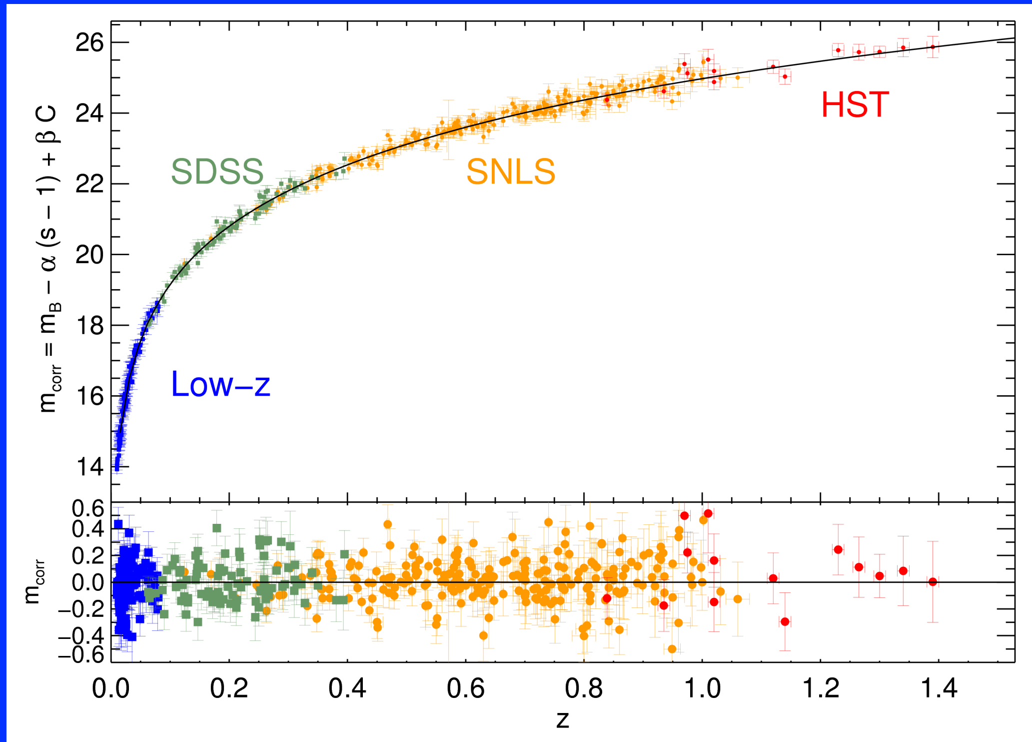
The Supernova Legacy Survey
in the Planck Era



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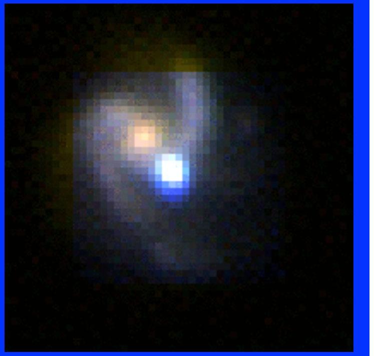
The Supernova Legacy Survey



- Using SN Ia to measure cosmology
- Latest SNLS cosmological constraints
- New SDSS-SNLS joint analysis
- Ongoing and future SN programs

Experimental Principle

2 observables :
flux: f
Redshift: z

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

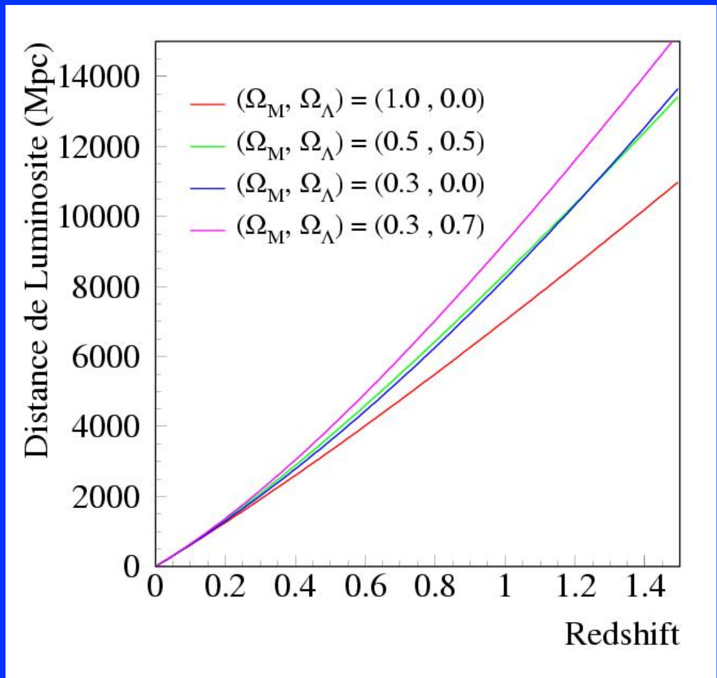
Use Supernovae as distance indicators to measure the Luminosity distance d_L

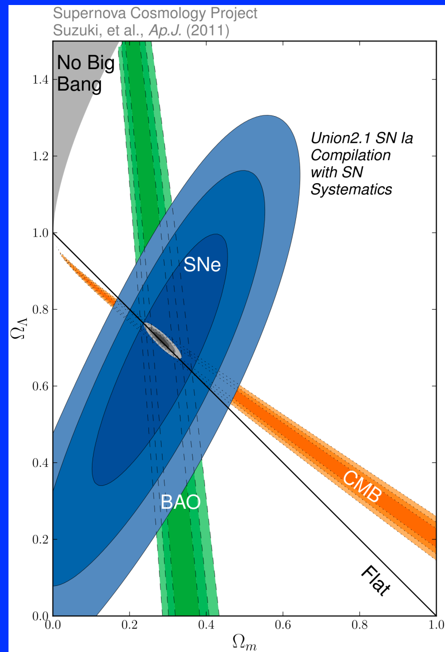
d_L is sensitive to the expansion rate and to the Energy content of the Universe

The Luminosity Distance

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

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



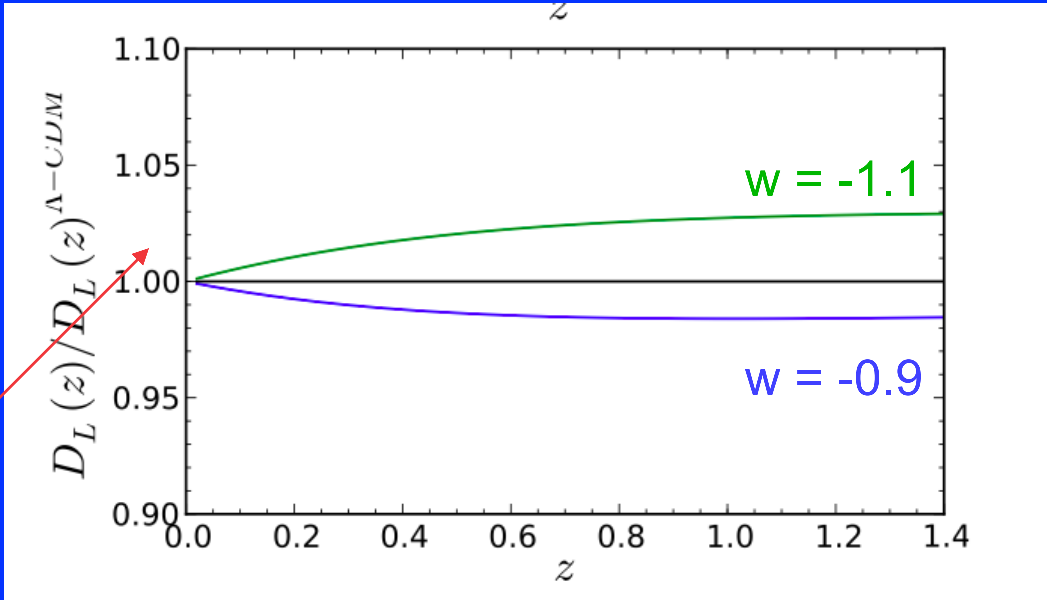


Union 2.1 sample (2012)

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

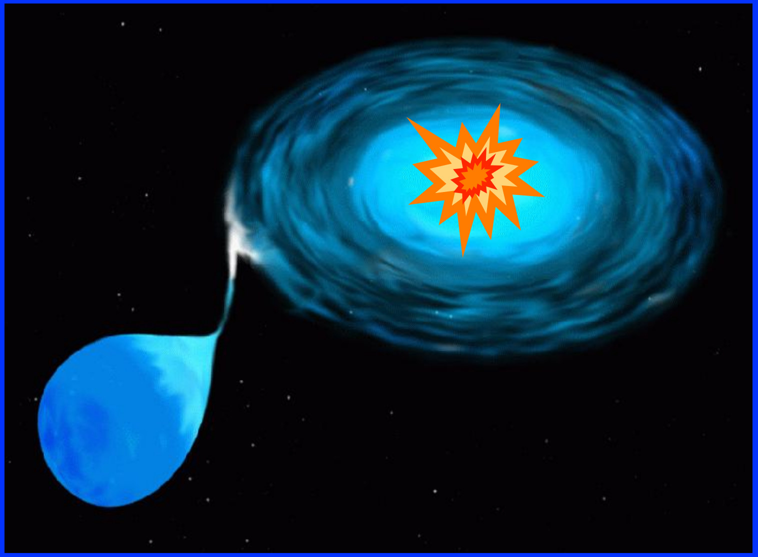
e.g. distance to NGC 4258 and propagate it to galaxies hosting SNe (using cepheids for example)

