FRONTIERS OF ASTRONOMY

Alexandria, March 2006

Richard Ellis, Caltech

1. Role of Observations in Cosmology & Galaxy Formation

   Key Results and the Standard Model (ΛCDM)

   Observational Probes of the Dark Matter Distribution

2. High Redshift Galaxies:

   Cosmic Star Formation History and Mass Assembly

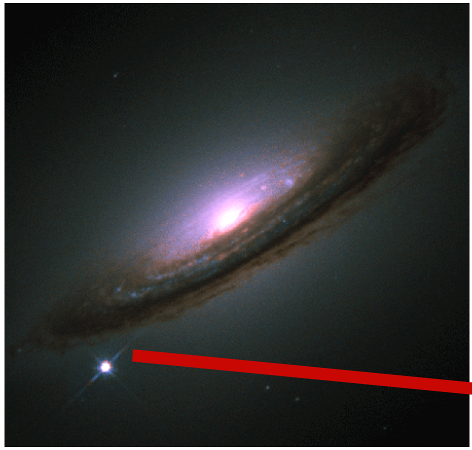
   Cosmic Dawn: Searching for the Earliest Sources

3. Observational Probes of Dark Energy

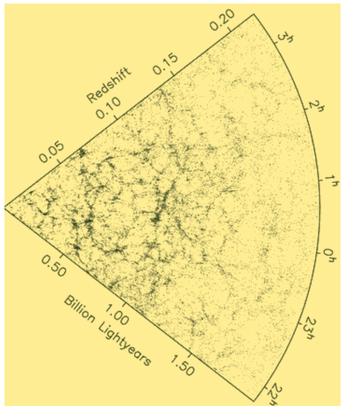
   Supernovae, weak gravitational lensing and studies of large scale structure

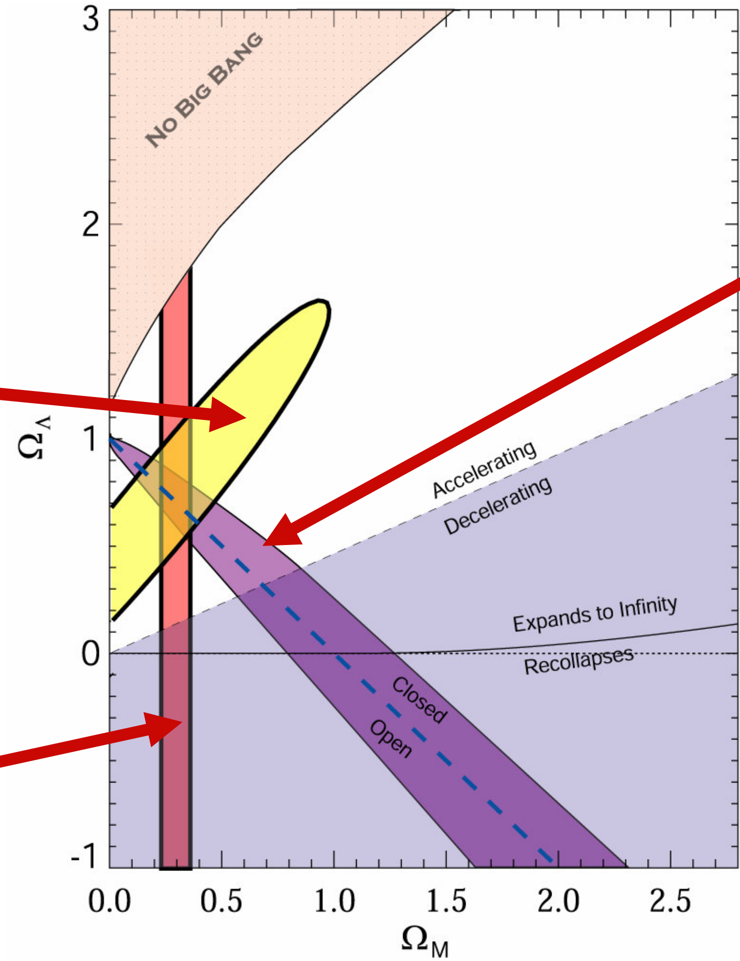
Dark Energy is here to stay…

SNe Ia

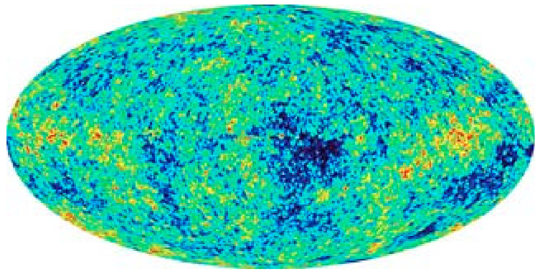


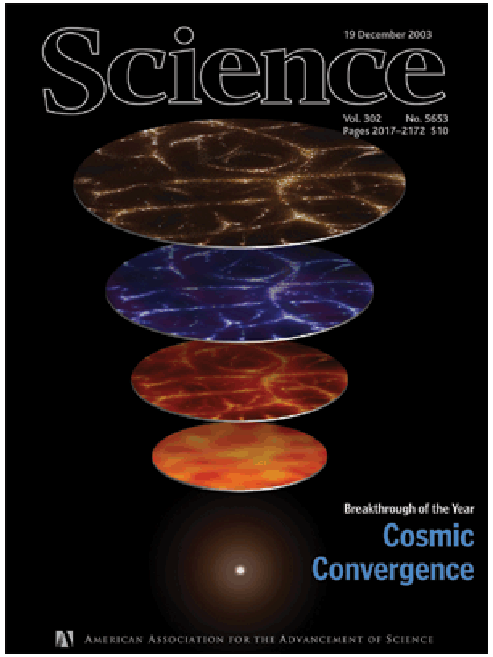
LSS





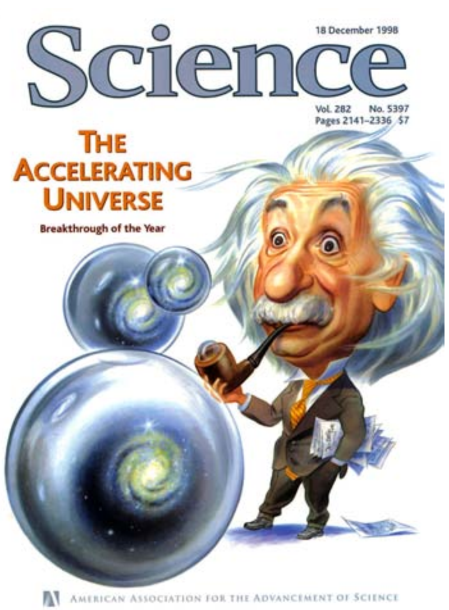
CMB(WMAP)





The Accelerating Universe

In 1998 two teams had measured ~100 SNe Ia at 0.01 <z<1.0 Surprise!
The Universe is accelerating, propelled by dark energy.



The Astronomical Journal, 116:1009–1038, 1998 September

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High-z

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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SCP

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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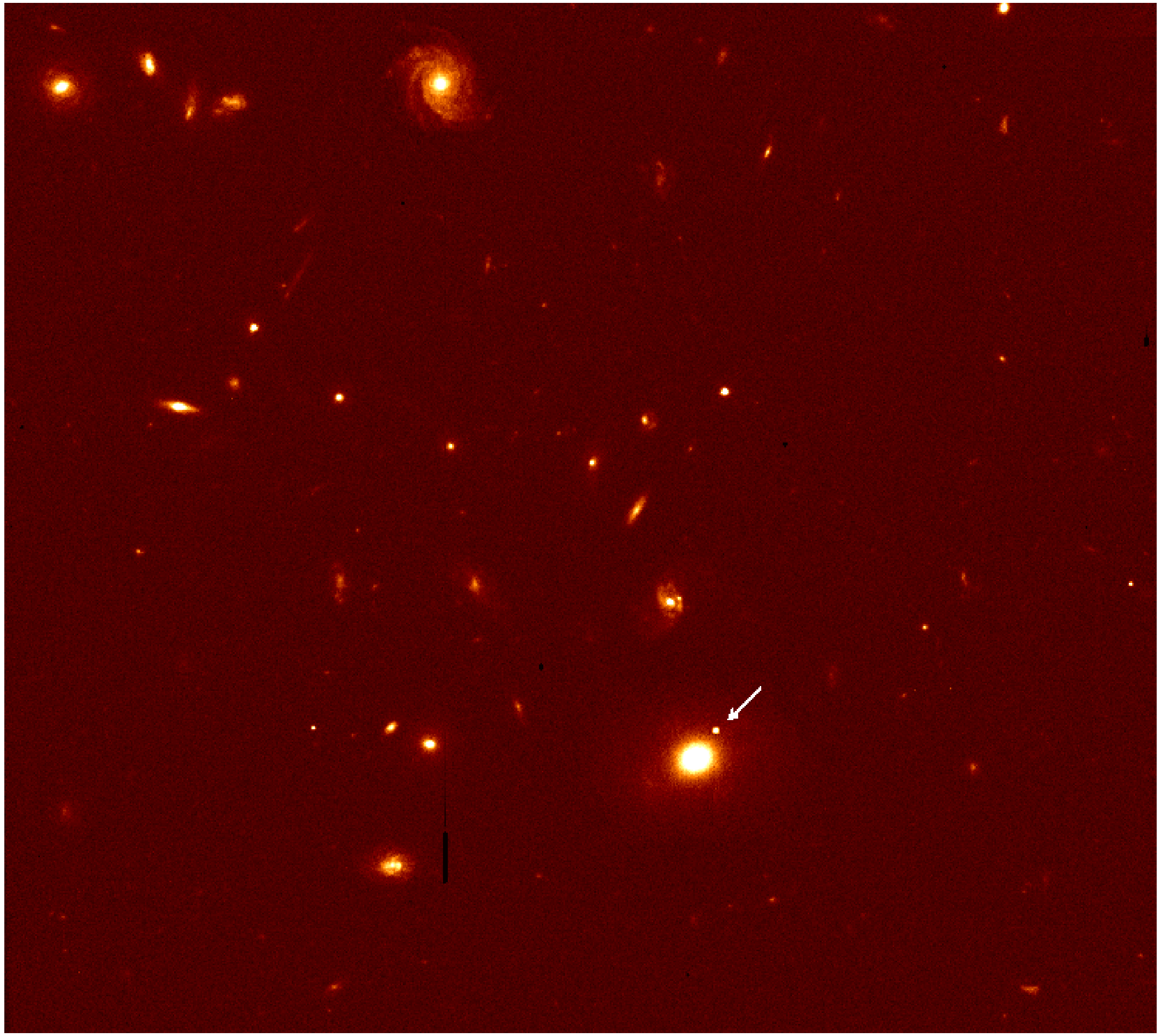
Why Do We Use Supernovae?

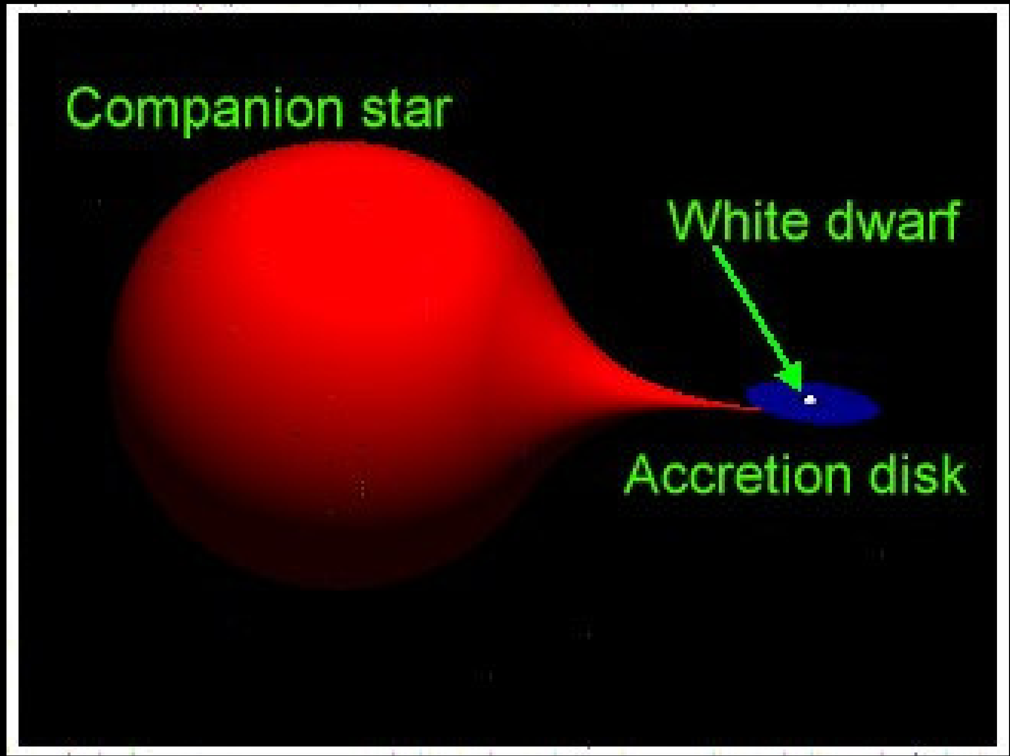
To measure distances and velocities over vast distances, we need ***luminous*** *sources whose properties are* ***homogeneous*** *and ideally well-understood.*

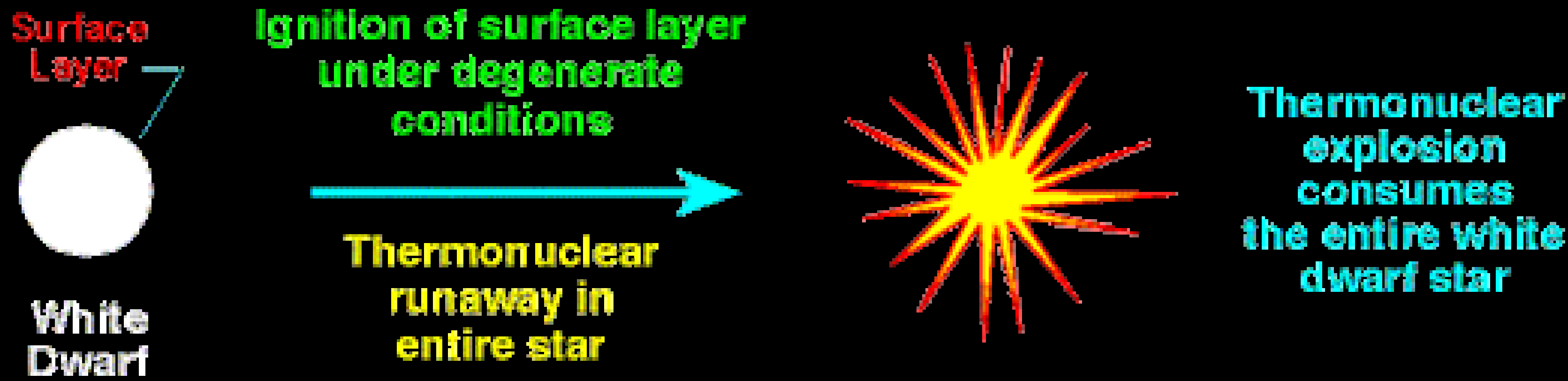
Supernova of type Ia are currently the best option



Type Ia Supernovae

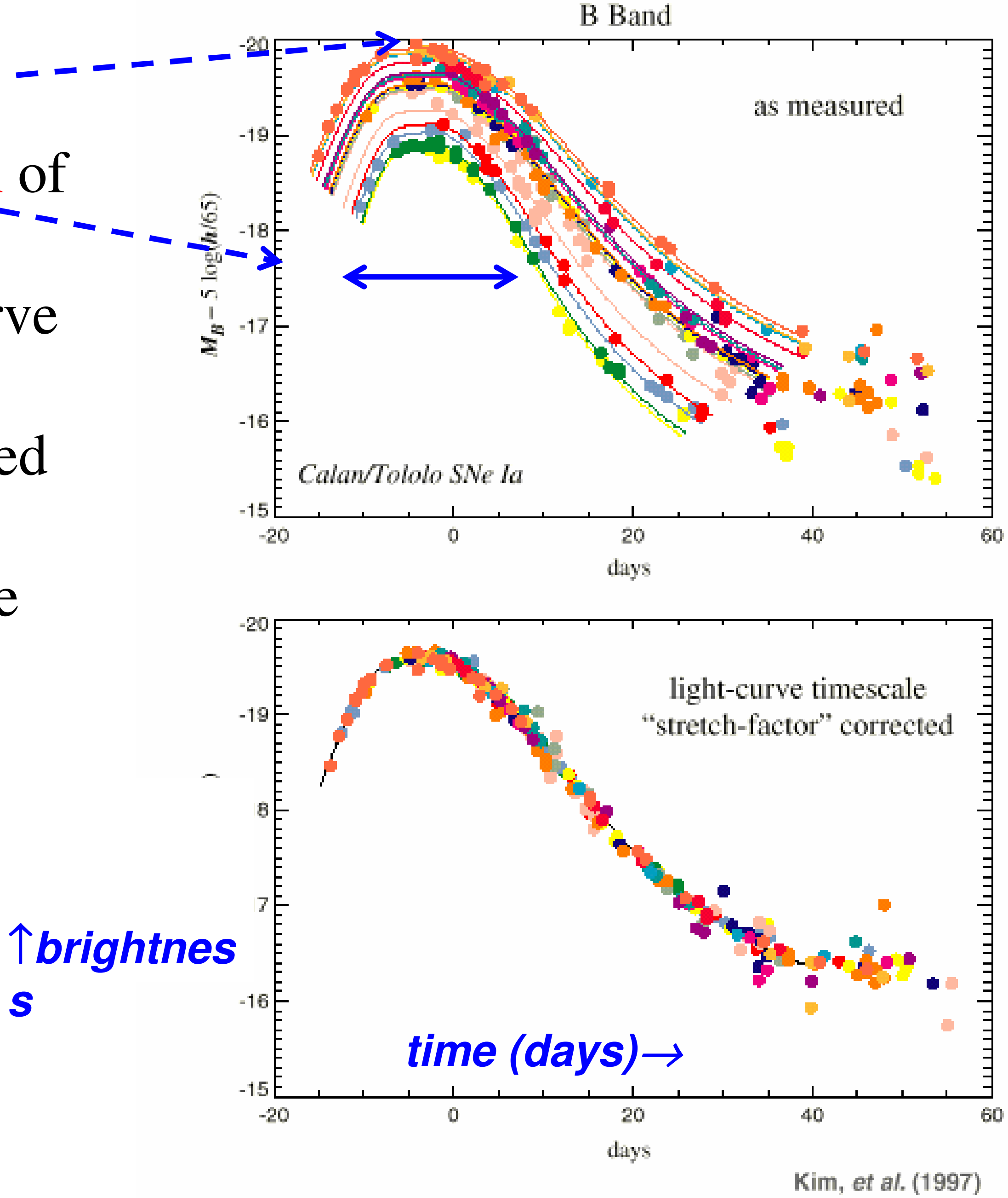
Thought to occur in binary systems containing an accreting white dwarf; models suggest explosion is very homogeneous

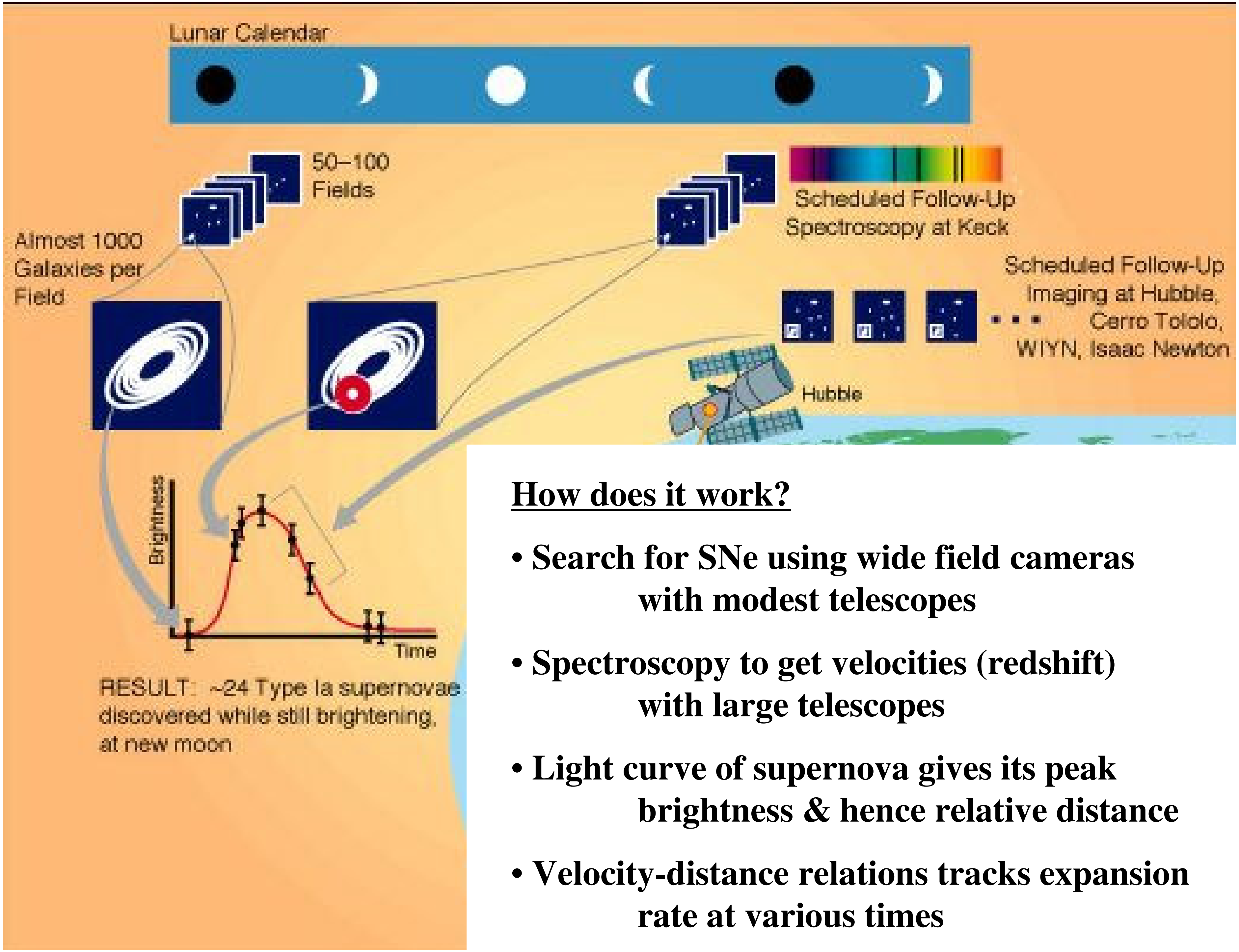




SNe Ia are not *perfect* standard candles

Peak luminosity correlates with width of light curves. If the shape of the light curve can be measured, empirically a corrected peak luminosity is a more precise measure of distance & can be used to trace cosmic expansion



