Supernovae at High z and Dark Energy

Pilar Ruiz-Lapuente
IFF (CSIC, Spain)
ICC (UB, Spain)

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SNeIa cosmology and dark energy

> ***SeeChange***
> ***WFIRST*** **and** ***JWST*** **prospects**

Dark energy into the dark ages

> **with other SNe**

Background

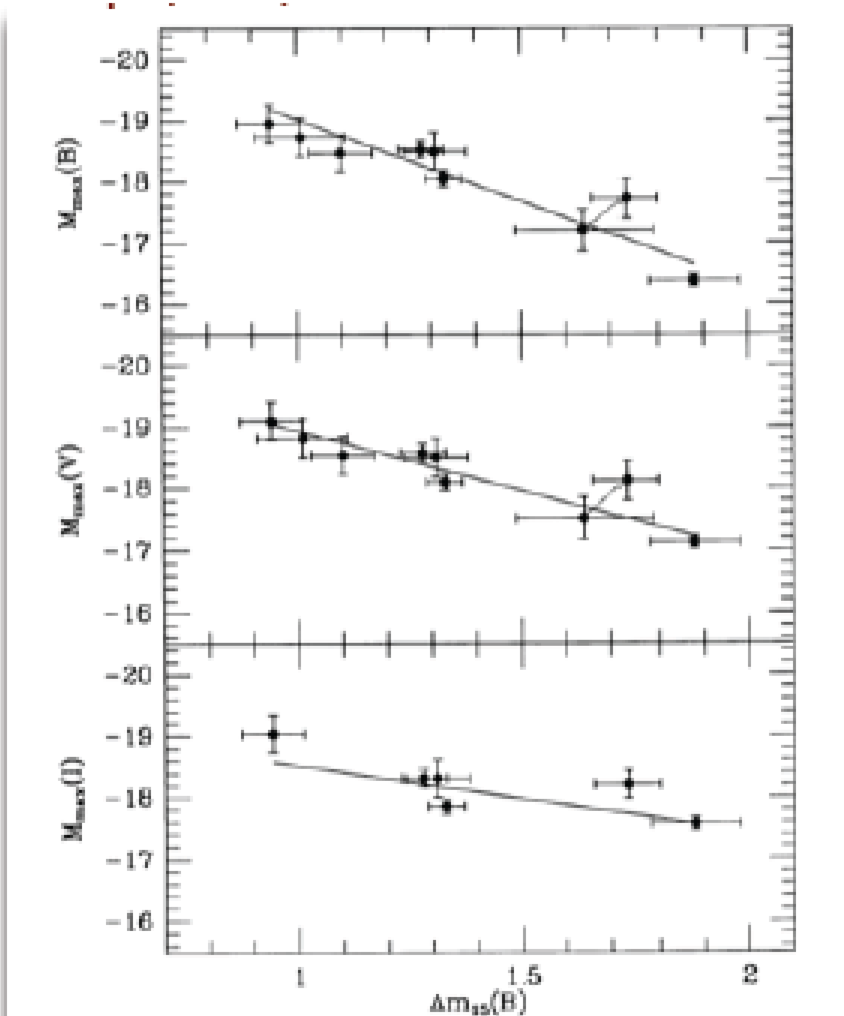
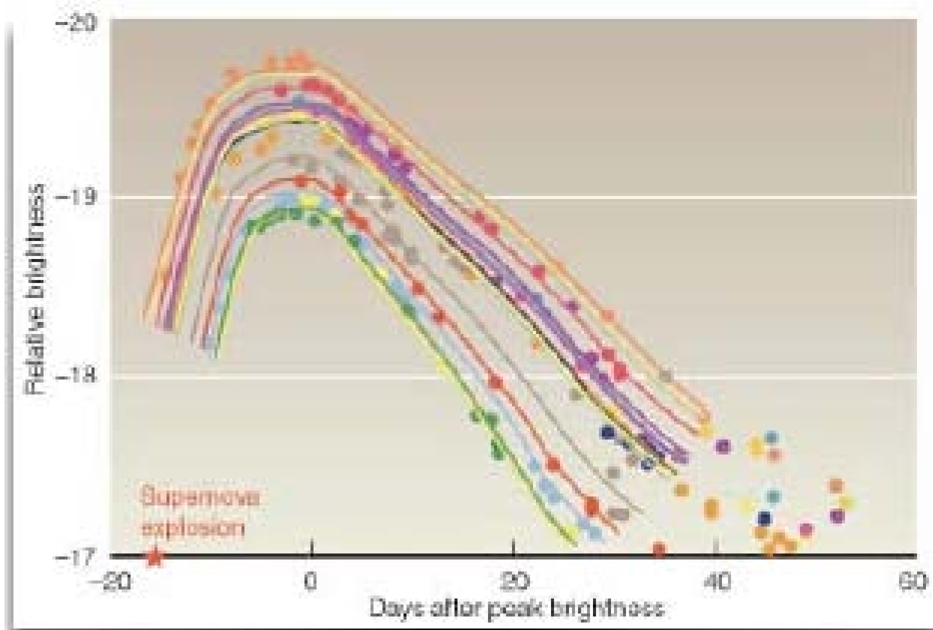
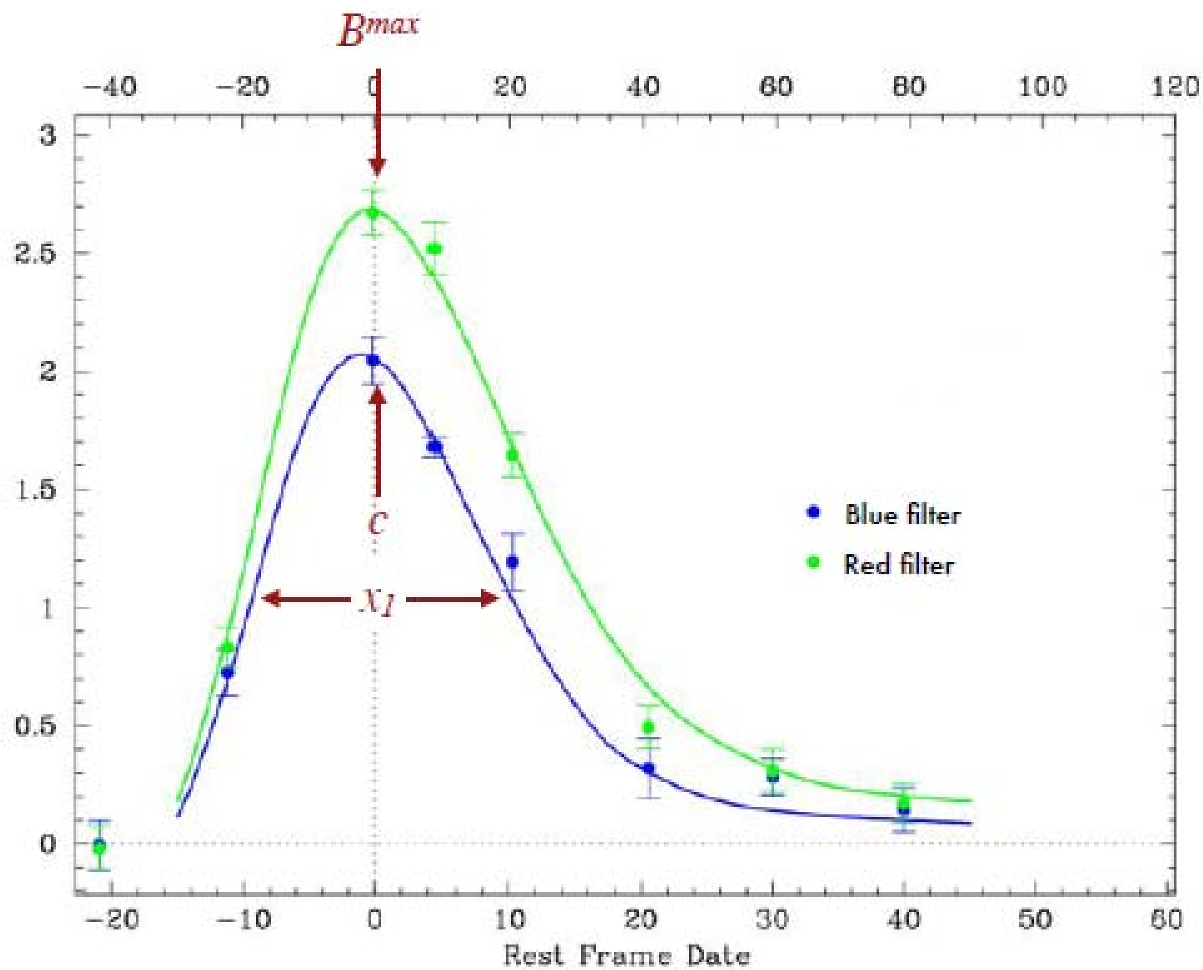


FIG. 1.—Decline rate–peak luminosity relation for the nine best-observed SN Ia's. Absolute magnitudes in *B*, *V*, and *I* are plotted vs. $\Delta m_{15}(B)$, which measures the amount in magnitudes that the *B* light curve drops during the first 15 days following maximum.



