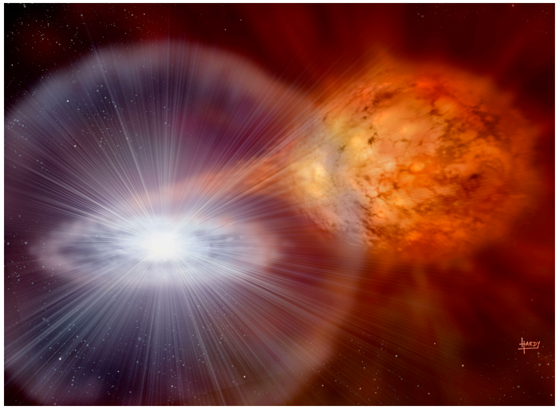
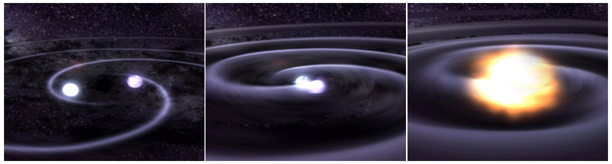
EXCELLENCE IN SCIENCE THE ROYAL SOCIETY

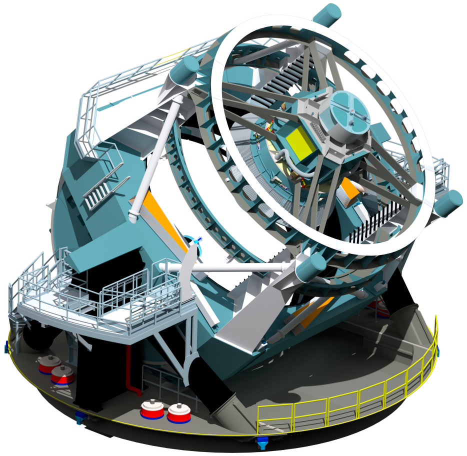
European Research Council
Established by the European Commission

Supernovae as cosmological probes

Mark Sullivan, Southampton



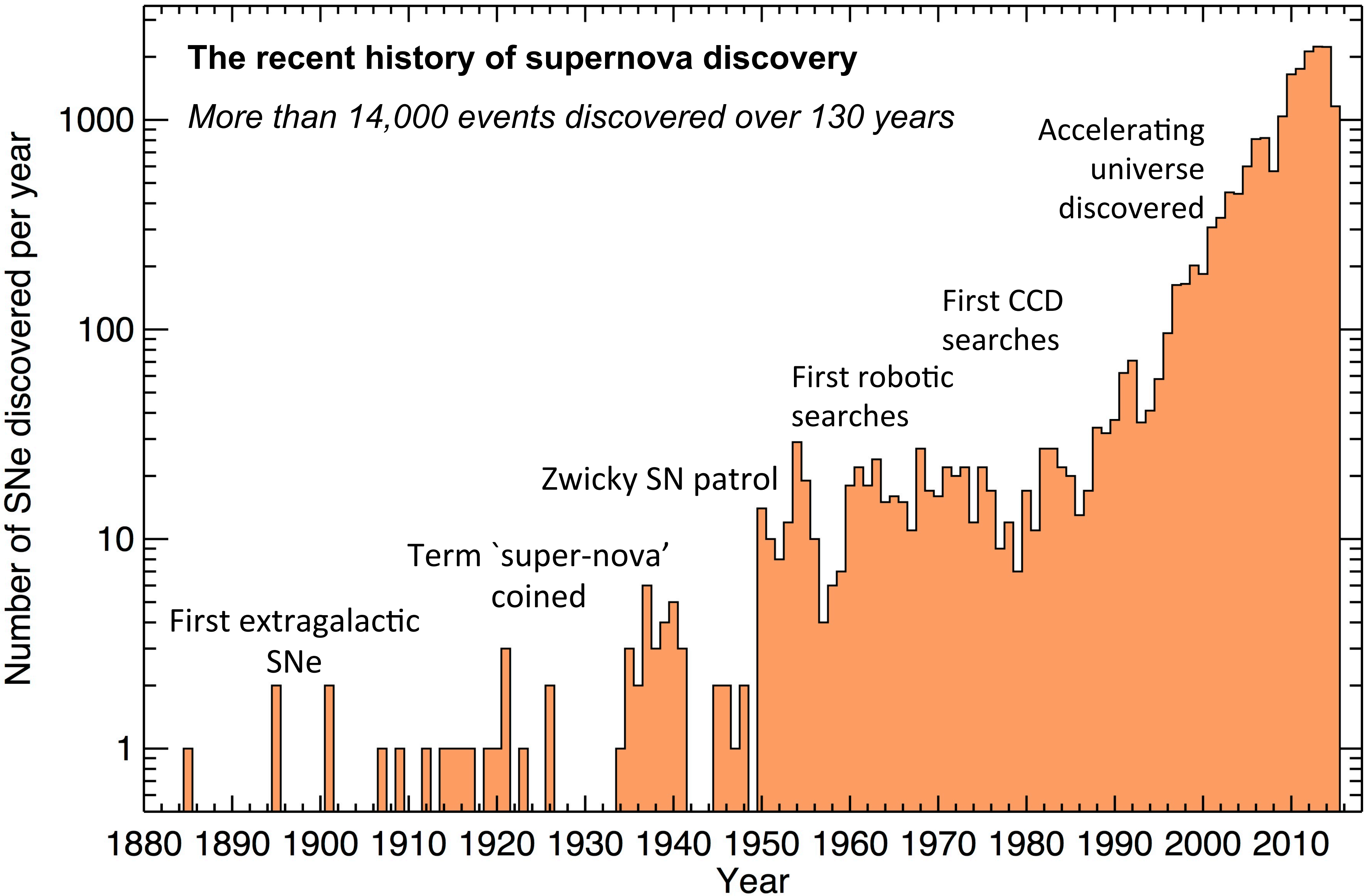




Supernovae in astrophysics

- Supernovae are exploding stars – endpoint of stellar evolution
- Nucelosynthesis:
  - Mechanism to synthesize and distribute heavy elements
  - Recycle elements into the ISM, source of dust
  - Main source of neutrinos beyond the Big Bang
- Significant energy input:
  - Accelerate cosmic rays
  - Trigger/suppress star formation ('feedback')
- Extreme Luminosity:
  - 'Standardised candles' probe dark energy
  - Trace star-formation on cosmic scales

Number of SNe discovered per year



Fritz Zwicky
(1898-1974)

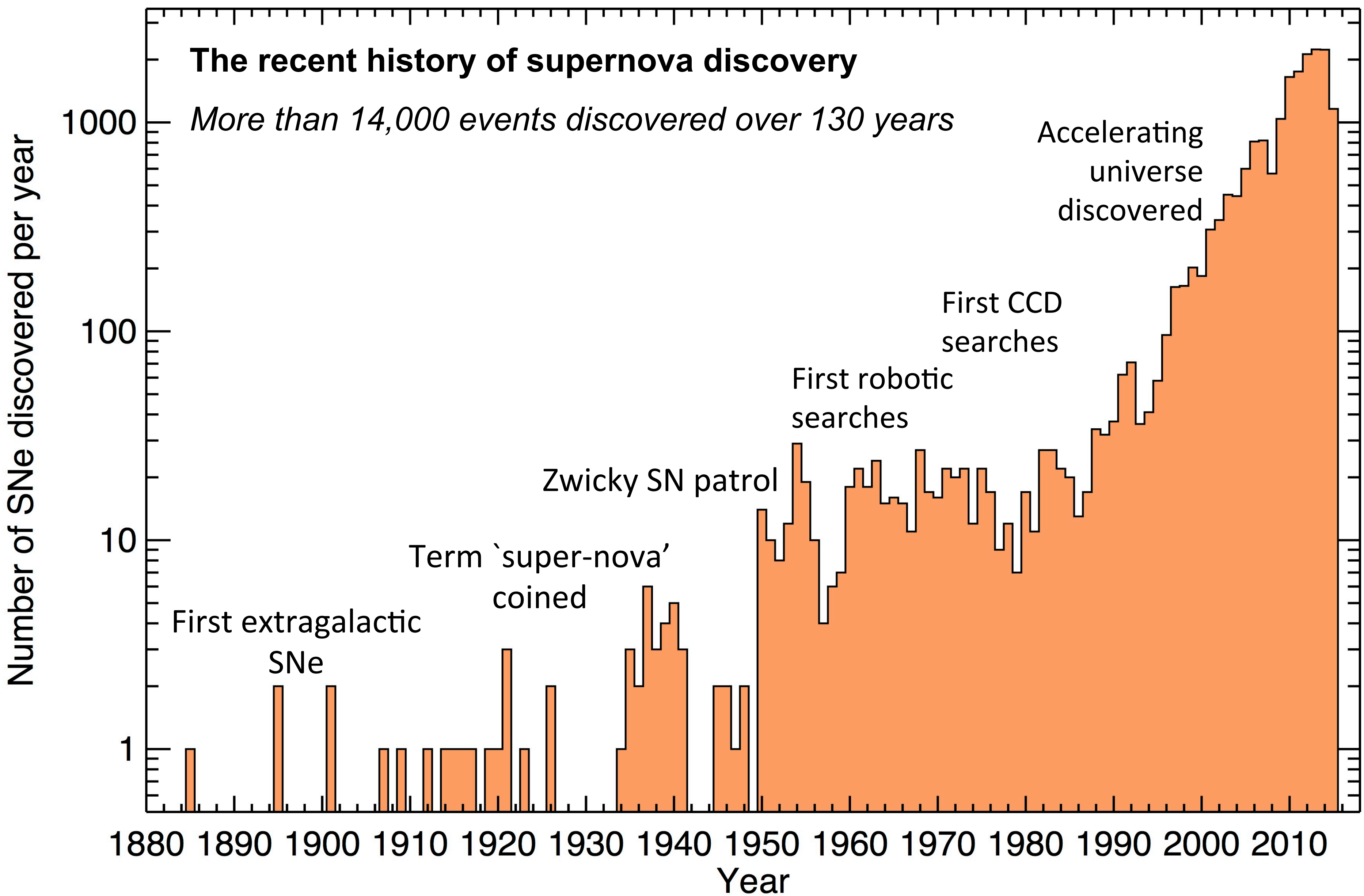
Coined term "*super-nova*"
(with Baade)

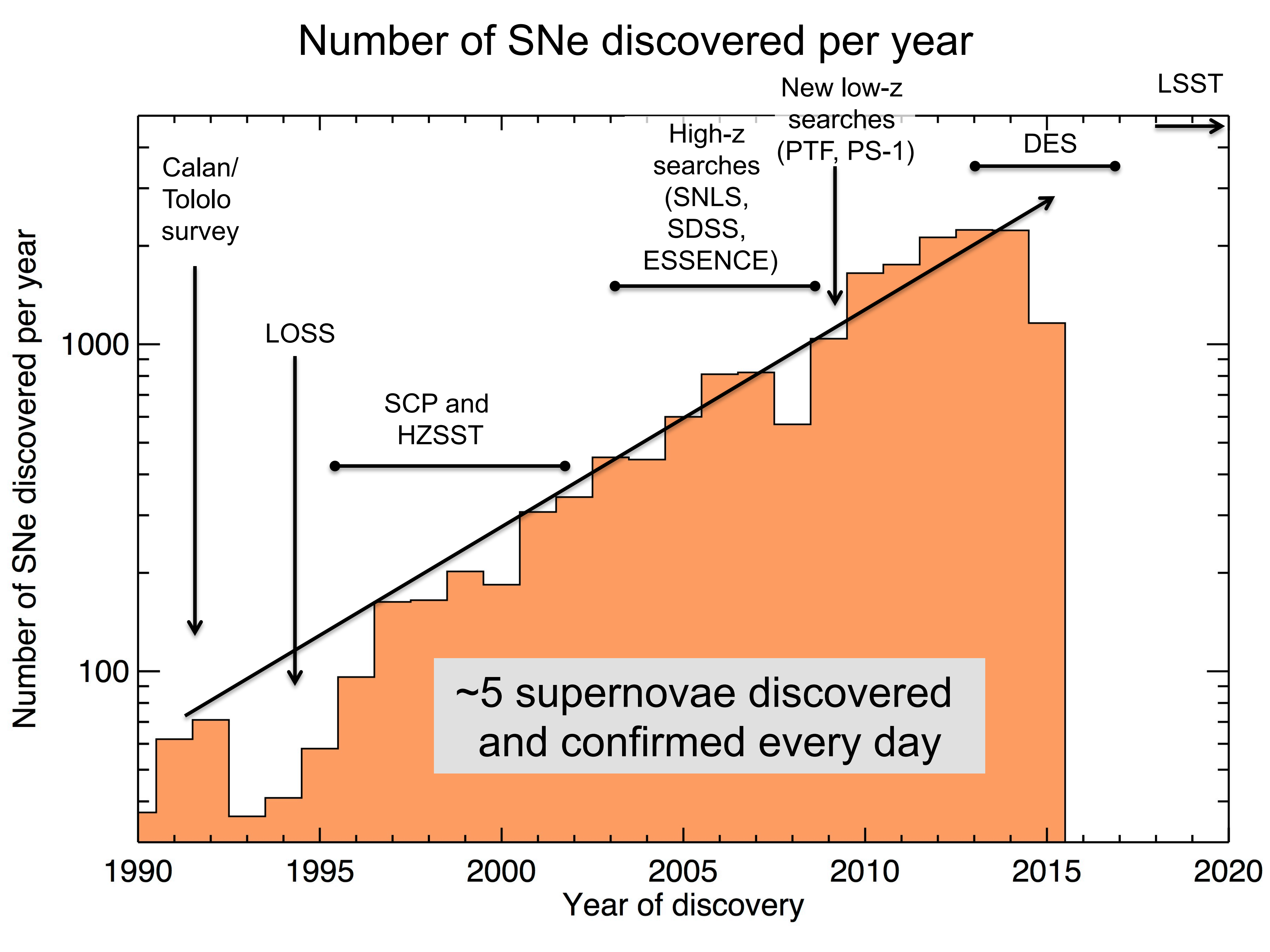
Discovered >100 supernovae, a feat not bettered until recently

Suggested (Type Ia) Supernovae as standard candles

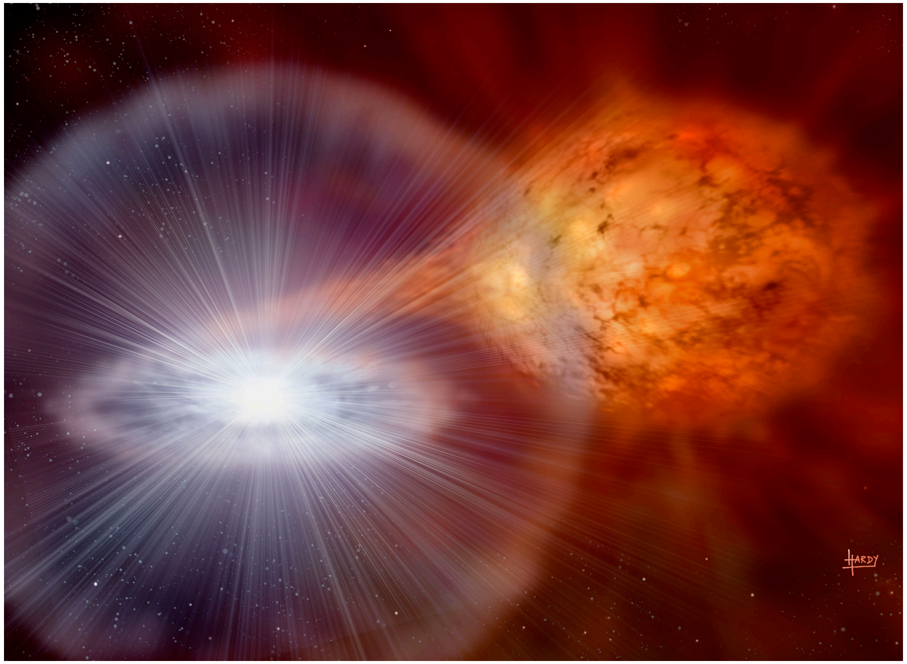
"It's somewhere between a nova and a supernova -- probably a pretty good nova."

