming a flat universe. We have found that in spite of their constraining power, the spectacular new high-z supernova measurements of provide no hints of departures from the vanilla model corresponding to Einstein s cosmological constant."

aastro-ph/0403687
"The case for dynamical dark energy revisited"
Alam, Sahni, Starobinsky
w(z)=w(1+z,A0,A1,A2)
"We find that, if no priors are imposed on omega_m and H0, DE which evolves with time provides a better fit to the SNe data than Lambda-CDM."
This is also true if we include results from the WMAP CMB data. However, DE evolution becomes weaker if omega_m=0.27 +/- 0.04 and Ho=71 +/-6 are incorporated in the analysis."

astro-ph/0404062
"Uncorrelated Estimates of Dark Energy Evolution"
Huterer and Cooray
w(z)=w(z_0.1,z_0.3,z_0.5,z_1.2); 4 bins
"Our results are consistent with the cosmological constant scenario...though we find marginal (2-sigma) evidence for w(z) < -1 at z < 0.2. With an increase in the number of type Ia supernovae at high redshift, it is likely that these interesting possibilities will be considered in the future.

astro-ph/0404378
Jassal, Bagla, Padmanabhan
"WMAP constraints on low redshift evolution of dark energy"
"We show that combining the supernova type Ia observations {\it with the constraints from WMAP observations} severely restricts any possible variation of w(z) at low redshifts. The results rule out any rapid change in w(z) in recent epochs and are completely consistent with the cosmological constant as the source of dark energy.

astro-ph/0508350
"Observational constraints on dark energy with generalized equations of state"
S. Capozziello, V.F. Cardone, E. Elizalde, S. Nojiri, S.D. Odintsov
"observations can be fitted adding inhomogeneous terms in the EoS.

astro-ph/0406608
"The foundations of observing dark energy dynamics..."
Corasaniti et al.
w(z)=w(a,w0,wm,at,delta)
"Detecting dark energy dynamics is the main quest of current dark energy research. Our best-fit model to the data has significant late-time evolution at z<1.5. Nevertheless cosmic variance means that standard LCDM models are still a very good fit to the data and evidence for dynamics is currently very weak."

astro-ph/0506371
"Phenomenological model for inflationary quintessence"
V.F. Cardone, A. Troisi, S. Capozziello
"phenomenologically motivated models can fit high and low redshift data using CMBR, SNeIa, radiogalaxies"

aastro-ph/0407094
"Constraints on the dark energy equation of state from recent supernova data"
Dicus,Repko
w(z)=w(z,w0,w1)
"Comparing models for the equation of state of the dark energy will remain something of a mug's game until there exists substantially more data at higher values of z." i.e., data not highly constrainin

Go get some data!

aastro-ph/0407364
"The essence of quintessence and the cost of compression"
Bassett, Corasaniti, Kunz
w(z)=w(a,a_t,w0,wm,delta); allows rapid changes
"Rapid evolution provides a superlative fit to the current SN Ia data...[significantly better than lambda]"

astro-ph/0407372
"Cosmological parameter analysis including SDSS..."
Seljak et al.
w(z)=w(a,w0,w1)
"We find no evidence for variation of the equation of state with redshift.."

astro-ph/0407452
Probing Dark Energy with Supernovae : a concordant or a convergent model?
Virey et al.
w(z)=w(z,w0,w')
Worries that wrong prior on omega_m will bias the result. Suggests weaker prior, data consistent with lambda or significant DE evolution.

astro-ph/0408112
"Scaling Dark Energy"
Capozziello,Melchiorri,Schirone
w(z)=w(z,zb,zs); phenomenological
"We found that the current data does not show evidence for cosmological evolution of dark energy...a simple but theoretically flawed cosmological constant still provides a good fit to the data."

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 $a(t)$, $G(t)$, $d_A(z)$

Physical Observables: probing DE

1. Luminosity distance vs. redshift: $d_L(z)$ $m(z)$

   Standard candles: SNe Ia

2. Angular diameter distance vs. z: $d_A(z)$

   Alcock-Paczynski test: Ly-alpha forest; redshift correlations

3. Number counts vs. redshift: $N(M,z)$

   probes: *Comoving Volume element $dV/dzd\Omega$

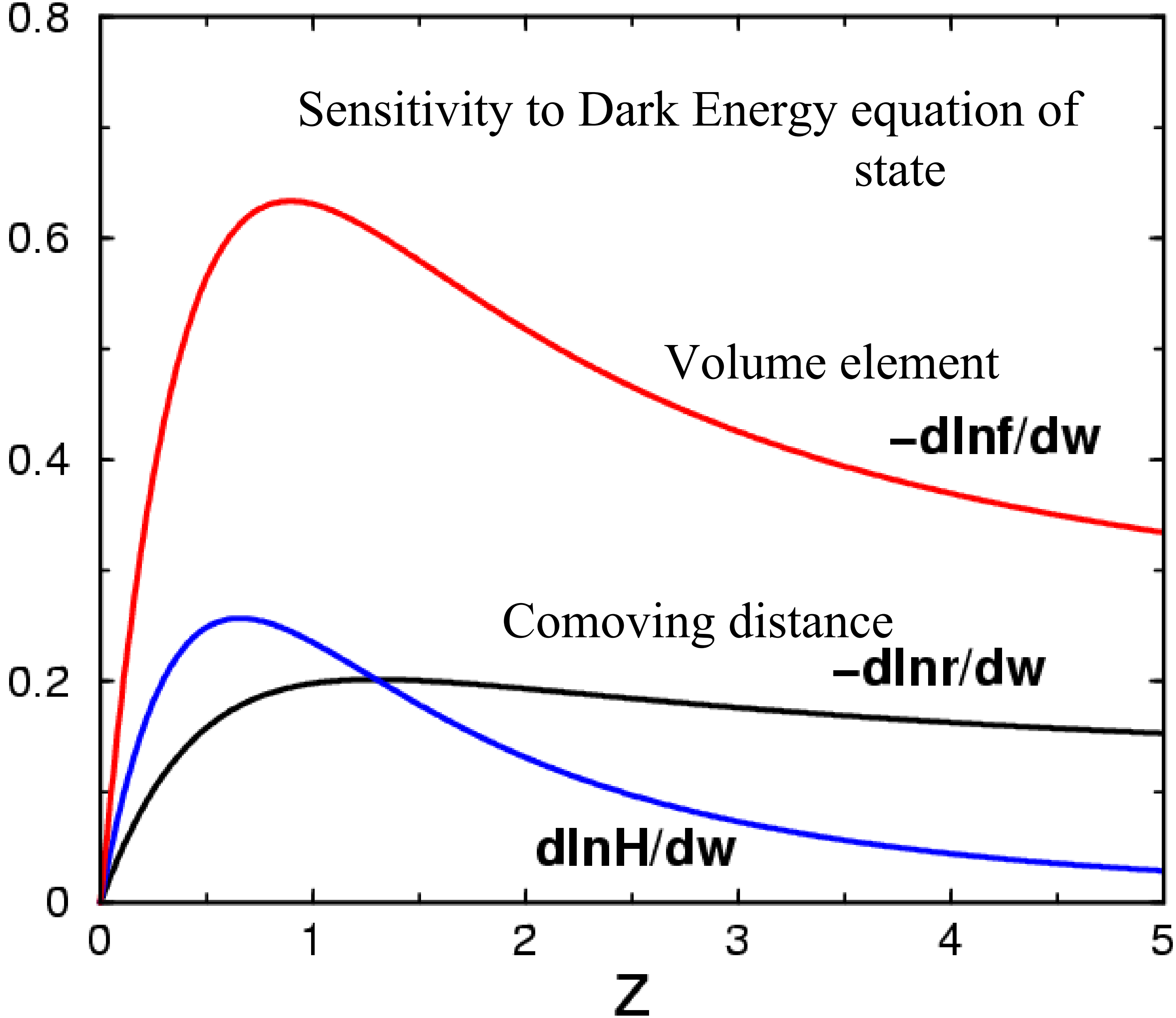
   *Growth rate of density perturbations $\delta(z)$

   Counts of galaxy halos and of clusters; QSO lensing

4. Lookback time vs. clusters and galaxies

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…



Sensitivity to Dark Energy equation of state
Volume element
-dlnf/dw
Comoving distance
-dlnr/dw
dlnH/dw
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
Z

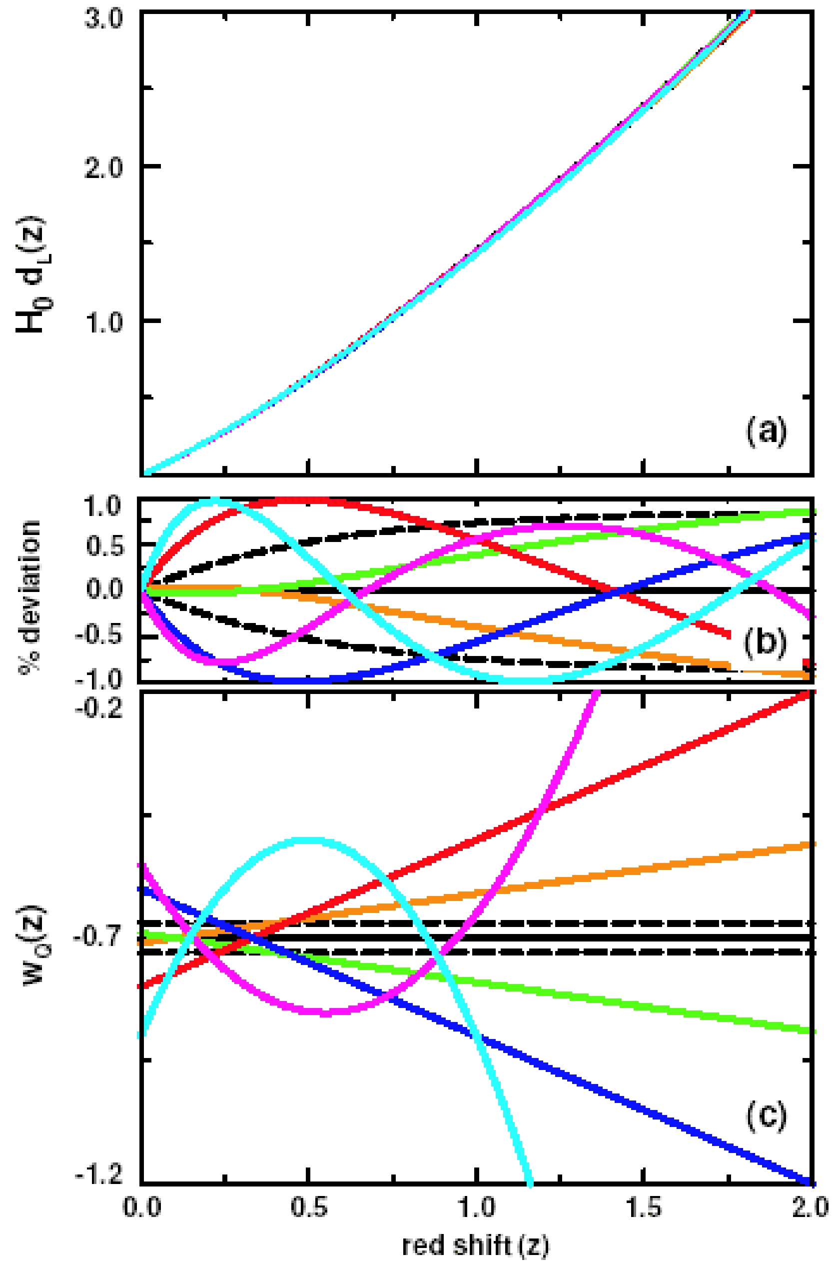
The imagination of “unconstrained” theorists!

7 “models” with <w>=-0.7 with identical (to 1%) relative distance-z relations

Assuming *w*=constant would provide incorrect conclusion if *w(z)* is more complex!

Need:

- more than one method
- span wide redshift ranges



Maor, Steinhardt et al 2000
SC 2007

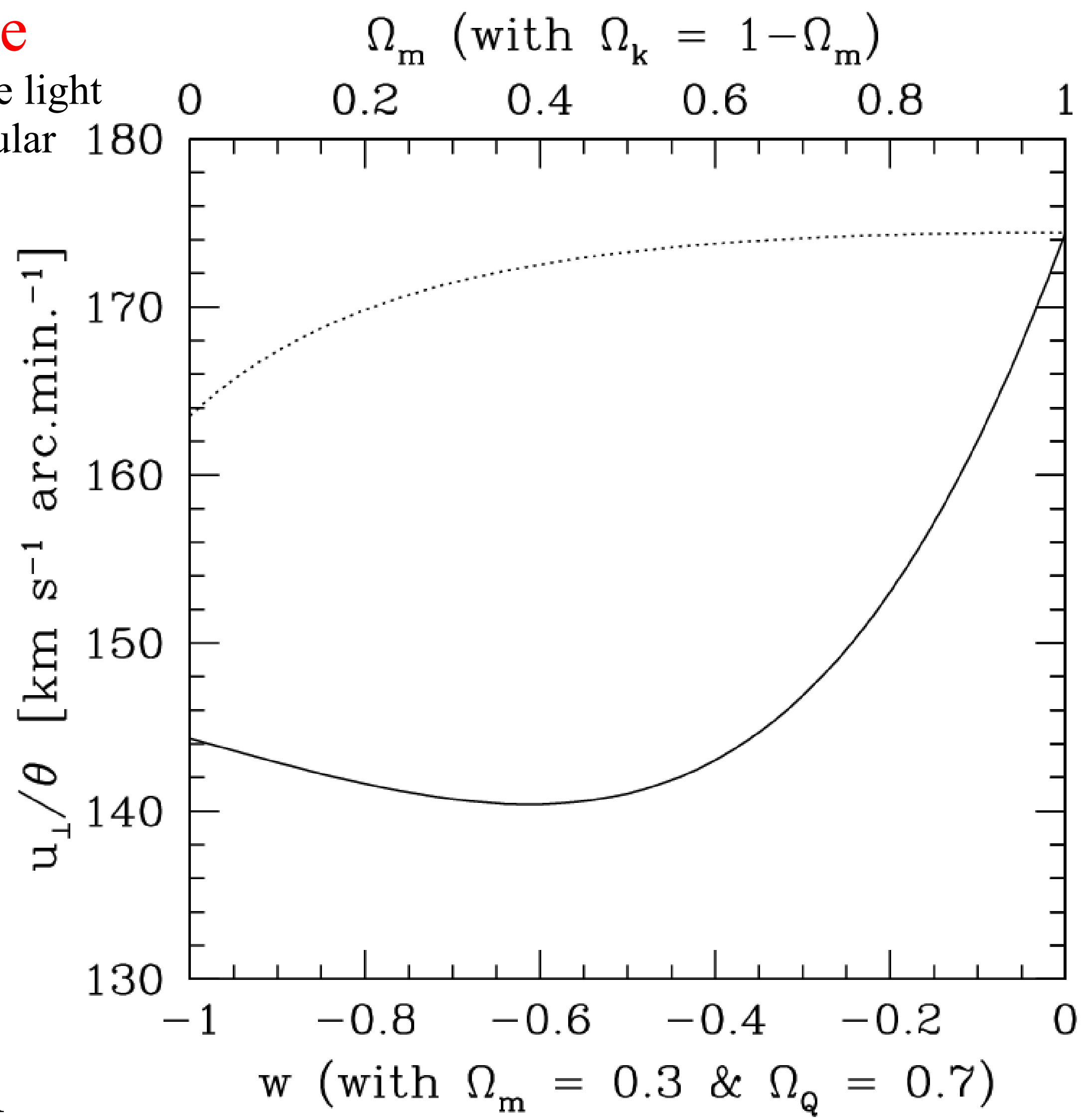
Angular Diameter Distance

(the physical size of the object when the light was emitted divided by its current angular diameter on the sky)

$$u_\perp(\theta) = \frac{\bar{H}}{1+\bar{z}} D_A(\bar{z})\theta$$

Transverse extent

Angular size



Intrinsically isotropic clustering: radial and transverse sizes are equal

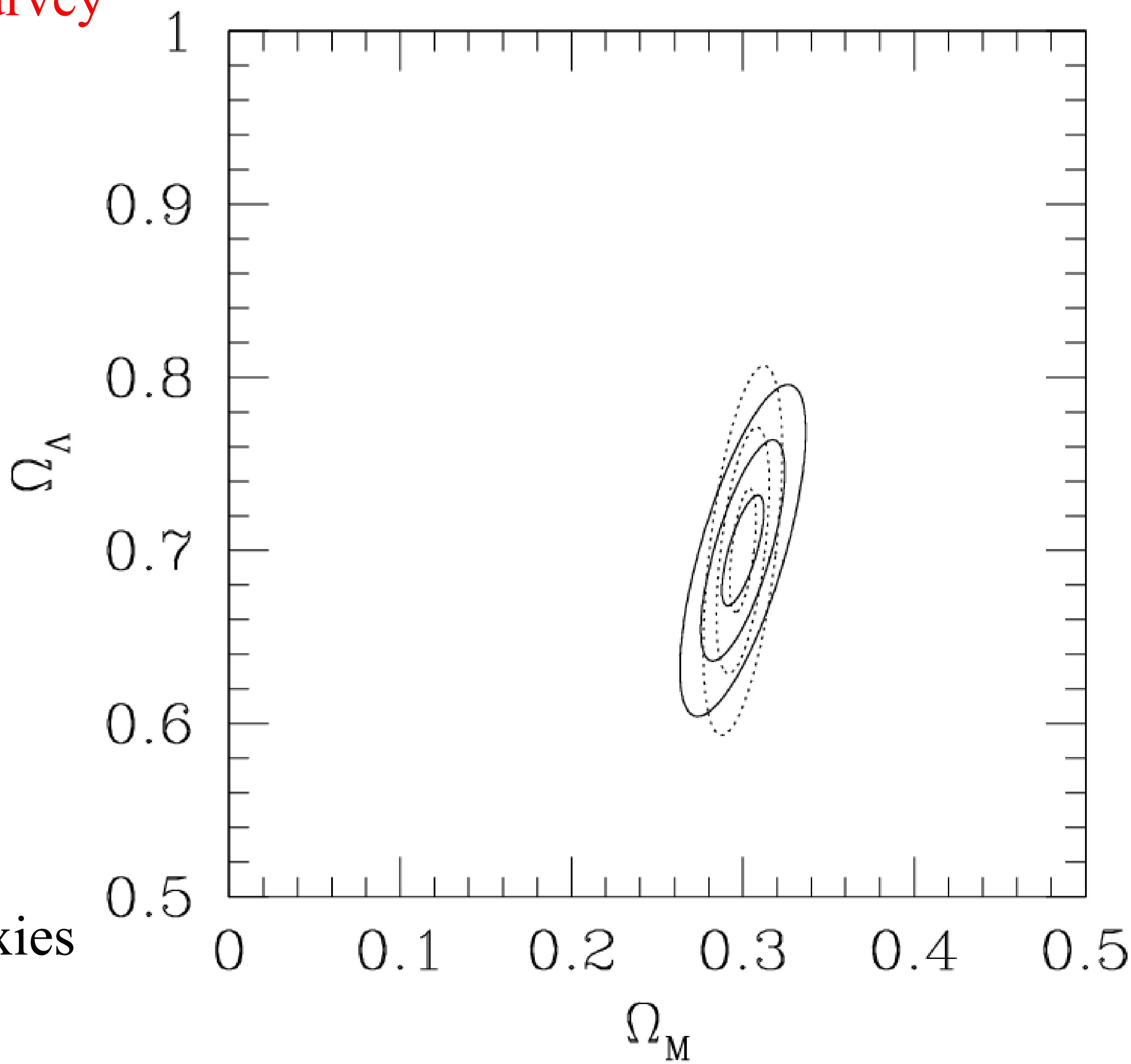
Lyman-alpha forest: absorbing gas along LOS to distant Quasars
clustering along line of sight

$$P^f_{||}(k_{||}) = \int_{k_{||}}^{\infty} \tilde{P}^f(k_{||}, k) k \frac{dk}{2\pi}$$

$$P^f_{\times}(k_{||}, \theta) = \int_{k_{||}}^{\infty} \tilde{P}^f(k_{||}, k) J_0[k_\perp \underline{u_\perp(\theta)}] k \frac{dk}{2\pi}$$

