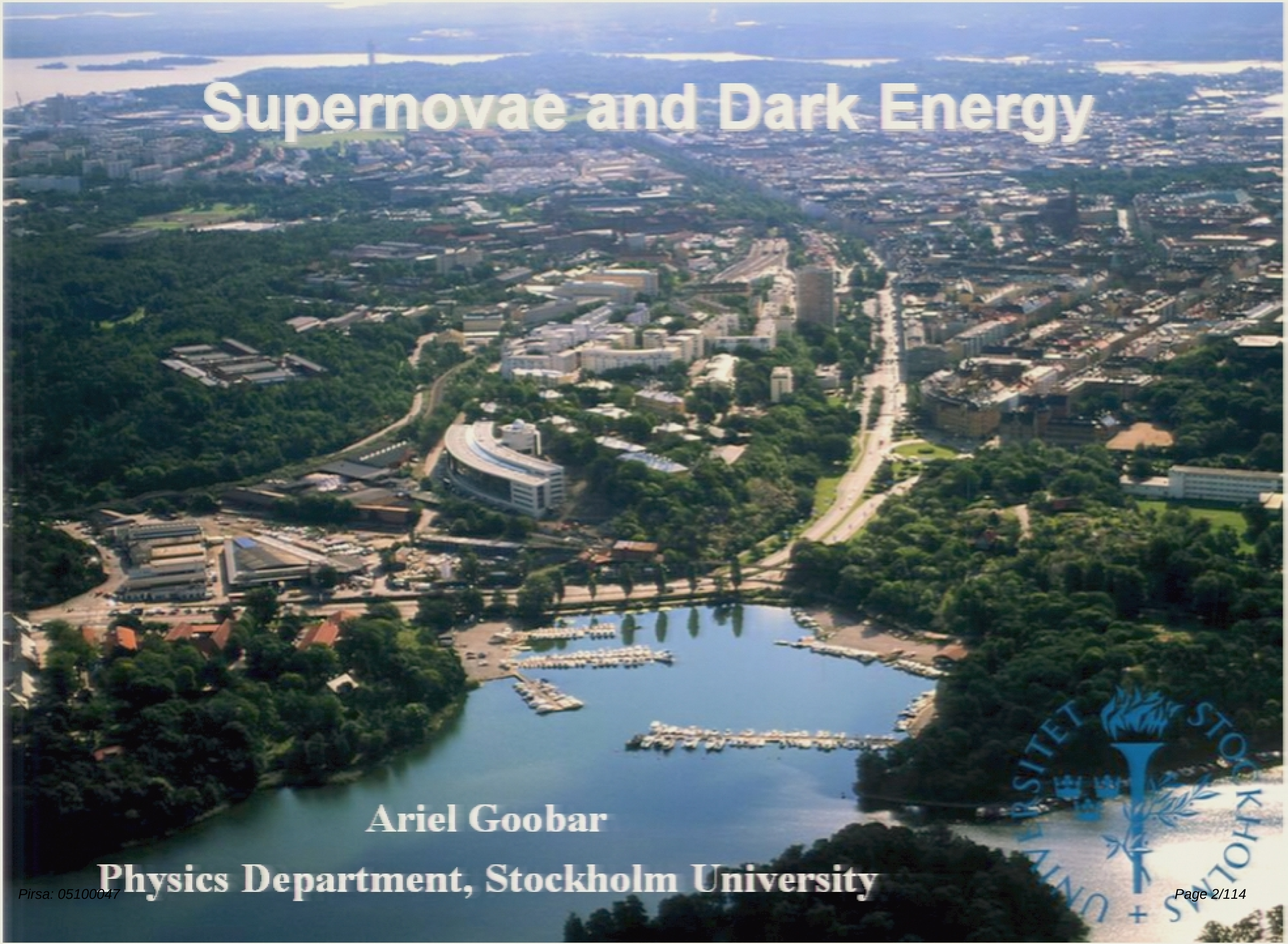
Title: Supernova observations and dark energy

Date: Oct 25, 2005 03:00 PM

URL: http://pirsa.org/05100047

Abstract:

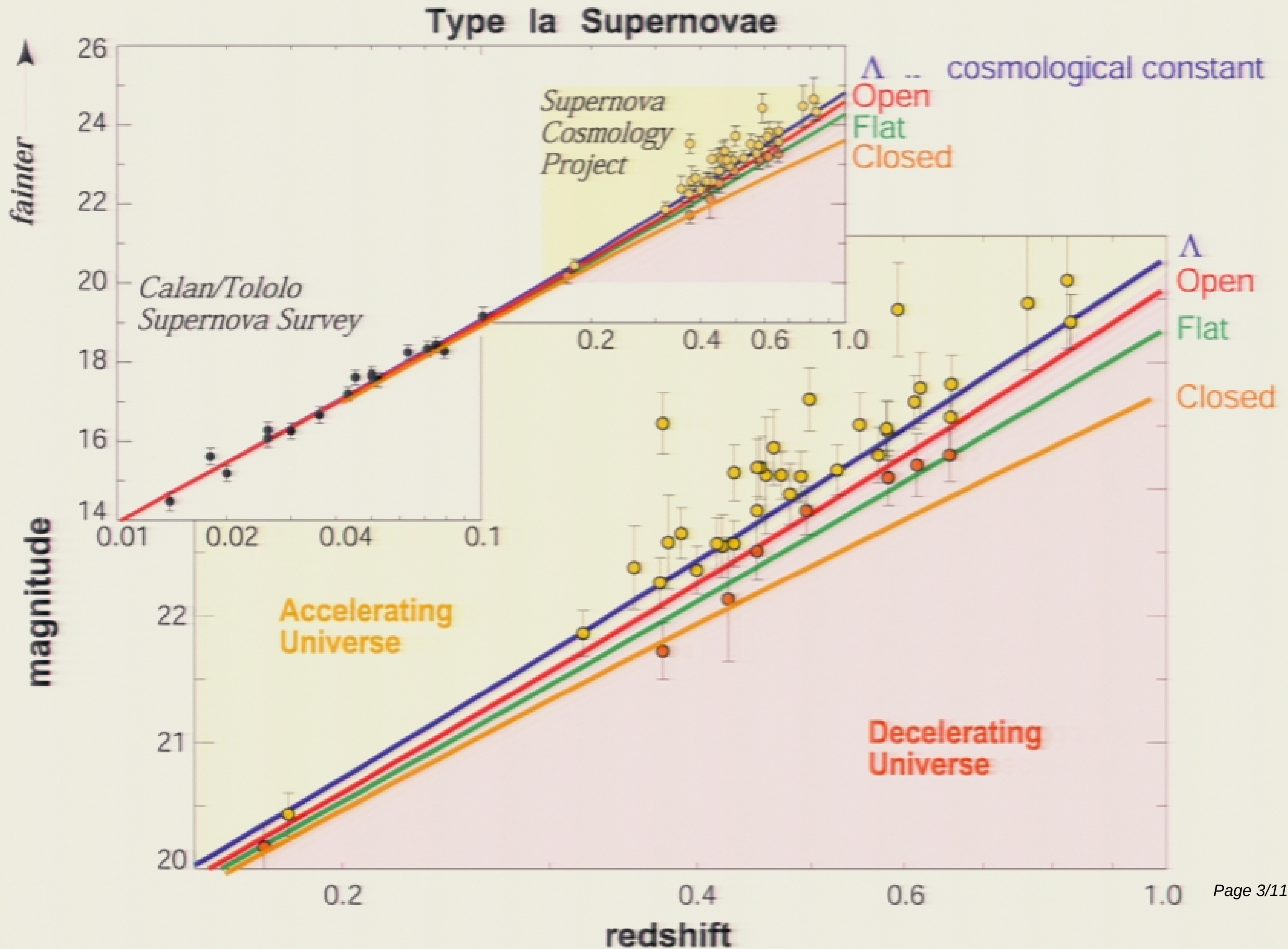
Supernovae and Dark Energy



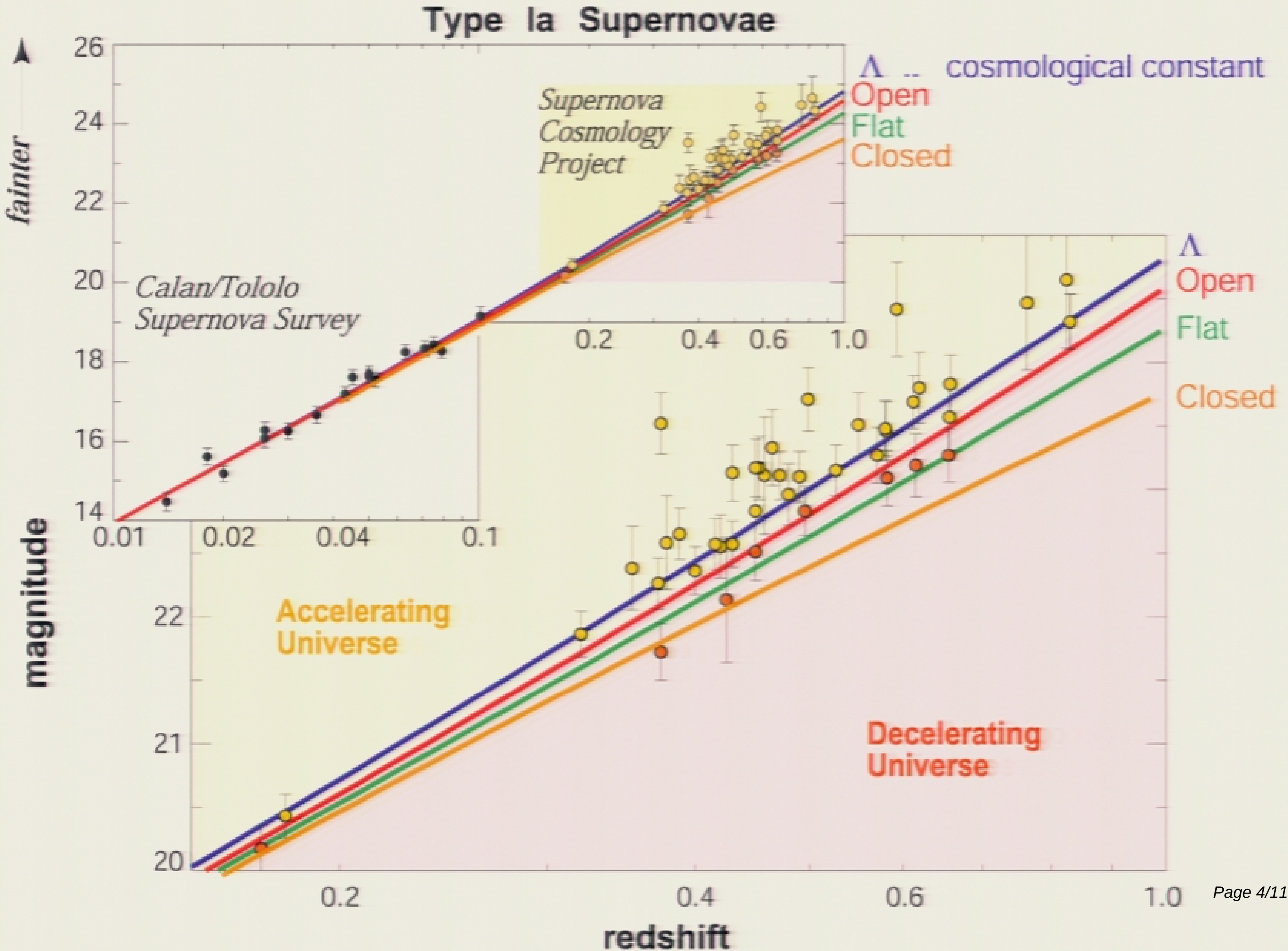
Ariel Goobar

Physics Department, Stockholm University

SCP:Perlmutter et al + High-Z Team:Riess et al

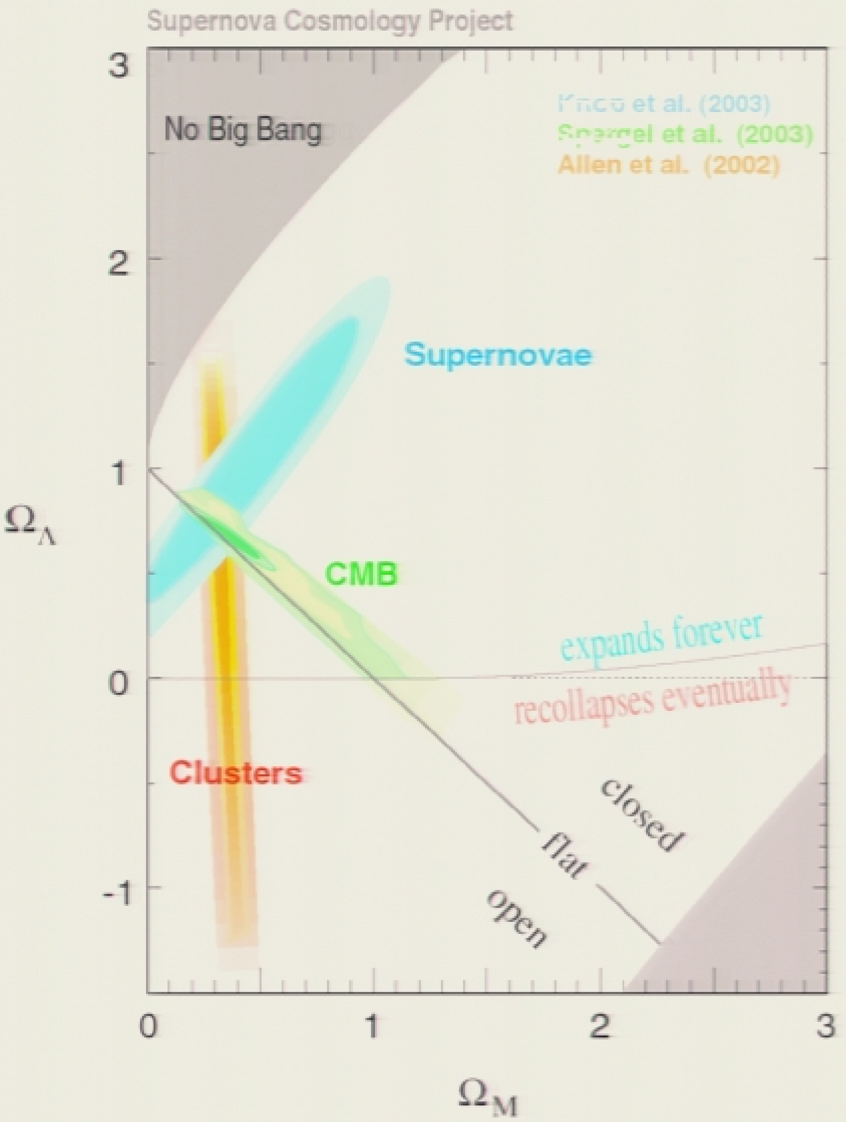


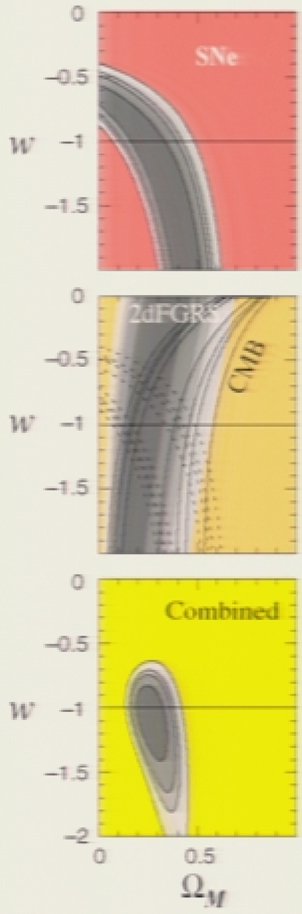
SCP:Perlmutter et al + High-Z Team:Riess et al



5 AD: concordance model

(see also Tonry et al 2003, Barris et al 2004)





Supernova Cosmology Project
Knop *et al.* (2003)

Assuming constant w

With limits from:
2dFGRS (Hawkins et al. 2002)
and CMB (Bennet et al. 2003,
Spergel et al. 2003)

$w = -1.05 \, ^{+0.15}_{-0.20}$ (statistical)
± 0.09 (systematic)

$$\Omega_\Lambda = 0.75 \, ^{+0.06}_{0.07} \pm 0.04$$

(Known) systematic effects

- SN brightness evolution
- Shape-brightness relation
- K-corrections and SN colors

Astrophysics of supernovae

- Non-Type Ia contamination
- Malmquist bias

Selection effects,contamination

- Host galaxy dust properties
- Intergalactic dust
- Gravitational lensing
- Exotica:axion-photon oscillations, etc

Line of sight effects

- Instrumental corrections
- Absolute calibration
- Lightcurve fitting technique/host galaxy subtraction

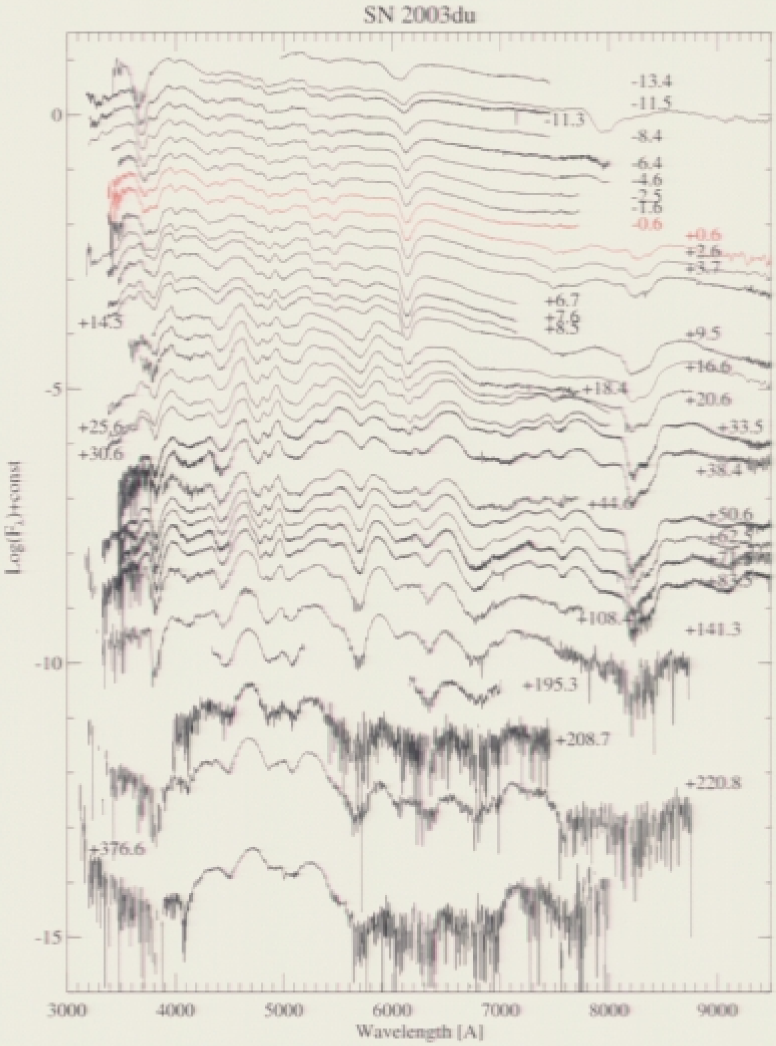
Measurement issues

- ...

Exploring the ”Standard Candle”

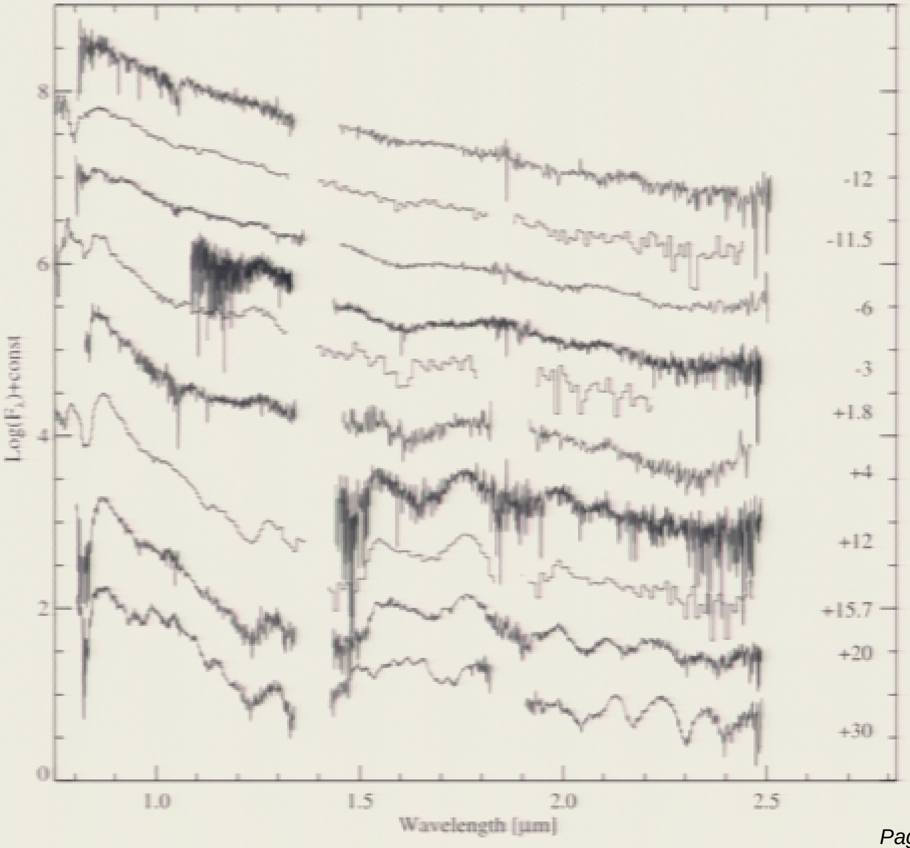
Studies of Near-by Supernovae

Ongoing European SNIa Network: up to now 15 near-by SNe: e.g SN03du



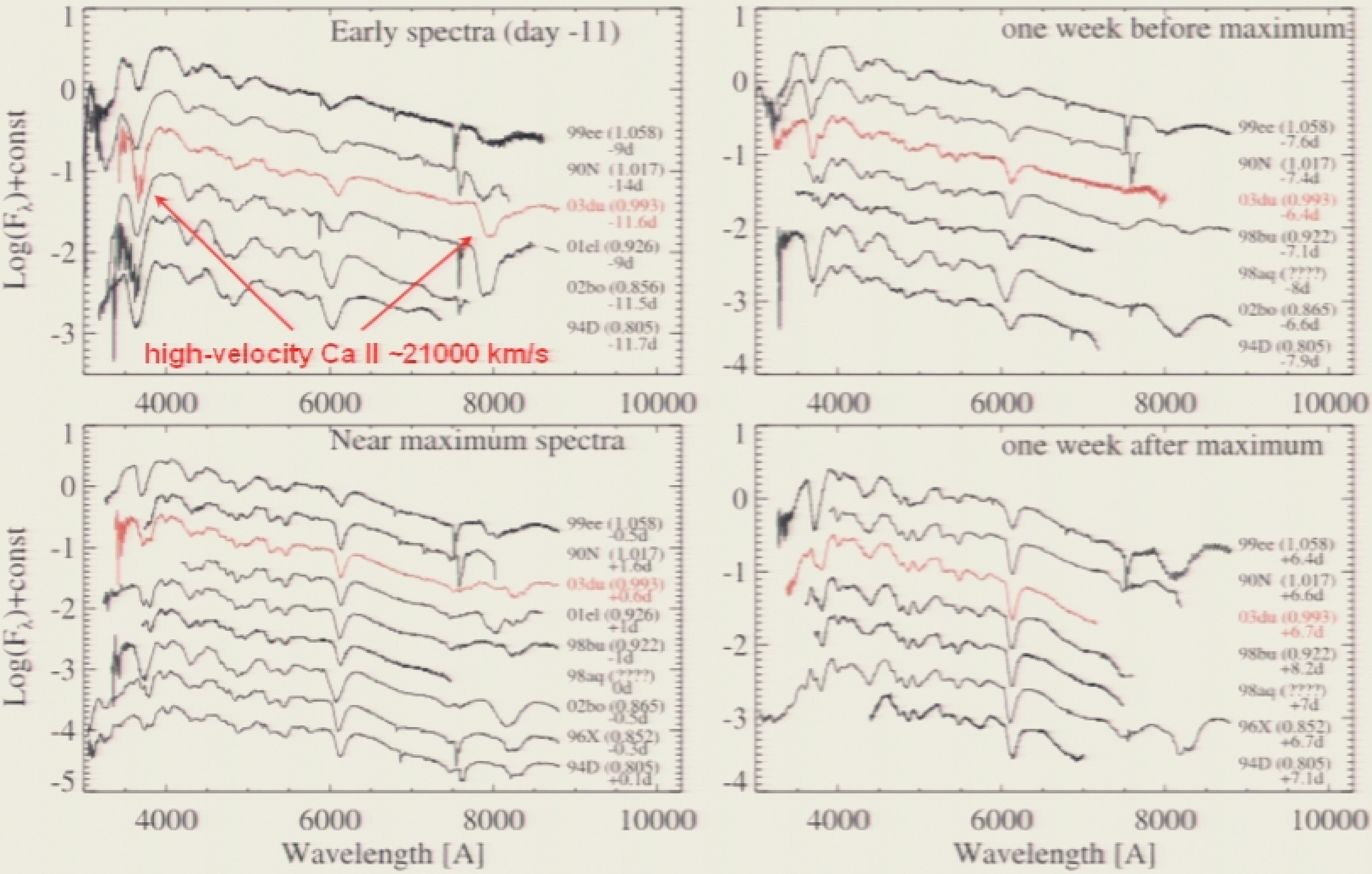
Optical spectra between -13 and +376 days

Infrared spectra between -13 and +30 days

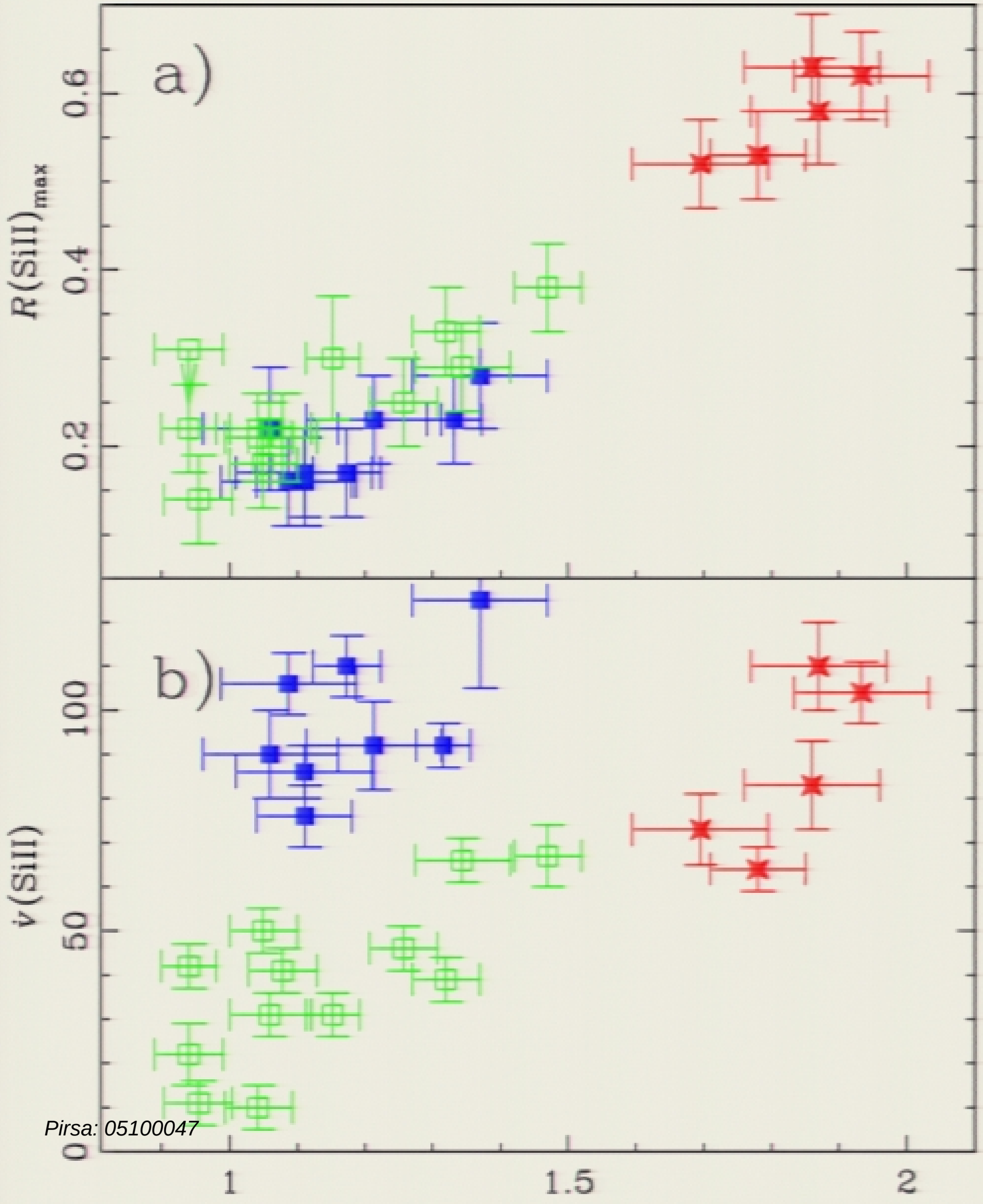


Stanishev et al 2005

Spectral diversity: could be used to sharpen ”standard candle”?



SNIa subgroups?

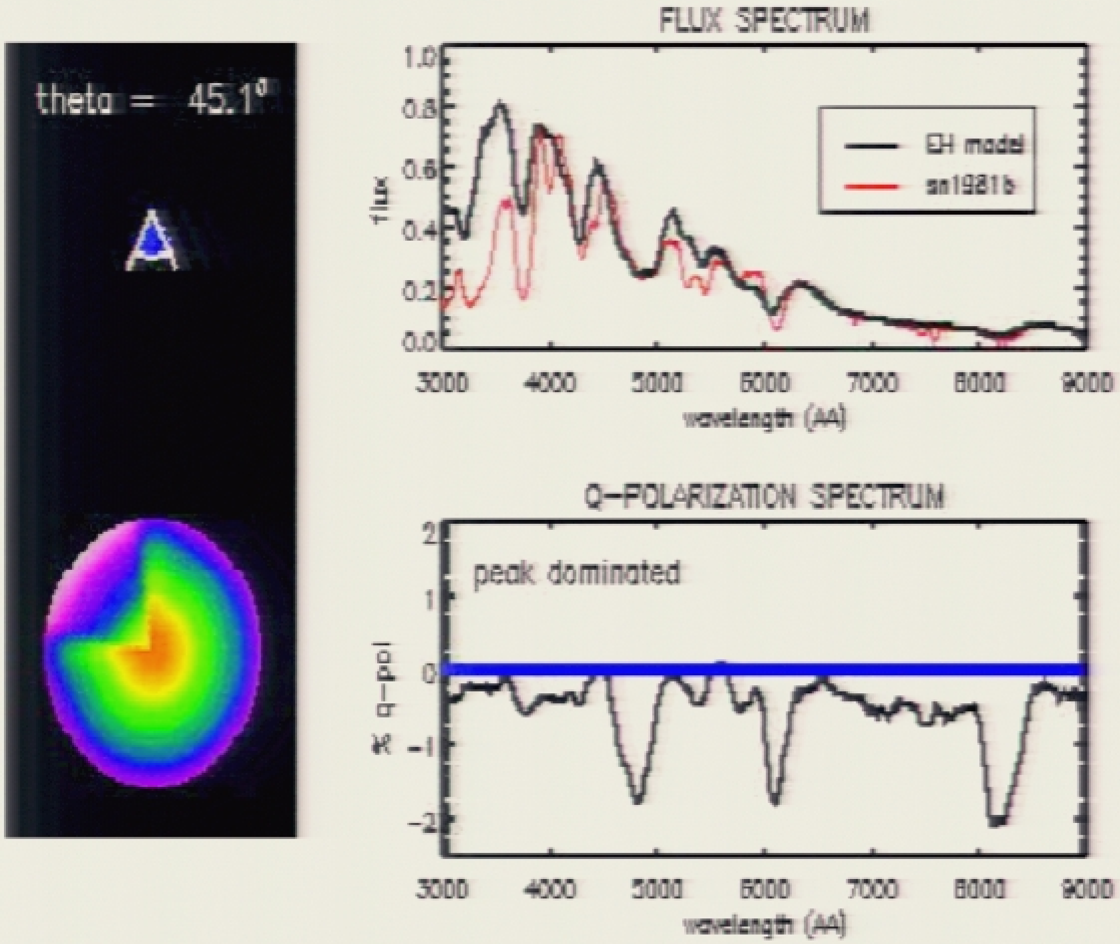


- Maybe the SNIa Hubble diagram could be made significantely sharper if it were made of ”like to like” SNe vs redshift.
- SN community is trying to find a spectroscopic parameter that identifies different luminosity subclasses.
- Understanding subgroups offers also important clues for predictions on brightness evolution of SNe

Benetti et al 04

Asymmetries linked to spectral diversity?

D.Kasen



Asymmetries linked to spectral diversity?

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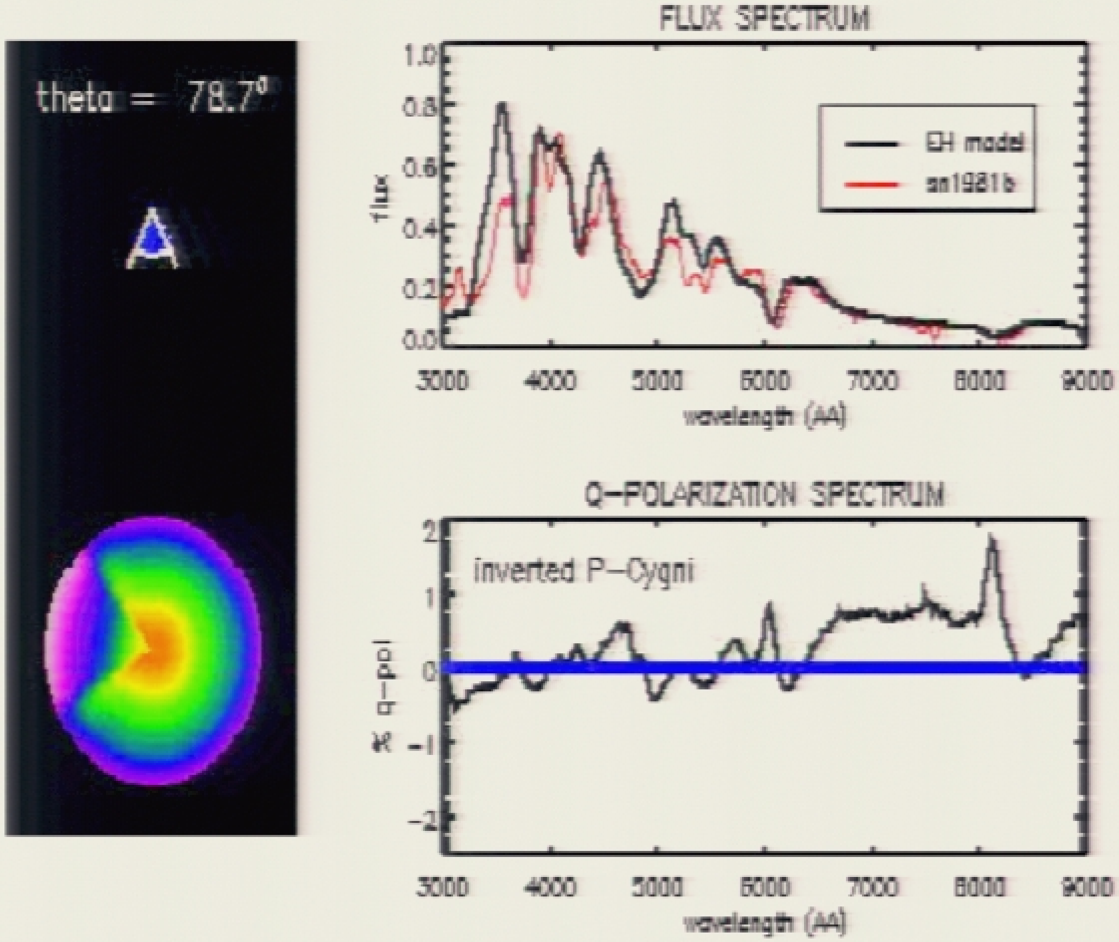

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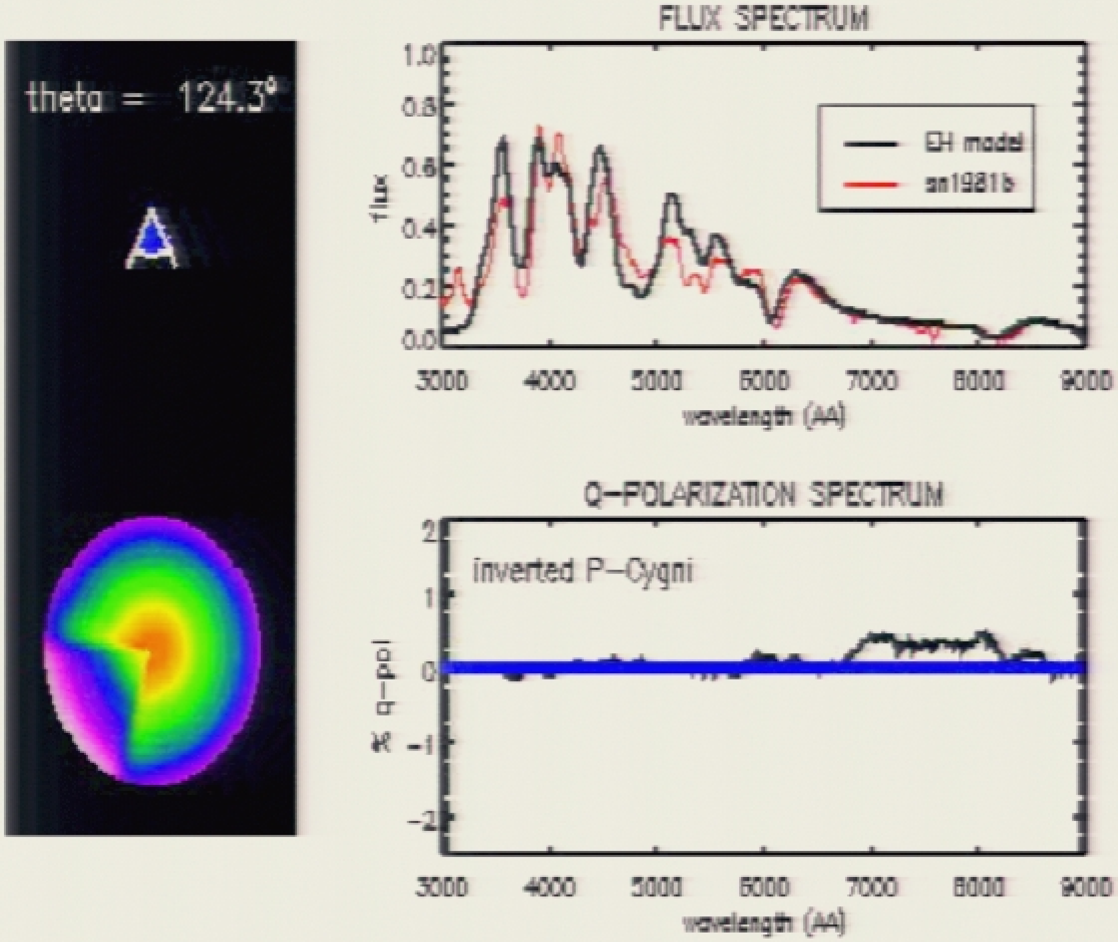

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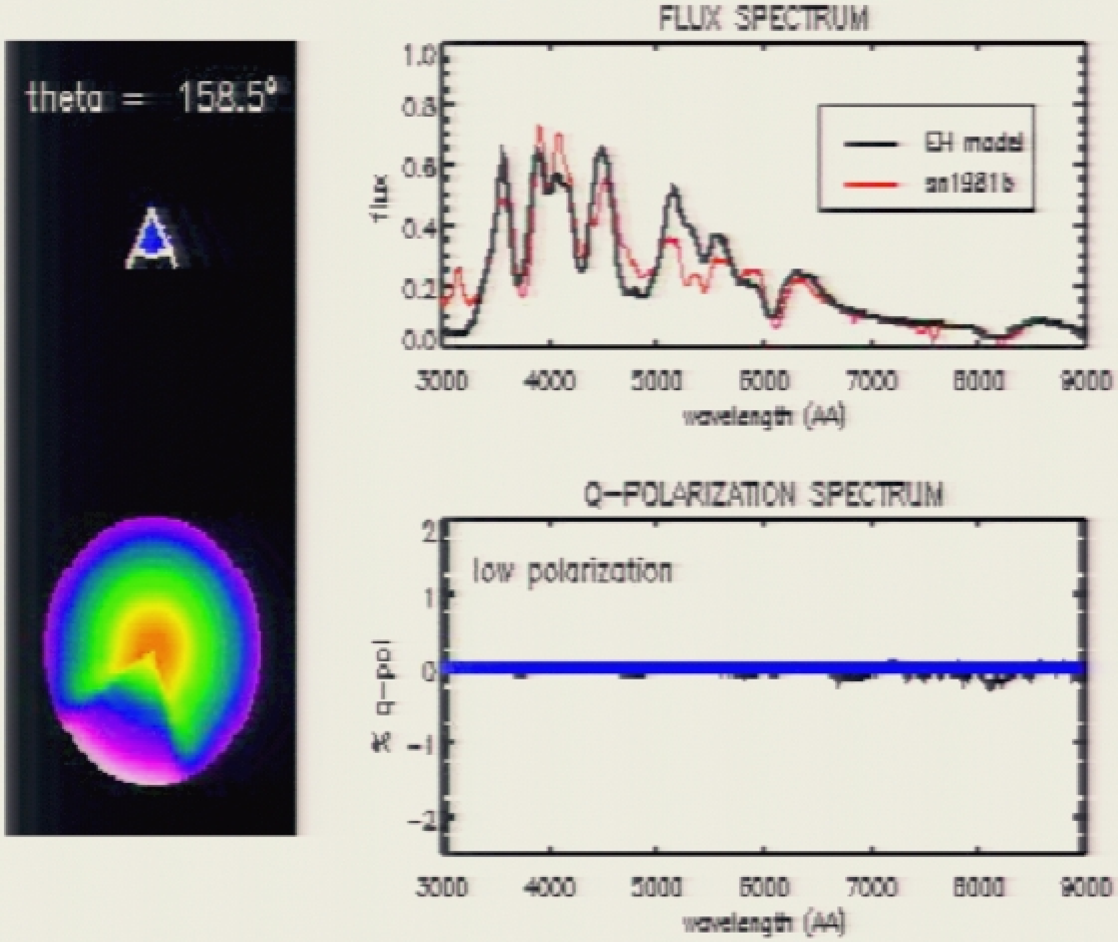

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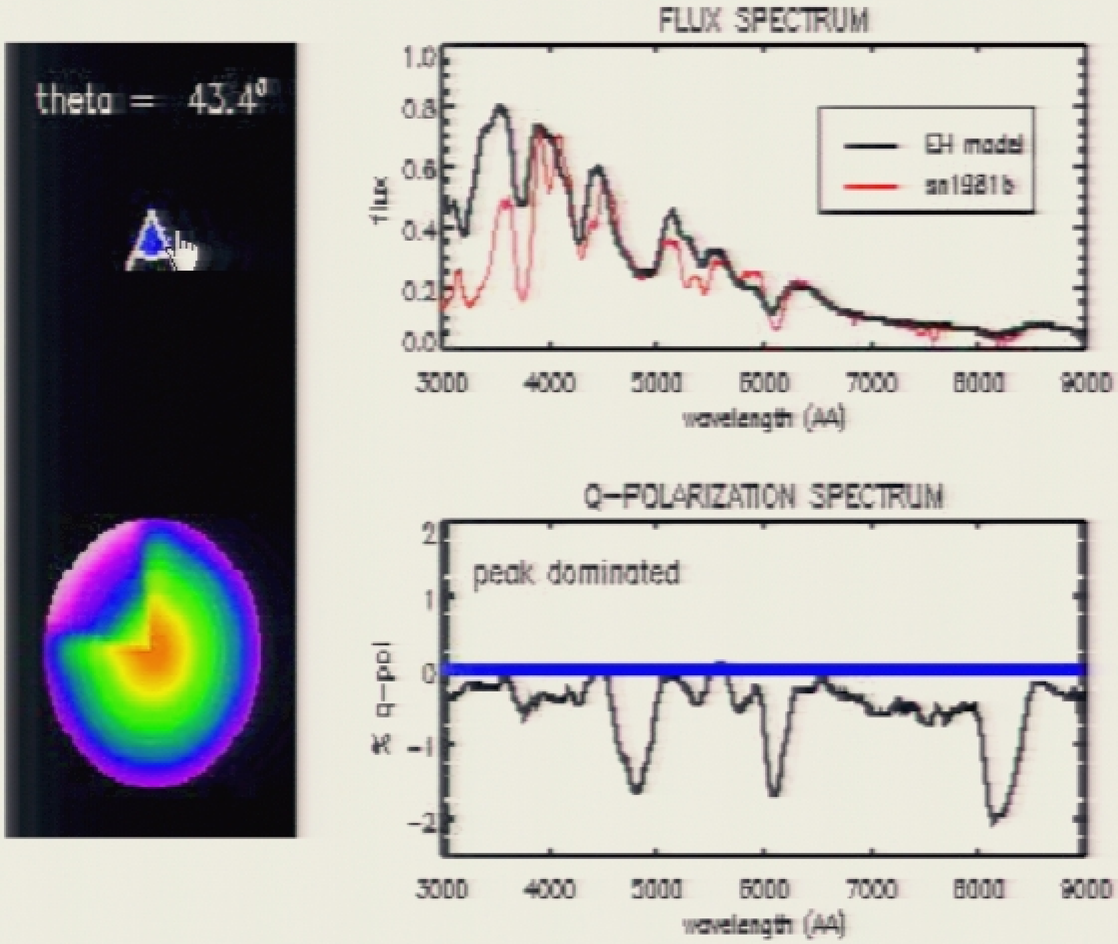

