Lecture I:
Discovery of Dark Energy

Dragan Huterer

Physics Department
University of Michigan

My three lectures roughly cover:

1.Dark energy basics, discovery with SNe, probes
2. DE phenomenology (parametrizations etc)
3. Statistical methods in cosmology (MCMC, Fisher, etc)

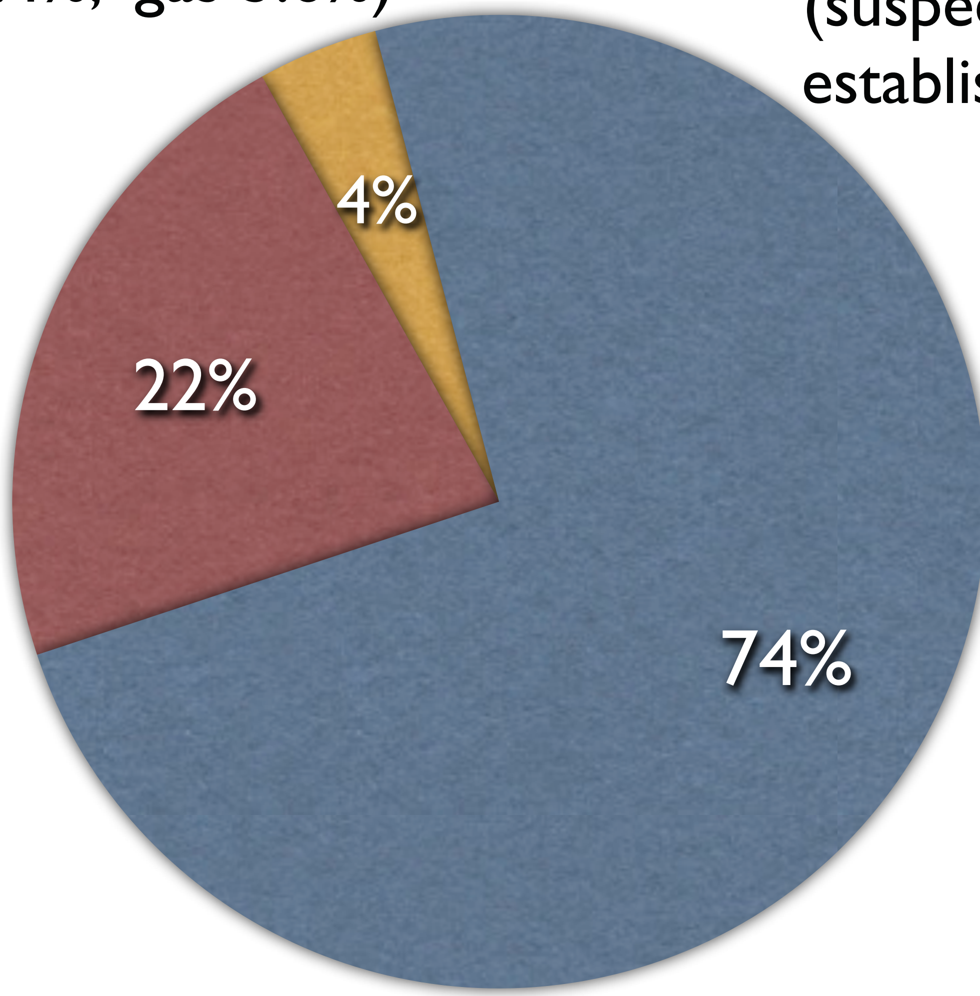
The universe today presents us with a grand puzzle:

What makes up 95% of it?

Scandalously, we still don't know.

But we are working to get closer to the answer.

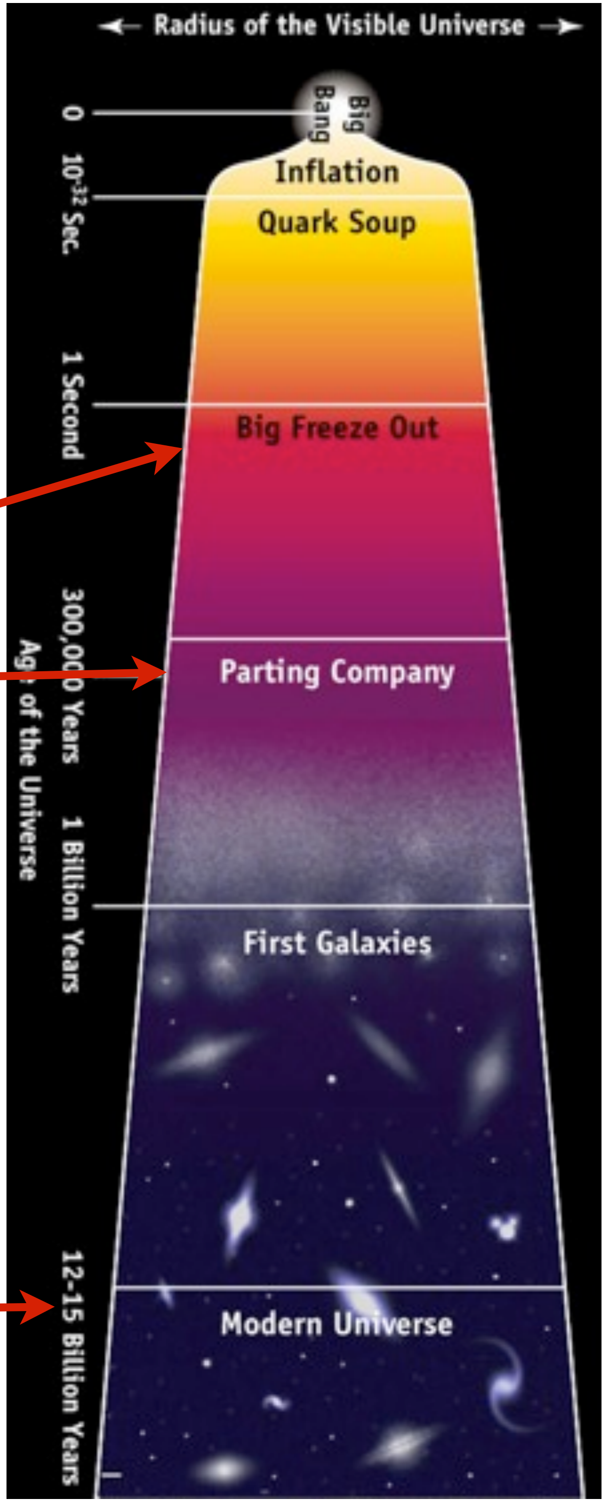
Makeup of universe today



Some of the early
history of the Universe
is actually understood better!

Physics quite well
understood

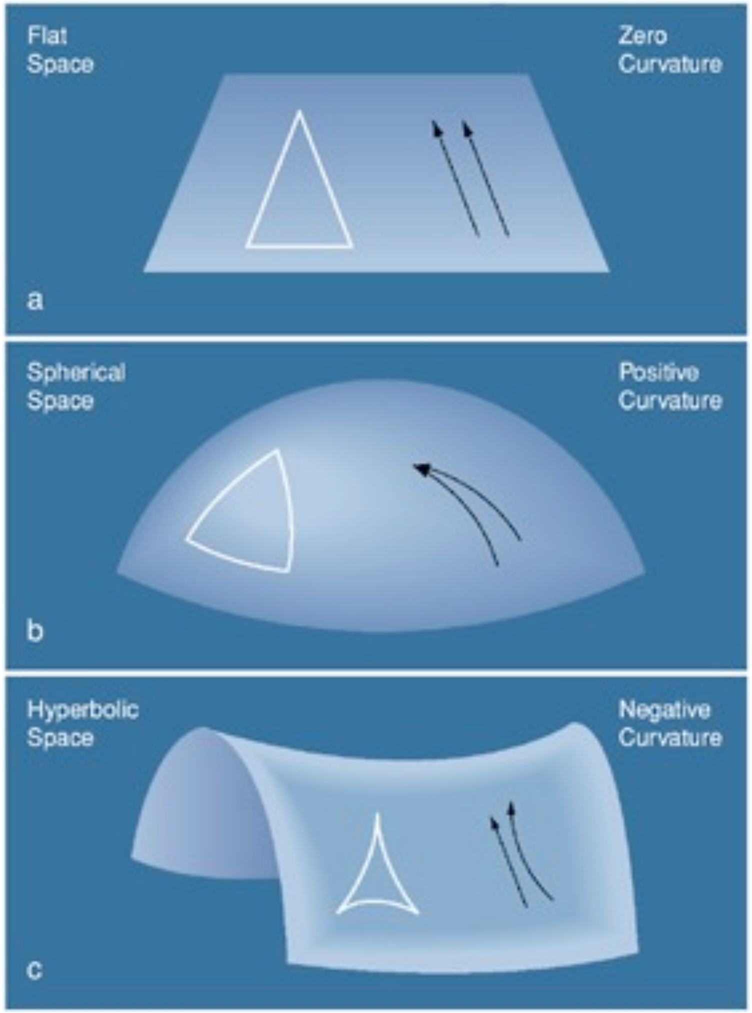
95% of contents only
phenomenologically
described



Friedmann Equation

$$H^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{a^2}$$

define $\Omega \equiv \rho \frac{8\pi G}{3H^2} \equiv \frac{\rho}{\rho_{\rm crit}}$



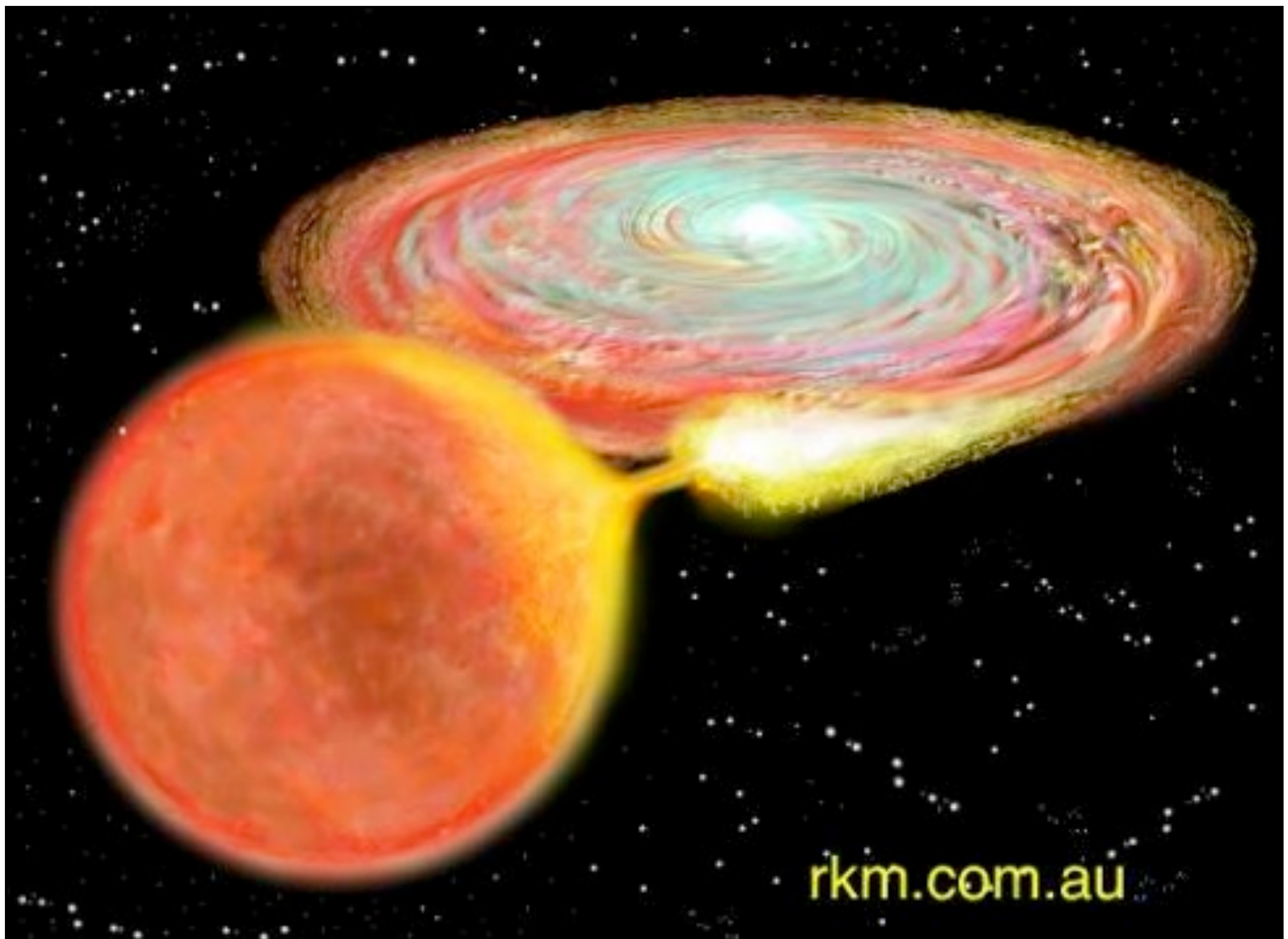
Inflation predicts, and
CMB anisotropy indicates
universe is flat (curvature is zero), so $\Omega_{\rm TOT} = 1$ (or $\kappa = 0$)

Galaxy distribution indicates matter makes up 25% of critical density, so $\Omega_{\rm M} \approx 0.25$

So where is 75% of the energy density?

Type Ia Supernovae

A white dwarf accretes matter from a companion.



