Supernova Observations for Dark Energy

Sep.1-4, 2007
RESCEU/DENET Summer School
@ Hakone

Mamoru Doi
Institute of Astronomy
Graduate School of Science
Univ. of Tokyo
東大・理・天文学教育研究センター
土居　守

Viewgraphs: Naoki Yasuda, Chris Lidman, Naohiro Takanashi, Kohichi Tokita, SCP team, Subaru Telescope, …

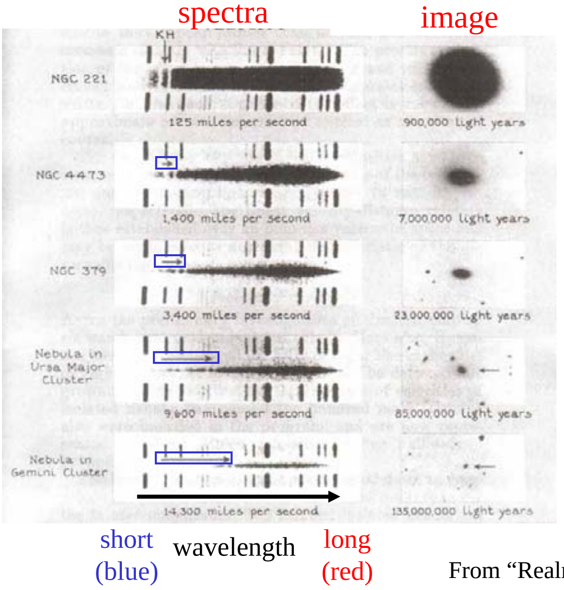
Contents

Photos
Subaru Observatory
Kiso Observatory
SDSS

1. Expanding Universe

1.1 How to measure Acceleration / Deceleration of the Universe

Optical Spectra of galaxies by Edwin Hubble



(Distance)

(900,000 light years)

(7,000,000 light years)

(23,000,000 light years)

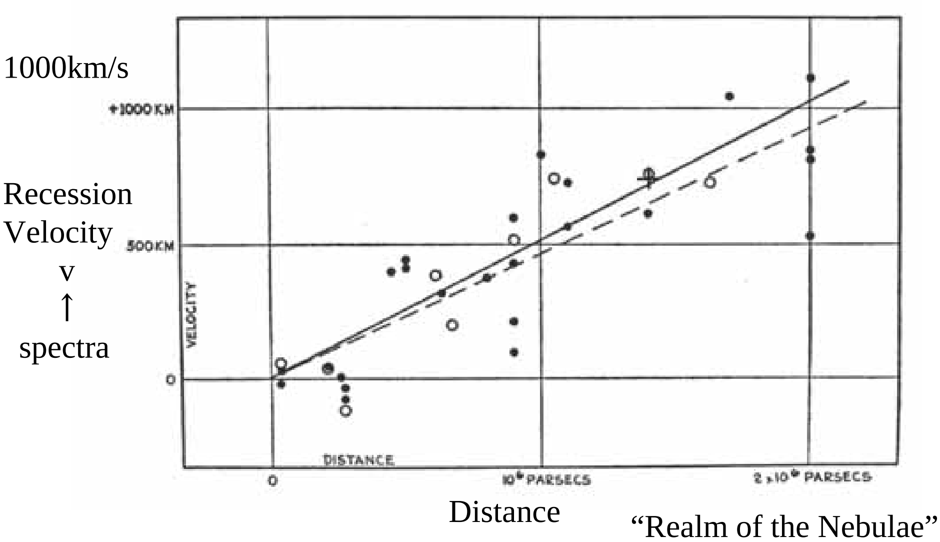
(85,000,000 light years)

(135,000,000 light years)

From "Realm of the Nebulae" (1936)

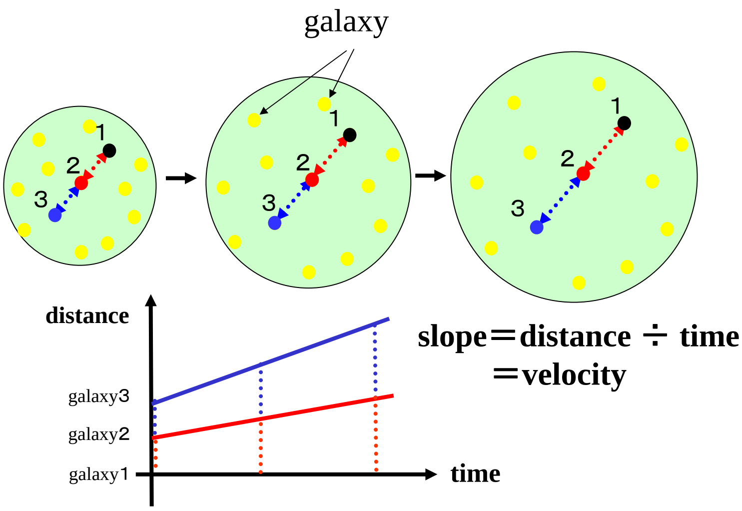
Wavelength : Longer as distance becomes larger.

Hubble's law



(Velocity)＝(Hubble constant) × (Distance)

Interpretation: Our universe is expanding!



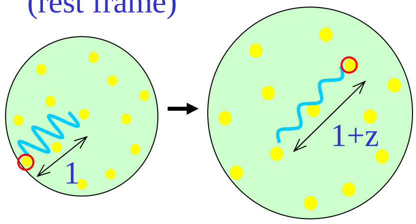
Velocity ∝ distance

"Redshift" z

(observed wavelength) ÷ (laboratory wavelength)
(rest frame)

$= 1 + z$

$v \sim c \cdot z$ $z \ll 1$
(c: speed of light)



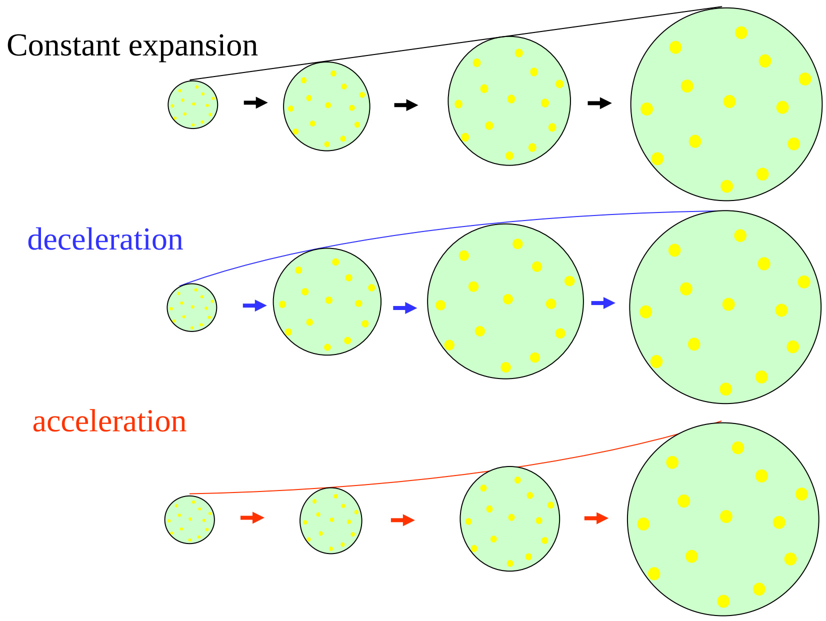
Wavelength, Distance between two galaxies :

× (1+z) larger

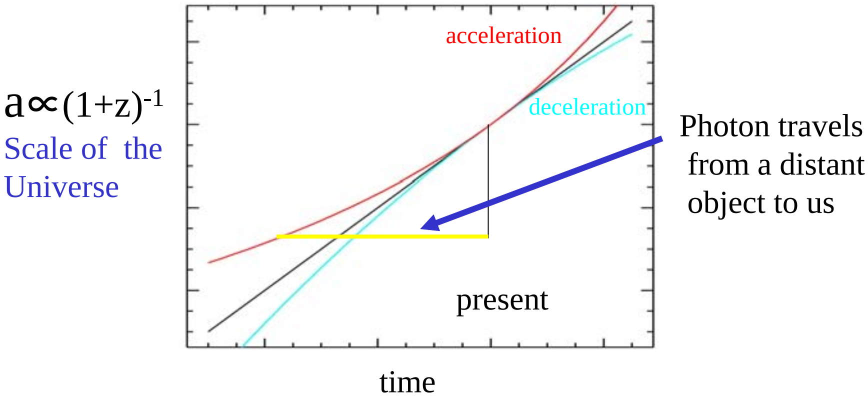
e.g. z=1→ ×2 z=3 → ×4

$(1+z)^{-1} \propto$ scale of the universe

Expanding velocity may change!



How we can measure acceleration/deceleration



Expanding speed : accelerate (decelerate)

light travels longer (shorter) than constant expansion

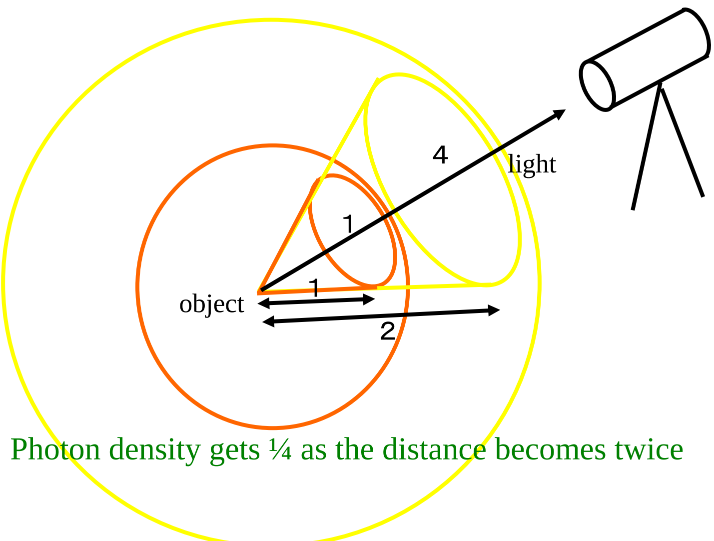
→ Distance: large (small)

(Distance) = (speed of light) × (time)

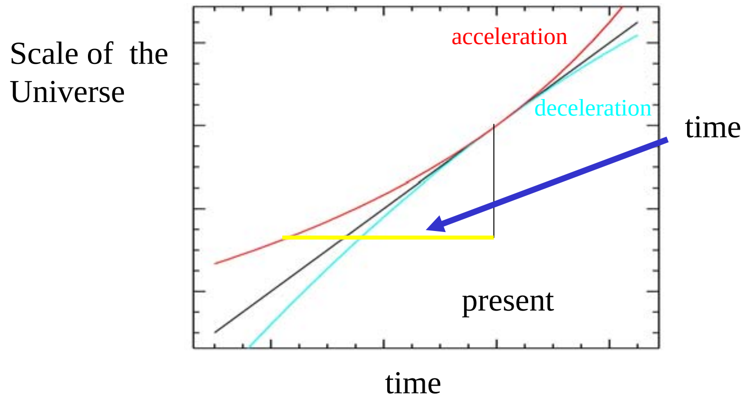
Apparent brightness (flux)

Energy / unit area / unit time

More distant → Fainter



Photon density gets ¼ as the distance becomes twice



Expanding speed : accelerate (decelerate)

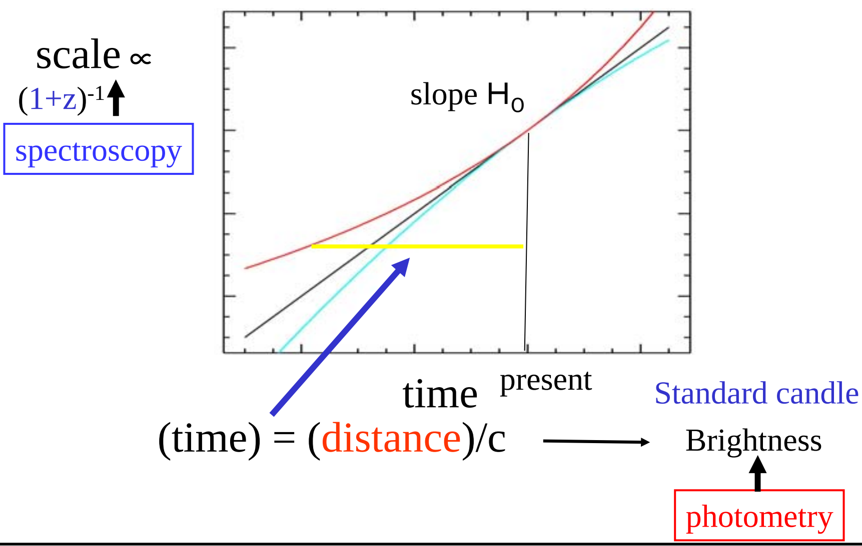
light travels longer (shorter) than constant expansion

→ Distance: large (small)

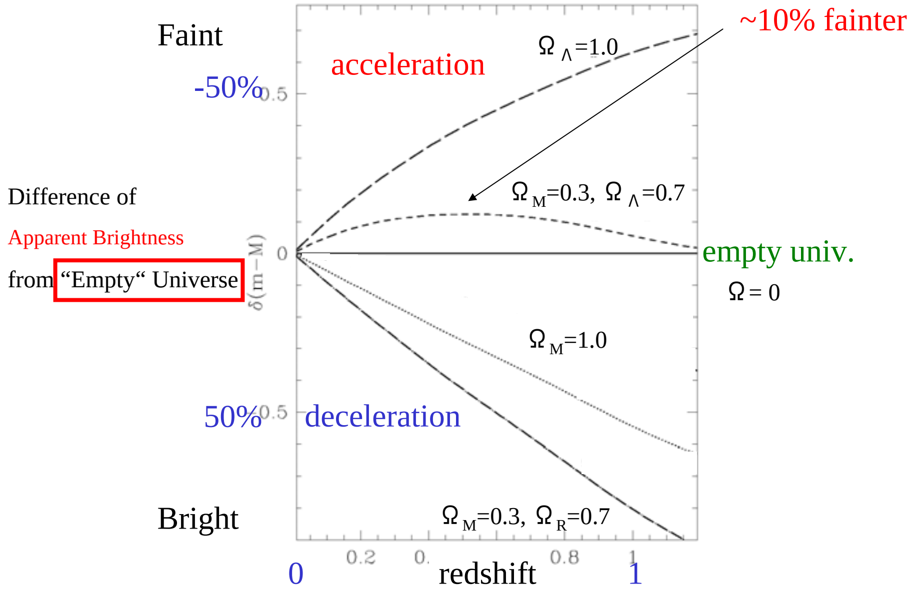
(Distance) = (speed of light) × (time)

→ Object looks fainter (brighter)
if the expansion accelerates (decelerates)

Redshift and Distance



Apparent brightness of a standard candle (constant luminosity)



Einstein eq.

General Relativity

→ Homogeneous, isotropic

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \Lambda/3$$

$a \propto (1+z)^{-1}$: scale factor ρ : density

k: "curvature" of the universe ±1 or 0

H: (scale expansion rate) ／ (scale) ⇔ Hubble's law

Λ: Einstein's cosmological constant (Dark Energy)

("Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie" 1917)

Expressions in “look back” formula, using Ω

normalization: $\rho_c = 3H_0^2/8\pi G$= (critical density 1×10^{-29} g/cm^3)

$$H^2 = H_0^2\{\Omega_M(1+z)^3 + \Omega_R(1+z)^4 + \Omega_\Lambda - \kappa_0(1+z)^2\}$$

where $1+z = a_0/a$ (z: redshift)

$\kappa_0 = kc^2/a(t_0)^2 H_0^2$ ($\kappa_0 = 0$ if $\Omega_{total} = 1$).

