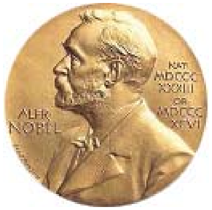
第五回超弦理論と宇宙　2012年2月22日　別府望海

超新星を使ったダークエネルギー測定

土居　守

東京大学・理・天文学教育研究センター

チリ・サンペドロデアタカマよりチャナントール領域を望む



The Nobel Prize in Physics 2011

Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

Supernova Cosmology Project

High-z Supernova Search Team

"for the discovery of
the accelerating expansion of the Universe
through observations of distant supernovae"

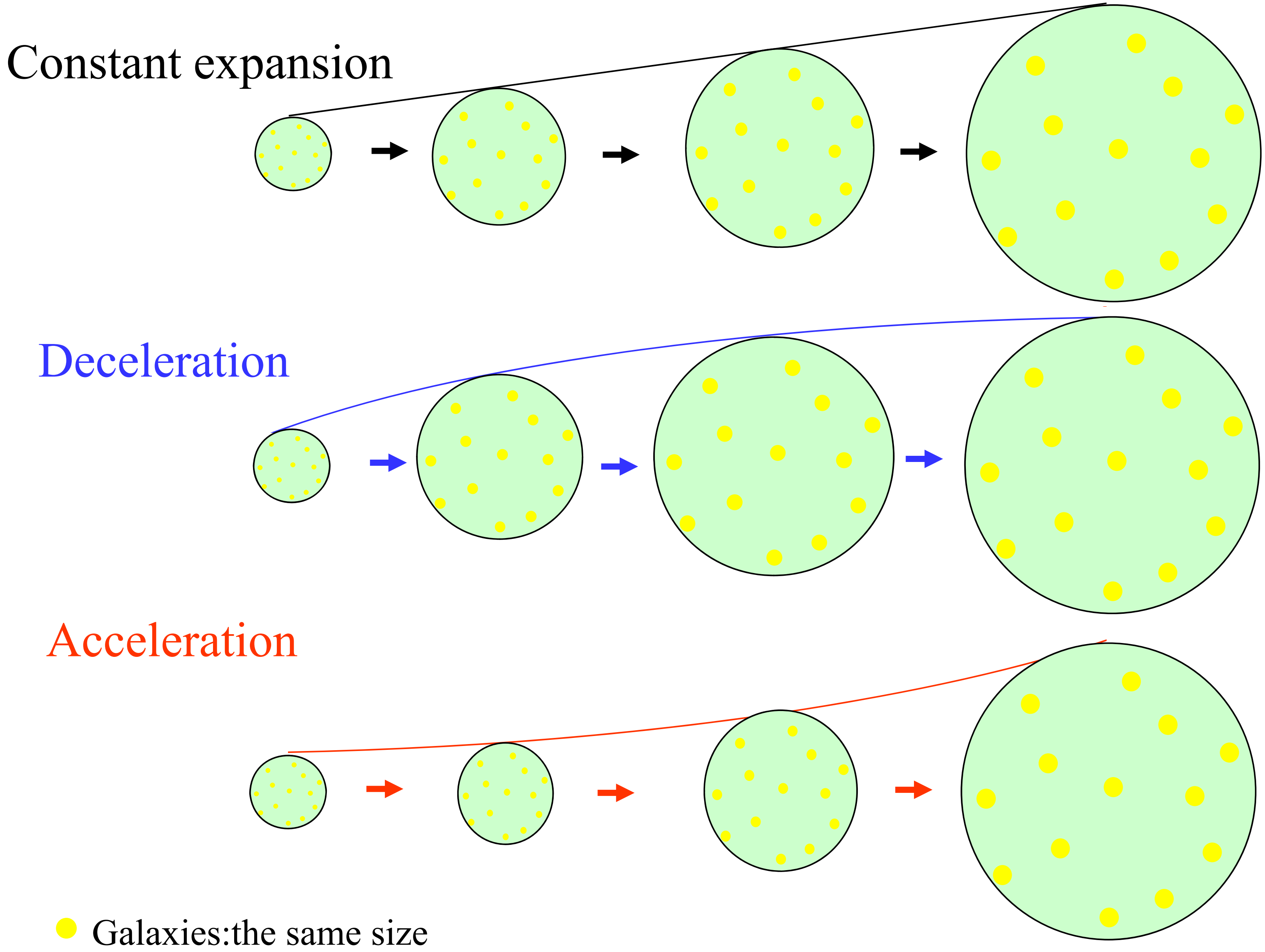
Congratulations!

Contents

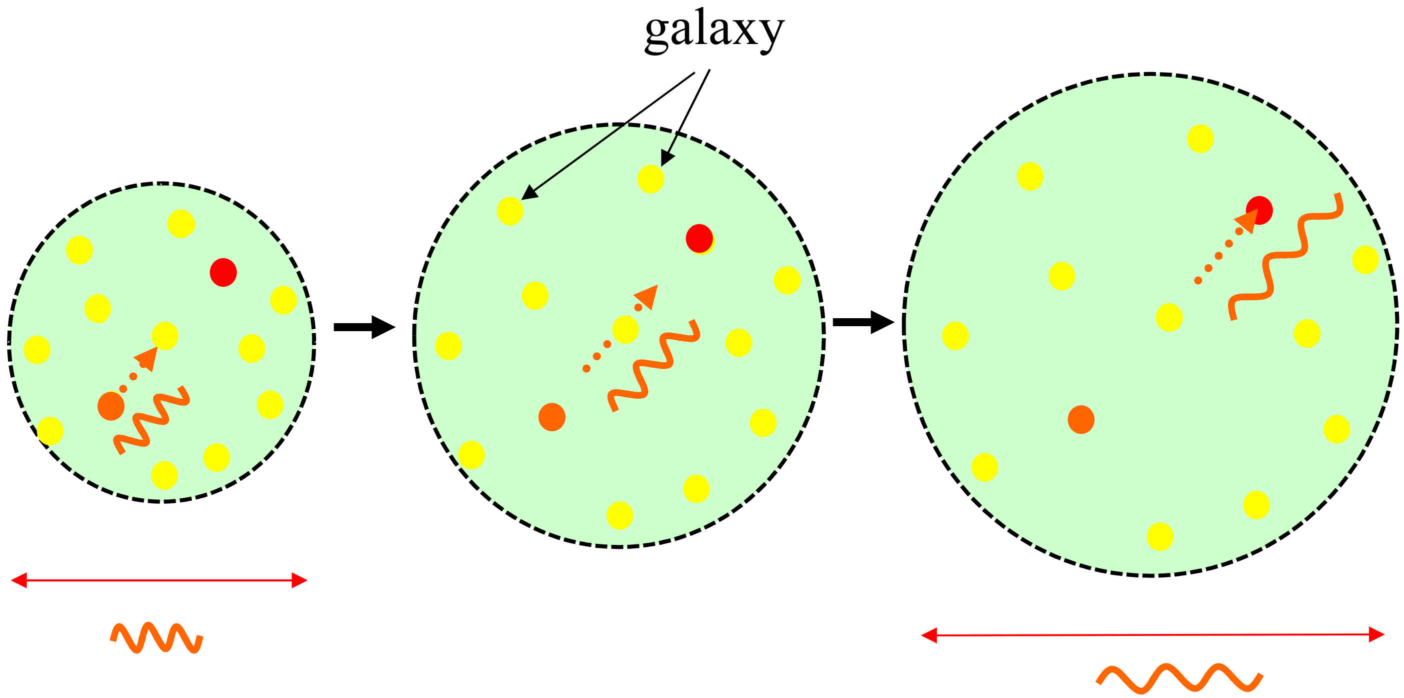
- Supernova Cosmology
  method and “break through”
  Recent SCP results

- Future prospect
  SNIa property
  NIR observations

How to measure expansion history of the universe

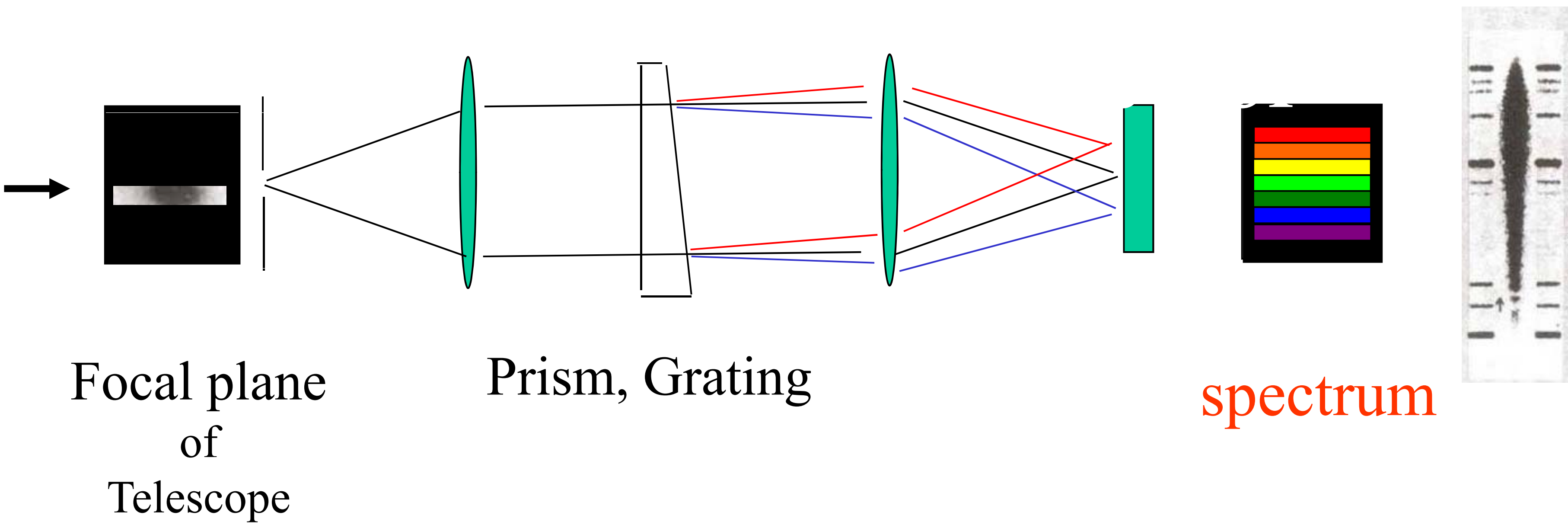


Scale factor of the universe ← Redshift

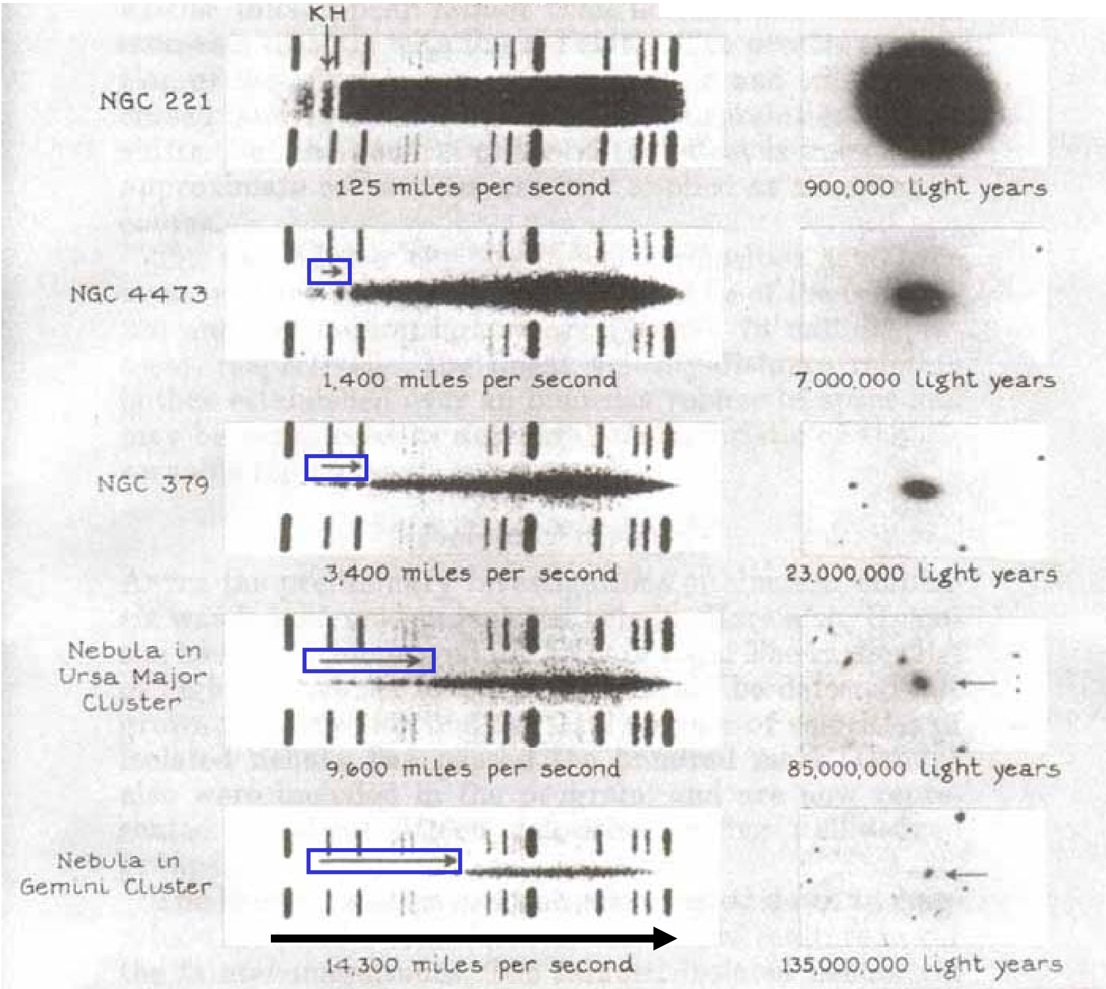


The wavelength of light from the distant object (1+z) is proportional to the scale factor due to Expansion of the Universe

spectroscopy



spectra image



(900,000 light years)

(7,000,000 light years)

(23,000,000 light years)

(85,000,000 light years)

(135,000,000 light years)

short (blue) wavelength long (red)

From “Realm of the Nebulae” (1936)

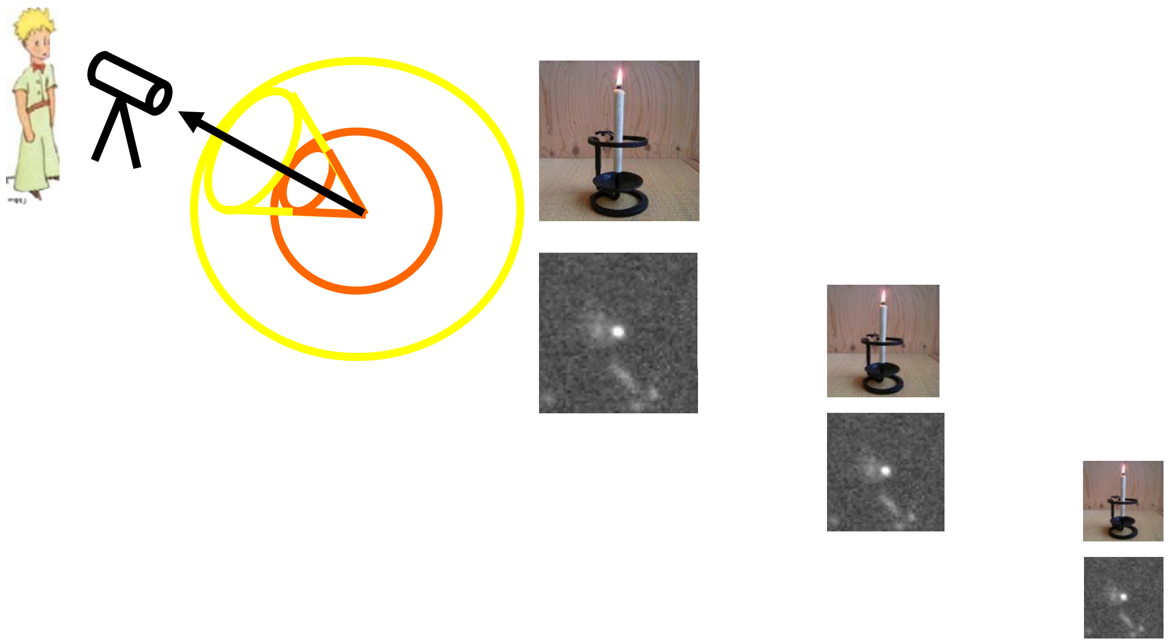
Wavelength : Longer as distance becomes larger.

How to measure Distance & Time

Ratio of apparent brightness → distance

→ time

(÷speed of light)



& cosmological expansion, general relativity

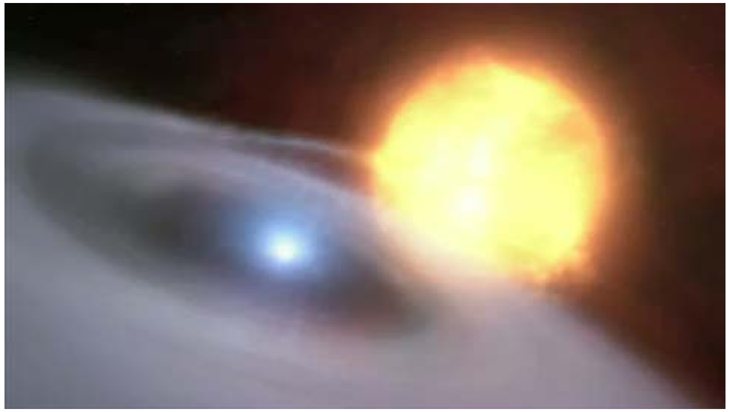
Type Ia Supernova

- Standard Candle (Luminosity~constant)

  a nuclear time bomb, C/O WD

  too heavy (~1.4 x M_sun) → thermo-nuclear explosion

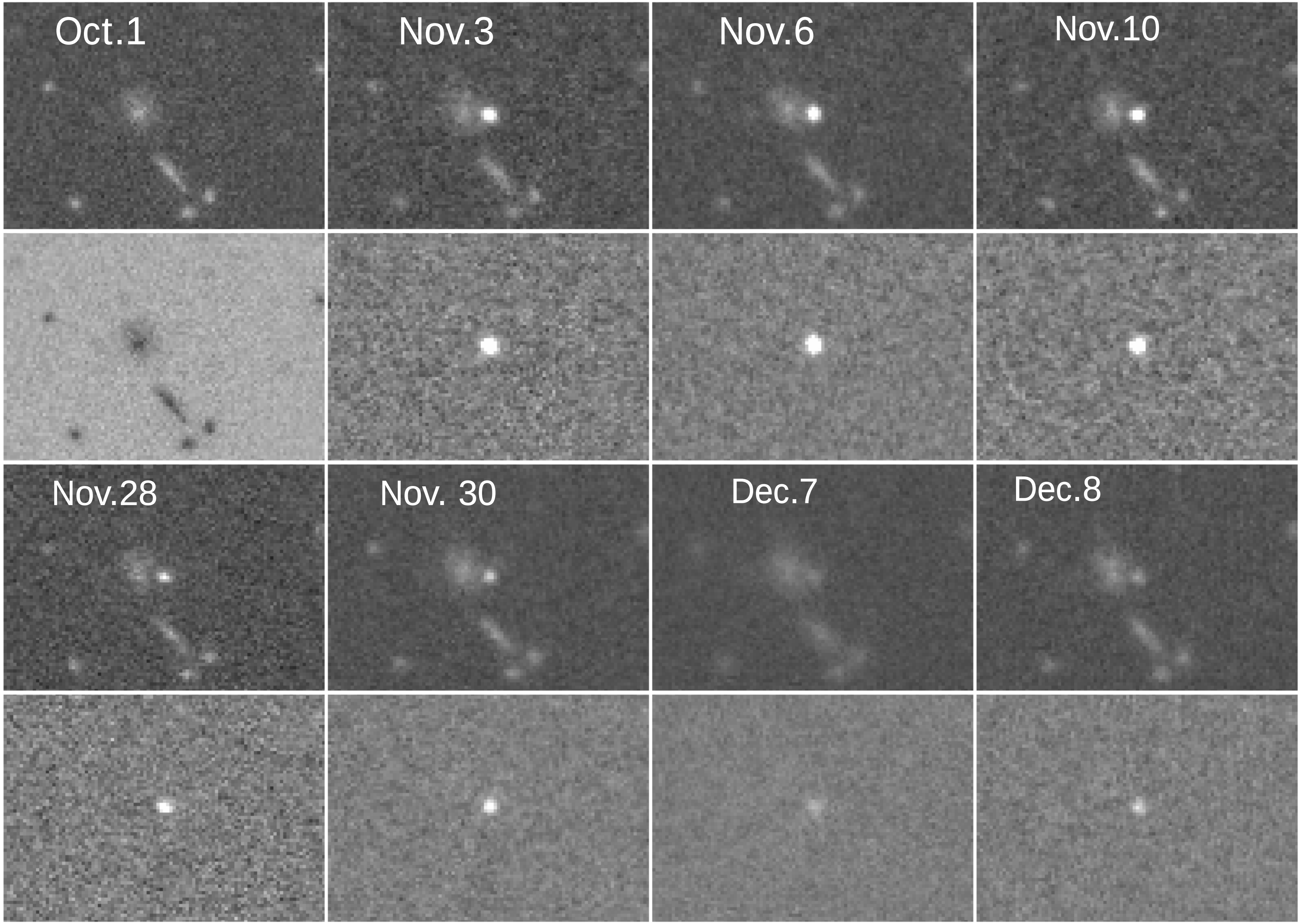
  Chandrasekhar 1931



Picture: Single Degenerate model
⇔
Double Degenerate model

- Large Luminosity (~whole galaxy)

