Measurements of Dark Energy

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The Career Change Handbook

How to find out what you're good at and enjoy – then get someone to pay you for it

GRAHAM GREEN

Course Outline

- The **Framework** for inferring Dark Energy parameters from data
- **Type Ia Supernovae and the CMB**: expansion kinematics
- Other Geometric Tests: **Cluster Gas Fractions** and **BAO**
- Growth of Structure: the **Cluster Mass Function** and **Cosmic Shear**

Joint analysis of multiple datasets:
  Breaks **parameter degeneracies**
  Probes **systematic errors**
  Ends in **concordance**

The next decade: **experiments** and **questions**

Lecture 1

1) Gentle recap of basic cosmology – in terms of the framework actually in use by observers

2) Type Ia Supernovae – the simplest acceleration probe. How they are found and measured

3) Combining datasets: SNe complement the CMB

4) Some of the details of supernova cosmology, and where the field is going: questions to ask in the next decade

Source Materials

Papers, web resources cited throughout

Review by Frieman, Turner & Huterer (2008), ARAA
(plus lecture notes by Frieman based on this review)

Slide material adapted from:

Andy Howell (SNe)
Martin White (BAO, CMB)
David Schlegel (BAO)
Mike Jarvis (WL)
Steve Allen (CL)

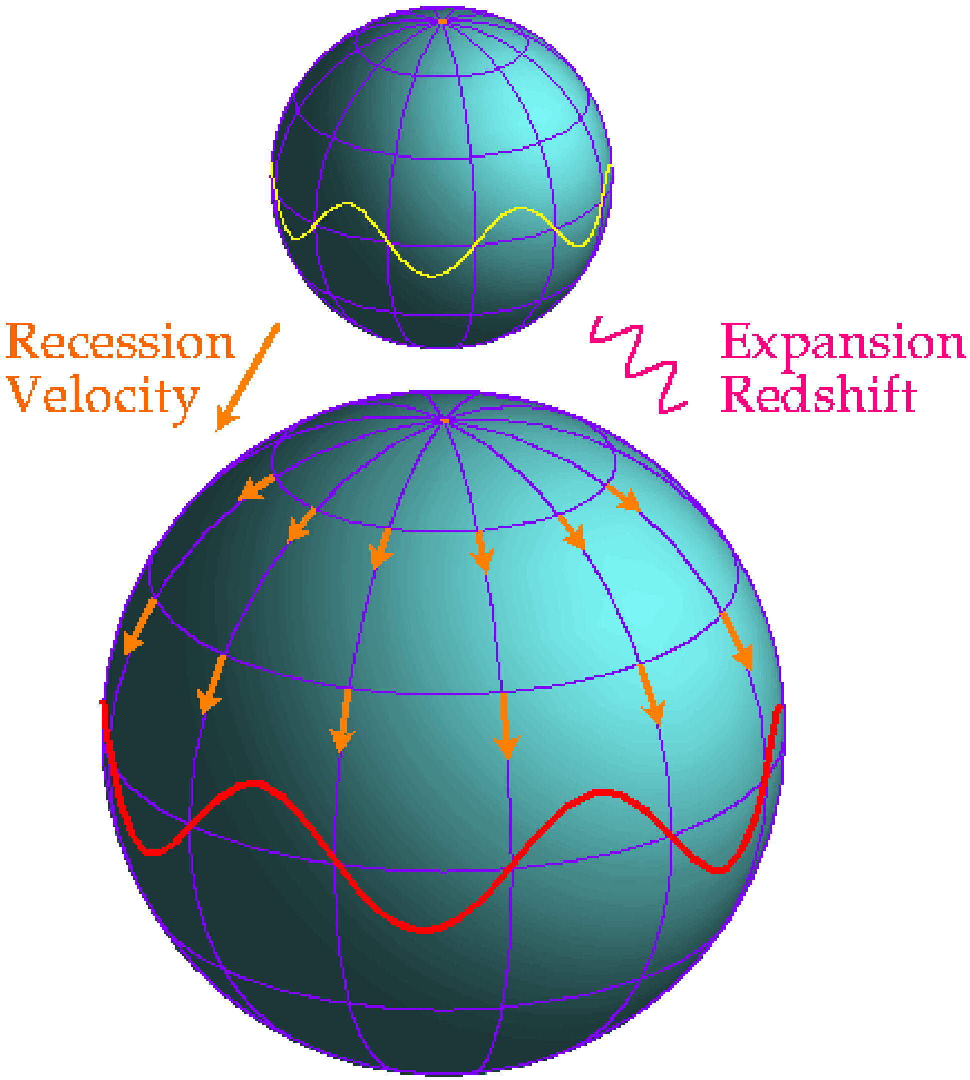
Part 1: Basic cosmology – for observers

Recap: Cosmological Dynamics

Cosmological principle: homogenous, isotropic universe whose expansion is described by a single function, the scale factor **a(t)**

a(t) describes the separation of galaxies in the past relative to their current separation

It applies to wavelengths as well: $\mathbf{a = 1/(1+z)}$
i.e.distant objects appear redshifted



GR: a theory for universal expansion

Einstein's equation(s) of General Relativity relate the curvature of (expanding) spacetime to the density and pressure of its contents:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} \boxed{T_{\mu\nu}}$$

Einstein curvature tensor

Stress-energy tensor – includes matter, radiation, everything...

Zel'dovich interpretation has become standard - but is vacuum energy the whole story?

"Dark Energy" (Turner & Huterer 1998)

What is this "Dark Energy"?

“Dark energy appears to be the dominant component of the physical Universe, yet there is no persuasive theoretical explanation for its existence or magnitude.”

“...the observed phenomenon that most directly demonstrates that our theories of fundamental particles and gravity are either incorrect or incomplete.”

“...nothing short of a revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration.”

“The nature of dark energy ranks among the very most compelling of all outstanding problems in physical science. These circumstances *demand an ambitious observational program to determine the dark energy properties as well as possible.*”

Albrecht et al 2006 DETF report

What is this "Dark Energy"?

Is it vacuum energy? Or quintessence, a new scalar field?
Or modified gravity (but not the simplest kind)?

Our best approach experimentally is to measure what we can as well as we can, and interpret it within some basic framework

- **"Dark Energy"**
- **Cosmological Dynamics**
- **Expansion phenomenology**

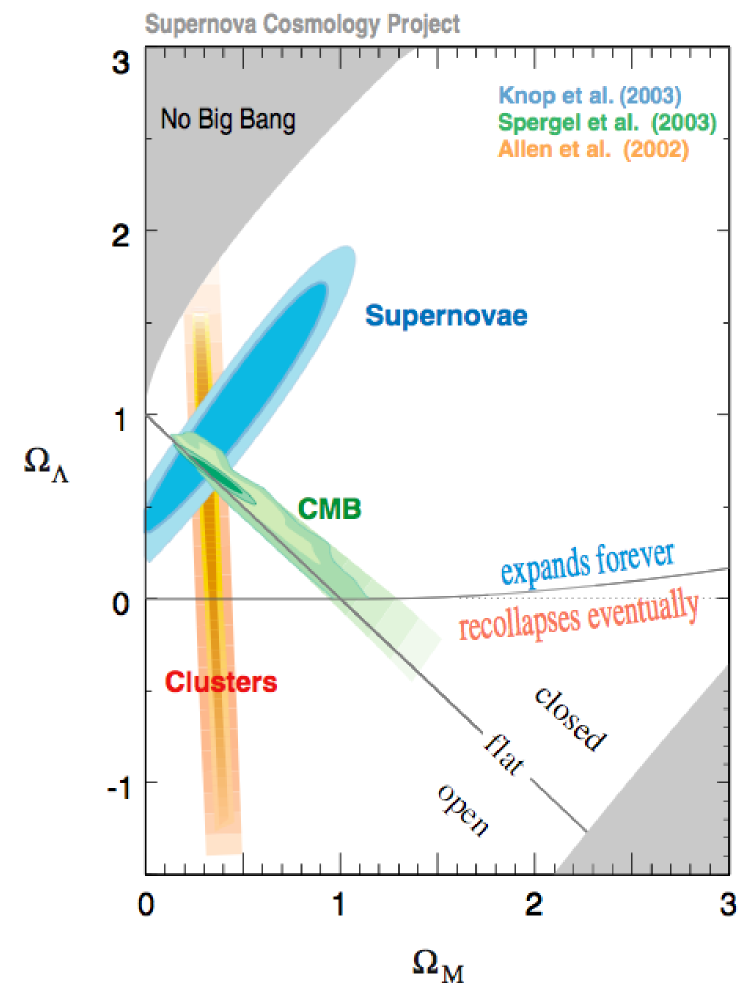
Does the lack of a theory affect the observational programs?

What is this "Dark Energy"?

In the absence of a compelling theory, observations drive progress
- this is more or less the typical situation in astronomy

Task for observers is to
present inferences from new data in a reusable form

Likelihood functions should encapsulate all relevant information including data, and
assumptions about the data model:



L = Pr (data | model(parameters), assumptions)

Our chosen basic framework

In an isotropic, homogeneous universe, Einstein's equations reduce to the **Friedmann equations:**

Hubble function

$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \boxed{H^2(t)} = \frac{8\pi G}{3}\sum_i \rho_i(t) - \frac{\boxed{k}}{a^2(t)}$$

Dimensionless curvature radius, flat geometry = 0

$$\frac{1}{a}\frac{d^2a}{dt^2} = -\frac{4\pi G}{3}\boxed{\sum_i (\rho_i + 3P_i/c^2)}$$

GR: gravitating energy density includes pressure

Each component has an **equation of state** relating pressure to energy density:

$$P_{\mathrm{m}} = 0$$ matter, w = 0

$$P_{\mathrm{R}} = \frac{1}{3}\rho_{\mathrm{R}}c^2$$ radiation, w = 1/3

$$P_{\mathrm{X}} = w(a)\rho_{\mathrm{X}}c^2$$ dark energy, w(a) = ?

Our chosen basic framework

Friedmann equations imply a continuity condition that tells us how the different components' density varies during the expansion:

internal energy

"work"

$$\frac{d}{da}(\rho_i c^2 V) = -P_i \frac{dV}{da}$$

$$\longrightarrow \frac{d\rho_i}{da} = -\frac{3\rho_i}{a}(1+w_i)$$

density evolution

We can write all densities in terms of a critical density:

$$\rho_m = \Omega_{\rm m}\rho_{\rm crit}a^{-3}, \rho_R = \Omega_{\rm R}\rho_{\rm crit}a^{-4},$$

$$\rho_X = \Omega_{\rm X}\rho_{\rm crit}\exp\left[3\int_{\log a}^{0}\boxed{(1+w)}\,d\log a\right]$$

Ω parameters are present-day (a=1) densities, in units of the critical density

w = -1 is special: density is constant regardless of expansion scale

Our chosen basic framework

The 1st Friedmann equation now looks like this:

$$H^2(a) = H_0^2 \left(\Omega_\mathrm{m} a^{-3} + \Omega_\mathrm{X} \exp\left[3 \int_{\log a}^{0} (1+w) d \log a \right] + \Omega_\mathrm{k} a^{-2} \right)$$

i.e. given parameters, expansion history a(t) can be solved for and plotted

where the radiation term has been ignored, and we've chosen the critical density to be

$$\rho_\mathrm{crit} = \frac{3H_0^2}{8\pi G} = 2.78 \times 10^{11} h^2 M_\odot Mpc^{-3}$$

One small galaxy per cubic Mpc - space is very empty

Note that this choice gives us

$$\Omega_\mathrm{k} = 1 - (\Omega_\mathrm{m} + \Omega_\mathrm{X})$$

i.e. matter (and energy) tells space how to curve

NB. Closed geometry, k = +1, has curvature density parameter < 0

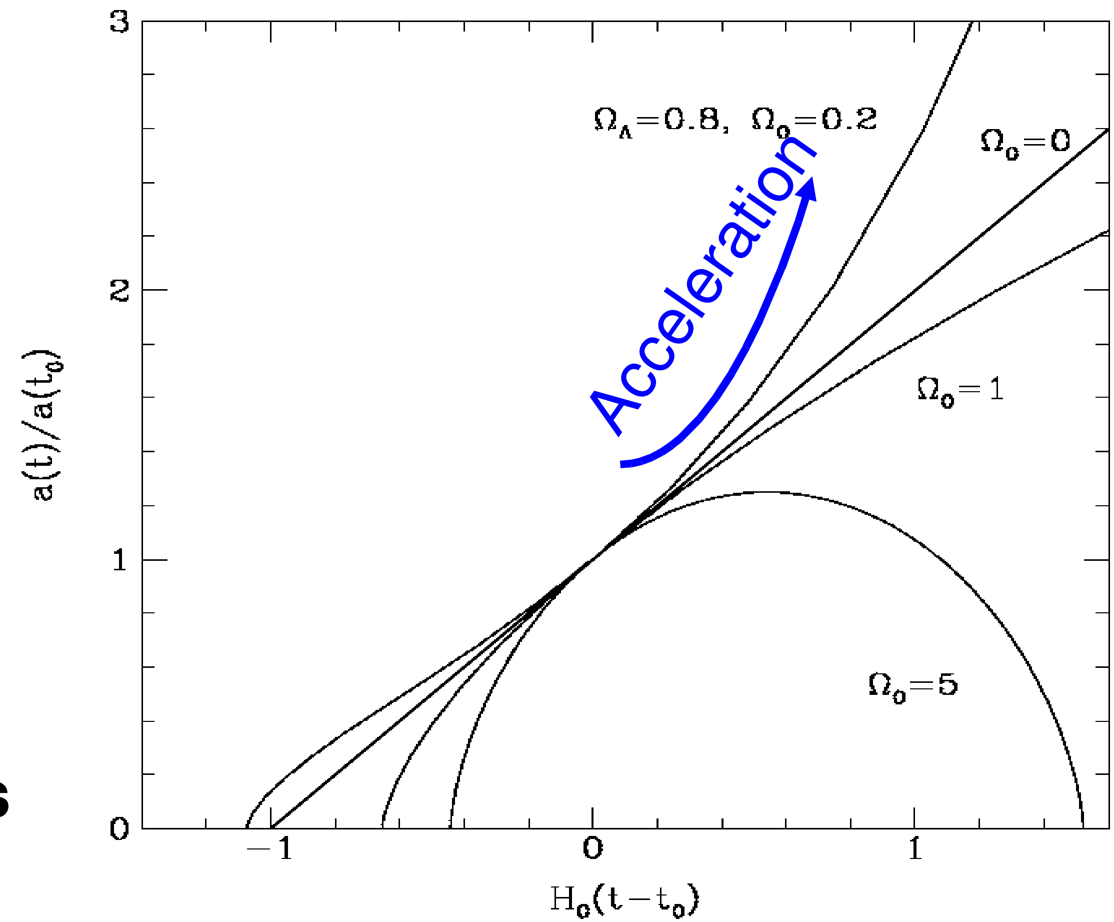
Cosmological Dynamics

Assuming an homogenous, isotropic universe whose expansion is described by a single function, the scale factor **a(t)**

We can use the Hubble function H(z) to calculate the scale factor and everything that depends on it,

predict observables,

and hence
infer the values of the "dark energy" parameters that govern the scale factor



Part 2: Type Ia Supernovae

Type Ia Supernovae

Measuring the distance to an object, and comparing with the standard model prediction for it given its redshift z where a = 1/(1+z), is the *simplest possible cosmological test*

a "kinematic probe"

In 1998, 2 groups announced they had detected **cosmic acceleration** exactly this way, using samples of Type Ia supernovae

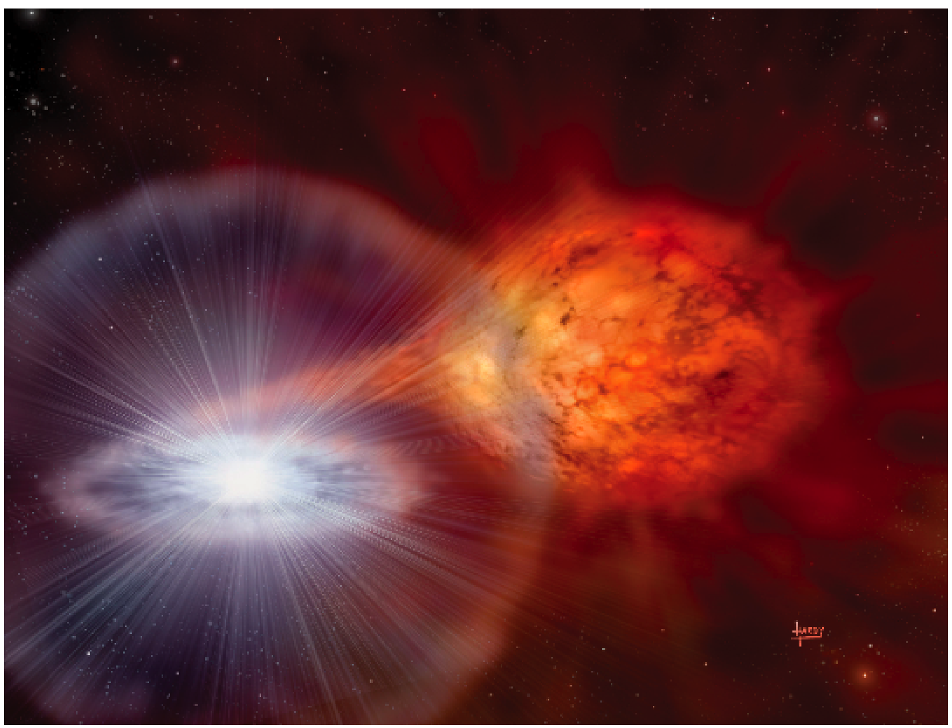
Why does SN cosmology work?

What do you have to do to make it work?

Type Ia Supernovae

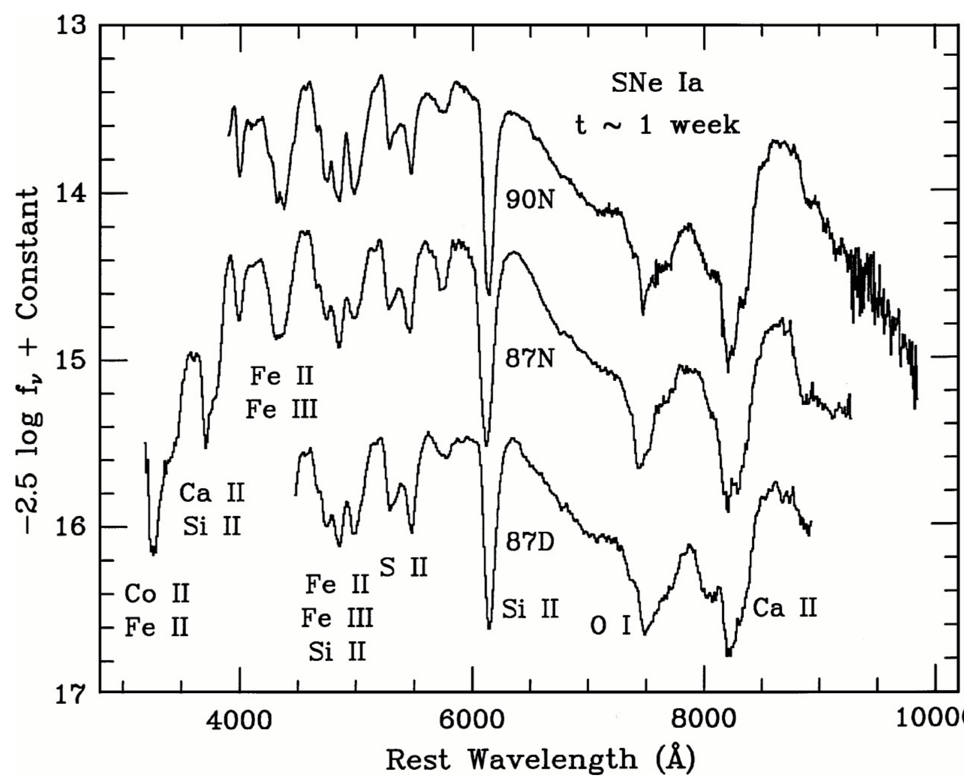
White dwarfs in close binaries accrete matter from their companions - when M ~ M_{ch}, WD becomes unstable: thermonuclear explosion releases ~0.6 M_o radioactive Nickel, whose decays are seen in the optical

Detailed physics of explosion seem unimportant...



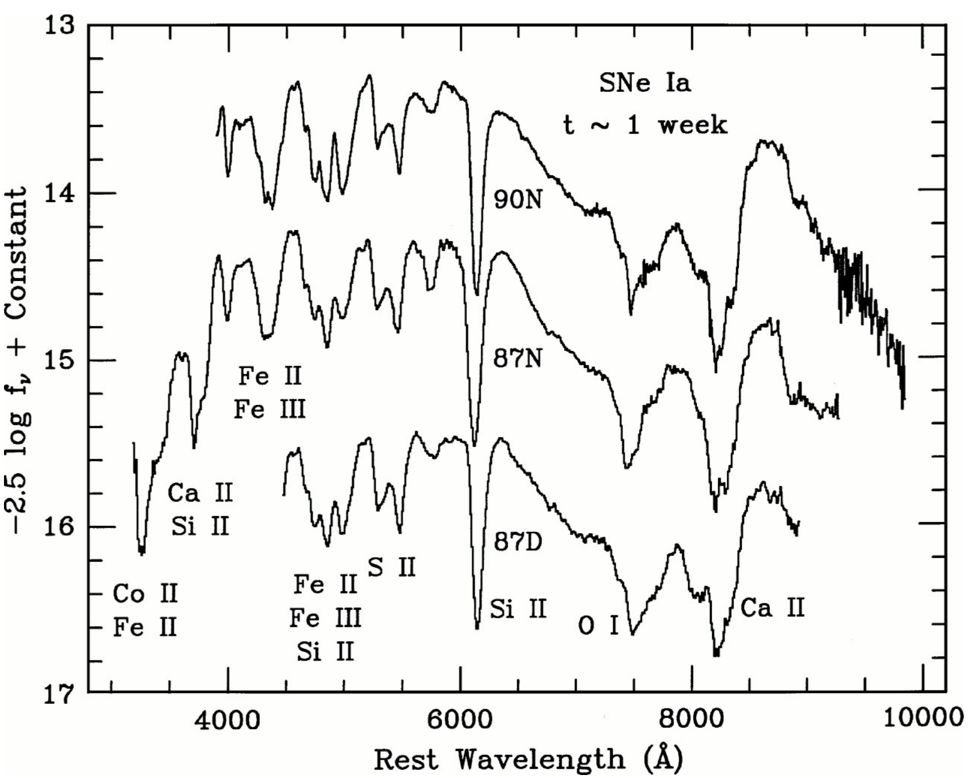
Artist's rendition of a white dwarf accumulating mass from a nearby companion star. This type of progenitor system would be considered singly-degenerate.

Image courtesy of David A. Hardy, © David A. Hardy/www.astroart.org.

