

Determining the Nature of Dark Energy: The Latest Results from ESSENCE and the Future of Observational Cosmology

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Harvard-Smithsonian Center for Astrophysics

SCALE OF THE UNIVERSE

BIG
BANG

PRESENT
TIME

FUTURE

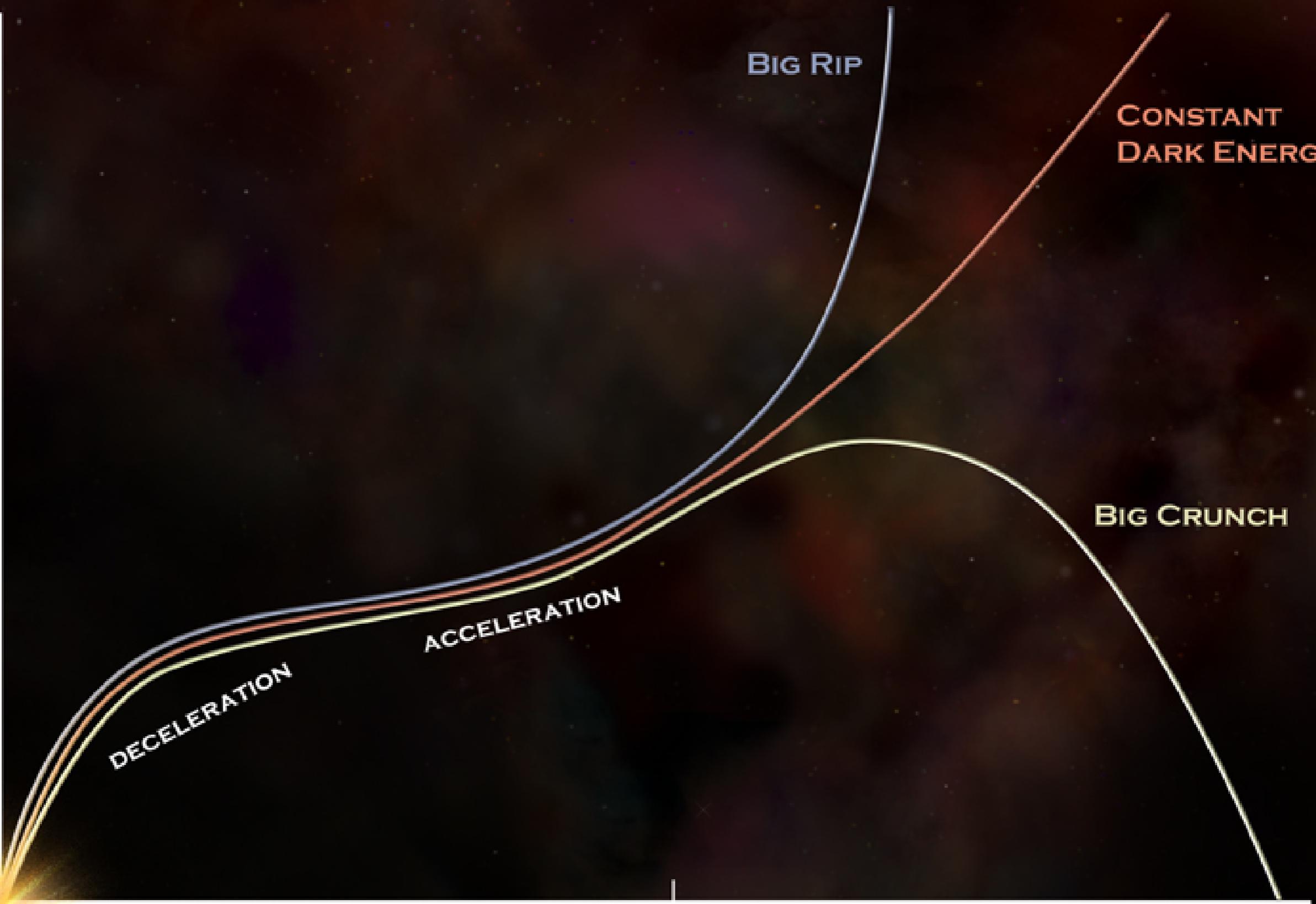
Big Rip

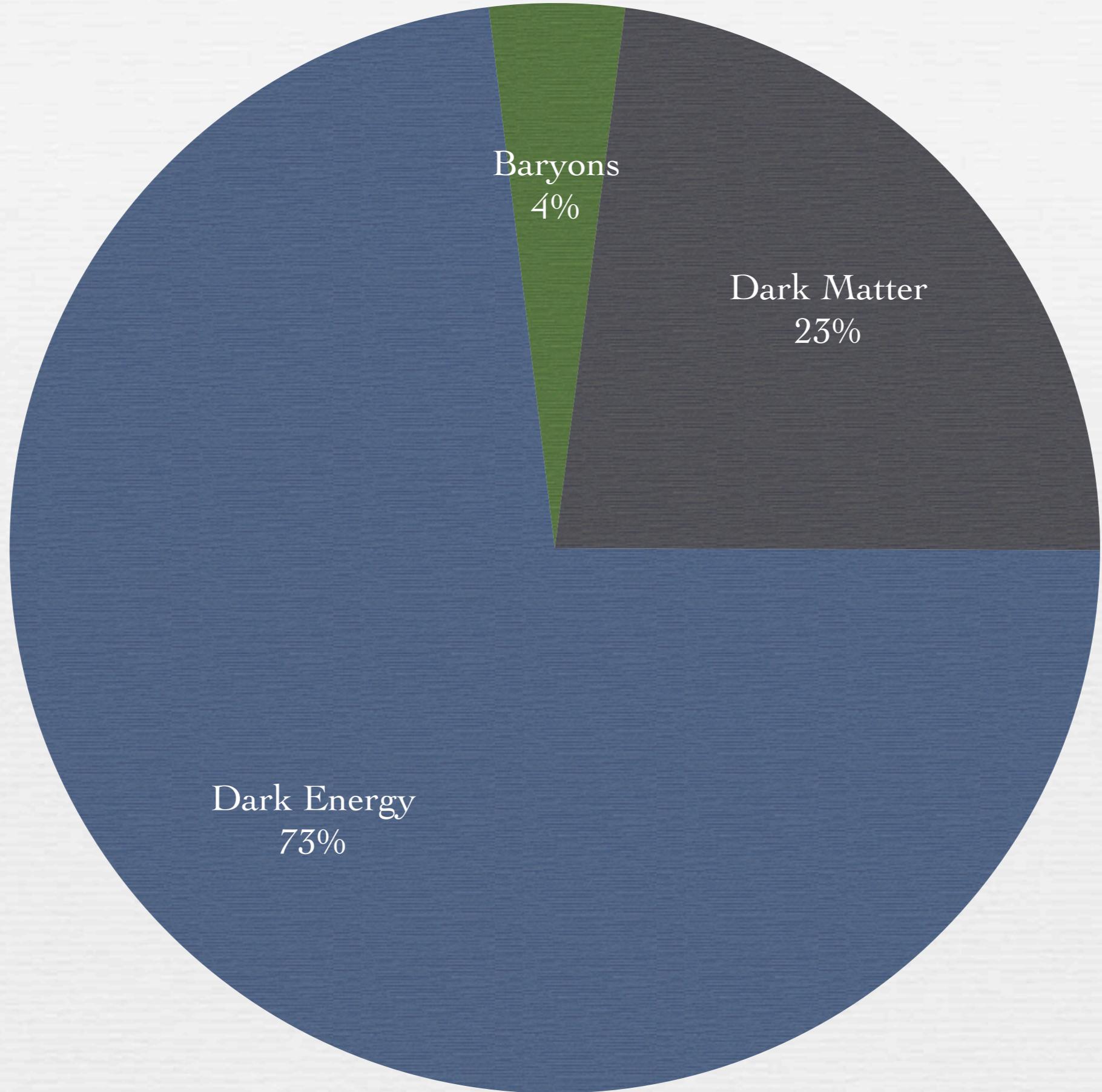
CONSTANT
DARK ENERGY

Big Crunch

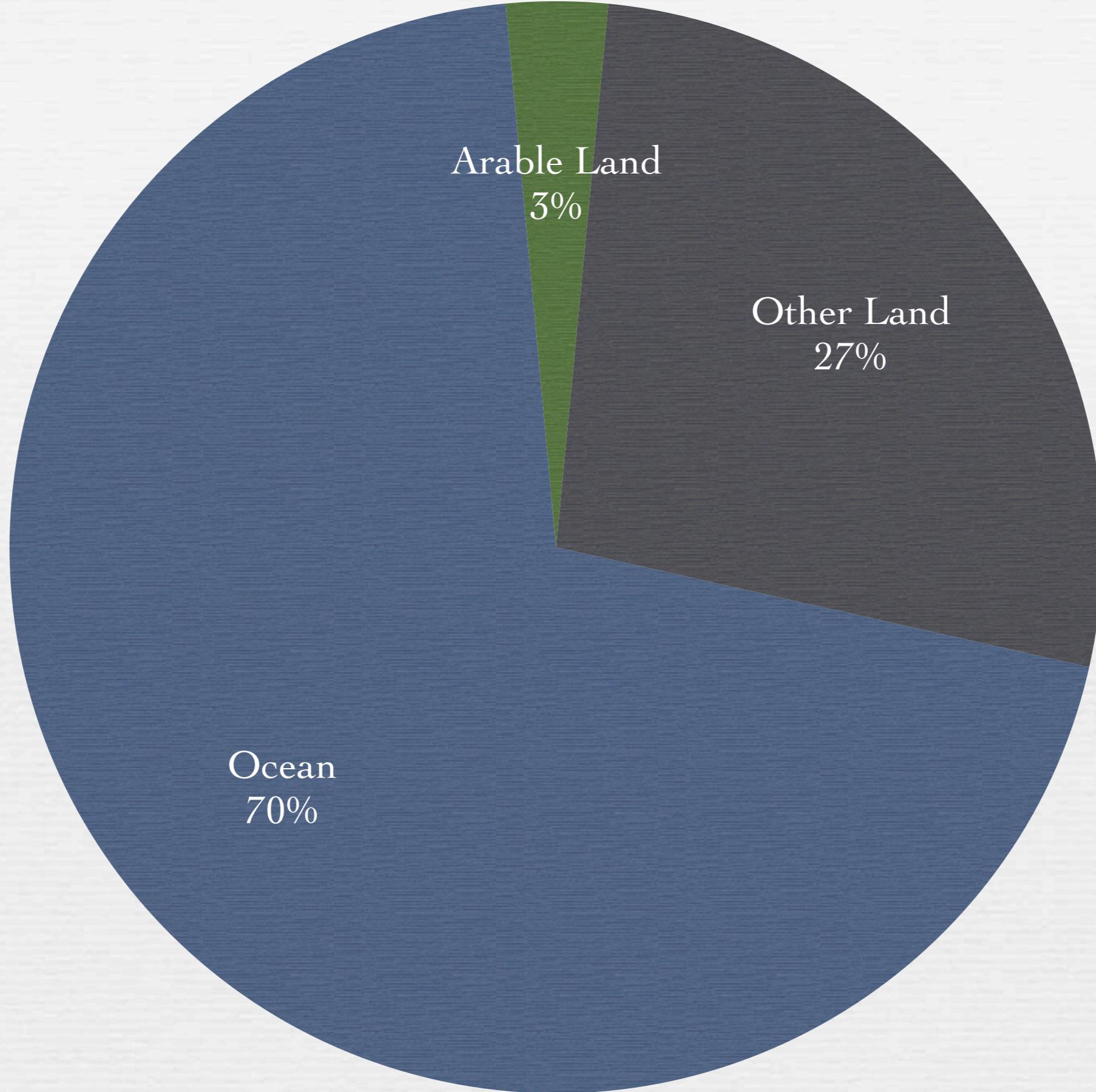
ACCELERATION

DECELERATION



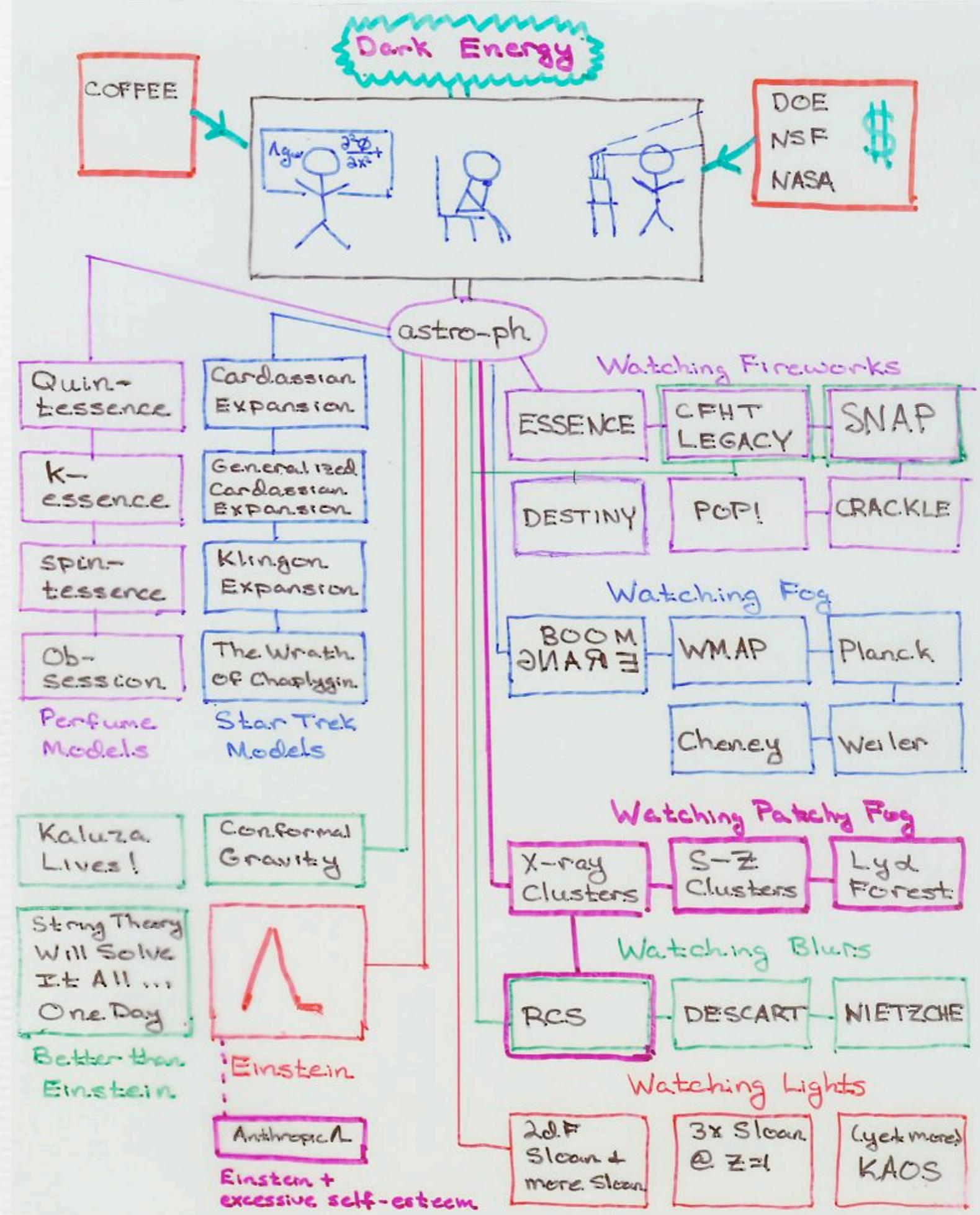


c.f. Astier06, Spergel06, Eisenstein05, Perlmutter99, Riess98



Food and Agriculture Organization of the United Nations

What is Dark Energy?



Courtesy of David Weinberg

Three philosophically distinct possibilities...

- ❖ A “classical” cosmological constant, as envisioned by Einstein, residing in the gravitational sector.
- ❖ A “Vacuum energy” effect, arising from quantum fluctuations in the vacuum, acting as a “source” term
- ❖ Departure from GR on cosmological length scales
- ❖ **Regardless, it’s evidence of new fundamental physics!**

The Basic Question:

Is a cosmological constant model
consistent with our observations of
the Universe?

The ESSENCE Survey

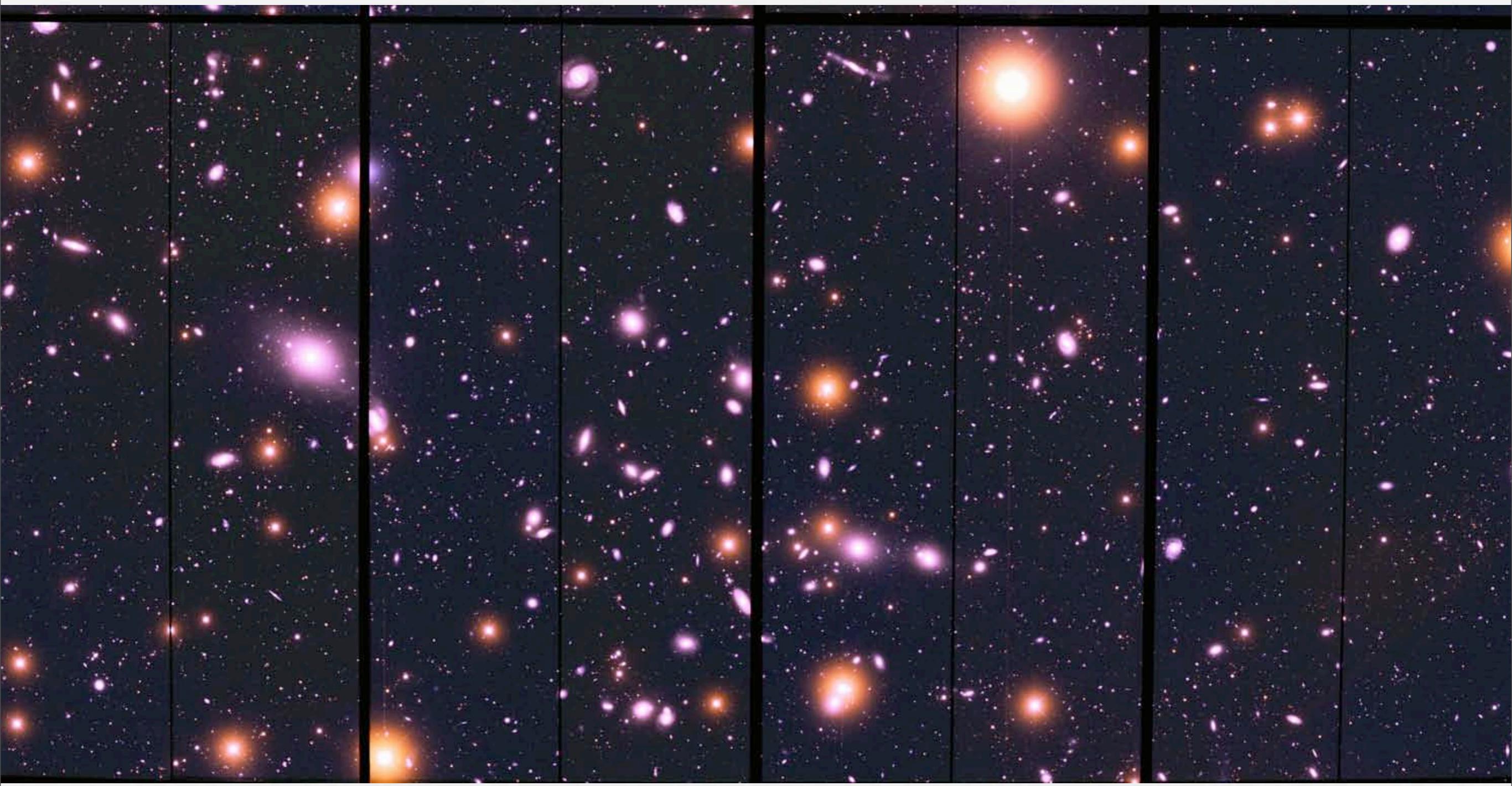


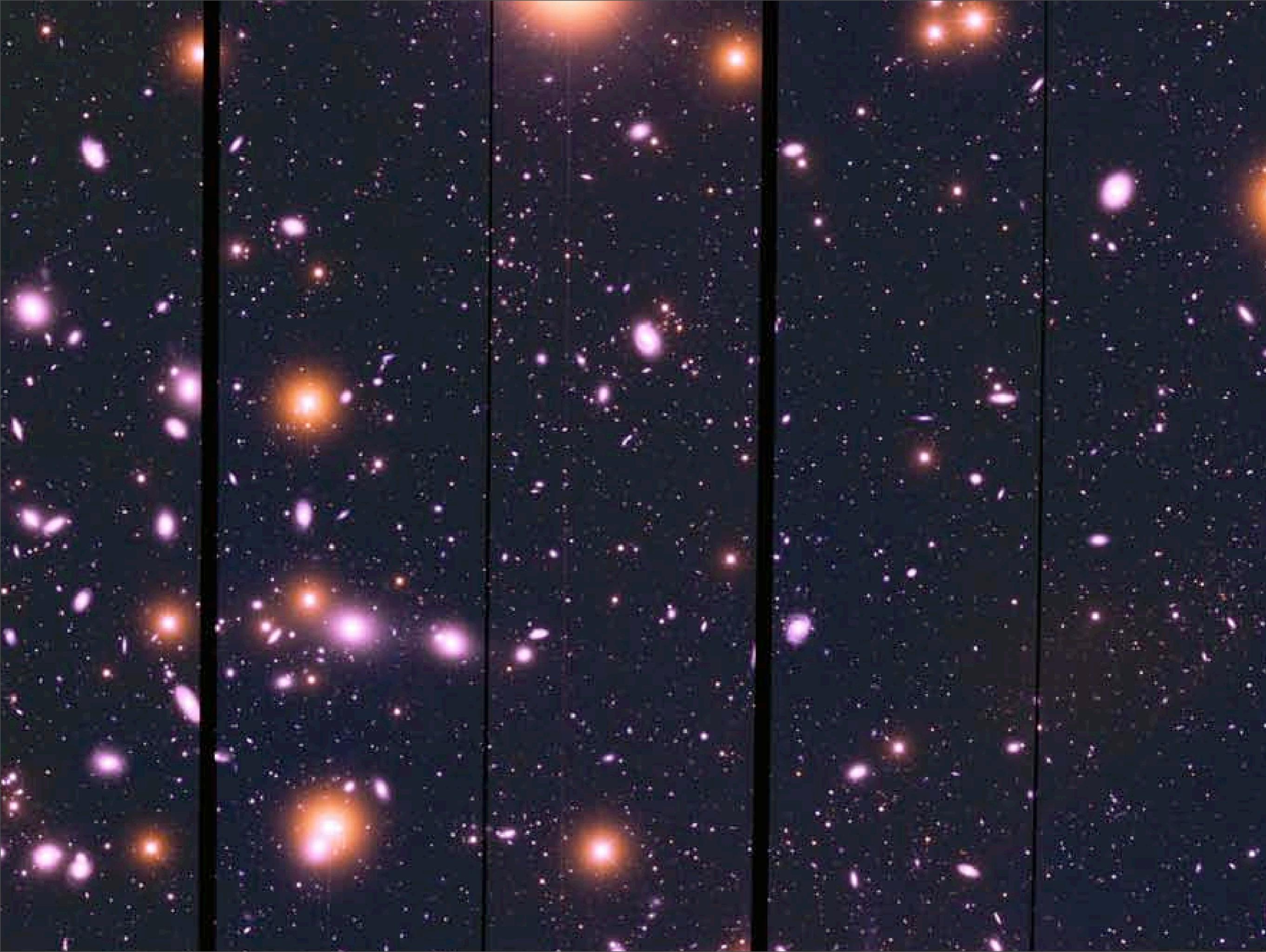
- ❖ Determine w to 10% or $w \neq -1$
- ❖ 6-year project on CTIO 4m telescope in Chile; 12 sq. deg.
- ❖ Wide-field images in 2 bands
- ❖ Same-night detection of SNe
- ❖ Spectroscopy
 - ❖ Keck, VLT, Gemini, Magellan
- ❖ Goal is 200 SNeIa, $0.2 < z < 0.8$
- ❖ Data and SNeIa public real-time



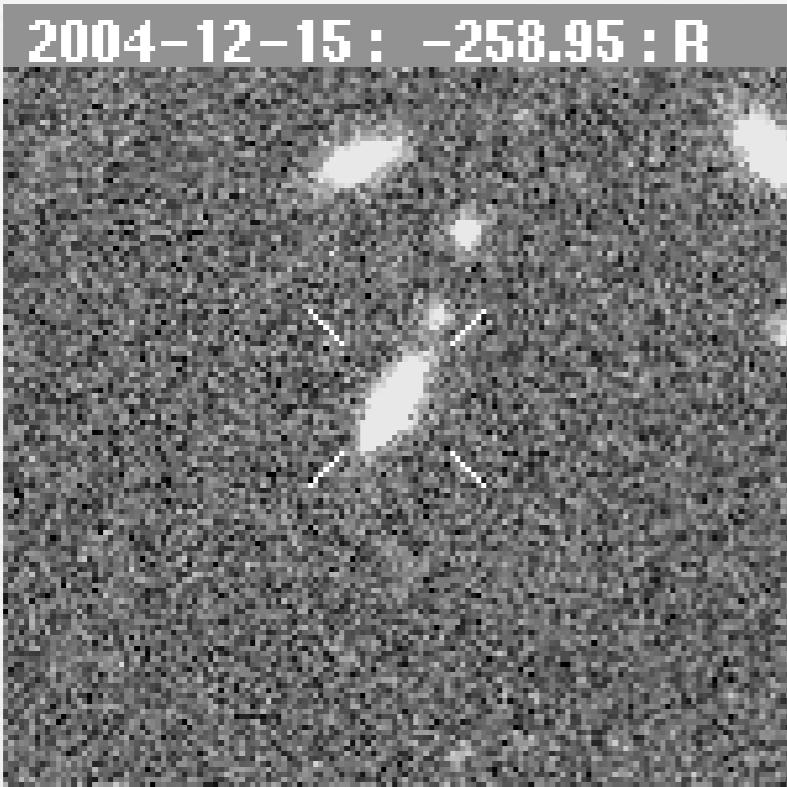
ESSENCE Survey Team

Claudio Aguilera	CTIO/NOAO	Bruno Leibundgut	ESO
Andy Becker	Univ. of Washington	Weidong Li	UC Berkeley
Josh Blackman	ANU/Stromlo/SSO	Thomas Matheson	NOAO
Stéphane Blondin	Harvard/CfA	Gajus Miknaitis	Fermilab
Peter Challis	Harvard/CfA	Gautham Narayan	Harvard University
Ryan Foley	UC Berkeley	Jose Prieto	OSU
Alejandro Clocchiatti	Univ. Católica de Chile	Armin Rest	NOAO/CTIO
Ricardo Covarrubias	Univ. of Washington	Adam Riess	STScI/JHU
Tamara Davis	Dark Cosmology Center	Brian Schmidt	ANU/Stromlo/SSO
Alex Filippenko	UC Berkeley	Chris Smith	CTIO/NOAO
Arti Garg	Harvard University	Jesper Sollerman	Stockholm Obs.
Peter Garnavich	Notre Dame University	Jason Spyromilio	ESO
Malcolm Hicken	Harvard University	Christopher Stubbs	Harvard University
Saurabh Jha	SLAC/KIPAC	Nicholas Suntzeff	Texas A&M
Robert Kirshner	Harvard/CfA	John Tonry	Univ. of Hawaii/IfA
Kevin Krisciunas	Texas A&M	Michael Wood-Vasey	Harvard/CfA