  → measurable at cosmological distance



SN luminosity varies

SN2002kp（z=0.928）

Luminotity of SNIa: not exactly constant

By N.Takanashi

brighter SNIa

→ larger time scale

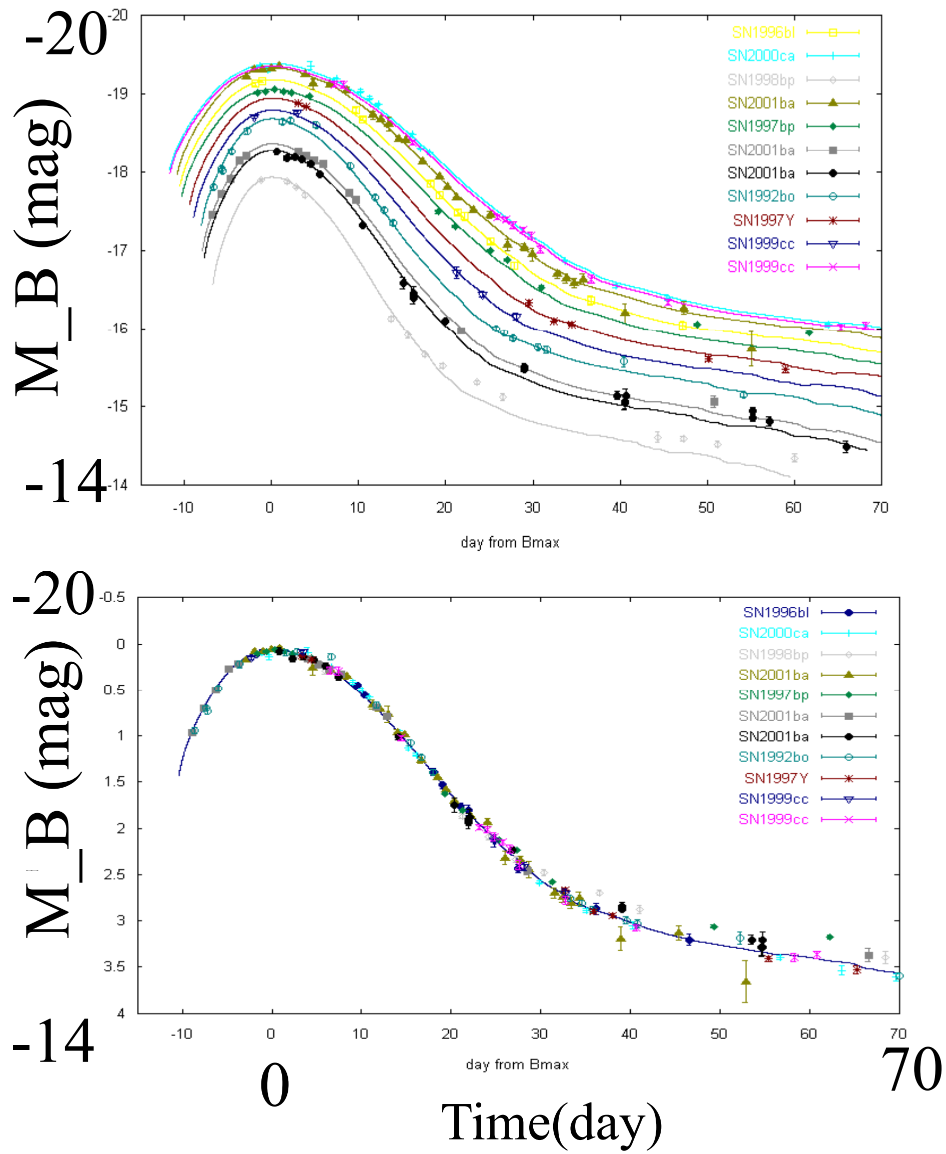
in light curve

Correction based on light curve is possible.

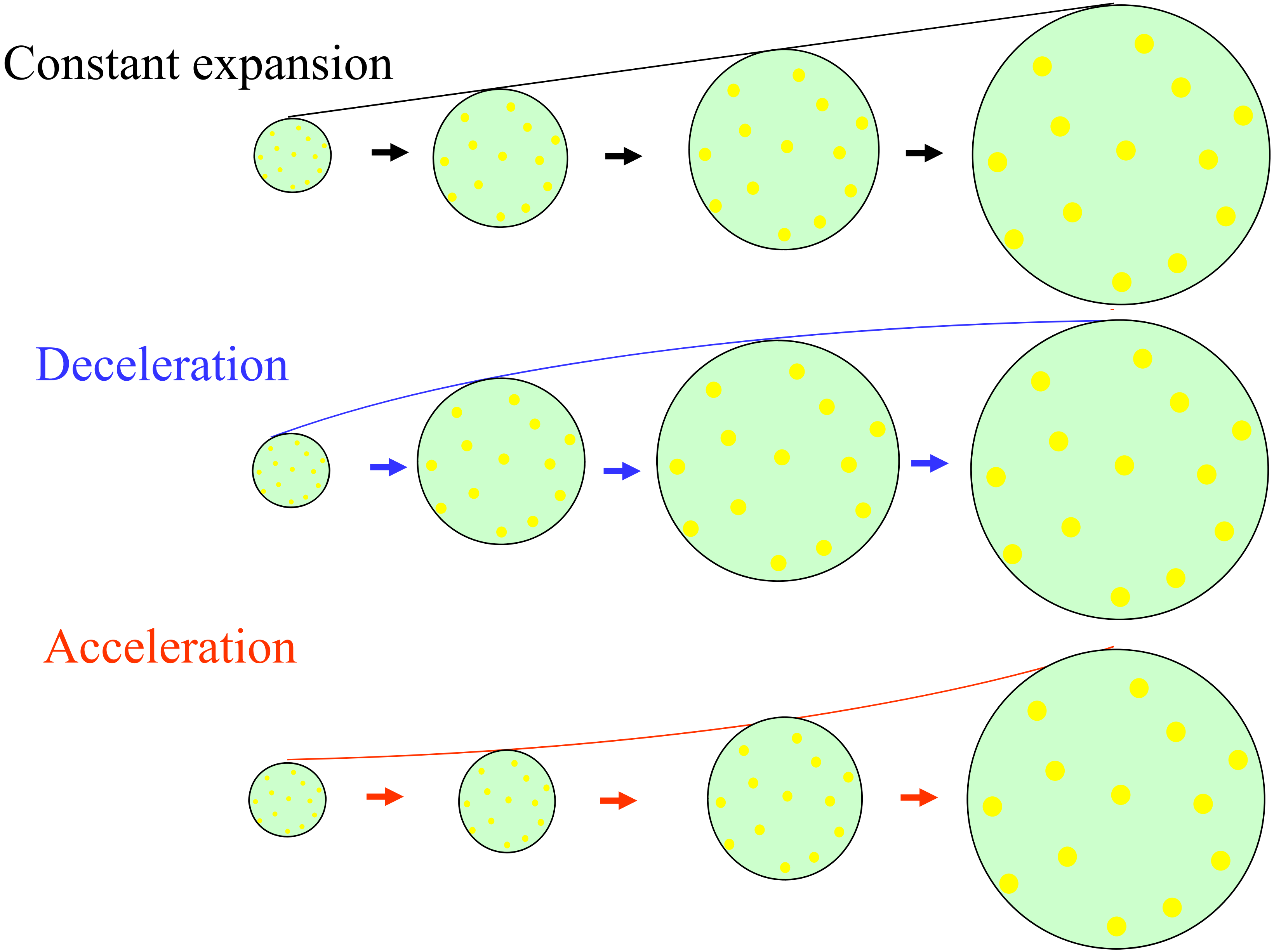
Error in luminosity ~ 15%

Phillips 1993

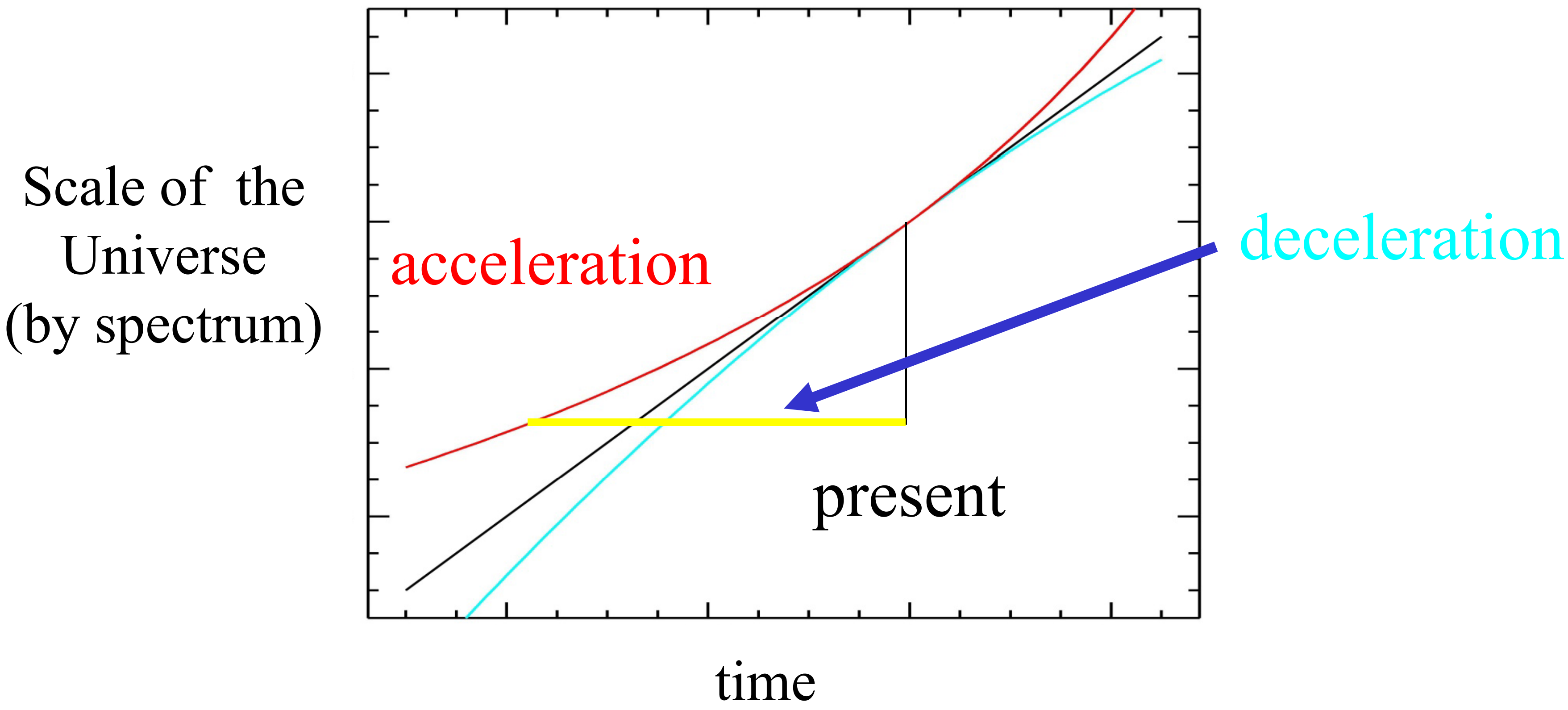
(Asymmetric explosion →Maeda et al. 2011)



How to measure expansion history of the universe



How we can measure acceleration/deceleration



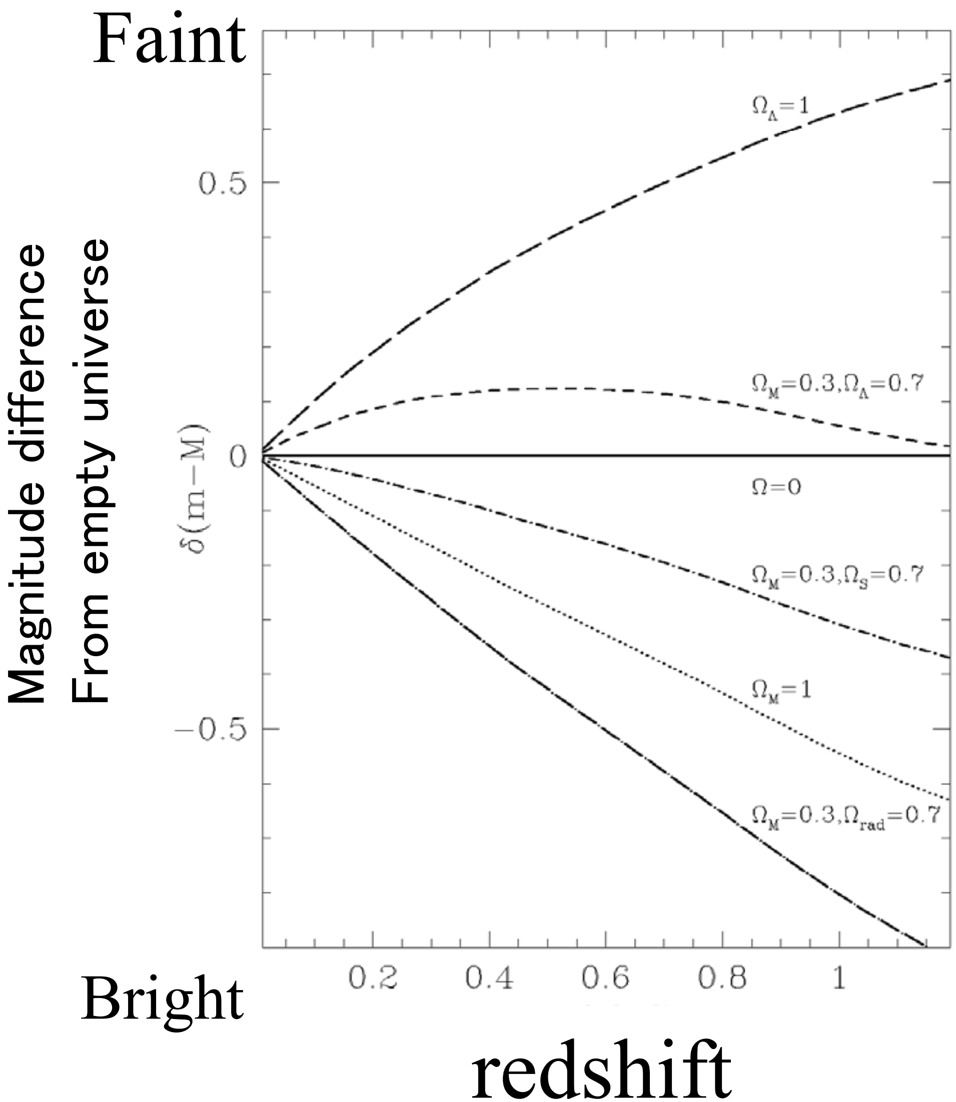
Expanding speed : accelerate (decelerate)

light travels longer (shorter) than constant expansion

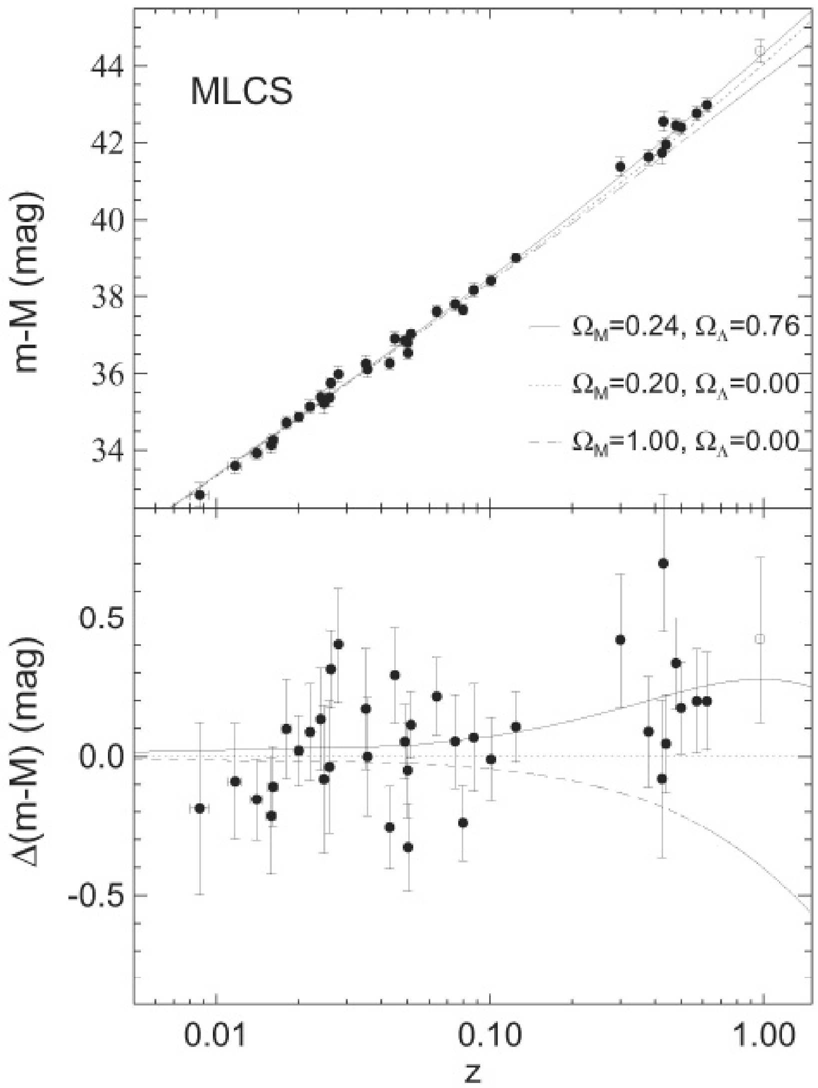
→ Distance: large (small)

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

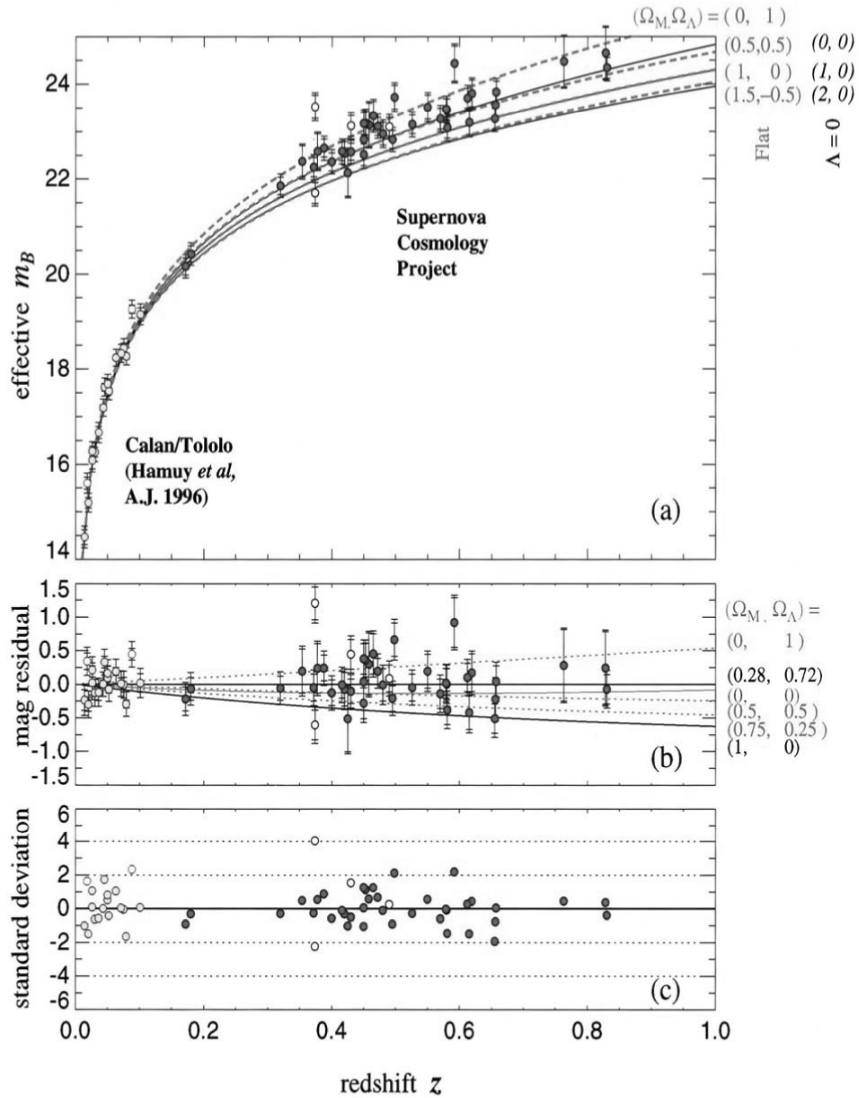
You can discriminate different cosmological models by measuring SNeIa



Schmidt +1998



Riess+1998



Perlmutter+1999

"Break Through Papers" for the Nobel Prize!

