The Abdus Salam International Centre for Theoretical Physics

2354-30

Summer School on Cosmology

16 - 27 July 2012

Supernova Cosmology

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Supernova Cosmology

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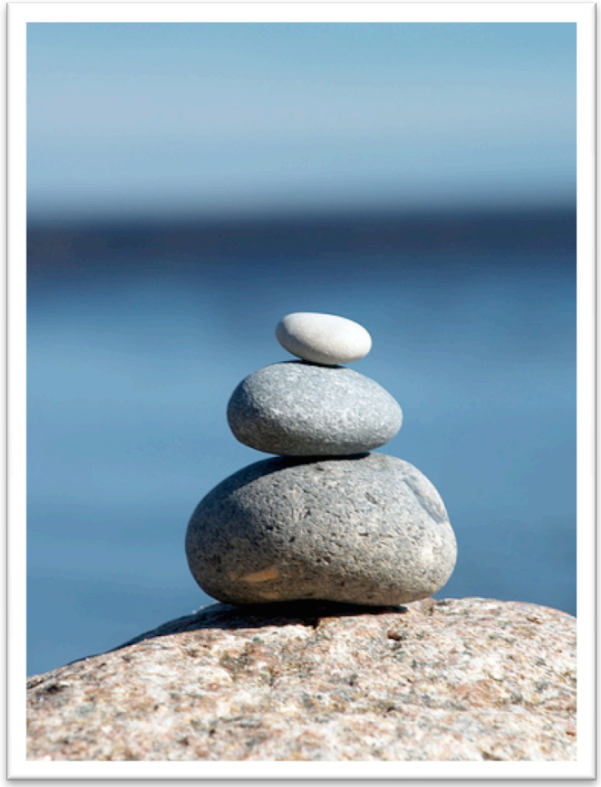
Parkinson Challenge

- Download the Union SNIa data online, write an MCMC algorithm in your favourite language and derive constraints on Ω_m, Ω_λ marginalising over H_0.

- Time frame: finish before I stop talking.

Overview

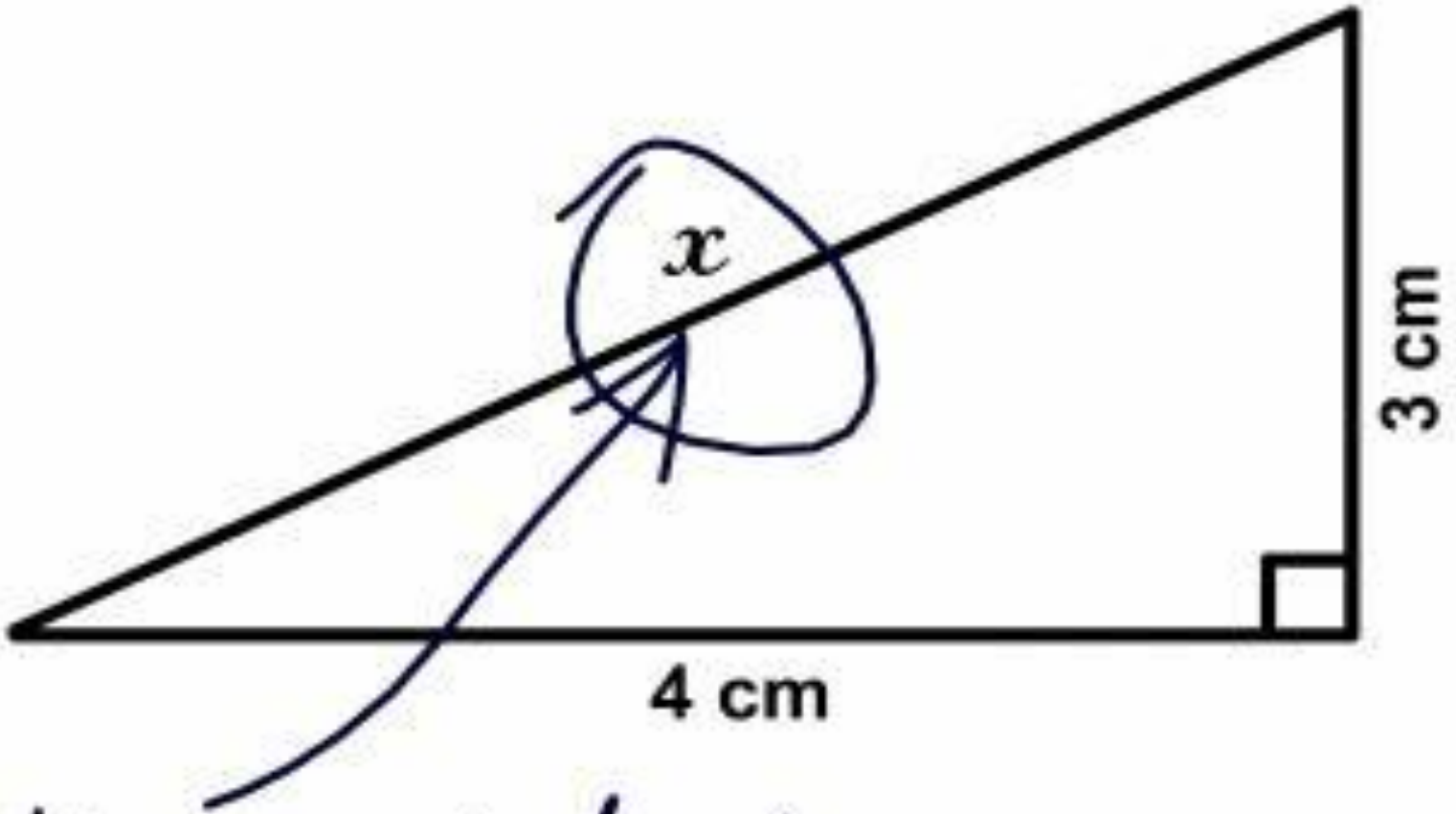
- What distances do
- The Good: SNIa and the Miracle
- The Ugly
- The Future



Our life is frittered away by detail.
Simplify, simplify, simplify!

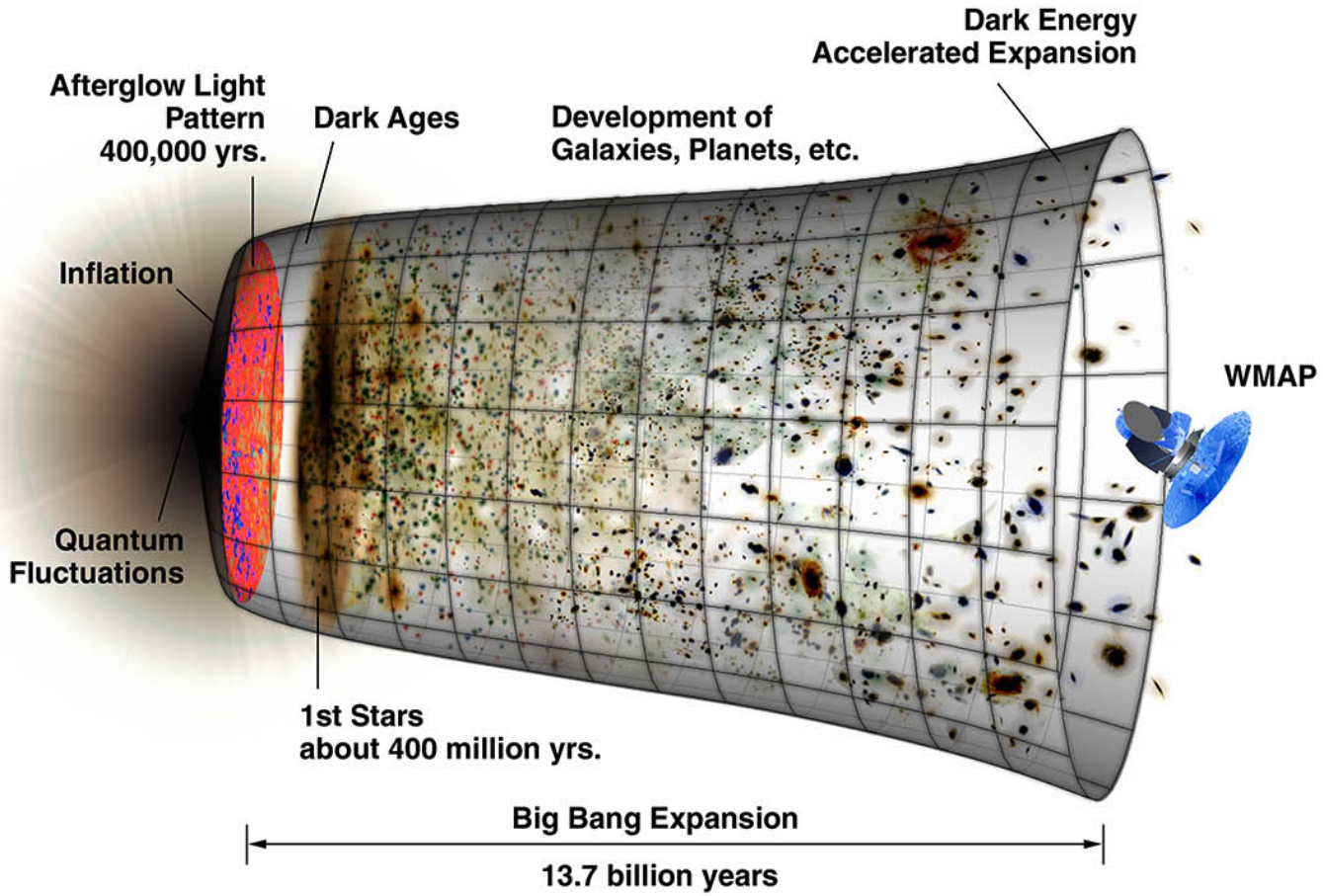
-- Henry David Thoreau

3. Find x.



Here it is

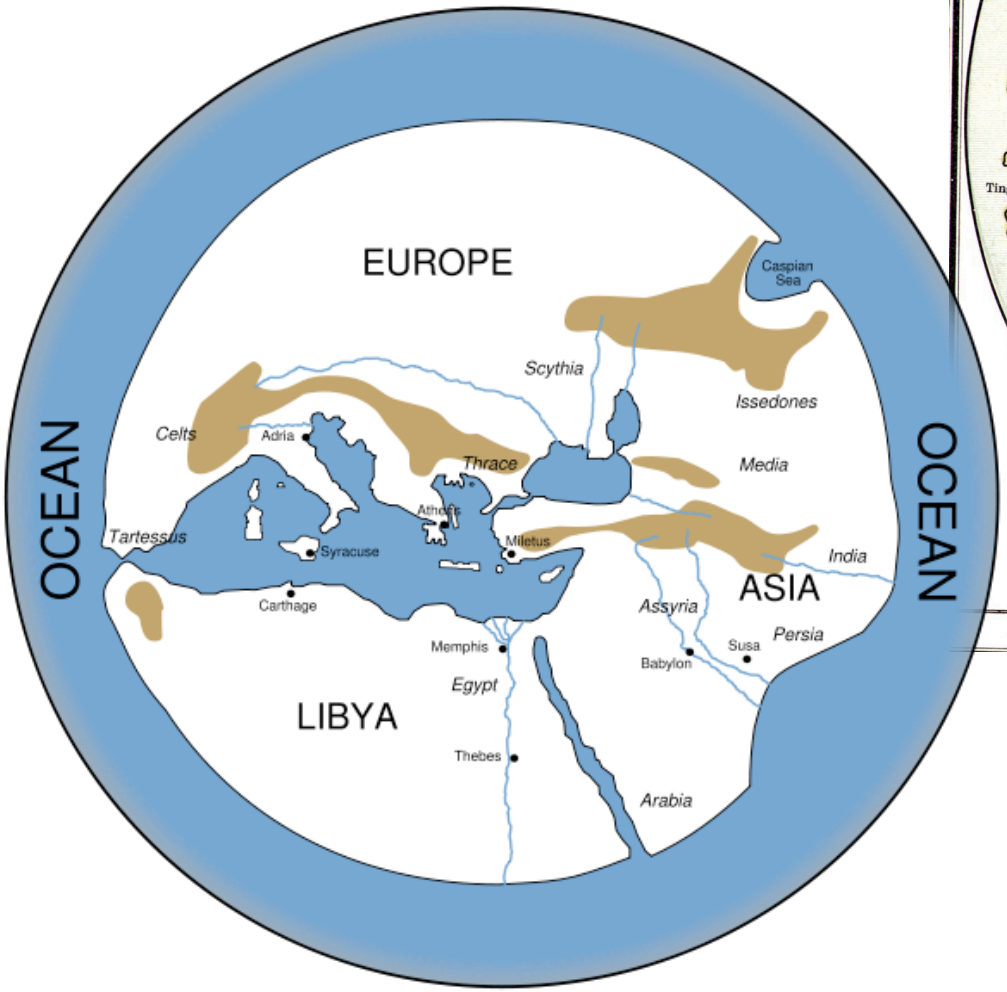
Ocular Trauma - by Wade Clarke ©2005



Redshift, colours, spectra, fluxes → Dynamics, scale and content of the cosmos

NASA/WMAP Science Team

H_0, Ω_{DE}, Ω_m, Ω_k etc…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Persia
Memphis
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LIBYA
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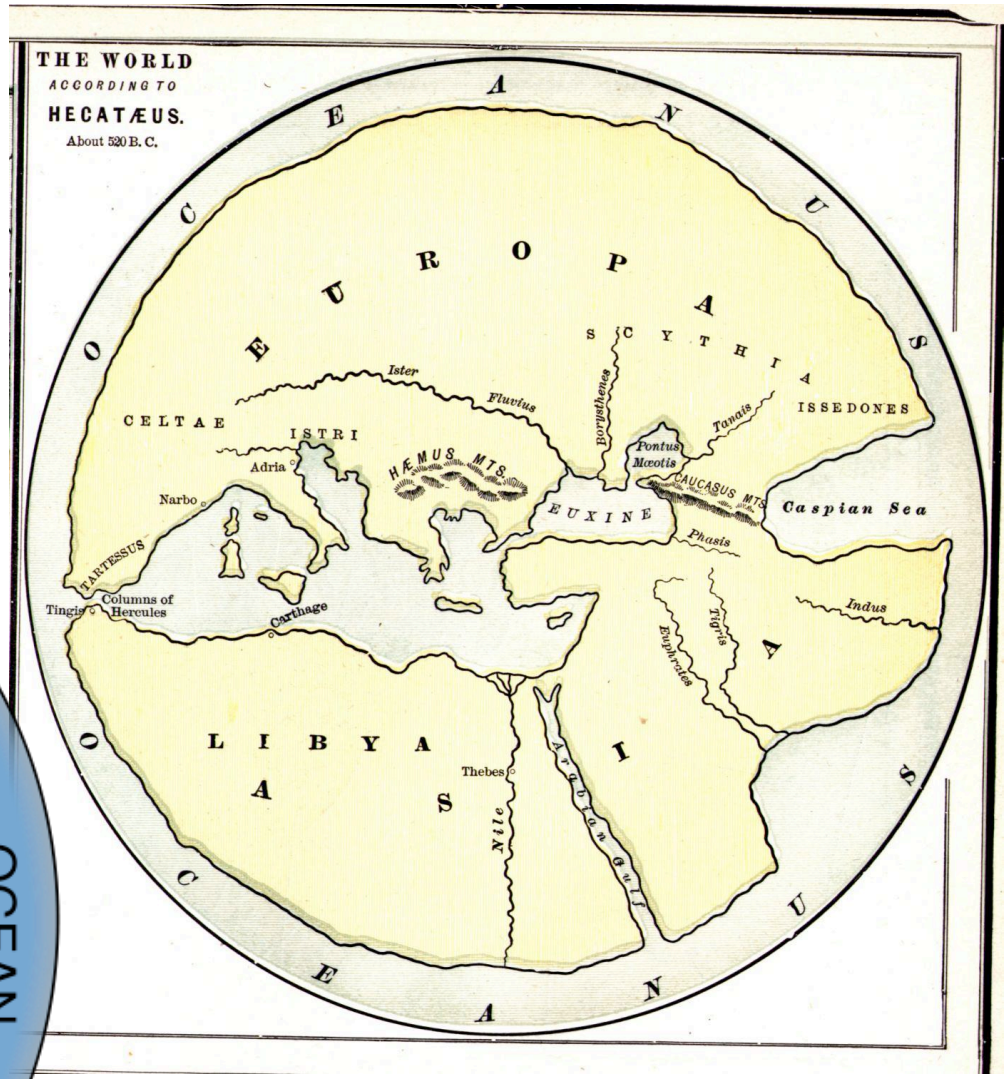
THE WORLD
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About 520 B. C.
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SCYTHIA
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Ister
Fluvius
Borysthenes
Tanais
Pontus Mœotis
Adria
HÆMUS MTS.
CAUCASUS MTS.
Caspian Sea
Narbo
EUXINE
Phasis
TARTESSUS
Columns of Hercules
Tingis
Carthage
Indus
Euphrates
Tigris
LIBYA
ASIA
Thebes
Nile
Arabian Gulf

How do we measure distances in everyday life?

