Unraveling progenitors of supernovae via multiwavelength observations

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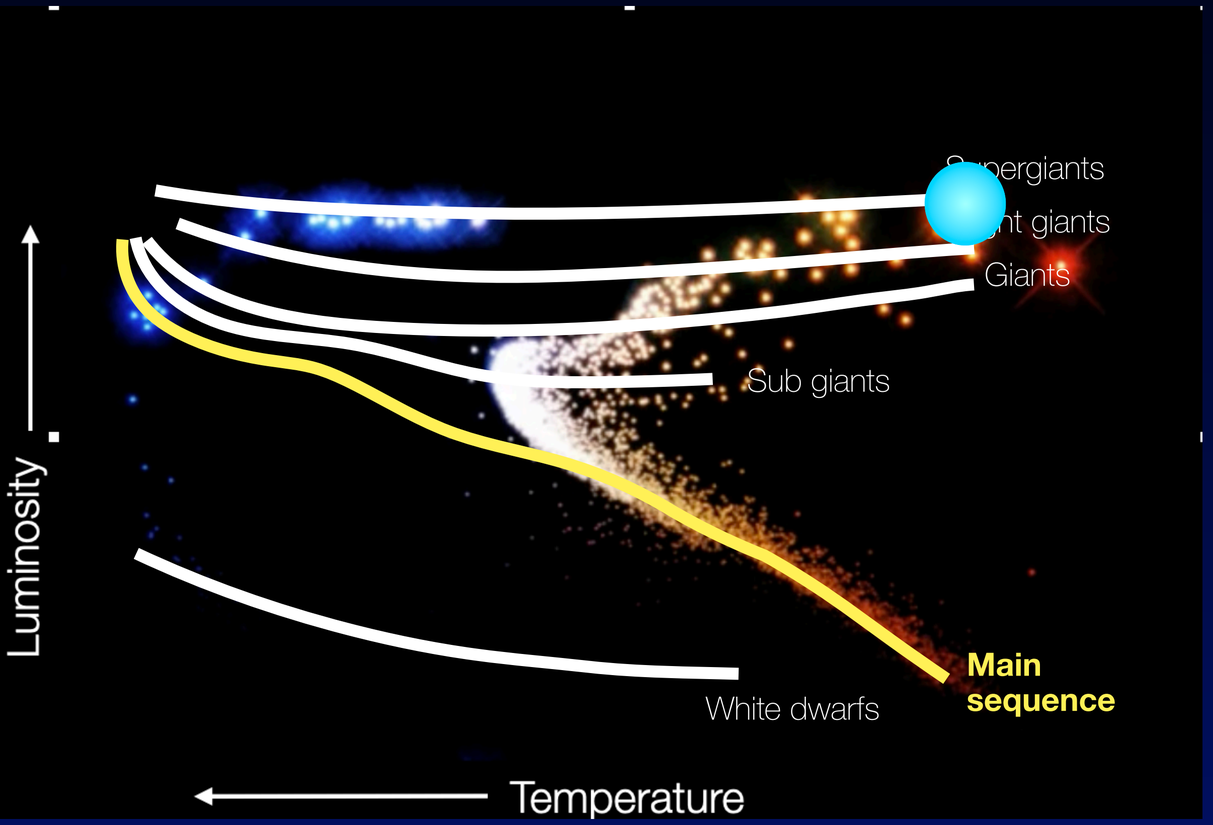
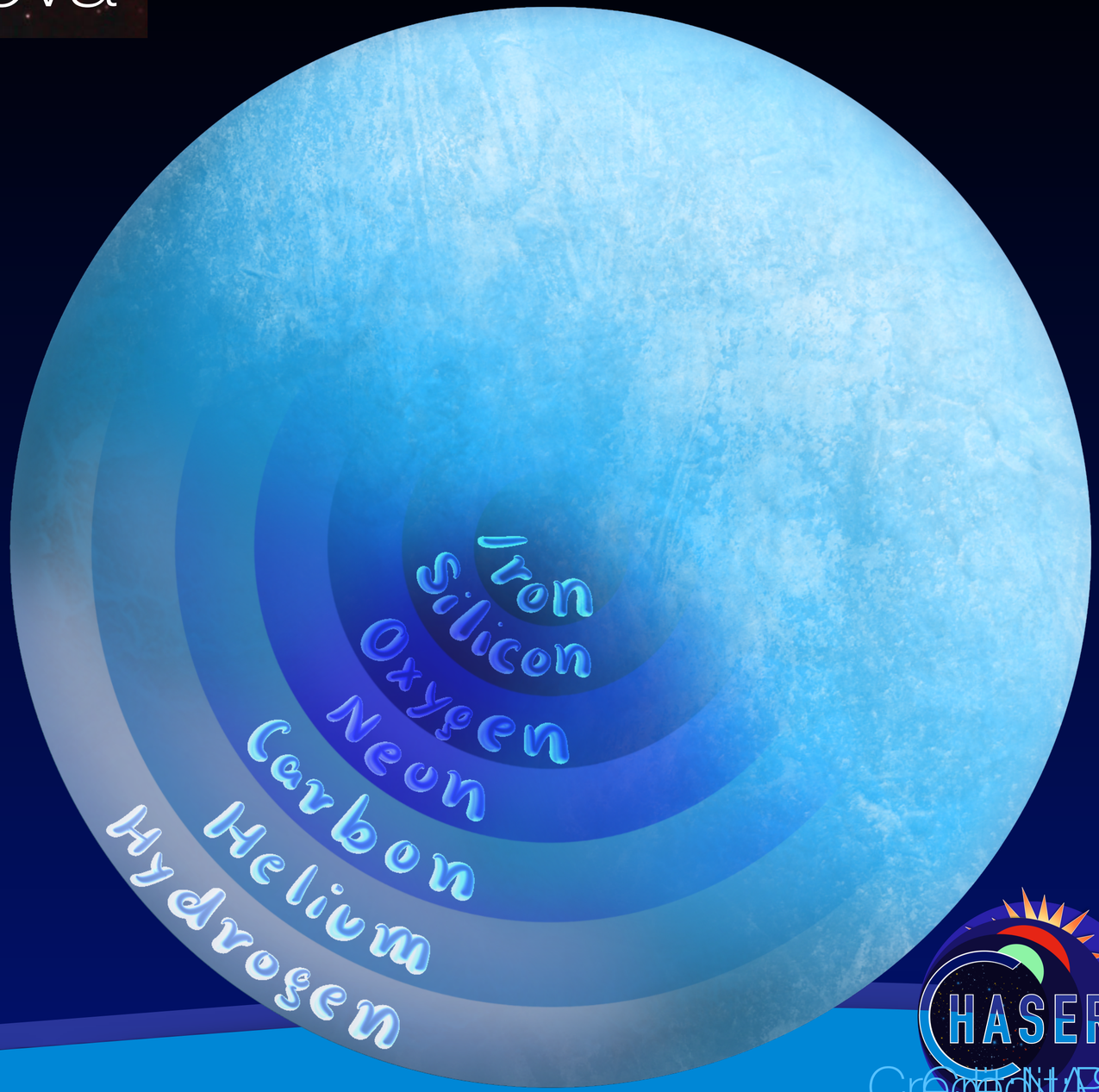
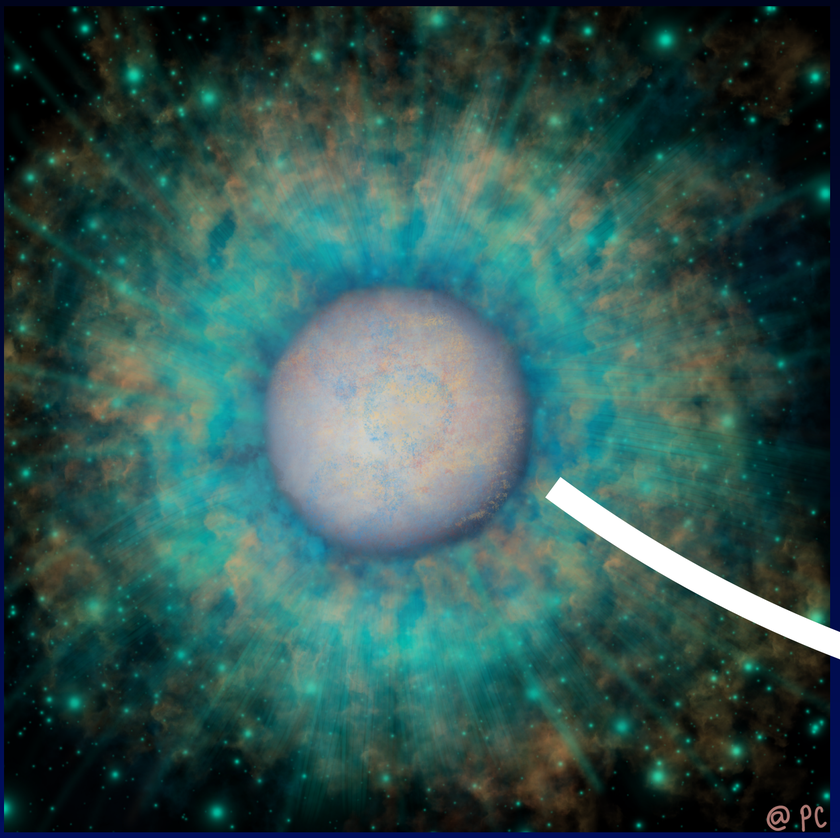
Stellar Explosion - Supernova



