Understanding the Properties of Dark Energy in the Universe

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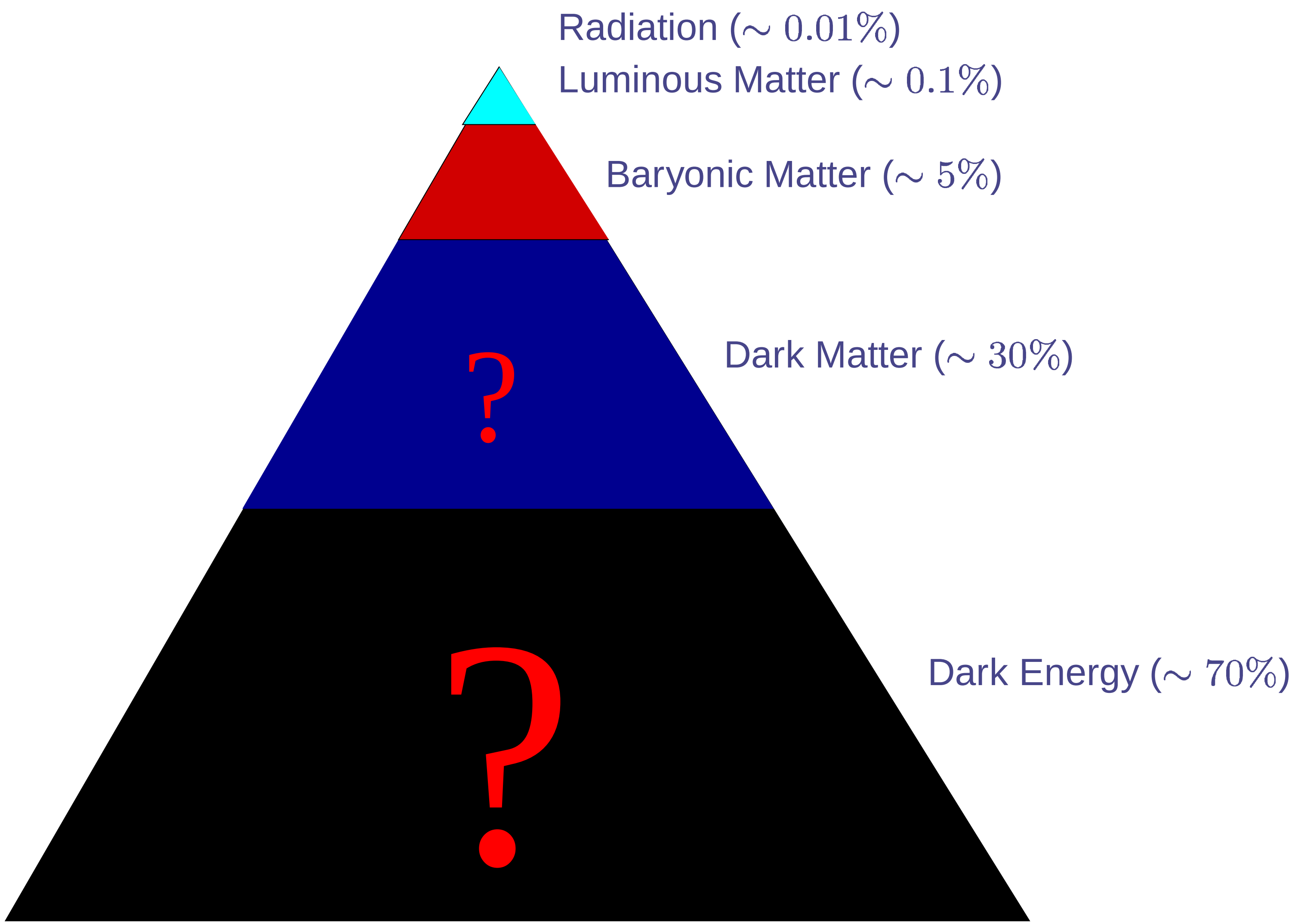
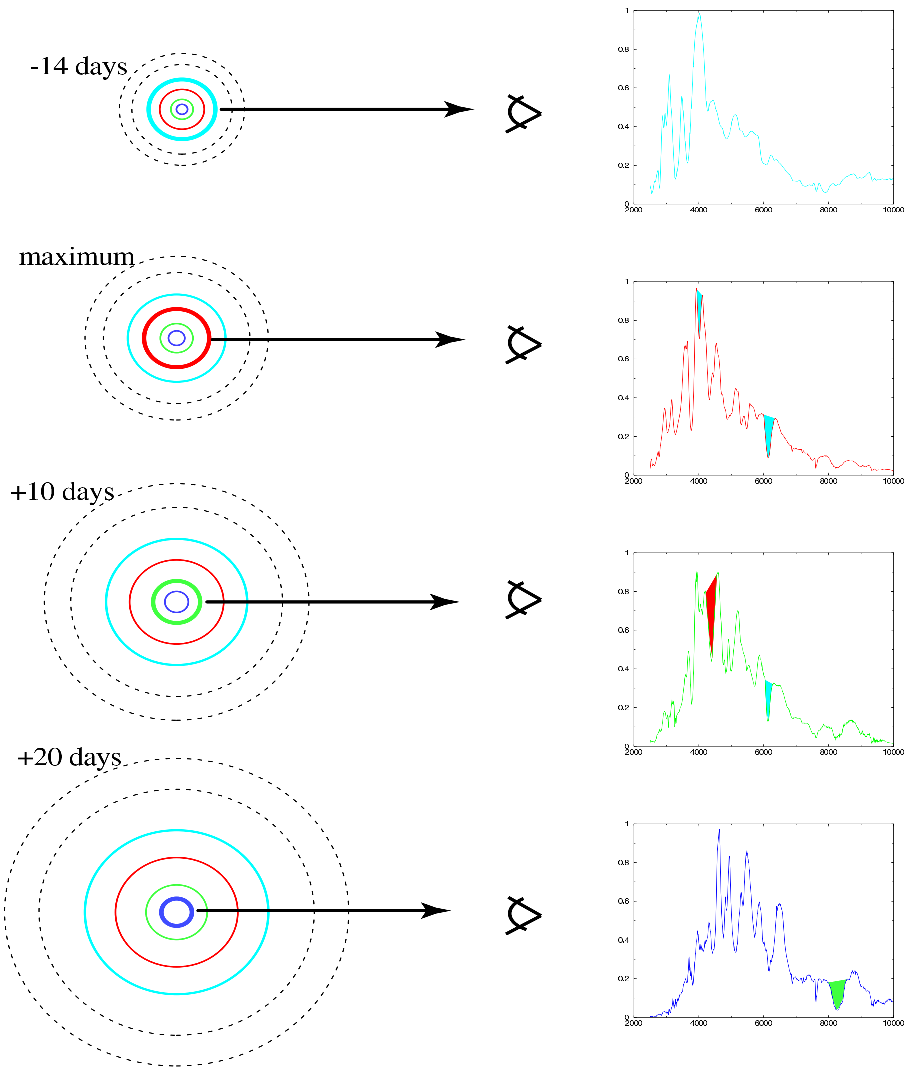
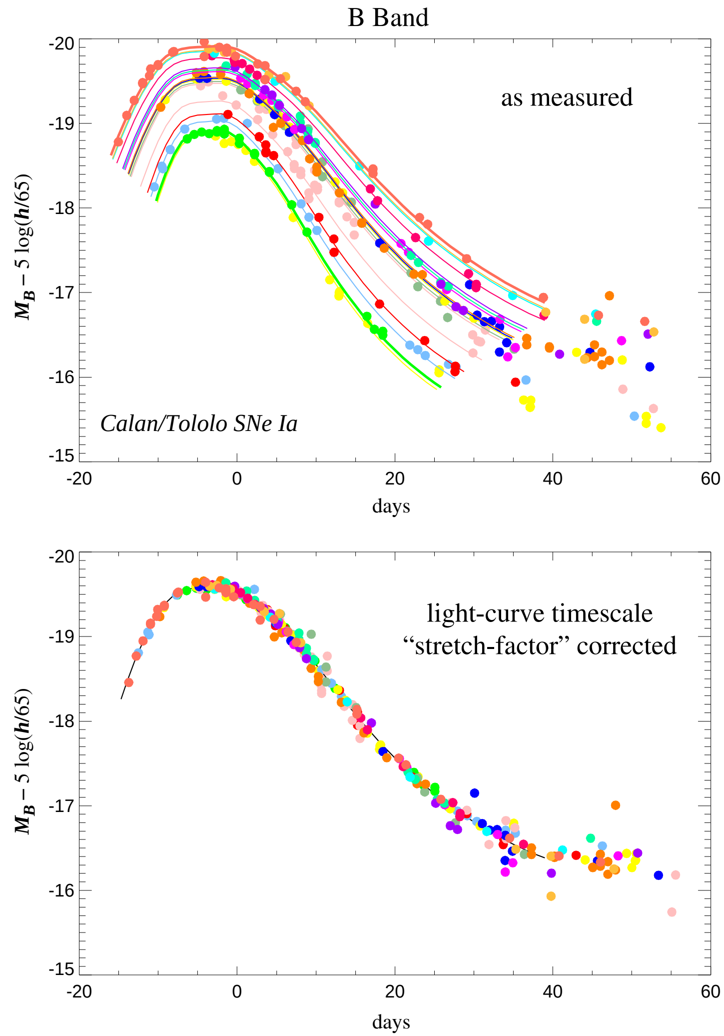
The Cosmic Food Pyramid



Type Ia Supernovae

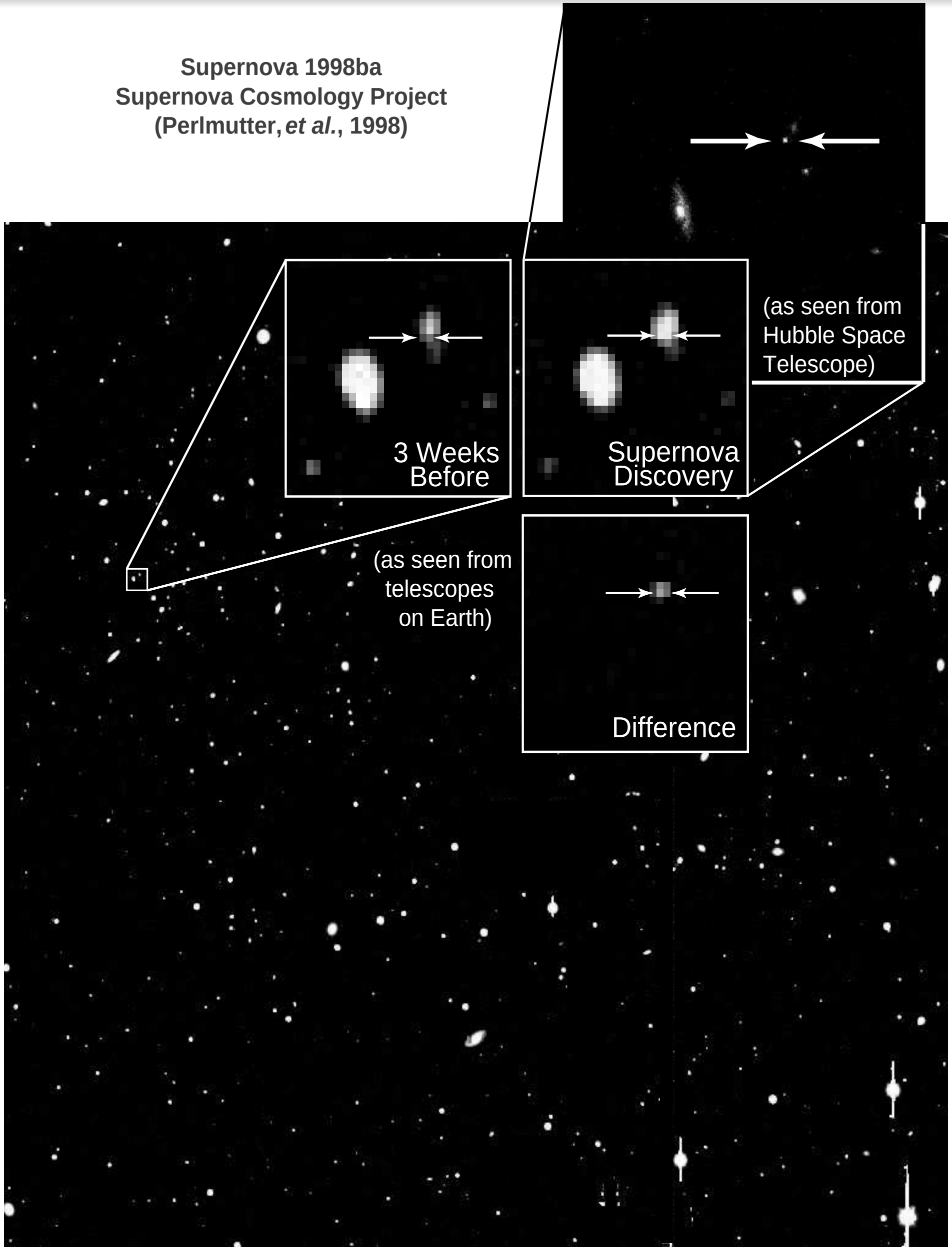
The time series of spectra is a “CAT Scan” of the Supernova



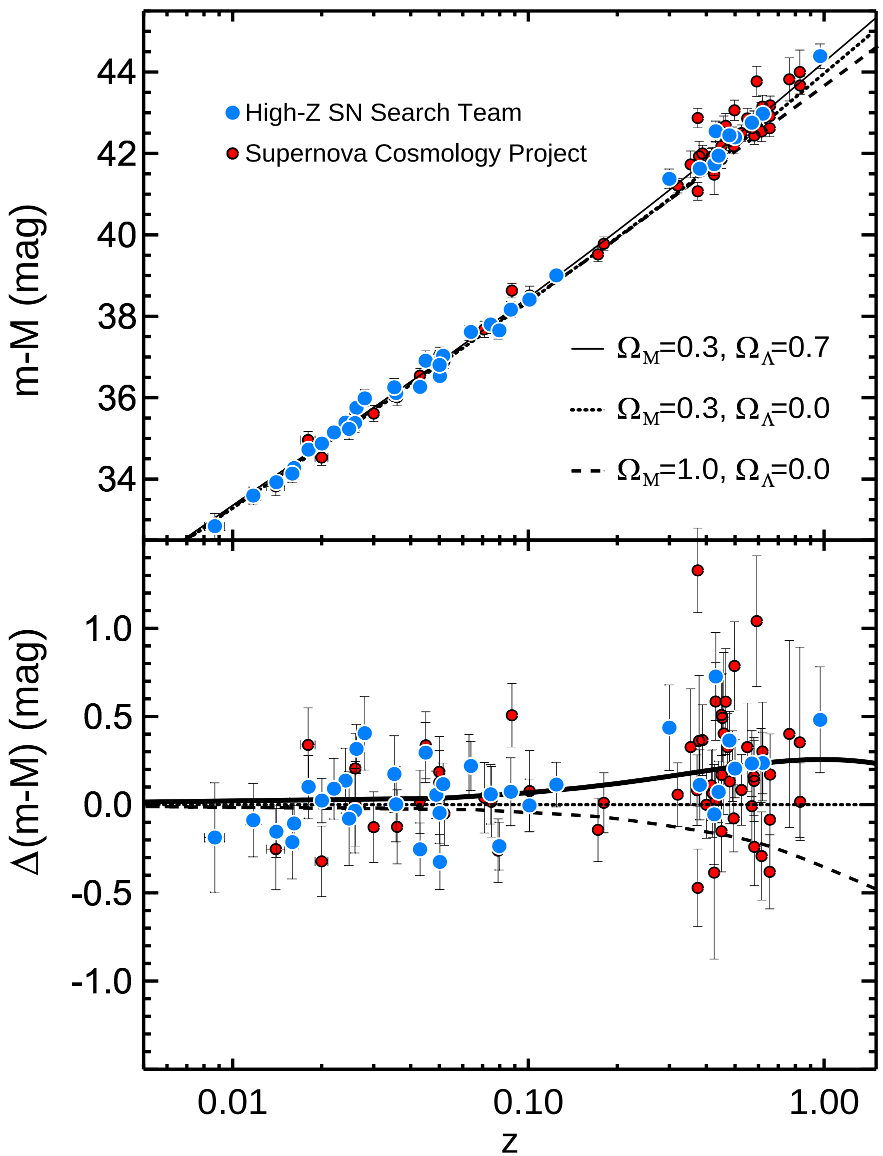


Kim, *et al.* (1997)