Number of SNe discovered per year




Number of SNe discovered per year
Number of SNe discovered per year
Year of discovery
1990
1995
2000
2005
2010
2015
2020
100
1000
Calan/ Tololo survey
LOSS
SCP and HZSST
High-z searches (SNLS, SDSS, ESSENCE)
New low-z searches (PTF, PS-1)
DES
LSST
~5 supernovae discovered and confirmed every day

Type Ia Supernovae



Type Ia supernovae: thermonuclear explosions of CO white dwarfs

→ Approaches Chandrasekhar mass

→ C-burning ignited

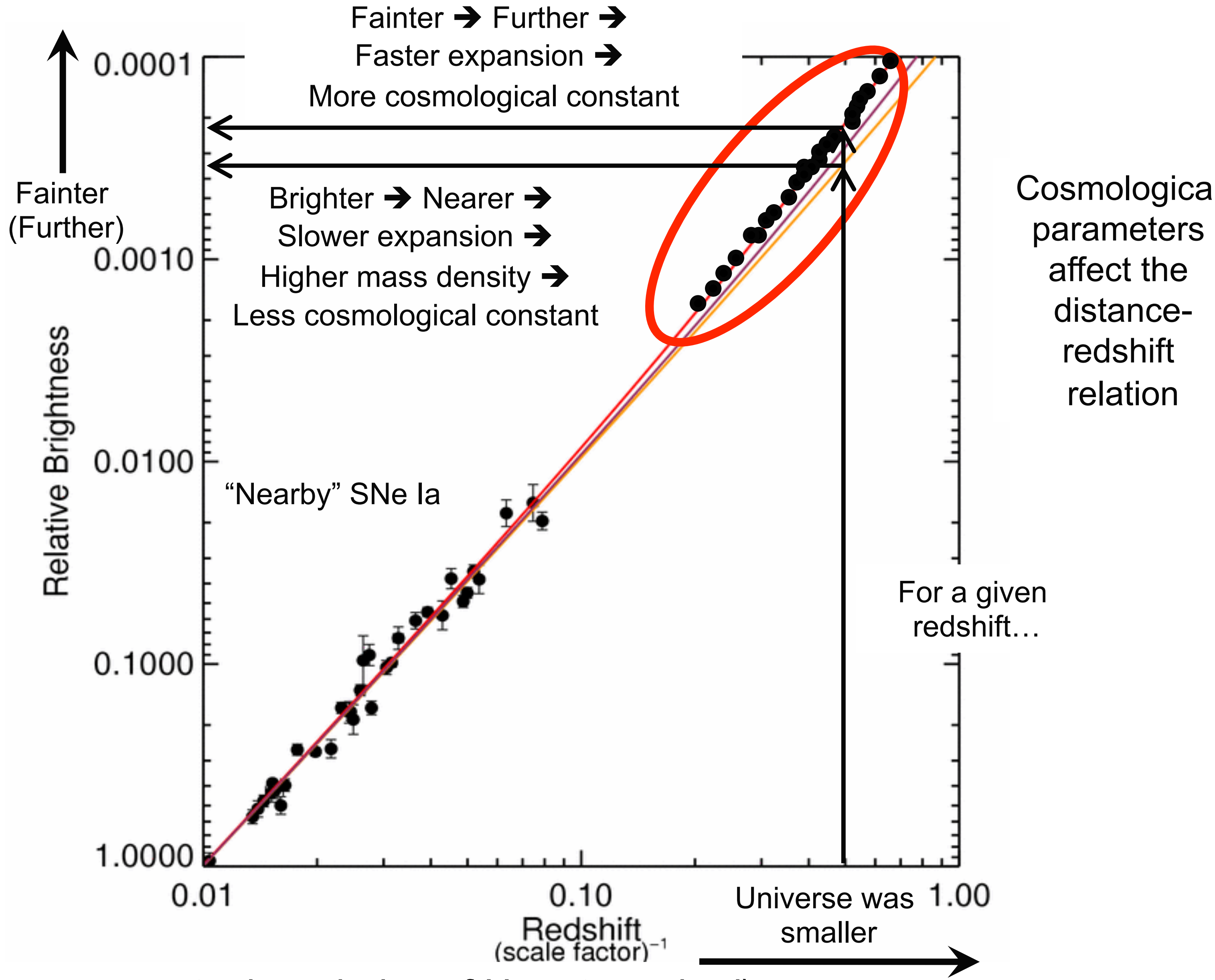
Resulting explosion is:

→ **Bright**: ~5-10 billion suns

→ **Powered by:** ^{56}Ni → ^{56}Co → ^{56}Fe

→ **Standardizable**: ≤5-6% in distance

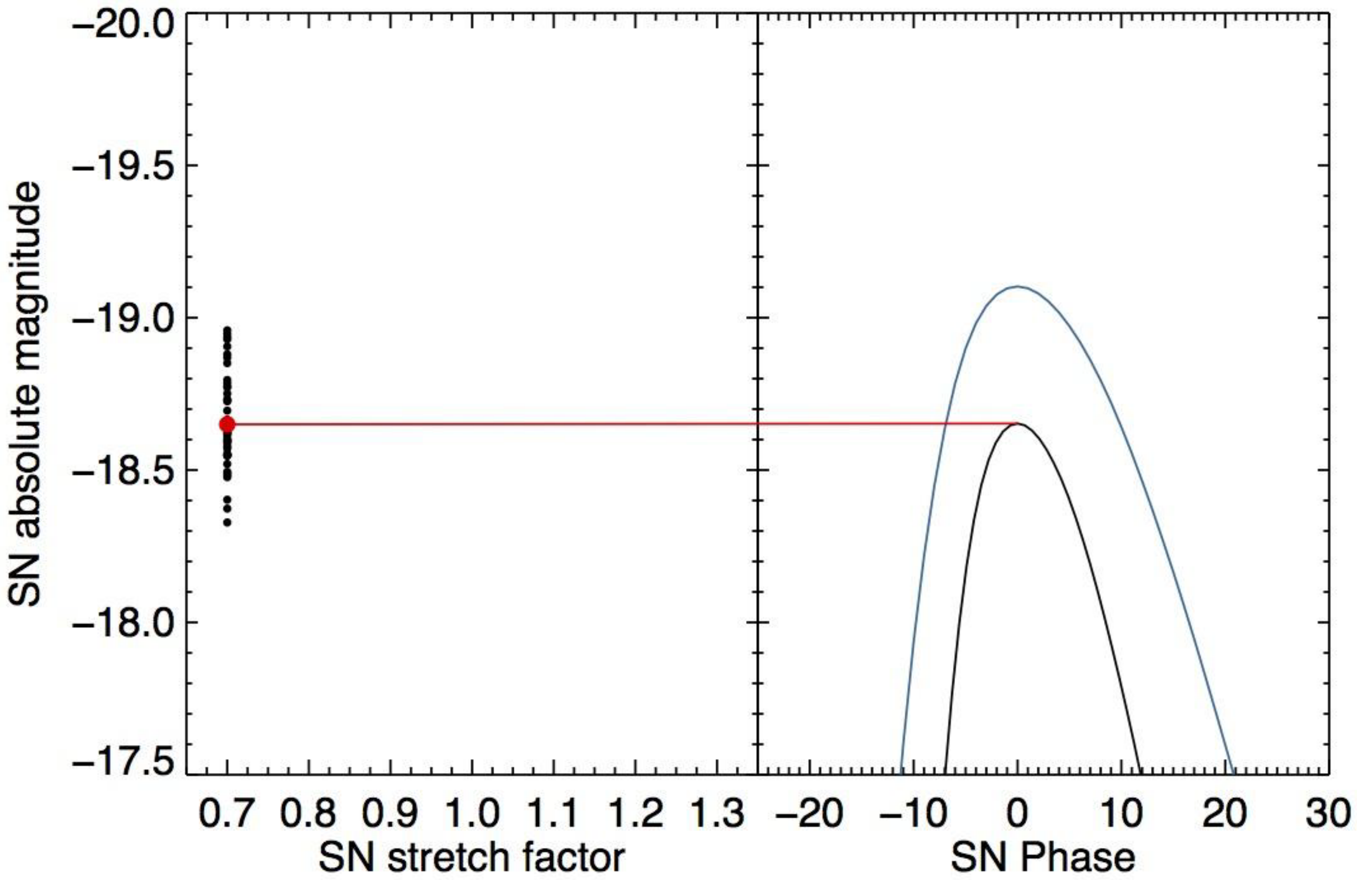
The modern day Hubble Diagram



(Differential measurement – knowledge of H_0 not required)

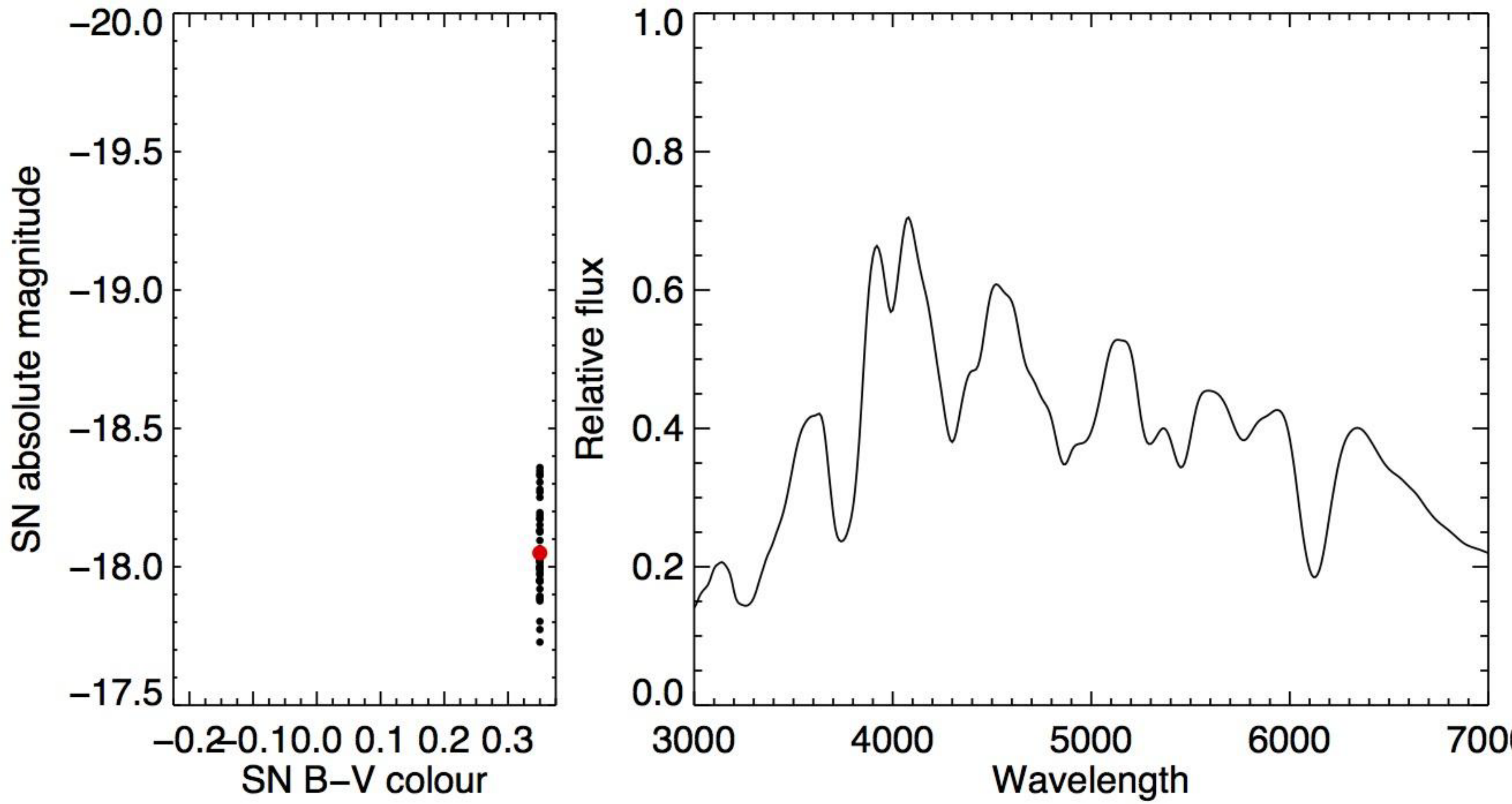
Type Ia Supernovae are not standard candles

- ➔ SNe Ia are *empirically* standardizable
- ➔ Brighter SNe:
  - → Have wider, slower light curves (classic Phillips relation),

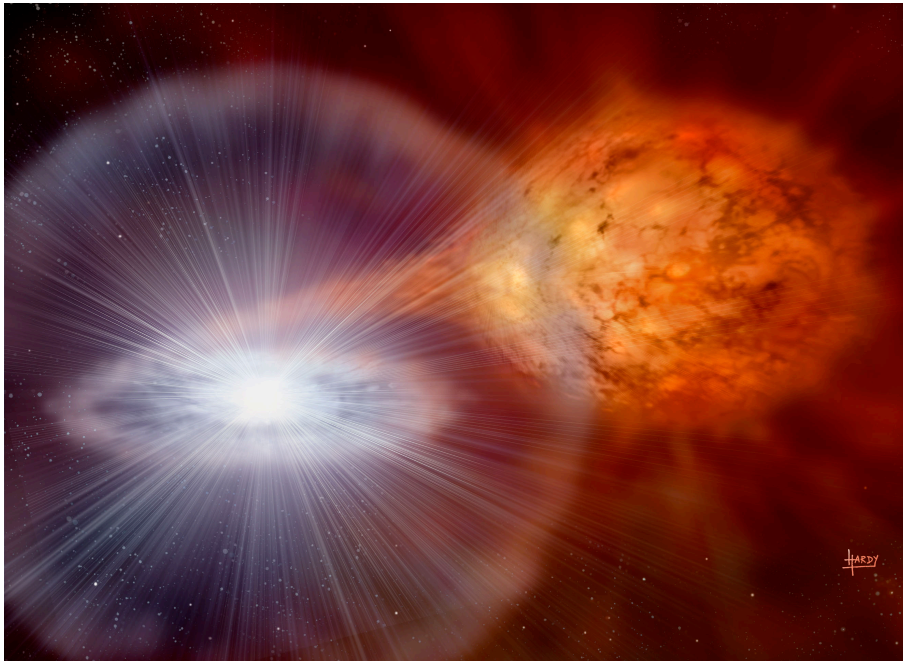


Type Ia Supernovae are not standard candles

- ➔ SNe Ia are *empirically* standardizable
- ➔ Brighter SNe:
  - → Have wider, slower light curves (classic Phillips relation),
  - → Are bluer in their optical colour,



Type Ia Supernovae



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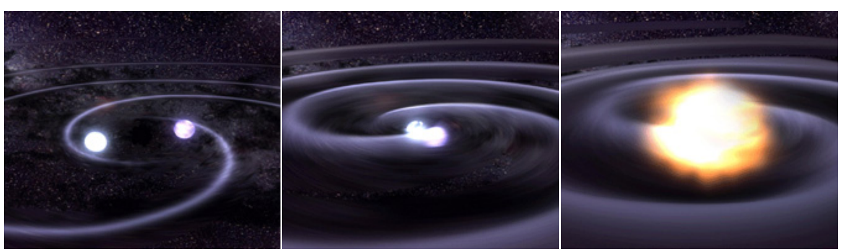
Single degenerate?

and/or

Double degenerate?



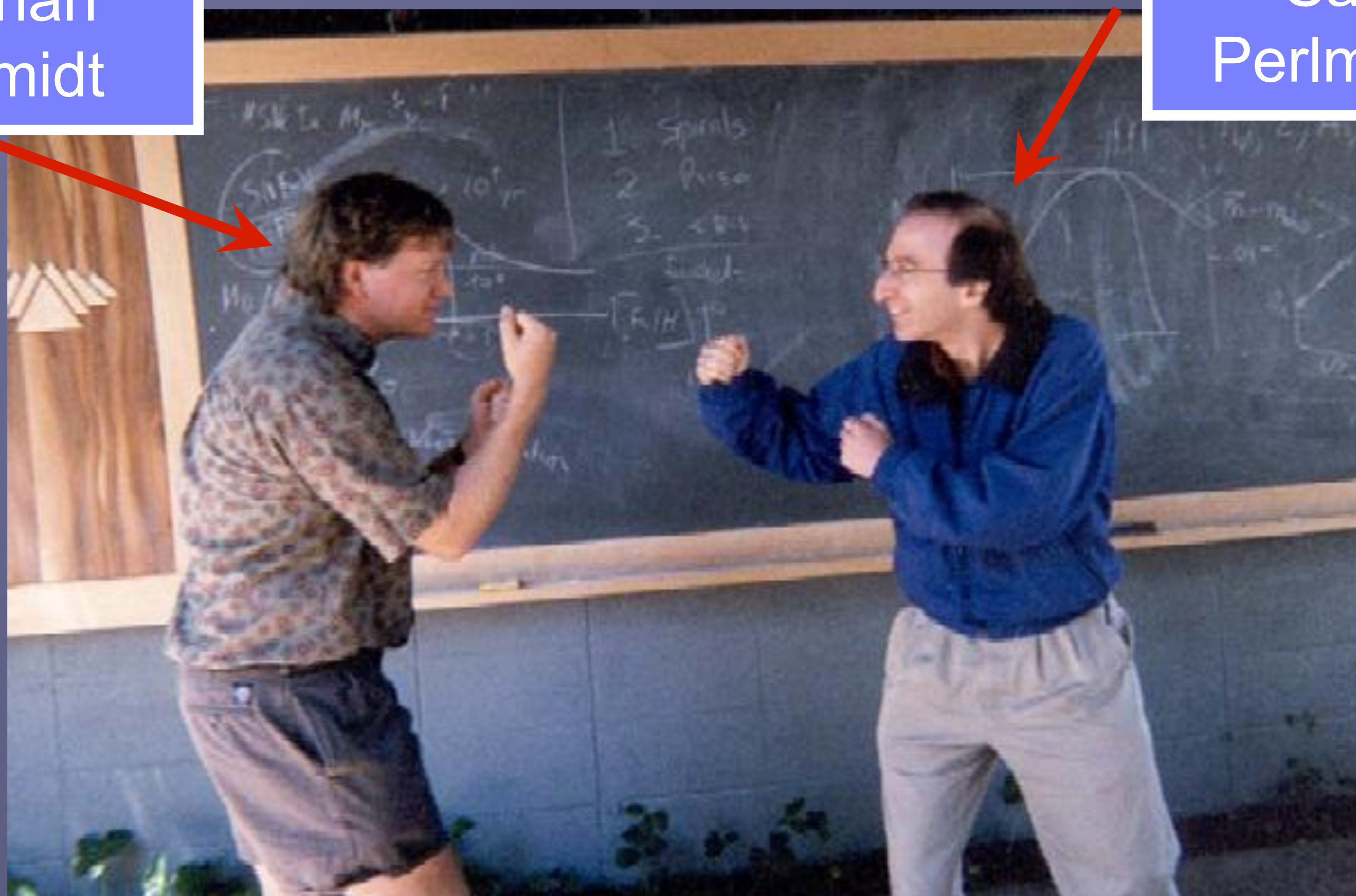
What are the progenitors of SNe Ia ?

Impact of progenitor diversity and physics?

