Supernova discoveries in the early Universe

Toward detecting the deaths of the first stars

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SWINBURNE CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

outline

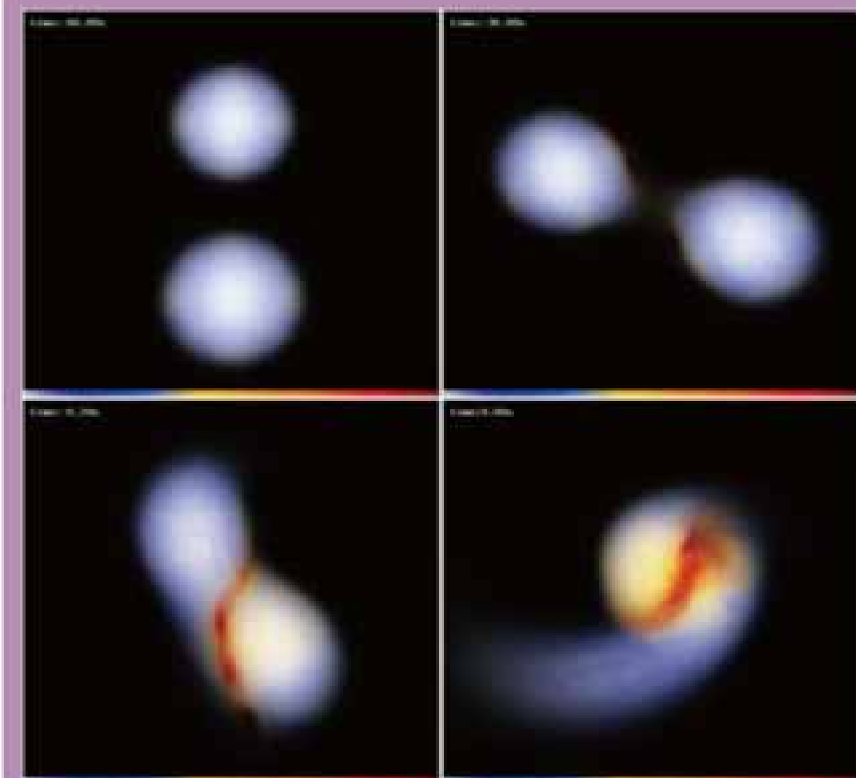
- Supernovae and supernova surveys
- High redshift program overview
- High redshift discoveries
- Rates and applications
- Future

Supernovae classification scheme

no hydrogen (type I)	hydrogen (type II)
Ia – white dwarf(s)	
	IIP – plateau decay
	IIL – linear decay
Ib – shows helium	
Ic – no helium	**IIn** – narrow lines
SLSN-I	**SLSN-II**
SLSN-R – pulsational events	
SLSN-R – ^{56}Ni decay rate	

supernovae

Thermonuclear explosion (SN Ia)



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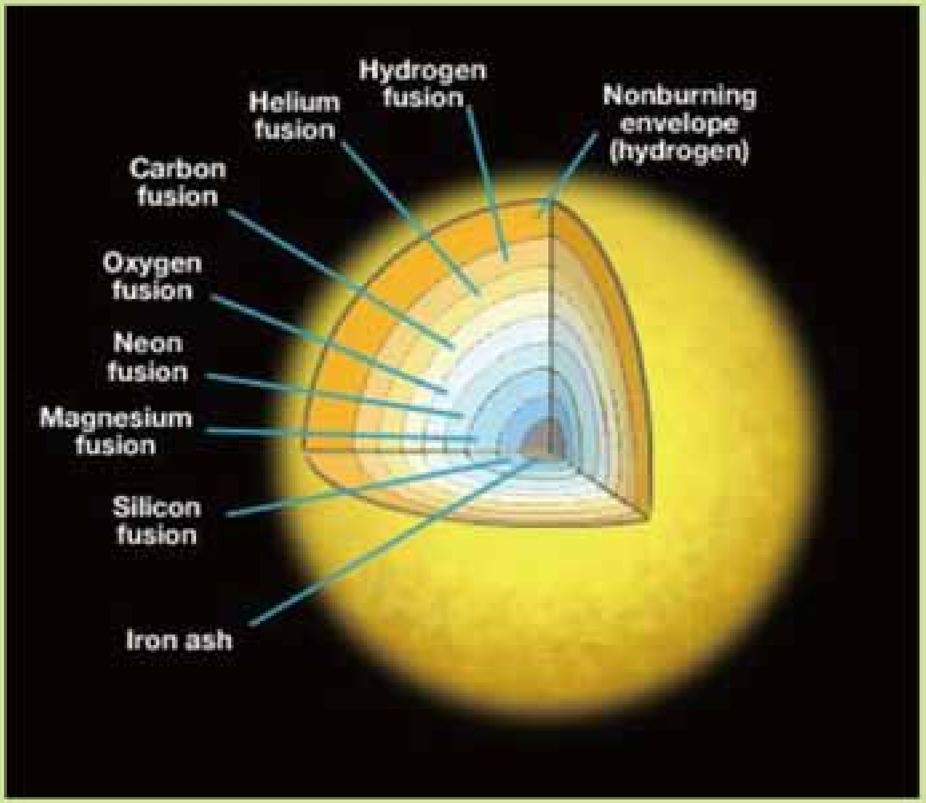
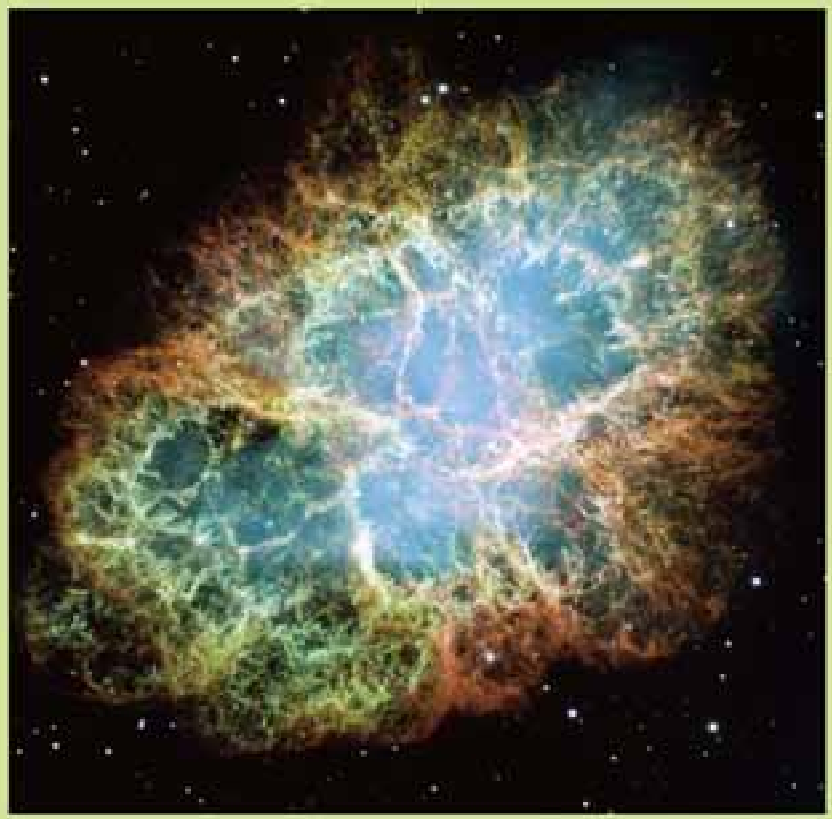
supernovae

Core-collapse supernovae (CCSNe)





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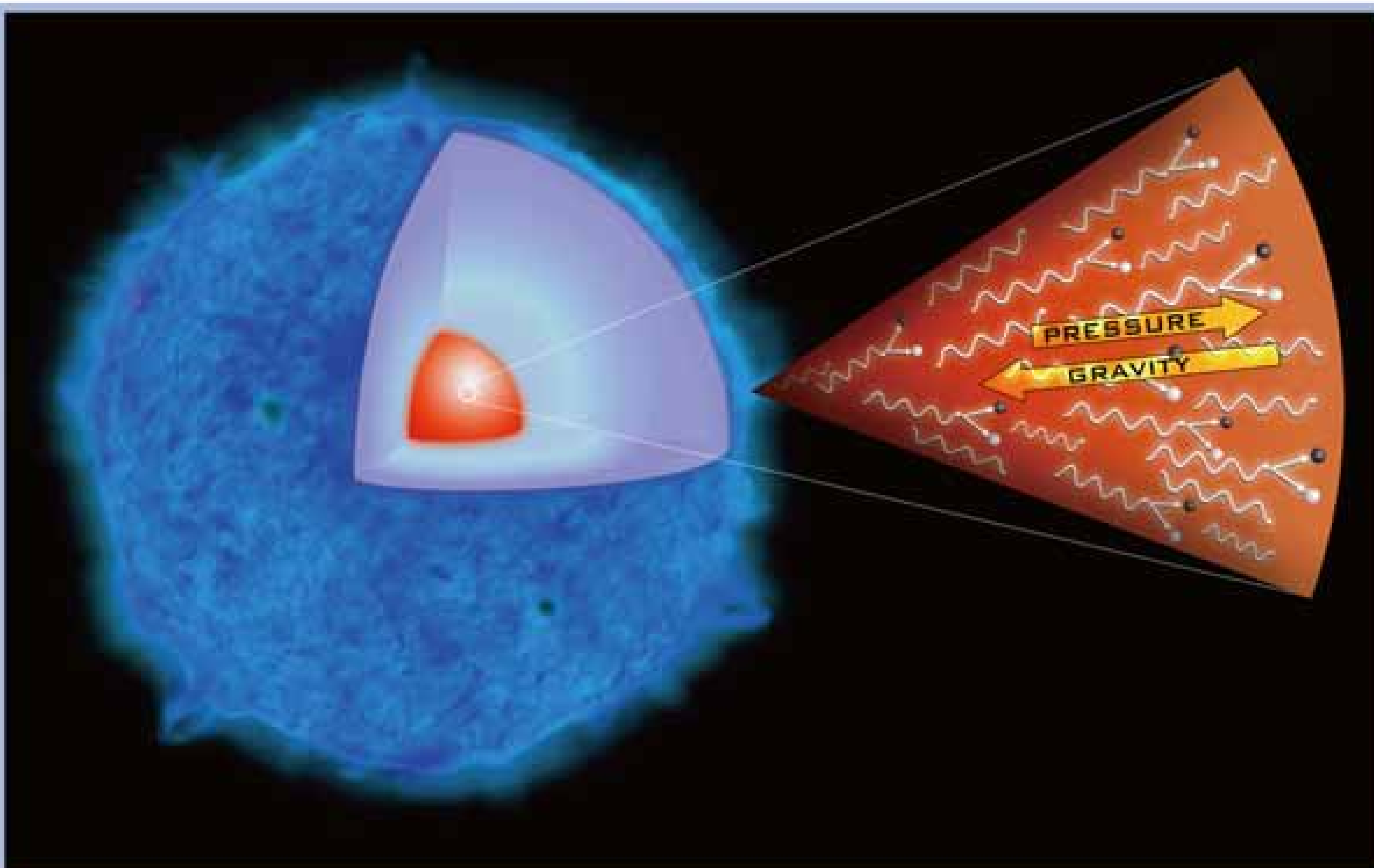
Pair-instability supernovae (PISNe)



Supernovae classification scheme

greater loss of outer layers/ loss rate ↓

no hydrogen (type I)	hydrogen (type II)	$\sim M_{Prog.}$ *(solar masses)*
Ia – white dwarf(s)		
	IIP – plateau decay	8-15
	IIL – linear decay	15-35
Ib – shows helium		↕ Wide range 35-80?
Ic – no helium	**IIn** – narrow lines	
SLSN-I	**SLSN-II**	
SLSN-R – pulsational events		80-140
SLSN-R – ^{56}Ni decay rate		140-260

e.g., Gal Yam et al. (2007), Elias Rosa et al. (2009,2010), Smith et al. (2011), Gal-Yam (2012)

Supernovae classification scheme

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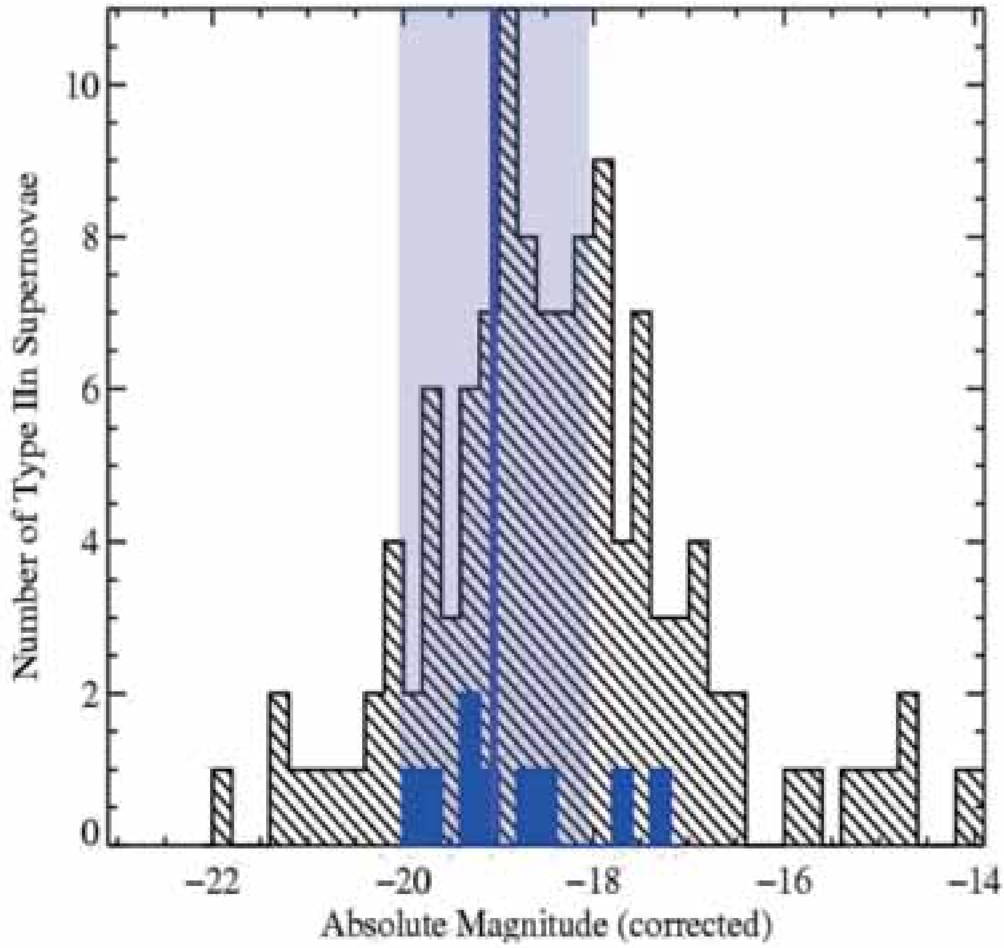
SLSN-I	**SLSN-II**	
SLSN-R – pulsational events		80-140
SLSN-R – ^{56}Ni decay rate		140-260

e.g., Gal Yam et al. (2007), Elias Rosa et al. (2009,2010), Smith et al. (2011), Gal-Yam (2012)

type IIn supernovae

SN mag distributions

type IIn

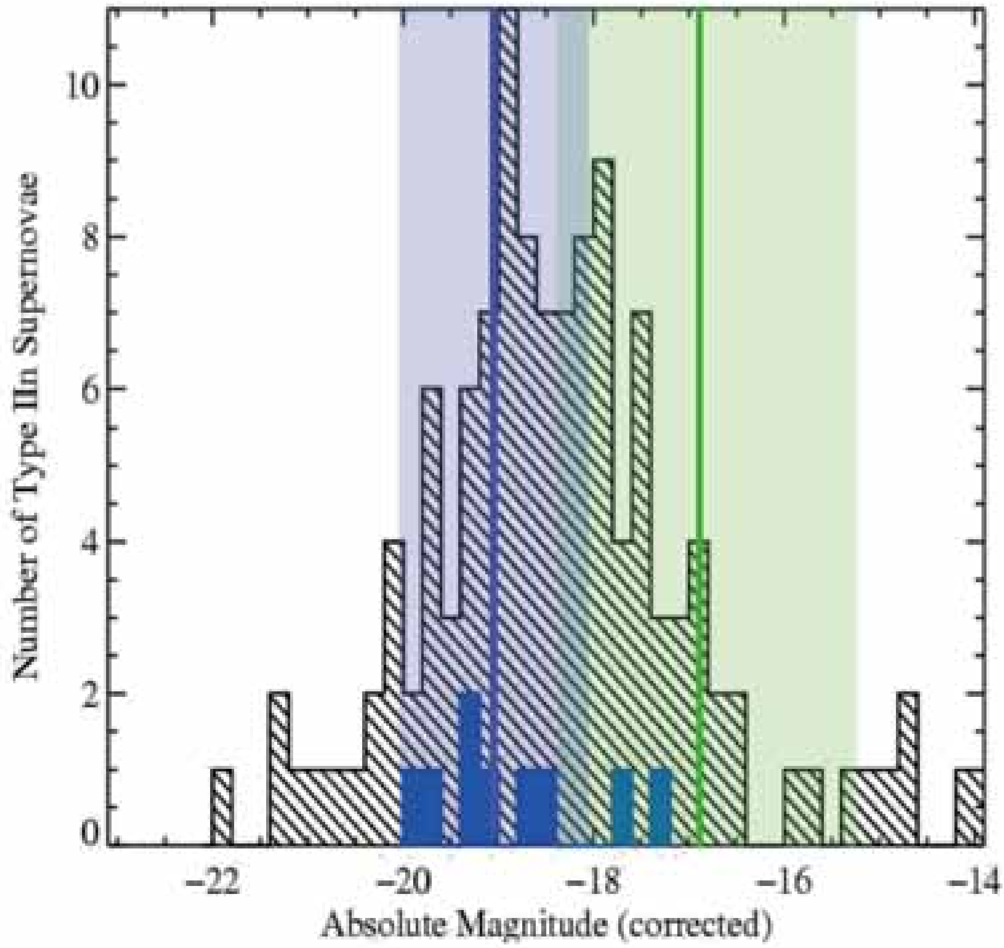


Richardson et al. (2002), Cooke (2008)

SN mag distributions

type IIn

type II-P



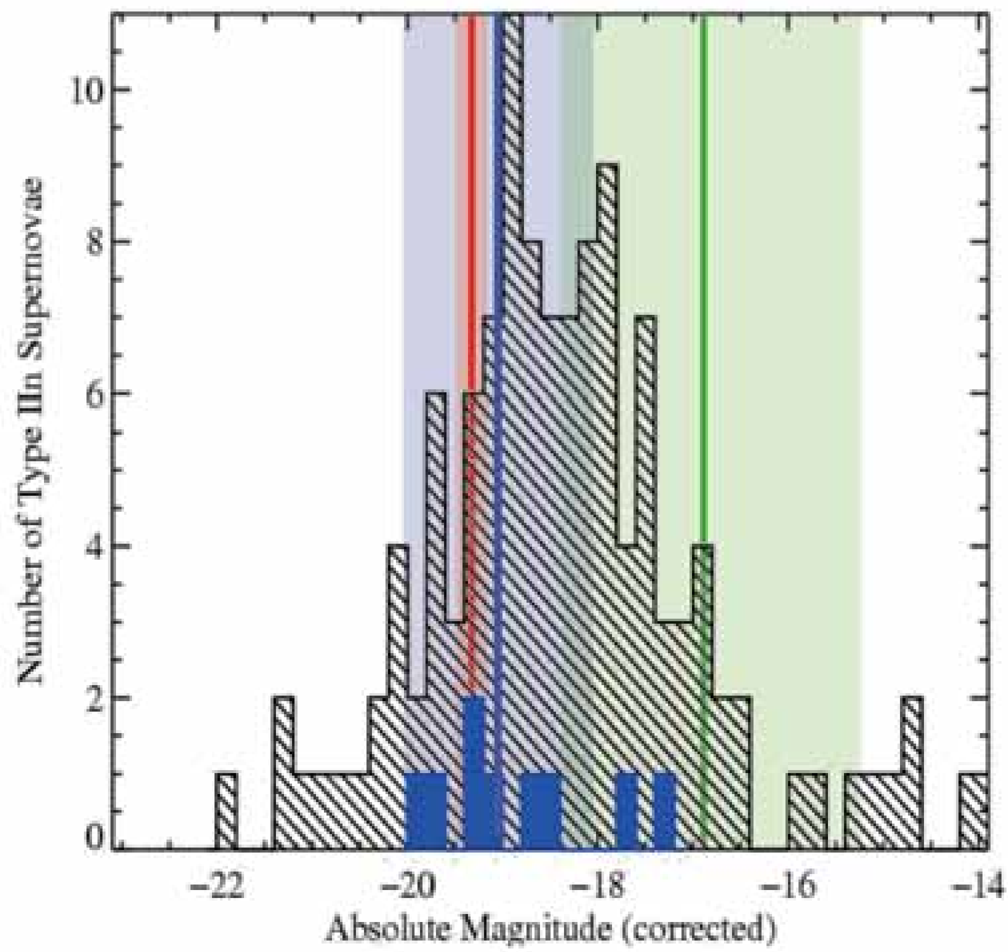
Richardson et al. (2002), Cooke (2008)

SN mag distributions

type IIn

type II-P

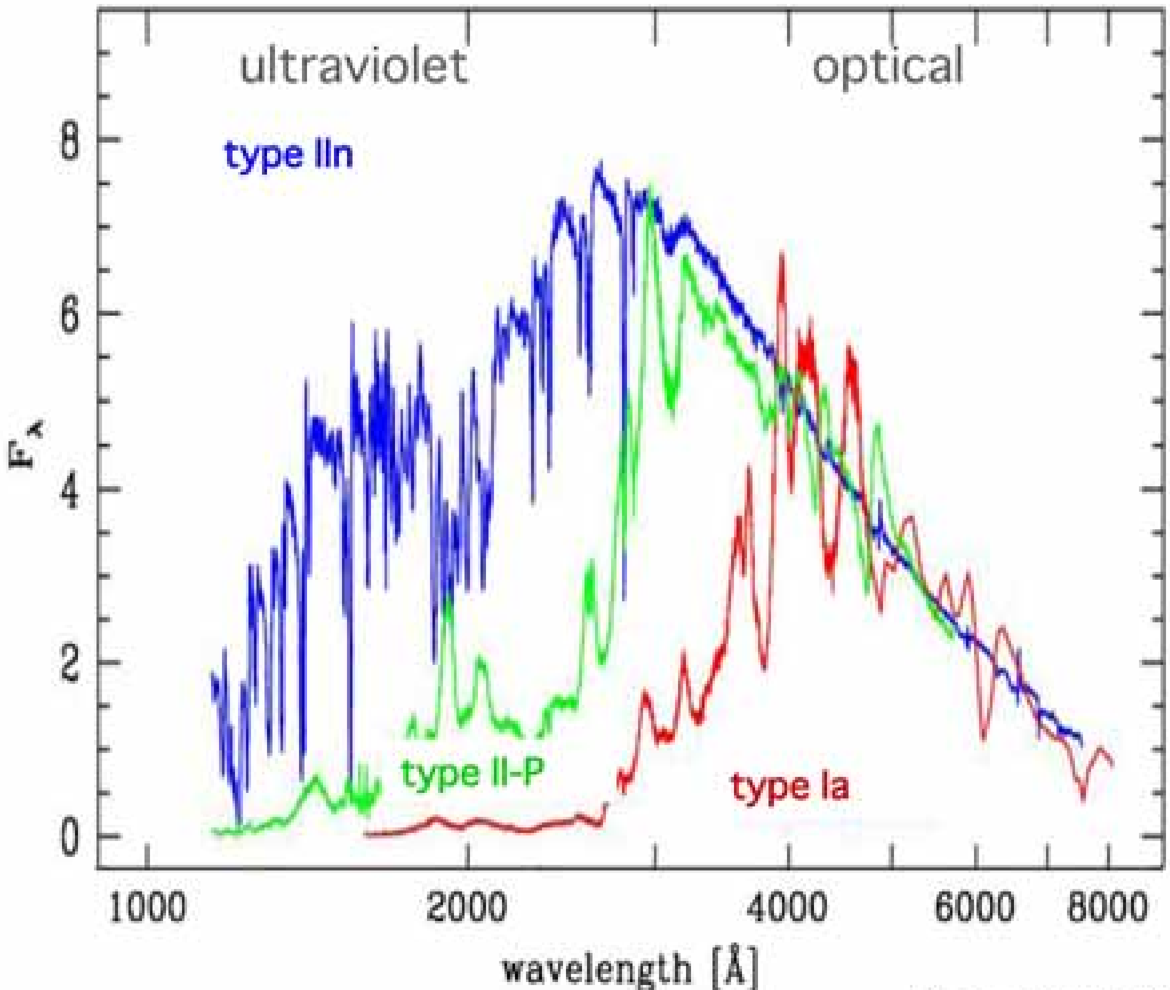
type Ia



Richardson et al. (2002), Cooke (2008)

type IIn supernovae

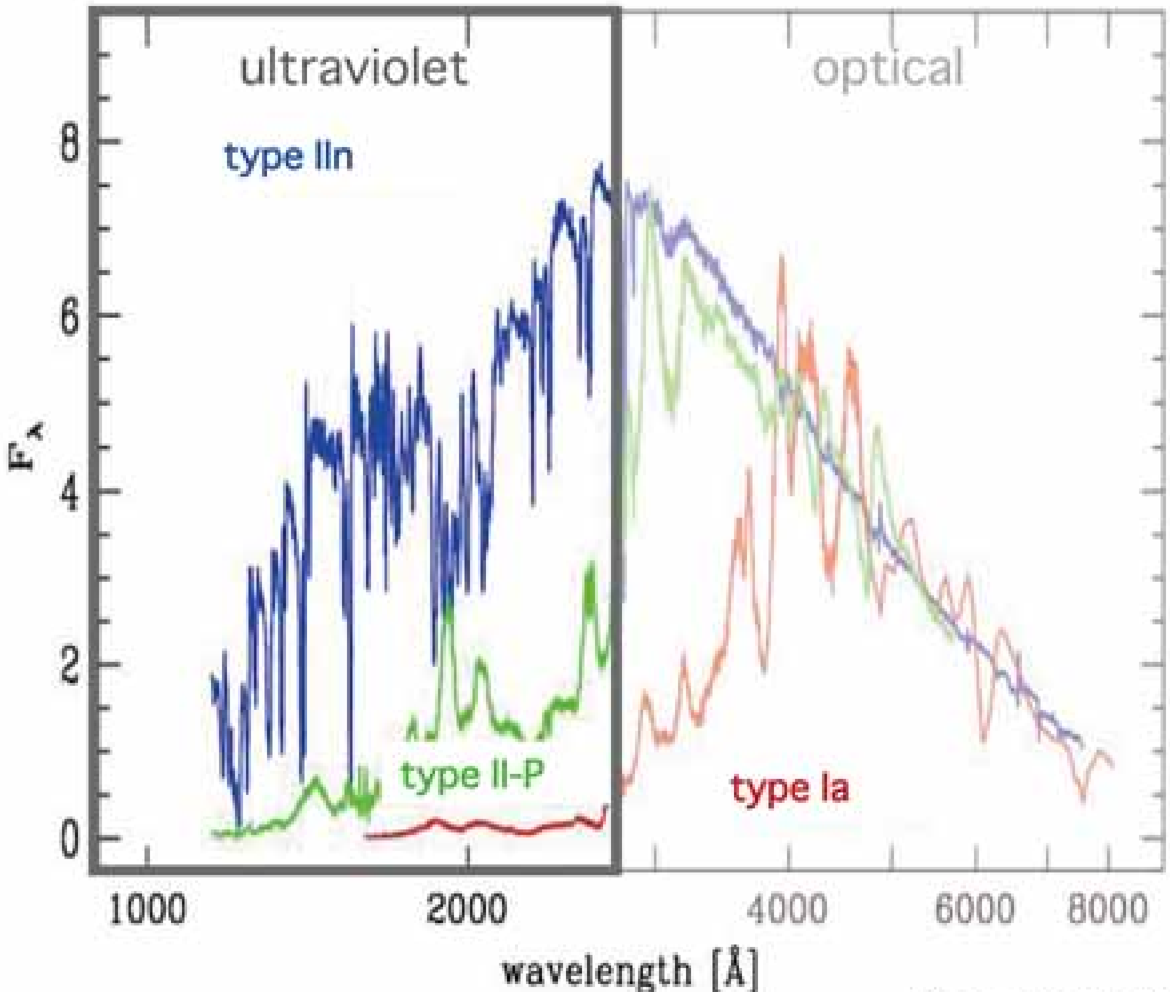
Type IIn are not just luminous in the optical



Riess et al. (2004)

