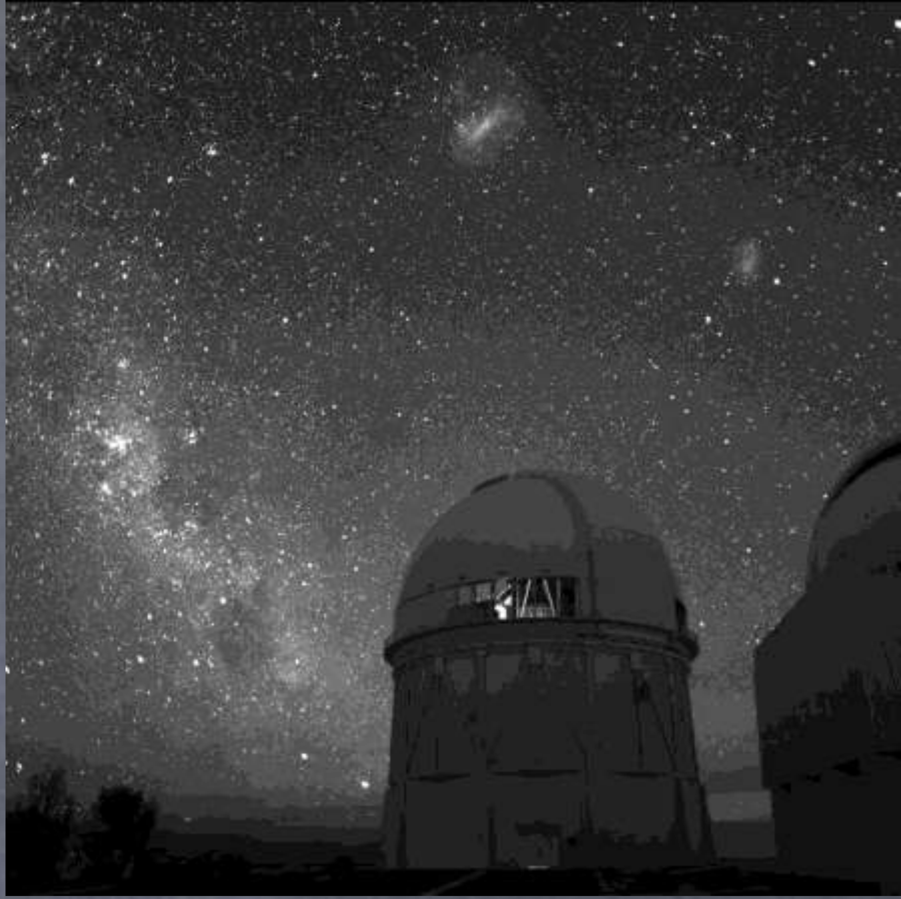
Supernovae, Acceleration, and Alternative Gravity



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ADM-50: A Celebration of Current GR Innovation 7/8 Nov2009

Dick Arnowitt

From the left, Richard Arnowitt, Charles Misner and Stanley Deser

Dynamical Structure and Definition of Energy in General Relativity*†

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and

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(Received July 6, 1959)

The problem of the dynamical structure and definition of energy for the classical general theory of relativity is considered on a formal level. As in a previous paper, the technique used is the Schwinger action principle. Starting with the full Einstein Lagrangian in first order Palatini form, an action integral is derived in which the algebraic constraint variables have been eliminated. This action possesses a "Hamiltonian" density which, however, vanishes due to the differential constraints. If the differential constraints are then substituted into the action, the true, nonvanishing Hamiltonian of the theory emerges. From an analysis of the equations of motion and the constraint equations, the two pairs of dynamical variables which represent the two independent degrees of freedom of the gravitational field are explicitly exhibited. Four other variables remain in theory; these may be arbitrarily specified, any such specification representing a choice of coordinate frame. It is shown that it is possible to obtain truly canonical pairs of variables in terms of the dynamical and arbitrary variables. Thus a statement of the dynamics is meaningful only after a set of coordinate conditions have been chosen. In general, the true Hamiltonian will be time dependent even for an isolated gravitational field. There thus arises the notion of a preferred coordinate frame, i.e., that frame in which the Hamiltonian is conserved. In this special frame, on physical grounds, the Hamiltonian may be taken to define the energy of the field. In these respects the situation in general relativity is analogous to the parametric form of Hamilton's principle in particle mechanics.

arXiv:gr-qc/0405109v1 19 May 2004

The Dynamics of General Relativity

1. Introduction[iv]

The general coordinate invariance underlying the theory of relativity creates basic problems in the analysis of the dynamics of the gravitational field. Usually, specification of the field amplitudes and their first time derivatives initially is appropriate to determine the time development of a field viewed as a dynamical entity. For general relativity, however, the metric field $g_{\mu\nu}$ may be modified at any later time simply by carrying out a general coordinate transformation. Such an operation does not involve any observable changes in the physics, since it merely corresponds to a relabeling under which the theory is invariant. Thus it is necessary that the metric field be separated into the parts carrying the true dynamical information and those parts characterizing the coordinate system. In this respect, the general theory is analogous to electromagnetic theory. In particular, the coordinate invariance plays a role similar to the gauge invariance of the Maxwell field. In the latter case, this gauge invariance also produces difficulties in separating out the independent dynamical modes, although the linearity here does simplify the analysis. In both cases, the effect

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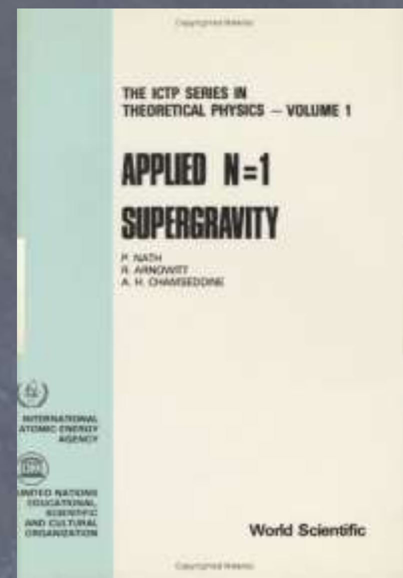
[iv]The work discussed in this chapter is based on recent research by the authors. In the text, the original papers will be denoted by Roman numerals, as given in the references.

1



1950	Peter G. Bergmann Paul Dirac	Work out the general hamiltonian theory c
1952	Suraj N. Gupta	Develops systematically the "flat space qu simply to introduce a fictitious "flat space", that is, Minkowski metric $\eta_{\mu\nu}$, and quantize the small fluctuations of the metric around Minkowski $h_{\mu\nu} = g_{\mu\nu} - \eta_{\mu\nu}$. The covariant approach is fully born. The first difficulty is recognized, in searching the propagator, as coming from the fact that the quadratic term of the Lagrangian is singular, as for the electromagnetic field, and as a consequence of gauge invariance. Gupta's treatment uses an indefinite norm state space as for the electromagnetic field.
1957	Charles W. Misner	Introduces the "Feynman quantization of general relativity". He quotes John Wheeler for suggesting the expression and studies how to have a well defined version of this idea. Misner's paper explains notions such as why the quantum hamiltonian must be zero, why the individual spacetime points are not defined in the quantum theory and the need of dealing with gauge invariance in the integral. The paper opens with a discussion of the possible directions for quantizing gravity, and lists the three lines of directions: **covariant, canonical** and **sum over histories**.
1961	Richard Arnowitt Stanley Deser Charles W. Misner	Complete what we now call the ADM formulation of GR, namely its hamiltonian version in appropriate variables, which simplify the hamiltonian formulation and make its geometrical reading transparent. In relation to the quantization, they present an influential argument for the finiteness of the self energy of a point particle in classical GR and use it to argue that nonperturbative quantum gravity should be finite.
		tree-amplitudes lead to the physics one expects from the classical theory.
1962	Bryce DeWitt	Starts developing his background field methods for the computation of perturbative transition amplitudes.

PHYSI … 117, NUMBER … 1960

…es for General …

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The general theory of relativity is cast into normal Hamiltonian form in terms of two pairs of independent conjugate field variables. These variables are explicitly exhibited and obey ordinary Poisson bracket relations. This form is reached by imposing a simple set of coordinate conditions. It is shown that those functionals of the metric used as invariant coordinates do not appear explicitly in the Hamiltonian and momentum densities, so that the standard differential conservation laws hold. The bearing of these results on the quantization problem is discussed.

REPORT OF THE

DARK ENERGY TASK FORCE

2006

Andreas Albrecht, University of California, Davis
Gary Bernstein, University of Pennsylvania
Robert Cahn, Lawrence Berkeley National Laboratory
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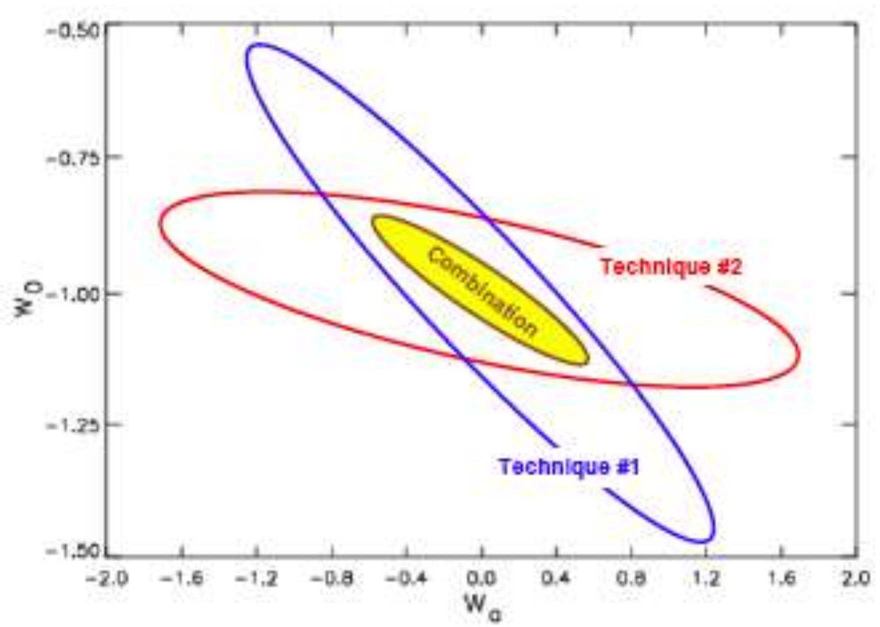

Illustration of the power of combining techniques. Technique #1 and Technique #2 have roughly equal DETF figure of merit. When results are combined, the DETF figure of merit is substantially improved.

IV. Findings of the Dark-Energy Task Force

1. Four observational techniques dominate the White Papers received by the task force. In alphabetical order:
   a. **Baryon Acoustic Oscillations (BAO)** are observed in large-scale surveys of the spatial distribution of galaxies. The BAO technique is sensitive to dark energy through its effect on the angular-diameter distance vs. redshift relation and through its effect on the time evolution of the expansion rate.
   b. **Galaxy Cluster (CL)** surveys measure the spatial density and distribution of galaxy clusters. The CL technique is sensitive to dark energy through its effect on a combination of the angular-diameter distance vs. redshift relation, the time evolution of the expansion rate, and the growth rate of structure.
   c. **Supernova (SN)** surveys use Type Ia supernovae as standard candles to determine the luminosity distance vs. redshift relation. The SN technique is sensitive to dark energy through its effect on this relation.
   d. **Weak Lensing (WL)** surveys measure the distortion of background images due to the bending of light as it passes by galaxies or clusters of galaxies. The WL technique is sensitive to dark energy through its effect on the angular-diameter distance vs. redshift relation and the growth rate of structure.

can't get no respect…

$H(z)$ using almost completely linear physics (unlike SNIa for example which involve highly complex, nonlinear, poorly understood stellar explosions). In addition, they offer the as yet unproven possibility of delivering constraints on growth though the change in the amplitude of the power spectrum. The time-dependence of the matter density perturbations, $\delta\rho/\rho$ obeys the equation

COSMOLOGY

Dark is the new black

Richard Massey

Rival experimental methods to determine the Universe's expansion are contending to become the fashionable face of cosmology. Fresh theoretical calculations make one of them the hot tip for next season.

Earth. However, the accelerating expansion of the Universe means that distant supernovae have already receded farther from us and look even fainter. Initial enthusiasm for using supernovae as cosmic distance indicators, and thus as a probe of the Universe's expansion, garnered vast allocations of time on ground- and space-based telescopes, and triggered the first plans for a dedicated, all-sky successor to the Hubble Space Telescope. Unfortunately, the explosions were later found to depend on the stars' environment and ingredients, which evolve over cosmic time. Such effects can be parameterized only to a certain precision, and the technique is falling out of fashion.

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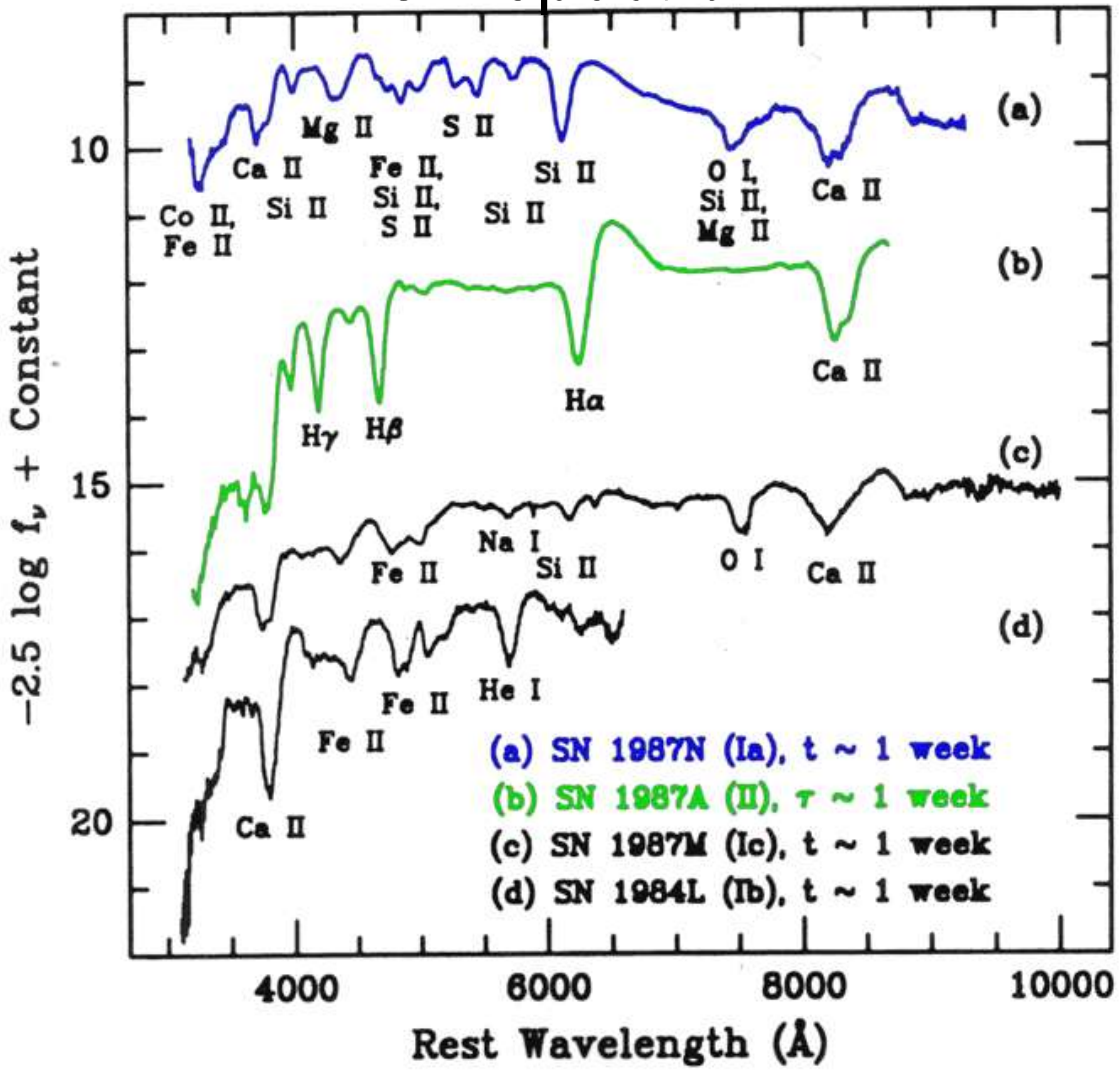
are needed to see this picture.

