# Studying the final evolution of massive stars through circumstellar environments around supernovae

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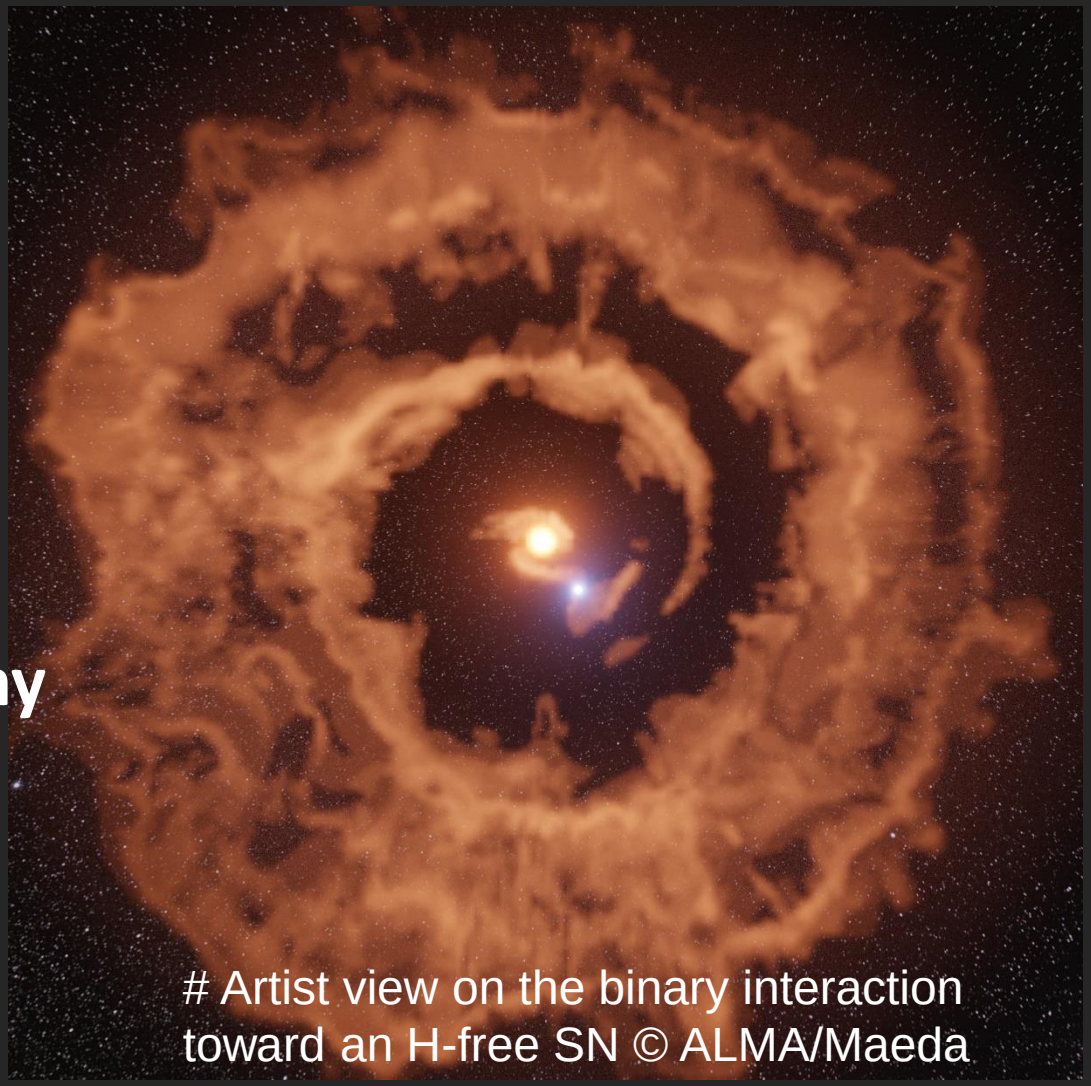
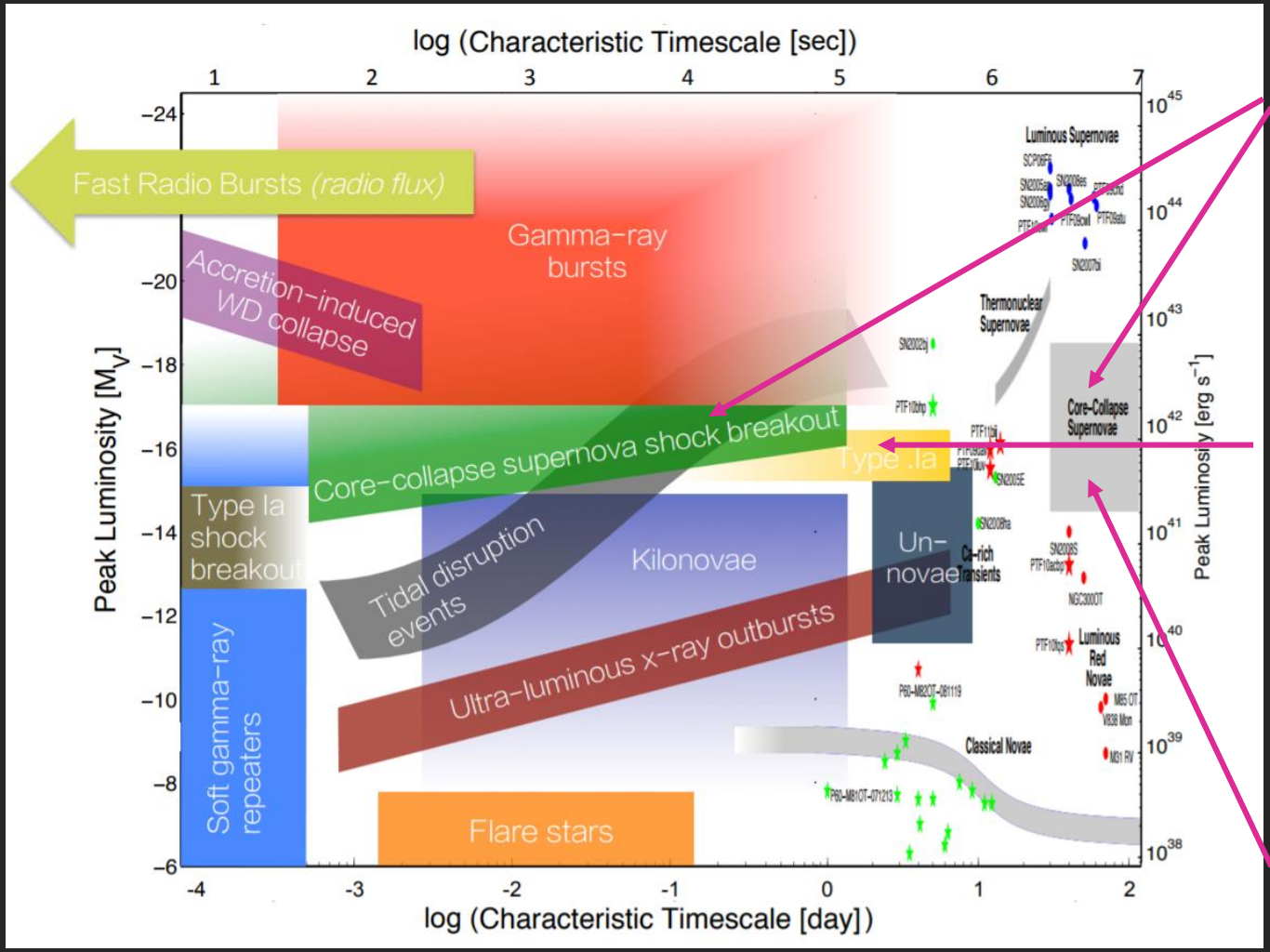


# Artist view on the binary interaction toward an H-free SN © ALMA/Maeda

YITP WS on “Exploring Extreme Transients: Emerging Frontiers and Challenges”,
2024.08.05-09

# Frontiers in Transient Science




Cooke+ 2015

## Higher cadence

**Known transients, but from the beginning.**

**Unknown short-time scale objects.**

## Larger samples

**Rare types of explosions.**

# New Time Domain Era

| Survey | Depth (mag) | Area ($deg^2$) | Cadence |
|---|---|---|---|
| BlackGEM | 21.5 | 10,000 | 2 weeks |
| DES | 23.5 | 5,000 | 1 week |
| KMTNet | ~21 | ~6,000 | 1 day |
| MOA | ~21 | ~1,000 | 1 day |
| TNTS | 20.0 | 2,000 | ? |
| PTSS | 20.5 | 4,000 | 1 day |
| HSC | 25 | 800 | 1 day |
| Tomo-e | 18/19 | 7,000 | 2 hr/1 day |
| **ZTF** | **21** | **23,000** | **3 days** |
| | 21 | 2,000 | 1 day |
| | 21 | 6,000 | 2 hr |
| ASAS-SN | 17 | 40,000 | 1 day |
| DLT40 | 20 | 600 gal | 1 dat |

M. Tanaka

**Ongoing surveys**
**+ Rubin/LSST to come**

**Catch transients/SNe even in the first day.**

**Discover rapidly-evolving transients/SNe.**

**Find unprecedented evolution (w/ monitoring).**

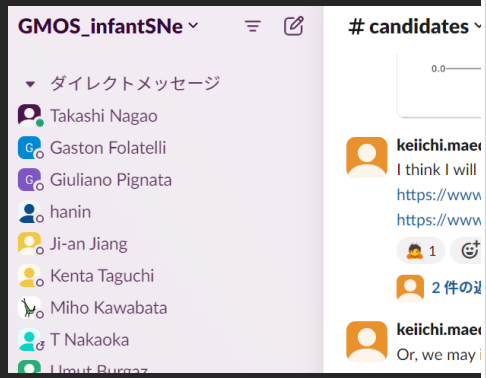
# SNe = Supernovae

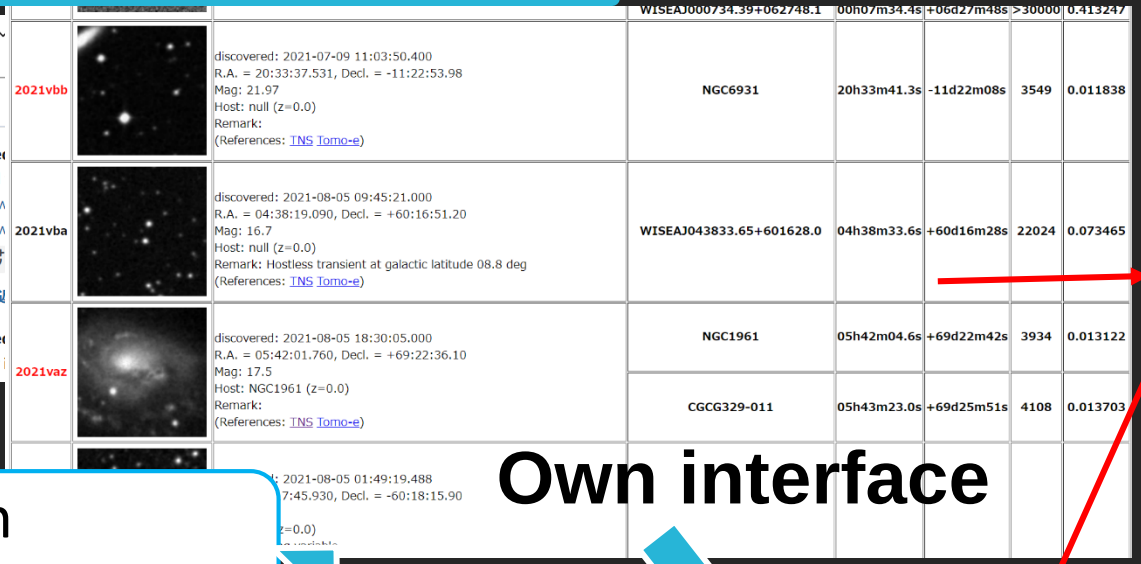
# Rapid follow-up observations as a key

- The survey information is very limited (only photometry, 1 or 2 bands in the optical).
- Need multi-bands, spec, multi-frequency, …

  ⇒ Need global collaborations.
- Our effort/contribution:
  - Model/interpretation.
  - Communication w/ surveys: Tomo-e, ZTF, WFST, …
  - Optical/NIR.
    - Seimei & Kanata telescopes as a “heavy user”.
    - Subaru and Gemini telescopes through open-use slots.
    - Regular collaborations w/ Finnish & Indian groups.
    - Case-by-case collaborations w/ various groups.
  - Radio & X-rays.
    - ALMA as a PI; VLA, ATCA, GMRT, JVN, SWIFT, etc. as a Co-I.

# Candidate selection

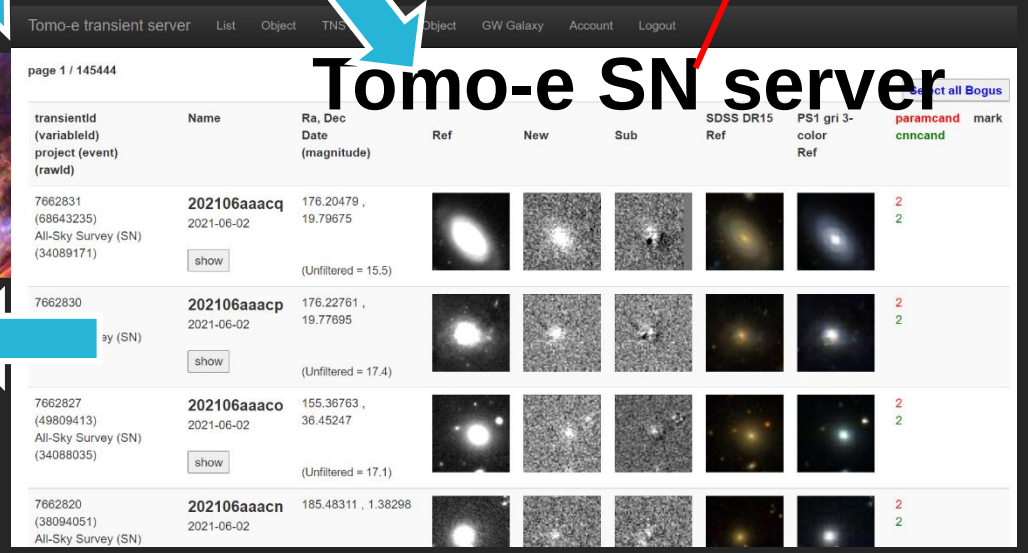



ToO

Own interface

Selection
（host galaxy, luminosity…）




ZTF, PS, ATLAS, WFST…

# Rapid follow-up Example

## Discovery certificate for object 2

TNS Astronomical Transient Report No. 207398 [ 2024TNSTR1020....1T ]

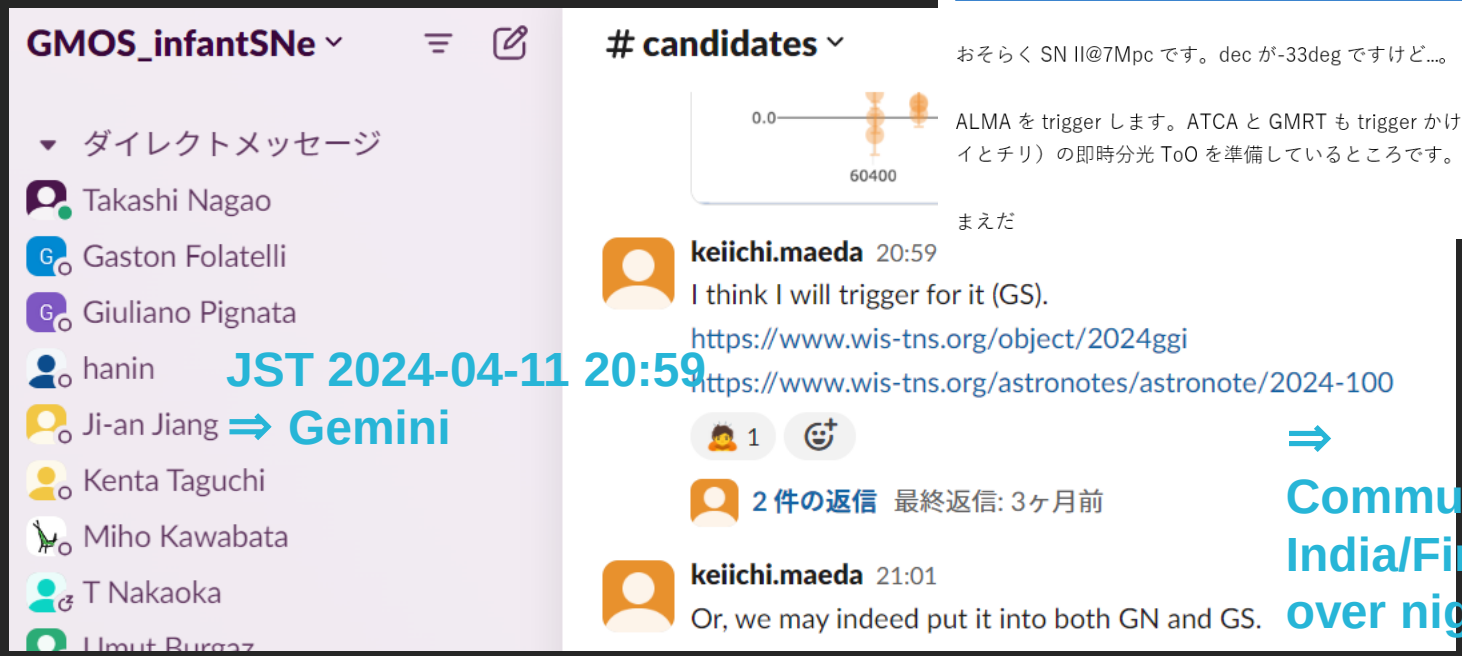
Date Received (UTC): 2024-04-11 09:03:14
Sender: ATLAS (ATLAS_Bot1)
Reporting Group: ATLAS  Discovery Data Source: ATLAS

J. Tonry, L. Denneau, H. Weiland, A. Lawrence, R. Siverd (IfA, University of
Nicholl, M. Fulton, M. McCollum, T. Moore, J. Weston, X. Sheng, P. Ramsde
(Oxford), A. Rest (STScI), T.-W. Chen (NCU), C. Stubbs (Harvard), J. Somm

IAU Designation: **SN 2024ggi**
Discoverer internal name: ATLAS24fsk
Coordinates (J2000): RA = 11:18:22.091 (169.592046667) DEC = -32:50:15
Discovery date: 2024-04-11 03:22:35.616 (JD=2460411.64069)