Type IIn are not just luminous in the optical

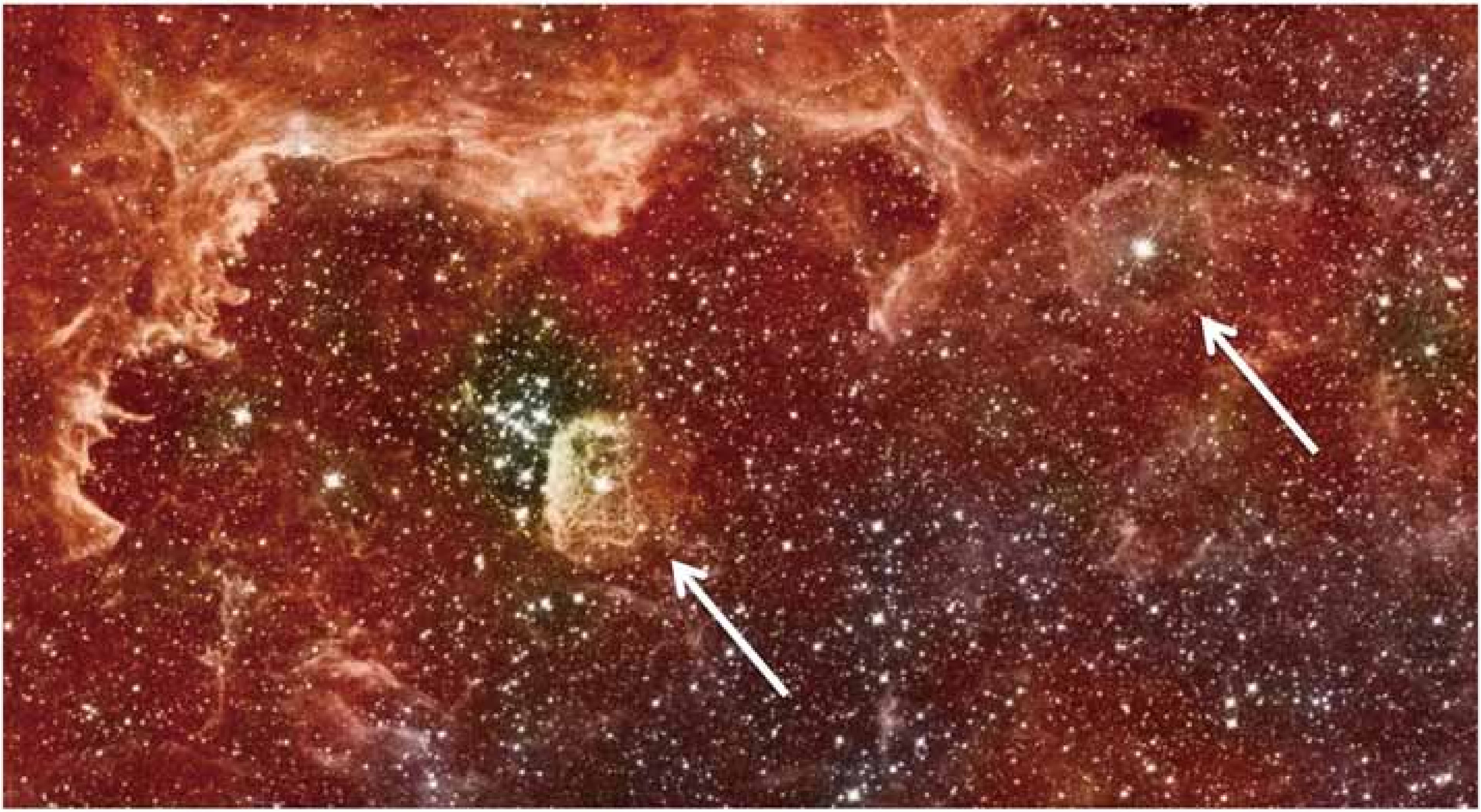
Type IIn are the most luminous "normal" supernova type in the ultraviolet



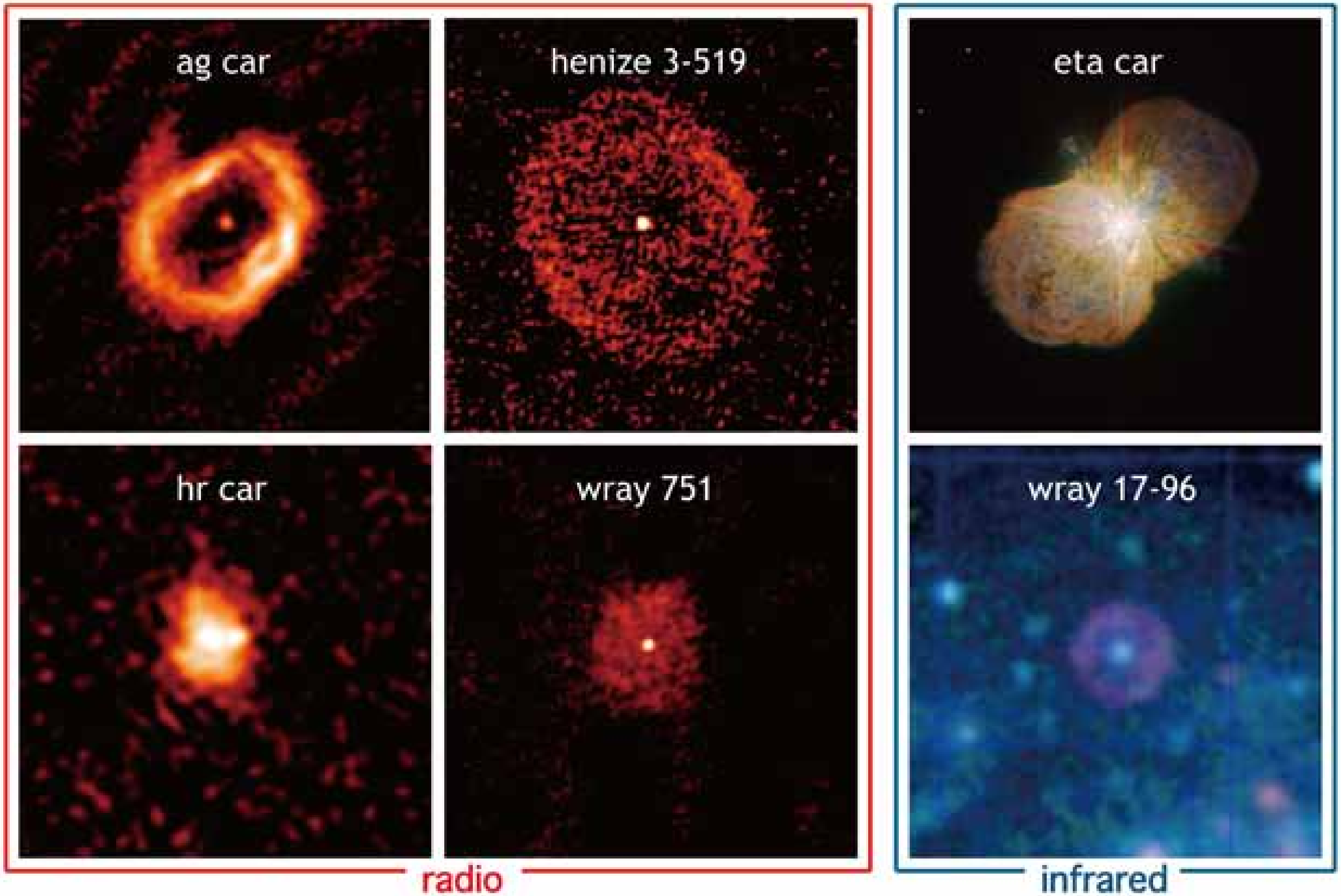
Riess et al. (2004)

Center of our Galaxy

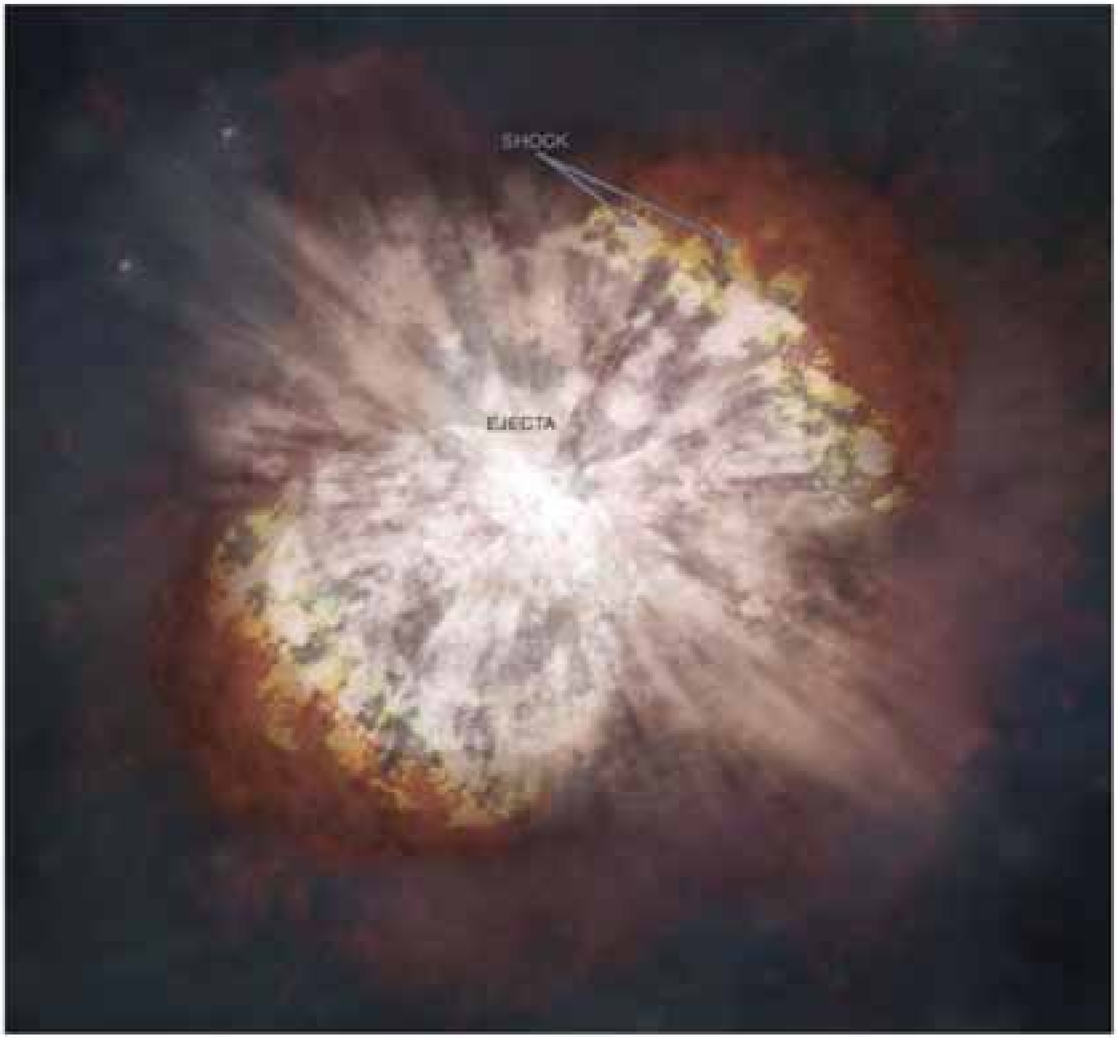
Center of our Galaxy



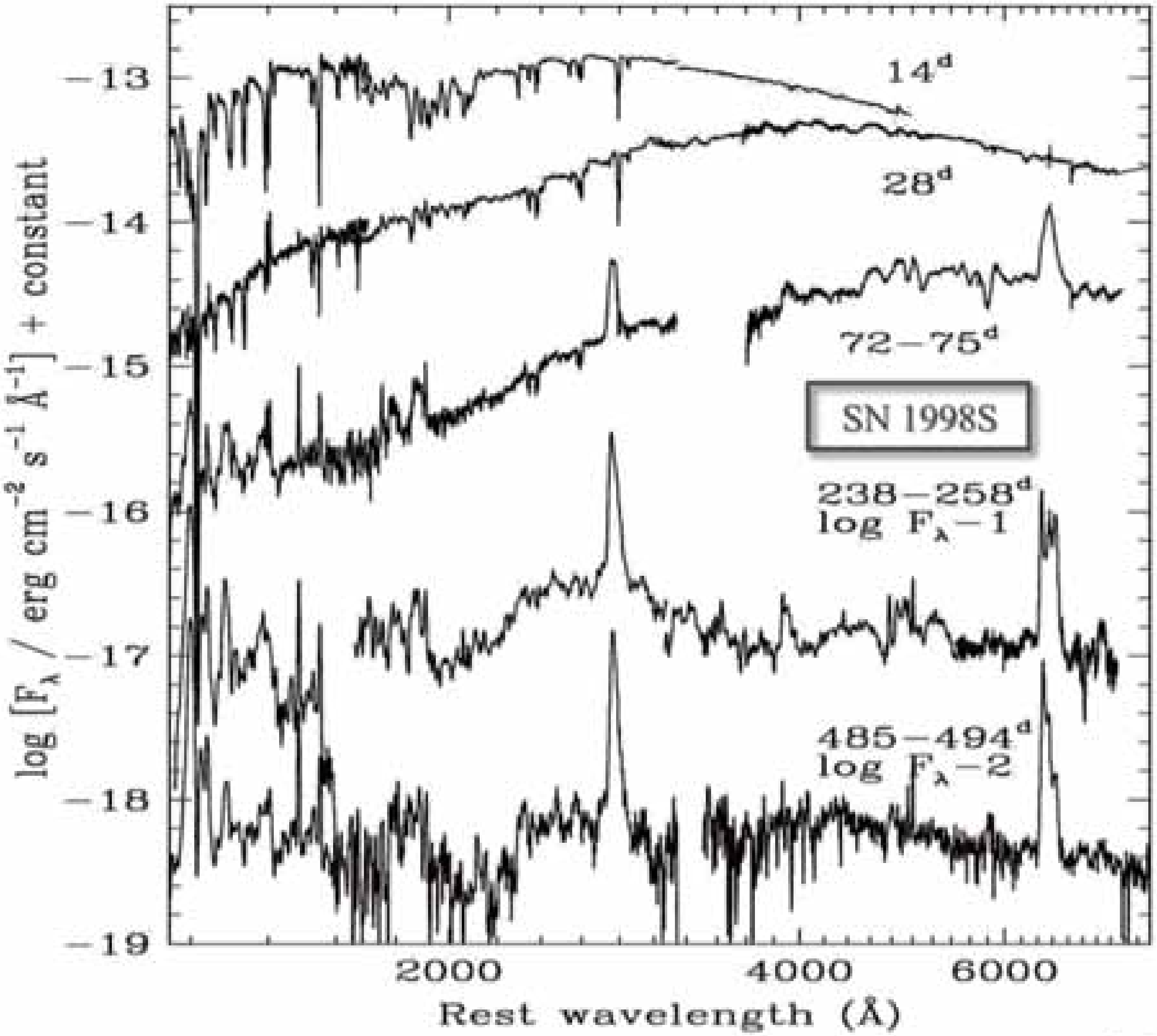

type IIn supernovae


ag car
henize 3-519
eta car
hr car
wray 751
wray 17-96
radio
infrared

type IIn supernovae

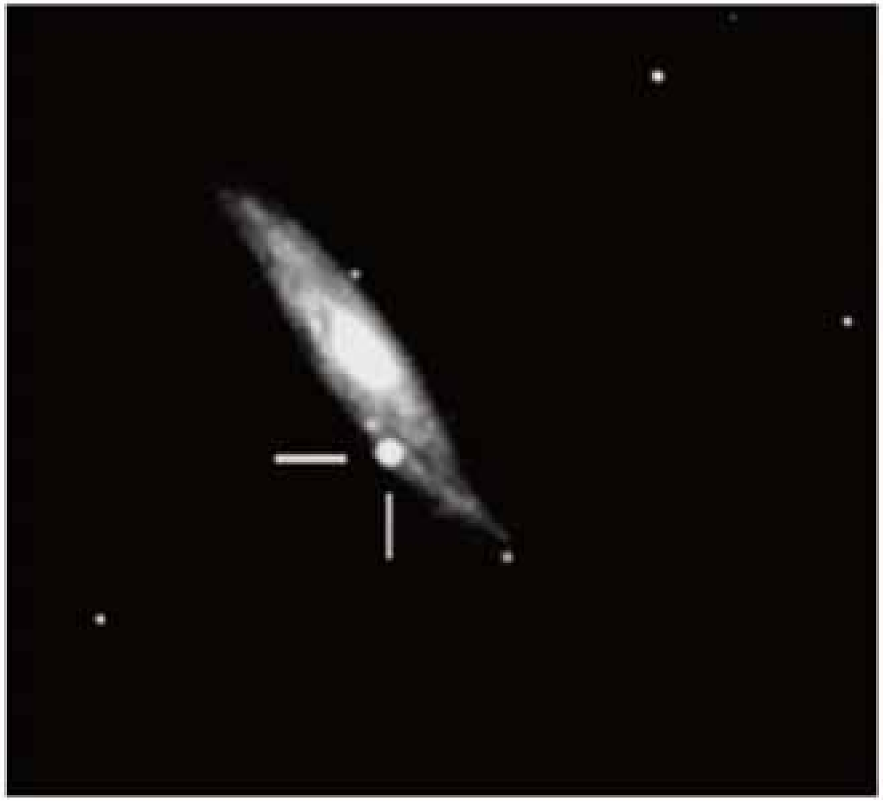


type IIn supernovae



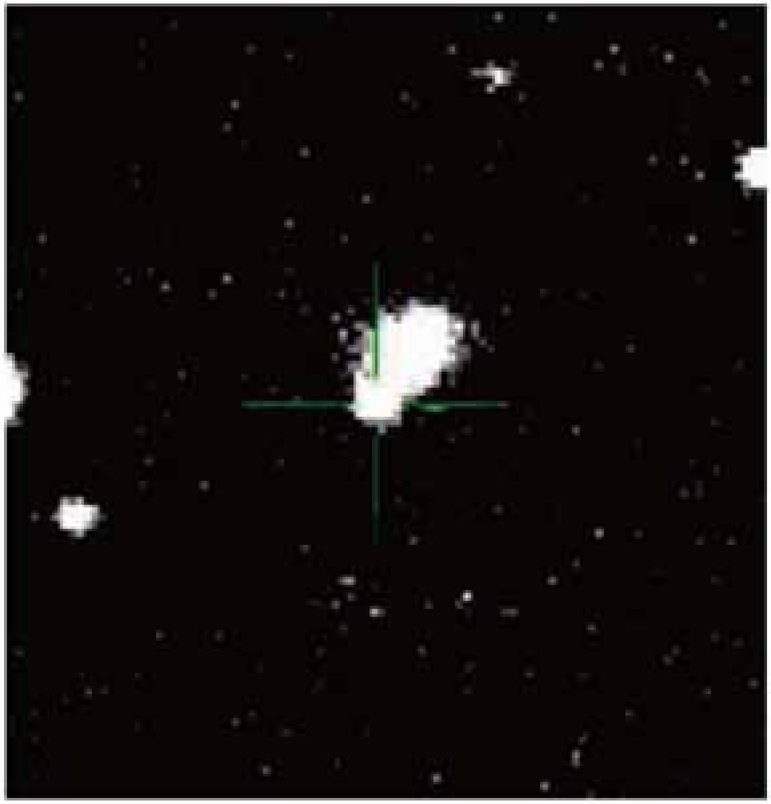
Fransson et al. (2005)

Conventional supernova searches image 100s of bright galaxies in real time



NGC 3877 - SN 1998S
$z = 0.006$

Current wide-area supernova searches image ~10^4 galaxies in real time



Limiting mag
$m_R \sim 20.5$

Anonymous host galaxy - PTF10daj
$z = 0.103$

Courtesy of the Palomar Transient Factory Team

Current wide-area supernova searches image ~10^4 galaxies in real time

At z > 2, this conventional approach is very difficult

Limiting mag
$m_R \sim 20.5$

Anonymous host galaxy - PTF10daj
$z = 0.103$

Courtesy of the Palomar Transient Factory Team

To detect supernovae at high redshift we need:

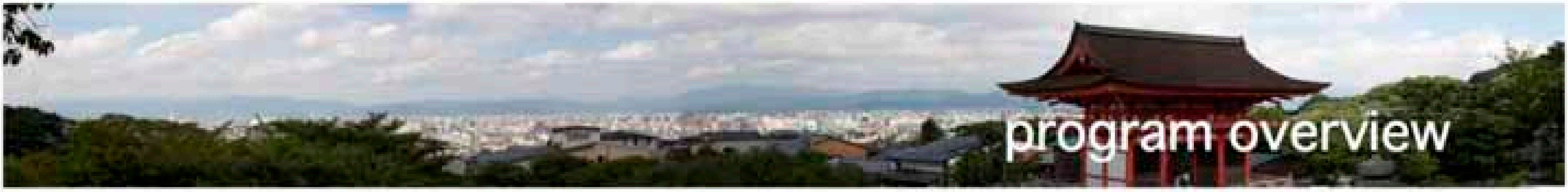
- **Very deep images** *(optical detectors are most efficient)*
  Need $m_R \sim 26$, deeper than current supernova surveys; focus on ultra-violet luminous supernovae

- **Long temporal baseline**
  Time dilation - need multiple epochs over one to several years

- **Wide-areal coverage** *(wide-field imaging)*
  Supernovae are rare and type IIn supernovae make up ~5%

- **Consistent imaging program** *(well-matched images)*
  For accurate relative magnitudes and clean image subtractions

- **Galaxy redshifts**
  Sorting and searching all spurious events without redshift information is daunting in deep wide-field images; deep spectroscopy of all the potential candidates is too expensive



Our program

Monitor Lyman break galaxies (LBGs) at desired redshifts for supernovae

JC 2008, ApJ, 677, 137

Search deep, wide-field, multi-epoch optical images *(image stacking)*

- *Canada-France-Hawaii Telescope Legacy Survey* (CFHTLS)

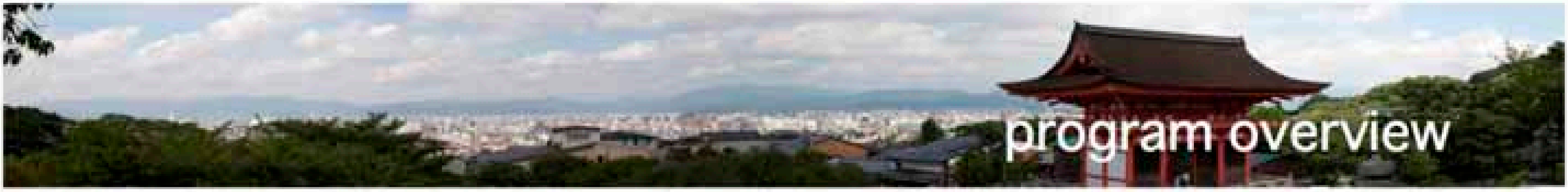
Use a new high redshift detection technique that includes

- monitoring galaxy flux in yearly stacked images
- a supernova analysis process for galaxies exhibiting flux variations

Highly successful program:

12 supernovae confirmed between $z = 2 - 4$ using the Keck telescopes

JC et al. 2009, Nature, 460, 237, JC et al. 2012, in prep.



Lyman break galaxies

Star forming high-redshift galaxies

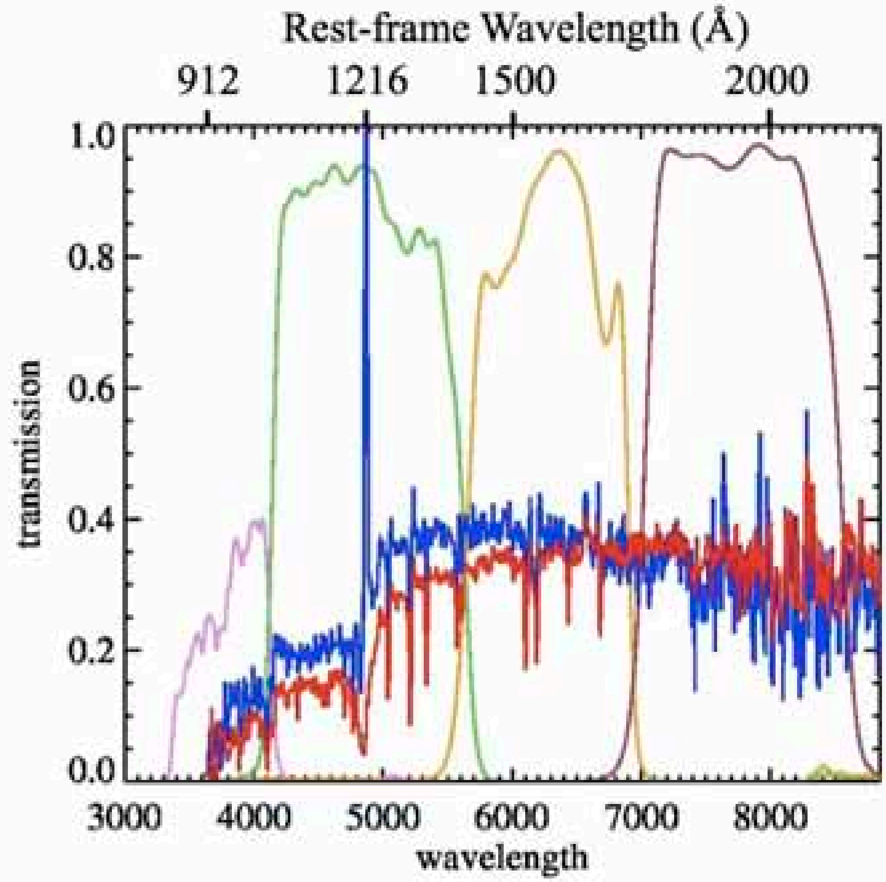
Optical observations detect the rest-frame ultraviolet (UV)

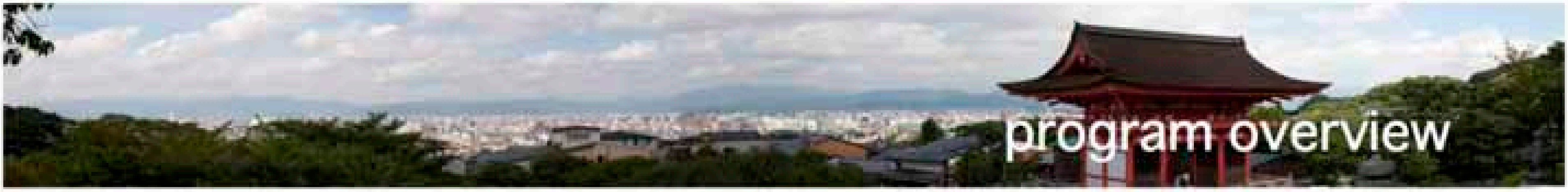
Selected by the attenuation of flux shortward of 912Å

Spectroscopy limited to R < 26 (photometry ~2 mag deeper)

LBGs estimated to represent ~70% of all high-redshift star-forming galaxies

e.g., Marchesini et al. (2007), Reddy et al. (2008)

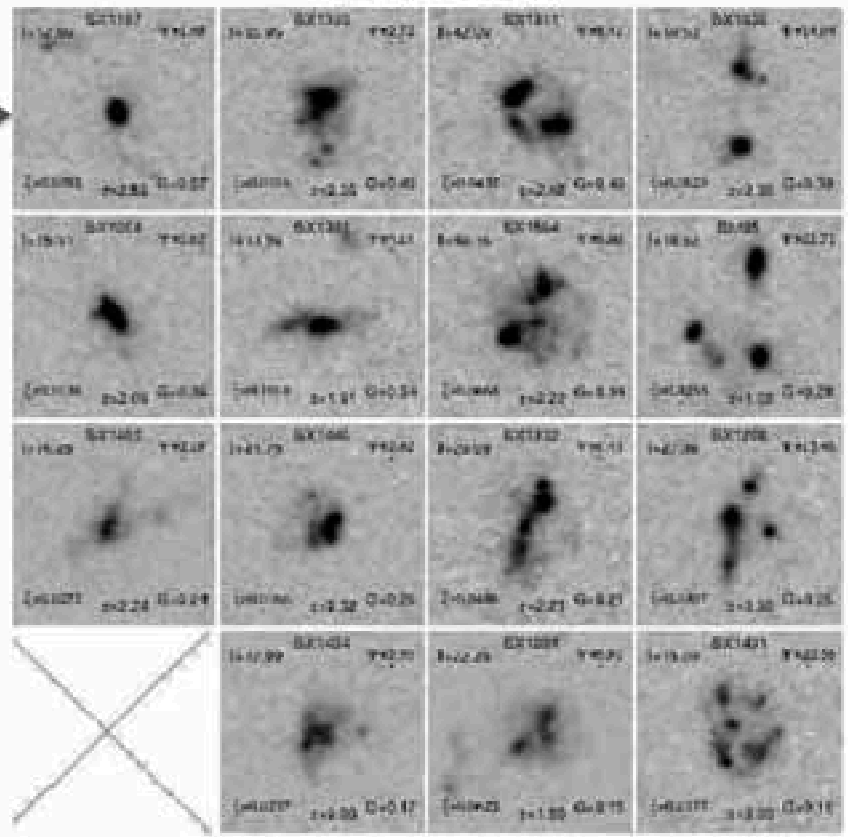




Lyman break galaxies

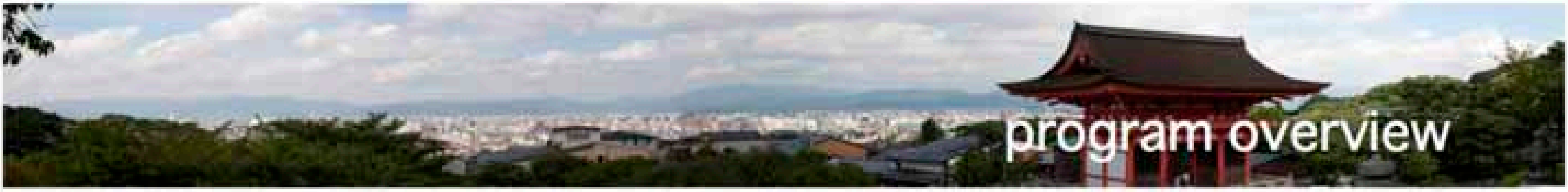
morphology

Space-based optical observations (restframe FUV) →



3''

Law et al. (2007)