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

SNe Ia are NOT standard candles

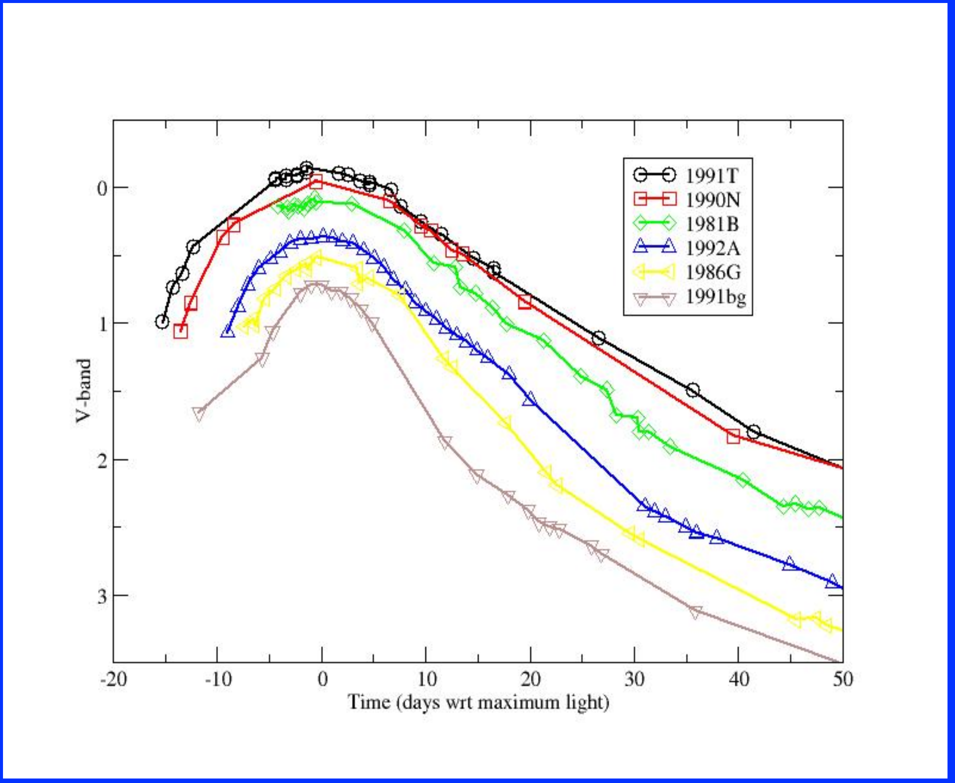
Very Luminous events

⇒ visible at cosmological distances



Show little luminosity dispersion

Supernovae Ia light curves

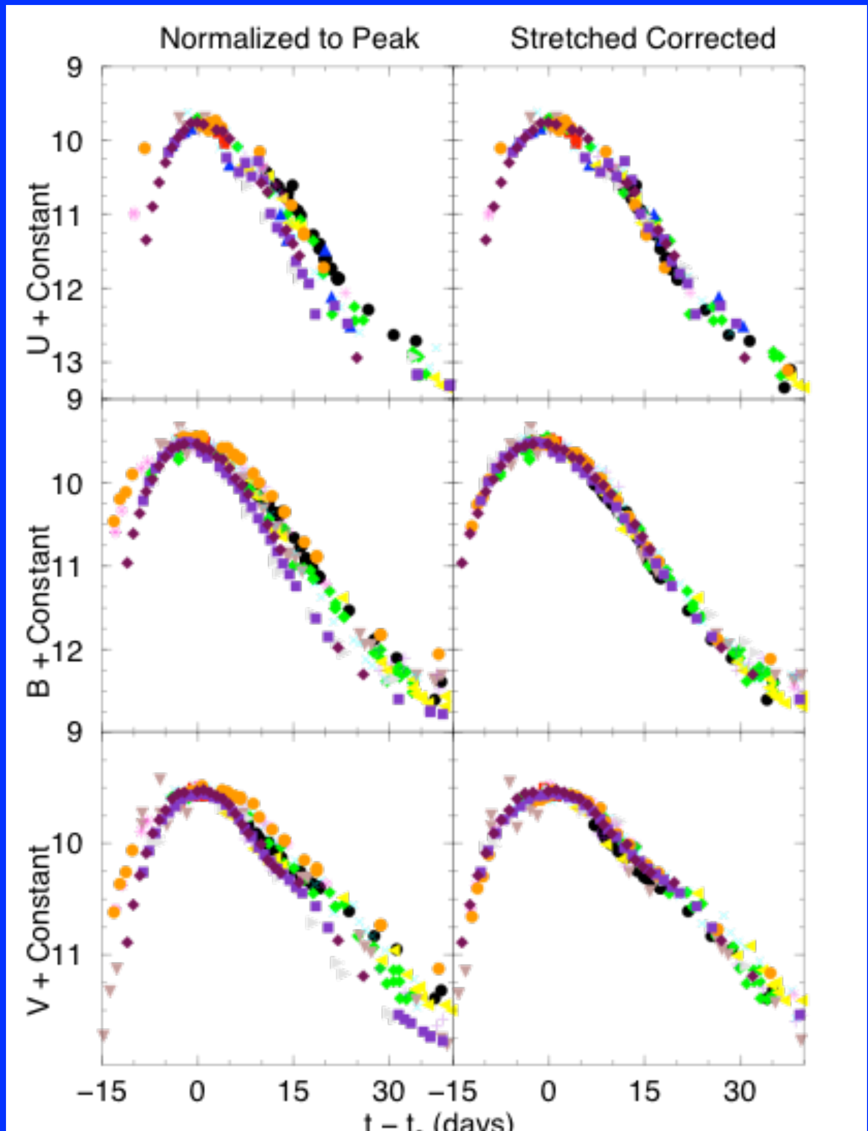


(inter)-calibrating Supernovae Ia

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



Cosmology with SNe Ia

An empirical approach

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

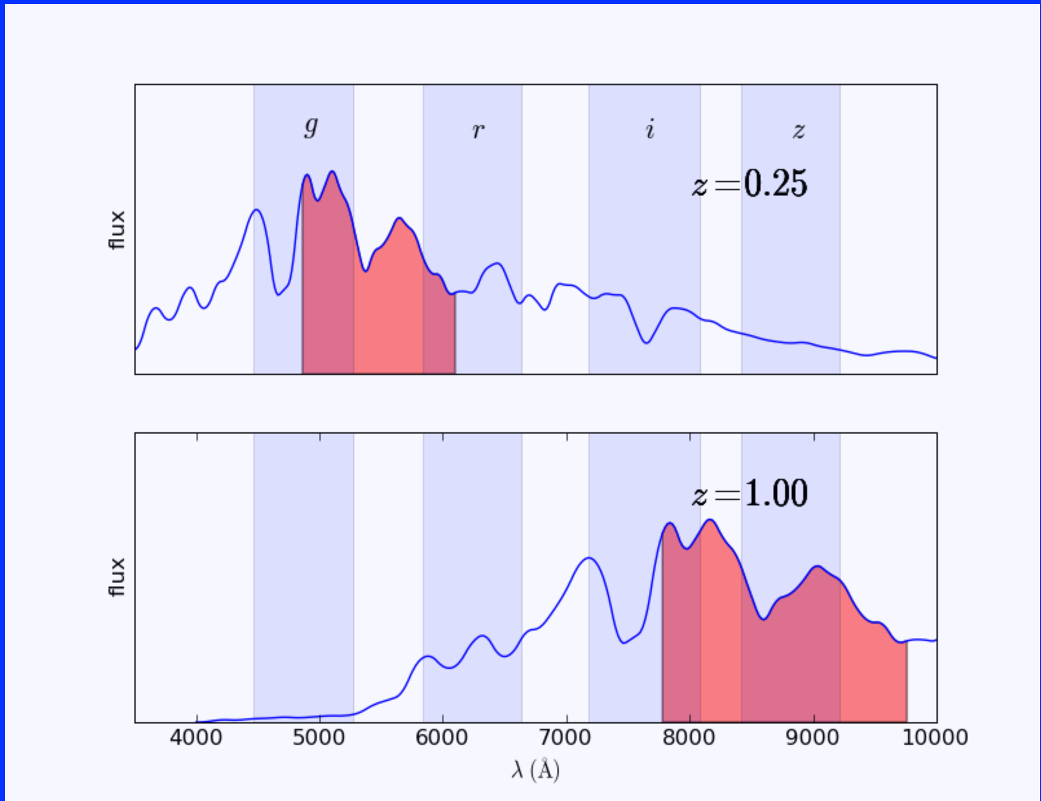
Absolute magnitude at maximum

Light curve shape correction

Resframe apparent magnitude at maximum

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

Extracting mb, s and c from observations



SN restframe fluxes at different redshifts

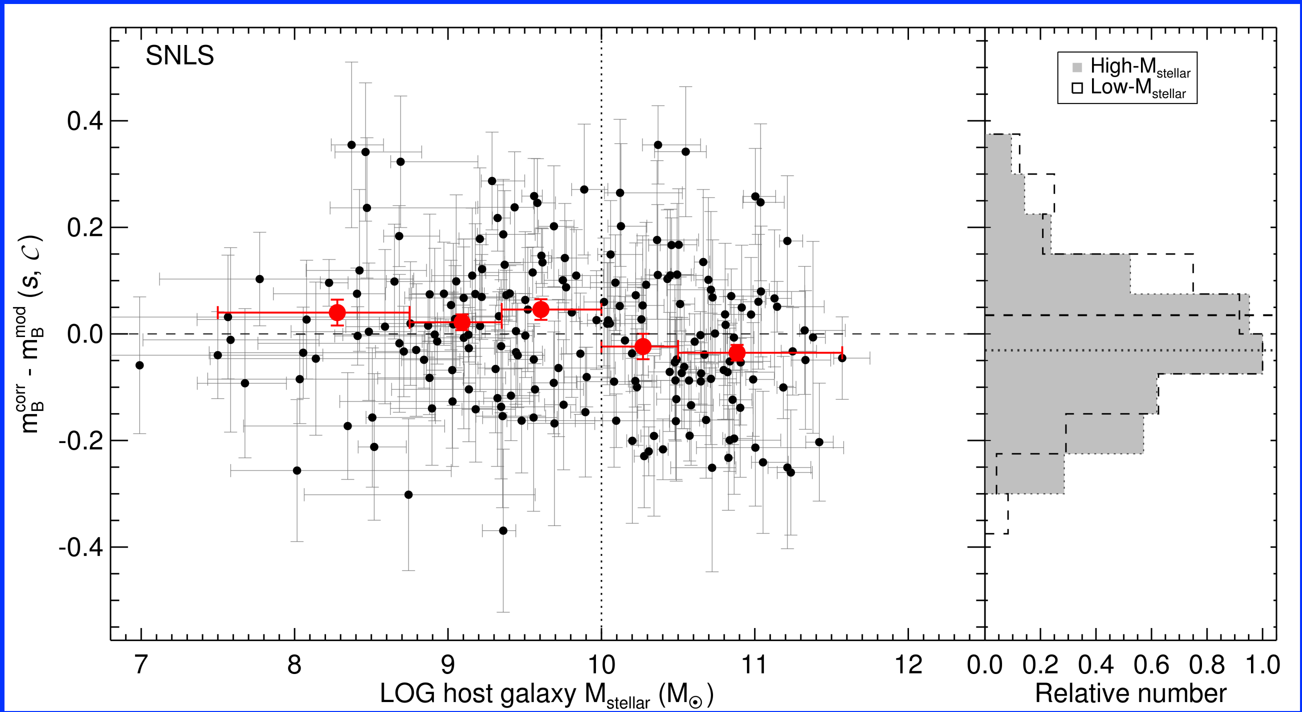
→ empirical model to interpolate between photometric measurements

→ 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), ...

Hubble residuals versus host mass

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

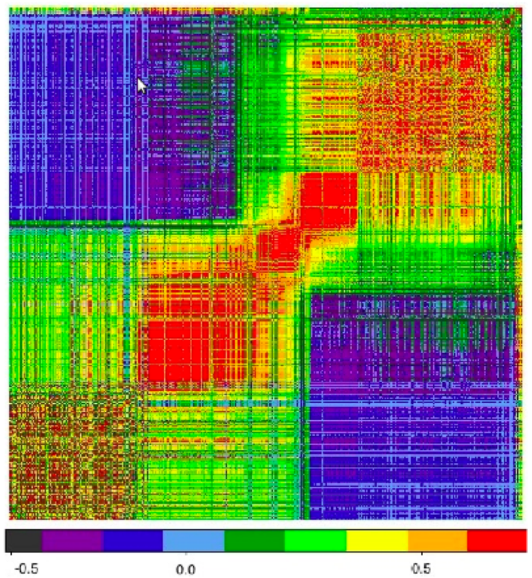


Subtle effect – 0.08mag – smaller than stretch and color corrections

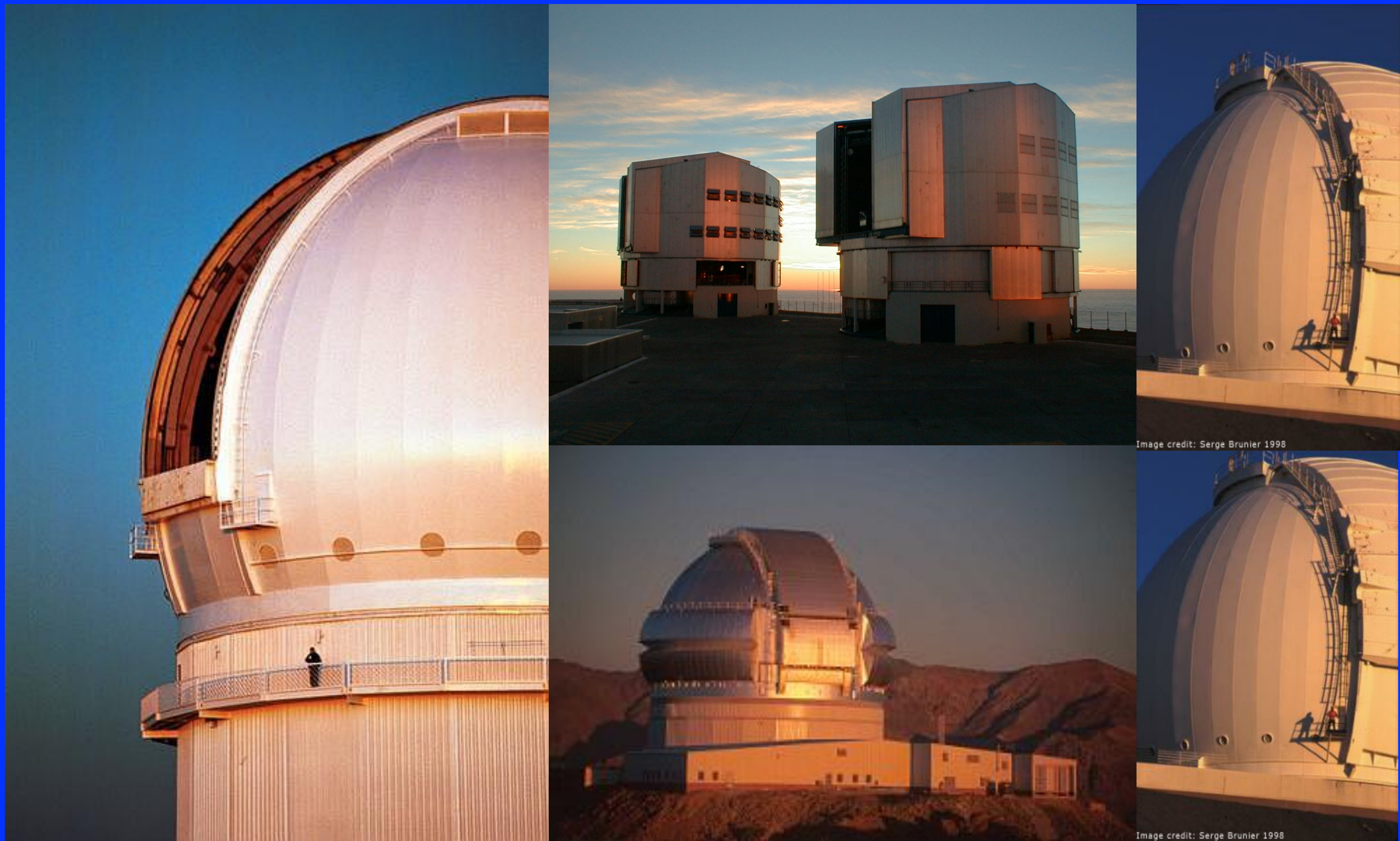
Other potential systematics

- 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) $C_{sys,ij} = \sum_k \frac{\partial \mu_i}{\partial S_k} \frac{\partial \mu_j}{\partial S_k} (\Delta S_k)^2$