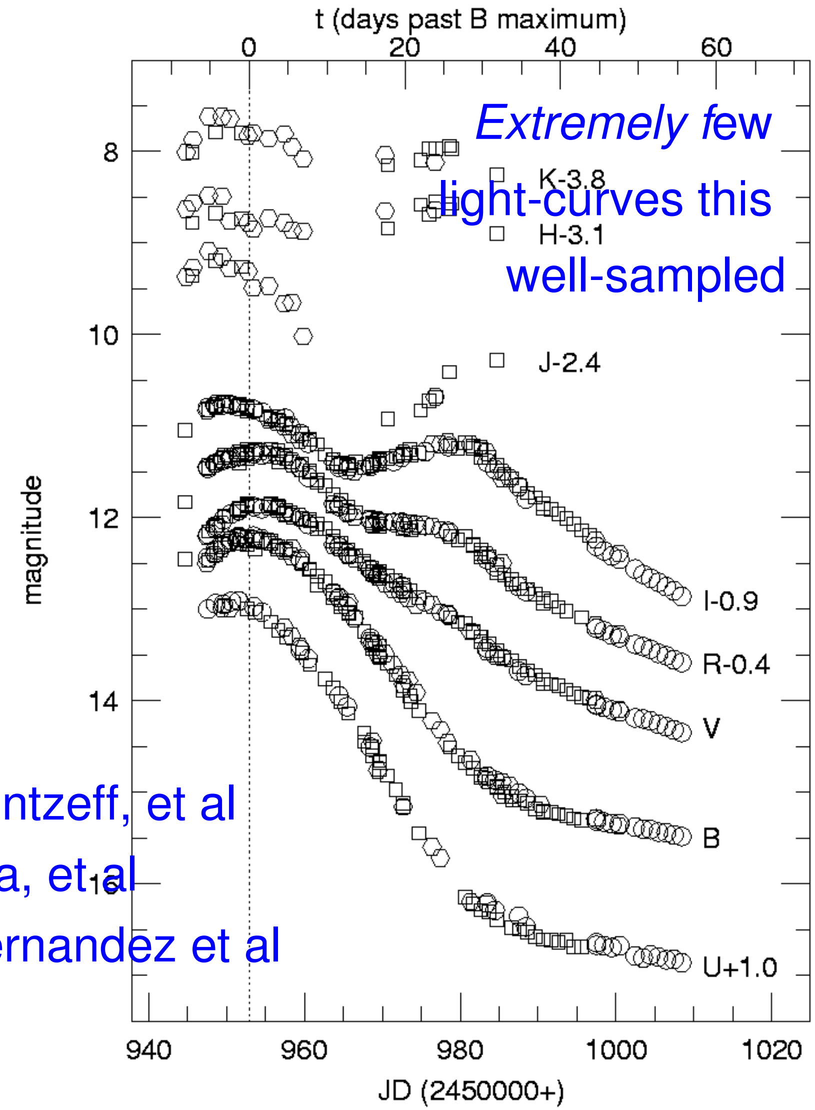


Type Ia Supernovae

- Remarkably uniform class of objects: spectra, lightcurves, luminosities, colors
- Identified by their silicon spectral absorption features
- 15-20 days to reach peak brightness,
  ~months to decay
- Found in all types of galaxies -
  including old ellipticals
- Can outshine their hosts (esp at high z)



Nearby SN1998bu



Extremely few light-curves this well-sampled

Suntzeff, et al
Jha, et al
Hernandez et al

Type Ia Supernova

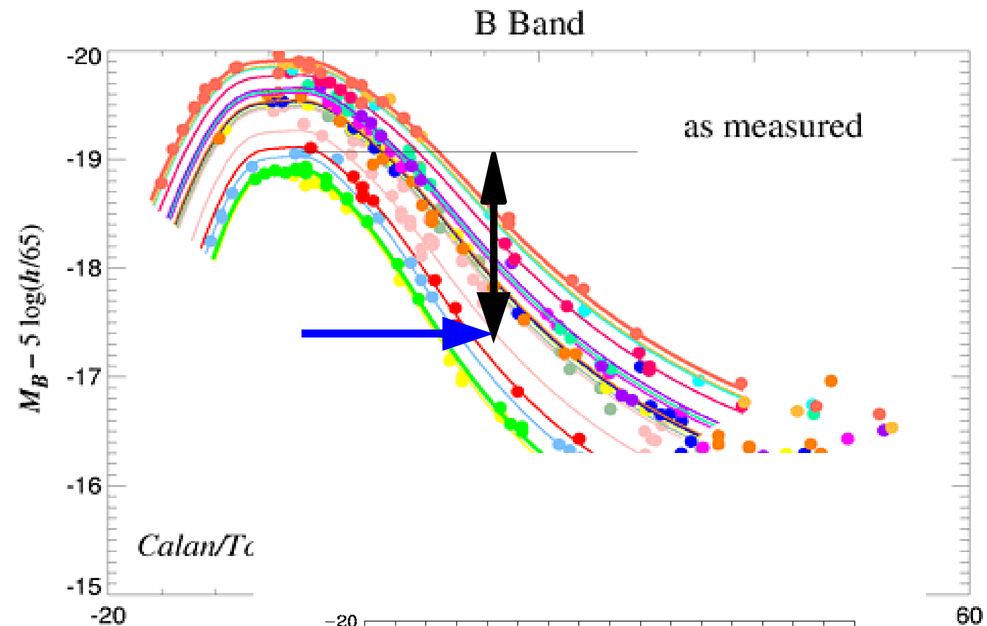
Nearby supernovae -
how similar in luminosity?

Absolute magnitude:
$M = -2.5 \log L + \text{const}$
Apparent magnitude:
$m = -2.5 \log F + m0$

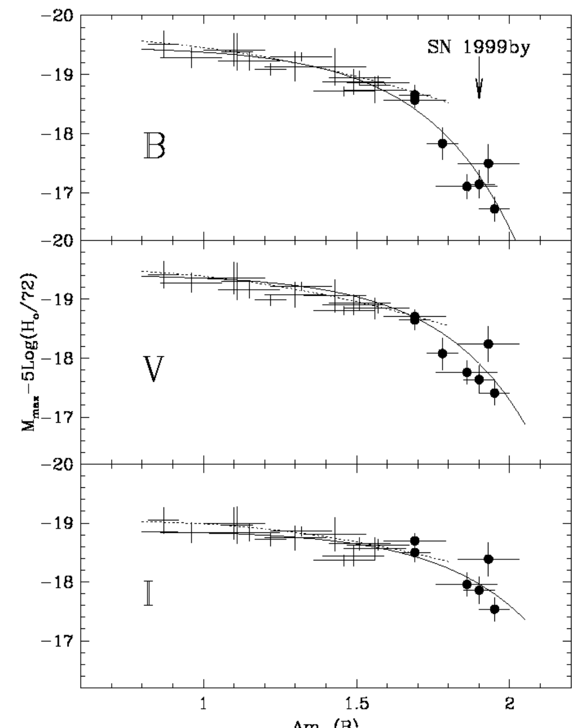
Absolute magnitudes have ~1 mag scatter (factor of 2.5 in L)

Bright SNe Ia decay more slowly (Phillips 1993)

Fit Δm_{15} or “stretch" s of time axis as function of SN luminosity



M_B



Dm_{15}

Type Ia Supernova

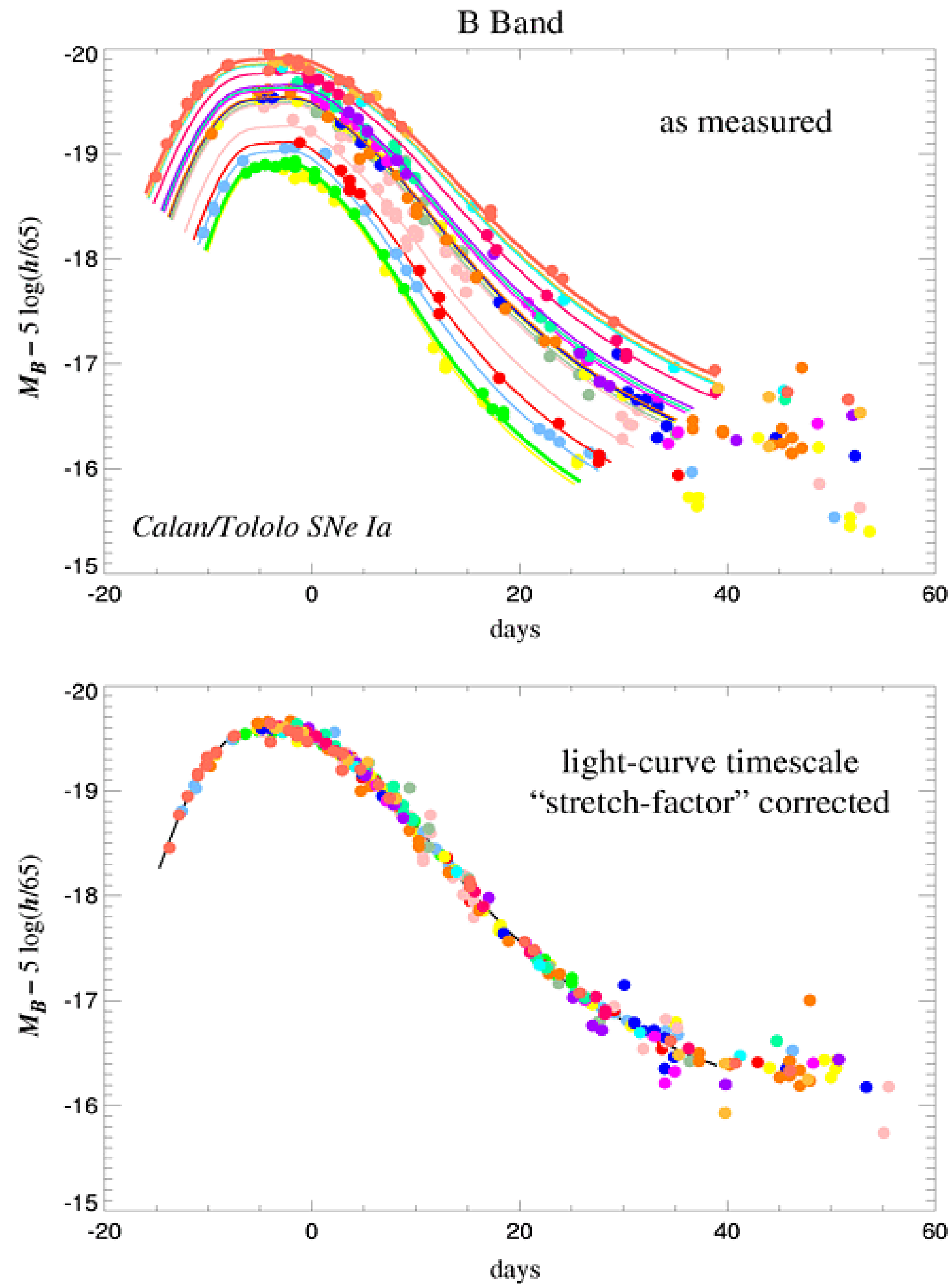
Nearby supernovae - how similar in luminosity?

Absolute magnitude:
$M = -2.5 \log L + \text{const}$
Apparent magnitude:
$m = -2.5 \log F + m0$

Absolute magnitudes have ~1 mag scatter (factor of 2.5 in L)

Bright SNe Ia decay more slowly (Phillips 1993)

Corrected SN magnitudes have ~15% scatter



Kim, *et al.* (1997)

Type Ia Supernovae

Nearby supernovae are
standardizable candles

Find them at high-z,
and plot m vs z

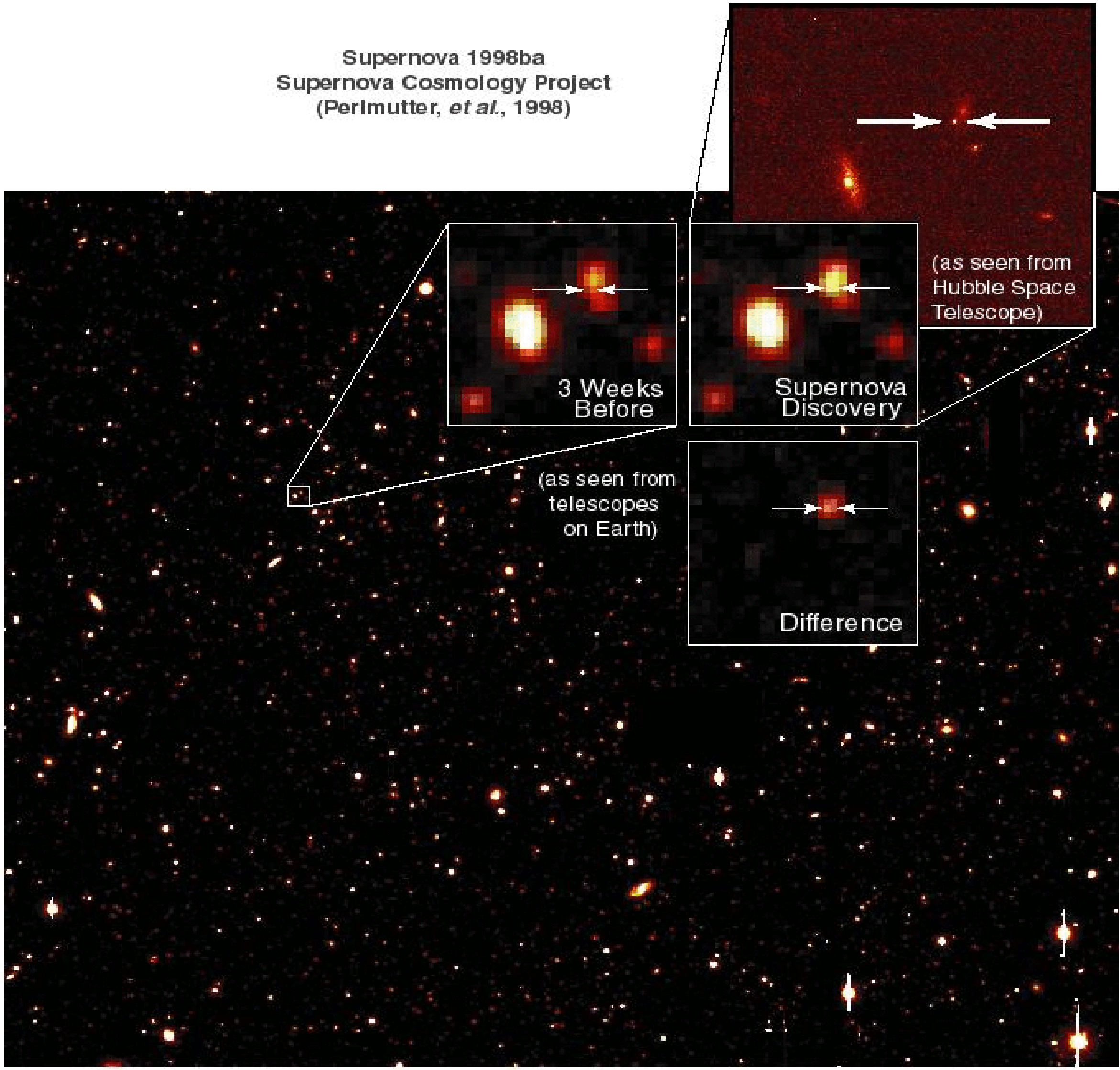
m and z are related by the "luminosity distance" to the SNe - since they all have the same L

$$F \sim L / D^2$$

$$m - M = 5 \log_{10} D - 25$$

Nearby SNe came from monitoring nearby galaxies

High z SNe come from monitoring "blank fields"



Type Ia Supernovae

Nearby supernovae are *standardizable candles*

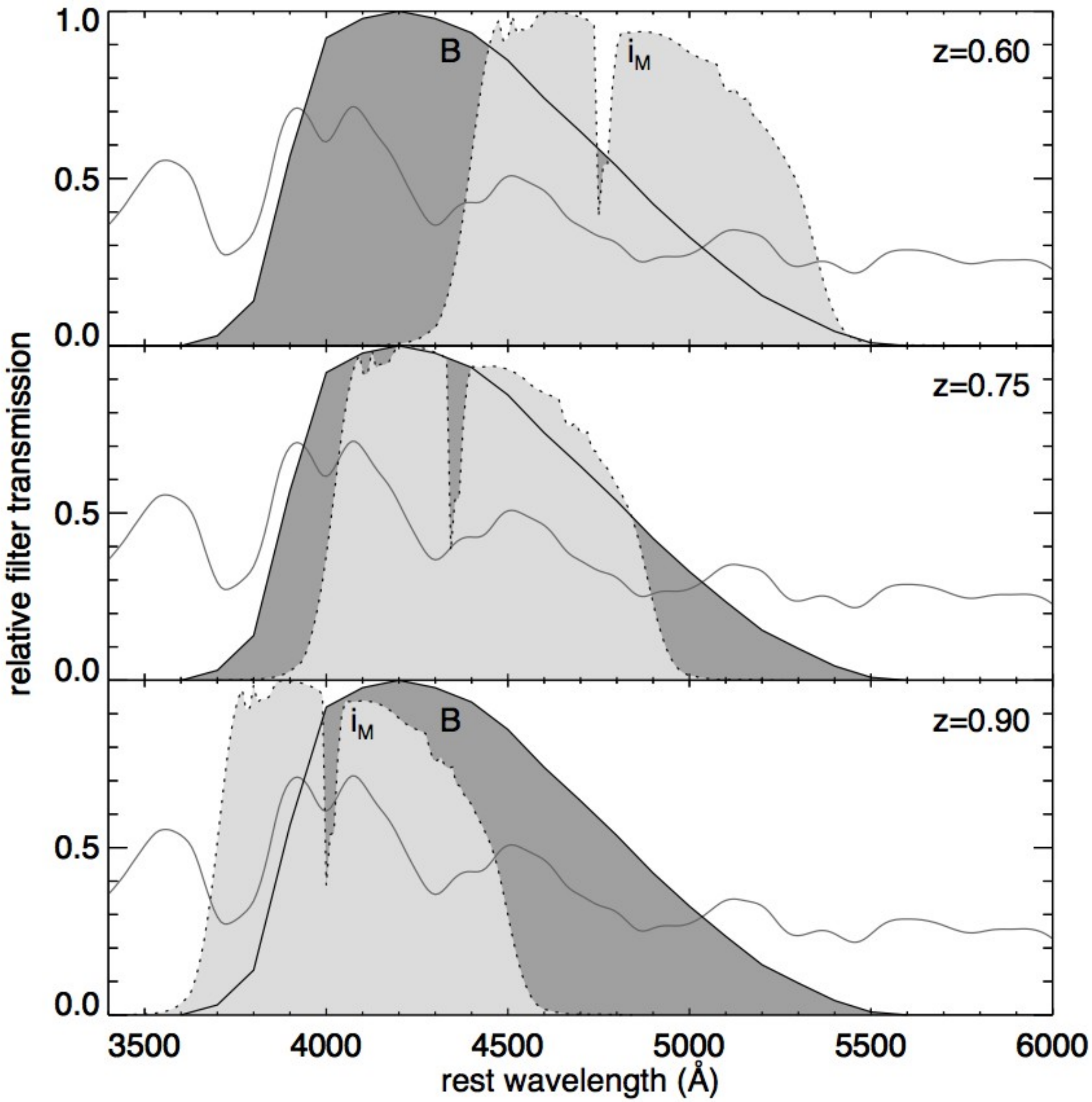
Find them at high-z, **and plot m vs z**

m and z are related by the "luminosity distance" to the SNe - since they all have the same L

$$F \sim L / D^2$$

$$m - M = 5 \log_{10} D - 25$$

K-correction: need to compare (eg) rest-frame B-band magnitudes for all objects



Type Ia Supernovae

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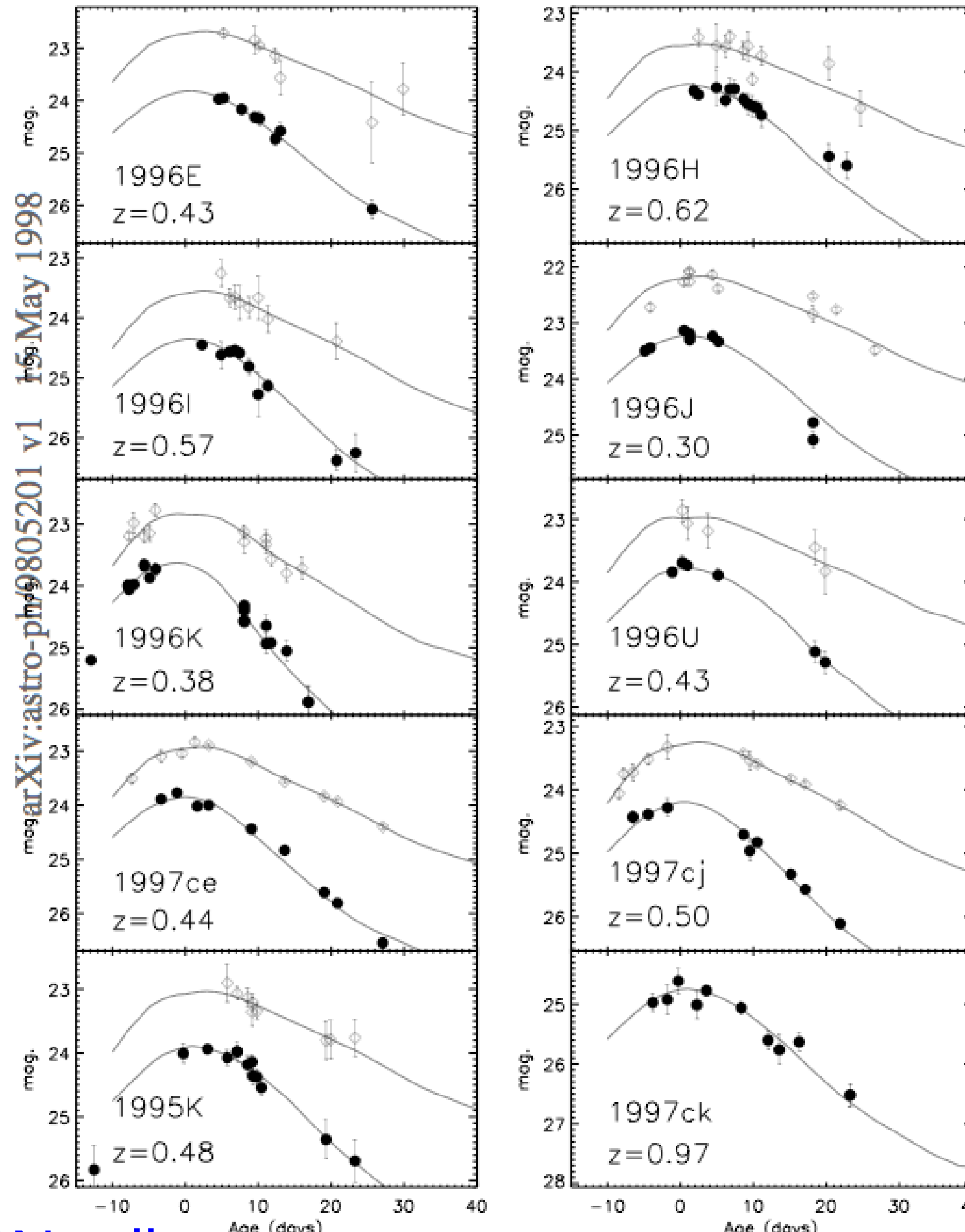