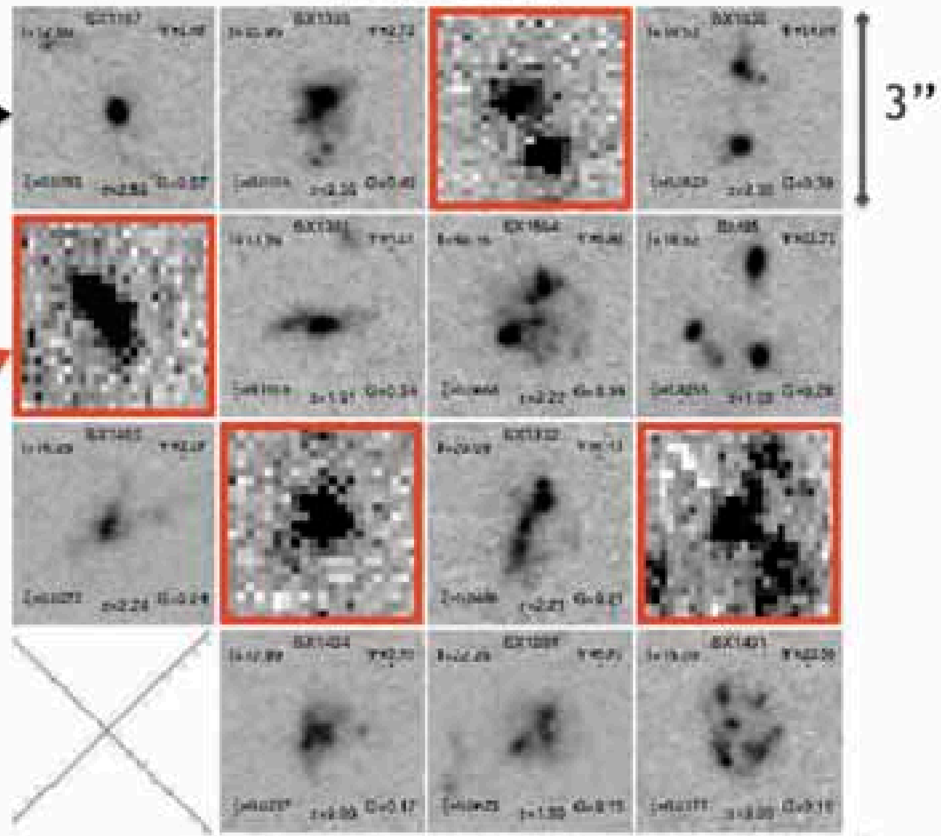
program overview

Lyman break galaxies

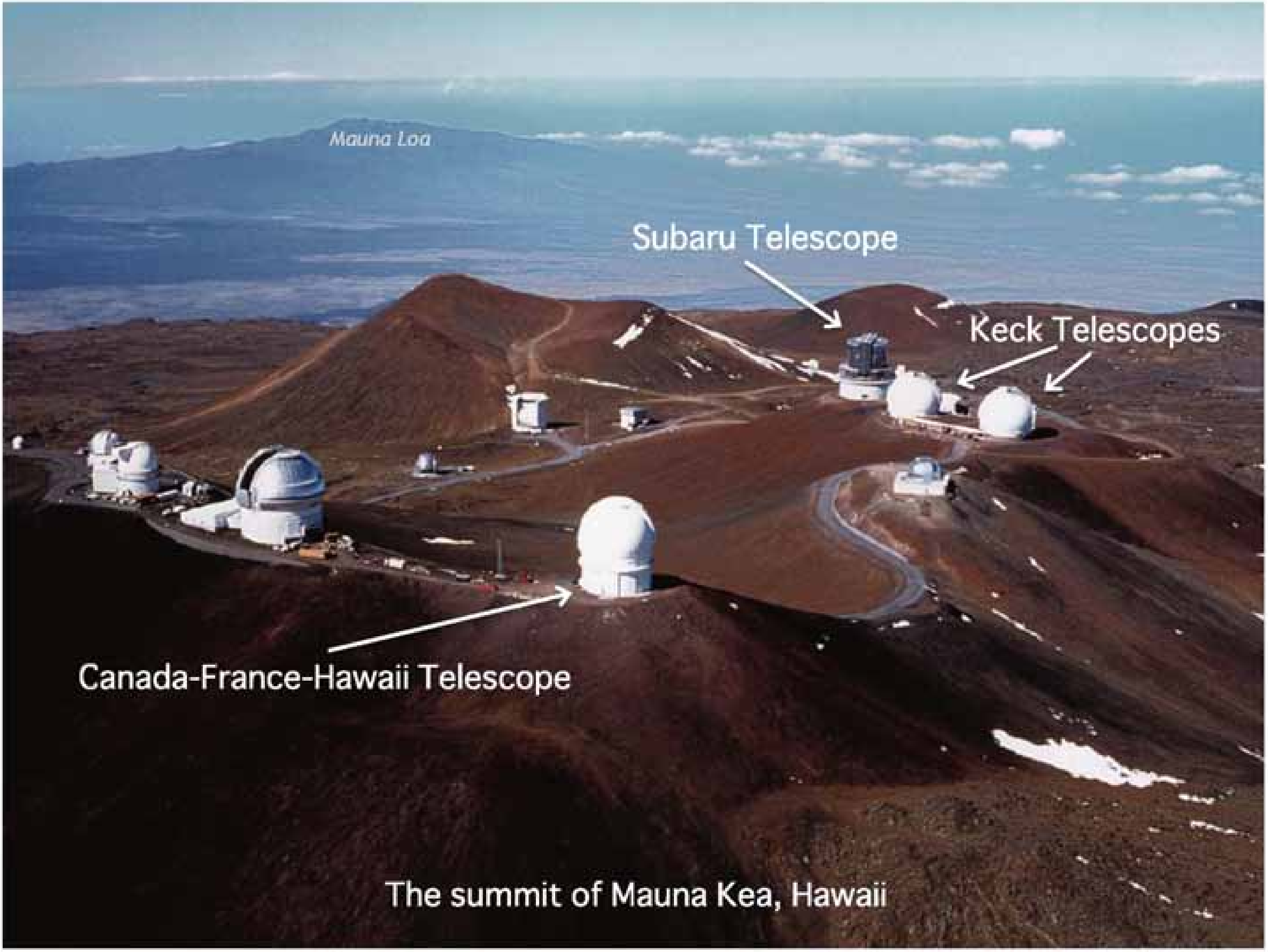
morphology

Space-based optical observations (restframe FUV)

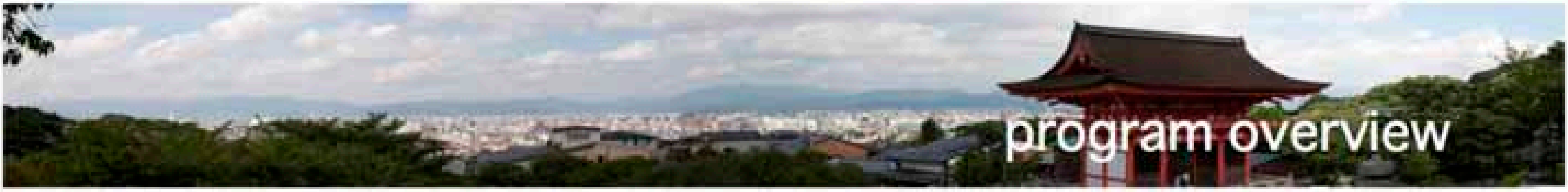
Ground-based optical observations for comparison



Law et al. (2007)

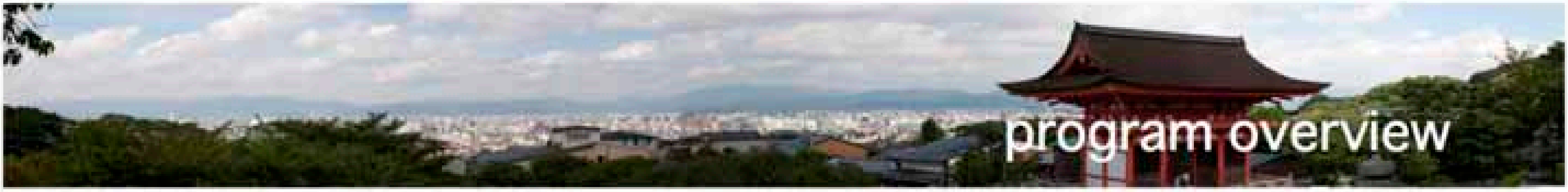

Mauna Loa
Subaru Telescope
Keck Telescopes
Canada-France-Hawaii Telescope
The summit of Mauna Kea, Hawaii


CFHTLS Deep Survey
4 square-degree Megacam pointings
25-30 nights over 5-6 months
for 5 years (2003-2008)
yearly-stacked images probe
to mag ~26 in 5 filters
(u* g' r' i' z')
More than 2 million sources detected



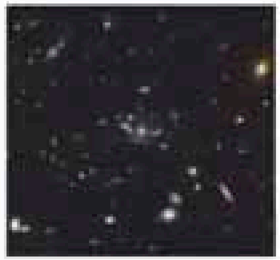
Nightly stacked observations *(25-30 nights per year)*

year 1 year 2 year 3 year 4

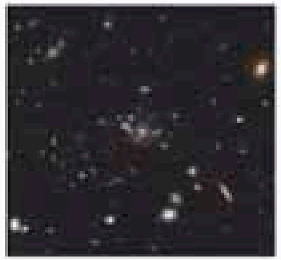


Seasonal-stacks

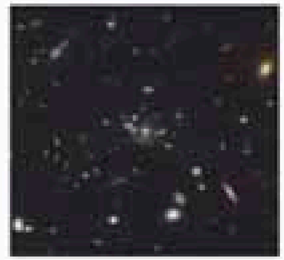
year 1



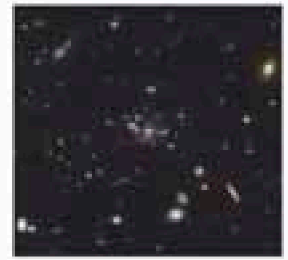
year 2

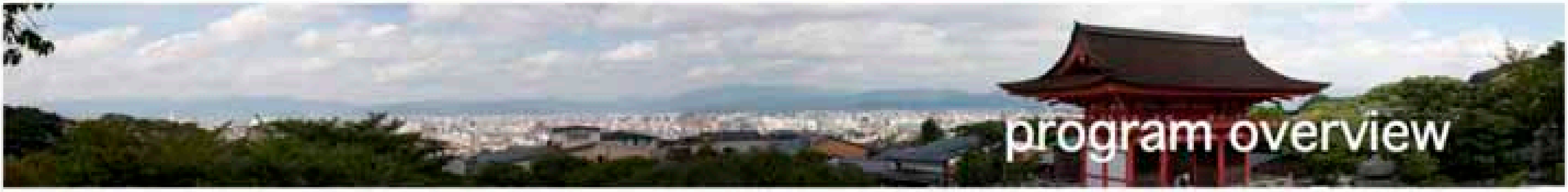


year 3

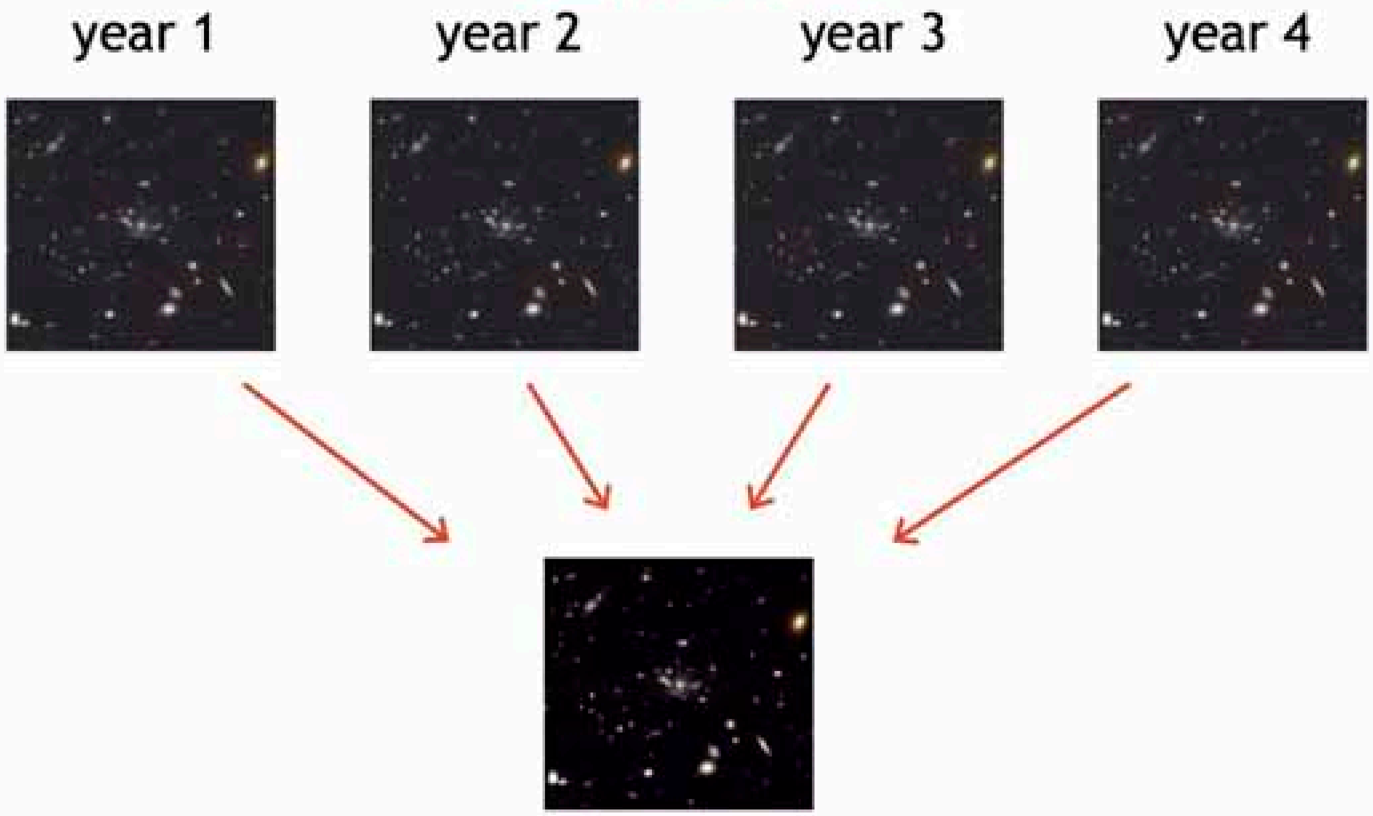


year 4

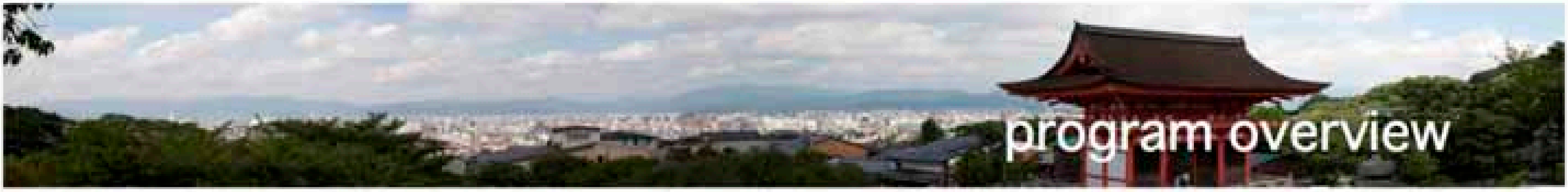




Seasonal-stacks

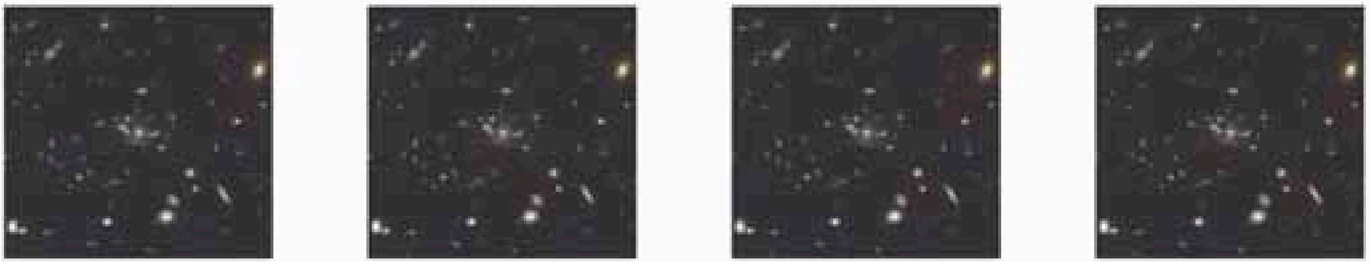


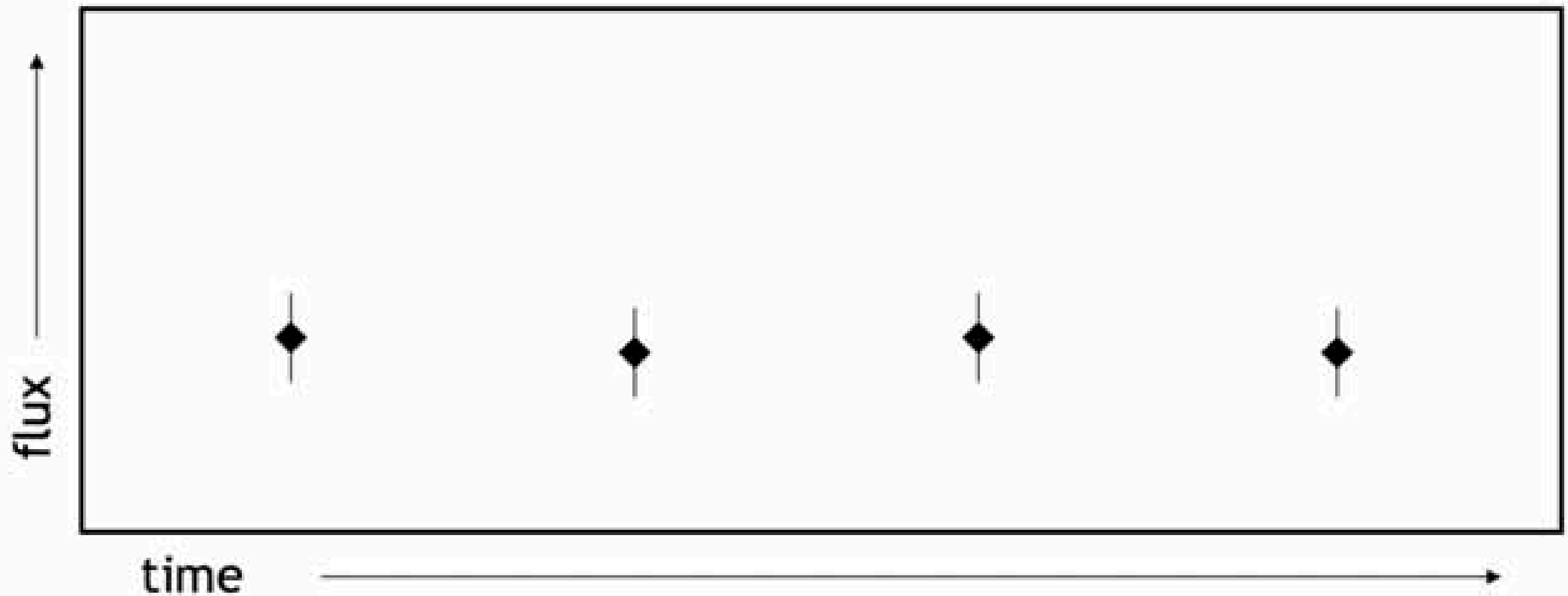
Combine the 4 stacks to create the deepest image *(need this in multiple filters)* to identify Lyman break galaxies via the efficient color selection method

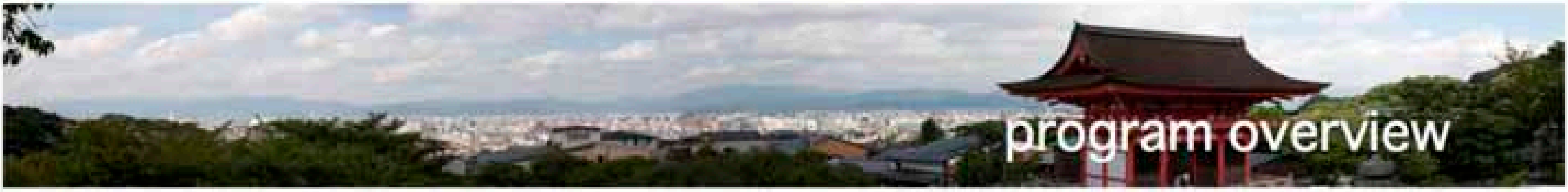


Seasonal-stacks

year 1 year 2 year 3 year 4







Seasonal-stacks

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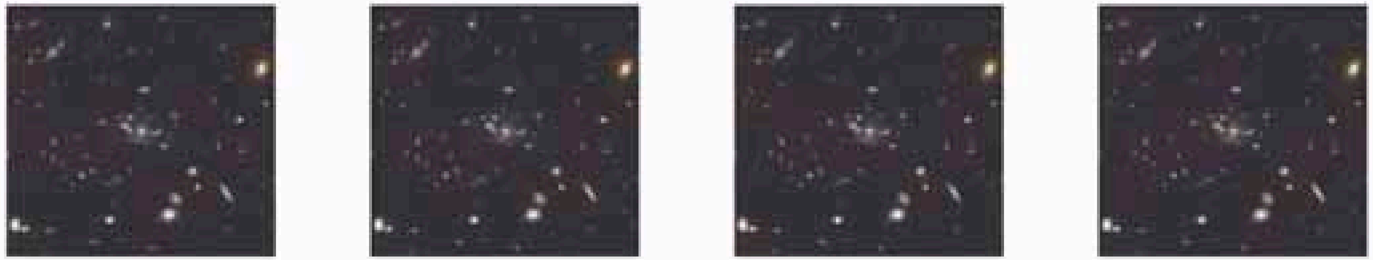
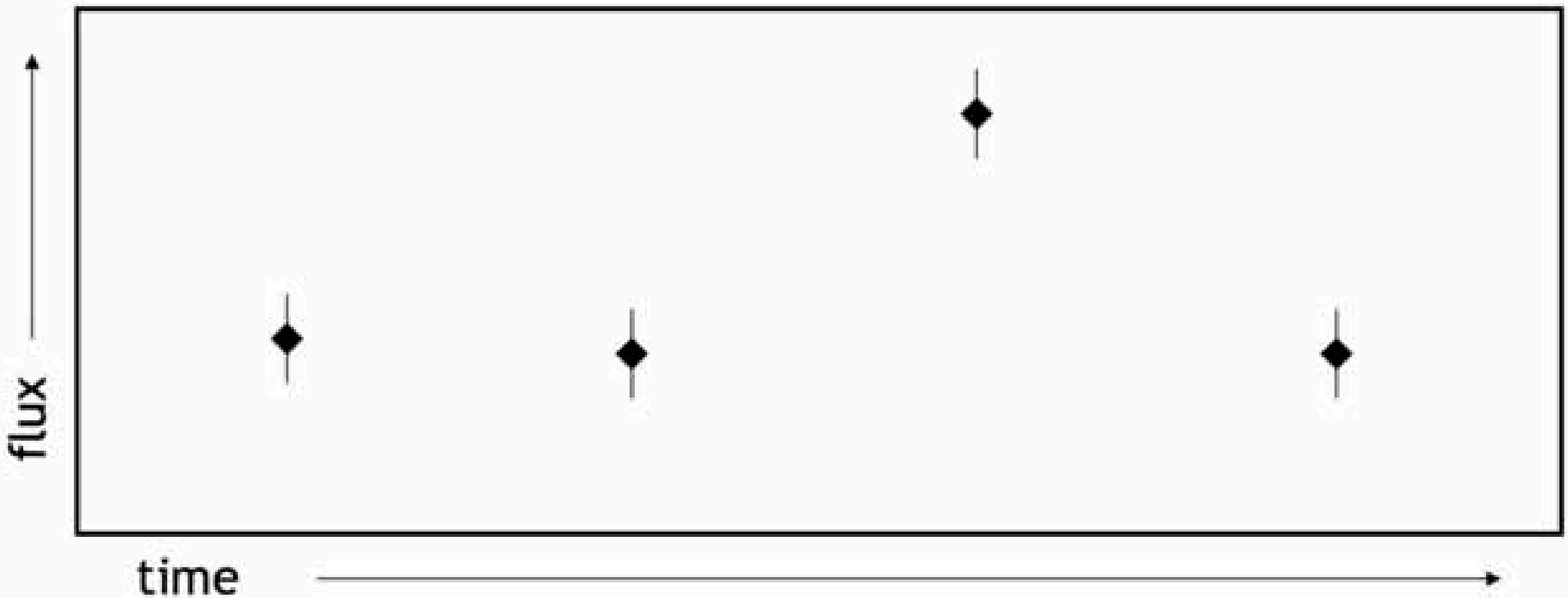
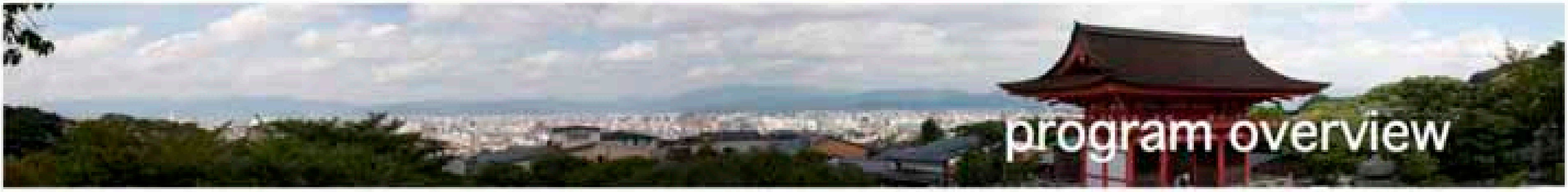
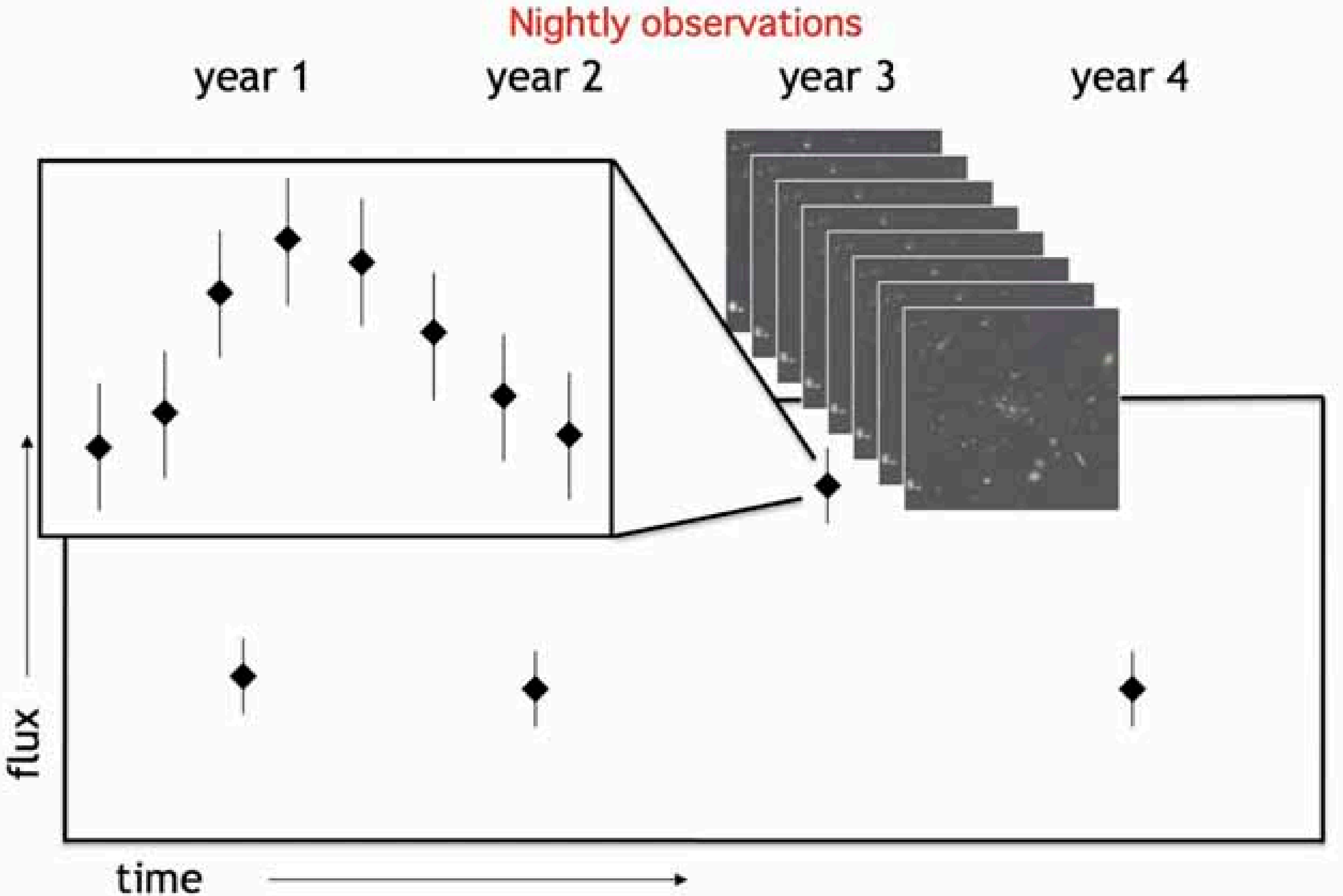





program overview

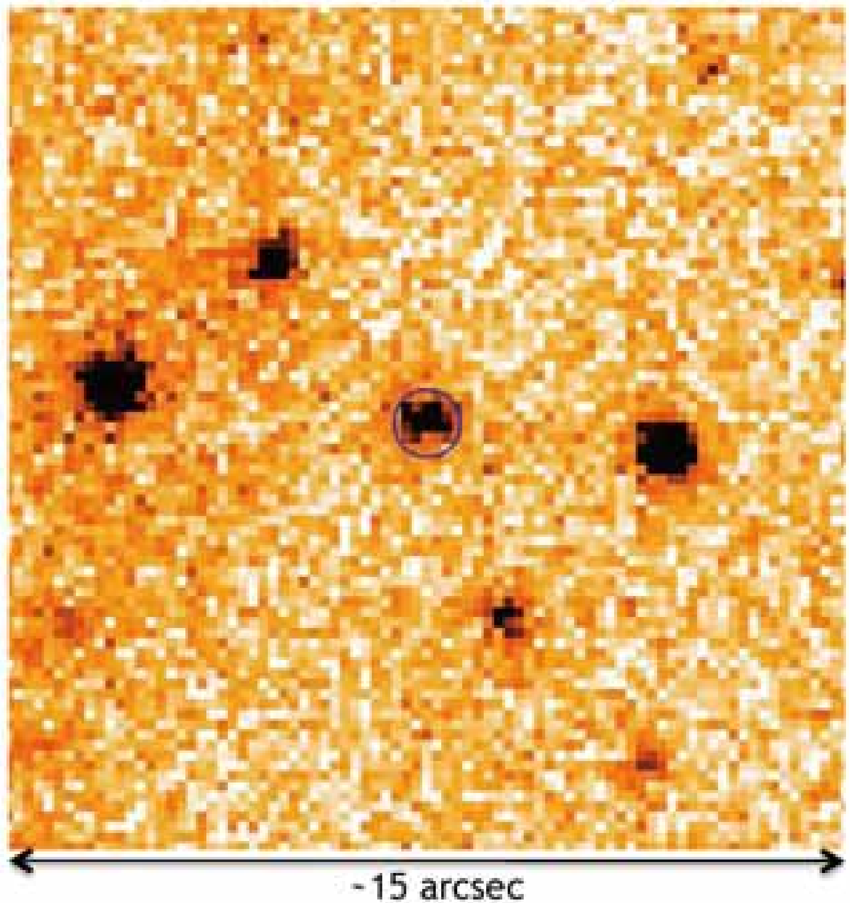

Nightly observations
year 1
year 2
year 3
year 4
flux
time

archival detections

object: 234161

<u>host galaxy</u>

$m_r = 24.9 \pm 0.07$
$M_{UV} = -19.8$



Circle has radius of 5 kpc (physical)