Ω_M : matter (density)∝(scale)$^{-3}$

Ω_R :radiation (density)∝(scale)$^{-4}$

Ω_Λ :cosmolog. const. (density)∝(scale)^{0}

(all present density)

Luminosity Disntance D_L

$D_L = (4\pi F)^{1/2}$

(F: flux…W/m2/sec/Hz)

Dimension of H: 1/second

→

$$D_L = c(1+z)/(H_0\sqrt{\Omega_k})\cdot$$

$$\chi\left(\sqrt{\Omega_k}\int_0^z dz'\{\Omega_k(1+z')^2 + \Sigma_i(\Omega_i(1+z')^{3(1+\omega i)}\}^{1/2}\right)$$

$\Omega_k = 1 - \Omega_{total}$

$\chi(x)$: sinh(x) for $\Omega_k > 0$

x for $\Omega_k = 0$

sin(x) for $\Omega_k < 0$

i

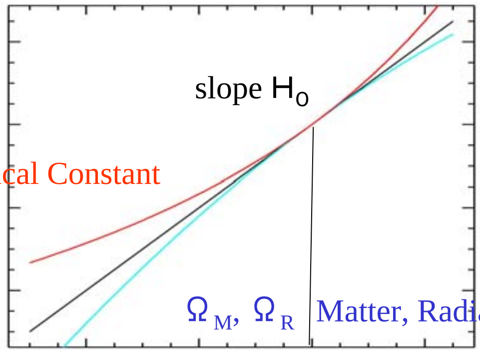
Matter: $\omega_i = 0$

Radiation: $\omega_i = -1/3$

Cos. Const.: $\omega_i = -1$

Acceleration/Deceleration

a ∝ $(1+z)^{-1}$



Deceleration Parameter

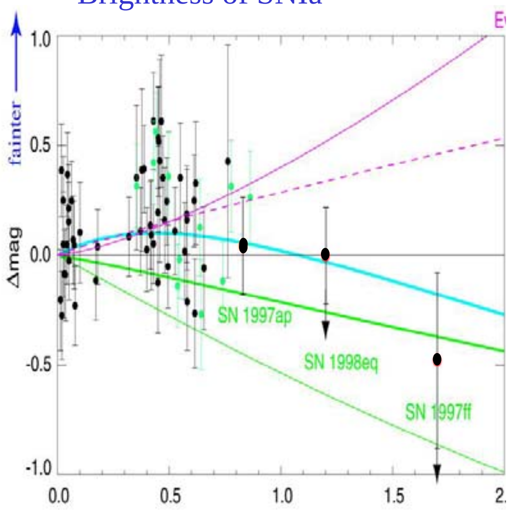
$$q_0 \equiv -\ddot{a}(t_0)a(t_0)/\dot{a}^2(t_0) = ½(\Omega_M - 2\Omega_\Lambda + 2\Omega_R)$$

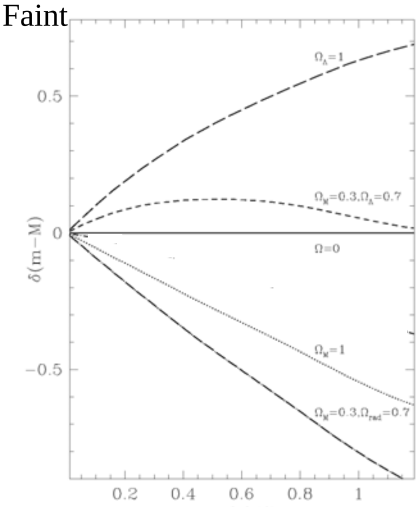
Accerelating!

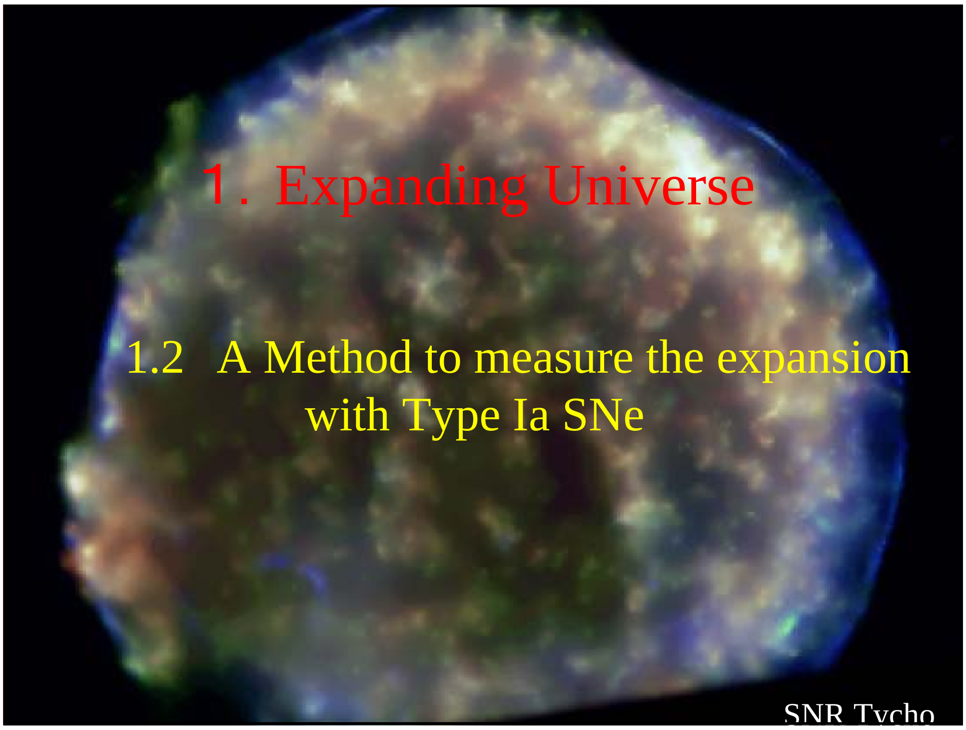
Perlmutter et al.1999

Riess et al. 1998, Schmidt et al. 1998

Brightness of SNIa

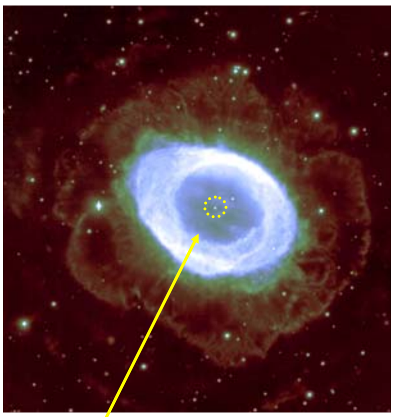






Planetary Nebula

(End of Low/Mid. Mass Stars)



Ring Nebula（M57）

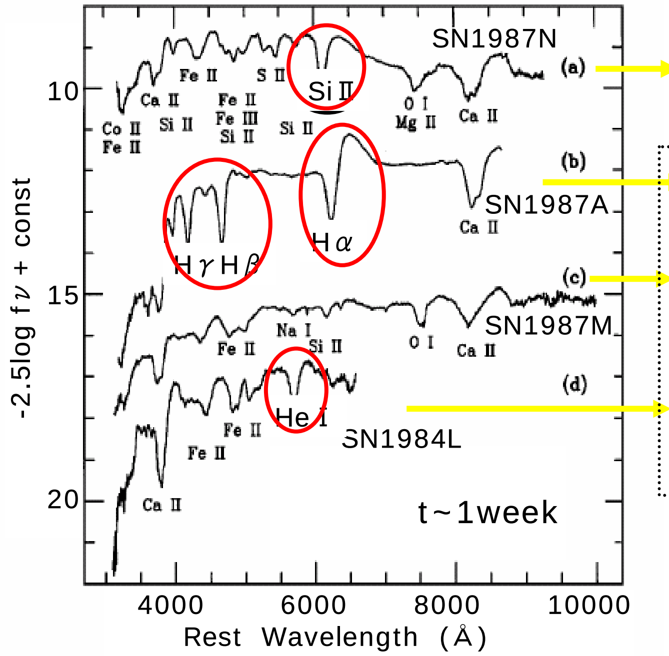
White Dwarf

Supernova Remnant

（End of Massive Stars）

Crab（M1）

Spectral Types of Supernovae



Type Ia
H × Si ○

Type II
H ○

Type I c
H × Si × He ×

Type I b
H × Si × He ○

Core Collapse SNe

Filippenko 1997

Type Ia Supernova

- Standard Candle
  Luminosity ~ constant
  r.m.s.~ 15-20% in (with corrections)
  →White Dwarf (@binary system) reaches
  Chandrasekar mass limit (1.4 solar mass)
  ⇔ other SNe (Core Collapse)
  Type II, Ib, Ic: end of massive stars
  ↑ Prof.Umeda's talk yesterday
- Large Luminosity (~whole galaxy)
  → measurable at cosmological distance

Observing Method for Cosmology

- Wide-Field imaging

  imaging with ~1 months interval

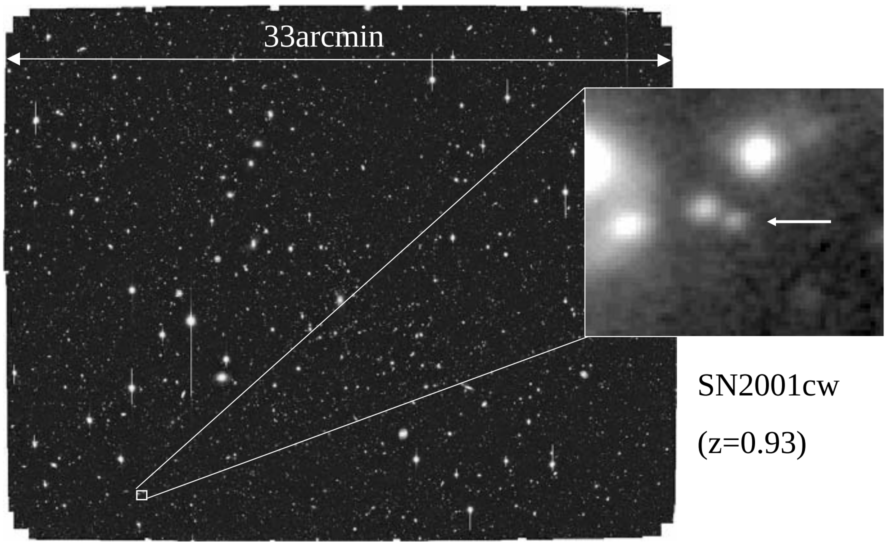
  → find candidates (significant increase in luminosity)
- Optical Spectroscopy

  confirmation of SN spectrum（⇔AGN, variable stars）

  SN type and redshift determination
- follow-up photometry

  light curve → brightness

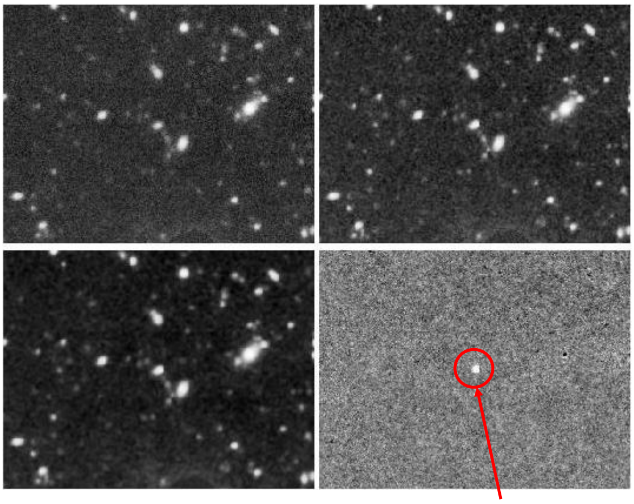
Wide-Field Imaging



SN2001cw

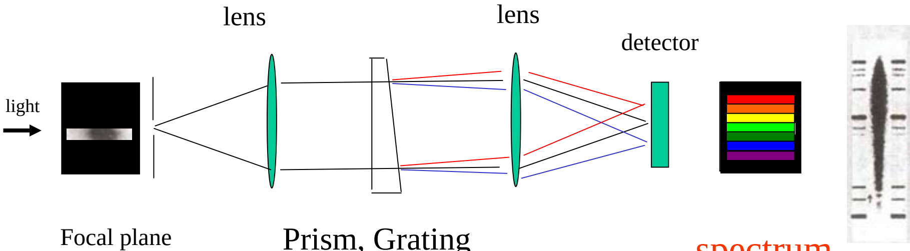
(z=0.93)

Image Analysis



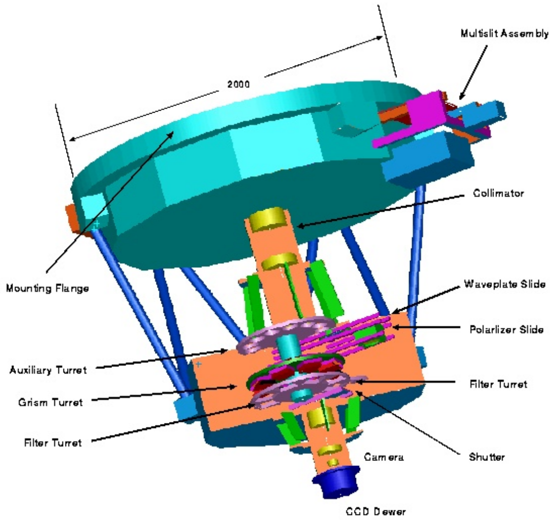
(Ref.Alard, C. and Lupton, R. H. 1998)

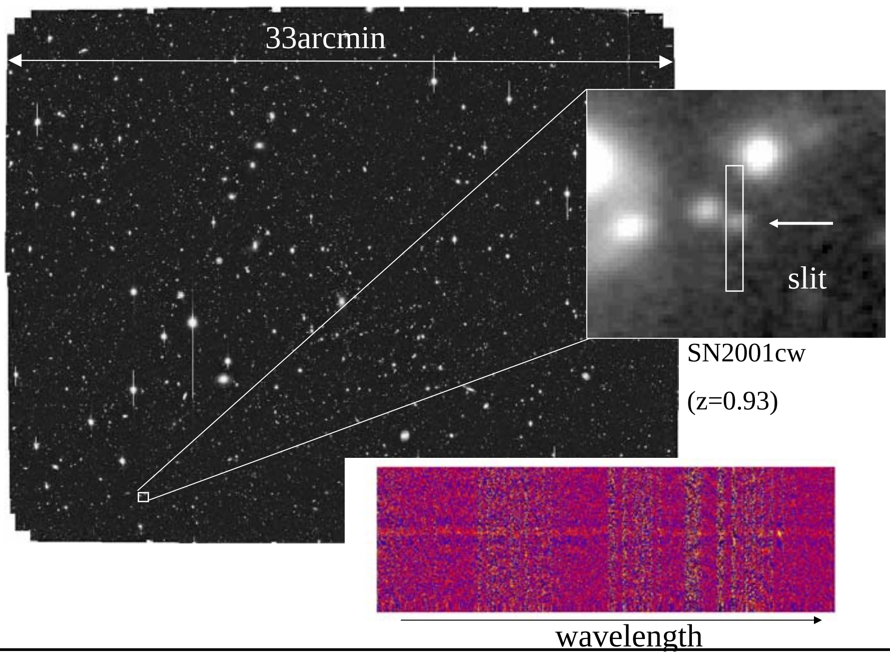
spectroscopy



FOCAS:

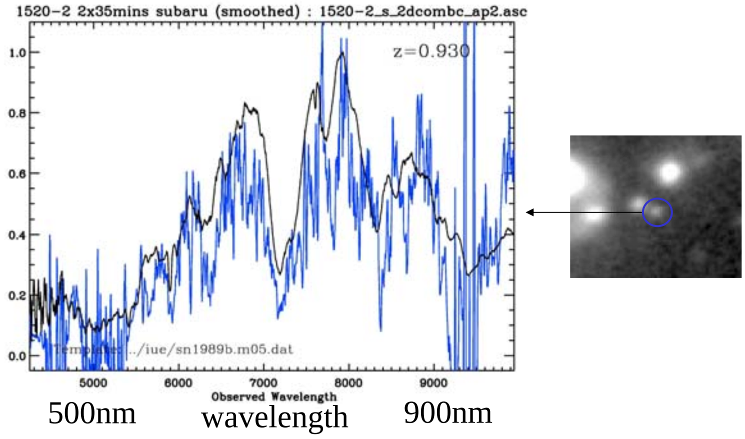
Low Resolution Spectrograph





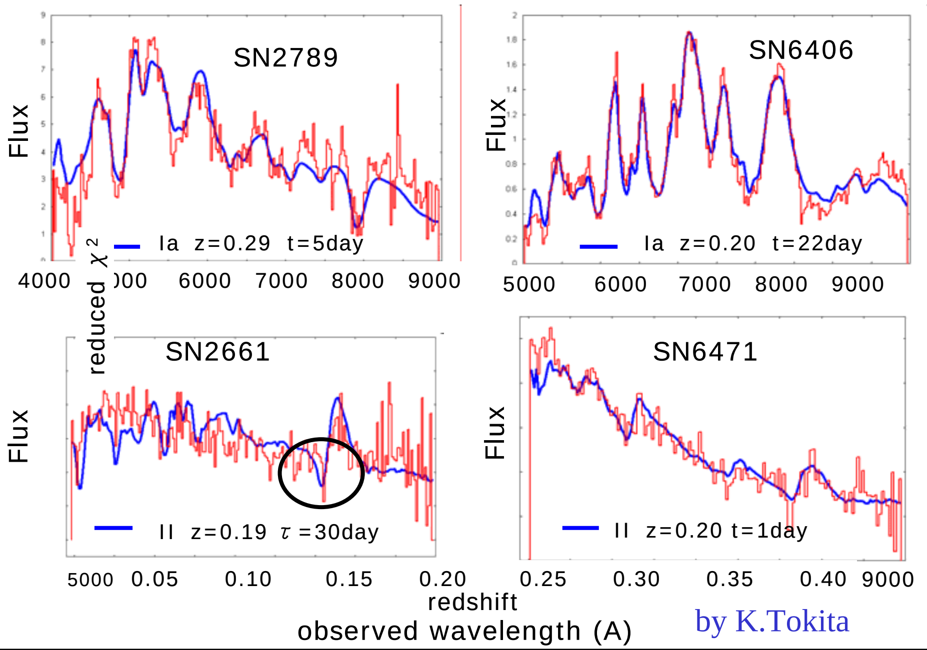
Spectroscopy

SN Type and redshift



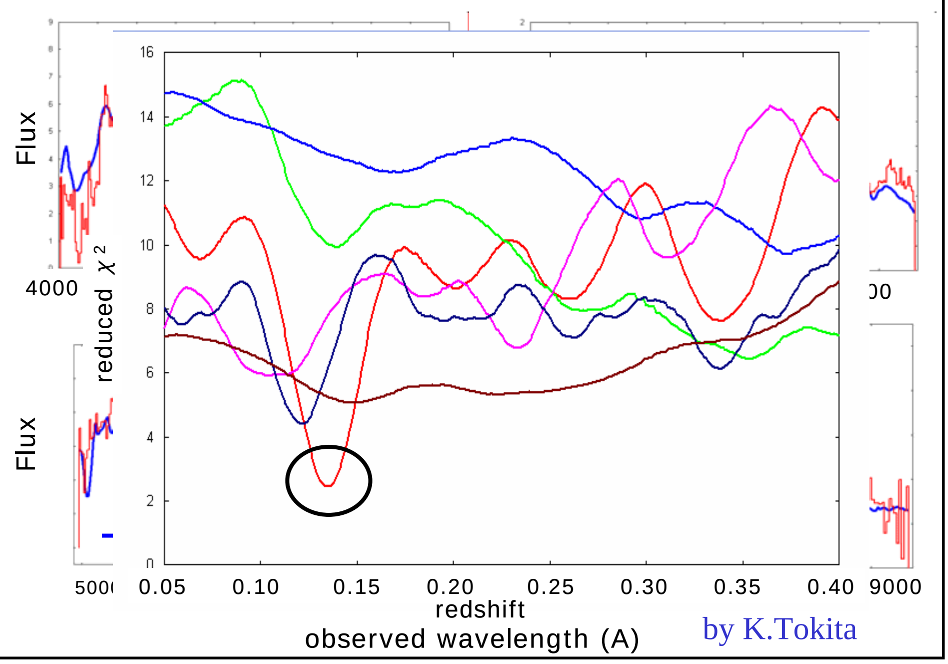
SN2001cw(z=0.93) taken with FOCAS/Subaru
superposed on SN1989b (nearby SNIa)

Lest χ2 fitting of Spectra for type, redshift & epoch

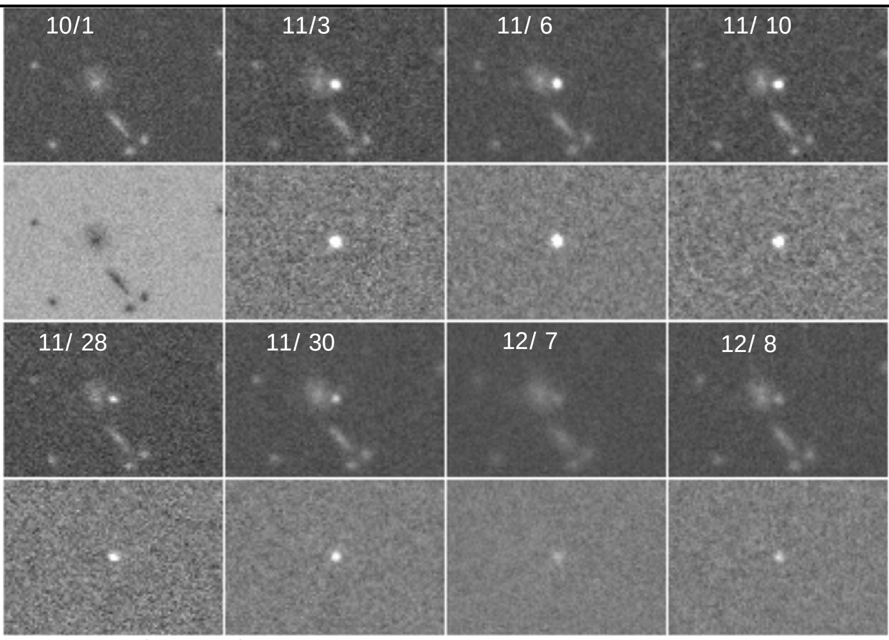


by K.Tokita

Least χ2 fitting of Spectra for type, redshift & epoch



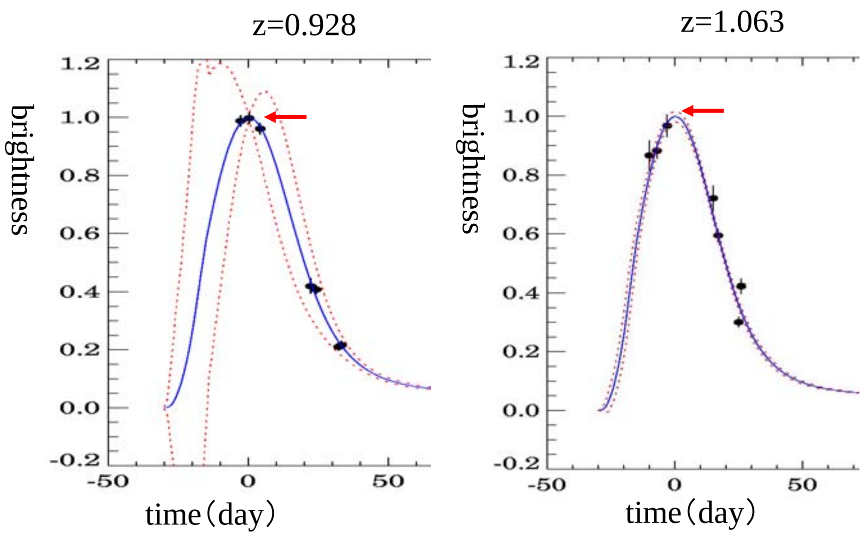
by K.Tokita



SN2002kp (z=0.928)

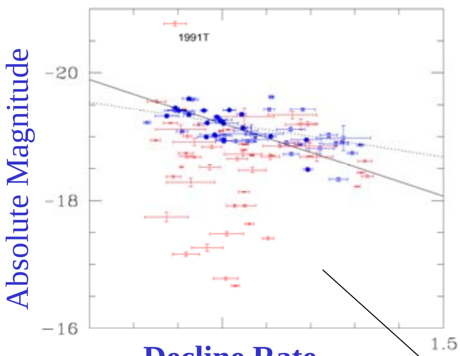
upper panels : original images lower pannels : image of Oct.1 subtracted

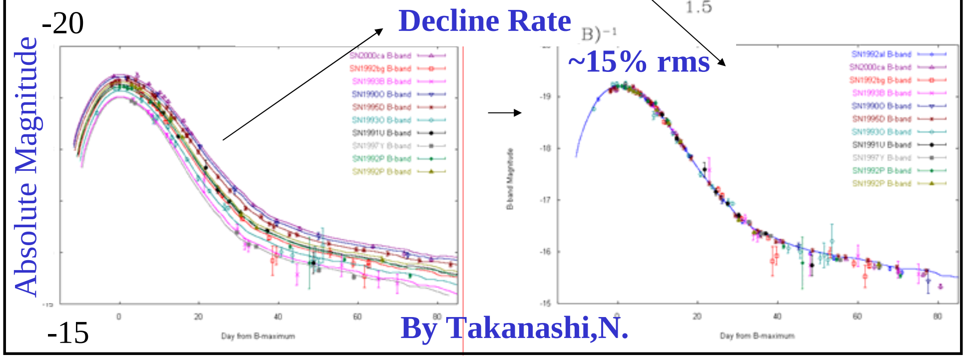
Light curves (exmaple)

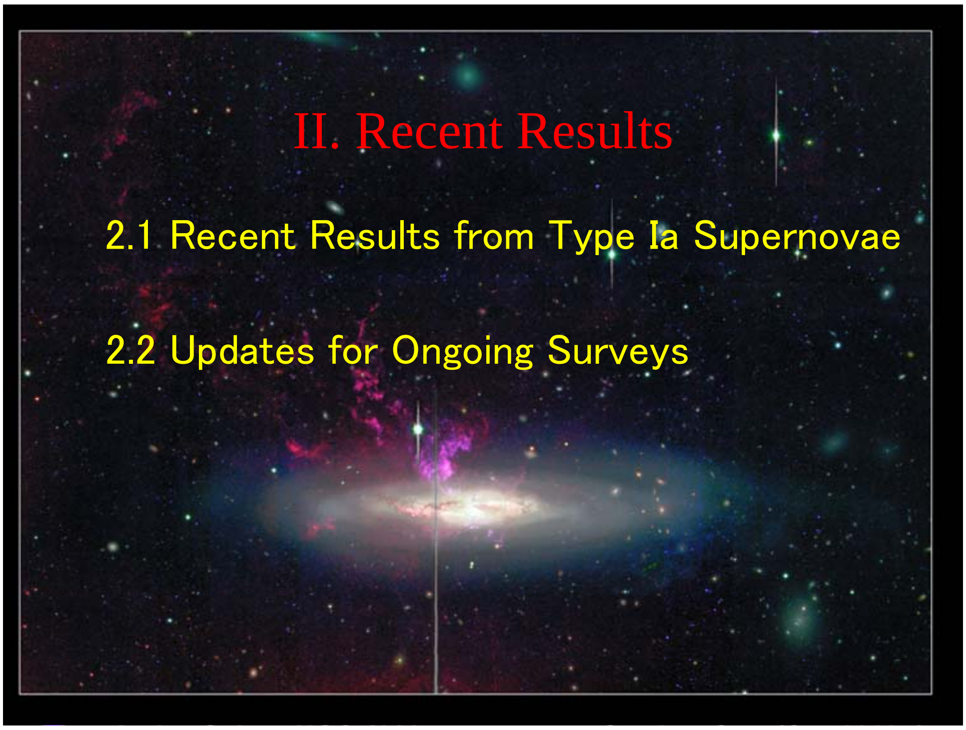


→ Maximum brightness

• Standard
→WD((
Chandı



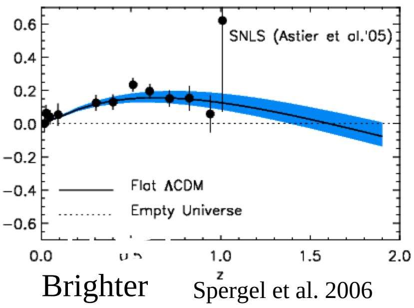




2.1 Recent Results from Type Ia Supernovae

Distance Difference from Empty Universe (mag.)

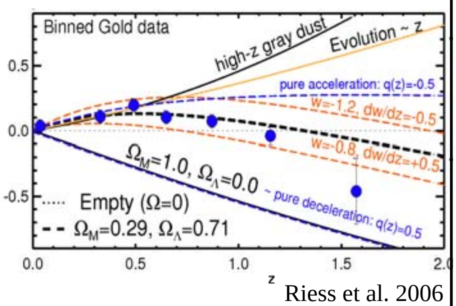
Fainter



Brighter

Spergel et al. 2006

redshift



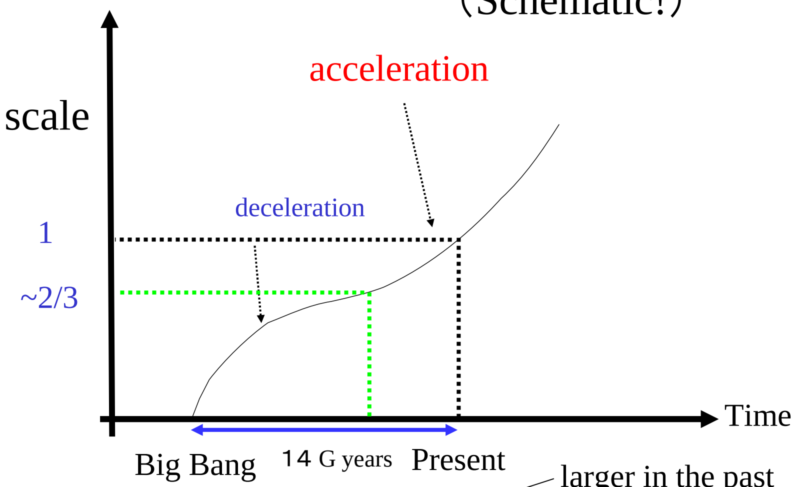
Riess et al. 2006

redshift

Consistent with $\Omega_{\Lambda} \sim 0.7$ $\Omega_{M} \sim 0.3$

History of expansion of Universe

(Schematic!)



larger in the past

deceleration $\propto (\Omega_M - 2\Omega_\Lambda + 2\Omega_R)$

constant

On going Large SNIa surveys

redshift	Projects
z~0-0.3	Supernova Factory
~1-2.5m	SDSS
z~0.3-0.8	SN Legacy
~4m	Essence
z~0.8-1.5	SCP (HST/GOODS)
~8m, HST	High-z

