Multi-wavelength and multi-messenger observations of core-collapse supernovae and their progenitors

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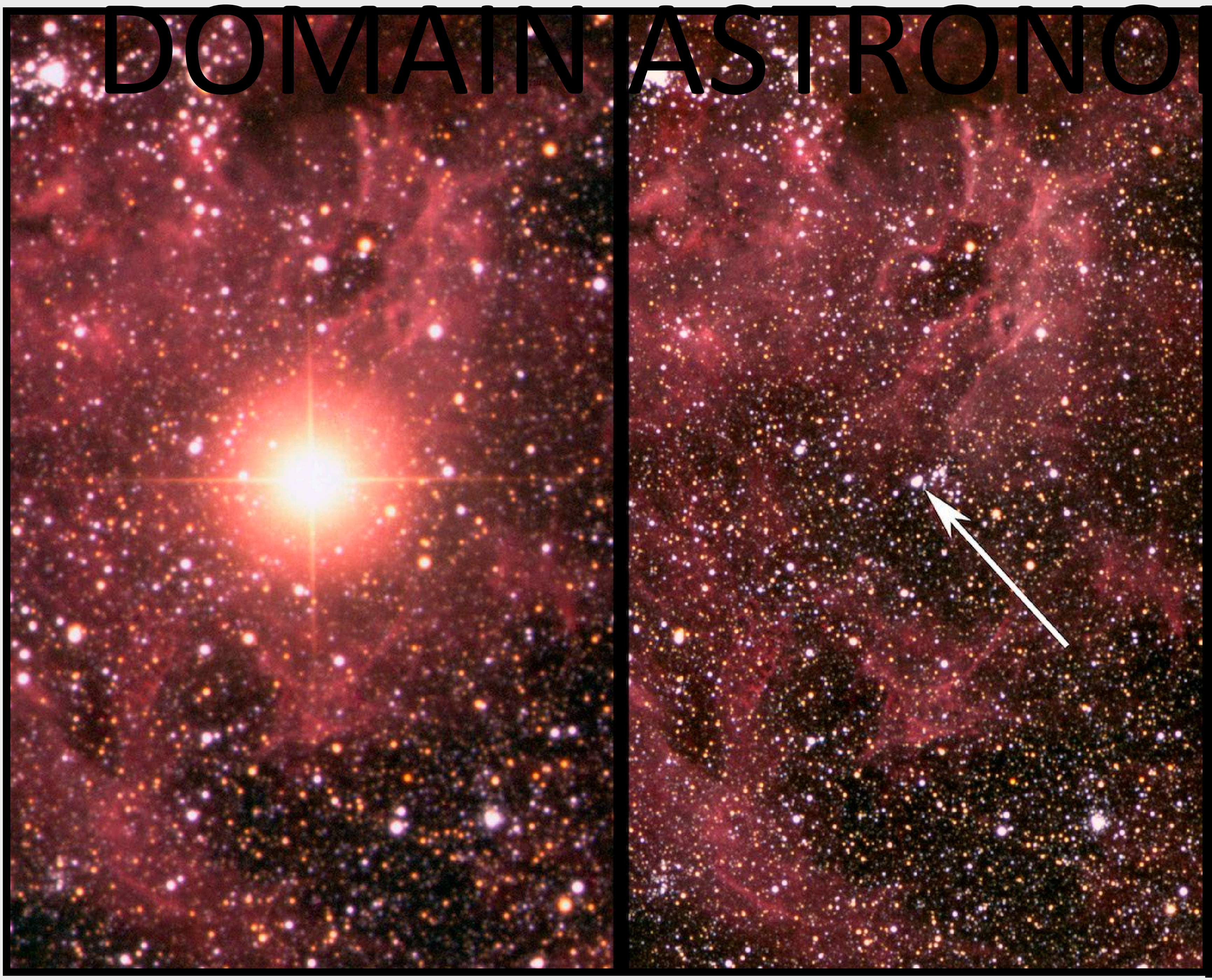
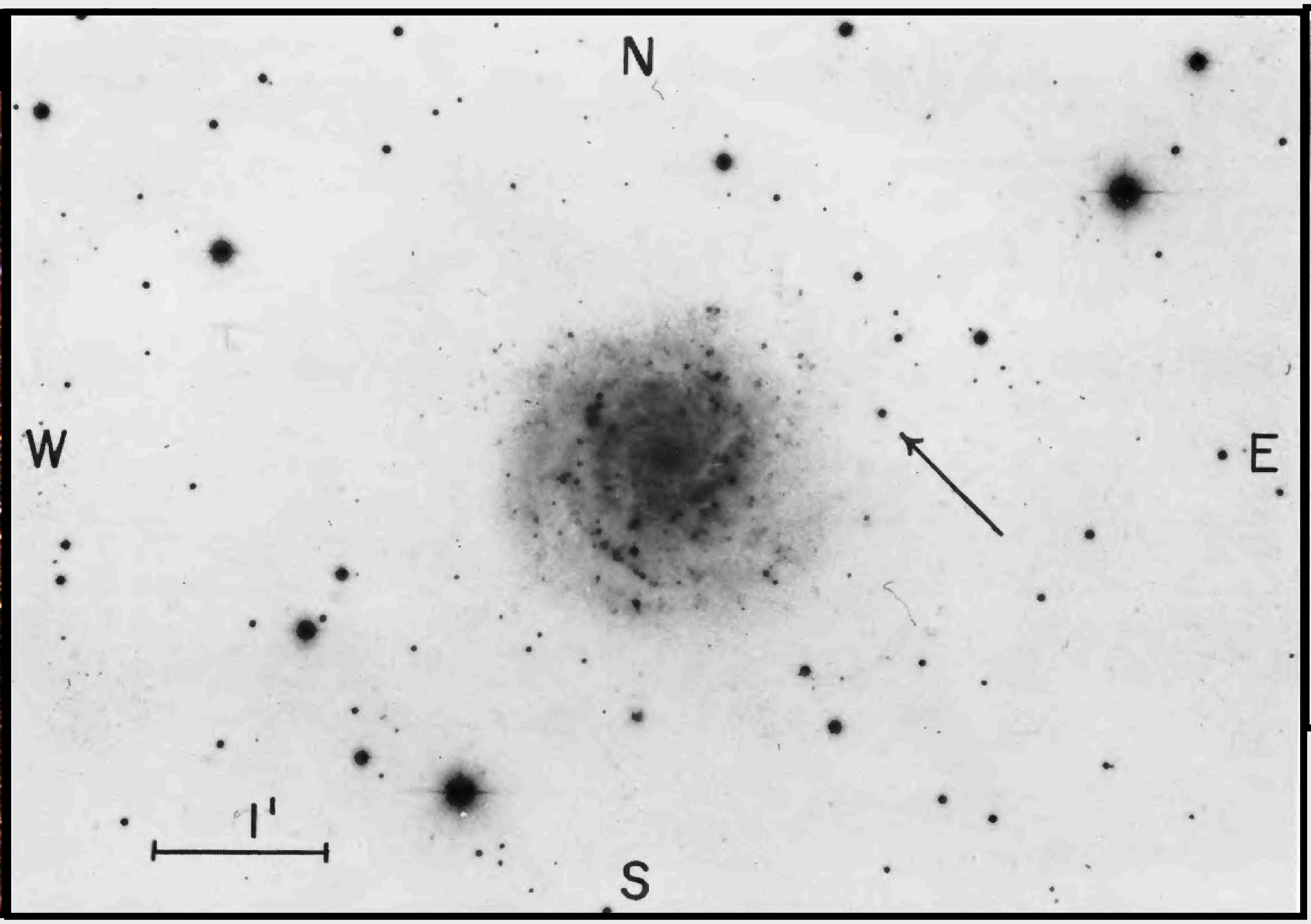
Young Supernova Experiment

CIERA

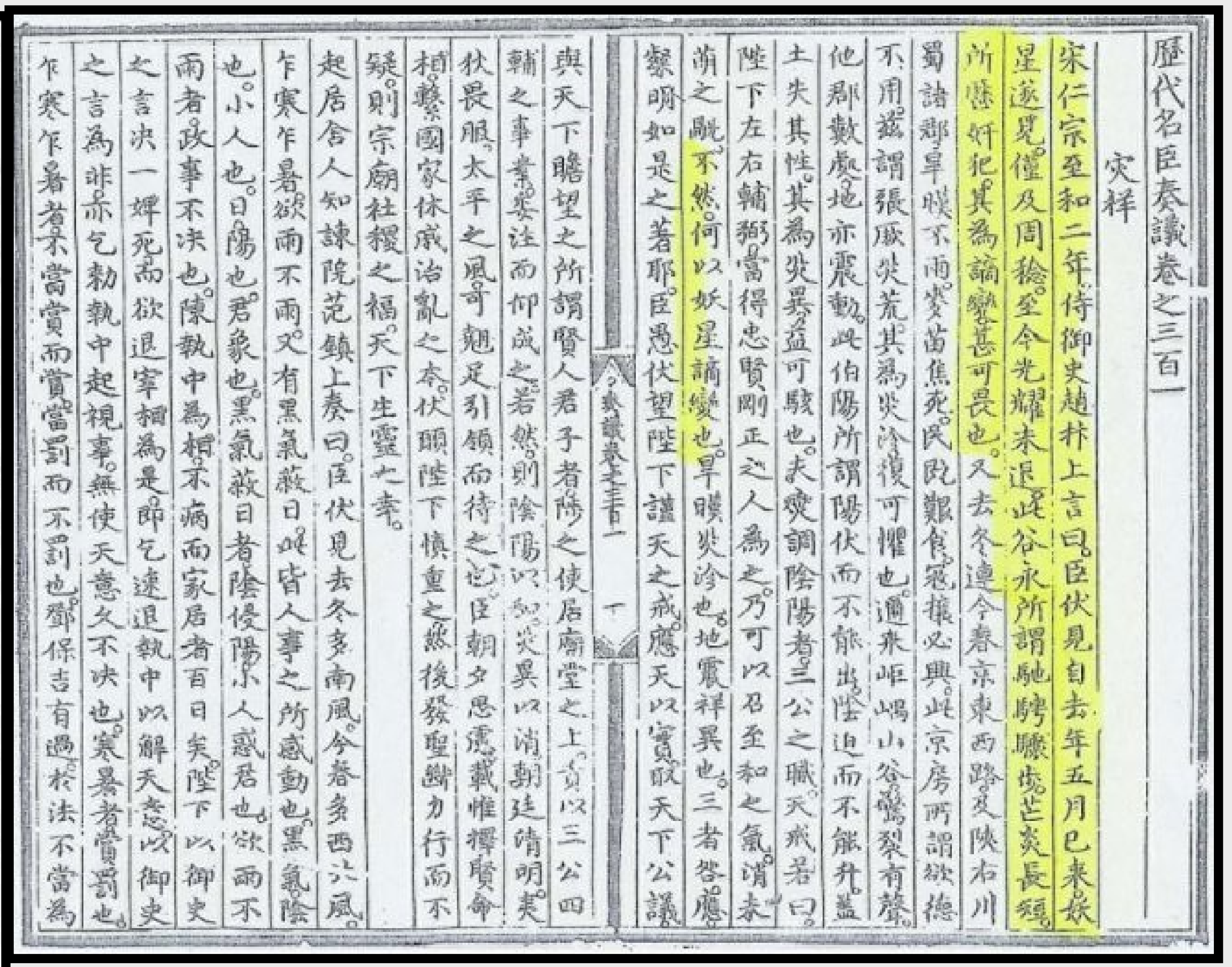
CORE-COLLAPSE SUPERNOVAE DRIVE DISCOVERY IN TIME-DOMAIN ASTRONO



SN1987A (ANO)



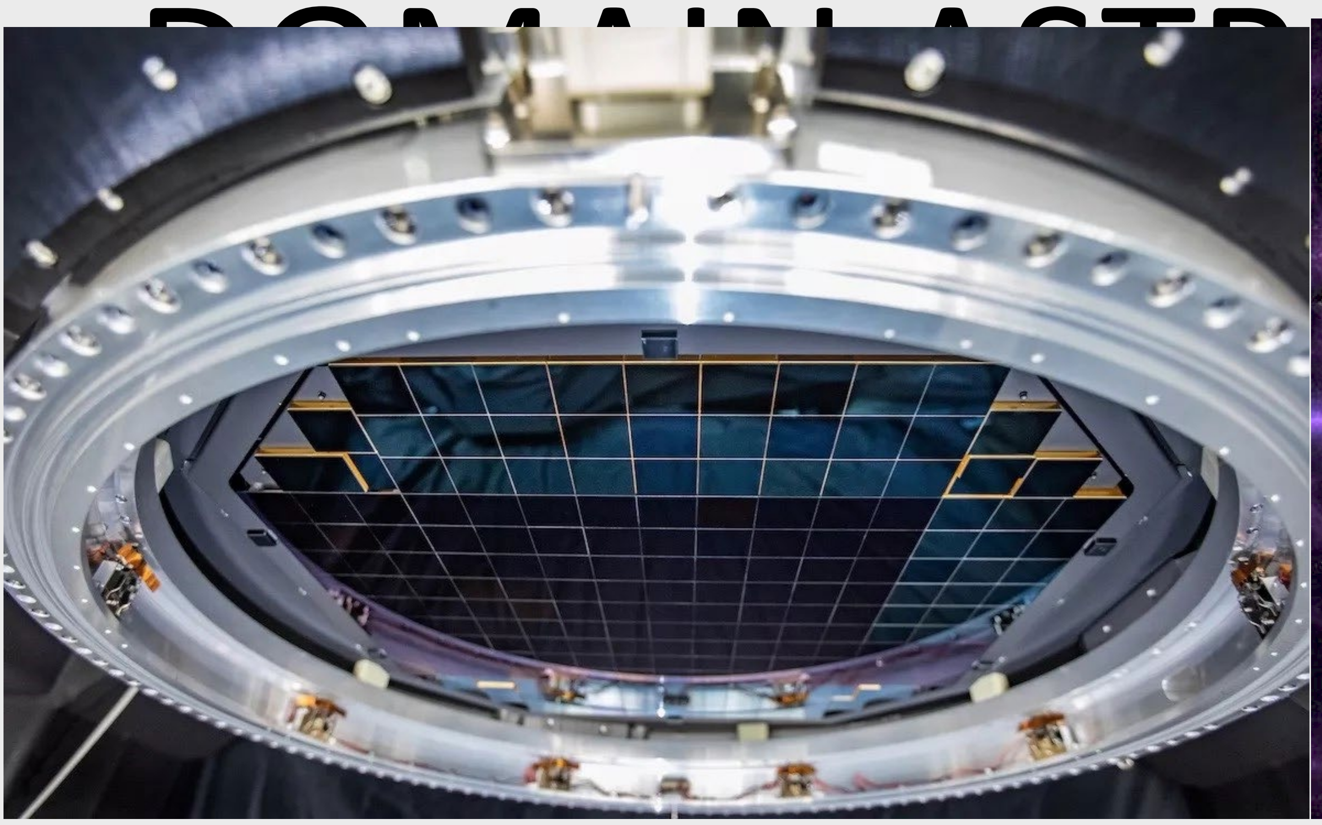
SN1961V (Zwicky 1964)



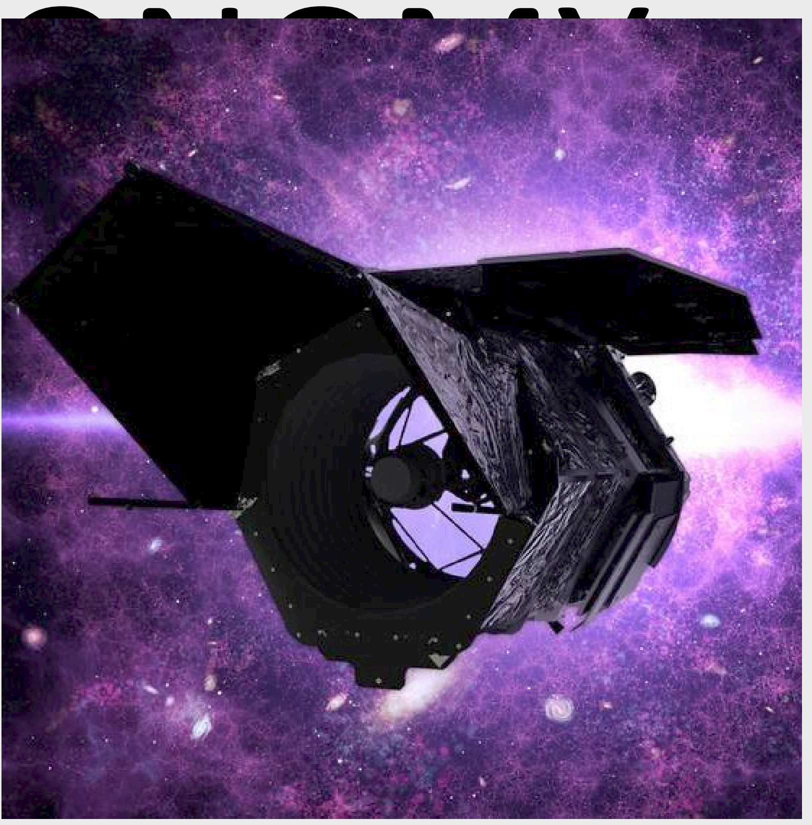
Record of SN1054 (Crab Nebula)

Core-collapse supernovae have always been at the cutting edge of science in time-domain astronomy, nuclear physics, stellar evolution, galaxy feedback

CORE-COLLAPSE SUPERNOVAE DRIVE DISCOVERY IN TIME-DOMAIN ASTRONOMY



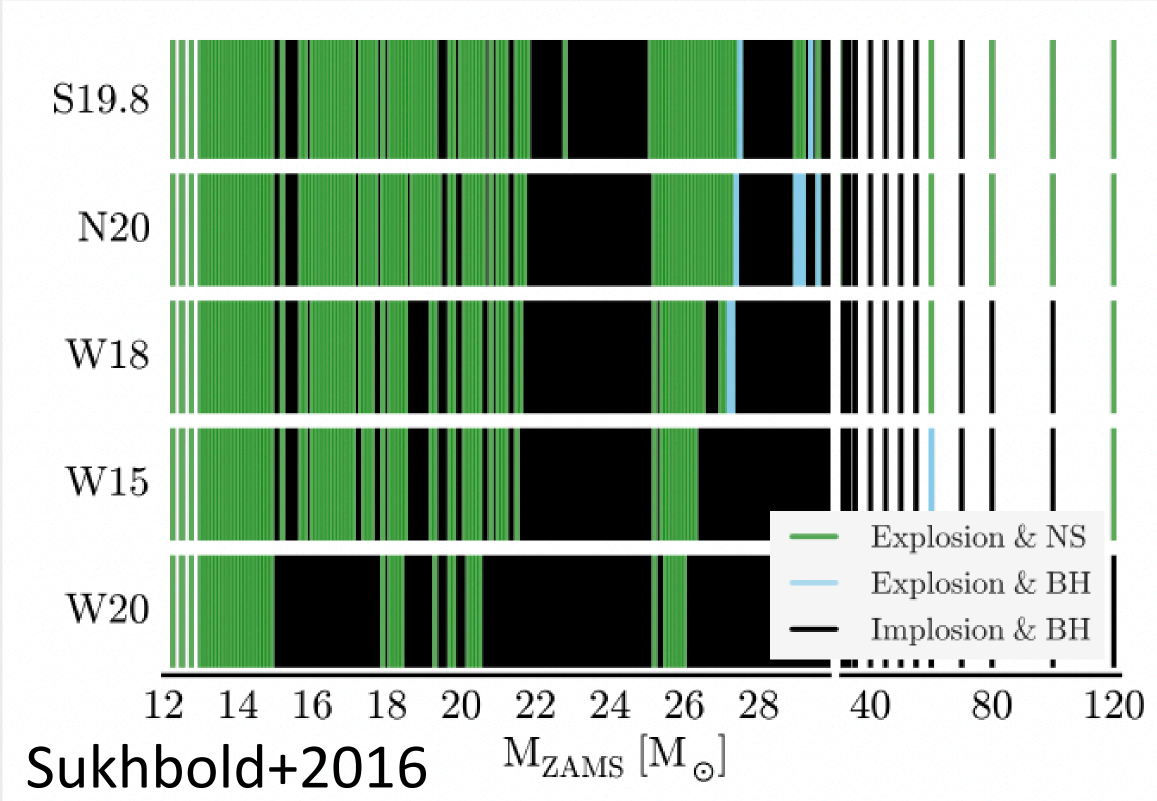
Rubin Observatory camera (SLAC)



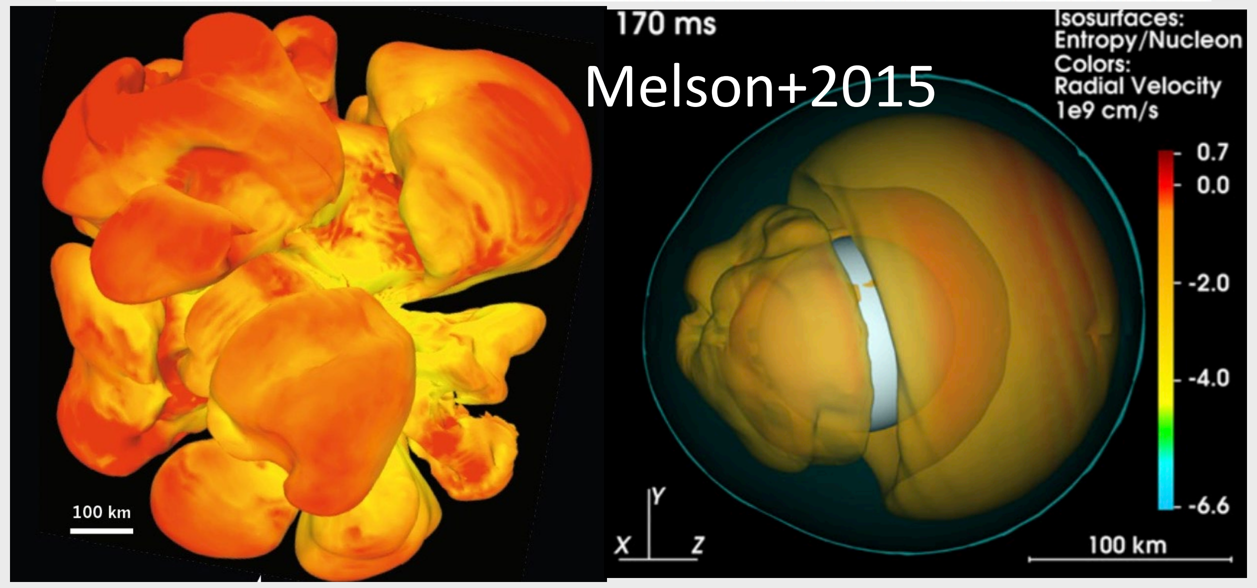
Roman Observatory (NASA)

Also MIDEX STAR-X and UVEX

Observational capabilities

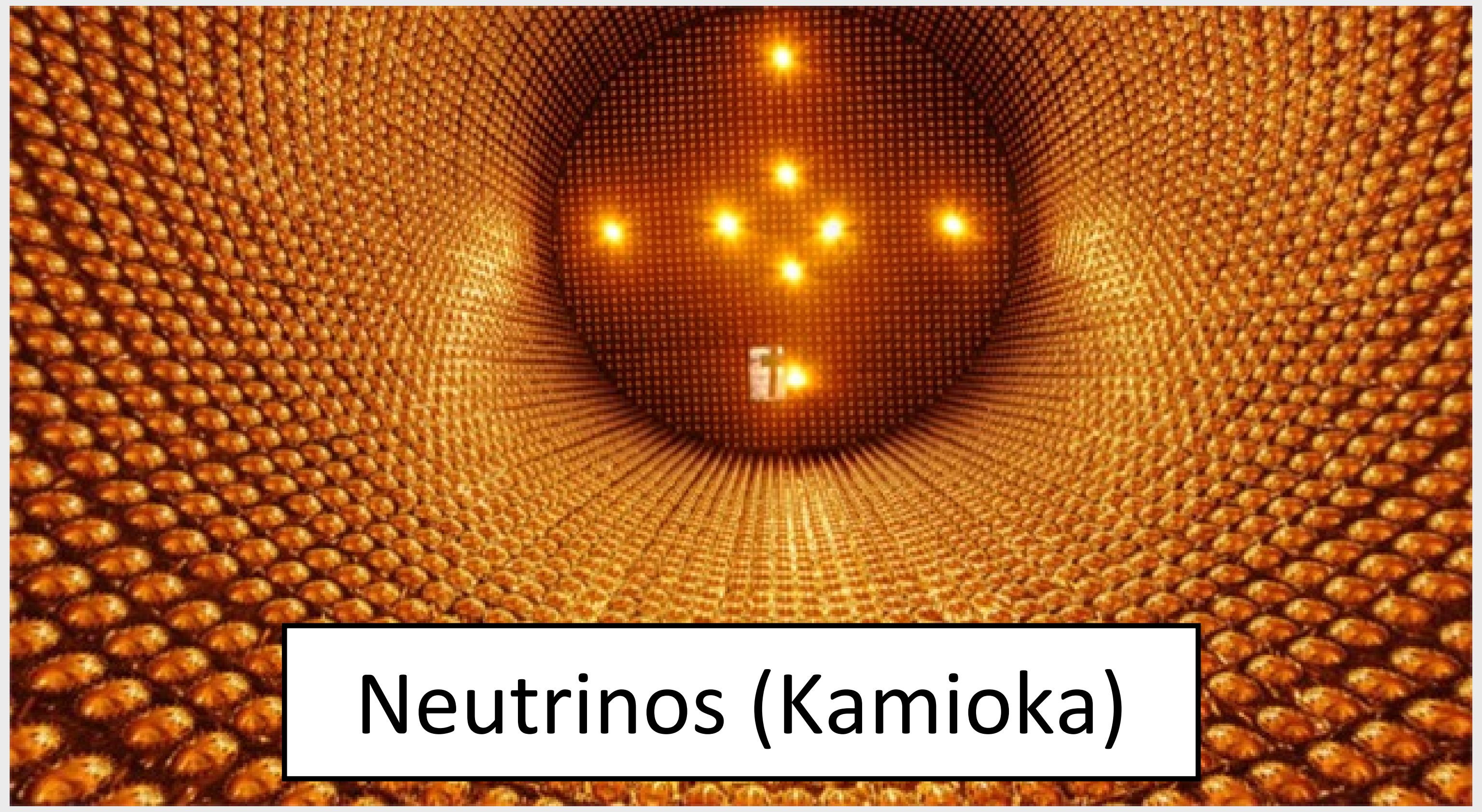


Sukhbold+2016



Melson+2015

Theory



Neutrinos (Kamioka)

GW (LIGO)

Multi-messenger

We live in a unique time for studies of core-collapse supernovae: how can we best **deploy these resources, advocate for ground-breaking science**, and **avoid losing out on any science** in the next ~10 years?

