Improving measurements of Dark Energy with Type Ia Supernovae by using the largest photometric samples

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2/26/2020

Outline

1: Cosmological context

2: Background on using stars for distance measurements

3: SNIa cosmology today

4: My contributions so far

5: Looking ahead to future work

Cosmology is the history of how the universe came to be

We are in a golden age for Cosmology –

- Current surveys run by international collaborations
- Mapping large areas of the night sky
- Vast amounts of data and information collected and processed each night
- Observational and theoretical improvements abound

A large and expanding universe

Today we know that the universe is infinite, isotropic, homogenous and expanding. A byproduct of this expansion is that most of what we see in the sky is undergoing a doppler shift to redder wavelengths. This redshift -

$$z \equiv \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$

is often colloquially used as both a velocity and a time scale. We use redshift to define the scale factor of the universe:

$a = (1+z)^{-1}$ which tracks the relative expansion

A Short Overview of Friedmann–Lemaître–Robertson–Walker (FLRW)

2 equations

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3} \times (\rho + 3p) + \frac{\Lambda}{3}$$

$$\frac{\dot{a}^2 + kc^2}{a^2} = \frac{8\pi G\rho + \Lambda c^2}{3}$$

FLRW assumes an adiabatic expansion of the universe. It is possible to treat the components of the universe as a liquid with the equation-of-state:

$$w \equiv \frac{p}{\rho}$$

Assuming *w* is a constant, then

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

G is Newton’s Gravitational Constant
ρ is energy density
P is pressure

k is curvature
c speed of light
Λ is the cosmological constant

Proof the universe is accelerating

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3} \times (\rho + 3p) + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -(\frac{4\pi G}{3}) \times \sum_i \rho_i (1 + 3w_i)$$

$$q \equiv -(\frac{\ddot{a}a}{\dot{a}^2}) = \Omega_R(z) + \frac{1}{2}\Omega_m(z) + \frac{(1+3w)}{2}\Omega_\Lambda(z)$$

We can split the second Friedmann equation into component parts – matter, radiation, curvature, and dark energy. Defining a critical density

$$\rho_c \equiv \frac{3H^2}{8\pi G}$$

And using the definition

$$\Omega_i = \frac{\rho_i}{\rho_c}$$

We can define the deceleration parameter q

Measuring distances

- Can’t just use a ruler
- But we know that light sources radiate as $1/d^2$
- So we can relate the apparent brightness (m) to the absolute luminosity (M) of an object:

$$m=\frac{M}{4\pi d^2}$$

- Astronomers typically express this in magnitudes as the distance modulus:

$$\mu=m-M=5\log\left(\frac{d}{10}\right)$$

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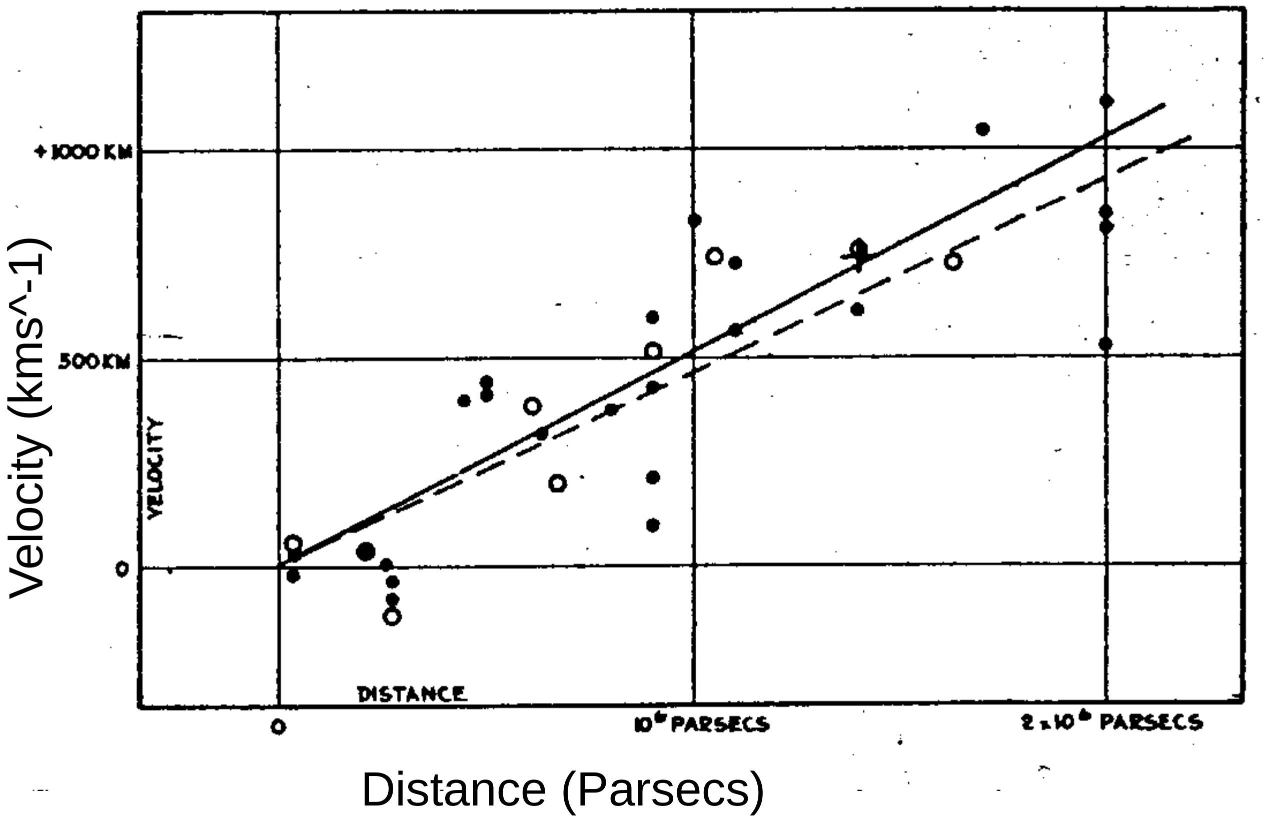
A Short History of Stellar Distance Measurements

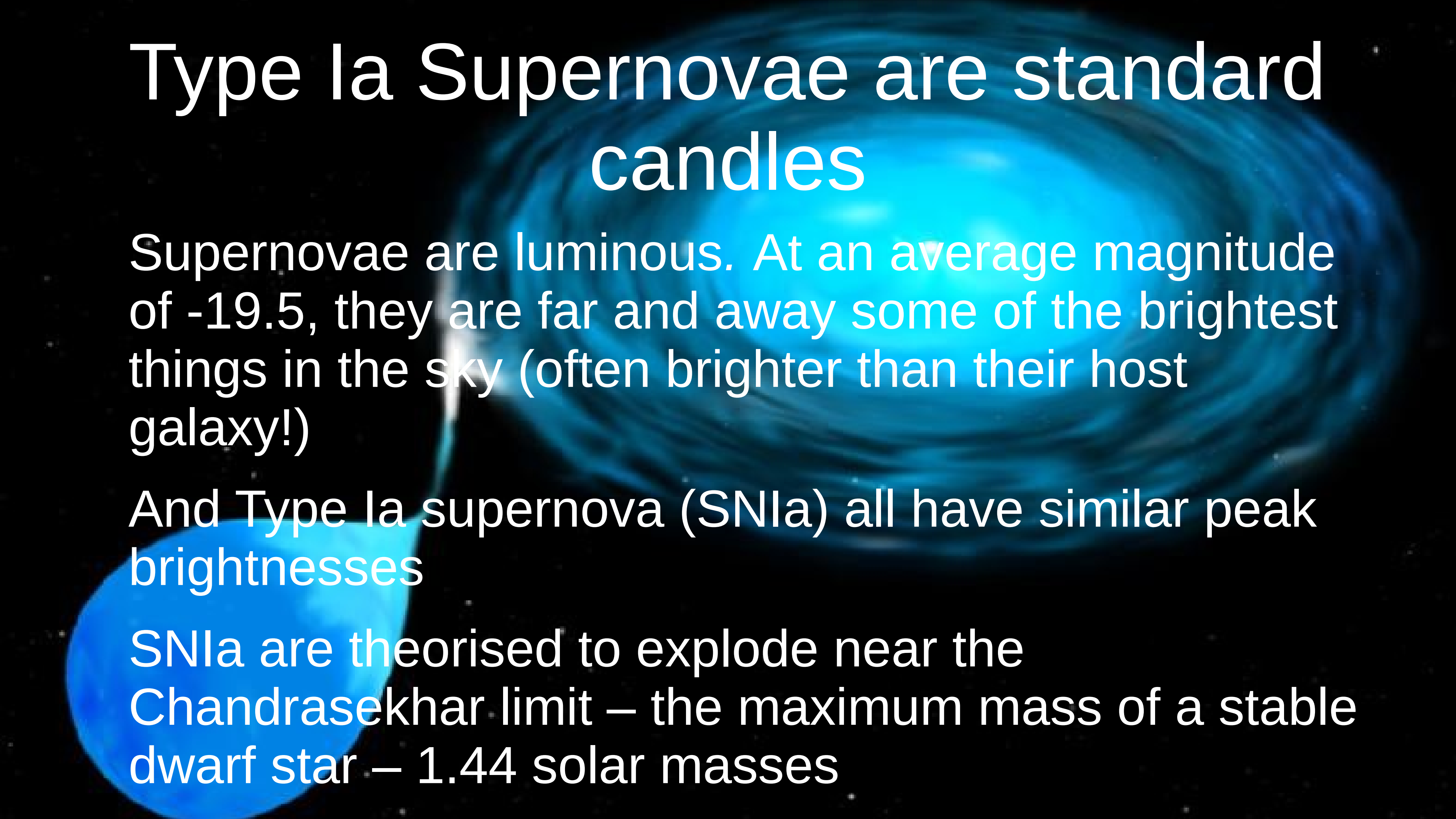
- 1912 – Cepheids (a class of star with variable brightness) discovered as a viable measurement tool
- 1929 – Hubble measures an expanding universe
- 1970 – Supernovae suggested as a potential option
- 1998 – Accelerating expansion of the universe discovered with supernovae

The universe is expanding



Hubble used Cepheids to measure the expansion of the universe (Hubble 1929)

This is the *first time* we have proof that the universe is larger than our galaxy!



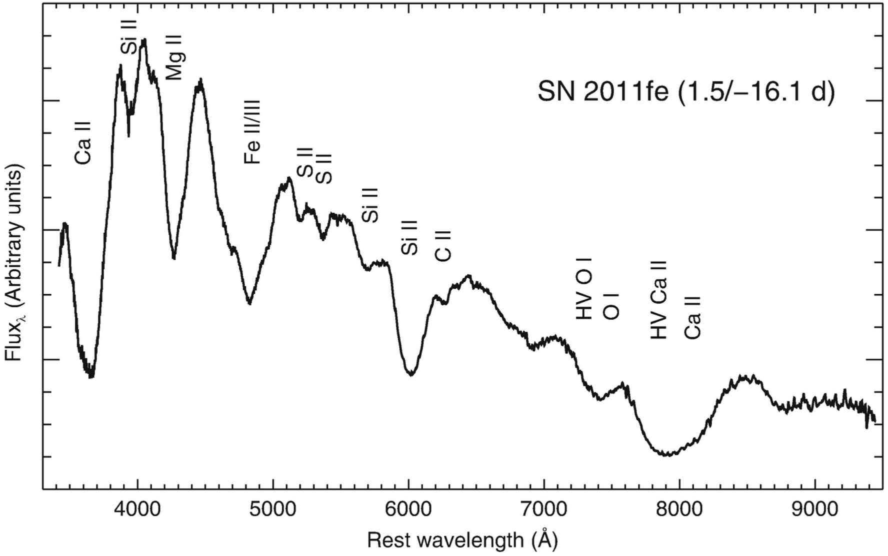
Type Ia Supernovae are standard candles

Supernovae are luminous. At an average magnitude of -19.5, they are far and away some of the brightest things in the sky (often brighter than their host galaxy!)

