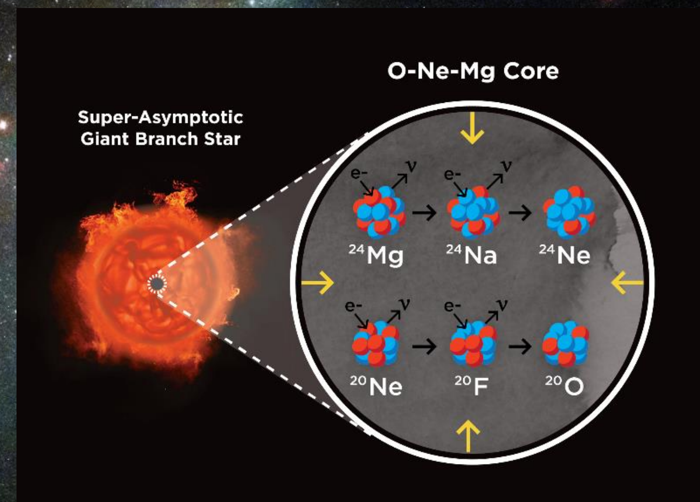
連星中性子星への進化における超新星の役割
（Supernovae from the NS/WD formation boundary）

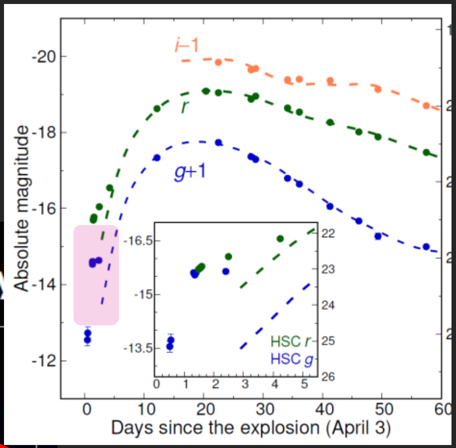


Keiichi Maeda

Kyoto University

第12回光赤外線天文学大学間連携ワークショップ(online) 2021.11.26

The Seimei SN/Transient Prog.



Some numbers

© Tanaka

*** Numbers for all sky**

Distance (Mpc)	Volume (Mpc^3)	# of galaxies	# of SNe (yr^{-1})	mag (abs mag -15 mag)	mag (abs mag -13 mag)
10	4×10^3	40	0.4	15.0	17.0
30	1×10^5	10^3	10	17.4	19.4
50	5×10^5	5×10^3	50	18.5	20.5
70	1×10^6	1×10^4	100	19.2	21.2
100	4×10^6	4×10^4	400	20.0	22.0
200	3×10^7	3×10^5	3,000	21.5	23.5
500	5×10^8	5×10^6	50,000	23.5	25.5

~ 5 / yr.

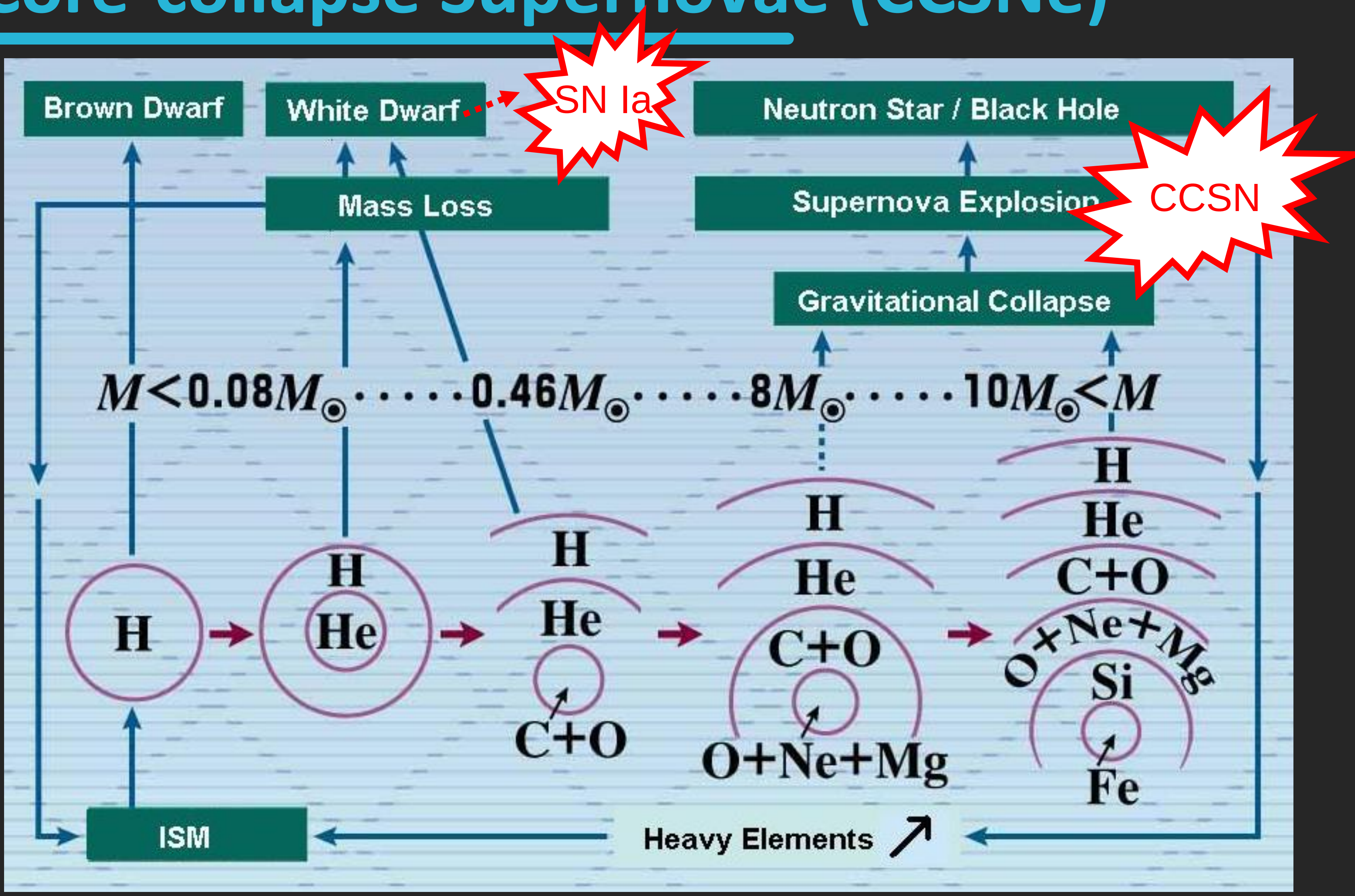
~ 50 / yr.

There are ~ 50 SNe / yr for which it can be observed spectroscopically in the infant phase (~ 3-4 mag below the peak).

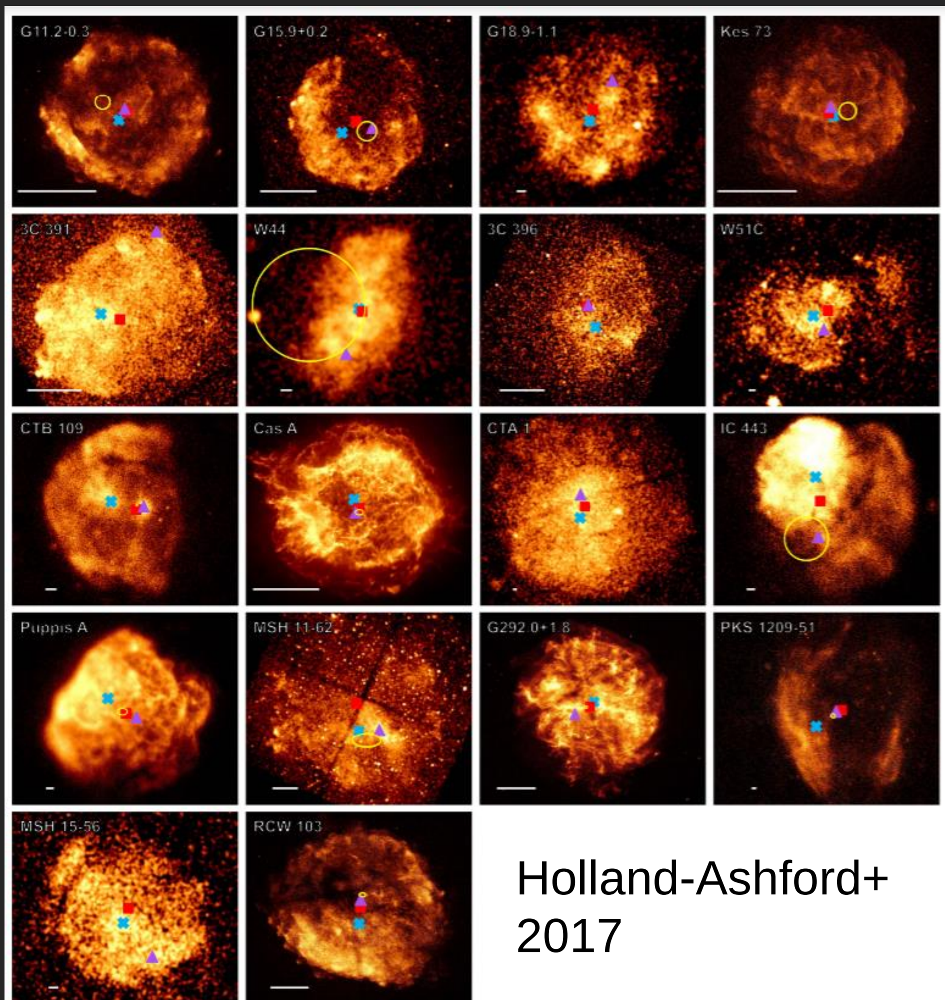
Telescope time and ToO flexibility can be practically more important than the depth (no need to go deeper than the survey).

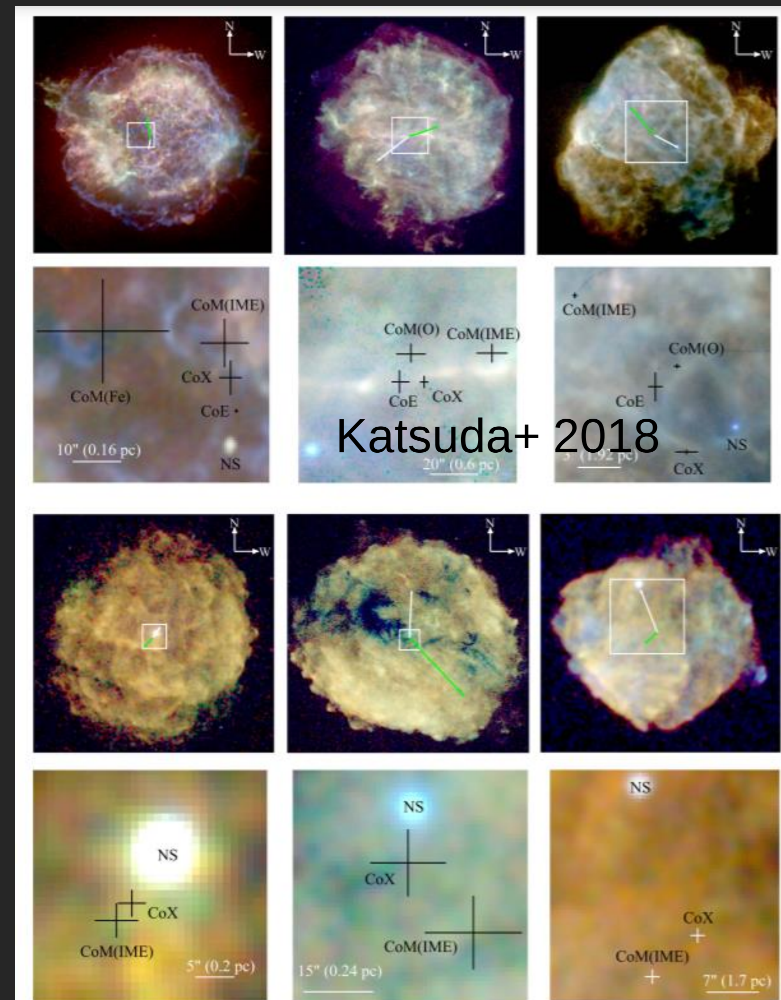
One key project: SNe leaving double NS systems.