**Discovery report**
**JST 2024-04-11 18:03**


**JST 2024-04-12 00:50**
**⇒ ALMA**



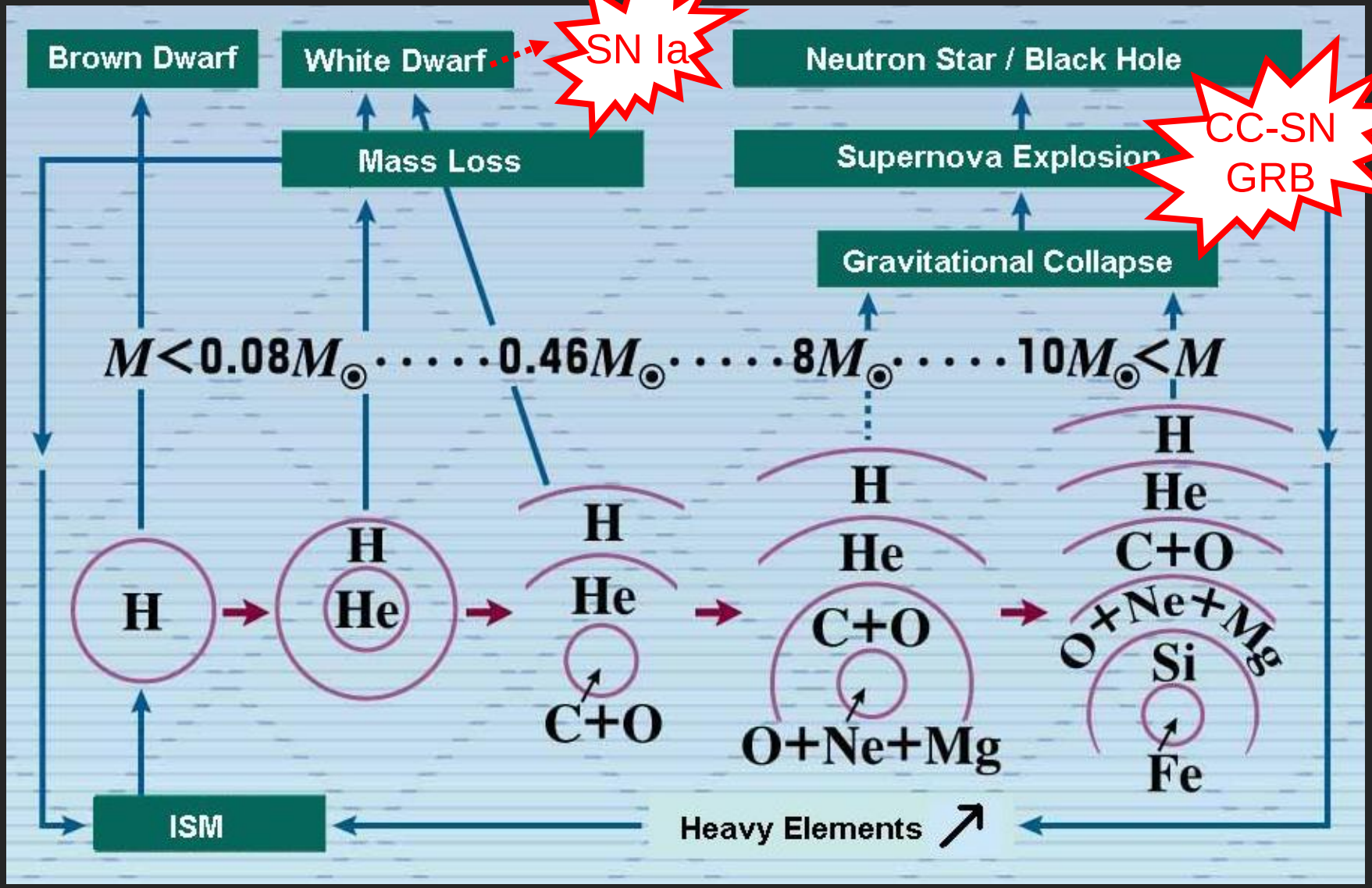

**JST 2024-04-11 20:59**
**⇒ Gemini**

**⇒**
**Communications w/ India/Fin/Chile/Argentina over night**

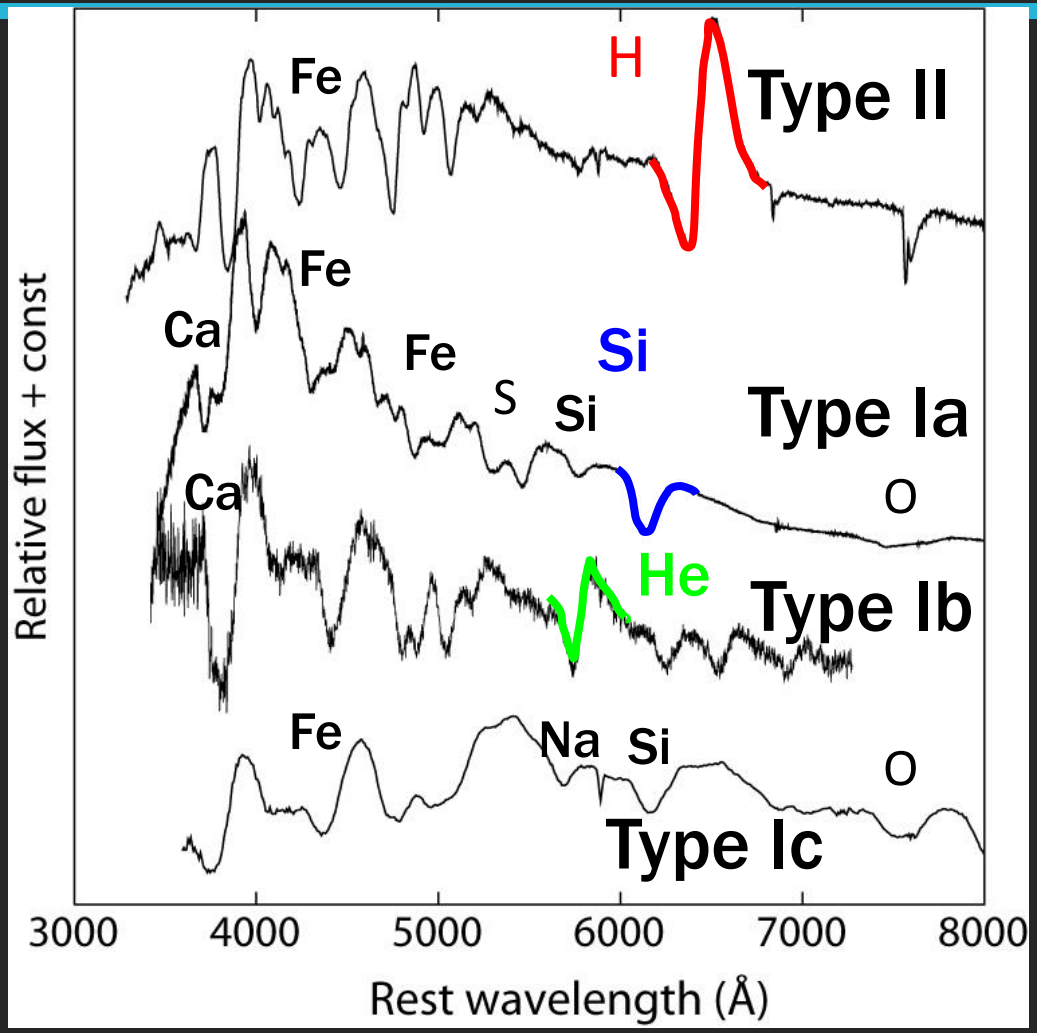
Type Ia supernova

Core-collapse supernova
Gamma-ray bursts

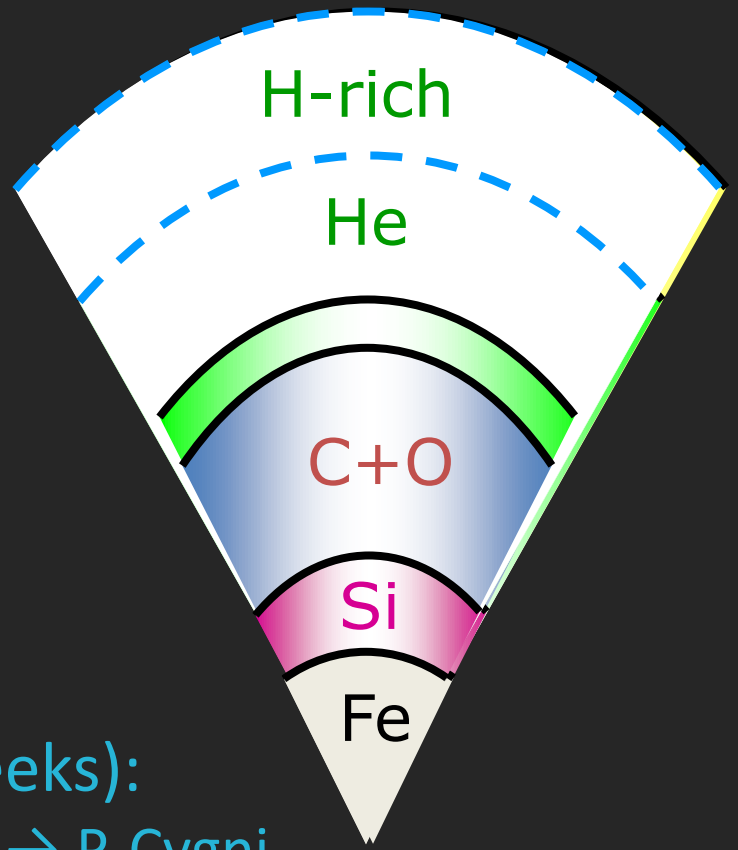
# Stellar Evolution and Supernovae (SNe)



# Supernova Classification




**II (but for SNe 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.

# Mass loss as a key process:
# A probe to (challenge for) stellar evolution theory

Progenitor

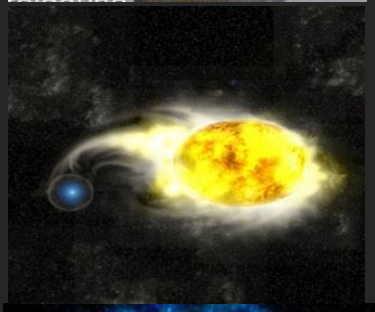
Mass loss

Main issue:
***Progenitor evolution, mapping stars ⇔ SNe***

**IIP/L**


RSG

**IIb**



YSG

BSG

**Ib**

**Ic**

WR

Dense CSM
in the vicinity

**IIn**

LBV?
CE?

**Mass stripping sequence**

Single star or binary?

Timing?

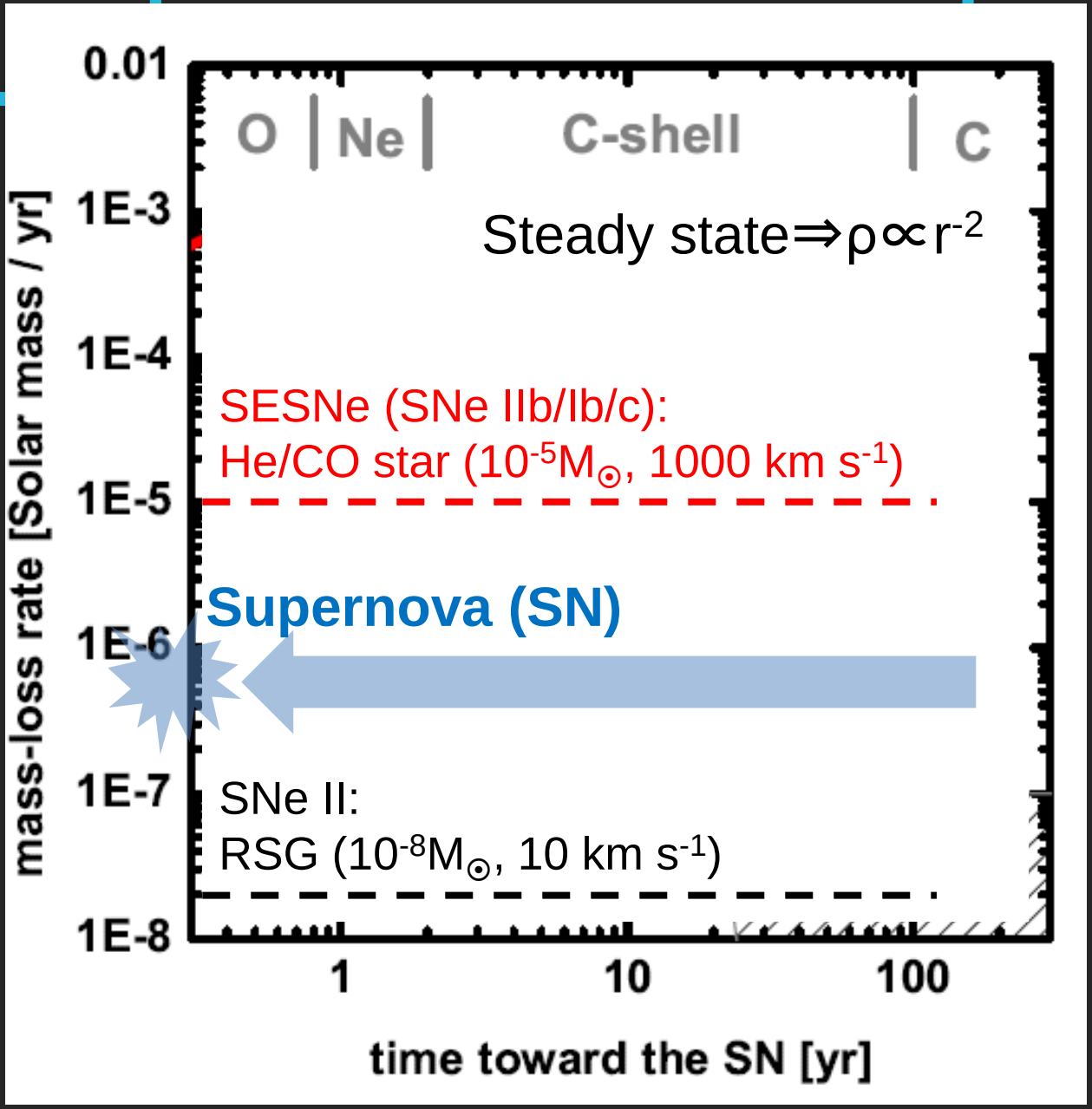
Mass-loss mechanisms?

**CSM – where and how much?**

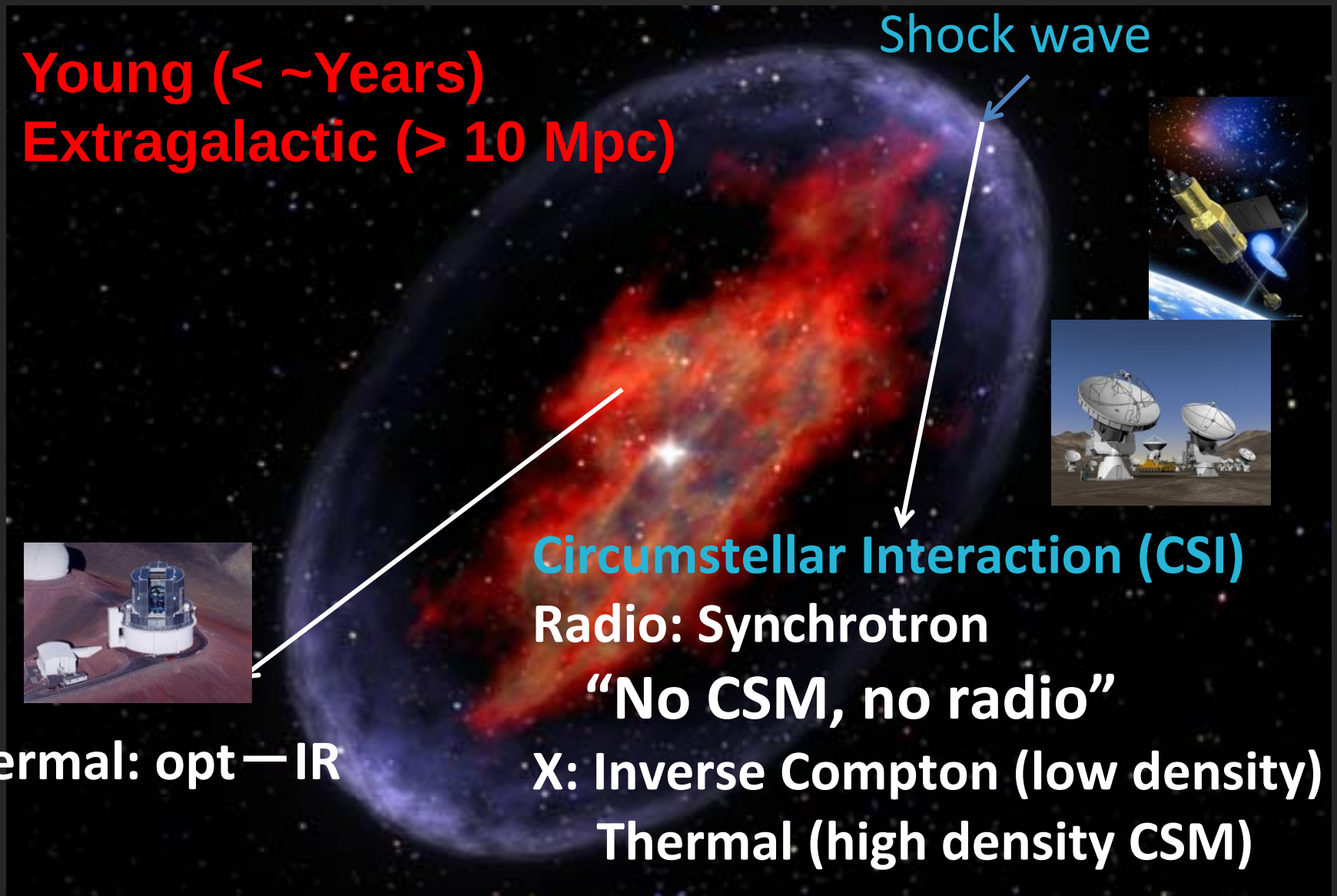
Decreasing
radius

More CSM
(where?)