Discovering SNe Ia



Recent Supernova data



$$m - M = 5 \log \left(\frac{d_L(z, \Omega_M, \Omega_{DE})}{10\,\mathrm{pc}} \right)$$

Parameterizing Dark Energy

- $\Omega_{DE} \equiv \dfrac{\rho_{DE}(z=0)}{\rho_{\rm crit}(z=0)}, \qquad w \equiv \dfrac{p_{DE}}{\rho_{DE}}$
- $H^2(z) = H_0^2 \left[\Omega_M (1+z)^3 + \Omega_{DE}\ (1+z)^{3(1+w)}\ \right]$ (flat)
- $d_L(z) = (1+z)\displaystyle\int_0^z \frac{dz'}{H(z')}$
- $\dfrac{\ddot{a}}{a} = -\dfrac{4\pi G}{3}(\rho_M + \rho_{DE} + 3p_{DE})$

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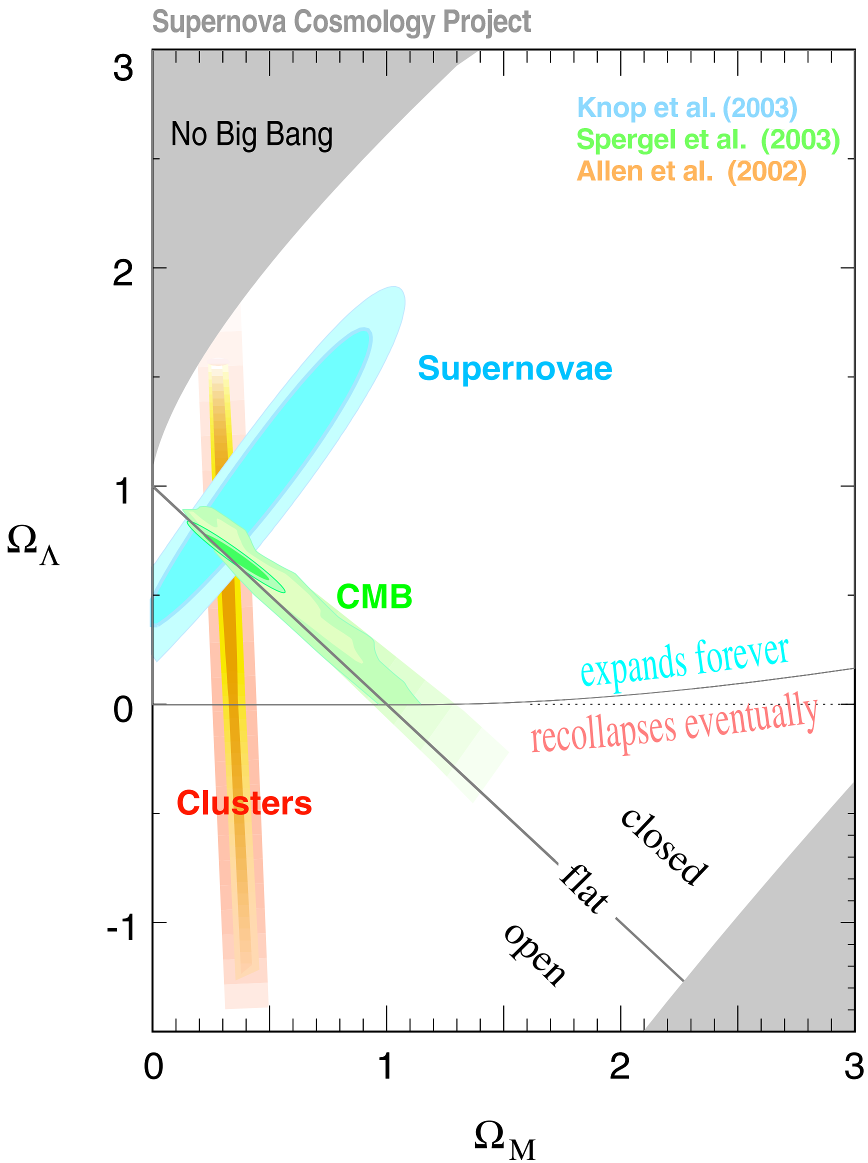
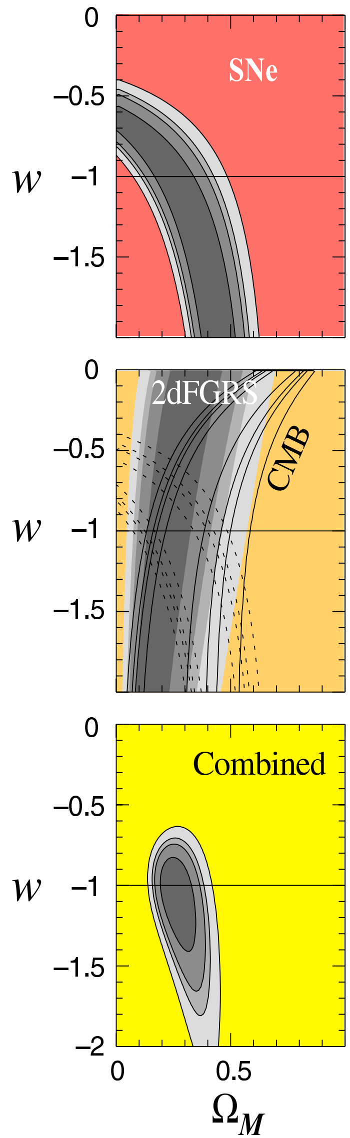
- w may be varying:

  $\exp\left[3\int_0^z (1+w(z'))\,d\ln(1+z')\right]$

Current Supernova Constraints





Supernova Cosmology Project
Knop *et al.* (2003)

Assuming constant w

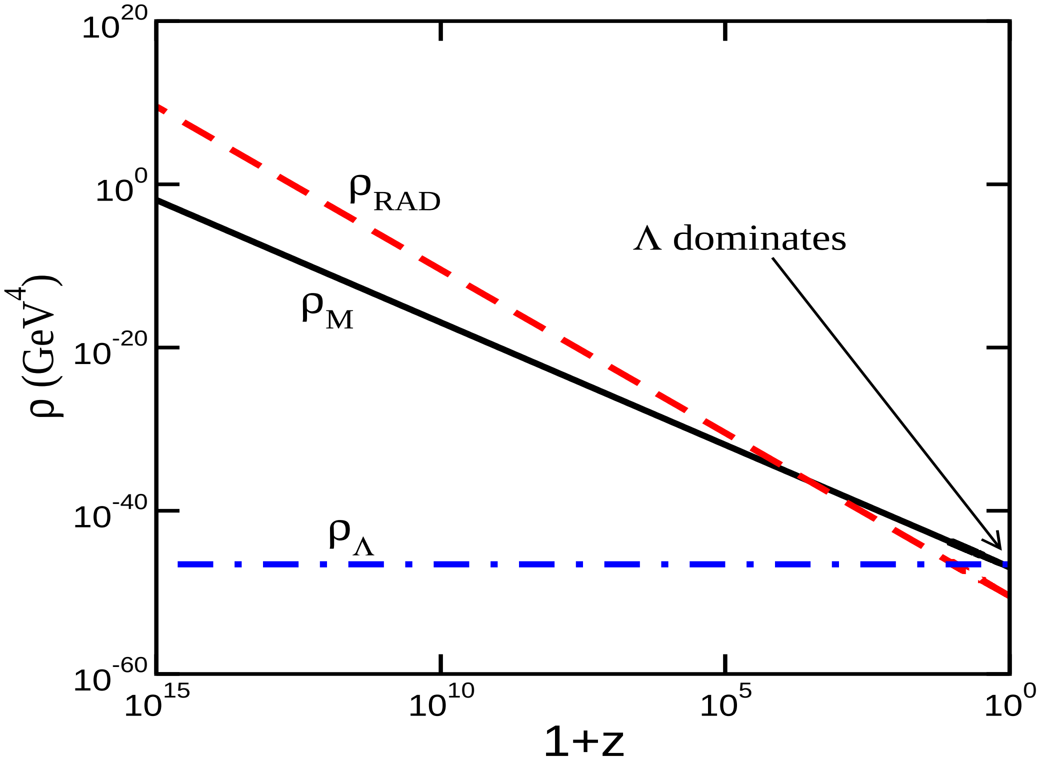
With limits from;
2dFGRS (Hawkins et al. 2002)
and CMB (Bennet et al. 2003, Spergel et al. 2003)

$$w = -1.05 \,^{+0.15}_{-0.20} \text{ (statistical)} \quad \pm 0.09 \text{ (systematic)}$$

Fine-Tuning Problems I: “Why Now ?”

DE is important only at $z \lesssim 2$, since

$$\rho_{DE}/\rho_M \approx \frac{\Omega_{DE}}{\Omega_M}(1+z)^{3w} \qquad \text{and} \qquad w \lesssim -0.8$$



Fine-Tuning Problems II: “Why so small ?”

- Refers to the vacuum energy, $\rho_\Lambda \equiv \dfrac{\Lambda}{8\pi G}$.

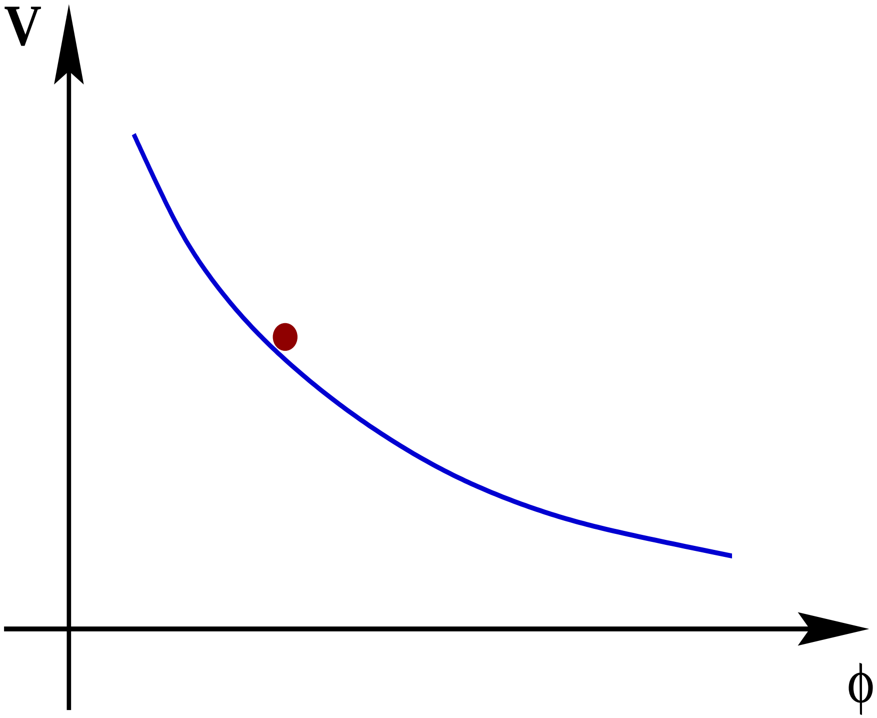
  (recall $G_{\mu\nu} + \mathbf{\Lambda}\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$)

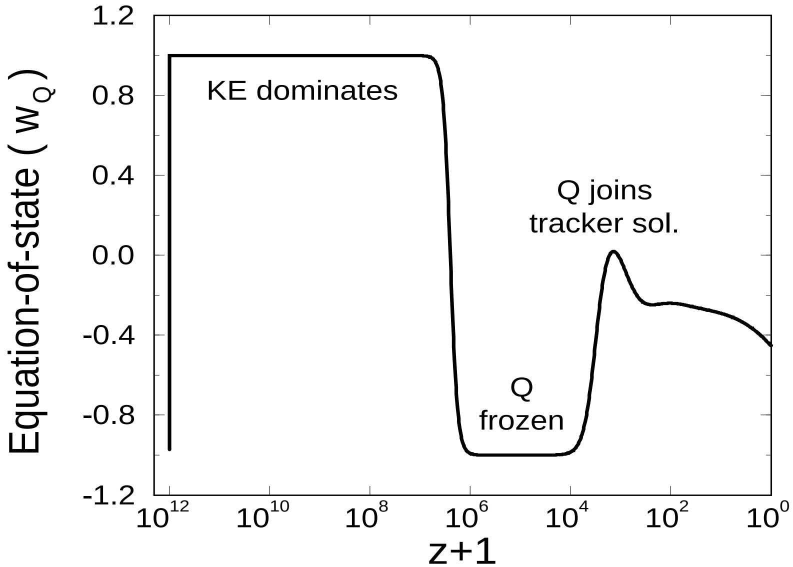
- $\rho_\Lambda \;\simeq\; (10^{-3}\,\mathrm{eV})^4 \;<<<\; (M_{\mathrm{PL}} = 10^{+19}\,\mathrm{GeV})^4$

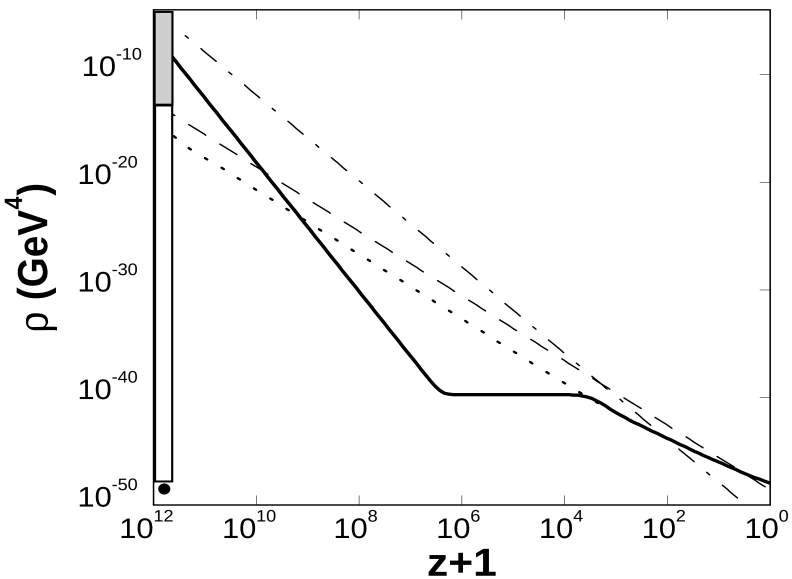
- $\Rightarrow$ 50 – 120 orders of magnitude discrepancy!

