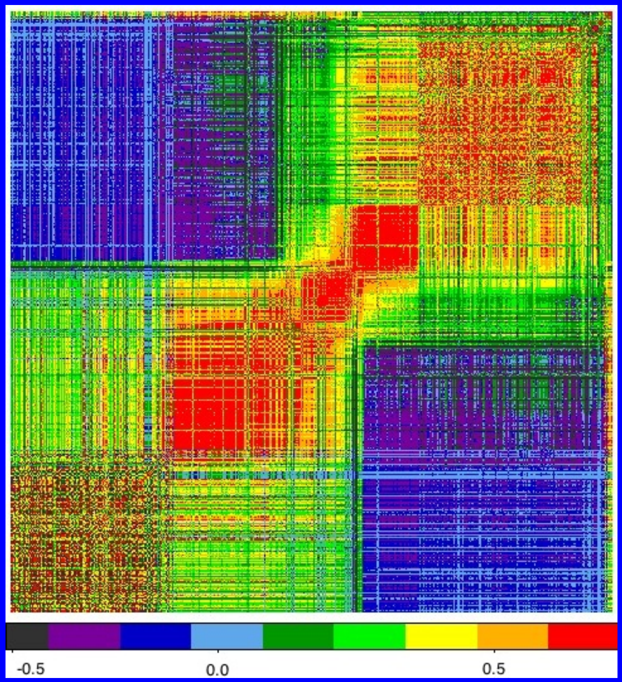
Precision Cosmology with SNe Ia



Reynald Pain

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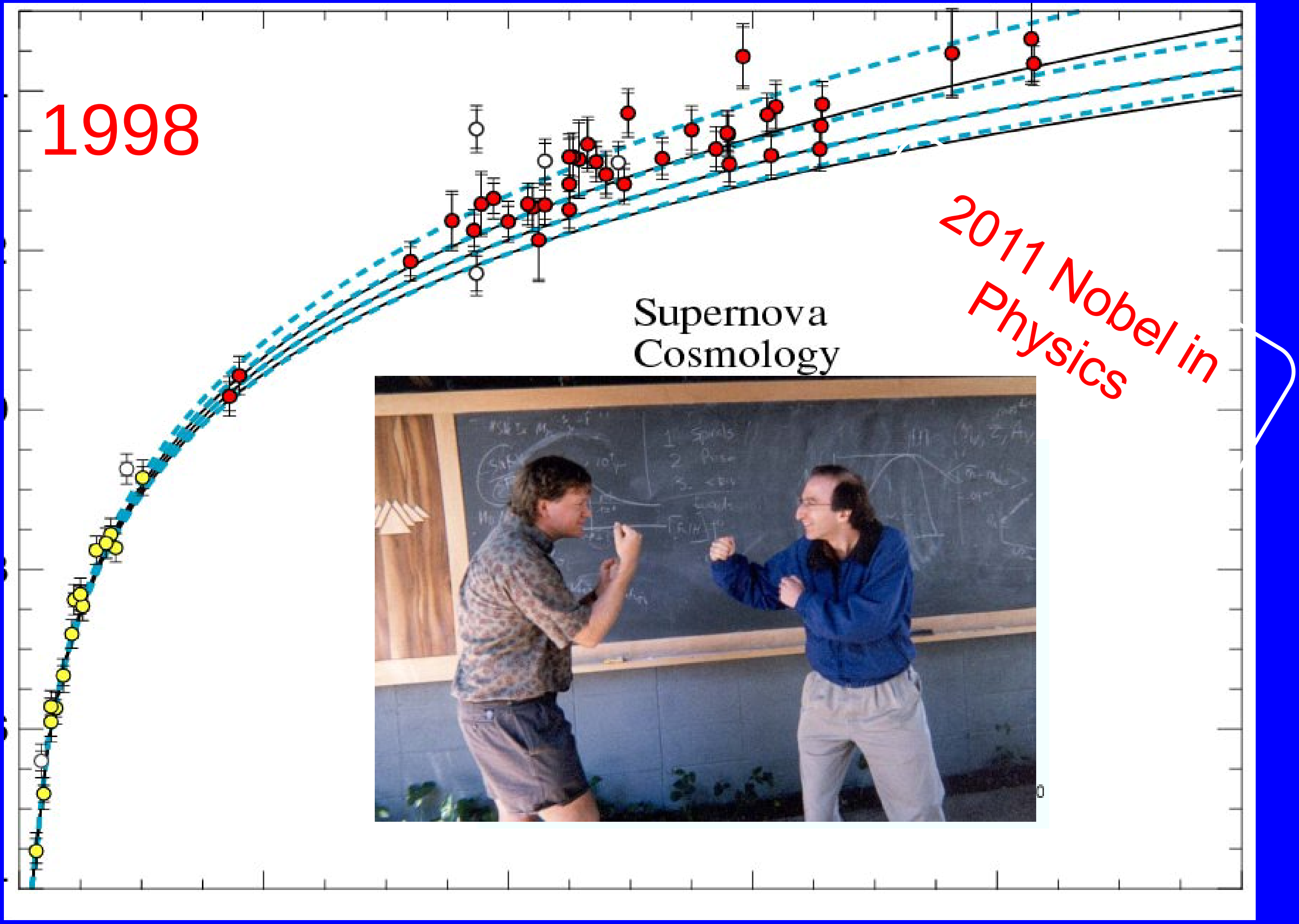
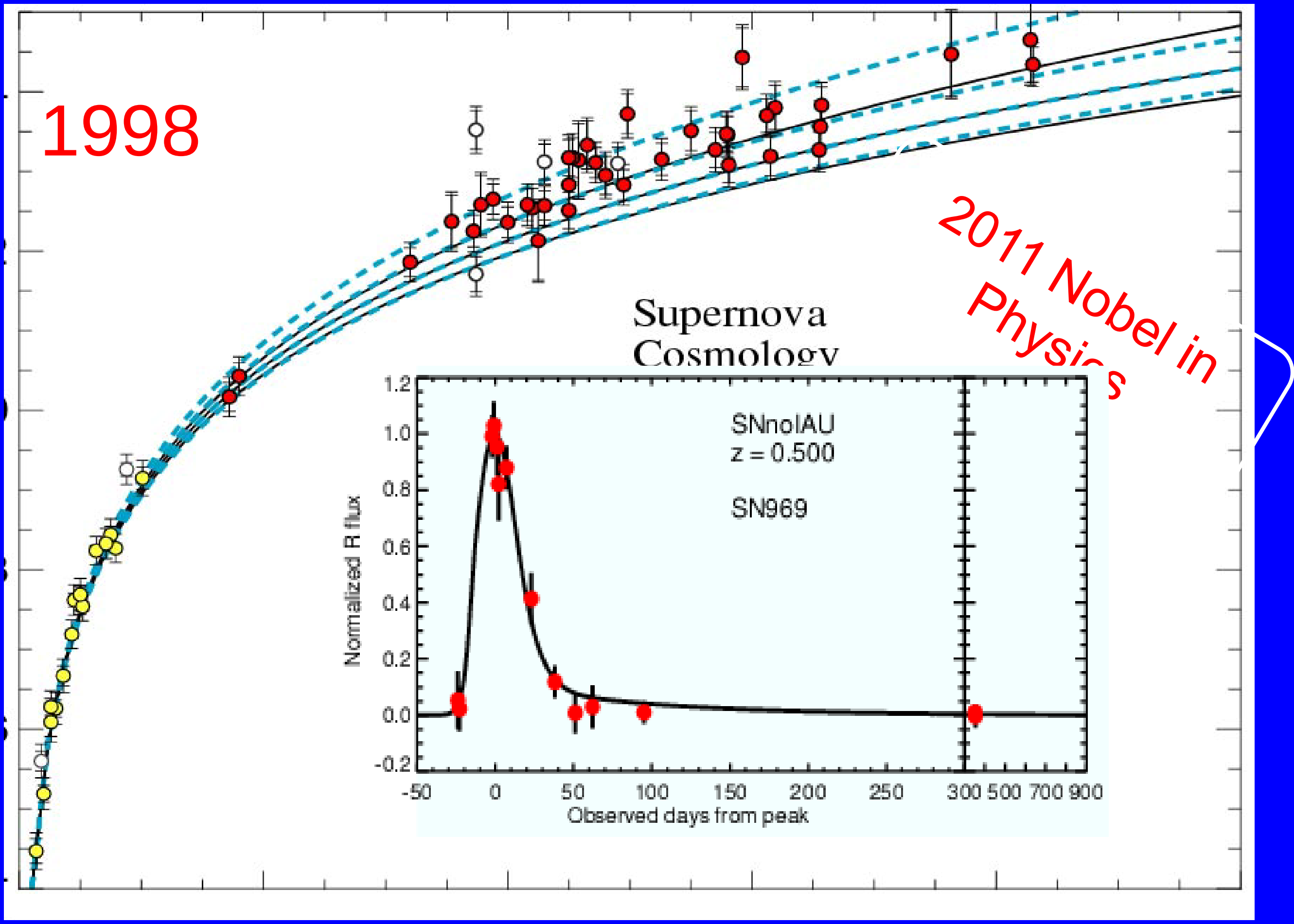
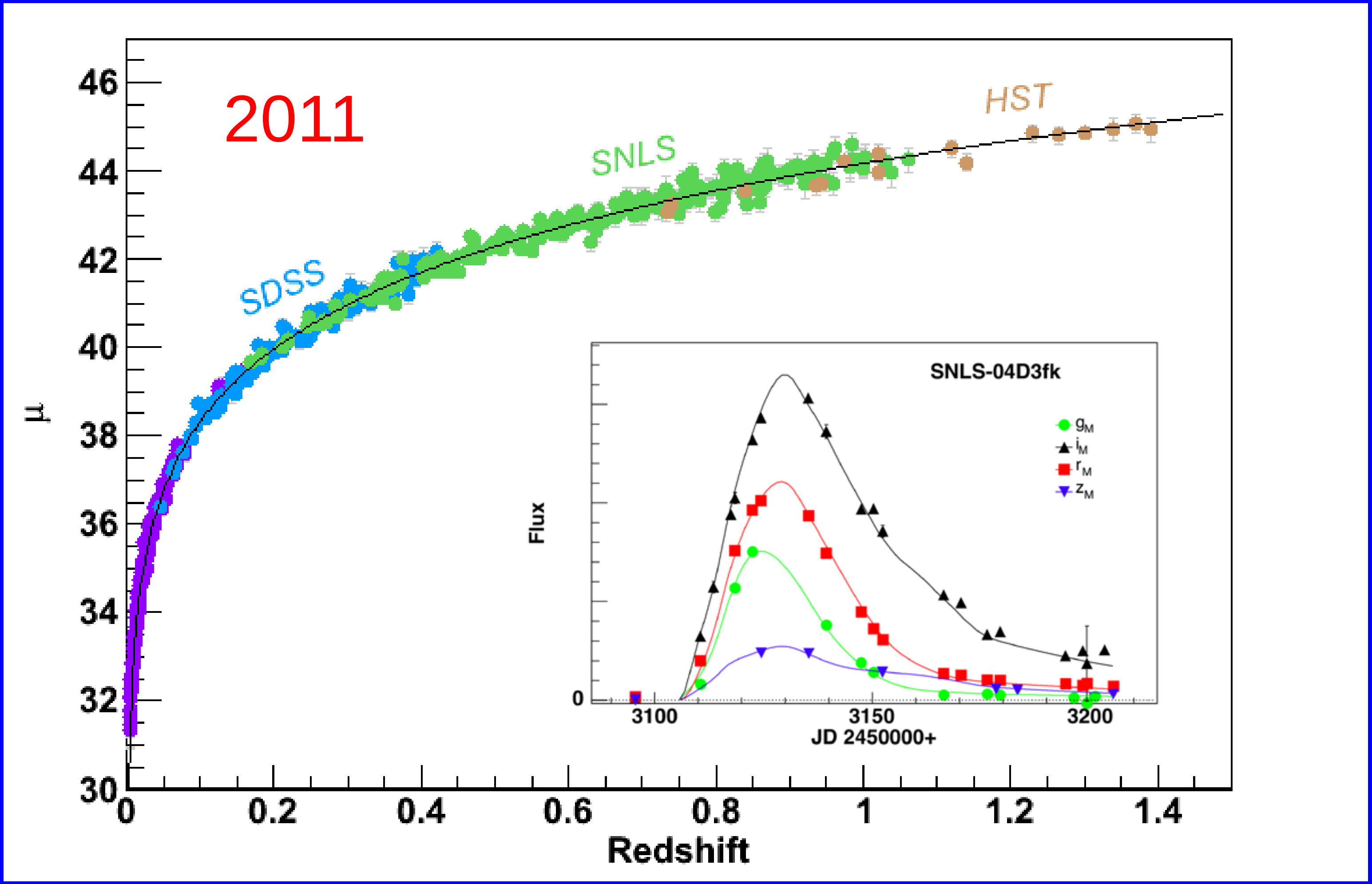
1998 : the systematic floor is reached?



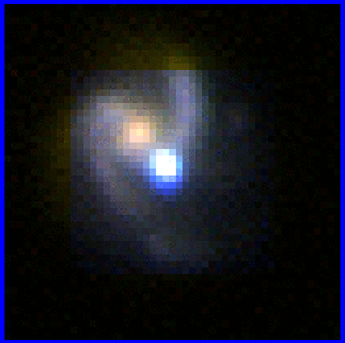
Systematic floor reached ?



Systematic floor reached ?