Supernovae

SN spectra



Type Ia

Core Collapse

Type Ib/c & Type II

SN SEDs

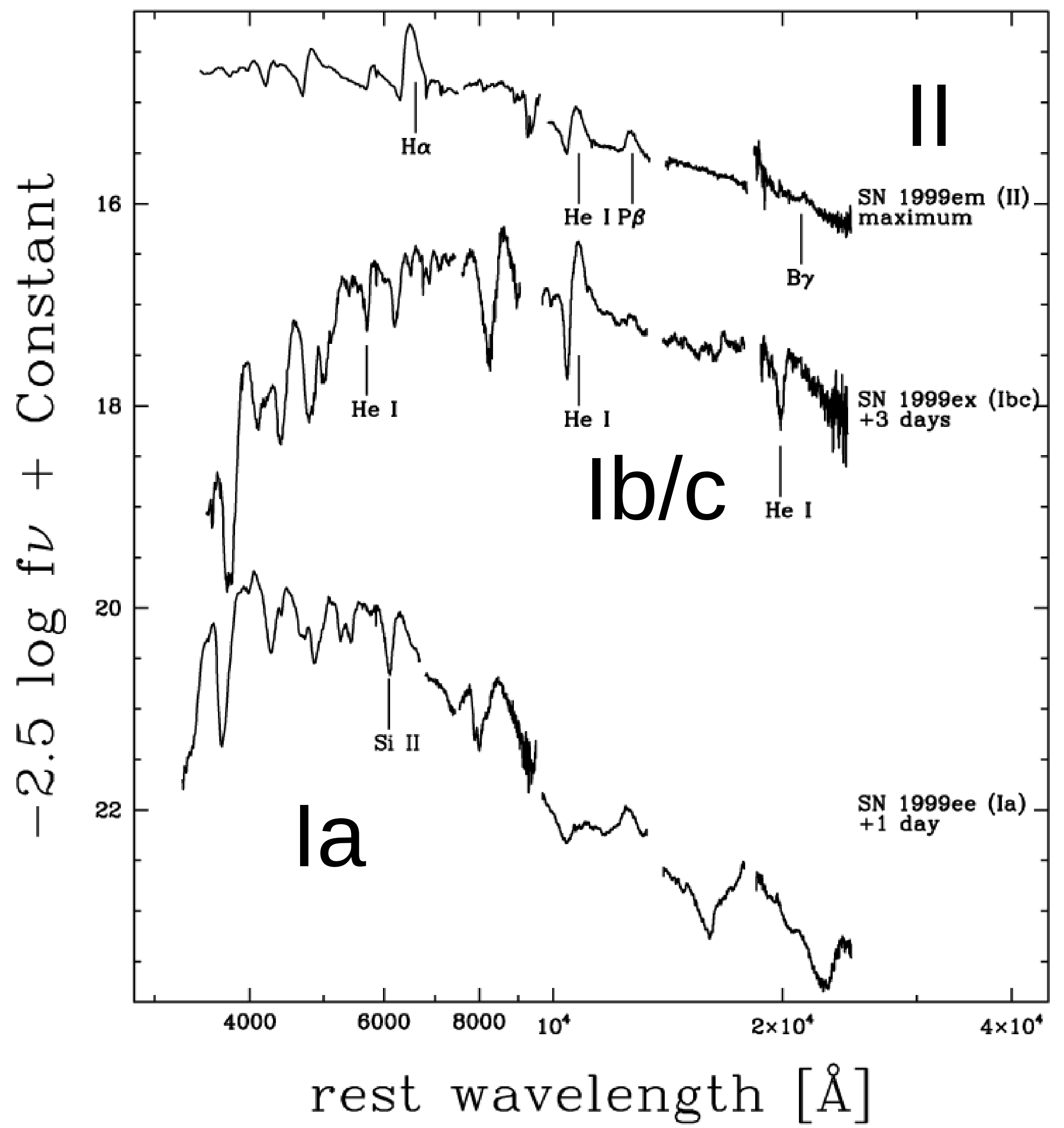
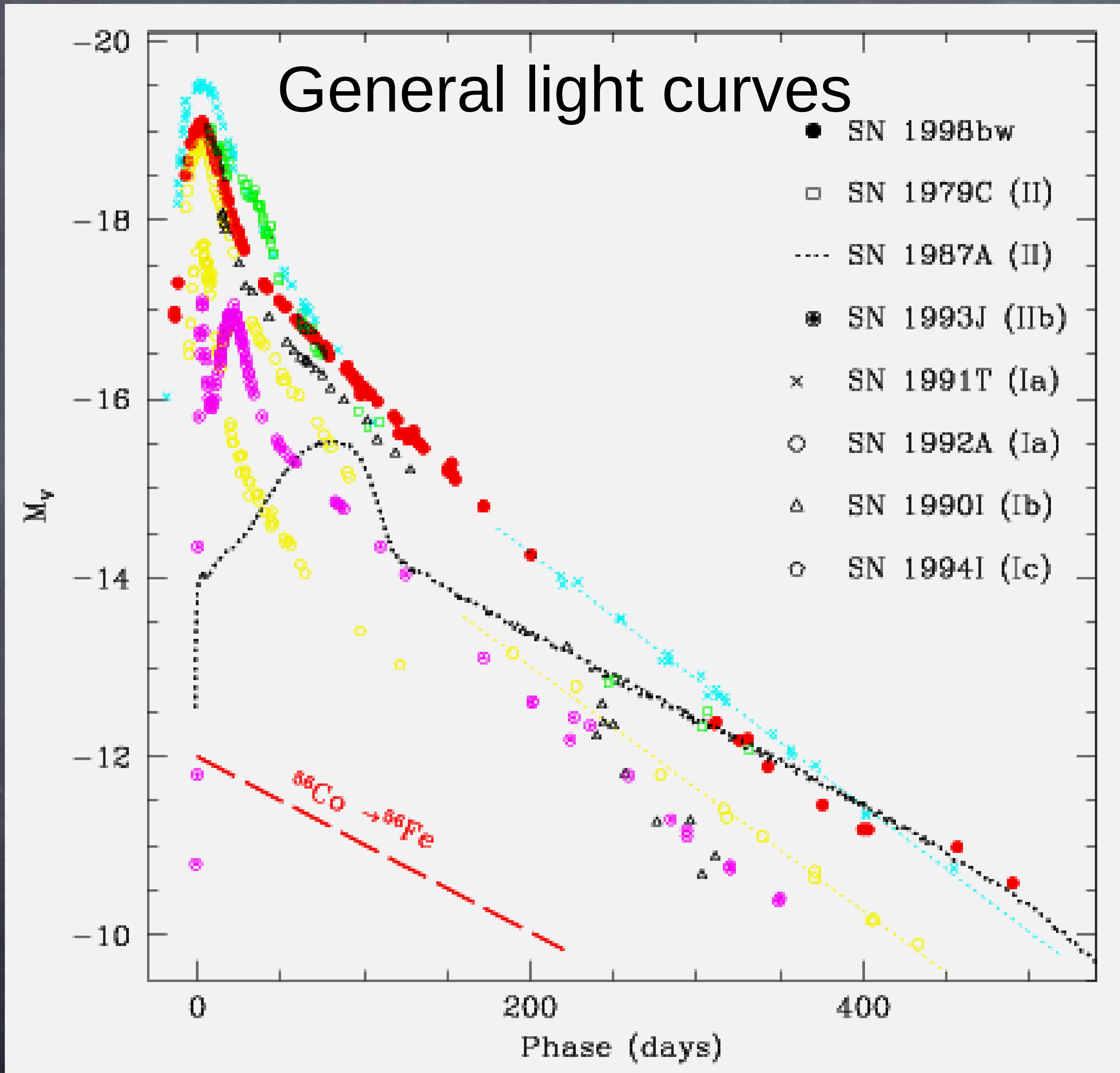


Fig. 13.— Combined optical and IR maximum-light spectra of the Type II SN 1999em, the Type Ib/c SN 1999ex, and the Type Ia SN 1999ee.