Core-collapse Supernovae (CCSNe)



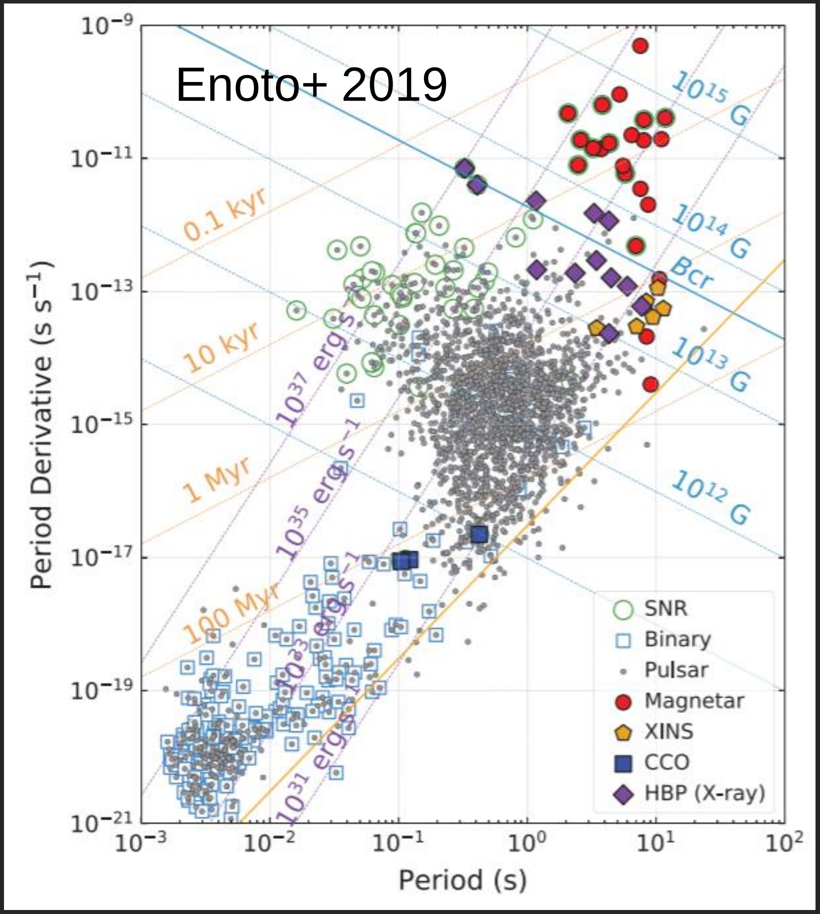
Neutron stars formed behind CCSNe



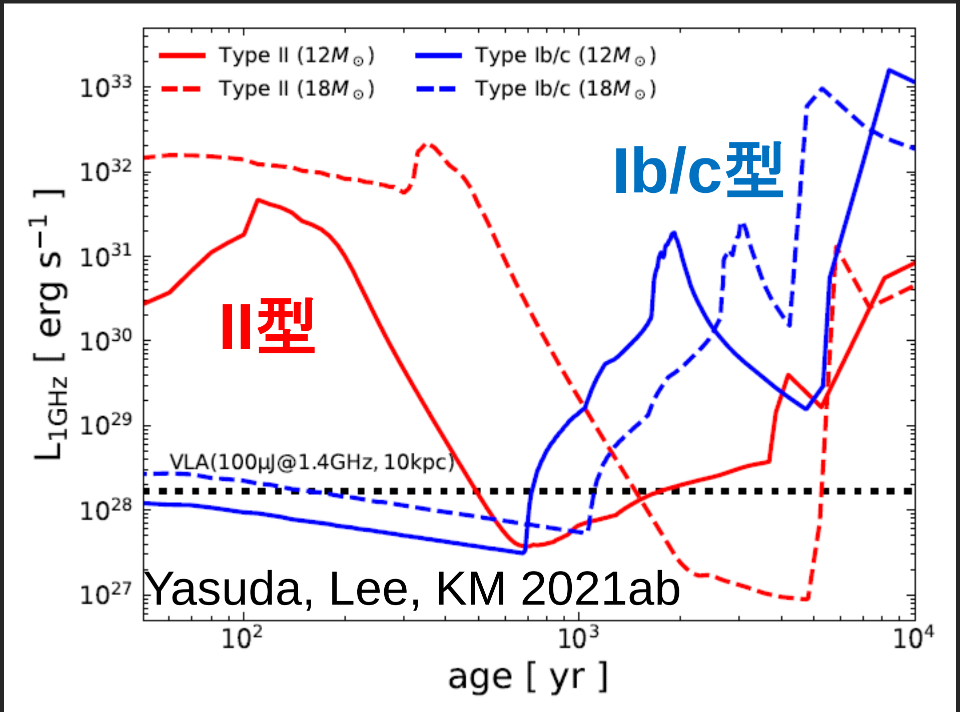


NSs are formed at SNe (or SNe are triggered by NS formation).

NS diversities: Relation to properties of SNe?



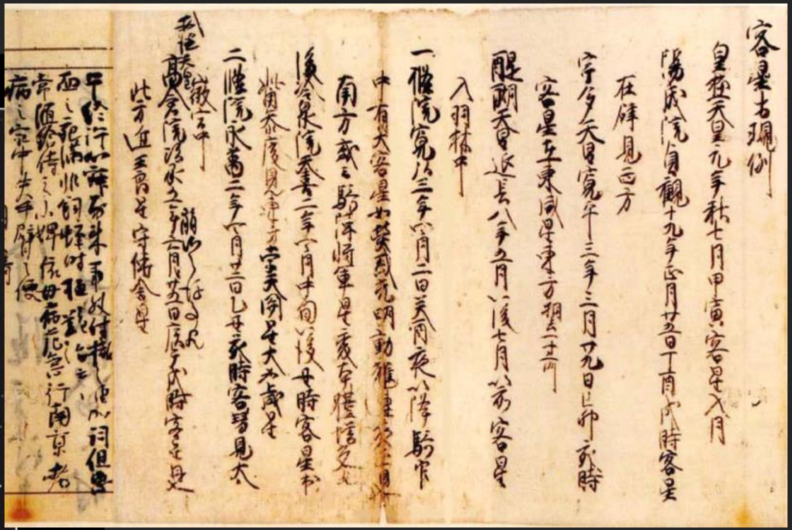
What determines the properties of a NS at birth? Relation to the properties of SNe (and then progenitor)?



The NS-SNR sample may be biased.

The best we know: SN 1054=Crab

The best observed NS.
Progenitor and SN?



Electron-capture SN?

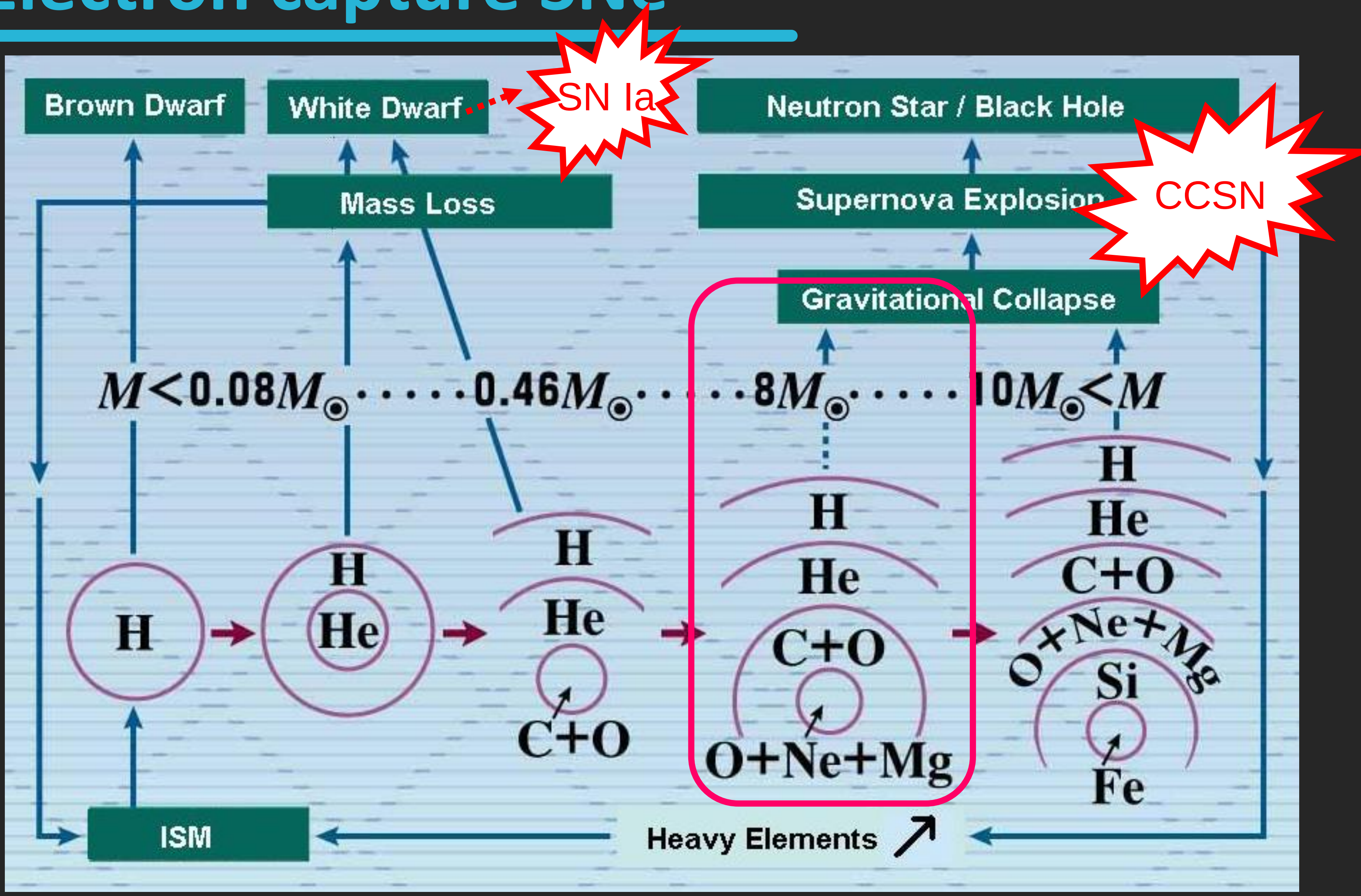
CSM Composition

SN Nucleosynthesis

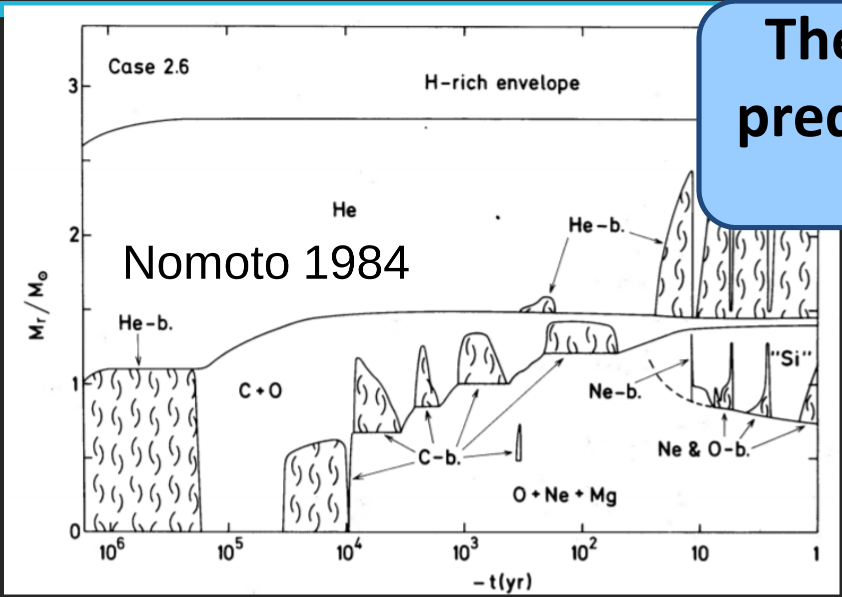
Historical light curve

(e.g., Tominaga+ 13)