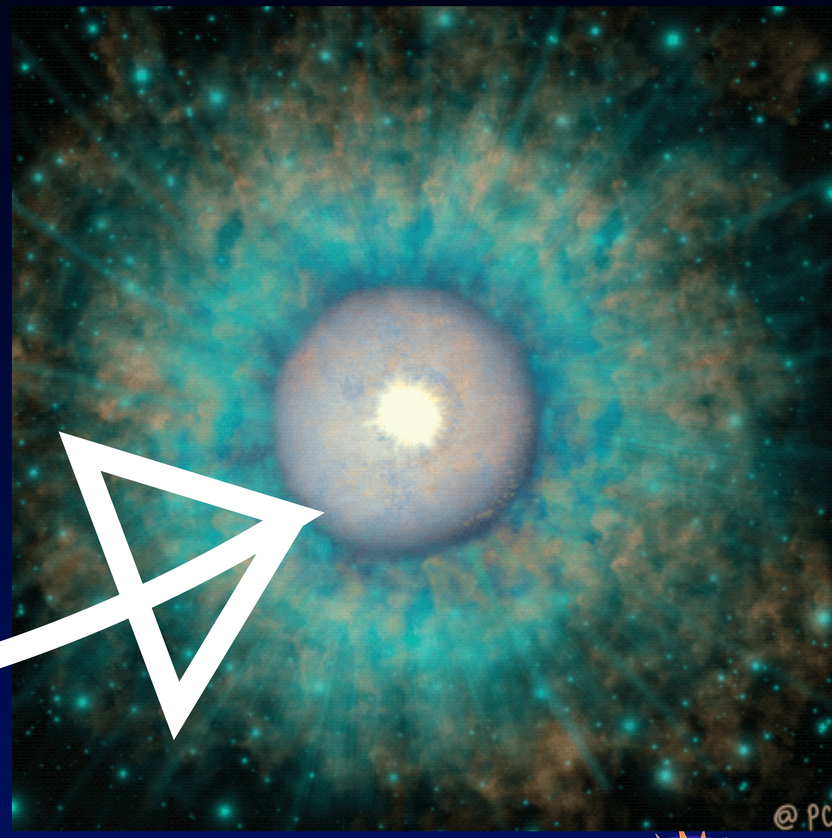


Credit: ASA

Journey between massive star to their explosions



Credit: PC



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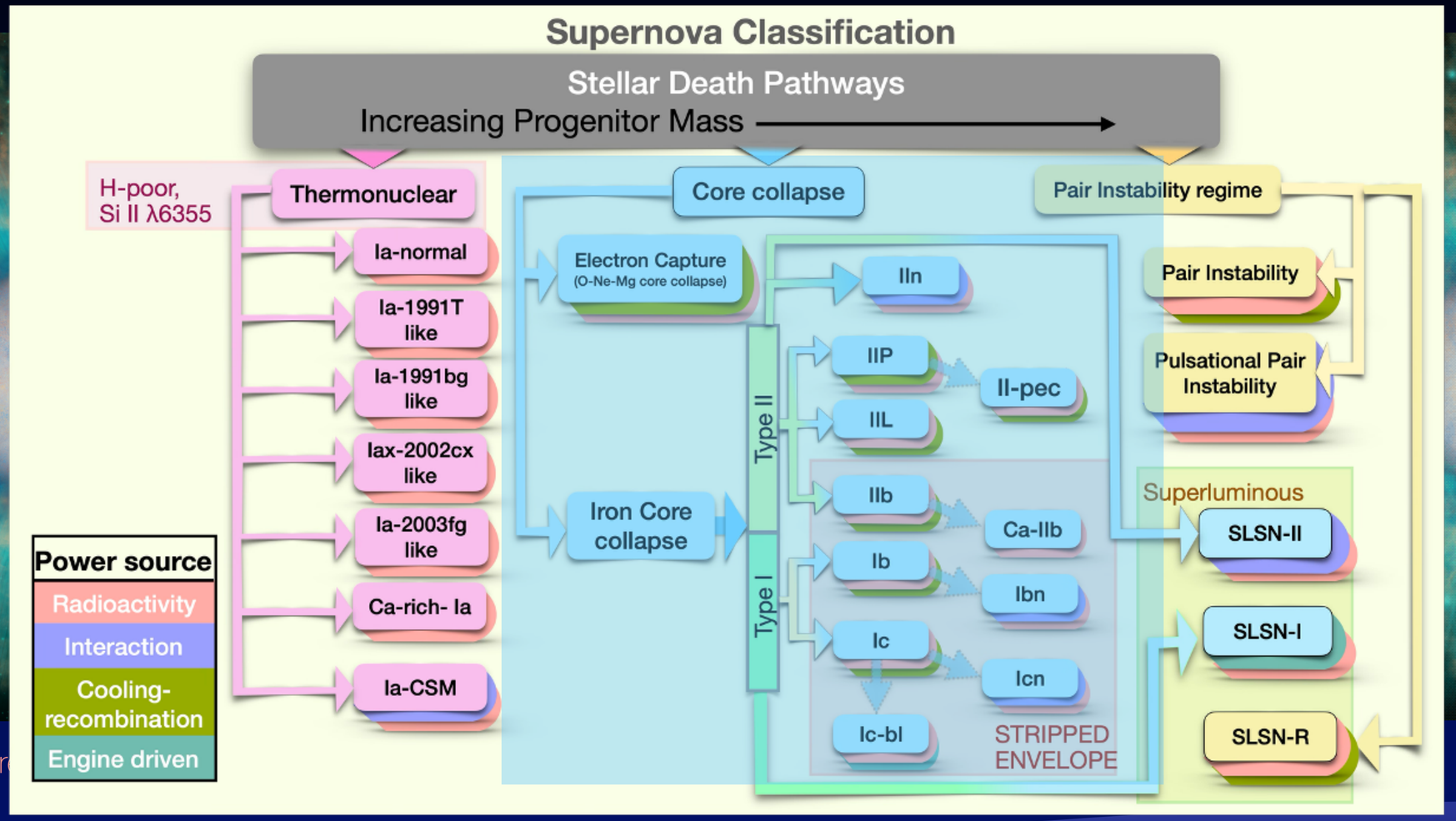

Credit: PC

Journey between massive star to their explosions

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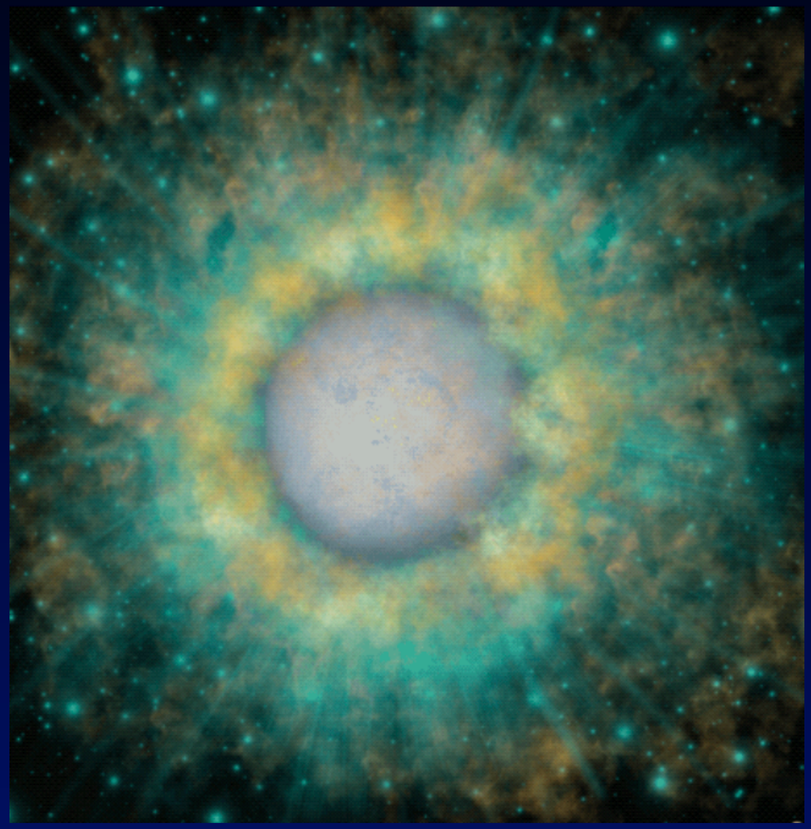
Mass-loss



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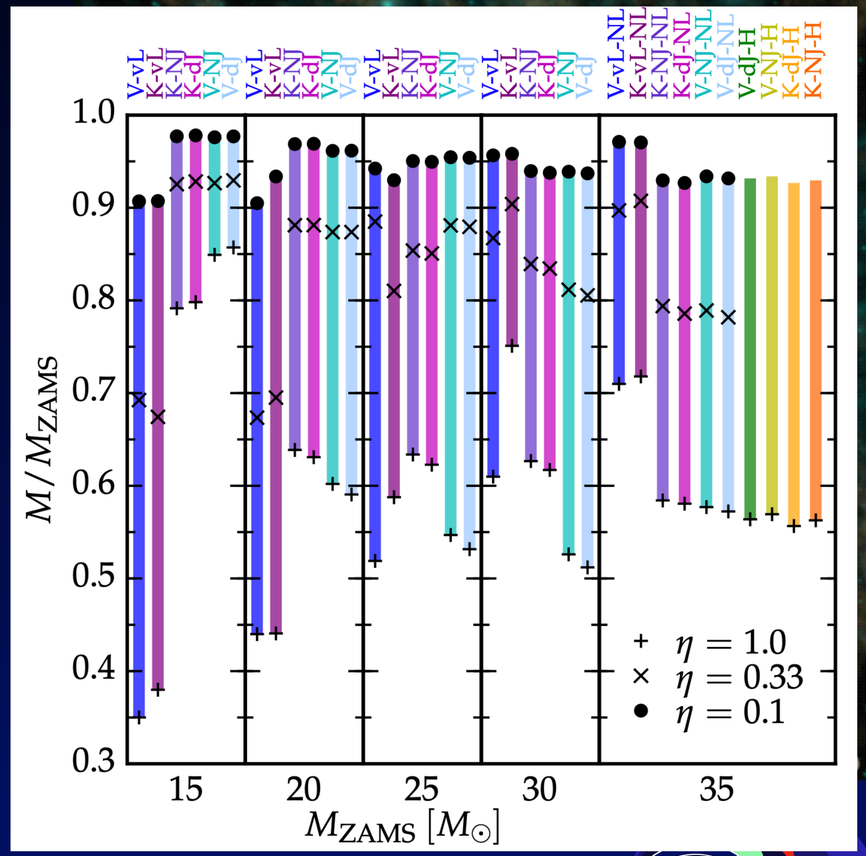
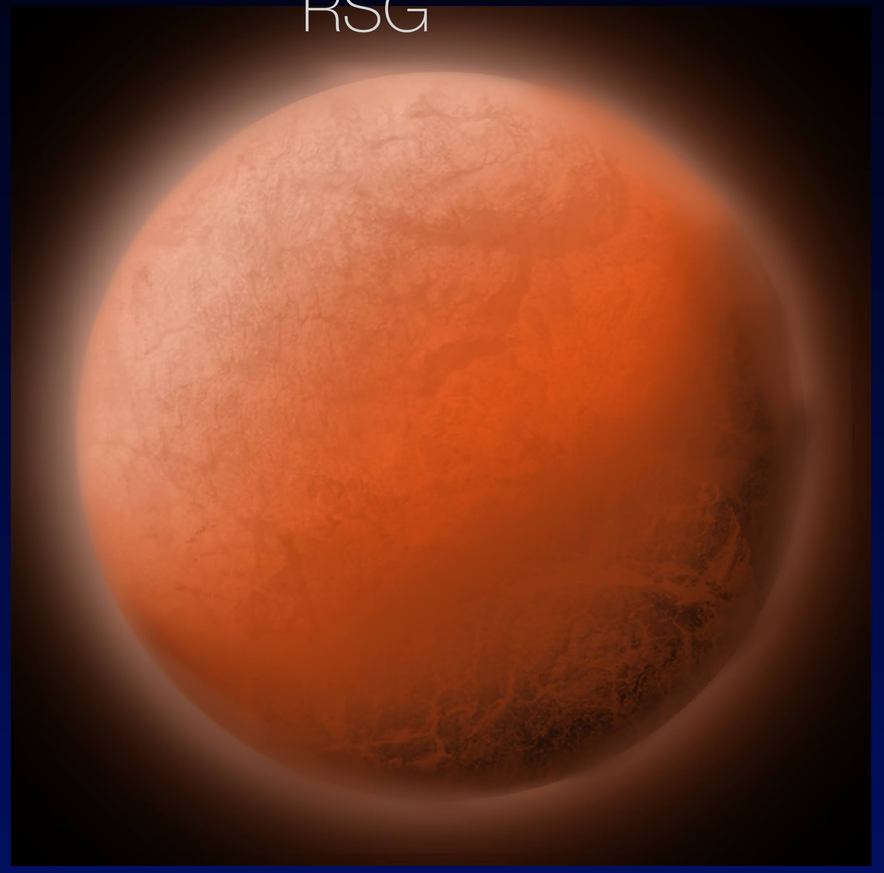
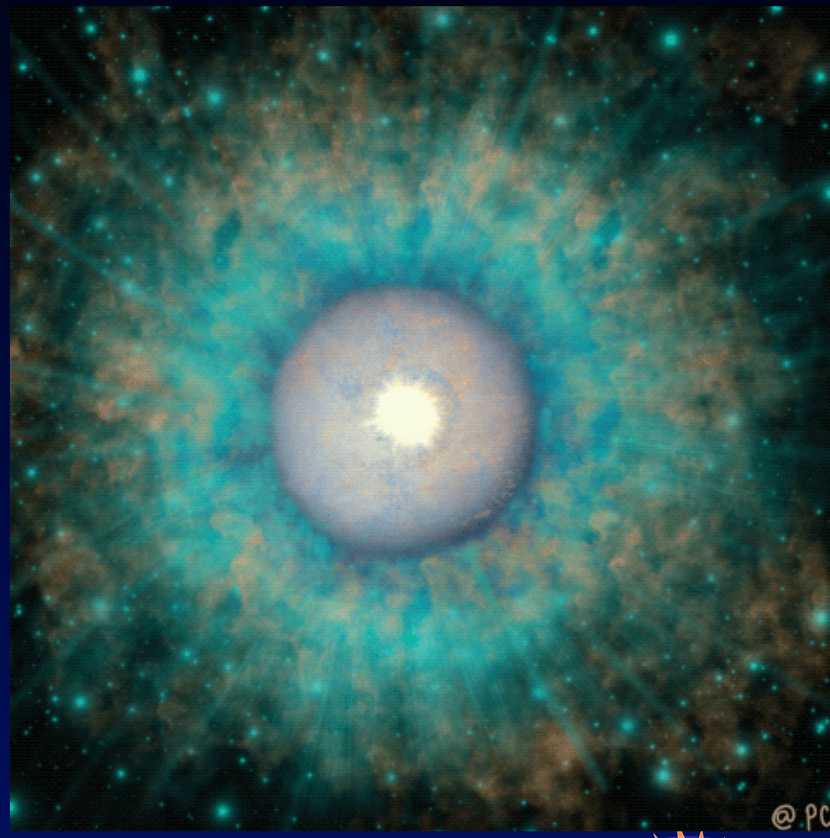
Zapartas+2021