Learn more about SNIa

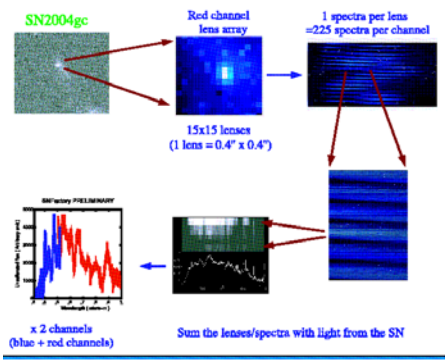
cosmological constant more effective

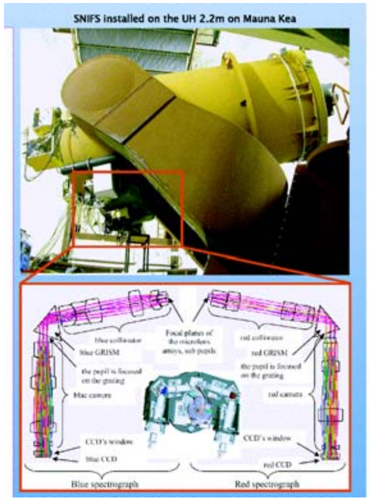
look back time larger

NearbySNFactory

goal:300SNe @z=0.03-0.08

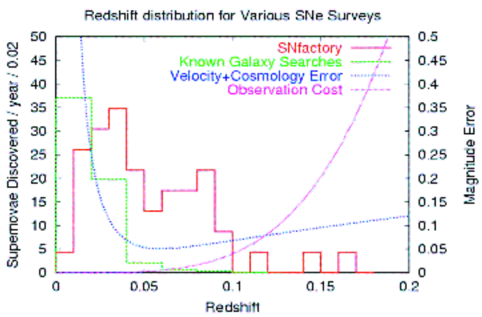
Finding SNe with 1m class telescopes
NEAT(NEAR-EARTH ASTEROID TRACKING)
QUEST(Palomar Schmidt)

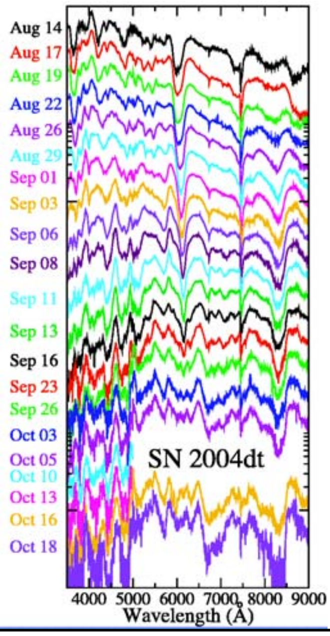




Spectroscopy with SNIFS
At UH88 telescope

Preliminary Results from Nearby SNFactory (AAS poster, 2005)





ESSENCE+SNLS

Wood-Vasey 2006

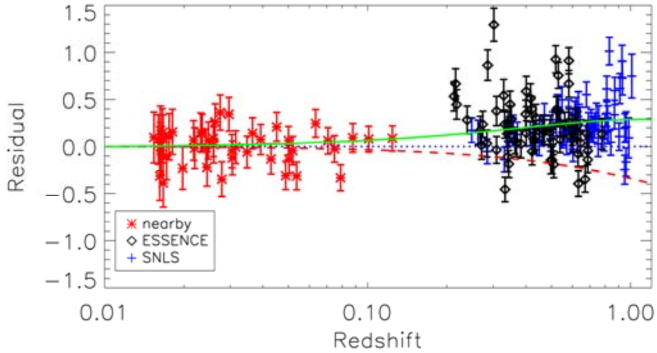
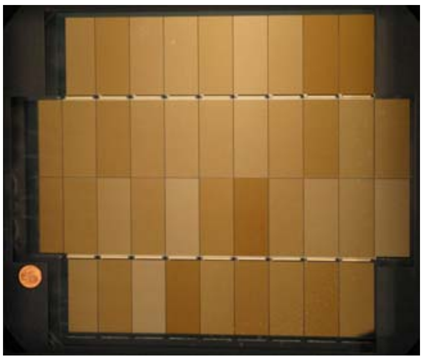


Fig. 9.— Luminosity distance modulus vs. redshift for the ESSENCE, SNLS, and nearby SNe Ia for SALT. For comparison the overplotted solid line and residuals are for a ΛCDM $(w, \Omega_M, \Omega_\Lambda) = (-1, 0.27, 0.73)$ Universe.

Nearby 45 ESSENCE 60 SNLS 73?

CFHT MEGACAM

3.6-m telescope since 1977
Large modification in 2003
to have wide field of view
CCD 4.5kx2kx40



Results of SNLS 1st year

(71 SNIa → goal: 700SNe? in 5 years)

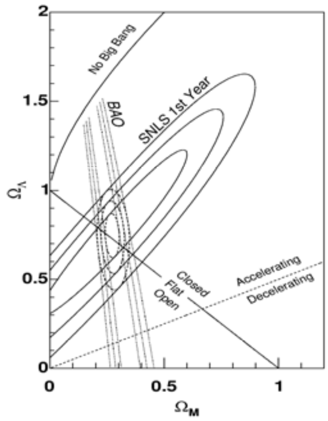


Fig. 5 Contours at 68.3%, 95.5% and 99.7% confidence levels for the fit to an $(\Omega_M, \Omega_\Lambda)$ cosmology from the SNLS Hubble diagram (solid contours), the SDSS baryon acoustic oscillations (Eisenstein et al. 2005, dotted lines), and the joint confidence contours (dashed lines).

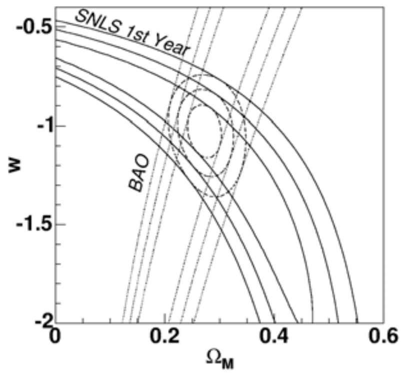
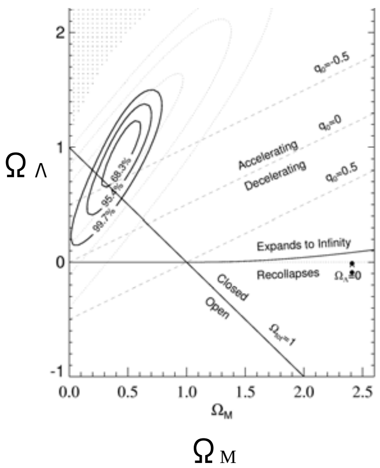


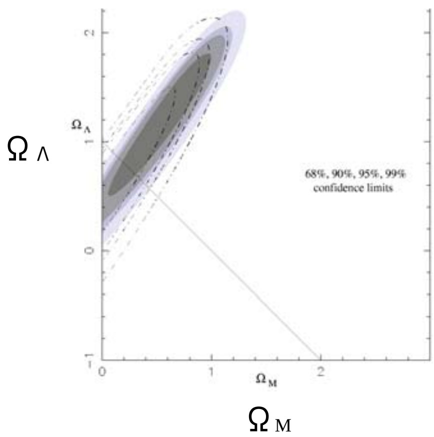
Fig. 6 Contours at 68.3%, 95.5% and 99.7% confidence levels for the fit to a flat (Ω_M, w) cosmology, from the SNLS Hubble diagram alone, from the SDSS baryon acoustic oscillations alone (Eisenstein et al. 2005), and the joint confidence contours.

Astier et al. 2006

Measurements of Ωs with SNe only
(Riess et al. 2004)

(Knop et al. 2003)





Not inconsistent with “Flat Universe”

ESSENCE+SNLS

Wood-Vasey 2006

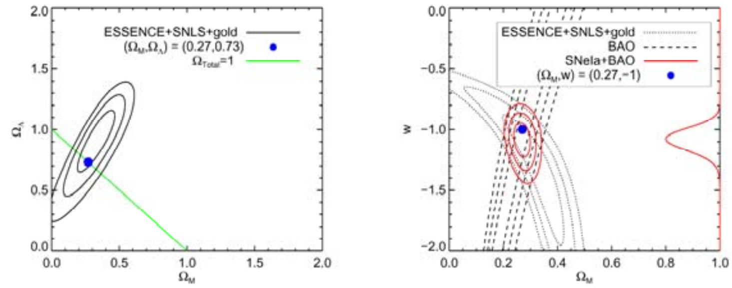


Fig. 12.— The SN Ia (Ω_M, Ω_Λ) and (Ω_M, w) contours from combining the MLCS2k2 luminosity distances for the ESSENCE SNe Ia analyzed here in combination with the nearby SNe Ia, SNLS SNe Ia, and the Riess "gold" sample. The diagonal line in the (Ω_M, Ω_Λ) plot represents a flat Universe, $\Omega_{total}=\Omega_M+\Omega_\Lambda= 1$. From the SNe Ia data alone, an empty Universe is ruled out at 4.5 σ, an (Ω_M, Ω_Λ) = $(0.3, 0)$ Universe at 10 σ, and an (Ω_M, Ω_Λ) = $(1, 0)$ σ Universe at > 20 σ. The best combination of data will come after a complete analysis of the calibration and systematic errors of all the data sets. We offer this interim result to indicate the potential of combining low-z, ESSENCE, and supernovae at redshifts beyond 1.

ESSENCE+SNLS

Wood-Vasey 2006

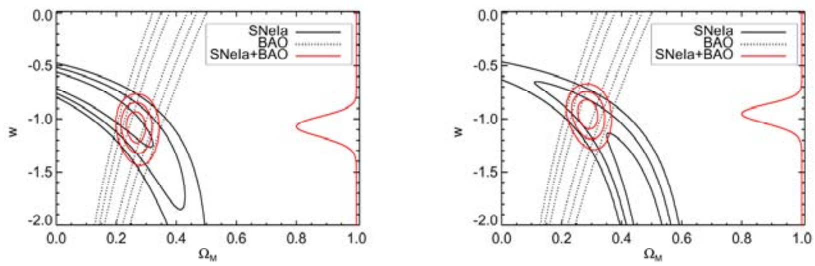
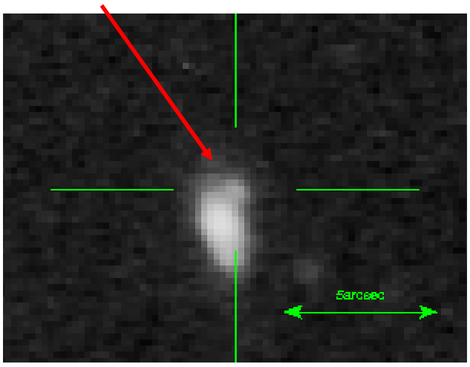
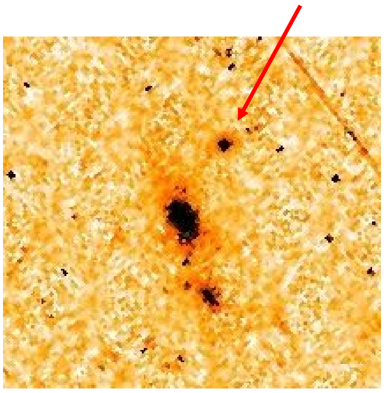


Fig. 11.— The Ω_M-w contours from the SNLS + ESSENCE + nearby sample for MLCS2k2 with "glosz" A_V prior and for the SALT fitter. The baryon acoustic oscillation (BAO) constraints are from Eisenstein et al. (2005).

Space is powerful (HST)

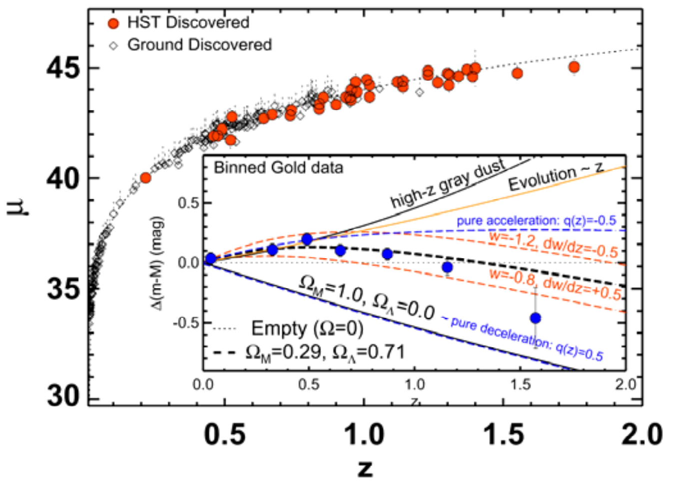




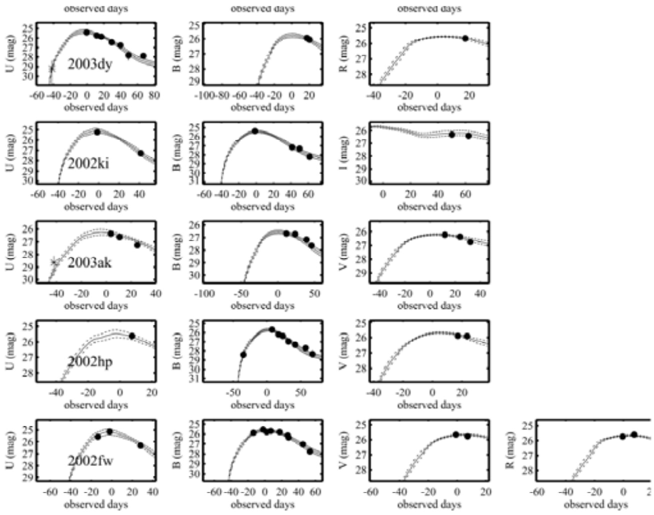
~1hour exposure time
Suprime-Cam

~15min exposure time
HST/ACS

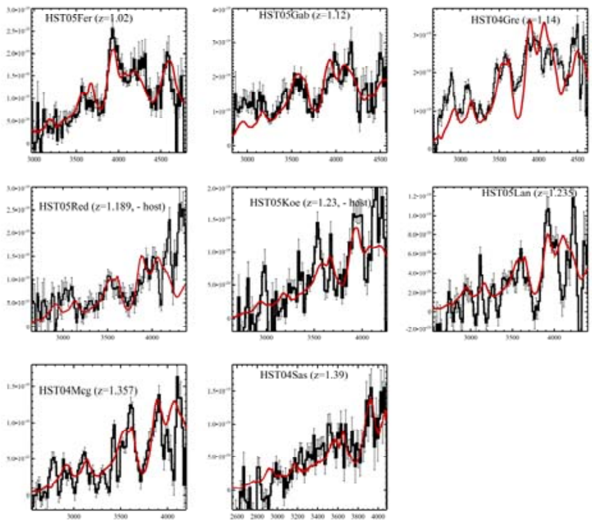
High-z SNe by HST "Higher-Z" team (Riess et al. 2006)



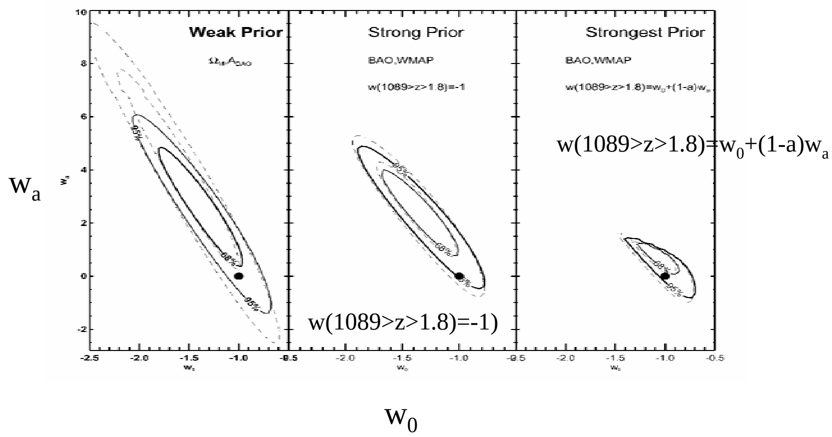
High-z SN light curves by
HST "Higher-Z" team
(Riess et al. 2006)



High-z SN spectra by
HST "Higher-Z" team
(Riess et al. 2006)



Cosmological Parameters by Riess et al. 2006



$w = w_0 + (1-a) w_a$

On going Large SNIa surveys

redshift — Projects

z~0-0.3 — Supernova Factory

~1-2.5m — SDSS

z~0.3-0.8 — SN Legacy

~4m — Essence

z~0.8-1.5 — SCP (HST/GOODS)

~8m, HST — High-z

Learn more about SNIa

cosmological constant more effective

look back time larger

Wide Field Imagers

Survey power
(for same image quality)

Camera Name	Telescope D [m]	A [m^2]	F	CCD Vendor	Format	N_{CCD}	FOV Ω [deg^2]	AΩ	First Light
WFPC2	2.5	3.46	12.9	Loral	800×800(15)	3	0.0015	0.01	Dec-93
UH8K	3.6	9.59	4.2	Loral	4k2k(15)	8	0.25	2.40	Sep-95
SDSS	2.5	3.83	5	SITe	2k2k(24)	30	6.0	22.99	May-98
NOAO8K	3.8	9.98	2.7	SITe	4k2k(15)	8	0.36	3.59	Jul-98[a]
CFH12K	3.6	9.59	4.2	MIT/LL	4k2k(15)	12	0.375	3.60	Jan-99
Suprime-Cam	8.2	51.65	2.0	MIT/LL	4k2k(15)	10	2.555	13.17	Jul-99
MegaCam	3.6	9.59	4.2	Marconi	4.5k2k(13.5)	40	1	9.59	Jan-03
VISTA Opt.	4.0	11.33	1.0	Marconi	4.5k2k(13.5)	50	2	22.67	2010?
LSST[b]	8.4	46.34	1.25				(7.1)	329	2012?
PanSTARRS	3.6(4)	10		MIT/LL			7	50	2007-09?
DarkEnergyS.	4.0	10		LBNL			3	30	2009?