A candidate: Quintessence

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$

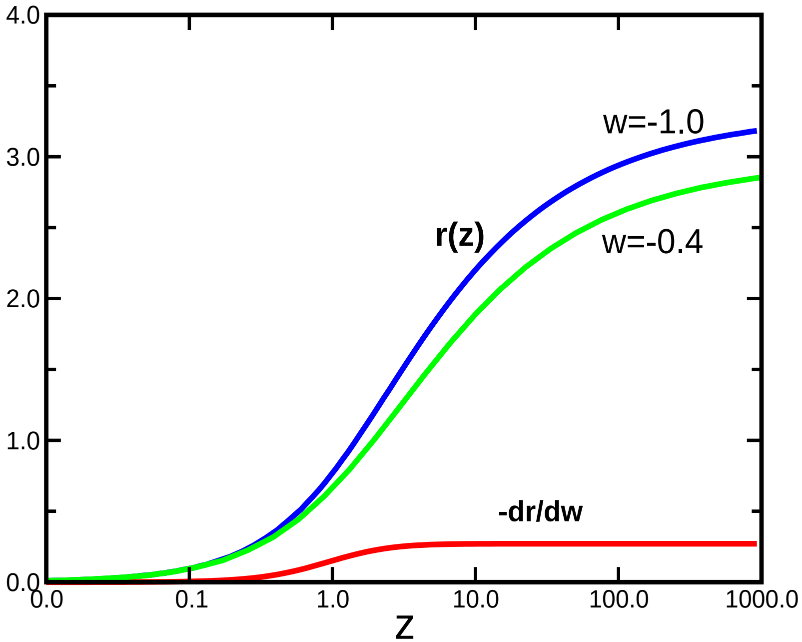


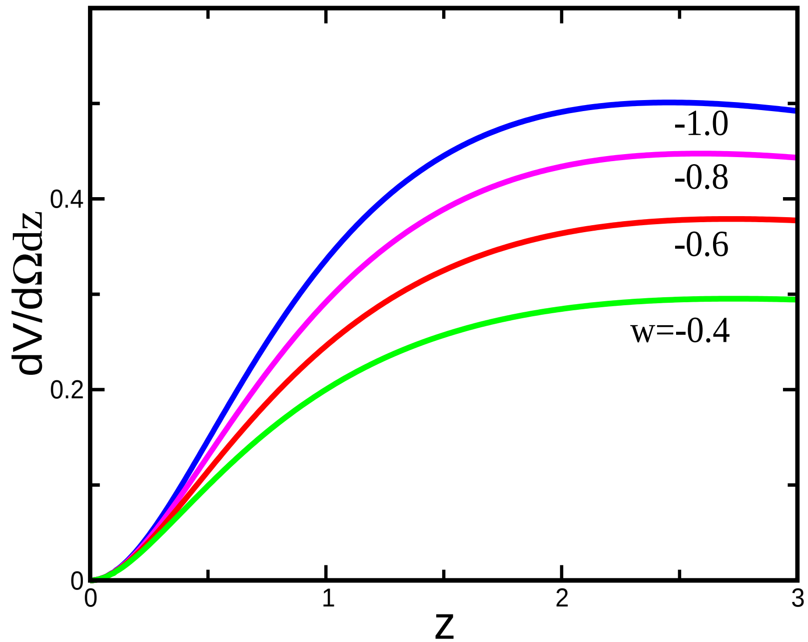


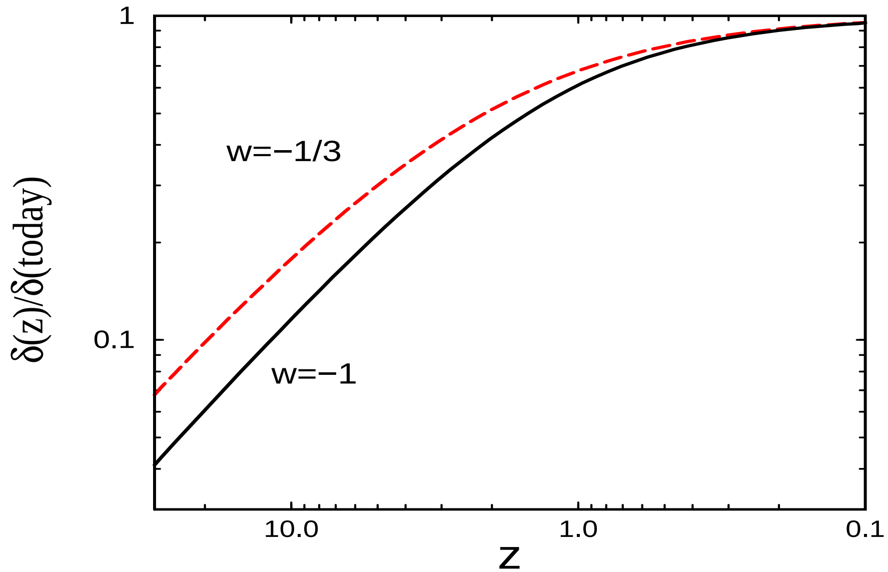


Peebles & Ratra 1987, Caldwell, Dave & Steinhardt 1998

Classical Tests







Wish List

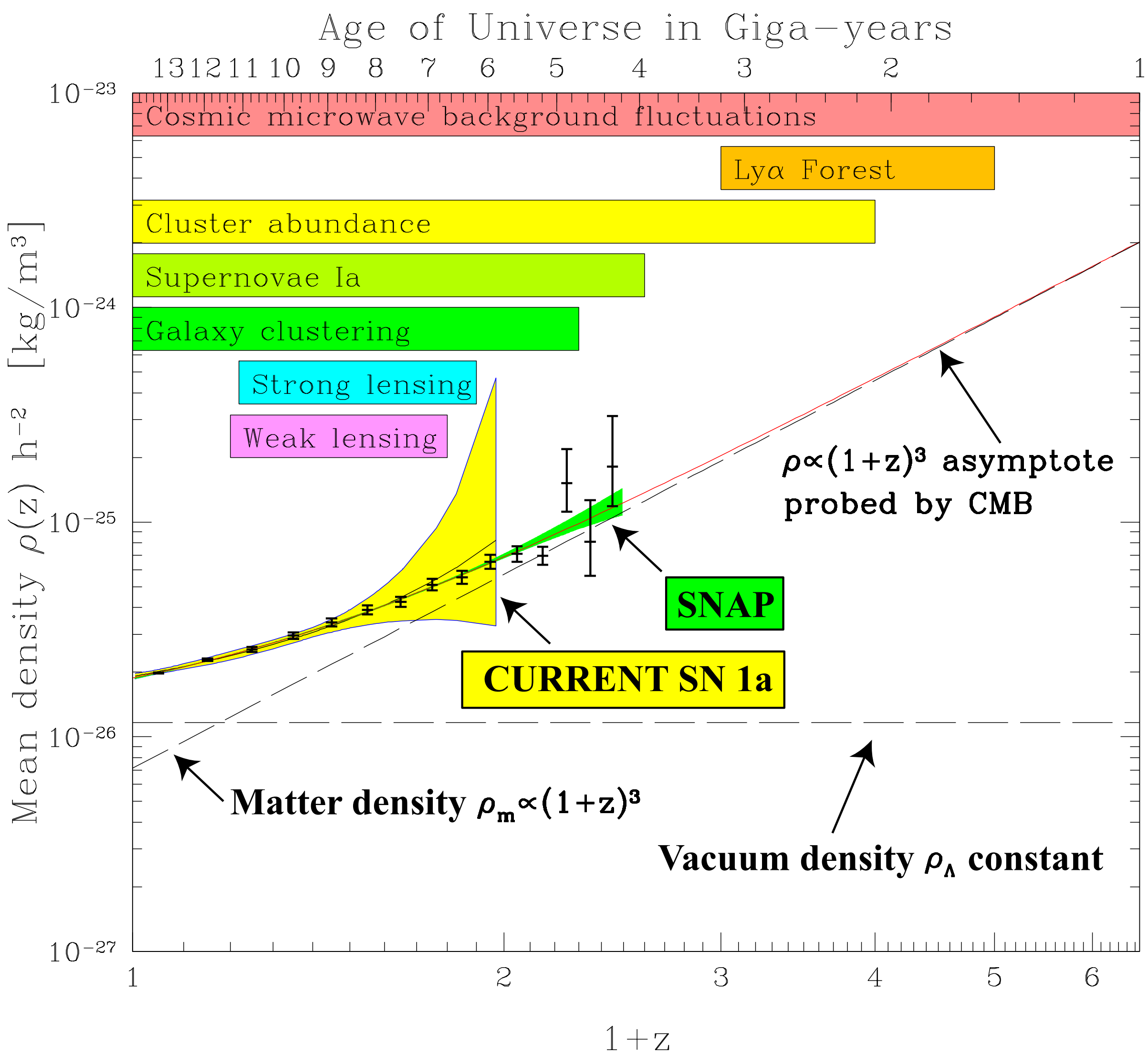
- Goals:
  - Measure Ω_{DE}, w
  - Measure $w(z)$ – equivalently, $\rho_{DE}(z)$
  - Measure any clustering of DE
- Difficulties:

$$r(z) = \int_0^z \frac{dz'}{H(z')}$$

$$H^2(z) = H_0^2 \left[\Omega_M (1+z)^3 + \Omega_{DE} \exp\left(3 \int_0^z (1 + \mathbf{w(z')}) d\ln(1+z')\right)\right]$$

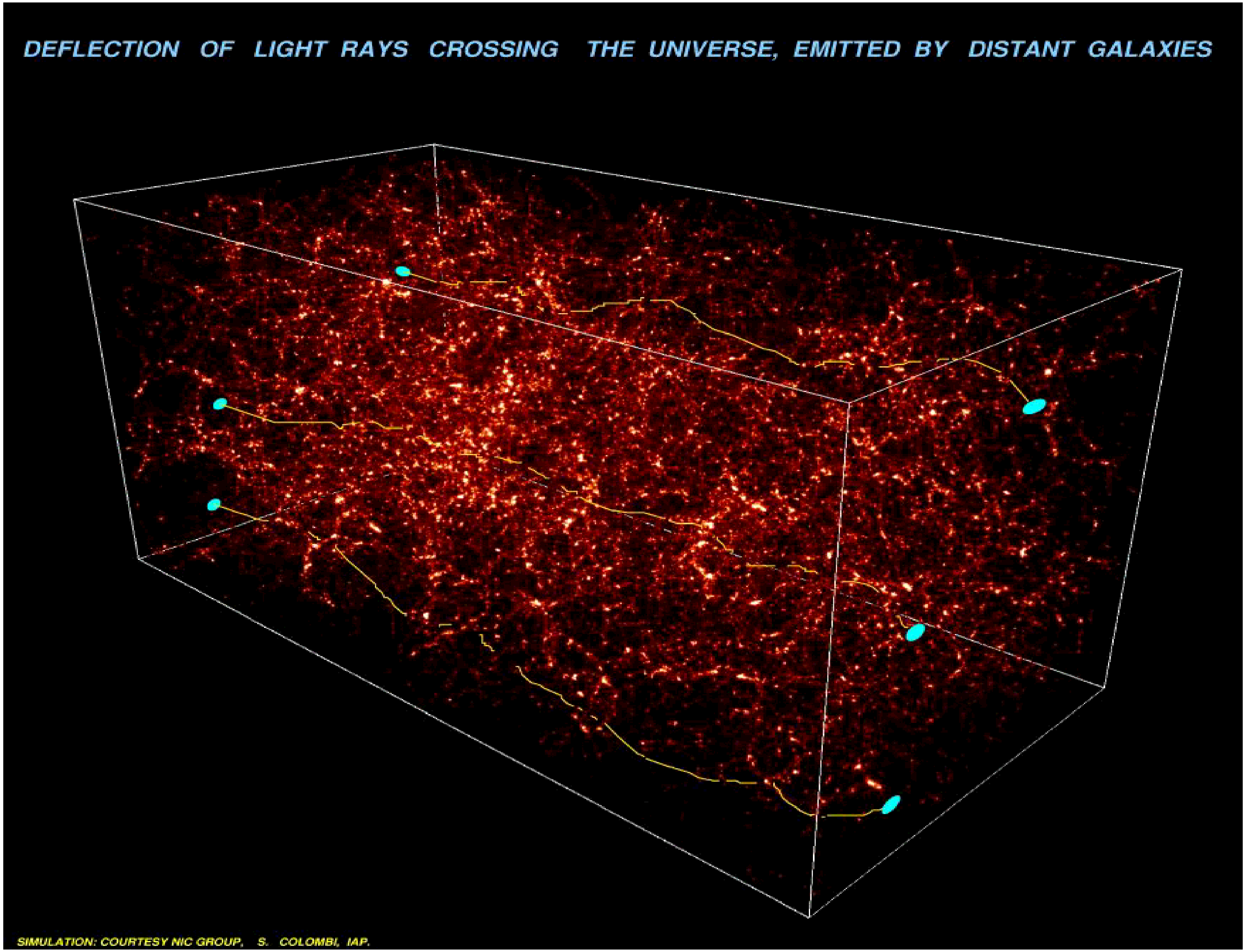
DE may cluster at scales $\sim H_0^{-1}$

Cosmological Tests of Dark Energy

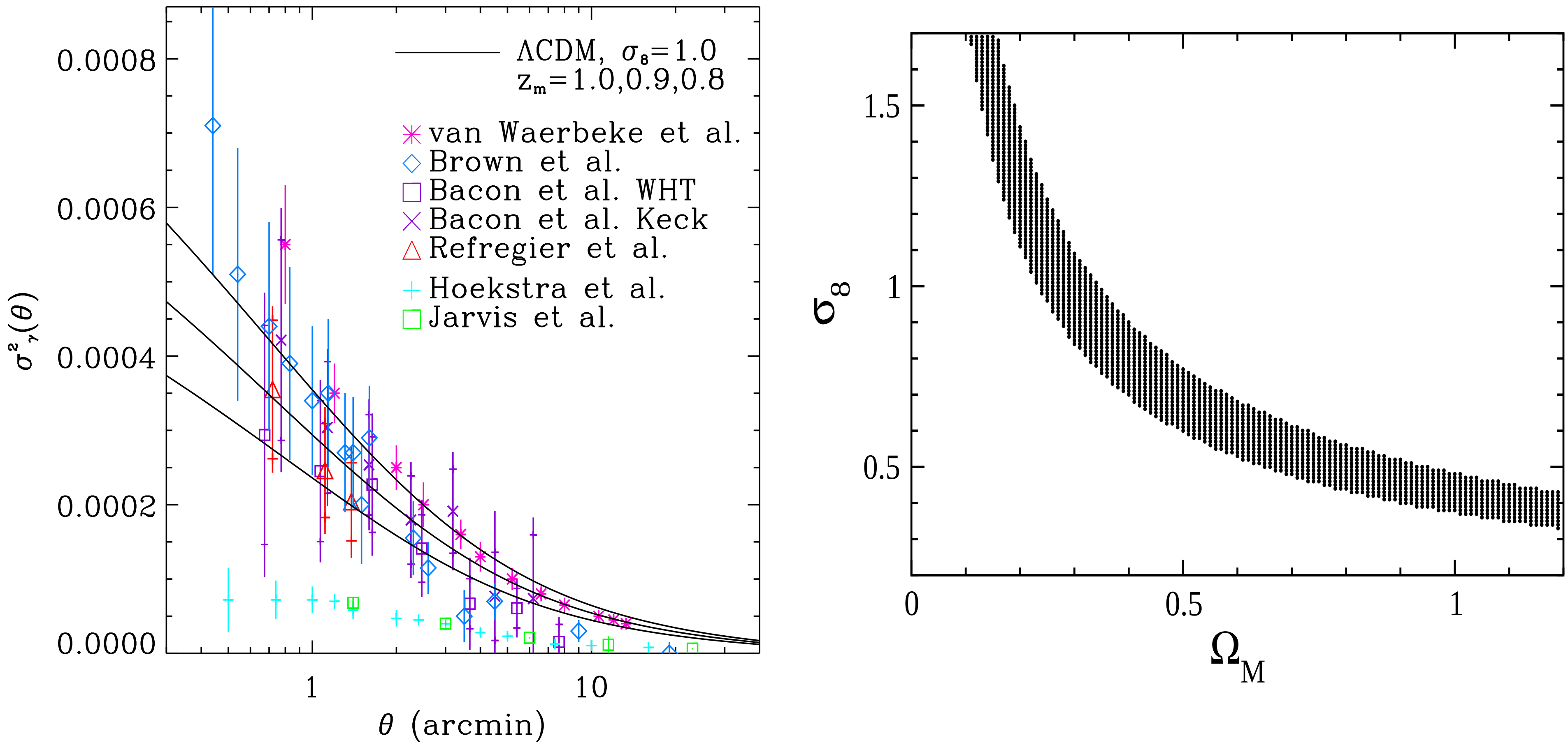


Tegmark 2001

Weak Gravitational Lensing



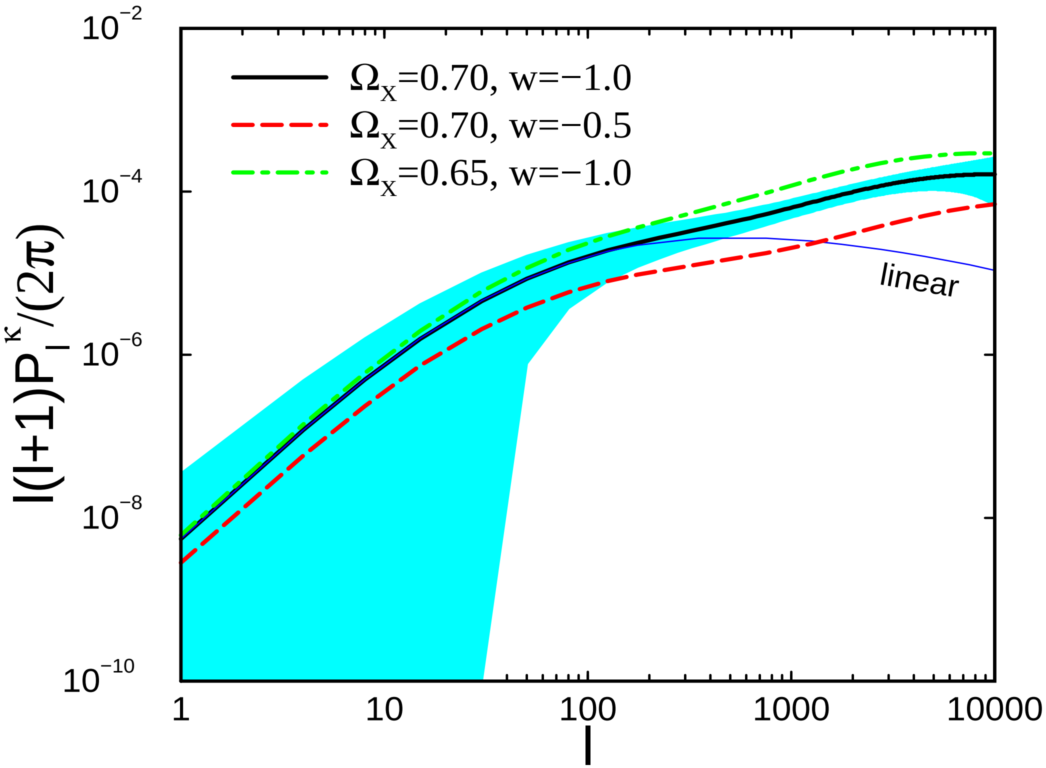
Current Data and Constraints



Refregier 2003, Bacon et al. 2003

Weak Lensing and DE

$$P_l^{\kappa} = \frac{2\pi^2}{l^3} \int_0^{z_s} dz\, W_1(z)\, \Delta^2 \left(\frac{l}{r(z)}; z \right)$$