# A classical picture - is it that simple?

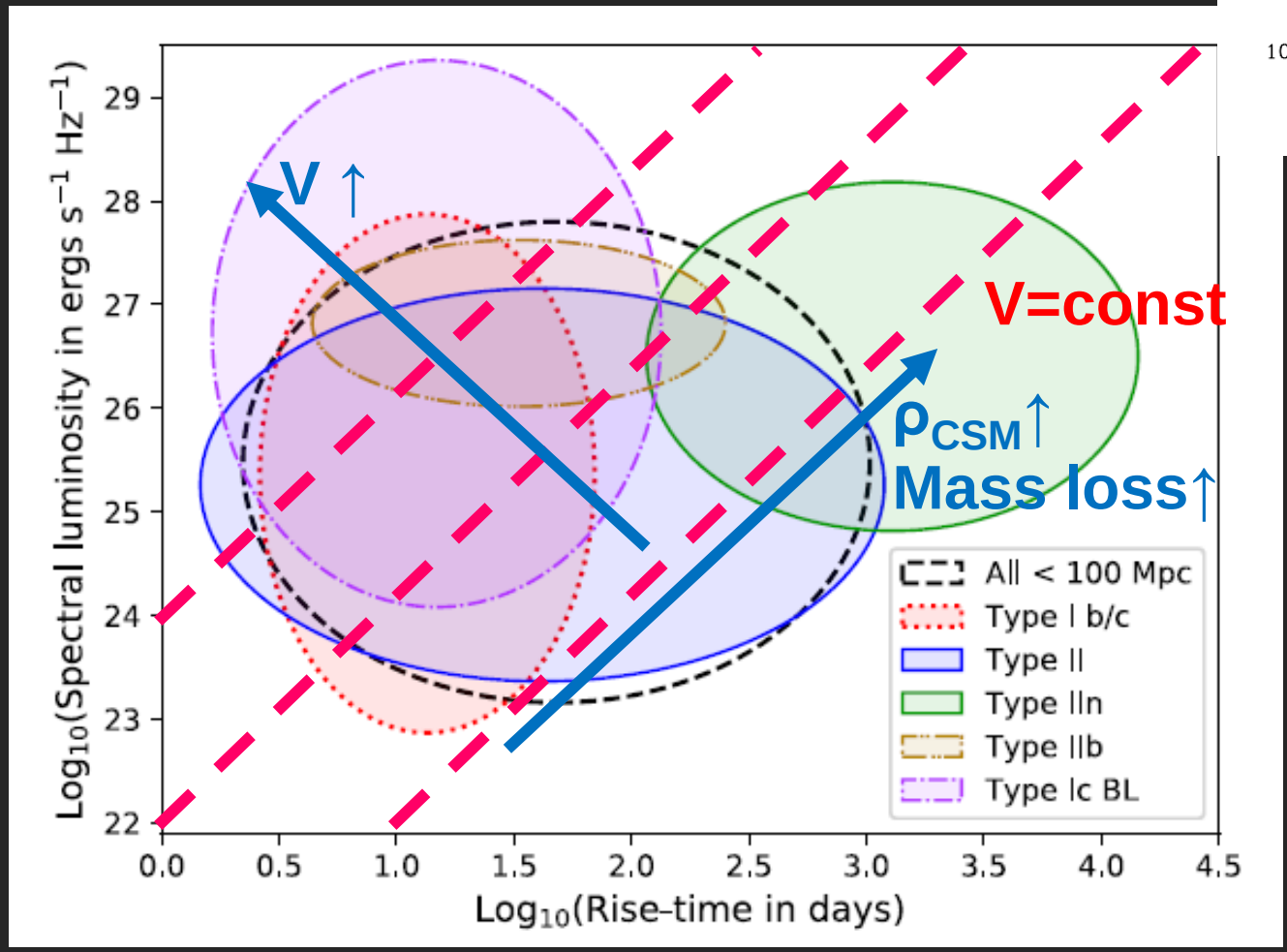


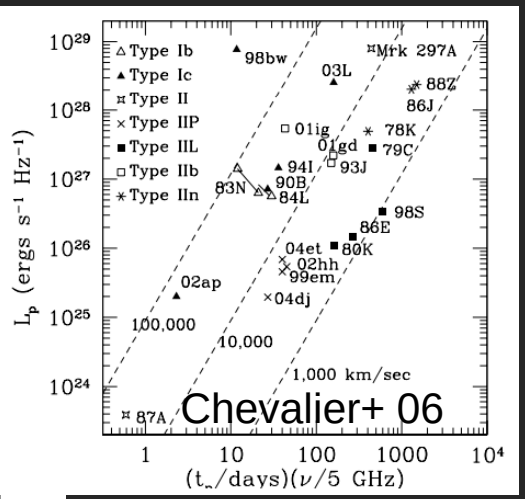
# Radio (and X): Unique probe to the CSM



# Radio Supernova Phase Space

## Peak time vs. Peak L




Bietenholz+2021

**Mostly ~month to year → ~>100 yrs before the explosion**

# SNe II (RSG?) vs. SNe Ib/c (He/C+O?)

RESULTS FOR RADIO SUPERNOVAE

| SN | $t(\tau_{ff} = 1)$ at 1.4 GHz (days) | $\dot{M}_{-6} v_{w1}^{-1} T_{cs5}^{-3/4}$ |
|---|---|---|
| 1999em | 52 | 5 |
| 2002hh | 62 | 7 |
| 2004dj | ... | 2–3 |
| 2004et | ... | 9–10 |

Chevalier+ 2006

SNe IIP

~(0.1-1) $10^{-5}$ $M_\odot$ $yr^{-1}$

In line with

SN IIP = RSG, Ib/c = WR?

SNe Ib/Ic

~(1-30) $10^{-5}$ $M_\odot$ $yr^{-1}$

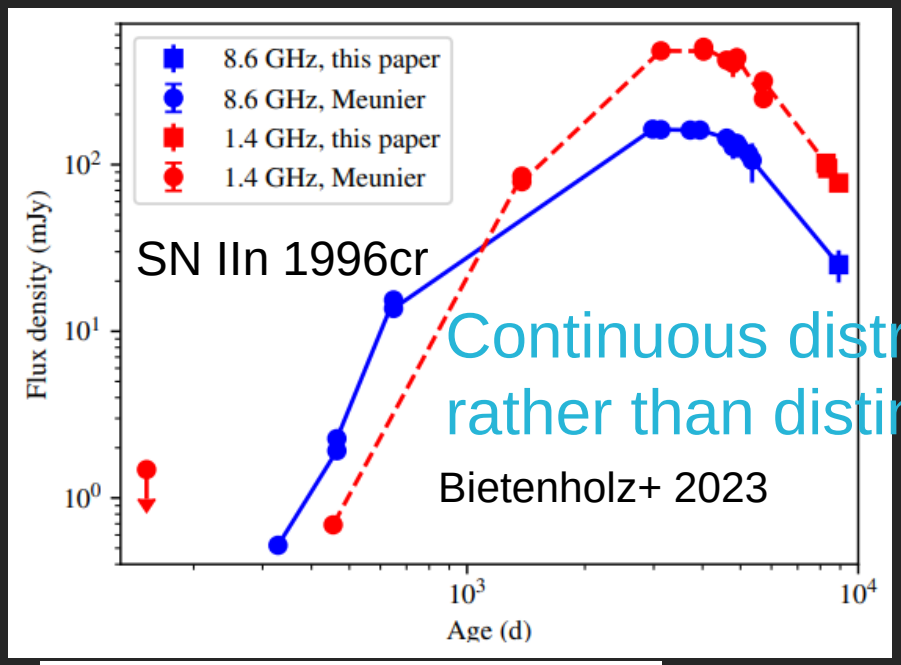
PROPERTIES OF TYPE Ib/c SUPERNOVAE IN A SYNCHROTRON SELF-ABSORPTION MODEL

Chevalier+Fransson 2006

| Supernova | $t_p$ (days) | $\nu_p$ (GHz) | $F_{op}$ (mJy) | $D$ (Mpc) | $B_p$ (G) | $\epsilon_{B-1} A_* \alpha^{8/19}$ | $R_p/t_p$ (km $s^{-1}$) |
|---|---|---|---|---|---|---|---|
| 1983N | 21 | 4.88 | 18 | 5.1 | 0.56 | 1.15 | 42,000 |
| 1990B | 91 | 1.49 | 1.6 | 18.0 | 0.17 | 2.0 | 33,000 |
| 1994I | 36 | 4.86 | 17 | 8.3 | 0.51 | 2.8 | 38,000 |
| 2001ig | 42 | 4.8 | 18 | 12.3 | 0.46 | 3.1 | 49,000 |
| 2002ap | 8 | 1.43 | 0.3 | 10.4 | 0.26 | 0.04 | 105,000 |
| 2003L | 170 | 4.9 | 2.4 | 96 | 0.38 | 34 | 32,000 |
| 2003bg | 60 | 8.46 | 40 | 19.5 | 0.68 | 13 | 44,000 |

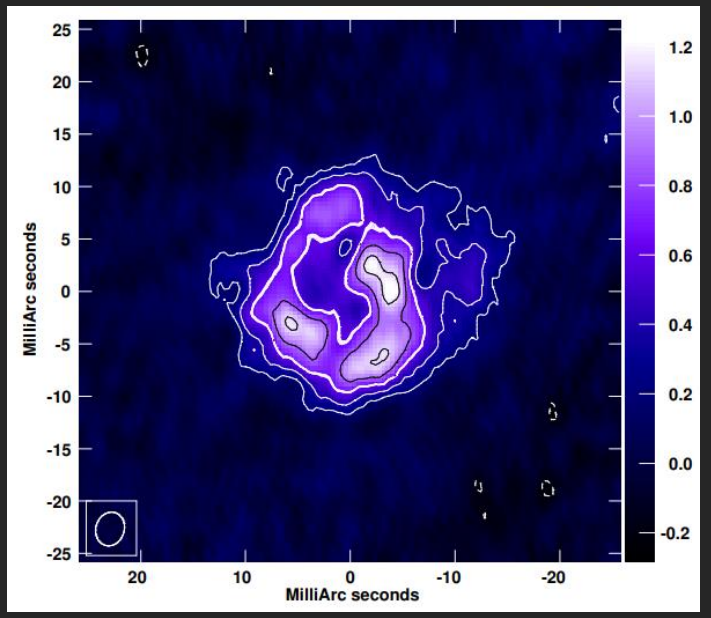
# Maybe biased toward the dense CSM (radio strong).

# Type IIn SNe: dense CSM

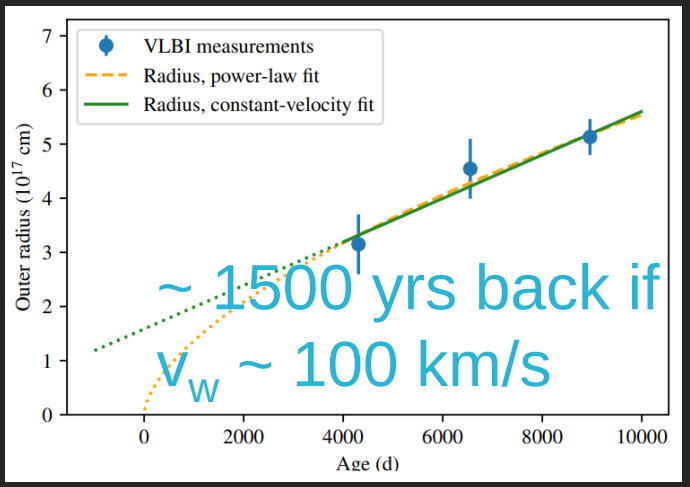



Continuous distribution rather than distinct shell(s)?

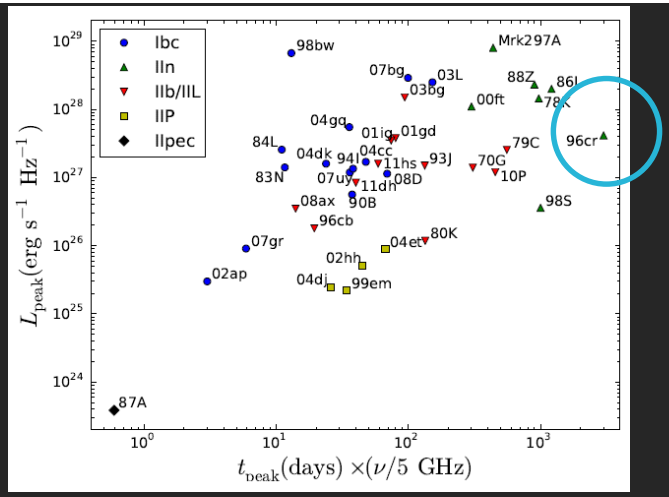
Bietenholz+ 2023




~shell, not disk?

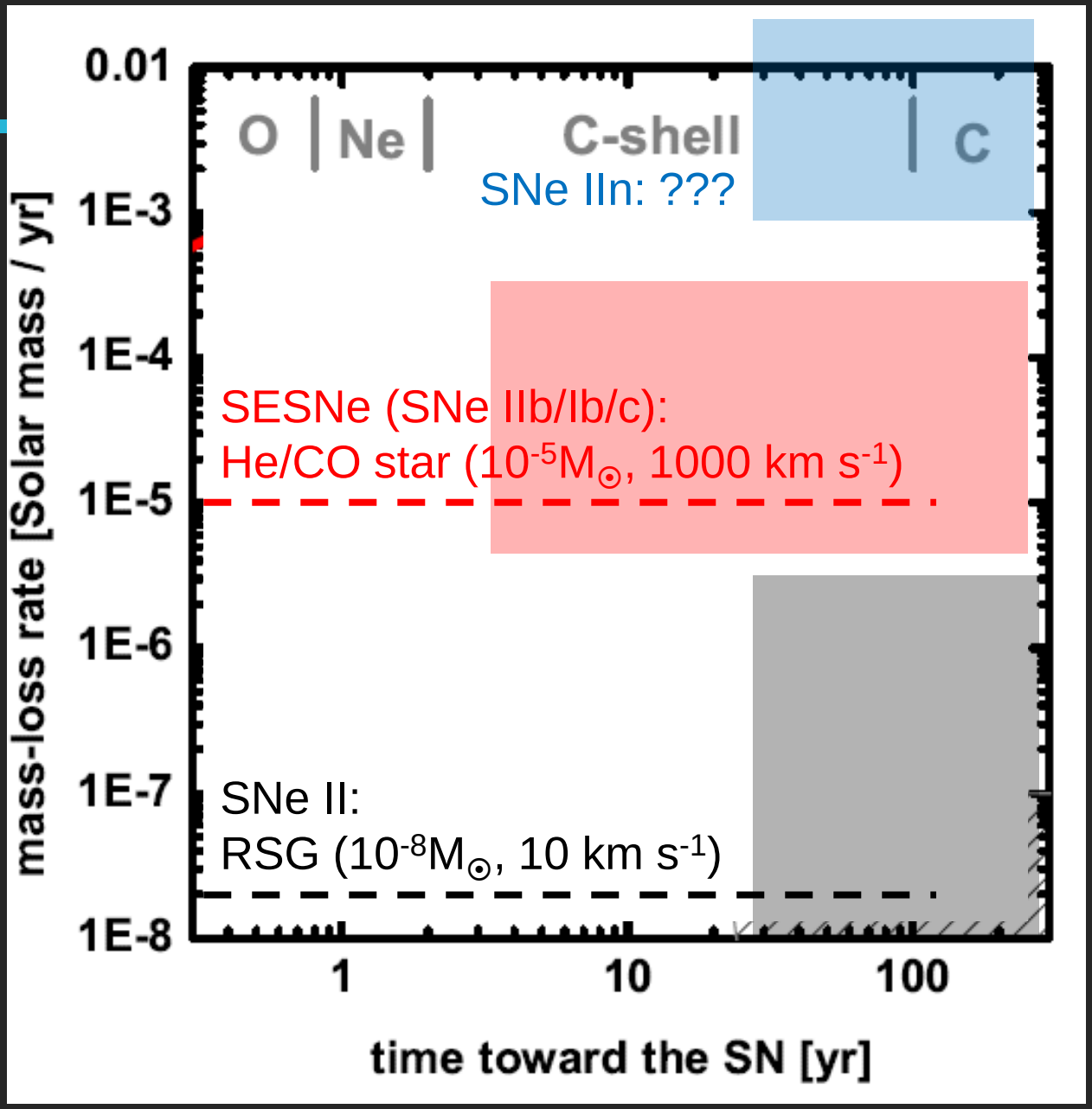


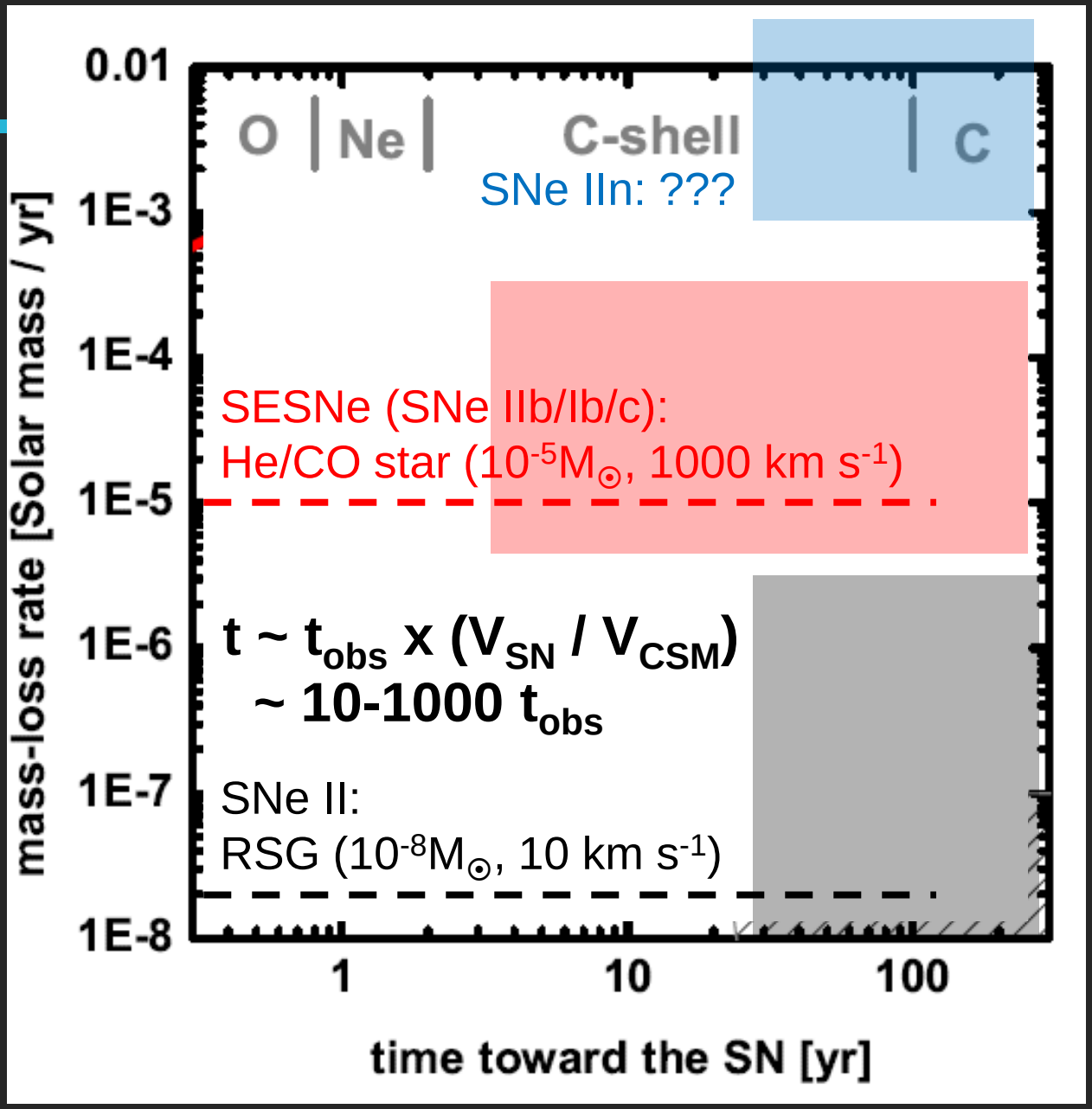

~ 1500 yrs back if $v_w$ ~ 100 km/s




**Dense CSM: Thermal X→optical**

**SNe IIn: $10^{-3}$ ~ a few $M_\odot$ yr$^{-1}$**


0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
mass-loss rate [Solar mass / yr]
O
Ne
C-shell
C
SNe IIn: ???
SESNe (SNe IIb/Ib/c):
He/CO star ($10^{-5}M_{\odot}$, 1000 km $s^{-1}$)
SNe II:
RSG ($10^{-8}M_{\odot}$, 10 km $s^{-1}$)
1
10
100
time toward the SN [yr]

