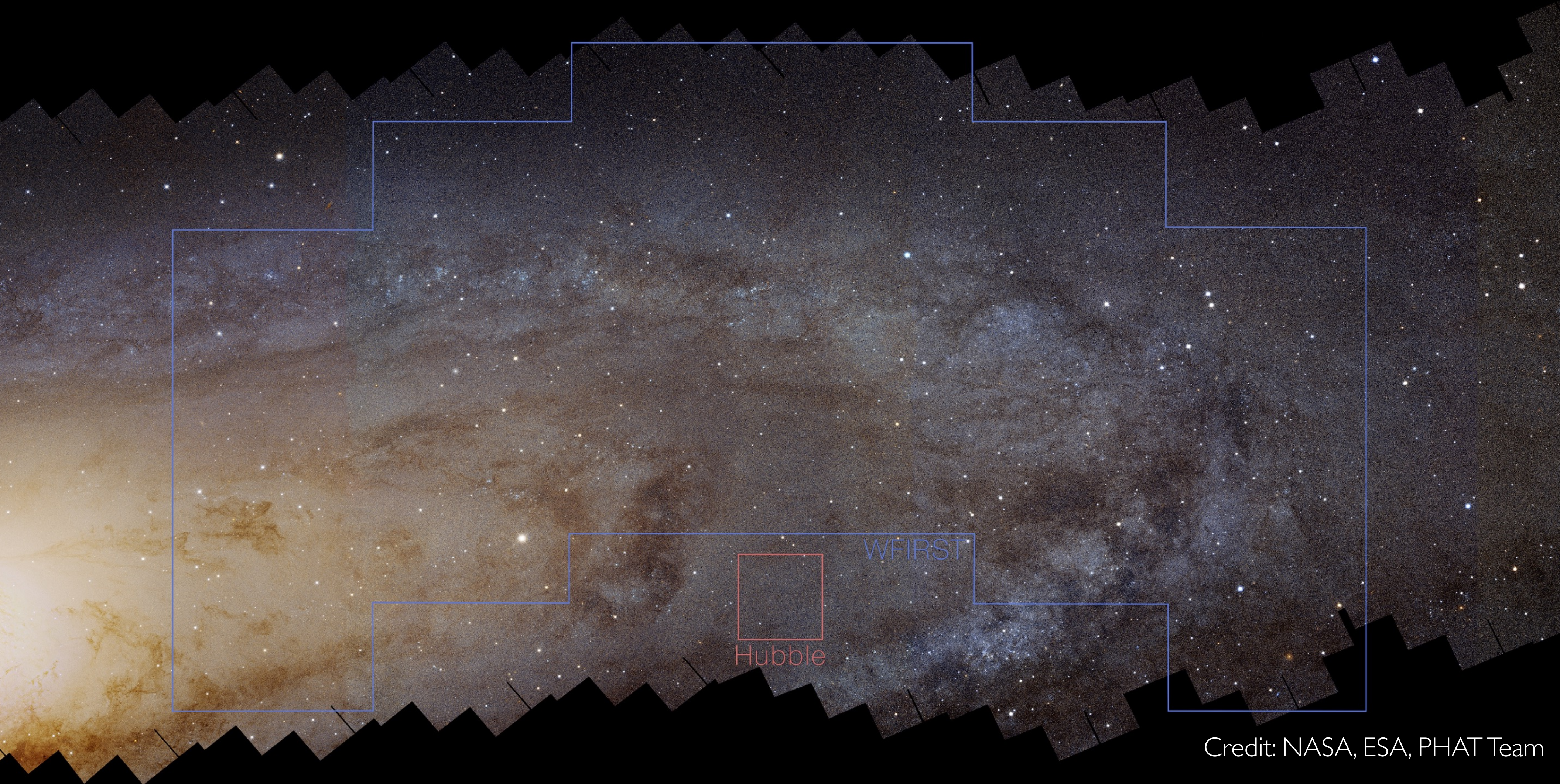


Credit: NASA, ESA, PHAT Team

EXPLORING THE DYNAMIC INFRARED SKY WITH WFIRST

Jacob Jencson
Caltech Astronomy
Advisor: Mansi Kasliwal

WFIRST Local Group Conference
Pasadena, CA
June 20, 2019

THE DYNAMIC INFRARED SKY IS PRISTINE!

THE INFRARED SKY *IS* DYNAMIC!

REALLY

SPitzer **I**nfra**R**ed **I**ntensive **T**ransients **S**urvey: A targeted search of nearby galaxies for transients in the infrared.

1690 hours over 6 years with *Spitzer*/IRAC

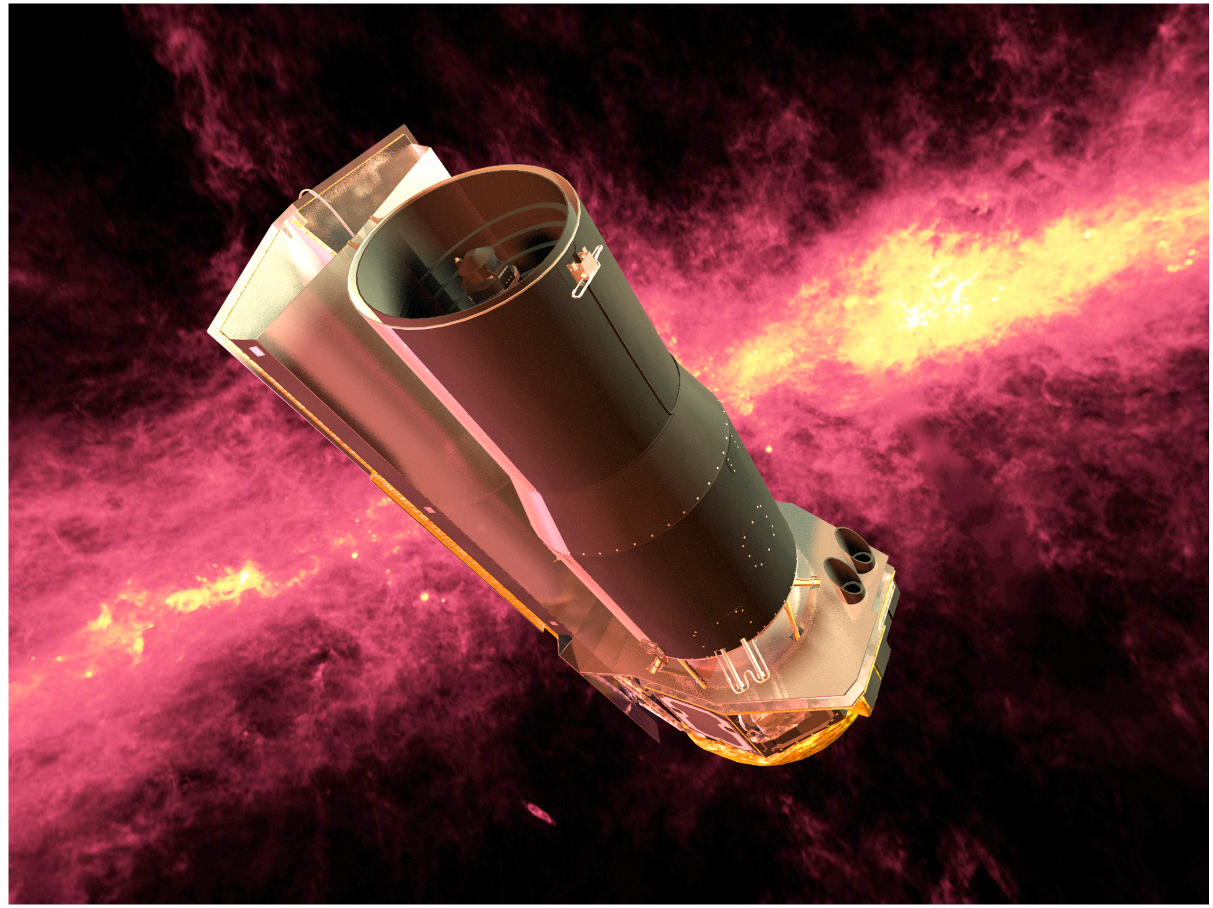
Cycles 10-12 (2014-2016)
194 galaxies x 10 epochs

Cycles 13-14 (2017-2019)
105 galaxies x 8 epochs

Sample within ~ 35 Mpc

Depth of 20 mag (Vega) at [3.6] and 19 mag at [4.5]

Cadence baselines spanning one week to several years



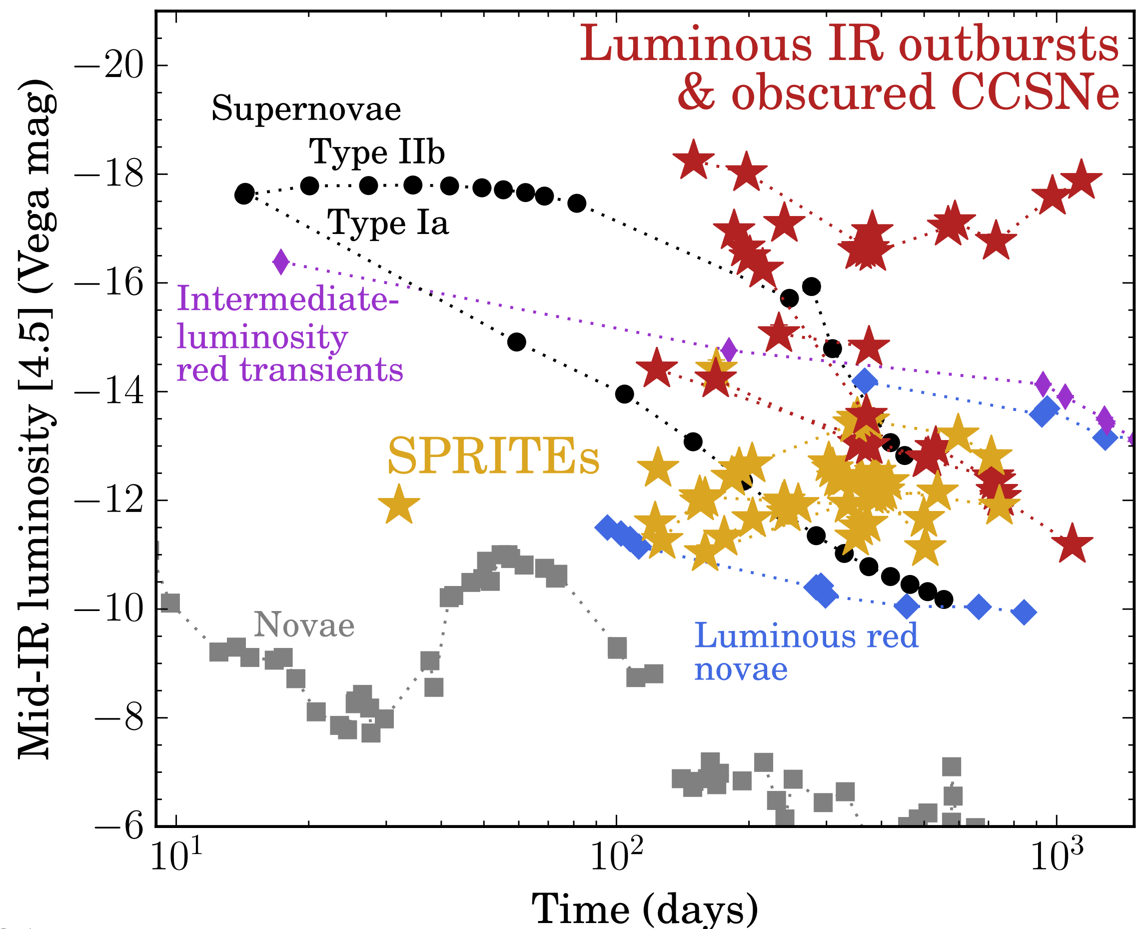
PI: M Kasliwal, Project Scientist: J Jencson
Team: S Adams, R Lau, S Tinyanont, M Hankins, V Karambelkar, L Armus, G Helou, F Masci, S Van Dyk, A Cody, M Boyer, H Bond, J Bally, O Fox, R Williams, P Whitelock, R Gehrz, N Smith, J Johansson, D Perley, E Hsiao, M Phillips, N Morell, C Contreras, M Ressler, D Cook+

SPIRITS had discovered a diverse array of IR transient sources.

Identified 98+ transients:
- 49 known supernovae
- 5 likely novae
- 35+ eSPecially Red Intermediate-Luminosity Transient Events (SPRITEs; e.g., Kasliwal+ 2017, Jencson+ in prep.)

Jencson PhDT: 9 newly discovered luminous IR transients

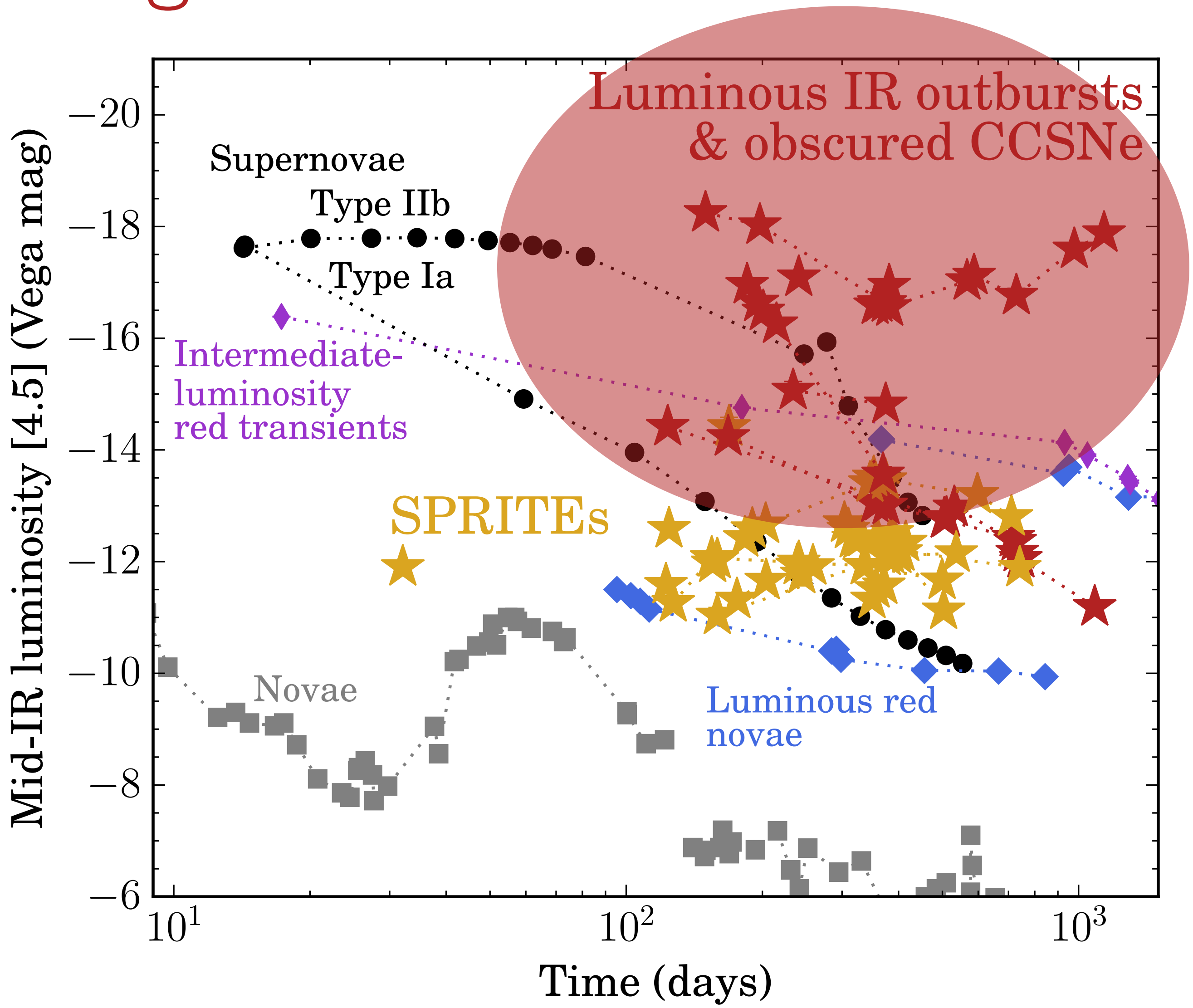
ATels: Kasliwal+ 2014: #6644
Jencson+ 2015-19: #7929, 8688, 8940, 9434, 10171, 10172, 10488, 10903, 11575, 12089, 12675



WFIRST will enable rapid coverage of large, local galaxies.

Credit: NASA/JPL-Caltech

Luminous IR transients: Obscured SNe and dust-forming massive star outbursts.



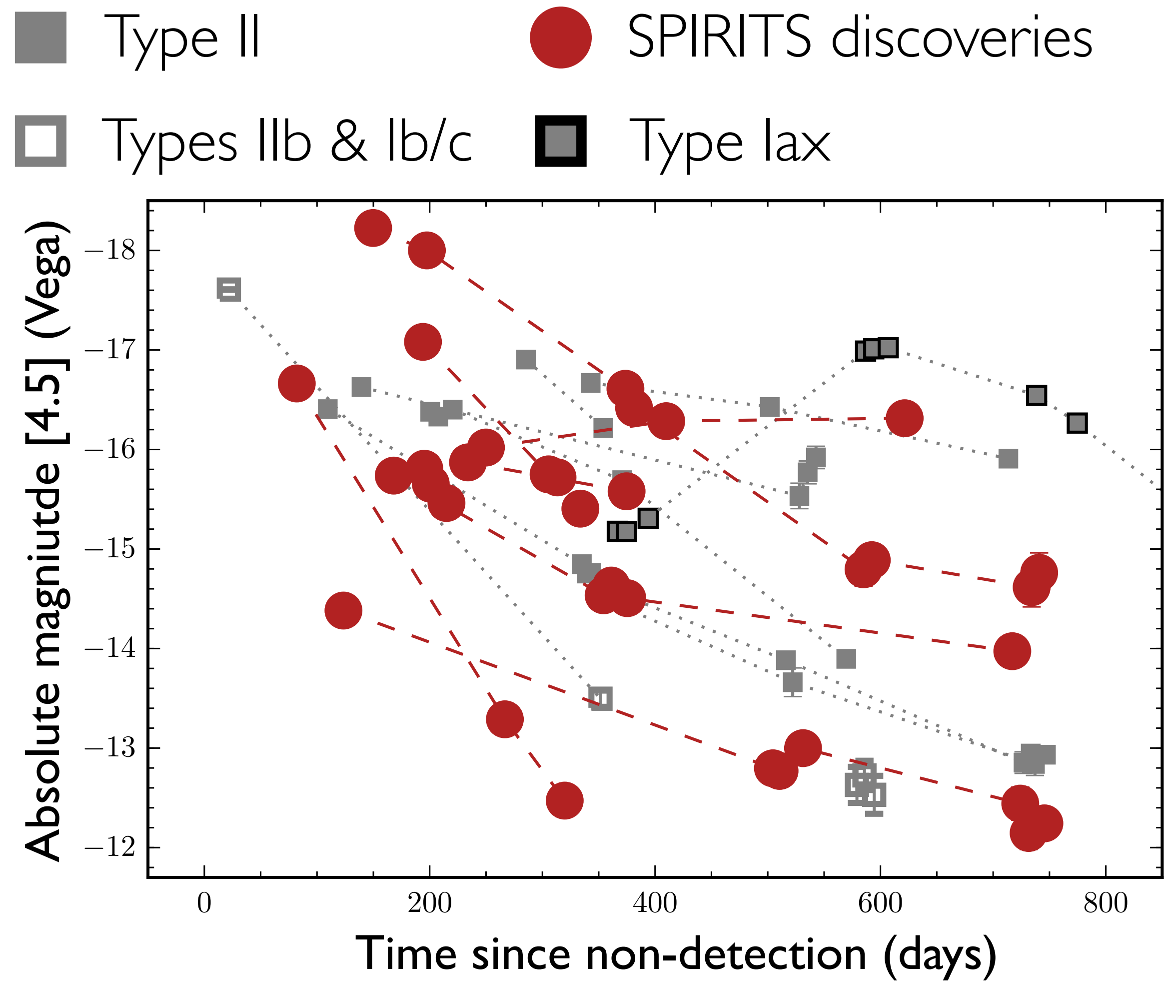
IR-discovered transients compared to optically known events in SPIRITS

Selection criteria:

I. $M_{IR} < -14$ mag

II. At least 2 *Spitzer* detections

III. Pre-explosion non-detection in SPIRITS data



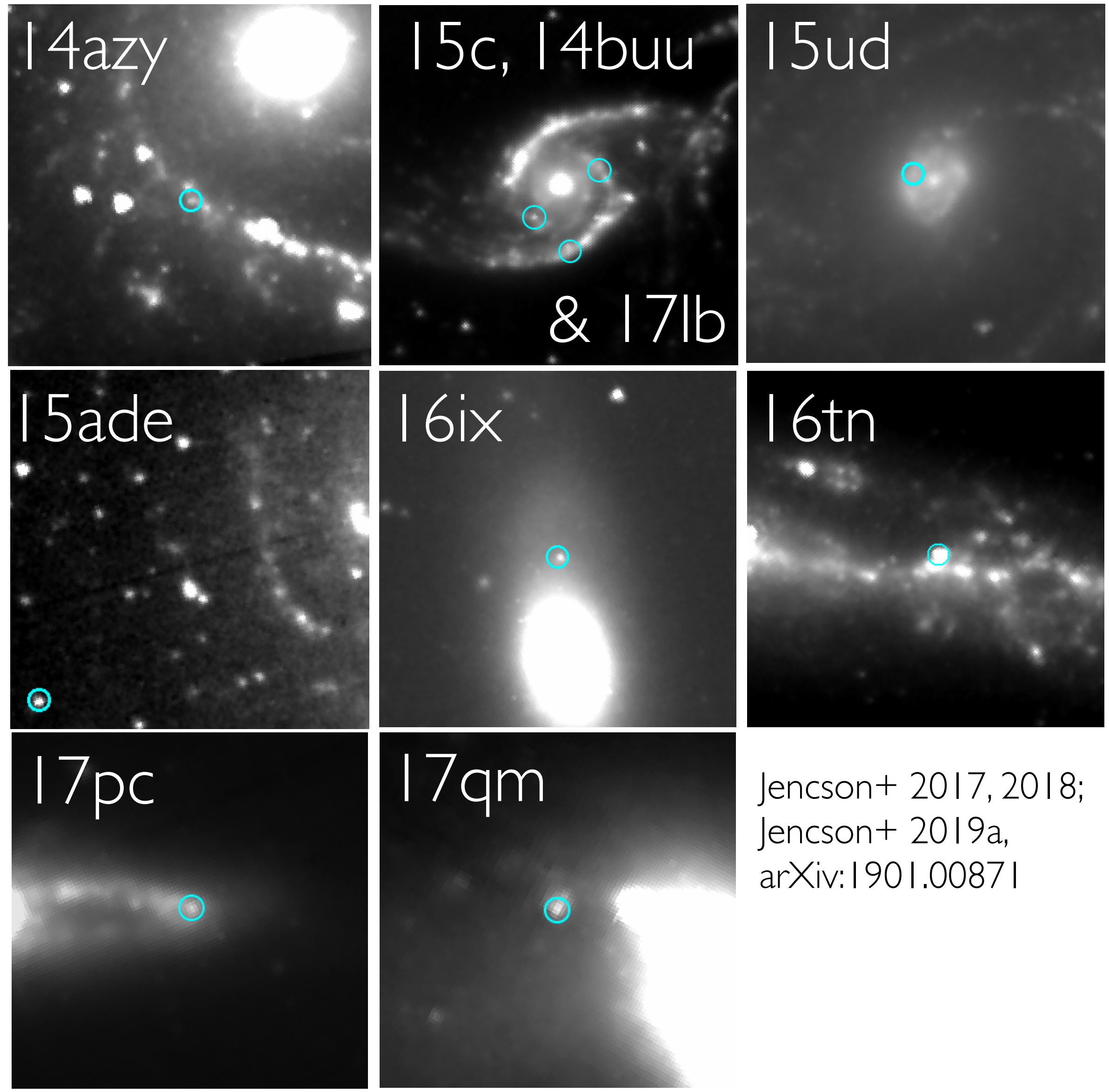
Jencson+ 2017, 2018;
Jencson+ 2019a, arXiv:1901.00871

SPIRITS events found predominantly in star-forming hosts.