SNe Ia are "Standard Candles"

(car headlights example)

If you know the intrinsic brightness of the headlights, you can estimate how far away the car is

A way to measure (relative) distances to objects far away

ON SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

A. Common Novae.—The extensive investigations of extragalactic systems during recent years have brought to light the remarkable fact that there exist two well-defined types of new stars or novae which might be distinguished as *common novae* and *super-novae*. No intermediate objects have so far been observed.

Common novae seem to be a rather frequent phenomenon in certain stellar systems. Thus, according to Bailey,[1] ten to twenty novae flash up every year in our own Milky Way. A similar frequency (30 per year) has been found by Hubble in the well-known Andromeda nebula. A characteristic feature of these common novae is their absolute brightness (M) at maximum, which in the mean is -5.8 with a range of perhaps 3 to 4 mags. The maximum corresponds to 20,000 times the radiation of the sun. During maximum light the common novae therefore belong to the absolutely brightest stars in stellar systems. This is in full agreement with the fact that we have been able to discover this type of novae in other stellar systems near enough for us to reach stars of absolute magnitude -5 with our present optical equipment

B. Super-Novae.—The novae of the second group (super-novae) presented for a while a very curious puzzle because this type of new star was found, not only in the nearer systems, but apparently all over the accessible

Baade & Zwicky 1934

THE ASTROPHYSICAL JOURNAL, **232**:404–408, 1979 September 1

SUPERNOVAE AS A STANDARD CANDLE FOR COSMOLOGY

STIRLING A. COLGATE
New Mexico Institute of Mining and Technology, and Los Alamos Scientific Laboratory
Received 1978 September 5; accepted 1979 March 9

ABSTRACT

Supernovae can perhaps be found at $Z \approx 1$ using the Space Telescope and the Focal Plane Camera (cryogenic charge coupled devices) at a rate of approximately four per week using 3 hours per week of viewing time. If Type II supernovae are used as a self-calibrating candle at $Z \ll 1$, then Type I's can be calibrated from Type II's as a secondary standard candle (2 mag brighter) and used instead of Type II's for a less difficult determination of q_0. This assumes all Type I's are the same independent of Z whereas each Type II is self-calibrated. Adequate statistics of supernovae in nearby galaxies $Z \lesssim 1$ can further verify the uniqueness of Type I's. Three-color wide-band photometry performed over the period of the maximum luminosity of a Type I gives the time dilation $\propto (1 + Z)^{-1}$, color shift $\propto (1 + Z)^{-1}$, and apparent luminosity $\propto Z^{-2}[1 + 0.5(1 + q_0)Z + O(Z)]^{-2}(1 + Z)^{-2}$. A Type I supernova at maximum and $Z = 1$, $H_0 = 50$, should give rise to a statistically meaningful maximum single pixel signal of ~ 250 photoelectrons compared to an average galaxy center background of ~ 25 photoelectrons for an 80 s integration time. An average of ~ 100 large galaxies ($10^{10}\ L_\odot$) per field allows $\sim 10^4$ galaxies to be monitored using 3 hours of viewing time. Z can be determined by time dilation and color shift sufficiently accurately that the determination of q_0 will have twice the error of the calibration of Type I as a standard candle.

Colgate 1979

But how do you find SNe?

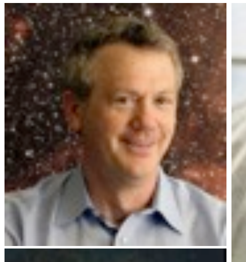
Rate: 1 SN per galaxy per 500 yrs!

Solution:
a combination of using world's large telescopes, scheduling them to find, then "follow-up" SNe and heroic hard work by two teams of researchers

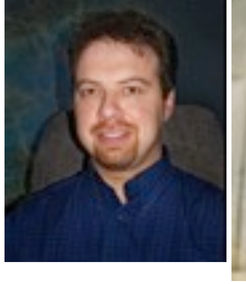
Saul Perlmutter,
Supernova Cosmology Project

Brian Schmidt,
High-redshift Supernova Team

Bob Kirshner



Adam Riess



The discovery of a type Ia supernova at a redshift of 0.31

Hans U. Nørgaard-Nielsen*, Leif Hansen†, Henning E. Jørgensen†, Alfonso Aragón Salamanca‡, Richard S. Ellis‡ & Warrick J. Couch§

* Danish Space Research Institute, Lundtoftevej 7, DK-2800 Lyngby, Denmark
† Copenhagen University Observatory, Øster Voldgade 3, DK-1350 Copenhagen K, Denmark
‡ Physics Department, University of Durham, South Road, Durham DH1 3LE, UK
§ Anglo-Australian Observatory, Epping Laboratory, PO Box 296, Epping, New South Wales 2121, Australia

could be found and if they revealed a closely distributed (tight) Hubble diagram, precise photometry of a sufficiently deep sample could provide an interesting constraint on q_0. The effect of a change in q_0 from 0.1 to 0.5 is only 0.13 mag at $z=0.3$, rising to 0.22 mag at $z=0.5$, so many accurately measured supernovae would be required. Our distant-supernova search programme has been described previously[2,3]. Our recent estimate of the frequency of occurrence of type Ia supernovae[3] lies at the lower end of the range determined in nearby galaxies[4–6]. Furthermore, even at maximum light such type Ia supernovae would be fainter than $V \approx 21.5$ mag, and thus any search strategy needs to reliably detect an absolute change in a galaxy's flux equivalent to $V \approx 23$ mag.

Using the 1.5-m Danish telescope at La Silla, Chile, we have monitored ~60 clusters in the redshift interval $0.2 < z < 0.5$ over a period of two years. One-hour CCD exposures in good condi-

Just a single SN caught, and it was past the peak!

Norgaard-Nielsen et al 1989

Standardizing the candles

THE ASTROPHYSICAL JOURNAL, 413:L105–L108, 1993 August 20

THE ABSOLUTE MAGNITUDES OF TYPE Ia SUPERNOVAE

M. M. PHILLIPS
Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories,[1] Casilla 603, La Serena, Chile
Received 1993 March 22; accepted 1993 June 2

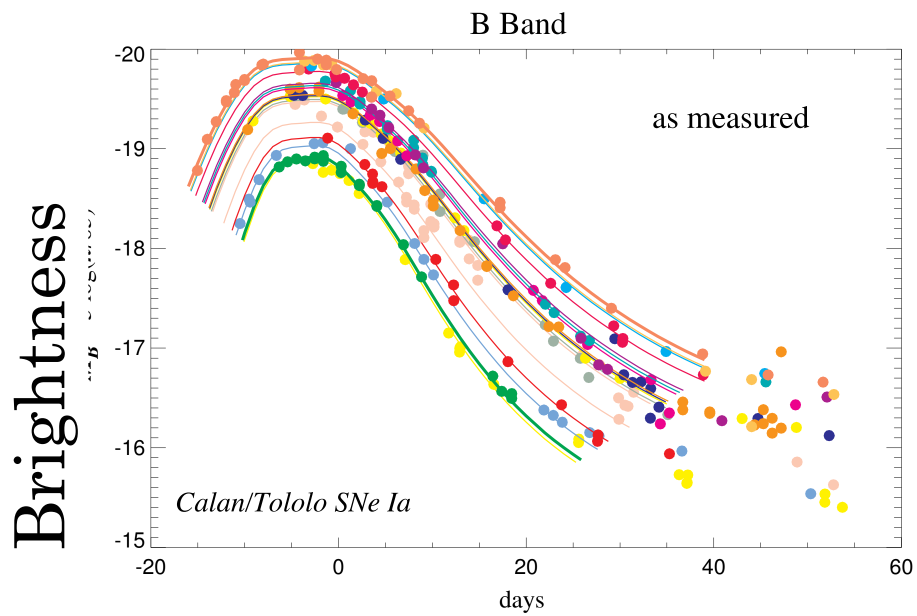
ABSTRACT

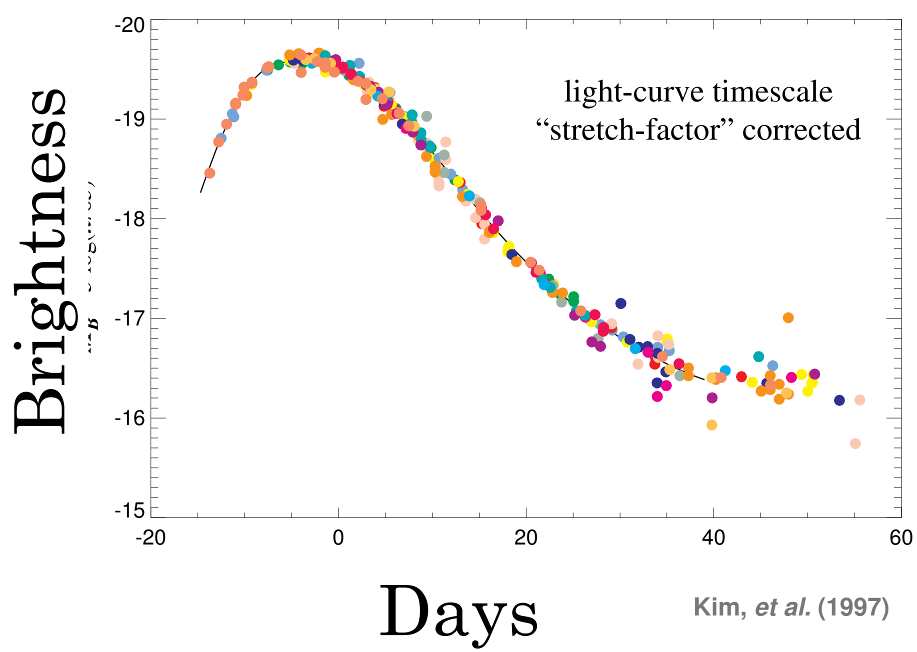
Absolute magnitudes in the *B*, *V*, and *I* bands are derived for nine well-observed Type Ia supernovae using host galaxy distances estimated via the surface brightness fluctuations or Tully-Fisher methods. These data indicate that there is a significant intrinsic dispersion in the absolute magnitudes at maximum light of Type Ia supernovae, amounting to ± 0.8 mag in *B*, ± 0.6 mag in *V*, and ± 0.5 mag in *I*. Moreover, the absolute magnitudes appear to be tightly correlated with the initial rate of decline of the *B* light curve, with the slope of the correlation being steepest in *B* and becoming progressively flatter in the *V* and *I* bands. This implies that the intrinsic $B-V$ colors of Type Ia supernovae at maximum light are not identical, with the fastest declining light curves corresponding to the intrinsically reddest events. Certain spectroscopic properties may also be correlated with the initial decline rate. These results are most simply interpreted as evidence for a range of progenitor masses, although variations in the explosion mechanism are also possible. Considerable care must be exercised in employing Type Ia supernovae as cosmological standard candles, particularly at large redshifts where Malmquist bias could be an important effect.

Subject headings: distance scale — supernovae: general

Phillips 1993

Standardizing the candles





Phillips relation simply says:

"Broader
is
Brighter"

Measuring distance from SNe

$$DM \equiv m - M = 5\log_{10}\left(\frac{d_L}{10\mathrm{pc}}\right)$$

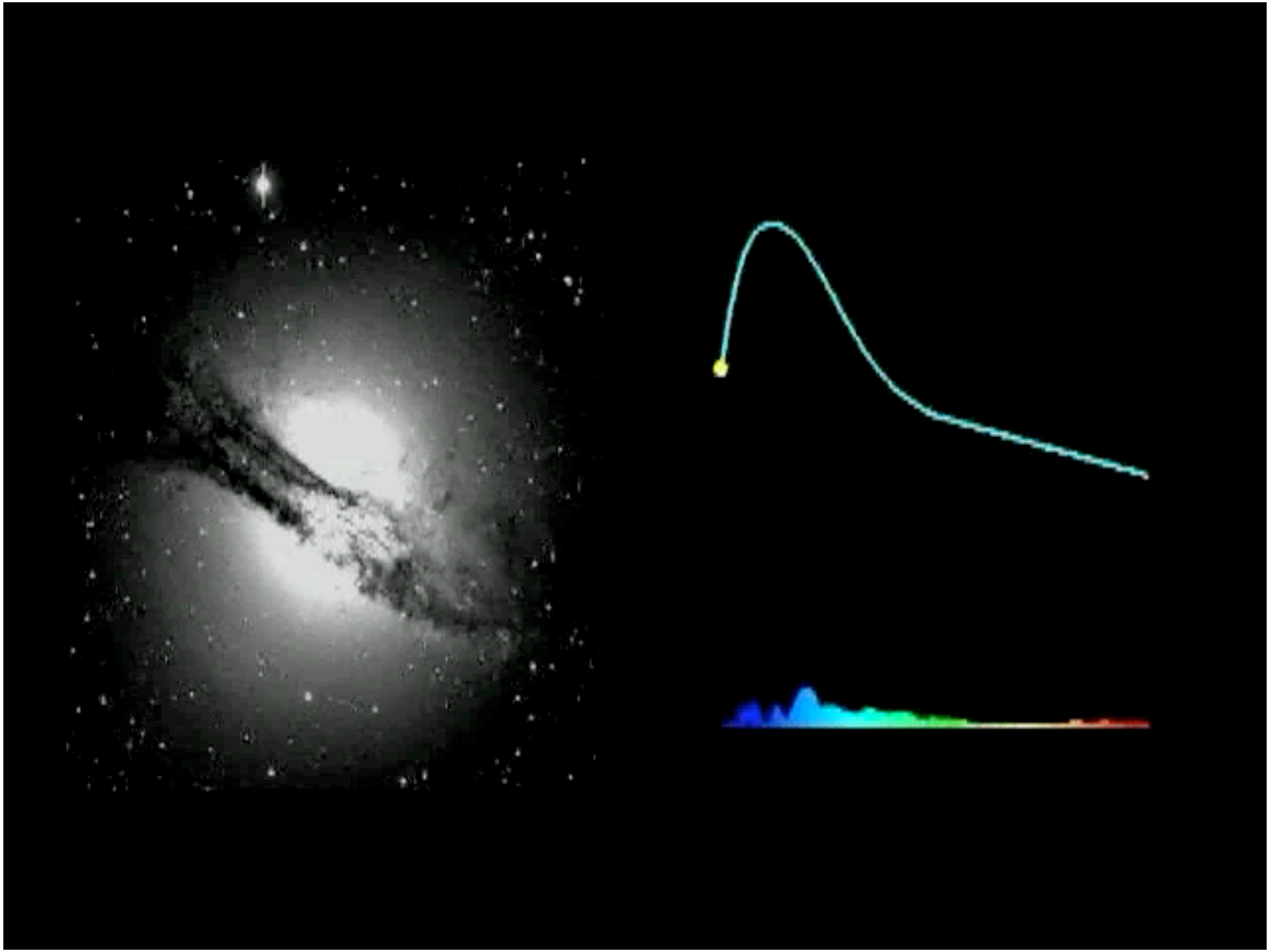
$$\Rightarrow\ m = M + 5\log_{10}(H_0 d_L) - 5\log_{10}\left(H_0 \times 10\mathrm{pc}\right)$$

$$\Rightarrow\ \boxed{m \equiv 5\log_{10}(H_0 d_L) + \mathcal{M}}$$

$$\mathcal{M} \equiv M - 5\log_{10}\left(\frac{H_0}{\mathrm{Mpc}^{-1}}\right) + 25$$

