Resolved stellar populations in the Rubin/JWST Era: Identifying stars right before their cataclysmic explosions

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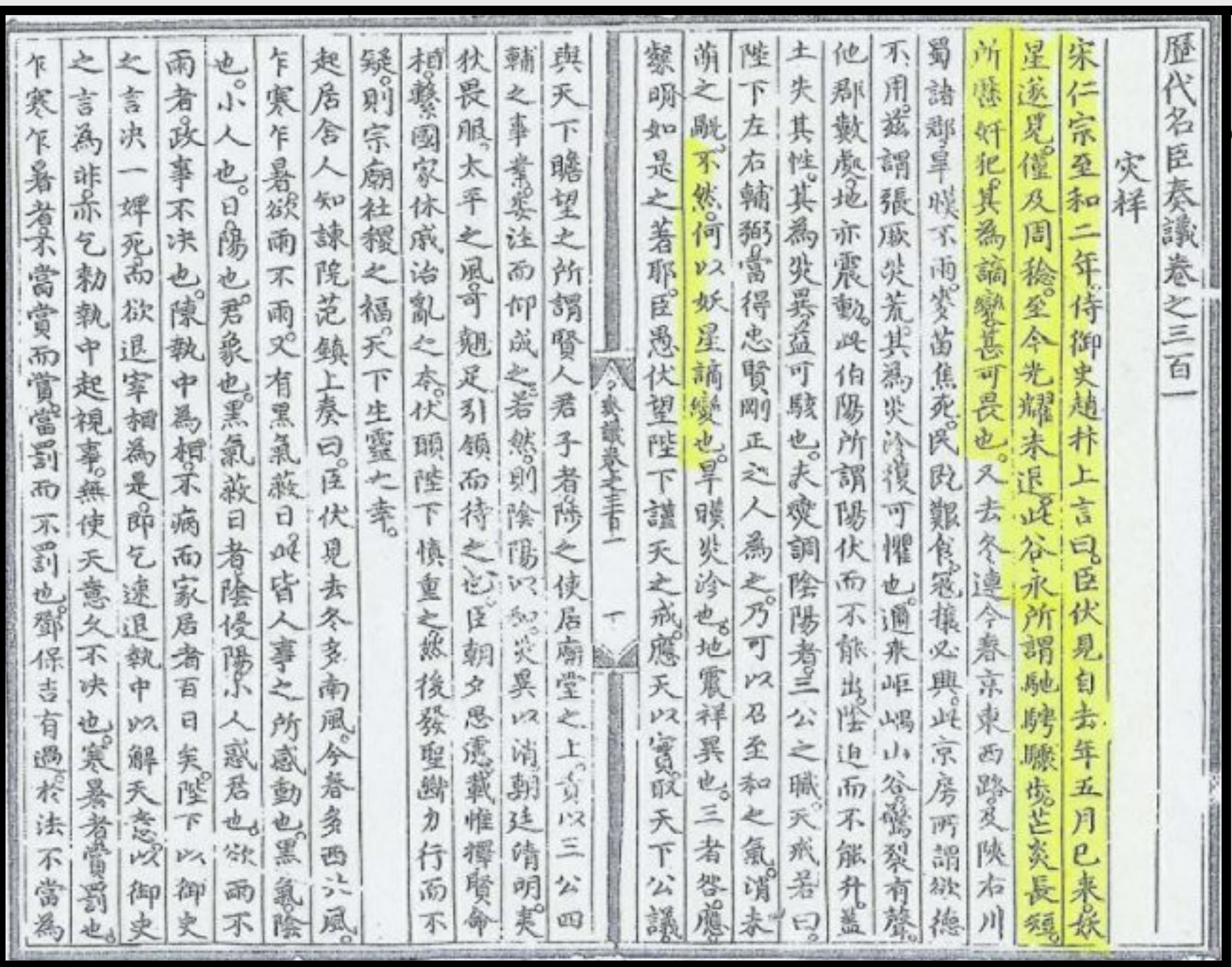
Young Supernova Experiment

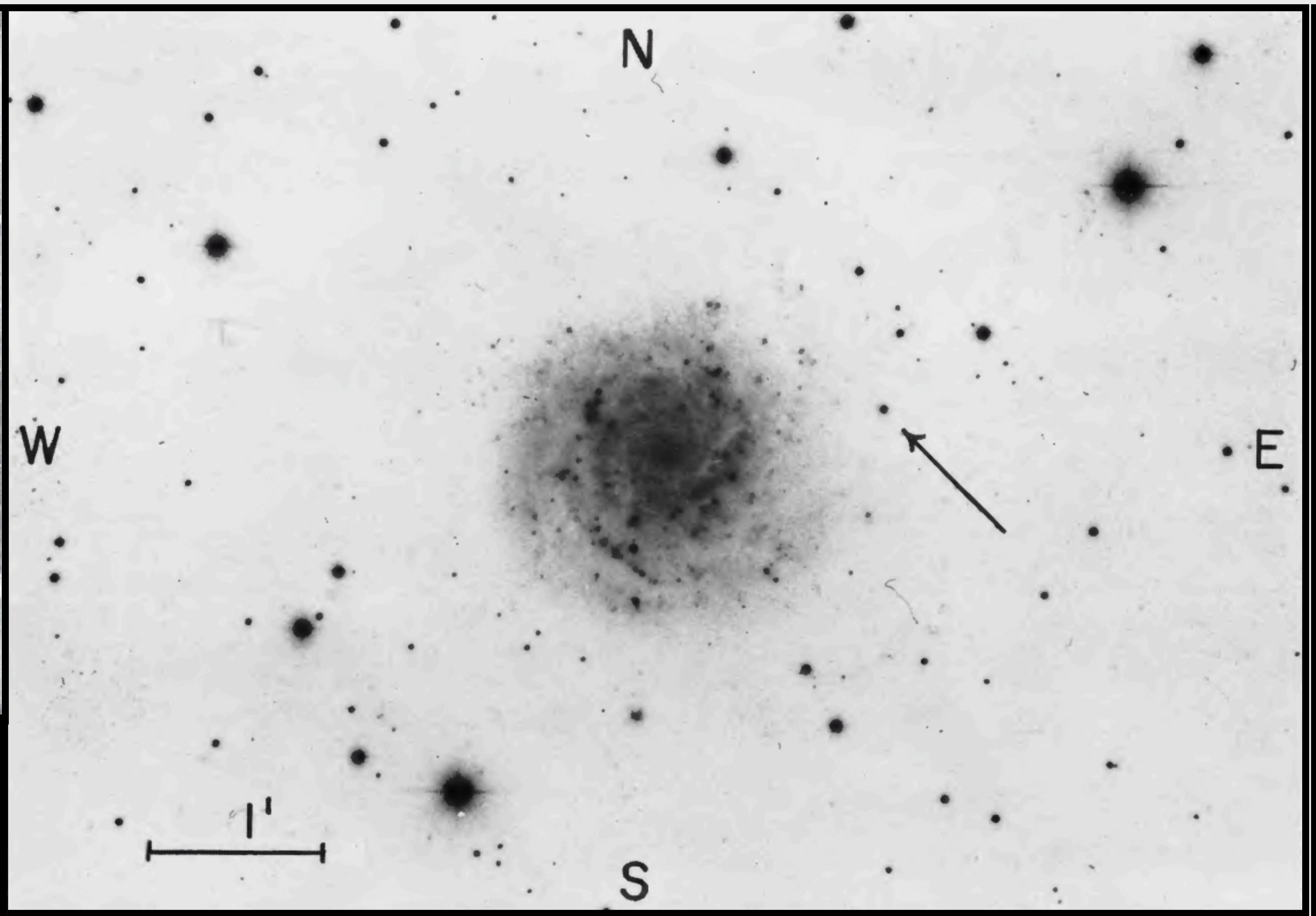
ENABLING ASTRONOMICAL TRANSIENT DISCOVERIES IN THE RUBIN ERA: THE FINK-BRAZIL WORKSHOP, MAY 2024

CIERA

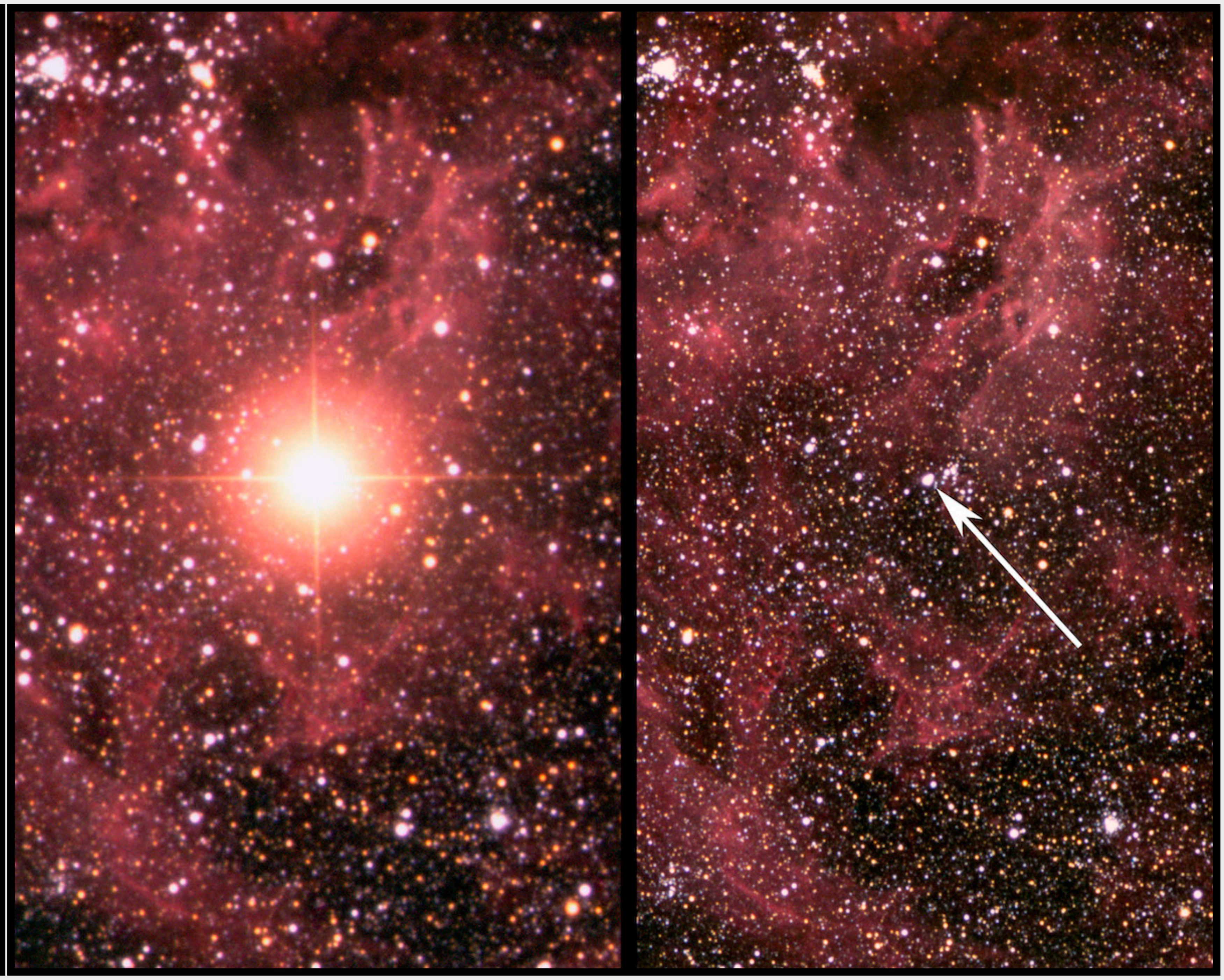
HISTORICAL OBSERVATIONS OF MASSIVE STAR EXPLOSIONS



Record of SN1054 (Crab Nebula)



SN1961V (Zwicky 1964)

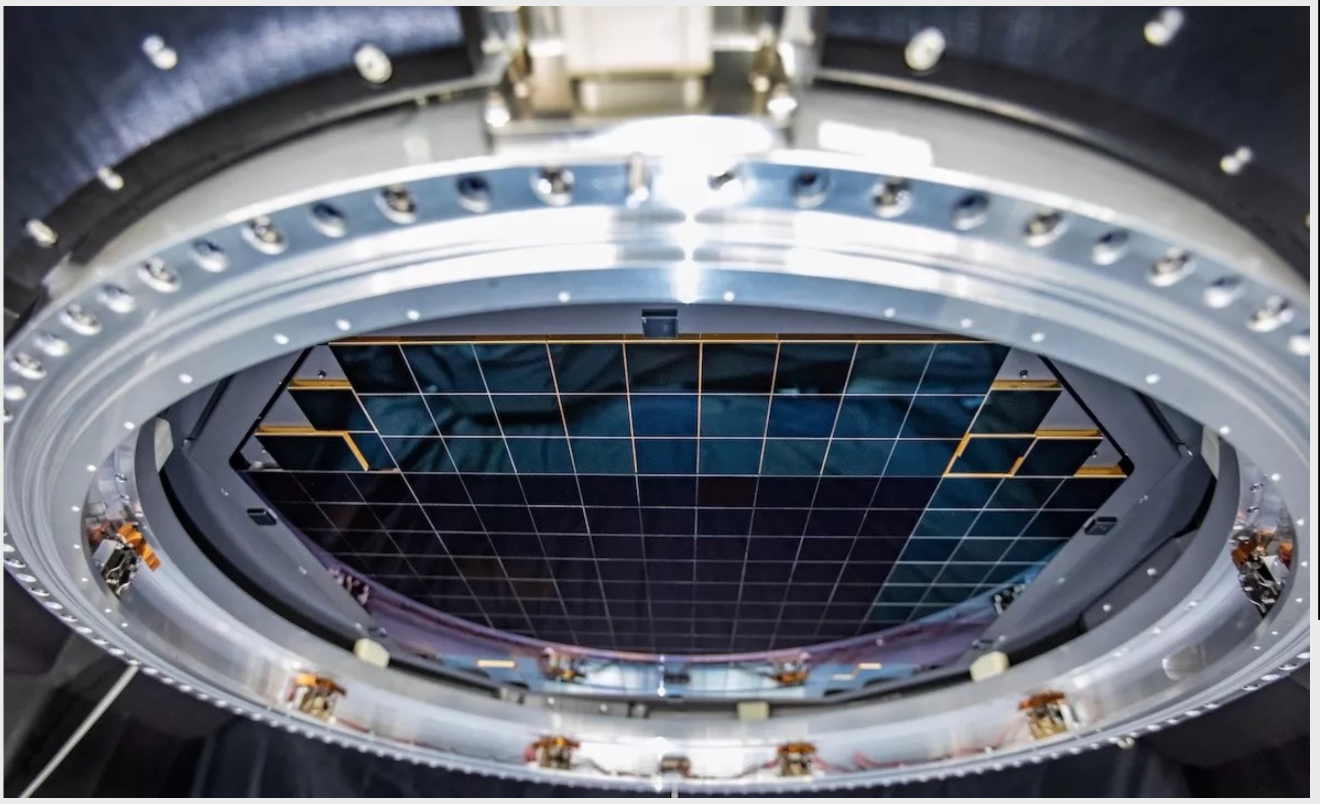


SN1987A (ANO)