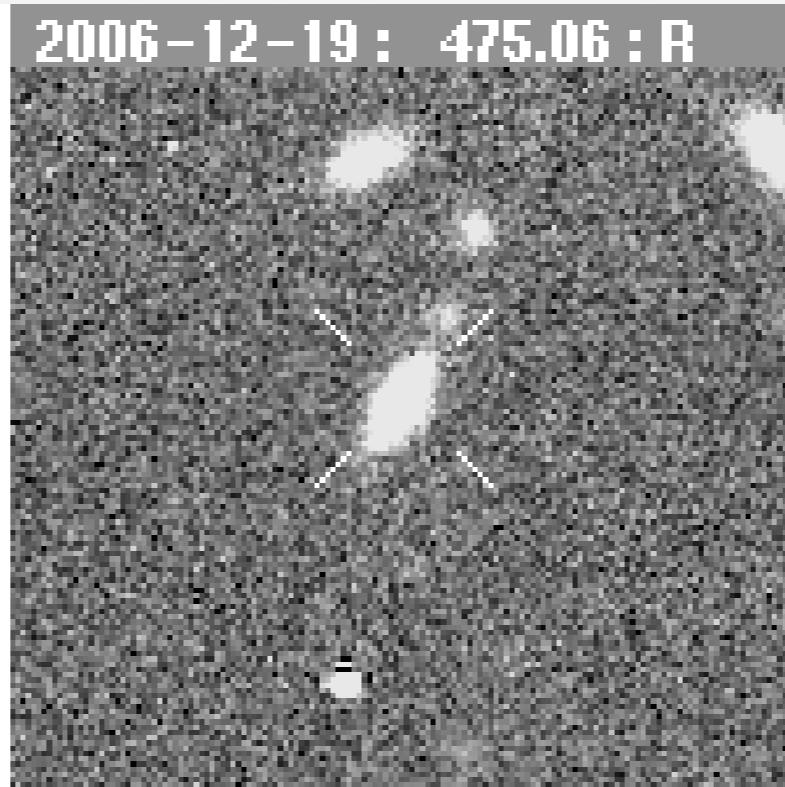




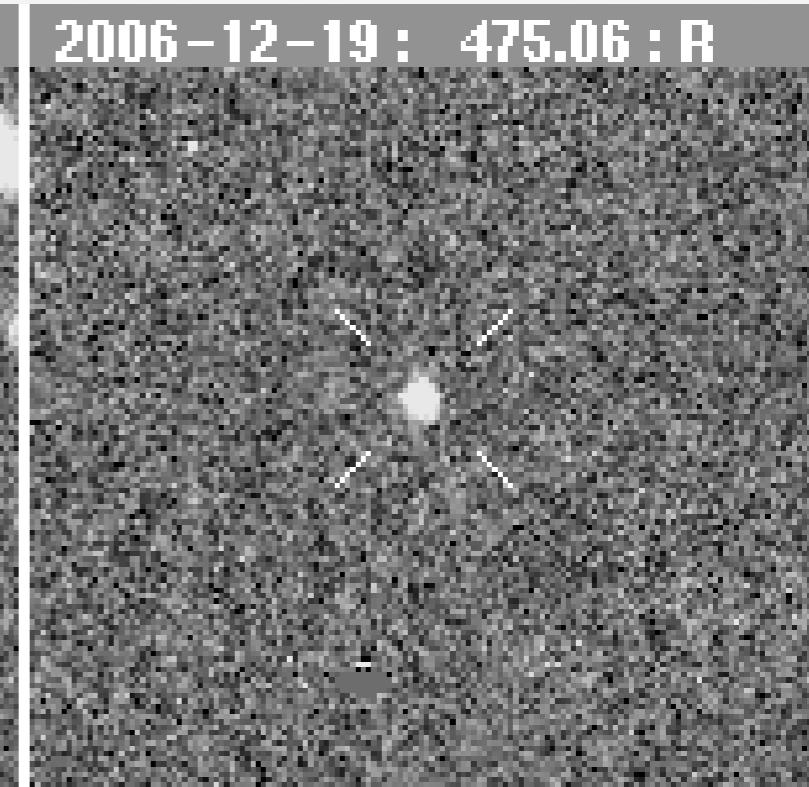
2004-12-15 : -258.95 : R



2006-12-19 : 475.06 : R



2006-12-19 : 475.06 : R



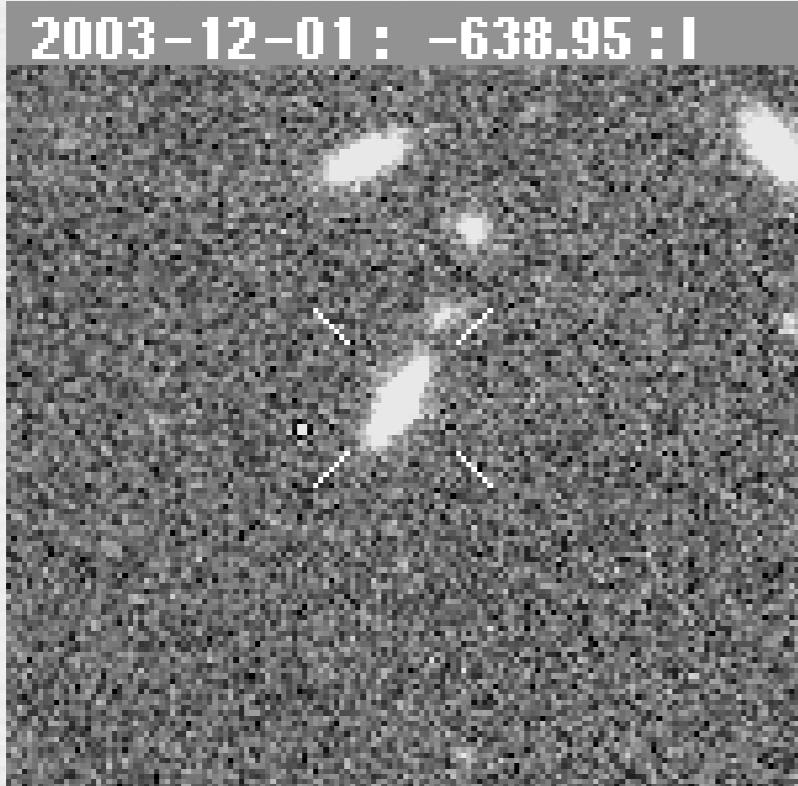
R

Reference

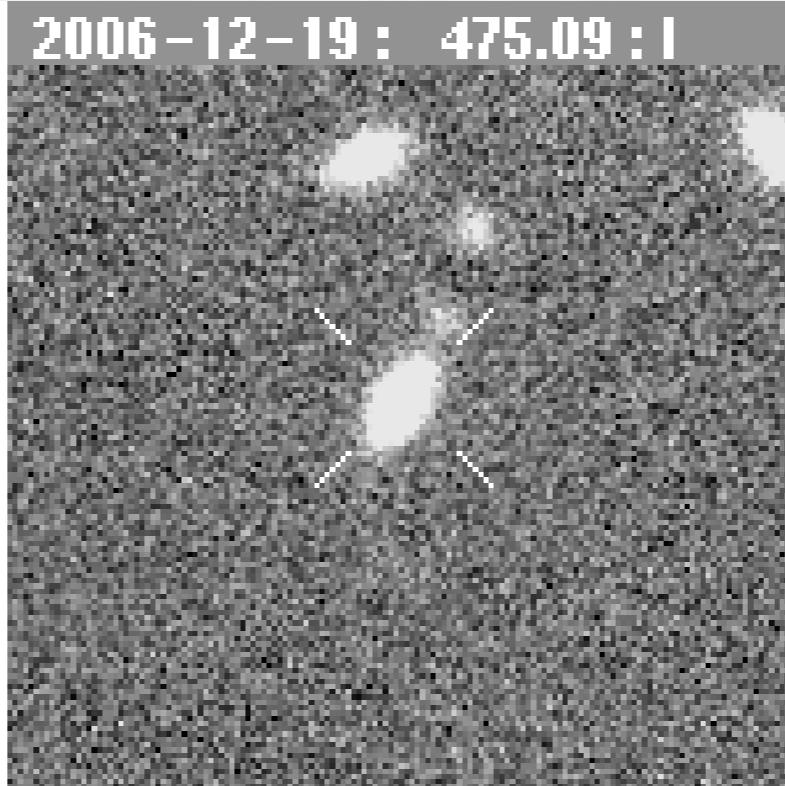
New

Difference

2003-12-01 : -638.95 : I



2006-12-19 : 475.09 : I



2006-12-19 : 475.09 : I

I

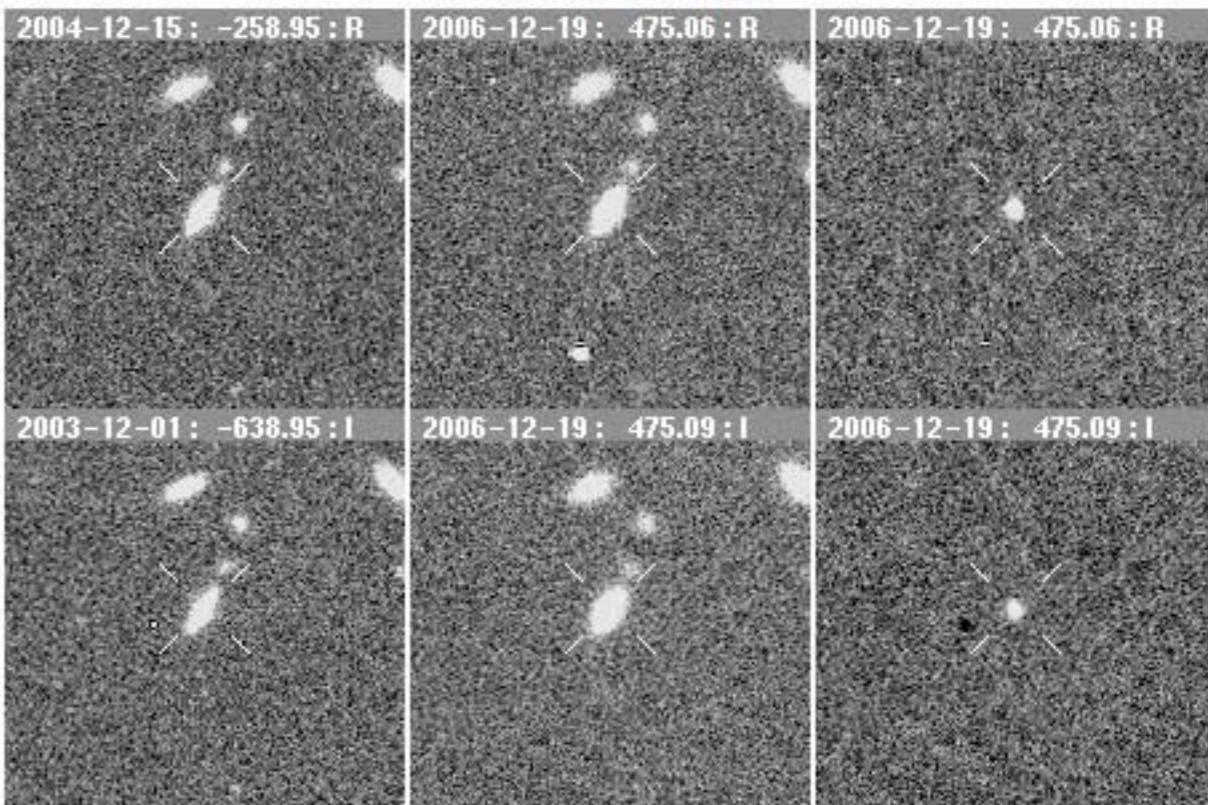
2006-S-349

previous event: [2006-S-347](#) next event: [2006-S-350](#) [Alert Page](#) [Spectroscopy Page](#)

Event Info

RAaverage	01:09:17.296
DECaverage	+00:09:11.31
Ninside	2
R mag (54098.044880)	21.53 +/- 0.07
R avg offset	1.09 pix, 0.29" (Type : Galaxy)
I mag (54098.039070)	21.50 +/- 0.10
I avg offset	1.11 pix, 0.30" (Type : Galaxy)
R-I:	0.03
field/amp	wbb6/12
last update	12/30/06_16:28PM_CLST

Postage Stamps



Spectroscopy Info

Spec. status	confirmed
Spec. Priority	1
Spec. Telescope	VLT
Spec. Date	2006/12/21
Spec. Type	Ia
Spec. Comment	-
specz	0.23
speczssource	-

Links

[R,I difference flux lightcurve](#)

[Object file](#)

Finding Chart - Image: [ps](#) [pdf](#)

Finding Chart - Template: [ps](#) [pdf](#)

Fits files: [tmpl](#) [im](#) [sub](#)

[commands](#) [logfile](#)

SNfit : $\chi^2=4.0, z_{phot}=0.24$ (*forced photometry*)

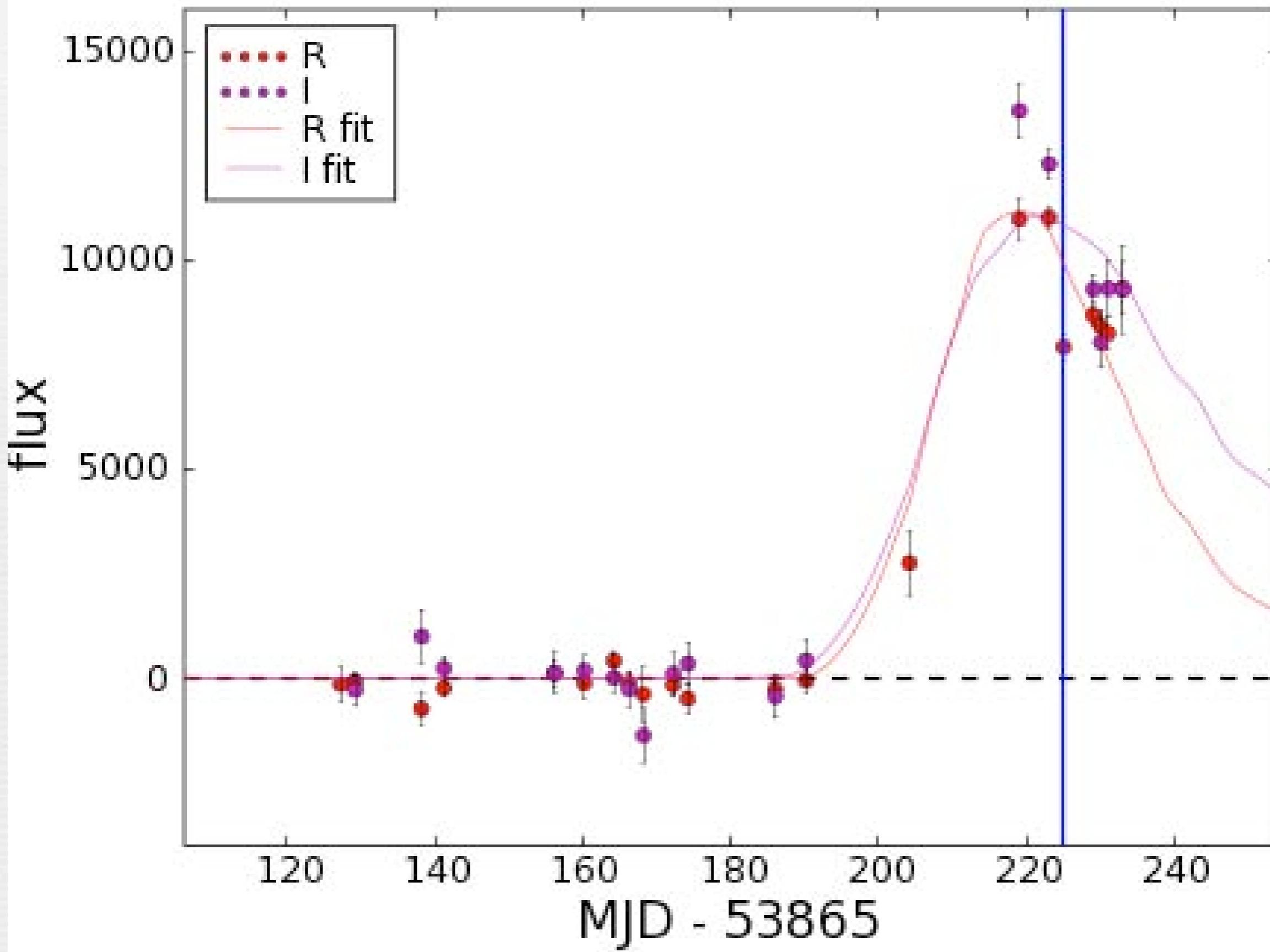


Magnitude plot (forced photometry)

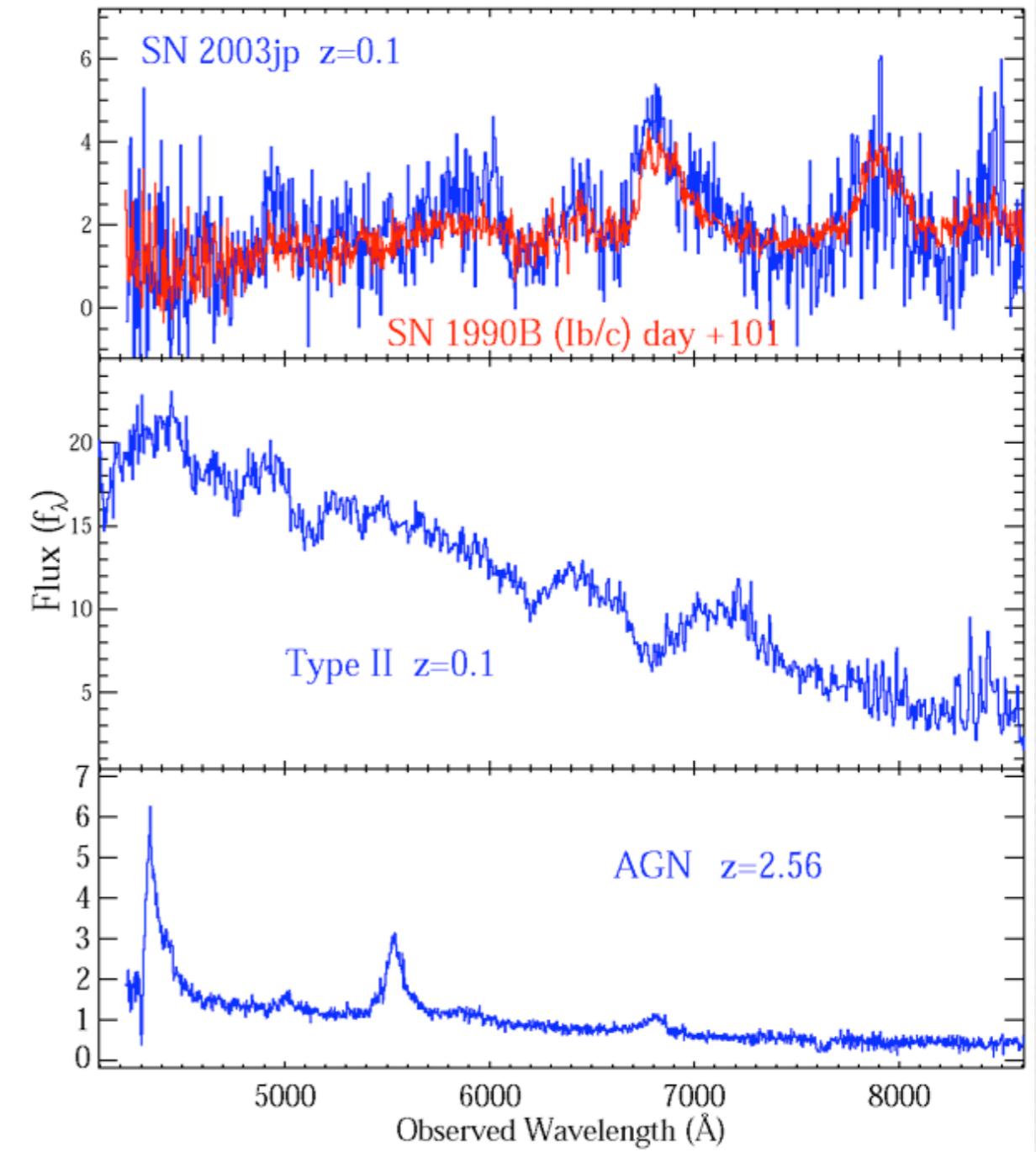
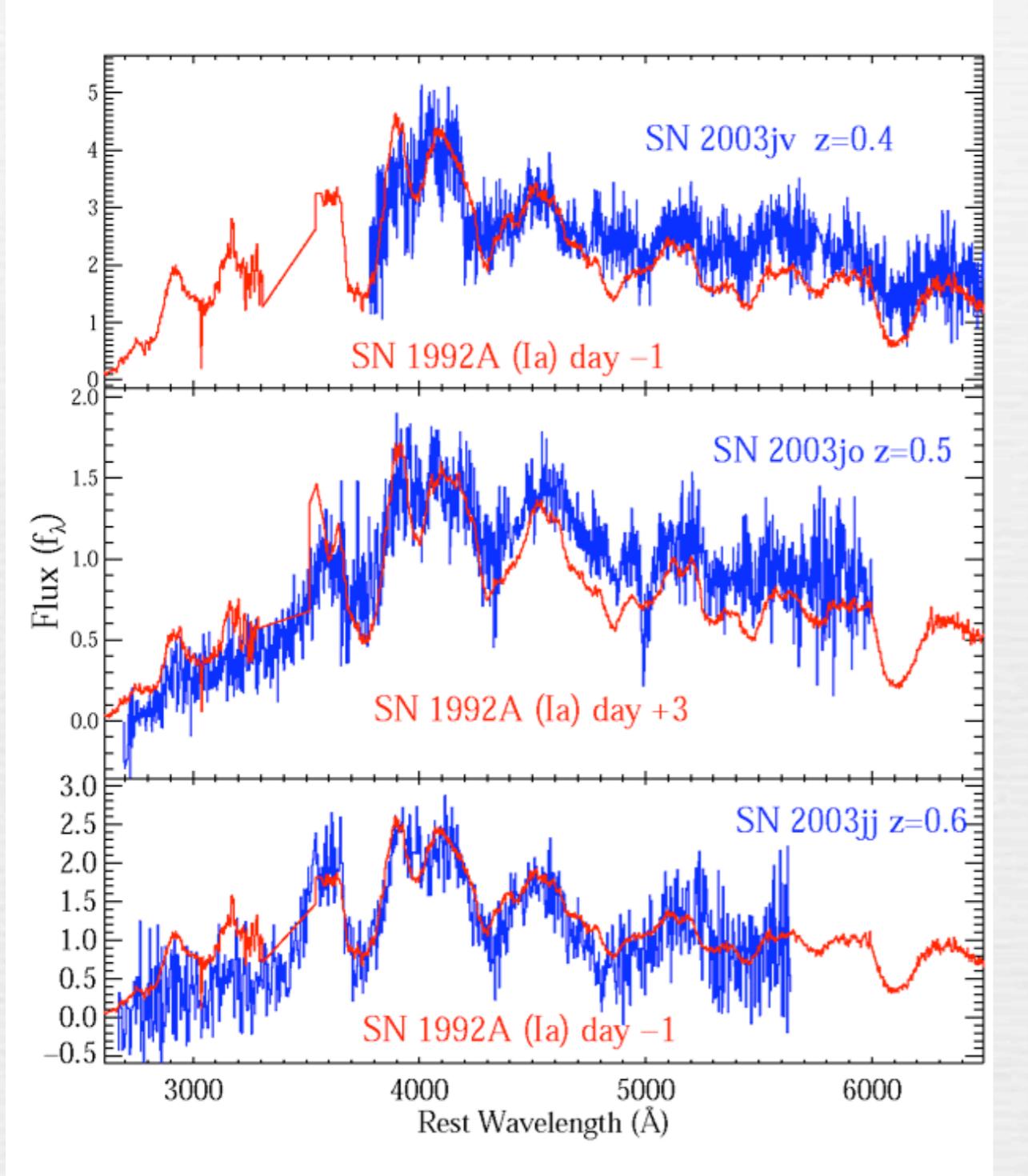


2005-11-22 : 83.07 : R	2006-09-14 : 379.29 : R	2006-09-16 : 381.21 : R	2006-09-25 : 390.22 : R	2006-09-28 : 393.25 : R	2006-10-13 : 408.23 : R
2005 Time	2006 Sep				Oct
2006-10-17 : 412.22 : R	2006-10-21 : 416.23 : R	2006-10-23 : 418.24 : R	2006-10-25 : 420.22 : R	2006-10-29 : 424.23 : R	2006-10-31 : 426.22 : R
2006-11-12 : 438.04 : R	2006-11-16 : 442.19 : R	2006-11-30 : 456.19 : R	2006-12-15 : 471.06 : R	2006-12-19 : 475.06 : R	2006-12-21 : 477.06 : R
Nov			Dec		
2006-12-25 : 481.06 : R	2006-12-26 : 482.08 : R	2006-12-27 : 483.05 : R	2006-12-29 : 485.04 : R		

SNfit : $\chi^2=4.0, z_{phot}=0.24$ (forced photometry)