OBSERVATIONAL DOMAIN OF CORE-COLLAPSE SUPERNOVAE

Progenitor stars
(stellar radius, mass, explosion time, shock velocity, local extinction)

Failed Supernovae
(core compactness, comparing supernova to star formation rates)

Variability
(binary evolution, late-stage nuclear burning, explosive mass loss)

Shock cooling
(stellar radius, mass, explosion time, shock velocity, local extinction)

Flash spectroscopy
(local CSM density, composition)

Multi-messenger
(nuclear physics, core-collapse mechanism, NS/BH formation)

Explosion properties
(energy, ejecta mass, nickel mass, velocities)

CSM interaction
(structure, composition environment, mass-loss history)

Light echoes
(geometry of explosion, probing older events)

Years to days

Hours to days

Months to years+

Core collapse

Post-maximum

OBSERVATIONAL DOMAIN OF CORE-COLLAPSE SUPERNOVAE

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Progenitor stars

<40 Mpc

Shock cooling
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Flash spectroscopy
(local CSM density, composition)

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Early emission

<150-200 Mpc (z<0.04)

closer for MM

Explosion properties
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CSM interaction
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Light echoes
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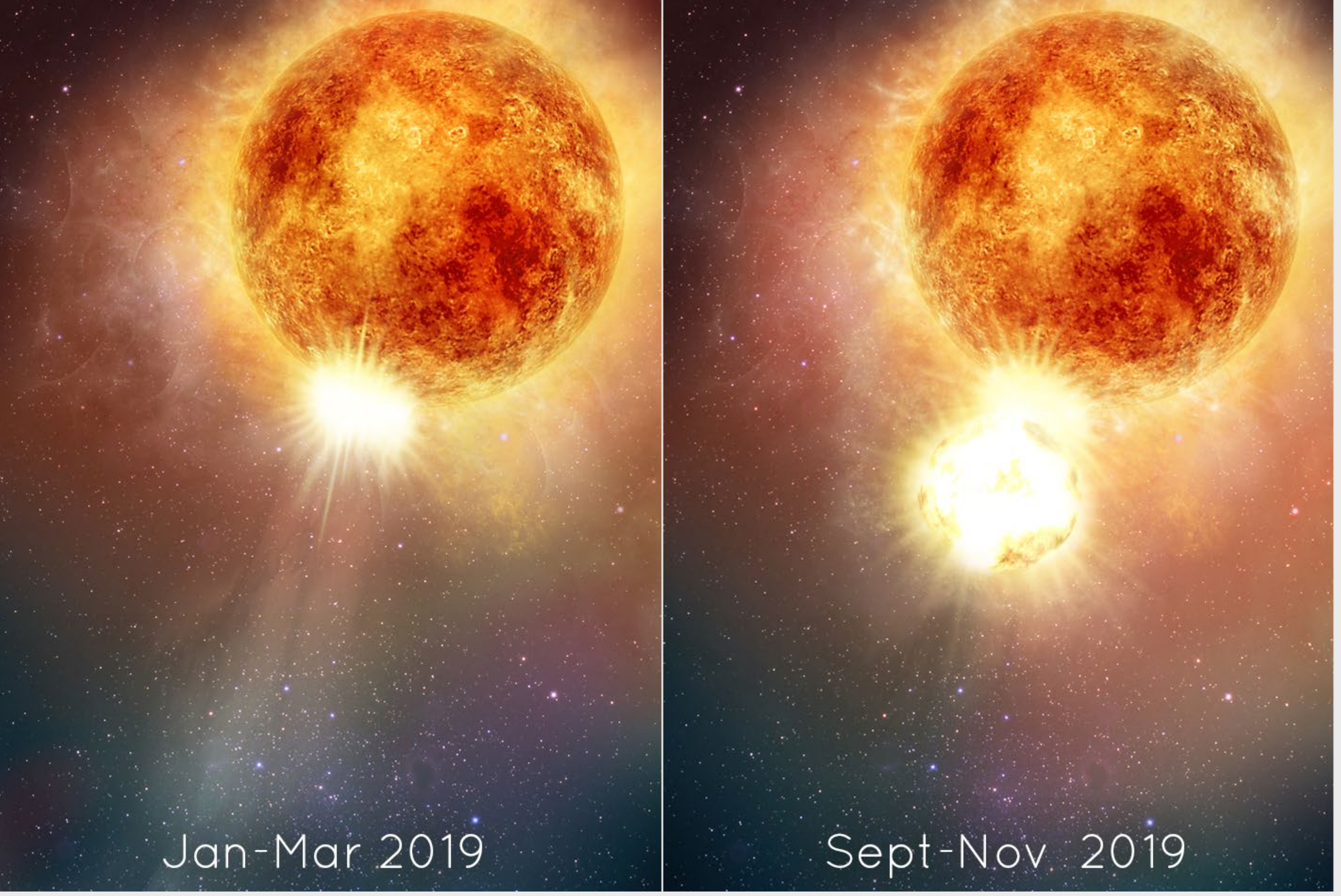
Peak/late-time emission

<1 Gpc (z<0.2)

LEs are <10 Mpc



Red supergiants and Betelgeuse
(Credit: NASA/ESA)

Progenitor stars

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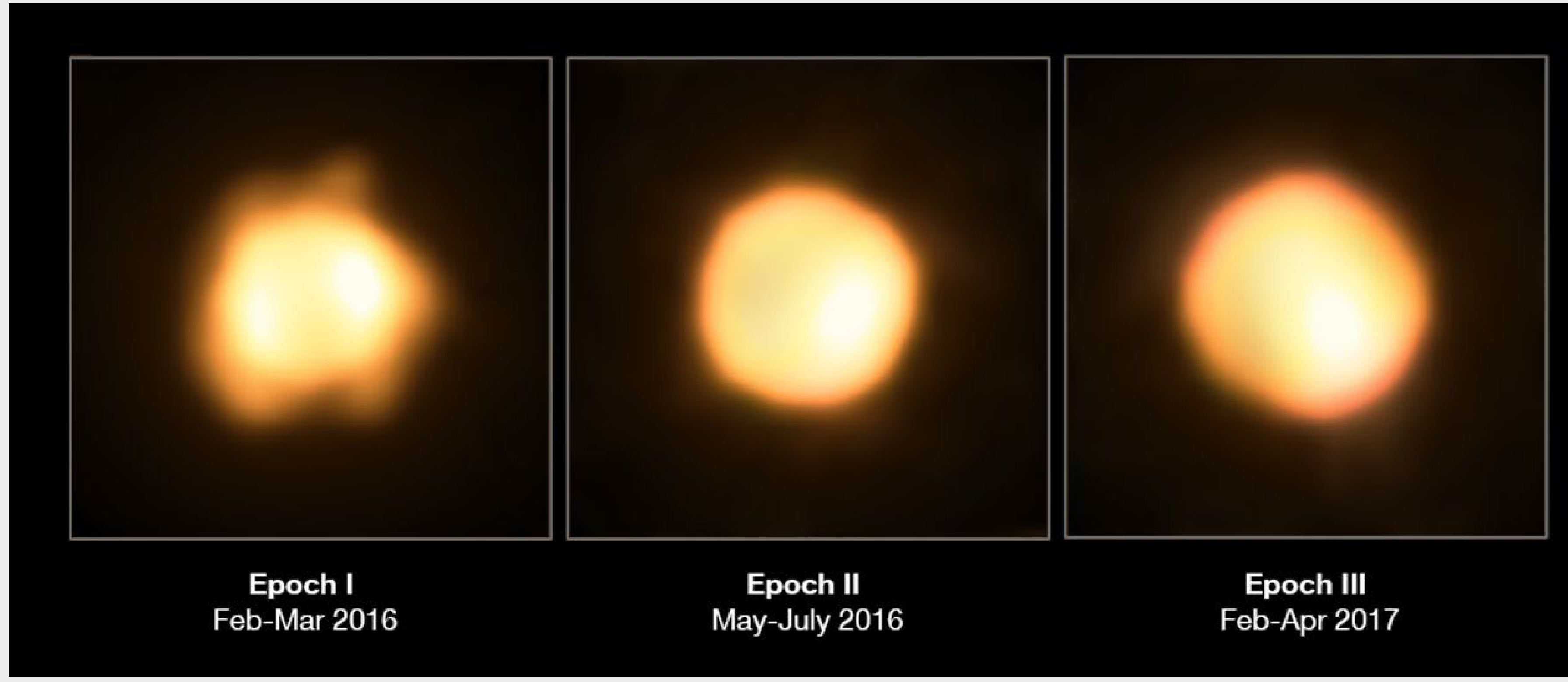
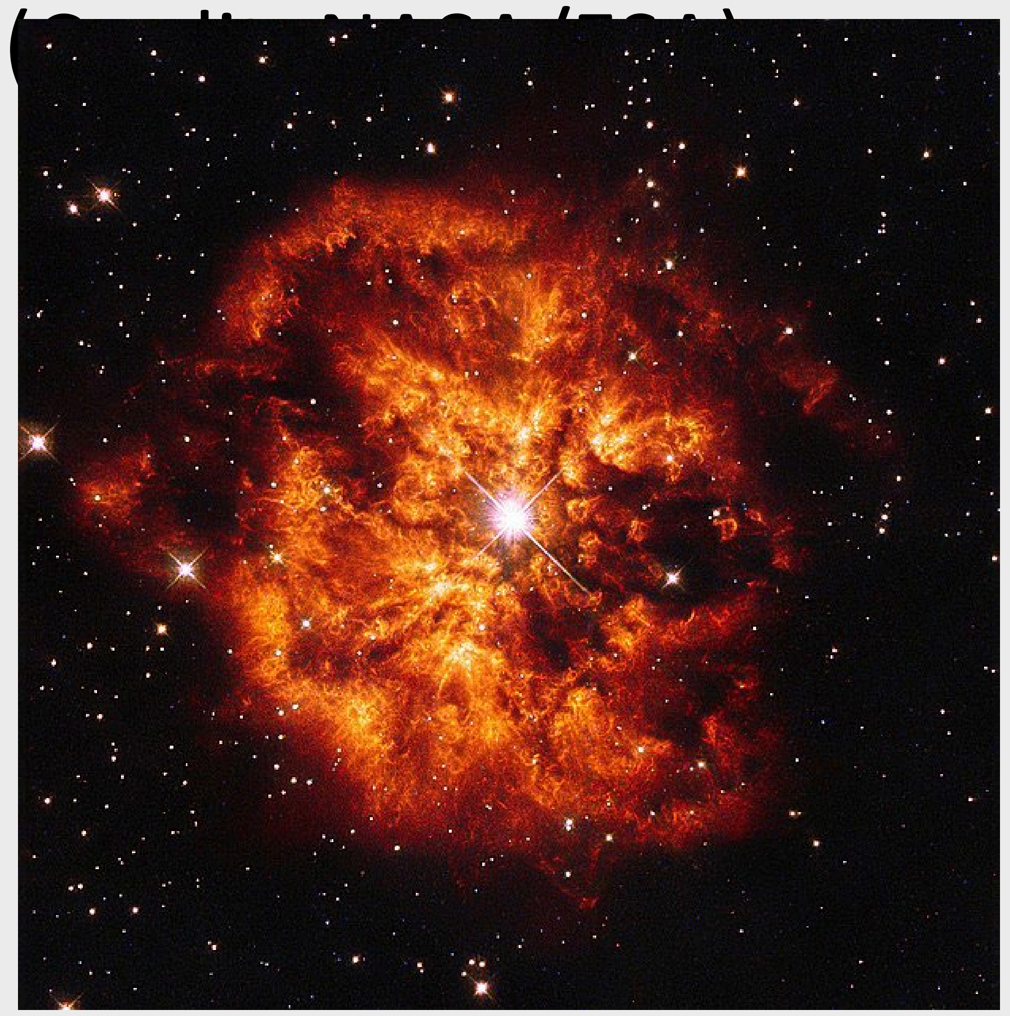
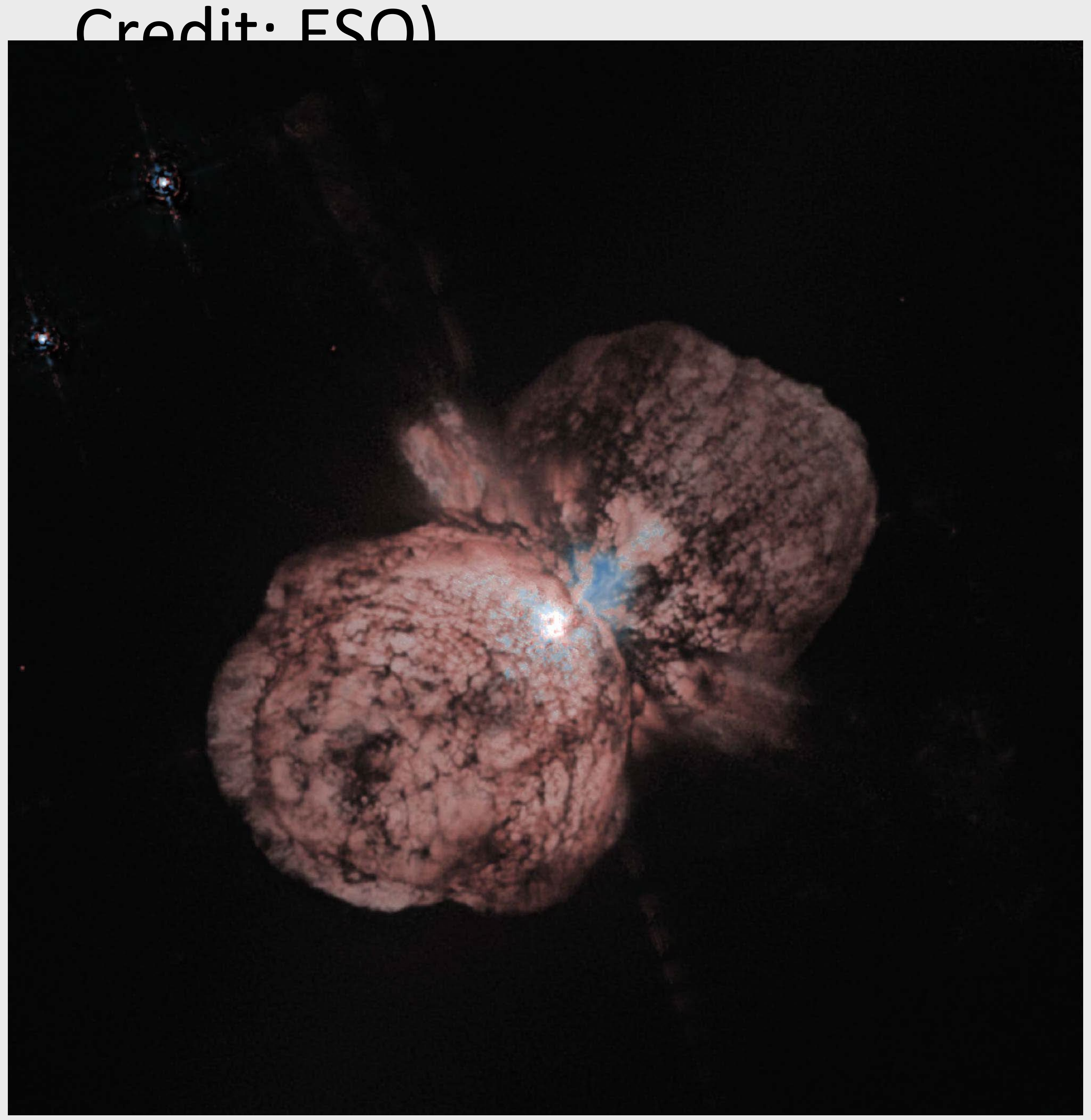


Yellow supergiants (HR 5171, Credit: ESO)



Wolf Rayet stars (WR124, Credit: NASA/ESA)



Luminous blue variables (Eta Car, Credit: NASA/ESA)

Red Supergiant

Type II-P

Blue Supergiant

SN 1987A (faint, slow)

LBV (η Car)

SN 2005gl
Gal-Yam et al. 2007

Type IIn (dense CSM)

Late W-R (WN)

Type IIL/IIb (little H)

Early W-R (WC/WO)

Type Ib (~~H~~, He)

Massive Binaries

Type Ic (~~He~~)

Red Supergiant — Type II-P

Blue Supergiant — SN 1987A (faint, slow)

LBV (η Car) — Type IIn (dense CSM)

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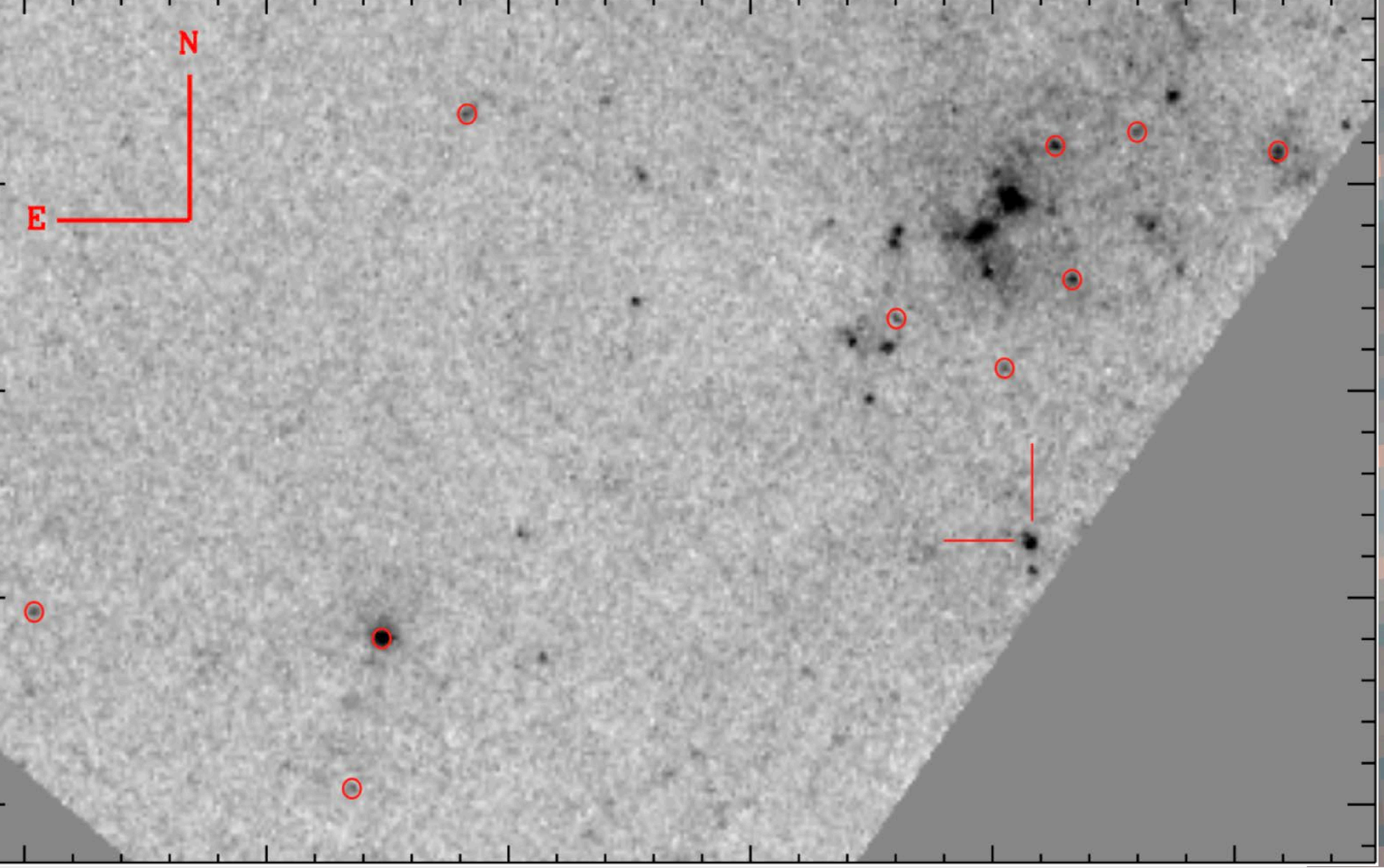
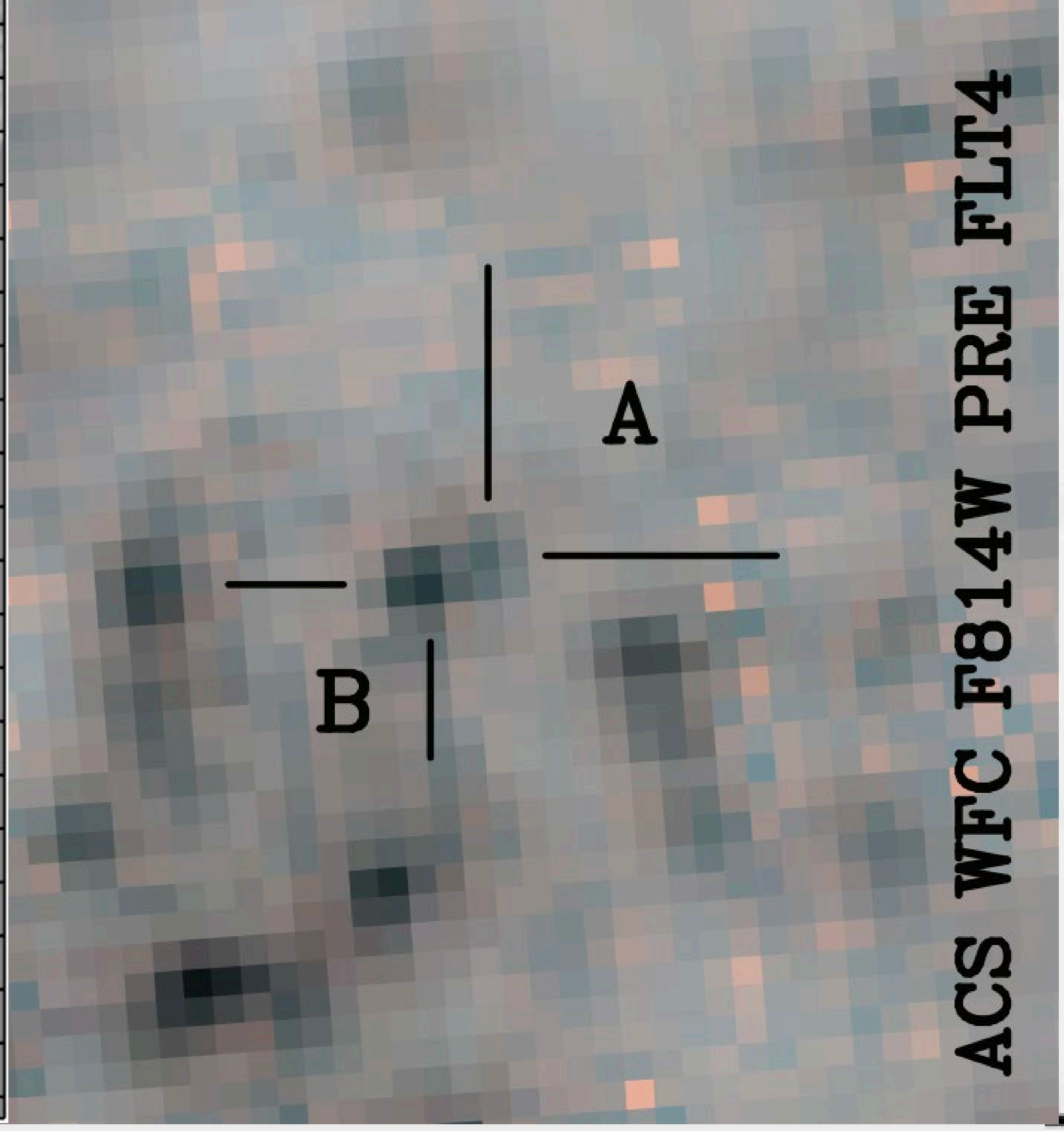
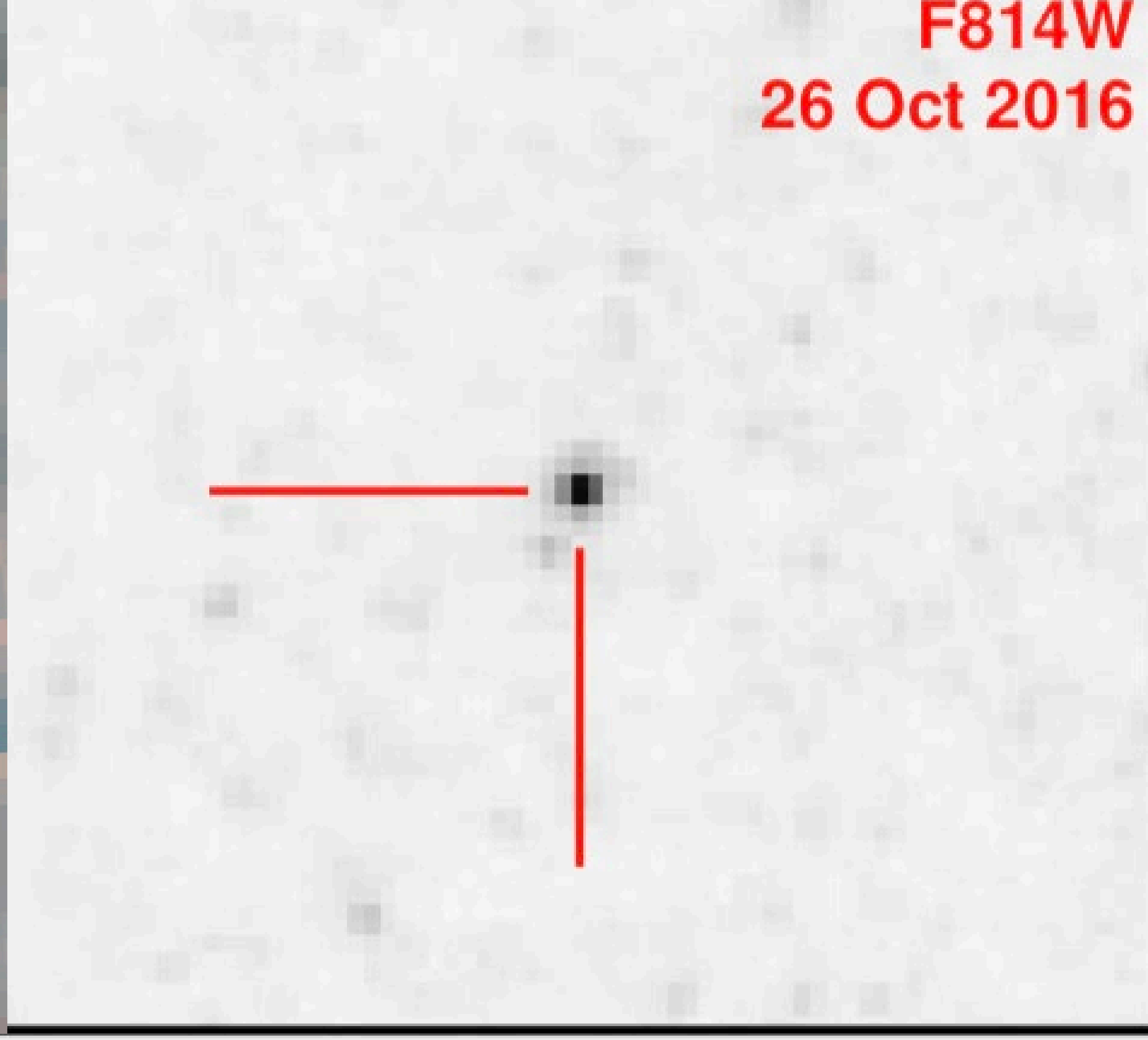


SN 2016gkg
(26 Mpc; Kilpatrick+2017)