"The real benefit is the fact that it's easier for others to figure out how far away you are… I can say that, after putting two headlinghts on one of my bikes, I had much fewer near-incidence of people stepping out right in front of me"

www.bikeforums.net

A tale of two distances

- Two main distances in cosmology: Luminosity distance (d_L) and angular-diameter distance (d_A)

$$\text{Photon Flux} \;\alpha\; d_L^{-2}$$

- They are related by distance duality:

$$d_L(z) = (1+z)^2 d_A(z)$$

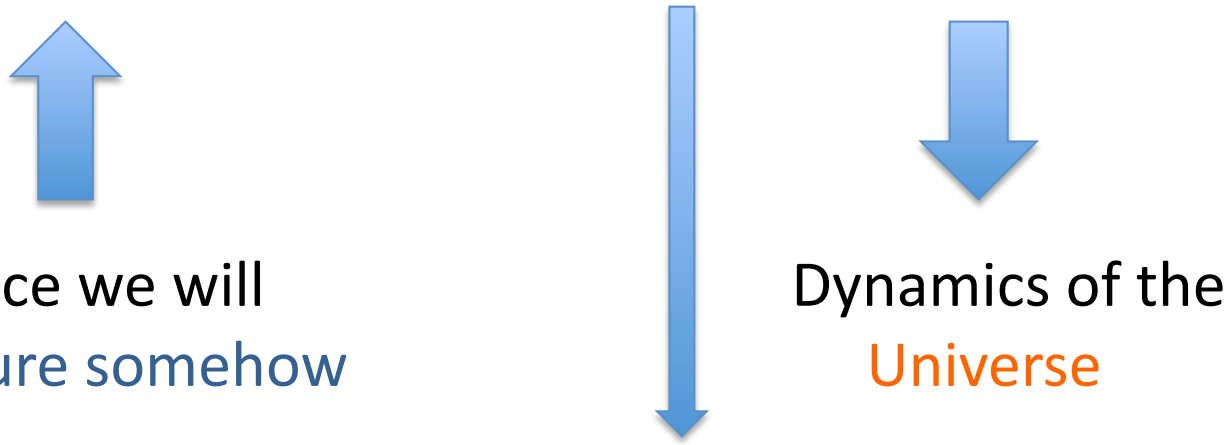
This is true in any metric theory of gravity with photon conservation and any metric

What do distances tell us?

Let's assume the Universe is flat ($\Omega_k = 0$) to start with.

Then…

$$d_L(z) = (1+z)$$



What do distances tell us?

Let's assume the Universe is flat ($\Omega_k = 0$) to start with.

Taylor expanding to second order gives…

$$d_L(z) = \frac{c}{H_0}\left[z \right]$$

H_0 sets the overall *scale* for *all* Distances (Hubble's law is true for all models)

What do distances tell us?

Let's assume the Universe is flat ($\Omega_k = 0$) to start with.

Taylor expanding to second order gives…

$$d_L(z) = \frac{c}{H_0}\left[z + \frac{1}{4}(1 + 3\Omega_\Lambda)z^2 ...\right]$$

H_0 sets the overall *scale* for *all* Distances (Hubble's law is true for all models)

The *shape* of the Hubble Diagram depends on Ω_Λ

What do distances tell us?

What happens when we don't assume flatness?

$$d_L(z) = (1+z)\,\frac{c}{H_0}\,\sin\left(\sqrt{-\Omega_K}\int \frac{dz'}{E(z')}\right)$$

χ

Encodes the effect of the curved null geodesics …

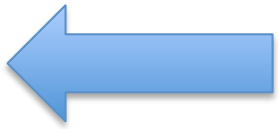
What do distances tell us?

What happens when we don't assume flatness?

Taylor expanding to second order gives…

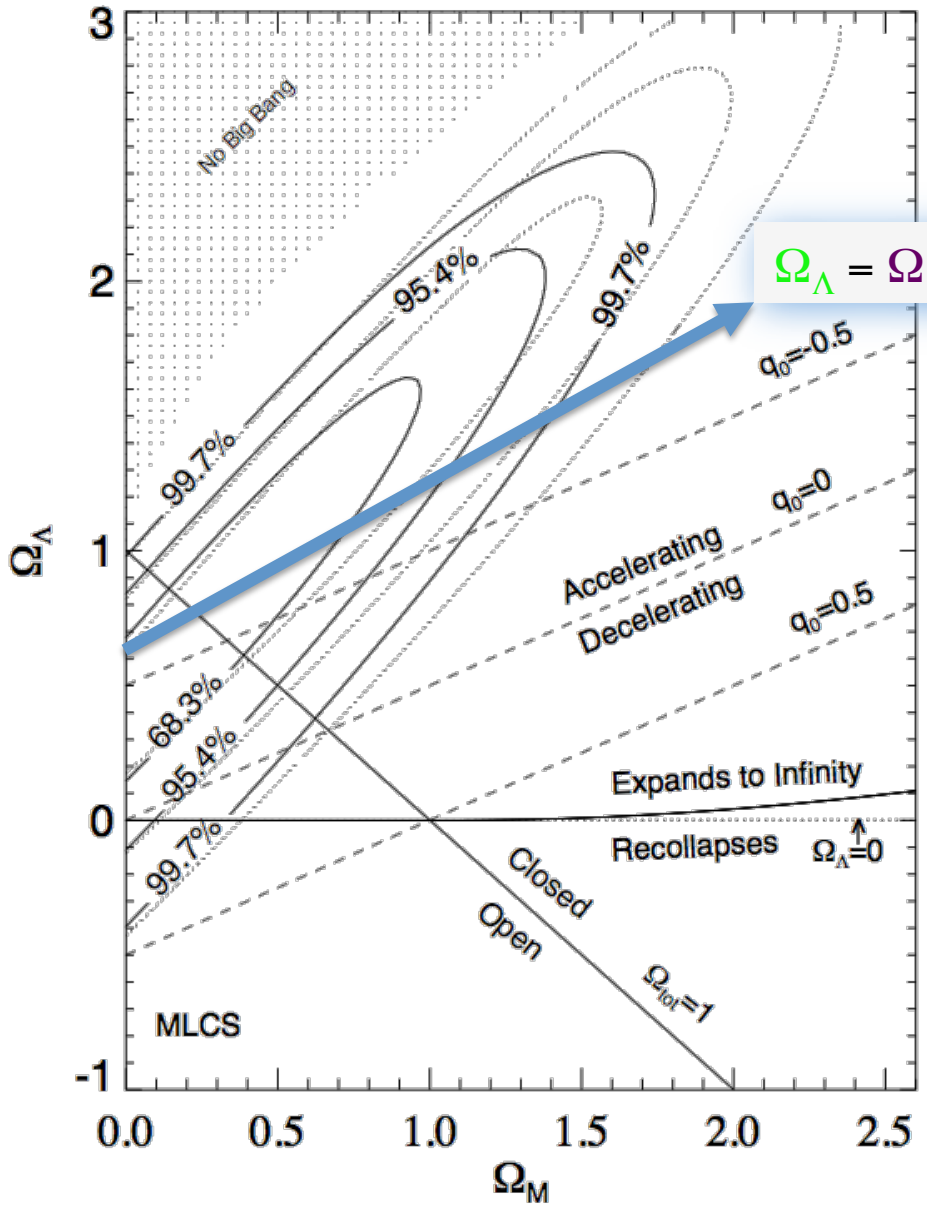
$$d_L(z) = \frac{c}{H_0}\left[z + \frac{1}{4}(1 + \Omega_K + 3\Omega_\Lambda)z^2 \ldots\right]$$

The *curvature* of the Hubble Diagram now depends on the Amount of dark energy AND the spatial curvature, Ω_K



2nd order term is degenerate on the line:

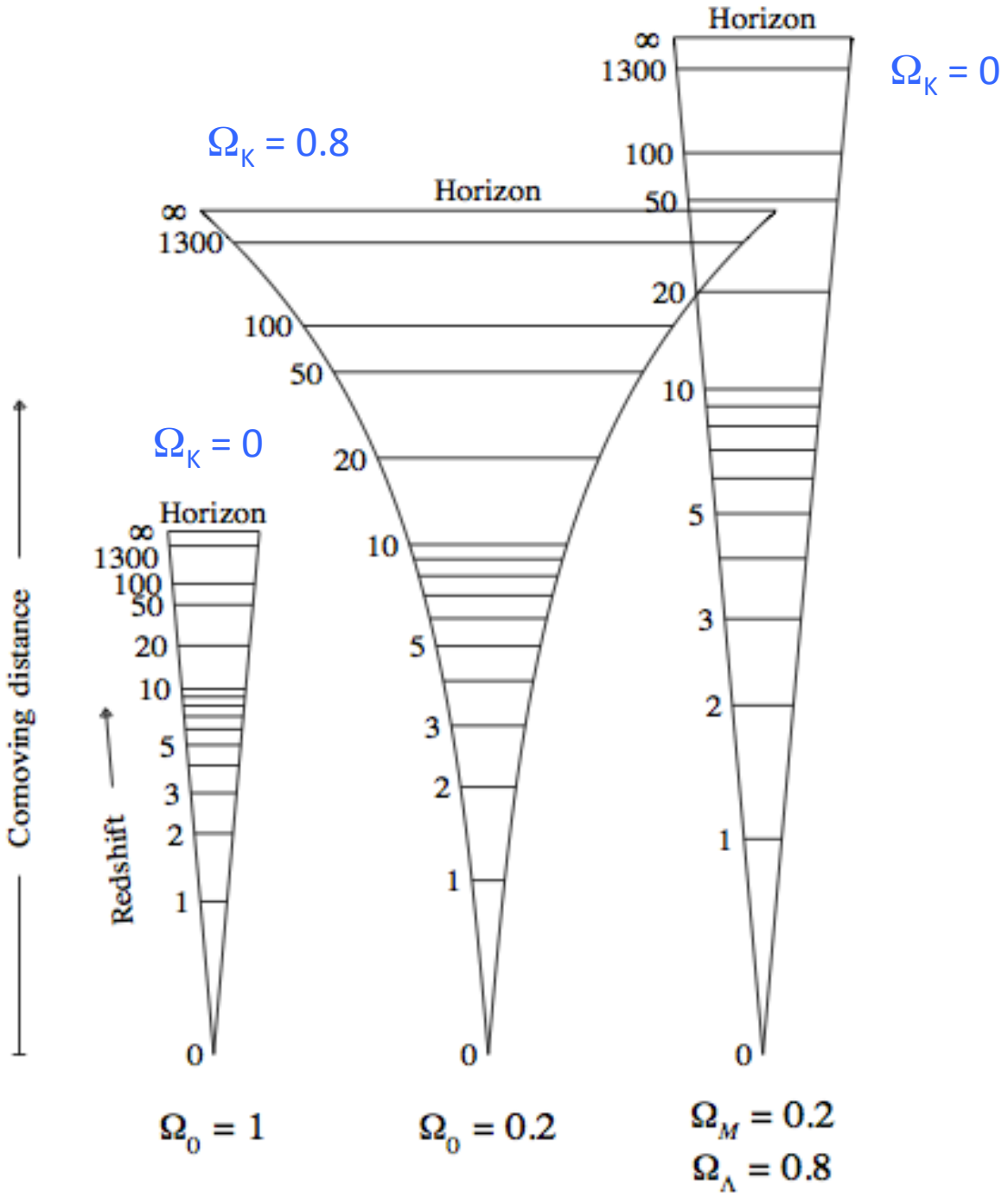
$\Omega_\Lambda = \Omega_M/2 + \text{const.}$



$\Omega_\Lambda = \Omega_M/2 + \text{const.}$

Riess et al, 1998

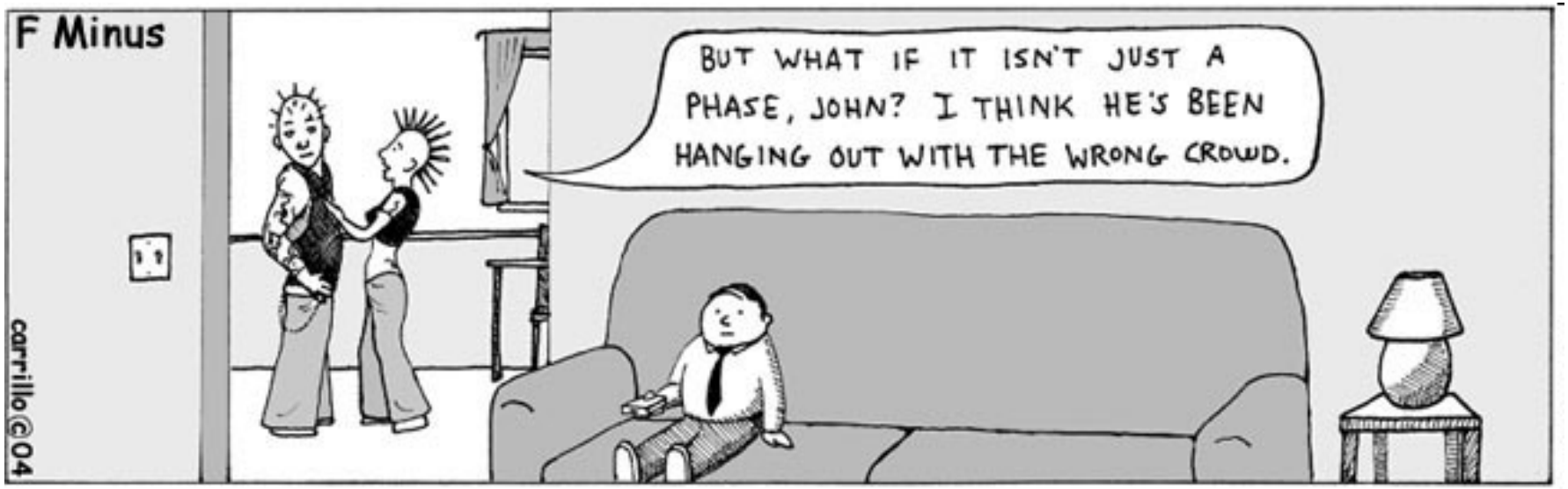
$$\frac{c}{H_0}\underbrace{\int \frac{dz'}{E(z')}}_{\chi}$$



Hamilton 97

So how do we measure a luminosity distance?