Hu 1999, Huterer 2002, Refregier et al. 2003

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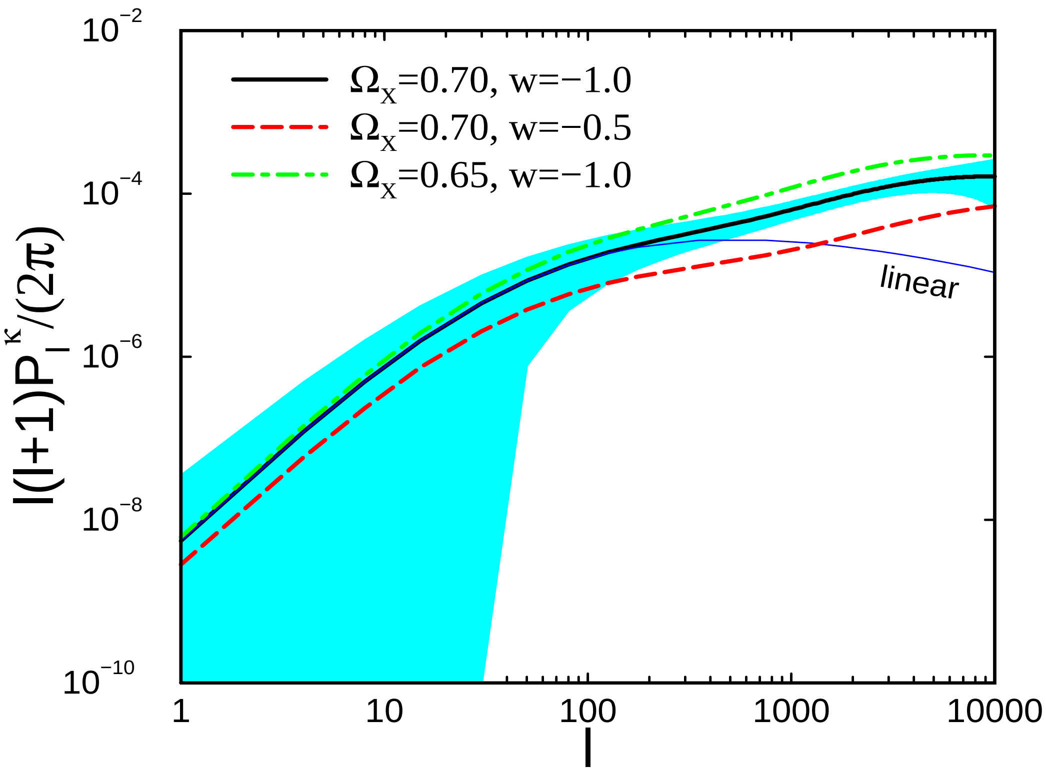
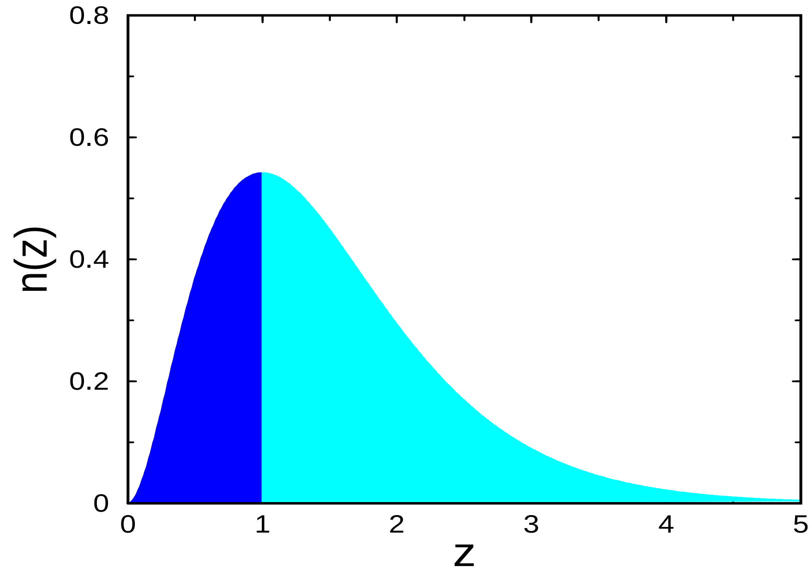
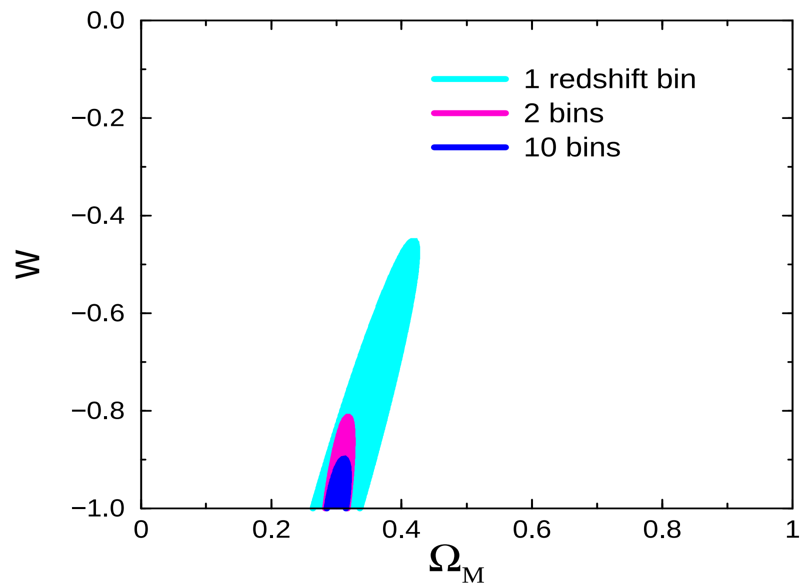
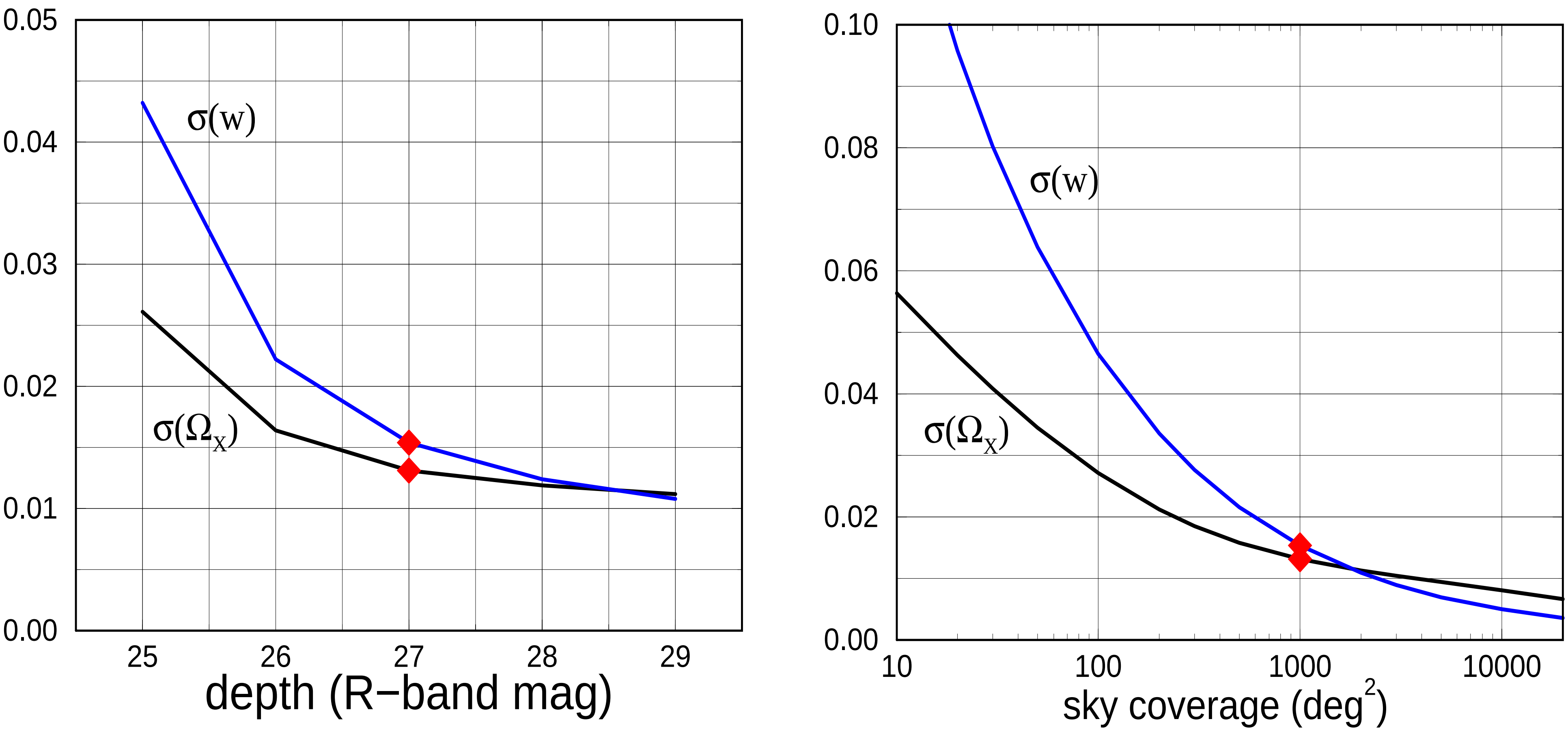






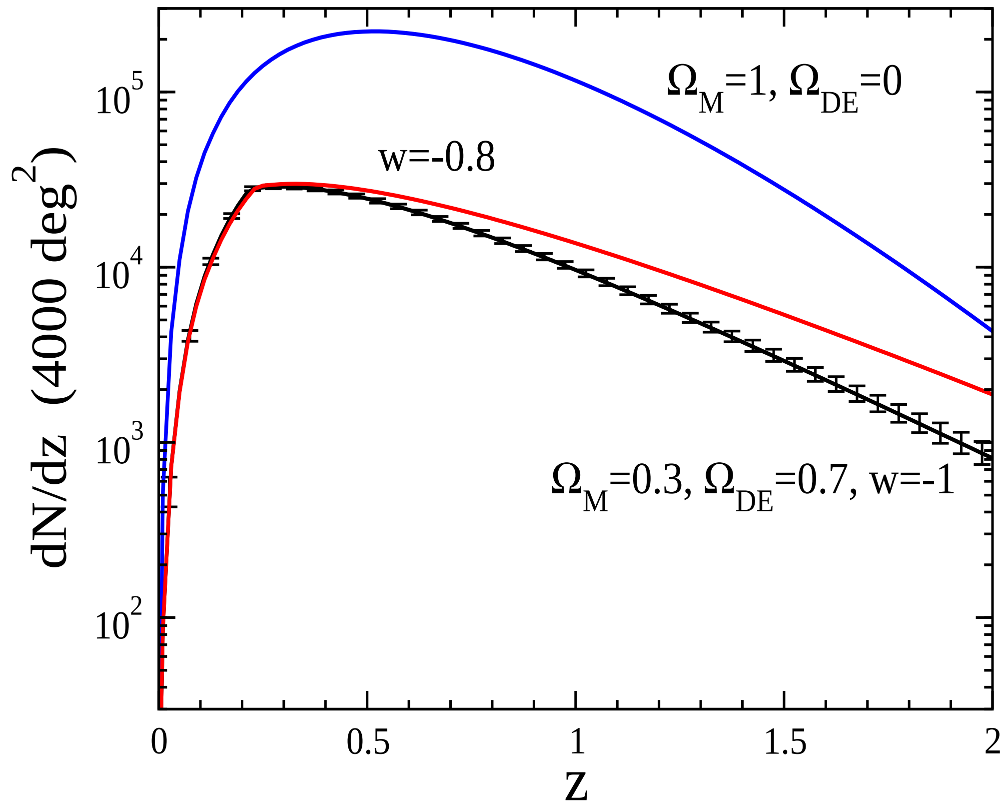
Hu 1999, Huterer 2002, Refregier et al. 2003