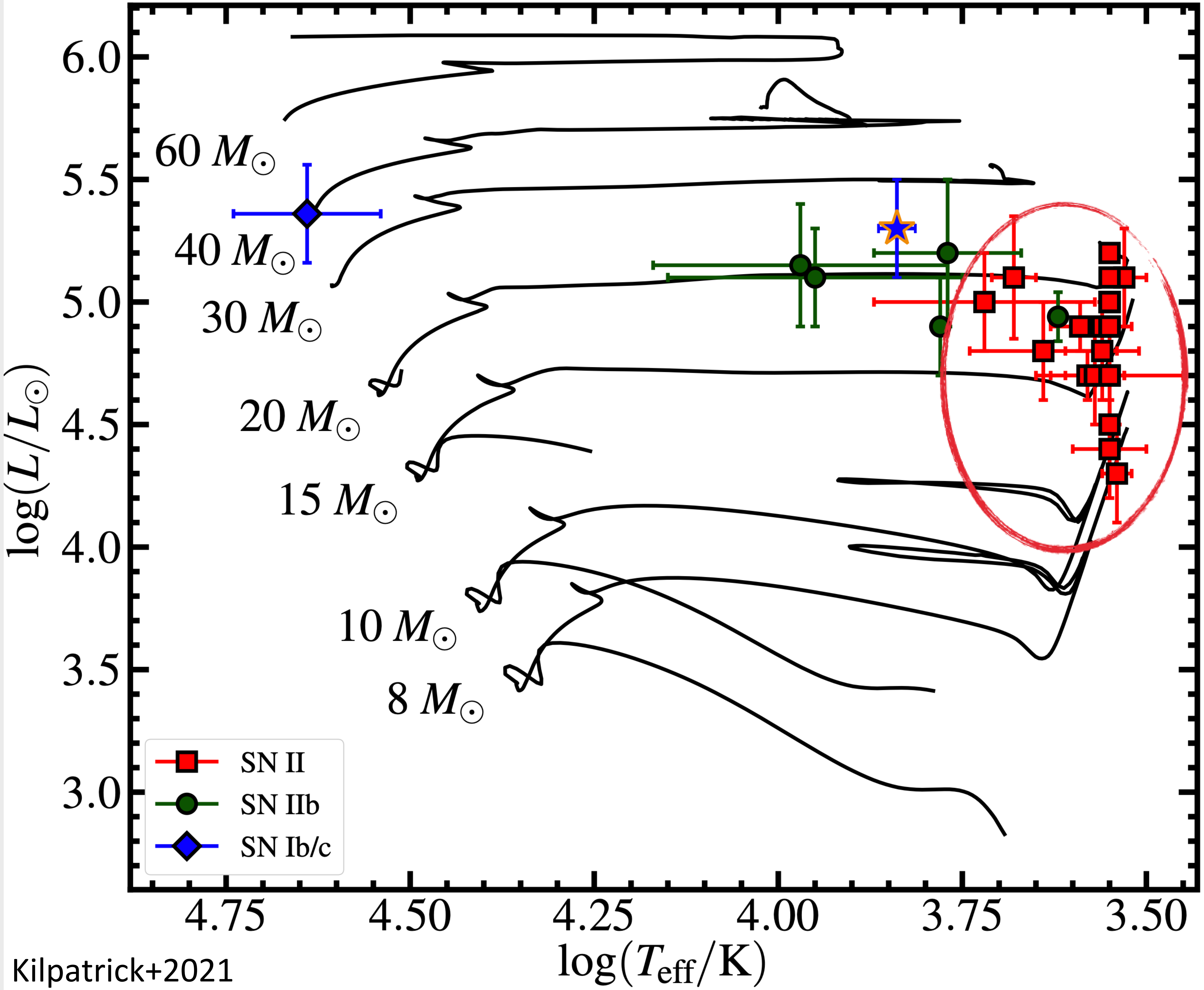
SN 2012ec
(17 Mpc; Maund+2013)



SN 2017eaw
(6.5 Mpc; Kilpatrick+2018)

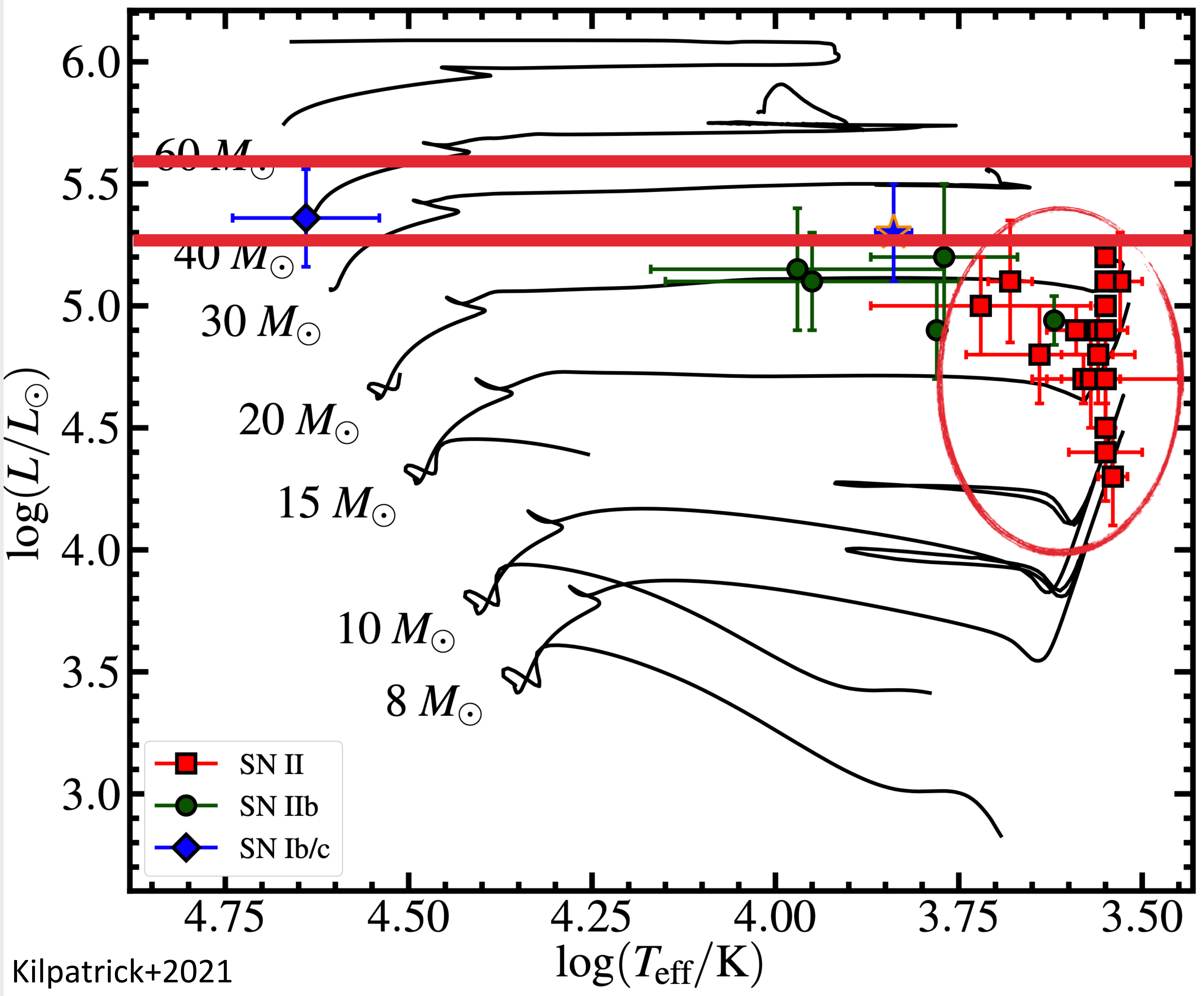
There are ~20 confirmed, directly-imaged progenitor stars of SNe

Mostly RSG progenitors of SNe II-P



Type II SNe

Kilpatrick+2021



Kilpatrick+2021

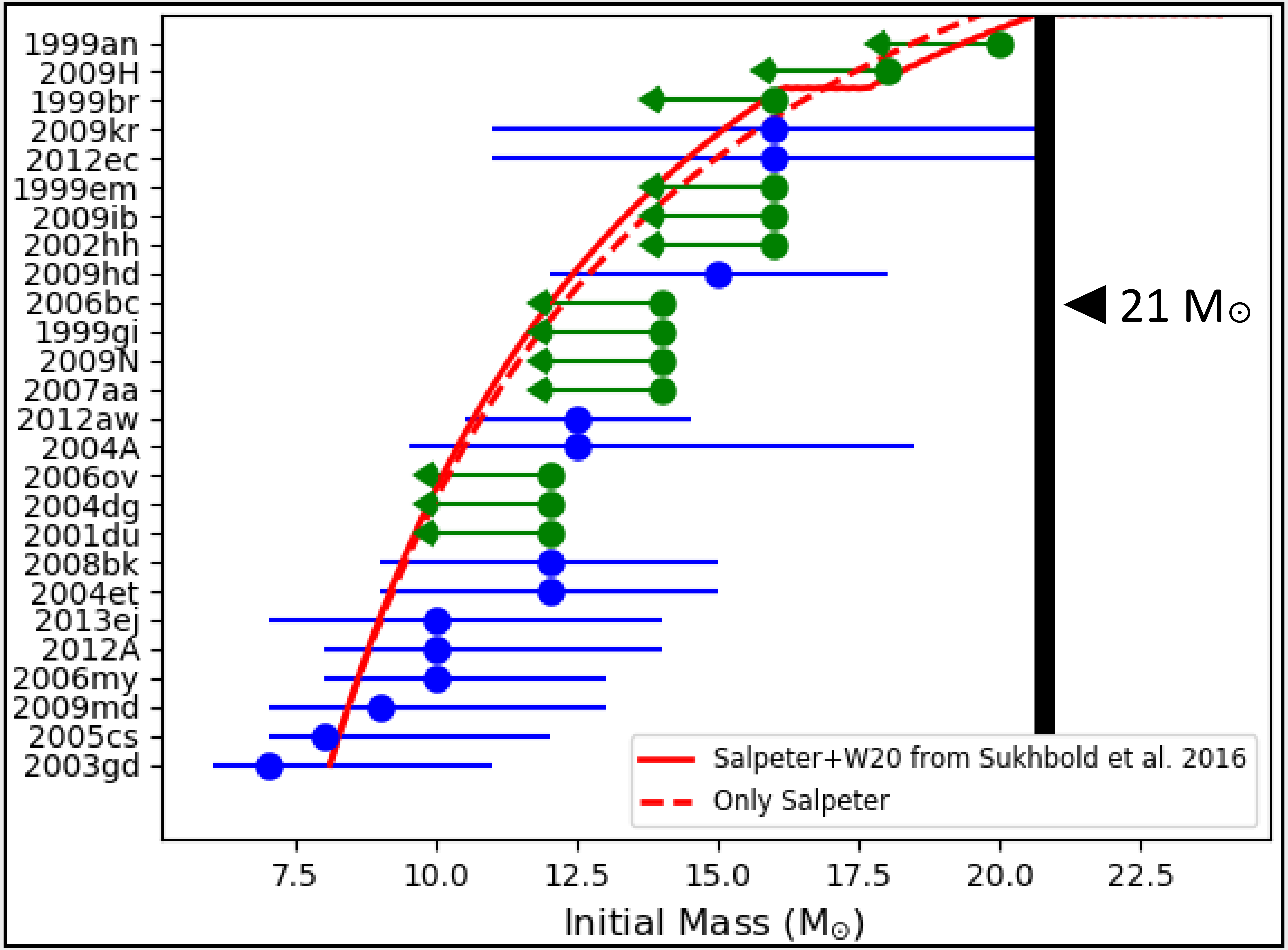
H-D limit

Highest L progenitor

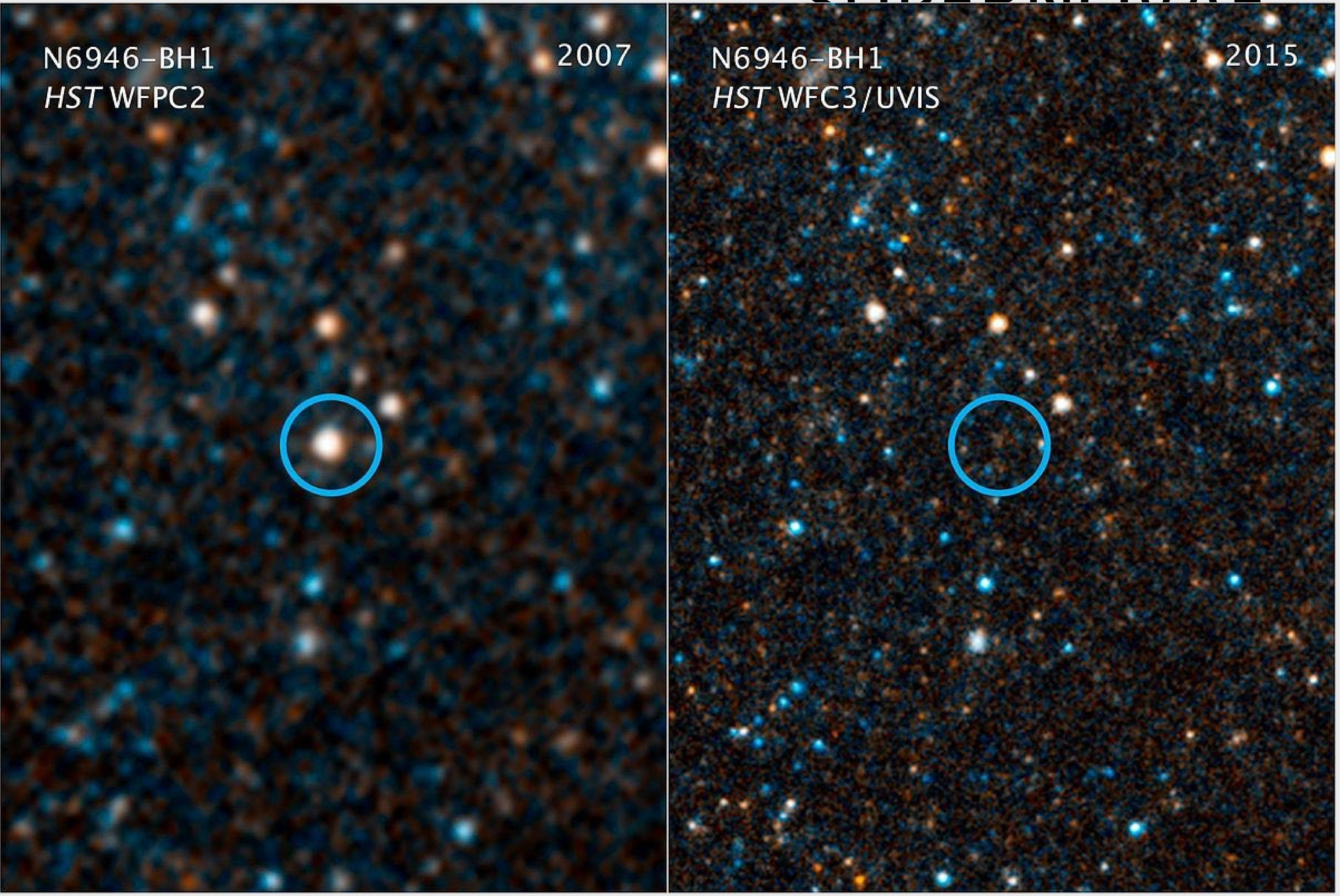
Type II SNe

Constraints on the upper limit is dominate by the highest mass progenitor known

A 3x increased population size can distinguish Salpeter from theoretical "final mass functions"



FAILED SUPERNOVAE

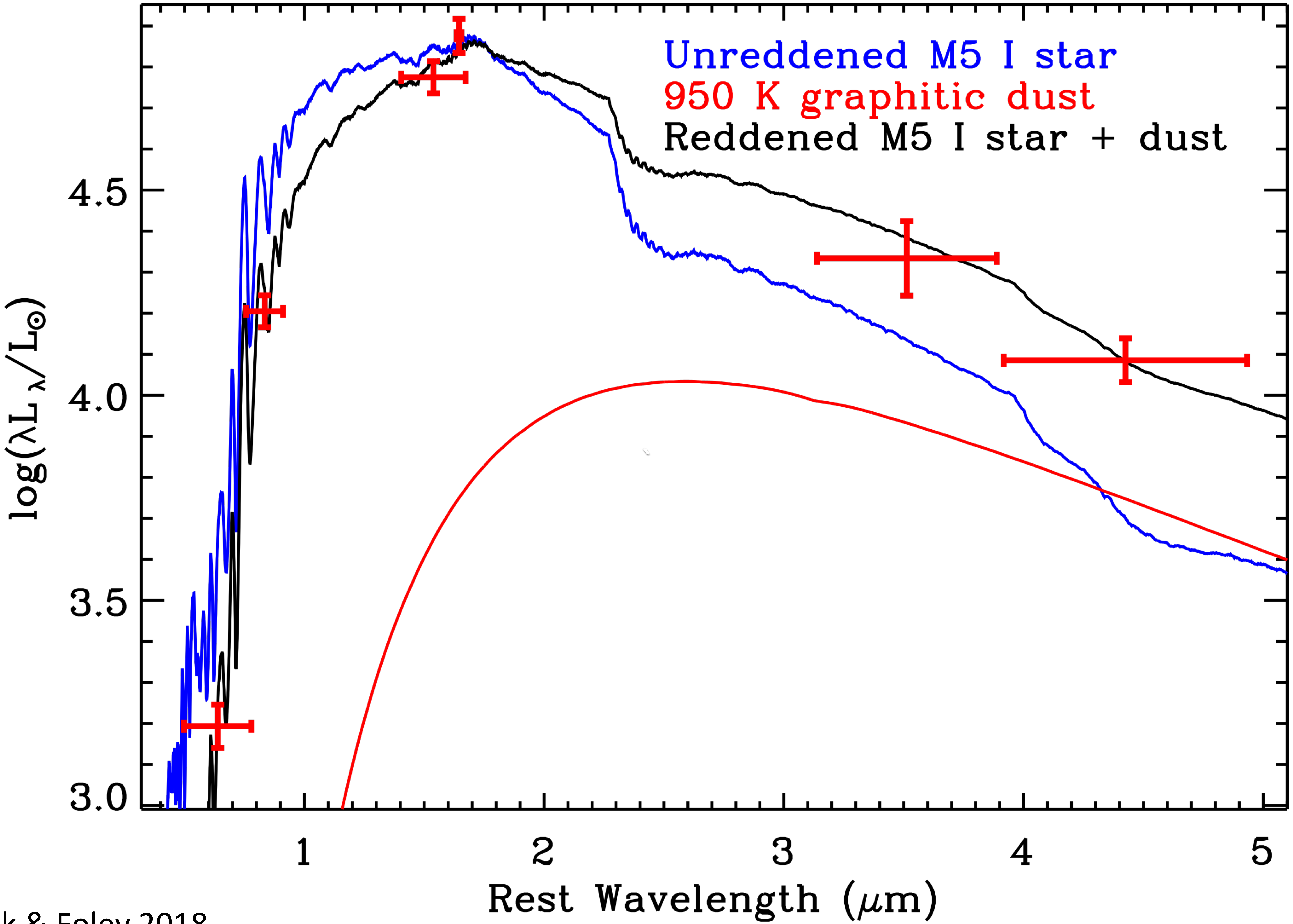


One possible explanation is red supergiants collapse into black holes as "failed supernovae"

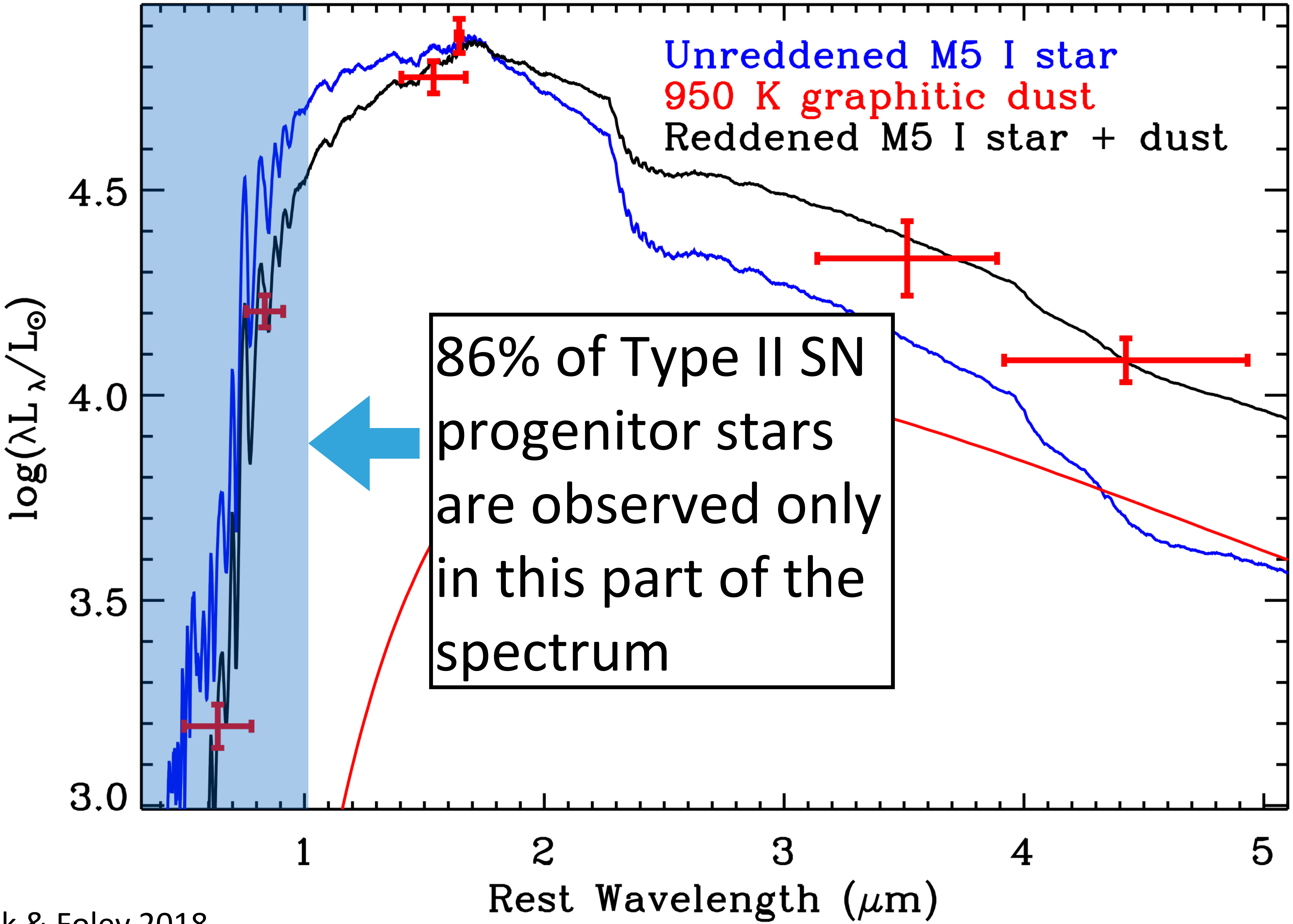
Could also be an extreme dimming event (see recent work by Jencson+2021).

Rubin and Roman can observe this phenomenon across nearby galaxies

Credit: NASA/OSU
See Adams+2017

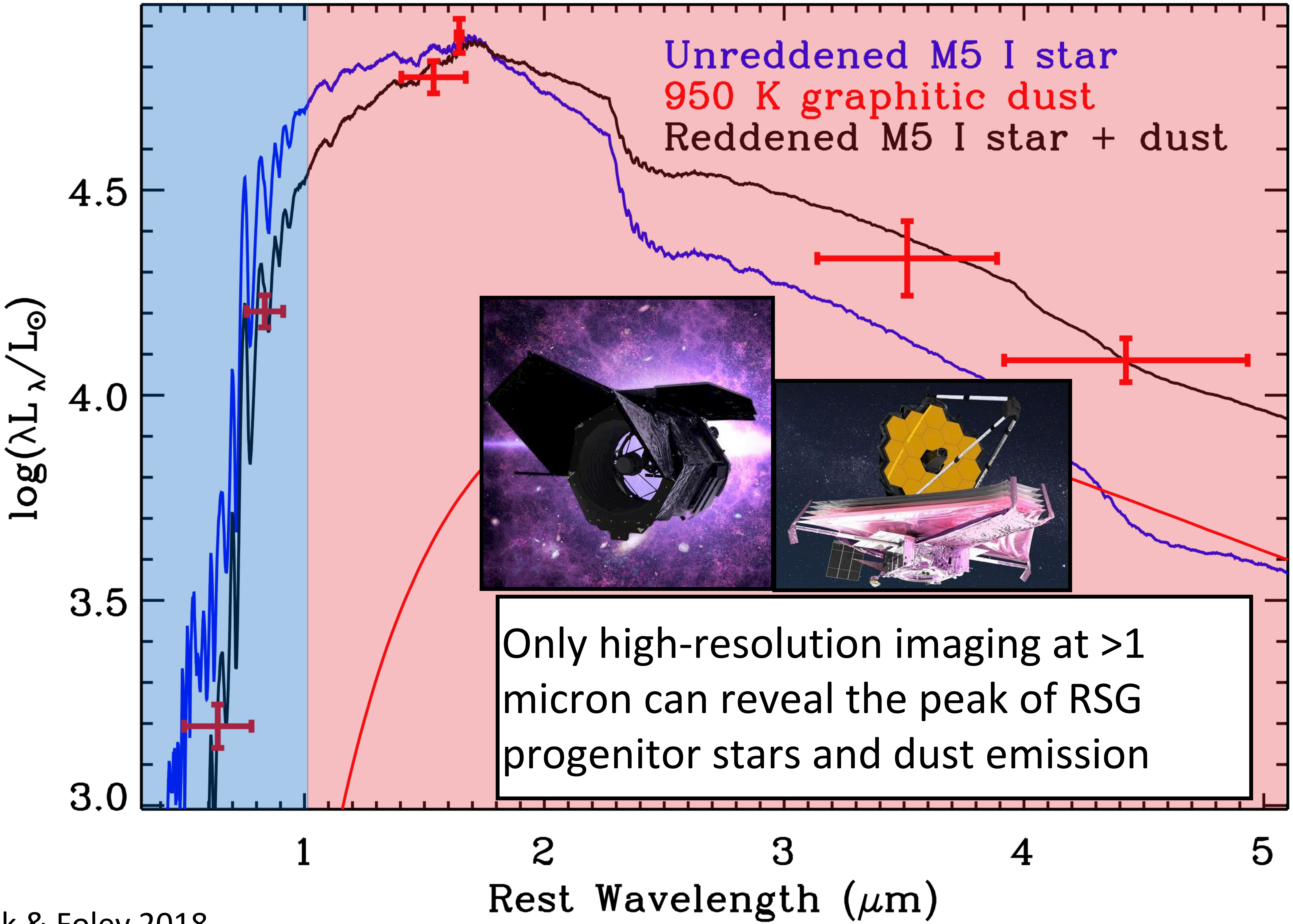


Kilpatrick & Foley 2018



86% of Type II SN progenitor stars are observed only in this part of the spectrum