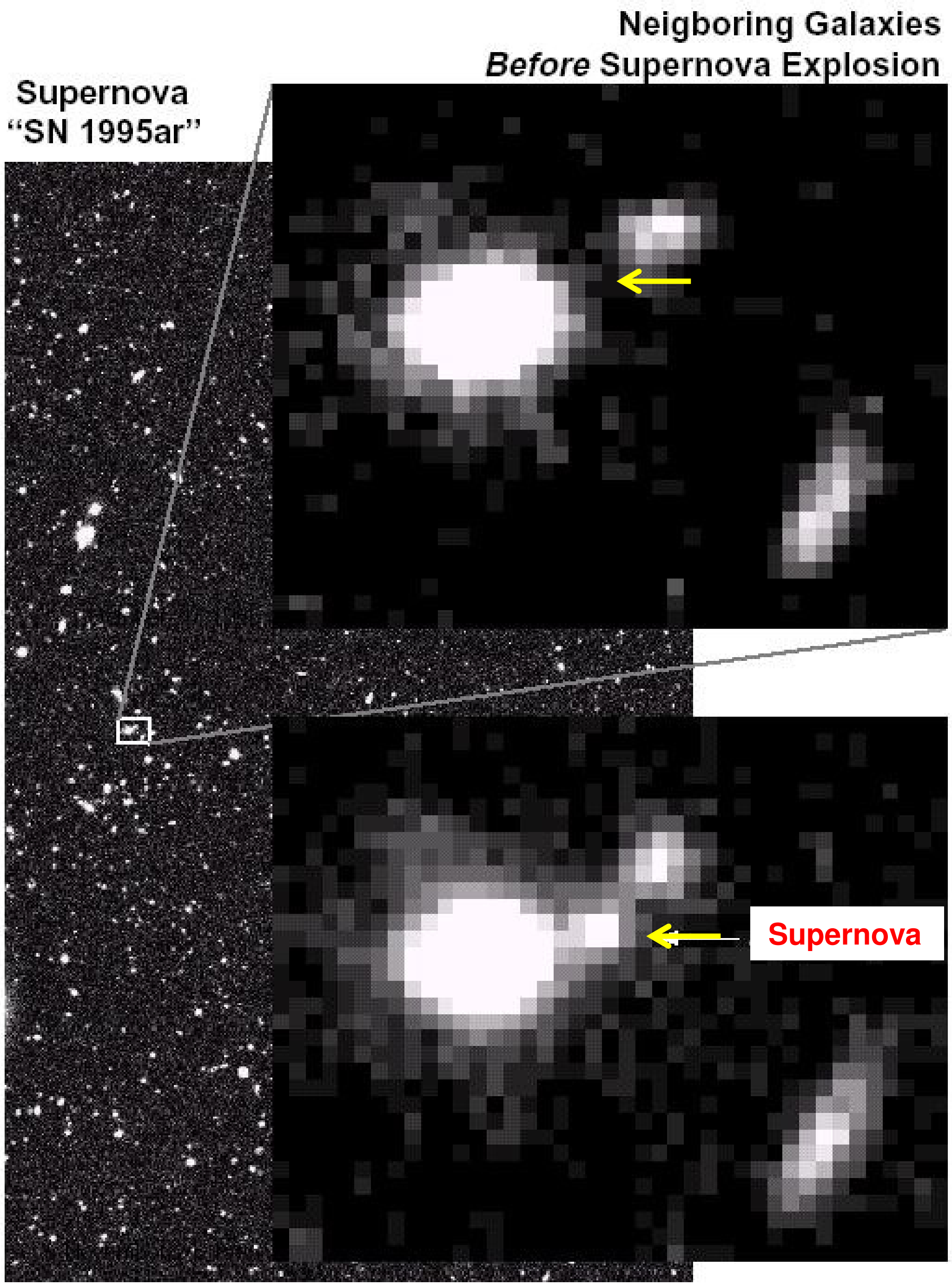


How does it work?

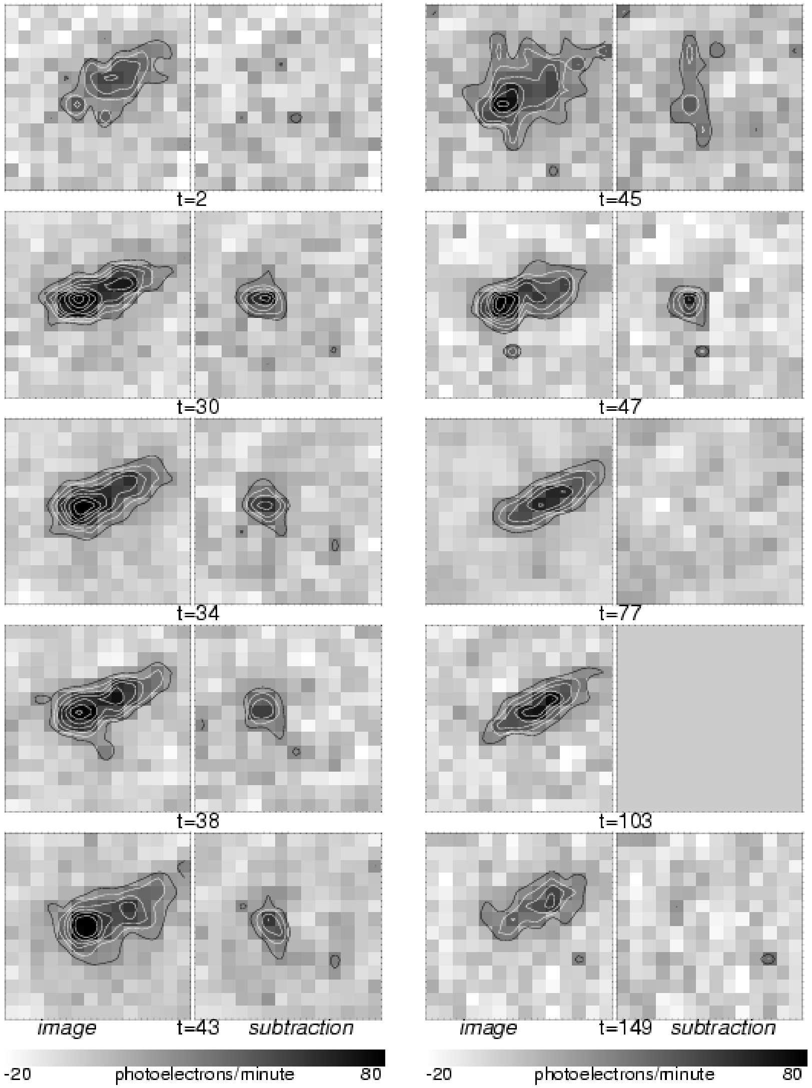
- Search for SNe using wide field cameras with modest telescopes
- Spectroscopy to get velocities (redshift) with large telescopes
- Light curve of supernova gives its peak brightness & hence relative distance
- Velocity-distance relations tracks expansion rate at various times

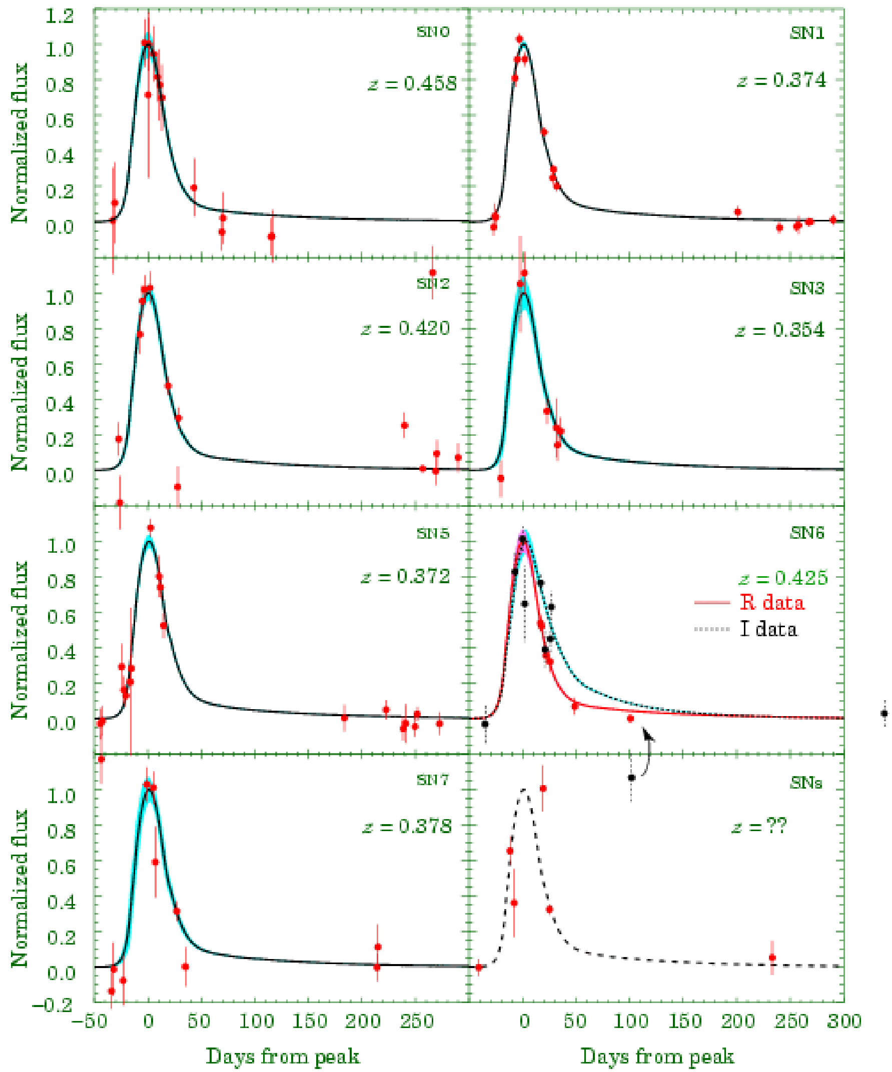
Discovery of supernovae with wide field cameras

- comparison of “reference” and “search” images separated by a few weeks
- panoramic cameras enable thousands of galaxies to be surveyed
- guarantees timely delivery of dozens of supernovae



Monitoring the Supernova: Light Curves

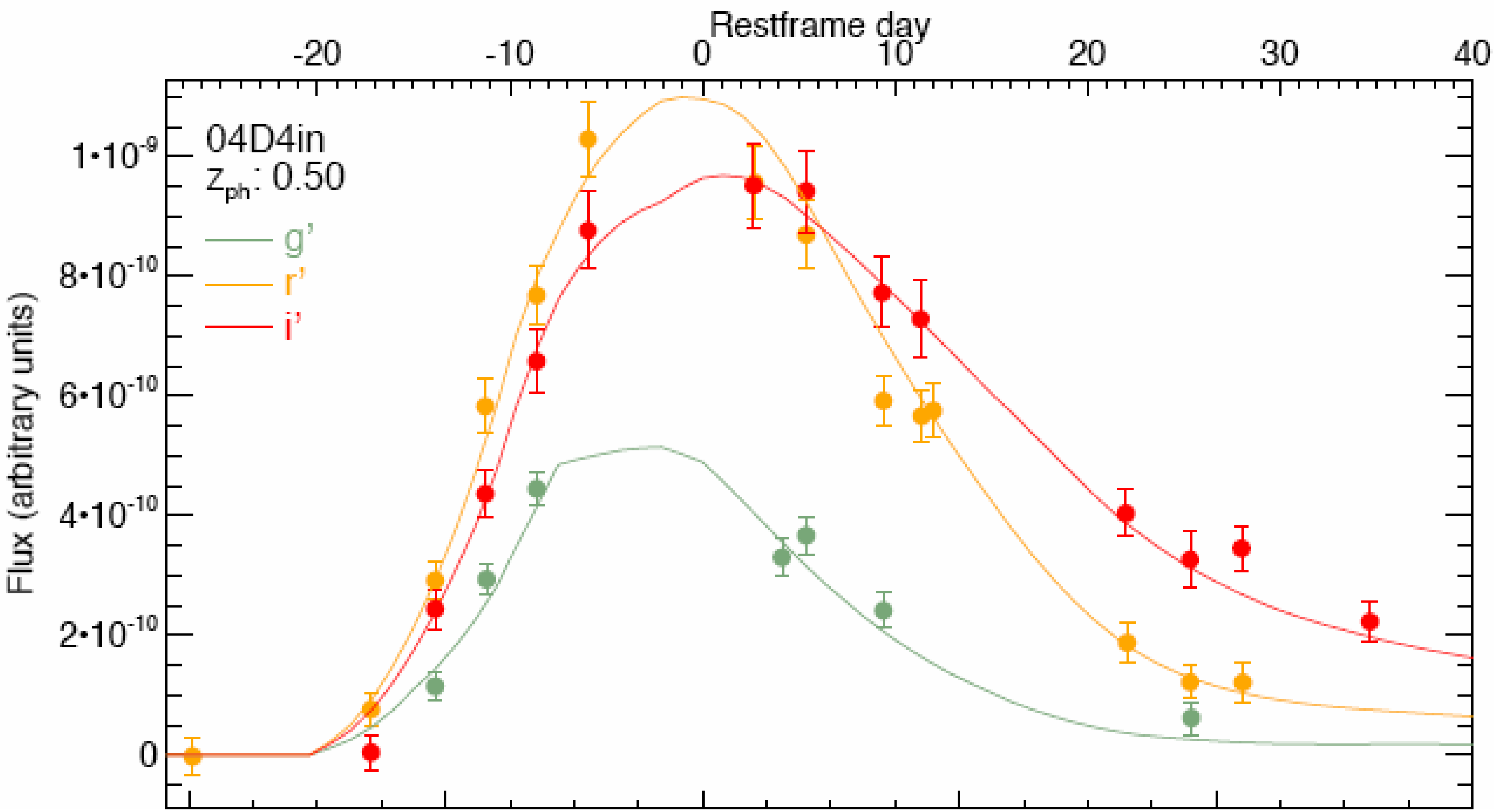




Time sequence with subtraction

Light Curves

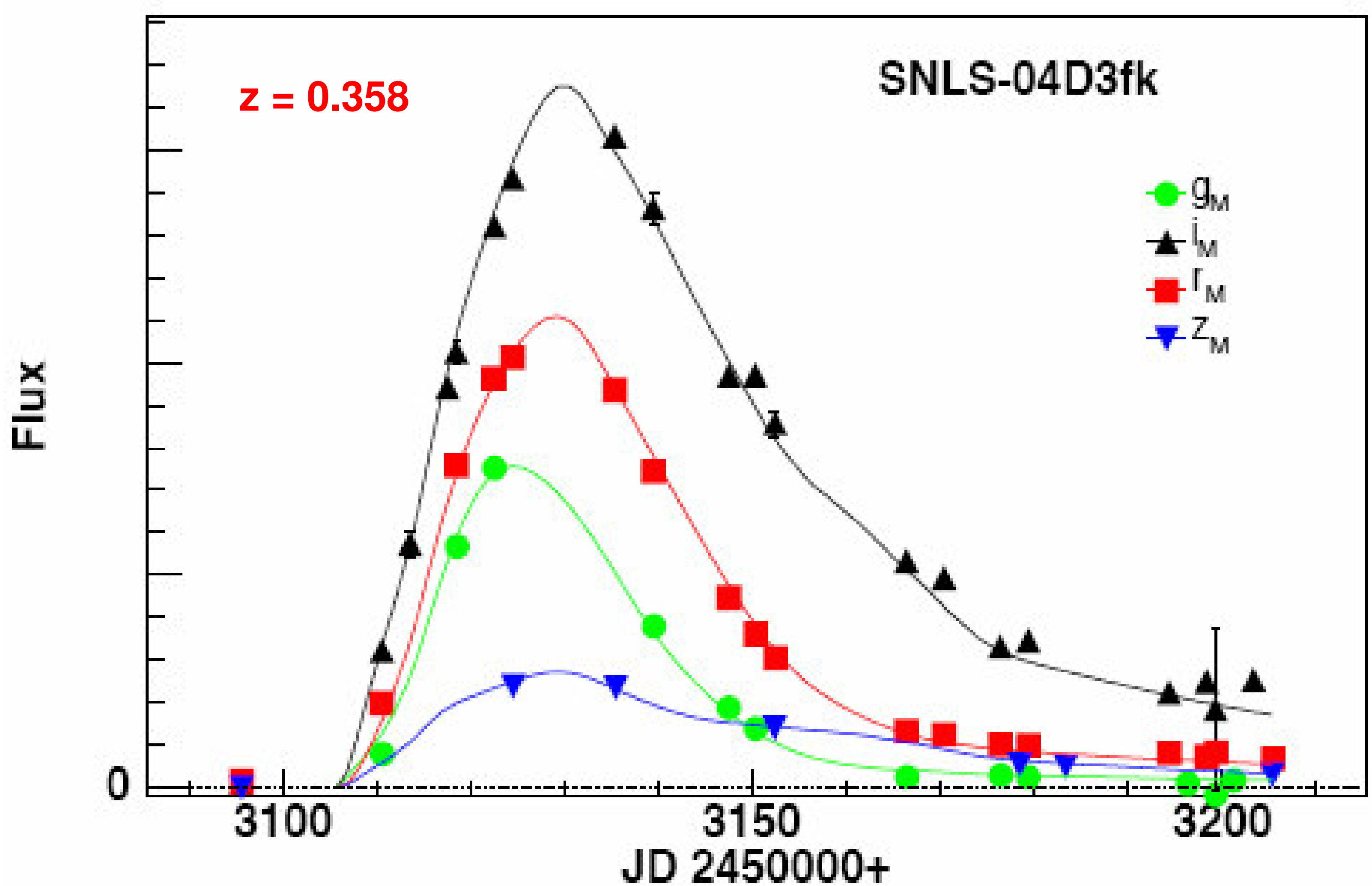
Supernovae Multi-Color Light Curves



Can monitor supernovae in many bands (g=green, r=red,i=near infrared)