SNLS -The SuperNova Legacy Survey



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

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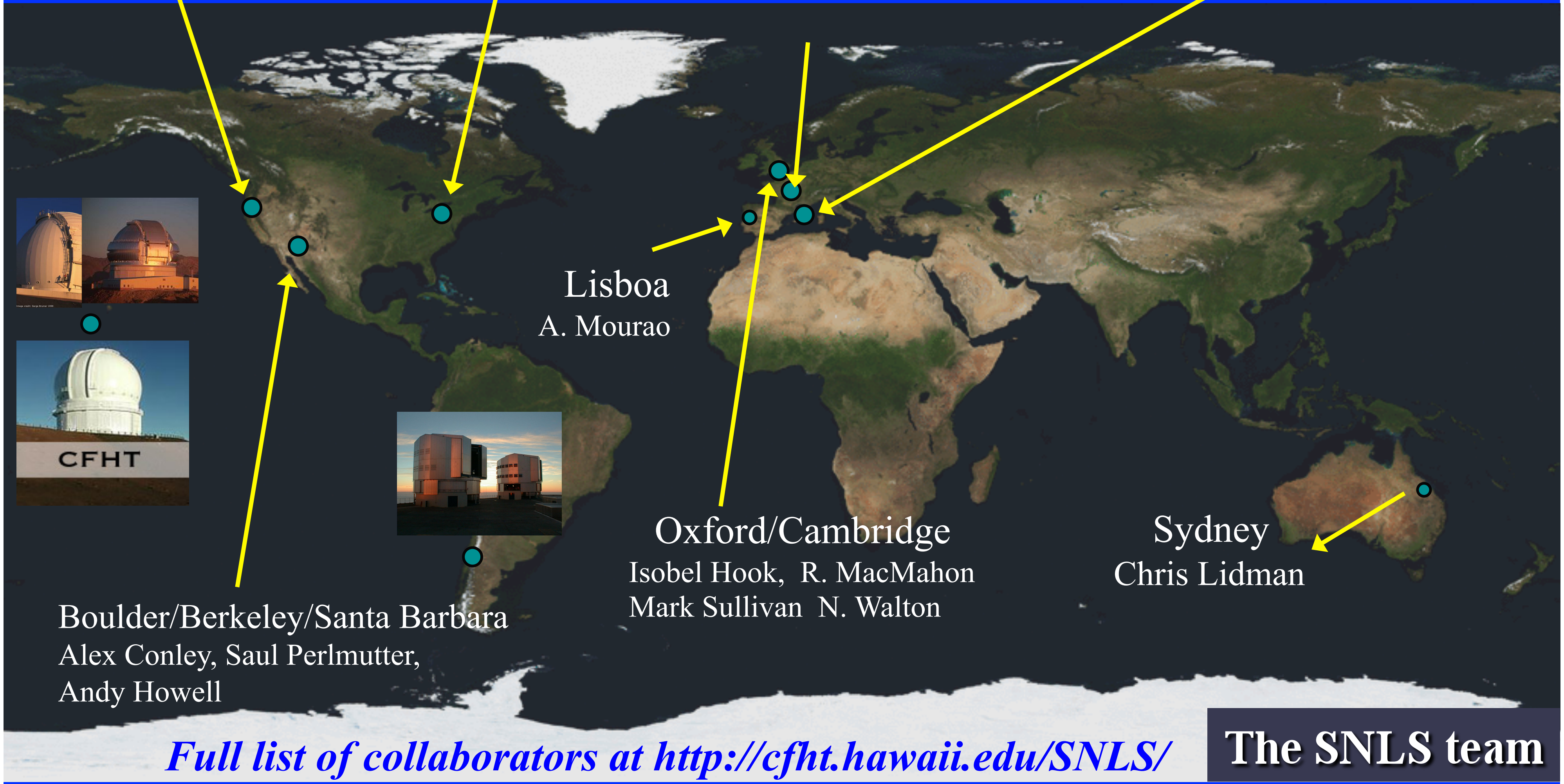
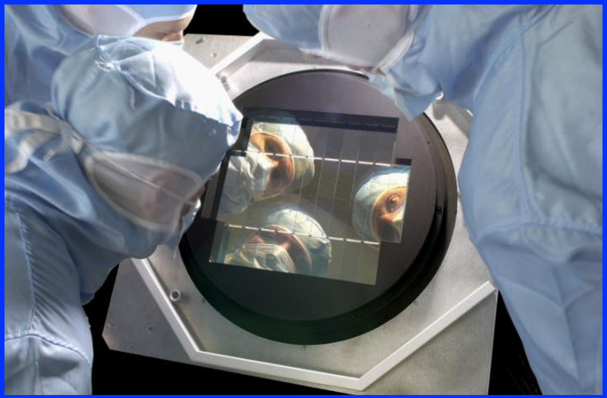
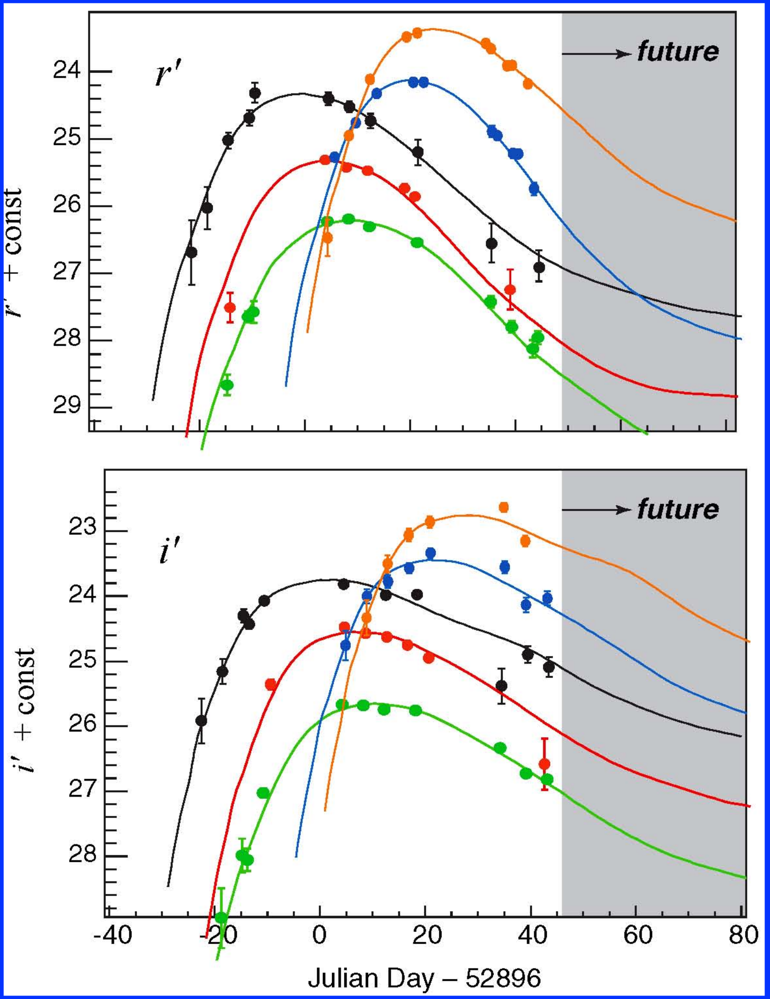


SNLS : a "Rolling Search" survey with MegaCam



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)

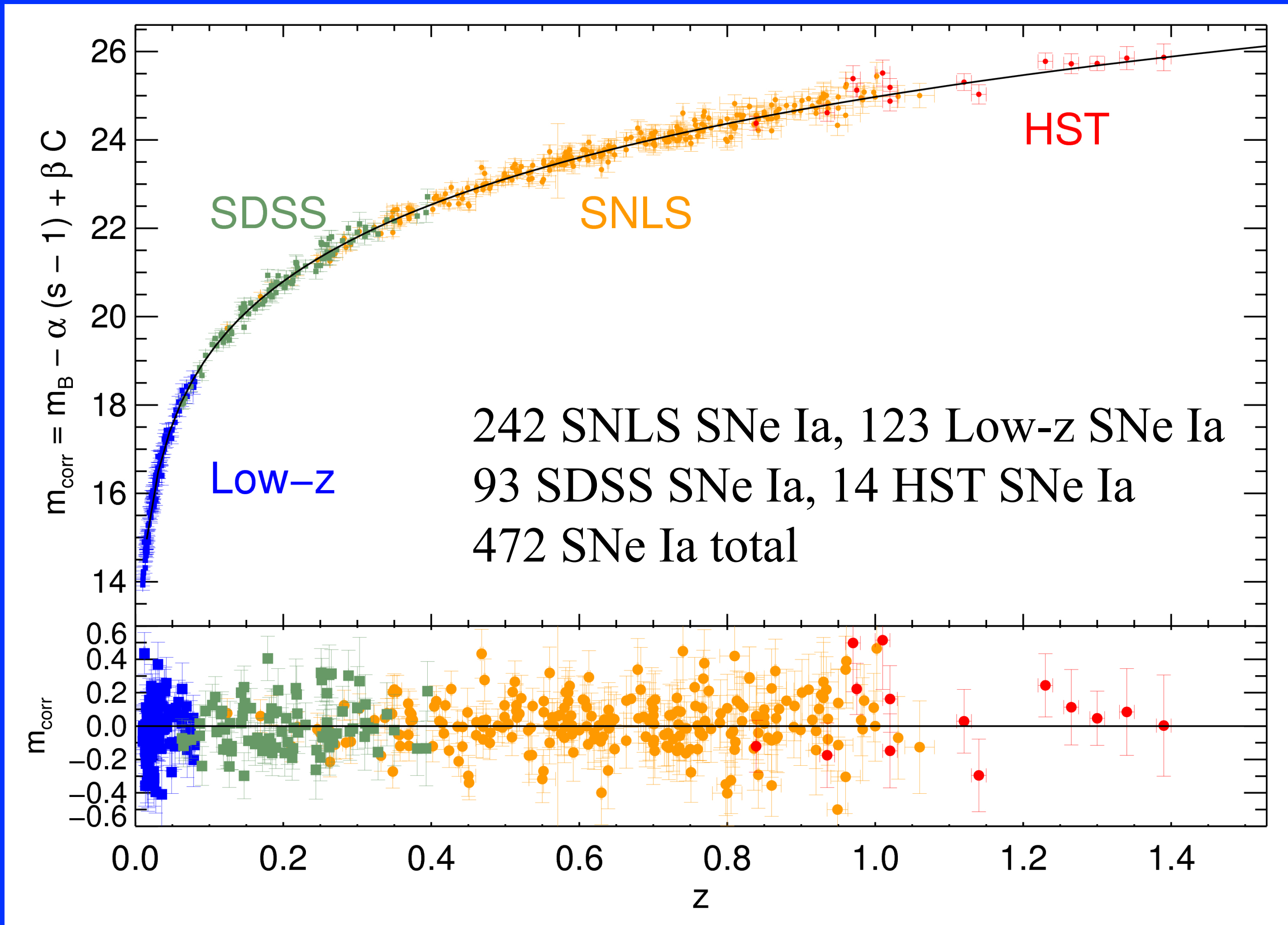
=> ~500 SN Ia identified
(+ ~300 « photometric »)
observed between 2003 and 2008