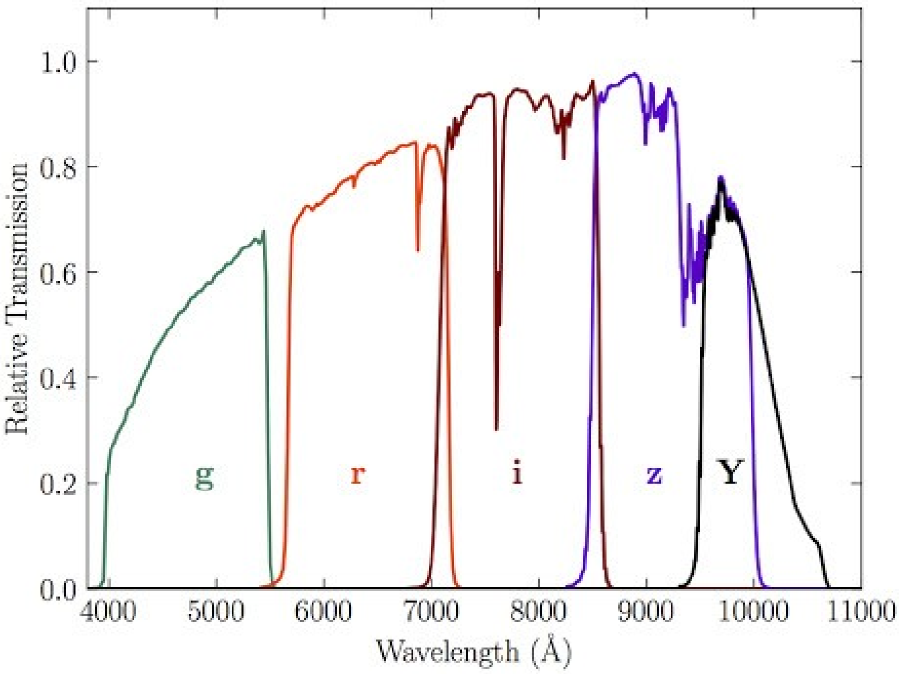
And Type Ia supernova (SNIa) all have similar peak brightnesses

SNIa are theorised to explode near the Chandrasekhar limit – the maximum mass of a stable dwarf star – 1.44 solar masses

Spectroscopy and Photometry



Spectroscopy – Continuous range



Photometry – integrated bands

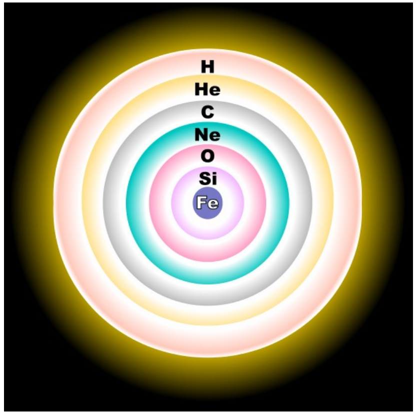
Types of Supernovae

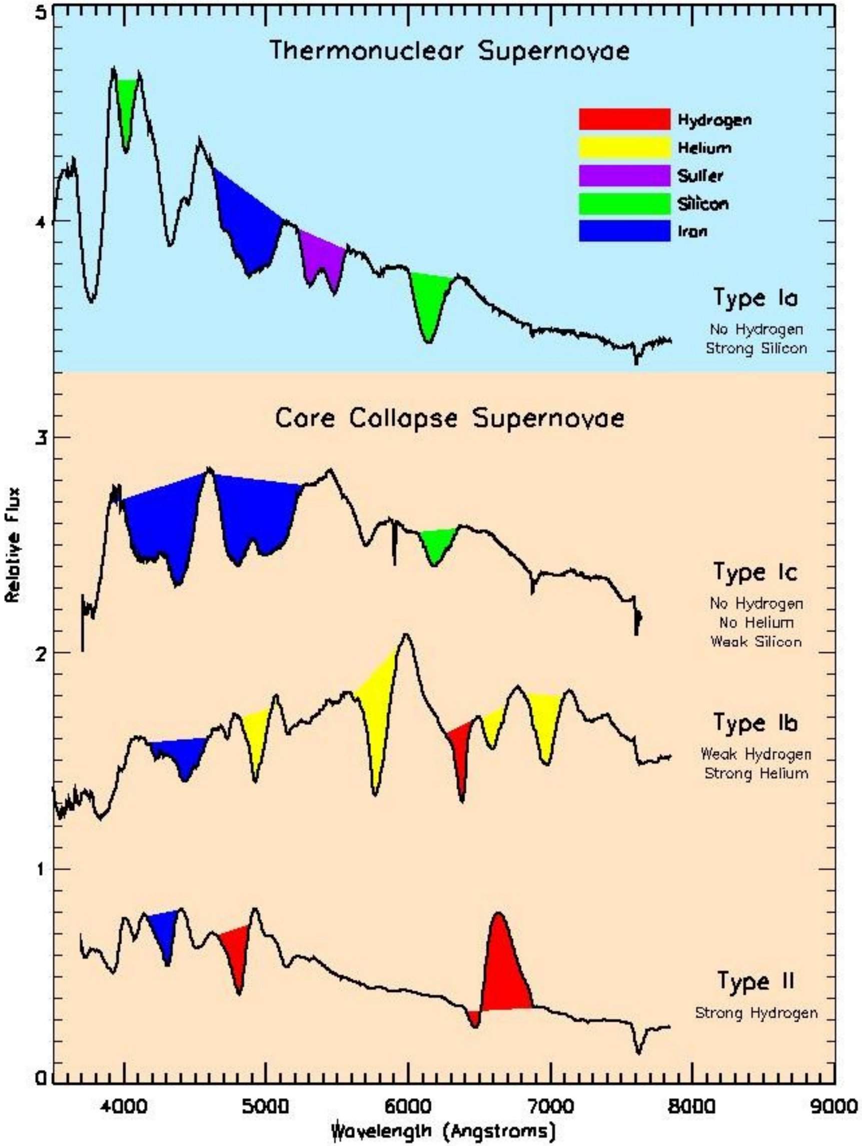
Over the next several years, we learn that Type I comprises three subtypes: Ia, Ib, and Ic.

Ib and Ic are more similar to Type II – core collapse.

Core collapse

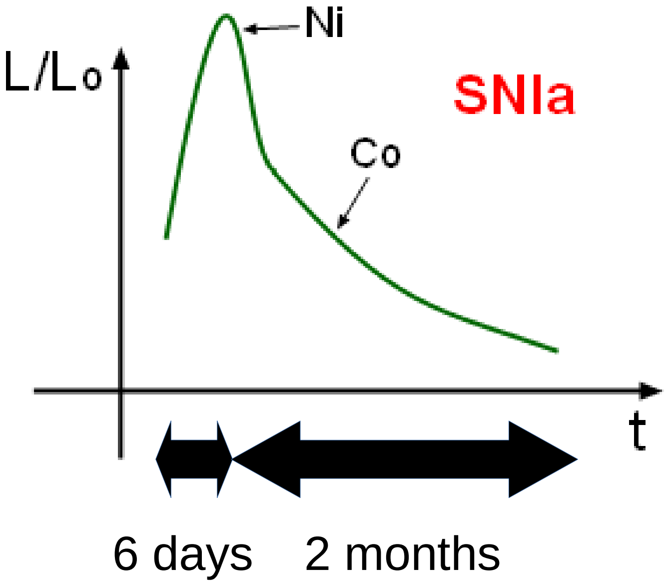
occurs in active stars





SNIa Light-curves

- The peak brightness is dominated by the radioactive decay of Nickel
- Once Nickel is burned through, Cobalt decays into Iron.
- $Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$