All have optical/near-IR photometric coverage

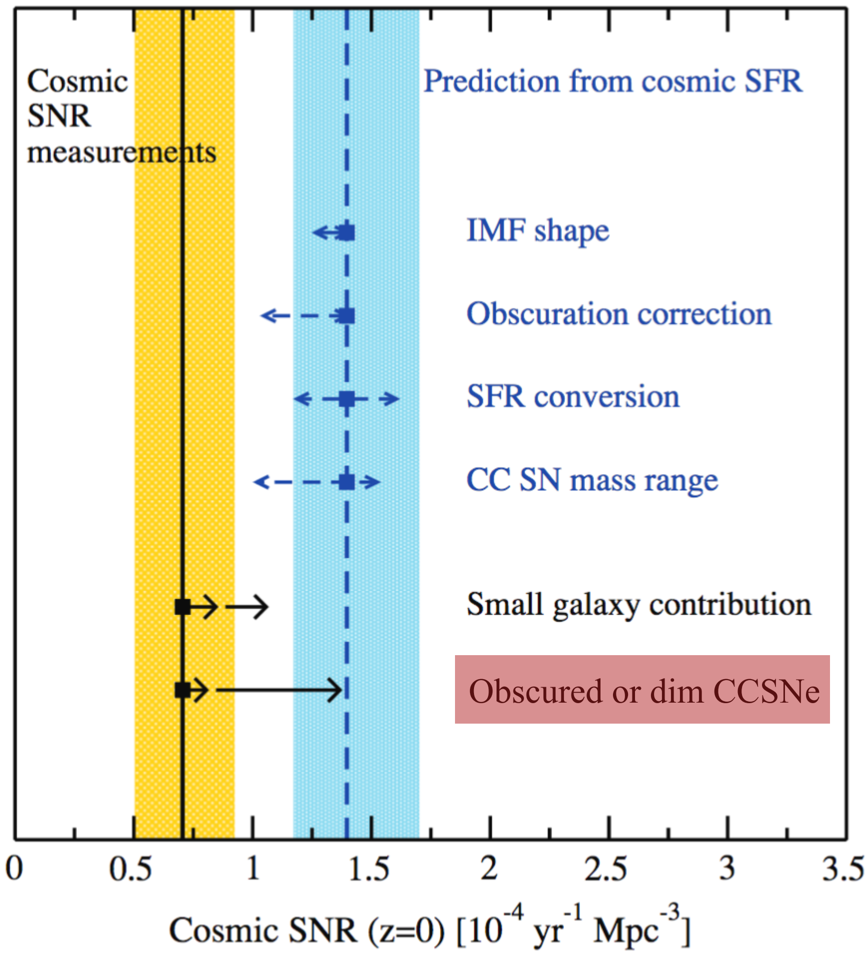
6 with optical/near-IR spectroscopy

Radio follow-up with VLA and ATCA



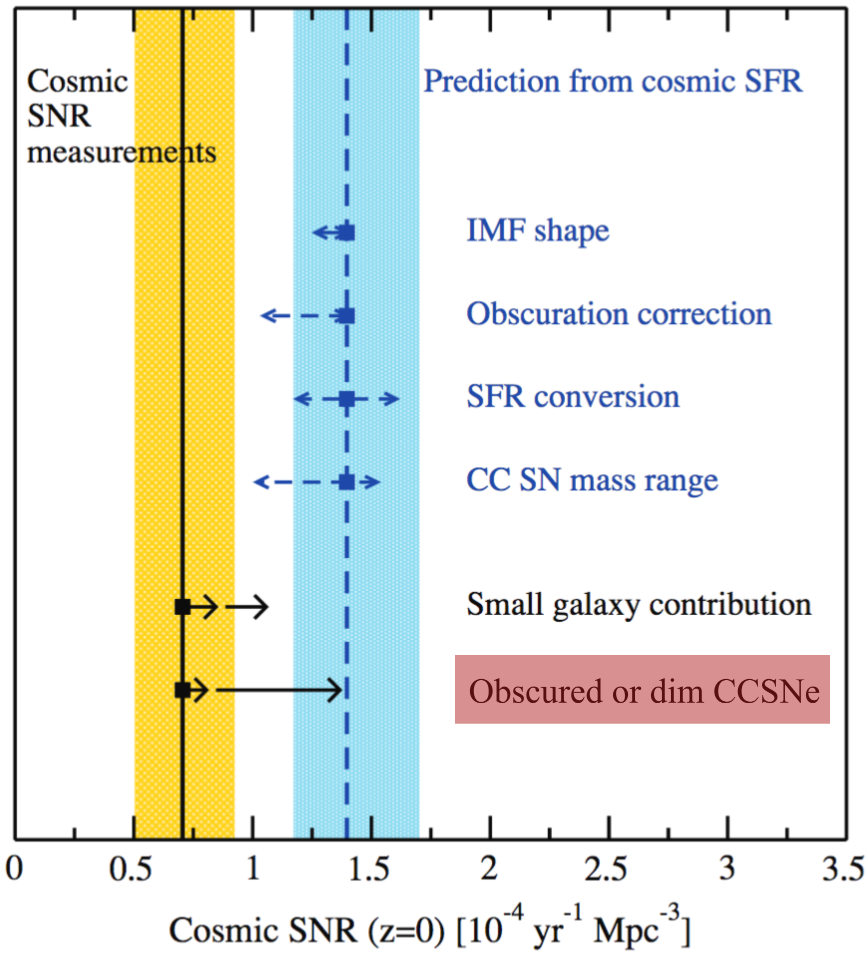
Jencson+ 2017, 2018; Jencson+ 2019a, arXiv:1901.00871

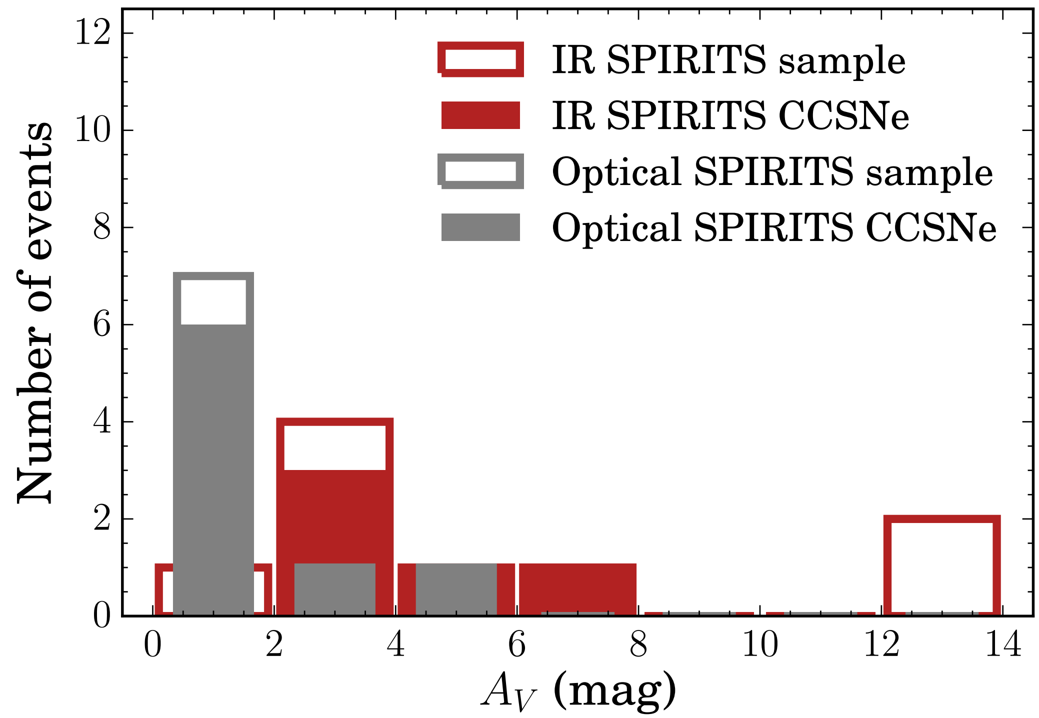
"Supernova Rate Problem": Does the core-collapse supernova rate match the formation rate of massive stars?



Horiuchi+ 2011, but see, e.g., Botticella et al. 2012; Horiuchi et al. 2013; Cappellaro+ 2015; Xiao & Eldridge 2015

Fraction of optically missed, nearby supernove in SPIRITS galaxies is $38.5^{+26.0}_{-21.9}$%





Jencson+ 2017, 2018;
Jencson+ 2019a, arXiv:1901.00871

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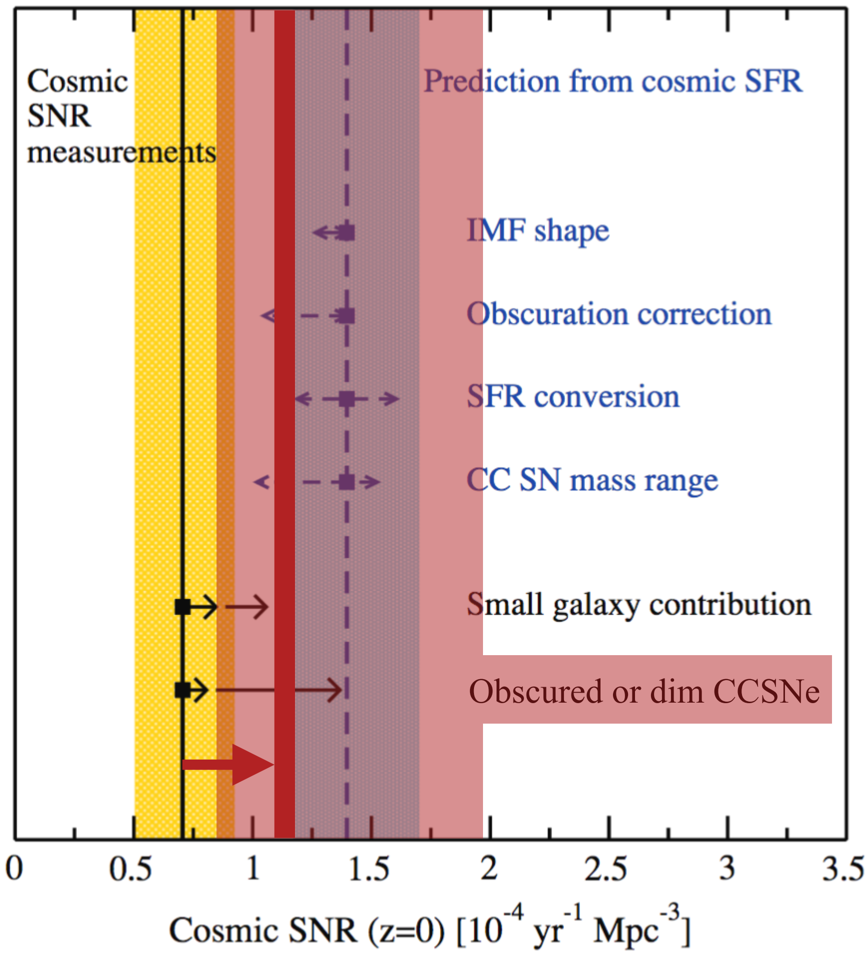
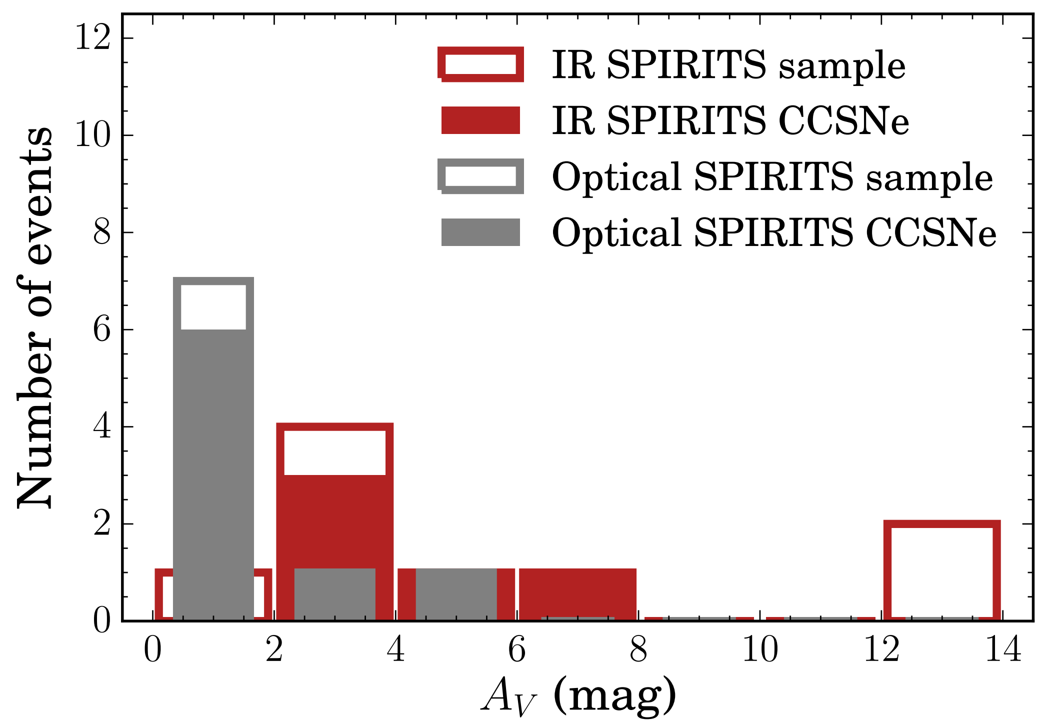
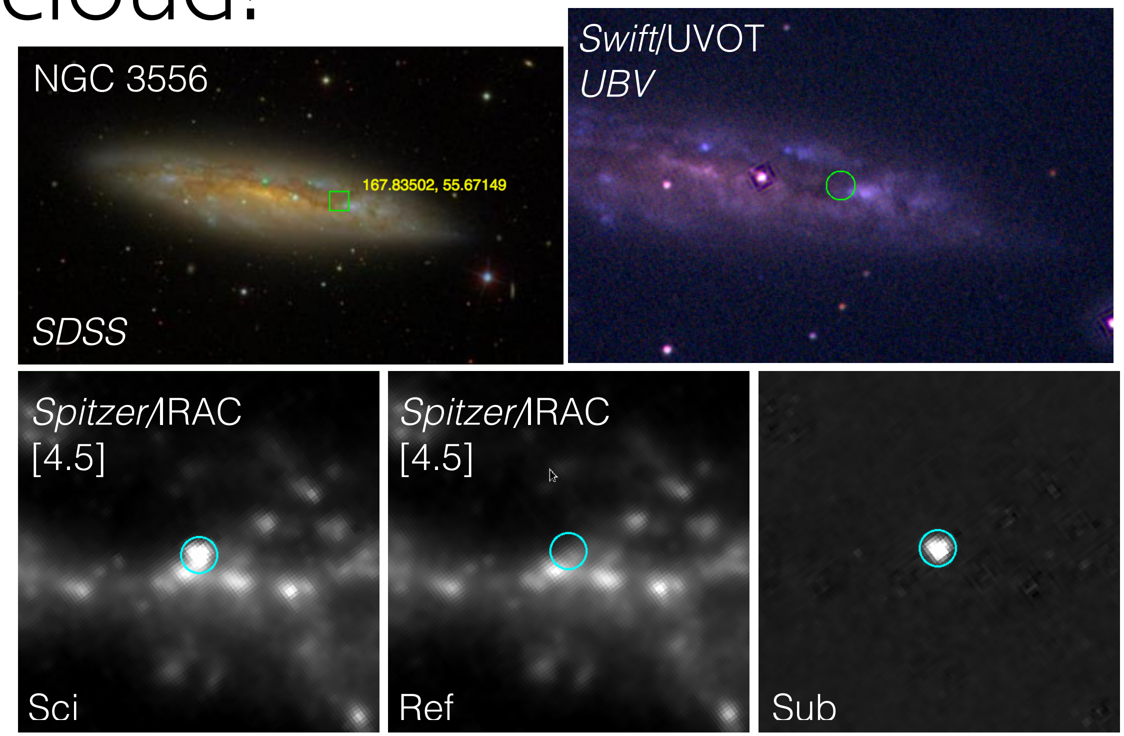
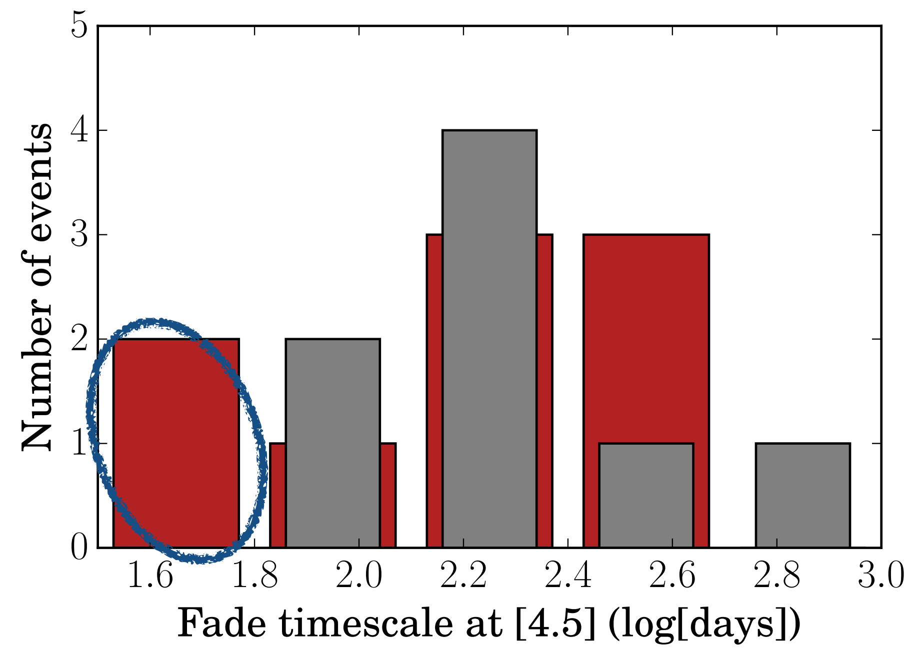




Jencson+ 2017, 2018;
Jencson+ 2019a, arXiv:1901.00871

SPIRITS 16tn: an explosion in a giant molecular cloud?



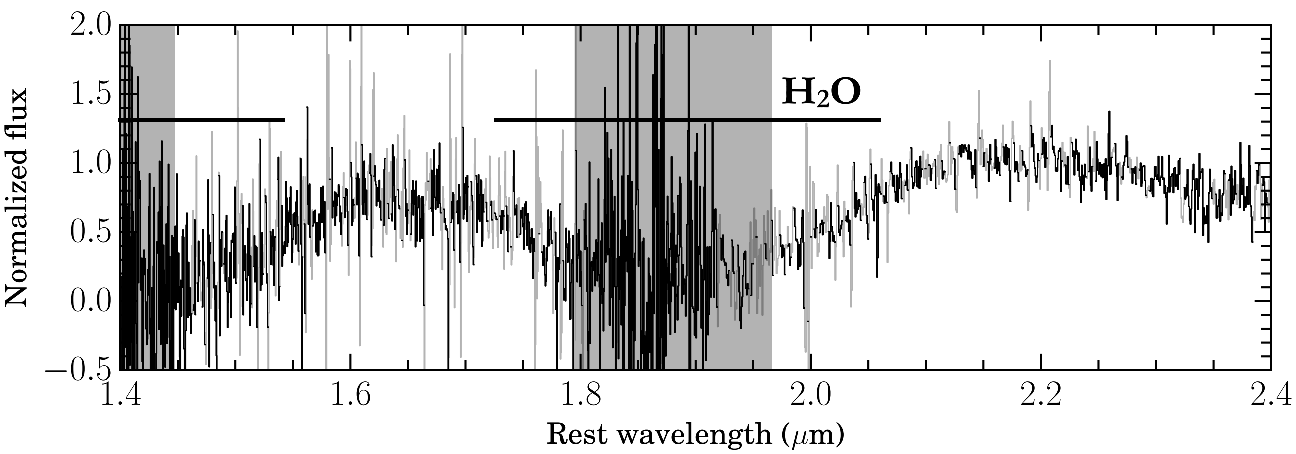


SPIRITS 16tn: $A_V = 8$ mag

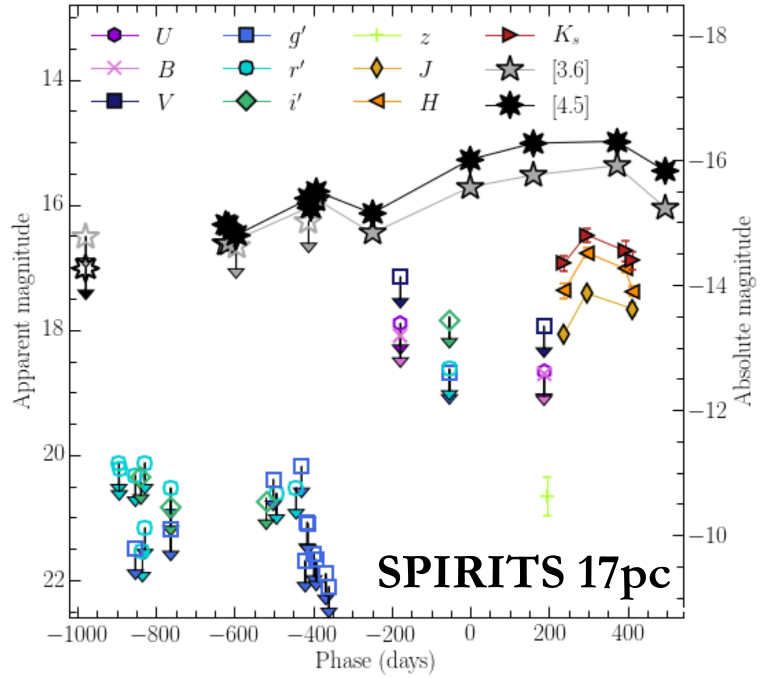
SPIRITS 16ix: $A_V > 5.5$ mag

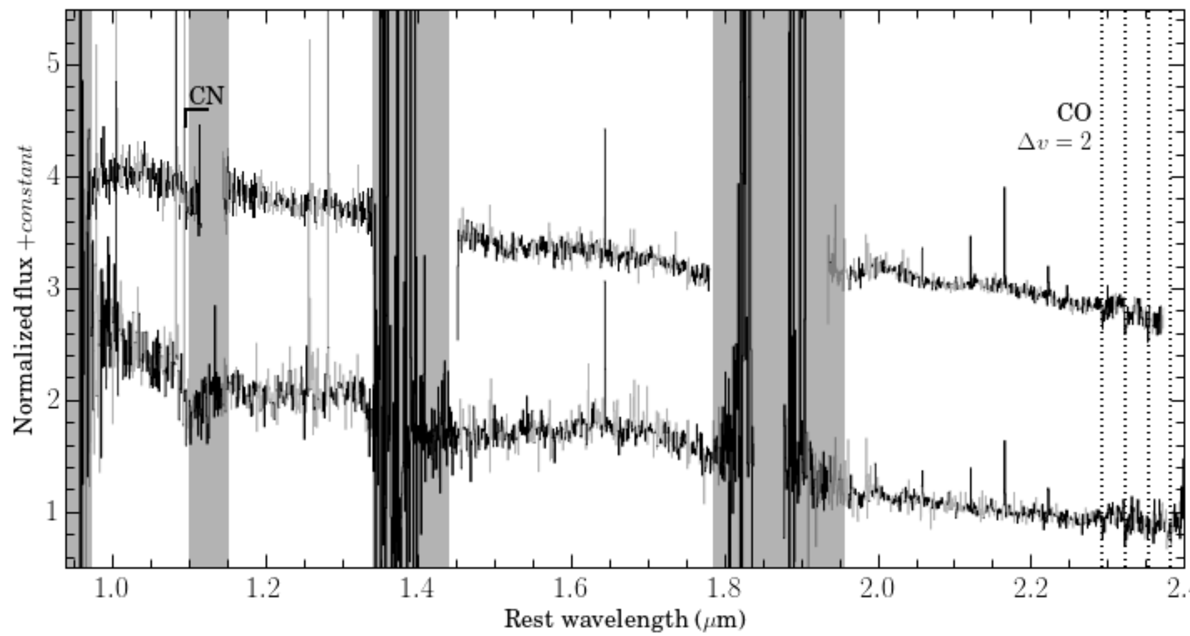
Jencson+ 2018;

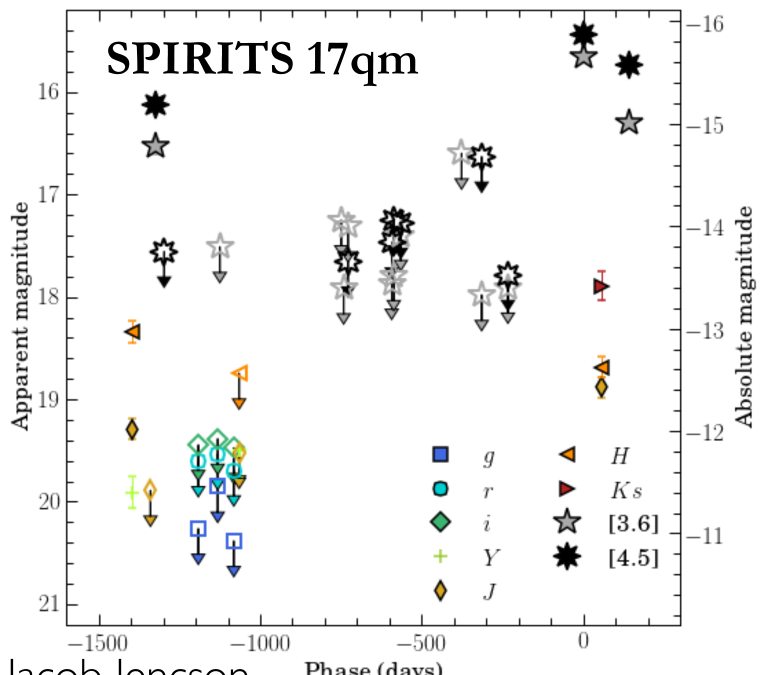
Jencson+ 2019a, arXiv:1901.00871

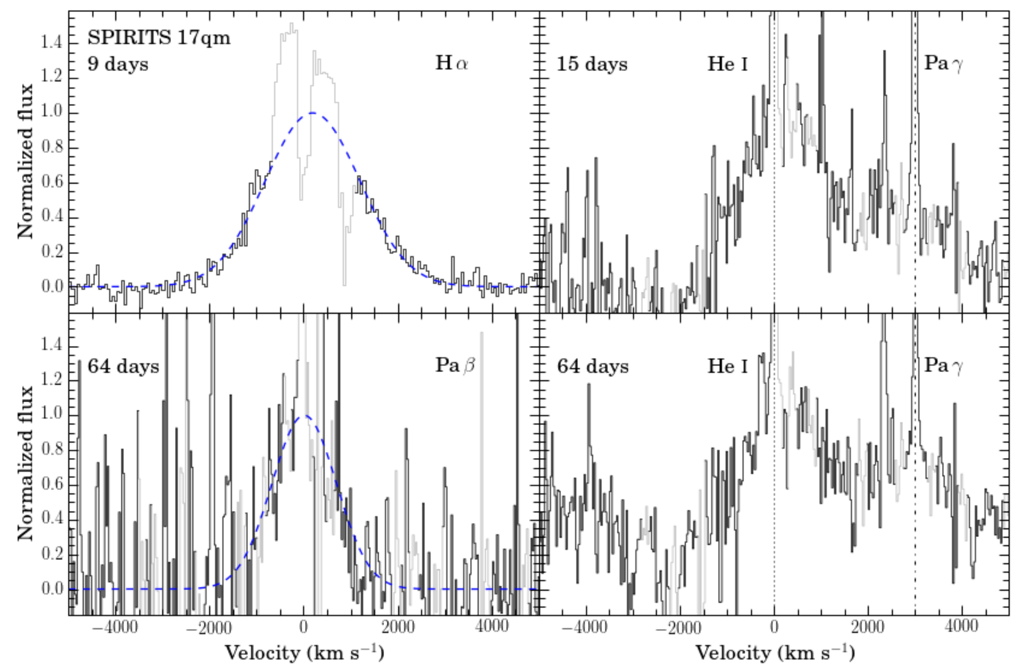


Two sources undergoing multiple IR outbursts.





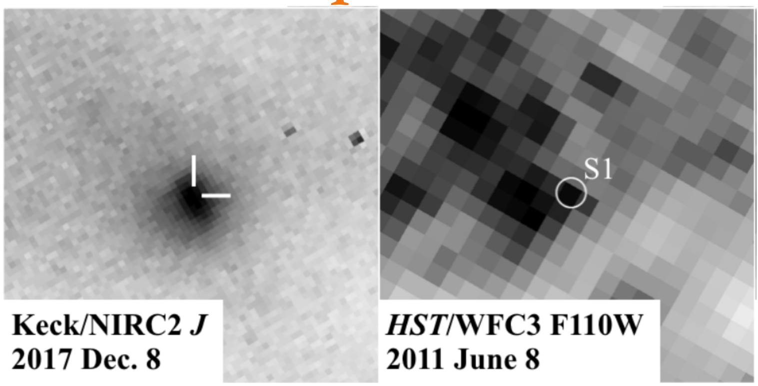




Jencson+ 2019a, arXiv:1901.00871

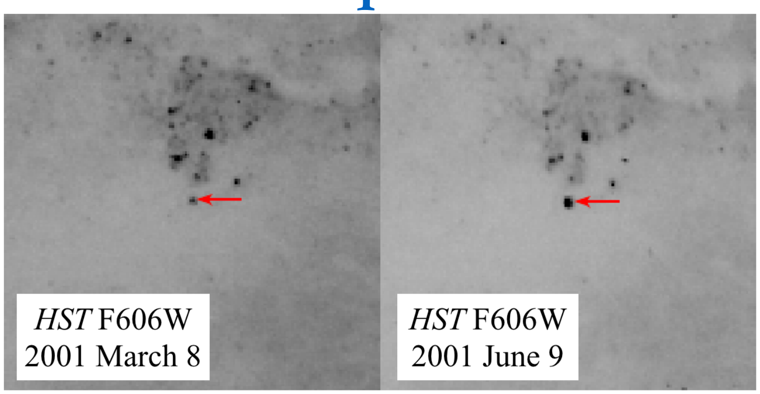
WFIRST will naturally enable detailed progenitor studies of IR transients.