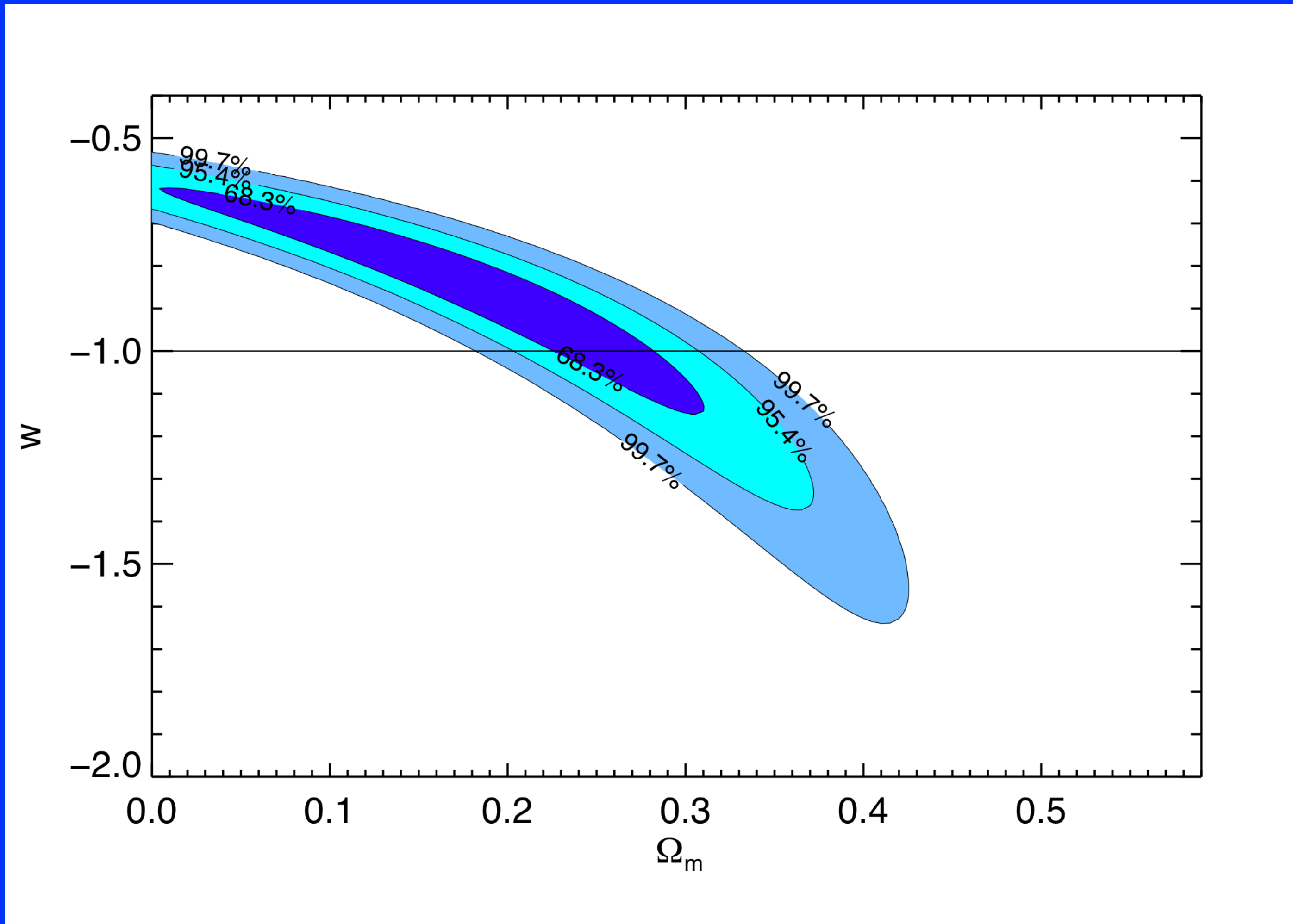
SNLS 3-yr analysis and combined constraints

- ~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

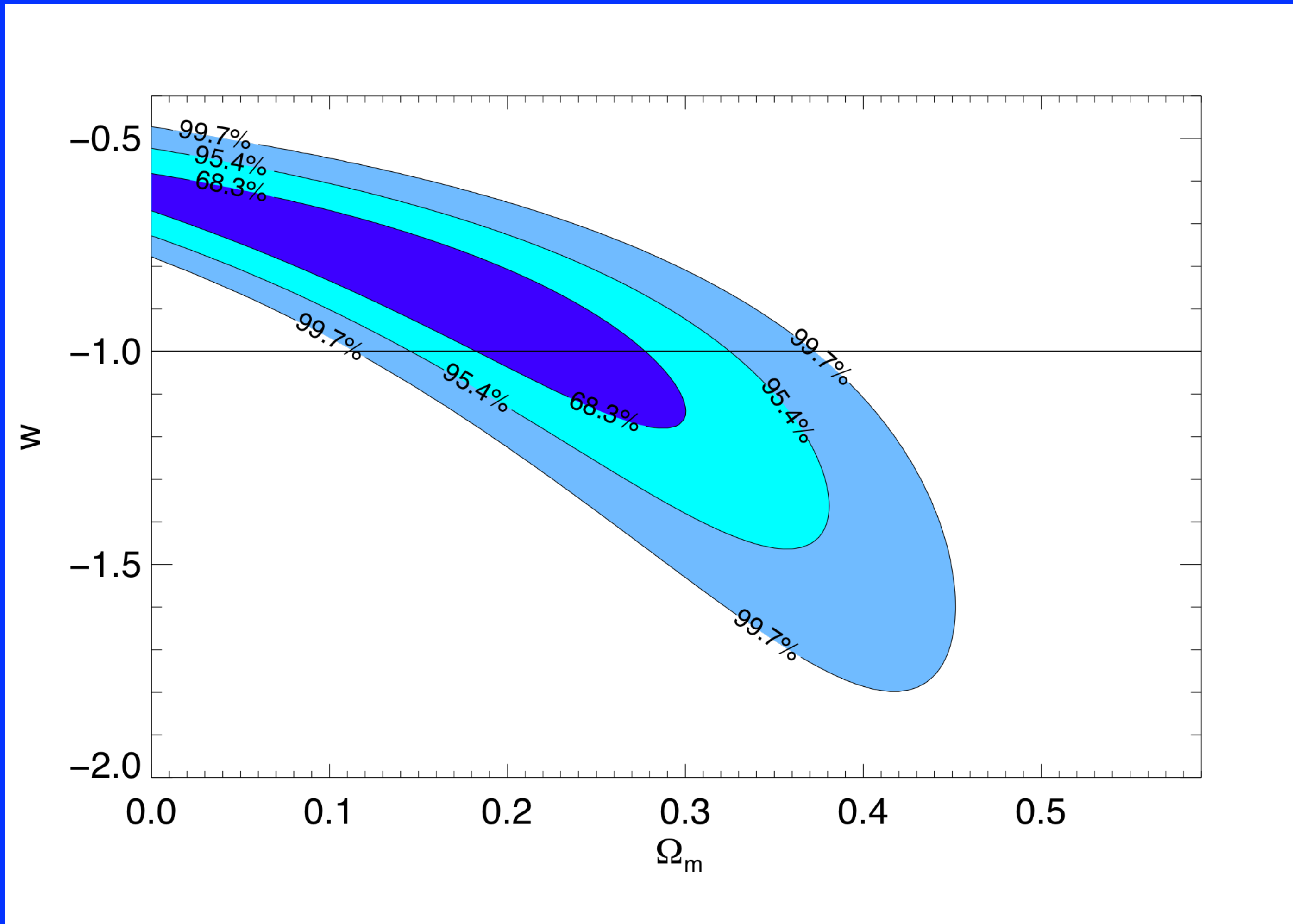
Combined SN Hubble diagram



SN only constraints on w



SN only constraints on w

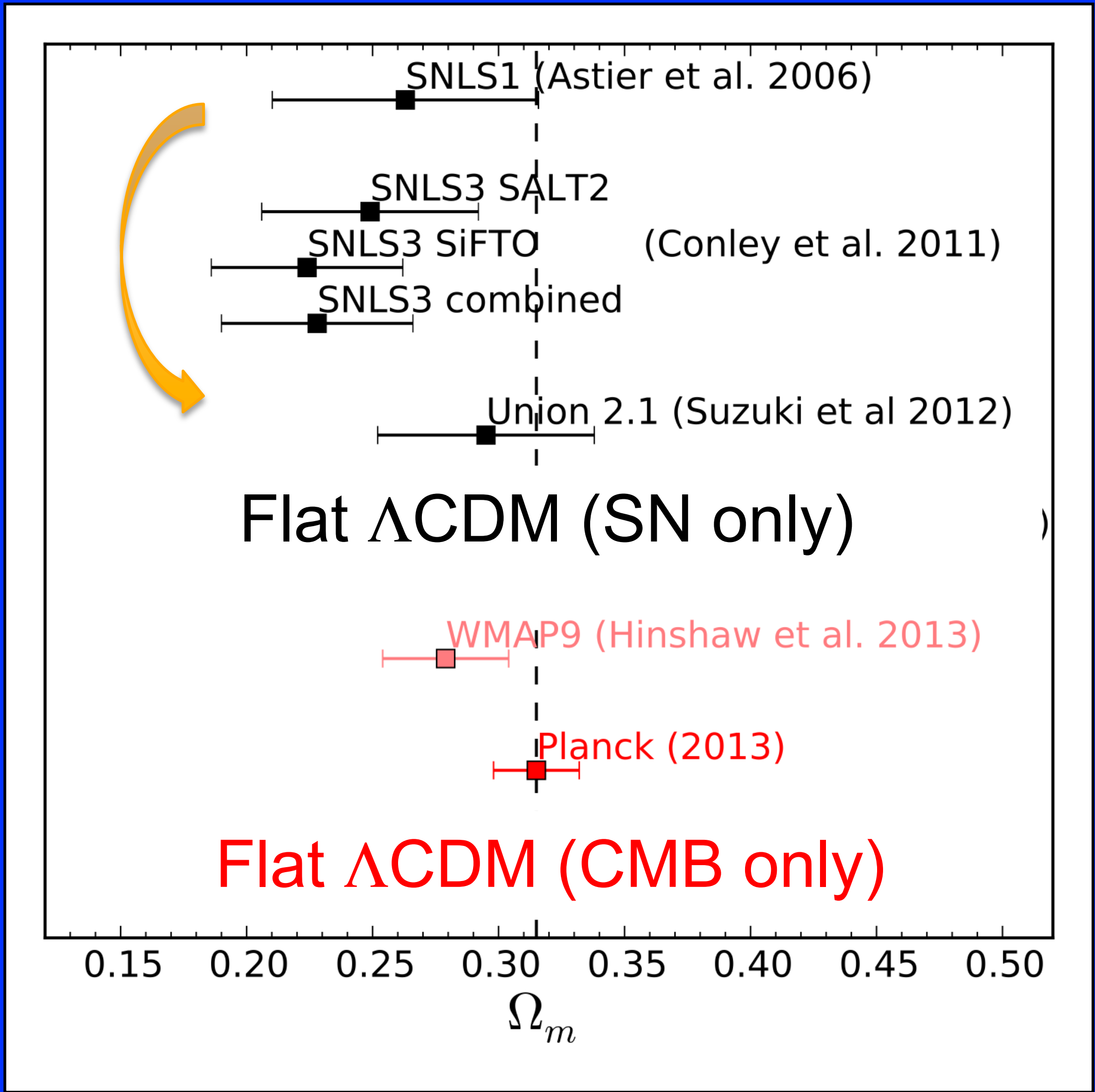


$$w = -0.91^{+0.15}_{-0.21}\,(\text{stat})\,^{+0.07}_{-0.14}\,(\text{syst})$$

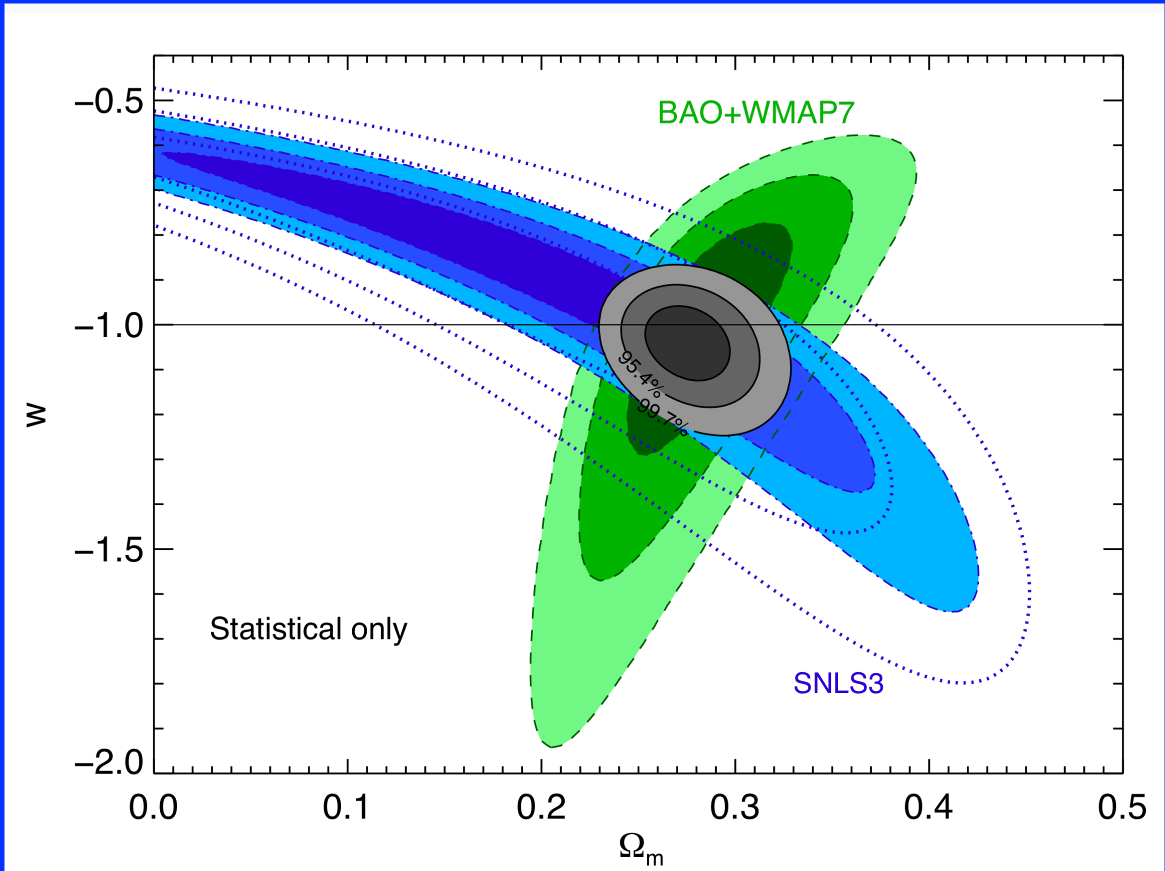
Which systematics are the most important (SN only) ?