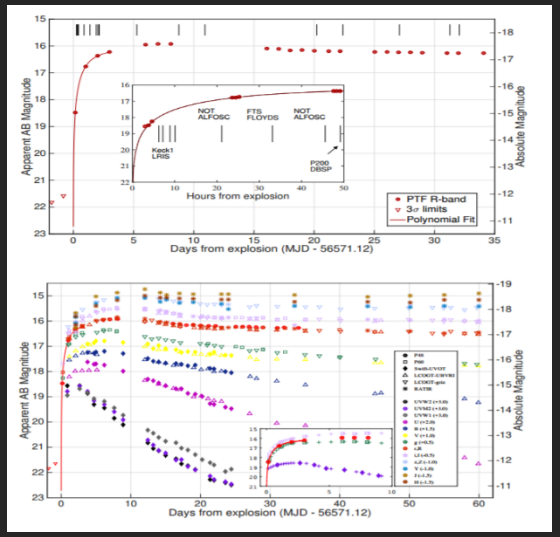

0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
mass-loss rate [Solar mass / yr]
O
Ne
C-shell
C
SNe IIn: ???
SESNe (SNe IIb/Ib/c):
He/CO star ($10^{-5}M_{\odot}$, 1000 km $s^{-1}$)
$t \sim t_{obs} \times (V_{SN} / V_{CSM})$
$\sim$ 10-1000 $t_{obs}$
SNe II:
RSG ($10^{-8}M_{\odot}$, 10 km $s^{-1}$)
1
10
100
time toward the SN [yr]

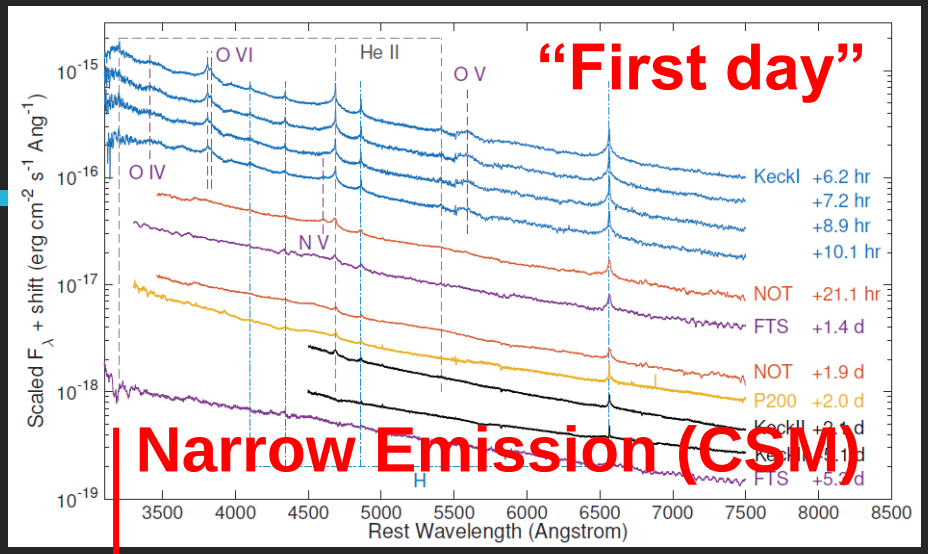
# “Flash” optical spectroscopy

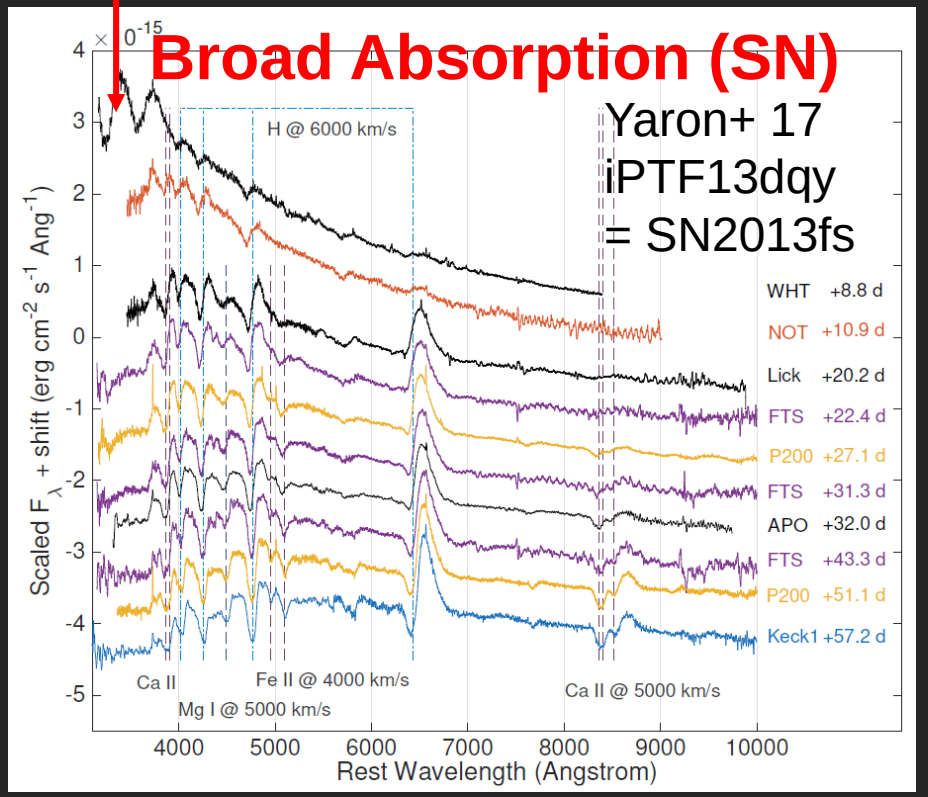
Recombination from the massive CSM near the SN???

→ **So far mostly for SNe II (RSG). Potentially biased toward the dense CSM.**

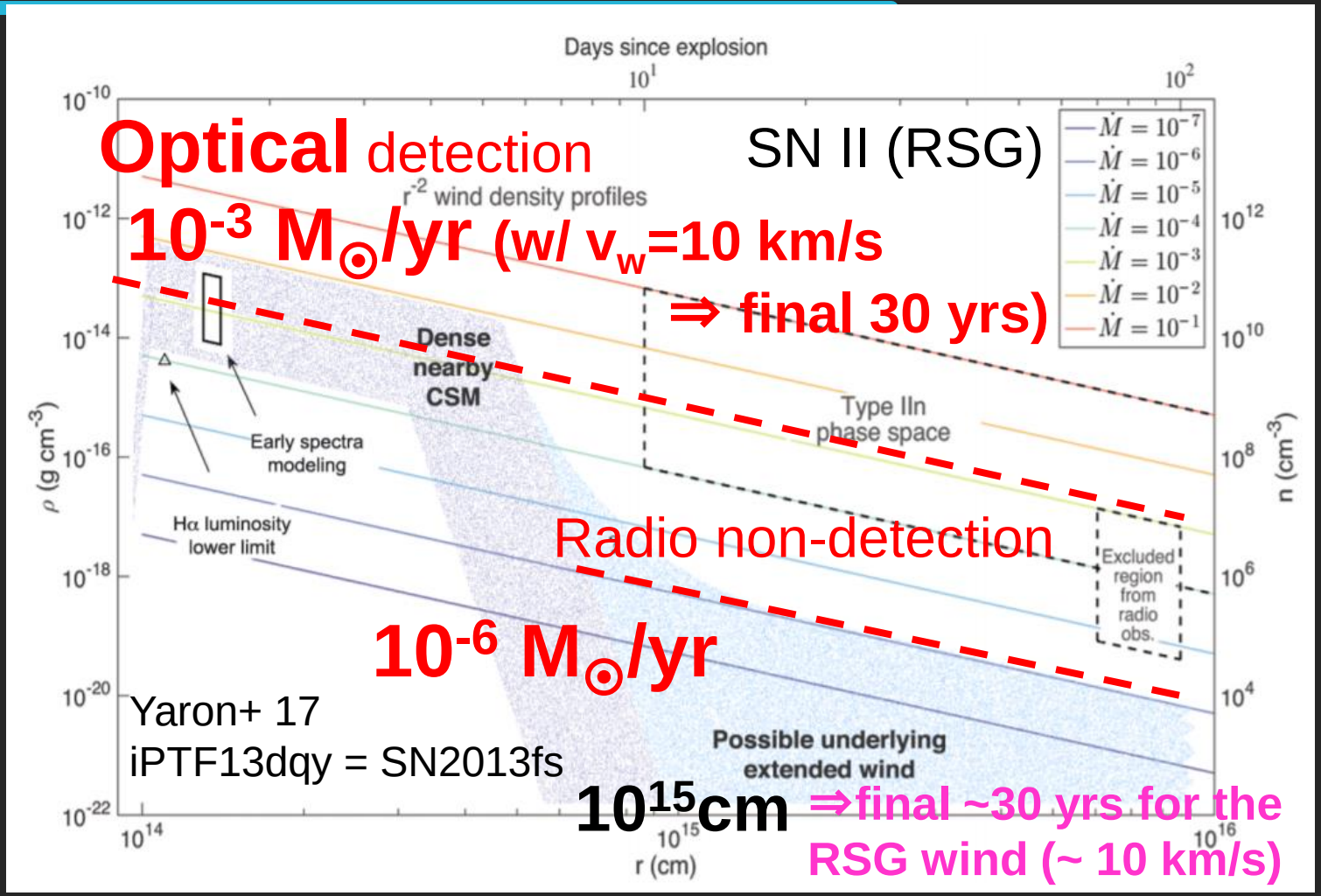
Gal-Yam+ 14, Khazov+ 16, Yaron+ 17, Bruch+ 21/22



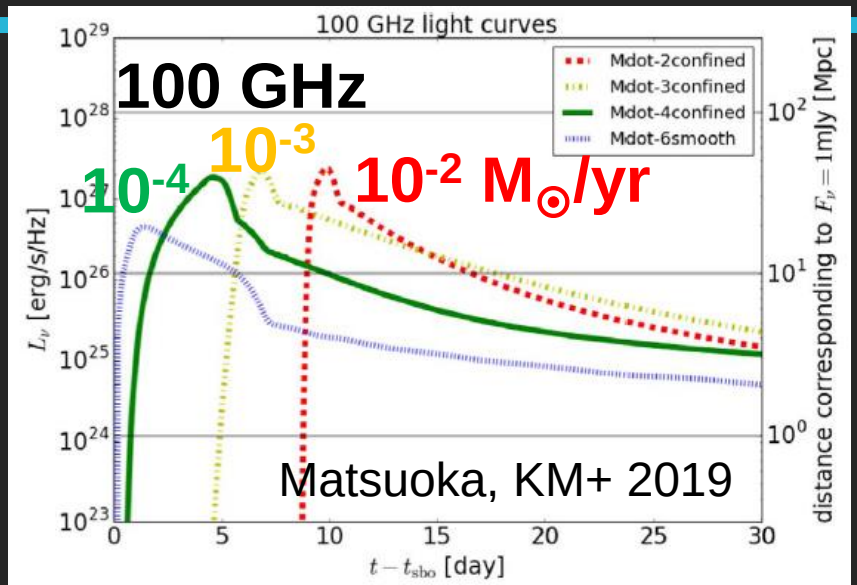



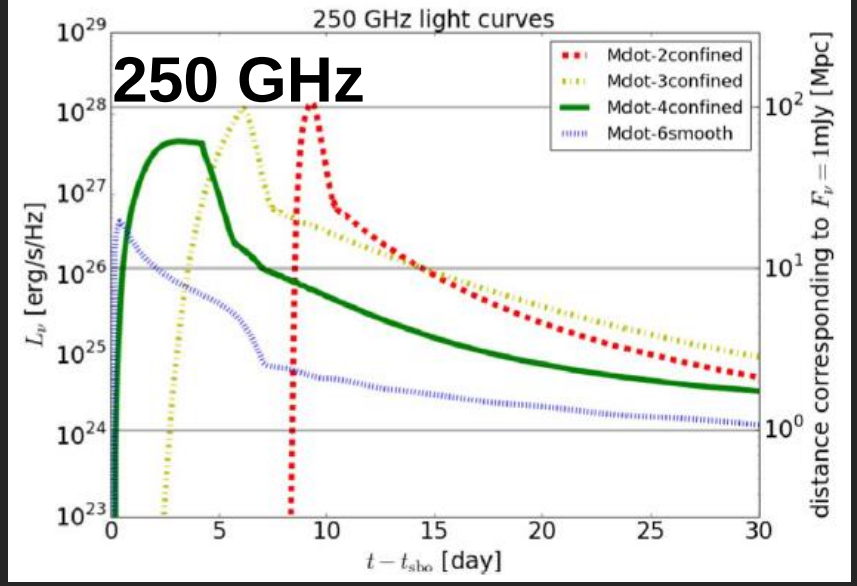
# From optical data:
# Mass loss in the final decades for some/most SNe IIP (RSG)




**Dense CSM within $10^{15}$cm (Type II SN = RSG progenitor)**
**Optical data probably biased toward dense CSM?**

# A key: Radio within 10 days




**SNe IIP (RSG) w/ "confined" CSM (+ outer low-density CSM).**

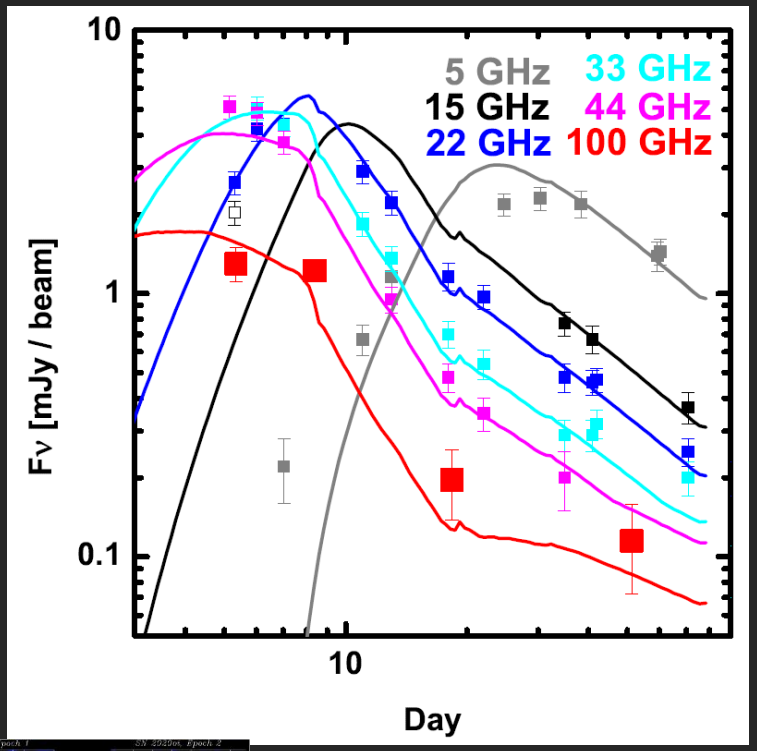
**Issues in the optical window:**
- **Interpretation complicated.**
- **Bias toward the dense(st) CSM.**
- **Probable bias toward SNe II (RSG).**

**mm obs. overwhelms these difficulties: ALMA cycles 5-7, 9-10 (KM+)**
- **No CSM, no radio (⇔ optical).**
- **Optically thin (⇔cm suppressed).**

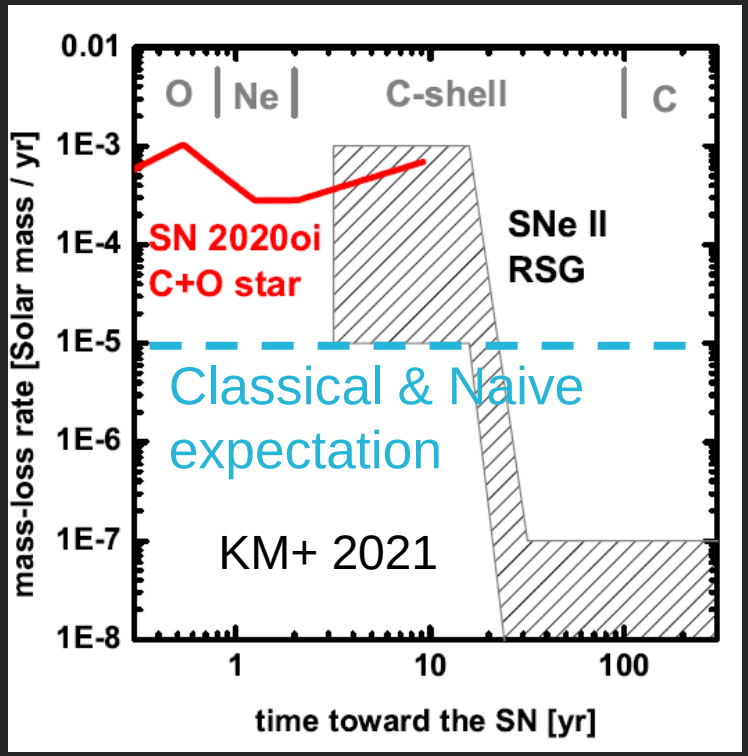
**Need: Quick observations within ~ a week (challenging but doable).**