High-z SNe discovery data Riess et al

Type Ia Supernovae

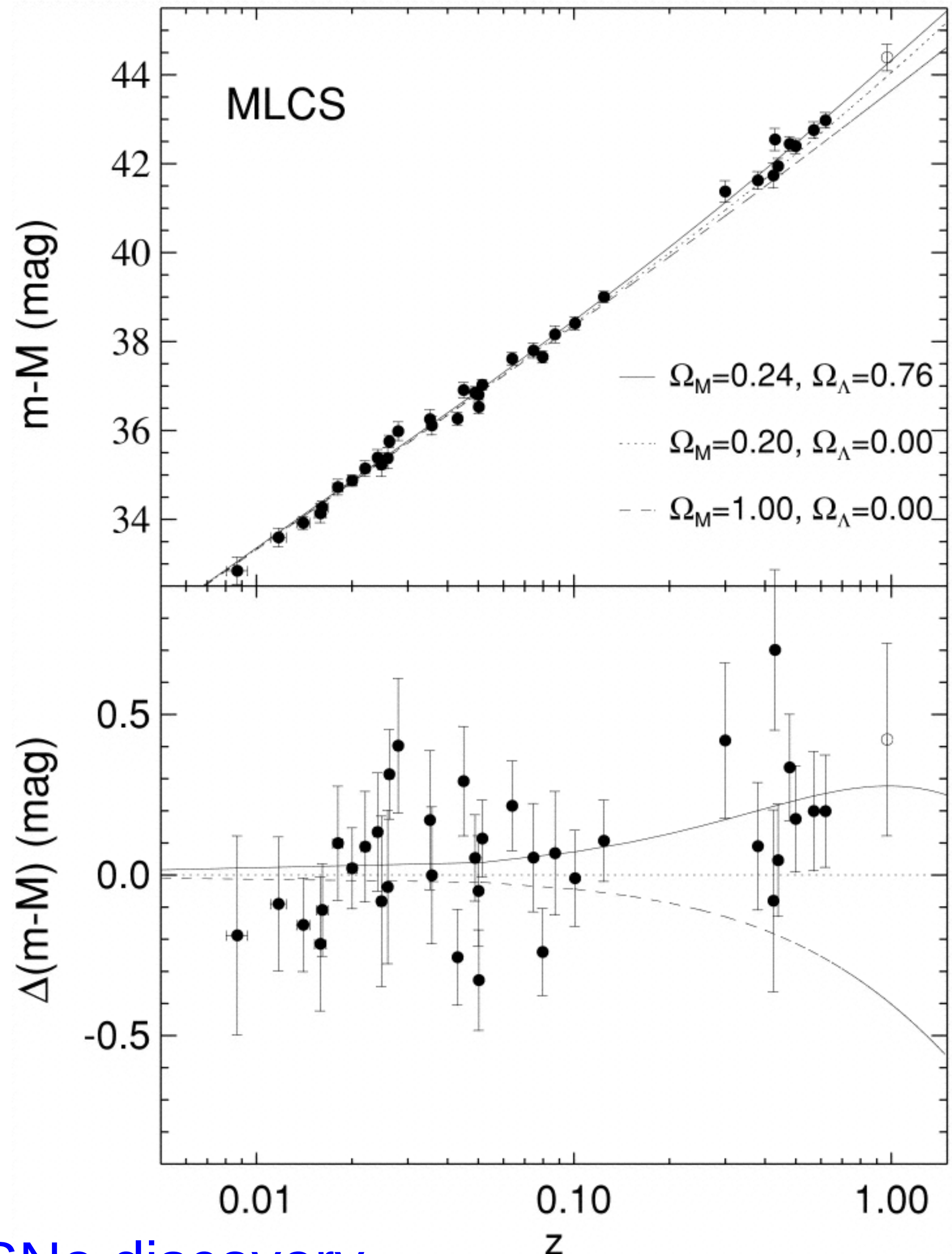
Nearby supernovae are *standardizable candles*

Find them at high-z, and plot m vs z

m and z are related by the "luminosity distance" to the SNe - since they all have the same L

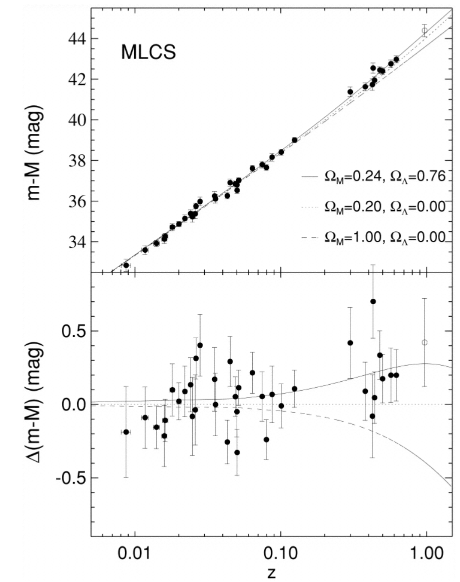
$$m - M = 5 \log_{10} D - 25$$

The modern Hubble diagram



High-z SNe discovery data Riess et al

Inferring cosmological parameters



Have a noisy corrected peak magnitude for each SN,

$$m_\mathrm{B}$$

and a prediction of the same thing:

$$m_\mathrm{B}^p = M_\mathrm{B} + 5\log_{10}\left(\frac{D_L}{\mathrm{Mpc}}\right) - 25$$

Assuming Gaussian noise, write the likelihood as:

$$\begin{aligned}\mathcal{L} &= \Pr(\{m_\mathrm{B}, z\}|\Omega_\mathrm{m}, \Omega_\mathrm{X}, \ldots) \\ &= \prod_i \Pr(m_{\mathrm{B},i}, z_i|\Omega_\mathrm{m}, \Omega_\mathrm{X}, \ldots) \\ &\propto \exp\left[-\sum_i \left(\frac{m_{\mathrm{B},i} - m^p_{\mathrm{B},i}(z_i, \Omega_\mathrm{m}, \Omega_\mathrm{X}, \ldots)}{2\sigma_i^2}\right)\right]\end{aligned}$$

$$\boxed{D_L = D_L(z, H_0, \Omega_\mathrm{m}, \Omega_\mathrm{X}, \ldots)}$$

For each SN, we can predict its distance given its redshift and some choice of cosmological parameters

Multiply by prior PDF to get posterior PDF for parameters:

$$\Pr(\Omega_\mathrm{m}, \Omega_\mathrm{X}, \ldots|\{m_\mathrm{B}, z\}) \propto \Pr(\{m_\mathrm{B}, z\}|\Omega_\mathrm{m}, \Omega_\mathrm{X}, \ldots)\Pr(\Omega_\mathrm{m}, \Omega_\mathrm{X}, \ldots)$$

Cosmological Distances

FRW metric describes space-time - light rays have ds = 0:

$$ds^2 = (cdt)^2 - a^2(t)\left[dr^2 + S_k^2(r)(d\theta^2 + \sin^2(\theta)d\phi^2)\right]$$

$S_k(r) = \sin(r),\ r,\ \sinh(r)\ \text{ for }\ k = 1,\ 0,\ -1$

So, co-moving coordinate distance r is:

$$cdt = a(t)dr \longrightarrow r = \int_0^z \frac{cdz}{H(z)}$$

cosmological parameters

Rod of some length appears to have some angular size - need to consider light rays emitted at time t:

$$\Delta x = a(t)S_k(r)\Delta\theta$$

$$\begin{aligned} D_A &= D_A(z, H_0, \Omega_{\mathrm{m}}, \Omega_{\mathrm{X}}, \ldots) \\ &= \frac{S_k(r)}{(1+z)} \end{aligned}$$

Source luminosity is spread over sphere of some angular diameter distance - but emission rate and redshift reduce power received:

$$\begin{aligned} D_L &= D_L(z, H_0, \Omega_{\mathrm{m}}, \Omega_{\mathrm{X}}, \ldots) \\ &= (1+z)^2 D_A \end{aligned}$$

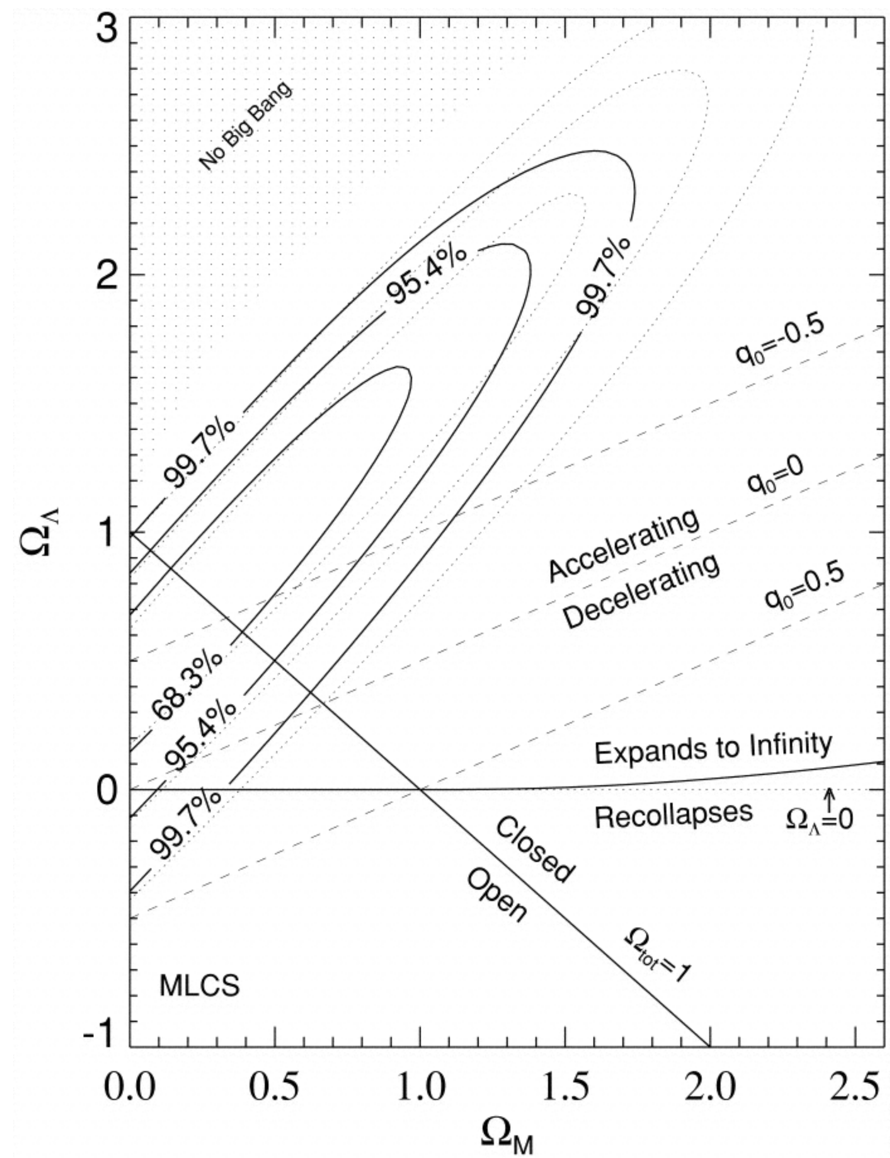
Inferring cosmological parameters

Things to notice:

• Hubble's constant and the mean SN luminosity are degenerate - you cannot infer each separately from these data alone

• With only 3 parameters, the PDF could be computed on a fine grid, marginalisation of M (or H) could be done by simple numerical integration (not true later...)

• A universe with matter density 0.2 and no DE lies just outside the 95% confidence region - but Pr(acceleration) = 99.6%



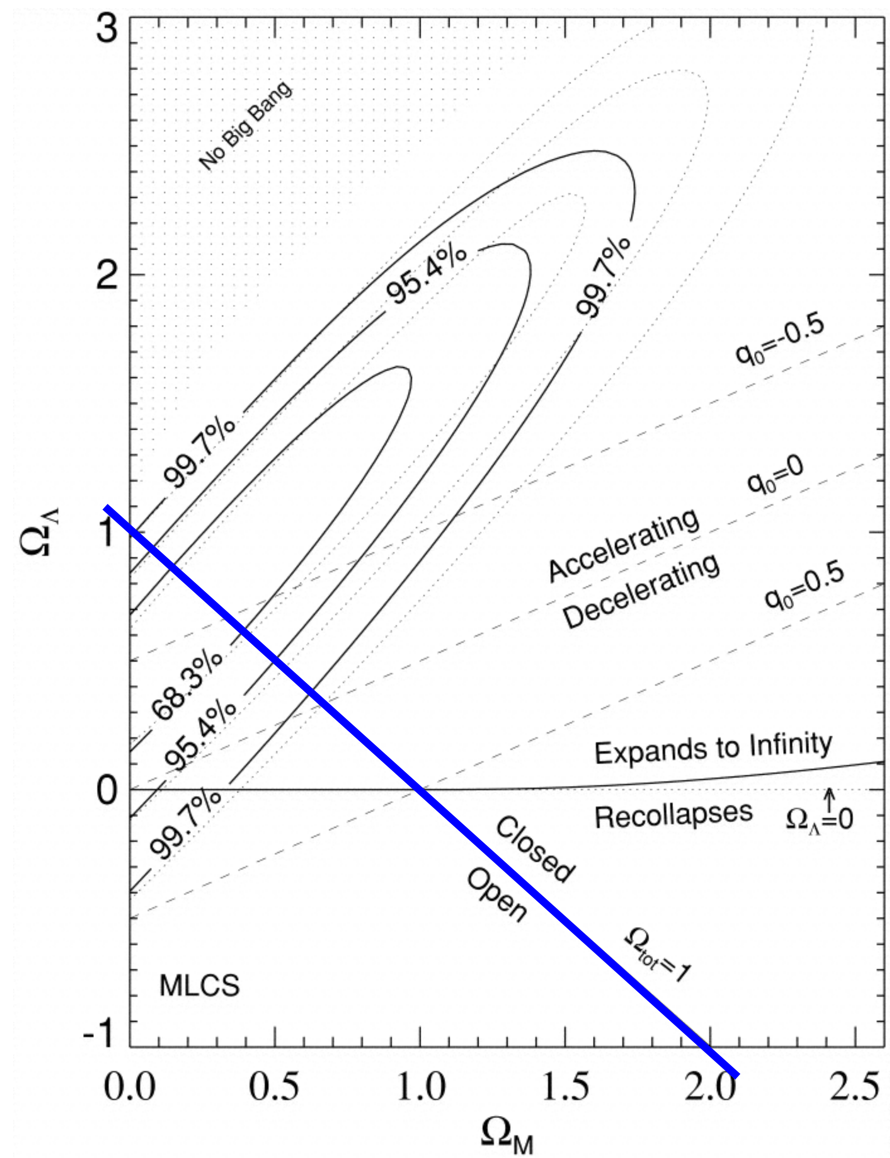
$$\Pr(\Omega_\mathrm{m}, \Omega_\mathrm{X} | \{m_\mathrm{B}, z\}) = \int \Pr(\Omega_\mathrm{m}, \Omega_\mathrm{X}, \mathcal{M} | \{m_\mathrm{B}, z\}) d\mathcal{M}$$

Breaking degeneracies

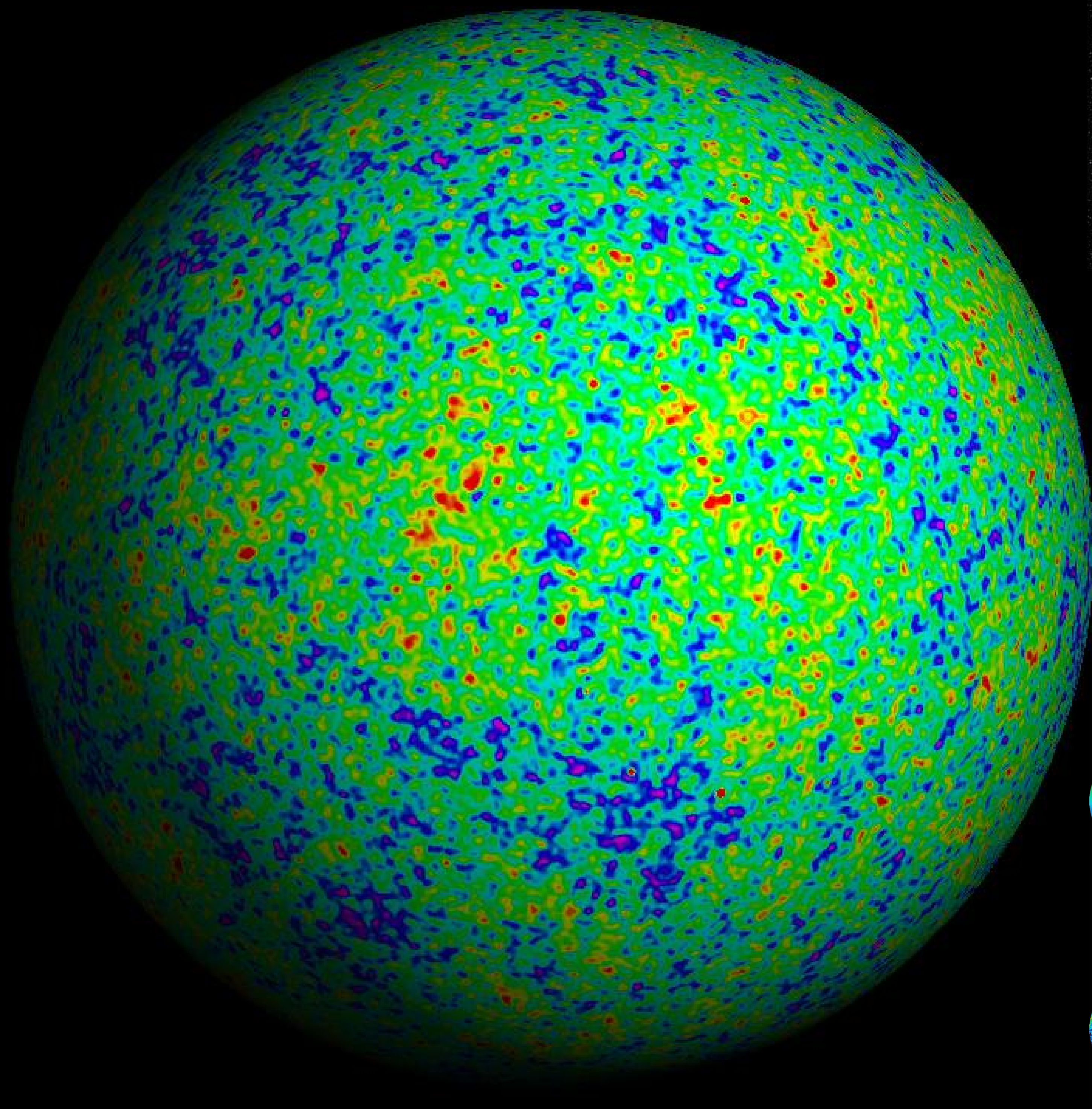
1998 SNe (Riess et al, Perlmutter et al) were important because they detected acceleration - enough to motivate even the simplest dark energy scenario (vacuum energy)

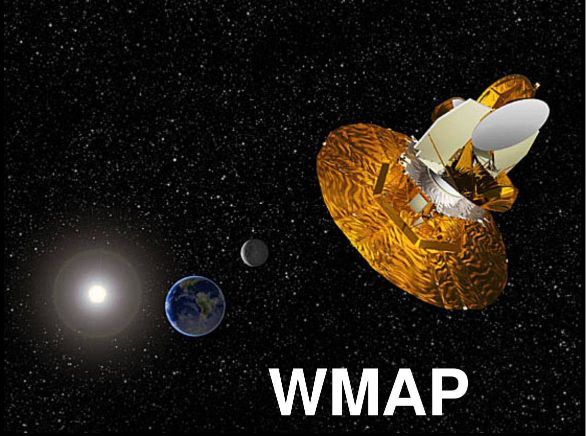
Quantifying the dark energy began with the assumption of flat geometry - later to be replaced at lower precision by combination with the CMB

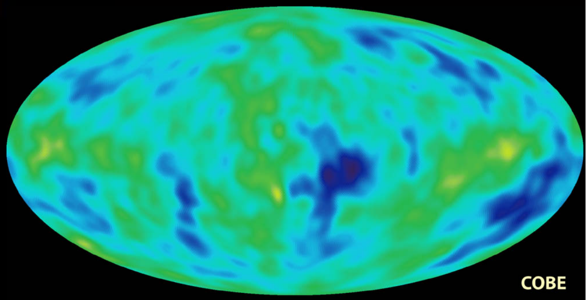
Skip forward to the present day - what do we know about flatness now?

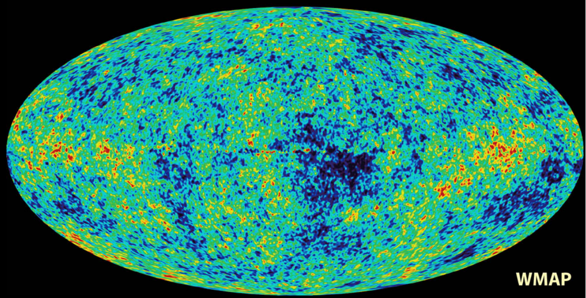


Part 3: Combining with the CMB




WMAP


COBE


WMAP

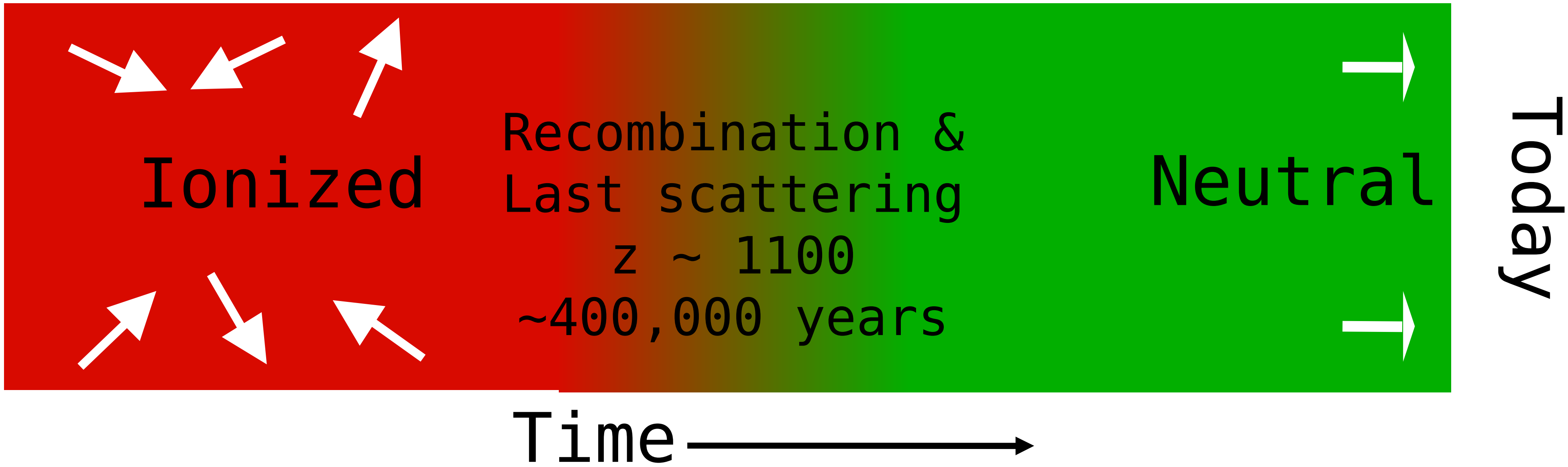
CMB: Sound Waves in the Early Universe

Before recombination:

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Photon-baryon perturbations oscillate as acoustic waves.