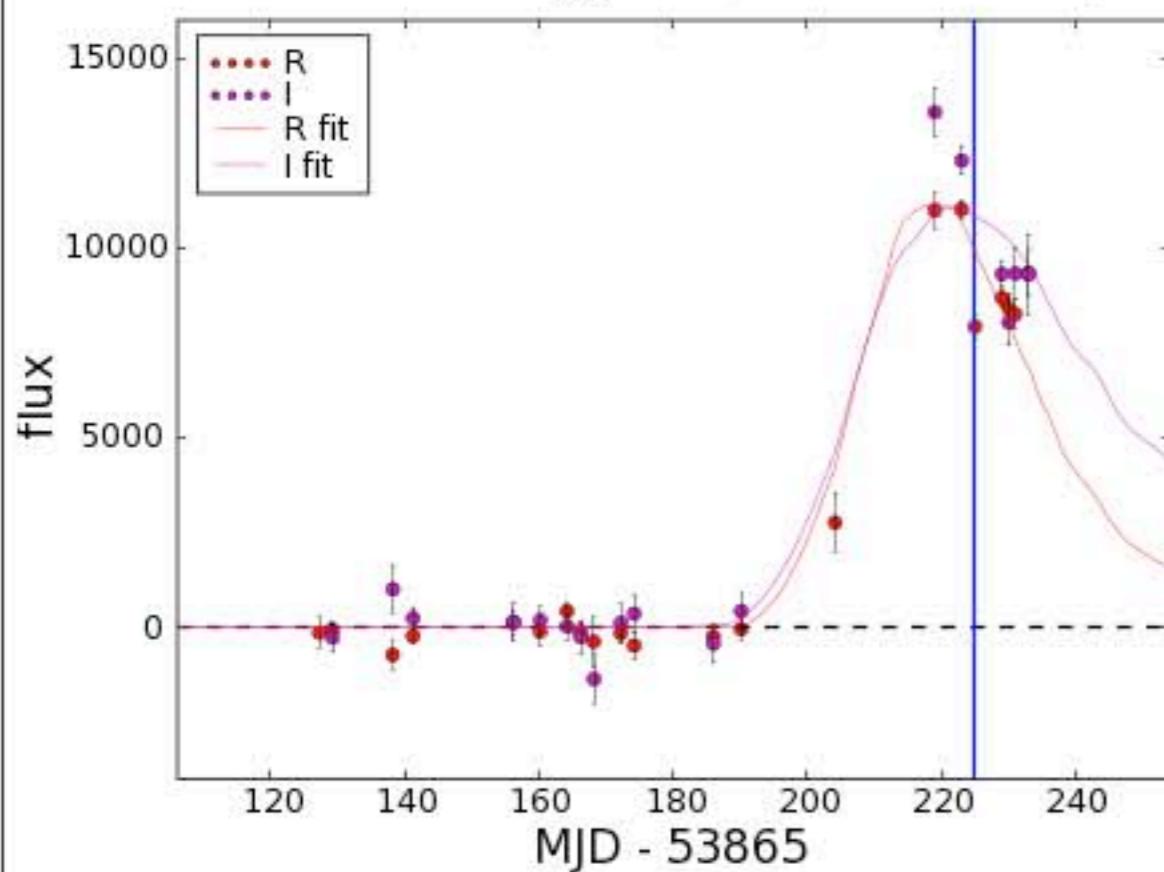


ESSENCE Spectra

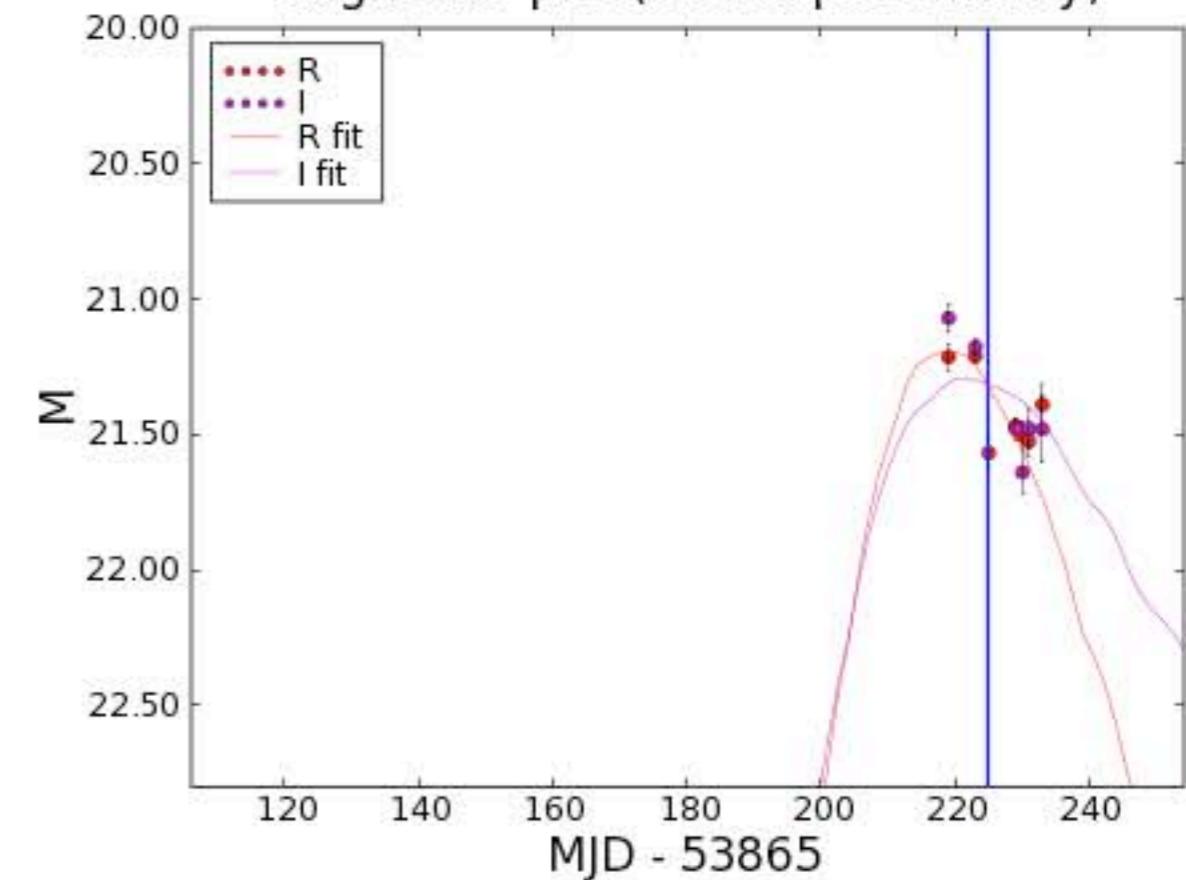


Matheson et al. (2005)

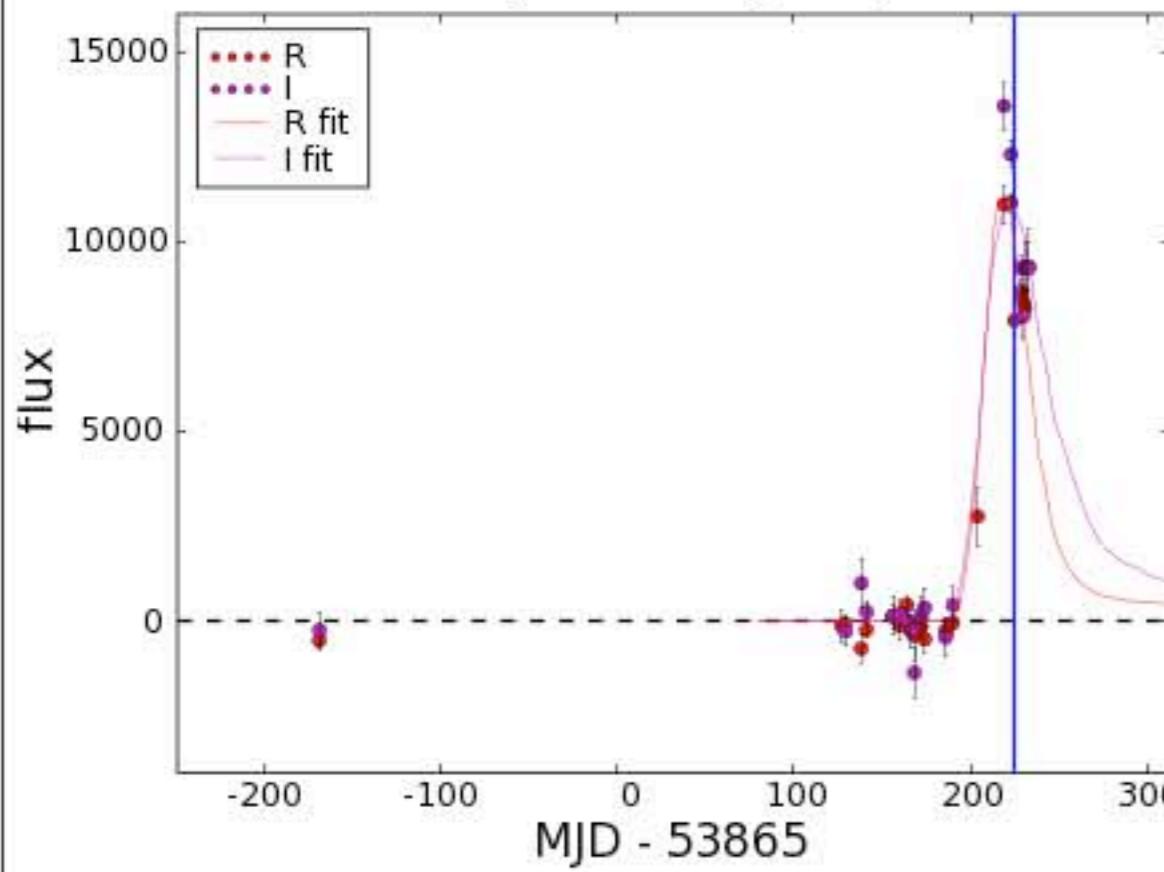
SNfit: $\chi^2=4.0, z_{phot}=0.24$ (forced photometry)



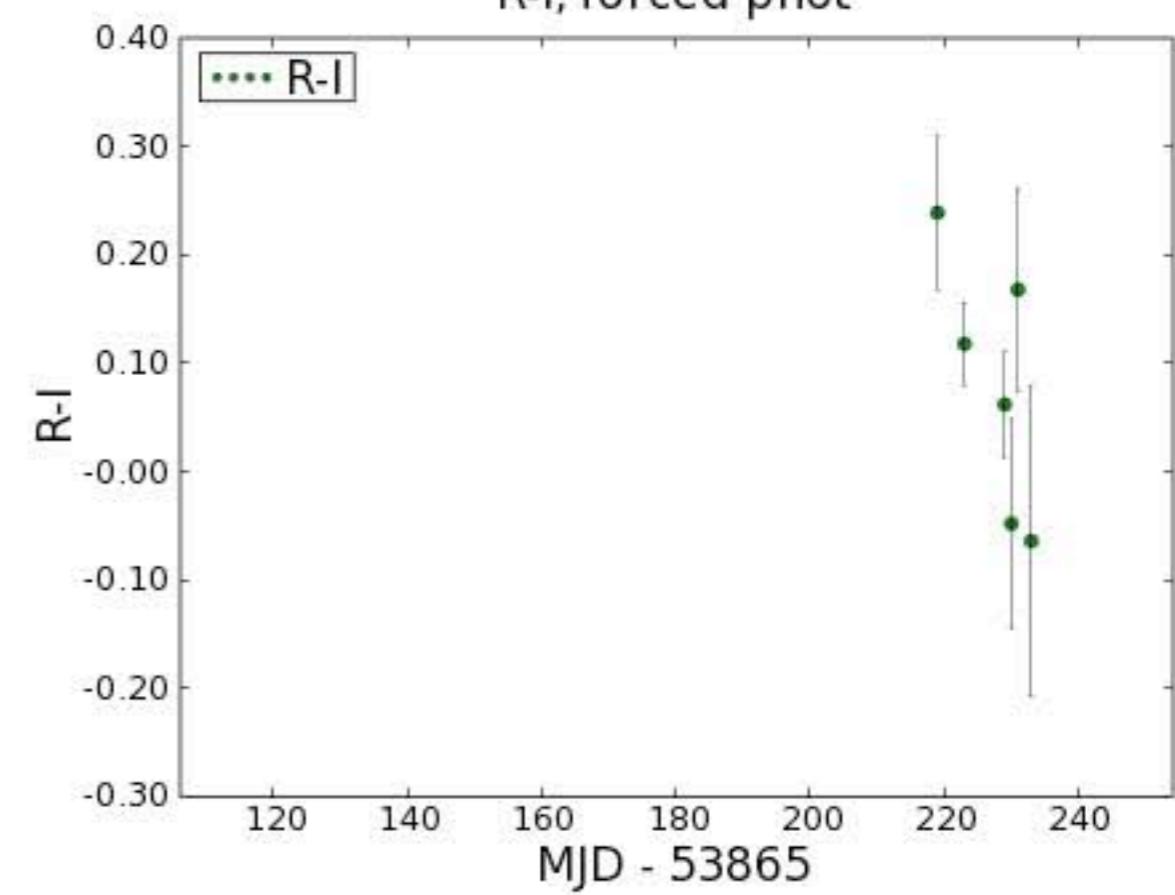
Magnitude plot (forced photometry)



forced photometry, all years



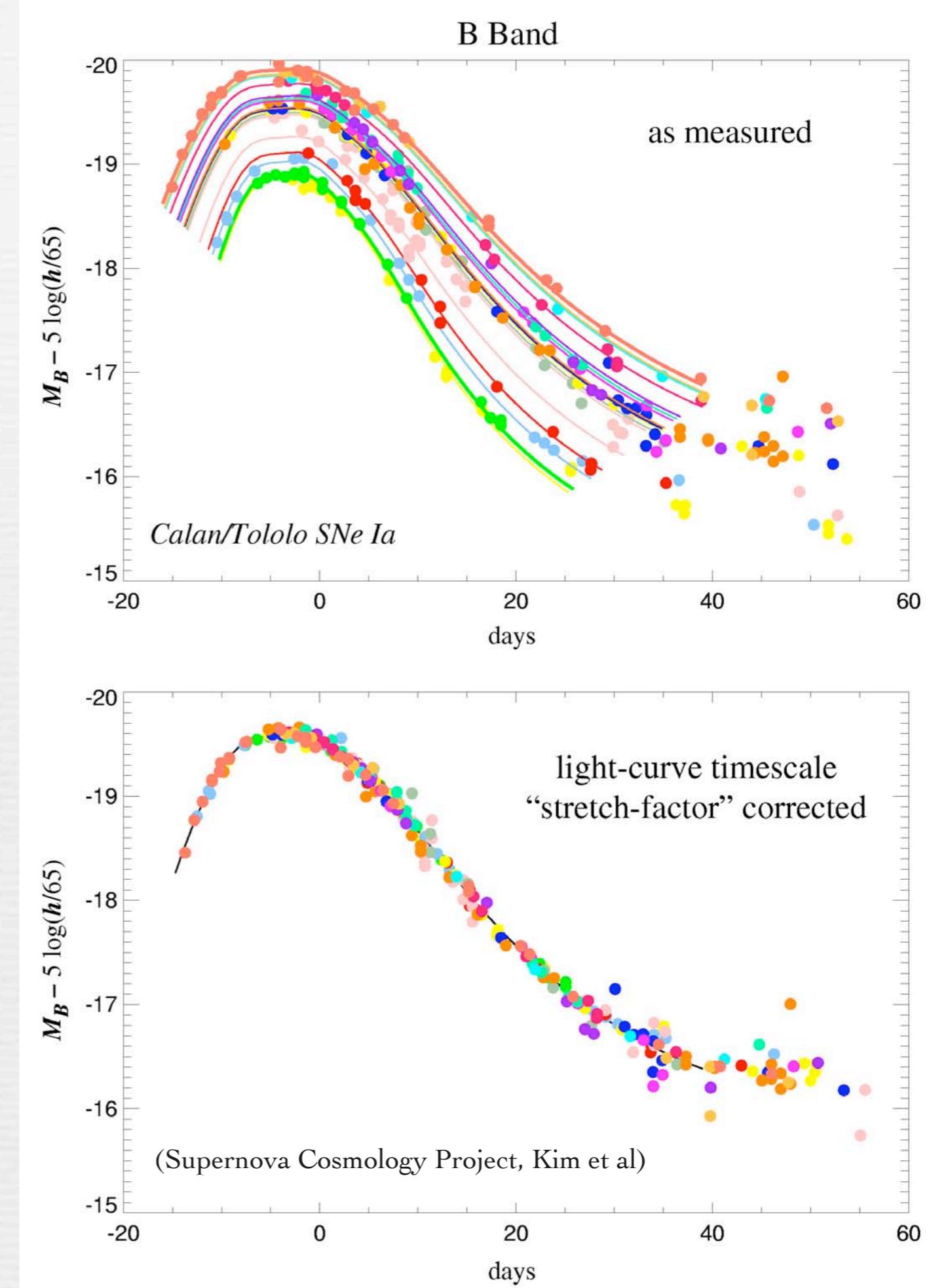
R-I, forced phot



One-parameter family

Δ {

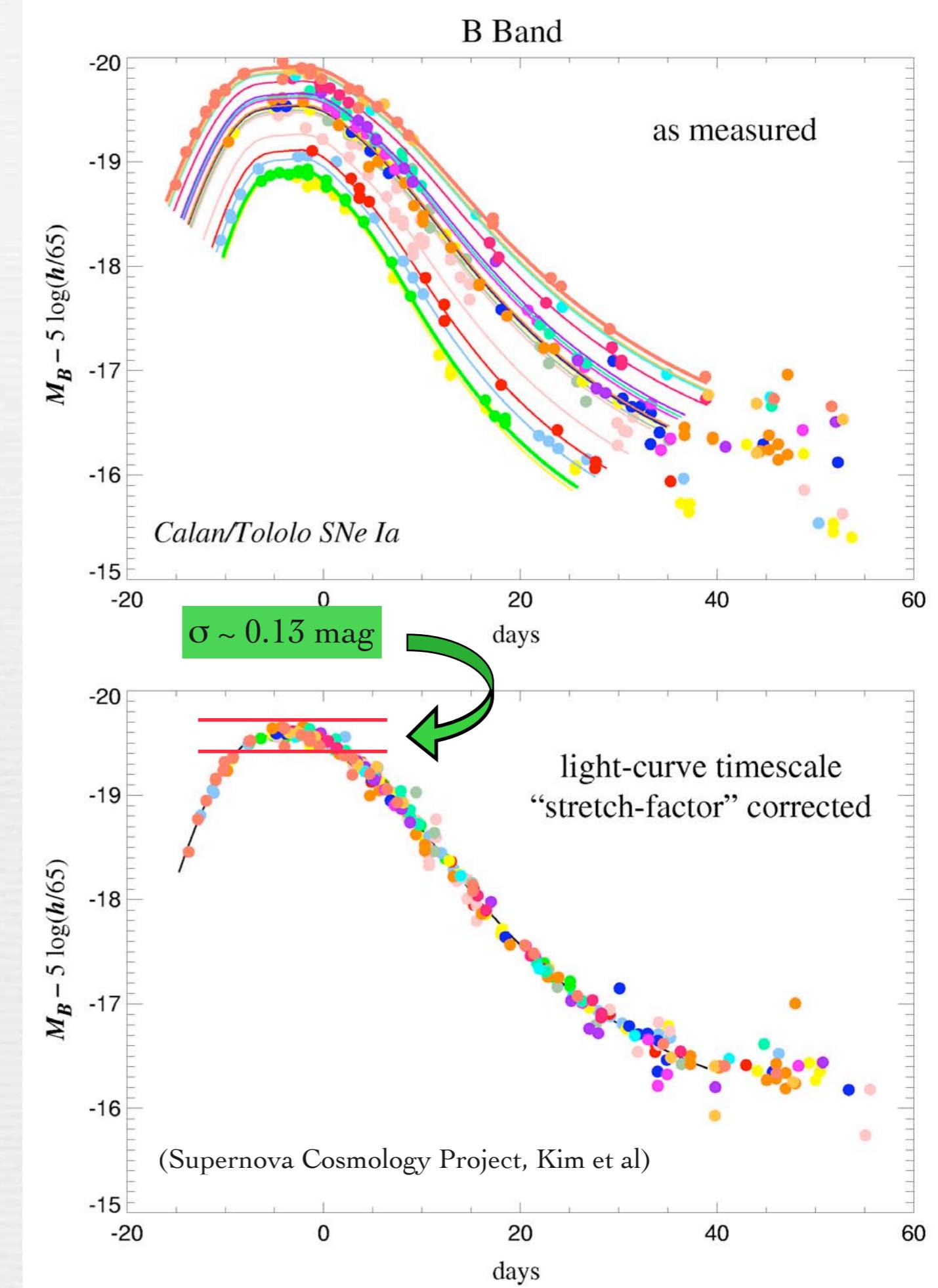
- Color
- Rate of decline
- Peak brightness