This helps derive rest-frame colors of SNe and to correct for dust extinction

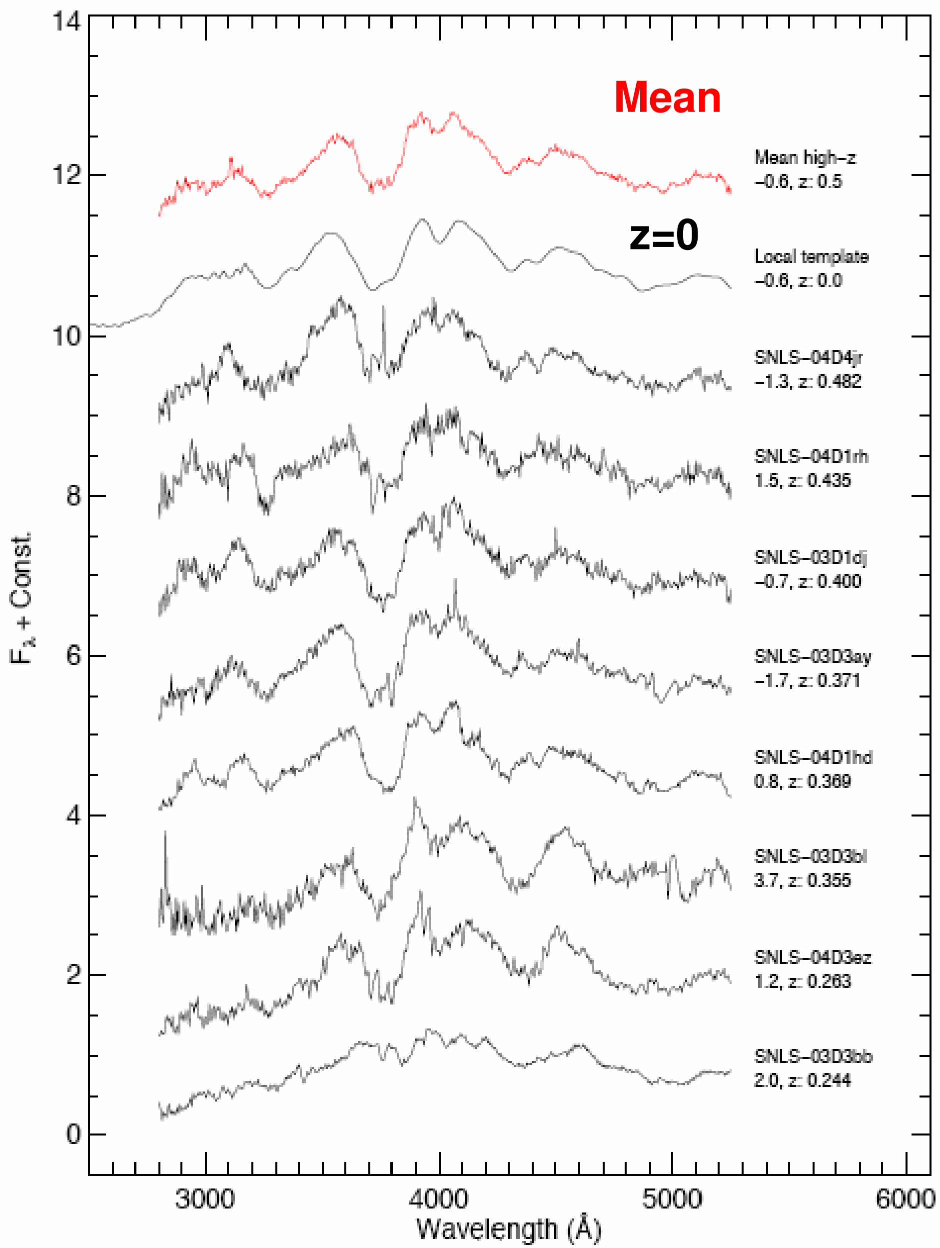
Supernovae Multi-Color Light Curves



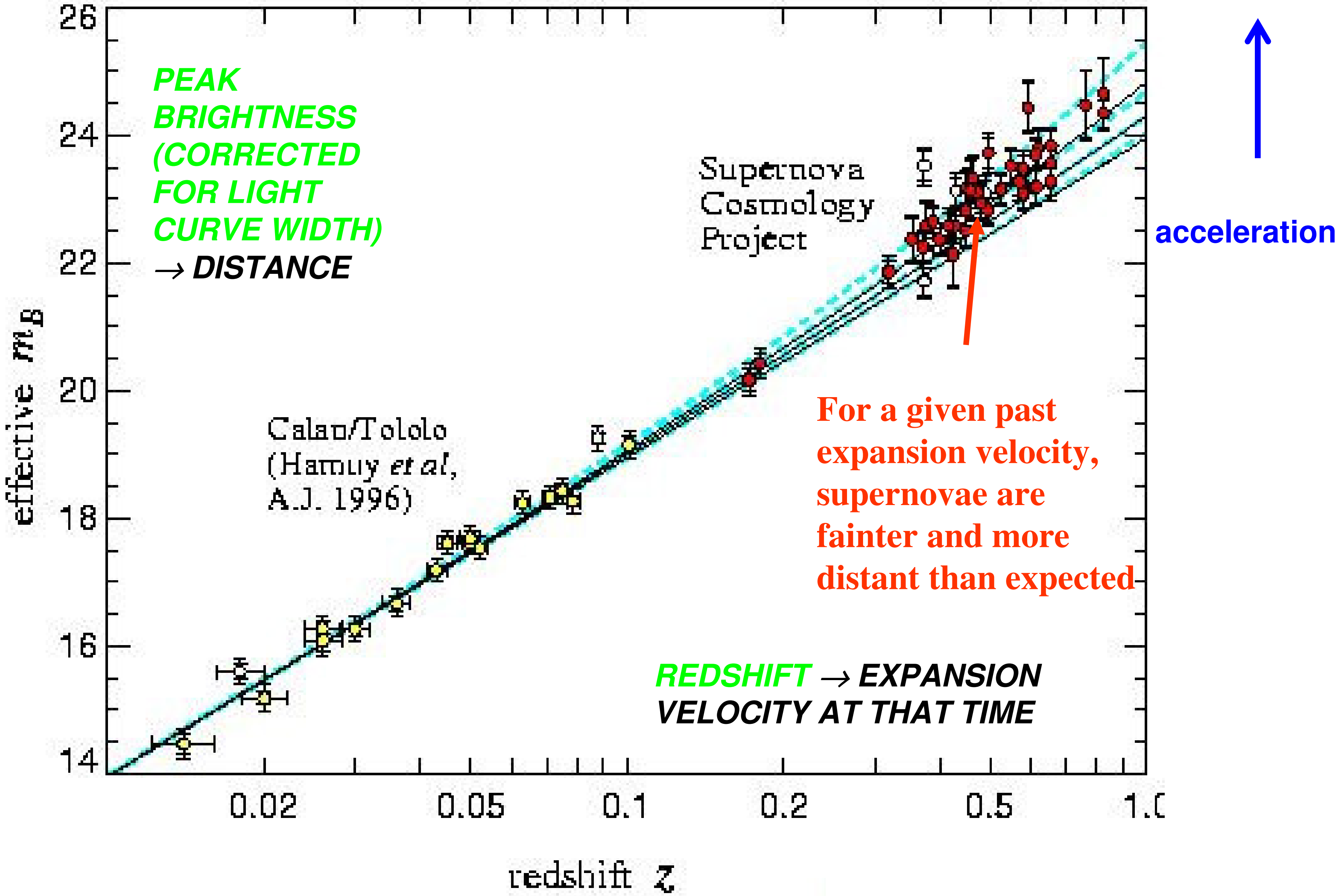
A model fits the multi-color data to get the width of the light curve, the rest-frame peak brightness and color (and dust extinction)

Keck spectra of SNe Ia

Spectra confirm the type of supernova (Ia), give the redshift which measures the expansion rate of the Universe in the past



`Hubble diagram' of 42 Distant SNe



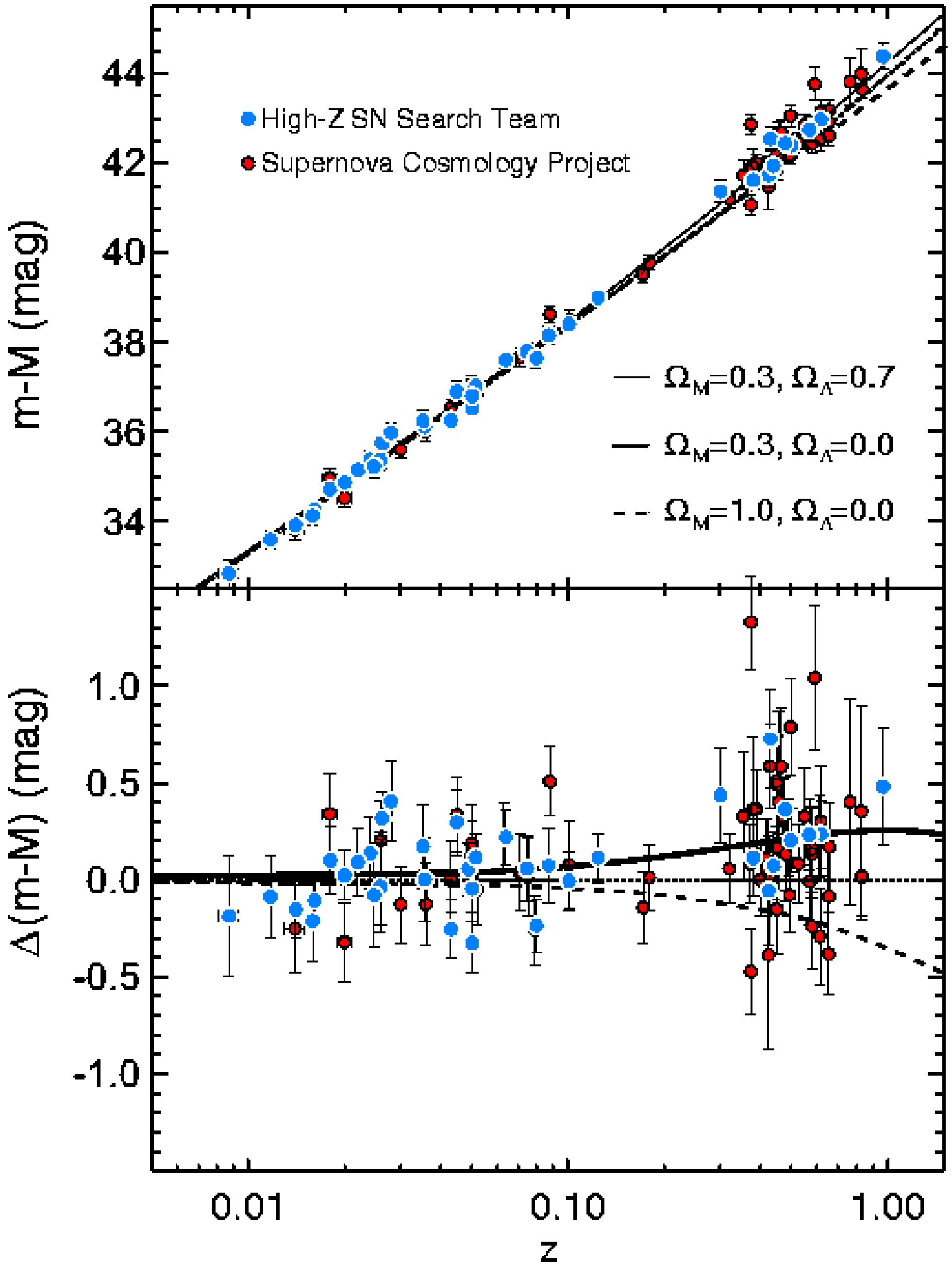
Surprising Result!

Two (independent) teams agree

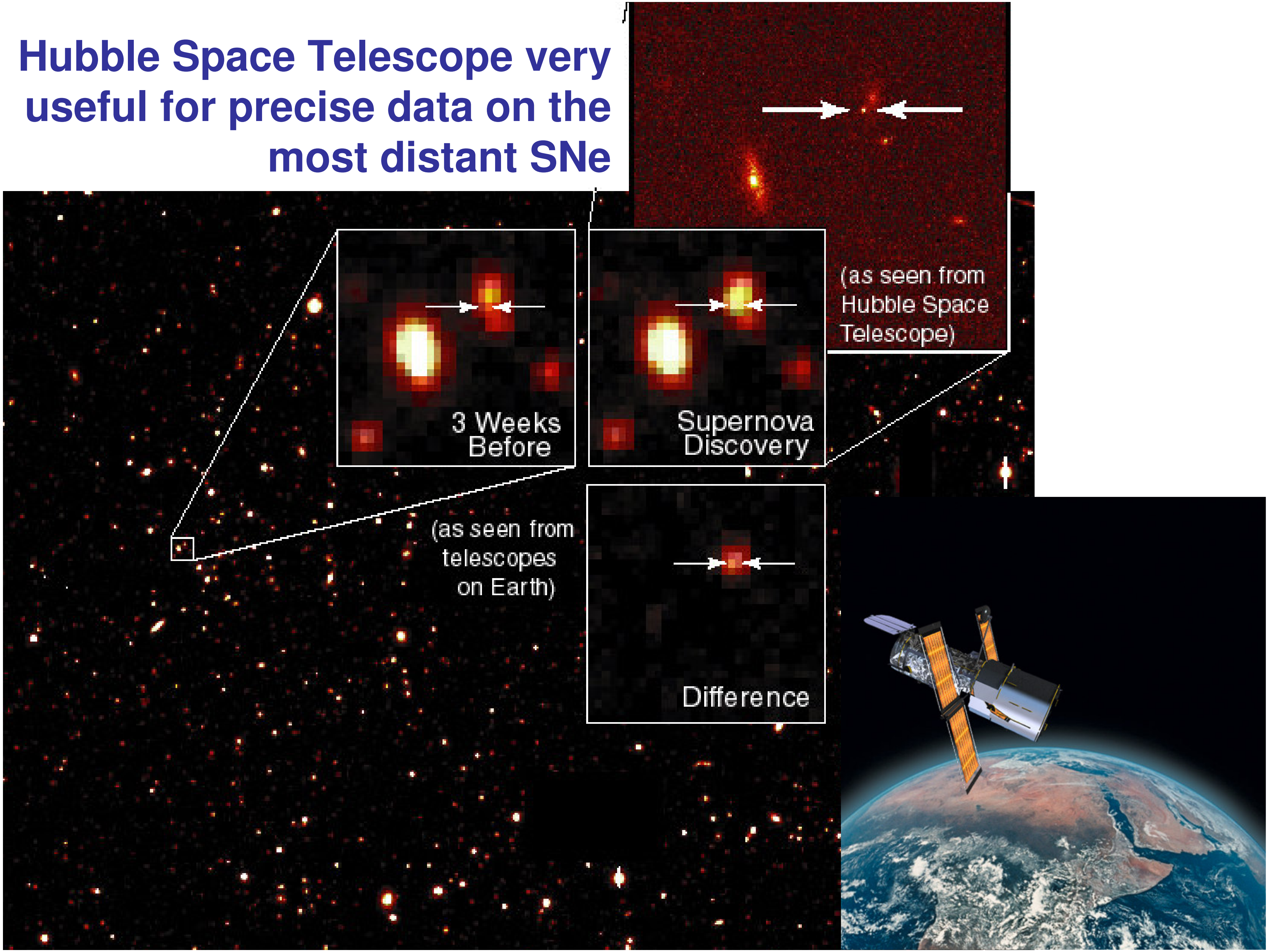
• Supernova Cosmology Project

• High Z SN Search Team

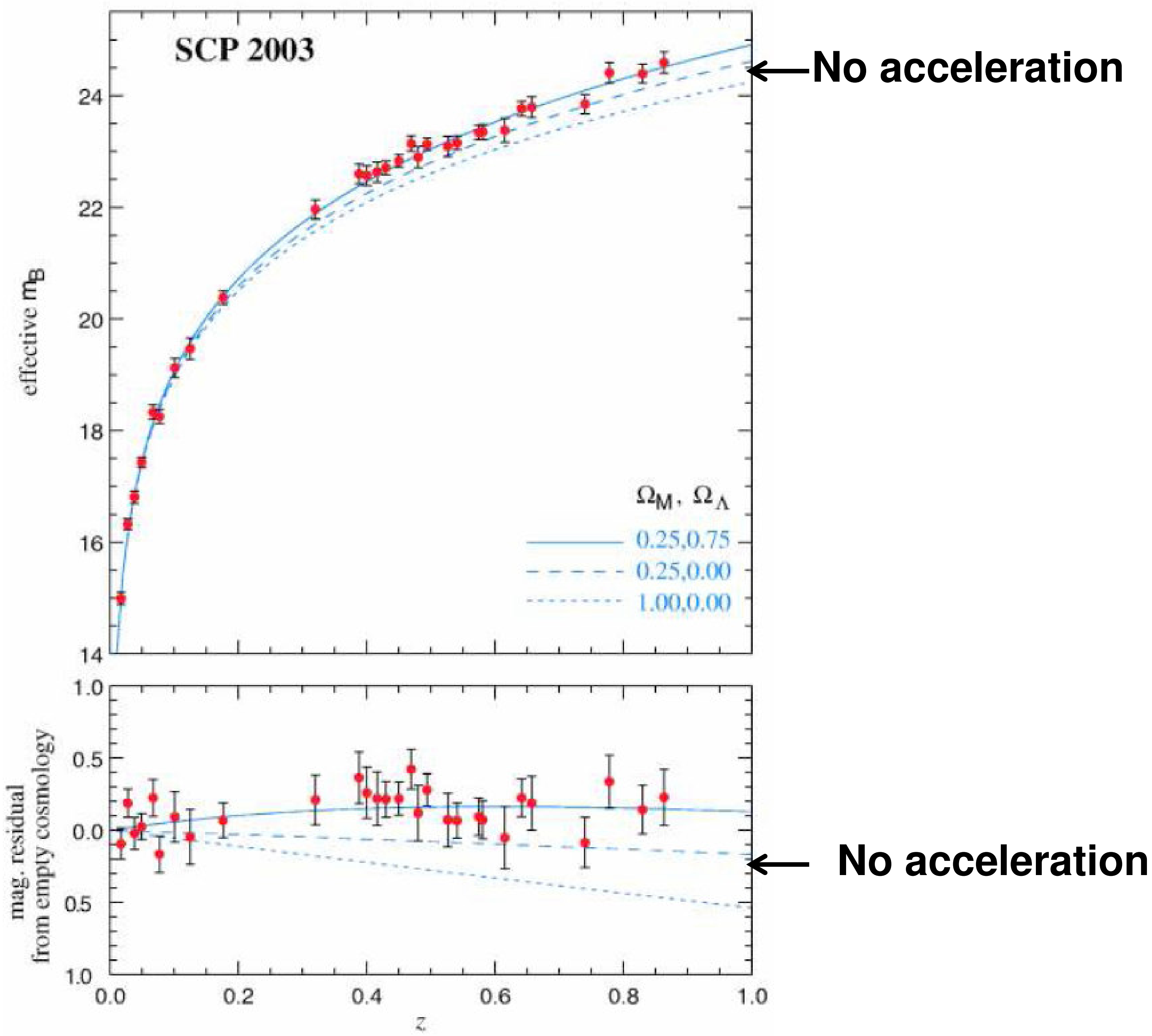
the supernovae are too faint at a given redshift!



Hubble Space Telescope very useful for precise data on the most distant SNe



Improved Data from Hubble Space Telescope



How Can We Be Sure This Remarkable Result is Correct?!

Is there any other way for dimming distant supernovae that would not require a cosmic acceleration?