Journey between massive star to their explosions

RSG





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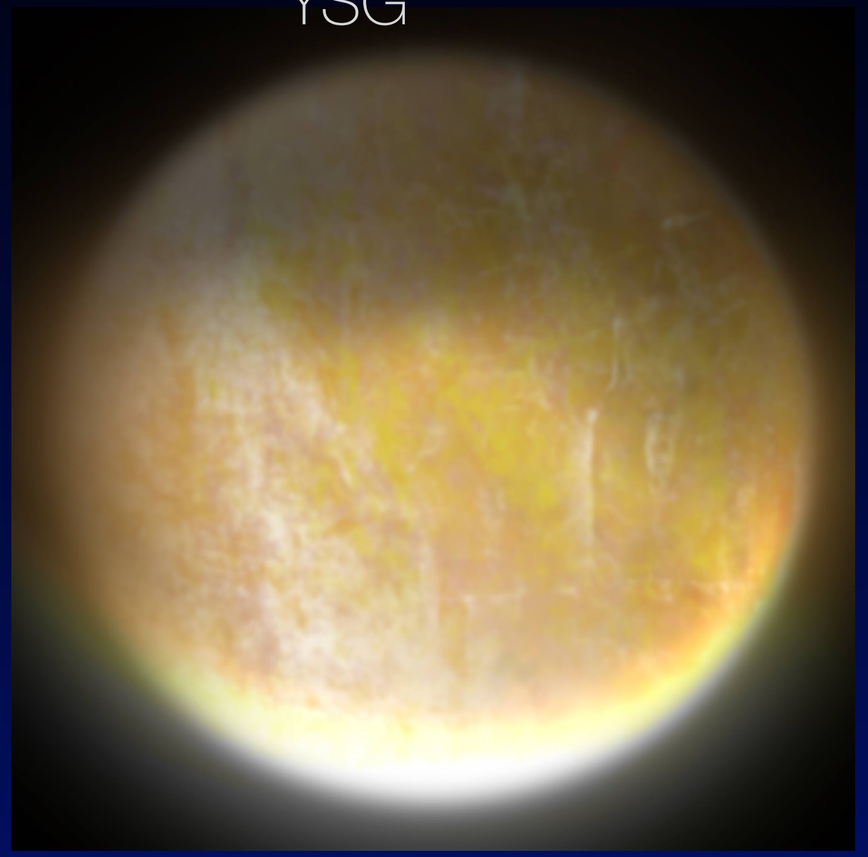
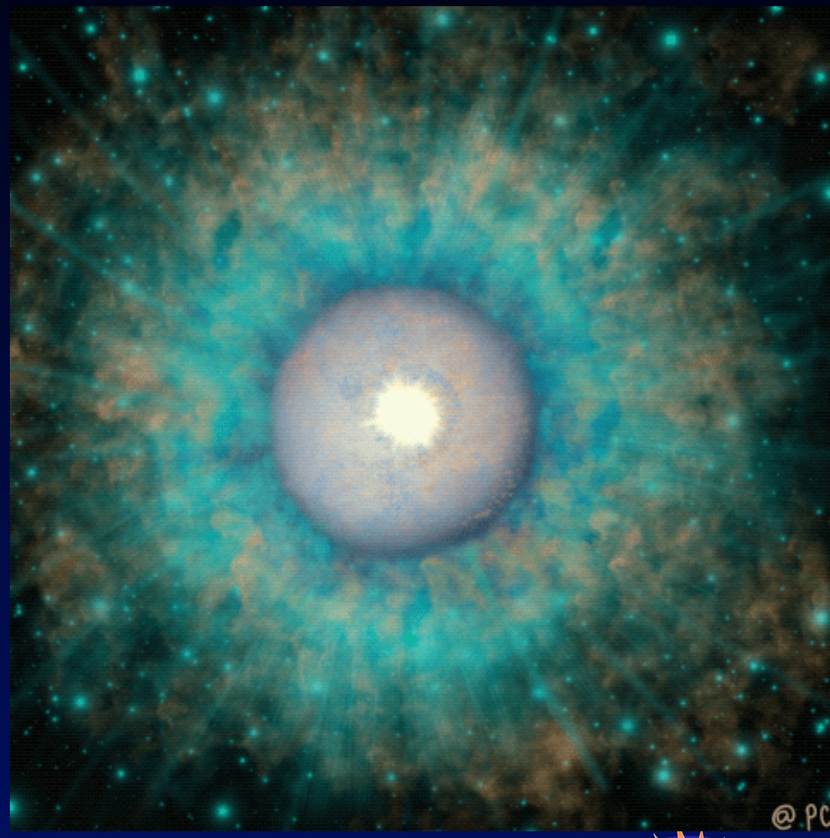
Journey between massive star to their explosions

YSG





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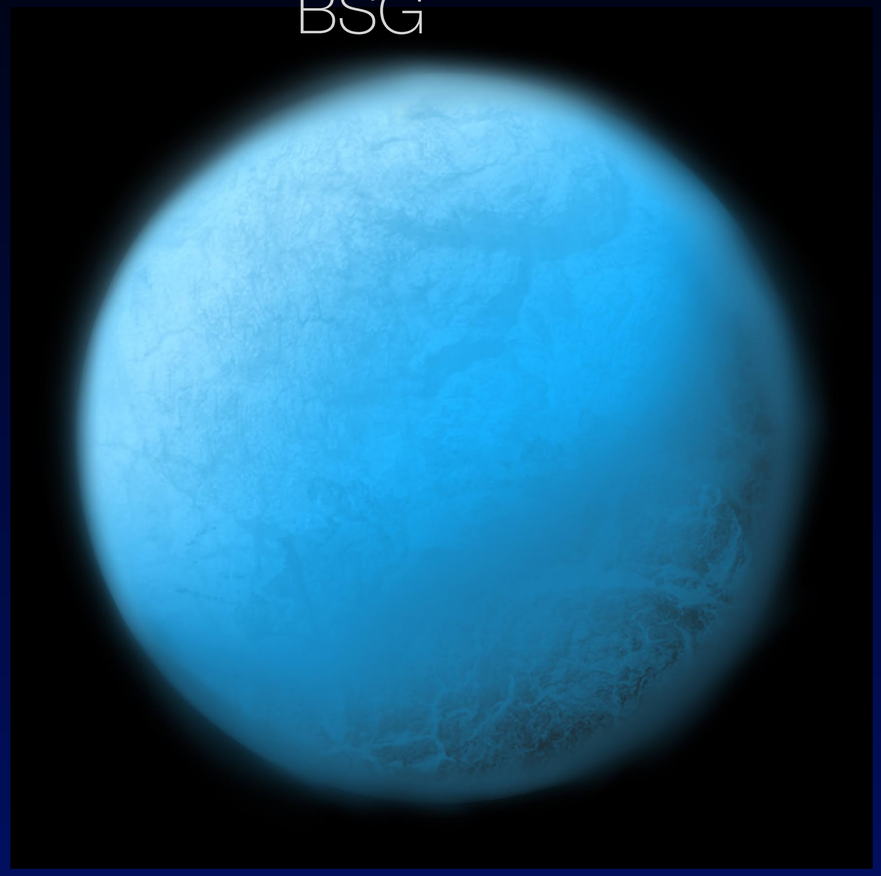
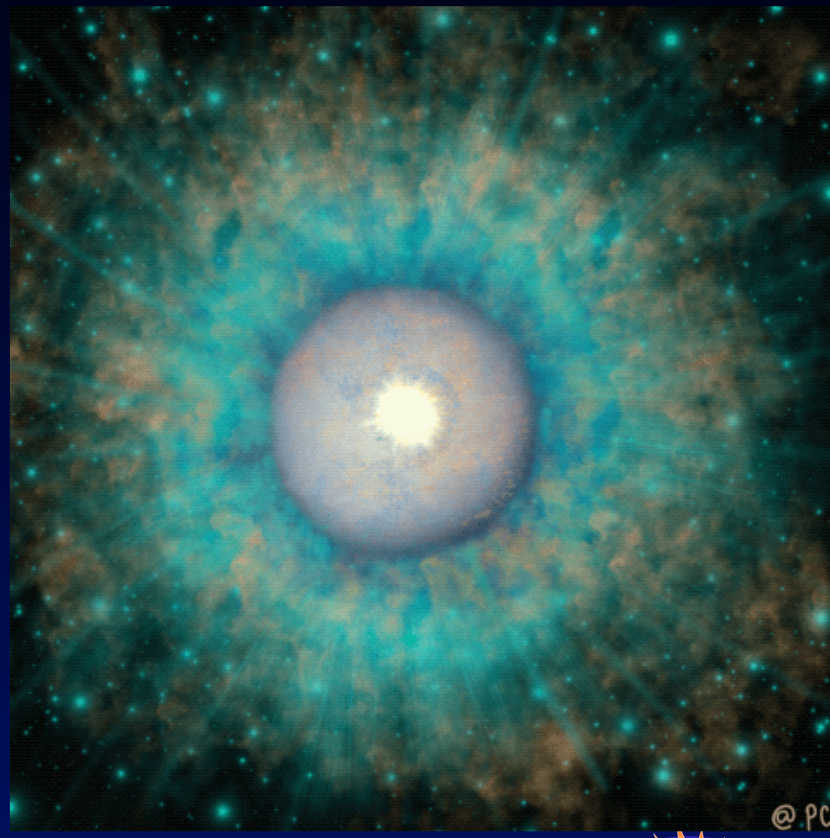
Journey between massive star to their explosions