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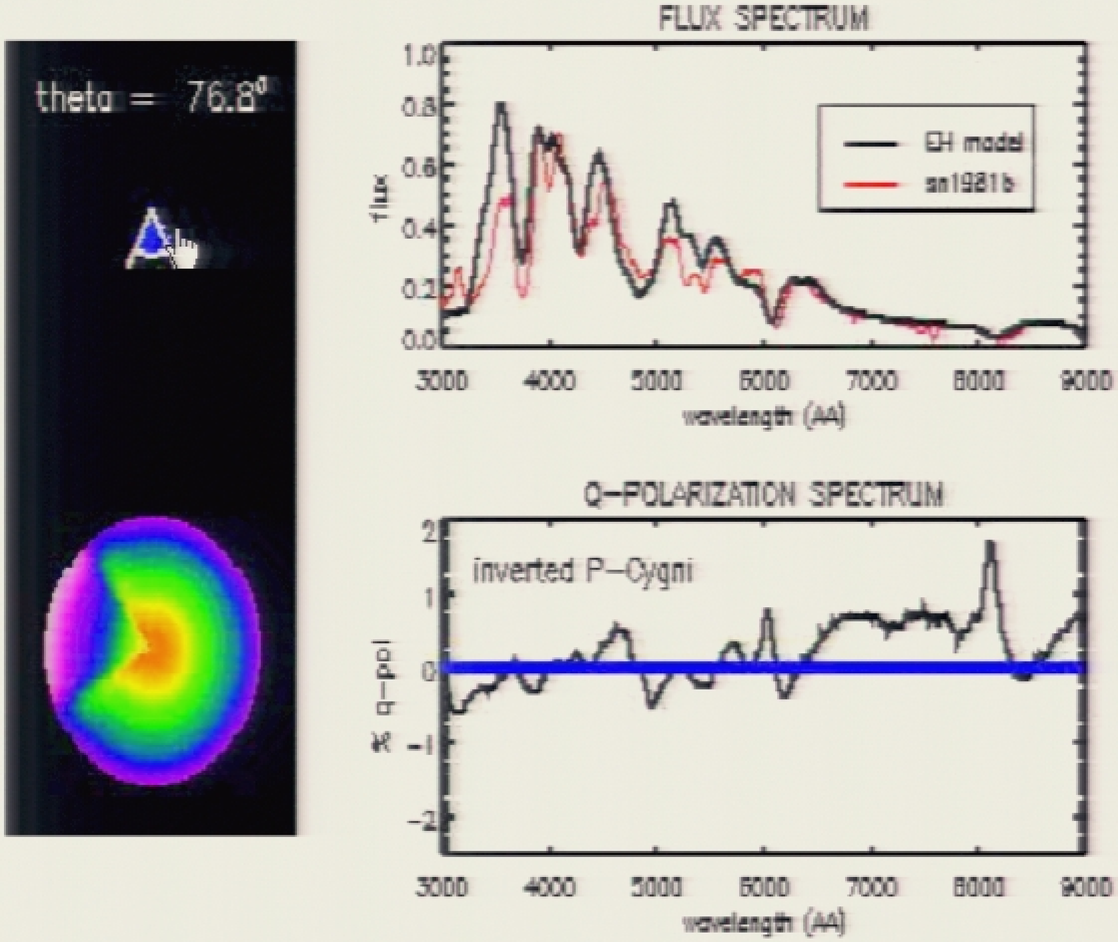

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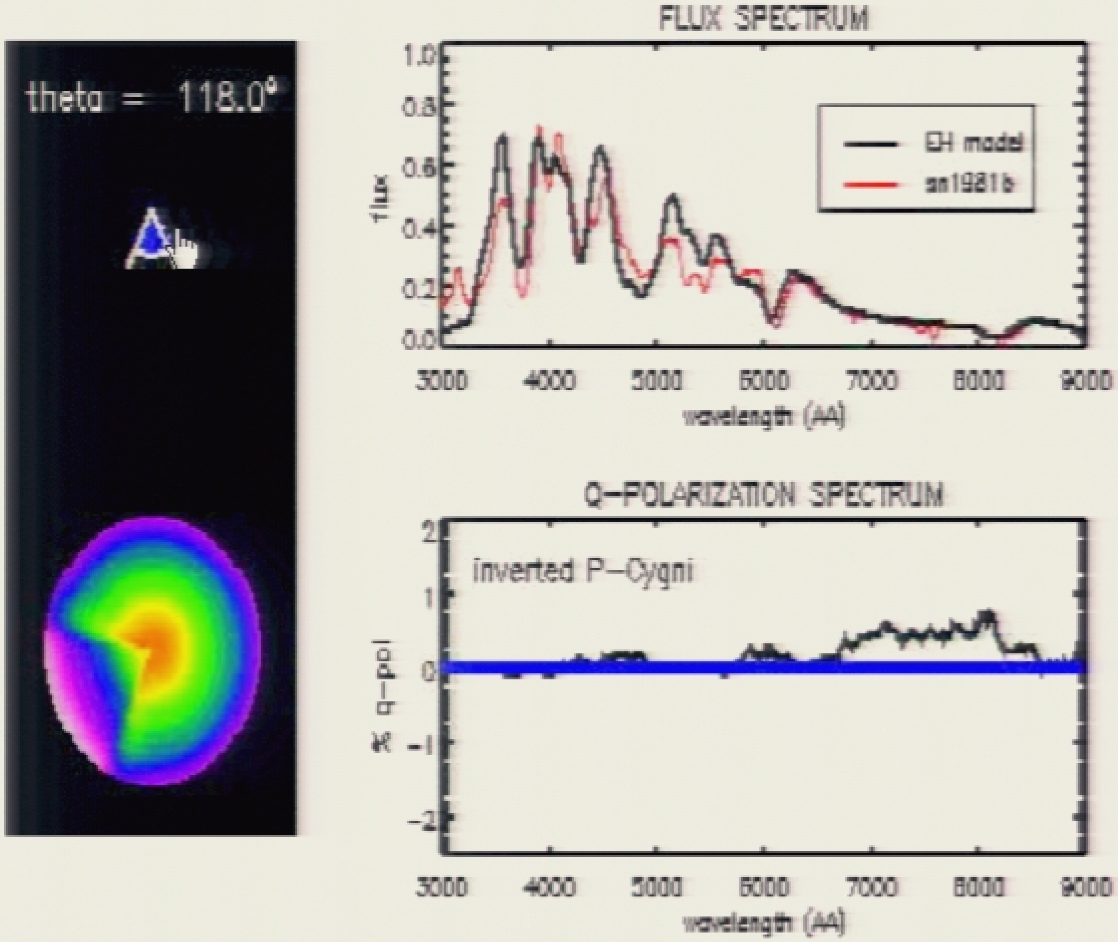

Asymmetries linked to spectral diversity?

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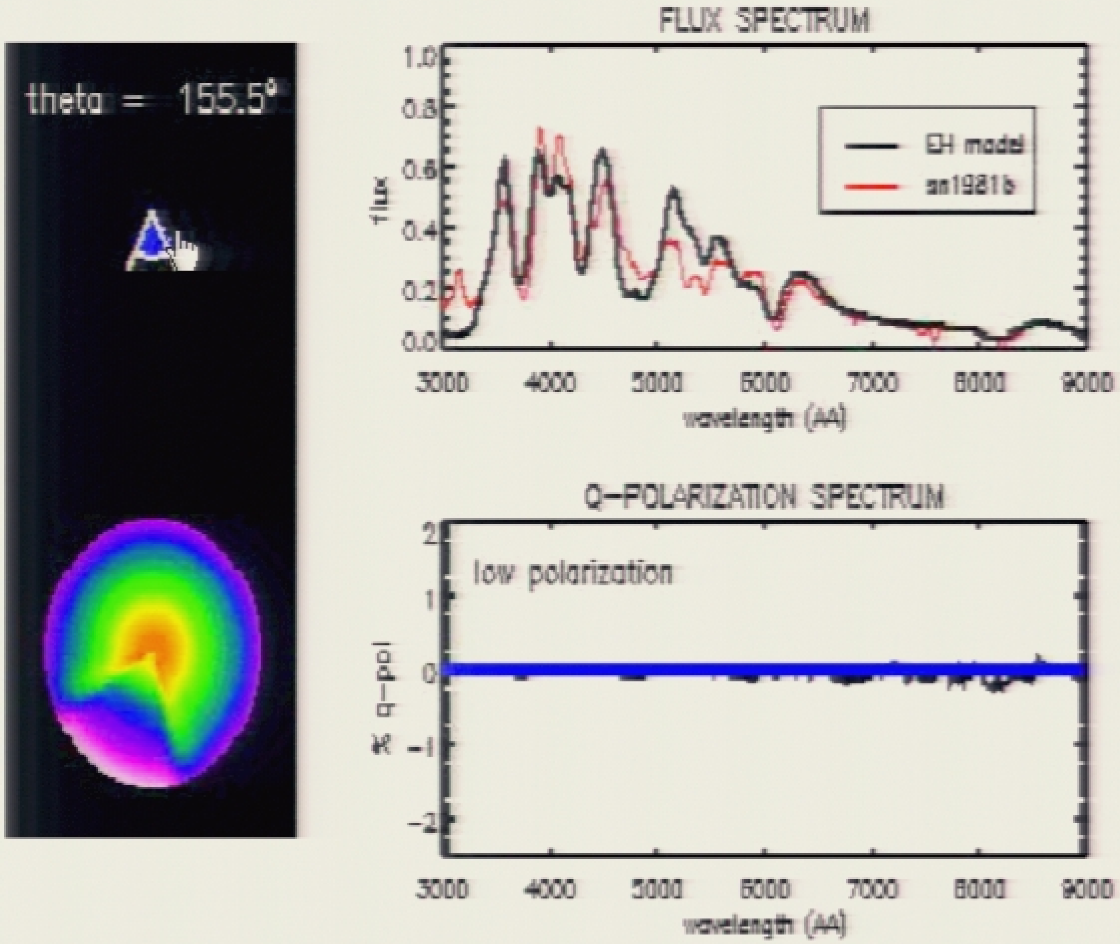
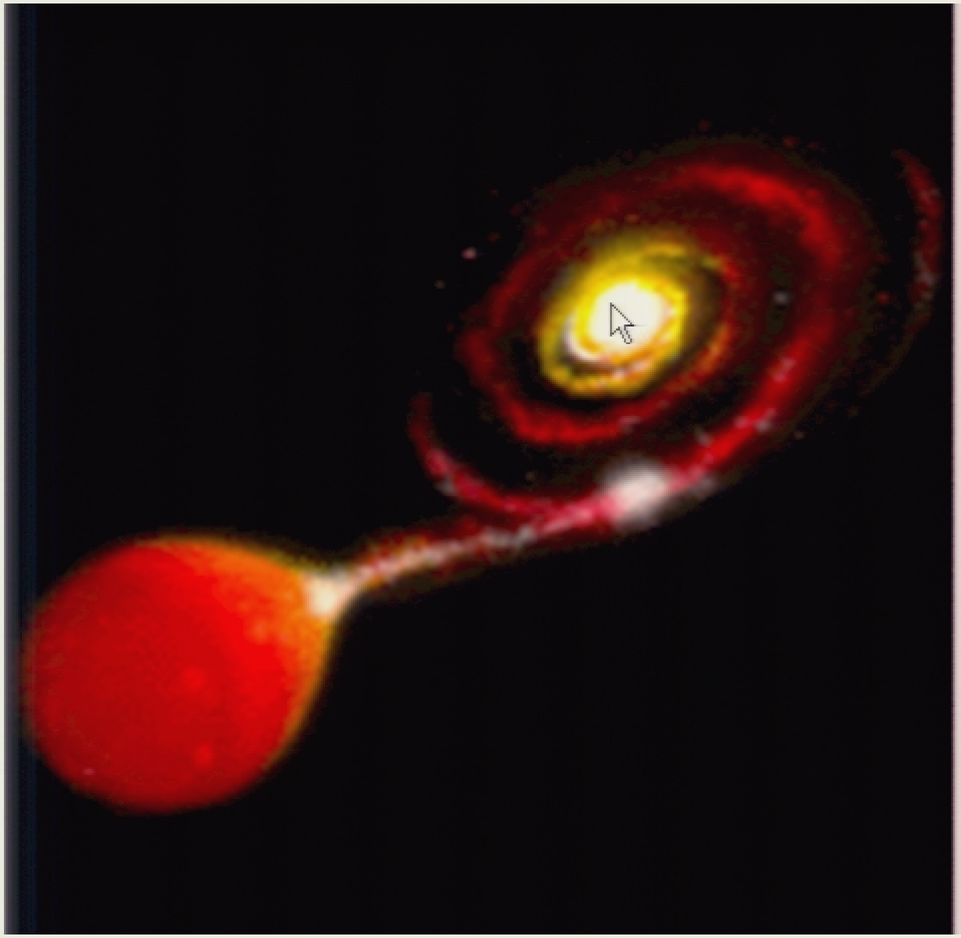
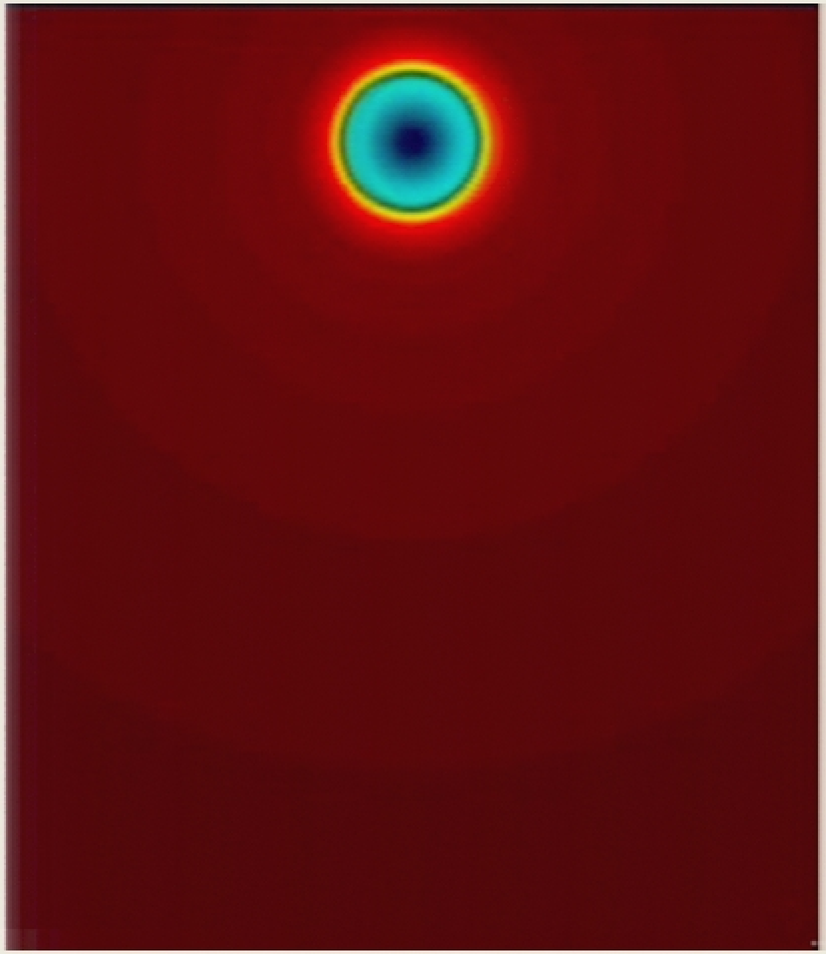


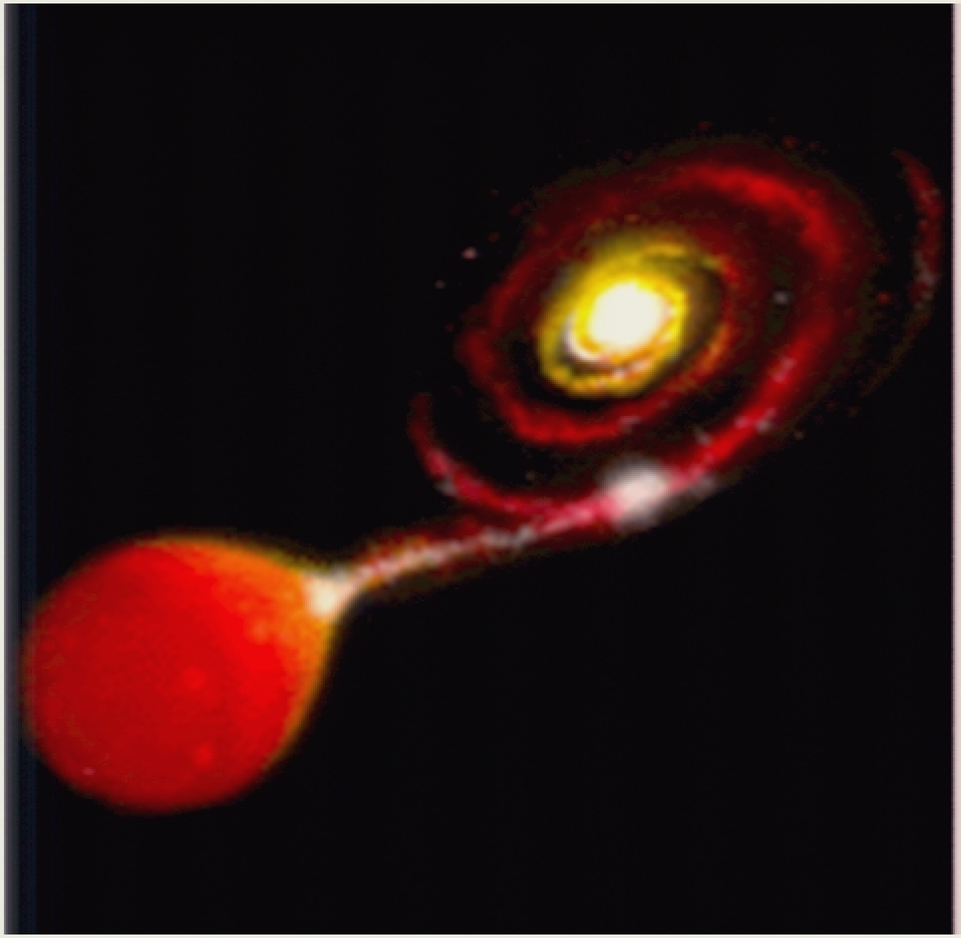
Interaction with companion star?

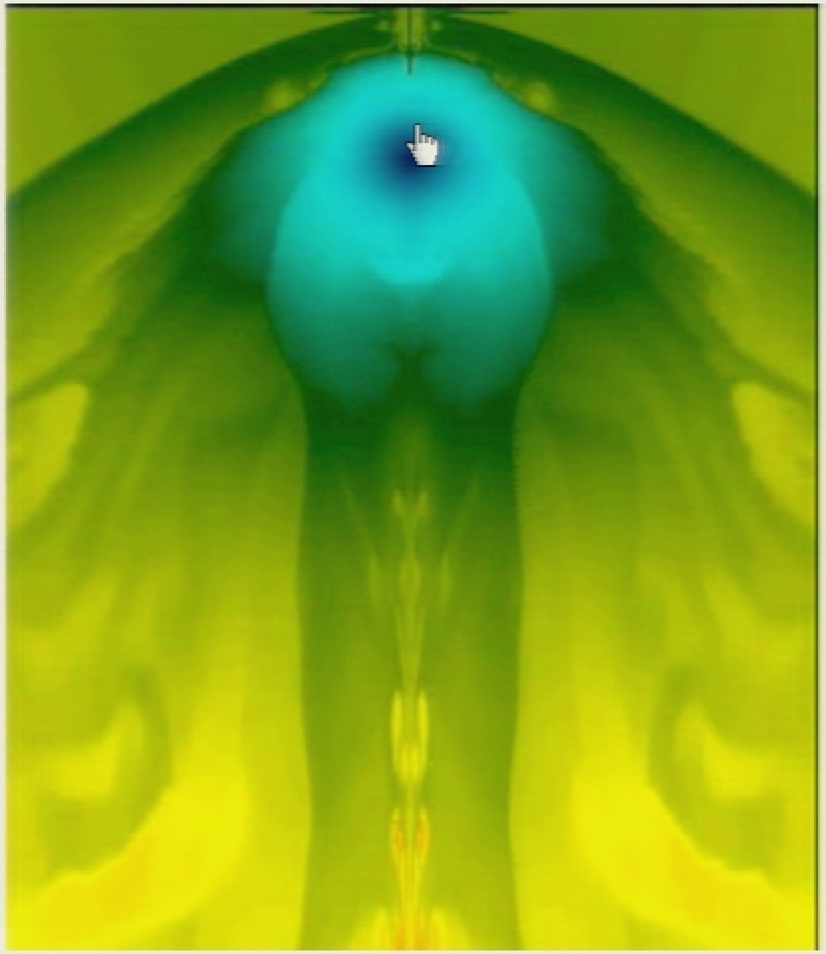




Marietta et al. 2000

Interaction with companion star?





Marietta et al. 2000

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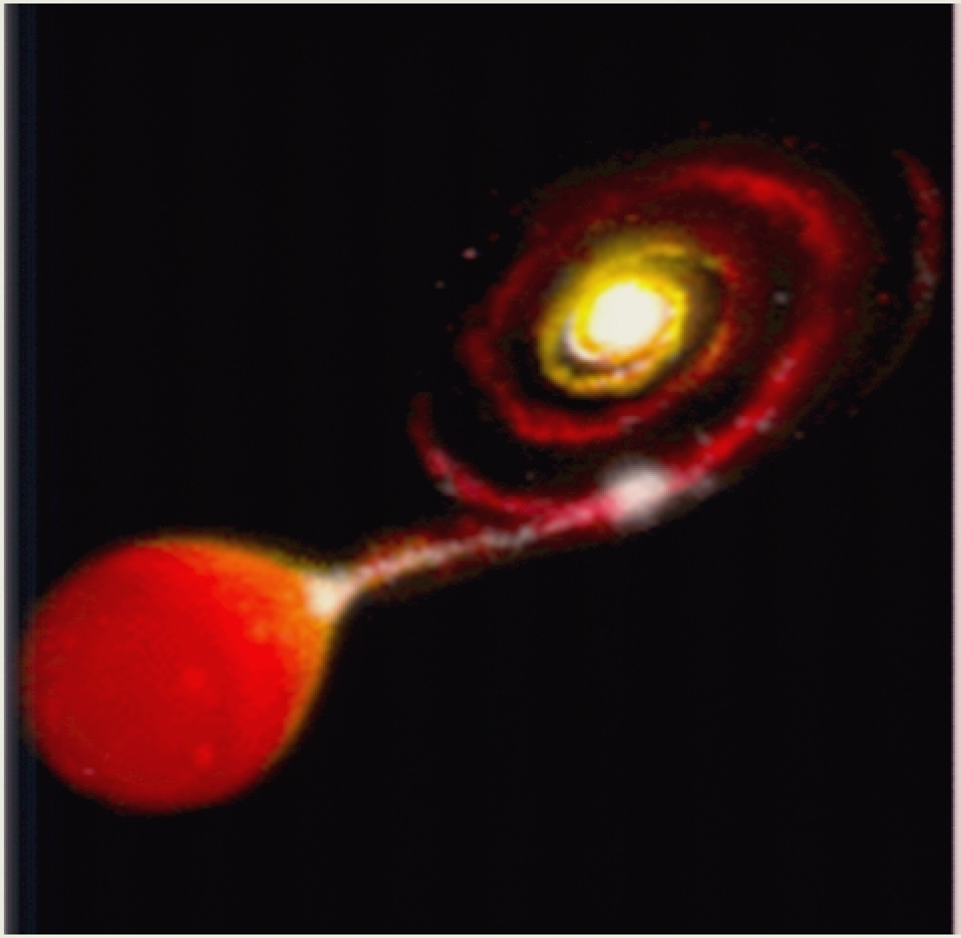

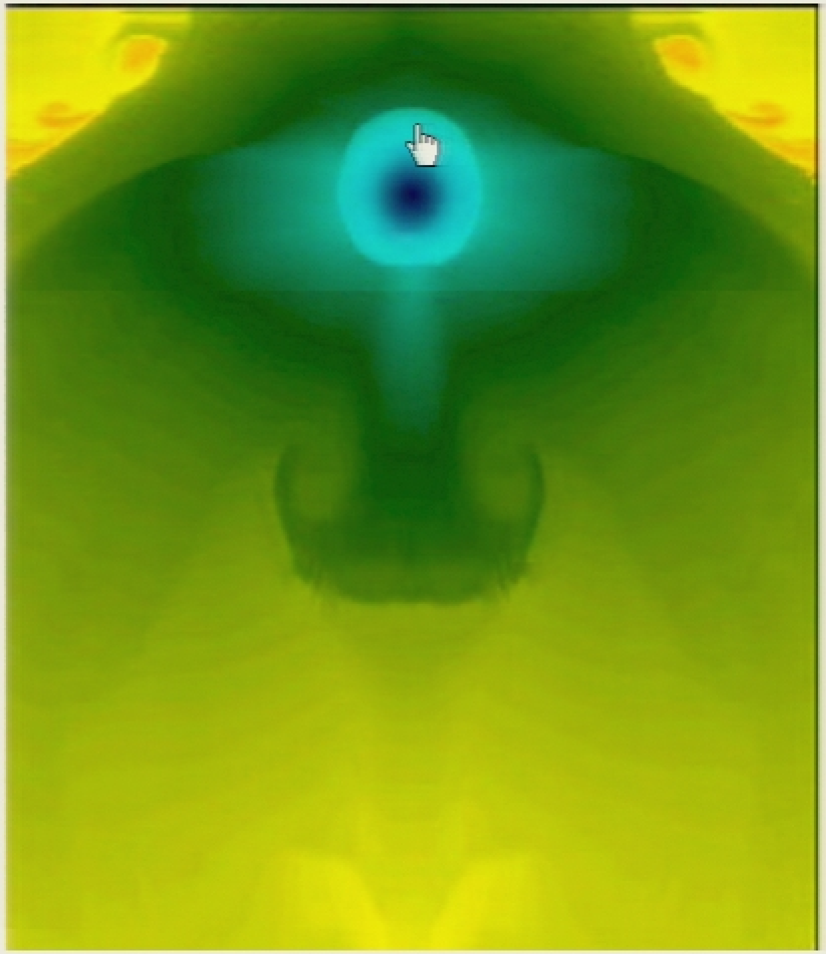

Marietta et al. 2000

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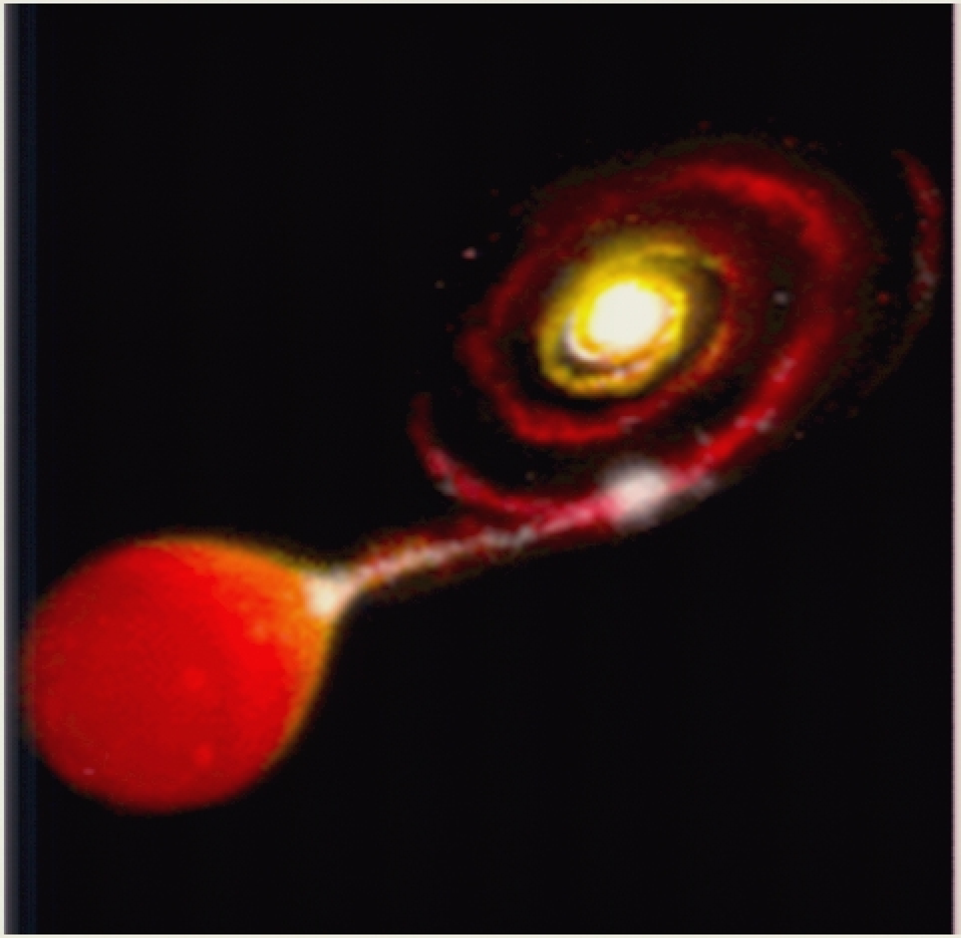
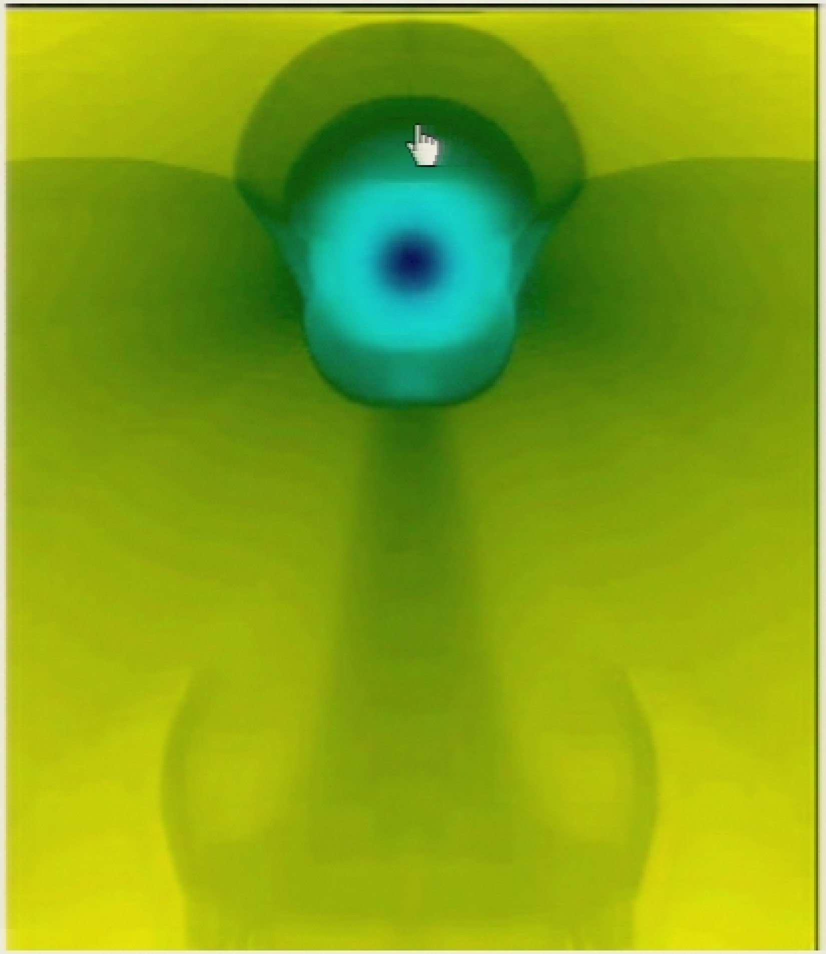
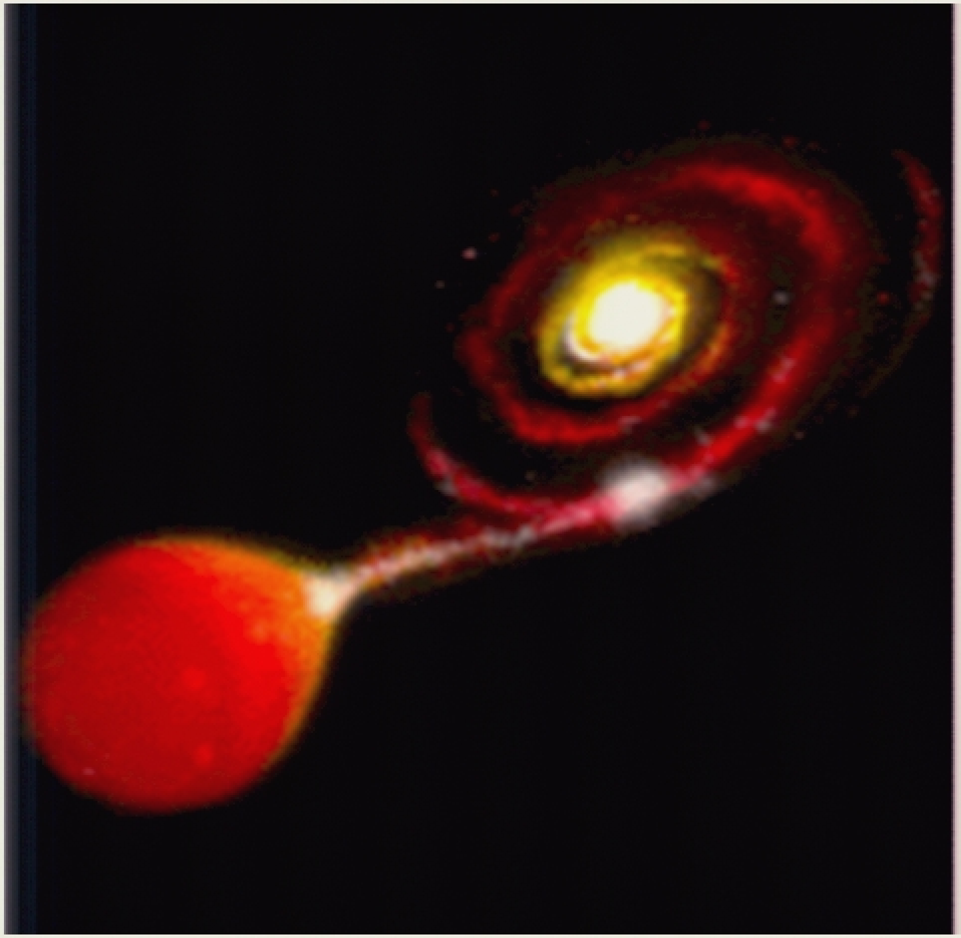
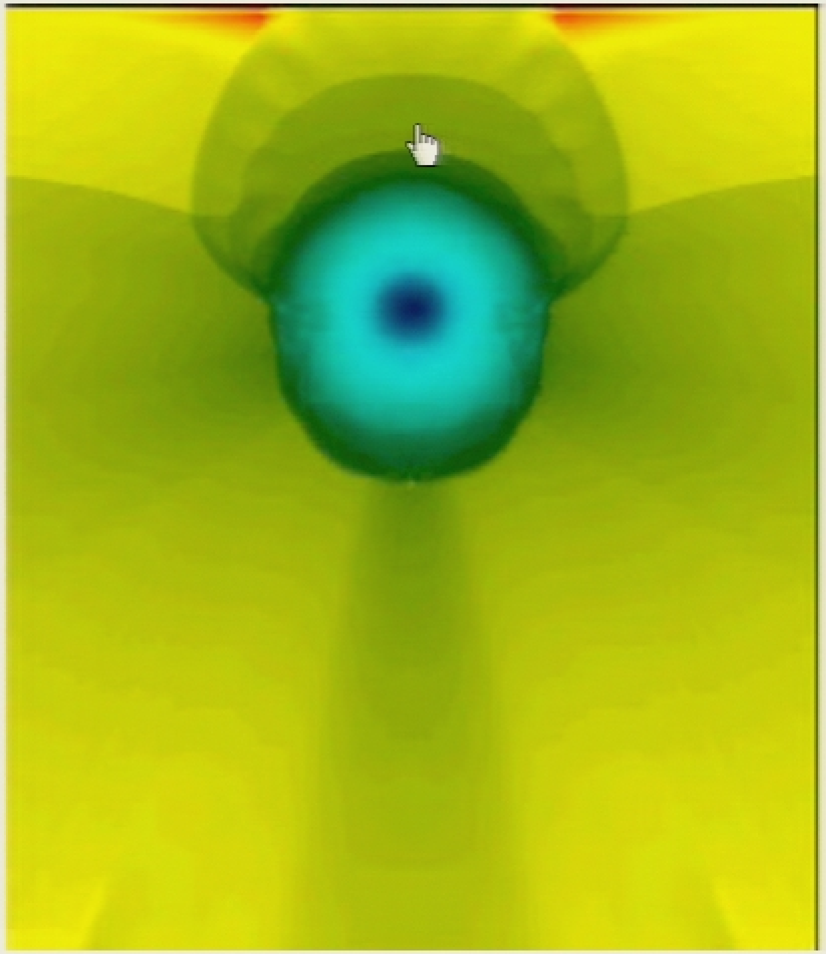




Marietta et al. 2000

Interaction with companion star?





Marietta et al. 2000

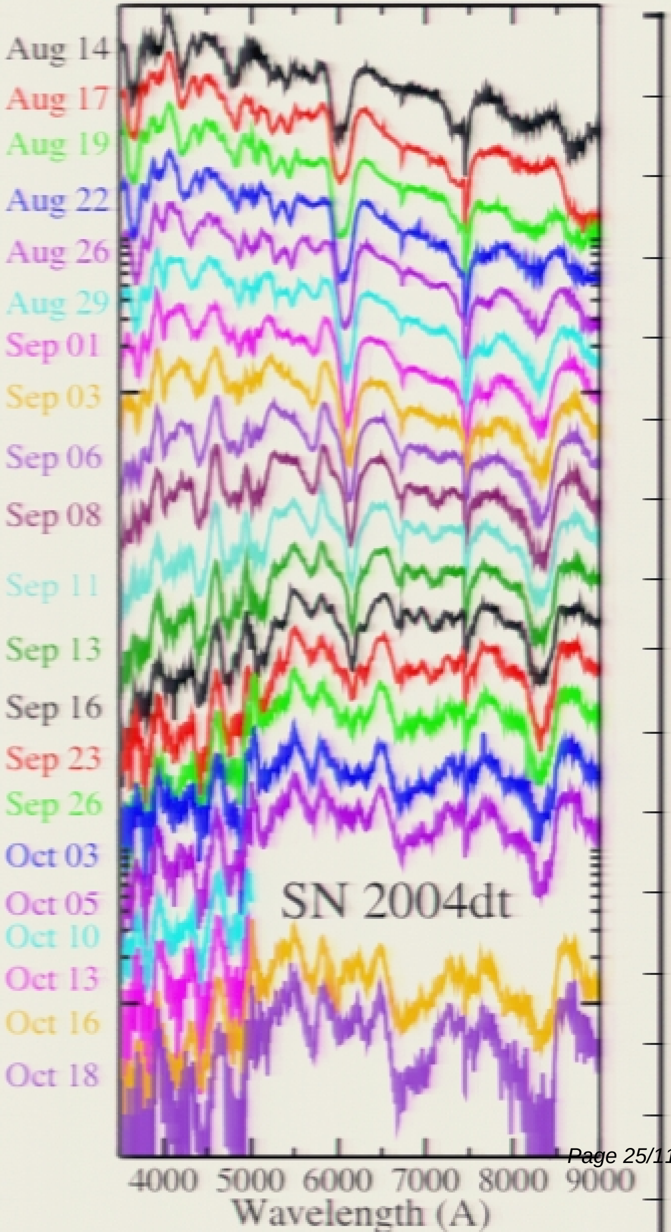
Ongoing <u>high-statistics</u> low-z projects

- Supernova Factory: search + optical spectrophotometry of a few hundred SNe. (Search at Palomar, IFU follow-up at UH2.2m)
- Carnegie Supernova Project: high precision optical and NIR lightcurves of ~200 SNe ($z<0.07$). Already > 70 SNe, about ½ Ia's.