Future

Sloan Digital Sky Survey (SDSS)

International collaborations (US, Japan, Germany,..)

2.5m wide-field telescope

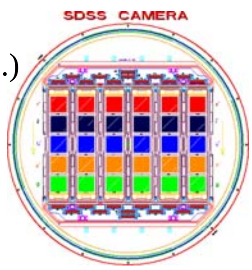
wide field imager : 54 CCDs

SDSS-II SN survey

5-band photometry

find and measure brightness of SNe

~300 SNIa ← 2005-2007

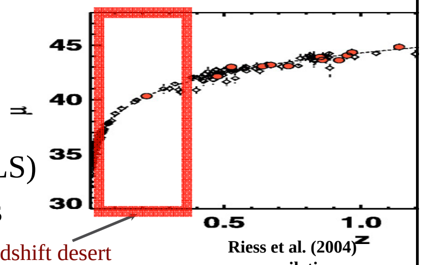


2.5 degree

Science goals

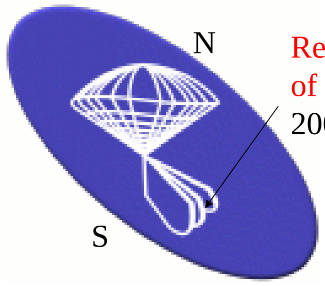
Type Ia supernovae (SNe)

- "well-measured" light curves of
  ~200 SN Ia from z = 0.05 ~ 0.4
- bridge low-z (z<0.05; LOSS, SNF) and high-z (0.3<z<1.0; ESSENCE, SNLS)
- understand and minimize systematics of SN Ia as distance indicators

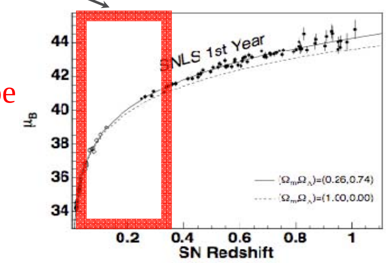


redshift desert

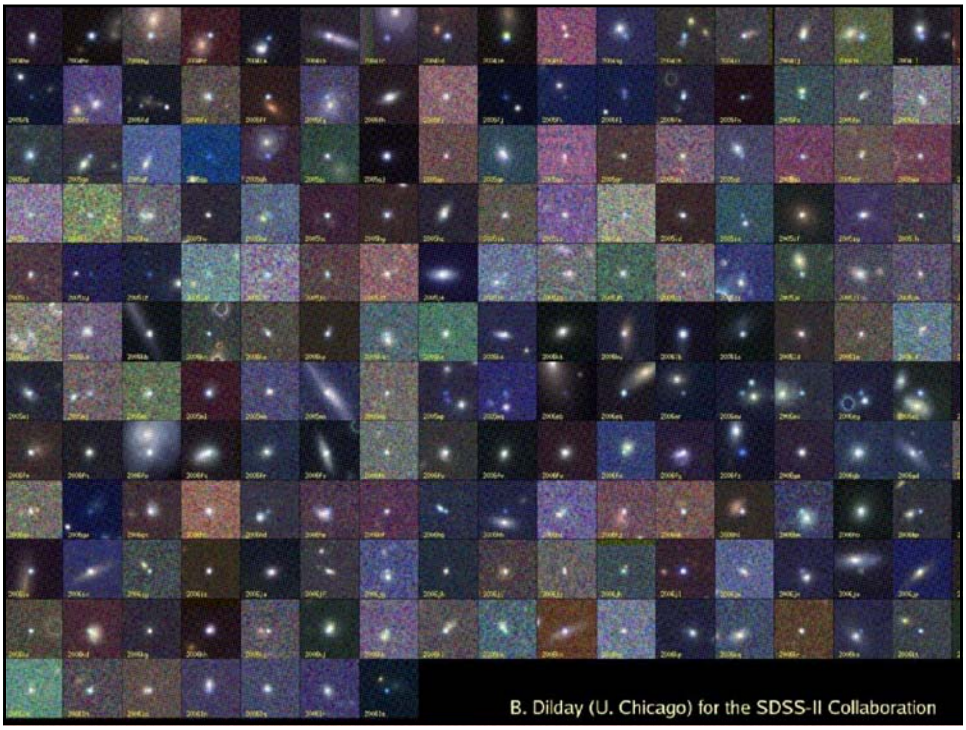
Riess et al. (2004) compilation



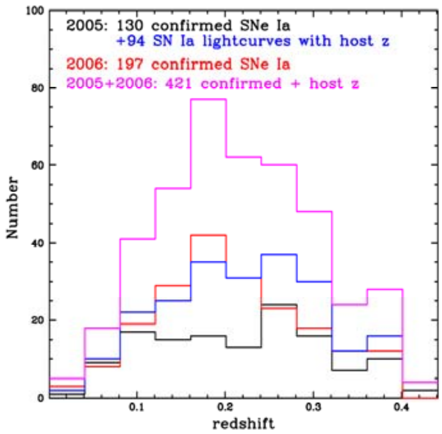
Repeated Imaging of Equatorial Stripe 2005-2008 fall



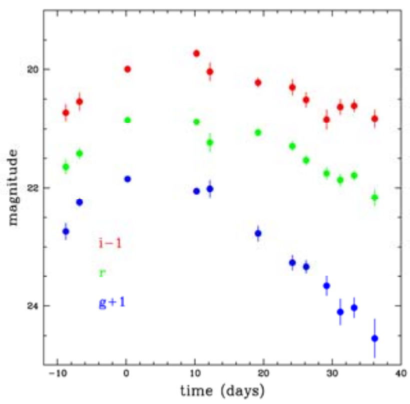
Astier et al. (2005)



SDSS SN survey 2005-2006



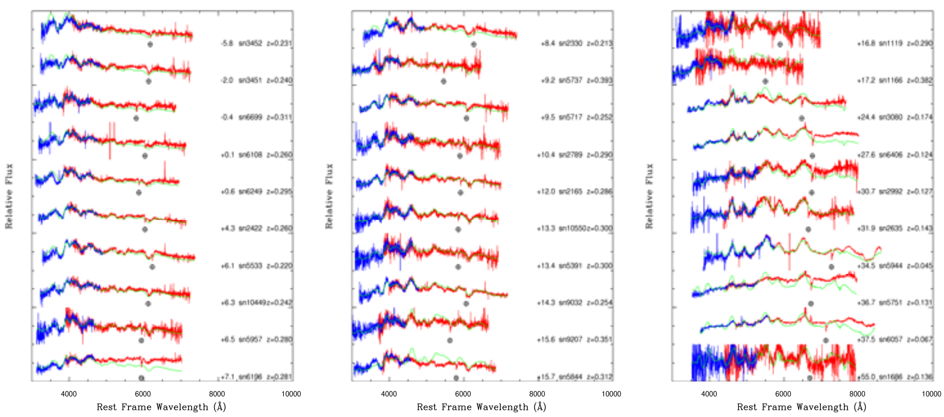
327 spectroscopicaly
Confirmed SNIa



nice light curves

Frieman et al. 2007

Spectroscopy for SDSS SNe →classified ~327 SNIa in 2005-2006
MDM 2.4m NOT 2.6m APO 3.5m NTT 3.6m KPNO 4m
WHT 4.2m Subaru 8.2m HET 9.2m Keck 10m SALT 10m



SDSS SN spectra with Subaru(Yasuda et al.)

→ nearby SN Ia

2005-2006: 50 new SNIa

Frieman et al. 2007, Sako et al. 2007

Supernova Cosmology Project

Suprime-Cam

SCP 2001-

SUBARU 8.2m telescope

33×27 arcmin^2 Field of View

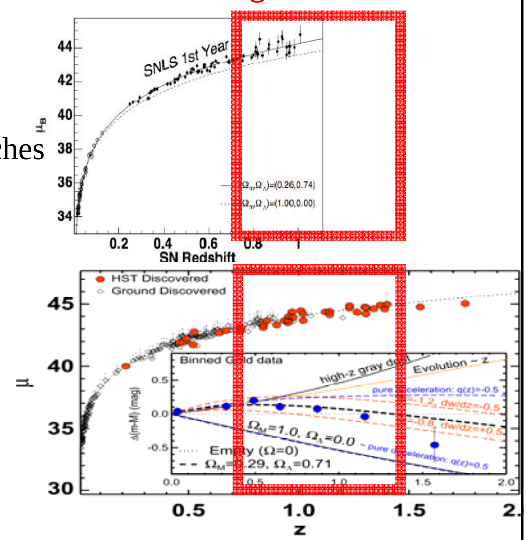
the largest among 8-10m telescopes

High–z SNe by Supernova Cosmology Project

High-z

1. Suprime-Cam Searches
   2001-2002

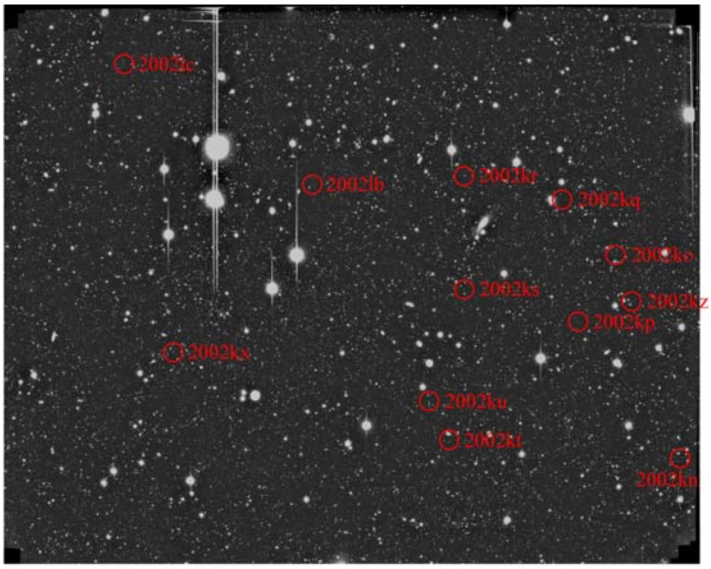
2. HST/ACS cluster Searches
   2005-2006