SPIRITS 17pc



$T \sim 1900$ K
$L \sim 2 \times 10^5 L_\odot$

SPIRITS 17qm



M_V = -9.3 mag
$L \sim 10^6 L_\odot$
Δm = 1.7 mag

Jencson+ 2019a, arXiv:1901.00871

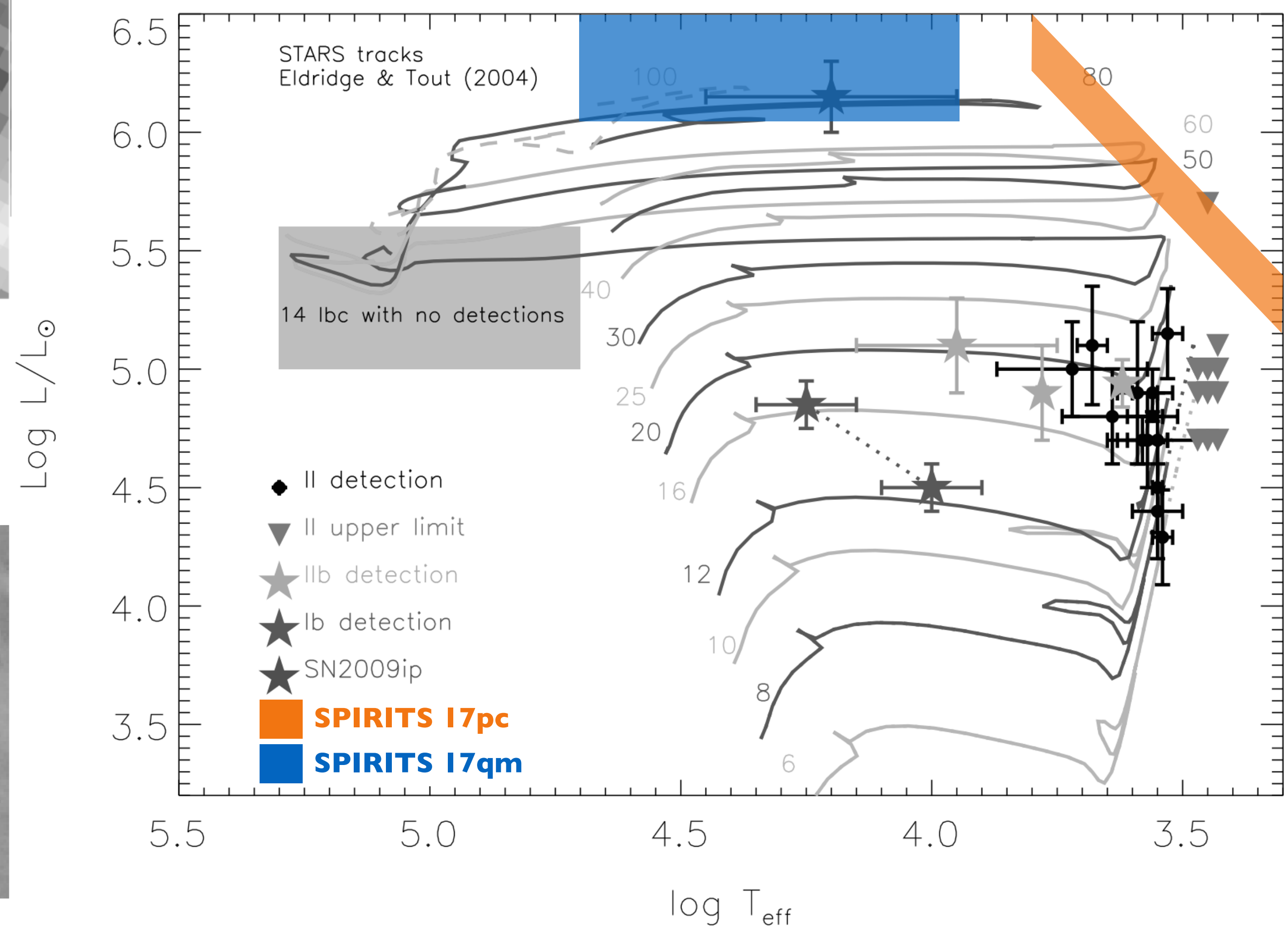
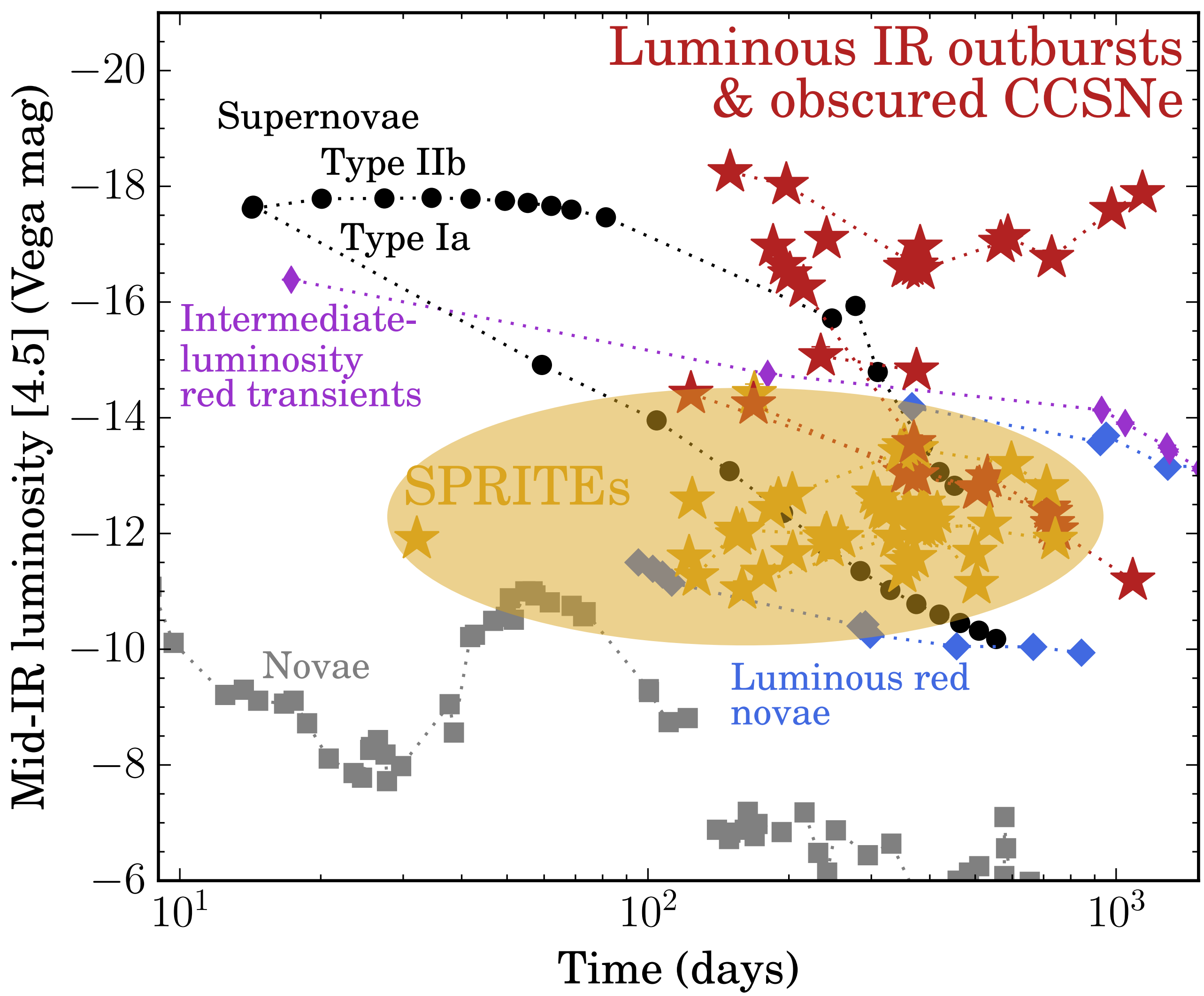
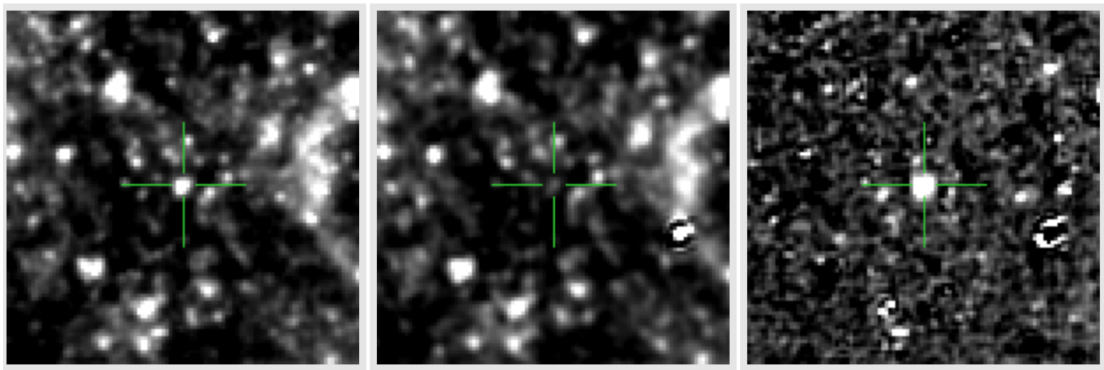


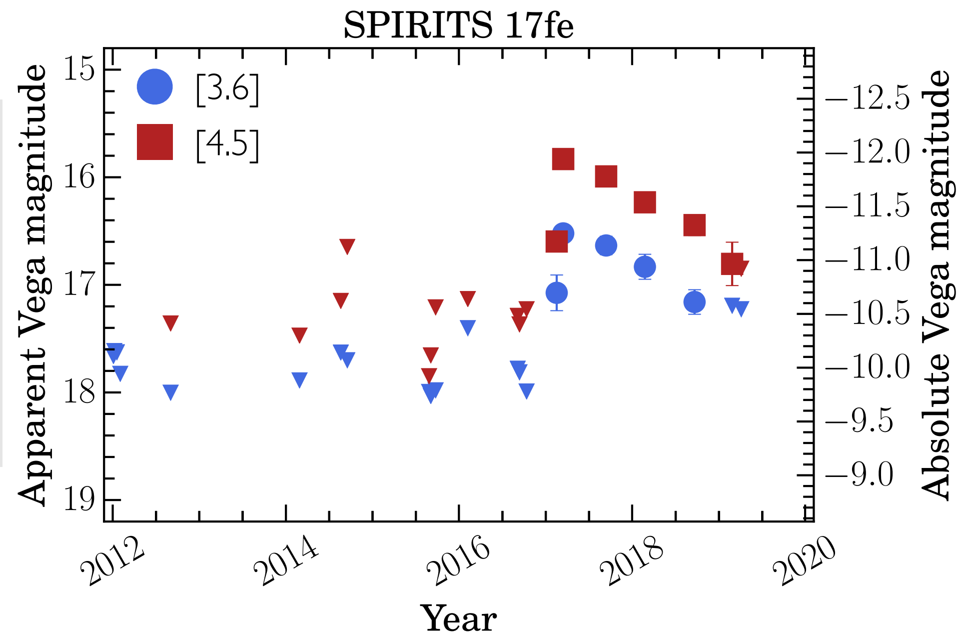
Fig. adapted from Smartt 2015

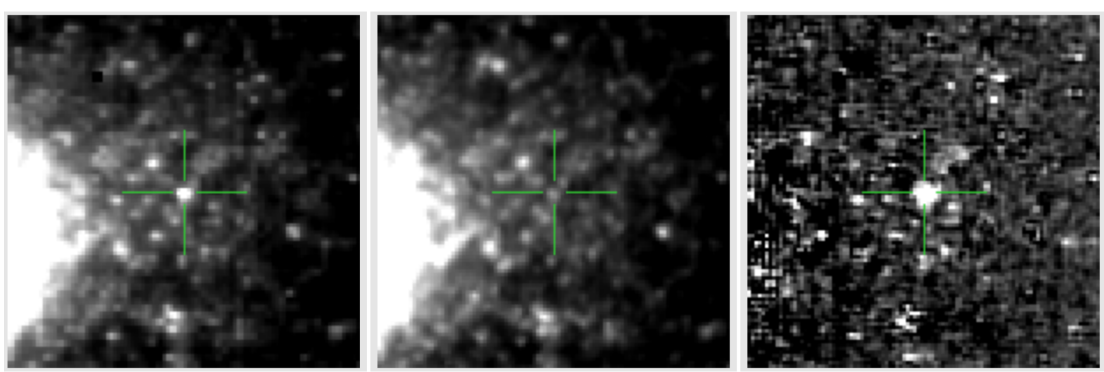
eSPecially Red Intermediate-Luminosity Transient Events

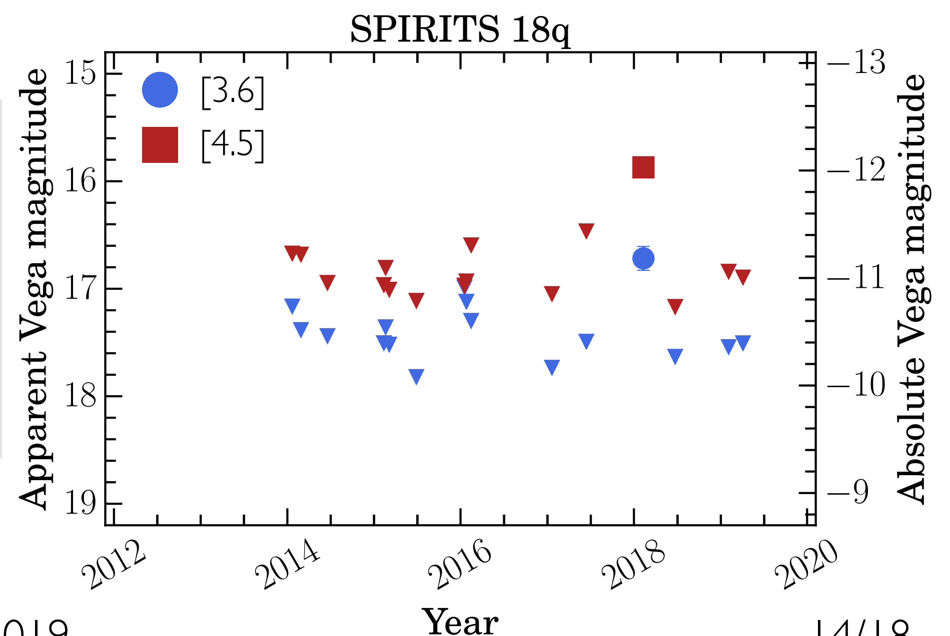


SPRITEs likely represent a range of diverse origins.





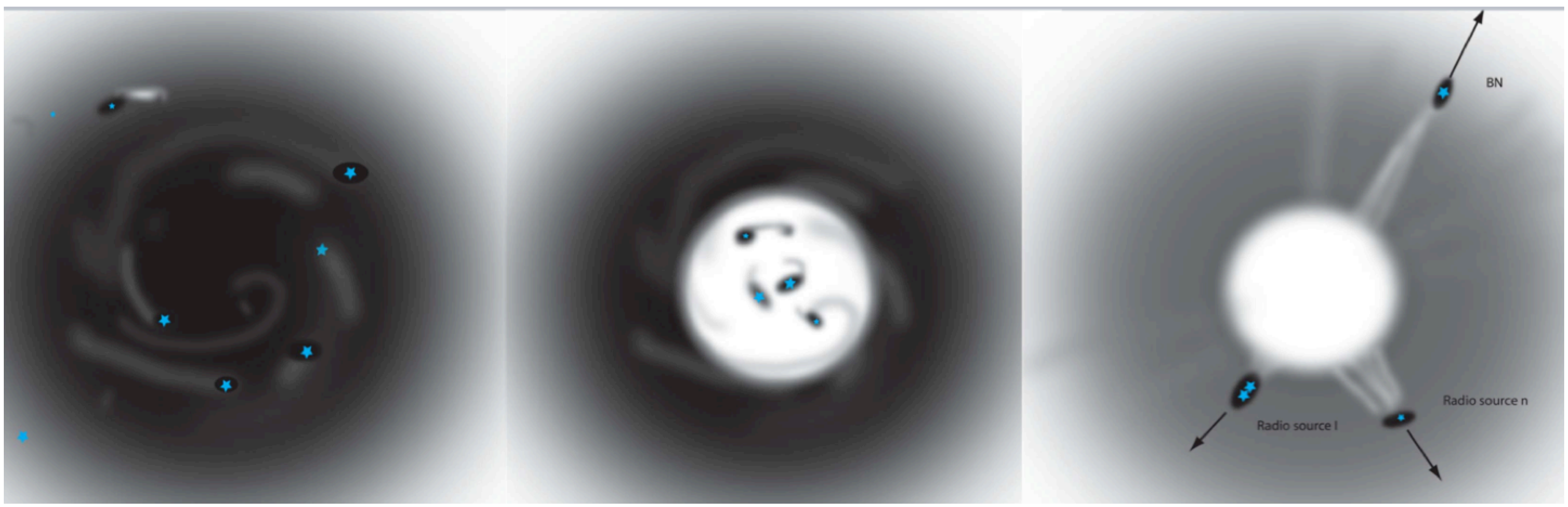




Kasliwal+ 2017, Jencson+ in prep.

Possible SPRITE origins:

Dynamical interactions in star-forming regions

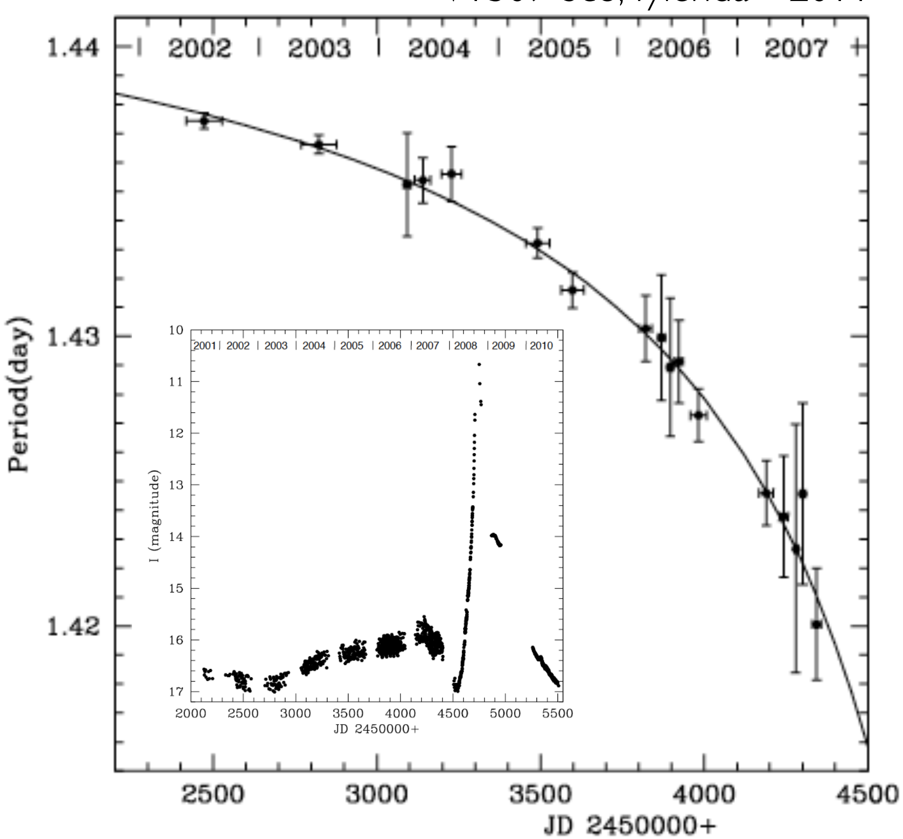


Bally & Zinnecker 2005, Kasliwal+ 2017, Jencson+ in prep.

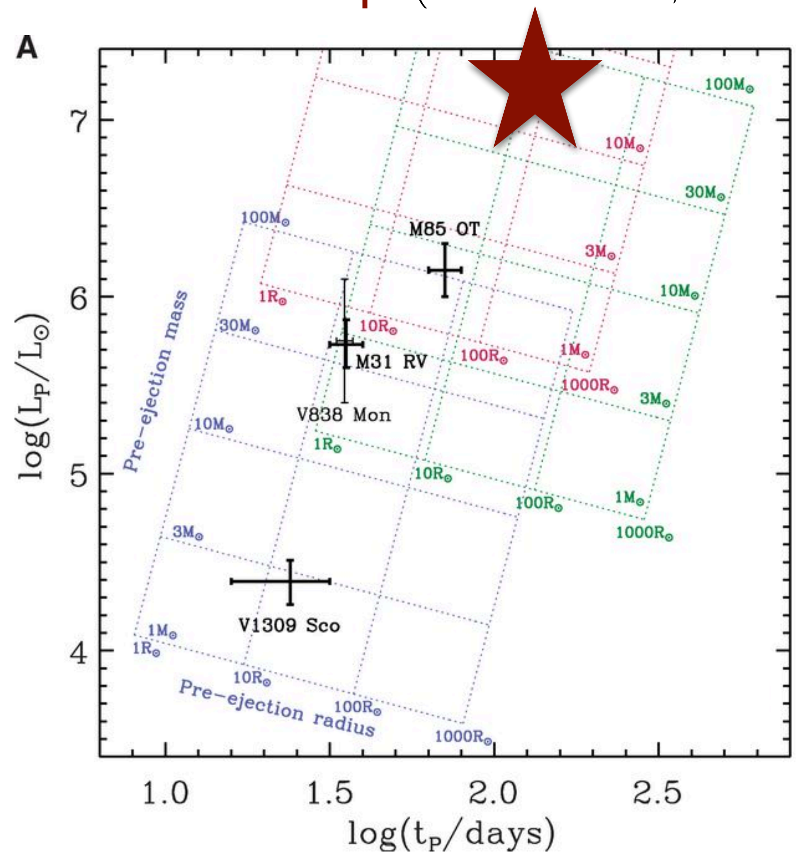
Possible SPRITE origins:

Common-envelope ejections and stellar mergers

V1309 Sco, Tylenda+ 2011



SPIRITS 14pz (NGC 4490 OT, Smith+ 2016)



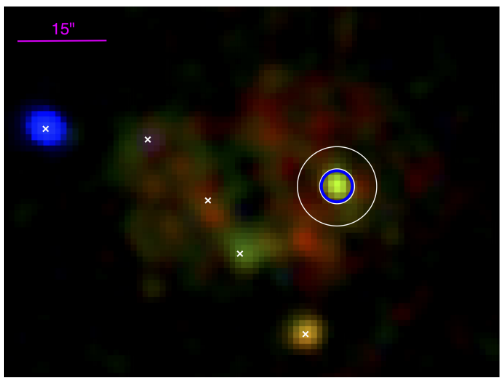
Ivanova et al. 2013

See also, e.g., Blagorodnova+ 2017, Metzger & Pejcha 2017

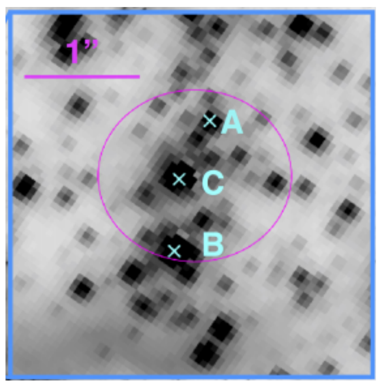
Possible SPRITE origins:

Colliding-wind binaries:

First candidate in M33 (Garofali+ 2019):

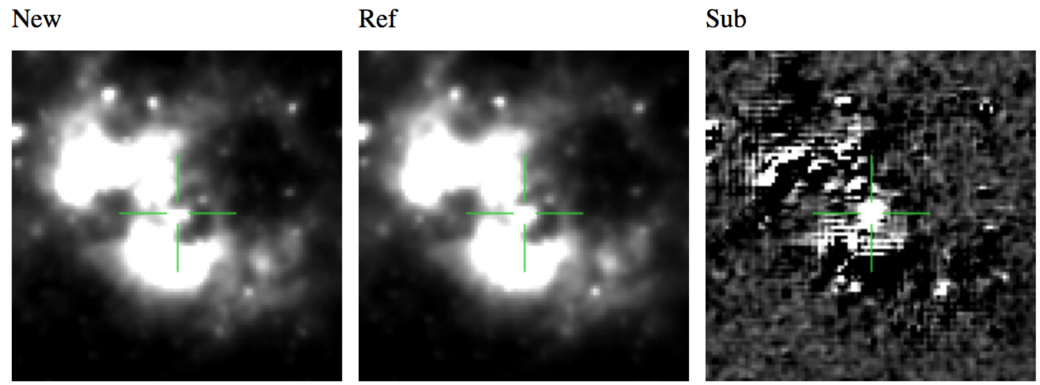


X-ray (Chandra)



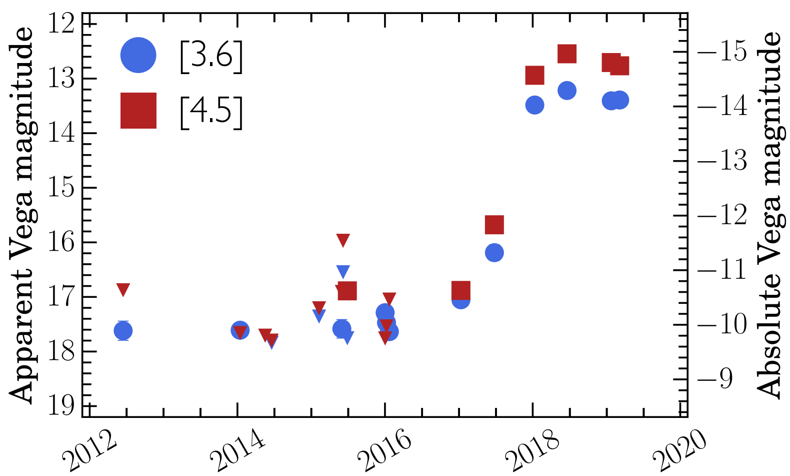
Optical (HST)

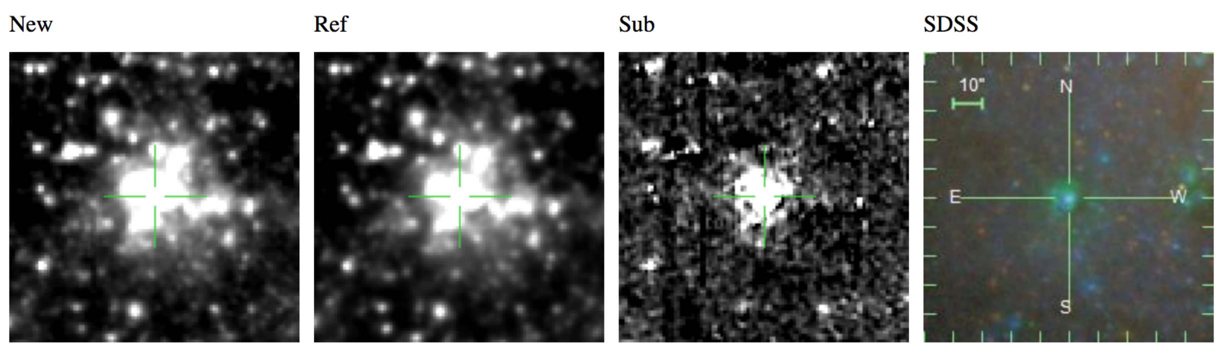
SPIRITS 16ln:



Infrared (Spitzer)

SPIRITS 19q:





M Hankins, R Lau, et al., in prep.

Conclusions

The dynamic IR sky is wide open for exploration!

WFIRST is unquily equiped to probe emergaing classes of diverse IR transient phenomena.