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

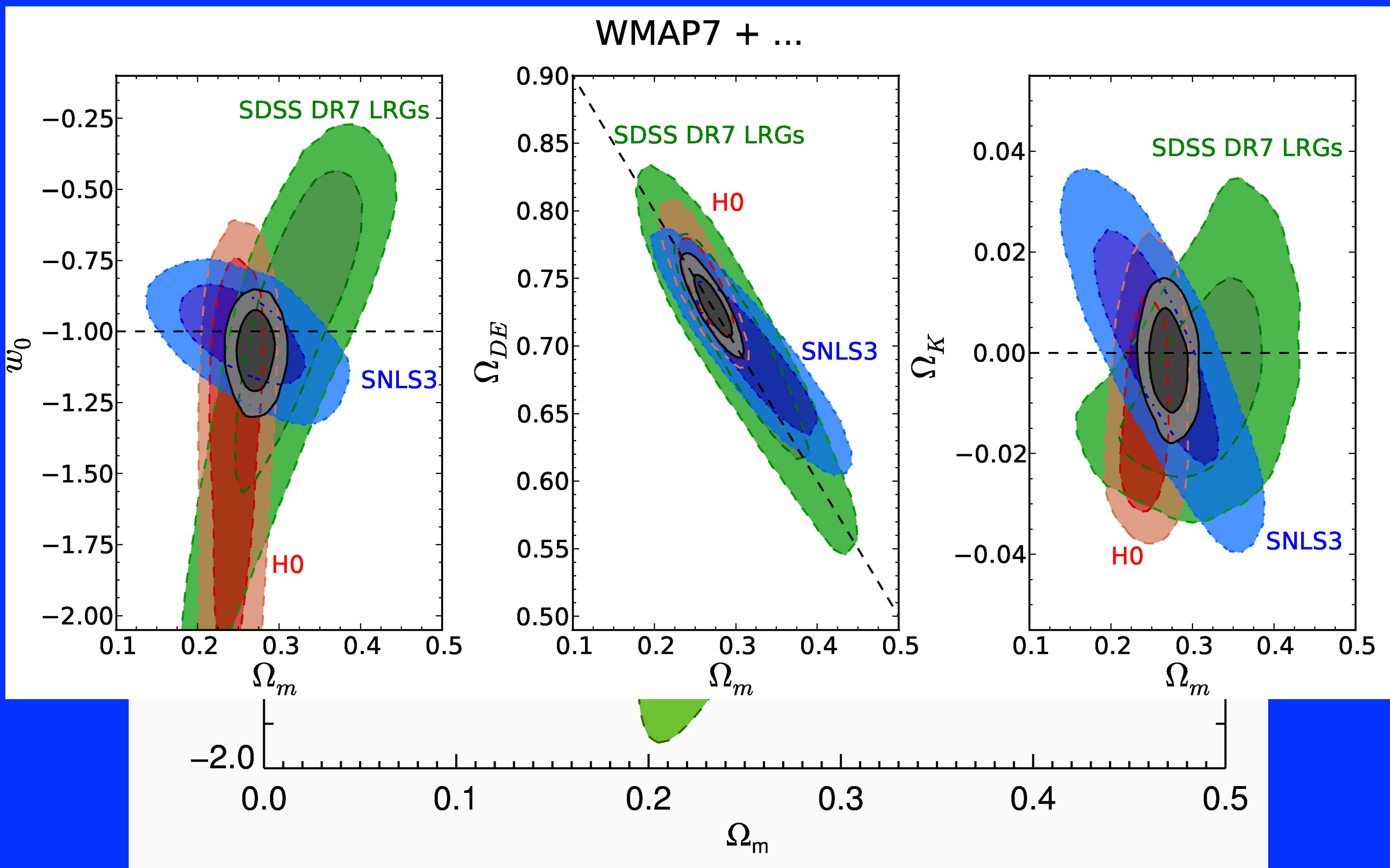
Comparison with Planck results



SNLS (stat. only) +WMAP7+BAO/DR7+H_0



SNLS+WMAP7+BAO/DR7+H_0



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:

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

Consistent with cosmological constant

Error in w: **<5% (stat)** w/ flatness, **~7% w/ systematics**

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

In terms of w, adding BAO/DR7 reduces w error from 11% to 9%

Preliminary constraints from the SNLS-SDSS joint analysis

SNLS-SDSS joint Analysis

Joint SDSS-SNLS analysis

SNLS data sample

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

for which we are acquiring host spectra (VLT, .. AAT)

SDSS data sample

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

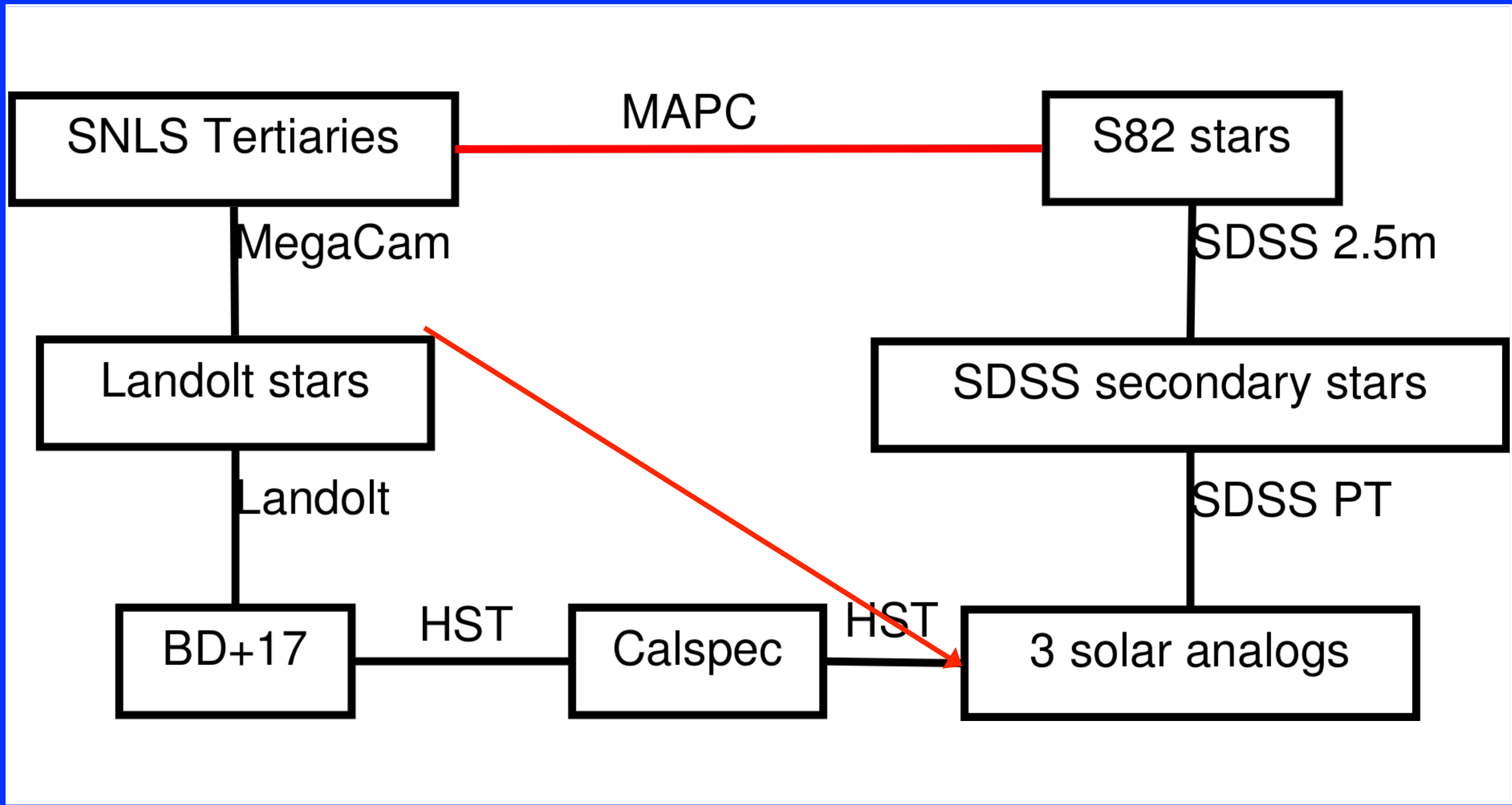
Joint SDSS-SNLS analysis goals:

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

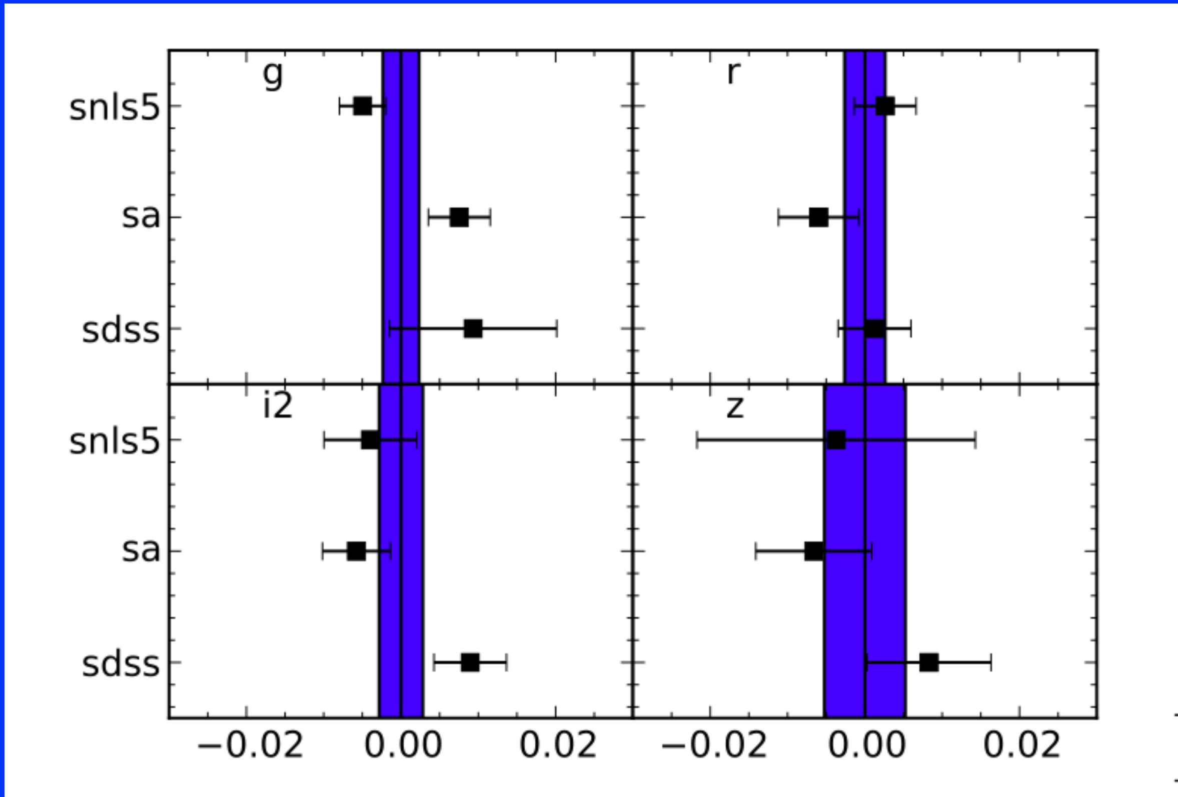
– Validate LC fitter and joint LC training