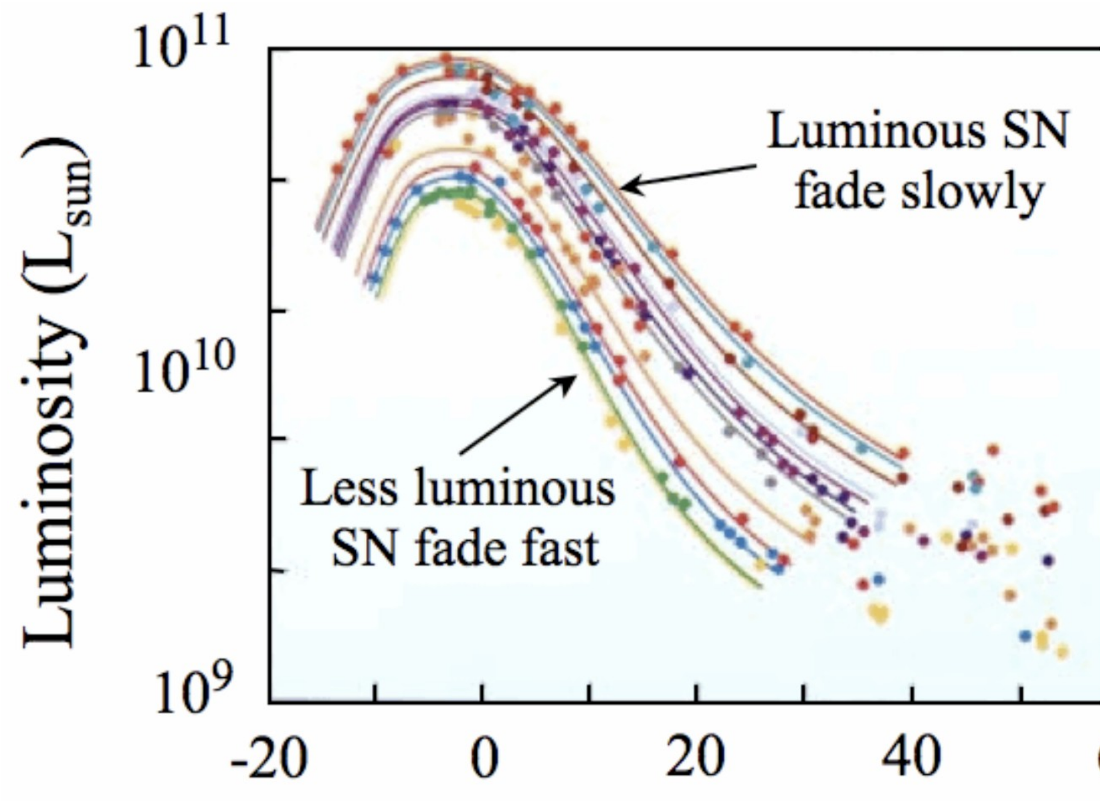


SNIa are standardisable candles

By the mid-1990s, observed ~0.5 mag dispersion in SNIa peak brightness

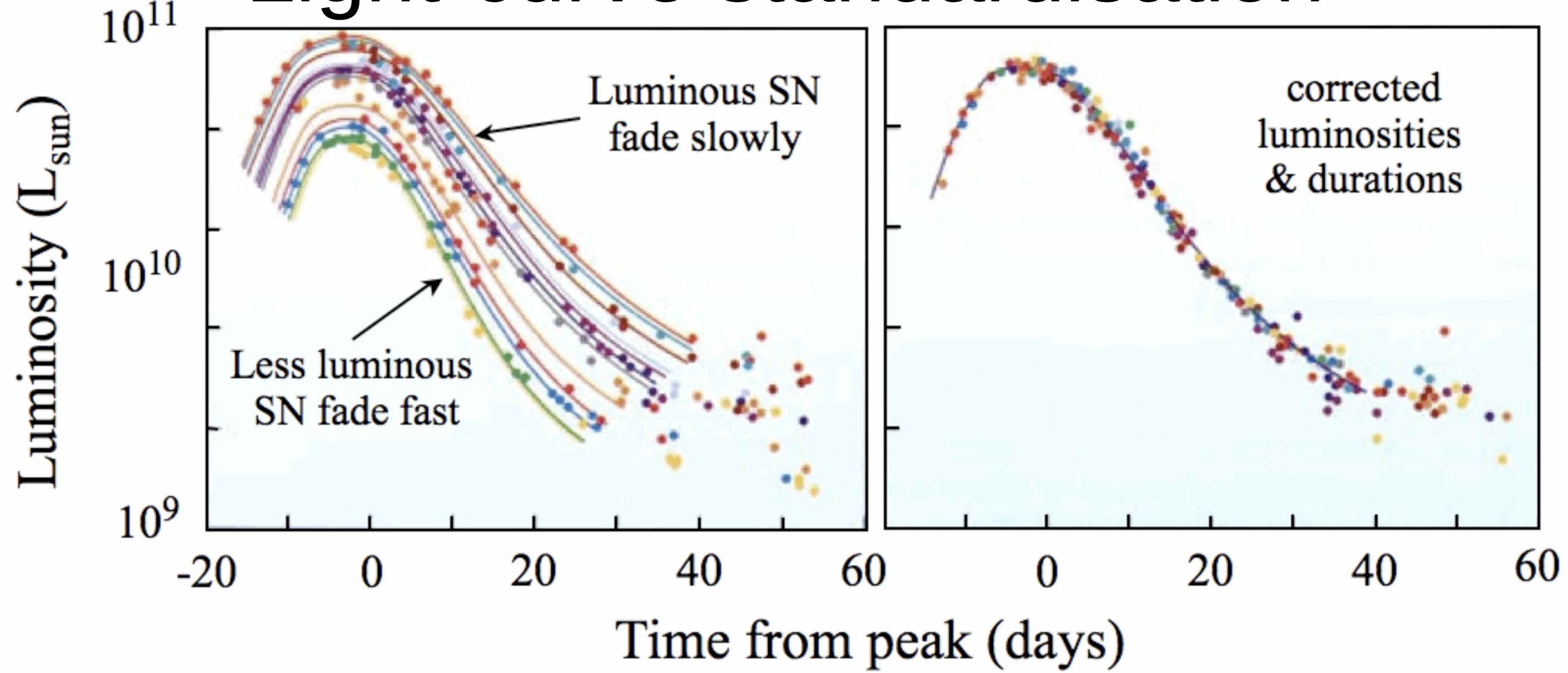
Related to decline rate of light-curve

Amount of reddening also related to peak brightness.



Time (days)

Light-curve standardisation

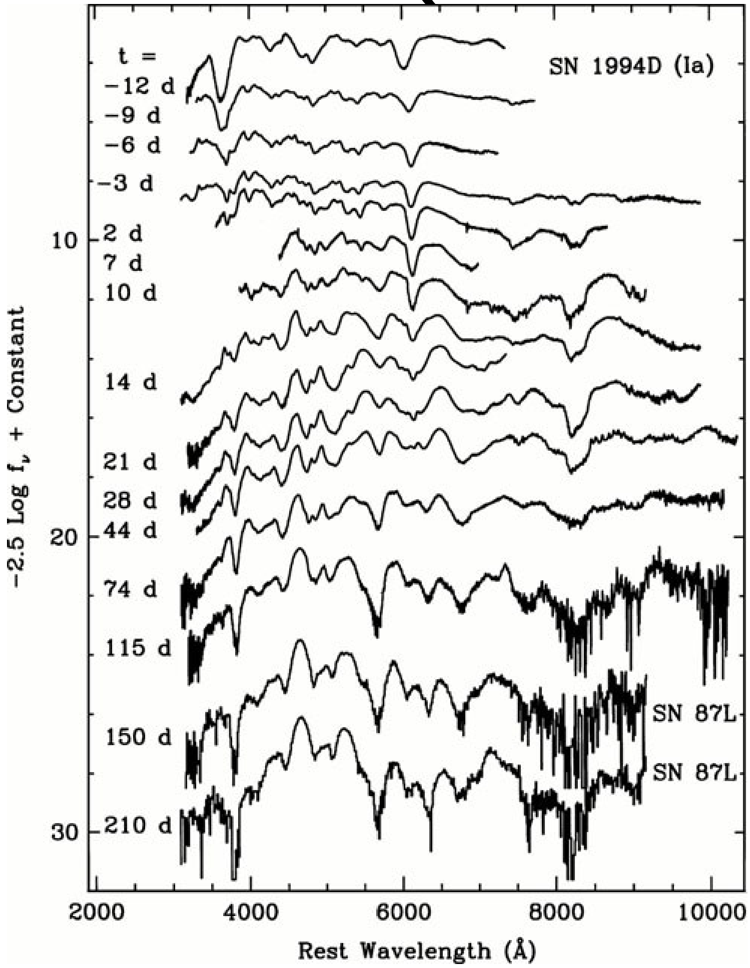


This standardisation decreases SNIa dispersion from 0.5 mag to 0.1 mag – a factor of x5 improvement in precision!

SALT2 is the gold standard(isation)

The modern method for standardising SNIa is SALT2 (Guy et al. 2010). It uses a functional flux model fit to a number of high quality SNIa light-curves and spectra.

Works in spectral space and integrates over specified filters to produce light-curves.



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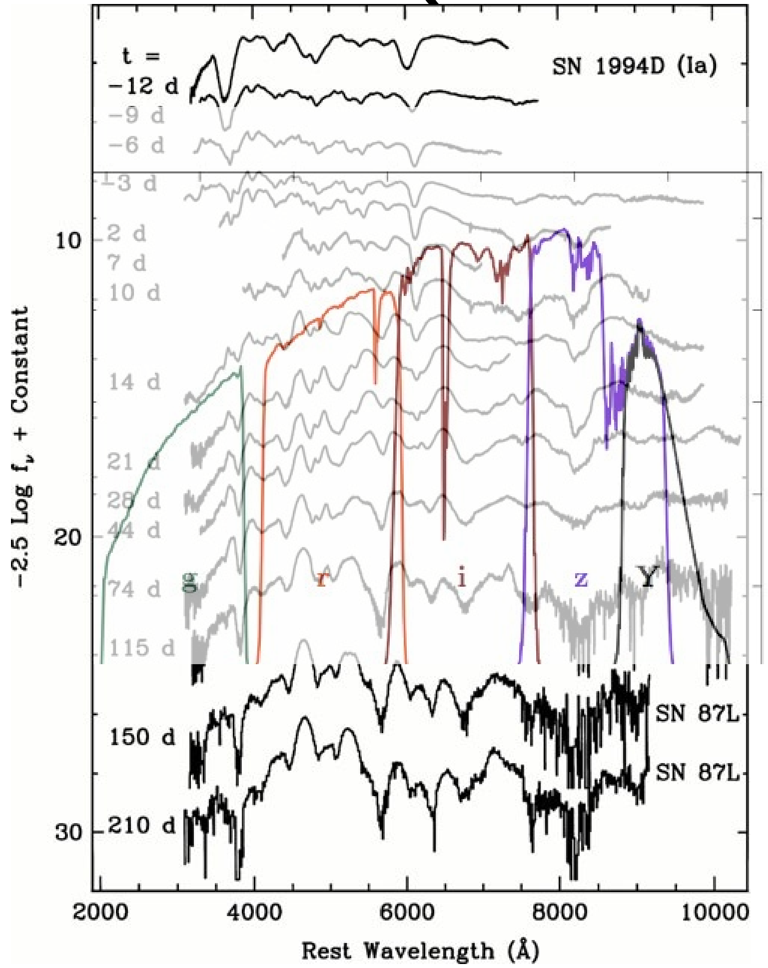


SALT2 gives distance measurements

Now we have a model – what good is it?

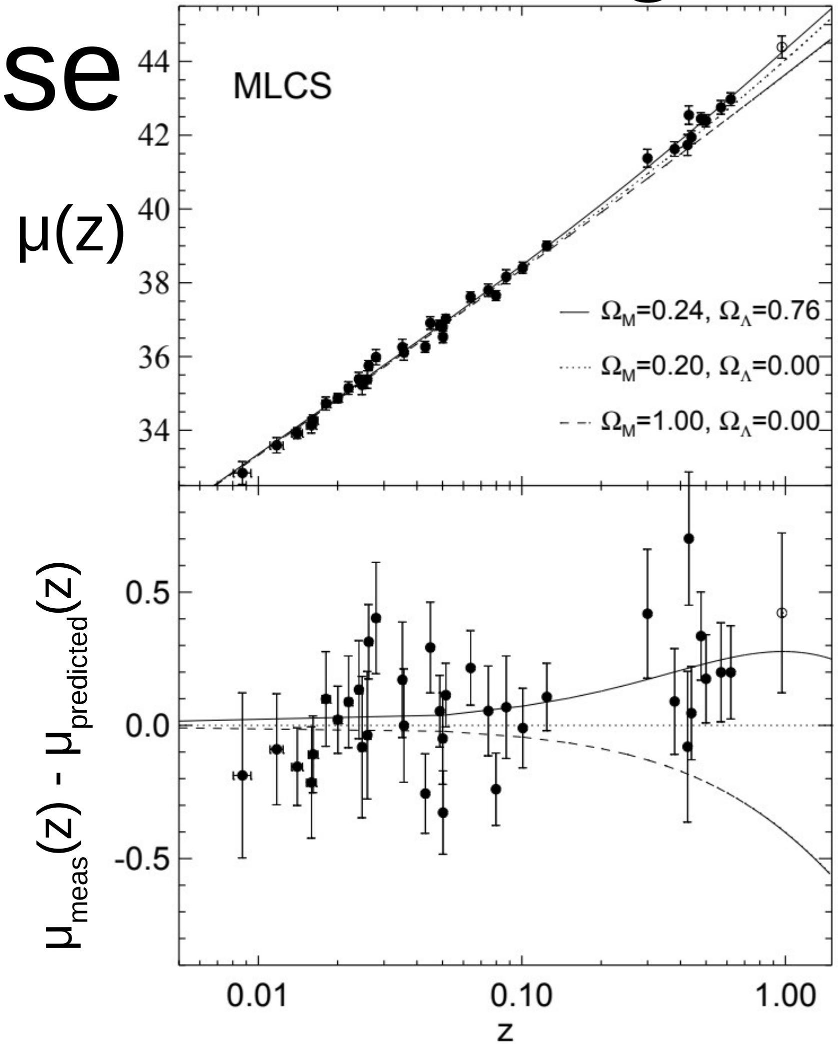
We can use the output of SALT2 to normalise the SNIa distance!

$$\mu = M - m = m_B + \alpha x_1 - \beta c - M_0$$

- m_B is peak brightness
- x_1 is related to the light-curve width
- c is colour, or the difference in flux between two filters
- M_0 is the average absolute luminosity of an SNIa (~-19.5 mags)
- α and β are global nuisance parameters

SNIa discover an accelerating universe

Riess et al. (1998) and Perlmutter et al. (1999) use SNIa to discover that the expansion of the universe is accelerating.