Kilpatrick & Foley 2018



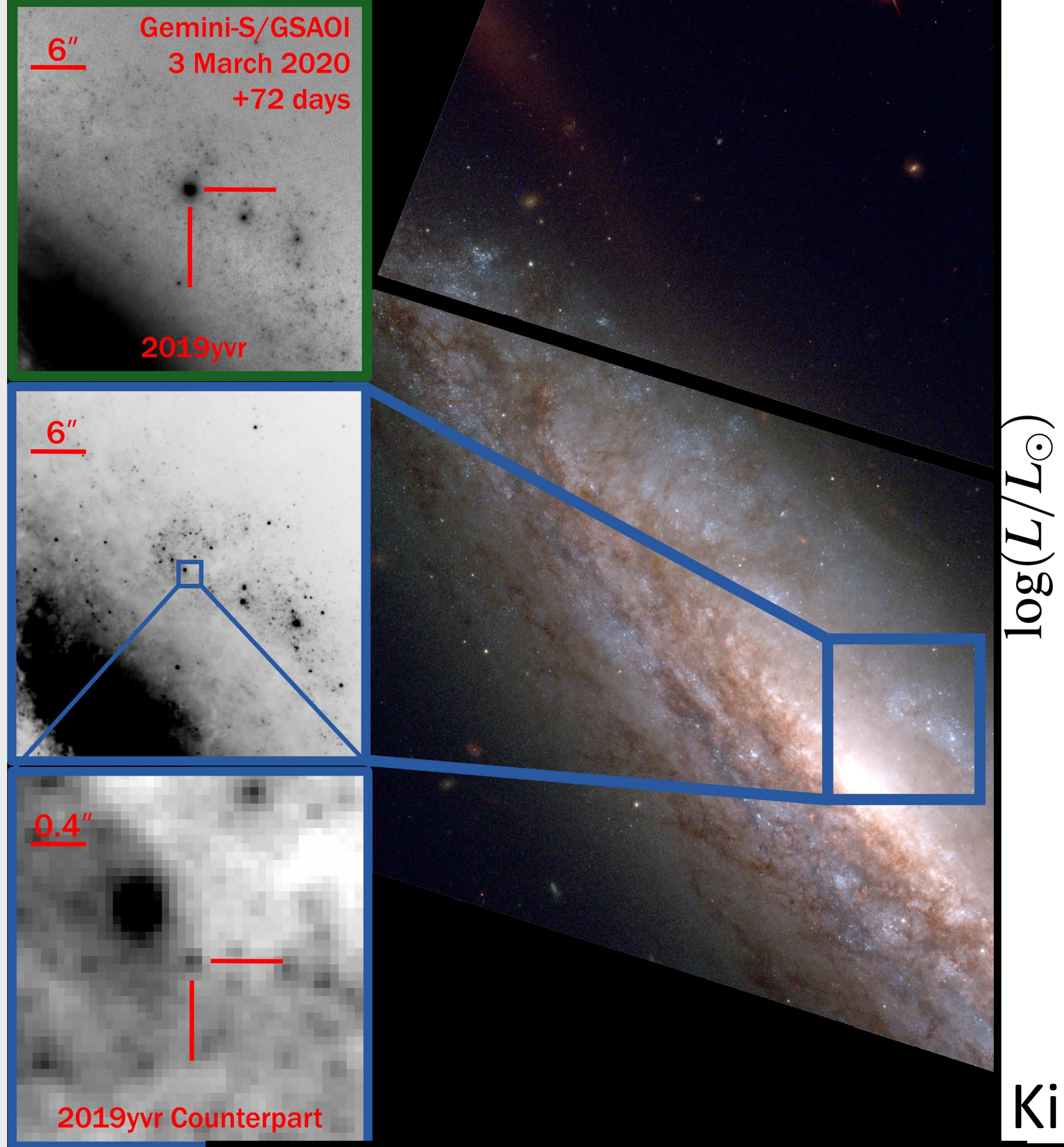
Only high-resolution imaging at >1 micron can reveal the peak of RSG progenitor stars and dust emission

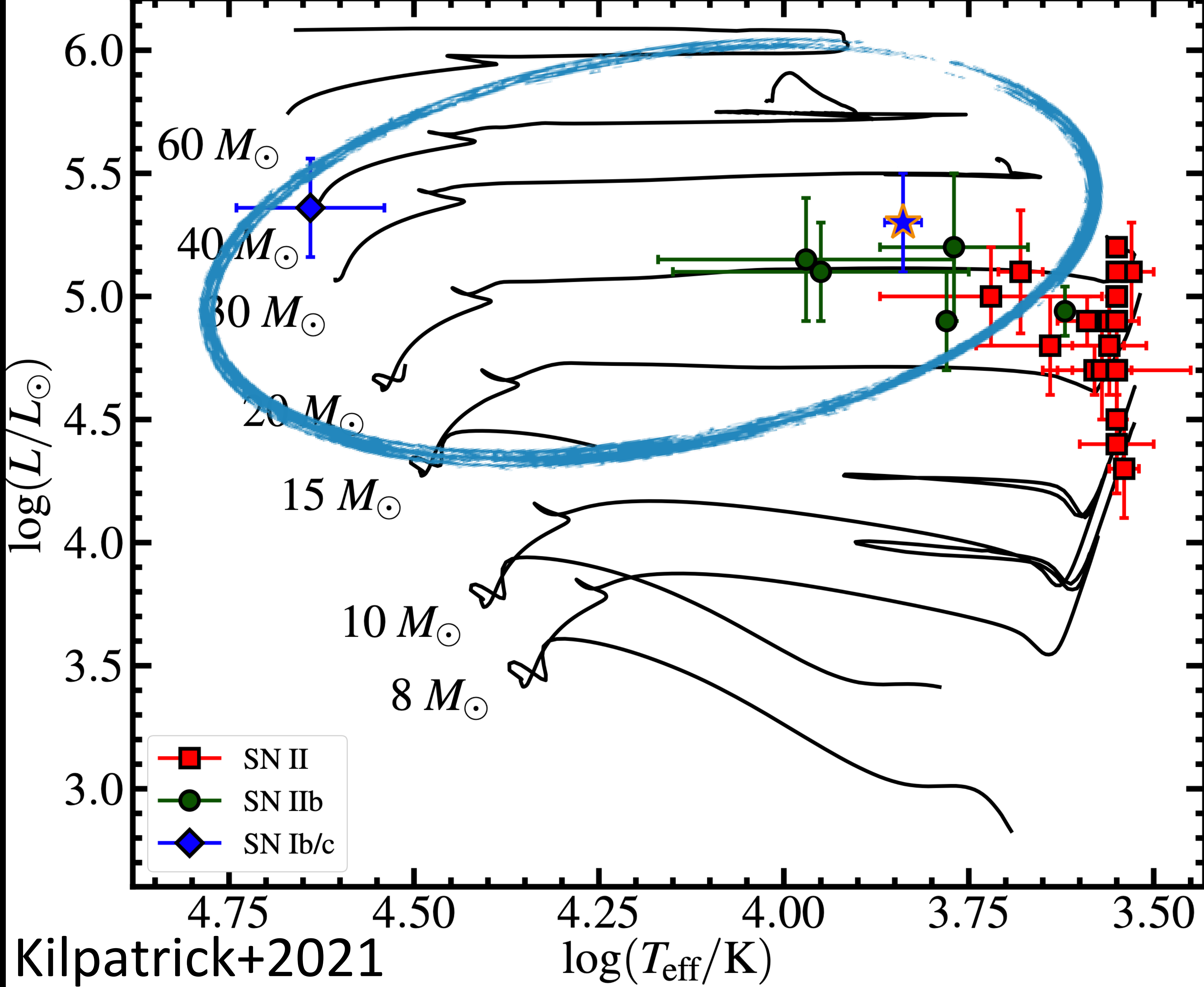
Kilpatrick & Foley 2018

Stripped-envelope stars from HST/optical + UV imaging

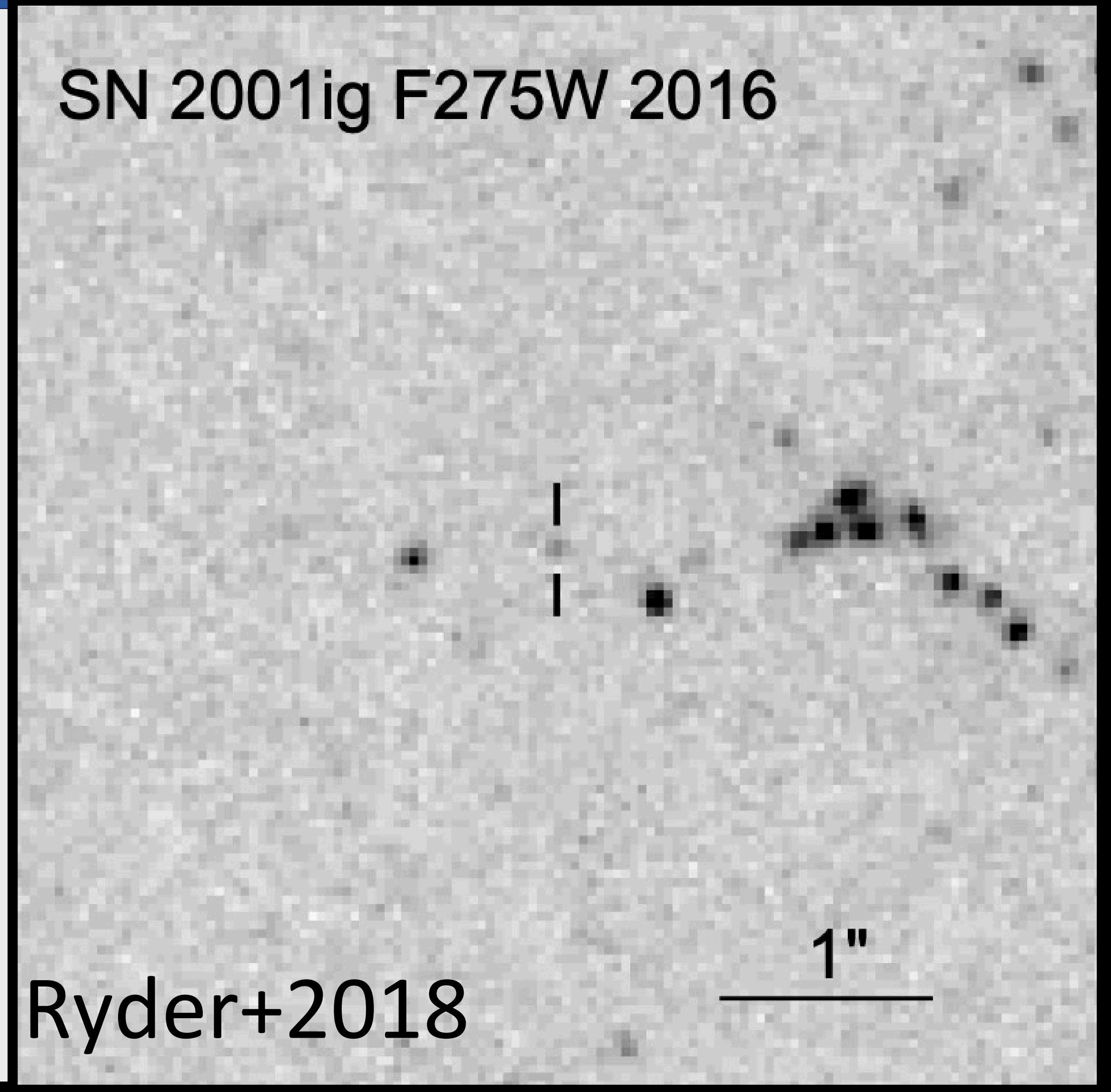
Rubin light curves down to ~24.5 mag, but **UV and faint optical companion stars will be inaccessible after HST**

Resolution and blue sensitivity key

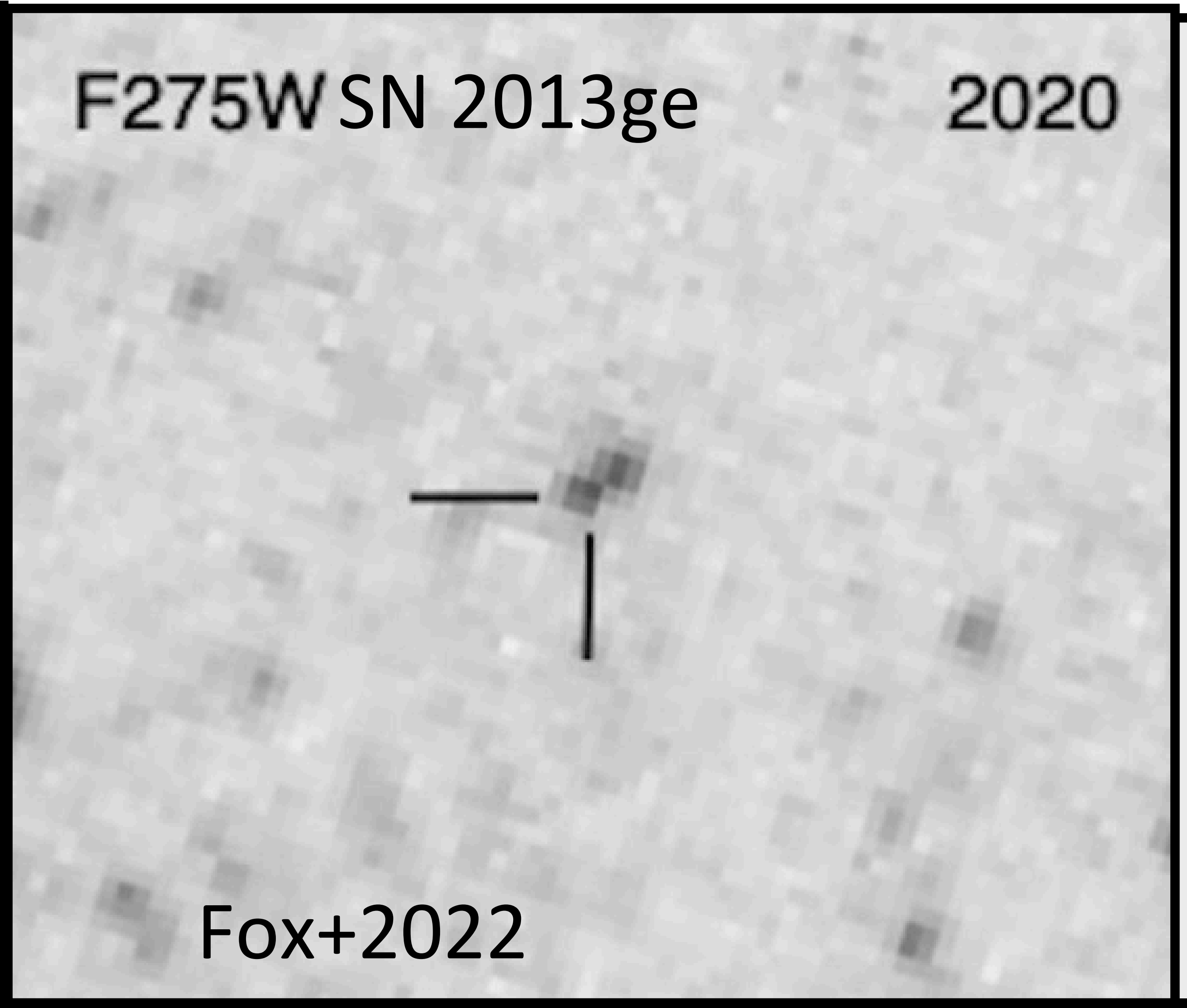




Kilpatrick+2021



Ryder+2018

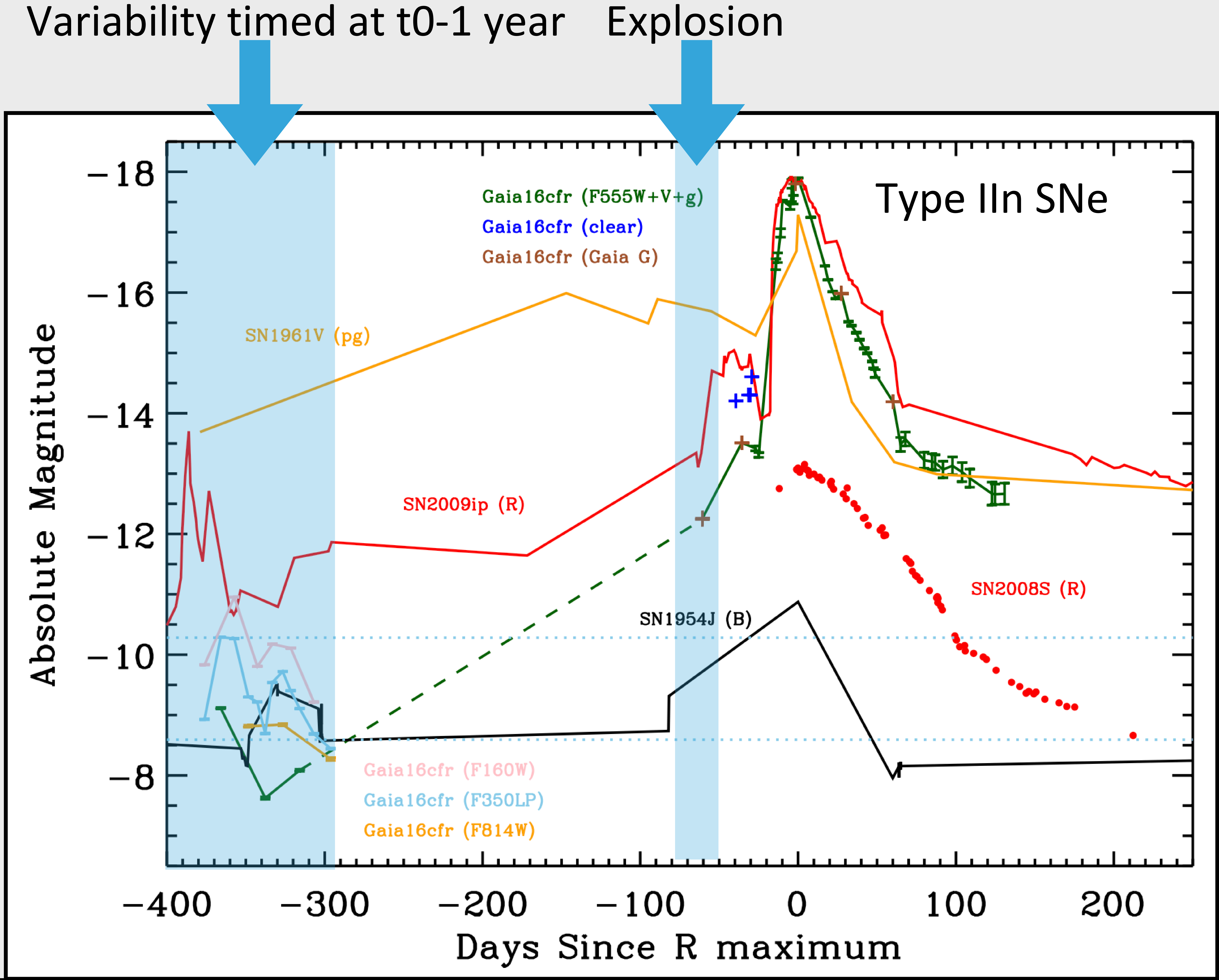


Fox+2022

Rubin will enable light curves of progenitor stars and variability before they explode

Most of this science has been achieved with HST to date, but at limited cadence and optical coverage

Are these even CCSNe or terminal explosions?


Variability timed at t0-1 year

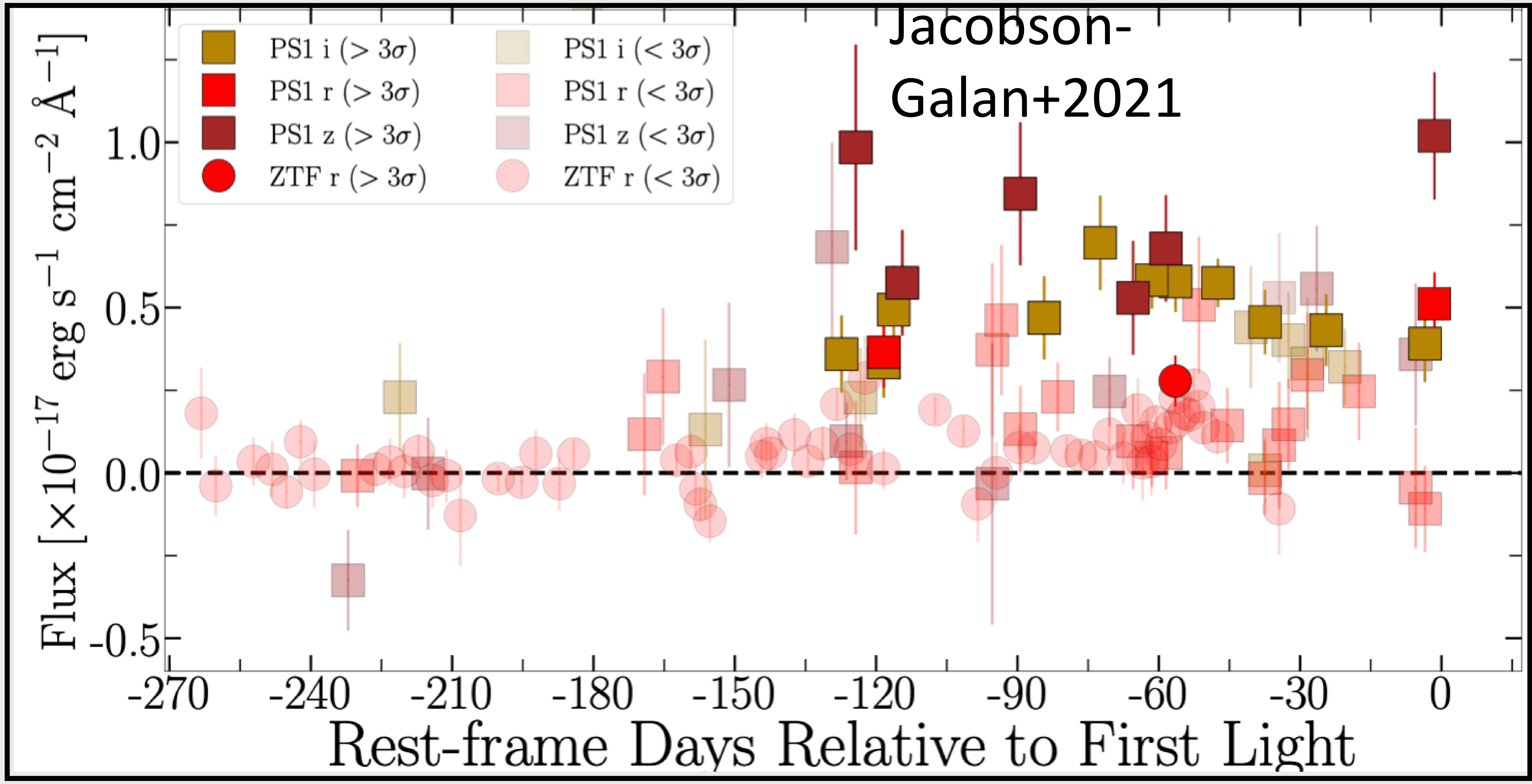
Explosion

SN 2020tlf precursor

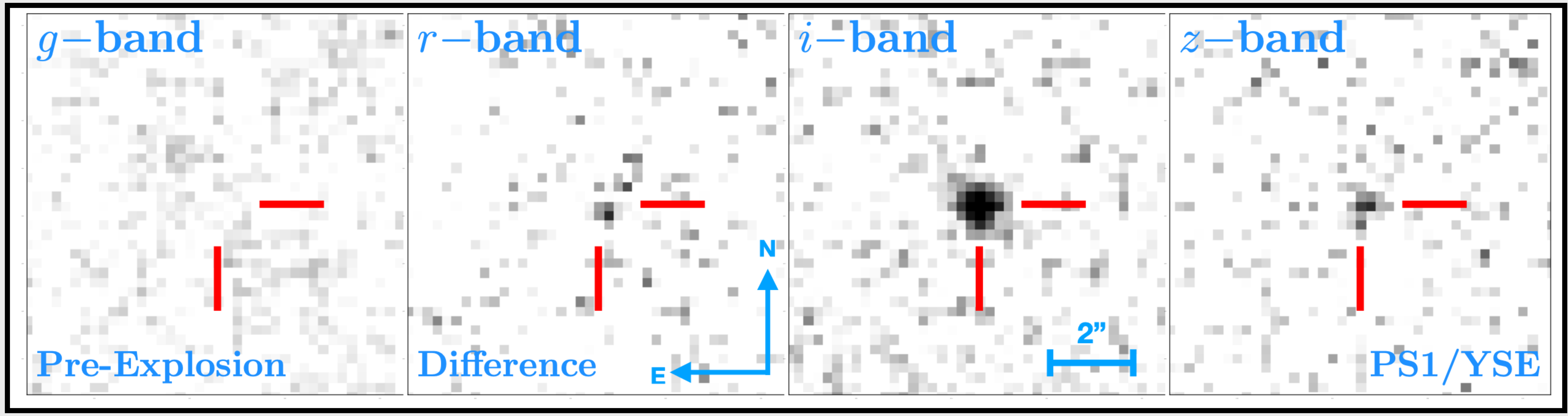
Pre-SN imaging with PS1 showed detections in riz-bands

First evidence for pre-SN activity in a “normal” type II supernova!