Precision Cosmology with SNe Ia



- Using SNe Ia to measure cosmology
- The Supernova Legacy Survey
- Recent SDSS-SNLS JLA results
- Ongoing and future SN Cosmology programs

Experimental Principle

2 observables :
flux: f
Redshift: z

$$d_L^{\,2} = \mathcal{L}/4\pi f$$

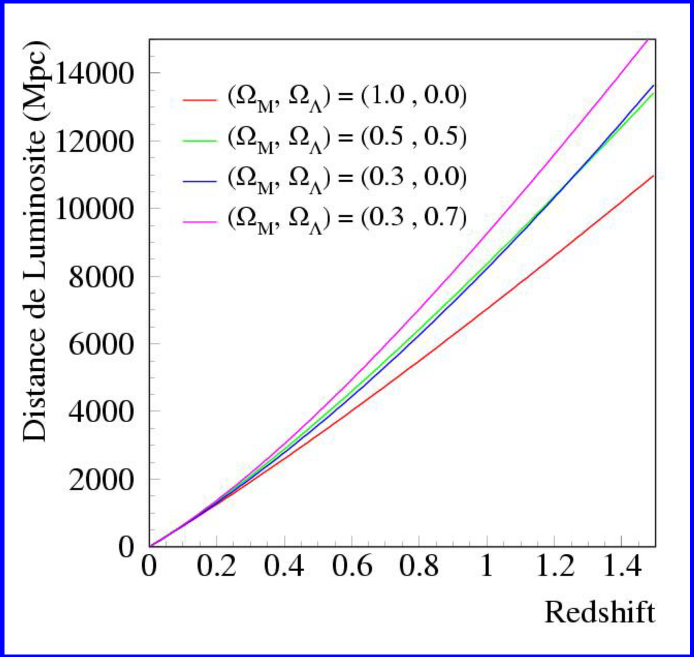
Use Supernovae as distance indicators to measure the Luminosity distance d_L

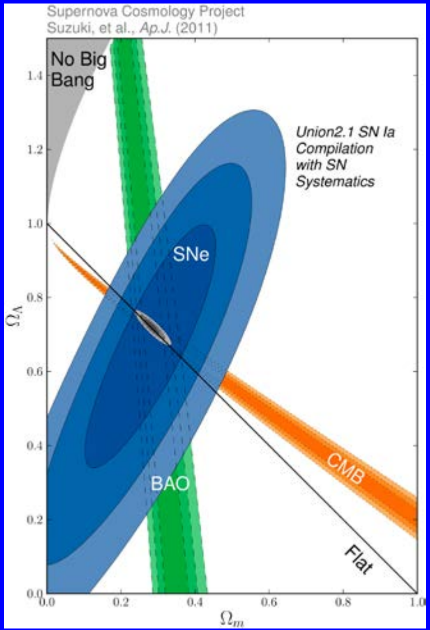
d_L is sensitive to the expansion rate and to the Energy content of the Universe

The Luminosity Distance

Assuming the Universe is composed of 2 « fluids » : Masse and X of density ρ_X

$$d_L(z) = (1+z)\frac{c}{H_0}\int dz'\left(\Omega_M(1+z')^{-3} + (1-\Omega_M)\frac{\rho_X(z')}{\rho_X(0)}\right)^{-1/2}$$



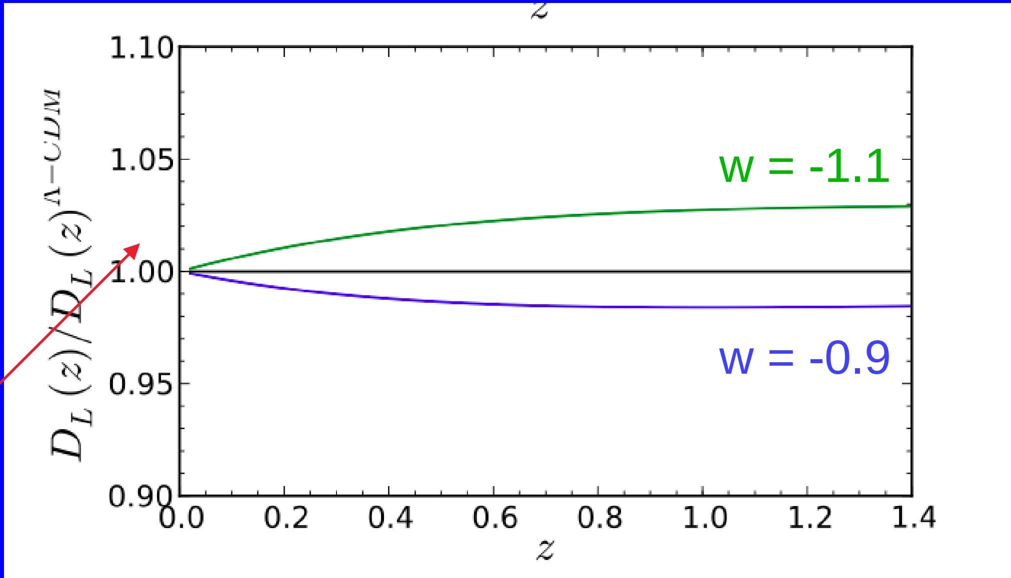


Union sample
Suzuki et al, 2012

What is dark energy ?

$$\rho(z) = \rho_0 \exp\left(\int 3\frac{w(z)+1}{1+z}dz\right)$$

Equ. of State $$w = \frac{p}{\rho}$$



δw (w=-1) ~ 2.5 δm

Measurement ingredients:

- (High) redshift Type Ia Supernovae (SN Ia)
- additional constraint on Ω_M-> increase precision

A word on H_0

Cosmological constraints on Ω_m, Ω_Λ and w come from a comparison of distant and nearby SN brightness

SN alone do not constrain H_0

One needs to start with an absolute distance scale

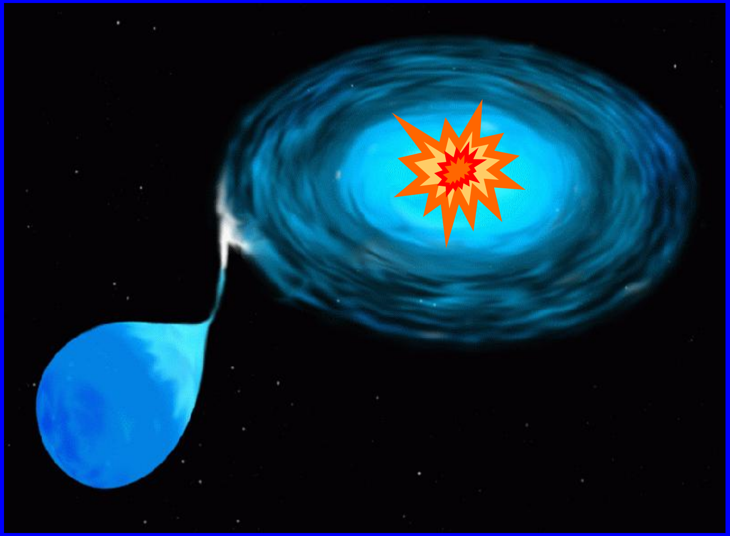
e.g. distance to NGC 4258 and propagate it to galaxies hosting SNe (using cepheids for example)

=> Additional (non SN) systematic uncertainties may affect this measurement

SNe Ia are NOT standard candles

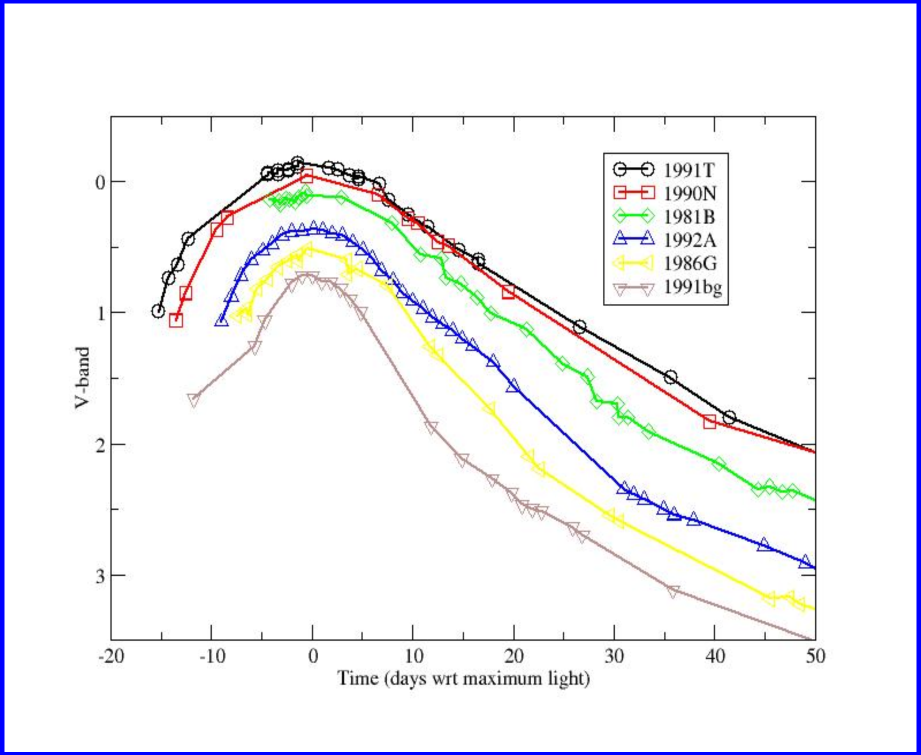
Very Luminous events

⇒ visible at cosmological distances



Or is the progenitor a double degenerate system ?

Supernovae Ia light curves



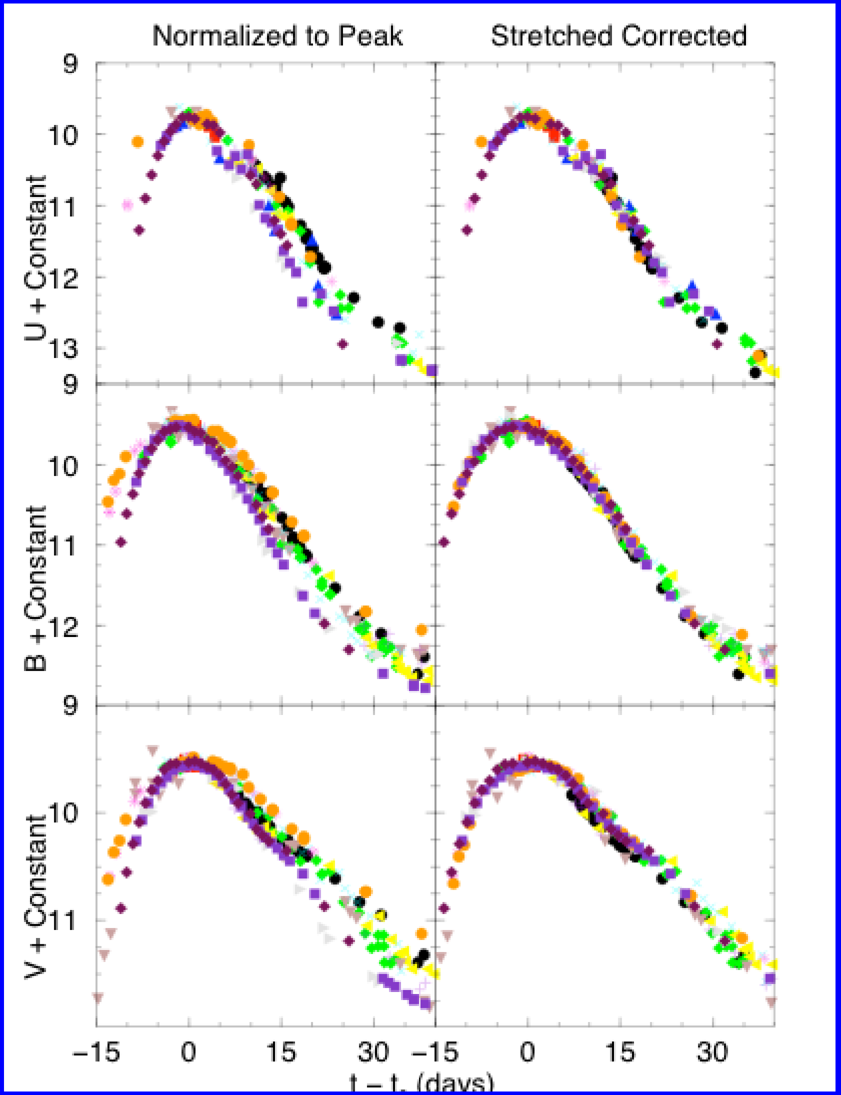
Show little luminosity dispersion

(inter)-calibrating Supernovae Ia

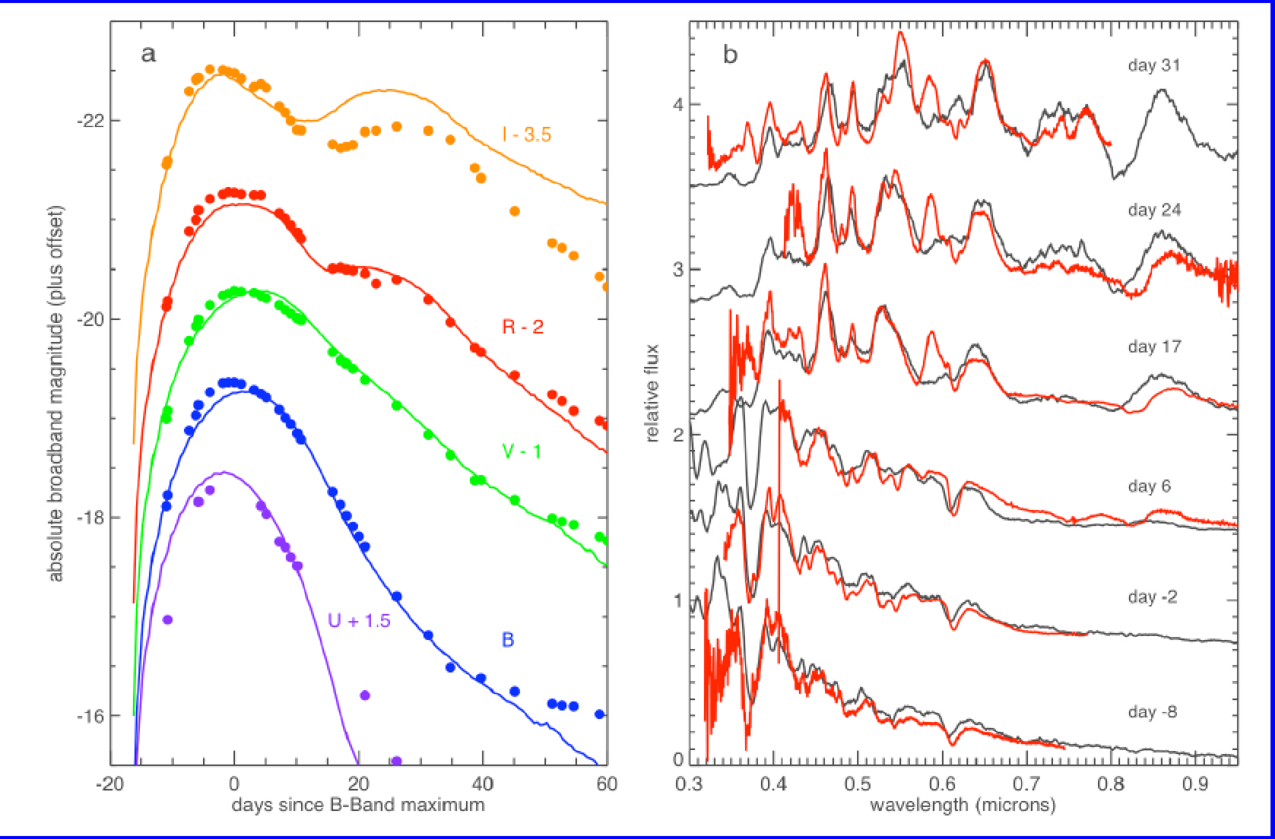
SNe Ia show Light Curve shape-luminosity relationships (similar to Cepheids P-L relation)

They also exhibit color luminosity relation (brighter-bluer)

⇒Allows us to measure
- after empirical corrections -
distances to ~5% precision



Modelling SNe Ia LC and spectra

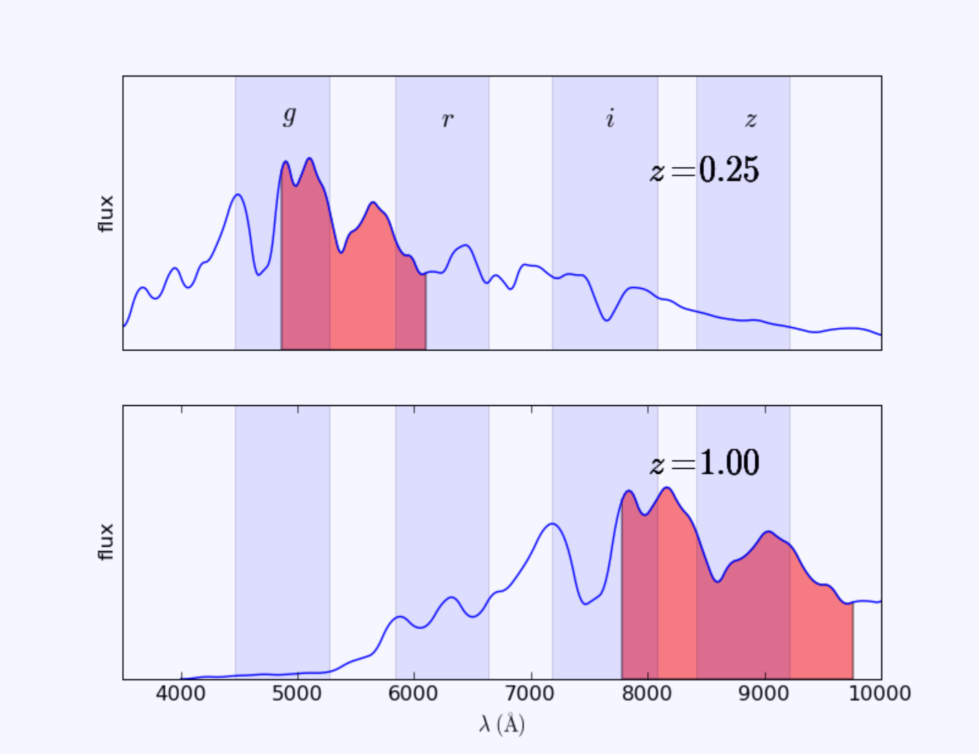


Kasen et al, 0907.0708

Not (yet) accurate enough to measure distances

=> Treat SNe Ia empirically

Extracting mb, s and c from observations



SN restframe fluxes at different redshifts

→ empirical model to interpolate between photometric measurements

→ Trained on sets of nearby & distant SNe

Several LC fitters : SALT2 (Guy et al, 2007), SIfTO (Conley et al, 2008), MLCS2k2 (Jha et al, 2007), CMAGIC (Wang et al, 2003), ...