Proof the universe is accelerating

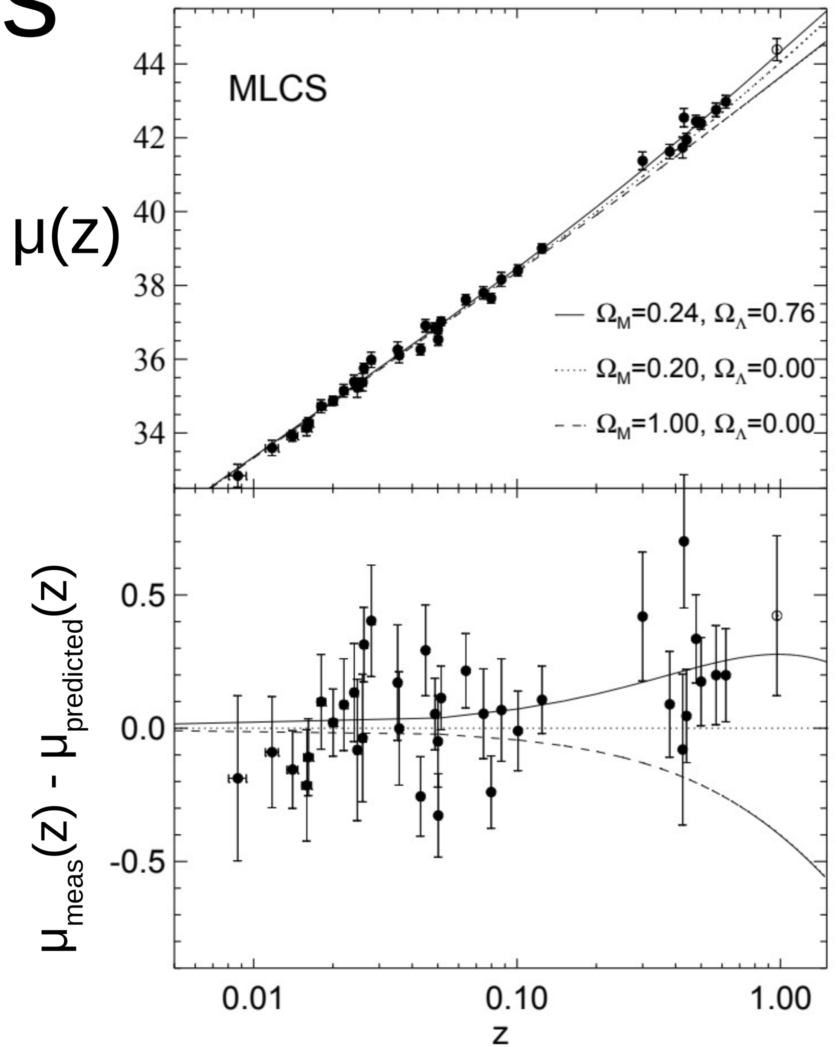
Remember our deceleration parameter:

$$q \equiv -\left(\frac{\ddot{a}\,a}{\dot{a}^2}\right) = \Omega_R(z) + \frac{1}{2}\Omega_m(z) + \frac{(1+3w)}{2}\Omega_\Lambda(z)$$

Evaluated at z=0, *w* = -1:

$$q_0 = \frac{1}{2}\Omega_m - \Omega_\Lambda$$

Riess et al. 1998 find q_0 = -0.9!



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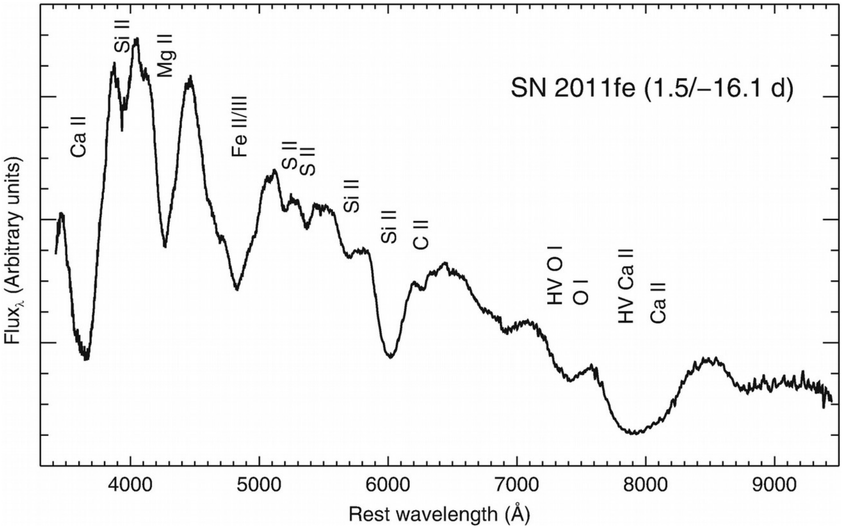
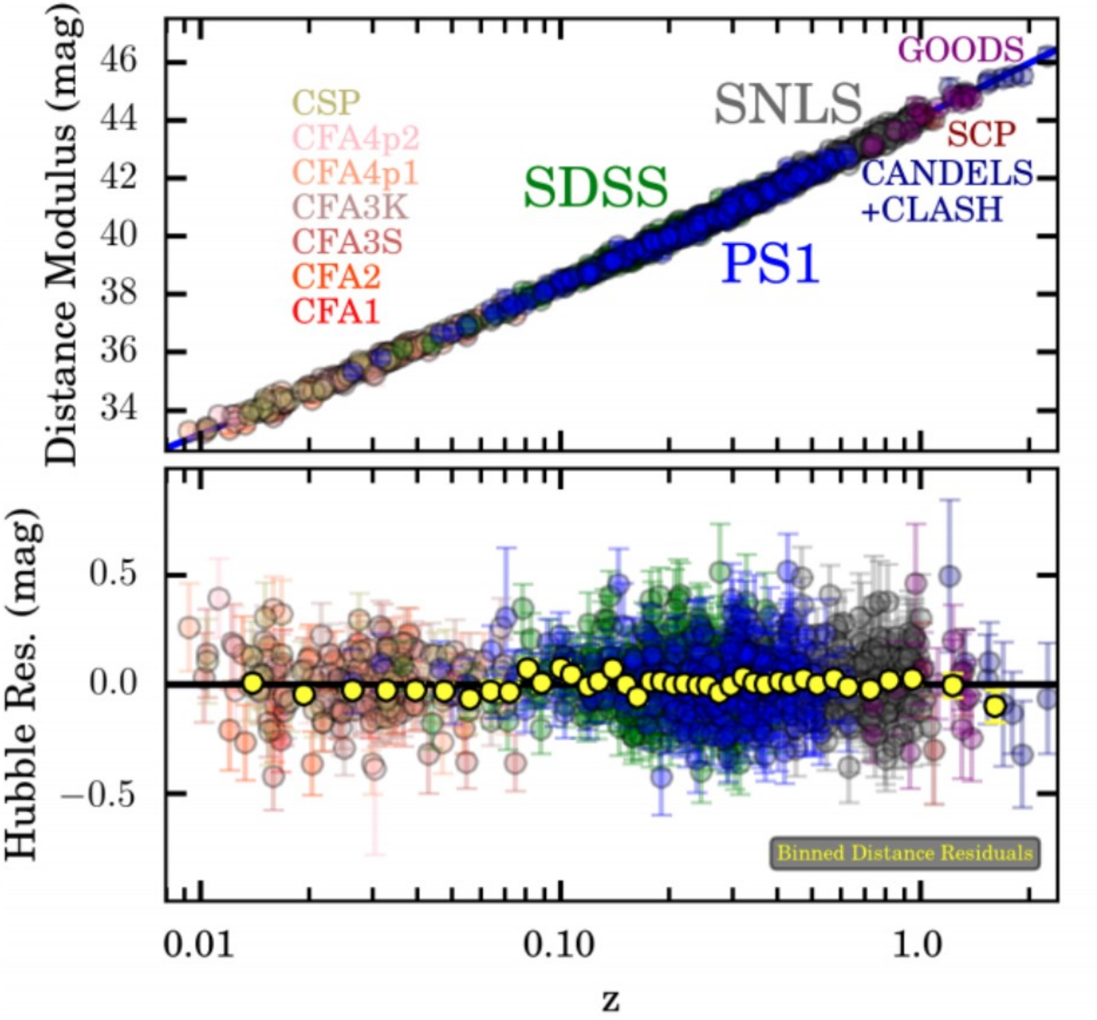
SNIa cosmology today

- Primarily done with spectroscopically confirmed samples
- This makes identification of SNIa easy, and keeps core collapse (CC) contamination minimal. ~0%
- Easier to get redshift – SNIa itself and the host galaxy
- Unfortunately spectroscopy is expensive – takes an hour per night per supernova! We'd need hundreds of spectrographs!



Modern SNIa cosmology



BAO: Baryon Acoustic Oscillations

CMB: Cosmic Microwave Background

Scolnic et al., 2018

Modern problems require modern solutions

- We are statistically limited right now.
- Need a way to work with larger volumes of data
- This is what simulations aim to do – use high quality Spectral Evolution Distributions (SEDs) to generate light-curves of supernovae and build simulacra of surveys that might have been.
- *Not* simulating explosions, but drawing from and modifying observed SNIa and CC SEDs/light-curves to produce new ones

SuperNova Analysis software

- The Supernova Analysis software (SNANA) is the leading simulation program
- Used for validation, bias corrections, and methods testing
- Incredibly helpful to know ‘true’ values
- Are able to forward-model assumptions about Sne/the universe and see if it replicates results

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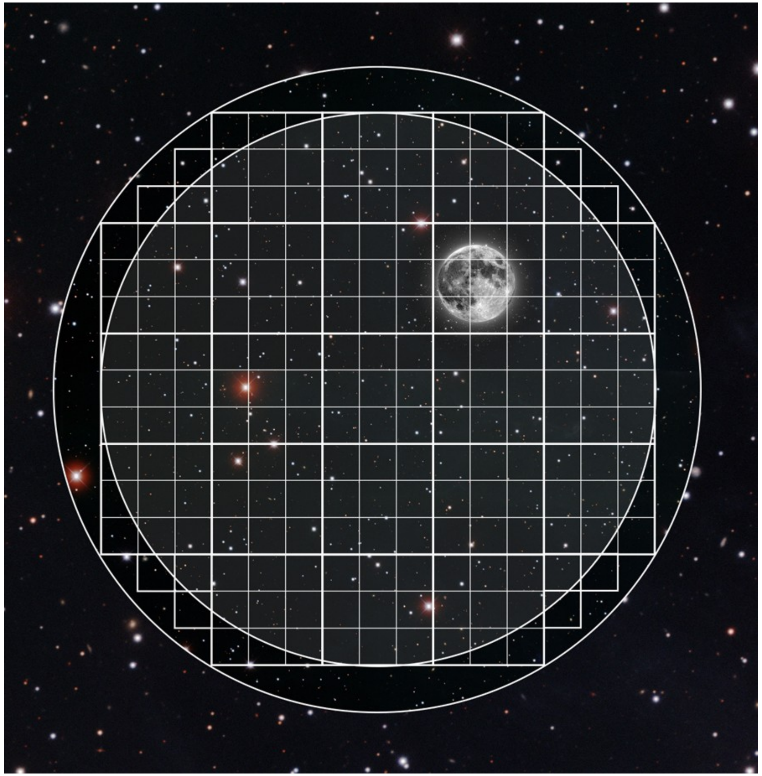
SNIa cosmology is moving away from spectroscopy

- Current individual samples from surveys comprise hundreds of usable (ie with spectra) SNIa
- Very impressive, but as mentioned, spectroscopy is unfeasible for larger samples
- Will need to move towards photometry for classification and redshift to properly use all the SNe that will be observed



3.5 square degrees!