Cosmology

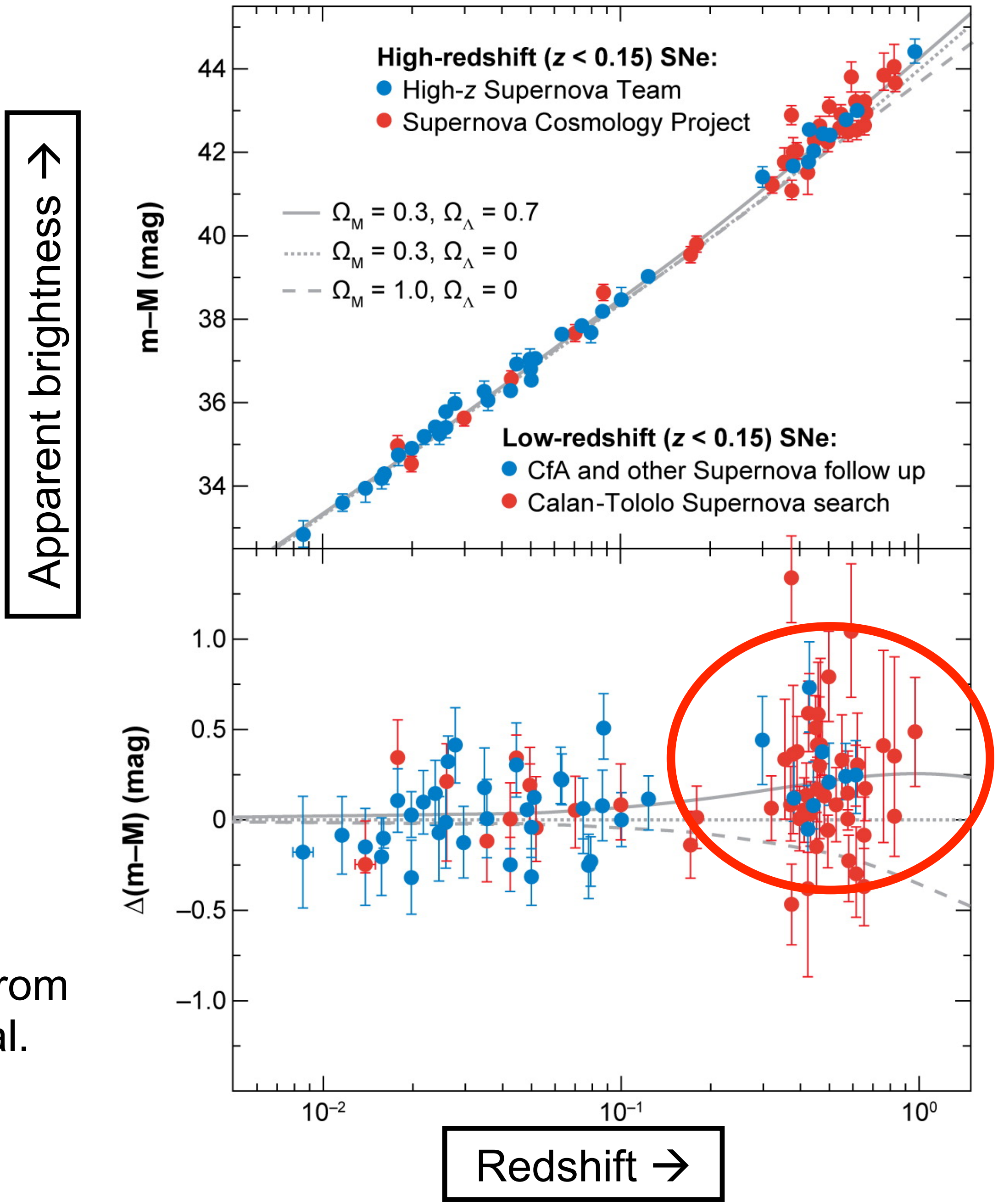
In the nineties, two teams chased the cosmological parameters

HZSST, led by Brian Schmidt



SCP, led by Saul Perlmutter

1998/9: Led to cosmological parameters



The (then) “surprising” result of Ω_M=0.3 Ω_Λ=0.7

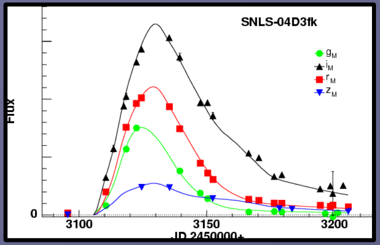
2011 Nobel Prize for Physics

(Compilation from Frieman et al. 2008)

Supernova Legacy Survey: 2003—2008

Imaging

Distances from light-curves

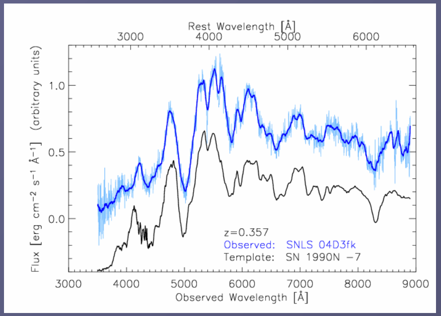


Discoveries Lightcurves

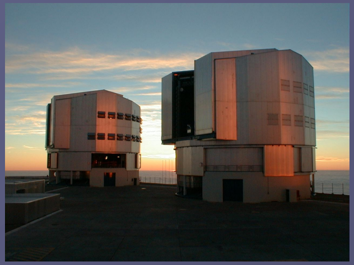
g′r′i′z′ every 4 days during dark time

Spectroscopy

Redshifts → Distances from cosmological model



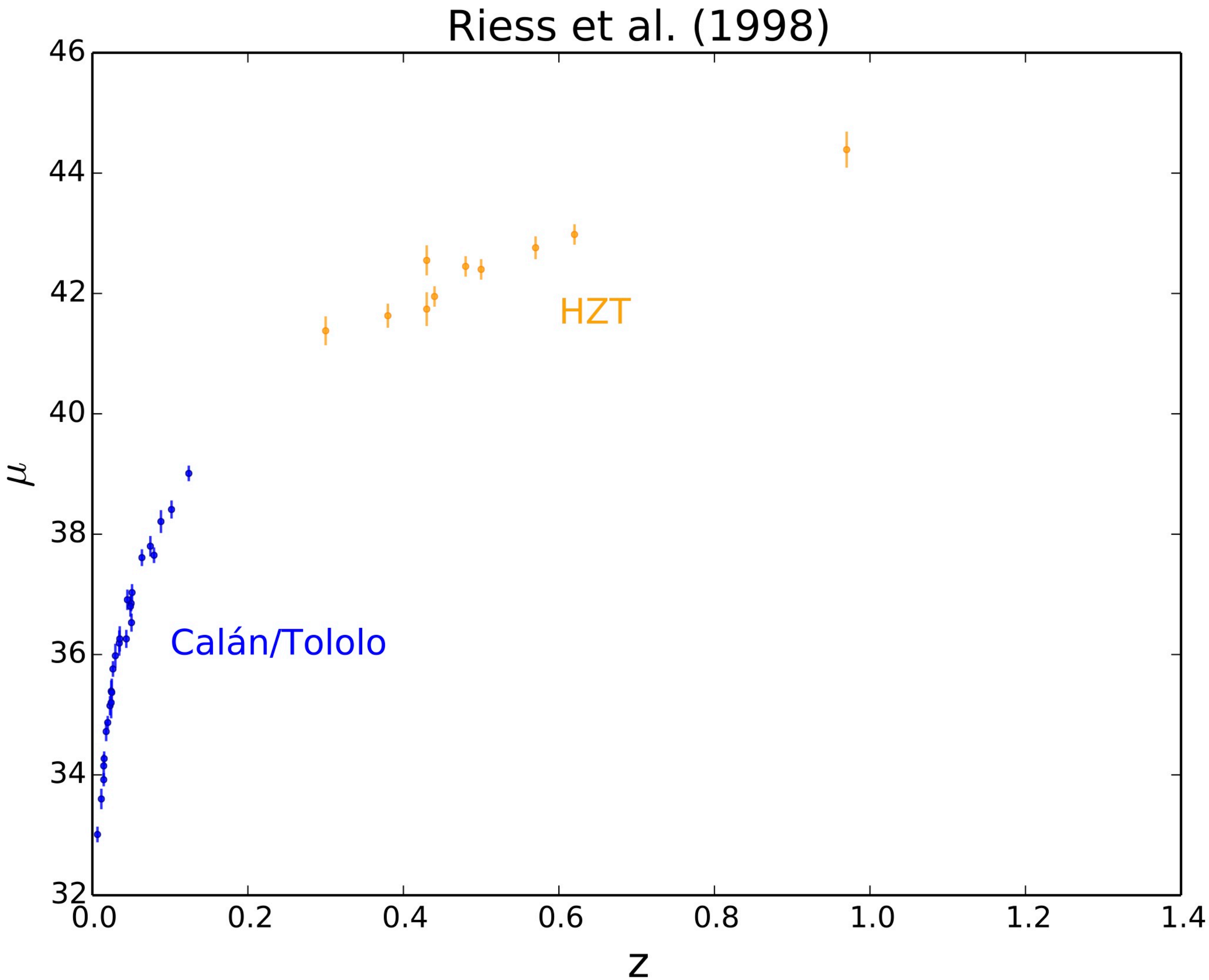
Gemini N & S (120 hr/yr)

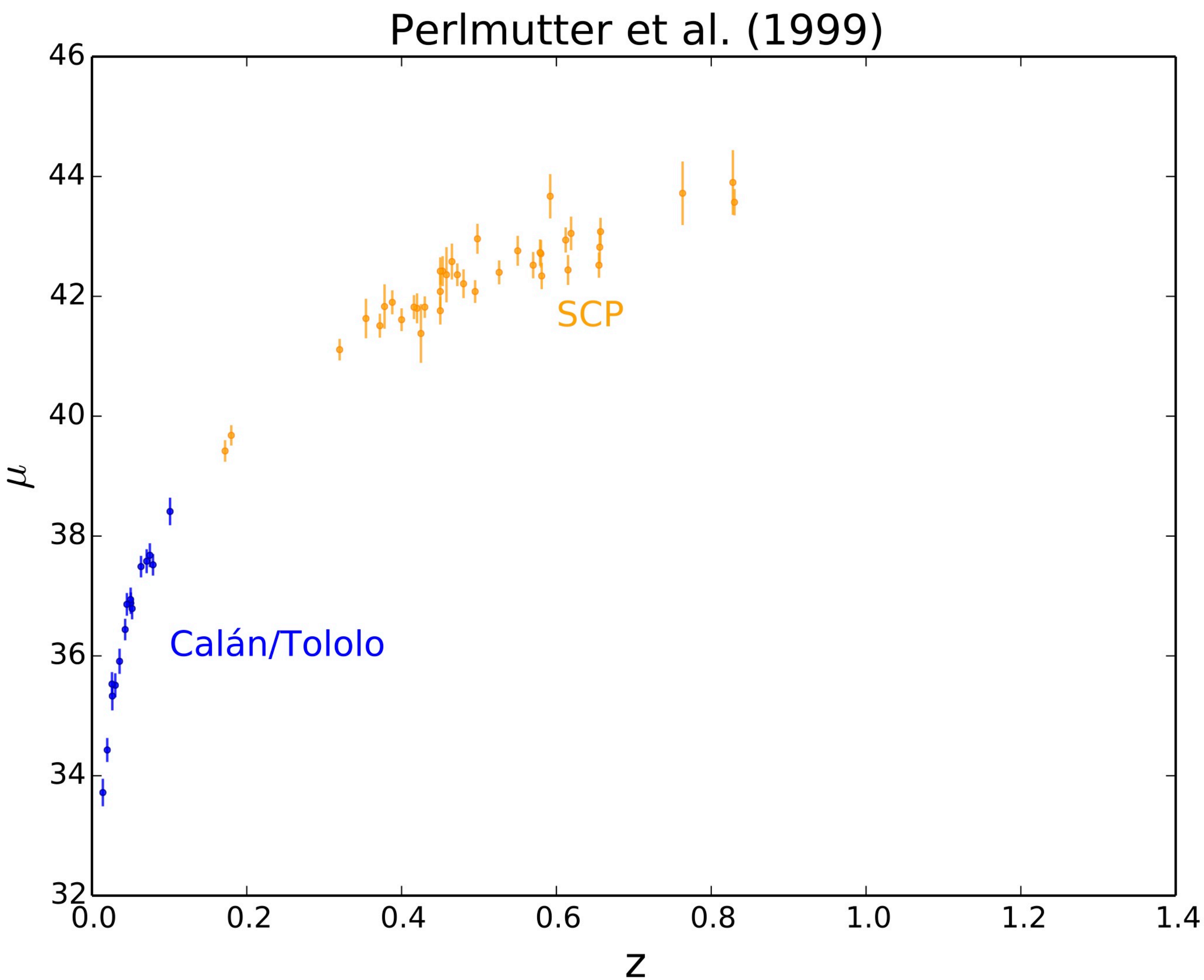


VLT (120 hr/yr)

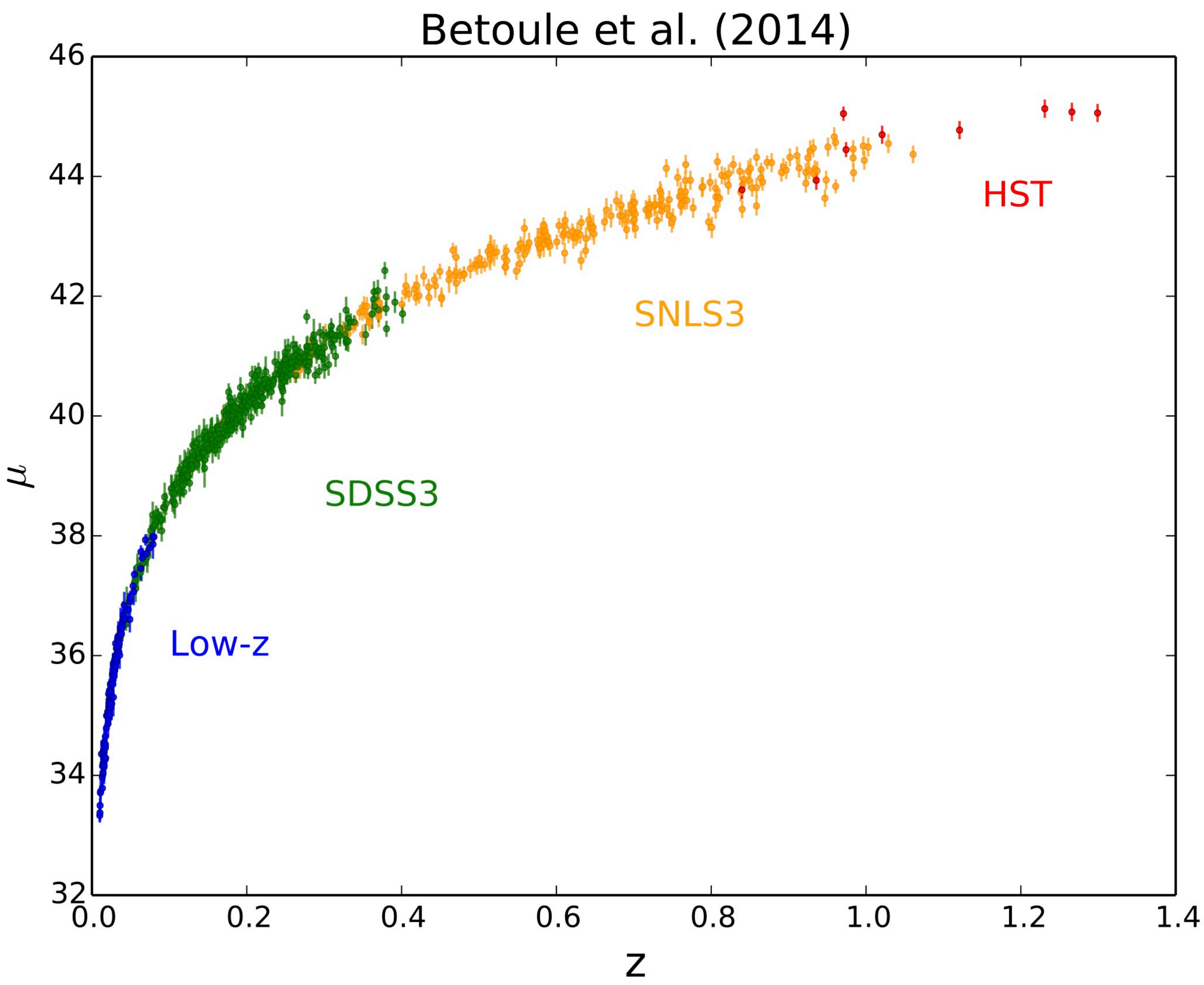
Keck (8 n/yr)

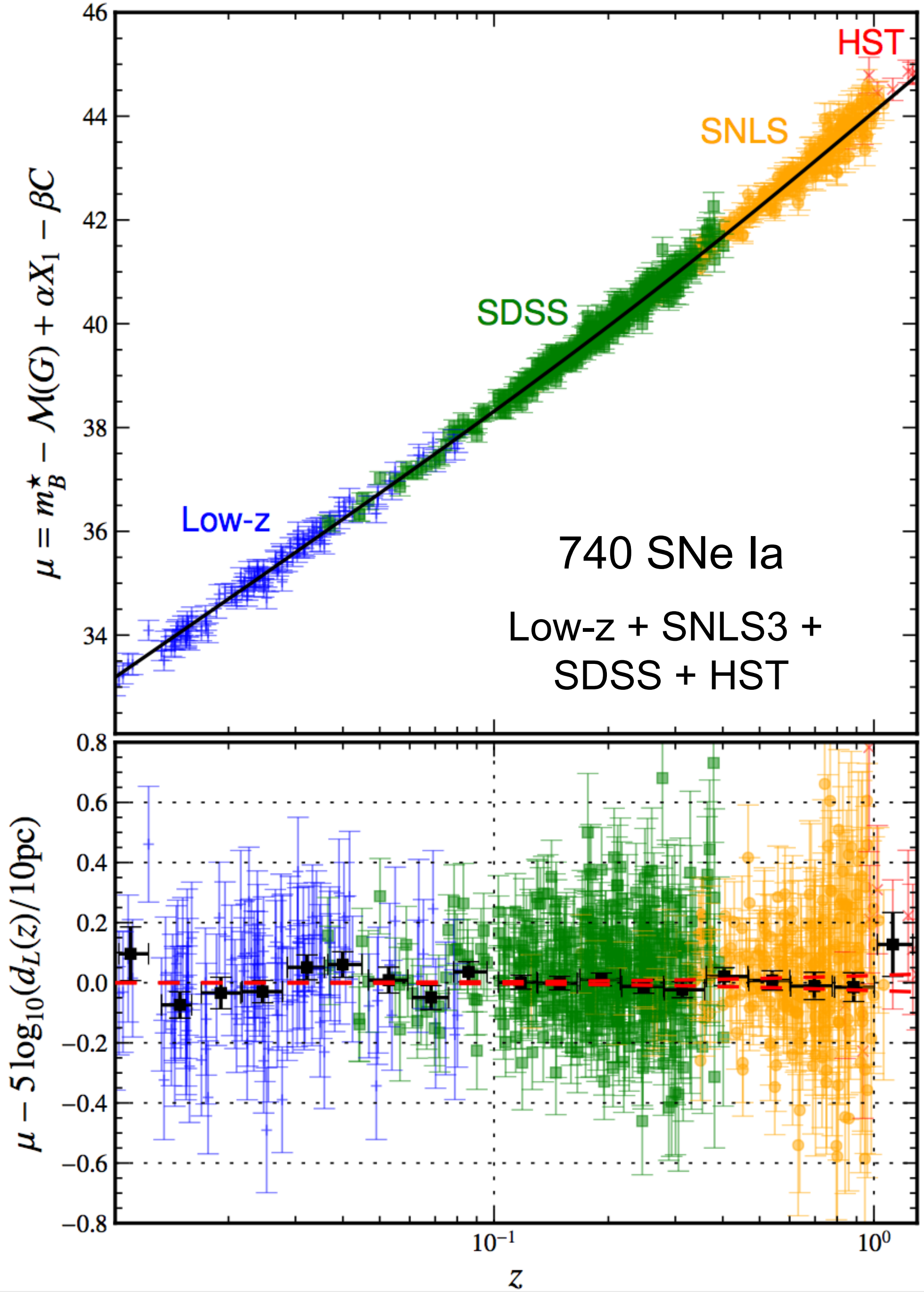
First real rolling search: discovery and follow-up on the same telescope