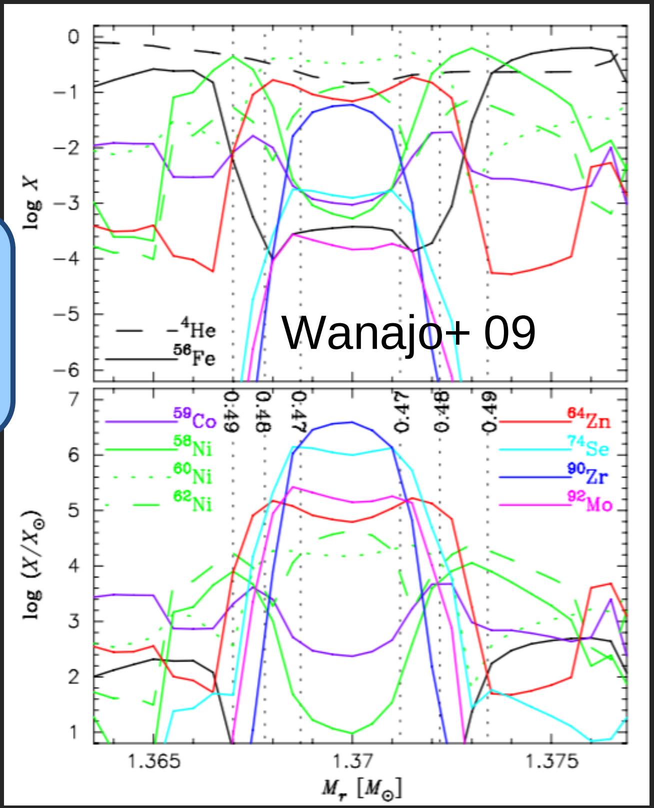
Electron capture SNe

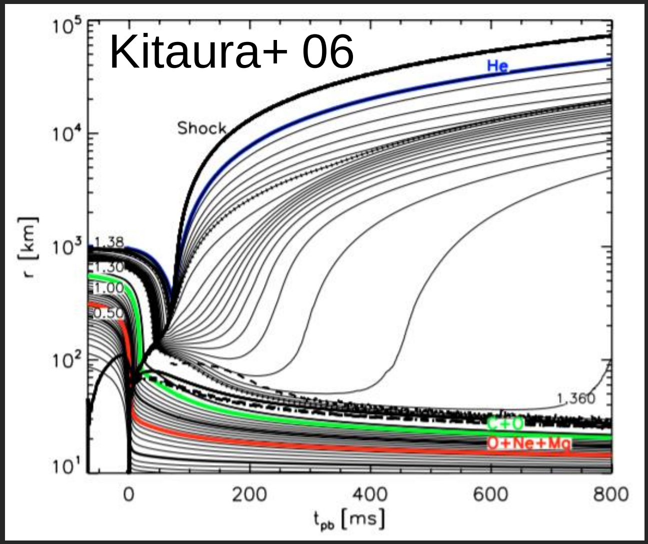


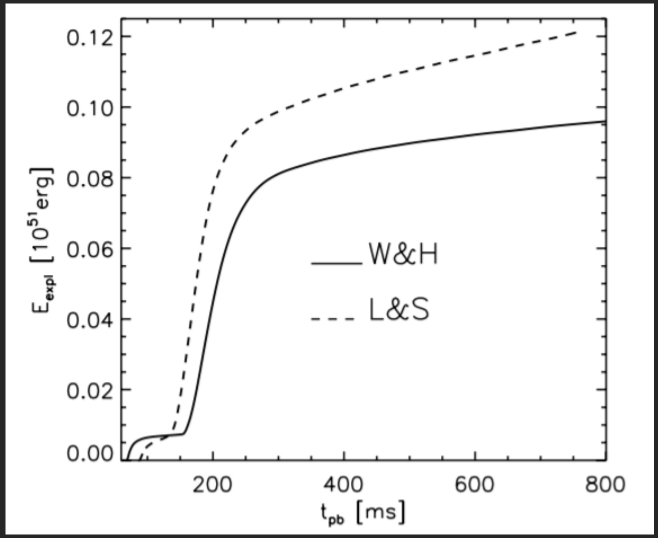
Electron capture SN



Theoretically predicted since 1980's

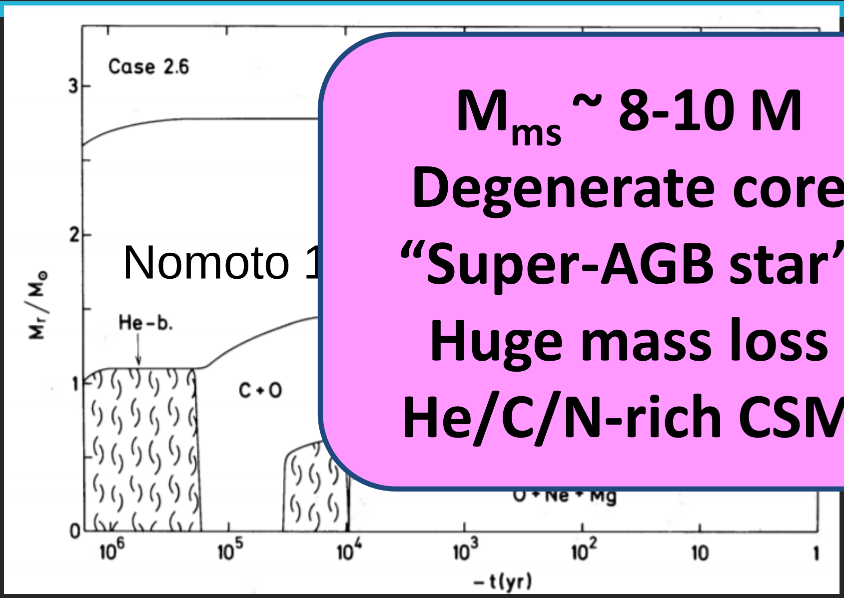




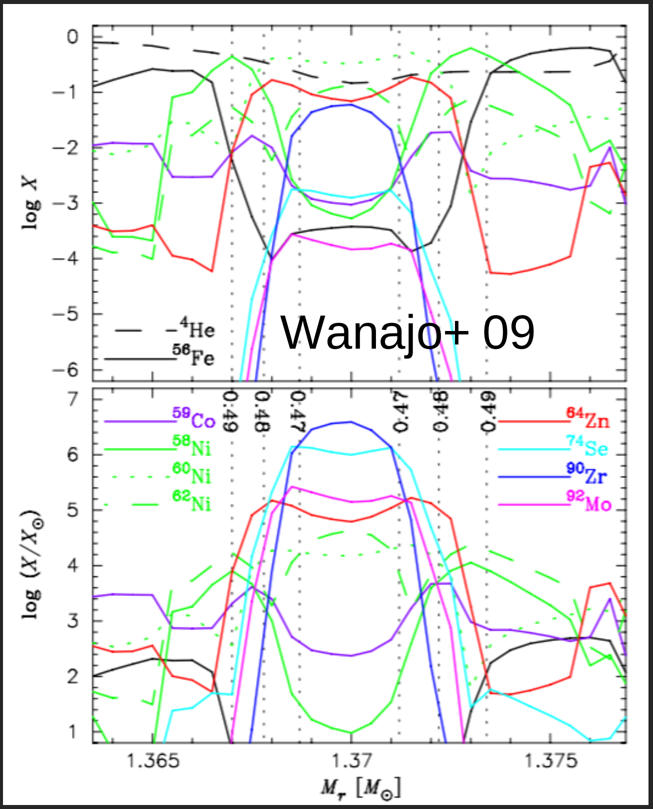


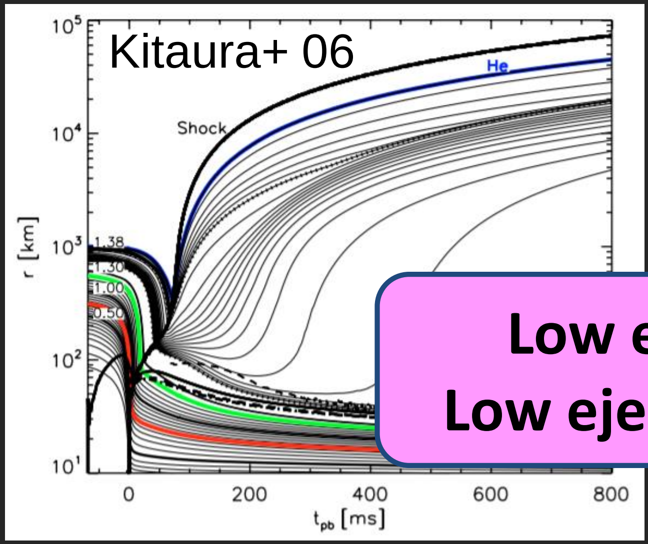
Robust SN explosion mechanism

Electron capture SN

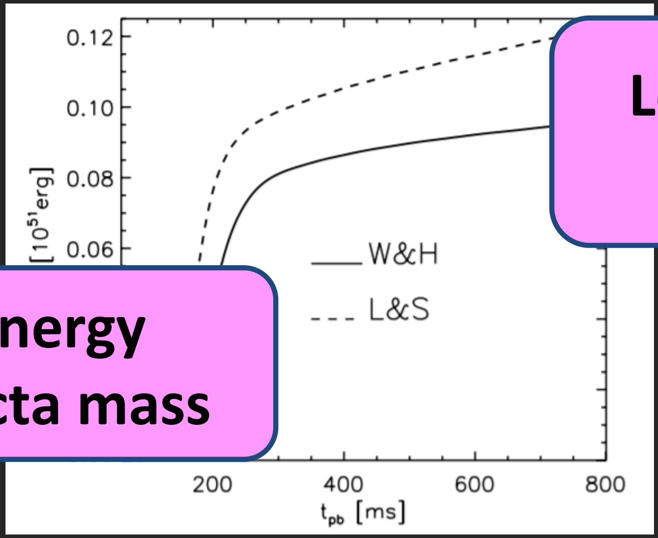


M_{ms} ~ 8-10 M
Degenerate core
"Super-AGB star"
Huge mass loss
He/C/N-rich CSM



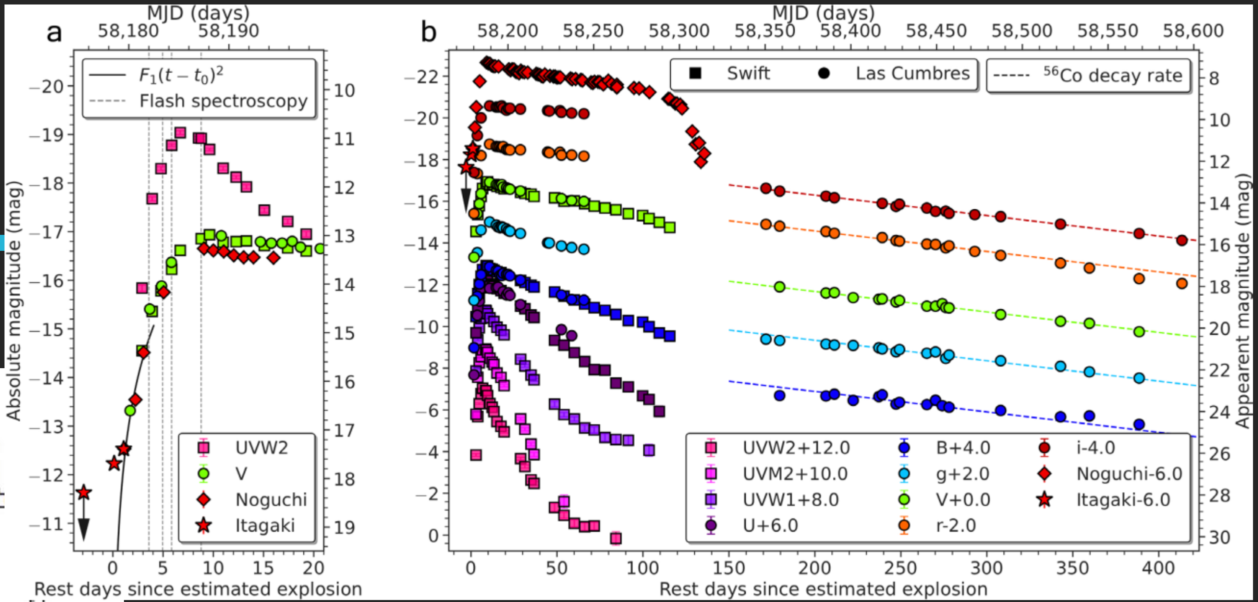


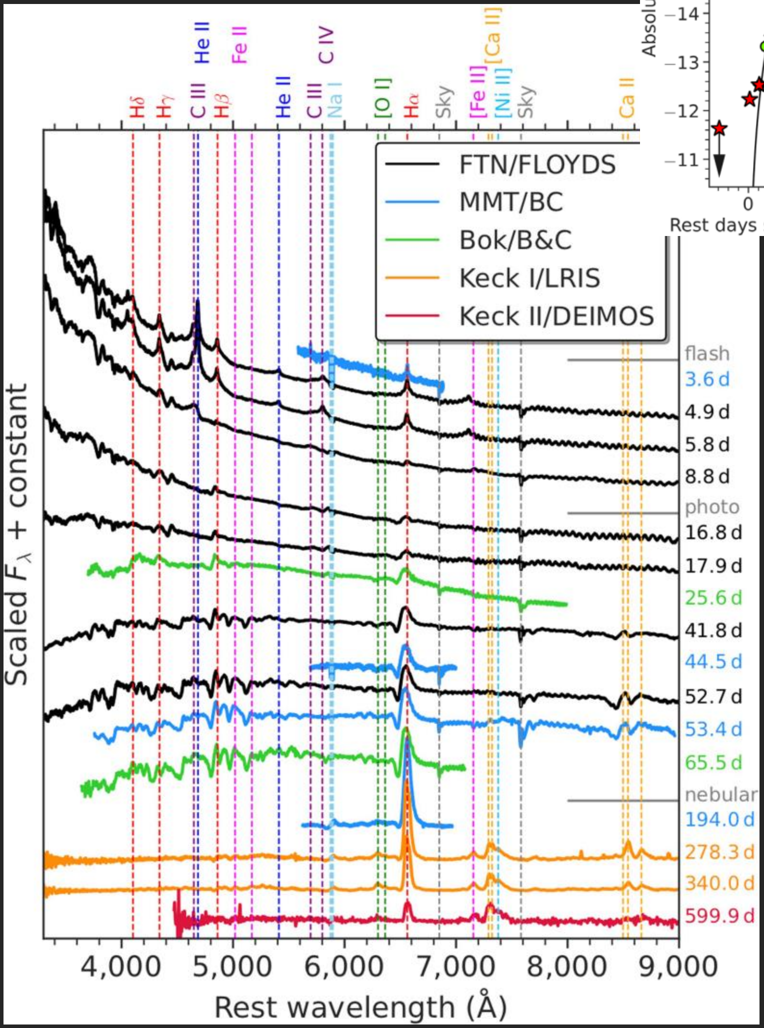
Low energy
Low ejecta mass



Low ^{56}Ni production
High Ni/Fe, ...

SN 2018zd





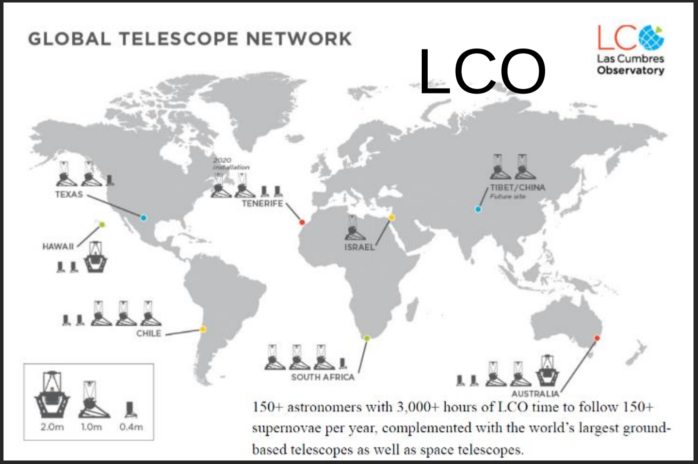