Cross-correlations between nearby lines of sight

Sloan Digital Sky Survey

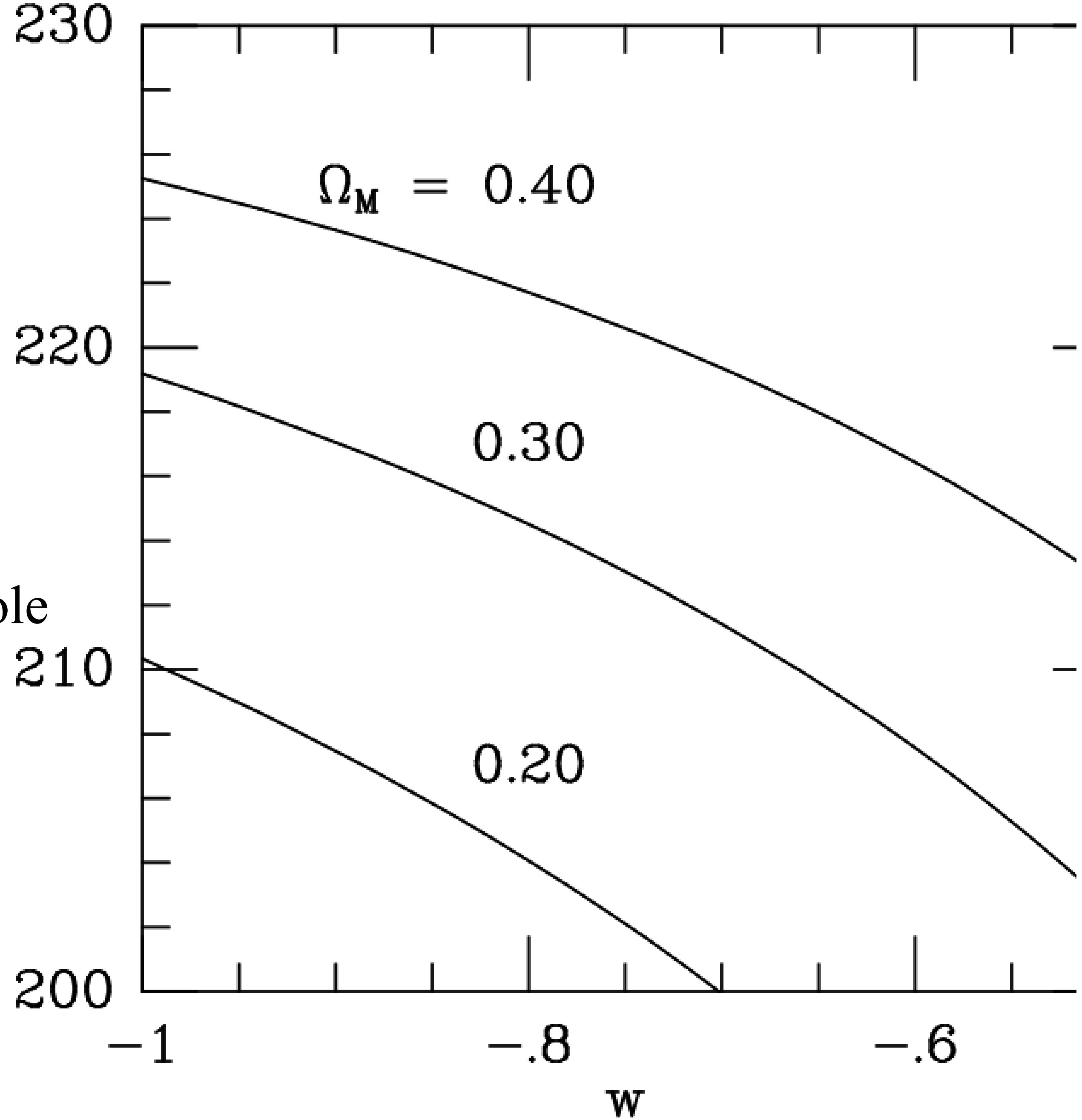


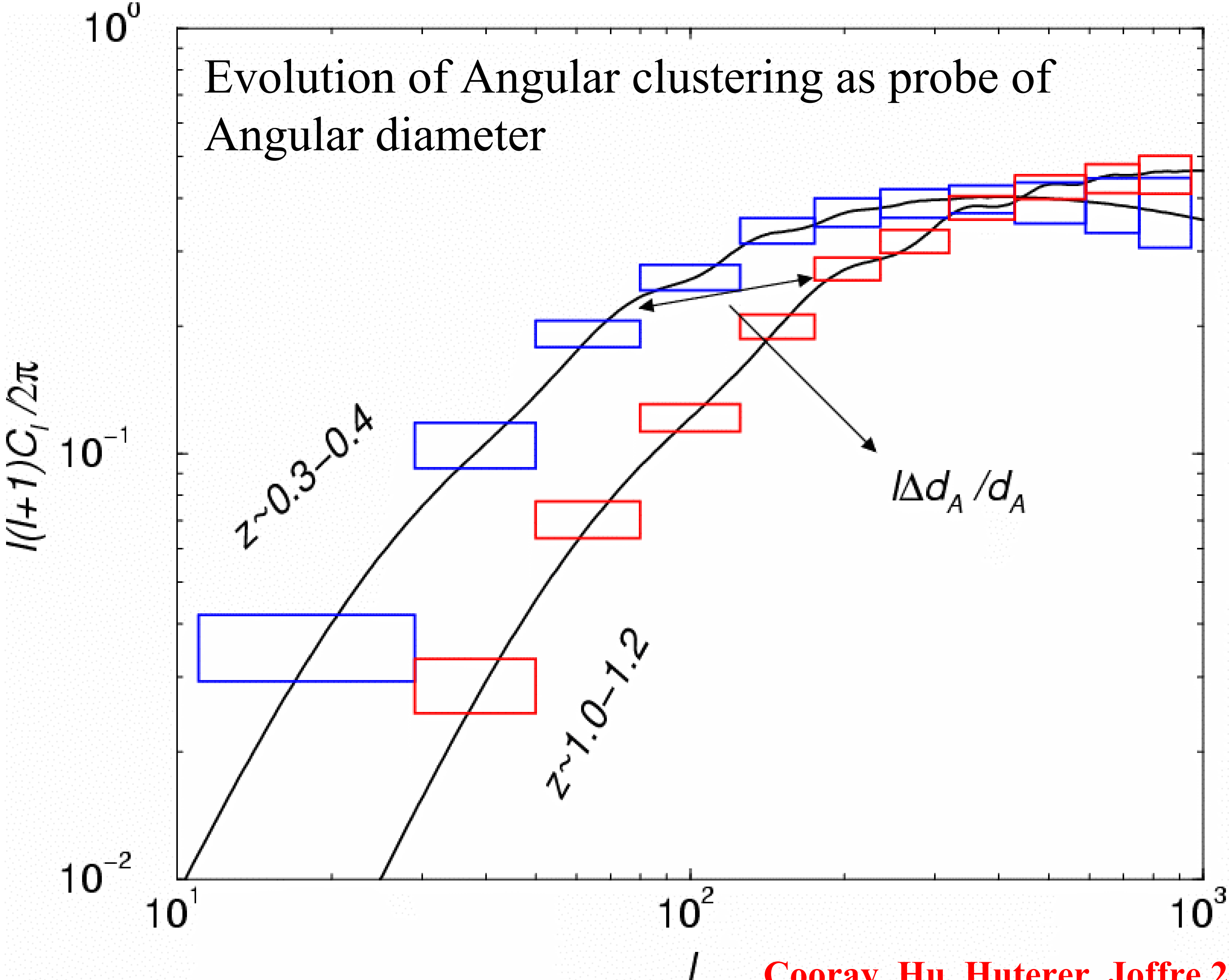
Projected constraints from redshift space clustering of 100,000 Luminous Red Galaxies ($z \sim 0.4$)

Matsubara & Szalay 2005

CMB Anisotropy:

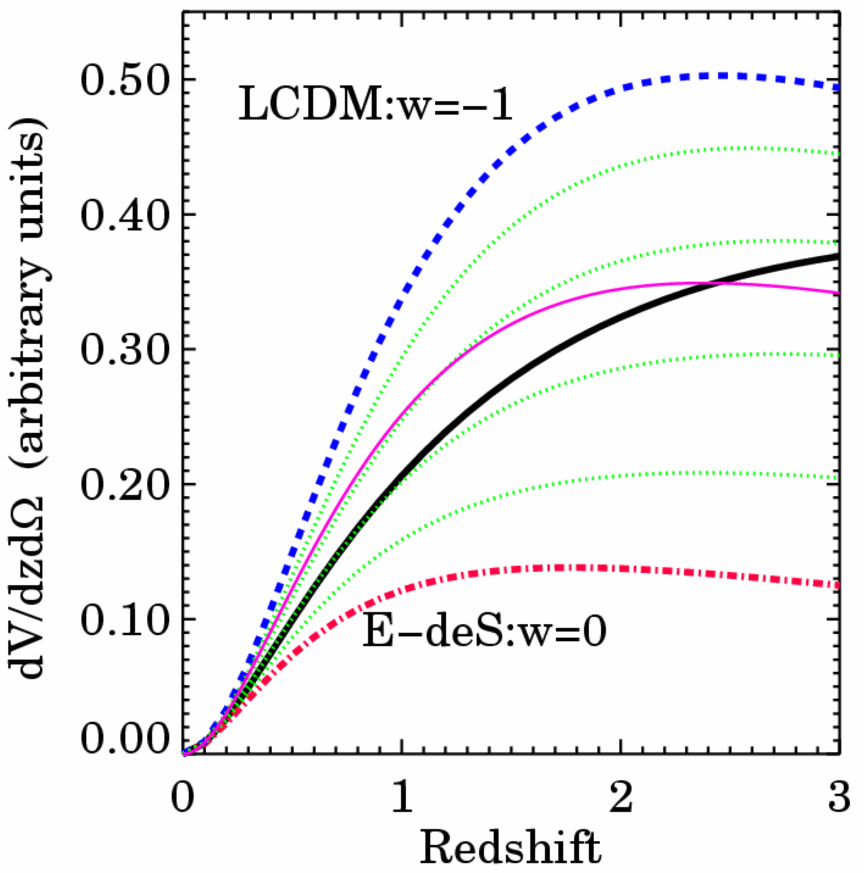
Angular diameter
Distance to last
Scattering surface

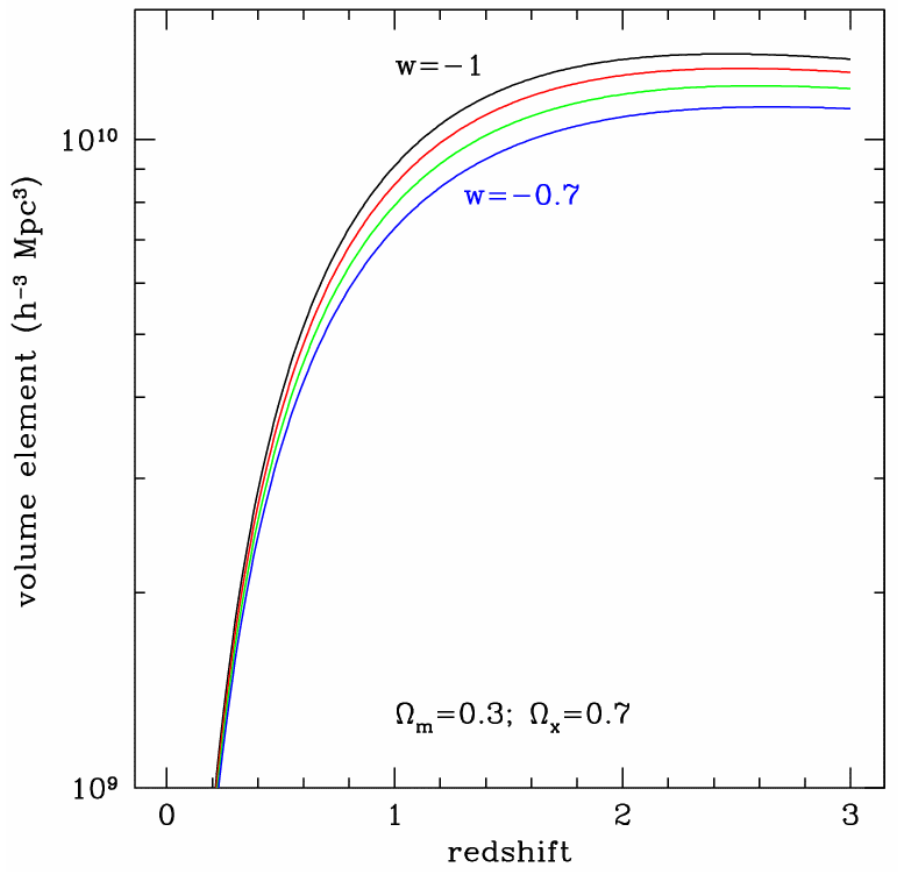




Cooray, Hu, Huterer, Joffre 2006

Volume Element as a function of *w*

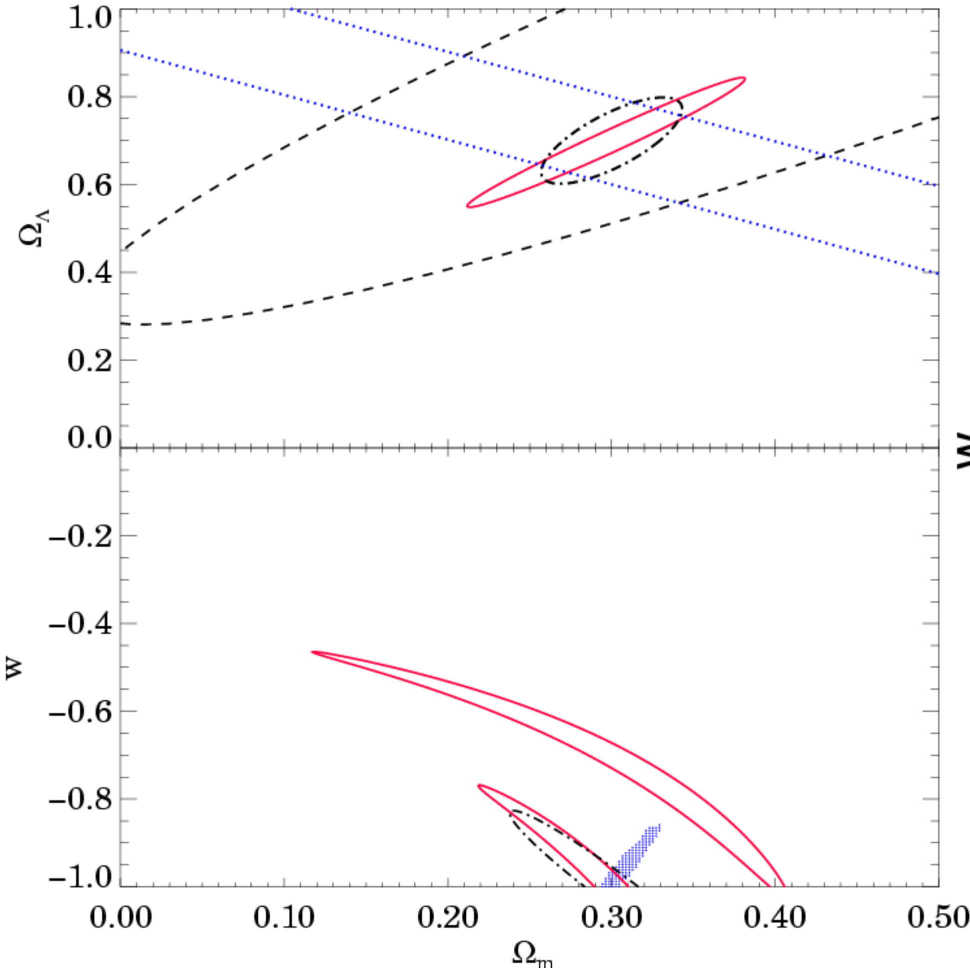




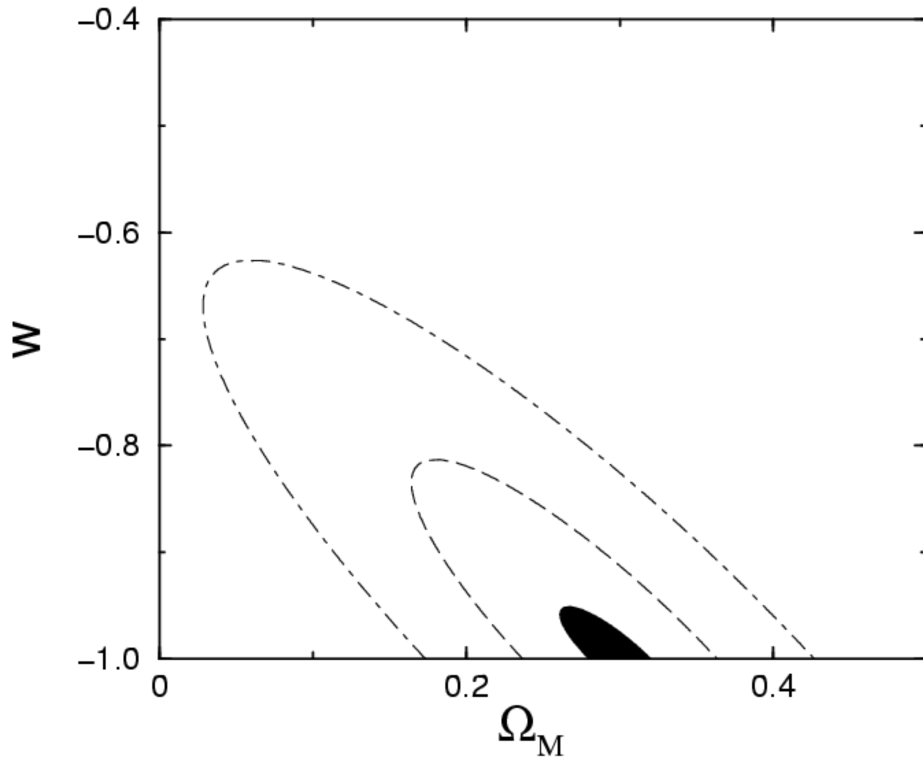
Dark Energy → More volume at moderate redshift