General light curves



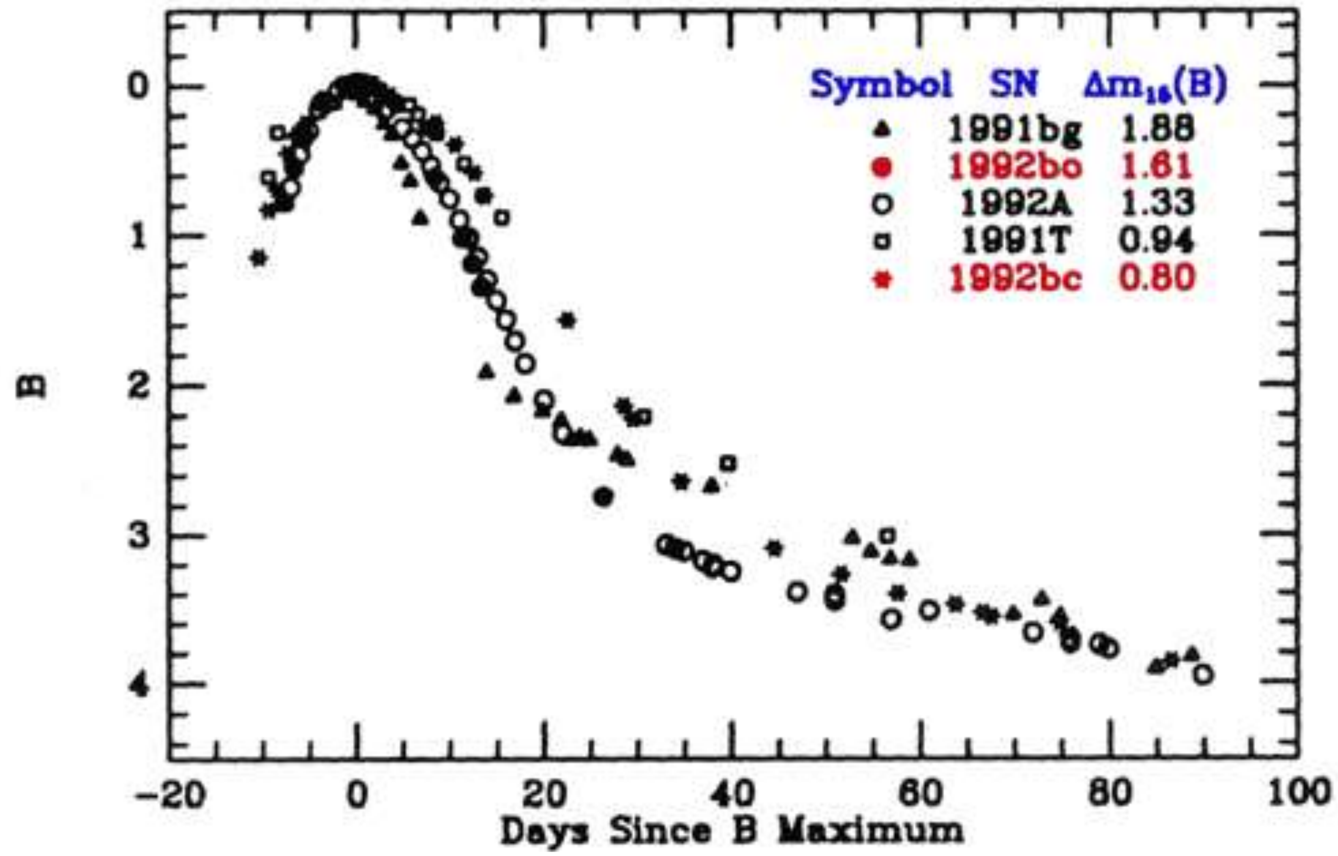
^{56}Ni →
^{56}Co →
^{56}Fe

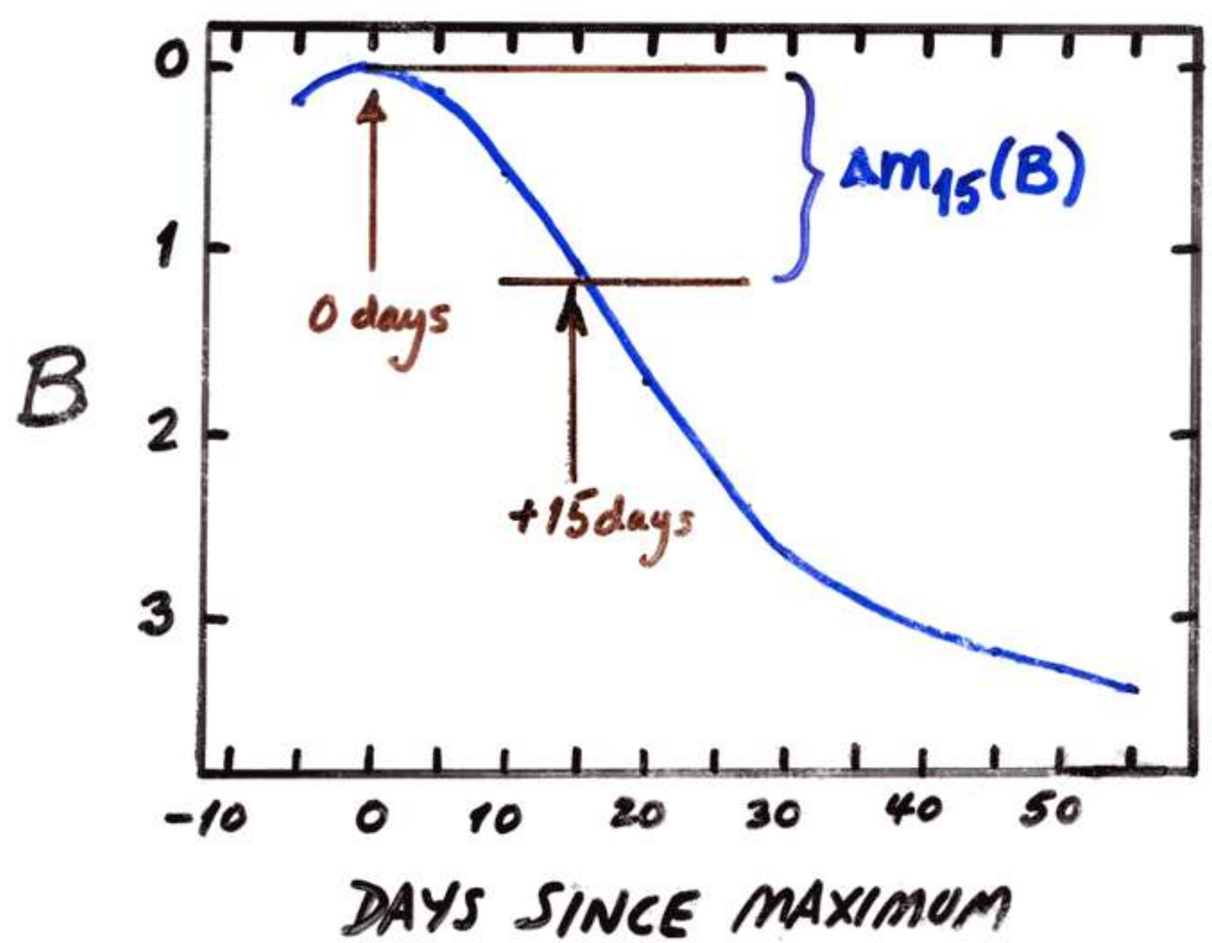
One parameter family

Color

Rate of decline

Peak brightness





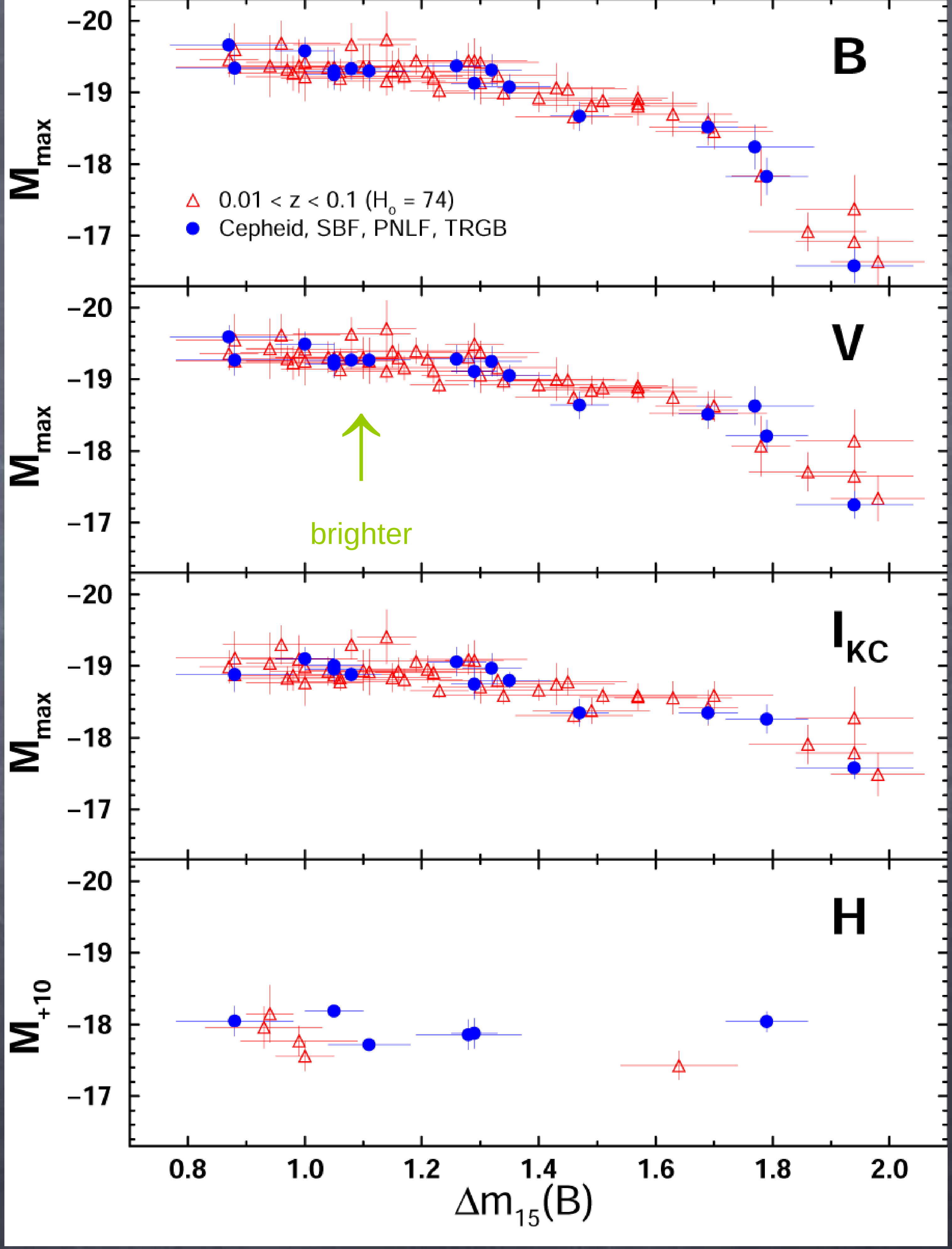
Suntzeff (1996)

Phillips (1993)

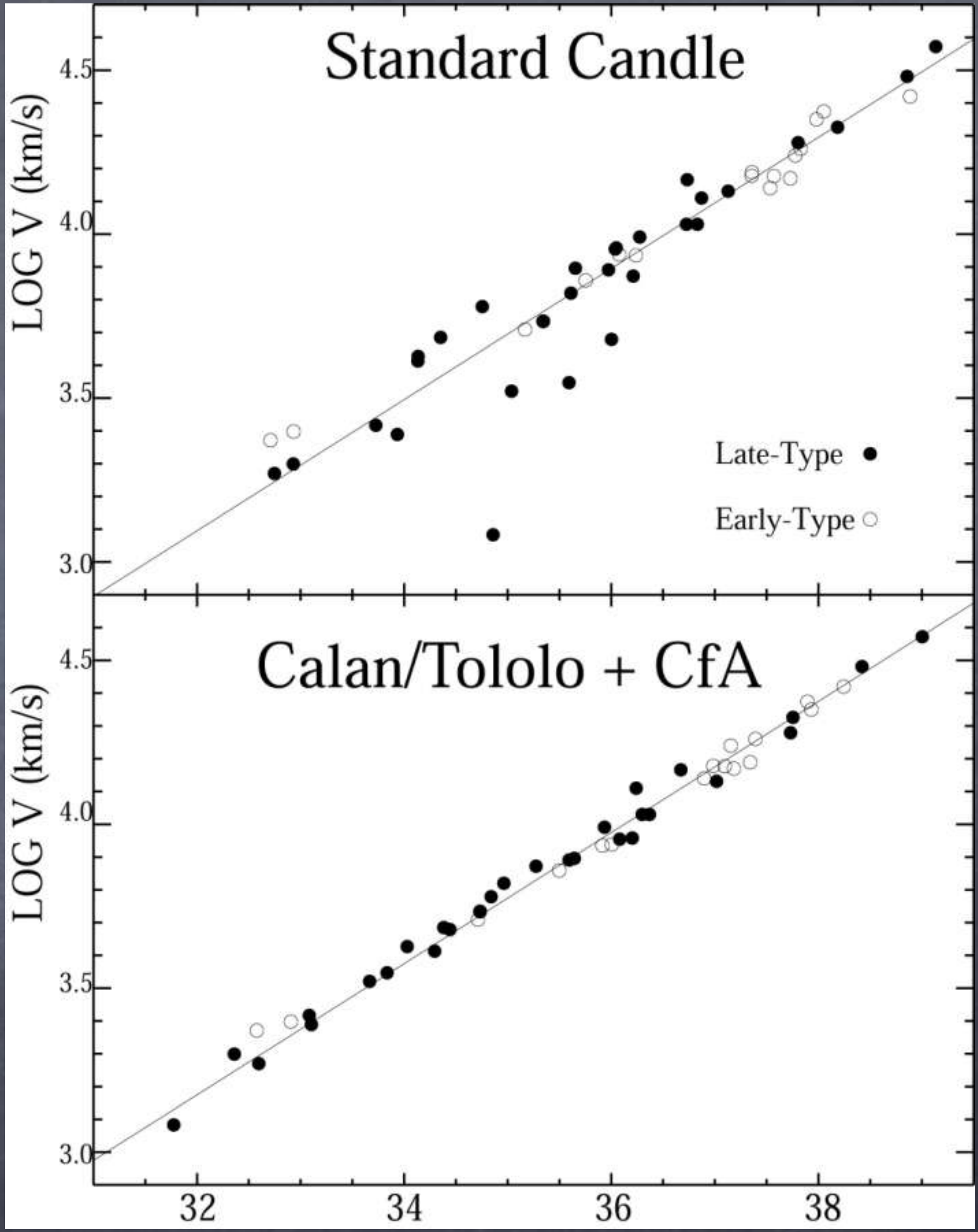
Absolute magnitudes of Type Ia SNe

$M_{max} = -2.5\log_{10}(Lum) + c$

H, K probable standard candles →



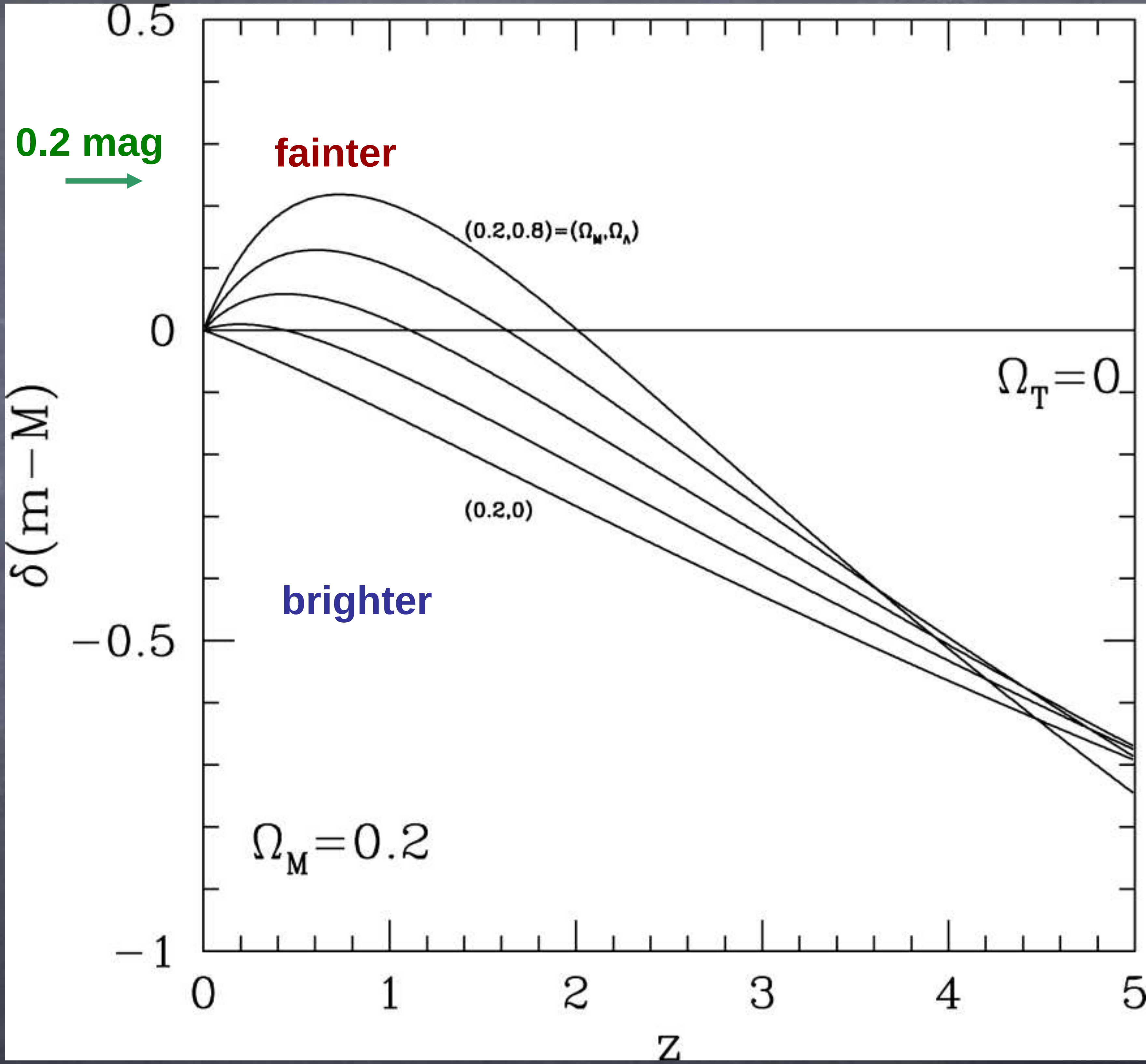
Hubble Diagram effects of correction to Δm_{15}



Distance Modulus II

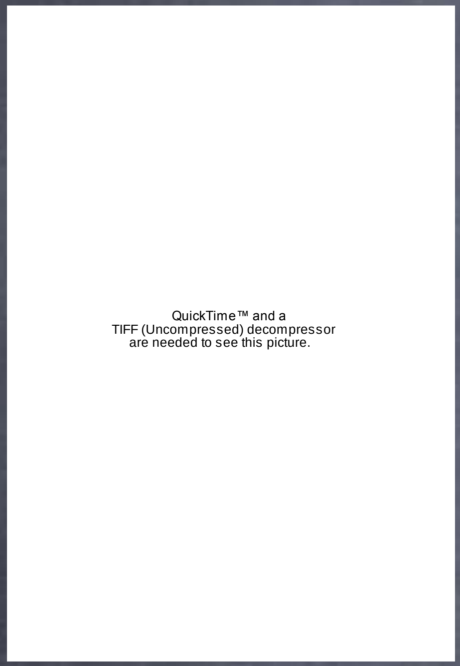
Peak effect for L is at about z~0.8.

We are looking for about a 0.25m effect.