The Phillips (1993) relationship in different filters (left) and the stretch factor used by the SCP (Perlmutter et al. 1999) to calibrate the peak luminosities of SNeIa (above)

Background



The maximum brightness *B^{max}*, together with color information *c* and light curve width *x_1* , are used to make *SNeIa calibrated candles*

The parameters *β*, *α* and *M_B* are derived from the observations

$$B^{\max} - \beta \cdot c + \alpha \cdot x_1 - M_B = 5 \log_{10} d_L(\Omega_M, \Omega_X, w; z)$$

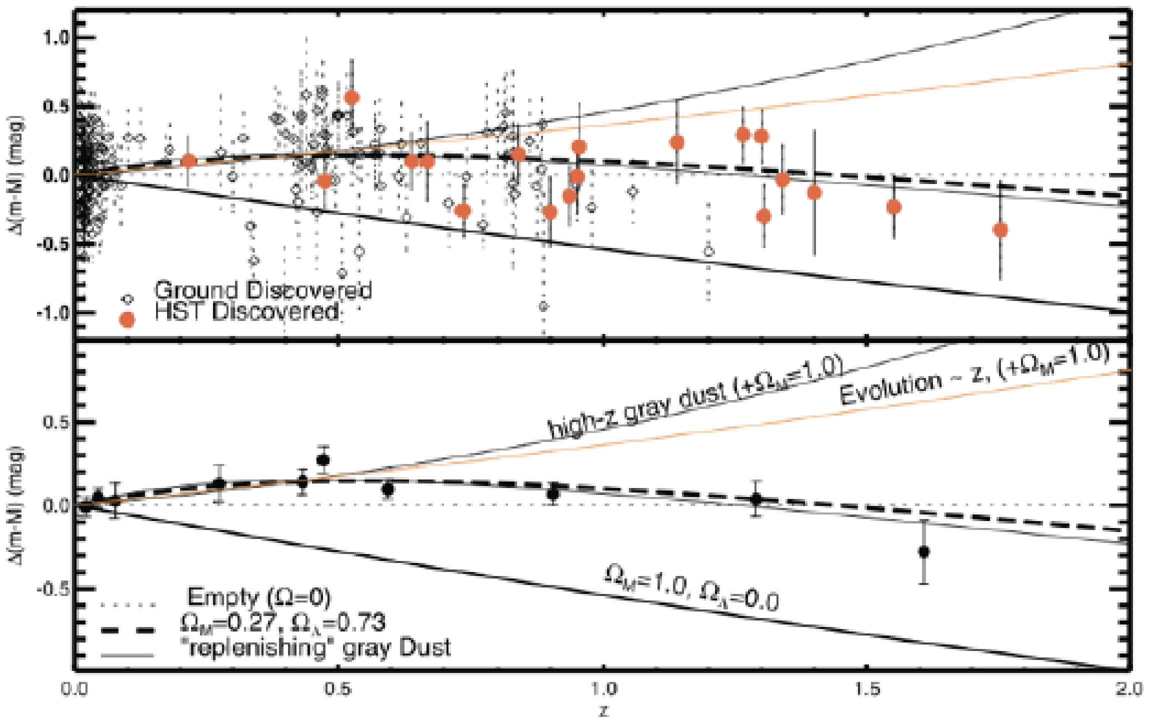
Background

$$\mu_{Bi}^{\rm obs} = m_{Bi}^{\rm obs} + \alpha\, x_{1i}^{\rm obs} - \beta\, c_i^{\rm obs} + \delta\,(M_\star > 10^{10} M_\odot) - M_B$$

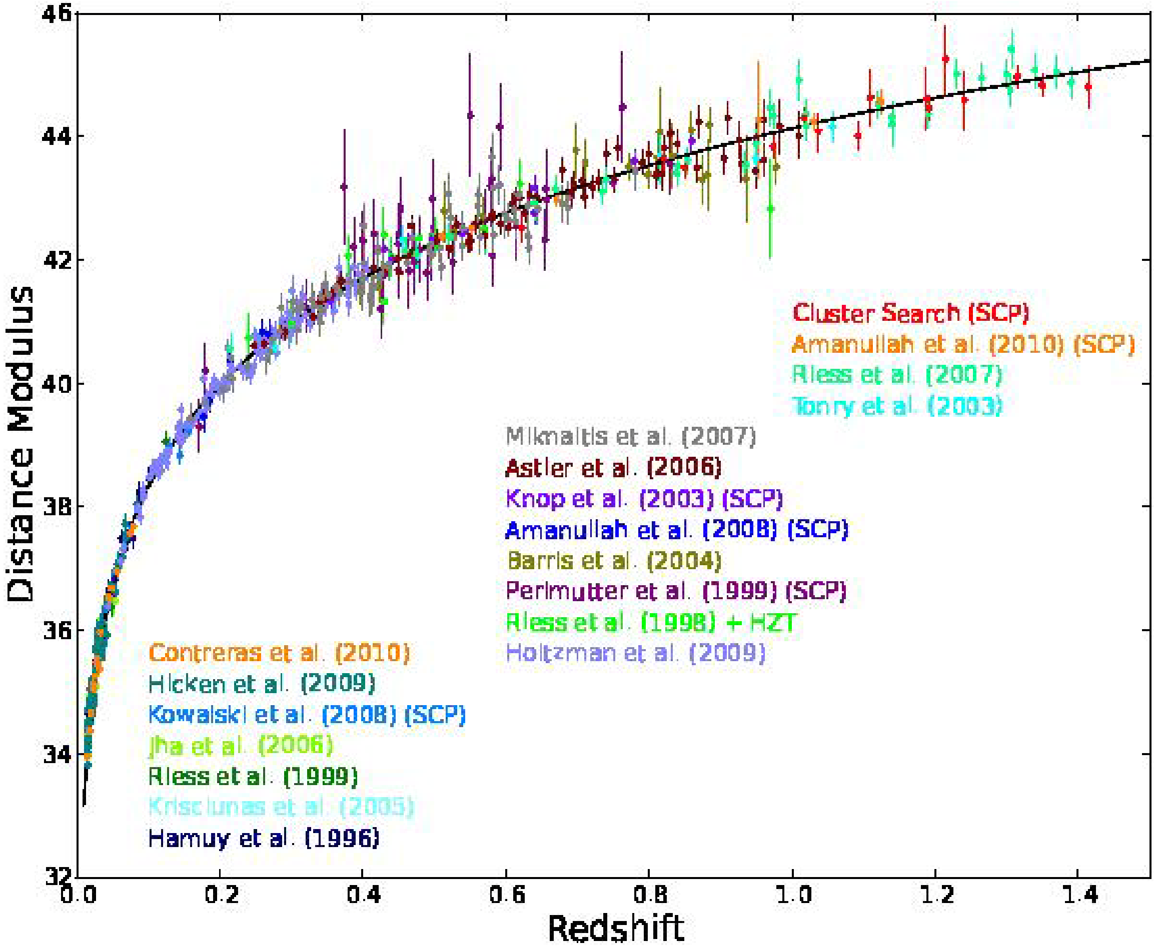
δ captures residual luminosity correlations with host galaxy mass

There is indirect evidence that this correlates with age of the progenitor system of the SN