First SN-factory results

Aldering et al

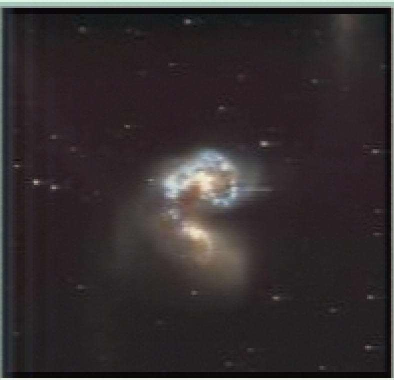
Target	Redshift	Epochs	
2004dt	0.020	27	
2004gc	0.031	16+1	
2004ef	0.031	11+1	
2004gs	0.027	11+1	
2005bc	0.012	16	
2005M	0.022	11	
2005bg	0.023	11	
2005ag	0.029	9	
2005L	0.070	7+1	
2004gk	0.000	8	
2005bl	0.024	8	
2005ak	0.027	4+1	
2004il	0.107	4	
2005cf	0.001	2+	
2005cg	0.031	1+	



Carnegie Supernova Project

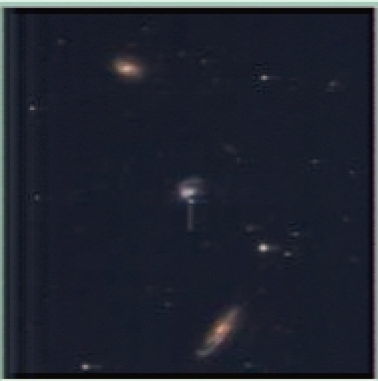

sn2004fx


sn2004gq


sn2004gt


sn2004gv

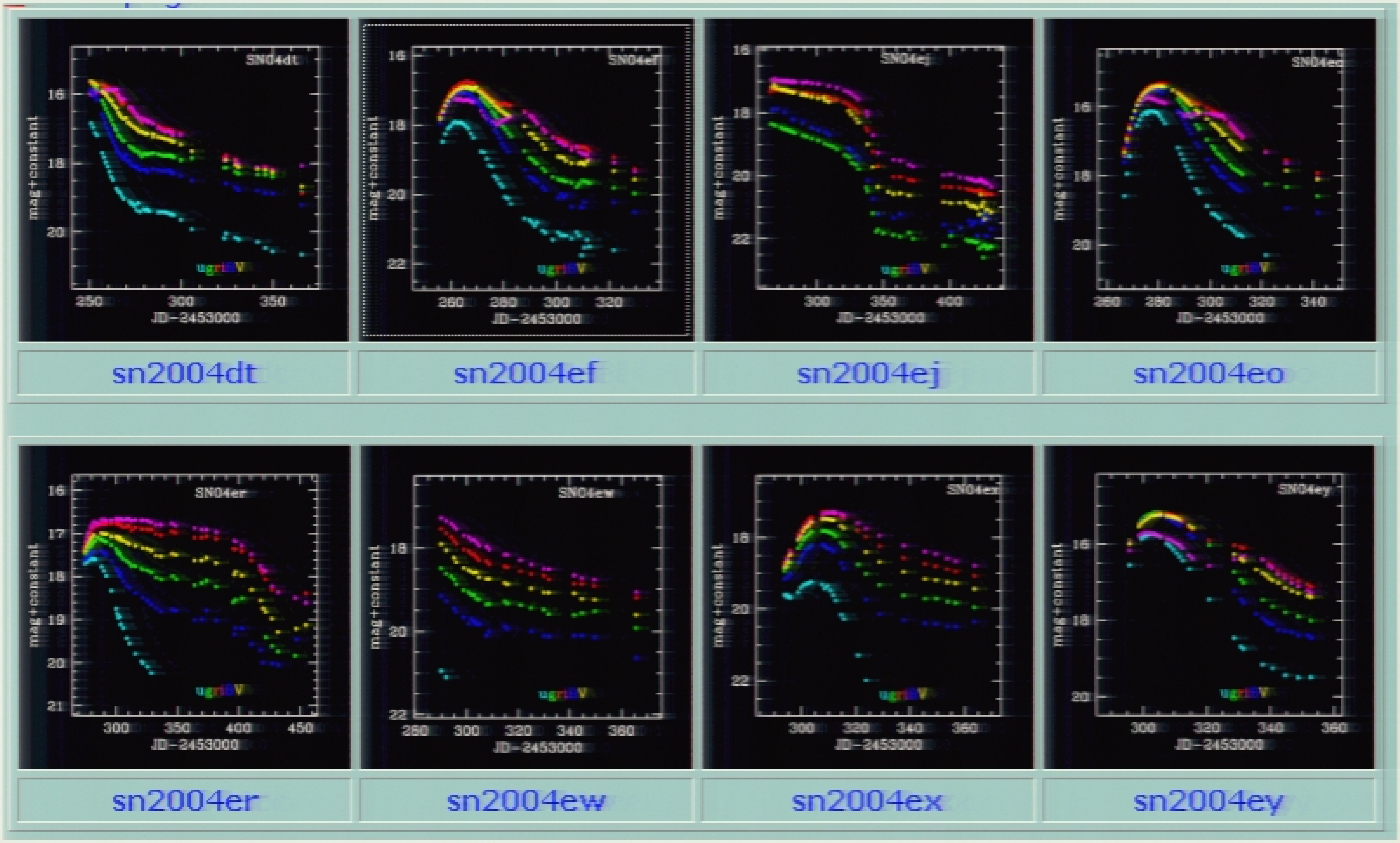

sn2005A


sn2005M


sn2005P


sn2005Q

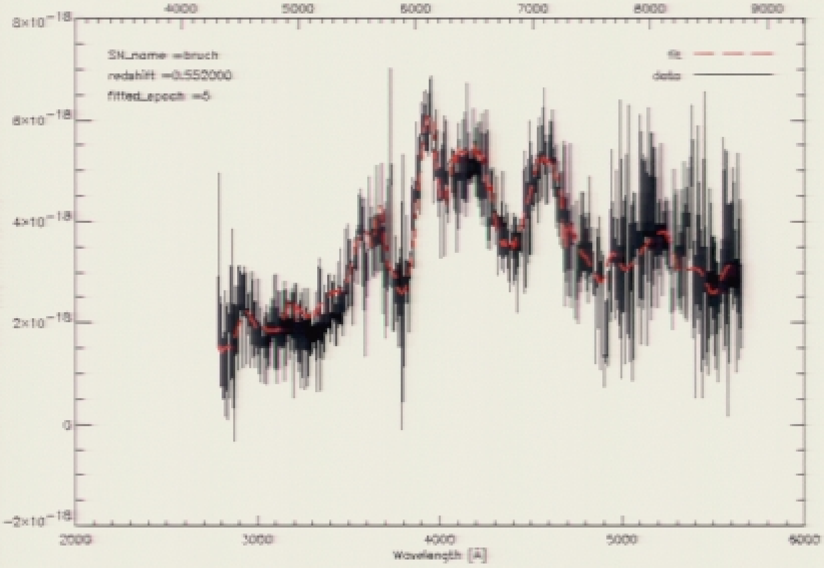
High-Quality lightcurves in optical and NIR

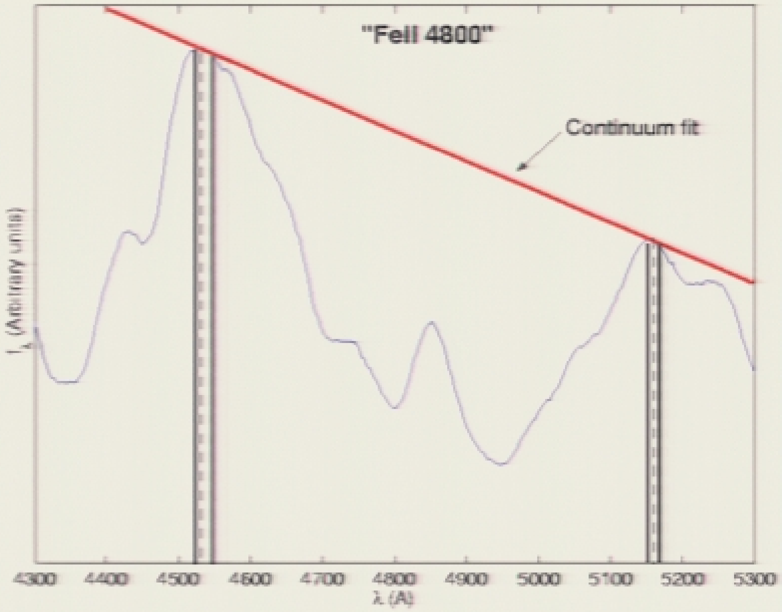


Supernovae at z~0.5

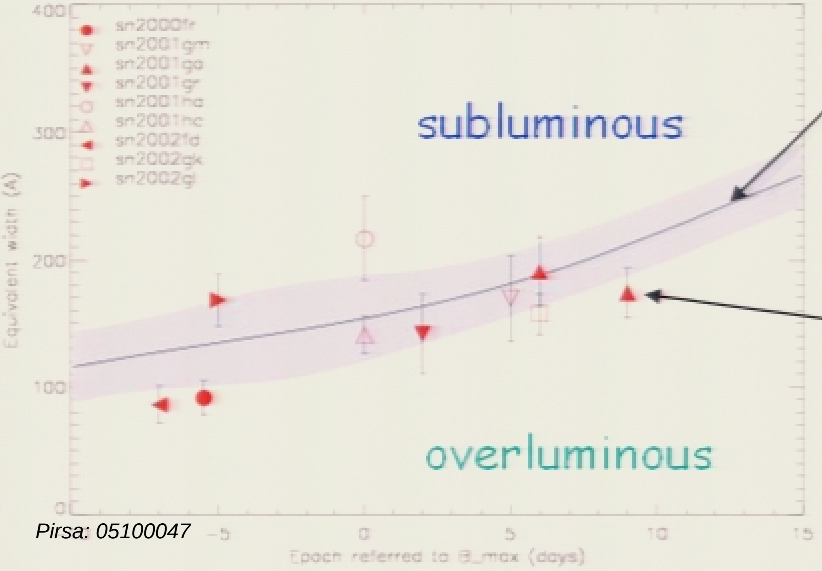
New data-sets

Spectroscopic tests of standard candle

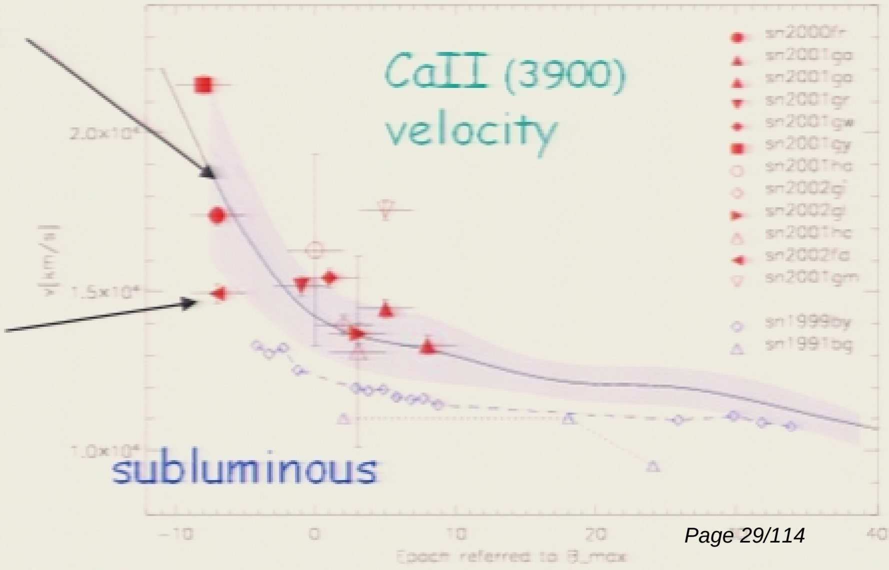




Low-z average



z~0.5

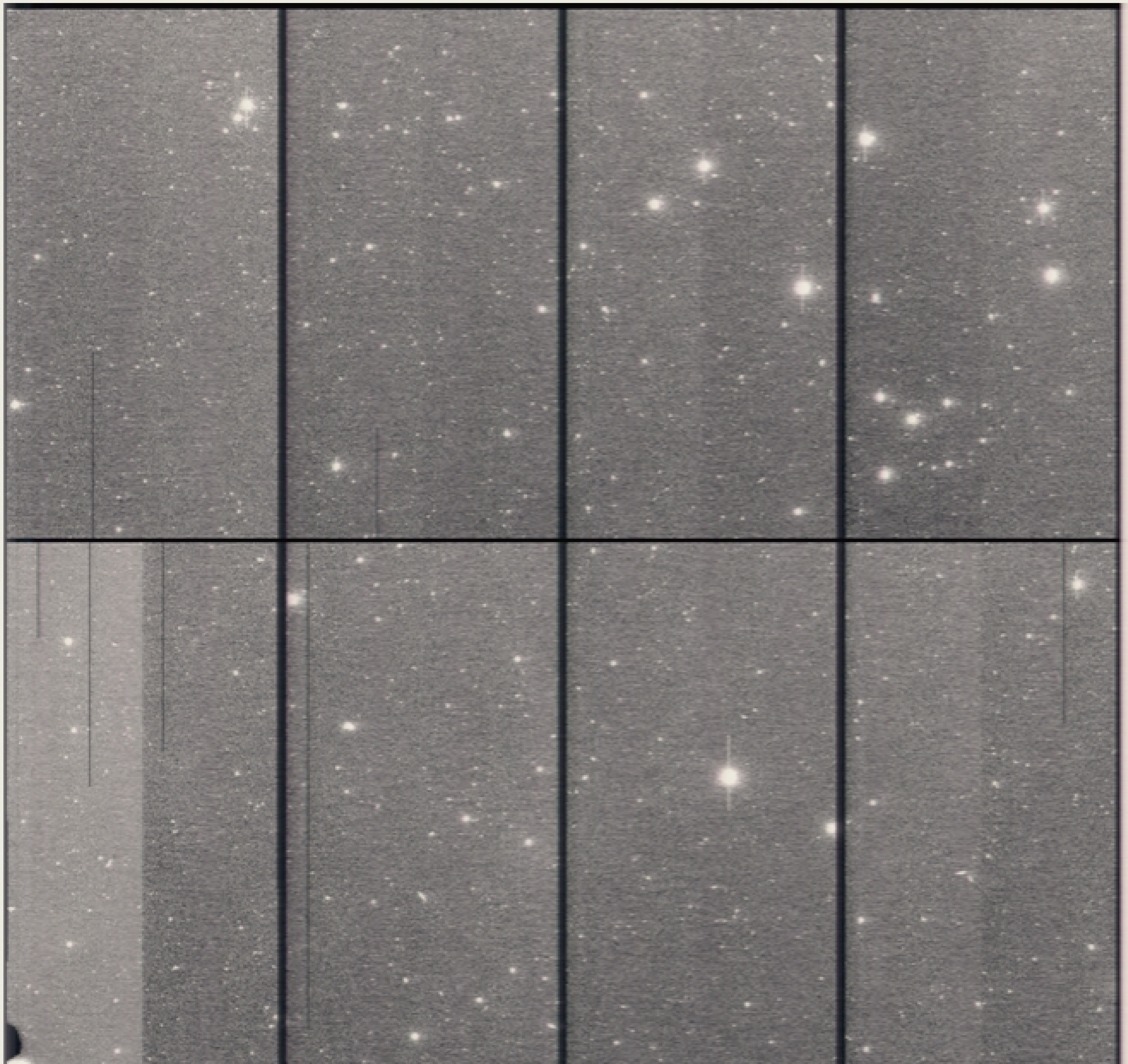


Folatelli et al, Garavini et al, Lidman et al

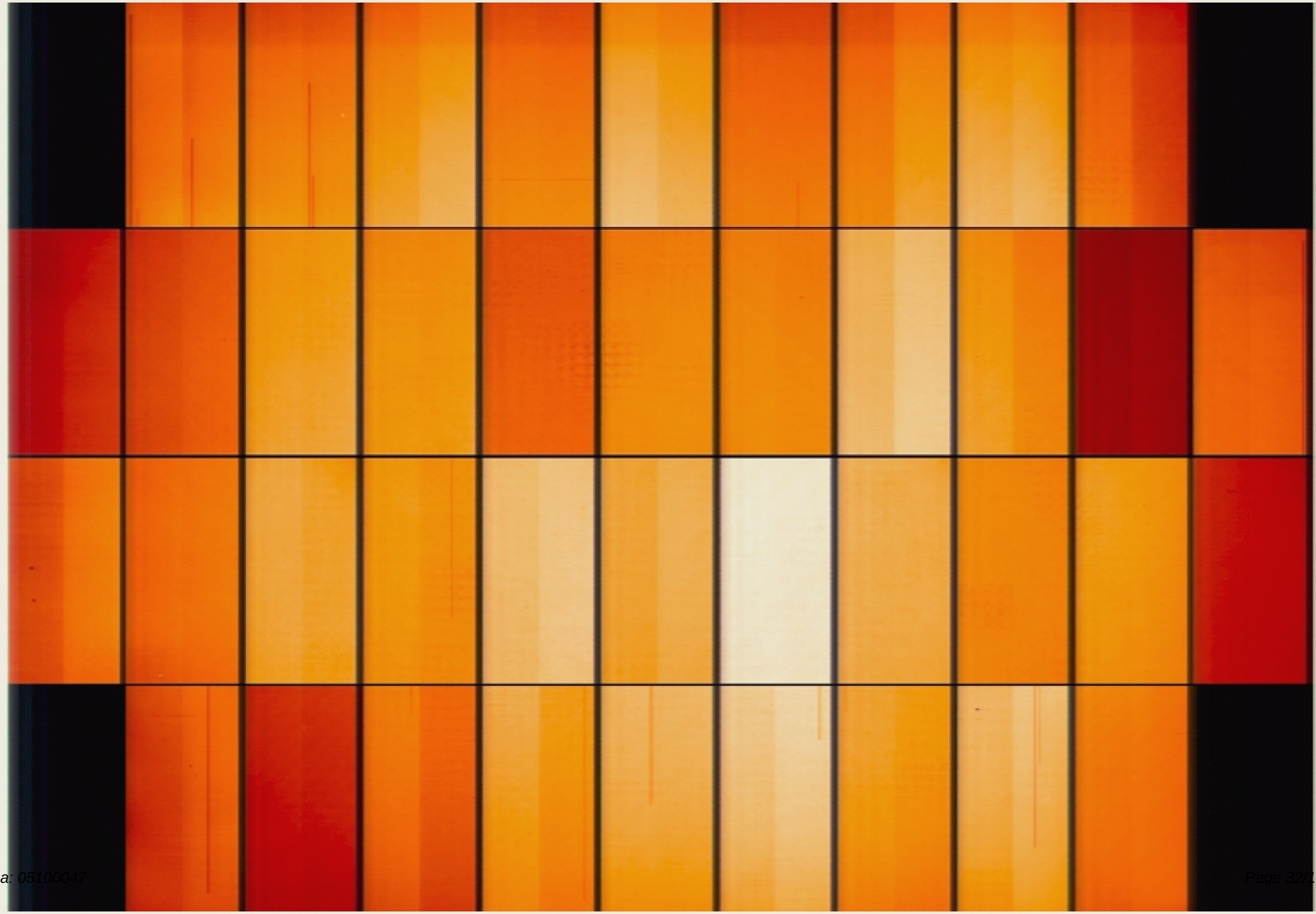
Large ongoing 0.2<z<1 SNIa projects

- ESSENCE at CTIO 4-m: to collect ~200 SNIa
- CFHT (3.7-m) SuperNova Legacy Survey: 5 year ”rolling search”in (u)griz. Up to ~1000 spectroscopically confirmed SNIa.

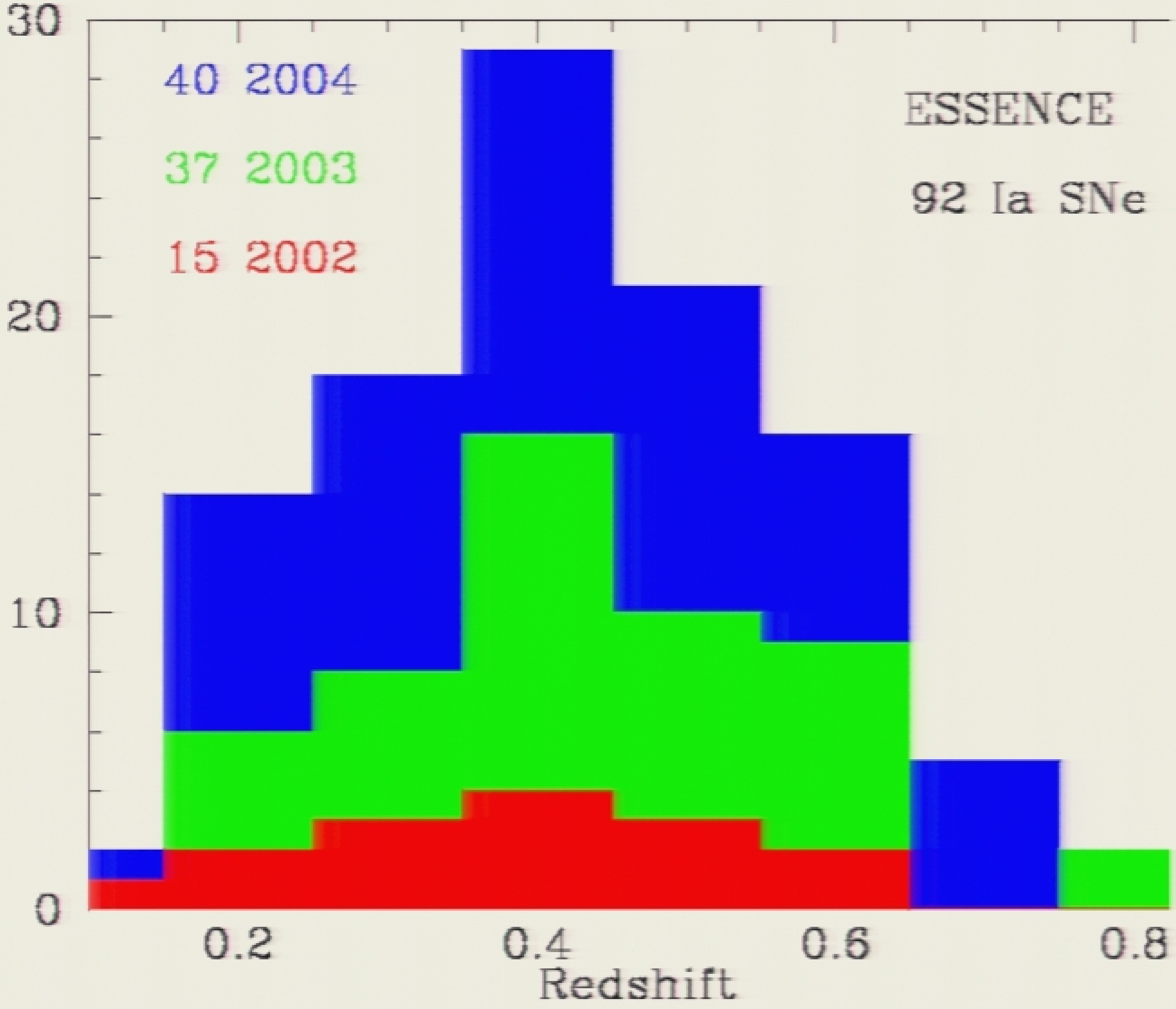
Huge Cameras! CTIO: 8 CCD's ½°x½°



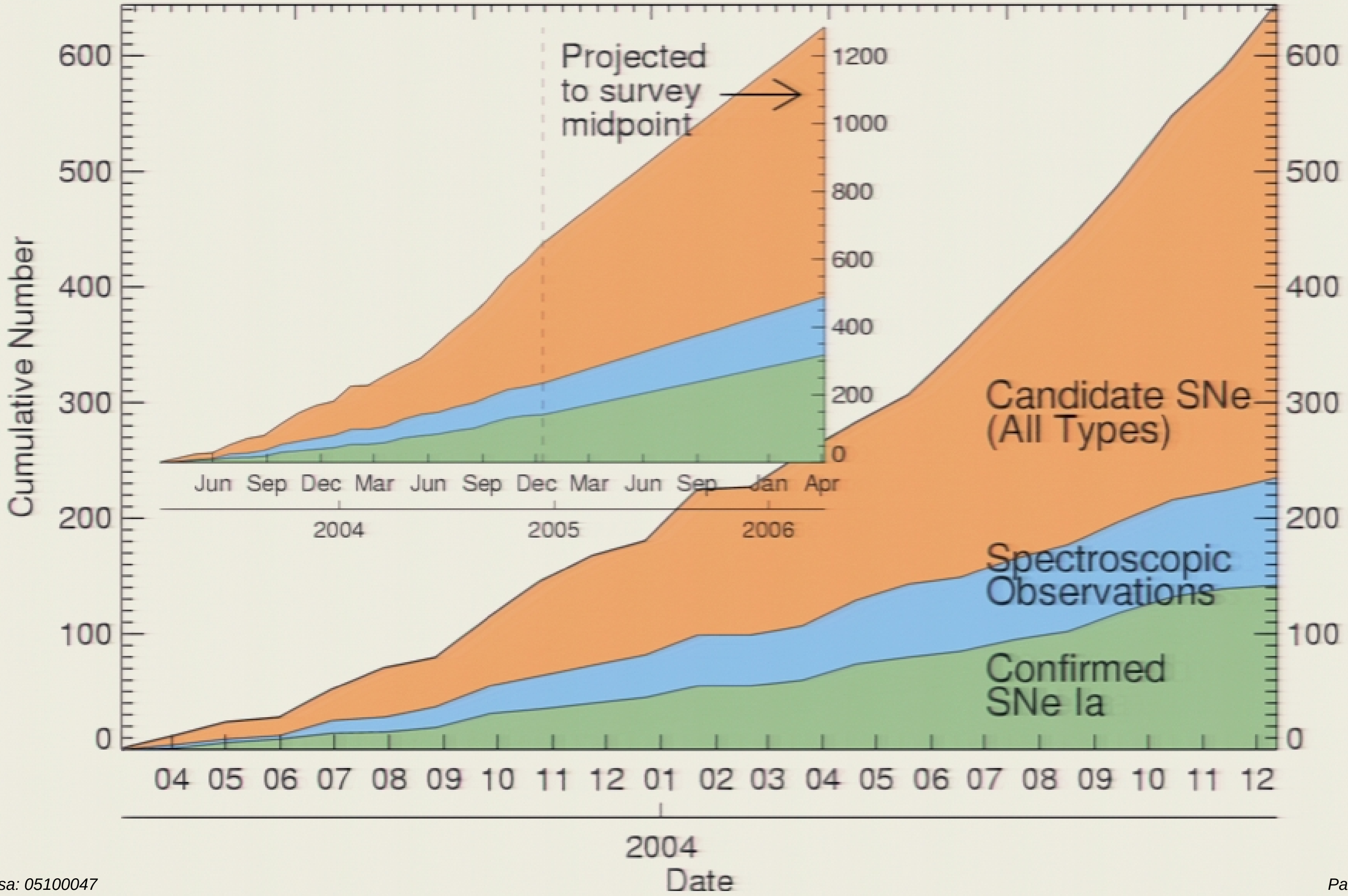
CFHT: 40 CCDs, 4 times bigger!



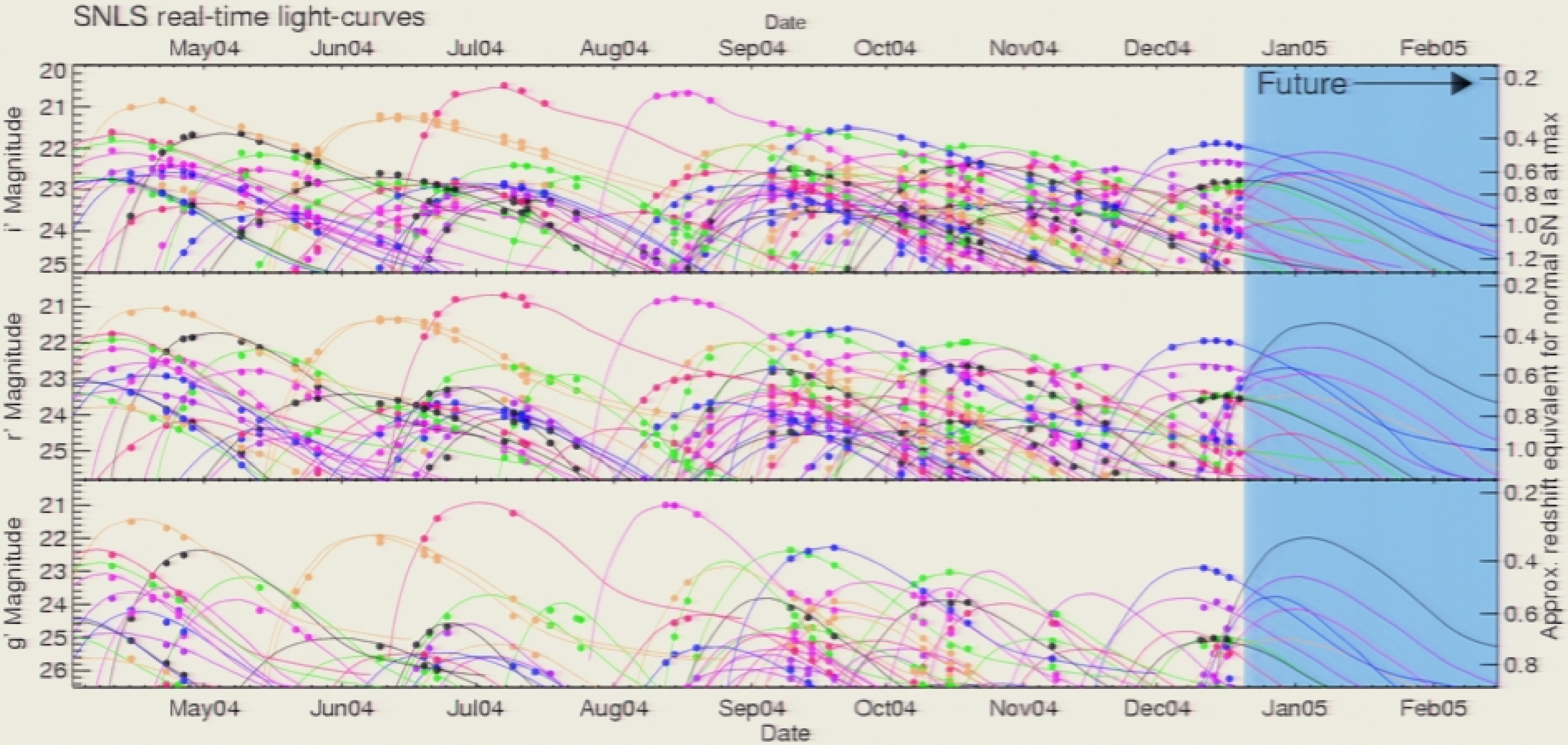
Essence first 3 years (5 total)



SNLS progress



CFTH-SNLS

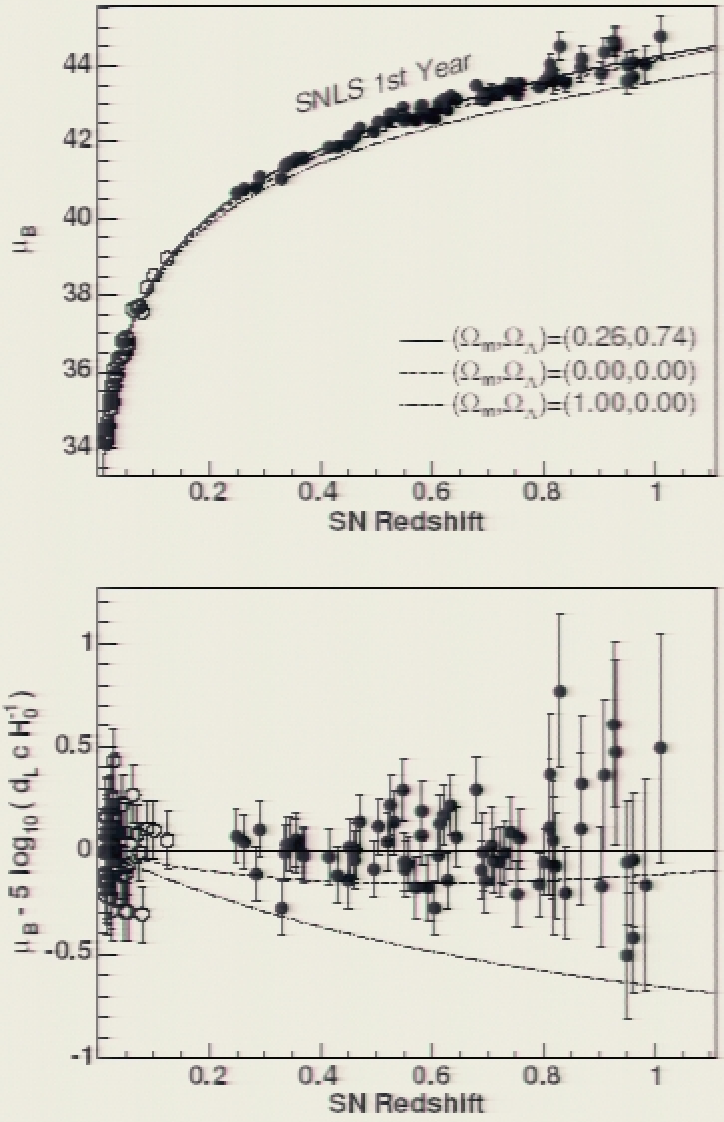

SNLS real-time light-curves
Date
May04
Jun04
Jul04
Aug04
Sep04
Oct04
Nov04
Dec04
Jan05
Feb05
Future
i' Magnitude
20
21
22
23
24
25
r' Magnitude
21
22
23
24
25
g' Magnitude
21
22
23
24
25
26
Approx. redshift equivalent for normal SN Ia at max
0.2
0.4
0.6
0.8
1.0
1.2
0.2
0.4
0.6
0.8
1.0
0.2
0.4
0.6
0.8
Date

The Supernova Legacy Survey: Measurement of Ω_M, Ω_Λ and w from the First Year Data Set ⋆

P. Astier[1], J. Guy[1], N. Regnault[1], R. Pain[1], E. Aubourg[2,3], D. Balam[4], S. Basa[5], R.G. Carlberg[6], S. Fabbro[7], D. Fouchez[8], I.M. Hook[9], D.A. Howell[6], H. Lafoux[3], J.D. Neill[4], N. Palanque-Delabrouille[3], K. Perett[6], C.J. Pritchet[4], J. Rich[3], M. Sullivan[6], R. Taillet[1,10], G. Aldering[11], P. Antilogus[1], V. Arsenijevic[7], C. Balland[1,2], S. Baumont[1,12], J. Bronder[9], H. Courtois[13], A. Darbon[14], R.S. Ellis[15], M. Filliol[5], A. Goobar[16], D. Guide[1], D. Hardin[1], V. Lusset[3], C. Lidman[12], R. McMahon[17], M. Mouchet[14,2], A. Mourao[7], S. Perlmutter[11], P. Ripoche[8], C. Tao[8], N. Walton[17]

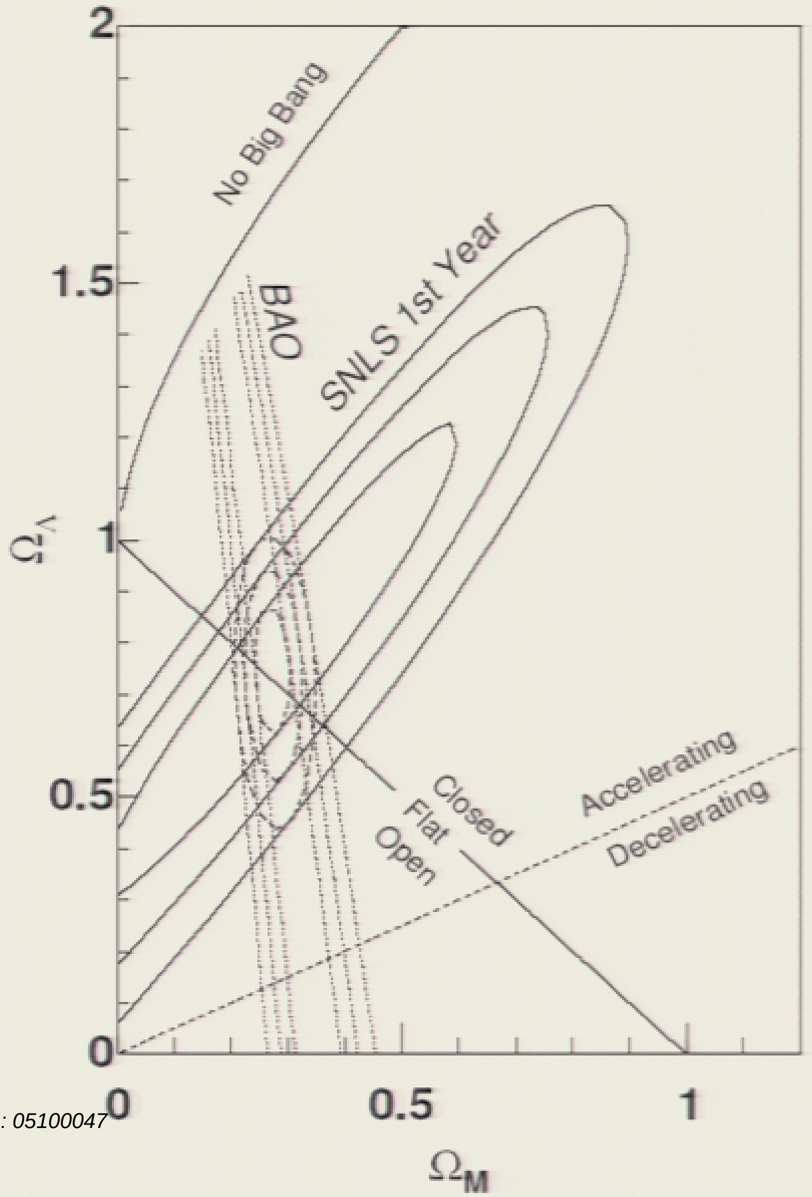
astro-ph/0510447

1st Year Hubble diagram



- 71 high-z SNe discovered at CFHT
- 44 low-z SNe from Hamuy et al, Riess et al & Jha et al (Cfa1 & Cfa2)
- High-z: SDSS *ugriz* filter system
- Derived "intrinsic" scatter in CFHT sample 0.12 mag
- Excellent agreement with concordance model ($\Omega_M = 0.263 \pm 0.042$ for flat universe)

SNLS 1-yr + BAO prior: w=-1.02±0.09 (stat)±0.054 (syst) (Astier et al , 2005)



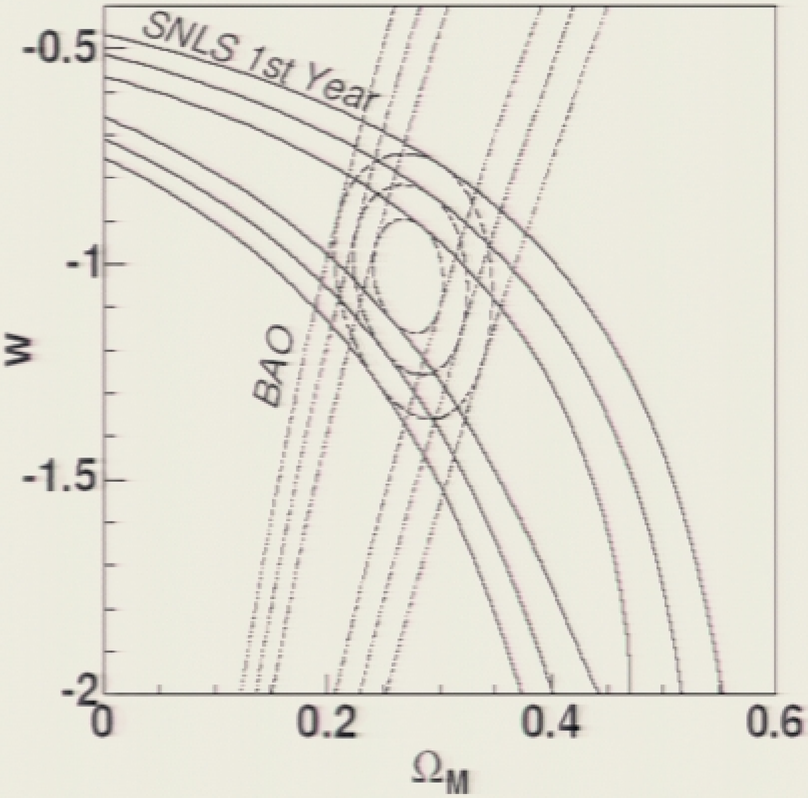


Fig. 6 Contours at 68.3%, 95.5% and 99.7% confidence levels for the fit to a flat (Ω_M, w) cosmology, from the SNLS Hubble diagram alone, from the SDSS baryon acoustic oscillations alone (Eisenstein et al. 2005), and the joint confidence contours.

Systematics about ½ than earlier SCP results

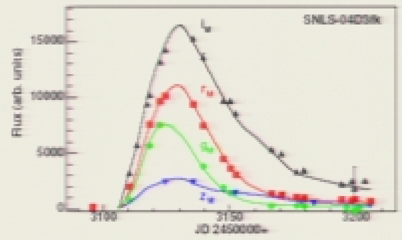


Fig. 1 Observed light curves of the SN Ia SNLS-04D3fk in g_M, r_M, i_M and z_M bands, along with the multi-color light-curve model (described in sect. 5.1). Note the regular sampling of the light curves both before and after maximum light. The light-curves points are fitted simultaneously with only four free parameters (photometric normalization, date of maximum, and a stretch and a color parameters). With a SN redshift of 0.358, the four measured pass-bands lie in the wavelength range of the light-curve model, defined by rest-frame U to R bands.

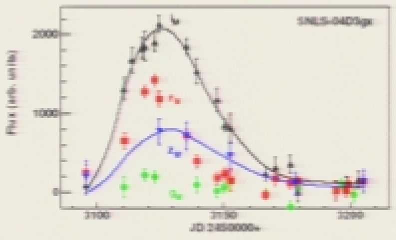


Fig. 2 Observed light curves of the SN Ia SNLS-04D3gx at z=0.91. With a SN redshift of 0.91, two of the measured pass-bands lie in the wavelength range of the light-curve model, defined by rest-frame U to R bands, and are therefore used in the fit. Note the excellent quality of the photometry at this high redshift value. Note also the clear signal observed in r_M and even in g_M, which correspond to central wavelength of respectively $\lambda \sim 320nm$ and $\lambda \sim 250nm$ in the SN rest frame.

P. Astier et al, SNLS Collabor.

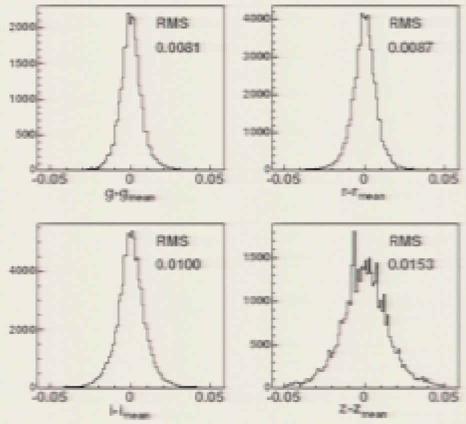
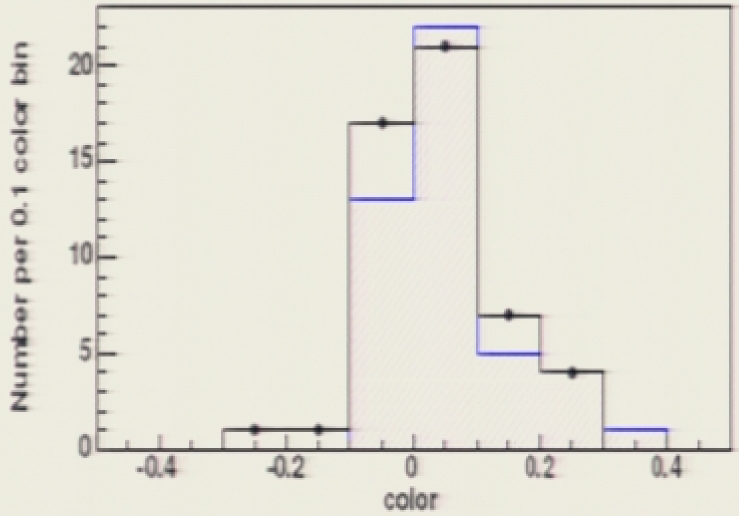
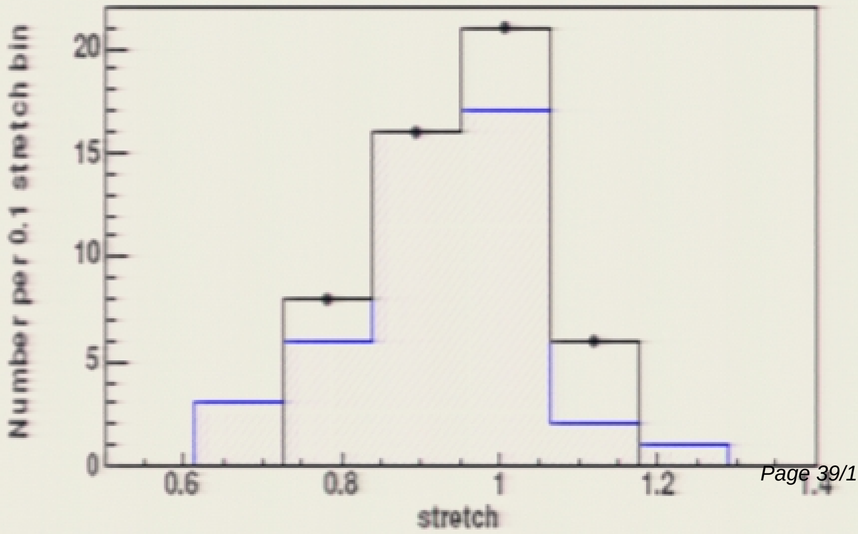


Fig. 3 The calibration residuals — *i.e.* the residuals around the mean magnitude of each DEEP field tertiary standard— in the bands g_M, r_M, i_M and z_M, for all CCDs and fields, with one entry per star and epoch. The dispersion is below 1% in g_M, r_M and i_M, and about 1.5% in z_M.





mag vs stretch and mag vs color

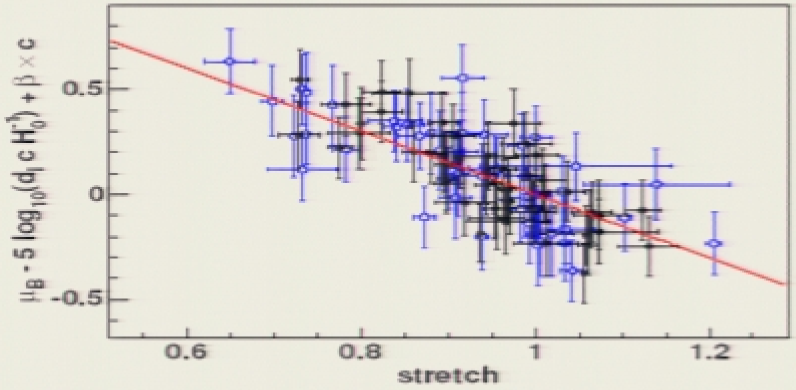


Fig. 9 Residuals in the Hubble diagram as a function of stretch, for nearby (blue open symbols) and distant ($z < 0.8$, black filled symbols). This diagram computes distance modulus μ_B without the stretch term $\alpha(s-1)$, and returns the well-known brighter-slower relationship with a consistent behavior for nearby and distant SNe Ia.

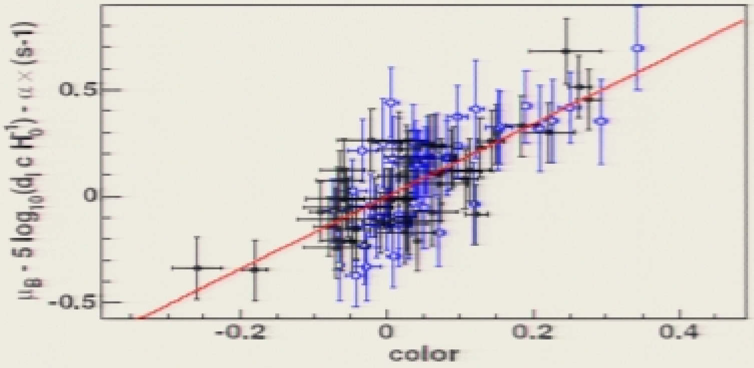


Fig. 10 Residuals in the Hubble diagram as a function of color, for nearby (blue open symbols) and distant ($z < 0.8$, black filled symbols). This diagram computes distance modulus μ_B without the color term βc, and returns the brighter-bluer relationship with a consistent behavior for nearby and distant SNe Ia. Notice that the bluest SNLS objects are compatible with the bulk behavior.

mag vs stretch and mag vs color

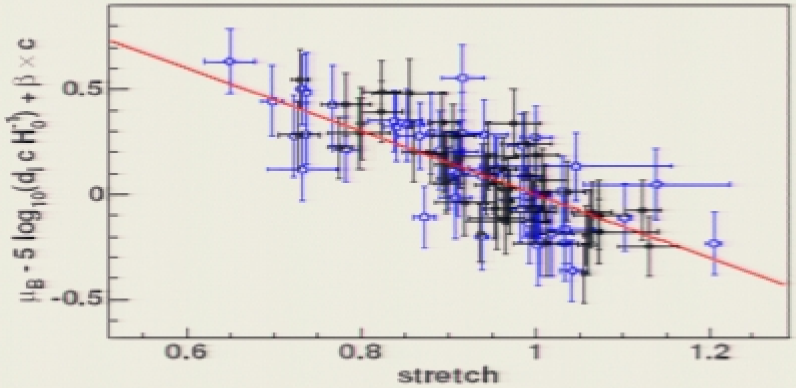


Fig. 9 Residuals in the Hubble diagram as a function of stretch, for nearby (blue open symbols) and distant ($z < 0.8$, black filled symbols). This diagram computes distance modulus μ_B without the stretch term $\alpha(s-1)$, and returns the well-known brighter-slower relationship with a consistent behavior for nearby and distant SNe Ia.