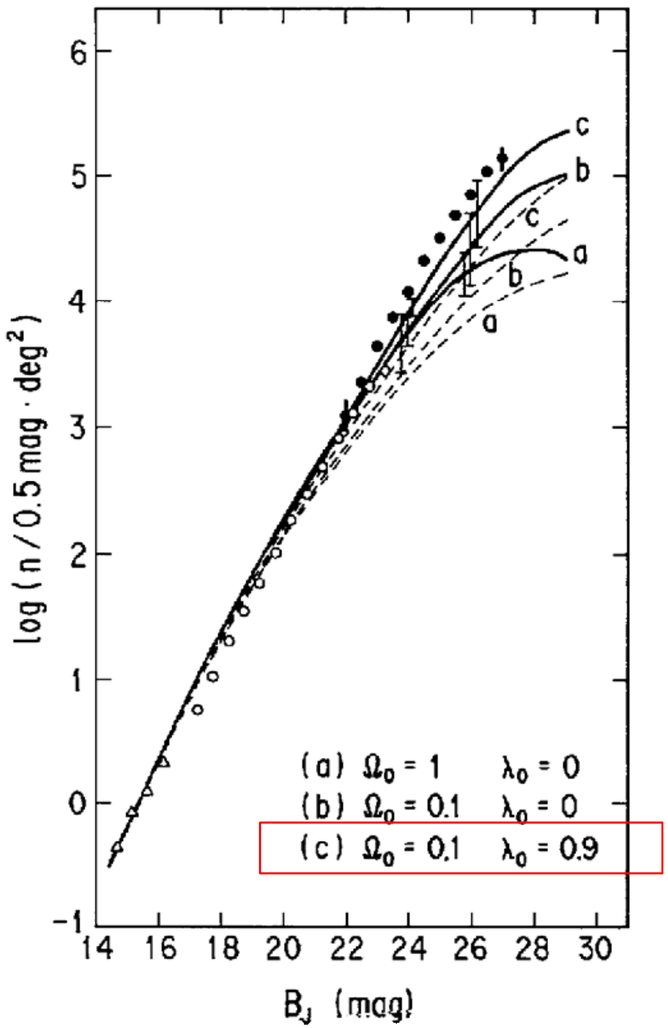
Supportive results in 1990's

Galaxy Number Count
Cosmic age
…

See Caroll+ 1992
Ann.Rev.A&A "Cosmological Constant"

"Cosmology with x-matter"
Chiba, Sugiyama & Nakamura 1997

Fukugita+ 1990



SNIa surveys

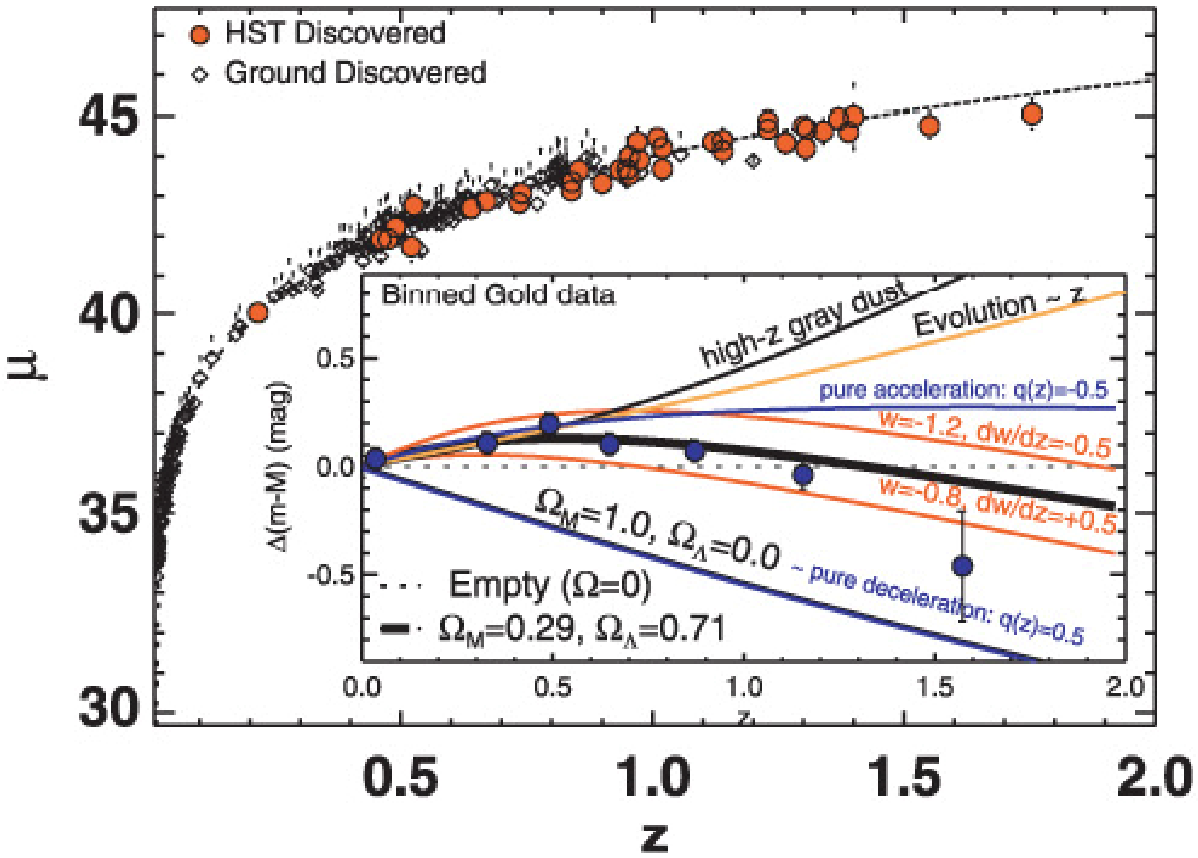
past 12 years

- redshift Projects

imaging

z~0-0.3	SDSS
~1-2.5m	Carnegie Supernova Projects
	Nearby Supernova Factory, … many
z~0.3-0.8	SN Legacy
~4m	Essence
z~0.5-1.5	SCP
8m, HST	Higher-z

Higher-z team



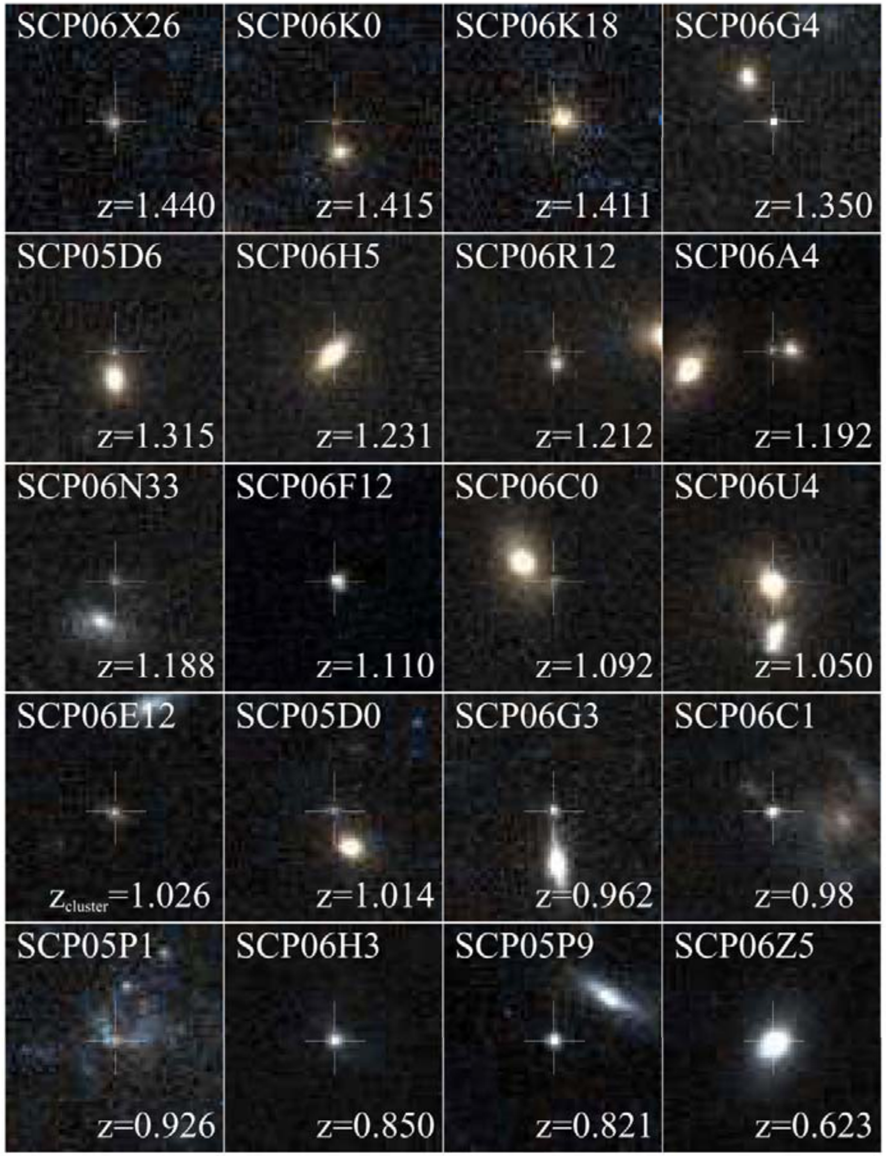
Riess+2007
Riess+2004

Distant SN observations with HST

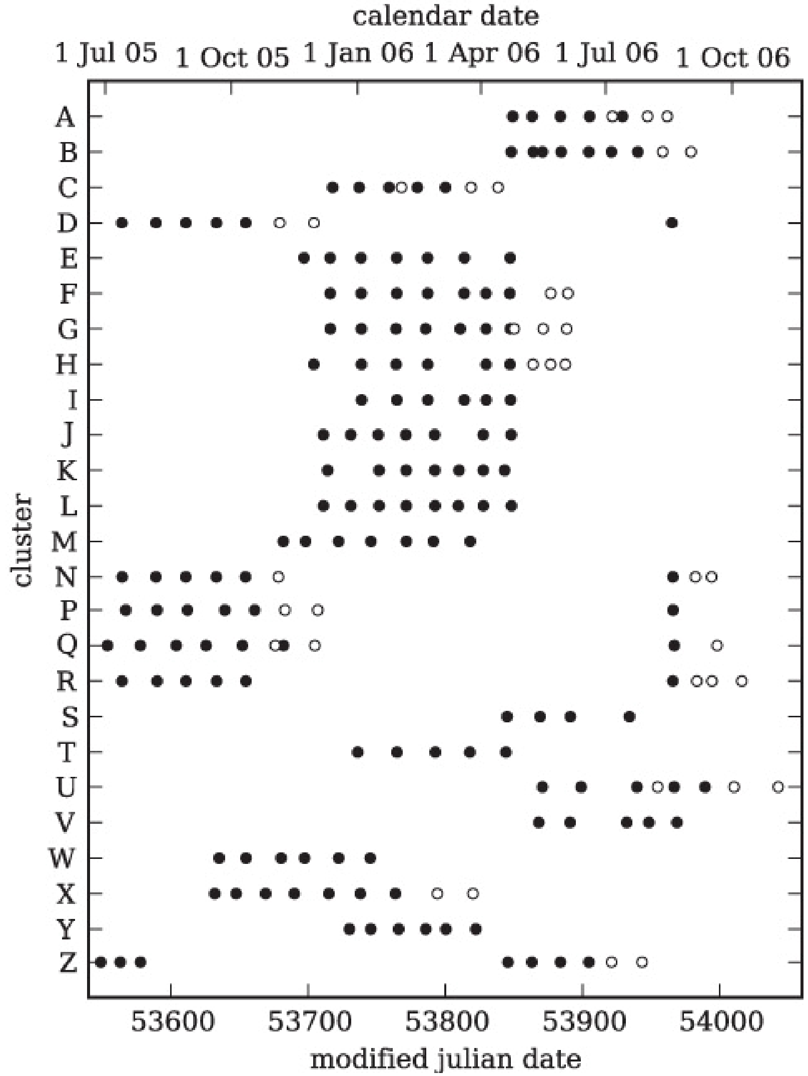
SNe become brighter at high-z

SCP HST cluster SN search Dawson+2010

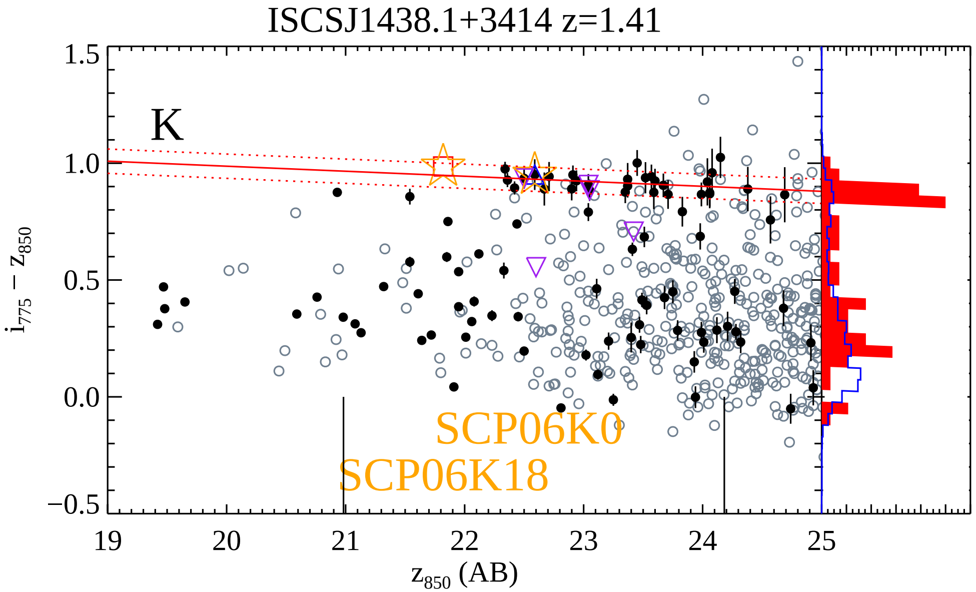
HST repeated imaging (2005-2006)

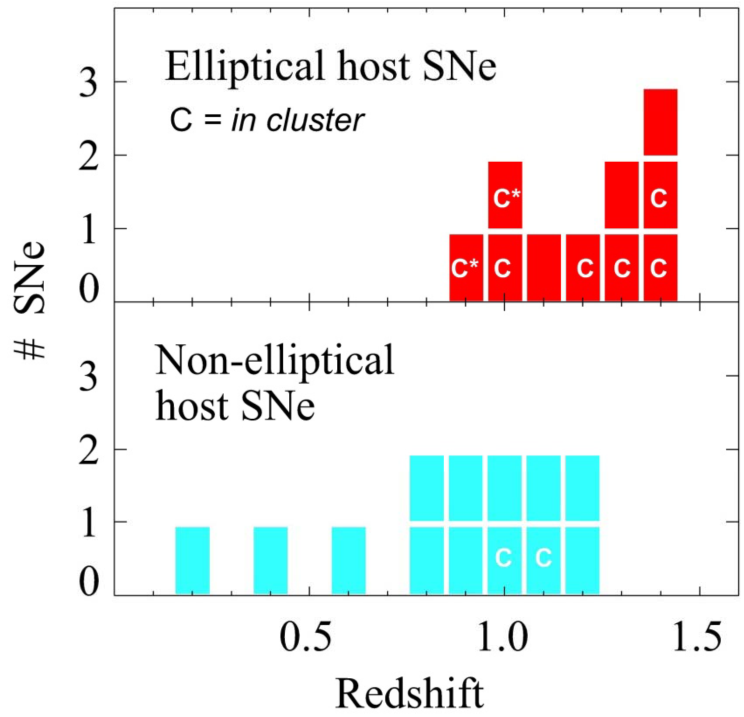


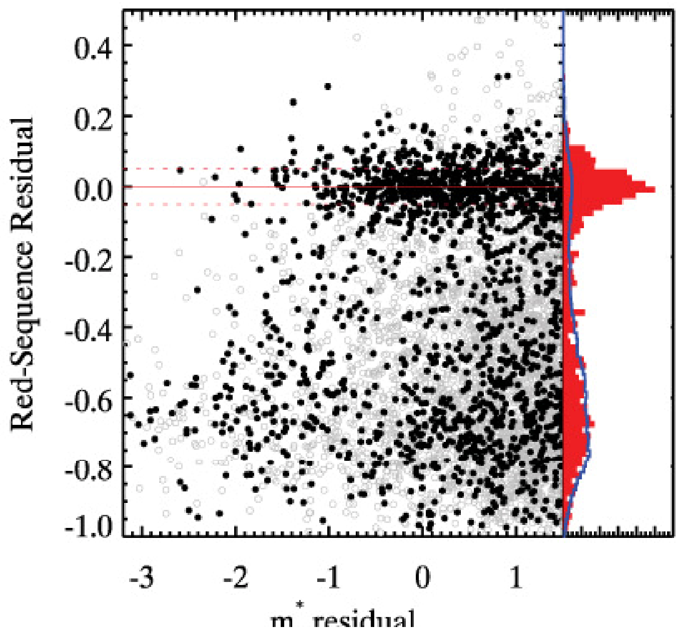
Targeting 25 high-z clusters (z~0.9-1.46)