Cosmology with SNe Ia

An empirical approach

$$\mu_B = m_B - M_B + \alpha(s-1) - \beta c$$

Absolute magnitude
at maximum

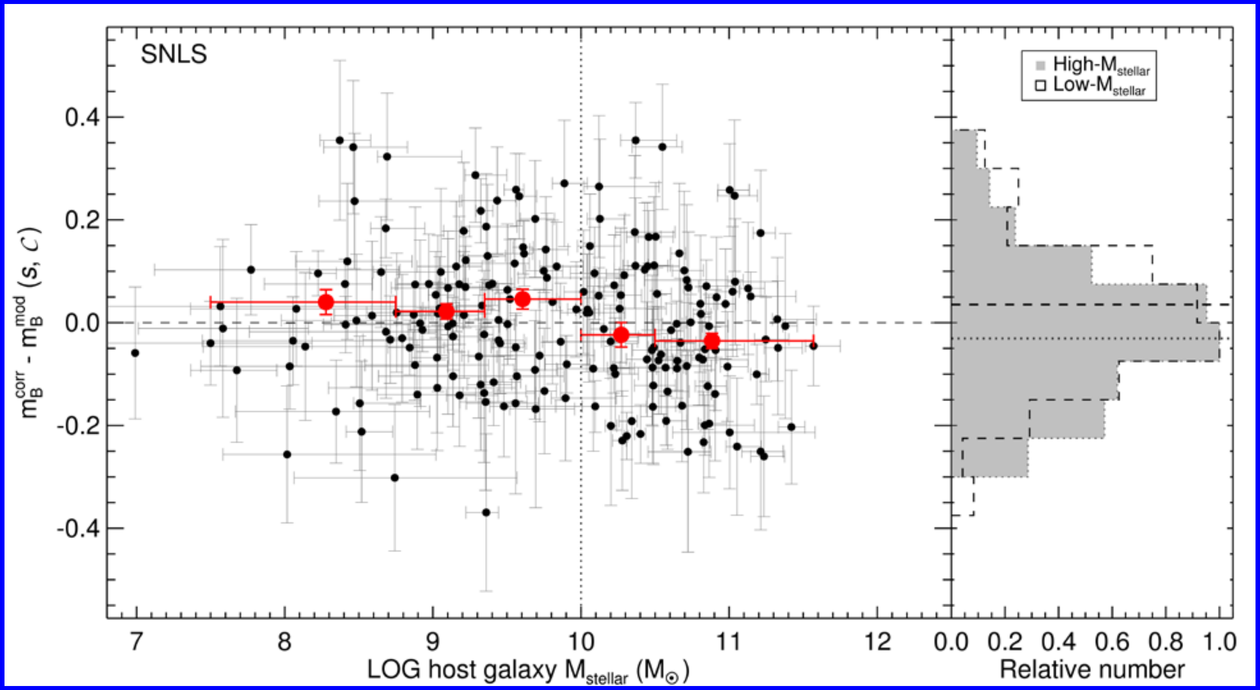
Light curve shape
correction

Resframe apparent magnitude
at maximum

Color correction. Accounts for
- extinction by dust
- intrinsic color variations

Hubble residuals versus host mass

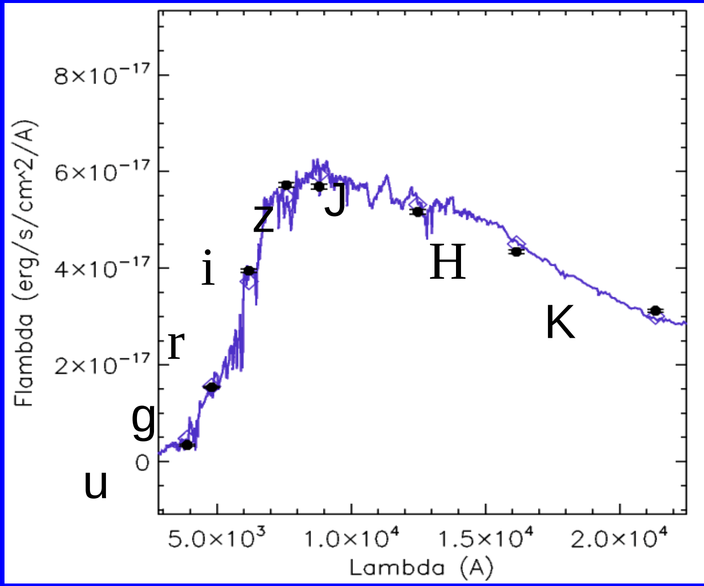
SNe Ia appear brighter (4σ) in massive galaxies after lightcurve shape and color correction

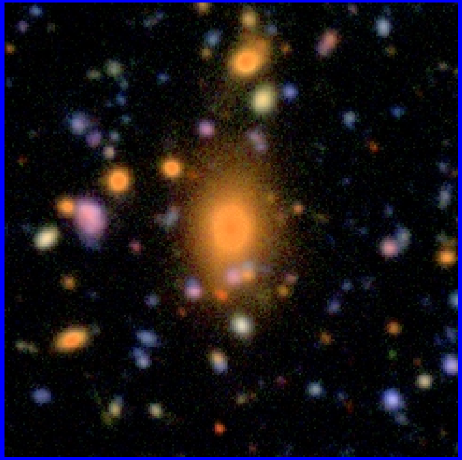


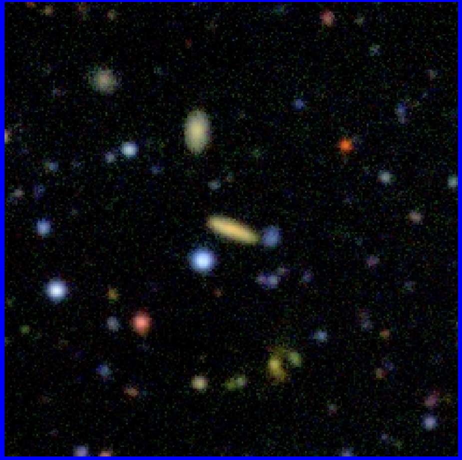
Subtle effect – 0.08mag – smaller than stretch and color corrections

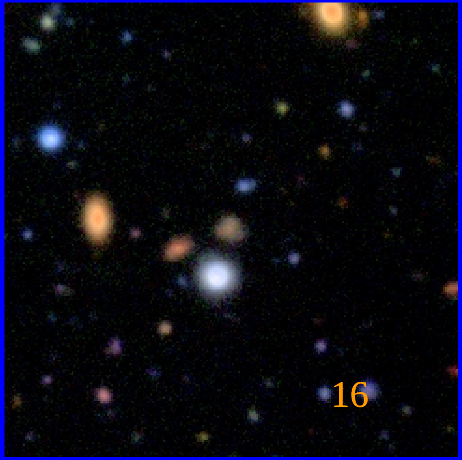
SN Ia brightness vs Host type

- No detailed understanding of SN Ia progenitors
- Are M_B, α and β "universal" parameters? Any age or metallicity (environmental) dependence?
- ugrizJHK host data allows estimations of:
  - Host star formation rate
  - Host stellar mass content









Improved Cosmological analysis

Two possible simplest ways to proceed:

1) Add a further linear host term, H, to the analysis:

$$m_B = m_B - M_B + a(s-1) - bc + gH$$

– *Requires very precise measure of H, and robust errors*

2) Use two M_B – one for high-mass galaxies and one for low-mass

$$m_B = m_B - M_B^1 + a(s-1) - bc \quad \text{when } H < H_{\text{split}}$$
$$m_B = m_B - M_B^2 + a(s-1) - bc \quad \text{when } H > H_{\text{split}}$$

SNLS -The SuperNova Legacy Survey

http://www.cfht.hawaii.edu/SNLS

The SNLS team

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Reynald Pain, Nicolas Regnault,
N. Palanques, J. Rich, V. Ruhlman

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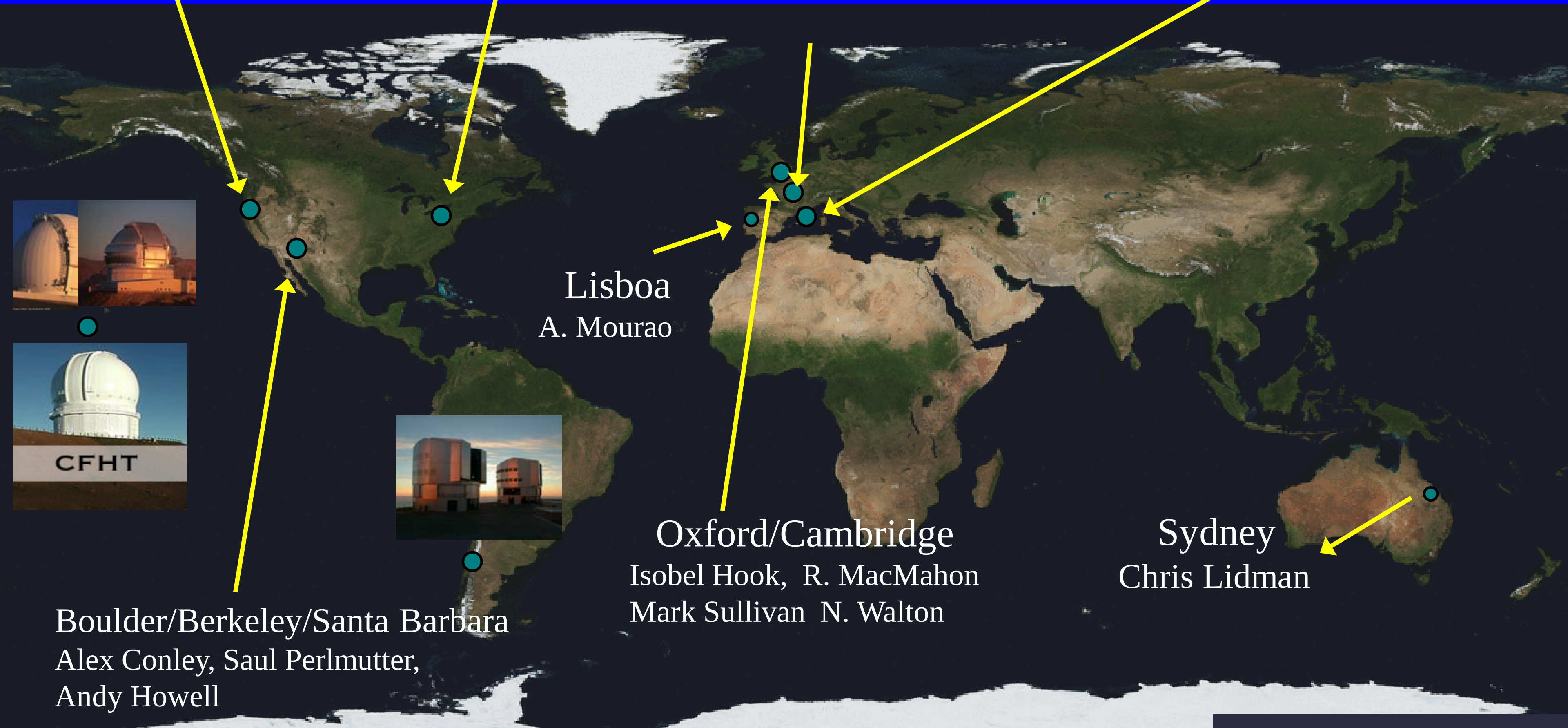
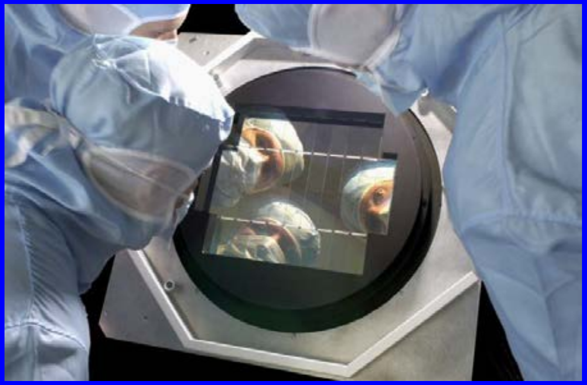


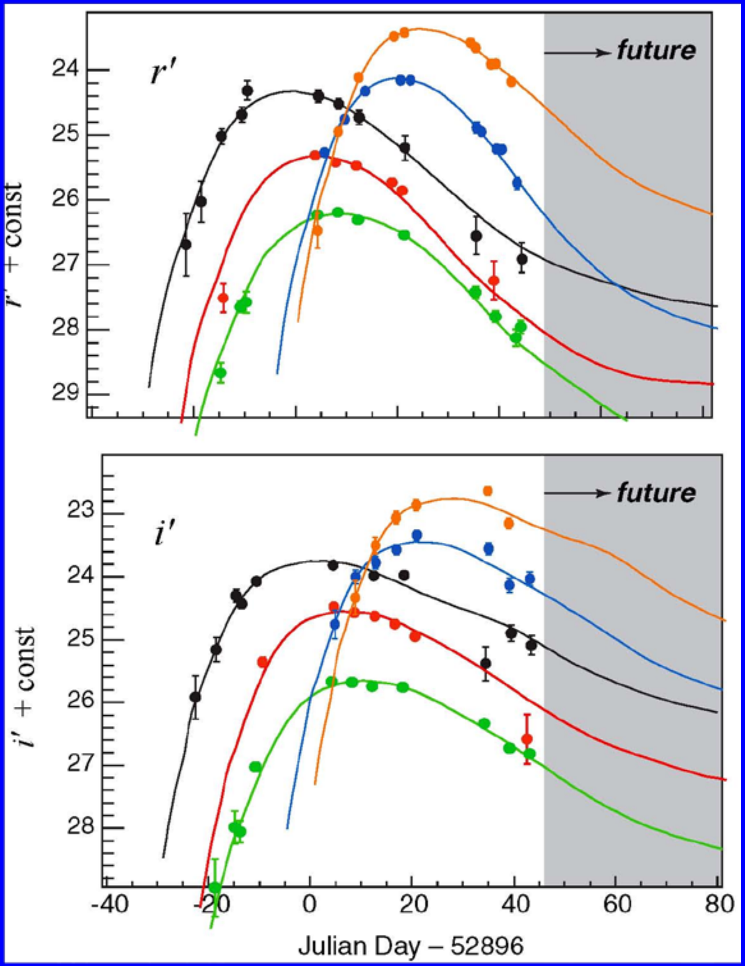
Full list of collaborators at http://cfht.hawaii.edu/SNLS/