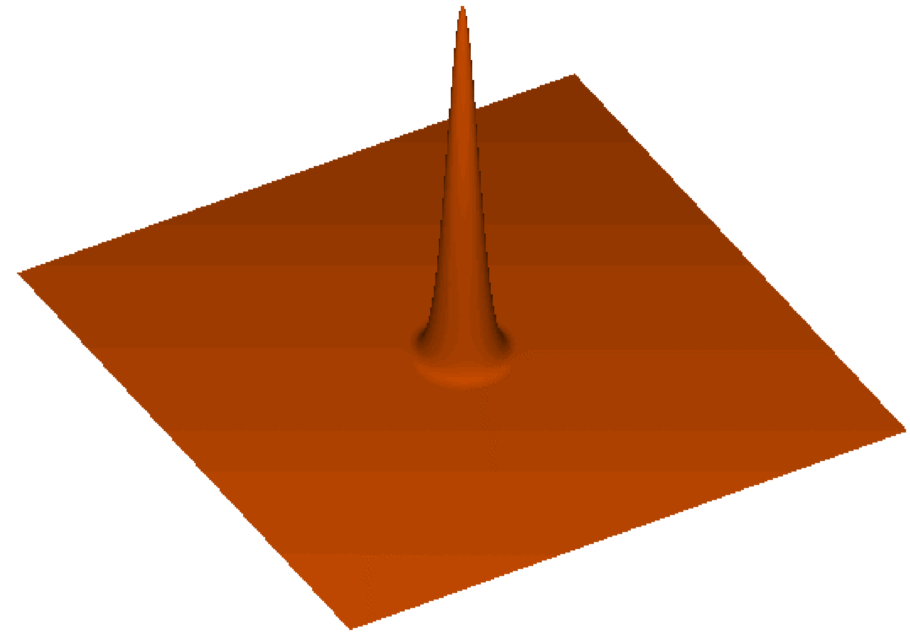
After recombination:

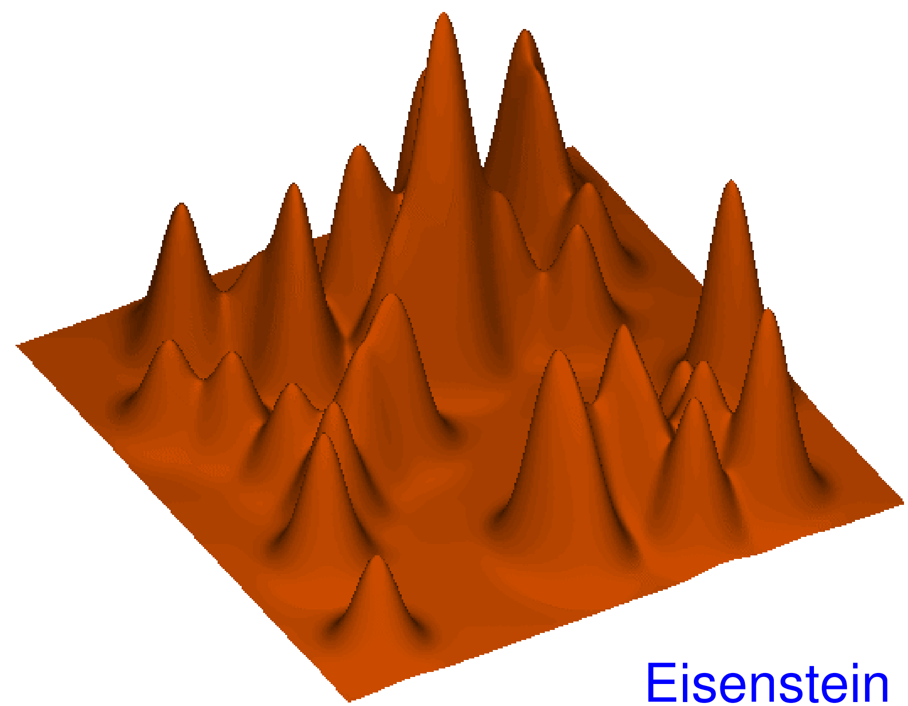
- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at t_{rec} determines late-time amplitude.



Sound Waves

- Each initial overdensity (in dark matter & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at the sound speed c_s-
  57% of the speed of light.
- Pressure-providing photons decouple at recombination - CMB radiation travels to us from these spheres.
- There is a maximum distance travellable by each wave, corresponding (roughly) to c_s times the age of the universe at last scattering: the sound horizon

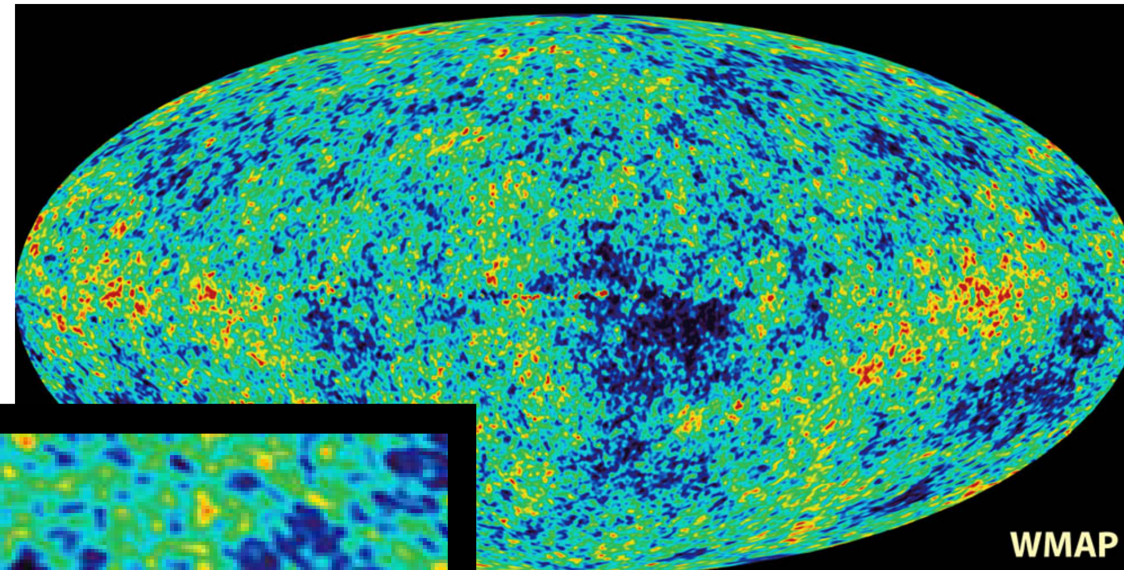


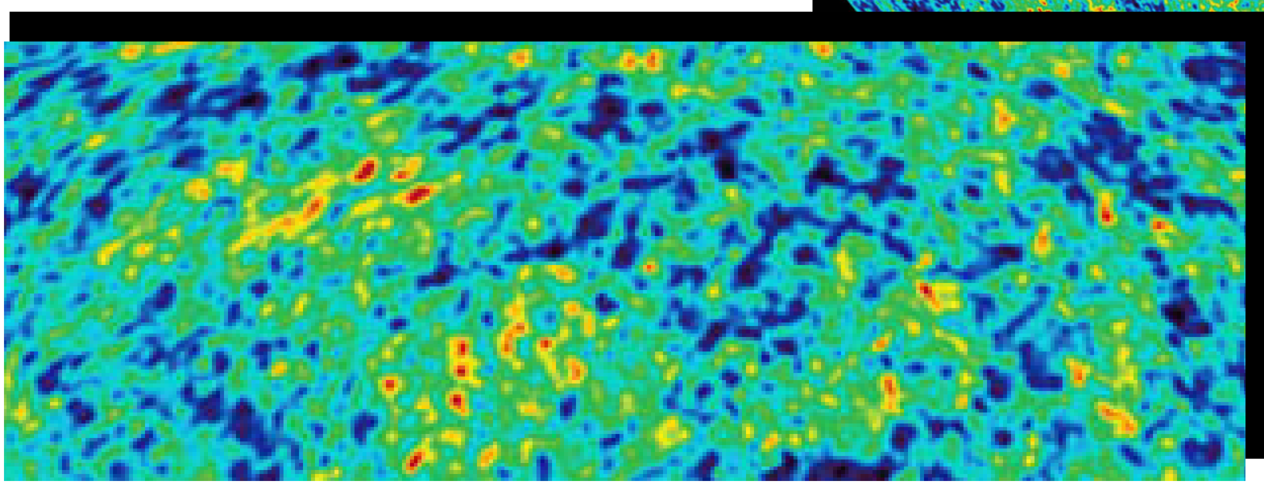


Eisenstein

Acoustic Oscillations in the CMB

Temperature map of the cosmic microwave background radiation





Although there are fluctuations on all scales, there is indeed a characteristic angular scale, ~ 1 degree on the sky:

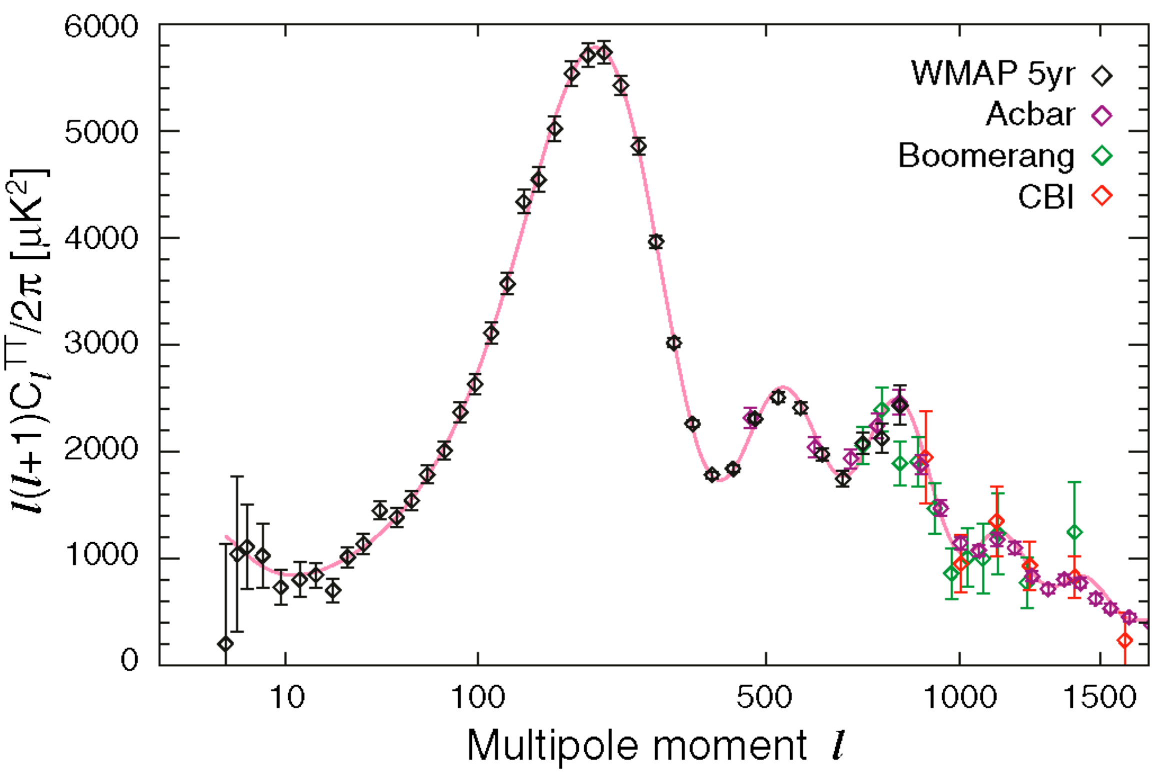
the angular size of the sound horizon ~ s = $c_s t_{ls}$

Acoustic Oscillations in the CMB

Decompose the temperature map into spherical harmonics, infer power in each mode

Should see high power in modes of typical scale ~1 degree

and then at higher (harmonic + velocities) spatial frequencies (compressions and rarefactions, Doppler shifts)



WMAP science team
(Nolta et al 2008)

l ~ 180 / (angular scale / deg)

Sound horizon more carefully

$$s = \int_0^{t_{\rm rec}} c_s\,(1+z)dt = \int_{z_{\rm rec}}^{\infty} \frac{c_s\,dz}{H(z)}$$

Standard ruler

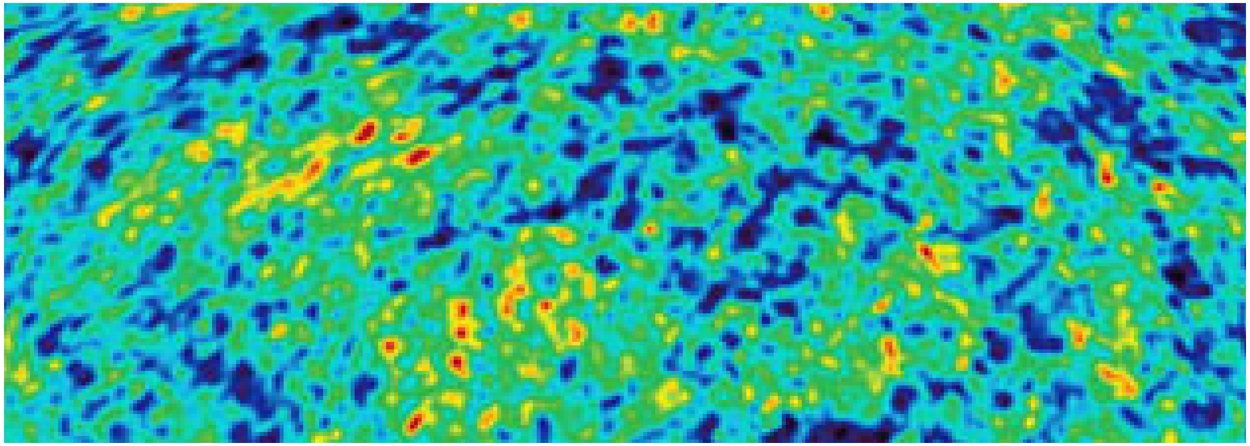
- Depends on
  - Epoch of recombination
  - Expansion of universe
  - Baryon-to-photon ratio (through c_s)

$$c_s = [3(1+3\rho_b/4\rho_\gamma)]^{-1/2}$$

Main uncertainty remaining is in baryon density

Photon density is known exquisitely well from CMB spectrum.

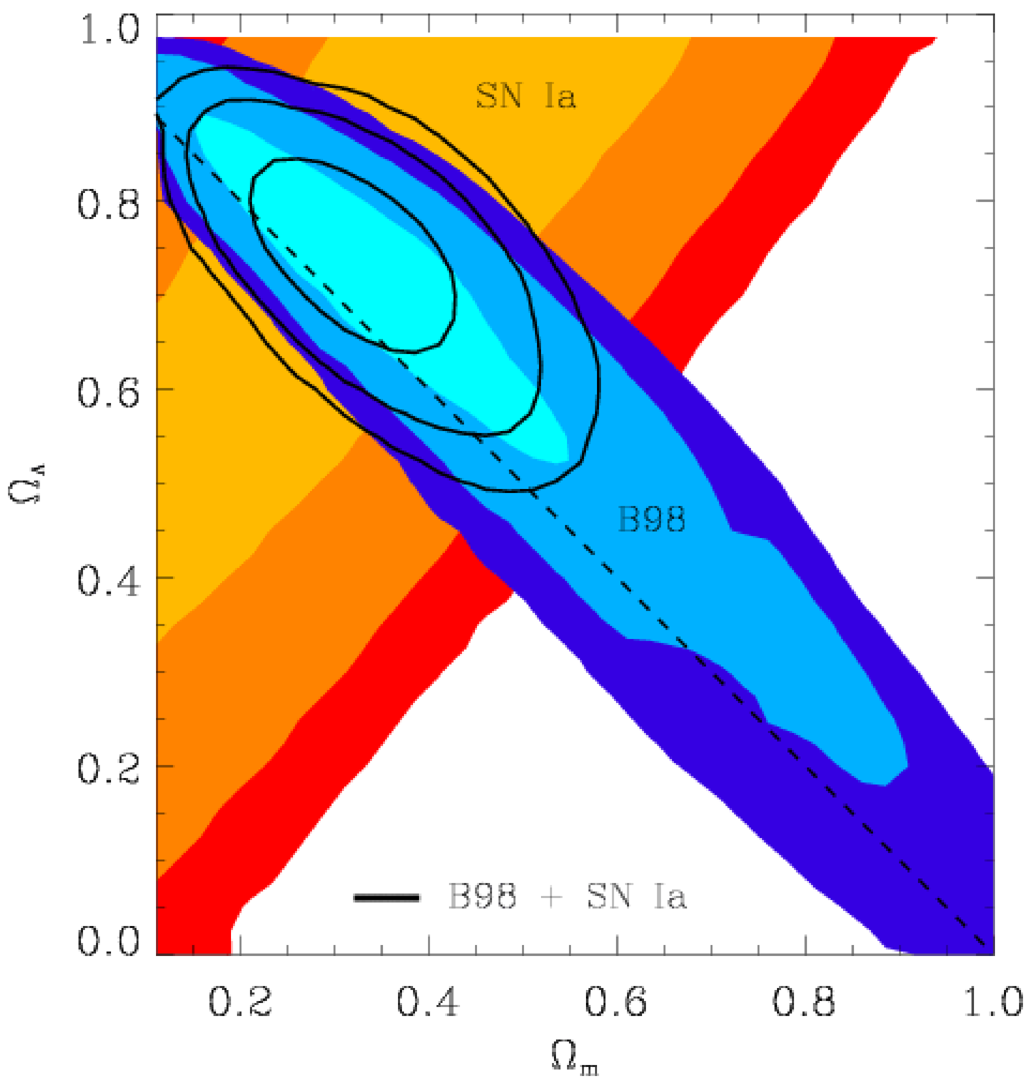
Acoustic Oscillations in the CMB



Acoustic oscillations gives us a characteristic physical scale (the sound horizon) and a well-measured angular scale (the sequence of peaks starting at ~1 deg):
they are standard rulers at z~1100

When we fit a physical model of the recombination universe to the noisy power spectrum data (eg with CMBFAST, or CAMB), most of the Dark Energy constraints come from this - at z~1100, universe was essentially matter-dominated! Only propagation...

CMB and Supernovae (2001)



- de Bernardis et al (2001)
- Boomerang + SNIa
- orthogonal constraints, CMB ~ favours flat geometry
- still assumes *w* = -1

Black contours come from *product of SN and CMB likelihood functions*

(and the same uniform prior)

$\Omega_m = 0.31 \pm 0.13$

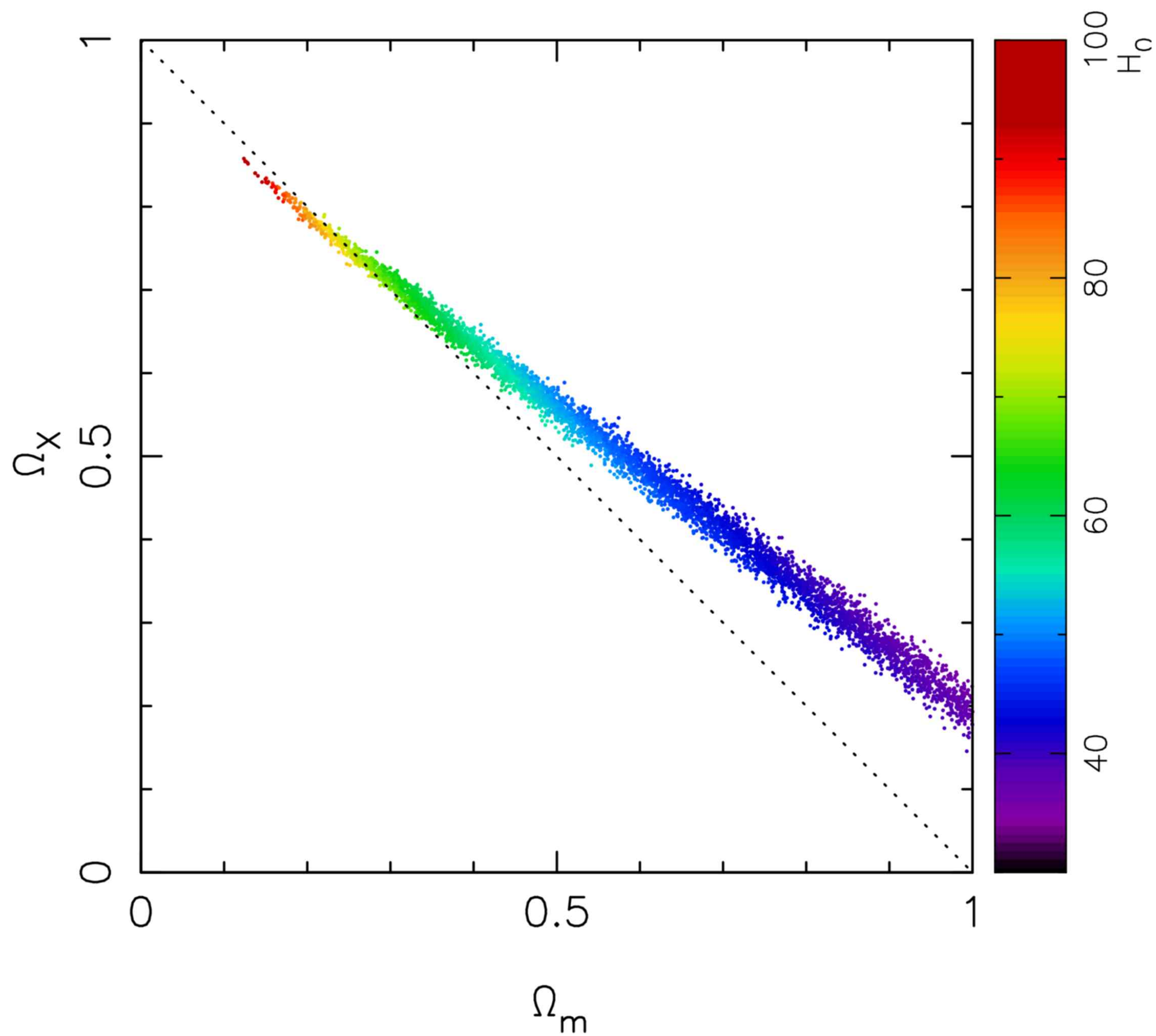
$\Omega_\Lambda = 0.71 \pm 0.11$

WMAP5 Results (2009)

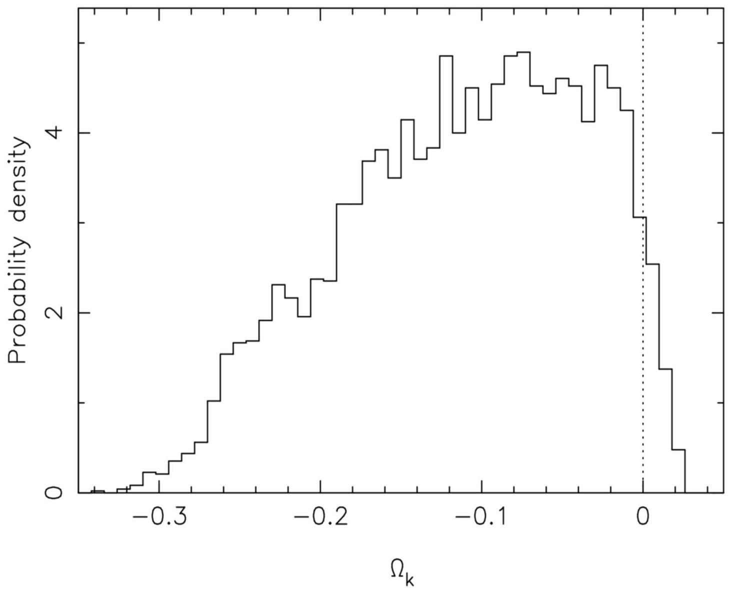
Dunkley et al 2009

Komatsu et al 2009

http://lambda.gsfc.nasa.gov/



still assuming $w = -1$

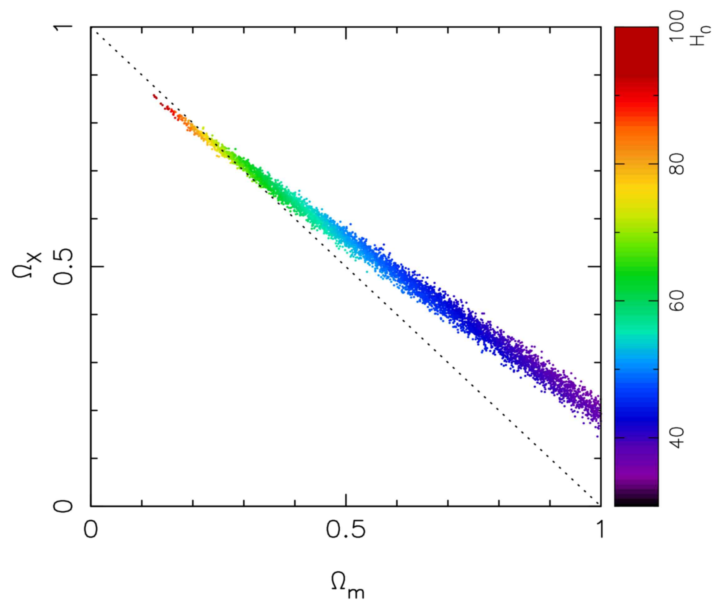


CMB does not (quite) measure curvature - or favour flat geometry

Degeneracy: one distance to one redshift

Home-made plots

Try it yourself!