Background



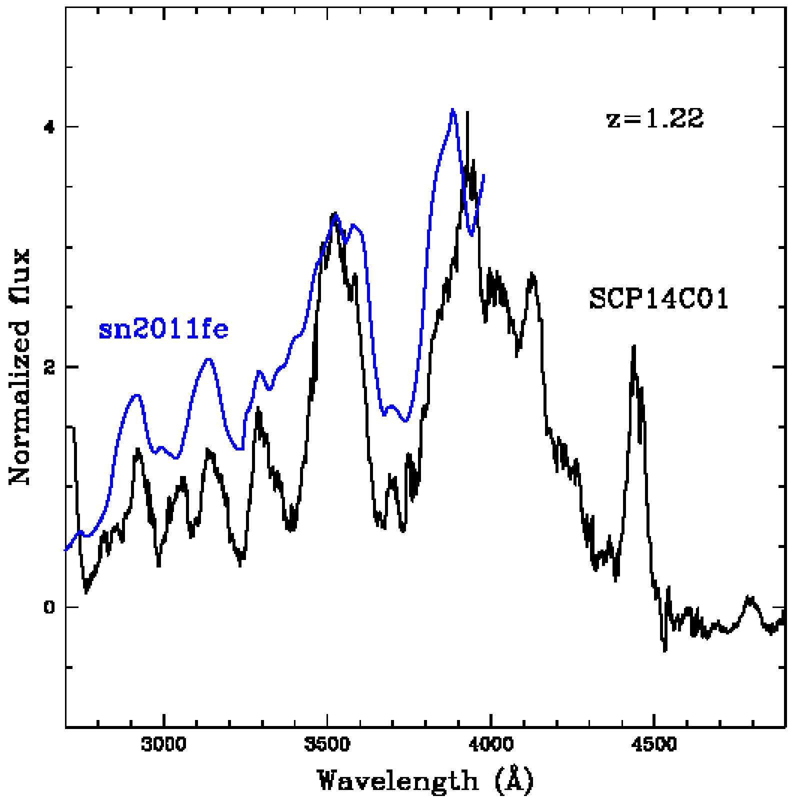
Riess et al., 2004

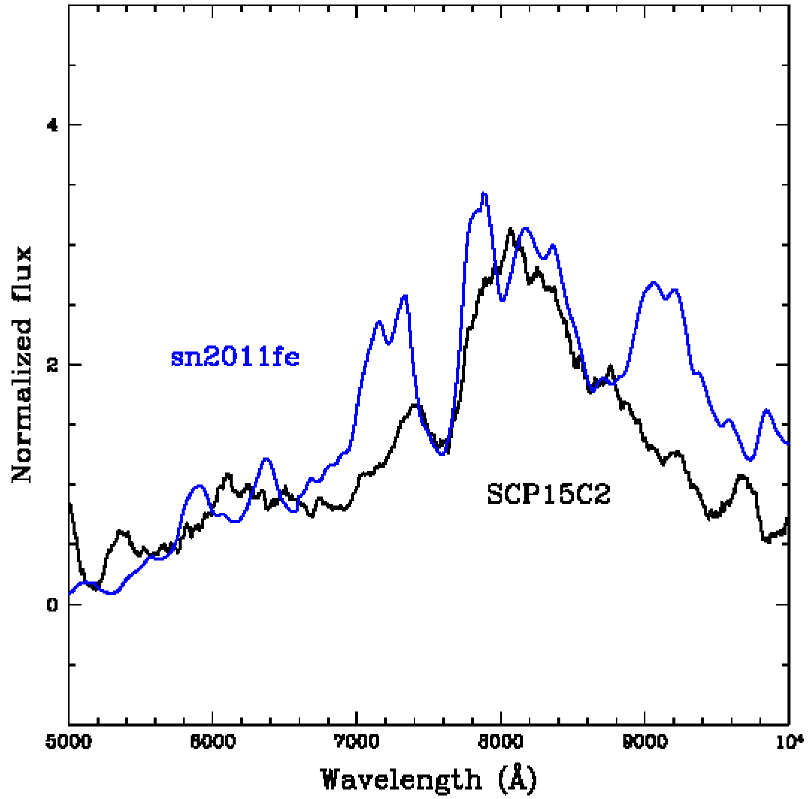


Hubble diagram for the *Union2.1* compilation

The *SeeChange Program*, of observations of supernovae at very high redshifts: 1 < z < 2, in massive galaxy clusters, has been completed. We have used, for that, 174 orbits of the *Hubble Space Telescope*, combined with ground-based observations made with the 10.4m *Gran Telescopio de Canarias* and the 10m *Keck telescopes* in Hawaii. We have studied 30 supernovae within that range of z, in the most massive and highest z galaxy clusters known. With that, we have made an unprecedented probe of the time evolution of the equation of state of dark energy, allowing us to improve its constraints by a factor of 3, relative to what had been done to date.

SeeChange program





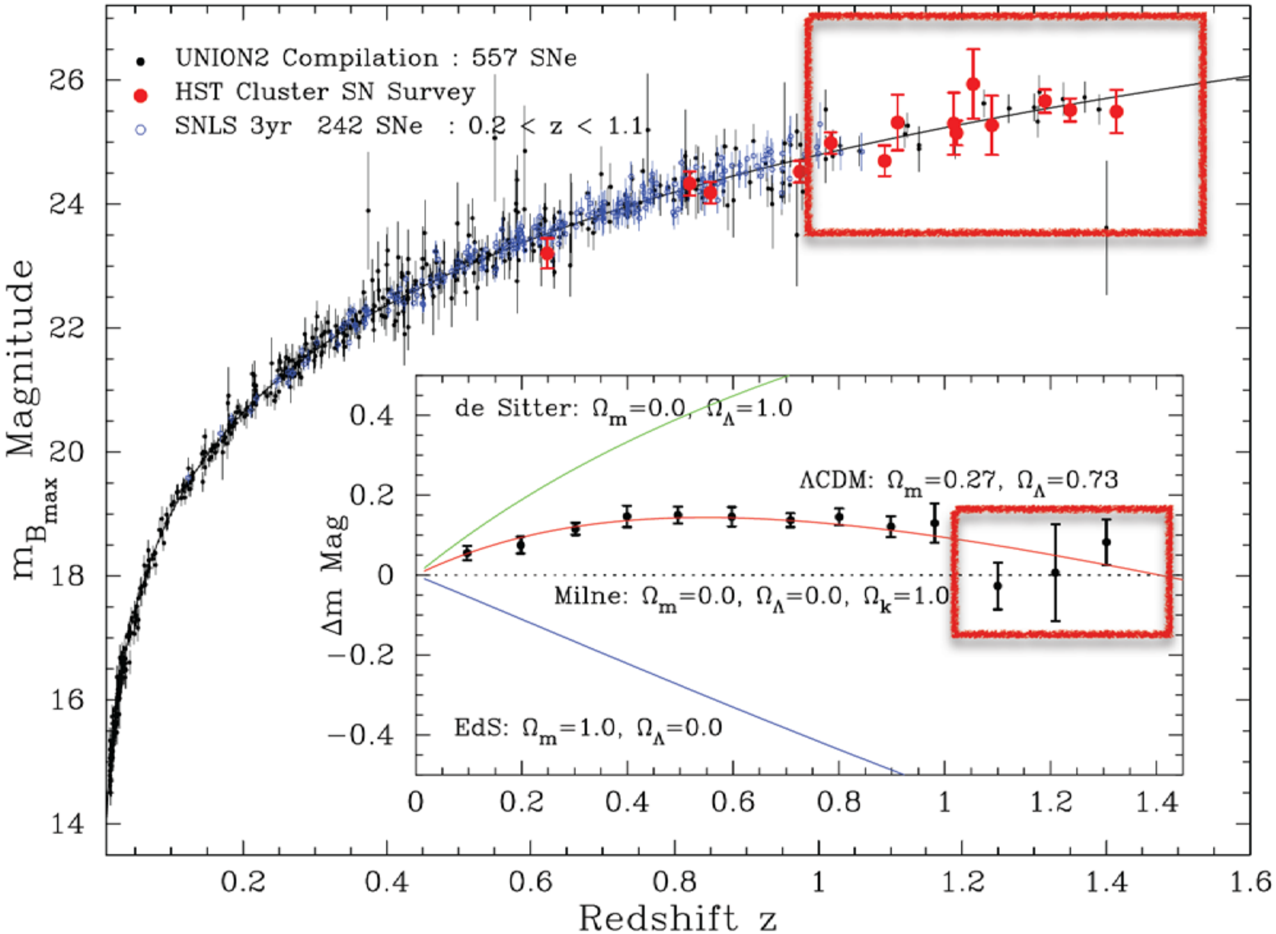
Spectra taken at the *GTC* with *OSIRIS*

SeeChange program

The 10.4m *Gran Telescopio de Canarias (GTC)*

Main collaborators in the *SeeChange* program: David Rubin, Brian Hayden, Jacob Nordin & Greg Aldering (*SCP*)

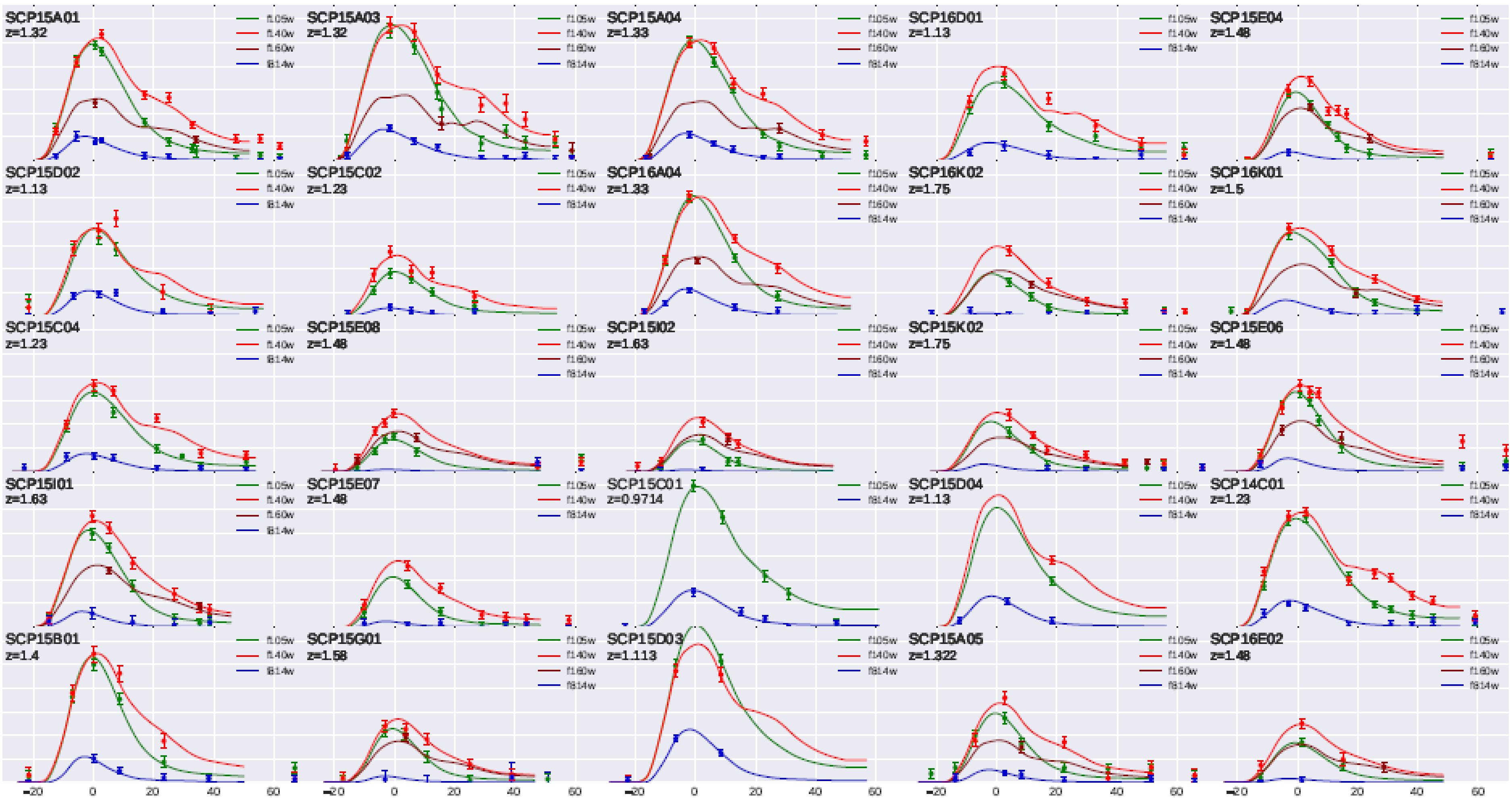
SeeChange program



Preview of the *Union3* compilation (around 3,000 SNeIa), including early results of the *SeeChange* program