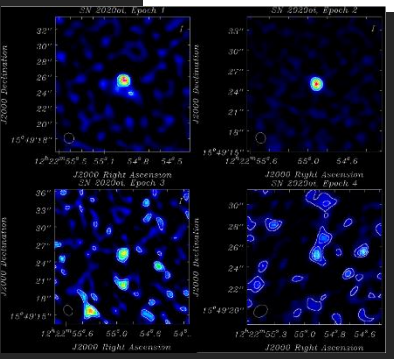
# First infant SN seen by ALMA: SN Ic 2020oi

## Multi-band LC



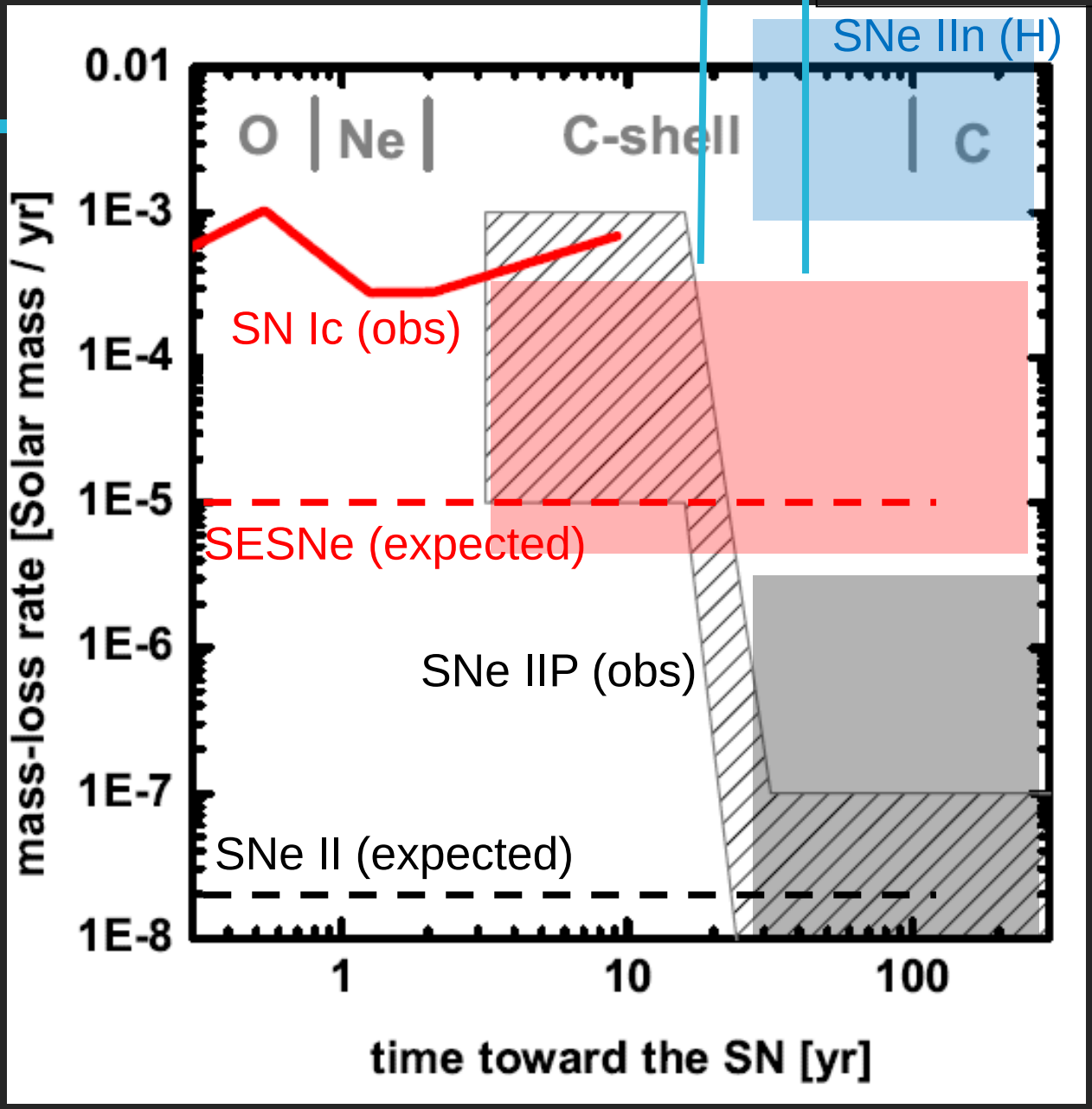

## Derived mass-loss history



Overall mass-loss rate in the final few yrs for SN Ic 2020oi
~ the (enhanced) mass-loss rate in the final decades for SN II.

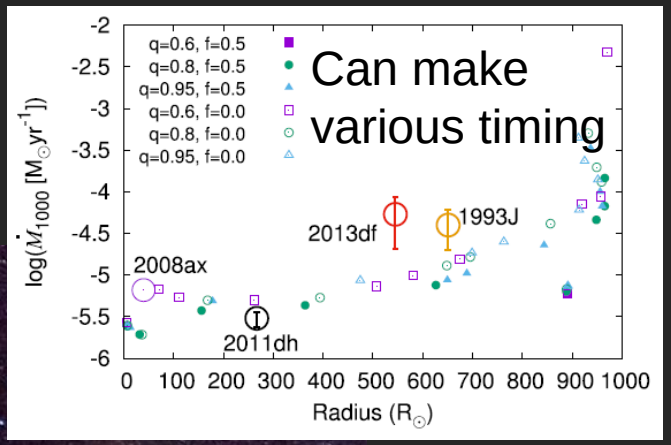
**Sub-year timescale variability toward the SN.**


Ib→IIn (H)
SNe IIn (H)
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
O
Ne
C-shell
C
SN Ic (obs)
SESNe (expected)
SNe IIP (obs)
SNe II (expected)
mass-loss rate [Solar mass / yr]
1
10
100
time toward the SN [yr]

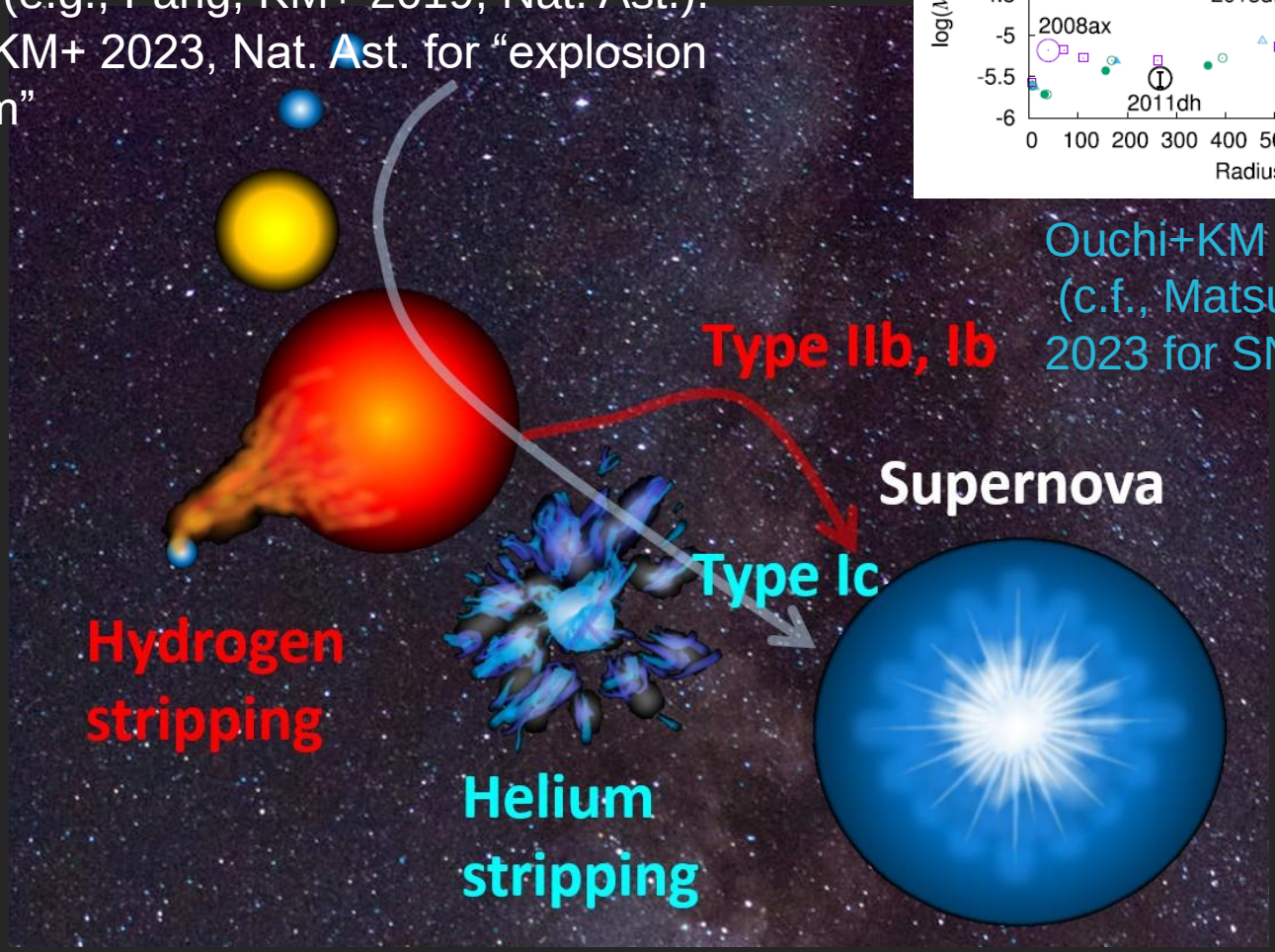
2017
(c.f.,
Yoon)

# Binary evolution: Shaping the CSM for SESNe?

Binary interaction is probably a main driver of the H-envelope for (normal) SESNe (e.g., Fang, KM+ 2019, Nat. Ast.).
c.f. Fang, KM+ 2023, Nat. Ast. for "explosion mechanism"




Ouchi+KM 2017
(c.f., Matsuoka & Sawada 2023 for SN 2023ixf)



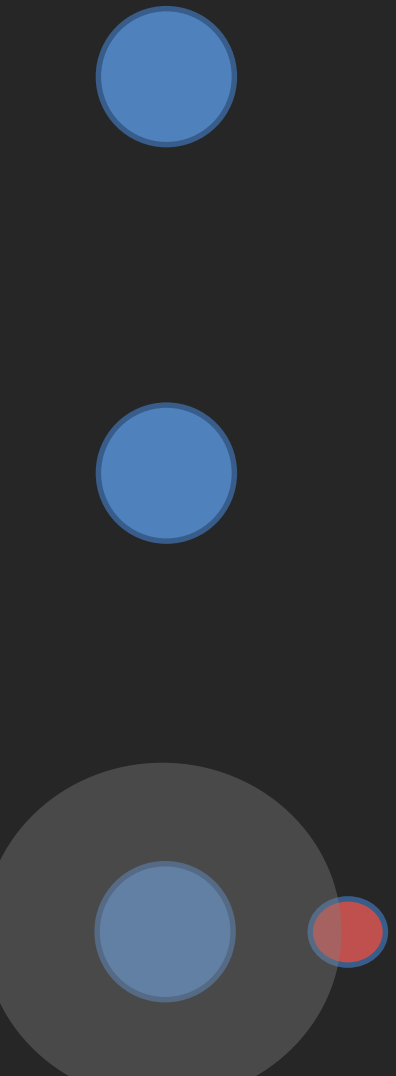
# IIP⇒IIL⇒IIb transition in the binary?

Controlled by the separation?

Binary can have a range of the initial orbital separation.

# IIP⇒IIL⇒IIb transition in the binary?

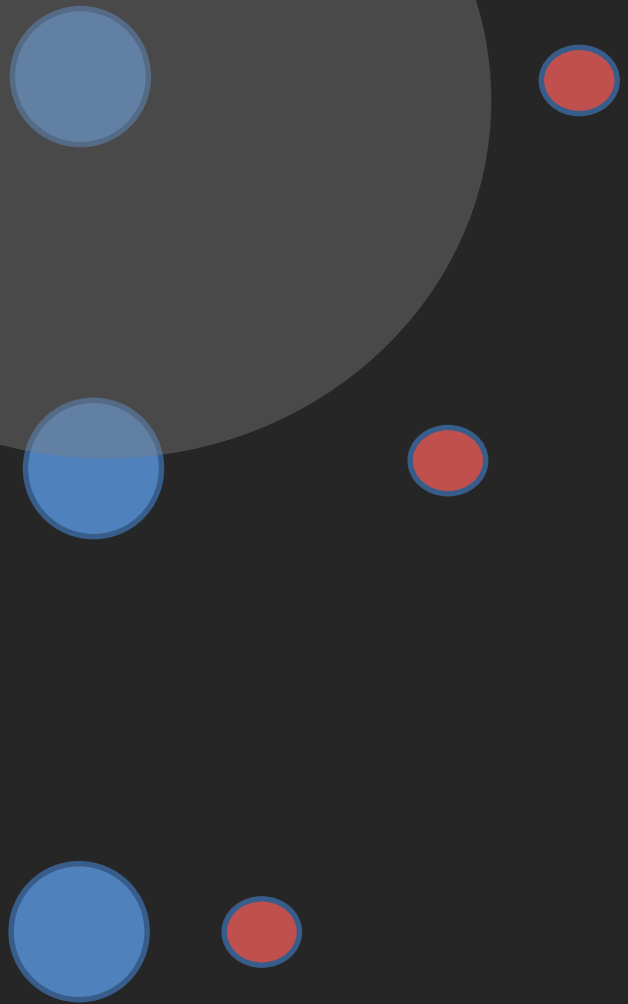
Controlled by the separation?



Interaction ~ $10^6$ yrs before the SN
=> He or C+O star ⇒ IIb/Ib/Ic

# IIP⇒IIL⇒IIb transition in the binary?

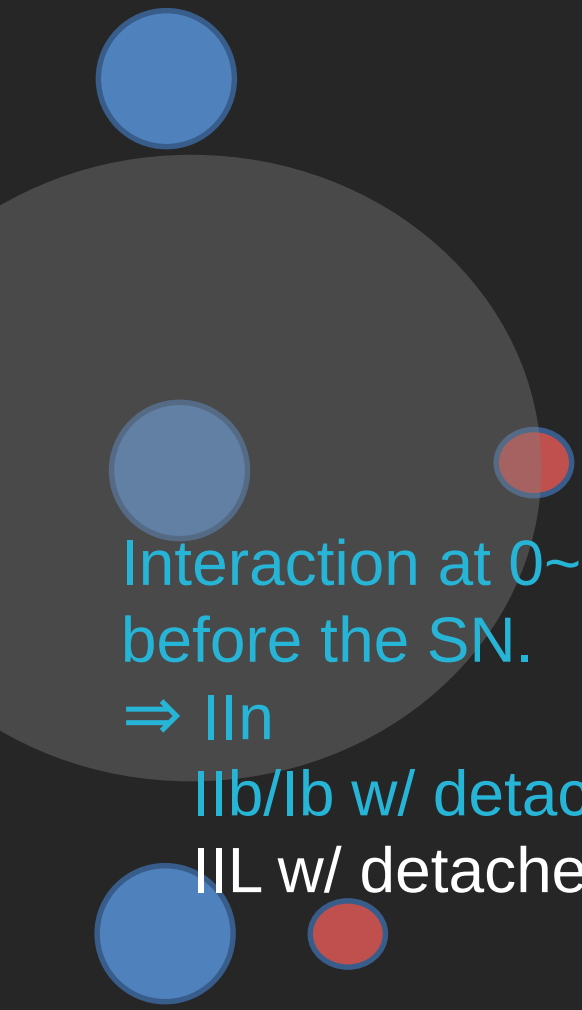
Controlled by the separation?



No Interaction over the entire life of the primary
=> H-rich giant ⇒ IIP

# IIP⇒IIL⇒IIb transition in the binary?

Controlled by the separation?

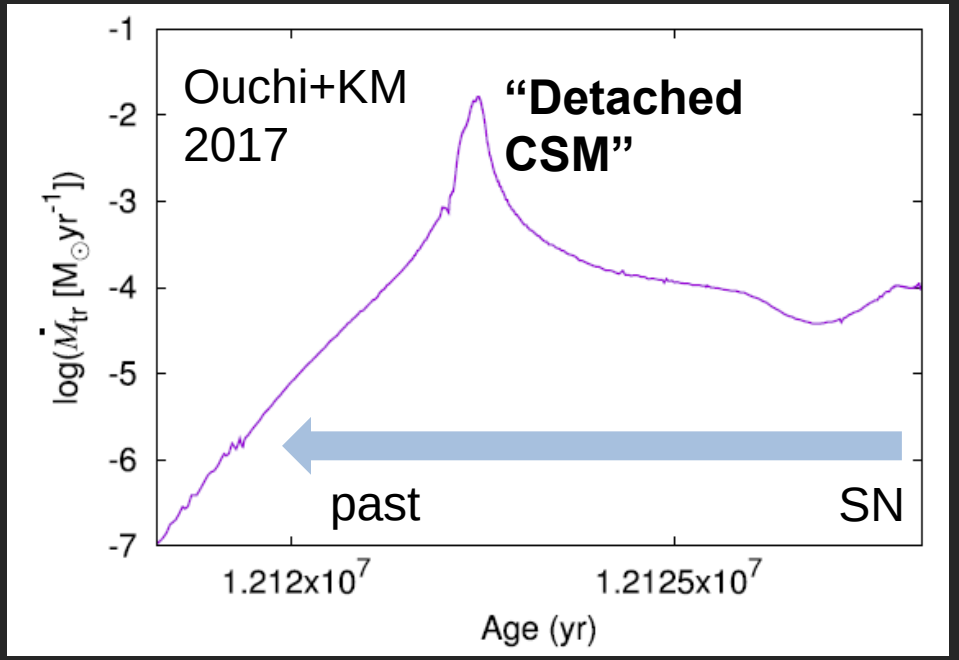


Interaction at 0~1000 yrs before the SN.