SN II @ 9.6 Mpc.

Very early discovery by K. Itagaki.

Intensive follow-up by LCO network.

Unfortunately, Seimei was not ready.

Hiramatsu+, 2021,
Nature Astronomy



Electron capture check list

Hiramatsu+, 2021, Nature Astronomy

The "real-time" counterpart of the Crab.

ECSN	Progenitor			Explosion		
Candidate	Identification	CSM	Chemical Composition	Energy	Light Curve	Nucleosynthesis
SN 2018zd	✓?	✓	✓	✓?	✓	✓
SN 1054 (Crab)	–	✓?	✓	✓	✓?	✓
ILRT	✓?	✓	?	×	×	?
Low-Lum. II-P	×	?	×	✓?	✓	×
IIn-P	?	✓	?	✓?	✓	✓?

HST

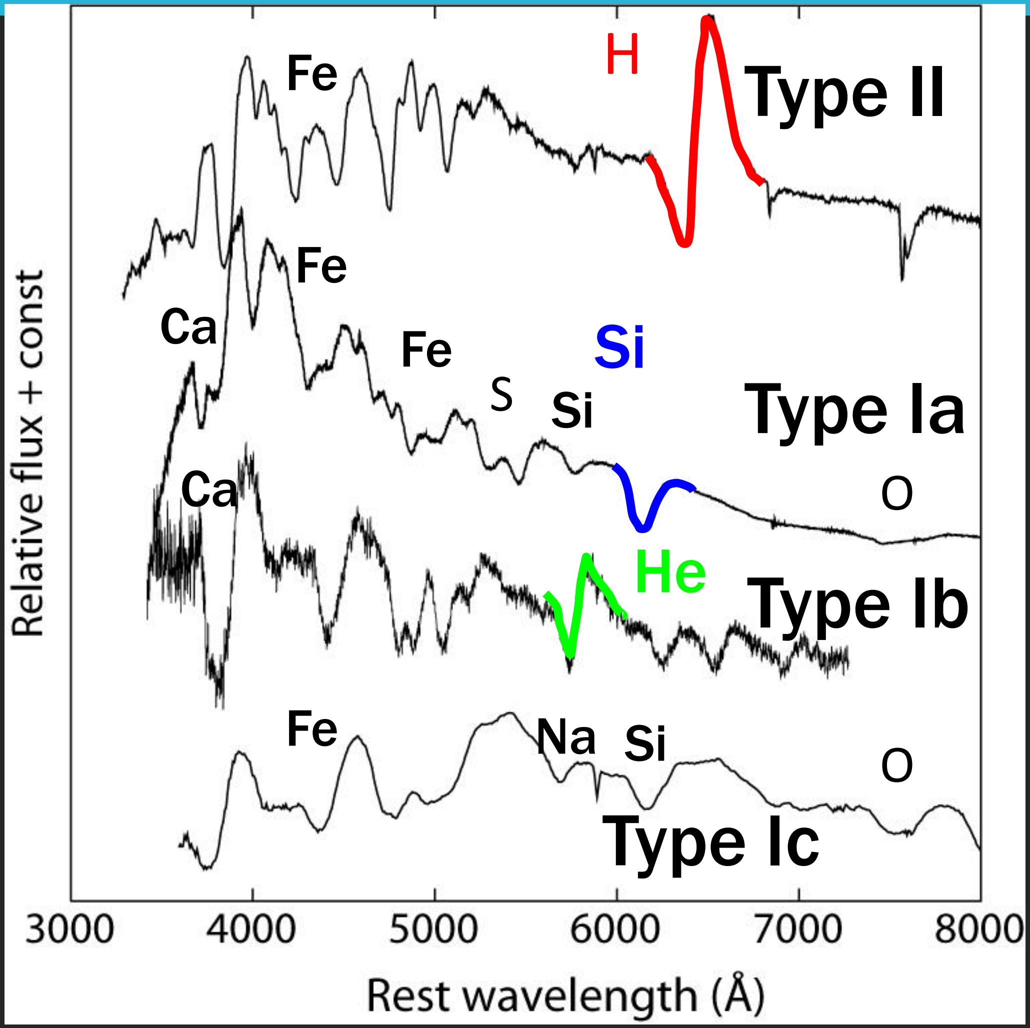
SWIFT+ gound < a few days of the explosion.

spectroscopy < a few days.

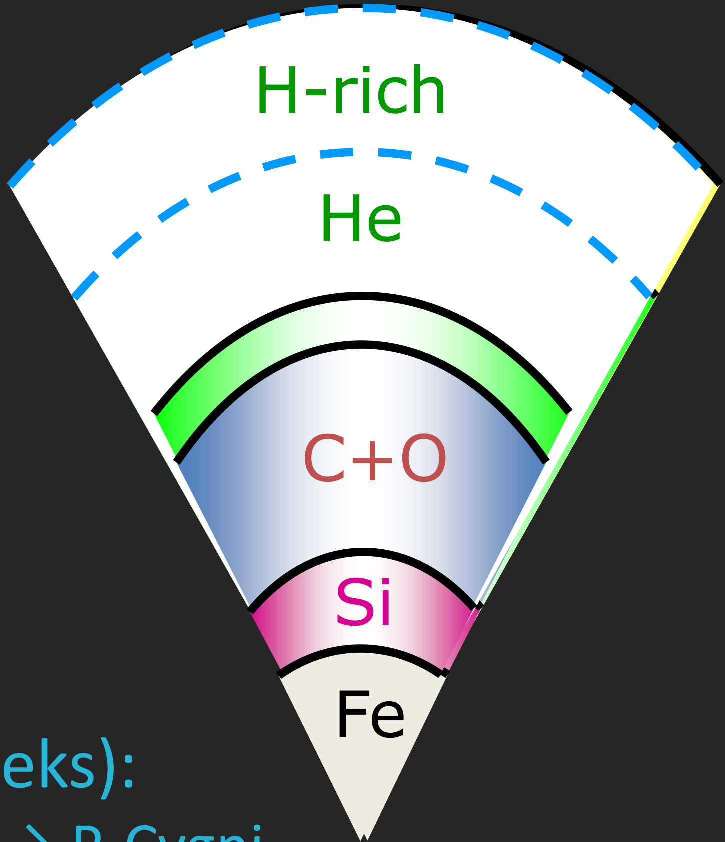
Deep spectroscopy at ~year (faint, Keck, etc).