-> update cosmological constraint combining SNLS3+SDSS

SNLS-SDSS cross-calibration



SNLS-SDSS cross-calibration



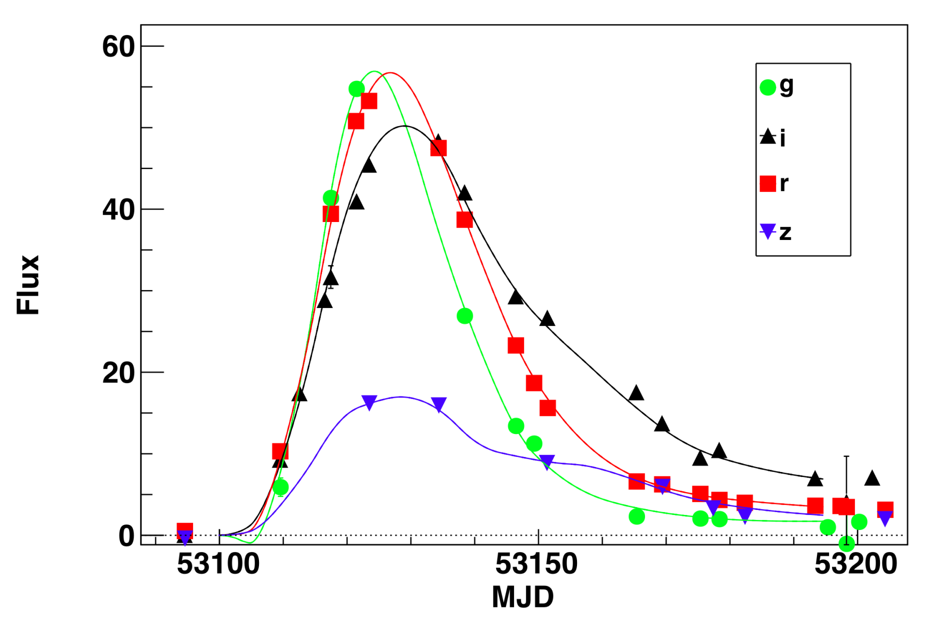
Betoule et al. (2013)

Combined precision of ~ 0.5% in the 4 bands

band	combined uncertainties
g	0.002
r	0.003
i2	0.003
z	0.006

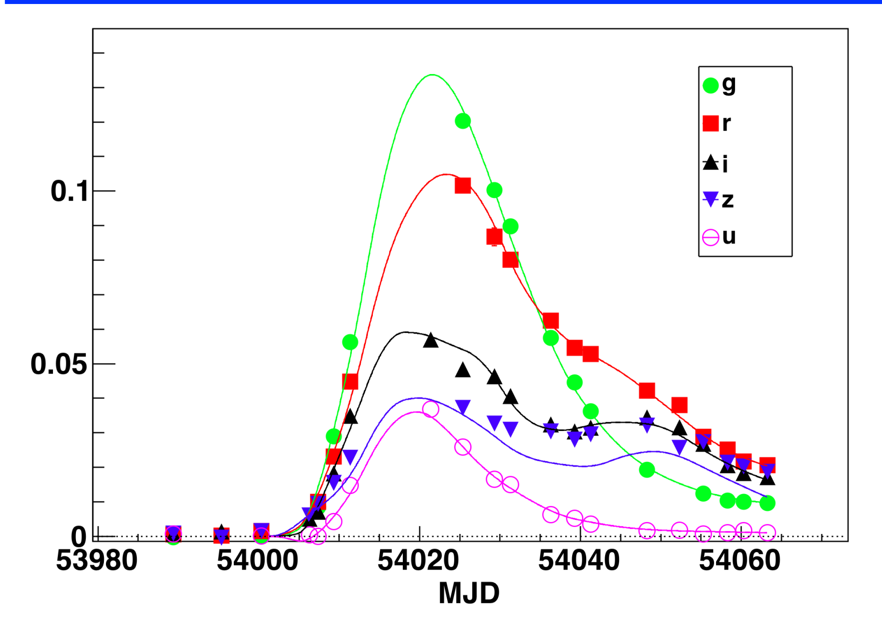
Overall uncertainty now dominated by the uncertainty in the flux reference