⇒ IIn

IIb/Ib w/ detached CSM

IIL w/ detached CSM



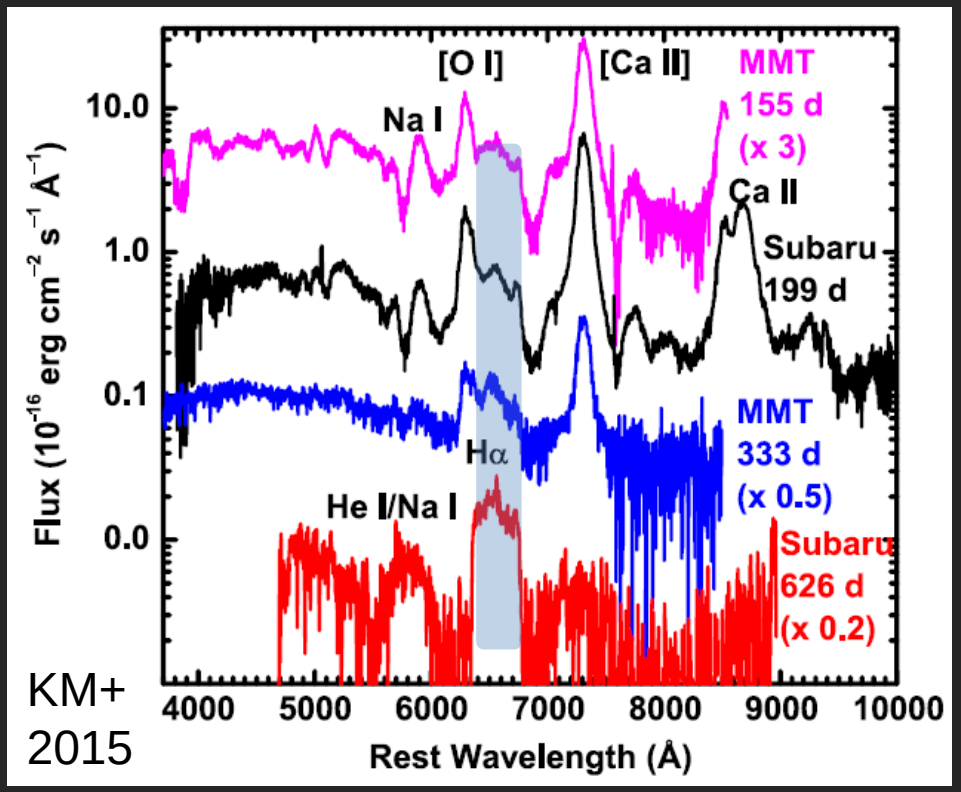

High-mass loss rate.

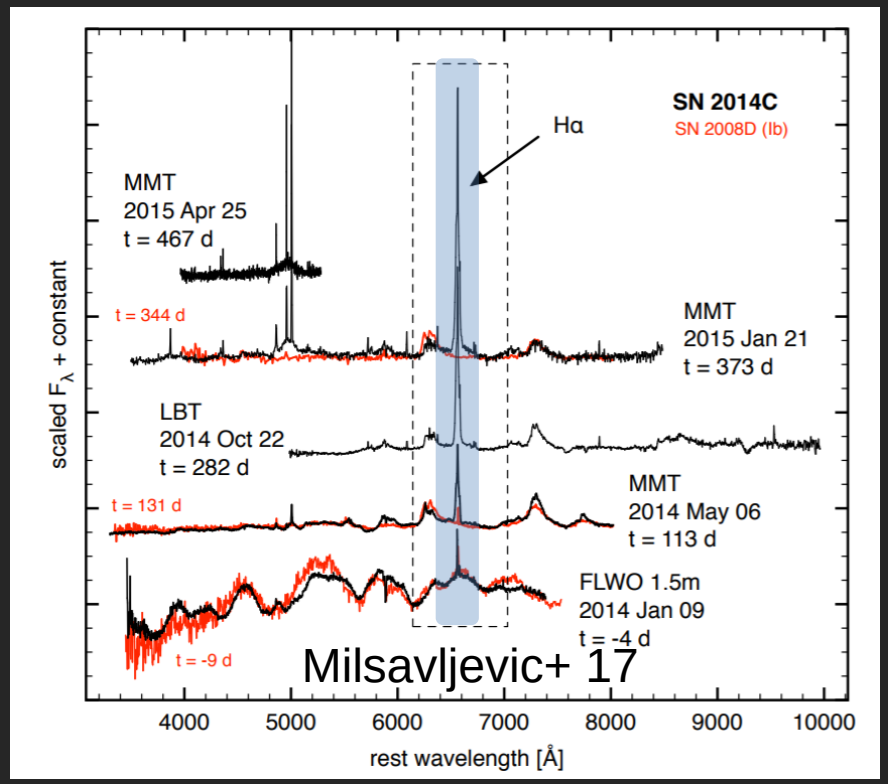
Expected rate~ 10% of SNe IIb (roughly ok with the observed fraction of SNe IIL).

Detached shell?

See also Gangopadhyay, KM+ 2024

# “delayed” CSM interaction (CSM signatures in late phases): Some SNe even change the morphology



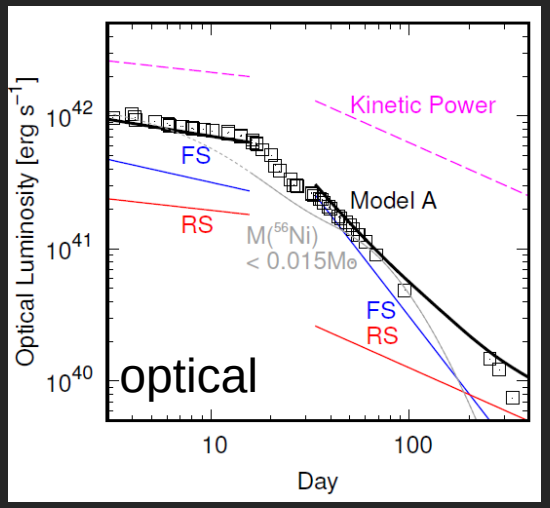



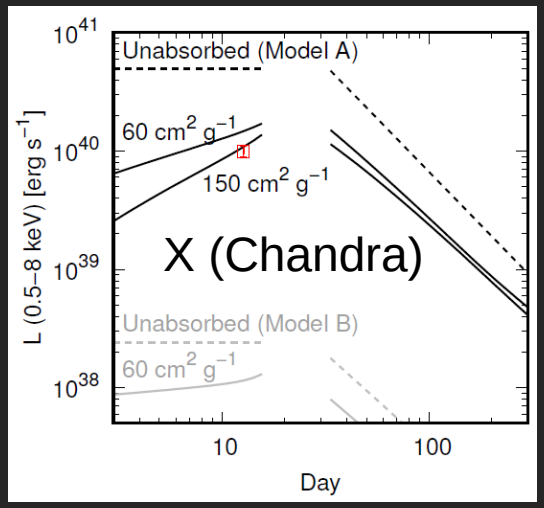

SN IIb 2013df (He star + thin H env.):
Broad Hα from the SN-CSM interaction showing up in ~ 1 year.
Relatively dense and H-rich CSM.
**Binary interaction (stable transfer?)**

SN Ib 2014C (He star):
Narrow Hα from the SN-CSM interaction showing up in ~ 1 year.
Very dense and detached H-rich CSM.
**Binary (unstable transfer, CE?)**

# A case for (peculiar) SN IIL 2018ivc: Optical/X/radio (ALMA) observation & model

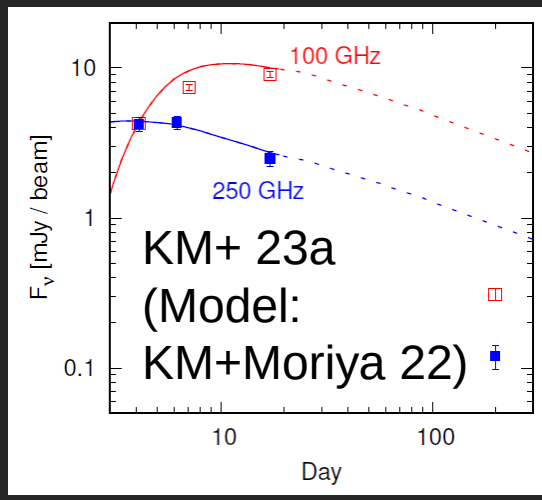
CSM interaction dominates in all the wavelengths.

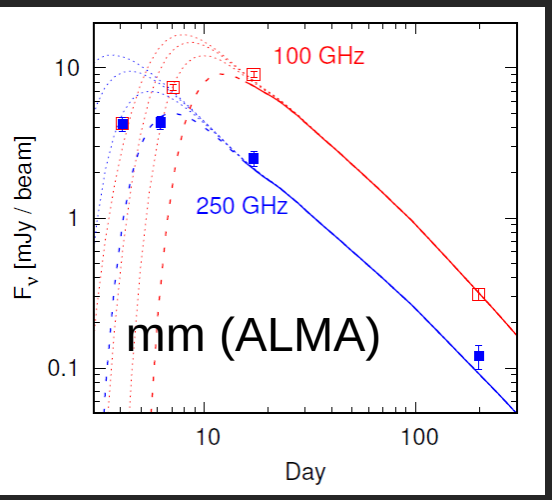


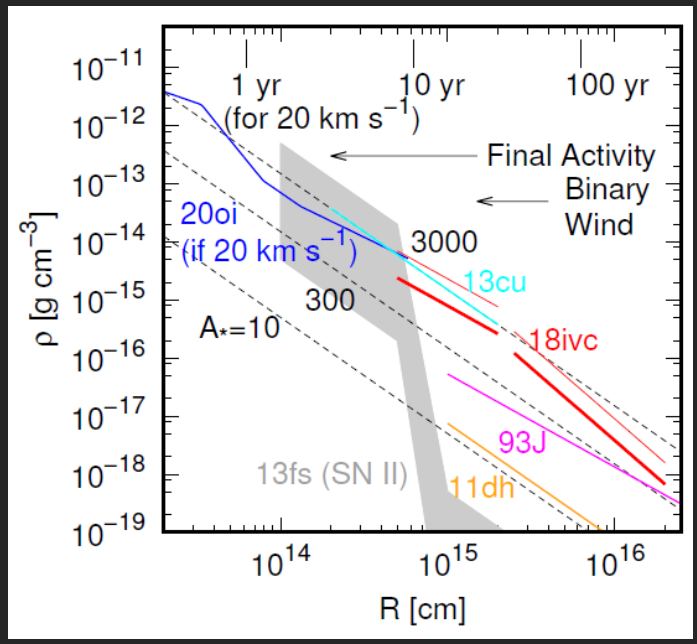




SNe IIL: progenitor unknown.

At least this one is **"SN IIb (He)" in a binary.**

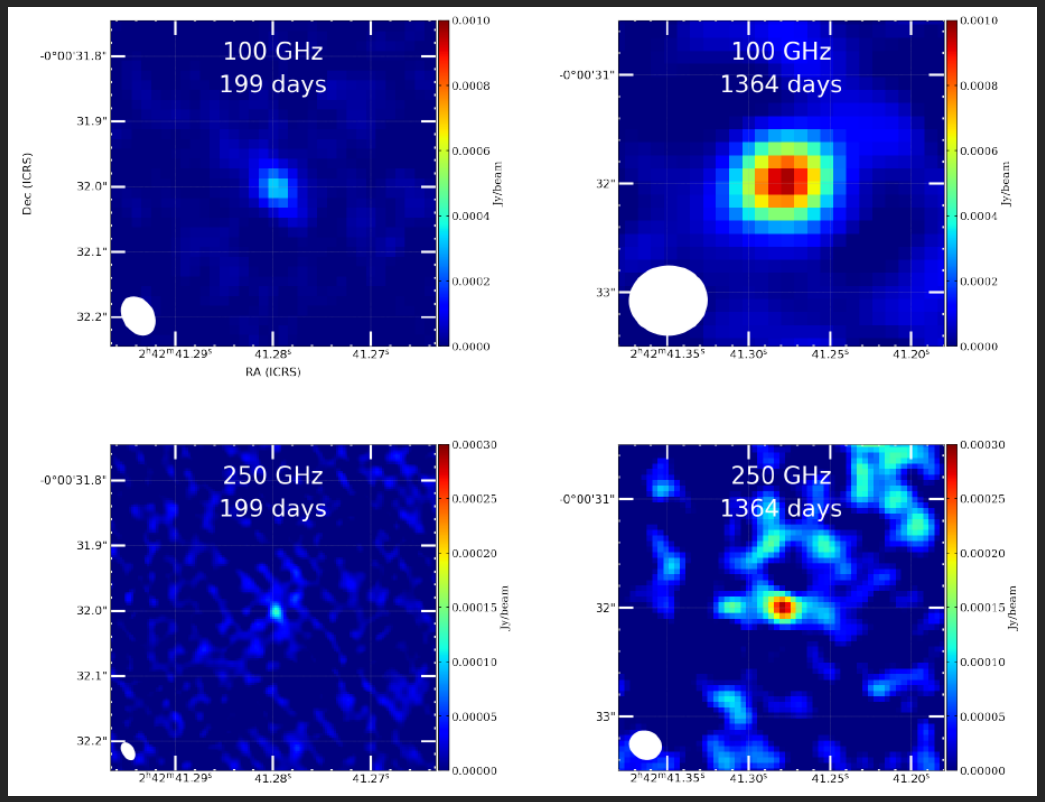


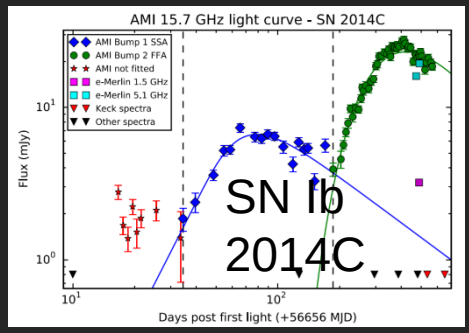



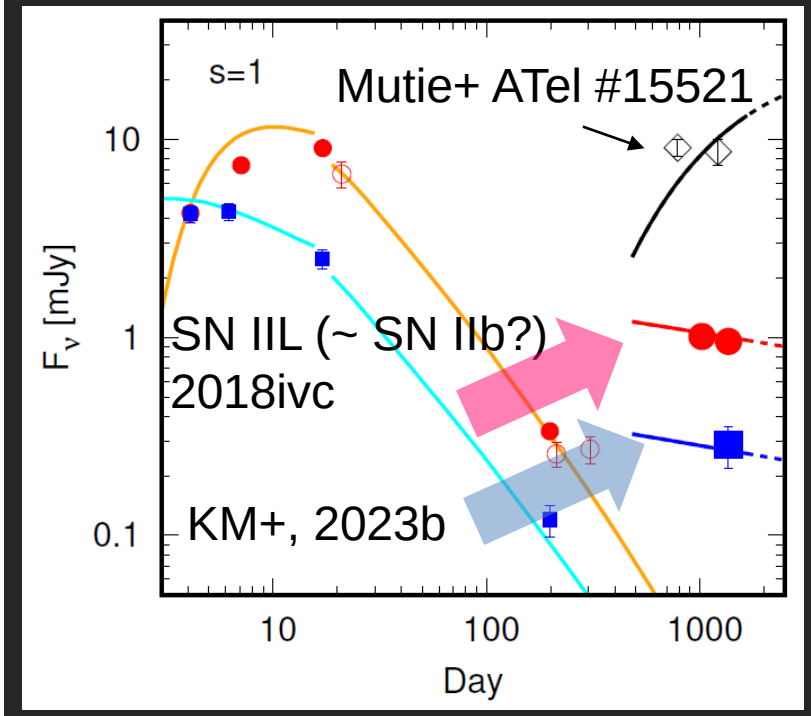



# SN 2018ivc: resurrection

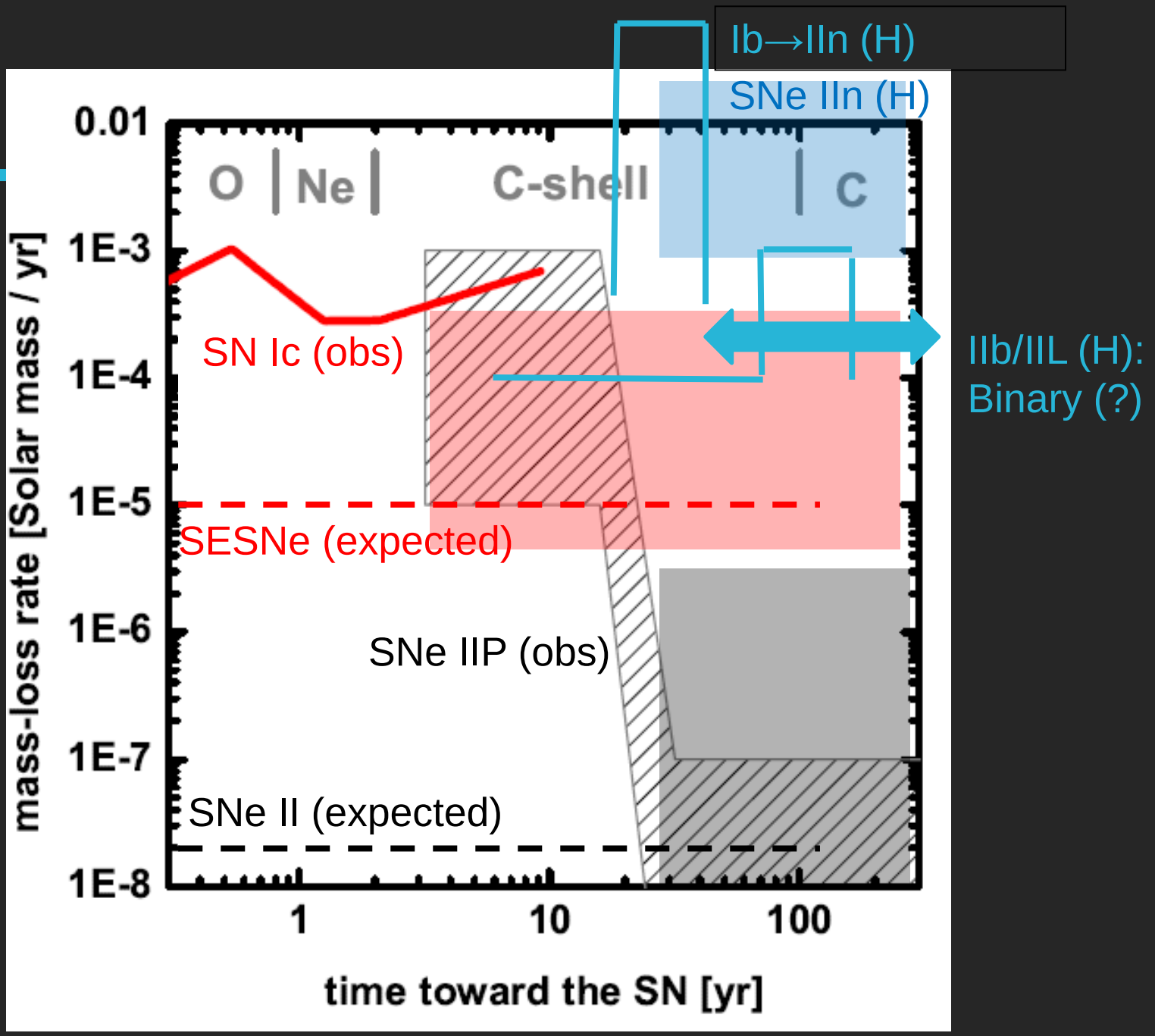
Keeps looking at it : archival + DDT



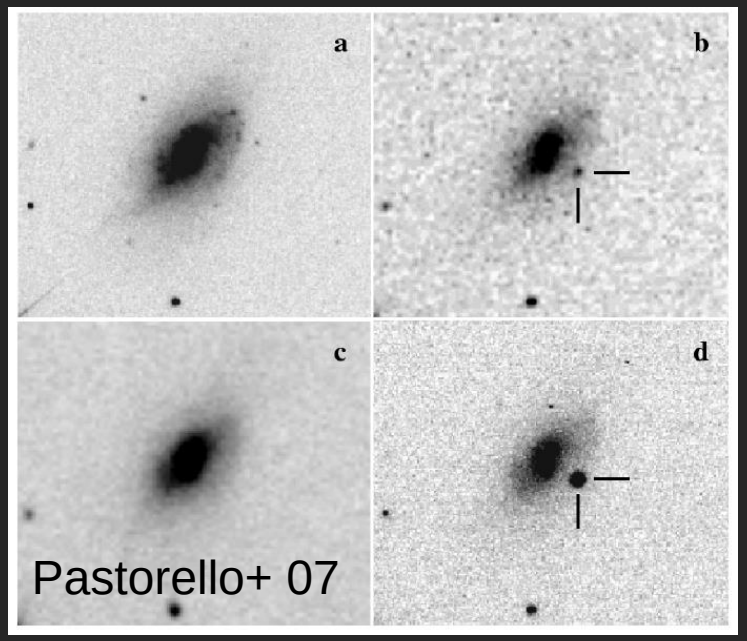




The first example of the rebrightening in mm (to my knowledge). The second example of the “SN IIb” late-time interaction clearly seen in the radio (as long as I am aware of).