SNLS : a “Rolling Search” survey with MegaCam



Each lunation (~18 nights) :
repeated observations
(every 3-4 night) of
2 fields in four bands (griz)+u
for as long as the fields stay
visible (~6 months)

=> ~500 SN Ia identified
(+ ~300 « photometric »)
observed between 2003 and 2008



using ~1500h of 4m for imaging
and ~1500 h of 8m for spectroscopy

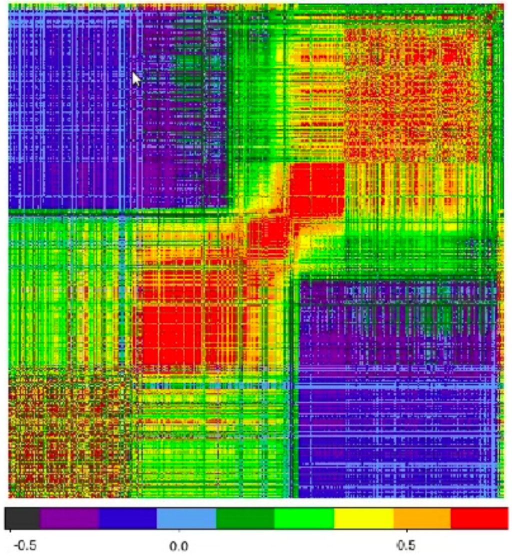
SNLS 3-yr analysis and combined constraints

- ~250 Supernovae at $0.3 < z < 1.1$
- Two independent analyses (SN photometry, photometric calibration, light curve fitters)
- precise photometric calibration
- Improved supernova LC modeling (models trained on the SNLS data → bluer part of the restframe spectrum constrained without using observer frame U)
- Include host mass term
- Systematics included in the cosmology fit

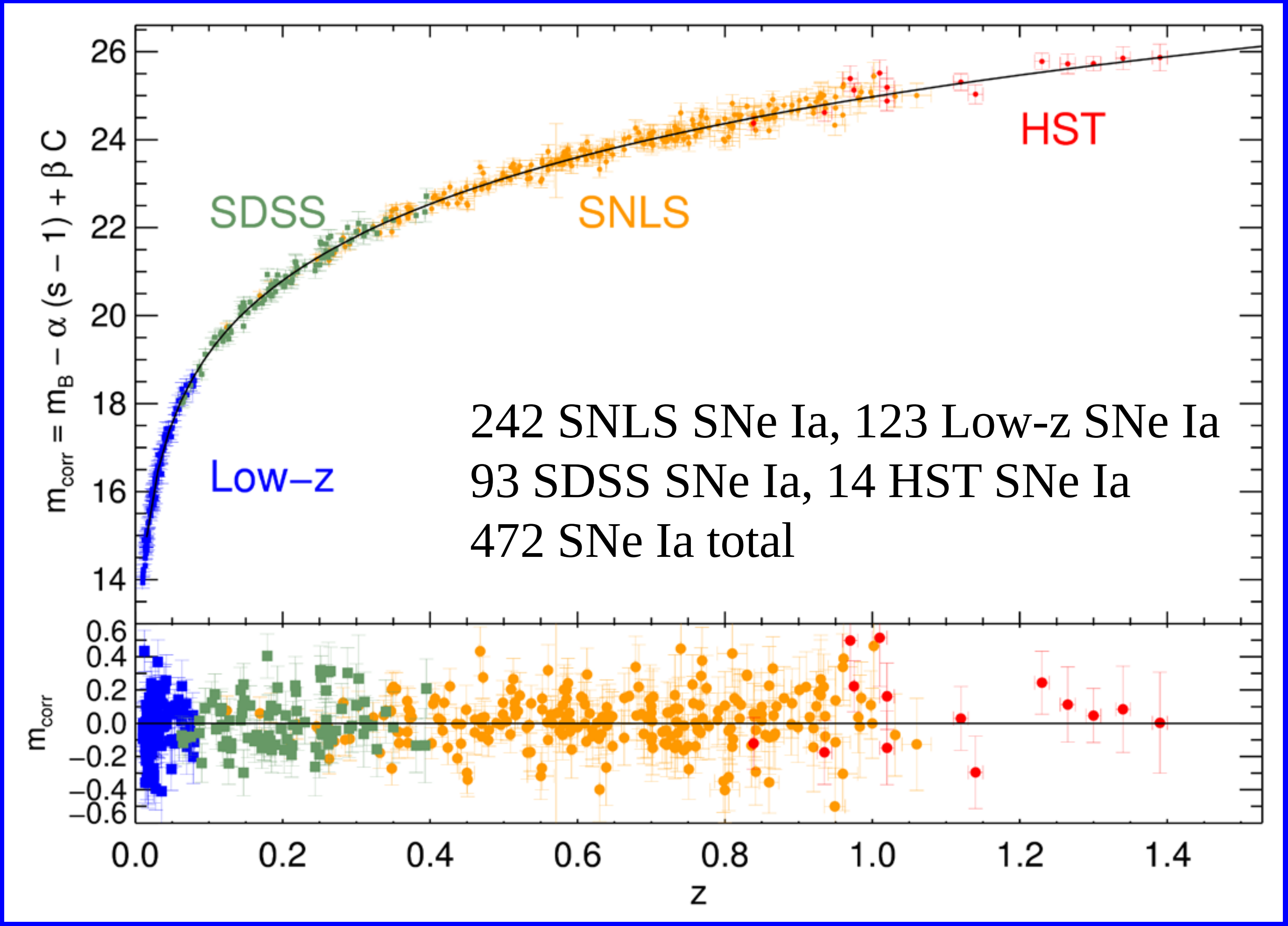
Include systematics in the cosmological fit

- Peculiar velocities for low-z SNe
- Contamination by Core collapse SNe for high-z SNe
- **Evolution of color-luminosity relation with redshift**
- **Evolution of SNe with z : age of stellar population or metallicity**
- Gravitational magnification

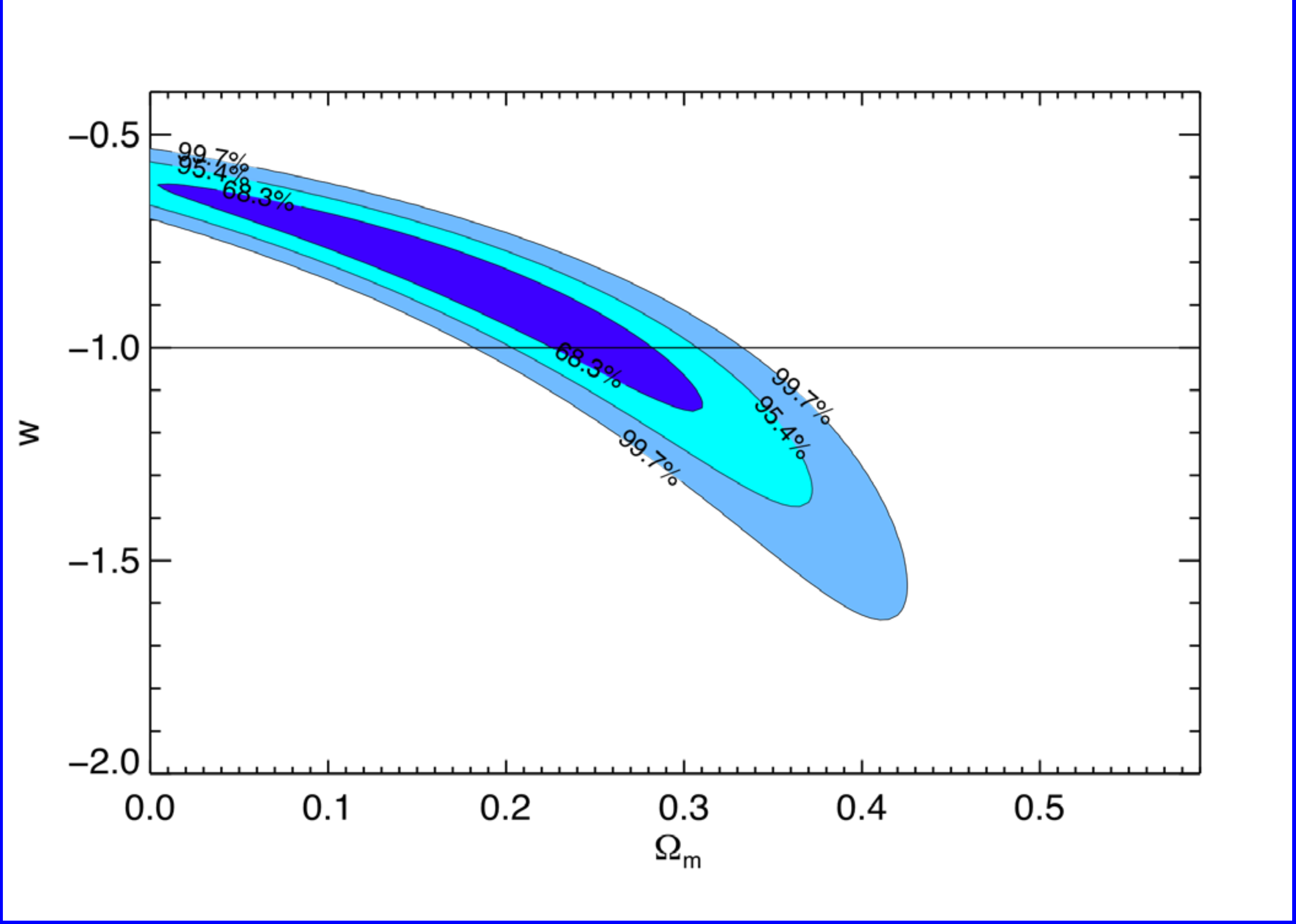
- about 200 different systematics (S_k) identified.
- Conversion of those systematics into a covariance matrix of SNe distance moduli (μ_i) $C_{sys,ij} = \sum_k \frac{\partial \mu_i}{\partial S_k} \frac{\partial \mu_j}{\partial S_k} (\Delta S_k)^2$



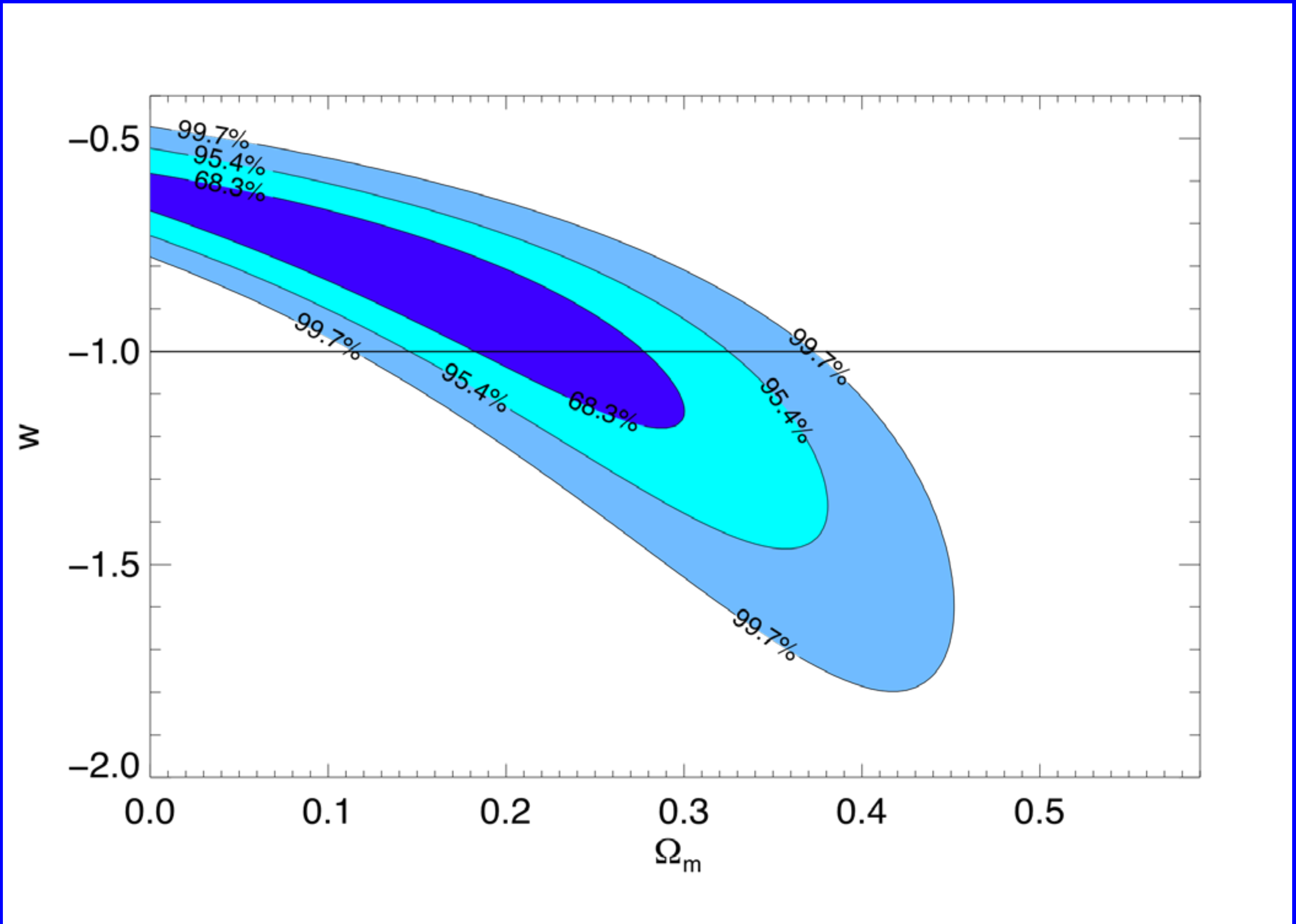
Combined SN Hubble diagram



SN only constraints on w



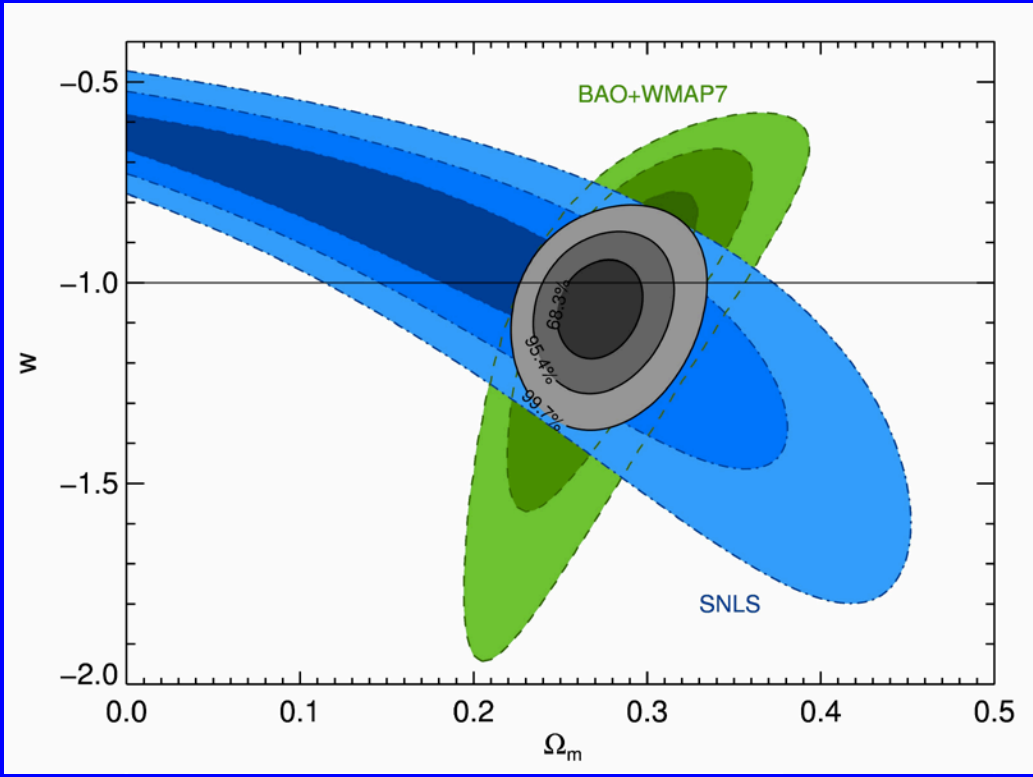
SN only constraints on w



Which systematics are dominant (SN only) ?