- Or "why cosmologists care about stars"



Distance modulus and magnitudes

Apparent Magnitude

$$\mu = m - M \equiv 5\log_{10}\left[\frac{d_L(z)}{1Mpc}\right] + 25$$

Distance Modulus

Absolute Magnitude

d_L converts M → m

Common in Supernova cosmology to plot μ or m_B vs redshift

d_L Wish list…

We want objects that are:

- Very Bright…so we can see them across the observable universe
- Known: We know each object's intrinsic luminosity.
- Standard: no environmental dependence of the intrinsic luminosity
- Time-invariant: their intrinsic luminosity doesn't change with redshift
- Easy to find…
- Emit most of their light in the optical
  (counter example: binary black holes as GW sirens)

Problem: if we don't know M

What can we do?

$$m = M + 25 + 5\log_{10} d_L(z)$$

$$\int \frac{dz'}{E(z')}$$

$$= M + 25 + 5\log_{10}\left(\frac{c}{H_0\sqrt{-\Omega_k}}\right) + 5\log_{10}(1+z) + 5\log_{10}\left(\sin(\sqrt{-\Omega_k}\cdot\chi(z)\right)$$

Constants

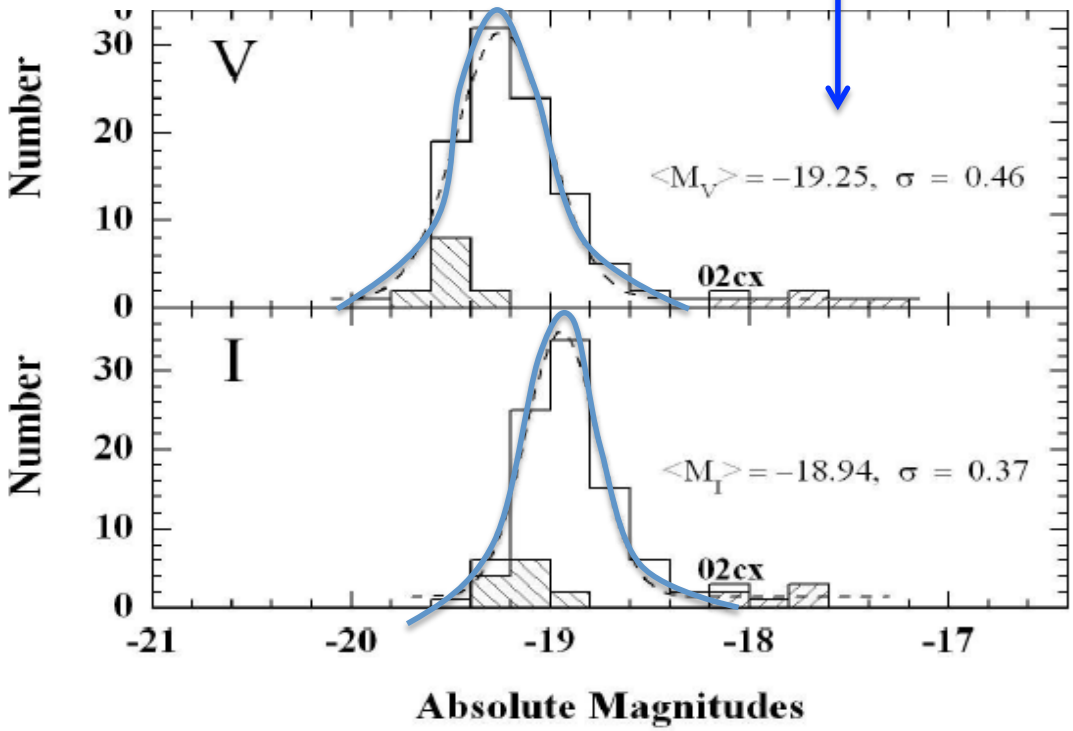
Redshift dependent

If we subtract the apparent magnitudes of two objects with the same M at different redshifts, all the unknown constants disappear…

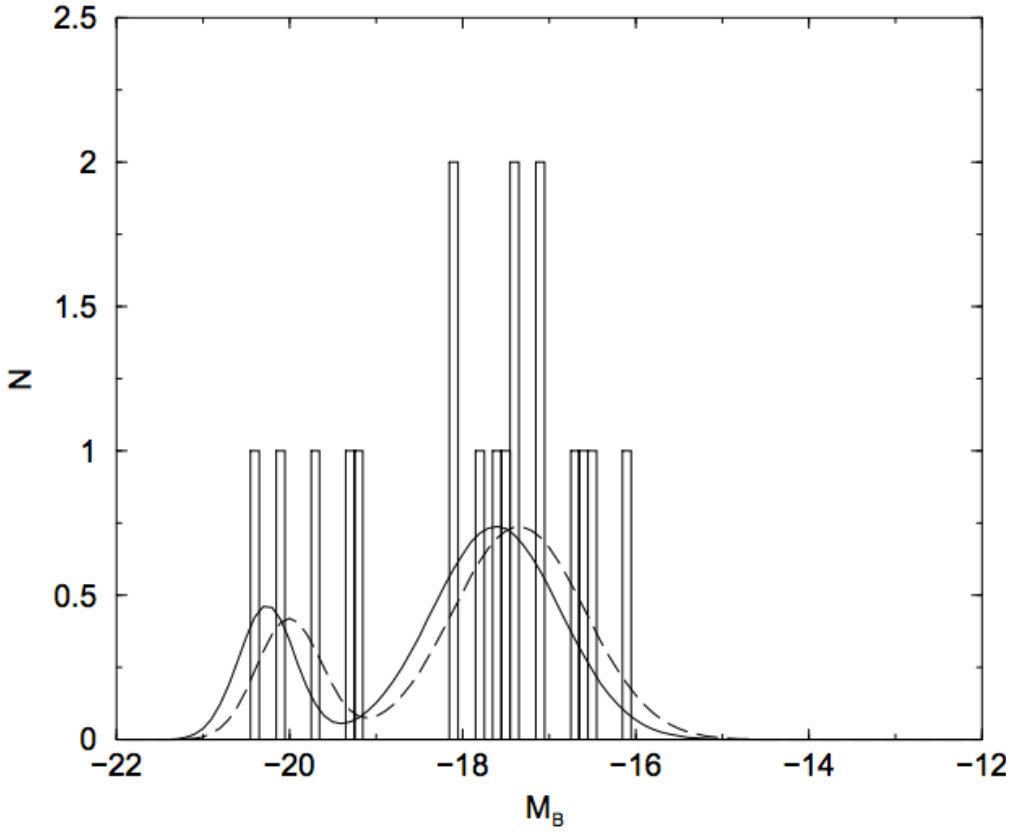
Type Ia Supernovae (SNIa)

- Very Bright…at peak they can outshine their host galaxies
- Stable: Don't seem to evolve with redshift
- Fairly standard:
  σ = 0.4 mag
- Easy to find…