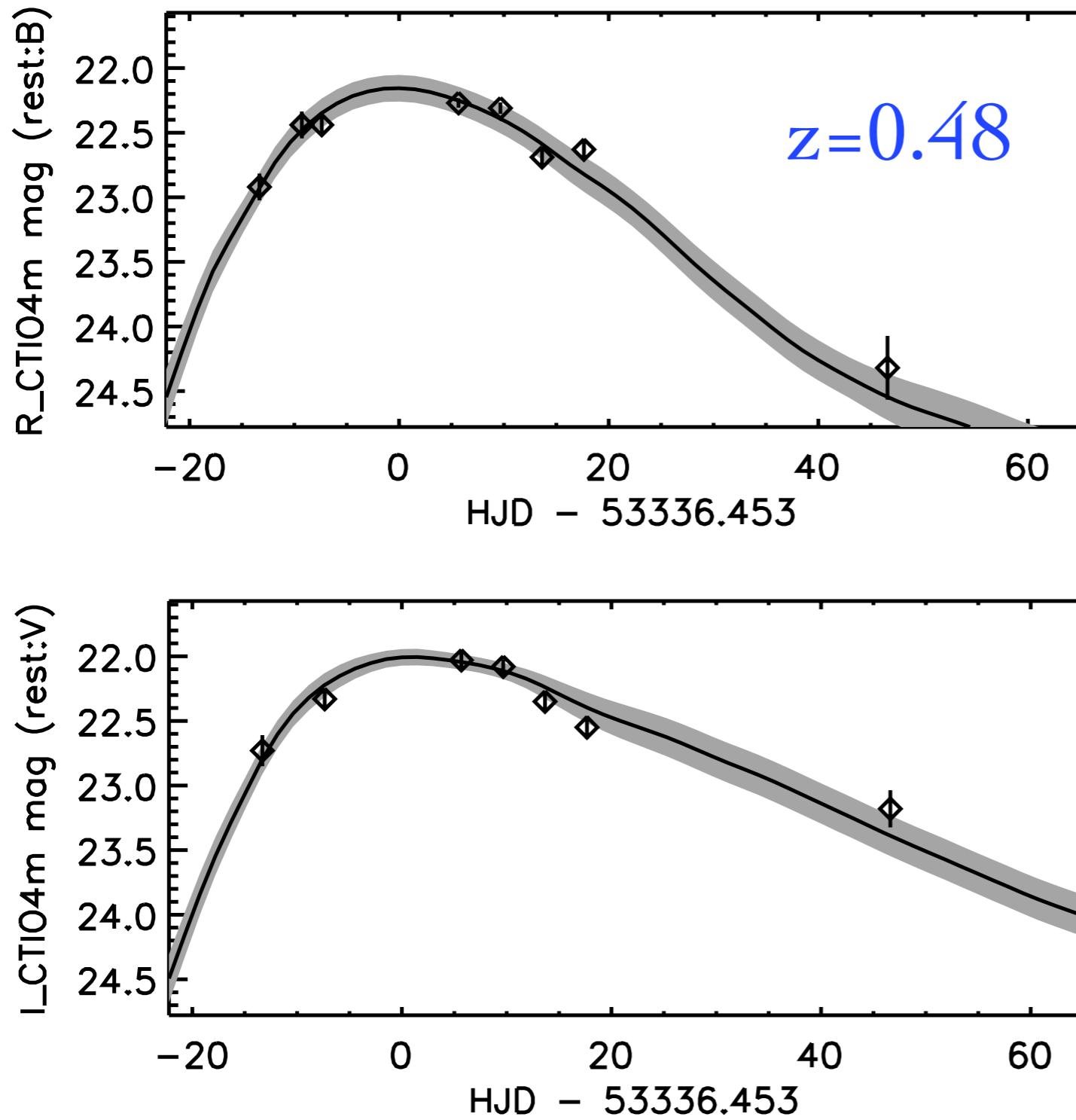
One-parameter family

Δ {

- Color
- Rate of decline
- Peak brightness

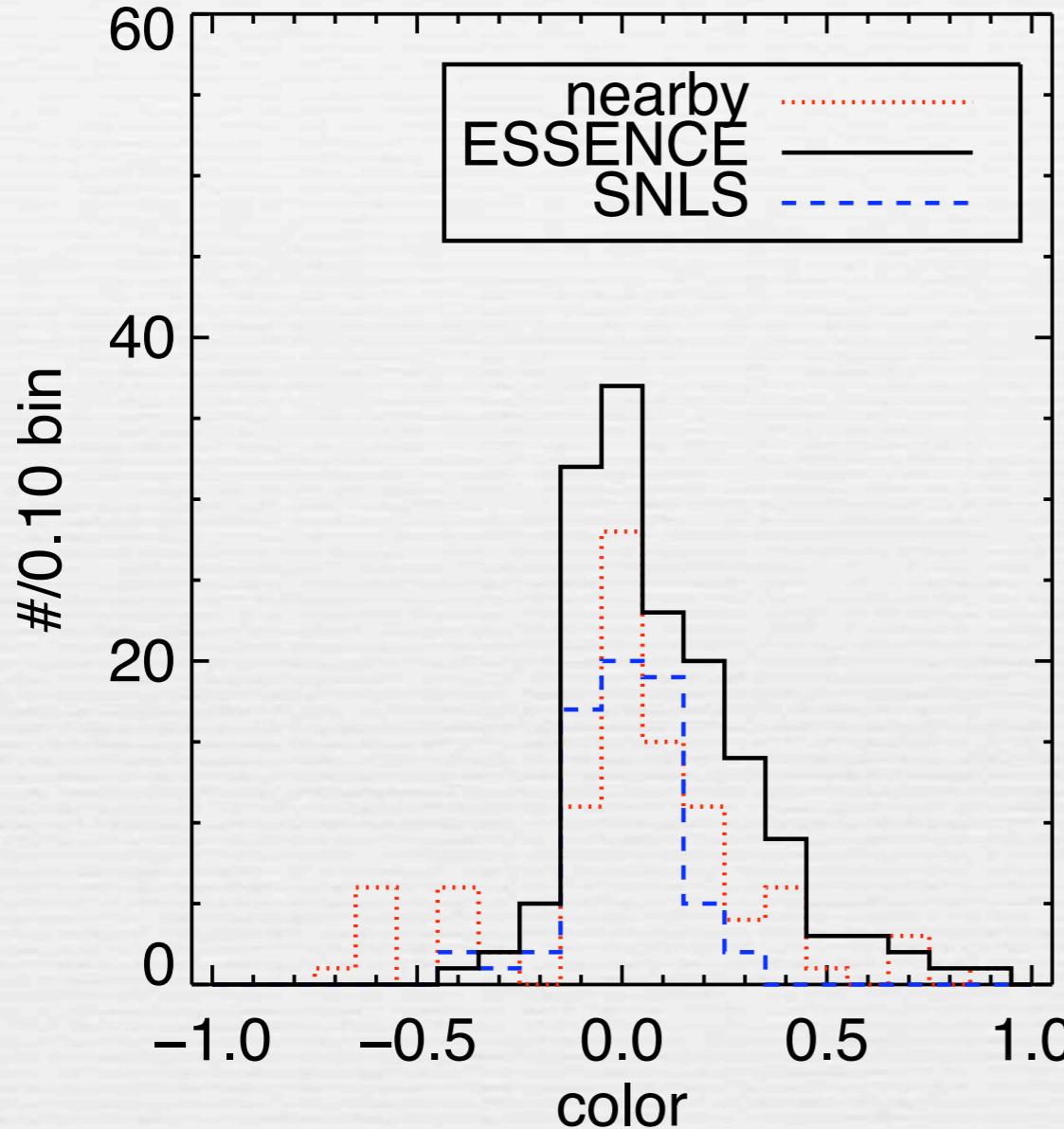


Apparent Brightness

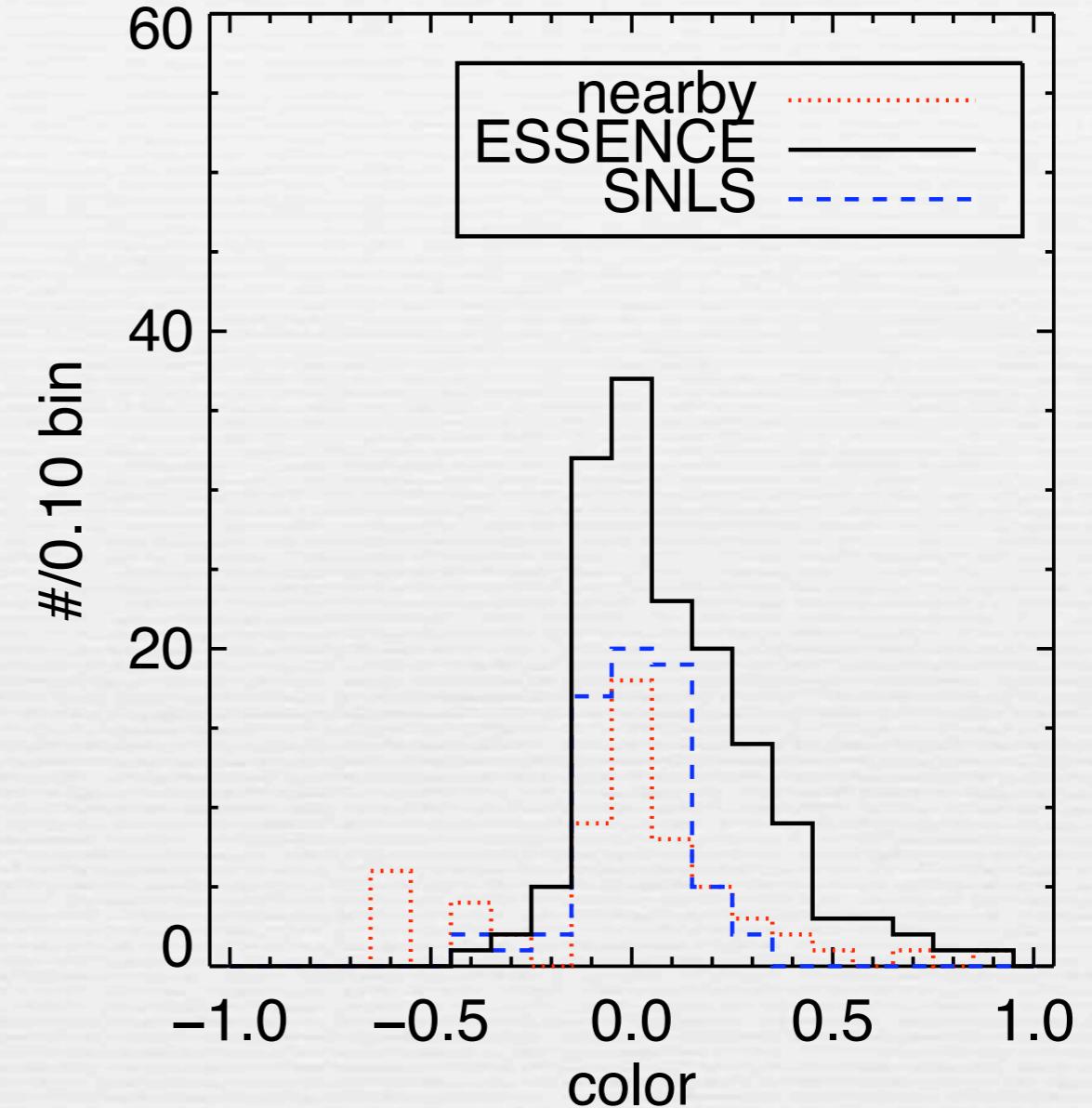


$$m_V^0 = 22.75 \pm 0.20$$
$$\Delta = -0.15 \pm 0.07$$
$$A_V = 0.19 \pm 0.17$$
$$R_V = 3.10 \pm 0.00$$
$$\mu_0 = 42.25 \pm 0.20$$

All good nearby SNeIa

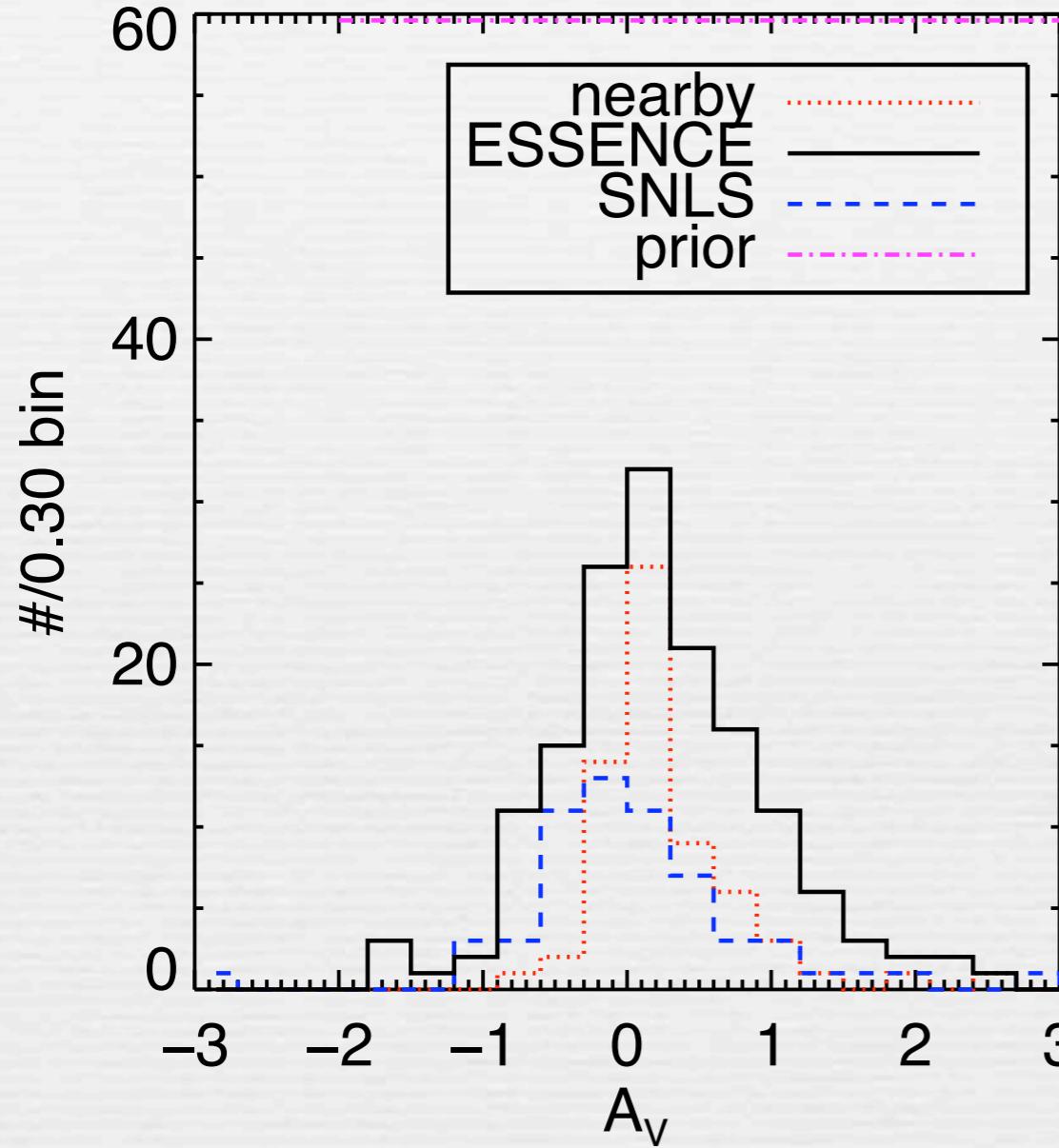


Only $z > 0.015$

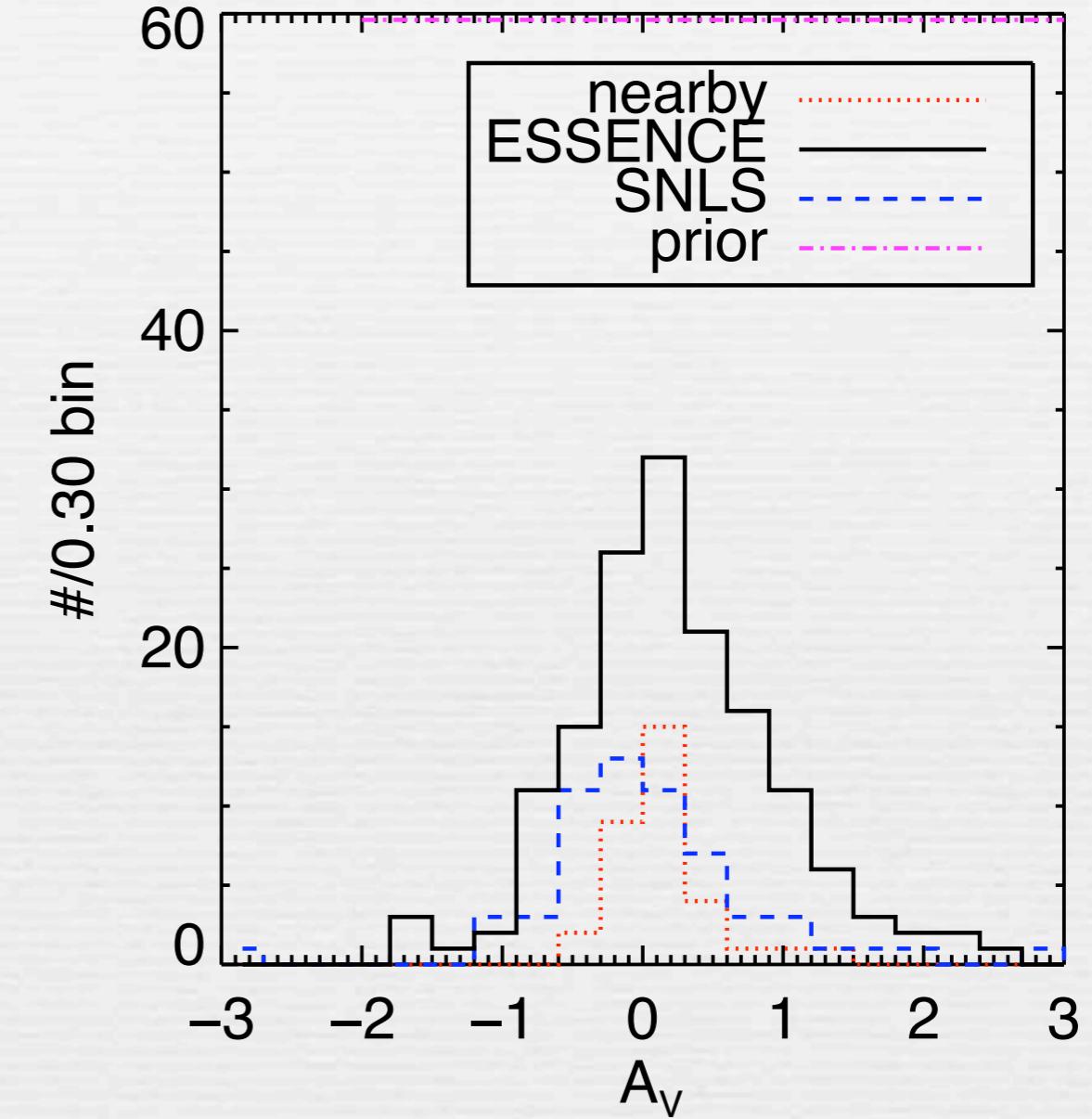


SALT2 (Guy07)

All good nearby SNeIa

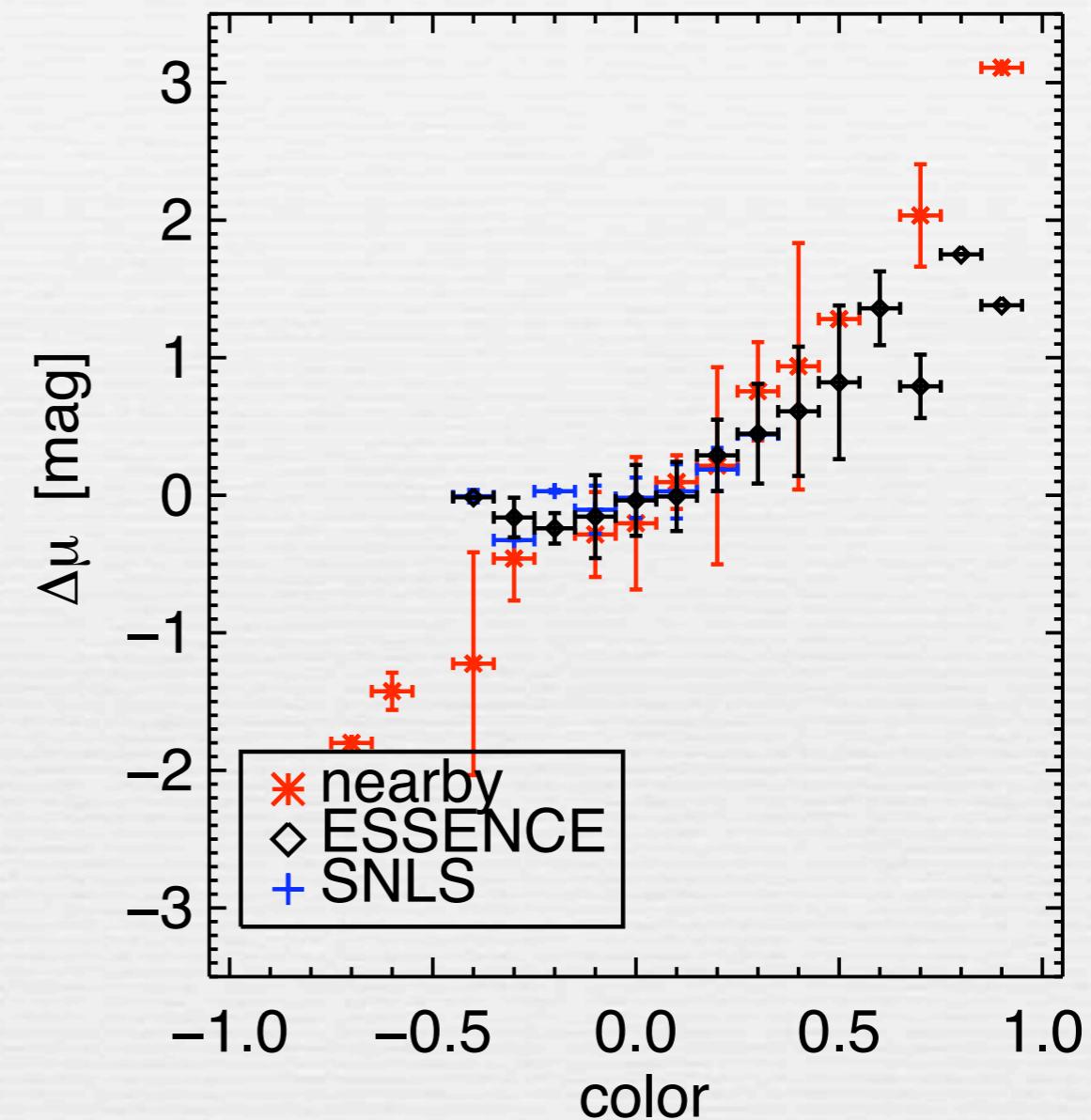
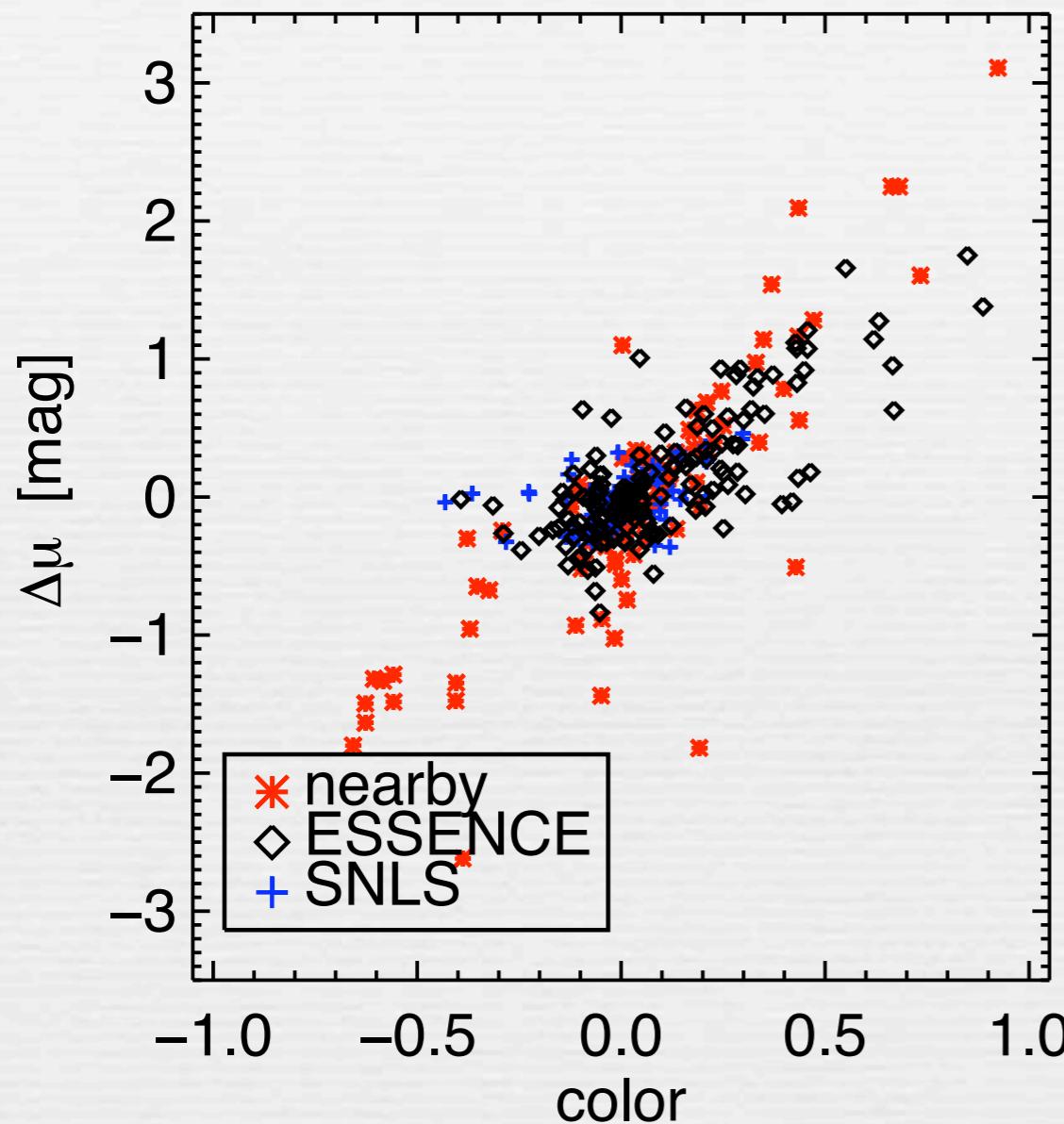


Only $z > 0.015$



MLCS2k2 (Jha07) flatnegav

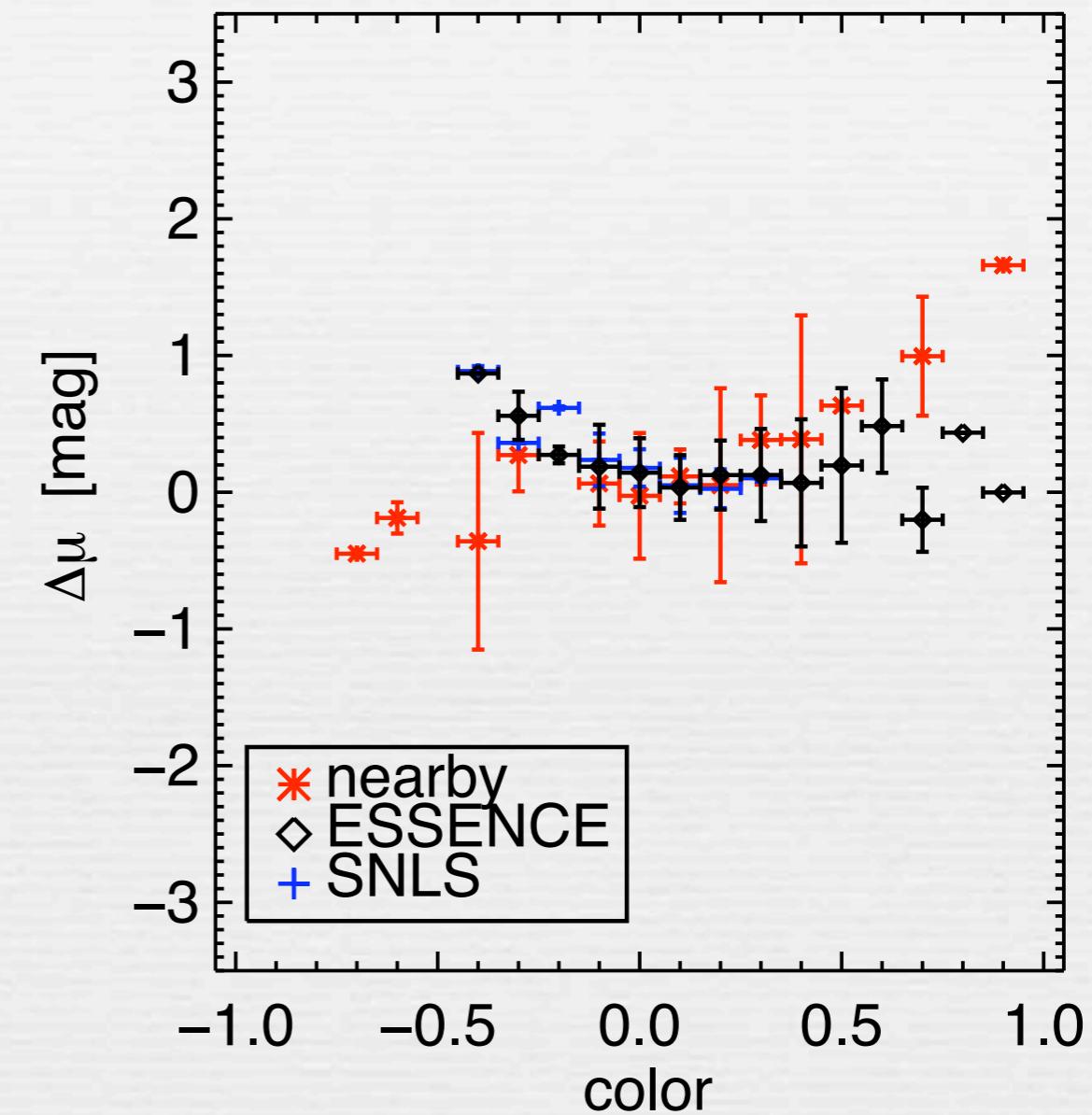
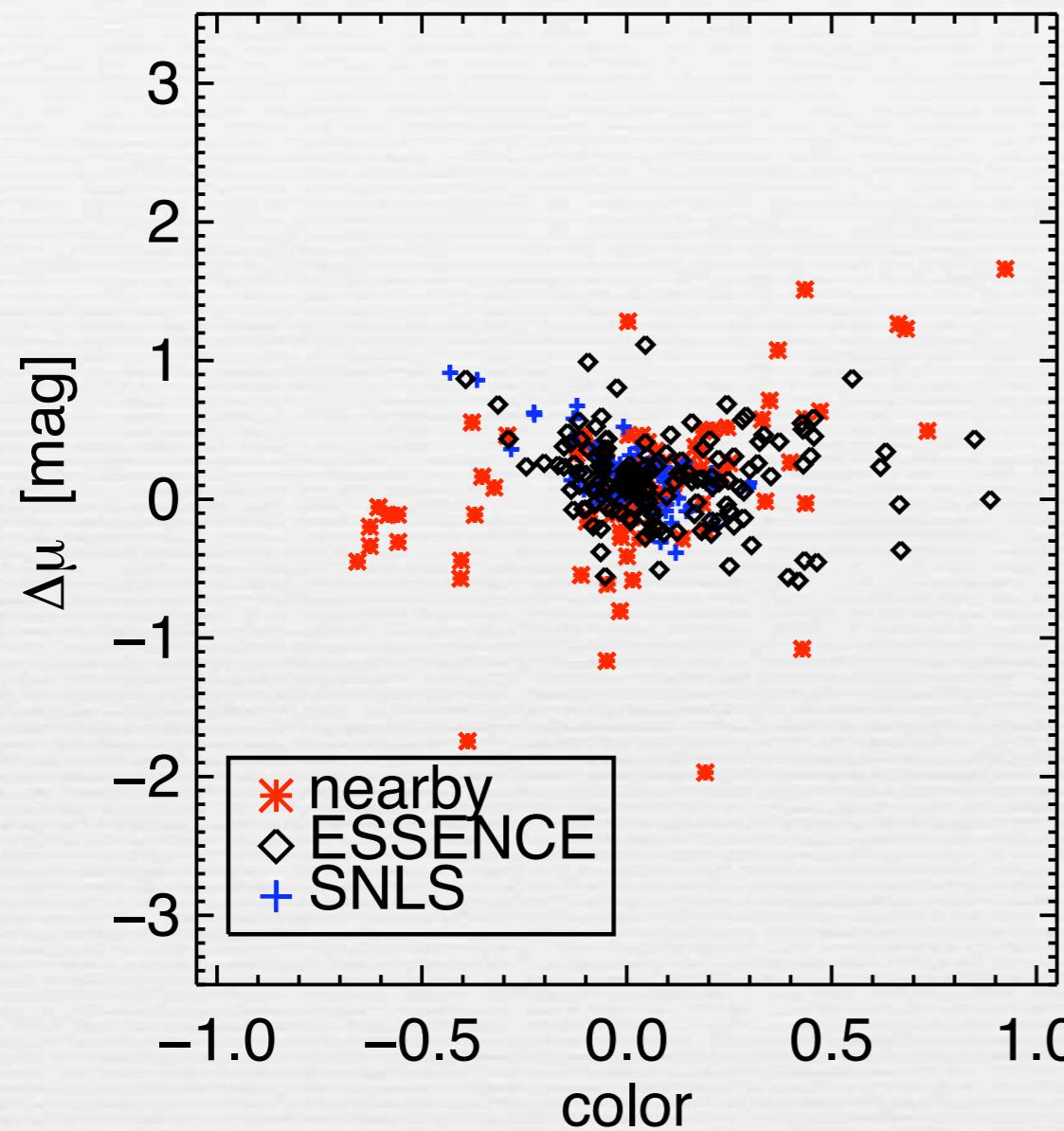
Luminosity vs. Color