(nuisance parameter)

Need to always fully marginalize over $\mathcal{M}$
(may lose ~50% precision in cosmo parameters)



credit: Supernova Cosmology Project

The Astrophysical Journal, 483:565–581, 1997 July 10

MEASUREMENTS[1] OF THE COSMOLOGICAL PARAMETERS Ω AND Λ FROM THE FIRST SEVEN SUPERNOVAE AT $z \geq 0.35$

S. Perlmutter,[2,3] S. Gabi,[2,4] G. Goldhaber,[2,3] A. Goobar,[2,3,5] D. E. Groom,[2,3] I. M. Hook,[3,6] A. G. Kim,[2,3] M. Y. Kim,[2] J. C. Lee,[2] R. Pain,[2,7] C. R. Pennypacker,[2,4] I. A. Small,[2,3] R. S. Ellis,[8] R. G. McMahon,[8] B. J. Boyle,[9,10] P. S. Bunclark,[9] D. Carter,[9] M. J. Irwin,[9] K. Glazebrook,[10] H. J. M. Newberg,[11] A. V. Filippenko,[3,6] T. Matheson,[6] M. Dopita,[12] and W. J. Couch[13]

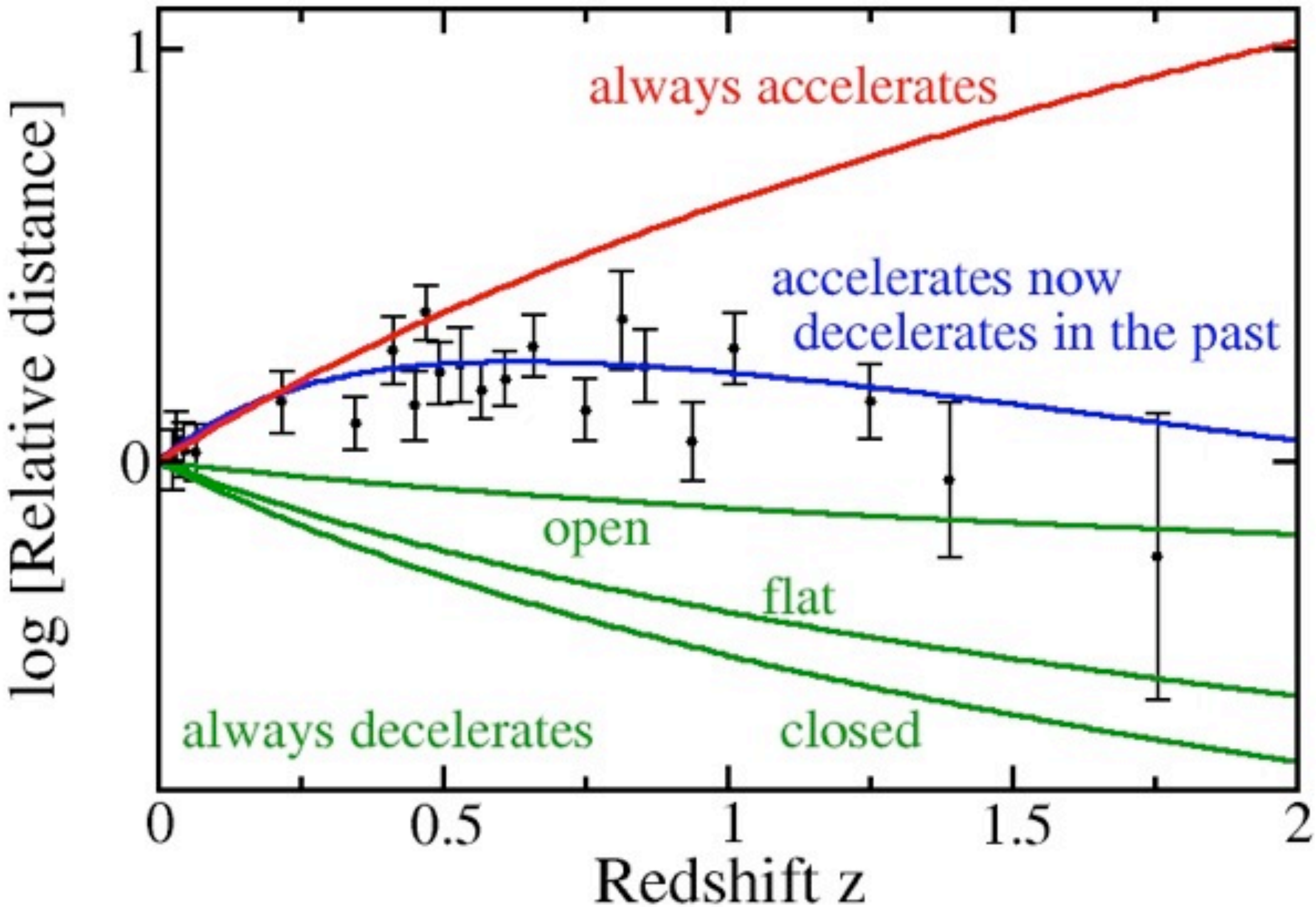
(The Supernova Cosmology Project)
Received 1996 August 26; accepted 1997 February 6

ABSTRACT

We have developed a technique to systematically discover and study high-redshift supernovae that can be used to measure the cosmological parameters. We report here results based on the initial seven of more than 28 supernovae discovered to date in the high-redshift supernova search of the Supernova Cosmology Project. We find an observational dispersion in peak magnitudes of $\sigma_{M_B} = 0.27$; this dispersion narrows to $\sigma_{M_B,\mathrm{corr}} = 0.19$ after "correcting" the magnitudes using the light-curve "width-luminosity" relation found for nearby ($z \leq 0.1$) Type Ia supernovae from the Calán/Tololo survey (Hamuy et al.). Comparing light-curve width–corrected magnitudes as a function of redshift of our distant ($z = 0.35$–0.46) supernovae to those of nearby Type Ia supernovae yields a global measurement of the mass density, $\Omega_M = 0.88^{+0.69}_{-0.60}$ for a $\Lambda = 0$ cosmology. For a spatially flat universe (i.e., $\Omega_M + \Omega_\Lambda = 1$), we find $\Omega_M = 0.94^{+0.34}_{-0.28}$ or, equivalently, a measurement of the cosmological constant, $\Omega_\Lambda = 0.06^{+0.28}_{-0.34}$ (<0.51 at the 95% confidence level). For the more general Friedmann-Lemaître cosmologies with independent Ω_M and Ω_Λ, the results are presented as a confidence region on the Ω_M-Ω_Λ plane. This region does not correspond to a unique value of the deceleration parameter q_0. We present analyses and checks for statistical and systematic errors and also show that our results do not depend on the specifics of the width-luminosity correction. The results for Ω_Λ-versus-Ω_M are inconsistent with Λ-dominated, low-density, flat cosmologies that have been proposed to reconcile the ages of globular cluster stars with higher Hubble constant values.

First results (only 7 distant SNe): universe is matter dominated; with more SNe, acceleration established, however

Supernova Hubble diagram (binned)



Dark Energy Parametrization

Distant Sne are dimmer than expected ⇨
the expansion of the universe is accelerating

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

so, pressure of dark energy is strongly negative

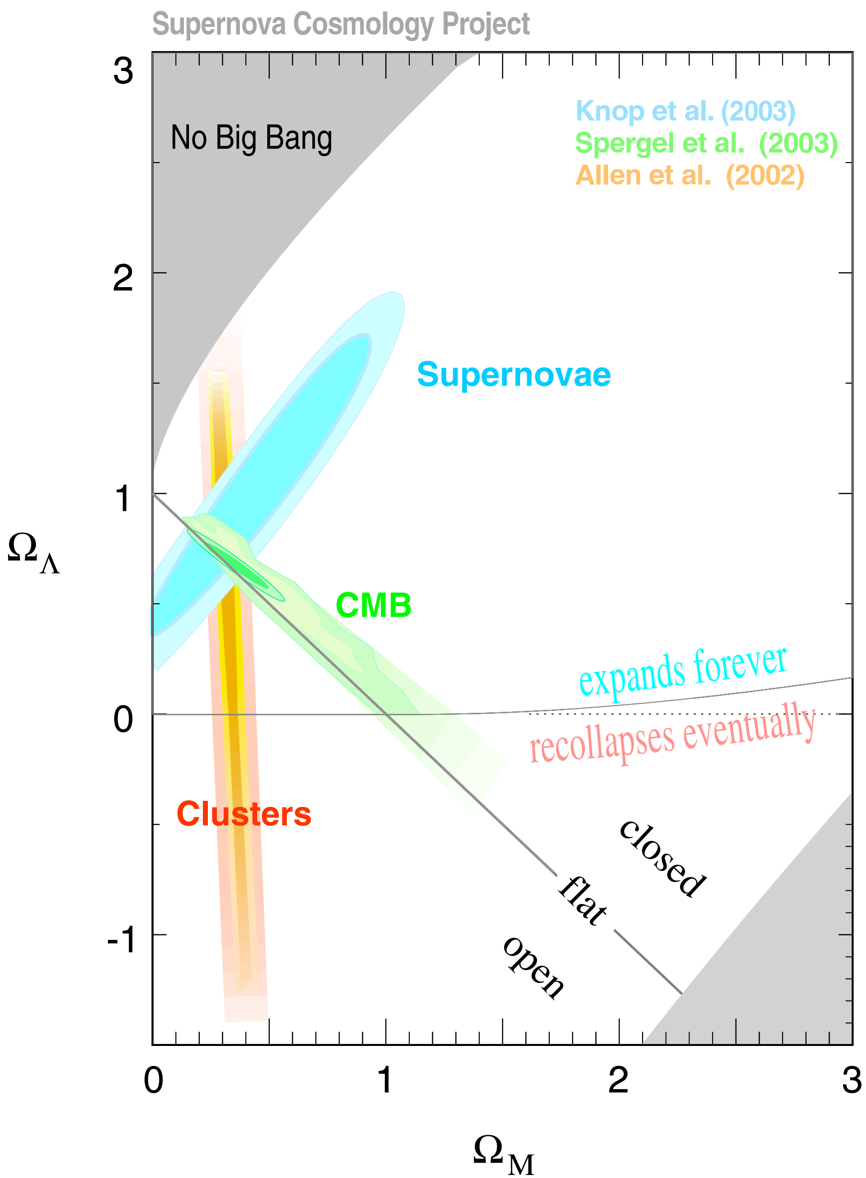
Equation of state ratio: $$w = \frac{p_{\rm DE}}{\rho_{\rm DE}}$$