Thanks to very-early discovery and intensive follow-up observations, for a (rare) very nearby and faint SN.

What if it is in a binary



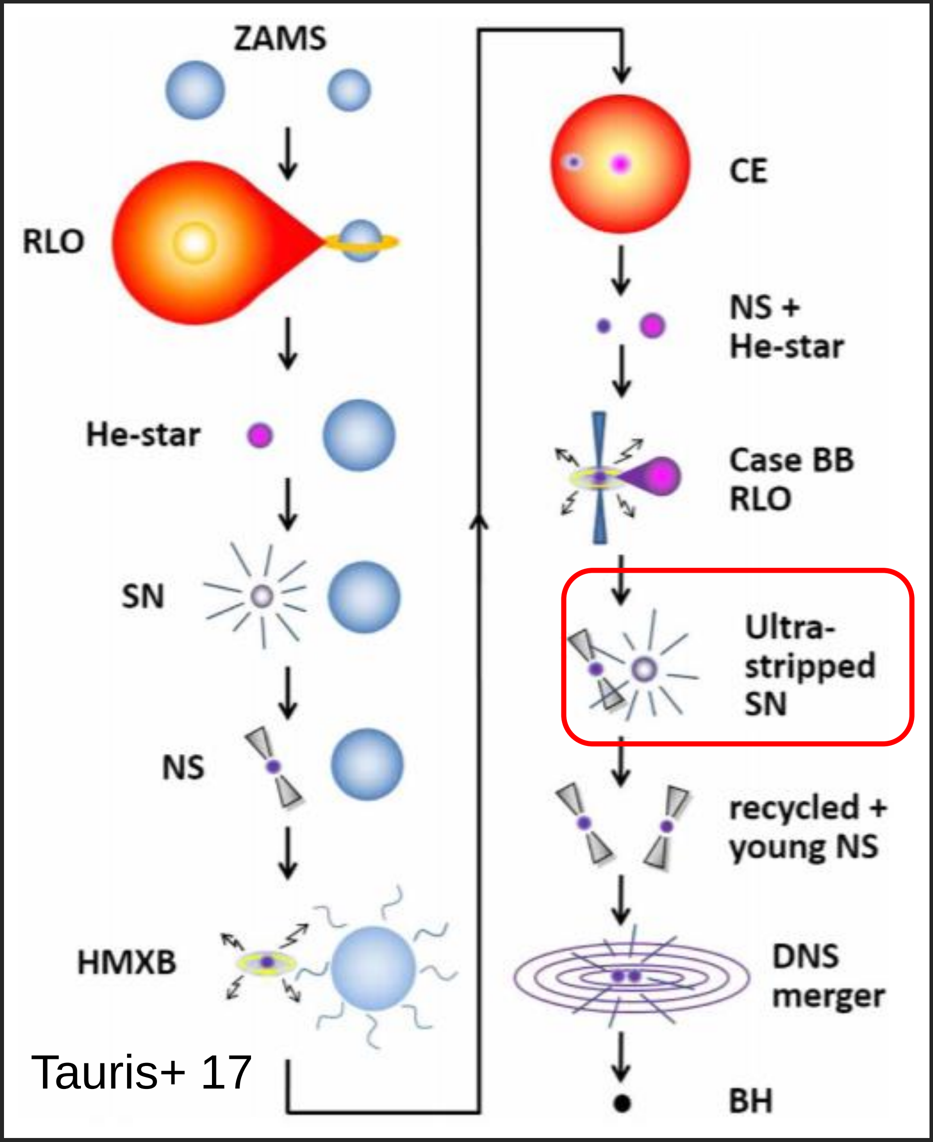
II (but for IIn)
Red Supergiant
IIb/Ib/Ic
(Stripped Envelope SNe, SESNe)
Wolf-Rayet-like star



@ maximum brightness (~ a few weeks):

– Expanding optically thick medium → P-Cygni.

Ultra-stripped envelope SNe (USSNe)



Tauris+ 17

2nd SN toward the formation of compact binary NSs.

Close orbit: C+O or He star.

No binary disruption:

low mass ejecta ($< 0.5M_\odot$).

⇒ <~ 2 $M_\odot$ He or C+O star.

⇒ corresponding to

$M_{ZAMS} < 11$ or $12\ M_\odot$.

⇒ Low-E + low M(^{56}Ni)

(e.g., Suwa+ 2015).

Prediction:

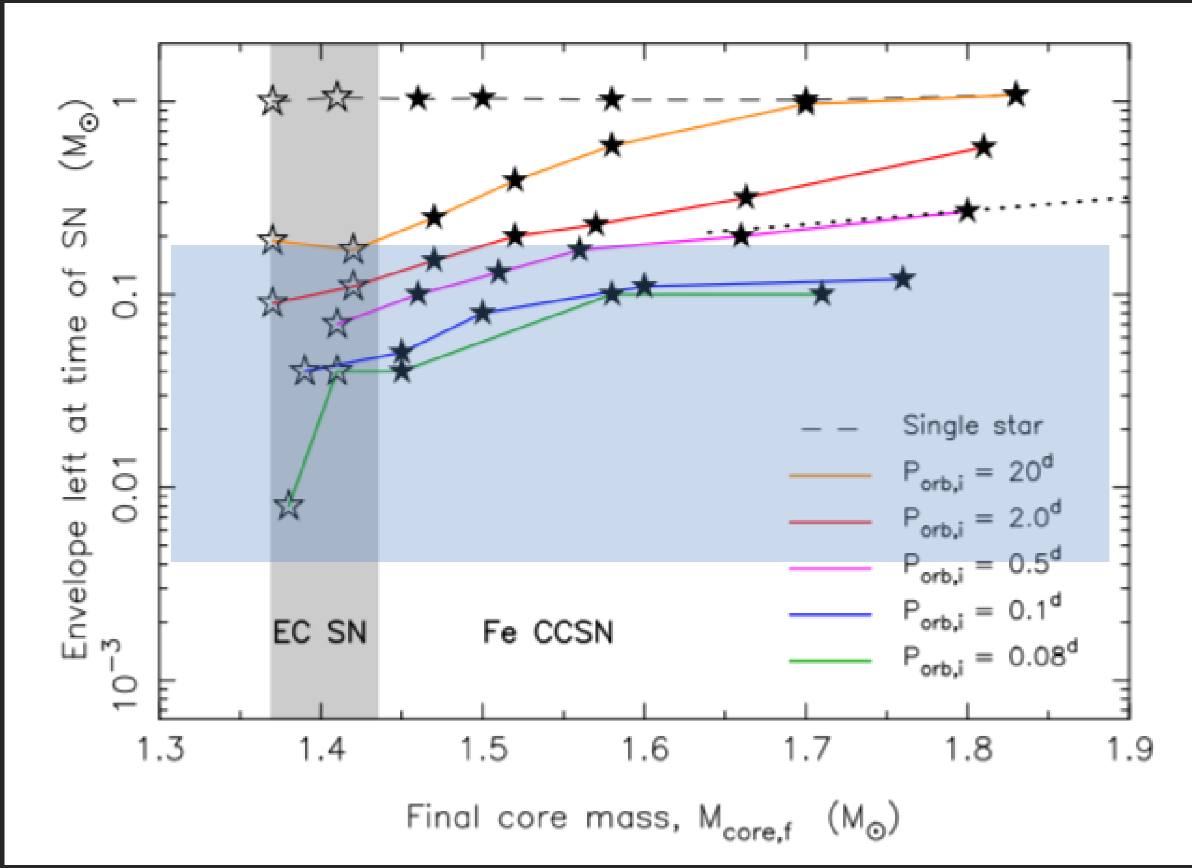
“Faint” and “Fast” transients

(e.g., Tauris+ 13, 15; Moriya+ 17).

Note: low mass SNe ⊃ USSNe, not =

- A low-mas He/C+O SN can arise from the following configurations:
  - A. a low-mass SN leaving short-period double NSs.
  - B. a low-mass SN leaving long-period double NSs.
  - C. a low-mass SN w/ a massive star companion.
    - Genuine USSN (toward DCNS binary)= case A.
- It is still important to find low-mass SNe and their nature in general:
  - Includes USSNe anyway.
  - The SN properties should be more like the same.
  - Rate in the stellar evolution context.

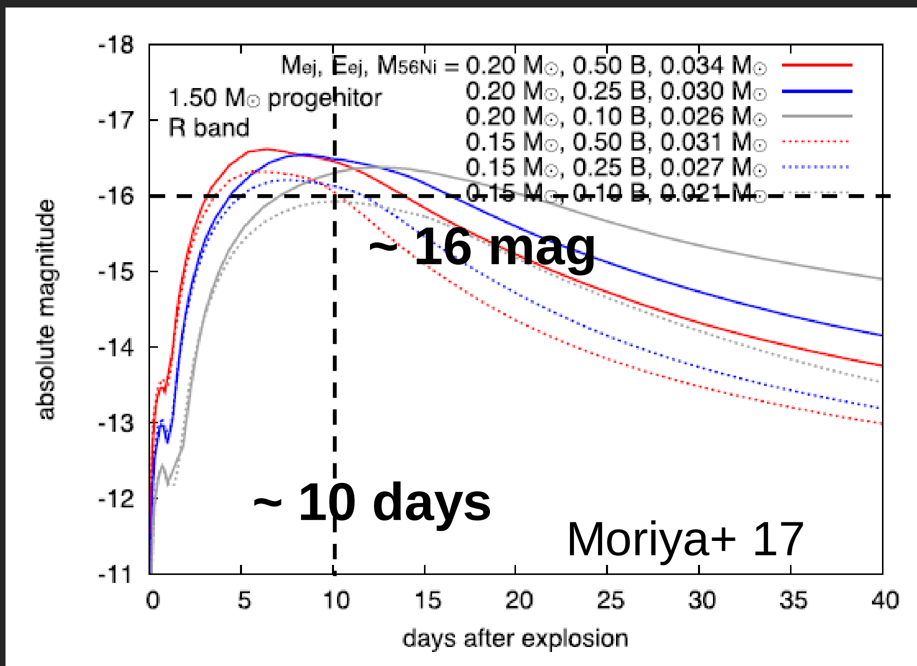
Ultra-stripped envelope SNe (USSNe)

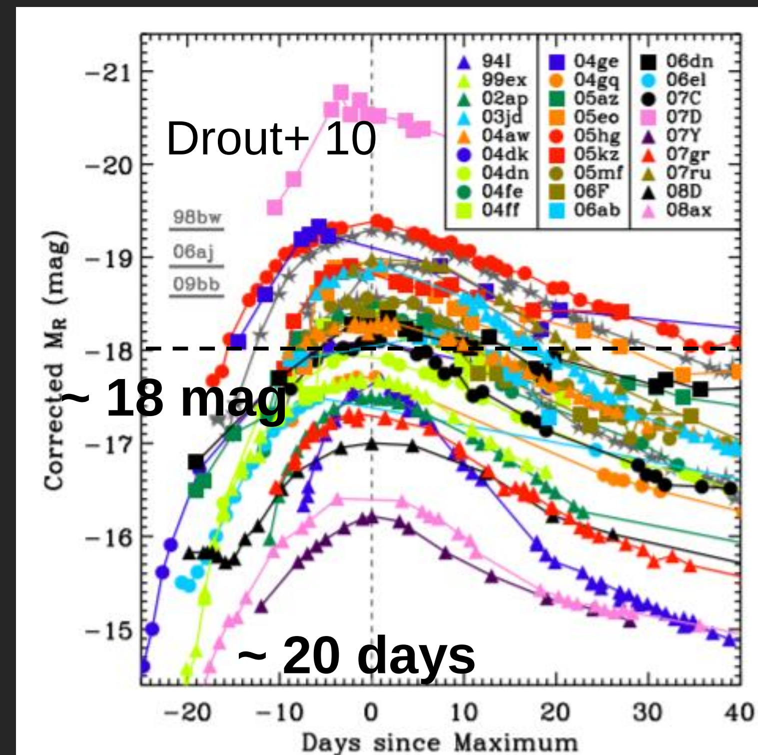


Electron capture or Fe CCSNe near the white dwarf – SN boundary (SN properties are probably the same within this mass range).