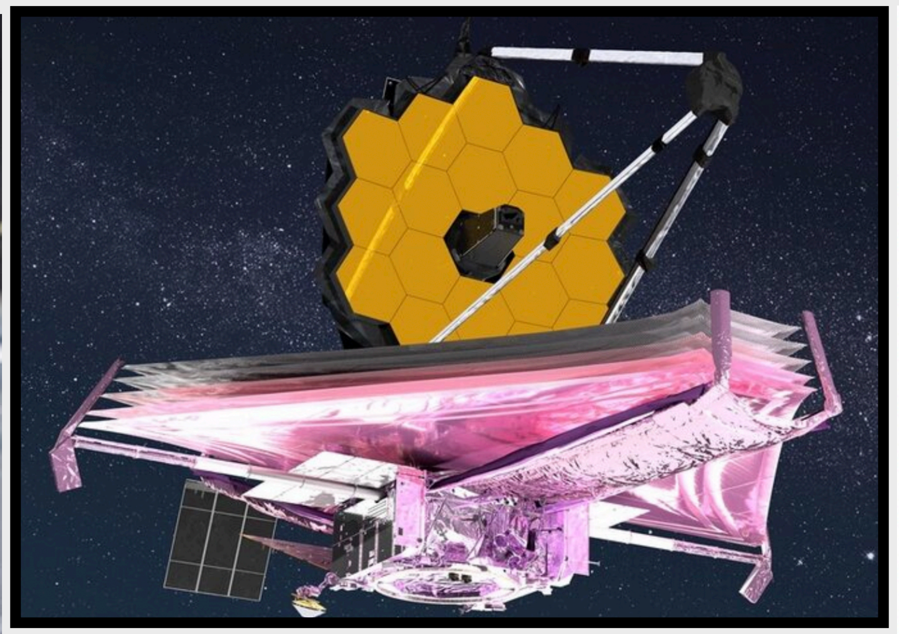
Core-collapse supernovae have always been at the cutting edge of science in time-domain astronomy, nuclear physics, stellar evolution, galaxy feedback


EXPLODING MASSIVE STARS
GRAVITATIONAL WAVES
NUCLEAR PHYSICS
NEUTRON STARS/BLACK HOLES
STELLAR EVOLUTION
METAL ENRICHMENT
EPOCH OF REIONIZATION
COSMIC RAY ACCELERATION
TRIGGERED STAR FORMATION
HIGH-ENERGY RADIATION
STRONG SHOCK PHYSICS
DEGENERATE MATTER

MASSIVE STAR TRANSIENTS DRIVE DISCOVERY IN TIME-DOMAIN ASTRONOMY

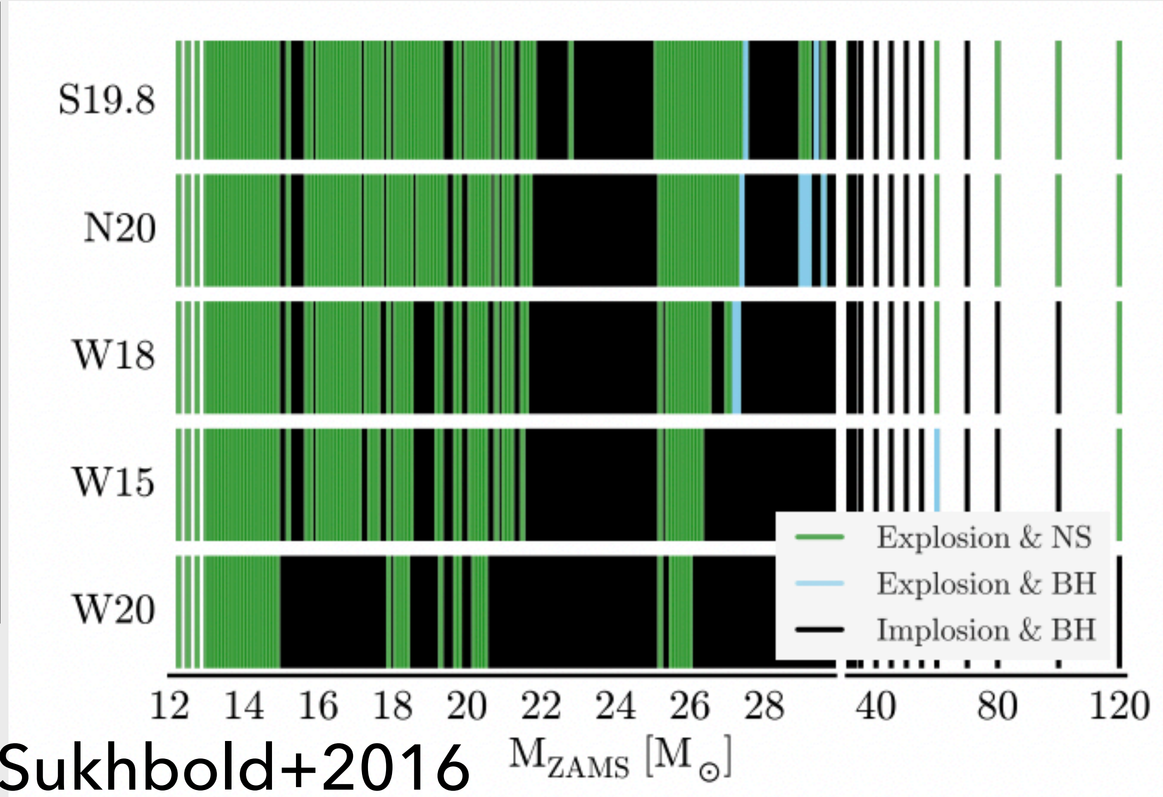


Rubin Observatory camera (SLAC)

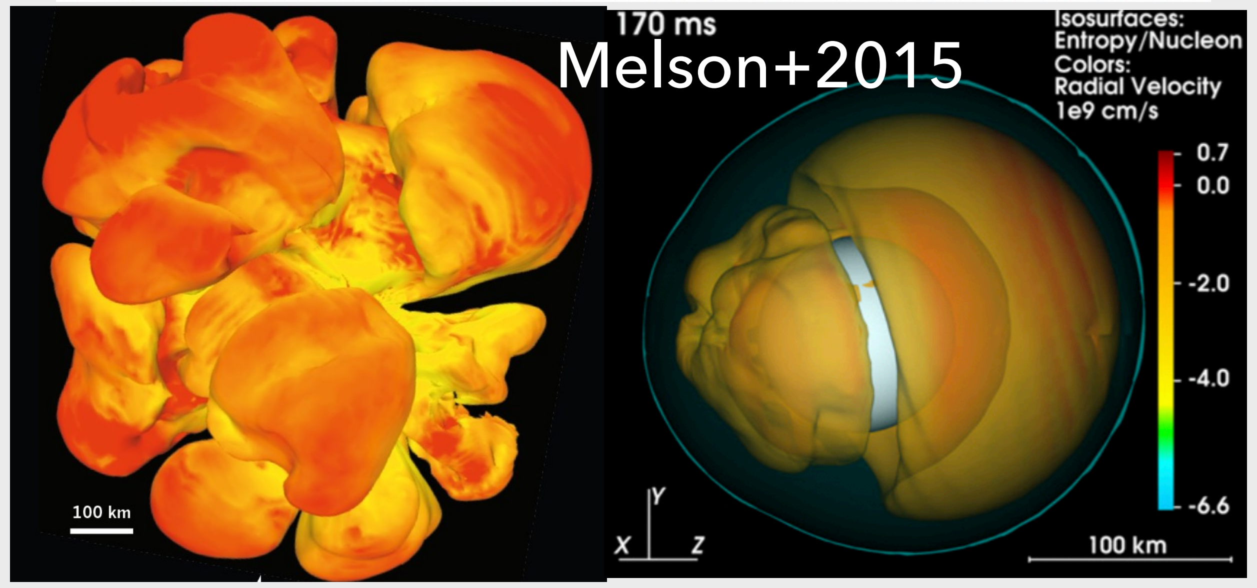


JWST (NASA/ESA)

Electromagnetic capabilities



Sukhbold+2016



Theory

Multi-messenger

New observational capabilities, theory, and messengers are accelerating to make the next 10 years revolutionary for studying massive stars and their terminal explosions

Direct identification of supernova progenitor stars


Red Supergiant
Blue Supergiant
LBV (η Car)
Late W-R (WN)
Early W-R (WC/WO)
Massive Binaries
Type II-P
SN 1987A (faint, slow)
Type IIn (dense CSM)
Type IIL/IIb (little H)
Type Ib (H, He)
Type Ic (He)
SN 2005gl
Gal-Yam et al. 2007
SN 1999em

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Kilpatrick+2024

Red supergiant progenitors to Type II supernovae
80 $M_\odot$
60 $M_\odot$
40 $M_\odot$
30 $M_\odot$
23 $M_\odot$
17 $M_\odot$
15 $M_\odot$
10 $M_\odot$
8 $M_\odot$
SN II
SN IIb
SN Ib/c
SN IIn
SN1987A
$\log(L/L_\odot)$
$\log(T_{\rm eff}/{\rm K})$
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
Kilpatrick+2024