Highlights: Wide field, high angular resolution, superior depth

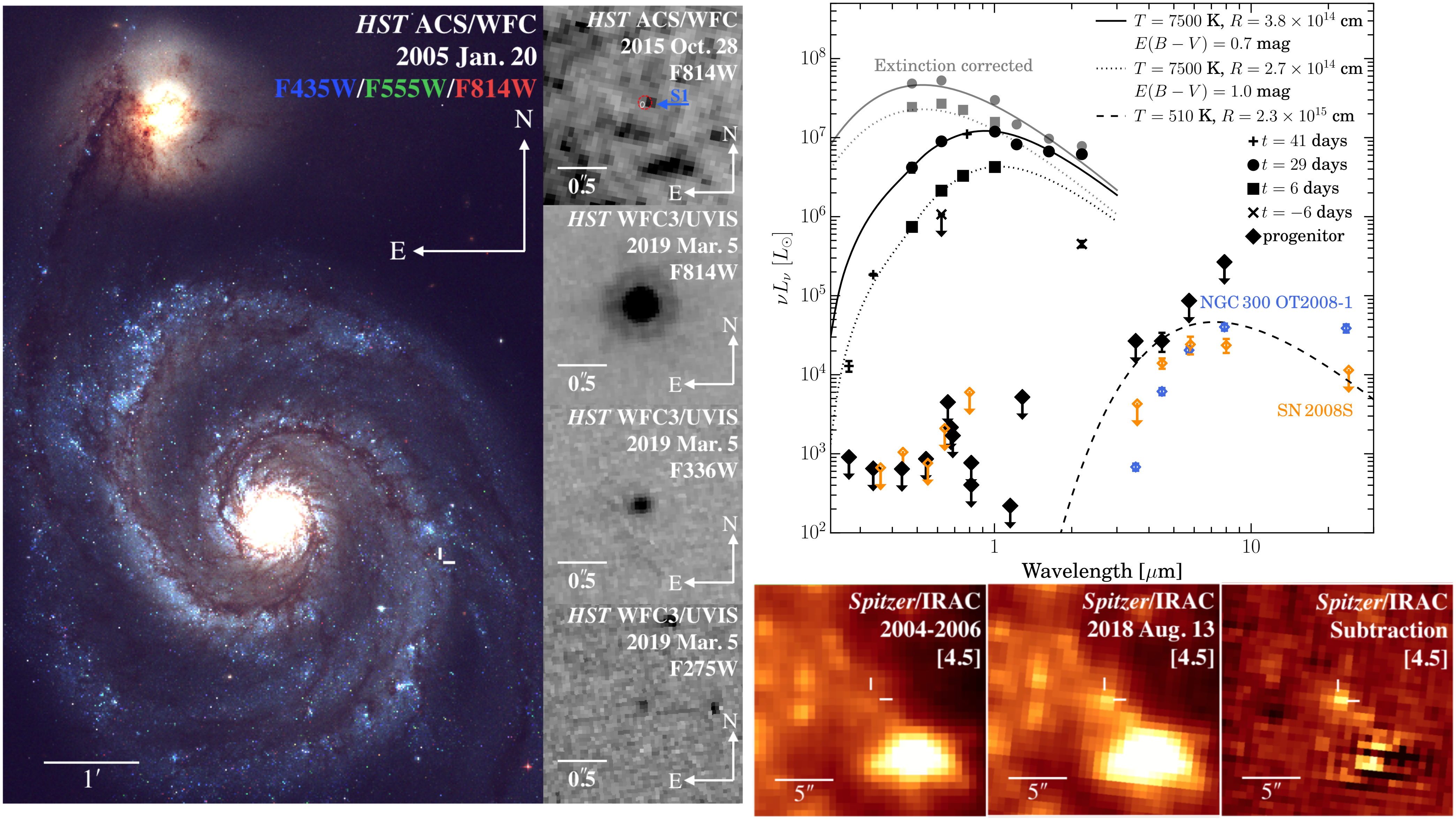
Optimizing WFIRST for transient science:

-Cadenced observations of local group, nearby galaxies, and MW star-forming reigons

-Filters as red as possible

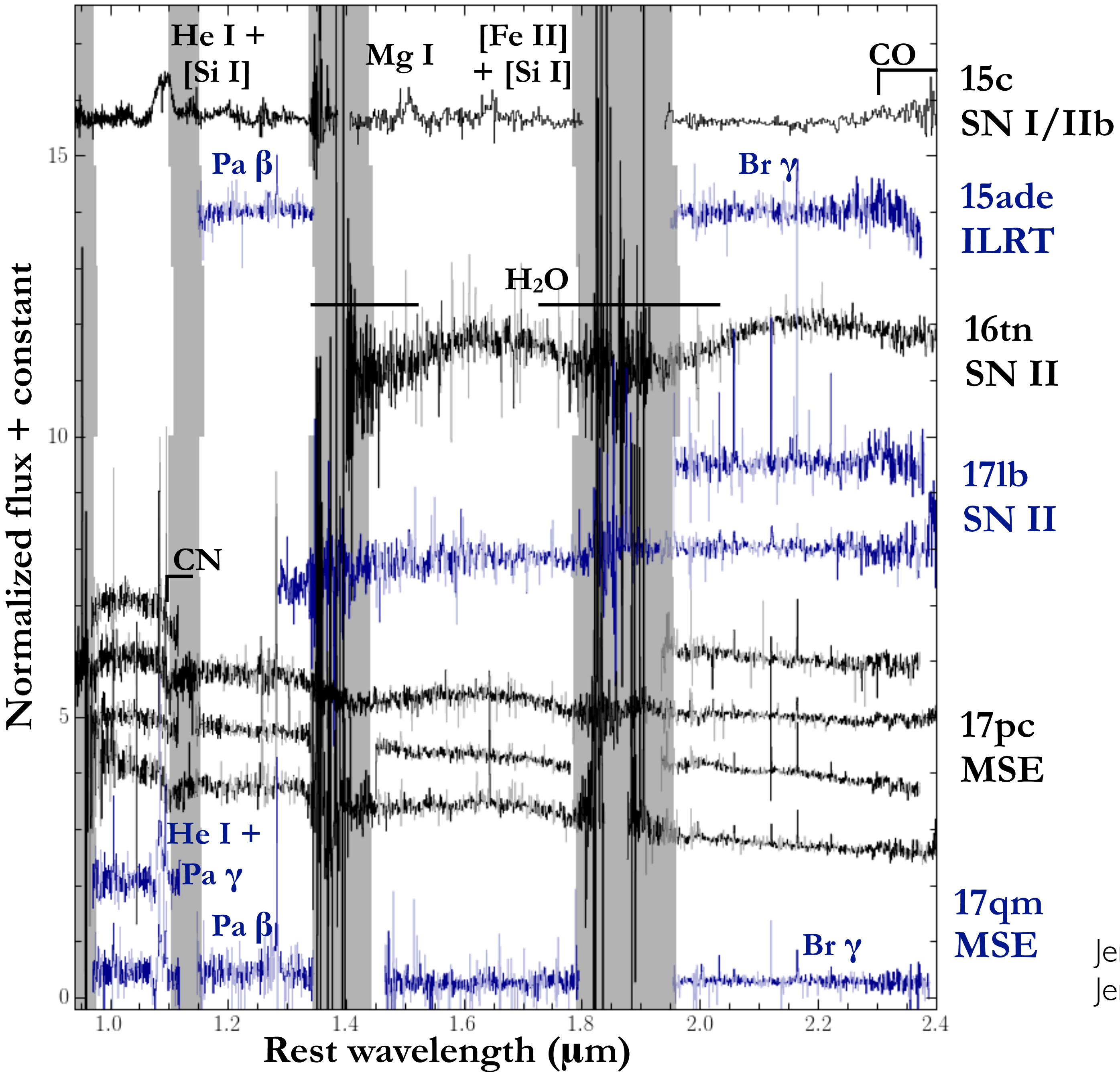
Auxiliary Slides

A new intermediate-luminosity red transient in M51 from a massive, dust-obscured progenitor



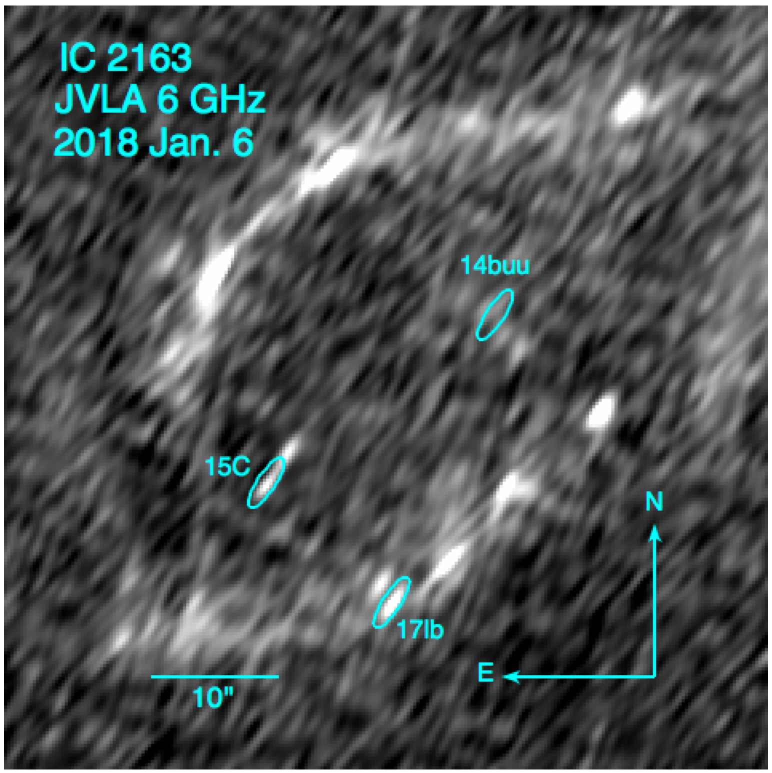
Jencson+ 2019b, arXiv:1904.07857

The sample shows a wide range of spectral properties.



Jencson+ 2017, 2018;
Jencson+ 2019a, arXiv:1901.00871

Radio observations provide confirmation, type information, and probe pre-SN mass loss.



Jencson+ 2018;
Jencson+ 2019a, arXiv:1901.00871

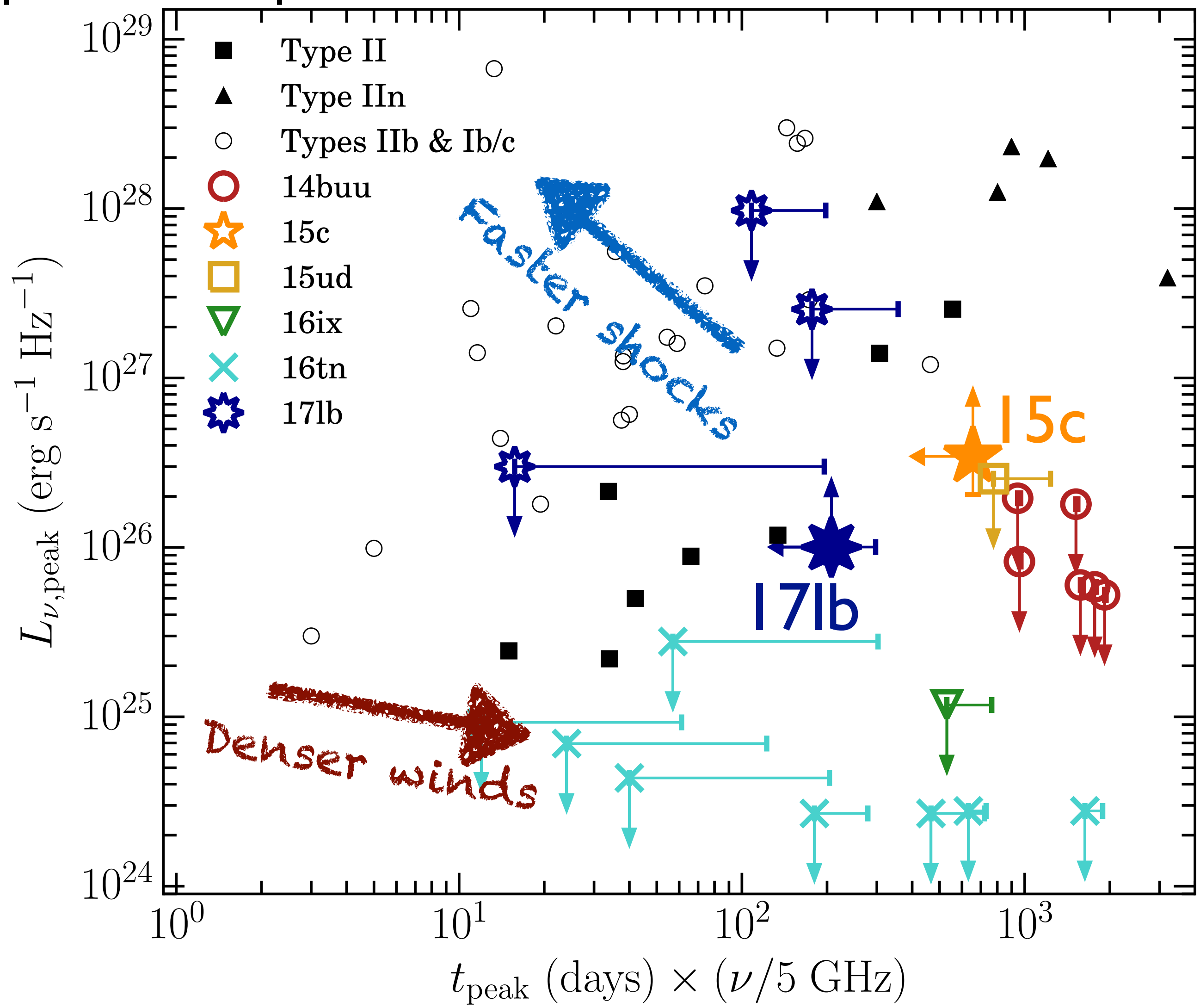
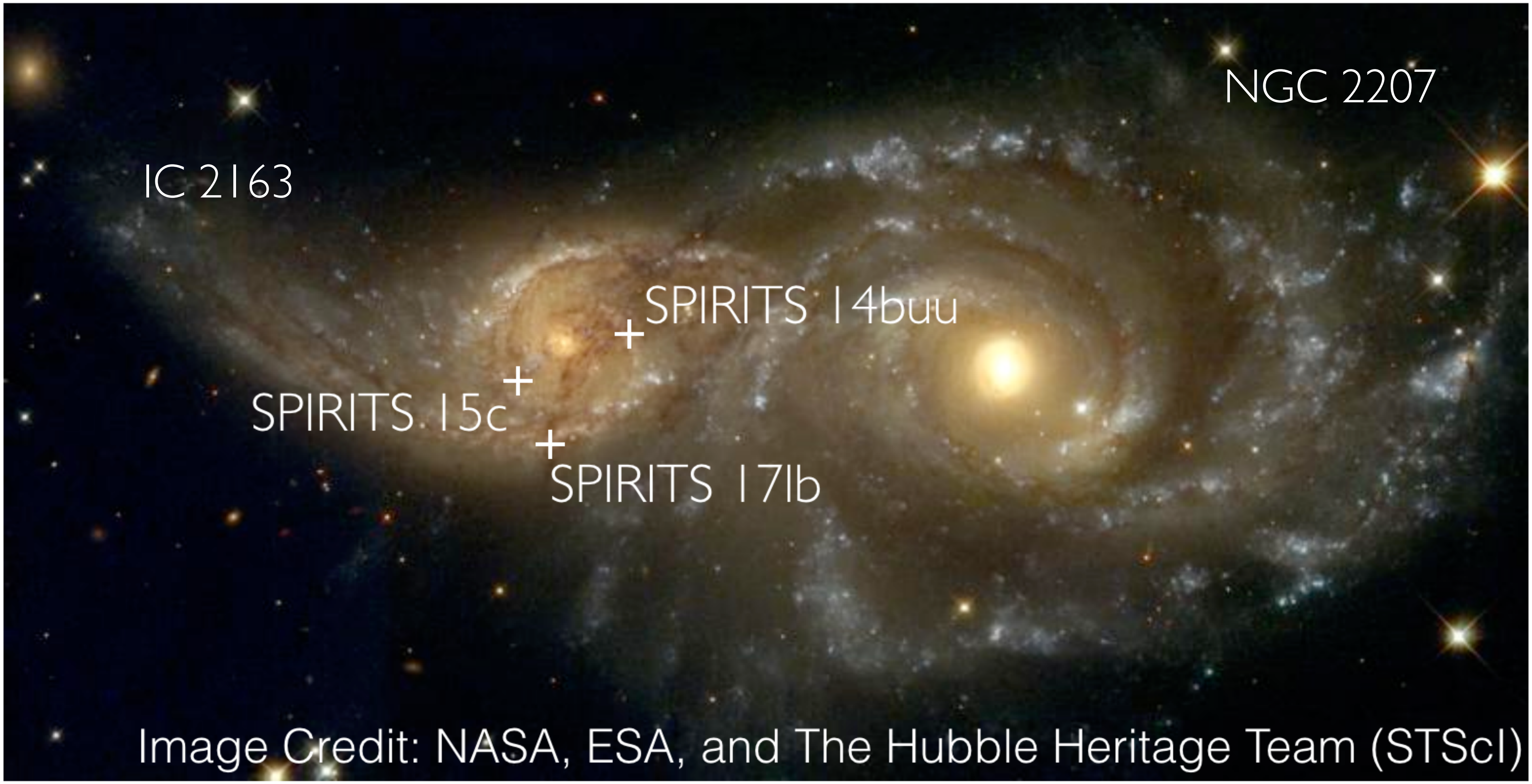


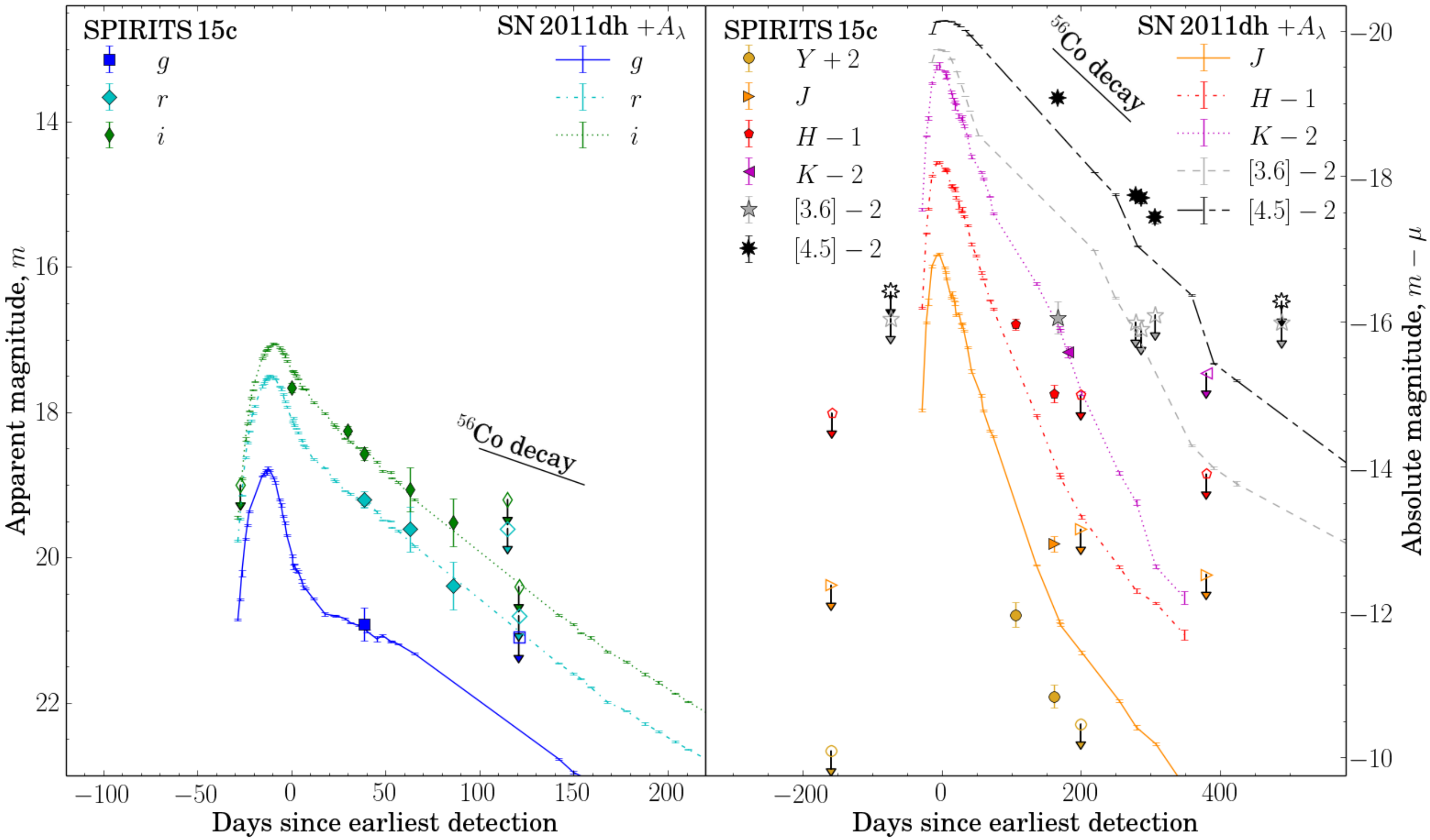
Fig. adapted from, e.g.,
Chevalier et al. 2006,
Romero-Cañizales et al. 2014

SPIRITS 14buu, 15c, & 17lb: 3 SNe in 4 years in IC 2163.



A simple reddening law can explain the observed light curves.

A_V =2.2 mag, $E(B\text{-}V)$ = 0.72 mag, R_V =3.1 (Fitzpatrick 99)



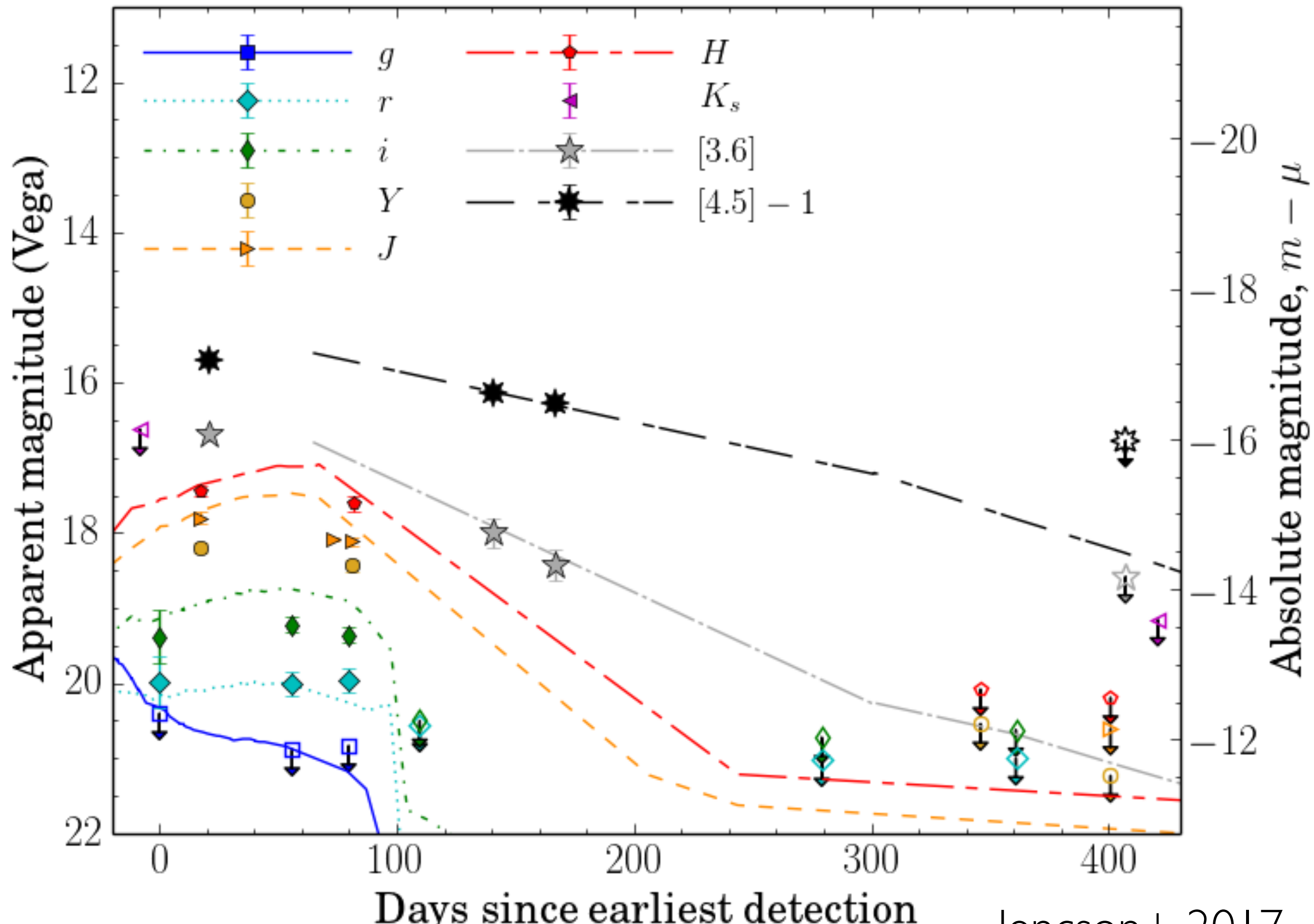
SN 2011dh data, Ergon et al. 2014,2015

Jencson+ 2017

Light curves of SPIRITS 14buu consistent with a reddened SN IIP.

Appears similar to the type IIP SN 2005cs in the optical and near-IR with $A_V = 1.5$ mag.

Mid-IR evolution similar to SN 2004et (shifted by 2.4 mag).