- **Dimming by dust – there could be more dust at high redshift (in host galaxies or in intergalactic space)**
- **Evolutionary differences in supernovae - chemical composition may be different at early times affecting the peak brightnesses**
- **SN properties may depend on type of host galaxy – and the mix of galaxies may evolve with cosmic time**

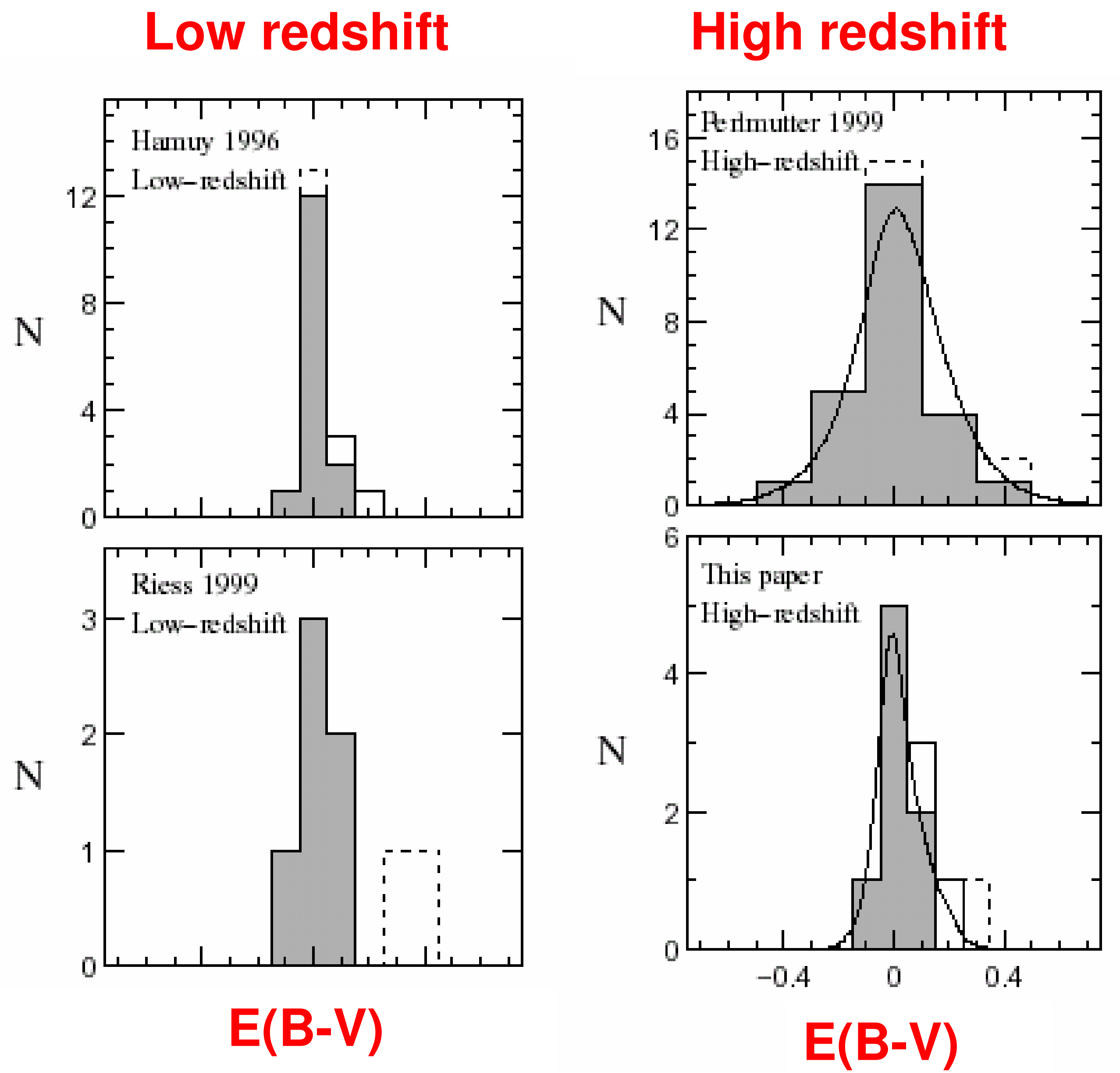
Dust in the Milky Way


Optical image revealing obscuration effects of dust

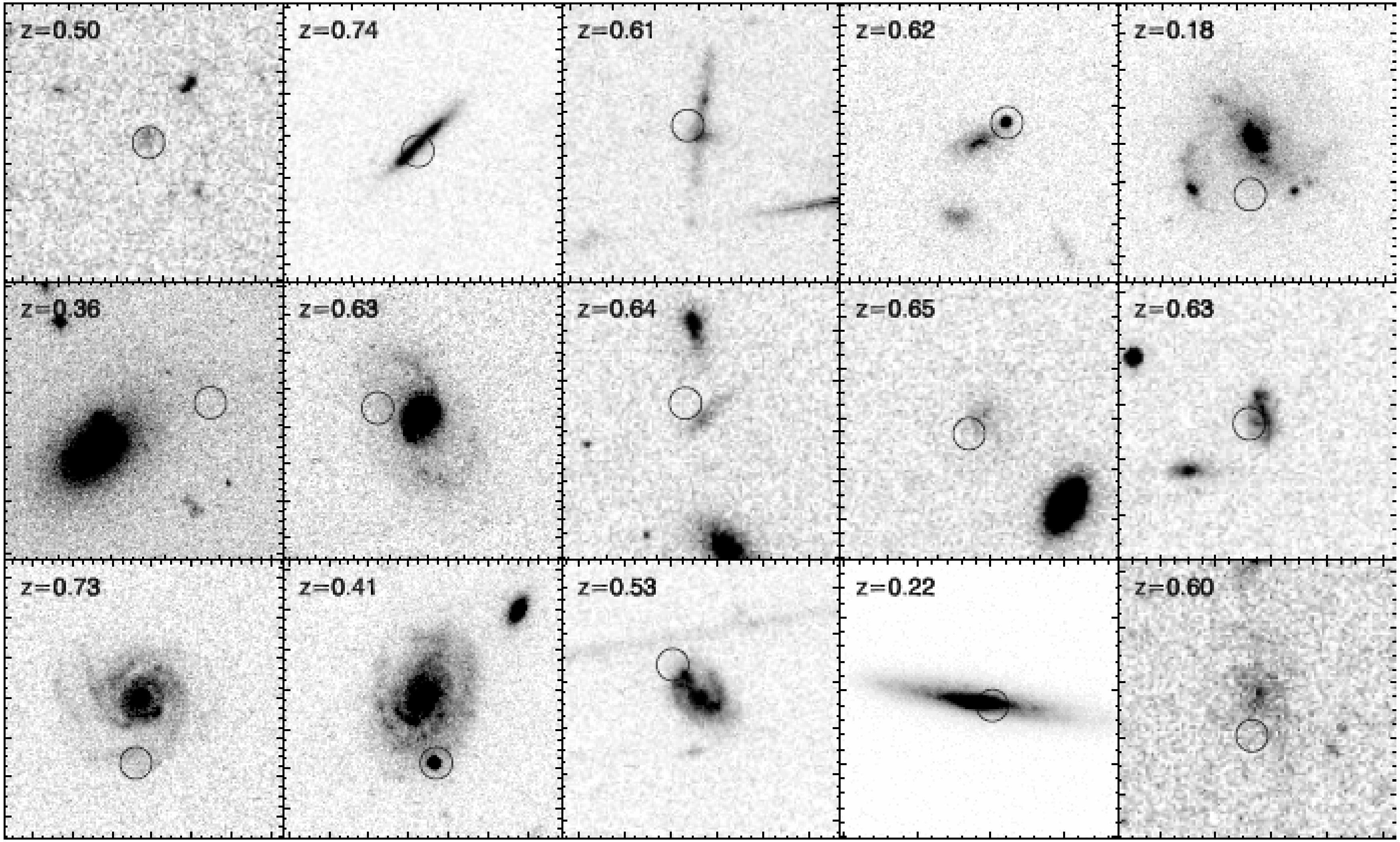

Far infrared image revealing radiation glow from warm dust

Reddening distribution for low and high z SNe

By comparing *rest-frame colors* of SNe we can show that higher z SNe are not generally more dusty and dimmed than local examples



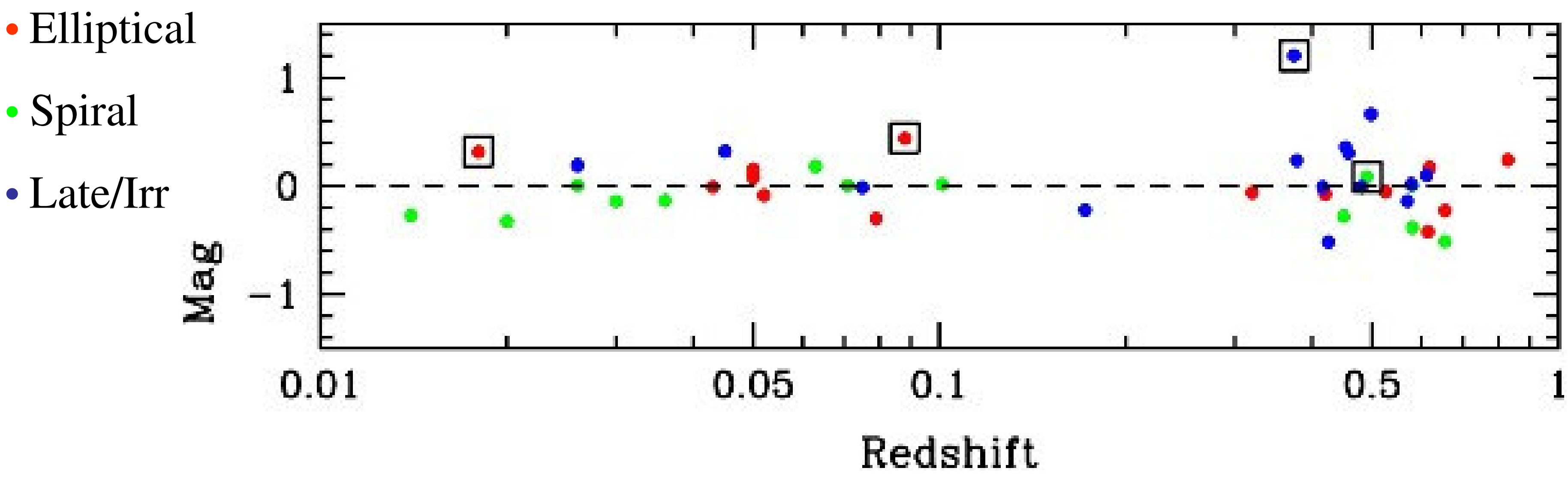
Supernovae Classed by Host Galaxy Environment



Hubble Space Telescope imaging gives galaxy morphology & SN location

The SCP Hubble Diagram by Host Galaxy Type

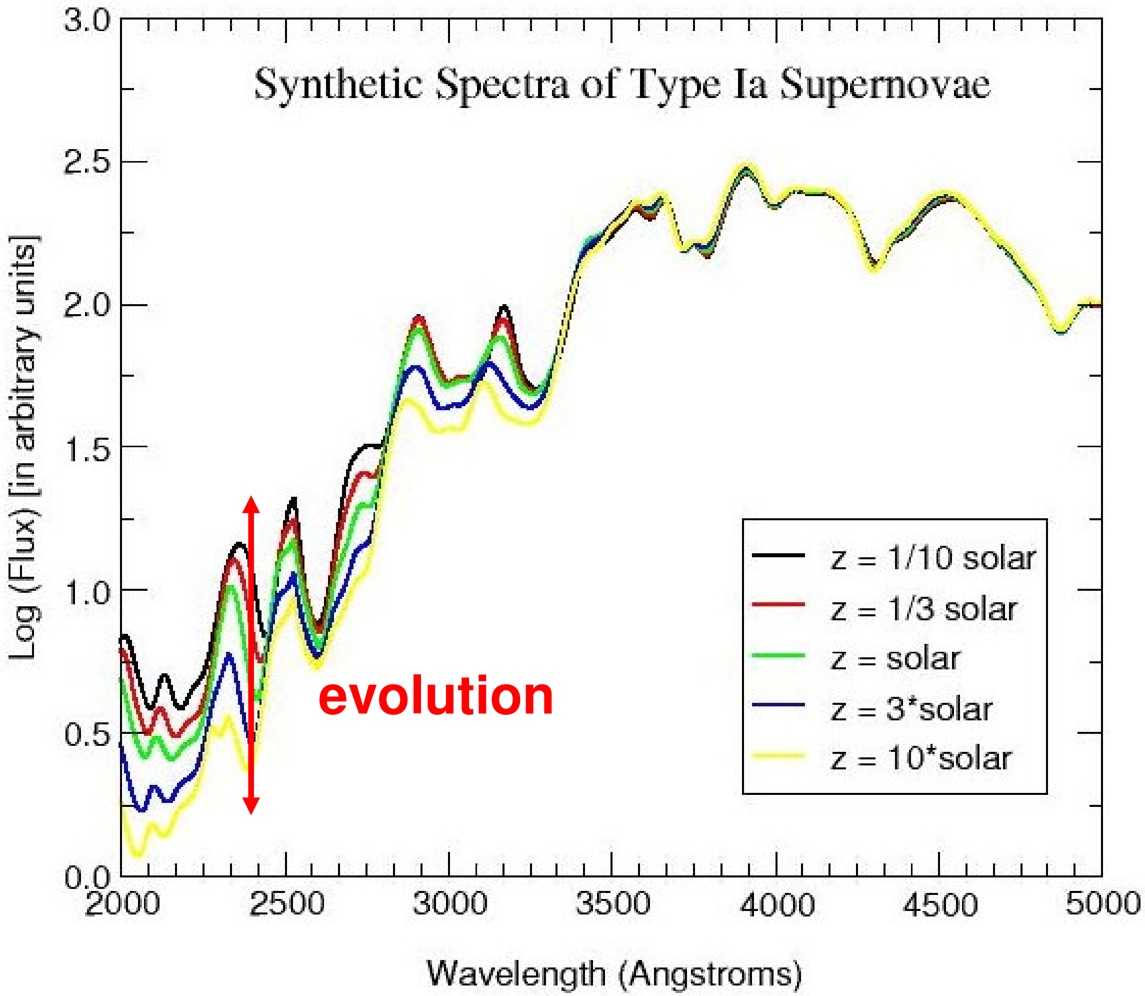
(uncorrected for extinction)



Type	*N*	*Dispersion (no s)*	*Λ (no s)*
Spheroidals	14 (12)	0.195 (0.210)	0.58 (0.63)
Spiral	13 (12)	0.270 (0.280)	0.30 (0.25)
Late/Irr	16 (15)	0.300 (0.286)	0.83 (0.75)

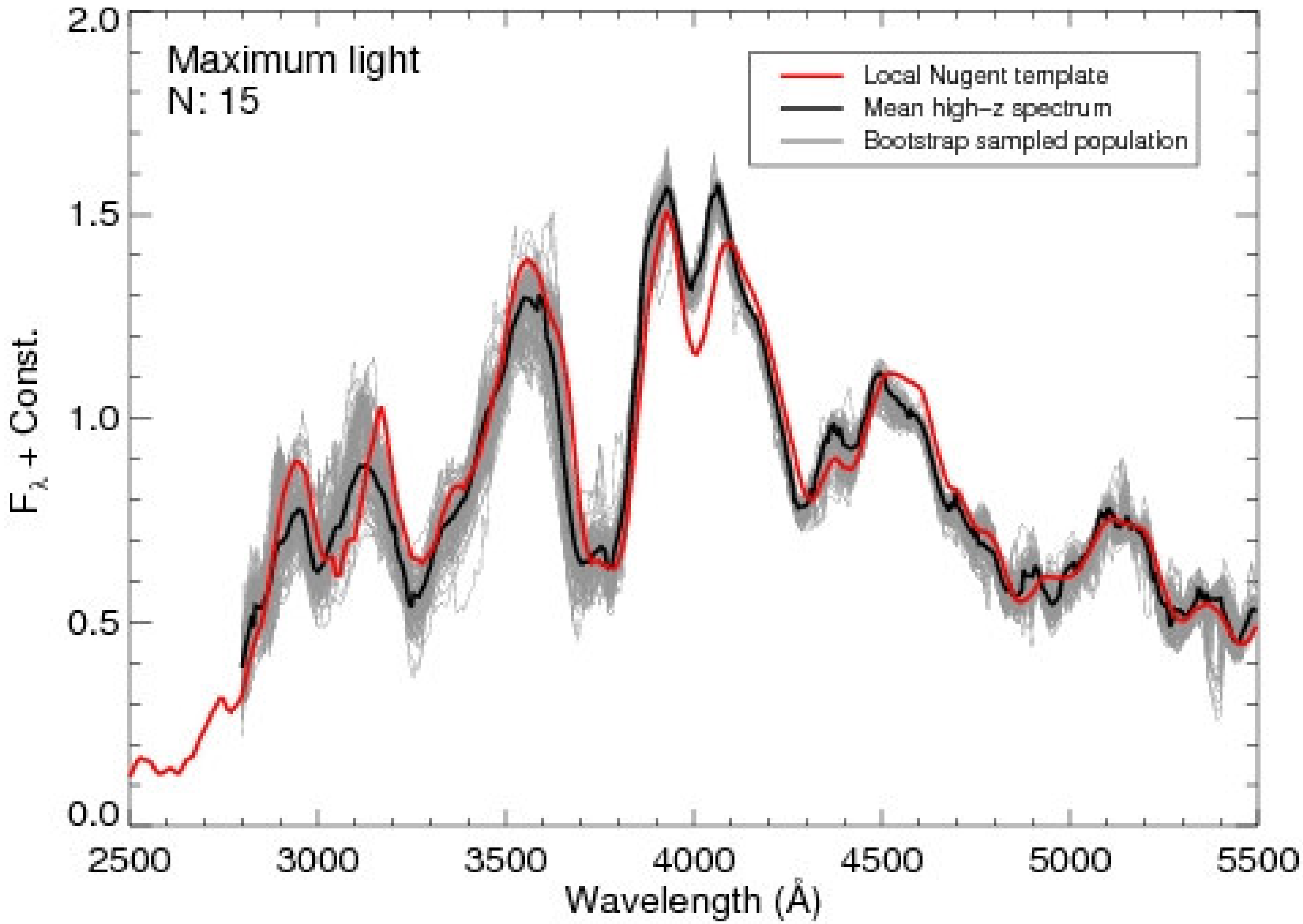
Can deduce acceleration just from SN in dust-free ellipticals

Could Supernovae be Evolving?



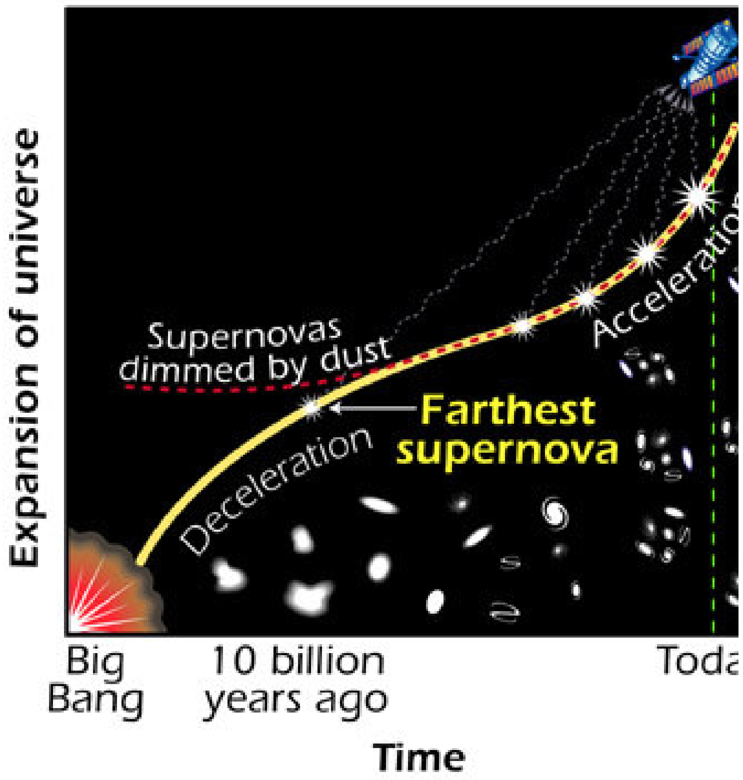
The most likely evolutionary trend is in chemical composition: might expect earlier SNe to have less heavy elements - affects UV spectrum

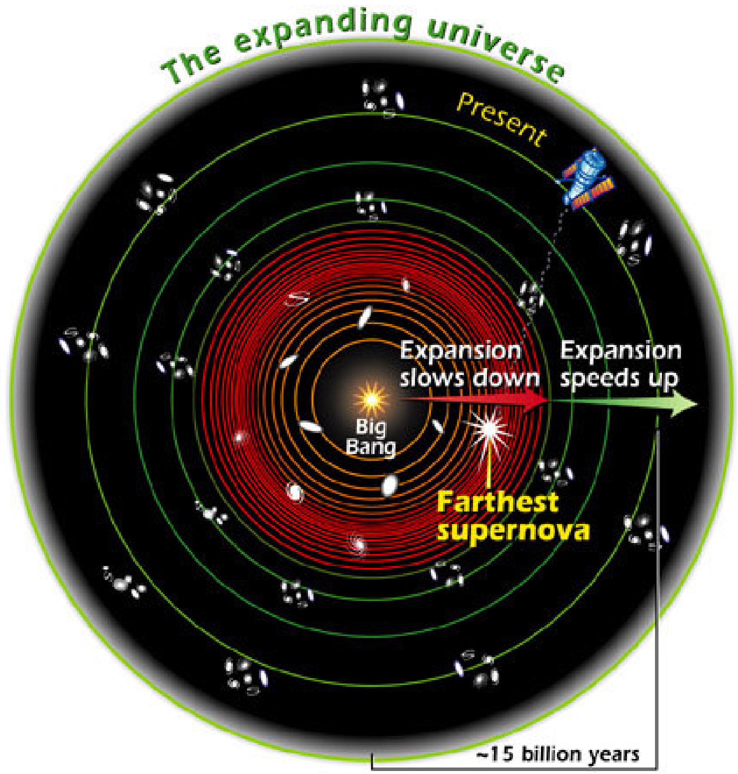
Mean Spectra of Nearby and Distant SNe



Over the redshift range where acceleration is seen, not much has changed in mean SN properties

Cosmic Expansion – big surprises!