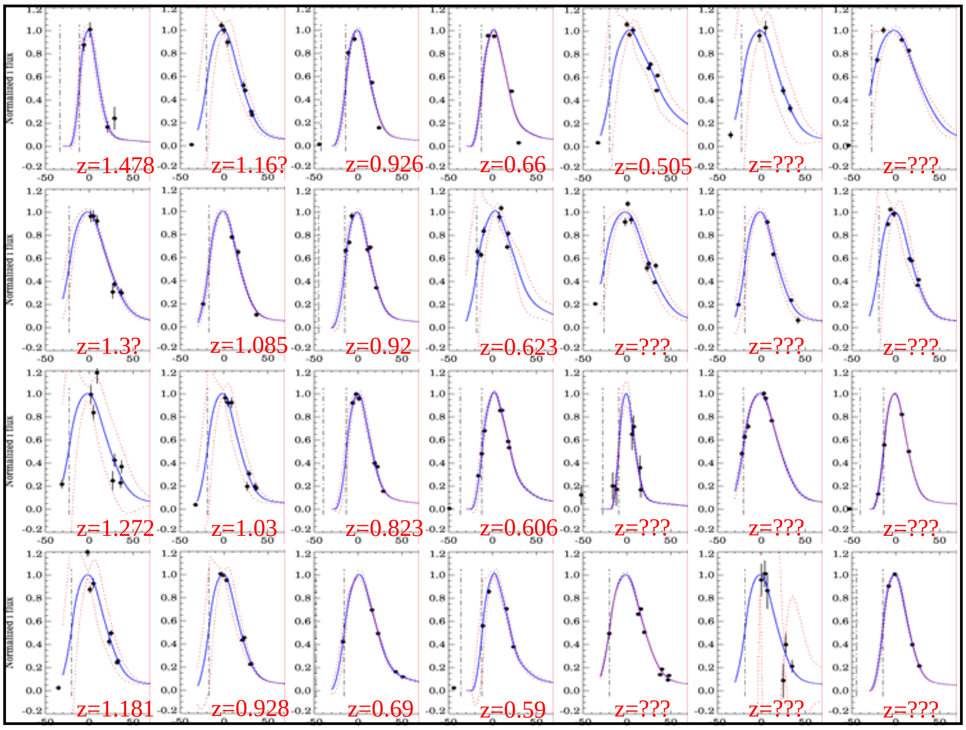


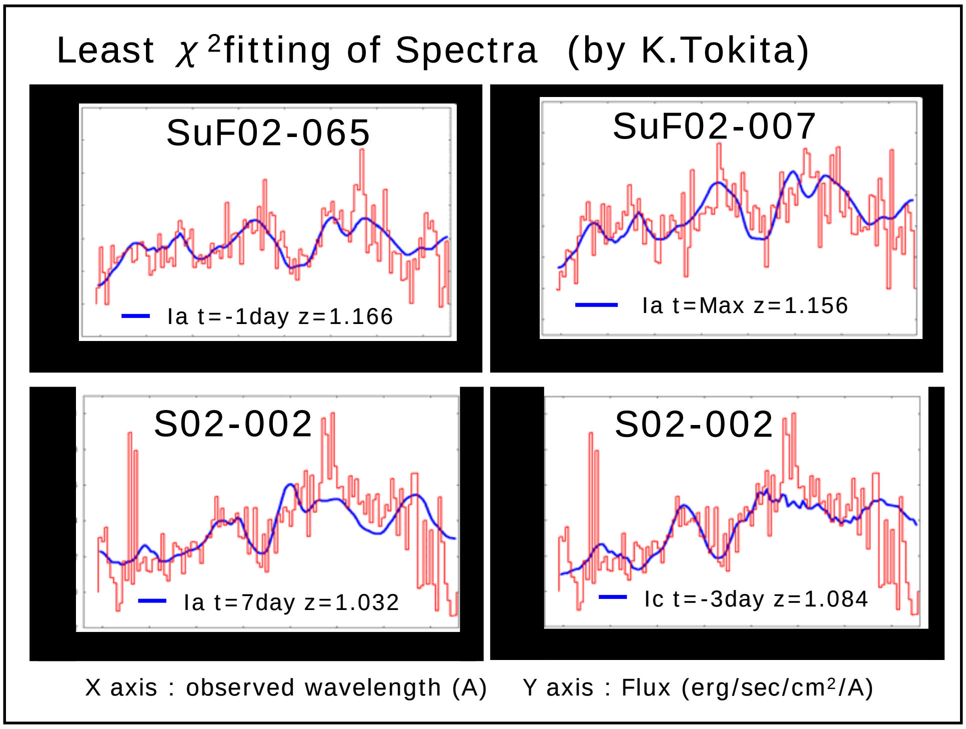
Riess et al. (2006) compilation

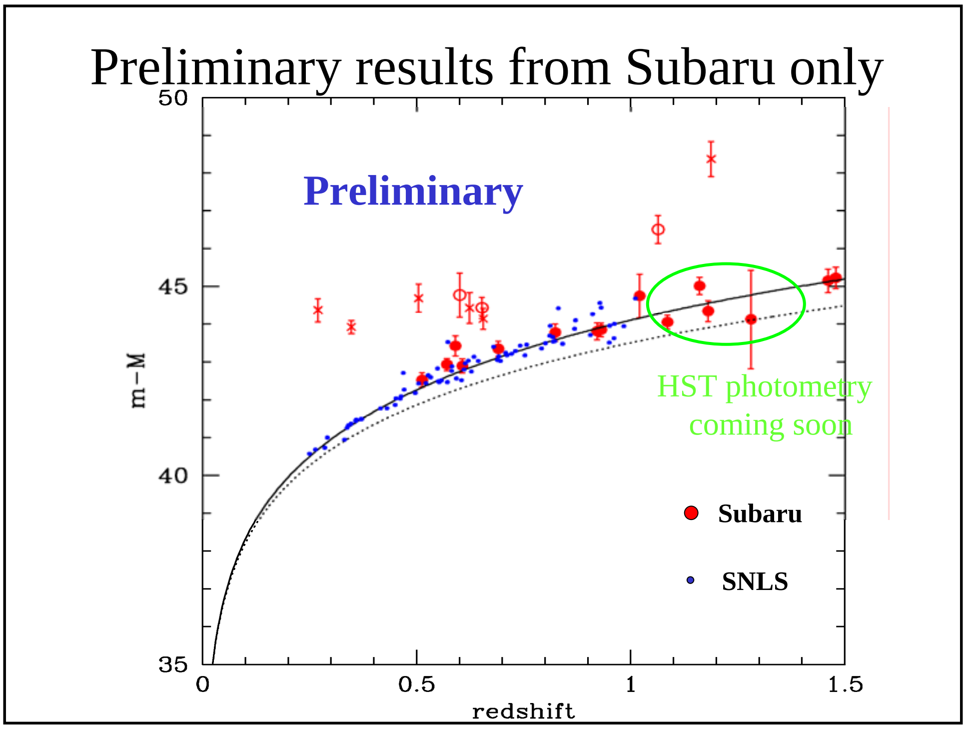
Suprime-Cam@Subaru:
12 SNe per "Shot"

found by Supernova Cosmology Project






Least χ 2fitting of Spectra (by K.Tokita)
SuF02-065
Ia t=-1day z=1.166
SuF02-007
Ia t=Max z=1.156
S02-002
Ia t=7day z=1.032
S02-002
Ic t=-3day z=1.084
X axis : observed wavelength (A)
Y axis : Flux (erg/sec/cm2/A)


Preliminary results from Subaru only
Preliminary
HST photometry
coming soon
Subaru
SNLS
m−M
redshift
50
45
40
35
0
0.5
1
1.5

3.1 Items to be improved for Supernova Cosmology

On-going surveys: 200-700 SNIa in several years

→ systematic errors, high redshift(>0.8)

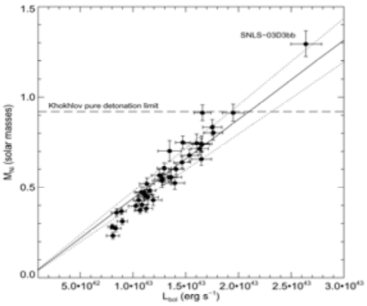
- SNIa as a Standard Candle
  - homogeneity
    - (host environment, progenitor)
  - possible evolution
- Dust extinction due to host galaxy
- K-correction
  - different observed wavelengths → correction
- accurate photometric zero points

SNIa as a Standard Candle

Origin not understood

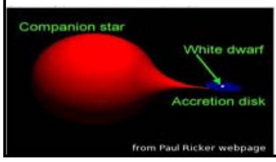
A. Double Degenerate Model

Merging of Two White Dwarfs
(e.g.Iben&Tutukov 1984, Webbink 1984)
A Super Chandrasekar Mass SNIa found?
(Howell et al. 2006)
→ in any case Super Chandra: very rare



B. Mass accretion to the Progenitor (C+O WD) from a companion star

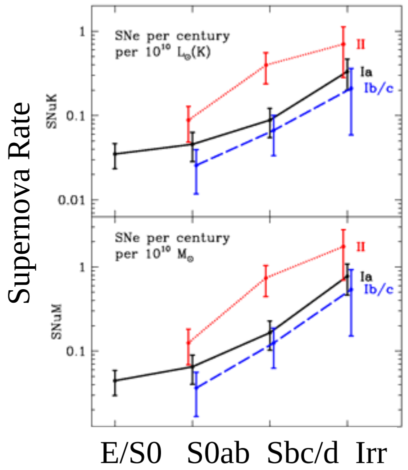
(e.g. Hachisu, Kato & Nomoto 1996, 1999)
A companion star found? (Ruiz-Lupuente et al. 2004)
→ based on line velocity only
not confirmed by other methods yet
(Ozaki and Shigeyama 2006, Ihara et al. 2007)



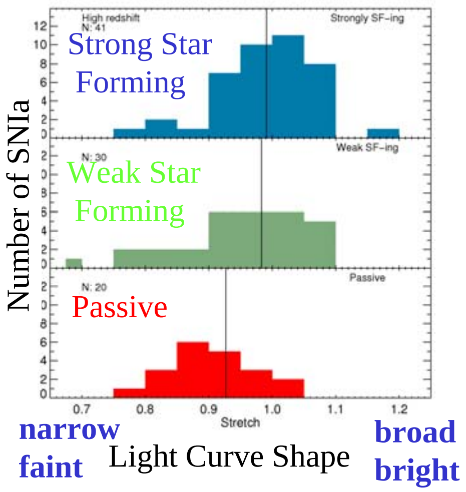
Homogeneity of SNIa

Possible two populations for Type Ia?
SNIa rate is larger for late-type or star-forming host galaxies.

Mannucci et al. 2005



Sullivan et al. 2006



Galaxies

Elliptical S0 Spiral Irregular

Old/Red Stars Young/Blue Stars

Star Formation

Inactive ⟷ Active

SN Ia Rate Evolution?

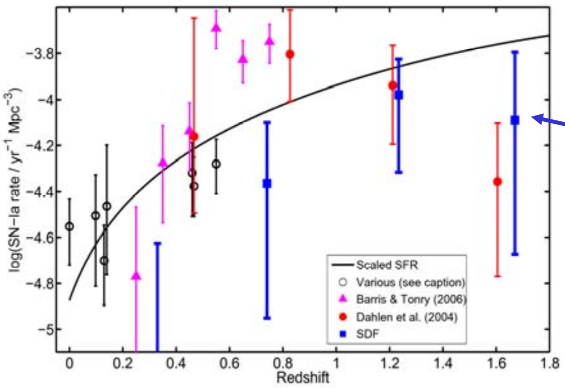
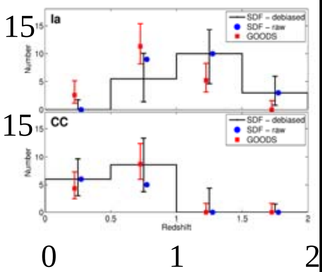


Figure 8. Type Ia SN rate from the SDF, compared to results from the literature (compiled by Neill et al. 2006). Empty circles for Cappellaro et al. (1999), Hardin et al. (2000), Pain et al. (2002), Madgwick et al. (2003), Tonry et al. (2003), Blanc et al. (2004), and Neill et al. (2006); triangles for Barris & Tonry (2006); filled circles for Dahlen et al. (2004); and filled squares for our derived SDF rate. The line shows the SFH from Hopkins & Beacom (2006), scaled to fit the $z < 0.5$ points.

33 SNe with SupC



SNIa 55%
SNII 45%

Poznanski et al. 2007

3.1 Items to be improved, checked for Supernova Cosmology

On-going surveys: 200-700 SNIa in several years

→ systematic errors, high redshift(>0.8)

- SNIa as a Standard Candle
  - homogeneity
    - (host environment, progenitor)
  - possible evolution
- Dust extinction due to host galaxy
- K-correction
  - different observed wavelengths → correction
- accurate photometric zero points

Evolution of SNIa?

Possible evolution of SNIa

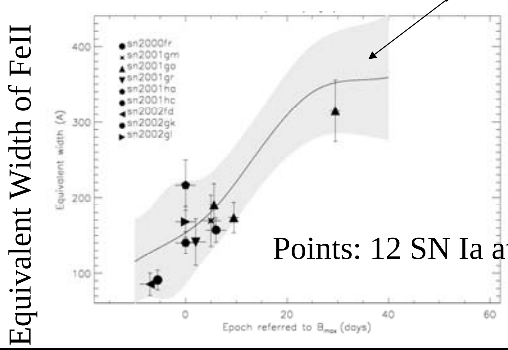
high redshift → lower metalicity

some model predictions (Hoeflich et al. 1998, Lenz et al. 2000)

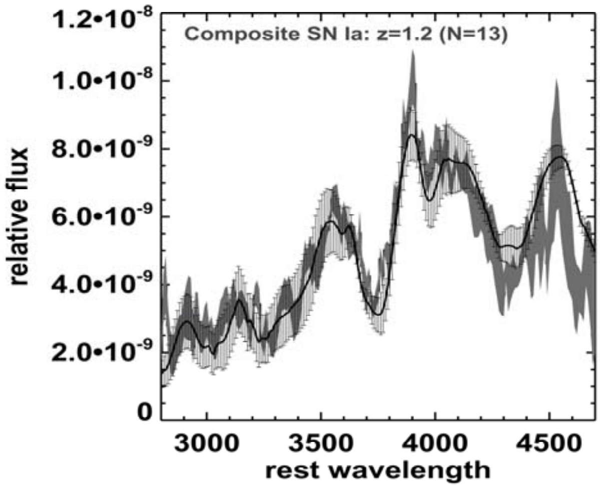
→ weaker optical absorption features, enhanced UV flux, etc.

No clear evolution observed yet

(e.g. Garavini et al. 2007 Altavilla et al. 2007)



Evolution of SNIa? (II)



Riess et al. 2006

Nearby and high-z Spectra: no difference

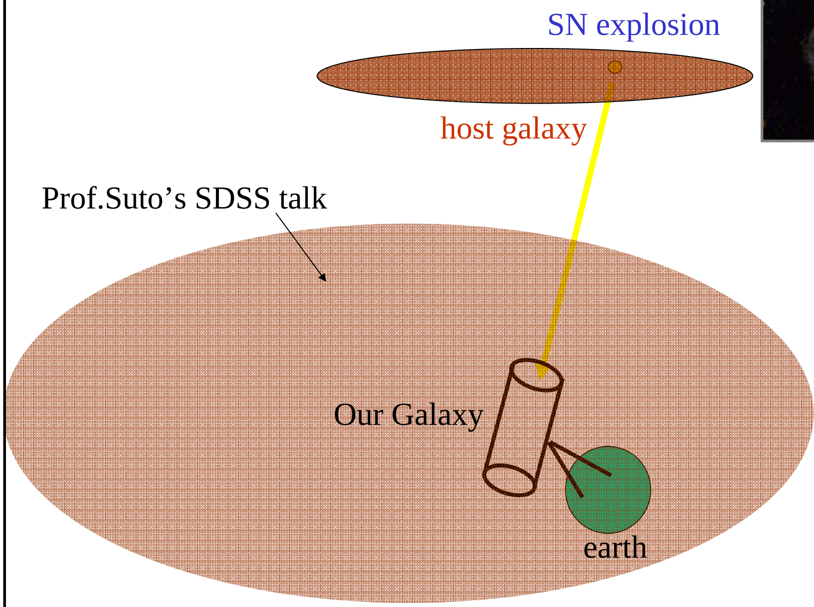
3.1 Items to be improved, checked for Supernova Cosmology

On-going surveys: 200-700 SNIa in several years

→ systematic errors, high redshift(>0.8)

- SNIa as a Standard Candle
  - homogeneity
    - (host environment, progenitor)
  - possible evolution
- Dust extinction due to host galaxy
- K-correction
  - different observed wavelengths → correction
- accurate photometric zero points

Dust Extinction

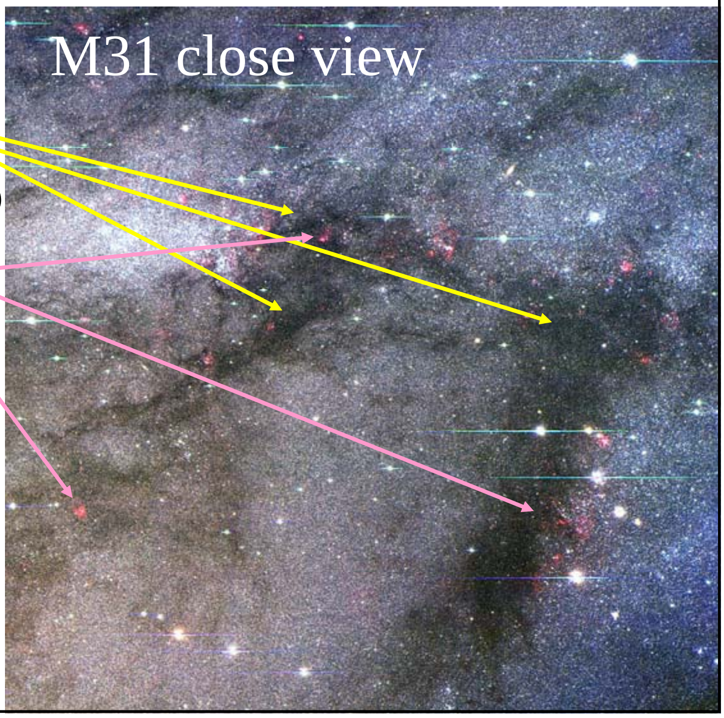


M31

Andromeda Nebula

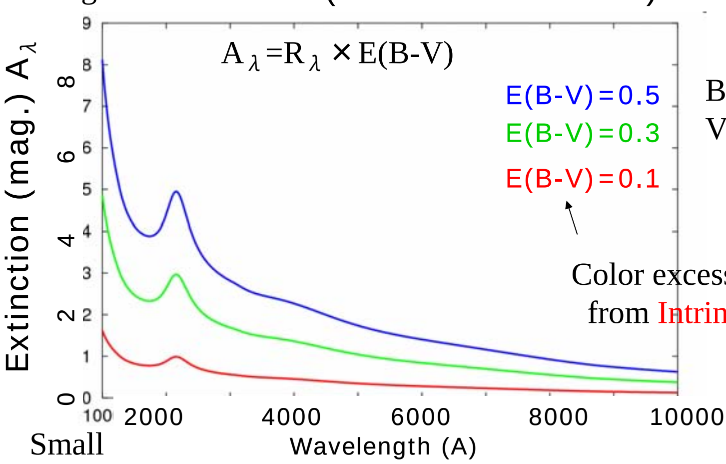
1m Kiso Schmidt

- Dust & Gas
  (Dark Cloud)
- Star Forming Region
  (HII region)



Reddning law (normal galaxy)

Large Rv=3.1 (Cardelli et al. 1989)



B : 440nm
V : 550nm

Color excess
from Intrinsic color

Small

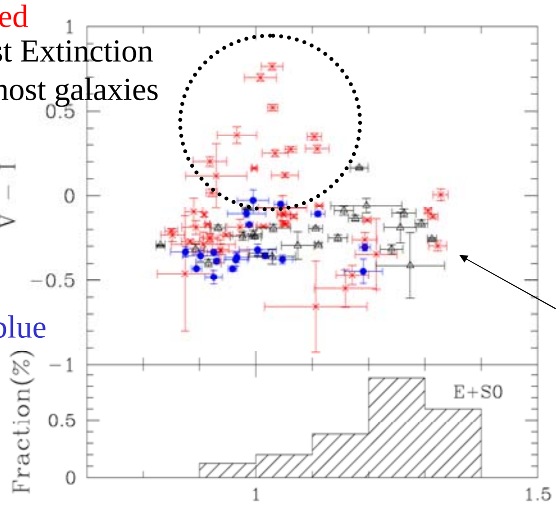
Different Extinction Correction
among different analysis code (MLCS2k2, SALT, SALT2, …)

Optical color of SNIa

Not simple e.g. Conley et al. 2007 ⇔ “Hubble Bubble” Jha et al. 2007

red

Dust Extinction in host galaxies



blue

Decline Rate

Blue in B-V

B : 440nm
V : 550nm
I : 800nm

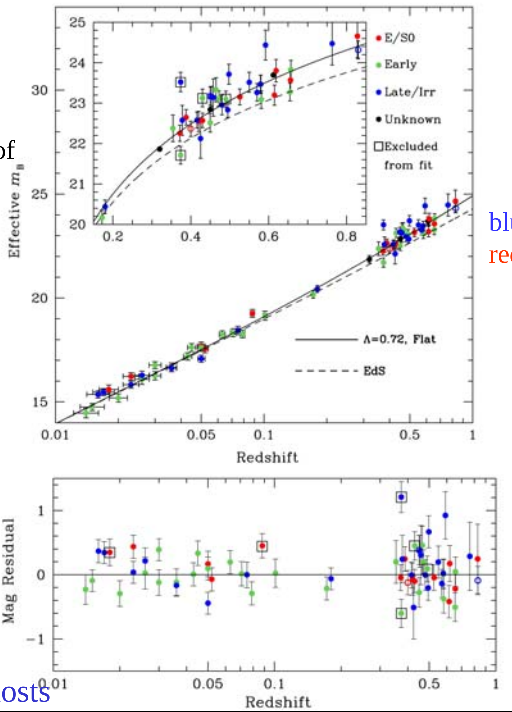
Intrinsic Color Dispersion?
Dust property Different?
e.g. Altavilla et al. 2005

Takanashi et al. in prep.