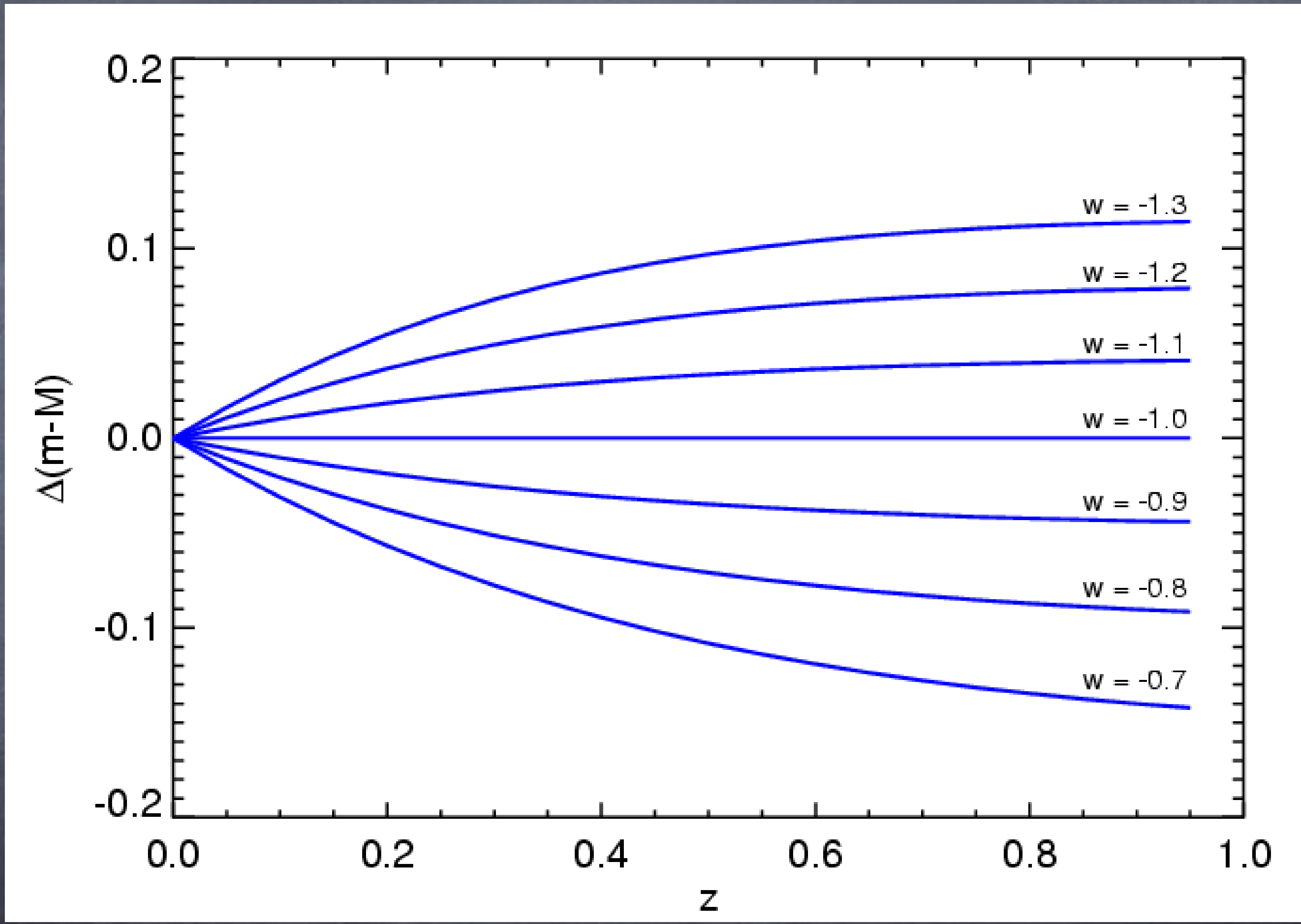


Equation-of-State Signal

Assume
P = $w\rho c^2$



Georges Lemaître



Difference in apparent SN brightness vs. z

Ω_Λ=0.70, flat cosmology

My history in SNe or I am not part of the Harvard Group - they are a part of my group.

- 1986G & 1989B with Mark Phillips
- 1989 - Sandage challenge to measure H_0 and q_0 with Ia's
- 1990-4 - Calan/Tololo Survey to calibrate Ia: Hamuy, Maza, Phillips, & Suntzeff
- 1994 - Schmidt & Suntzeff start High-Z SN Search Team
- 1998 - Riess et al. & Perlmutter et al. announce $q_0 < 0$
- 2002 - ESSENCE founded
- 2005 - Carnegie Supernova Project founded

The ESSENCE Survey

- Determine w to 10% or w!=-1
- 6-year project on CTIO/NOAO 4m telescope in Chile; 12 sq. deg.
- Wide-field images in 2 bands
- Same-night detection of SNe
- Spectroscopy
  - Keck, VLT, Gemini, Magellan
- Goal is 200 SNeIa, 0.2<z<0.8
- Data and SNeIa public real-time

ESSENCE Status Summary

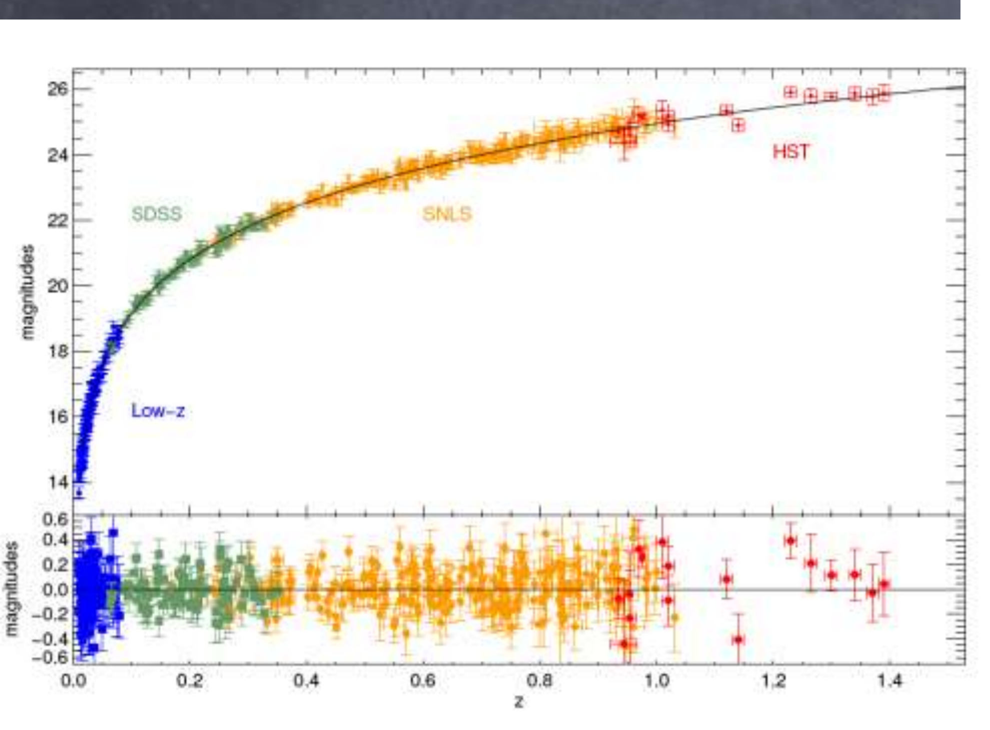
- 200 SNeIa from 2002-2007
- 60 good light curves (Wood-Vasey, et al 2007)
- Data from Keck, Gemini, VLT, CTIO, HST
- 6.2 Ia per sq-deg per month

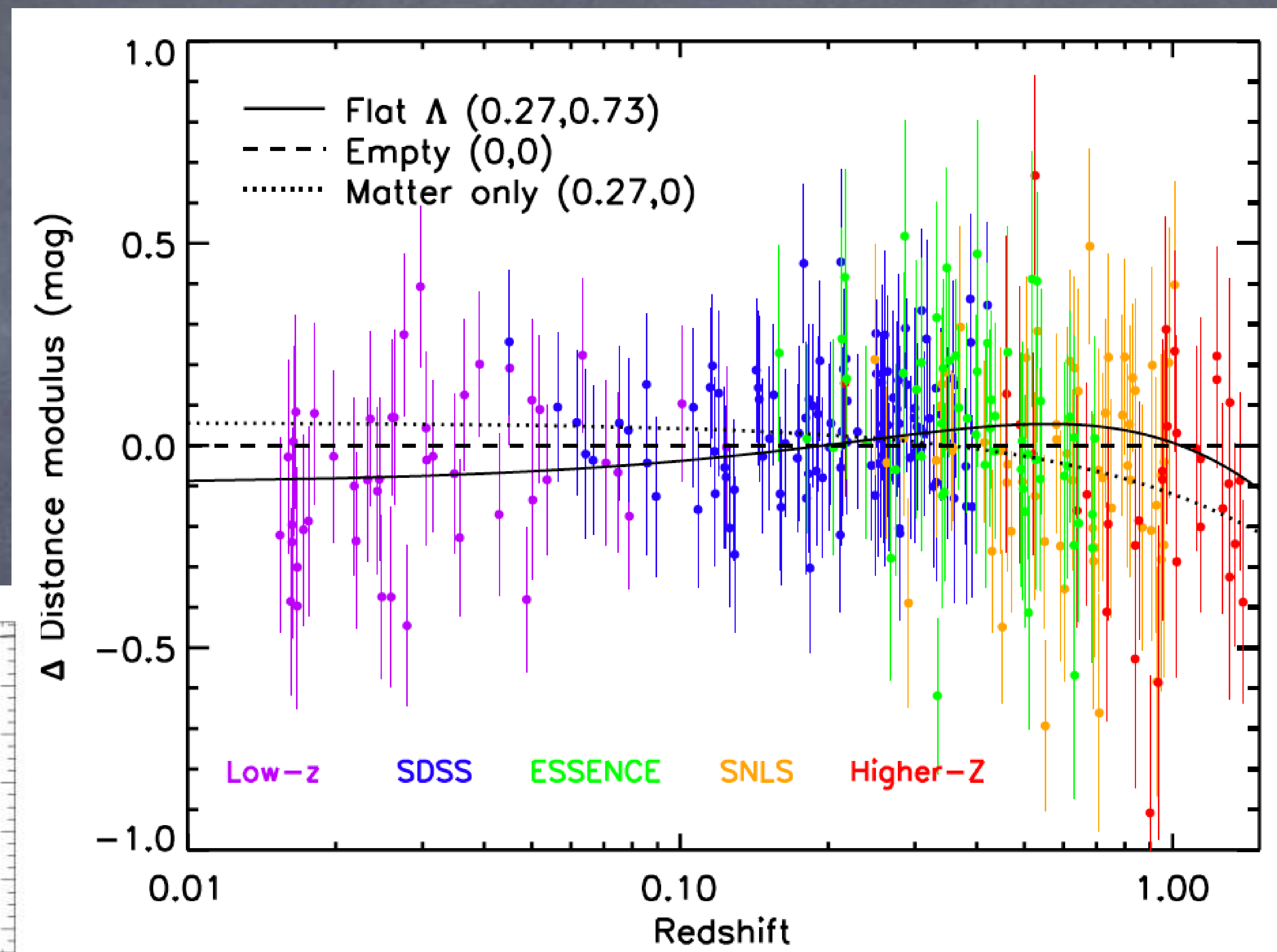
Gold⇒Union⇒Constitution⇒?? set

SDSS SN plot

Lesson in plotting

⇓





Being from Texas, I suggest the Confederate Set is next

Carnegie Supernova Project

- Phillips, Freedman, Hamuy, Madore, Burns, Follatelli, Cadenas, Suntzeff

High-z project

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

I-band measurements

Cosmology fits

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TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Carnegie Low-z Sample

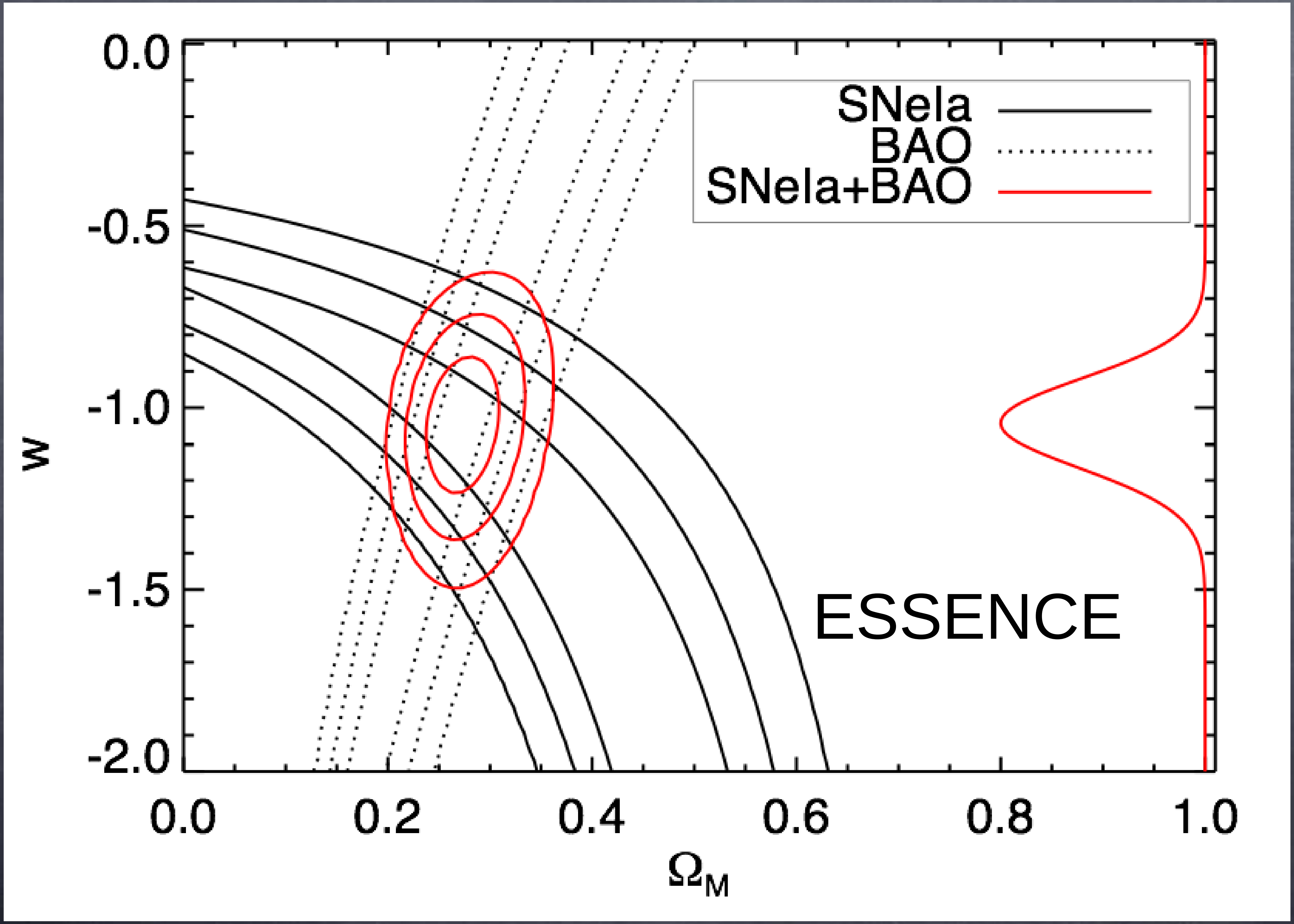
- 5-year project, 270n per year on 1m Swope + nights on Magellan, du Pont, VLT
- Ending 2009 (around now)
- *ugriBVYJH*(K_s). K_s with WIRC on duPont
- Spectra where we can [more hot spectrographs on 2m telescopes are needed]
- Follow all types with z≤0.08 (if caught early)
- 200 Sne with 100 Type Ia

What we are trying to do

- So many data samples with so many methods of analysis have confused us
- We want to “rewrite” history, that is, start with a clean data set and redo our analyses to find the weaknesses of our techniques.
- Purely phenomenological guided by simple physics
- Basic parameter - Δm_{15}, *measured from the light curves, NOT from a black box program*
- Measure photometry in the natural system with measured precise transmission functions
- Ultimately the goal is an accuracy of <1% in distance for cosmology with no systematics.