BSG





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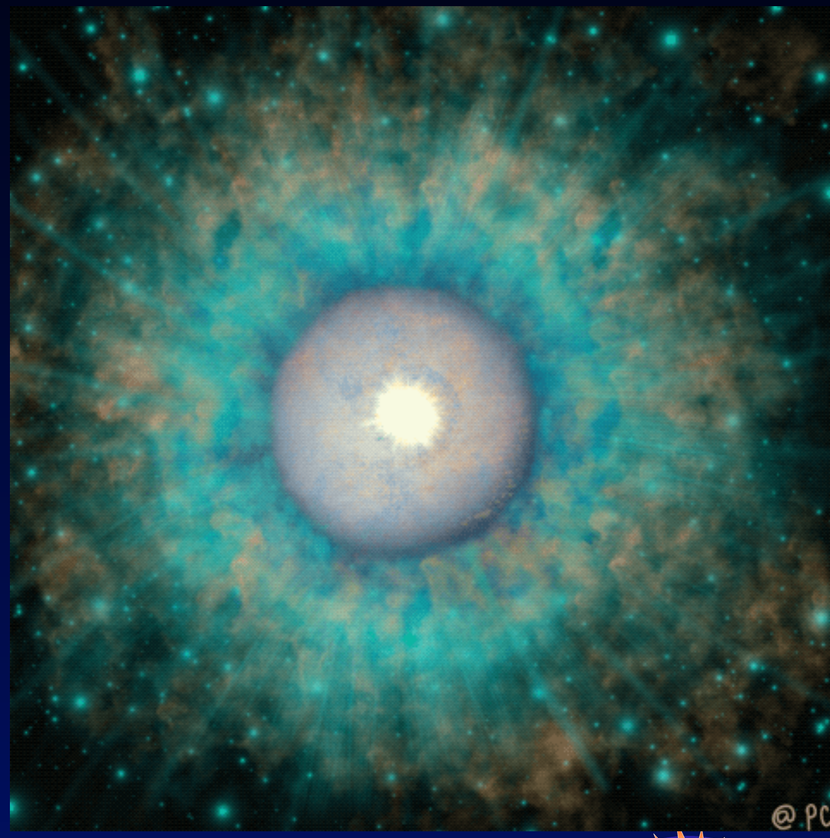
Journey between massive star to their explosions

Binary

Credit: PC

Credit: K. Maeda, ALMA

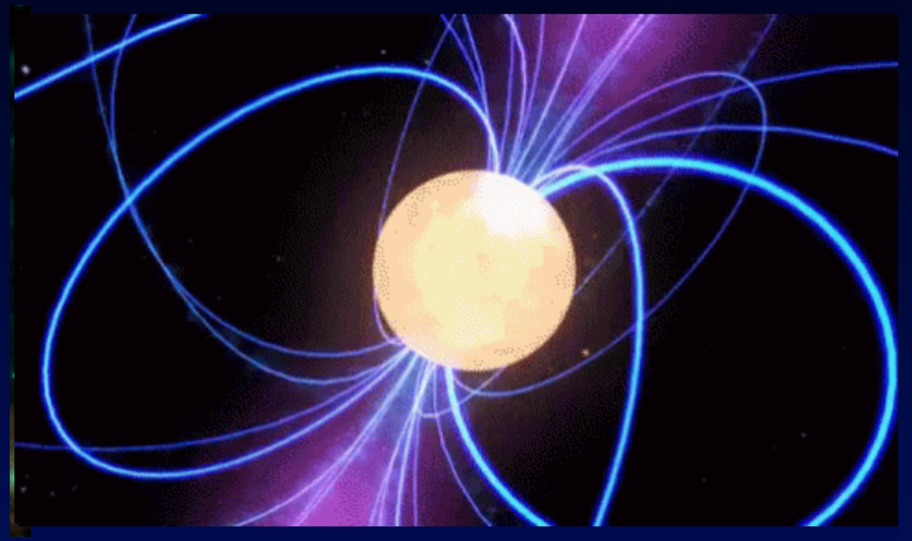


Credit: PC

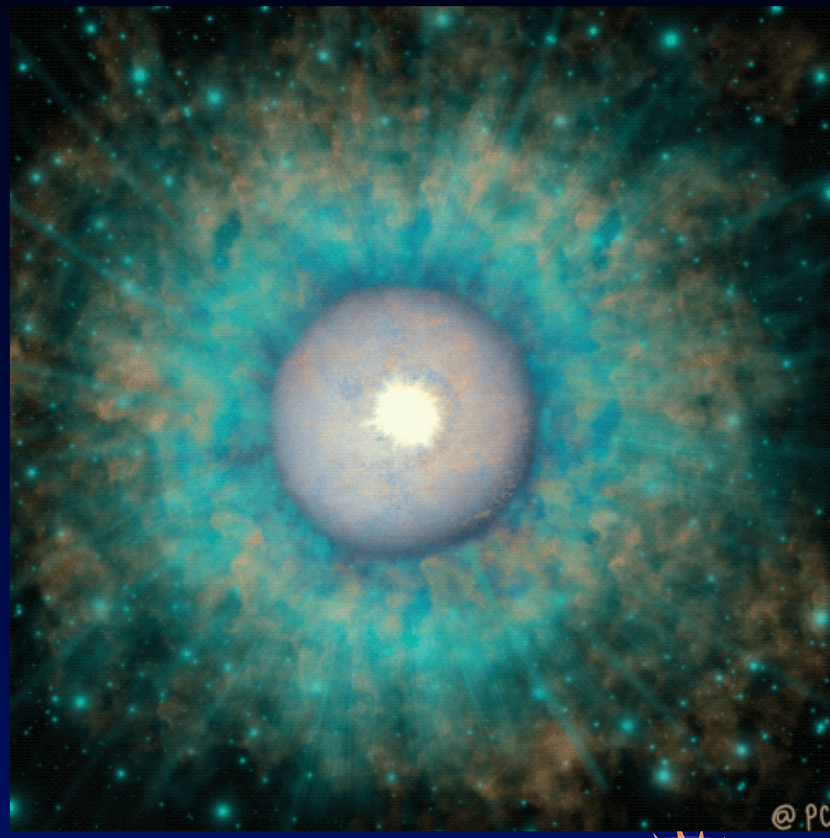
Journey between massive star to their explosions

Magnetism

Credit: PC



Credit: Wiki



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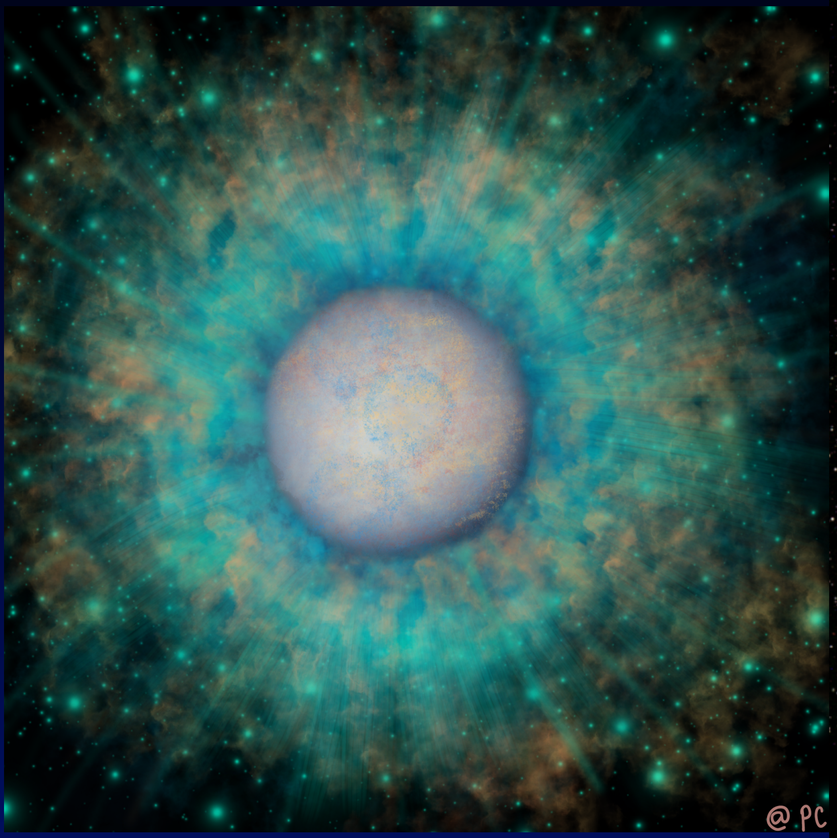