Deeper and Wider



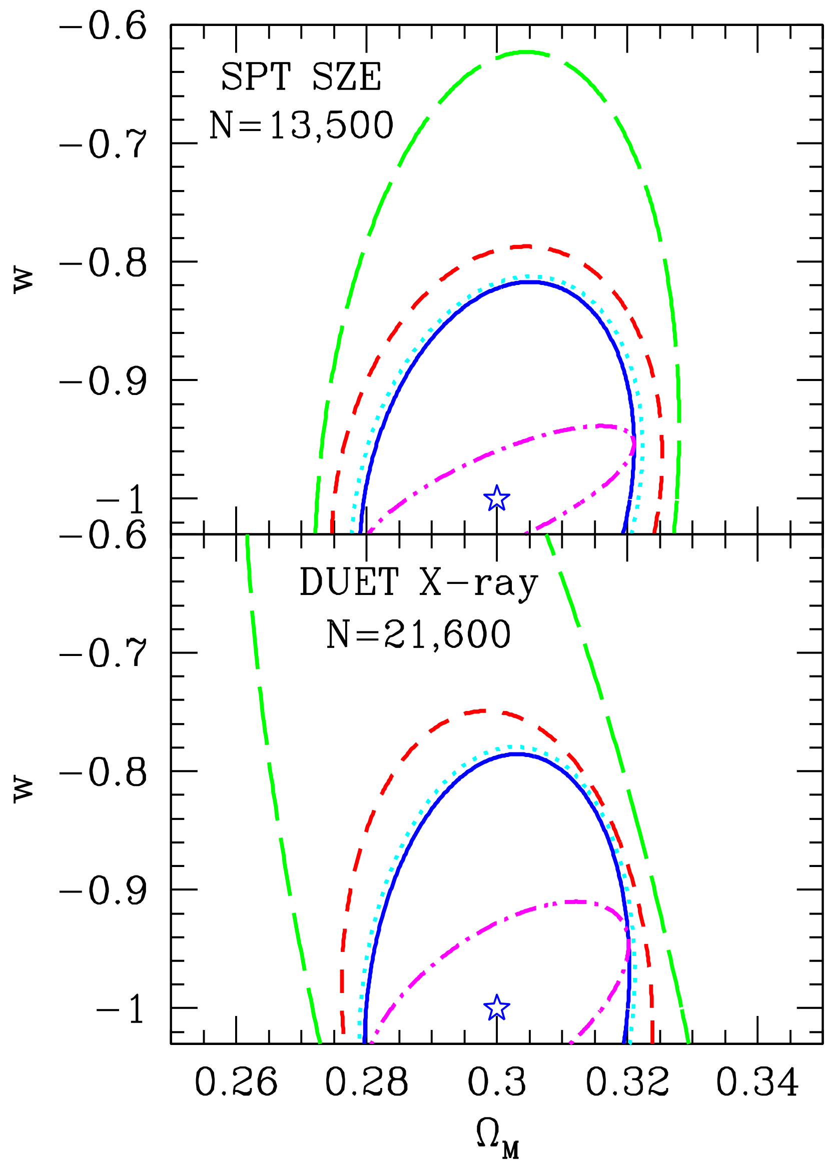
Huterer 2002

Number Counts



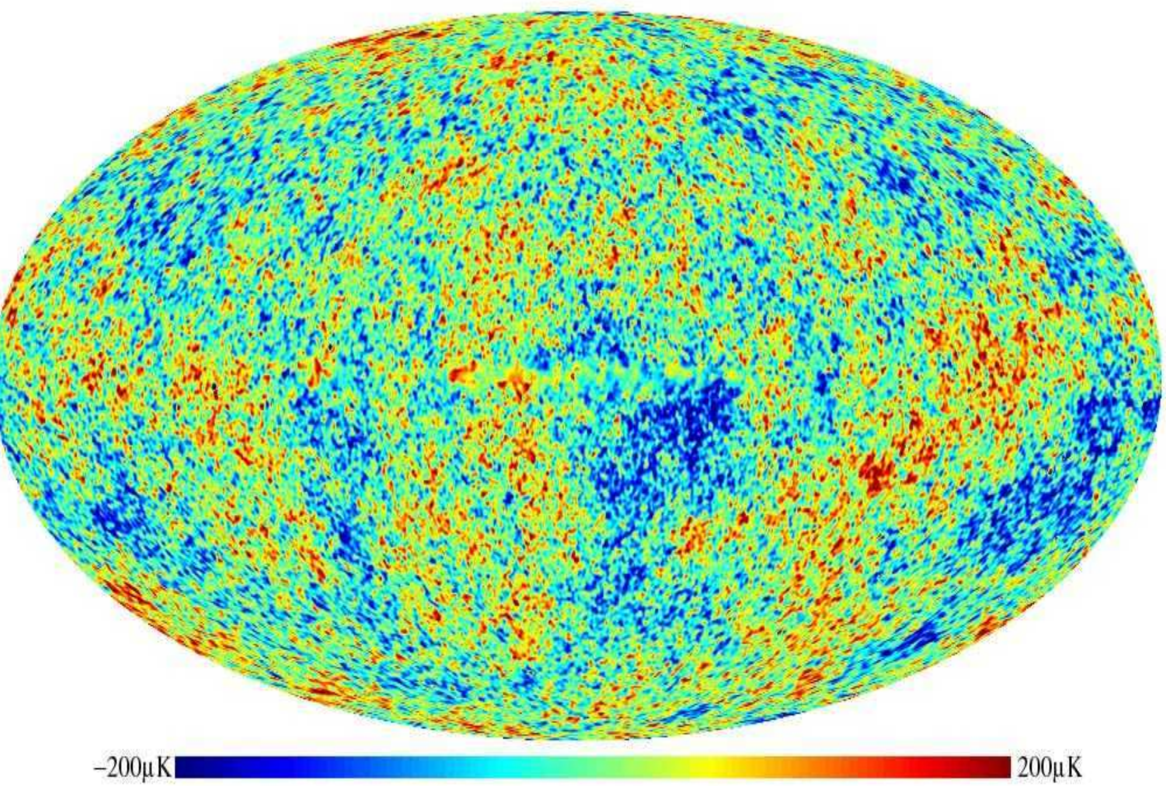
Number Counts

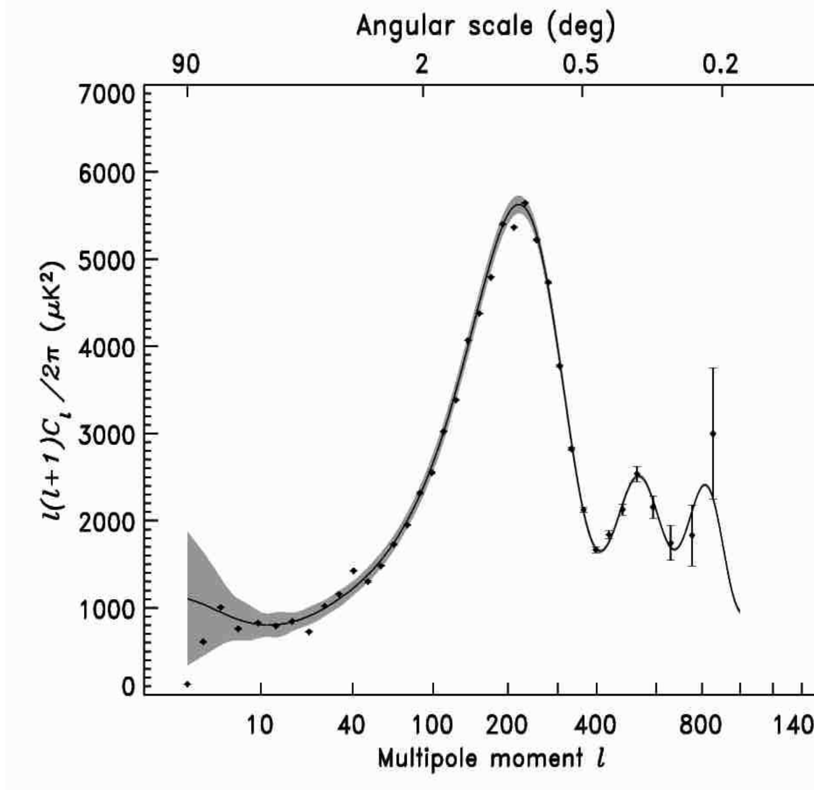
- Count clusters using X-ray, SZ, weak lensing...
- $$\frac{dN}{dz d\Omega}(z) = \left[\frac{dV}{dz d\Omega}(z) \int_{M_{\min}(z)}^{\infty} dM \frac{dn}{dM}\right]$$
- $\frac{r^2(z)}{H(z)}$
- Mass-observable relation



Haiman, Mohr & Holder 2001, Majumdar & Mohr 2003

Cosmic Microwave Background Anisotropie



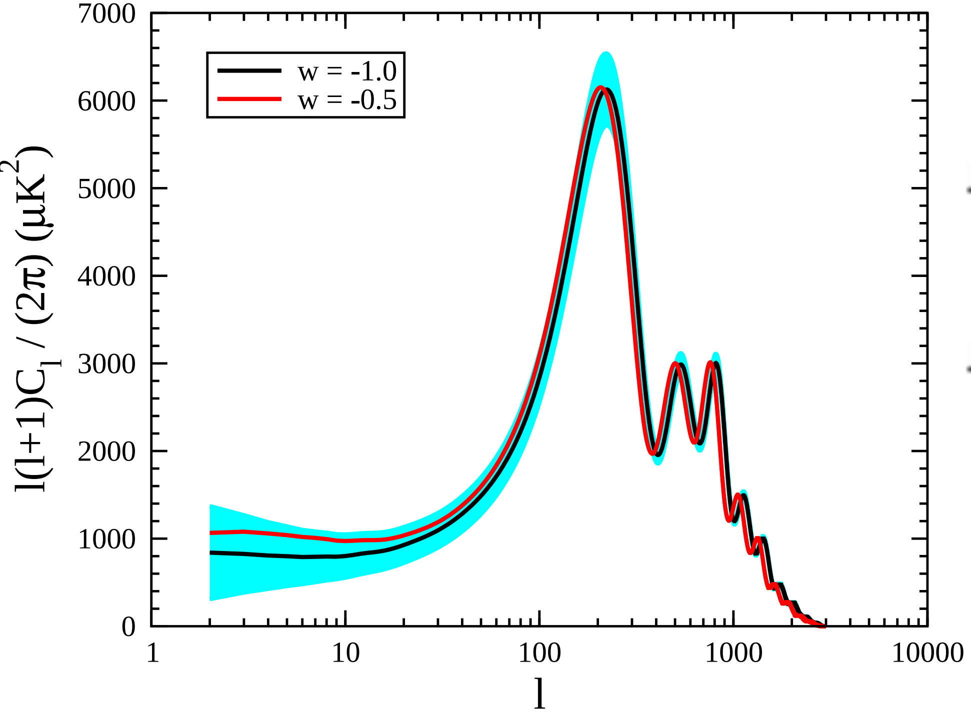


Bennett et al. 2003 (WMAP collaboration)

CMB Sensitivity to Dark Energy

Peak locations are sensitive to dark energy (but not much):

$$\frac{\Delta l_1}{l_1} = -0.084\Delta w - 0.23\frac{\Delta\Omega_M h^2}{\Omega_M h^2} + 0.09\frac{\Delta\Omega_B h^2}{\Omega_B h^2} + 0.089\frac{\Delta\Omega_M}{\Omega_M} - 1.25\frac{\Delta\Omega_{\rm TOT}}{\Omega_{\rm TOT}}$$



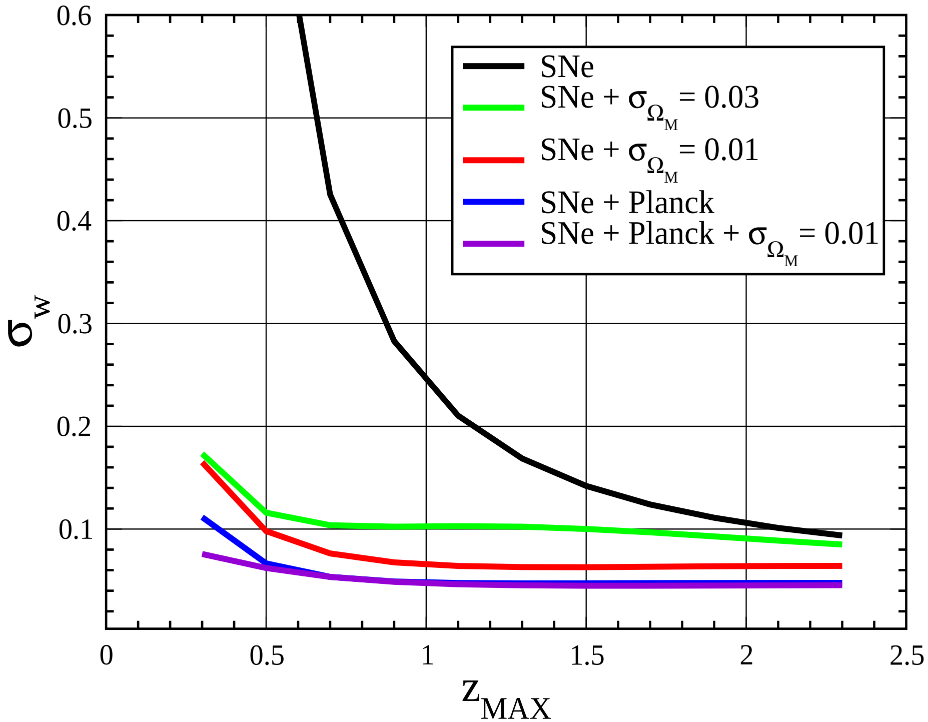
- Same as measurement of $d_A(z \approx 1000)$ *with $\Omega_M h^2$ fixed*
- End up constraining: $\mathcal{D} \equiv \Omega_M - 0.28(1+w) \approx 0.3$ (Planck: $\mathcal{D}$ to $\sim 10\%$)

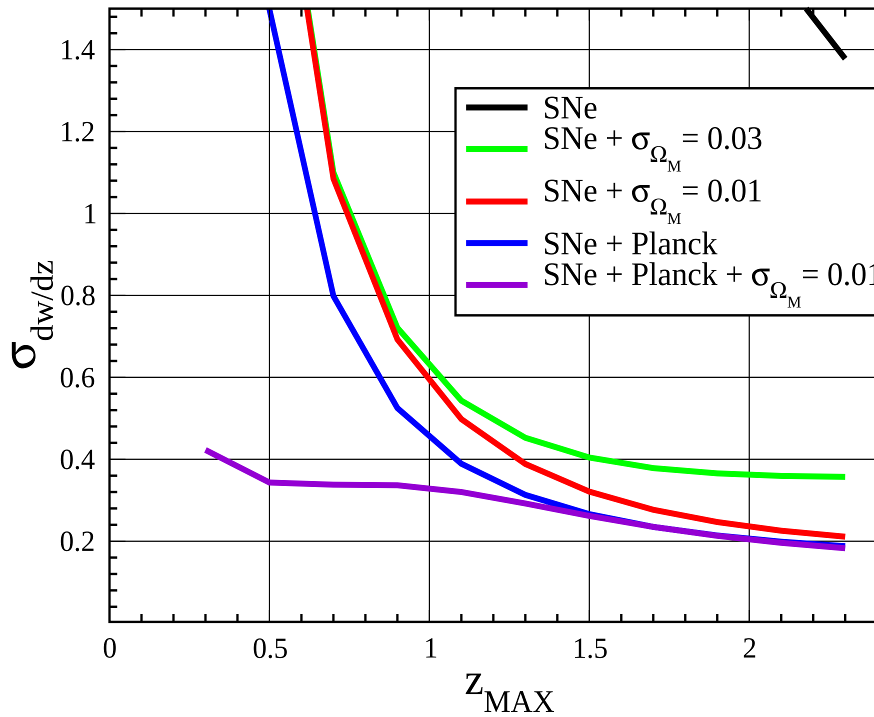
Huterer & Turner 2001, Frieman et al. 2003

SNe plus CMB

constant w

$$w(z) = w_0 + z(dw/dz)$$





Frieman, Huterer, Linder & Turner 2003

CMB-LSS cross-correlation

$$\Delta T^{\rm ISW}(\hat{\mathbf{n}}) = -2\int_0^{\eta_{\rm rec}} d\eta' \, \frac{d\Phi(\eta')}{d\eta'}$$

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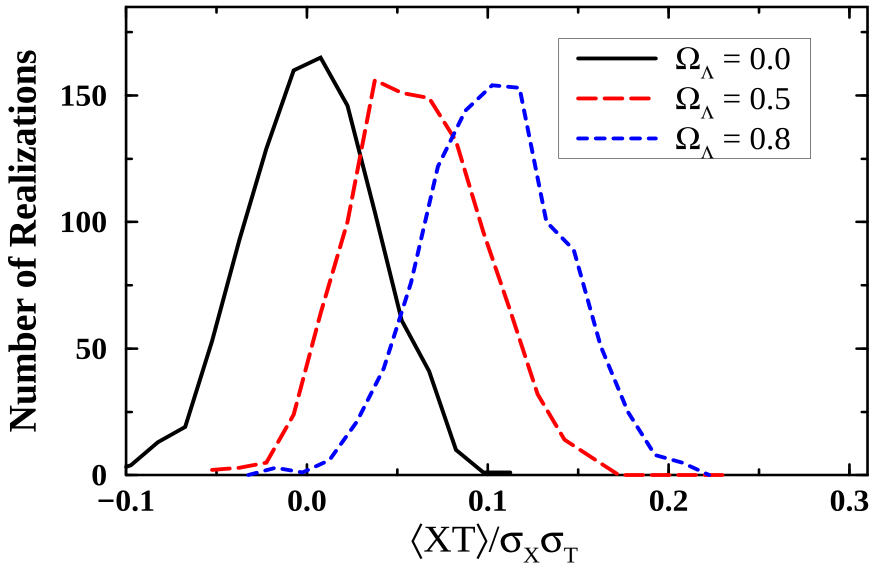