Description	Ω_m	w	Rel. Area [a]
Stat only	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1
All systematics	0.18 ± 0.10	$-0.91^{+0.17}_{-0.24}$	1.85
Calibration	$0.191^{+0.095}_{-0.104}$	$-0.92^{+0.17}_{-0.23}$	1.79
SN model	$0.195^{+0.086}_{-0.101}$	$-0.90^{+0.16}_{-0.20}$	1.02
Peculiar velocities	$0.197^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.03
Malmquist bias	$0.198^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.07
non-Ia contamination	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1
MW extinction correction	$0.196^{+0.084}_{-0.100}$	$-0.90^{+0.16}_{-0.20}$	1.05
SN evolution	$0.185^{+0.088}_{-0.099}$	$-0.88^{+0.15}_{-0.20}$	1.02
Host relation	$0.198^{+0.085}_{-0.102}$	$-0.91^{+0.16}_{-0.21}$	1.08

SNLS3+WMAP7+BAO/DR7+H_0



Consistent with cosmological constant

Error in w (flat): ~**7% w/ systematics**

Error is <9% (total) when Ω_k=0 relaxed

Adding BAO/DR7 reduces w error from 11% to 9%

Flat:

$$w = -1.061 \pm 0.069$$
$$\Omega_M = 0.269 \pm 0.015$$

Non-Flat:

$$w = -1.069 \pm 0.091$$
$$\Omega_M = 0.271 \pm 0.015$$
$$\Omega_k = -0.002 \pm 0.006$$

Minus BAO:

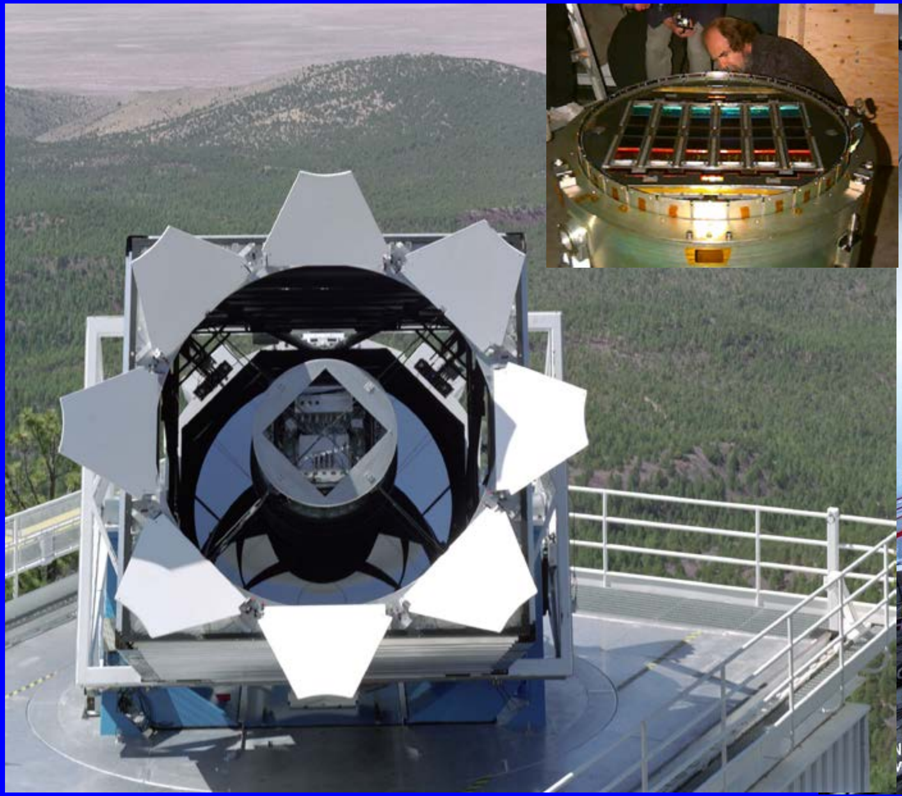
$$w = -1.018 \pm 0.111$$
$$\Omega_M = 0.259 \pm 0.049$$
$$\Omega_k = 0.001 \pm 0.015$$

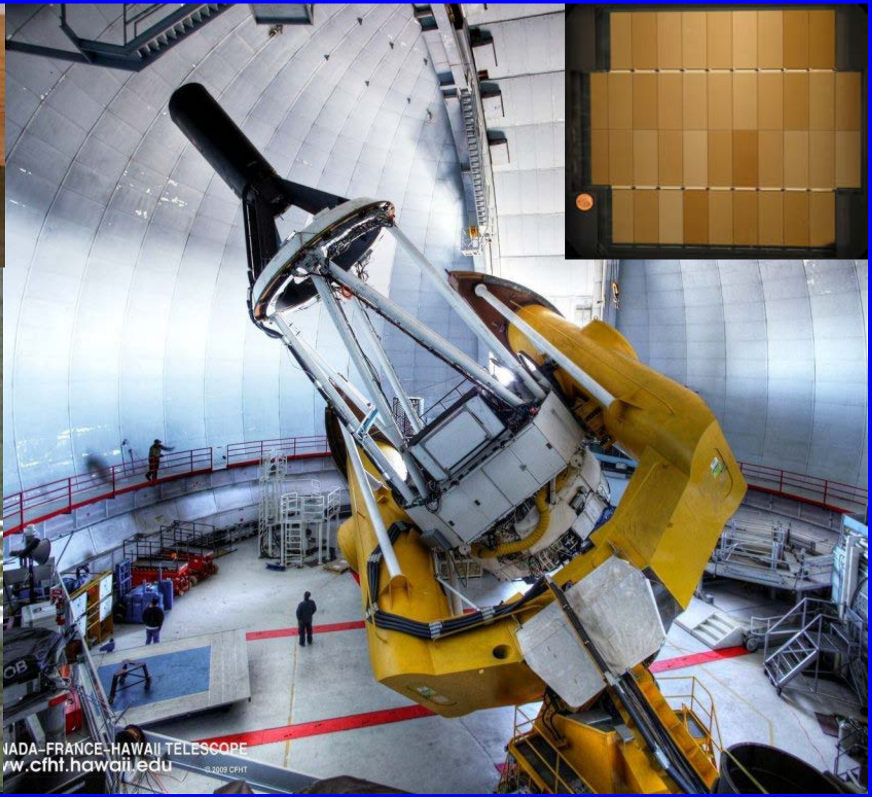
Minus SNe:

$$w = -1.412 \pm 0.333$$
$$\Omega_M = 0.259 \pm 0.030$$
$$\Omega_k = -0.009 \pm 0.008$$

Recent results results from the SNLS-SDSS joint analysis

SNLS-SDSS joint Analysis





SDSS/SNLS Joint Light Curves Analysis

SNLS SN data sample

5 yr rolling search ~500 SNe Ia + ~300 “photometric” Ia

=> 3 yr “spectroscopic” sample : ~250 SNe Ia

SDSS SN data sample

3 yr rolling search ~ 500 SNe Ia + ~300 “photo Ia”

=> good quality spectrocopic sample : ~250 SNe Ia

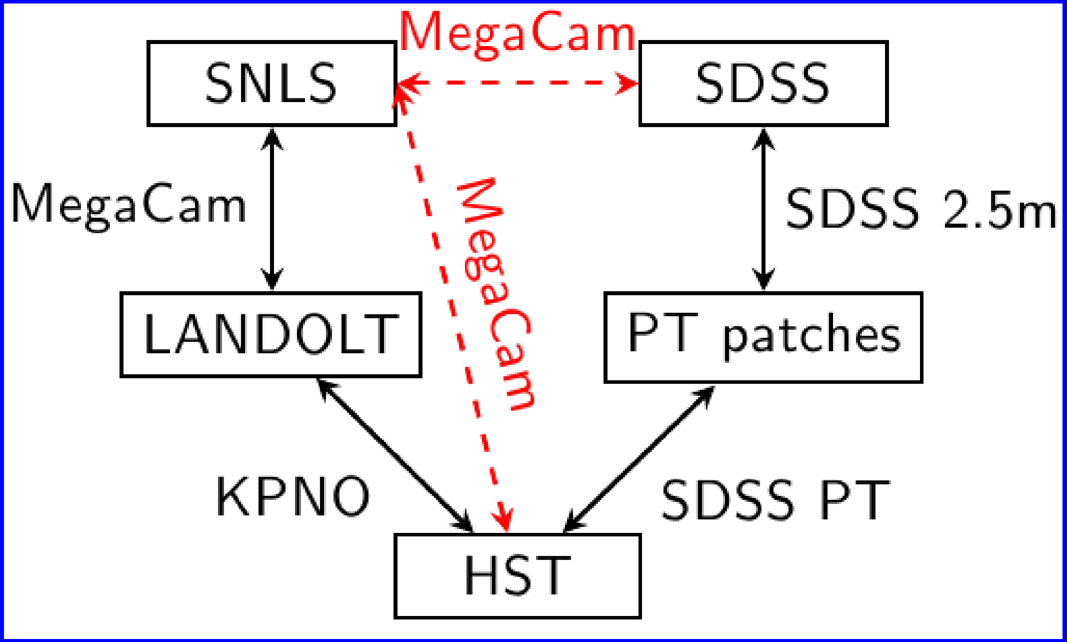
Joint SDSS-SNLS analysis goals:

– Cross-calibrate (gain : ~2 in calib uncertainty)

– Validate LC fitter and joint LC training => reduce syst.

=> update cosmological constraint combining SNLS3+SDSS

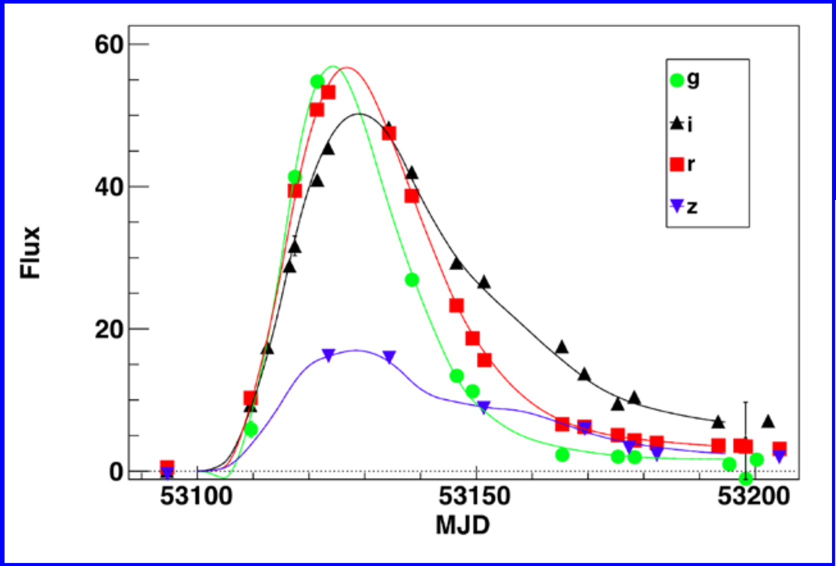
SNLS-SDSS (photometric) cross-calibration



- direct observations of SDSS & HST stars
- several calibration paths

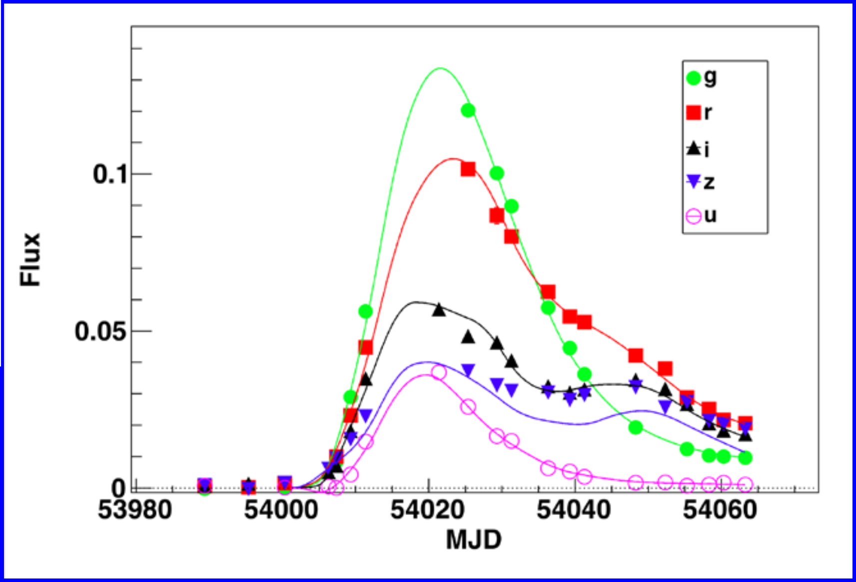
=> Achieve ~0.3% precision in g, r and i