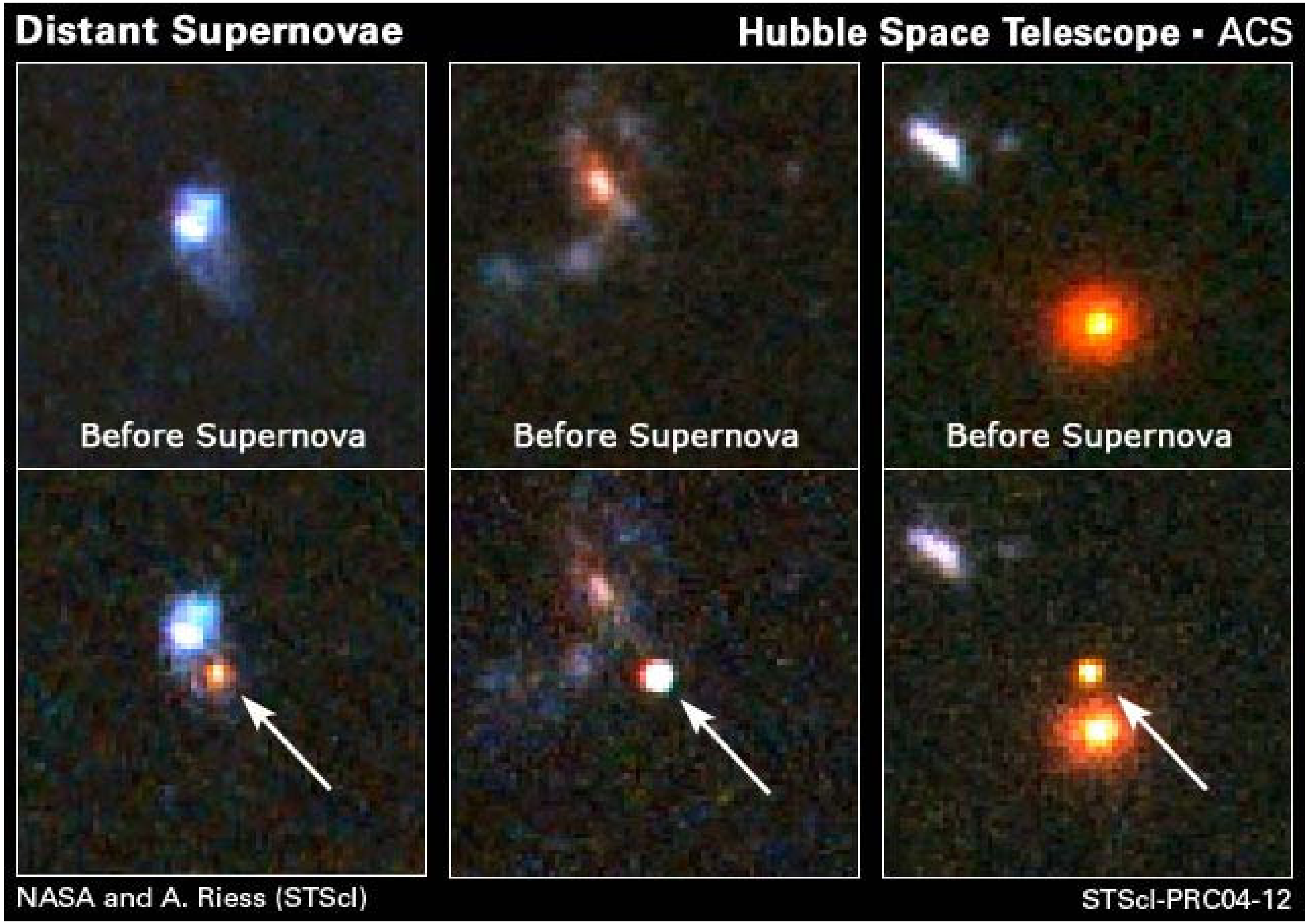


The rate of cosmic expansion could be affected by **two** ingredients:

Matter – this gravitationally slows down the expansion but by an amount which varies as the density of matter is reduced, initially dominant

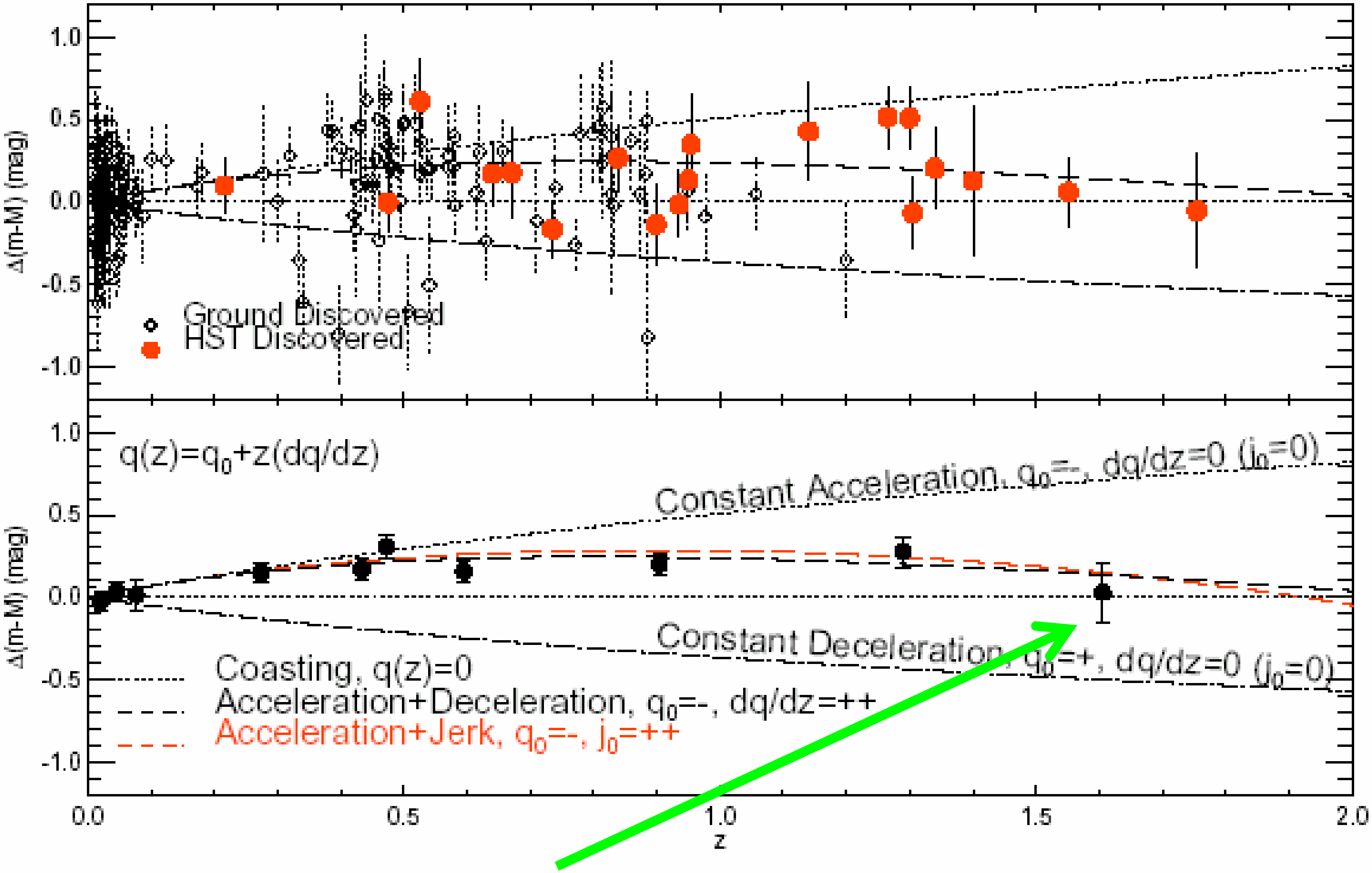
Dark energy – a more general explanation of unknown form which acts as a repulsive term (possibly equivalent to the original term introduced by Einstein?)

Can we see back to the period when the Universe was *not* accelerating?



Hubble Space Telescope has found ~15 events with $z > 1$

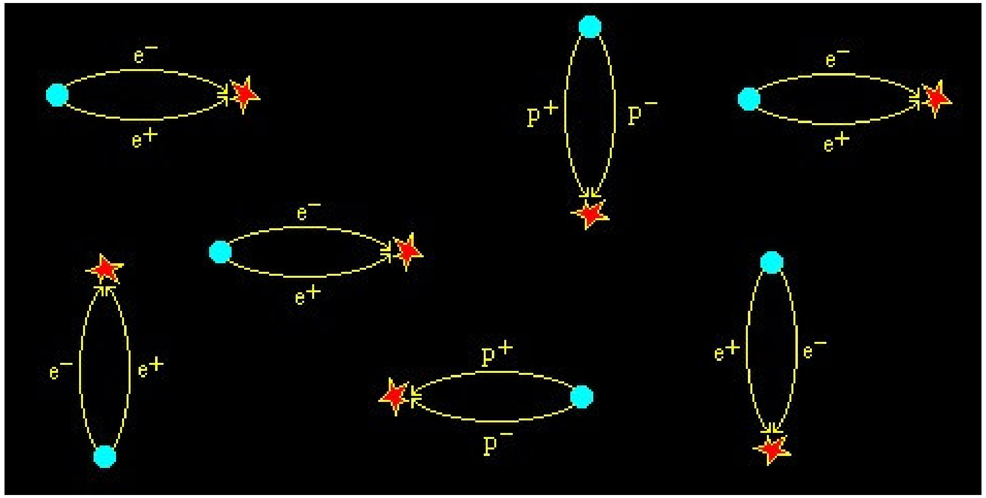
The situation so far - exciting but need more data!

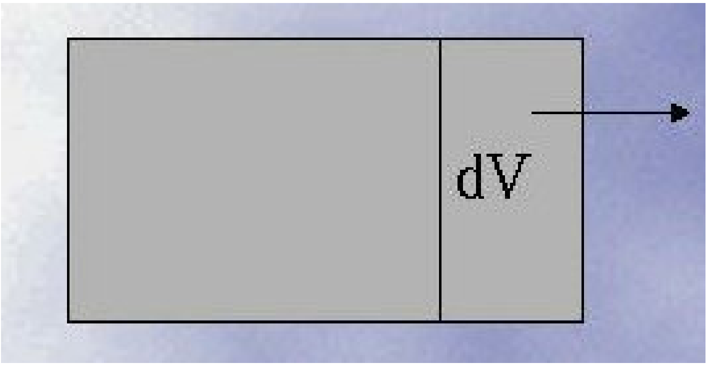


The most distant SNe tentatively suggest deceleration

So What Could "Dark Energy" Be?

Particle physicists believe a vacuum can still be full of particles and anti-particles in constant creation/annihilation. These exert a *negative pressure* and a repulsion over large distances





A piston expanding with positive pressure loses energy; *negative pressure* means gaining energy in expansion by an amount which means the *vacuum energy density* is constant

Why is a non-zero cosmological constant worrying?

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

  VACUUM ENERGY: $p = -\rho \rightarrow \rho \propto \textit{constant}$

What are the alternatives?

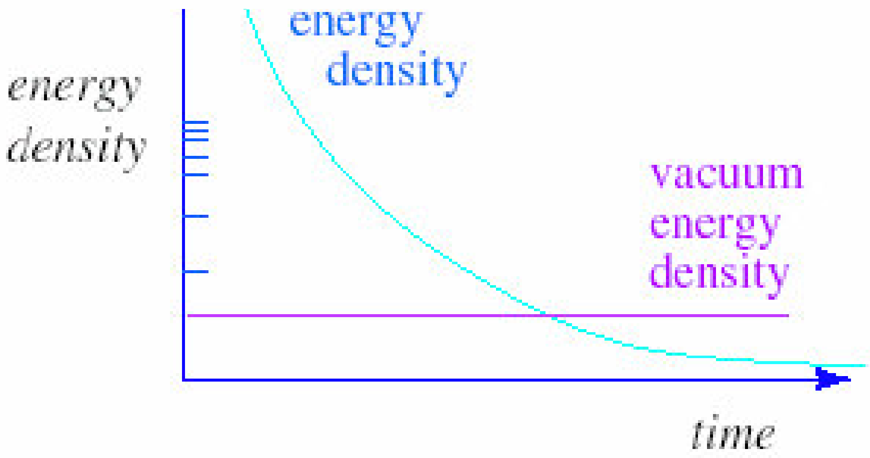
New Physics: "Dark energy":

Dynamical scalar fields, "quintessence",...

General Equation of State:

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

and w can vary with time



Do theorists really know what's going on?!

"The issue of dark energy dynamics is perhaps the most pressing today in cosmology" **(Bassett et al 2004)**

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/0404468
"No evidence for Dark Energy Metamorphosis ?"
Jonsson et al
w(z)=summation(Ak,z), power series
"For the ansatz proposed by Alam et al. dark energy evolution is both favored and forced...Our best fit to real data with 16 additional high redshift supernovae was consistent with the cosmological constant at the 68% confidence level.

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/0406672
"Rejoinder to "No Evidence of Dark Energy Metamorphosis", astro-ph/0404468"
Alam et al
w(z)=w(1+z,A0,A1,A2)
"Contrary to the claims in Jonsson et al...the current supernova data favours the evolving dark energy models over the cosmological constant at 1-2 sigma still holds...Better quality data expected in the future from different cosmology experiments (SNe, CMB, LSS etc.) will allow us to draw firmer conclusions about the nature of dark energy.

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

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]"

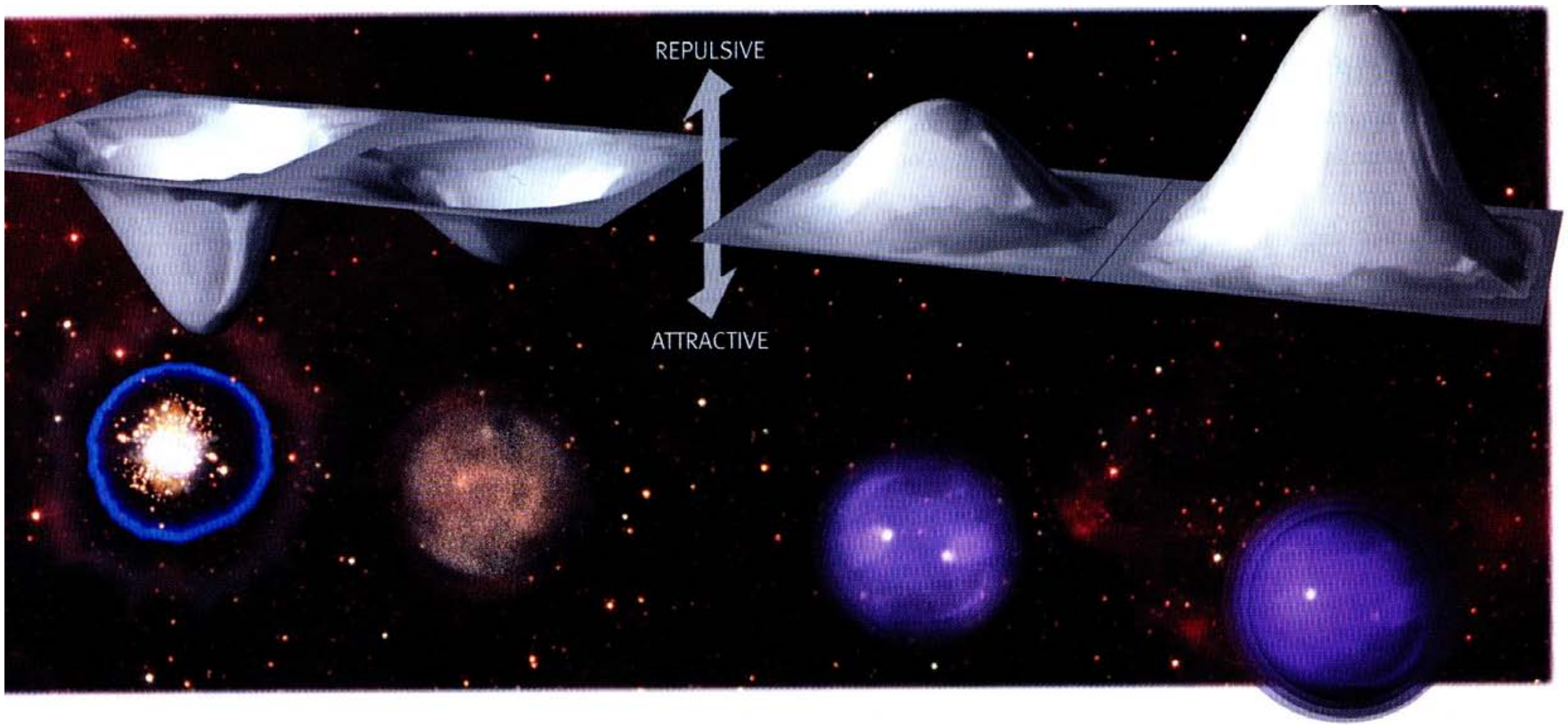
astro-ph/0407372
"Cosmological parameter analysis including SDSS..."
Seljak et al.
w(z)=w(a,w0,w1)
"We find no evidence for variation of the equation of state with redshift.."

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."

Dark Energy and *w*

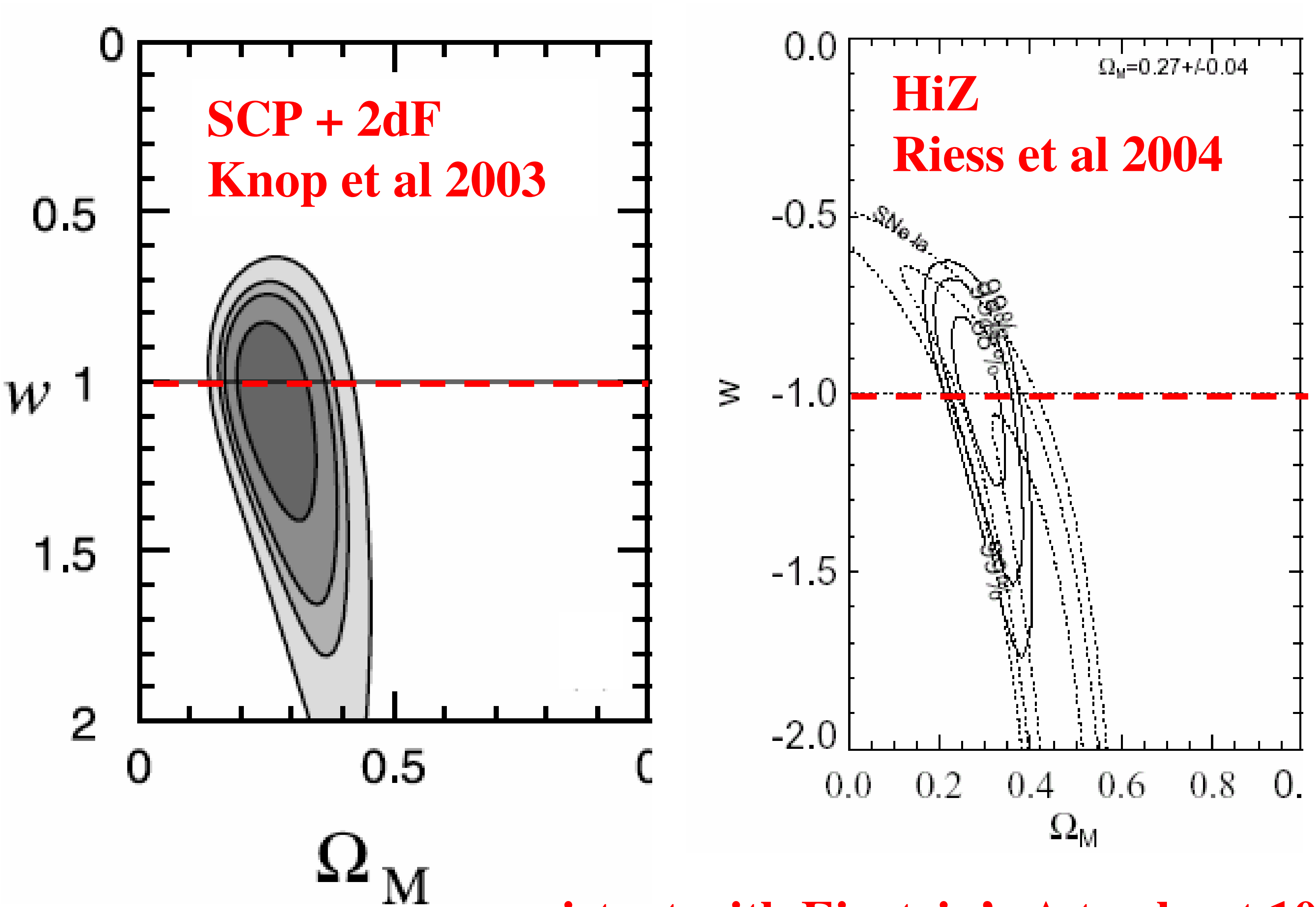
In General Relativity, force ∝ (ρ + 3p)
Equation of state has index *w* = p/ρ



	RADIATION	ORDINARY MATTER	QUINTESSENCE (MODERATELY NEGATIVE PRESSURE)	Cosmological Constant (vacuum)
w =	**+1/3**	**0**	**-1/3 <w< -1**	**-1**

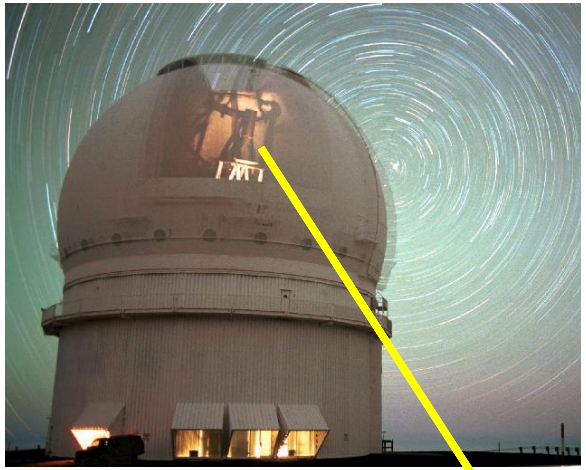
If w < -1/3 the Universe accelerates

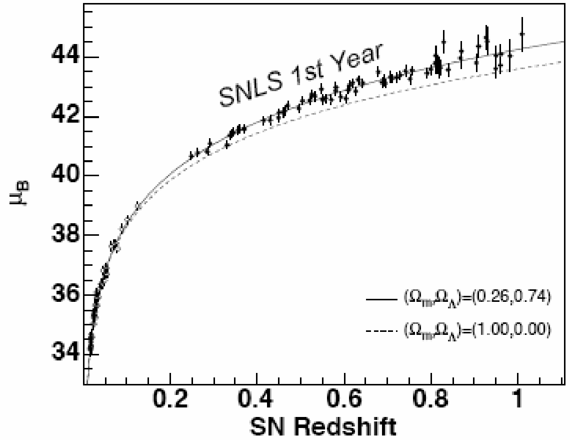
SNe Ia: how close to Einstein's Λ are we?