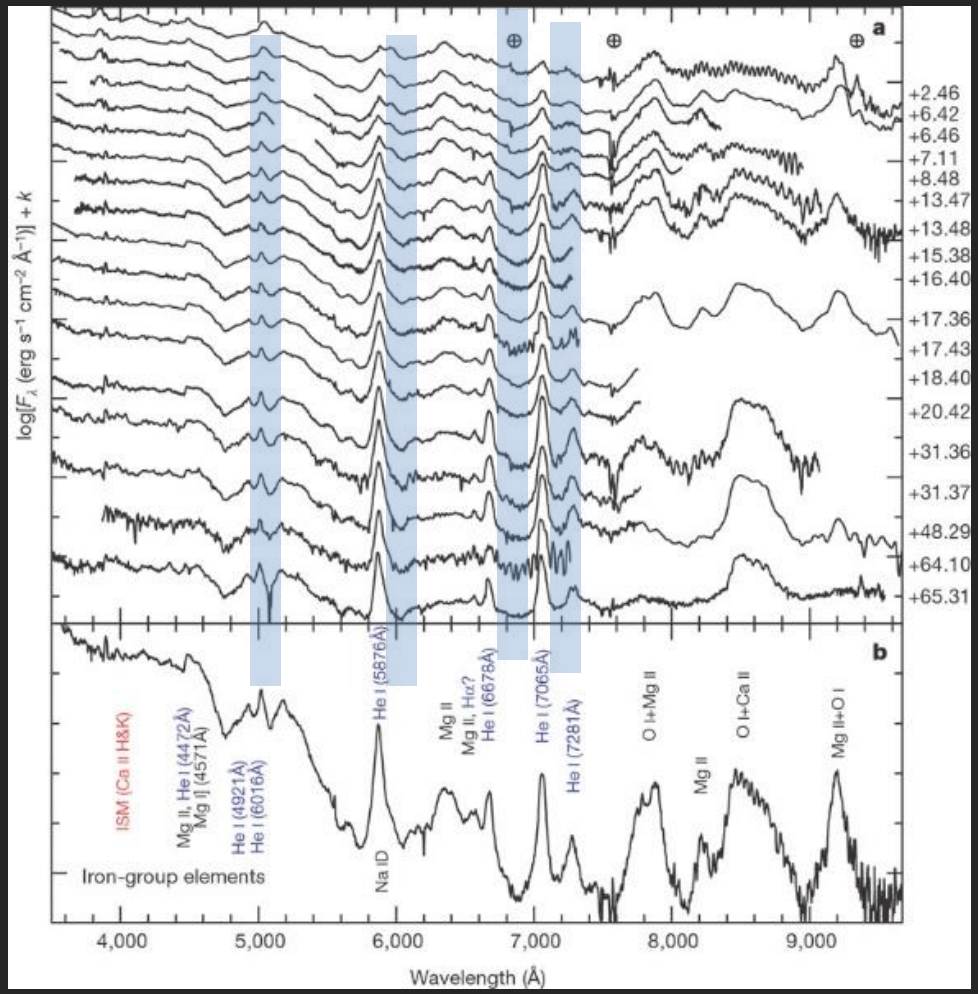

Ib→IIn (H)
SNe IIn (H)
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
O
Ne
C-shell
C
SN Ic (obs)
SESNe (expected)
SNe IIP (obs)
SNe II (expected)
IIb/IIL (H):
Binary (?)
mass-loss rate [Solar mass / yr]
1
10
100
time toward the SN [yr]

# Further diversity: H-poor CSM interaction

## SNe Ibn: SNe interacting with He-rich CSM



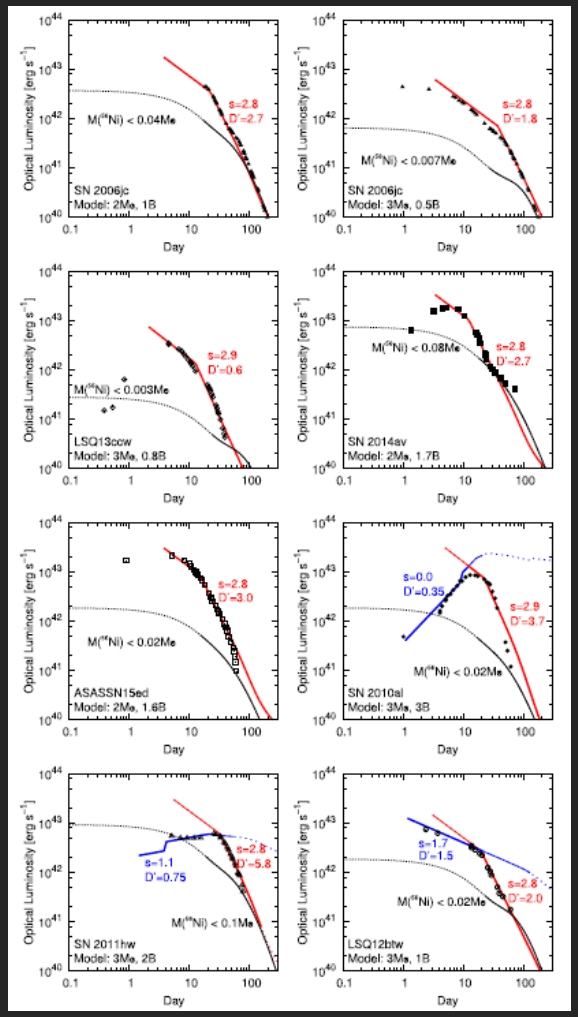

Pre-SN eruption (2 yrs ago).
He emission lines from the SN-CSM interaction.
No hydrogen.
Why different w/ canonical SNe Ib? Progenitor different?

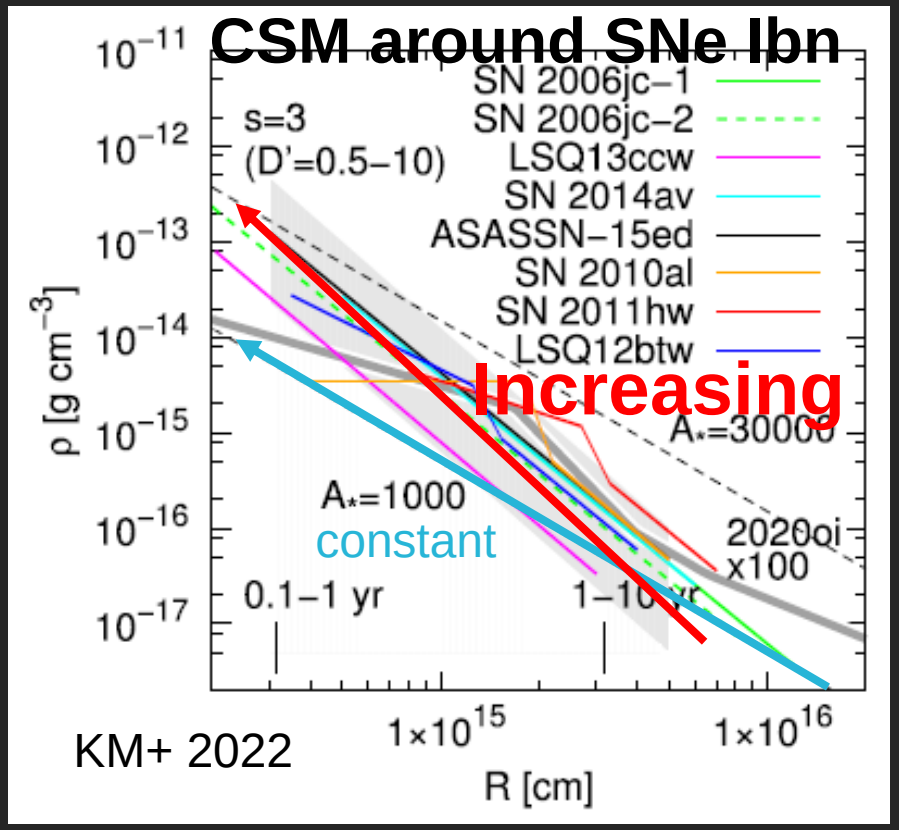



# New entries: SNe Ibn 2018jmt and 2019cj
Wang, Pastorello, KM+ 2024, submitted

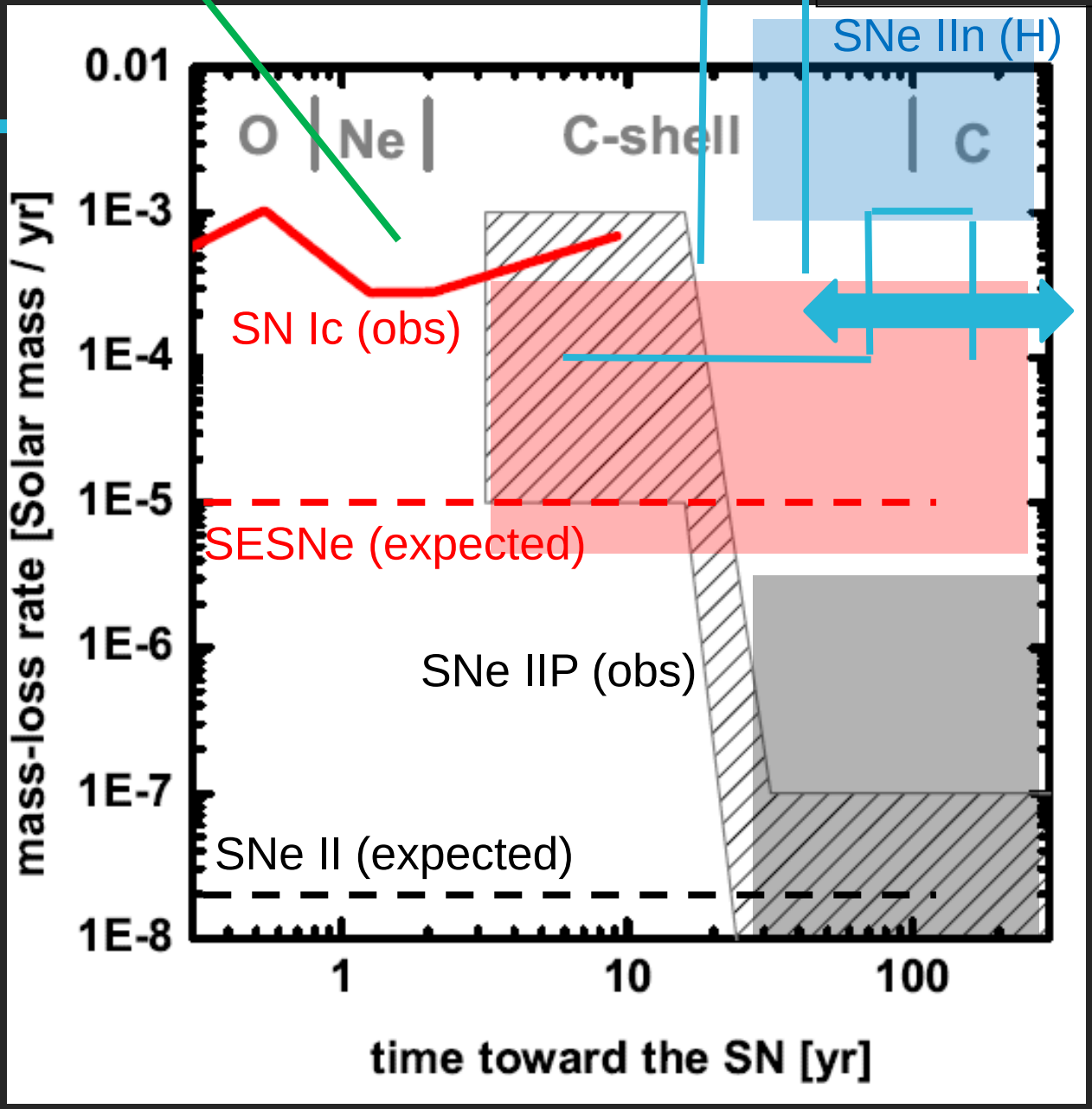
# Mass-loss history of SN Ibn progenitors

LC models (KM+Moriya 2022)




Mass-loss increasing in the final ~10 yrs.
Reaches to x1000 of canonical SNe Ib.
Something different than SNe Ib…
**Single massive star (Ibn) vs. binary (Ib)?**


Ibn (He-rich)
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SNe IIn (H)
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Ne
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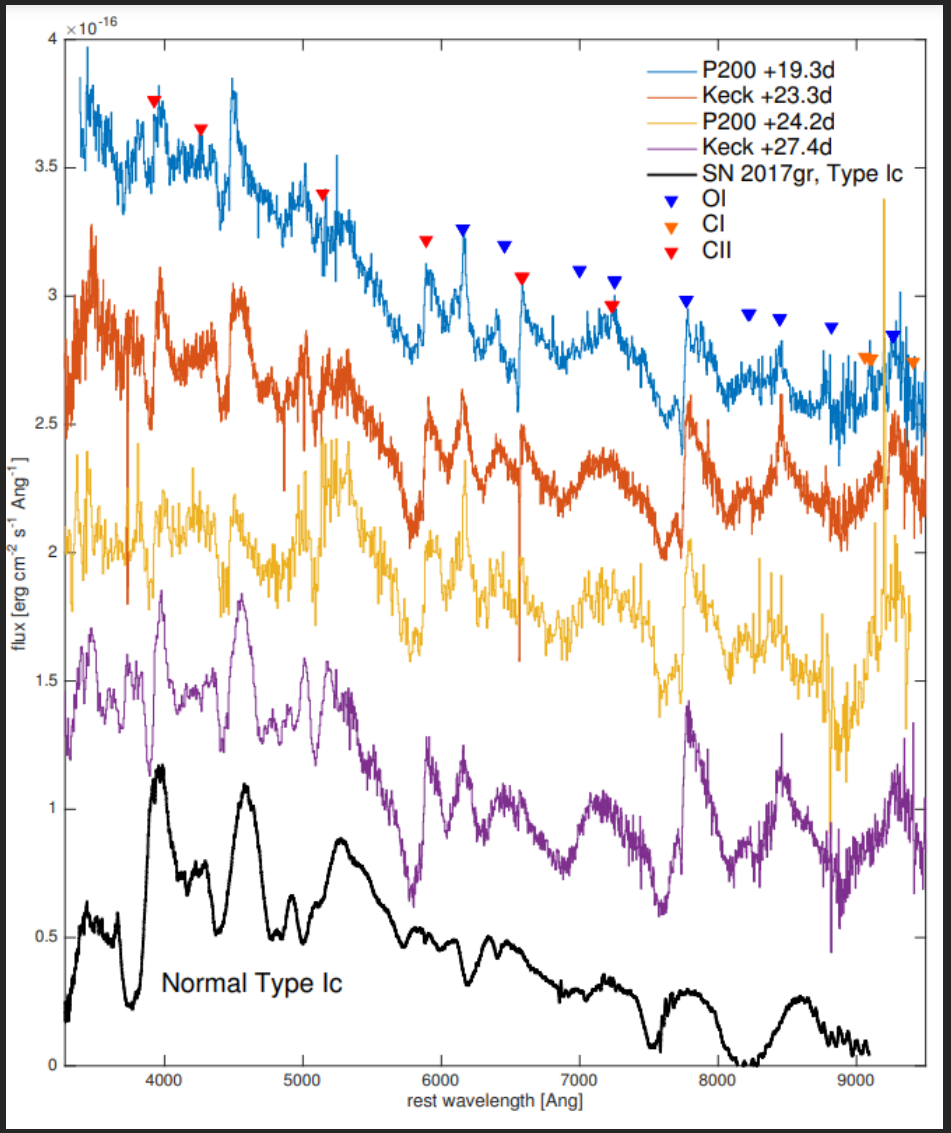
C
SN Ic (obs)
IIb/IIL (H):
Binary (?)
SESNe (expected)
SNe IIP (obs)
SNe II (expected)
mass-loss rate [Solar mass / yr]
1
10
100
time toward the SN [yr]