WMAP5 parameter inferences were made using a Markov Chain Monte Carlo algorithm to draw samples from the posterior PDF

These samples ("chains") are available from the WMAP website:

http://lambda.gsfc.nasa.gov/product/map/dr3/parameters.cfm

Samples are *the most convenient way to characterise PDFs:*

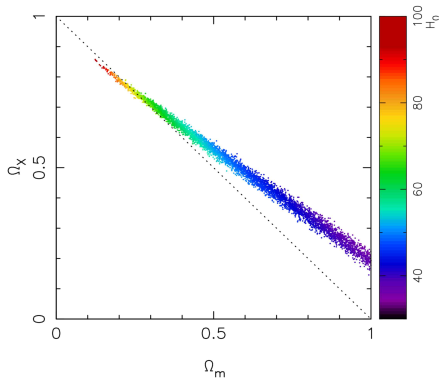
• Marginalisation is trivial - just plot histograms

• Changing variables (eg matter and DE densities to curvature) is trivial - apply the transformation one sample at a time

• Apply new constraints by re-weighting - "importance sampling"

MCMC primer

Try it yourself!

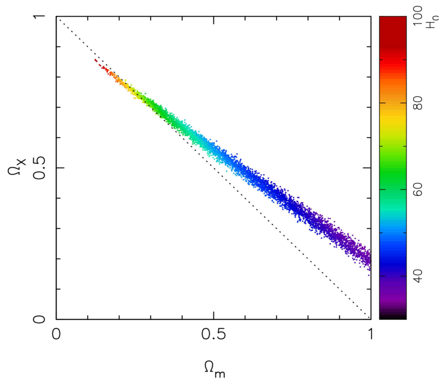


Most cosmological parameter estimation is now done using MCMC

NB. Astronomers are implicitly Bayesian

```
10  Compute numerical value of posterior PDF
    at current point: P_i
20  Draw a nearby point in parameter space from a
    proposal distribution: P_j
30  Compare P_j and P_i:
        if ( P_j > P_i ) then
            move to position j
        else
            move to position j with probability P_j / P_i
40  Record current position (as a "sample")
50  Go to 10
```

MCMC primer



Runtime scales linearly with the number of free parameters, statistical uncertainties can be computed accurately, false maxima and important degeneracies are mapped.

What can go wrong?

•As the number of dimensions increases, it gets progressively harder to move away from a false maximum: "cooling" the process (starting by sampling from the prior, and gradually increasing the weight of the likelihood during a "burn-in" phase) can help. Don't forget to discard burn-in samples...

• Very narrow degeneracies lead to high sample rejection rates and low efficiency: proposal design is key! Updated covariance matrices are popular (intuition: best proposal distribution is the target PDF), but the updating must be done carefully. Re-parameterisation works well - but a uniform prior in A is never a uniform prior in B(A)

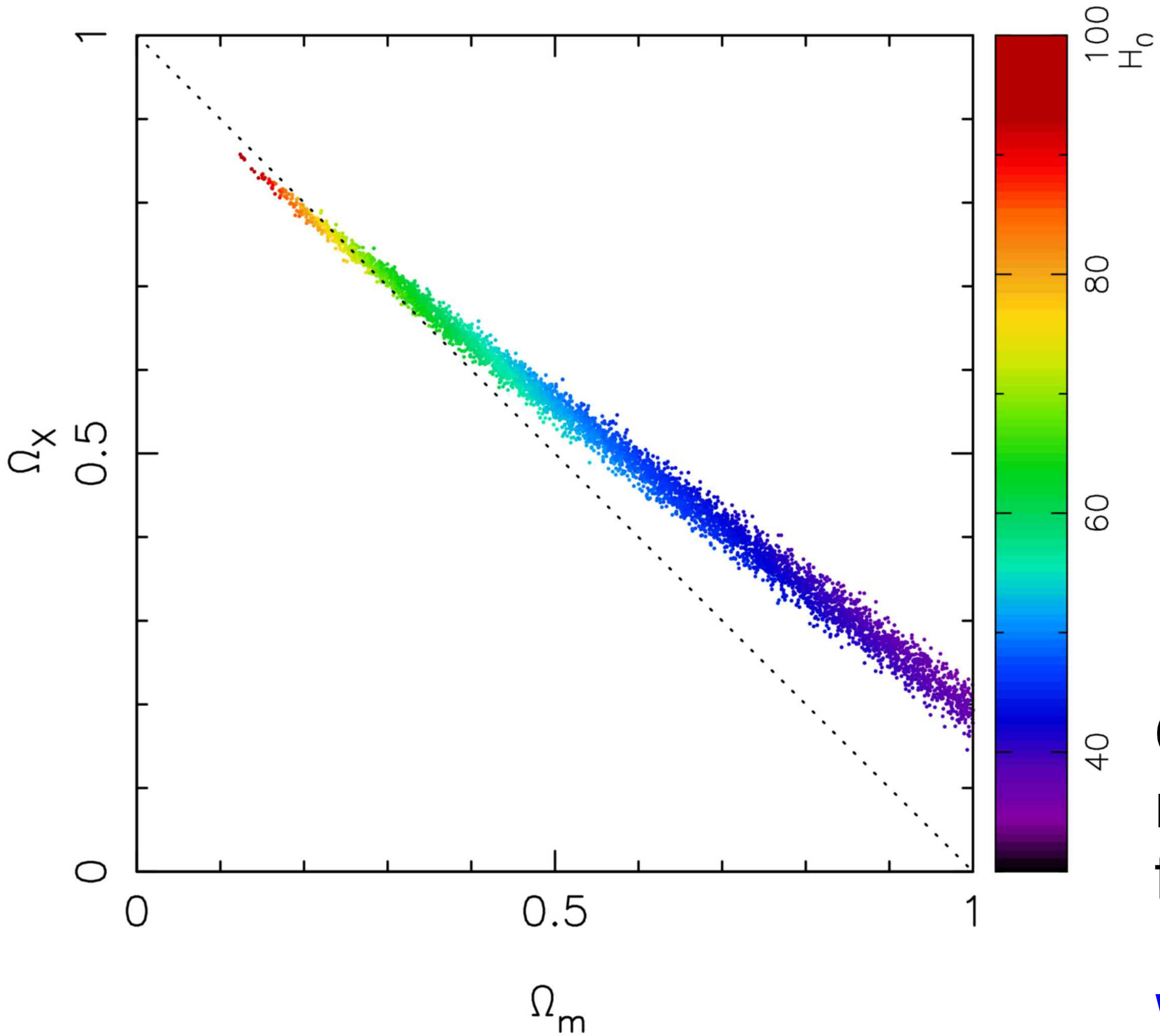
• How do you know when you are finished? Various convergence tests on the chains (eg Gelman-Rubin); Dunkley et al look at the power spectrum to check for unwanted correlations. Multiple chains allow more tests

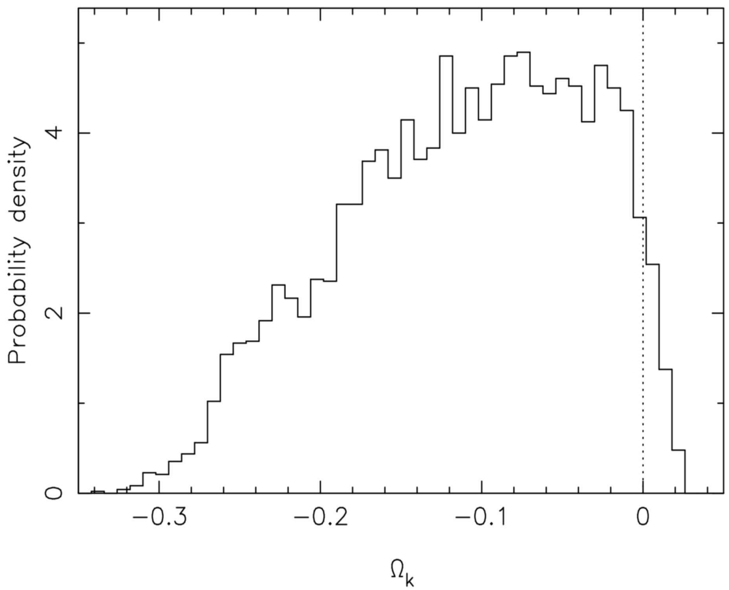
WMAP5 Results

Dunkley et al 2009

Komatsu et al 2009

http://lambda.gsfc.nasa.gov/

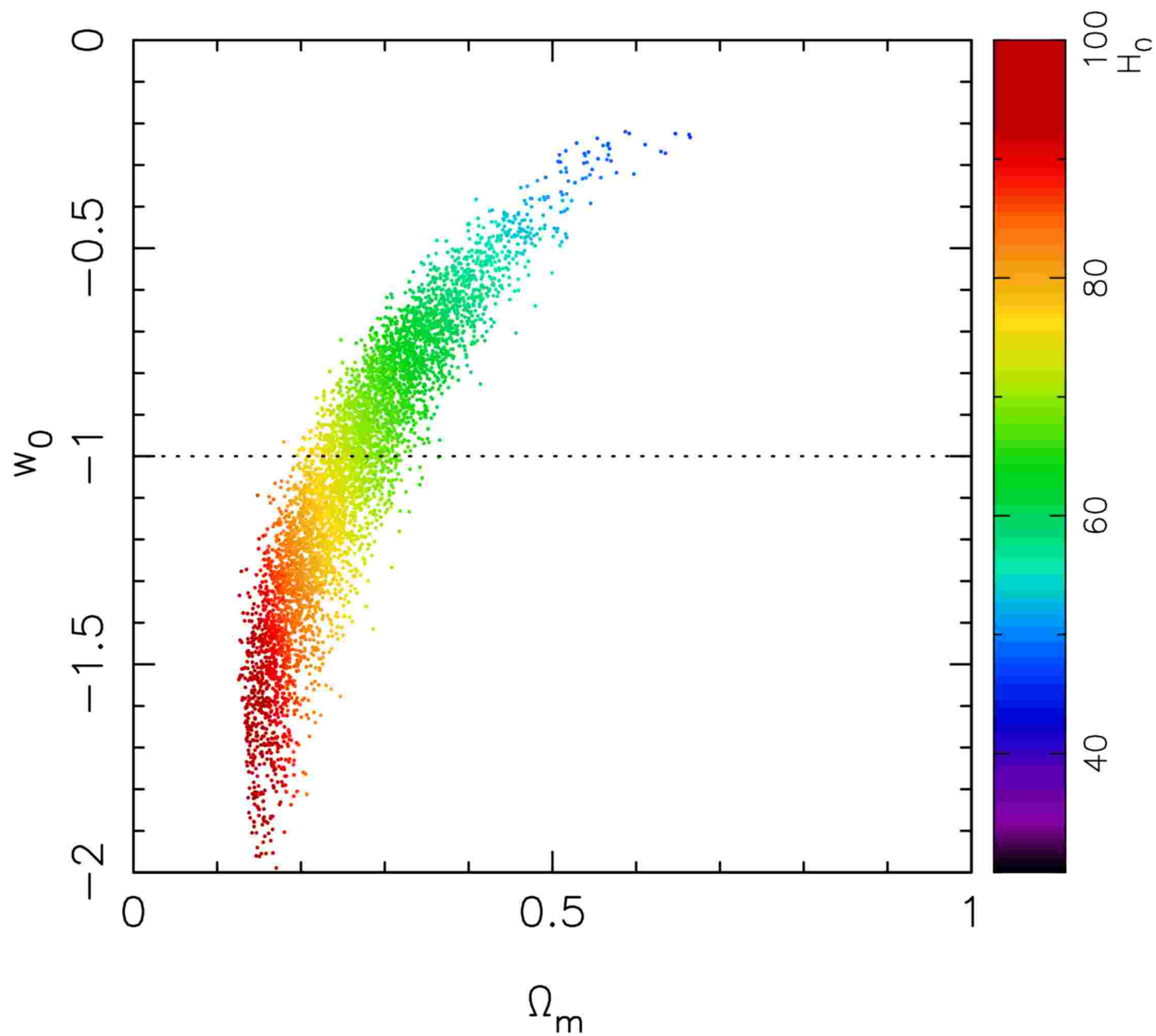




CMB does not (quite) measure curvature - or favour flat geometry

What if we assume flatness instead of w = -1?

WMAP5 Results



now assuming *flat geometry*

If flat geometry is assumed, CMB constrains DE density very well: 0.75+/-0.08

We can spend the spare information on w:

w = -1.04 +/- 0.35

from CMB plus flatness assumption alone

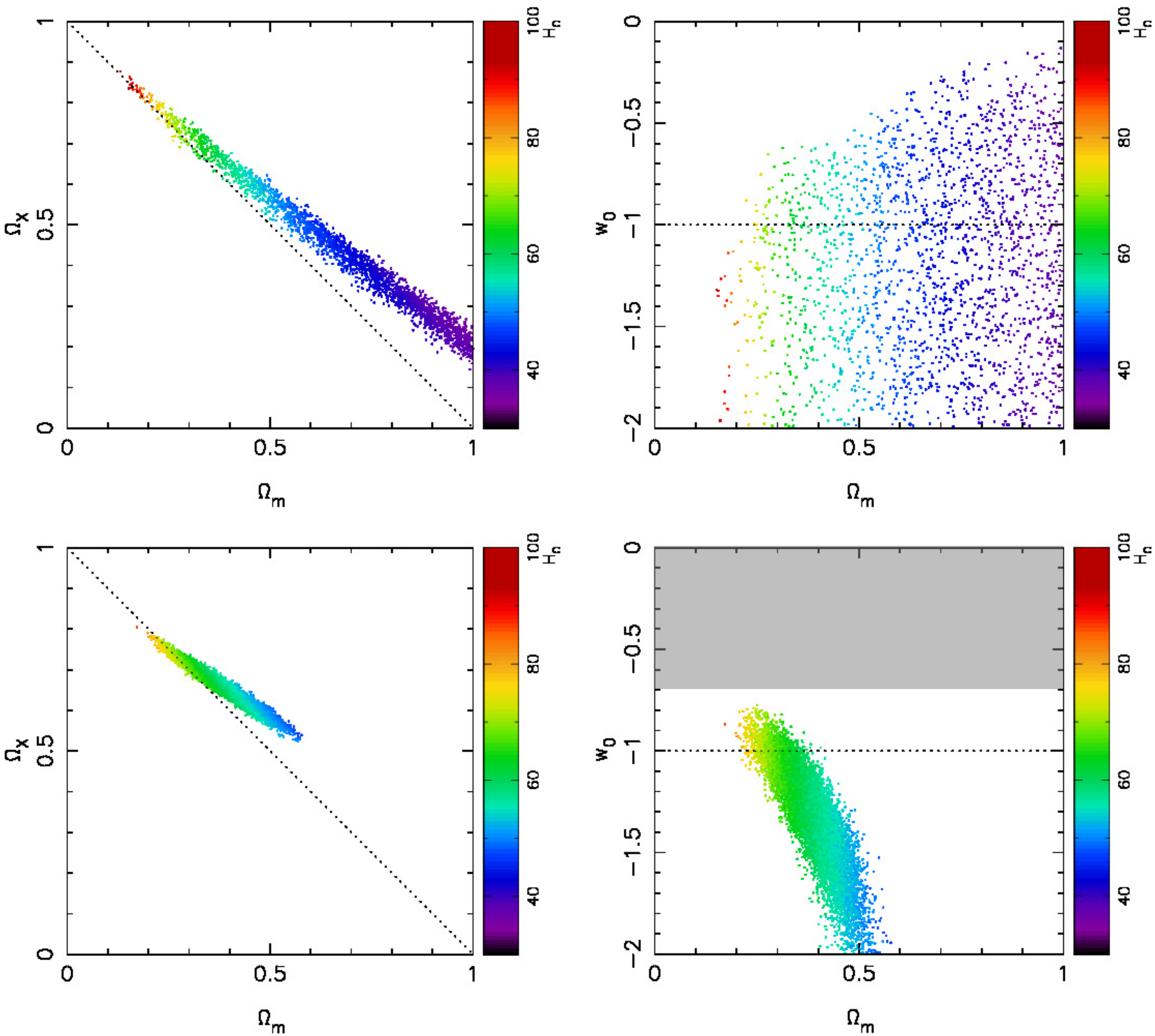
This is a common premise: flatness is seen as a good bet!

CMB and Supernovae (2009)

Uniform priors on
w and curvature

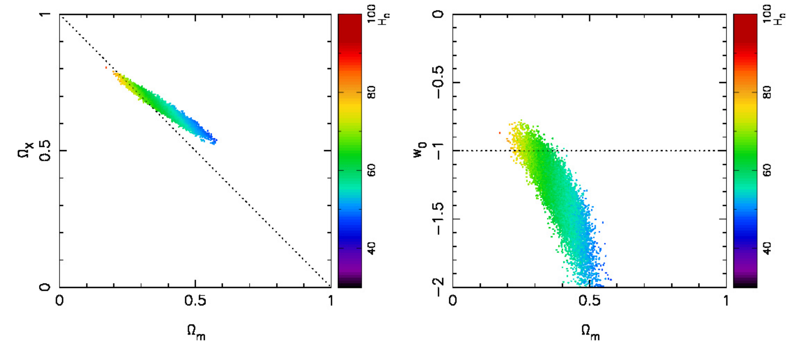
WMAP5
alone

WMAP5
+ "SN all"



CMB and Supernovae (2009)

Type Ia supernovae and the acoustic peaks in the CMB power spectrum are powerful **distance indicators**



Neither on its own constrains the dark energy density or its equation of state - the flatness assumption, or an additional dataset, are needed to start **breaking parameter degeneracies**

In fact, the combination of the two has got us to the point where **we can measure curvature and dark energy density at the same time** **-** and start ruling out high w dark energy (qunitessence) models

- What is this "SN all" dataset?
- Did we really get our uncertainties correct?
- How can we measure H better, to start narrowing down w?

Part 4: Supernova systematics

Type Ia Supernovae

Measuring the distance to an object, and comparing with the standard model prediction for it given its redshift z where a = 1/(1+z), is the simplest possible cosmological test

In 1998, 2 groups announced they had detected **cosmic acceleration** exactly this way, using samples of Type Ia supernovae

Why does SN cosmology work?

What do you have to do to make it work?