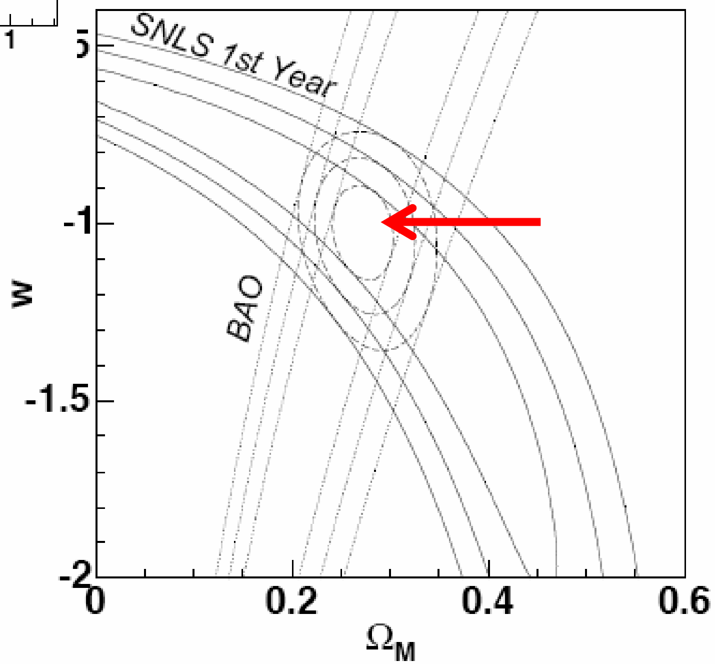


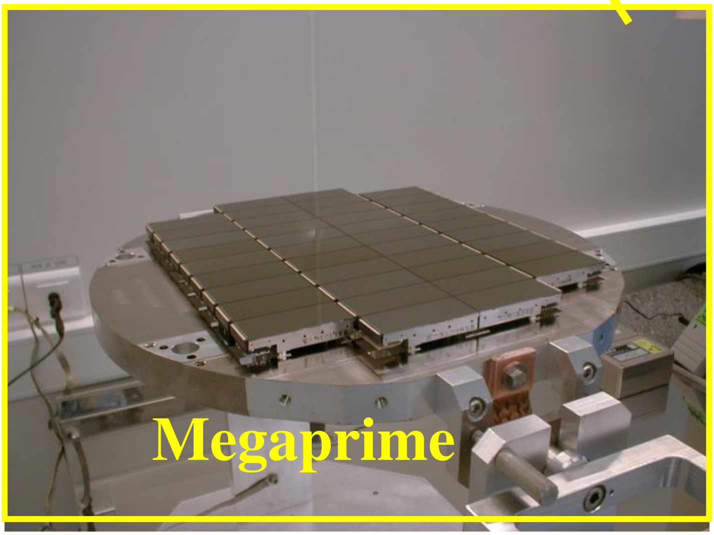
→ consistent with Einstein's Λ to about 10%

CFHT SN Legacy Survey (2003-2008)





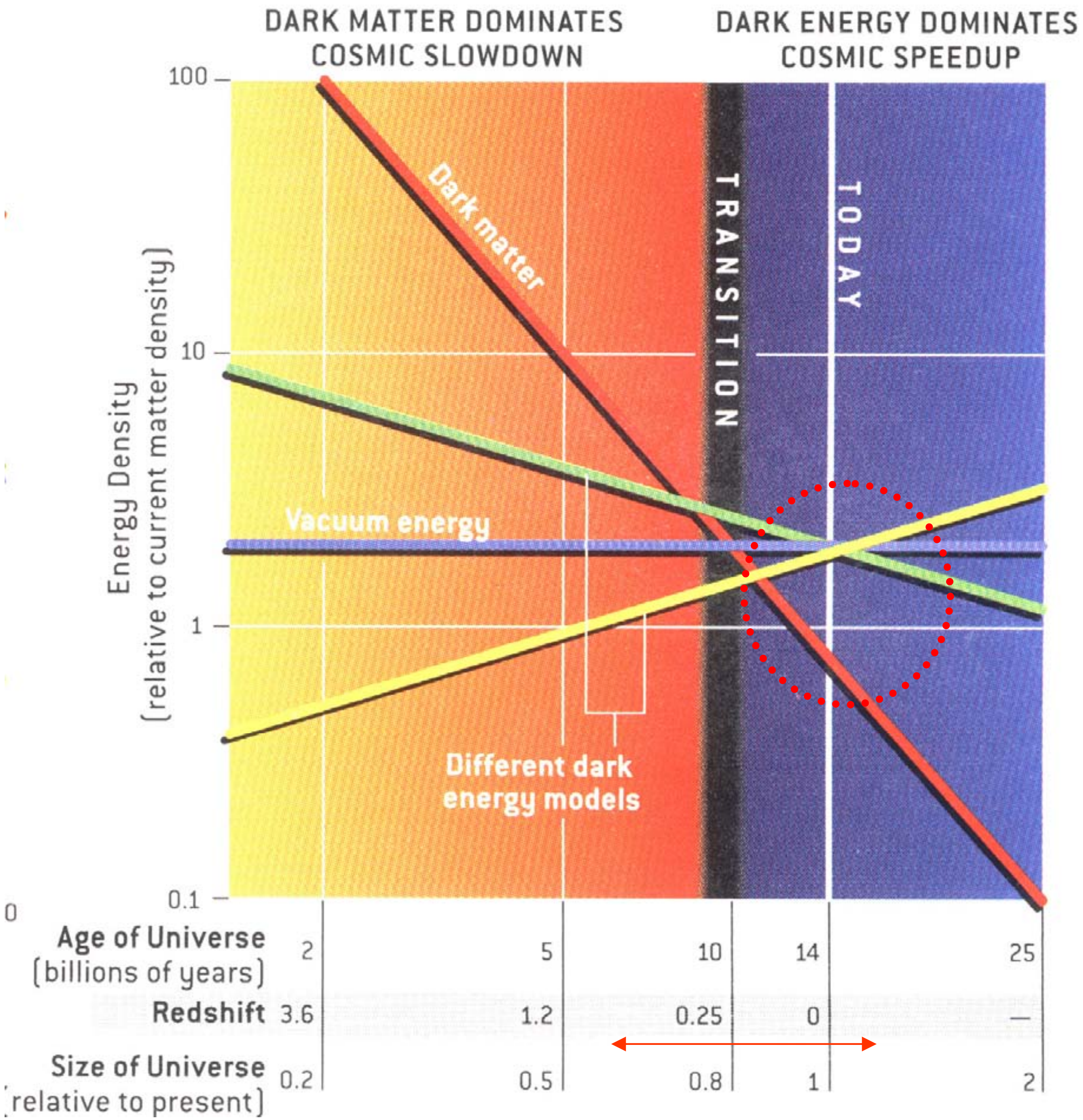




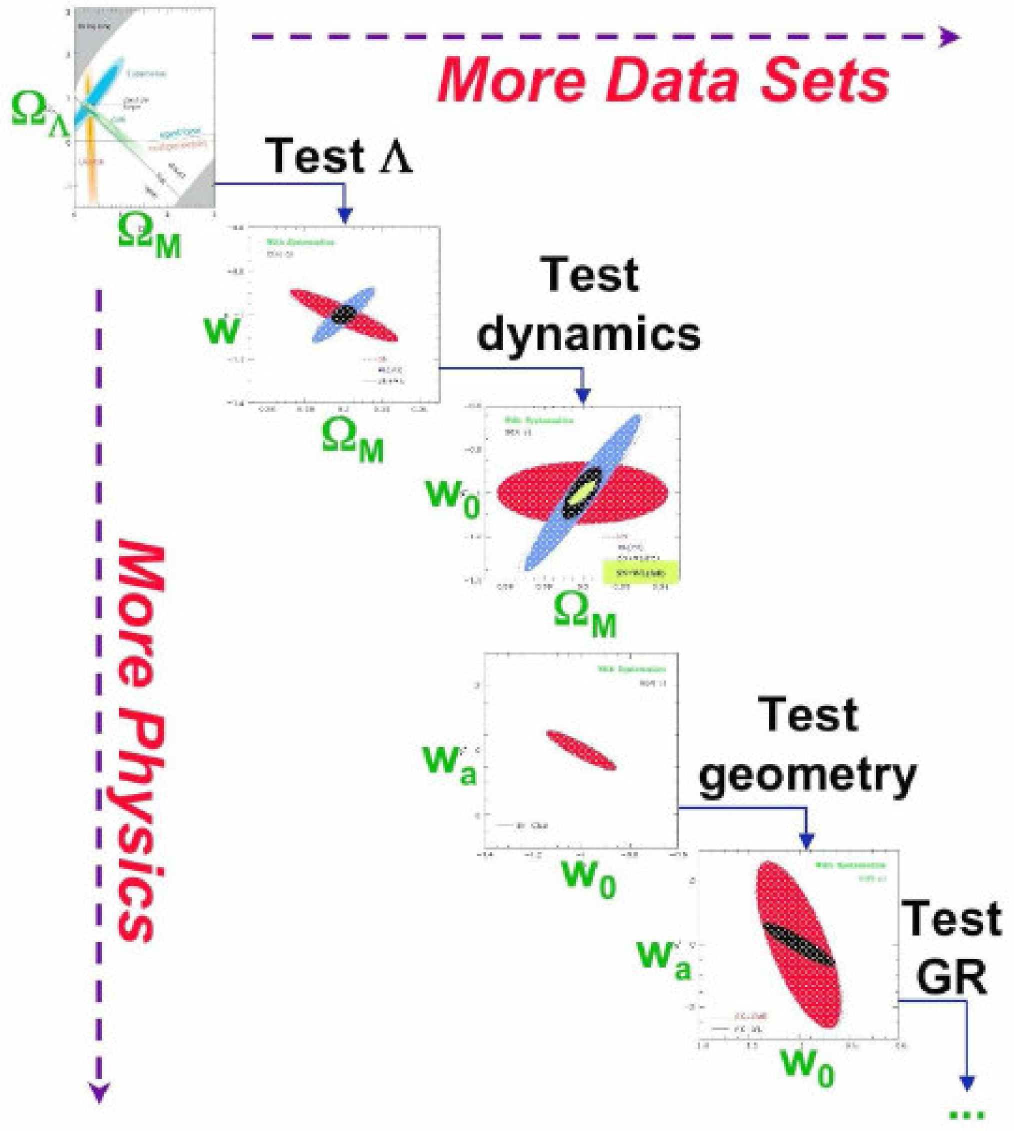
71 homogenously studied SNe Ia

w = -1.023 ± 0.090

Could Dark Energy be Dynamic - w(z)?

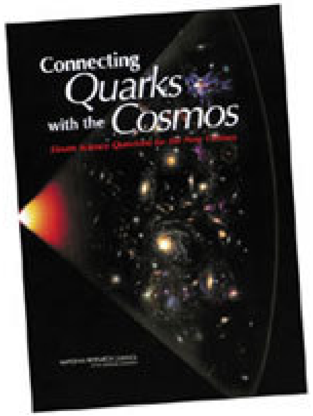


Incremental Exploration of the Unknown



Linder (astro-ph/0511197)

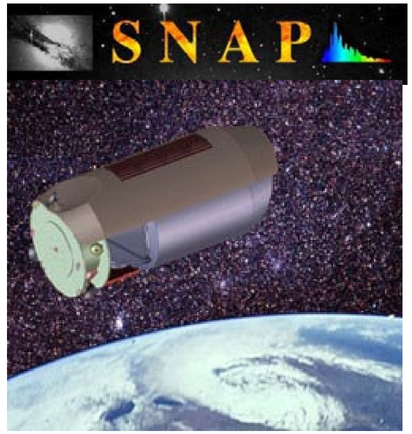
Tracking Dark Energy

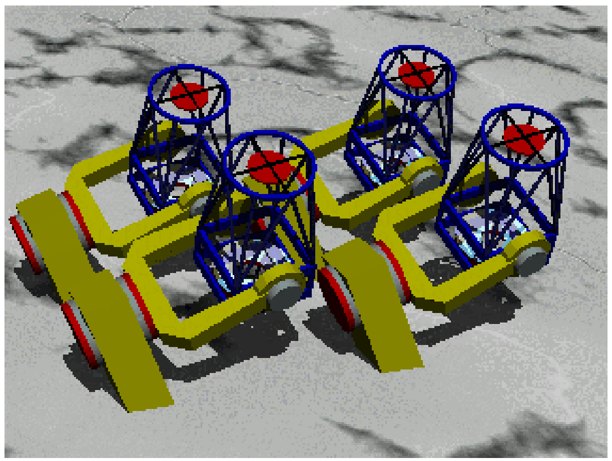


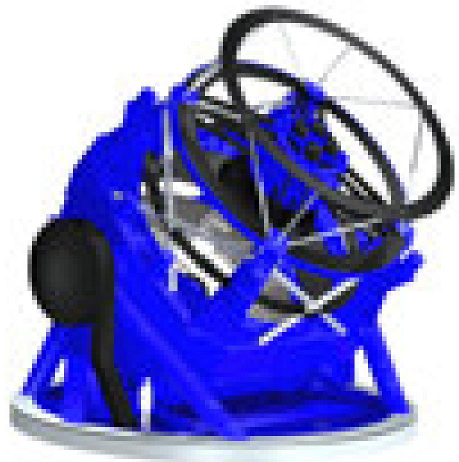
Much interest in new experiments (ground and space) to track Dark Energy

- measure w, is it -1.00 ± 0.01?

- see if w ≠ constant with redshift







How to Measure Dark Energy

- **Type Ia Supernovae: velocity-distance to $z \approx 2$**
  - Most well-developed with rich datasets
  - Ongoing with various ground-based/HST surveys
  - Key issue is physics/evol^{n}: *do we understand SNe Ia?*
- **Weak lensing: growth of structure to $z \approx 1.5$**
  - Less well-developed but promising
  - Might need a space telescope as distortion is weak
  - Key issues are *fidelity, calibration*
- **Baryon features in galaxy clustering to $z < 3$**
  - Late developer: cleanest but *requires huge surveys*

Measuring the vacuum

Vacuum affects H(z):

$H^2(z) = H^2_0\ [\ \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_V (1+z)^{3(1+w)}\ ]$

matter　　radiation　　vacuum

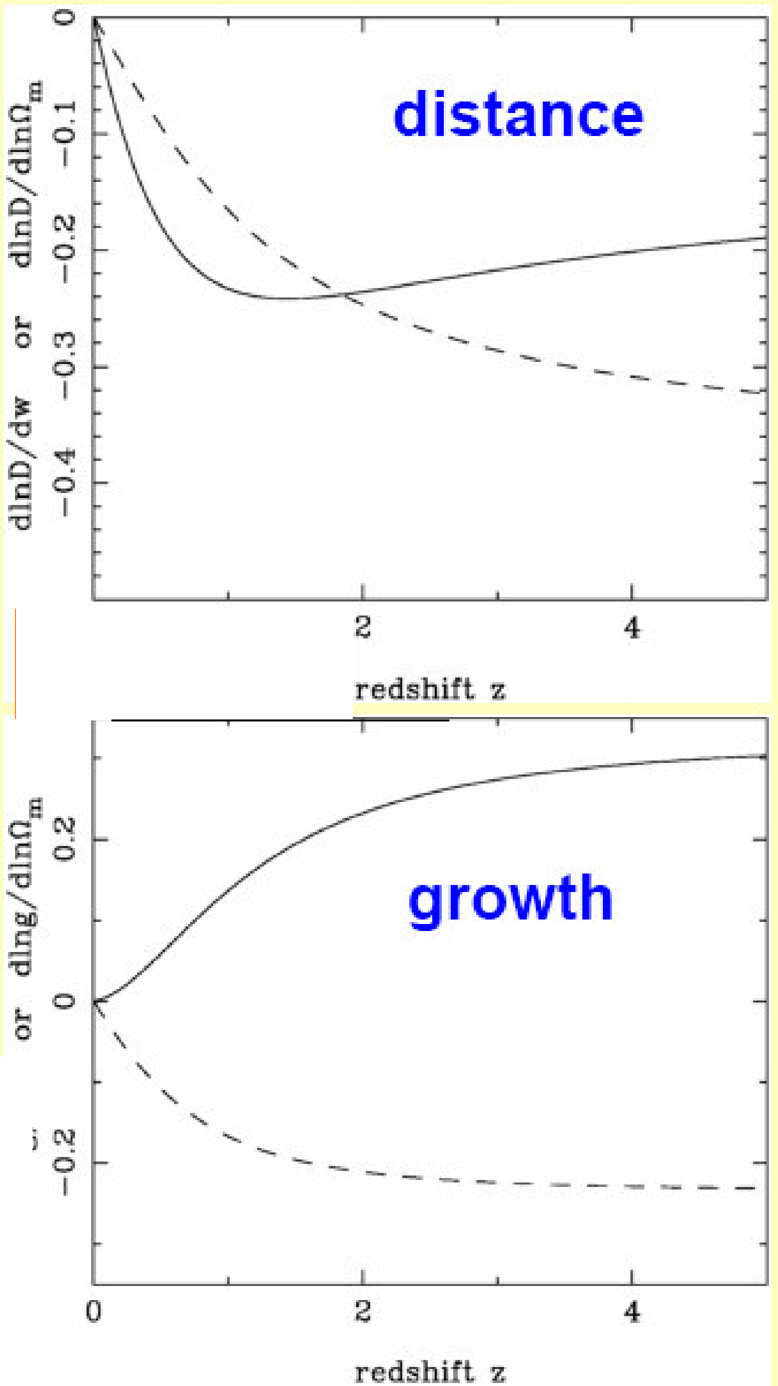
Alters D(z) via $r = \int c\ dz/H$

And growth via 2H dδ/dt term in growth equation

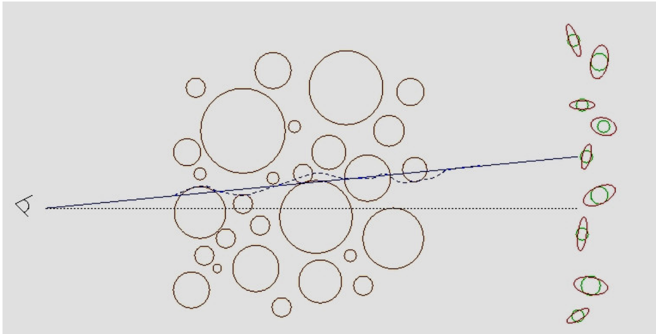
Both effects are

(1) Small (need D to 2% for w to ± 0.1)

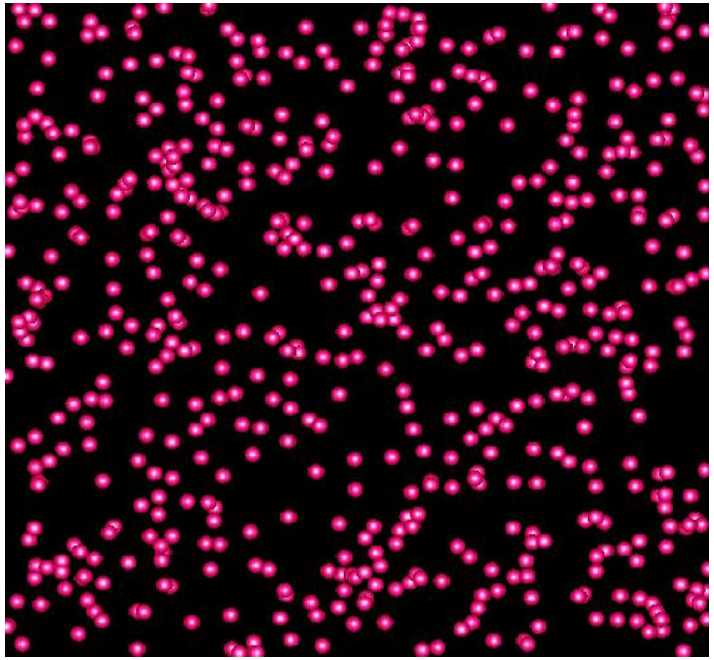
(2) Degenerate with changes in Ω_m



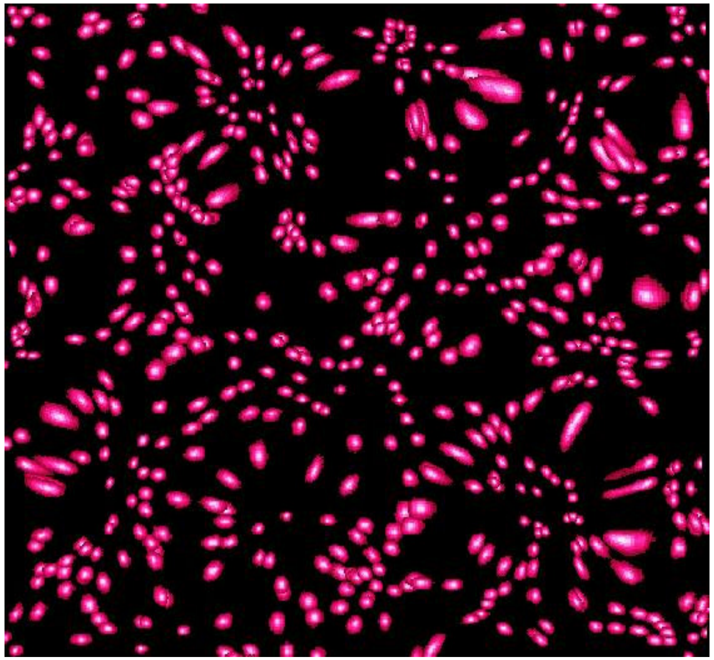
How Gravitational Lensing Works



Weak distortion of background images by foreground mass
Signal is tiny: need to detect shape distortions of 1% or so!