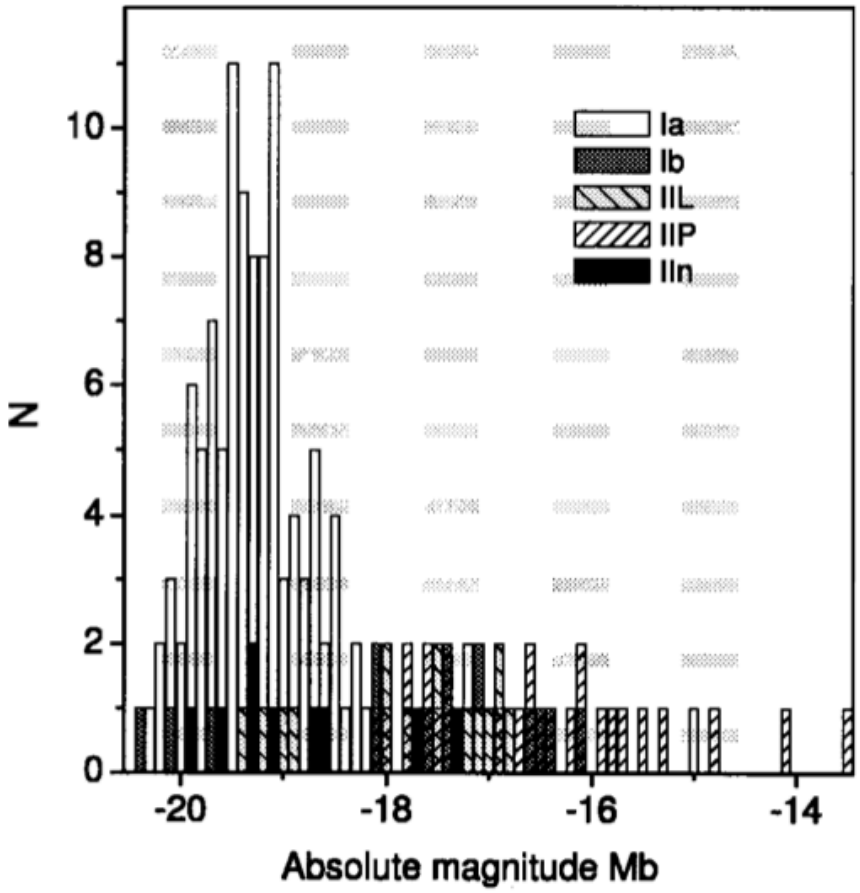
~ 1 per century per galaxy



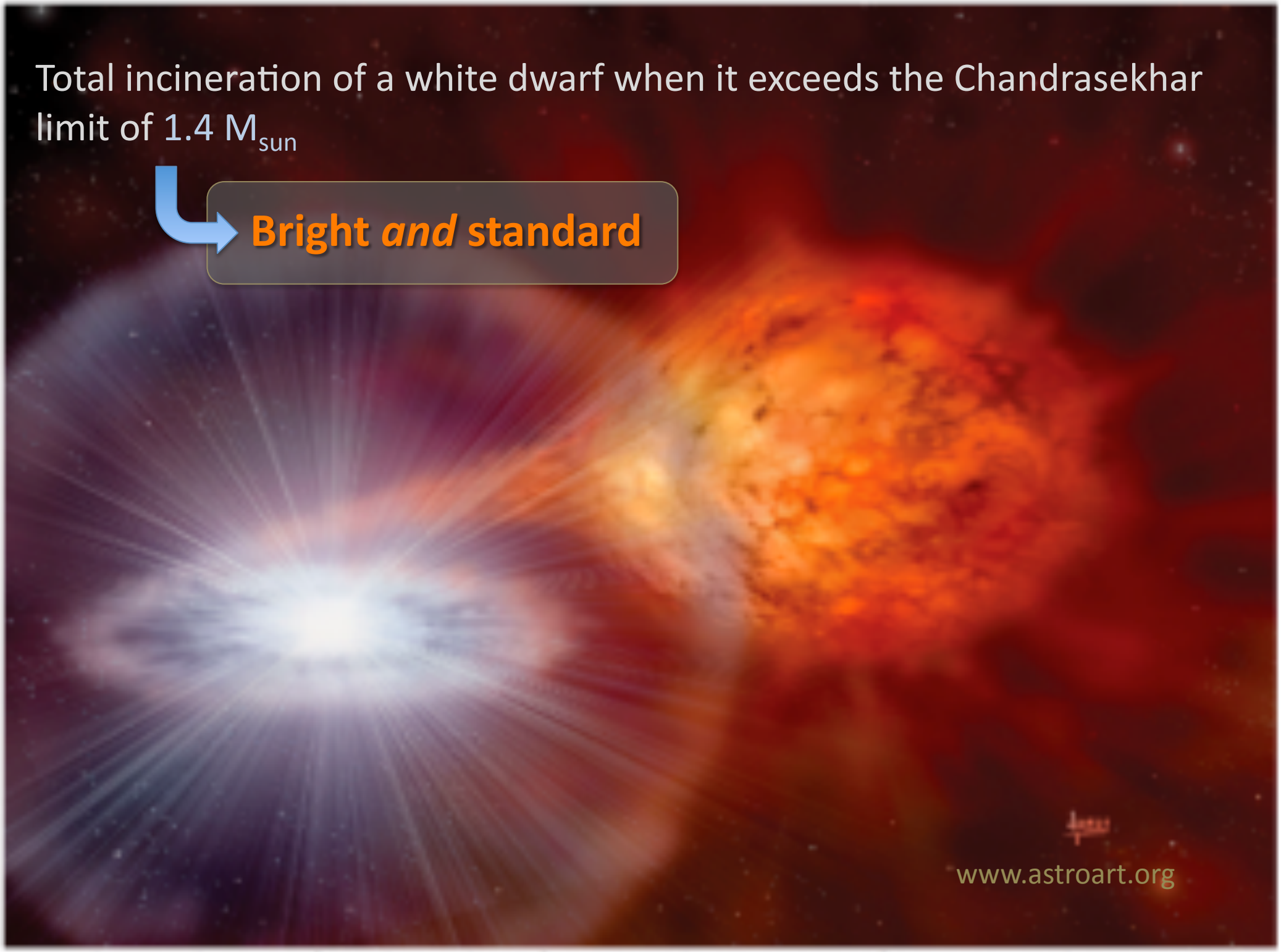
Non-Ia diversity



Richardson et al, 2001



Sveshnikova, 2003

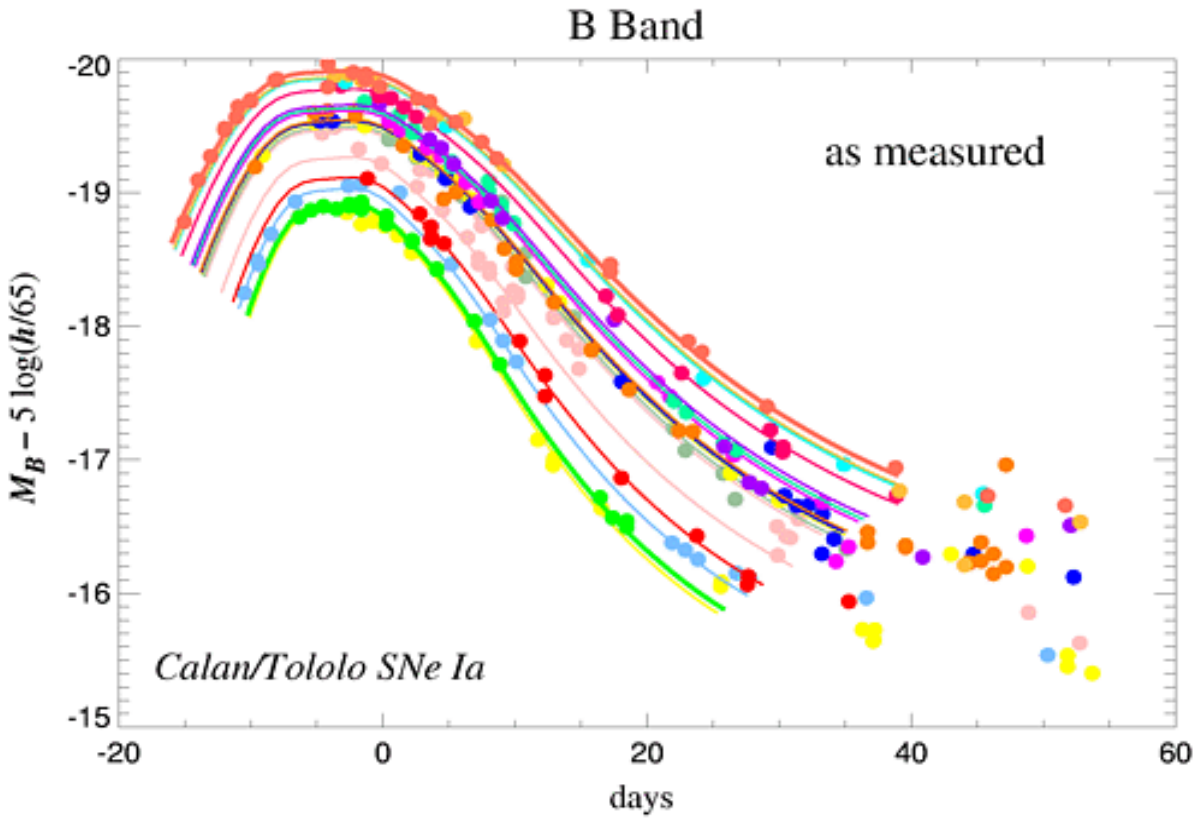


Artist's rendition of a white dwarf accumulating mass from a nearby

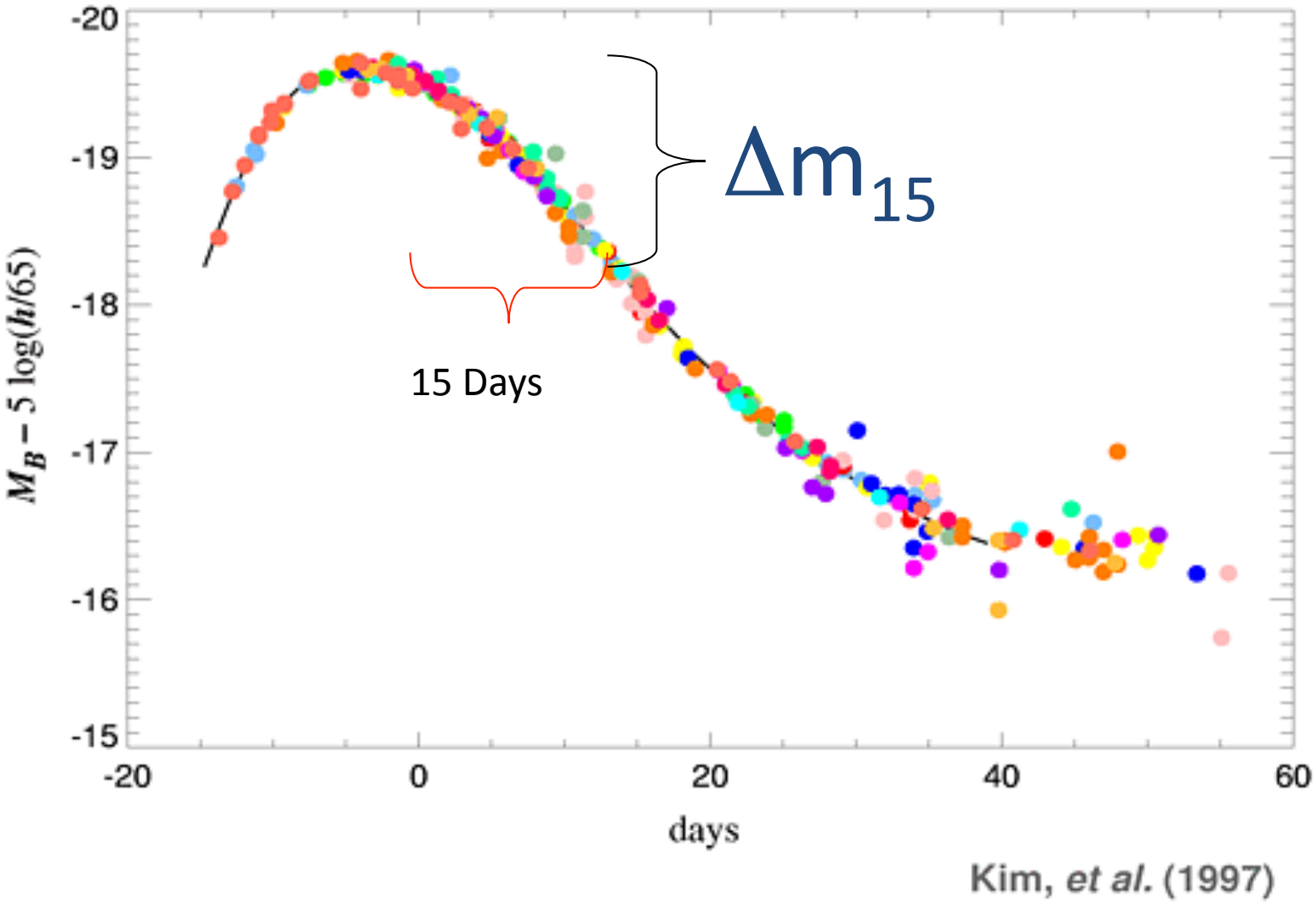
But wait, there's more…

- We can make SNIa even more standard reducing variation in peak brightness to
  σ = 0.12 mag

- Exploit observed correlation between peak brightness, colours and shape of the lightcurve
  (Phillips, 1993).



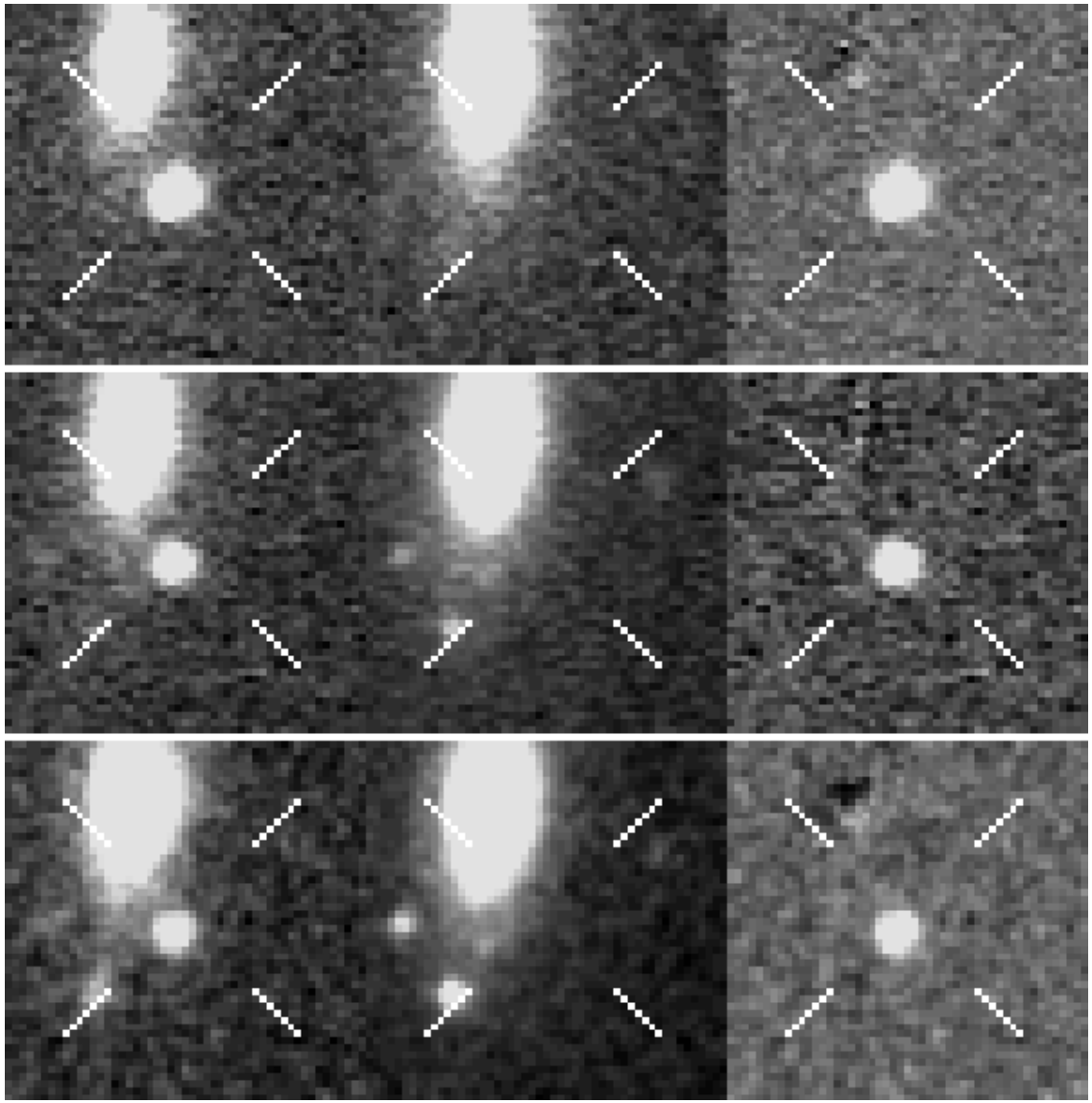
After Standardisation…



Why does
intrinsically brighter → slower decline?

How are SNe found these days?

NEW Image OLD Image Difference



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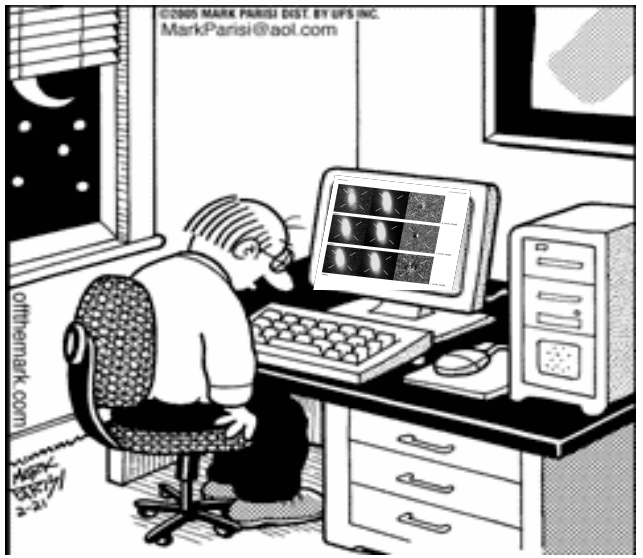
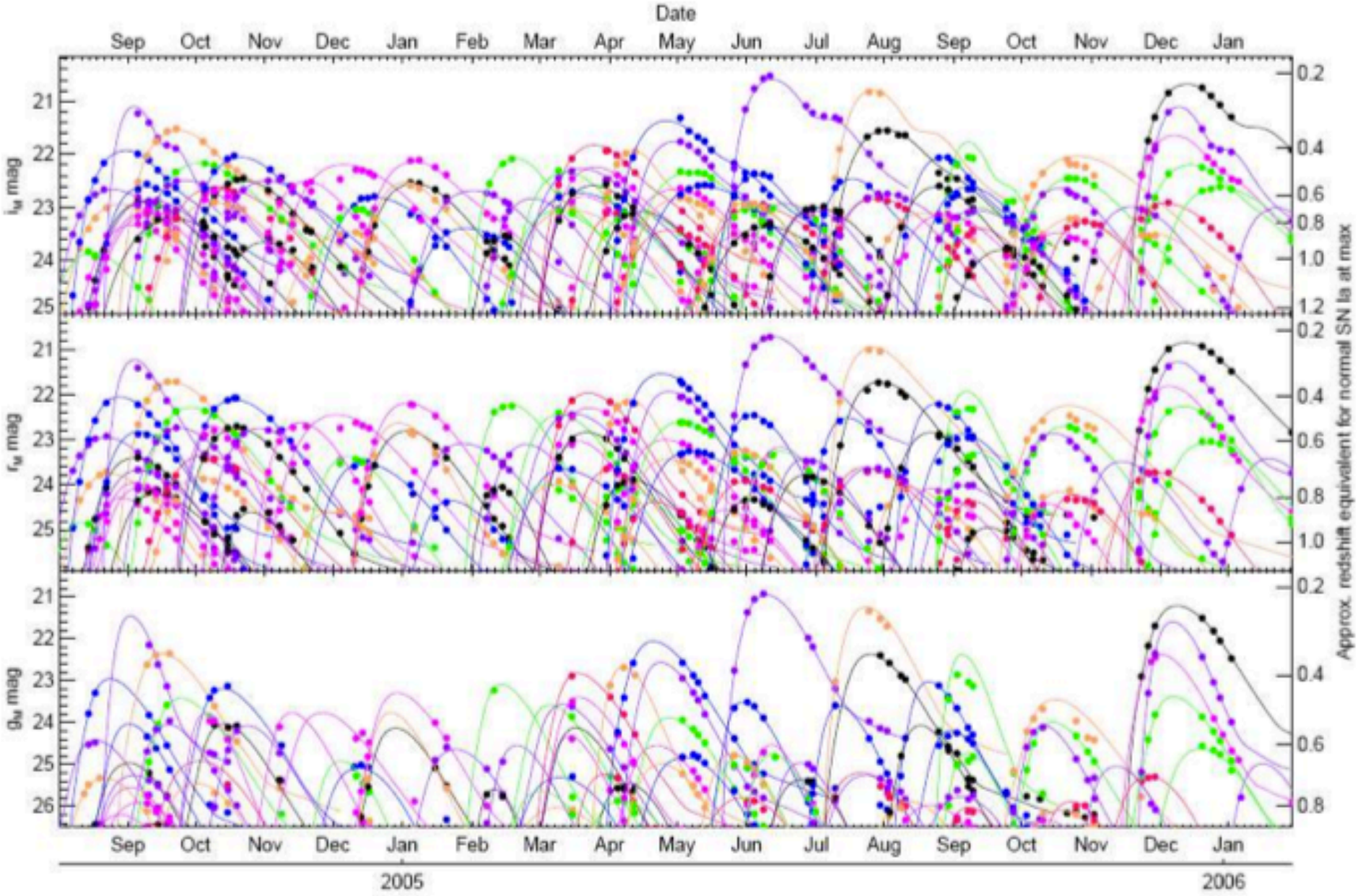