Host extinction

Sullivan et al. 2003

Host galaxy morphology of SNe with HST



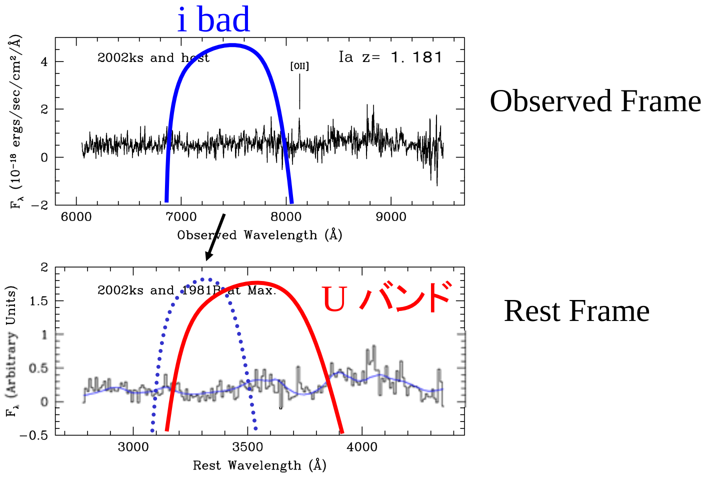
blue : late type
red : E/S0

E/S0
σ =0.16 mag
⇔
All sample
σ ~0.5 mag

→SNIa in Elliptical hosts

K correction

flux correction between
rest wavelength & observed wavelength



SNIa spectra (as a function of time) should be well known
Band Pass Shape should be well known

On going Large SNIa surveys

redshift	Projects
z~0-0.3	Supernova Factory
~1-2.5m	SDSS
z~0.3-0.8	SN Legacy
~4m	Essence
z~0.8-1.5	SCP
~8m, HST	Higher-z

→Methods & understanding of SNIa to Improved
as well as real measurements

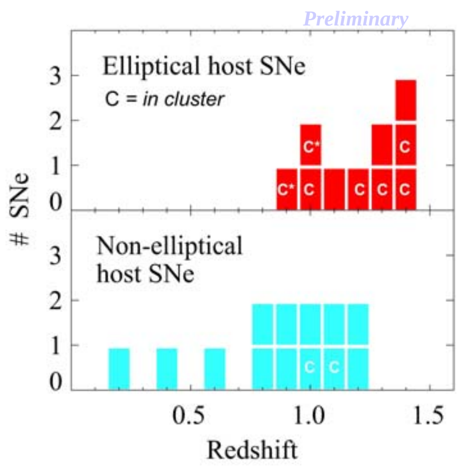
High-z Cluster surveys by SCP (2005-2006)

HST imaging (S.Perlmutter et al)	219 orbits
Subaru spectroscopy (M.Doi et al.)	14 nights
VLT spectroscopy (C.Lidman et al.)	16 hours+DDT
Keck spectroscopy (S.Perlmutter et al.)	6 nights+

with cluster search/study teams
- RCS (Gladders, Yee et al.)
- RDCS (Rosati et al.)
- IRAC (Eisenhardt et al.)
- XMM (Mullis et al.)

RDCS 1252.9 @ z=1.23 (ISAAC and ACS)

SNe Discoveries in HST Program

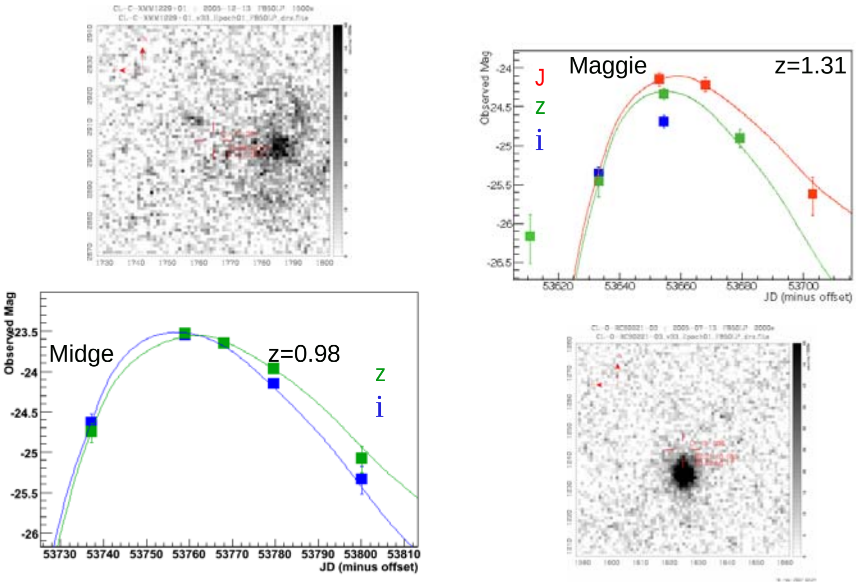


Efficiency to find SNe on ellipticals

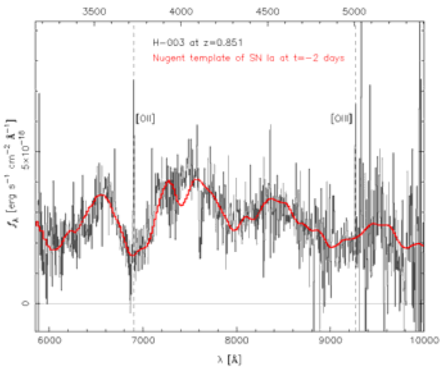
higher ← clusters

Successfully 10 SNe found on ellipticals

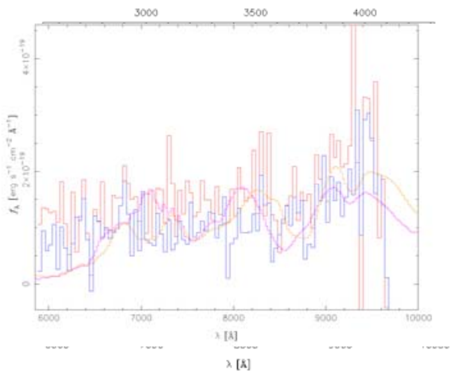
SN Lightcurves



Example spectra with FOCAS



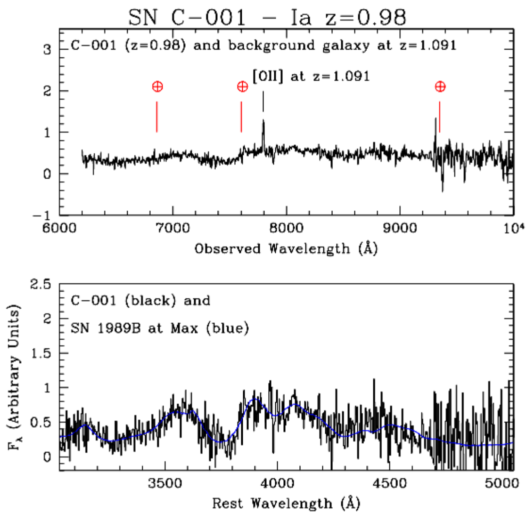
z=0.851

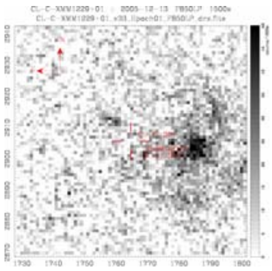


z=1.3

Spectroscopic follow-up - II

An example of a clear Ia



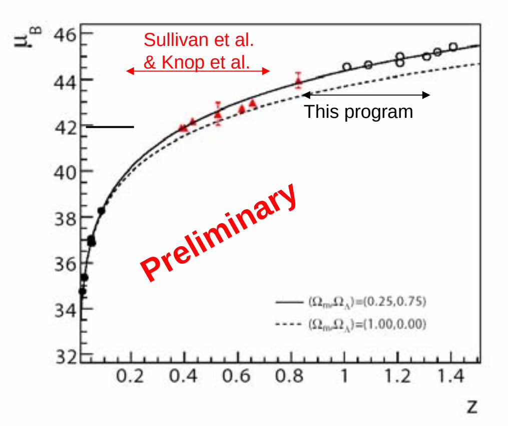


FORS2, Antu

by C.Lidman

The Elliptical host Hubble Diagram

Example of E–only Hubble Diagram



7 SNe Ia from this program.

Another 13 SNe Ia at lower z from published works.

No extinction correction

Surprisingly small scatter

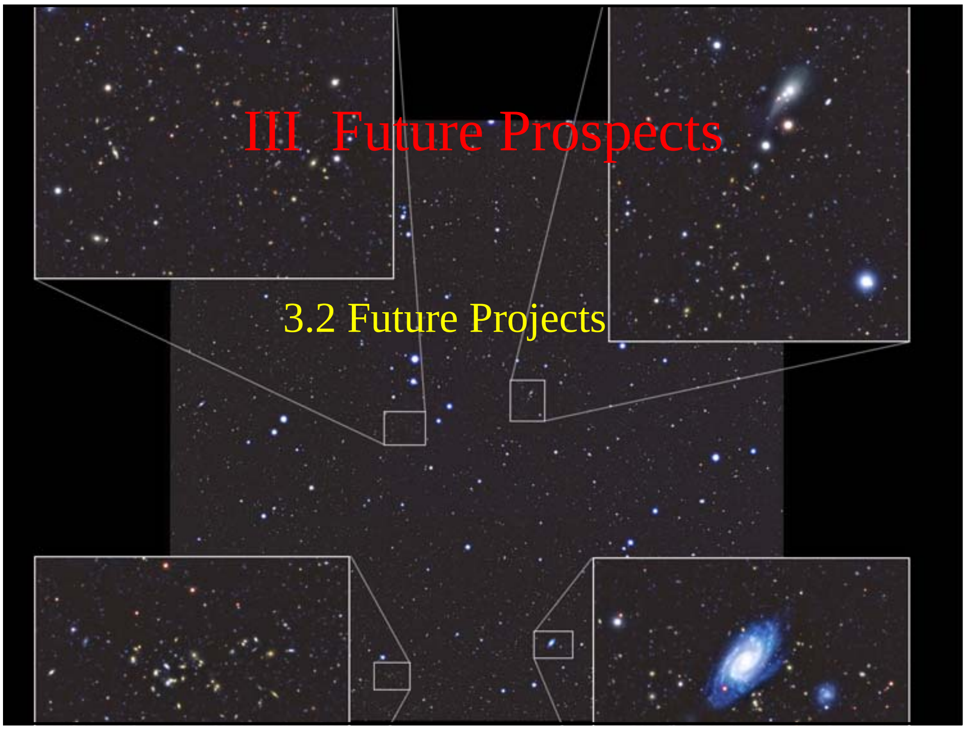
Blind analysis (we will not know the answer until we remove the blind).

Unfortunately HST/ACS is broken!

SCP

III Future Prospects

3.2 Future Projects

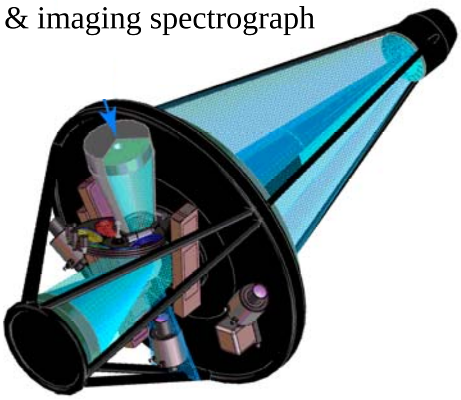


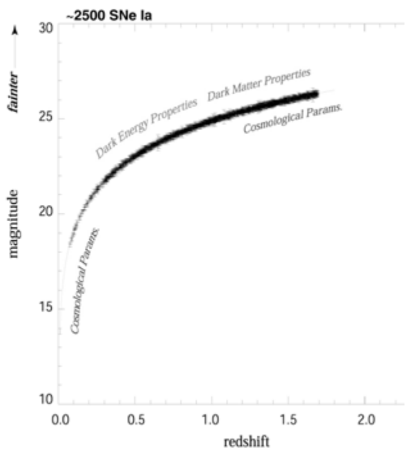
SNAP (SuperNova Acceleration Probe)

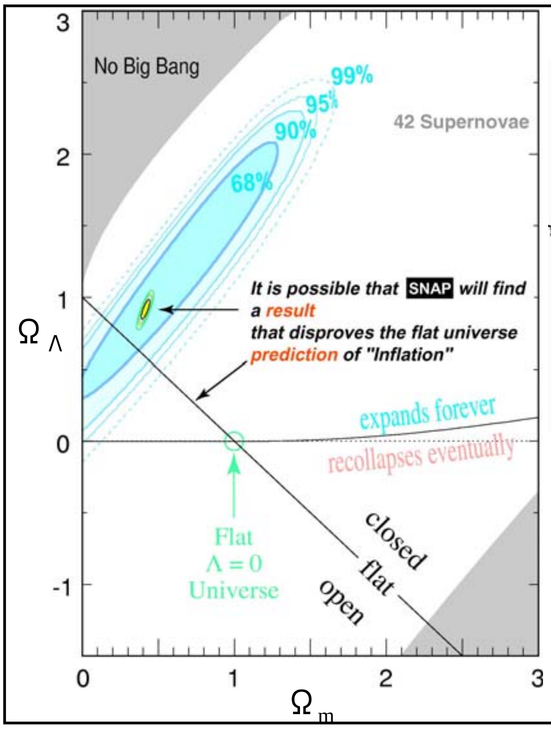
- 2m wide-field space telescope

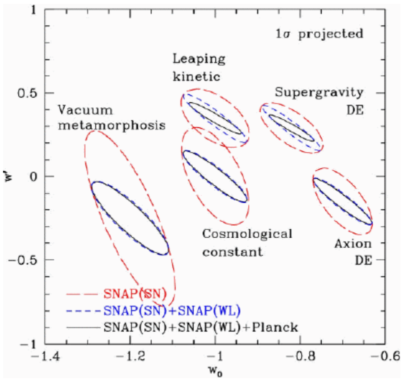
10 years later???