Counting Galaxy Dark Matter Halos with the DEEP Redshift Survey

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



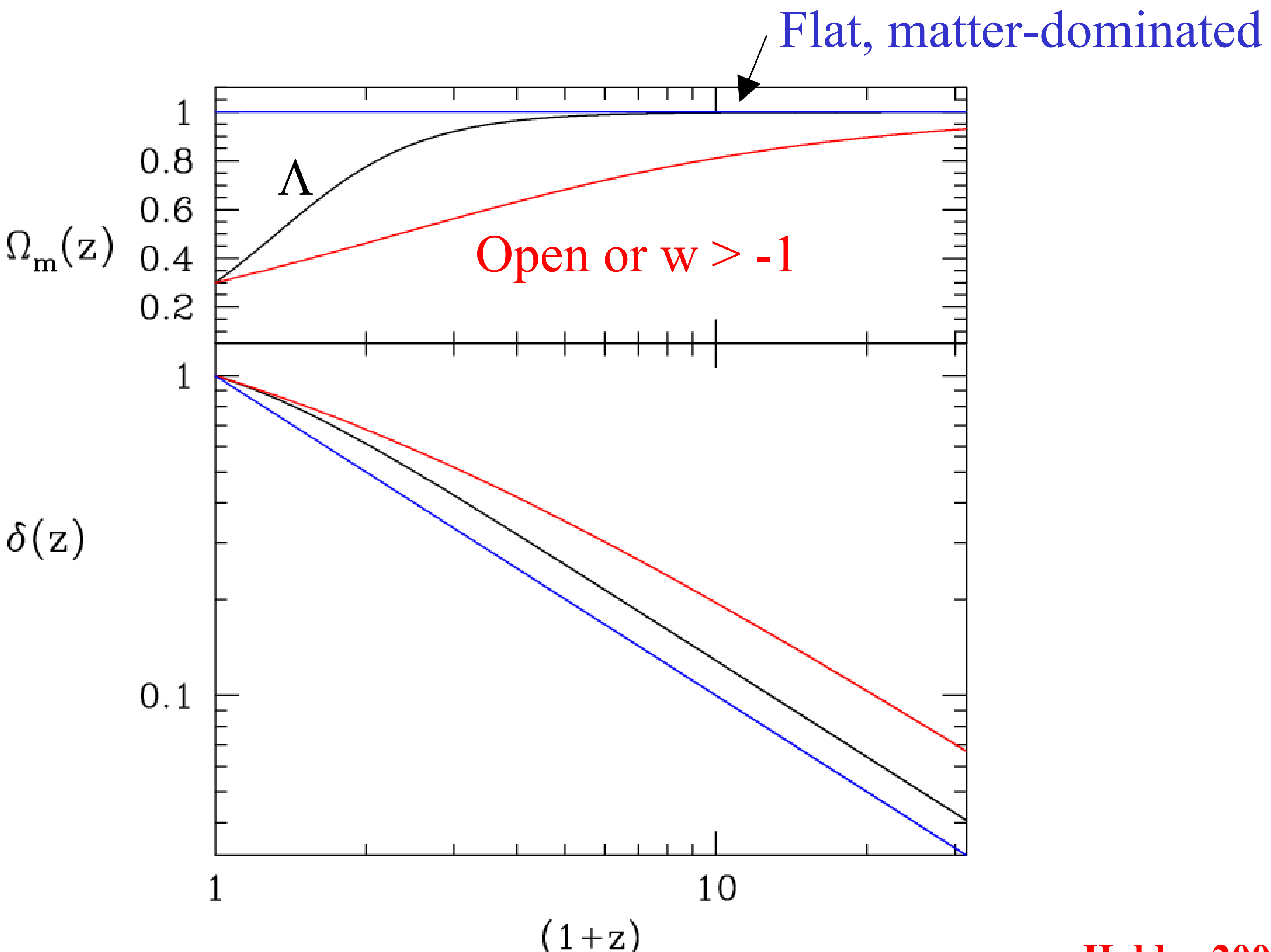
Newman & Davis 2004



NB: must probe Dark Matter-dominated regions

Huterer & Turner 2005

Growth of Density Perturbations



Holder 2005

Counting Clusters of Galaxies

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

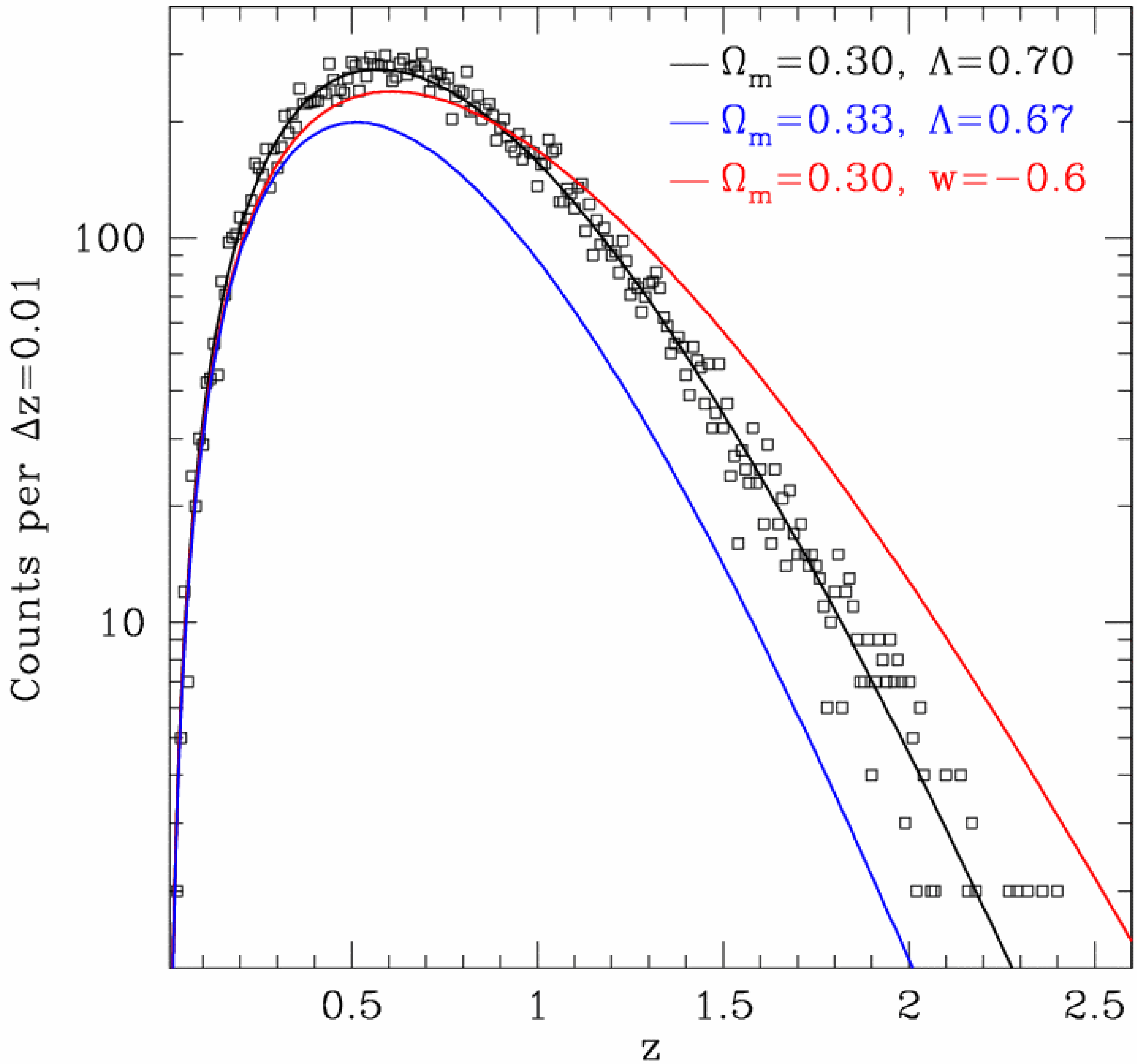
$$\frac{dN}{dz\,d\Omega}(z) = \left[\frac{dV}{dz\,d\Omega}(z) \underline{\int_{M_{\min}(z)}^{\infty}} dM \frac{dn}{dM}\right]$$

Simulations:

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

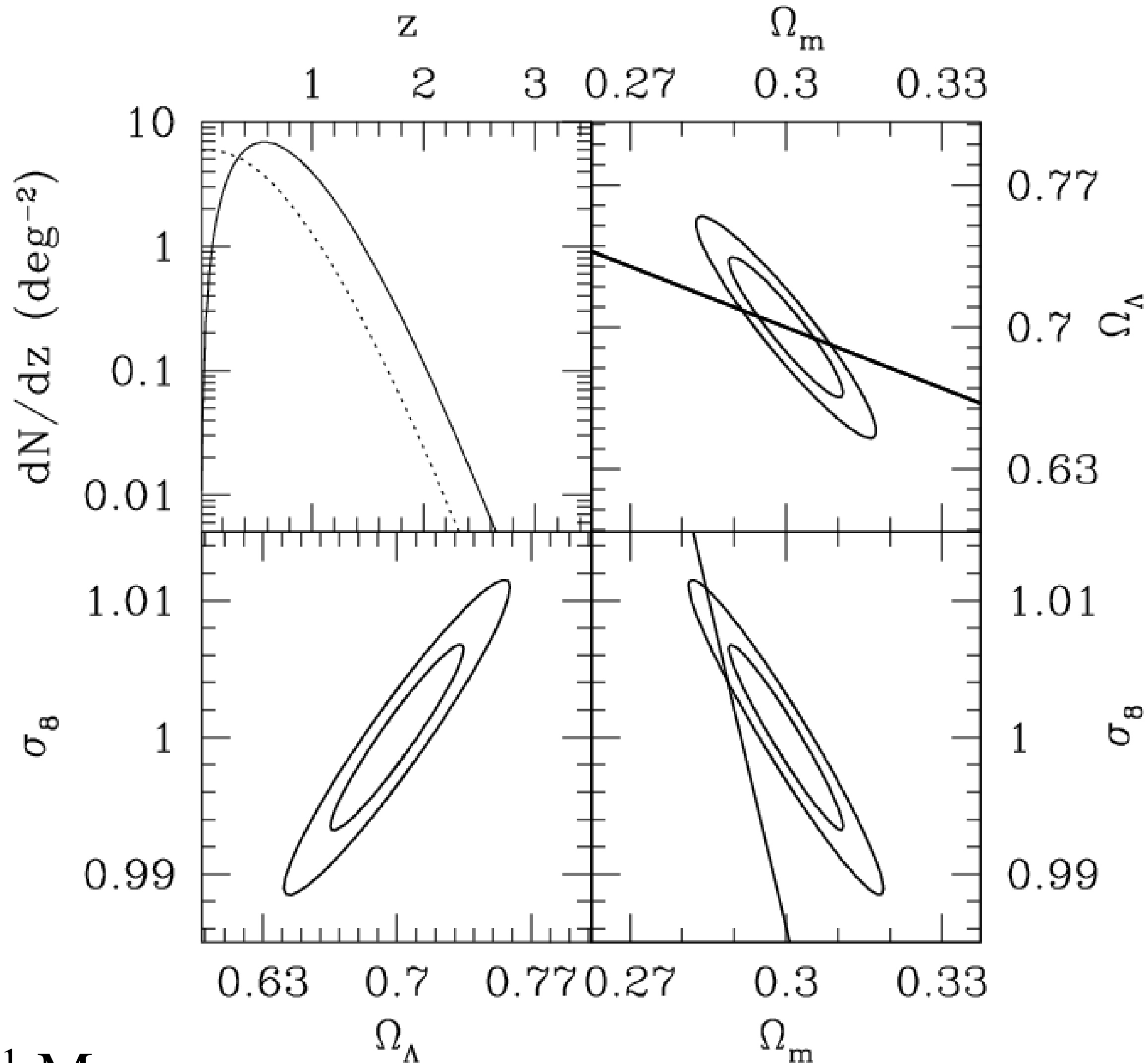
growth factor

Expected Cluster Counts in a Deep, wide Sunyaev Zel'dovich Survey



Holder, Carlstrom, et al 2004

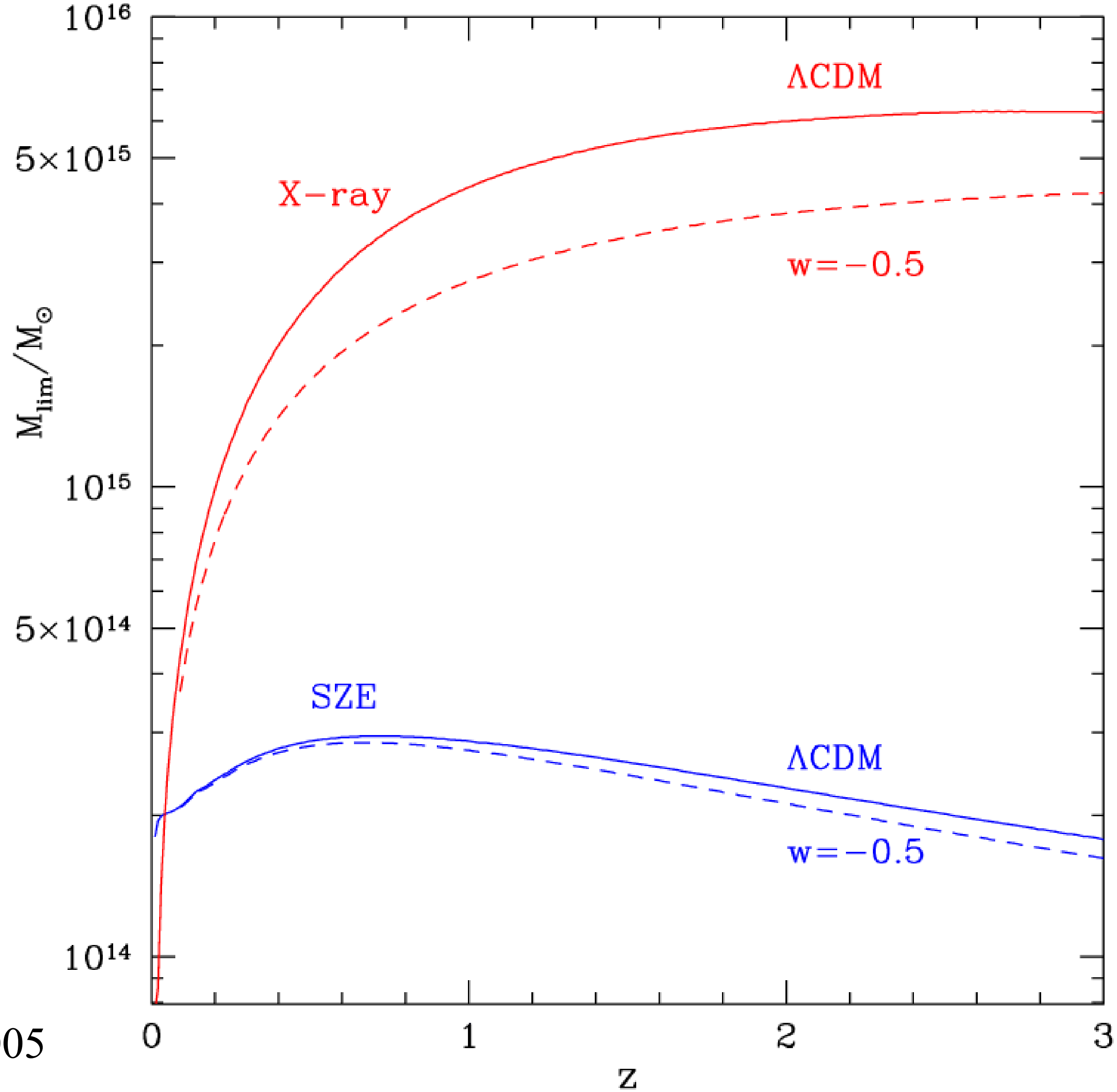
Constraints from
a 4000 sq. deg.
SZE Survey



$M_{lim} = 2.5 \times 10^{14}\ h^{-1}\ M_{sun}$

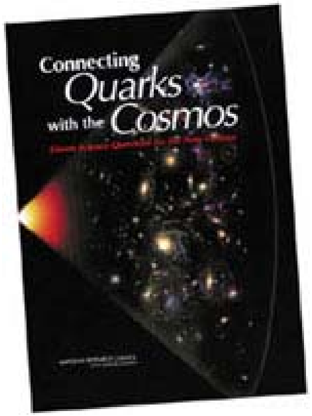
Holder, Haiman, Mohr 2005

Detection Mass thresholds



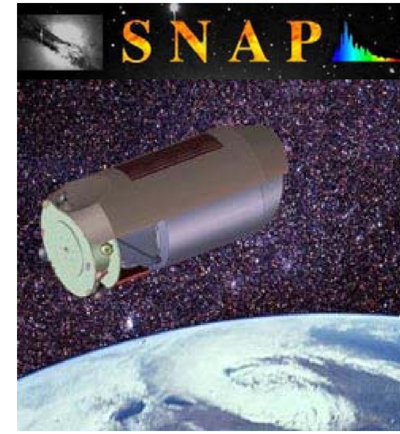
Haiman, Holder, Mohr 2005

New Proposals for Tracking Dark Energy



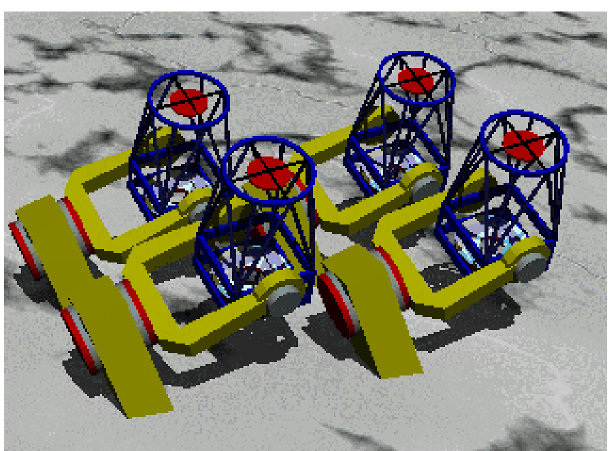
DoE/NASA initiated studies for a Joint Dark Energy space mission (JDEM, 2015+), also ESA/France

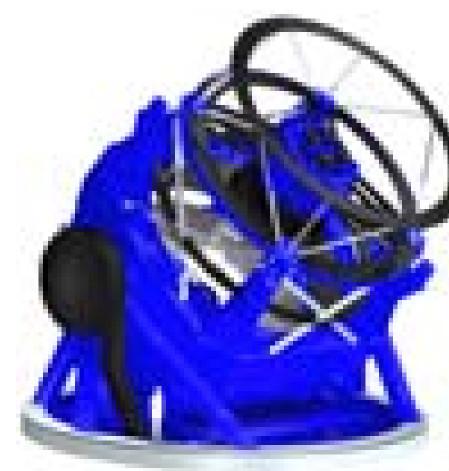
Contenders: SNAP, Destiny, JEDI, ADEPT + DUNE



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

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



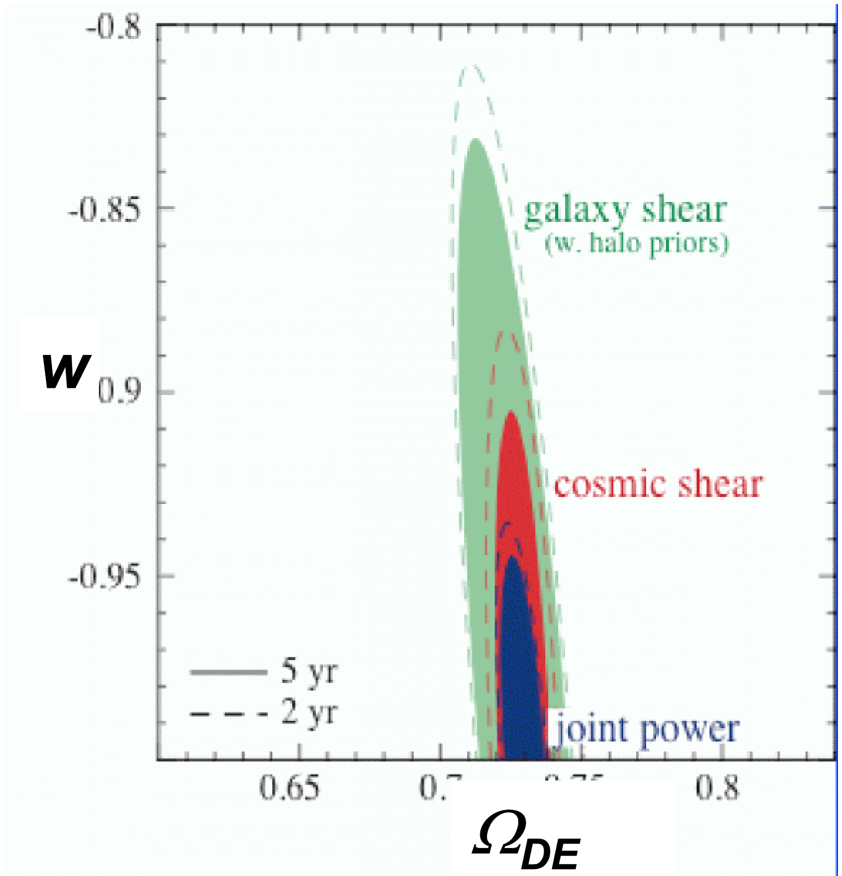


Dark Energy Strategy

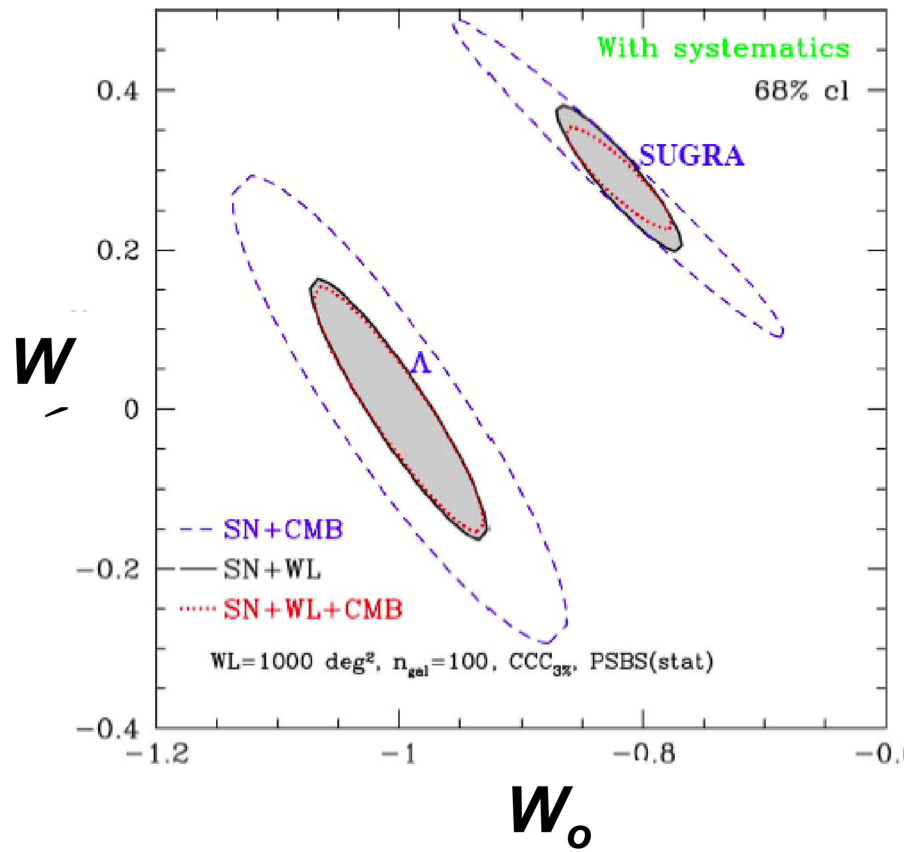
Initial goal: verify whether *w* = -1 (NB: precision depends on value)