This is the past/current/future status of SNIa surveys

	Past/Current	Current/Future	More Future
Low-z: z<0.1	CfA1-4, SNF, CSP	CSP,PTF, Foundation	LSST? ZTF?
Mid-z: 0.1<z<1.0	SDSS,SNLS, ESSENCE	PS1,DES 10% spec. followup!	LSST/WFIRST
High-z: 1.0<z	HST	HST-CANDELs/ Frontier,SUSHI	WFIRST
#s:	~1000	~6,000 →	~400,000

LSST
Legacy Survey of Space and Time

WFIRST
Wide-Field Infrared Survey Telescope

PS1
Pan-STARRs

DES
Dark Energy Survey

SDSS
Sloan Digital Sky Survey

My thesis in a single sentence

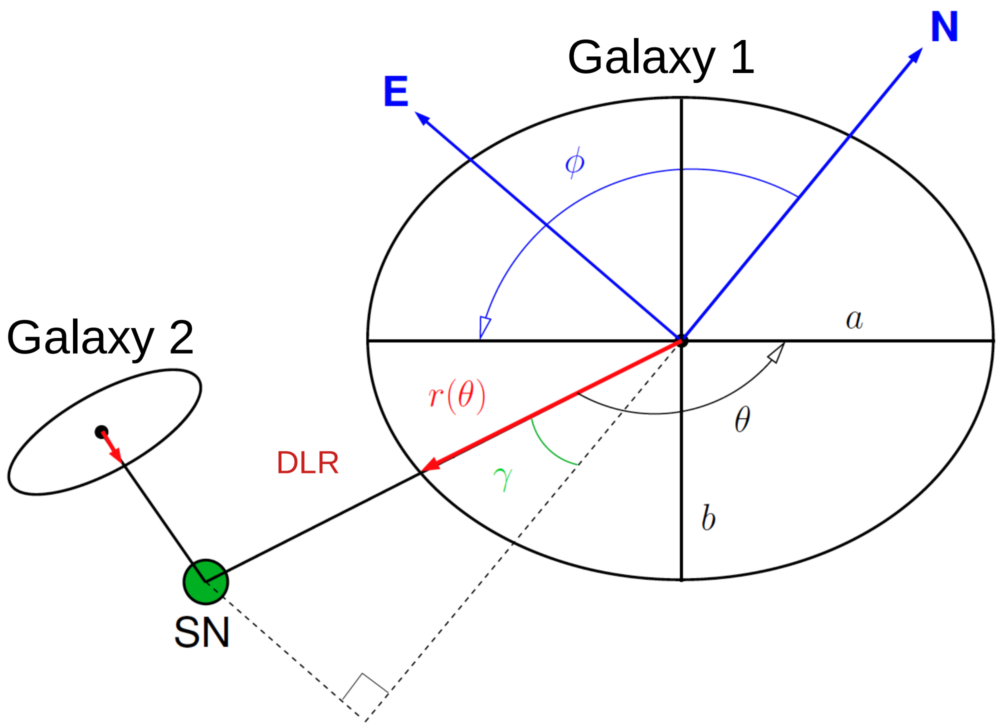
"Determine the best constraint on dark energy by using photometric samples after overcoming challenges unique to photometric samples"

Unique challenges I’ve tackled in photometric surveys

- Mis-associated redshifts
  - Will have to rely on follow-up spectroscopic measurements of galaxies. Galactic redshift is more accurate than the SNIa based. Did we choose the right galaxy?
- Core Collapse contamination
  - Without Spectroscopy, identification becomes more difficult. No Si or H lines to identify! Will need to classify from light-curves.
- Improved Systematics
  - Right now, ~70% of our uncertainty is statistical. As we get more statistics, this will put a greater emphasis on mitigating systematic uncertainties.

Finding redshifts without spectroscopic confirmation of SNIa

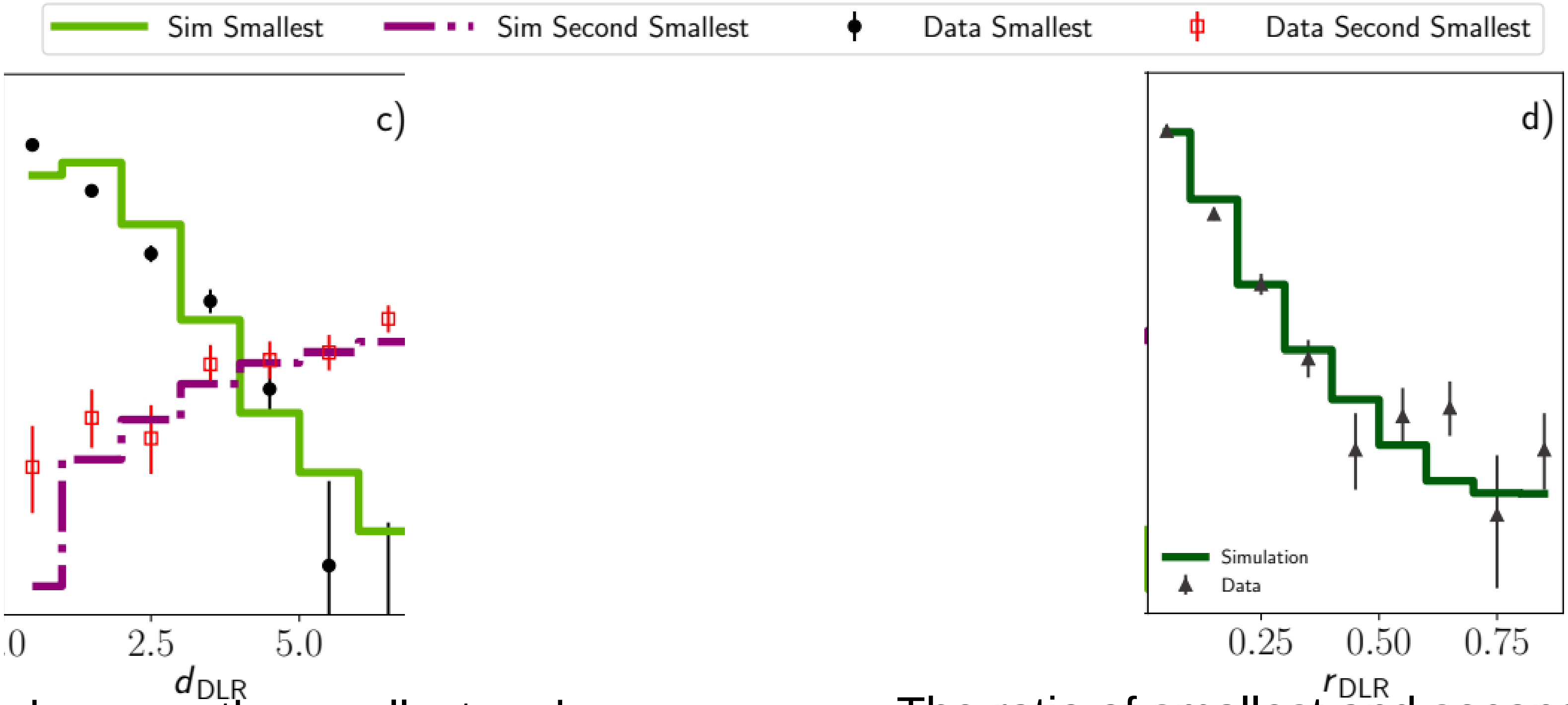
- We need to find redshift for our SNe!
- Gupta et al. 2014 suggest the Directional Light Radius (DLR) method
- DLR is the effective radius of the galaxy at a given angle
- Divide the angular separation by DLR to get d_{DLR}



We can use simulations to predict mis-association

- Take a large patch of the sky from your survey
- Develop a library of all observed galaxies within
  - Mass, photometry, shape, redshift
- Simulate supernovae in the sky, matching distance and shape distributions
- Calculate likely hosts
- Compare with true values
- Popovic et al. 2020 was the first time this was ever done!

Popovic et al. (2020) validates and predicts mis-association



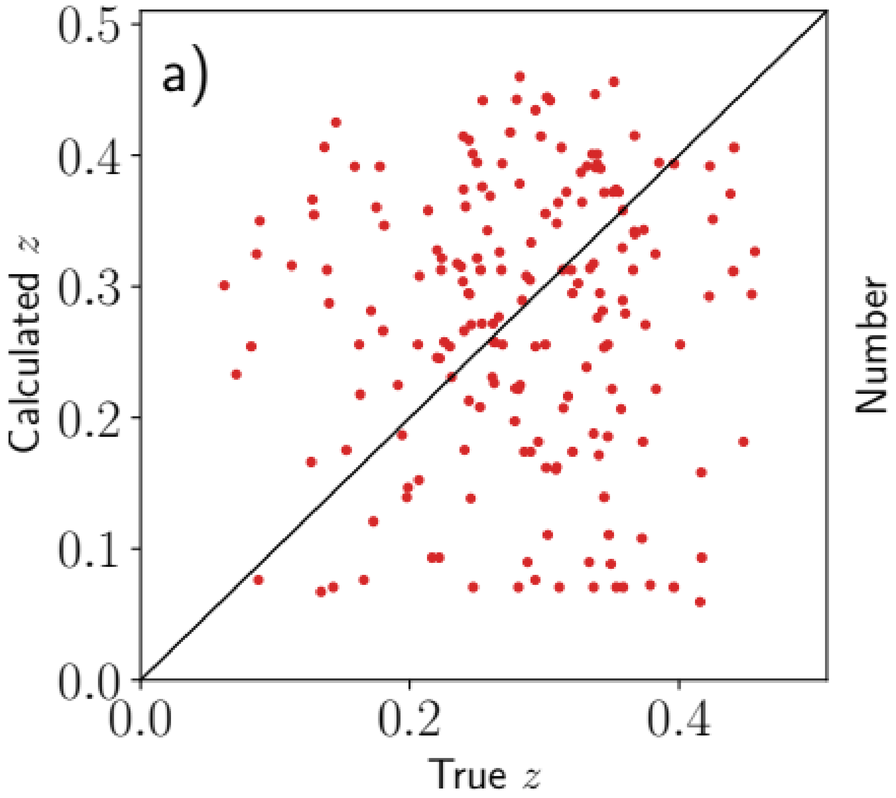
Shown here are the smallest and second smallest values of d_{DLR} for data and simulation

The ratio of smallest and second smallest d_{DLR} values can indicate host galaxy confusion

We want to measure biases due to the problem

- Data are one realisation of existing distribution
- Compare systematic on vs systematic off
- Use simulations to create 40 survey simulacra - 40 datasets that could have been.
- Can derive a mean *w* and a root mean square on *w*
- One of the first times using such a technique, and more descriptive than a single measurement

Mis-associations are varied in z range



Here we compare 40 samples with no host assignment errors to 40 samples where we can mis-associate hosts

Systematic Test	Δw_{sim}	w_{RMS}	Δw_{data}	N_{σ}
Mis-associated host	+0.007 (09)	0.0059	N/A	N/A

Statistical uncertainty is 0.1 in *w*
This is much smaller than that!