SNLS-SDSS Joint Lightcurve Analysis

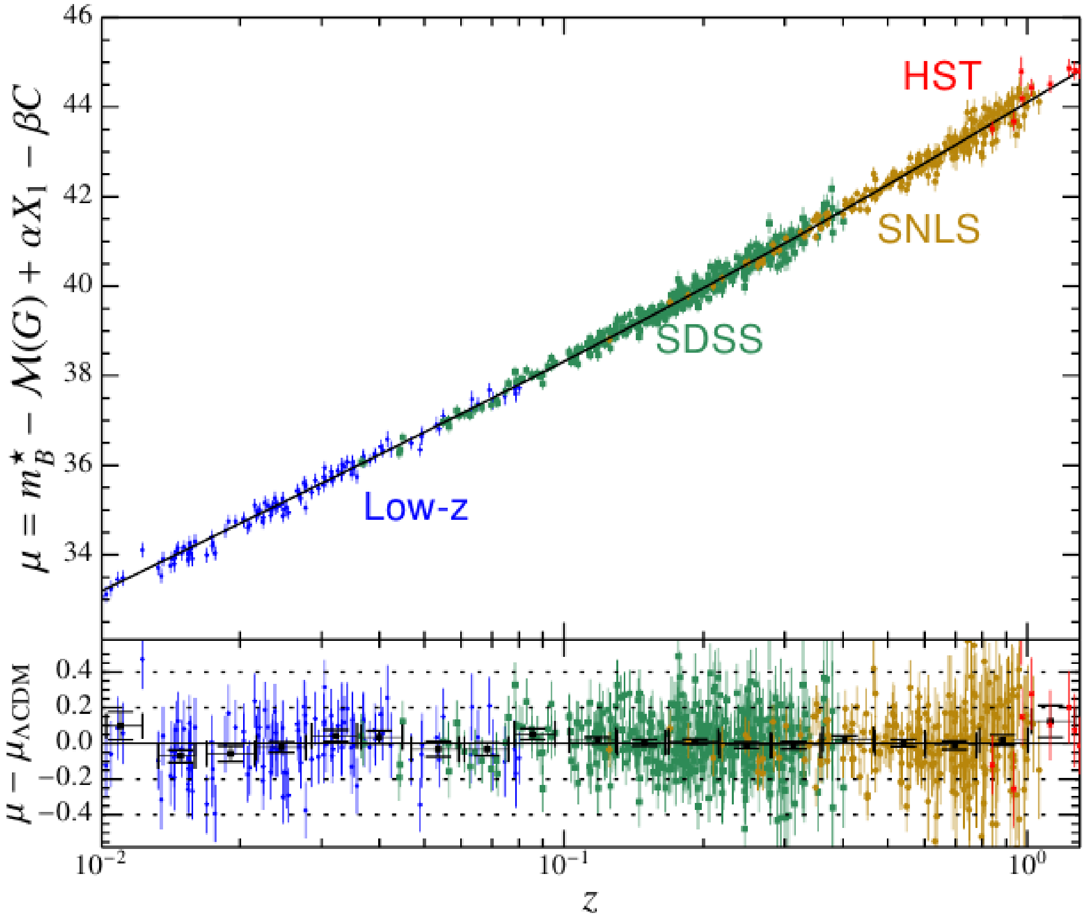


SNLS SN LC @ Z ~0.5

SDSS SN LC @ Z ~0.2



SDSS/SNLS Joint Light Curves Analysis



- 118 nearby SNe
- 93 SDSS SNe
- 242 SNLS SNe
- 14 HST SNe

Minimal update

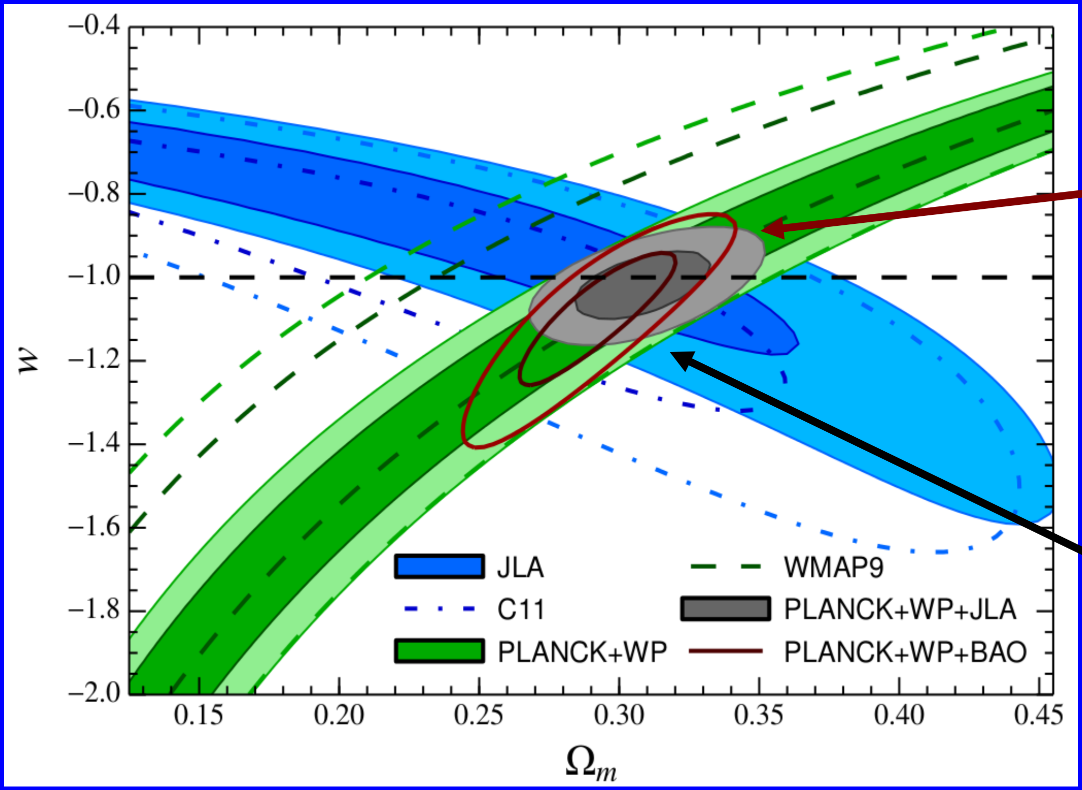
1. Recalibrate SNLS and SDSS
2. Add $\sim$ 270 SNe-Ia

JLA sample: 740 SNe (Betoule et al. 2014)

LPNHE PARIS

25/40

JLA constraints in a flat wCDM model



Planck + BAO

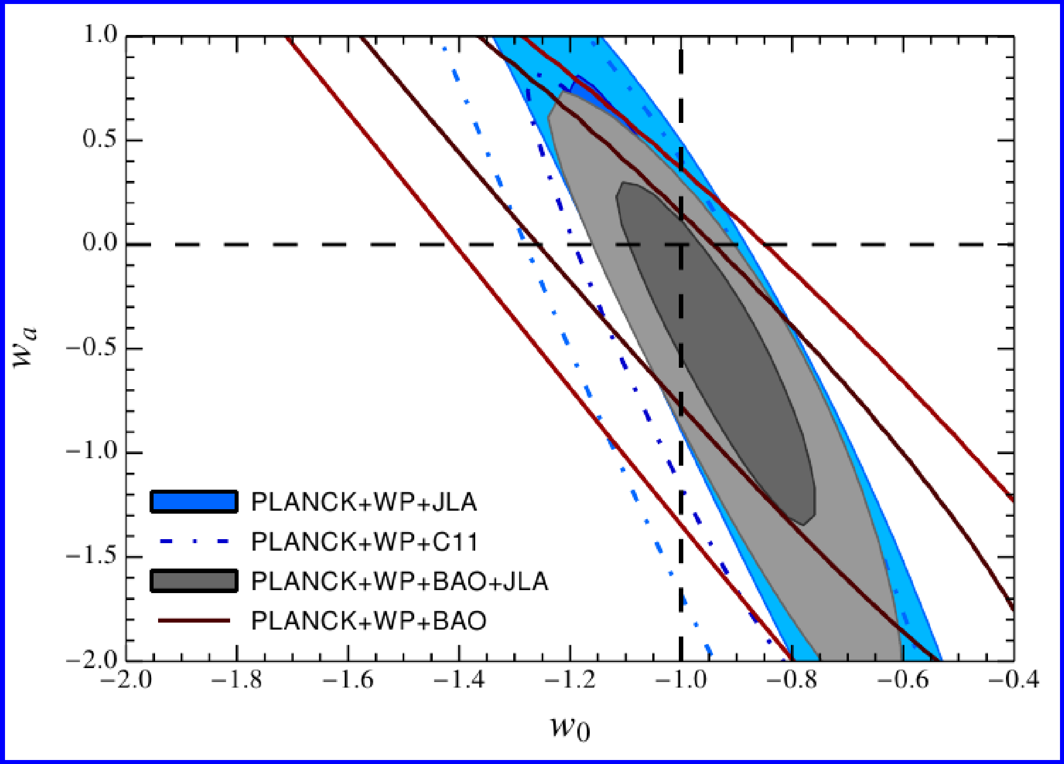
w = -1.01 ± 0.08

Planck + SNe

w = -1.018 ± 0.057

(Betoule et al, 2014)

Is Dark Energy the cosmological constant ?

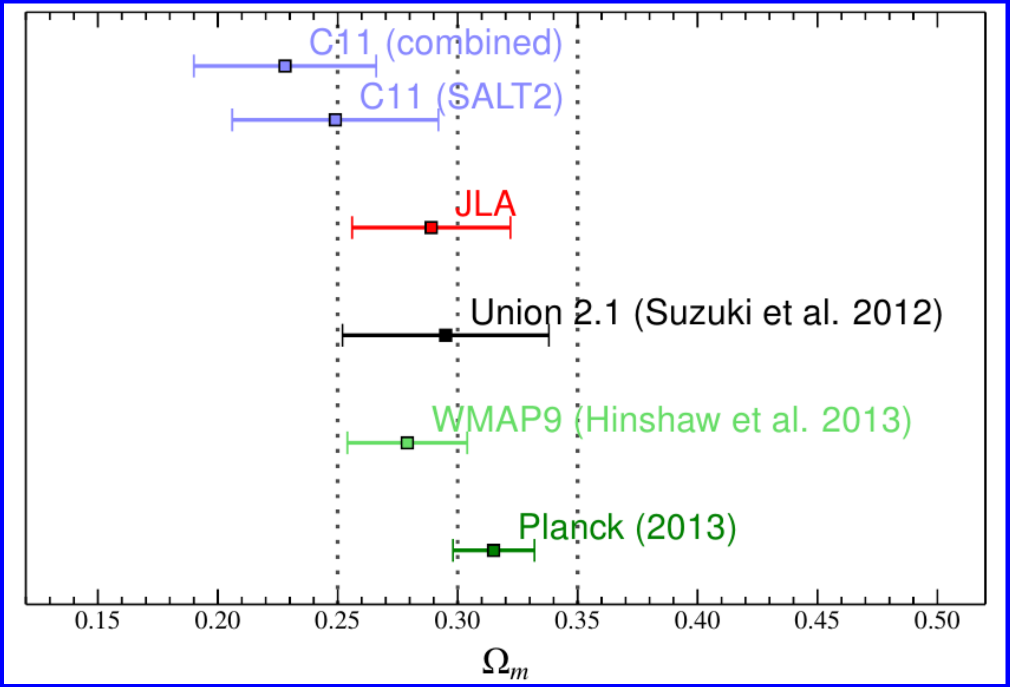


Ingredients

- Large SDSS dataset
- Calibration accuracy
- Better CMB + BAO

=> DETF FoM ~30

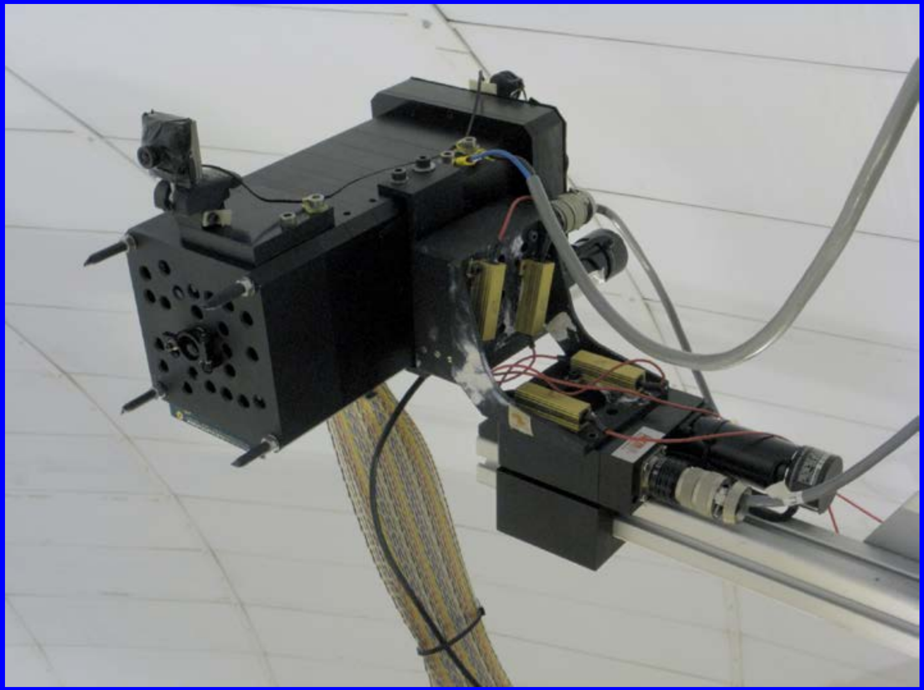
Ω_m in a Flat ΛCDM model



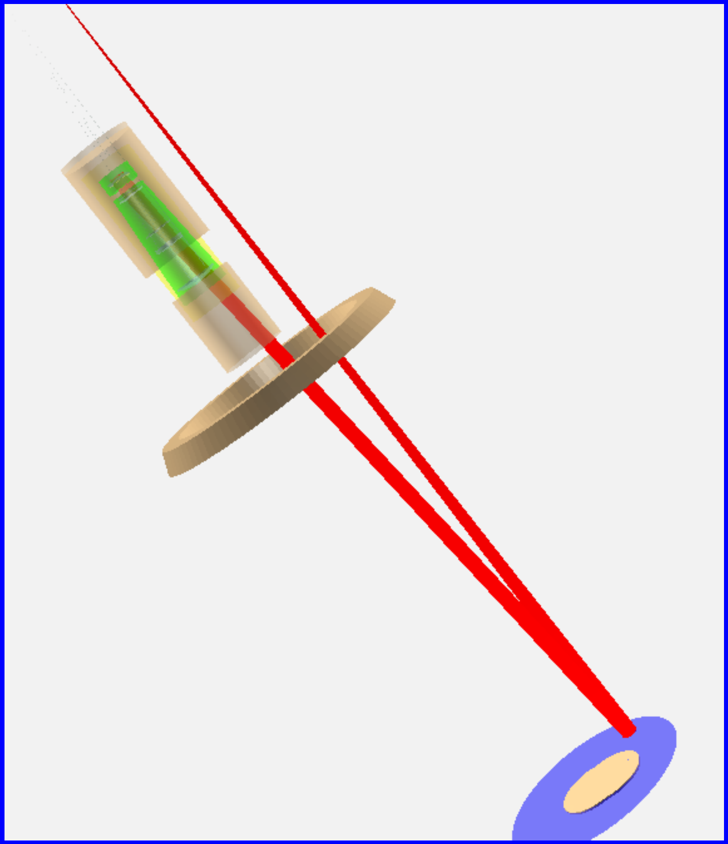
Ω_m measurement independent of CMB and compatible with Planck.