Humphreys-Davidson Limit
Maximum Luminosity Type II progenitor star
Red supergiant progenitors to Type II supernovae
80 $M_\odot$
60 $M_\odot$
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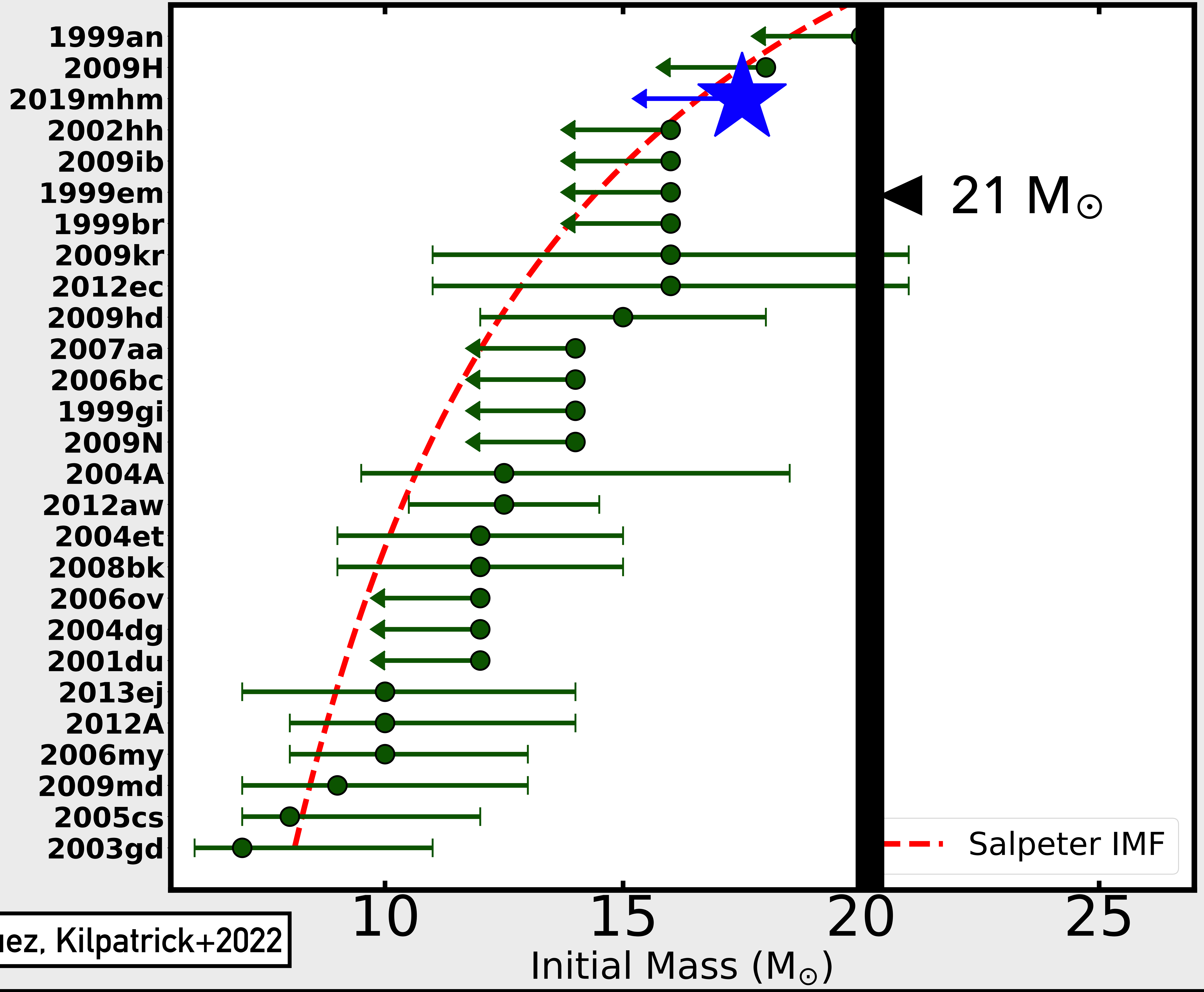
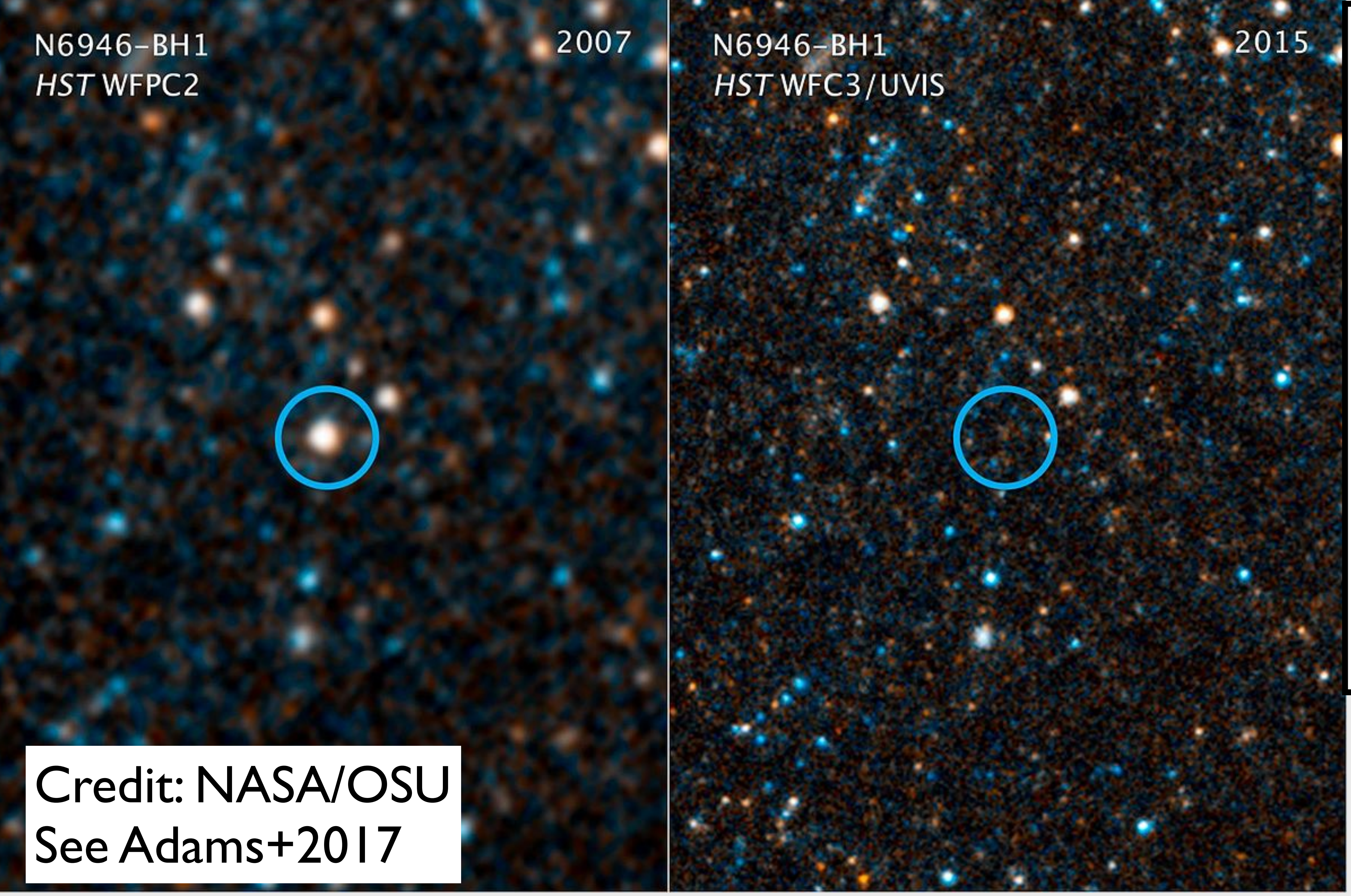
Kilpatrick+2024

Constraint on the upper limit is dominated by the highest mass progenitor known

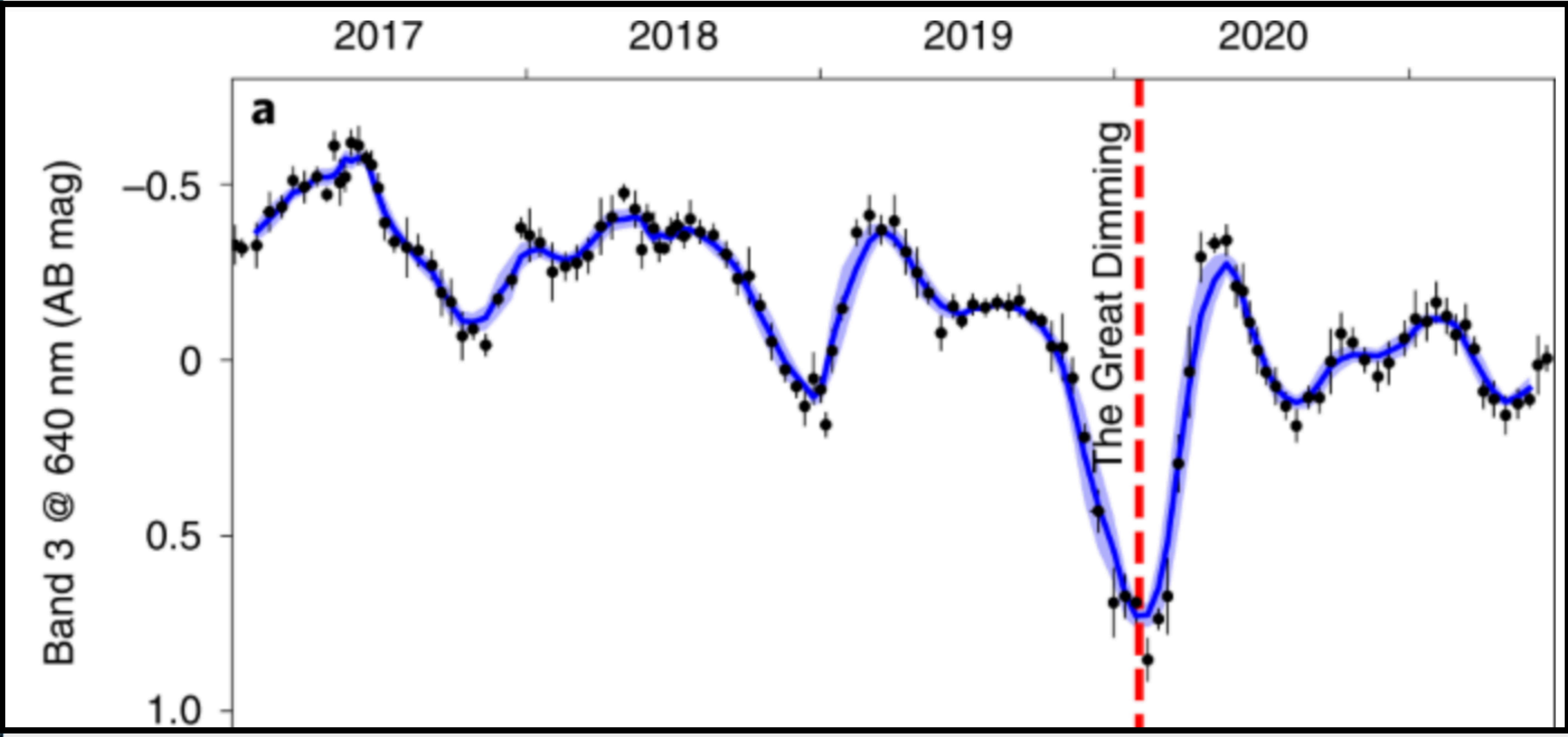
Are these measurements biased or do they indicate something physical about massive star evolution?



Vazquez, Kilpatrick+2022



Credit: NASA/OSU
See Adams+2017



Betelgeuse; Taniguchi+2022

Intrinsic VERSUS **Observational Bias**

No high-mass RSG progenitors because they do not produce hydrogen-rich supernovae (they produce "failed" SNe or evolve away from RSG branch)

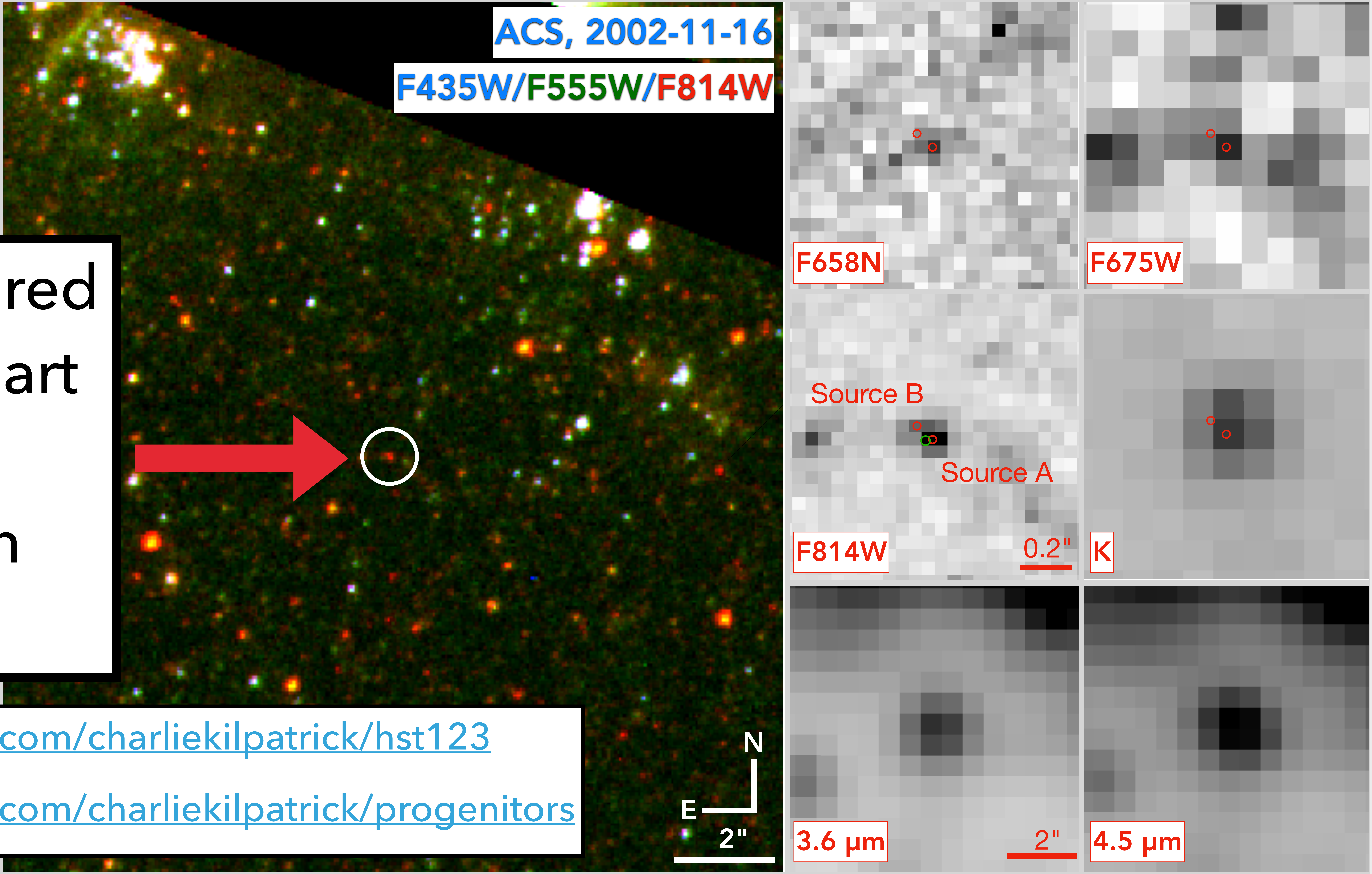
No high-mass RSG progenitors because they are in our data but we underestimate their true initial masses