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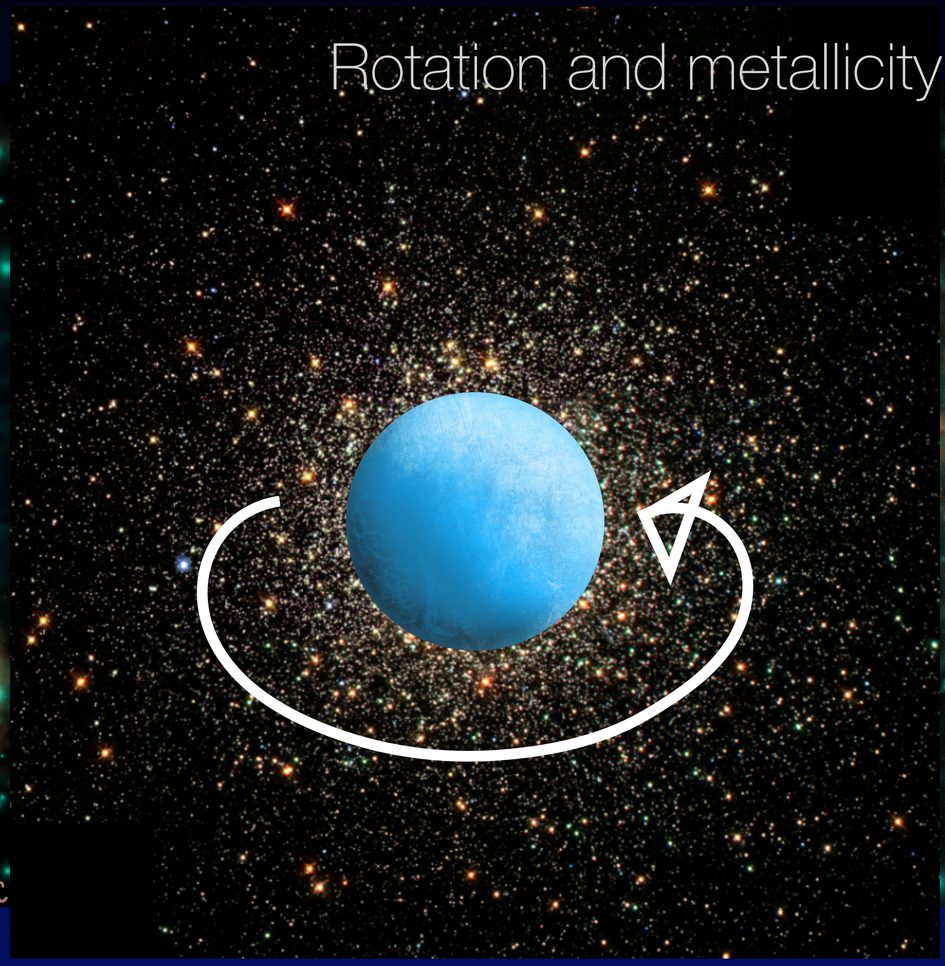
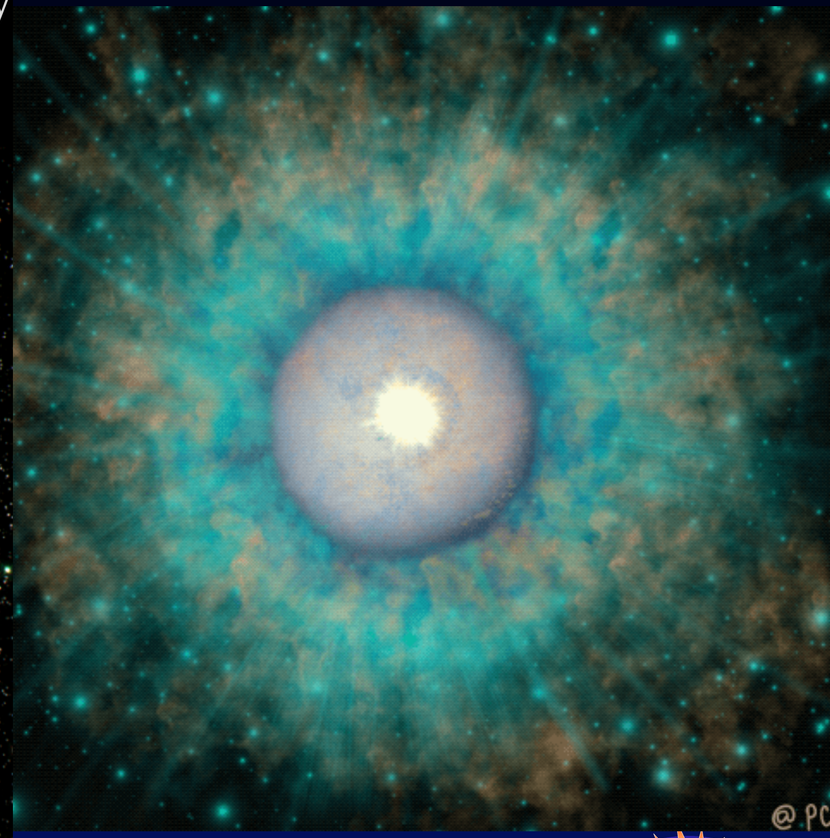
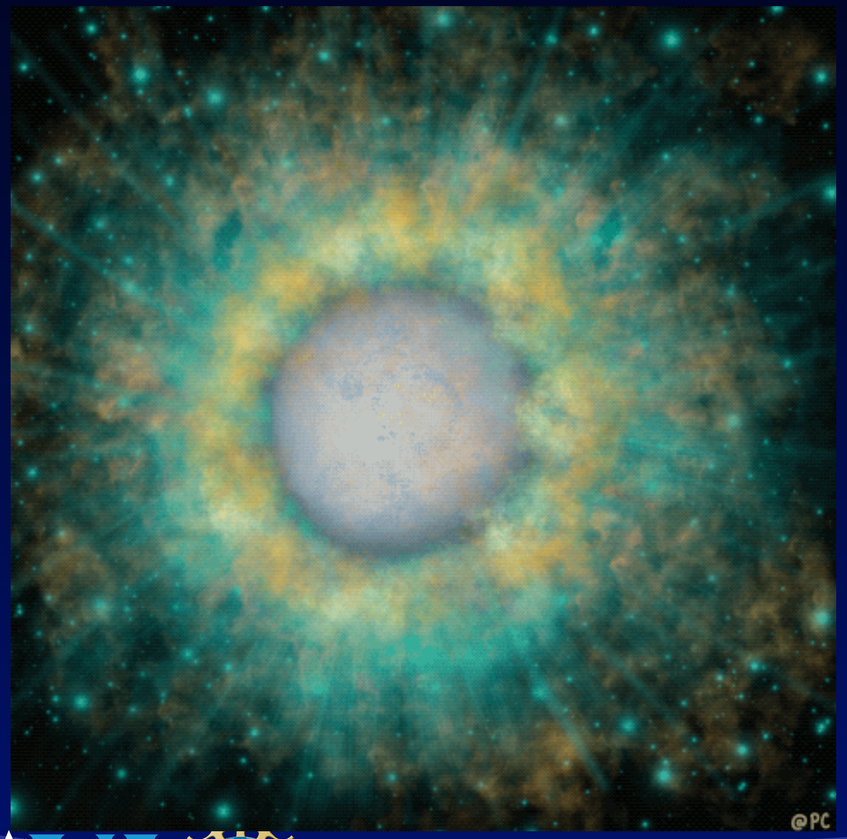
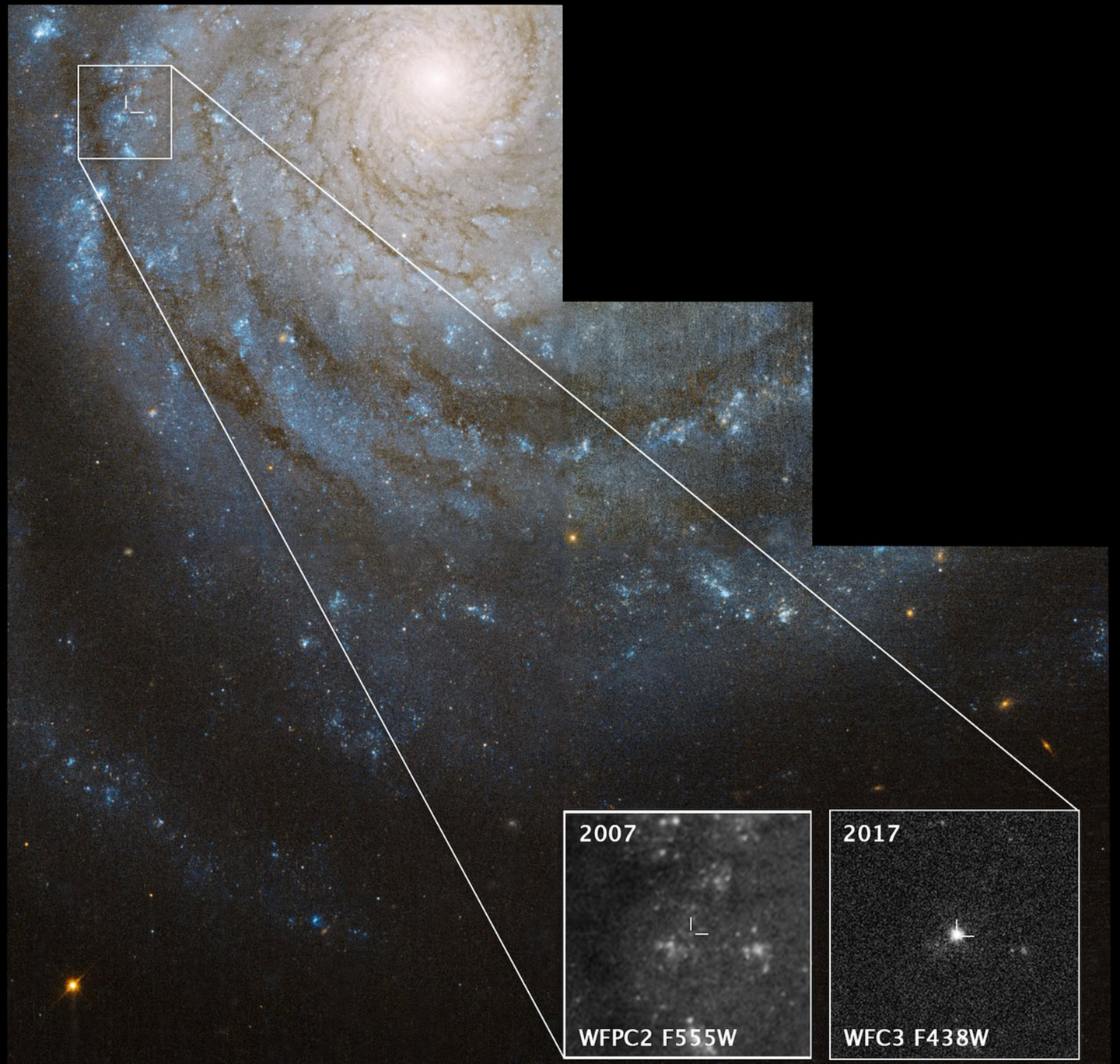




Credit: PC

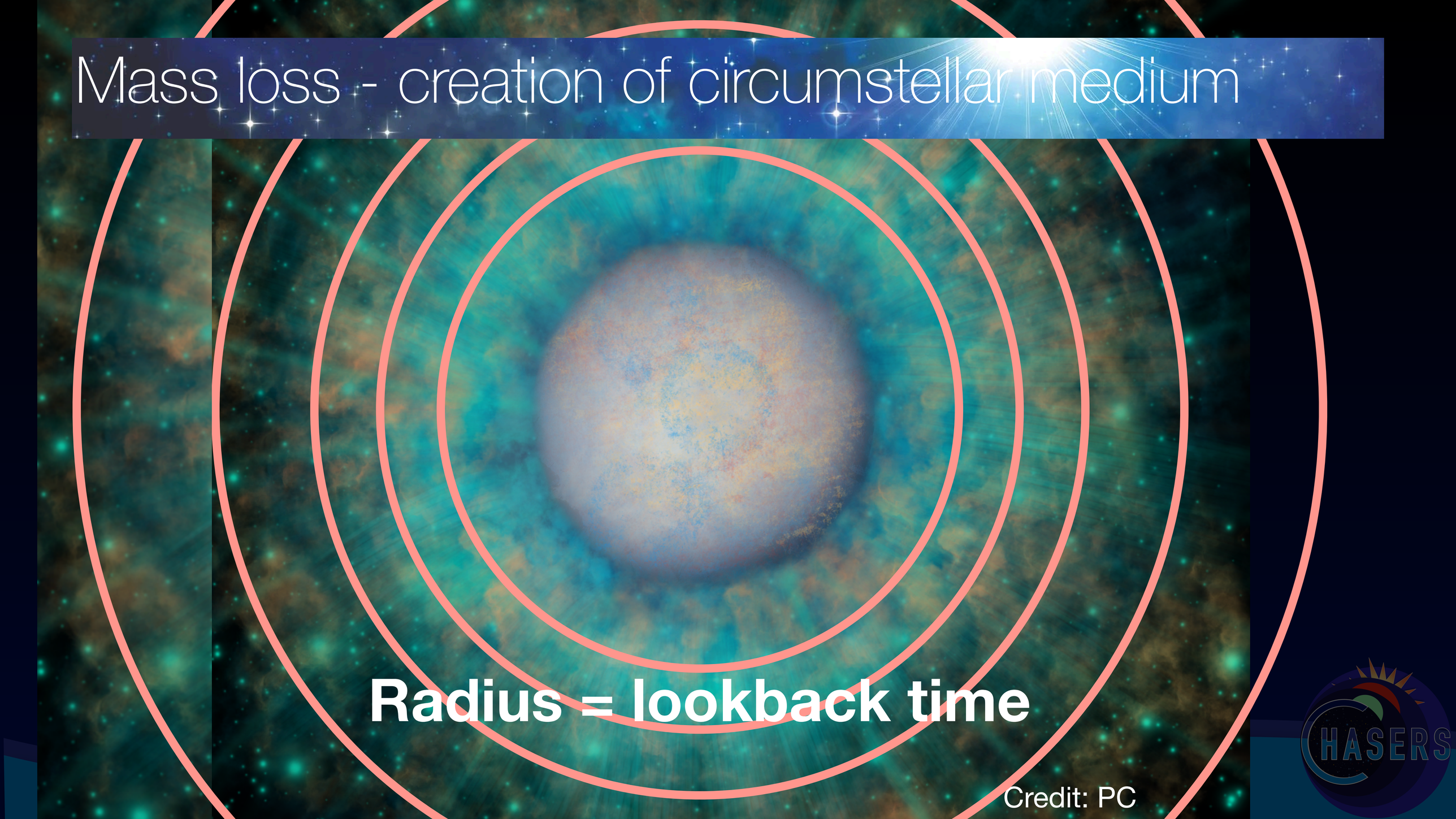
- Archival data- moments before death
- Limited to nearby supernovae