JC et al. 2009, Nature, 460, 237

archival detections

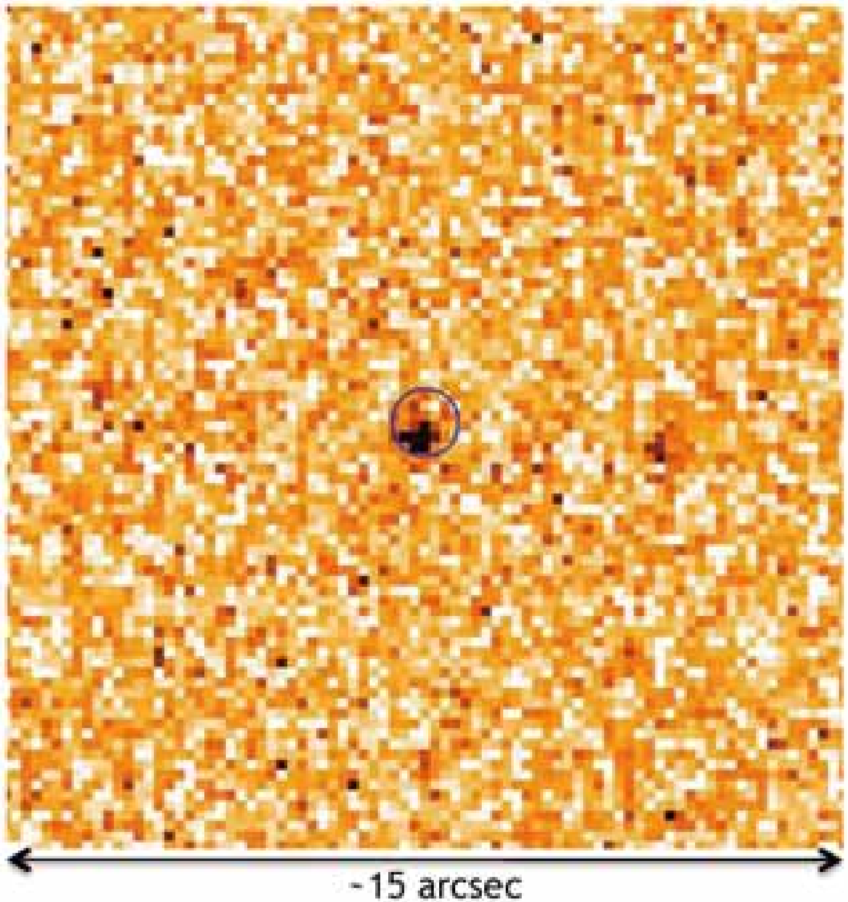
object: 234161

host galaxy

$m_r = 24.9 \pm 0.07$
$M_{UV} = -19.8$

SN event

integrated mag
$m_r = 26.3 \pm 0.14$

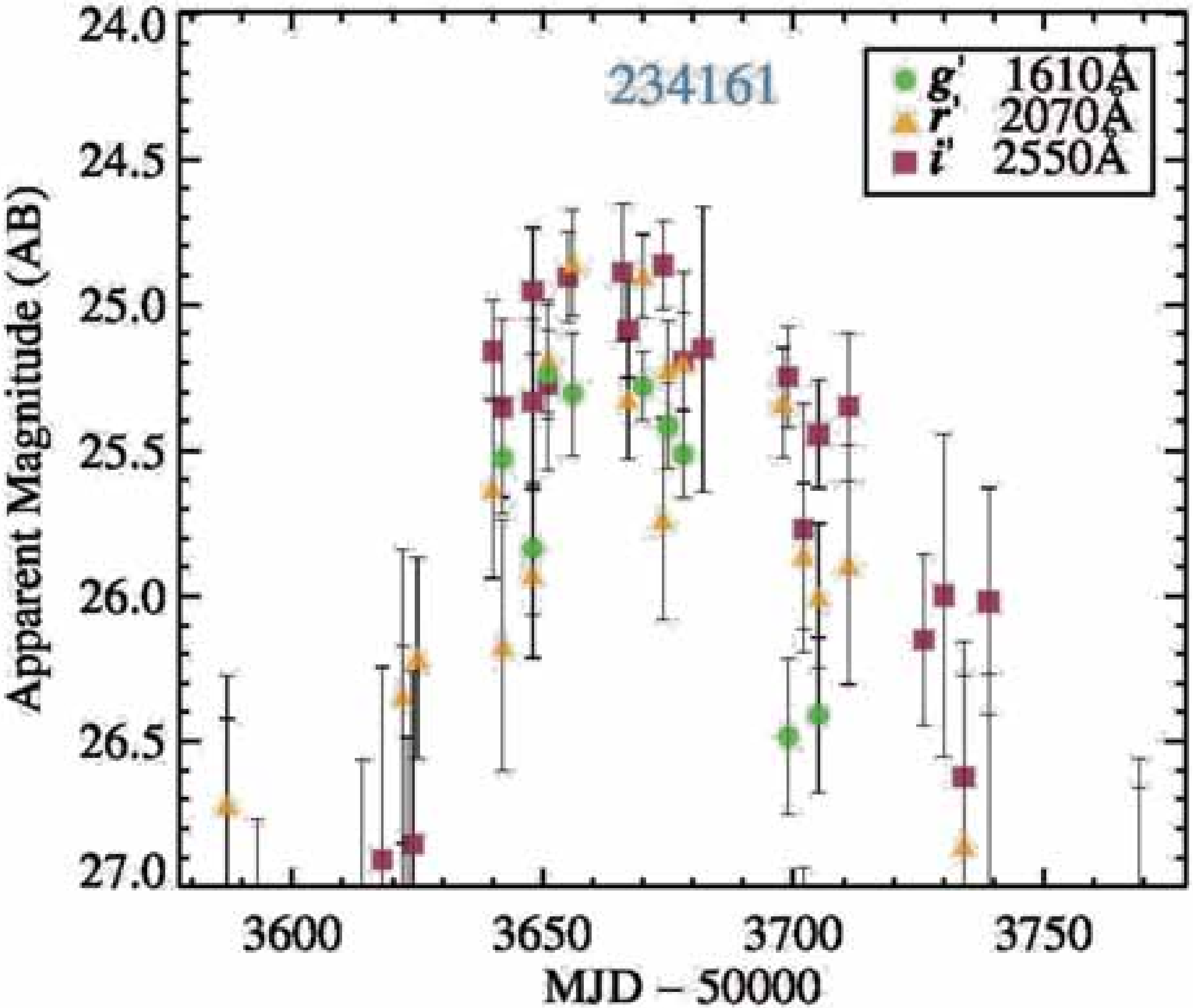


Circle has radius of 5 kpc (physical)

SN is offset from host centroid by 2.8 ± 0.4 kpc

JC et al. 2009, Nature, 460, 237

archival detections



Field "D1"
Event 234161

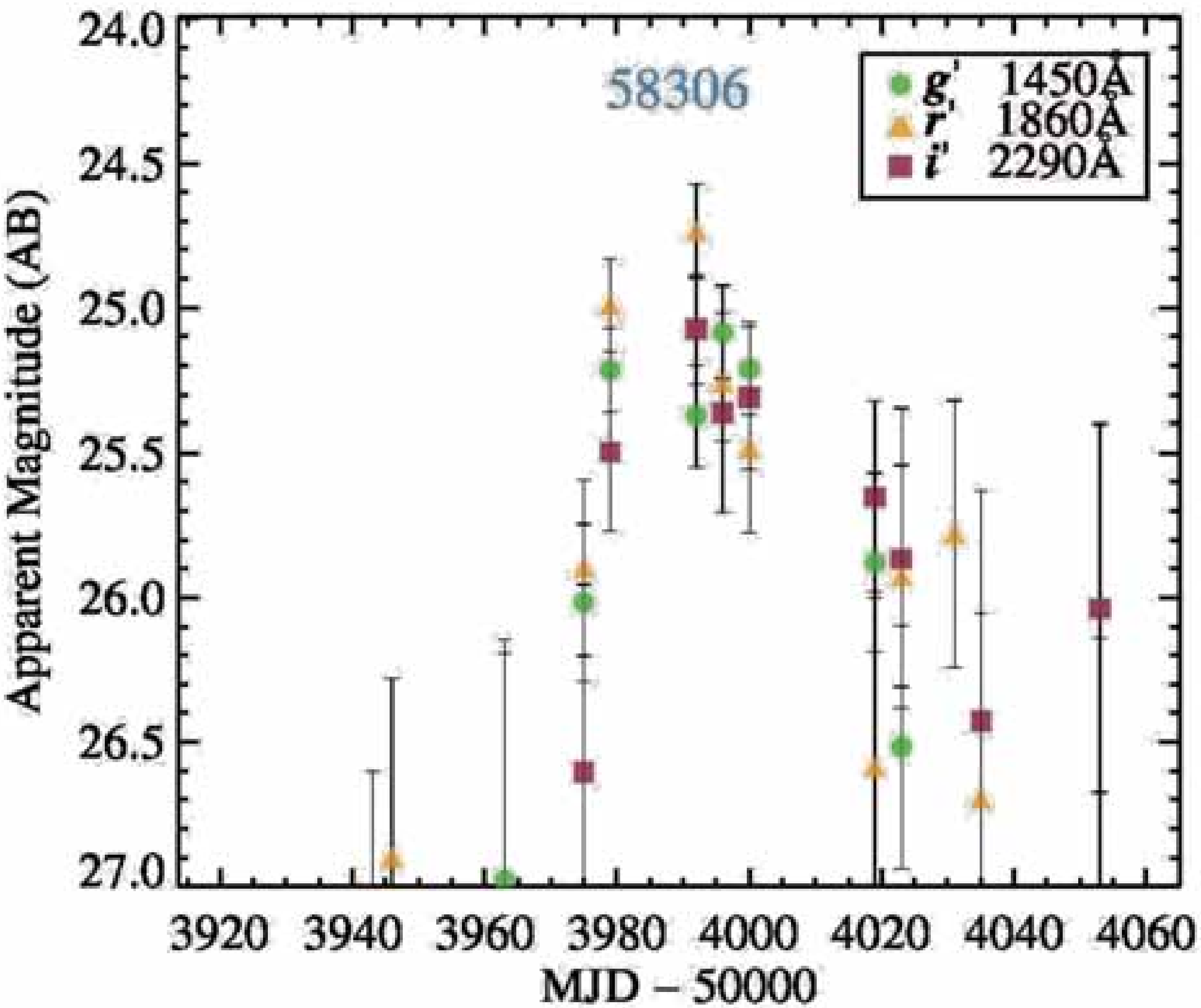
FUV luminous

$z = 2.013$

M_{UV}(peak) ~ -20.0
(~3x10^{43} erg s^{-1})

Typical peak luminosities of ~10^{43} erg s^{-1}

archival detections



Field "D4"
Event 58306

FUV luminous

$z = 2.357$

M_{UV}(peak) ~ -20.0
(~3x10^{43} erg s^{-1})

Typical peak luminosities of ~10^{43} erg s^{-1}

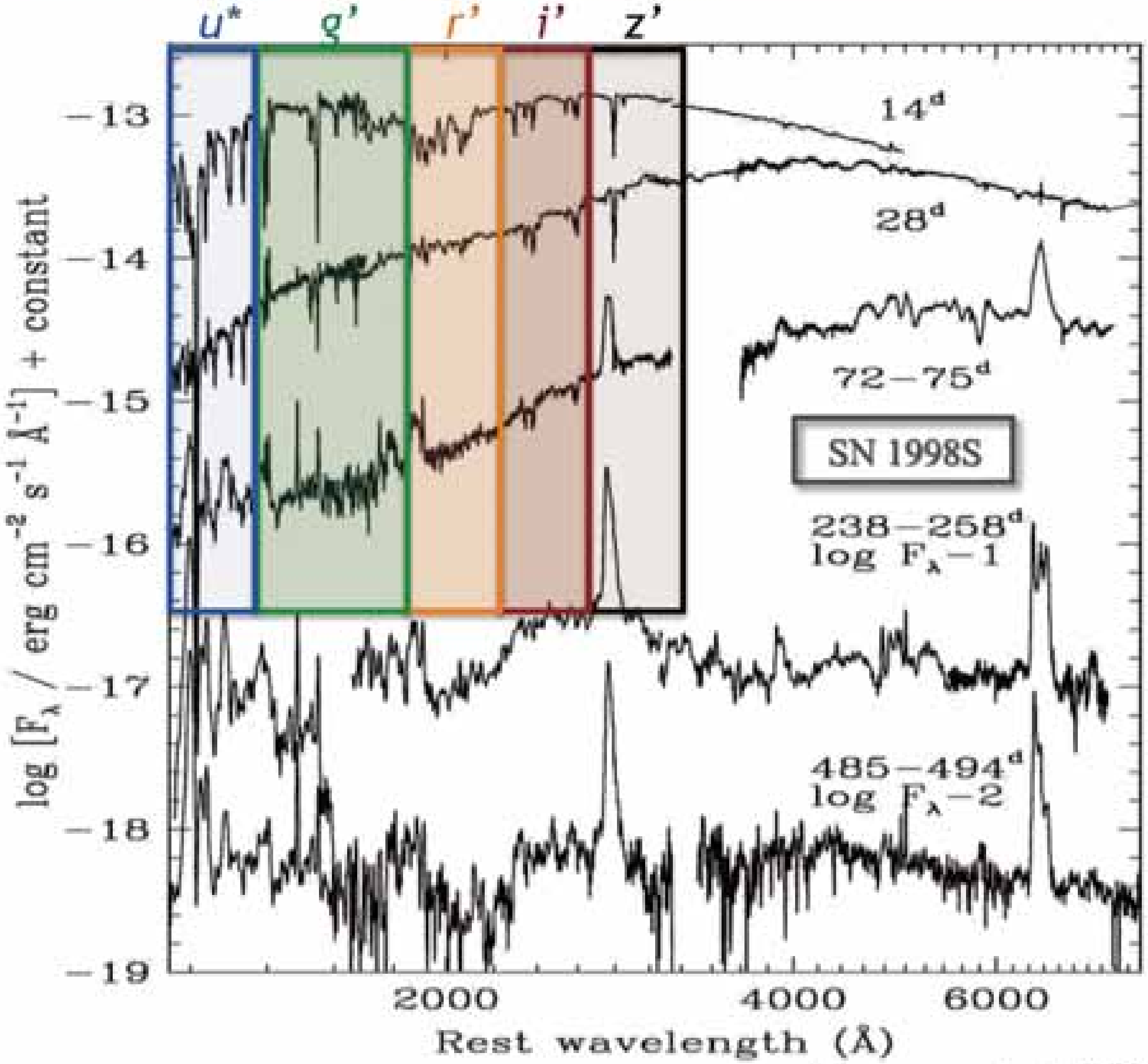
late-time spectroscopy

Optical filter coverage at:

z ~ 2

CFHTLS filters shown here

Two ~6 mo. seasons and one ~6 mo. off-season equate to ~180d, restframe



Fransson et al. (2005)

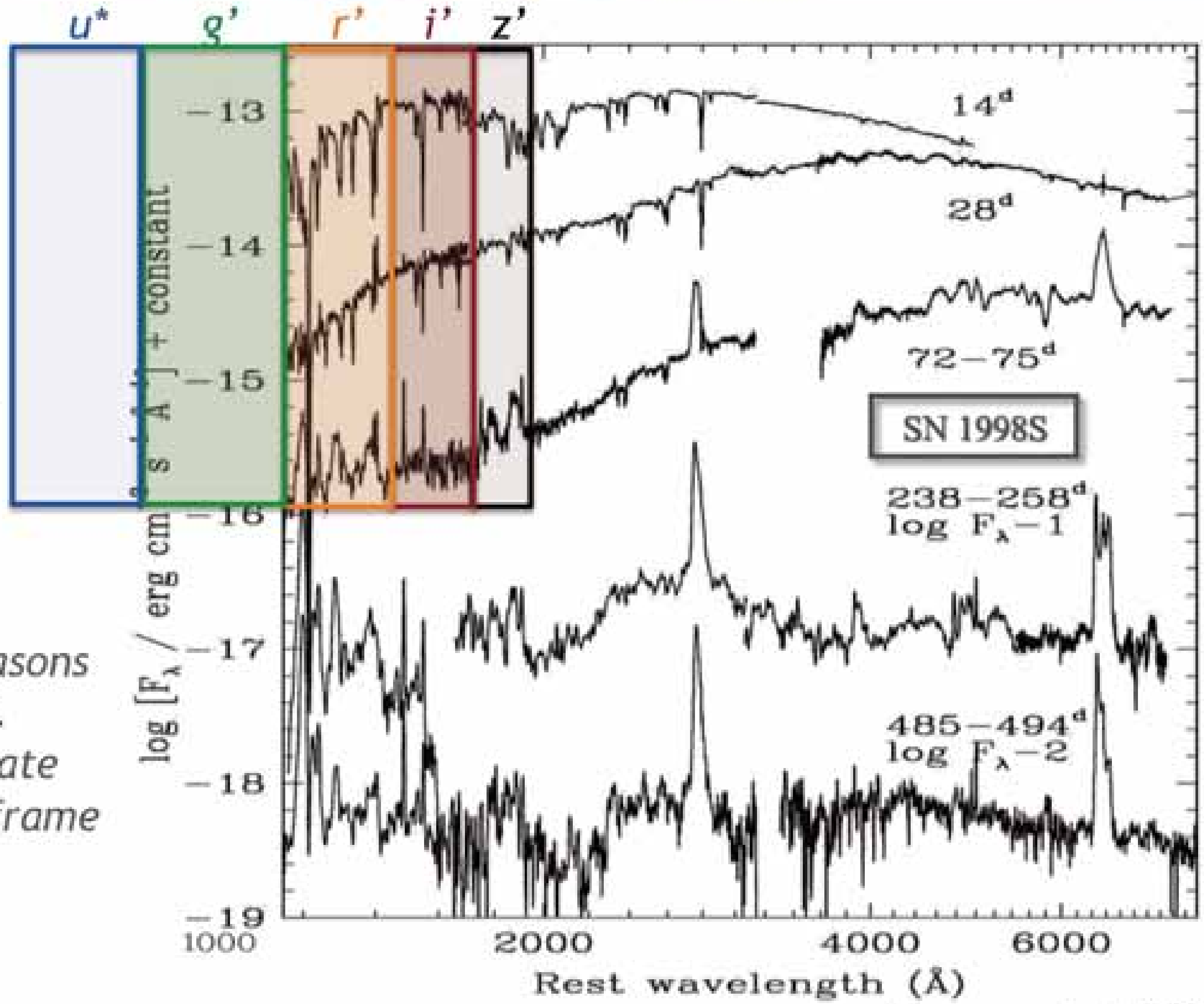
late-time spectroscopy

Optical filter coverage at:

z ~ 4

CFHTLS filters shown here

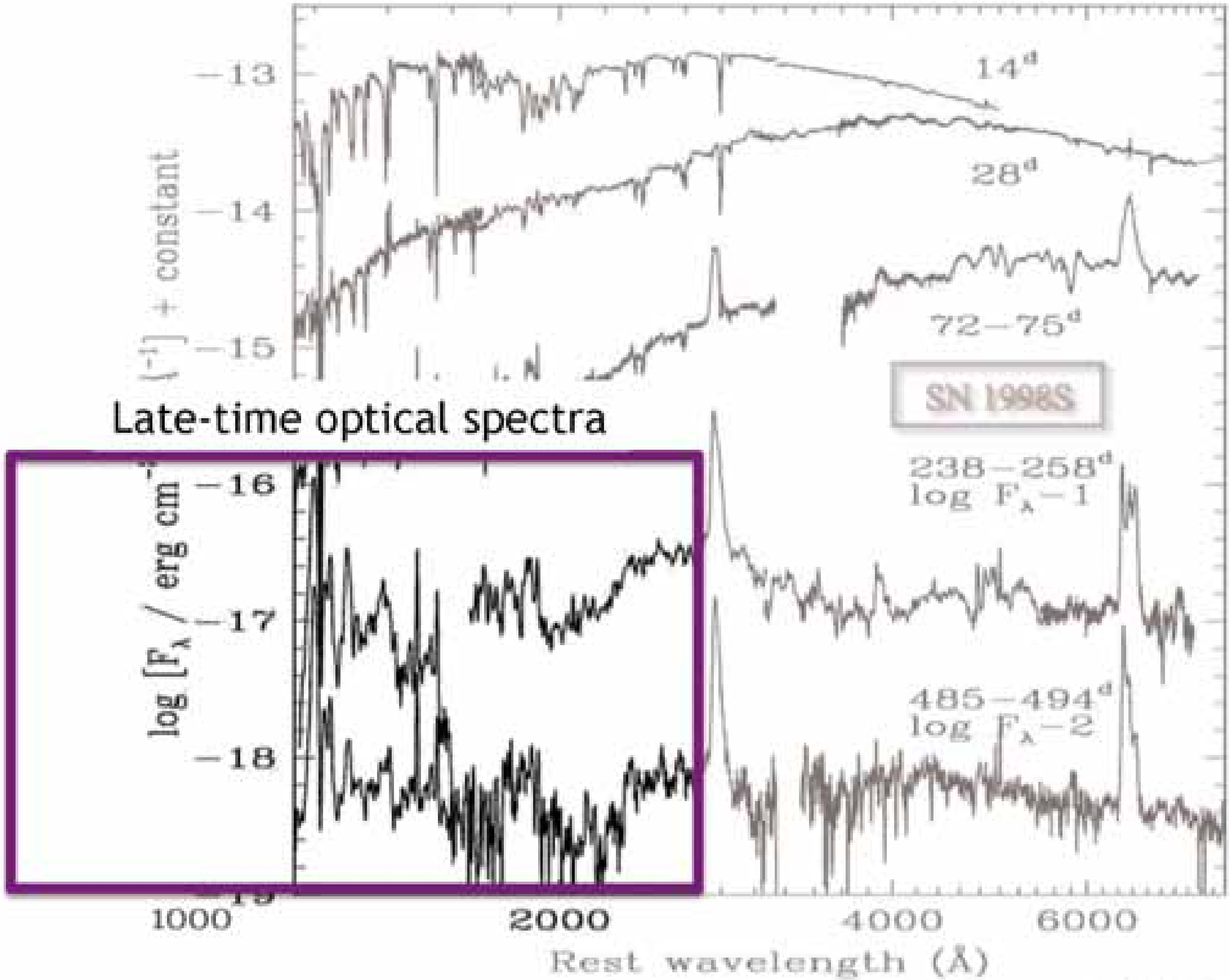
Two ~6 mo. seasons and one ~6 mo. off-season equate to ~110d, restframe



Fransson et al. (2005)

late-time spectroscopy

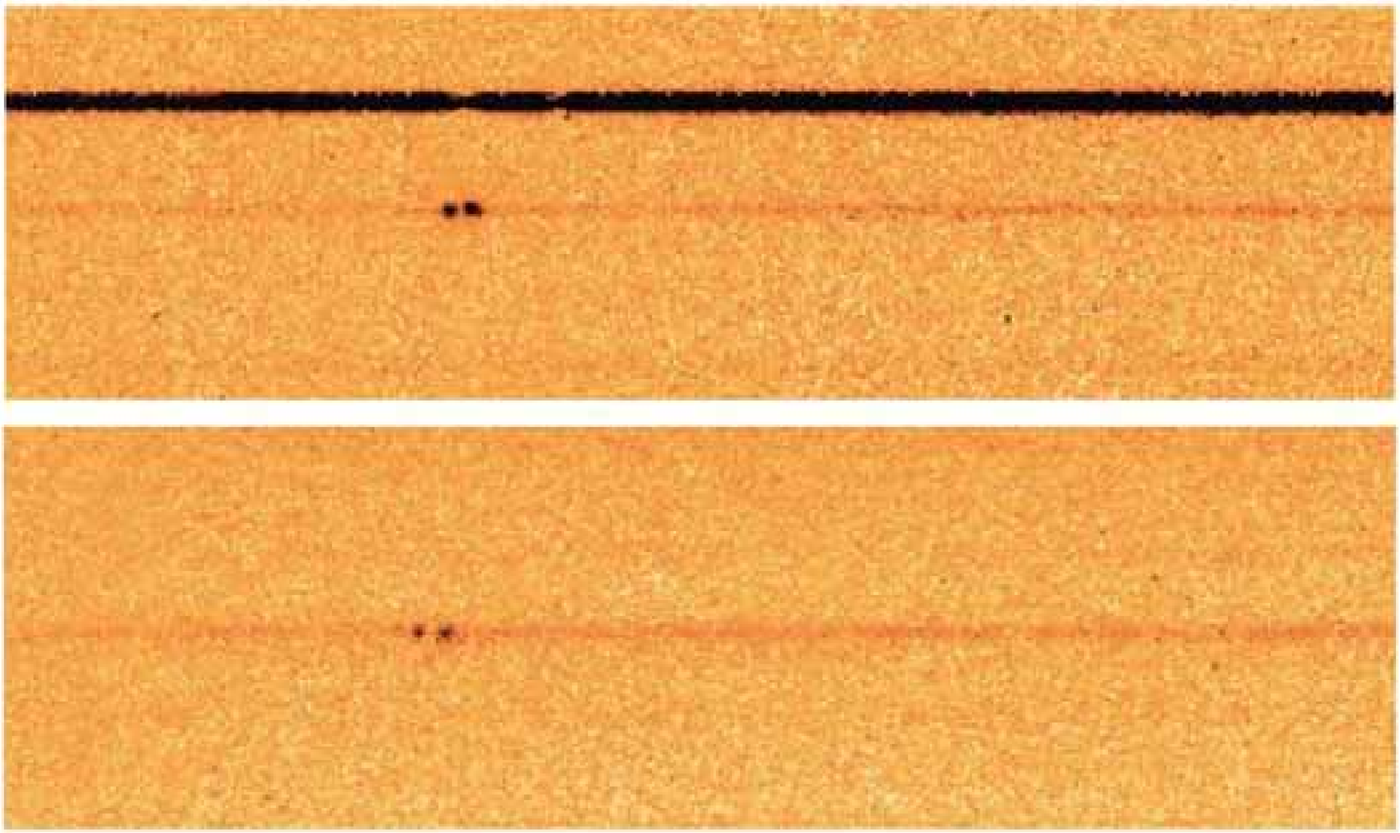
Long-lived emission lines from circumstellar interaction



Fransson et al. (2005)

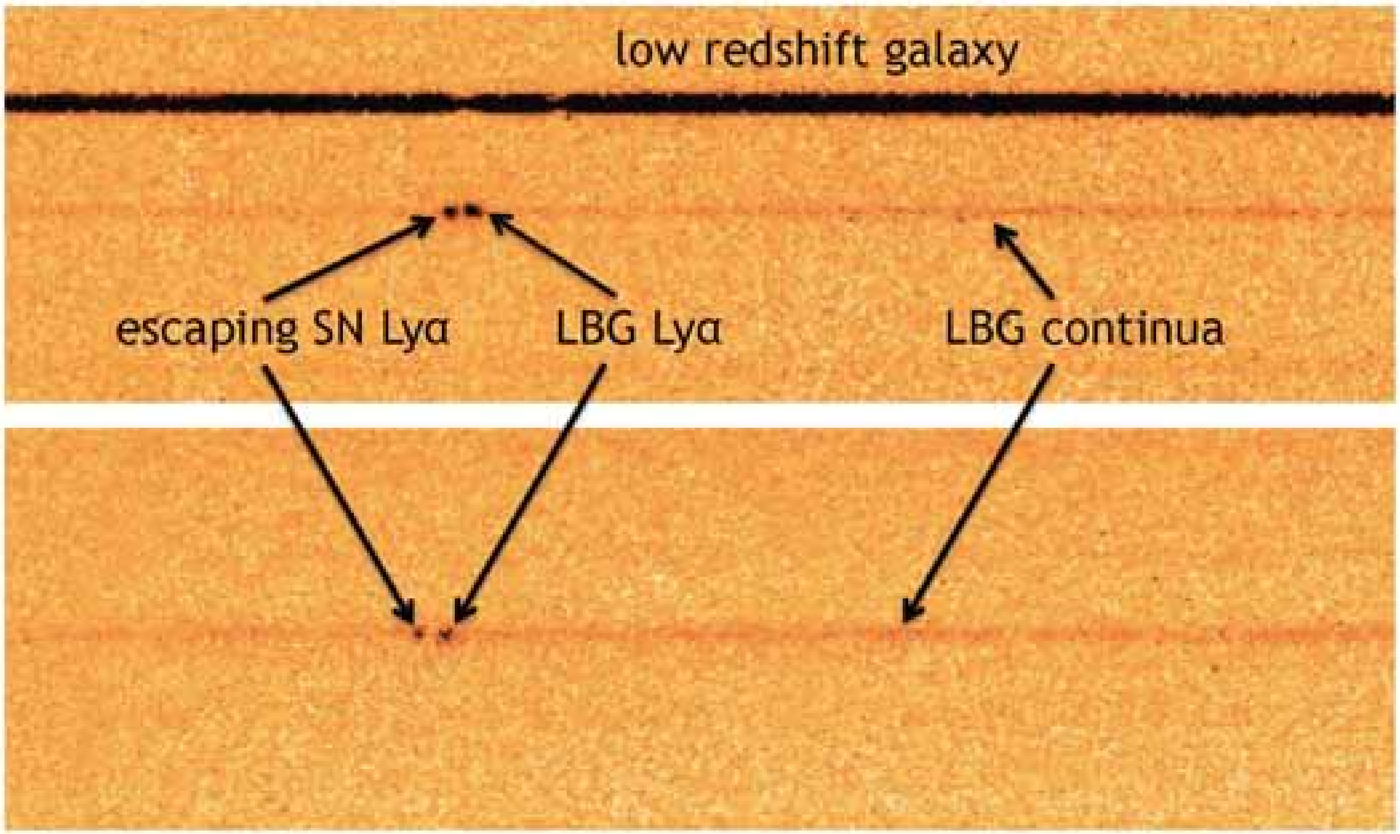

The twin 10-meter Keck telescopes

Most $z > 2$ detections to date show potential evidence for circumstellar interaction in deep late-time Keck spectroscopy: Type IIn-like