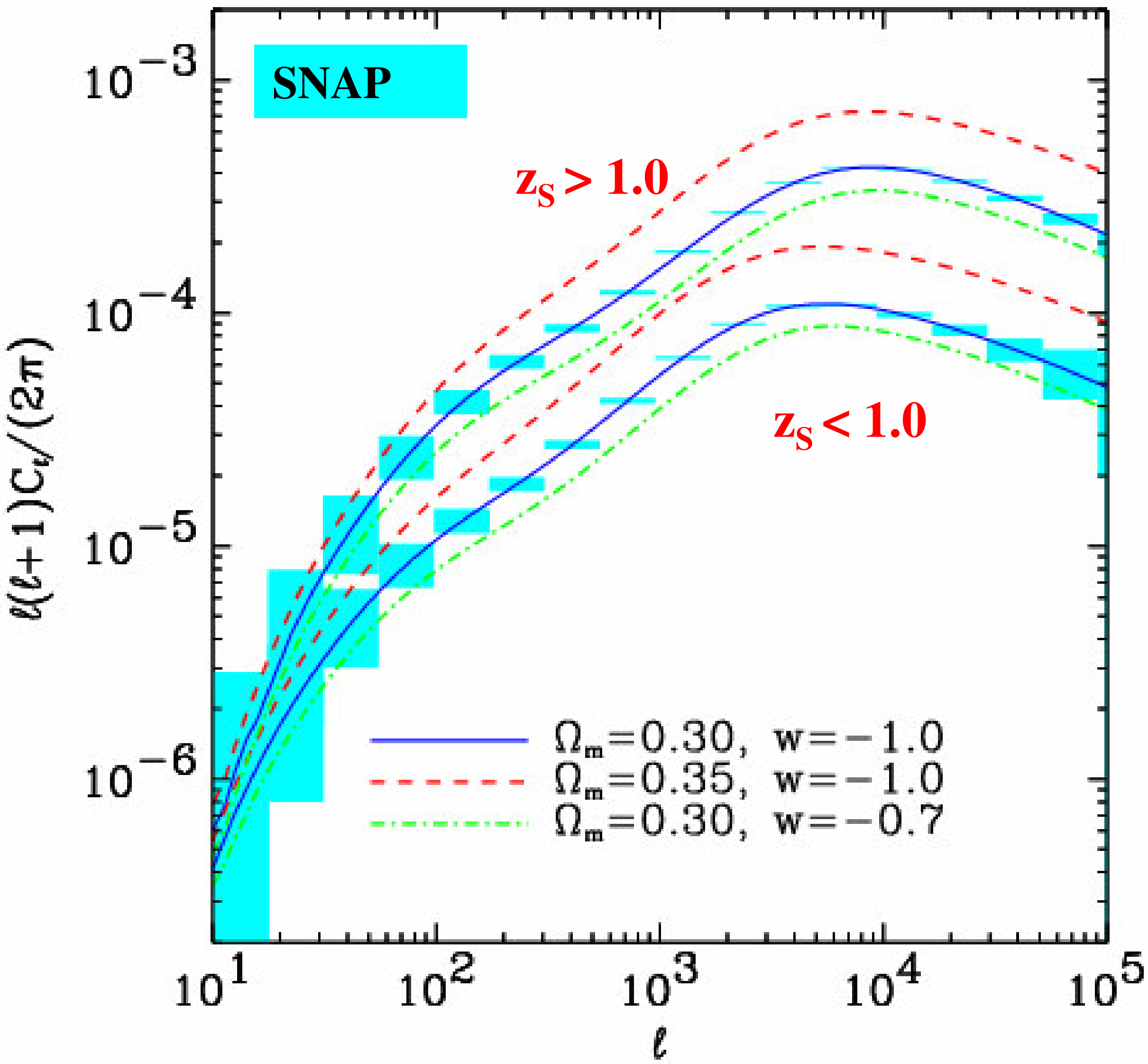


Unlensed



Lensed

Evolution of the DM Power Spectrum

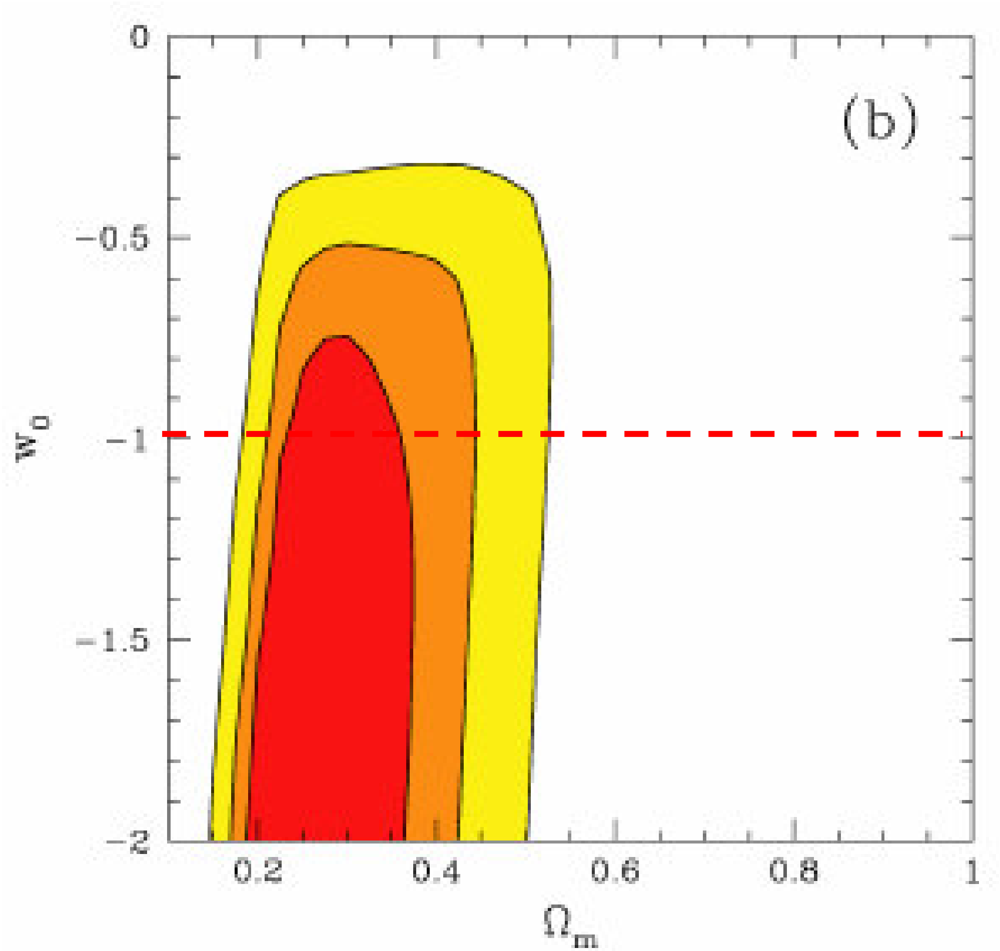


Growth of DM power spectrum is a battle between dark energy and gravity

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

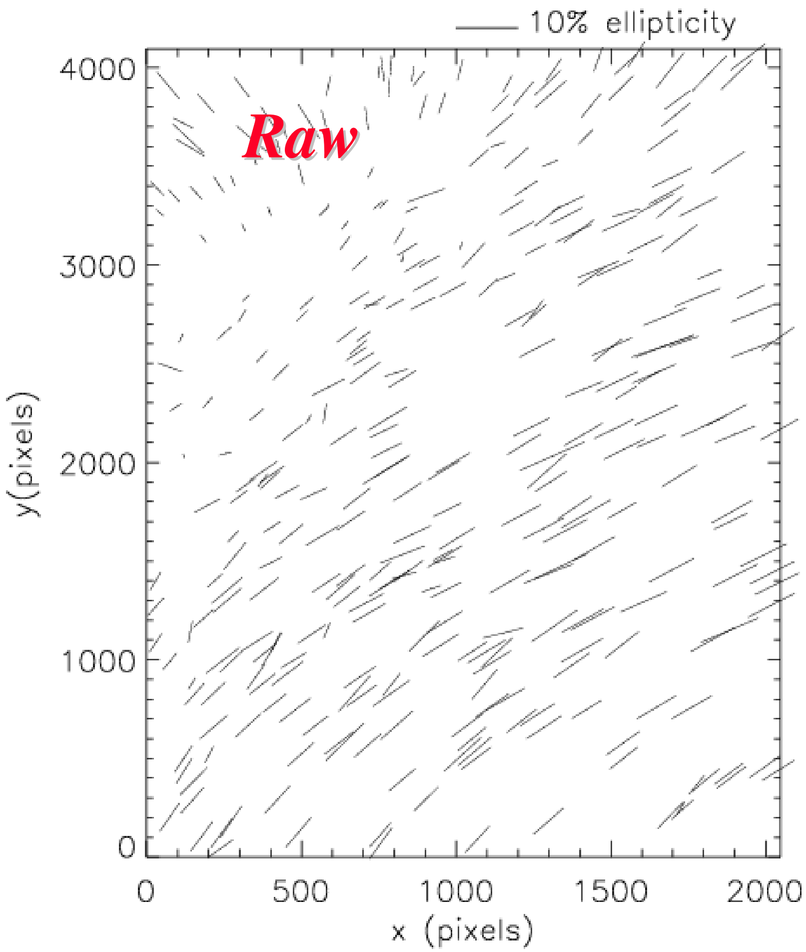
Current Limits from Weak Lensing
CFHT Wide Field Survey

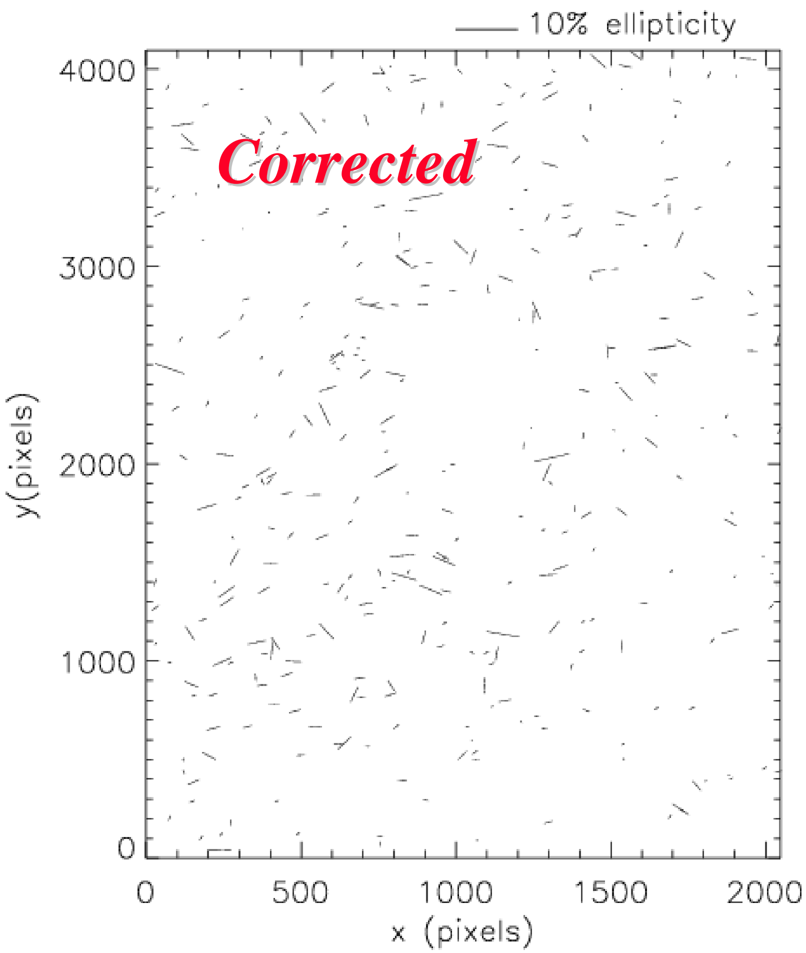


Not yet as developed as SNe but promising

Major issue is recovering the weak signal (technical)

For Example: Telescope Tracking

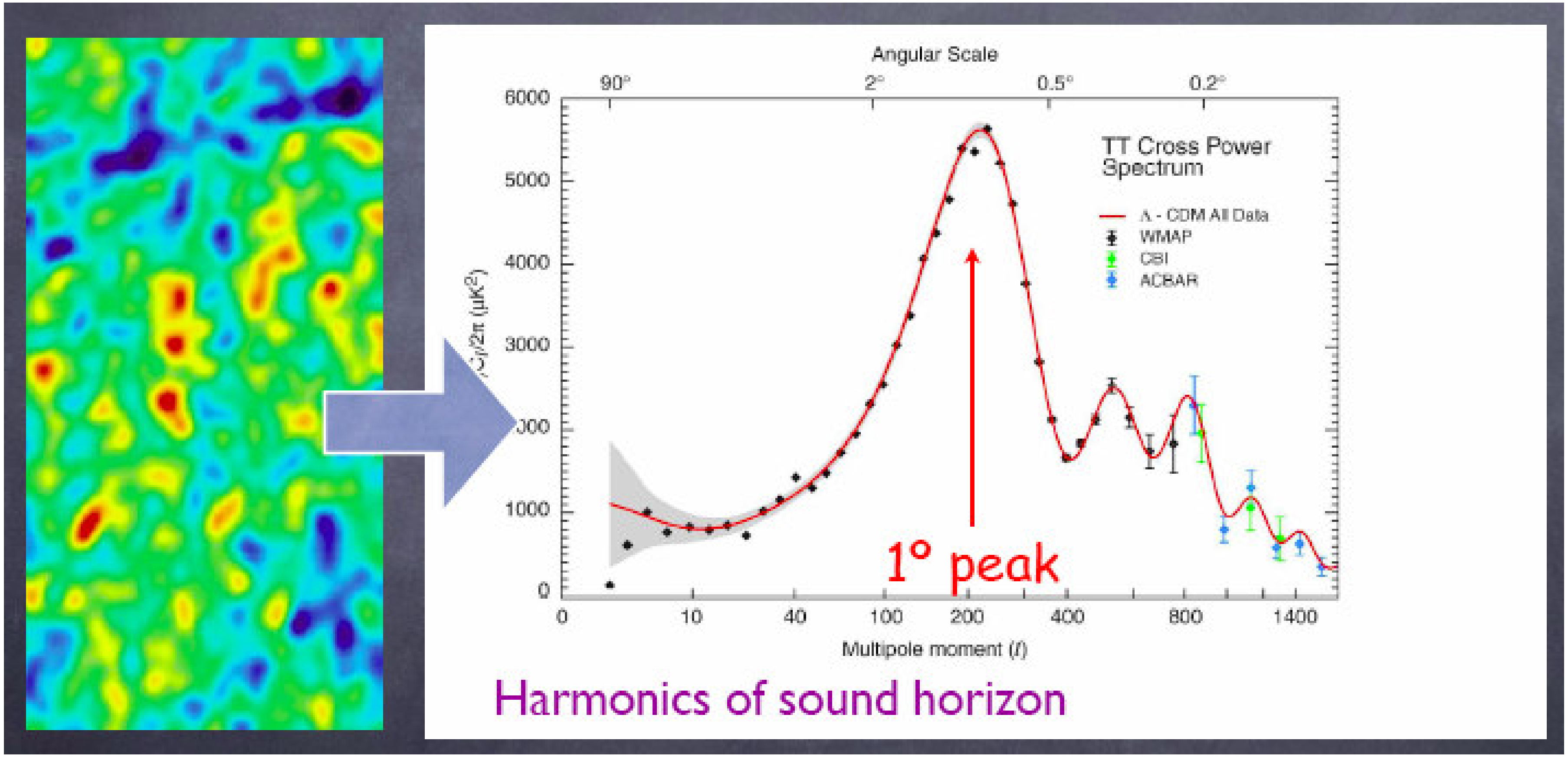




At the level required, even stars are not round on best telescopes!

Raw ellipticities: 3-10% reduced to ~ 0.1% by fitting stellar data

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:

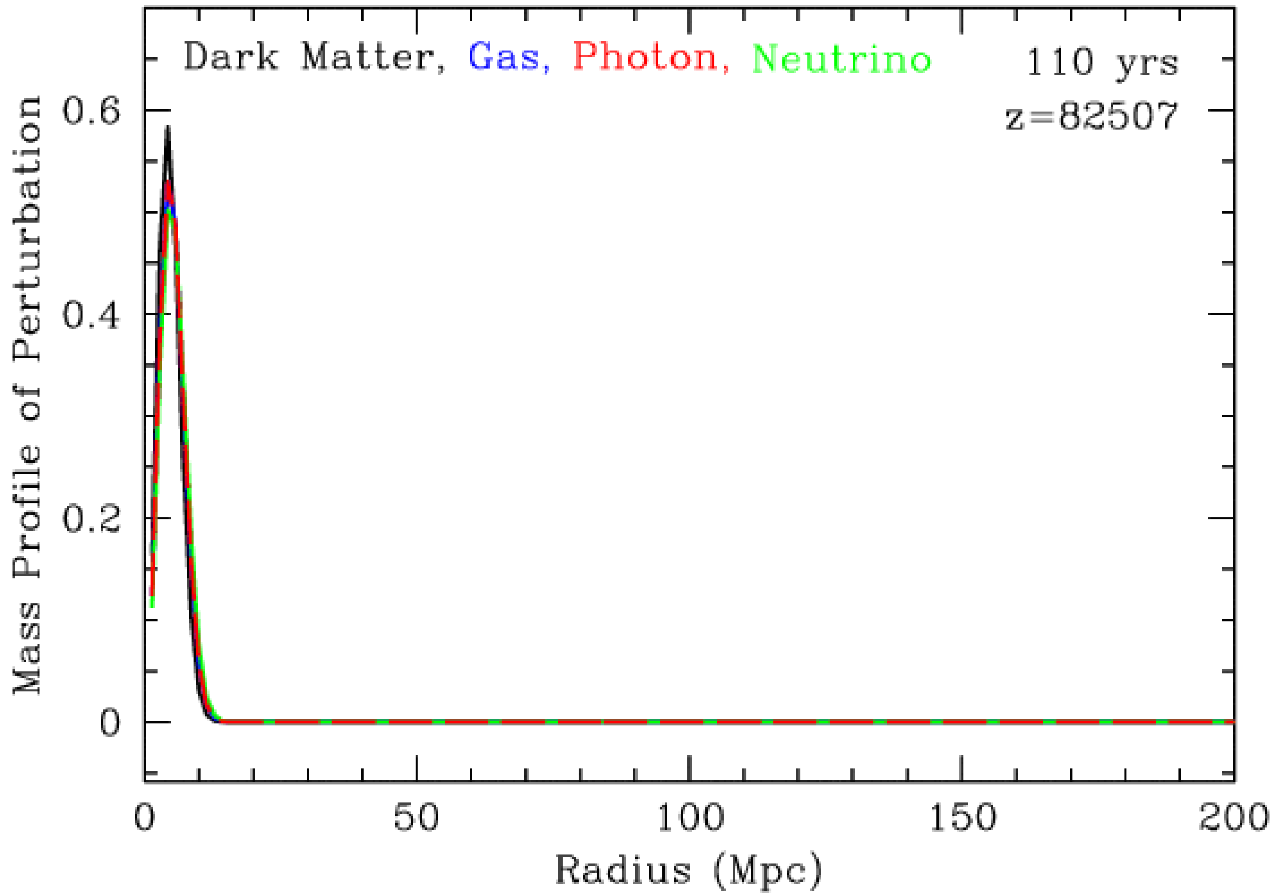
$$\lambda_s = \frac{1}{H_0\Omega_m^{1/2}} \int_0^{a_r} \frac{c_s}{(a+a_{eq})^{1/2}} da \quad = 150 \text{ Mpc}$$