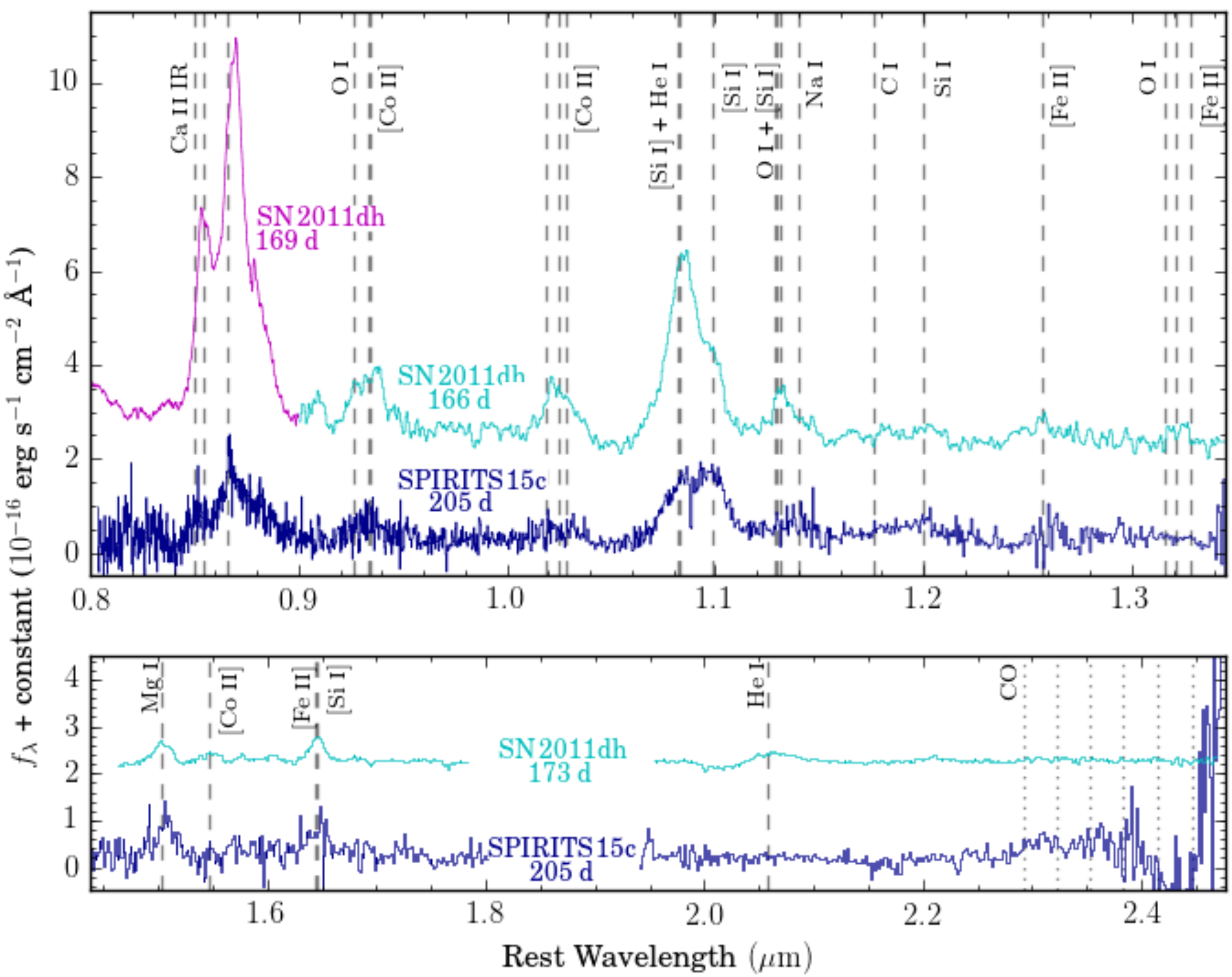


Jencson+ 2017

SN 2005cs data, Pastorello et al. 2009

SN 2004et data, Kotak et al. 2009

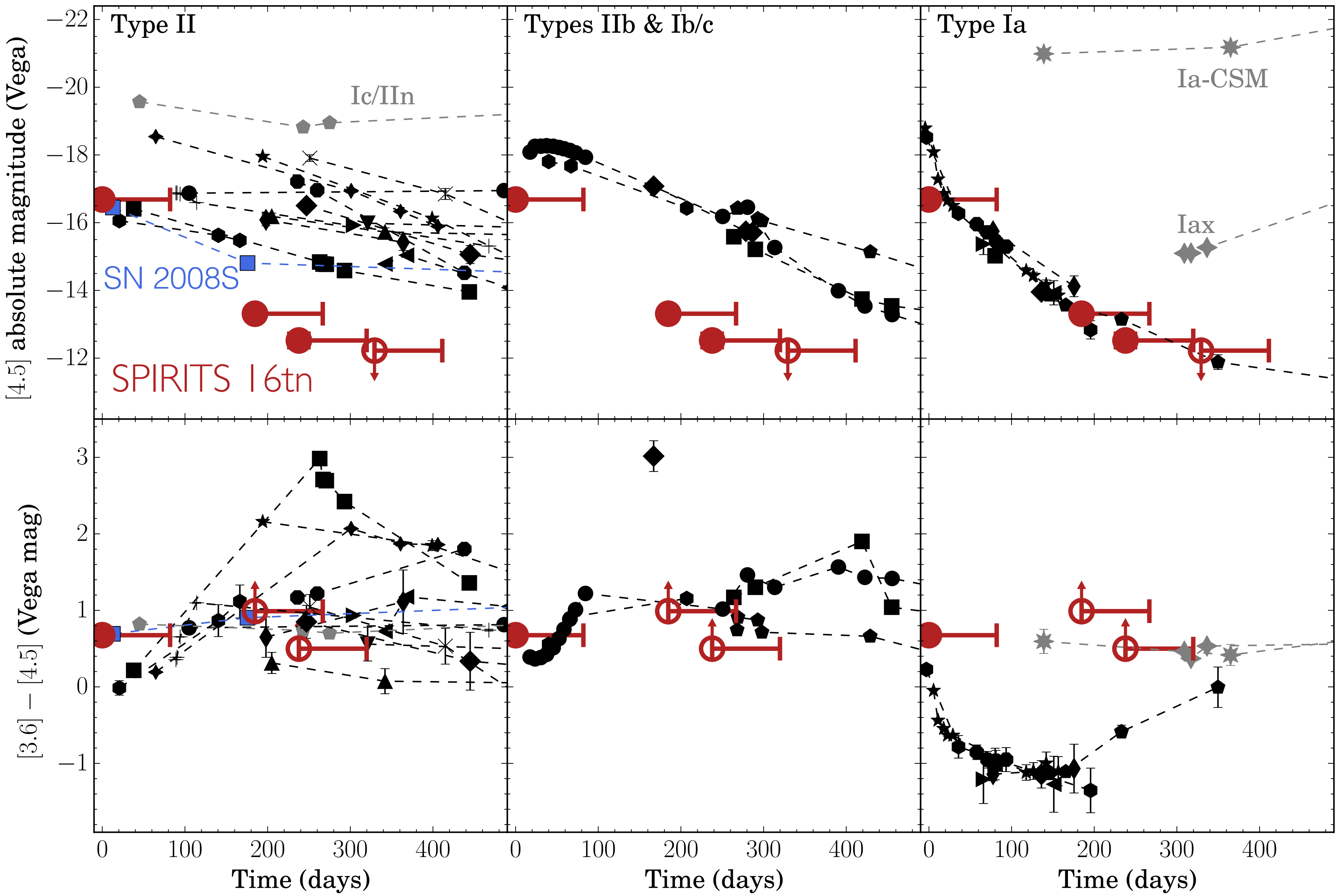
The near-IR spectrum of SPIRITS 15c is similar to that of Type IIb SN 2011dh.



SN 2011dh spectra and line IDs, Ergon et al. 2015, Jerkstrand et al. 2015

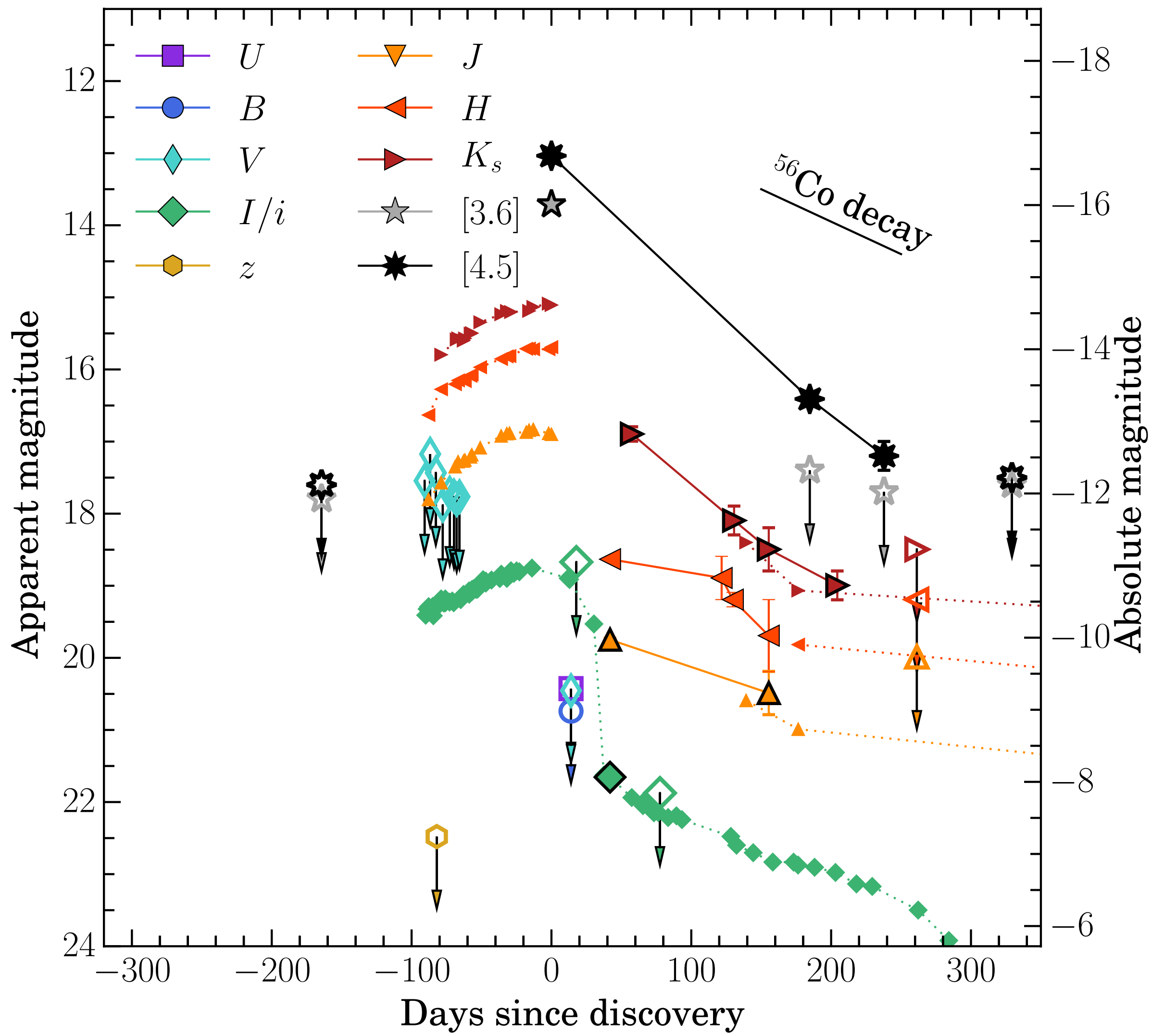
Jencson+ 2017

SPIRITS 16tn is unique in its mid-IR properties.

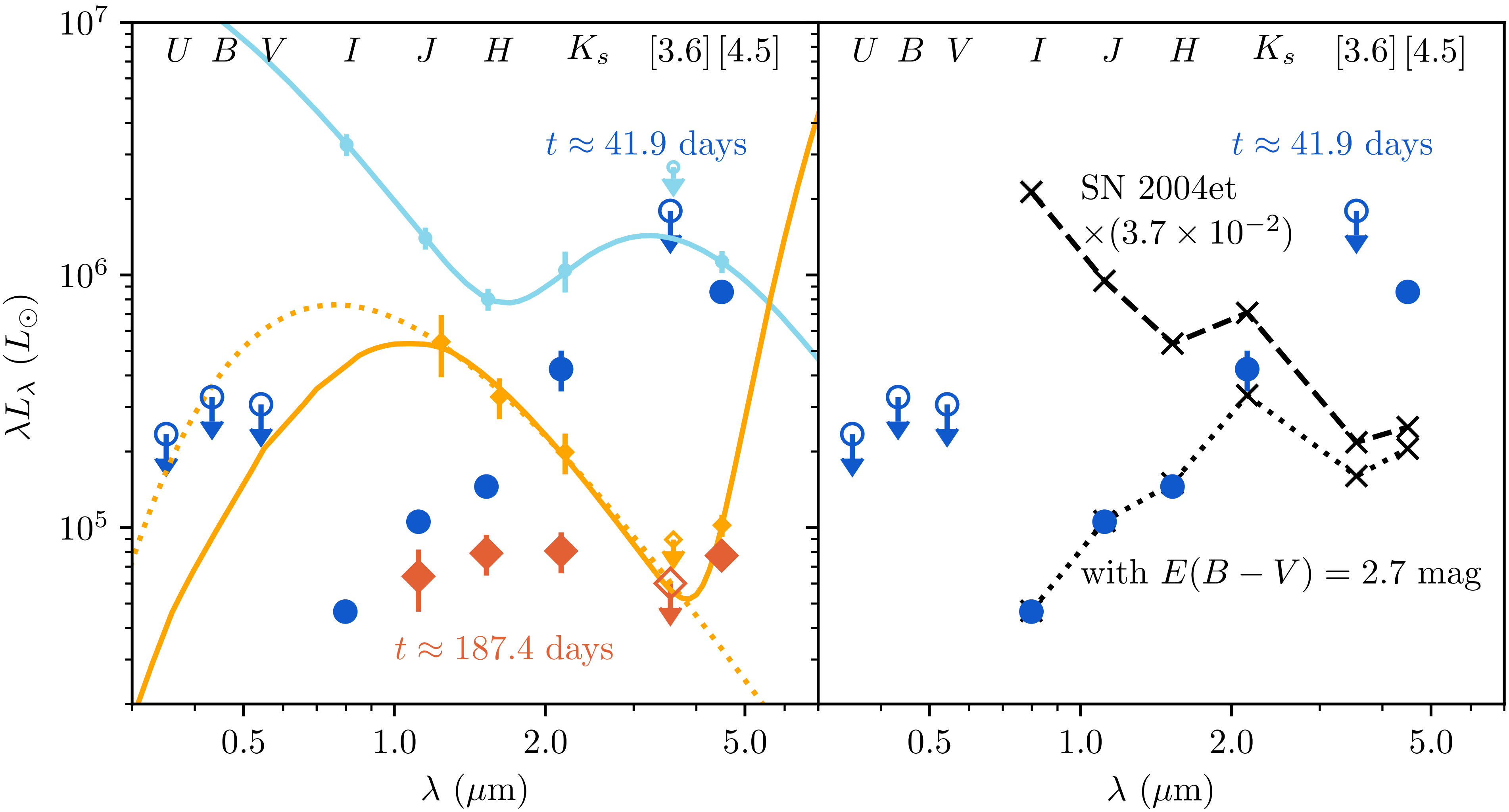


Jencson+ 2018

SPIRITS 16tn comparison to SN 2005cs suggests $A_V = 8$ mag.

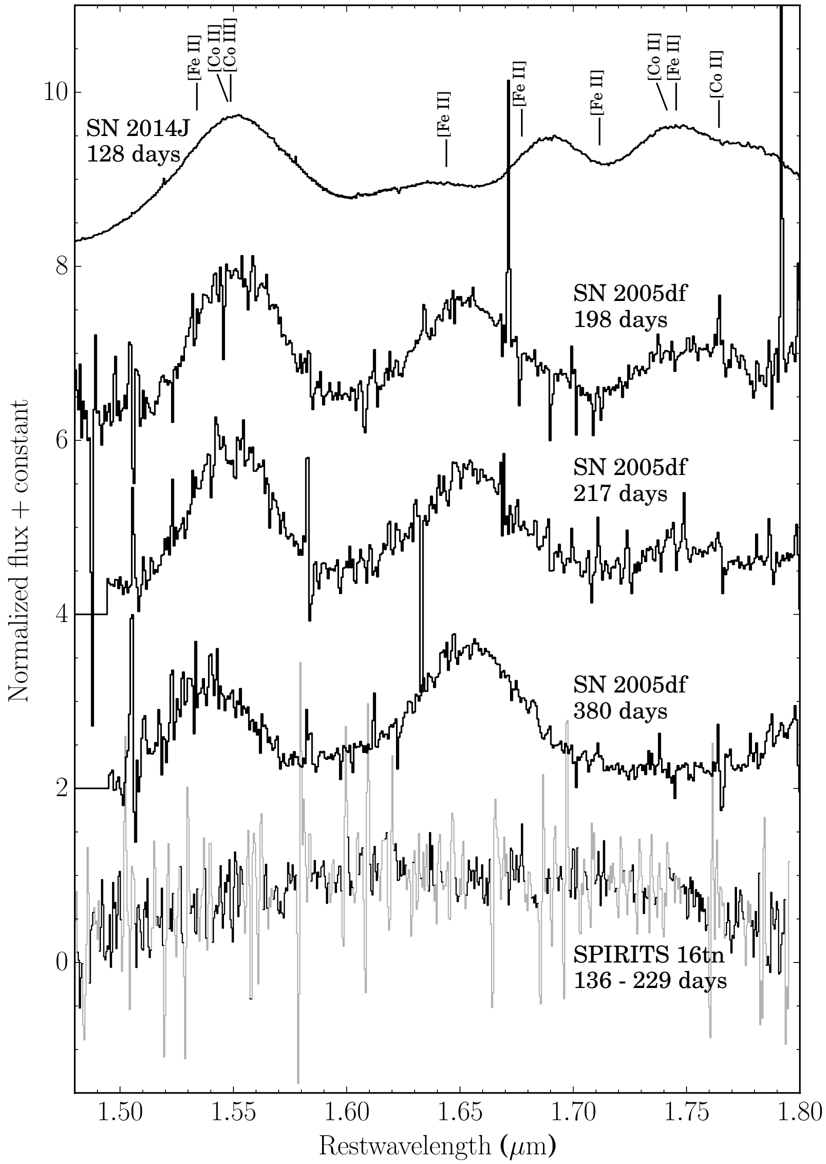


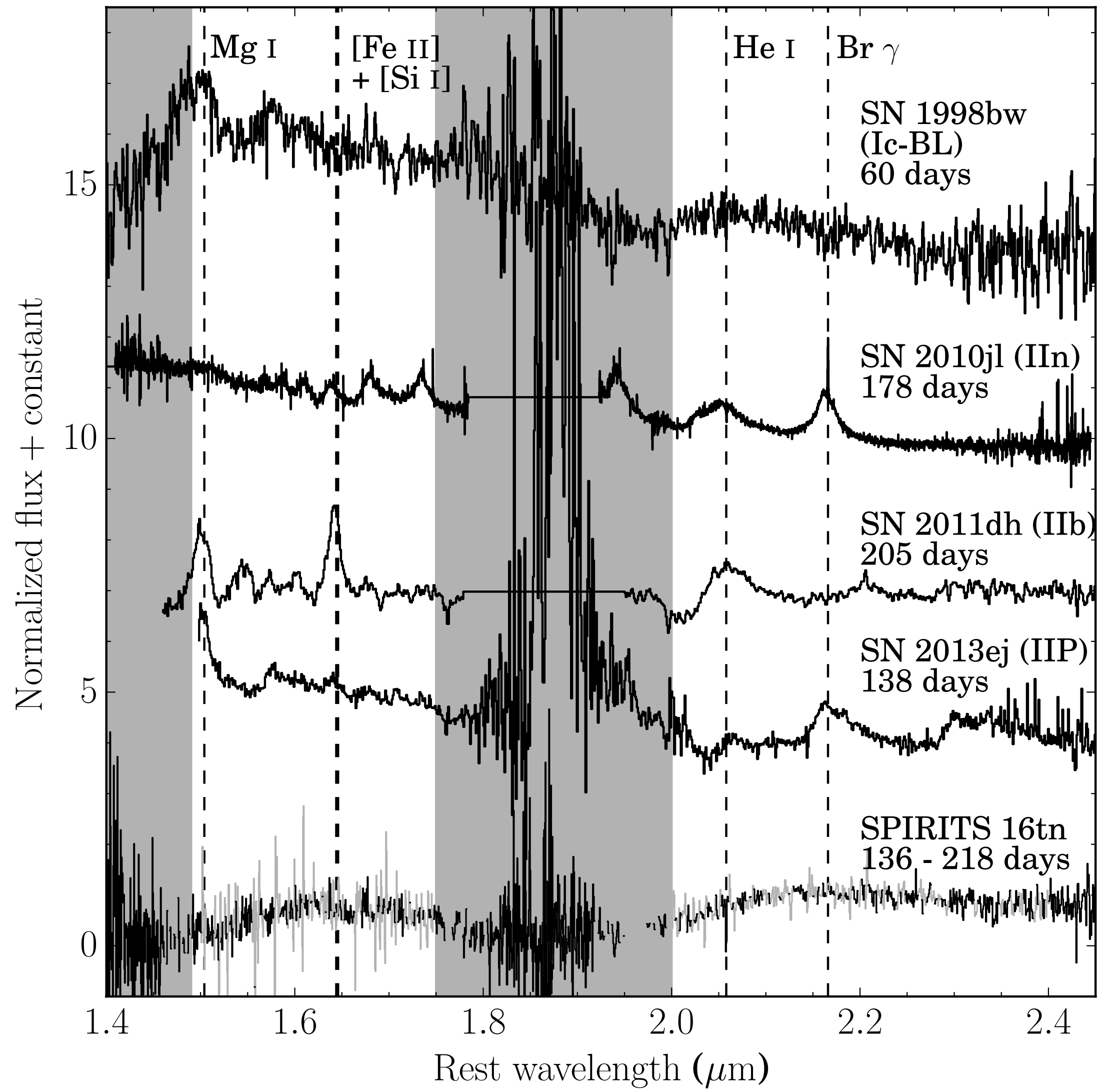
Comparisons with Type II SNe suggest A_V ~ 7 - 9 mag for SPIRITS 16tn.



Jencson+ 2018

Near-IR spectrum of SPIRITS 16tn rules out an SN Ia.



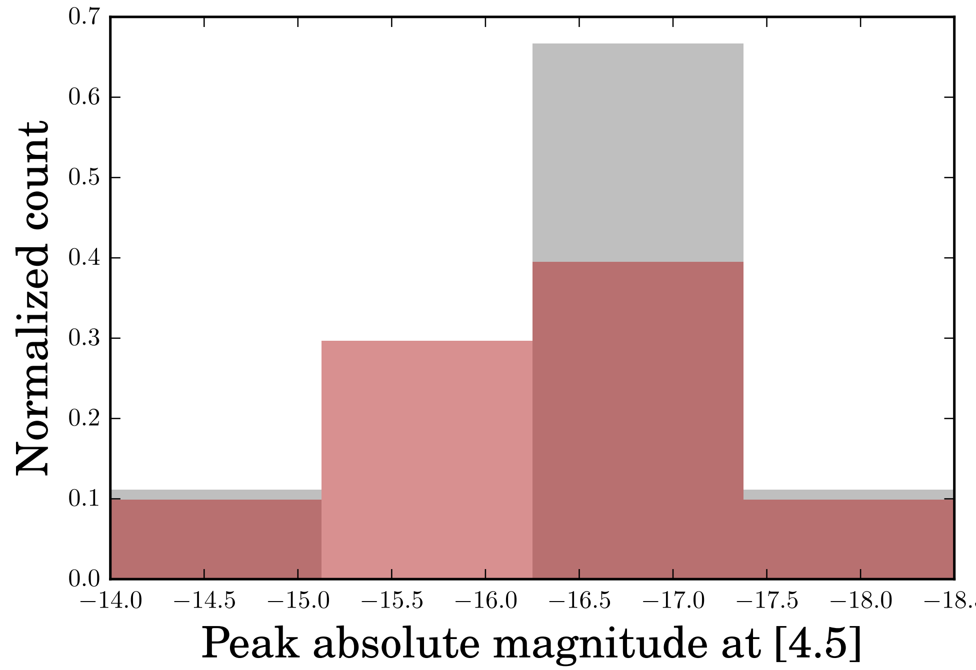


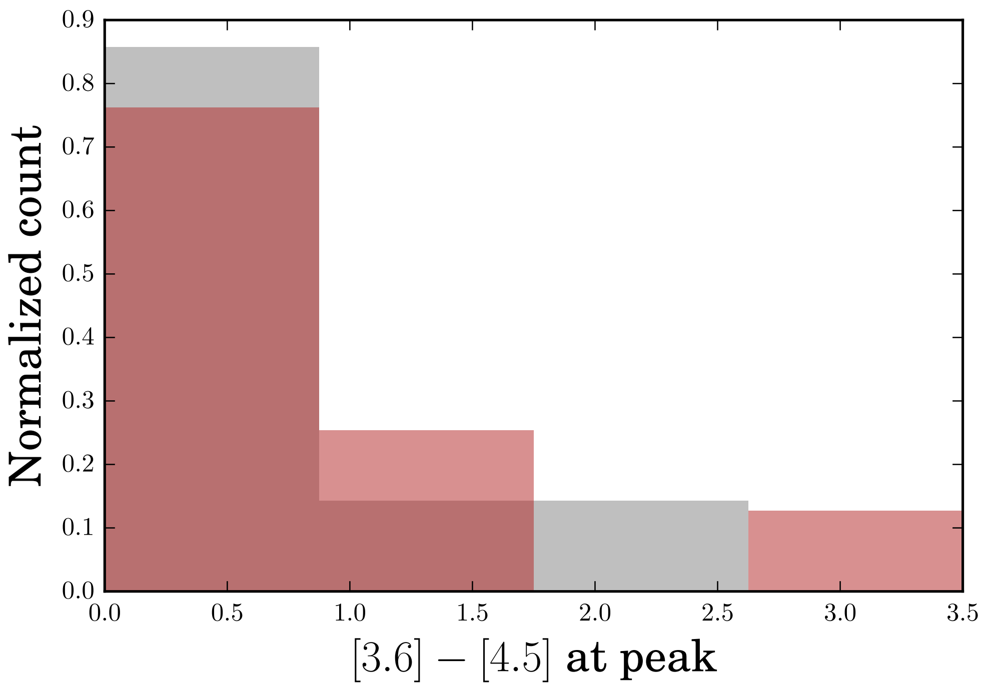
Jencson+ 2018

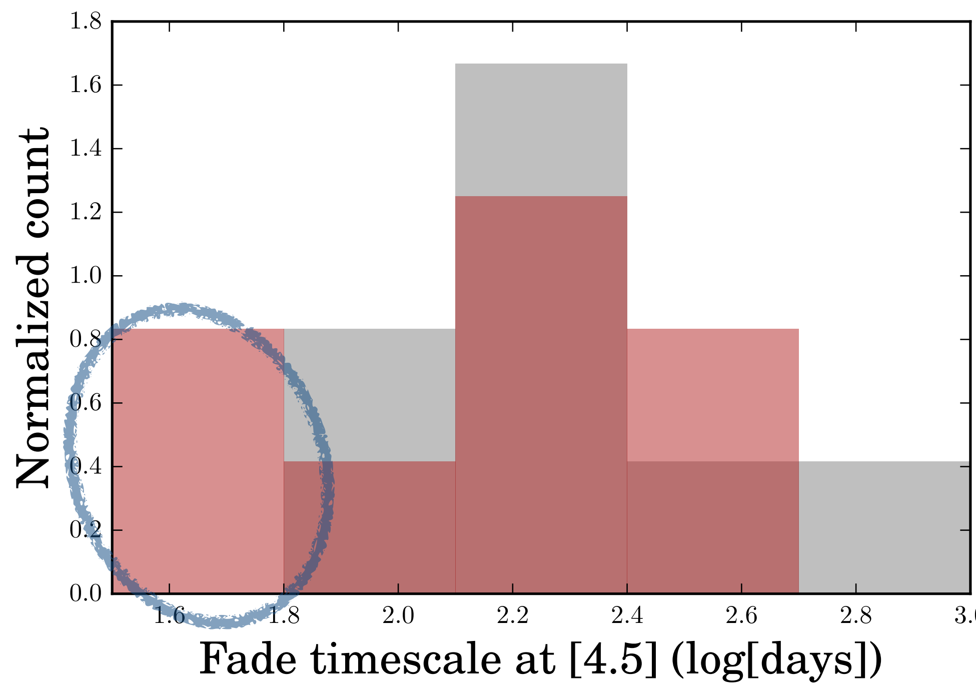
Optical and IR samples are similar in their IR properties.