Union3: **Rubin et al. (*SCP*) (2017)**

SeeChange program

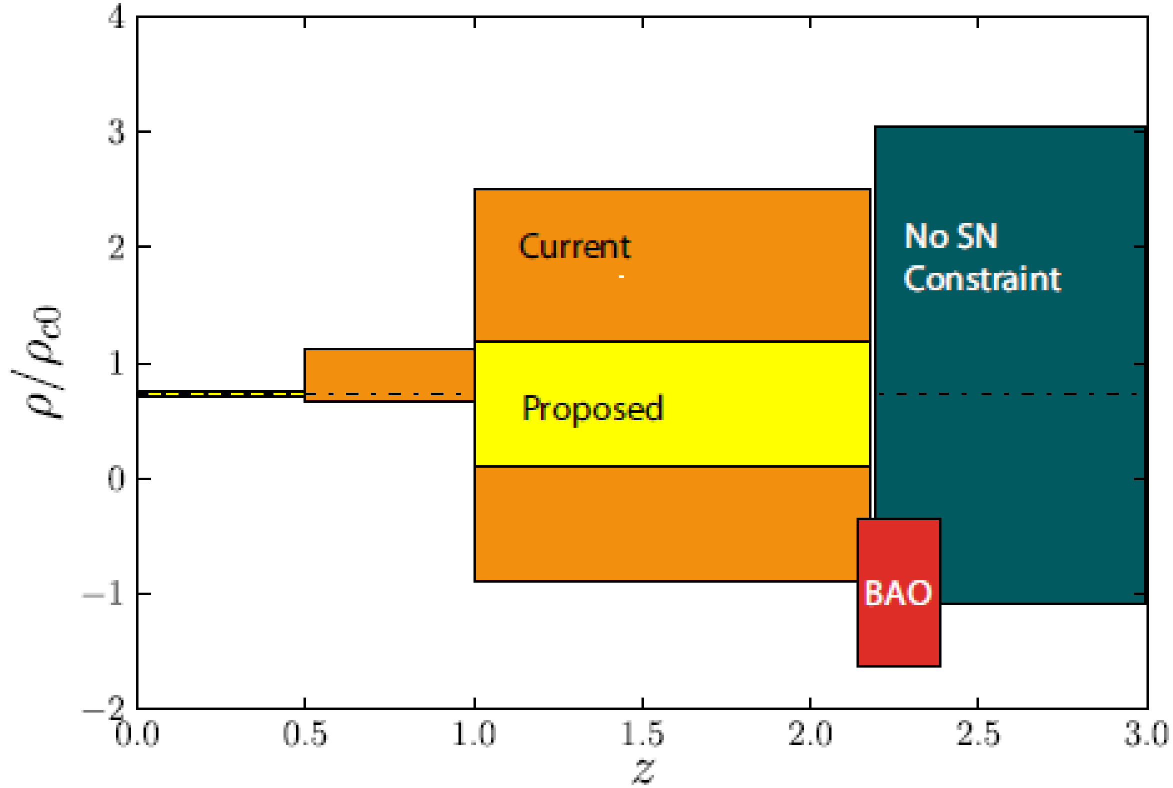


The light curves of 25 SNeIa, obtained within the *SeeChange* program

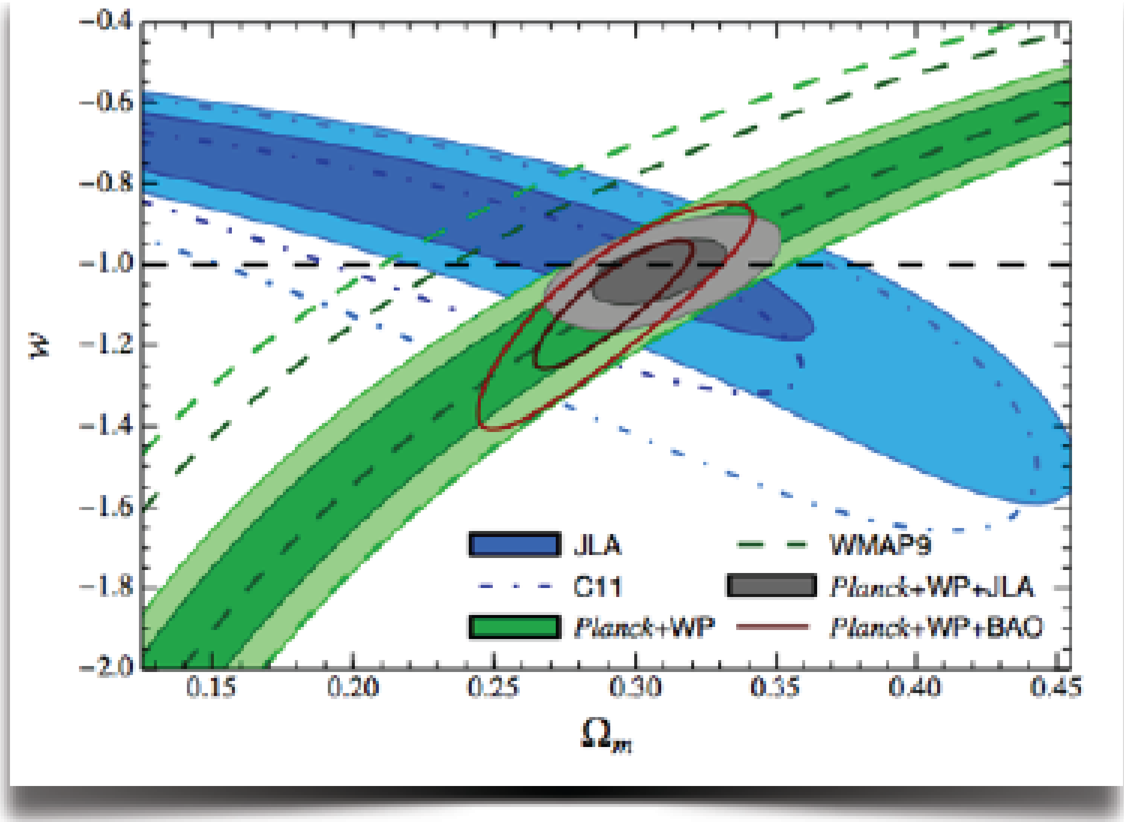
SeeChange program

We have found 30 SNeIa at 1 < *z* < 2

Once the analysis is completed, we will be able to reduce the constraints on the *EOS* of dark energy by a factor of 3, in that redshift interval, most significant for the nature of DE



Results from redshifts below 1 (JLA)

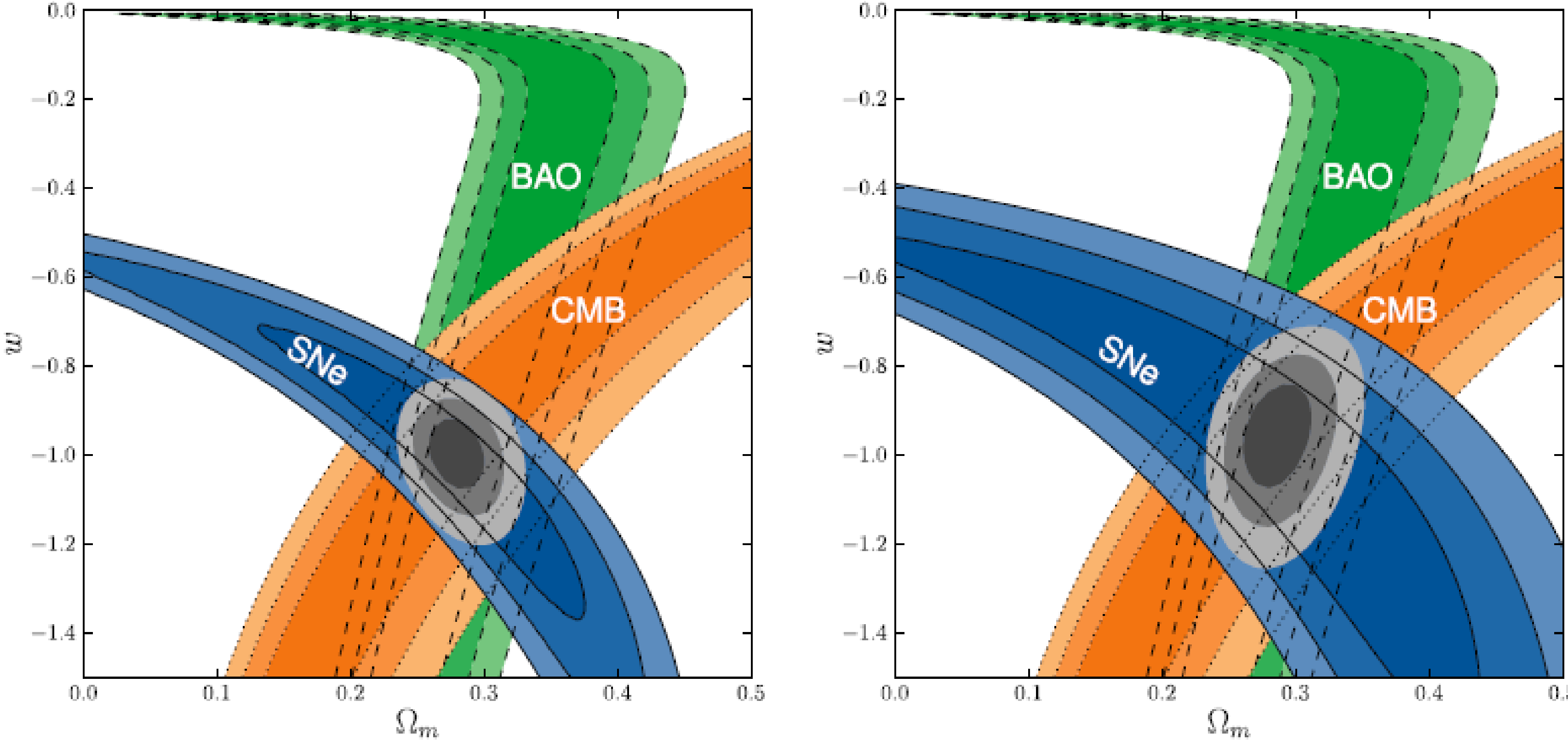


Betoule et al. (*JLA*) (2014)