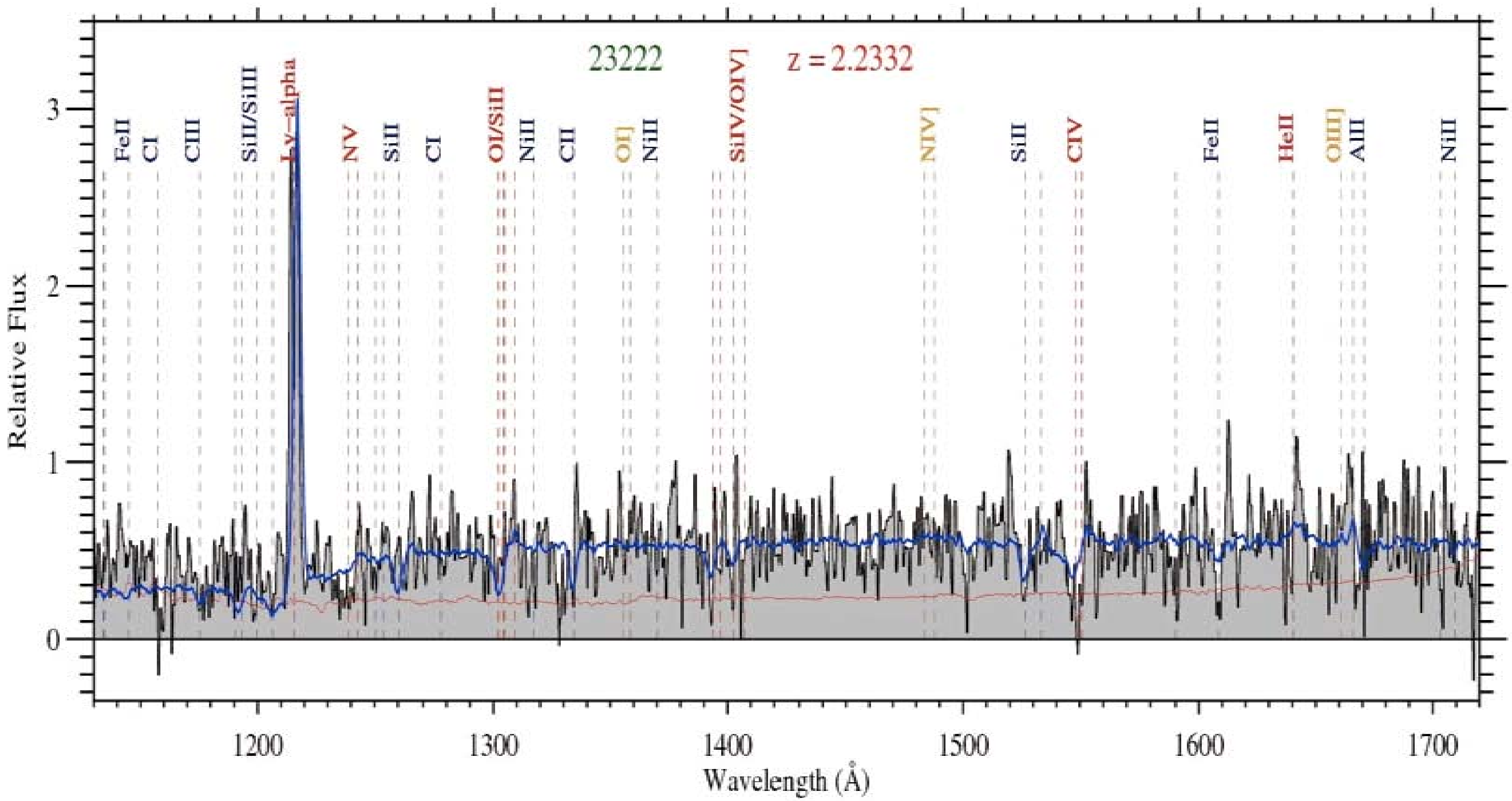
(observed ~200 - 600 days after outburst, restframe)

Most $z > 2$ detections to date show potential evidence for circumstellar interaction in deep late-time Keck spectroscopy: Type IIn-like

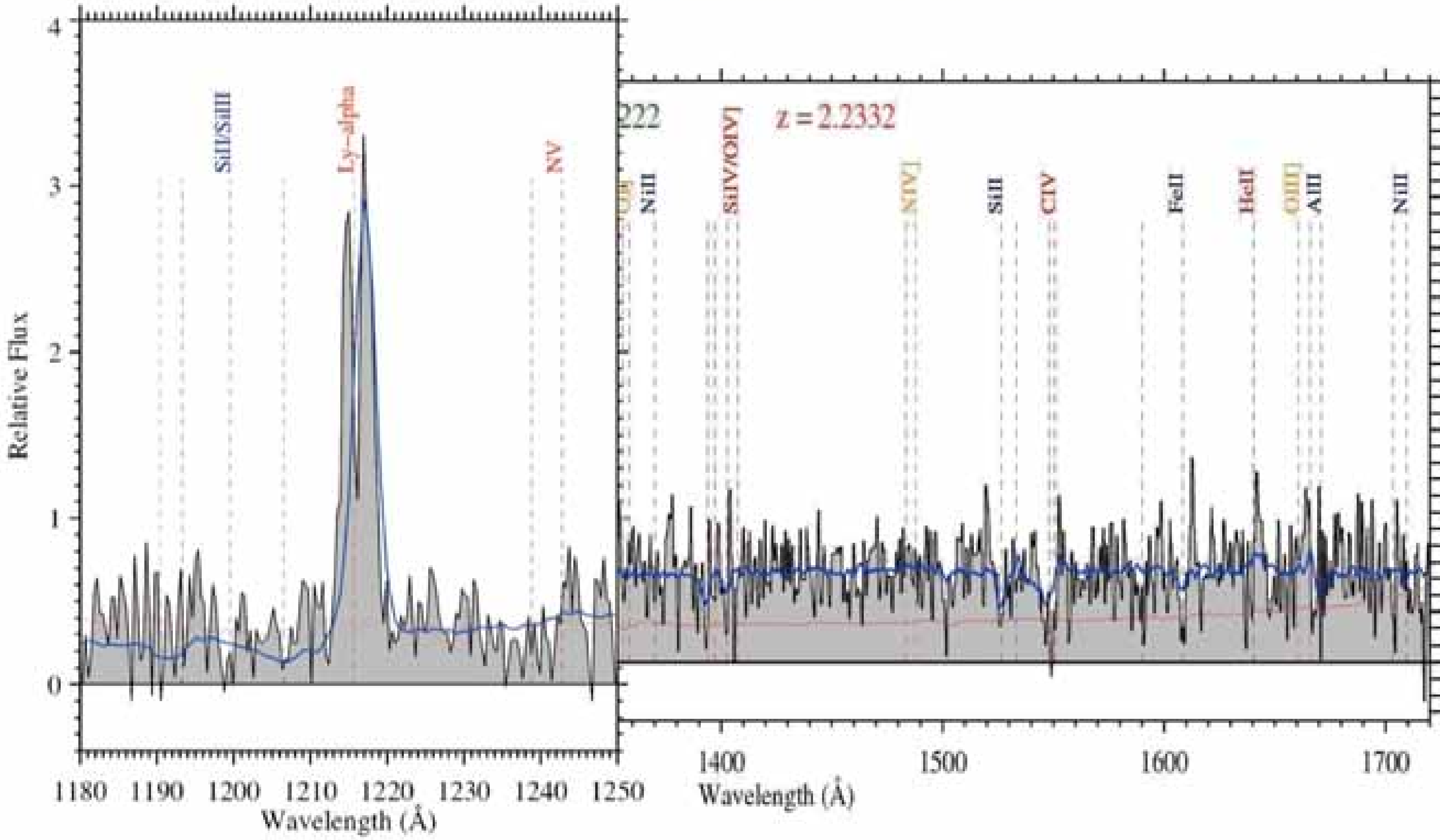


(observed ~200 – 600 days after outburst, restframe)

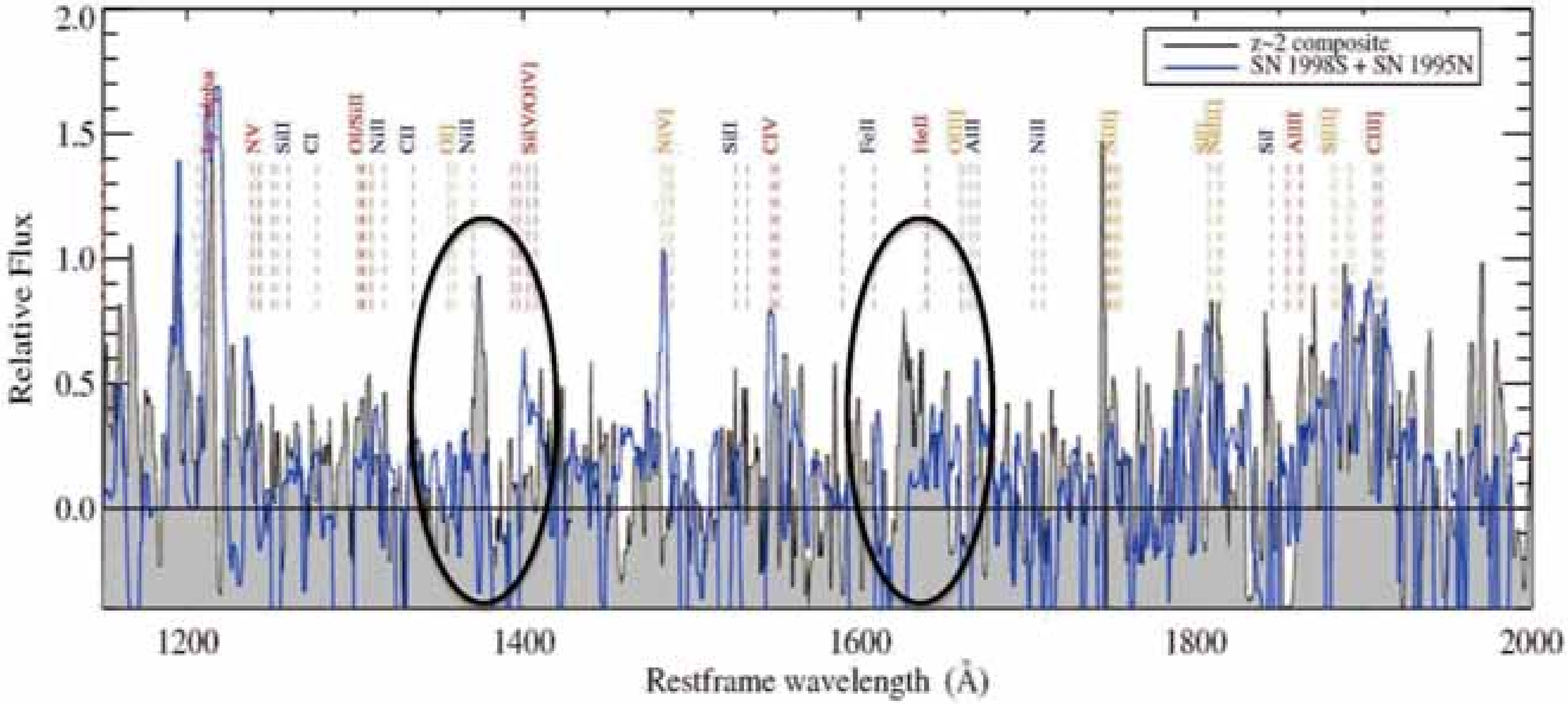
late-time spectroscopy



late-time spectroscopy



z ~ 2 SNe: day ~400 Local SNe: day 485 and day 943



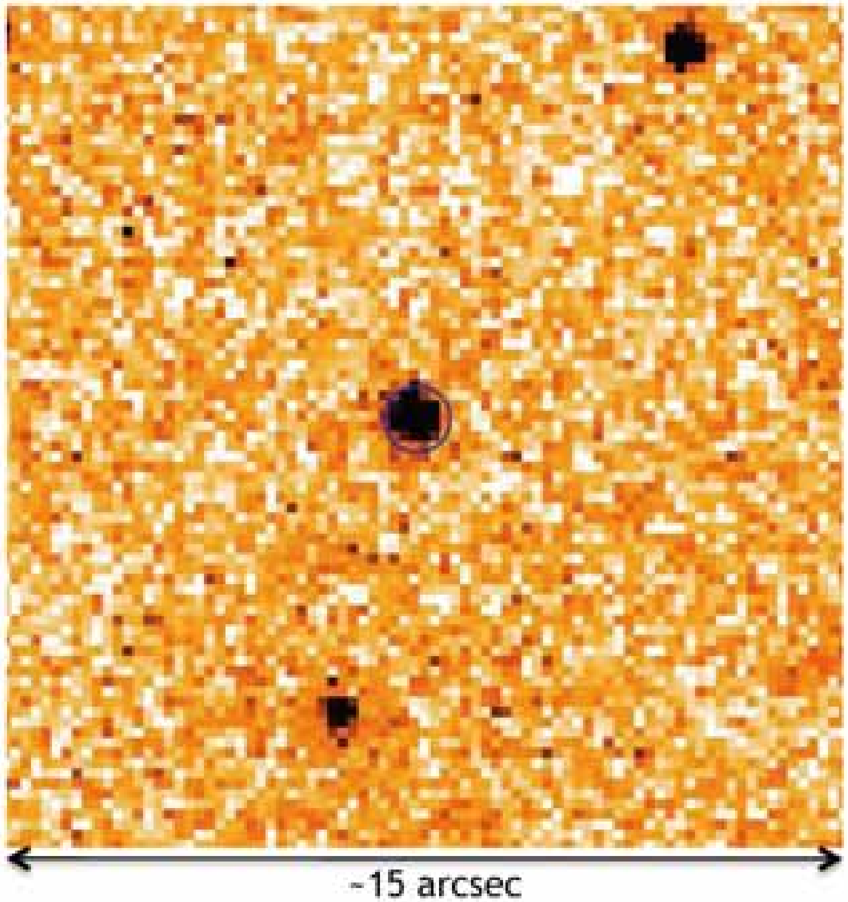
Beacons probing high-z galaxies similar to GRBs, but longer duration

super-luminous supernovae

object: 235017

host galaxy

$m_r = 25.9 \pm 0.10$
$M_{UV} = -19.3$



Circle has
radius of 5 kpc
(physical)

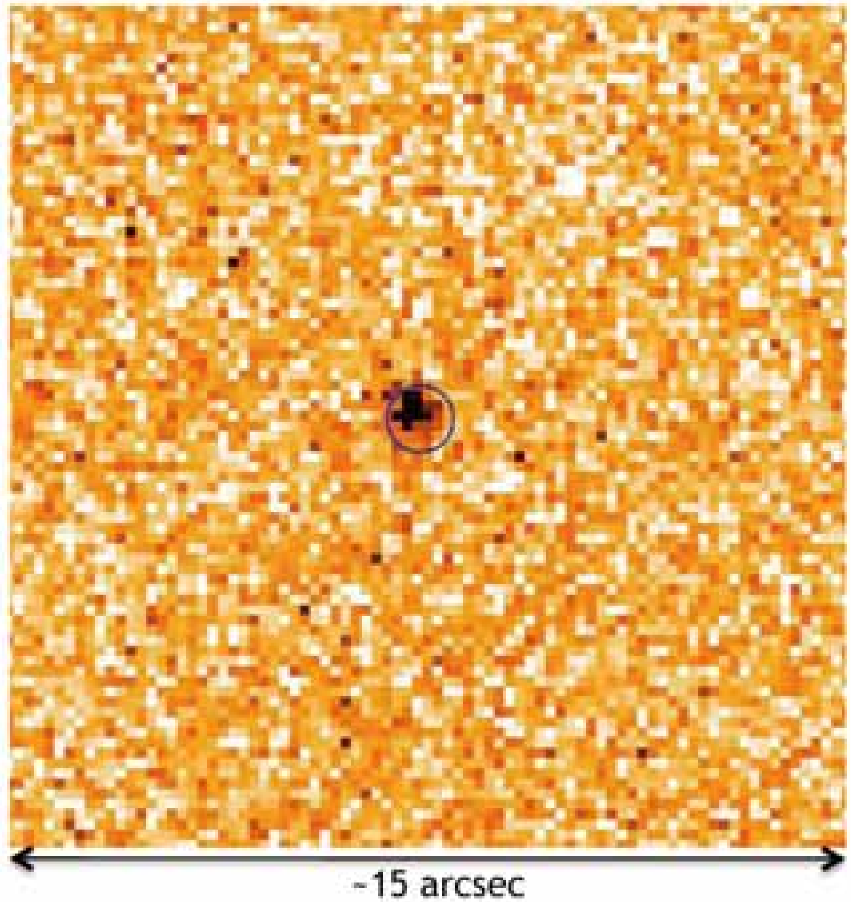
object: 235017

host galaxy

$m_r = 25.9 \pm 0.10$
$M_{UV} = -19.3$

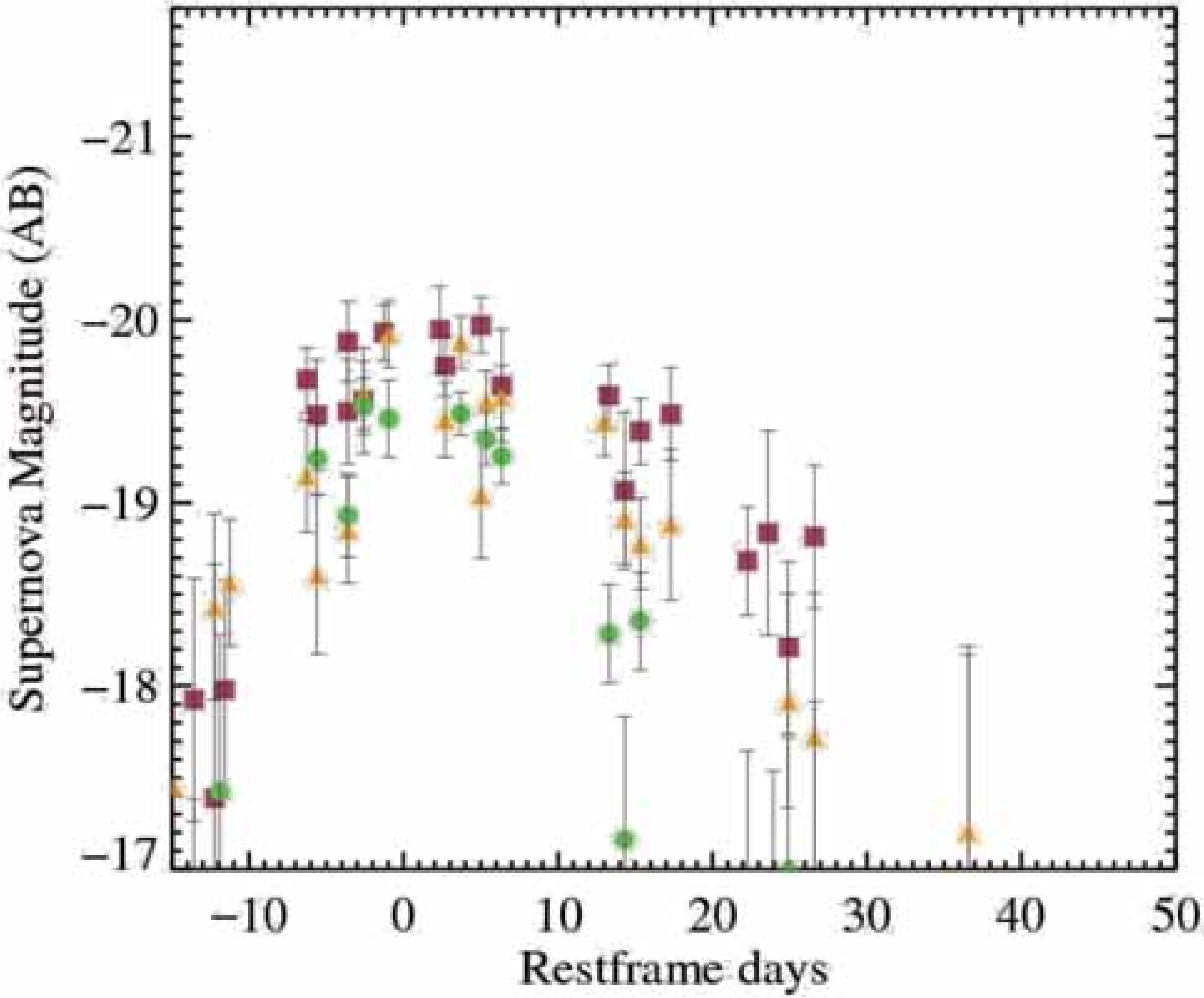
SN event

integrated mag
$m_r = 25.2 \pm 0.08$



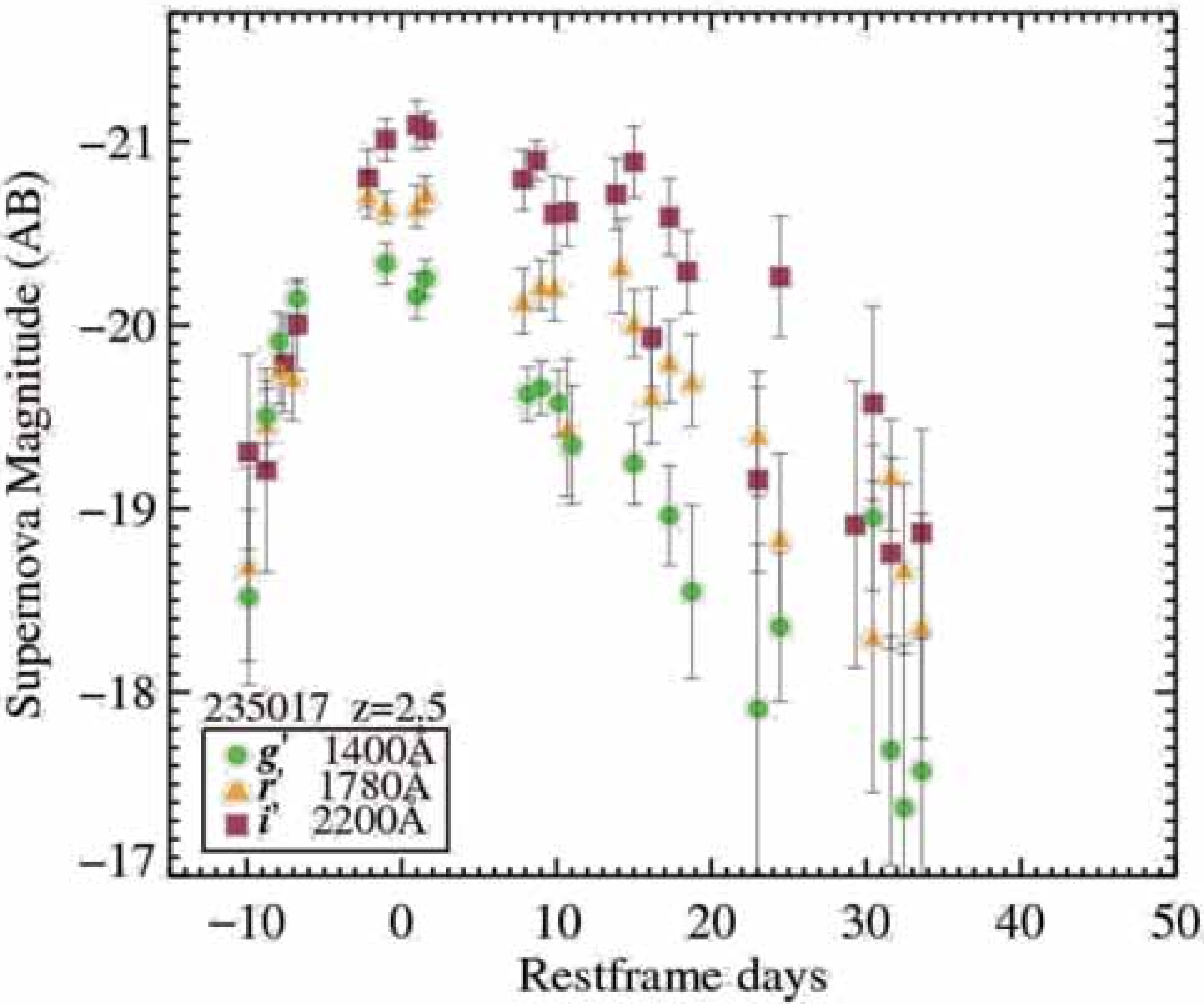
Circle has radius of 5 kpc (physical)

SN is offset from host centroid by 1.7 ± 0.5 kpc



Field "D1"
Event 234161

FUV luminous
Type IIn
(for comparison)

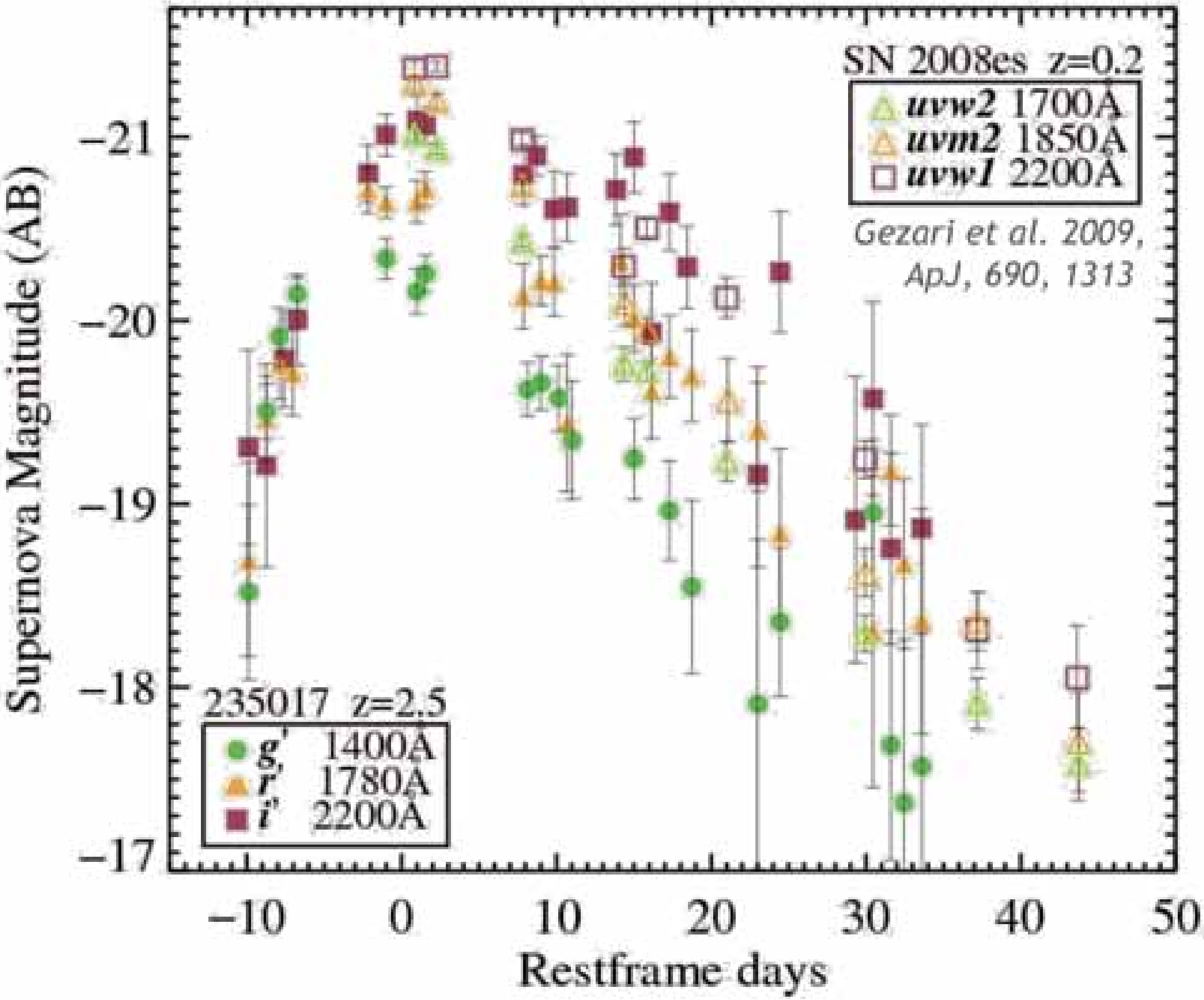


Field “D3”
Event 235017

SLSN

M_{UV}(peak) ~ -21.1
(~8x10^{43} erg s^{-1})