# SNe Icn: SNe interacting with C+O-rich CSM

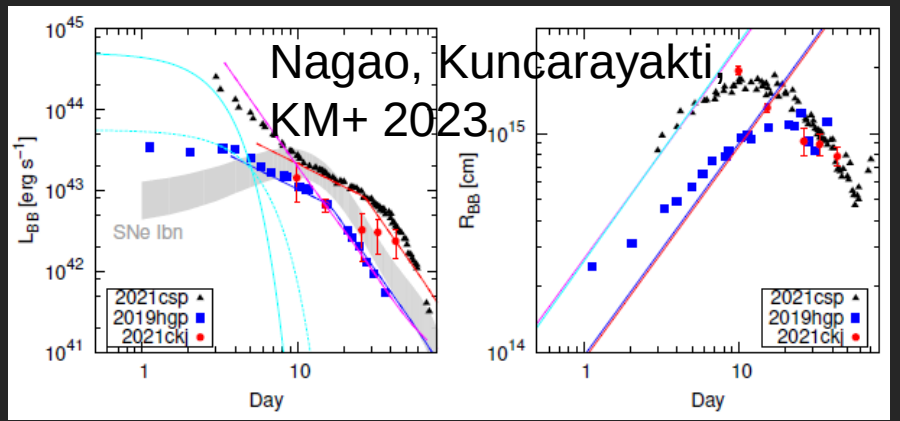


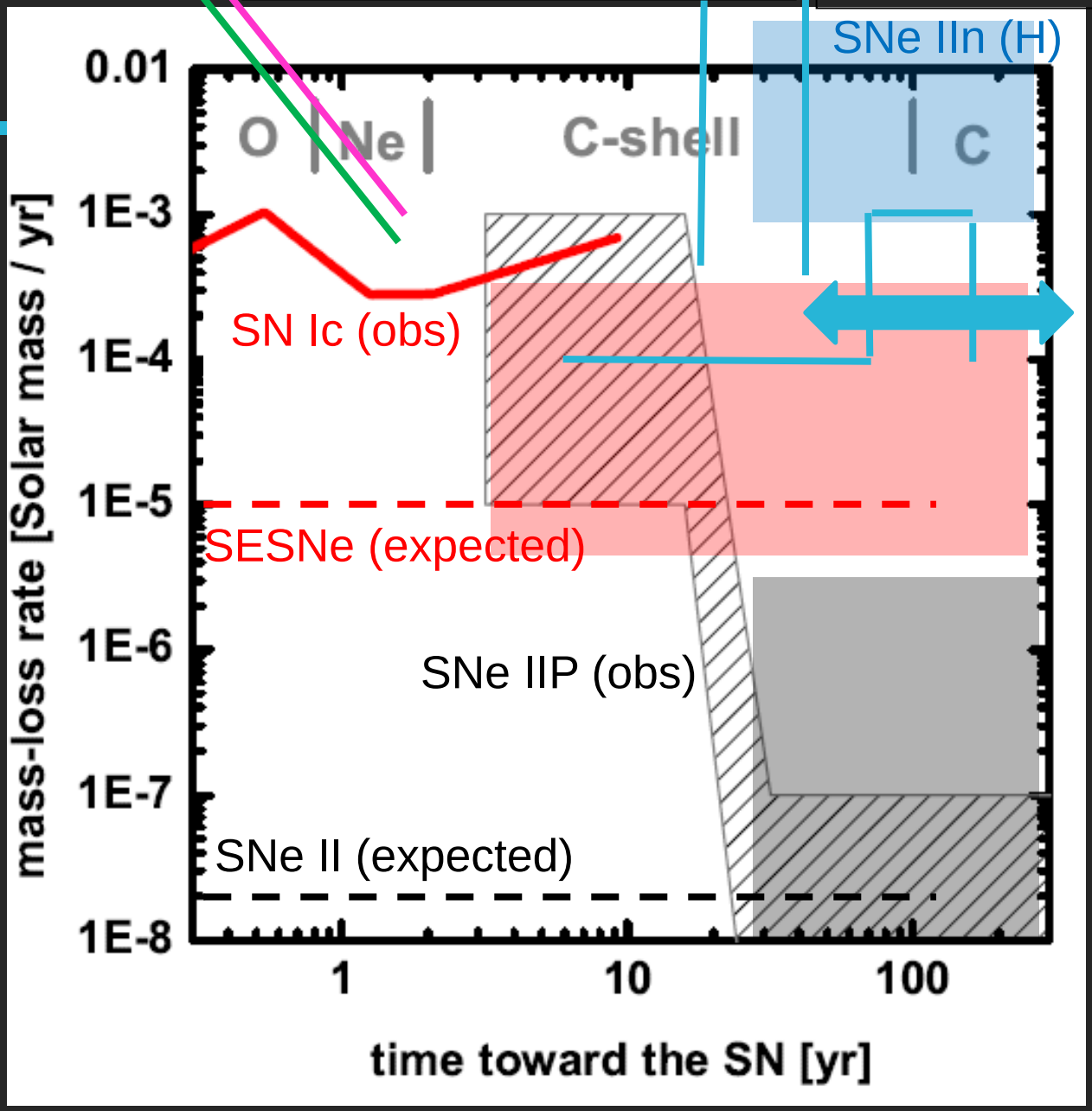

Gal-Yam et al. 2022, Nature

SN “Icn” 2019hgp

C+O emission lines originated in the CSM.
~ 5 examples so far.

C+O-rich dense CSM at the vicinity of the exploding star.




Ibn (He-rich)
Icn (C-rich)
Ib→IIn (H)
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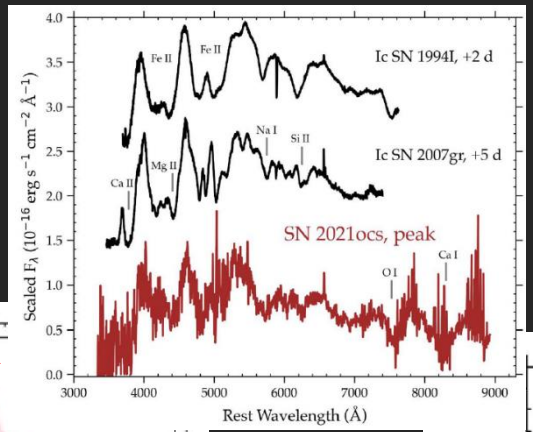
.O-rich & detached CSM

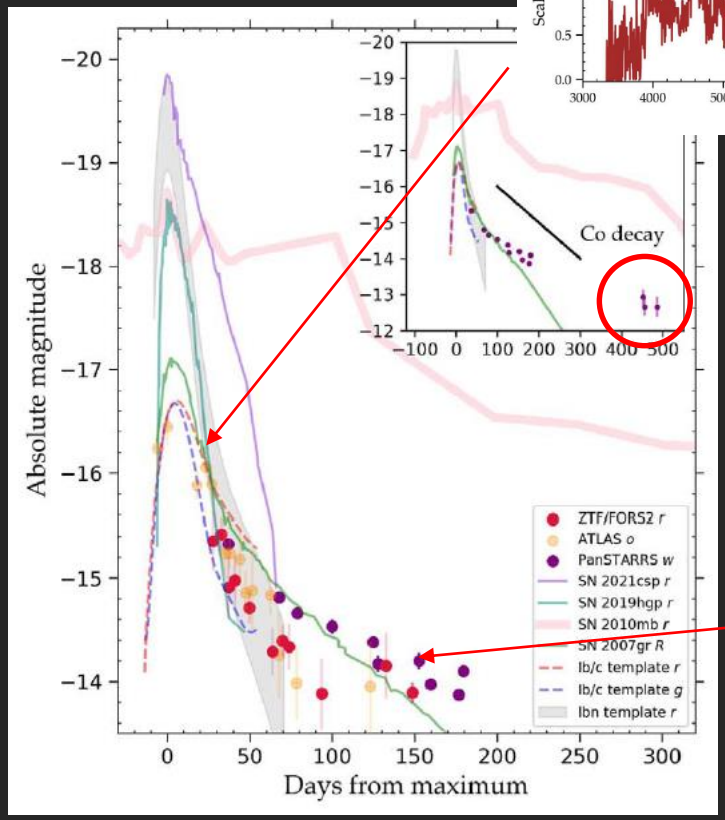
# Another C+O (even O+Mg)-rich CSM population

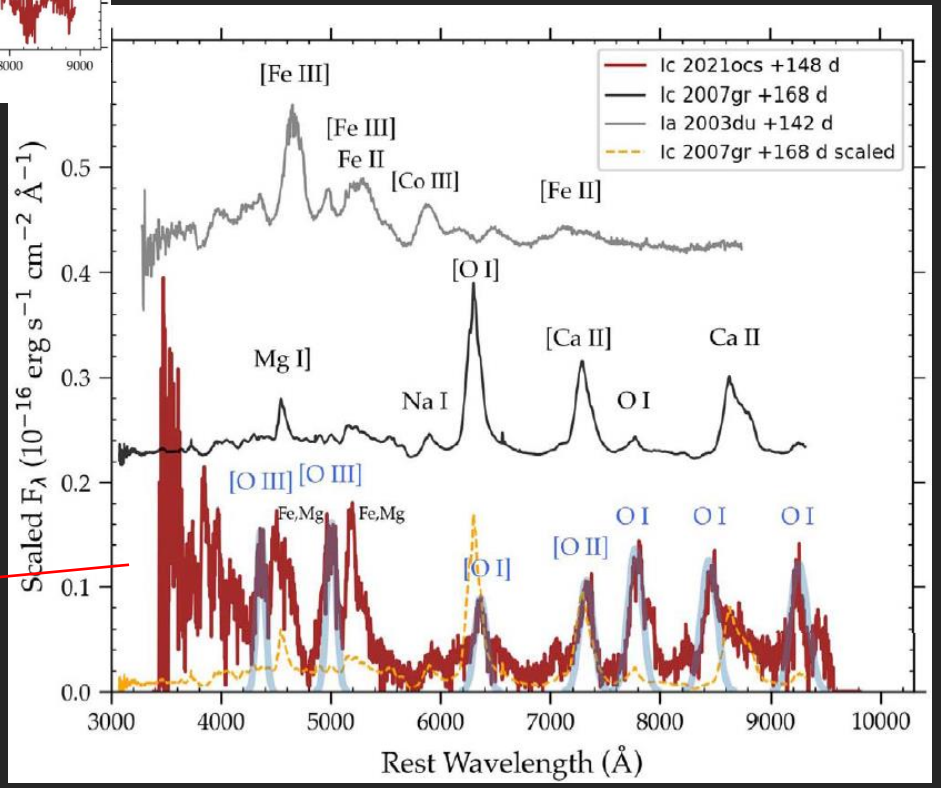



"Ic-CSM" 2021ocs

Canonical SN Ic

→ relatively narrow emission lines of O and Mg



.O-rich & detached CSM

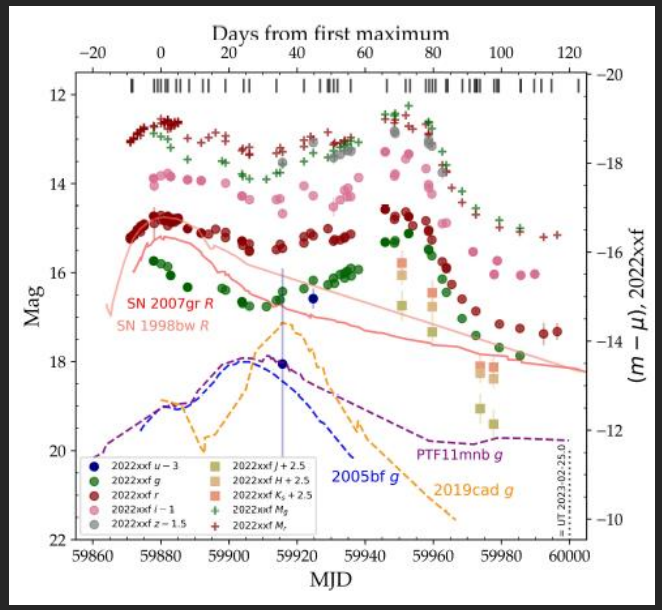
# Another C+O (even O+Mg)-rich CSM population

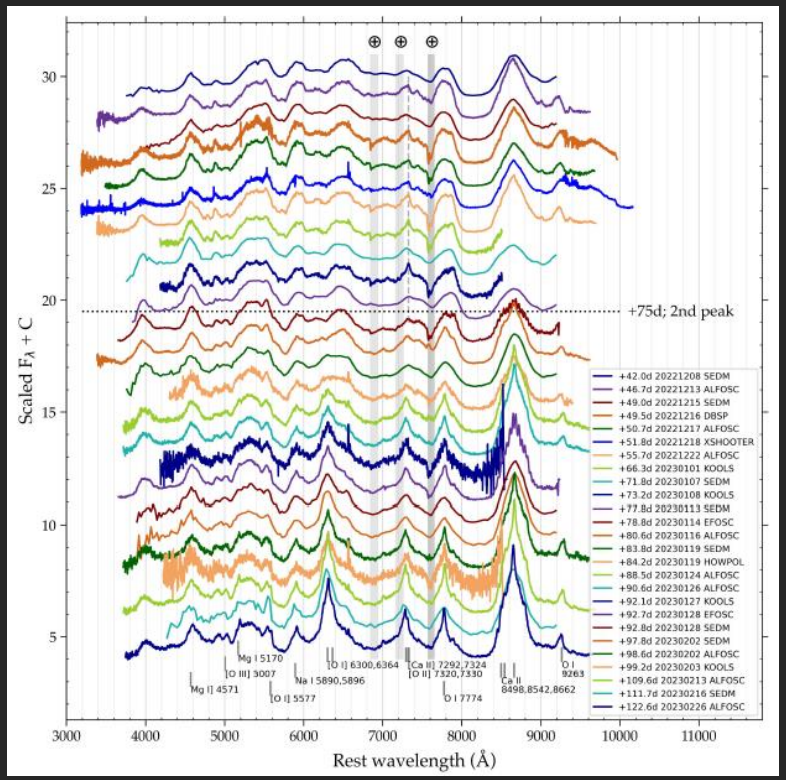
"Broad-lined Ic-CSM" 2022xxf

Double-peaked LCs (very rare).

Broad lined-SN Ic (energetic Ic, a link to GRBs)

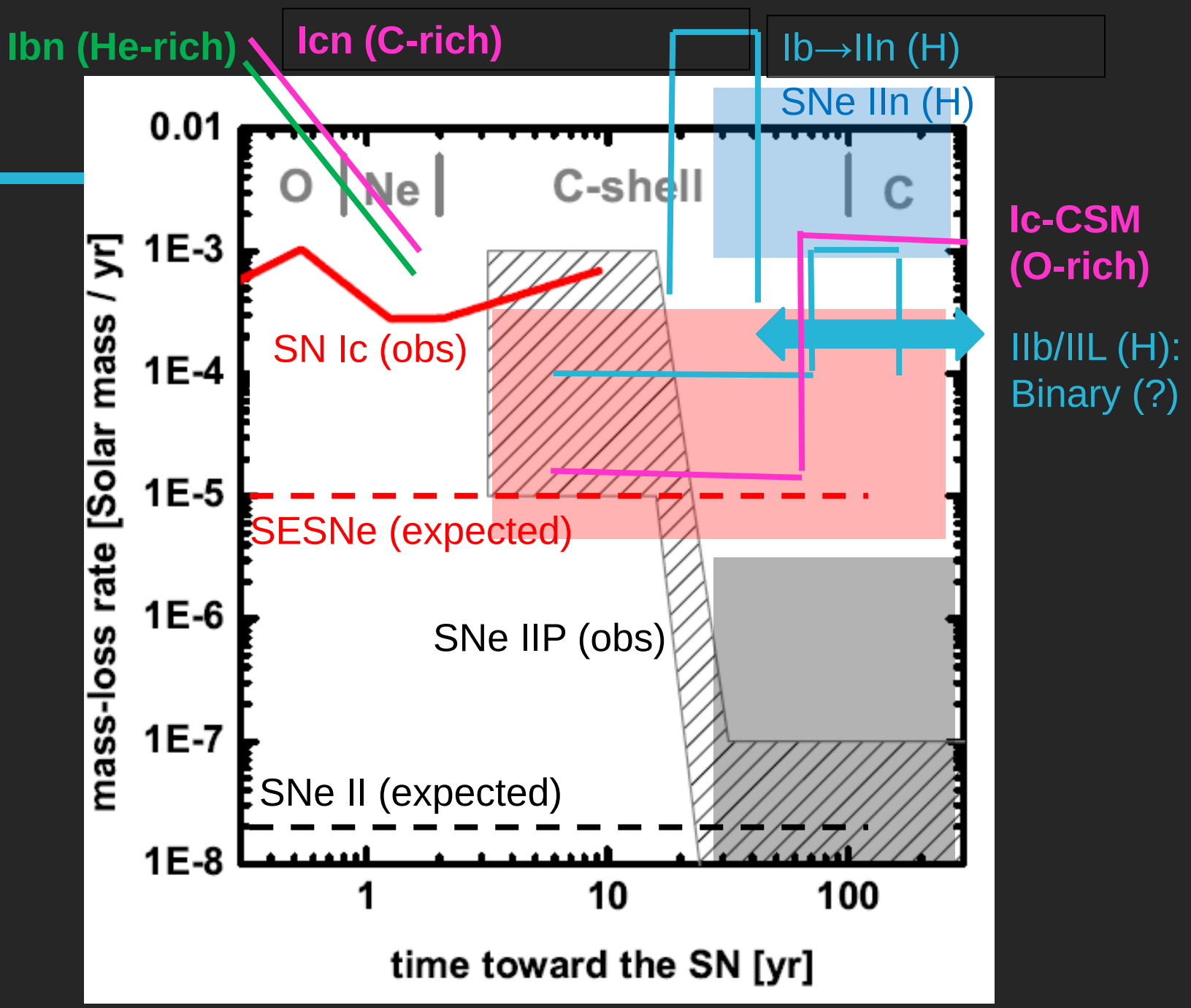
→ relatively narrow (a few 1000km/s) emission lines of O and Mg.




(To my knowledge)

No "Ib" counterpart (no Ib-CSM)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Ib→IIn (H)
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mass-loss rate [Solar mass / yr]
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time toward the SN [yr]

# Summary

- Transient science **rapidly expanding**.
  - Key = **rapid follow-up + multi-wavelengths**.
  - Need global collaboration.

- One key science: **Final** evolution of stars
  - **Frontier** in stellar physics
- Increasing samples do **not** look like "what we assumed".
  - **Final activity (single or binary?).**
  - **binary interaction (stable vs. unstable).**
  - **At different phases.**
  - **Various channels?**
- **Need**: observations, emission models, evolution models.