Constraints on the combined values of the dark energy parameter *w* and the matter density parameter Ω_m

$$w = -1.027 \pm 0.055$$ (JLA Planck + BAO + SNe)

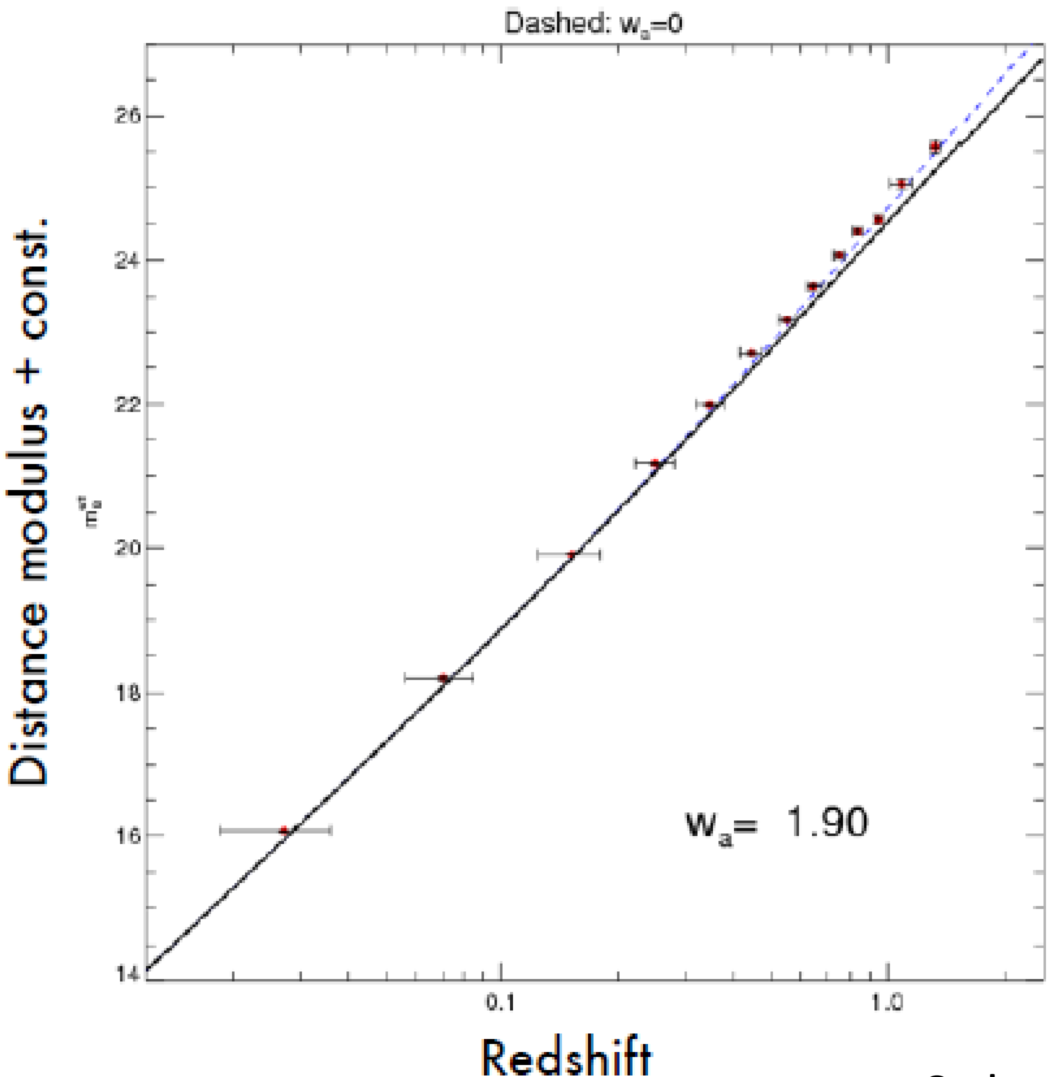
Union2.1 results



Suzuki et al. (*SCP*) (2012)

Confidence regions in the (Ω_m, *w*) plane. Only statistical uncertainties (left), and including both statistical and systematic uncertainties (right)

Distance measurements and DE



Out to distances corresponding to $z = 1$, a 5% change in w corresponds to a 1% change in distances

Goobar & Amanullah (2015)

SUSHI program

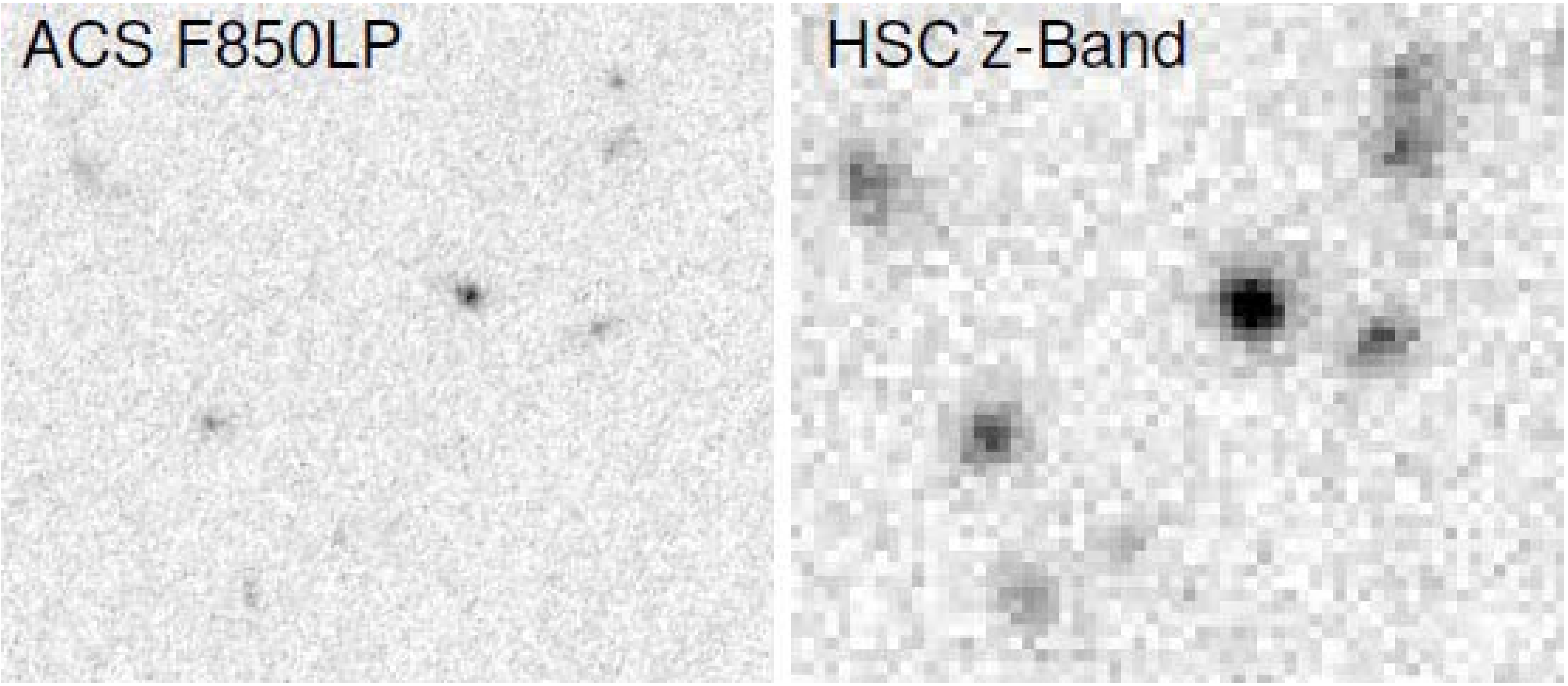
The *Su*baru *Su*pernovae with *H*ubble in the *I*nfrared (*SUSHI*) program aims to observe 150 SNeIa at 1 < *z* < 2

SNe are detected with the *Hiper Suprime-Cam* in the ultra-deep field of the *Subaru Strategic Project*. The *HSC*, mounted at the primary focus of the 8.2m *Subaru* telescope, has a field of view of 1.77 sqdeg and can take images at the limit of seeing , below 0.5’’ in the Y-band (0.5 hr there are equivalent to 1 orbit of the *HST* using the *ACS*)