SNeIa from cluster elliptical hosts

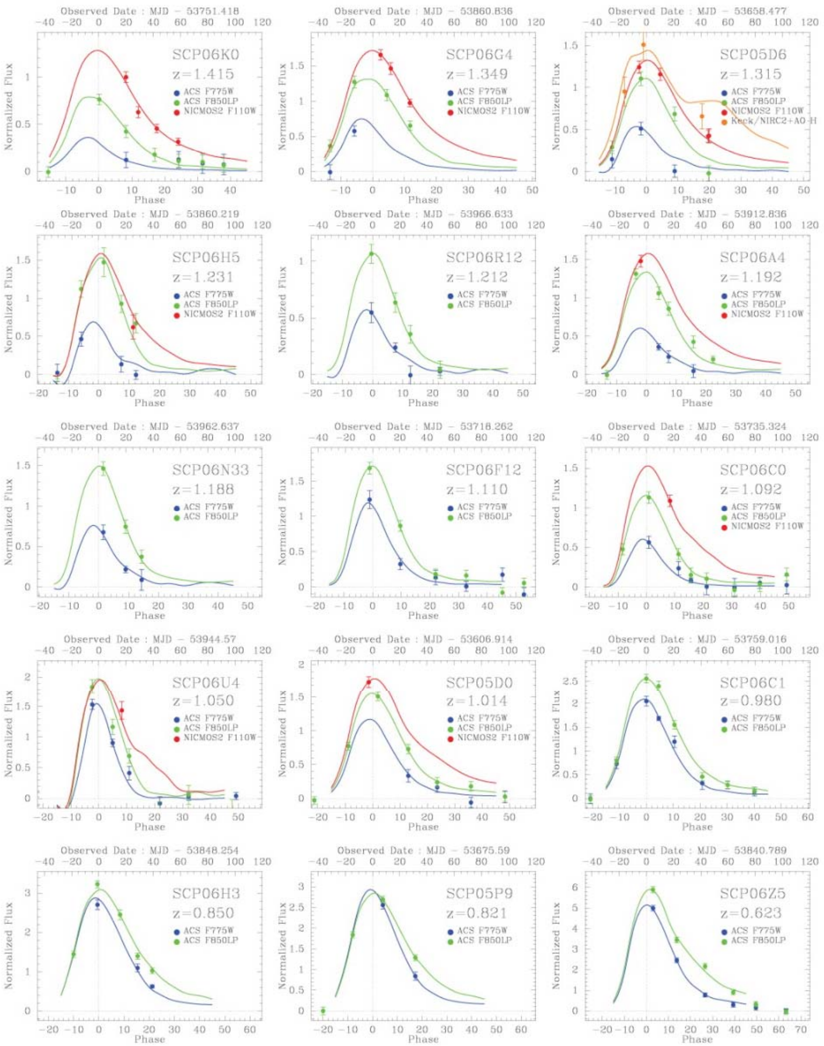


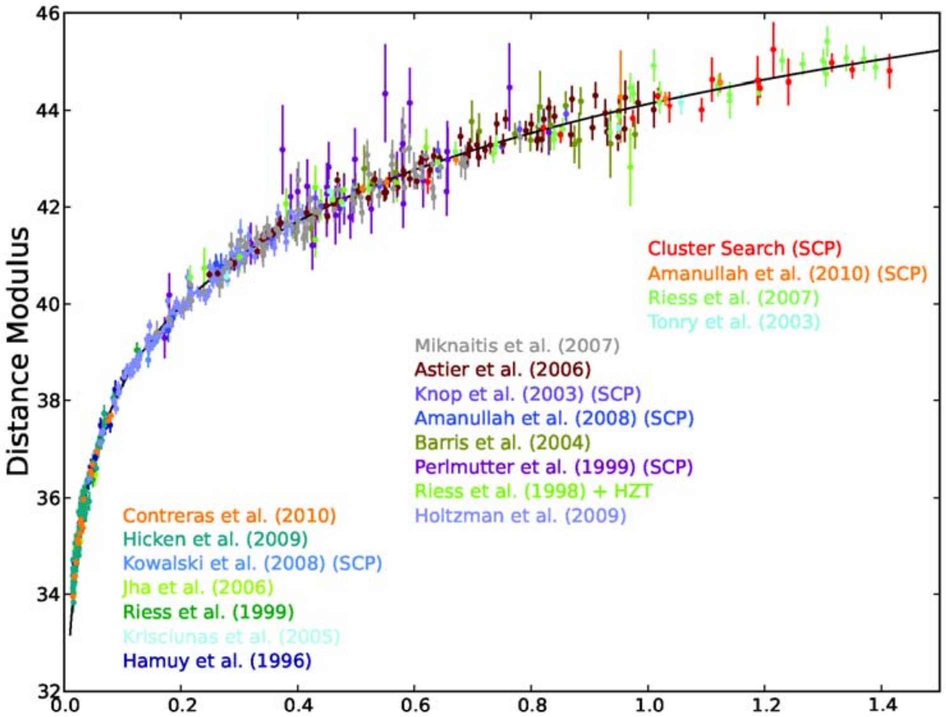




Meyers+2011

SCP latest results for supernovae cosmology





580 SNeIa

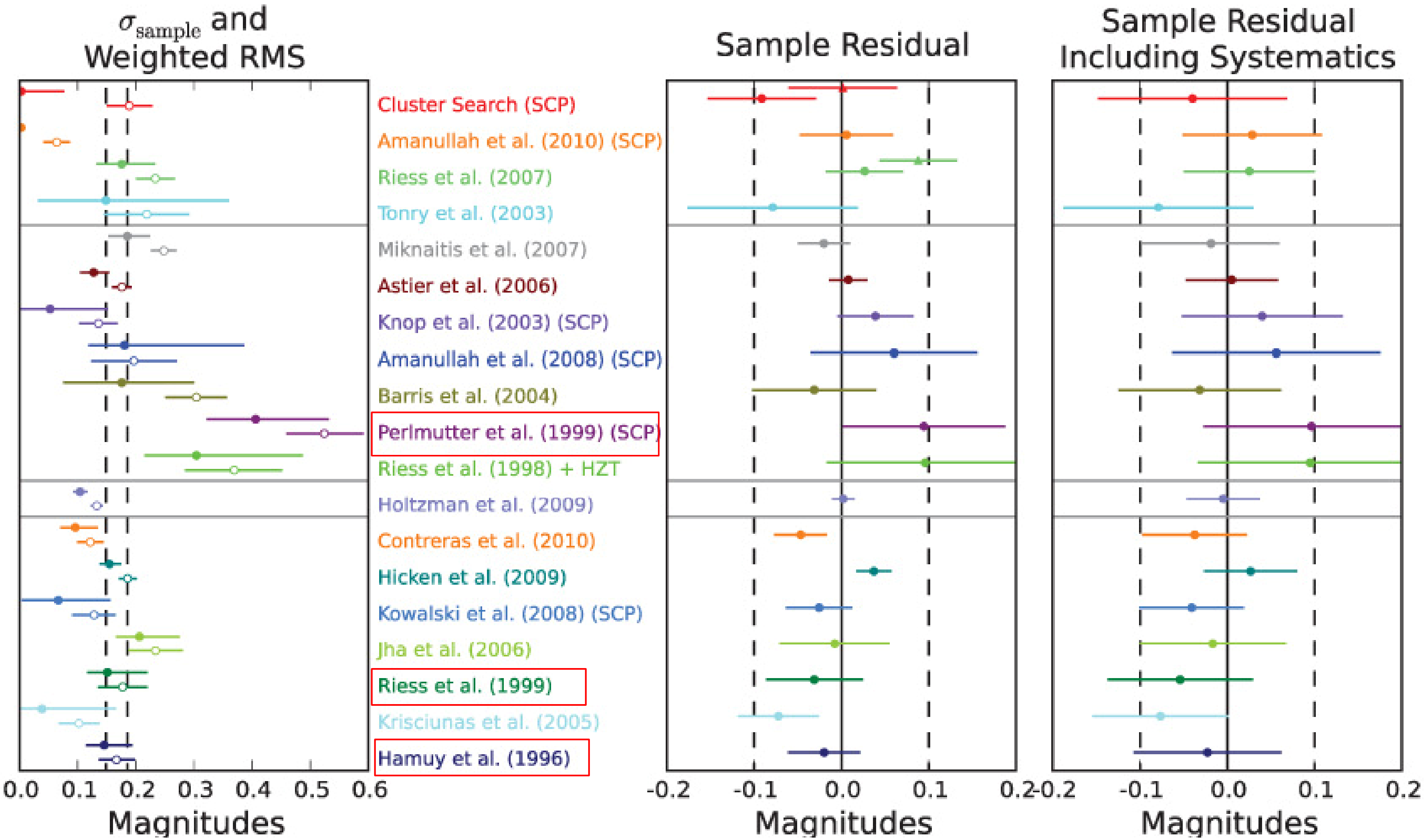
20 new high-z SNeIa

(0.623 < z < 1.415)

Suzuki+2011

Data used

580 SNeIa, 20 new high-z SNeIa (0.623 < z < 1.415)

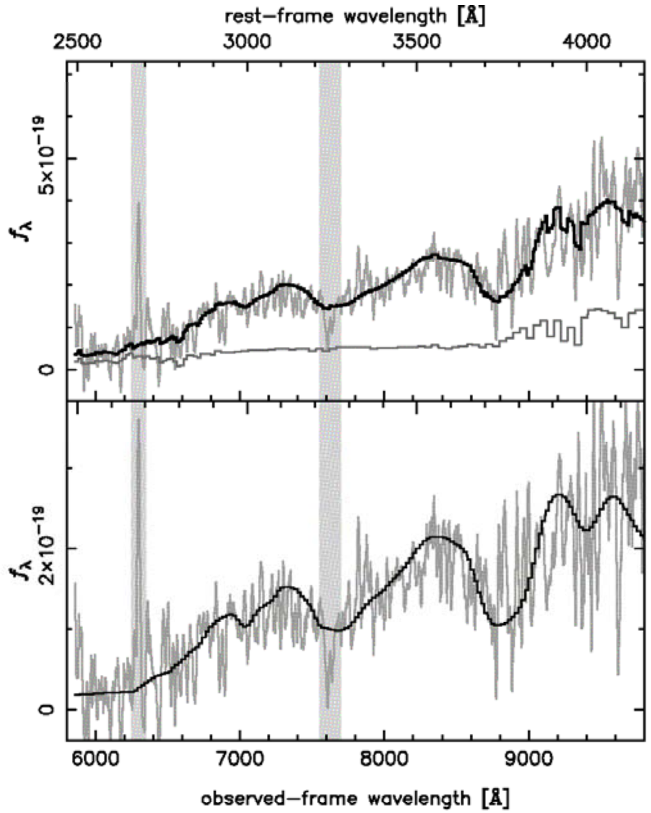


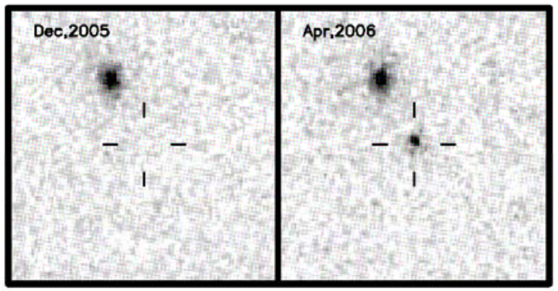
Suzuki+2011

Spectroscopy of new 20 SNeIa/hosts

14 SNe Subaru/FOCAS (Morokuma+2010)

4 SNe Keck /DEMOS (Meyers+2010) 2 Sne VLT/FORS1,2 (Barbary+2011)

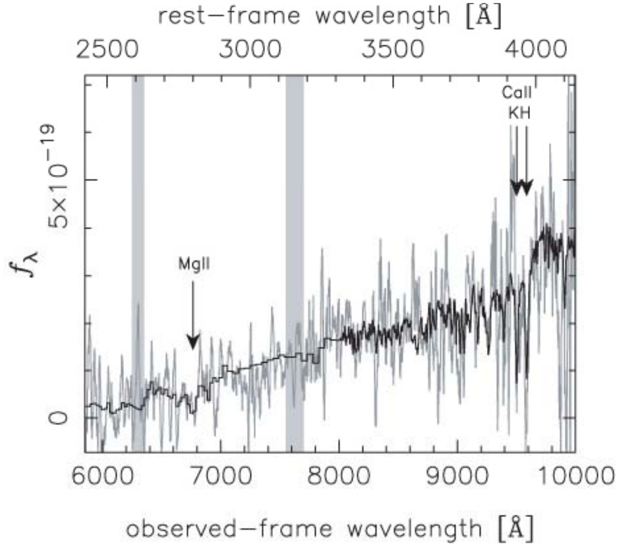




SCP06G4

z=1.35

FOCAS 3.3 hours



SCP06K0 (host)

z=1.416

FOCAS 3 hours

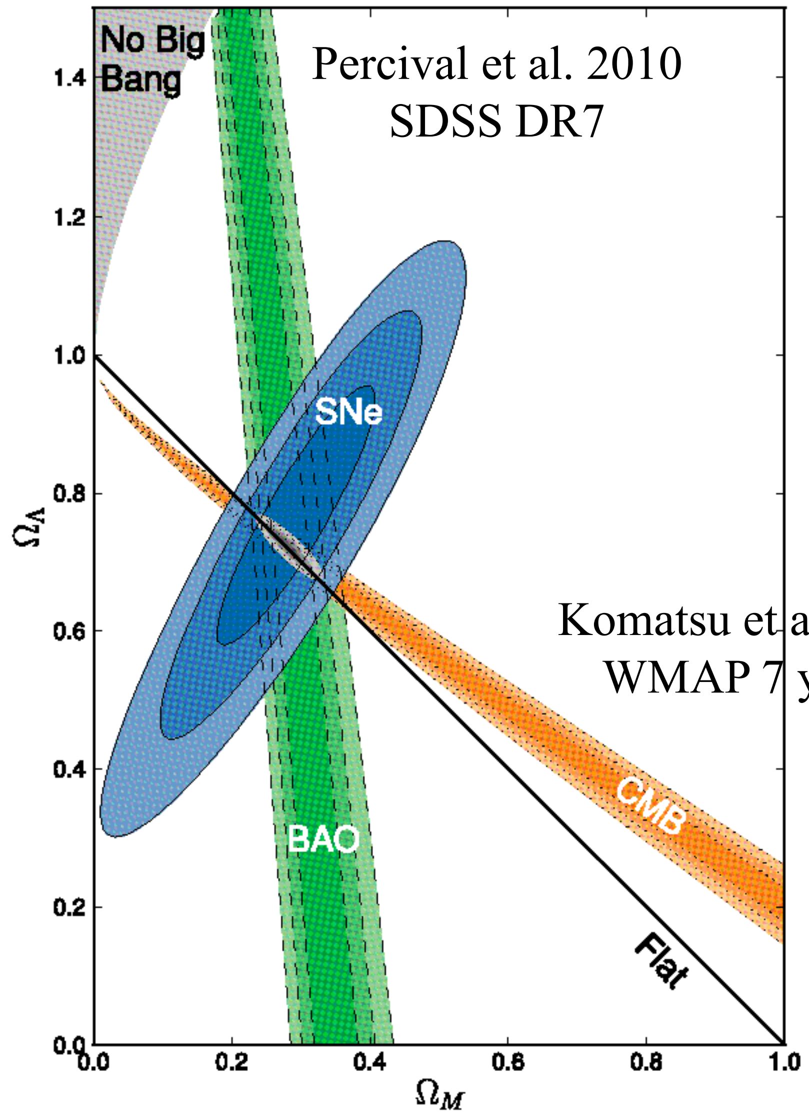
Cosmological Fit of 580 SNeIa

Suzuki et al.2011

$\Omega_\Lambda = 0.729 \,^{+0.014}_{-0.014}$ for ΛCDM

Dark energy density

density constant



density ∝ 1/volume

Matter density

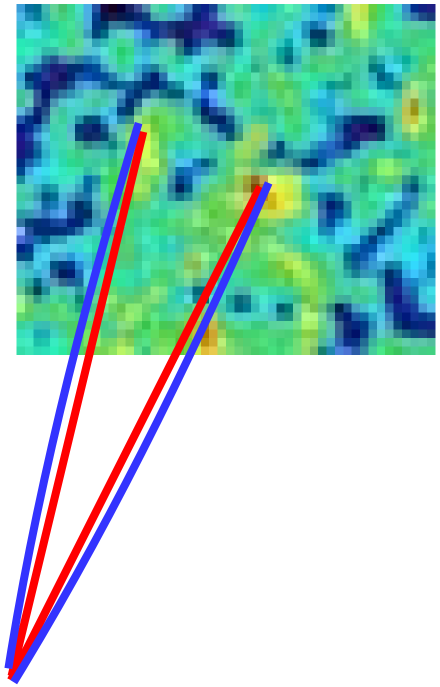
CMB Fluctuations has typical scale “Standard Lod”

→ We can measure “Light Path”

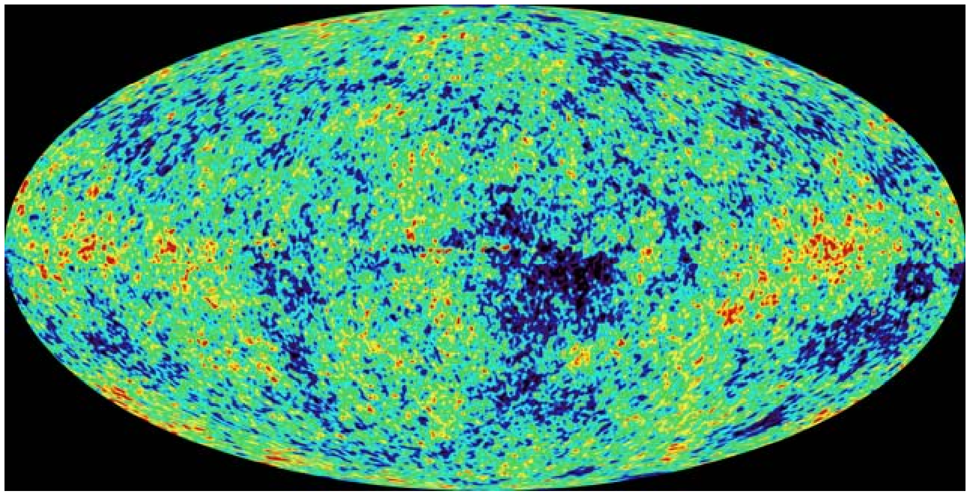
Light propagates “straight” from z~1000

not 凸 lens nor 凹 lens

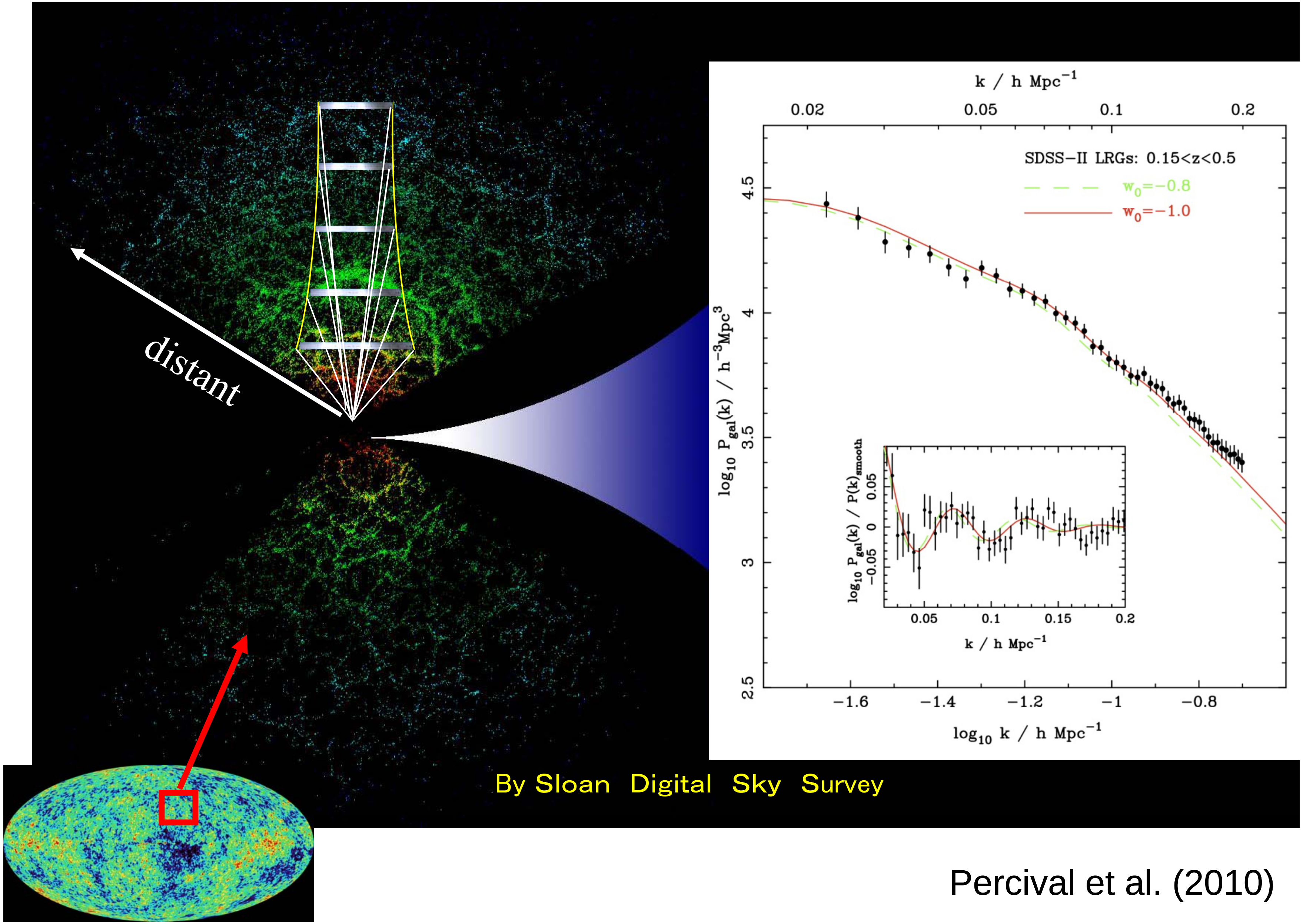
→ Geometry of Universe「FLAT」



Spergel et al. 2003, Komatsu et al. 2011



Acoustic peak in Galaxy Distributions



Percival et al. (2010)