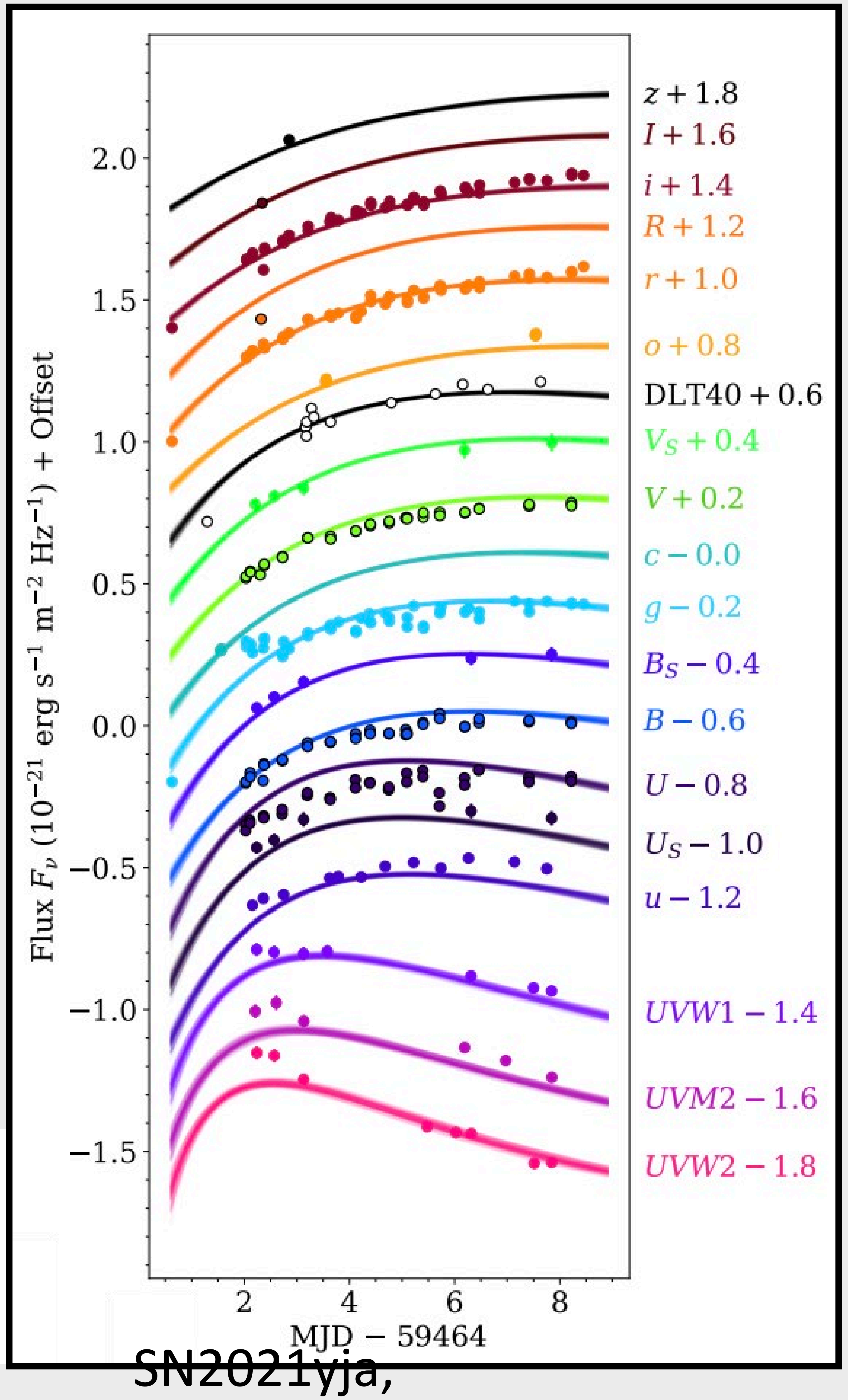
This type of emission will be detectable for Rubin SNe within z<0.02



Jacobson-Galan+2021



OBSERVATIONAL DOMAIN OF CORE-
E SUPERNOVAE



SN2021yja, Hosseinzadeh, Kilpatrick+2022

Shock cooling

(stellar radius, mass, explosion time, shock velocity, local extinction)

Flash spectroscopy

(local CSM density, composition)

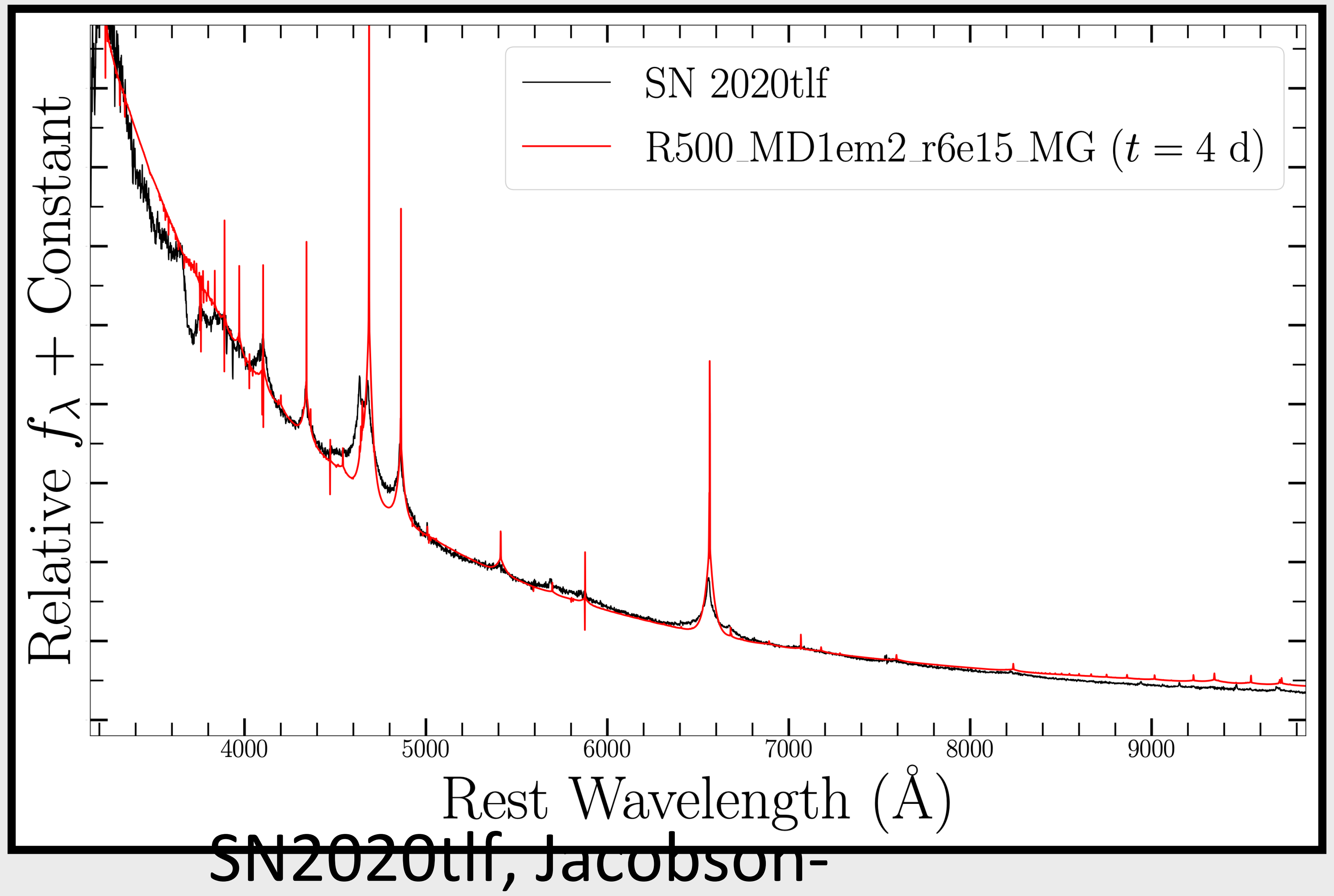
Multi-messenger

(nuclear physics, core-collapse mechanism, NS/BH formation)

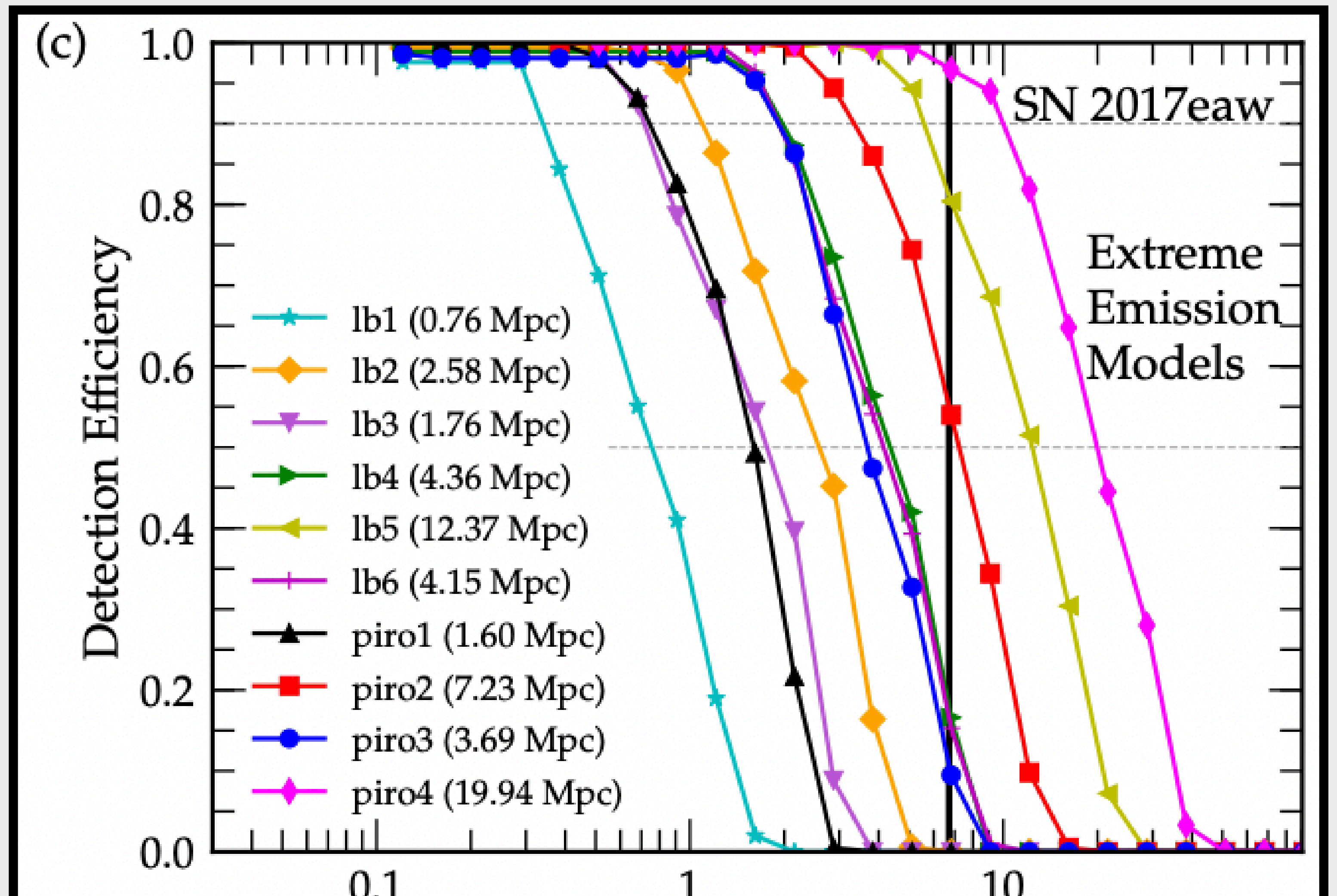
Early emission

<150-200 Mpc (z<0.04)

closer for MM



SN2020tlf, Jacobson-Galan+2022



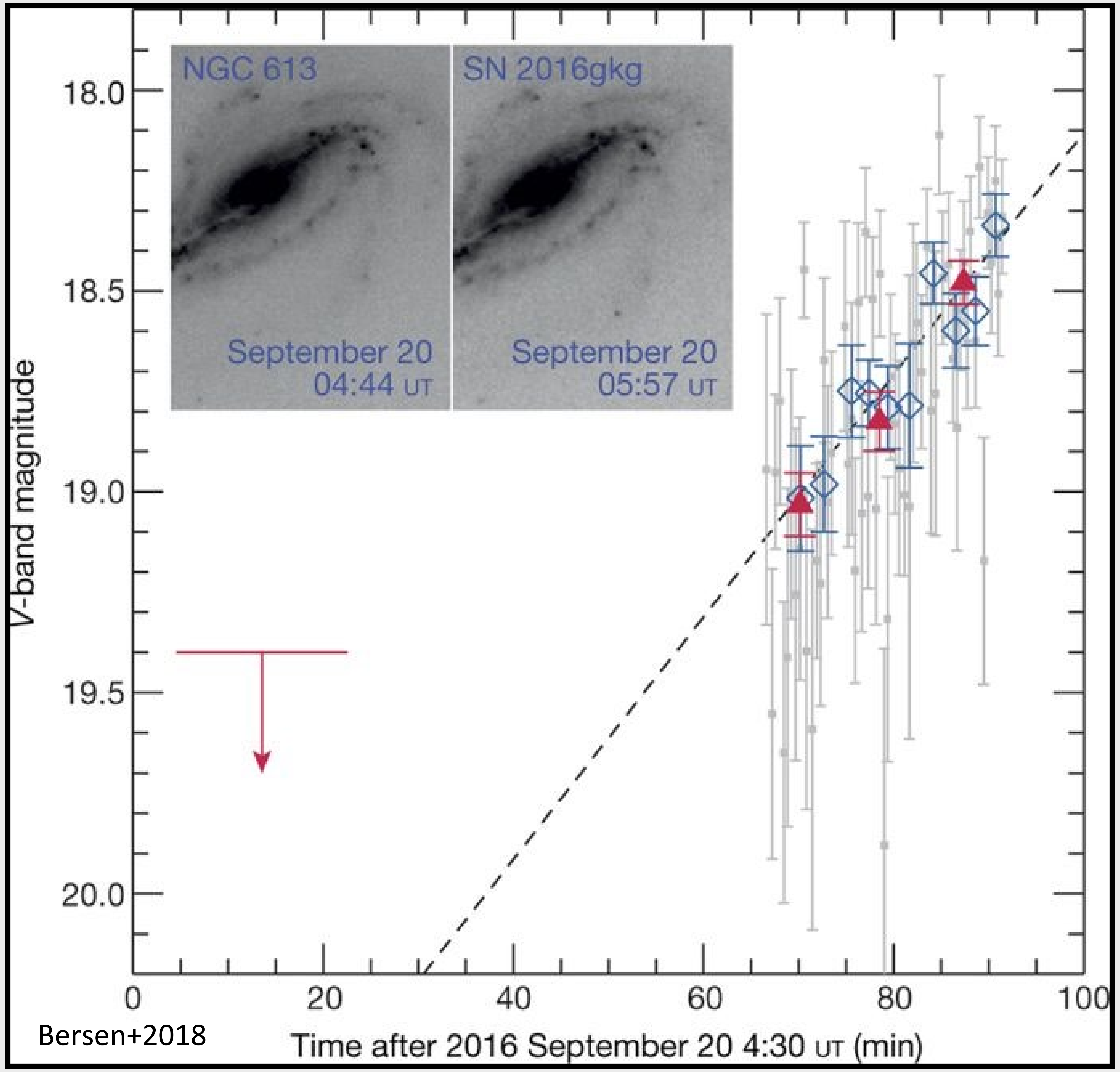
Abbott+2019

EARLY-TIME SCIENCE USUALLY ENABLED BY SERENDIPITOUS OBSERVATIONS

He Took a Picture of a Supernova While Setting Up His New Camera

Astronomers using the Swope telescope captured Supernova 2016gkg, between the two red lines, in the galaxy NGC 613, which is 80 million light-years from here.

C. Kilpatrick/UC Santa Cruz and Carnegie Institution for Science, Las Campanas Observatory, Chile



Bersen+2018

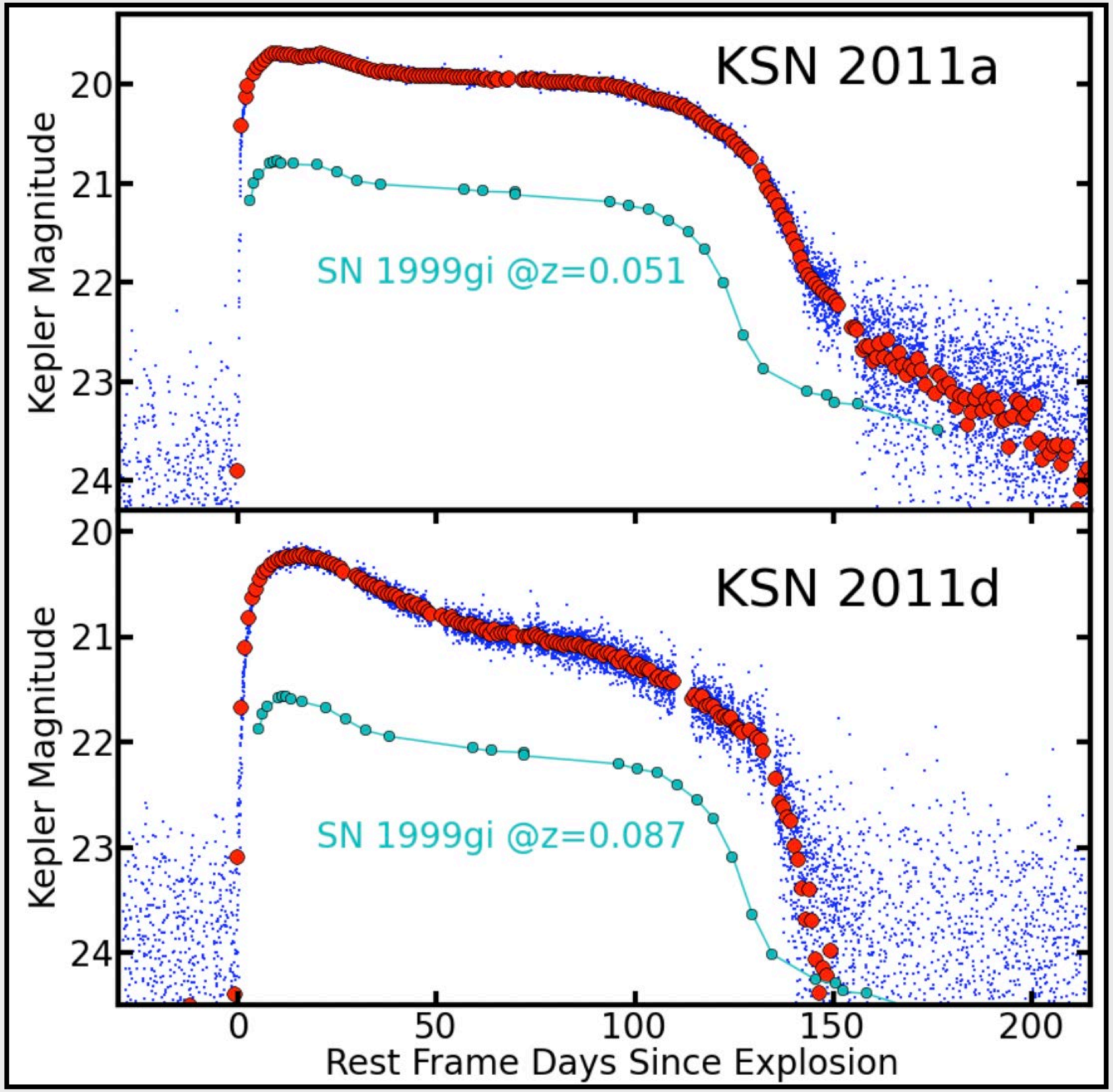
How can we prepare to guarantee ~hours turnaround for some fraction of targets?

EARLY-TIME SCIENCE USUALLY ENABLED BY SERENDIPITOUS OBSERVATIONS

Dedicated, high-cadence surveys can capture events such as the Kepler SNe

There are trade-offs in cadence, depth, area that can be surveyed (Kepler vs. TESS)

No color information and follow up may be limited because we cannot trigger from these surveys.



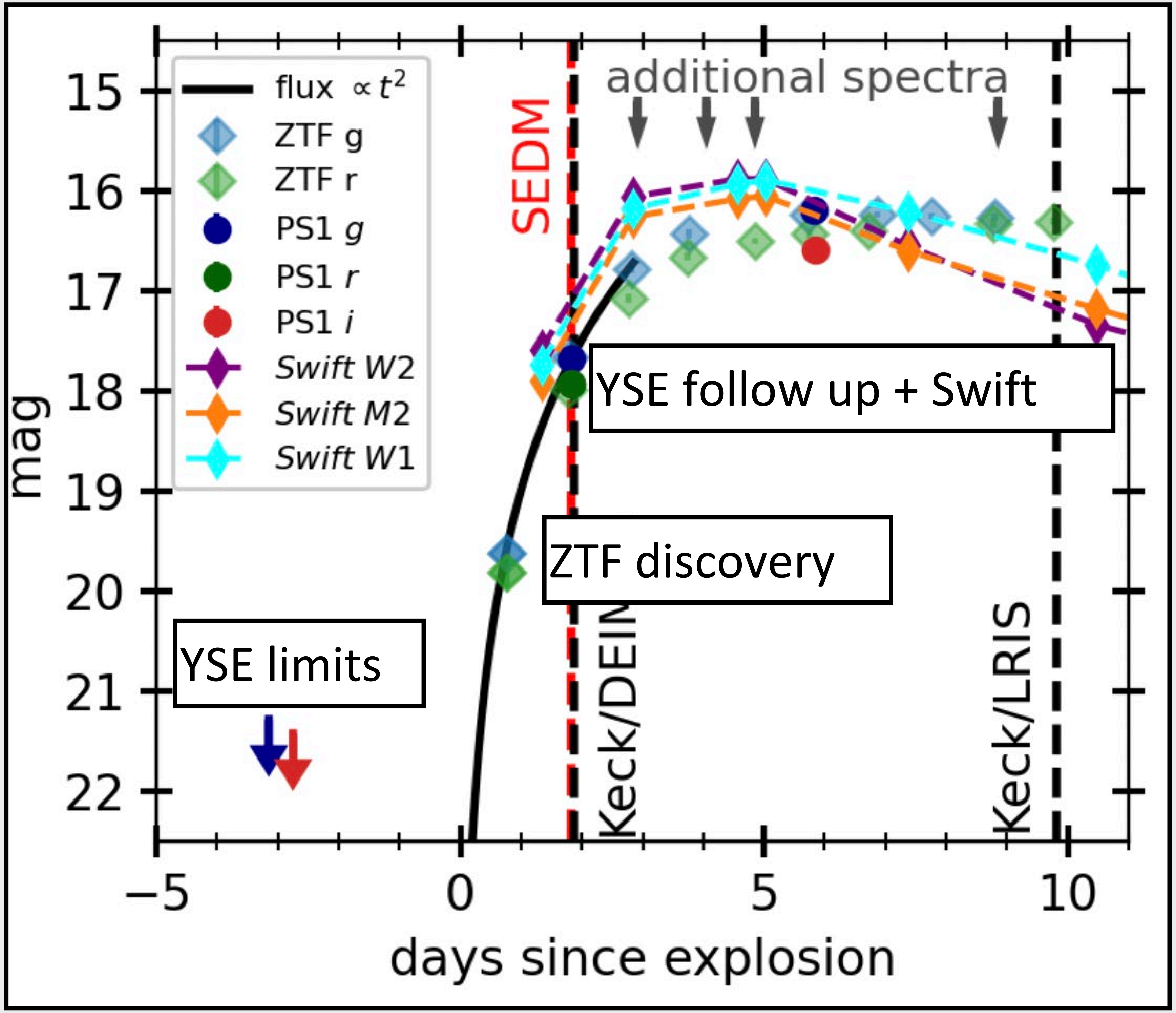
rnavich+2016 (see also Rubin+2017, Rest+2018, Dimitriadis+2018, Shappee+2019, Li+2019, Vallely+2019, Tinyanont+2022)

YOUNG SUPERNOVA EXPERIMENT

Combined observations from multiple surveys enable extremely young transient discoveries

Shadowed observations can guarantee some transients are found within hours of explosion (~1 per month with YSE) and within 2 days of explosion (~18 per month with YSE)

SN 2020pni (Jones+2021, Terreran+2022)



YSE follow up + Swift

ZTF discovery

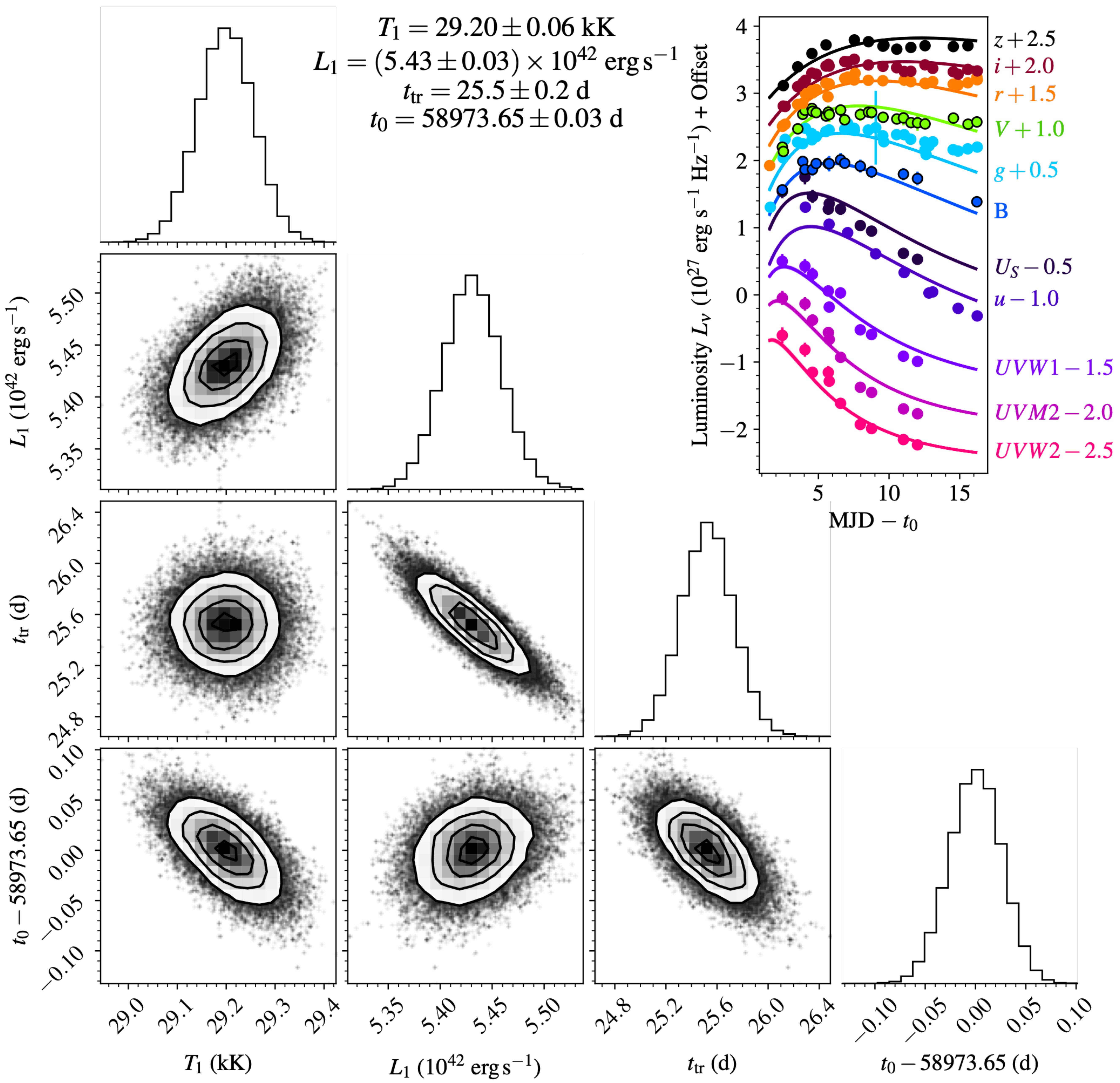
YSE limits

YOUNG SUPERNOVA EXPERIMENT

Can compare large populations of SNe to expectations for their radii, CSM properties, envelope mass

UV/X-ray follow up is key when SN is blue or has strong X-ray emission from CSM shock

Swift is the main resource for this follow up - STAR-X follow up and spectroscopy of nearby events with UVEX will be critical