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

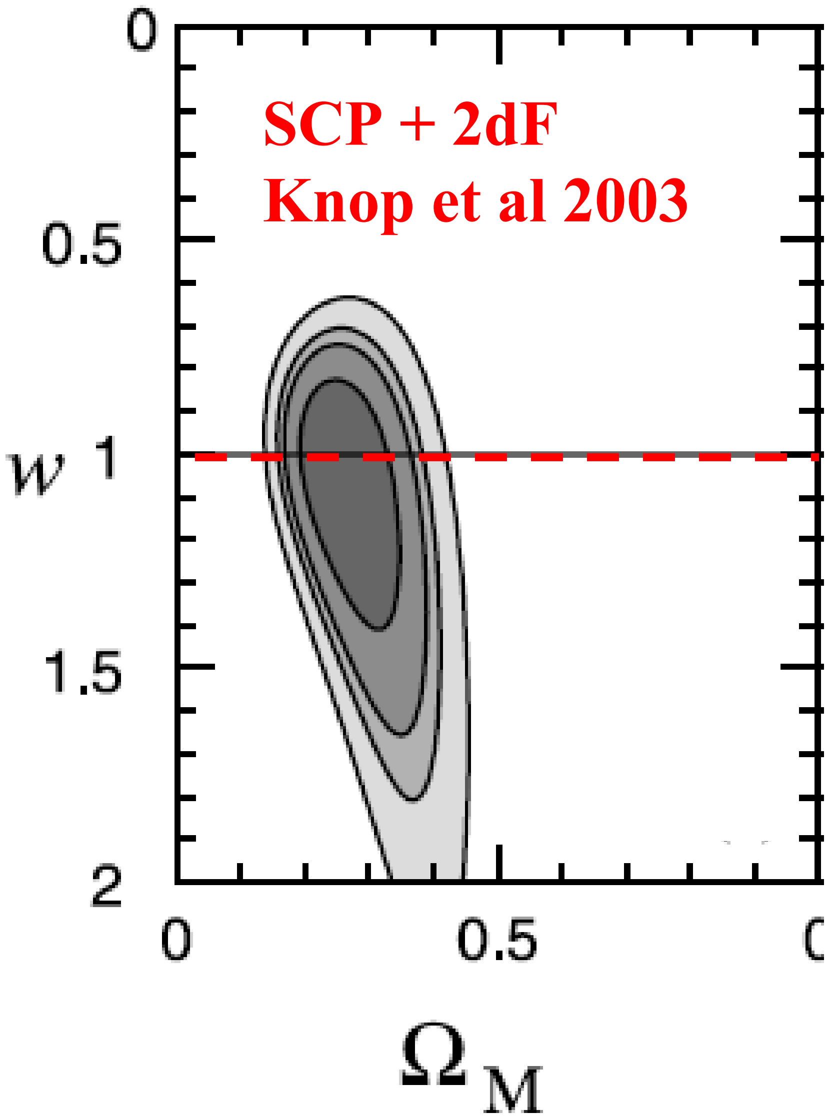
$$d_L = \frac{1+z}{H_0}(1+g)^{1/2} \int_1^{1+z} \left\{ g + \exp\left[3 \int_1^x w_Q(y) \frac{dy}{y} \right] \right\}^{-1/2} \frac{dx}{x^{3/2}}$$

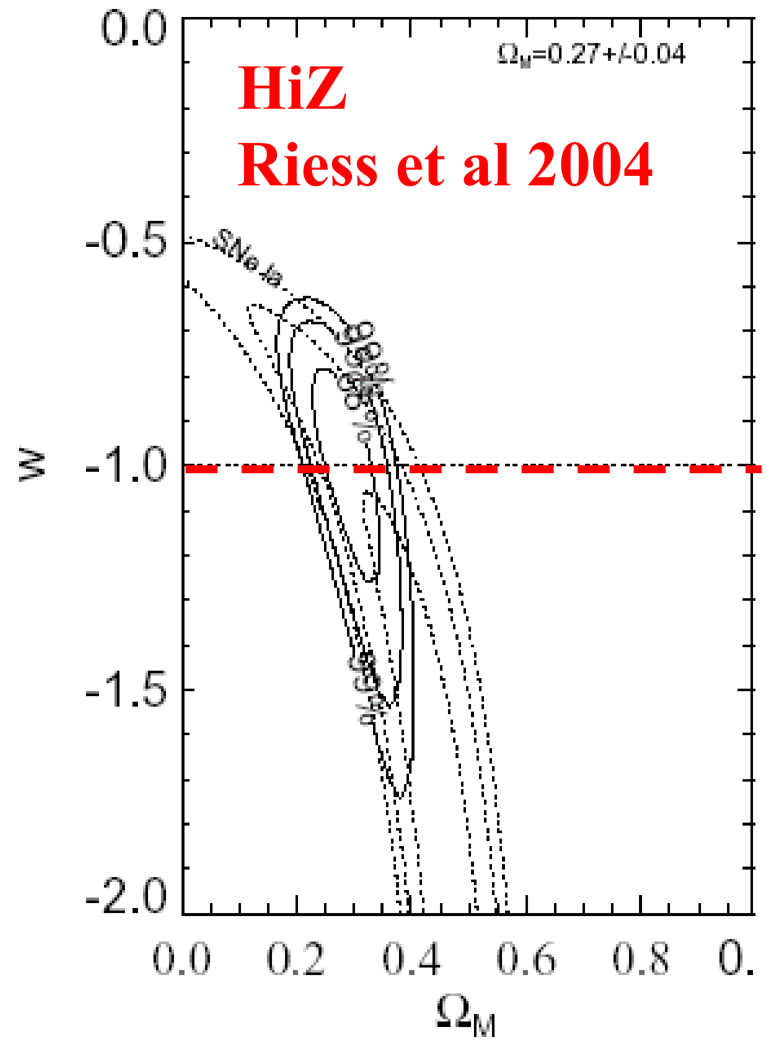
- Fit to the SNeIa Hubble diagram

➢ *Double integration over $w_Q(z)$*

➢ *Similar degeneracy problem for other tests*

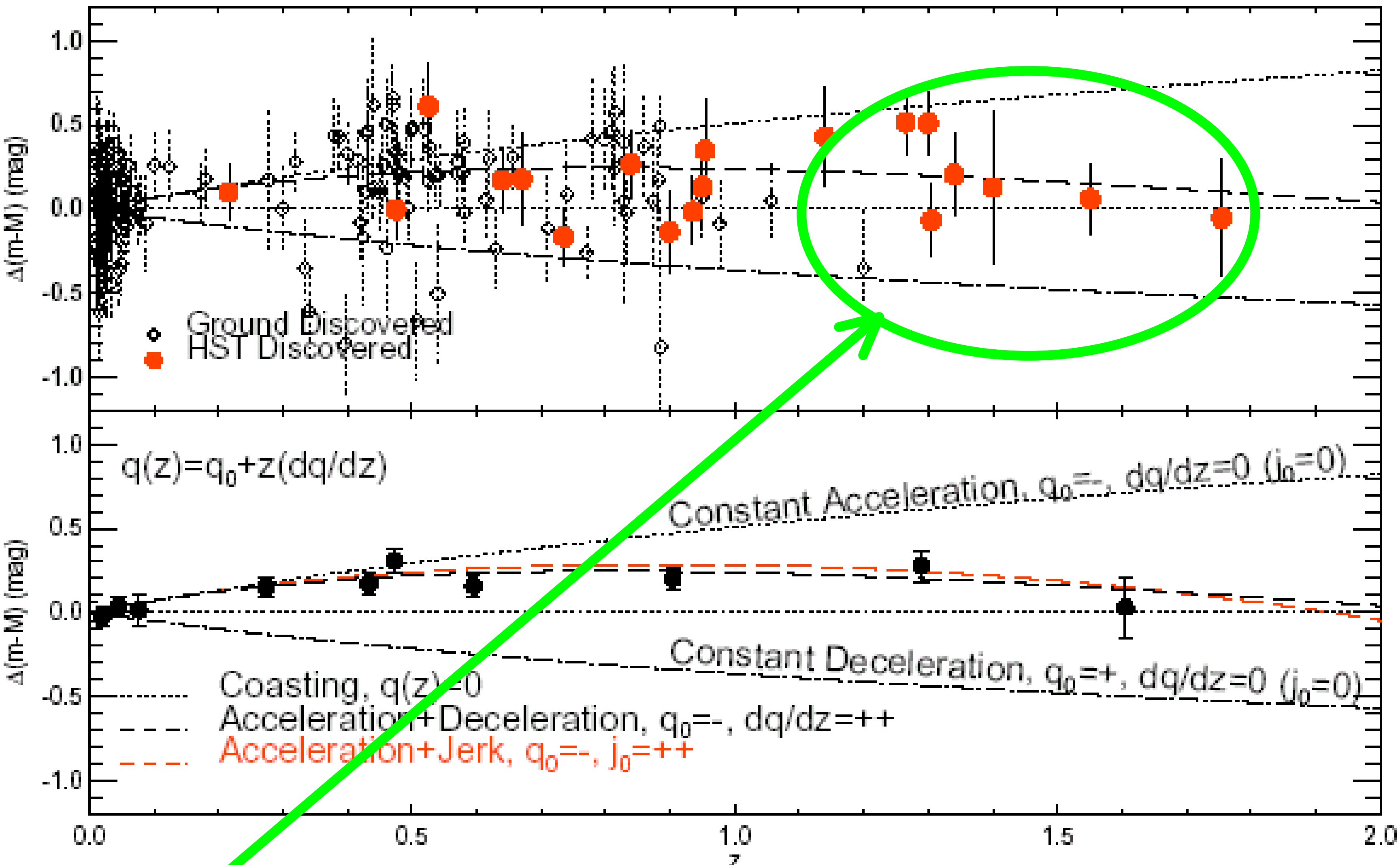
SNe Ia: early constraints on *w* + LSS data



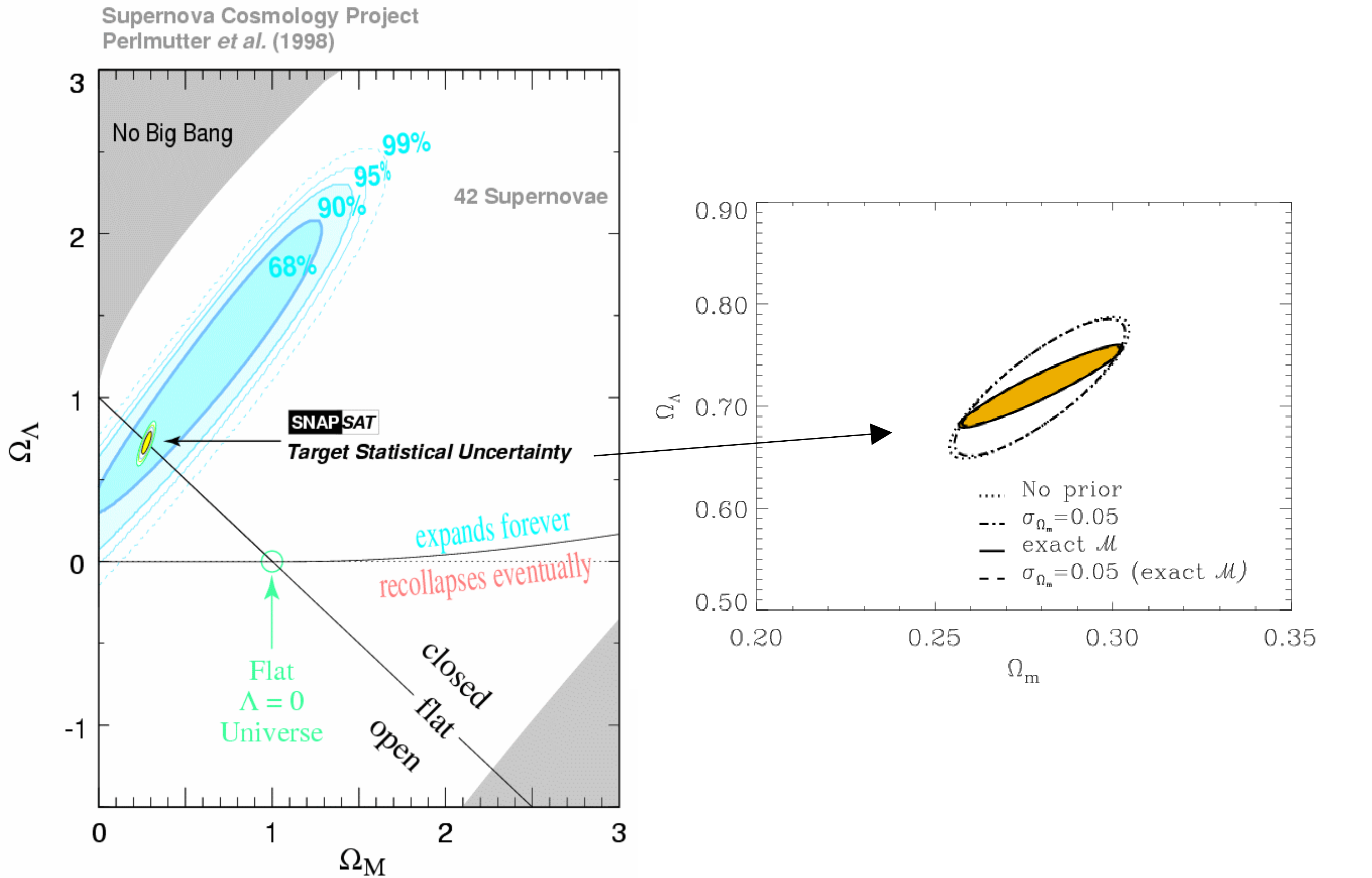


→ consistent with Einstein's Λ

GOODS sample of z > 1 SNe (Riess et al 2004)

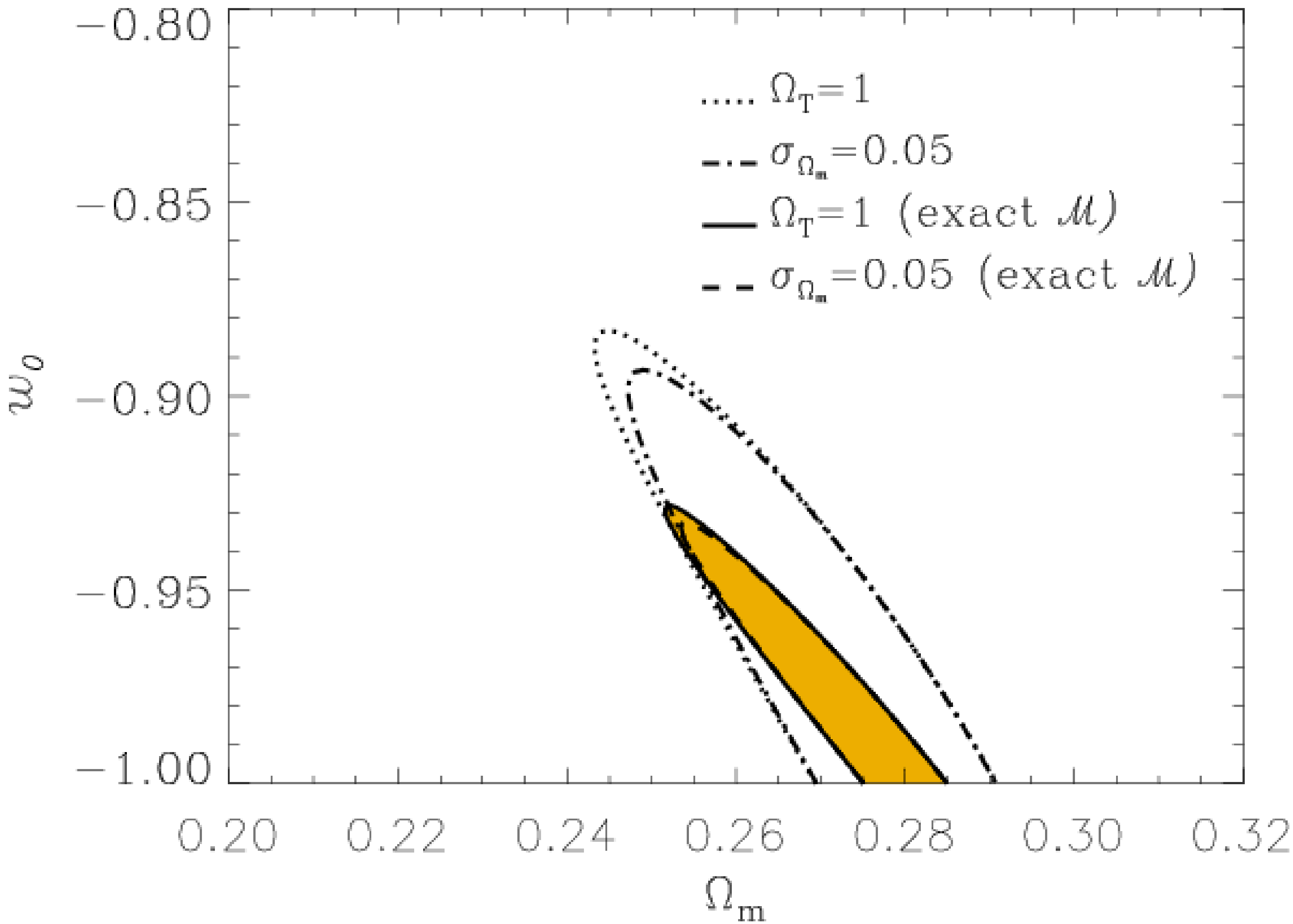


Interpretation depends crucially on UV spectrum

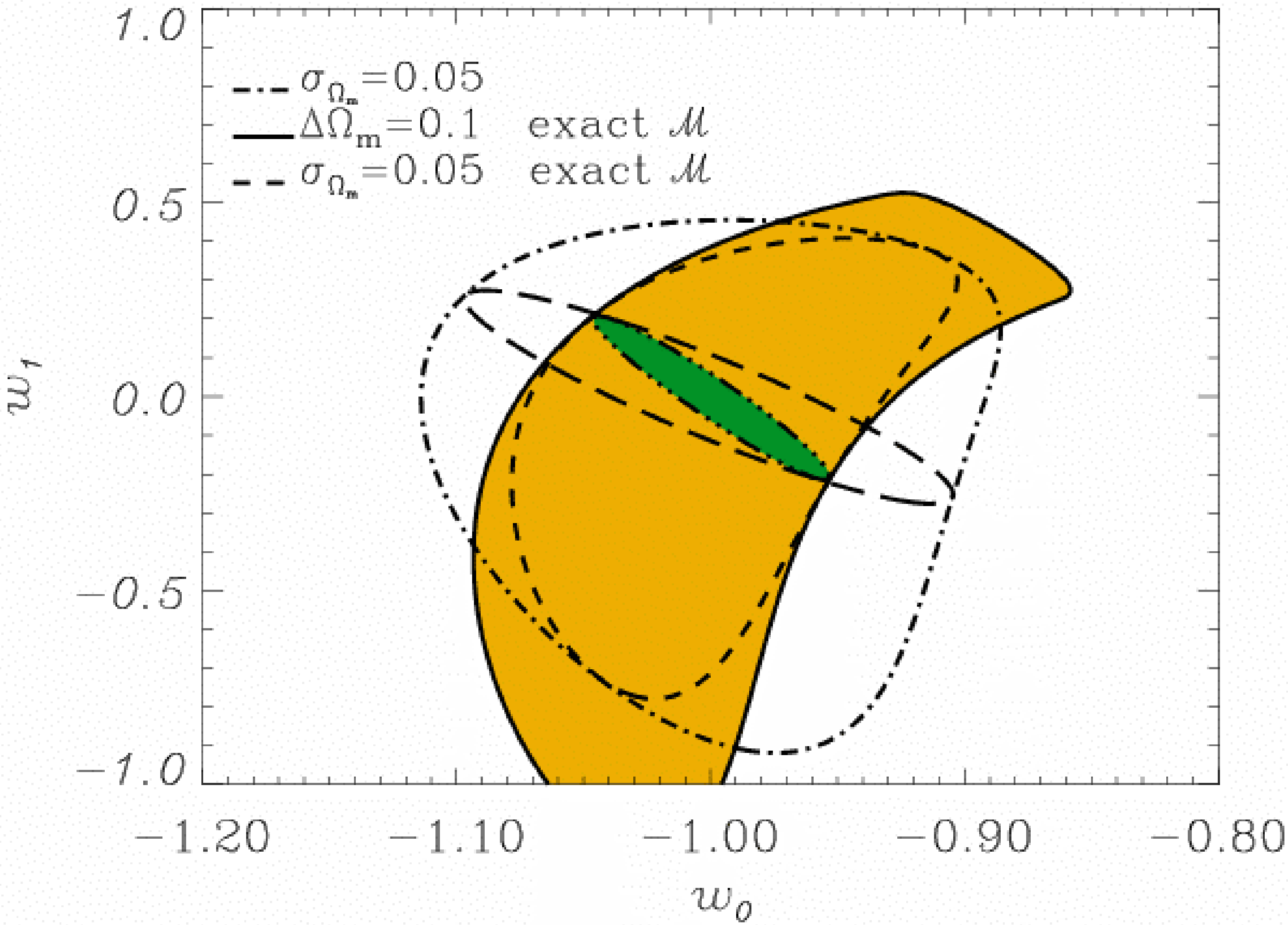


Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAP SAT
Target Statistical Uncertainty
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
Ω_Λ
Ω_M
Ω_Λ
Ω_m
No prior
σ_{Ω_m}=0.05
exact $\mathcal{M}$
σ_{Ω_m}=0.05 (exact $\mathcal{M}$)