Tauris+ 17

Expected Properties from the low-mass He/C+O star explosion → rapid & faint





Low-mass CCSN Ib/c:

He 1.5 $M_\odot$ (C+O 1.45$M_\odot$)

← M_{ms} ~ 10$M_\odot$

The "least" massive star to explode as a CCSN.

Possible pathway to binary NSs.

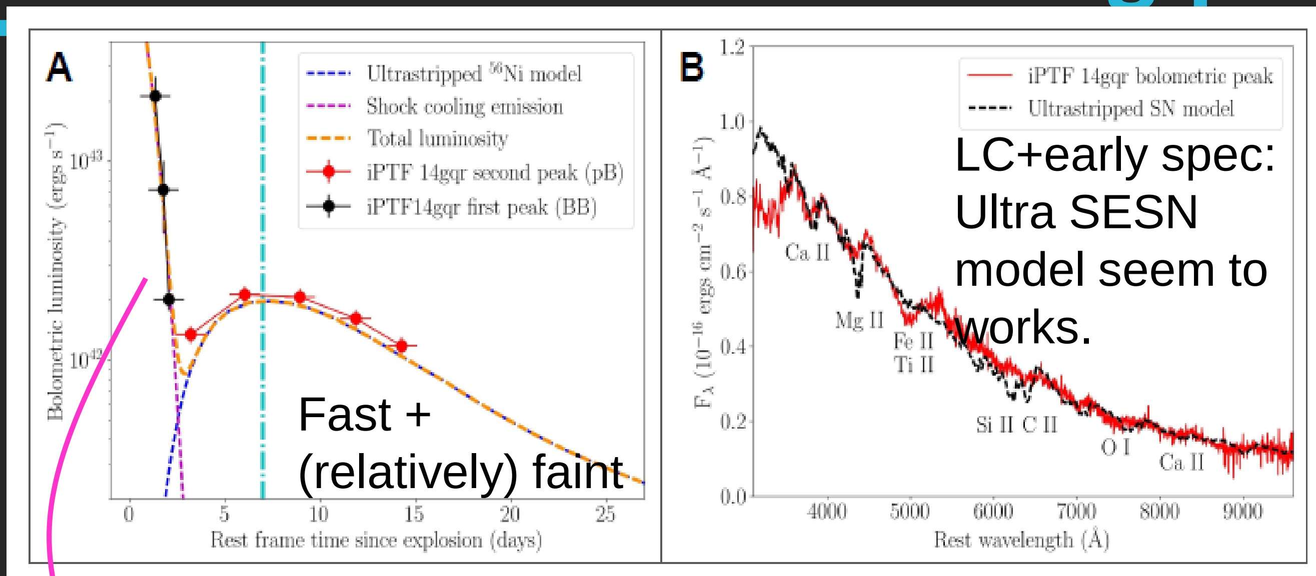
"Normal" SNe Ib/c:

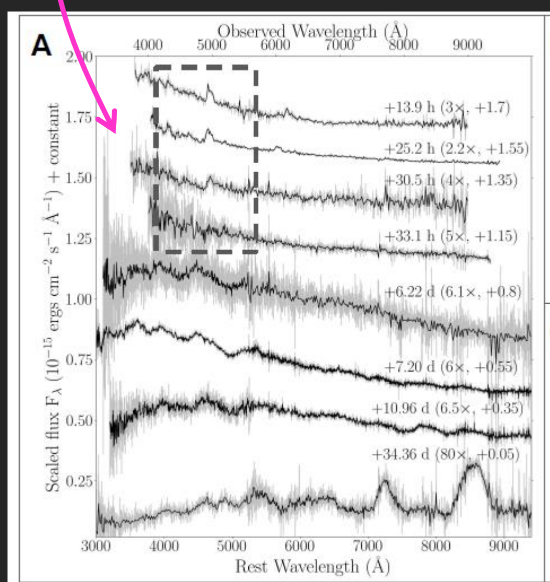
He 4 $M_\odot$ (C+O 2.5 $M_\odot$)

← M_{ms} ~ 15$M_\odot$

De+ 18, Science

Ultra-SESN candidate iPTF14gqr

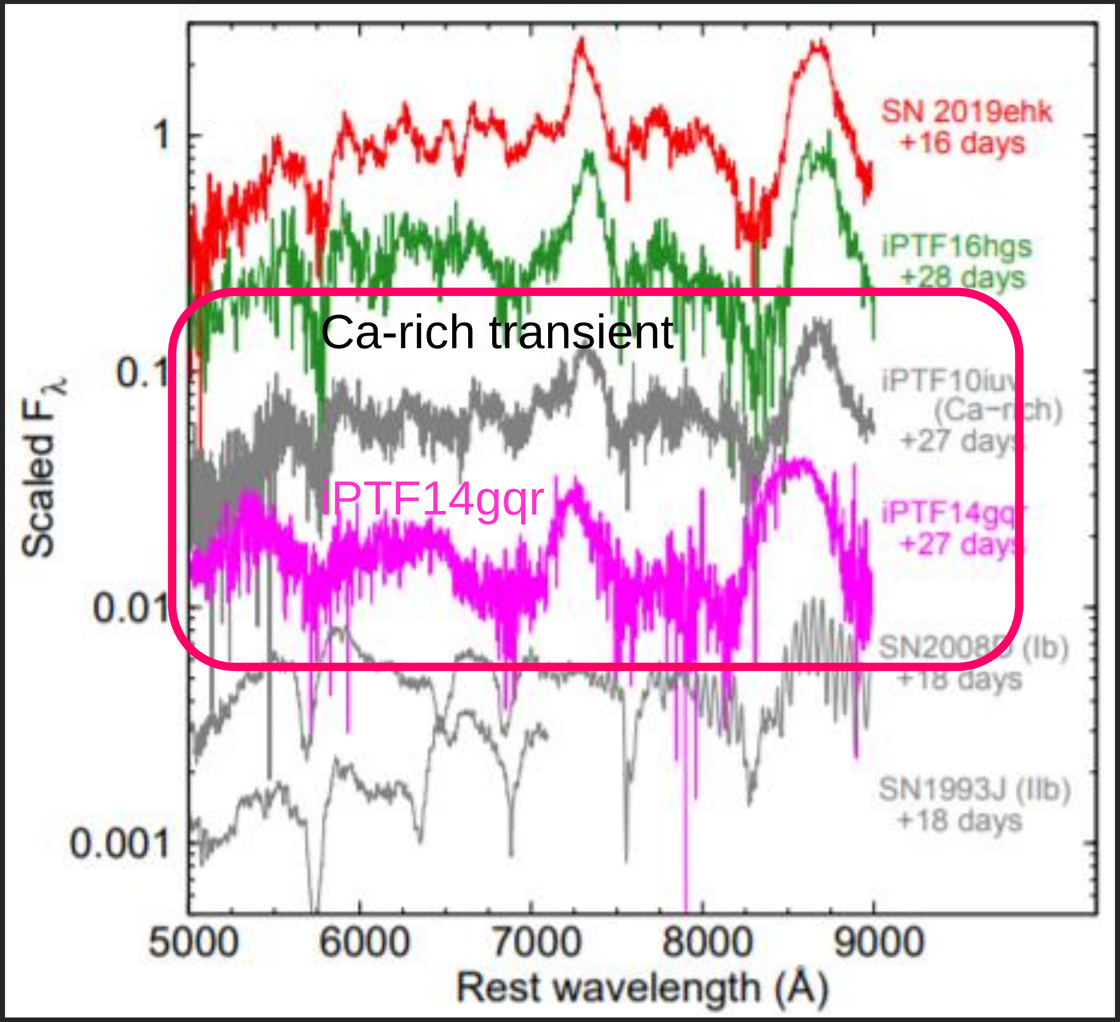




Rapid light curve, with spectral signature of a C+O star explosion (= The USSN expectation).

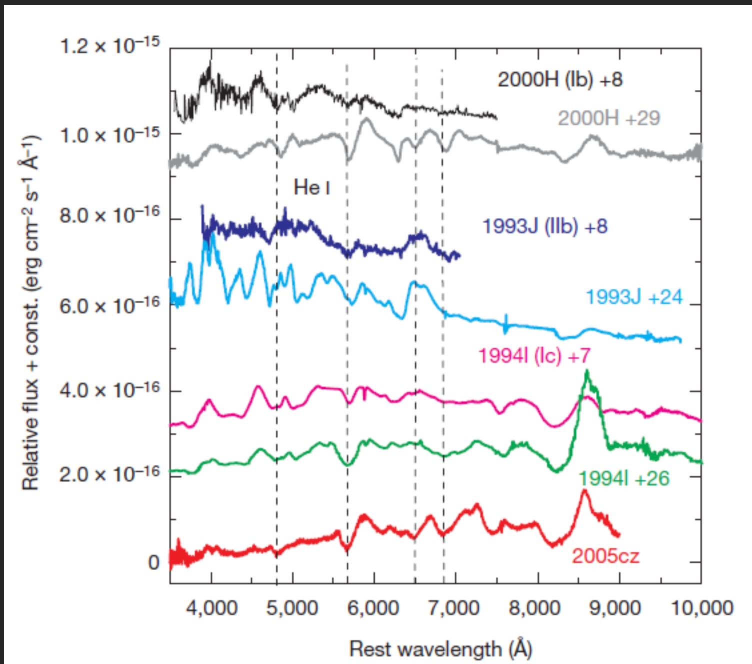
First peak in the LC:
Dense CSM
⇒massive star origin (=USSN).