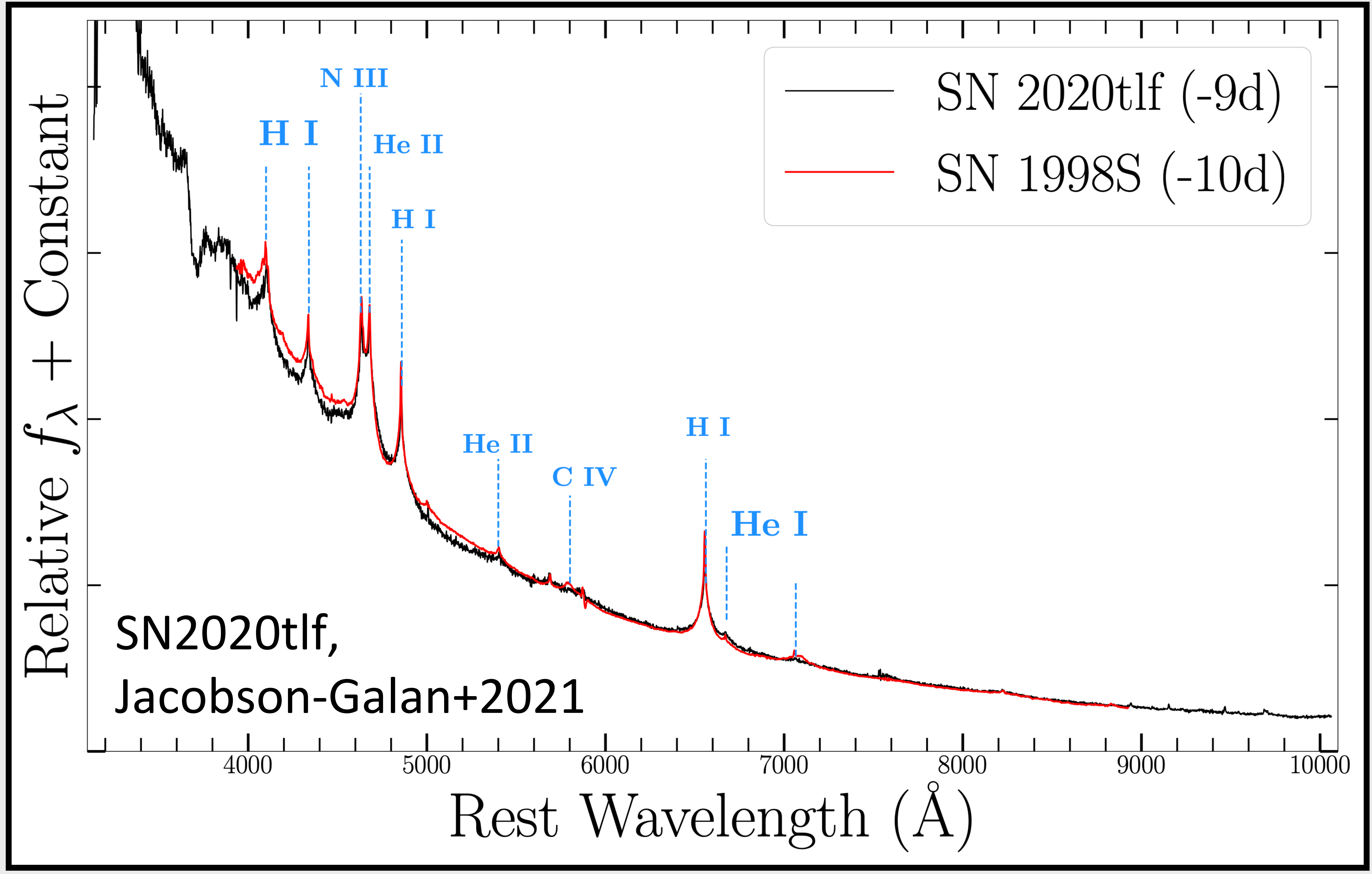
SN2020jfo, Kilpatrick+2022

FLASH IONIZATION SPECTROSCOPY

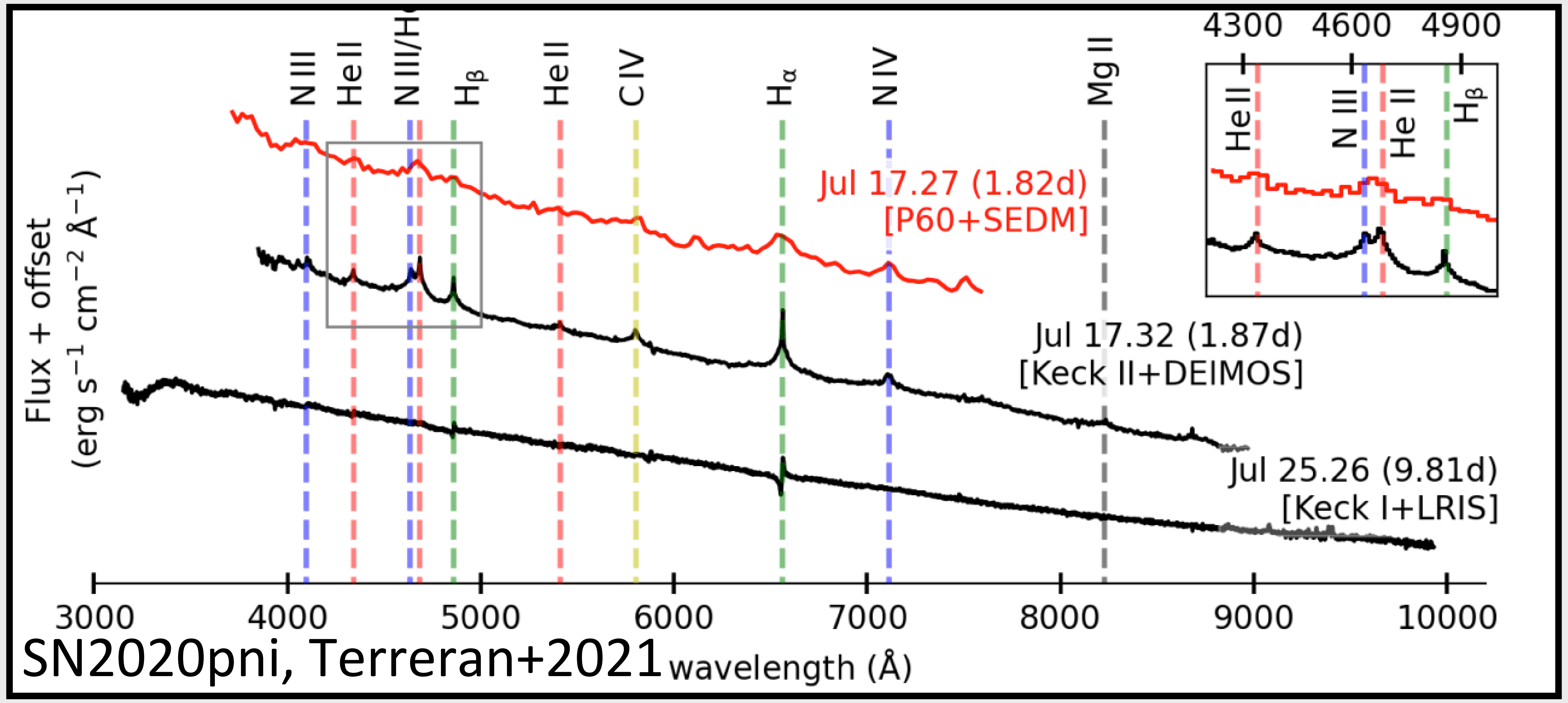
Flash ionization provides a unique probe of the composition, temperature, and density of CSM immediately around SNe

Observations are challenging - mostly limited to the closest SNe (<100 Mpc) that can be detected early and with enough signal to model spectra.

Spectral modeling is also a challenge - geometry

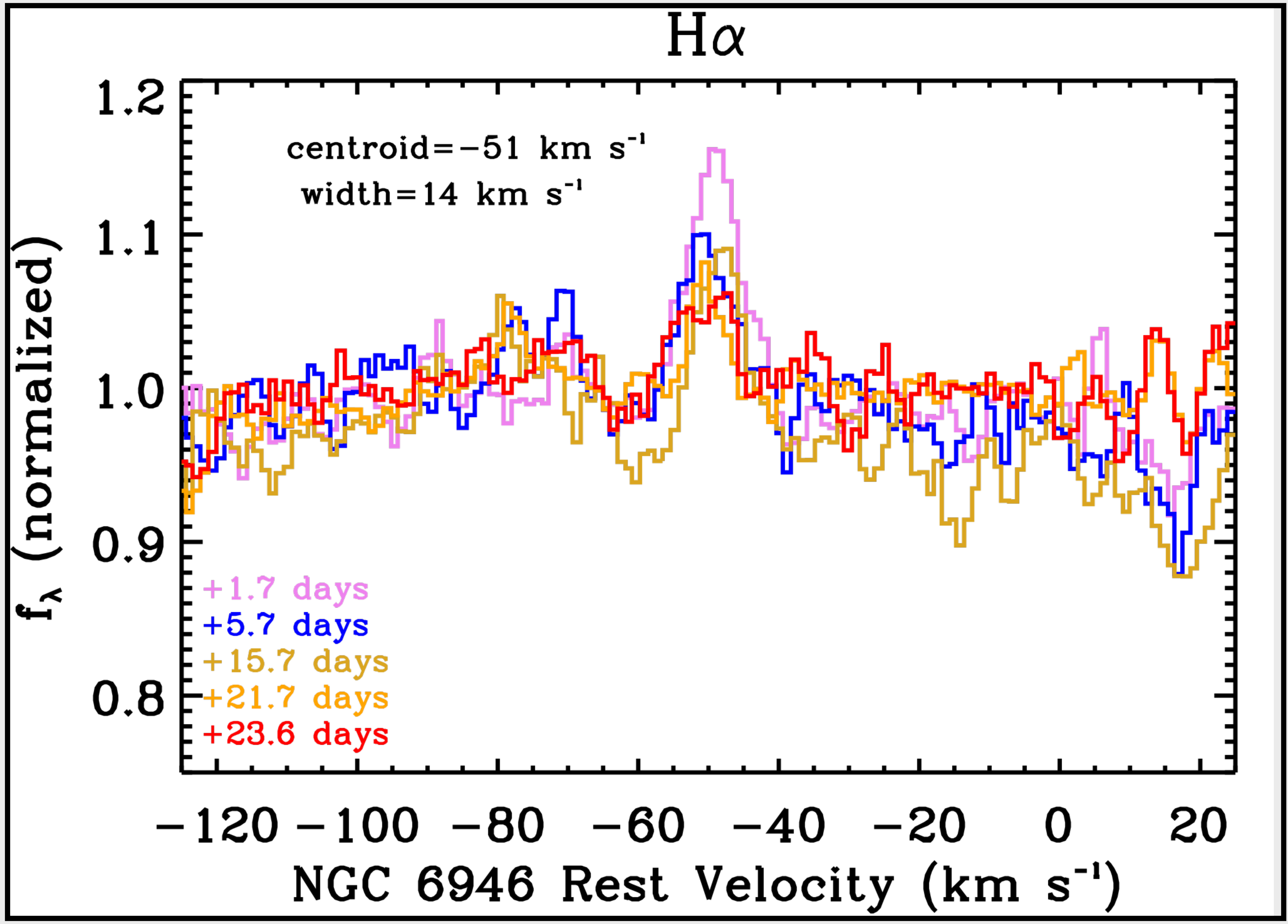


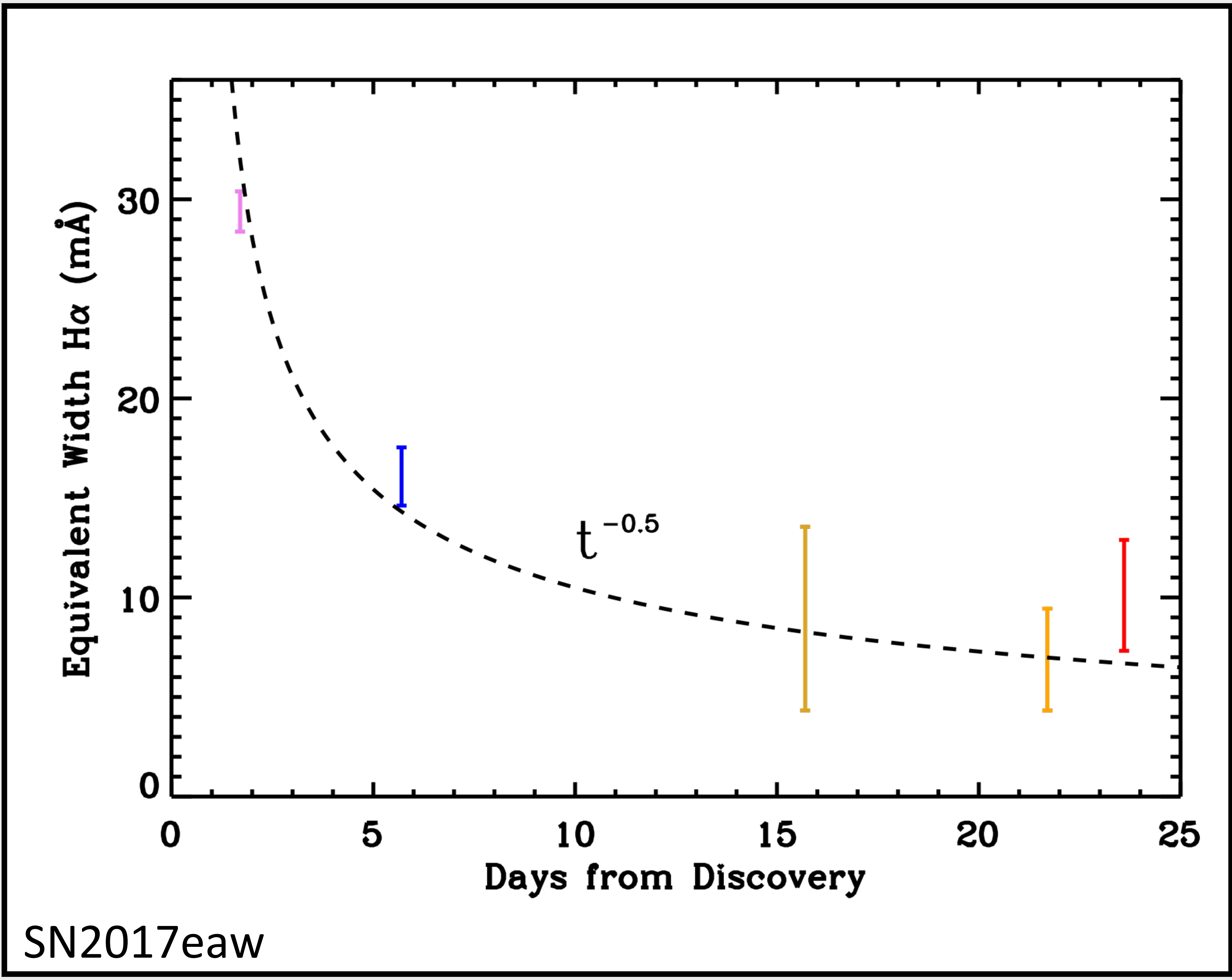
SN2020tlf, Jacobson-Galan+2021



SN2020pni, Terreran+2021

LIKELY ALL SUPERNOVAE HAVE FLASH IONIZATION FEATURES

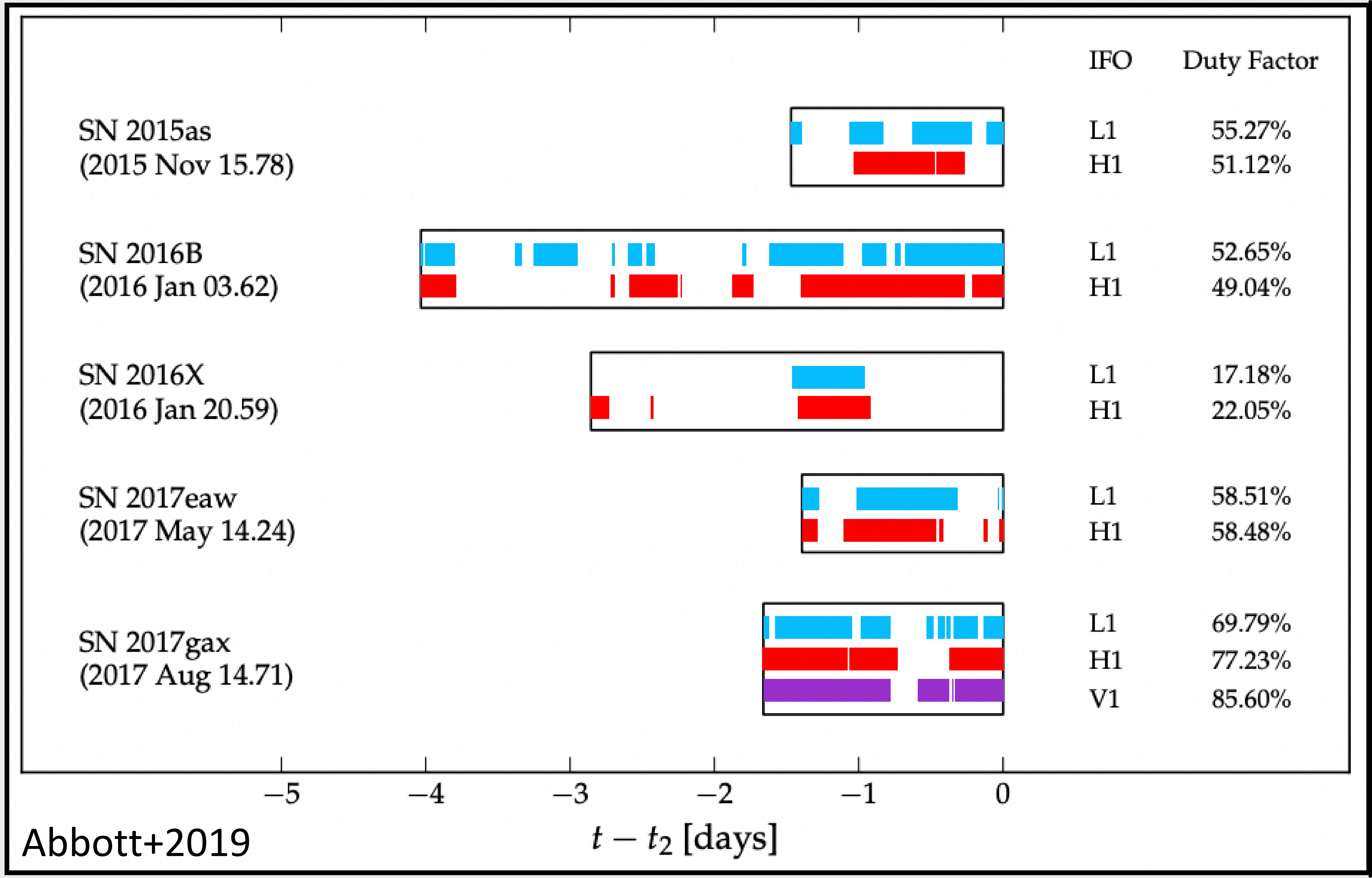




Hα implies wind speed = 14 km s^{-1}

mass-loss rate = 10^{-5} M☉/yr

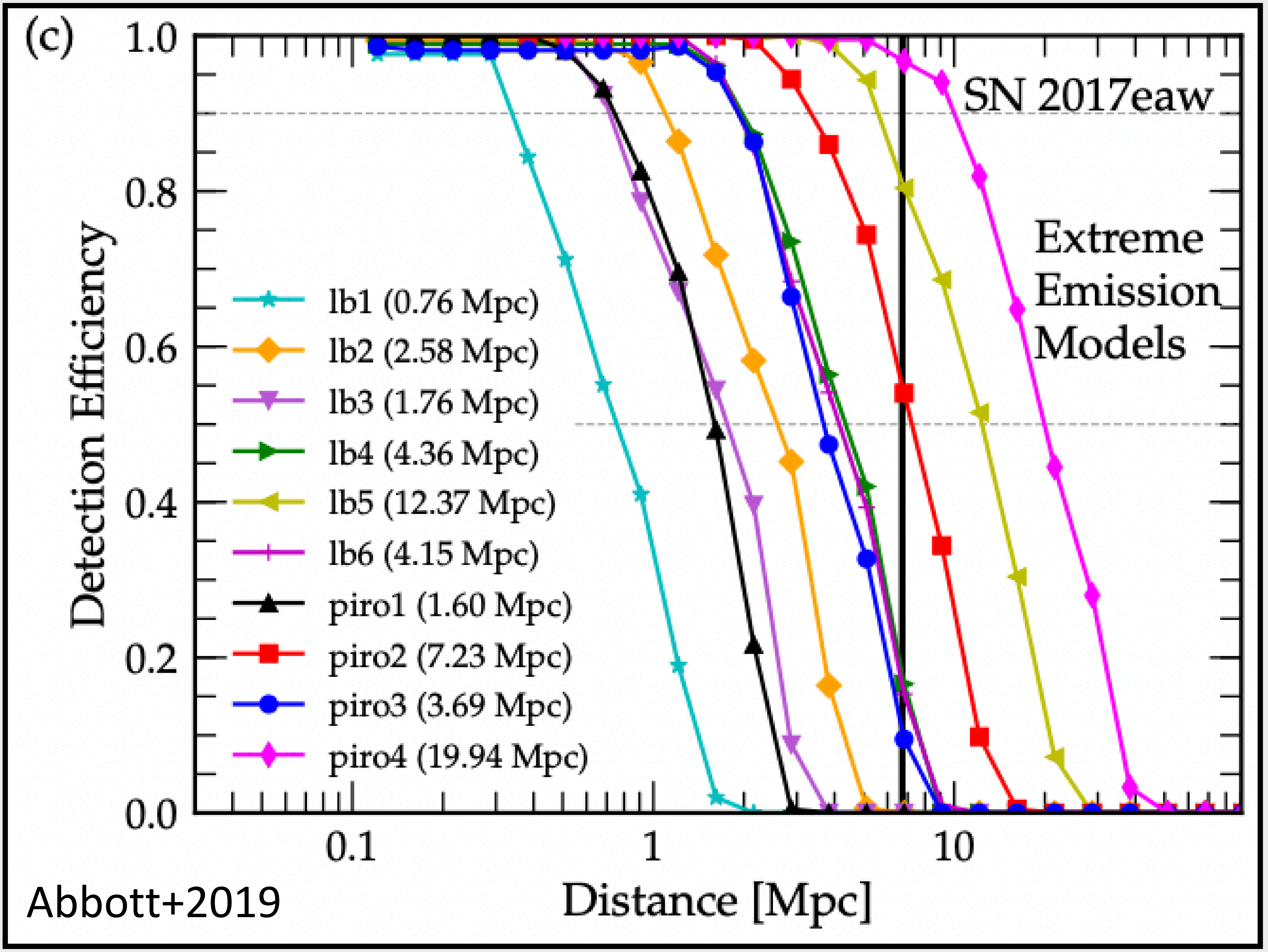
GRAVITATIONAL WAVE EMISSION FROM SUPERNOVAE



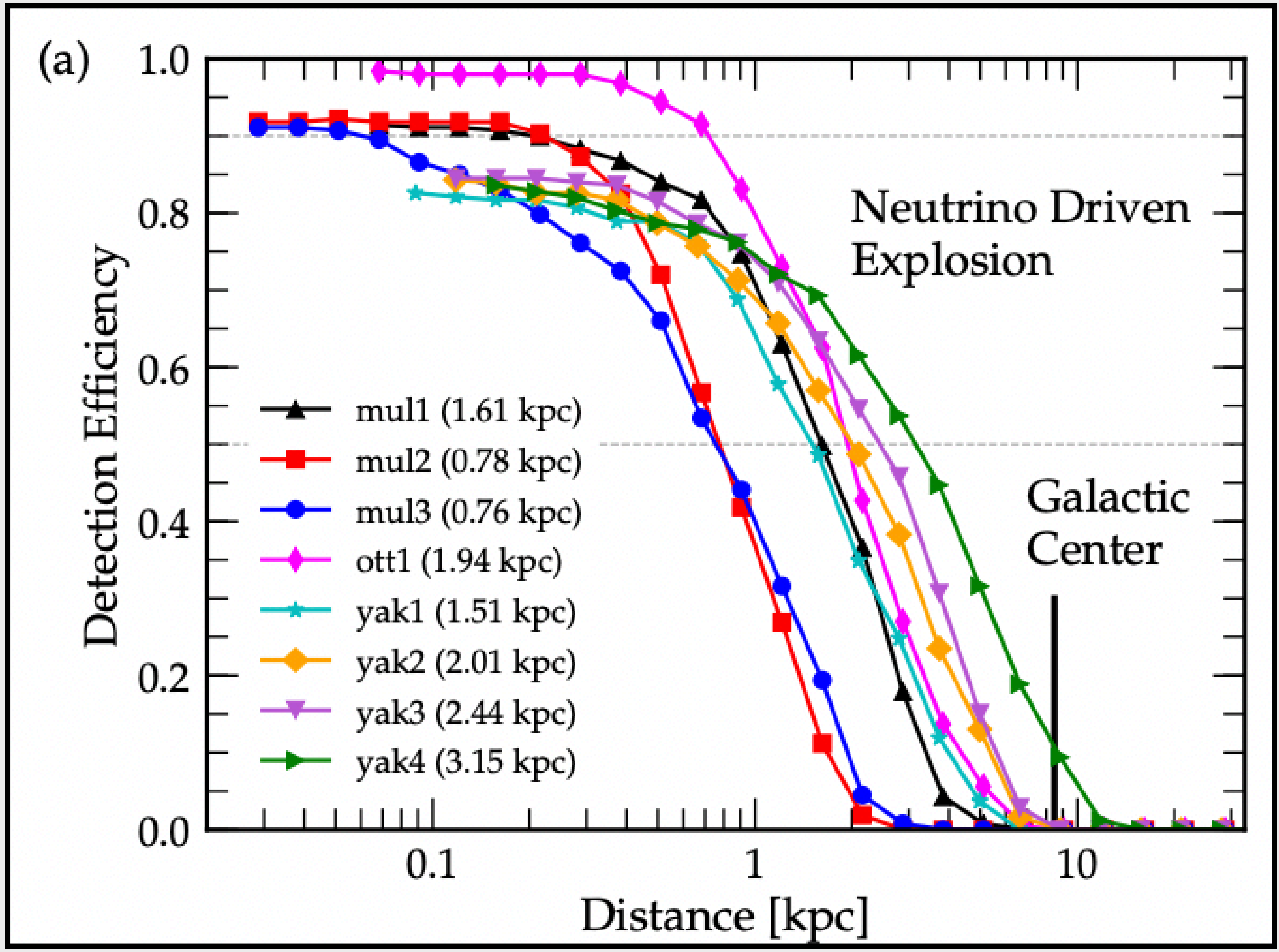
Abbott+2019

Optically-targeted searches have looked for signatures from relatively nearby (<20 Mpc) supernovae that exploded during LIGO observing runs. Expectation is a standing accretion shock instability can produce strong gravitational quadrupole.