Hosseizadeh+2023

Closest and brightest core-collapse supernova in >10 years

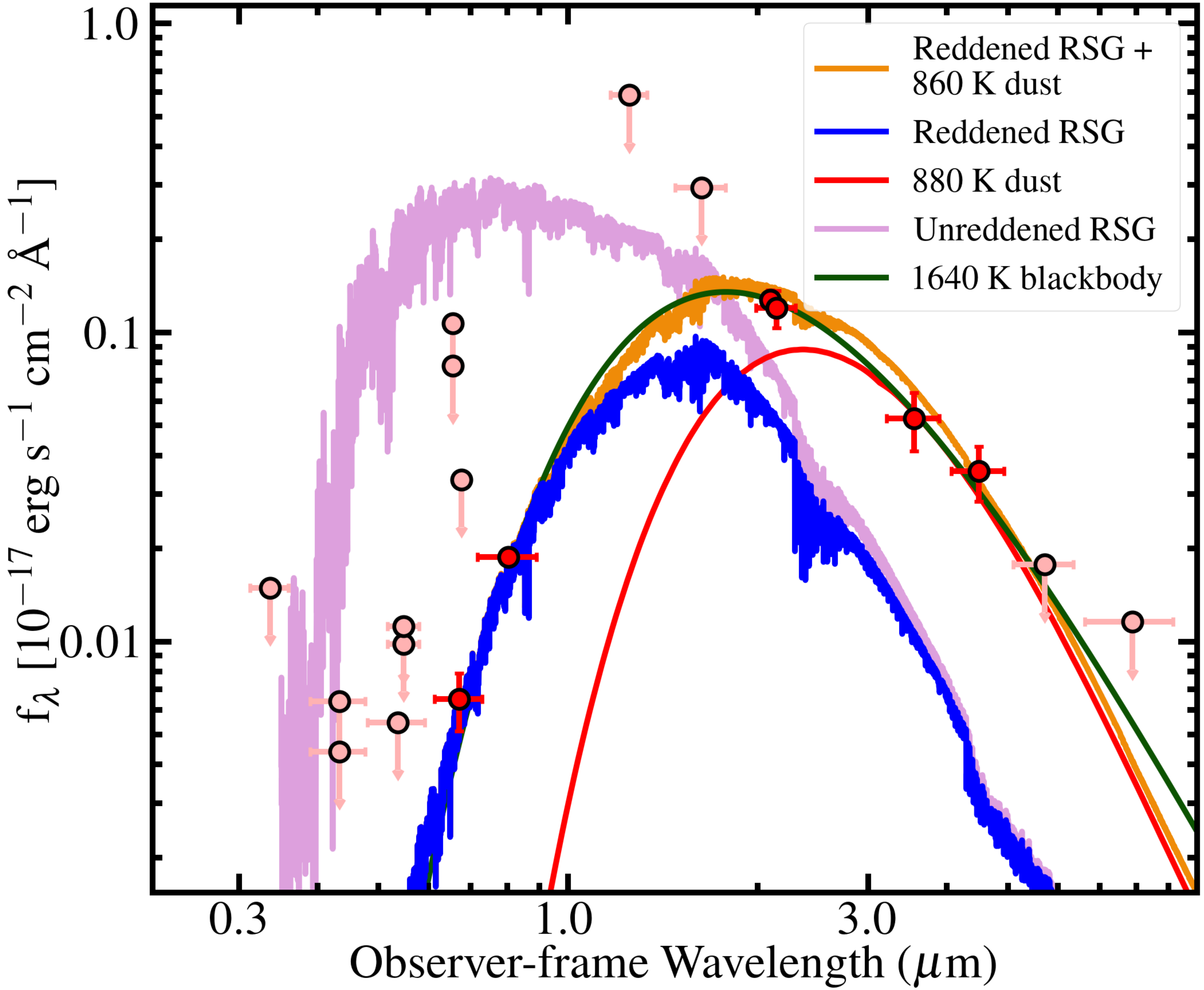
Kilpatrick+2023

A single, red counterpart in pre-explosion imaging



https://github.com/charliekilpatrick/hst123

https://github.com/charliekilpatrick/progenitors

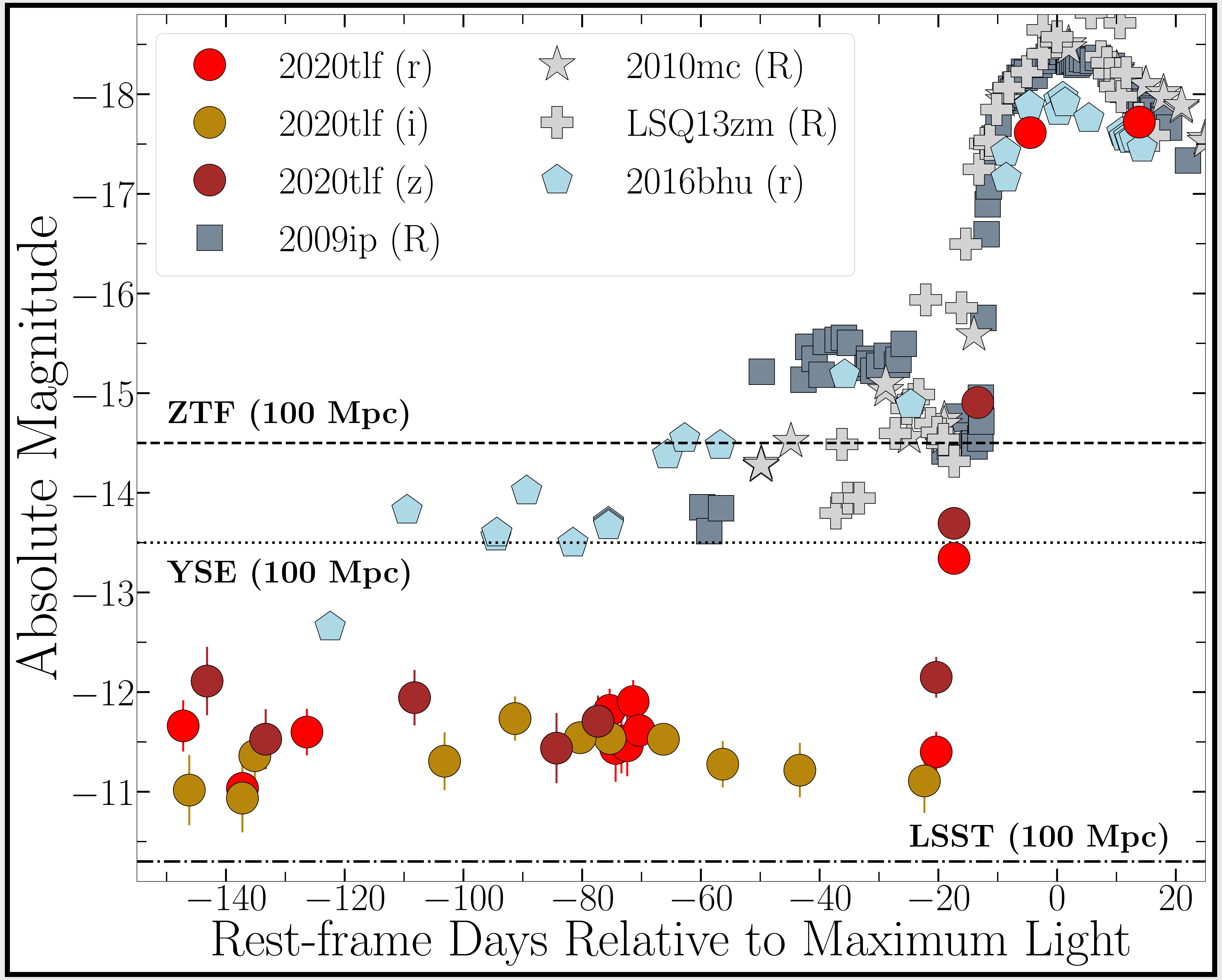


Photometry of the star is consistent with a single ~11 $M_\odot$ heavily reddened (A_V>5 mag) red supergiant.

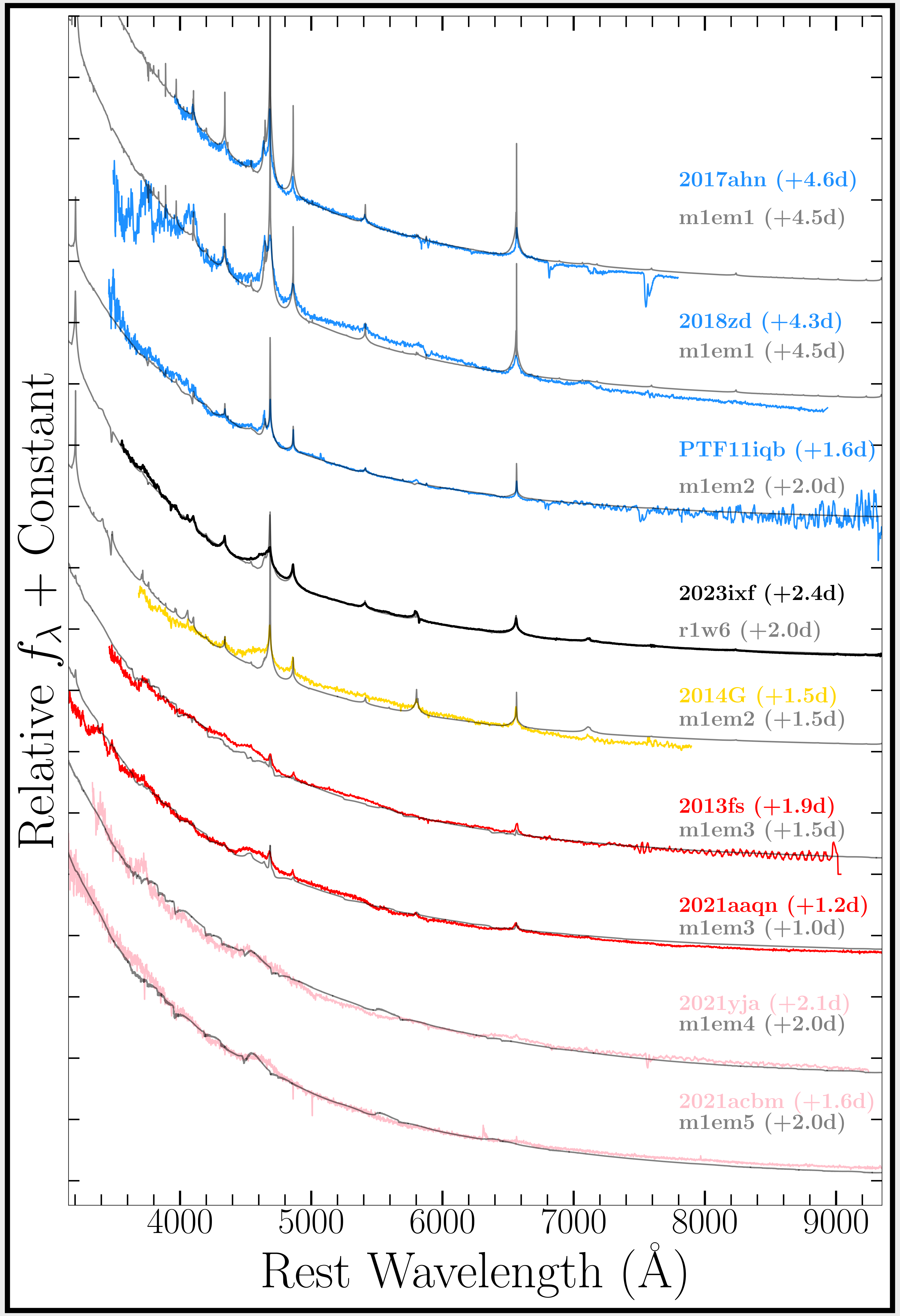
This spectrum was averaged over ~19 yr of data. Was the star variable during that time?

Comparison to Betelgeuse shows variability several times more extreme in the IR

What exactly is causing such extreme variations in a photosphere that should be extended several thousand Solar radii from the star?

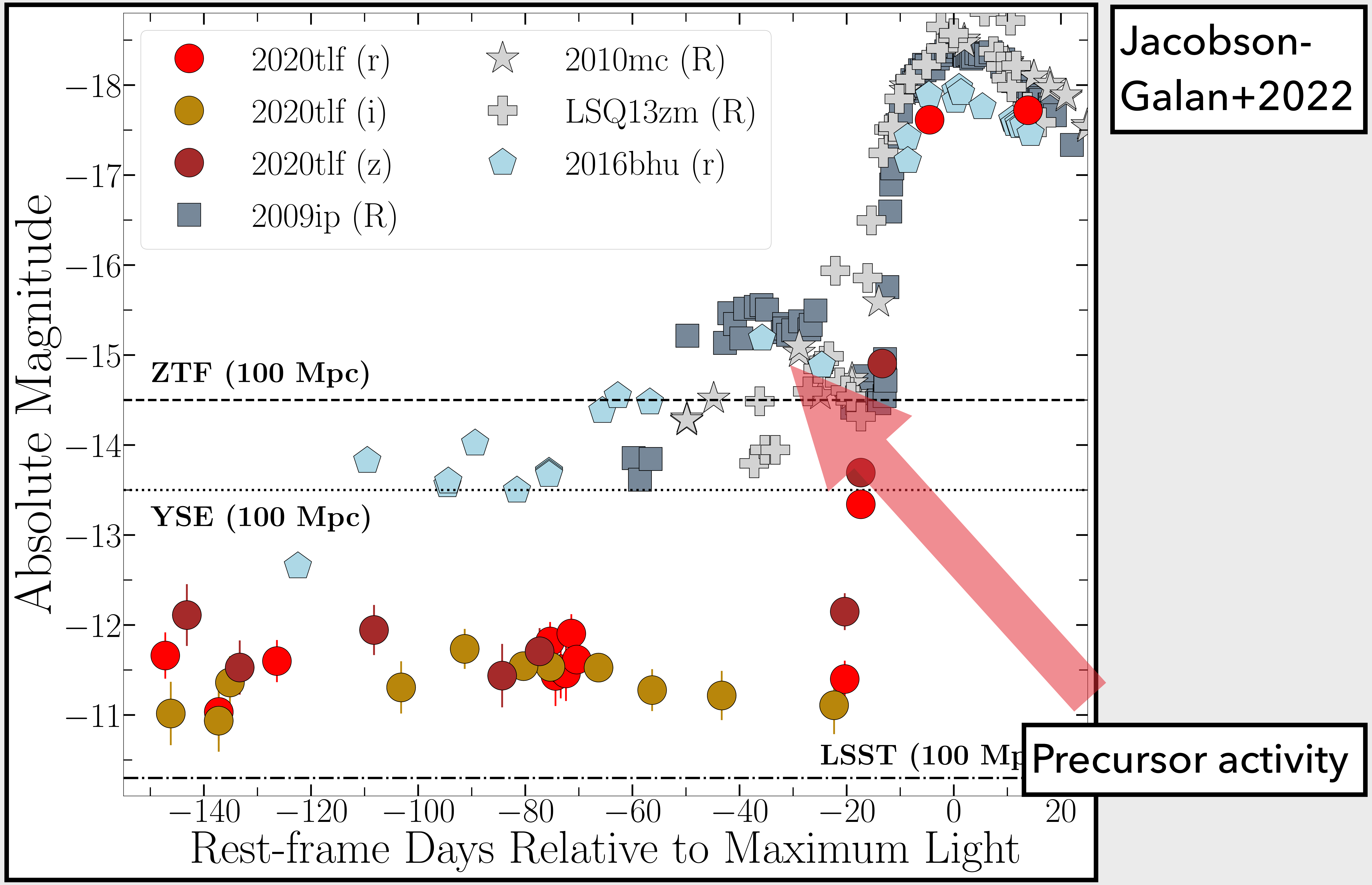


Jacobson-Galan+2022



>40% of Type II supernovae exhibit evidence for dense, confined circumstellar material within 2 days of explosion