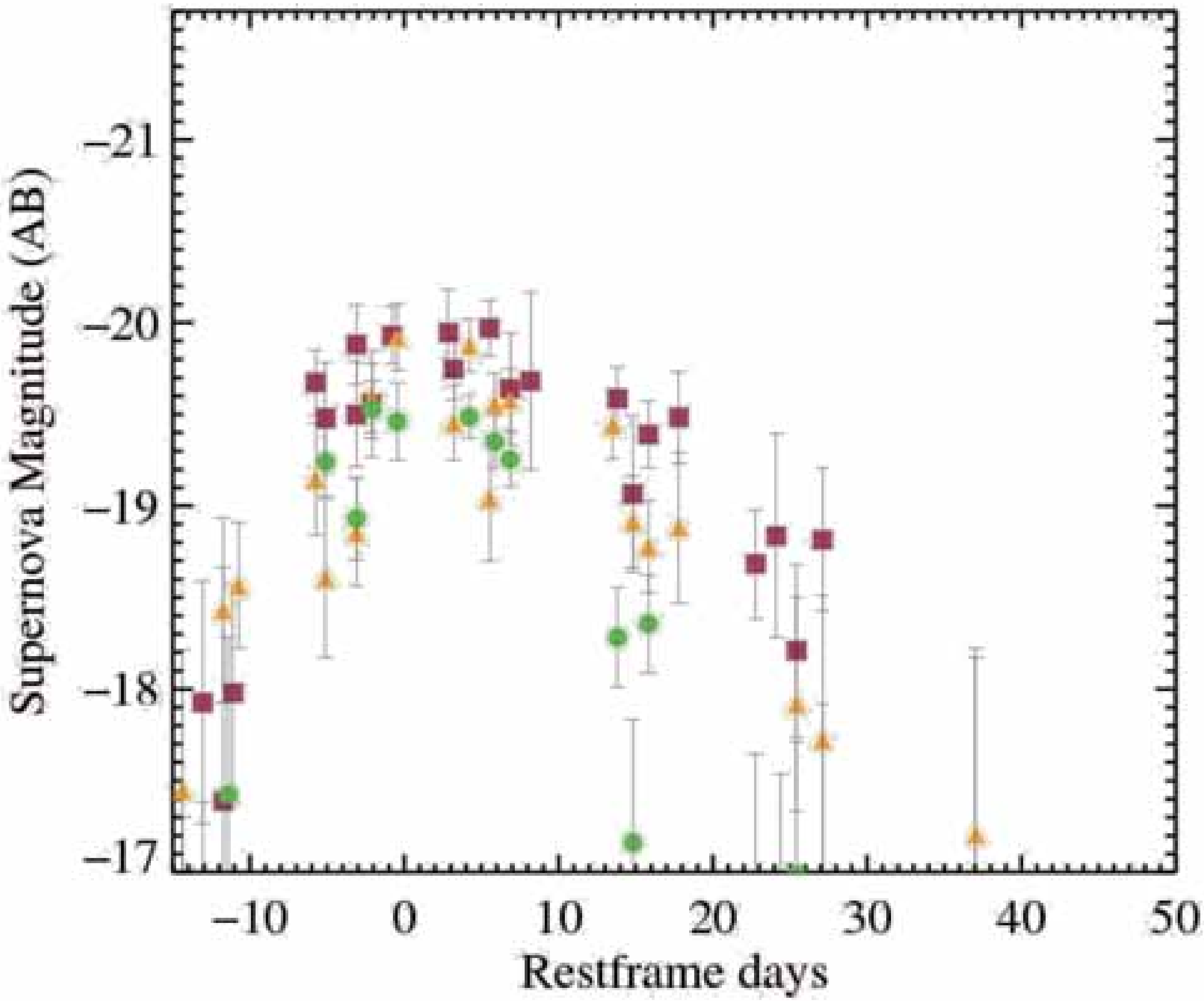
super-luminous supernovae



Field "D3"
Event 235017

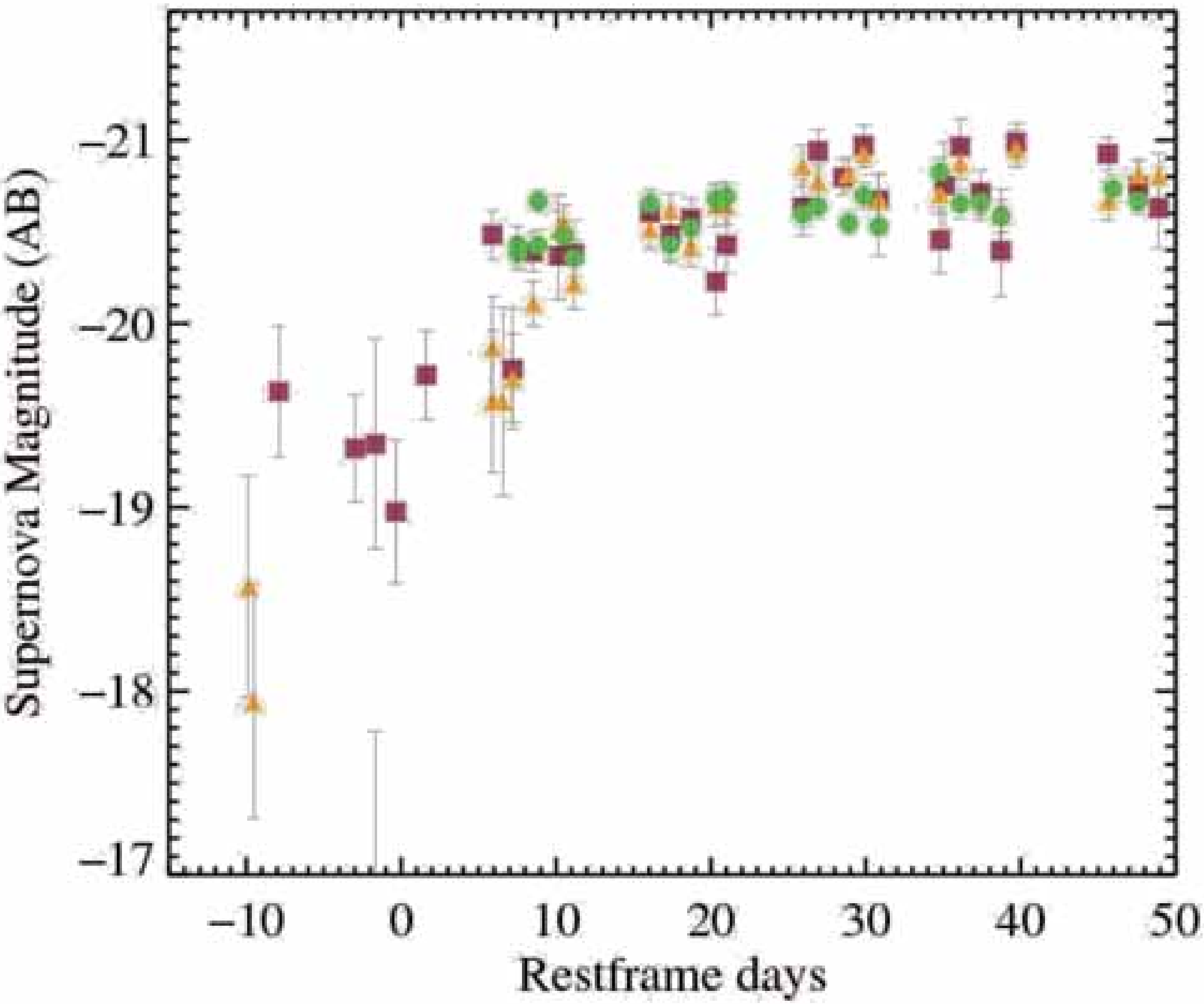
SLSN-I(?)
Type-IIL(?)

M_{UV}(peak) ~ -21.1
(~8x10^{43} erg s^{-1})



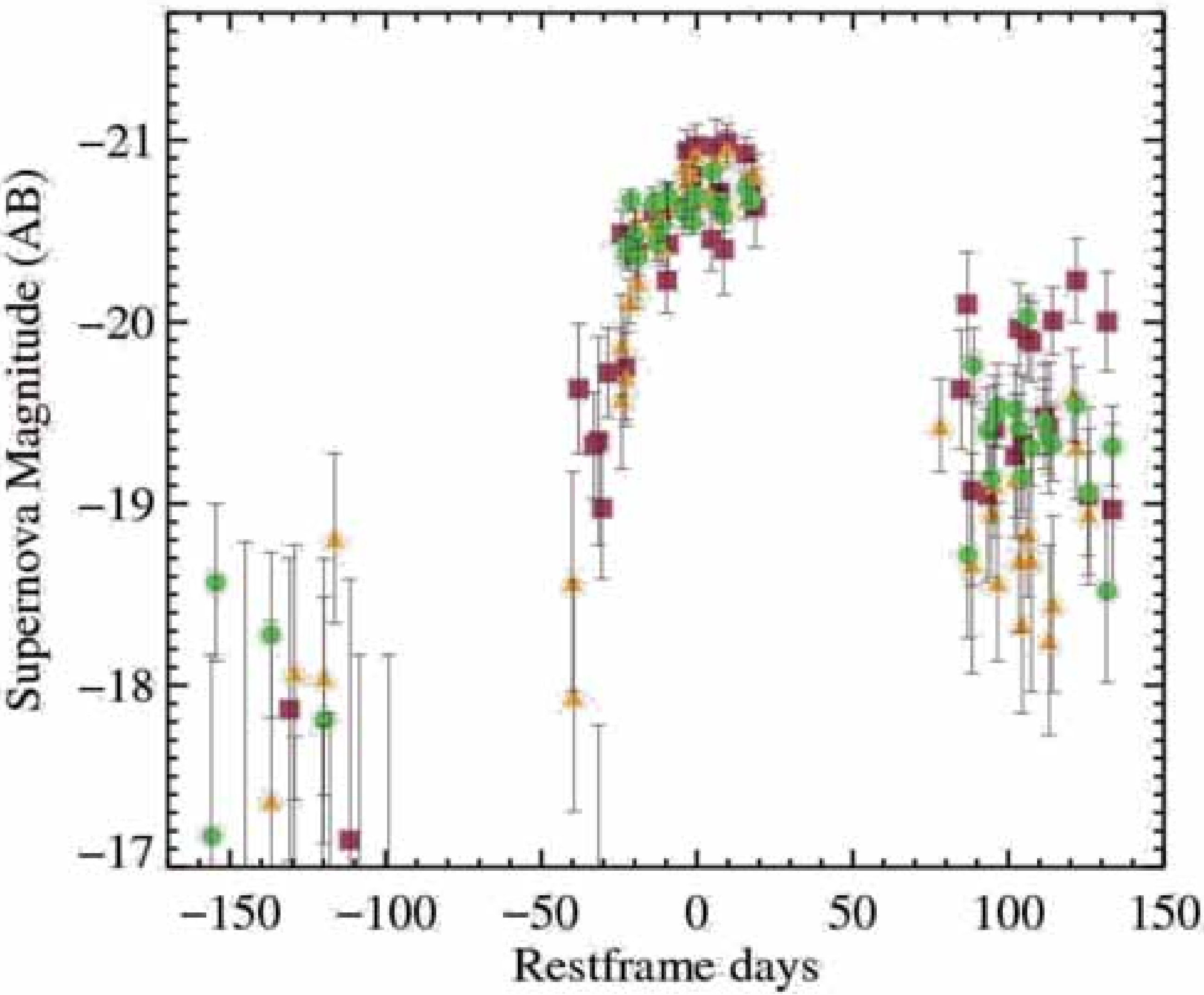
Field "D1"
Event 234161

FUV luminous
Type IIn
(for comparison)



Field “D4”
SN 2213-1745

SLSN



Field "D4"
SN 2213-1745

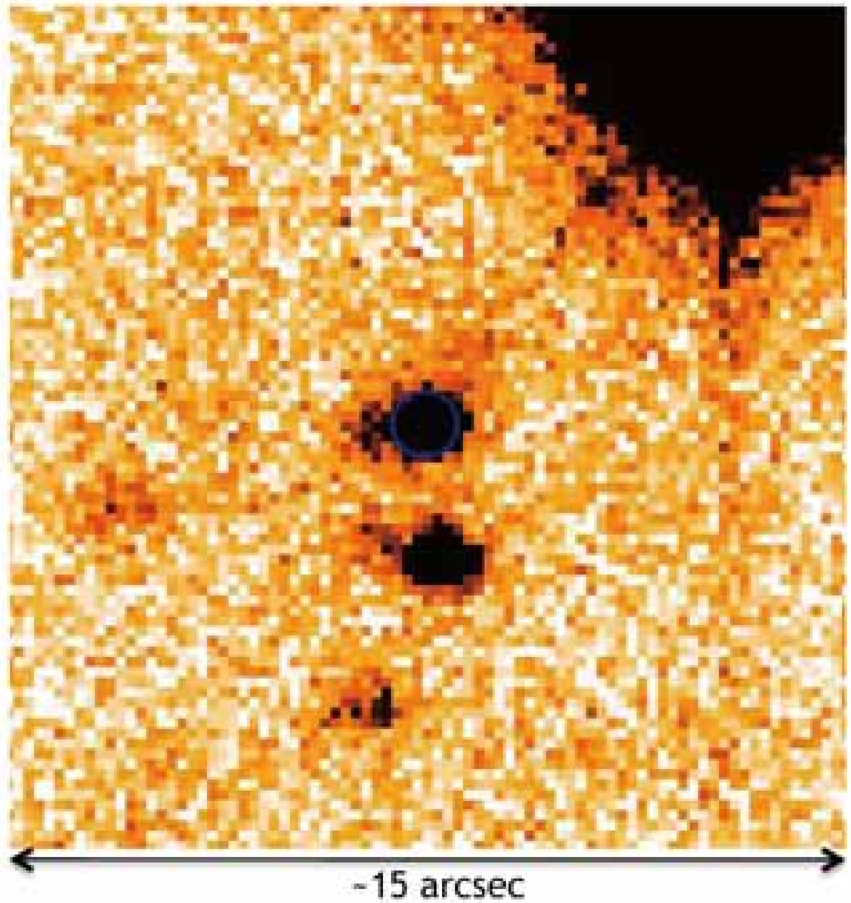
SLSN

super-luminous supernovae

object: 224556

host galaxy

$m_r = 23.4 \pm 0.02$
$M_{UV} = -21.4$



Circle has radius of 5 kpc (physical)

super-luminous supernovae

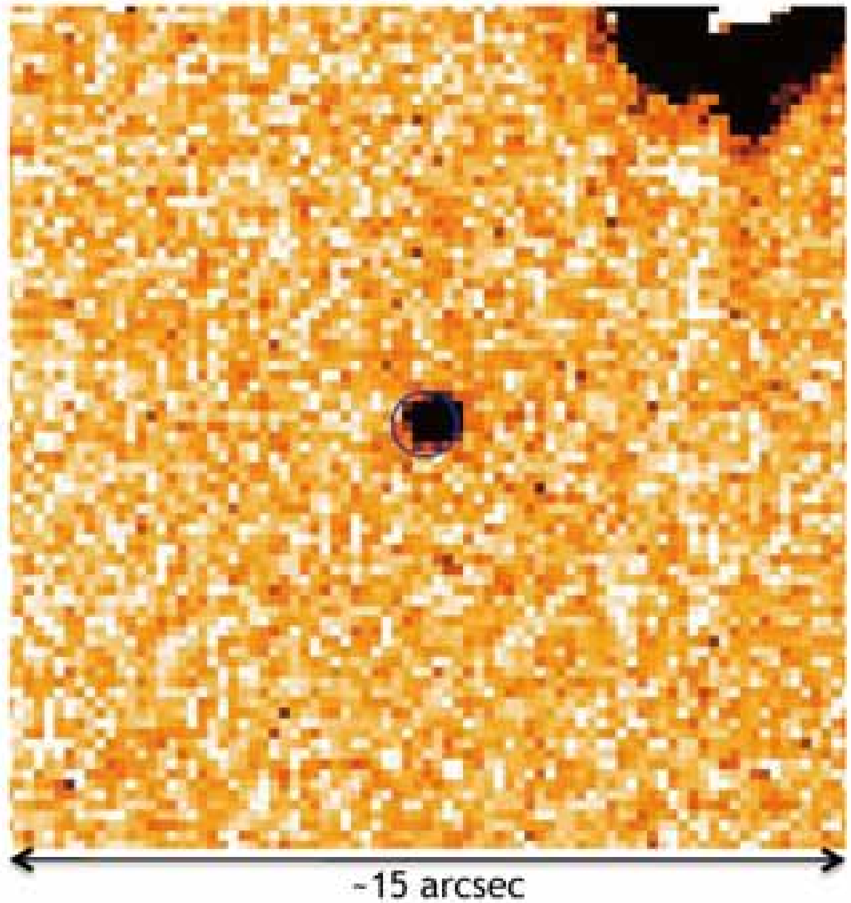
object: 224556

host galaxy

$m_r = 23.4 \pm 0.02$
$M_{UV} = -21.4$

SN event

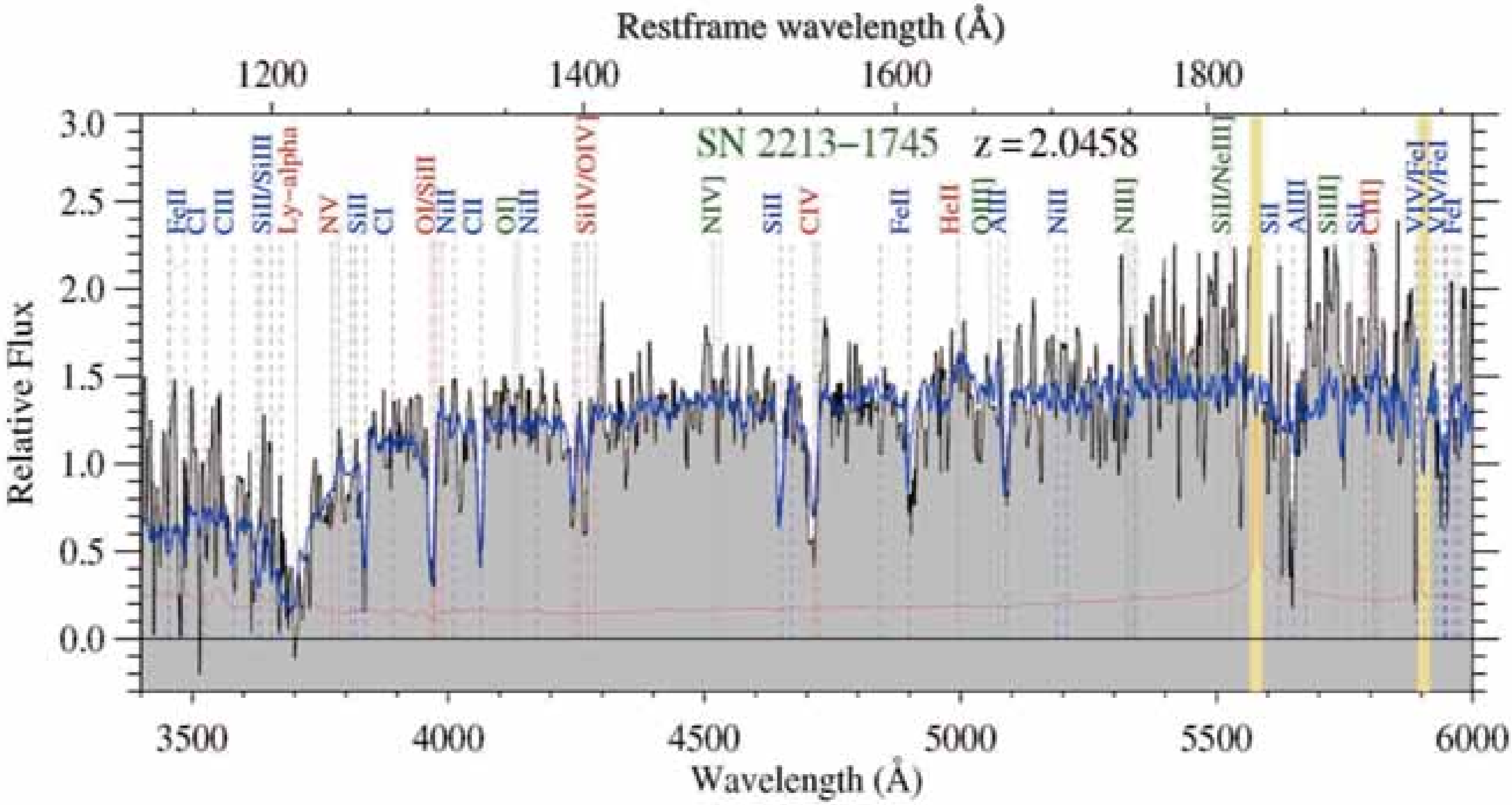
integrated mag
$m_r = 24.3 \pm 0.04$

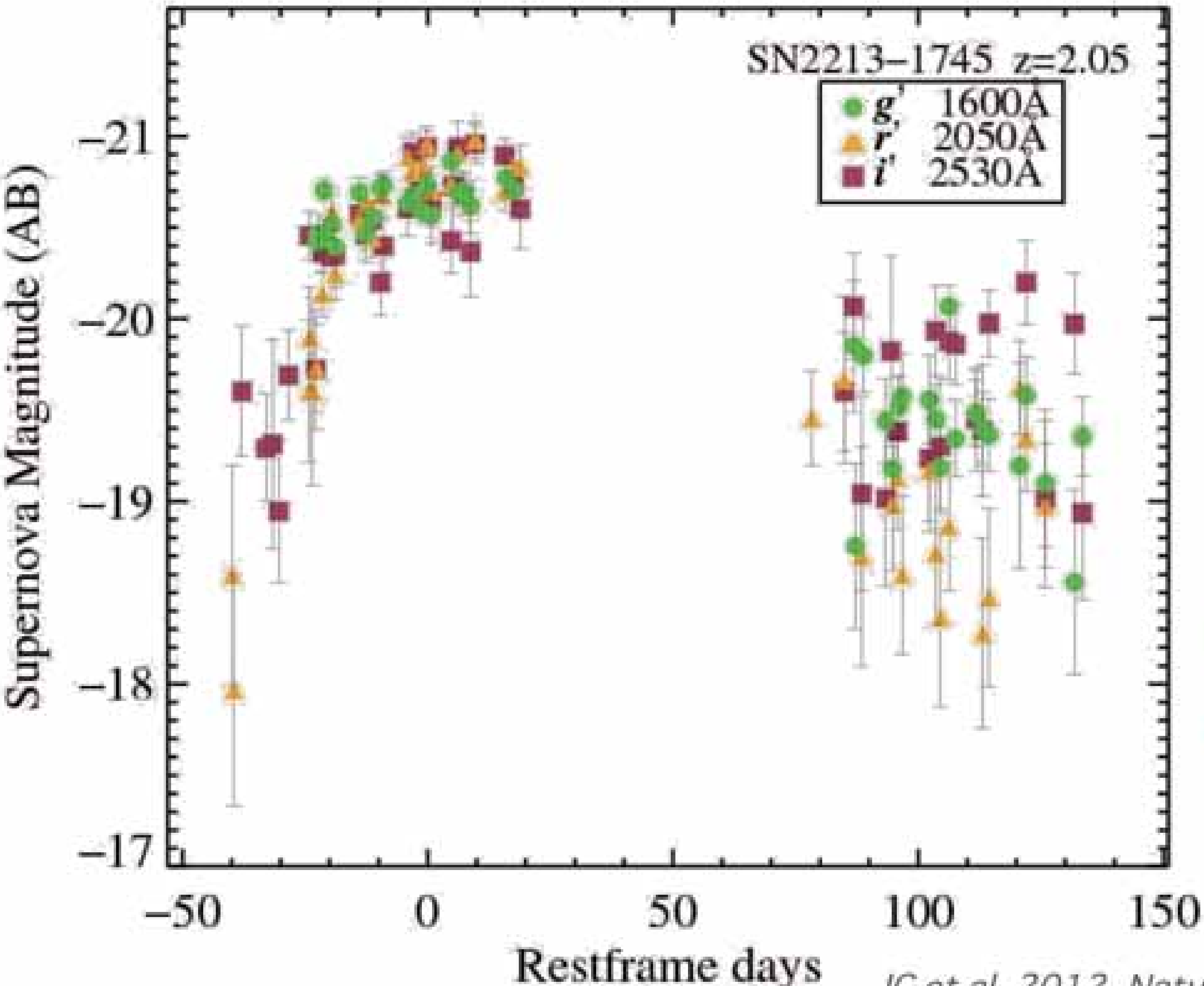


Circle has radius of 5 kpc (physical)

SN is offset from host centroid by 0.8 ± 0.3 kpc


super-luminous supernovae


Restframe wavelength (Å)
1200
1400
1600
1800
SN 2213−1745 z = 2.0458
FeII
CI
CIII
SiII/SiIII
Ly-alpha
NV
SiII
CI
OI/SiII
NiII
CII
OI]
NiII
SiIV/OIV]
NIV]
SiII
CIV
FeII
HeII
OIII]
AlII
NiII
NIII]
SiII/NeIII]
SiI
AlIII
SiIII]
SiI
CIII]
VIV/FeI
NIV/FeI
FeI
Relative Flux
3.0
2.5
2.0
1.5
1.0
0.5
0.0
3500
4000
4500
5000
5500
6000
Wavelength (Å)