SDSS SN search



SNLS Rolling Search

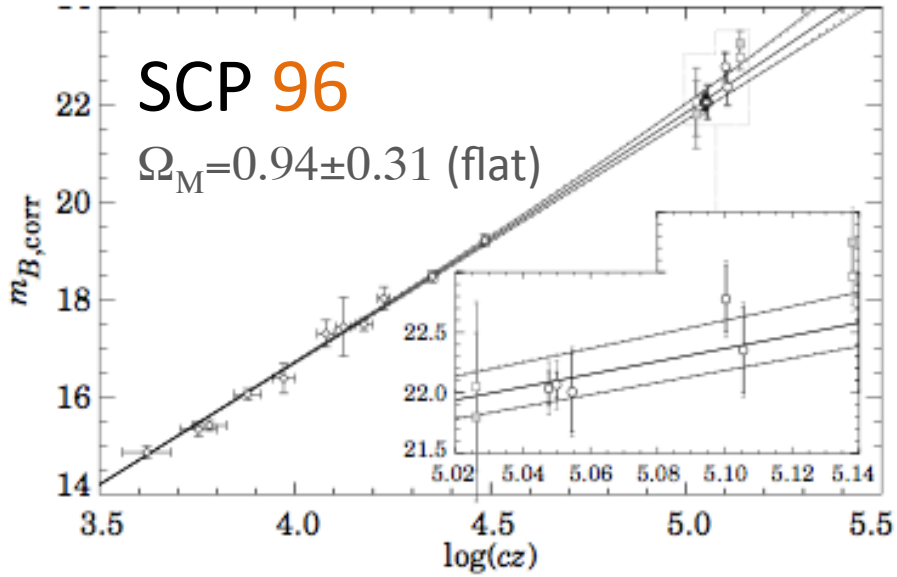
Distance modulus and magnitudes

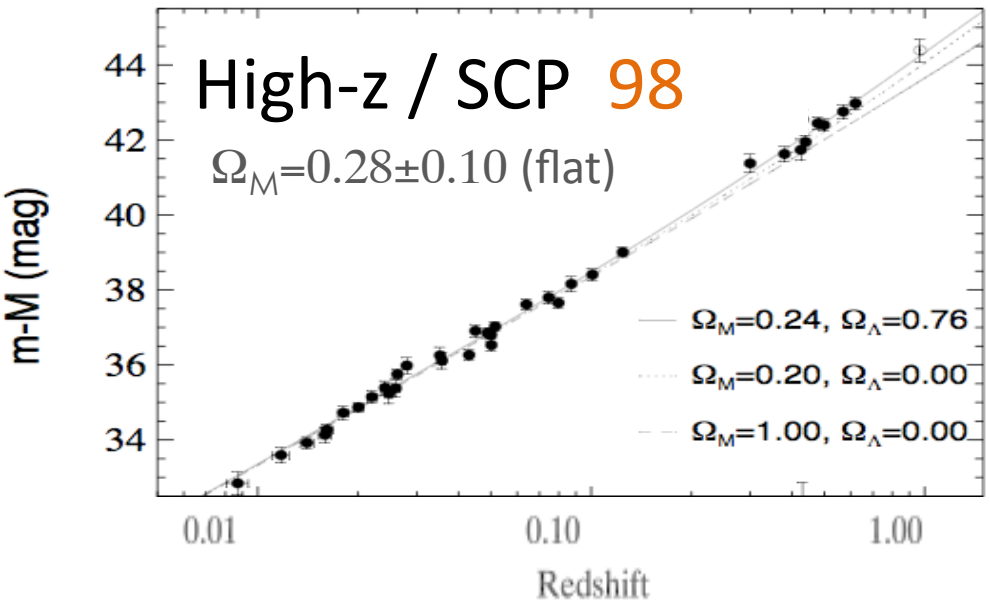
Apparent Magnitude

$$\mu = m - M \equiv 5\log_{10}\left[\frac{d_L(z)}{1Mpc}\right] + 25$$

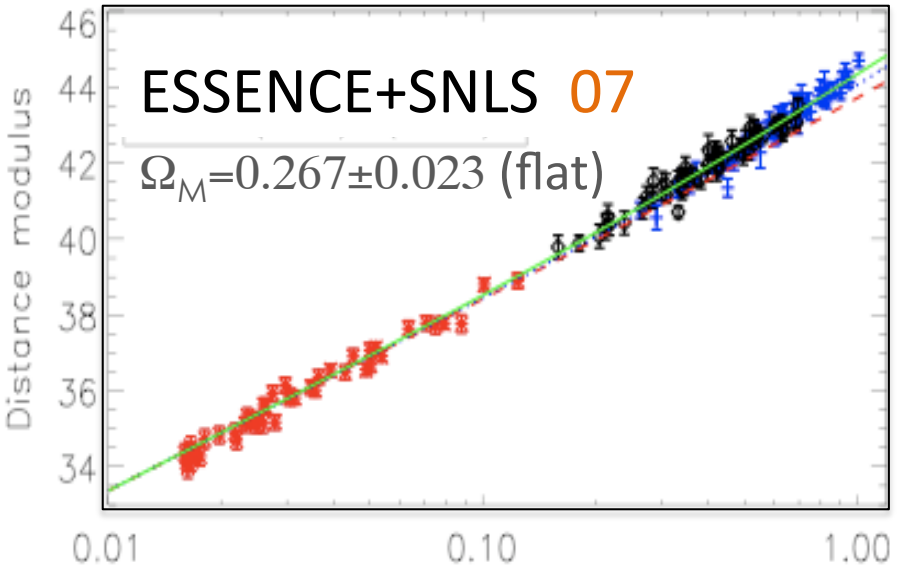
Distance Modulus

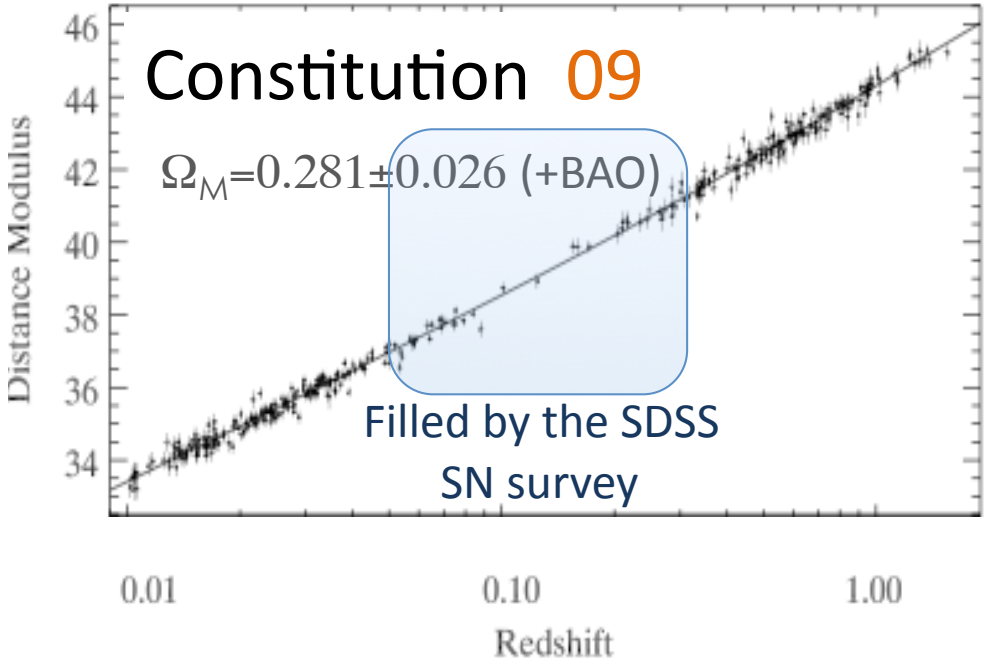
Absolute Magnitude



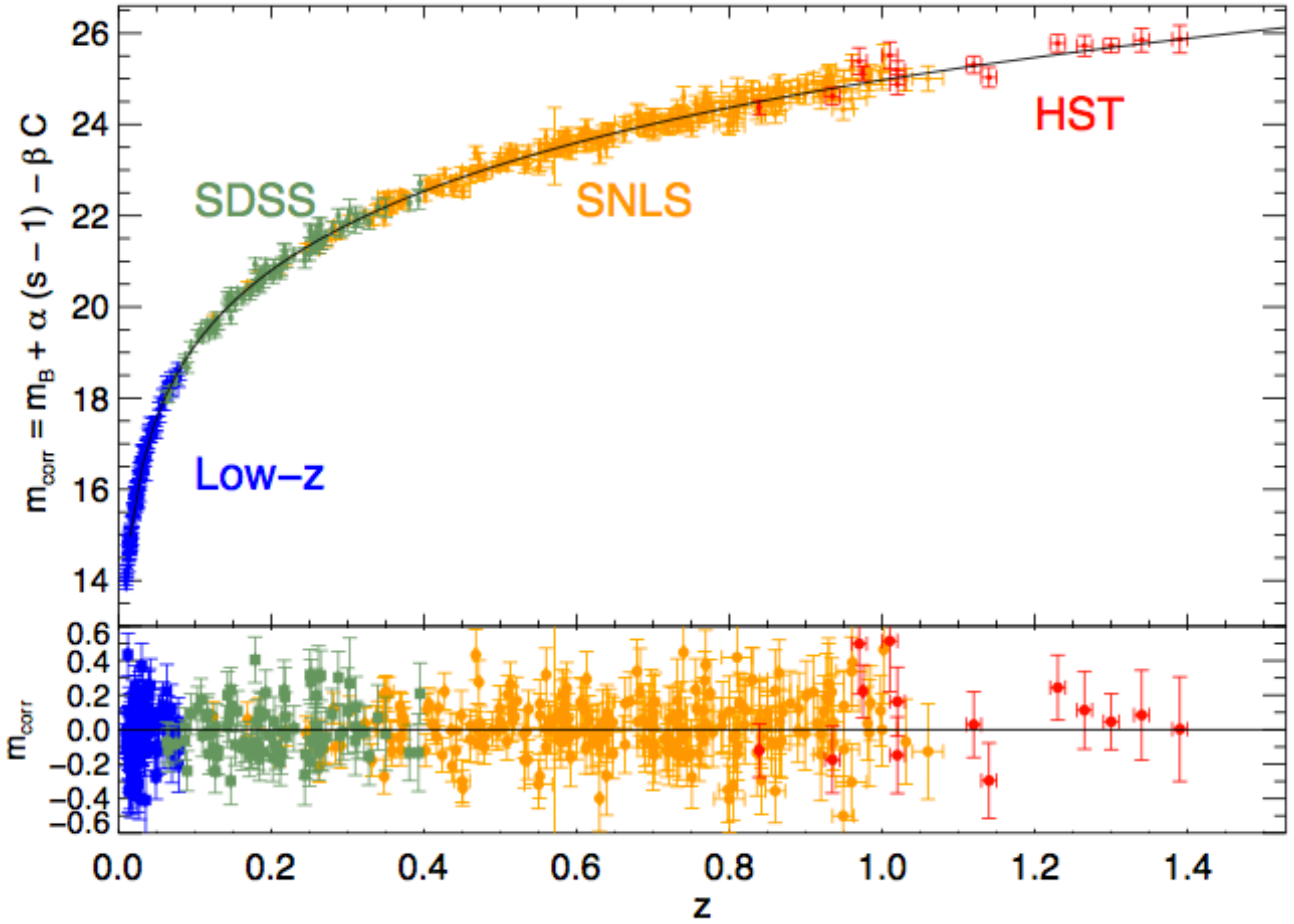


Evolution of the Hubble Diagram 1996-2009





Current state-of-the art

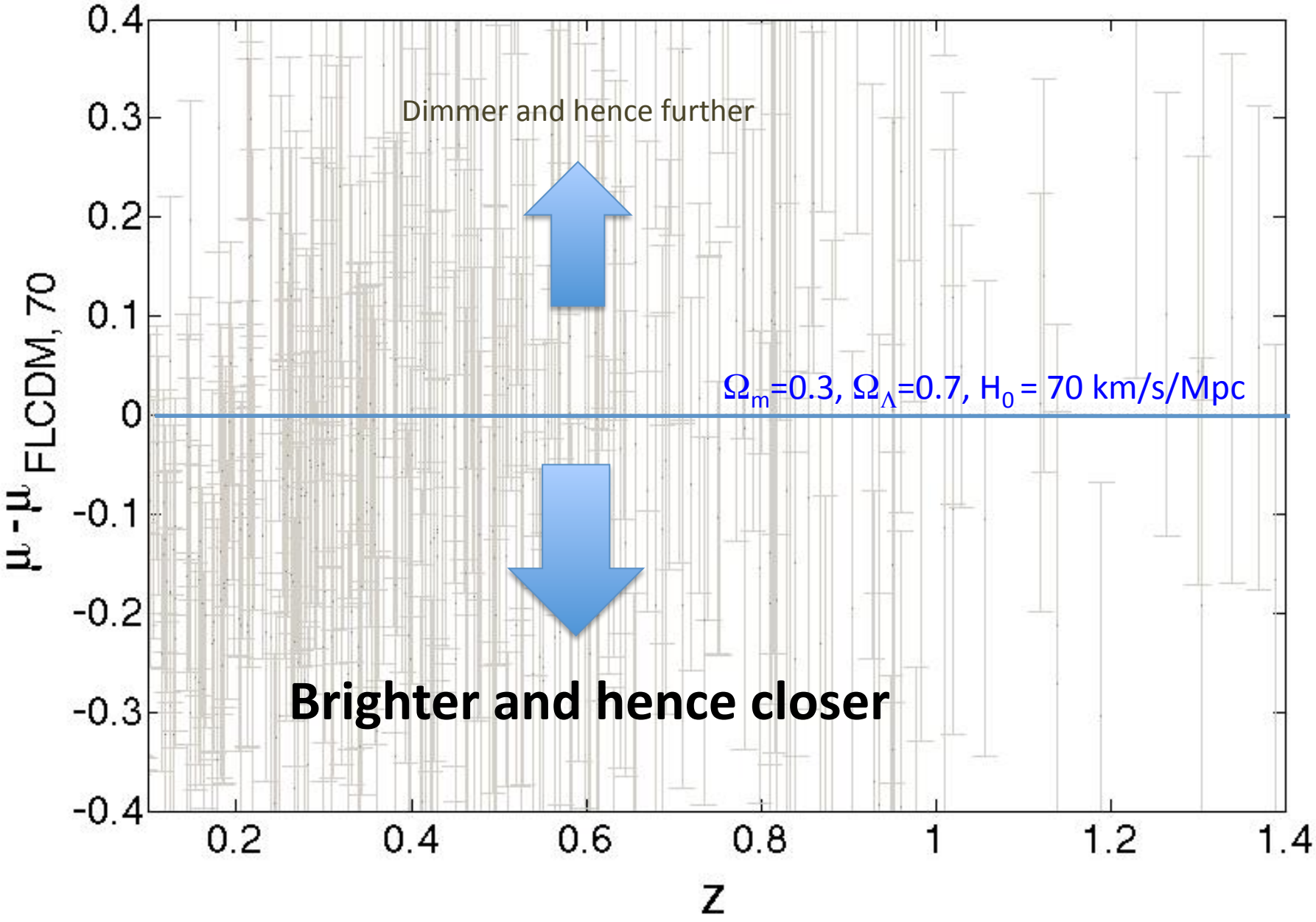


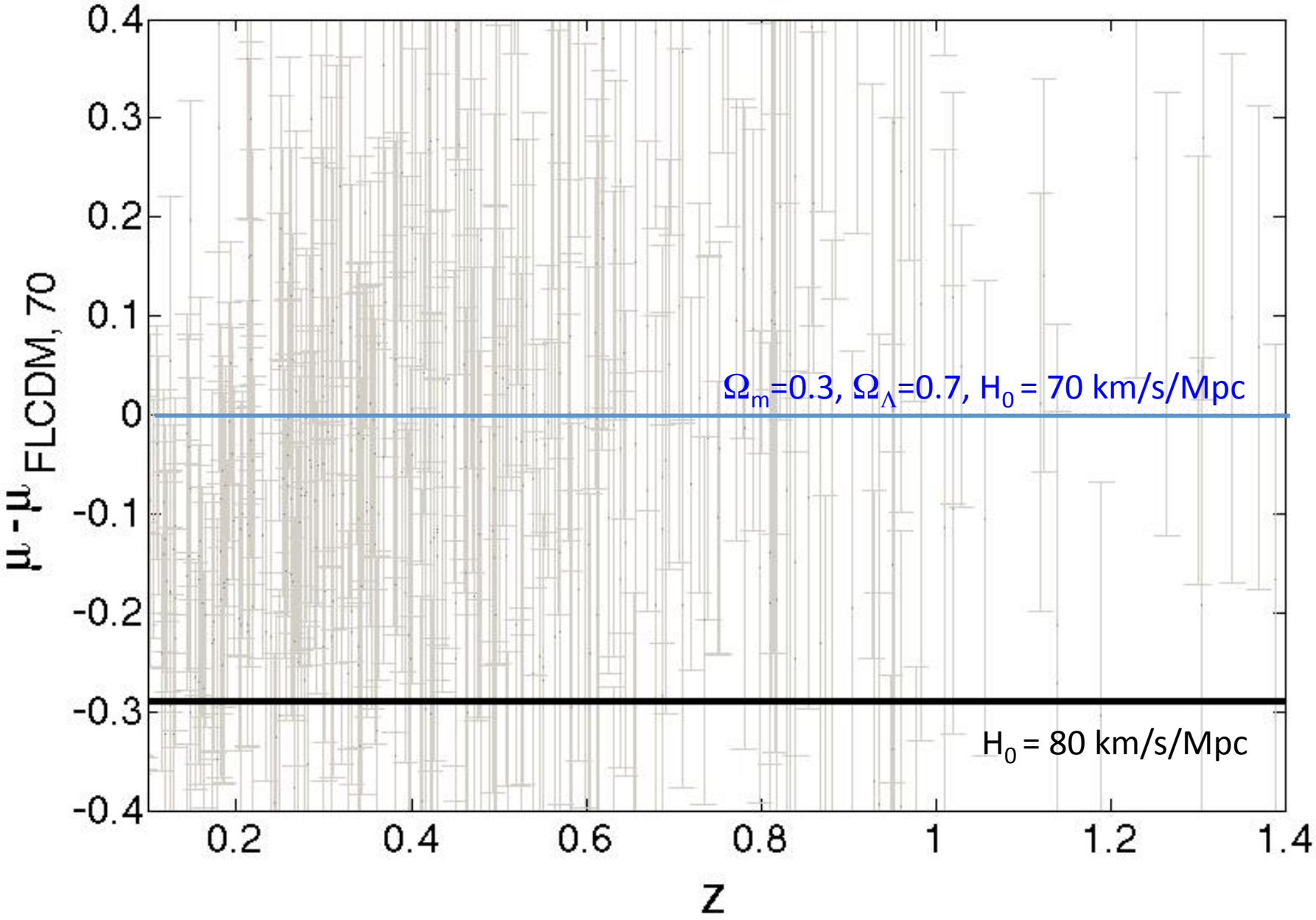
Conley et al, 2011

So what can we learn?

http://abductit.com/files/articles/3d_art/image_01.jpg

Relative Hubble Diagram

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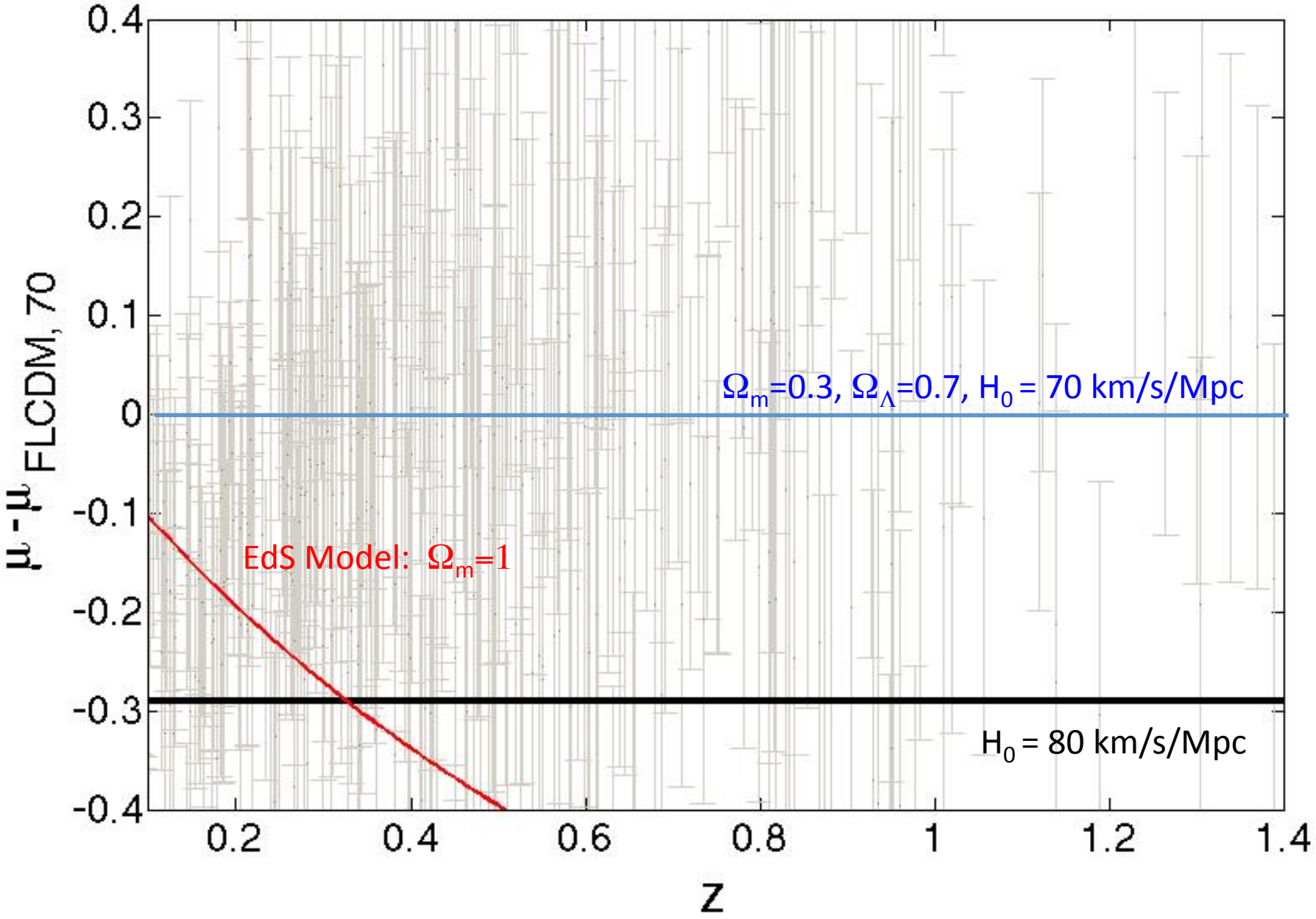