GRAVITATIONAL WAVE EMISSION FROM SUPERNOVAE

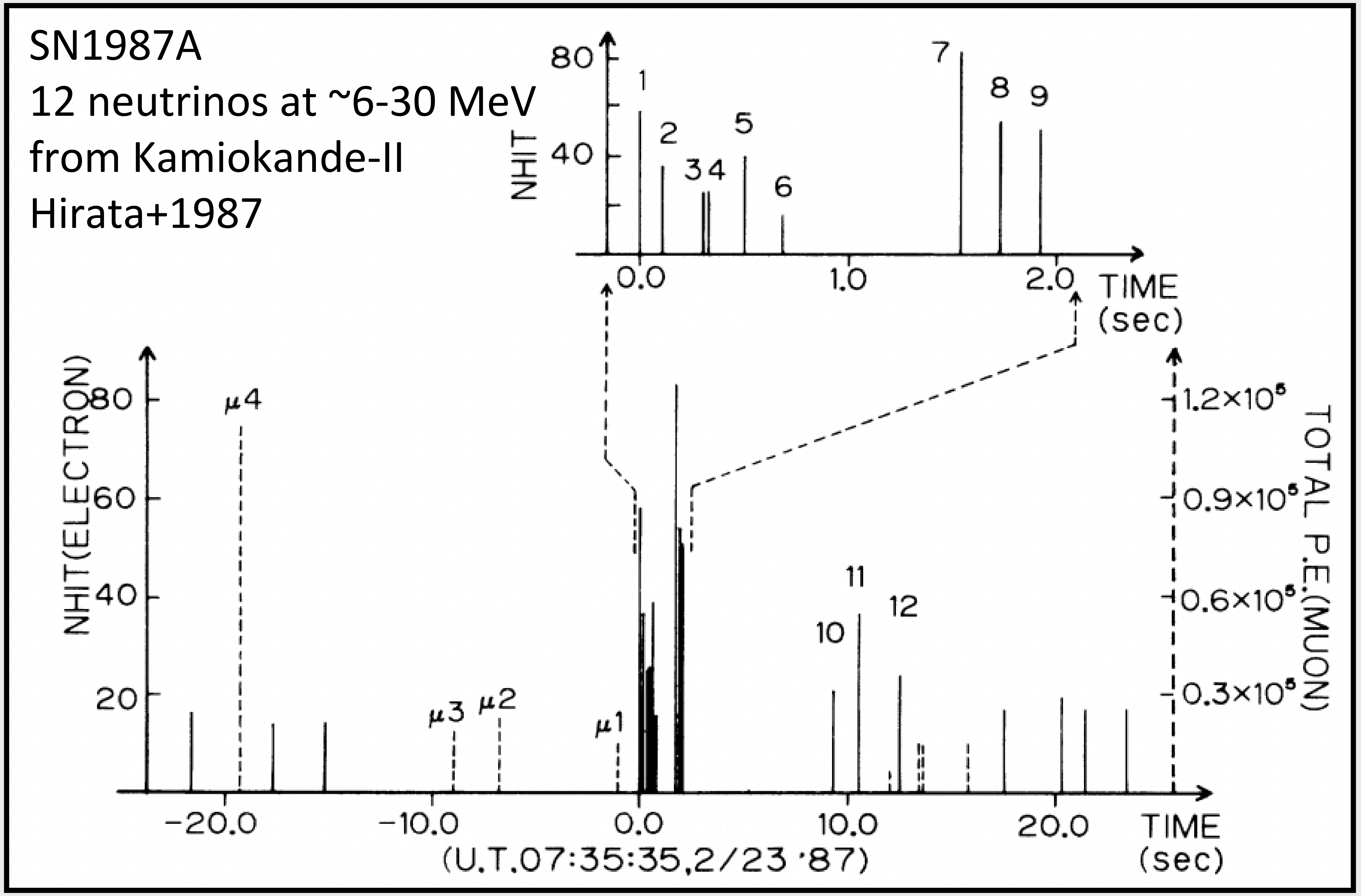


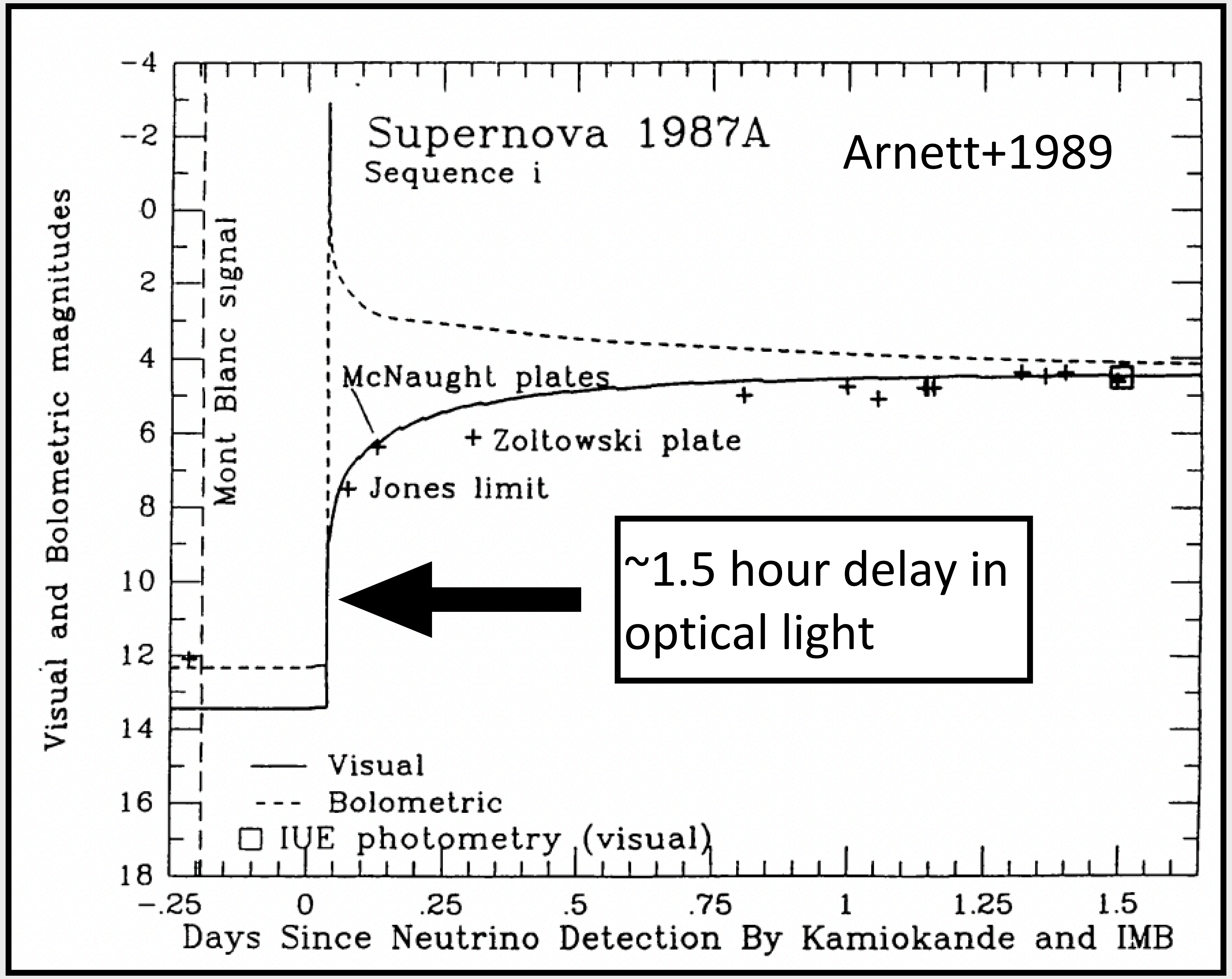
Abbott+2019



Some optimistic models extend to nearby supernovae, but realistic models suggest only GW emission from a Galactic supernova would be detected

NEUTRINO EMISSION FROM SUPERNOVAE

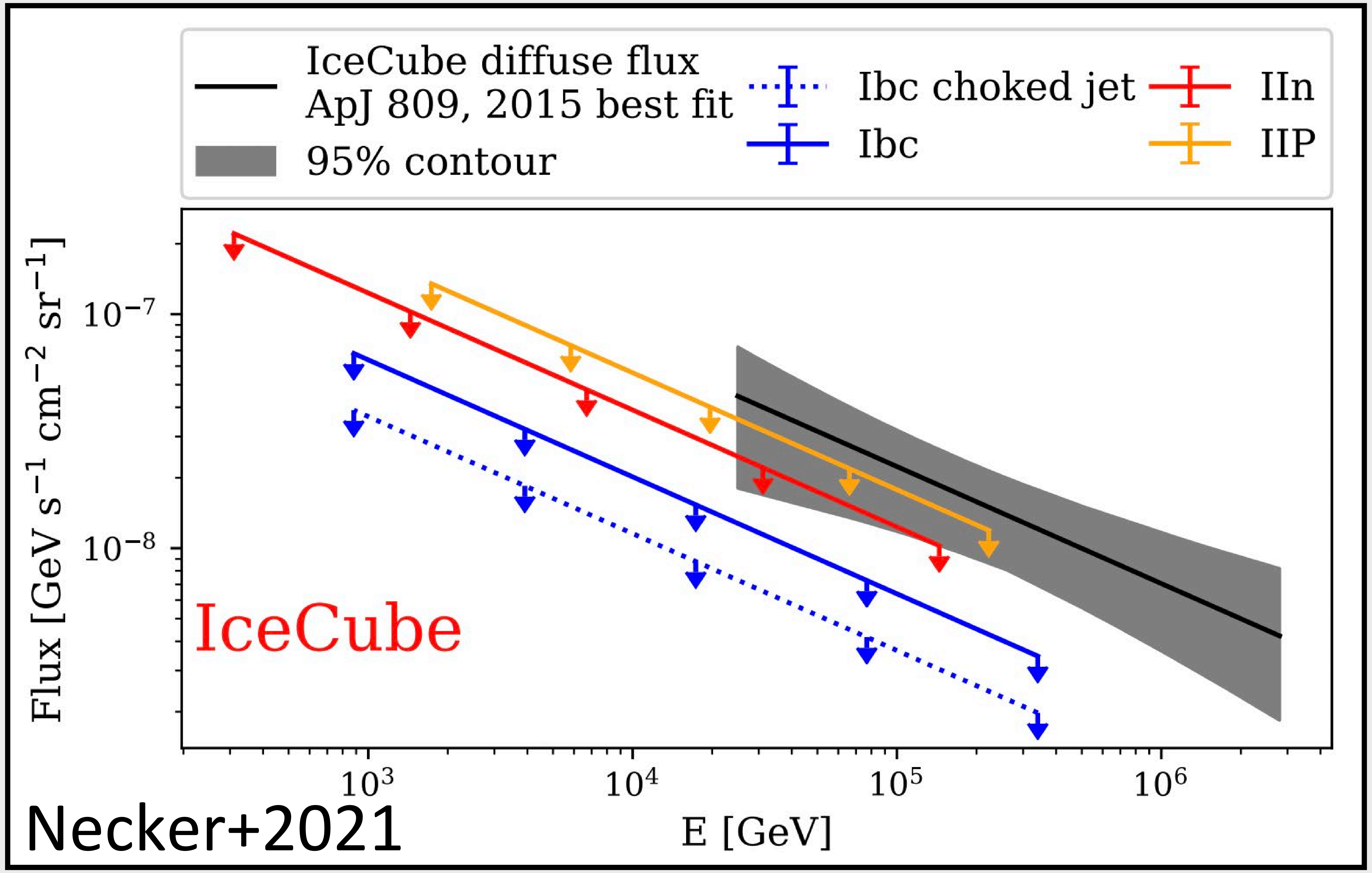

SN1987A
12 neutrinos at ~6-30 MeV
from Kamiokande-II
Hirata+1987


Arnett+1989

~1.5 hour delay in optical light

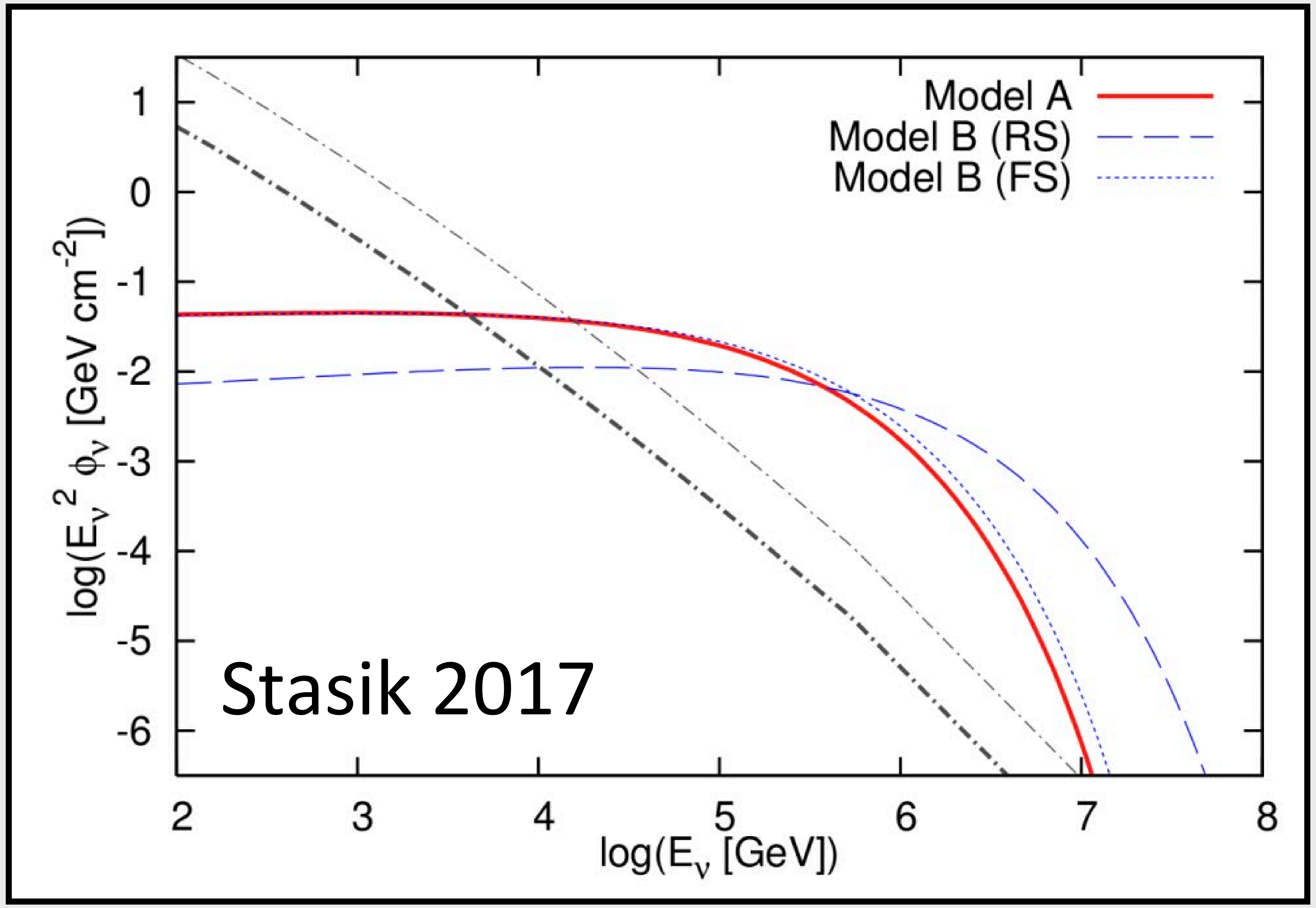
We have a benchmark for neutrino emission from supernovae - what are the prospects for detecting more SN neutrinos as detectors become more sensitive?

NEUTRINO EMISSION FROM SUPERNOVAE



Necker+2021

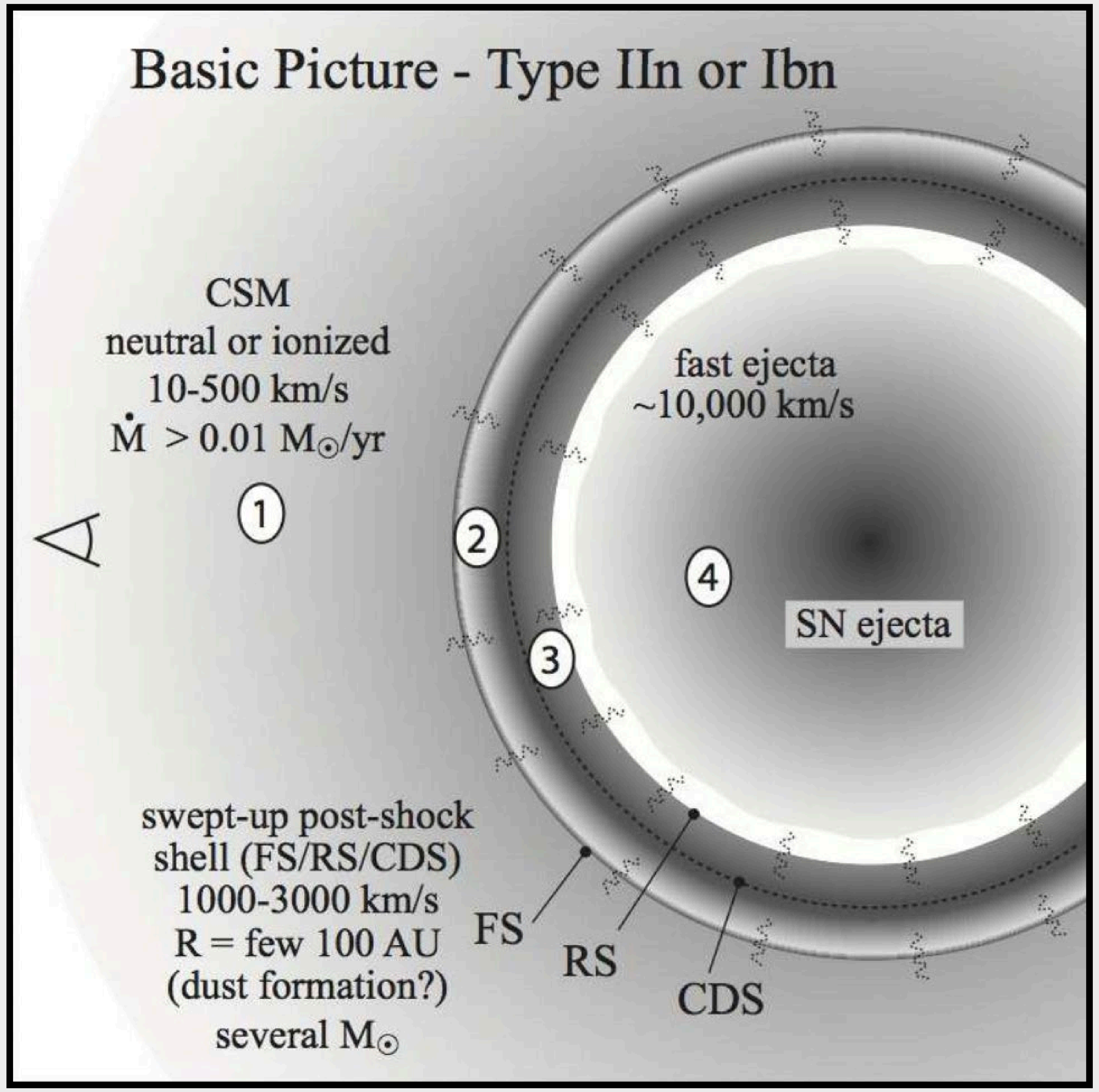
Results from stacking 54 SN IIn, II-P, Ib/c



Stasik 2017

Neutrino flux and energy depend on size of core, core accretion rate

Precise timing from light curves is key: <1 day uncertainty on explosion time can reduce probability of chance coincidence and need for large samples



Interacting supernovae
Smith 2016

Explosion properties

(energy, ejecta mass, nickel mass, velocities)

CSM interaction

(structure, composition environment, mass-loss history)

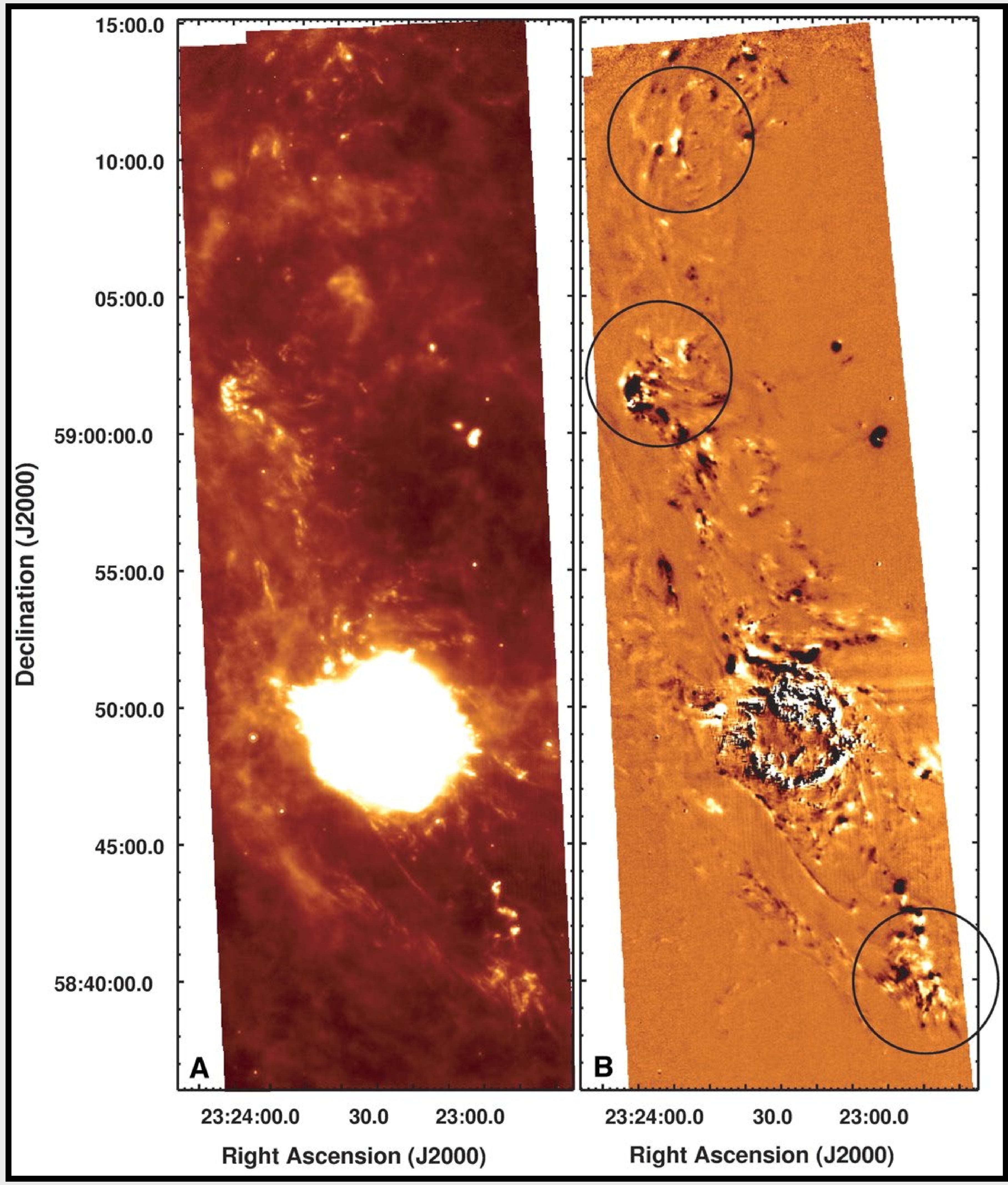
Light echoes

(geometry of explosion, probing older events)

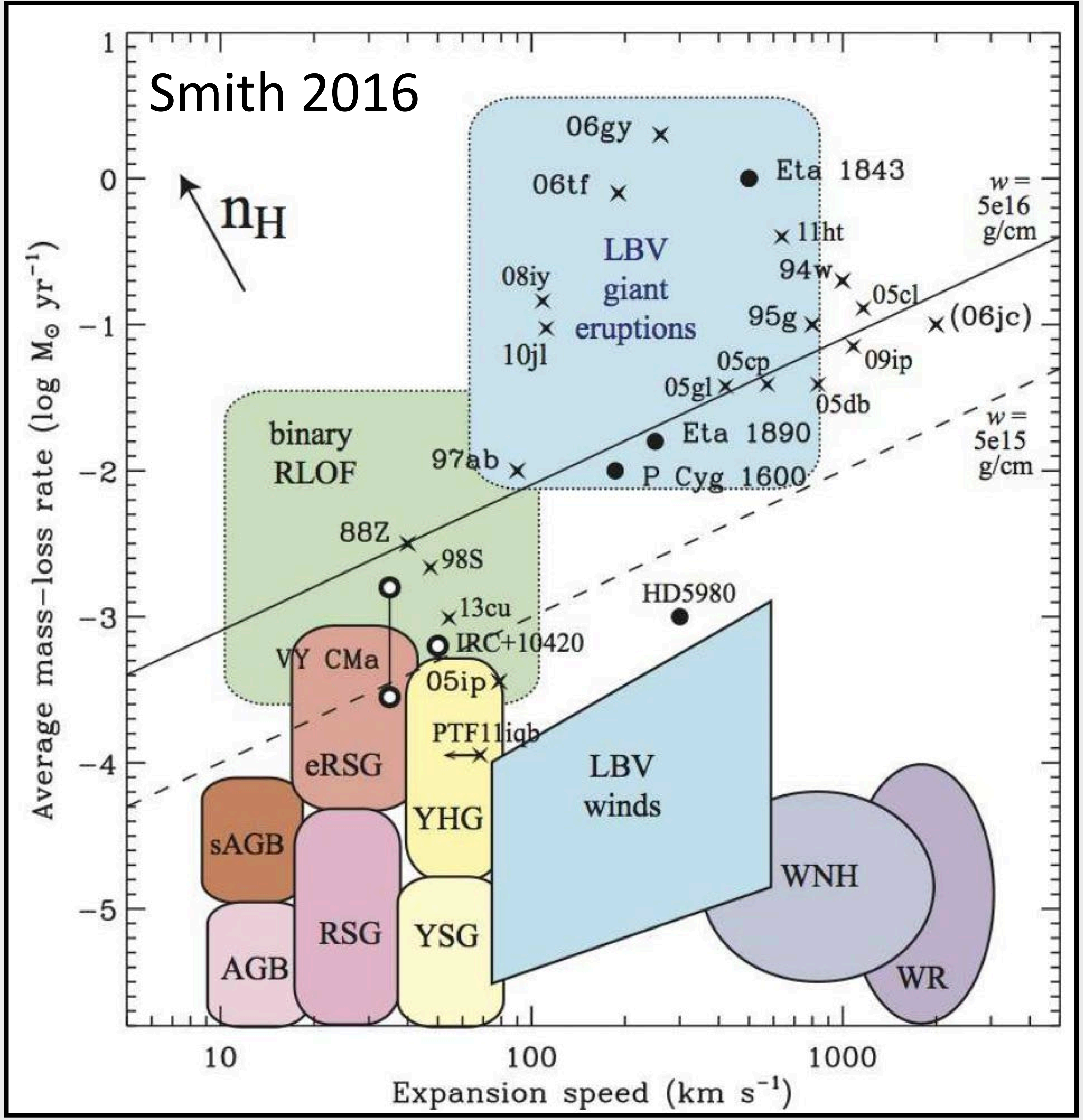
Peak/late-time emission

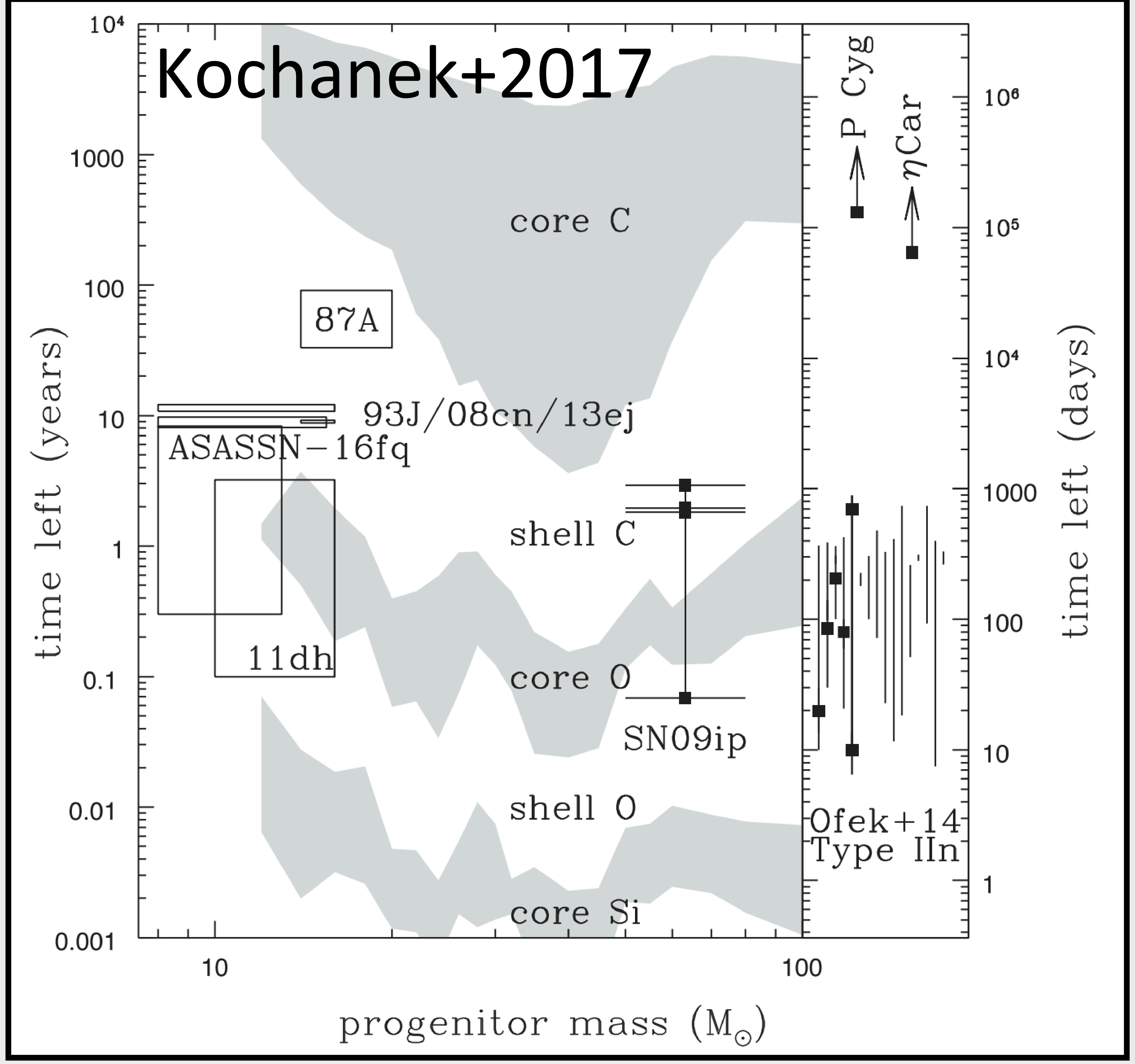
<1 Gpc (z<0.2)