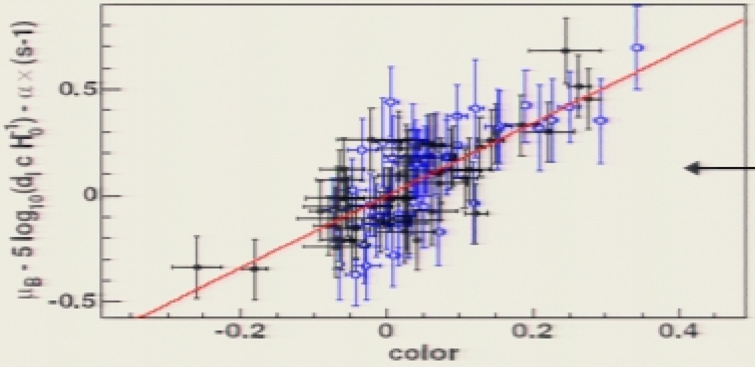
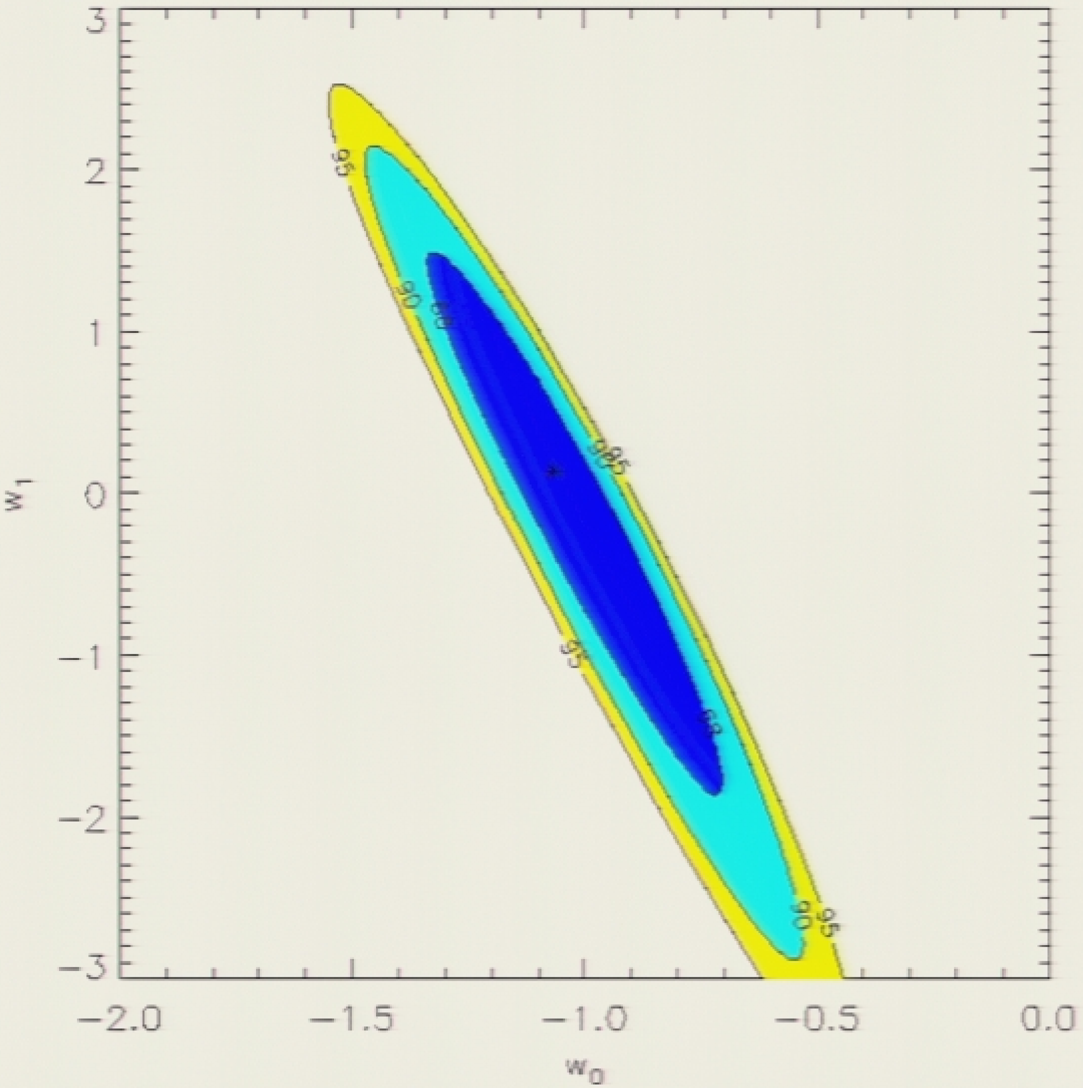


Fig. 10 Residuals in the Hubble diagram as a function of color, for nearby (blue open symbols) and distant ($z < 0.8$, black filled symbols). This diagram computes distance modulus μ_B without the color term βc, and returns the brighter-bluer relationship with a consistent behavior for nearby and distant SNe Ia. Notice that the bluest SNLS objects are compatible with the bulk behavior.

Slope less steep than expected if due to Galactic type dust... More later!

SNLS 1-year + BAO prior + flatness



$W=W_0 + W_1 \cdot Z$

Gravitational leakage into X-dimension

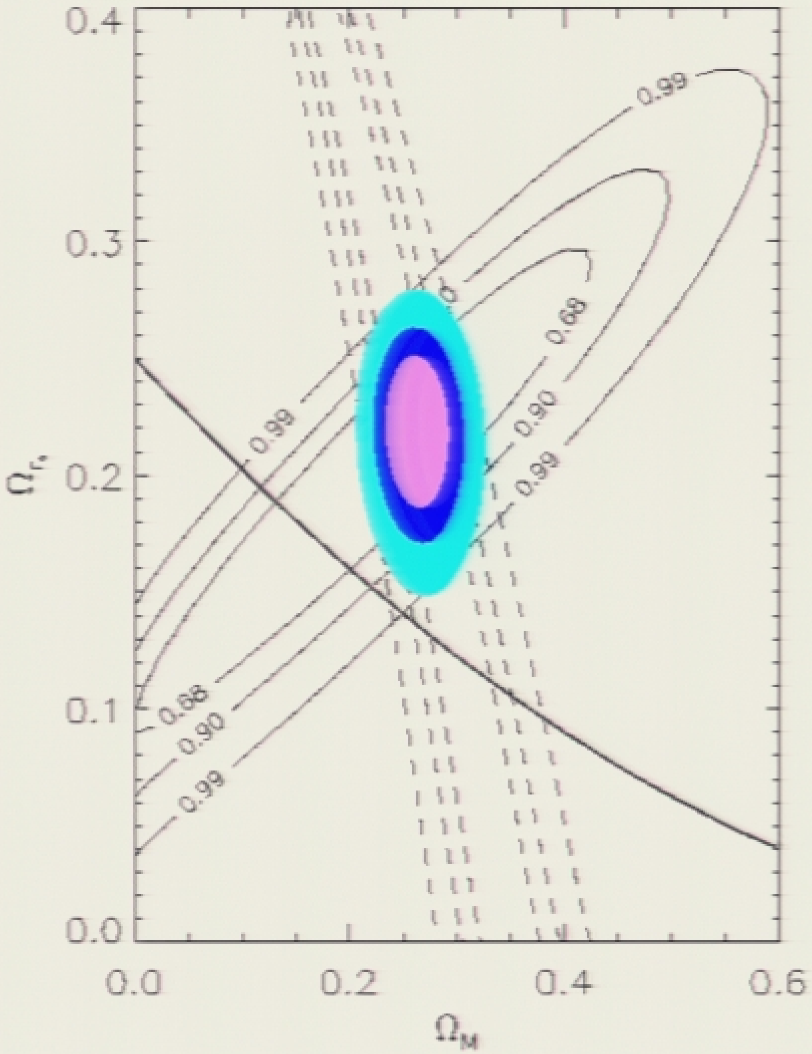
- Use SNLS (Astier et al 2005) + Baryon oscillations (Eisenstein et al 2005) to examine 5D extention of Friedmann eqn suggested by Dvali, Gabadadge,Porrati 2000; Deffayet, Dvali, Gabadadze 2001.

$$H^2 \pm \frac{H}{r_c} = \frac{8\pi G}{3}\rho$$

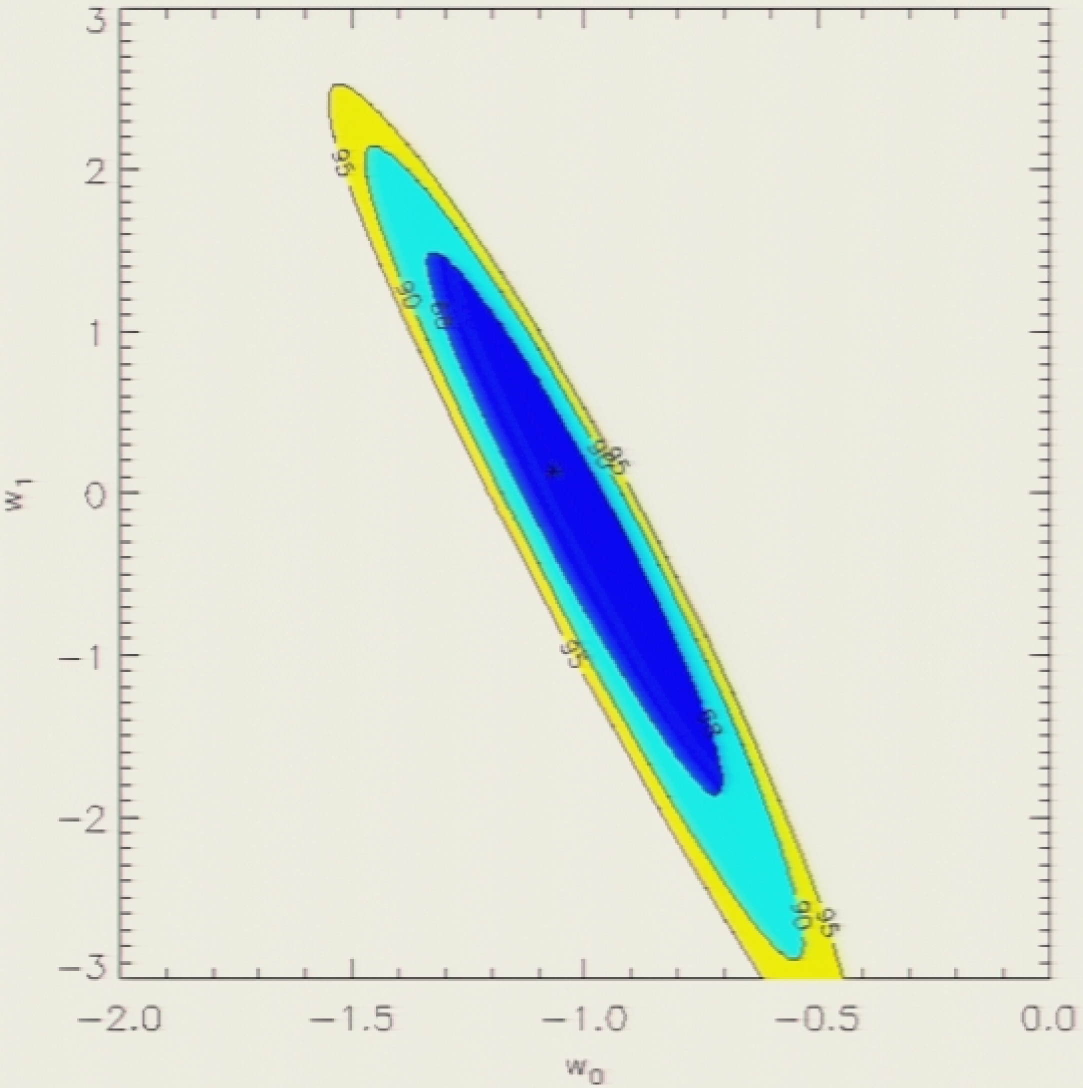
$$H^2(z) = H_0^2\left\{\Omega_k(1+z)^2 + \left(\sqrt{\Omega_{r_c}} + \sqrt{\Omega_{r_c} + \Omega_M(1+z)^3}\right)^2\right\}.$$

We can compare this equation with the conventional Friedmann equation:

$$H^2(z) = H_0^2\left\{\Omega_k(1+z)^2 + \Omega_M(1+z)^3 + \Omega_X(1+z)^{3(1+w_X)}\right\}.$$

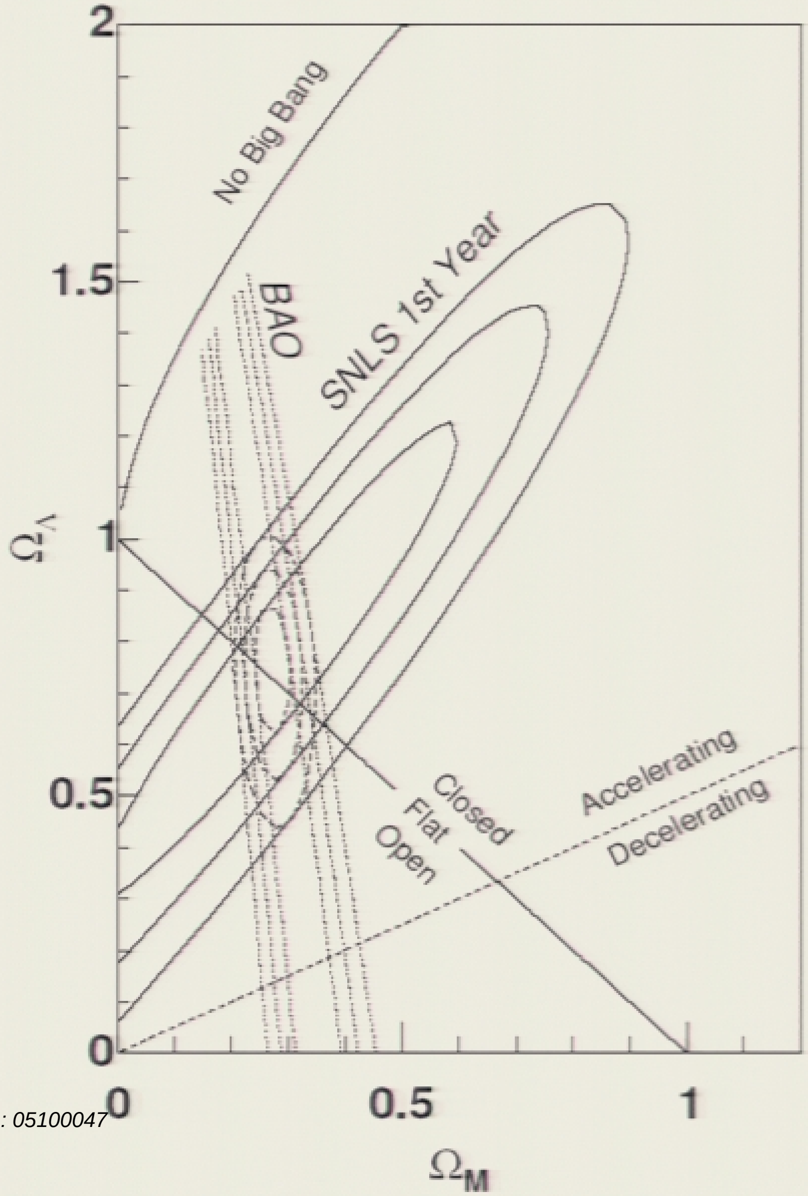


SNLS 1-year + BAO prior + flatness



$w = w_0 + w_1 \cdot z$

SNLS 1-yr + BAO prior:
w=-1.02±0.09 (stat)±0.054 (syst) (Astier et al , 2005)



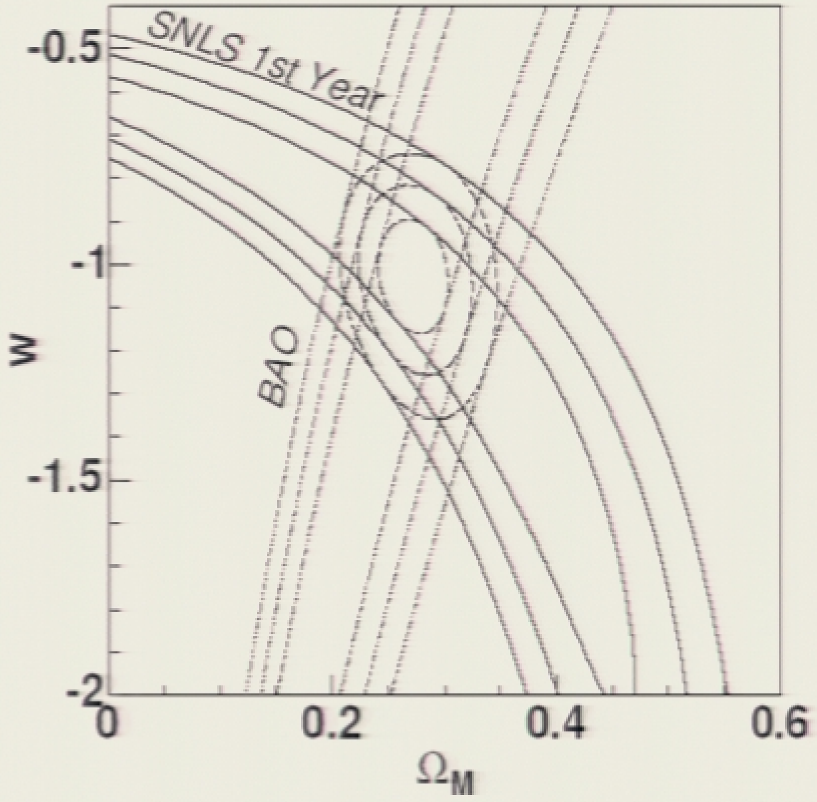


Fig. 6 Contours at 68.3%, 95.5% and 99.7% confidence levels for the fit to a flat (Ω_M, w) cosmology, from the SNLS Hubble diagram alone, from the SDSS baryon acoustic oscillations alone (Eisenstein et al. 2005), and the joint confidence contours.

Systematics about ½ than earlier SCP results

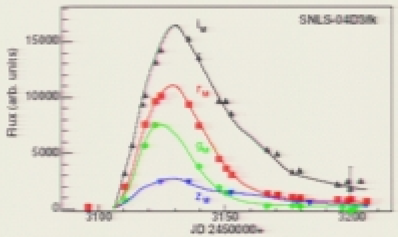


Fig. 1 Observed light curves of the SN Ia SNLS-04D3fk in g_M, r_M, i_M and z_M bands, along with the multi-color light-curve model (described in sect. 5.1). Note the regular sampling of the light curves both before and after maximum light. The light-curves points are fitted simultaneously with only four free parameters (photometric normalization, date of maximum, and a stretch and a color parameter). With a SN redshift of 0.358, the four measured pass-bands lie in the wavelength range of the light-curve model, defined by rest-frame U to R bands.

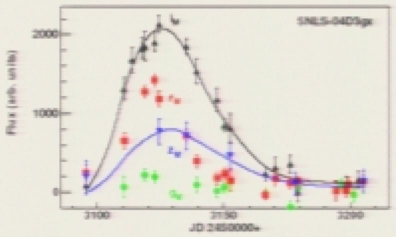


Fig. 2 Observed light curves of the SN Ia SNLS-04D3gx at z=0.91. With a SN redshift of 0.91, two of the measured pass-bands lie in the wavelength range of the light-curve model, defined by rest-frame U to R bands, and are therefore used in the fit. Note the excellent quality of the photometry at this high redshift value. Note also the clear signal observed in r_M and even in g_M, which correspond to central wavelength of respectively $\lambda \sim 320nm$ and $\lambda \sim 250nm$ in the SN rest frame.

P. Astier et al, SNLS Collabor

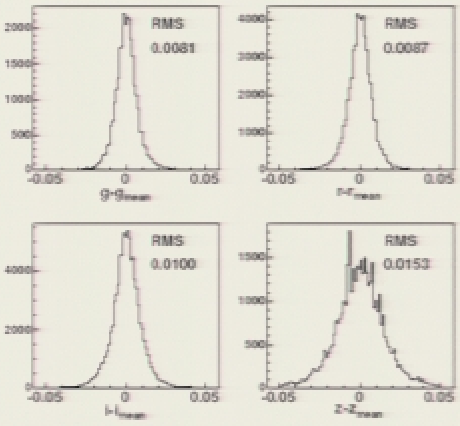
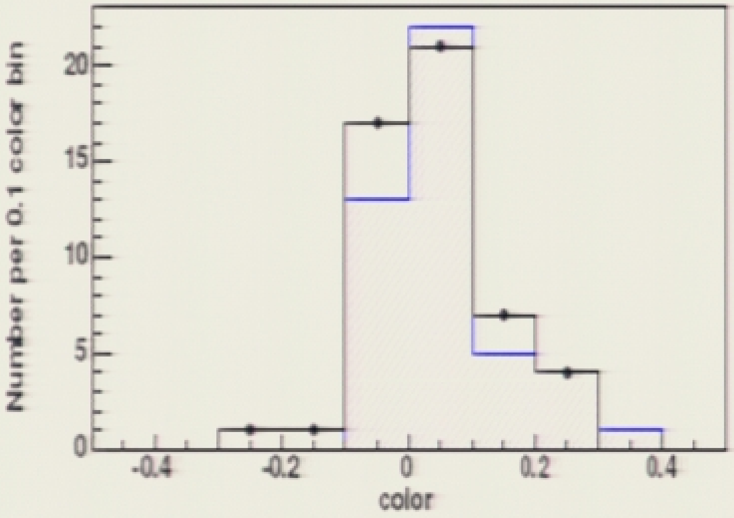
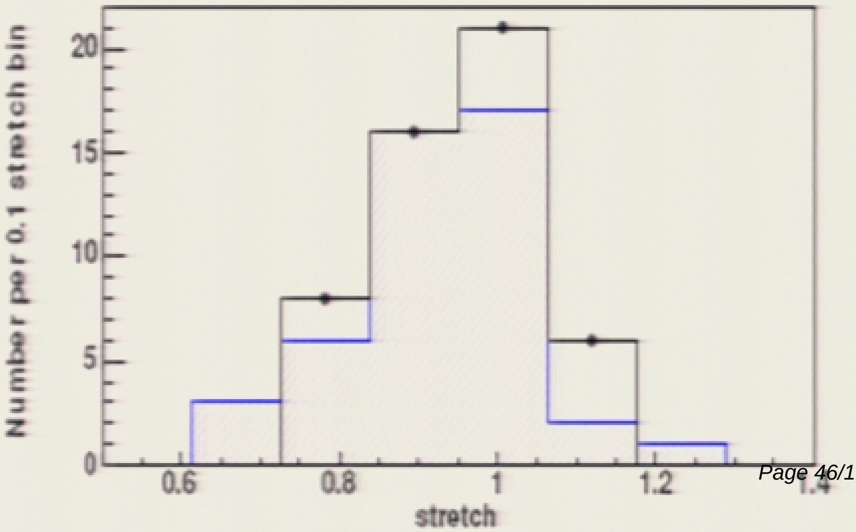


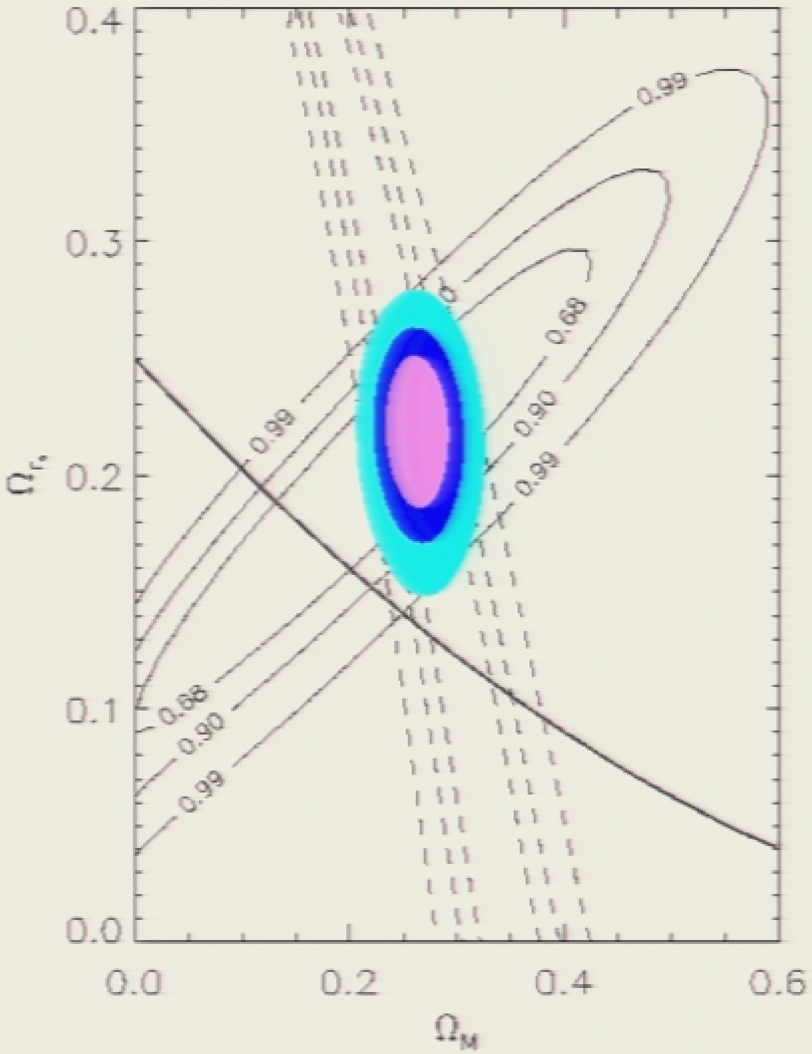
Fig. 3 The calibration residuals — *i.e.* the residuals around the mean magnitude of each DEEP field tertiary standard— in the bands g_M, r_M, i_M and z_M, for all CCDs and fields, with one entry per star and epoch. The dispersion is below 1% in g_M, r_M and i_M, and about 1.5% in z_M.





Gravitational leakage into X-dimension

- Use SNLS (Astier et al 2005) + Baryon oscillations (Eisenstein et al 2005) to examine 5D extention of Friedmann eqn suggested by Dvali, Gabadadge,Porrati 2000; Deffayet, Dvali, Gabadadze 2001.



$$H^2 \pm \frac{H}{r_c} = \frac{8\pi G}{3}\rho$$

$$H^2(z) = H_0^2\left\{\Omega_k(1+z)^2 + \left(\sqrt{\Omega_{r_c}} + \sqrt{\Omega_{r_c} + \Omega_M(1+z)^3}\right)^2\right\}.$$

We can compare this equation with the conventional Friedmann equation:

$$H^2(z) = H_0^2\left\{\Omega_k(1+z)^2 + \Omega_M(1+z)^3 + \Omega_X(1+z)^{3(1+w_X)}\right\}.$$

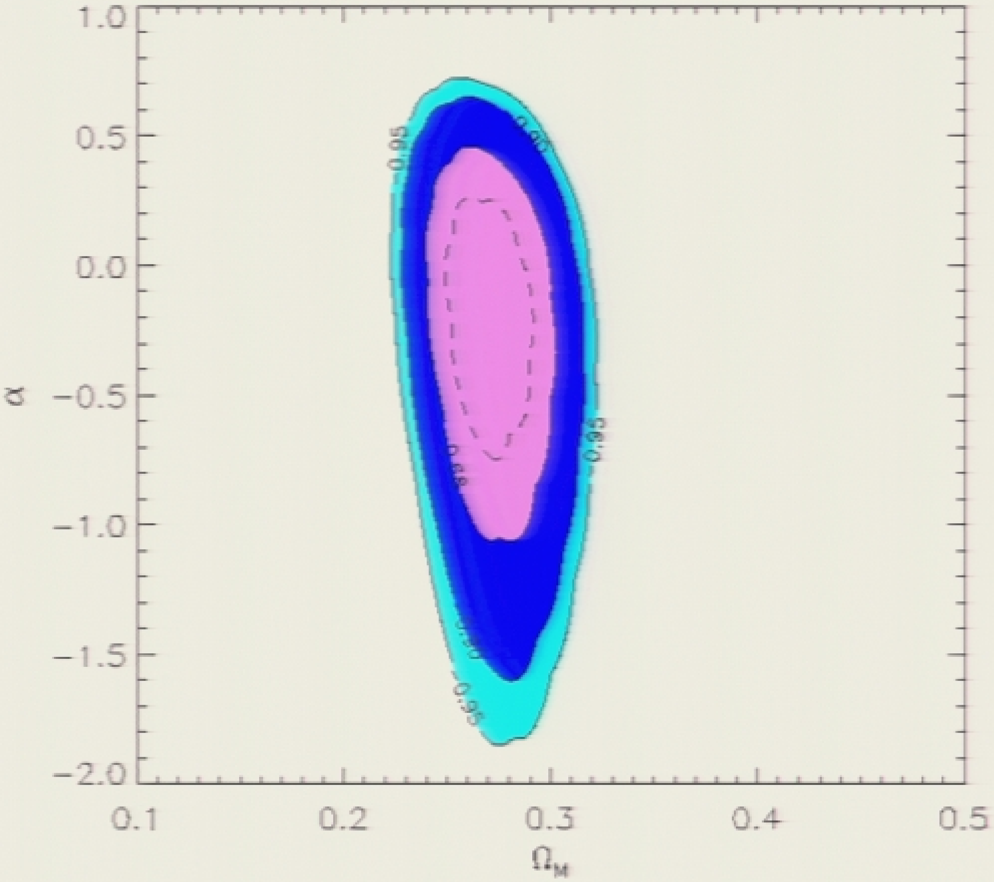
Gravitational leakage into X-dimension (2)

- Consider more general corrections to Friedmann eqn (as in Dvali & Turner, 2003)

$$H^2 - \frac{H^\alpha}{r_c^{\,2-\alpha}} = \frac{8\pi G}{3}\rho$$

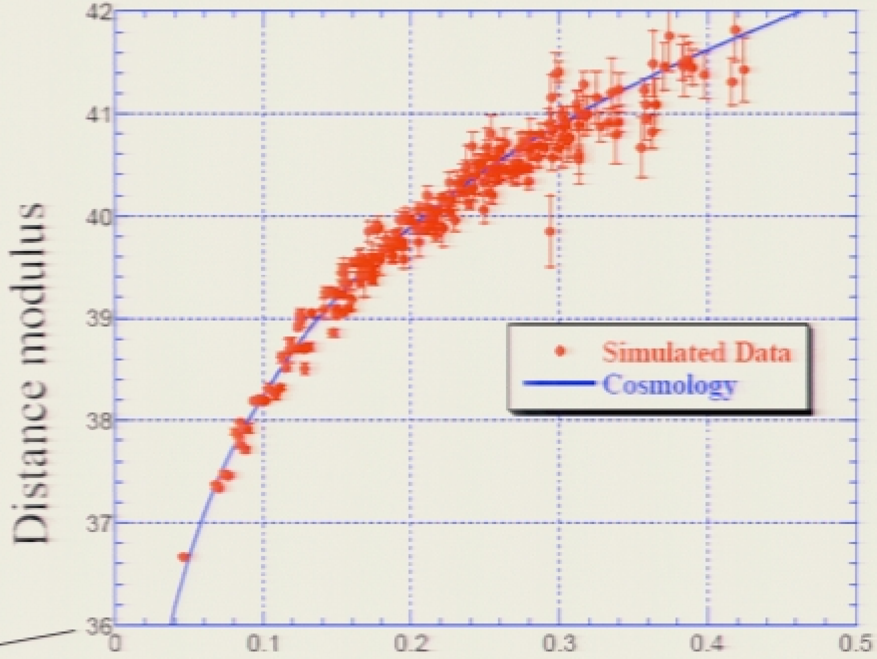
Fit SNLS data + baryon oscillations AND flat universe

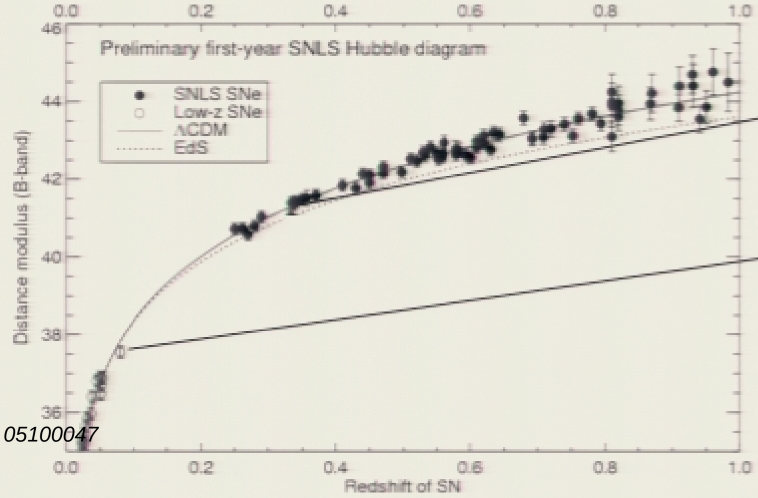
(Malcolm Fairbairn & AG, work in progress)



SDSS II: intermediate-z SNe

- Three year project started in September 2005.
- Aiming at filling in the "gap" left by eg SNLS and ESSENCE with 200 well measured, accurately calibrated, multicolor LCs





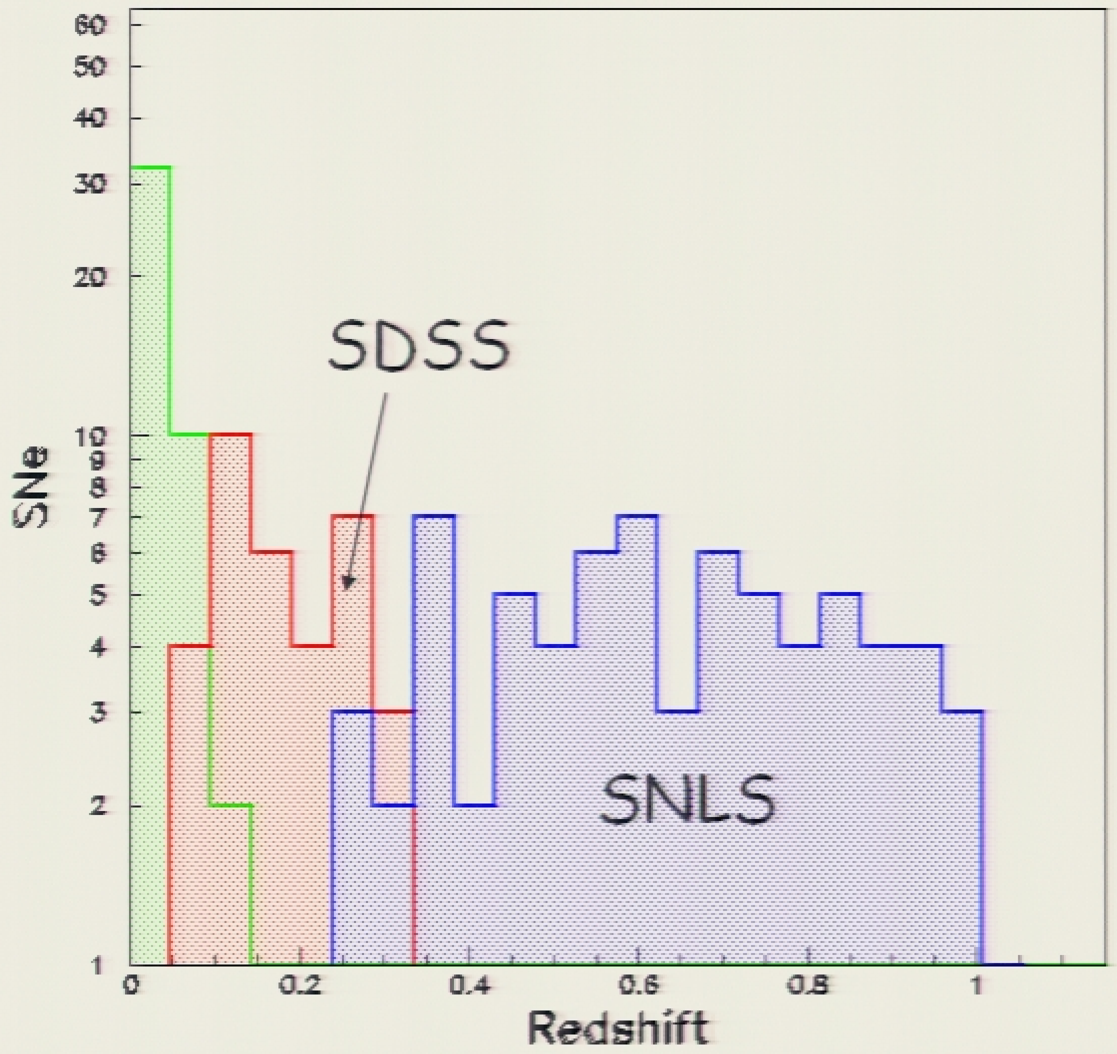
First batch of (int-z) SDSS-II SNe!

SUPERNOVAE 2005eh and 2005ex-2005gj

Further to CBET 229, J. Barentine, Apache Point Observatory (APO); B. Bassett, University of Portsmouth (UP); A. Becker, University of Washington; M. Bremer, University of Bristol; H. Brewington, APO; F. DeJongh, Fermilab; J. Dembicky, APO; D. L. DePoy, Ohio State University (OSU); B. Dilday, University of Chicago (UC); M. Doi, University of Tokyo; A. Edge, University of Durham; E. Elson, South African Astronomical Observatory (SAAO); J. Frieman, Fermilab and UC; P. Garnavich, University of Notre Dame; A. Goobar, Stockholm University; M. Harvanek, APO; J. Holtzman, New Mexico State University; J. Krzesinski, APO; D. Lamenti, San Francisco State University; H. Lampeitl, Fermilab; R. Kessler, UC; B. Ketzeback, APO; K. Konishi, University of Tokyo; D. Long, APO; J. Marriner, Fermilab; J. L. Marshall, OSU; R. McMillan, APO; J. Mendez, University of Barcelona (UB); R. Nichol, UP; K. Pan, APO; J. L. Prieto, OSU; M. Richmond, Rochester Institute of Technology; A. Riess, Space Telescope Science Institute; R. Romani, Stanford University (SU); K. Romer, University of Sussex; P. Ruiz-Lapuente, UB; M. Sako, SU; D. Schneider, Pennsylvania State University; M. Smith, UP; S. Snedden, APO; M. Subbarao, UC and Adler Planetarium; N. Takanashi, University of Tokyo; K. van der Heyden, SAAO; and N. Yasuda, University of Tokyo, on behalf of the Sloan Digital Sky Survey II collaboration, report the discovery of 39 supernovae on multiple g', r', and i' images taken with the SDSS 2.5-m telescope at Apache Point Observatory by the SDSS observing team. Spectroscopy was obtained with the William Herschel telescope, the Hobby Eberly Telescope, Subaru telescope, the ARC 3.5-m telescope, and the MDM 2.4-m telescope, showing thirty of them to be of type Ia and six to be probable type-Ia events (SNe 2005ex, 2005ez, 2005fh, 2005fq, 2005gh, and 2005ge); SN 2005fk is a type-Ibc hypernova, SN 2005gi is a type-II supernova, and SN 2005gj is a probable type-IIn supernova. The magnitudes tabulated below are all g' magnitudes unless followed by an asterisk, in which case they are r' magnitudes due to non-detection in g' on the discovery date. The spectroscopic redshifts in the column labelled z. The peak magnitudes and dates (all 2005) are estimated from fits to the light curves.

SN	Discov. Date	R.A. (2000.0)	Decl.	Mag.	z	Estimated Peak Date	Mag.
2005ex	Sep. 3	1 41 51.24	- 0 52 35.00	19.2	0.09	Aug. 23	19.0
2005ey	Sep. 3	2 17 05.50	+0 16 49.08	20.9	0.13	Sep. 14	19.5
2005ez	Sep. 3	3 07 10.97	+1 07 10.36	21.4*	0.13	Sep. 10	20.3
2005fa	Sep. 10	1 39 36.08	- 0 45 31.54	21.1	0.15	Sep. 20	20.3
2005fb	Sep. 10	3 01 17.54	- 0 38 38.69	21.2	0.16	Sep. 16	20.6
2005fc	Sep. 10	21 21 39.25	+0 53 40.74	21.7	0.29	Sep. 9	21.7
2005fd	Sep. 10	21 35 11.76	+0 09 47.16	22.3	0.26	Sep. 20	21.1
2005fe	Sep. 10	22 19 27.32	+0 29 39.92	21.1	0.21	Sep. 3	20.9
2005ff	Sep. 10	22 30 41.41	- 0 46 35.76	21.0	0.07	Sep. 21	19.3
2005fg	Sep. 10	22 36 04.20	- 0 22 30.83	21.8	0.26	Sep. 13	21.6
2005fh	Sep. 10	23 17 29.71	+0 25 45.79	19.8	0.12	Sep. 19	19.1
2005fi	Sep. 11	0 07 58.69	+0 38 17.45	22.4	0.26	Sep. 23	21.1
2005fj	Sep. 11	21 11 20.85	- 0 26 43.30	20.2	0.14	Sep. 7	20.2
2005fk	Sep. 12	21 15 19.83	- 0 22 58.62	21.8*	0.24	Aug. 3	20.4
2005fl	Sep. 13	20 47 21.99	- 1 15 11.89	21.6	0.24	Aug. 29	21.1
2005fm	Sep. 13	20 48 10.37	- 1 10 17.11	20.5	0.13	Sep. 20	19.9
2005fn	Sep. 13	20 48 53.05	+0 11 28.02	18.9	0.10	Sep. 1	18.7
2005fo	Sep. 13	21 55 46.40	+0 35 36.71	21.7	0.26	Sep. 19	21.5
2005fp	Sep. 14	0 27 13.69	+1 07 14.22	22.1	0.21	Sep. 18	21.7
2005fq	Sep. 14	0 53 44.05	- 0 33 36.76	21.5	0.14	Sep. 13	21.5
2005fr	Sep. 14	1 08 22.02	- 0 05 46.74	21.6	0.29	Sep. 14	21.6
2005fs	Sep. 14	2 04 52.97	- 0 19 35.26	22.1	0.33	Sep. 18	21.7
2005ft	Sep. 14	2 42 04.98	- 0 32 26.99	21.2	0.16	Sep. 19	20.5
2005fu	Sep. 14	2 50 32.09	+0 48 28.13	21.0*	0.20	Sep. 18	20.6
2005fv	Sep. 15	3 05 22.43	+0 51 30.13	21.1	0.11	Sep. 23	19.8
2005fw	Sep. 15	3 30 49.04	- 1 14 17.16	20.9	0.16	Sep. 23	19.9
2005fx	Sep. 15	22 56 48.34	+0 24 03.92	21.8	0.29	Sep. 21	21.6
2005fy	Sep. 16	3 20 21.70	- 0 53 08.09	21.0	0.20	Sep. 13	20.9
2005fz	Sep. 21	22 03 41.21	+0 34 10.31	20.8	0.12	Sep. 25	20.4
2005ga	Sep. 22	1 07 43.76	- 1 02 22.20	21.3	0.16	Sep. 29	20.3
2005gb	Sep. 22	1 16 12.58	+0 47 31.01	19.4	0.09	Sep. 30	18.7
2005gc	Sep. 22	1 21 37.62	- 0 58 38.03	21.2	0.17	Sep. 30	20.4
2005gd	Sep. 22	1 59 51.03	+0 38 26.21	21.2	0.16	Sep. 29	20.4
2005ge	Sep. 22	2 18 14.72	+0 47 47.62	22.1	0.19	Oct. 2	21.2
2005gf	Sep. 22	22 16 16.63	+0 42 29.23	21.3	0.24	Sep. 25	21.1
2005gg	Sep. 22	22 18 41.16	+0 38 21.12	21.7	0.23	Sep. 29	21.1
2005gh	Sep. 23	20 50 36.35	- 0 21 14.76	21.8	0.25	Sep. 25	21.7
2005gi	Sep. 24	0 55 52.68	+0 30 17.82	19.8	0.05	Sep. 25	19.7
2005gj	Sep. 26	3 01 11.95	- 0 33 13.90	18.6	0.06	Oct. 1	17.8

C-T/CfA low-z, SDSS 1-run + SNLS 1-yr



First batch of (int-z) SDSS-II SNe!