SALT2, $\beta = 0$

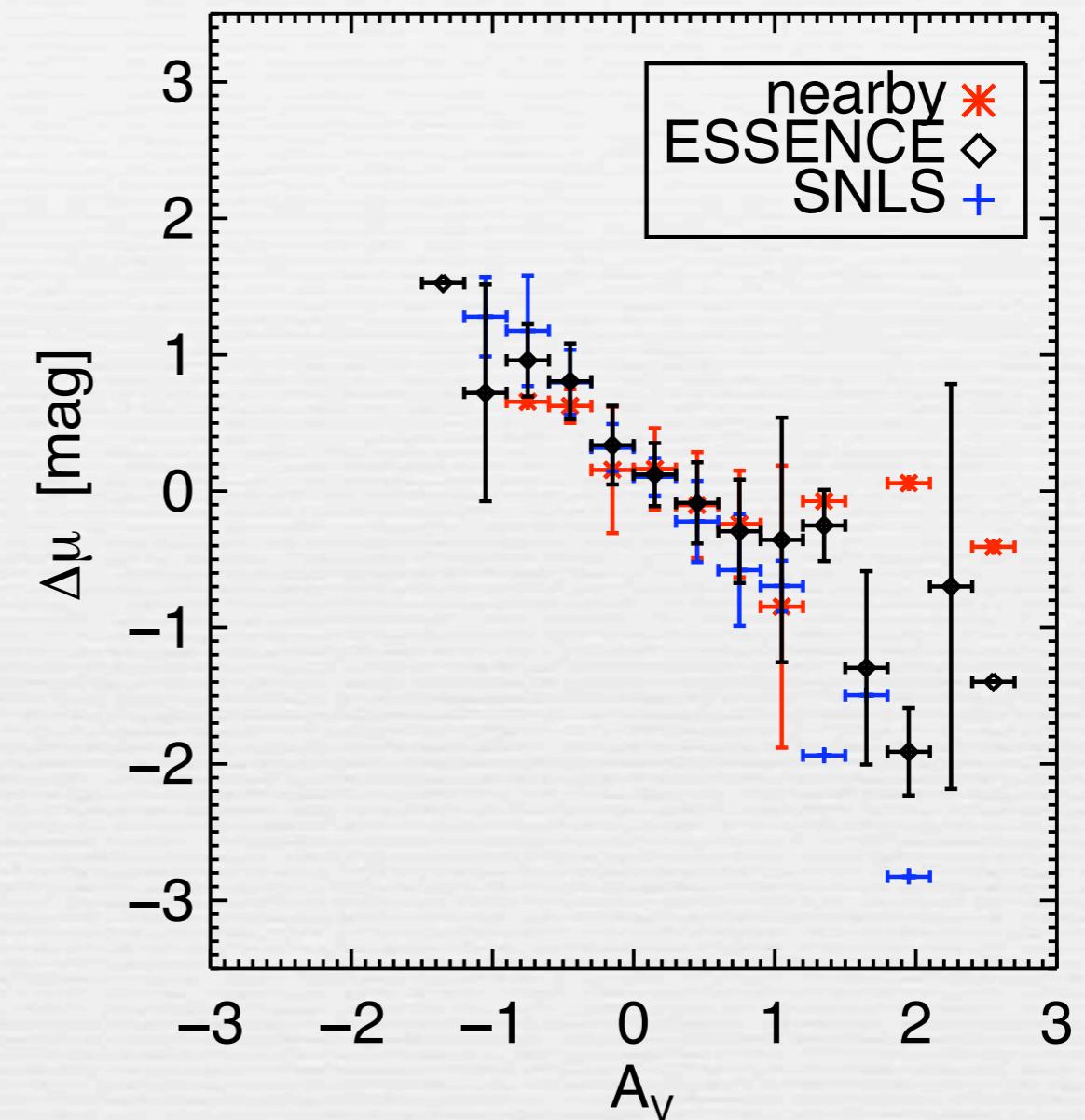
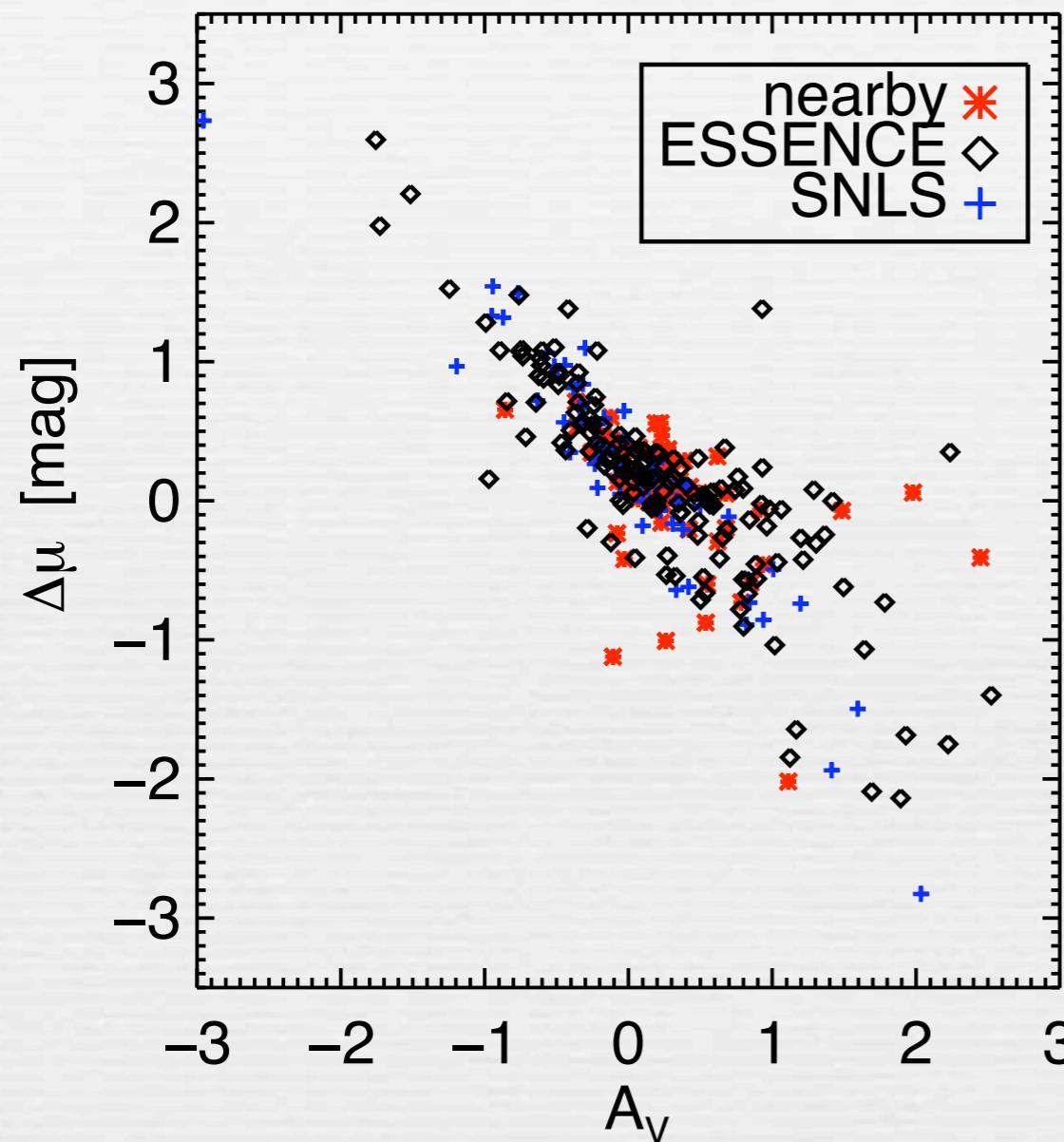
All good nearby SNeIa

Corrected Luminosity vs. Color



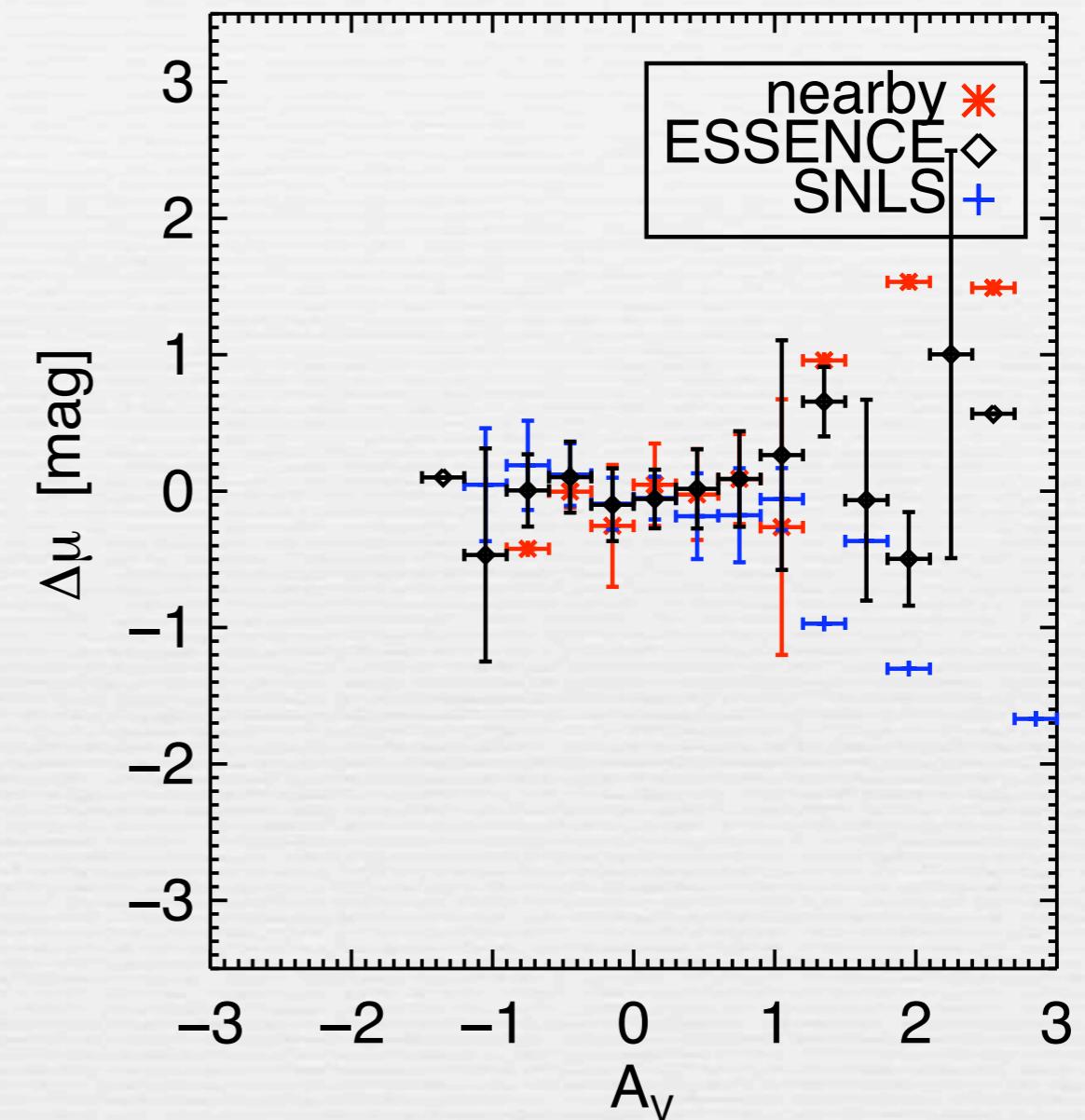
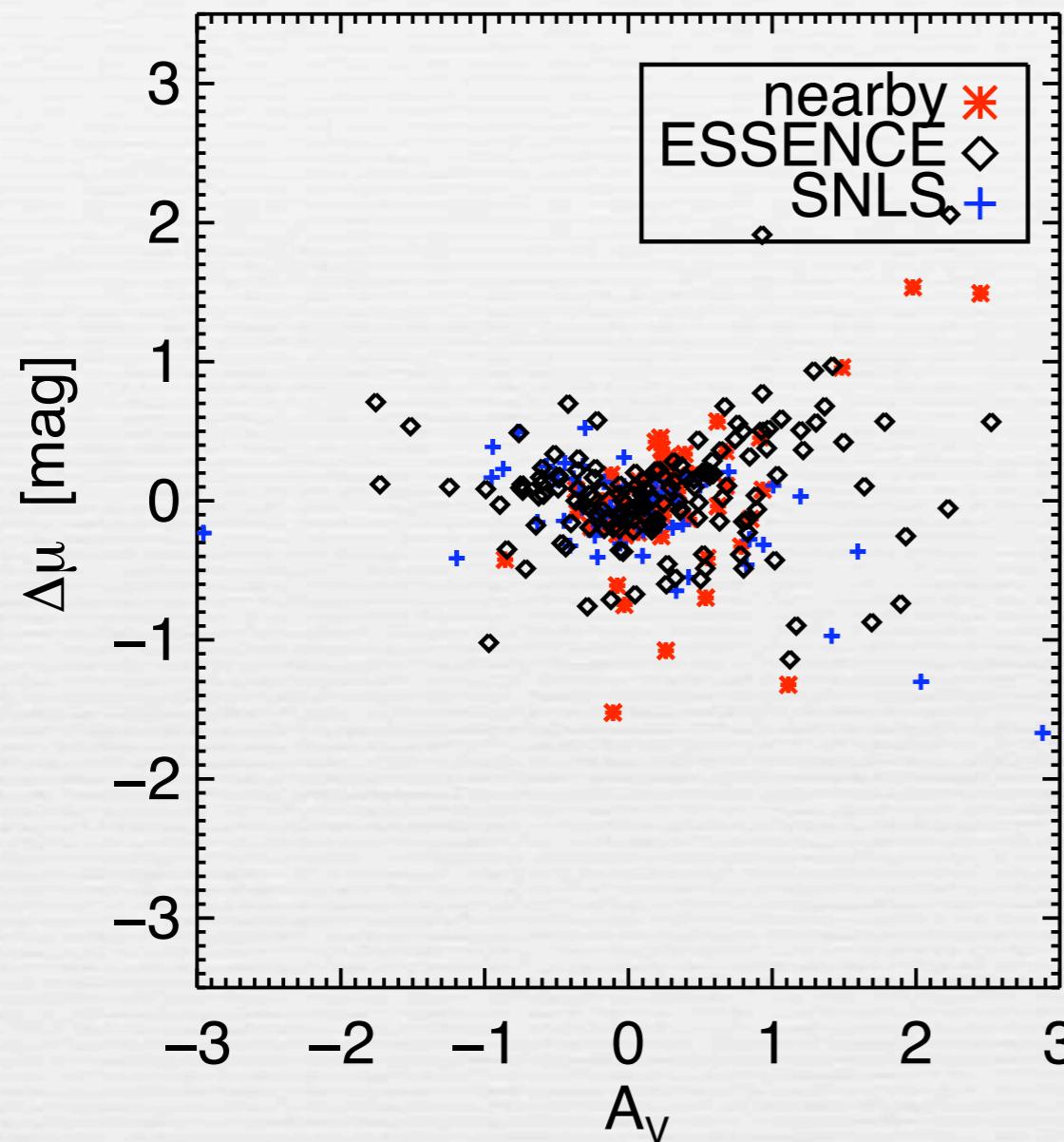
SALT2, beta=1.77 (Guy07)

Anti-Corrected Luminosity vs. Color



MLCS2k2 flatnegav
beta=0, R_V=3.1

Corrected Luminosity vs. Color



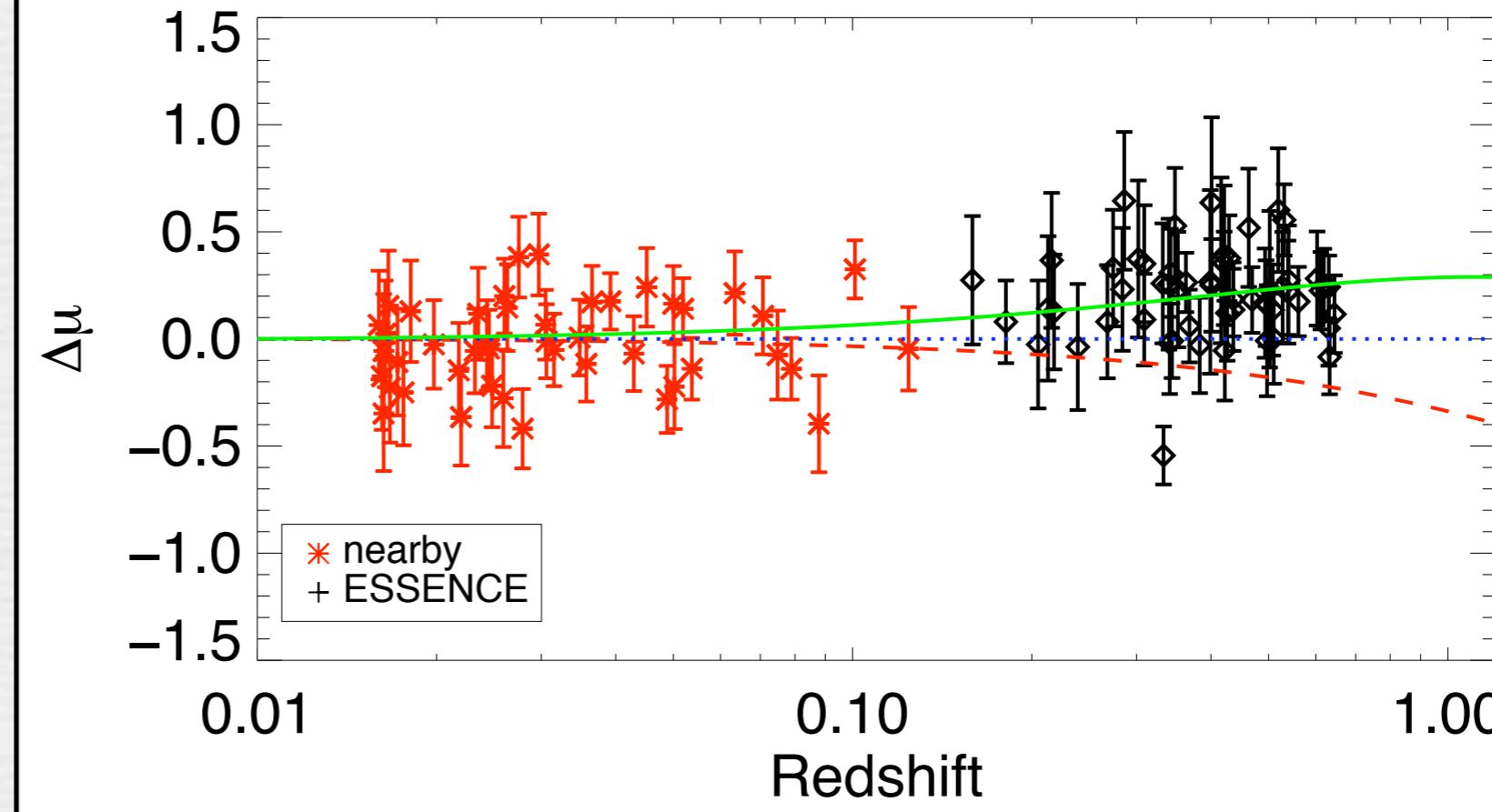
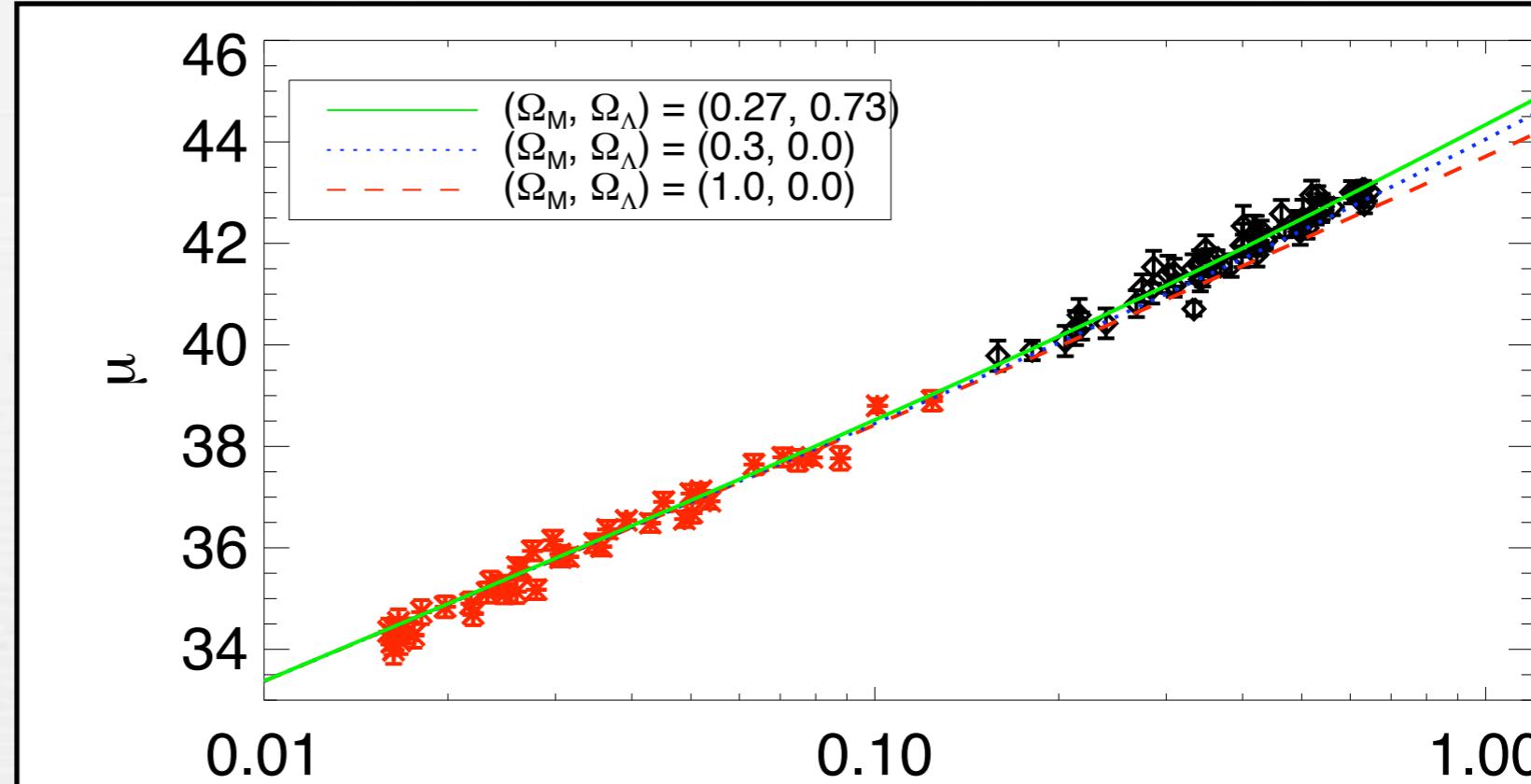
MLCS2k2 flatnegav
beta=-0.9, R_V=3.1

ESSENCE Hubble Diagram

Wood-Vasey et al.,
2007, ApJ, 666, 694

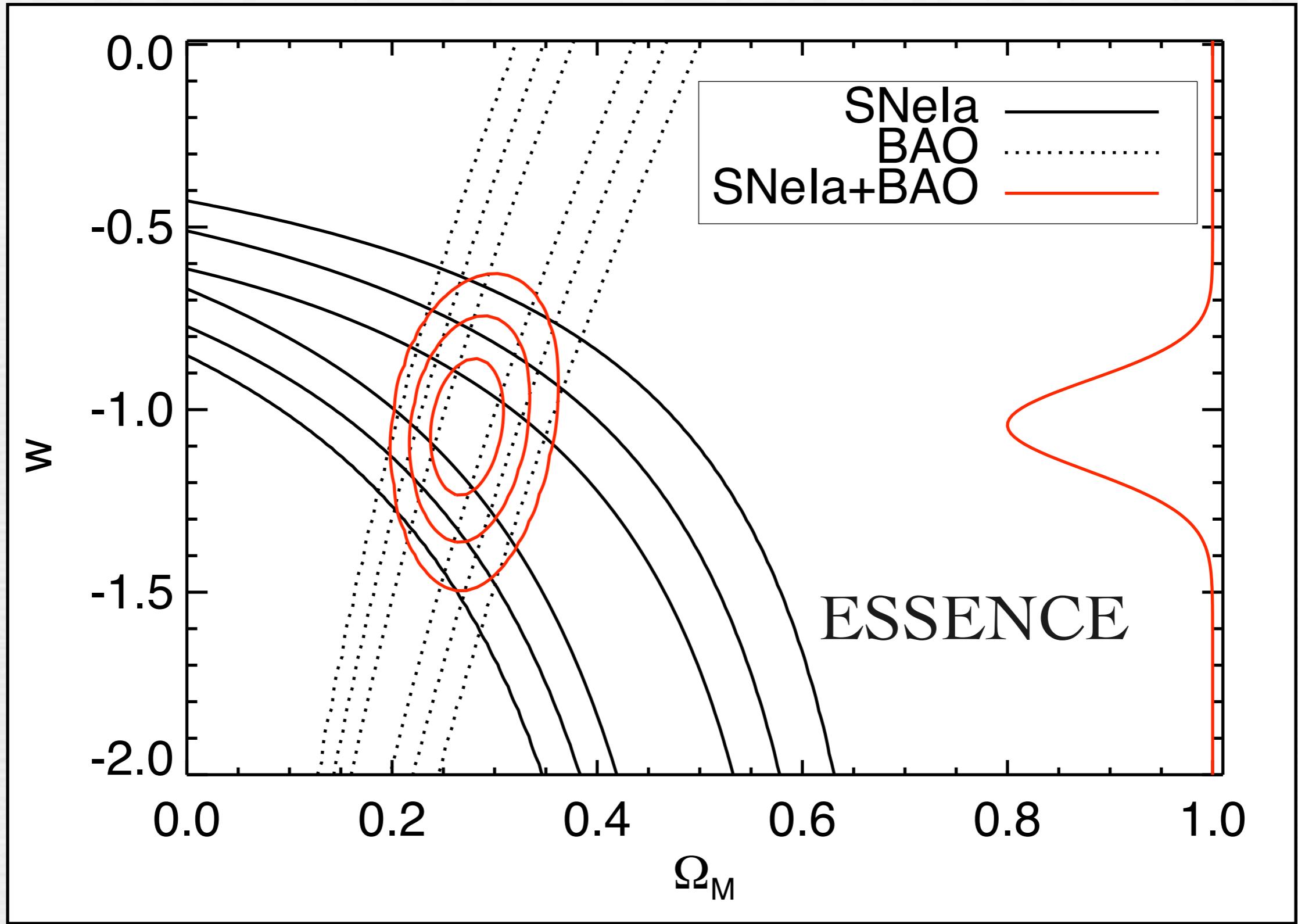
see also
Miknaitis et al.,
2007, ApJ, 666, 674