z
μ-μ FLCDM, 70
Ωm=0.3, ΩΛ=0.7, H0 = 70 km/s/Mpc
H0 = 80 km/s/Mpc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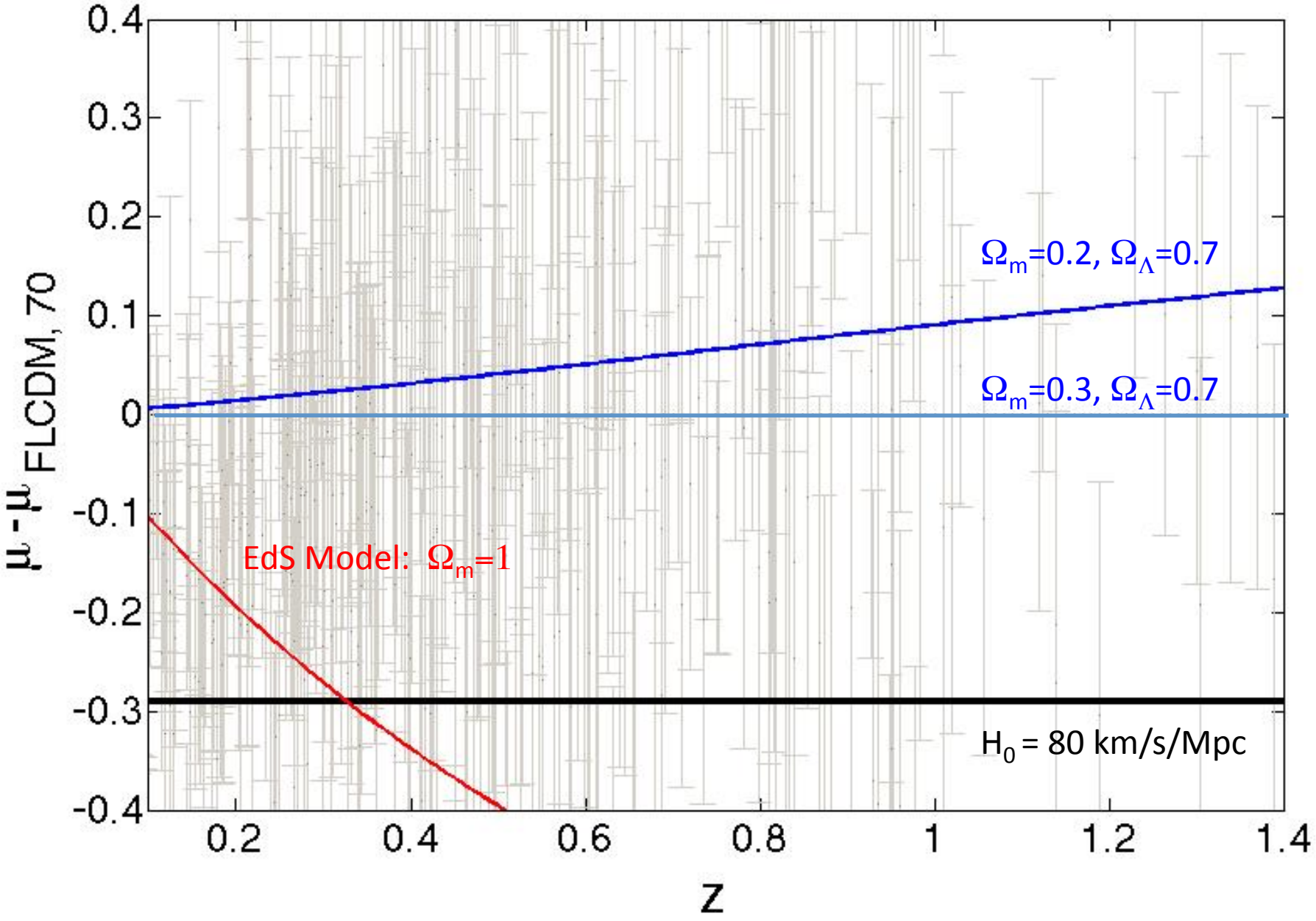
z
μ - μ FLCDM, 70
ΩM=0.3, ΩΛ=0.7, H0 = 70 km/s/Mpc
EdS Model: ΩM=1
H0 = 80 km/s/Mpc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Ωm=0.2, ΩΛ=0.7
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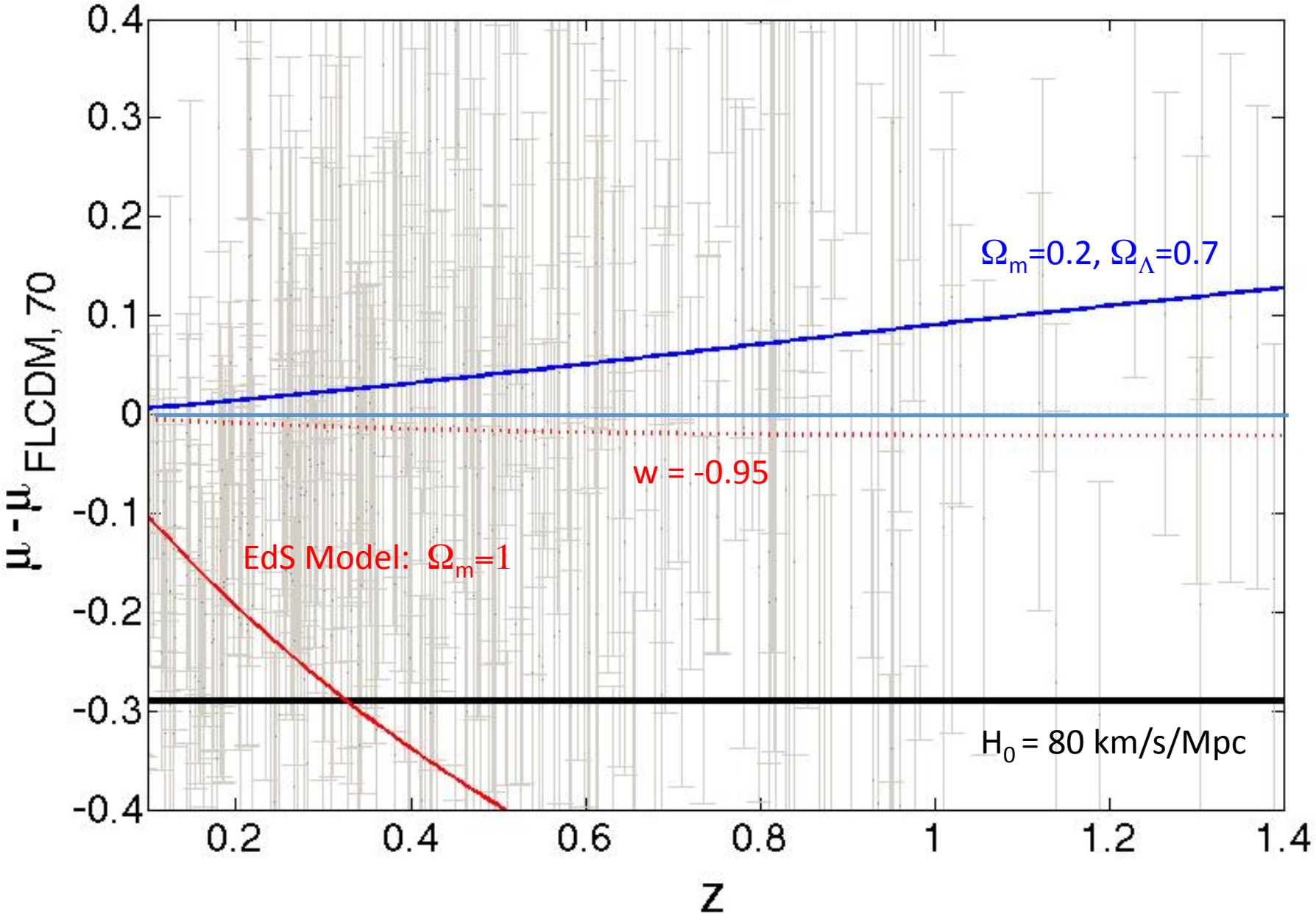
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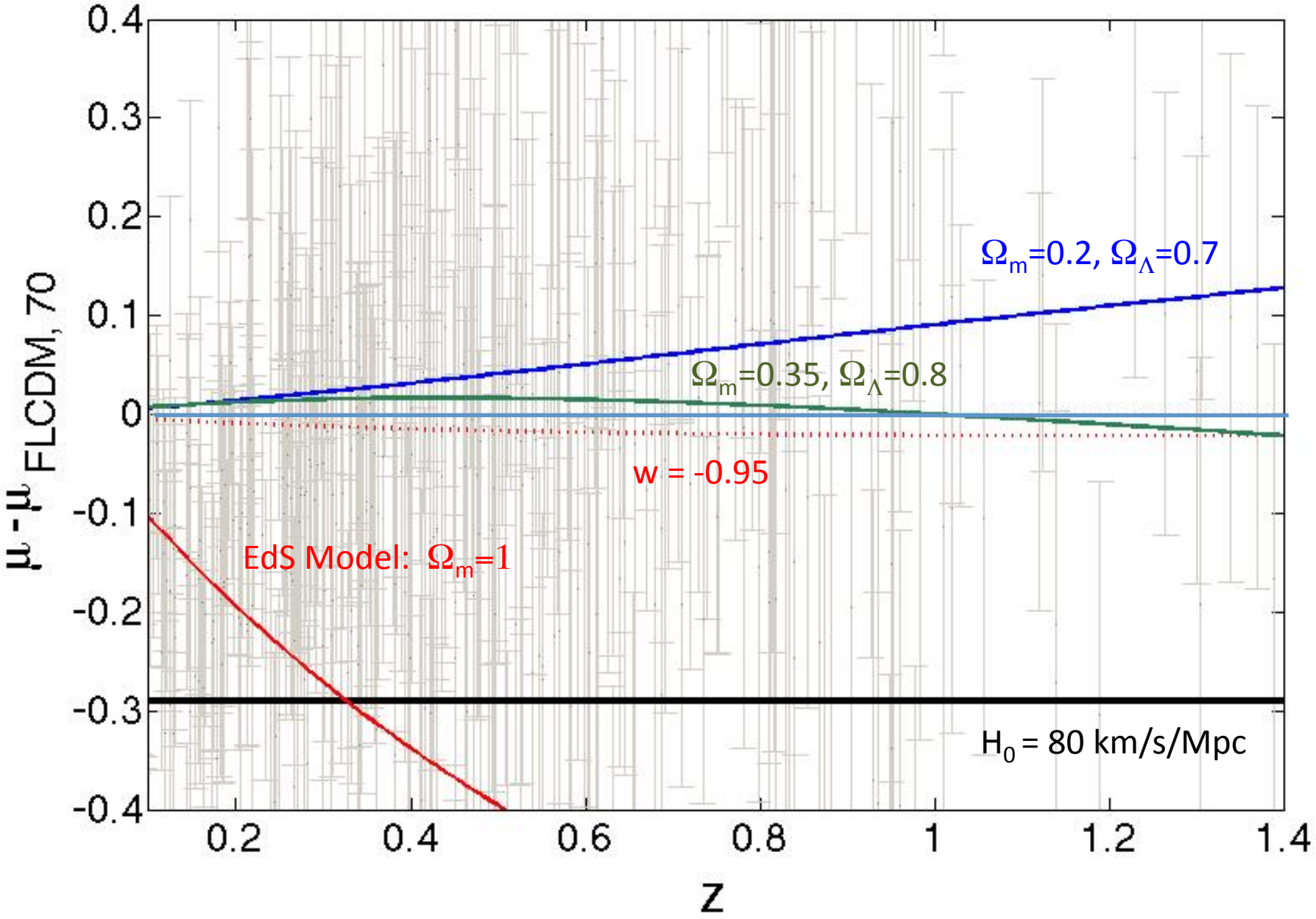
1.4
z
μ - μ FLCDM, 70
Ωm=0.2, ΩΛ=0.7
w = -0.95
EdS Model: Ωm=1
H0 = 80 km/s/Mpc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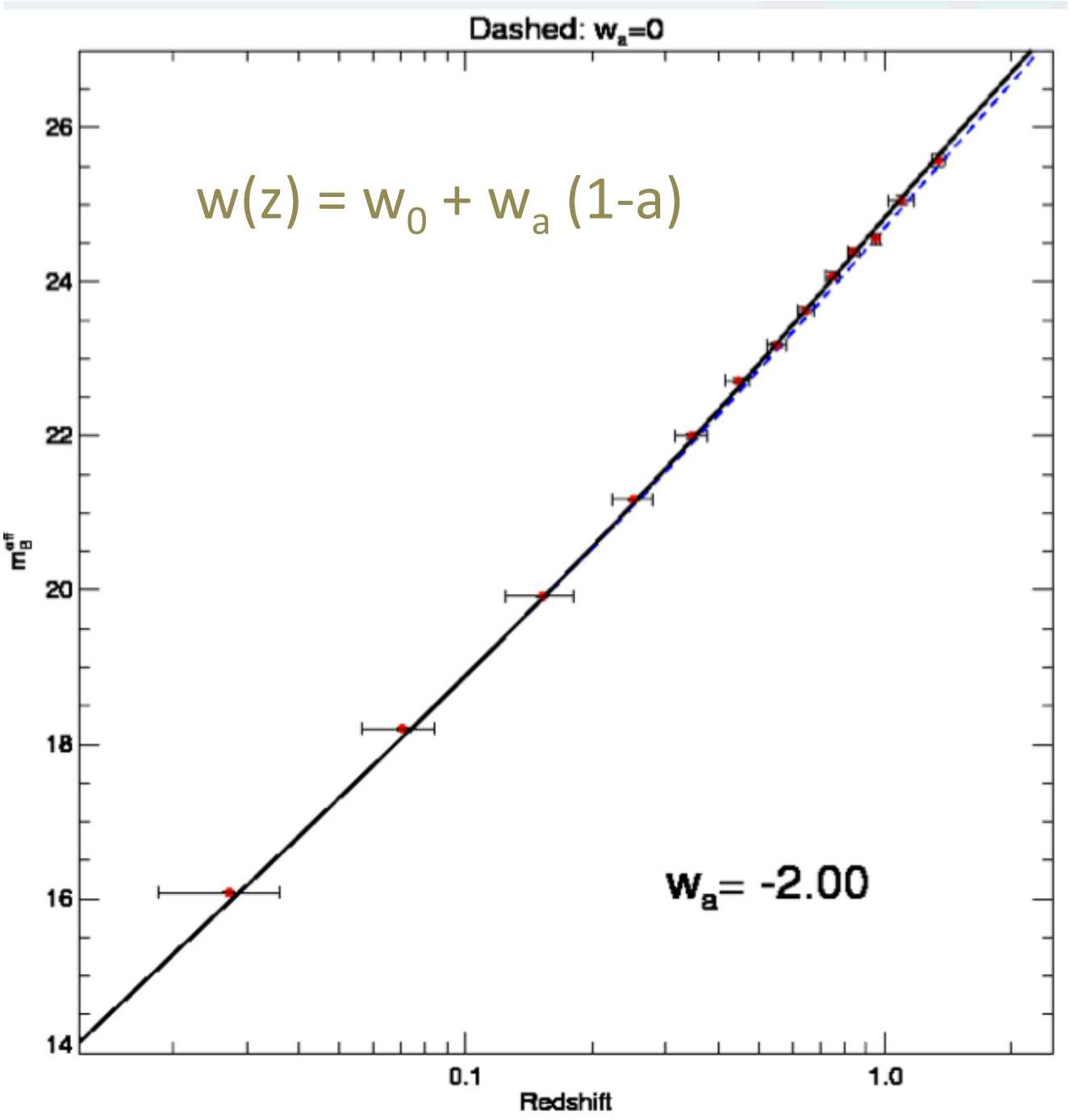
μ - μ FLCDM, 70
Ωm=0.2, ΩΛ=0.7
Ωm=0.35, ΩΛ=0.8
w = -0.95
EdS Model: Ωm=1
H0 = 80 km/s/Mpc