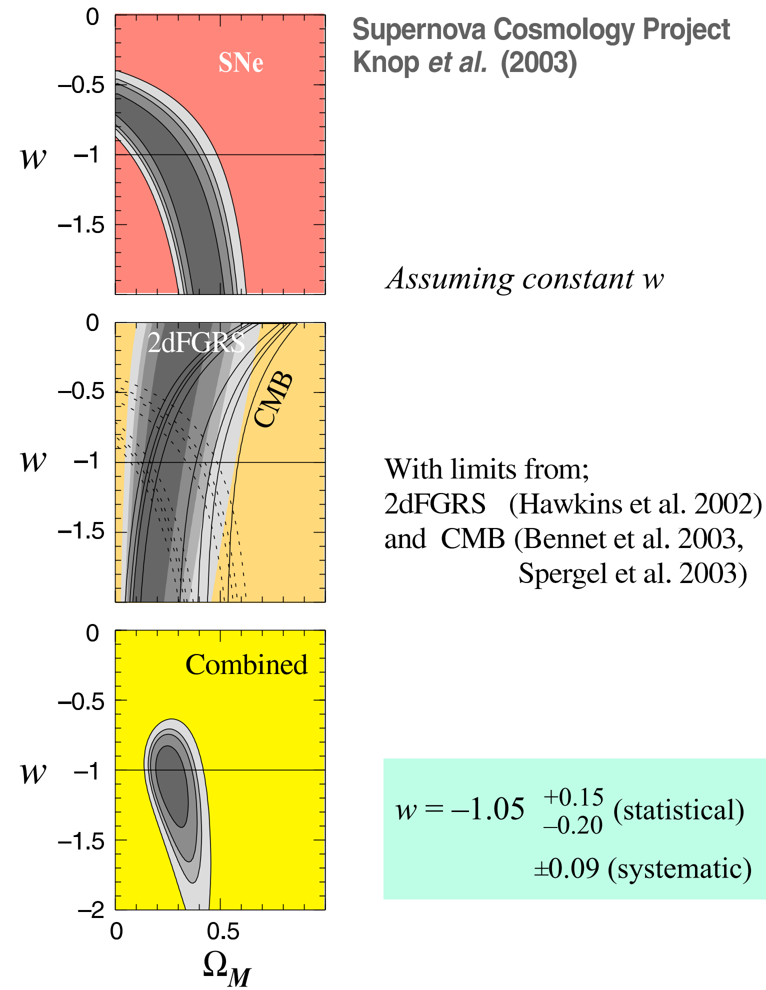
Energy density today (relative to critical): $$\Omega_{\rm DE} = \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

For vacuum energy $w = -1 \;\; (G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu})$

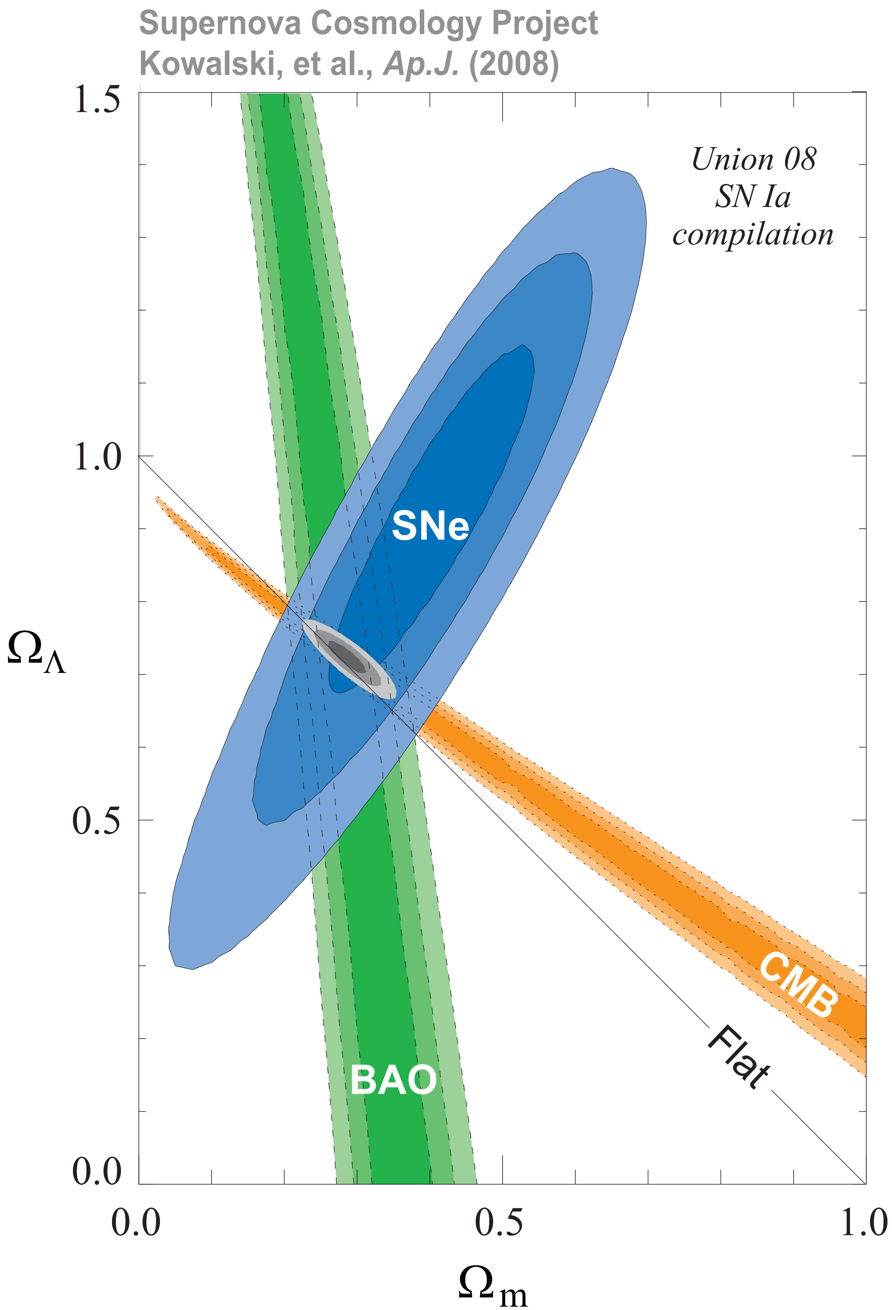
Constraints circa 2003

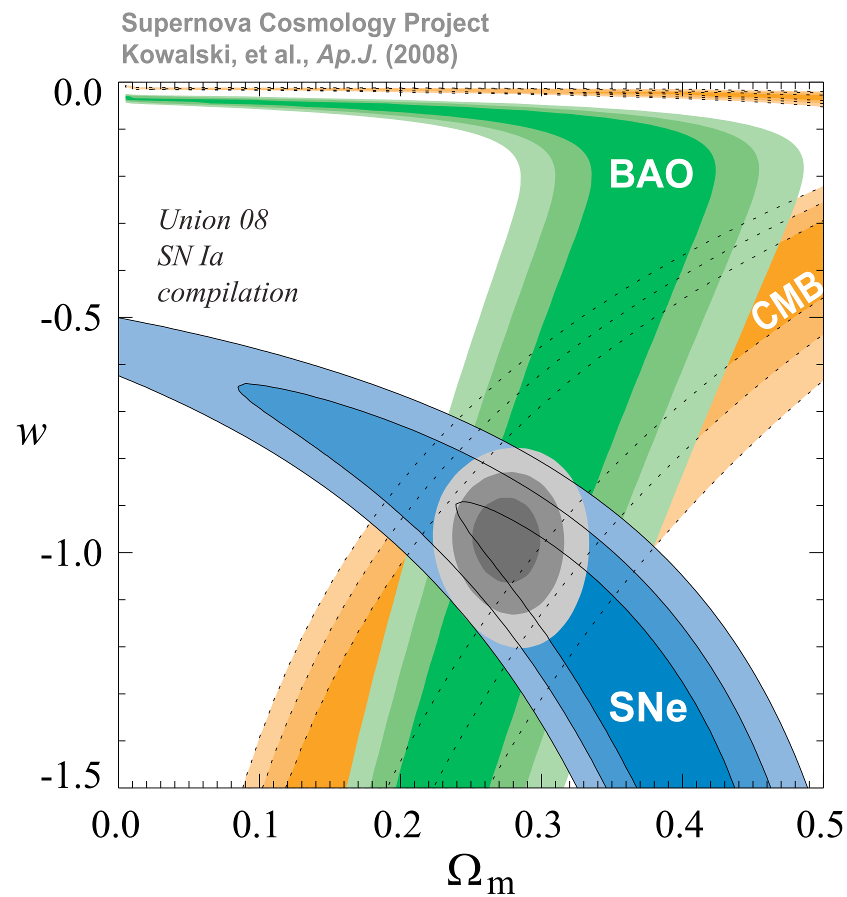
$m(z) = 5\log_{10}(d_L/10\,\mathrm{pc}) + \mathcal{M}; \qquad \mathcal{M} \equiv M - 5\log_{10}[H_0/(\mathrm{km/s/Mpc})] + 25$





Constraints circa 2008



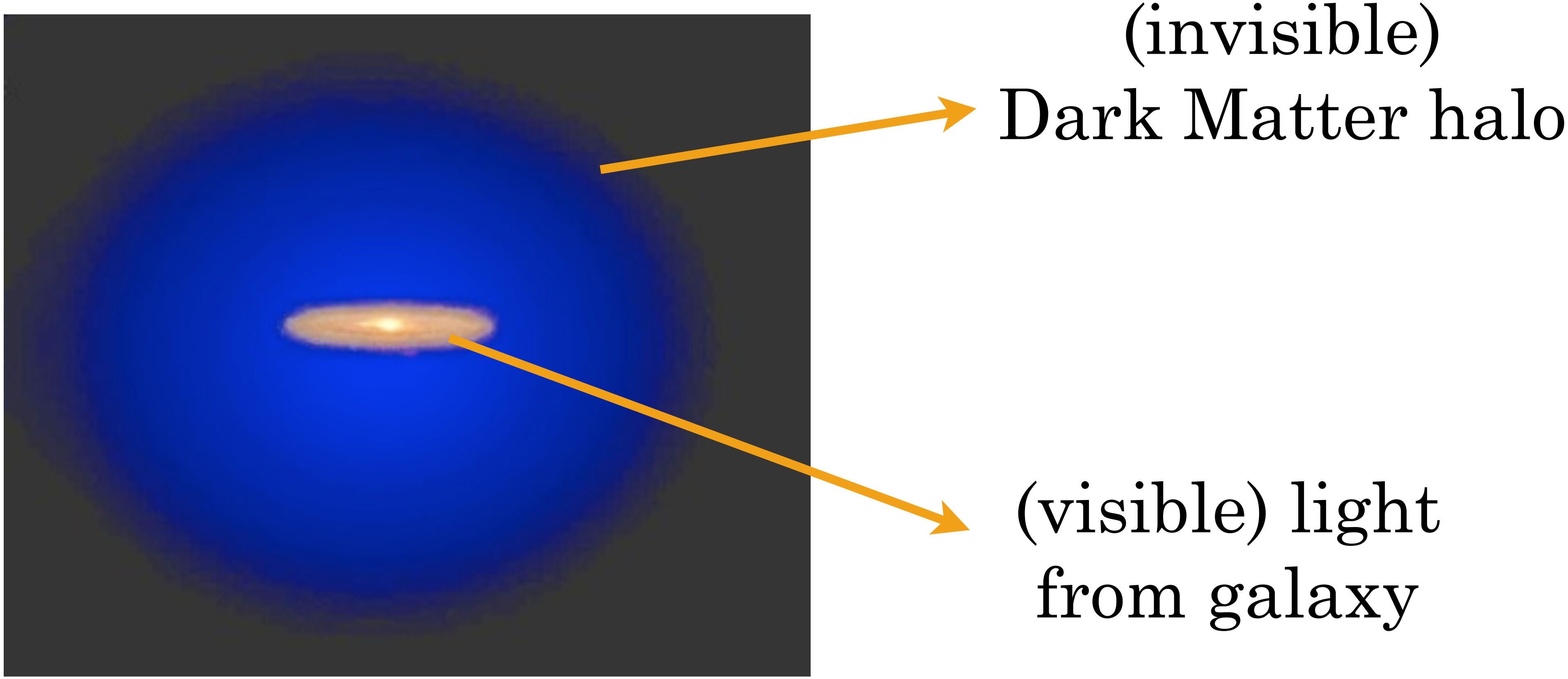


Dark Energy

Michael Turner
University of Chicago

- Universe is dominated by something other than dark matter
- This new component - “dark energy” - makes the universe undergo accelerated expansion
- This new component is largely smooth
- Other than that, we don’t know much!

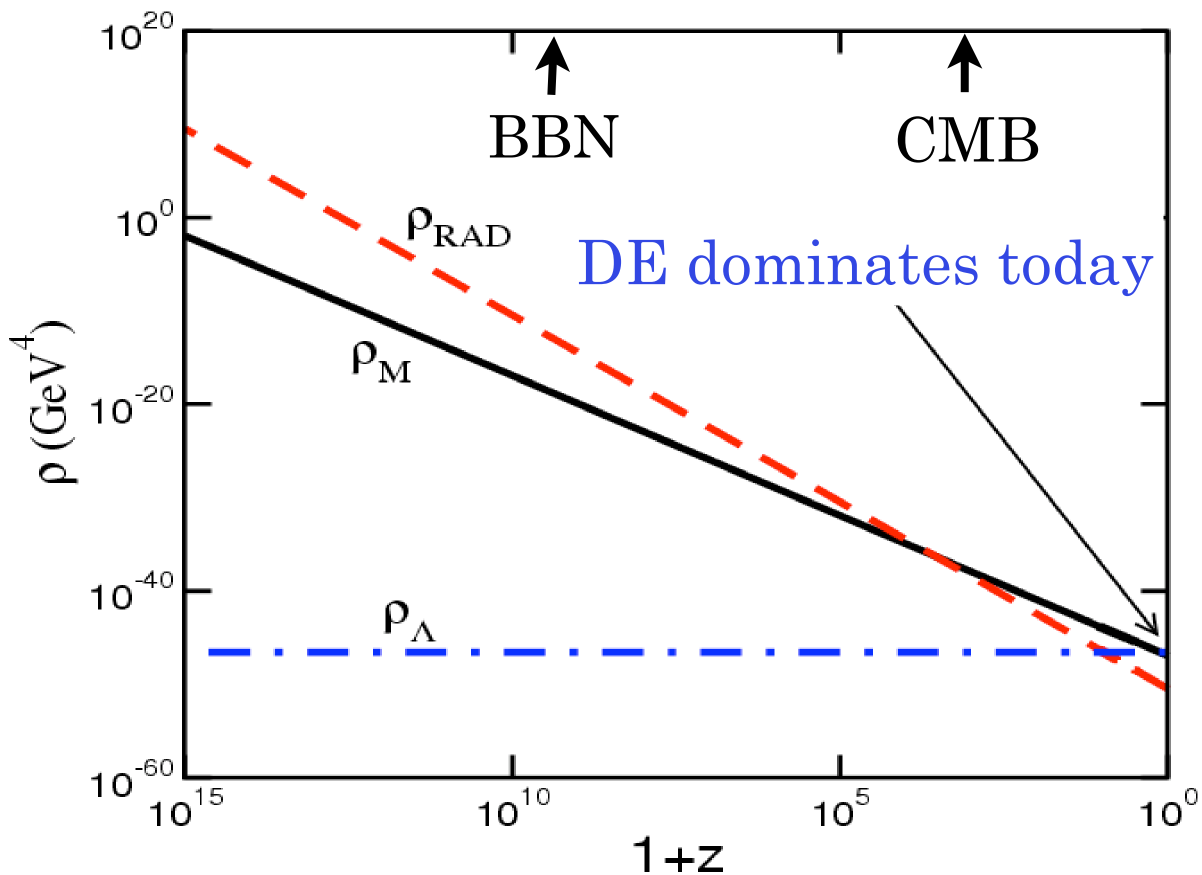
Recall: Dark Matter is in “halos” around galaxies



Fine Tuning Problems I: "Why Now?"