Peebles & Yu 1970; Sunyaev & Zel'dovich 1970

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

Physics of Baryon Oscillations

CMB features arise from acoustic waves in *photons and baryons,* whereas galaxy distribution depends on *dark matter and baryons*



Courtesy: Eisenstein/CMBfast

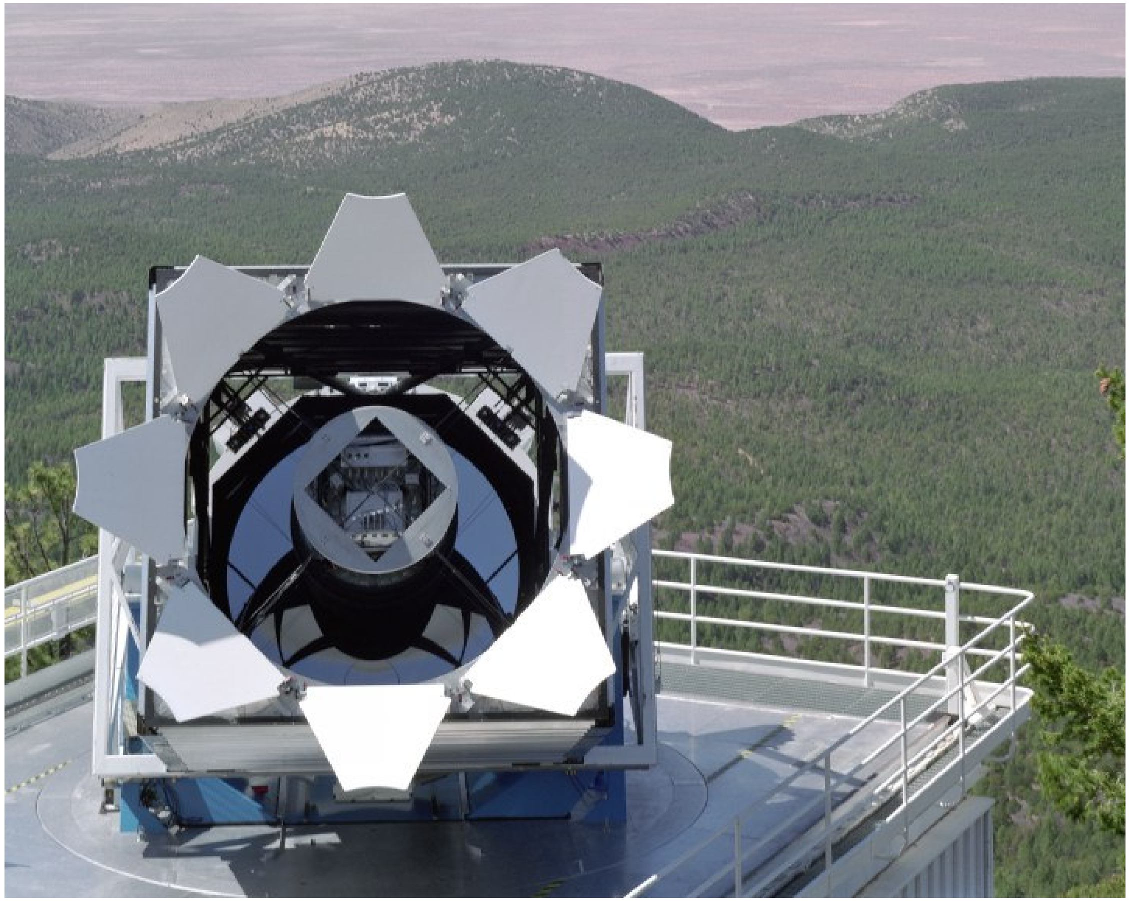
comoving scale

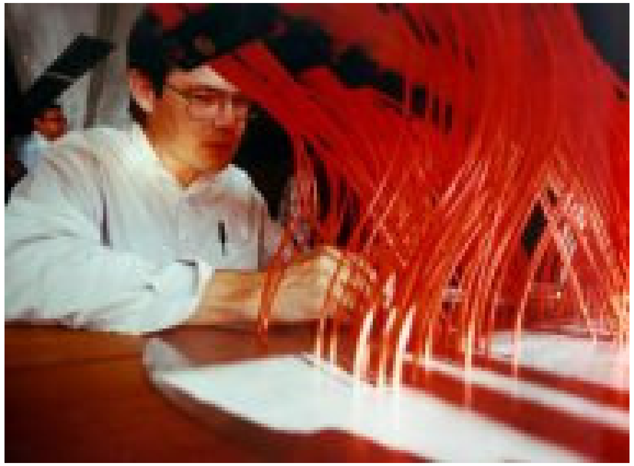
Importance of Baryonic Oscillations

- *Aren't we just revisiting and confirming the physics of the CMB?*
- *Signal is weak: need to probe large volumes $\cong$ Gpc^3 with enormous redshift surveys to even see the signal.*

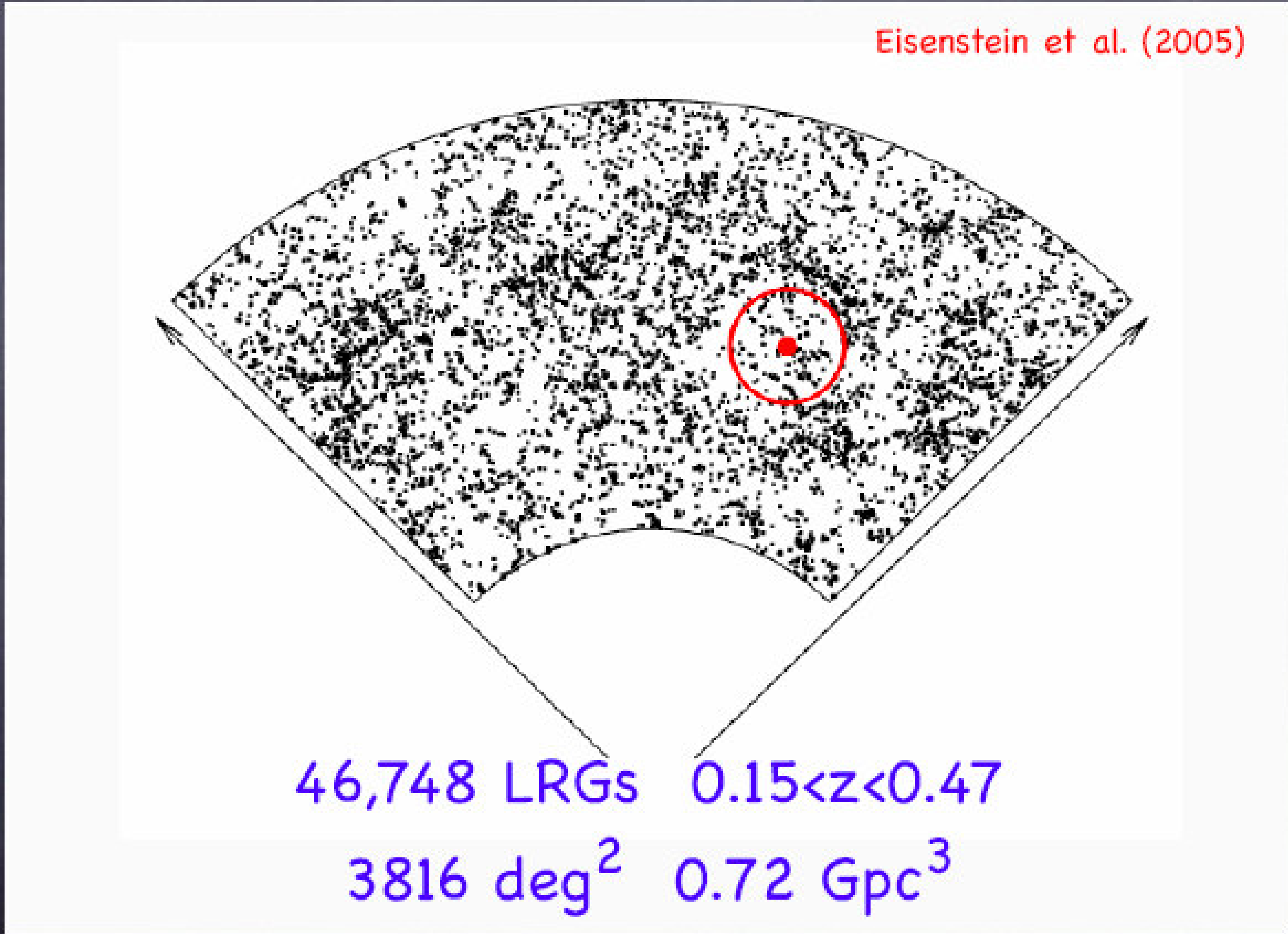
- Provides clear evidence for gravitational instability picture: more convincing than indirect probes of growth of small-scale clustering usually confused by "bias"
- Confirms role of dark matter at z=1100, since without DM, signal would be much stronger
- Provides characteristic yardstick which, in principle, enables us to determine, geometrically, the angular diameter distance - redshift relation and hence a clean constraint on dark energy

Detection from the Sloan Digital Sky Survey

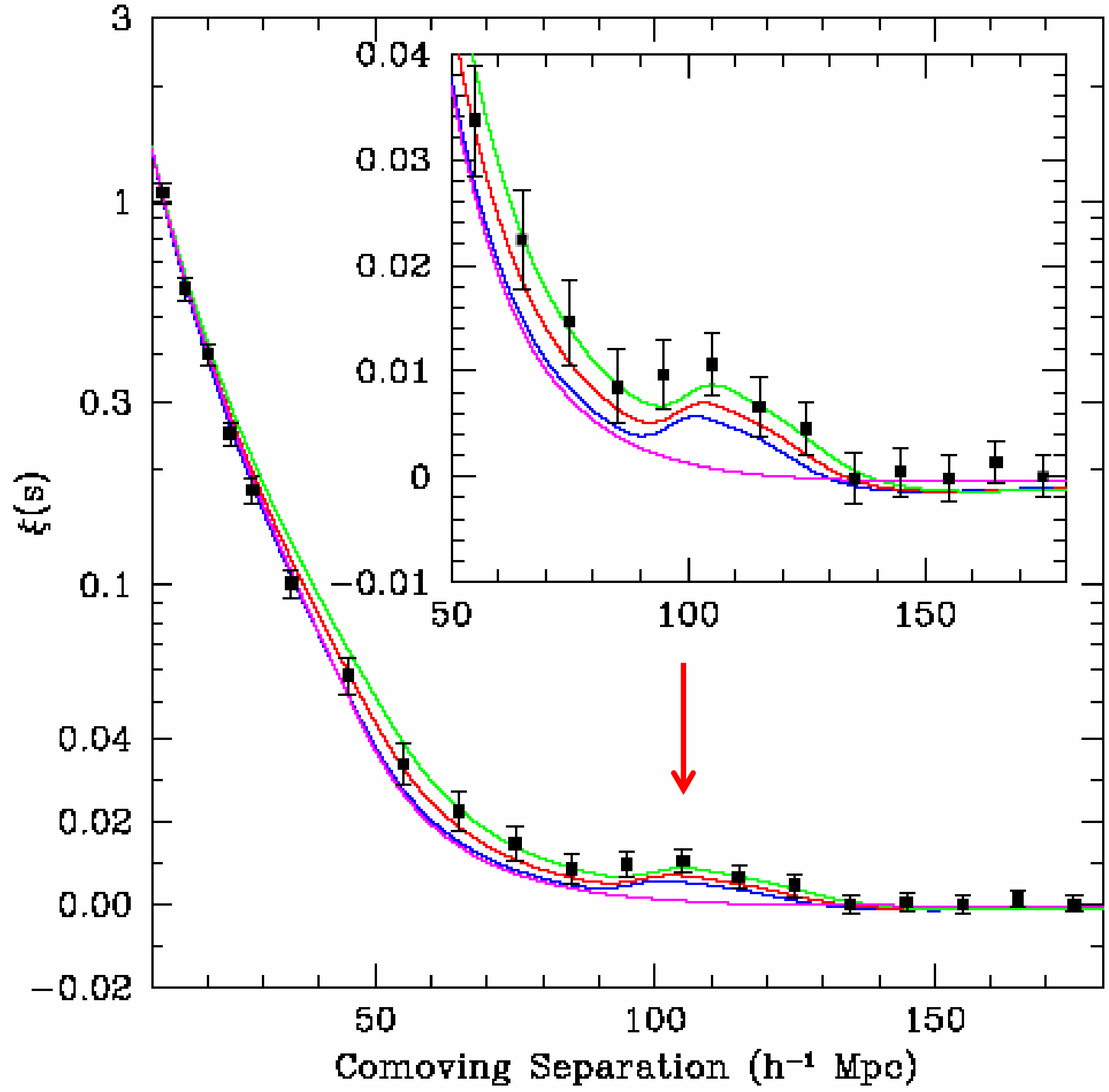




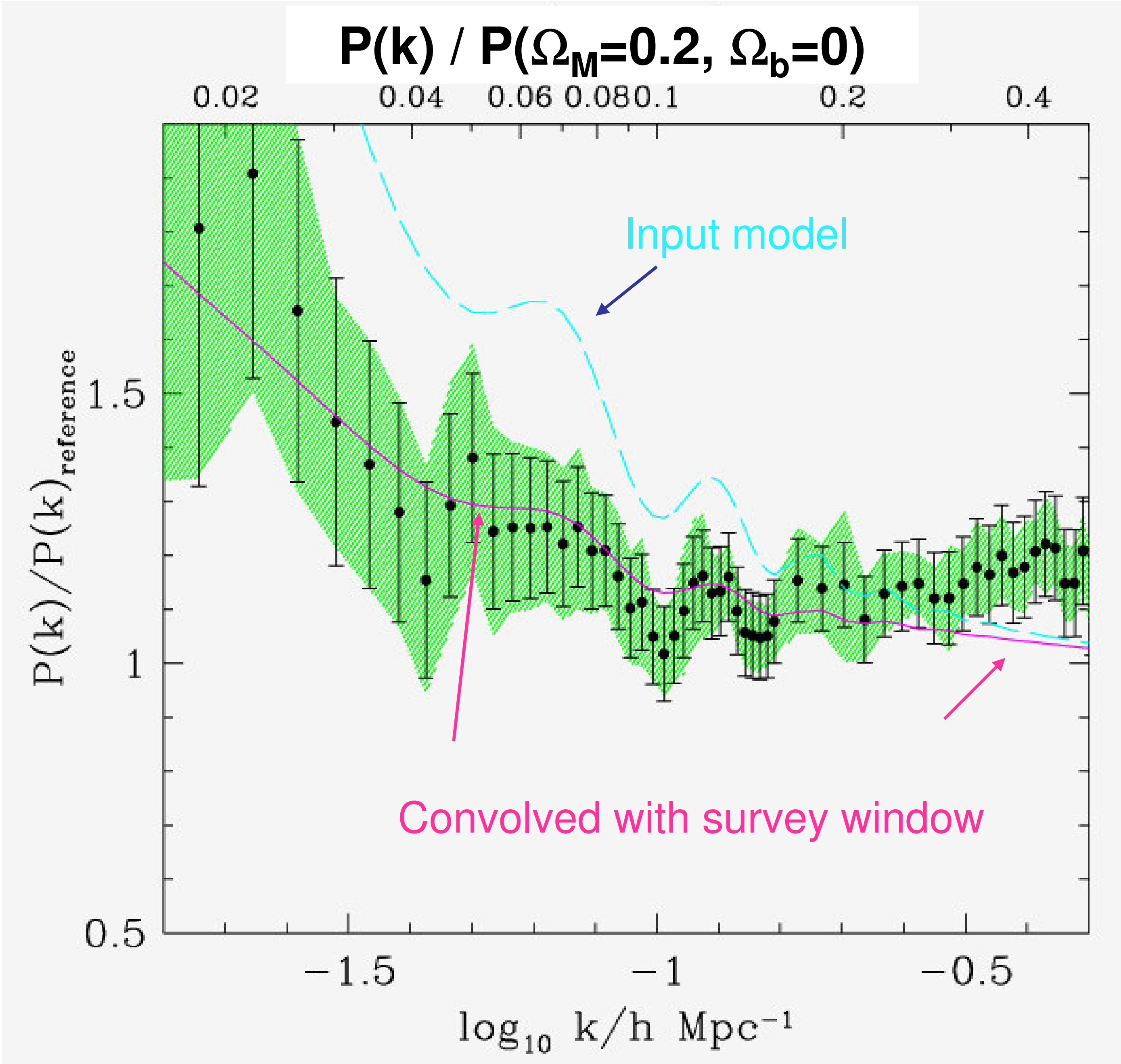
SDSS Luminous Red Galaxy Sample



Correlation function ξ(s) for SDSS LRG sample



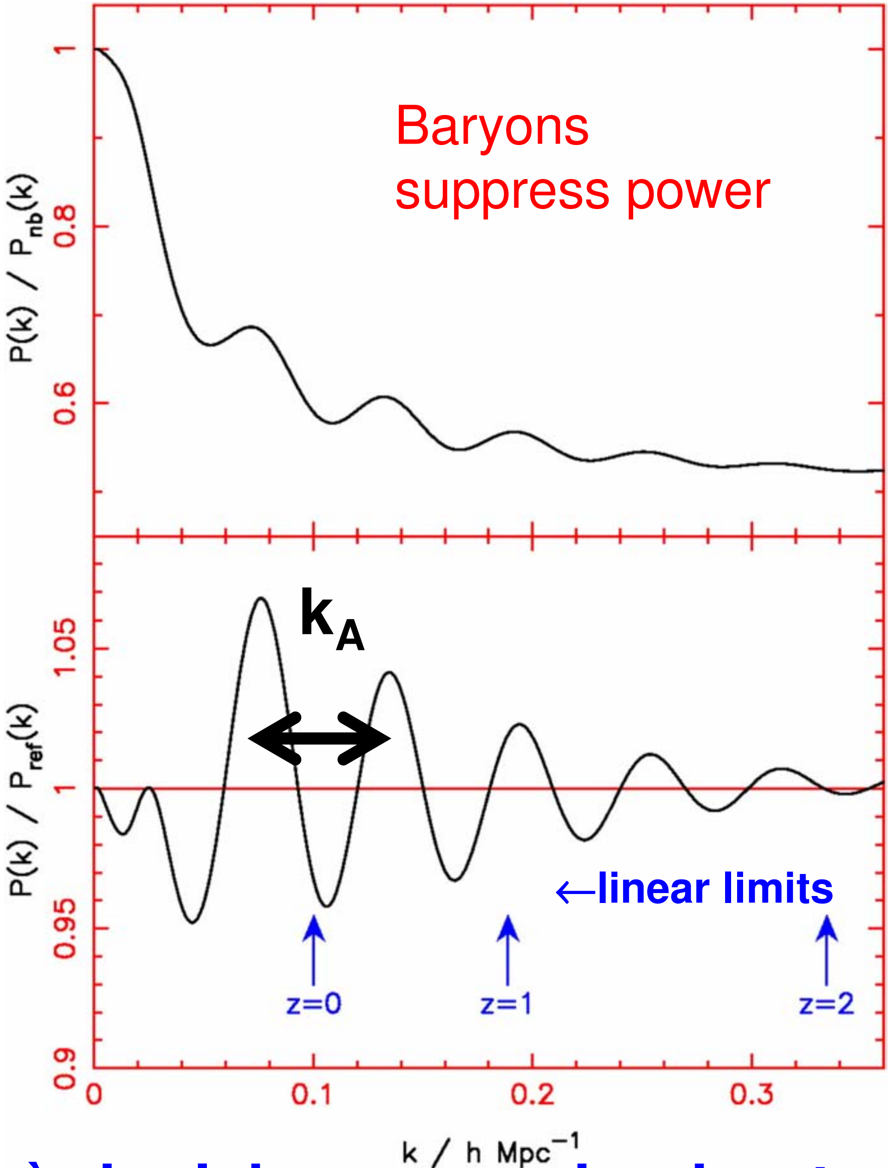
2dF Power Spectrum ÷ baryon-free version



Baryon Wiggles: how it works

$P(k)/P_{nb}(k)$

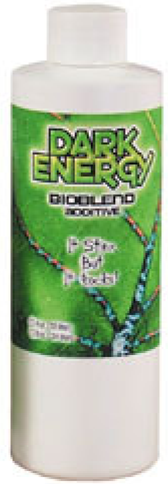
Divided by smooth fit



k_A is the "standard rod": a periodic feature in power spectrum

Must measure `wiggle' wavenumber k_A at various redshifts

Summary Lecture #3



- Dark energy is here to stay: it represents the new cosmological unknown
- Characterizing dark energy requires precise data at $z<3$; CMB measures will not be sufficient
- There is a sound incremental strategy: Is $w \neq -1$? $\rightarrow$ Is $w \neq$ const? $\rightarrow$ What is $w(z)$?
- Observers are promoting 3 probes: supernovae, weak lensing and big redshift surveys; probably need more than one method spanning $0<z<3$
- Observationally there are big technical challenges. It may take a long time but we will get there eventually!