Riess et al. (1998)
46
44
42
40
38
36
34
32
μ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
z
HZT
Calán/Tololo



Perlmutter et al. (1999)
46
44
42
40
38
36
34
32
μ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
z
SCP
Calán/Tololo


Betoule et al. (2014)
46
44
42
40
38
36
34
32
μ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
z
Low-z
SDSS3
SNLS3
HST



A modern day Hubble Diagram "JLA"

w = −1.018 ± 0.057 *(stat+sys)*
(SN+CMB)

w = −1.027 ± 0.055
(SN+CMB+BAO)

σ_{coh} = 0.08-0.11 mag
(4-6% in distance)

Betoule et al. 2014

Simplified SN systematic-error budget ("JLA")

Experimental | Astrophysical (non-SN) | Astrophysical (SN)

Uncertainty sources	$\sigma_x(\Omega_m)$	% of $\sigma^2(\Omega_m)$
Calibration	0.0203	36.7
Milky Way extinction	0.0072	4.6
Light-curve model	0.0069	4.3
Bias corrections	0.0040	1.4
Host relation[a]	0.0038	1.3
Contamination	0.0008	0.1
Peculiar velocity	0.0007	0.0
Stat	0.0241	51.6

Photometric calibration is (by far) the dominant systematic uncertainty

Betoule et al. 2014

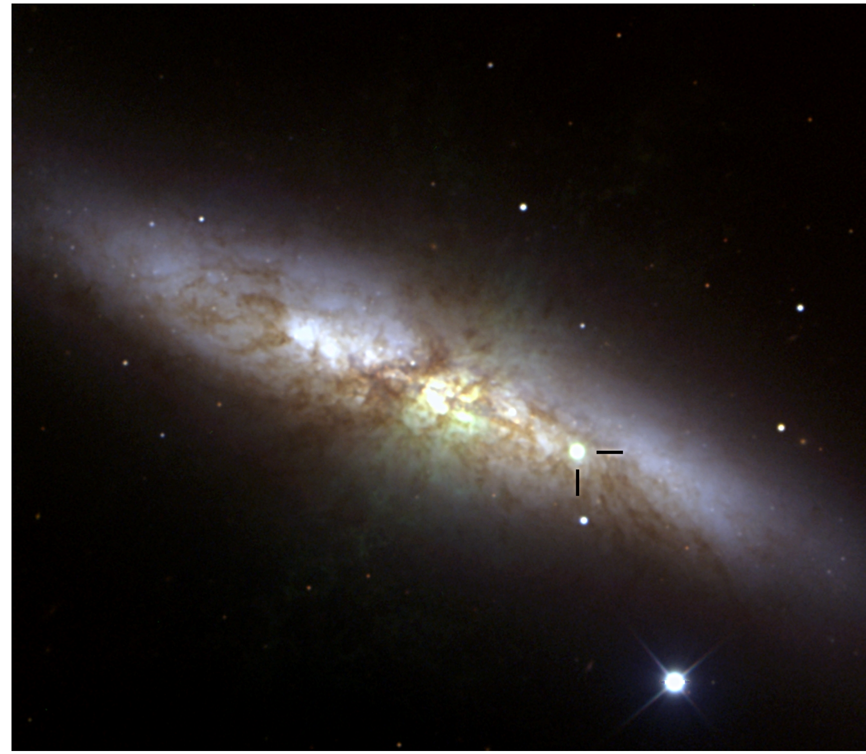
Uncertain astrophysics?

- **Stellar evolution:** Pre-supernova stellar evolution
  - *White dwarf composition, age, metallicity*
- **Progenitors:** Configuration of system
  - *Single or double degenerate system*
- **Accretion:** Accretion process
  - *Mass transfer rate, composition of material*
- **Explosion:** Explosion physics
  - *Triggering conditions, ignition spots, flame propagation*
- **Aftermath:** Radiative transfer processes
  - *Ejecta composition, local environment, dust*

Astrophysics from nearby SNe

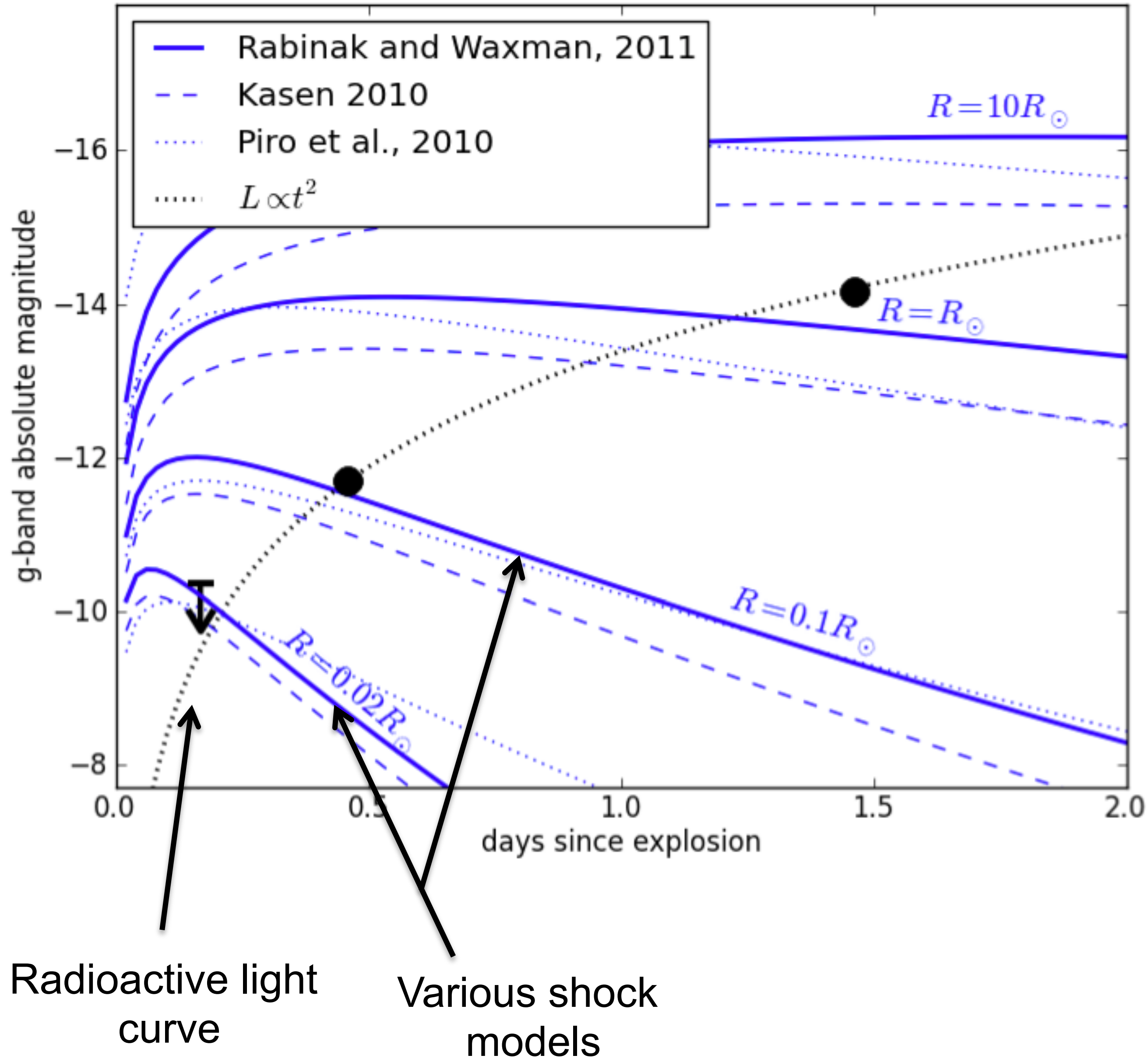
SN2011fe in M101

~6.5 Mpc



SN2014J in M82

~3.5 Mpc



SN2011fe:

It's a white dwarf

Size constraint: $R<0.02R_\odot$

i.e. a white dwarf

Carbon & oxygen in the very-early spectra:

i.e. a C-O WD

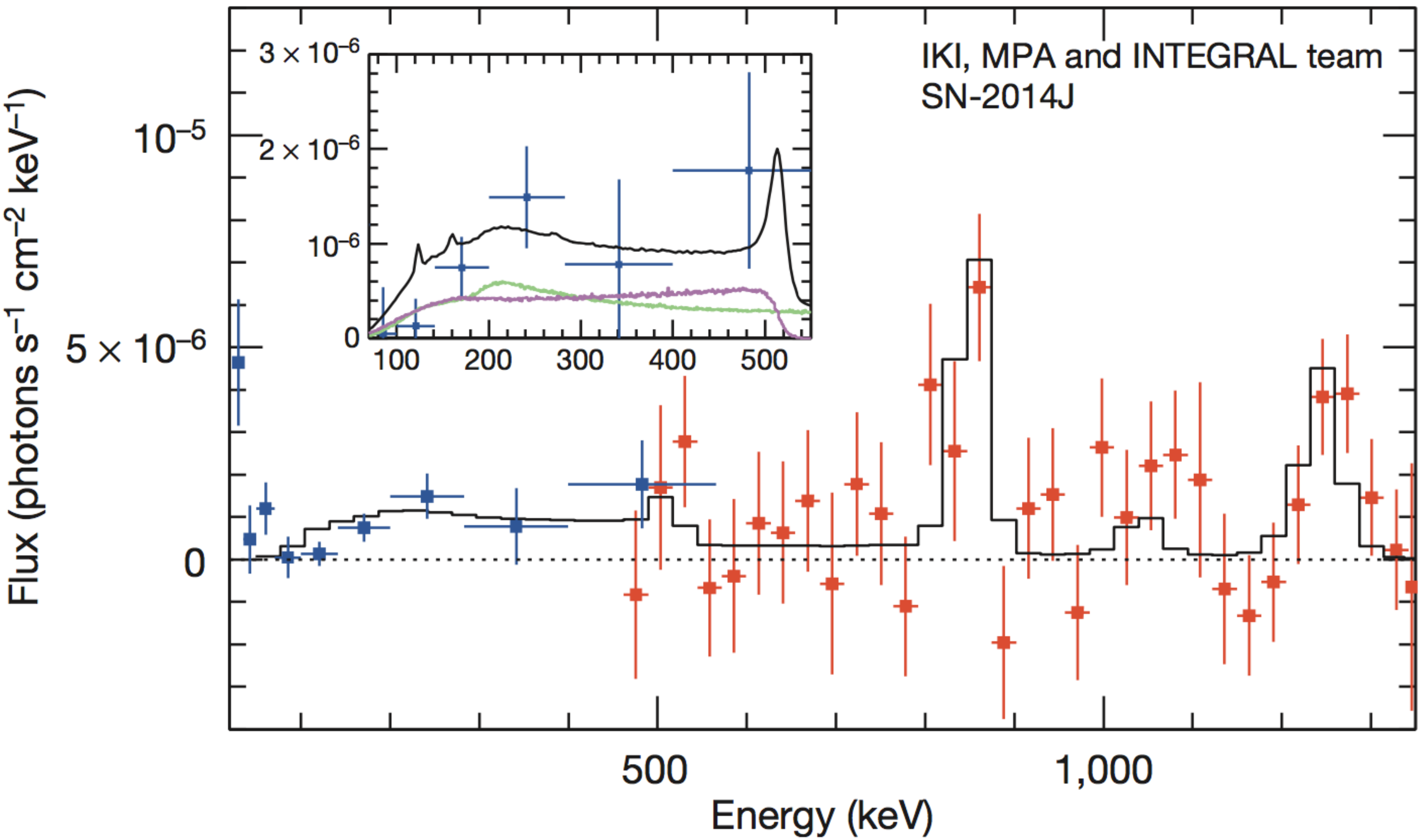
Nugent et al 2011, Nature
Bloom et al 2013

SN2014J:
It's ^{56}Ni

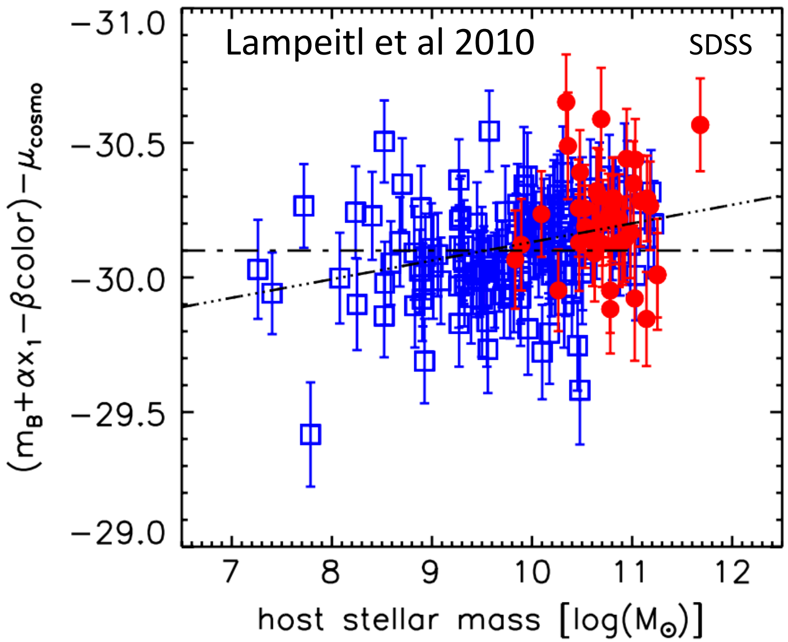
Strength of lines: 0.6$M_\odot$ of ^{56}Ni

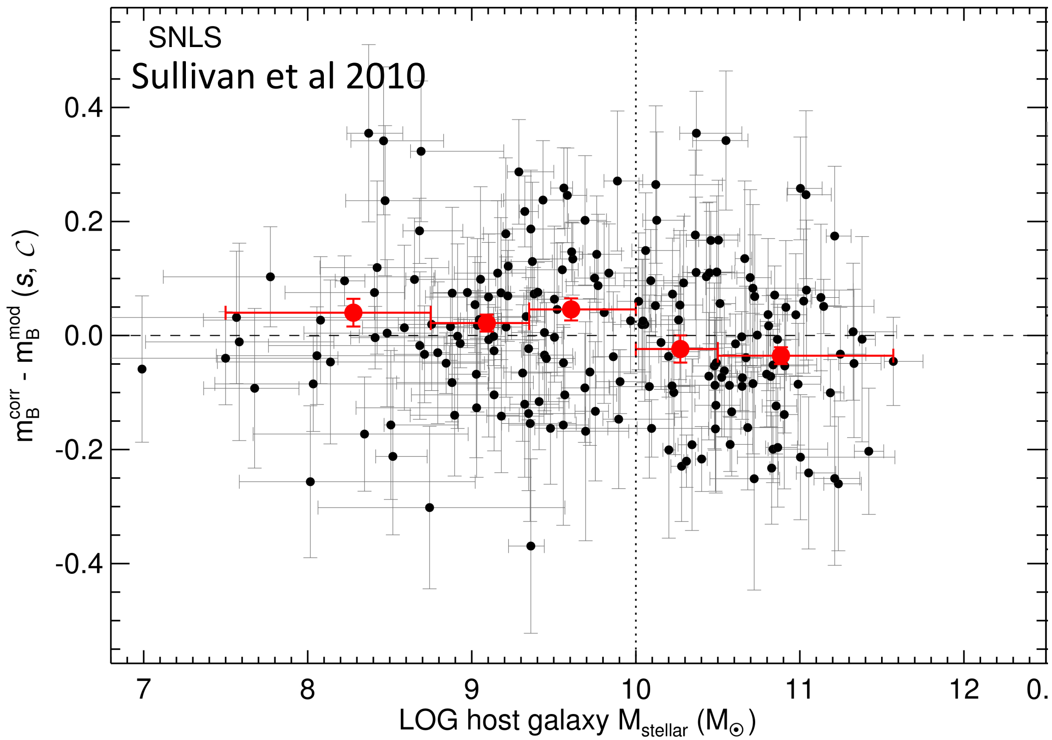
Width of lines: material moving at 10,000 km/s

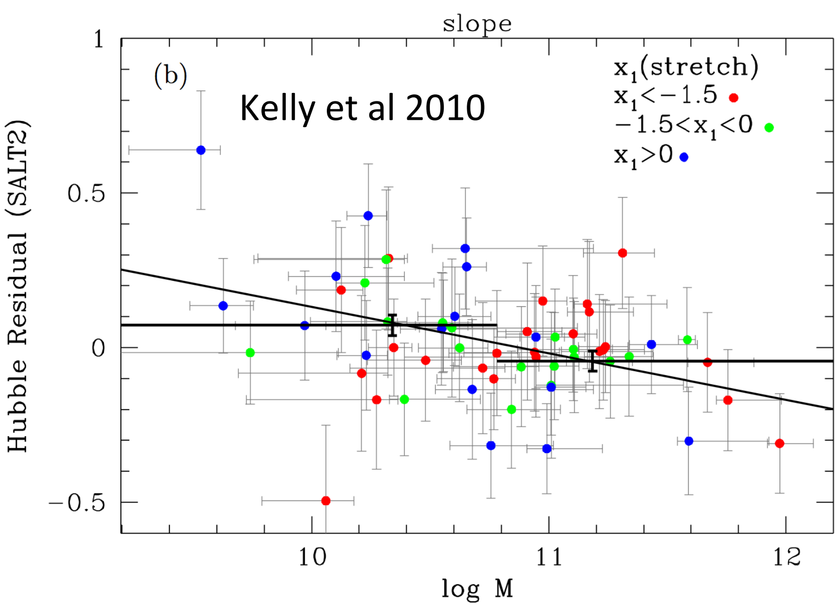
Consistent with values inferred from optical