Davis et al.,
2007, ApJ, 666, 716

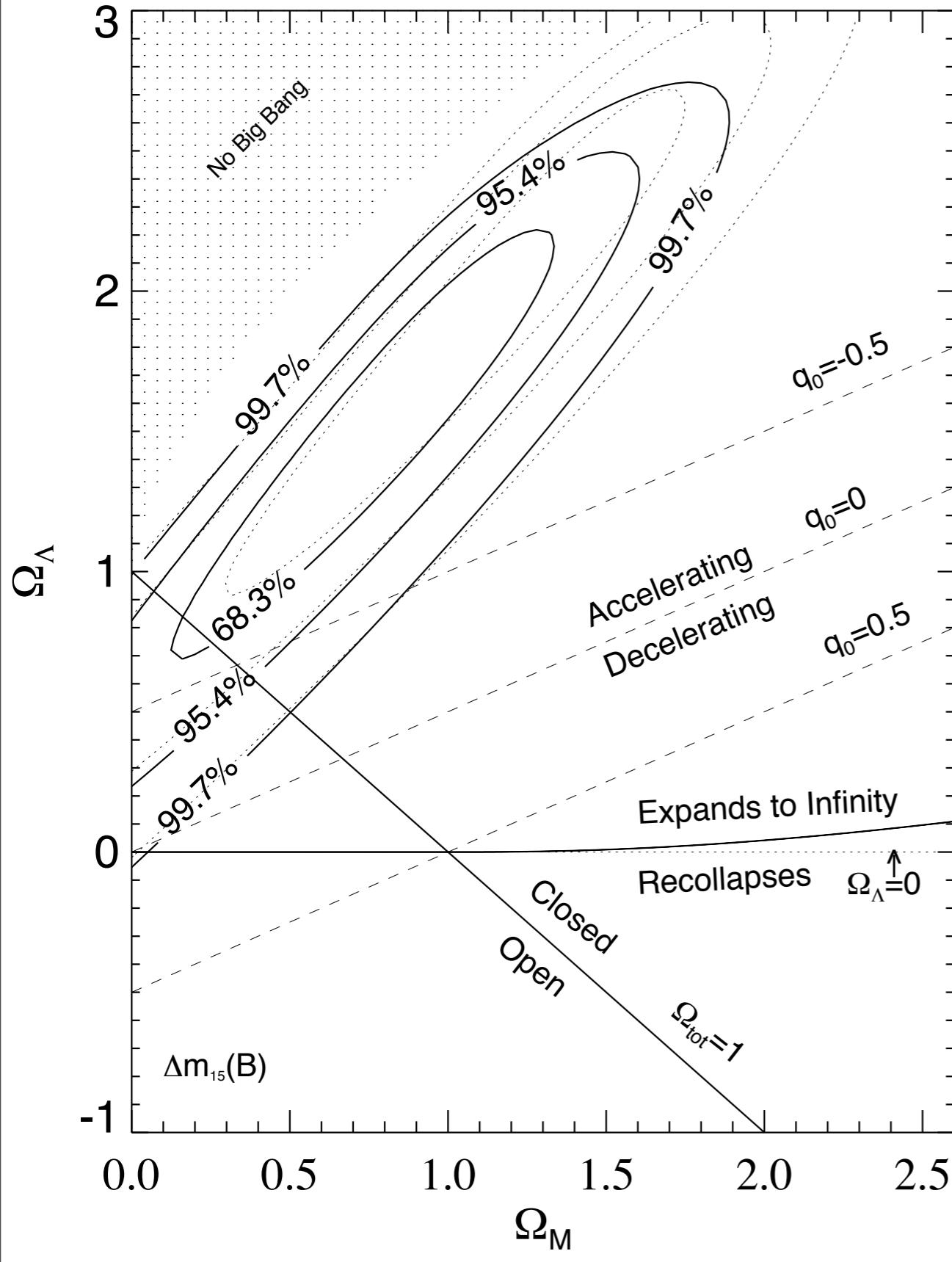


Flat,
constant-w

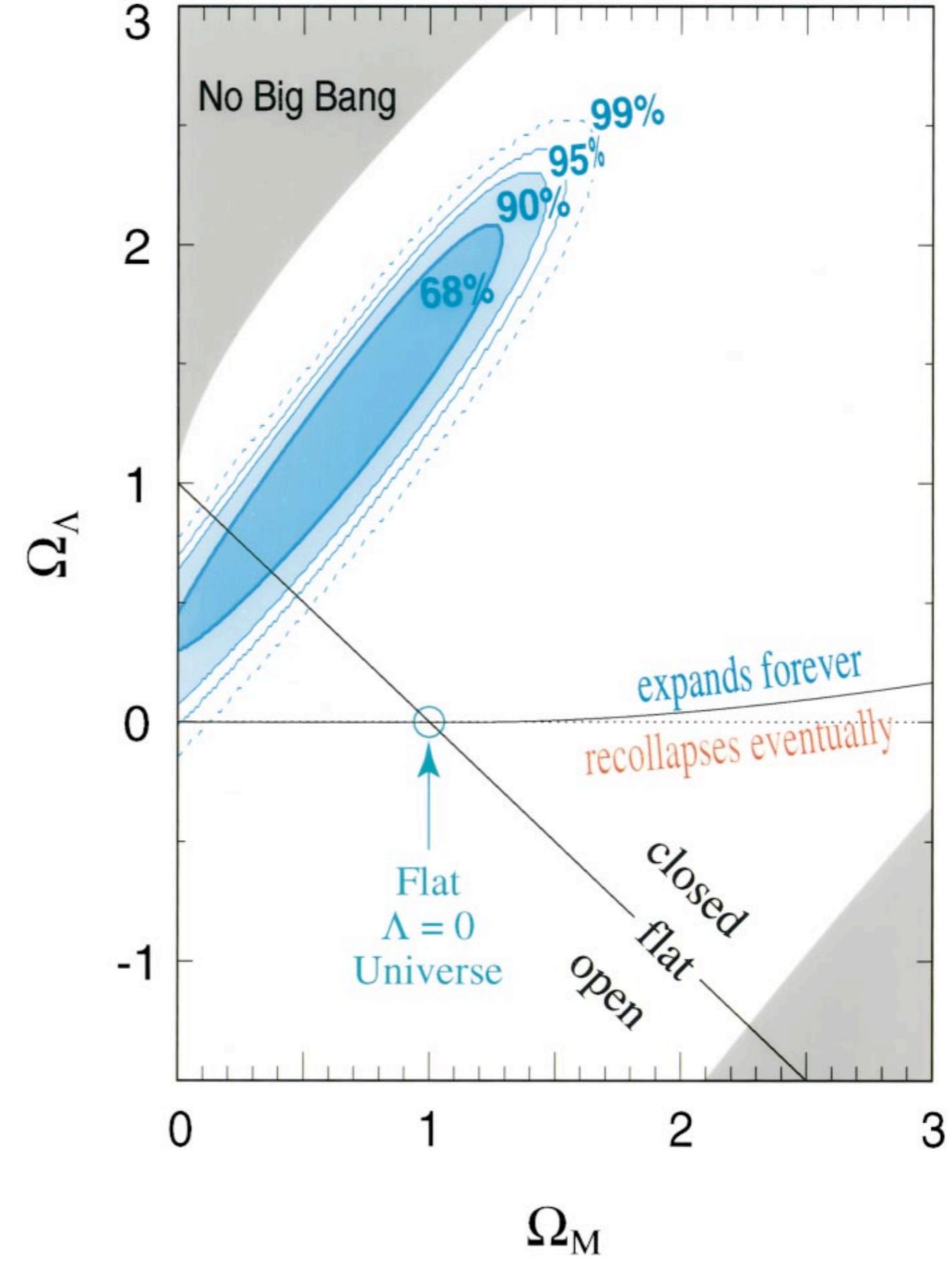
$$w = -1.05 \pm 0.11 \pm 0.13$$

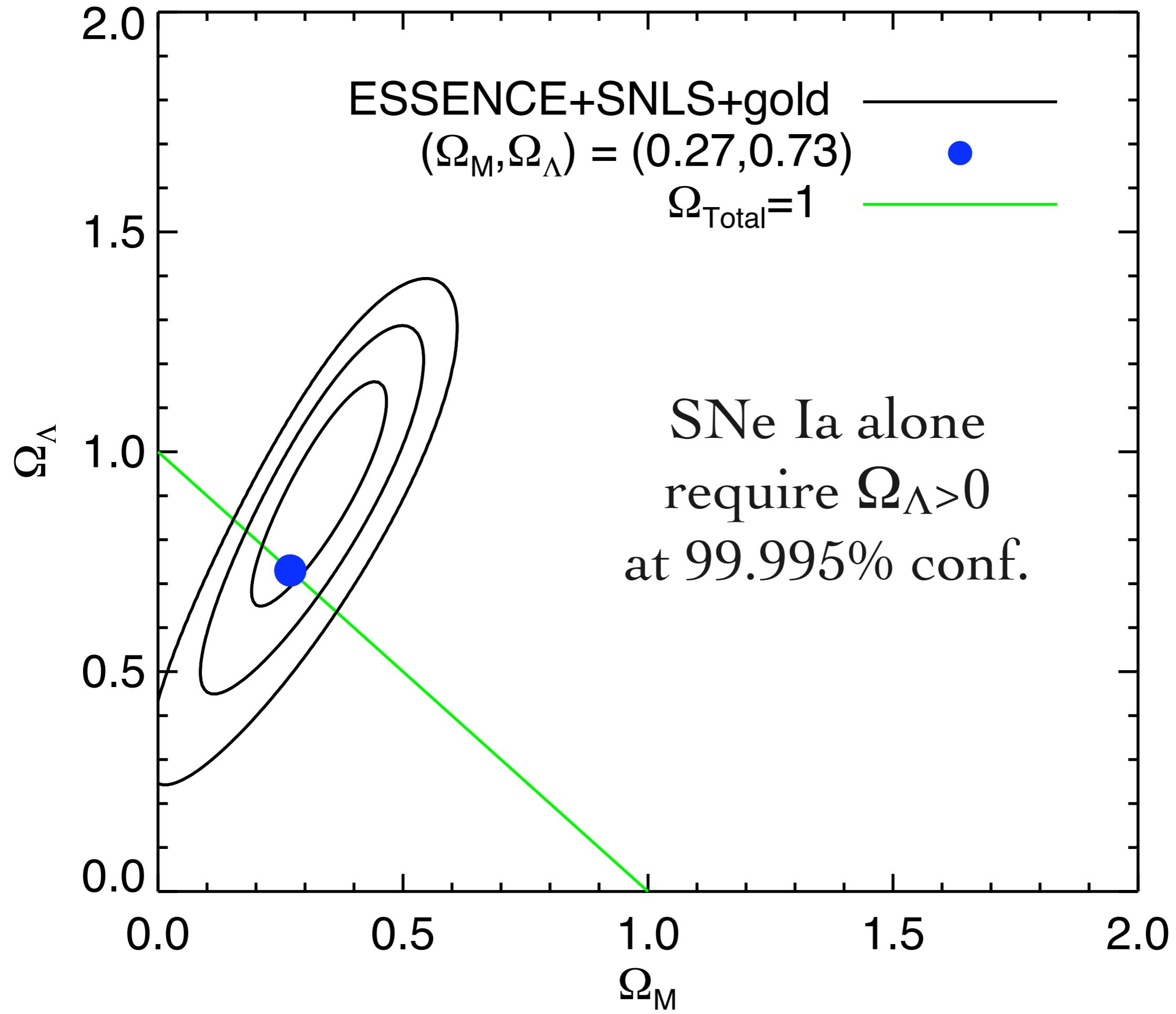


Riess et al. (1998, AJ)



Perlmutter et al. (1999, ApJ)

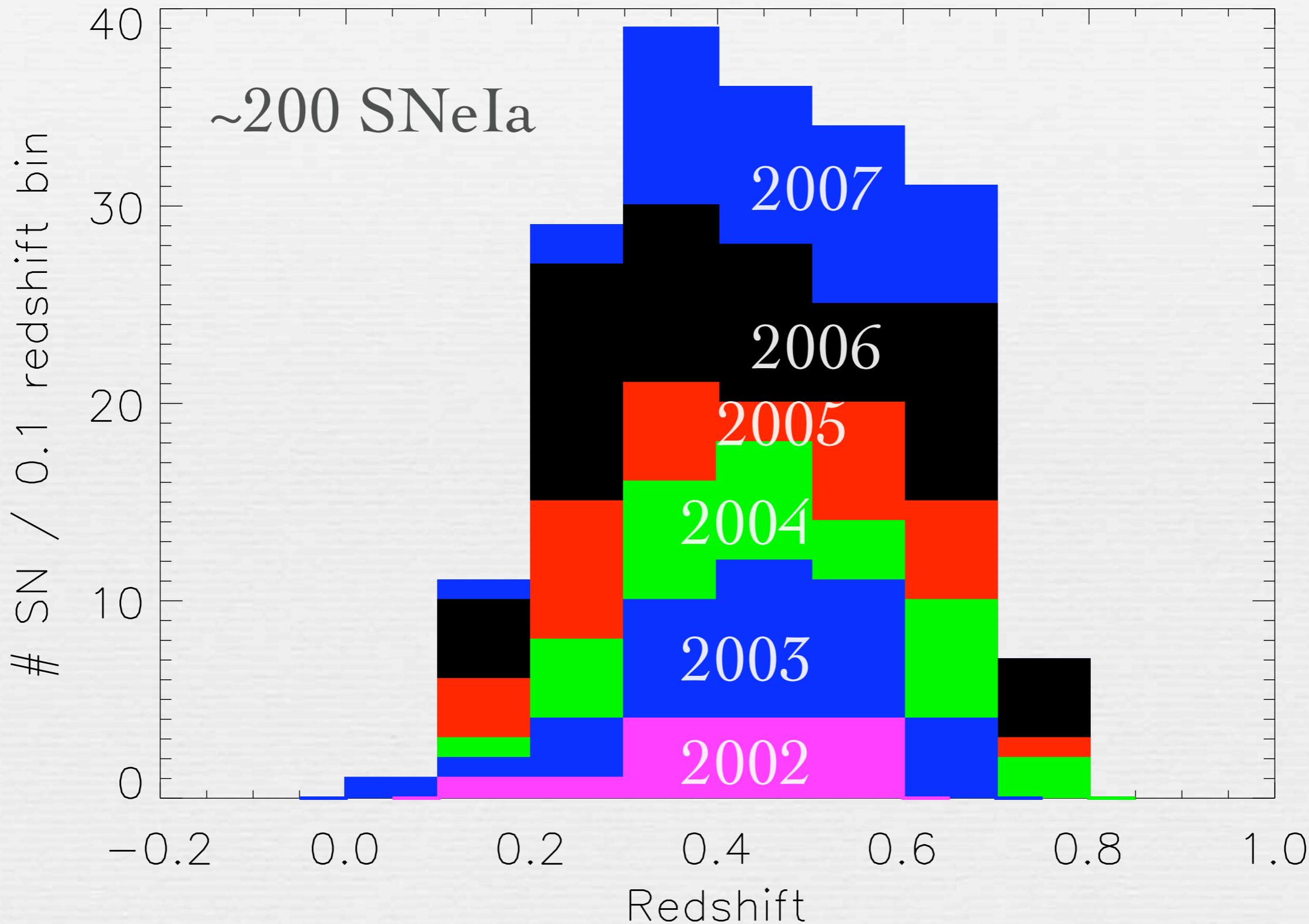




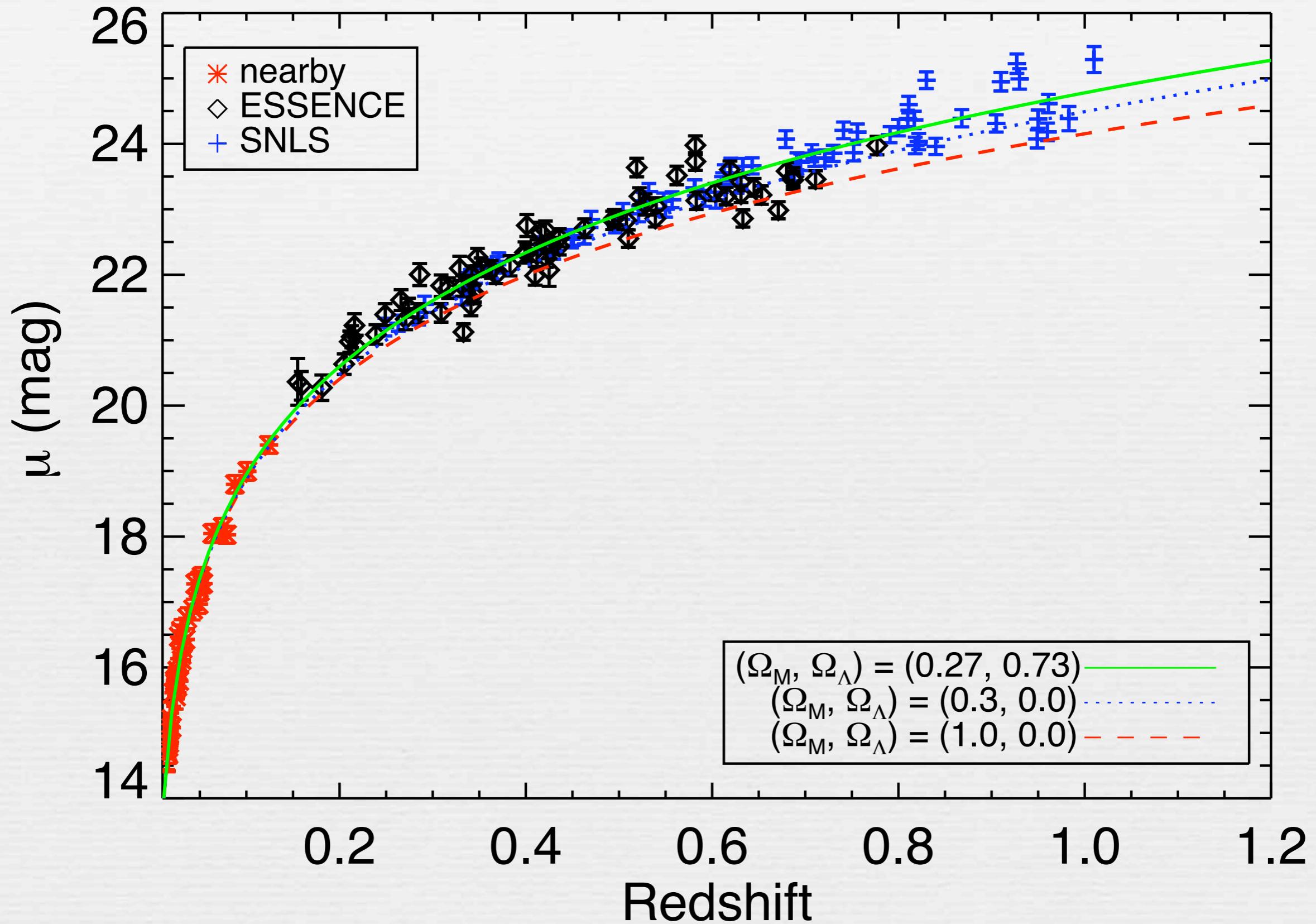
What To Do?

- ❖ Think carefully
 - ❖ Different samples
 - ❖ Different splits of color vs. extinction
- ❖ Understand dust in other galaxies
- ❖ Understand any evolution of dust vs. redshift

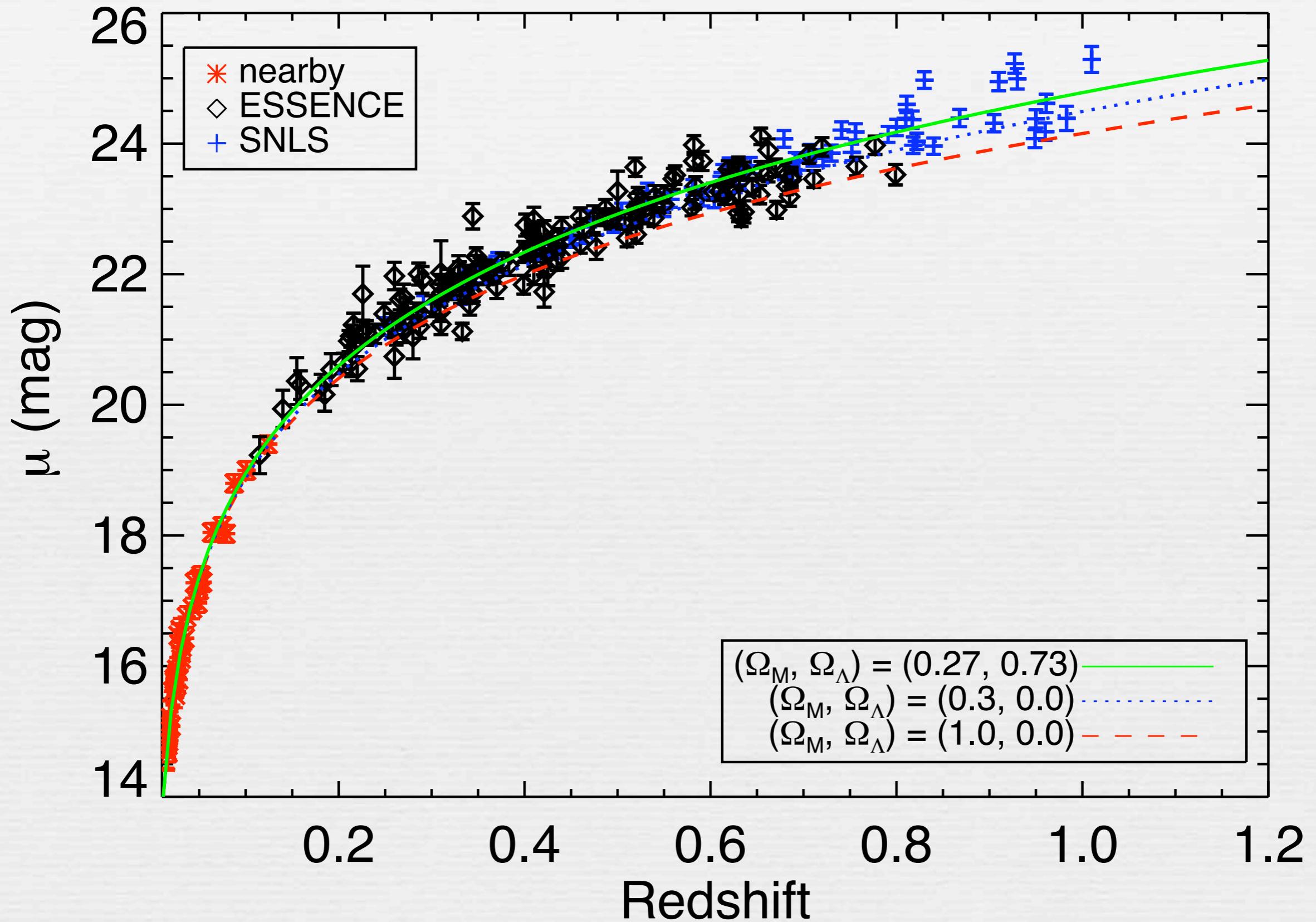
ESSENCE SNeIa From All 6 Years



Previous ESSENCE Hubble Diagram



Preliminary Current ESSENCE Hubble Diagram



Summary & Future

- ❖ The State of LCDM is Strong
- ❖ Tackle Extinction vs. Intrinsic Color
 - ❖ UV - Optical - NIR data
- ❖ More nearby SNeIa: +300 from KAIT, CSP, CfA
- ❖ SDSS-II, ESSENCE, SNLS joint analysis
- ❖ Pan-STARRS1, Dark Energy Survey, LSST
- ❖ JDEM with supernovae

ESSENCE Status Summary

- ~ Flat Universe model with a cosmological constant works fine.
- ~ $w = -1.05 \pm 0.11 \text{ (stat)} \pm 0.13 \text{ (sys)}$
- ~ Final ESSENCE results: due in 2008
 - ~ Double sample
 - ~ Improve systematics
 - ~ Reach goal: w to 10%

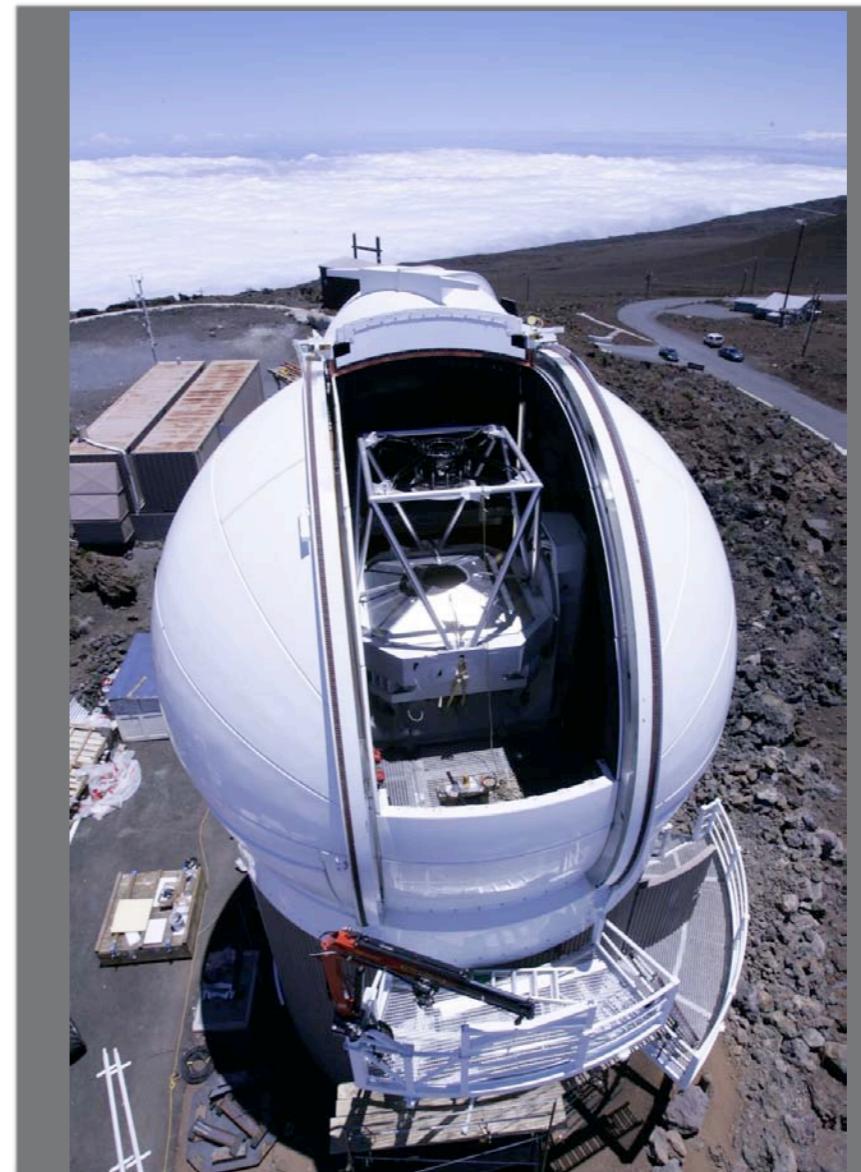
Future of Probing the Nature of Dark Energy

- ❖ SN cosmology tests
 - ❖ Gravitational lensing
 - ❖ Galaxy cluster abundances
 - ❖ Baryon oscillations
 - ❖ Particle physics experiments
 - ❖ Tests of gravity on all scales
- 
- signal!