Wide-field camera
& imaging spectrograph









DUNE (Dark Universe Explorer)

1.2-m Space Telescope 0.5 sq. degree Refregier et al. 2007

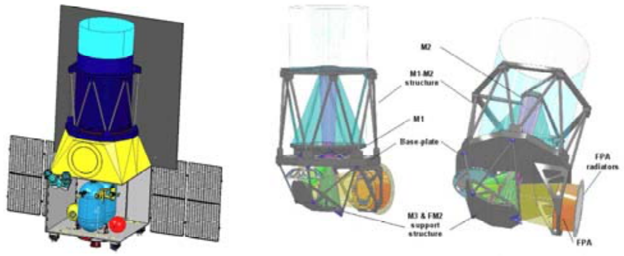
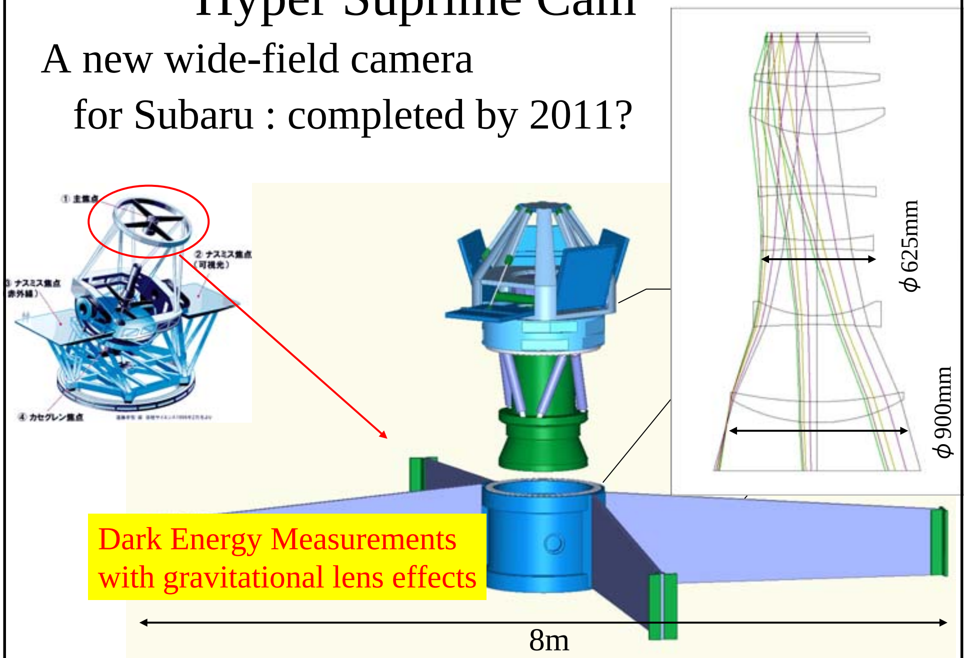


Figure 6. Spacecraft configuration with the Mars Express propulsion module (left). Payload Module with the telescope, focal plane assembly, filter wheel and SiC structure (right).

Weak Lens
SNe

Hyper Suprime Cam

A new wide-field camera
for Subaru : completed by 2011?



Wide Field Imagers

Survey power
(for same image quality)

Camera Name	Telescope D [m]	Telescope A [m²]	Telescope F	CCD Vendor	CCD Format	CCD N_{CCD}	FOV Ω [deg²]	AΩ	First Light
WFPC2	2.5	3.46	12.9	Loral	800×800(15)	3	0.0015	0.01	Dec-93
UH8K	3.6	9.59	4.2	Loral	4k2k(15)	8	0.25	2.40	Sep-95
SDSS	2.5	3.83	5	SITe	2k2k(24)	30	6.0	22.99	May-98
NOAO8K	3.8	9.98	2.7	SITe	4k2k(15)	8	0.36	3.59	Jul-98[a]
CFH12K	3.6	9.59	4.2	MIT/LL	4k2k(15)	12	0.375	3.60	Jan-99
Suprime-Cam	8.2	51.65	2.0	MIT/LL	4k2k(15)	10	2.555	13.17	Jul-99
MegaCam	3.6	9.59	4.2	Marconi	4.5k2k(13.5)	40	1	9.59	Jan-03
VISTA Opt.	4.0	11.33	1.0	Marconi	4.5k2k(13.5)	50	2	22.67	2010?
LSST[b]	8.4	46.34	1.25				(7.1)	329	2012?
PanSTARRS	3.6(4)	10		MIT/LL			7	50	2007-09?
DarkEnergyS.	4.0	10		LBNL			3	30	2009?

Future

Hyper Suprime: New Wide Field Corrector for Subaru ~1.5° φ?
AΩ>~100 (FoV ×9 of Suprime-Cam)

Advantage of HSC

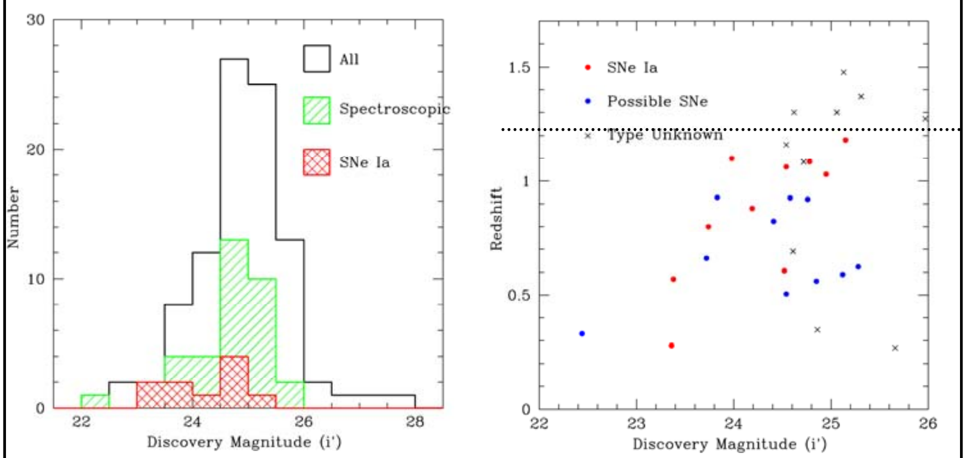
- Large aperture
  - Other SN surveys except for LSST use 4m telescopes
  - SN Ia samples are limited to z<0.9
    → Extend to z~1.2
- Wide field
  - 1FoV is comparable to survey area of SNLS
- High sensitivity in red bands (z-, Y-band)
  - Most energy of SN Ia @ z=1 fall in z-band

- 1,000 SNe @ z=0.6-1.2
  from 4FoV and 3month duration observation

Suprime-Cam searches 2002

~1 hour / exposure, ~5epochs, 5 SupC fields

Yasuda et al. 2004



Spectroscopic follow-up

z~<1

WFMOS   >50SNe/night?

z~>1

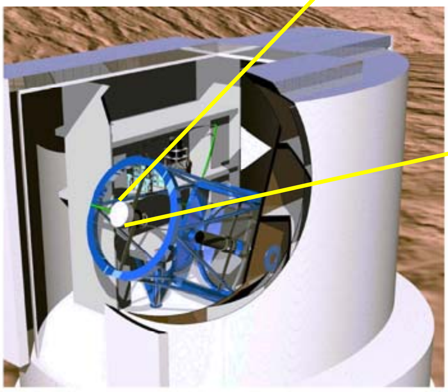
Adaptive Optics with a Laser Guide Star

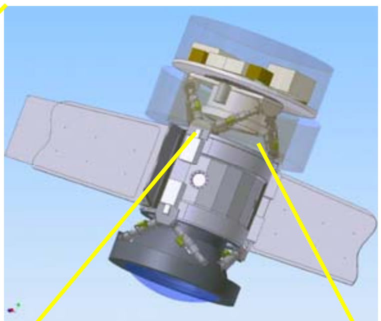
→ sharp PSF

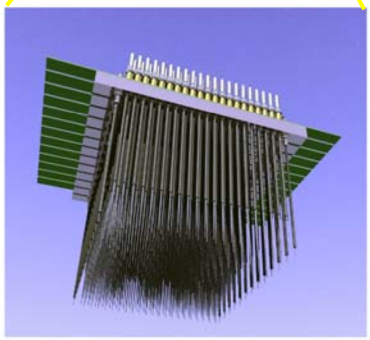
→ several SNe/night?

→ ability to make a new set of SNe quickly and efficiently

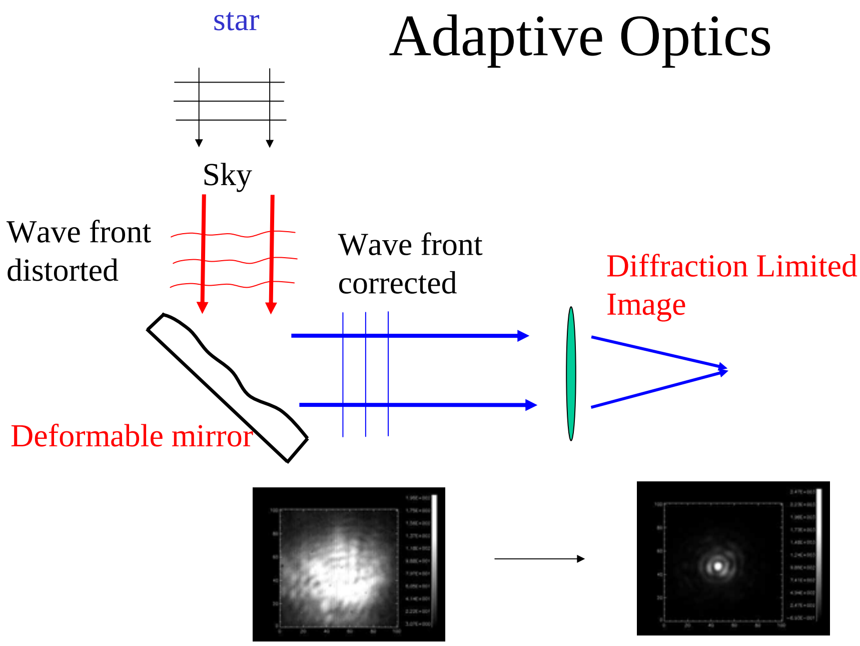
WFMOS (multi fiber spectrograph)
to Subaru?   4000spectra at the same time







Adaptive Optics



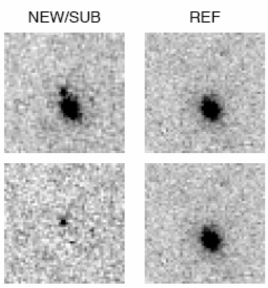
LGAO for distant SNe

KeckII+NIRC2+LGAO

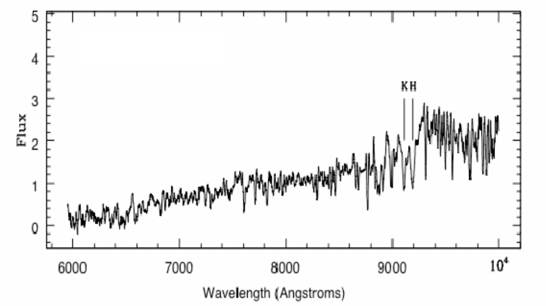
Rest-Frame R-band Lightcurve of a $z \sim 1.3$ Supernova Obtained with Keck Laser Adaptive Optics

Melbourne et al. 2006

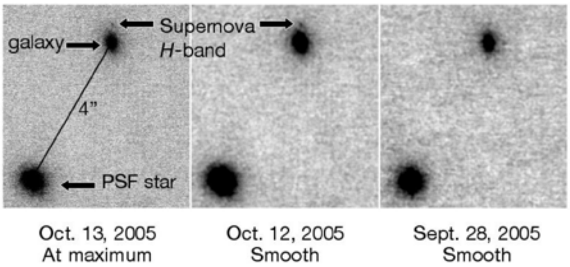
Found with HST/ACS

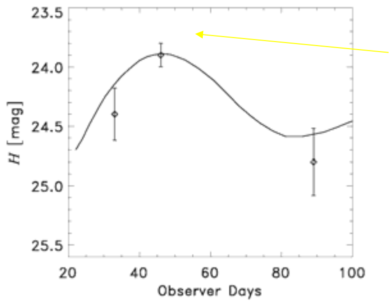


Spectroscopy with Subaru/FOCAS



Keck+LGAO+NIRC2





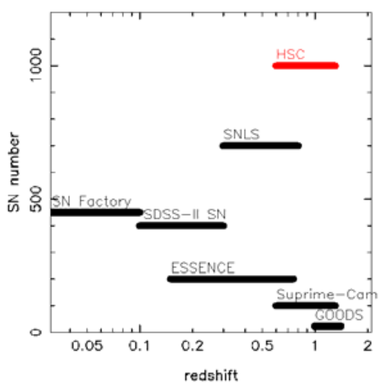
H=23.9±0.14mag
Exposure time 3600sec
PSF(FWHM) 0.053 arcsec

Pretty good accuracy

Comparison with on-going SN Surveys

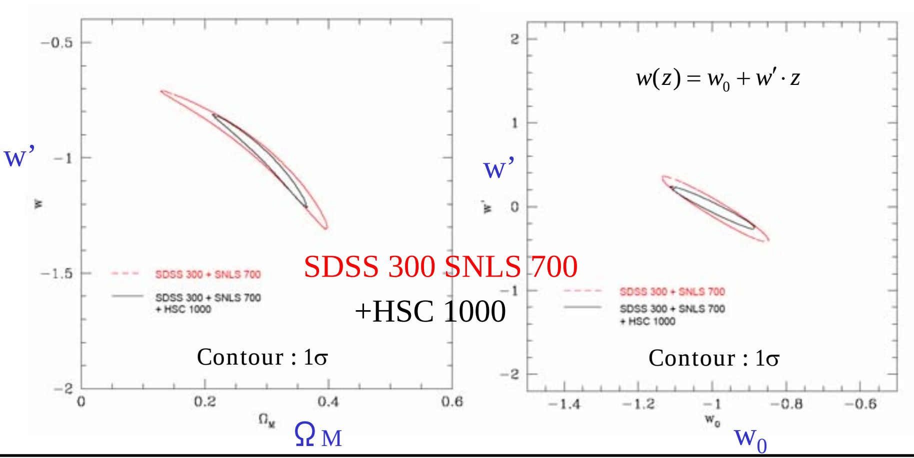
- SDSS-II : ~60nights/yr x 3yrs (2.5m) 0.1 < z < 0.3
- SNLS : ~60nights/yr x 5yrs (3.6m) 0.3 < z < 0.8
- HSC : ~30nights/yr x 1yr (8.2m) 0.6 < z < 1.2
  - 1,000 SNe from 4FoV, 3months
  - Much cheaper than HST

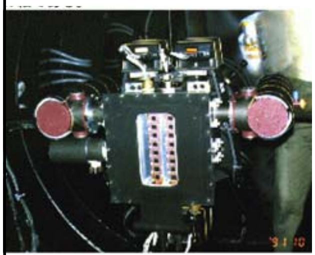
Many items to be improved for SNIa as standard candles by 2011



Cosmology

- Errors on Ω_M and w reduce by a factor of 2
- Area encircled reduce by a factor of 2





1991 1kx1k CCDx16
1.05m Kiso Schmidt Tel.

1994 1kx1k CCDx40
Las Campanas 1m
WHT 4.2m

2000 4kx2k CCDx10
8.2m Subaru

Dr. Maki Sekiguchi

1999 2kx2k CCD x30
2.5m Sloan Digital Sky Survey


END