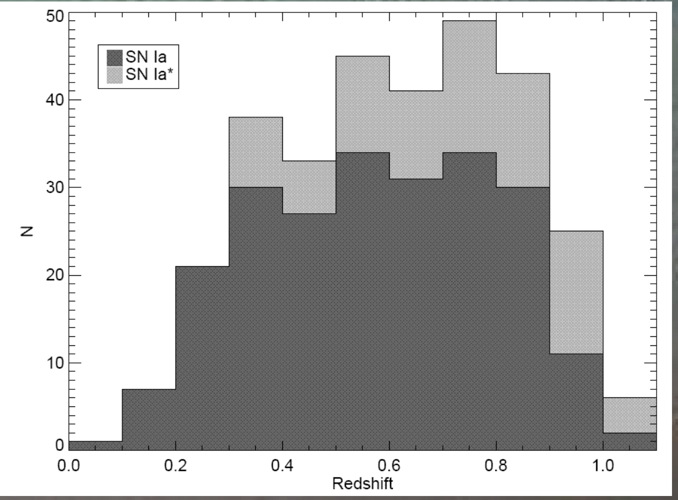
The Supernova Legacy Survey (SNLS)

Legacy
10% of time on 3.6m telescope for 5 years (2003-2008)

Canada-Frace-Hawaii Telescope
g'r'i'z' imaging of two 1 sq deg fields every 4 days during dark time

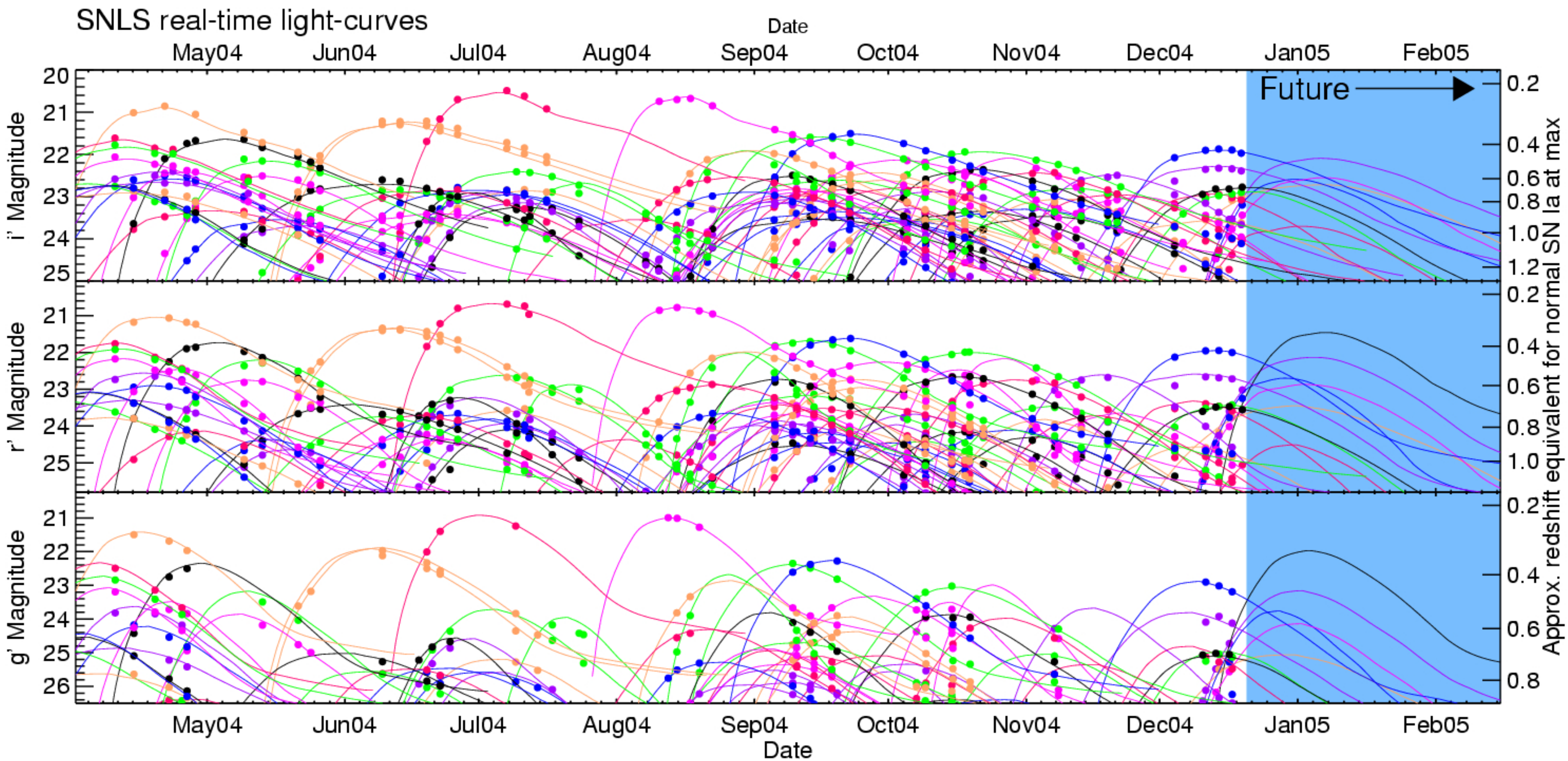
Discoveries:
2000 SN candidates,

>400 spectroscopically confirmed SNe Ia



Slides from A. Howell

SNLS Rolling Search



Deep survey catches SNe early in their light curves

Spectra

SN Identification

Redshifts

VLT

120 hr/yr: France/UK
FORS 1&2 for types, redshifts

Magellan

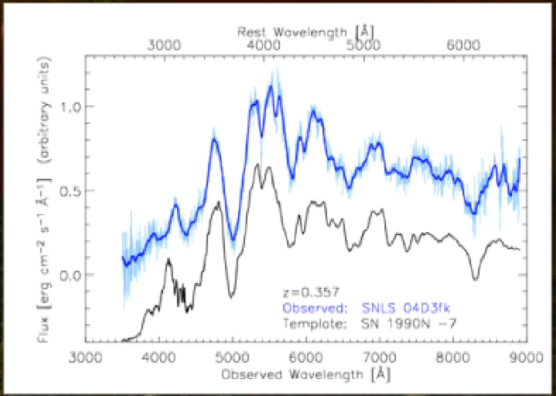
3 nights/yr: Toronto
IMACS for host redshifts

Keck

8 nights/yr: LBL/Caltech
DEIMOS/LRIS for types, intensive study, cosmology with SNe II-P

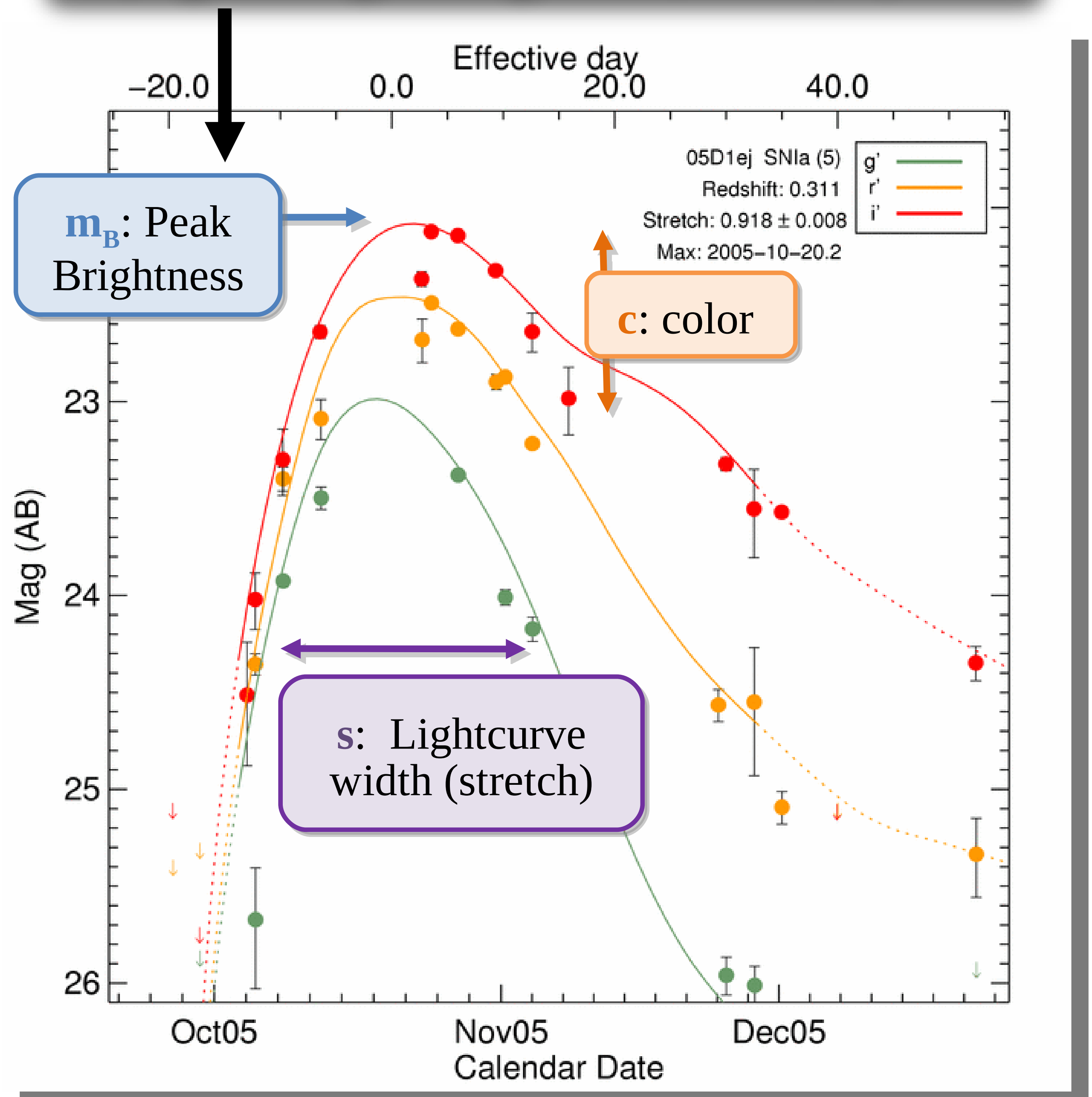
Gemini

120 hr/yr: Canada/US/UK
GMOS for types, redshifts



$$\mu_B = m_B - M_B + \alpha(s-1) - \beta c$$

Typical SNLS SN Ia



μ_B:distance expressed in magnitudes

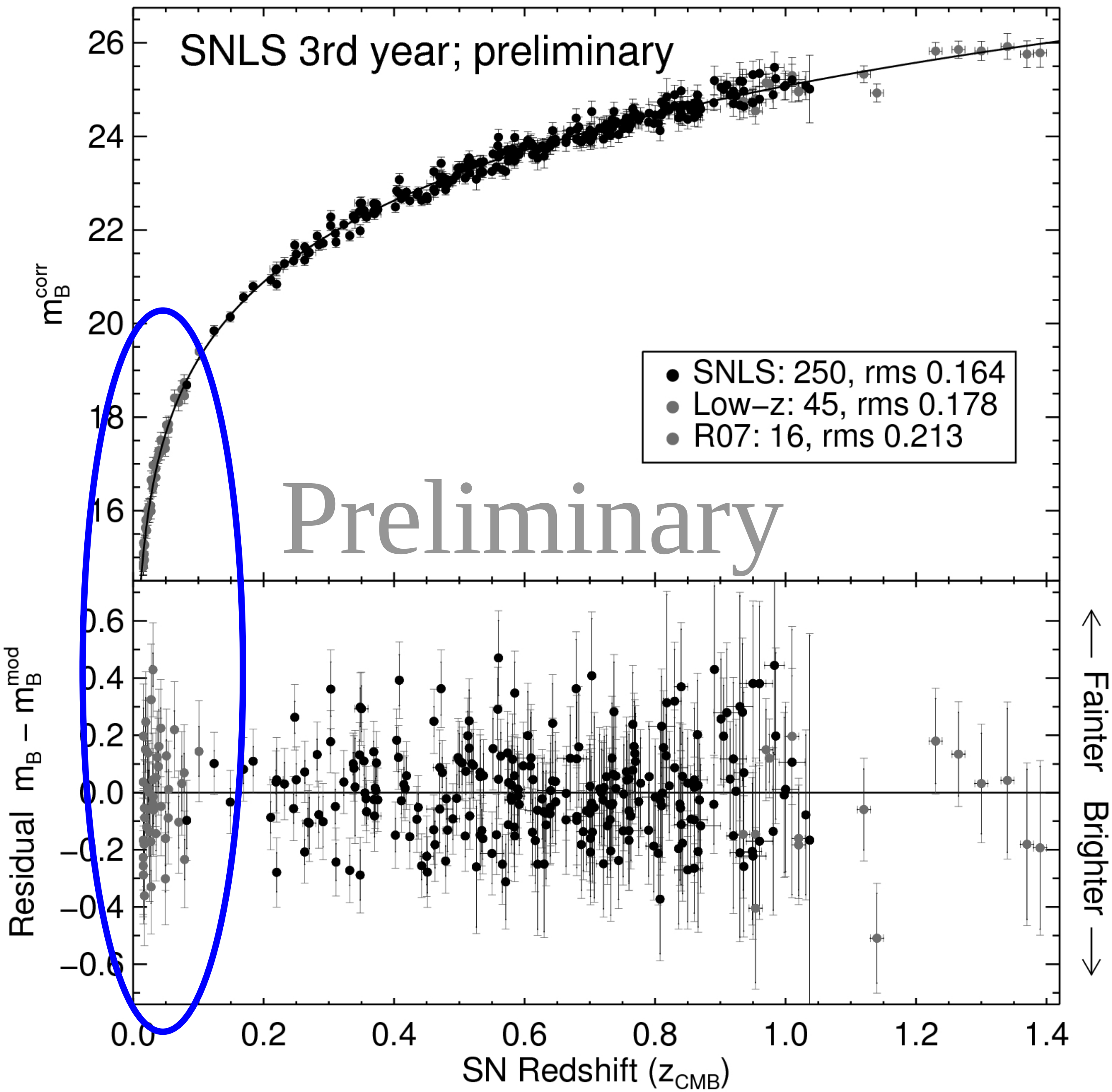
M_B, α, β: nuisance parameters solved for in cosmological fit

Recall: M contains Hubble's constant and the mean SN luminosity

New parameters to begin exploring and quantifying systematic effects: they are assumed properties of the *population*

Howell

3rd year Hubble Diagram



3/5 years' data
~250 SNLS SNe Ia

Cosmological information is in shape of curve

Low redshift sample improves precision in DE parameters by a factor of 3

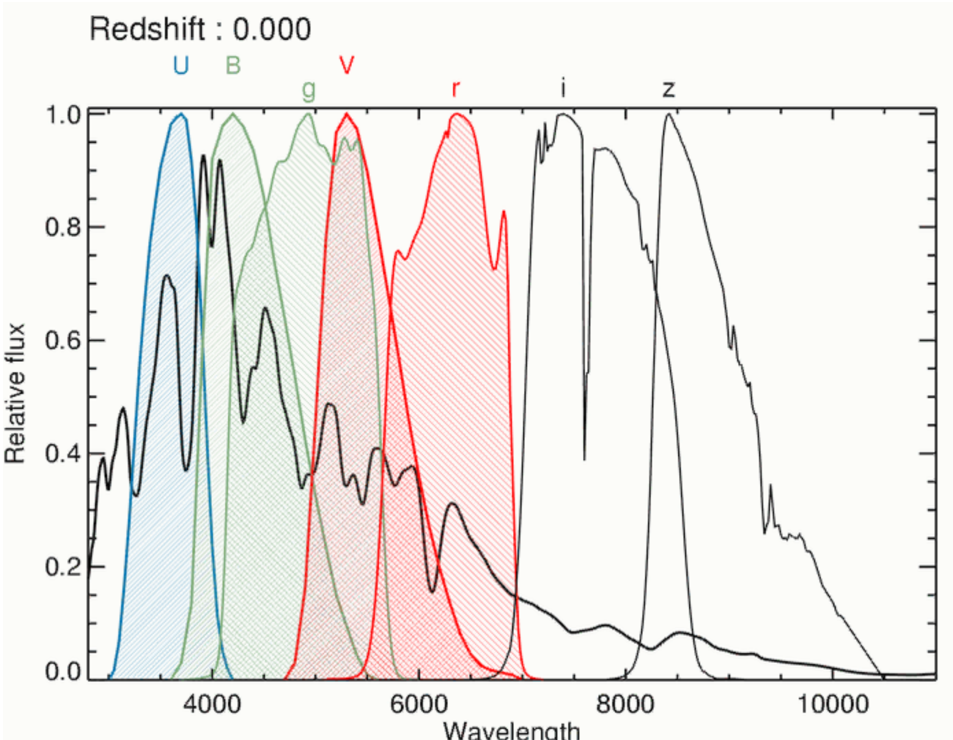
SNLS: "Systematic Errors are Well-understood"

Systematic	w Error
Flux reference (e.g. Landolt)	0.053
Low-z photometry	0.02
Landolt bandpasses	0.01
Host galaxy flows	0.014
SNLS zero points	0.01
SNLS bandpasses	0.01
Malmquist bias (both)	0.01
Evolution in color-luminosity (β)	0.02
Total systematic	**0.06-0.07**

Well, these are the known unknowns...

Stat plus systematic error on w is about 9%

1% Photometry is Hard



K-correction: transform observed (g,r,i,z) fluxes into rest-frame (U,B,V) fluxes using mean spectrum: M_B

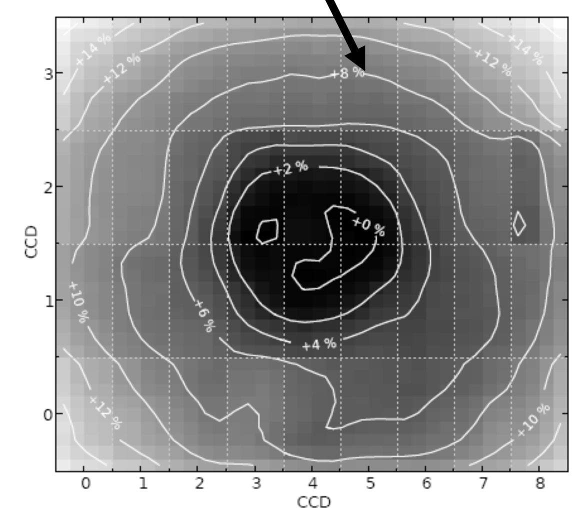
Need to know the following very well:

g, r, i, z:
Observed CFHT MegaCam **filters,** and the **zero points (from faint standard stars), as a function of position on the detector**

U, B, V:
Landolt (historical) **filters** that must be transformed to (to compare with low-z SNe)

and the **zero points for those old observations**

AND the **definition of the historical (Landolt/Vega) magnitude system**



Regnault, Hsiao, Conley + SNLS, ongoing...

Next advance: improve the low-z sample

Systematic	w Error
Flux reference (e.g. Landolt)	**0.053**
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Evolution in color-luminosity (β)	0.02
Total systematic	**0.06-0.07**

Dominant systematic is due to **matching high-z MegaCam magnitude system to low-z sample,** which - uses Landolt standard stars in the Vega system

Need a fainter standard (BD+17) observed in same (modern) system, better linked to high-z sample

Stat plus systematic error on w is about 9%

Next advance: improve the low-z sample

e.g. **The Palomar Transient Factory**

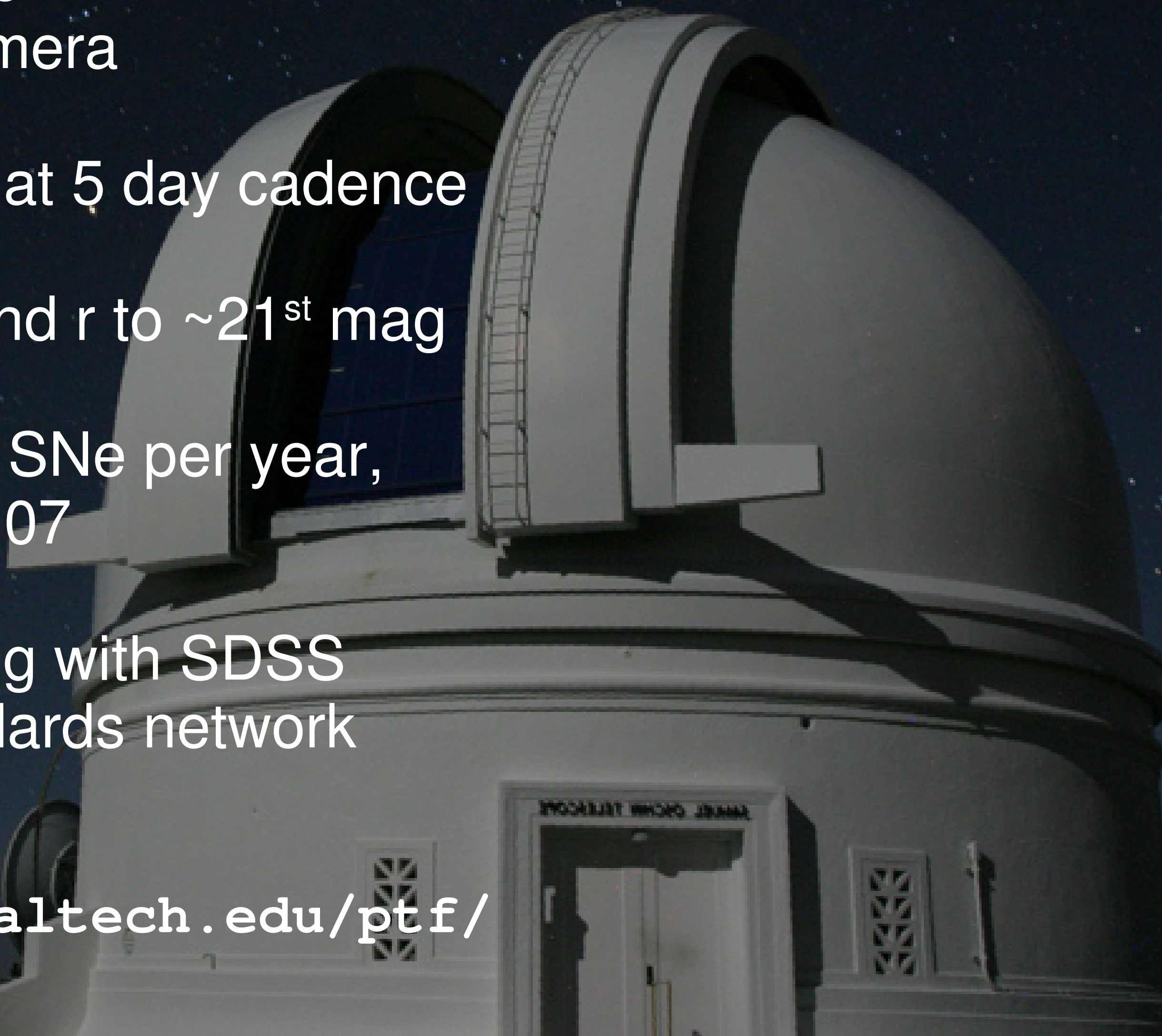
Palomar 48" telescope
Refitted CFHT12k camera

8000 sq deg per year at 5 day cadence

60sec exposures, g and r to $\sim 21^{st}$ mag

Follow up 150 type Ia SNe per year,
in range $0.03 < z < 0.07$

Photometric monitoring with SDSS
filters, improved standards network



http://www.astro.caltech.edu/ptf/

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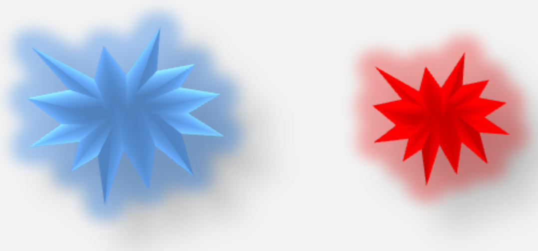
Color correction: technique matters

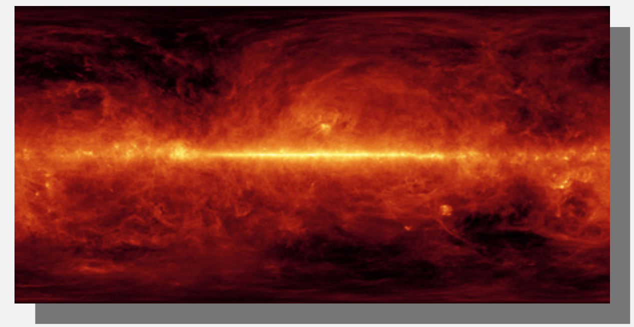
Redder SNe are fainter because of:

Intrinsic SN color



and

Dust extinction



Extinction correction methods:

MLCS: Separate effects of intrinsic color and dust

- Must assume intrinsic SN color distribution with stretch, phase
- Use color to get extinction from assumed dust extinction law