SUPERNOVAE 2005eh and 2005ex-2005gj

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2005fb	Sep. 10	3 01 17.54	- 0 38 38.69	21.2	0.16	Sep. 16	20.6
2005fc	Sep. 10	21 21 39.25	+0 53 40.74	21.7	0.29	Sep. 9	21.7
2005fd	Sep. 10	21 35 11.76	+0 09 47.16	22.3	0.26	Sep. 20	21.1
2005fe	Sep. 10	22 19 27.32	+0 29 39.92	21.1	0.21	Sep. 3	20.9
2005ff	Sep. 10	22 30 41.41	- 0 46 35.76	21.0	0.07	Sep. 21	19.3
2005fg	Sep. 10	22 36 04.20	- 0 22 30.83	21.8	0.26	Sep. 13	21.6
2005fh	Sep. 10	23 17 29.71	+0 25 45.79	19.8	0.12	Sep. 19	19.1
2005fi	Sep. 11	0 07 58.69	+0 38 17.45	22.4	0.26	Sep. 23	21.1
2005fj	Sep. 11	21 11 20.85	- 0 26 43.30	20.2	0.14	Sep. 7	20.2
2005fk	Sep. 12	21 15 19.83	- 0 22 58.62	21.8*	0.24	Aug. 3	20.4
2005fl	Sep. 13	20 47 21.99	- 1 15 11.89	21.6	0.24	Aug. 29	21.1
2005fm	Sep. 13	20 48 10.37	- 1 10 17.11	20.5	0.13	Sep. 20	19.9
2005fn	Sep. 13	20 48 53.05	+0 11 28.02	18.9	0.10	Sep. 1	18.7
2005fo	Sep. 13	21 55 46.40	+0 35 36.71	21.7	0.26	Sep. 19	21.5
2005fp	Sep. 14	0 27 13.69	+1 07 14.22	22.1	0.21	Sep. 18	21.7
2005fq	Sep. 14	0 53 44.05	- 0 33 36.76	21.5	0.14	Sep. 13	21.5
2005fr	Sep. 14	1 08 22.02	- 0 05 46.74	21.6	0.29	Sep. 14	21.6
2005fs	Sep. 14	2 04 52.97	- 0 19 35.26	22.1	0.33	Sep. 18	21.7
2005ft	Sep. 14	2 42 04.98	- 0 32 26.99	21.2	0.16	Sep. 19	20.5
2005fu	Sep. 14	2 50 32.09	+0 48 28.13	21.0*	0.20	Sep. 18	20.6
2005fv	Sep. 15	3 05 22.43	+0 51 30.13	21.1	0.11	Sep. 23	19.8
2005fw	Sep. 15	3 30 49.04	- 1 14 17.16	20.9	0.16	Sep. 23	19.9
2005fx	Sep. 15	22 56 48.34	+0 24 03.92	21.8	0.29	Sep. 21	21.6
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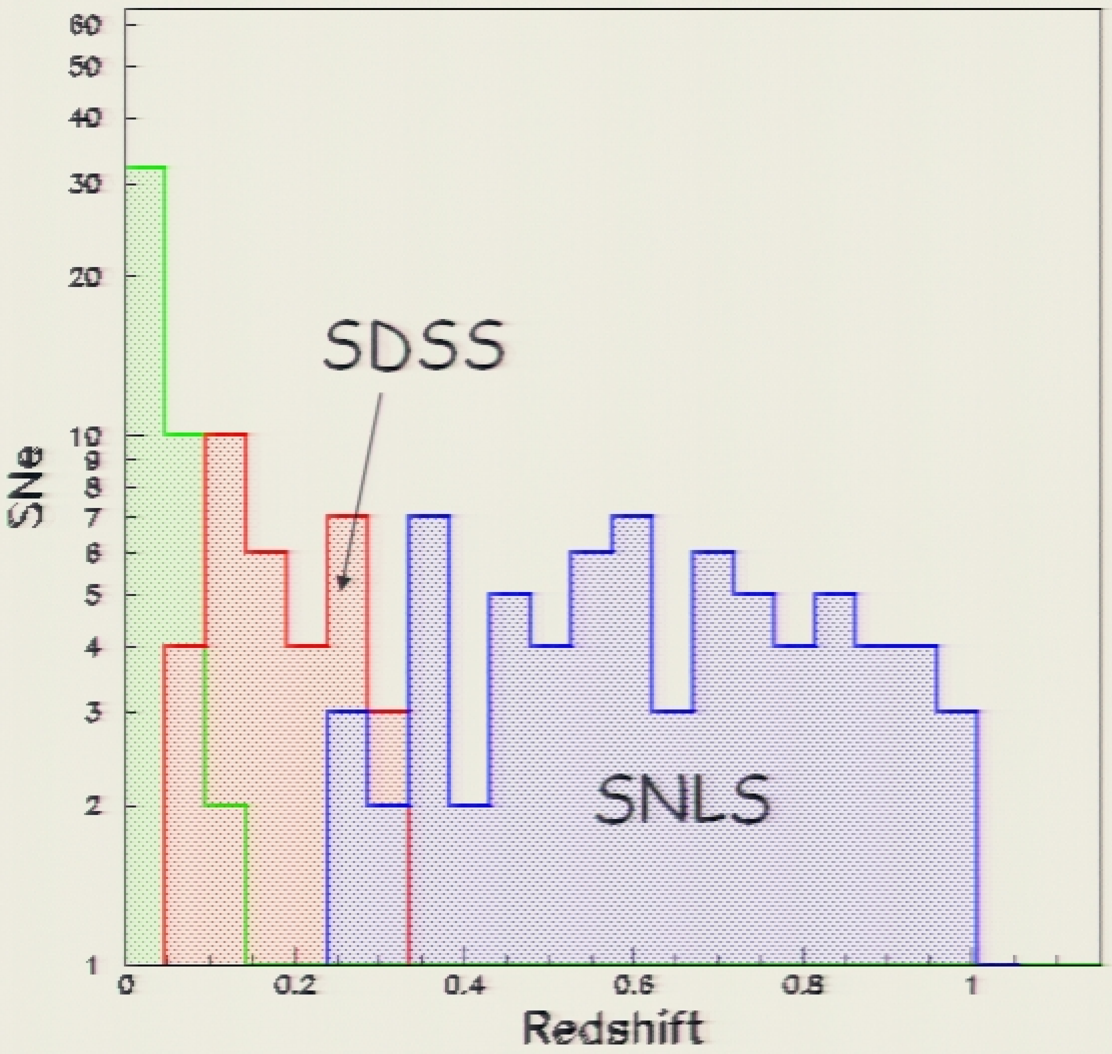
2005fz	Sep. 21	22 03 41.21	+0 34 10.31	20.8	0.12	Sep. 25	20.4
2005ga	Sep. 22	1 07 43.76	- 1 02 22.20	21.3	0.16	Sep. 29	20.3
2005gb	Sep. 22	1 16 12.58	+0 47 31.01	19.4	0.09	Sep. 30	18.7
2005gc	Sep. 22	1 21 37.62	- 0 58 38.03	21.2	0.17	Sep. 30	20.4
2005gd	Sep. 22	1 59 51.03	+0 38 26.21	21.2	0.16	Sep. 29	20.4
2005ge	Sep. 22	2 18 14.72	+0 47 47.62	22.1	0.19	Oct. 2	21.2
2005gf	Sep. 22	22 16 16.63	+0 42 29.23	21.3	0.24	Sep. 25	21.1
2005gg	Sep. 22	22 18 41.16	+0 38 21.12	21.7	0.23	Sep. 29	21.1
2005gh	Sep. 23	20 50 36.35	- 0 21 14.76	21.8	0.25	Sep. 25	21.7
2005gi	Sep. 24	0 55 52.68	+0 30 17.82	19.8	0.05	Sep. 25	19.7
2005gj	Sep. 26	3 01 11.95	- 0 33 13.90	18.6	0.06	Oct. 1	17.8

C-T/CfA low-z, SDSS 1-run + SNLS 1-yr

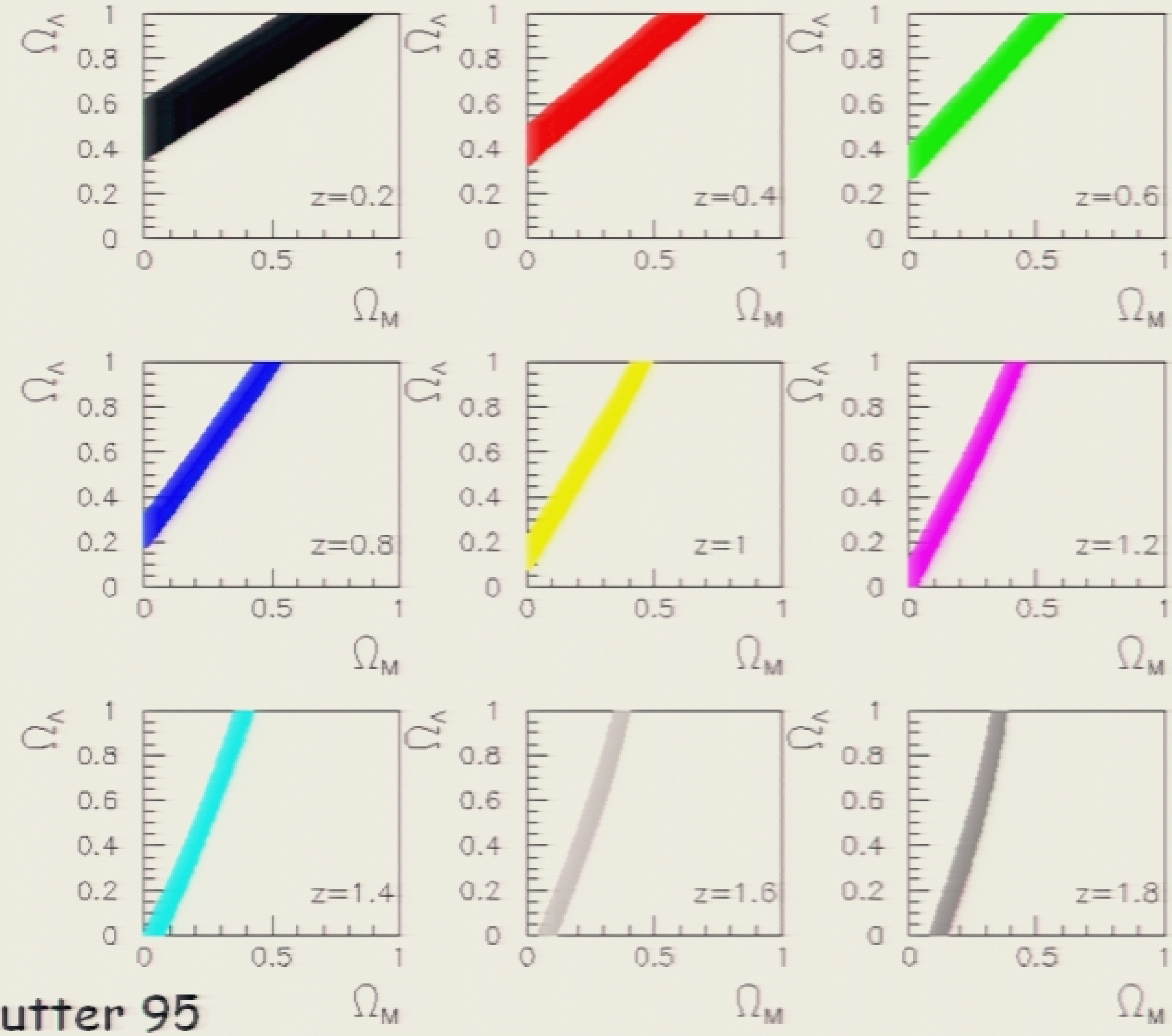


The highest redshifts

Working at $z>1$

Statistical uncertainty: Redshift dependence

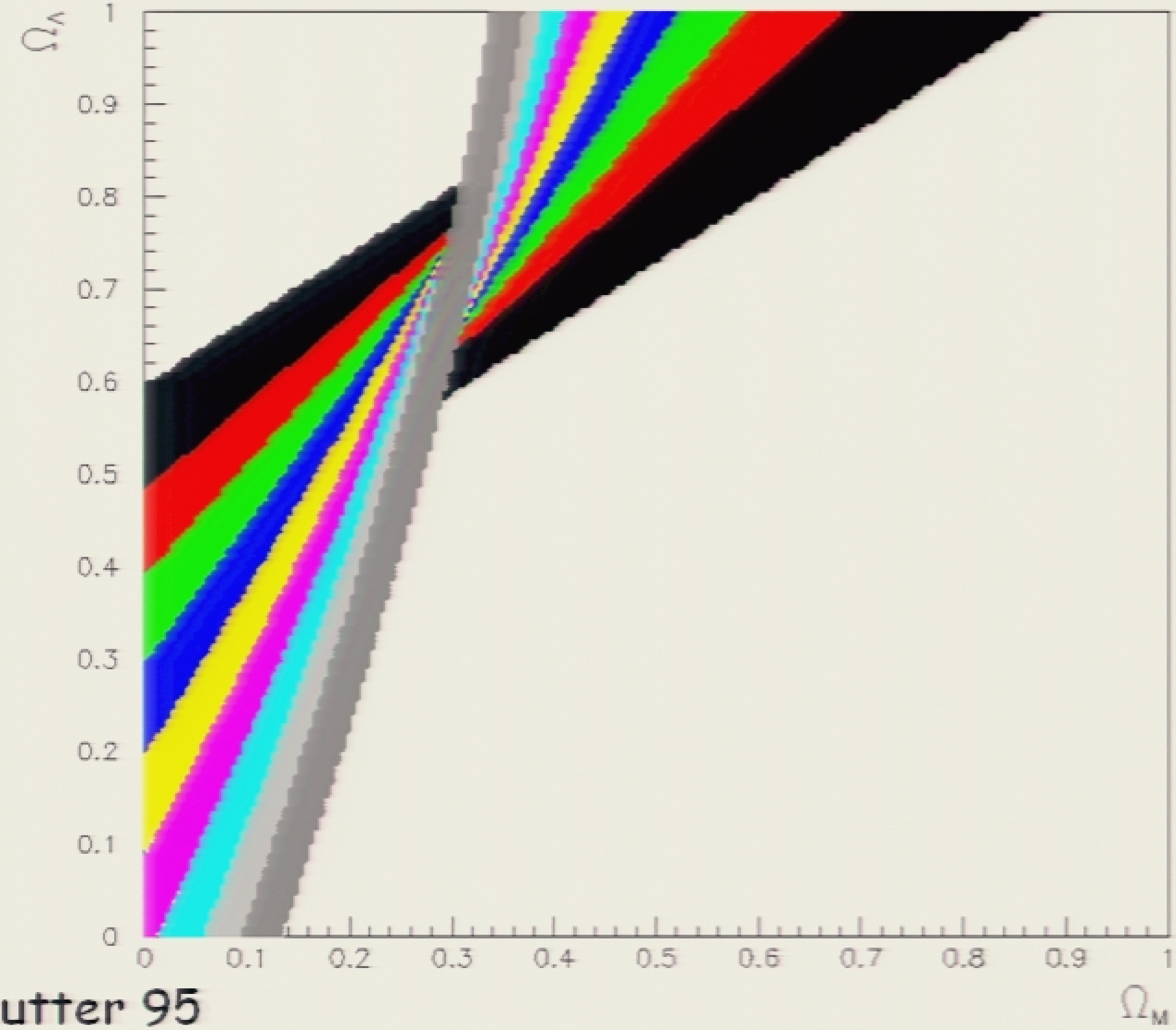
1σ bands at each redshift for Δm=0.02 mag



AG & Perlmutter 95

Statistical uncertainty: Redshift dependence

1σ bands at each redshift for Δm=0.02 mag



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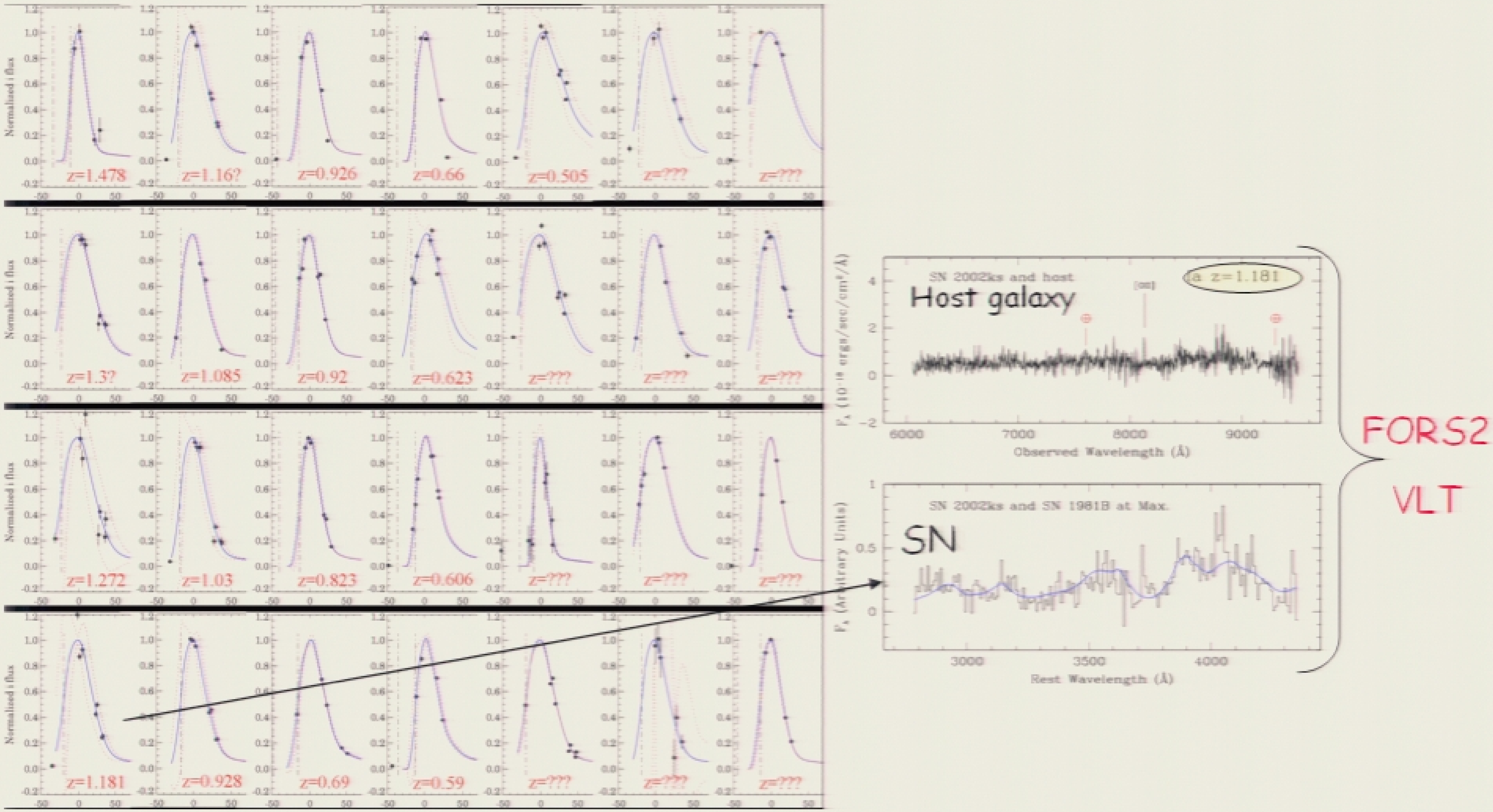
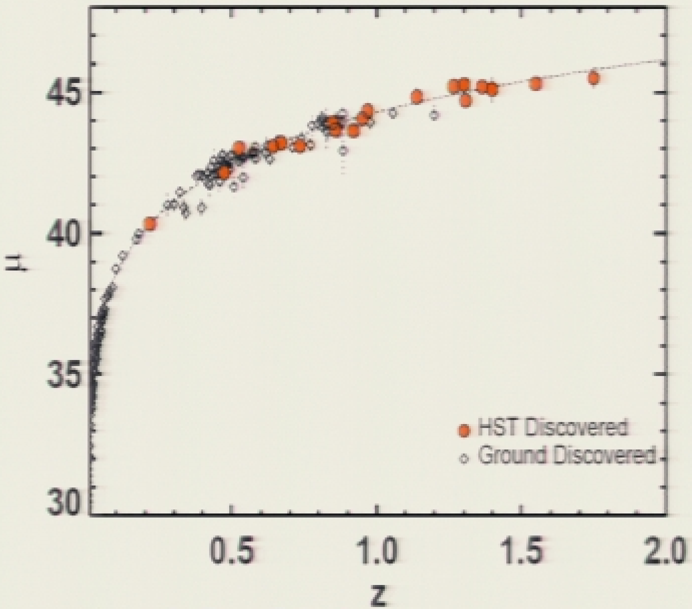
SNe discovered at Subaru (i')

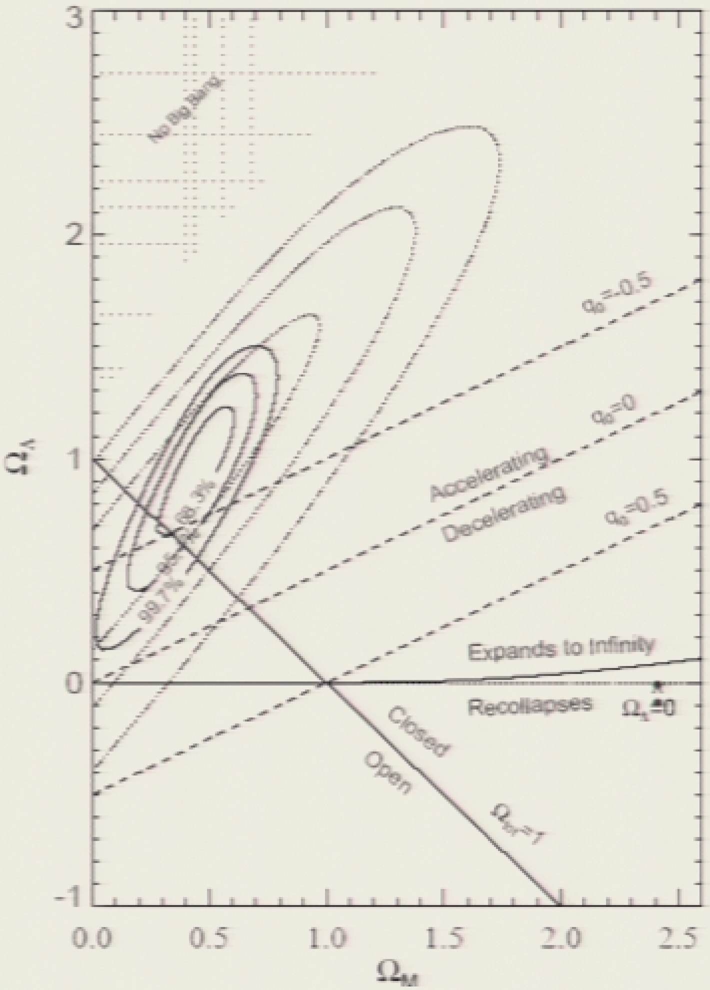


Subaru search 2002,
~30 candidates i'_{AB}=23-26

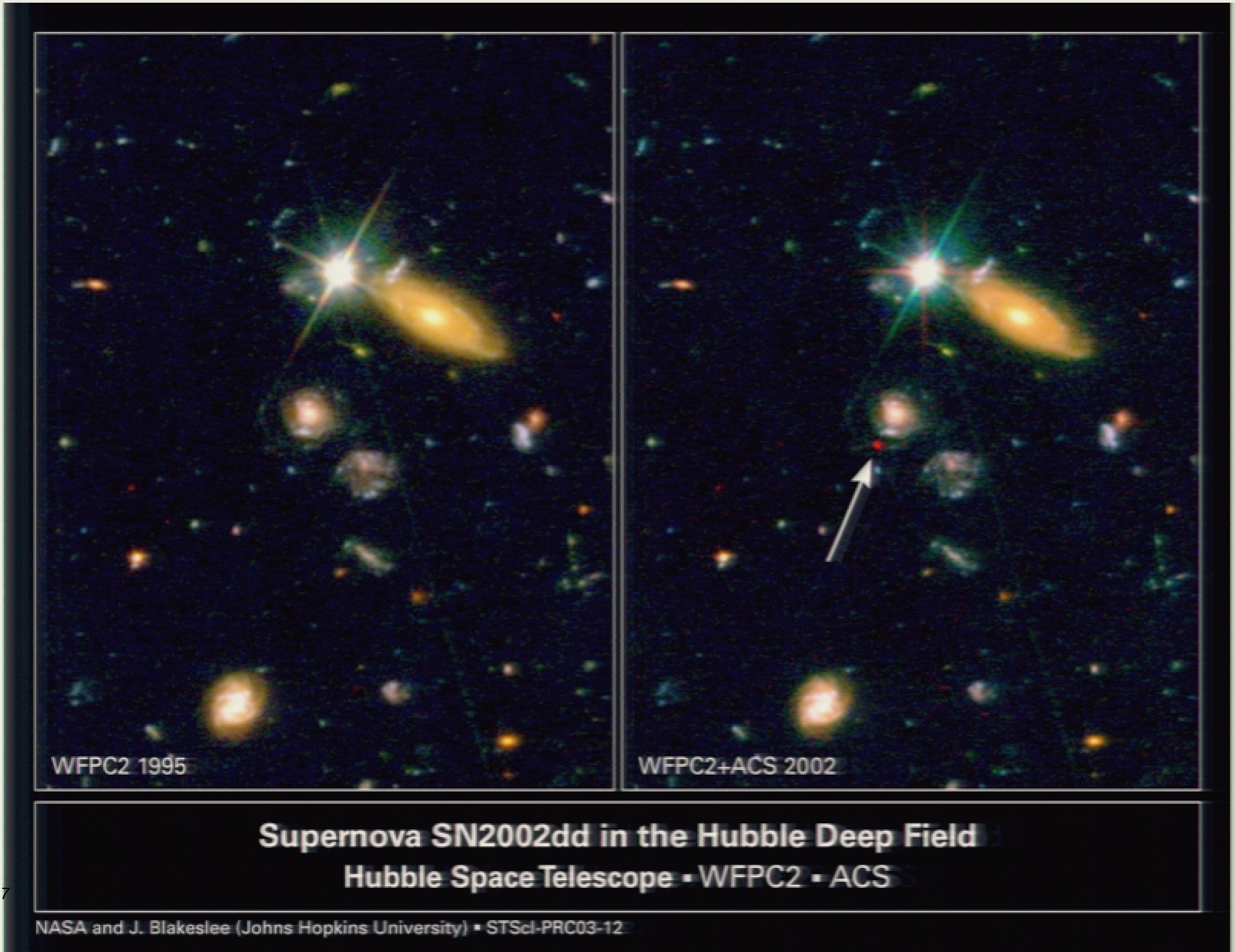
Very-high Z supernovae from ACS/HST

(Riess et al 2004)





- By now >40 SNe discovered from space, up to z=1.7
- Reported CL-regions due to *statistical* errors

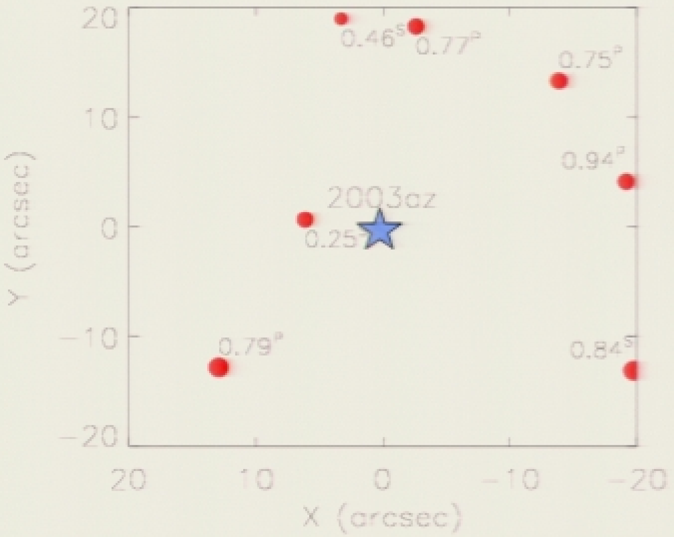


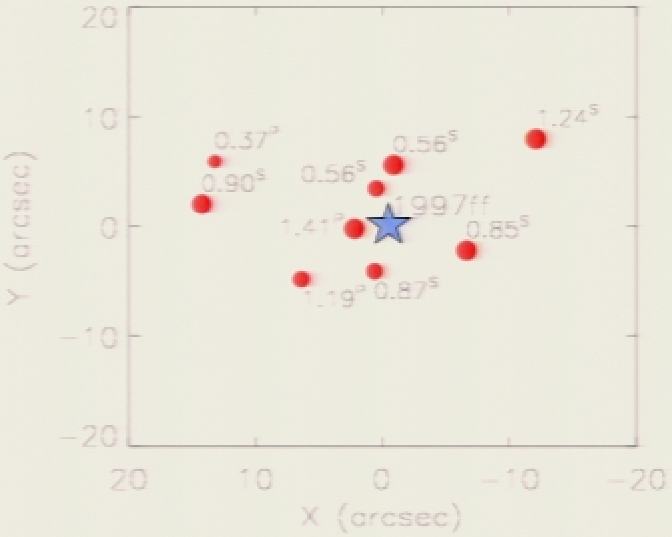
Supernova SN2002dd in the Hubble Deep Field

Hubble Space Telescope • WFPC2 • ACS

NASA and J. Blakeslee (Johns Hopkins University) • STScI-PRC03-12

Lensing (de)magnification

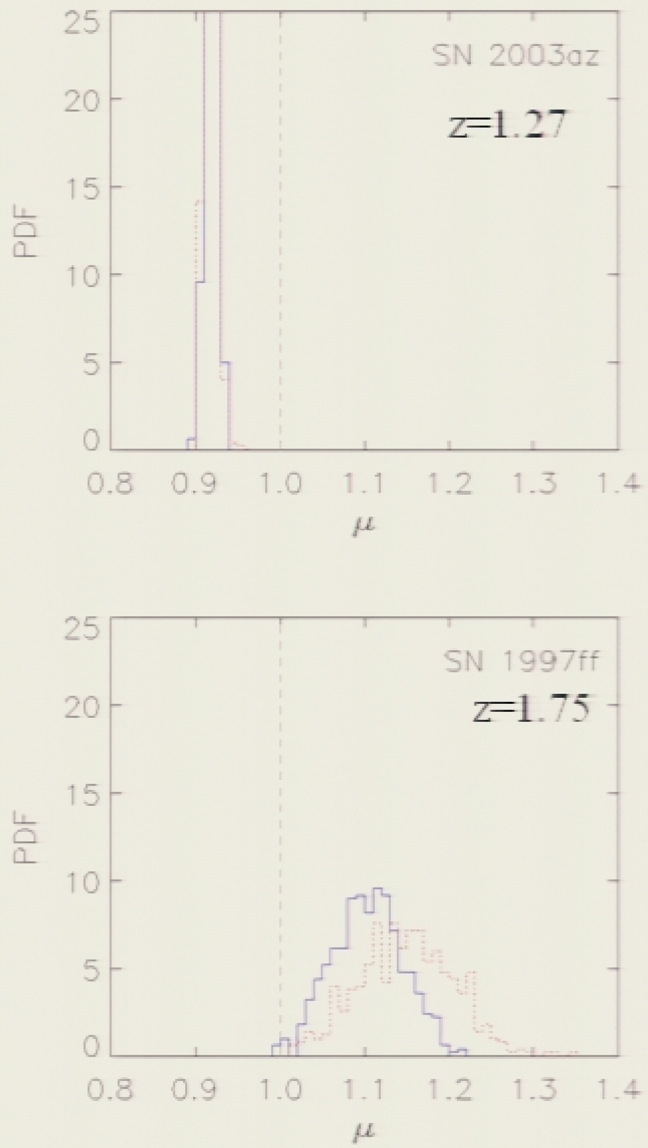




- **The photometric redshift catalogue for GOODS used to study the line-of-sight properties of the SNIa in the Riess et al 2004 sample**

  (see Gunnarsson et al astro-ph/0506764 and Jönsson et al astro-ph/0506765)
- **Faber-Jackson & Tully Fischer relations used for M/L**
- **Galaxy halos modelled as truncated SIS or NFW**
- **Self-consistency loop: mass density in galaxies + unresolved matter=Ω_M**

Magnification probability

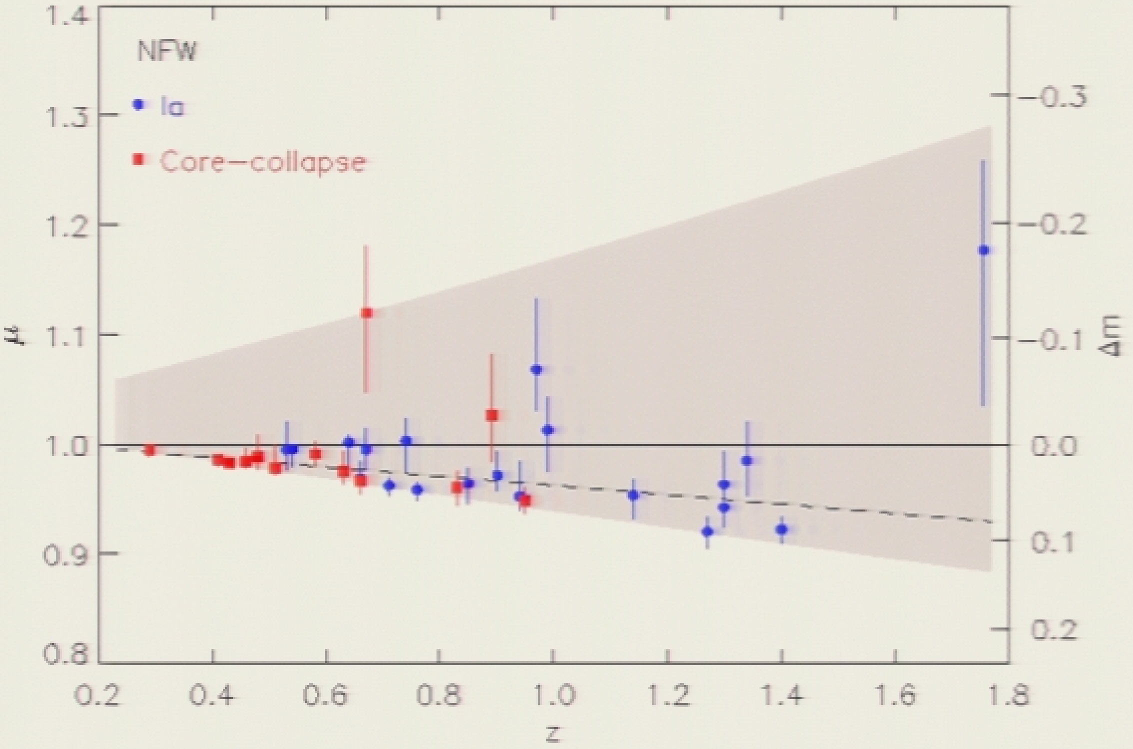


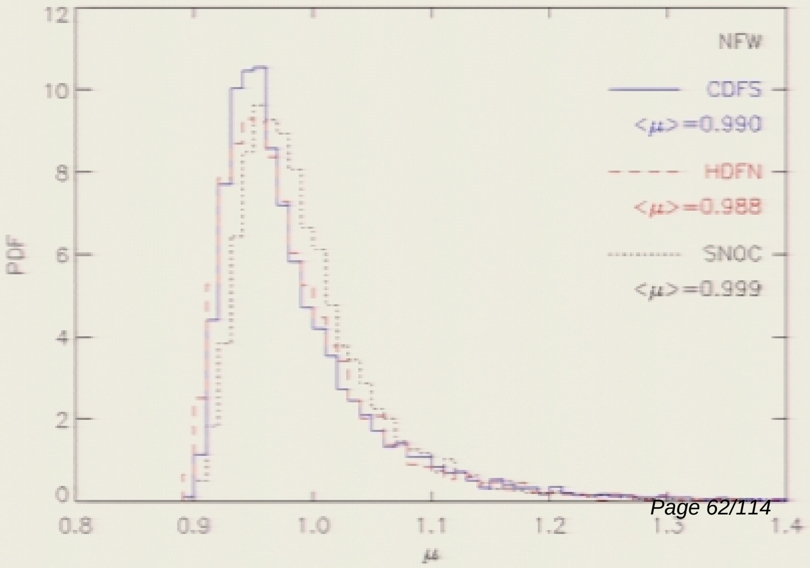
- We find evidence for magnified and demagnified supernovae ($\mu \neq 1$)
- Uncertainty computed by error progation from:
  - Finite field size error
  - Redshift and position errors
  - Scatter in FJ&TF relations
  - Survey magnitude limit (incompleteness)

PDF built up by randomizing the contributions above according to their individual uncertainties,

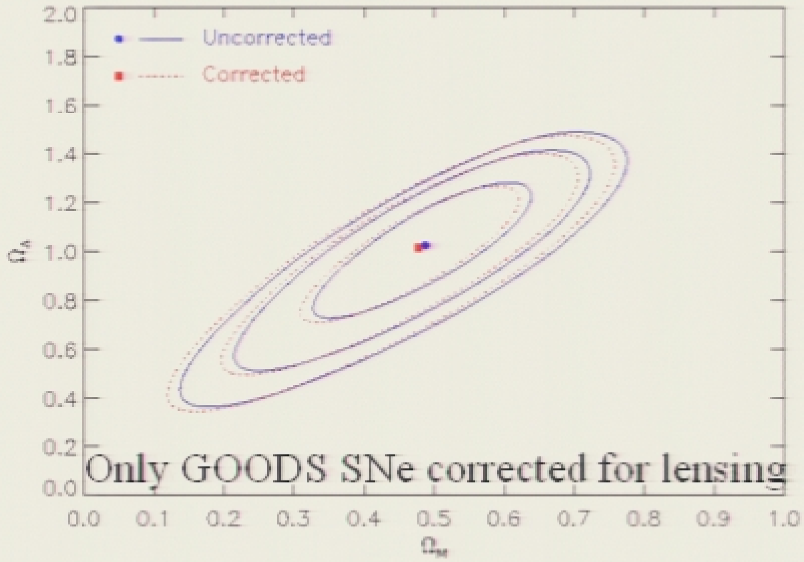
- Estimate of magnification in SN1997ff smaller than in Benitez et al 2002, Riess et al 2004. This is understood, both these authors do now agree with us.

Lensing PDFs for GOODS SN-sample

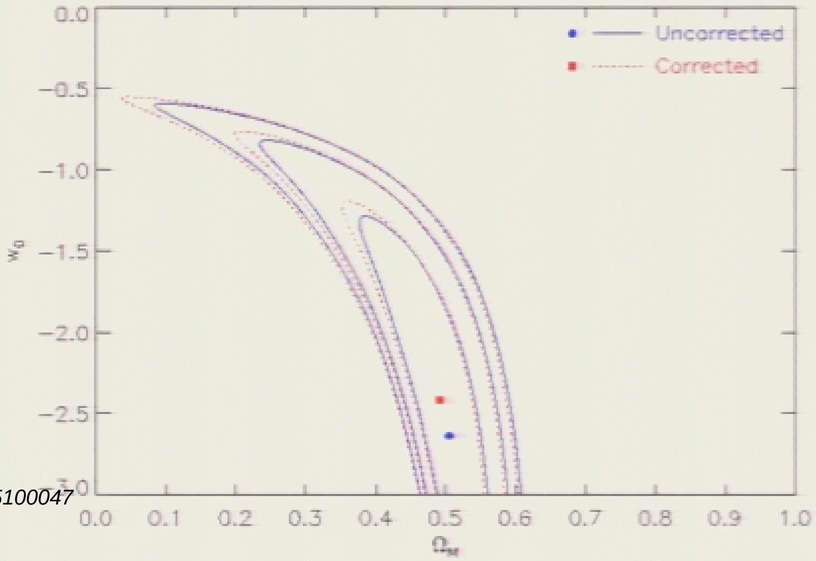




Cosmological parameters

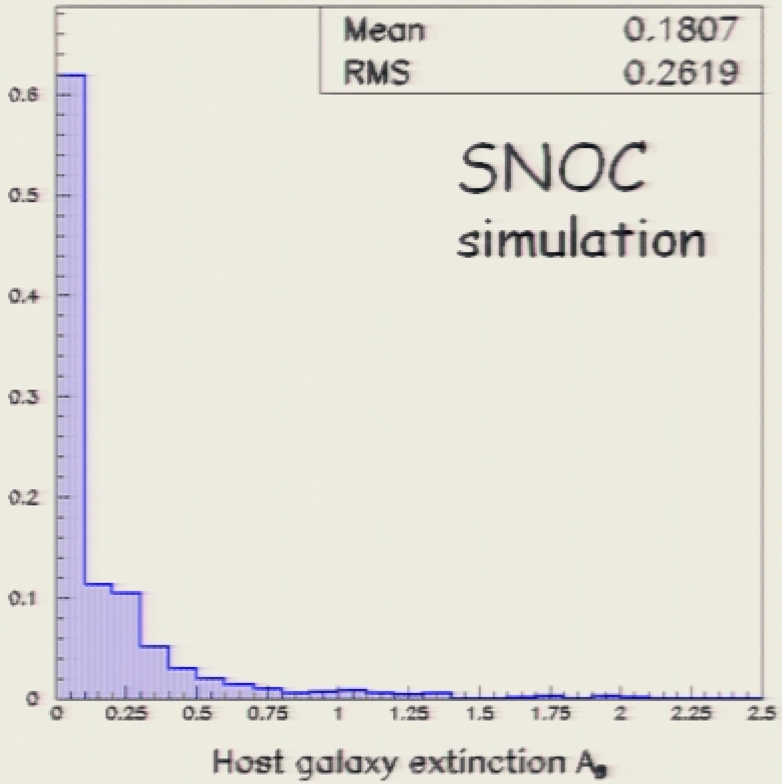


Only GOODS SNe corrected for lensing



- We found NO evidence for selection effects due to lensing in the GOODS SN sample.
- Lensing distributions compatible with simulations, e.g SNOC.
- JDEM: statistical uncertainty due to weak lening can be reduce by about 50% by including l-o-s galaxy (and LSS) information measured with same instrument.
- Possible lensing bias on SNLS results is small: $|\delta\Omega_M|$ ~0.01 in Ω_M-Ω_Λ plane. Added uncertainty on w_0 (after prior on baryon oscillations) is σ_w~0.014

Extinction corrections



- Dust in SN host galaxy (or along line of sight)
- Correction assumes some reddening law, typically Galactic type dust
- Can only be estimated with

  a) accurate multi-wavelength data

  b) good knowledge of intrinsic ”color” of SNe
- Extinction probabilty in a given galaxy depends on where the SN explosion happens

Milky Way dust

- Wavelength dependence parametrized by R_v,
- $A_v = R_v E(B-V)$
- Average value $R_v = 3.1$
- $R_v \sim 1 \rightarrow$ Rayleigh scattering , $A_\lambda = k\lambda^{-4}$
- R_v » 3 → "Grey" dust, weak wavelength dependence (especially in UV and optical)

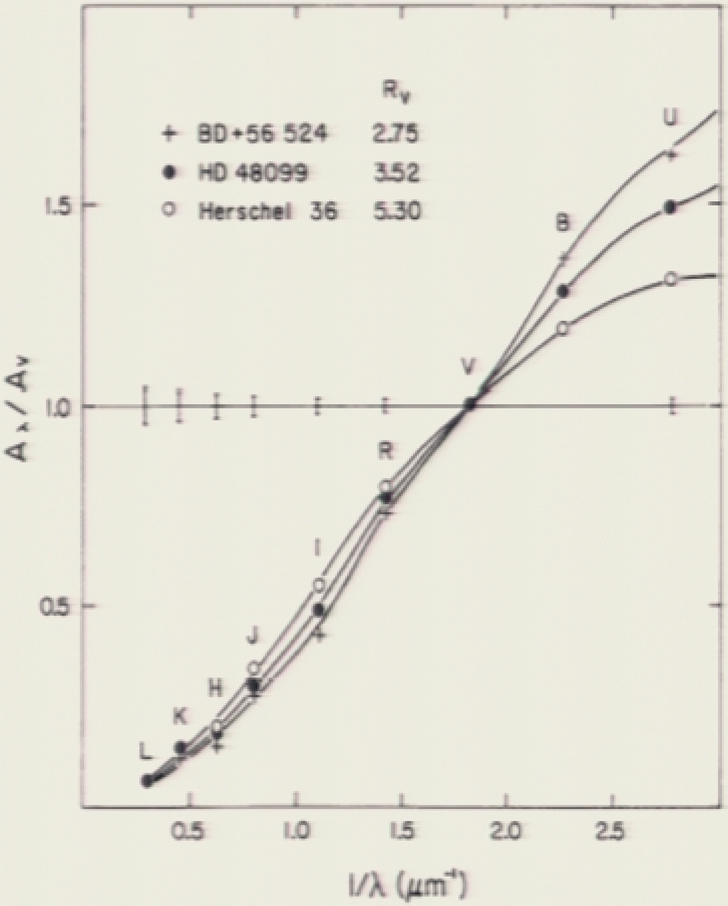


FIG. 3.—Comparison between the mean optical/NIR R_V-dependent extinction law from eqs. (2) and (3) and three lines of sight with largely separated R_V values. The wavelength position of the various broad-band filters from which the data were obtained are labeled (see Table 3). The "error" bars represent the computed standard deviation of the data about the best fit of $A(\lambda)/A(V)$ vs. R_V^{-1} with $a(x) + b(x)/R_V$ where $x \equiv \lambda^{-1}$. The effect of varying R_V on the shape of the extinction curves is quite apparent, particularly at the shorter wavelengths.