Flat, isotropic, constant-w

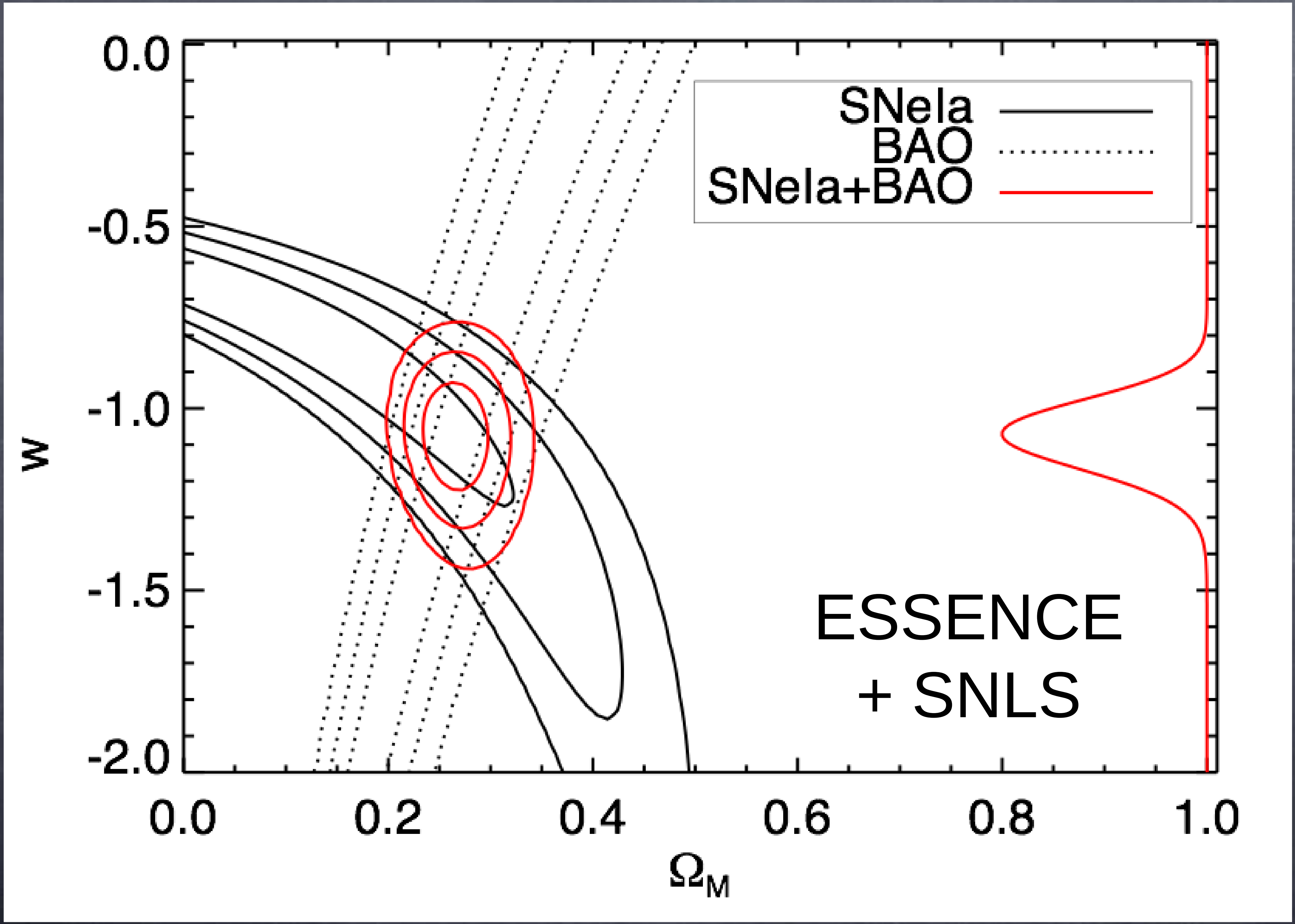
w=-1.05 +- 0.11 +- 0.13



(Wood-Vasey et al., submitted to ApJ)

Flat, isotropic, constant-w

w=-1.07 +- 0.09 +- 0.13



(Wood-Vasey et al., submitted to ApJ)

Summary of Sample

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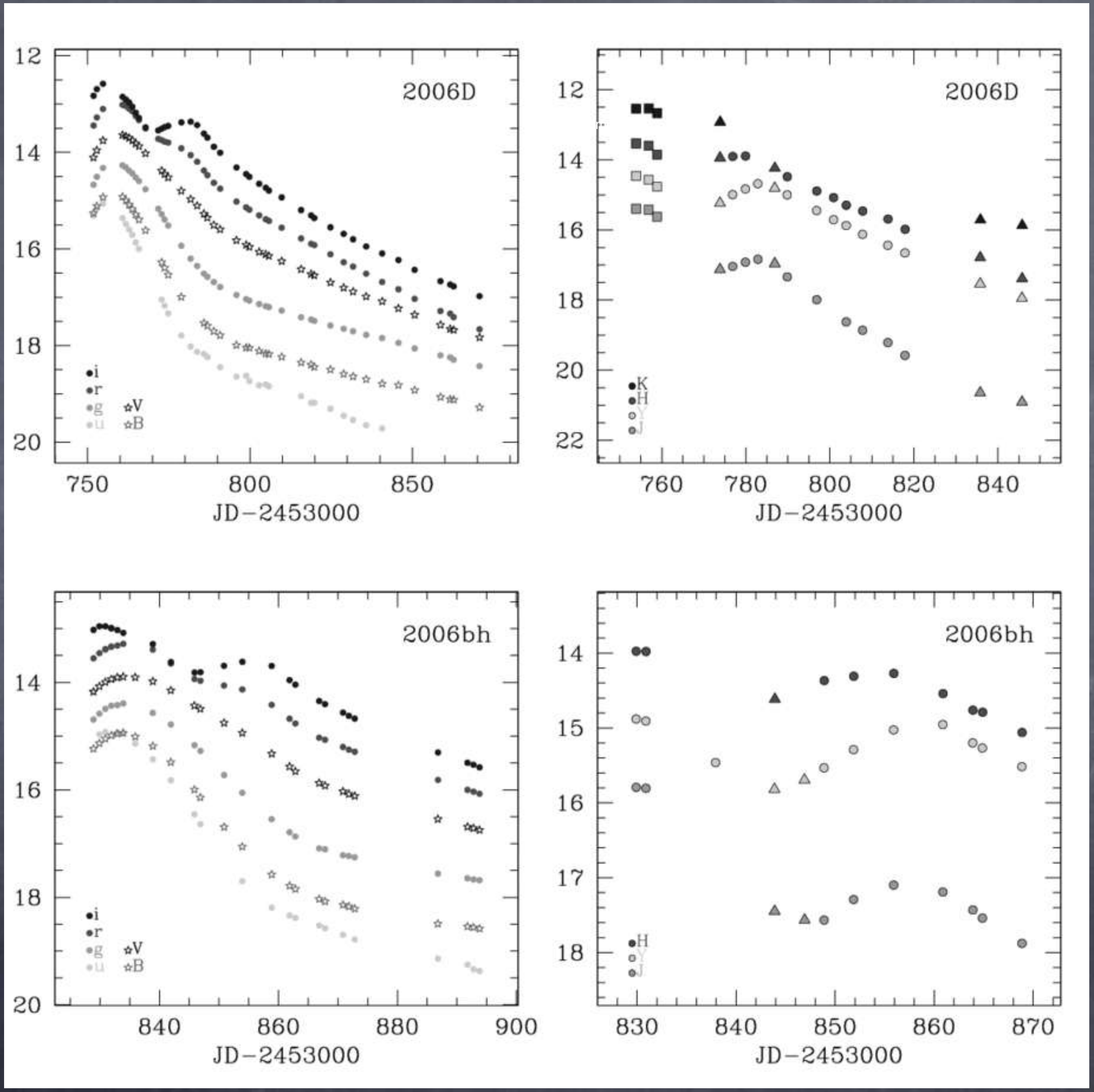
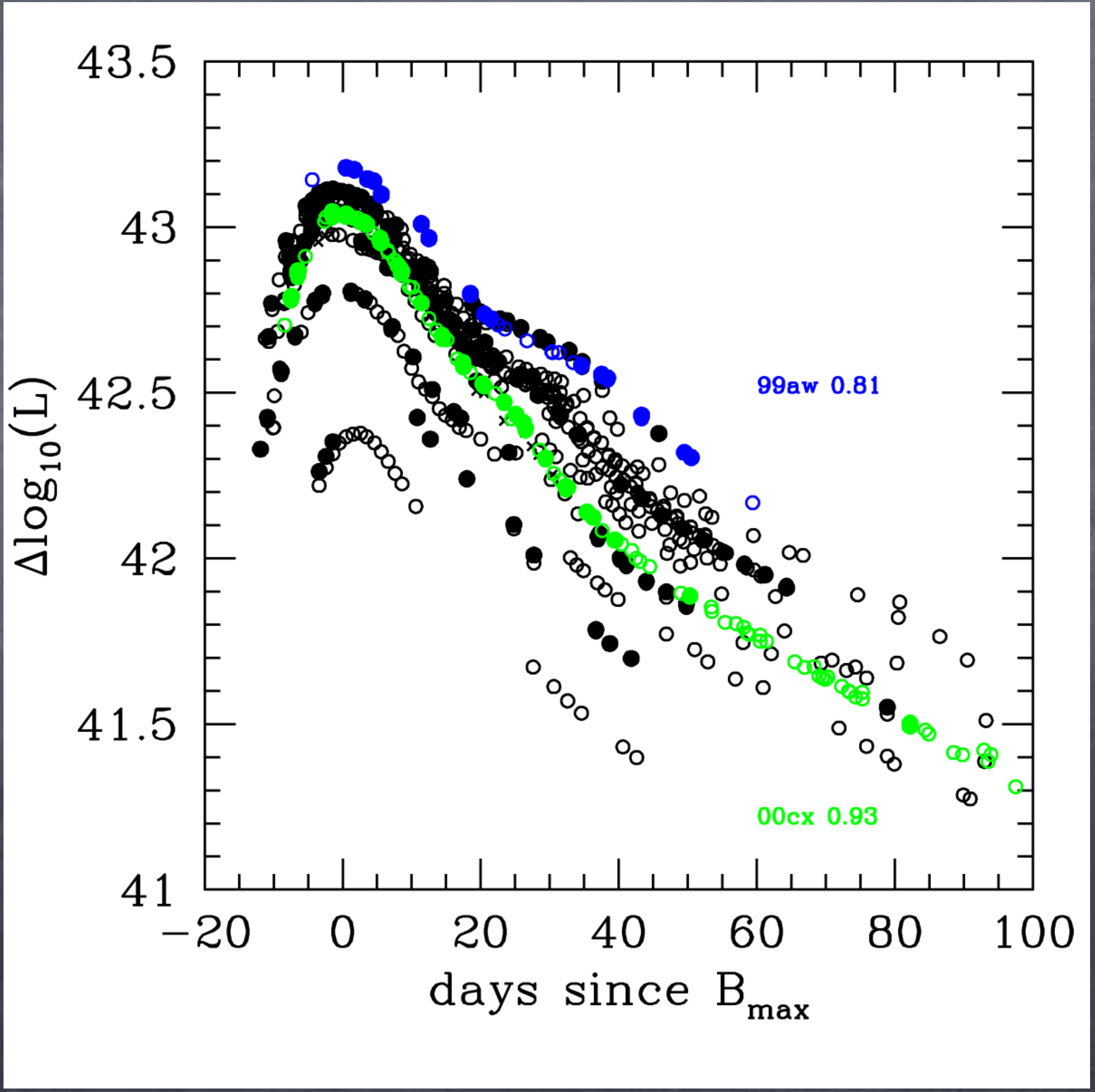

2006D
2006D
2006bh
2006bh
JD−2453000
i
r
g
u
V
B
K
H
Y
J

Bolometric light curves

The secondary maximum is not tightly correlated with the peak luminosity.



Hubble Diagram

QuickTime™ and a
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are needed to see this picture.

$\delta m=0.12$

$\delta z=0.001$

Potential sources of systematic error

- Flux calibrations
- Bias in distance determination codes
- Extinction
    - Host galaxy
    - Our Galaxy
    - Atmosphere
- Extinction law
- Passband errors
    - K corrections
    - Photometry normalization
- Nonlinearity in flux measurements

More Potential Systematics

- “Hubble bubble” trouble
- Gravitational lensing
- Evolutionary effects in SNe
- Biases in low redshift sample
- Search efficiency/selection

Table 5. Potential Sources of Systematic Error on the Measurement of w

Source	dw/dx	Δx	Δ_w	Notes
Phot. errors from astrometric uncertainties of faint objects	1/mag	0.005 mag	0.005	
Bias in diff im photometry	0.5 / mag	0.002 mag	0.001	
CCD linearity	1 / mag	0.005 mag	0.005	
Photometric zeropoint diff in R,I	2 / mag	0.02 mag	0.04	
Zpt. offset between low and high z	1 / mag	0.02 mag	0.02	
K-corrections	0.5 / mag	0.01 mag	0.005	
Filter passband structure	0 / mag	0.001 mag	0	
Galactic extinction	1 / mag	0.01 mag	0.01	
Host galaxy R_V	0.02 / R_V	0.5	0.01	"glosz"
Host galaxy extinction treatment	0.08	prior choice	0.08	different priors
Intrinsic color of SNe Ia	3 / mag	0.02 mag	0.06	interacts strongly with prior
Malmquist bias/selection effects	0.7 / mag	0.03 mag	0.02	"glosz"
SN Ia evolution	1 / mag	0.02 mag	0.02	
Hubble bubble	$3/\delta H_{\rm effective}$	0.02	0.06	
Gravitational lensing	$1/\sqrt{N}$ / mag	0.01 mag	< 0.001	Holz & Linder (2005)
Grey dust	1 / mag	0.01 mag	0.01	
Subtotal w/o extinction+color	···	···	0.082	
Total	···	···	0.13	
Joint ESSENCE+SNLS comparison	···	···	0.02	photometric system
Joint ESSENCE + SNLS Total	···	···	0.13	

(Wood-Vasey et al., 2007, ApJ)

SNe and GRB's
Wright (2007)

– 7 –

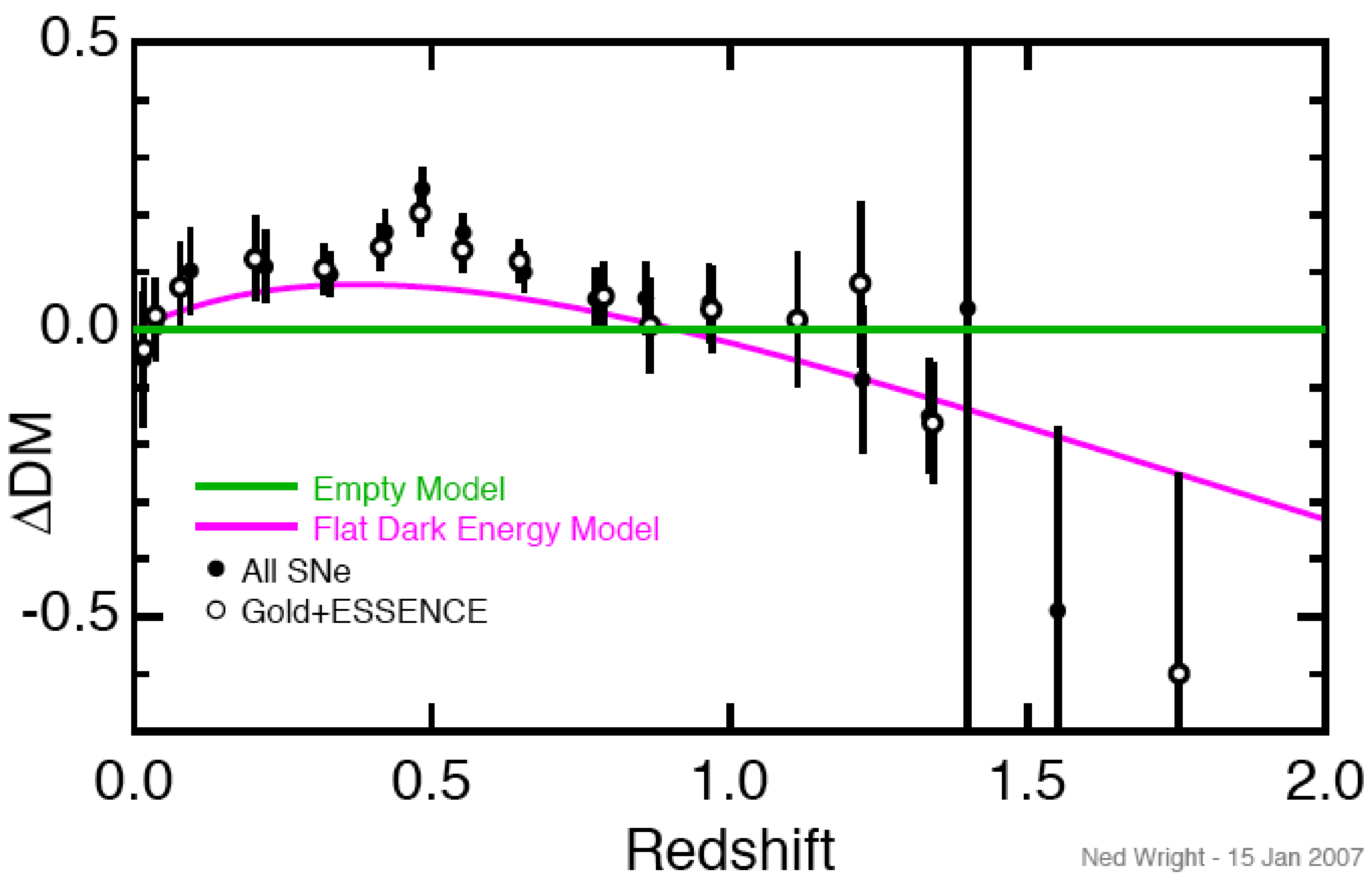


Fig. 2.— Binned supernova data *vs.* redshift compared to a flat ΛCDM model with Ω_M = 0.369. The filled circles are binned points from the full dataset, while the open circles have omitted the "Silver" subset.