Ongoing and future SN programs

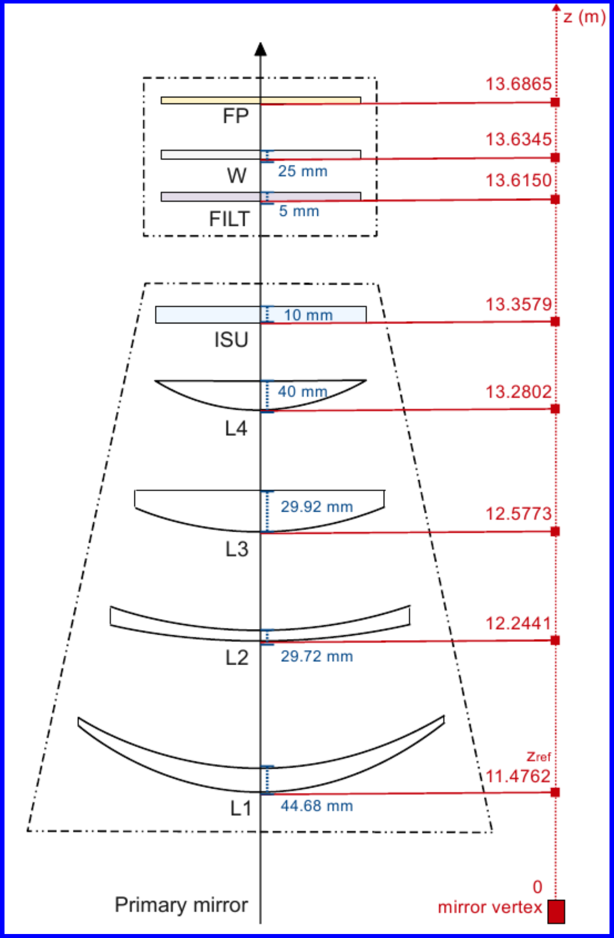
DICE: Direct Imaging Calibration Experiment

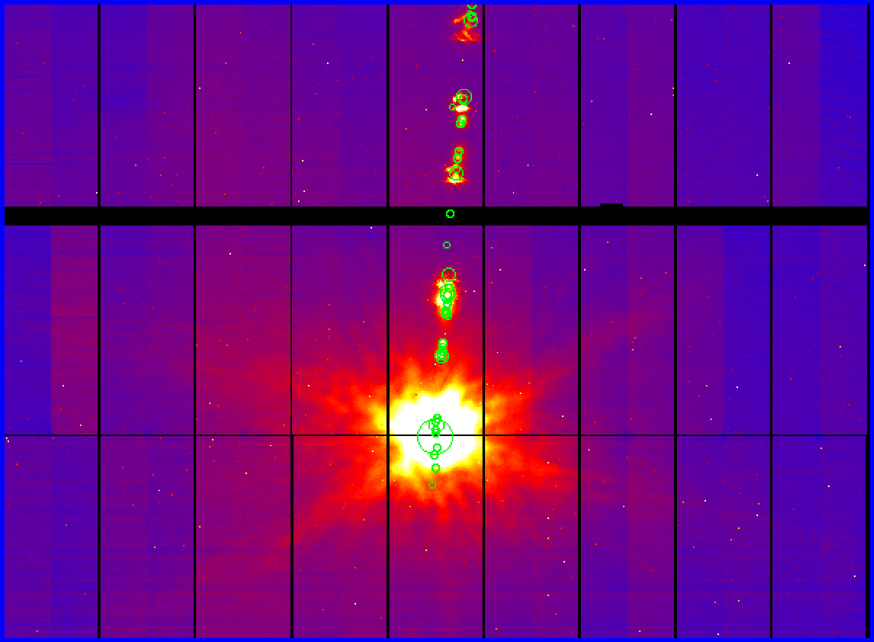


LED base light source for a direct illumination of the primary mirror



DICE : Model building and validation (alignment exposures)

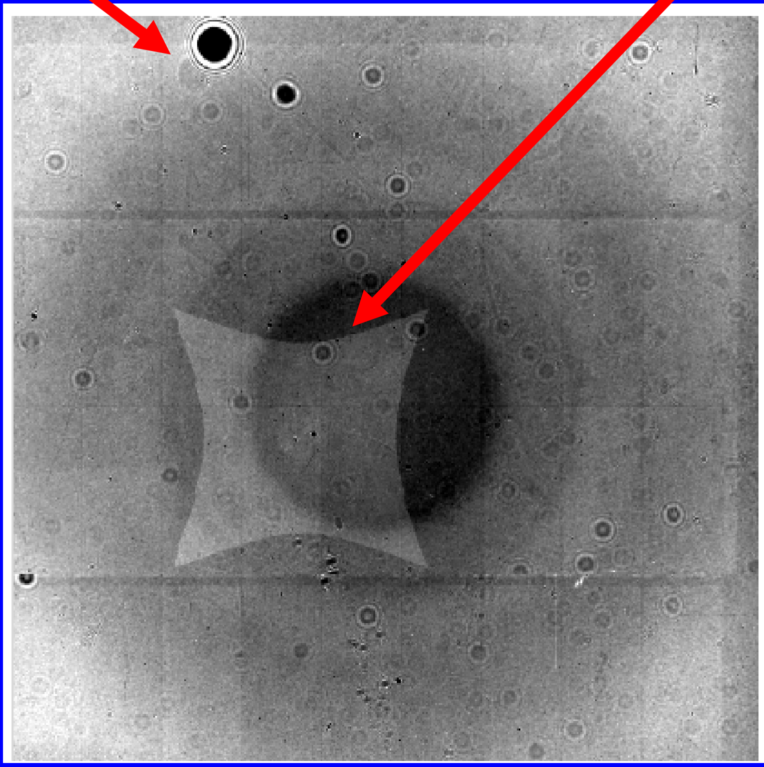




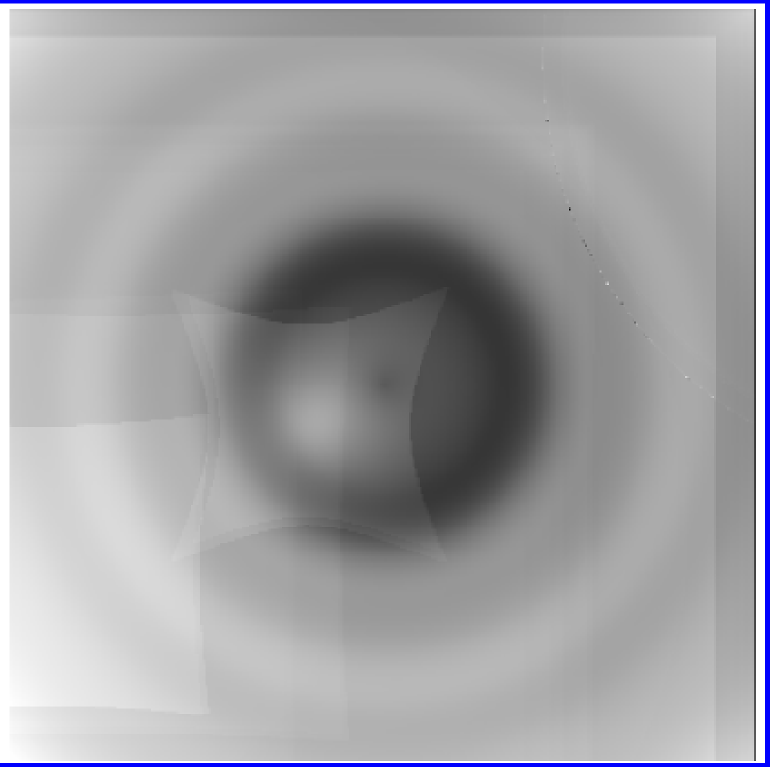
DICE : Use for calibration and photometry

Diffraction patterns
(dust + imperfections)

Ghosts



Observed r band LED image



Simulated Image (incl. ghosts)

Ongoing SN Ia Cosmology programs

Z<0.8 :

SNF (200 z~0.05 SN with multi-epoch spectrophotometry

PTF/LSQ : similar z, rolling trigger search+ follow-up

CSP : VIS follow-up + NIR follow-up

Pan Starrs/PS1 : target several 100 SNe up to z0.6

SNLS 5-yr : ~450 “specstrocopic” Ia + ~200 “photometric” Ia

z>1 :

HST measurement of o(10) SN to study specific issues (cluster selected SN, …) and constrain wa

Aim : robust combined statistic+systematic uncertainty on constant w and attempt at (precisely) measuring wa

New (starting) DETF « STAGE III » SN programs

Pan-starrs PS1+2 : 1.8m + 7 deg2, goal : o(1000) up to z=0.8
ZPTF (starts in 2015?) z~0.1

DES : CTIO 4m + new 3deg2 mosaic camera
2012-2018 (primarily weak lensing)
goal: 4000 SNe up to z=1

Skymapper : 1.35m MSSO (Australia)
2015-2019 Rolling nearby (z~0.1) - yield ~100 SN Ia /yr

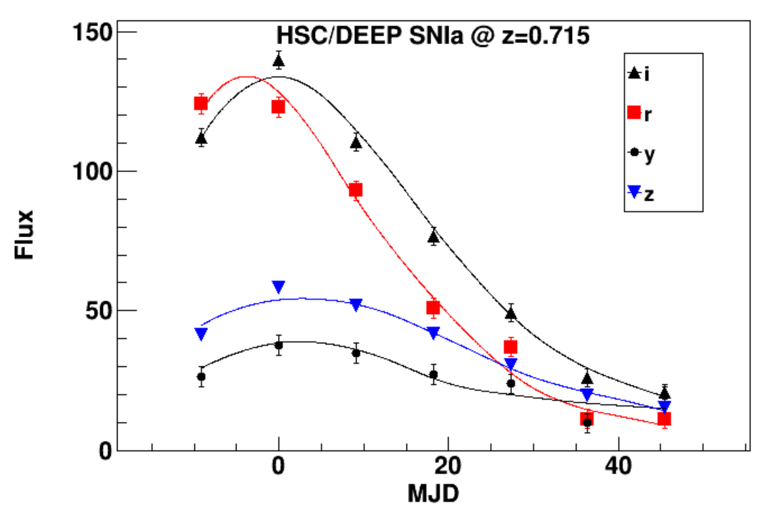
Z =0.8-1.3 :

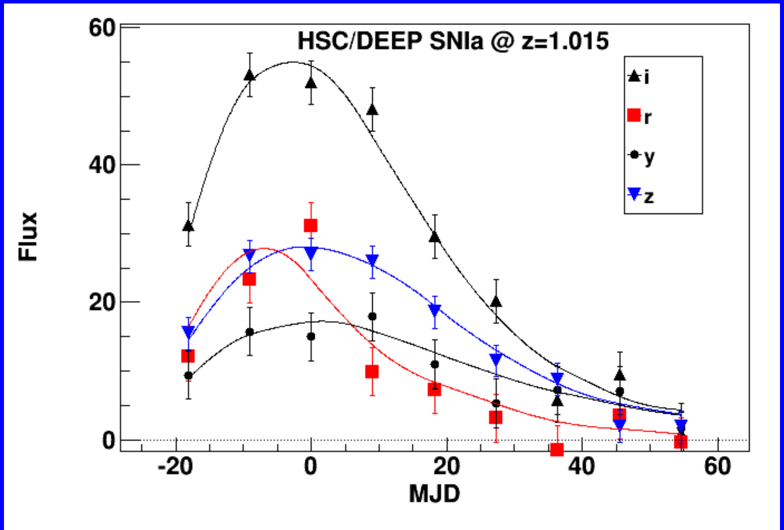
Subaru : 8.4m with HSC (1.5 deg FoV) : several 100 SNe per seasons
and up to z~1.6 when/if combined with HST

A SN Ia Rolling Search with Subaru

- 8-meters, 1.8 deg^2
- Excellent Image Quality
- red sensitive sensors → good distances to higher-z SNe

Ideal to measure SNe Ia at z = 0.8-1.3 and up





Next decade: DETF « Stage IV » ground based SN projects

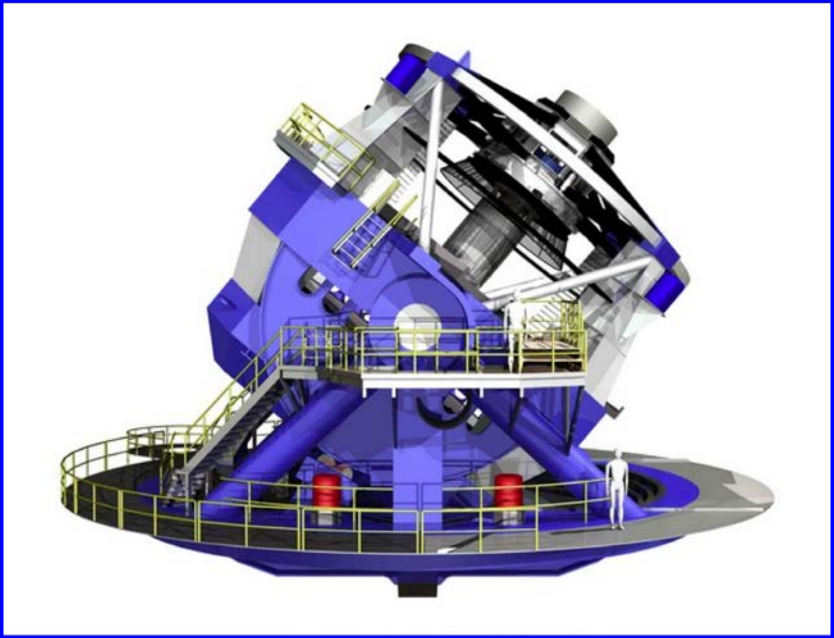
The Large Synoptic Survey Telescope (LSST)

8m telescope with 9 deg2 fov

First light expected in ~2020

Wide Deep and Fast

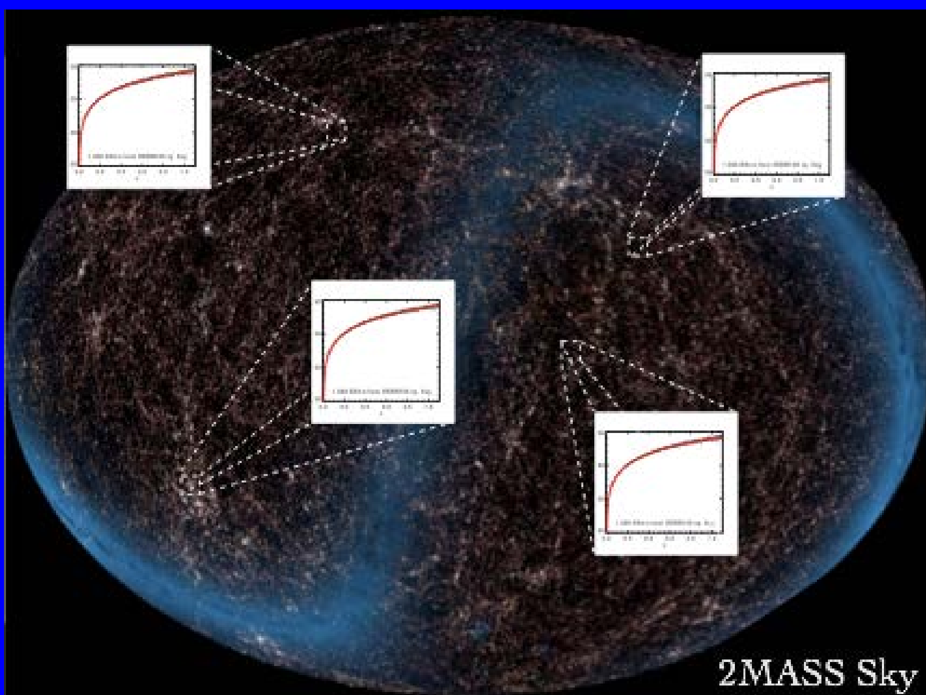
=> will yield 250000 SN/yr !