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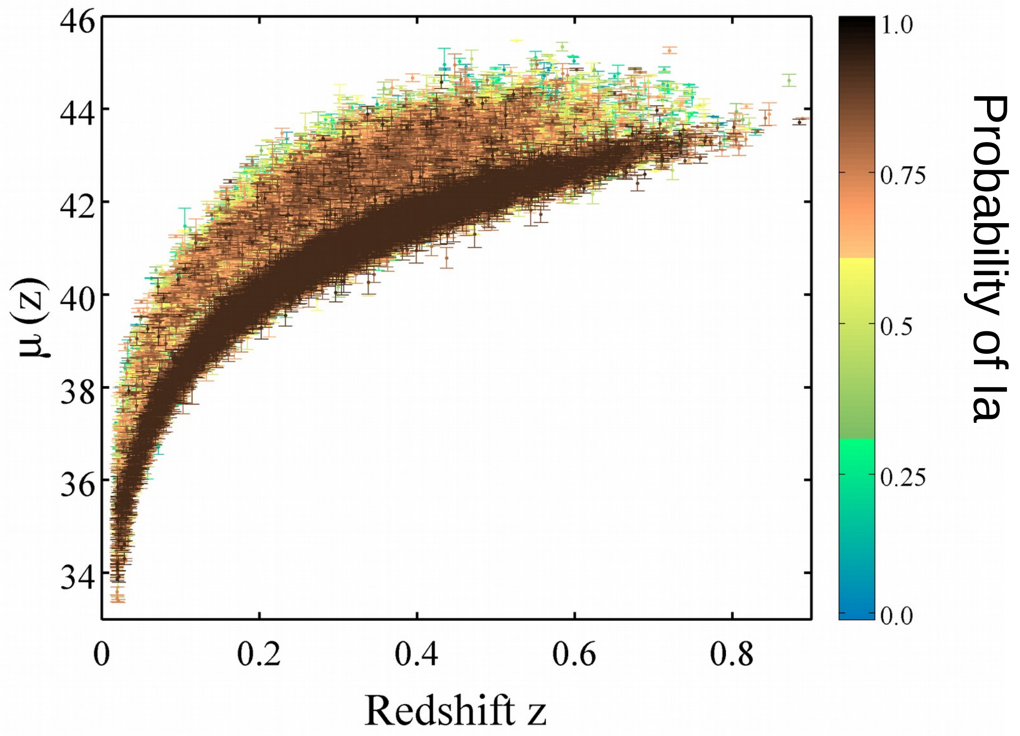
Bayesian Estimation Applied to Multiple Species (BEAMS)

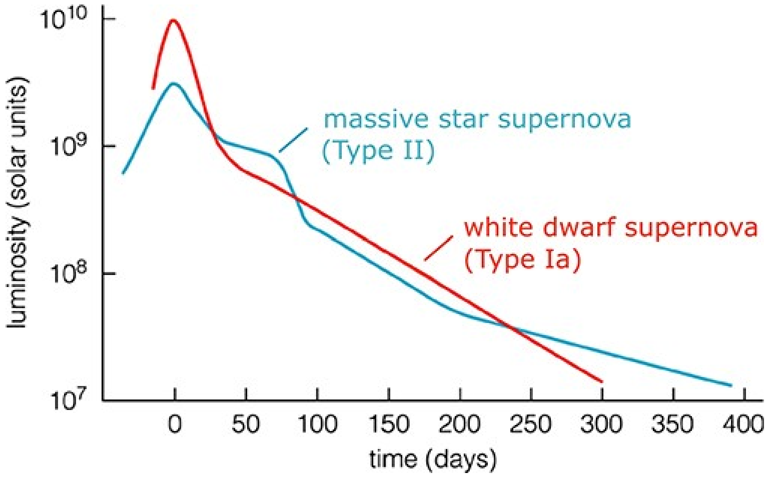
- We know there are two SNe populations – Ia and non-Ia
- Using probabilities, we can marginalise over CC contamination that pass cuts.
- Ethical
- Kessler and Scolnic (2016) combined this with other techniques in a process called BEAMS with Bias Corrections (BBC)



Hlozek et al. 2011

CC light-curves look different, but we are information limited

- We preferentially target SNIa: CC libraries are biased towards brighter events
- No way we can encapsulate the diversity of CC SNe with current information
- The Photometric LSST Astronomical Time-series Classification Challenge (PLAsTiCC) is the largest current library of non-Ia events (real and modeled).



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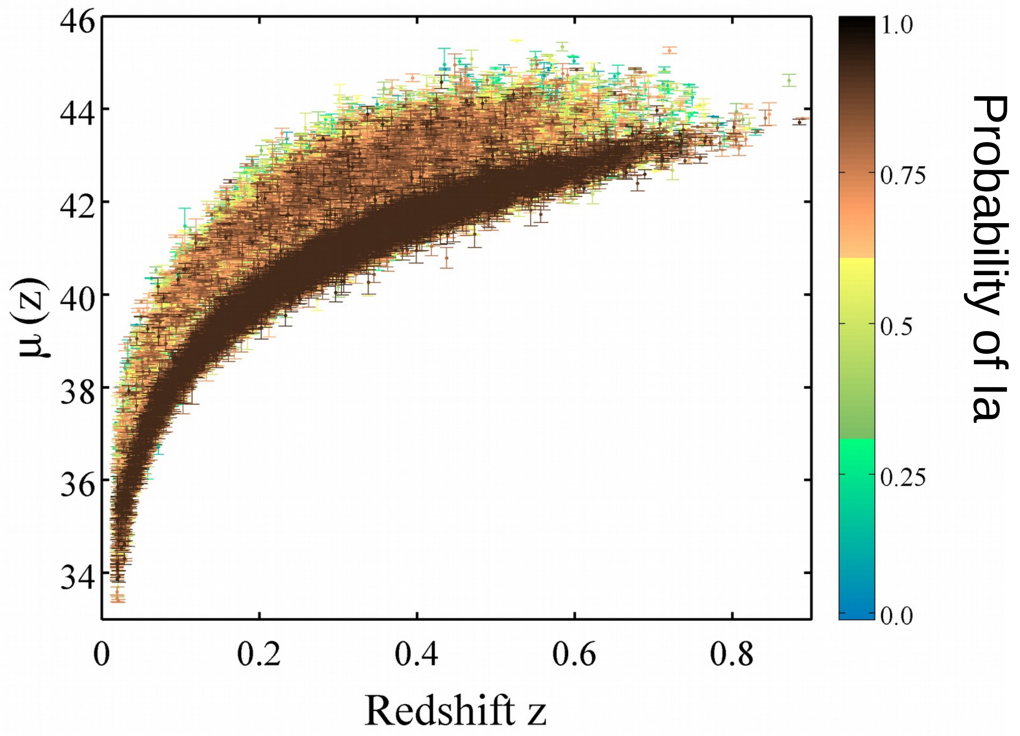
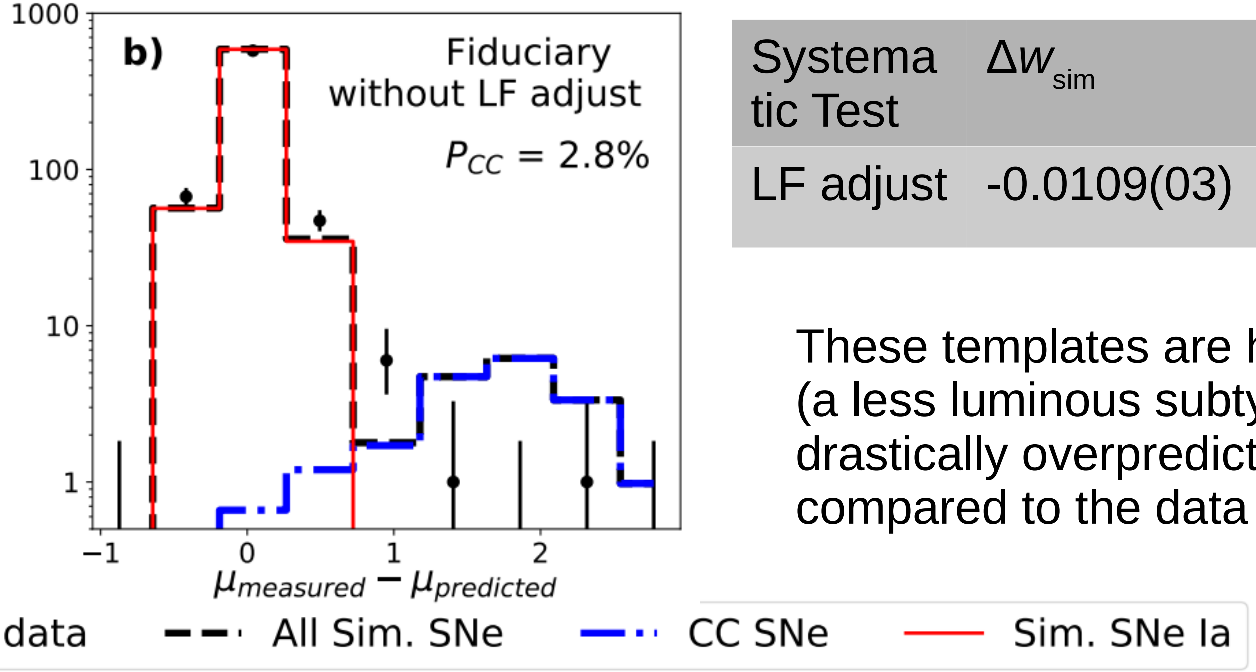


Hlozek et al. 2011

Incomplete CC information affects our results

This is a histogram of the difference between data and predicted theory – a perfect sample would be a delta function at 0



If Core Collapse SNe obey a different luminosity function (LF) than we predict, it affects our measurements.