Churazov et al 2014, Nature





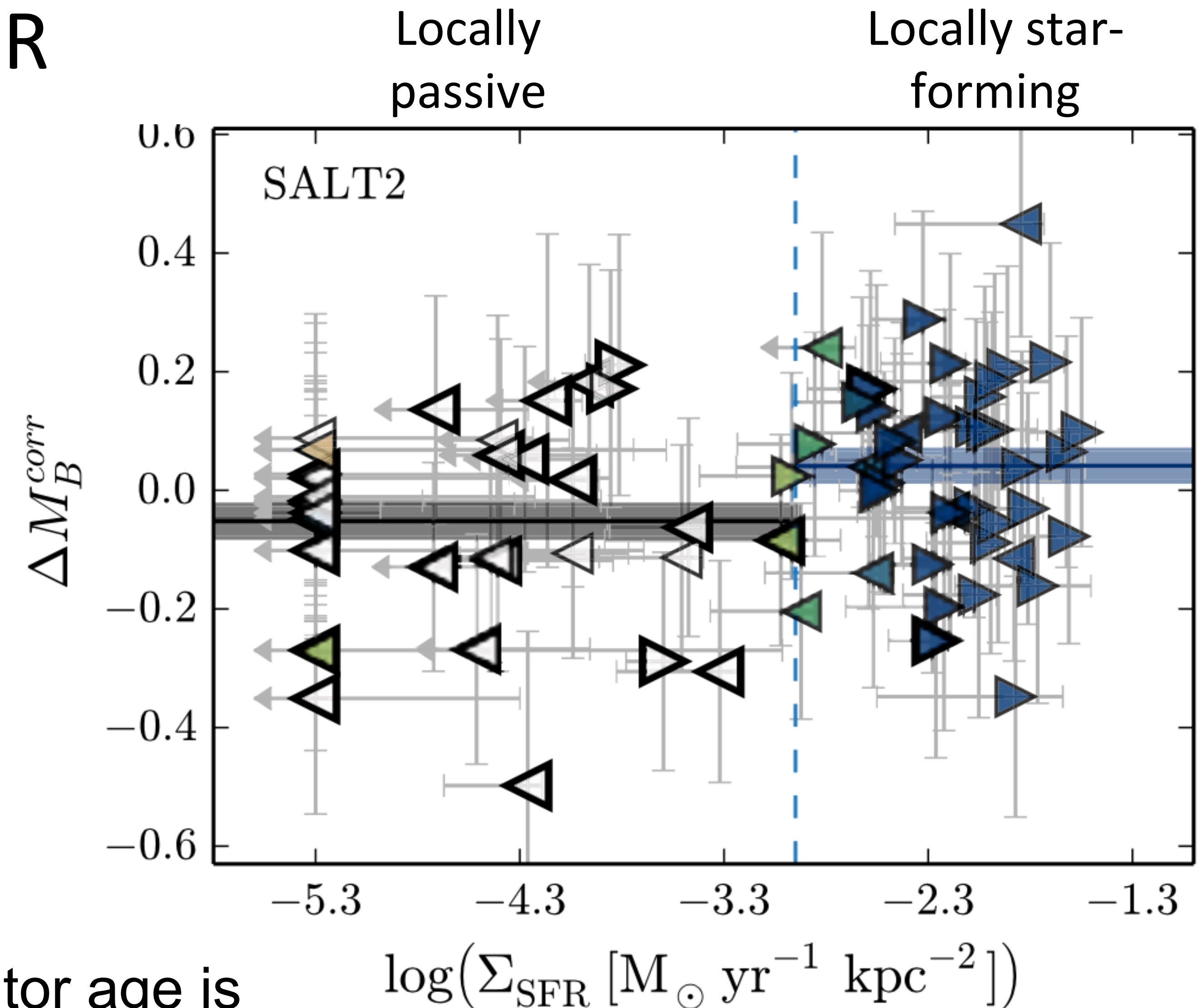


Hubble residuals depend on host galaxy properties

0.061 ± 0.012 mag

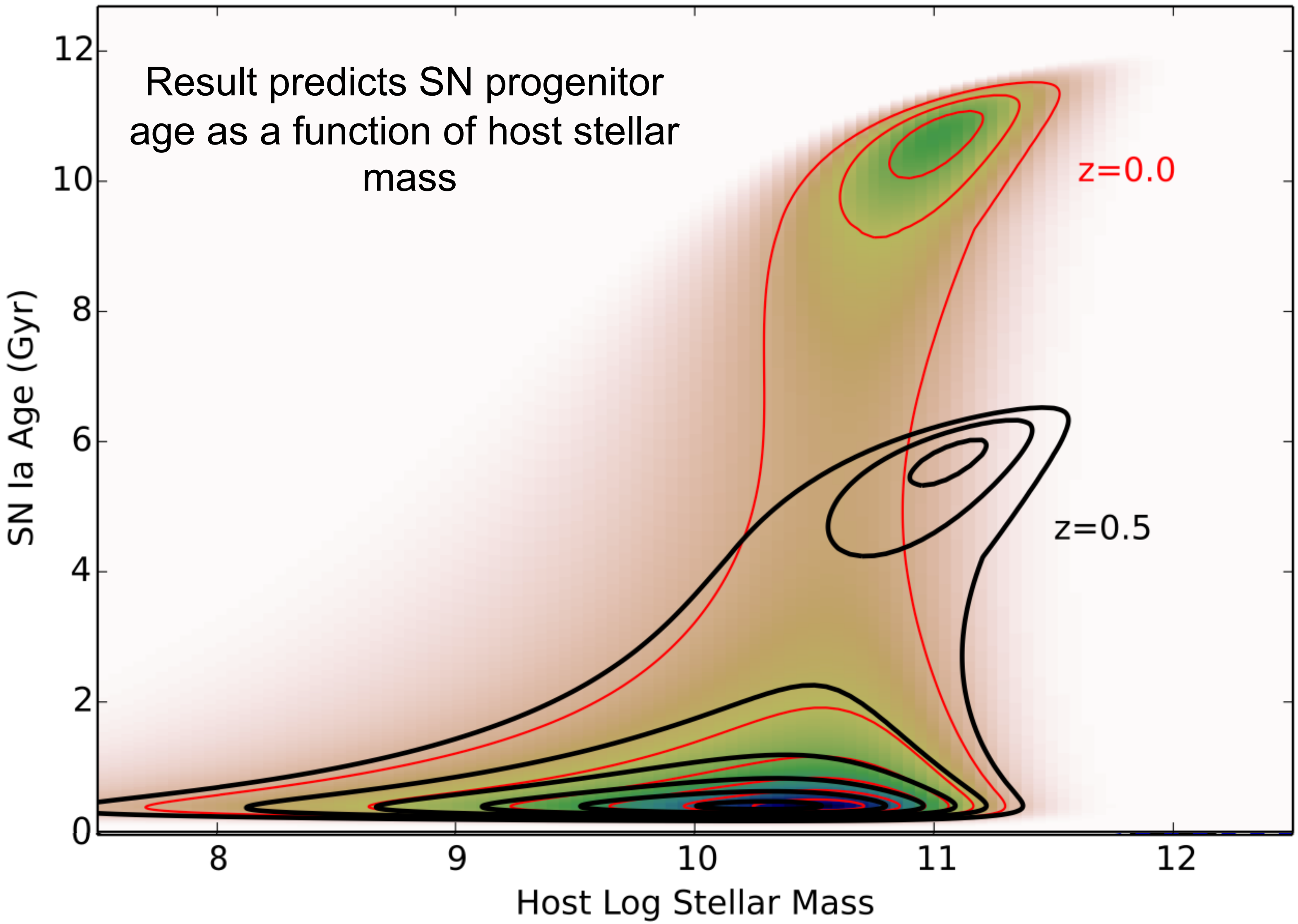
Correlation with local SFR (age)

Correlation between Hubble residuals and local star-formation rate



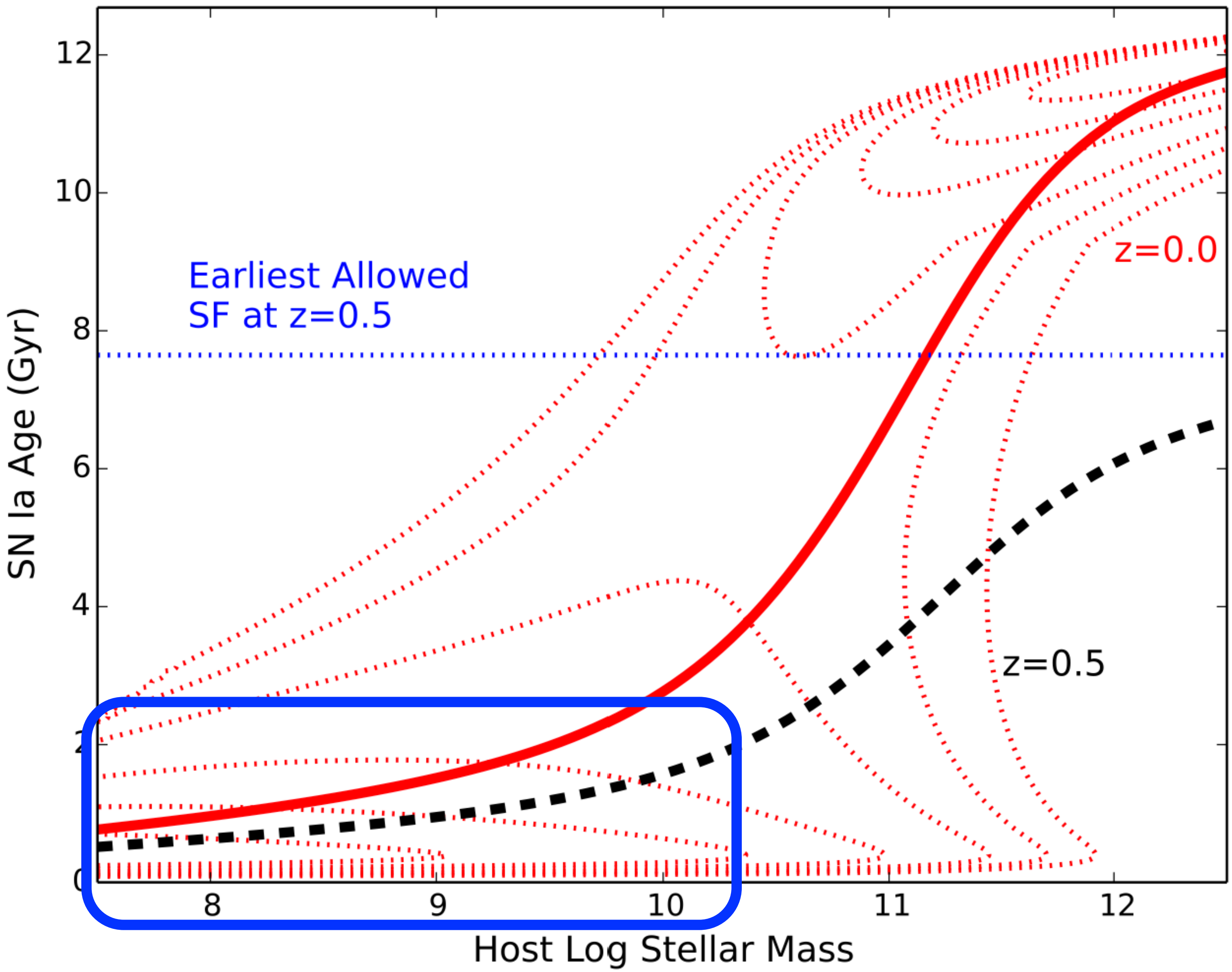
Indicates progenitor age is the key variable

Rigault et al. (2015)



Simulation combining SN Ia formation rate and galaxy evolution

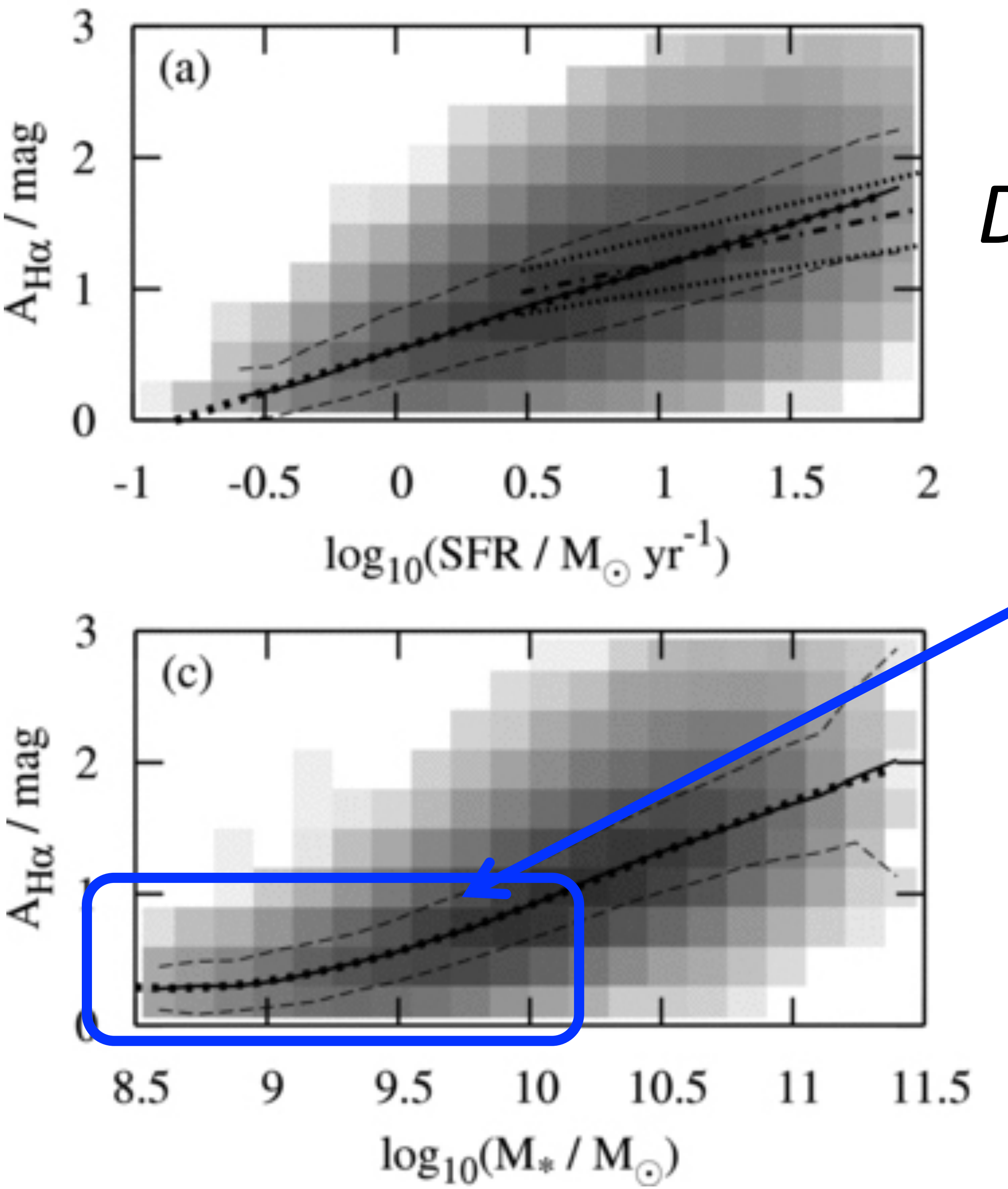
Childress et al. (2014)



The most homogeneous SN Ia events are in lower mass galaxies

Childress et al. (2014)

(Relations for star-forming SDSS galaxies)



Dust versus SFR

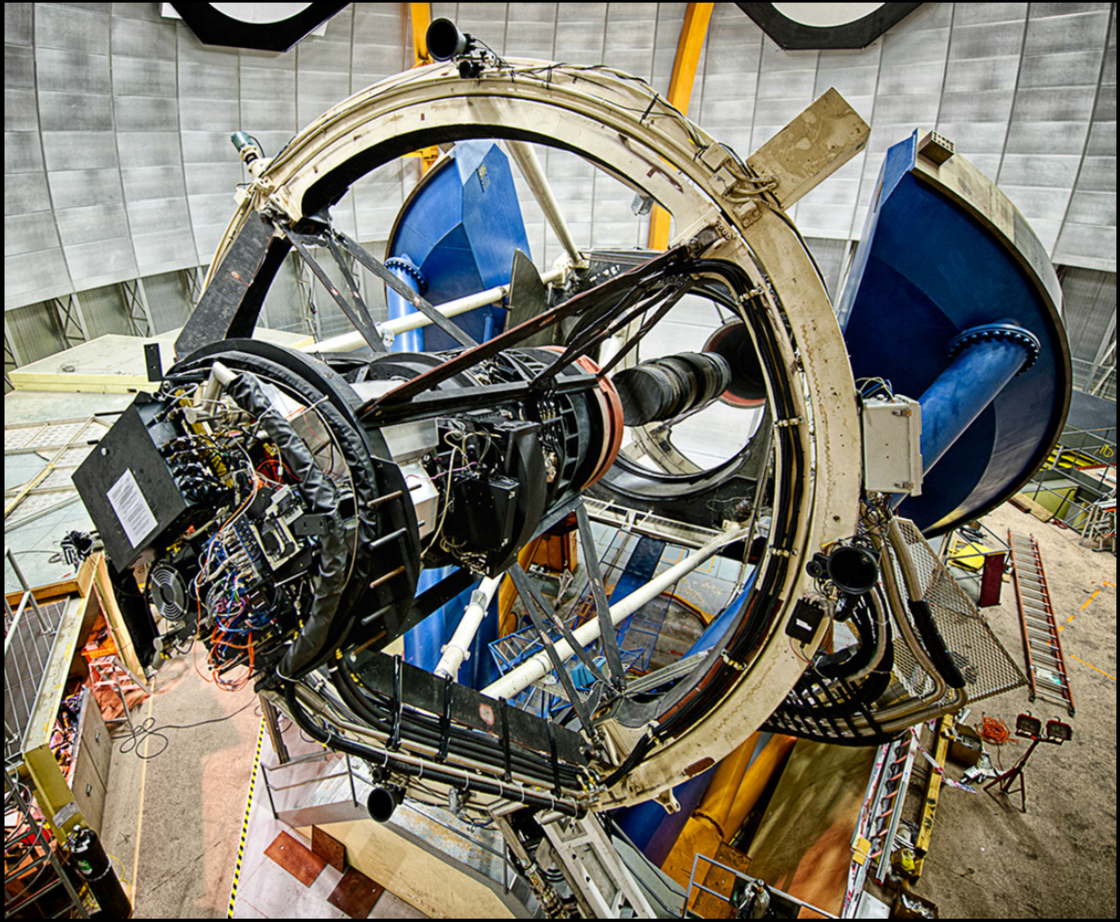
SN Ia events with low extinction are more likely to be in lower mass galaxies