Dashed: w_a=0
$w(z) = w_0 + w_a (1-a)$
m_B^{eff}
26
24
22
20
18
16
14
0.1
1.0
Redshift
w_a= -2.00

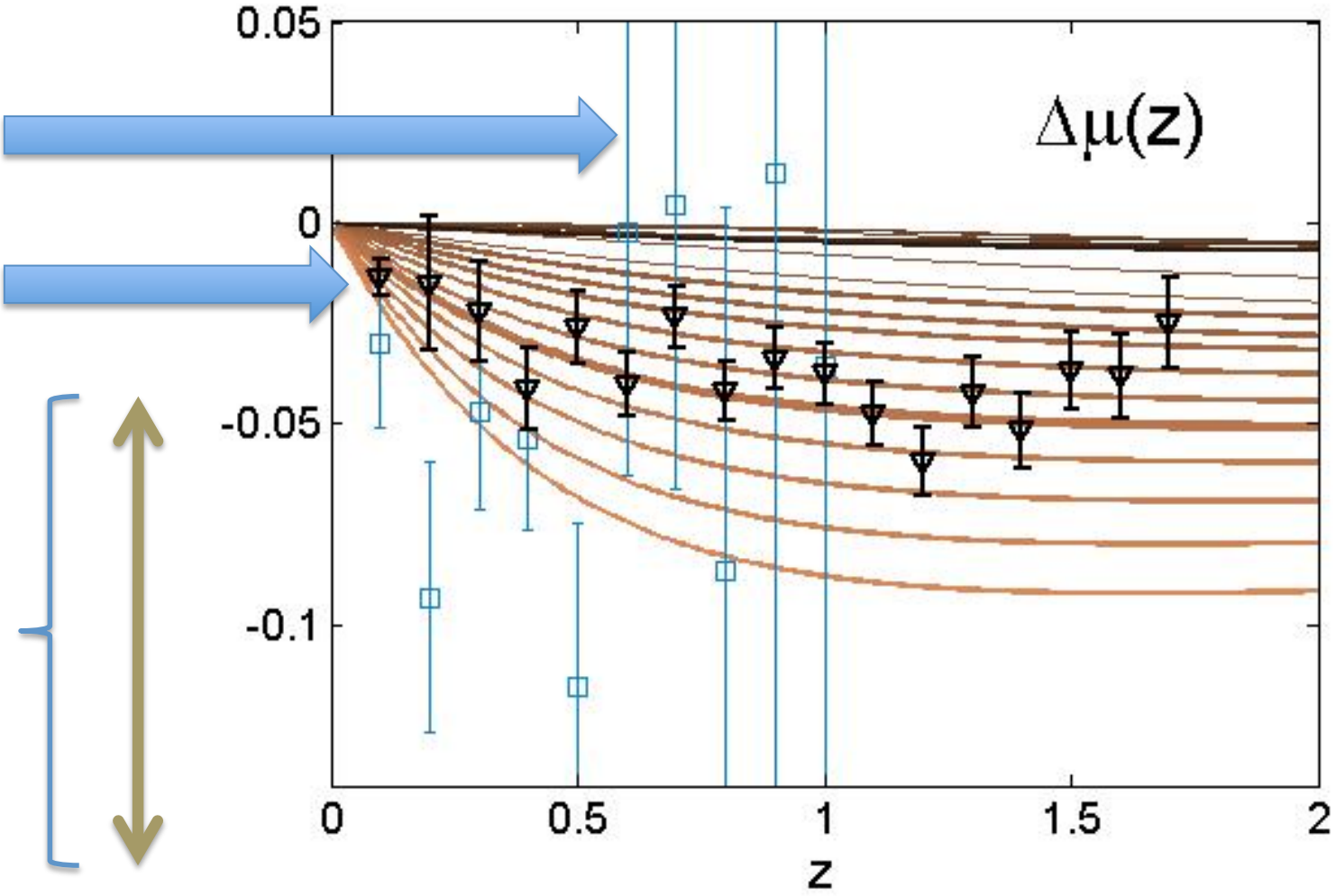
Goobar

It is very hard to distinguish tracking quintessence and ΛCDM…

DES-like SNIa Survey (2015)

SNAP-like SNIa Survey (2020)

Size of current systematic error bar 0.12 mag



Arxiv:0709.0526

Other difficulties…

- Degeneracies…
- Gravitational lensing…
- Dust obscuration…
- Peculiar objects...
- Host dependence…
- UV evolution…
- The Spectroscopic desert
- The future…

Geometry – Dynamics Degeneracy

- Even with perfect **distance** measurements there is a perfect degeneracy between **the curvature** (Ω_k) and **H(z)** (Weinberg, '73)