The light curves are obtained with the *Hubble Space Telescope*

Spectra are obtained with the *GTC*, the *Keck* and the *VLT* telescopes

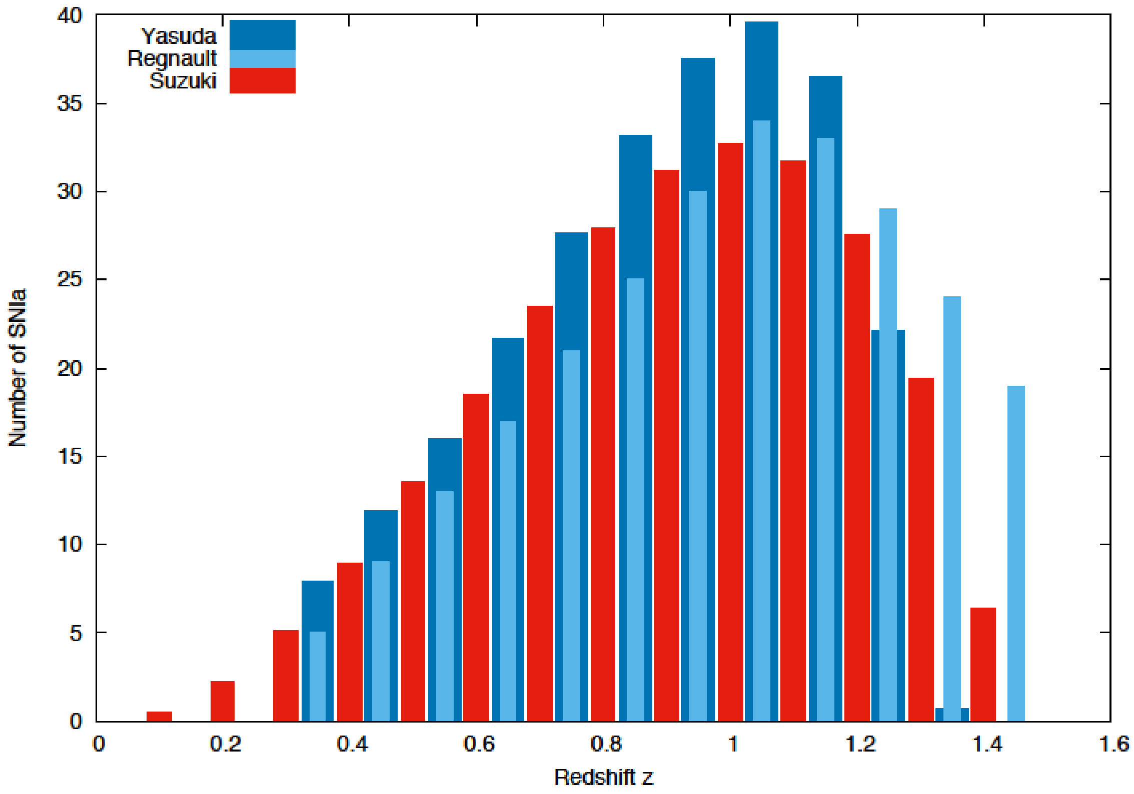
SUSHI program



Comparison of images obtained in one orbit of the *HST* ACS F850LP (left) and in a visit of 0.5 hr in *Subaru* with the HSC, in the z-band (right)

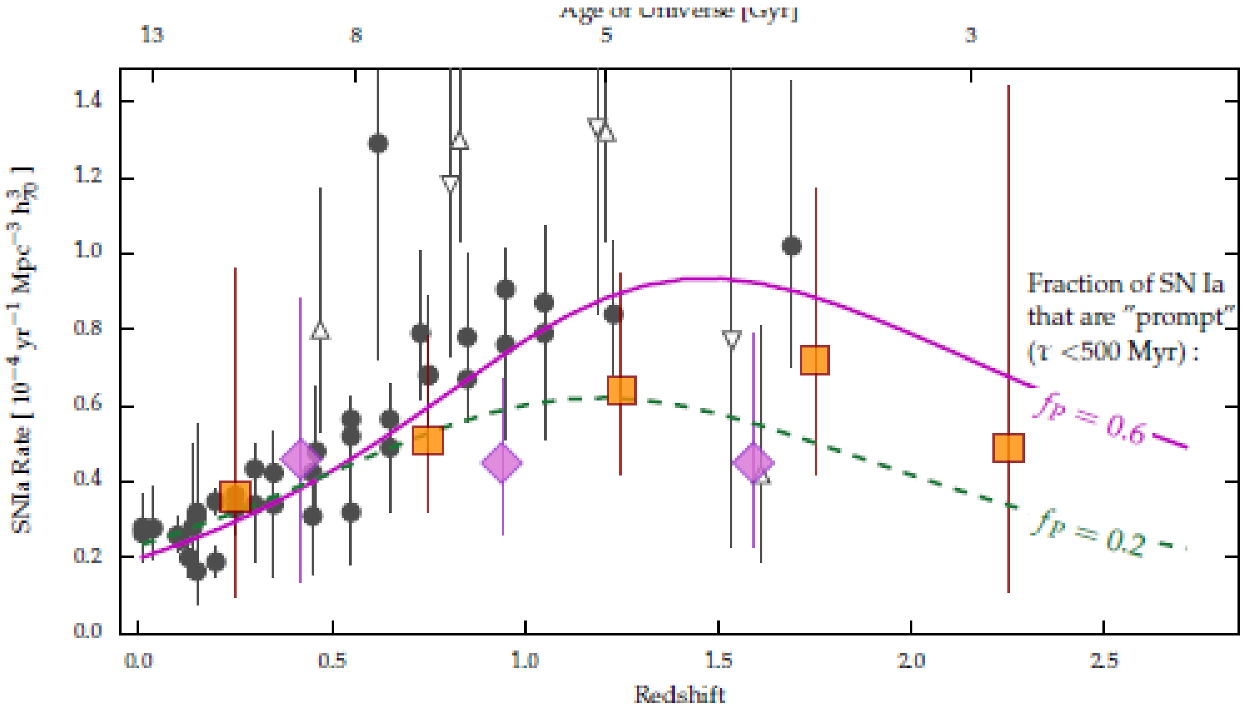
SUSHI program

SUSHI prediction



Expected number of SNeIa with well sampled light curves, that can be used for cosmology. More than 120 SNeIa at z > 1 are expected. The number of those just discovered, with incomplete light curves, should be more than 500 (also at z > 1)

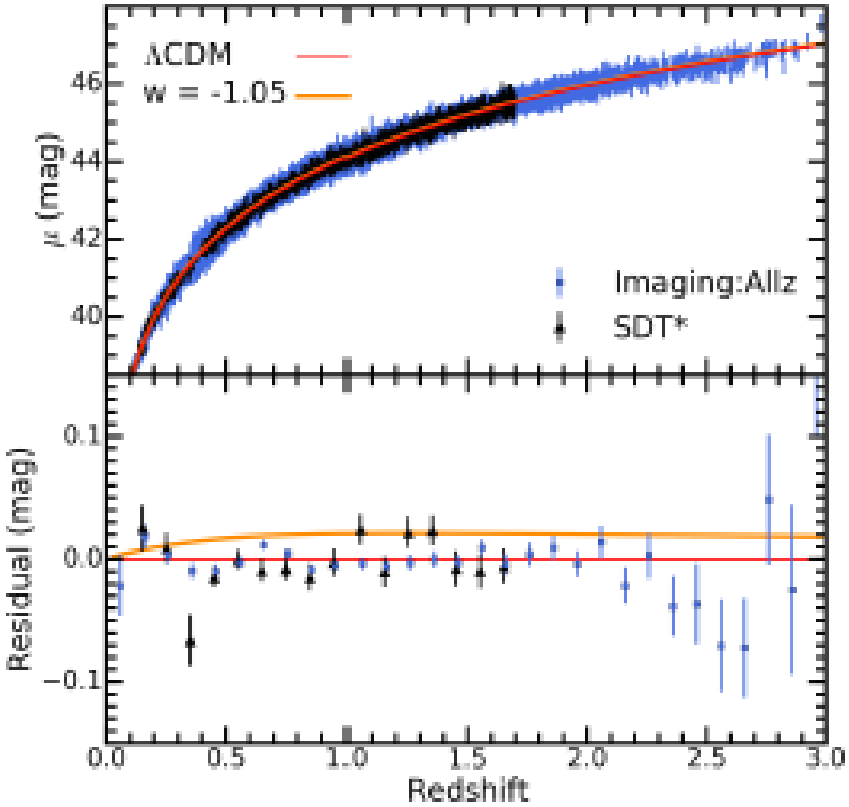
Cosmic SNeIa rates



The cosmic **SNeIa rate** as a function of redshift. The rates steadily **decrease** past $z \approx 1.5$-2

Rodney et al. (2014)

In the future: *WFIRST*



Hubble diagram of simulated WFIRST samples (upper diagram) and the residuals (lower diagram), referred to two fiducial models: ΛCDM (red lines) and *w*DM with w = -1.05 (golden lines)

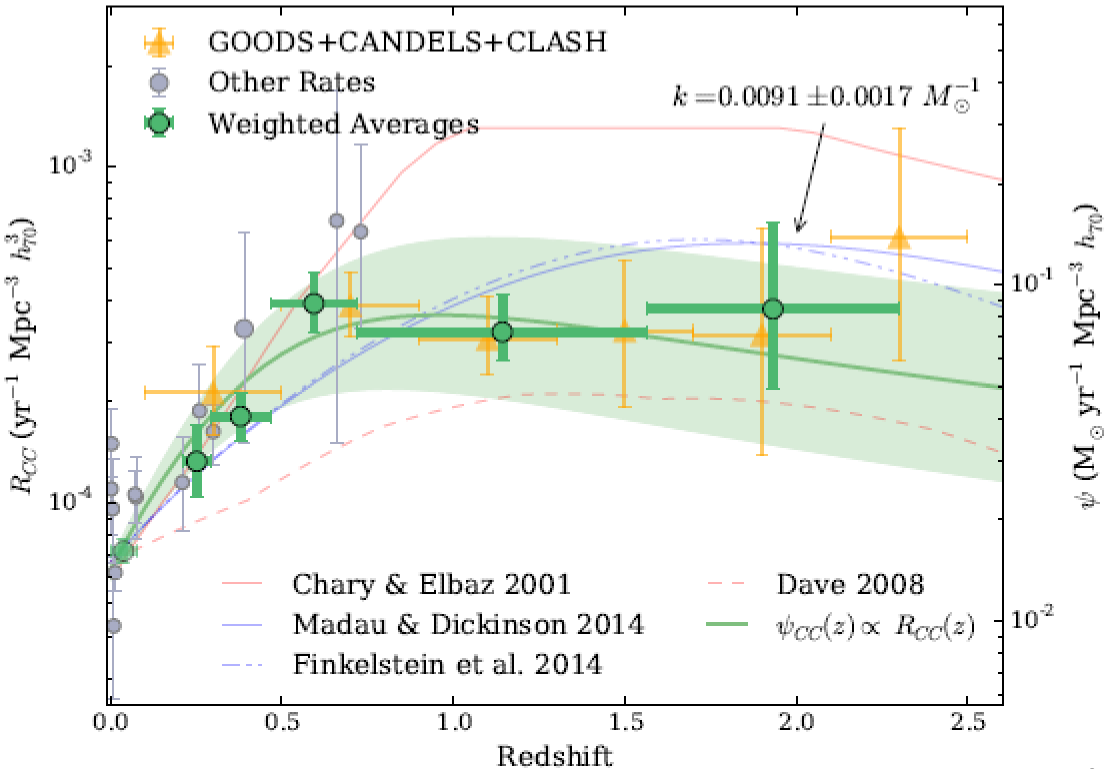
Hounsell et al. (2017)