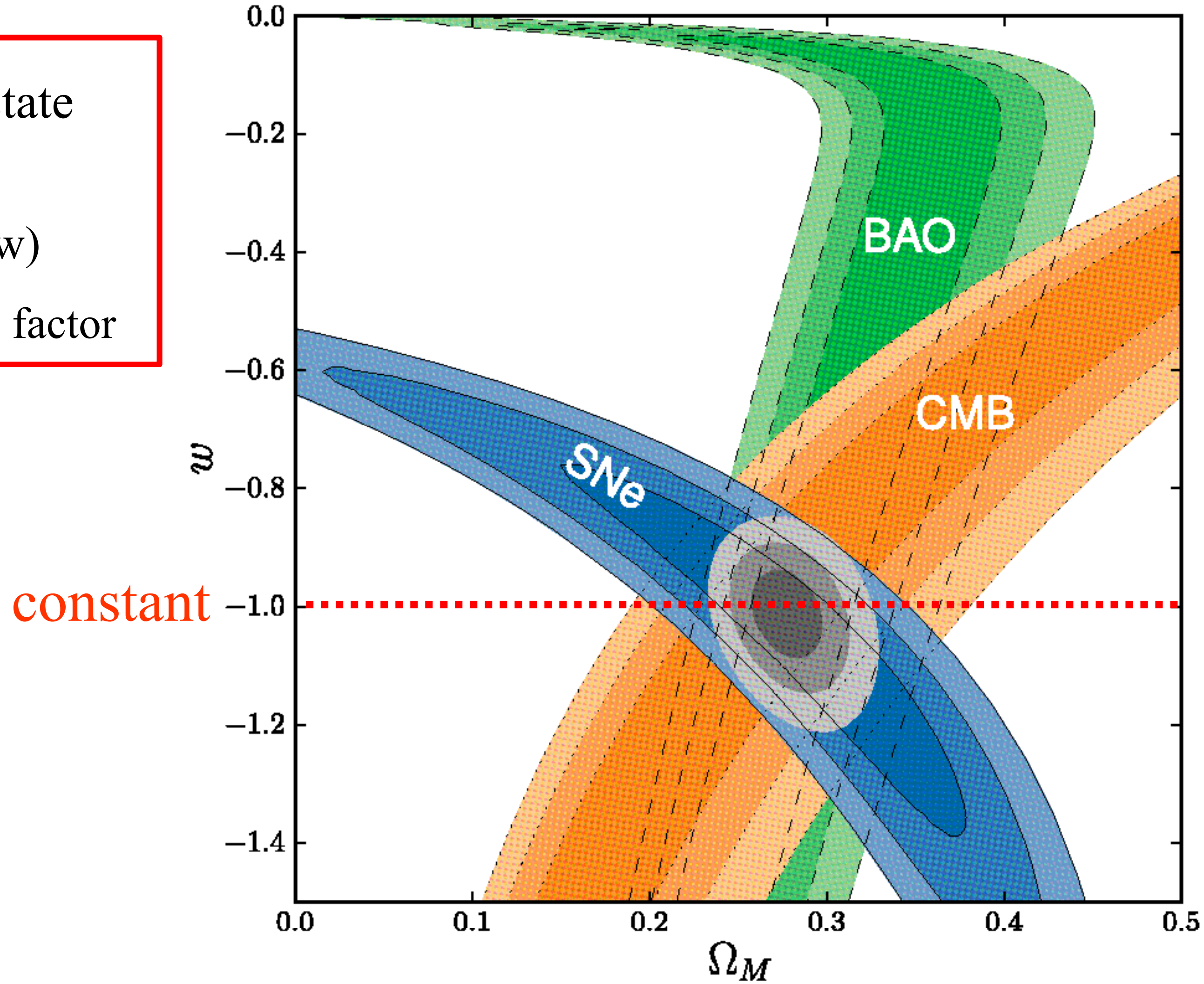
Dark energy parameters

- $w = -1.013^{+0.068}_{-0.073}$ for flat univ. Suzuki+2011

Equation of state
w

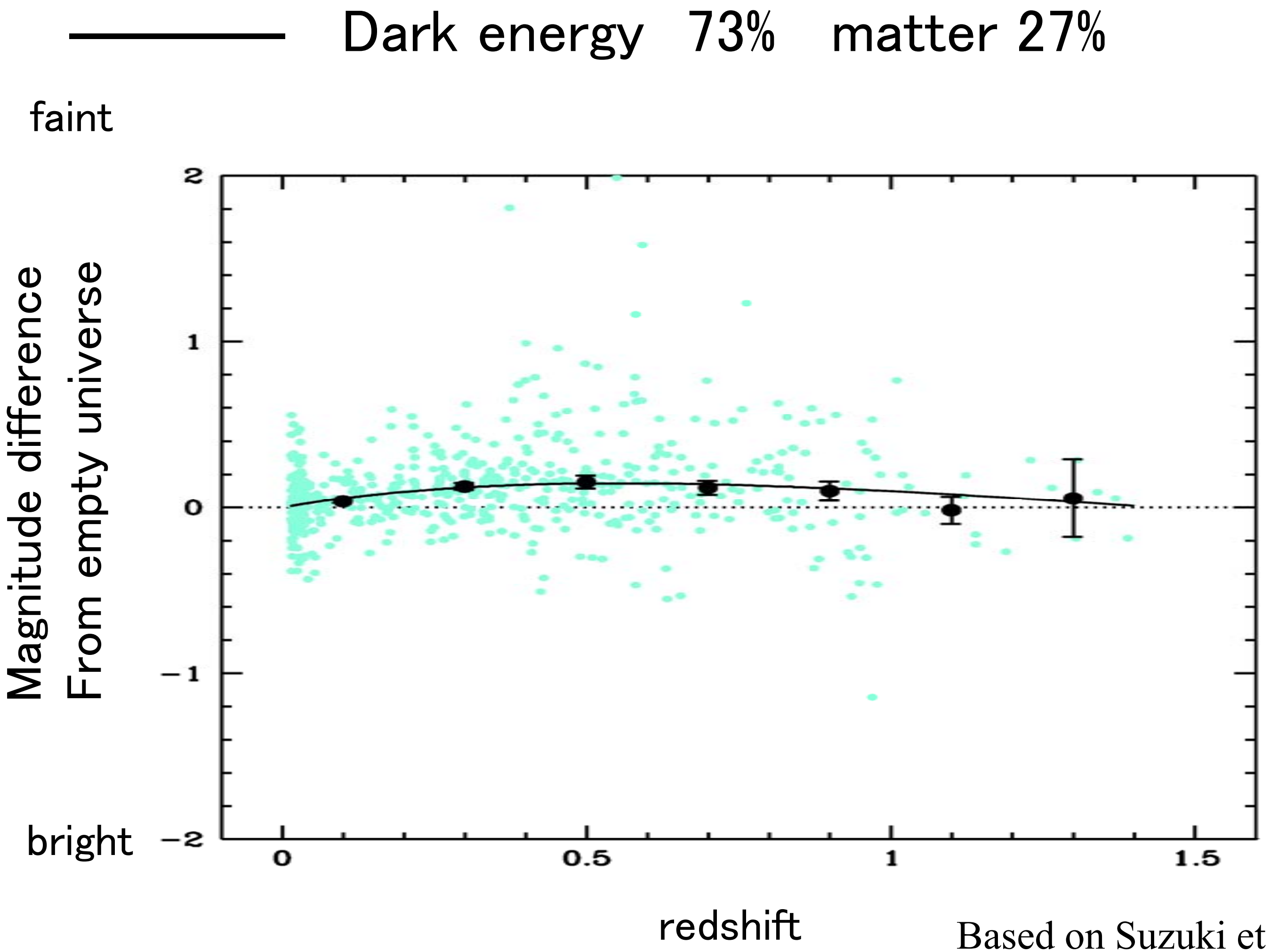
$\rho \propto a^{-3(1+w)}$

$a = 1/(1+z)$: scale factor



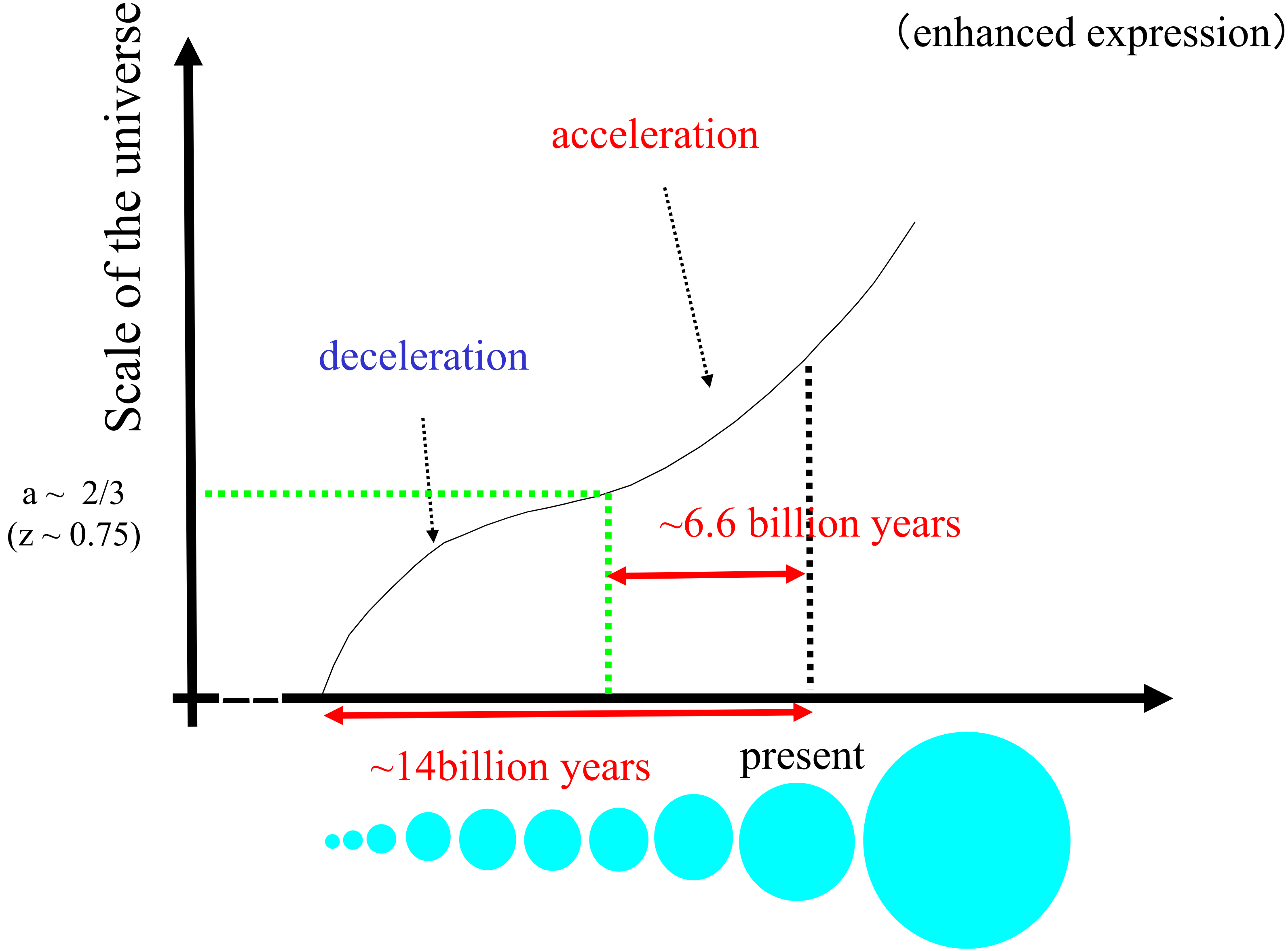
Matter density

Consistent with dark energy model



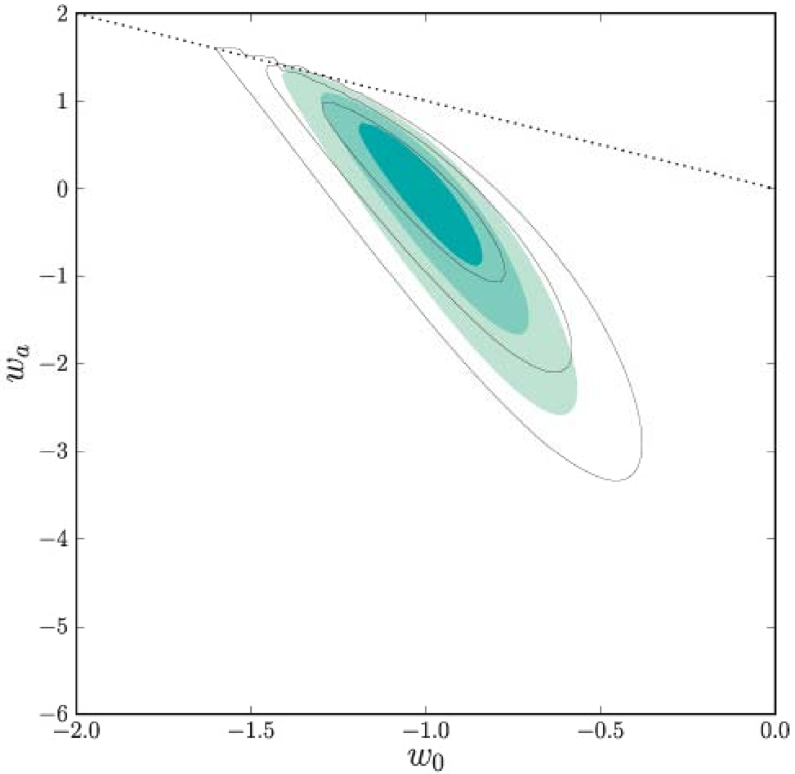
Based on Suzuki et al. 2011

Expansion history of the universe



Dark energy:time variation?

w_a



w_0: present w

Suzuki+2011

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

a = 1/(1+z) : scale factor

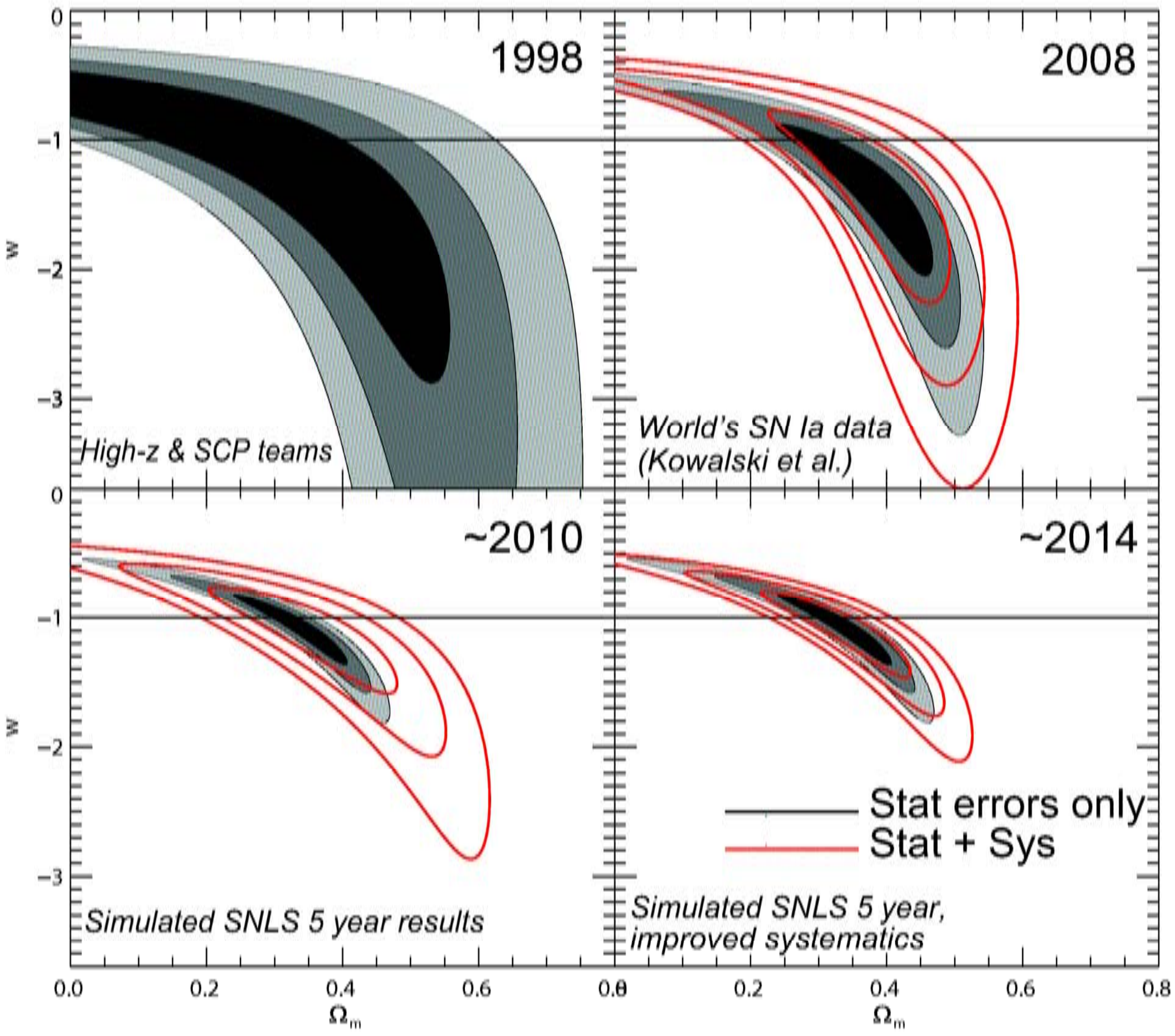
Various Fitting cases

Table 7

Fit results on cosmological parameters Ω_m, w_0, w_a and Ω_k. The parameter values are followed by their statistical (first column) and statistical and systematic (secon column) 1σ ($\Delta\chi^2 = 1$) uncertainties. For the fits including curvature and time-varying w, the confidence intervals can be quite non-gaussian and we also show $\Delta\chi^2 =$ confidence intervals (with and without systematics) for comparison.

Fit	Ω_m	Ω_m w/ Sys	Ω_k	Ω_k w/ Sys	w_0	w_0 w/ Sys	w_a	w_a w/
				ΛCDM				
SNe	$0.277^{+0.022}_{-0.021}$	$0.295^{+0.043}_{-0.040}$	0 (fixed)	0 (fixed)	−1 (fixed)	−1 (fixed)	0 (fixed)	0 (fix
SNe+BAO+CMB	$0.278^{+0.014}_{-0.013}$	$0.282^{+0.017}_{-0.016}$	0 (fixed)	0 (fixed)	−1 (fixed)	−1 (fixed)	0 (fixed)	0 (fix
SNe+BAO+CMB+H_0	$0.271^{+0.012}_{-0.012}$	$0.271^{+0.014}_{-0.014}$	0 (fixed)	0 (fixed)	−1 (fixed)	−1 (fixed)	0 (fixed)	0 (fix
				oΛCDM				
SNe+BAO+CMB	$0.282^{+0.015}_{-0.014}$	$0.286^{+0.018}_{-0.017}$	$-0.004^{+0.006}_{-0.006}$	$-0.004^{+0.006}_{-0.007}$	−1 (fixed)	−1 (fixed)	0 (fixed)	0 (fix
SNe+BAO+CMB+H_0	$0.271^{+0.013}_{-0.012}$	$0.272^{+0.014}_{-0.014}$	$0.002^{+0.005}_{-0.005}$	$0.002^{+0.005}_{-0.005}$	−1 (fixed)	−1 (fixed)	0 (fixed)	0 (fix
				wCDM				
SNe	$0.281^{+0.067}_{-0.092}$	$0.296^{+0.102}_{-0.180}$	0 (fixed)	0 (fixed)	$-1.011^{+0.208}_{-0.231}$	$-1.001^{+0.348}_{-0.398}$	0 (fixed)	0 (fix
SNe+BAO+H_0	$0.309^{+0.029}_{-0.028}$	$0.320^{+0.035}_{-0.033}$	0 (fixed)	0 (fixed)	$-1.097^{+0.091}_{-0.106}$	$-1.076^{+0.117}_{-0.133}$	0 (fixed)	0 (fix
SNe+CMB	$0.271^{+0.018}_{-0.017}$	$0.279^{+0.025}_{-0.023}$	0 (fixed)	0 (fixed)	$-0.983^{+0.051}_{-0.056}$	$-0.955^{+0.075}_{-0.079}$	0 (fixed)	0 (fix
SNe+BAO+CMB	$0.278^{+0.014}_{-0.014}$	$0.285^{+0.018}_{-0.017}$	0 (fixed)	0 (fixed)	$-0.993^{+0.052}_{-0.055}$	$-0.951^{+0.075}_{-0.081}$	0 (fixed)	0 (fix
SNe+BAO+CMB+H_0	$0.272^{+0.013}_{-0.013}$	$0.271^{+0.014}_{-0.014}$	0 (fixed)	0 (fixed)	$-1.008^{+0.050}_{-0.054}$	$-1.013^{+0.068}_{-0.073}$	0 (fixed)	0 (fix
				owCDM				
SNe+CMB	$0.281^{+0.069}_{-0.087}$	$0.295^{+0.109}_{-0.161}$	$-0.003^{+0.034}_{-0.027}$	$-0.005^{+0.067}_{-0.041}$	$-1.007^{+0.179}_{-0.194}$	$-0.993^{+0.299}_{-0.331}$	0 (fixed)	0 (fix
SNe+BAO+CMB	$0.283^{+0.016}_{-0.015}$	$0.287^{+0.018}_{-0.017}$	$-0.004^{+0.007}_{-0.007}$	$-0.002^{+0.008}_{-0.008}$	$-1.012^{+0.058}_{-0.062}$	$-0.975^{+0.094}_{-0.098}$	0 (fixed)	0 (fix
SNe+BAO+CMB+H_0	$0.272^{+0.013}_{-0.013}$	$0.272^{+0.015}_{-0.014}$	$0.002^{+0.006}_{-0.006}$	$0.002^{+0.007}_{-0.007}$	$-1.006^{+0.056}_{-0.060}$	$-1.003^{+0.091}_{-0.095}$	0 (fixed)	0 (fix
				w_zCDM				
SNe+CMB	$0.273^{+0.022}_{-0.020}$	$0.281^{+0.043}_{-0.028}$	0 (fixed)	0 (fixed)	$-1.006^{+0.165}_{-0.182}$	$-0.993^{+0.263}_{-0.307}$	$0.11^{+0.75}_{-0.77}$	0.17^{+}_{-}
SNe+BAO+CMB	$0.278^{+0.014}_{-0.014}$	$0.284^{+0.018}_{-0.017}$	0 (fixed)	0 (fixed)	$-1.052^{+0.126}_{-0.120}$	$-1.013^{+0.183}_{-0.173}$	$0.30^{+0.48}_{-0.62}$	0.26^{+}_{-}
SNe+BAO+CMB+H_0	$0.271^{+0.013}_{-0.013}$	$0.270^{+0.015}_{-0.014}$	0 (fixed)	0 (fixed)	$-1.021^{+0.123}_{-0.117}$	$-1.046^{+0.179}_{-0.170}$	$0.07^{+0.49}_{-0.60}$	0.14^{+}_{-}
				ow_zCDM				
SNe+CMB	$0.177^{+0.086}_{-0.093}$	$0.190^{+0.208}_{-0.154}$	$0.075^{+0.065}_{-0.128}$	$0.073^{+0.115}_{-0.141}$	$-0.988^{+0.176}_{-0.202}$	$-0.969^{+0.284}_{-0.345}$	$0.90^{+0.26}_{-3.88}$	0.89^{+}_{-}
SNe+BAO+CMB	$0.283^{+0.019}_{-0.017}$	$0.286^{+0.022}_{-0.023}$	$-0.004^{+0.017}_{-0.010}$	$-0.001^{+0.037}_{-0.013}$	$-1.010^{+0.169}_{-0.178}$	$-0.997^{+0.266}_{-0.293}$	$-0.01^{+1.04}_{-1.05}$	0.13^{+}_{-}
SNe+BAO+CMB+H_0	$0.270^{+0.014}_{-0.013}$	$0.274^{+0.016}_{-0.015}$	$0.025^{+0.008}_{-0.008}$	$0.027^{+0.012}_{-0.011}$	$-1.218^{+0.069}_{-0.072}$	$-1.198^{+0.100}_{-0.112}$	$1.21^{+0.10}_{-1.14}$	1.19^{+}_{-}
SNe+BAO+CMB+H_0 ($\Delta\chi^2 = 4.0$)	$0.270^{+0.029}_{-0.026}$	$0.274^{+0.032}_{-0.029}$	$0.025^{+0.016}_{-0.035}$	$0.027^{+0.026}_{-0.036}$	$-1.218^{+0.425}_{-0.147}$	$-1.198^{+0.293}_{-0.227}$	$1.21^{+0.19}_{-2.49}$	1.19^{+}_{-}