Cardelli, Clayton & Mathis, 1989

Extinction in UV

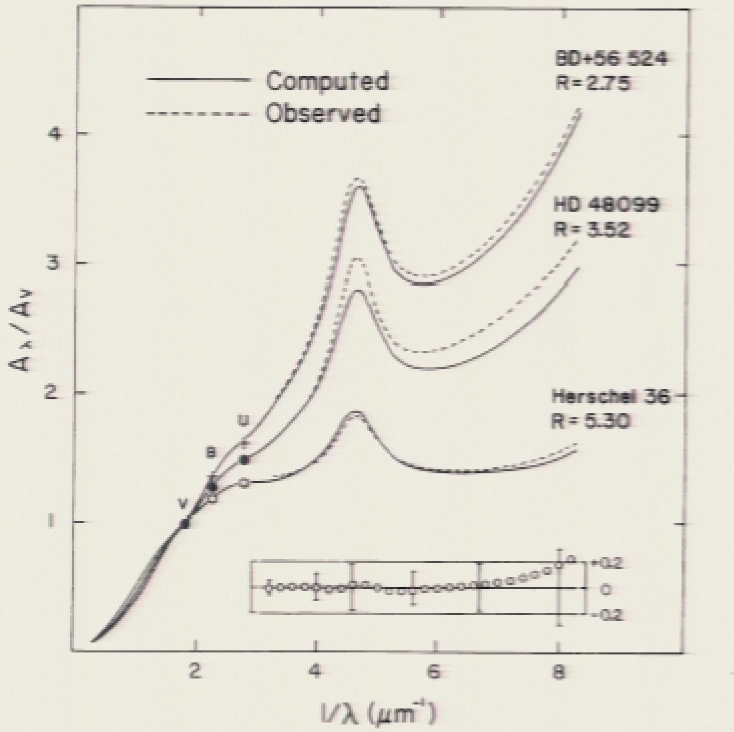
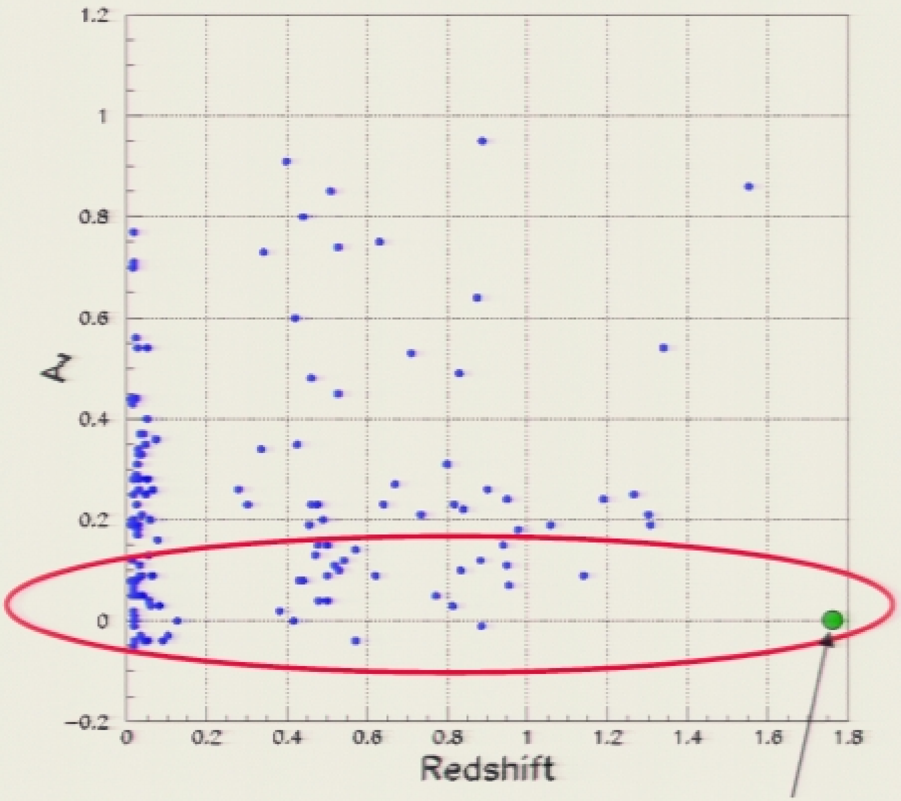


FIG. 4.—Same as Fig. 3 except for the UV portion of the mean R_V-dependent extinction law from eq. (4). The data at *U*, *B*, and *V* from Fig. 3 are also plotted. Again, the "error" bars in the lower inset represent the computed standard deviation of the data about the best fit of $A(\lambda)/A(V)$ vs. R_V^{-1} with $a(x) + b(x)/R_V$. The open symbols in the inset represent the difference between $A(\lambda)/A(V)$ from eq. (4) and the average curve of Seaton (1979) for $R_V = 3.2$. The only serious deviation occurs for $x > 7\ \mu m^{-1}$ (see text).

Extinction corrections

Riess et al 2004 (gold sample)



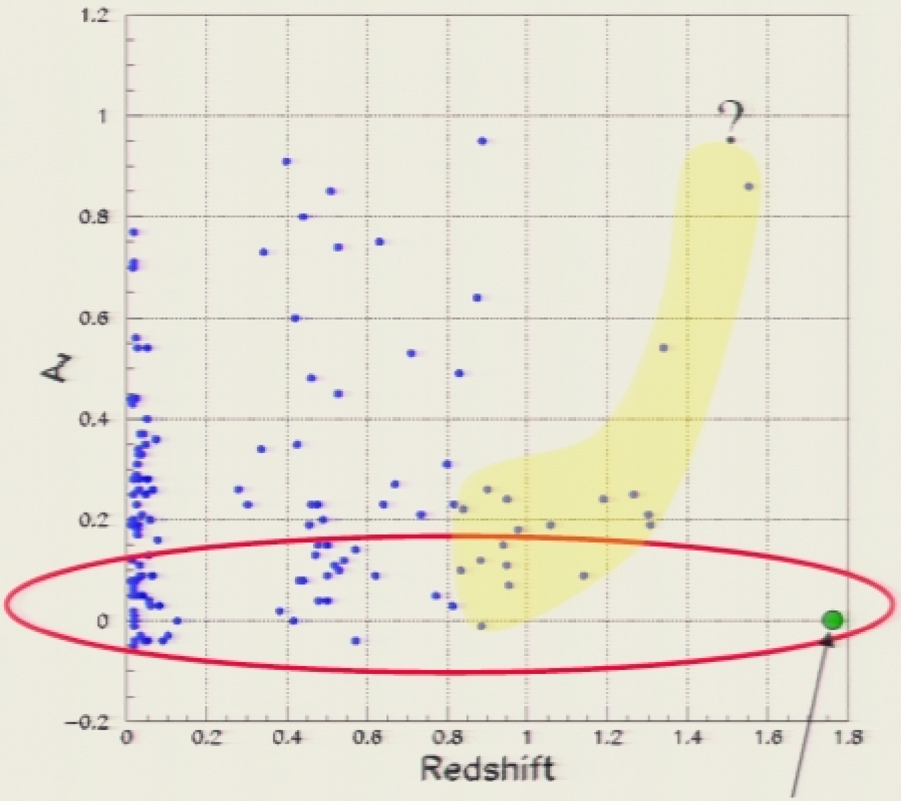
SN97ff: assumed extinction-free, E-host

- z-dependence in reported A_v ?
- Problems with K-corrections/assumed intrinsic colors in UV part of the SNIa spectrum?
- Changing dust properties ?
- Selection effects?
- Watch out for priors on A_V! Riess et al assume $P(A_v) \sim \exp(-A_v)$

Uncertainties ?

Extinction corrections

Riess et al 2004 (gold sample)



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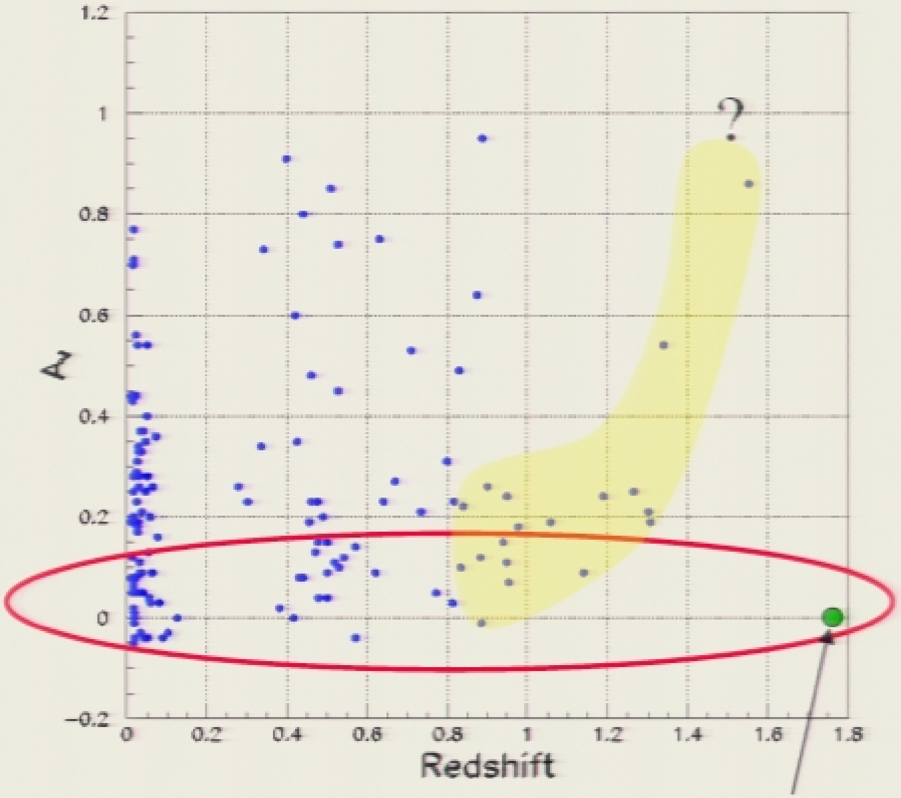
- Selection effects?
- Watch out for priors on A_V! Riess et al assume $P(A_v) \sim \exp(-A_v)$
- A careful study of extinction correction systematics for z>0.9 SNe [illegible] missing?

Uncertainties ?

Extinction corrections

Riess et al 2004 (gold sample)



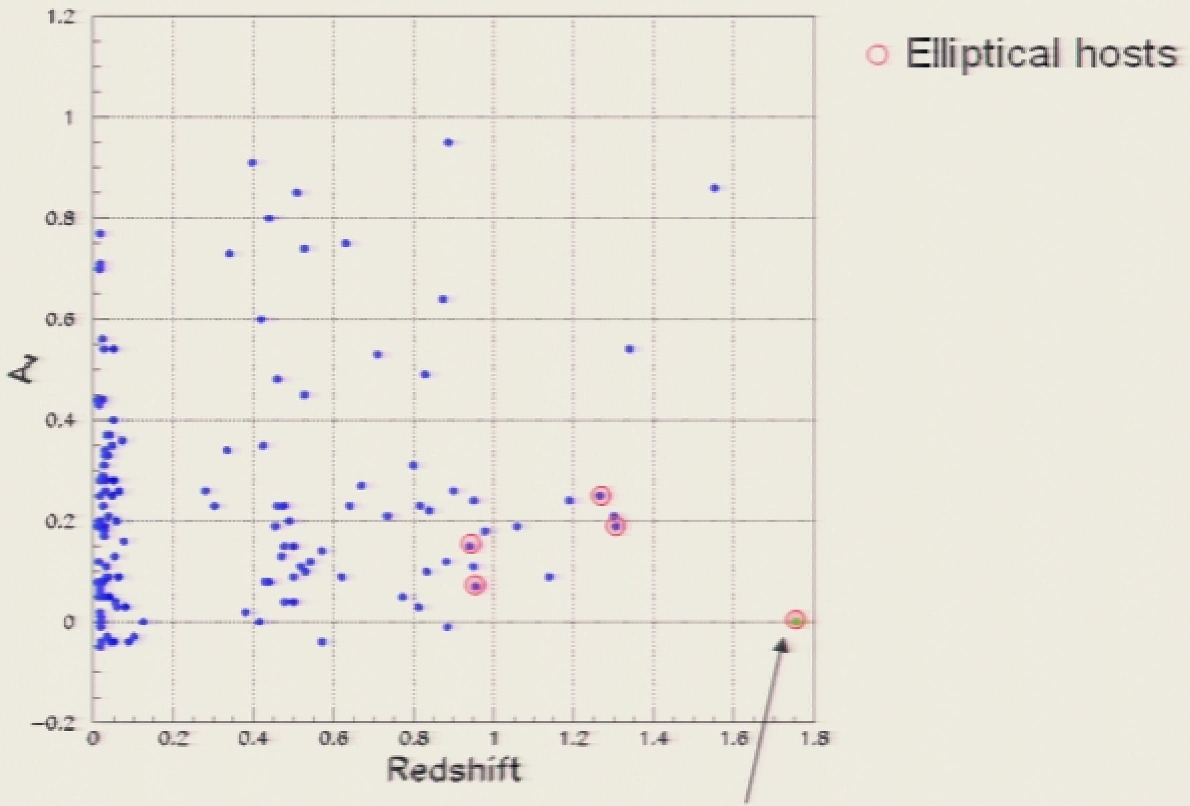
SN97ff:
assumed
extinction-
free, E-host

- z-dependence in reported A_v ?
- Problems with K-corrections/assumed intrinsic colors in UV part of the SNIa spectrum?
- Changing dust properties ?
- Selection effects?
- Watch out for priors on A_V! Riess et al assume $P(A_v) \sim \exp(-A_v)$
- A careful study of extinction correction systematics for z>0.9 SNe (as done in Knop et al for z<0.9) is still missing.

Uncertainties ?

Extinction corrections

Riess et al 2004 (gold sample)

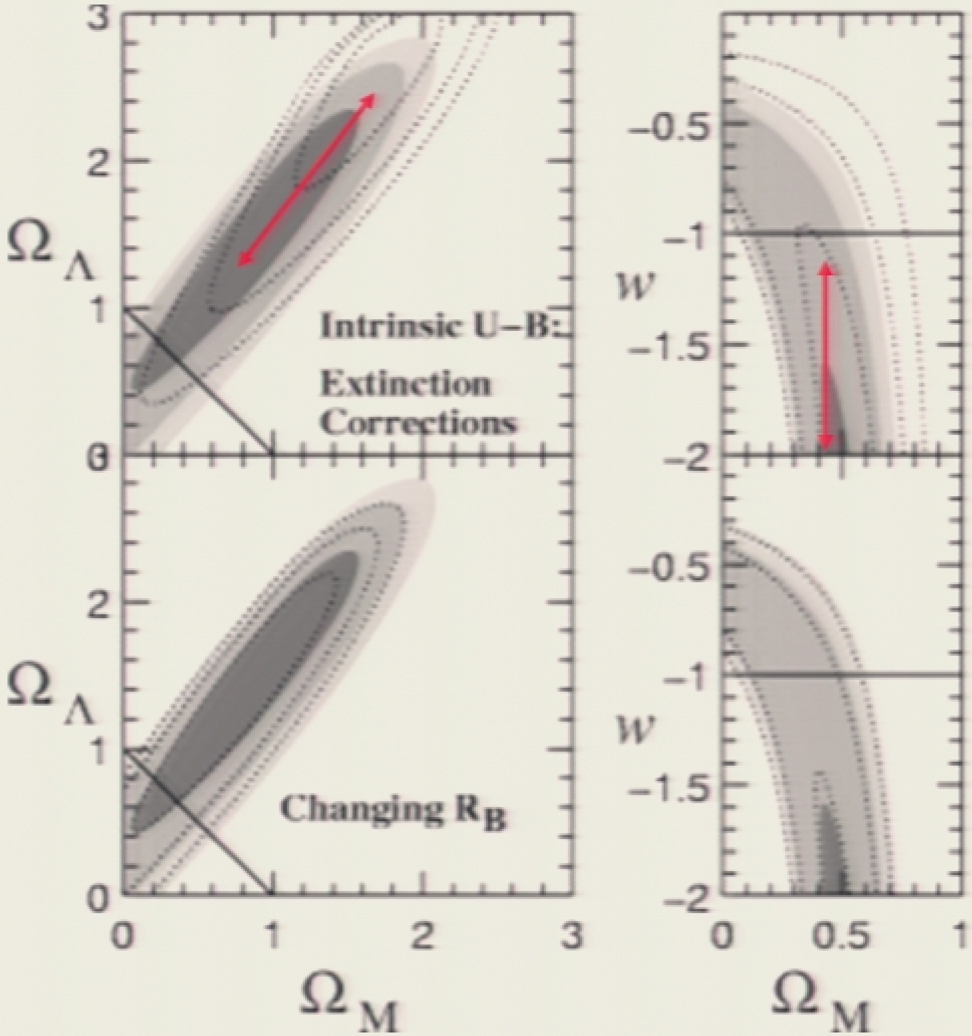


SN97ff:
assumed
extinction-
free, E-host

My fitted colors on ACS-gold SNe (i.e. no prior, "SCP-style"

Name	z	stretch	$E(B-V)^{Rv1.0}$	E(B-V)	E(U-B)	host
sn2002fw	1.30	0.949 ±0.038	0.030±0.075	-0.065±0.071	0.127 ±0.080	Late
sn2002hp	1.305	0.868 ± 0.028	0.101±0.113	0.008±0.099	0.235 ±0.136	Early
sn2002hr	0.526	1.199 ± 0.056	0.348 ±0.085	0.381 ±0.082	0.262±0.089	Late
sn2002kd	0.735	0.955 ± 0.015	0.264 ±0.054	0.048 ±0.051	0.461± 0.058	Late
sn2002ki	1.141	1.102 ± 0.130	0.375 ±0.138	*	0.319± 0.138	Late
sn2003ak	1.551	1.078 ± 0.003	0.308 ±0.080	0.309 ±0.076	0.261± 0.085	Late
sn2003az	1.27	1.066 ± 0.057	0.104 ±0.065	0.088 ±0.062	0.106± 0.070	Early
sn2003bd	0.67	0.957 ± 0.028	0.127±0.113	0.112 ±0.097	0.137± 0.142	Late
sn2003be	0.64	0.929 ± 0.023	0.012 ±0.114	0.053 ±0.095	-0.081± 0.152	Late
sn2003dy	1.34	1.093 ± 0.041	-0.033±0.090	*	-0.028 ± 0.090	Late
sn2003eb	0.899	1.002± 0.023	0.002±0.041	0.043 ± 0.037	-0.049± 0.045	Late
sn2003eq	0.839	0.987 ± 0.038	0.136 ±0.041	0.185 ±0.036	0.031± 0.050	Late
sn2003es	0.954	0.856 ± 0.040	-0.217±0.139	-0.342 ±0.135	-0.062± 0.144	Early
sn2003lv	0.935	0.865 ± 0.053	0.027±0.090	0.008 ±0.076	0.060± 0.113	Early

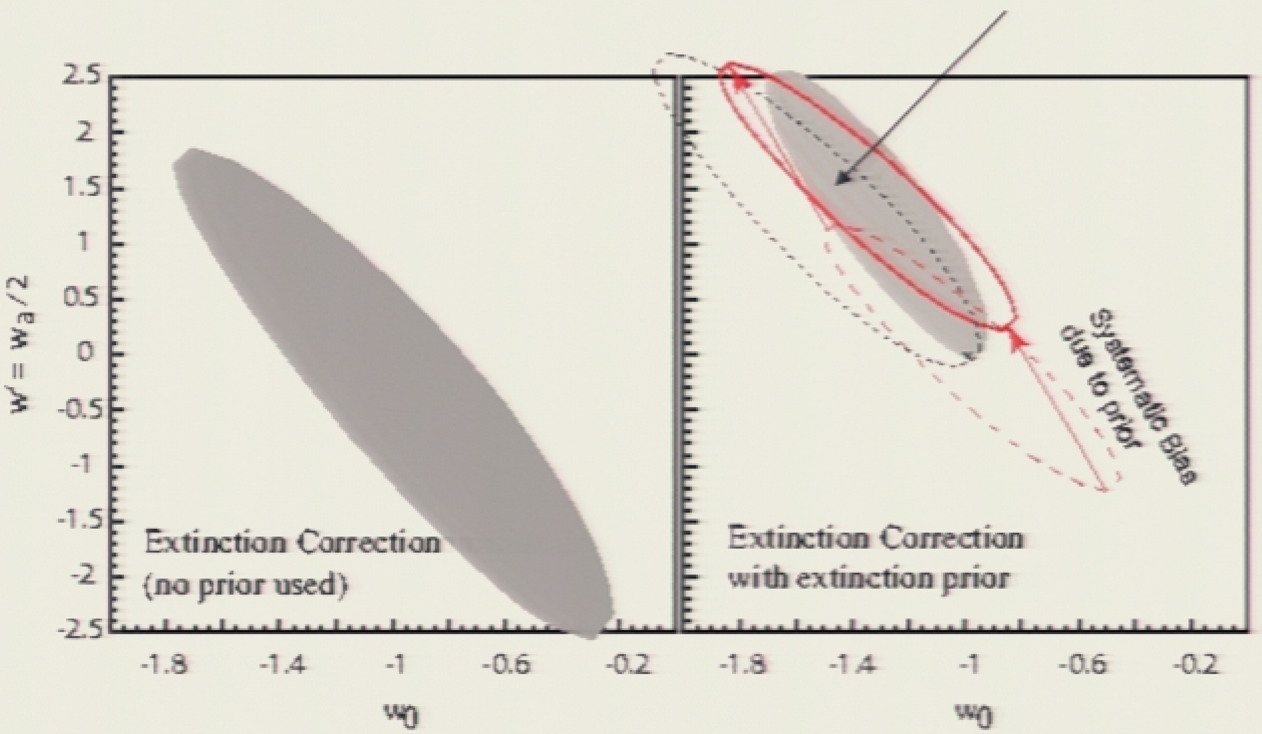
How the ellipses move due to extinction related uncertainties



Knop et al 03

Extinction corrections: simulated (-1,0) data-set vs ACS

(Grey) Riess et al 2004



Linder & Miquel

Extinction and dust properties

- **Extinction corrections of SNe brightness rely on:**

1. **Good color measurements**
2. **Good understanding of intrinsic colors and K-corrections**
3. **Assumptions on dust properties of host galaxies**

”Conventional” assumption, Galactic type dust: R_V=3.1 (not true for e.g. SALT/SNLS analysis)

❑ **However, measured colors of (mostly) low-z SNe suggest lower values, R_V~0-2** (R_B=R_V+1)

Jöeveer(1982) R_B=1.8; Tammann(1987) R_B=1;Cappaccioli et al (1990) R_B=1.7; Miller&Branch(1990) $R_{B=}$1.3±0.2;Branch&Tammann(1992) R_B=0.7±0.1; della Valle & Panagia(1992) R_B=3.35 ±0.25; Riess,Press&Kirshner(1996) R_B=3.55±0.3 ;Parodi et al(2000) R_B=2.46±0.46; Reindl et al (2005) R_B =3.65±0.16; Guy et al (2005) R_V=1.19±0.33

Extinction and dust properties

- Measured SN color variations may not only be related to host galaxy dust, but include an intrinsic color-brightness correlation (see e.g Tripp 1998), or be due to circumstellar dust (see e.g.Branch&Tammann 1992)
- Independent measurements of dust properties in other galaxies needed
- Redshift dependence on R_V?

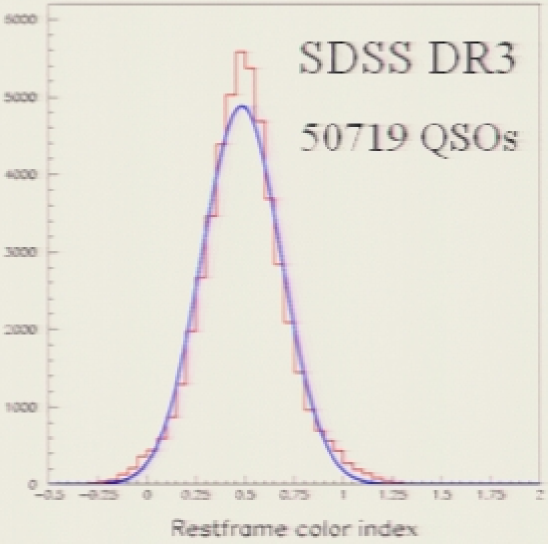
Dust properties: R_V

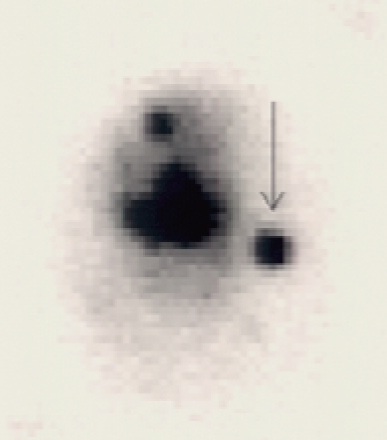
- Falco et al (1999) analysed (lensed) multiple images of QSO's and found $1.5<R_V<7.2$
- Critique:

1. Results robust if one of lines of sight are dust free, but not otherwise
2. Lensing picks heavy FG objects, i.e. hard to measure R_V on spiral galaxies
3. Lensing galaxies "half-way" to source, i.e hard to study dust on low-z galaxies
4. Time variability of QSO affects interpretation

- Together with L.Östman & E.Mörtsell have looked at QSO colors when galaxies along line of sight: *can QSO colors be used to study dust properties in foreground galaxies? (astro-ph/0509904)*
- Spectral template of QSOs from SDSS extended with HST to shorter wavelengths.
- Using it to K-correct SDSS QSO sample to restframe colors yields

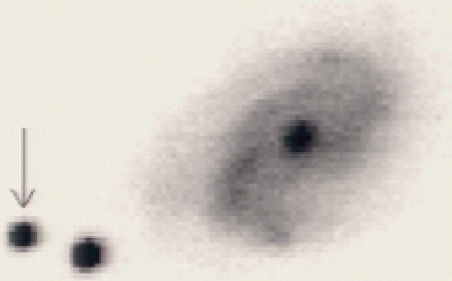
~0.2 mags intrinsic color

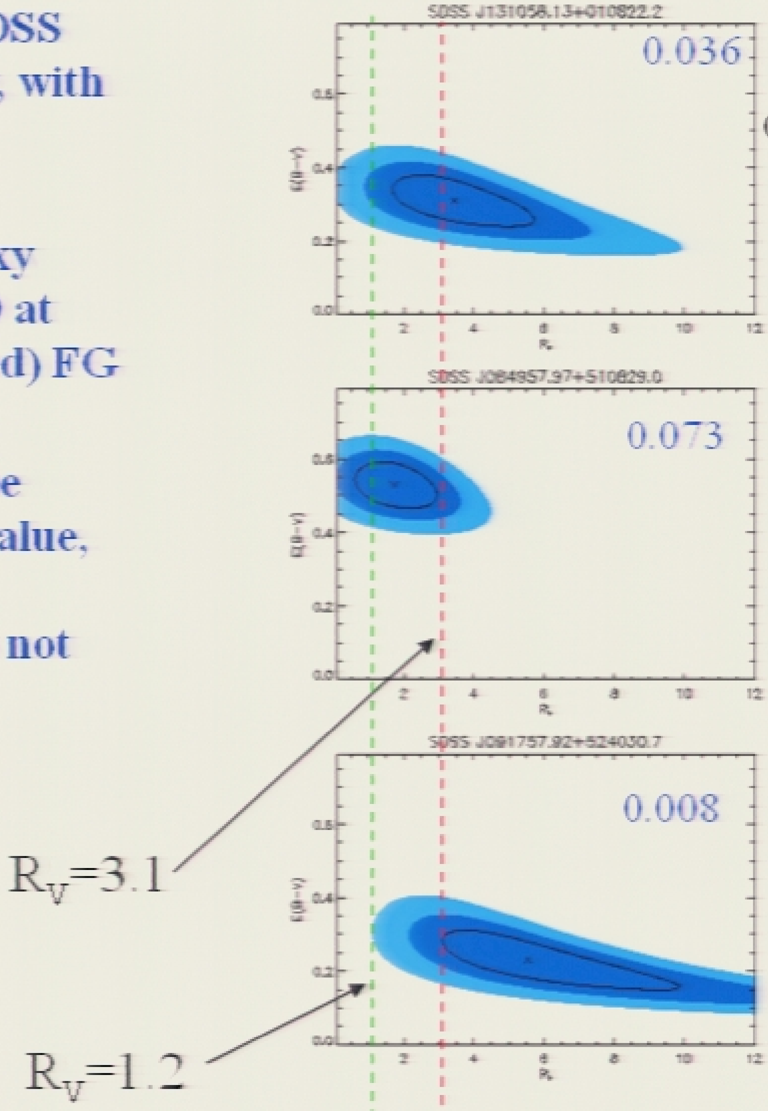




Looking at QSOs through galaxies

- **180 QSO-galaxy pairs found in SDSS +NYU value added galaxy catalog, with impact parameter < 30 kpc.**
- **χ^2 analysis performed on *ugriz* photometry comparing QSO-galaxy pairs with controll sample of QSO at same redshift but without (resolved) FG galaxy.**
- **<u>Three</u> systems, z_G<0.08, likely to be affected, R_v consistent with MW value, but uncertainties are large! Spectroscopic absorption features not seen.**



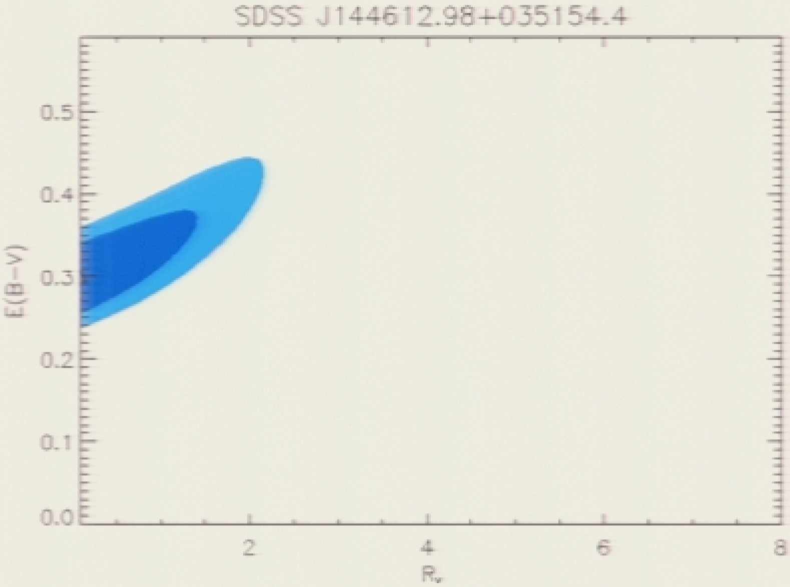


CCM extinction-law

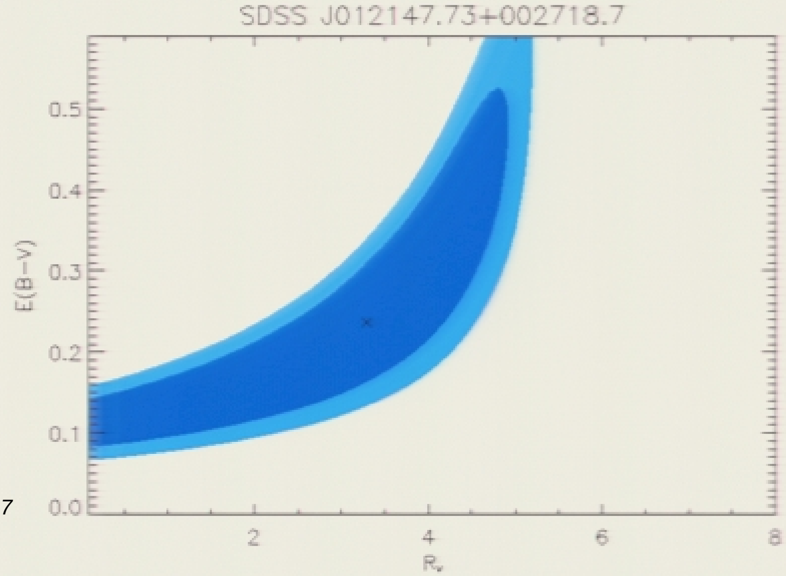
Fig. 3. Confidence levels for the three low-redshift galaxies corresponding to 1 σ (black line), 68 % (dark blue region) and 90 % (pale blue) as defined by the χ^2 test.

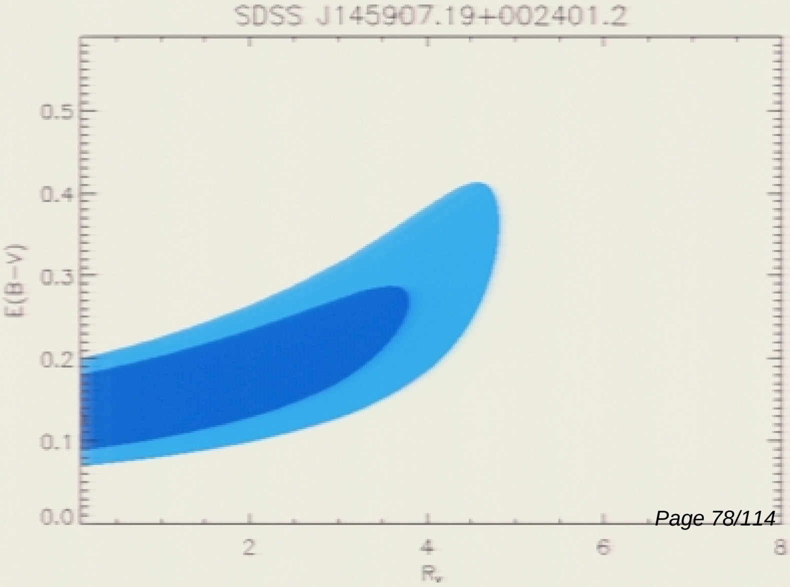
R_v for z~1.5 galaxies

- J.Wang et al (Apj 2004) found evidence for 2175 Å dust feature at z_G~1.5 (i.e. redshifted to the optical range) in QSO spectra at higher redshifts, consistent with absorption by intevening galaxy.
- Two of these systems give a best fit for very low, $R_v<2$, but uncertainties are large!

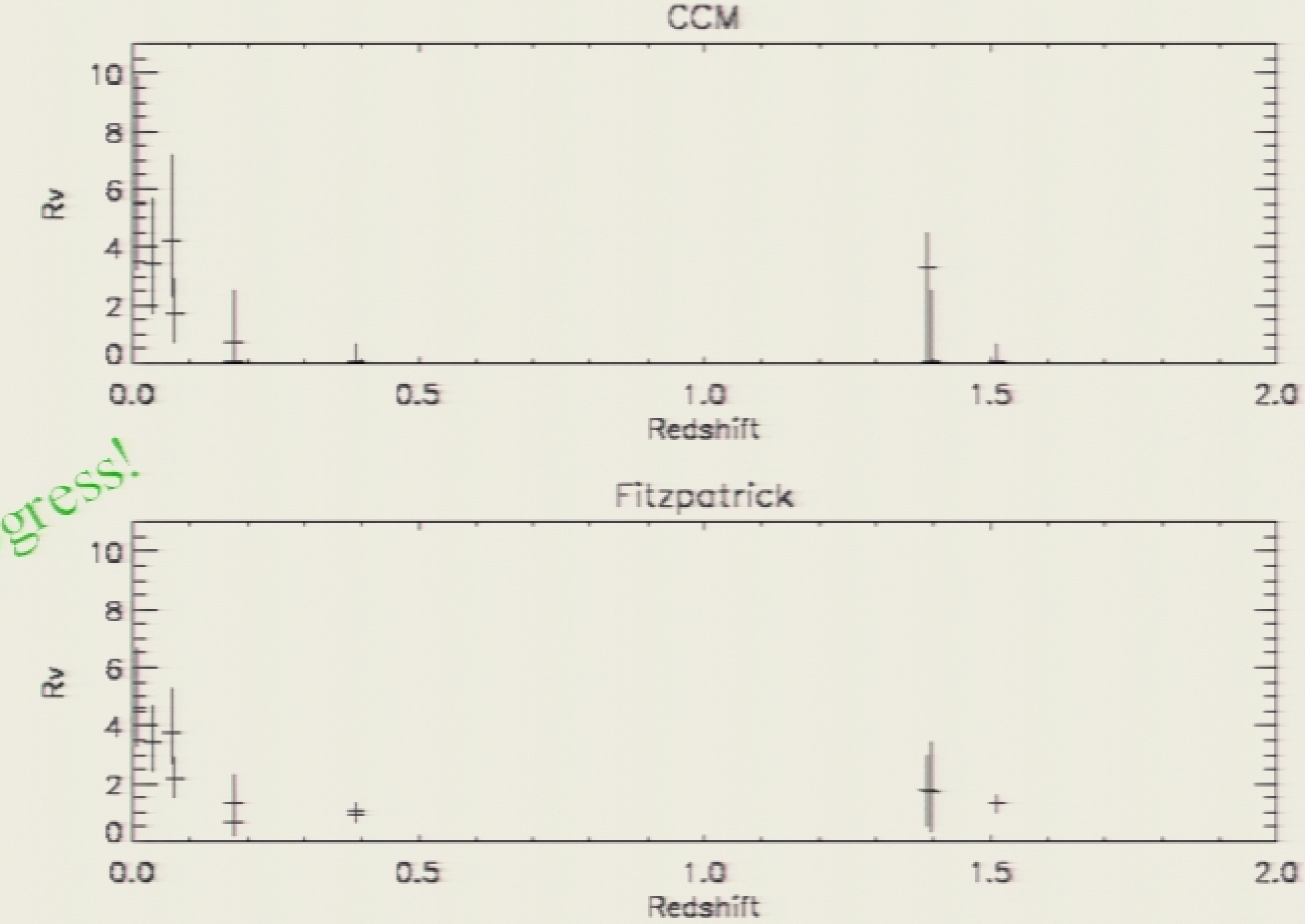

SDSS J144612.98+035154.4

CCM extinction law


SDSS J012147.73+002718.7

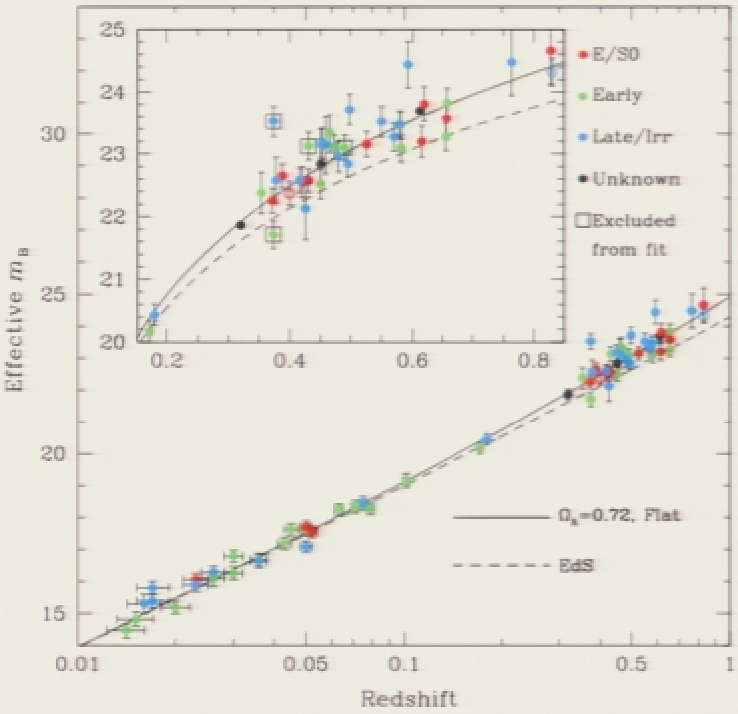

SDSS J145907.19+002401.2

Evidence for evolution of dust properties? Selection/systematic effects?

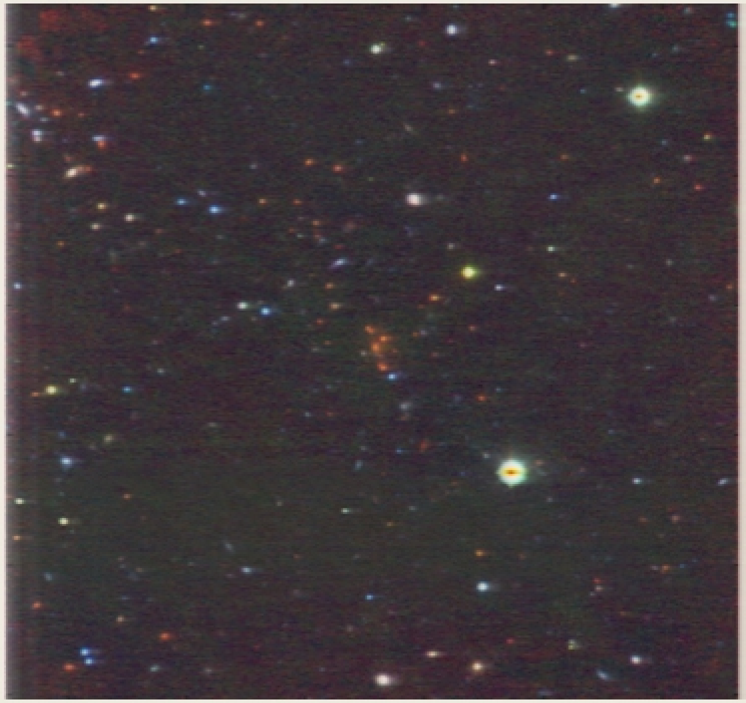


Work in progress!