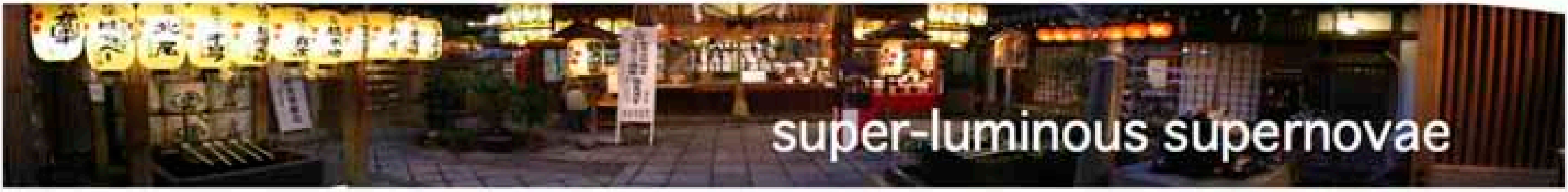
JC et al. 2012, Nature, submitted

Field "D4"
SN 2213-1745

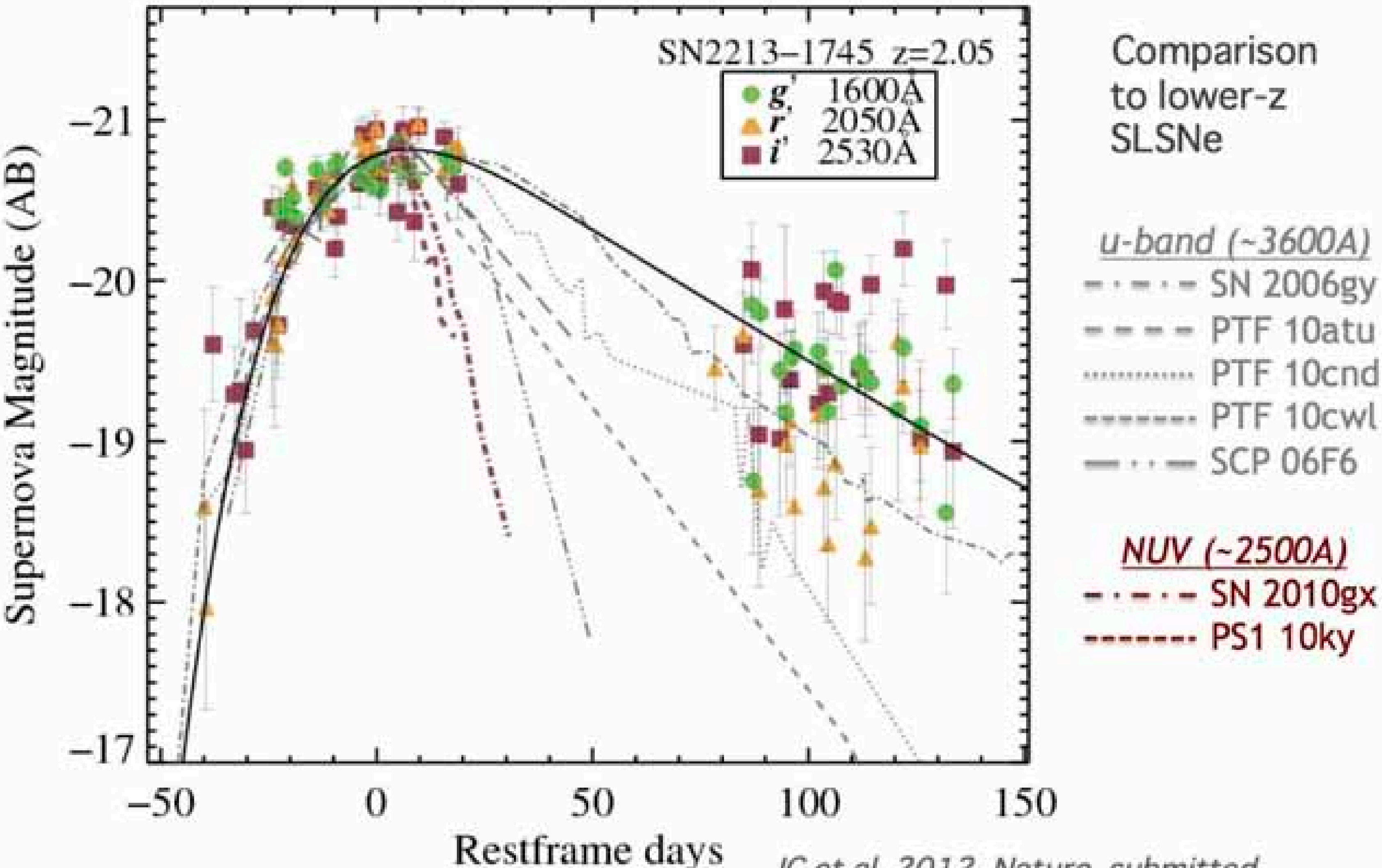
SLSN

Peak ~7x10^{43} erg s^{-1}

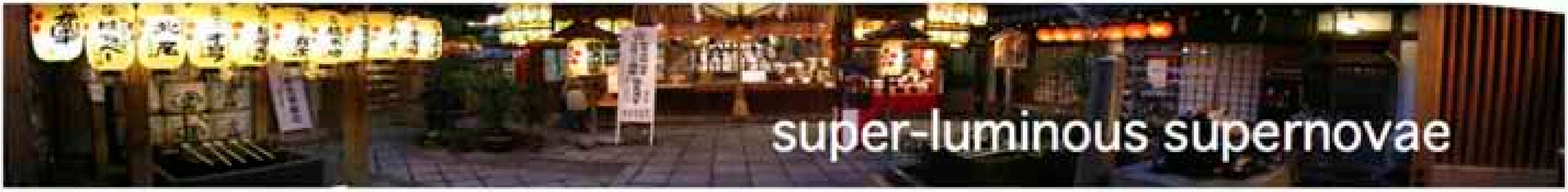
~10^{51} erg integrated FUV radiation



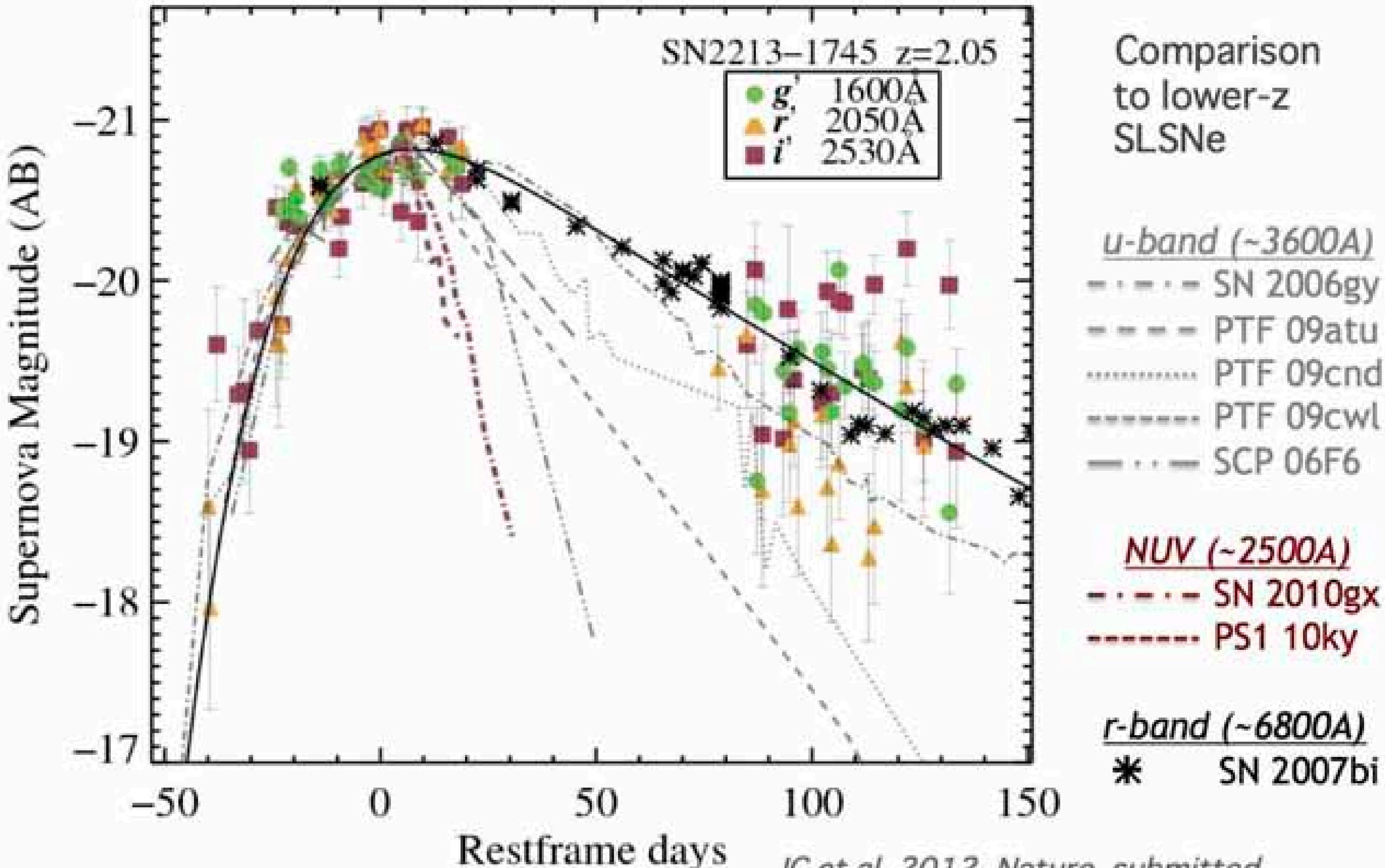
super-luminous supernovae



JC et al. 2012, Nature, submitted

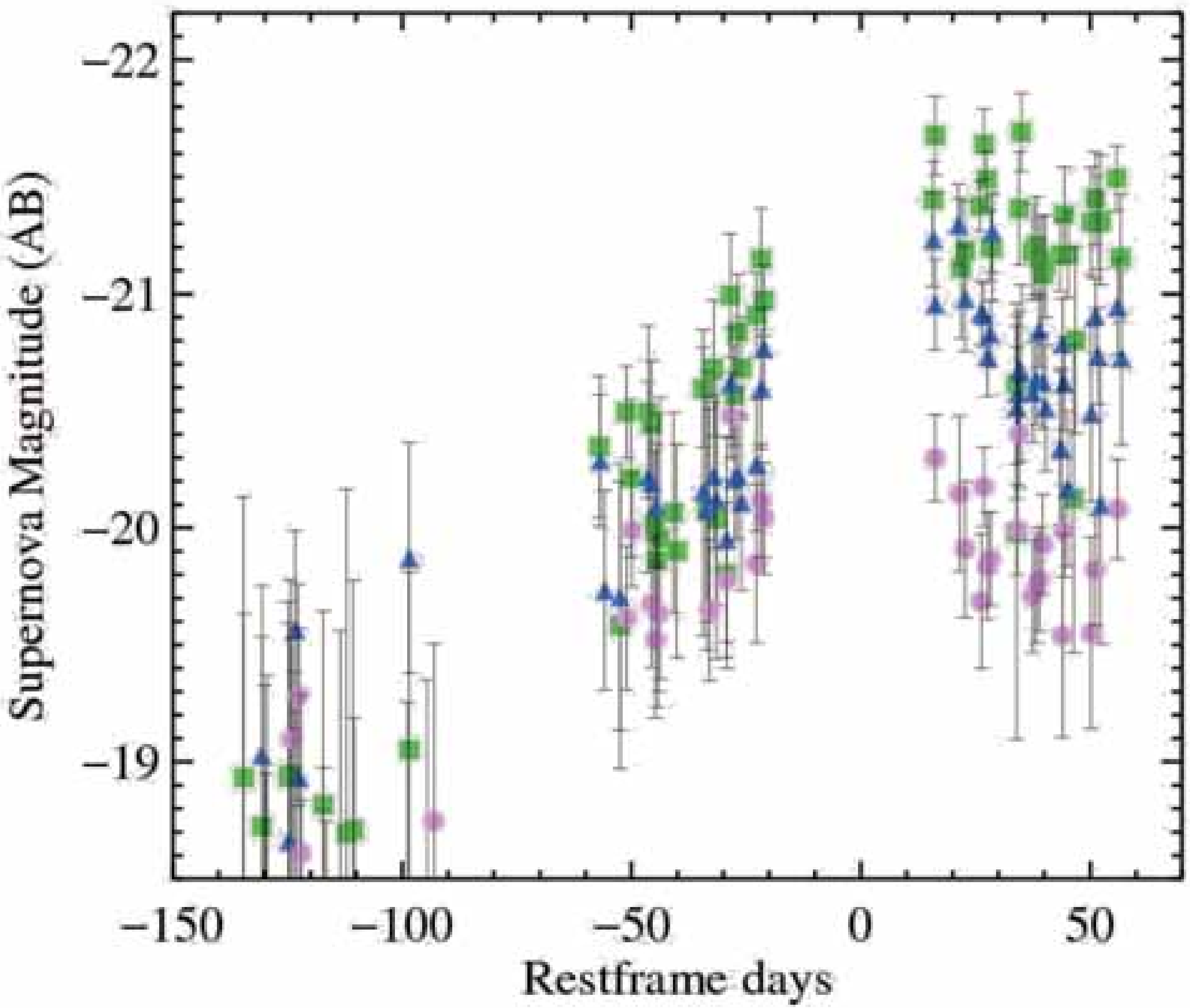


super-luminous supernovae



JC et al. 2012, Nature, submitted

super-luminous supernovae



Field "D2"
SN 1000+0216

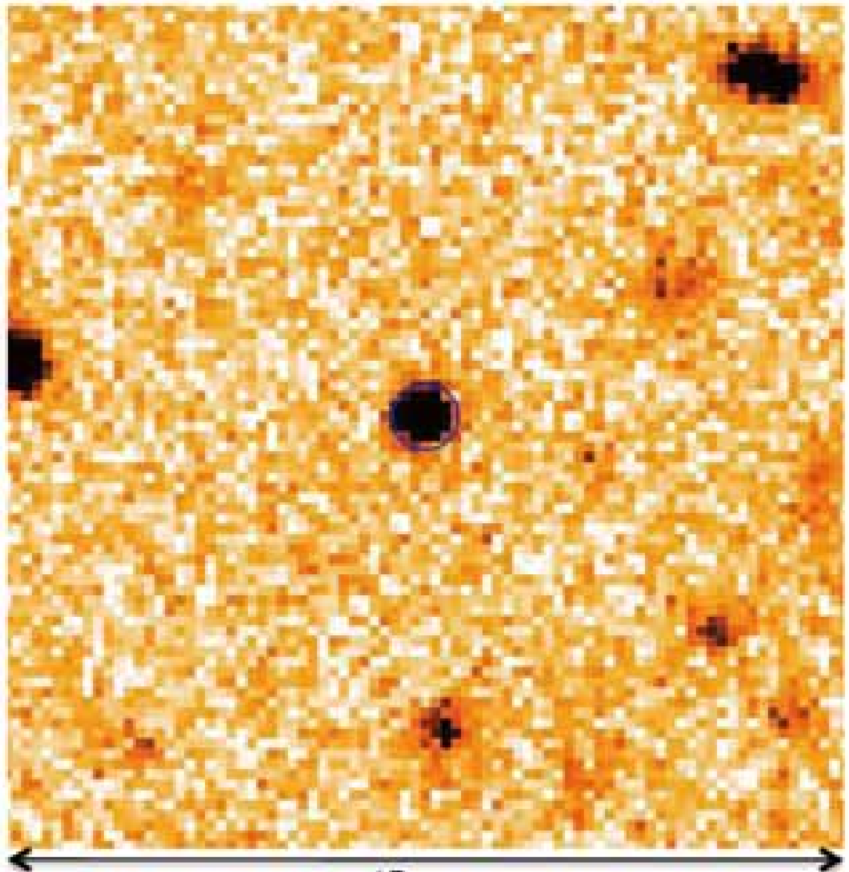
SLSN

super-luminous supernovae

object: 279200

host galaxy

$m_i = 24.8 \pm 0.04$
$M_{UV} = -21.2$



Circle has radius of 5 kpc (physical)

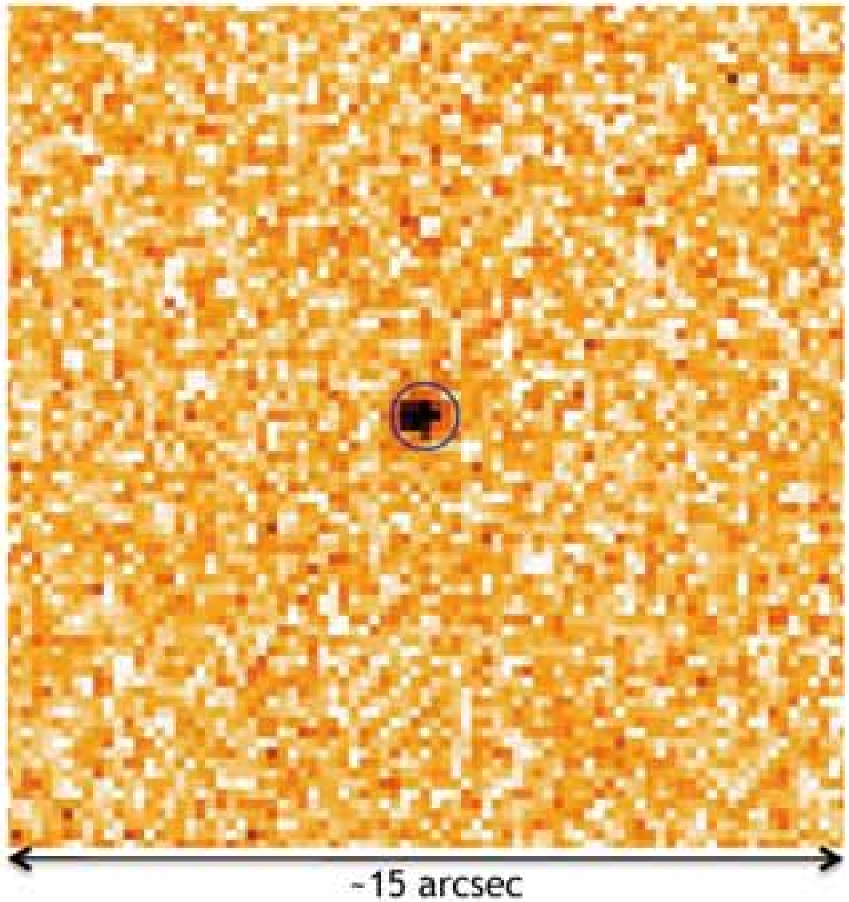
object: 279200

host galaxy

$m_i = 24.8 \pm 0.04$
$M_{UV} = -21.2$

SN event

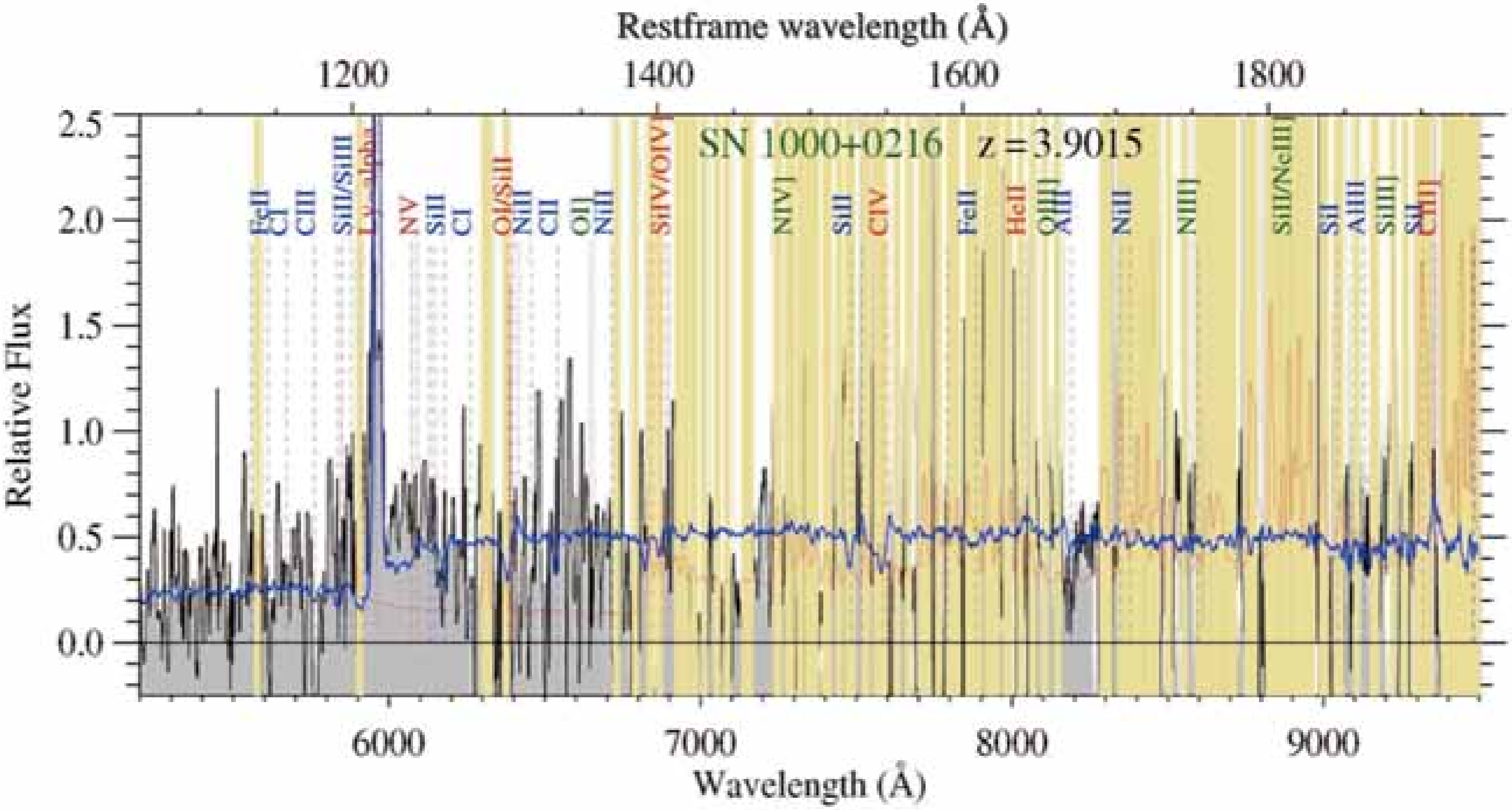
integrated mag
$m_r = 25.3 \pm 0.08$

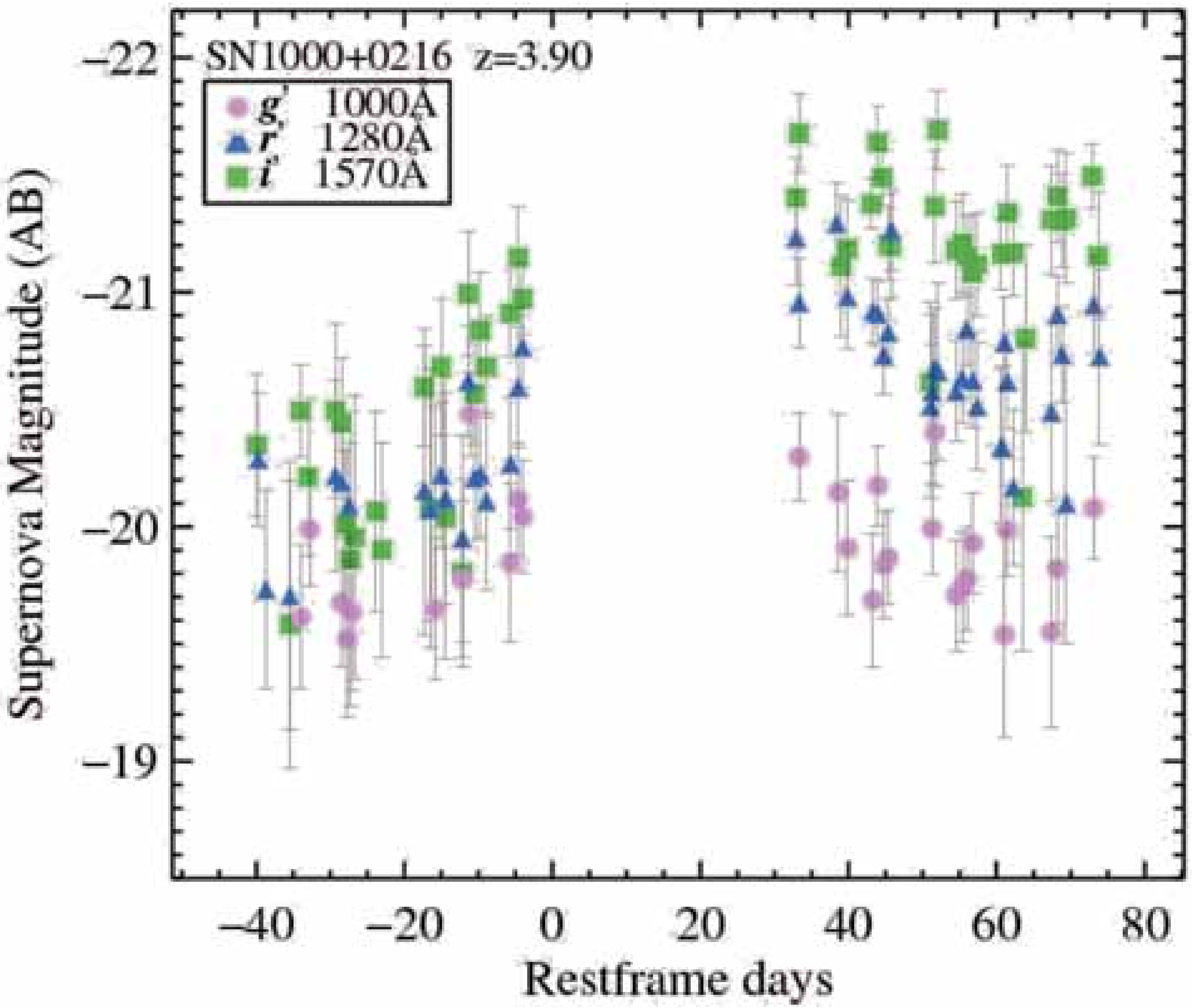


Circle has radius of 5 kpc (physical)

SN is offset from host centroid by 0.7 ± 0.4 kpc

super-luminous supernovae





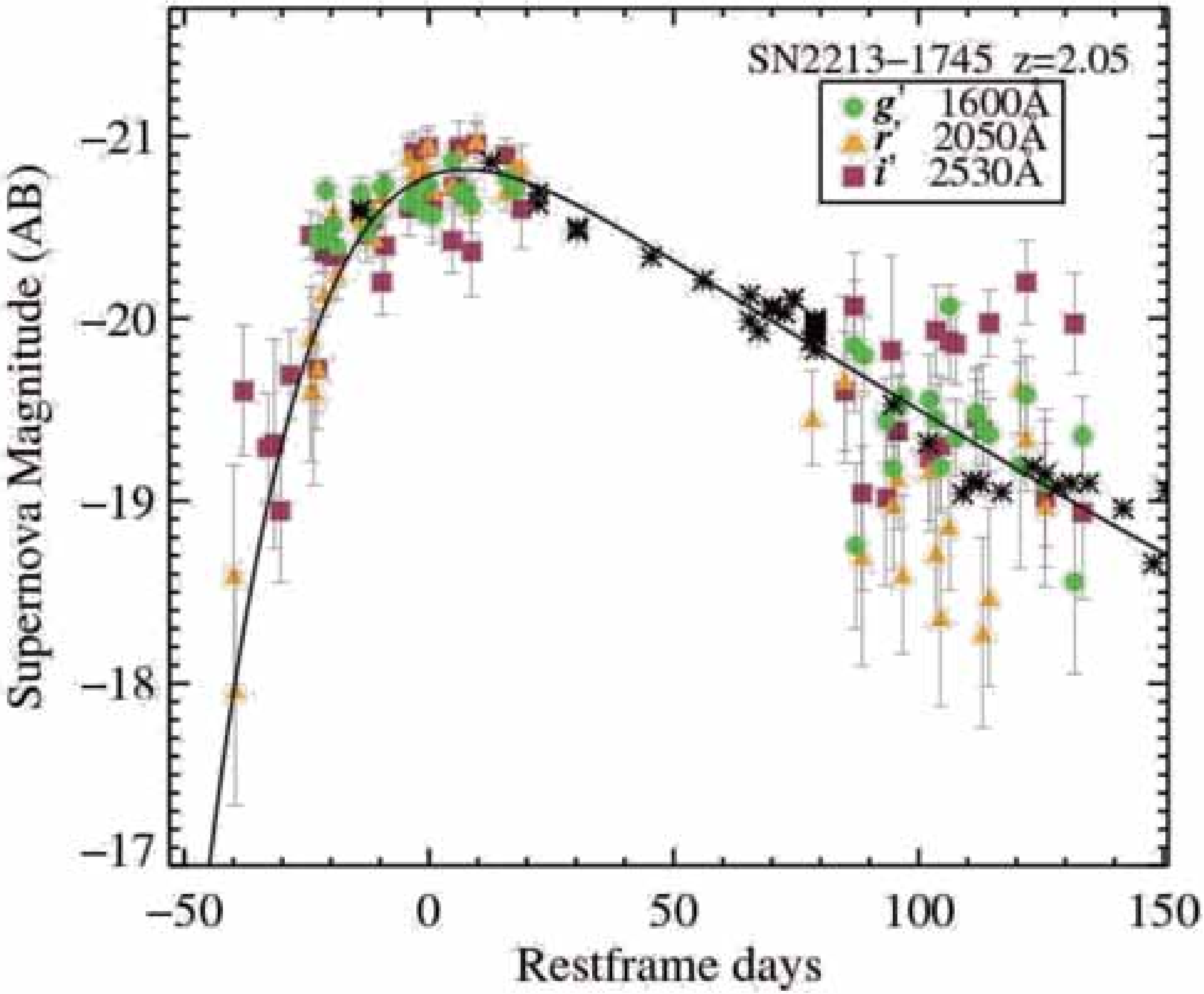
Field "D2"
SN 1000+0216

SLSN

M_{UV}(peak) ~ -21.7
(~1x10^{44} erg s^{-1})

g' (and u*) filters probe blueward of the Lyman limit!

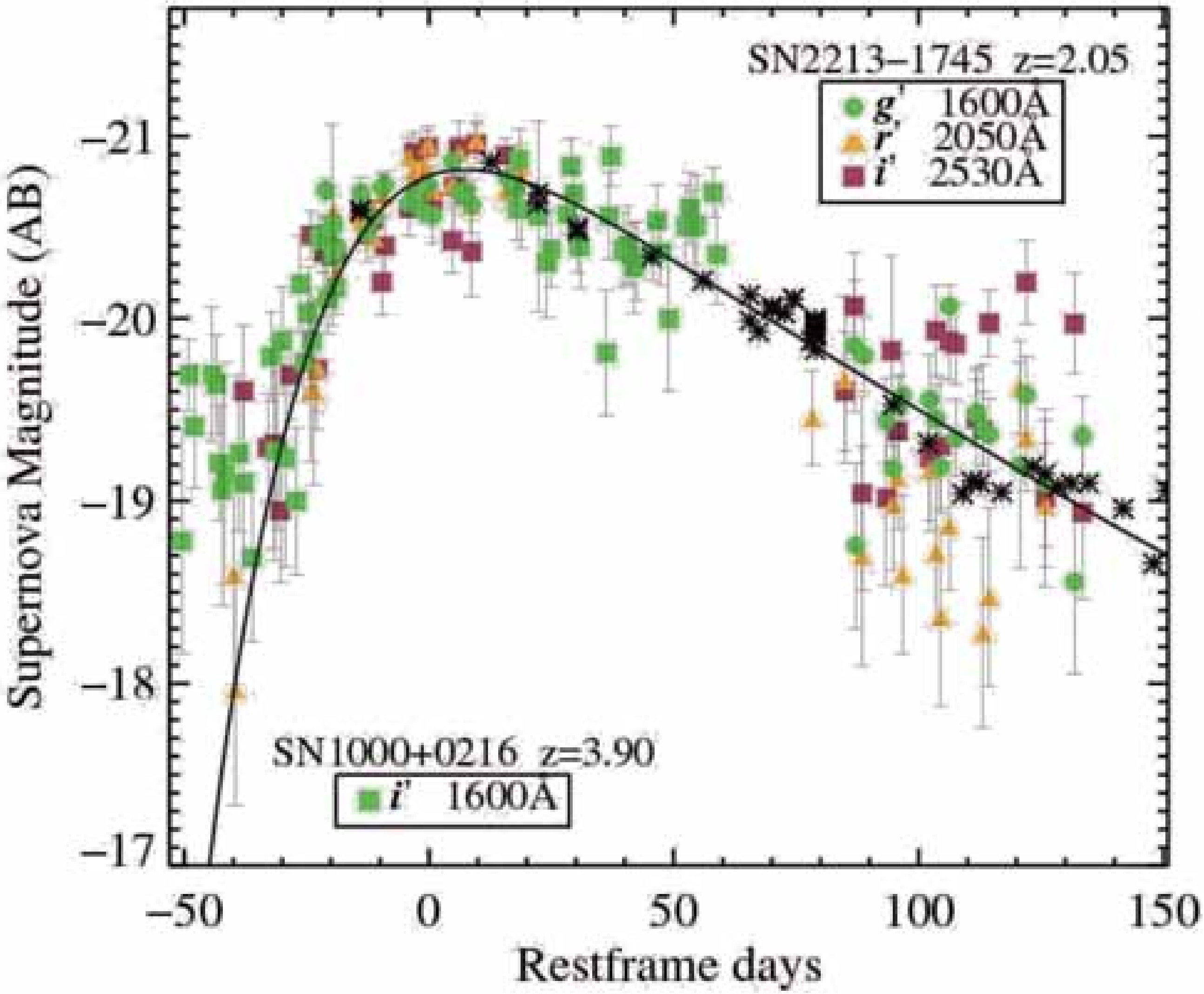
super-luminous supernovae



Field "D4"
SN 2213-1745

SLSN *(-R?)*
PISN*?*

super-luminous supernovae



Field "D4"
SN 2213-1745

SLSN *(-R?)*
PISN *?*

Field "D2"
SN 1000+0216

SLSN
Type *?*

Pulsational
pair-instability
w/interaction?

Massive progenitor
core-collapse?