Systematic Test	Δw_{sim}	w_{RMS}	Δw_{data}	N_{σ}
LF adjust	-0.0109(03)	0.0192	-0.041	1.57σ

These templates are human made – I found the Iax (a less luminous subtype of Ia) templates drastically overpredicted Iax in simulations compared to the data

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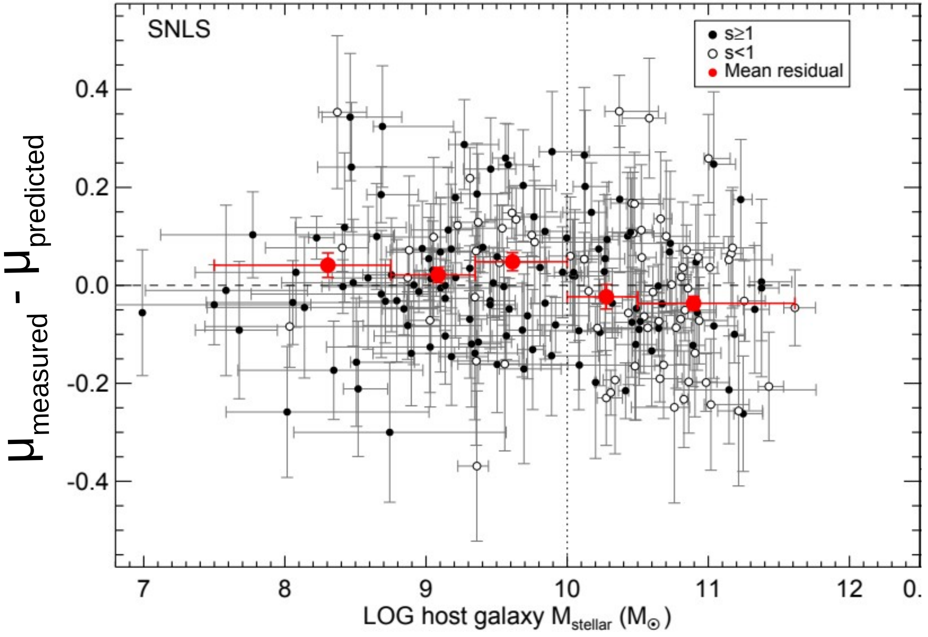
SNIa are affected by local environs

- Sullivan et al. 2010 discovered that SNIa properties seemed to correlate with their host galaxy.
- SNIa in host galaxies with stellar log mass > 10 are, on average, brighter than their low mass counterparts.
- If host galaxies evolve with redshift, this could be a cosmological bias!!



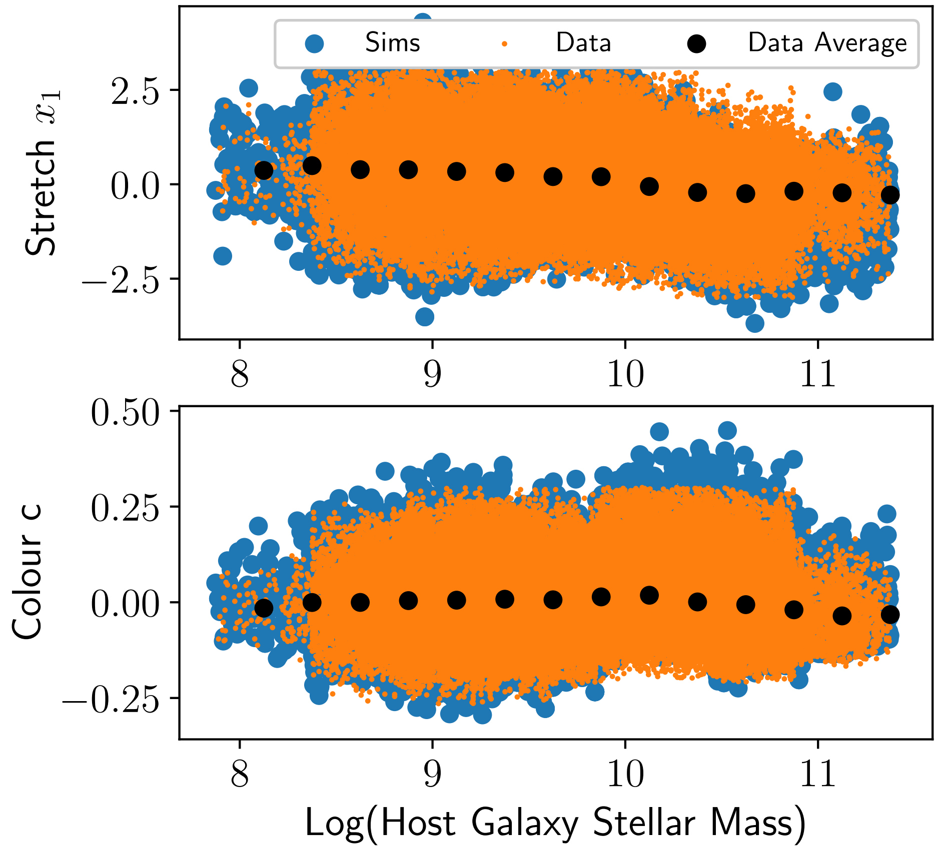
This is referred to as the mass step, or γ

The challenging part is that host galaxy properties correlate with SNIa properties

The stretch parameter correlates especially strongly with log mass.

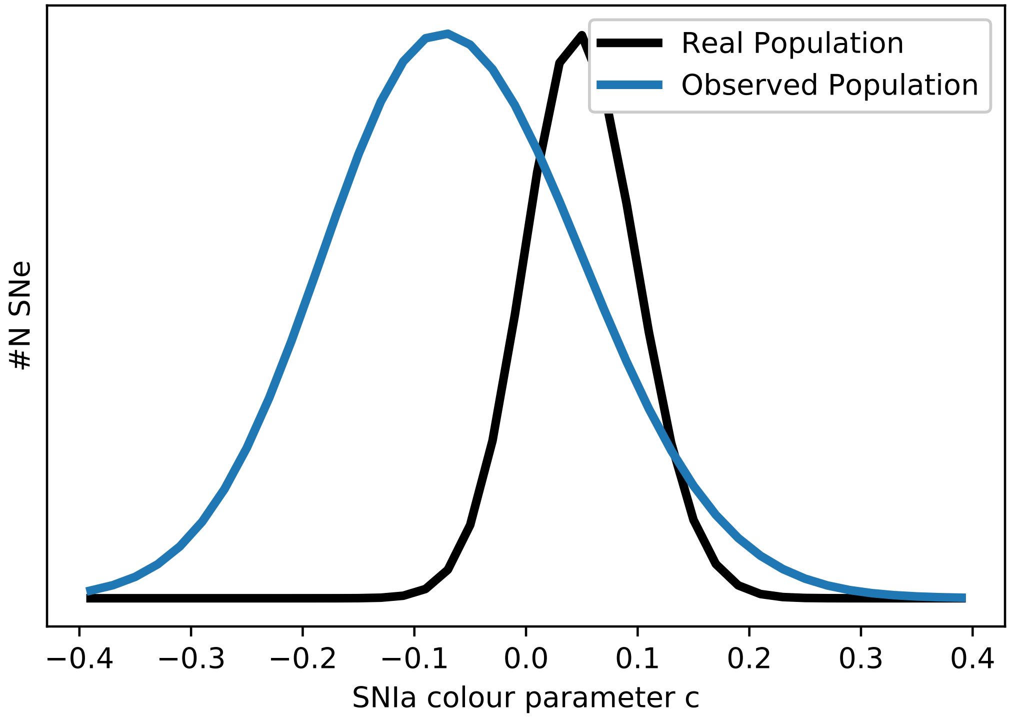
Want to do simultaneous fit for Hubble Diagram; however, high covariance among parameters

Do the parent populations of c and x_1 depend on mass?



Selection effects bias our results!

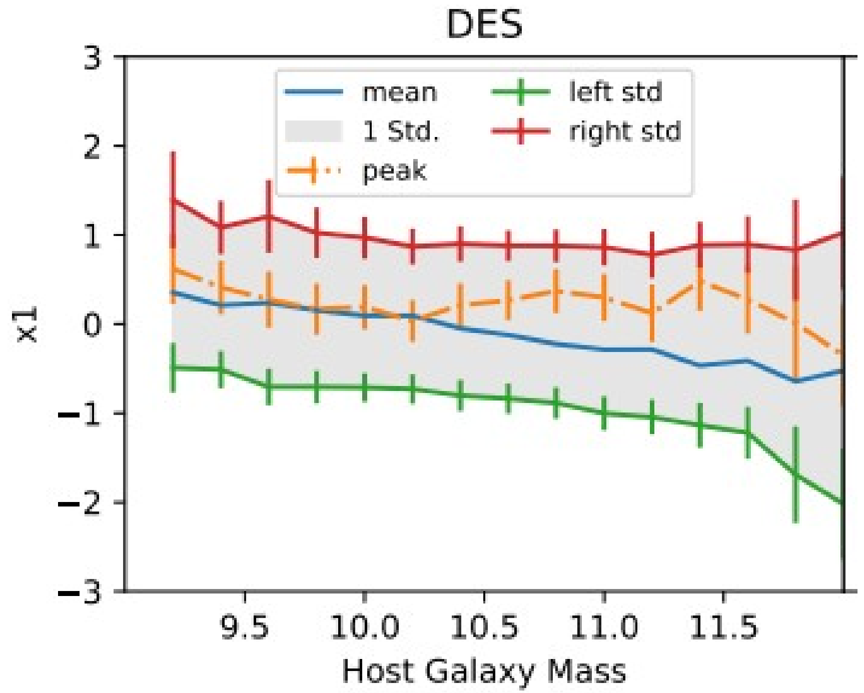
- We know that measurement noise, intrinsic scatter, and selection effects distort our observed values.
- We can forward model this with an asymmetric Gaussian and simulations – what inputs are likely to come out matching our data?
- If we know how our distributions change, we can correct for it



c is an observed value!

Popovic et al. 2020b (in prep) has made first measurement of underlying correlation between x_1 and mass

Using simulations I derived the dependence of parent populations with host galaxy mass. Shown here is stretch.