Jacobson-Galan+2023



Jacobson-Galan+2022

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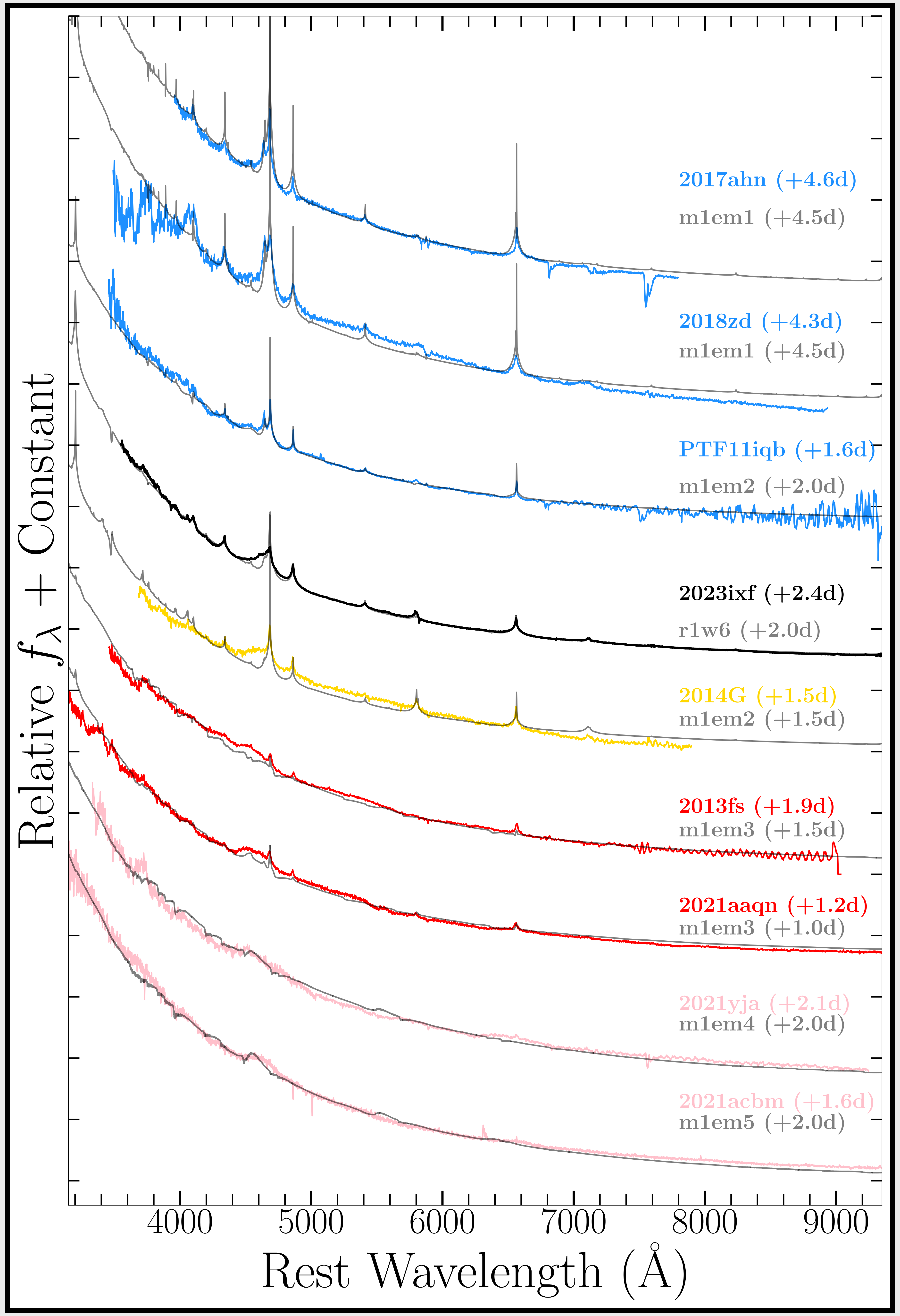

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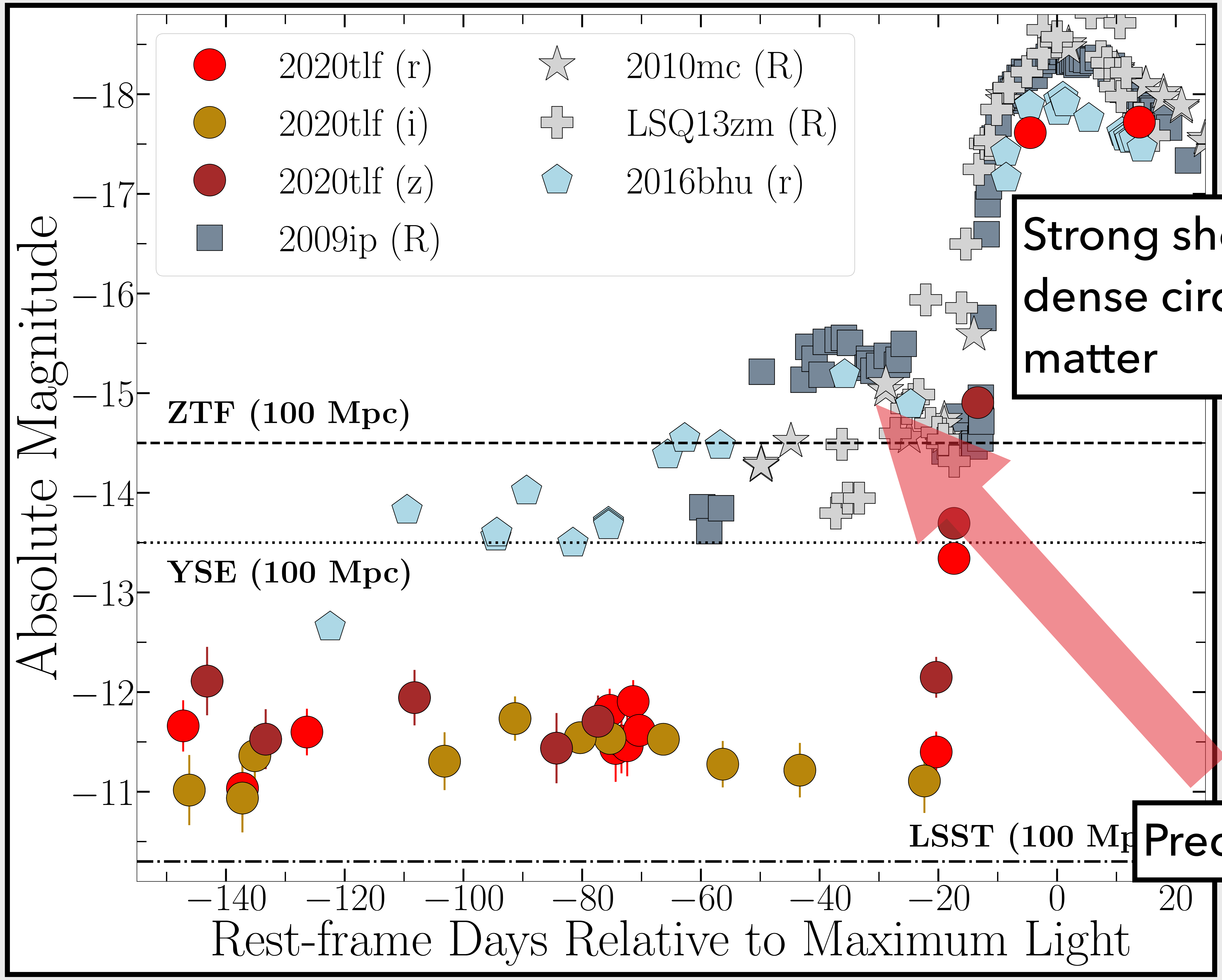
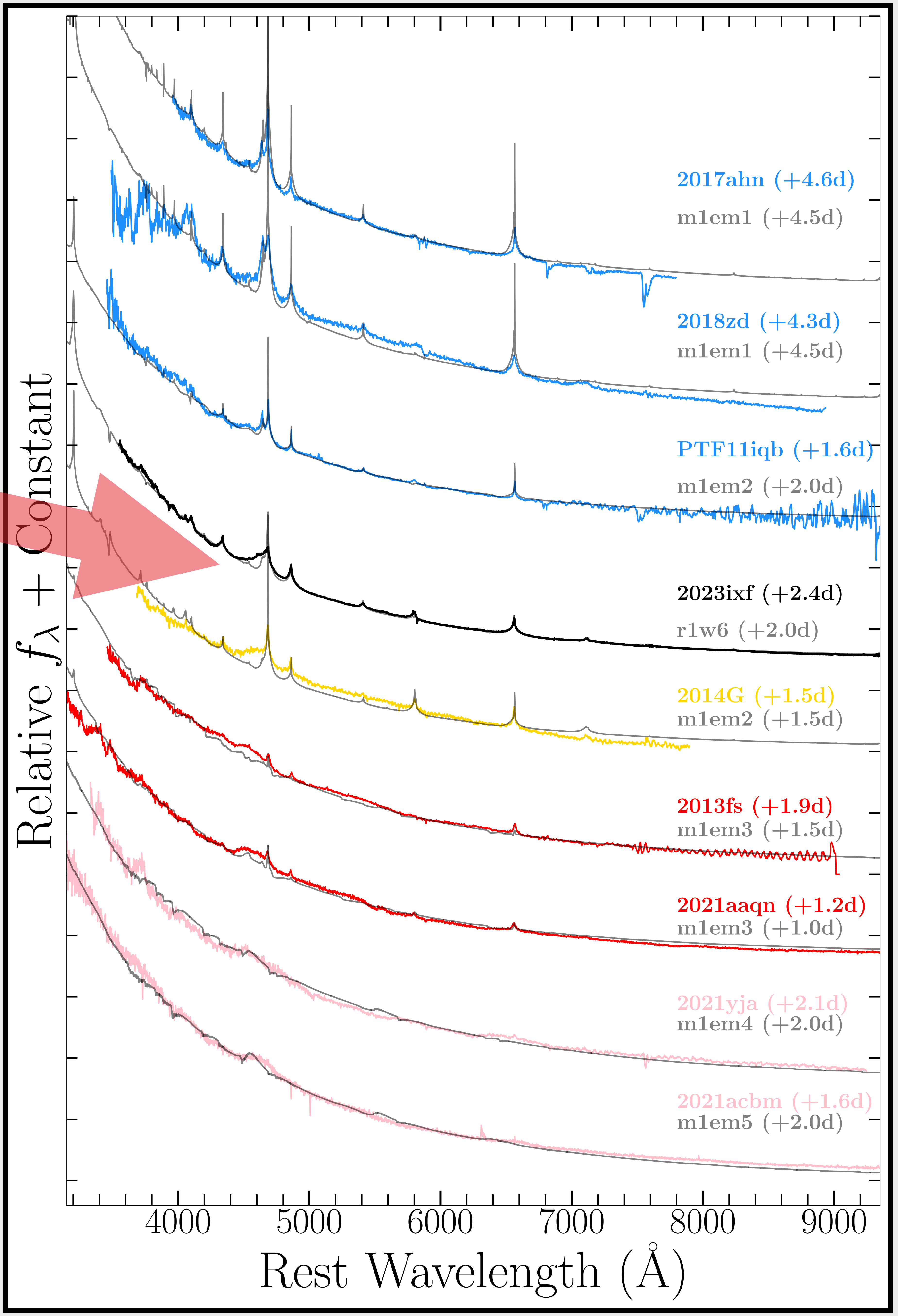