Low AND high-z SN from the same instrument …
Repeat imaging (calibration <0.5%) + « sky » calibration

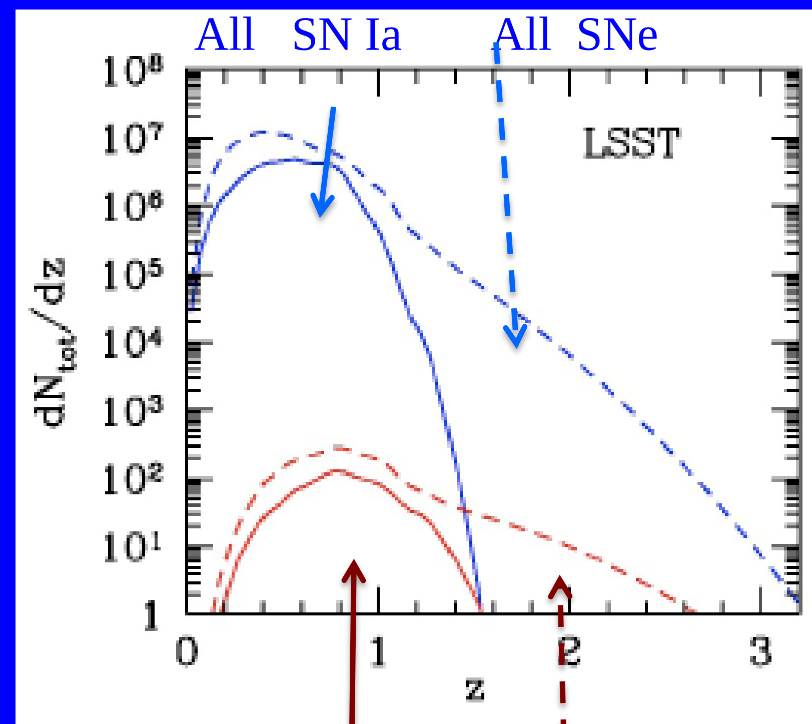
LSST : DE science with high statistics SN Ia

The large SN Ia statistic will allow to build SN Ia Hubble diagram for different directions in the sky.



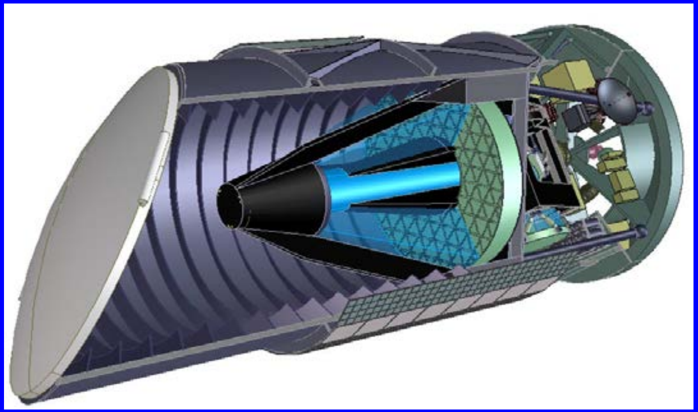
Will provide time-dependent imaging of an unprecedented sample of rare strong gravitational lensing events.

=> sensitive to H(z) at the lens location



Space based cosmology with SN Ia

Detect/follow distant SN Ia from Space



First proposed in 1999 (SNAP)
ϕ~2m telescope 0.6 deg. carrés -
Vis+NIR 0.4->1.7 μ
2000 SNe $0.2<z<1.7$ in 3 yrs

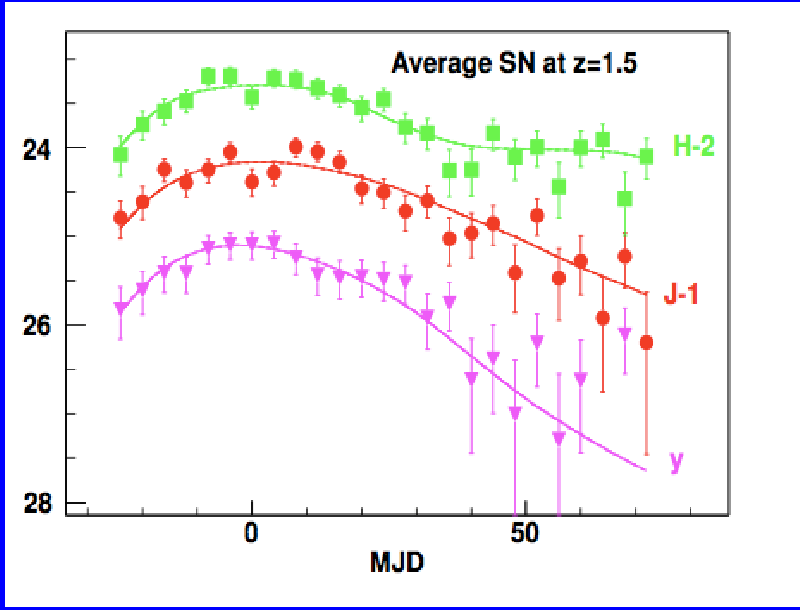
+ Several incarnations : DESTINY, JEDI, JDEM, DUNE(+), EUCLID,
… now WFIRST, most aiming at weak lensing and/or BAO

2011 study based on a modified EUCLID concept (+filter wheel)
All space SNe, no onboard spectroscopy
13000 SN up to z~1.5 with rest-frame NIR for a subsample
$\sigma(w_p)$ = 0.03 incl. systematics

A combined ground+EUCLID SN survey?

Euclid observation program :
20 deg2 → 40 pointings, 4-day cadence
visit : 1200(y) + 2100 (J) + 2100 (H)= 1.5 h

Over 6 months : 45 visits in total (2 mags deeper than one visit)



LSST deep drilling fields :
Current baseline : 4-day cadence
g:300 s, r:600s, i:600s, z : 780s, y4 : 600s

Total area ~ 4 fields over 10 seasons

Expected precision on w :
~2000 « well measured » SNe
Lightcurves in z=(0.7-1.5)
=> δw ~0.03 (foM = 80)

Combined with lowz : foM~300

Summary

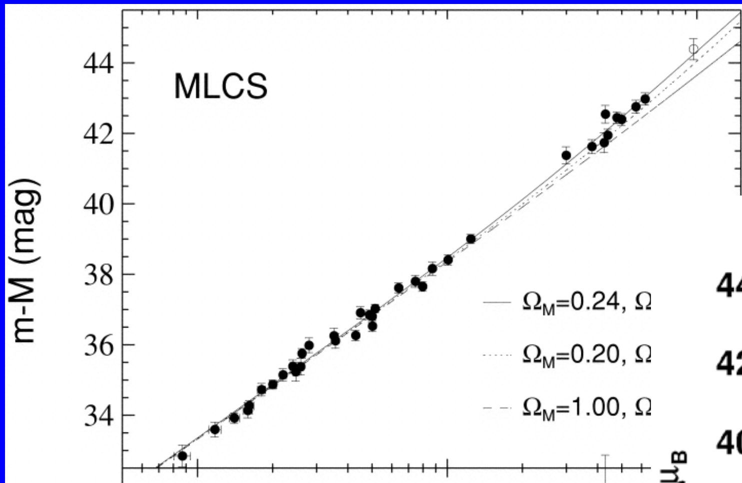
- SNe Ia distances combined with CMB and/or BAO remain the best probe to constraint the DE equation of state :
  - a 5% measure of a constant DE EoS, w, is achievable
  - currently little sensitivity to w(z)

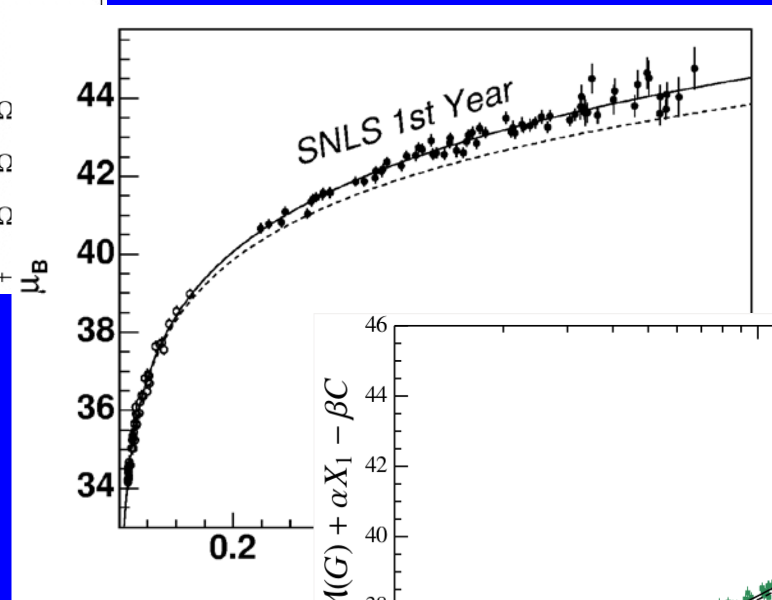
- Including systematics and combined with BAO and CMB : w (cte) = -1.018 ± 0.057 (~6%) compatible with a cosmological constant

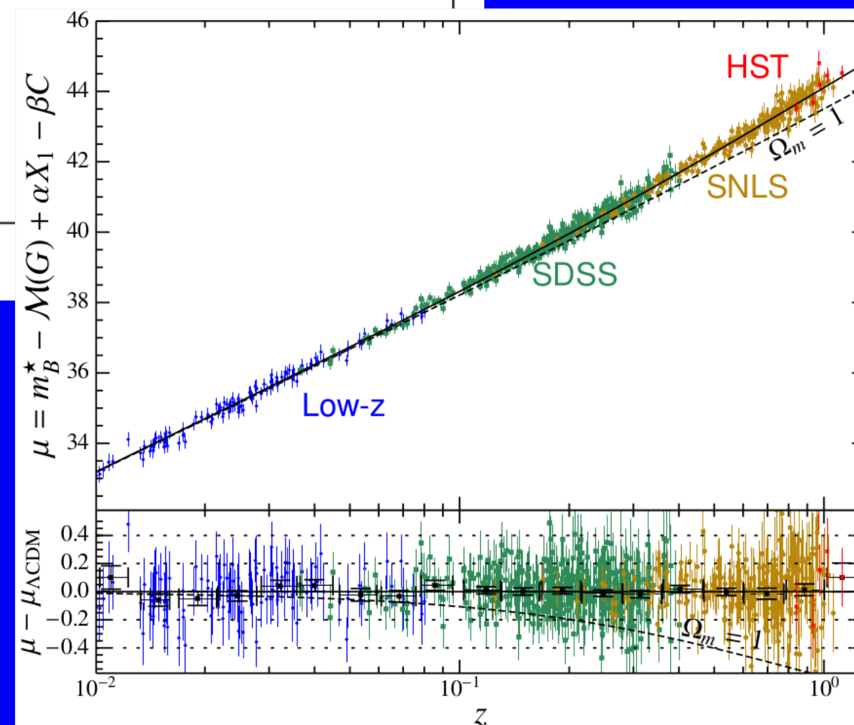
- Photometric calibration is (by far) the dominant (known) systematics today. Good prospects to improve precision in the near future

- Expect further improvements with upcoming SN programs at Subaru and future large scale projects.

SN Cosmology from 1998 to 2014







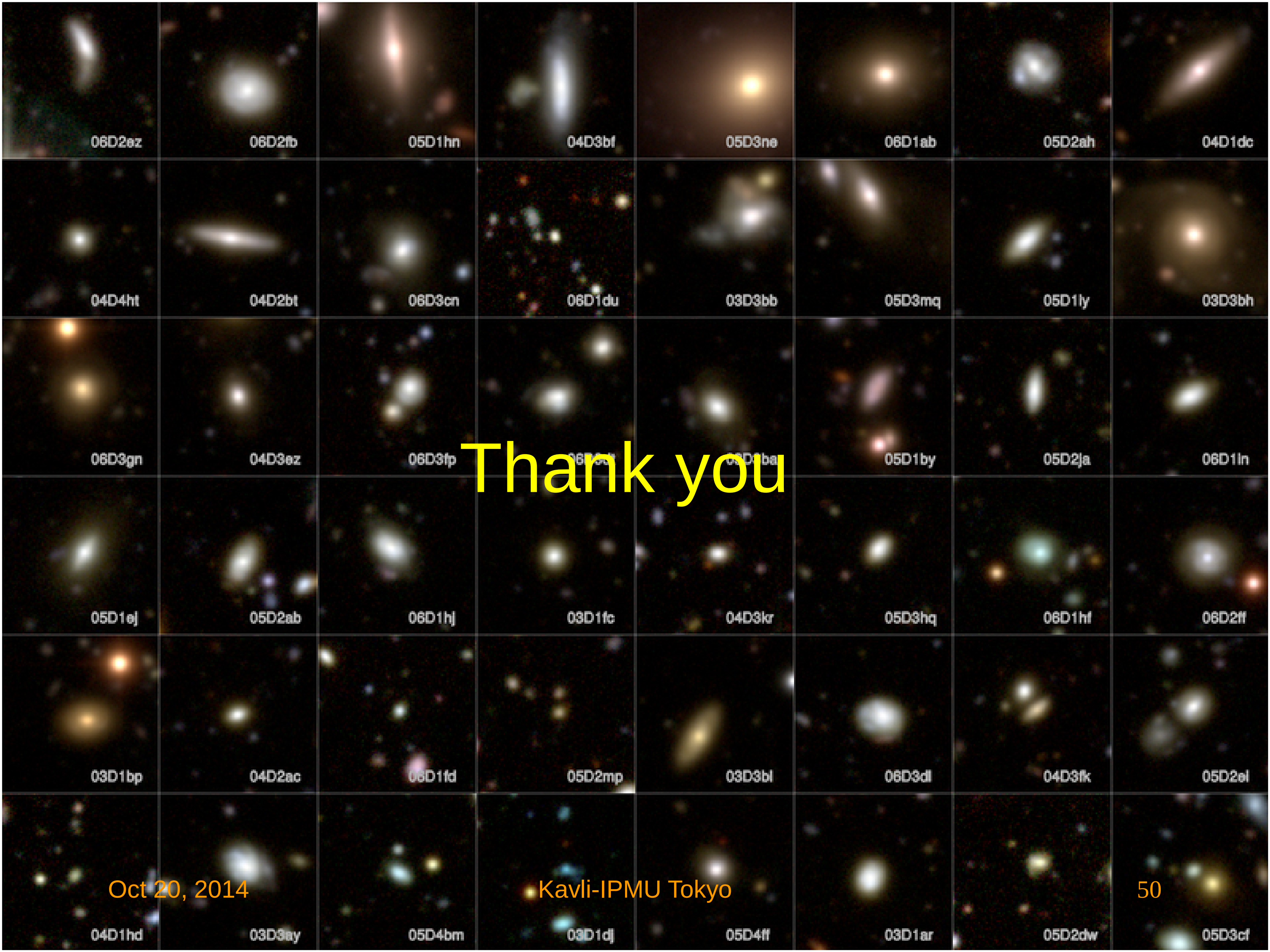
1998 : O(50) SNe

2006 : O(100) SNe

2014 : O(1000) SNe

A factor 20 increase in statistics

+ greatly reduced systematics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06D1du
03D3bb
05D3mq
05D1ly
03D3bh
06D3gn
04D3ez
06D3fp
05D1by
05D2ja
06D1ln
05D1ej
05D2ab
06D1hj
03D1fc
04D3kr
05D3hq
06D1hf
06D2ff
03D1bp
04D2ac
05D2mp
03D3bl
06D3dl
04D3fk
05D2el
04D1hd
03D3ay
05D4bm
03D1dj
05D4ff
03D1ar
05D2dw
05D3cf

Thank you