SDSS/SNLS Joint Light Curves Analysis

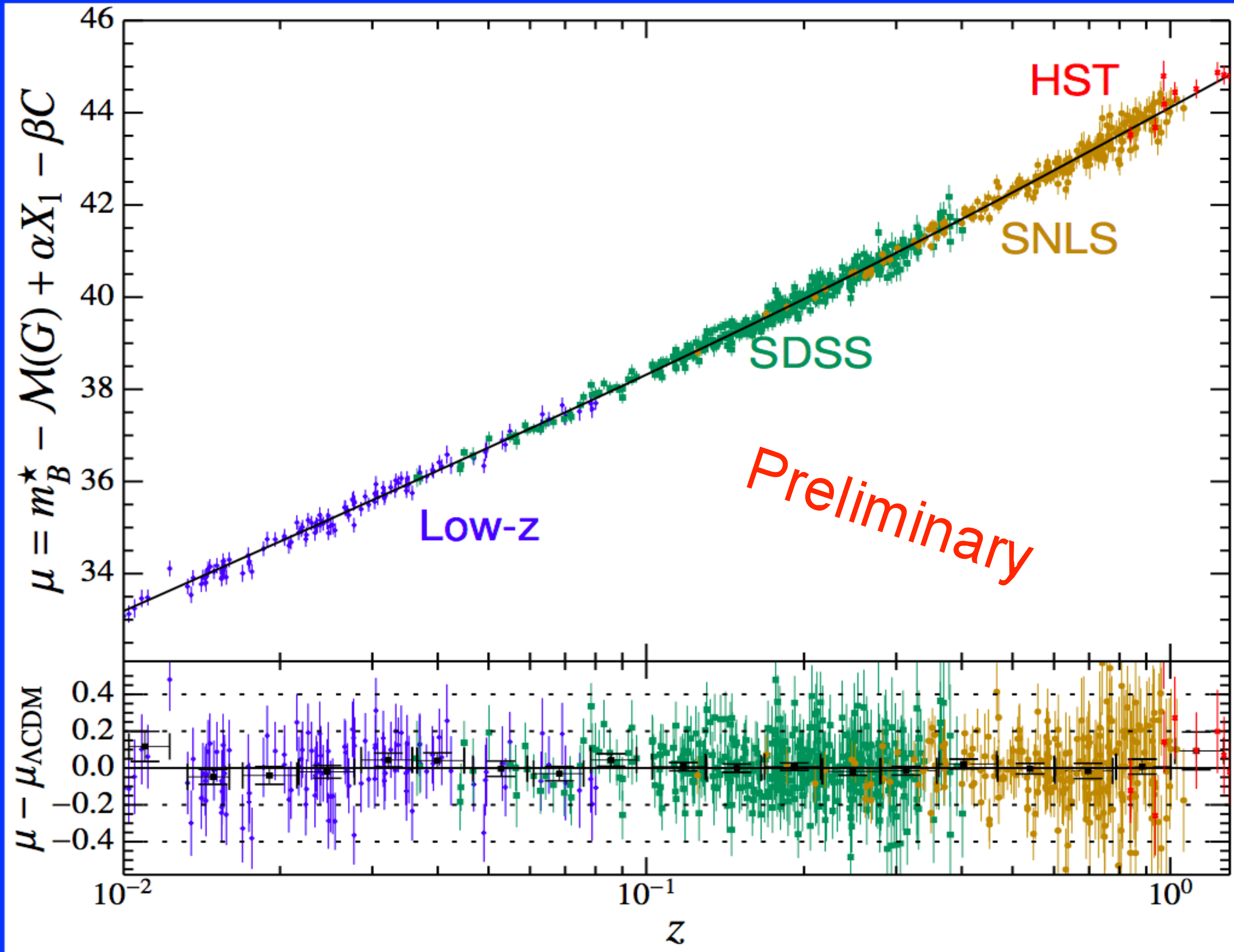


SNLS SN LC @ Z ~0.5

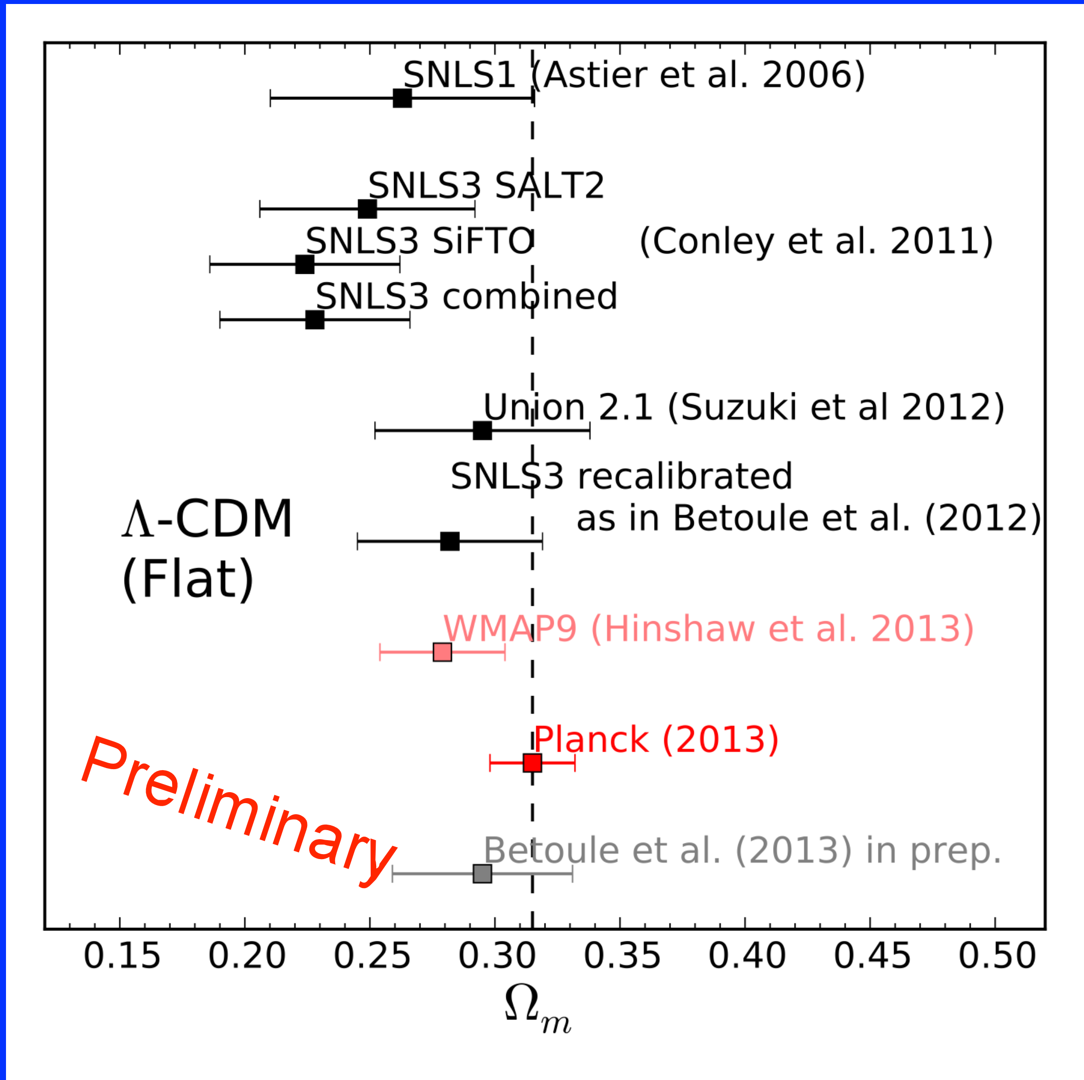
SDSS SN LC @ Z ~0.2



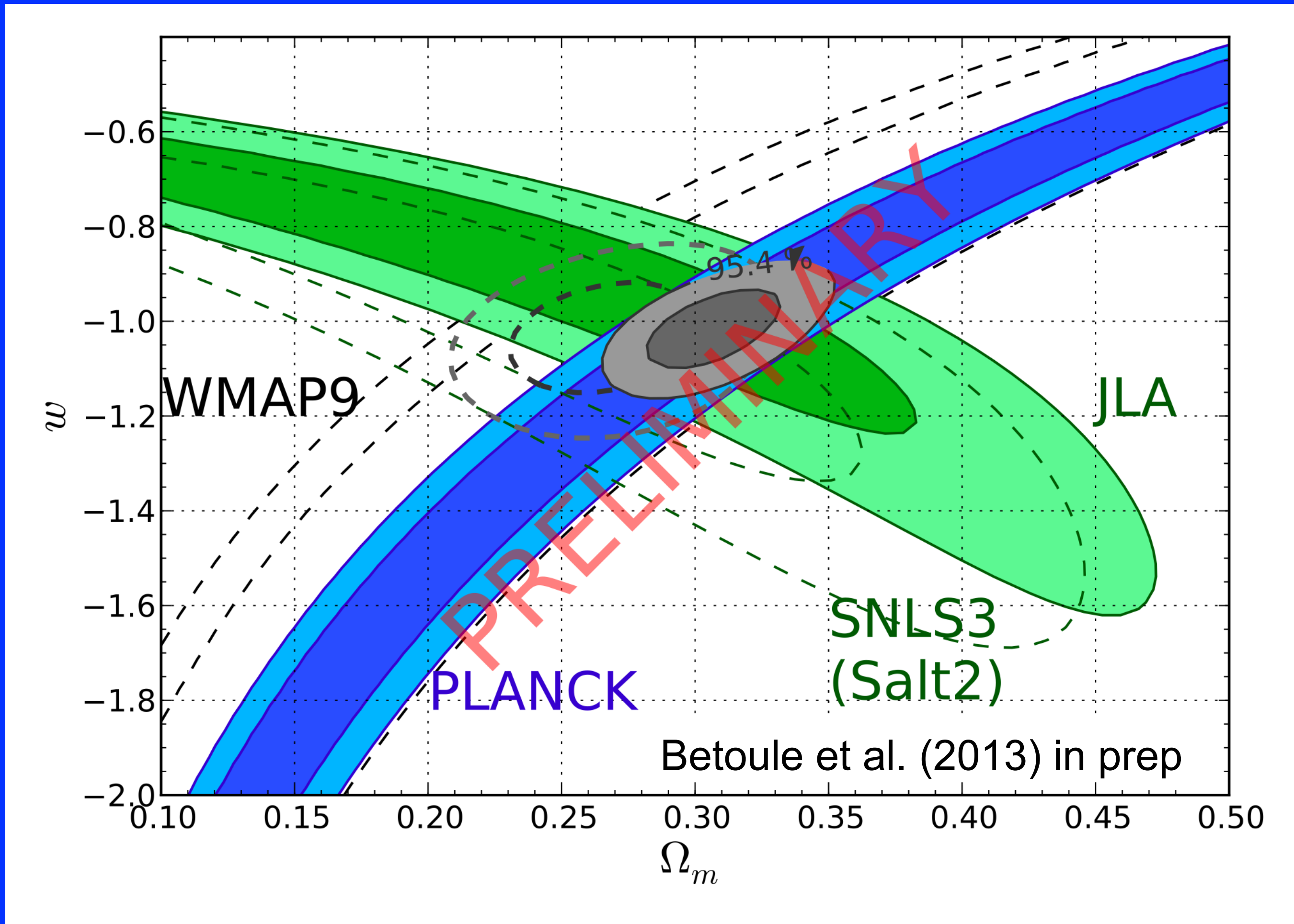
SNLS-SDSS joint Hubble diagram



Comparison with Planck results



SNLS-SDSS Planck combined constraint on w



Future SN programs

Near Future : currently active SN programs

Low/intermediate-z :

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

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

Pan Starrs/PS1 : target several 100 SNe up to z=1 -> arXiv

CSP : VIS follow-up + NIR follow-up

z>1 :

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

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

« DETF STAGE III » SN programs

Pan-starrs PS1+2 : 1.8m + 7 deg2
2012-2016? (primarily weak lensing)
goal : o(1000) up to z=1

DES : CTIO+new 3deg2 mosaic camera
2012-2016 (primarily weak lensing)
goal: 4000 SN up to z=1

Skymapper : 1.35m MSSO (Australia)
2013-2018 Rolling nearby (z~0.1) - yield ~100 SN Ia /yr

Subaru : 8.4m with HSC (1.5 deg FoV) – target (0.8-1.2)

Will collect more and address some of the possible systematics.
But very difficult to significantly (x10) improve on w precision

Stage IV ground based SN projects

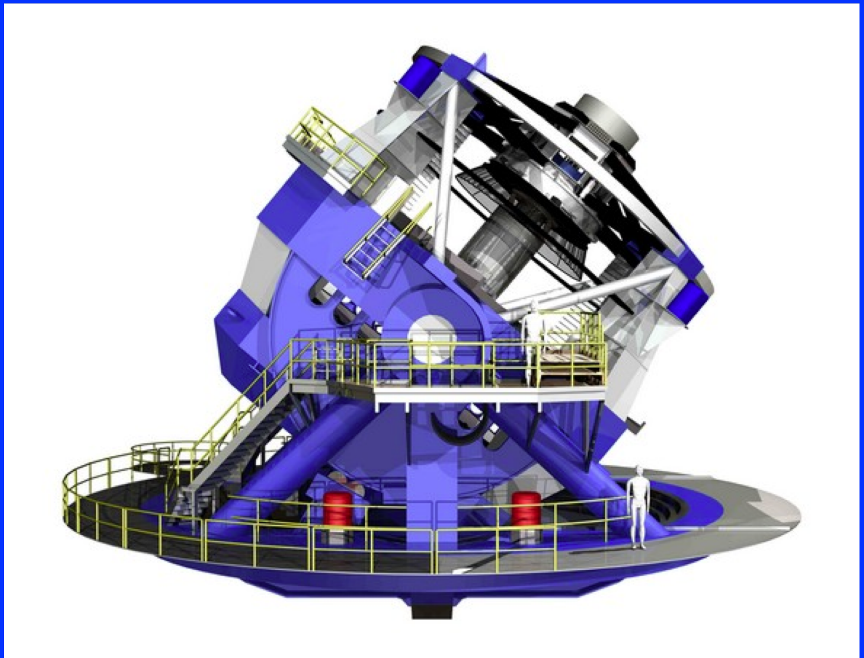
The Large Synoptic Survey Telescope (LSST)

One 8m telescope with 9 deg2 fov

Passed DOE CD1 and NSP PDR

First light expected in ~2020

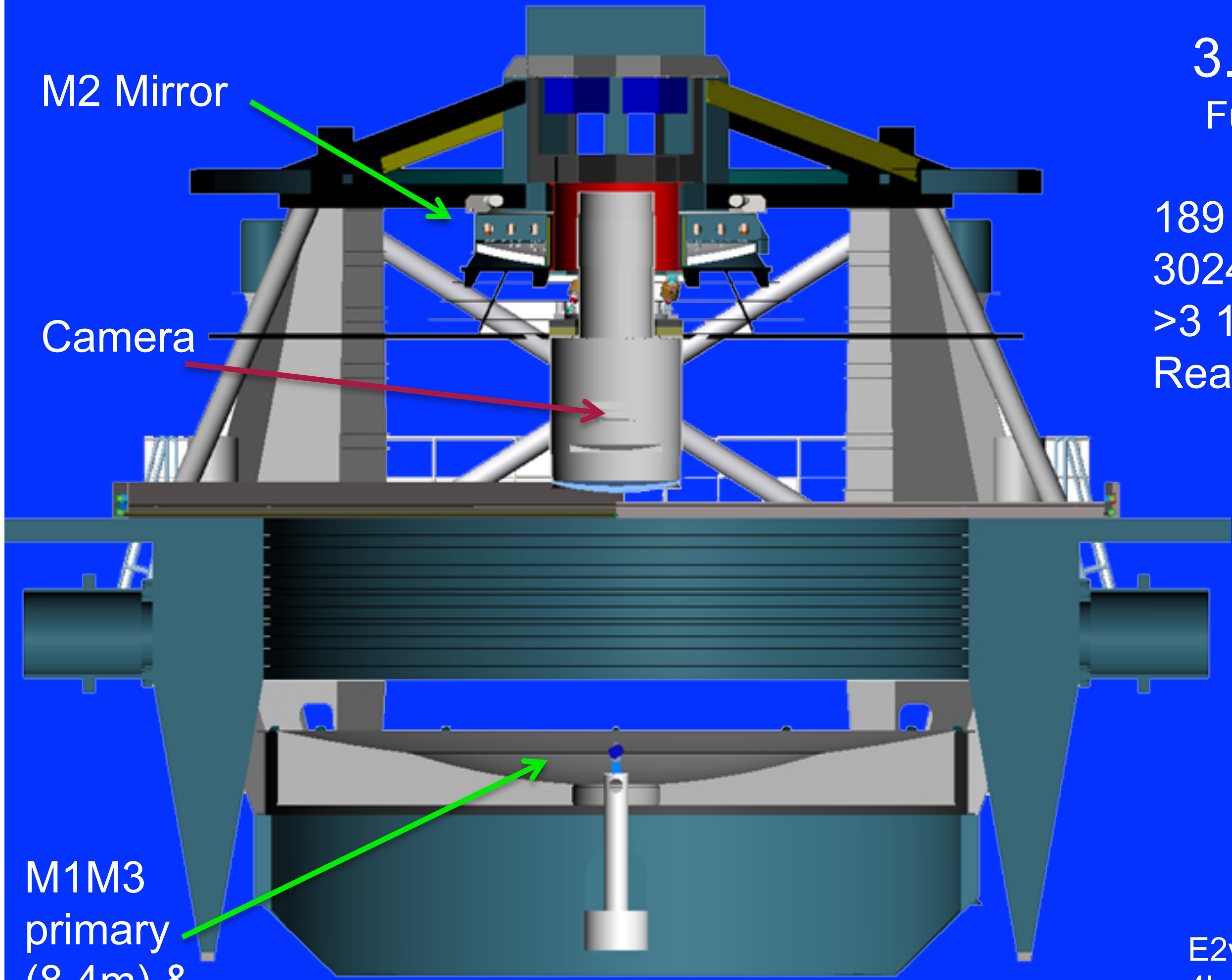
Will yield 250000 SN/yr !



Low AND high-z SN from the same instrument …

Repeat imaging (calibration <0.5%) + « sky » calibration

LSST : Wide Deep and Fast



Moving Structure 350 tons
60 tons optical systems

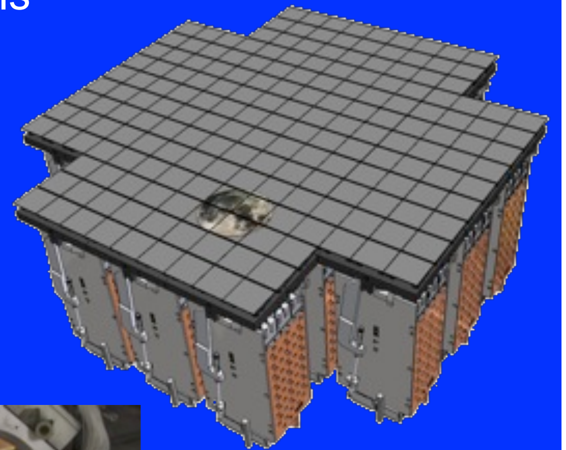
Field of view :

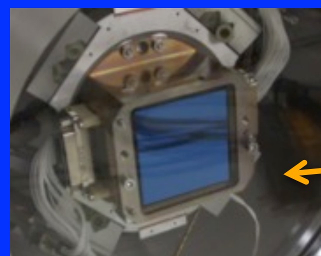
3.5 deg (9.6 deg^2 =.023% sky sphere)

Full moon = 0.5 deg = 4.8 10^{-6} of sky sphere

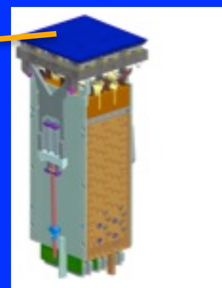
Focal plane diameter : 64 cm

189 science CCD (21 rafts)
3024 Channels
>3 10^9 pixels
Readout: 2s





E2v CCD 250 ,
4kx4k , 10 μm pixels
100 μm deep depleted
UV to IR sensitive
16 channels output
Designed by Dedicated R&D for LSST



1 raft = 3x3 CCD
150 M pixels
(1/2 Megacam)