SNLS: Empirical correction

$$\mu_B = m_B - M_B + \alpha(s-1) - \beta c$$

$\beta \sim R_B = A_B/E(B-V)$

4.1 if MW dust

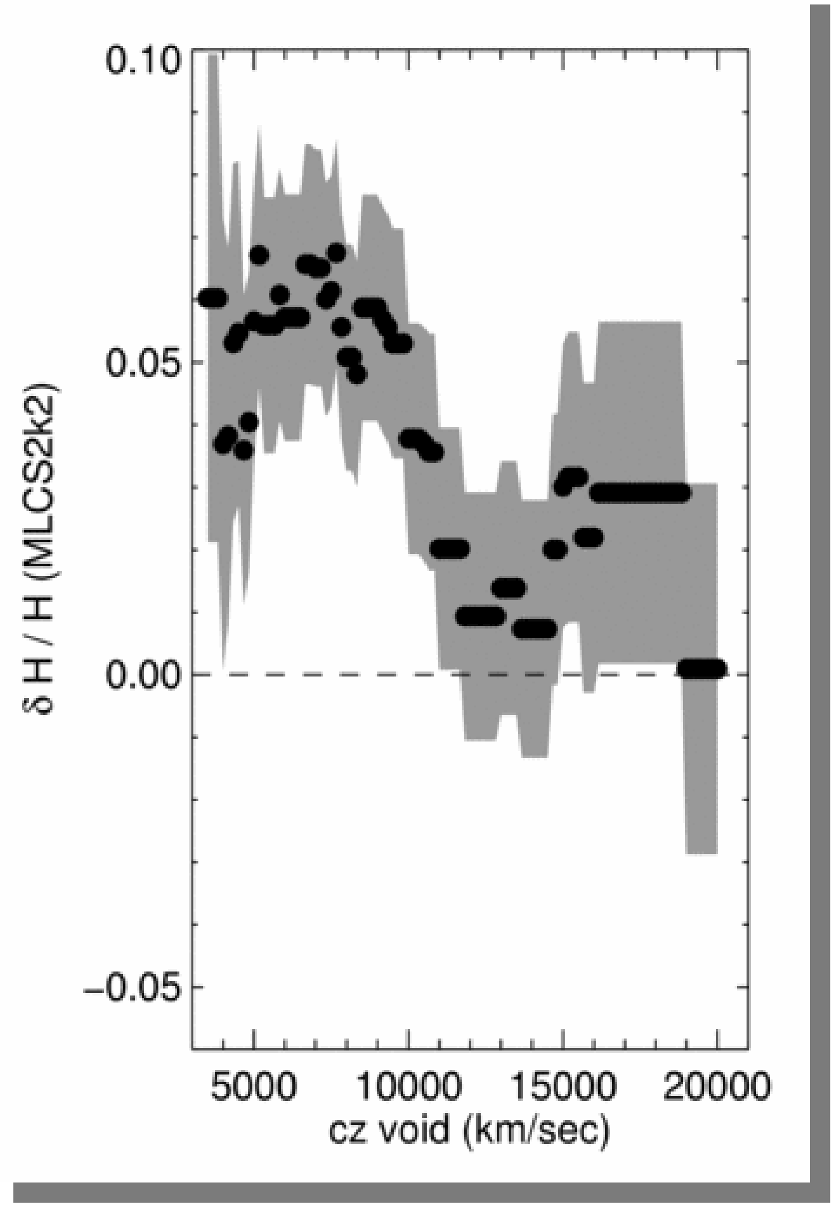
Hubble Bubble

Jha et al. 2007: H_0 is 6% (3σ) higher within ≈7400 km/s – local “bubble” expanding faster than rest of universe

(Split sample, treat M as H)

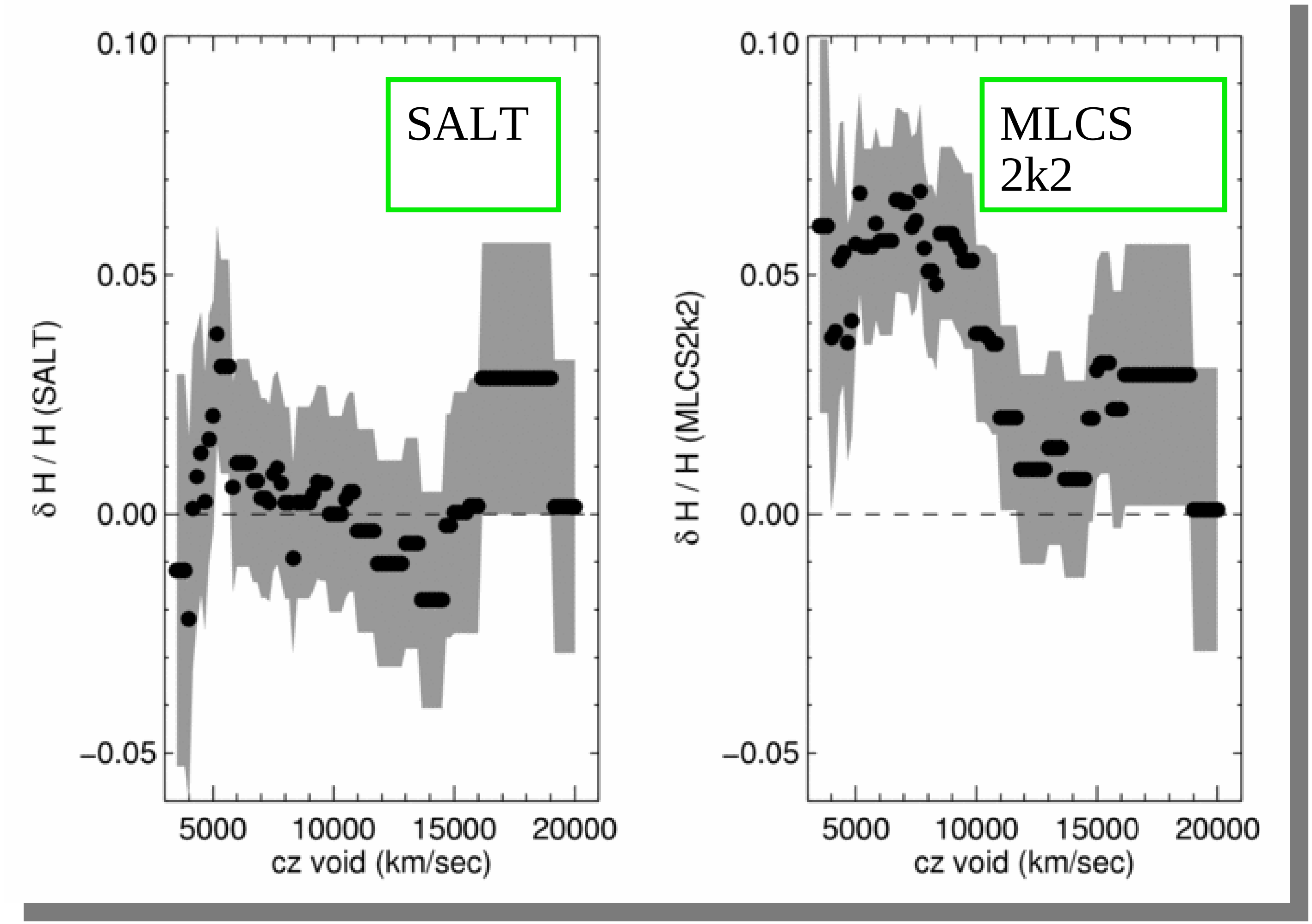
Local void in mass density?

6% systematic error on *w* for ESSENCE (Wood-Vasey et al. 2007)



Hubble Bubble
Conley et al. 2007

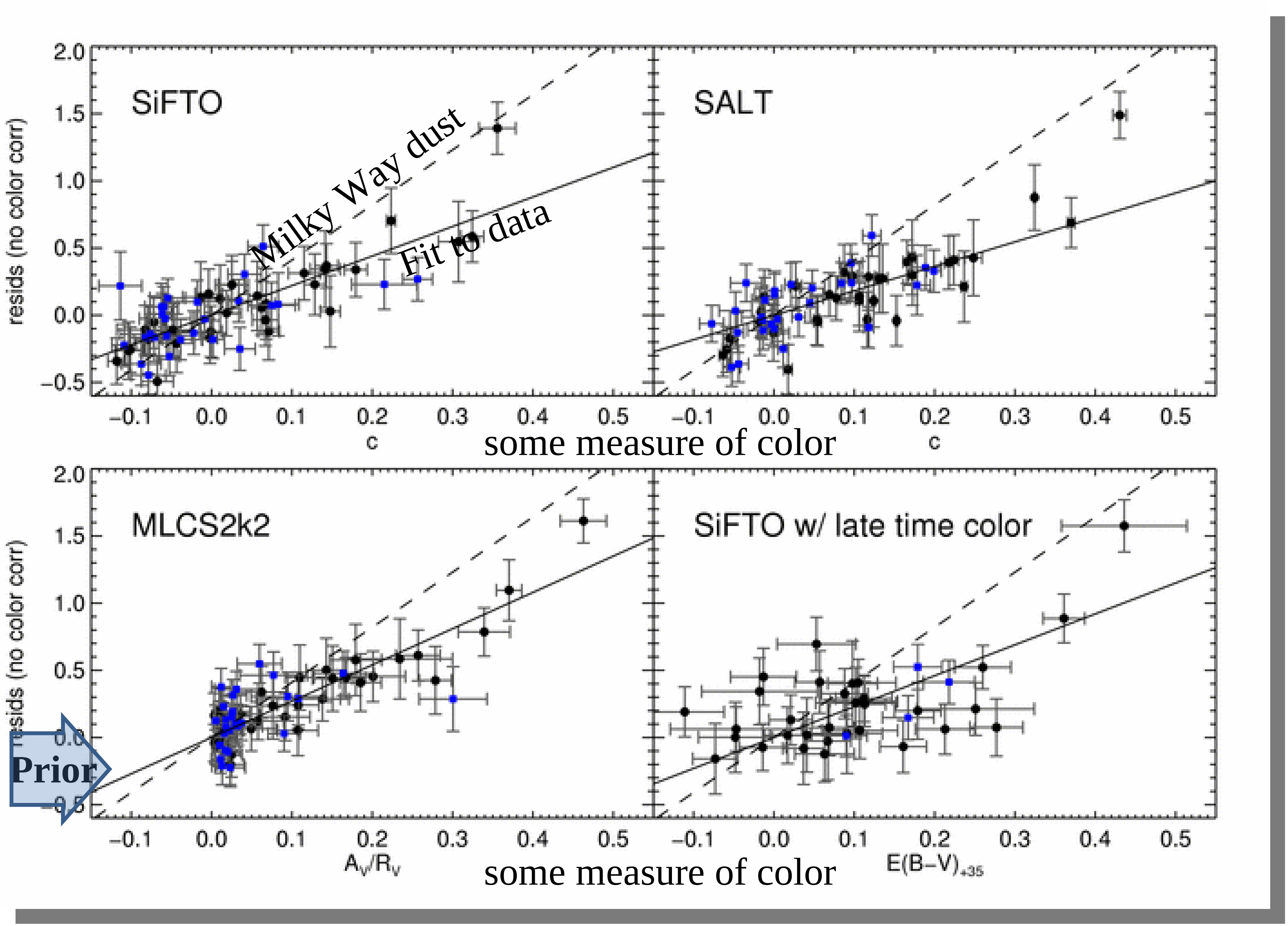
No Bubble with other light-curve fitters!



Color correction

Conley et al. 2007

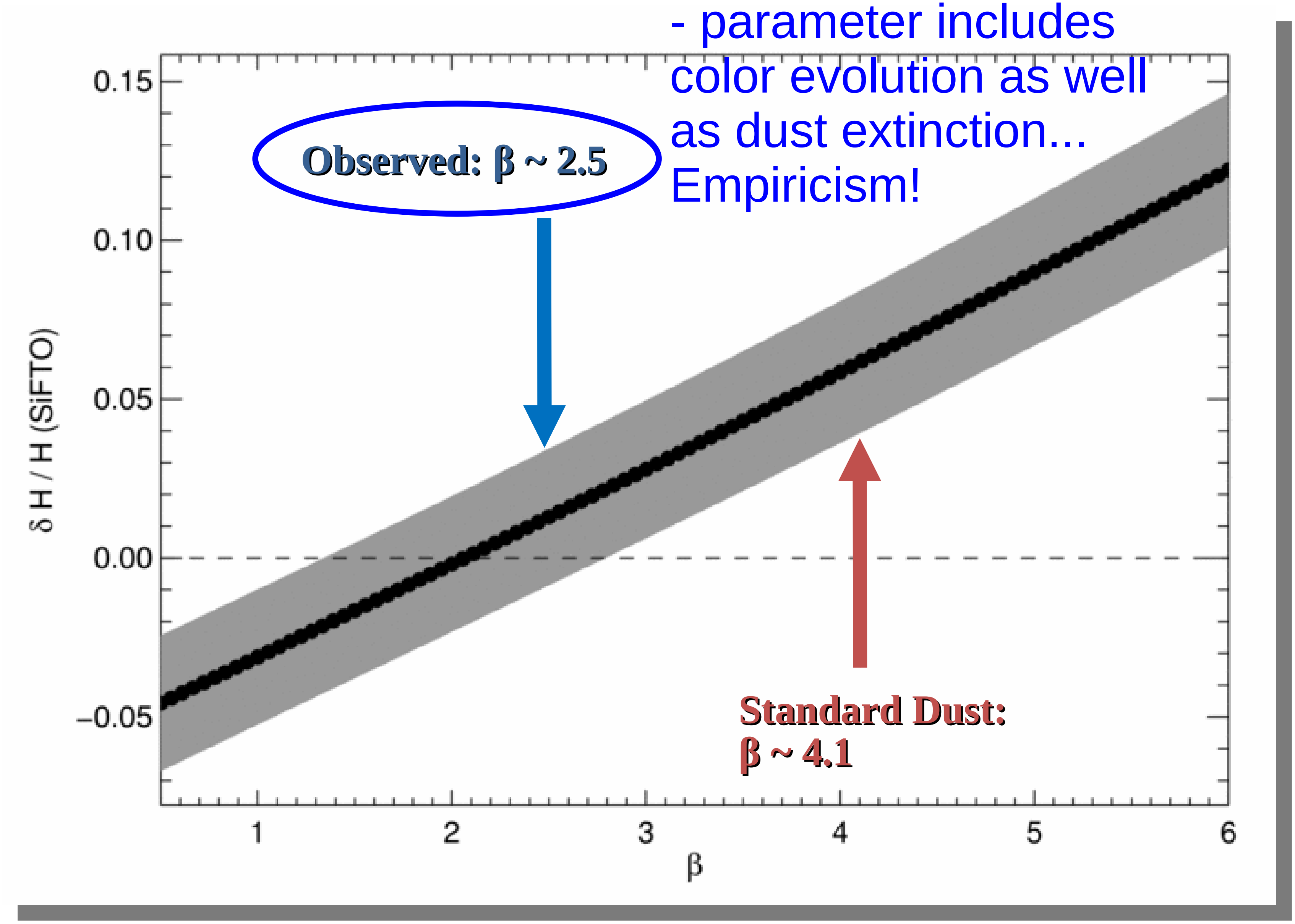
SNe do not look like they've been obscured by MW dust



Hubble Bubble Significance

Conley et al. 2007

Non-standard dust type
- parameter includes color evolution as well as dust extinction...
Empiricism!



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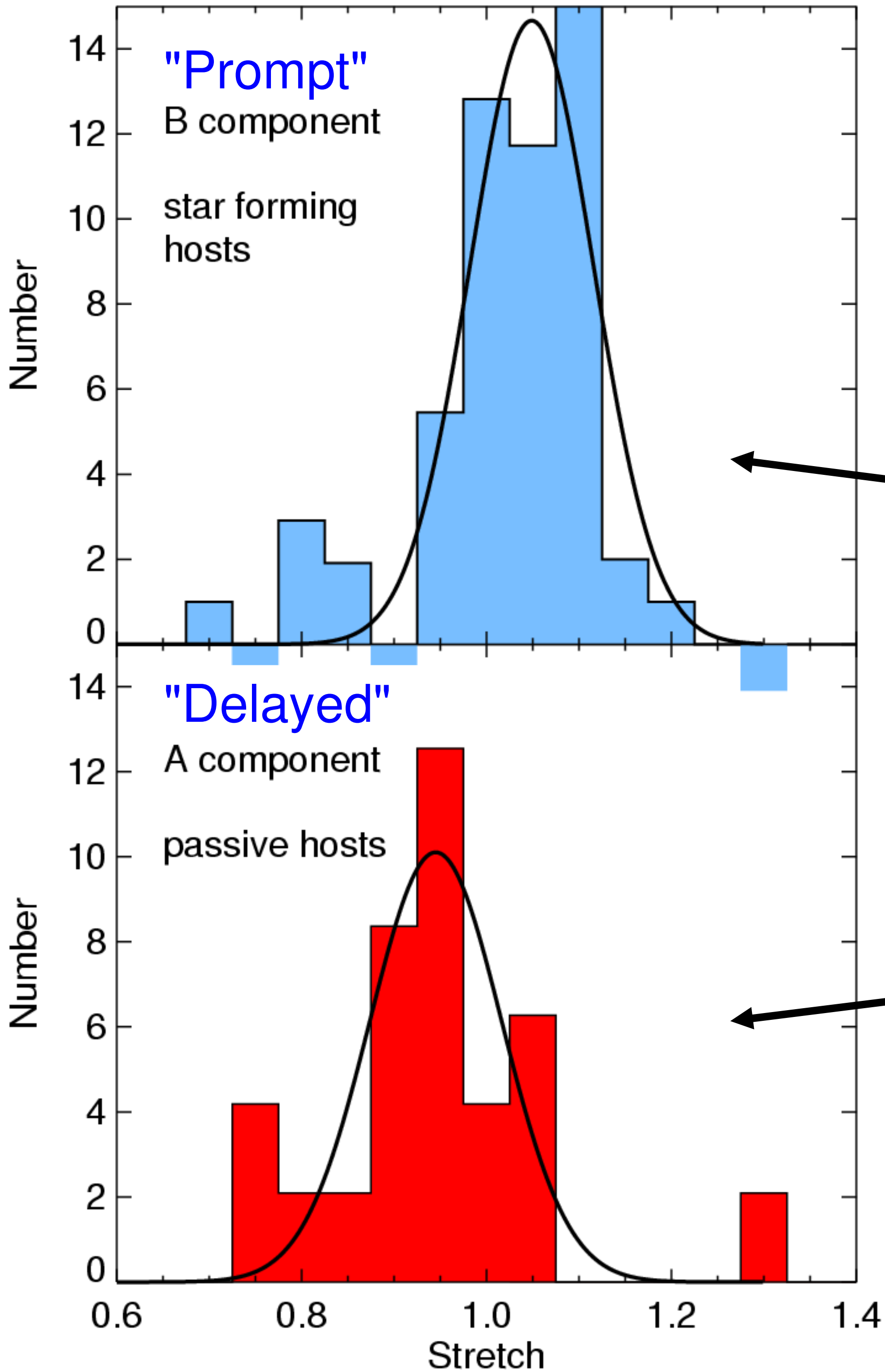
Population affects SN Ia Luminosity

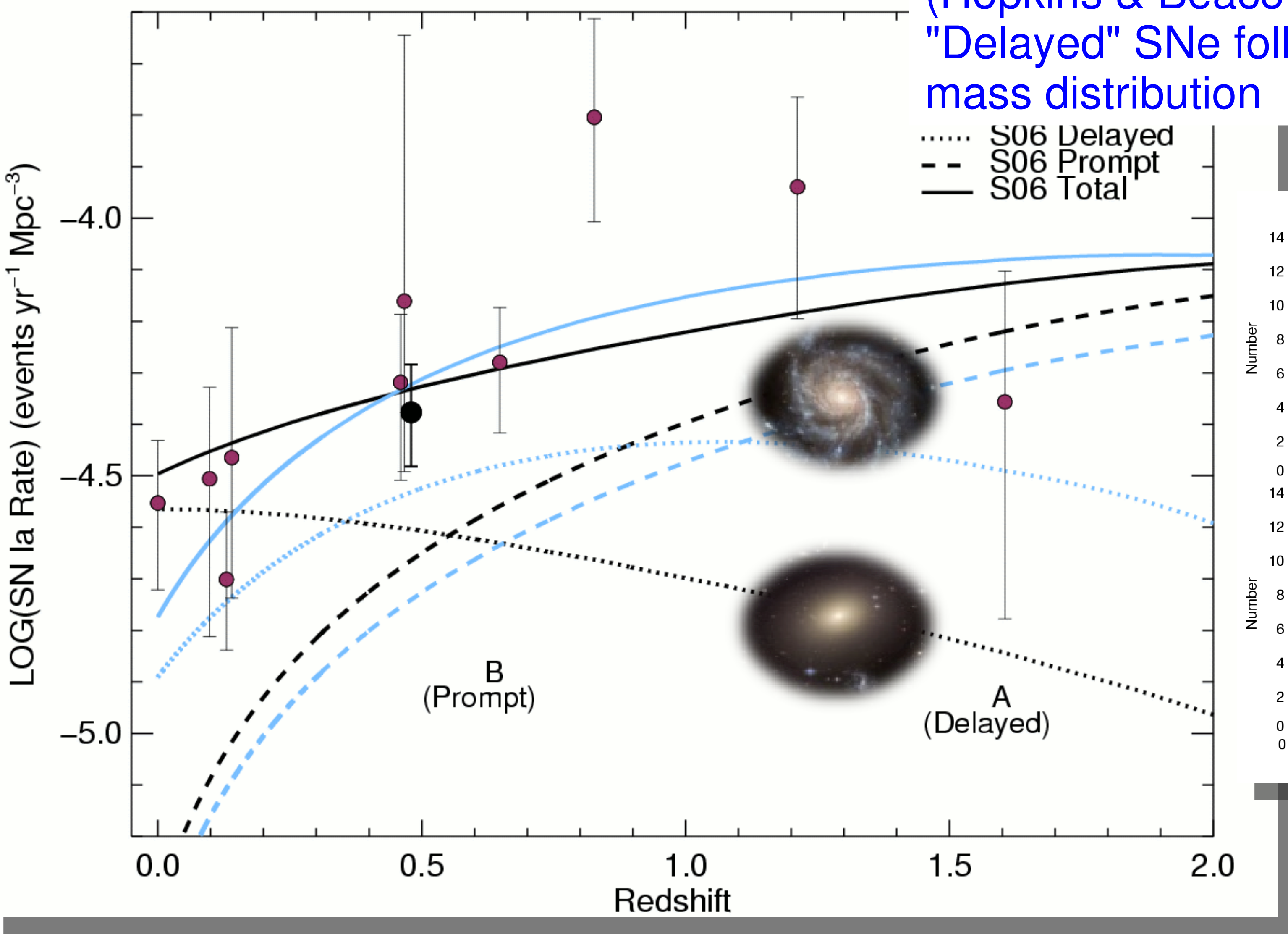
Sullivan et al. 2006, Howell et al. 2007

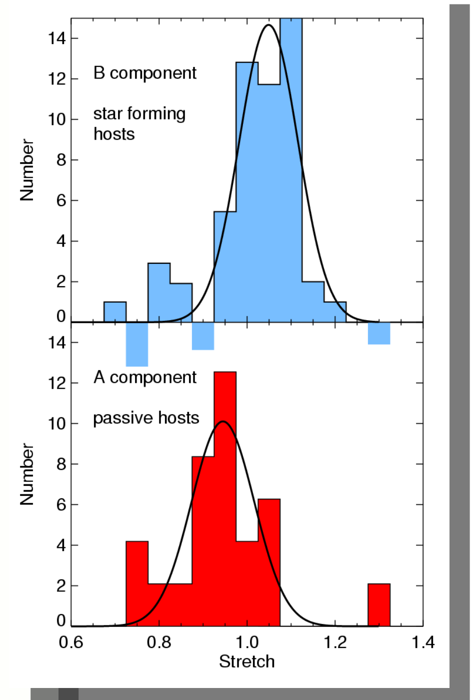


SN Rates vs. redshift

Sullivan et al. 2006, Howell et al. 2007

"Prompt" SNe follow declining cosmic star formation history (Hopkins & Beacom 2006), "Delayed" SNe follow growing stellar mass distribution