Dark Energy was much less important at earlier epochs.

So why is it comparable to matter today?



$$\frac{\rho_{\rm DE}(z)}{\rho_{\rm M}(z)} = \frac{\Omega_{\rm DE}}{\Omega_M}(1+z)^{3w}$$

Fine Tuning Problems II: "Why so small"?

Vacuum Energy: QFT predicts it to be cutoff scale

$$\rho_{\rm VAC} = \frac{1}{2}\sum_{\rm fields} g_i \int_0^\infty \sqrt{k^2+m^2}\,\frac{d^3k}{(2\pi)^3} \simeq \sum_{\rm fields}\frac{g_i k_{\rm max}^4}{16\pi^2}$$

Measured: $(10^{-3}{\rm eV})^4$

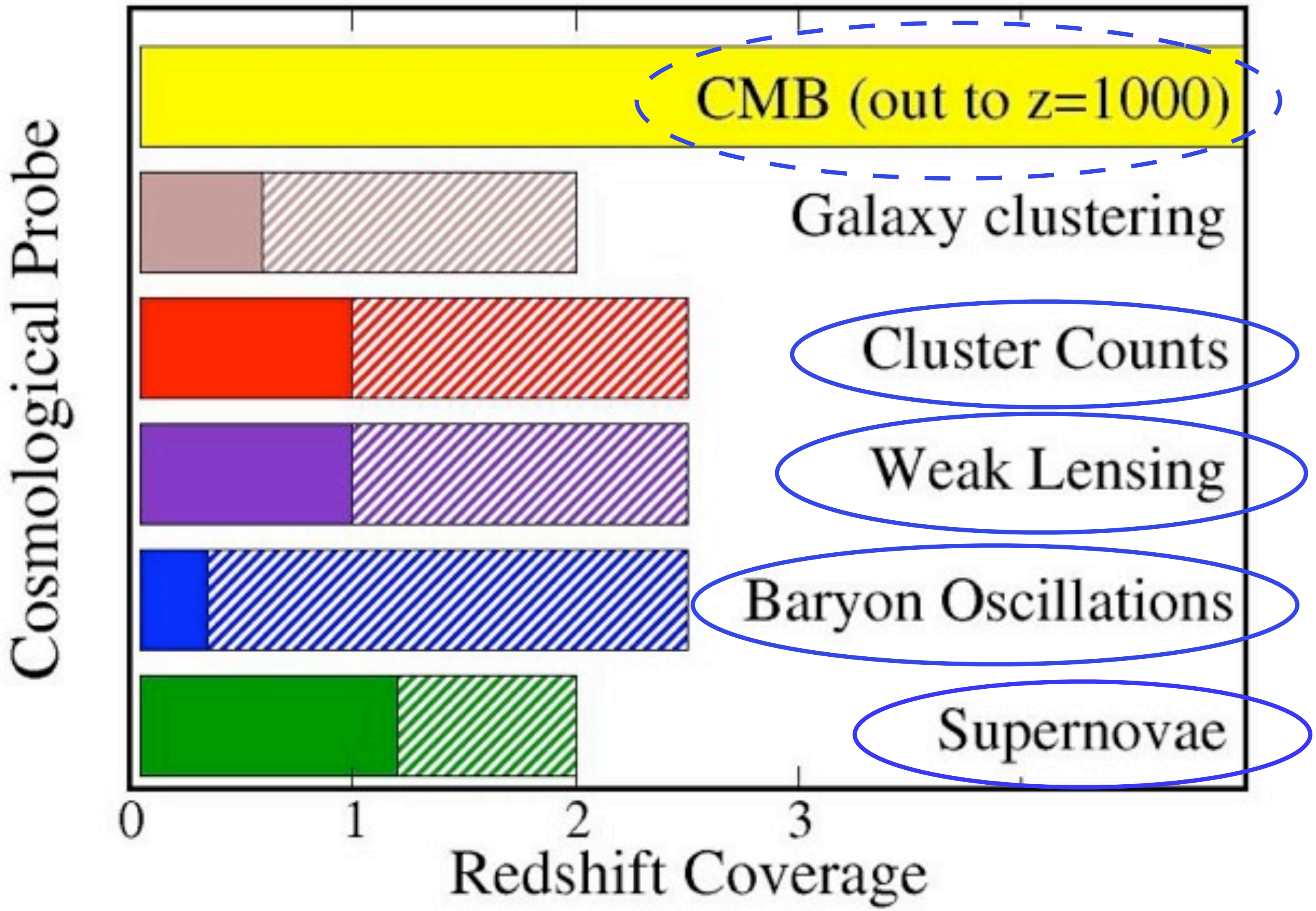
SUSY scale: $(1\,{\rm TeV})^4$

Planck scale: $(10^{19}\,{\rm GeV})^4$

60-120 orders of magnitude smaller than expected!

In other words: $\Lambda\left(\frac{\hbar G}{c^5}\right) \equiv \Lambda t_{\rm pl}^2 \approx \left(H_0^{-1}/t_{\rm pl}\right)^{-2} \sim 10^{-120}$

Cosmological Probes of Dark Energy

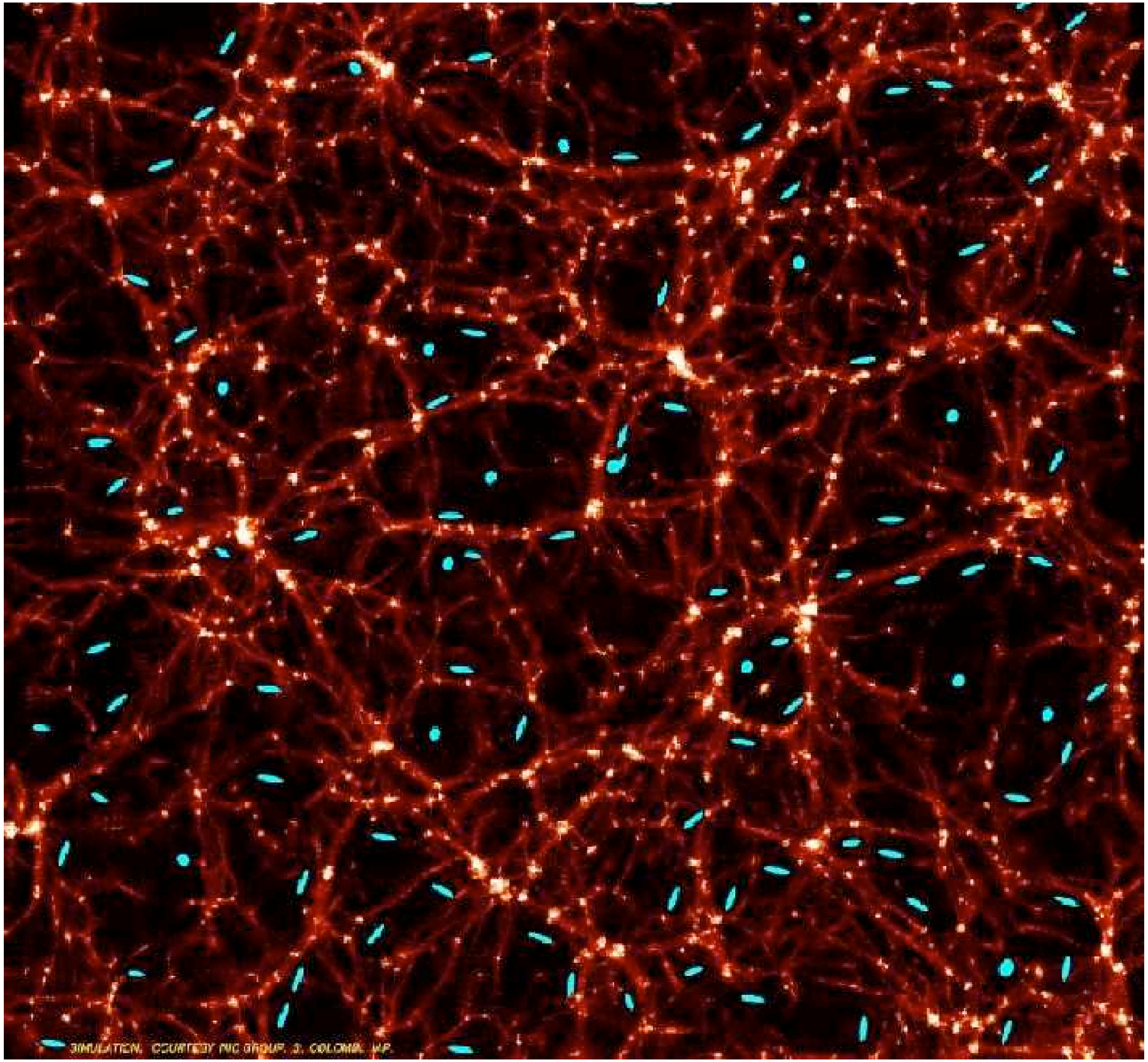


Weak Gravitational Lensing

Credit: NASA, ESA and R. Massey (Caltech)

Key advantage: measures distribution of matter, not light

Weak Gravitational Lensing



Credit: Colombi & Mellier

Weak Lensing and Dark Energy

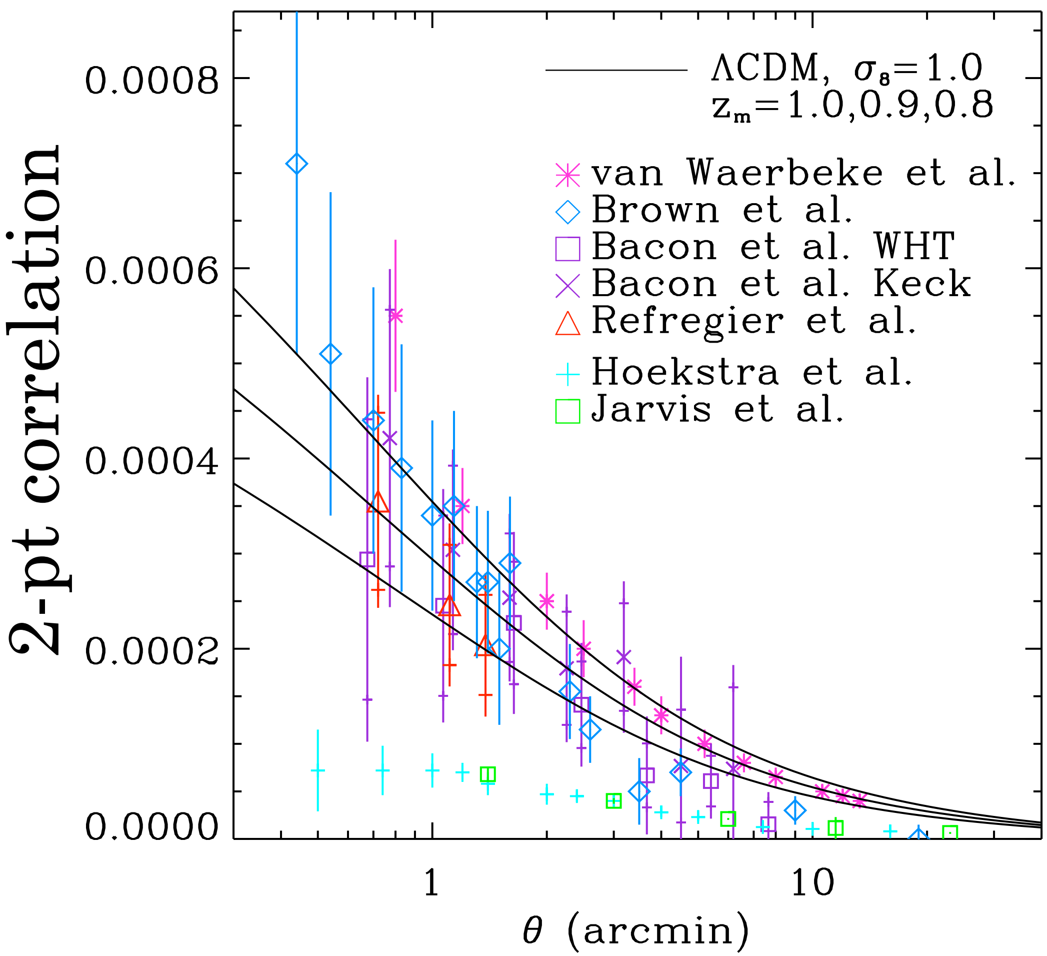
WL measures integral over the line of sight:

$$P_{\rm shear} \simeq \int_0^\infty W(r) P_{\rm matter}(r) dr$$

distance, volume factors

(dark) matter clustering

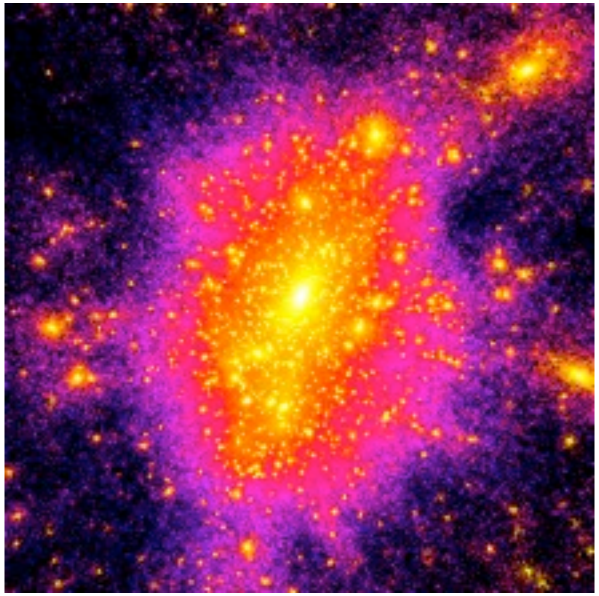
- Probes integrated matter density
- Also sensitive to Dark Energy through distance, volume factors