Dust versus stellar mass

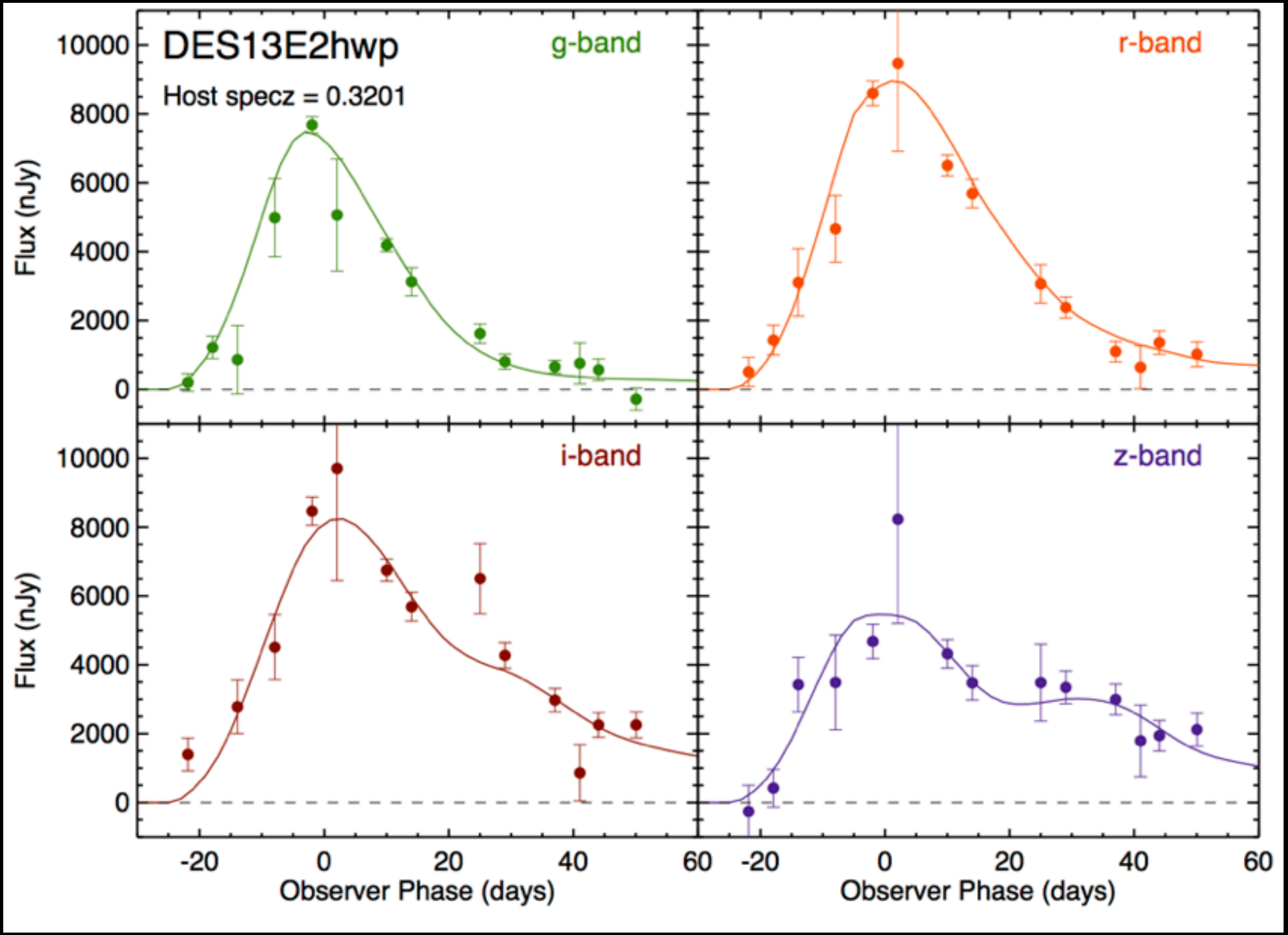
Garn & Best (2010)

THE DARK ENERGY SURVEY

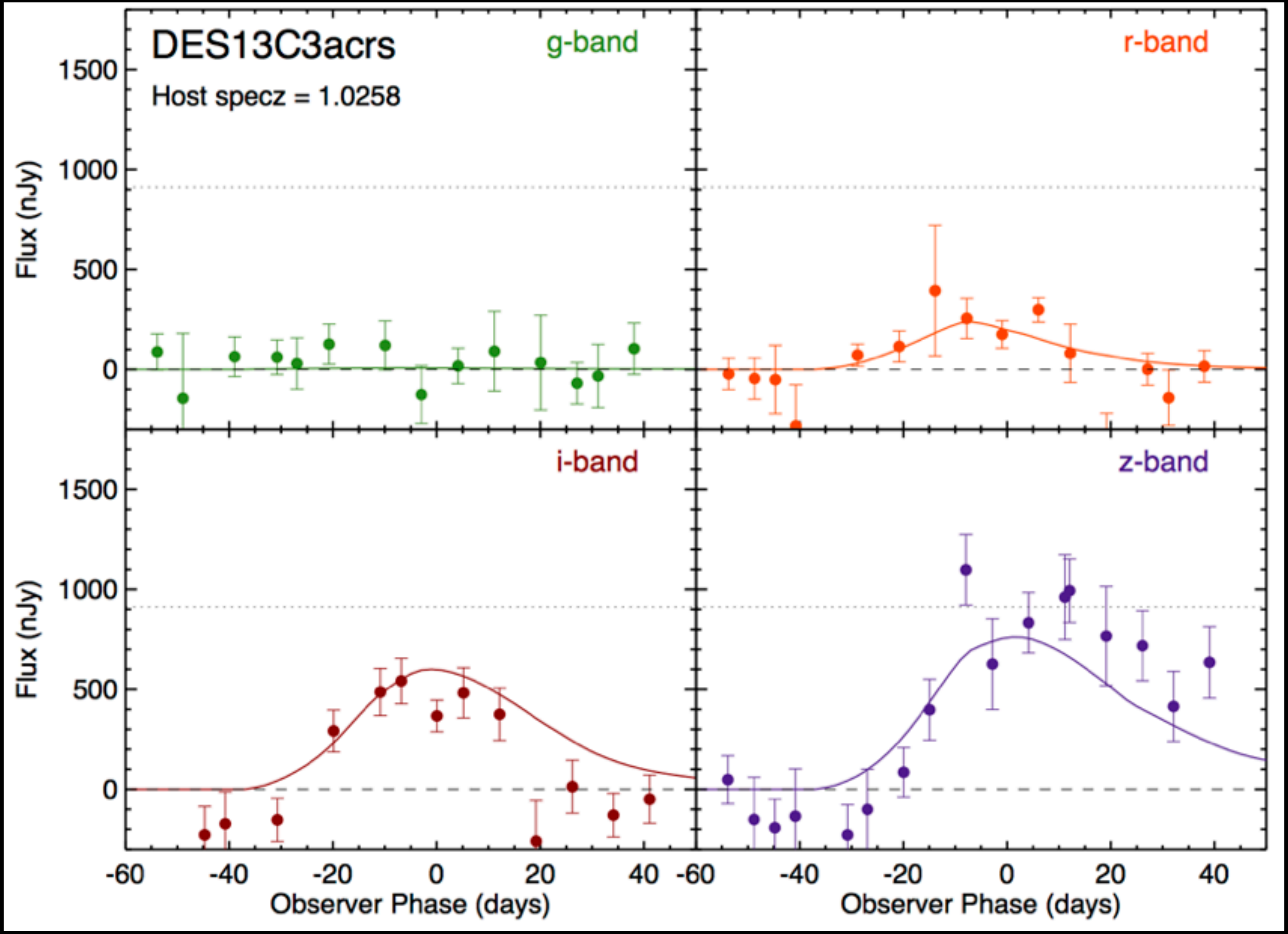
- Probe Dark Energy and the origin of Cosmic Acceleration
  - Distance vs. redshift
  - Growth of Structure
- Two multicolor surveys:
  - 300 M galaxies over 1/8 sky
  - 3500 supernovae (30 deg^2)
- Built new camera for CTIO Blanco telescope
  - Facility instrument
- Five-year Survey
  - 525 nights (Aug - Feb)



Low-z SALT fits (shallow)



High-Z SALT Fits (deep)



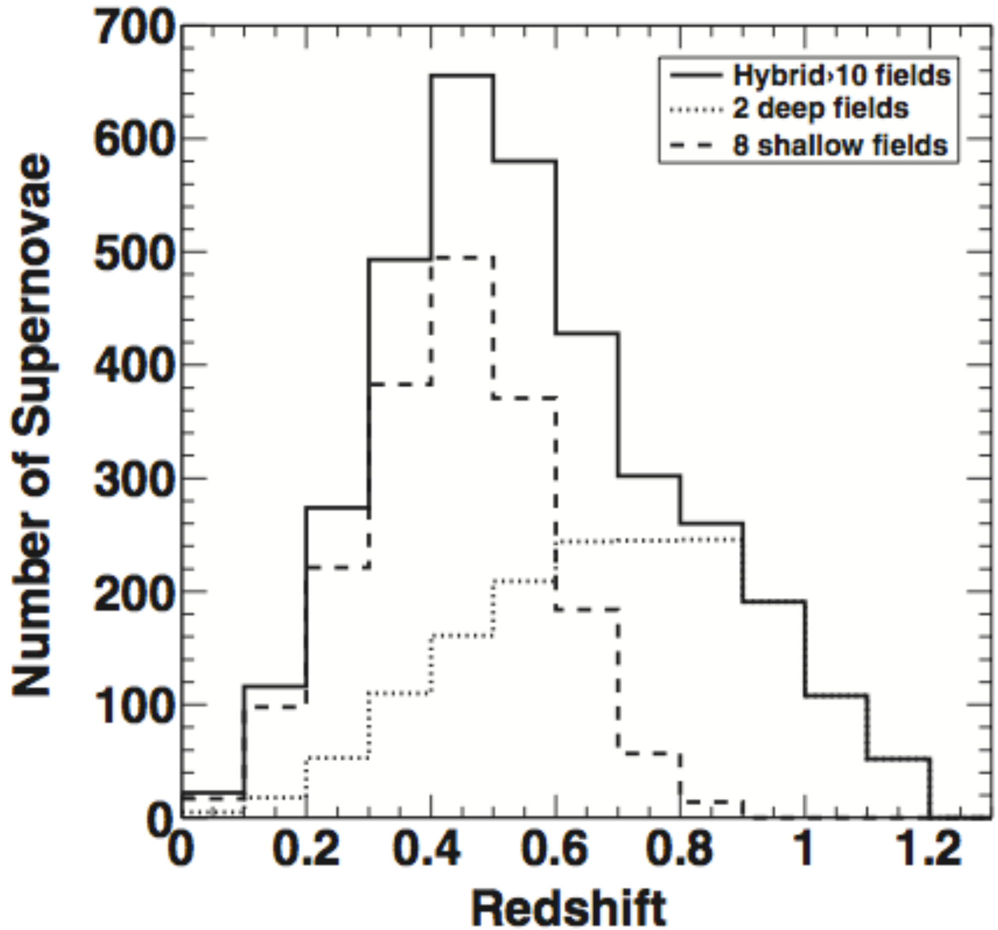
DES Supernova Survey

3000+ SNe Ia in the data

FoM=120

Major challenges are:

- Photometric calibration
- SN photometric classification



"Supernova Simulations and Strategies For the Dark Energy Survey"

Bernstein et al., 2012

Calibration currently at 2% path to improvement

- Absolute photometry (currently using Pan-STARRs, developing own independent path with HST Calspec standards)
- Relative photometry across field (No trends larger than 1%)
- Field-to-field consistency (<1%)
- Regular measurements of bandpasses across focal plane
- Atmospheric effects – Depoy et al.

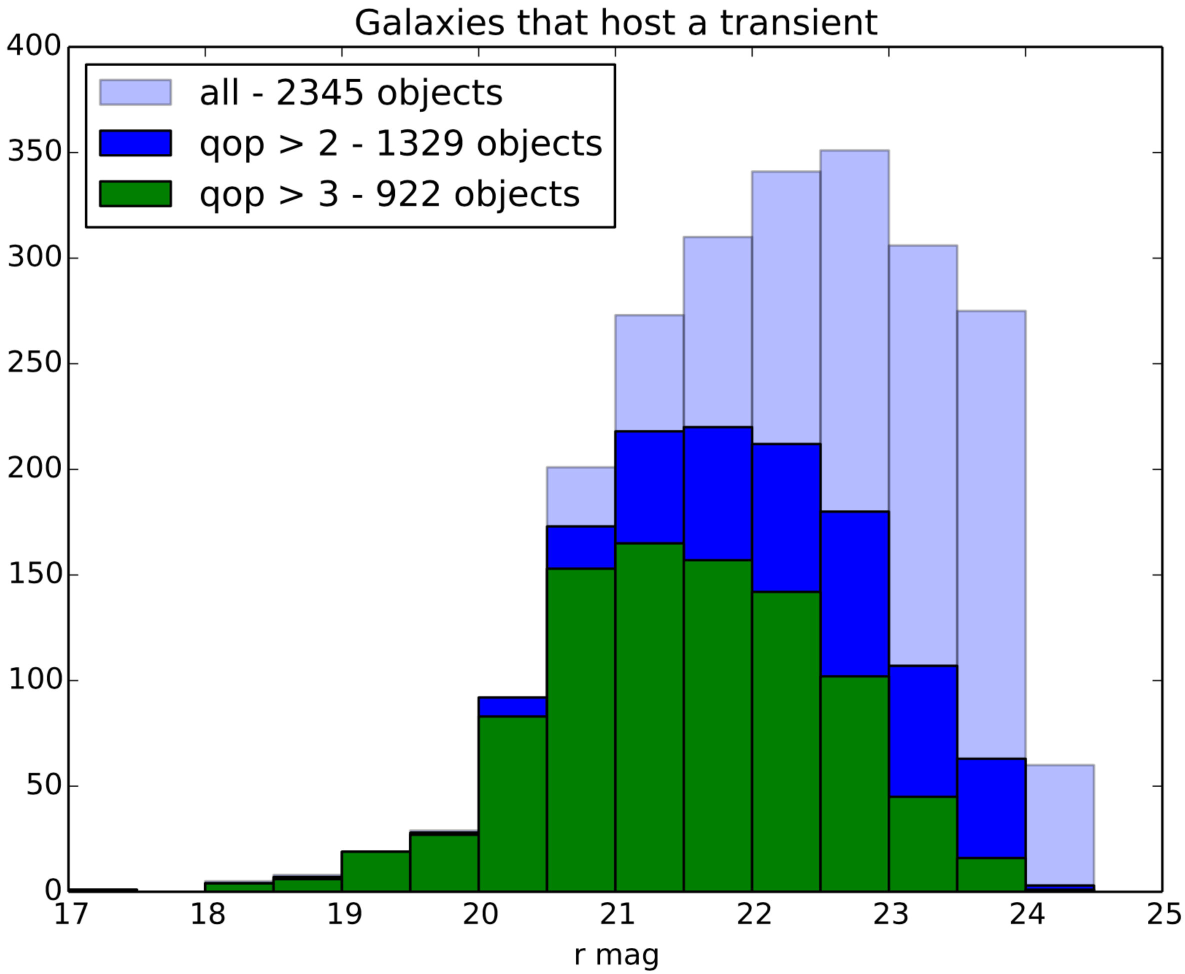
(Scolnic, Lasker, Wester, Tucker, Bernstein)

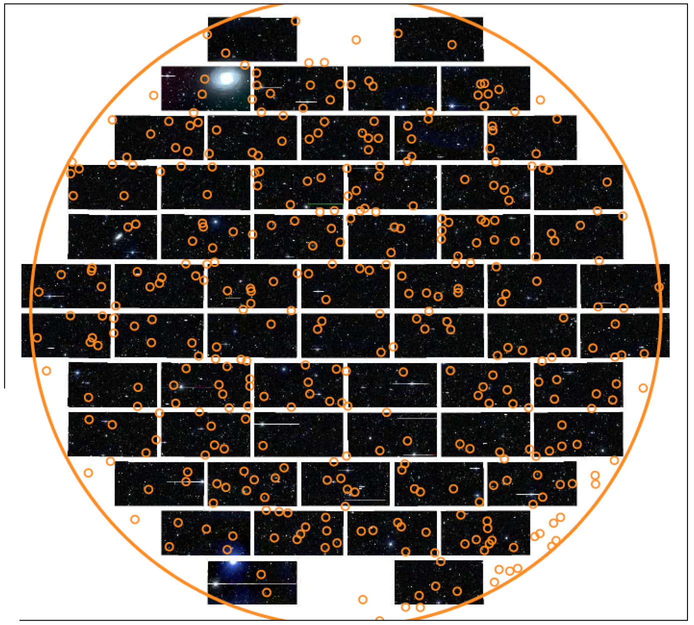
“Live” transients

Telescope	Time (2014-15)
VLT (Sullivan et al.)	7 nights
GTC (Castander et al.)	13hrs (ToO)
MMT/Magellan (Kirshner et al.)	9.5 nights
Keck (Nugent et al.)	5.5 nights + 8hrs ToO
Magellan (Kessler et al.)	0.5 nights
SALT (Smith et al.)	10.5 hrs

Telescope	Time (2015-16)
SALT (Kasai et al.)	22.5 hrs (ToO)
Magellan (Scolnic et al.)	2 nights
Magellan (Gonzalez et al.)	4 nights
Gemini (Galbany et al. + Foley et al.)	53.2 hrs (ToO)
GTC (Castander et al.)	26hrs (ToO)
VLT (Sullivan et al.)	7 nights
Keck (Nugent et al.)	6 nights

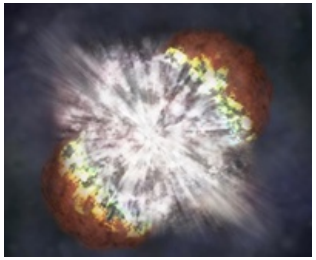
On target for ~4000 SN host redshifts





- AAOmega: perfect overlap with DECam
- SN hosts targeted repeatedly to build depth
- Fibers placed on live SNe (r < 21)
- **100 nights over 5 years**

Superluminous supernovae



Alternative standard candles to SNe Ia?