Jacobson-Galan+2022

Strong shock from dense circumstellar matter

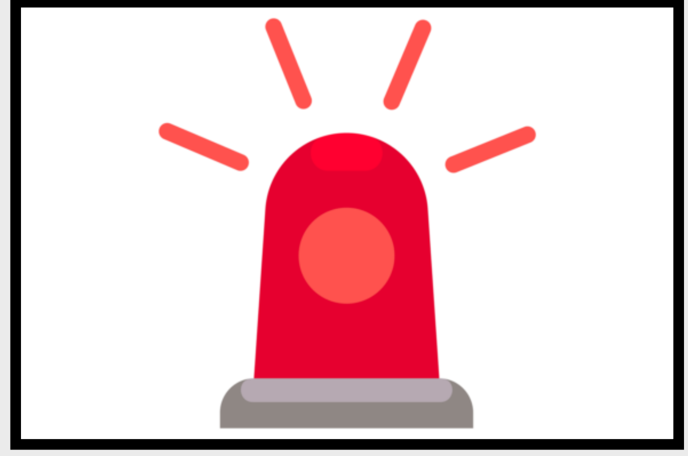
Precursor activity



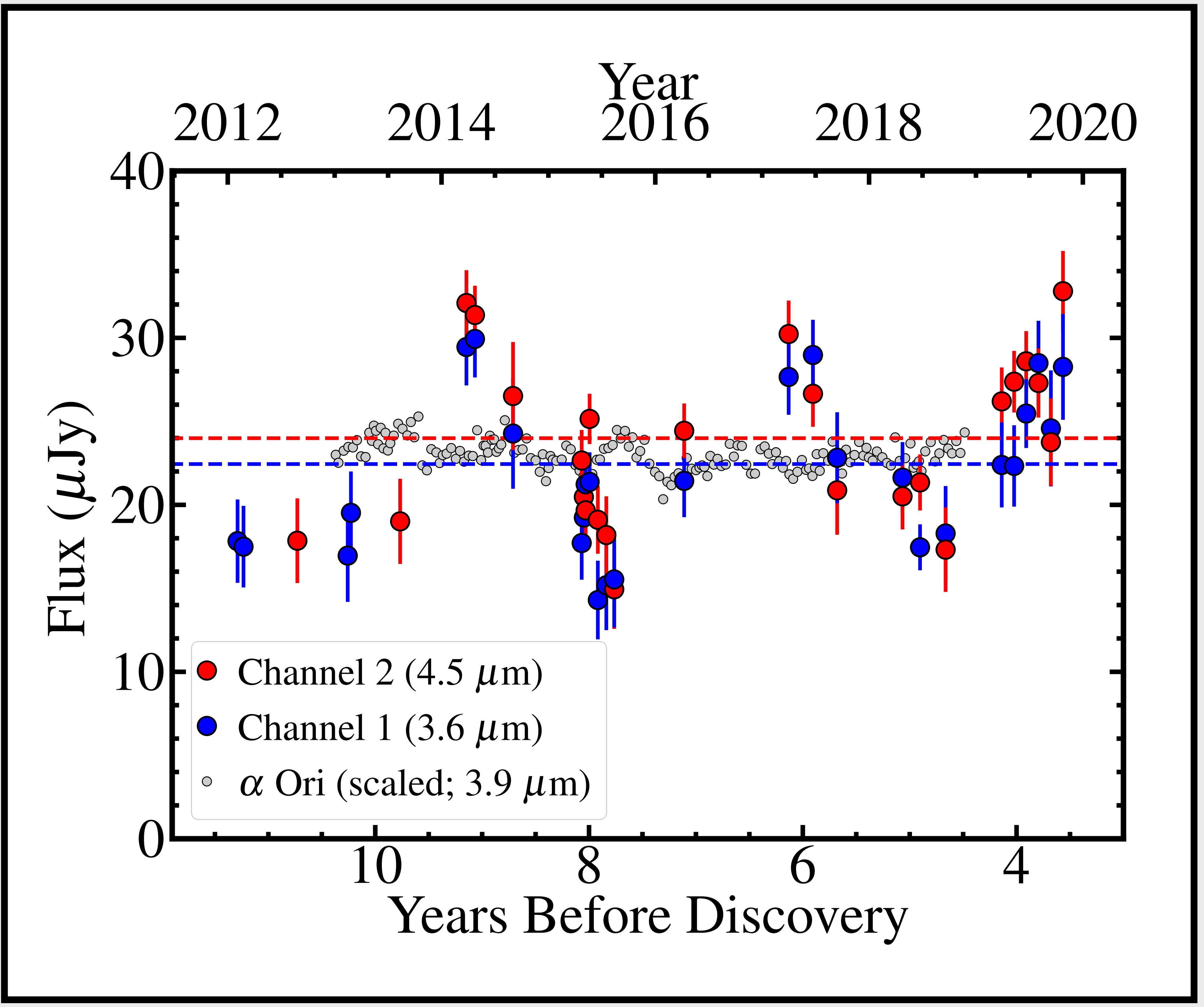
>40% of Type II supernovae exhibit evidence for dense, confined circumstellar material within 2 days of explosion

Jacobson-Galan+2023

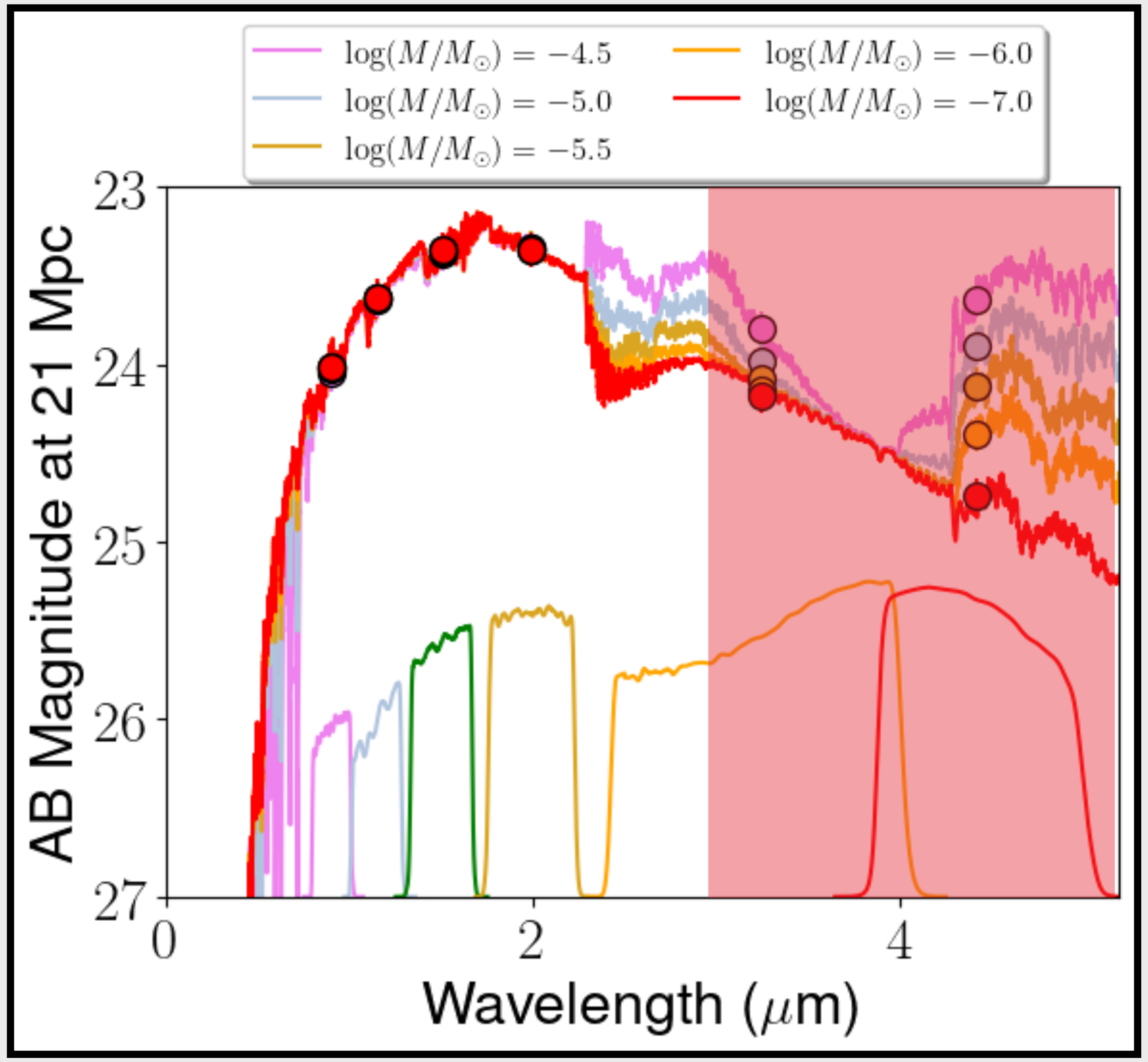
CAN WE FIND STARS THAT ARE ABOUT TO EXPLODE EARLY ENOUGH TO OBTAIN FOLLOW UP IN THEIR "FINAL MOMENTS"?



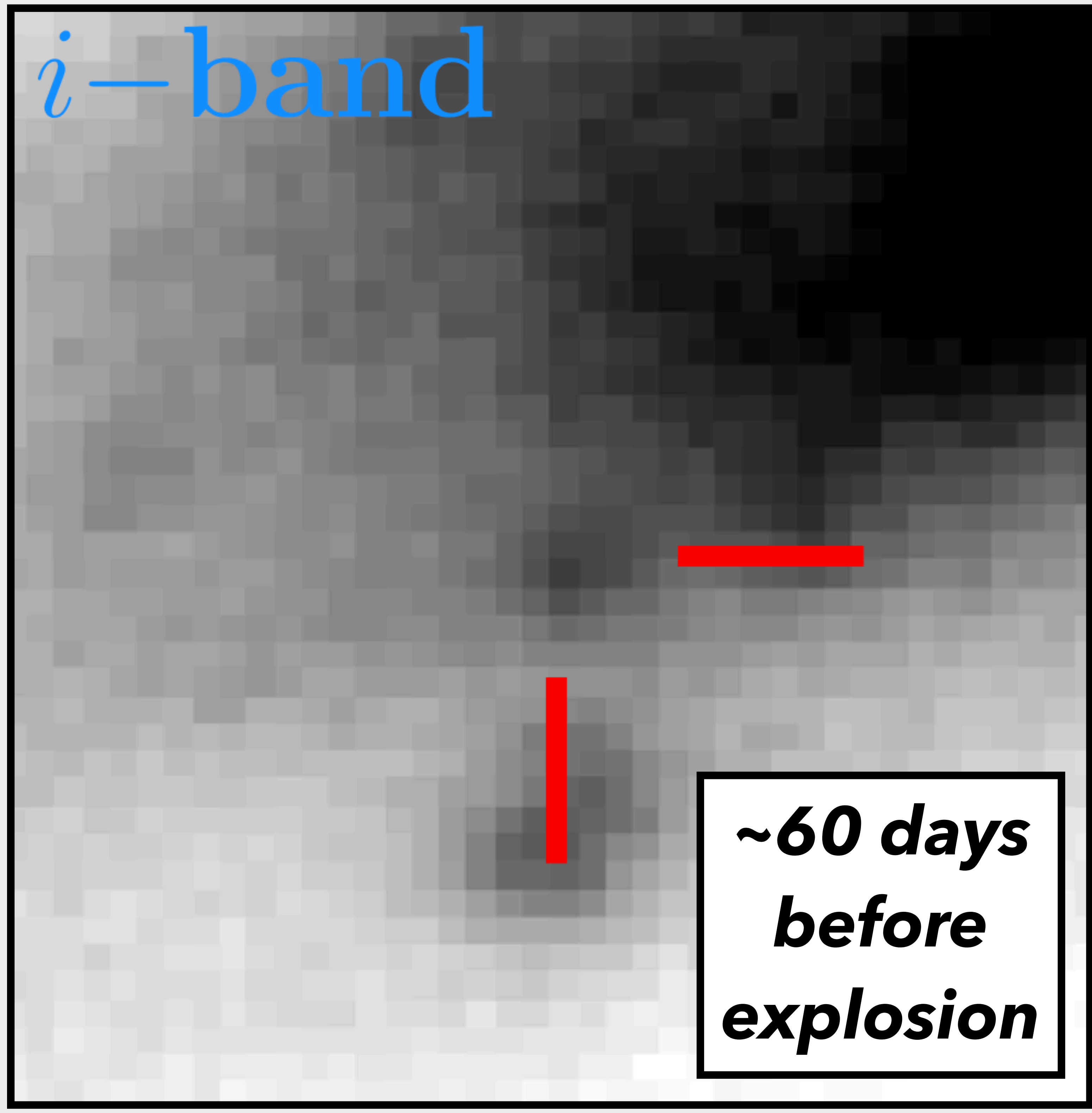
EXPLOSION IMMINENT!