Projected SNAP Sensitivity to DE Equation of State

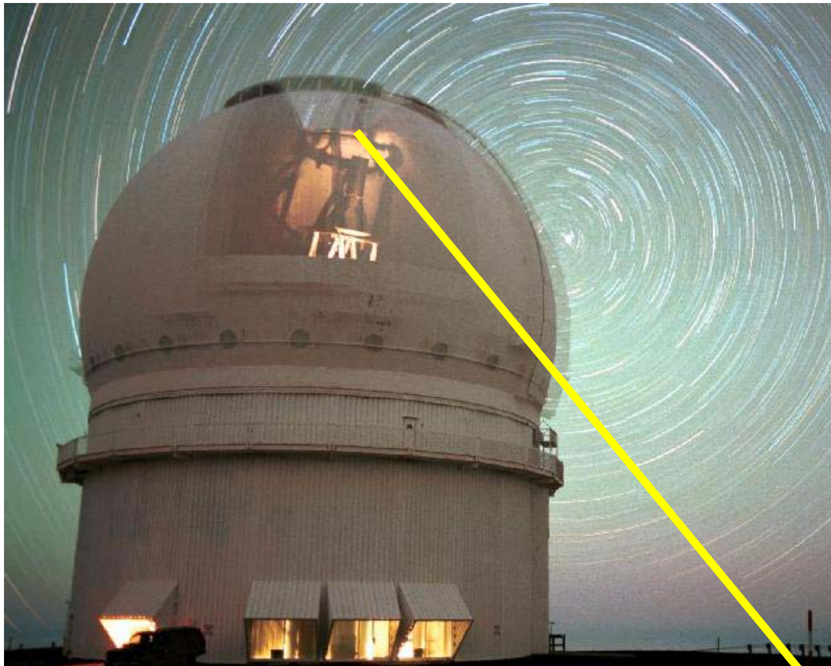


SNAP Sensitivity to Varying DE Equation of State



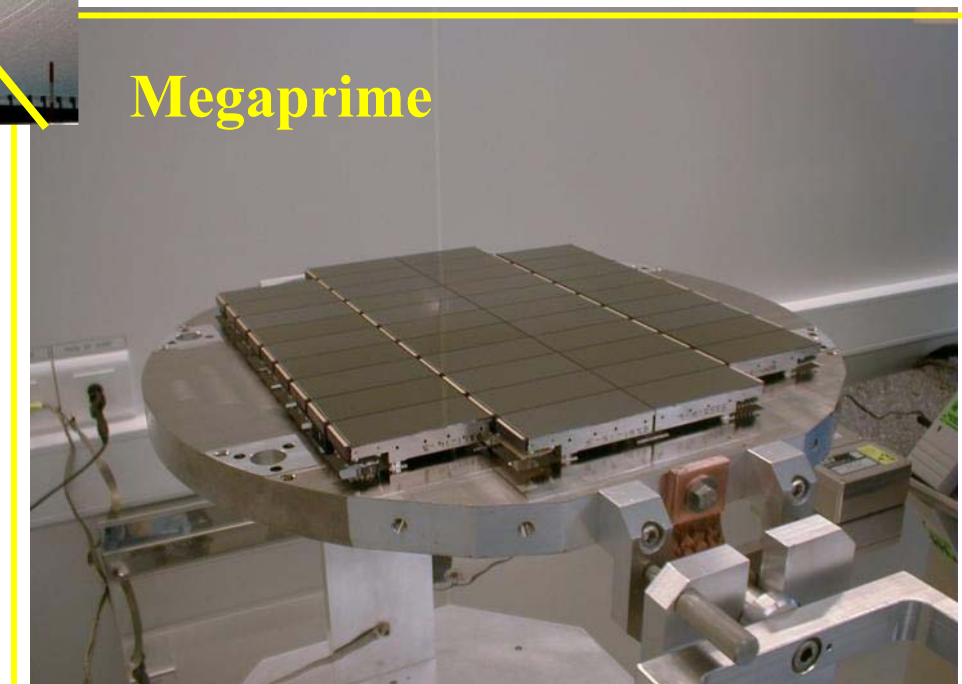
$w = w_0 + w_1 z + \ldots$

CFHT Legacy Survey (2003-2008)



Deep Synoptic Survey

Four 1 × 1 deg fields in 5 nights/lunation
5 months per accessible field
2000 SNe 0.3 < z < 1



Caltech role: verify utility of SNe for cosmology

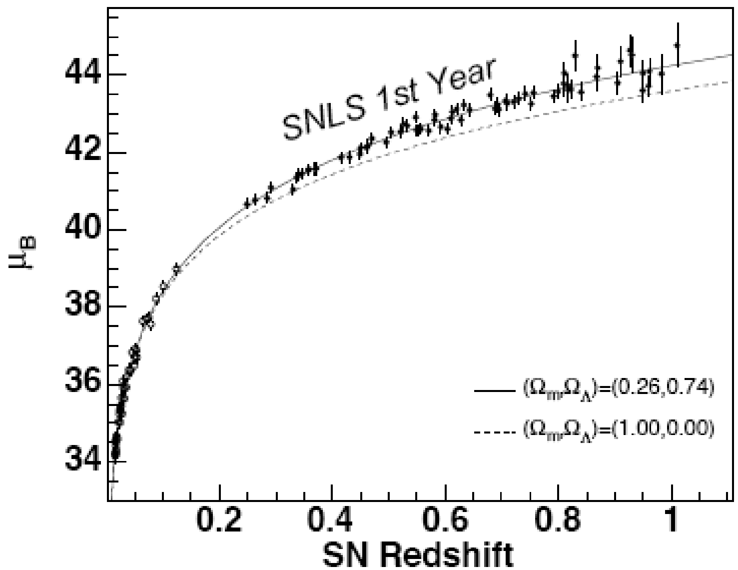
Detailed spectral followup of 0.4<z<0.6 SNe Ia

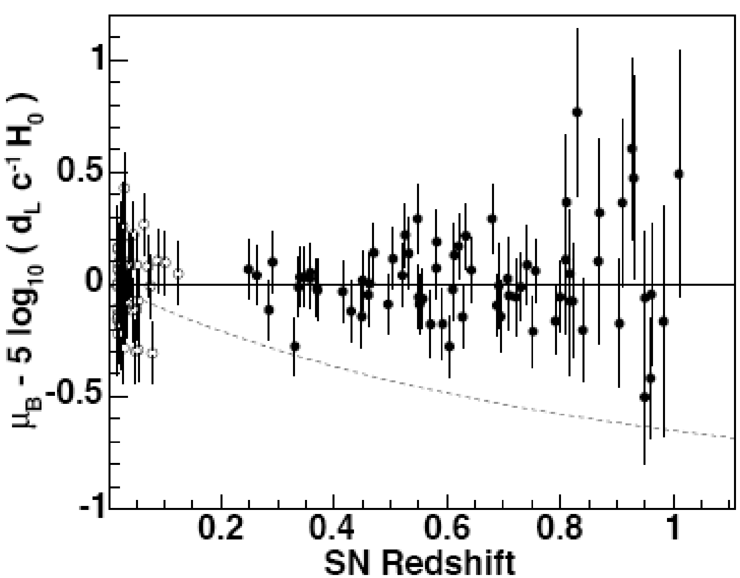
Tests on 0.2<z<0.4 SNe IIP

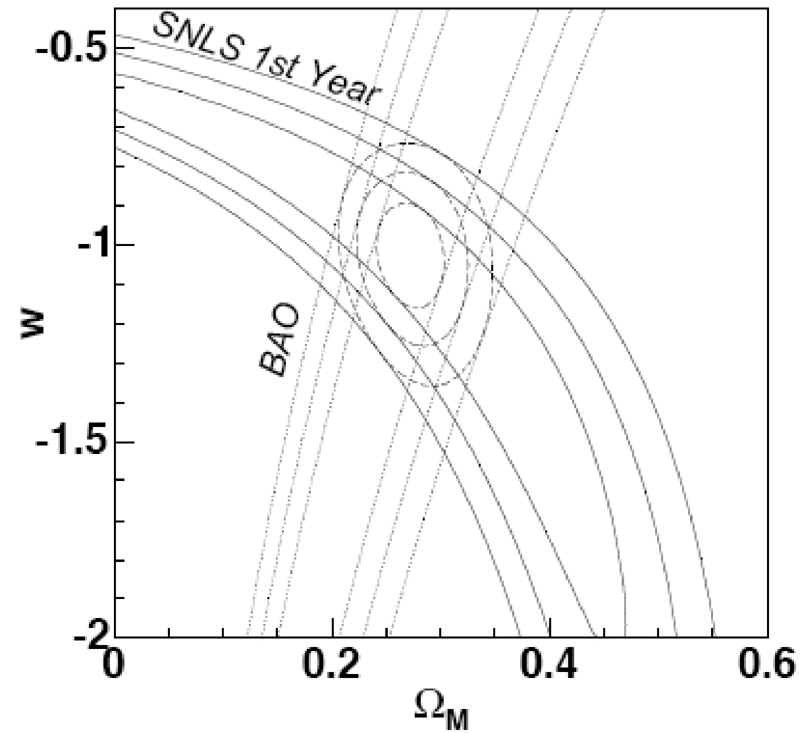
RSE+Sullivan+Nugent+Gal-Yam

Results from CFHT SNLS

Astier et al 2007



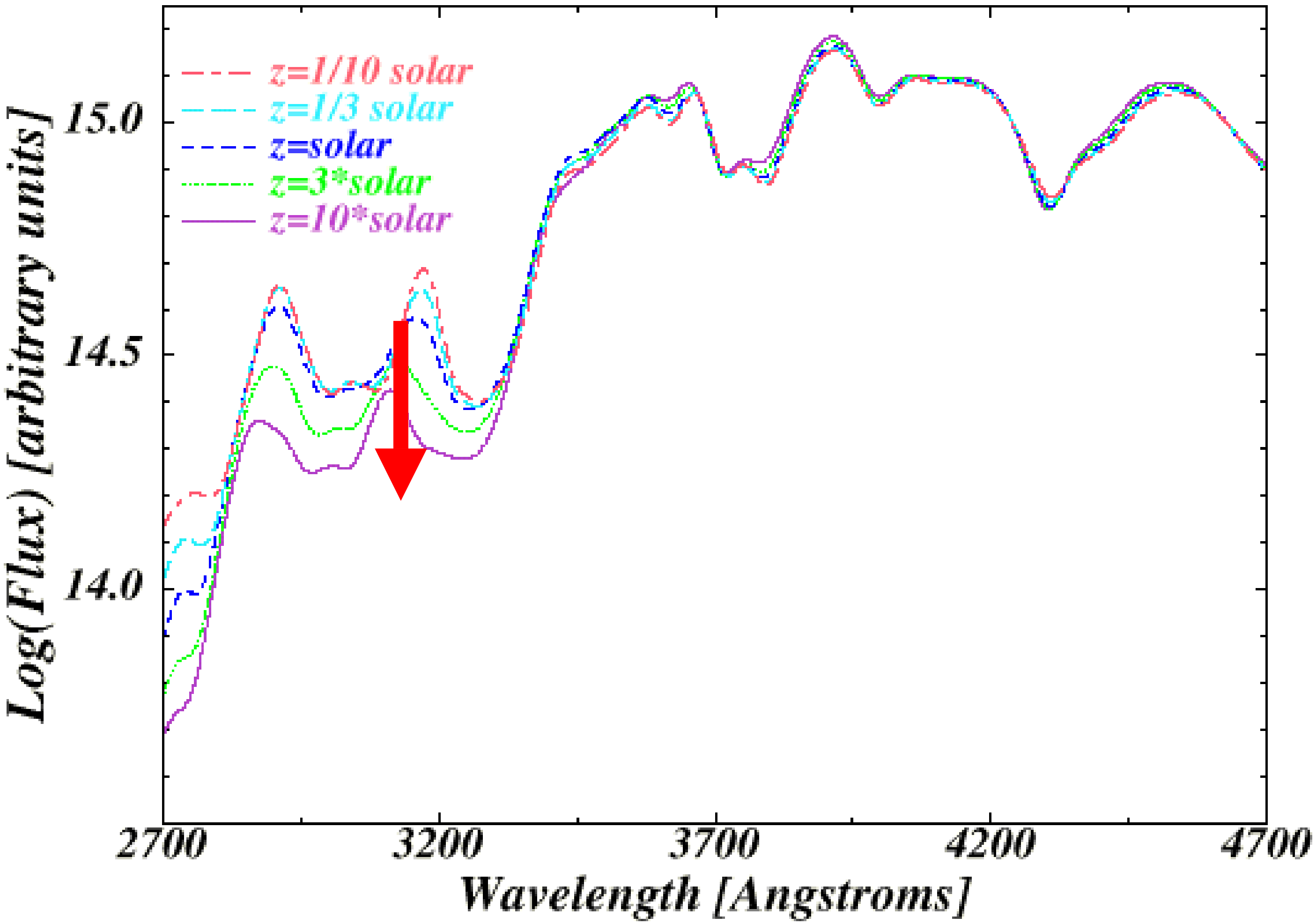




71 homogenously studied SNe Ia

$w = -1.023 \pm 0.090$

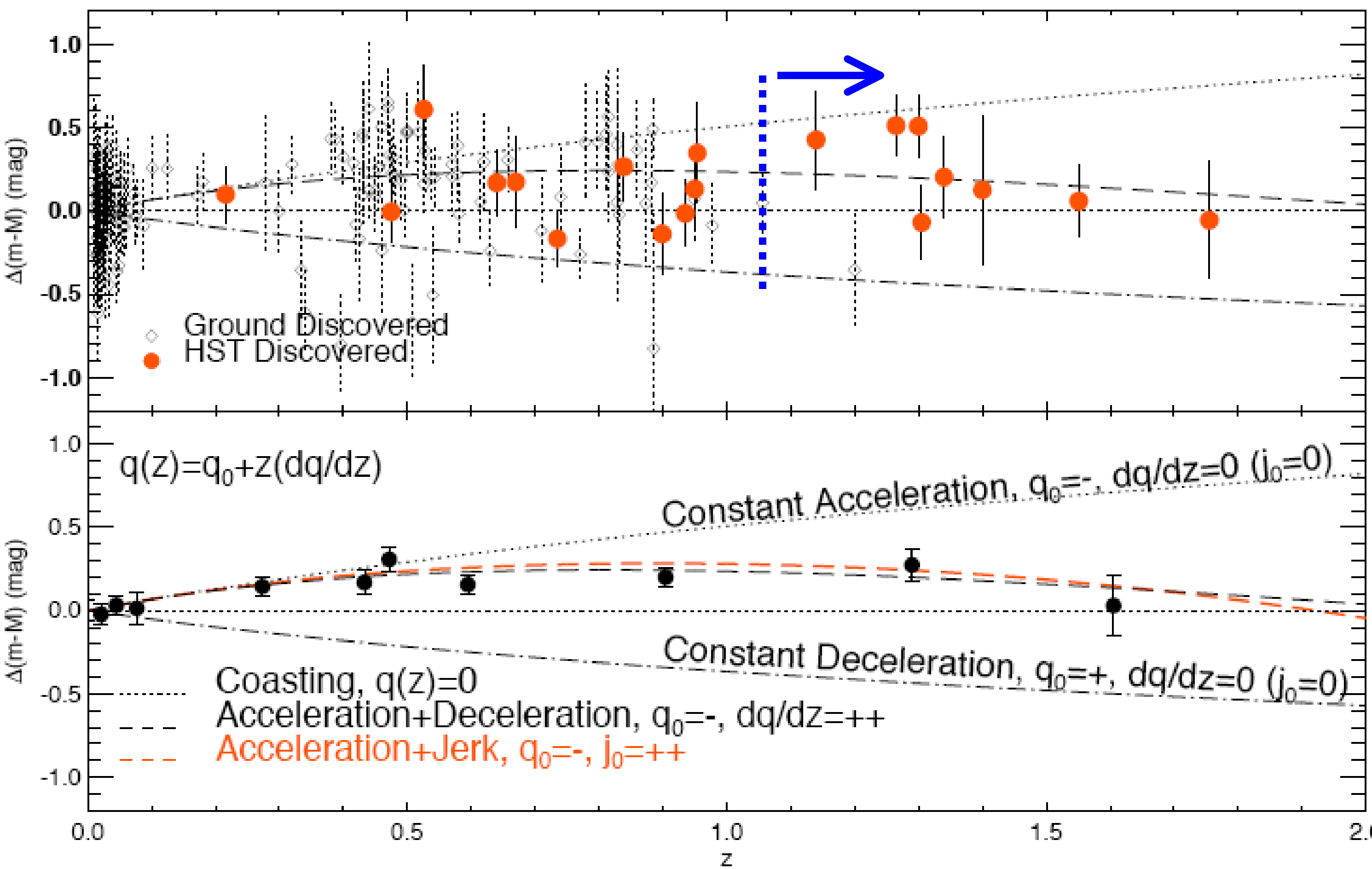
Do SNe Ia Evolve? UV Spectrum Probes Metallicity



Strong UV dependence expected from deflagration models when metallicity is varied in outermost C+O layers (Lenz et al 2005)

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

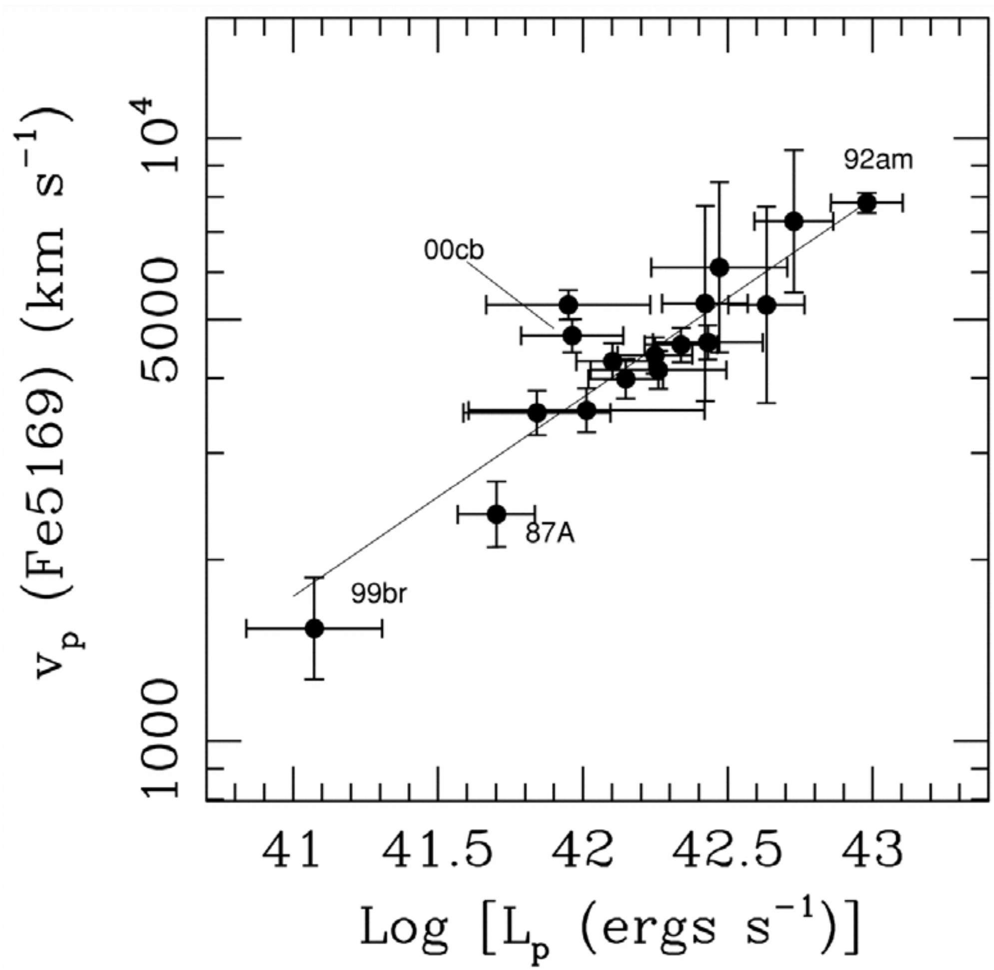
Beyond z~1, UV dispersion affects color k-correction



Can Acceleration be deduced from SNe IIP?

Hamuy & Pinto (2002) propose a new "empirical" correlation (0.29 mag, 15% in distance) between the expansion velocity on the plateau phase and the bolometric luminosity with reddening deduced from colors at the end of plateau phase.