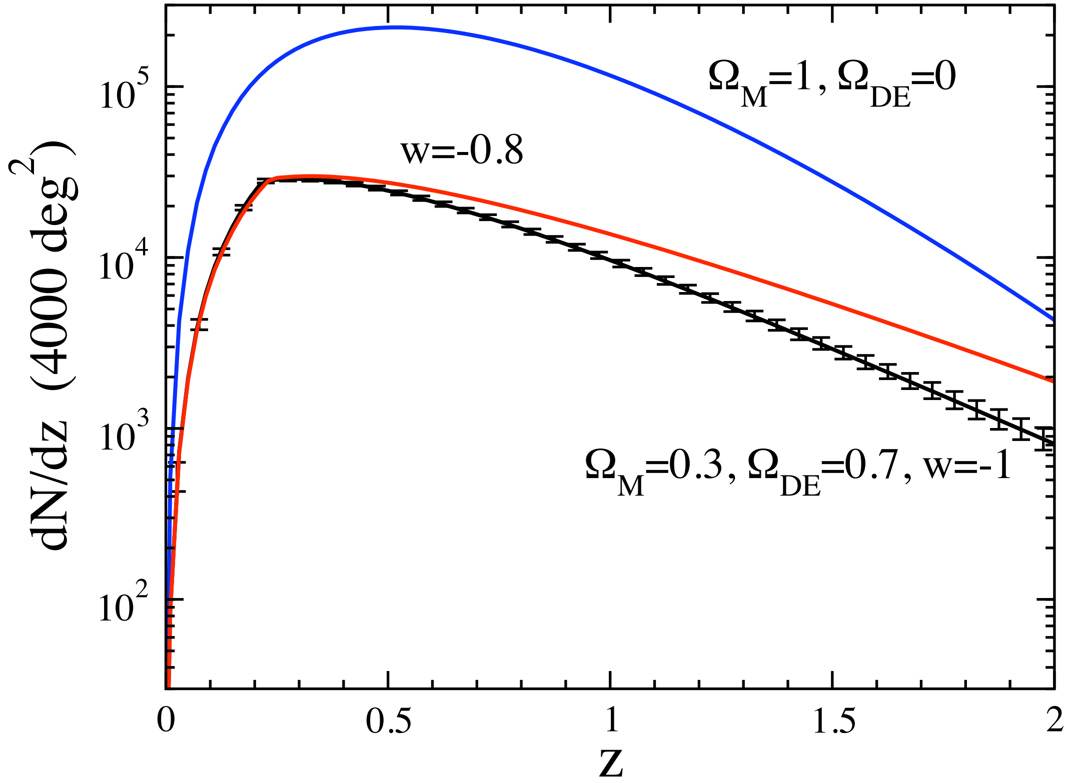
Refregier 2003

Galaxy clusters: number counts

$$\frac{d^2N}{d\Omega\,dz} = n(z)\,\frac{r(z)^2}{H(z)}$$



Credit: Quinn, Barnes, Babul, Gibson

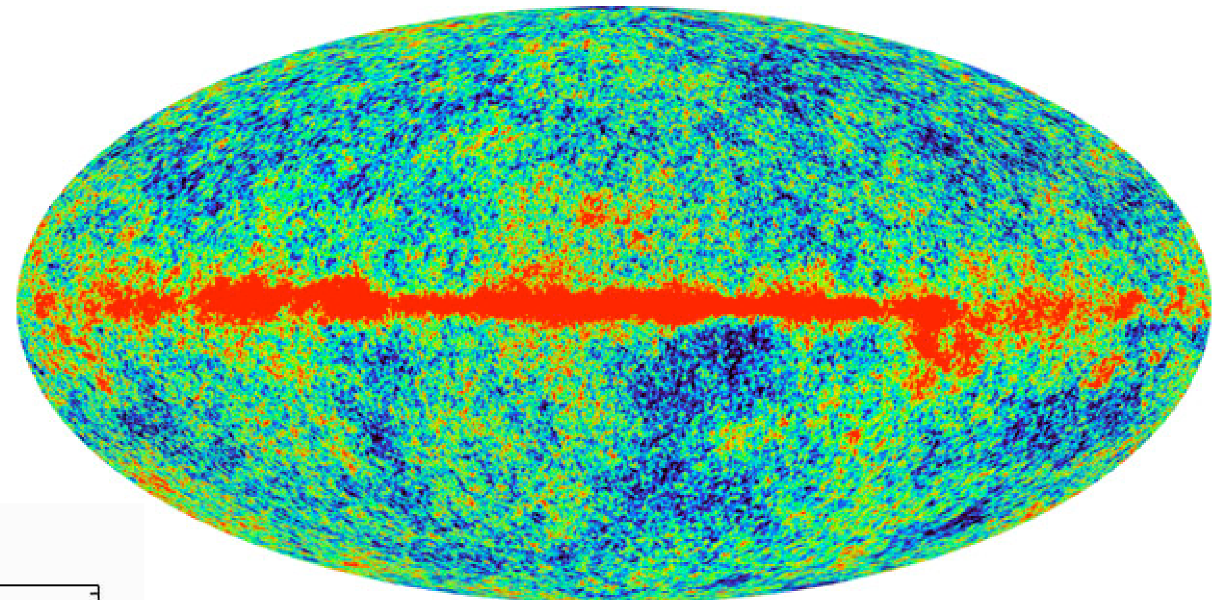


- Essentially fully in the nonlinear regime (scales ~1 Mpc)

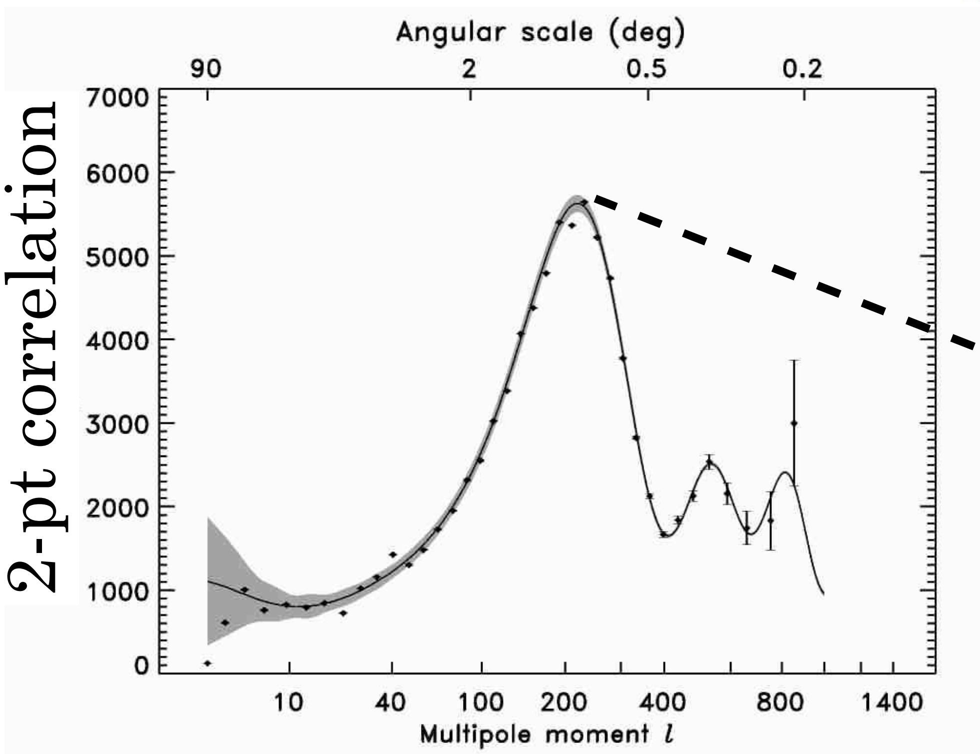
CMB and Dark Energy

$$T = 2.726\,\mathrm{K}$$

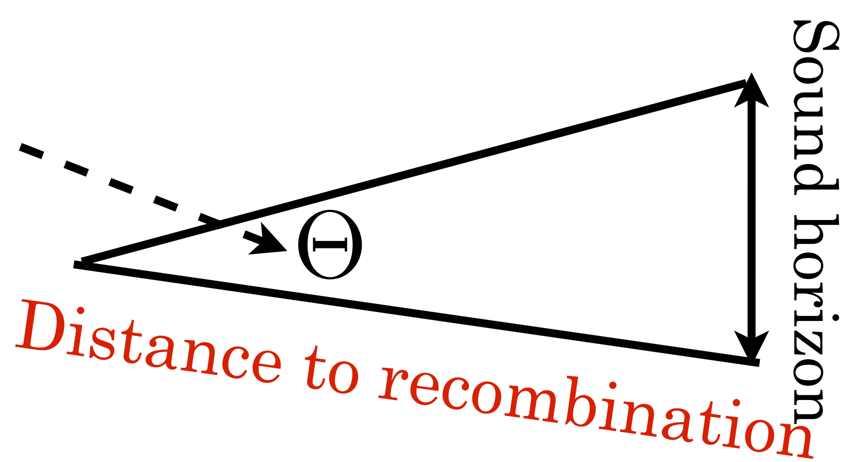
$$\frac{\delta T}{T} \approx 10^{-5}$$



Credit: WMAP team

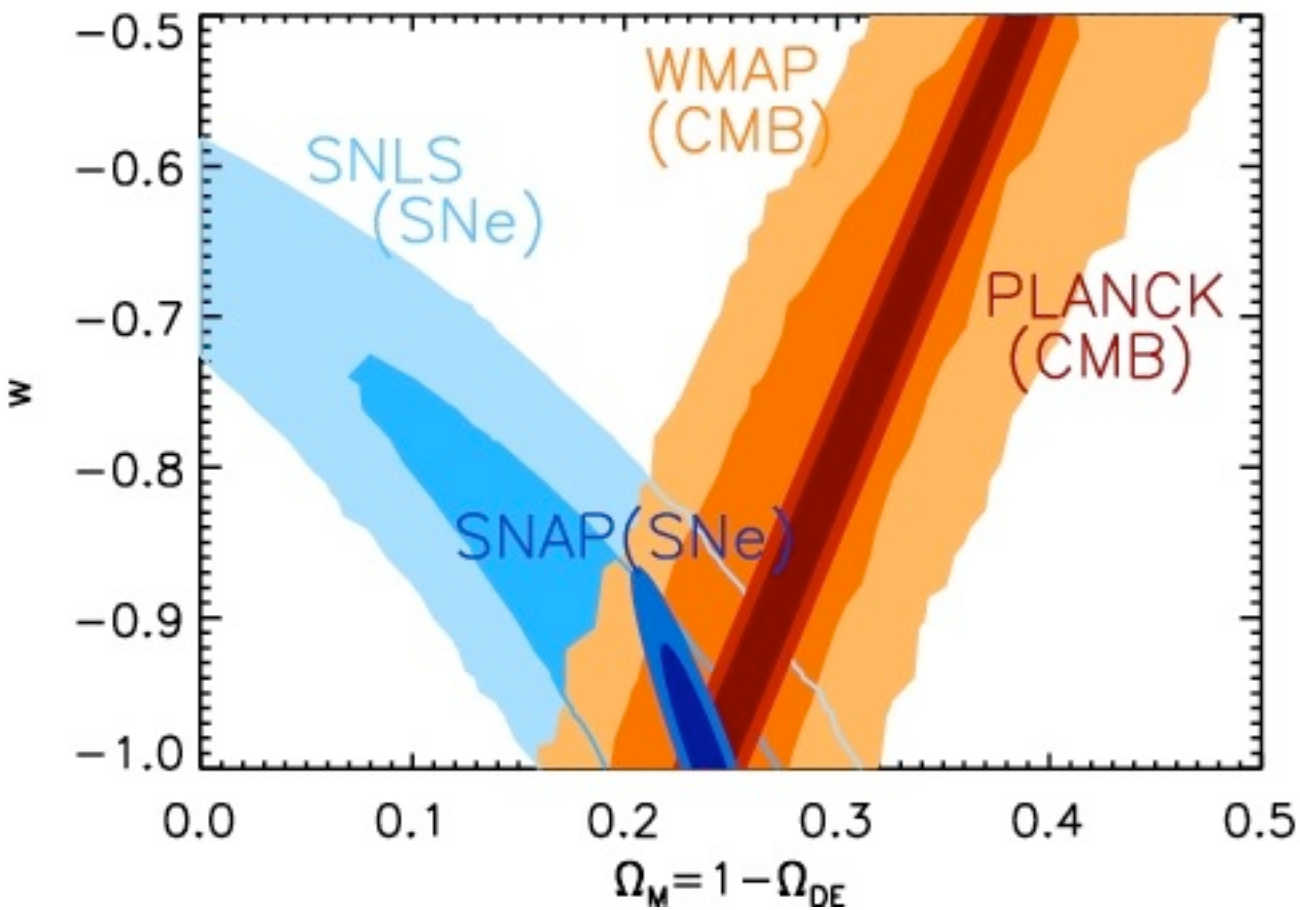


Bennett et al (WMAP collaboration)