New classes of superluminous SNe

→ 50 times brighter than SNe Ia

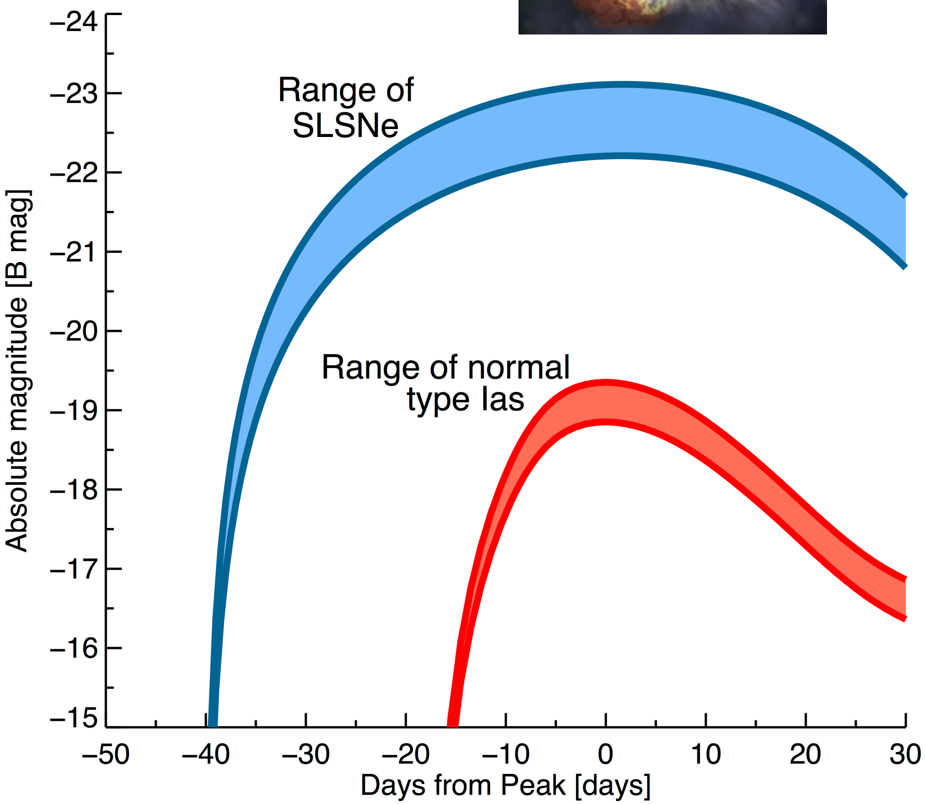
→ Seen to z=4

What is their physical nature?

→ Not ^{56}Ni! Magnetar?

Can they be standardised?

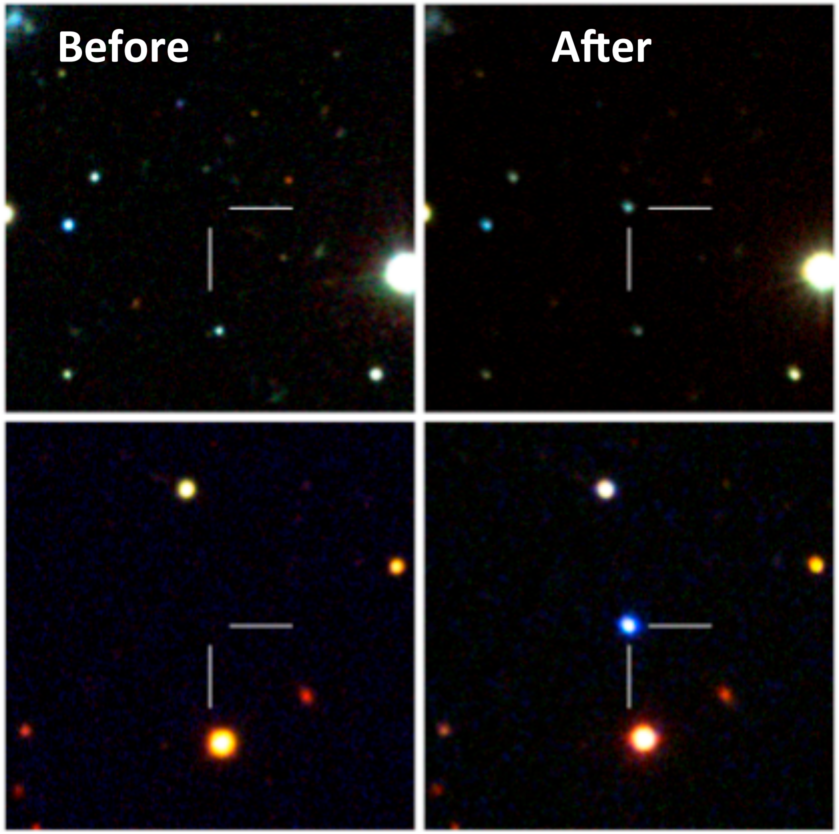
→ Current dispersion 0.25 mag

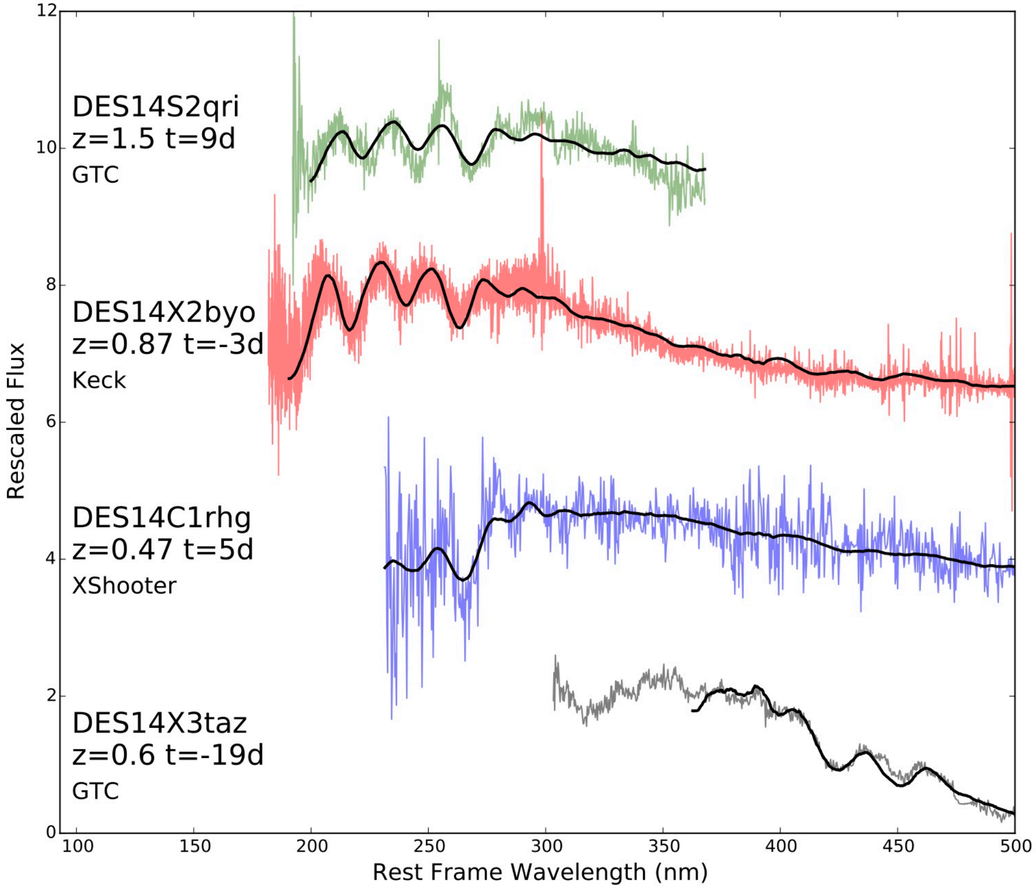


The next few years will see the first cosmological samples

Superluminous SNe

- Faint, prob. metal poor hosts
- Very bright (<-21 absolute mag)

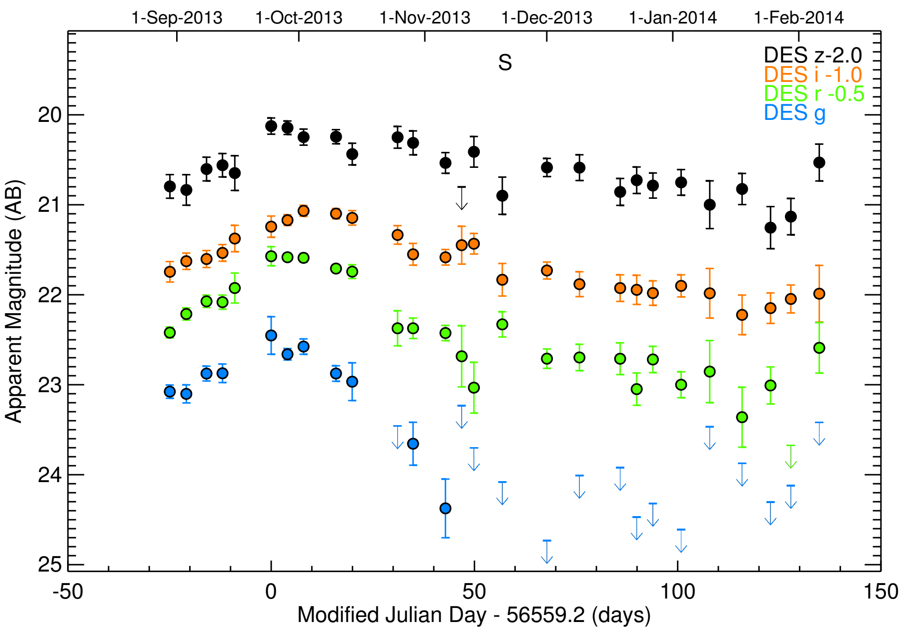


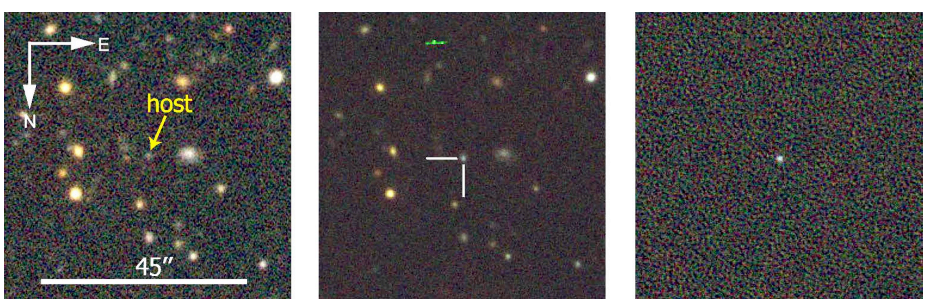


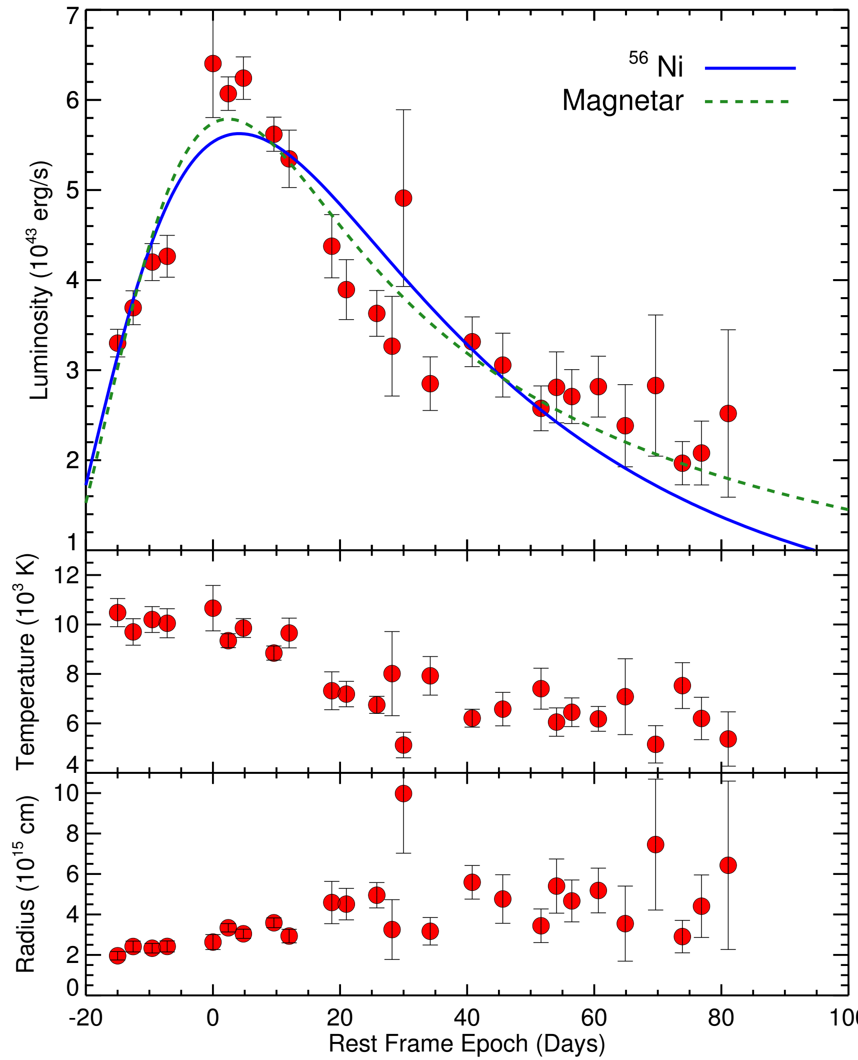
- No H, He, Ca, Si
- Lines of C, O, Mg,
- Extreme UV luminosity
  - (no line blanketing)

Power source is unknown

DES13S2cmm

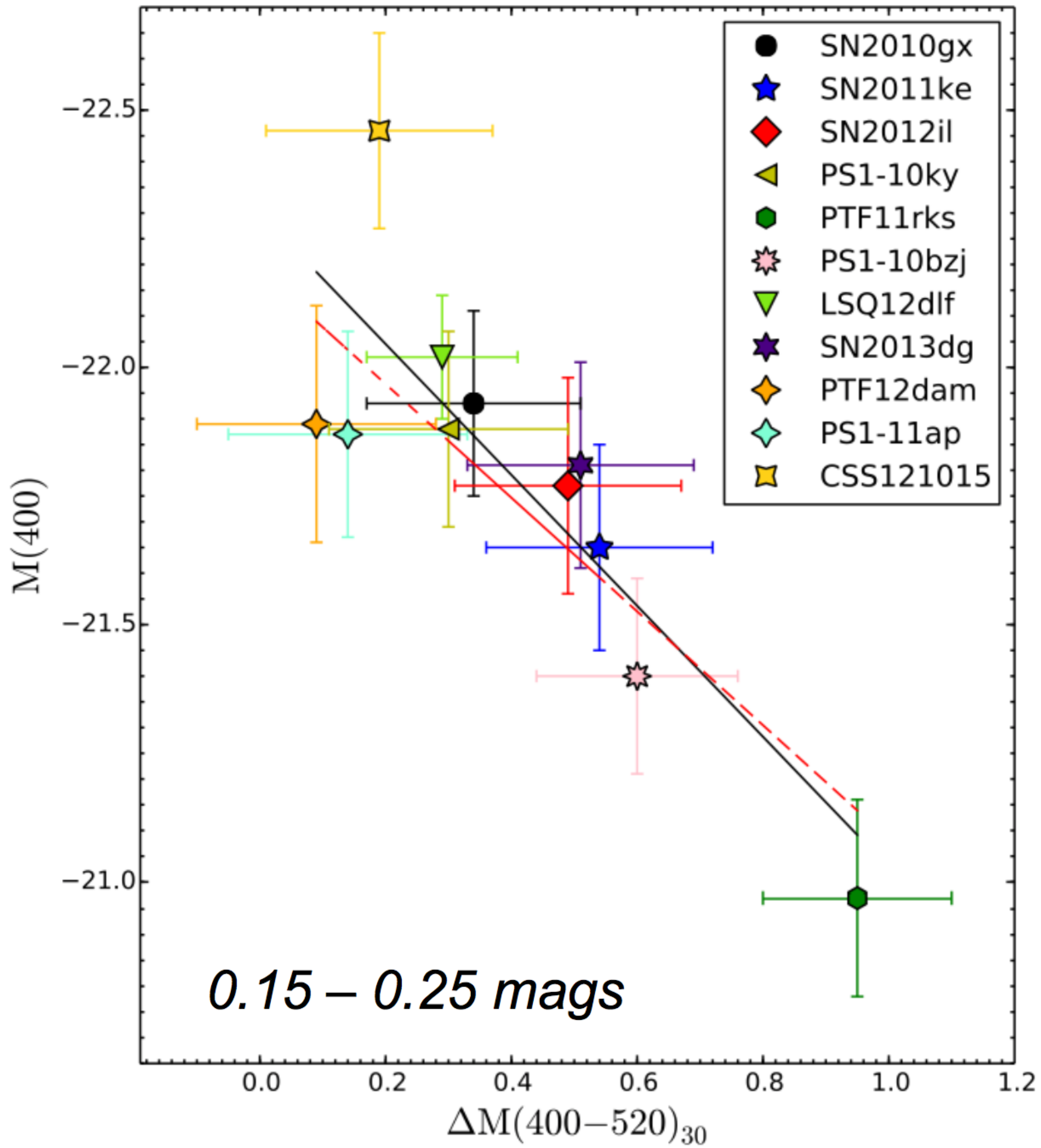






Papadopoulos et al. 2014

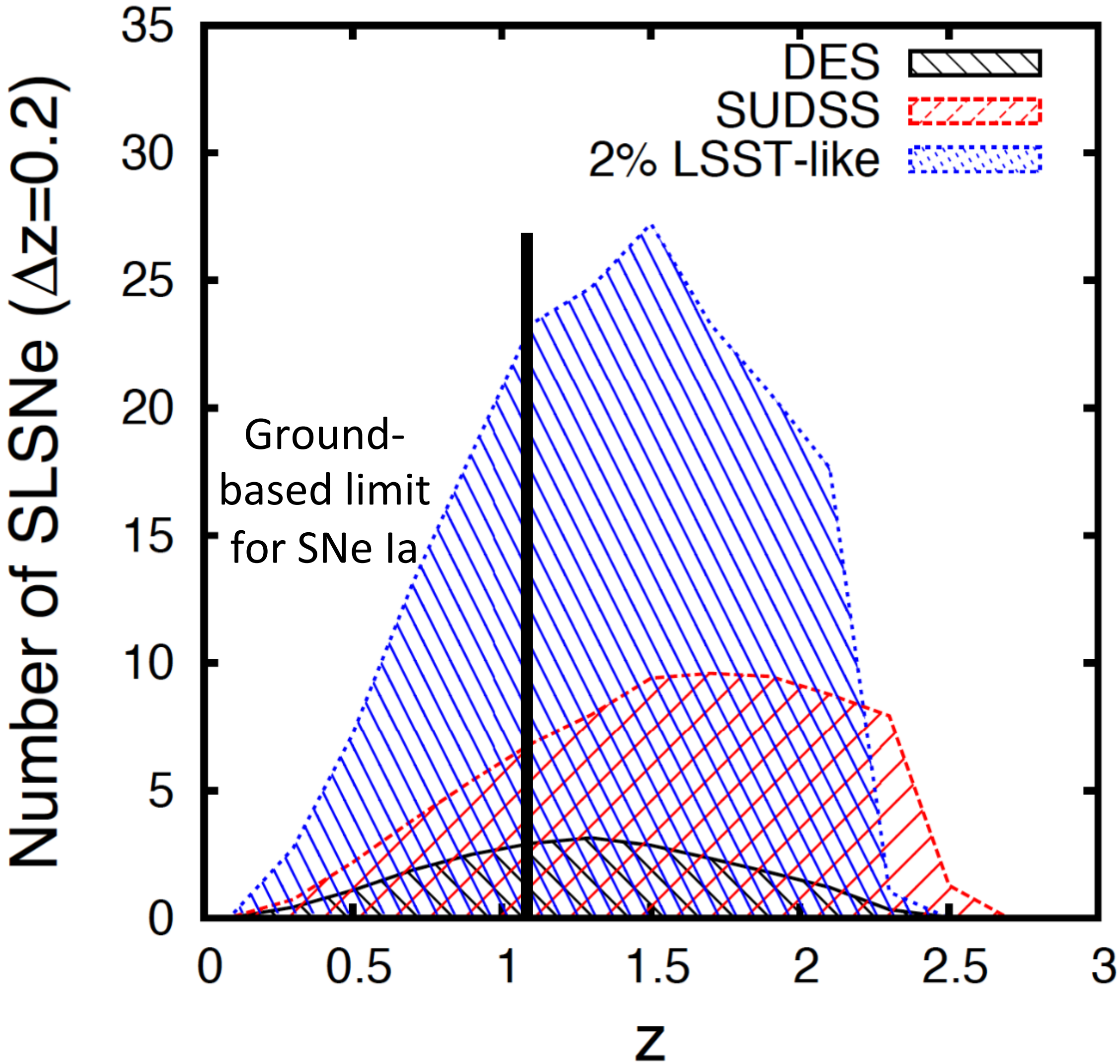
SLSNe may be standardisable



Inserra & Smartt 2014

Survey Using DECam for Superluminous Supernovae (SUDSS)