Superluminous Supernovae and CC SNE

WFIRST will detect SNe out to $z \approx 7$ (CC SNe) and $z \approx 14$-17 (SLSNe) in the coming decade

JWST and the ELTs will directly detect SLSNe up to $z \approx 22$ and CC SNe at $z = 10$-15

Cosmic CC SNe rates



The expanding photosphere method and the standardized candle method will be used to determine the distances to CC SNe

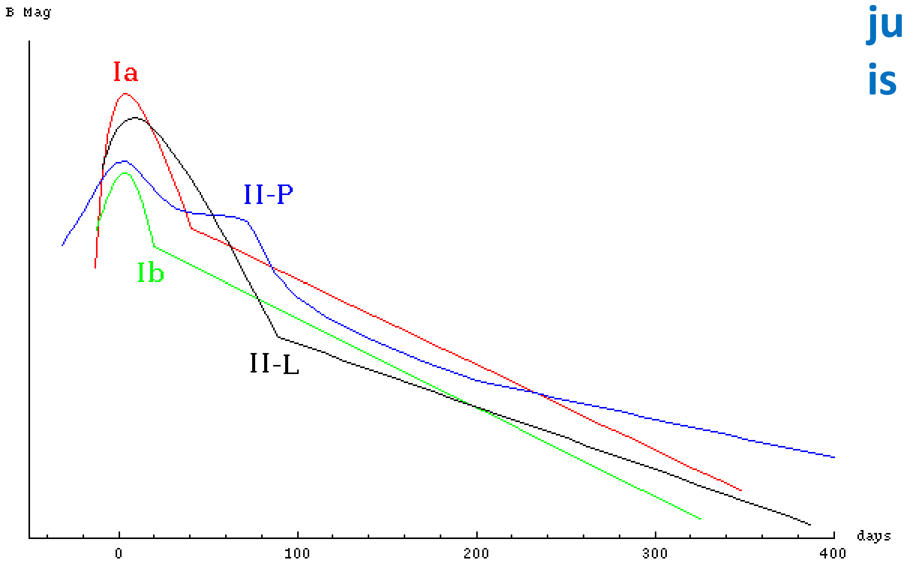
In contrast with SNeIa, the CC SN rate does not start any marked decrease at $z \approx$ 1.5-2 but follows the cosmic star formation rate

Strolger et al. (2015)

Cosmic evolution of the CC SN rate

CC supernovae

The **expanding photosphere method** (EPM: Kirshner & Kwan 1974) is a tool to measure distances to CC SNe.



The expansion velocity of the photosphere ***v*** is measured from its spectrum, and its radius ***R*** is just $R(t) = v(t-t_0)$, where t_0 is the time of the explosion.

CC supernovae

The photospheric angular size ϑ of the SN can be described as

$$\vartheta = 2\frac{R}{D} = 2\sqrt{\frac{f_\lambda}{\zeta_\lambda^2 \pi B_\lambda(T)}}$$

where D is the distance, f_λ the observed flux density, ζ_λ a dilution factor, and $B_\lambda(T)$ the Planck function evaluated at the photospheric temperature T . The dilution factor corrects for de discrepancy with perfect BB emission, due to the scattering opacities, and it is calculated from model atmospheres. Neglecting the initial radius of the exploding object, then

$$D = \frac{2v}{\vartheta}(t - t_0)$$

Therefore, with a minimum of two measurements, at different times, we can solve the last equation for D and t_0

CC supernovae

The **standardized candle method** (SCM: Hamuy & Pinto 2002) uses a correlation between the rest frame *I*-band magnitude, the absolute magnitude M_I , the rest frame (V-I) colour, and the **expansion velocity** at 50 days after explosion

$$M_{I_{50}} = -\alpha \log_{10}\left(\frac{v_{50,\mathrm{Fe\,II}}}{5000}\right) - 1.36\left[(V-I)_{50} - (V-I)_0\right] + M_{I_0},$$

with α = 5.81, M_{I0} = -17.52 (for a Hubble constant of 70 km s^{-1} Mpc^{-1}), and $(V\text{-}I)_0$ = 0.53 (Nugent et al. 2006)

The expansion velocity is usually estimated from the Fe II λ5169 line. Since the data at 50 days after explosion may not be available, one can use the relationship

$$v_{50} = v(t^{\star})\left(\frac{t^{\star}}{50}\right)^{0.464\pm0.017}$$

where $v(t^*)$ is the velocity of the line at time t^* after explosion

Superluminous Supernovae

Superluminous supernovae (SLSNe) have absolute magnitudes, at maximum light, of $M_V < -21$, while Type Ia supernovae (SNeIa) have $M_V = -19.2$

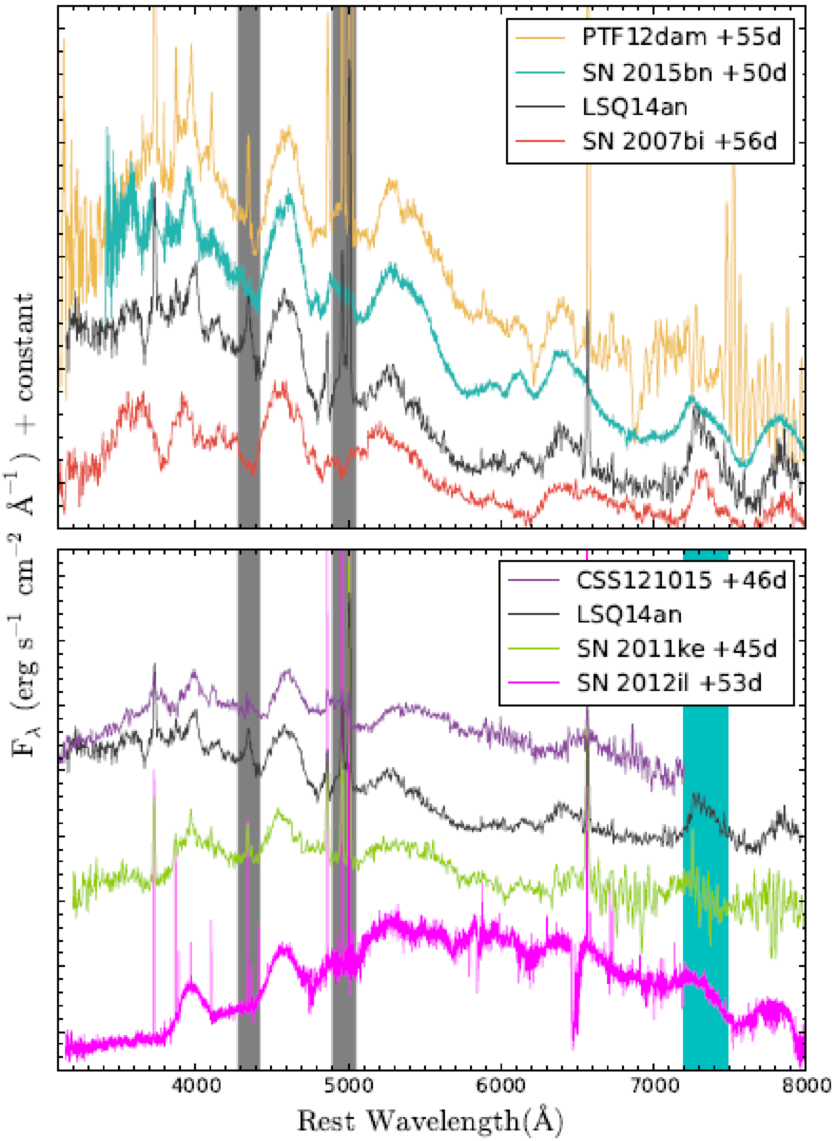
An object having an absolute visual magnitude $M_V = -21$ would have an apparent magnitude $m_J = 30$ at a redshift $z \approx 14$ (neglecting extinction)

Two mechanisms have been proposed to power SLSNe:

In the magnetar model, the energy source is the spinning-down of a rapidly rotating neutron star posessing a very strong magnetic field

The gravitational collapse of very massive stars, produced by the pair instability (PI) mechanism: photons produce $e^- e^+$ pairs, which drops pressure and starts collapse. The ensuing temperature increase eventually leads to a thermonuclear runaway that blows up the entire star.