IR sample

Control Sample



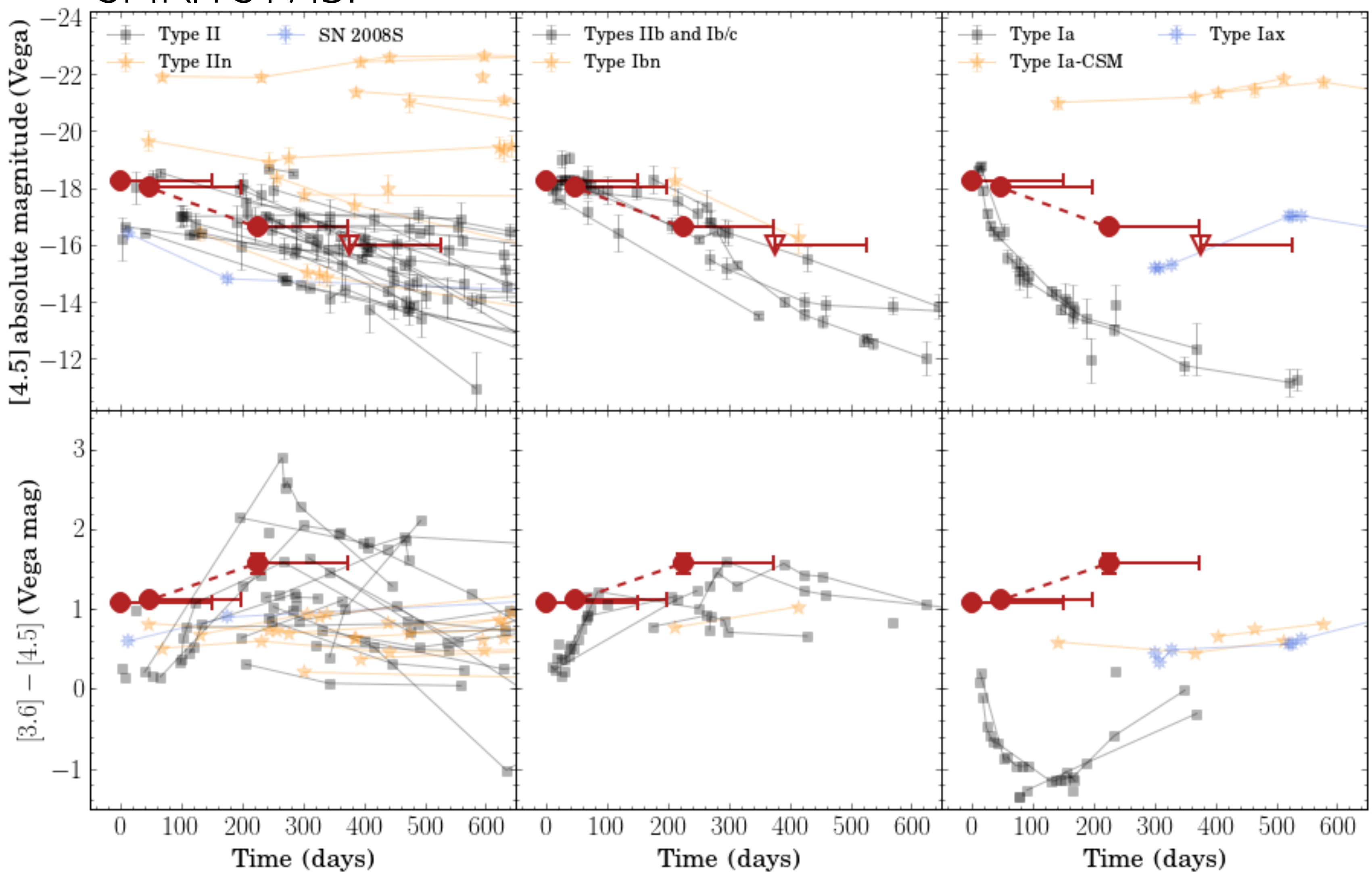




Jencson+ 2019a, arXiv:1901.00871

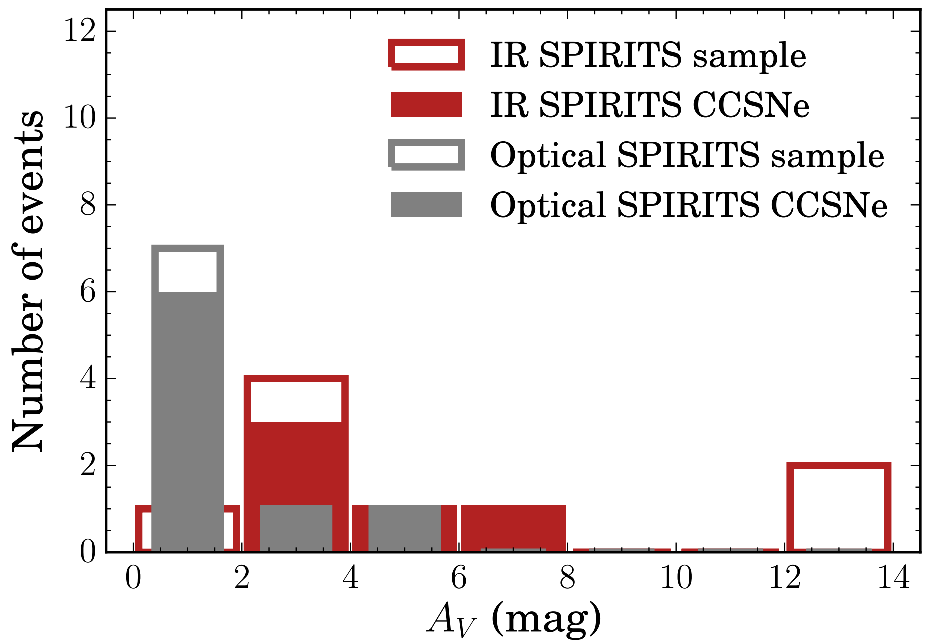
IR light curve diagnostics with full sample of *Spitzer* supernovae.

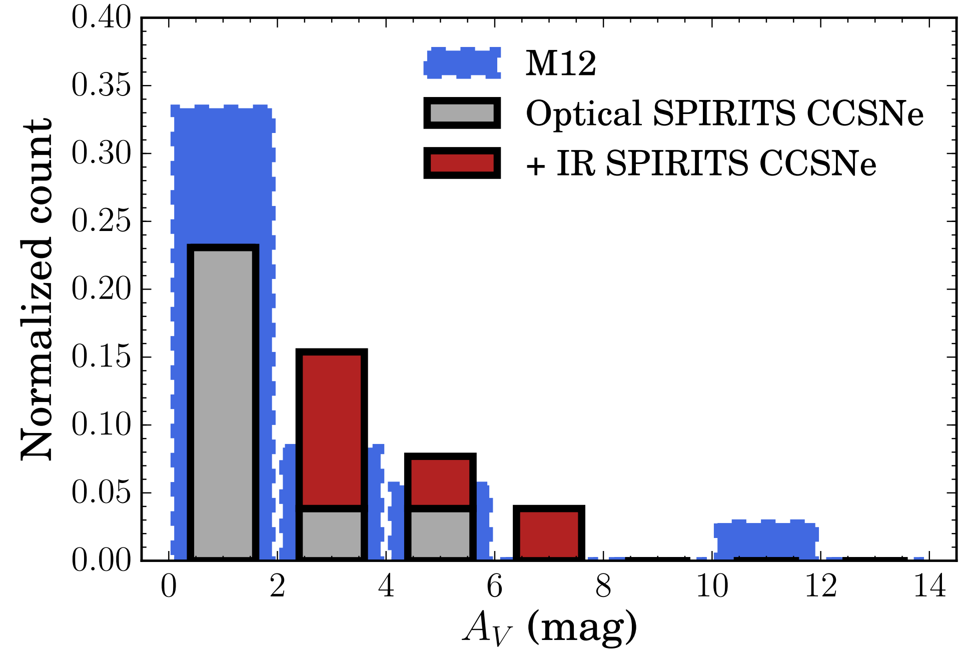
SPIRITS17lb:



Comparison light curves compiled in Szalai+ 2018

Fraction of optically missed, nearby supernove in SPIRITS galaxies is $38.5^{+26.0}_{-21.9}$%





Optical/near-IR coverage indicates significant extinction.

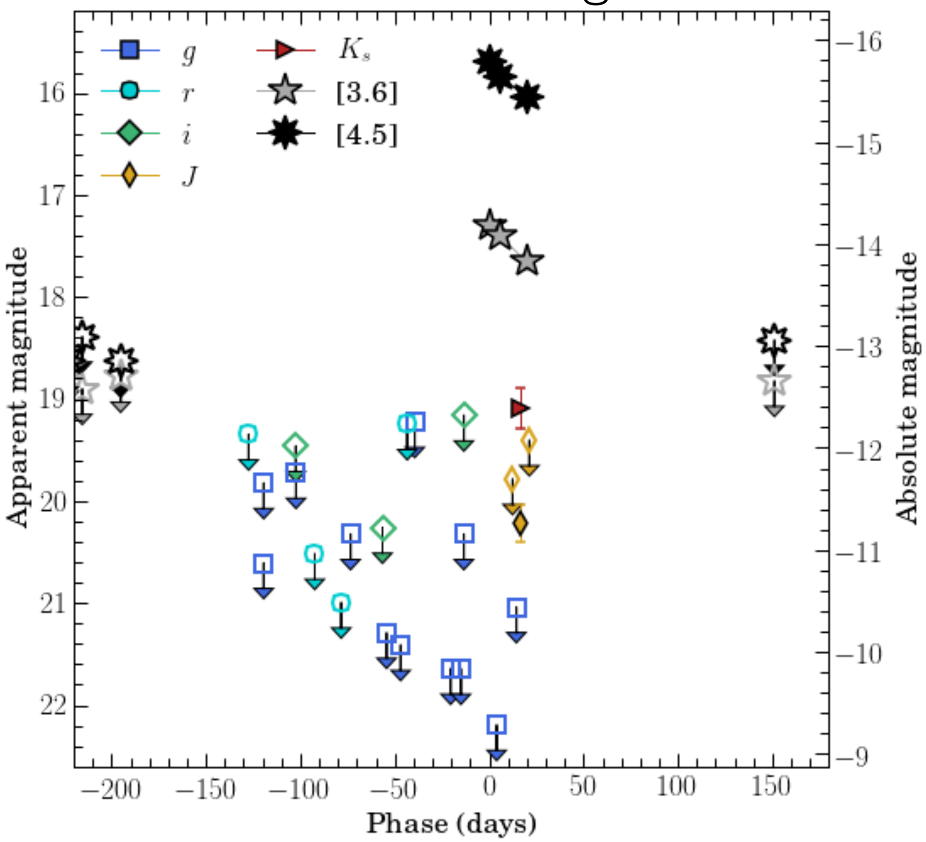
Based on direct SN light curve comparisons (Jencson+ 2017, 2018):

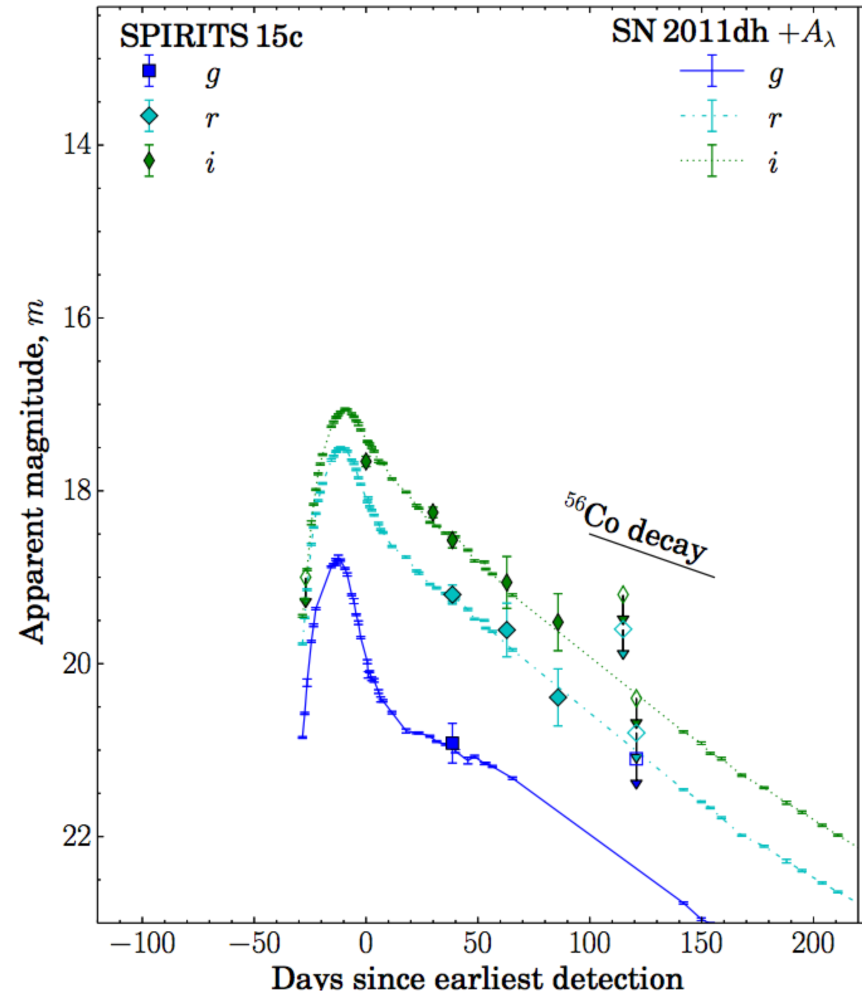
SPIRITS 15c: A_V = 2.2 mag (Type I or IIb)

SPIRITS 14buu: A_V = 1.5 mag (Type IIP)

SPIRITS 16tn: A_V = 7-9 mag (Type II?)

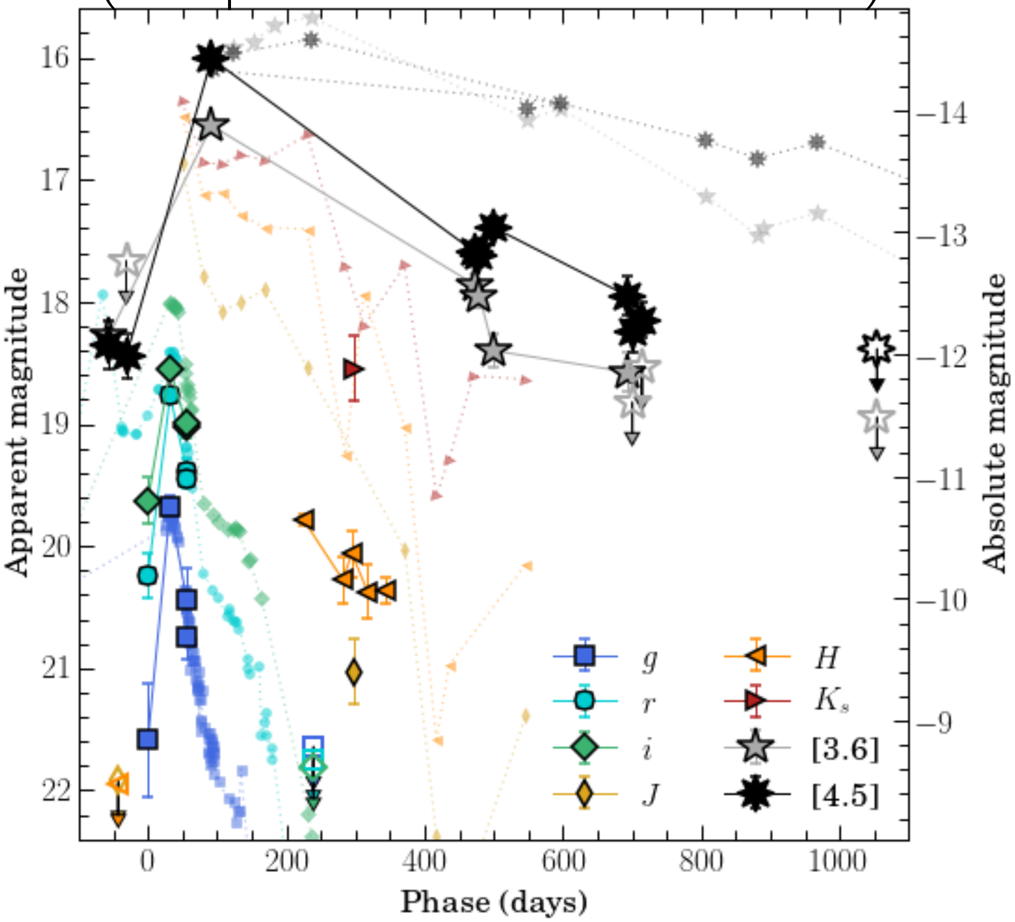
SPIRITS 16ix: A_V > 5.5 mag



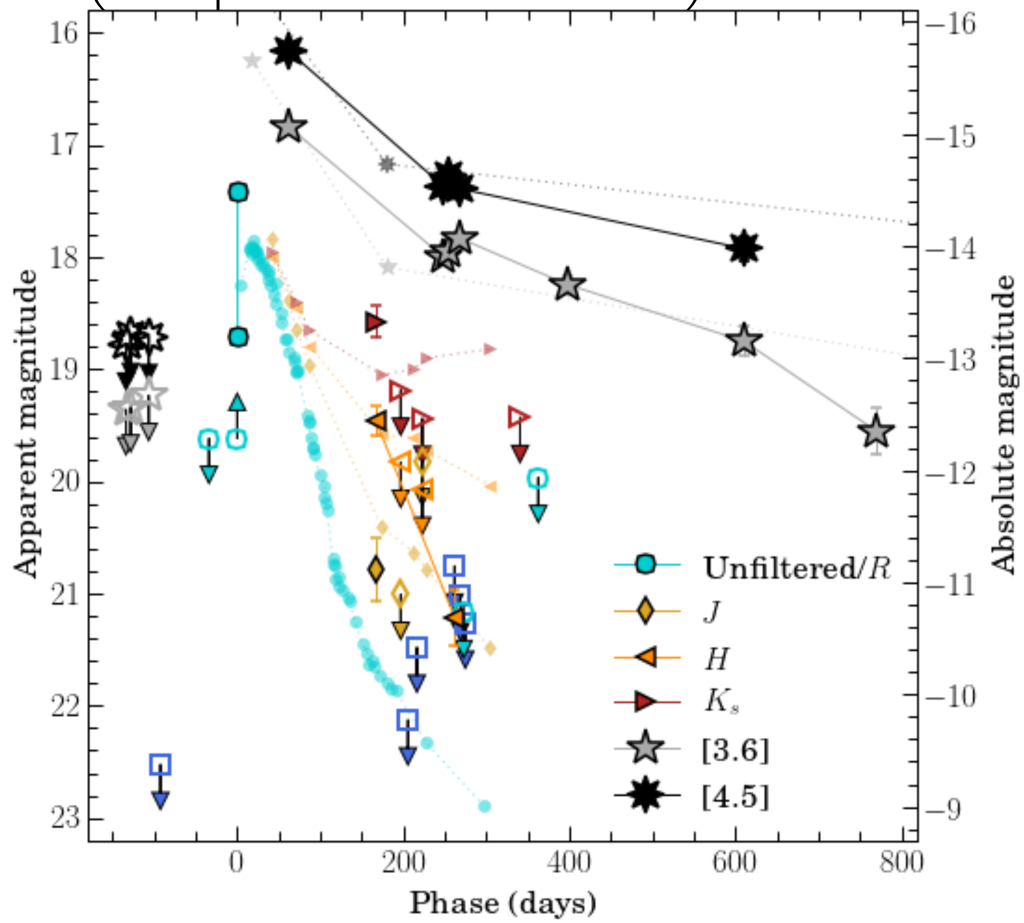


A stellar merger and an SN 2008S-like event:

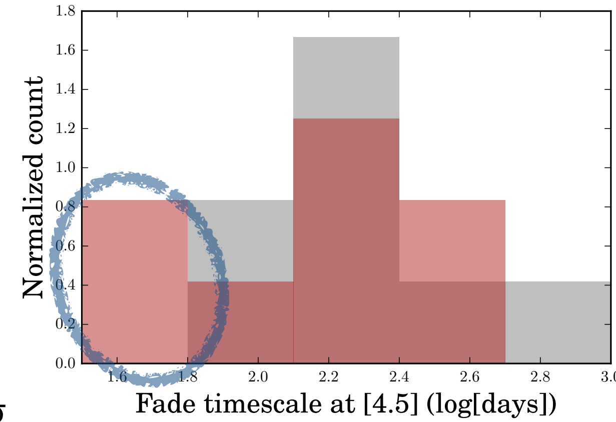
SPIRITS 14azy:
(compared to M101 OT2015-1)



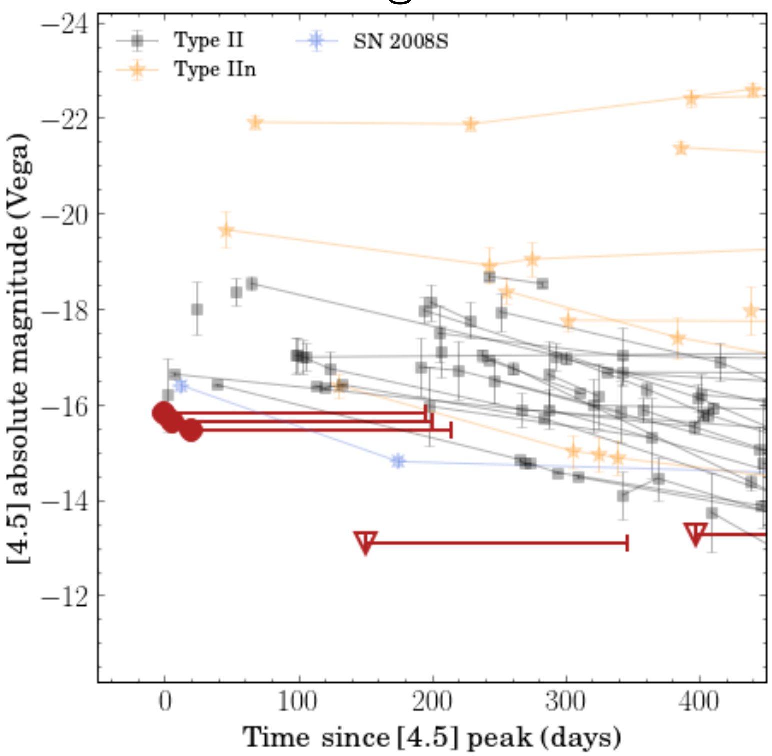
SPIRITS 15ade:
(compared to SN 2008S)



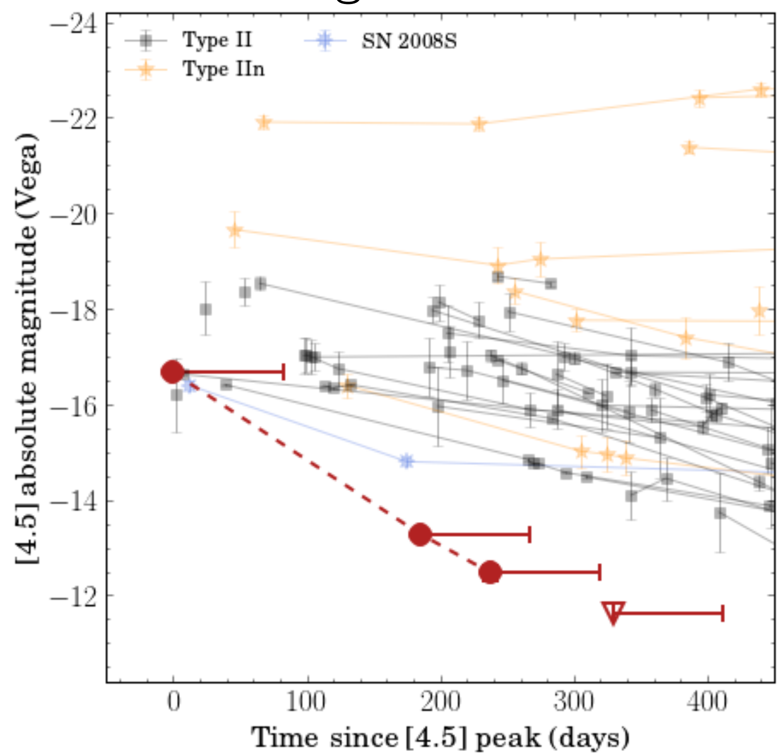
SPIRITS 16ix and SPIRITS 16tn: A unique pair of heavily obscured, IR SNe.