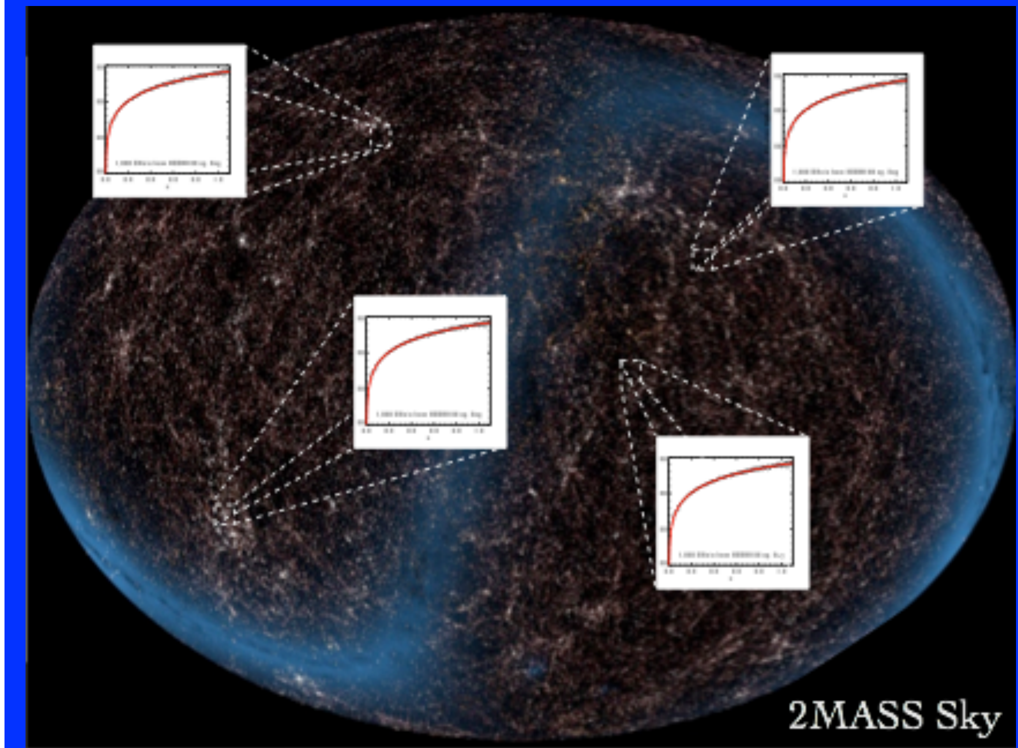
LSST : example of high statistic DE science with SN Ia

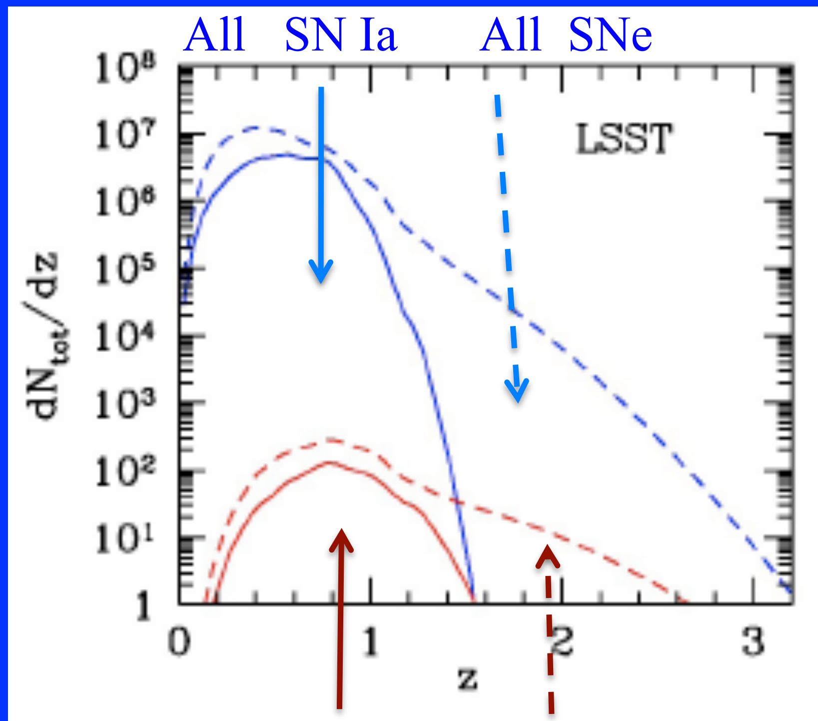
The large SNIa statistic will allow to build SNIa hubble diagram for different directions in the sky.

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

➔Strong lensed SN Ia

= sensitive to H(z) at the lens location

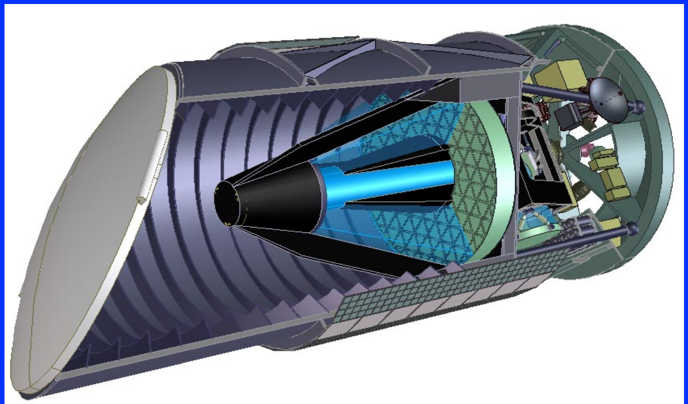




Lensed SN Ia All Lensed SNe

Space based cosmology with SN Ia

Detect/follow distant SN Ia from Space



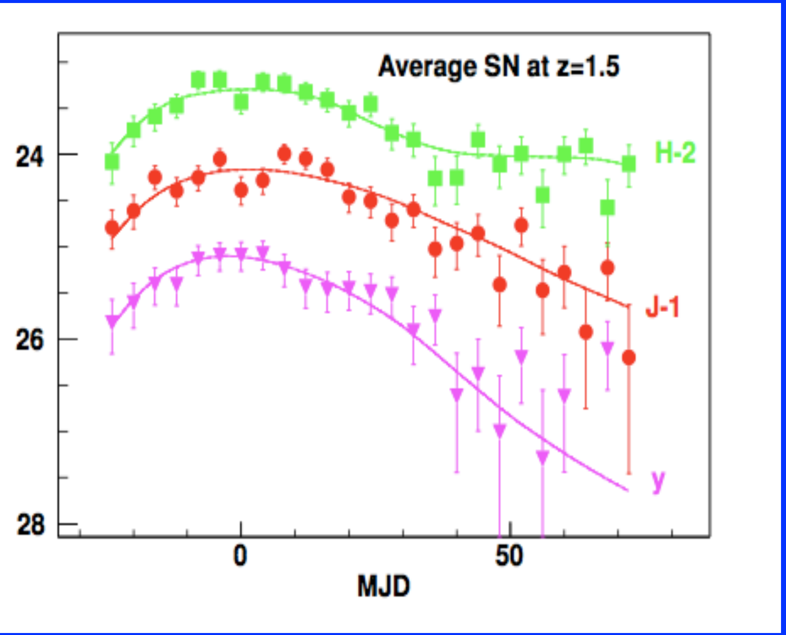
First proposed in 1999 (SNAP)
ϕ~2m telescope 0.6 deg. carrés -
Vis+NIR 0.4->1.7 μ
2000 SNe $0.2<z<1.7$ in 3 yrs

+ 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 : 10 pointings/day
1 visit : 1200(y) + 2100 (J) + 2100 (H)= 1.5 h
A lightcurve at z=1.5 lasts 40*2.5 = 100 days
Over 6 months : 45 visits in total (2 mags deeper than one visit)



LSST deep drilling fields :
Current baseline for SNe and LSS : 4-day cadence g:300 s, r:600s, i:600s, z : 780s, y4 : 600s
Total area ~ 4 fields over 10 seasons

Simultaneous observations in z and y bands

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

Combined with lowz=>foM~200

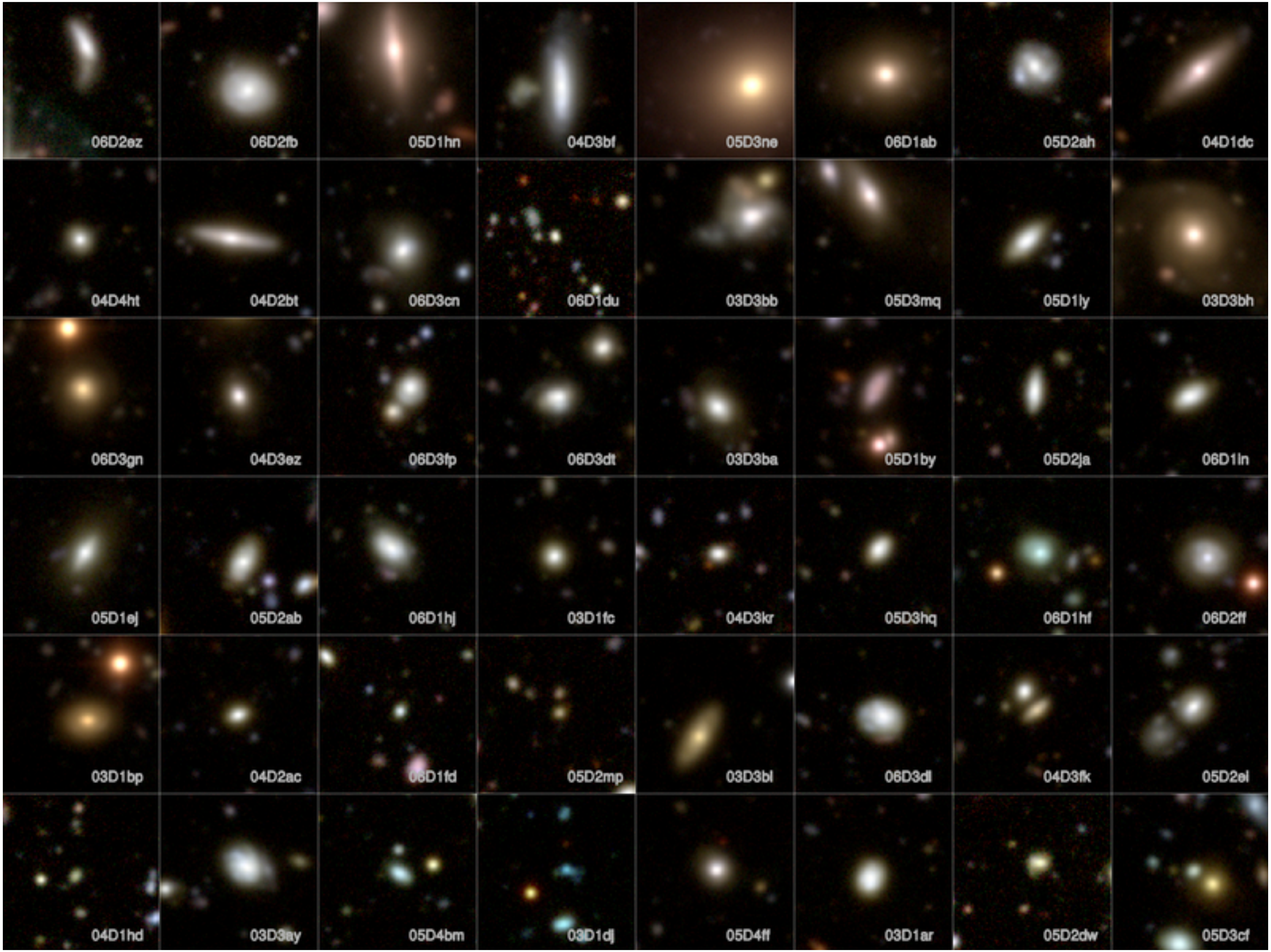
Summary

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

- Including systematics and combined with BAO and CMB : w (cte) = -1.061 ± 0.069 (~7%) compatible with a cosmological constant

- Photometric calibration is (by far) the dominant (known) systematics today. Prospects to improve in the near future -> δw(stat+syst)~5%

- Expect further (incremental) improvements in stage III SN programs and significant improvements with LSST and EUCLID


06D2ez
06D2fb
05D1hn
04D3bf
05D3ne
06D1ab
05D2ah
04D1dc
04D4ht
04D2bt
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06D1du
03D3bb
05D3mq
05D1ly
03D3bh
06D3gn
04D3ez
06D3fp
06D3dt
03D3ba
05D1by
05D2ja
06D1in
05D1ej
05D2ab
06D1hj
03D1fc
04D3kr
05D3hq
06D1hf
06D2ff
03D1bp
04D2ac
06D1fd
05D2mp
03D3bl
06D3dl
04D3fk
05D2el
04D1hd
03D3ay
05D4bm
03D1dj
05D4ff
03D1ar
05D2dw
05D3cf