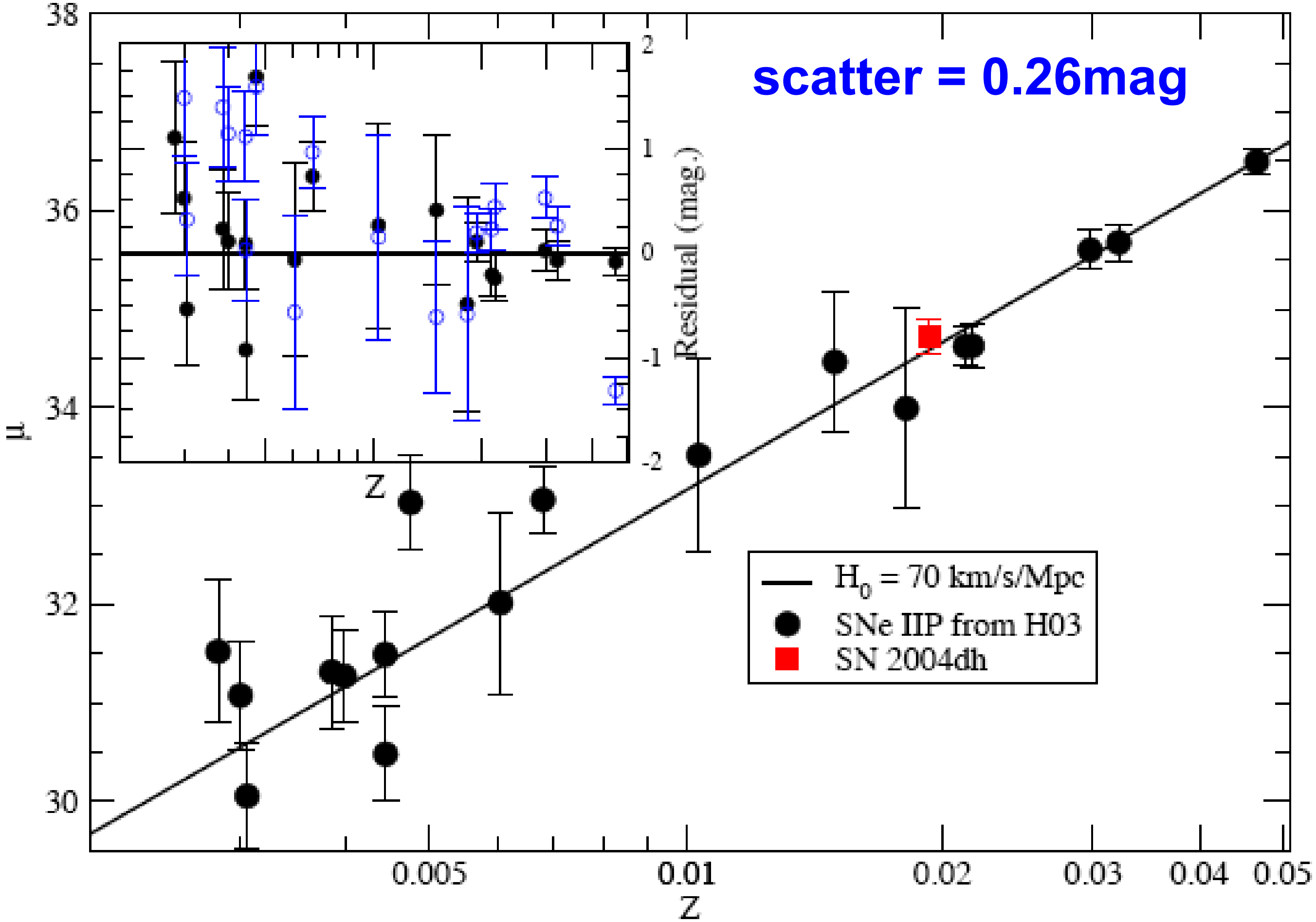
Ultimately the Hubble diagram of SNe IIP could provide an independent verification of the cosmic acceleration, but more importantly be more promising probe of dark energy with JWST/TMT



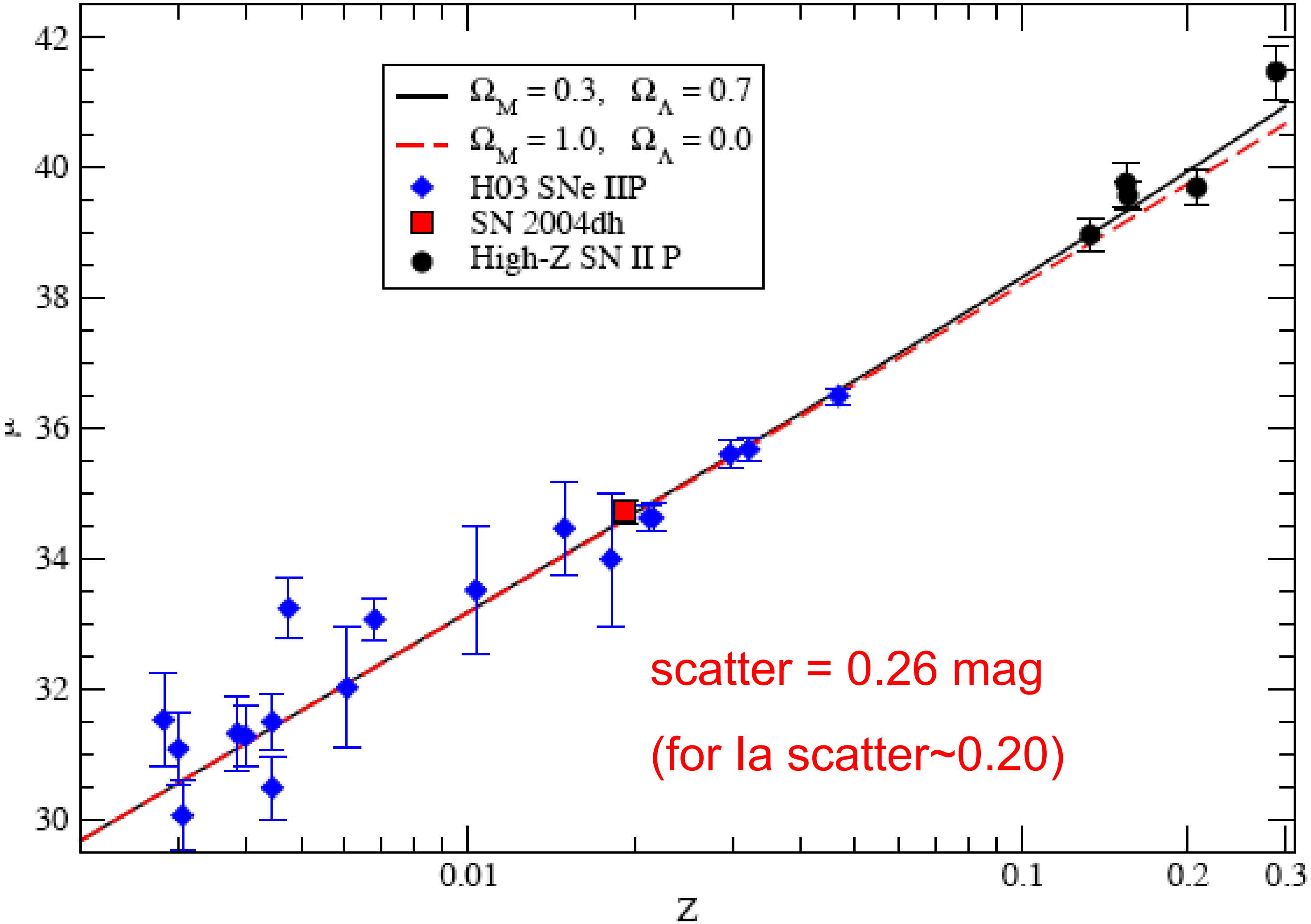
New Local Hubble Diagram for SN IIP

Modified Hamuy & Pinto (2002) method to make it easier for hi-z work:

- measure velocity, color & luminosity at t=50 days, not at end, of plateau phase
- increase choice of absorption lines for measuring expansion velocities



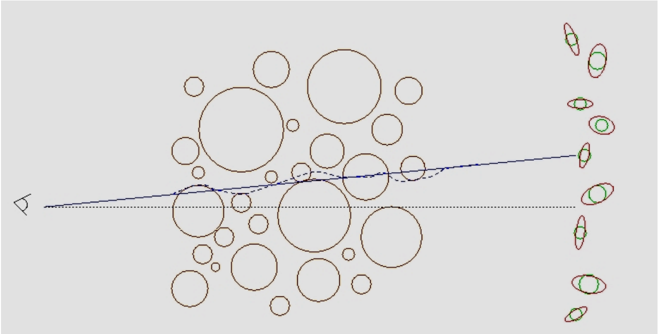
First Cosmological Hubble Diagram for SNe IIP



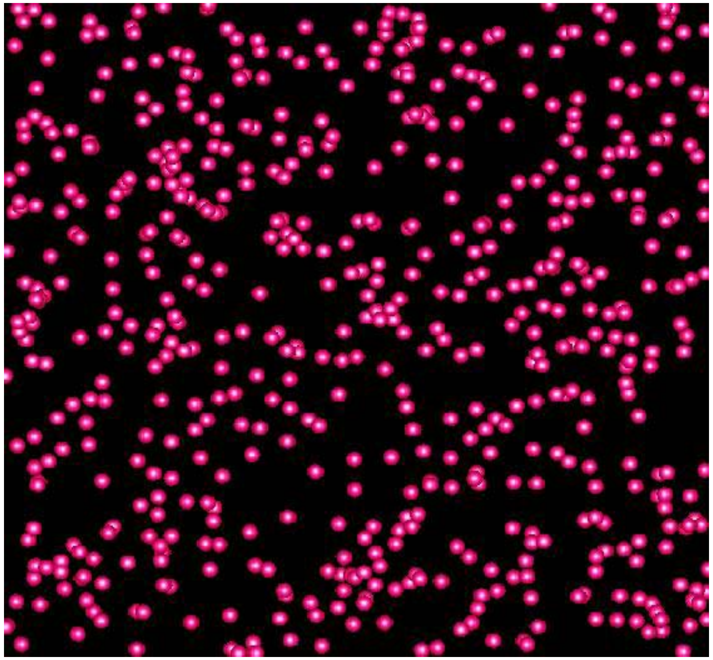
Will soon `detect' acceleration with present technology (~15 SNIIP)

More effectively probe to very high z with JWST/TMT (Nugent et al)

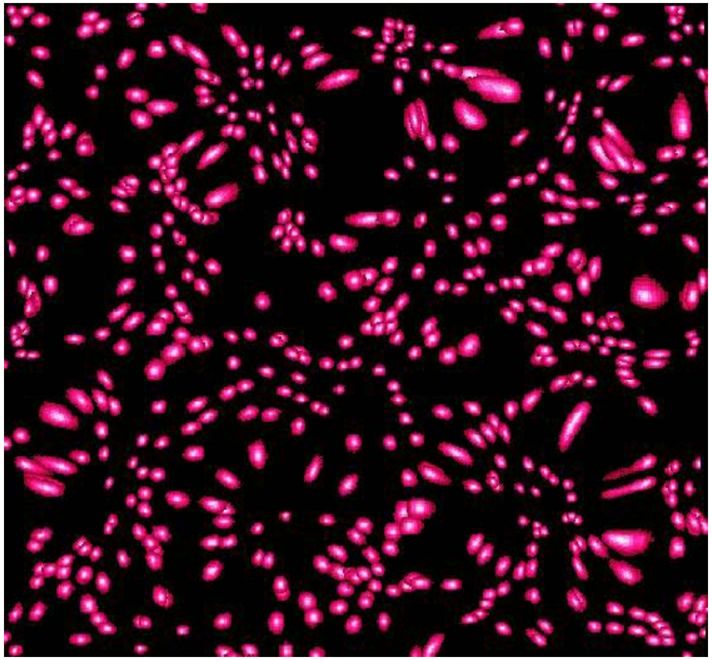
Weak Gravitational Lensing



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



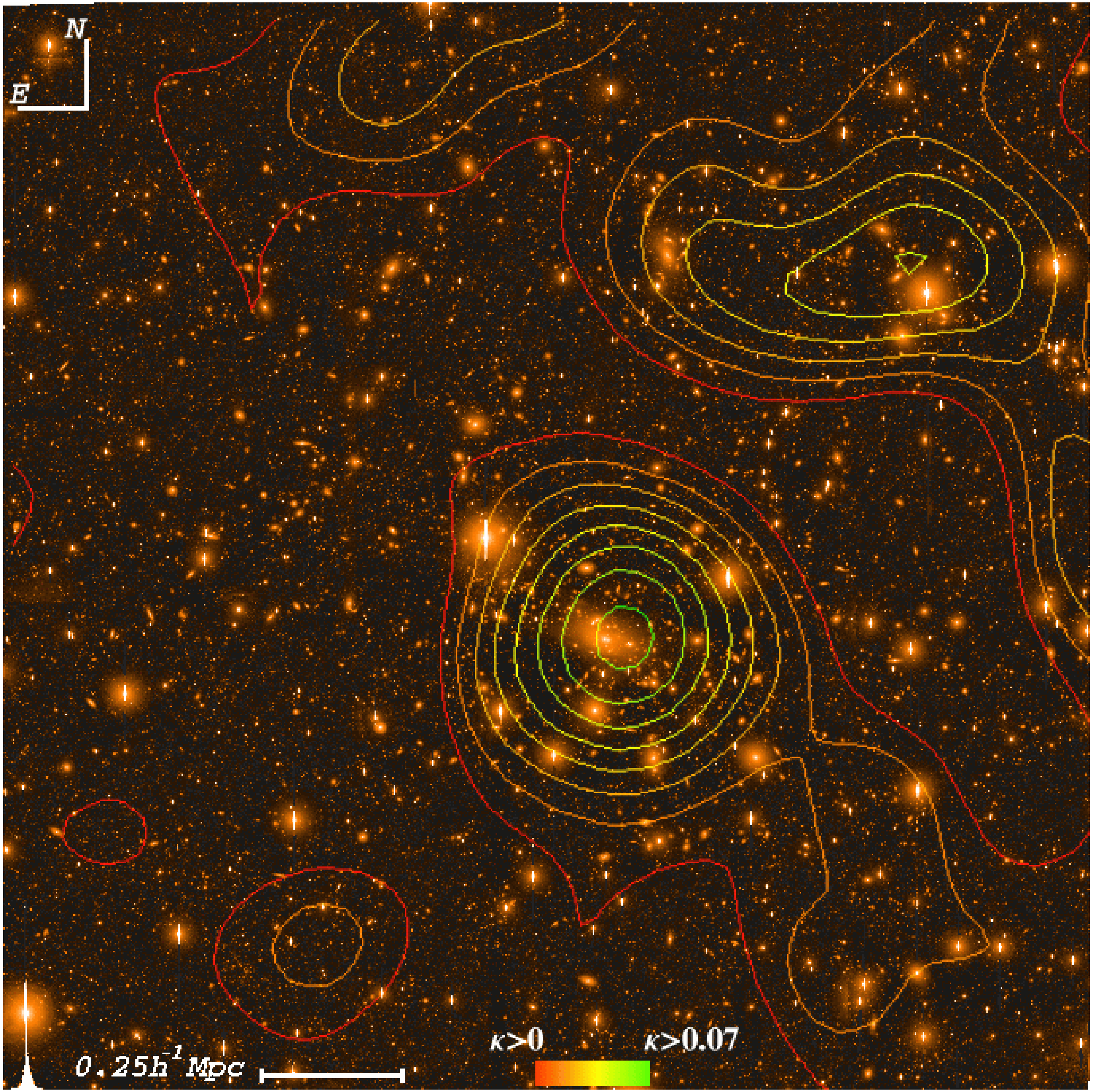
Unlensed



Lensed

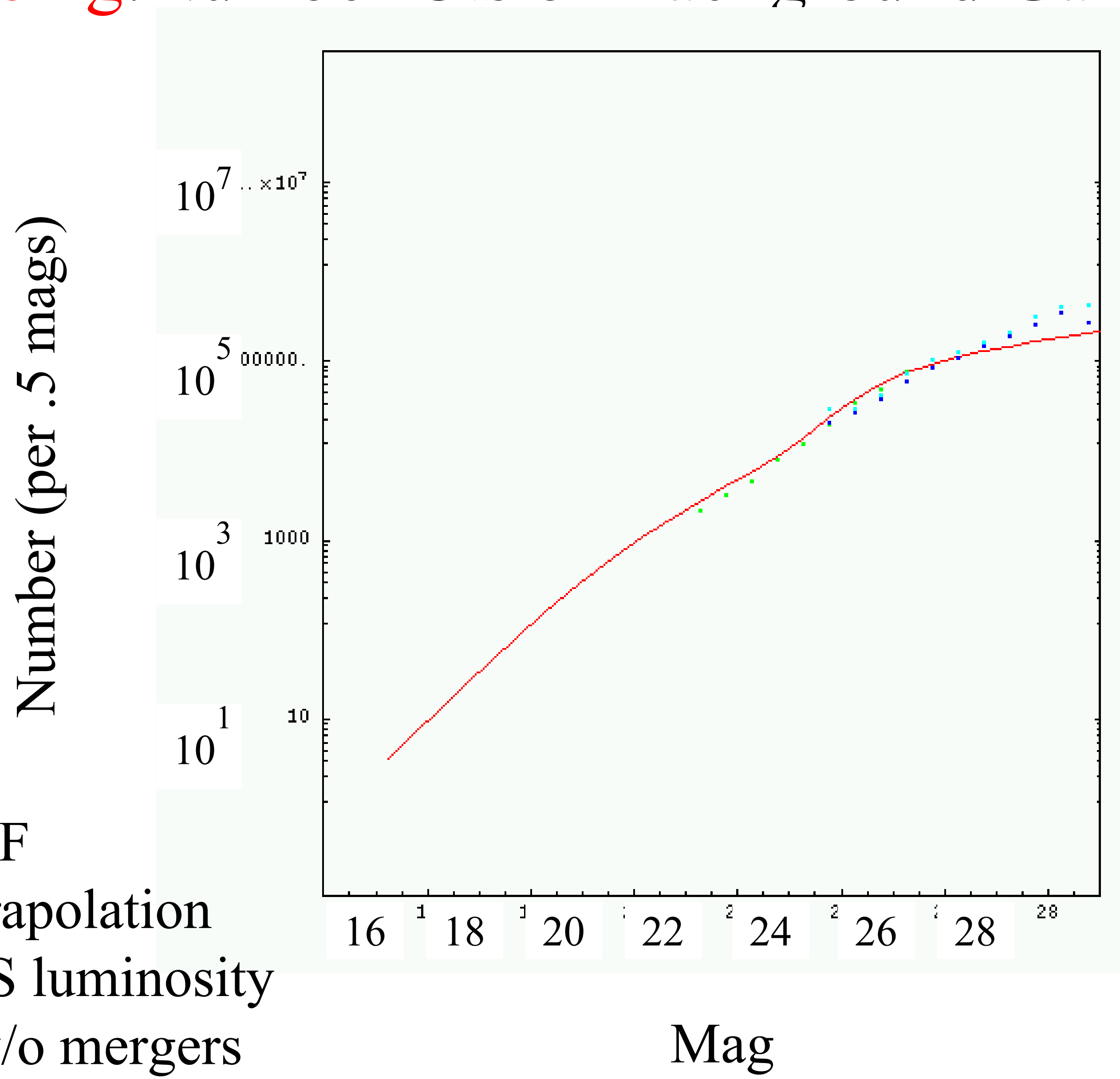
Abell 3667

z = 0.05



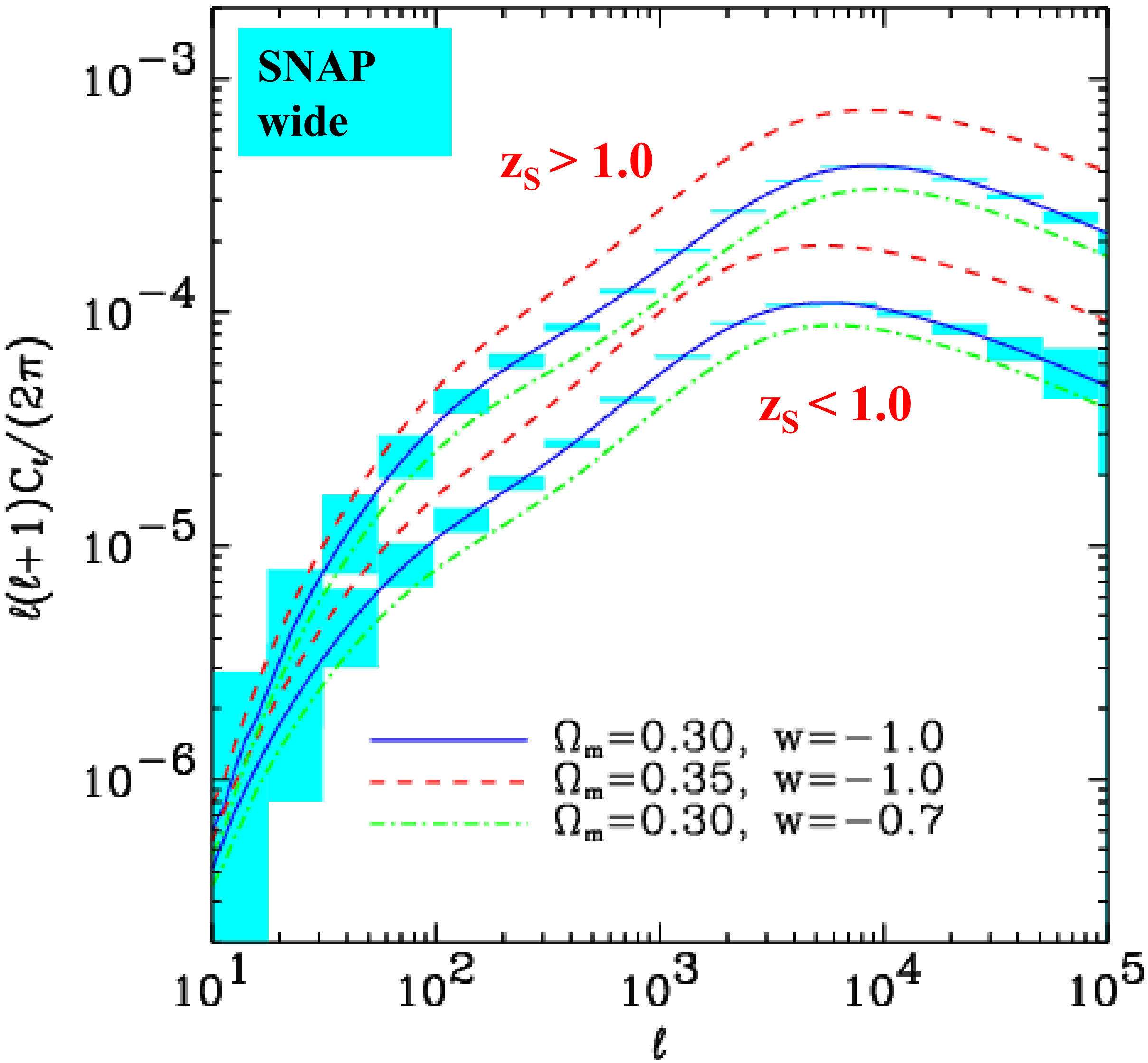
Joffre, et al 2005

Weak Lensing:Number Cts of Background Galaxies



Points: HDF
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)

Hubble "Cosmic Evolution Survey"

- 2 deg^2 Hubble data in 625 contiguous fields (largest ever Hubble program)
- > 2 million faint galaxies with measurable shapes
- Multicolor follow-up from Subaru to get photo-z
- First demonstration of lensing tomography!