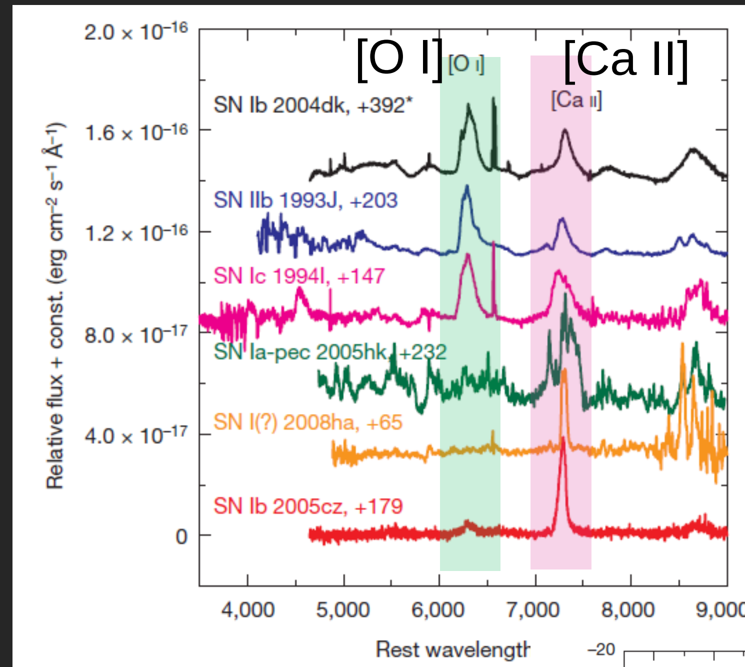
Emerging link between USSN candidates (or a low-mass SNe) and Ca-rich transients



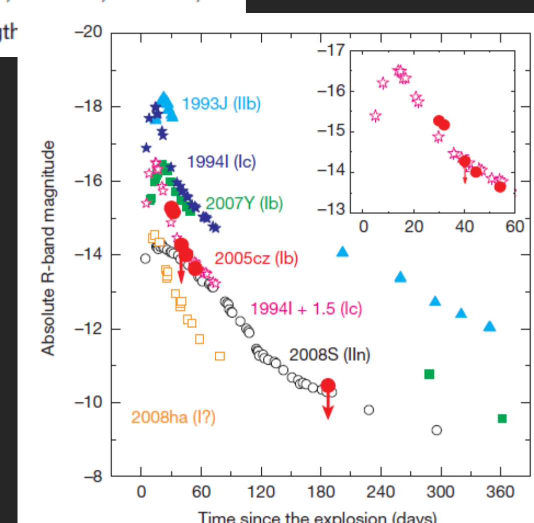
iPTF14qgr is a variant of enigmatic "Ca-rich transients"

Ca-rich Transients (rapid & faint)





"Ca-rich"



First reports: Kawabata, KM+ 10, Nature

2005cz (Kawabata+ 10) & 2005E (Perets+ 10)

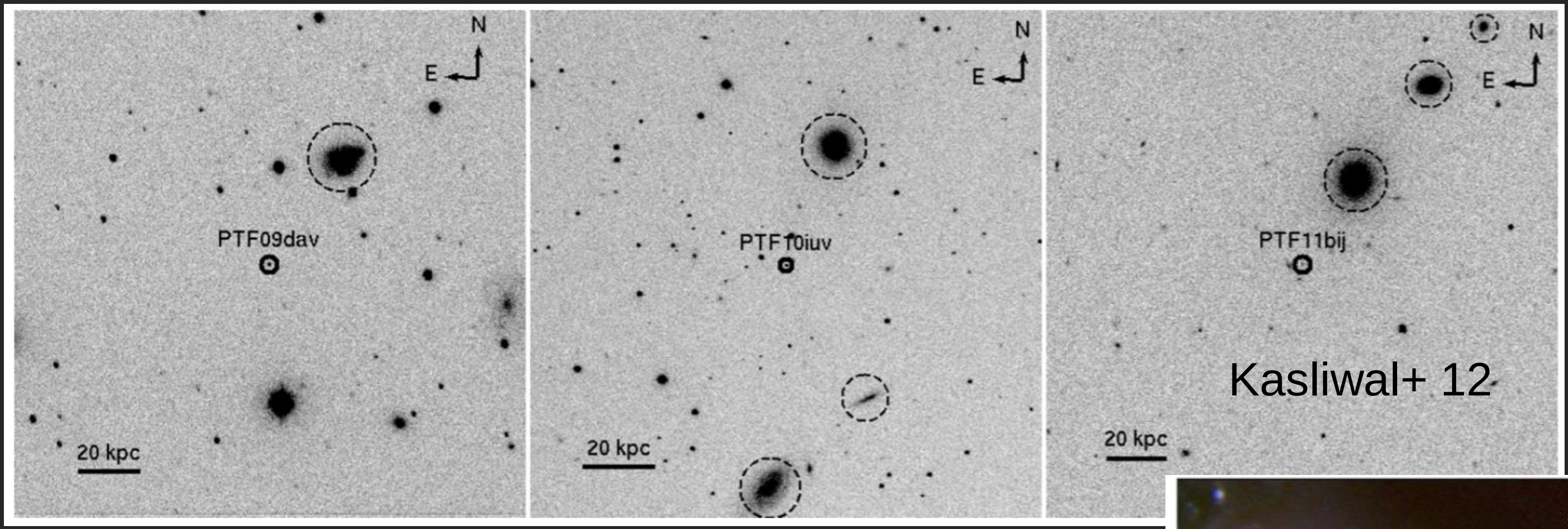
SN Ib, but later strong [Ca II], not [O I].

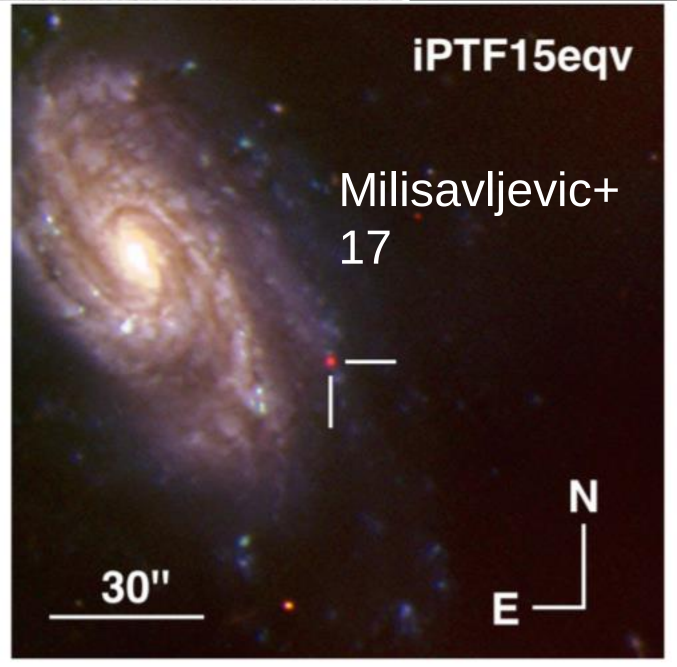
Faint and rapid. First suggestions:

Low-mass He/C+O star CCSN, or

WD explosion?

Ca-rich transients = old populations?





Against the CC (core-collapse) SN origin.

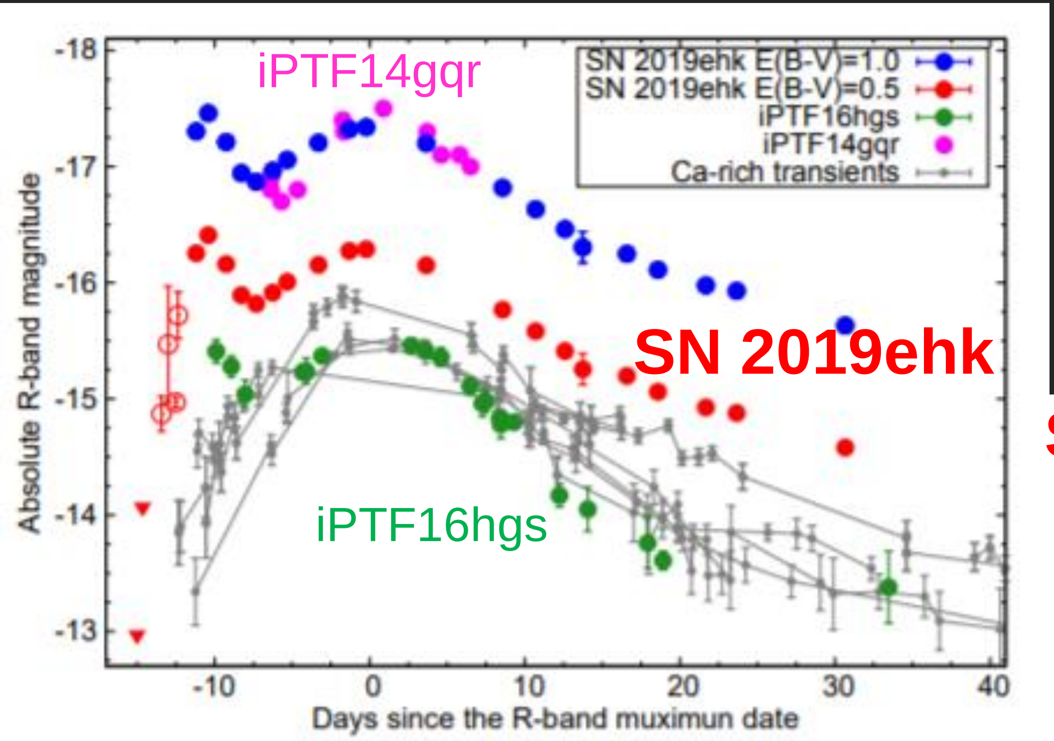
However…

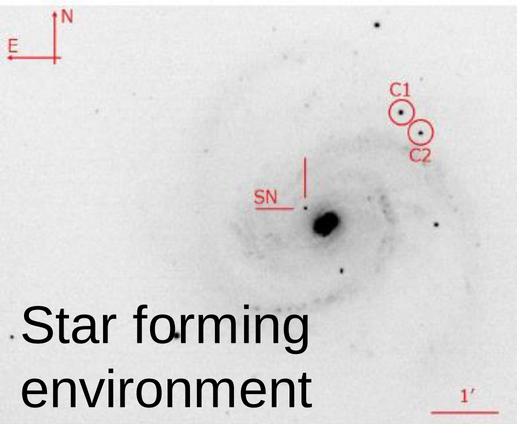
A small fraction are found in young environment.

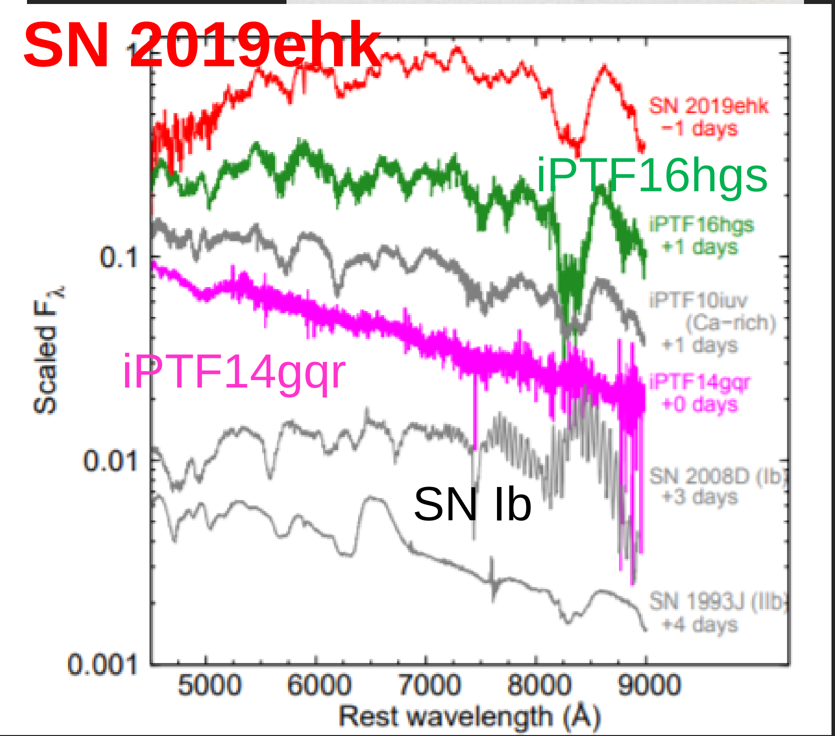
If they are CCSNe, it has several implications.