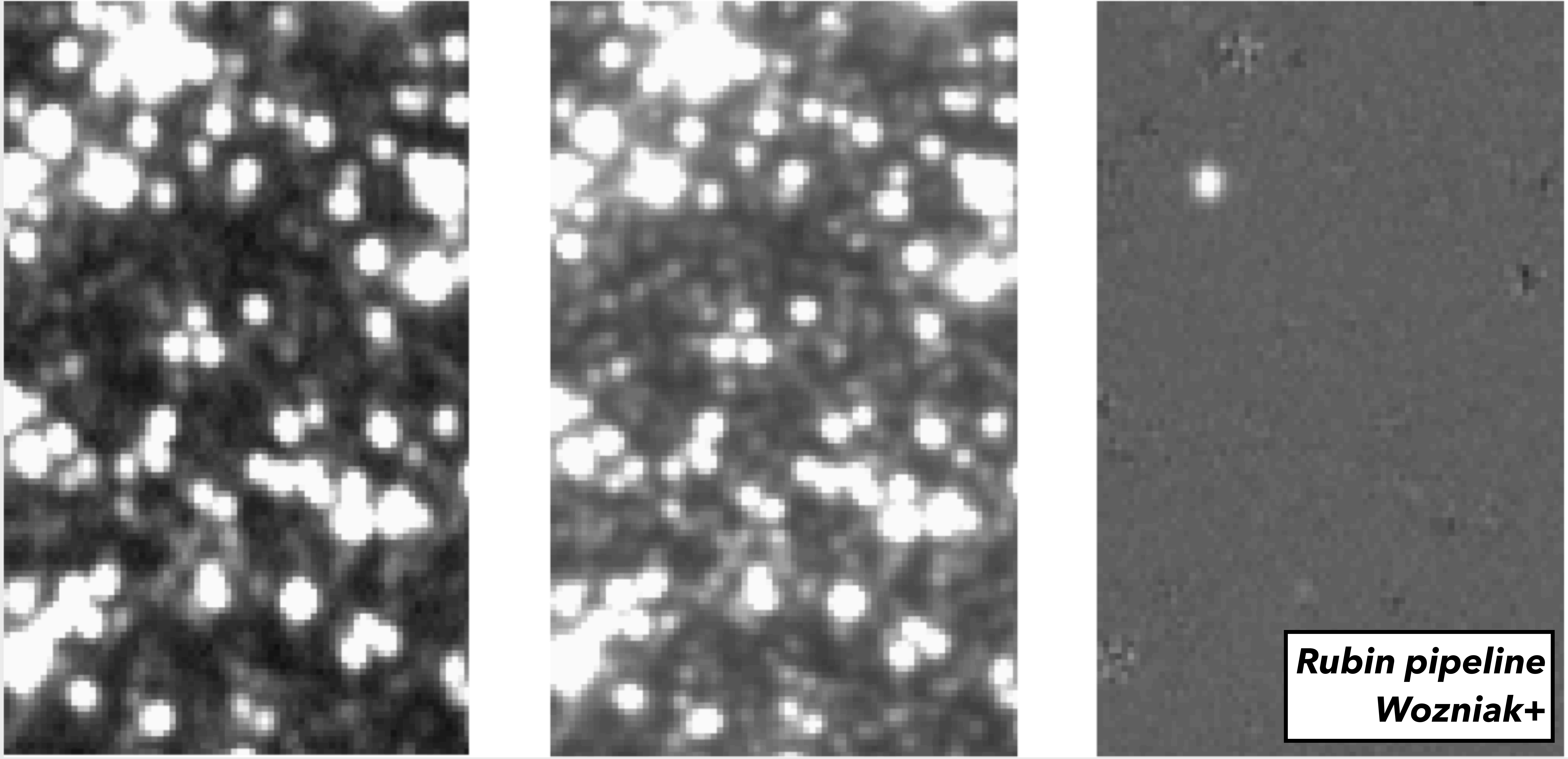
EXTREME VARIABILITY



MID-INFRARED EXCESS

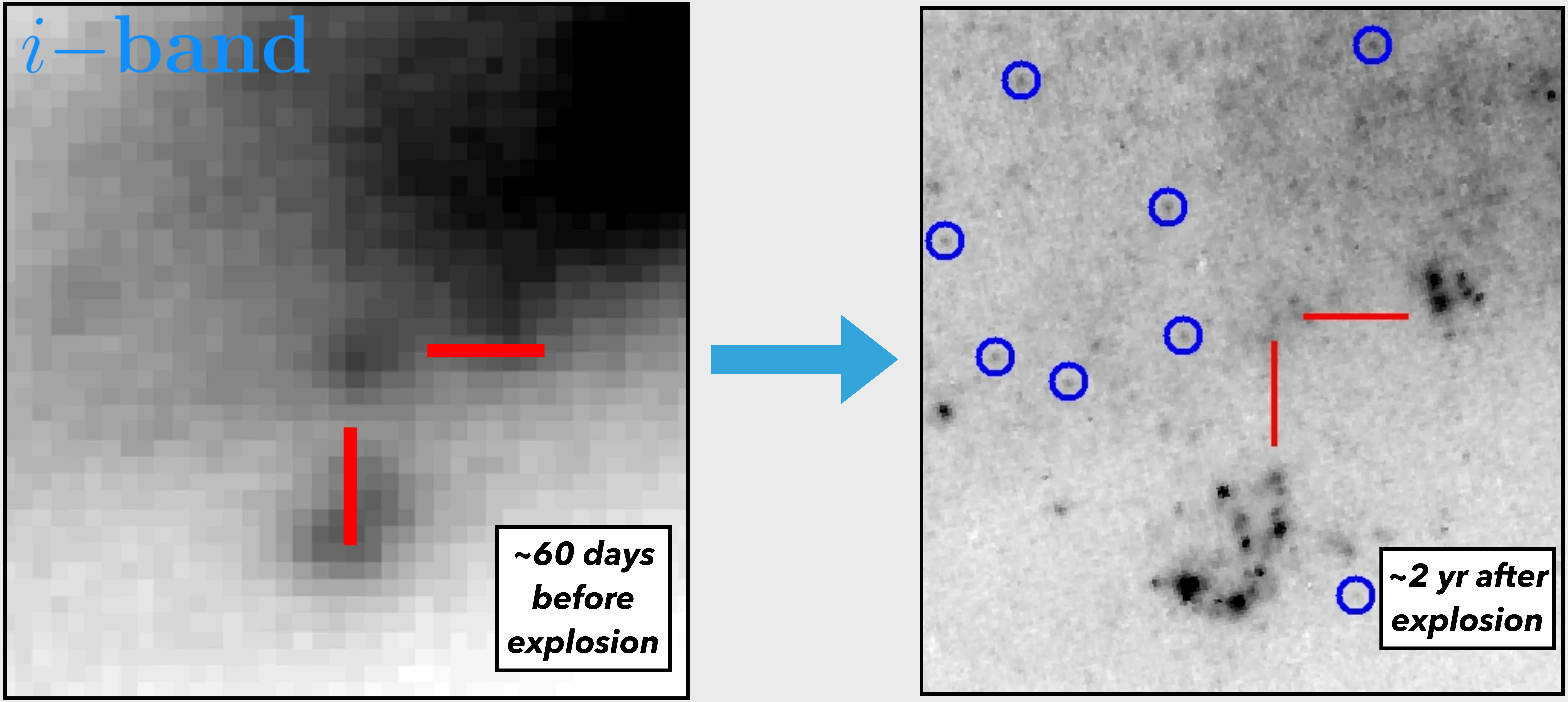


PRE-EXPLOSION ERUPTION



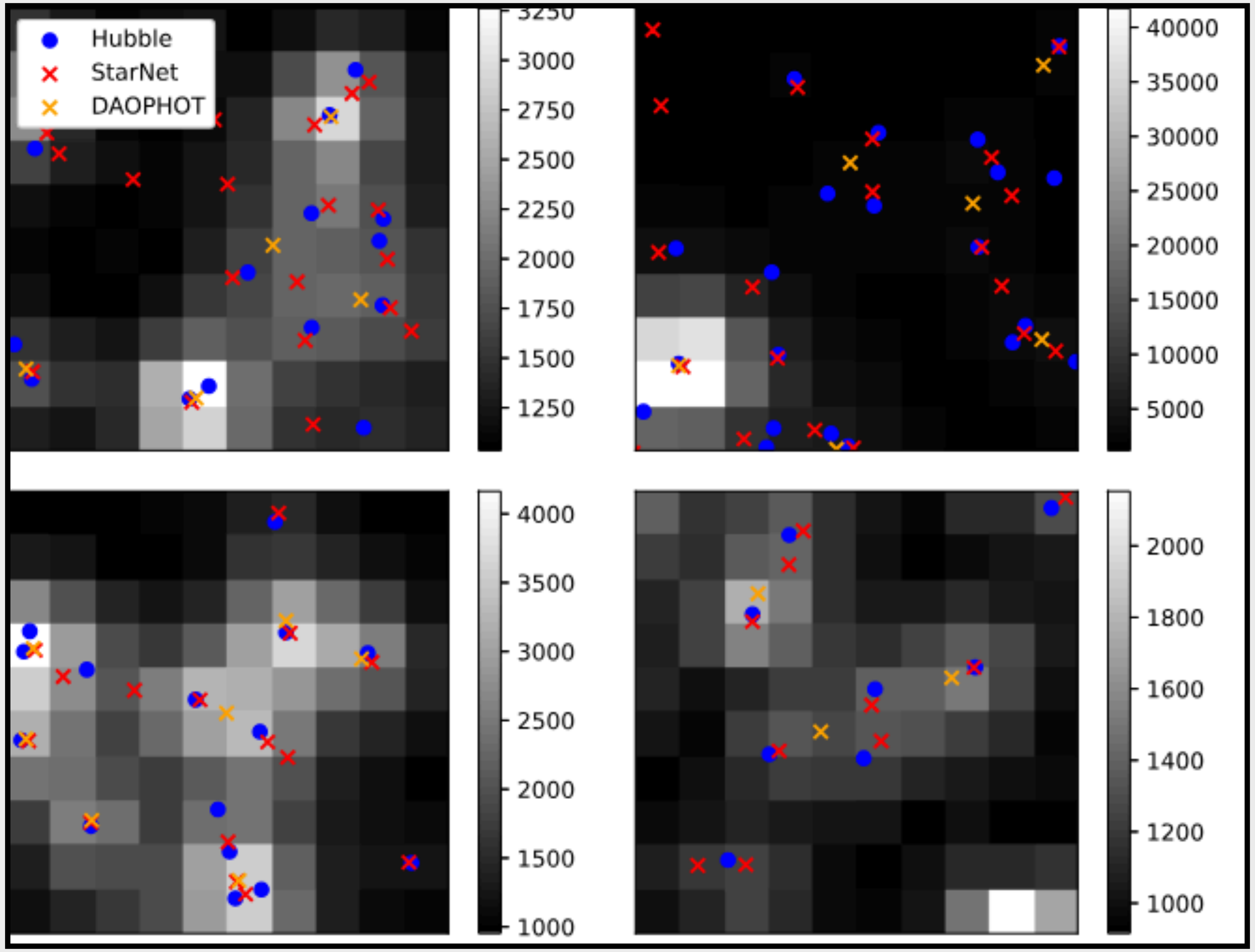
Rubin/LSST will provide the largest, most precise catalog of *ugrizy* stellar light curves
Combined with ***HST, JWST, Euclid,* and *Roman***, we will have precise ultraviolet to mid-infrared SEDs and light curves for tens of thousands of massive stars at ≲20 Mpc

STEP 1: FIND A LARGE NUMBER OF RED SUPERGIANTS



Knowing where to look for exploding stars simplifies querying in data streams from future surveys such as the Vera C. Rubin Legacy Survey of Space and Time

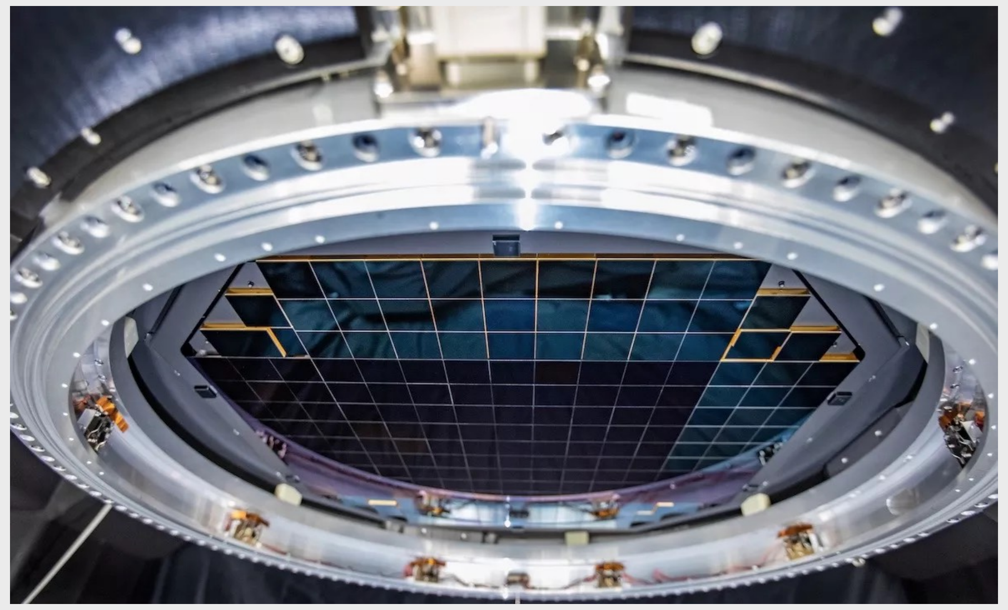
STEP 1: FIND A LARGE NUMBER OF RED SUPERGIANTS