Pan-STARRS

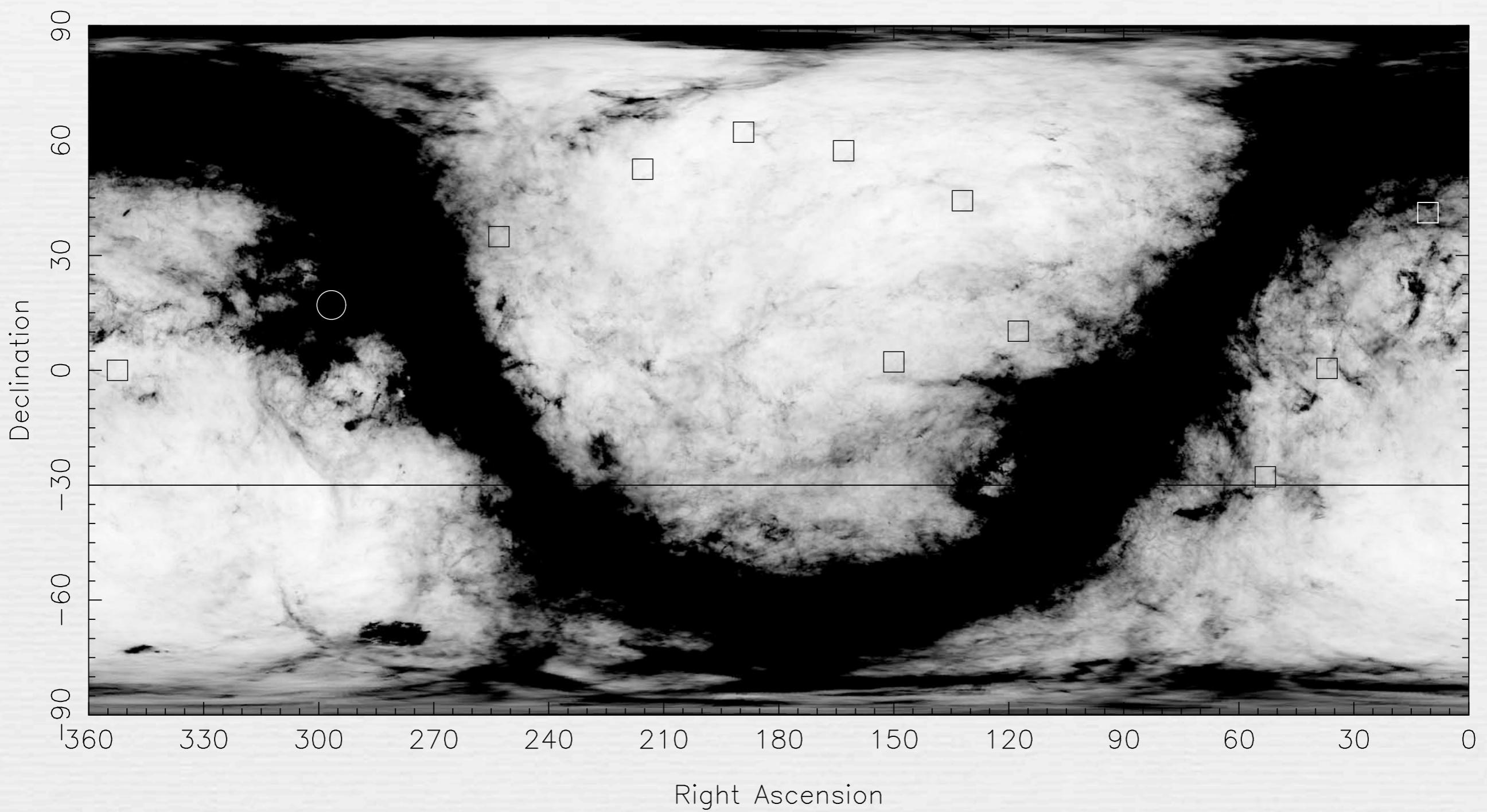
Panoramic Survey Telescope & Rapid Response System

- ~ 7 square degree field
- ~ 1.8m effective aperture
- ~ 24th magnitude in 300 sec
- ~ 1 TB / night
- ~ Real-time analysis
- ~ Will find 10,000s of SNe!
- ~ Lensing shear map

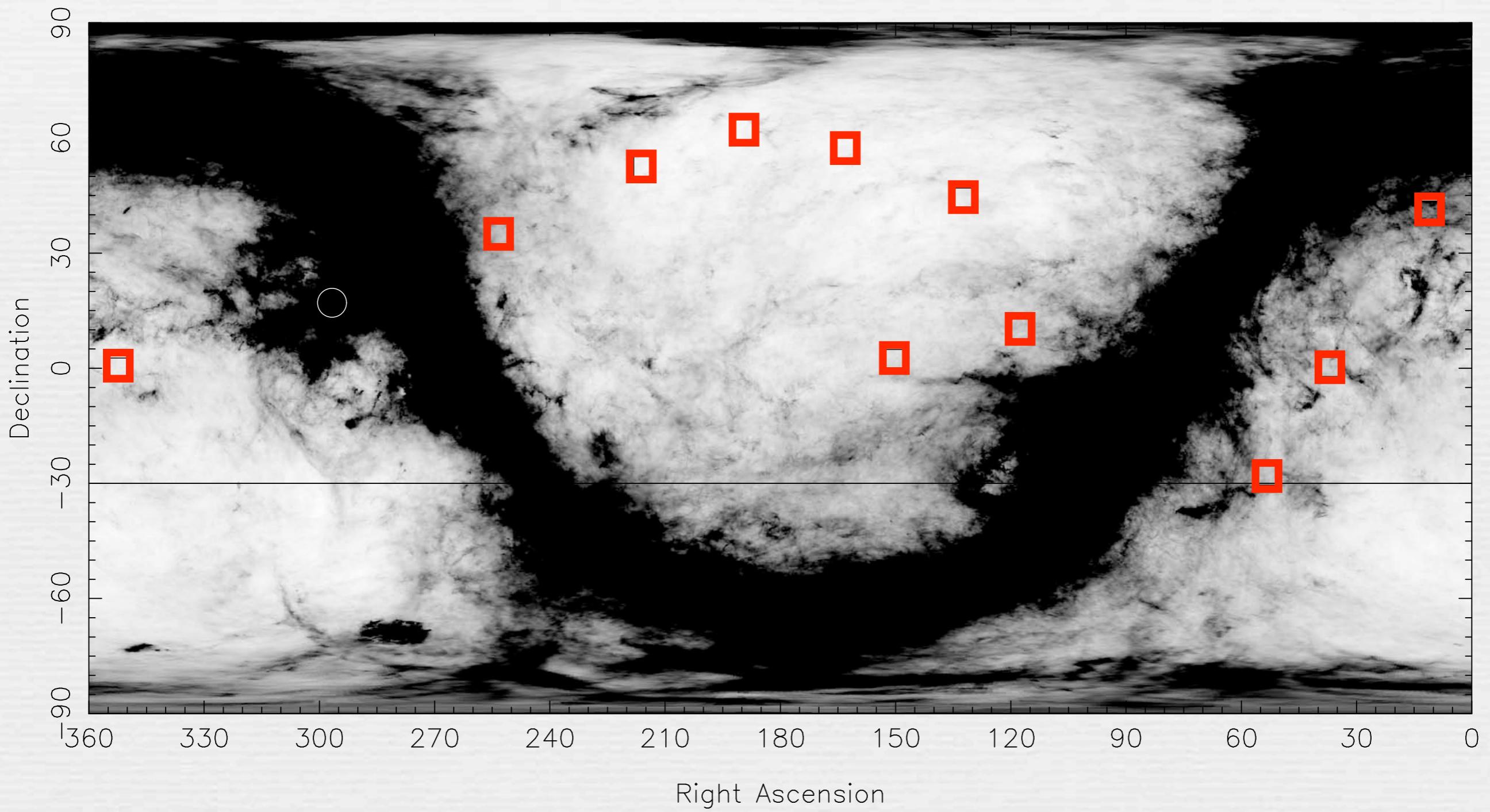


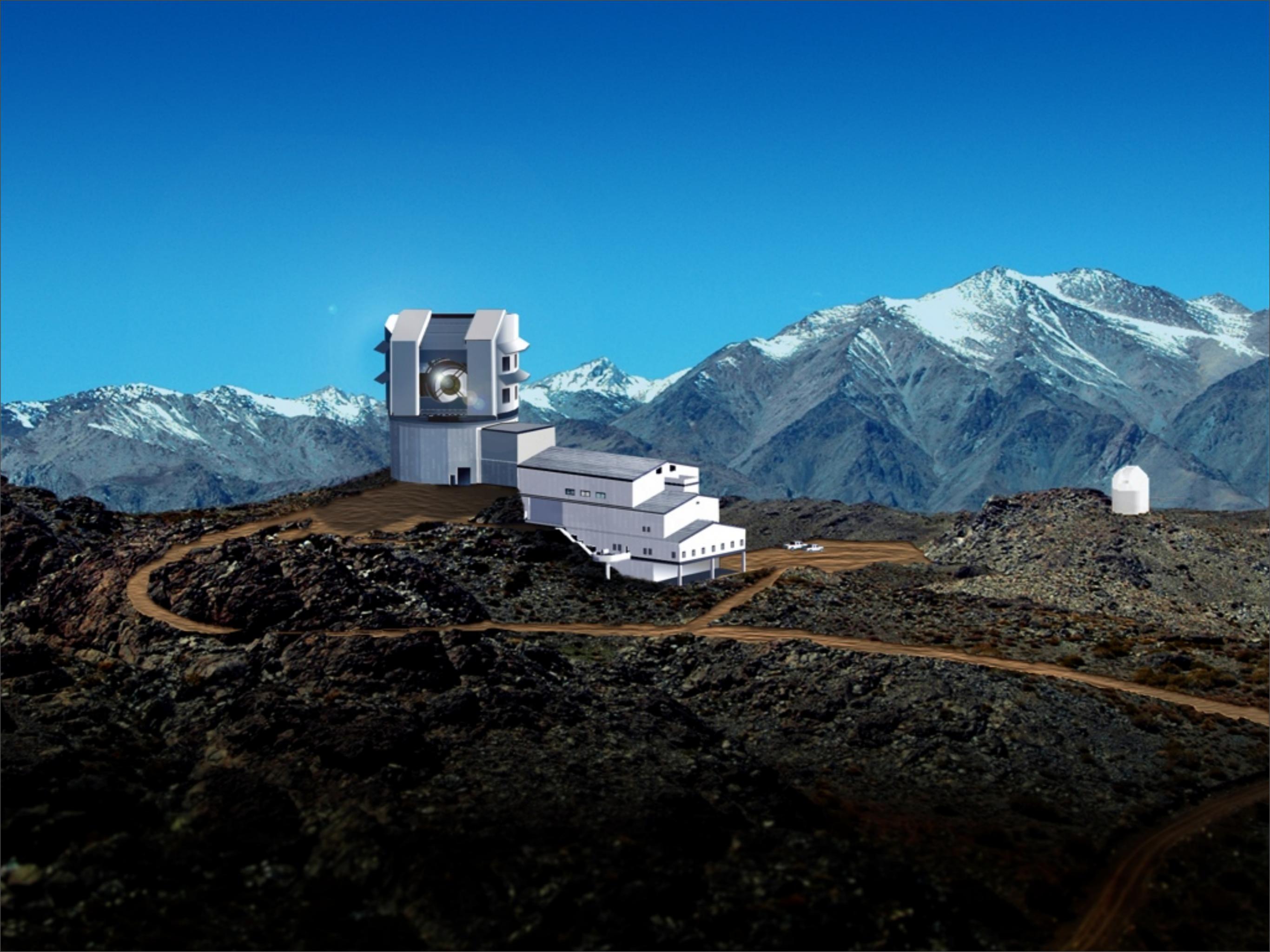
<http://pan-starrs.ifa.hawaii.edu/>

Medium-Deep Survey



Medium-Deep Survey

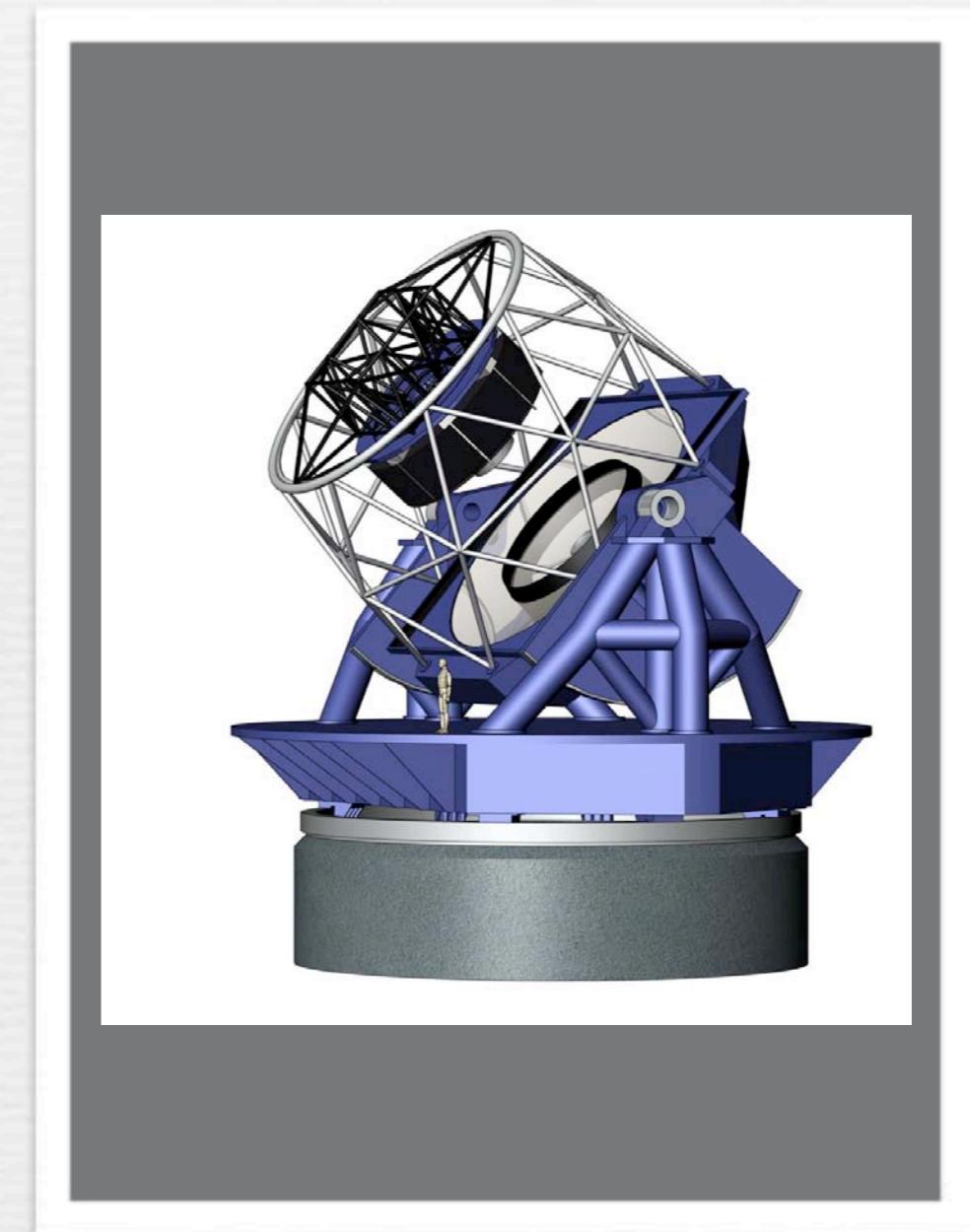




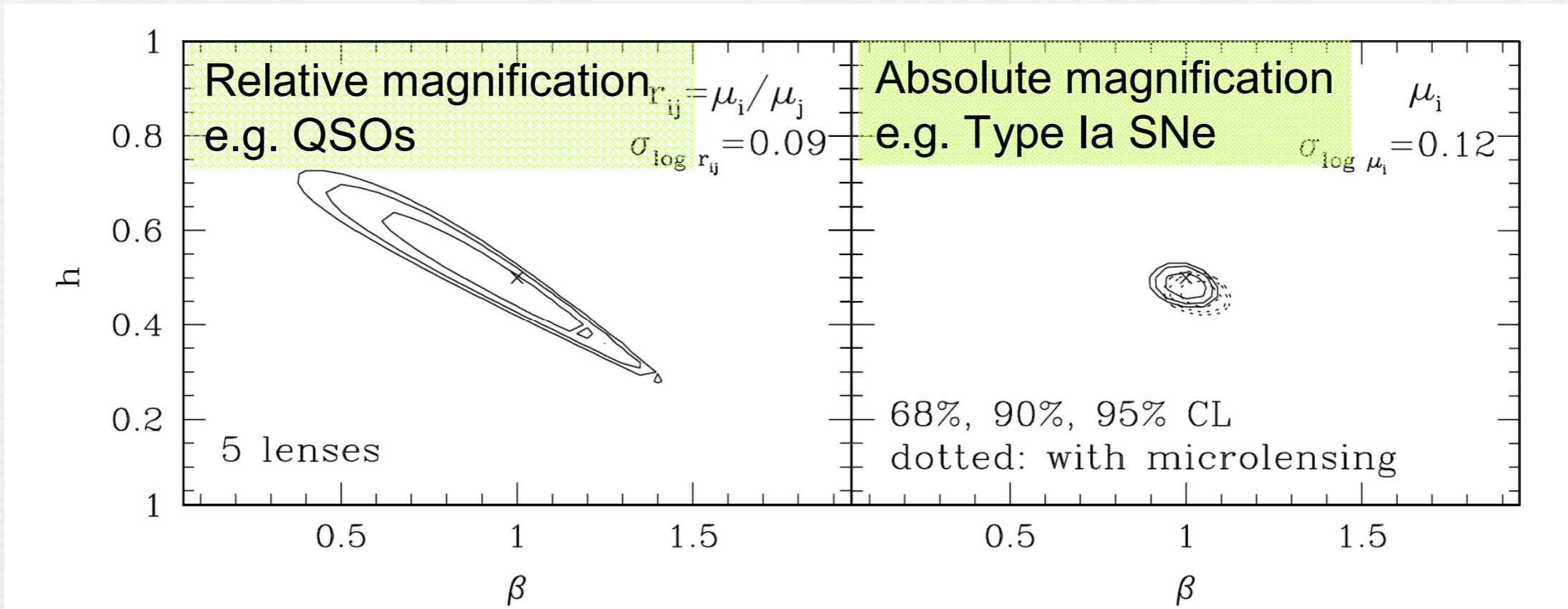
LSST

Large Synoptic Survey Telescope

- 10 square degree field
- 6.5m effective aperture
- 24th magnitude in 20 sec
- 20 TB / night
- Real-time analysis
- Will find millions of SNe!
- Lensing, BAO, Clusters



Strongly Lensed SNeIa



- ❖ 100,000s of high-z SNeIa
 - ❖ 0.1-1% should be strongly lensed
- ❖ Multiply-imaged SNeIa
 - ❖ time-delay with known magnification
 - ❖ Measure H_0
 - ❖ improve complementary cosmological constraints

Oguri & Kawano
(2003, MNRAS)

LSST Opens up the Skies

- ❖ Data will be immediately publicly available
- ❖ Allow all colleges and institutions to do research with big telescopes
- ❖ Will change the nature of research

LSST Dark Energy

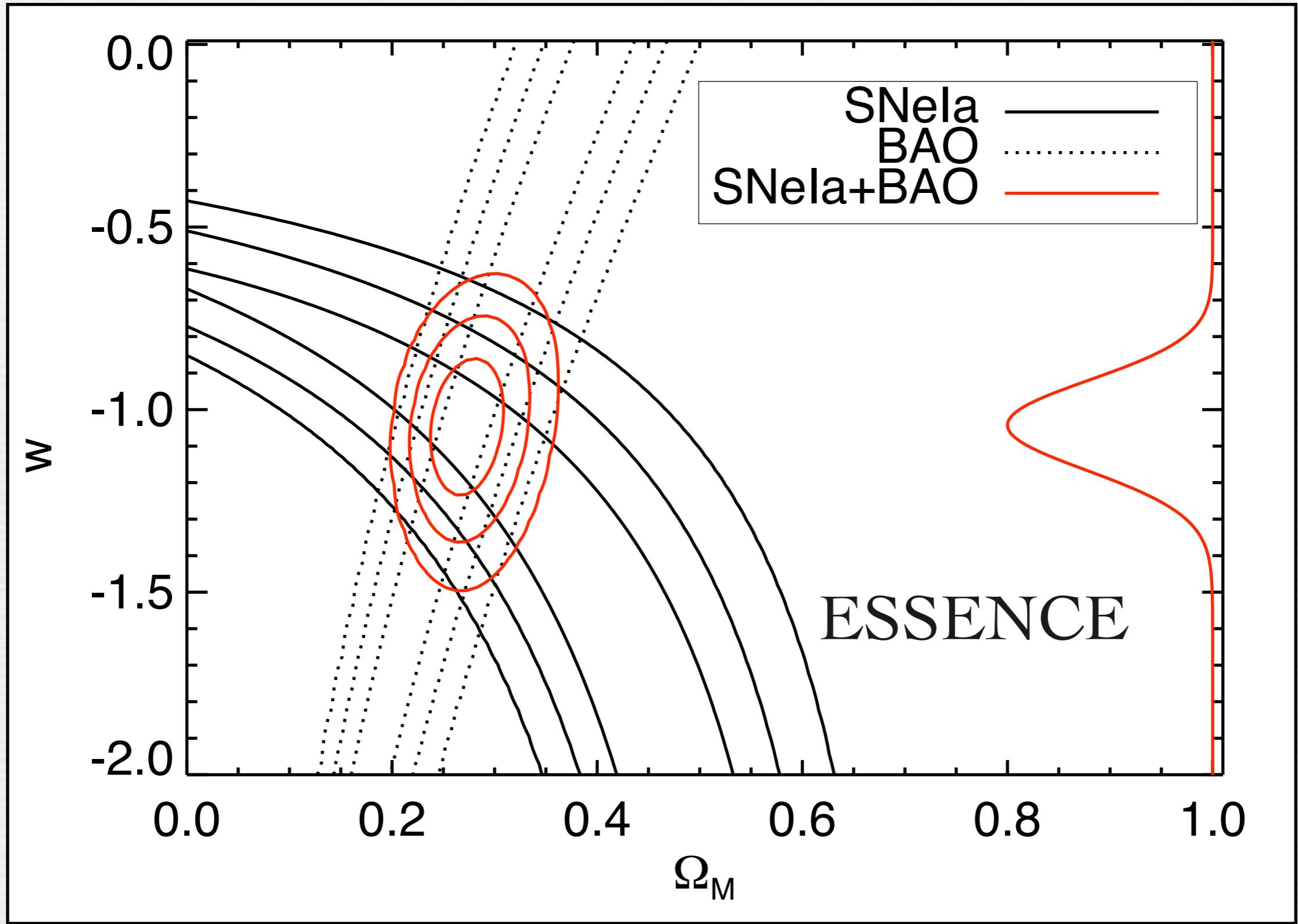
- ❖ Supernovae
- ❖ Weak Lensing
- ❖ Baryon Oscillations
- ❖ Galaxy Clusters

LSST & Supernovae

- ❖ LSST will find millions of supernovae
- ❖ Hundreds of thousands well-studied $z < 1.2$
- ❖ Tens of thousands $z < 0.3$
- ❖ Opportunity for SN science on a new level
 - ❖ Cosmology and Dark Energy
 - ❖ Supernovae qua supernovae
 - ❖ SNe trace structure
 - ❖ Rates: star-formation, galaxy environments
 - ❖ New brilliant ideas . . .