CMB and Dark Energy

One linear combination of DE parameters is measured by the CMB



Hu 2001; Frieman, Huterer, Linder & Turner 2003

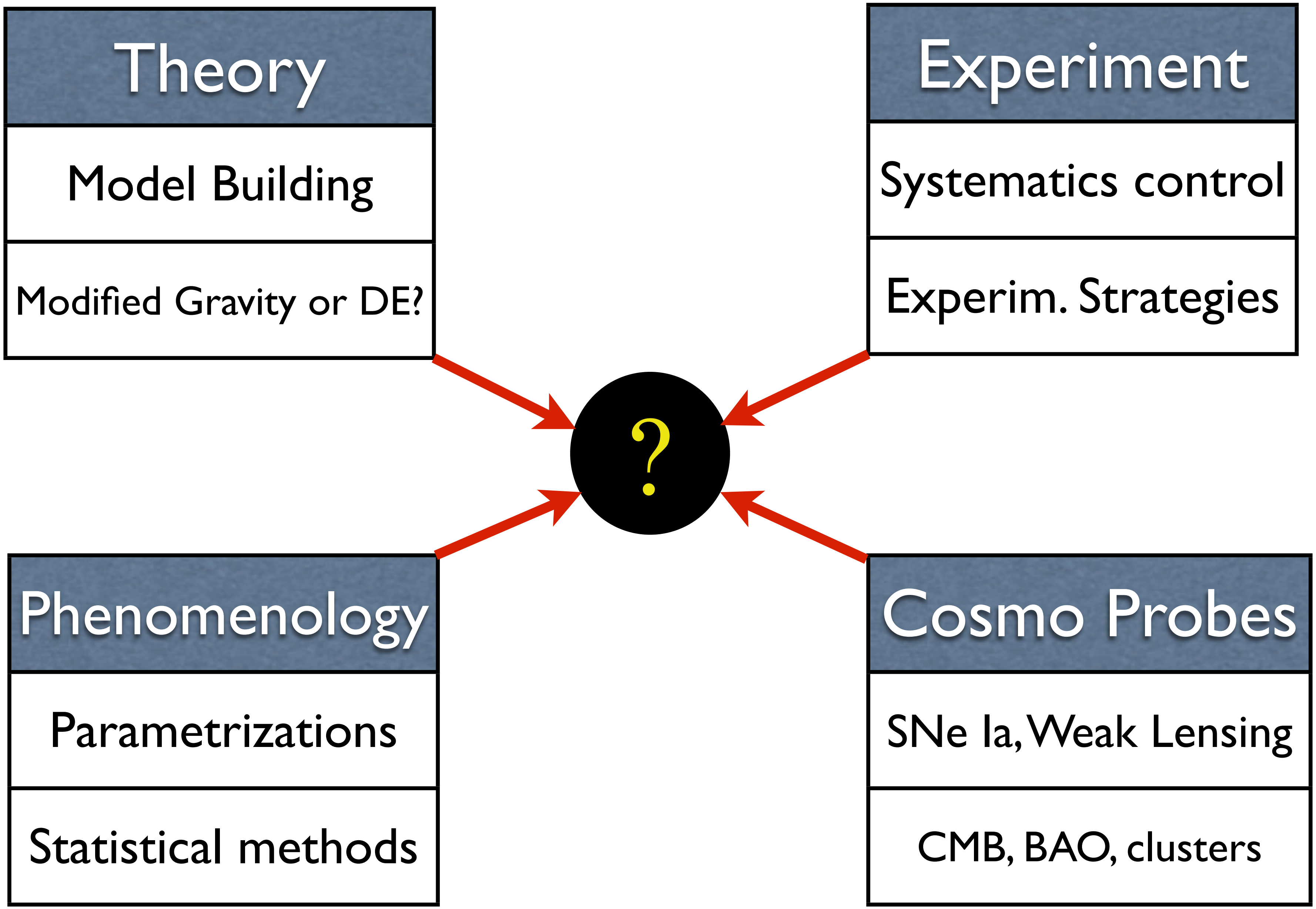

Theory
Model Building
Modified Gravity or DE?
Experiment
Systematics control
Experim. Strategies
?
Phenomenology
Parametrizations
Statistical methods
Cosmo Probes
SNe Ia, Weak Lensing
CMB, BAO, clusters

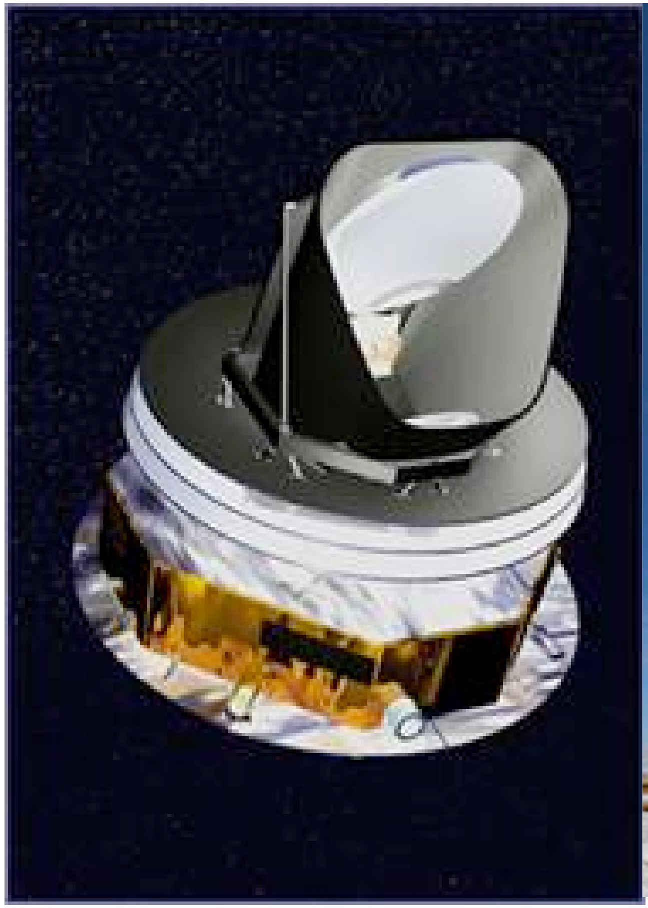
Table 3: Dark energy projects proposed or under construction. Stage refers to the DETF time-scale classification.

Survey	Description	Probes	Stage
Ground-based:			
ACT	SZE, 6-m	CL	II
APEX	SZE, 12-m	CL	II
SPT	SZE, 10-m	CL	II
VST	Optical imaging, 2.6-m	BAO,CL,WL	II
Pan-STARRS 1(4)	Optical imaging, 1.8-m(×4)	All	II(III)
DES	Optical imaging, 4-m	All	III
Hyper Suprime-Cam	Optical imaging, 8-m	WL,CL,BAO	III
ALPACA	Optical imaging, 8-m	SN, BAO, CL	III
LSST	Optical imaging, 6.8-m	All	IV
AAT WiggleZ	Spectroscopy, 4-m	BAO	II
HETDEX	Spectroscopy, 9.2-m	BAO	III
PAU	Multi-filter imaging, 2-3-m	BAO	III
SDSS BOSS	Spectroscopy, 2.5-m	BAO	III
WFMOS	Spectroscopy, 8-m	BAO	III
HSHS	21-cm radio telescope	BAO	III
SKA	km^2 radio telescope	BAO, WL	IV
Space-based:			
JDEM Candidates			
ADEPT	Spectroscopy	BAO, SN	IV
DESTINY	Grism spectrophotometry	SN	IV
SNAP	Optical+NIR+spectro	All	IV
Proposed ESA Missions			
DUNE	Optical imaging	WL, BAO, CL	
SPACE	Spectroscopy	BAO	
eROSITA	X-ray	CL	
CMB Space Probe			
Planck	SZE	CL	
Beyond Einstein Probe			
Constellation-X	X-ray	CL	IV

Frieman, Turner & Huterer, Ann. Rev. Astro. Astroph., 2008

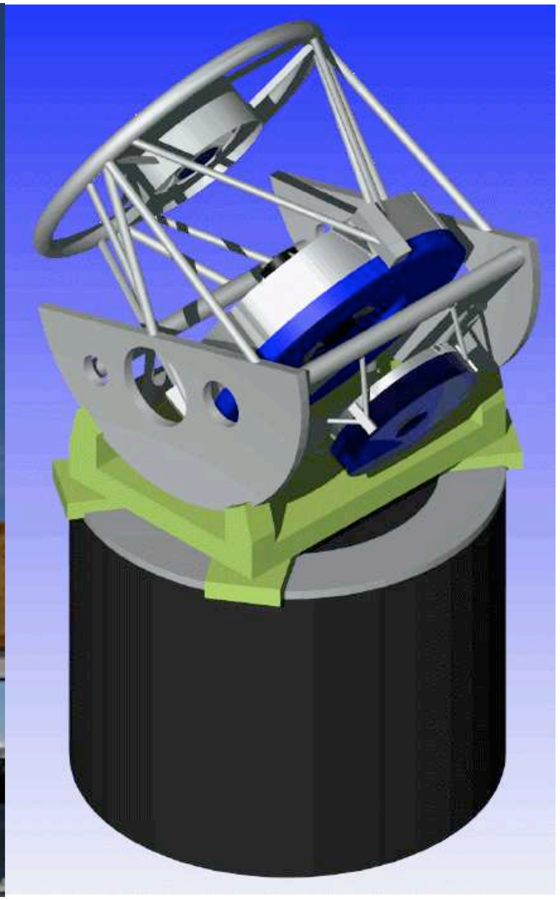
Upcoming Experiments

Planck



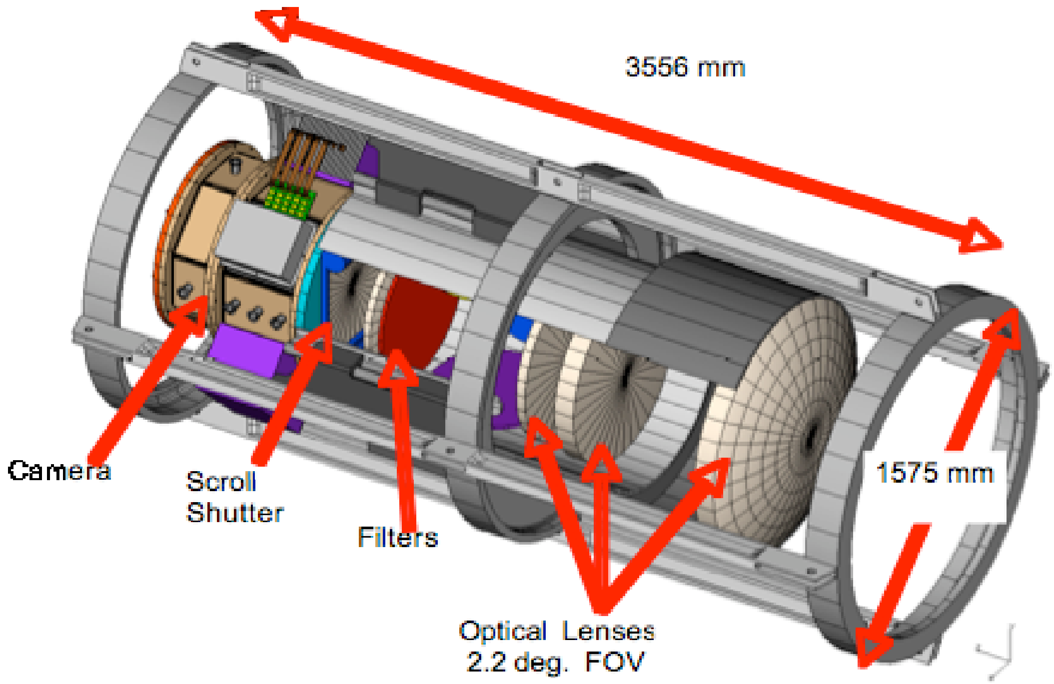
South Pole Telescope

LSST



Lots and lots of data coming our way

Dark Energy Survey



Blanco 4m telescope in Chile

Four techniques to probe Dark Energy:
1. Number Counts of clusters
2. Weak Lensing
3. SNe Ia
4. Angular clustering of galaxies