Higher-Z SN Team

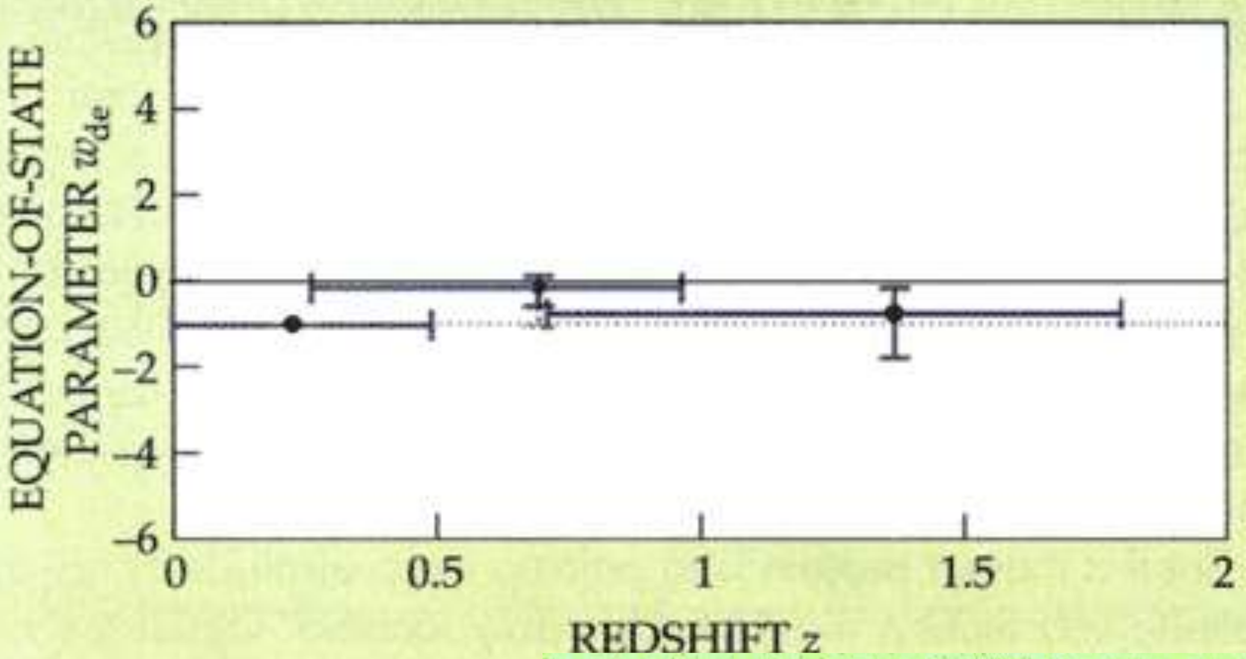


Figure 3. Evolution of w_{de}, the dark energy's ratio of pressure to energy density, as determined from the supernova data. Negative pressure tends to accelerate the cosmic expansion. If the dark energy is the vacuum energy of Einstein's cosmological constant, w_{de} is −1 forever (dotted line). Competing quintessence models let w_{de} change over time. The Higher-Z team concludes, with 98% confidence, that w_{de} was already negative from redshift 1.8 to 1.0, that is, from 10 to 6 billion years ago. (Adapted from ref. 3.)

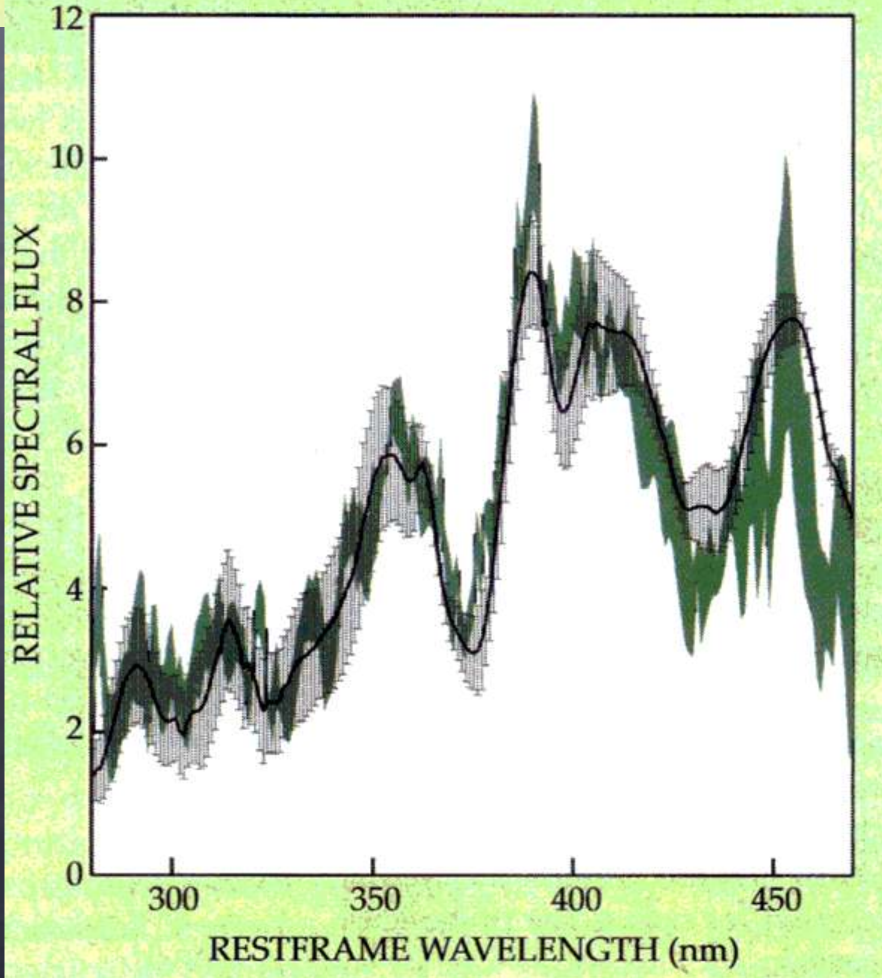


Figure 4. Ancient and recent spectra of type 1a supernovae show no evolutionary change over 10 billion years. The green band is a composite spectrum of the Higher-Z team's 13 best-measured supernovae with redshifts *z* above 1, transformed into each exploding star's rest frame. The black curve with gray error bars is a template used to verify the type 1a designation for supernovae with redshifts less than 0.1, which would have exploded within the past billion years or so. (Adapted from ref. 3.)

Riess, et al (2007)

Summary

- The accelerating Universe poses a significant challenge to theory, experiment and observation.
- Current goal: w to 10%
- The SNIa data are consistent with a flat Universe with a cosmological constant.

Time Dilation in the Universe

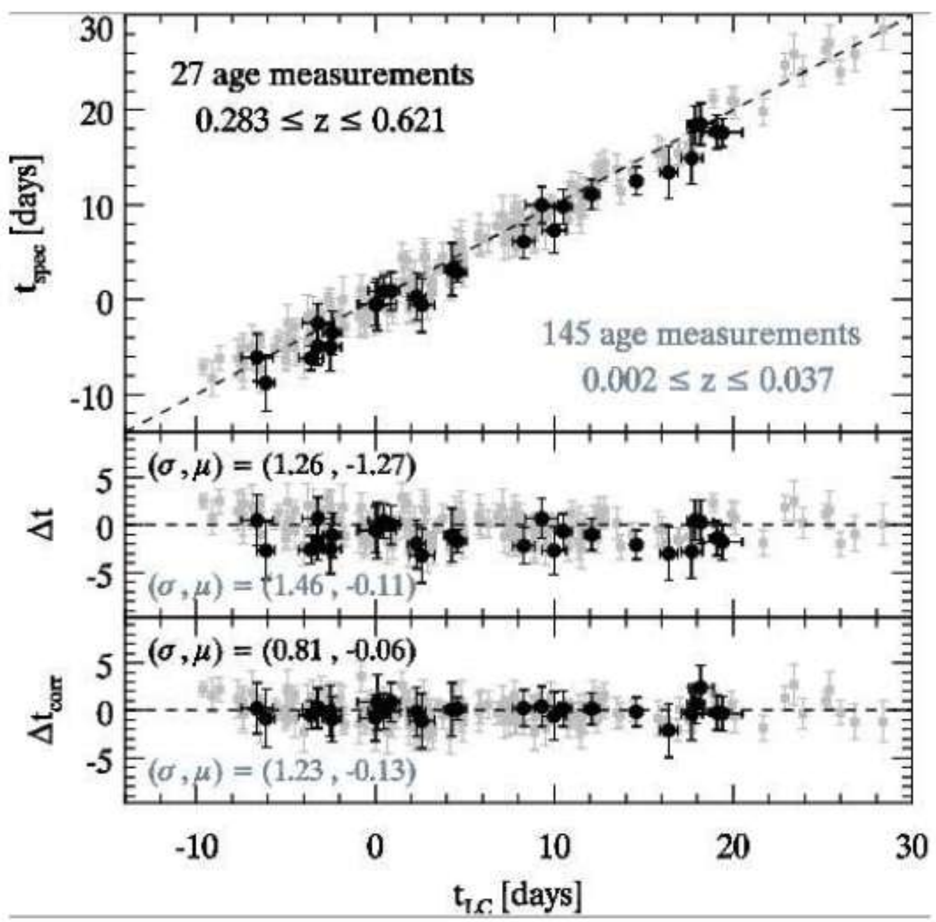
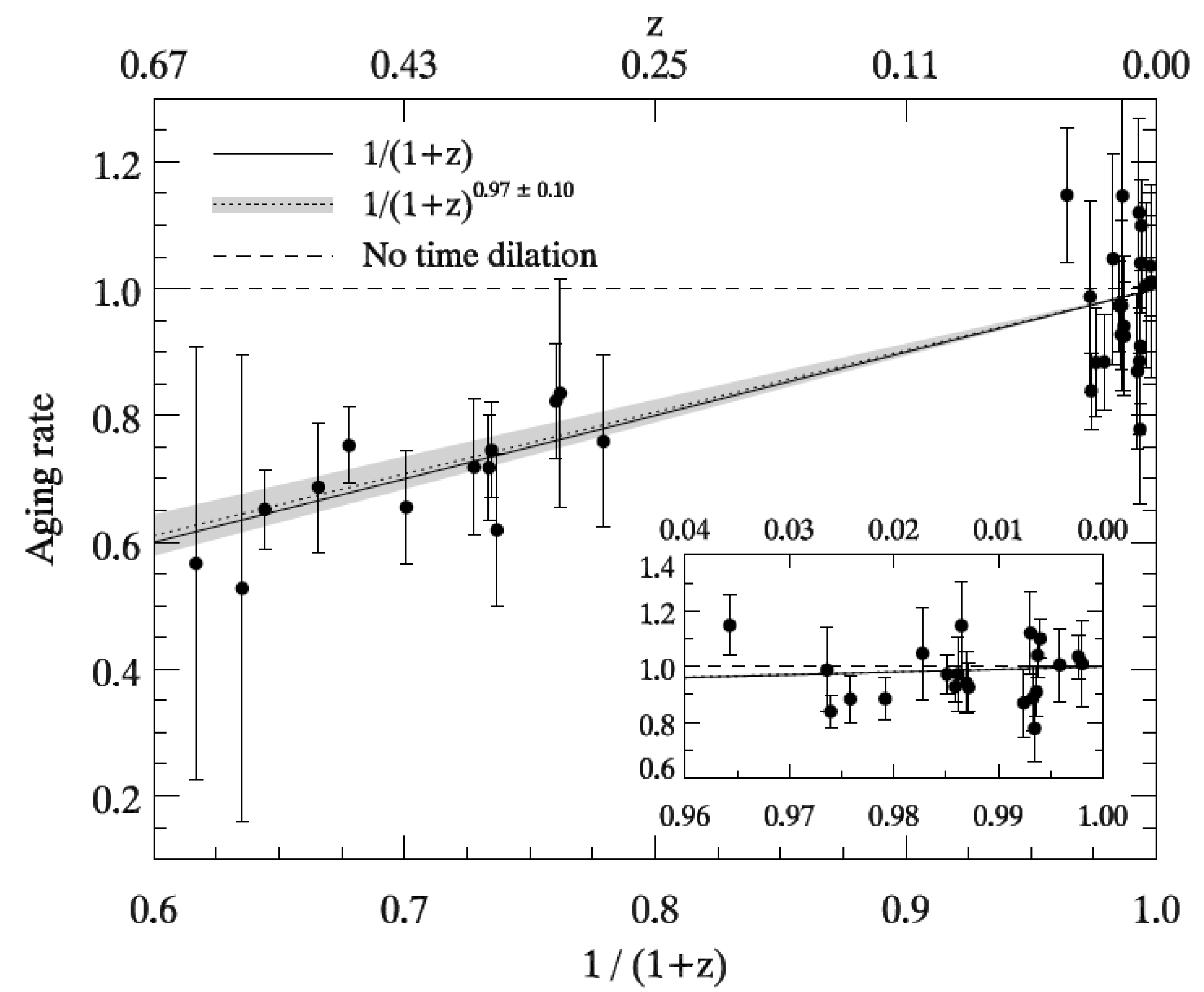


FIG. 10.— Upper panel: comparison of supernova *rest-frame* ages (in days from maximum light) obtained from cross-correlation with spectral templates ($t_{\rm spec}$) and from fits to the light curve ($t_{\rm LC}$). 145 age measurements for the subsample of 22 low-redshift SNe Ia are shown in gray. The dashed line represents the one-to-one correspondence between $t_{\rm LC}$ and $t_{\rm spec}$. Middle panel: Age residuals, $\Delta t = t_{\rm spec} - t_{\rm LC}$. We also indicate the standard deviation (σ) and mean residual (μ). Lower panel: Same as above, where each point has been corrected for the mean offset between $t_{\rm spec}$ and $t_{\rm LC}$ for a given supernova.