”Dustfree and decelerated”



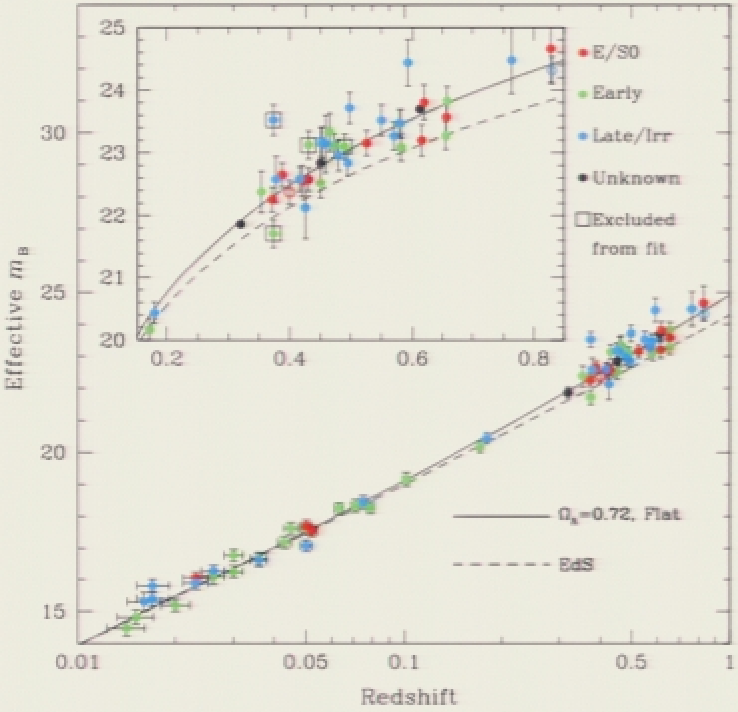
Sullivan et al 2003



Mullis et al

- 219 HST/ACS Orbits awarded (PI: Perlmutter) for rolling search for SNe on galaxy clusters 0.9<z<1.4. First references beginnig of july!
- Clusters are rich on elliptical galaxies which (at low-z) only host SNIa (no contamination) and extinction by dust should be minimal.
- Expect ~20 SNe z>1. Very sharp Hubble diagram expected. With little or no dust, each SN worth ~5 (or more?) in late type host.
- With some luck(!): use cluster as gravitational telescope to find SNe beyond cluster

"Dustfree and decelerated"



Sullivan et al 2003

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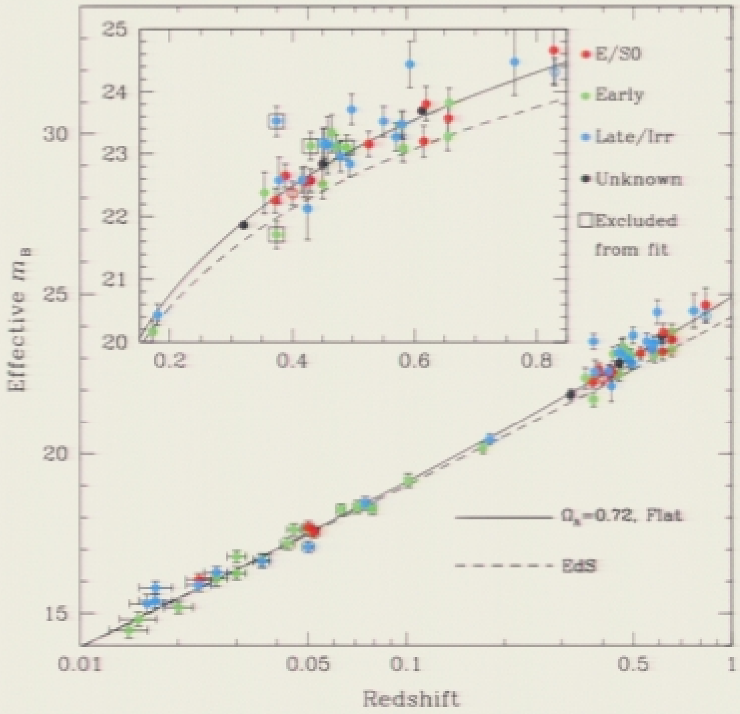
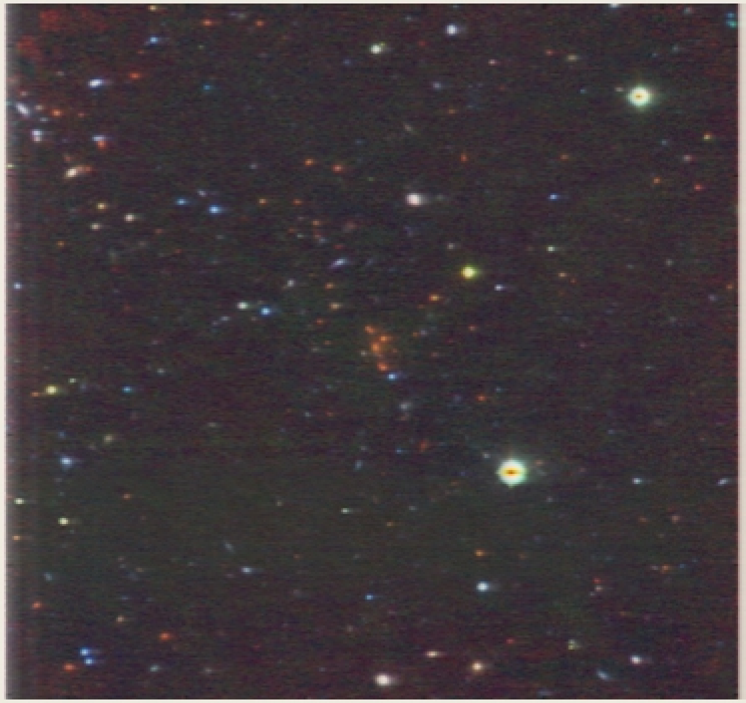


Sullivan et al 2003



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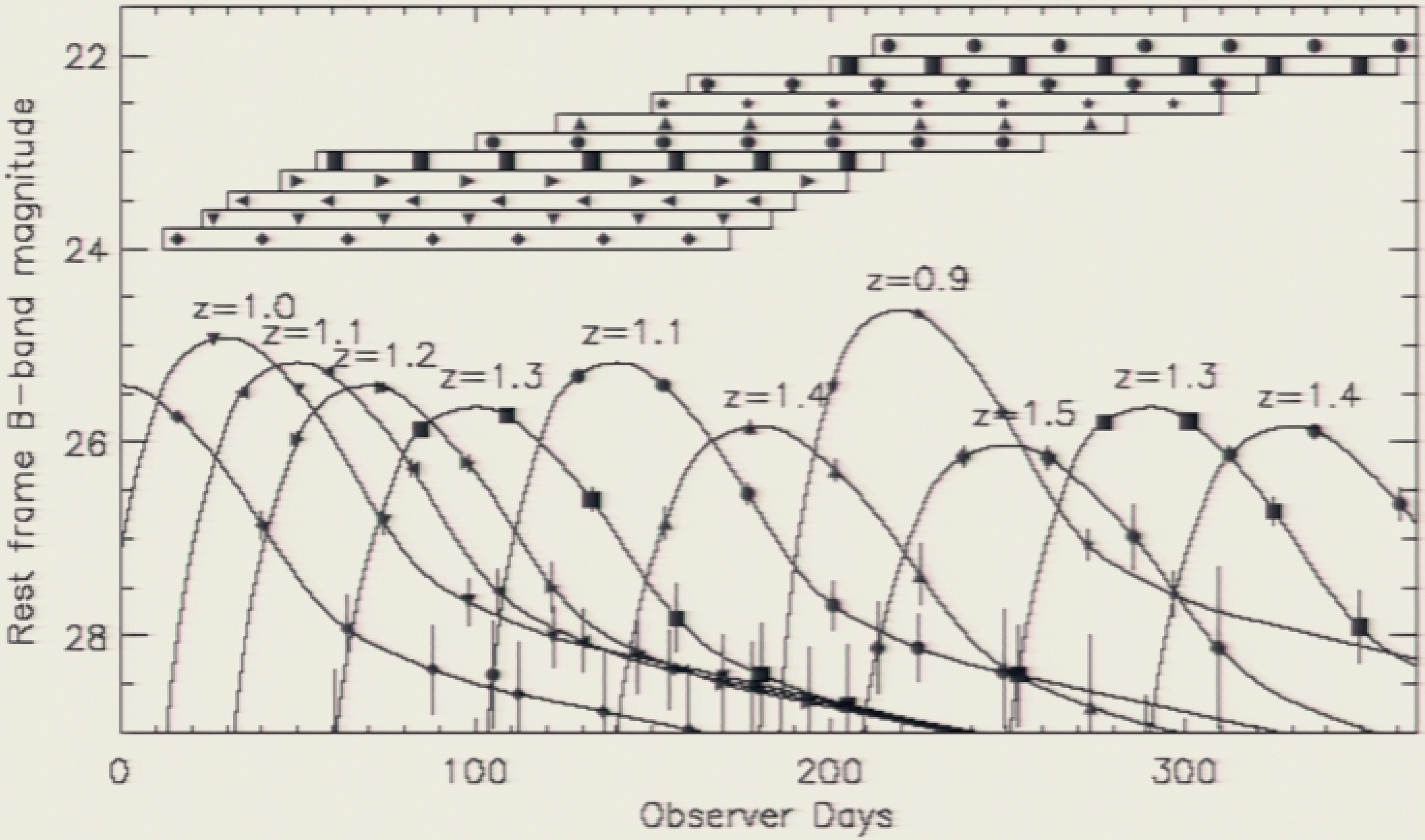
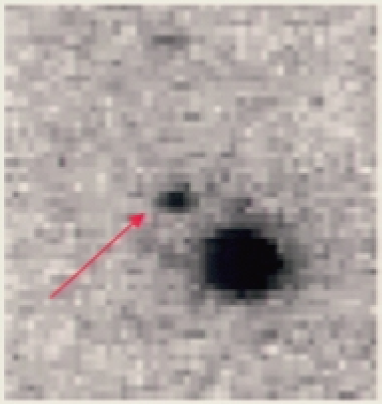
Predicted lightcurve quality



Frida, found in RCS0221-03

NEW/SUB



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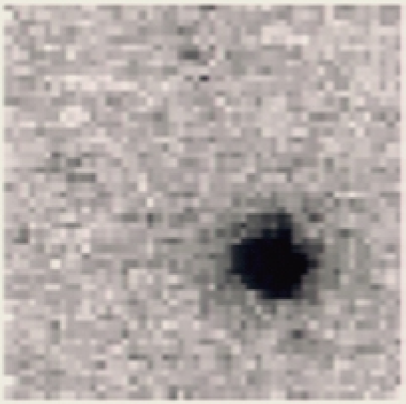
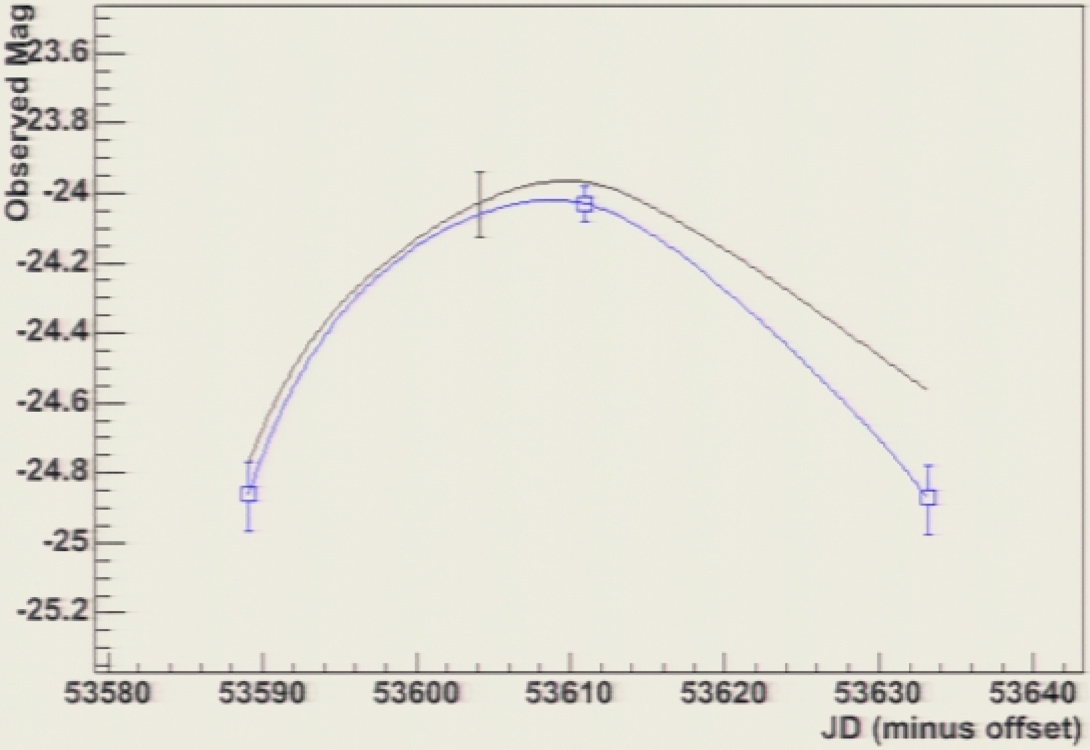
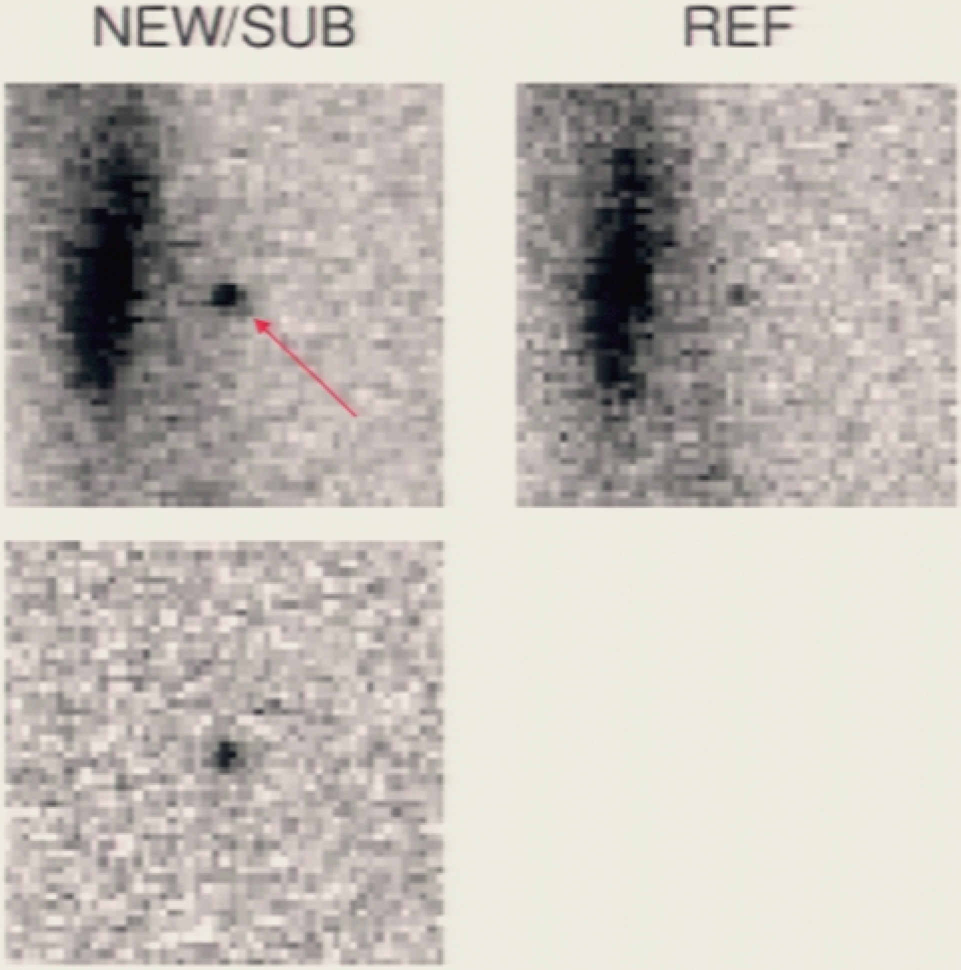


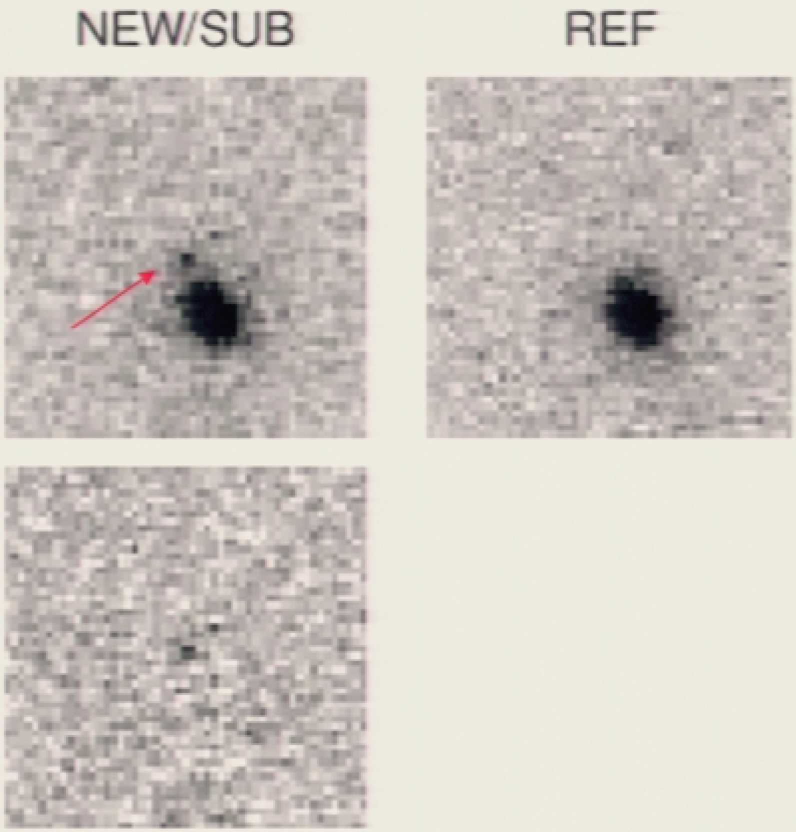


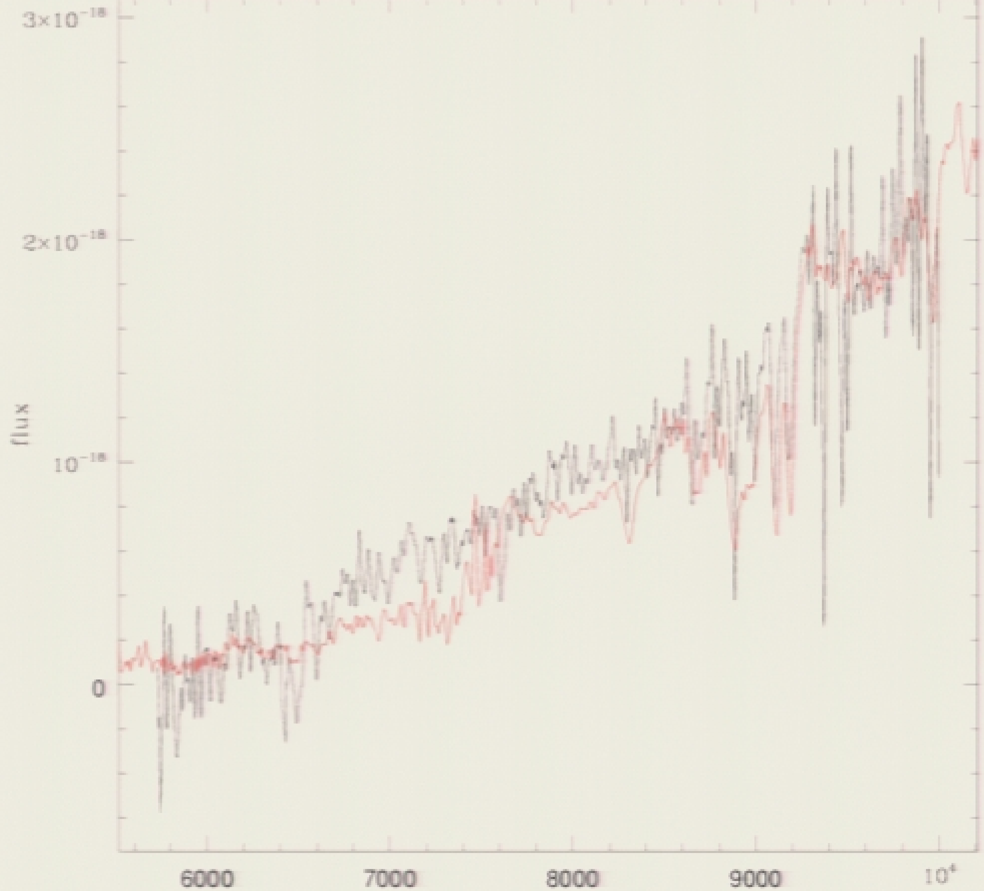
First cluster SN. We have three F850 epochs and one NICMOS F110W observation. VLT and Subaru spectral data → Host is elliptical at $z=1.02$



Foreground SN discovered in reference image. Four F850 epochs. Subaru spectral data → Host at $z=0.203$

Gabe, found in RCS0221-03





Most recent SN. ToO NICMOS observation. Subaru spectral data → Host is elliptical at $z=1.3$! i.e BEHIND cluster

Grey IG dust

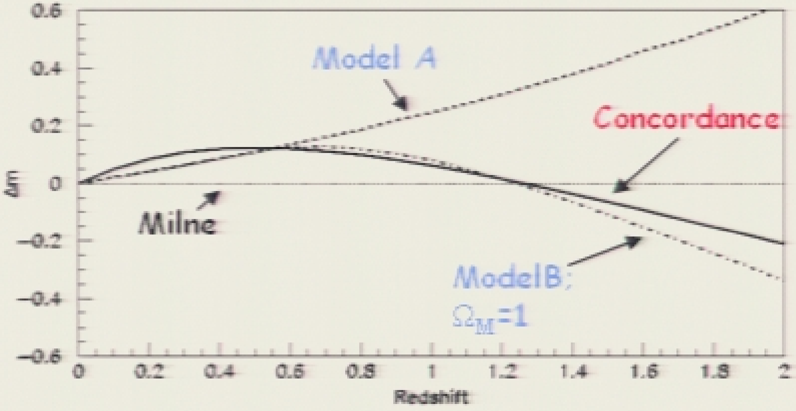
SNOC
SuperNova Observation Calculator

- Large dust grains (weak wavelength dependence) may exist in the IG-medium
- Evolution of dust density: two *limiting* cases:

1. $\rho_{dust} \alpha\ (1+z)^3$ [Model A]
2. $\rho_{dust} \alpha\ (1+z)^3$ for $z<0.5$ &
   $\rho_{dust}(z>0.5) = \rho_{dust}(z=0.5)$ [Model B]

- Hard to rule out from SN-colors (c.f Nobili et al, 2005)
- X-ray point-sources at very high-z, (e.g. Paerels et al) do not exclude e.g Model B

AG, Bergström & Mörtsell, A&A, 2002



Grey IG dust

SNOC
SuperNova Observation Calculator

- Large dust grains (weak wavelength dependence) may exist in the IG-medium
- Evolution of dust density: two *limiting* cases:

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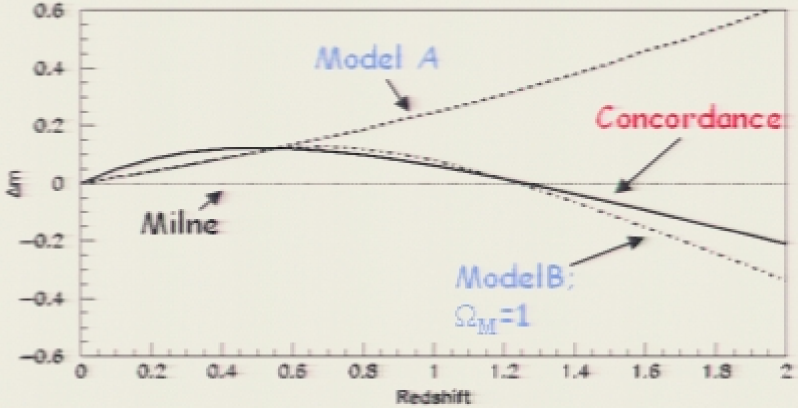
- SDSS QSO colors (>16000 objects, $z<2$) <0.1 mag extinction for SN1a at z=1; faintness of SNe cannot be *only* due to IG-dust

AG,Bergström & Mörtsell, A&A, 2002



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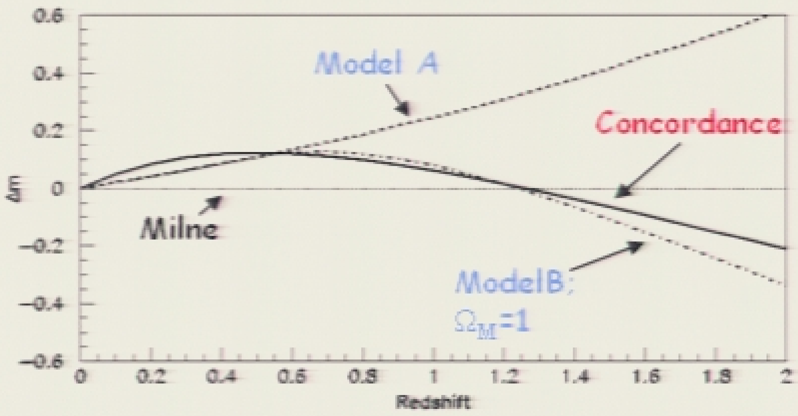
IG Dust cannot explain observed faintness of SNe - but is a serious concern for precision cosmology

AG,Bergström & Mörtsell, A&A, 2002



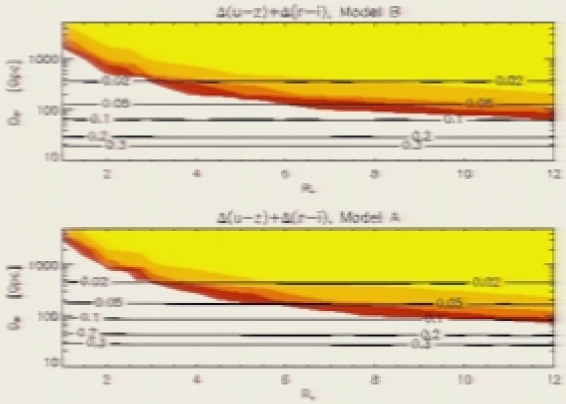


Figure 11. The confidence levels combining $\Delta(u-z)$ and $\Delta(r-i)$ for the two dust models and the attenuation of a SNIa at $z=1$. The palest region indicates the 68% confidence level allowed by the χ^2-test and the darker regions indicate 90%, 95%, and 99%. The almost horizontal lines show the B-band attenuation in magnitudes caused by dust for a SNIa at $z=1$.

Mörtsell & AG, 2003,

”Theoretical ” systematics

$\rho_{DE} = A_0 + A_1 x + A_2 x^2$, where $x = 1 + z$.

Hence, in a flat universe:

$$H(x) = H_0(\Omega_M x^3 + A_0 + A_1 x + A_2 x^2)^{\frac{1}{2}}.$$

$$1 = \Omega_M + A_0 + A_1 + A_2$$

$$w_{DE}(x) = \frac{(2x/3)d(\ln H)/dx - 1}{1 - (H_0/H)^2 \Omega_M x^3}.$$

$$\left\{ \begin{array}{l} \bullet\ w_{DE} = -1,\ A_1 = A_2 = 0 \\ \bullet\ w_{DE} = -\frac{1}{3},\ A_0 = A_1 = 0 \\ \bullet\ w_{DE} = -\frac{2}{3},\ A_0 = A_2 = 0 \end{array} \right.$$

- **Alam, Shani,Saini & Starobinski (2003) proposed fitting SN data with truncated Taylor expanasion for dark energy**

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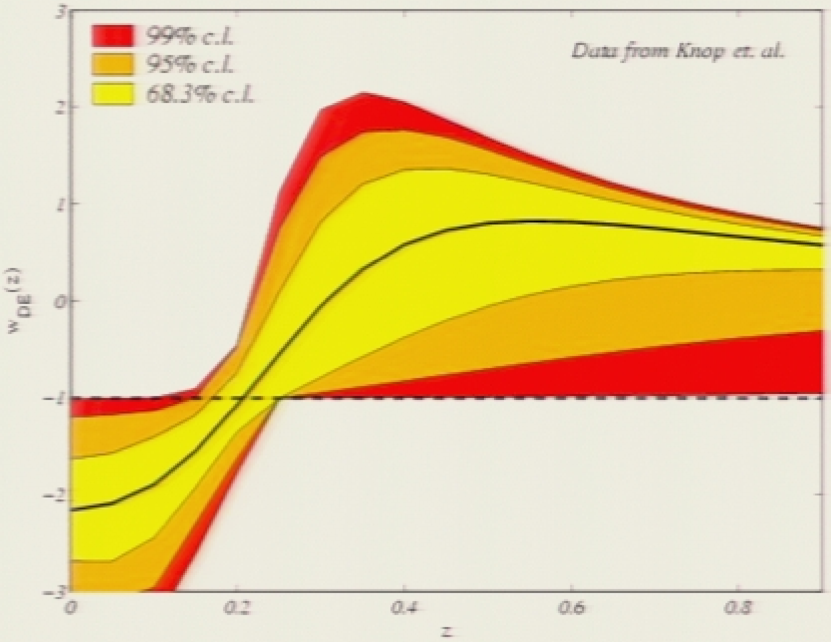
  - Claim: signs for *Metamorphosis*, crossing of the *phantom divide”*



"Theoretical " systematics

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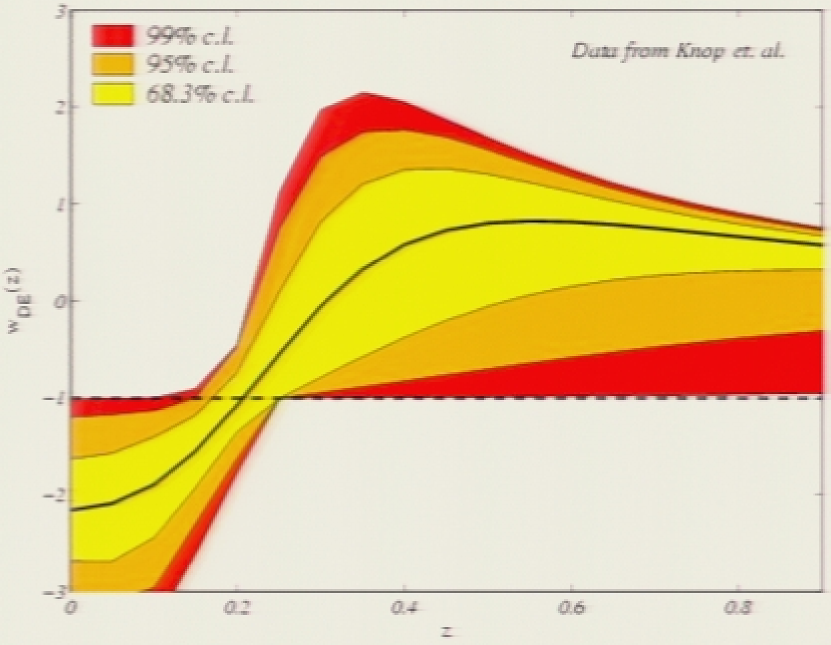
- **Alam, Shani,Saini & Starobinski (2003) proposed fitting SN data with truncated Taylor expanasion for dark energy**
- **Claim: signs for *Metamorphosis*, crossing of the *phantom divide"***

Seems like reasonable parametrization, however...

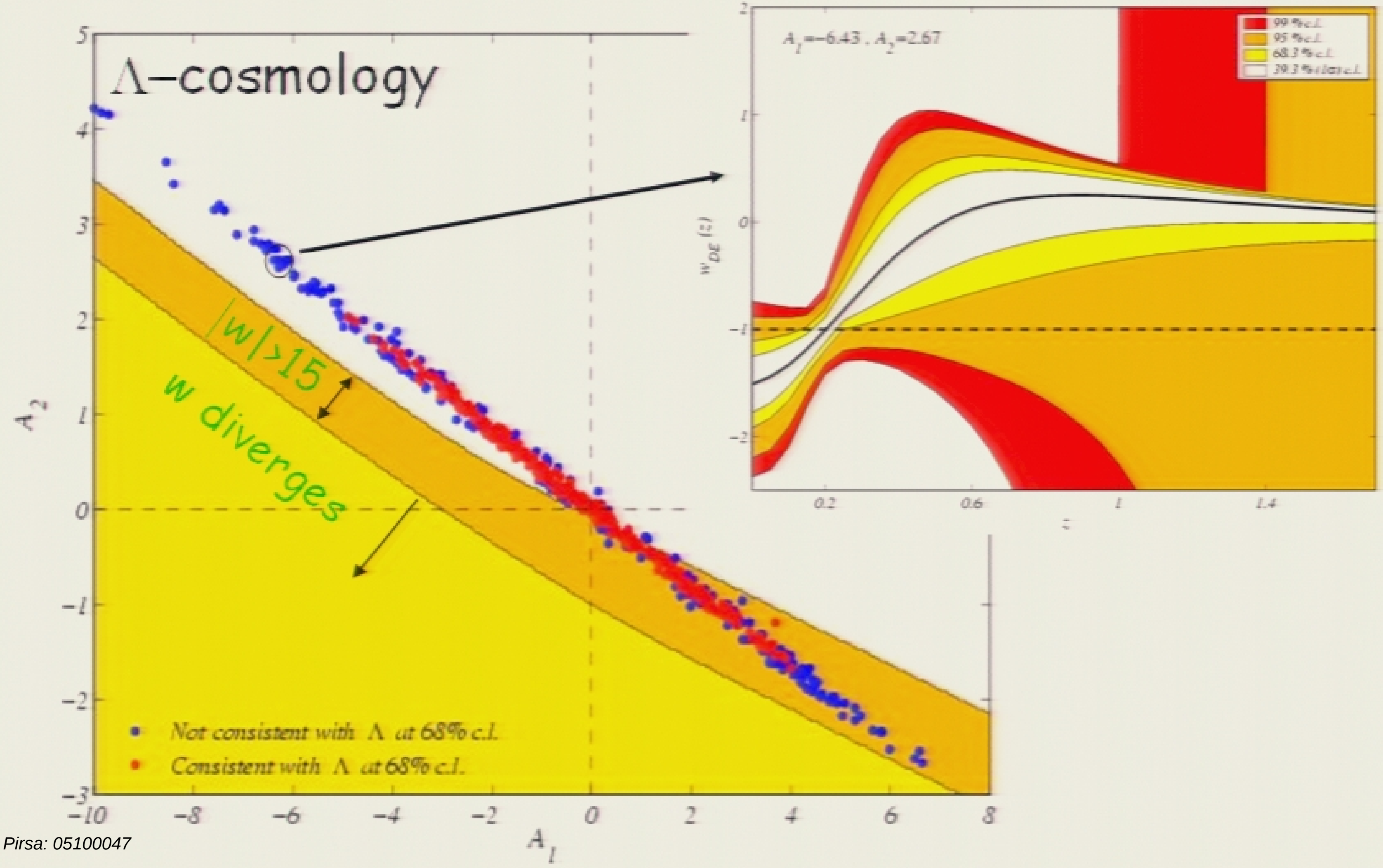
•Parts of parameter-space causes divergences
•As z increases, limiting value of $W_{DE} \neq -1$
•In fact, parametrization forces *Metamorphosis*



”Theoretical” systematics

SNOC
SuperNova Observation Calculator

Test: simulate + fit 500 experiments , z-distribution and uncertainties as in Tonry + Barris et al



Jönsson AG Amanullah Bergström 2004

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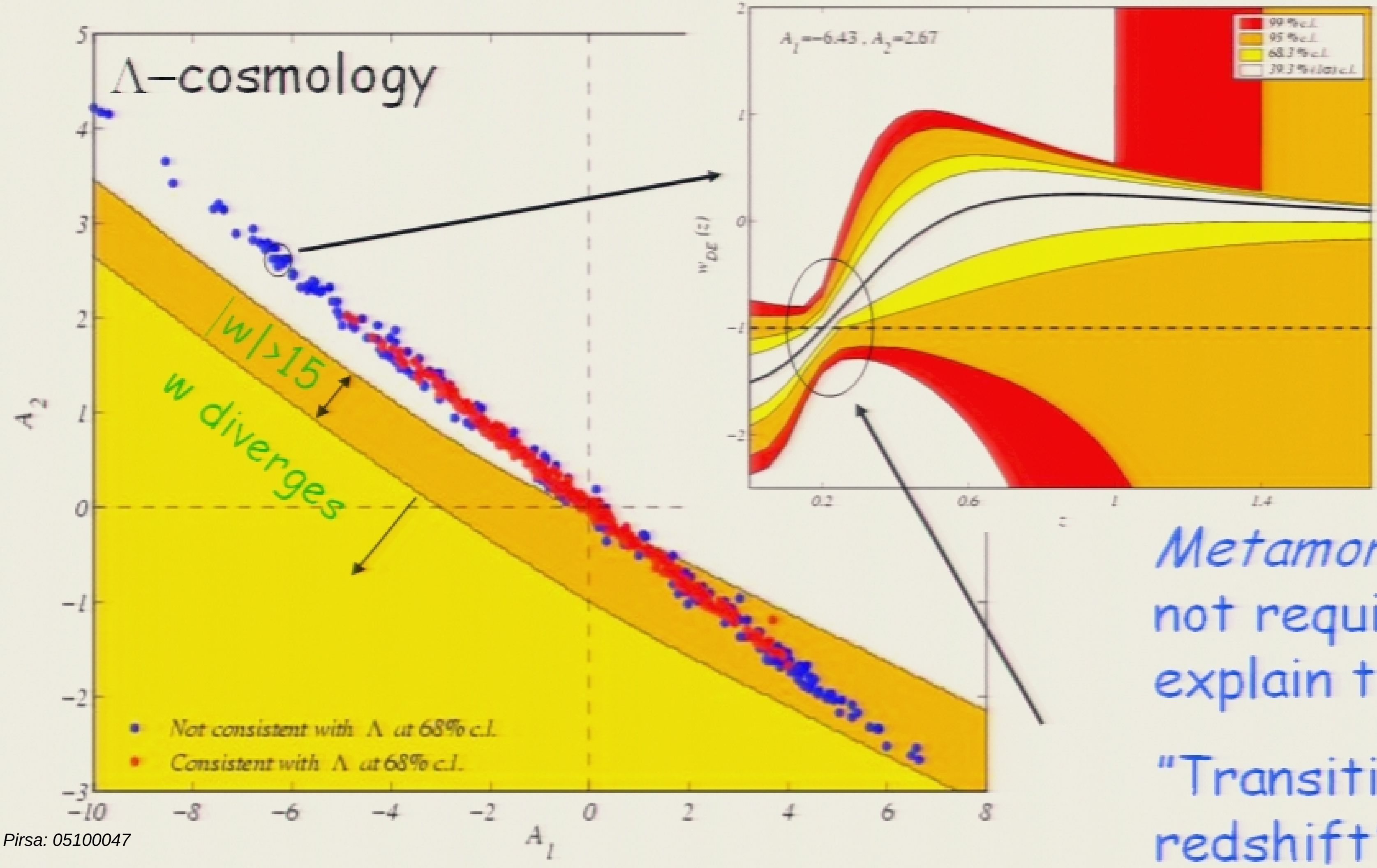

Metamorphosis not required to explain the fits!

"Transition redshift" set by prior on Ω

Jönsson, AG, Amanullah, Bergström, 2004

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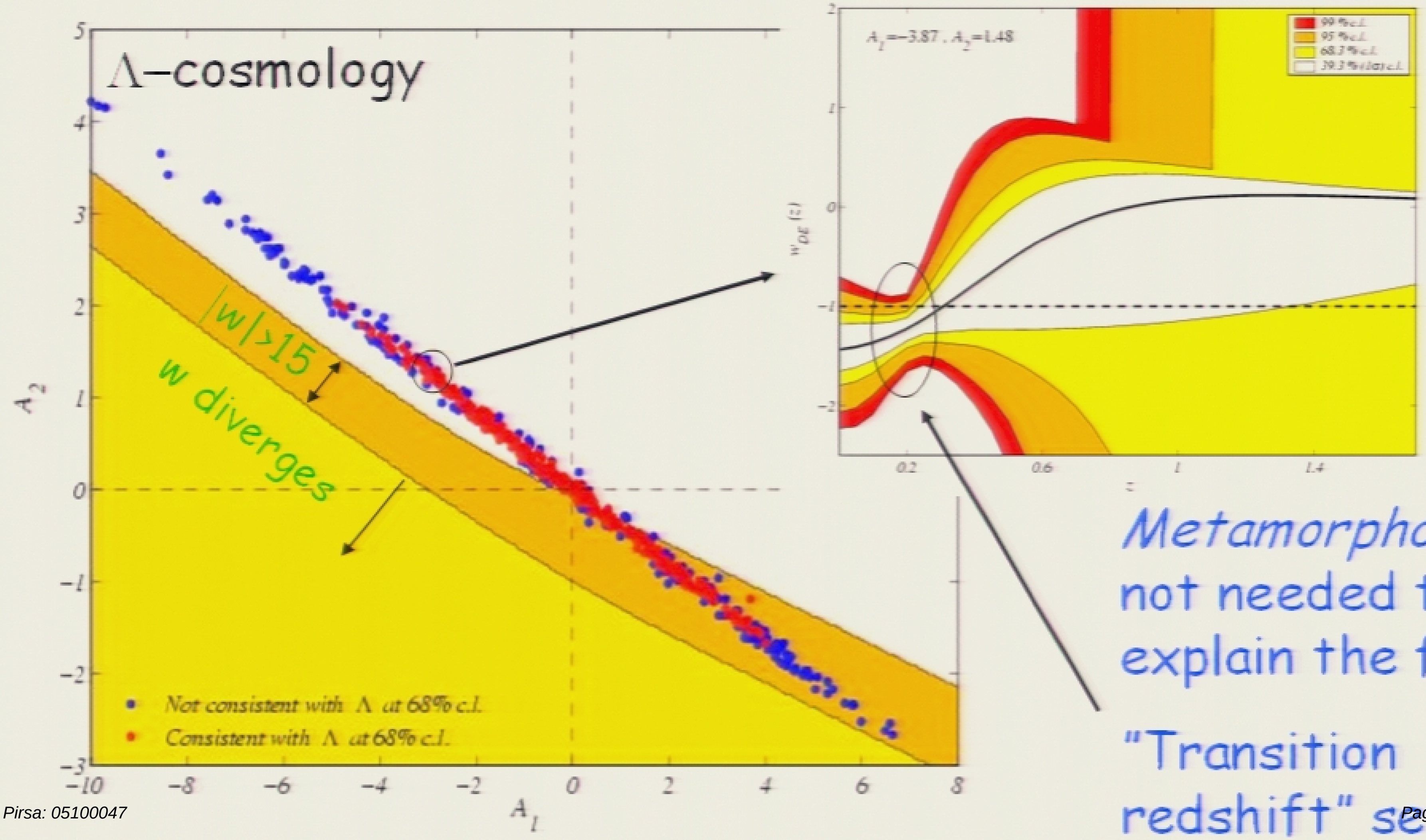

Metamorphosis not needed to explain the fits!

"Transition redshift" set by

Jönsson AG Amanullah Bergström astro-ph/0404468

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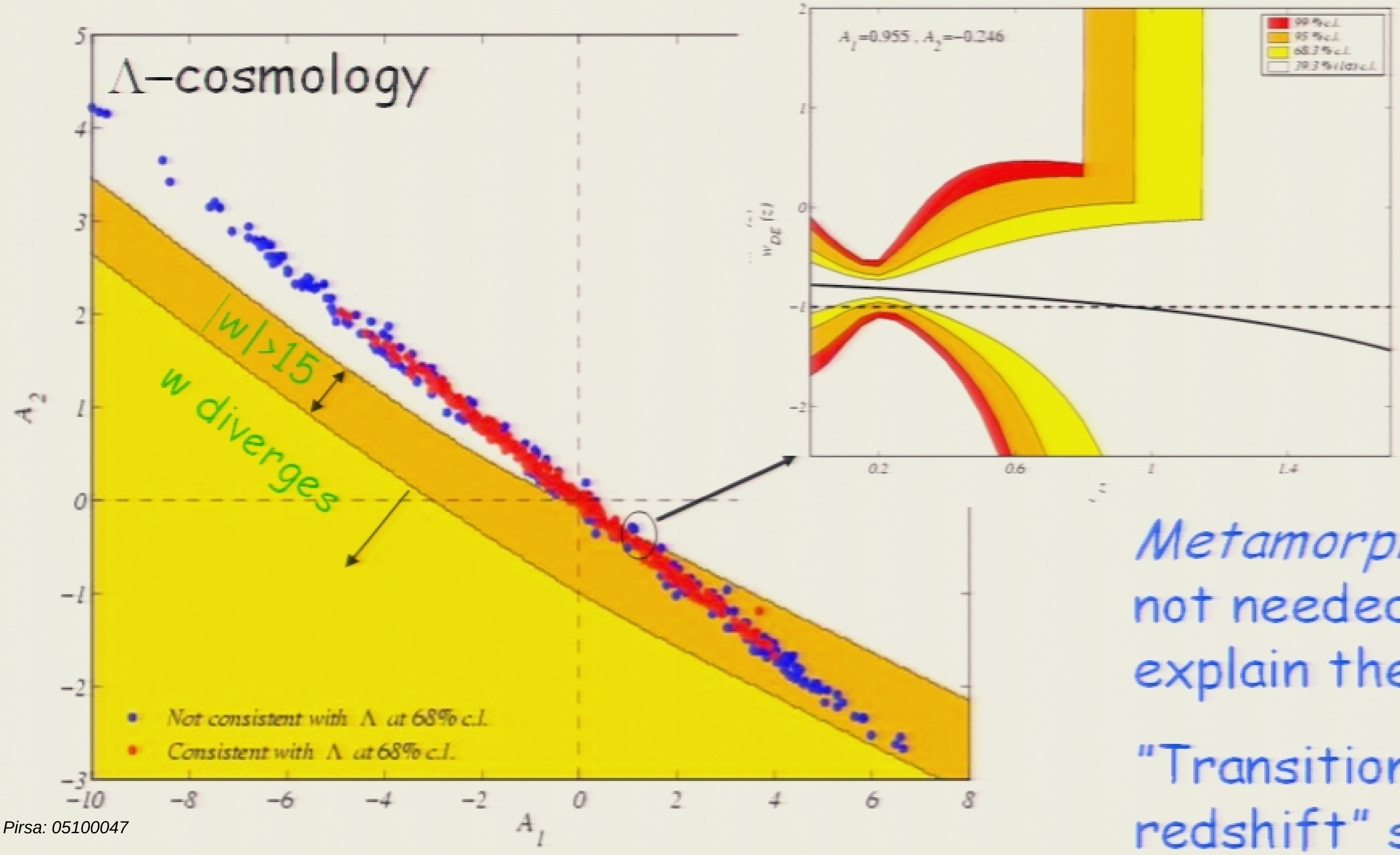


Metamorphosis not needed to explain the fits!

"Transition redshift" set by

Jönsson AG Amanullah Bergström astro-ph/0404468

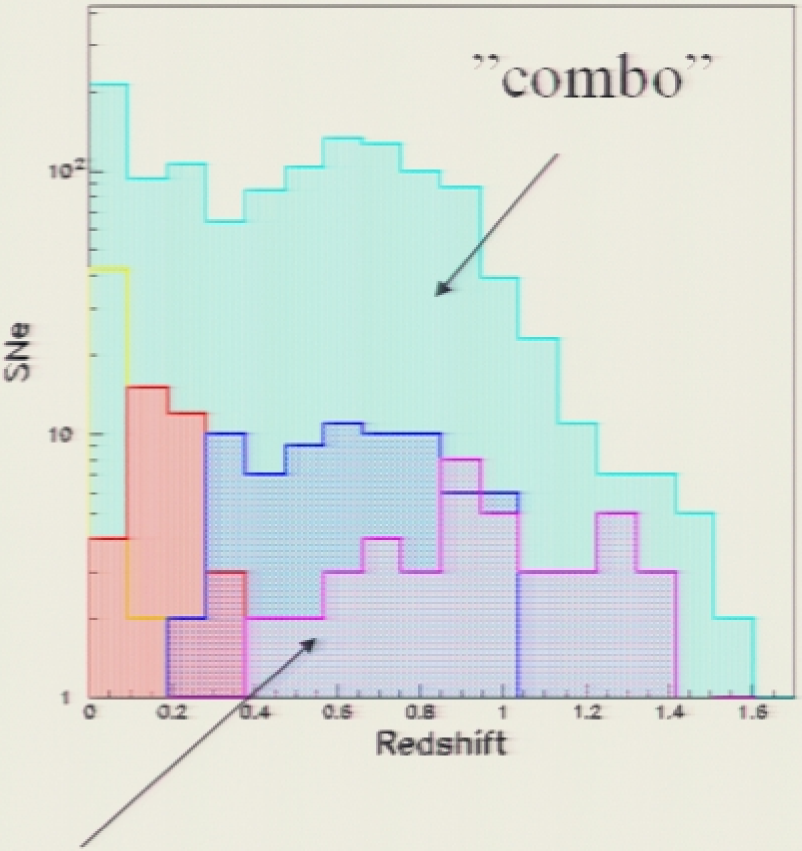
What improvement in understanding of dark energy can be expected in near future from SNIa?

What to expect from on-going efforts?