NASA, ESA, S. Van Dyk (Caltech), and W. Li (University of California)

Mass loss - creation of circumstellar medium



Credit: PC

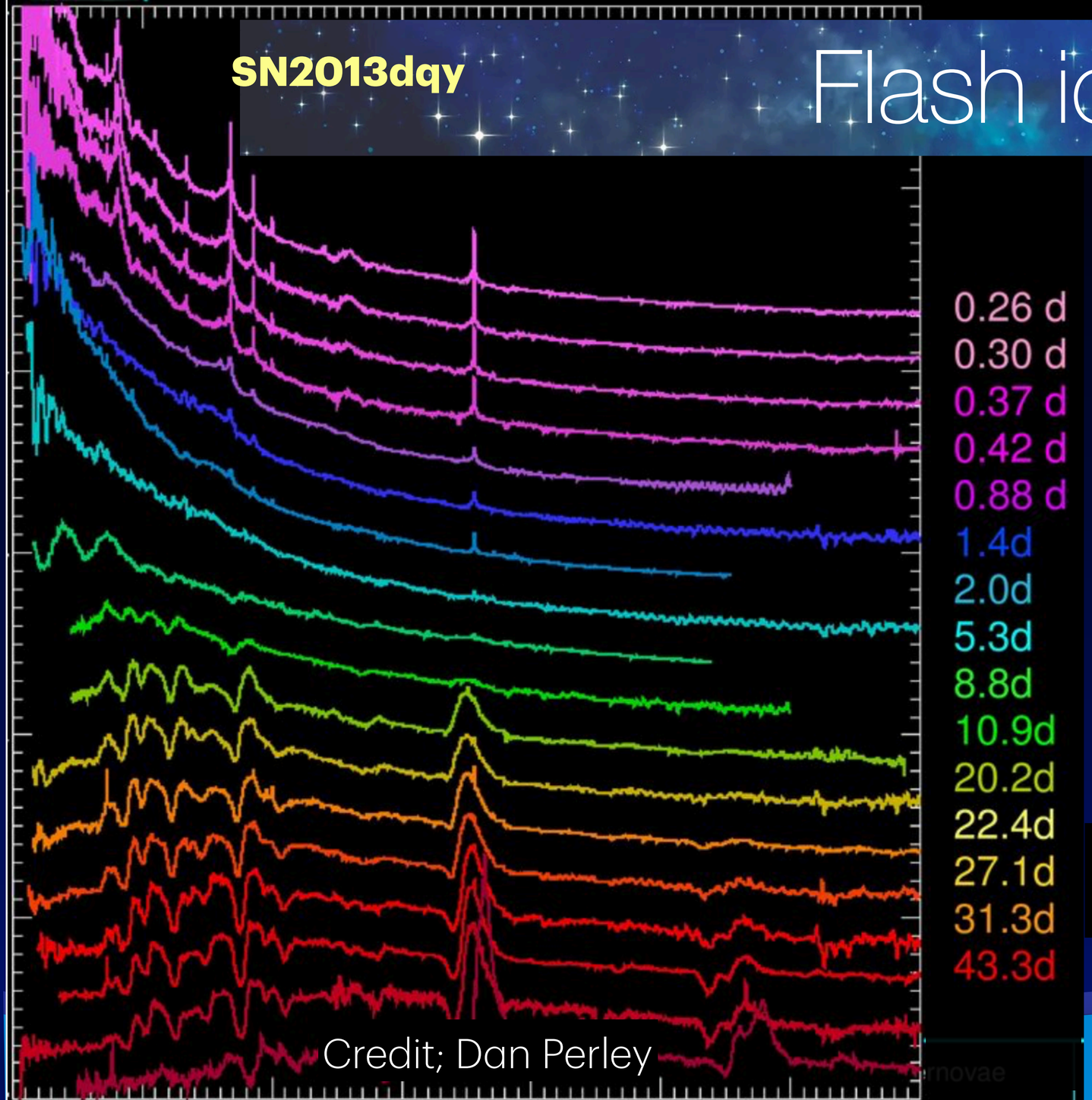
Mass loss - creation of circumstellar medium

CSM ejected at different epochs before explosion

- Direct mapping to:
  - episodic mass loss
  - eruptive outbursts
  - binary-driven density enhancements
  - Common envelope led mass-loss
-

Credit: PC

Flash ionization



- First signatures of CSM- few hrs to days
- Number of narrow emission lines from highly ionized species - flash ionization
- Ionization of CSM at shock breakout - earliest traces of CSM (Gal-Yam et al. 2014, Khazov et al. 2016, Kochanek 2019)
- Radiation driven process - Produced before sustained shock interaction turns on.
- Disappear within few days - confined CSM (Khazov+16)
- Mass loss rate ~ 10^{-3} $M_{\odot}$ yr^{-1}. Denser CSM extending to $<10^{15}$ cm

A note on flash ionization

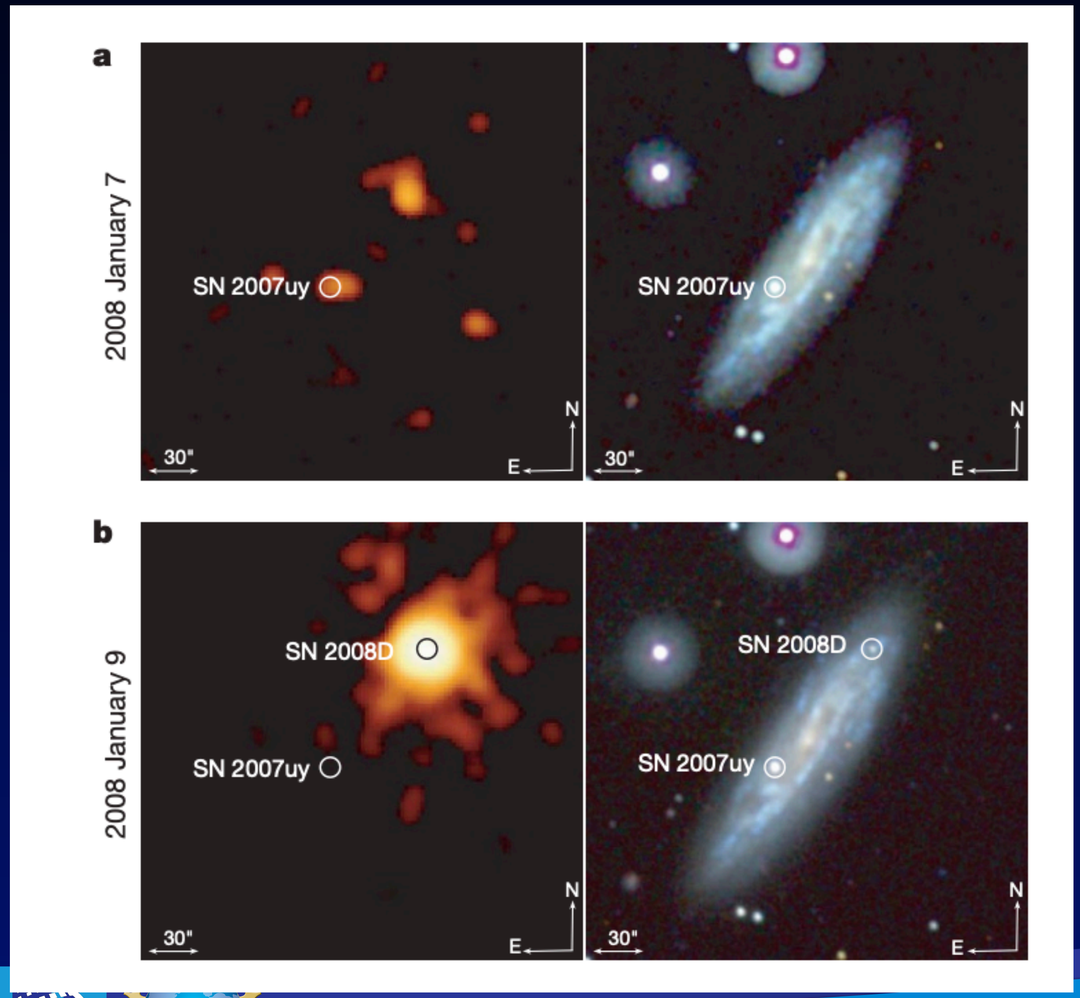
SN	Sub-type	First FI	Representative FI lines
SN 2006bp	IIP	+2 d	He II (λ4200, λ4686Å), C IV (λ5805Å)
SN 2013fs	IIP	+0.3 d	He II (λ4686Å), N V (λλ4604, 4620Å), N III & C III (λλ4634, 4640Å/λλ4647, 4650Å), O IV/V/VI
SN 2014G	IIL	2–3 d	He II (λ4686)Å, C IV λ5803, N III, IV (λλ4640Å, λλ4057, 5201, 7113Å)
SN 2016bkv	low-lum. IIP	≤ 5 d	H (λ4101, λ4340, λ4861, λ6563Å), He II (λ4686, λ5411Å), C III/N III blend
SN 2017ahn	fast-decl. II	+1 d	Narrow Balmer series, He II λ4686
SN 2020pni	II	+1 d	Hα, He II, C III/N III blend
SN 2020tlf	II-P/L	+0.7 d	Narrow symmetric H I and He II lines
SN 2022acko	low-lum. IIP	+2 d	He II λ4686, C III
SN 2022jox	II	+0.8 d	H I, He II, C IV, N IV
SN 2023ixf	IIP	+0.4 d	He II λ4686, C IV λλ5801, 5812, N V λλ4603, 4619
SN 2024ggi	IIP	+0.8 d	He II λ4686, C IV λλ5801, 5812, N IV λλ7109, 7123, O V λ5590