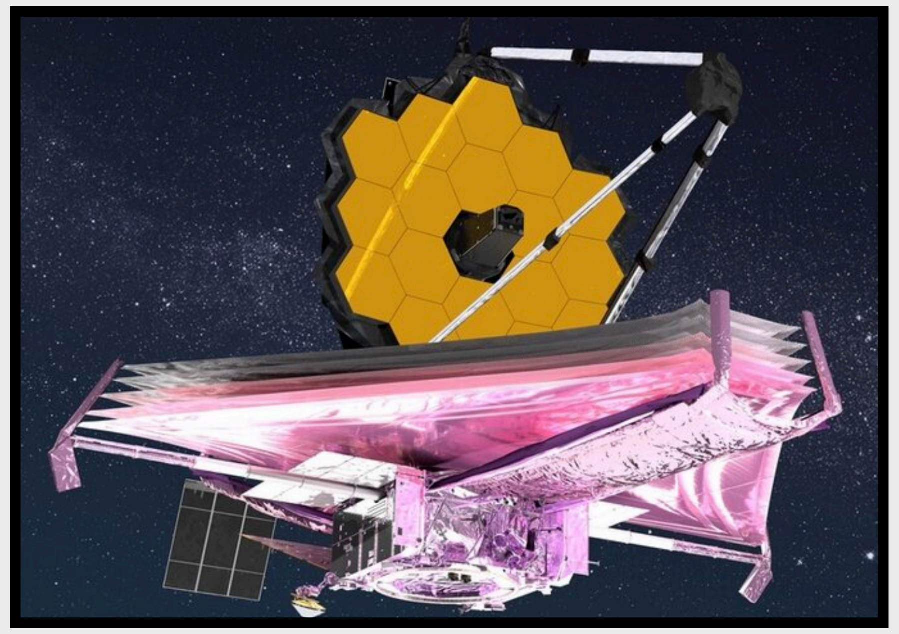


Precise catalogs are needed for these crowded star fields

Confusion will often be a limiting factor in analyzing Rubin imaging

JWST+Rubin can be used to analyze massive star populations in greater detail





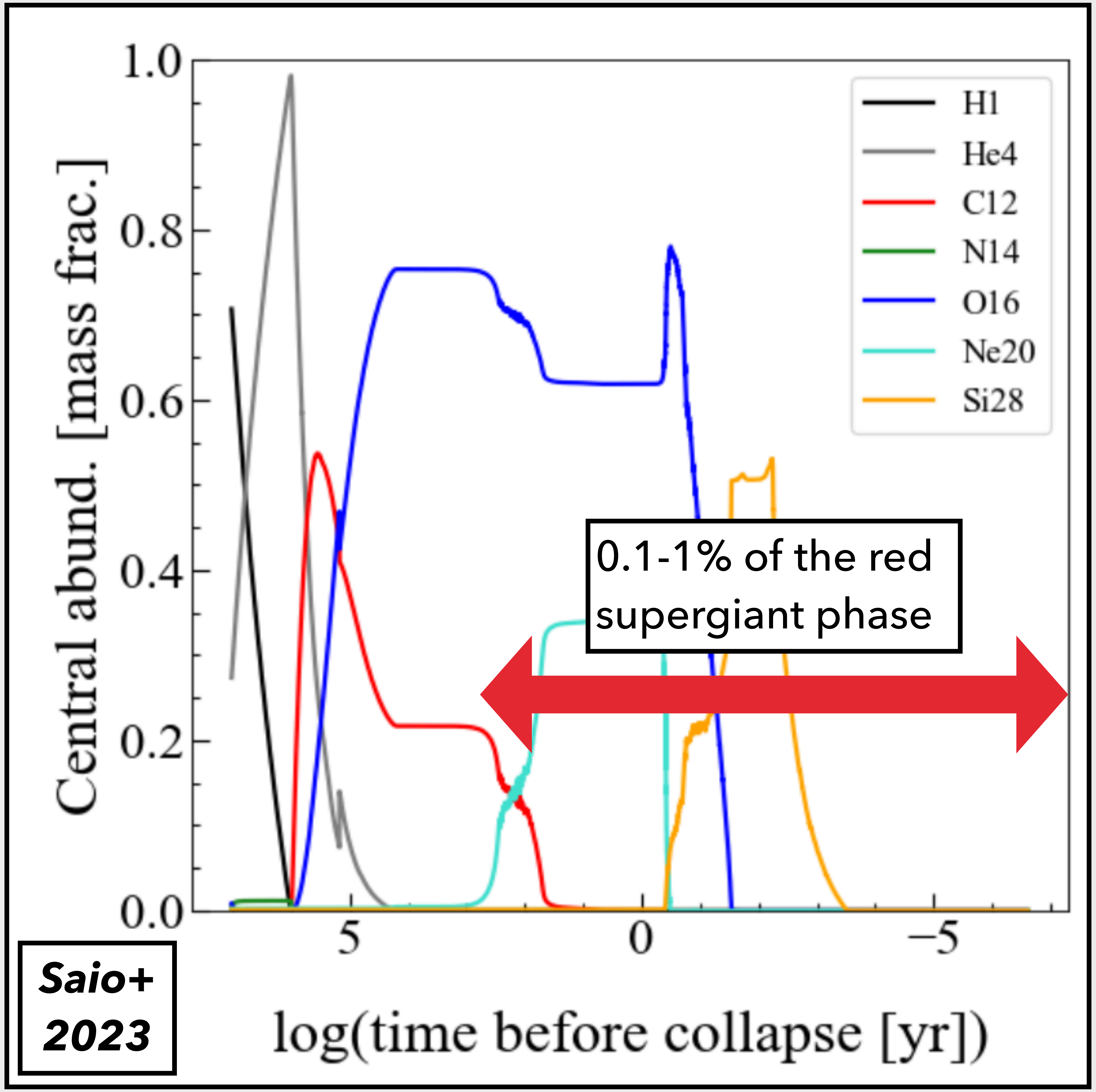
Cycle 3 JWST-AR-5441 (PI Kilpatrick) will construct the largest catalog to date of photometrically-identified red supergiants at ≲20 Mpc

STEP 2: IDENTIFY PROMISING CANDIDATES FOR FOLLOW UP

Enhanced mass loss will occur during the final 100-10,000 yr before core collapse.

- Assume 100,000 red supergiants,
- 100-1000 will be C-burning or later,
- 1 explosion per 1-10 years

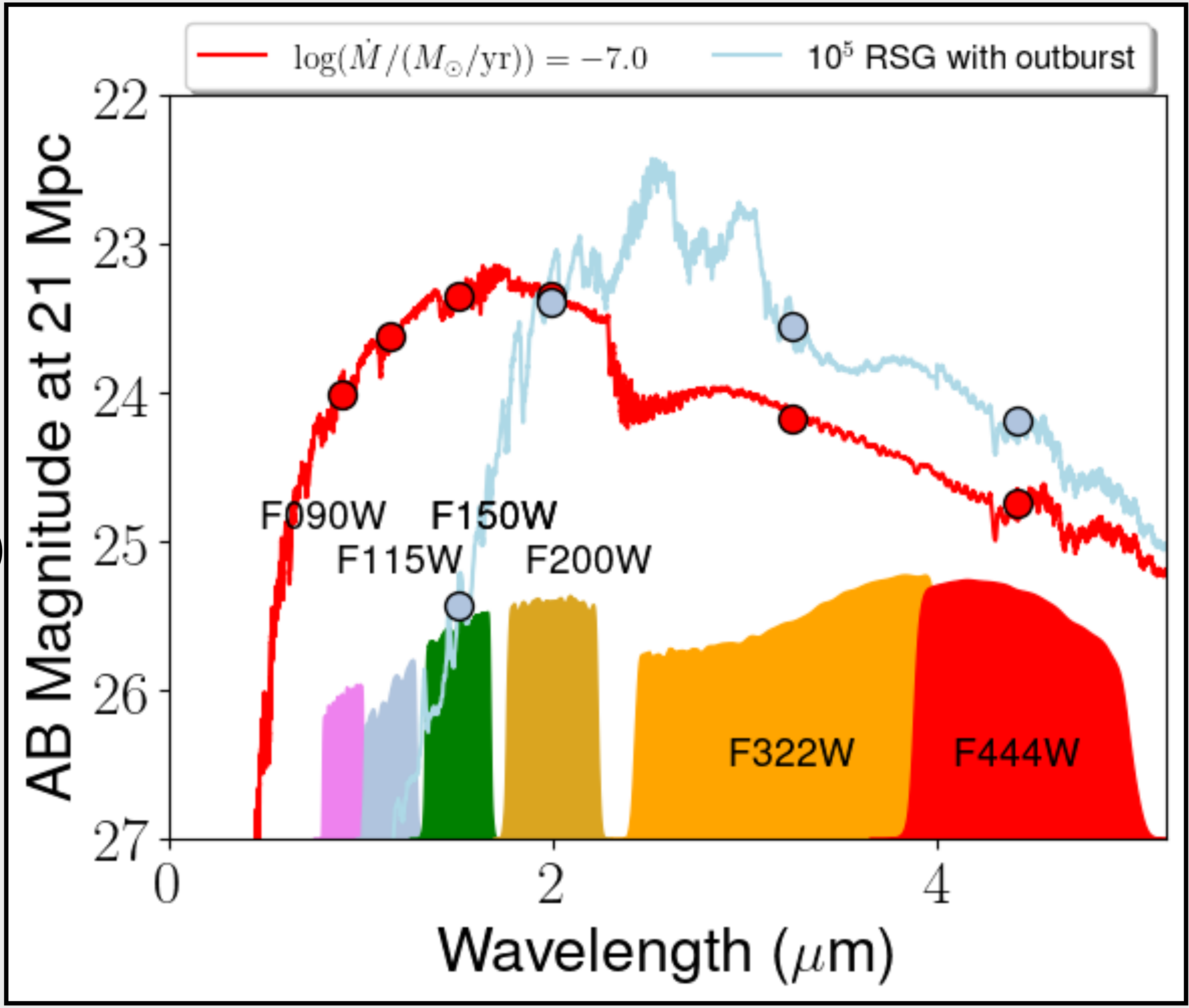
Element	Time (15 M☉)	Time (25 M☉)
C	6000 yr	170 yr
Ne	7 yr	1.2 yr
O	1.7 yr	6 mo
Si	1 week	1 day



STEP 2: IDENTIFY PROMISING CANDIDATES FOR FOLLOW UP

Enhanced mass loss is a clear signpost of later burning stages, similar to SN2020tlf and 2023ixf

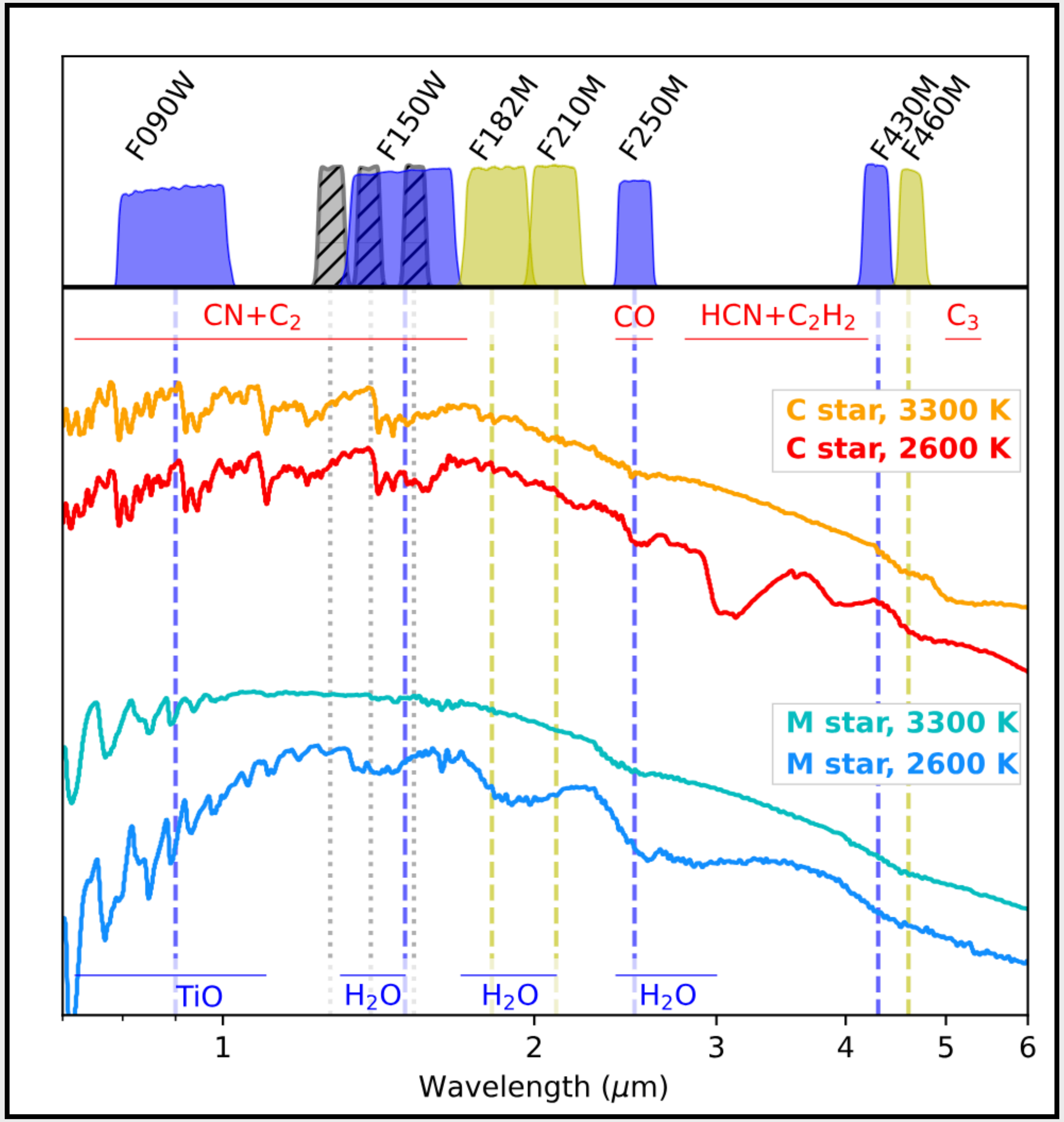
- Depressed optical emission (Rubin)
- Strong mid-IR emission (JWST)
- Optical/IR variability (Rubin)



STEP 3: OBTAIN SPECTROSCOPY OF PRE-SUPERNOVA STARS

Spectroscopy of promising pre-supernova stars can be used to identify:

- Precise luminosity and spectral type
- Composition (TiO, Si, C bands)
- Mass-loss rate (from mid-IR modeling)
- Mass from (surface gravity)
- Binaries/multiplicity (optical modeling)
- Combined with supernova data, constrain the compact object that forms



Boyer+2024

Why haven't existing surveys performed this science?

Mid-infrared surveys (**SPIRITS**; ~190 galaxies Kasliwal+2017, Jencson+2019)

Optical surveys with LSST-like sensitivity (**Search for Failed Supernovae**; ~27 galaxies, Adams+2017; Neustadt+2021)

Unprecedented sensitivity (JWST is ~1000x more sensitive than Spitzer) and coverage (Rubin will cover 200x more RSGs than Search for Failed Supernovae) means the ***grasp*** of both surveys will enable unprecedented statistics of massive stars

We require tens of thousands of red supergiants with optical/IR light curves - only possible with a combination of JWST and Rubin

CONCLUSIONS

- A large fraction of red supergiants exhibit unusually ***strong variability***, ***optical-infared colors***, and ***sometimes eruptions*** indicative of strong mass loss in the final years before explosion. This shows up in both pre-explosion data and supernova observations themselves.

- LSST will reveal variability and eruptions, but to identify and trigger on red supergiant stars ***before they explode*** we need a large enough population of red supergiants to find them in the final years and decades prior to explosion. ***This is now possible with JWST***.

- With careful selection and triggering based on these criteria, we can measure the precise ***type, luminosity, mass, and multiplicity*** of star that exploded, even constraining the type of compact object when combined with supernova data