Boughn, Crittenden & Turok 1997

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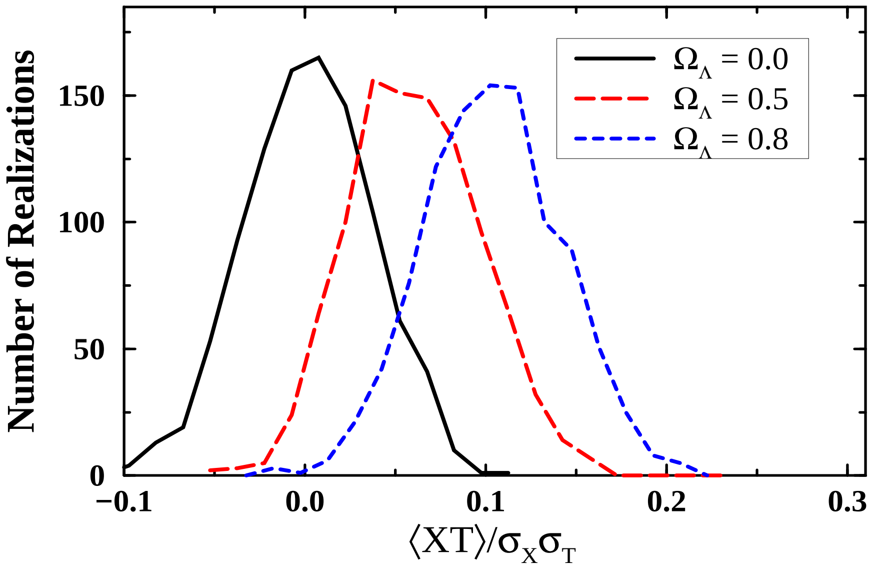
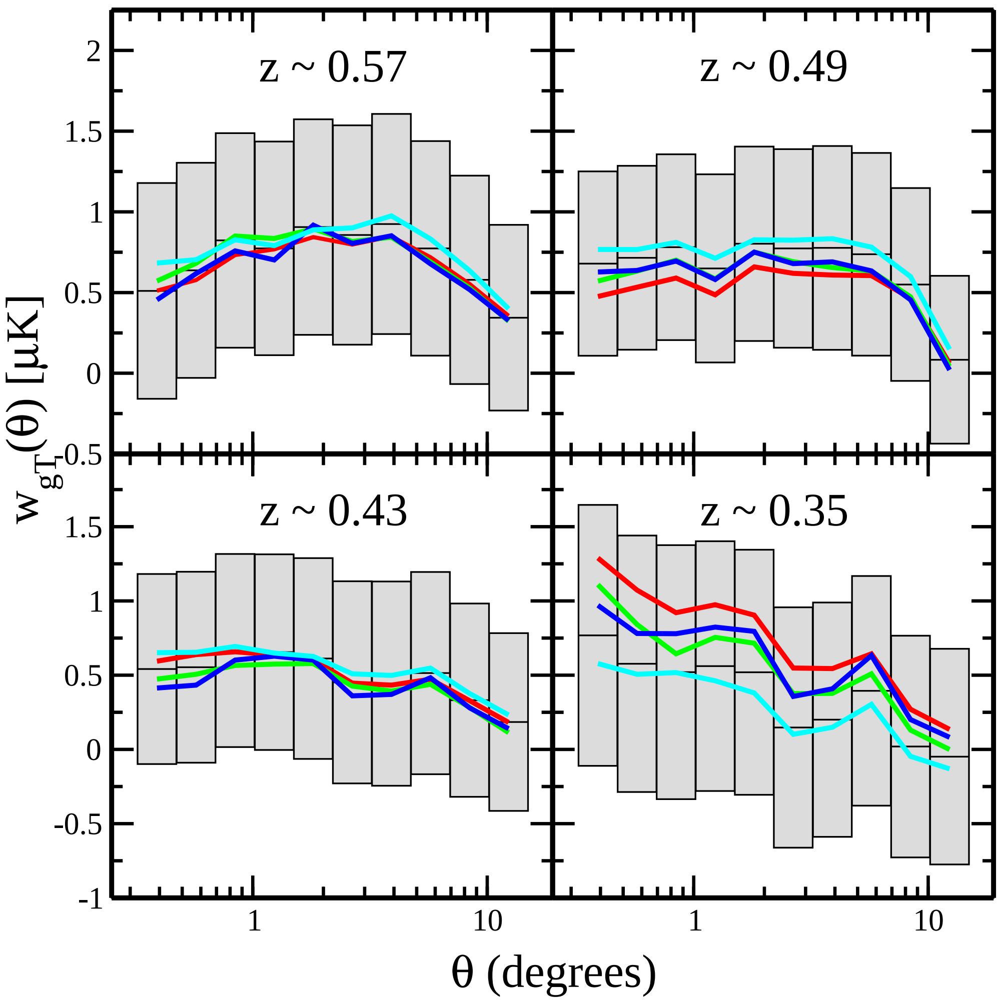
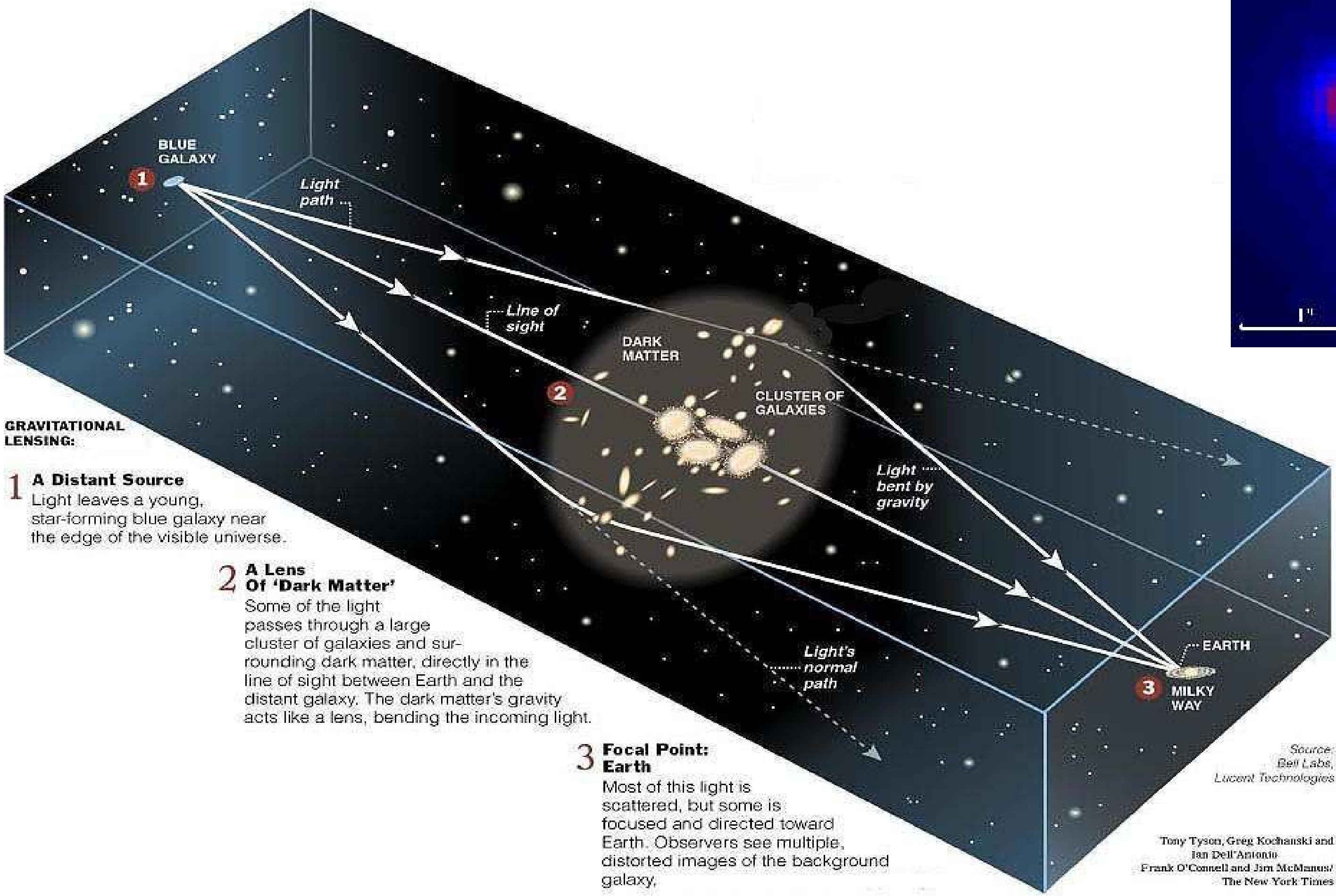
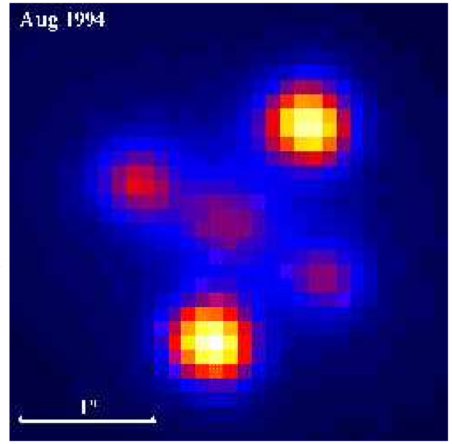




Boughn, Crittenden & Turok 1997, Scranton et al. 2003

Strong Gravitational Lensing



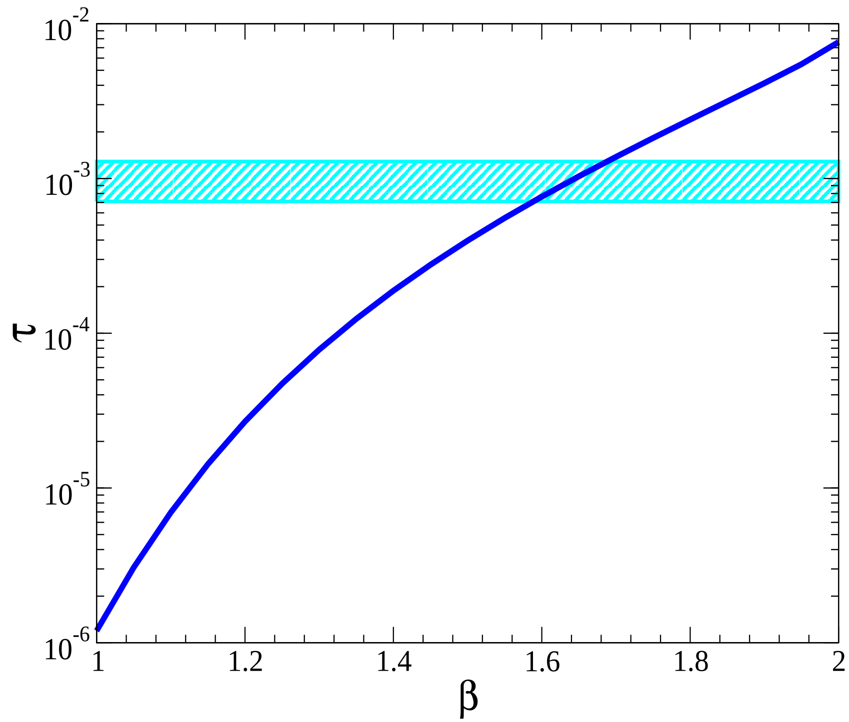


Strong Lensing Statistics

$$\tau = \int_0^{z_s} dz_l \frac{dD_l}{dz_l}(1+z_l)^3 \times \int_0^{\infty} dL \frac{d\phi}{dL}(L)\,\sigma(L, z_l, z_s) B(L, z_l, z_s)$$

Required input:

- **Cosmology** $(\Omega_M, \Omega_{DE}, w)$
- **Luminosity function** (galaxies)
  or **mass function** (all halos)
- **Density profile of lenses**
  e.g. SIS: $\rho(r) \propto r^{-2}$
  or generalized NFW: $\rho(r) \propto r^{-\beta}$
- **Magnification bias** $B(L, z_l, z_s)$



Kochanek 1993, 1996, Cooray & Huterer 1999, Chae 2003,
Davis, Huterer & Krauss 2003, Kuhlen, Keeton & Madau 2003

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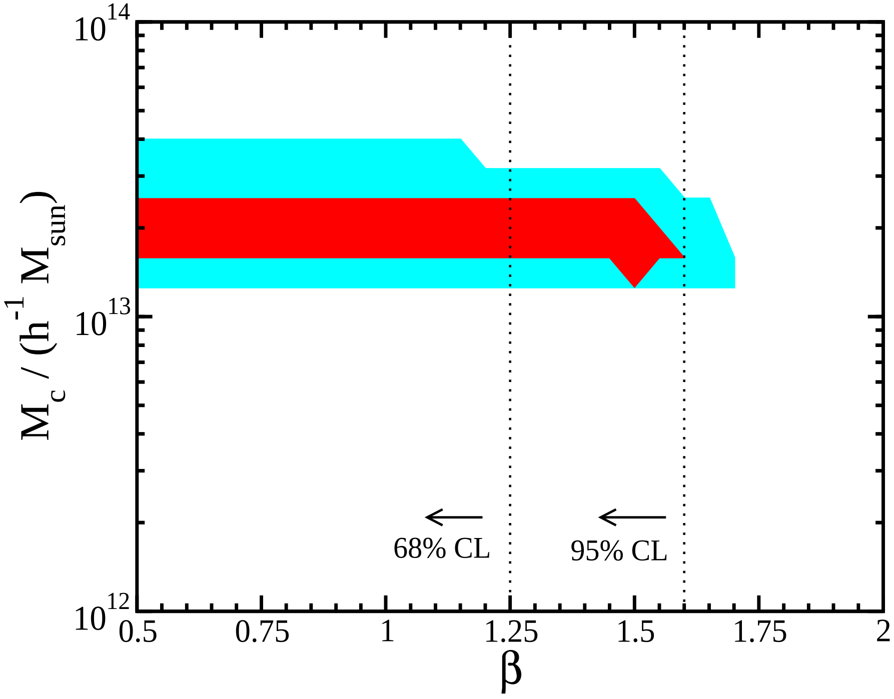
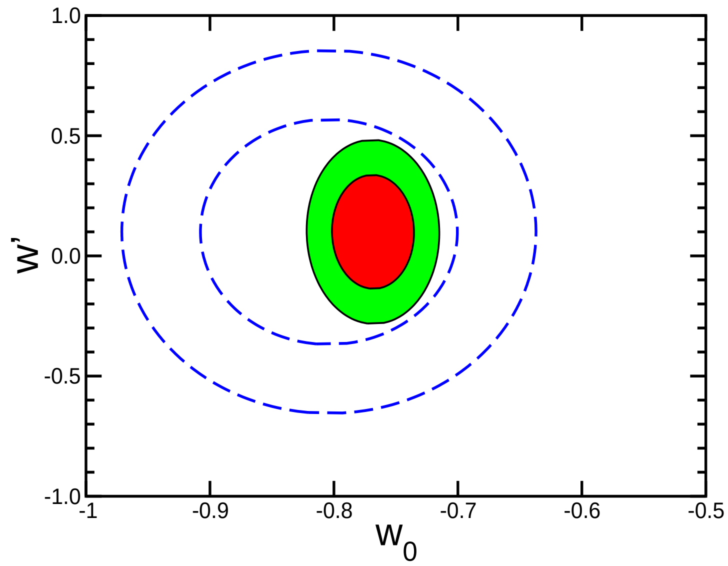