IG. 8.— Apparent aging rate versus $1/(1+z)$ for the 13 high-redshift ($0.28 \le z \le 0.62$) and 22 low-redshift ($z < 0.04$) SNe Ia in our aple. Overplotted are the expected $1/(1+z)$ time dilation (solid line) and the best-fit $1/(1+z)^b$ model (with $b = 0.97 \pm 0.10$; dotted and gray area). The dashed line corresponds to no time dilation, as expected in the tired-light model — clearly inconsistent with the a. The inset shows a close-up view of the low-redshift sample. These data are summarized in Table 3.

No “tired light”- whoopee

MOdified Newtonian Dynamics

$$m_g \mu(a/a_0)\boldsymbol{a} = \boldsymbol{F}, \qquad (1)$$

$$\mu(x \gg 1) \approx 1, \qquad \mu(x \ll 1) \approx x,$$

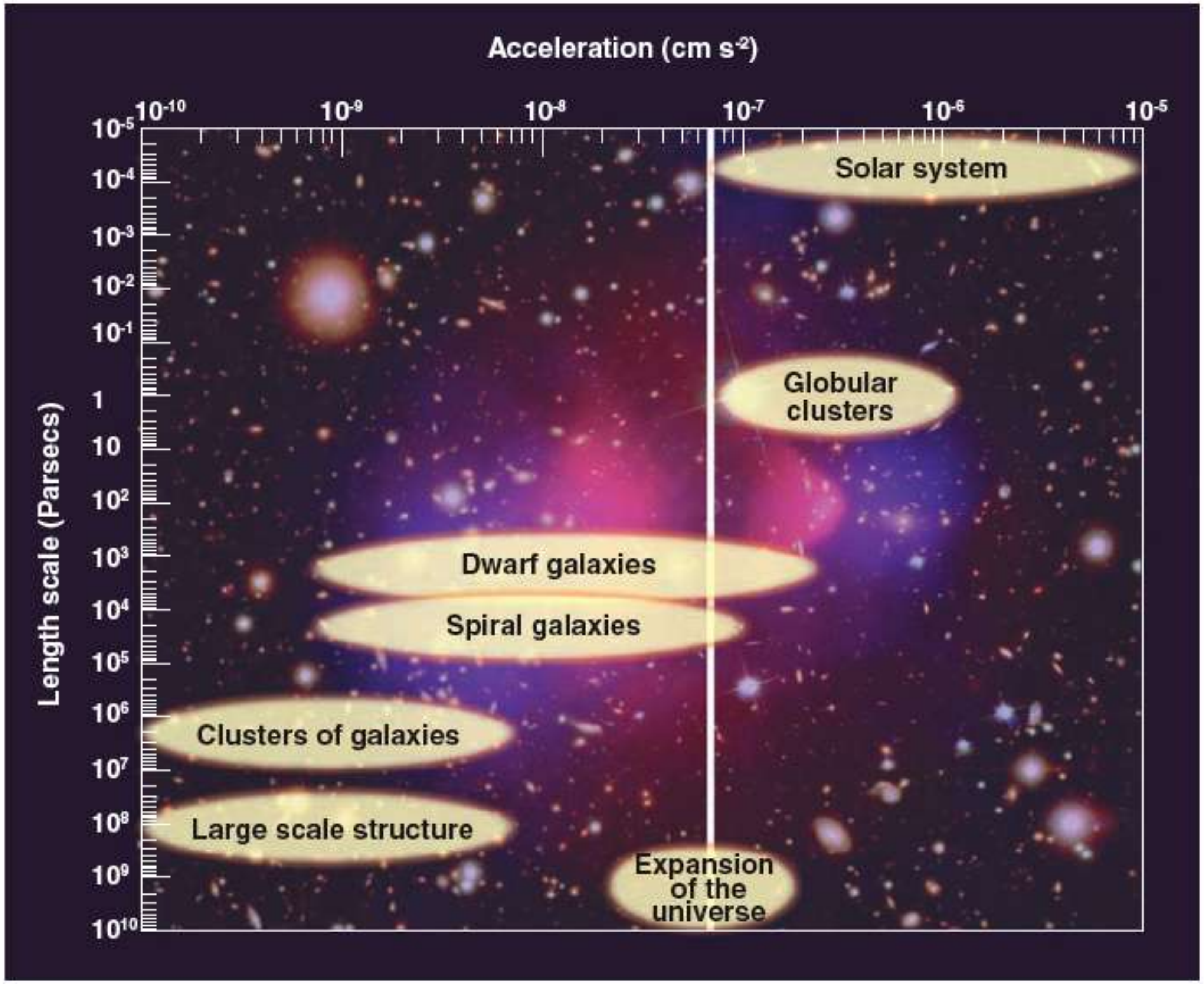


Fig. 1. Evidence for dark matter or for deviations from GR tend to appear in systems in which the acceleration scale is weak (below the solid horizontal line) at about 10^{-8} cm s^{-2}. There is strong evidence for either of the above in dwarf galaxies, spiral galaxies, clusters of galaxies, the large-scale structure of the universe, and in the expansion of the universe itself. [Source: X-ray: NASA/CXC/CfA/M. Markevitch *et al.*; Optical: NASA/STScI; Magellan/U. Arizona/D. Clowe *et al.*; Lensing Map: NASA/STScI; ESO WFI; Magellan/U. Arizona/D. Clowe *et al.*]

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

dSph galaxies

Dwarf Spheroidals in MOND

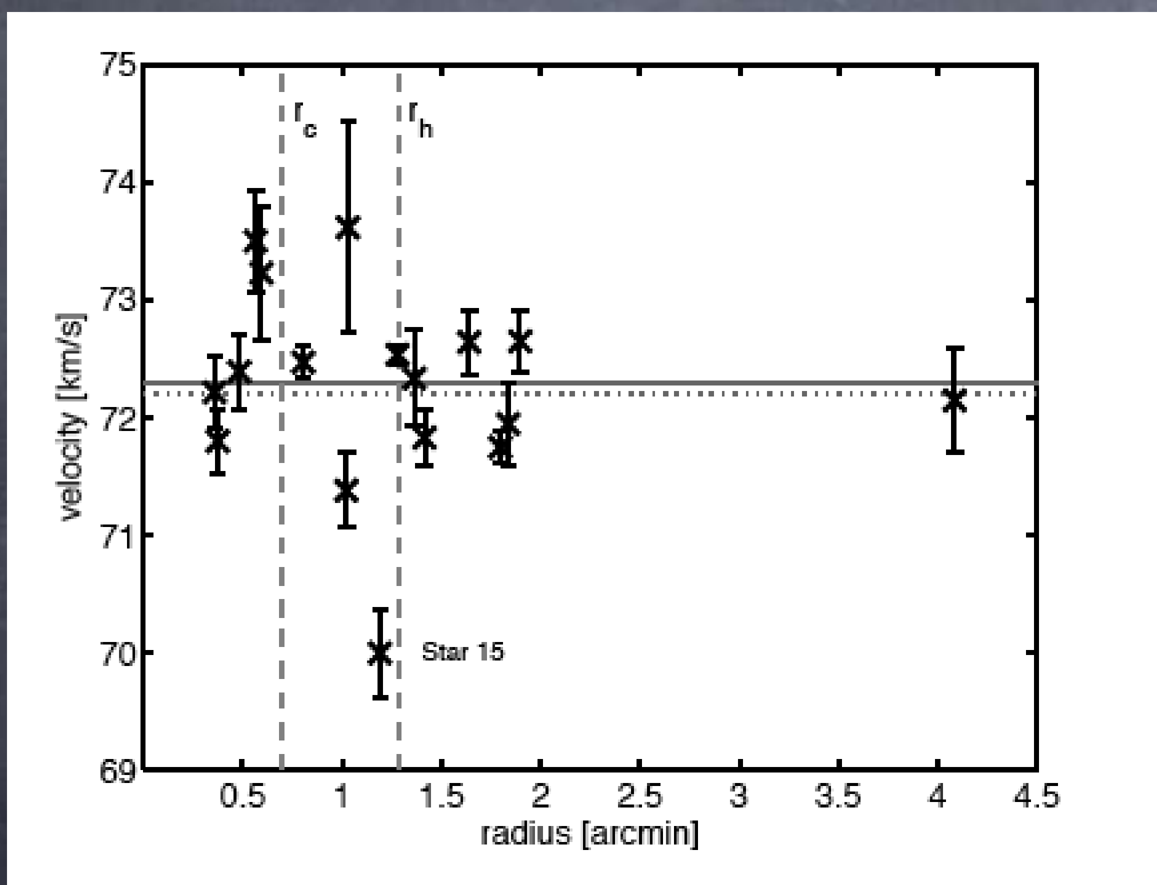
Name	R_{MW} kpc	c	R_t pc	M_v	L_v $10^5 L_\odot$	V_r $\mathrm{km\,s^{-1}}$	r_α pc	α_o	r_β pc	β_o	M/L_v	M/L_N	χ^2_{red}
Carina	101 ± 5	0.51 ± 0.08	581 ± 86	-9.3 ± 0.2	4.4 ± 1.1	8	2000	24	150^{+1050}_{-130}	0.6	$5.6^{+5.2}_{-2.9}$	80	0.72
Draco	93 ± 6	0.72 ± 0.05	1225 ± 80	-9.0 ± 0.3	3.3 ± 1.1	-294	1500	14	120^{+150}_{-85}	0.93	$43.9^{+29.0}_{-19.3}$	270	0.65
Leo I	257 ± 8	0.39 ± 0.07	1002 ± 50	-12.4 ± 0.2	76 ± 7	178	3700	22	$490^{+\infty}_{-400}$	0.1	$0.7^{+0.65}_{-0.3}$	10	0.47
Sextans	95.5 ± 3	0.98 ± 0.14	3445 ± 1141	-9.7 ± 0.2	6.3 ± 1.4	75	1200	6	1250^{+8500}_{-600}	0.0	$9.2^{+5.3}_{-3.0}$	102	1.2
Fornax	138 ± 8	0.72 ± 0.05	2078 ± 177	-13.2 ± 0.2	158 ± 16	-36	3200	14	770^{+1500}_{-450}	0.3	$1.4^{+0.45}_{-0.35}$	11	1.4
Sculptor	87 ± 4	1.12 ± 0.12	1329 ± 107	-11.1 ± 0.2	28 ± 4	95	1200	14	170^{+600}_{-140}	0.5	$3.7^{+2.2}_{-1.4}$	36	0.7
Leo II	233 ± 15	0.48 ± 0.1	554 ± 68	-9.9 ± 0.3	7.6 ± 3	22	2500	30	$280^{+\infty}_{-255}$	0.56	$1.85^{+2.0}_{-1.1}$	57	1.1
UMi	76 ± 4	0.64 ± 0.05	1977 ± 104	-10.3 ± 0.4	11.0 ± 4.8	-87	6000	25	$5000^{+\infty}_{-4750}$	0.73	$5.8^{+6.5}_{-3.6}$	440	0.86

Palomar 14

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Palomar 14

σ = 0.38 km/s



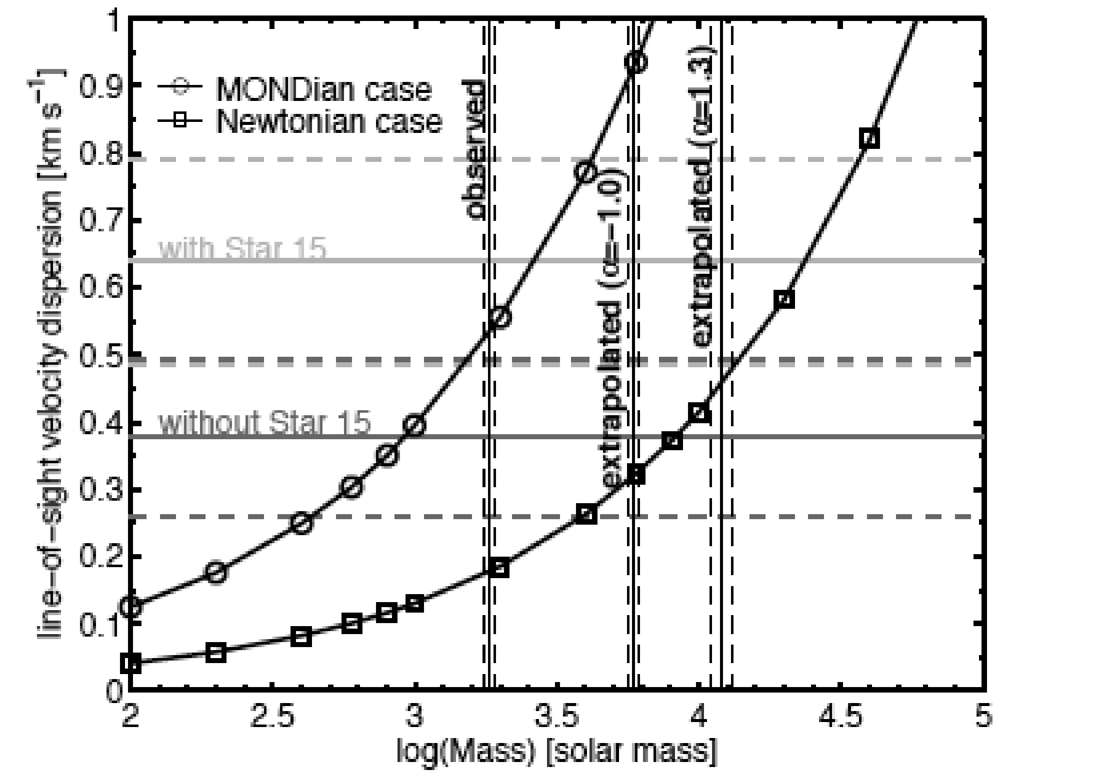


Fig. 10.— Theoretically predicted velocity dispersion as a function of mass. The two black curves are the predictions in MONDian dynamics (open circles) and in classical Newtonian dynamics (open squares). The observed velocity dispersions (and the errors) are drawn as the two horizontal lines, the light gray without Star 15, dark gray with Star 15. The vertical lines mark the observed lower mass limit and the two extrapolated lower mass limits.