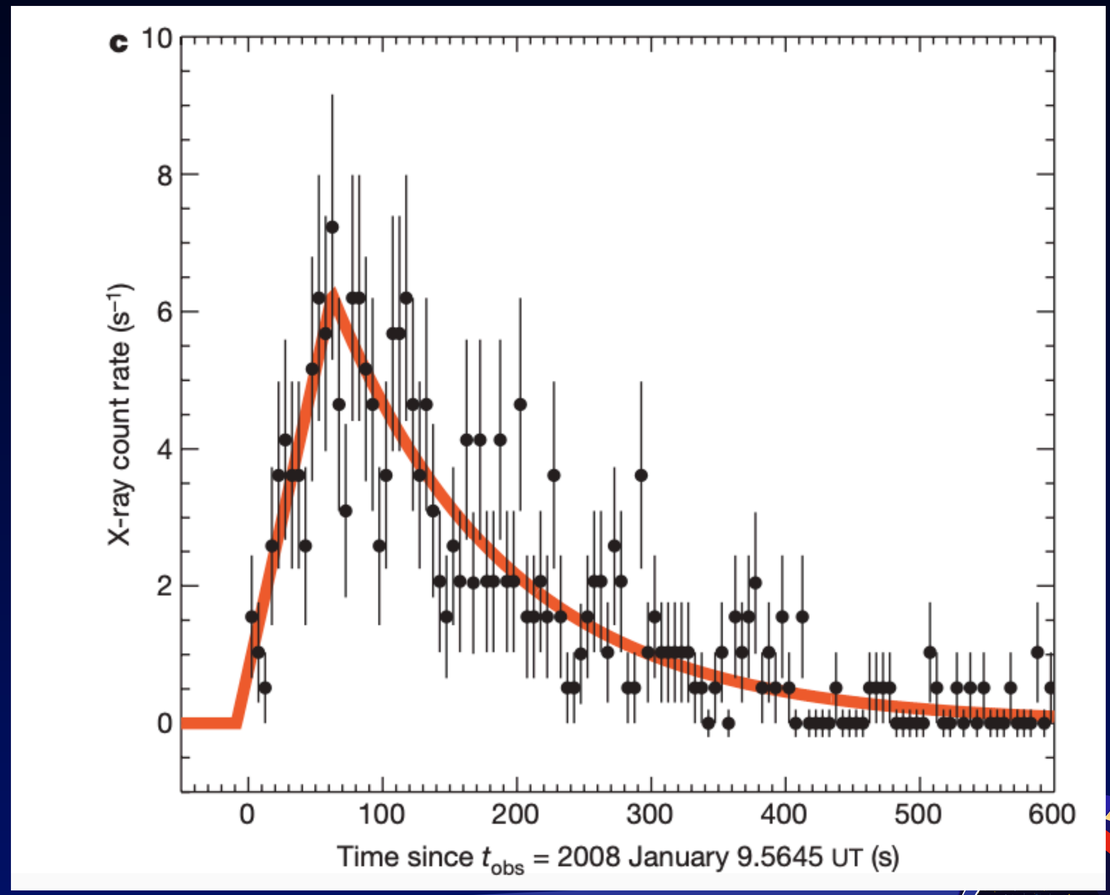
- Flash ionization signatures mostly in Type II supernovae
- Stripped envelope supernovae - very fast evolution, no nearby CSM
- Not usually seen in type IIn supernovae - so dense that the breakout radiation is trapped and shock interaction dominates from the start.
- Perfect amount of CSM needed!!!

PC2025

Connecting shock breakout to flash ionization

SN 2008D - Soderberg,…PC…2008





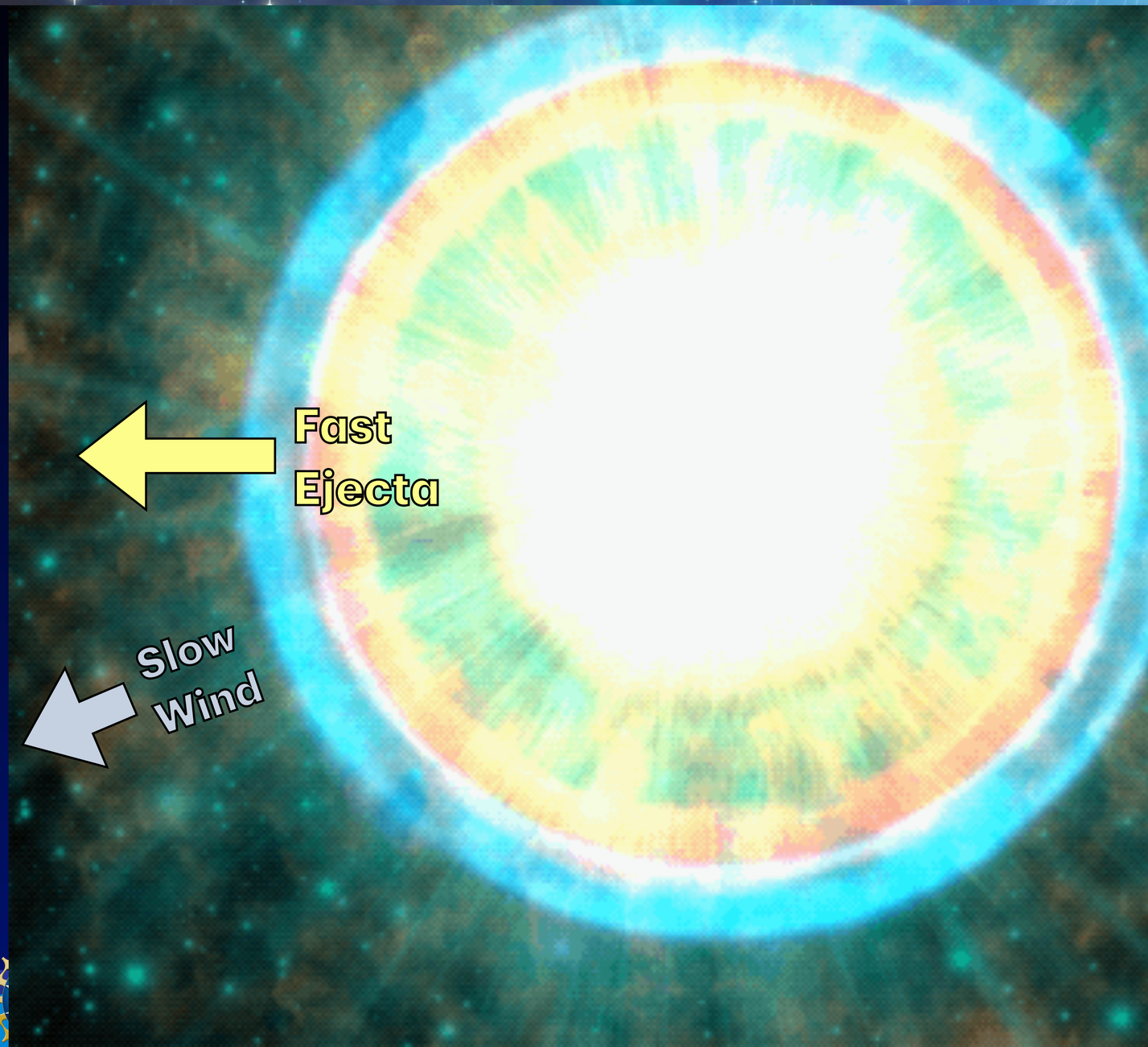
Soderberg,...PC... 2008

Connecting shock breakout to flash ionization

SN 2008D - Soderberg,…PC…2008, Why no flash spectra?

- X-ray outburst was the ionizing radiation.
- Why no flash spectra?
- Ib supernova - very fast evolution of shock breakout
- Non-favorable CSM geometry
- Very little CSM - even with non-negligible mass loss, the **column density can be small** due to large wind speed.
- Optically thick compact CSM, no radiation did not come out.

Circumstellar Interaction - collision of ejecta to CSM



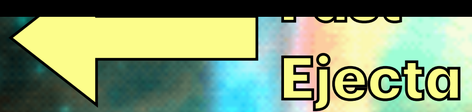
Forward Shock

Reverse Shock

Image Credit: PC

Circumstellar Interaction - collision of ejecta to CSM

Flash ionization - **months - years** of mass loss
CS interaction traces **years–centuries** of mass loss



Flash ionization is the “UV photograph” of the progenitor’s final days; sustained CSI is the long-exposure movie of its mass-loss history.

Image Credit: PC

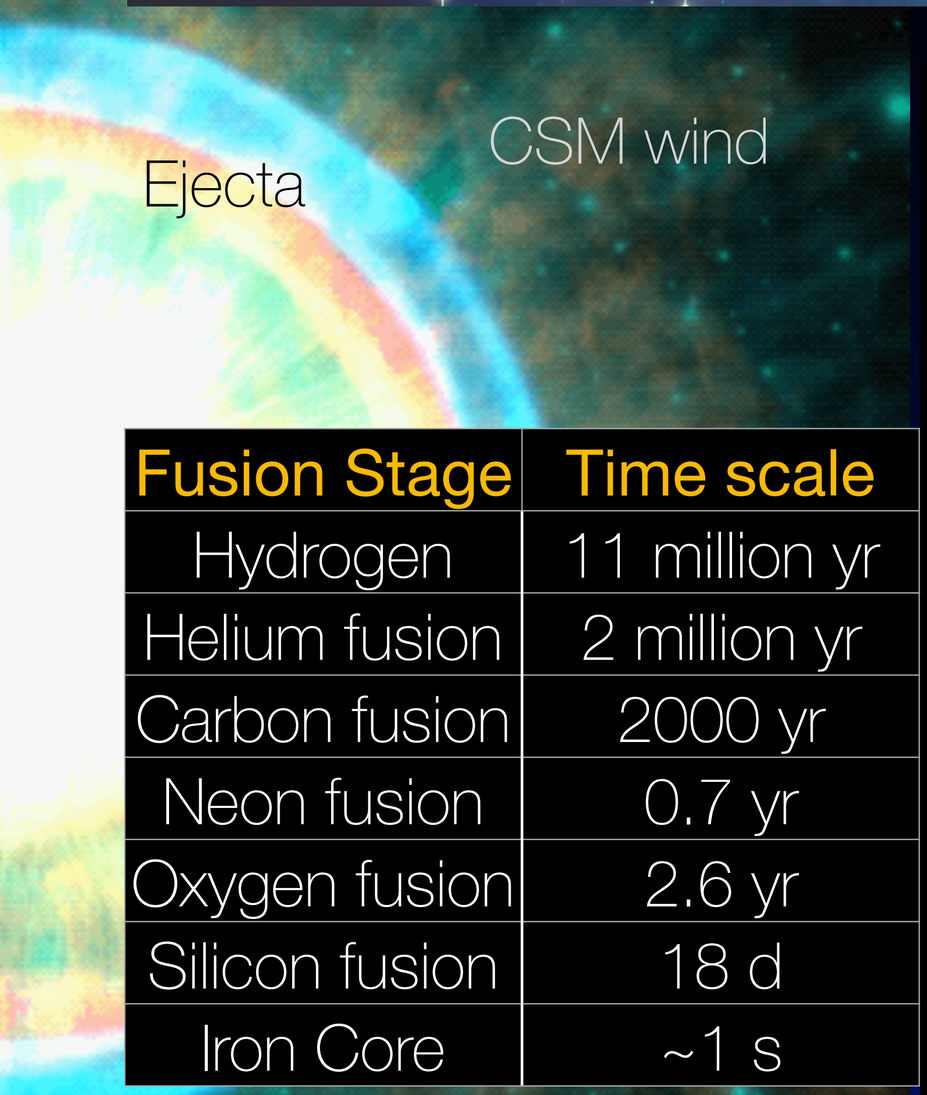
Circumstellar interaction

Energy conversion: kinetic → thermal → non-thermal → radiation

Radius = look-back time;
density = conversion efficiency

Credit: PC

Circumstellar Interaction - Time Machine



Fusion Stage	Time scale
Hydrogen	11 million yr
Helium fusion	2 million yr
Carbon fusion	2000 yr
Neon fusion	0.7 yr
Oxygen fusion	2.6 yr
Silicon fusion	18 d
Iron Core	~1 s