H_0: Cepheid distances <— Riess et al. 2011



Howell et al. 2009
"TYPE IA SUPERNOVA SCIENCE 2010 – 2020"

Cosmological Fit of 580 SNeIa
(Suzuki et al. 2012)

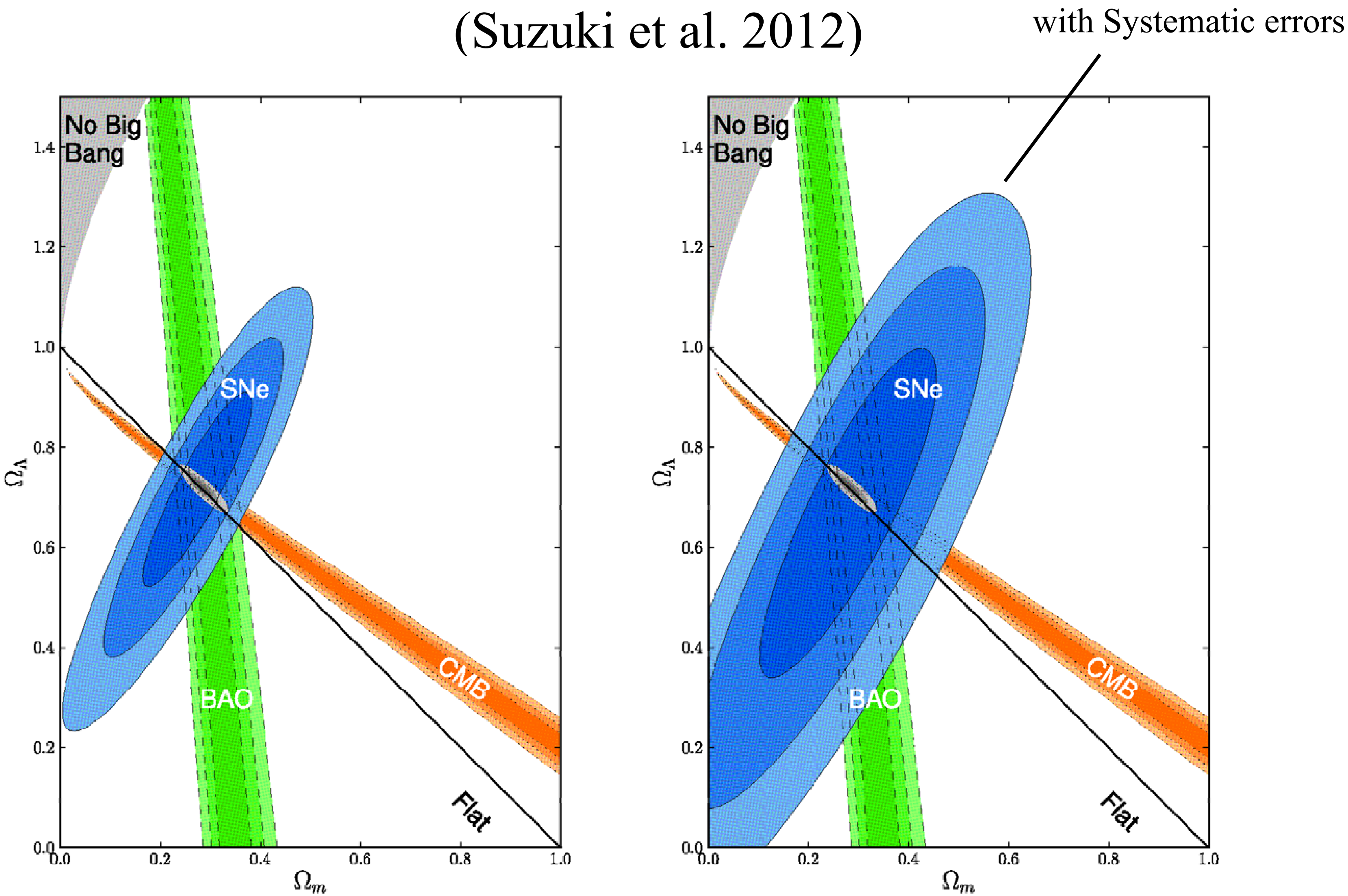


Figure 5. ΛCDM model: 68.3%, 95.4%, and 99.7% confidence regions of the $(\Omega_m, \Omega_\Lambda)$ plane from SNe Ia combined with the constraints from BAO and CMB. The left panel shows the SN Ia confidence region only including statistical errors while the right panel shows the SN Ia confidence region with both statistical and systematic errors.

Table 5

Effect on constant w error bars and area of the 95% $w_0 - w_a$ confidence contour (inverse DETF FoM) for each type of systematic error, when SN Ia constraints are combined with constraints from CMB, H_0, and BAO.

Source	Error on Constant w	Inverse DETF FoM
Vega	0.033	0.19
All Instrument Calibration	0.030	0.18
(ACS Zeropoints)	0.003	0.01
(ACS Filter Shift)	0.007	0.04
(NICMOS Zeropoints)	0.007	¡0.01
Malmquist Bias	0.020	0.07
Color Correction	0.020	0.07
Mass Correction	0.016	0.08
Contamination	0.016	0.05
Intergalactic Extinction	0.013	0.03
Galactic Extinction Normalization	0.010	0.01
Rest-Frame U-Band Calibration	0.009	¡0.01
Lightcurve Shape	0.006	¡0.01
Quadrature Sum of Errors/ Sum of Area (not used)	*0.061*	*0.68*
Summed in Covariance Matrix	0.048	0.42

Cosmological Fit of 580 SNeIa
(Suzuki et al. 2012)

with Systematic errors

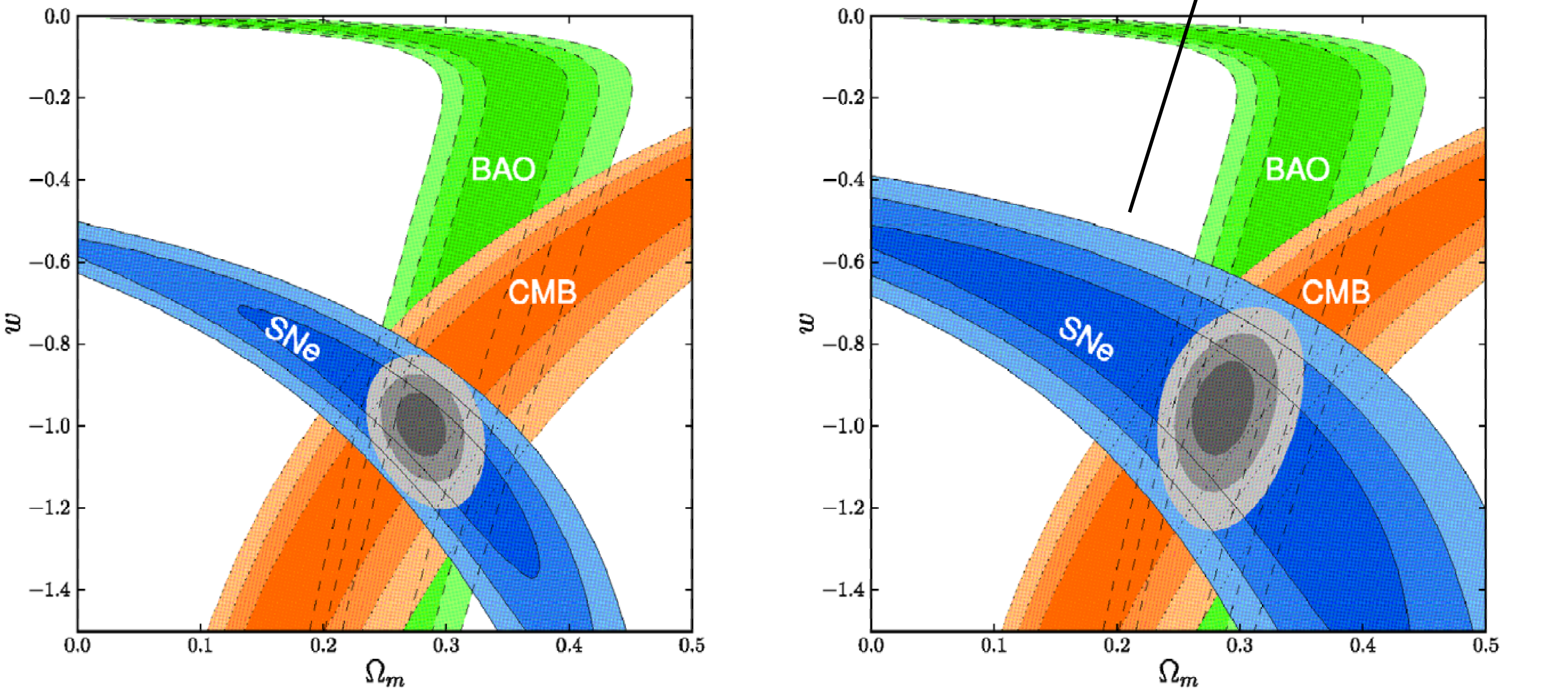


Figure 6. wCDM model: 68.3%, 95.4%, and 99.7% confidence regions in the (Ω_m, w) plane from SNe Ia BAO and CMB. The left panel shows the SN Ia confidence region for statistical uncertainties only, while the right panel shows the confidence region including both statistical and systematic uncertainties. We note that CMB and SN Ia constraints are orthogonal, making this combination of cosmological probes very powerful for investigating the nature of dark energy.

Redshift dependence
(Suzuki et al. 2012)

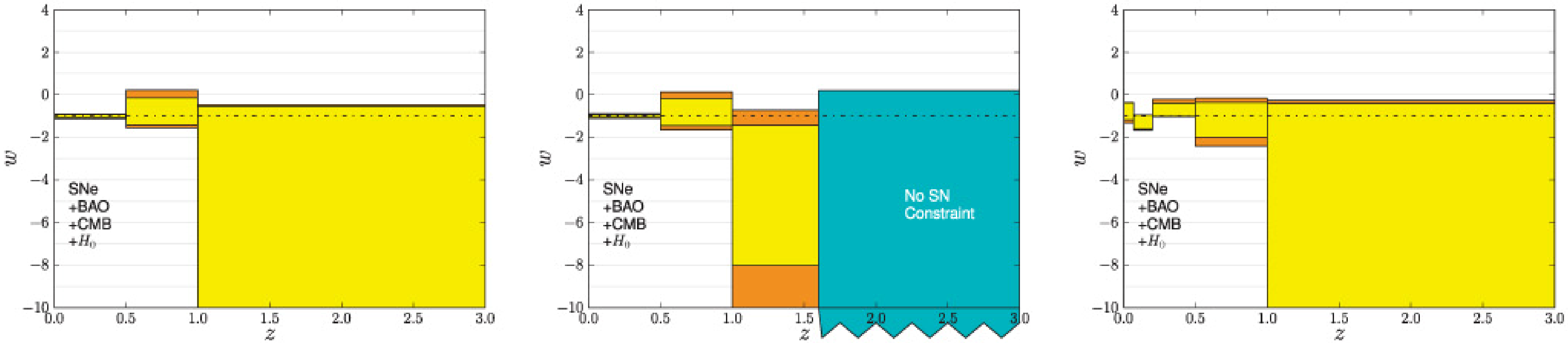


Figure 8. Constraints on $w(z)$, where $w(z)$ is assumed to be constant in each redshift bin, are plotted at the 68% probability level ($\Delta\chi^2 = 1$). Each panel shows different redshift binning. The results were obtained assuming a flat universe for the joint data set of SNe, BAO, CMB, and H_0, with (dark/orange) and without (light/yellow) SN systematics. The middle panel takes a closer look at the $z > 1$ constraints, while the right panel shows the effects of w binning at low redshift. In this panel the best fit values of w cross $w = -1$ twice at low redshift, an unusual feature in dark energy models. We note that the ΛCDM model is consistent with our $w(z)$ constraints for each of these binnings.

Future Prospects

Supernova Cosmology to be more precise

◎ Intrinsic diversity of SNIa

the explosion asymmetry

velocity-color correlation

☆**environmental effect ?**

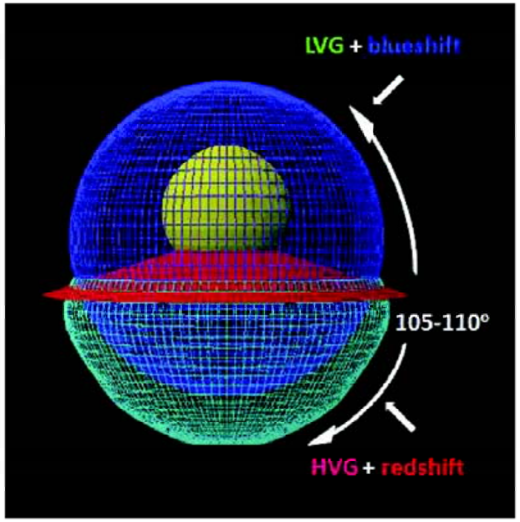
◎dust extinction correction in host galaxies

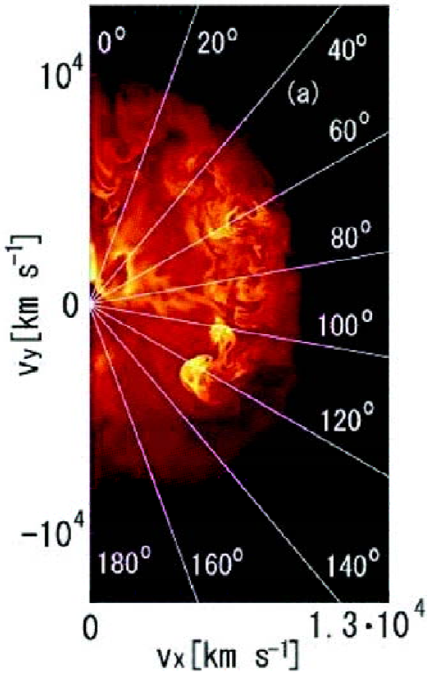
rest frame NIR observations

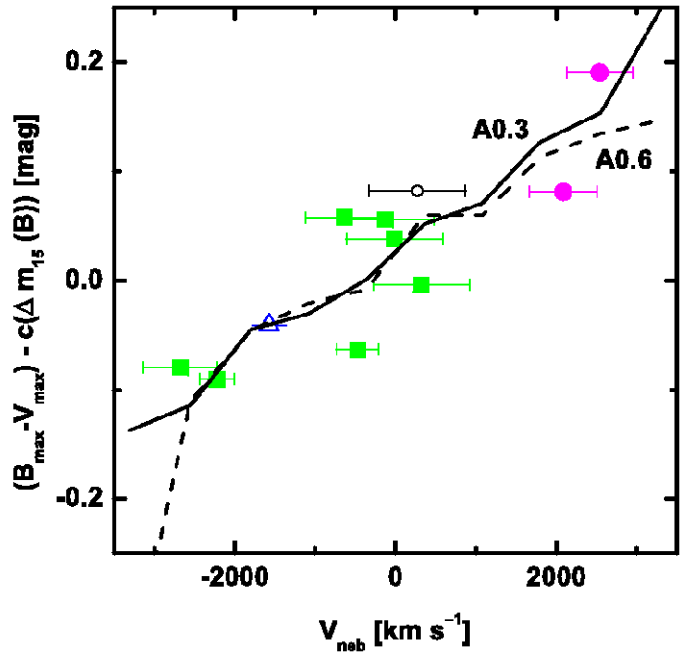
MW Extinction in H band

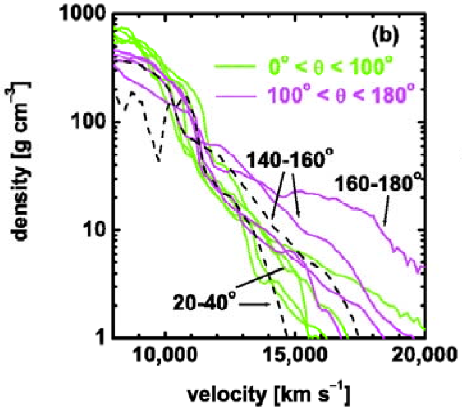
~5% of extinction in V band

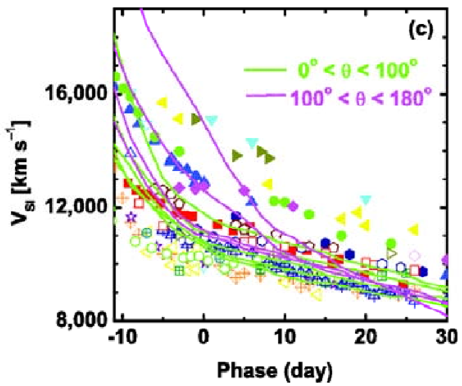
asymmetric explosion of SNIa











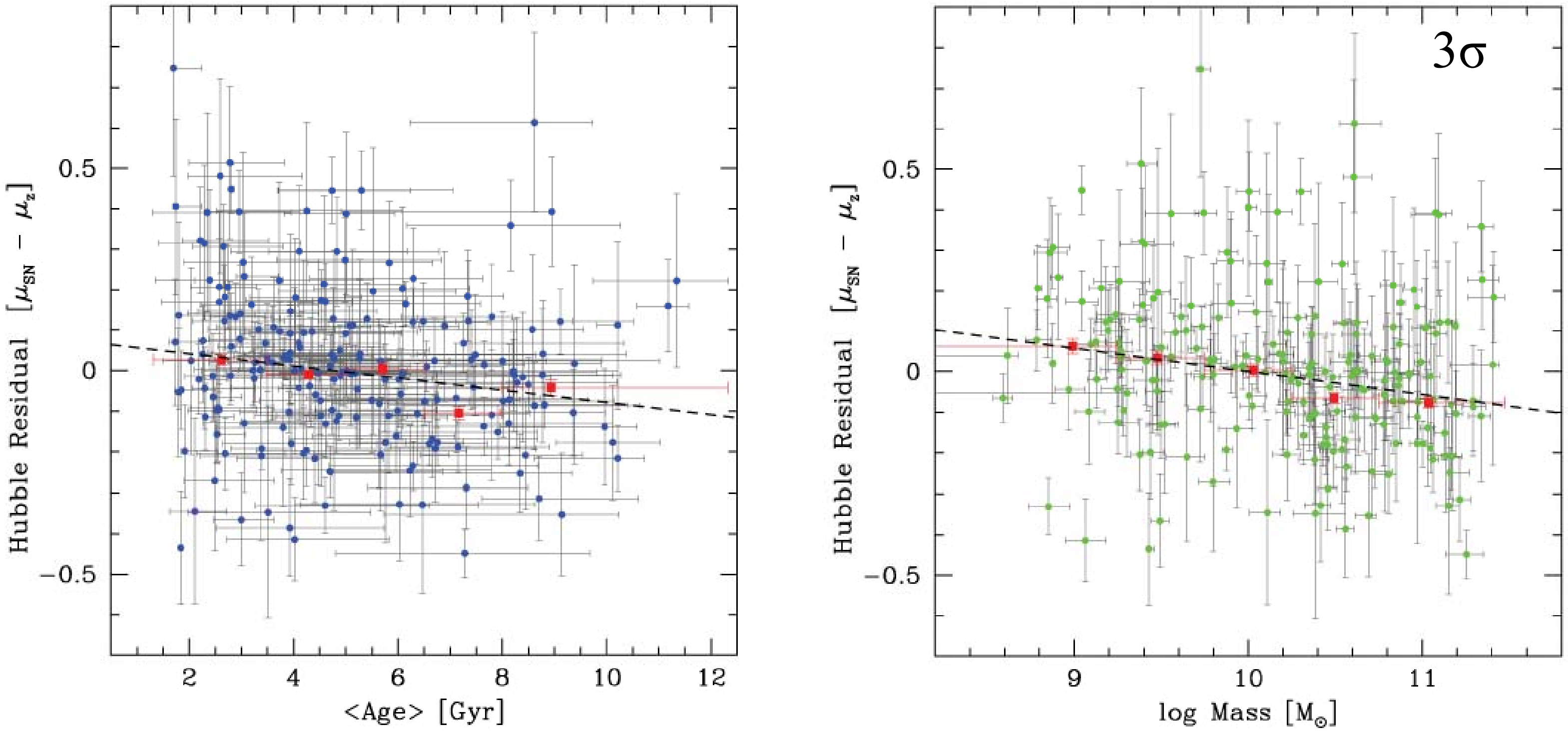
Maeda et al. 2010, 2011

Environments of SNIa

Gallagher+2005, Gallagher+2008, Sullivan+2010 Gupta+2011
D'Andrea+2011 Konishi+2011, …