The $z \sim 2$ and $z \sim 4$ LBGs monitored for the CFHTLS survey probe similar volumes: **~3 x 10^{7} h_{71}^{-3} Mpc^{3}**

The <u>confirmed detections</u> and detection window functions imply a rough rate of: **~few x10^{-7} h_{71}^{-3} Mpc^{3} yr^{-1}**

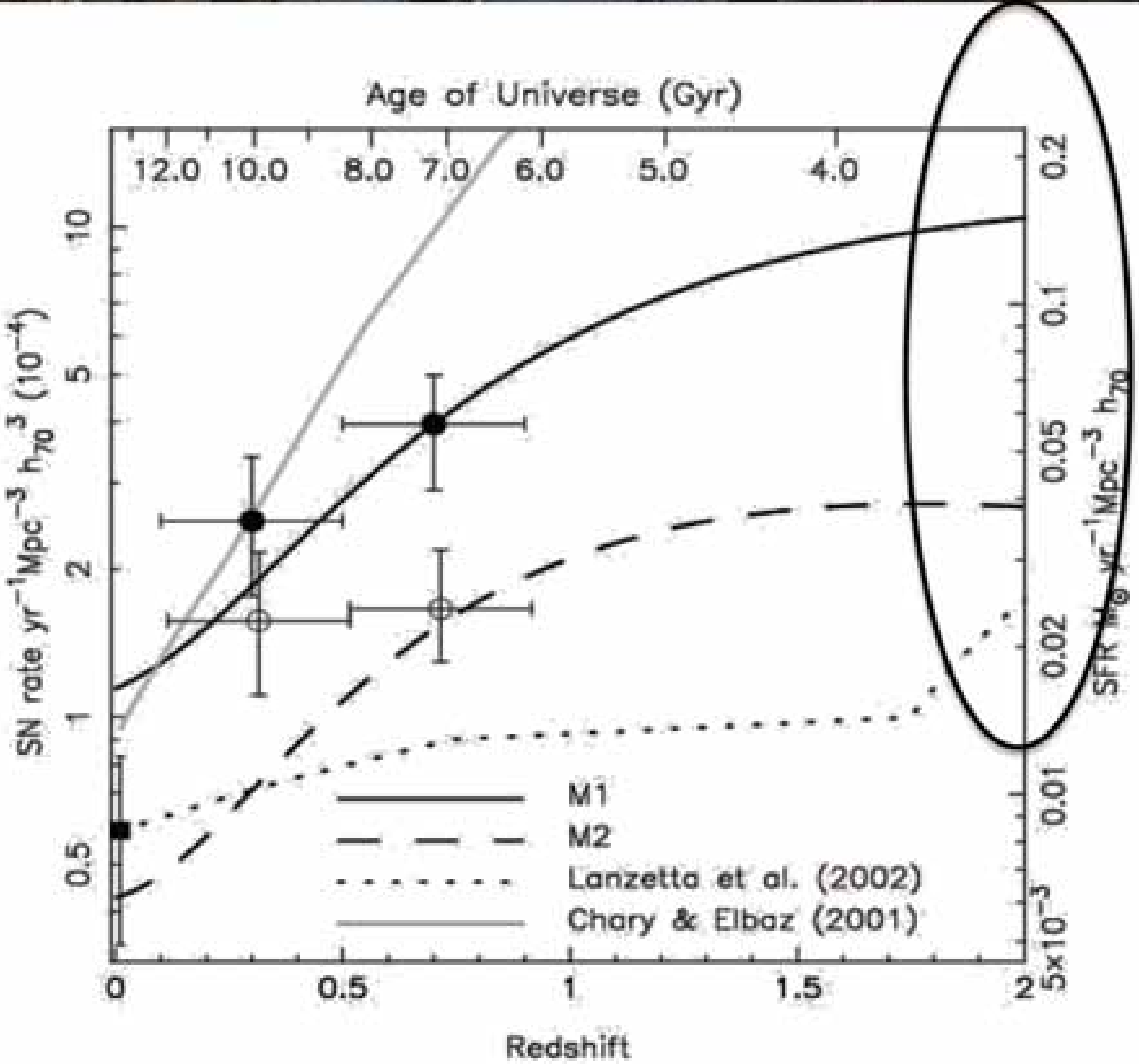
>10 times higher than the SLSN rate observed at lower-redshift

Quimby et al. (2011)

This is a lower limit because the SLSNe are detected in the FUV which is highly susceptible to metal-line absorption and dust extinction

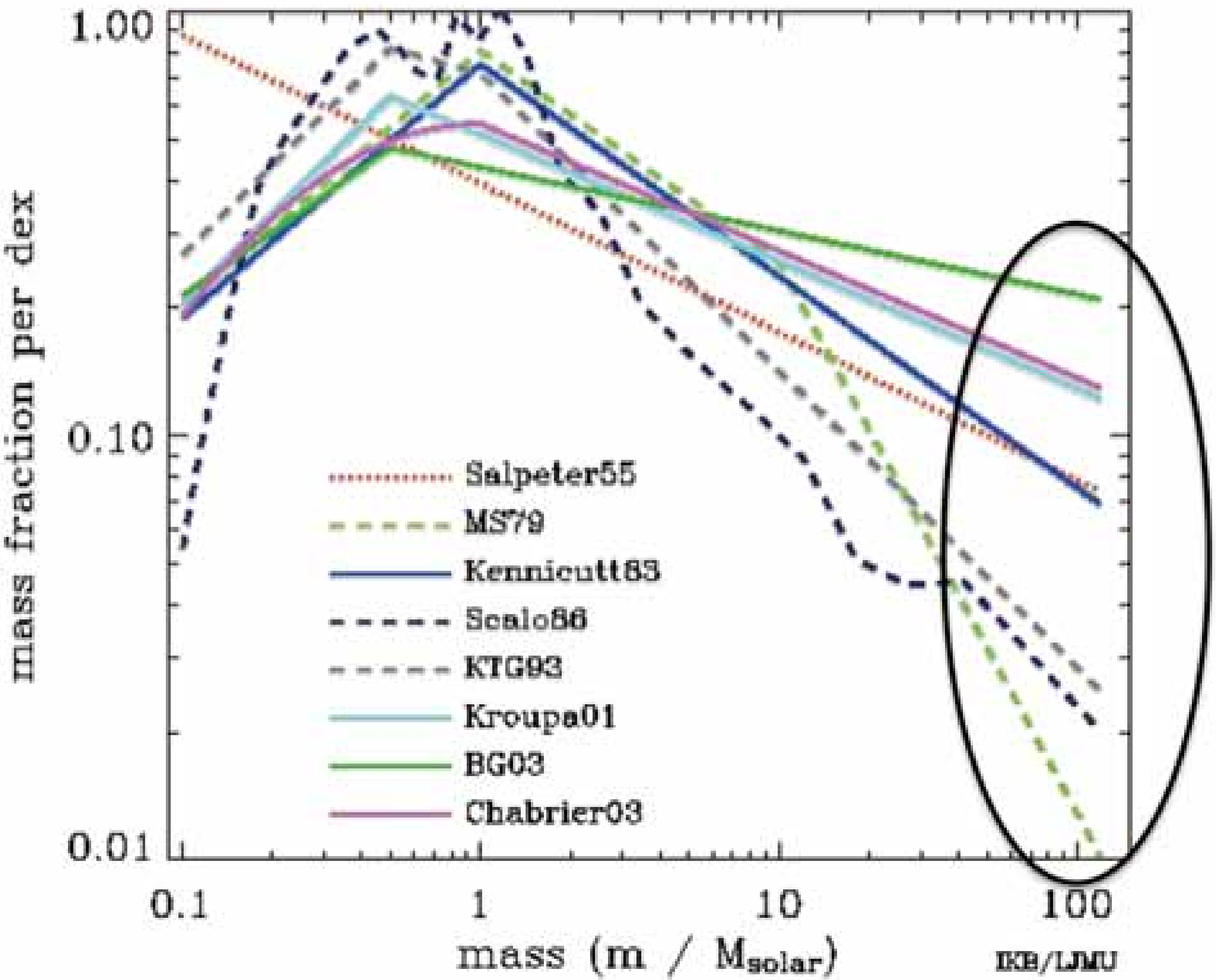
Confirmation of additional candidate events with Keck this Fall will provide strong evidence for a higher SLSN rate than observed at lower redshift

rates

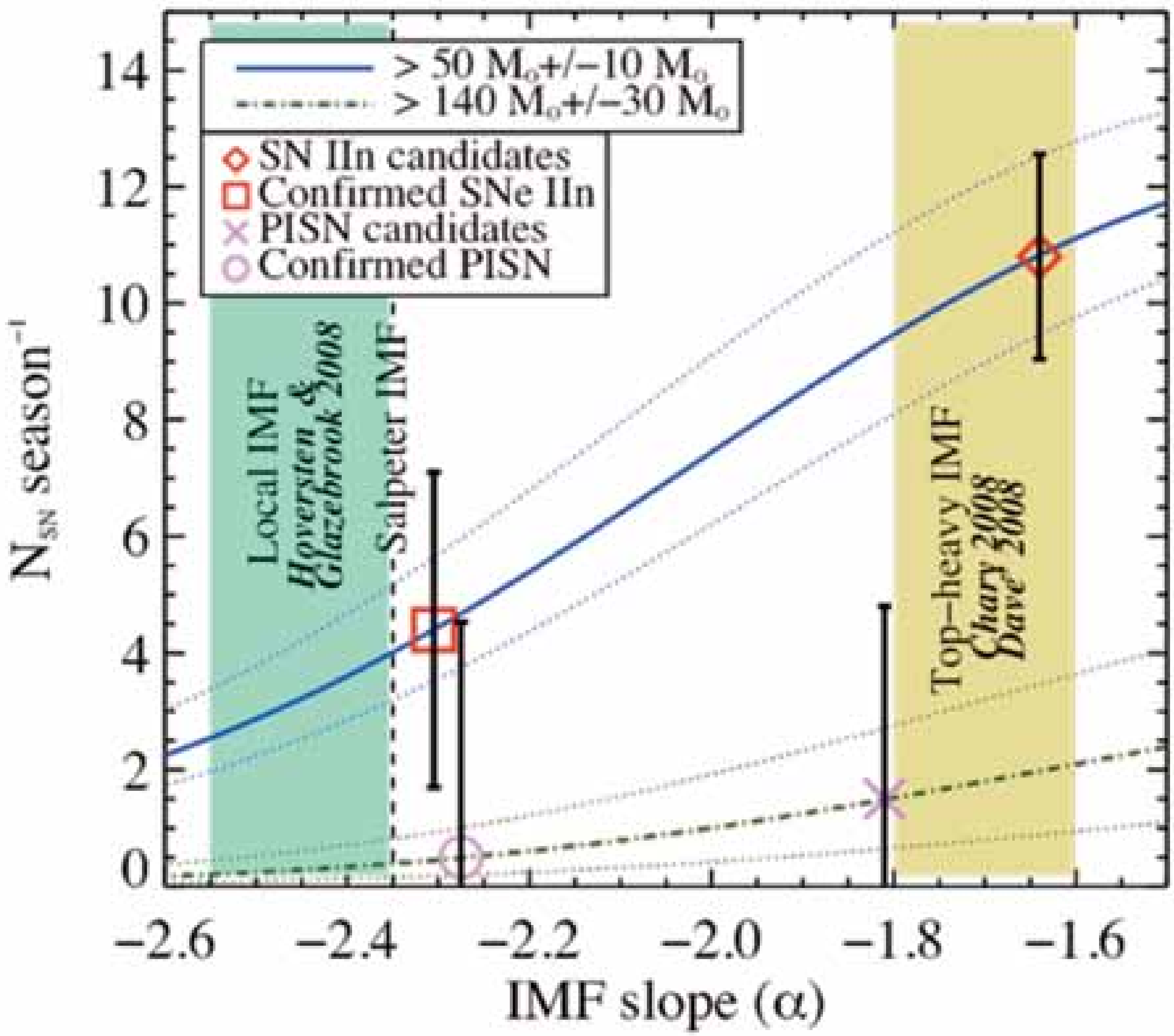


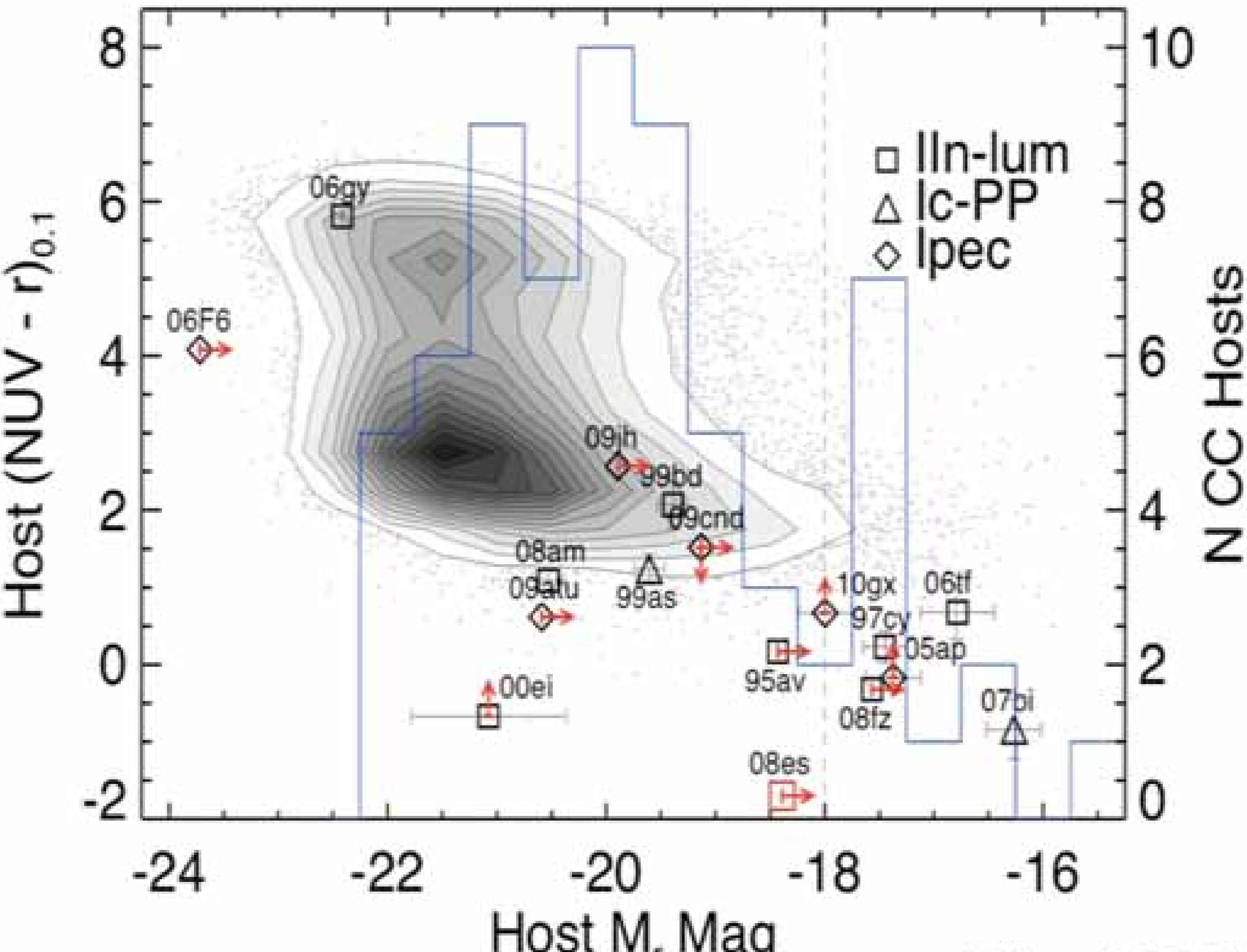
Age of Universe (Gyr)
12.0
10.0
8.0
7.0
6.0
5.0
4.0
SN rate yr^{-1}Mpc^{-3} h_{70}^{3} (10^{-4})
SFR $M_{\odot}$ yr^{-1}Mpc^{-3} h_{70}
10
5
2
1
0.5
0.2
0.1
0.05
0.02
0.01
5x10^{-3}
0
0.5
1
1.5
2
Redshift
M1
M2
Lanzetta et al. (2002)
Chary & Elbaz (2001)


stellar initial mass function

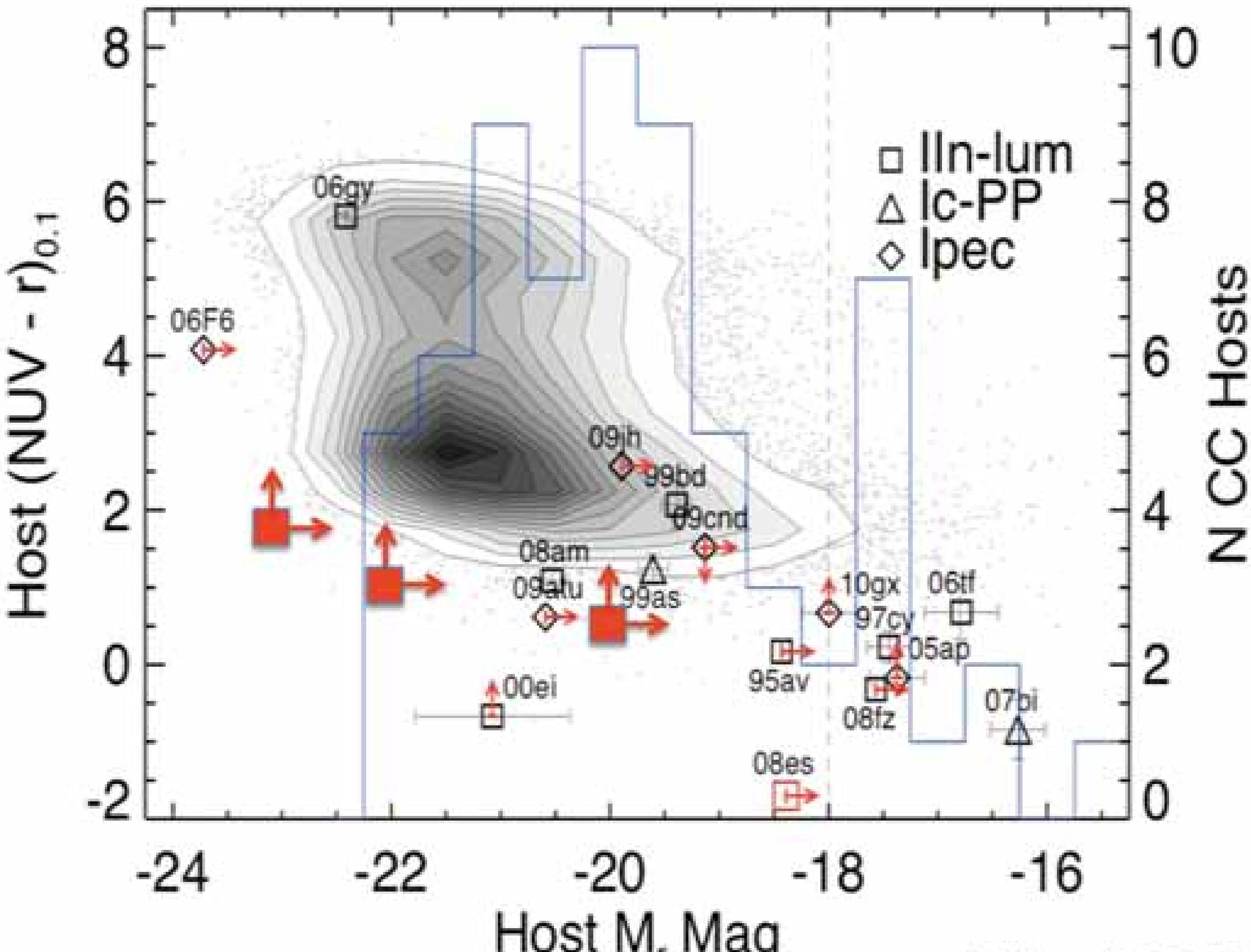

1.00
0.10
0.01
mass fraction per dex
0.1
1
10
100
mass (m / Msolar)
IKB/LJMU
Salpeter55
MS79
Kennicutt83
Scalo86
KTG93
Kroupa01
BG03
Chabrier03


stellar initial mass function


> 50 M☉+/−10 M☉
> 140 M☉+/−30 M☉
SN IIn candidates
Confirmed SNe IIn
PISN candidates
Confirmed PISN
Local IMF
Hoversten & Glazebrook 2008
Salpeter IMF
Top−heavy IMF
Chary 2008
Davé 2008
N_SN season⁻¹
IMF slope (α)
0
2
4
6
8
10
12
14
−2.6
−2.4
−2.2
−2.0
−1.8
−1.6



Neill et al. (2011)



Neill et al. (2011)

Expected long tail in the redshift distribution of metal-free regions and pockets of pristine gas corresponding to relatively late epochs *(below z ~ 4)*

Many Pop III stars at these late epochs are expected to be isolated (>150 kpc from host galaxies)

(e.g., Scannepieco et al. 2003, Furlanetto & Loeb 2005, Trenti, Stiavelli, & Shull 2009)

"Orphan" supernova search in progress

Detection of Pristine Gas Two Billion Years After the Big Bang

Michele Fumagalli,[1*] John M. O'Meara,[2] J. Xavier Prochaska[3]

In the current cosmological model, only the three lightest elements were created in the first few minutes after the Big Bang; all other elements were produced later in stars. To date, however, heavy elements have been observed in all astrophysical environments. We report the detection of two gas clouds with no discernible elements heavier than hydrogen. These systems exhibit the lowest heavy-element abundance in the early universe, and thus are potential fuel for the most metal-poor halo stars. The detection of deuterium in one system at the level predicted by primordial nucleosynthesis provides a direct confirmation of the standard cosmological model. The composition of these clouds further implies that the transport of heavy elements from galaxies to their surroundings is highly inhomogeneous.

In modern cosmological theory, the light elements and their isotopes were produced during the first few minutes after the Big Bang, when the universe cooled during expansion from temperatures $T \sim 10^9$ K to below $\sim 4 \times 10^8$ K. In this brief epoch, termed Big Bang nucleosynthesis (BBN), deuterium (D), ^{3}He, ^{4}He, and ^{7}Li were synthesized with an abundance ratio relative to hydrogen (H) that was sensitive to the cosmic density of ordinary matter (i.e., the baryon density $\Omega_{b,0}$). BBN theory also predicts that there was negligible production of the heavy elements with abundance ratios X/H < 10^{-10}, because the physical conditions now typical of stellar interiors did not yet exist (*1*).

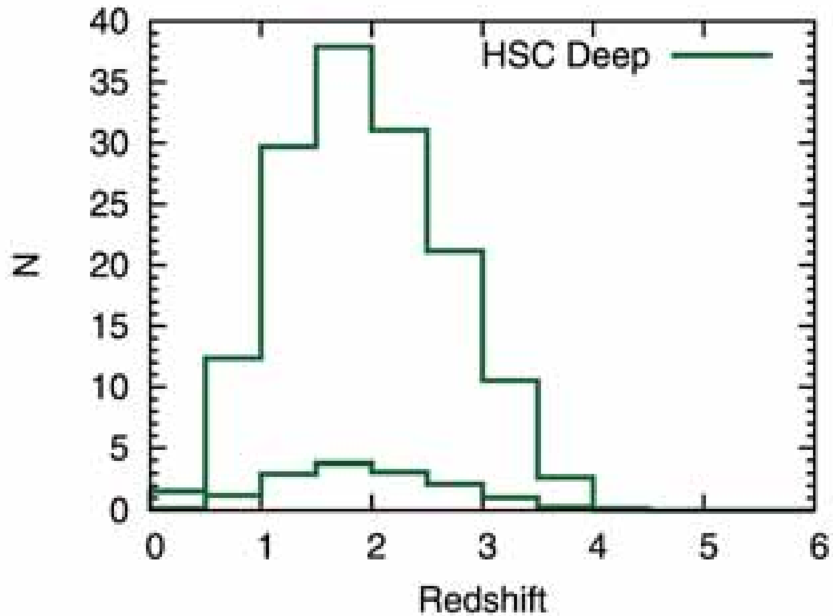
The analysis of gas observed in absorption along the lines of sight to high-redshift quasars, distant galaxies that host supermassive black holes, is a powerful probe of the BBN yields. Particular attention has been given to D, partly because of observational convenience, but also because the D/H abundance ratio is very sensitive to $\Omega_{b,0}$. For quasar sight lines, the measured log(D/H) = −4.55 ± 0.03 (*2*, *3*) translates into $\Omega_{b,0}h^2$(BBN) = 0.0213 ± 0.0010, which is fully consistent with the value inferred from the cosmic

[1]Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA, USA. [2]Department of Chemistry and Physics, Saint Michael's College, Colchester, VT, USA. [3]University of California Observatories–Lick Observatory, University of California, Santa Cruz, CA, USA.
*To whom correspondence should be addressed. E-mail: mfumagalli@ucolick.org

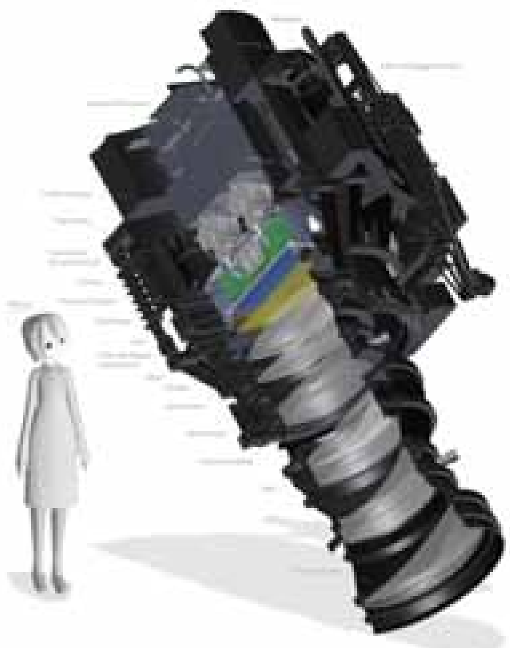
Hyper Suprime-Cam

<u>Deep and Ultra-Deep survey</u>

Targets for the next generation of large aperture telescopes and JWST



Tanaka et al. (2012)



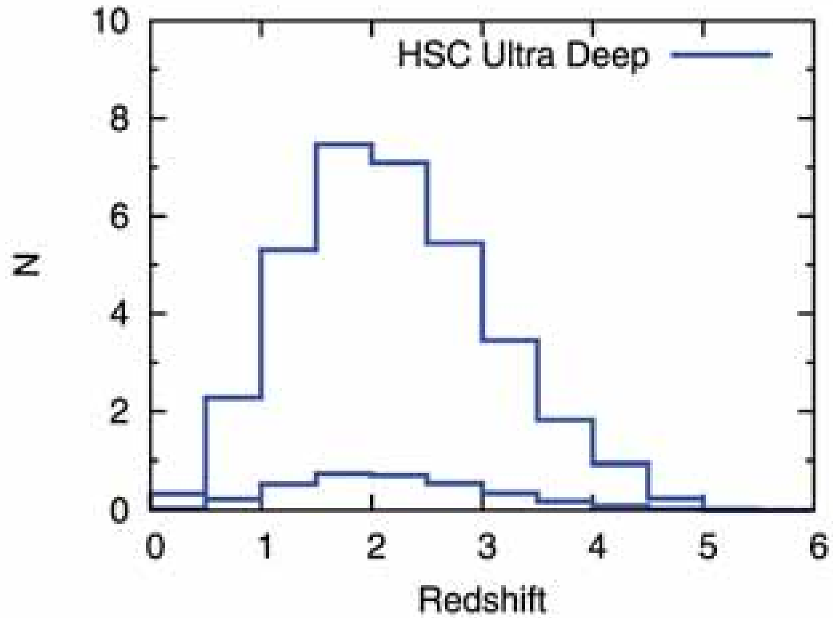
- characterize high-redshift SNe IIn and SLSNe properties via *<u>"real-time" spectra</u>*
- solidify high redshift supernova rates through the peak epoch of star formation in the Universe

Hyper Suprime-Cam

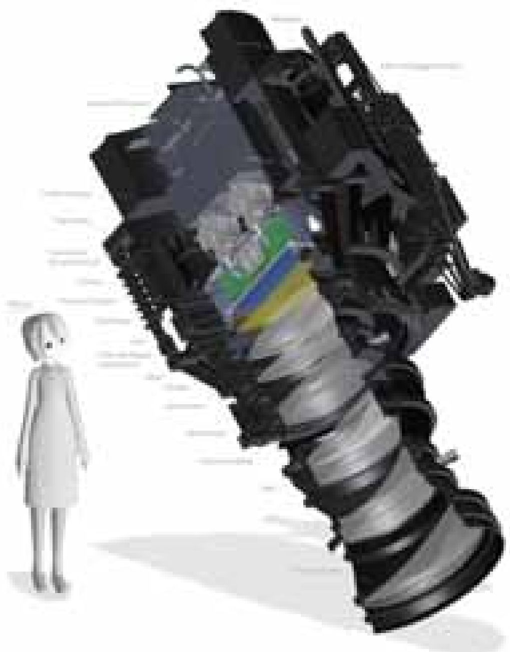
Deep and Ultra-Deep survey

Targets for the next generation of large aperture telescopes and JWST

Detections to z~6 and the epoch of reionization

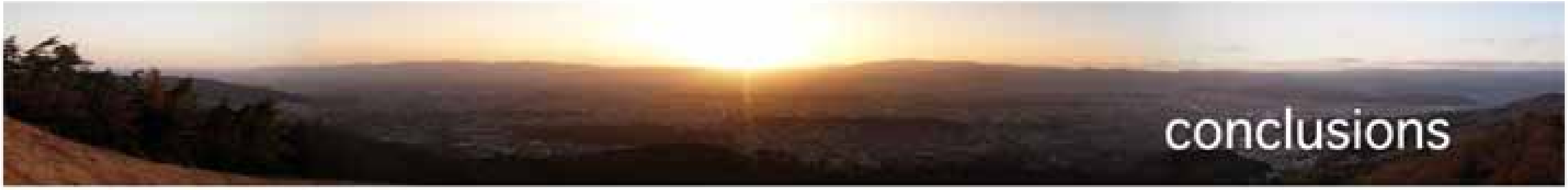


Tanaka et al. (2012)



- the ONLY survey to do so for z > 5

The cumulative density of detections produce a high density of targets to for efficient use of next generation multi-object spectrographs



- Our survey has been highly successful and has compiled 12 solid supernova confirmations at $z \sim 2 - 4$
- UV-luminous high redshift SNe are dominated by events that exhibit late-time circumstellar emission
- Three of the high redshift events are super-luminous supernovae
  One (two) may be (pulsational) pair-instability supernovae
- Our survey provides the largest and most densely-sampled SN IIn FUV data set and potentially the *only* existing FUV PISN data
- High-redshift UV-luminous supernovae may provide observational examples of the deaths of population III stars
- Surveys using *Hyper-SuprimeCam* have the capability to detect large numbers of $z \sim 2 - 4$ UV-luminous and the sensitivity to discover events out to $z \sim 6$ where the fraction of events is expected to be higher