NASA-DOE

~~Joint Dark Energy Mission~~

Wide-Field InfraRed Space Telescope (**WFIRST**)

Paul Hertz / NASA

Rob[illegible]ffin / DOE

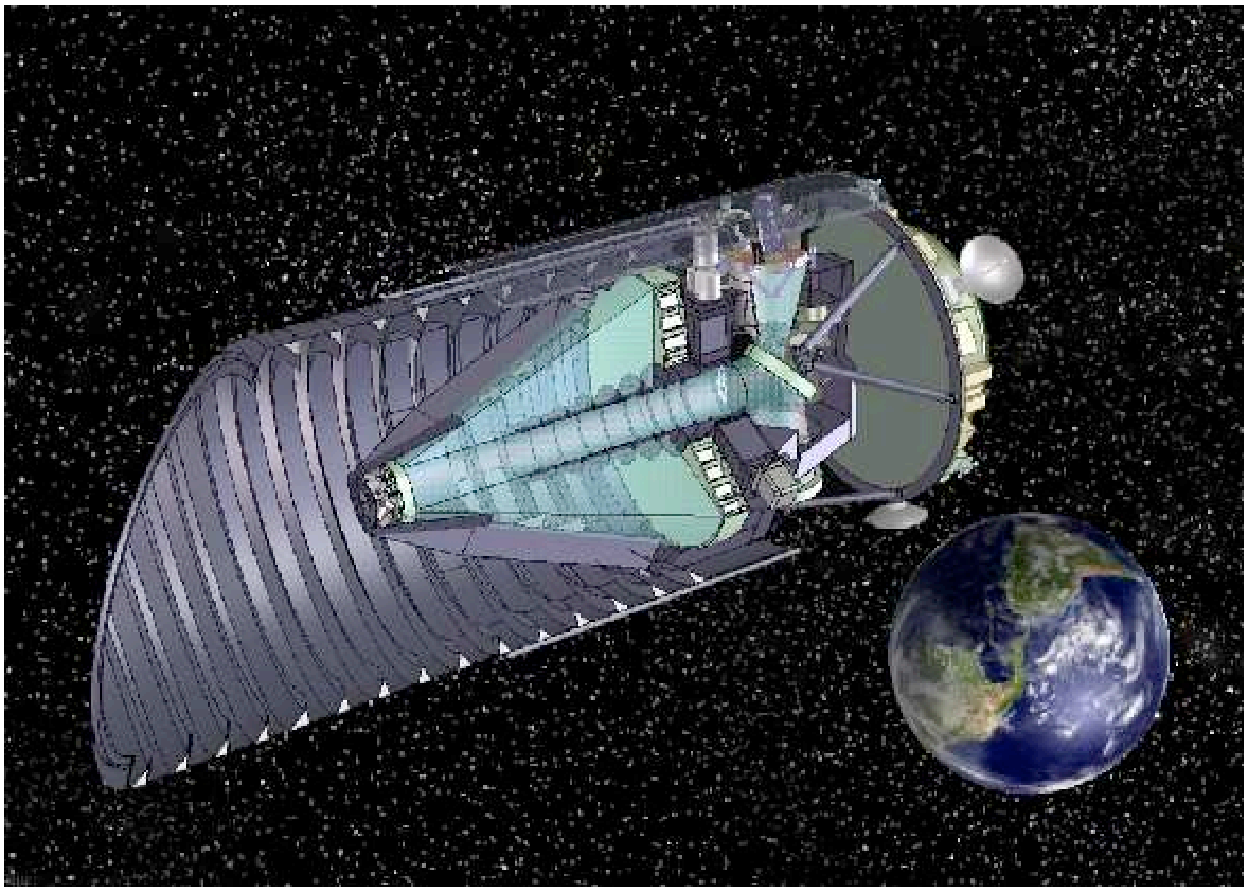
Endorsed by

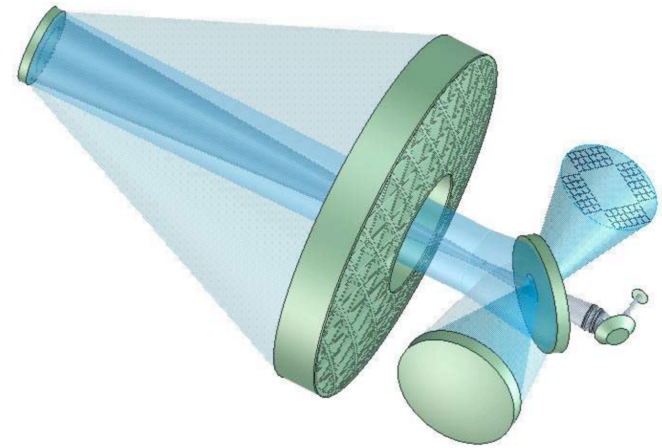
Raymond L. Orbach
Director of the Office of Science
Department of Energy
September 24, 2003

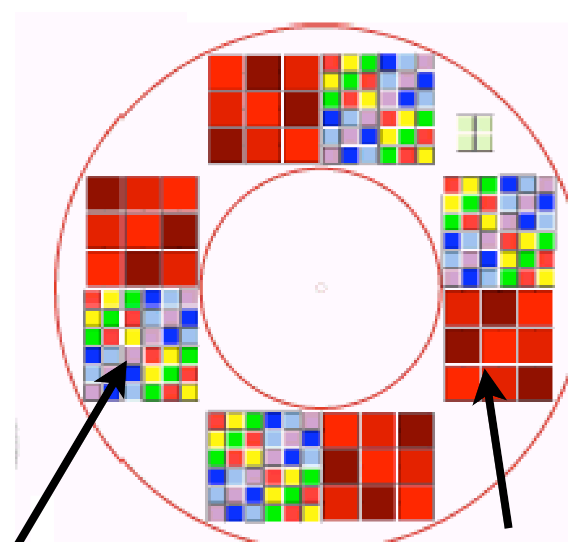
Edward J. Weiler
Associate Administrator for Space Science
NASA
September 25, 2003

SuperNova/Acceleration Probe

~2500 SNe at $0.1<z<1.7$



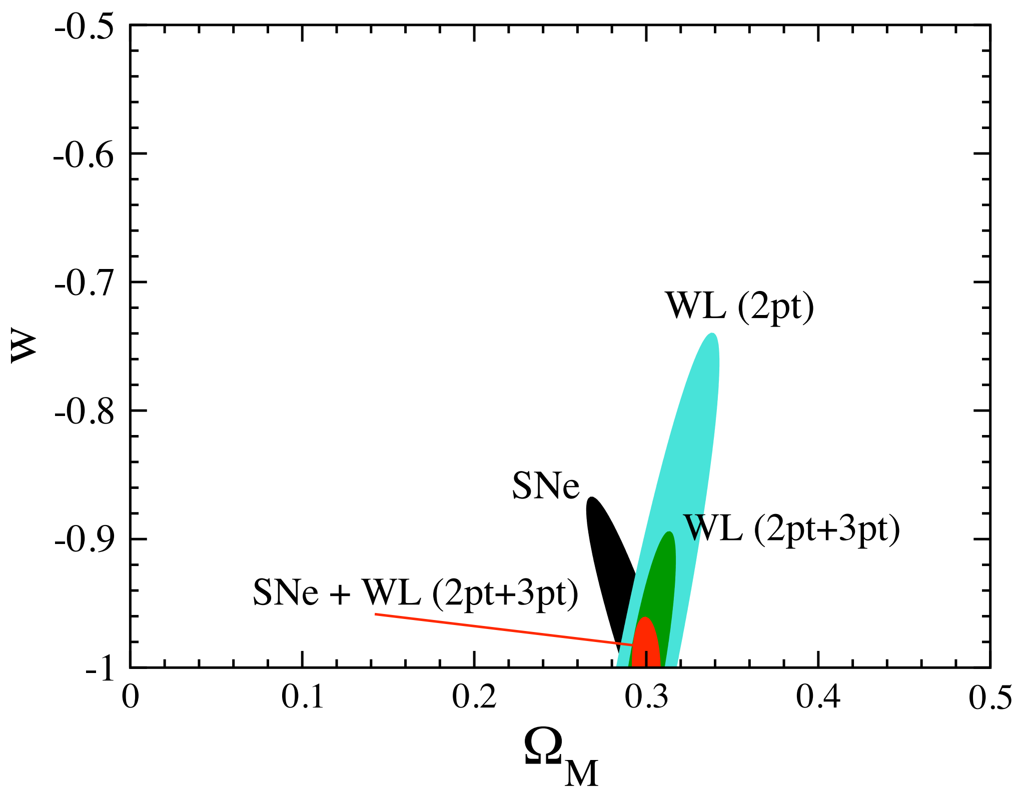


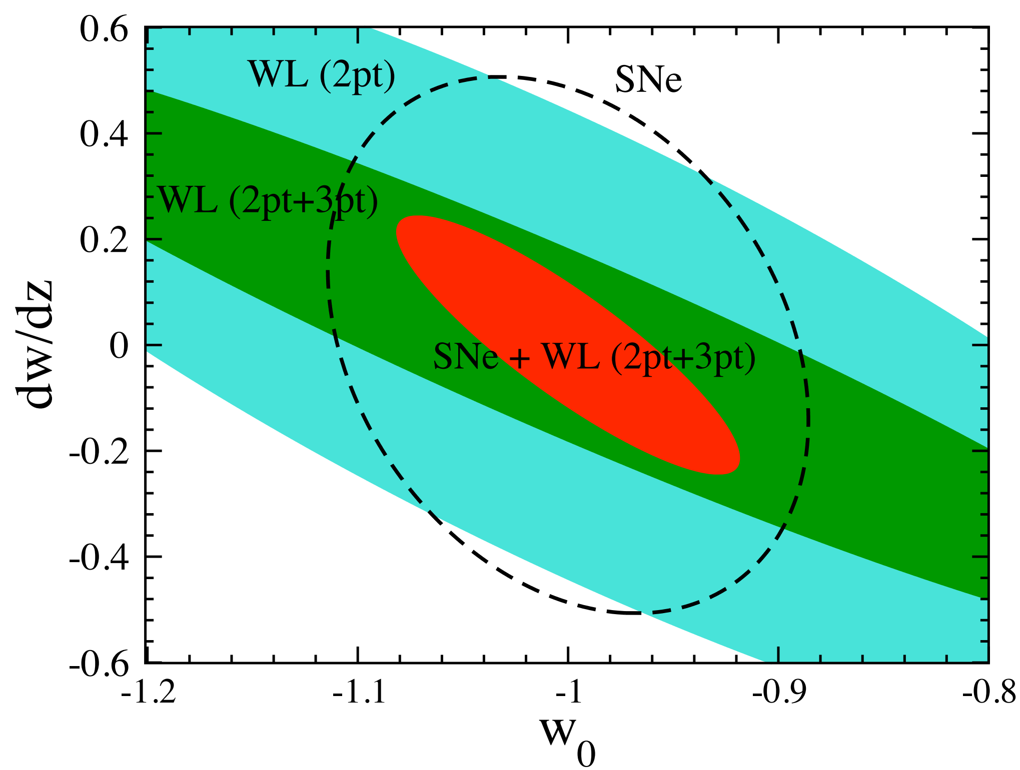


Visible (CCDs)

NIR (HgCdTe)

SNAP/JDEM expected constraints





1. Unprecedented SNa Ia dataset
2. Weak Lensing (2pt, 3pt function; cosmography)
3. Huge amount of other science
   (cluster counts, galaxy clustering, galaxy evolution,
   strong lensing, type II supernovae, GRBs, ...)

Systematics summary

Table 2: Comparison of dark energy probes.

Method	Strengths	Weaknesses	Systematics
WL	growth+geometric, statistical power	CDM assumption	image quality, photo-z
SN	purely geometric, mature	standard candle assumption	evolution, dust
BAO	largely geometric, low systematics	large samples required	bias, non-linearity
CL	growth+geometric, X-ray+SZ+optical	CDM assumption	determining mass, selection function

Conclusions

- Recent accelerated expansion of the universe is a great mystery of modern physics and cosmology
- Type Ia supernovae played - and still play - crucial role
- Constraints on the expansion history are becoming tight; however, fundamental understanding is lacking
- Incredible amount of new data is starting to come in, sophisticated analytical, statistical and numerical methods are required
- We need a combination of experiments that are
  - ground and space probes,
  - expansion and growth probes,
  - linear and nonlinear theory

Recommended reading

- General review:
  - Turner & Huterer, arXiv:0706.2186 (10-page)
  - Frieman, Turner & Huterer arXiv:0803.0982 (50-page)
- Cosmological Constant Problem:
  - Weinberg, Rev. Mod. Phys. 61, 1 (1989)
- DE Theory:
  - Copeland, Sami & Tsujikawa, Int. J. Mod. Phys. D15, 1753 (2006)
  - Padmanabhan, Phys. Rep. 300, 235 (2003)
- DE "reconstruction":
  - Sahni & Starobinsky, astro-ph/0610026
- Dynamics of DE:
  - Linder, arXiv:0704.2064
- Cosmological Probes of DE:
  - Huterer & Turner, PRD 64, 123527 (2001)
- Measuring cosmology with SNe:
  - Perlmutter & Schmidt in "SNe and GRBs" Lecture Notes, 195, 2003