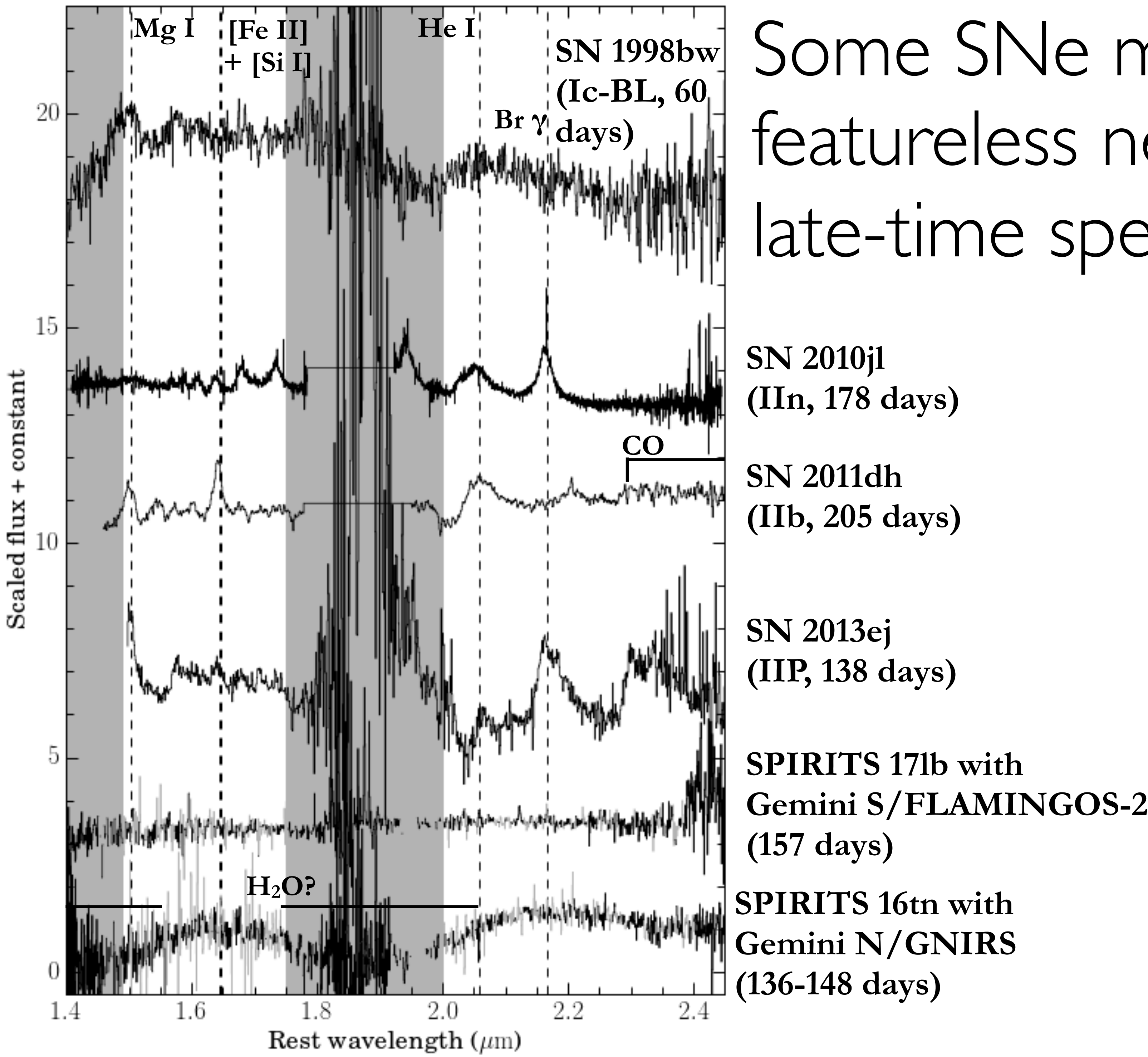
SPIRITS16ix:
A_V > 5.5 mag



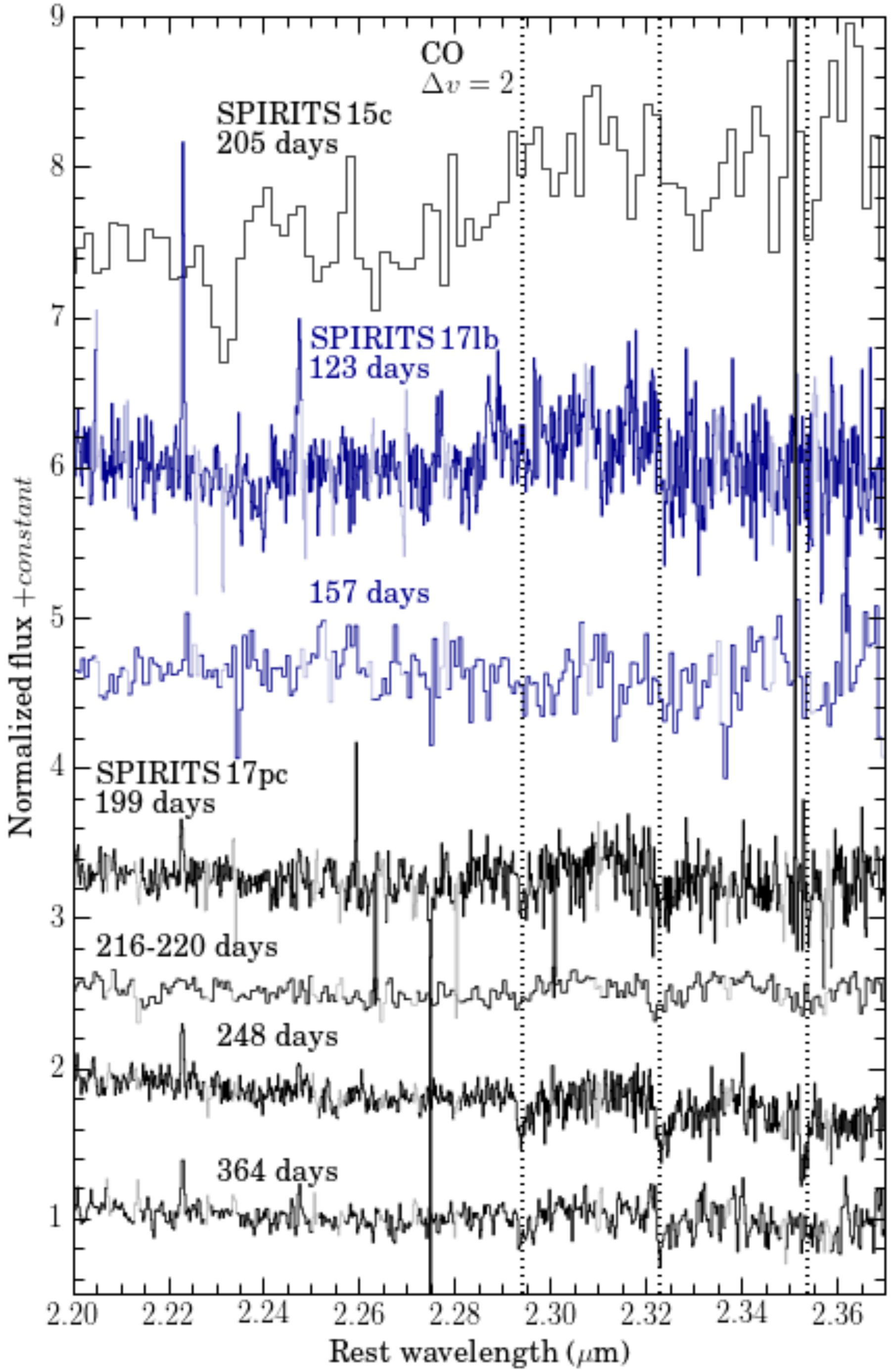
SPIRITS16tn:
A_V = 7 - 9 mag



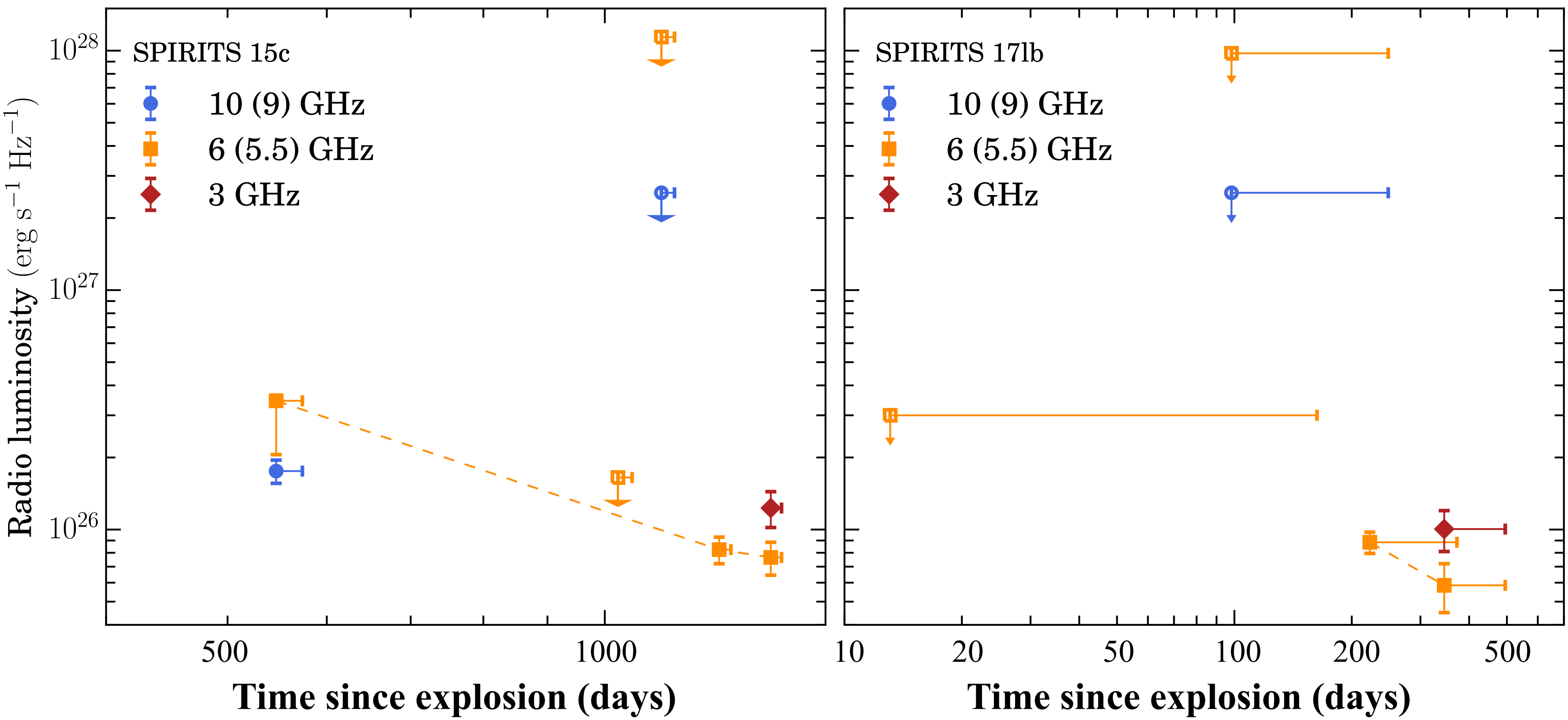
Some SNe may have featureless near-IR, late-time spectra.



CO features in luminous IR SPIRITS transients:



Radio light curves of SPIRITS 15c and SPIRITS 17lb



SPIRITS 17qm has likely not yet undergone terminal explosion.

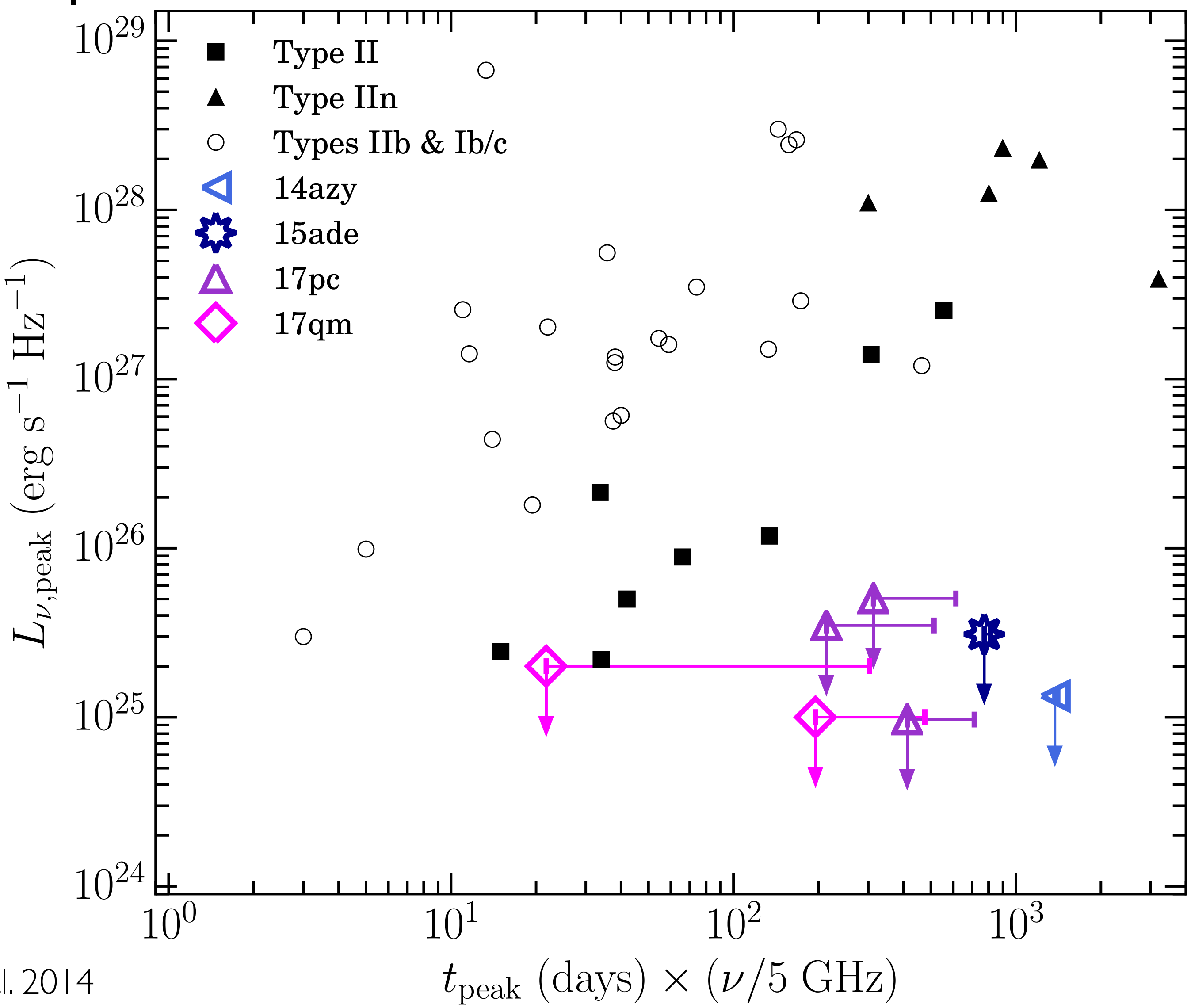
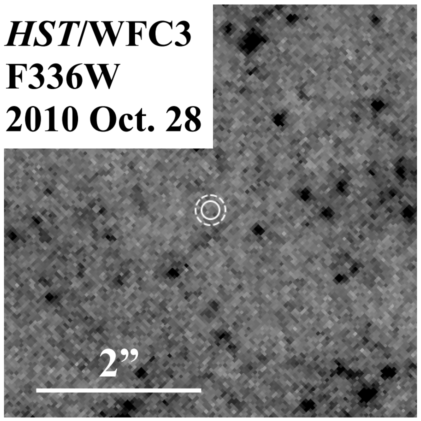


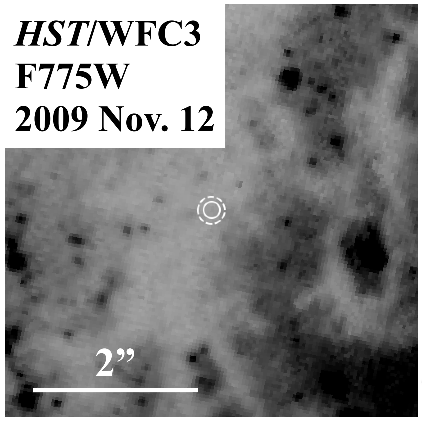
Fig. adapted from, e.g., Chevalier et al. 2006, Romero-Cañizales et al. 2014

Progenitors are obscured by dusty environments in archival *HST* imaging.

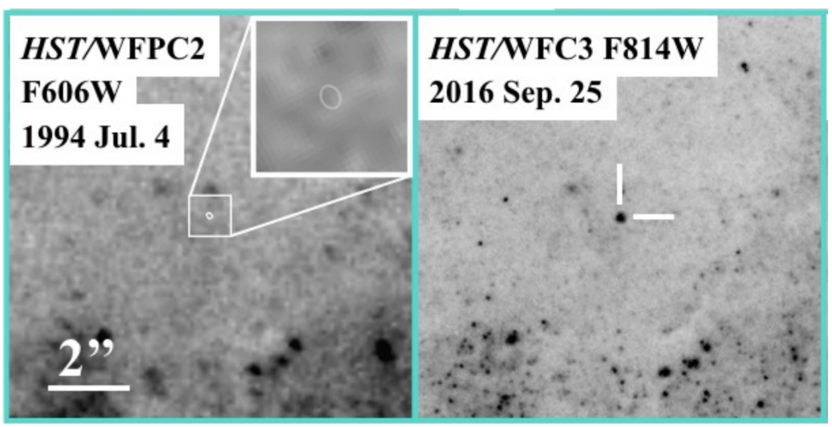
SPIRITS14azy

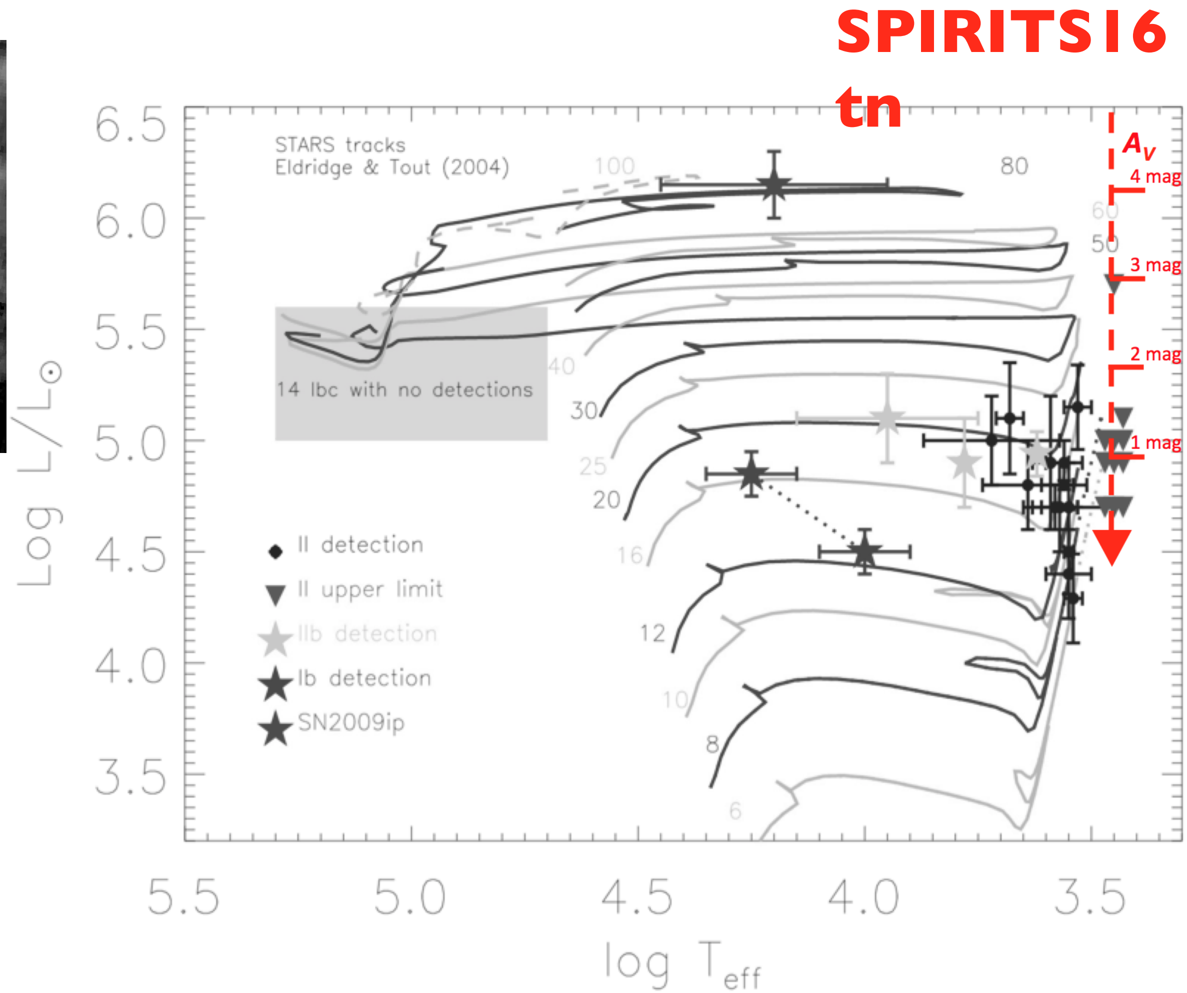


SPIRITS 15ud

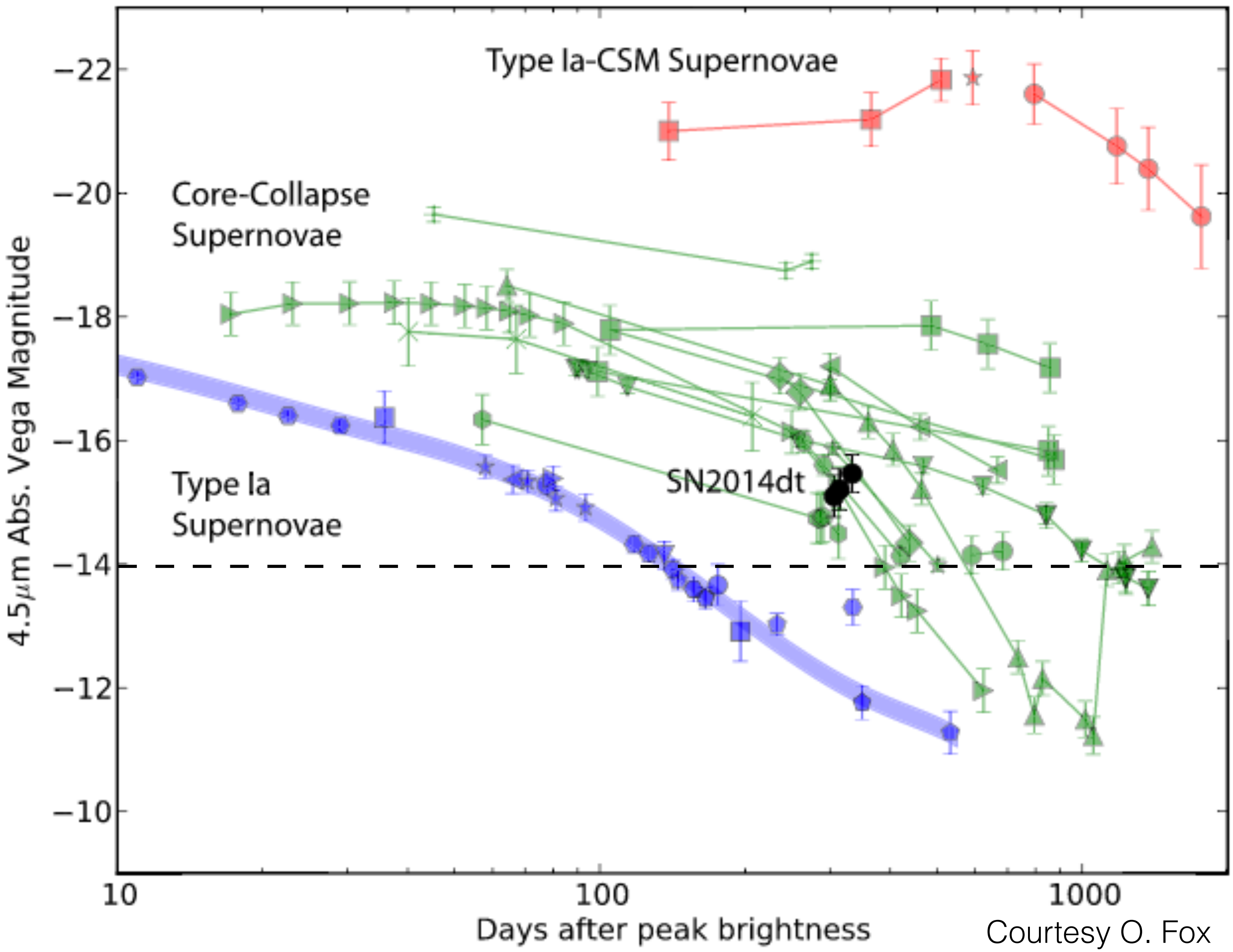


SPIRITS16tn





Optically-known SNe in SPIRITS



Courtesy O. Fox

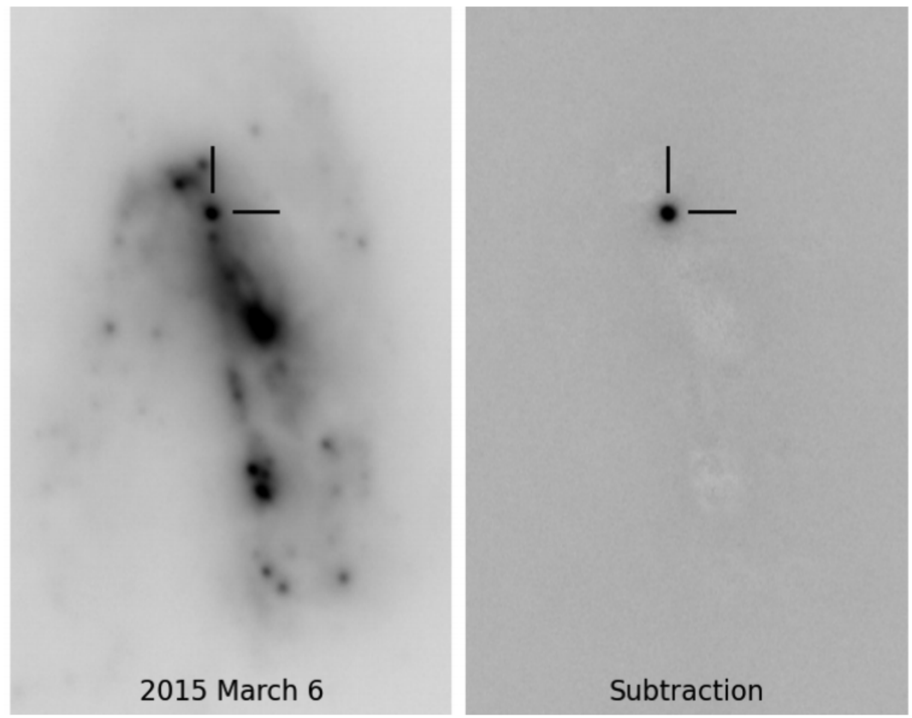
High-resolution searches have focused on extreme (U)LIRGs and starbursts.

8 confirmed obscured SNe from near-IR, high-resolution searches (e.g., Mattila+ 2007, 2008; Kankare+ 2008, 2012, Kool+ 2018).

Radio VLBI studies reveal scores of missed SNe (e.g., Perez-Torres+ 2009, Romero-Cañizales+ 2012).

Challenging with Spitzer in dense starbursts (e.g., O. Fox).

SN 2015cb in IRAS 17138-1017 with GeMS/GSAOI



$A_V \sim 5$ mag
Kool+ 2018

with 2013 reference

A combination of IR searches will be sensitive to obscured SNe at a range of distances.

SPitzer InfraRed Intensive Transients Survey (SPIRITS):

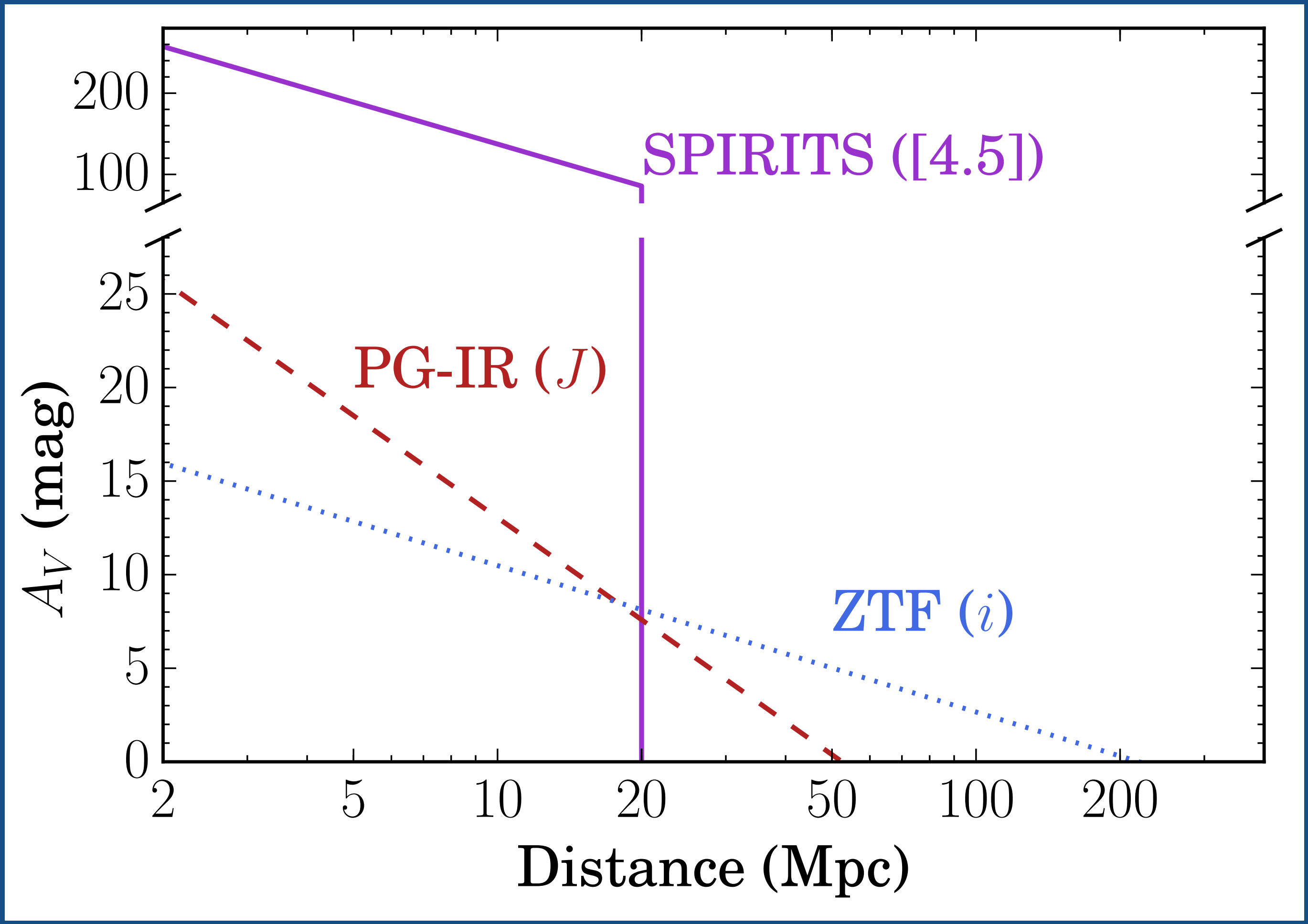
- 3.6 and 4.5 μm targeted survey of nearby galaxies.

Palomar Gattini-IR (PG-IR):

- Nightly J-band survey of 15000 deg^2.
- Expect ~ 13 SNe within 50 Mpc in 1 year.