Nakaoka, KM, Yamanaka+, 2021: **One of the first results from Seimei**

A new candidate of an Ultra-SESN?







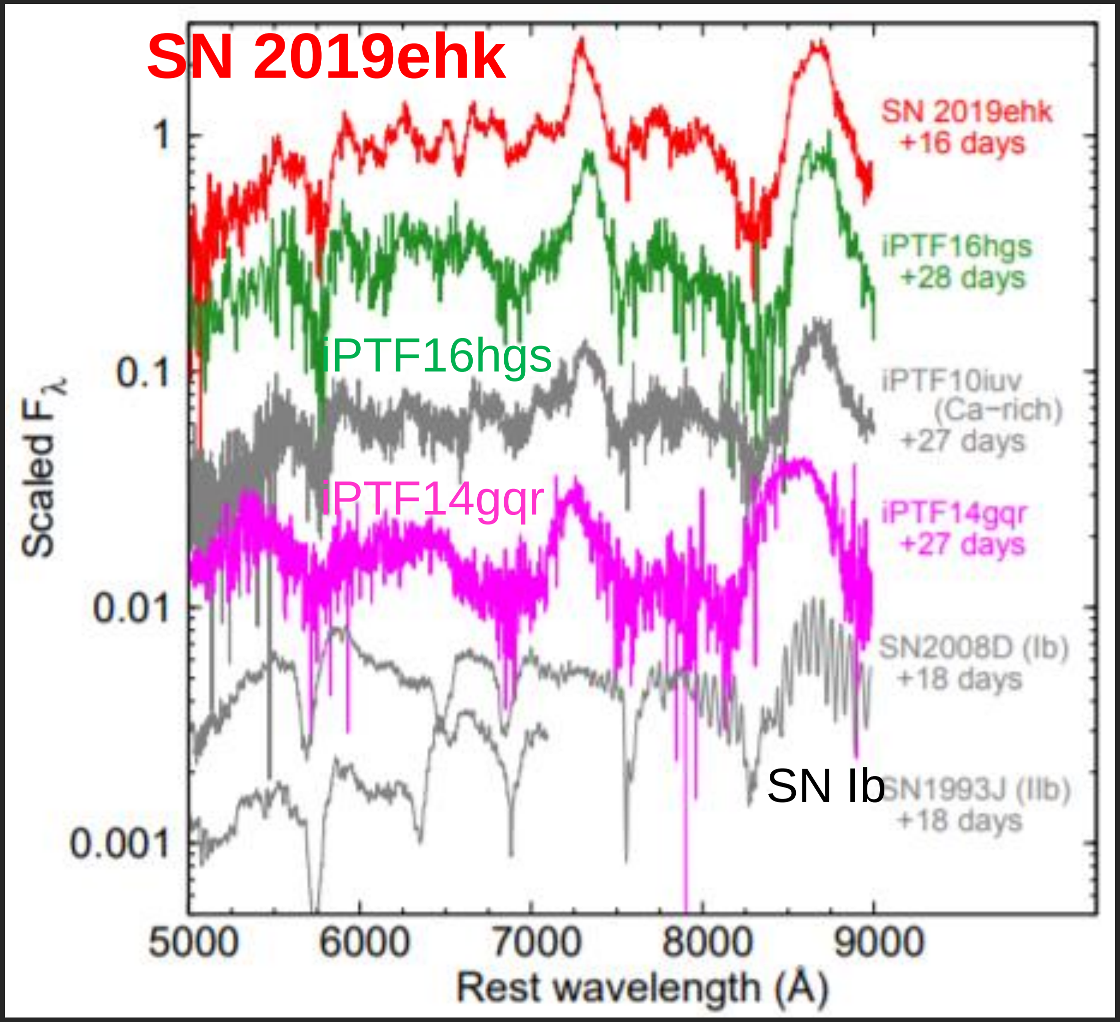
Maximum spectrum ~ a He star.

Rapid evolution & First peak.

⇒ USSN candidate.

Diversity between the USSN candidates.

Emerging link between USSN candidates (or a low-mass SNe) and Ca-rich transients



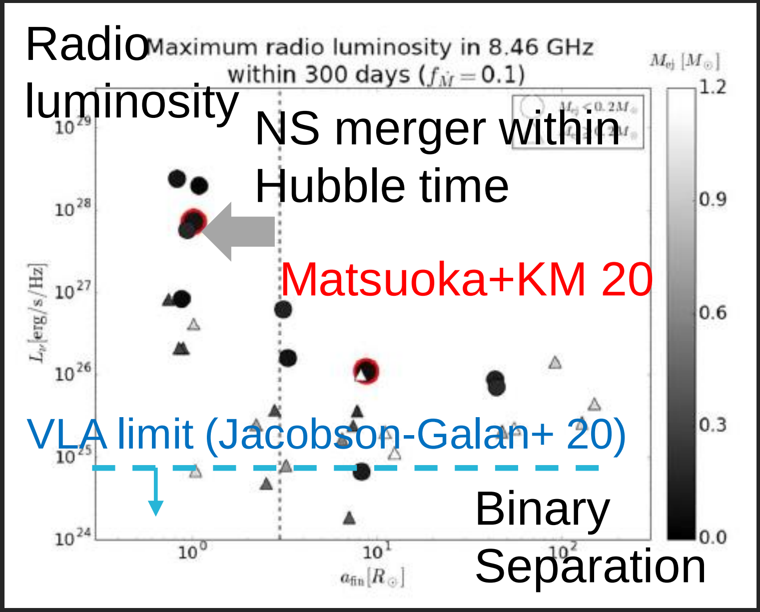
The difference disappears (or reduces) in the later epochs.
They all evolved to the (enigmatic) "Ca-rich transients" (c.f., Kawabata, KM+ 2010).

A need for more candidates: Consistent with the USSN expectation? (e.g., mass diversity)

Did SN 2019ehk leave NSs with close orbit?

- Optical observations would not discriminate the following scenarios (genuine USSN = case A):
  - A. a low-mass SN leaving short-period double NSs.
  - B. a low-mass SN leaving long-period double NSs.
  - C. a low-mass SN w/ a massive star companion.
- Go for radio.

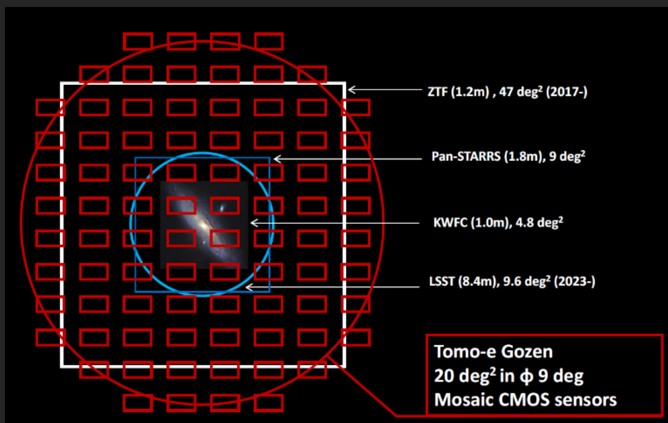
SN 2019ehk = either case B or C (unfortunately not leading to the NS merger in the future).
Note: it is important to explore a census of "low-mass SNe".



Search for USSNe: Requirements

- **High-cadence survey.**
  - They are rapid.
- **Quick and intensive follow-up observations.**
  - They are faint.
- **Multi-wavelength helps.**
  - The variant may look similar in the optical.

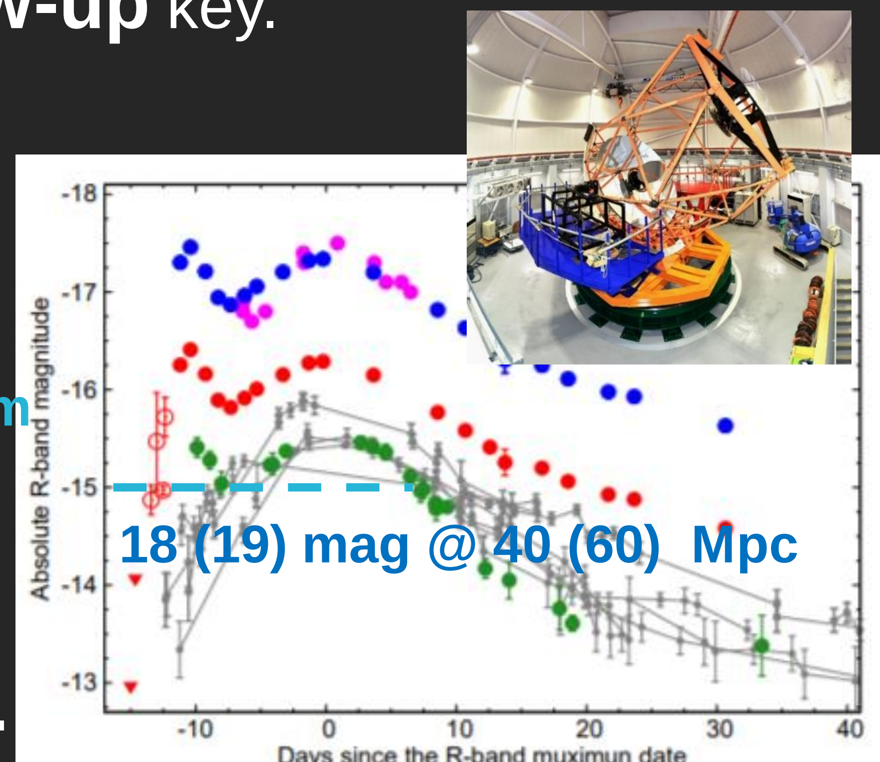
Search for USSNe with Seimei/Kanata



Survey capability already sufficient;
Follow-up key.

USSN rate ~ 1 / yr within 60 Mpc
(otherwise ≠ DNS formation)

Seimei telescope for spectra with
Rapid & intensive SN follow-up program
Kools-IFU (present):
limit: 18 (cons)-19 (best) mag
TriCCS:
Imaging available, spec to come.



18 (19) mag @ 40 (60) Mpc

Next OISTER should help

Systematic transient survey & follow-ups.
⇒ New transient sky.

New instruments becoming available.
Tomo-e, TriCCS, …
e.g., TriCCS may help establish the NS population by the sub-sec observations.
⇒ SN-NS synergy.

Multi-wavelength
NIR, radio, …
⇒ SN full characterization.
Identifying USSNe.

Summary

- Core-collapse SNe (CCSNe) from the lowest mass boundary.
  - A single star: **Electron-capture SNe.**
    - A key in understanding **stellar evolution and SN explosion mechanism**.
    - **SN 2018zd as the strongest candidate.**
      - **A "real-time" twin of the crab?**
  - In a binary system: **Ultra-stripped SNe** and calcium-rich transients.
    - A possible pathway toward **compact binary neutron star systems**.
    - **SN 2019ehk as a new candidate; a companion is not a NS?**
      - **The SN properties anyway shared with the USSNe.**
      - **A new link to Ca-rich transients.**
- **Search for SNe leaving double NS systems.**
  - **Doable and promising project for next OISTER.**