Correlation of SNIa luminosity with

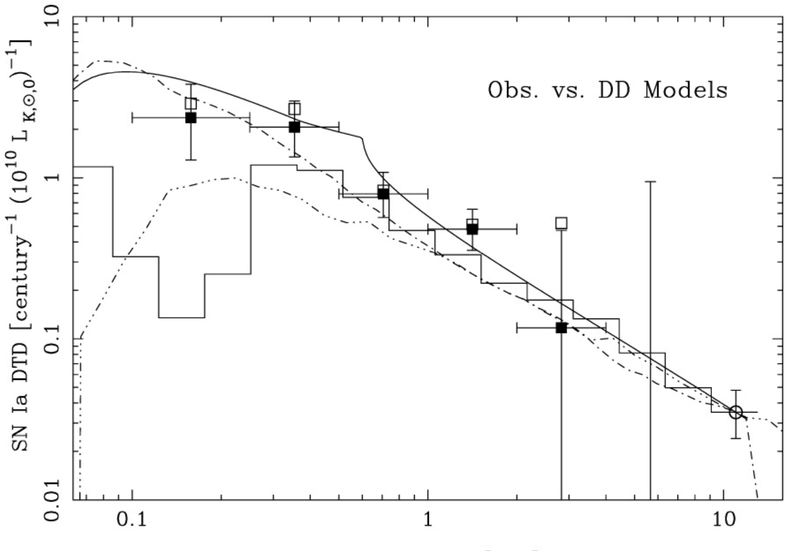
metallicity : little
Age: marginal
host galaxy mass: positive?