Huterer & Ma 2003

Beyond $w = const$

- $$w(z) = w_0 + w'(z - z_1)$$

  $$w(z) = w_0 + w_1 \frac{z}{1+z}$$



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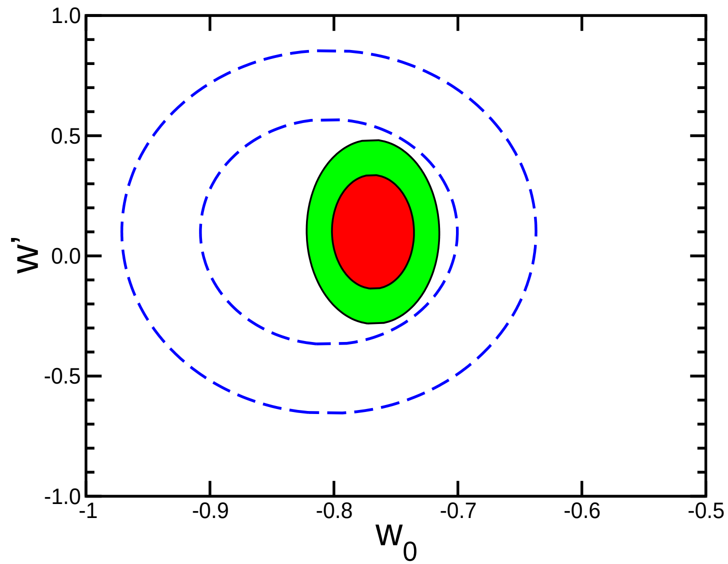
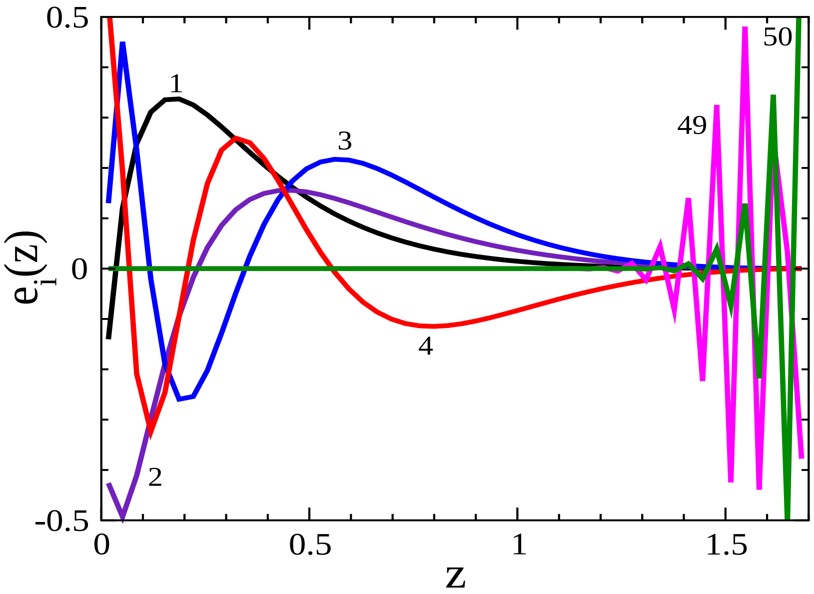


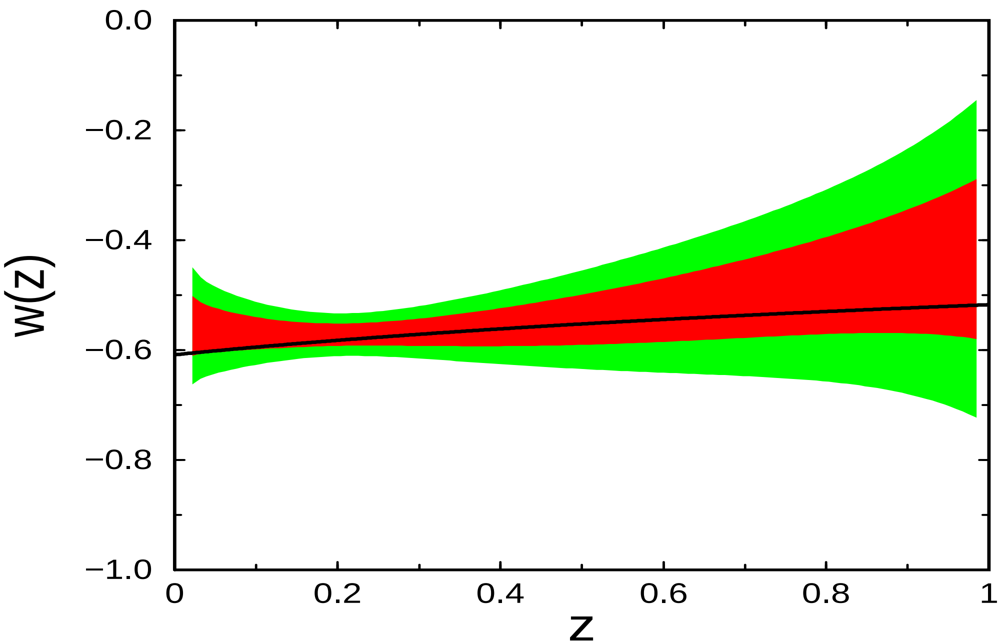
- Principal Components of $w(z)$



Huterer & Starkman 2003

Reconstruction of w

$$1 + w(z) = \frac{1+z}{3} \frac{3H_0^2\Omega_M(1+z)^2 + 2(d^2r/dz^2)/(dr/dz)^3}{H_0^2\Omega_M(1+z)^3 - (dr/dz)^{-2}}$$



Huterer and Turner 1999; Chiba and Nakamura 1999, Weller & Albrecht 2002

Requirements

Science

- Measure Ω_M and Λ
- Measure w and $w(z)$

Statistical Requirements

- Sufficient (~2000) numbers of SNe Ia
- ...distributed in redshift
- ...out to $z < 1.7$

Systematics Requirements

Identified & proposed systematics:

- Measurements to eliminate / bound each one to +/-0.02mag

Data Set Requirements

- Discoveries 3.8 mag before max.
- Spectroscopy with S/N=10 at 15 Å bins.
- Near-IR spectroscopy to 1.7 µm.

⋮

Satellite / Instrumentation Requirements

- ~2-meter mirror
- 1-square degree imager
- 3-channel spectrograph (0.3 µm to 1.7 µm)

Derived requirements:

- High Earth orbit
- ~5 Mb/sec bandwidth

⋮

SuperNova/Acceleration Probe

H. Oluseyi, N. Palaio, S. Perlmutter, K. Robinson, A. Spadafora H. von der Lippe, J-P. Walder, G. Wang

UC Berkeley: M. Bester, E. Commins, G. Goldhaber, S. Harris, P. Harvey, H. Heetderks, M. Lampton, D. Pankow, M. Sholl, G. Smoot

U. Michigan: C. Akerlof, D. Levin, T. McKay, S. McKee, M. Schubnell, G. Tarle, A. Tomasch

Yale: C. Baltay, W. Emmet, J. Snyder, A. Szymkowiak, D. Rabinowitz, N. Morgan

CalTech: R. Ellis, J. Rhodes, R. Smith, K. Taylor

Indiana: C. Bower, N. Mostek, J. Musser, S. Mufson

JHU / STScI: R. Bohlin, A. Fruchter

U. Penn: G. Bernstein

IN2P3/INSU (France): P. Astier, E. Barrelet, J-F. Genat, R.Pain, D. Vincent

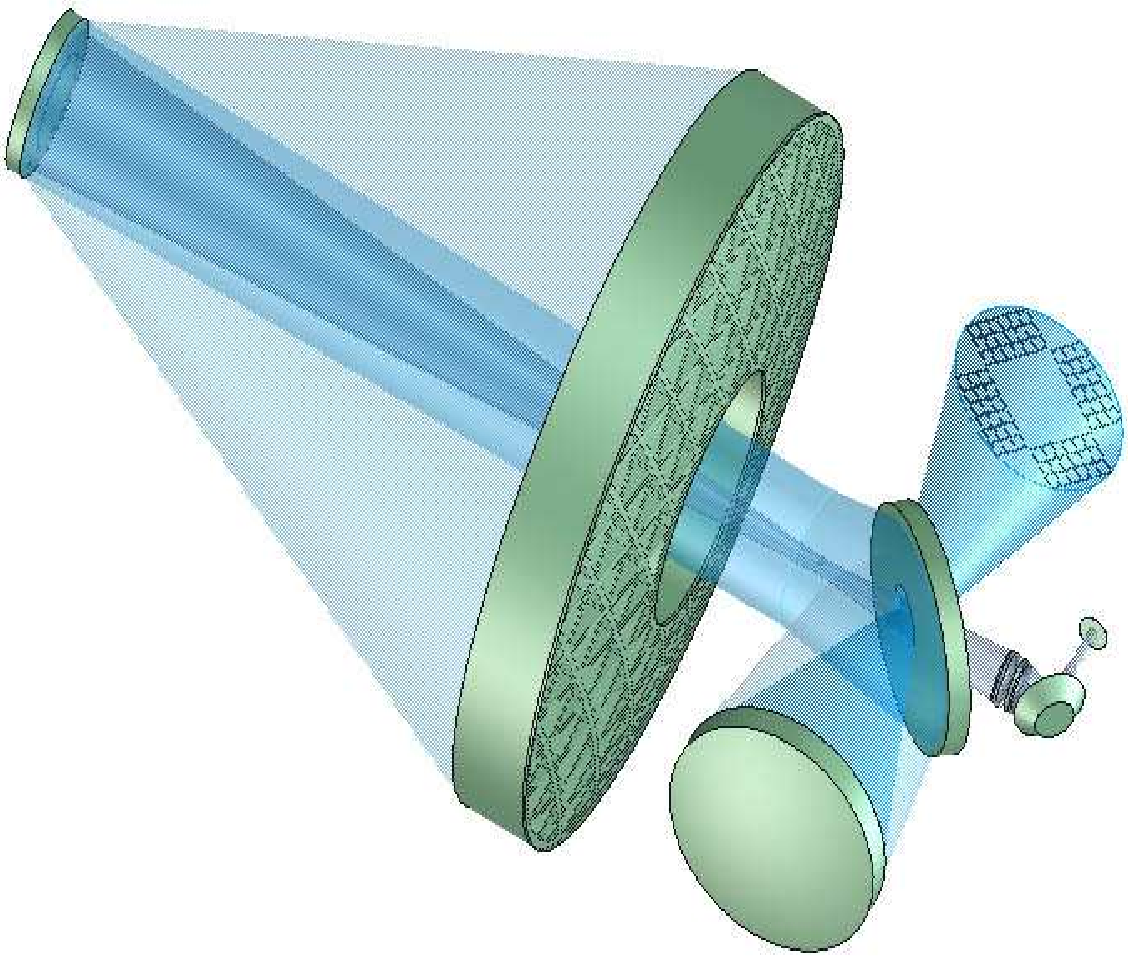
U. Stockholm: R. Amanullah, L. Bergström, M. Eriksson, A. Goobar, E. Mörtsell

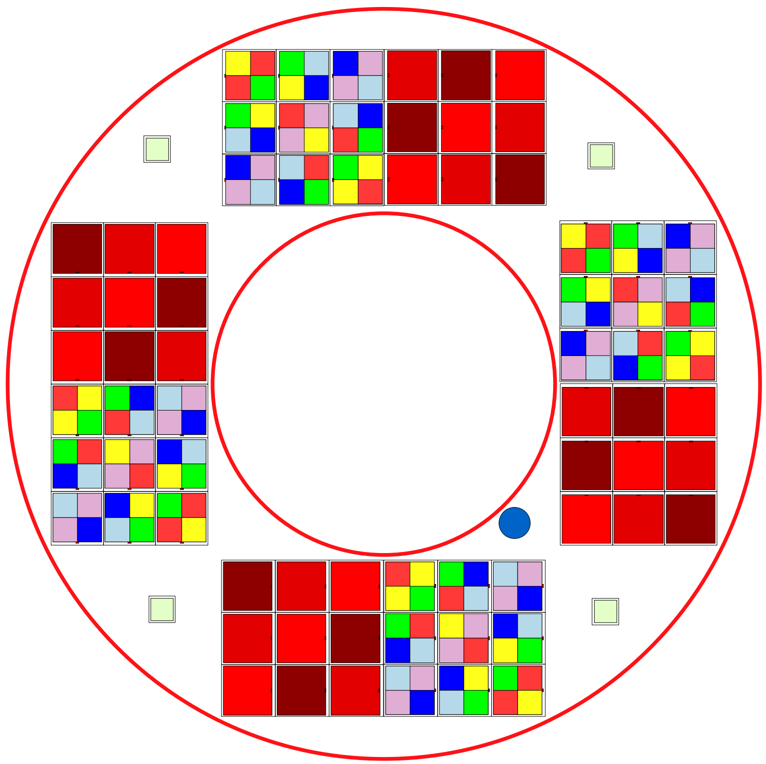
LAM (France):** S. Basa, A. Bonissent, A. Ealet, D. Fouchez, J-F. Genat, R. Malina, A. Mazure, E. Prieto, G. Smajda, A. Tilquin

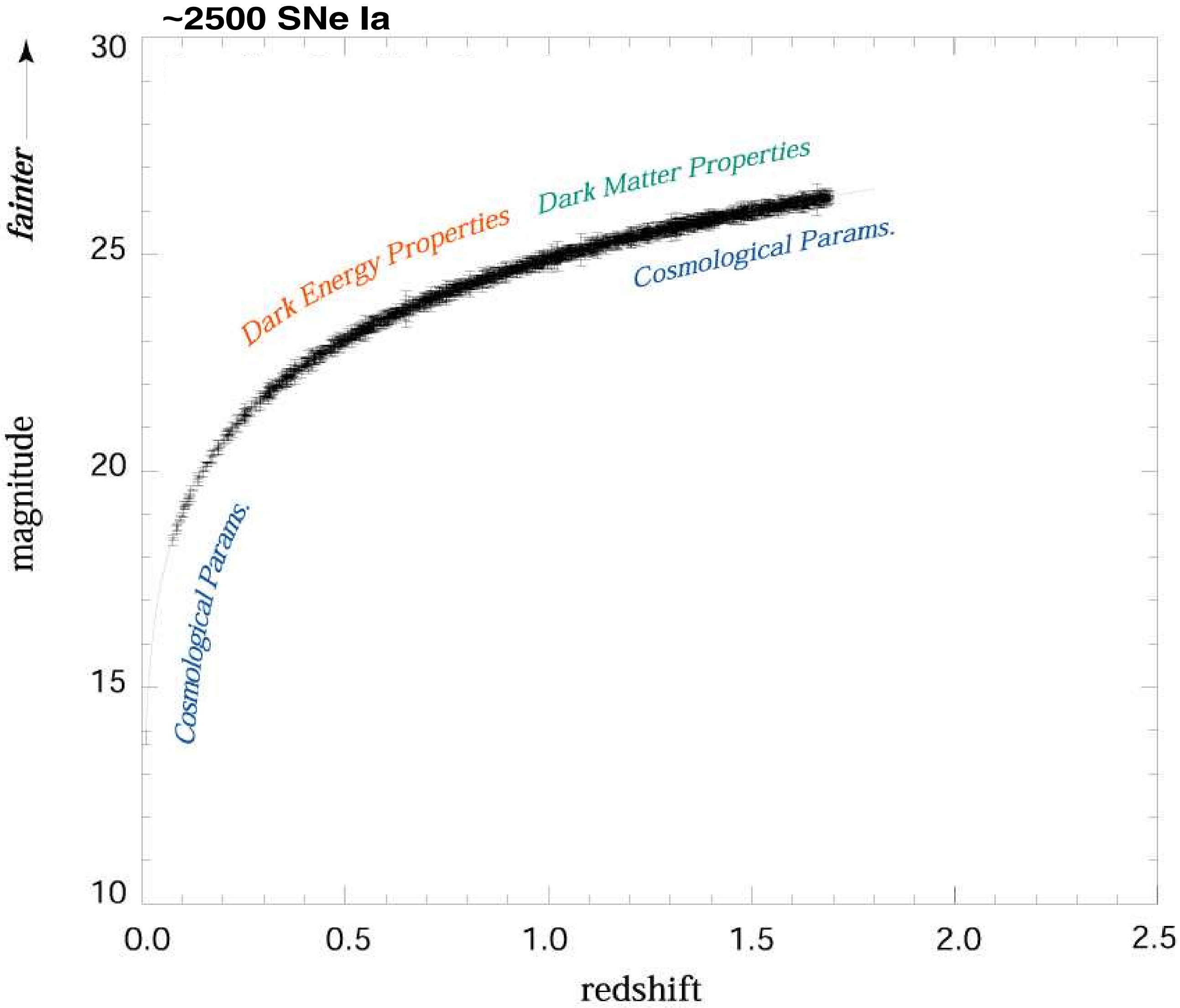
FNAL:** S. Allam, J. Annis, J. Beacom, L. Bellantoni, G. Brooijmans, M. Crisler, F. DeJongh, T. Diehl, S. Dodelson, S. Feher, J. Frieman, L. Hui, S. Jester, S. Kent, H. Lampeitl, P. Limon, H. Lin, J. Marriner, N. Mokhov, J. Peoples, I. Rakhno, R. Ray, V. Scarpine, A. Stebbins, S. Striganov, C. Stoughton, B. Tschirhart, D. Tucker