Alternative Gravities

TABLE 1
SUMMARY OF MODELS

Model	Abbrev.[a]	Parameters[b]	Section
Flat cosmo. const.	FΛ	Ω_m	4.1.1
Cosmological const.	Λ	Ω_m, Ω_Λ	4.1.2
Flat constant w	Fw	Ω_m, w	4.1.3
Constant w	w	Ω_m, Ω_k, w	4.1.4
Flat w(a)	Fwa	Ω_m, w_0, w_a	4.2.1
DGP	DGP	Ω_k, Ω_{r_c}	4.3.1
Flat DGP	FDGP	Ω_{r_c}	4.3.2
Cardassian	Ca	Ω_m, q, n	4.4
Flat Gen. Chaplygin	FGCh	A, α	4.5.1
Gen. Chaplygin	GCh	Ω_k, A, α	4.5.1
Flat Chaplygin	FCh	A	4.5.2
Chaplygin	Ch	Ω_k, A	4.5.2

[a] The abbreviations used in Figure 7.[b] The free parameters in each model. Note that when fitting the SN Ia data we also fit an additional parameter, $\mathcal{M}$, for the normalization of SN magnitudes. We include this in the number of degrees of freedom and in k, but have not listed it here as a parameter in each model.

TABLE 2
SUMMARY OF THE INFORMATION CRITERIA RESULTS

	χ^2/ dof	GoF (%)	ΔAIC	ΔBIC
Flat cosmo const	194.5 / 192	43.7	0	0
Flat Gen. Chaplygi	193.9 / 191	42.7	1	5
Cosmological const	194.3 / 191	42.0	2	5
Flat constant w	194.5 / 191	41.7	2	5
Flat w(a)	193.8 / 190	41.0	3	10
Constant w	193.9 / 190	40.8	3	10
Gen. Chaplygin	193.9 / 190	40.7	3	10
Cardassian	194.1 / 190	40.4	4	10
DGP	207.4 / 191	19.8	15	18
Flat DGP	210.1 / 192	17.6	16	16
Chaplygin	220.4 / 191	7.1	28	30
Flat Chaplygin	301.0 / 192	0.0	30	30

NOTE. — The flat cosmological constant (flat Λ) model is preferred by both the AIC and the BIC. The ΔAIC and ΔBIC values for all other models in the table are then measured with respect to these lowest values. The goodness of fit (GoF) approximates the probability of finding a worse fit to the data. The models are given in order of increasing ΔAIC.

Here we choose several of the most popular models discussed in the literature and examine whether they are consistent with the data currently available to us:

1. Standard dark energy models, including varying w.
2. Dvali-Gabadadze-Porrati (DGP) brane world model.
3. Cardassian expansion.
4. Chaplygin gas.

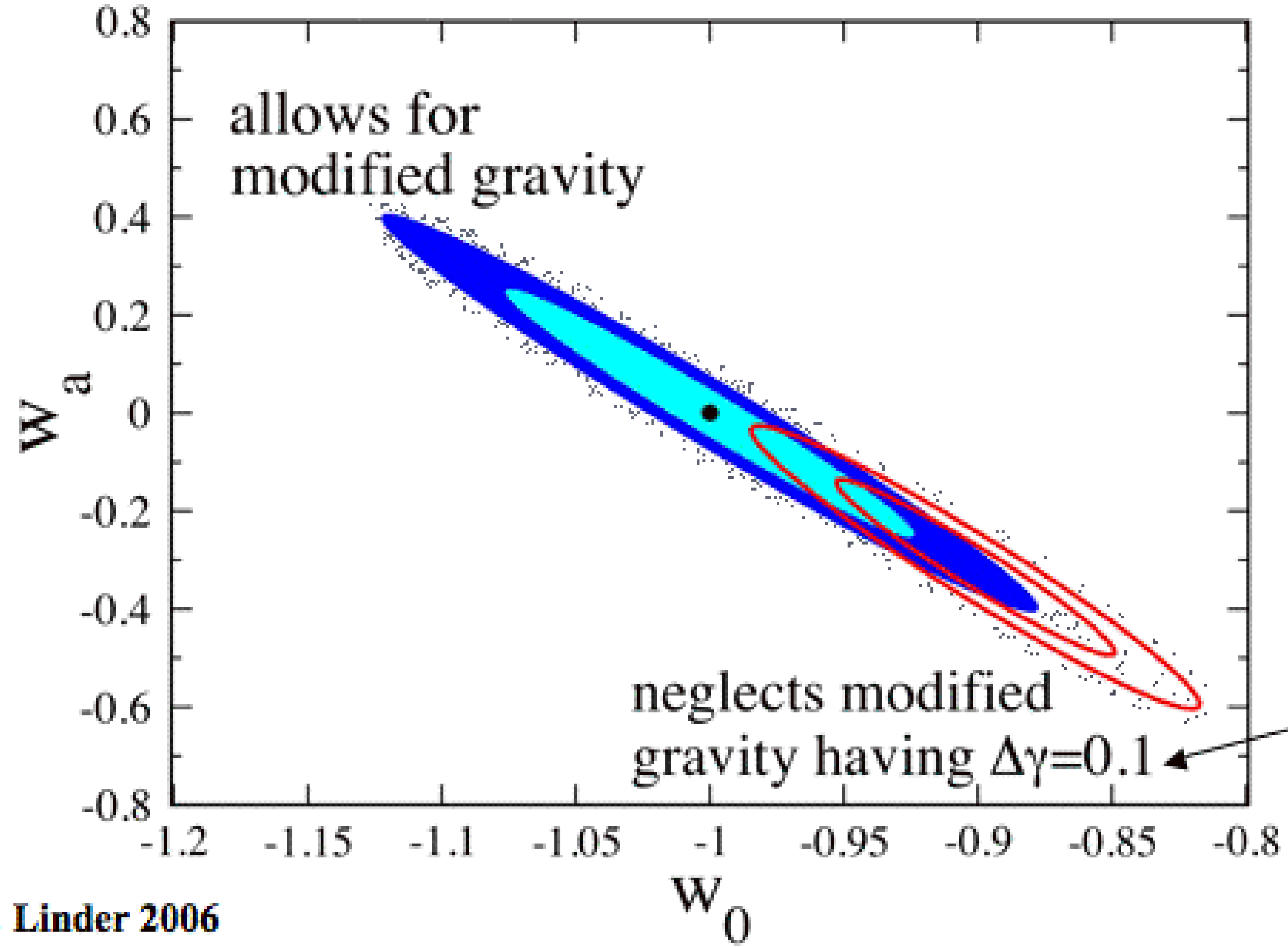
Davis et al (2007)

Using Baysean and Akaike Information Criteria

The Nature of Gravity

The growth of mass density perturbations depends on the expansion *and* the theory of gravity.

The tension between cosmic distance measurements and large scale structure mass growth measurements reveals deviations from GR.



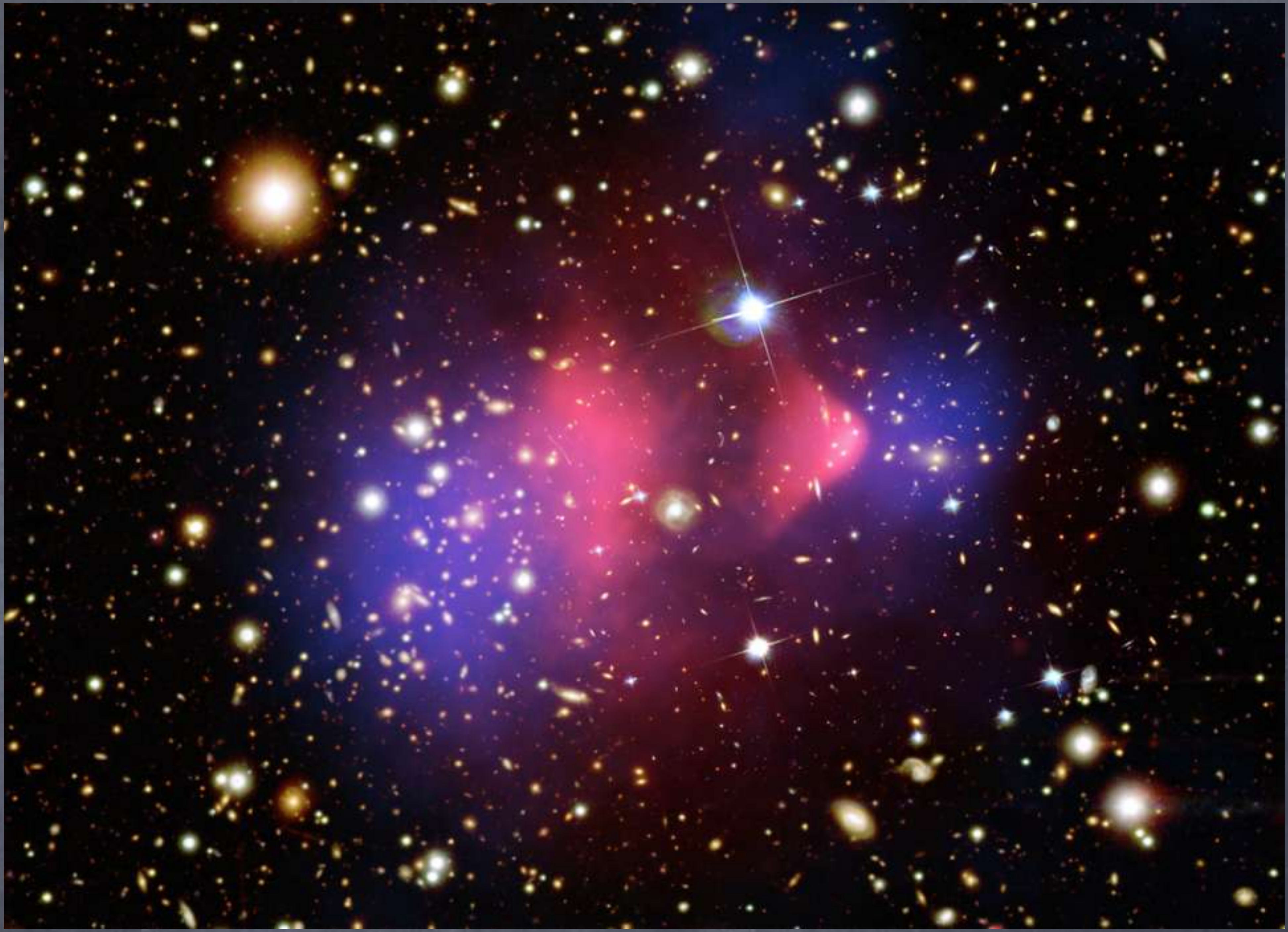
Δγ gives deviations in growth from GR

Huterer & Linder 2006

Closing thoughts

- The scale of dark matter
- DETF and future measures of dark energy
- The Hubble constant
- Gamma-ray bursts (a type of supernova)

The Bullet Cluster



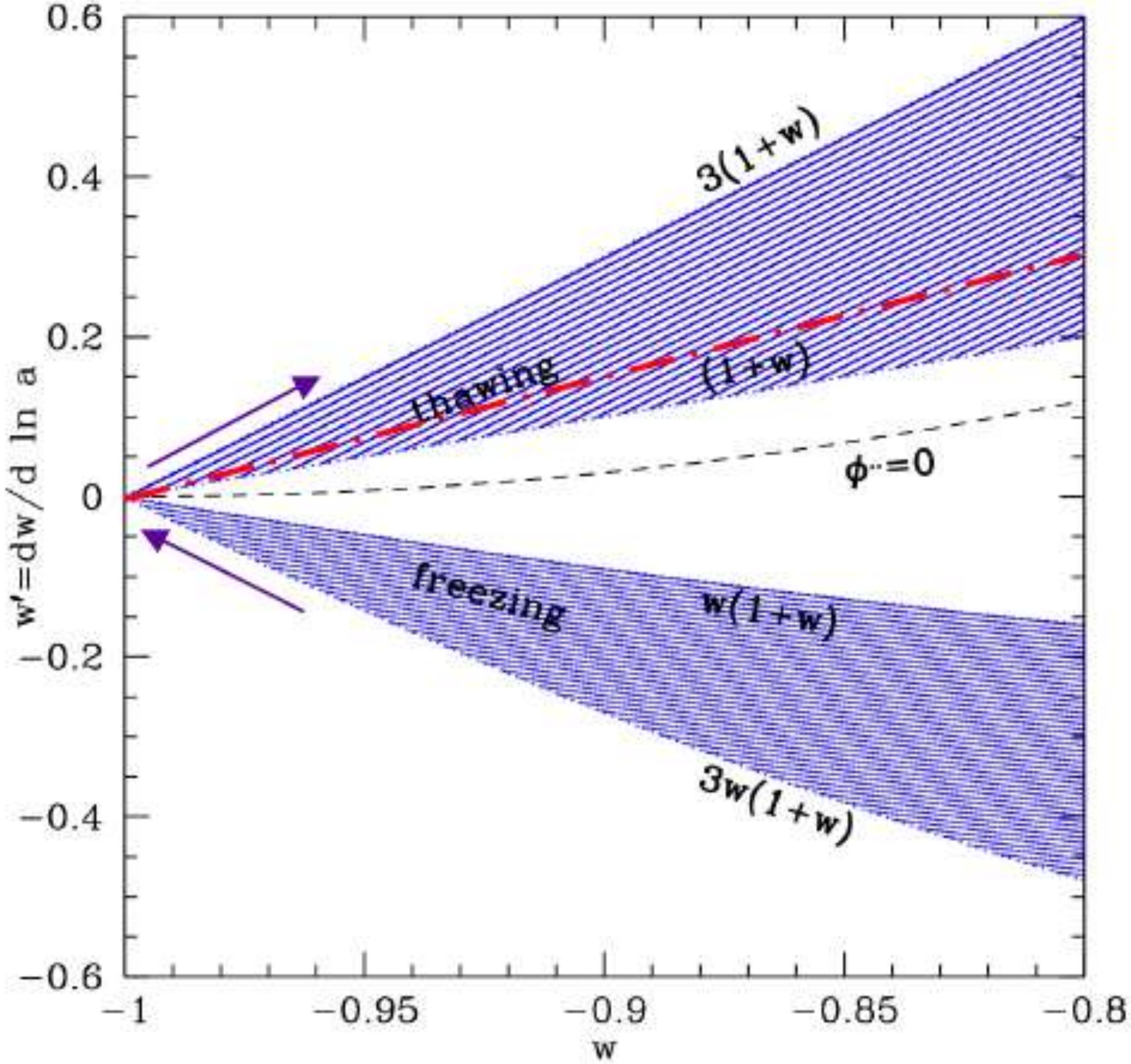
Direct evidence for dark matter?

DETF - minority (me) report

- Era of $(N)^{-1/2}$ statistics - beware!
- Sne, BAO, Clusters, WL - we need to do more than 1
- SNe, BAO, Clusters, WL. Can’t we do better?
- Is w’ even likely? That is, for $w=-1 \pm \varepsilon$ as $\varepsilon \Rightarrow 0$, does $P(w' \neq -1) \Rightarrow 0$? See Caldwell & Linder (2005) for restricting the search for w’ given errors on w - thawing/freezing.
- Help observers find *easier* observations to do. Don’t forget Spergel’s law!

Nature is more creative than we are

Science Definition



Distinct, narrow regions of w-w′

Steepness of potential vs. Hubble drag

Caldwell & Linder 2005
PRL 95, 141301; astro-ph/0505494

Entire "thawing" region looks like <w> = -1±0.05.

Need w′ experiments with σ (w′) ≈ 2(1+w).

Dark Energy and Gravity

Is cosmic acceleration revealing a new ingredient (dark energy) or new laws of gravity?

Track record for gravity puzzles:

Inner solar system motions → General Relativity
Outer solar system motions → Neptune
Galaxy rotation curves → Dark Matter

"Dark energy" could be new gravity.

Joint Dark Energy Mission (JDEM)
***is* a gravity experiment.**