from SDSSII SN survey

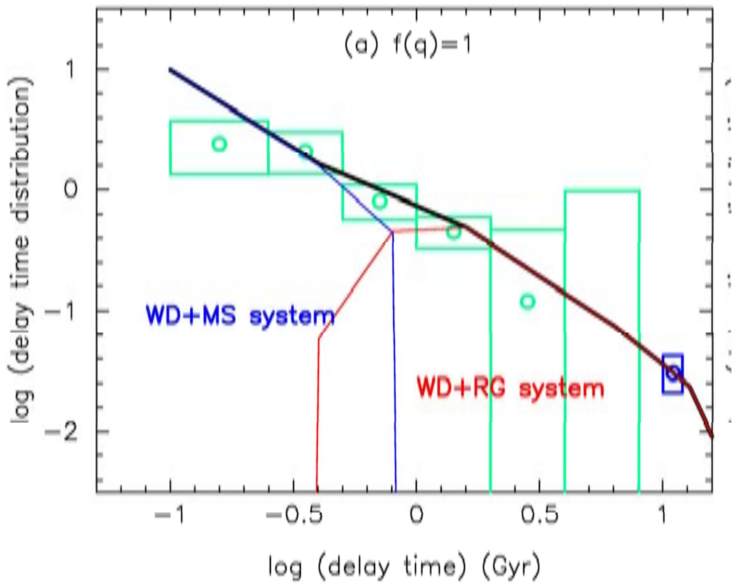
D'Andrea+2011

Delay Time Distribution of SNIa



100Myr 10Gyr

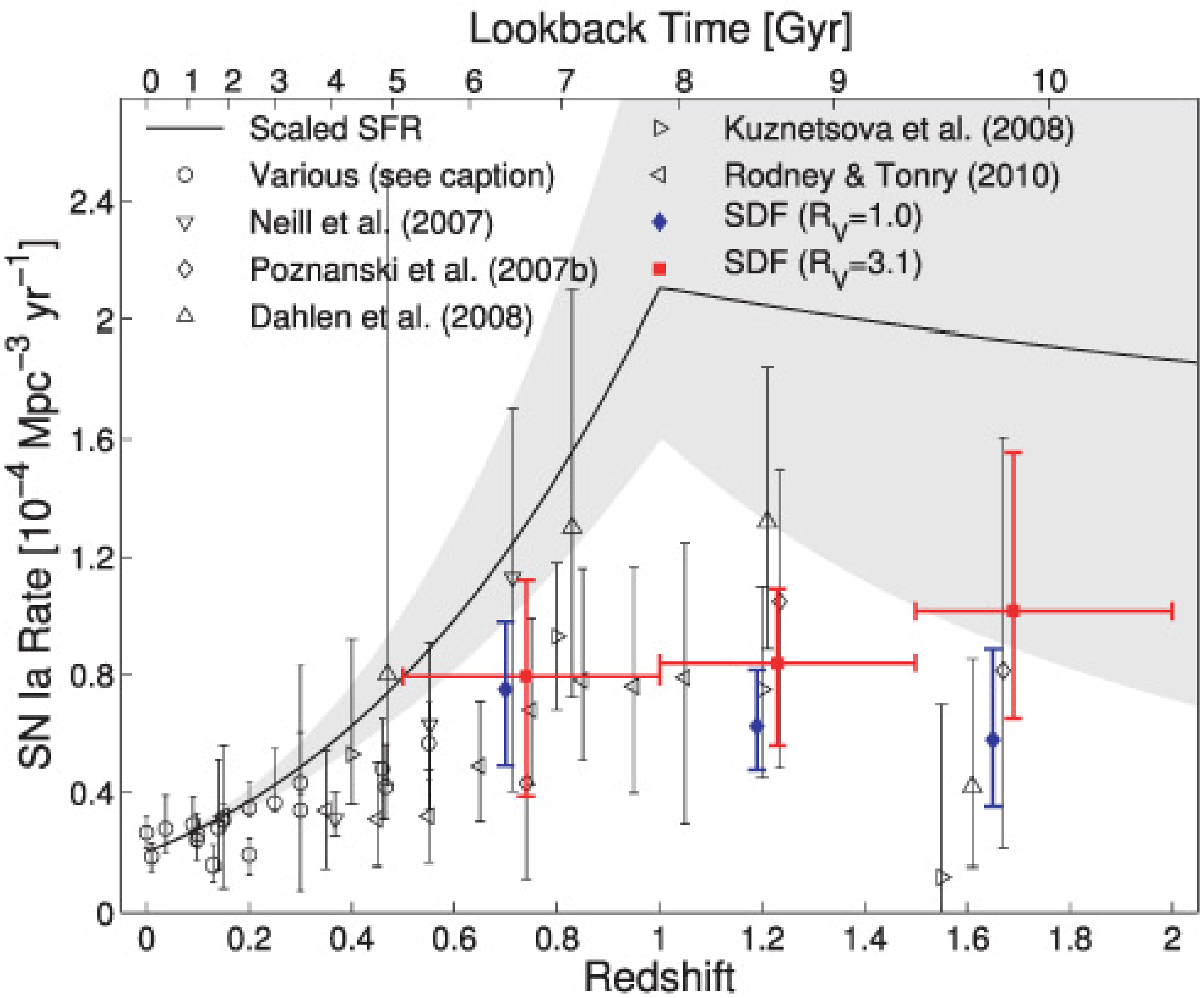
$\sim t^{-1}$



Totani+2008
Last starburst epoch of passive host galaxies
← SED with SuprimeCam

Comparison with SD model
Hachisu+2008

SNIa rate

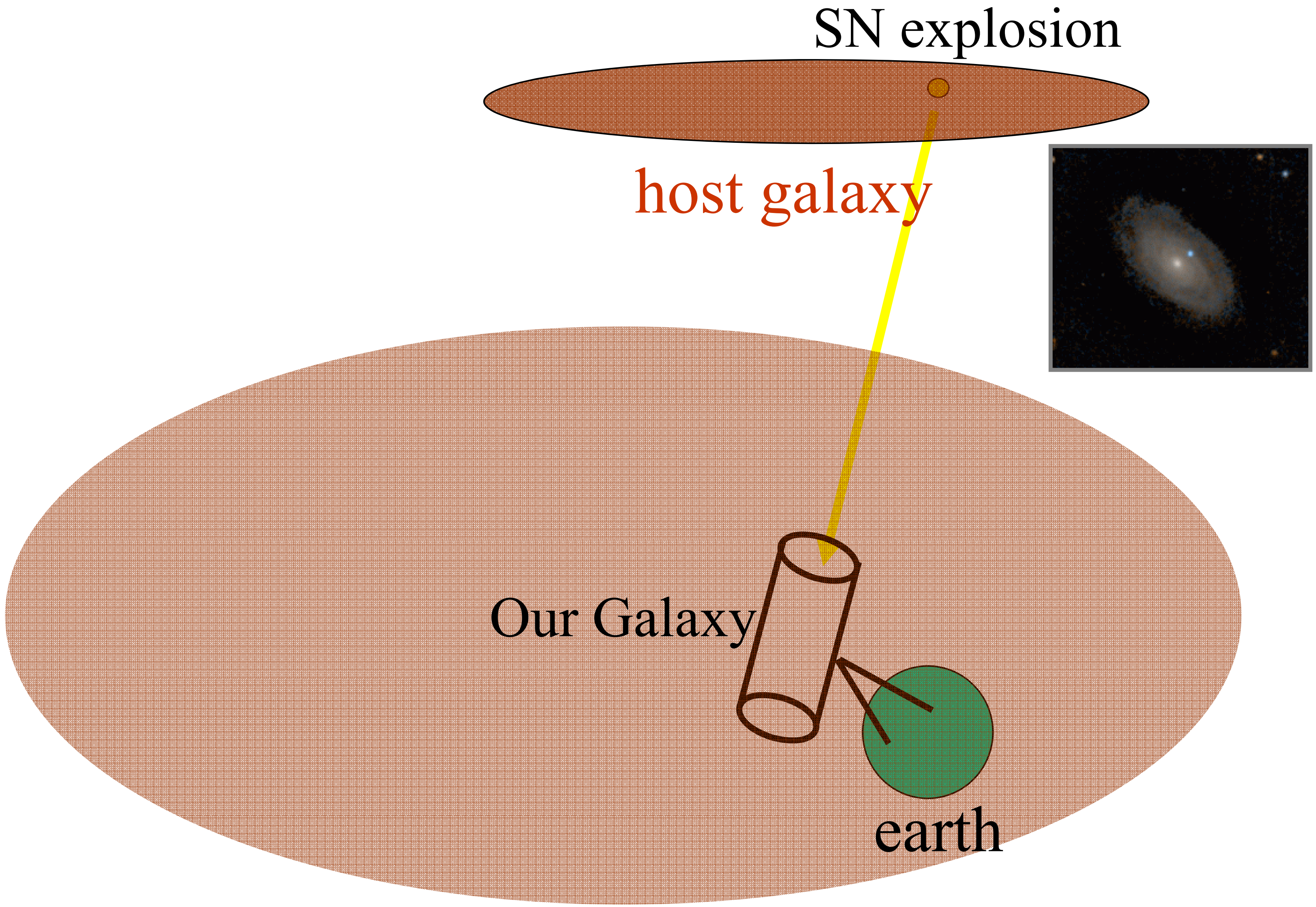


Suprime-Cam found ~150 SNe up to z~2

Exposure: R, i', z' 3-8hrs

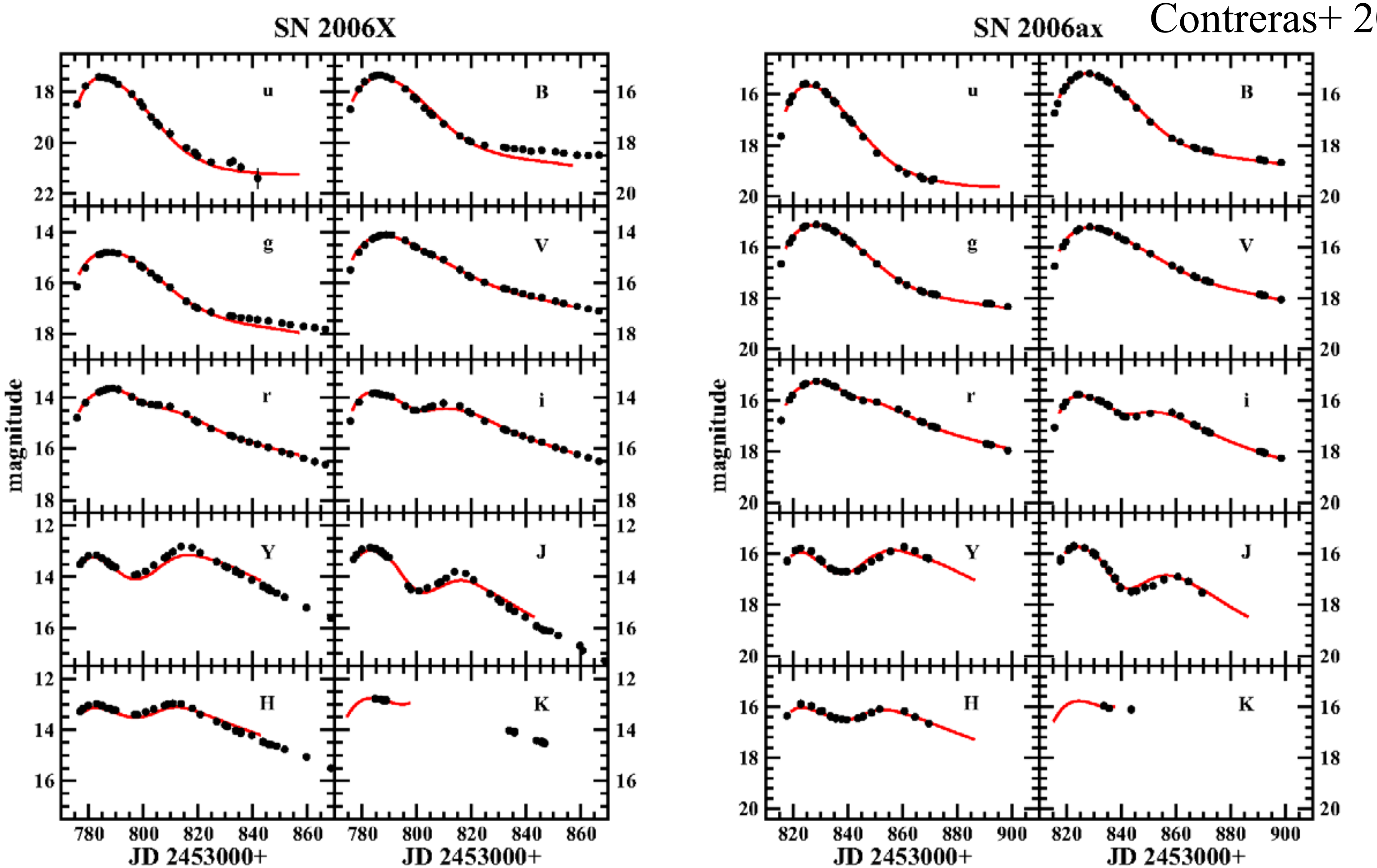
Graur+2011

Dust Extinction



for Precise SN cosmology: NIR photometry

Contreras+ 2010

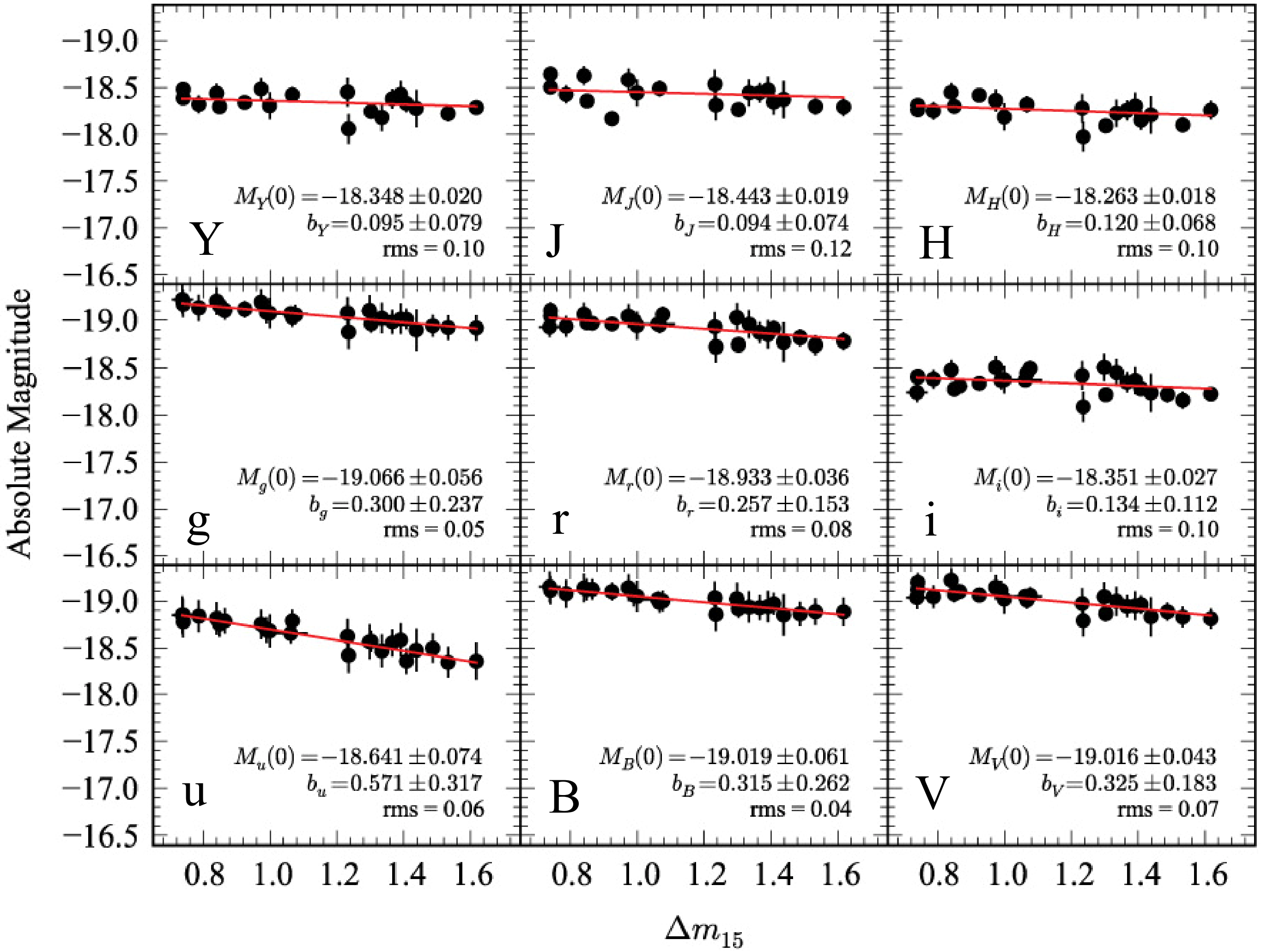


Wood-Vasey+2008 … σ ~0.15mag without any LC corrections

Contreras+ 2010 … NIR light curves of 25 SNe from CSP

MW Extinction in H band … ~5% of extinction in V band

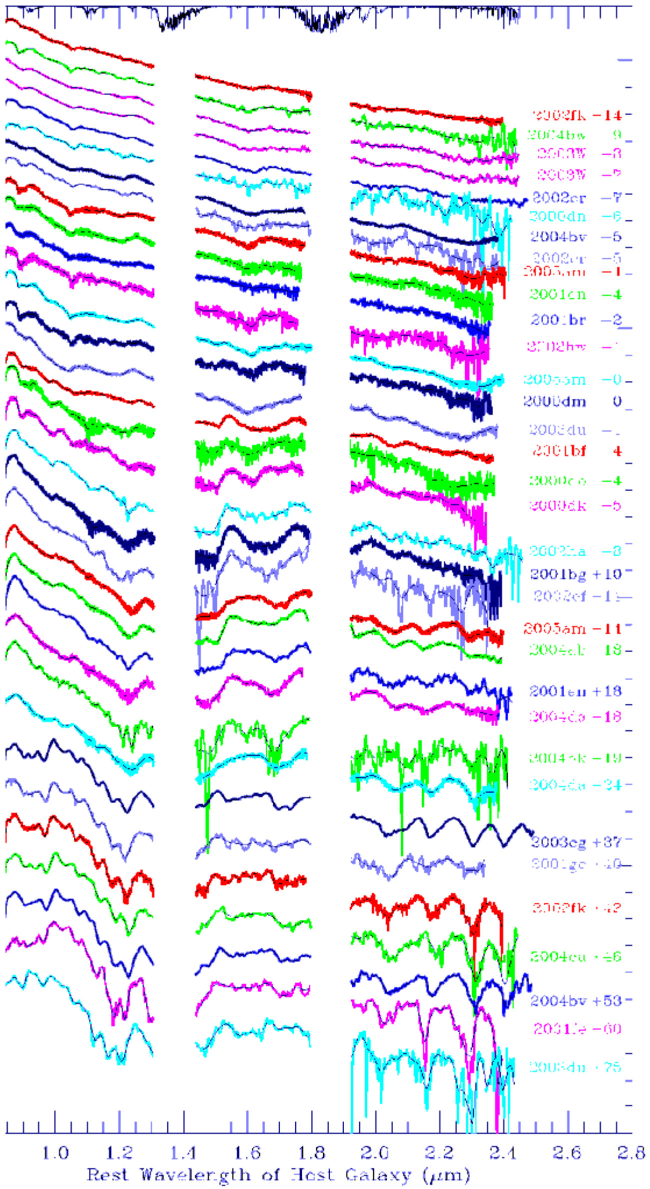
Examples: uBVgriYJH photometry



6% rms in magnitude (3% in distance) without systematic errors

Burns+2011

NIR spectra of SNIa : less features



1.0 Wavelength(μm) 2.8

Marionet al. 2009

Future distant SNIa cosmology

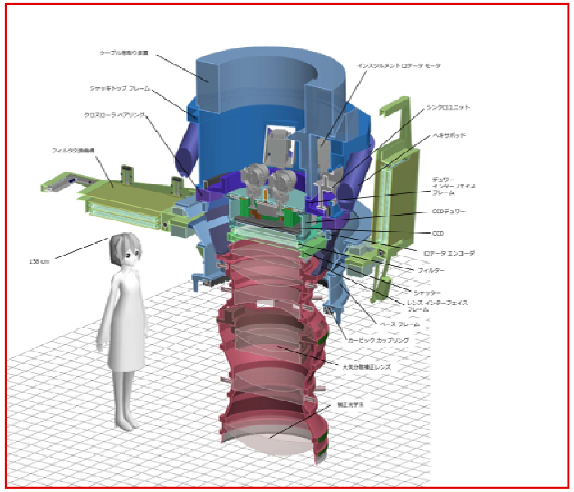
- Large imaging surveys

supernovae, gravitational lens, BAO

HyperSuprimeCam (HSC),

LSST, EUCLID, WFIRST

….



FoV 1.5 degree Φ

HSC can find ~500 SNe/ nights

too many to follow by spectroscopy

photometry

NIR very important

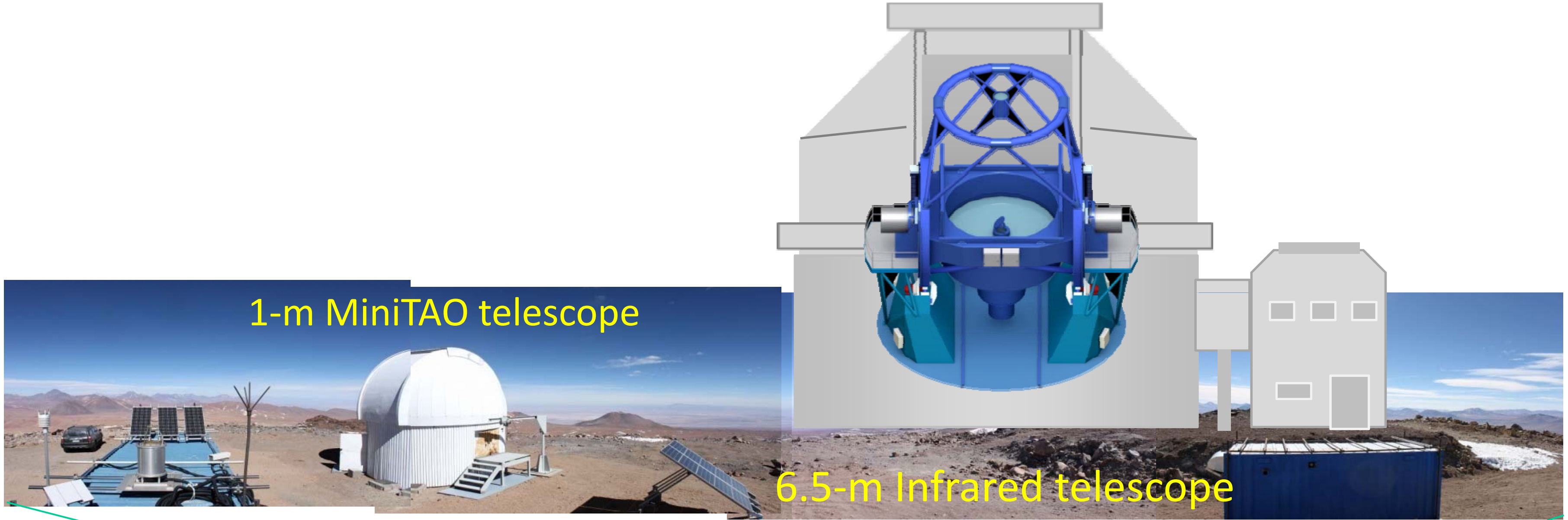
local calibrators

e.g. CANDLES: HST/MCT ~900orbits : rate studies

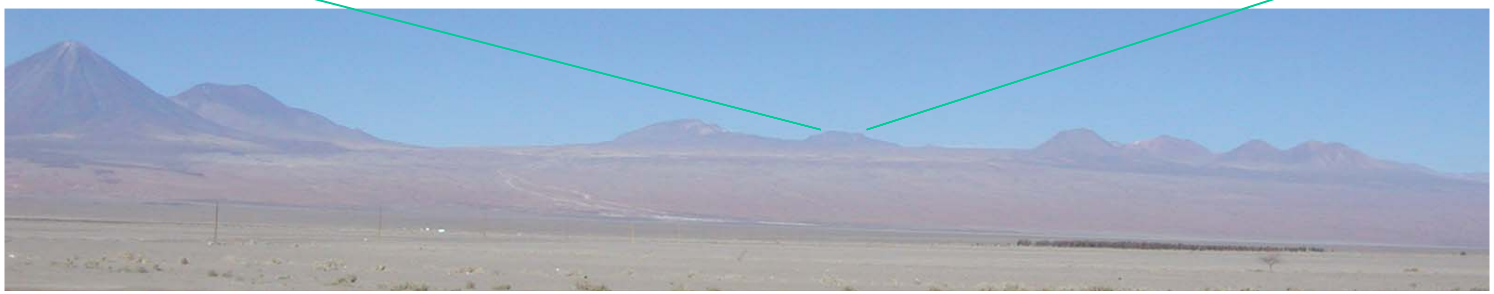
The University of Tokyo Atacama Observatory (TAO) Project

July 28,29, 2011 @LBNL Supernova Cosmology Porject collaboration meeting

Mamoru Doi, University of Tokyo for TAO project

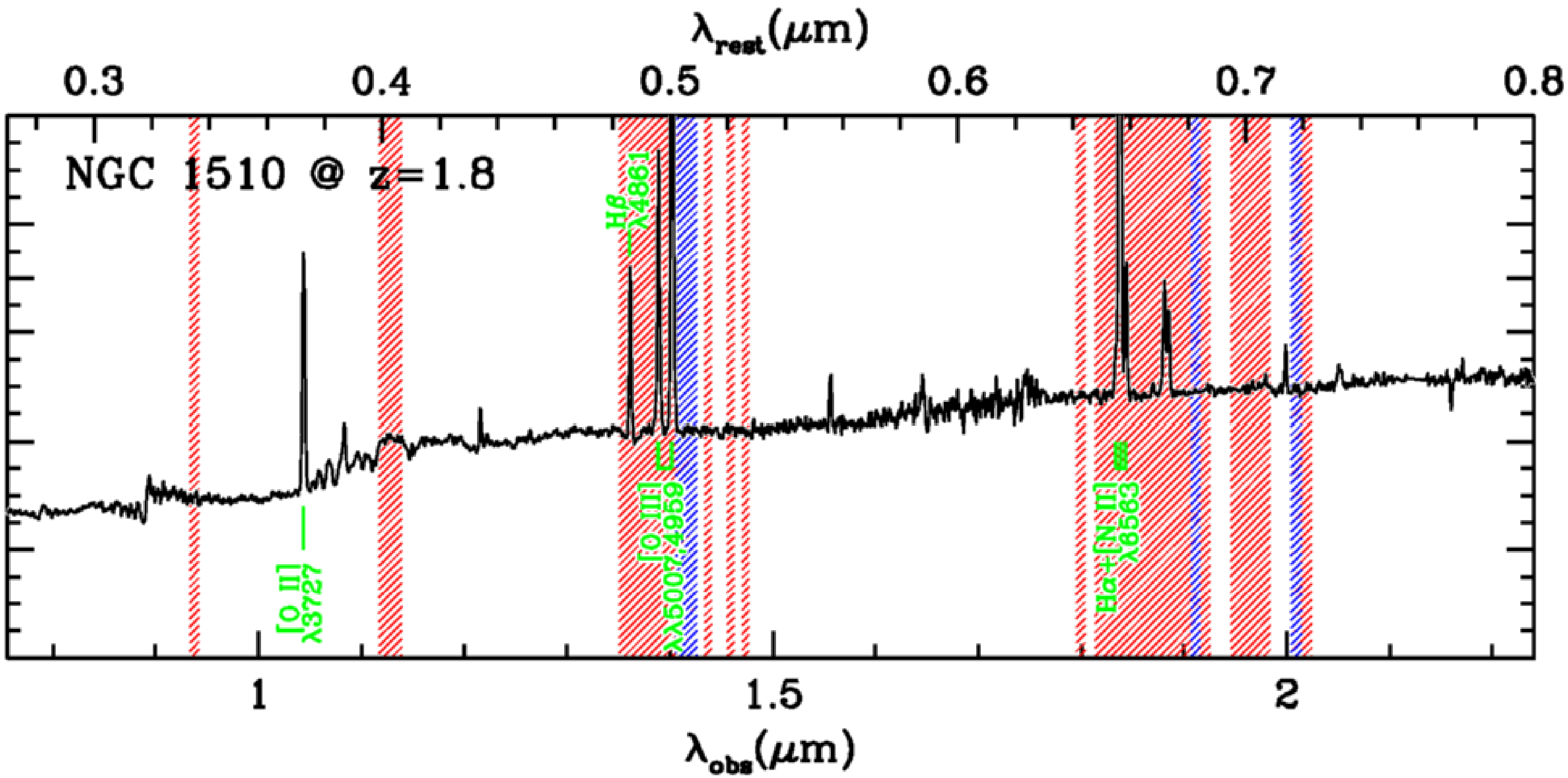


Chajnantor Summit (5640m) in the Parque Astronómico Atacama



NIR: almost continuous coverage

because of high altitude and dry climate



Little transmittance at TAO site

Little transmittance at ~2600m

Suitable for NIR template spectra of SNeIa

Observational Supportive Evidences

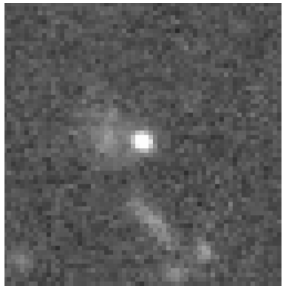
○SNe : slightly fainter

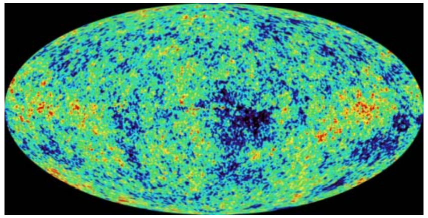
○Galaxy Distribution : typical scale slightly smaller

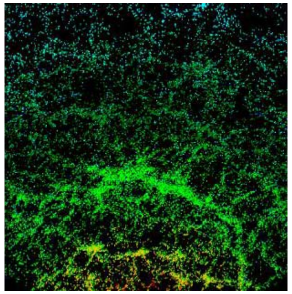
○CMB : flat geometry of the universe

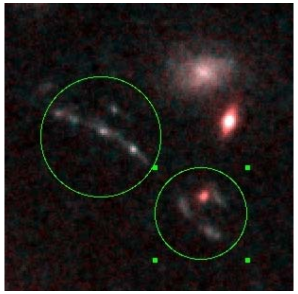
○Gravitational lens : distortion of galaxies slightly larger

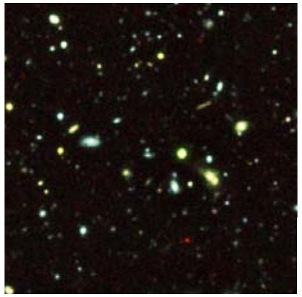
○number of faint galaxies : slightly numerous

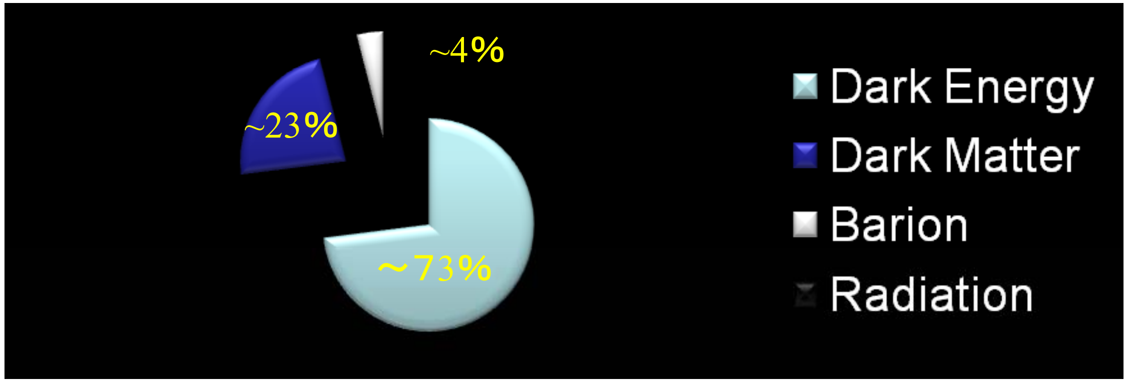












Future projects

- Large imaging surveys

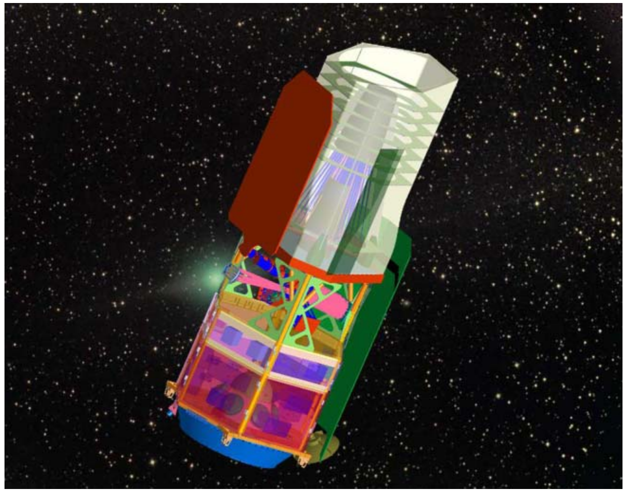
  gravitational lens, supernovae (, BAO)

  HyperSuprimeCam(8.2m, 2012), LSST(8.4m ?),

  EUCLID (1.2m space, 2019?),

  WFIRST(1.5m?, 2022??)

  ….



- Large spectroscopic surveys

  galaxy distribution (BAO)

  BOSS (on going)

  PFS@Subaru(SUMIRE, 2017?)

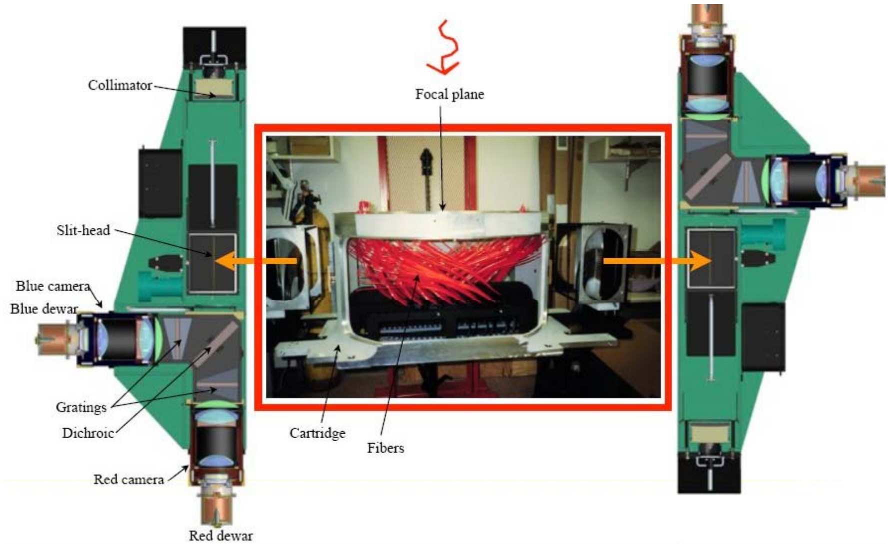
  BigBOSS, EUCLID

  …

- CMB fluctuations

  Planck(on going)

  …



Target: σ in w_0 ~5% (HSC)?

Summary

- Supernova Cosmology

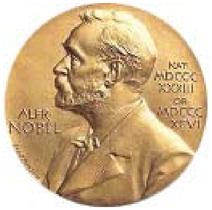
  Flat universe ?!

  systematic errors dominate for low and middle z

- Future … more accurate distance measurements

  understanding properties of SNIa

  rest frame NIR measurements



The Nobel Prize in Physics 2011

Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

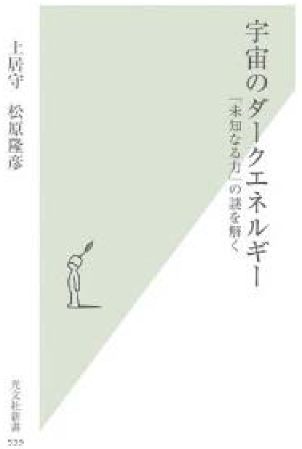
Supernova Cosmology Project

High-z Supernova Search Team

"for the discovery of
the accelerating expansion of the Universe
through observations of distant supernovae"

Congratulations!

A Letter from Dr. Brian Schmidt



Dear Mamoru

Thank you for your kind letter of congratulations on the announcement of my 2011 Nobel Prize in Physics. It is a great recognition for all the team that were a part of this discovery, and I am honoured to have been awarded such a prestigious prize.

Please also accept my thanks for the generous gift of your book, written with Dr Matsubara. I am also very grateful for the translation.

With best wishes,

Yours sincerely

Professor Brian P. Schmidt
ARC Laureate Fellow
ANU Distinguished Professor

Brian Schmidt博士講演会
2012年4月20日午後5時　東大安田講堂にて

Observations of SN candidates by Suprime-Cam
at Keck Waimea base with Dr.Saul Perlmutter (2002)