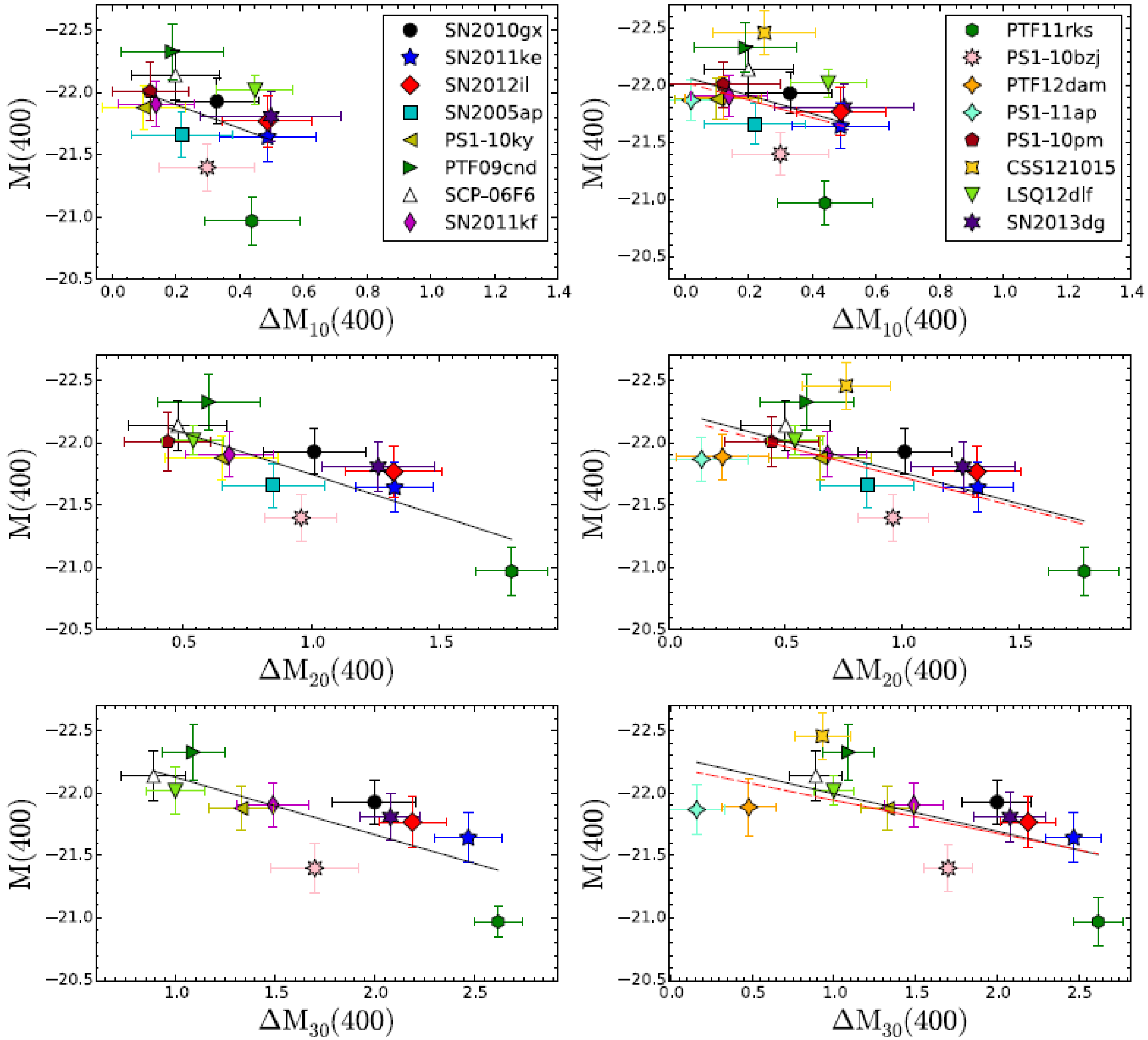
Superluminous Supernovae



Spectra of superluminous supernovae

Inserra & Smartt (2014)

Superluminous Supernovae

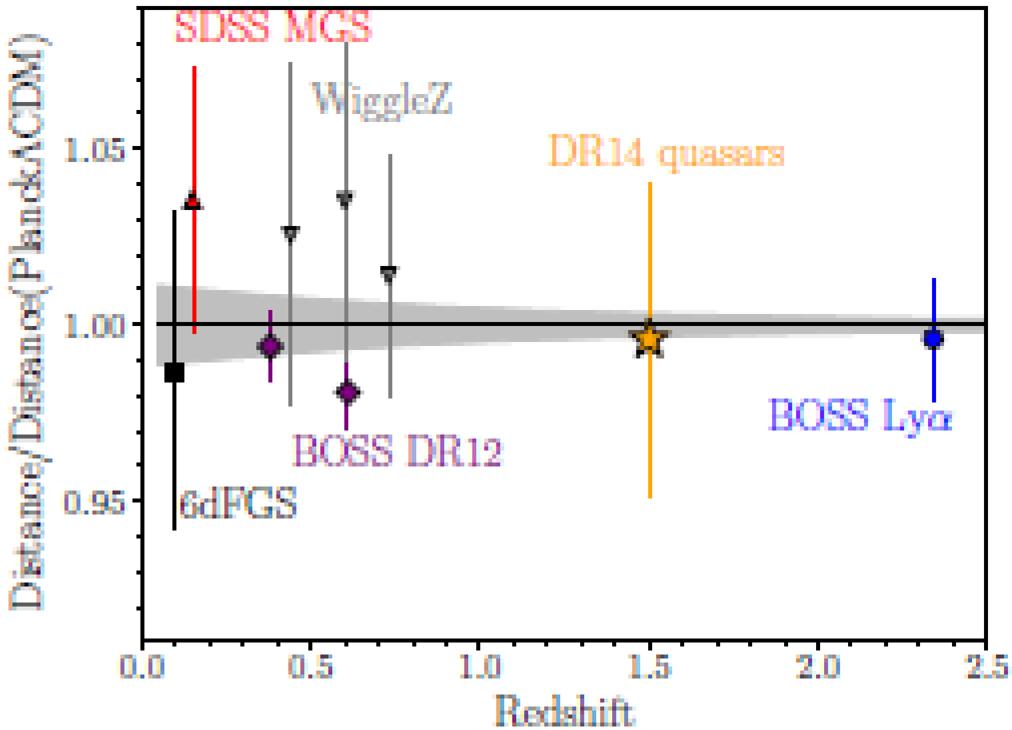


Correlation between luminosity and rate of decline of the light curve, for *SLSNe* (under study)

If *SLSNe* could be used as *calibrated candles*, they would become powerful probes of the very high *z* universe

Inserra & Smartt (2014)

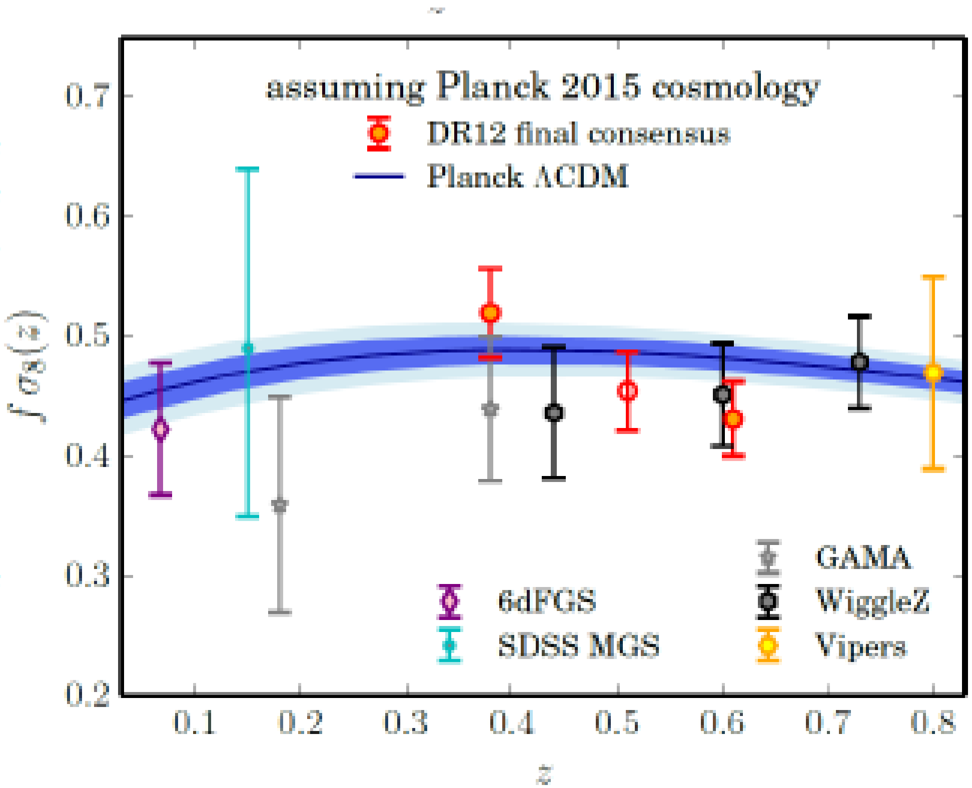
BAO information



Ata et al. (2017)

Spherically-averaged *BAO* distance measurements, compared to the Planck ΛCDM prediction and to its extrapolated 68% CL (gray area)

Information from galaxy clustering



Growth of structure from redshift-space distortions, measured at several redshifts

Alam et al. (2016)

SUMMARY

There are good prospects to reach just into the end of the "dark ages" with observation of SNe

Concerning SNeIa, *WFIRST* could be able to detect them even at $z > 7$, but their rate is predicted to progressively decline past $z \approx 1.5\text{-}2$

SLSNe, instead, will be detectable by *WFIRST* up to z = 14-17, and by the *JWST* and the future ultra-large telescopes up to $z \approx 22$, and there is the possibility of making them standardized candles (remember that an object having an absolute visual magnitude $M_V = -21$ would have an apparent magnitude $m_J = 30$ at a redshift $z \approx 14$, if we neglect extinction)

***SeeChange* has already the data to improve by a factor of 3 the current contraints on the *EOS* of DE, in the interval $1 < z < 2$**