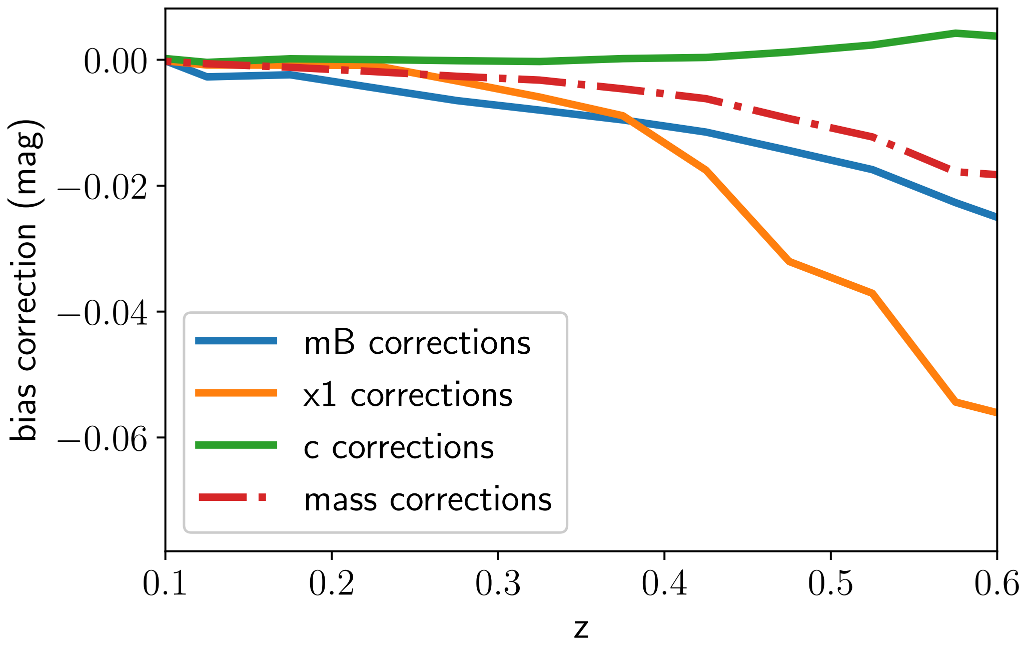


Host galaxy correction always done after the fact – here we can model it and track covariances for the first time

Make realistic libraries of galaxies

Bias Corrections with simulations

- We know our observed values stray from the truth. But we can fix this with simulations.
- Take a large, 5D phase space of $\{z, x_1, c, \alpha, \beta\}$
- Split it into cells, and find the average difference between observed and input values.
- I added two extra dimensions, mass and γ, to account for those correlations



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Lots of work left to do

- Working on analysing the first ever combined photometric sample (Popovic et al. 2020c)
- Dark Energy Survey (DES) 5 year analysis
- Popovic et al. 2020b in write-up stage
- Much left to do with assigning host galaxies

Future Work

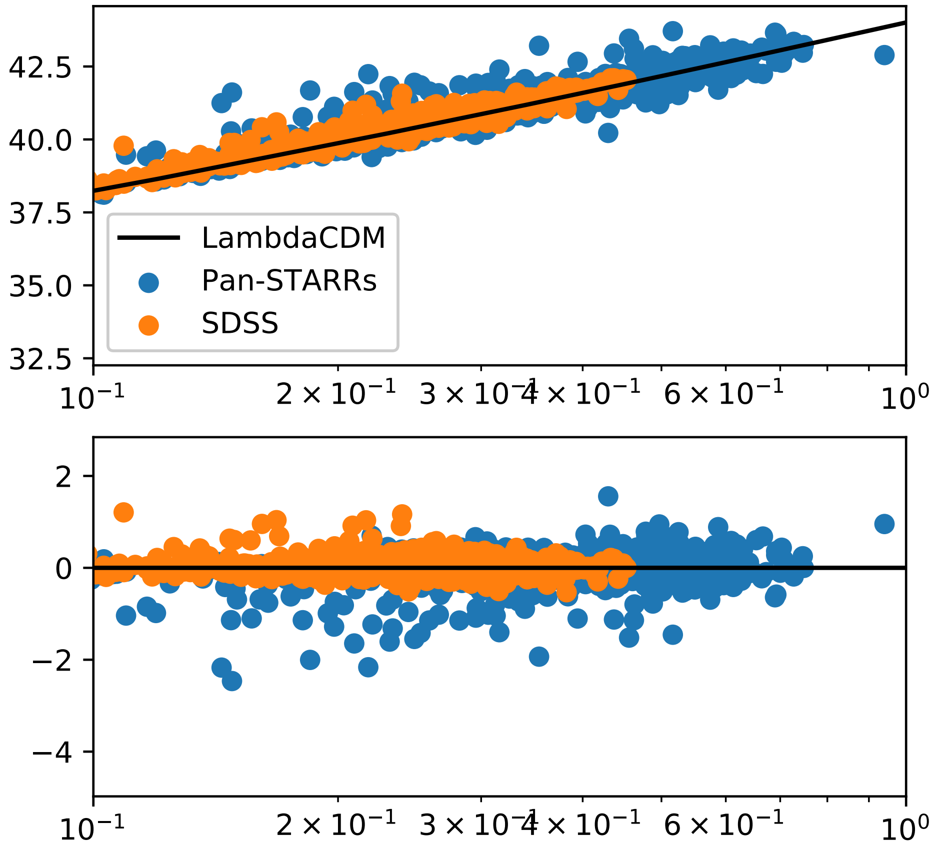
- 2020
  - First combined photometric sample: Pan-STARRs (PS1) + Sloan Digital Sky Survey (SDSS) (Popovic et al. 2020c)
  - Finish Popovic et al. 2020b
  - Continue collaboration with DES on implementing my work from current papers
- 2021
  - Dark Energy Survey (DES) 5 year sample
  - z-BEAMS
  - DES + PS1 + SDSS combined photometric sample
- 2022
  - Applications to LSST

Fin

Popovic et al. 2020c

Will be the largest photometric sample ever assembled! ~2000 likely SNIa!

With DES data, will be even larger



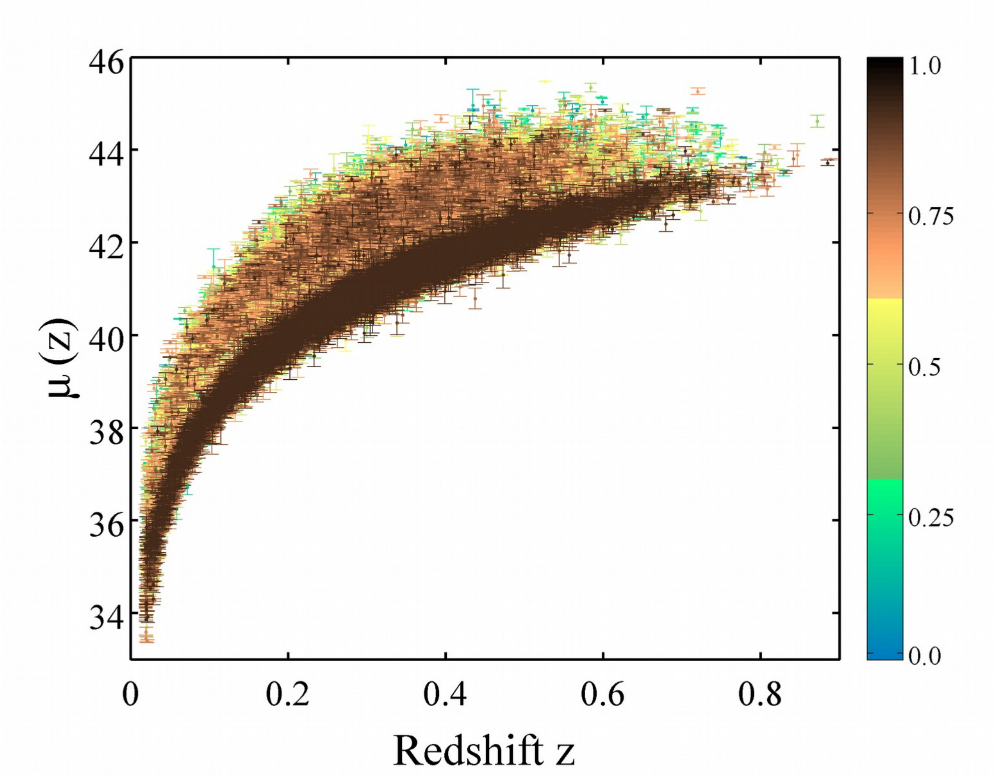
Dark Energy Survey

- Previously, the SN group did spectroscopic samples
- The 5 year sample will be the first photometric one!
- Will be using my host-association method and BBC7D!

Is there anything else we can do to marginalise mis-association issues?

BEAMS used SNIa likelihood and different luminosities to marginalise.

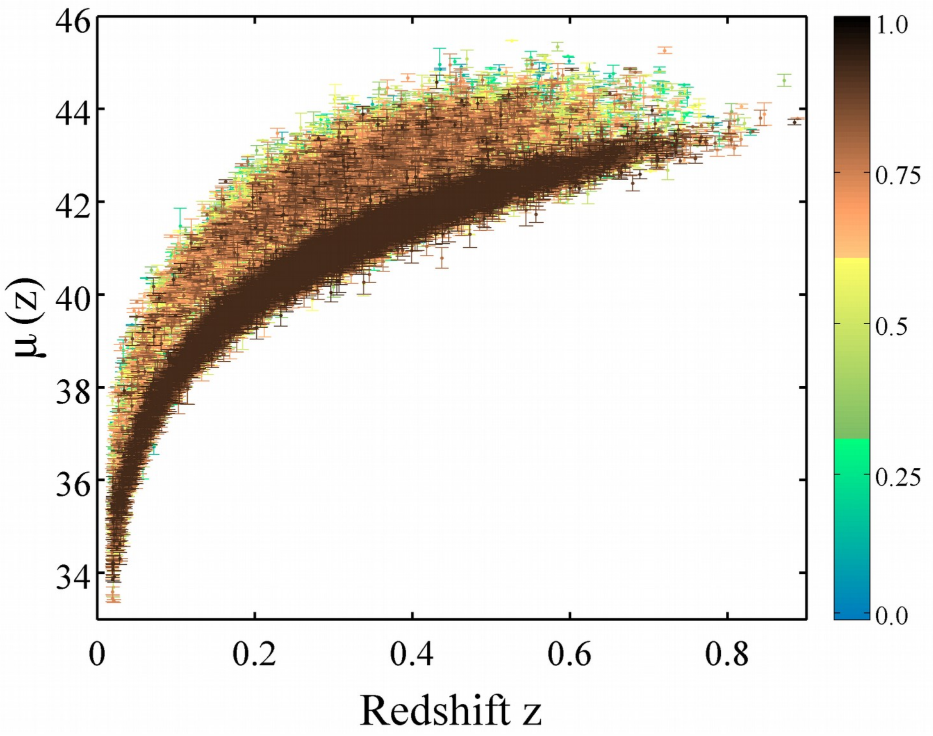
Functionally, there's no difference between a different redshift and different luminosity. But what replaces the likelihood?



z-BEAMS

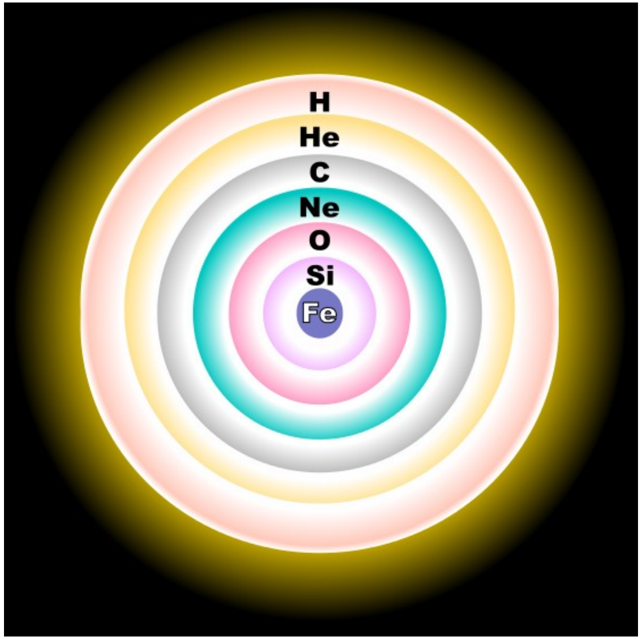
Roberts et al. (2017) suggest this is possible with redshift.

r_{DLR} can function well as the likelihood measure – possible to implement in SNANA.



More Core Collapse info

- Unlike SNIa, core collapse supernovae occur in active stars
- An Iron-Nickel core grows, but no longer produces energy
- Eventually, even electron degeneracy pressure can no longer support the inner core and it collapses
- This implosion, combined with the shock



References

On request