LEs are <10 Mpc



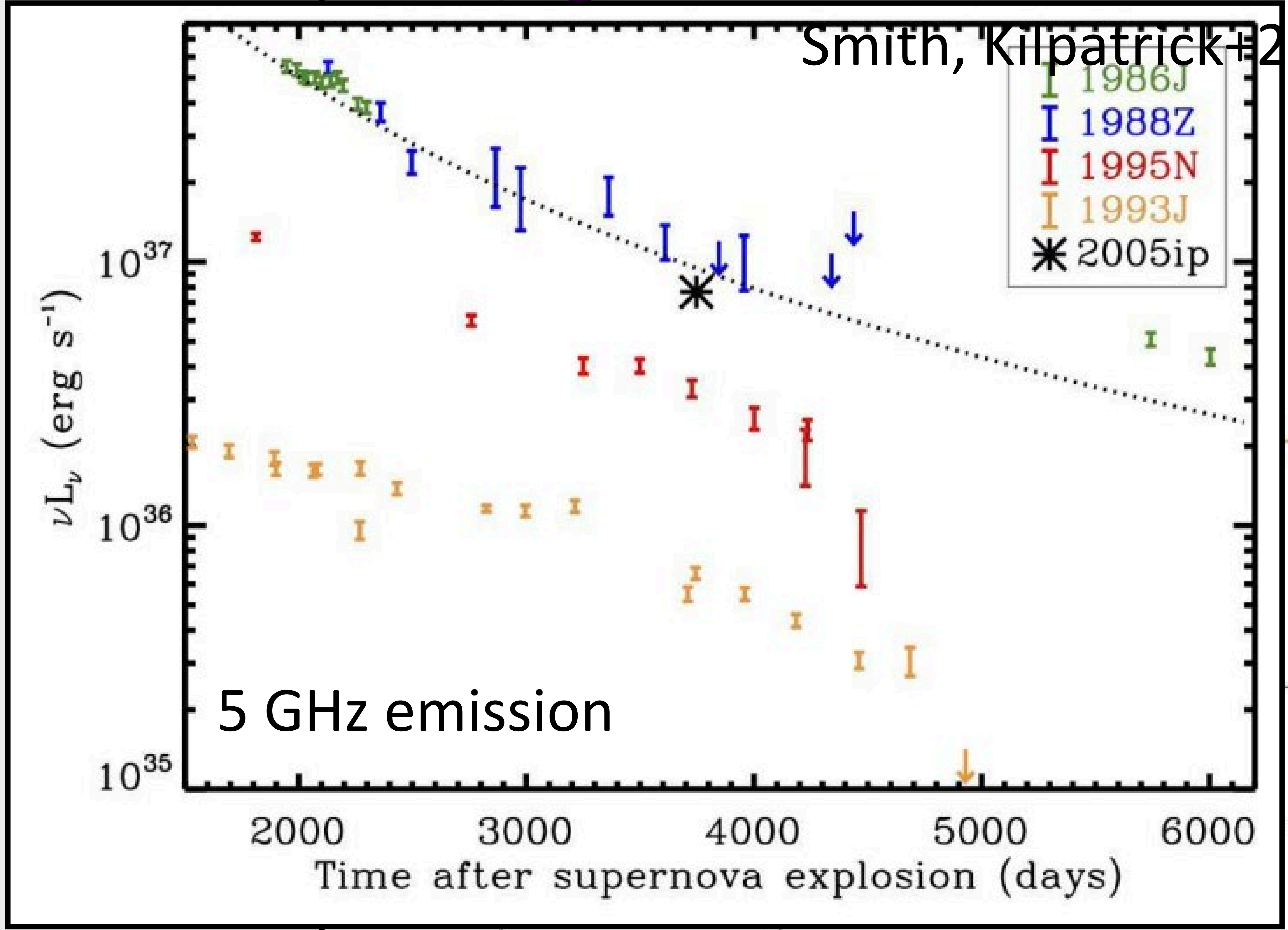
Cassiopeia A IR dust echoes
Krause+2008

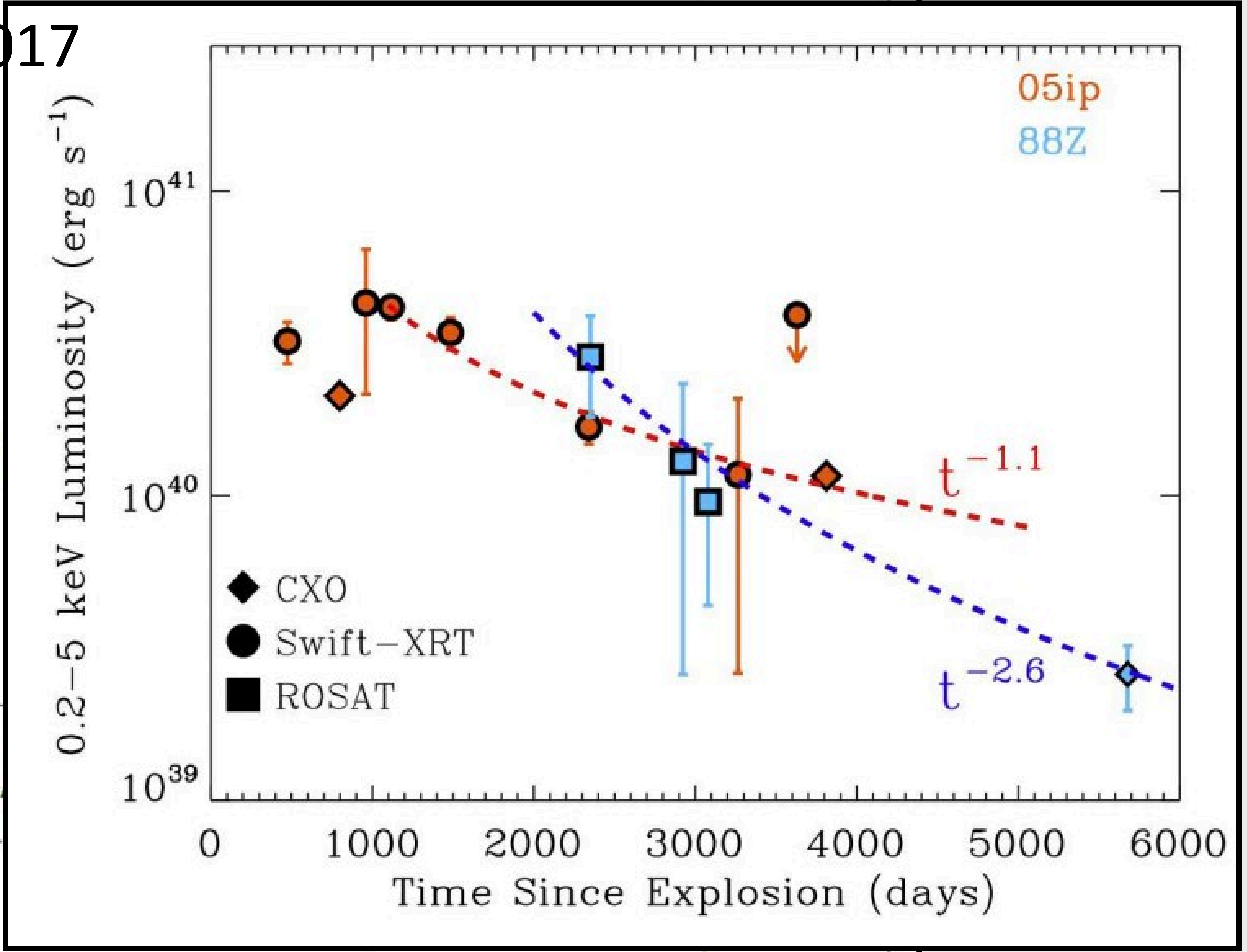

Smith 2016


Kochanek+2017

Inferred properties of CSM from circumstellar interaction can reveal progenitor type and evolution driving mass loss

Smith, Kilpatrick+2017



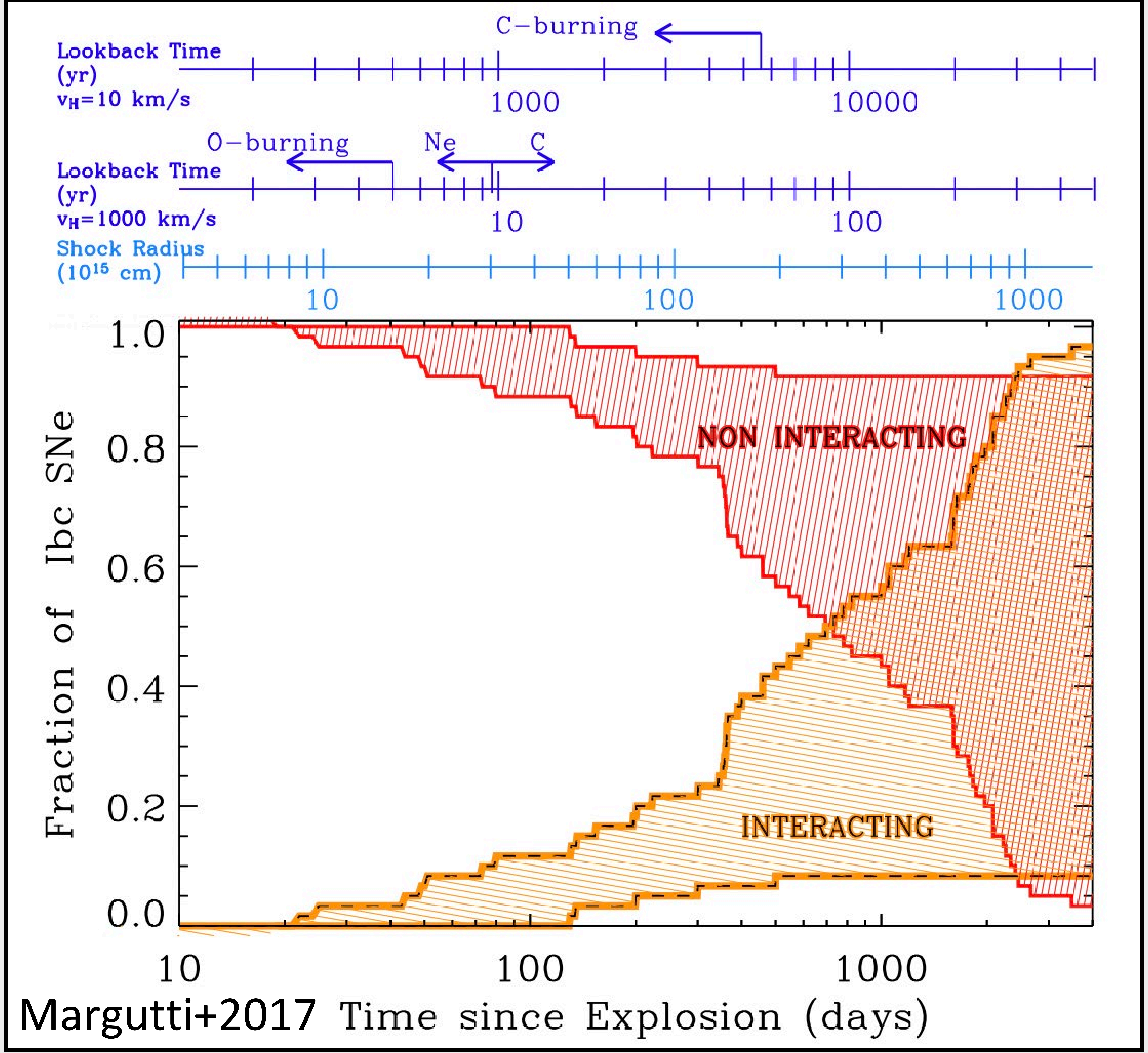


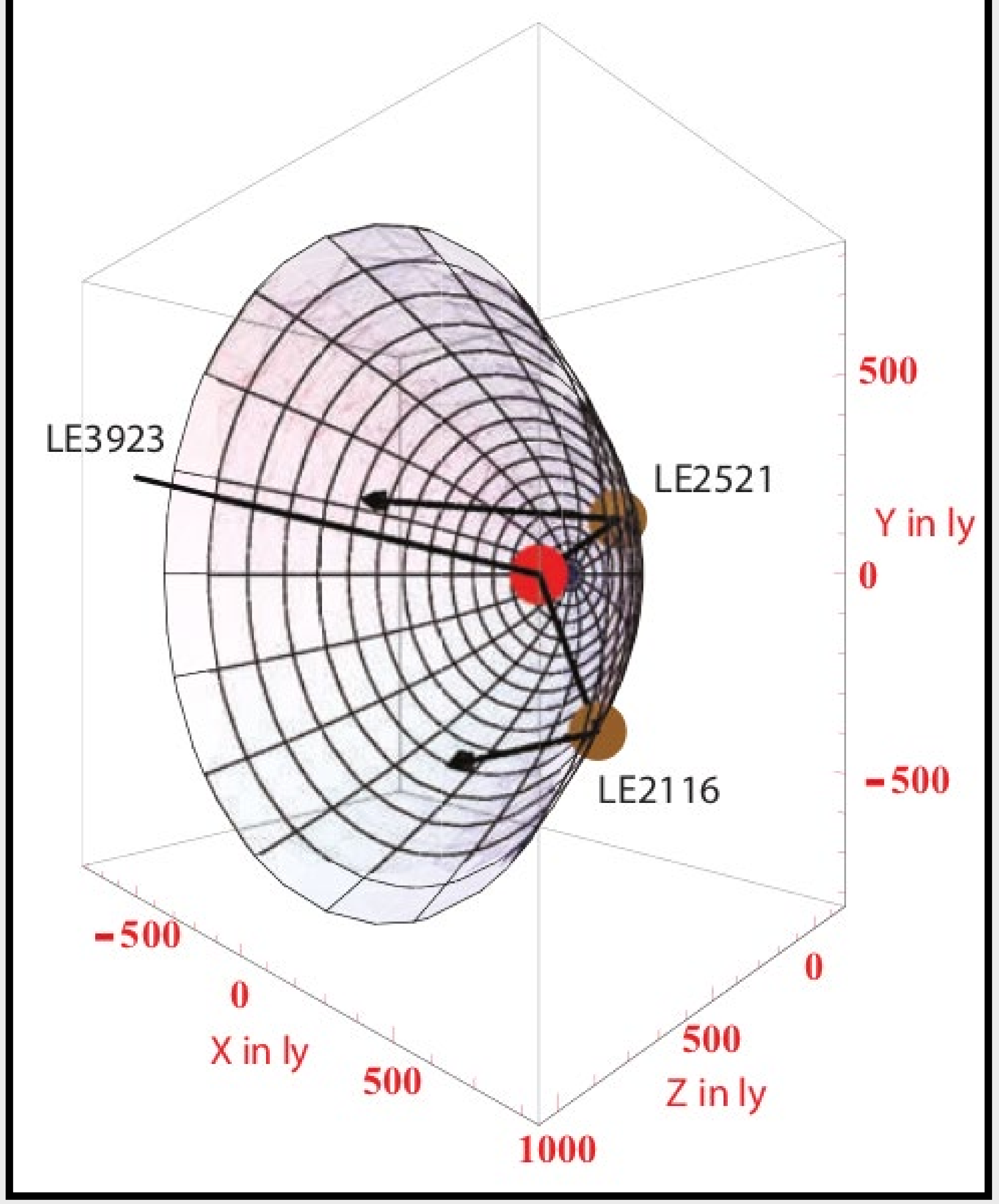
Radio and X-ray follow up are needed for these cases to constrain the intrinsic mass loss rate, shock velocity, microphysical parameters in the CSM

How often do supernovae interact with shells of CSM at very late times (>1000 days)?

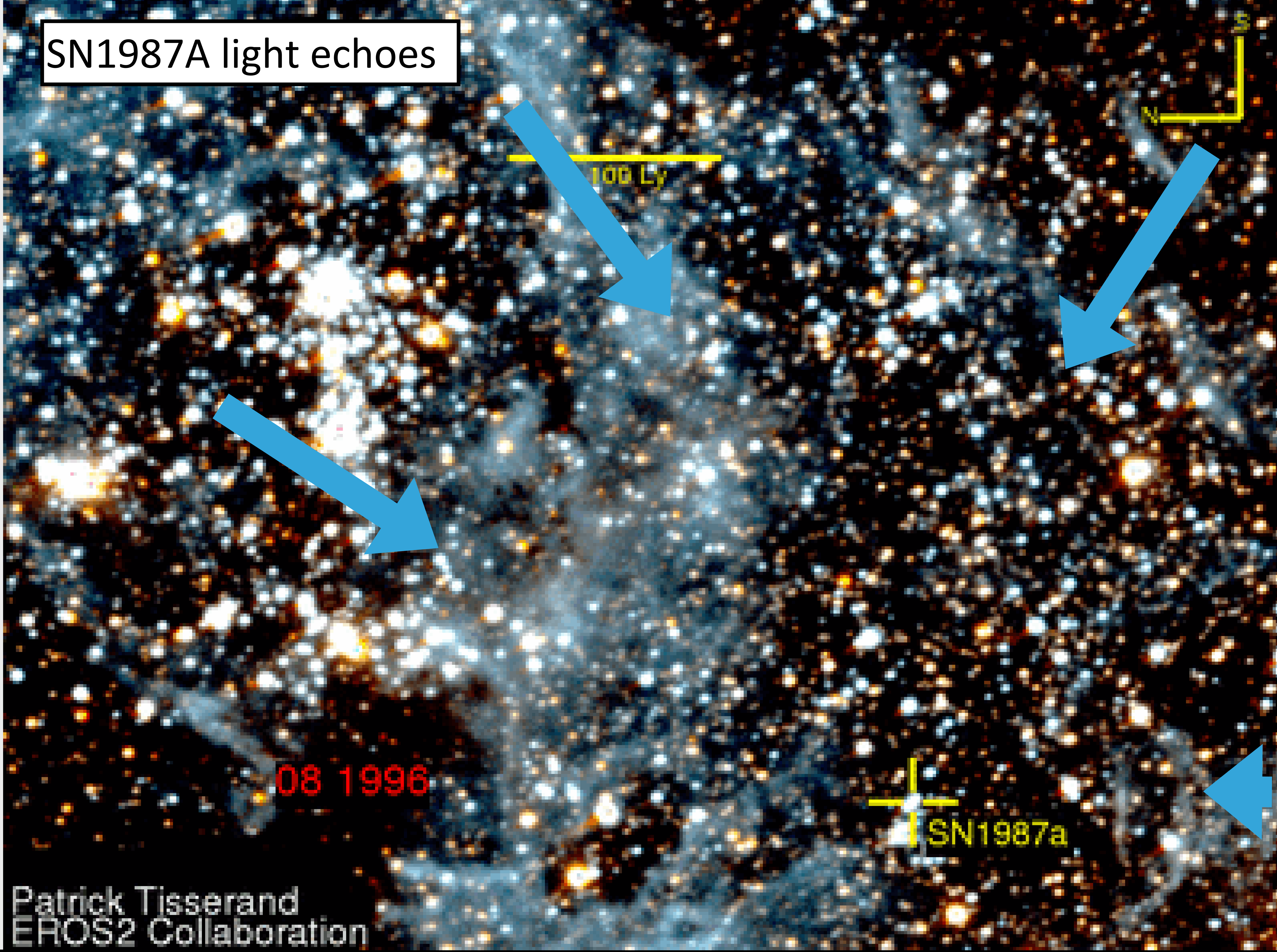
Type Ib/c SNe explode from stars that need to lose most of their hydrogen and/or helium envelopes prior to core collapse

When does this occur, and through what modes of mass loss (radiative, explosive, wave-driven, RLOF)?


Margutti+2017

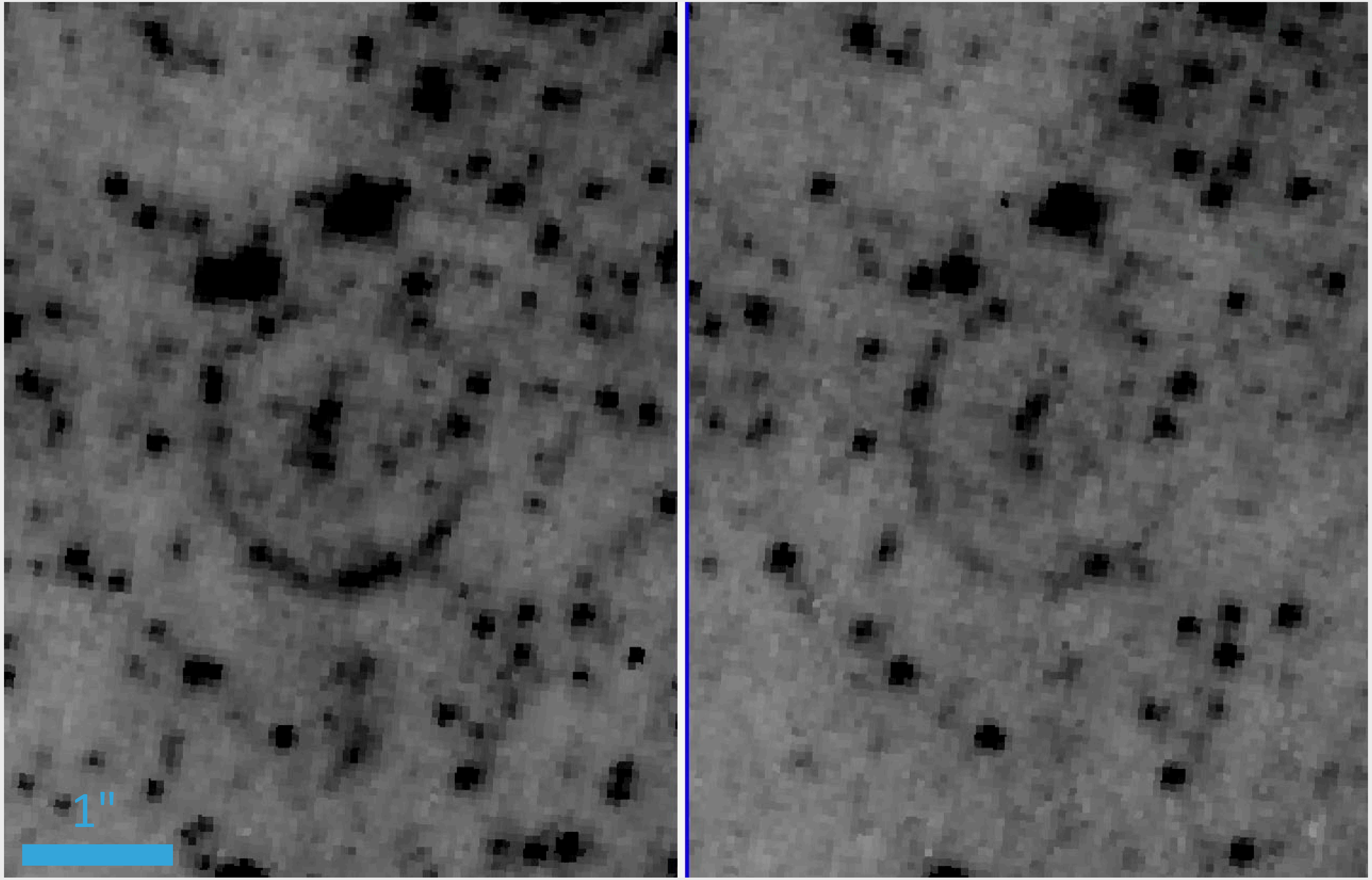


SN1987A light echoes



Patrick Tisserand
EROS2 Collaboration

Single event along multiple sight lines



Resolved spectroscopy is possible even with ground-based seeing (or AO-fed spectr

Searches for this type of emission will be possible with Rubin and Roman.

CONCLUSIONS

Progenitor stars to core-collapse supernovae reveal evolutionary pathways for events of different types. Rubin and Roman will provide light curves for these sources and searches for pre-explosion variability. More IR imaging (JWST+Roman) is key.

Combining optical survey data has provided several SN detections within hours-days of explosion. We can now build statistical samples of SNe with envelope structure from shock cooling and nearby CSM from flash ionization.

Multi-messenger observations are limited to nearby events in MW or local group.

Deeper surveys such as Rubin will provide extremely late time (>1000 days) light curves for SNe - a relatively unexplored regime. Multi-wavelength data are needed to fully explore CSM properties as well as spectroscopy for light echoes.