Scovacricchi et al. 2015

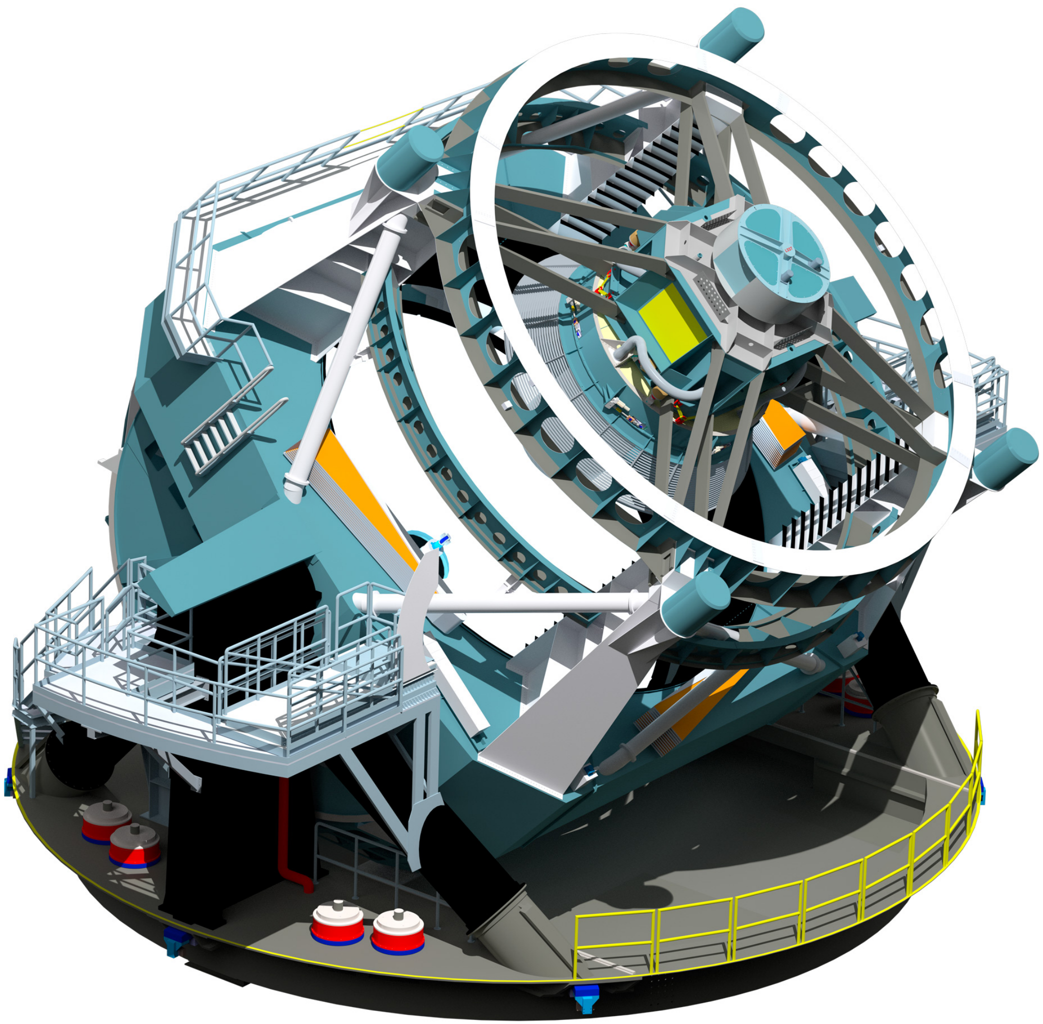


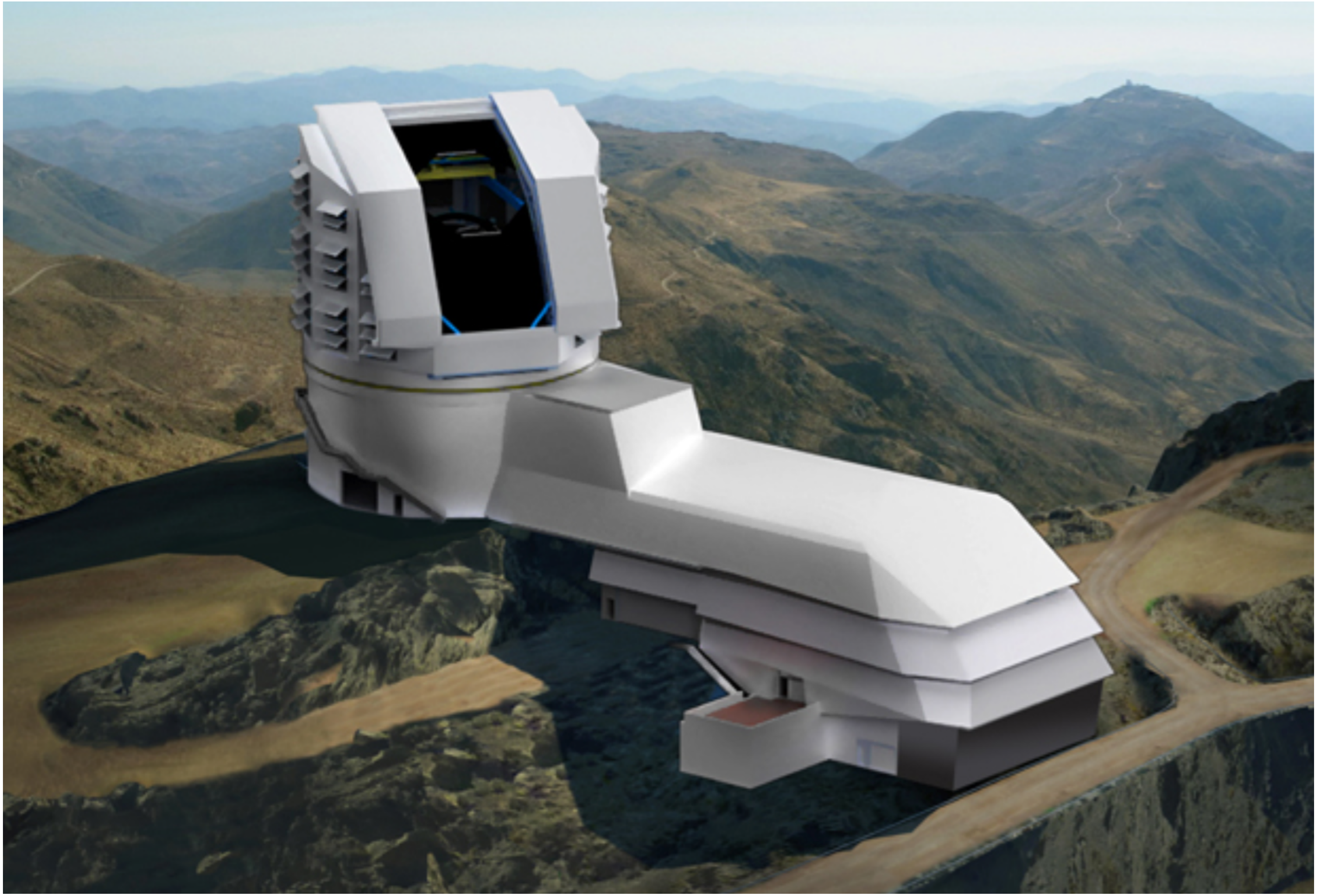
Increasing DES observing window helps significantly

24 deg² at ~14 day cadence for ~7 months to twice depth of DES shallow fields

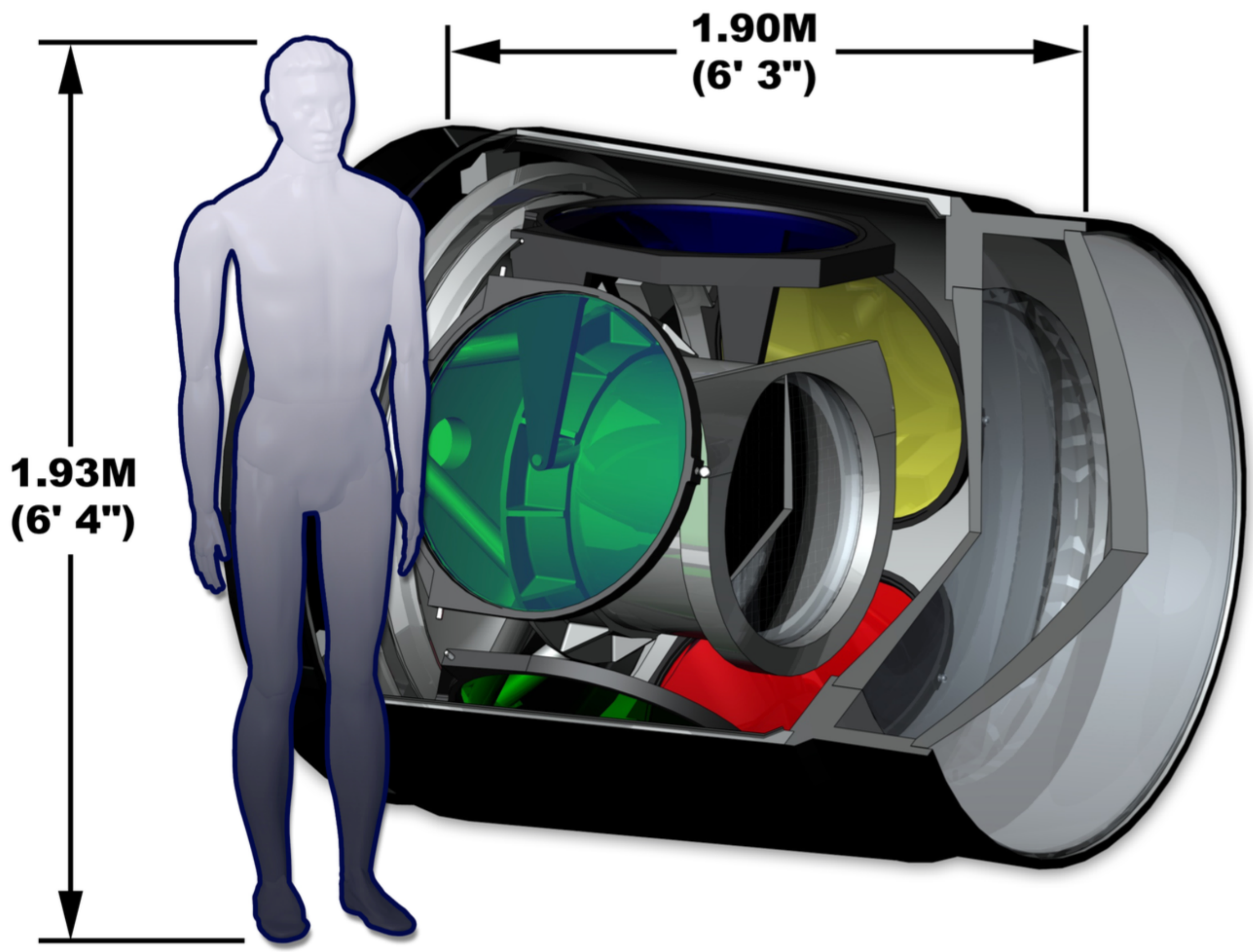
LSST: early 2020s

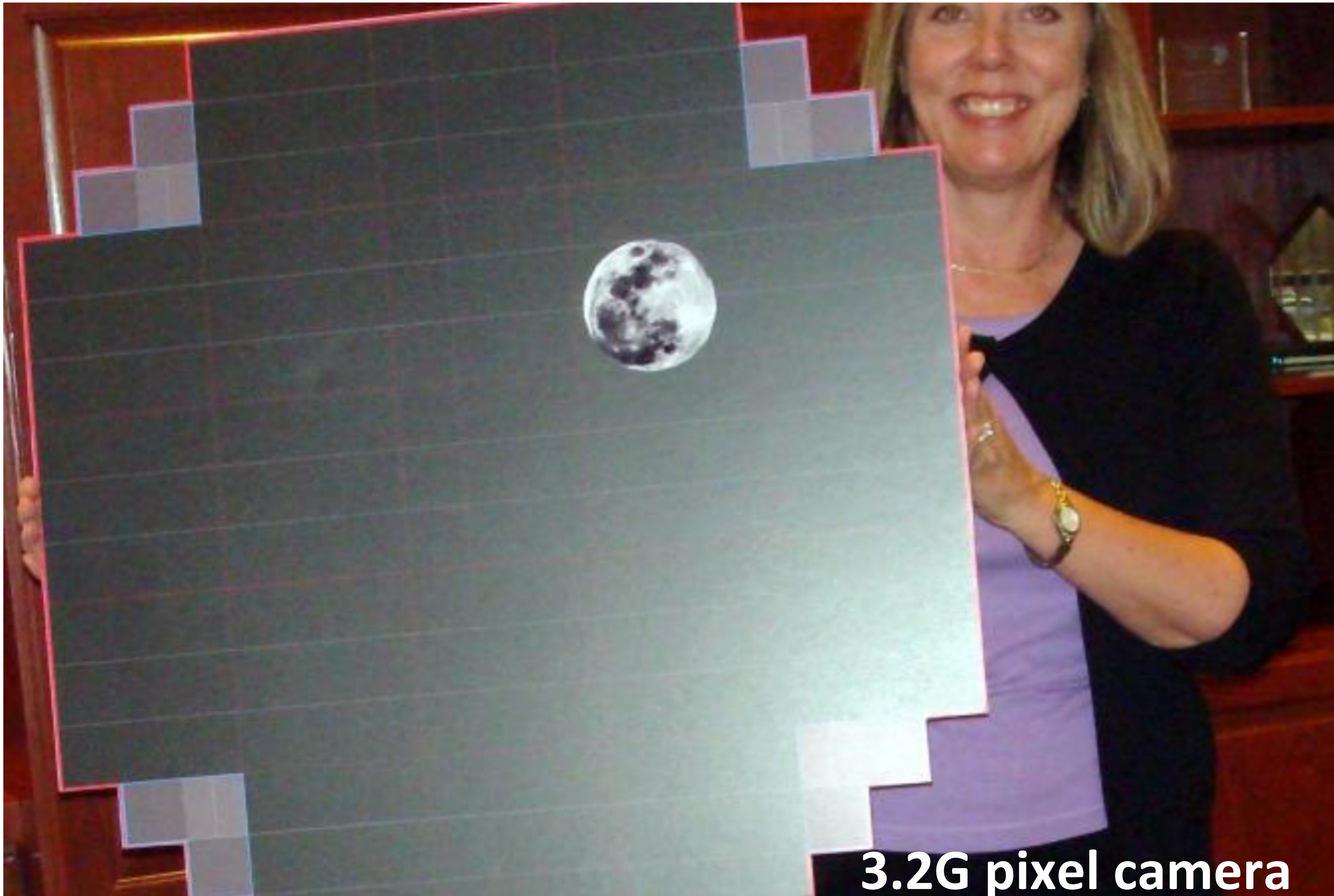
Image the whole sky every few days; millions of transients





Big Camera




3.2G pixel camera

Big data from LSST

- Within one month of operation, LSST will survey more of the universe than all previous telescopes
- 20TB per night, 100PB over 10 years
- 100,000 transient alerts per night
- 10 million supernovae
- 20,000 Superluminous SNe over 85% of the universe's age

Large Synoptic Survey Telescope

Expected Rate of Transients

Class	Mag	t (days)	Universal Rate	LSST Rate
Luminous SNe	-19...-23	50 - 400	10^{-7} Mpc^{-3} yr^{-1}	**20000**
Orphan Afterglows SHB	-14...-18	5 -15	3 x$10^{-7...-9}$ Mpc^{-3} yr^{-1}	**~10 - 100**
Orphan Afterglows LSB	-22...-26	2 - 15	3 x $10^{-10...-11}$ Mpc^{-3} yr^{-1}	**1000**
On-axis GRB afterglows	...-37	1 - 15	10^{-11} Mpc^{-3} yr^{-1}	**~50**
Tidal Disruption Flares	-15...-19	30 - 350	10^{-6} Mpc^{-3} yr^{-1}	**6000**
Luminous Red Novae	-9...-13	20 - 60	10^{-13} yr^{-1} Lsun^{-1}	**80 - 3400**
Fallback SNe	-4...-21	0.5 - 2	<5 x 10^{-6} Mpc^{-3} yr^{-1}	**$<$ 800**
SNe Ia	-17...-19.5	30 - 70	3 x 10^{-5} Mpc^{-3} yr^{-1}	**200000**
SNe II	-15...-20	20 - 300	(3..8) x 10^{-5} Mpc^{-3} yr^{-1}	**100000**

Table adapted from Rau et al. 2009

Slide by Lucianne Walkowicz , Co-Chair of Transients and Variable Stars Science Collaboration

SN Cosmology is mature: hundreds published

Control of systematics is vital:

- Astrophysical systematics are sub-dominant
- Photometric calibration is in-hand

New era of SN cosmology on horizon