Predict relative contribution from each component vs. redshift

SN population drift vs. z

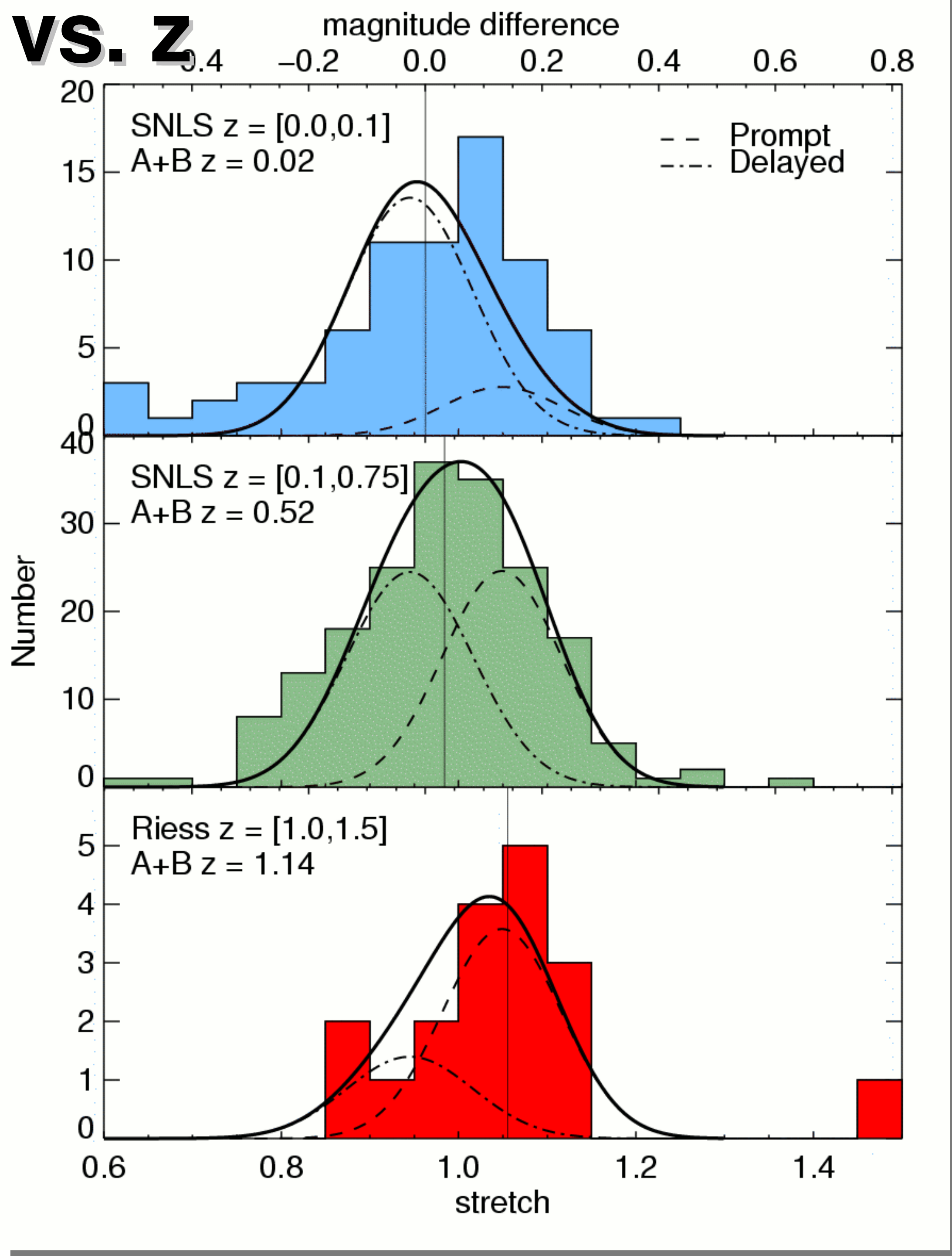
Howell et al. 2007

Histograms: data
Gaussians: prediction from rates

Conclusion: Average stretch, and thus average *intrinsic* brightness of SNe Ia **evolves with redshift.**

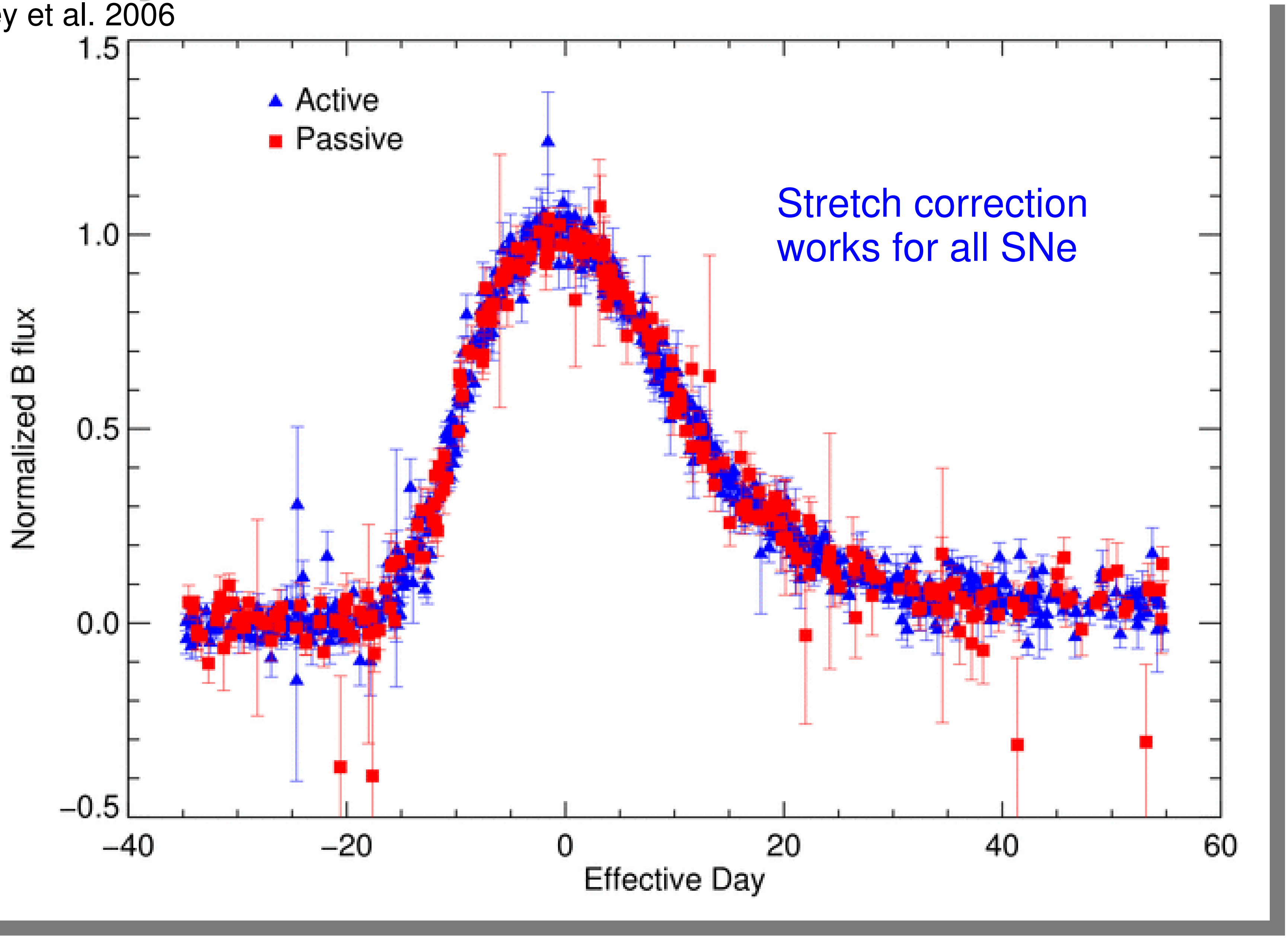
Average SN Ia was 12% brighter at z > 1.

If stretch correction works perfectly, this should not affect cosmology....

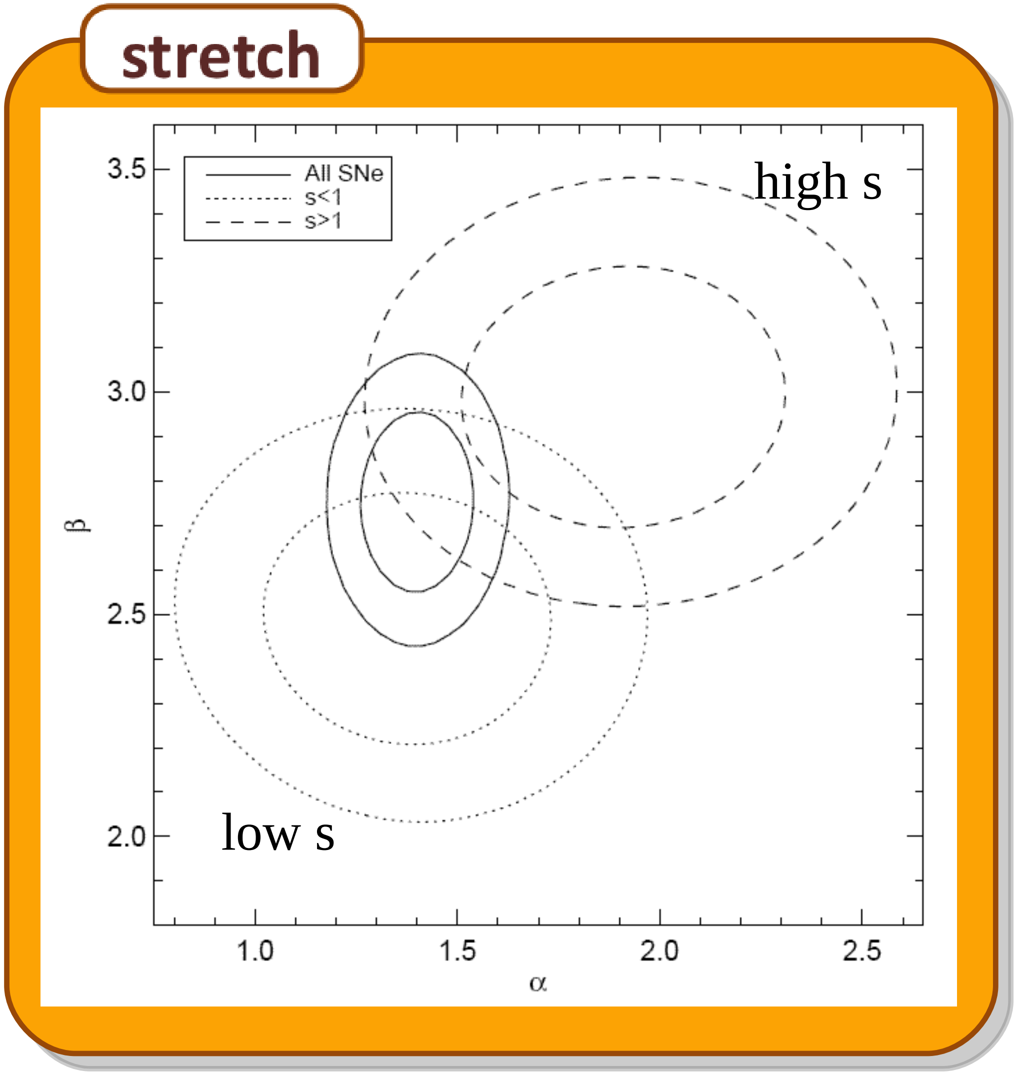


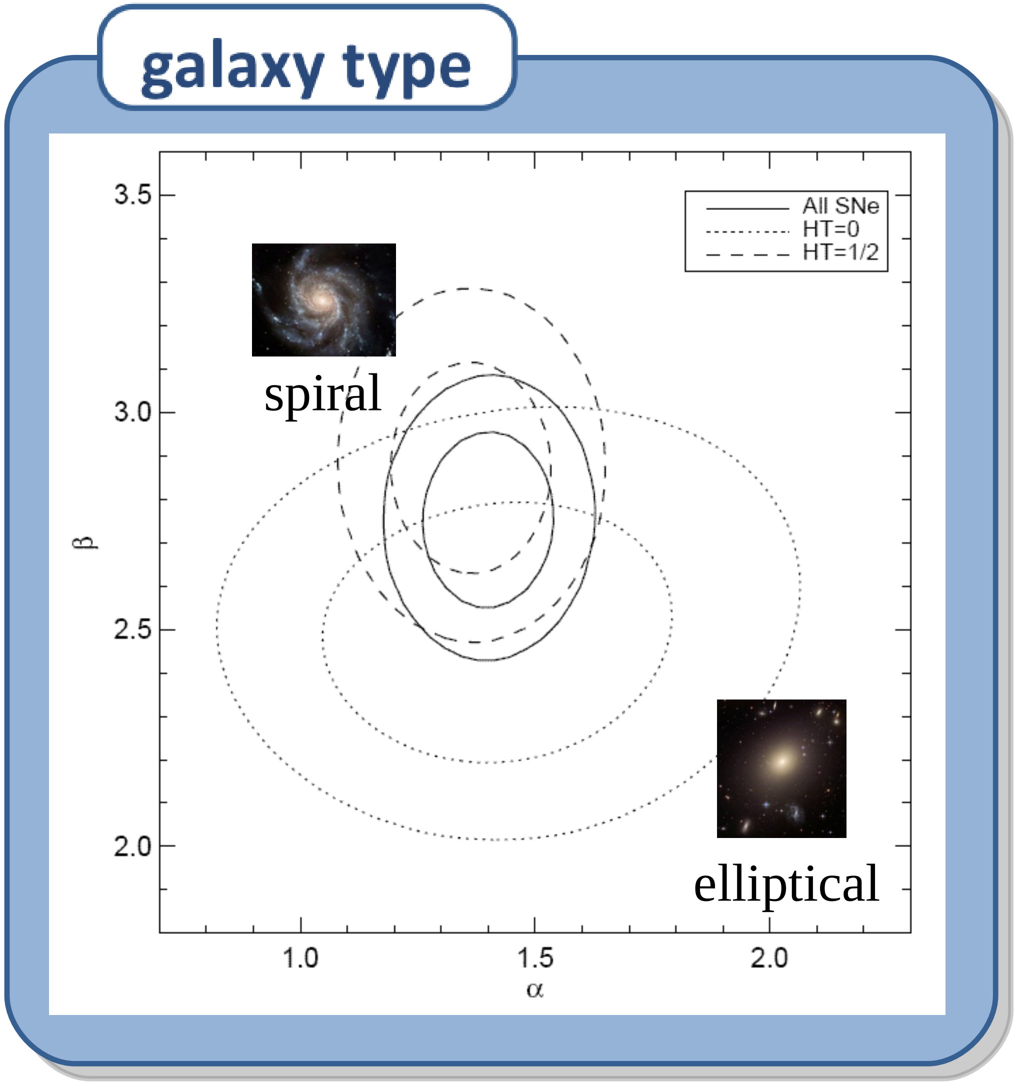
Composite restrame B lightcurve split by environment

Conley et al. 2006



Determine alpha (luminosity correction), beta (color correction), from subsamples split by…





Cosmology Split by Host Galaxy Type

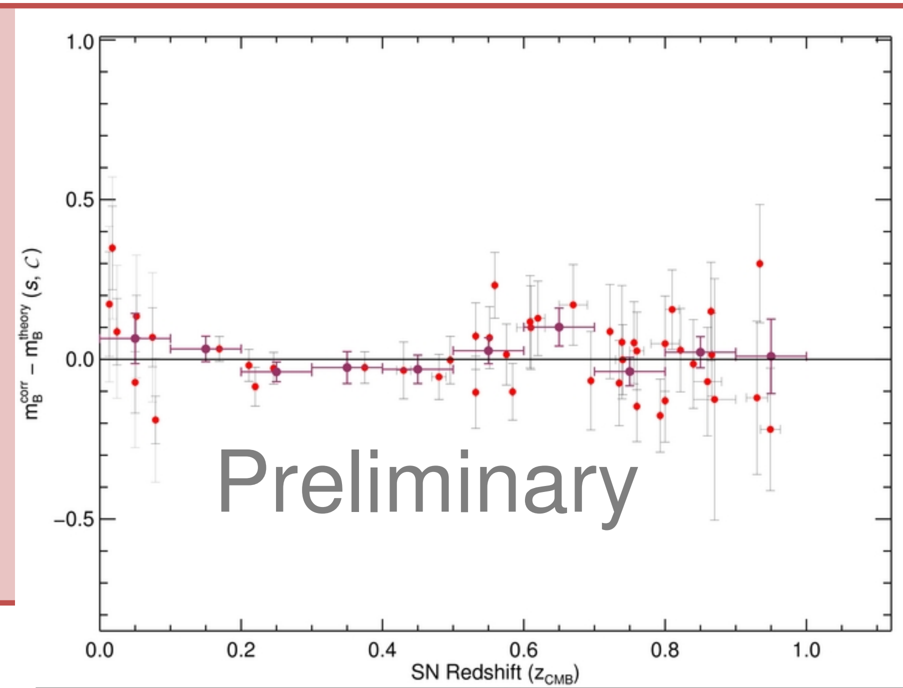
Passive

α=1.43 ± 0.25

β=2.51 ± 0.20

rms=0.127 mag

w = -1.03±0.12



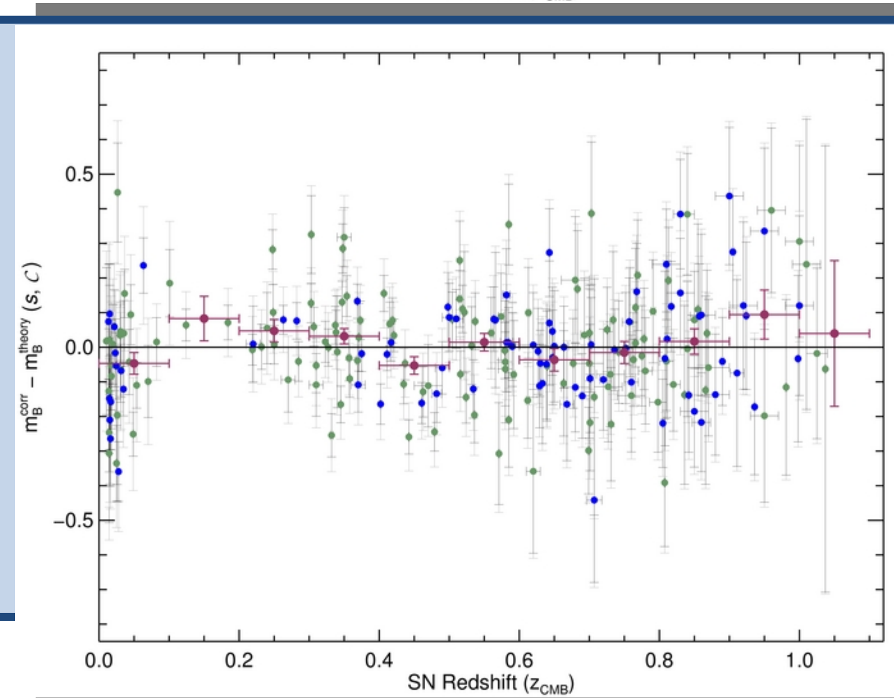
Star-forming

α=1.36 ± 0.12

β=2.88± 0.17

rms=0.159 mag

w = -1.04±0.07



Problems: Low-redshift sample very small, Malmquist correction likely to be different

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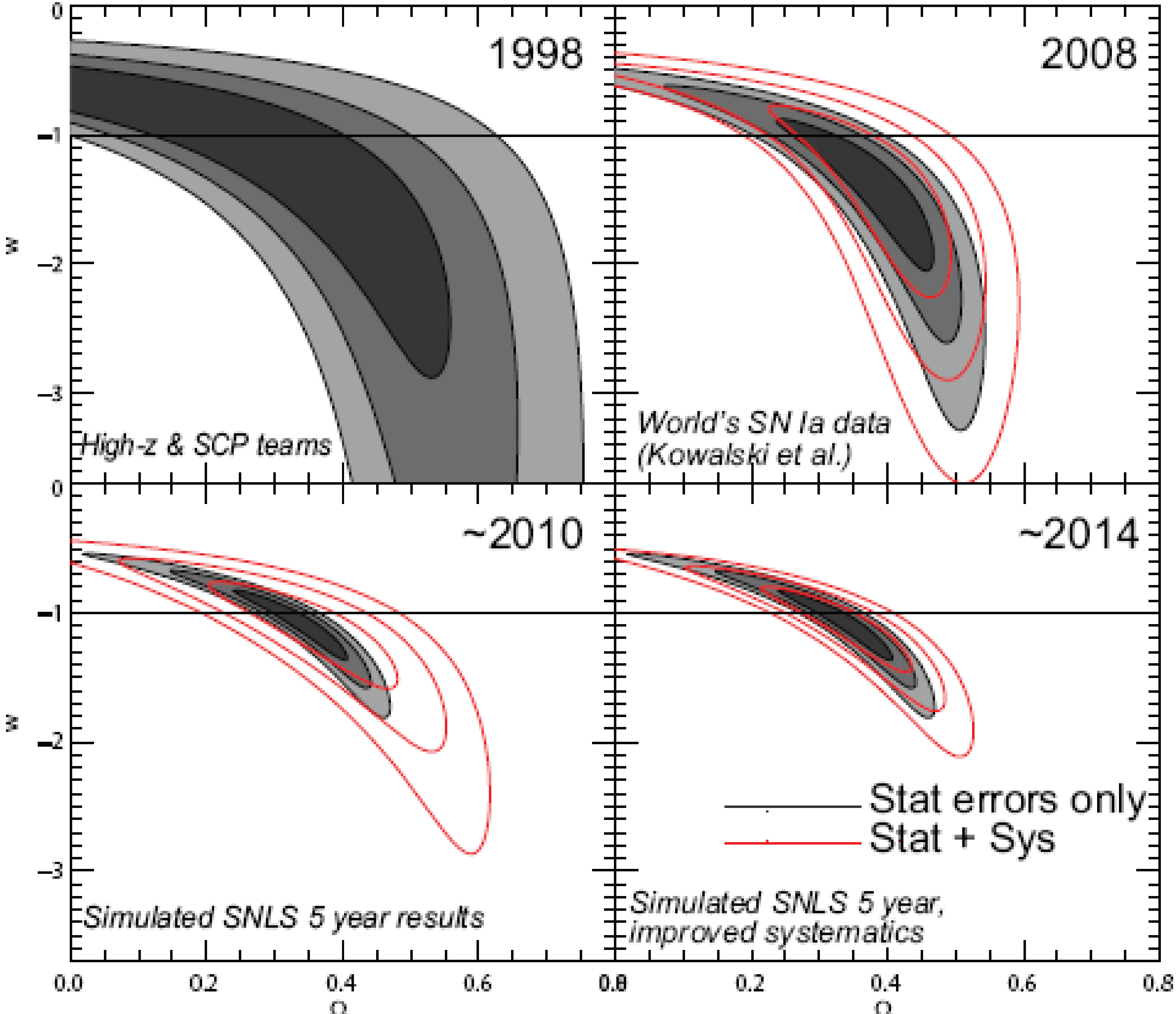
Systematics Forecast



Summary

Type Ia SNe provide a conceptually simple and mature way to measure distances as a function of redshift

The cosmological parameters from the latest surveys are already systematics limited – these errors are being probed empirically and this will probably continue

Future SN surveys will need more information rather than (just) more objects – low redshift, colours, spectra, IR...

As well as detecting acceleration, SNe play an important role in the joint analysis, breaking the key degeneracy from the CMB

WMAP5 provides the baseline prior for DE studies