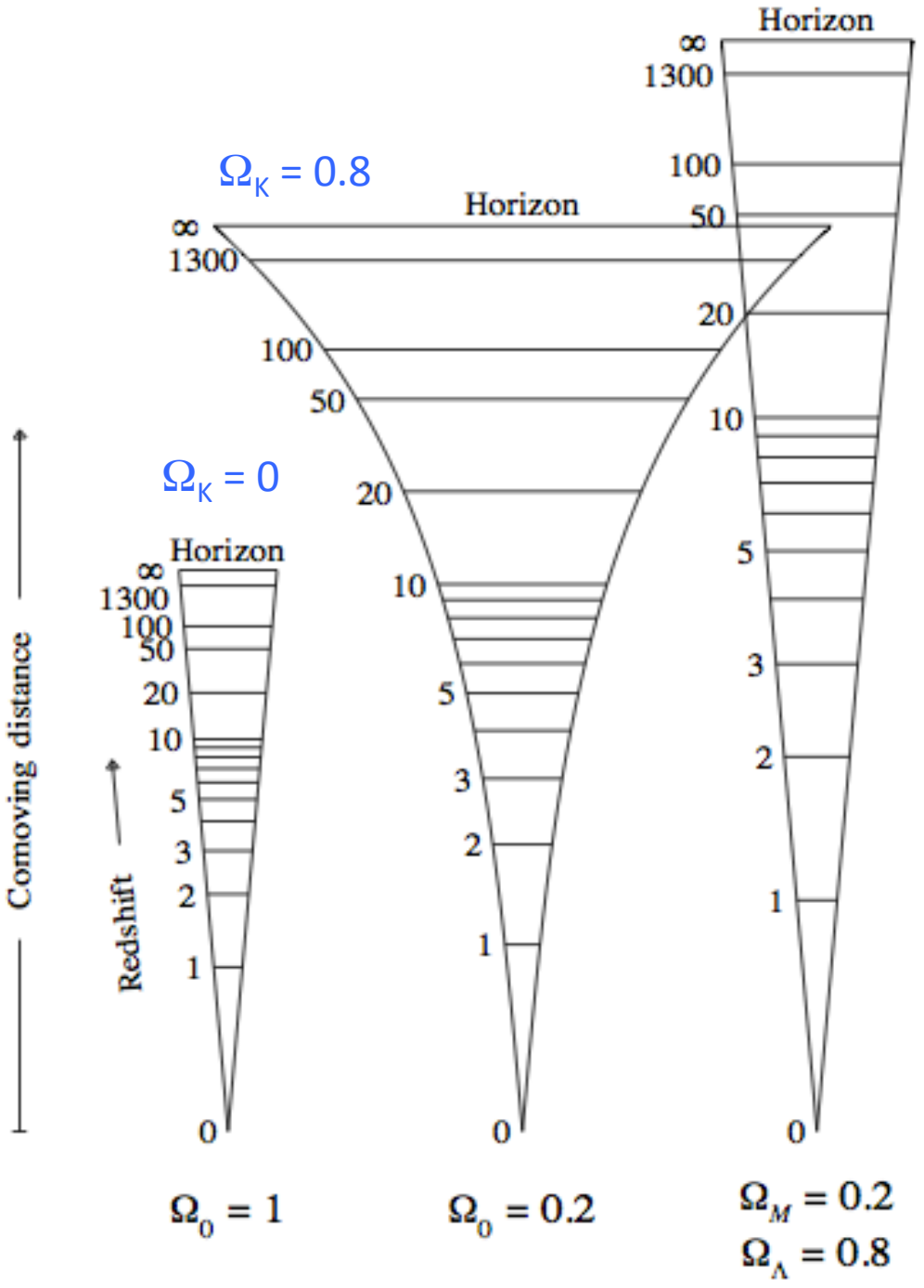
$$d_L(z) = \frac{(1+z)}{H_0\sqrt{-\Omega_k}} \sin\left(H_0\sqrt{-\Omega_k} \int \frac{dz'}{H(z')} \right)$$

$$\Omega_k = \frac{[H(z)D'(z)]^2 - 1}{[H_0 D(z)]^2}$$

Clarkson, BB, Liu

Dynamics

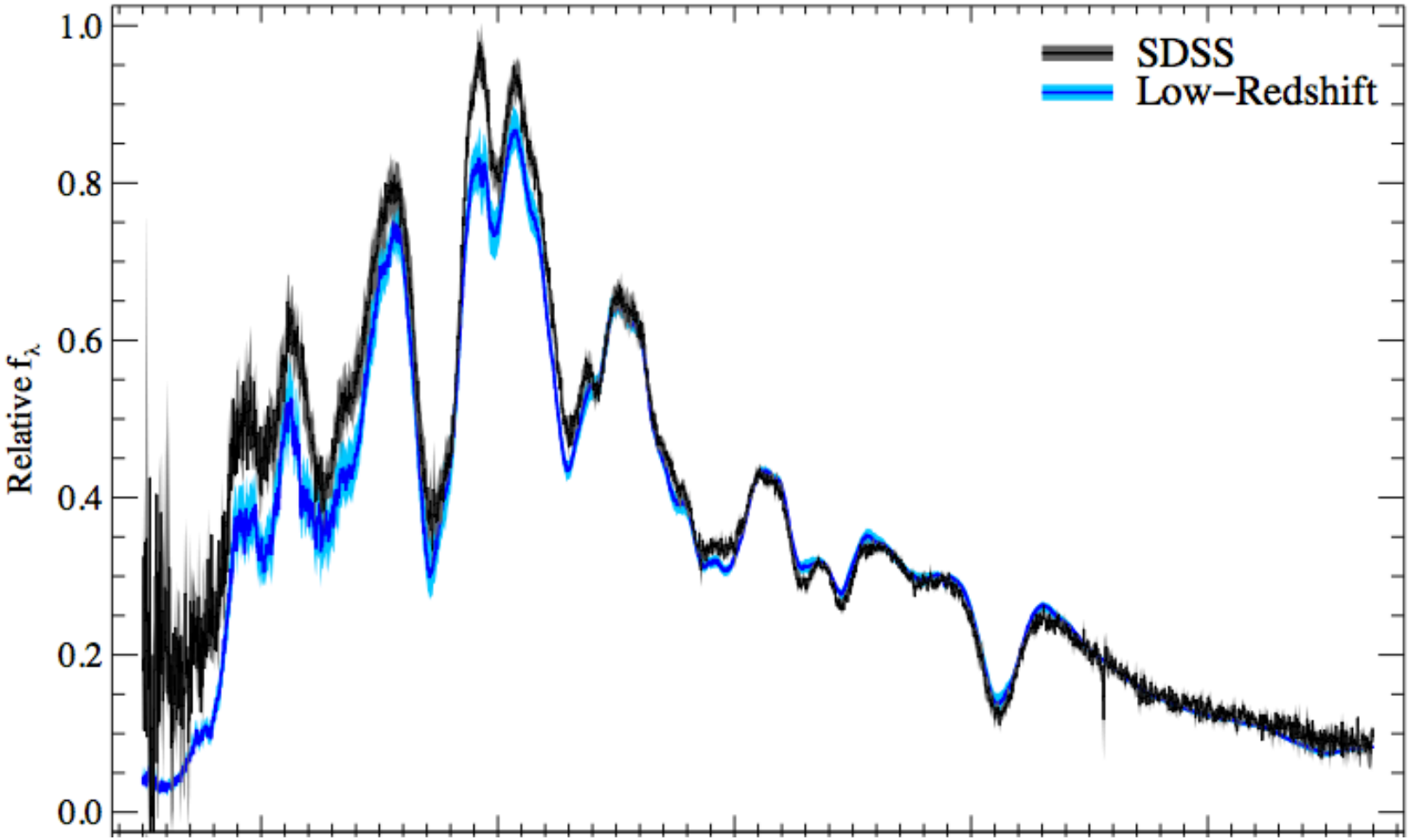
$$\chi = \int \frac{dz'}{E(z')}$$



The size of an object is not uniquely determined by χ – curvature must also be known

Hamilton 97

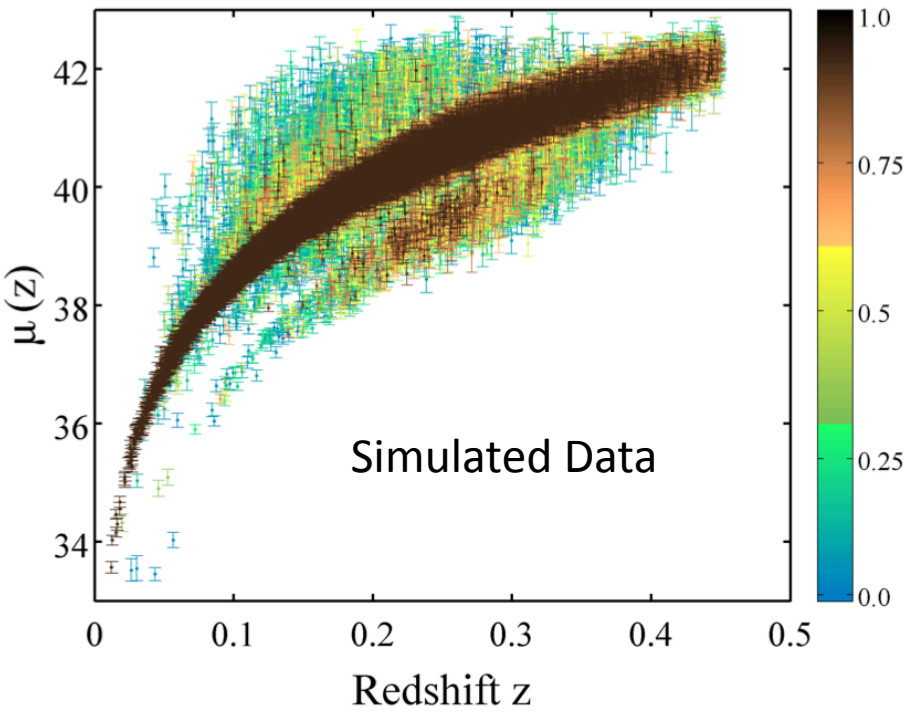
Evolution in the UV?

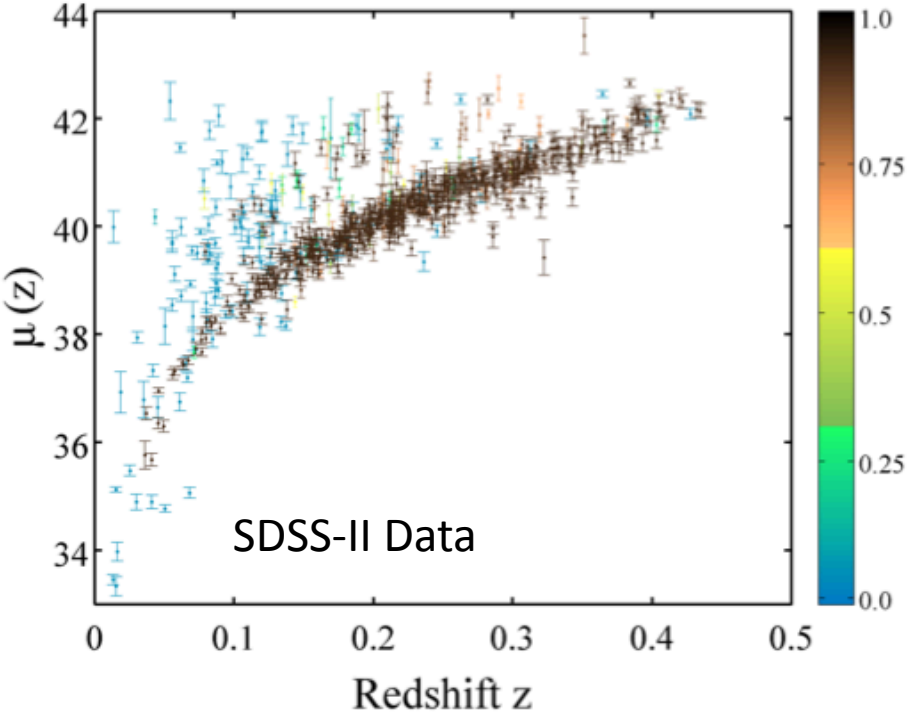


Foley et al. 2011

Future Surveys

- Current surveys are already spectroscopy limited
- LSST will discover up to 10^6 SNIa…only a fraction will have spectroscopic confirmation.
- Entering the era of photometric supernova cosmology
- Contamination from non-Ias will be unavoidable.

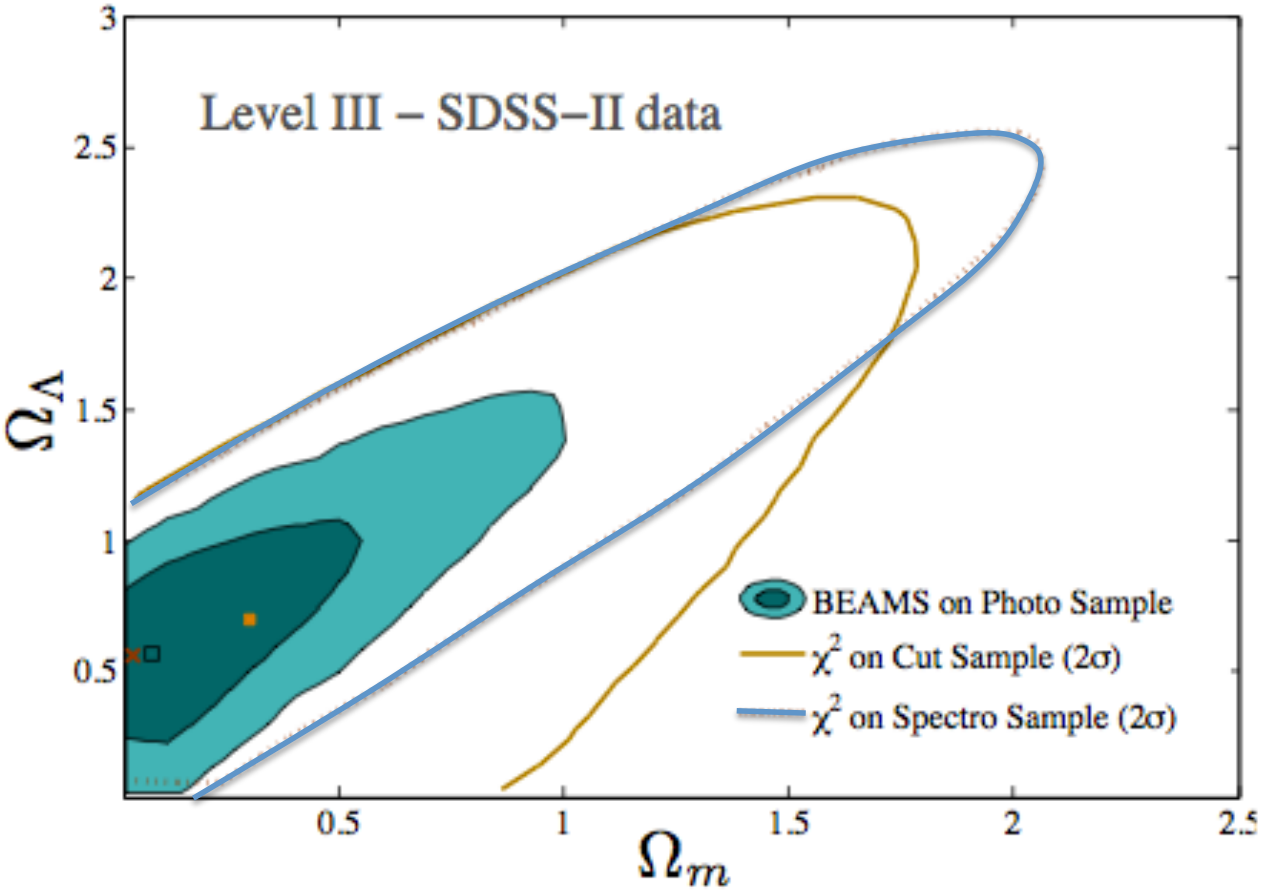




Photometric Supernova Cosmology

Basic Idea: use the lightcurves to work out the probability that an object is a SNIa…

Can use Bayesian Methods (BEAMS) to do Cosmological Parameter estimation with these probabilities.



Hlozek et al
Arxiv:1111.5328

Conclusions

- SNIa are arguably still the best evidence for dark energy that we have…
- But distances are fundamentally limited by the curvature-dynamics degeneracy. Requires additional H(z) data to break.

Conclusions II

- As with all methods, SNIa have a hard systematics floor that will need lots of work to break through…
- We are now entering an exciting new era of massive data and a switch to *photometric* supernova cosmology