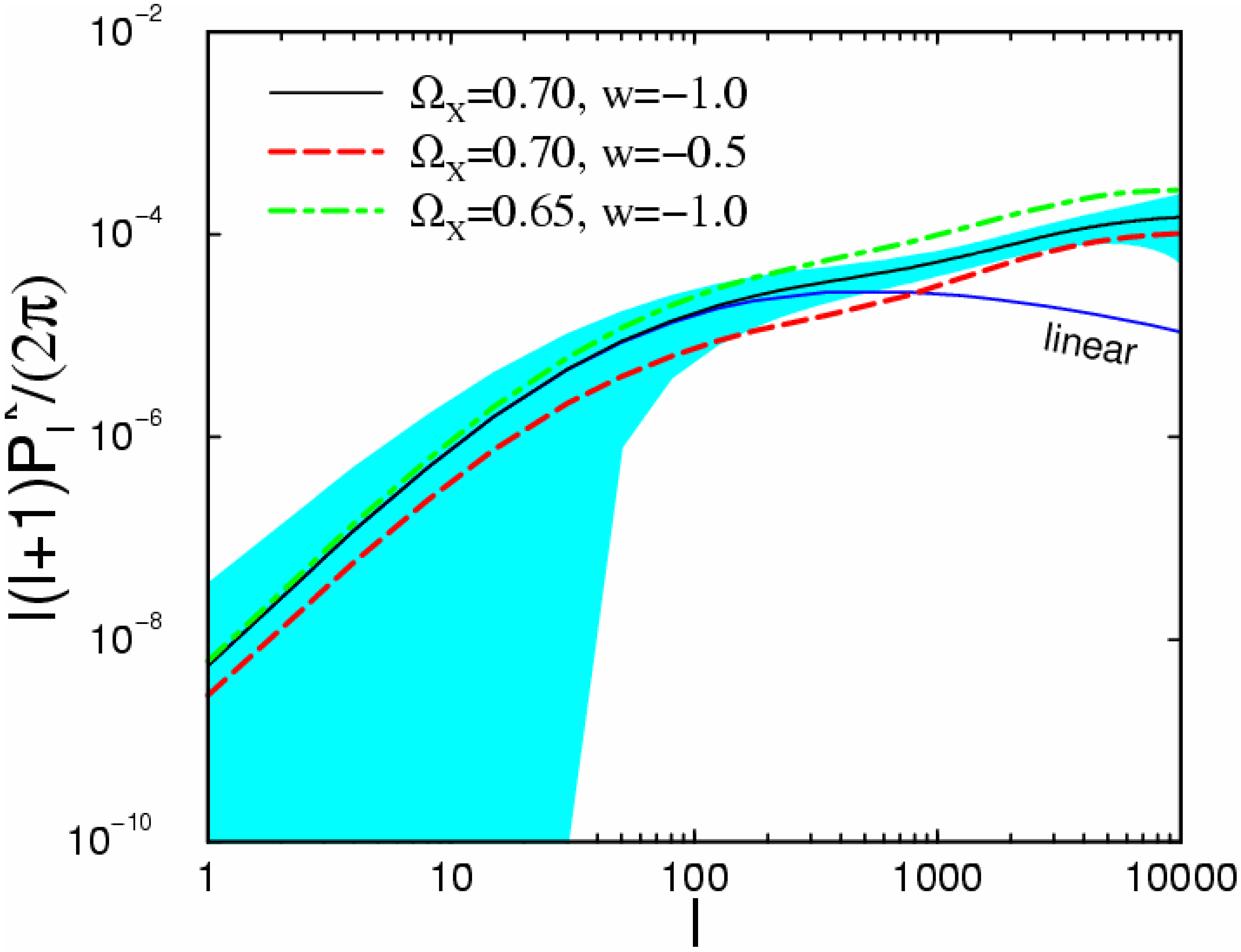
Massey, Rhodes 2005

Is Weak Lensing Going to Cut It..?

- Everyone agrees: WL is a promising probe
- Many believe it is more fundamentally reliable than SNe
- 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

Weak Lensing: Large-scale shear

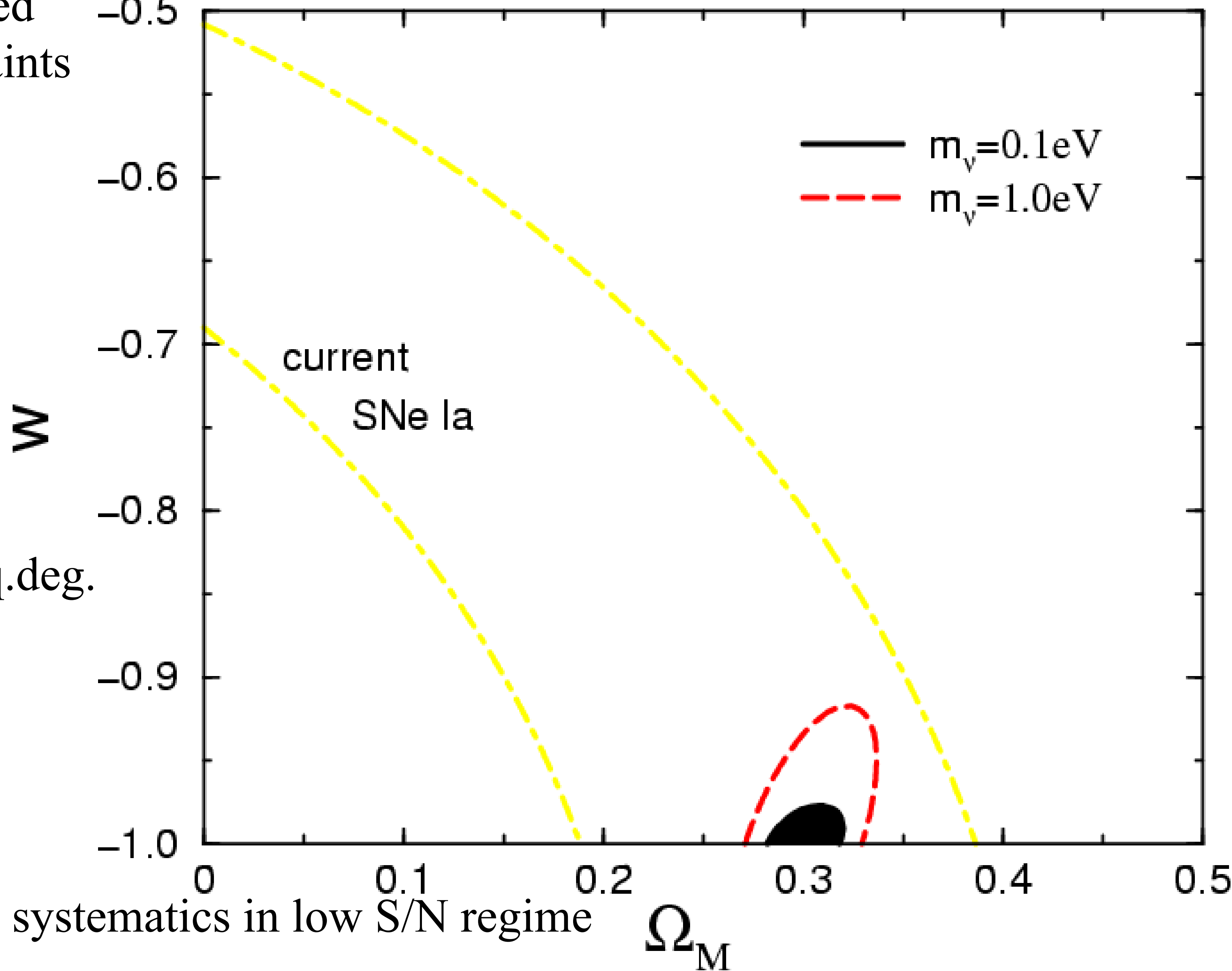
Convergence Power Spectrum



Huterer 2006

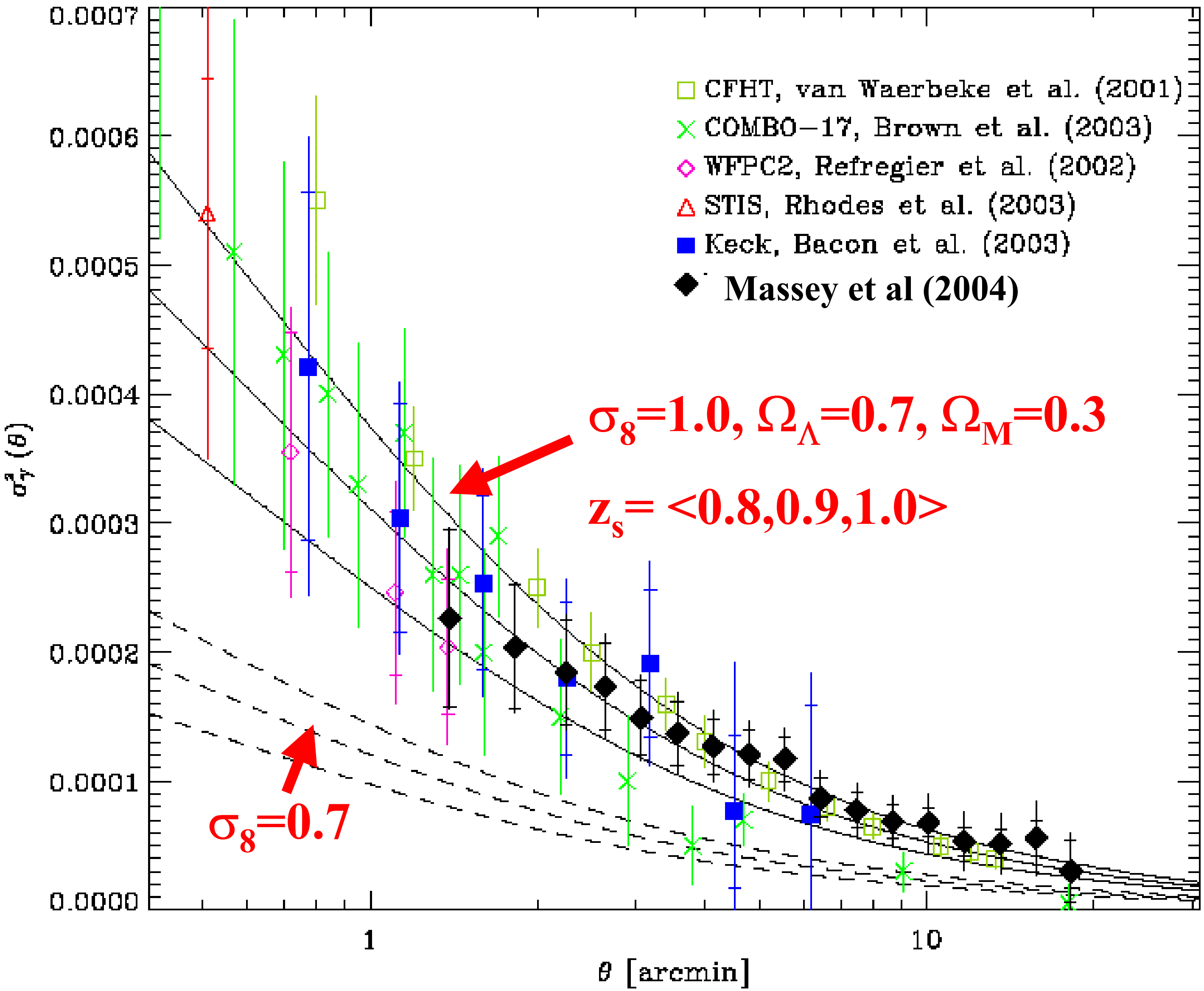
Projected Constraints From Cosmic Shear

1000 sq.deg.



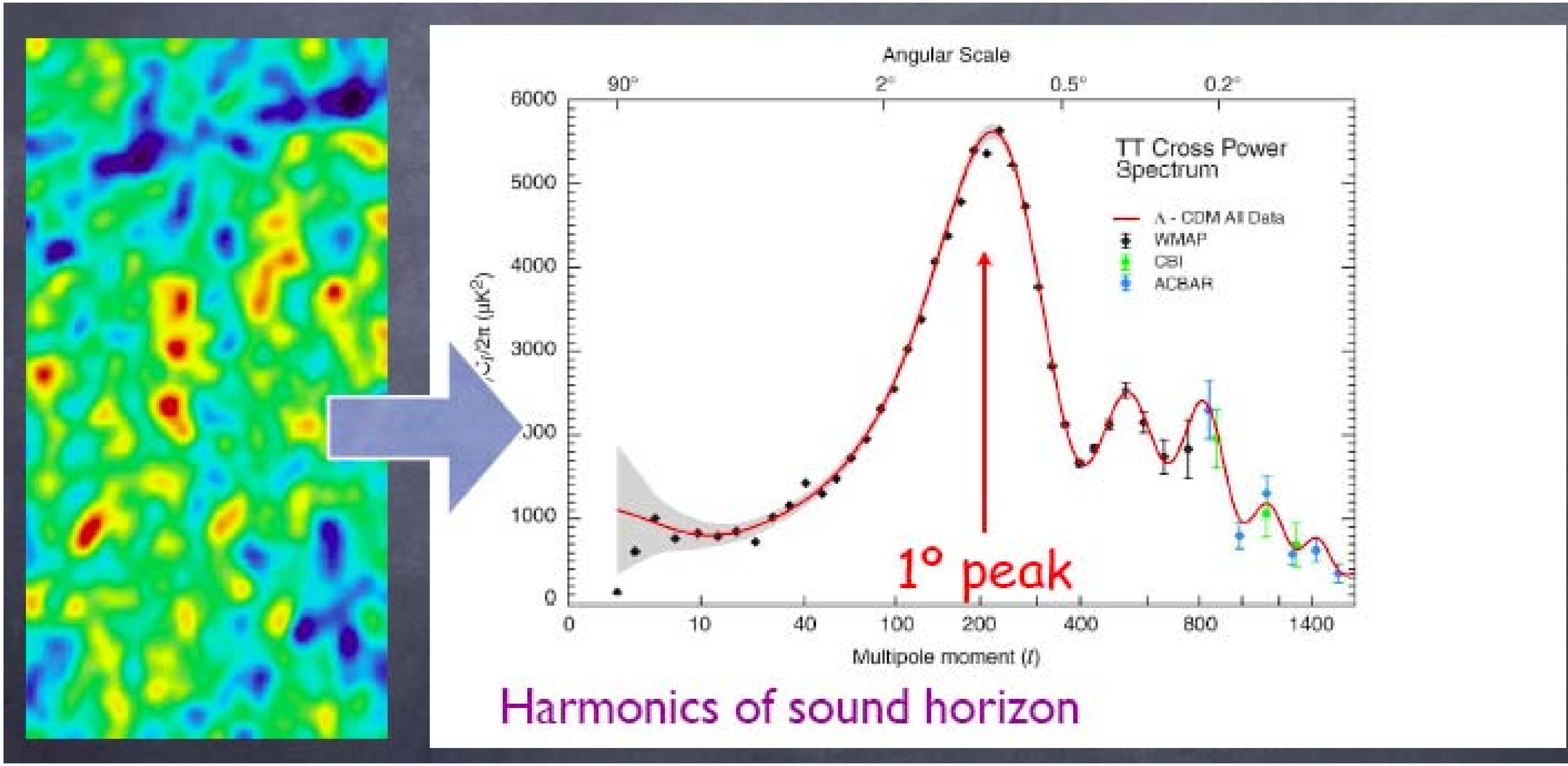
Caveat: systematics in low S/N regime

Shear Variance from Surveys



Clearly different methods give different results!

Baryonic Features in the Large Scale Structure



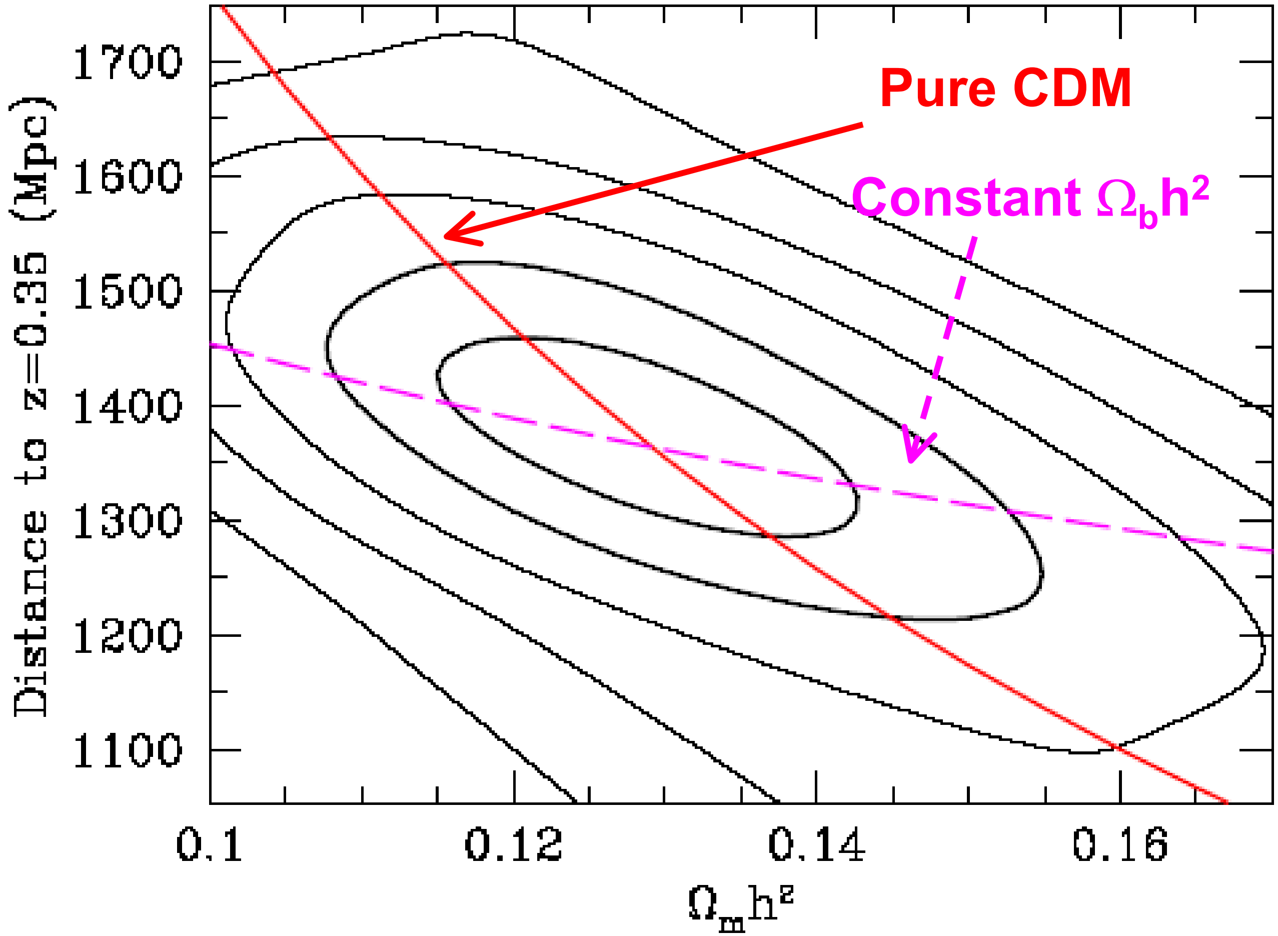
Weak residual of acoustic peaks will be seen in galaxy distribution.
Today, for flat geometry it should be at:

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

Peebles & Yu 1970; Sunyaev & Zel'dovich 1970

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

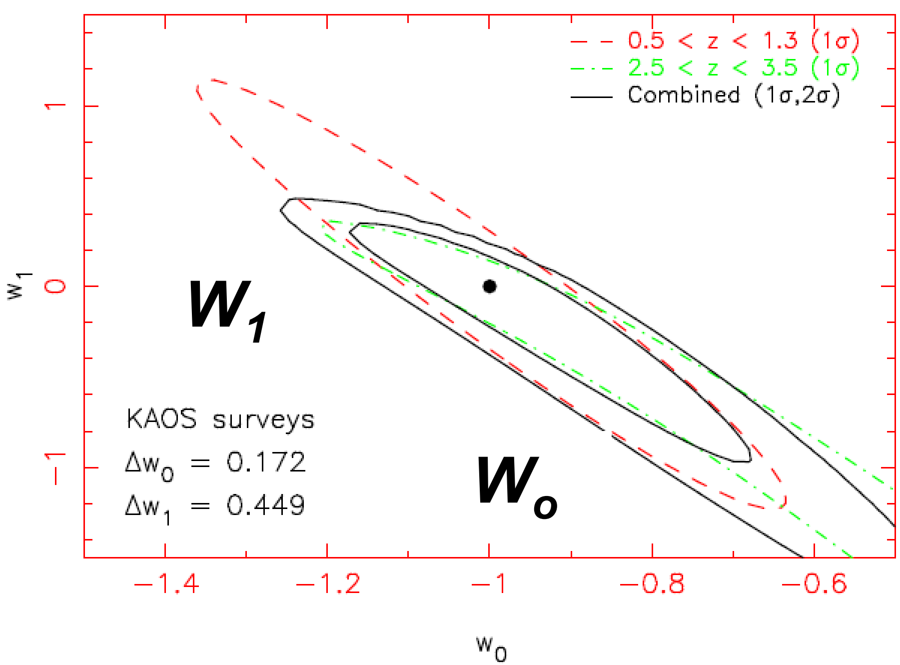
SDSS Constraints

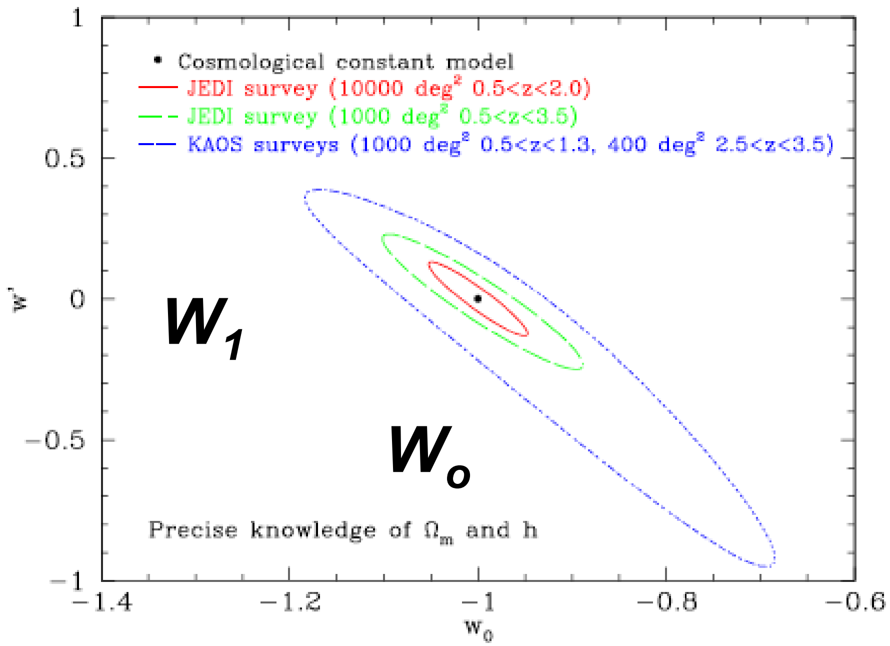


$D_V(z{=}0.35) = 1370 \pm 64$ Mpc (5%); $\Omega_M h^2 = 0.130 \pm 0.011$ (8%) fixed Ω_b, n

Baryon signature detected at 3.4σ; With CMB: $\Omega_K = -0.01 \pm 0.009$ ($w=-1$)

Baryon Oscillation Probes





WFMOS being considered for Subaru 8m telescope

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

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

4000 fibers, 200 clear nights

JEDI: contender for JDEM

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

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

Furthermore we can use time-based measurements using the

LOOKBACK TIME

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

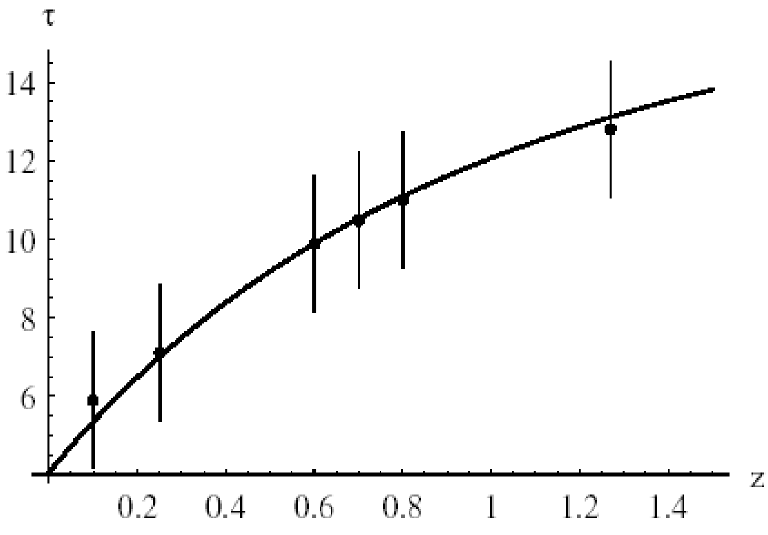
Light travel time from an object at redshift z

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

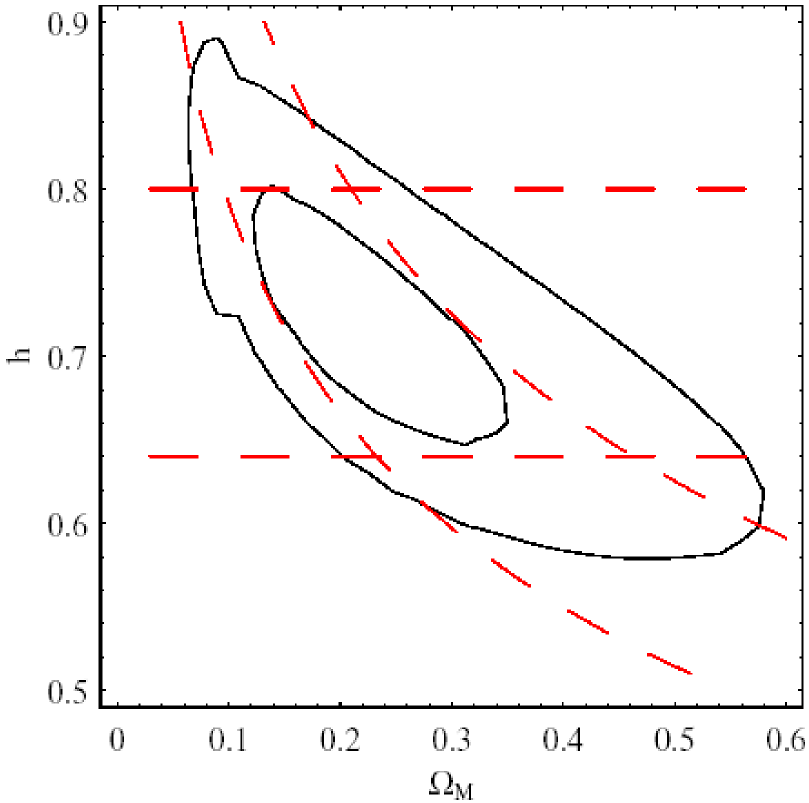
The estimated age of the Universe today minus the lb-time gives the delay factor related to the ignorance on the formation redshift z_F of the object. We used galaxy clusters, radio-galaxies and quasars.

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

ΛCDM models

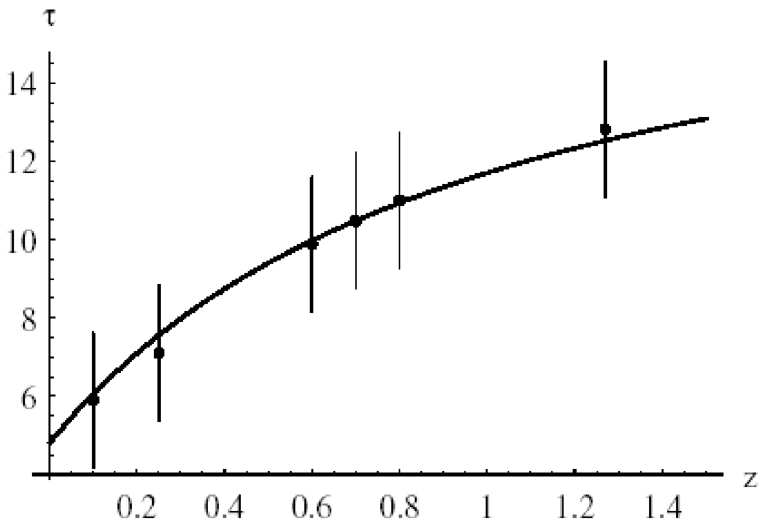


Comparison between predicted and observed values of $\tau(z) = t_{lb} + df$ for the best fit ΛCDM models

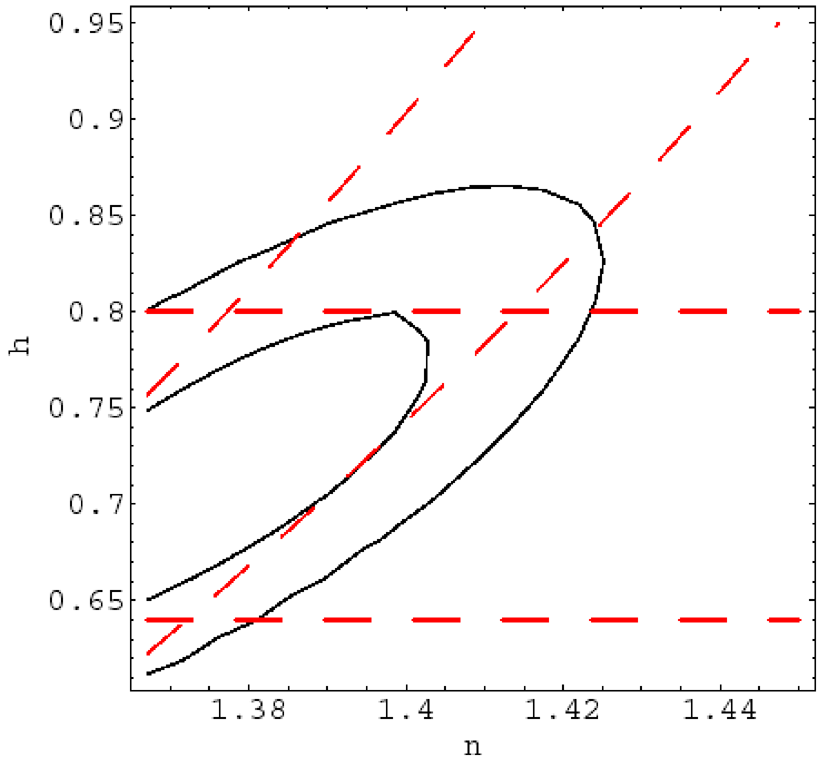


The 1σ and 2σ confidence regions for the ΛCDM models.

$f(R)$ Models

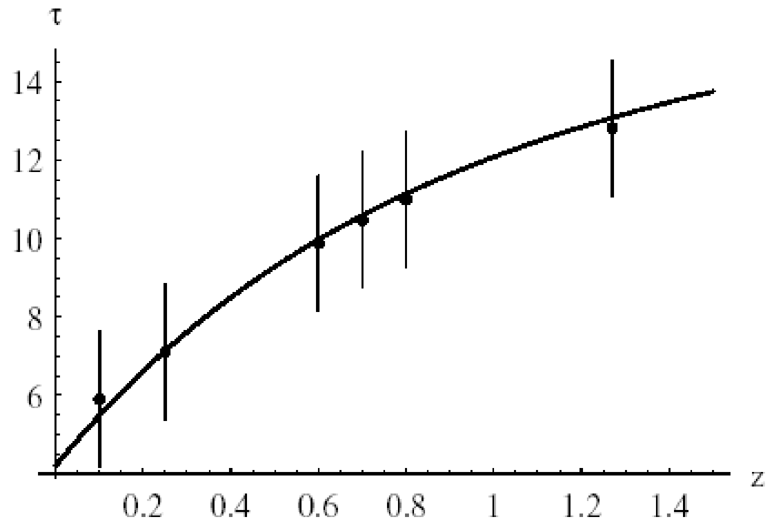


Comparison between predicted and observed values of $\tau(z) = t_{lb} + df$ for the best fit Curvature models

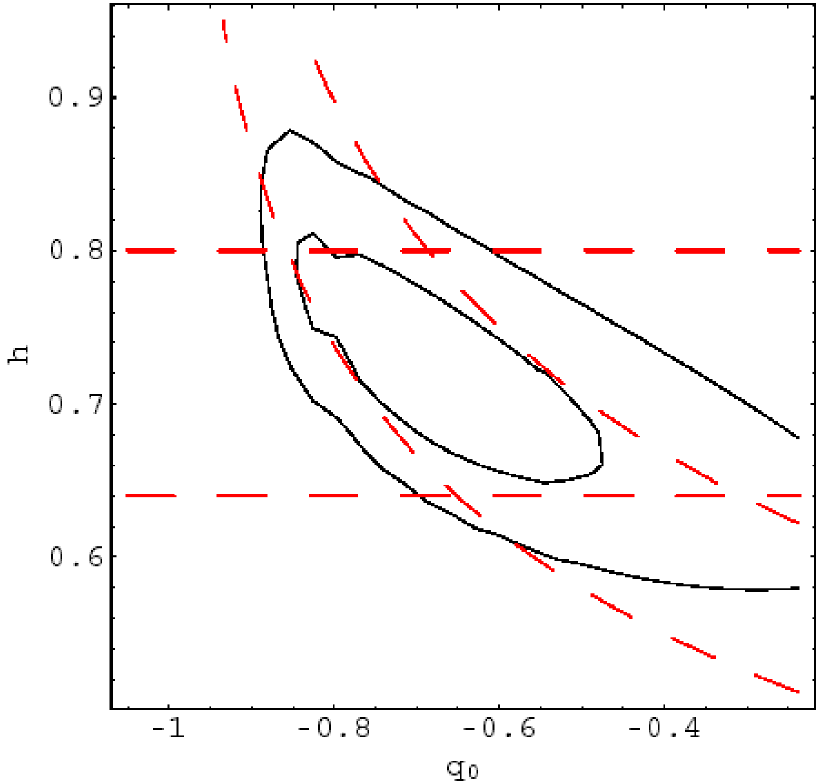


The 1σ and 2σ confidence regions for the Curvature models

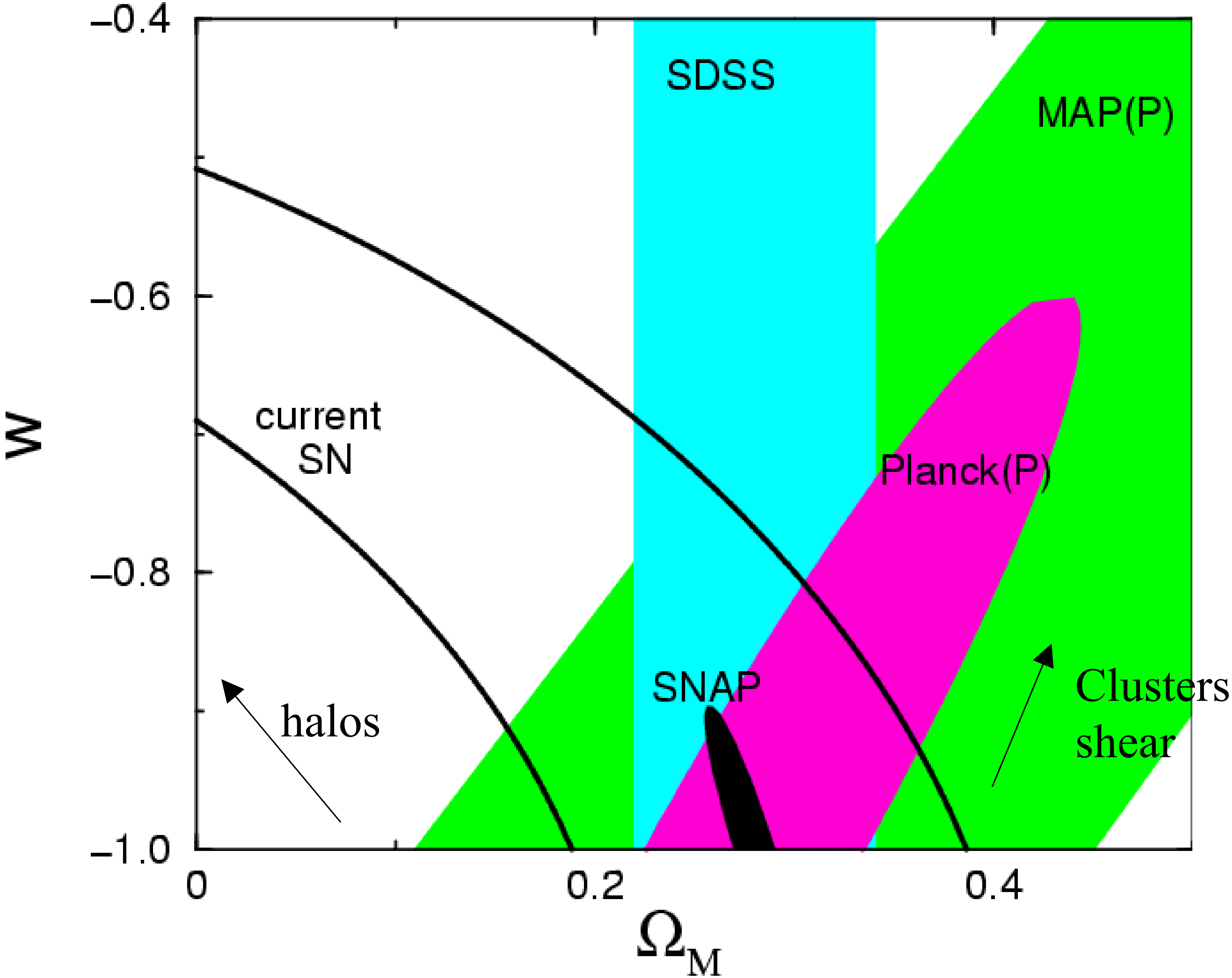
UDE/DM models



Comparison between predicted and observed values of $\tau(z) = t_{lb} + df$ for the best fit UDE/DM models



The 1σ and 2σ confidence regions for the UDE/DM models



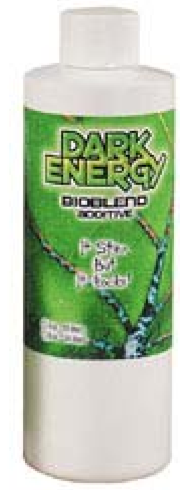
−0.4
−0.6
−0.8
−1.0
0
0.2
0.4
w
Ω_M
SDSS
MAP(P)
current SN
Planck(P)
SNAP
halos
Clusters, shear

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: it represents the new cosmological frontier
- Its characterization is largely the province of the $z<3$ universe; CMB measures will not be sufficient
- There is a sound incremental approach:
  $w\neq-1 \rightarrow w\neq\text{const} \rightarrow w(z)$
- Observers are promoting 3 probes: SNe, WL & BAO; probably need > 1 method spanning $0<z<3$
- Observationally there are formidable challenges
- 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 (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!!

References:

S.C., V. Cardone, M. Funaro, S. Andreon, ***PRD*** 70 (2004) 123501,

S. C., V. Cardone, A. Troisi, ***PRD*** 71 (2005) 043503,

S. C., ***Int. Jou. Geom. Meth.Mod. Phys.*** 4 (2007) 53,

S.C., P. Dunsby, E. Piedipalumbo, C. Rubano, ***A&A*** 472 (2007) 51,

S.C. and M. Francaviglia (Special Issue on Dark Energy) ***GRG*** 40 (2008) 357

S.C., V. Cardone, V. Salzano, to appear in ***PRD*** (2008) arXiv: 0802.1583