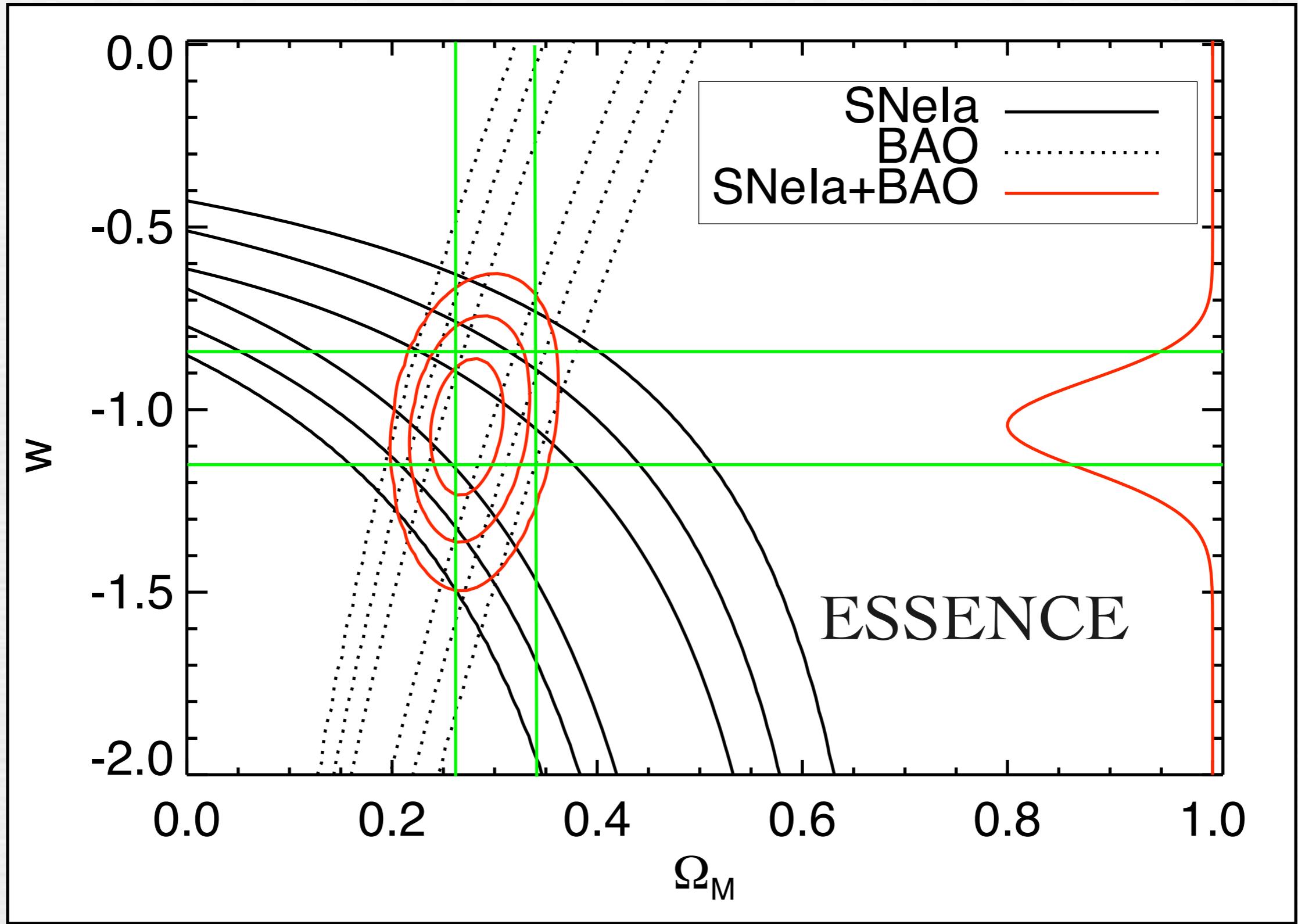
Flat,
constant-w

$$w = -1.05 \pm 0.11 \pm 0.13$$

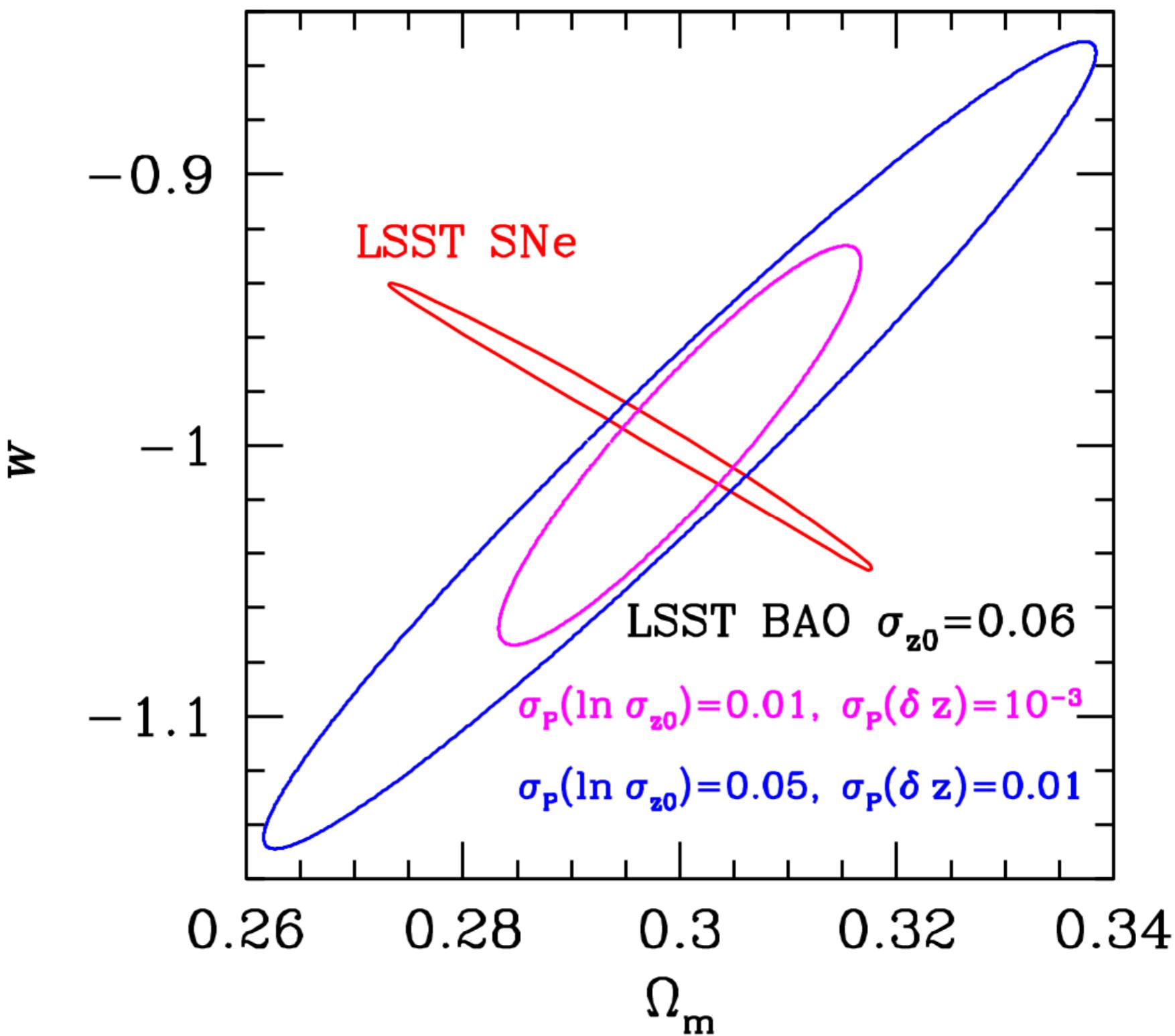


Flat,
constant-w

$$w = -1.05 \pm 0.11 \pm 0.13$$



LSST SN Ia (Ω_M , w)

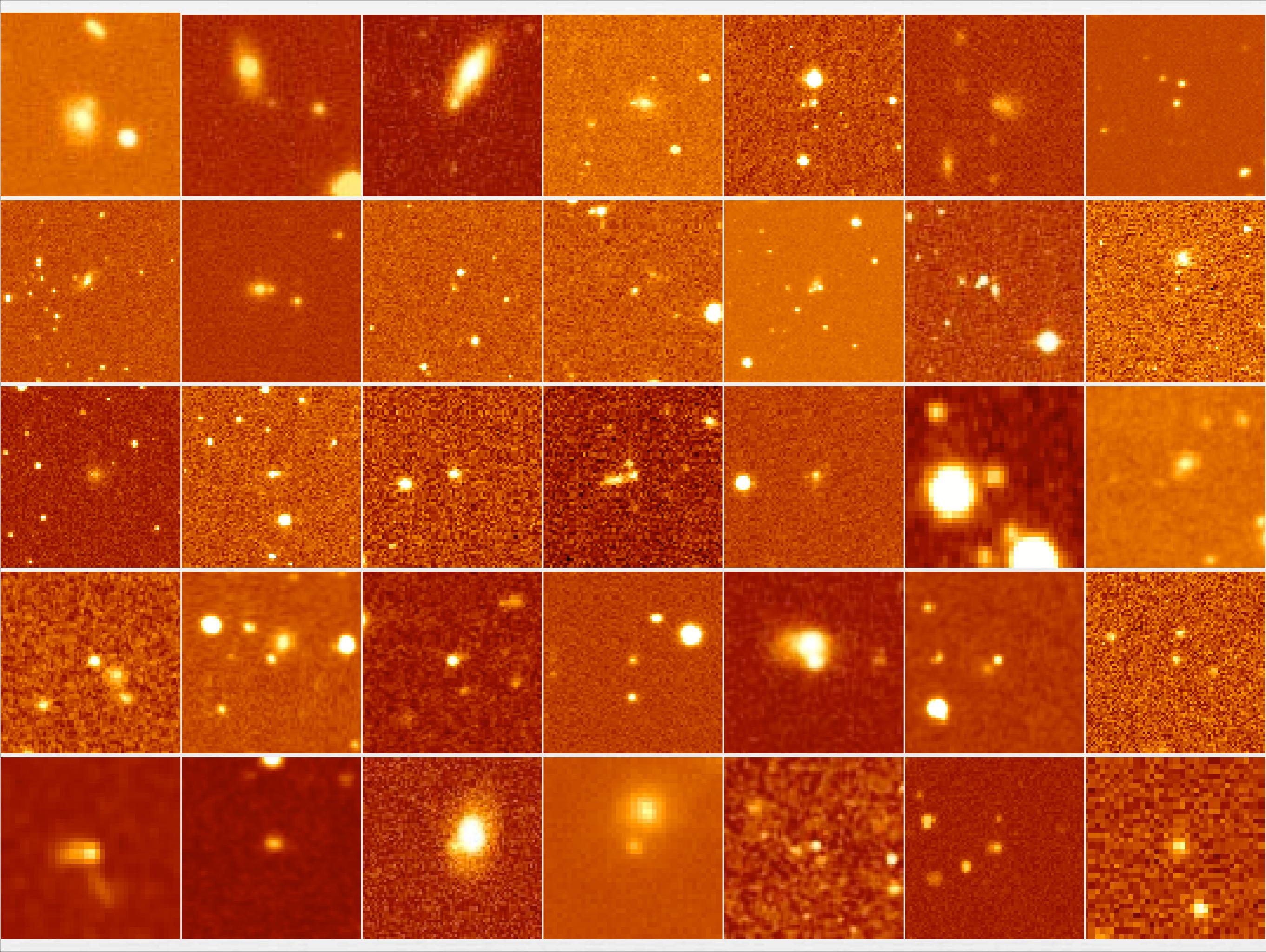


Future of Cosmology

- ❖ Luminosity Distance
 - ❖ SNeIa: SNAP; PanSTARRS, LSST
 - ❖ GRBs?
- ❖ Angular Diameter Distance
- ❖ Large Scale Structure
 - ❖ Baryon Acoustic Oscillations
 - ❖ Lensing/Shear
- ❖ Cosmic Microwave Background
 - ❖ Planck
- ❖ Gravity
 - ❖ LIGO, LISA

Summary

- ~ The accelerating Universe poses a significant challenge to theory, experiment and observation.
- ~ The current data are consistent with a “simple” $w = -1$, $\Omega = 1$
- ~ Upcoming projects have great potential to yield new insights into dark energy



MDS survey

Filter	Bandpass (nm)	m_{\perp} AB mag	μ AB mag/asec ²	exp time sec	5σ point source in 4 nts	5σ point source in 1 yr	5σ point source in 4 yrs
<i>g</i>	405–550	24.90	21.90	3 × 240	24.76	26.68	27.45
<i>r</i>	552–689	25.15	20.85	3 × 240	24.43	26.34	27.10
<i>i</i>	691–815	25.00	20.15	6 × 240	25.43	27.34	28.10
<i>z</i>	815–915	24.63	19.26	6 × 240	23.76	25.67	26.44
<i>y</i>	967–1024	23.03	17.98	6 × 240	22.32	24.23	25.00

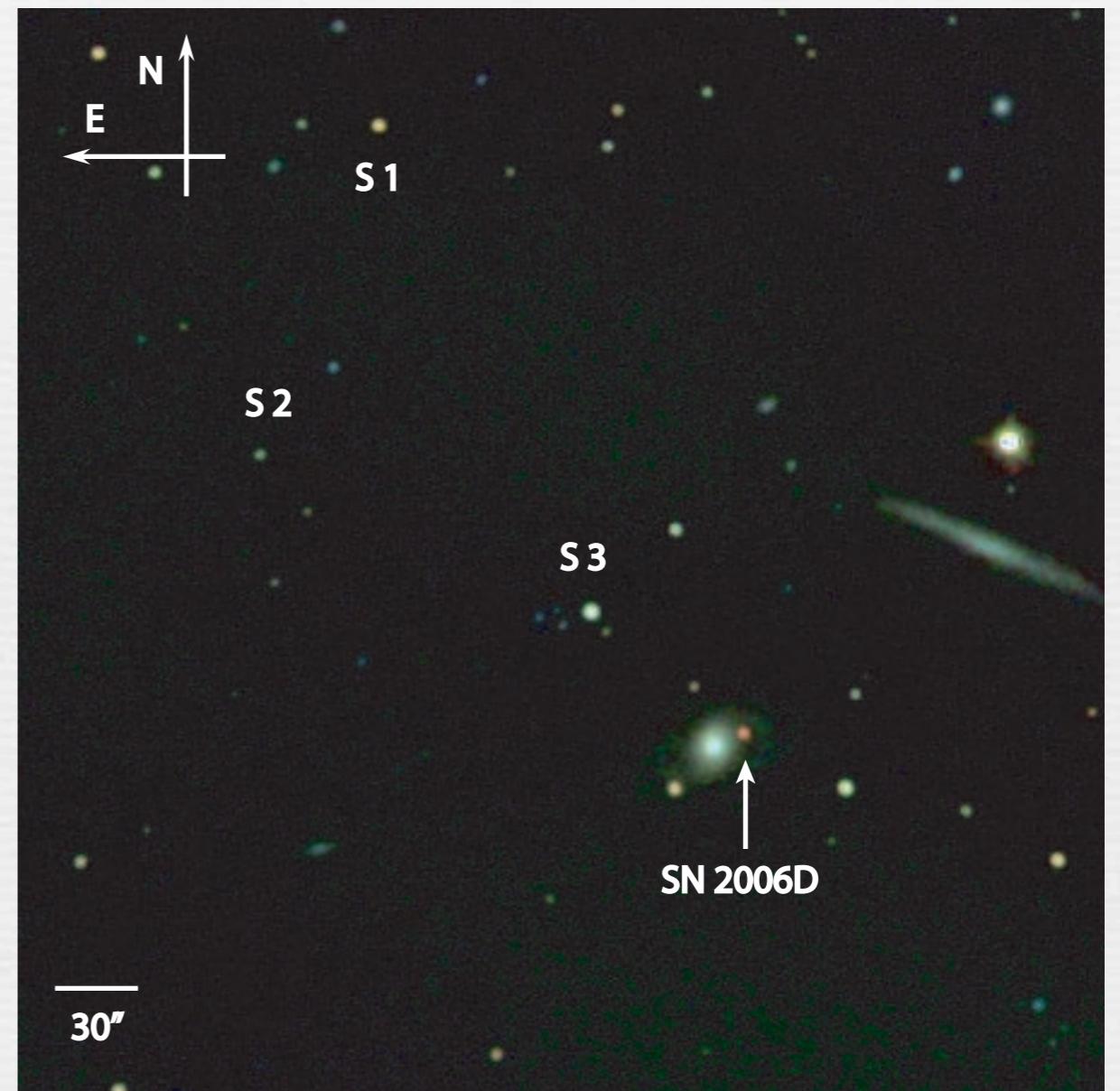
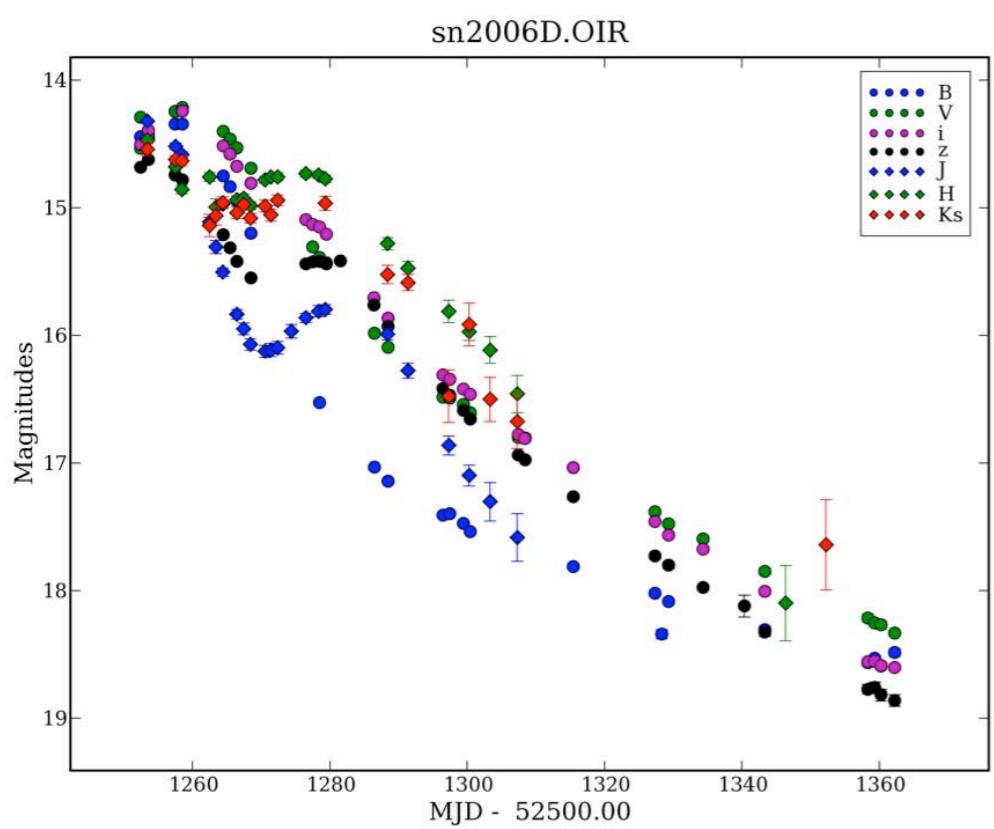
SN Ia Colors

- ❖ It's been hard to disentangle intrinsic SN Ia colors from reddening due to dust
- ❖ Do SNeIa have an intrinsic color-luminosity relationship?
 - ❖ $\Delta M_V = c E(B-V)$
- ❖ Dust extinction has the equivalent through R_V
 - ❖ $\Delta M_V = A_V = R_V E(B-V)$

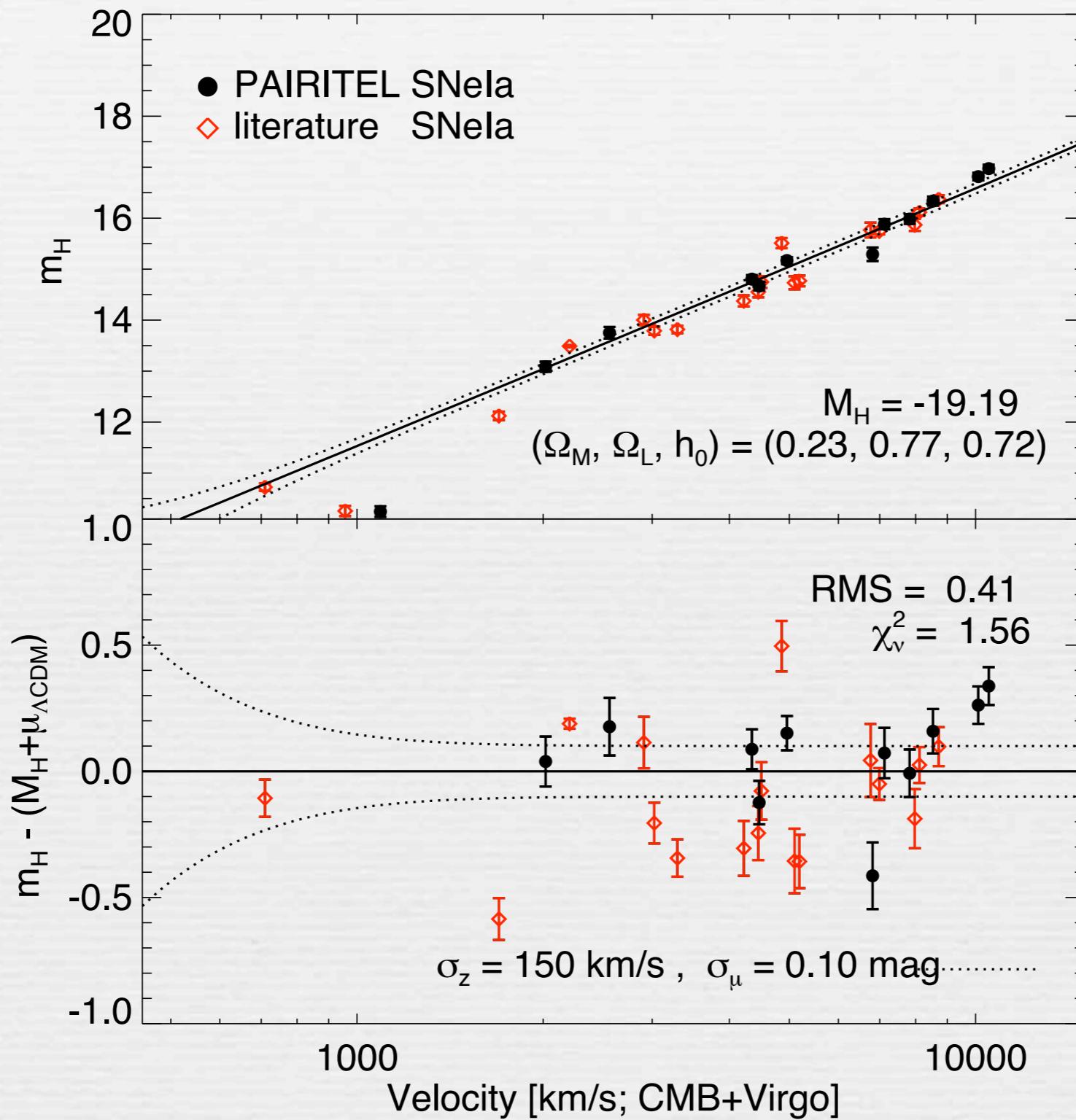
SNeIa in NIR

- ❖ SNeIa are more standard in near infrared
- ❖ Krisciunas seminal work 2000-2004 w/ 17 SNeIa
- ❖ Recent confirmation: Wood-Vasey 2007
 - ❖ New homogeneous sample from PAIRITEL
 - ❖ Doubled sample of SNeIa

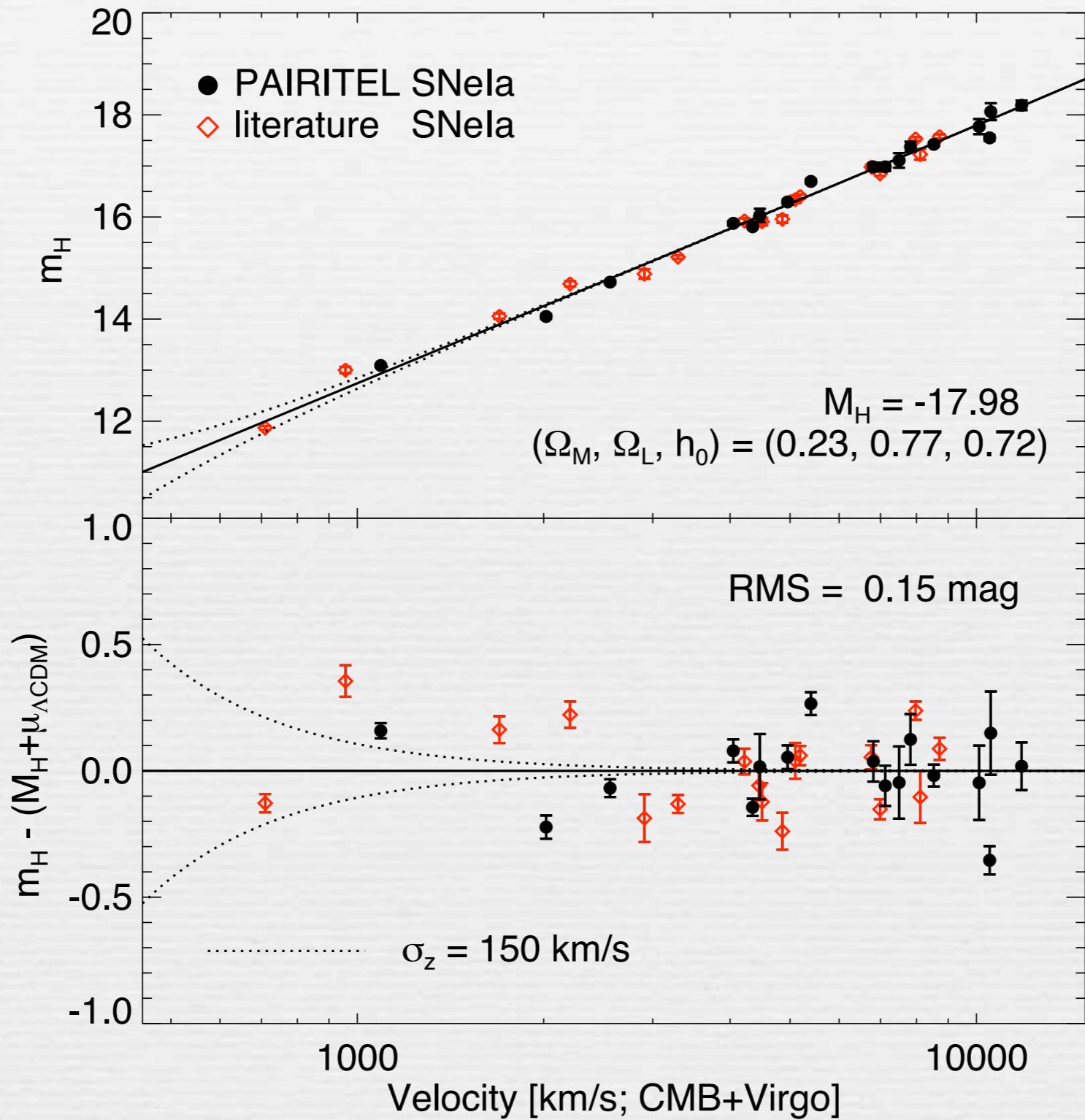
PAIRITEL: SN 2006D



Optical Hubble Diagram



H-band Hubble Diagram



No Trends in Residuals