***affiliated institution**
**** pending**

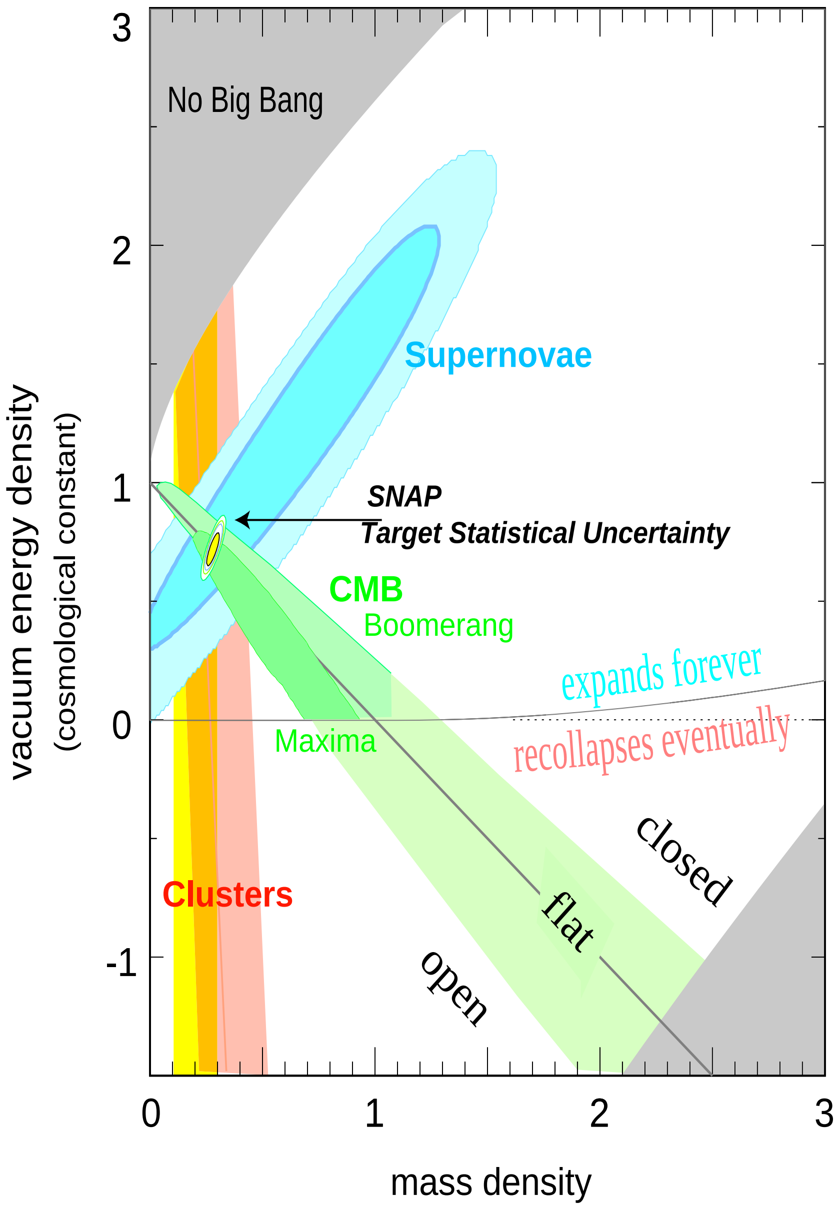
Mirror and Focal Plane

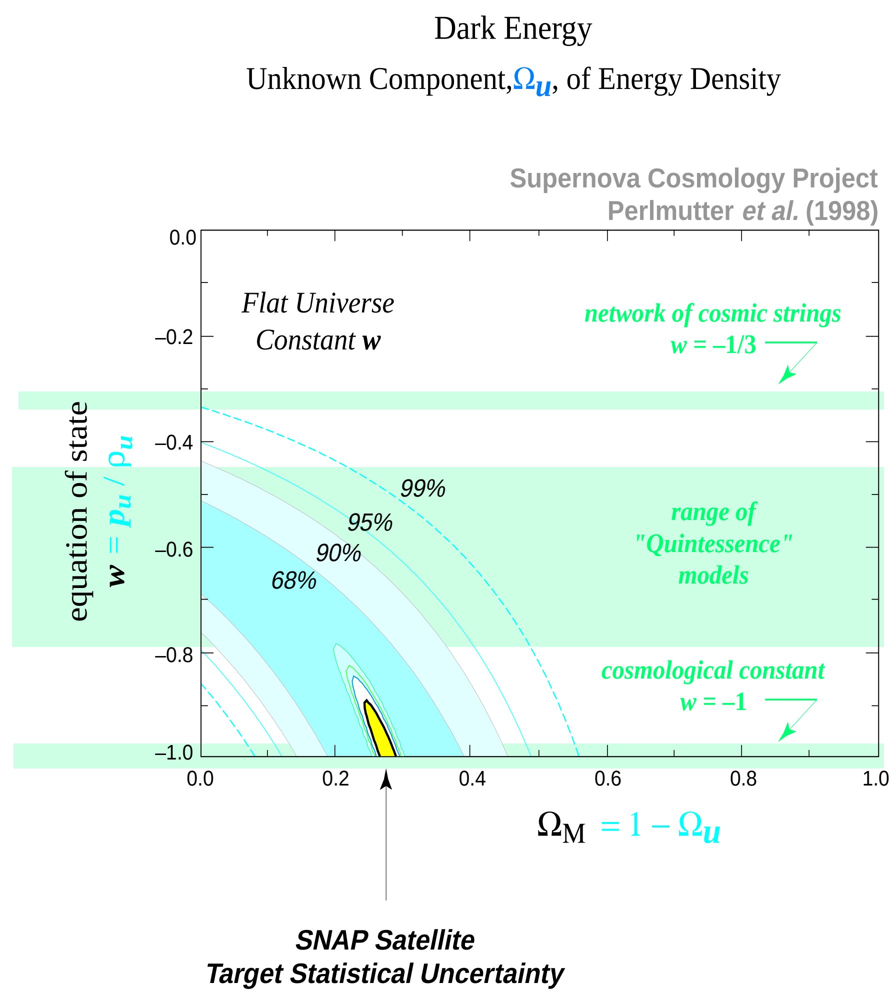




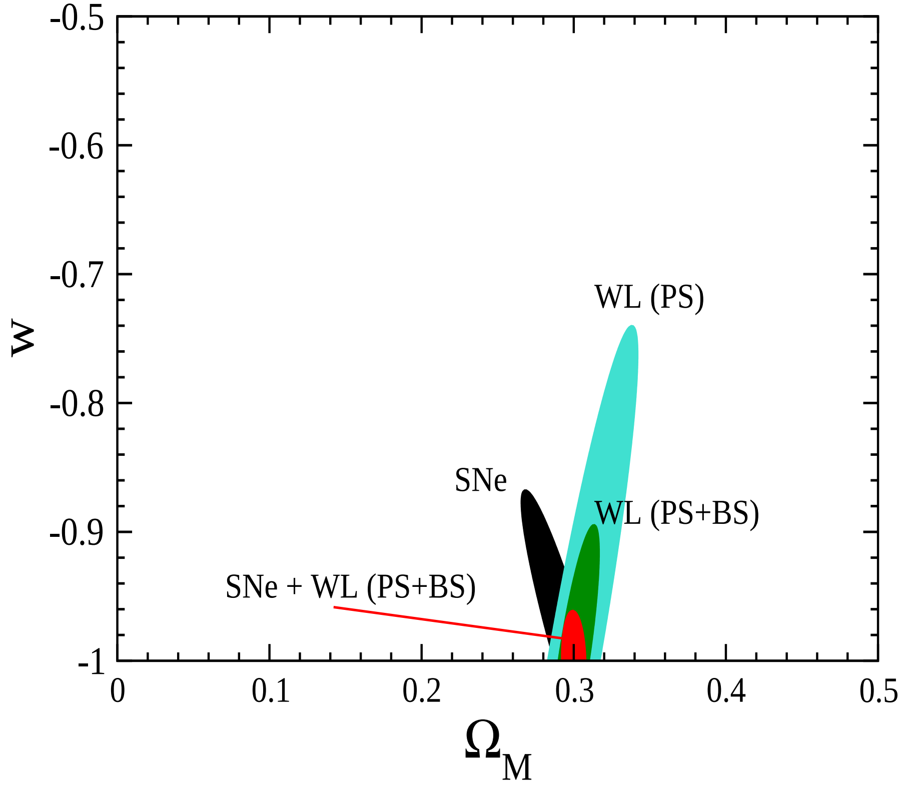

~2500 SNe Ia
fainter
magnitude
redshift
Dark Energy Properties
Dark Matter Properties
Cosmological Params.
Cosmological Params.
30
25
20
15
10
0.0
0.5
1.0
1.5
2.0
2.5

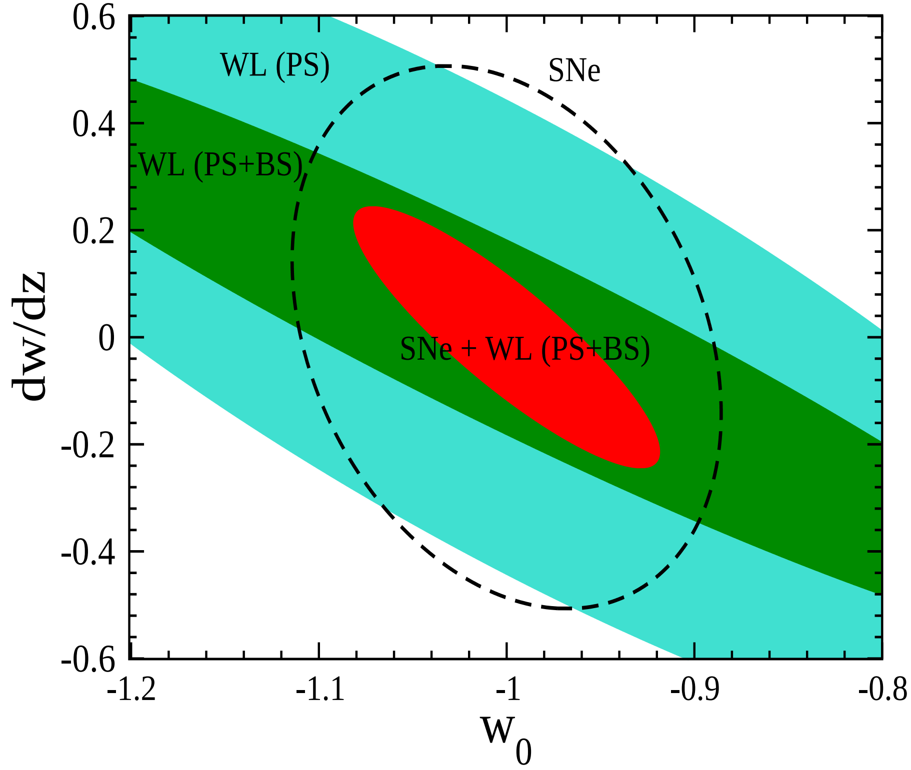
SNAP predicted constraints

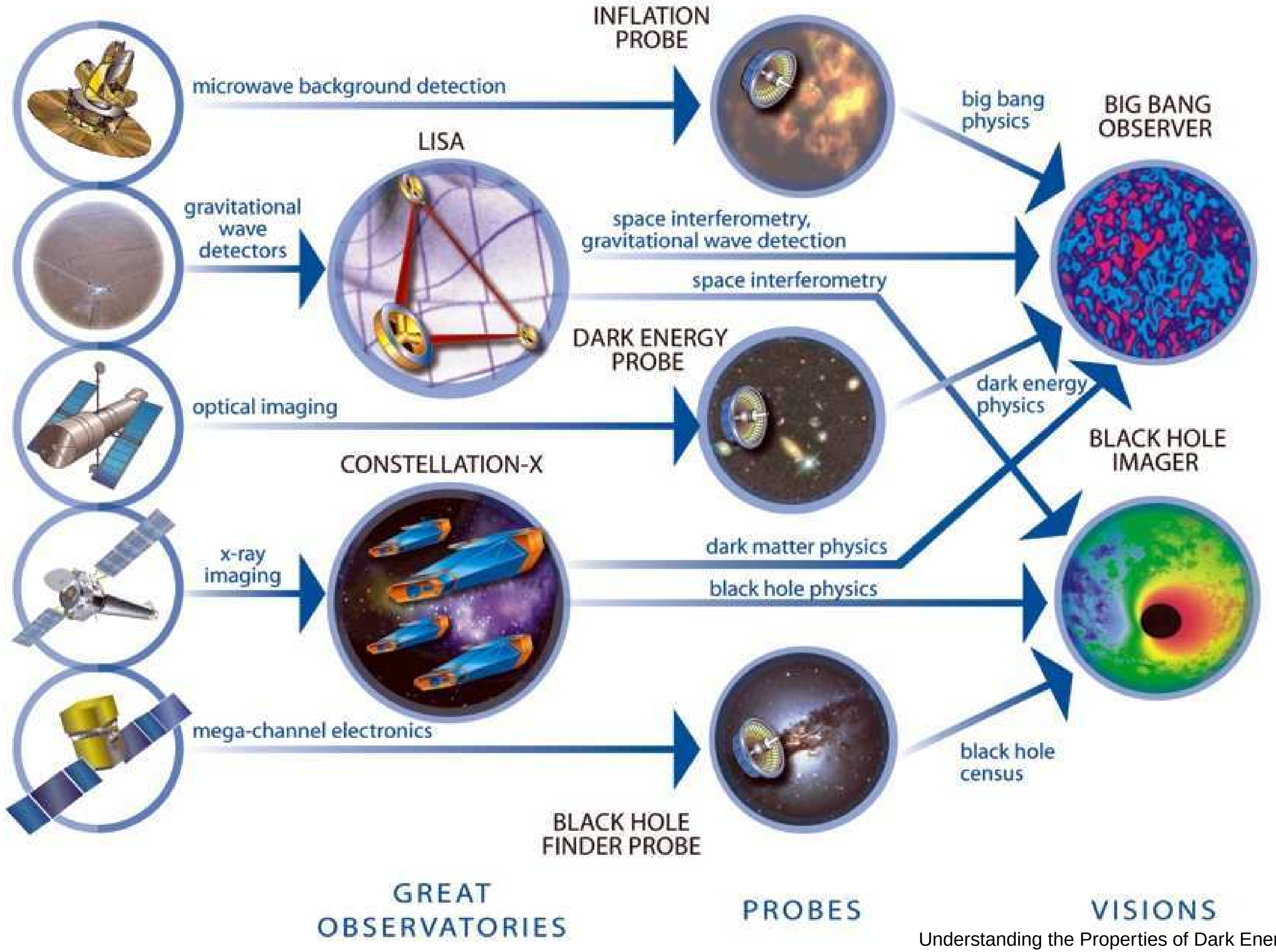




Weak Lensing with SNAP






INFLATION PROBE
microwave background detection
big bang physics
BIG BANG OBSERVER
LISA
gravitational wave detectors
space interferometry, gravitational wave detection
space interferometry
DARK ENERGY PROBE
dark energy physics
optical imaging
BLACK HOLE IMAGER
CONSTELLATION-X
x-ray imaging
dark matter physics
black hole physics
mega-channel electronics
black hole census
BLACK HOLE FINDER PROBE
GREAT OBSERVATORIES
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Office of Science
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NASA-DOE
Joint Dark Energy Mission

Paul Hertz / NASA

Robin Staffin / DOE

Endorsed by

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Director of the Office of Science
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September 24, 2003

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NASA
September 25, 2003

Conclusions

- Dark energy makes up $\sim 70\%$ of energy density in the universe. It is smooth and has negative pressure.
- We describe it via Ω_{DE} and w.
- It affects cosmology by modifying the expansion rate $H(z)$ at recent times ($z \lesssim 2$).
- SNe Ia, weak lensing and number counts are most promising probes; variety of other methods can help.
- Bright prospects with future wide-field surveys (SNAP, LSST, SPT,...)
- But to understand DE, major insights will be needed from theorists. This will be especially hard if $w(z) = -1$!