Zwicky Transient Facility (ZTF):

- i-band survey of 6700 deg^2 at 4-day cadence.
- Expect ~ 50 CCSN within 100 Mpc in 1 year.



Zwicky Transient Facility

Successor to iPTF on Palomar 48-in. Oschin Telescope

47 deg^2 FOV

Optical *g* and *R*-band surveys

i-band survey of 6700 deg^2 to 20.1 mag (AB) at 4 day cadence

Expect ~ 50 CCSNe within 100 Mpc in one year

16 6k x 6k e2v CCDs

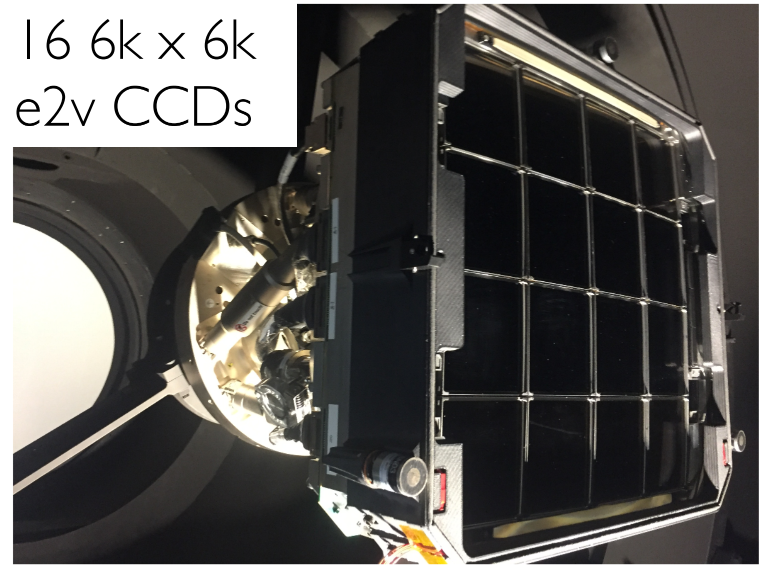
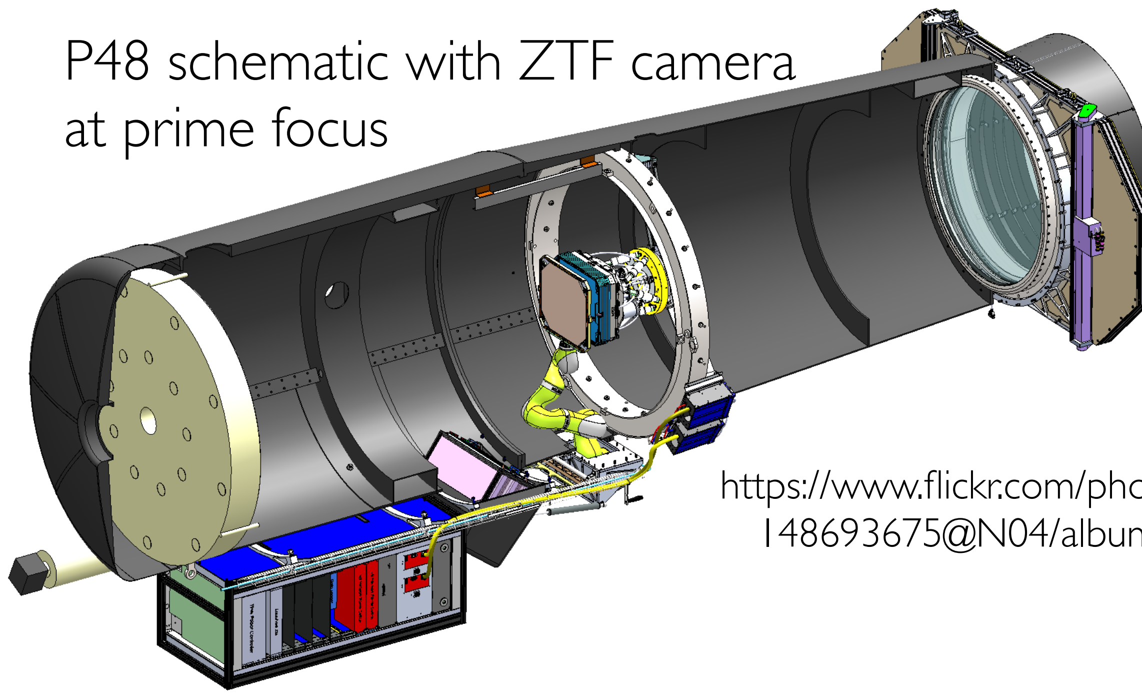


Photo credit: Michael Feeney

P48 schematic with ZTF camera at prime focus



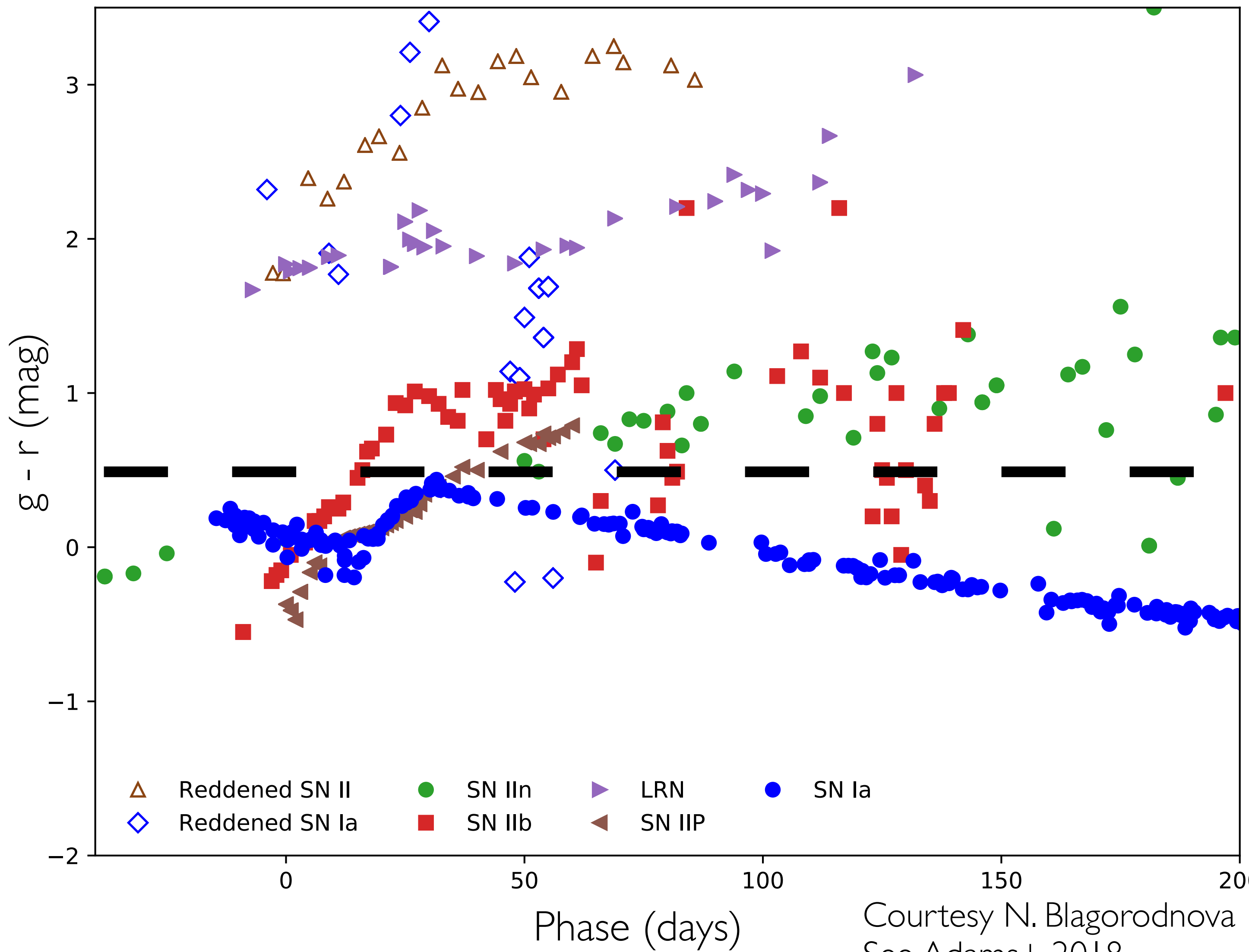
https://www.flickr.com/photos/148693675@N04/albums

ZTF will build spectroscopically complete samples of reddened SNe.

"Red Transients" filter selects g - r > 0.5 mag at early phase

Redshift **C**ompleteness **F**actor (**RCF**): Magnitude limited survey to < 18.5 mag

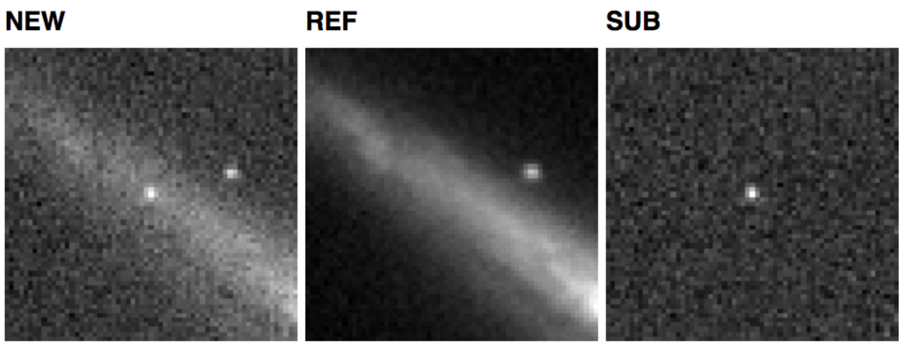
Census of the **L**ocal **U**niverse (**CLU**): Volume limited survey tranisnets in galaxies within 200 Mpc

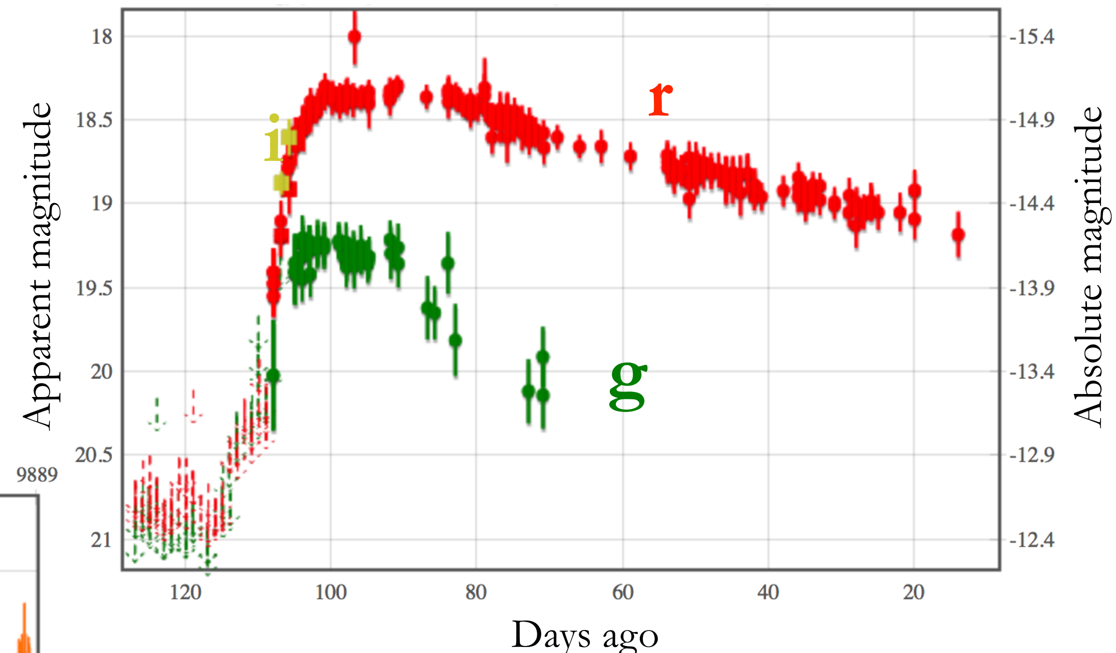


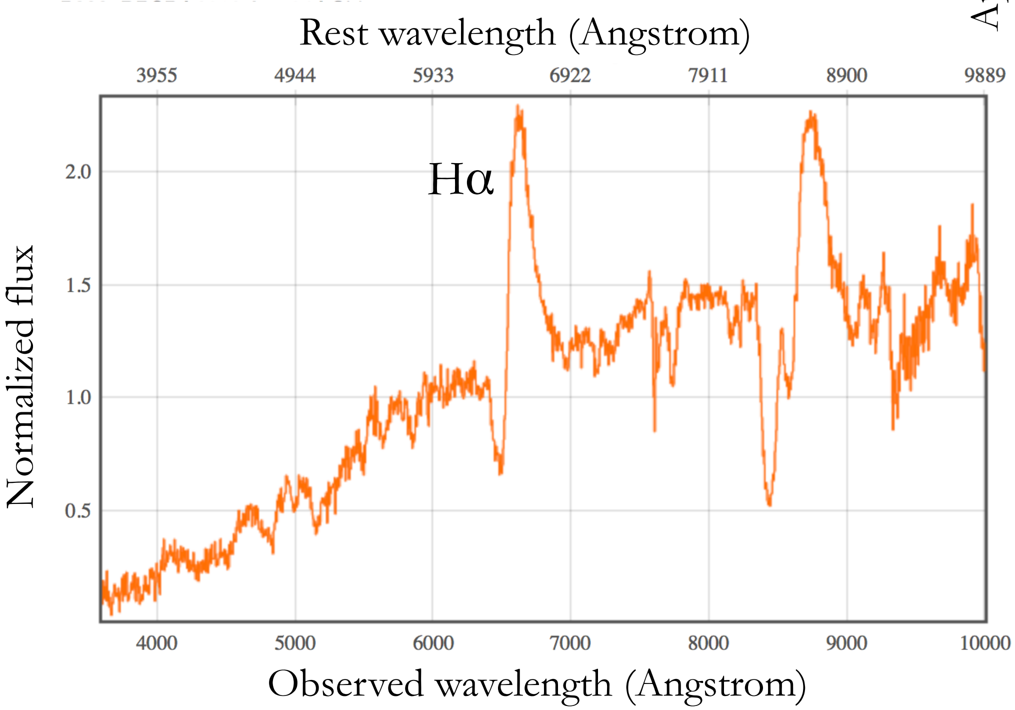
Courtesy N. Blagorodnova
See Adams+ 2018

Red Transient discoveries:

ZTF18abdbysy: Reddened SN IIP







$A_V \sim 2.7$ mag

Palomar Gattini-IR: A wide-field, ground-based IR transient survey

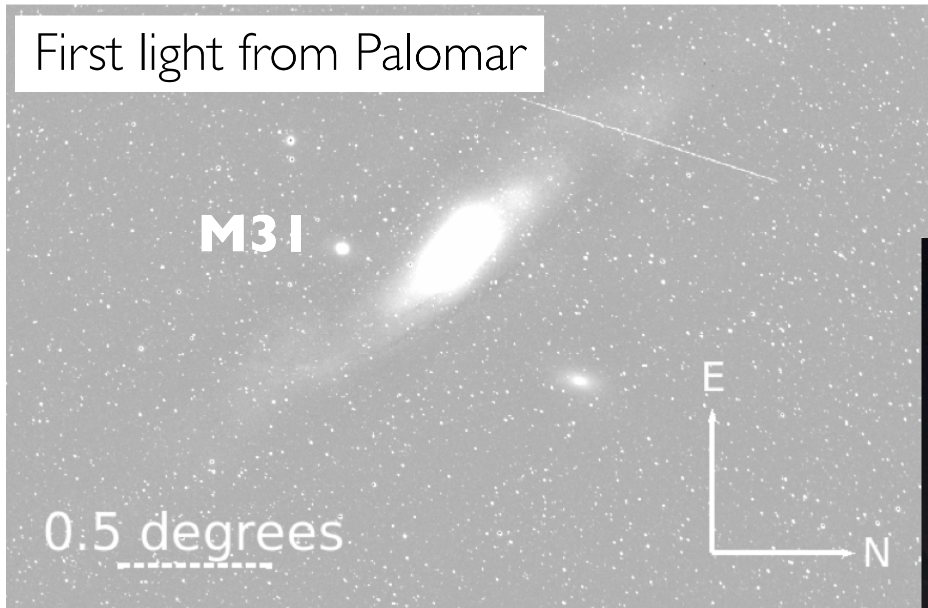
300 mm aperture telescope

25 deg^2 FOV

Survey 15000 deg^2 to J = 16.4 mag AB every night

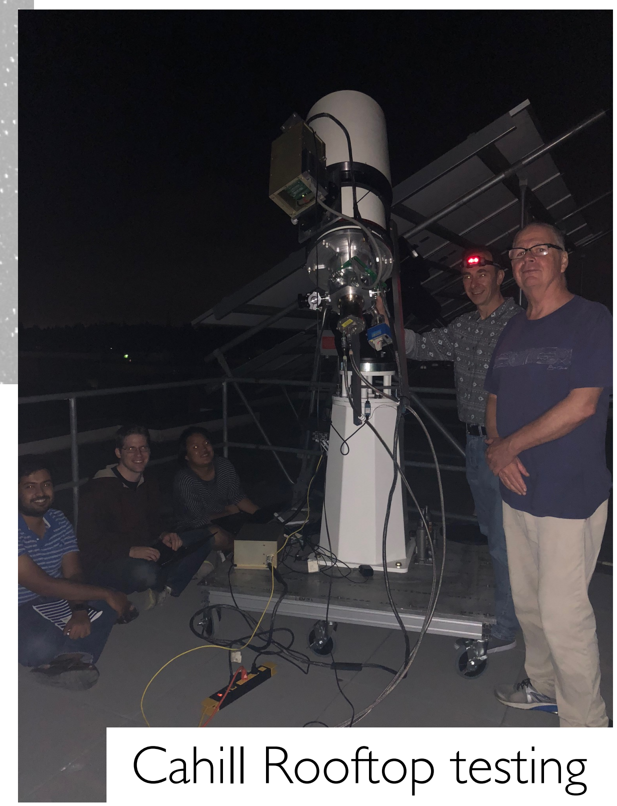
Reach 17.5 mag in one week stack

Expect ~ 13 SNe within 50 Mpc in one year



First light from Palomar

PG-IR Team: M Kasliwal, A Moore, A Delacroix, D McKenna, S Adams, R Lau, K De, J Soon, E Ofek, R Smith, T Travouillon, M Ashley, J Jencson+

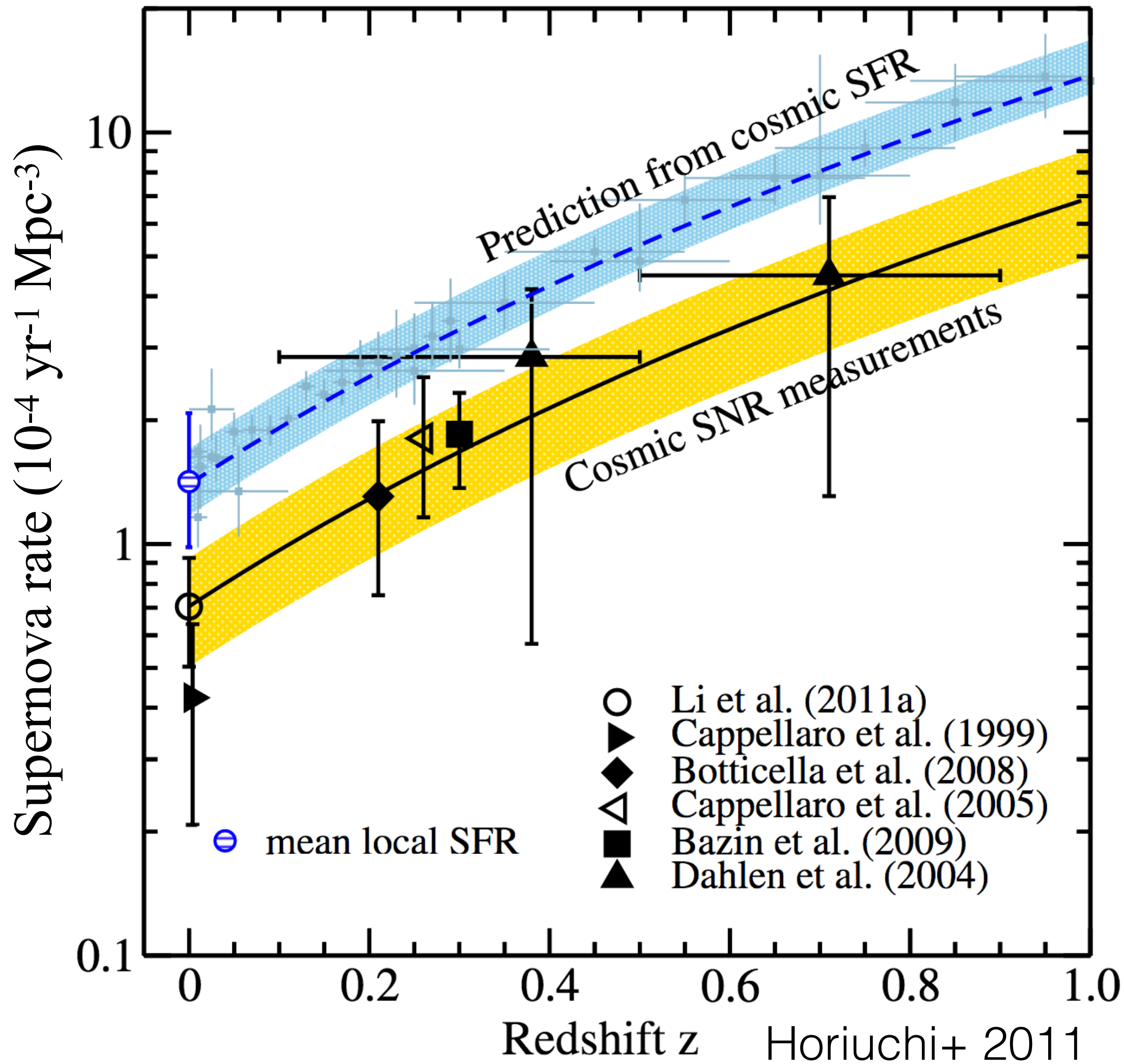

Cahill Rooftop testing

"Supernova Rate Problem": The core-collapse supernova rate does not match the formation rate of massive stars.

SN rate tracks trend in star formation

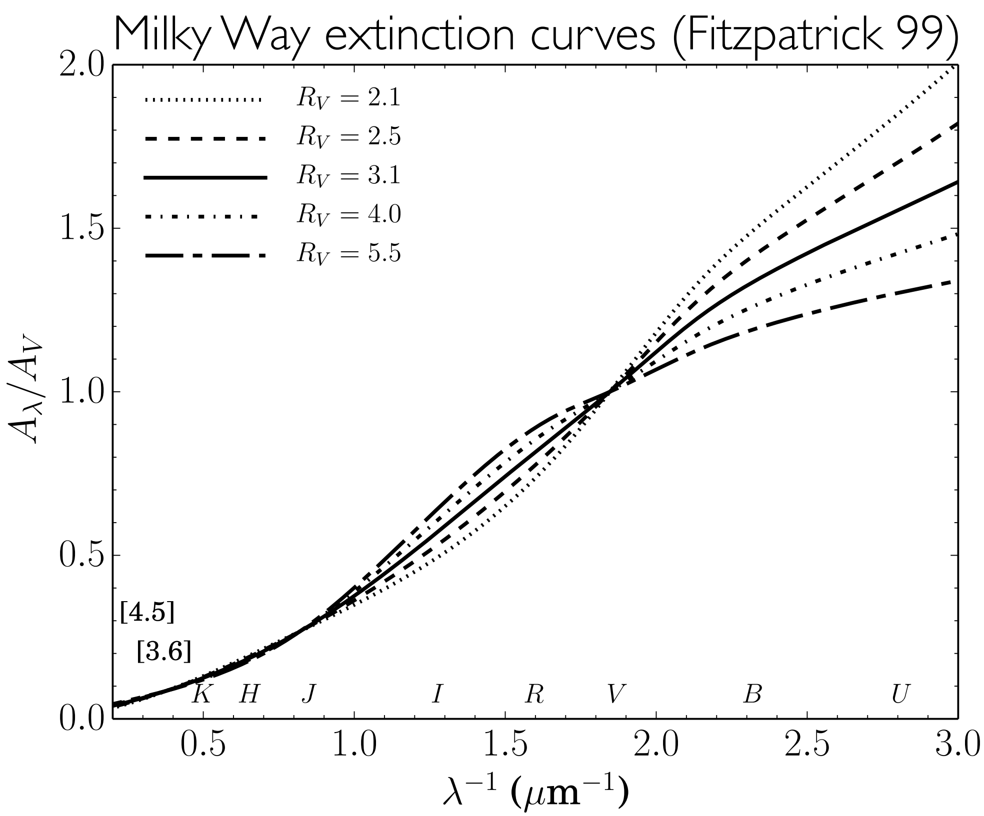
Overall normalization discrepancy by factor of 2

Not enough supernovae are seen for the number of massive stars formed in the Universe



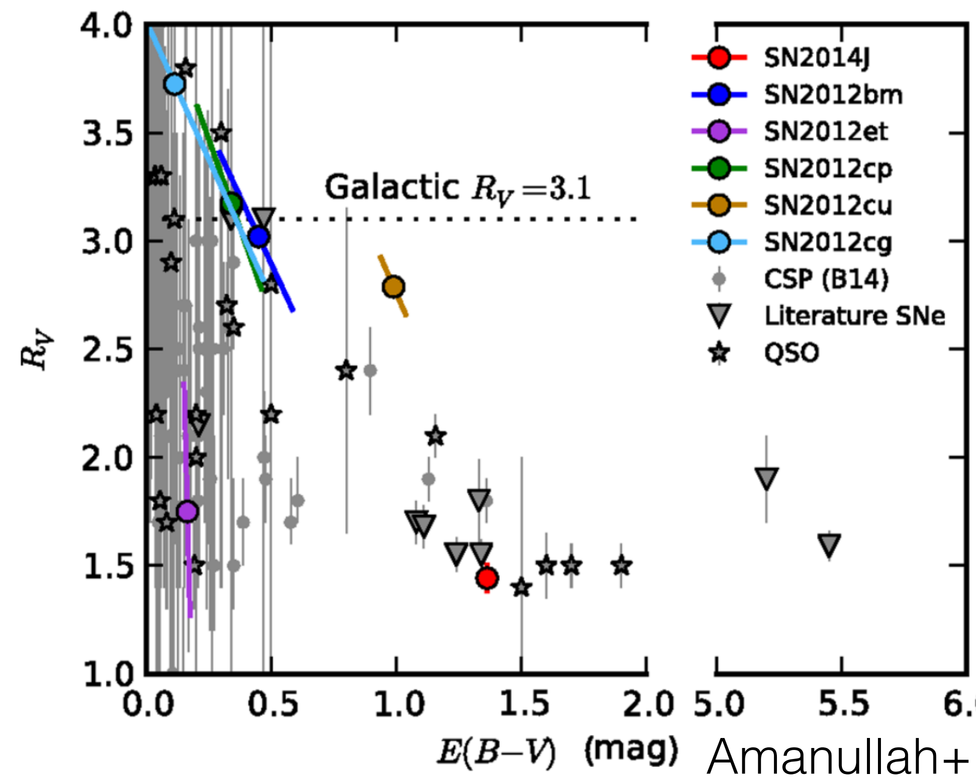
Horiuchi+ 2011

Characterizing the extinction in obscured SNe can probe local conditions.



$$R_V = A_V/E(B - V)$$

Low values of R_V observed in some SNe Ia



Amanullah+ 2015

R_V dependent extinction curves