- Data-sets in the making:

SNLS	~	700 SNe (+ ESSENCE)
SDSS- II	~	200 SNe
low-z	~	100 SNe
very high-z	~	100 SNe
Total		1200 SNe

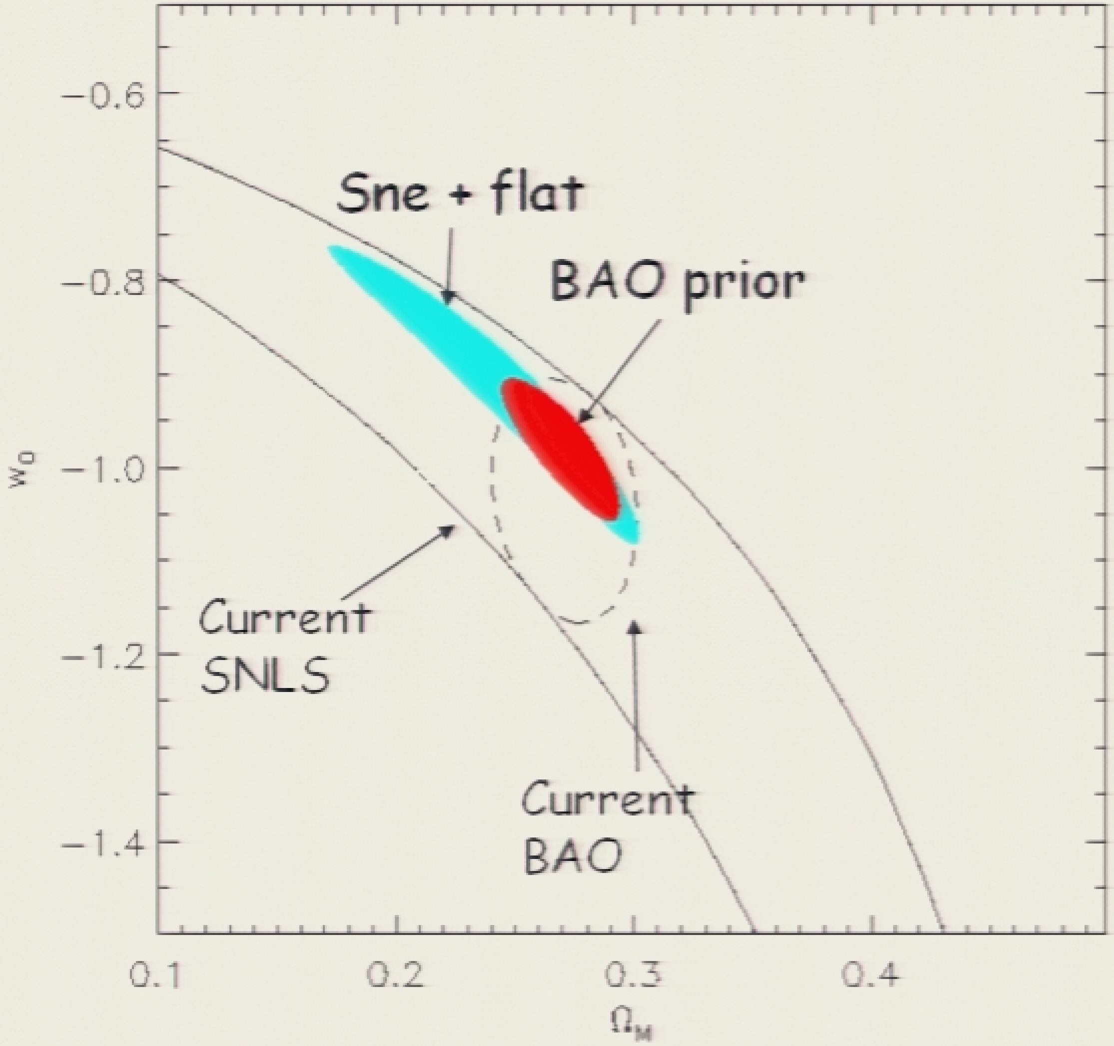
- Simulate a "combo" data-set using the same z-distributions as today, just scale up numbers
- Neglect systematics – to begin with!



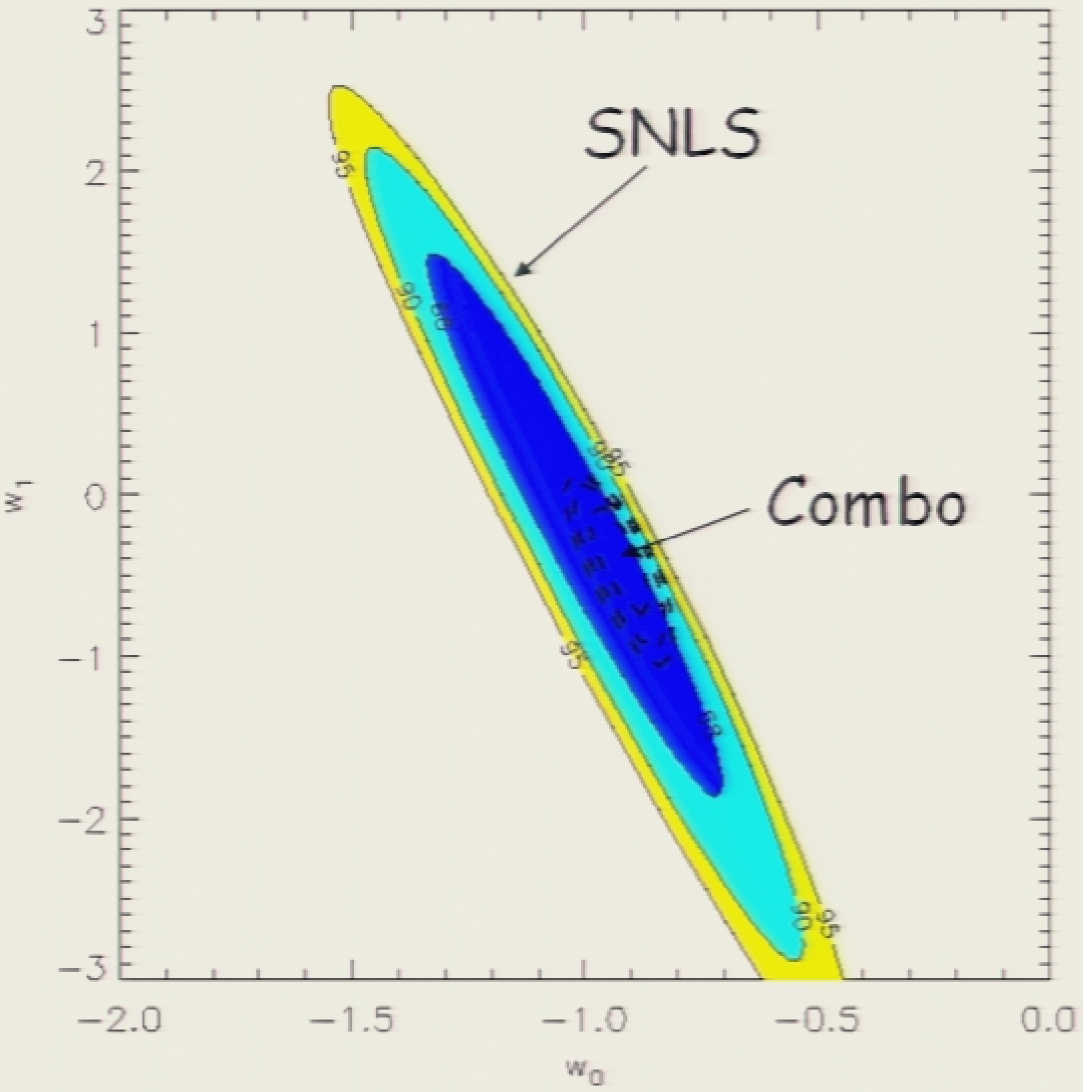
"combo"

today

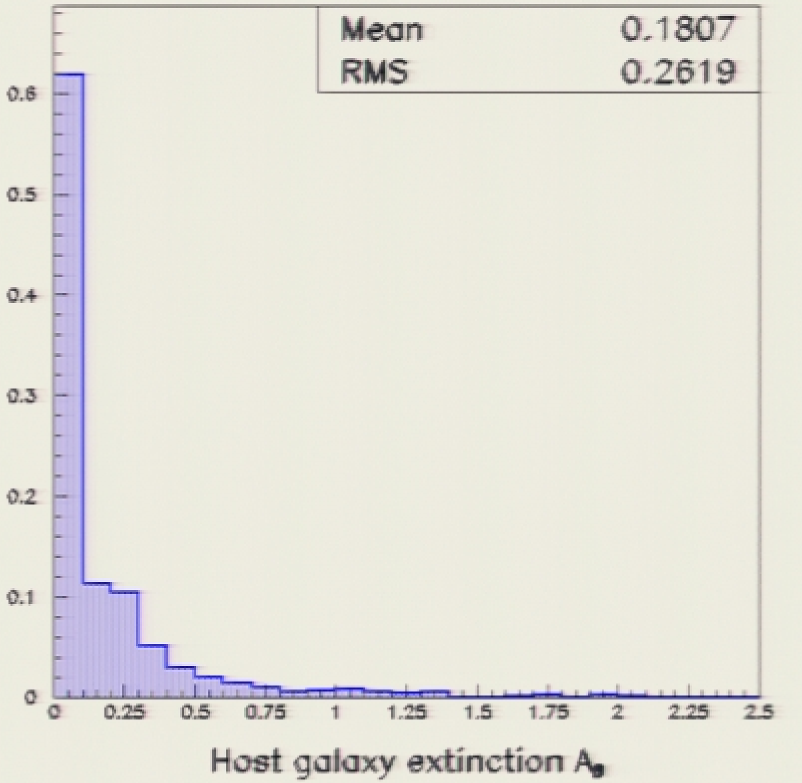
”Combo” MC data-set: w/o systematics

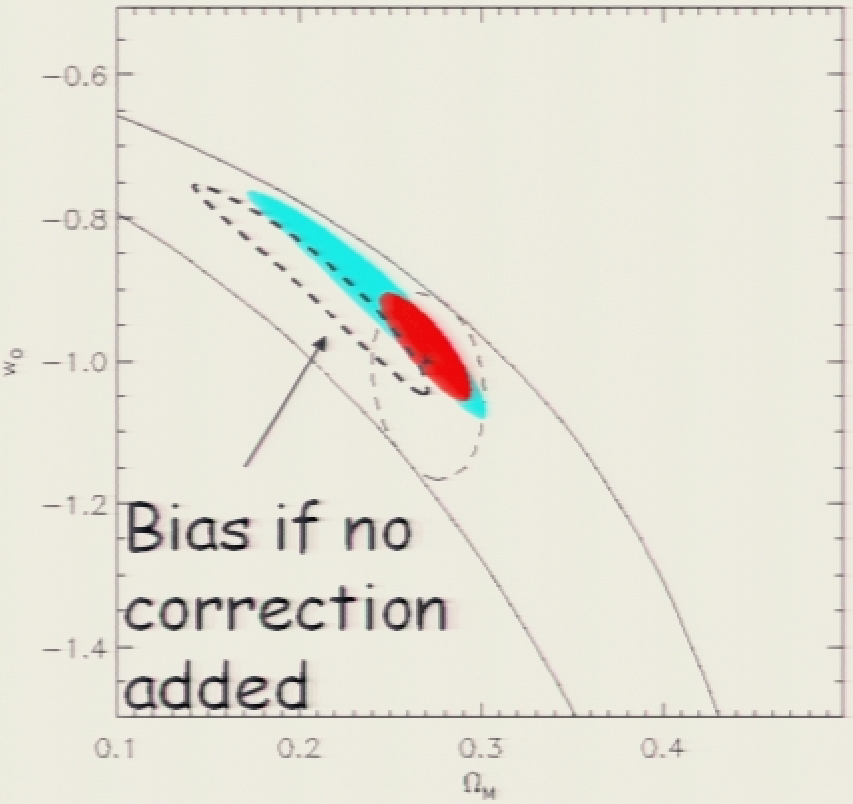


"Combo" MC data-set: w/o systematics



Host galaxy extinction systematics





Bias if no correction added

”Wish-list” for future SN projects

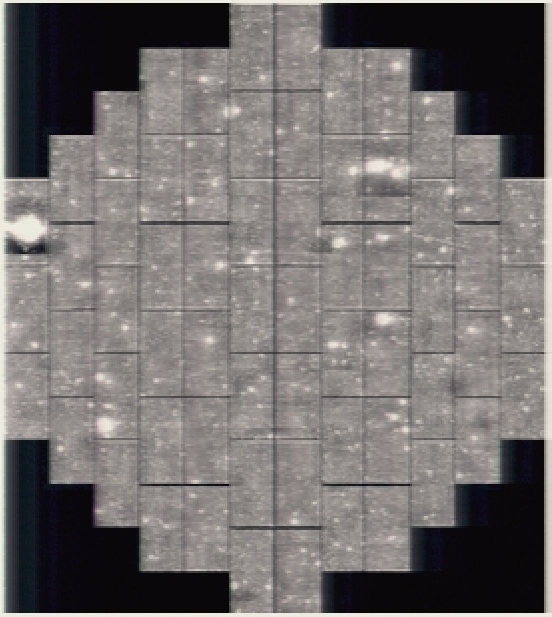
- Large statistics – also to constrain systematics: compare ”like to like”
- Ideally, build entire Hubble diagram with e.g. only SNe on ellipticals (less dust)
- Multi-wavelength coverage (UV-NIR):
  1) cover wider range of redshift
  2) fit extinction law in host and line-of- sight
  3) Find optimal match – minize K-correction uncertainty
  4) Accurate photometric redshifts

- Spectroscopic capability: hope to find a second parameter that sharpens the ”standarizable” candle, or else it seems unfeasible to reach below $\sigma_{w_1} < 0.2$ with current techniques.
- Instrument should allow a varity of complementary techniques: weak-lensing, baryon oscillations, cluster counting, strong lensing, other candles like Type II Sne, GRBs(?), etc.

Projects for the next 5-10 years?

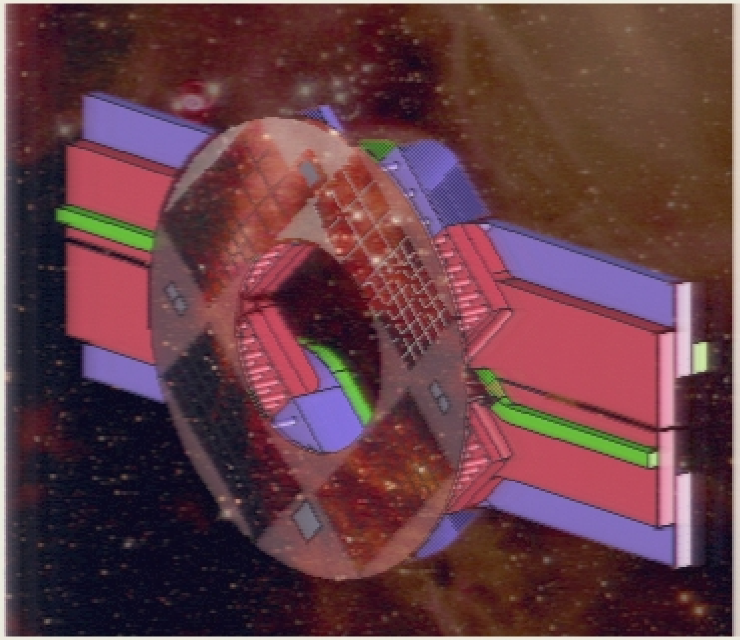
- Pan-STARRS, four 1-8-m telescopes, each with a 3 degrees FOV. First unit in 2006 in Haleakala on Maui (Hawaii)

- Dark Energy Camera: a new 2.2 deg. FOV optical CCD camera on the 4-m telescope at CTIO, Chile. Instrument R&D and Construction 2005-2009. Survey 2009-2014(?)

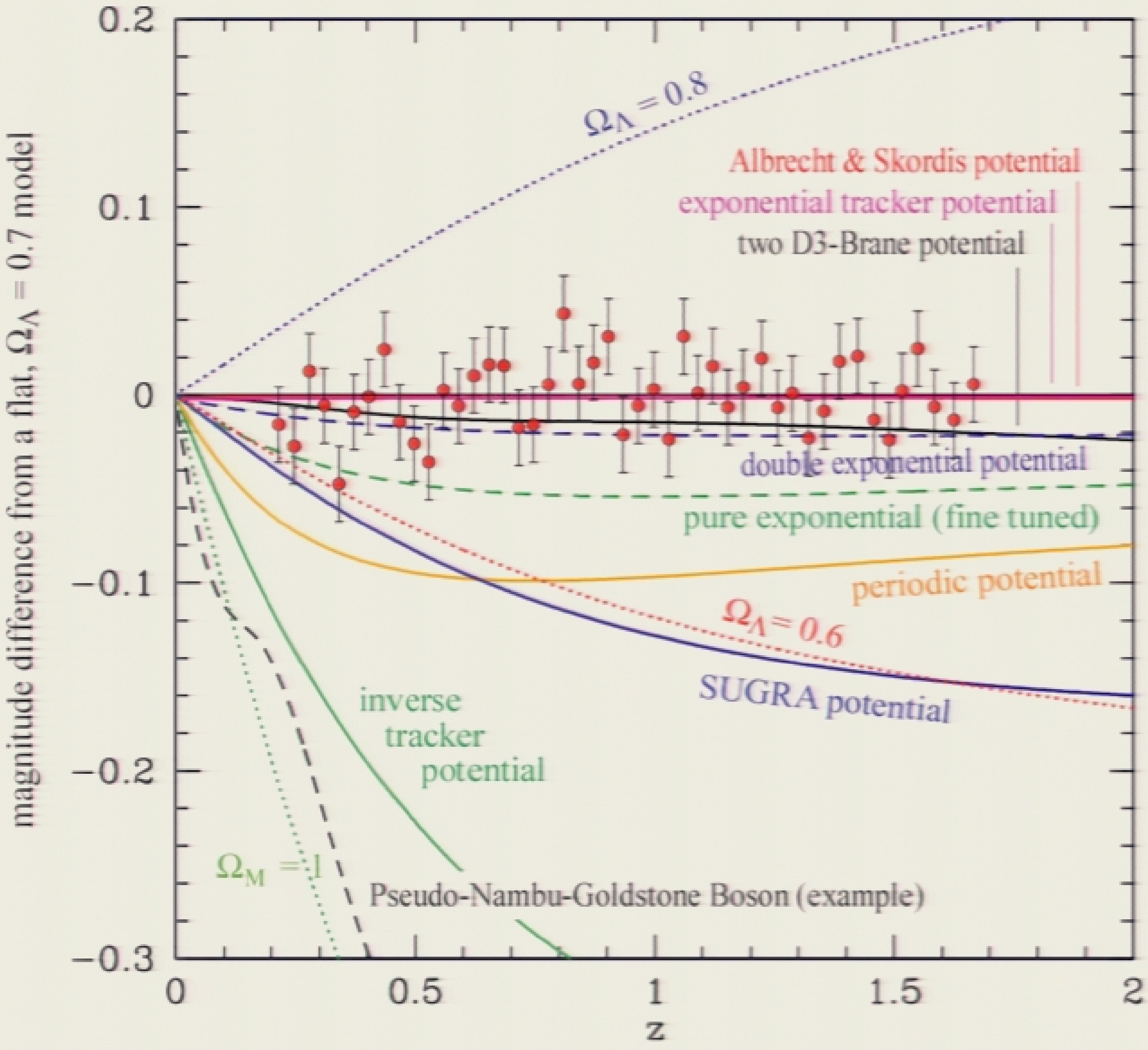


”Big” Future Projects

- LSST: 8-meter class telescope with 10 sq.degrees FOV
- JDEM: satellite mission:~2-meter class telescope reaching NIR. Either optical+NIR imaging + spectrosocopy (SNAP) or NIR optical+spectrsocopy (JEDI) NIR grism (DESTINY)
- It’s all about minimizing the systematics and (hopefully!) sharpen the standard candle by comparing ”like to like”
- Time scales ~10 years from now! Exact time for JDEM unknown but highest priority among ”Beyond Einstein Probes”



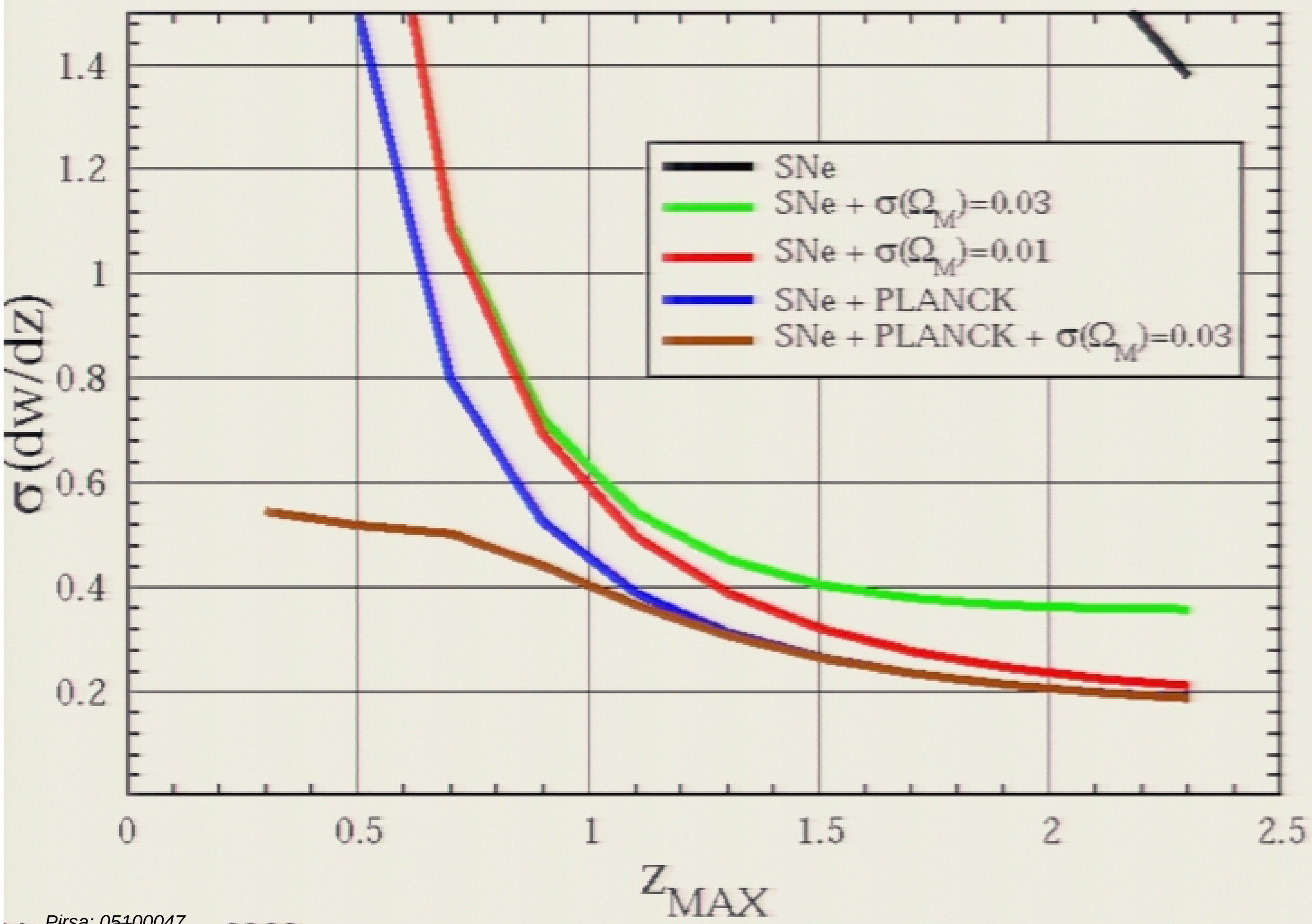
SNAP: probing Dark Energy models



based on

SNAP precision on w’

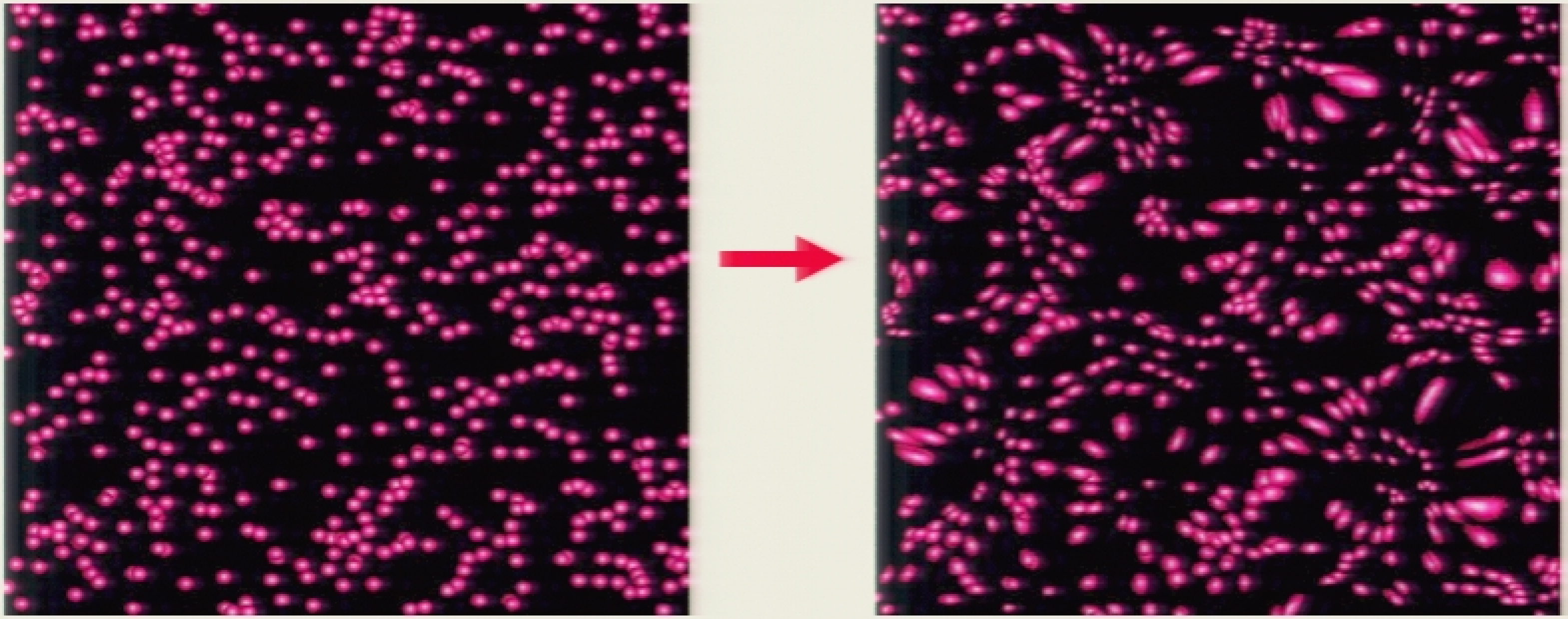
Irreducible Systematics of 0.02mag per Δz=0.1



Linder, Turner 2002

SNAP: Weak Gravitational Lensing

Distortion of background images by foreground matter

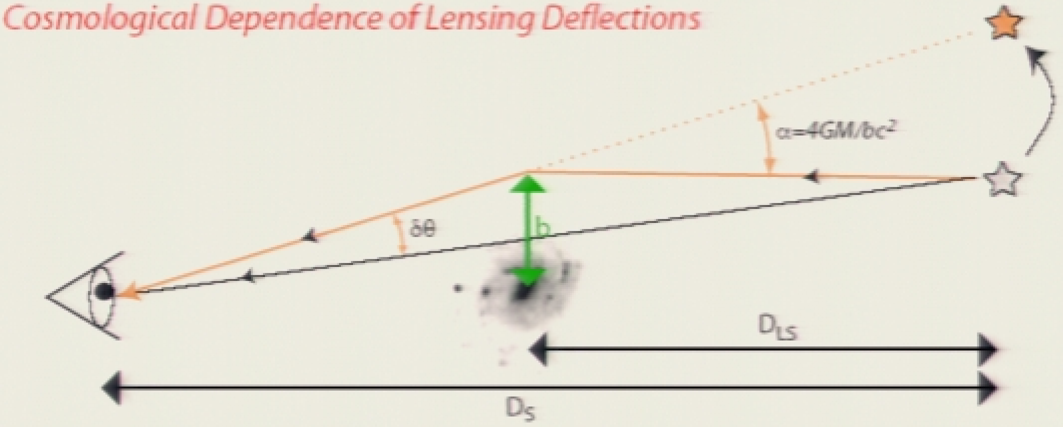


Unlensed

Lensed

Credits: R.Ellis

Cosmological Dependence of Lensing Deflections



$$\delta\theta = \frac{4GM}{bc^2} \; \frac{D_{LS}}{D_S}$$

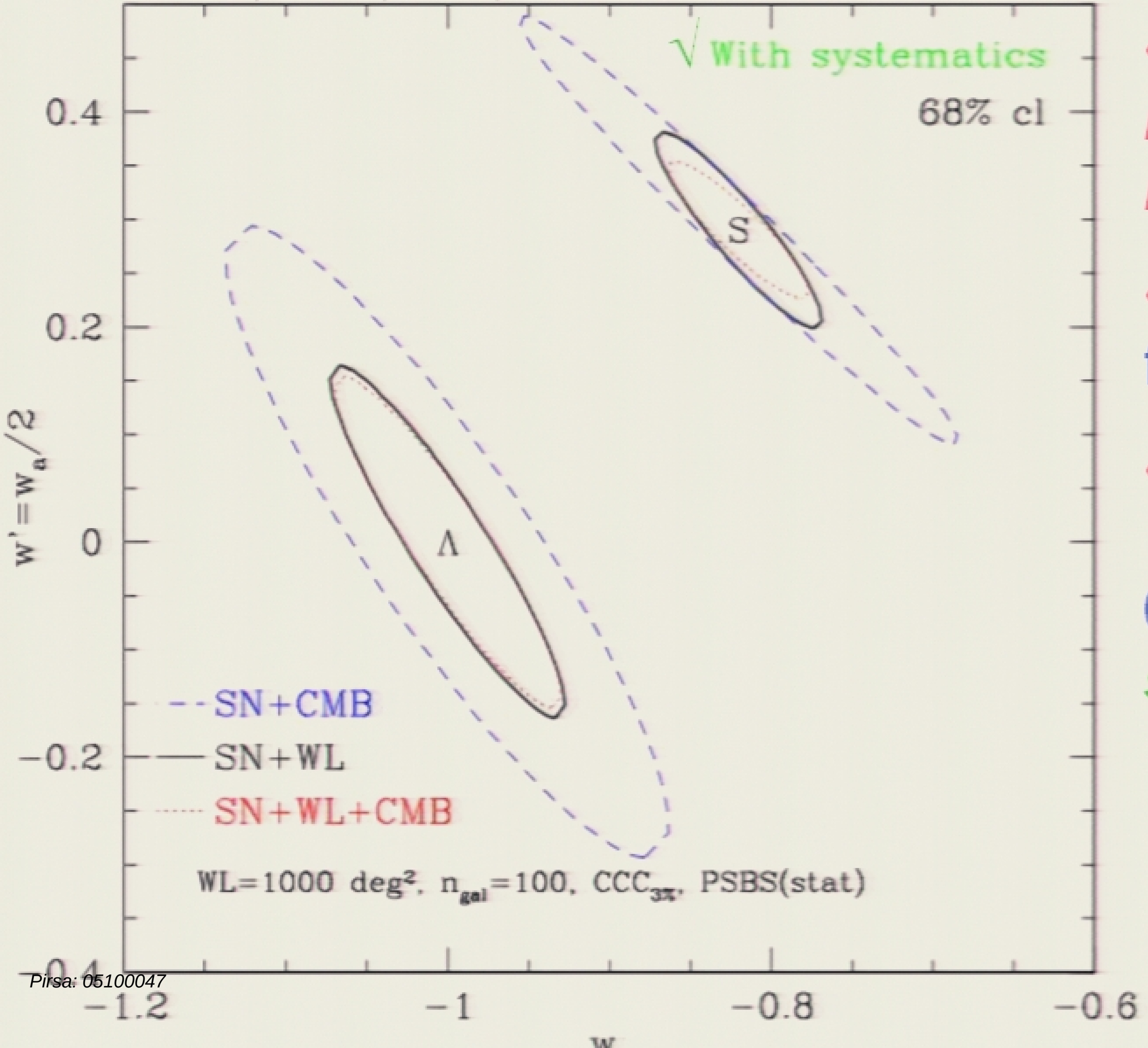
We observe this deflection angle (more precisely, gradients of the deflection angle).

Cosmology changes growth rate of mass structures in the Universe.

Cosmology changes the geometric distance factors.

SNe + Weak Lensing

Bernstein, Huterer, Linder, & Takada



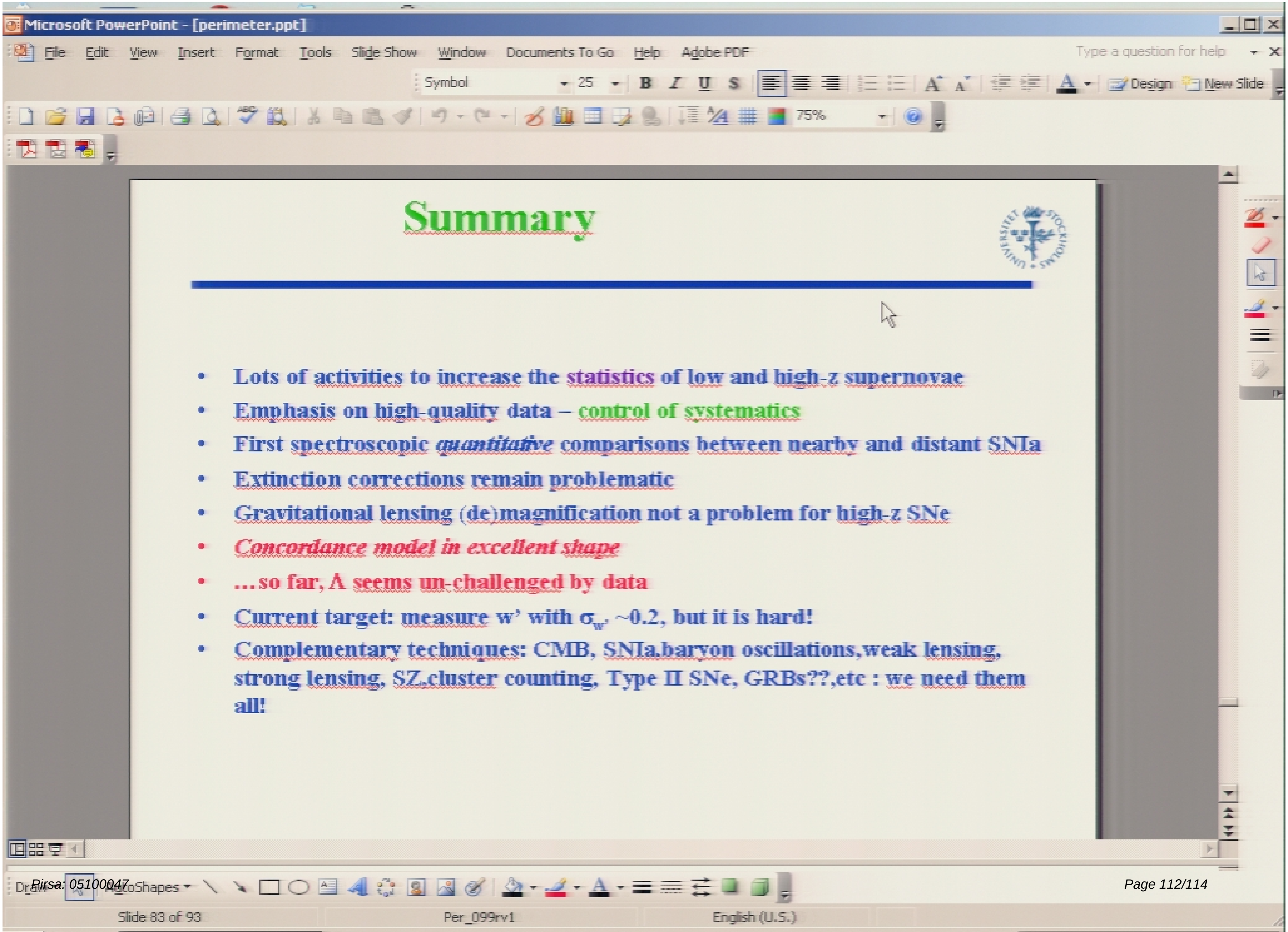
- **Comprehensive:** *no external priors required!*
- **Independent test of flatness to 1-2%**
- **Complementary:** w_0 to 5%, w' to 0.11 (*with systematics*)

+baryon oscillations?

More in Eric's talk!

Summary

- Lots of activities to increase the statistics of low and high-z supernovae
- Emphasis on high-quality data – control of systematics
- First spectroscopic *quantitative* comparisons between nearby and distant SNIa
- Extinction corrections remain problematic
- Gravitational lensing (de)magnification not a problem for high-z SNe
- *Concordance model in excellent shape*
- …so far, Λ seems un-challenged by data
- Current target: measure w' with $\sigma_{w'}$ ~0.2, but it is hard!
- Complementary techniques: CMB, SNIa,baryon oscillations,weak lensing, strong lensing, SZ,cluster counting, Type II SNe, GRBs??,etc : we need them all!



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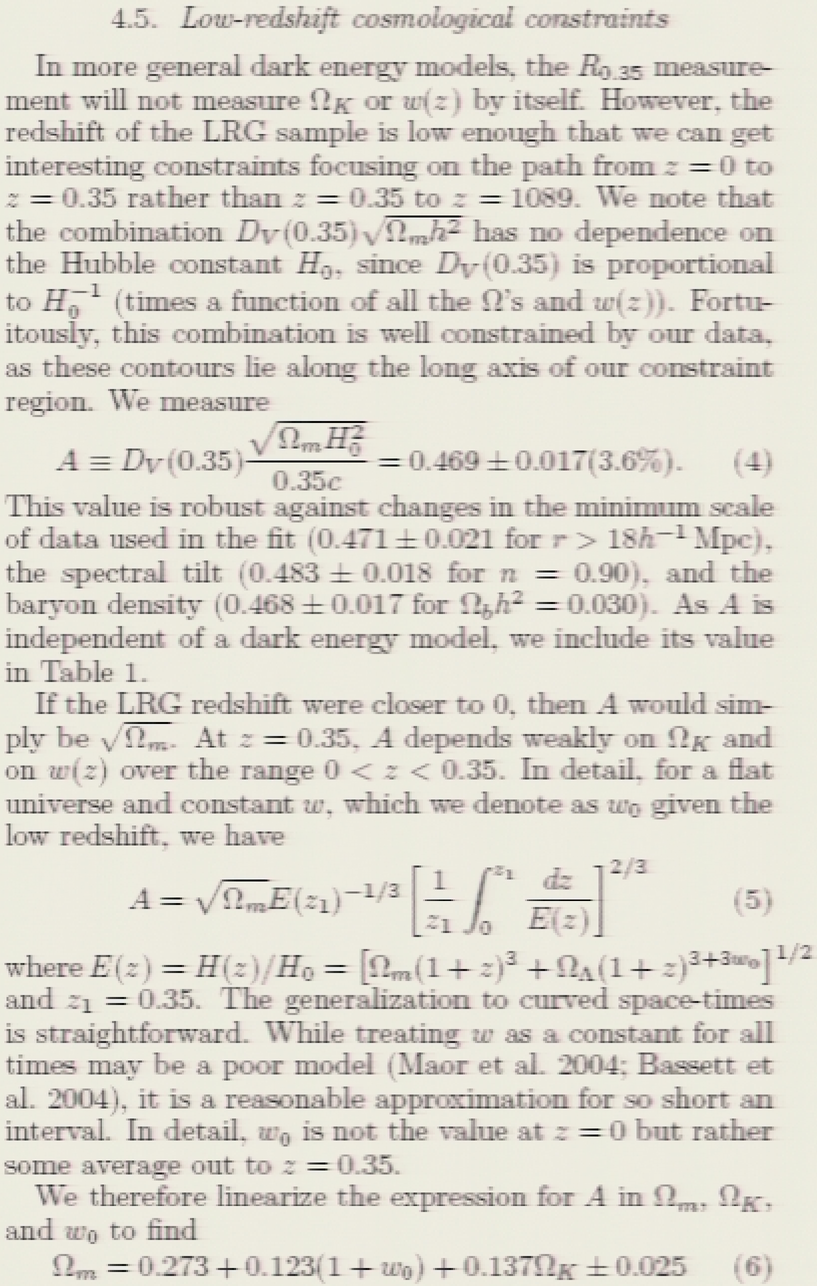


4.5. *Low-redshift cosmological constraints*

In more general dark energy models, the $R_{0.35}$ measurement will not measure Ω_K or $w(z)$ by itself. However, the redshift of the LRG sample is low enough that we can get interesting constraints focusing on the path from $z=0$ to $z=0.35$ rather than $z=0.35$ to $z=1089$. We note that the combination $D_V(0.35)\sqrt{\Omega_m h^2}$ has no dependence on the Hubble constant H_0, since $D_V(0.35)$ is proportional to H_0^{-1} (times a function of all the Ω's and $w(z)$). Fortuitously, this combination is well constrained by our data, as these contours lie along the long axis of our constraint region. We measure

$$A \equiv D_V(0.35)\frac{\sqrt{\Omega_m H_0^2}}{0.35c} = 0.469 \pm 0.017 (3.6\%). \qquad (4)$$

This value is robust against changes in the minimum scale of data used in the fit (0.471 ± 0.021 for $r > 18h^{-1}$ Mpc), the spectral tilt (0.483 ± 0.018 for $n = 0.90$), and the baryon density (0.468 ± 0.017 for $\Omega_b h^2 = 0.030$). As A is independent of a dark energy model, we include its value in Table 1.

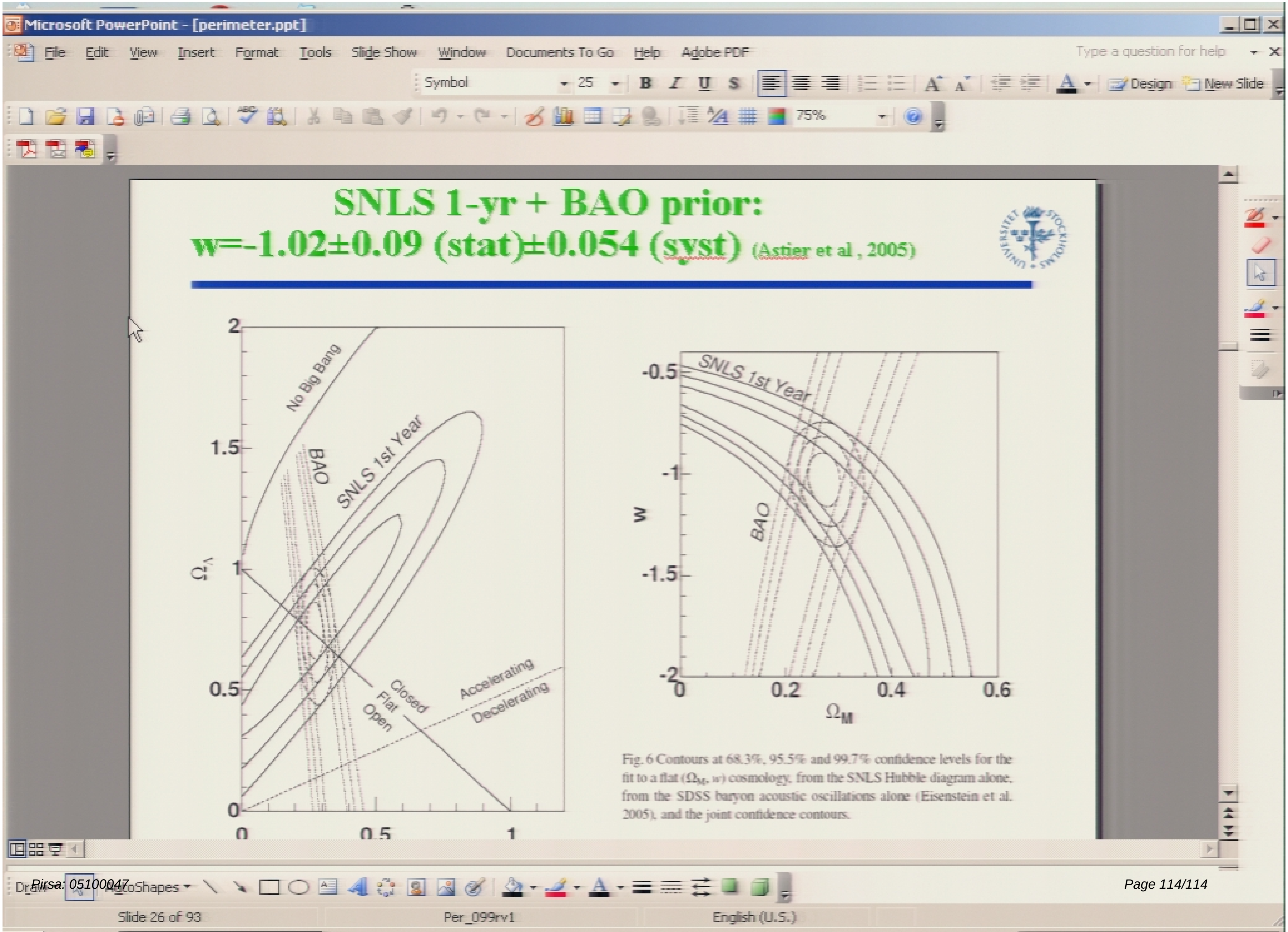
If the LRG redshift were closer to 0, then A would simply be $\sqrt{\Omega_m}$. At $z=0.35$, A depends weakly on Ω_K and on $w(z)$ over the range $0<z<0.35$. In detail, for a flat universe and constant w, which we denote as w_0 given the low redshift, we have

$$A = \sqrt{\Omega_m}E(z_1)^{-1/3}\left[\frac{1}{z_1}\int_0^{z_1}\frac{dz}{E(z)}\right]^{2/3} \qquad (5)$$

where $E(z) = H(z)/H_0 = \left[\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3+3w_0}\right]^{1/2}$ and $z_1 = 0.35$. The generalization to curved space-times is straightforward. While treating w as a constant for all times may be a poor model (Maor et al. 2004; Bassett et al. 2004), it is a reasonable approximation for so short an interval. In detail, w_0 is not the value at $z=0$ but rather some average out to $z=0.35$.

We therefore linearize the expression for A in Ω_m, Ω_K, and w_0 to find

$$\Omega_m = 0.273 + 0.123(1+w_0) + 0.137\Omega_K \pm 0.025 \qquad (6)$$



SNLS 1-yr + BAO prior:

$w=-1.02\pm0.09$ (stat)±0.054 (syst) (Astier et al , 2005)

Fig. 6 Contours at 68.3%, 95.5% and 99.7% confidence levels for the fit to a flat (Ω_M, w) cosmology, from the SNLS Hubble diagram alone, from the SDSS baryon acoustic oscillations alone (Eisenstein et al. 2005), and the joint confidence contours.