Image Credit: PC

- Time Machine - Look back time= ejecta speed/wind speed
- Wind velocities and ejecta speeds different for different kinds of supernovae
  - Type IIP, ejecta speed ~10,000 km/s, wind ~10 km/s, Look back time ~1000
  - Type IIn, ejecta speed ~6000 km/s, wind ~100 km/s, look back Time ~60
  - Type Ic, ejecta speed ~30,000 km/s, wind~1000 km/s, look back time ~30

Circumstellar interaction- Electromagnetic emission

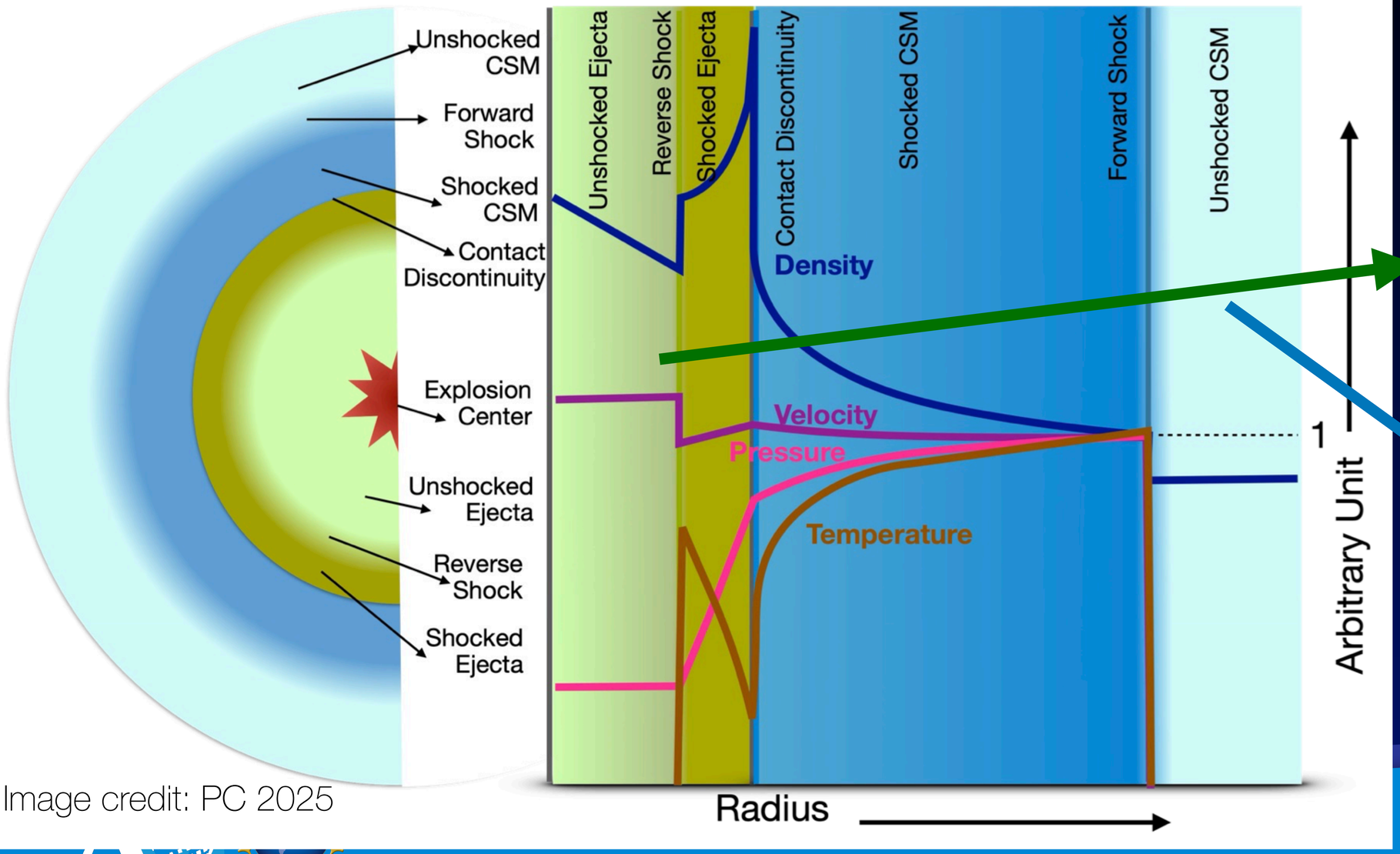


Image credit: PC 2025

Self-similar solutions
Evolution of shocks

$$\rho_{ej} \propto r^{-n}, n \geq 5$$

$$\rho_{CSM} \propto r^{-2}$$

Chevalier 1982

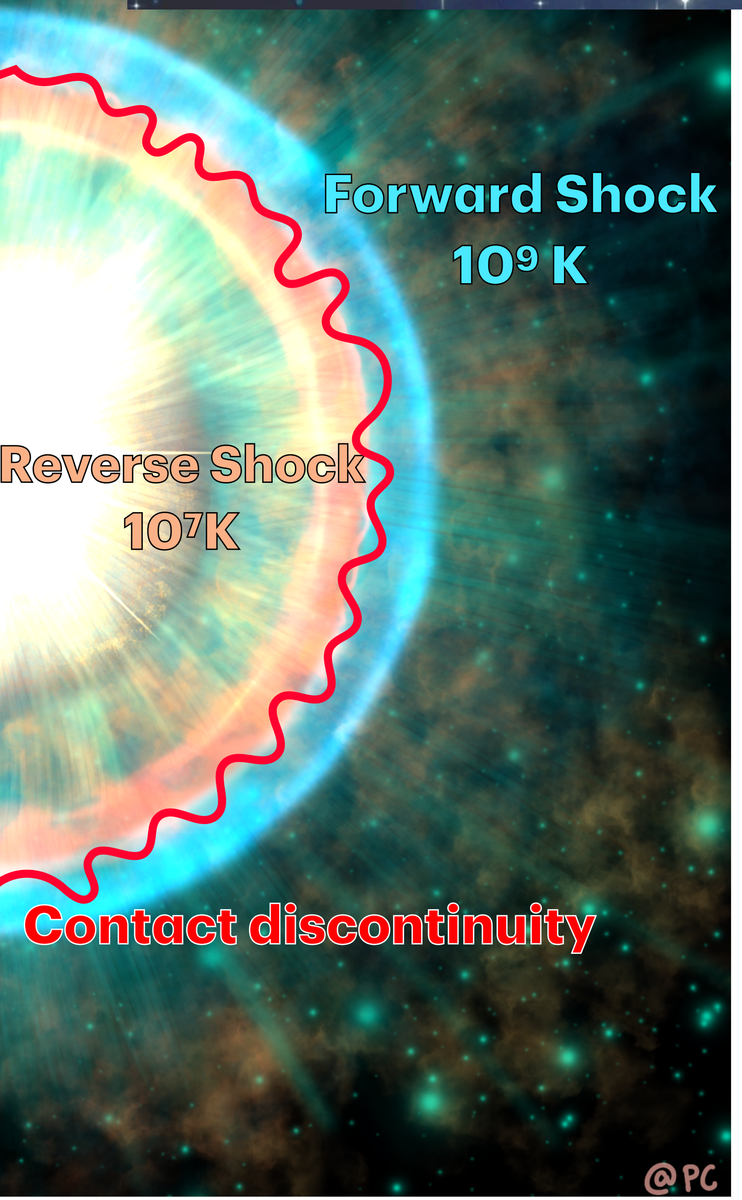
PC 2025

Image Credit: PC

CS Interaction - optical emission

- Shock heating → ionized gas → bright lines - **strong optical emission lines**, especially hydrogen
- **Narrow emission lines** (~100 km/s): from slow, unshocked CSM photoionized by the shock radiation
- **Broad wings or broad components** (thousands of km/s): from shocked gas or electron scattering
- If the CSM density is high enough, shock energy doesn't just go into lines—it powers a **bright optical continuum**
- Reprocessing of high-energy photons into **optical bands**
  - This reprocessing is key when X-rays are weak or undetected but optical emission is strong. - SN 2006gy (Ofek+06, Chevalier, Fransson 2008)

X-ray emission - circumstellar interaction



- Hot forward shock - 10^9K
- Reverse shock - 10^7K

n - ejecta density profile ρ^{-n}

- RS density (n-3)*(n-4)/2 x FS density ~factor of ~20
- Most dominant reverse shock ~1keV

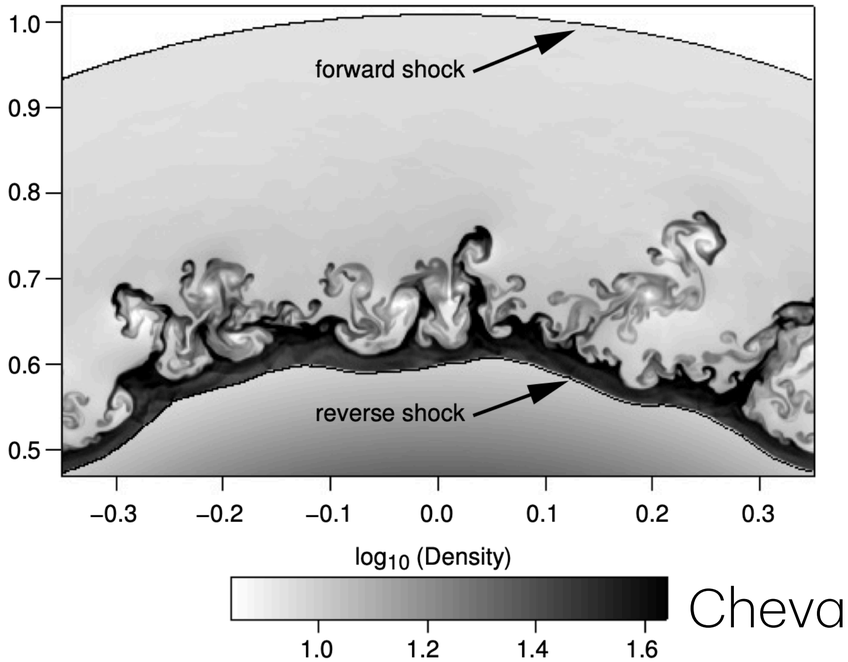
$$L_{\rm i} = 4\pi \int \Lambda_{\rm ff}(T_{\rm e}) n_{\rm e}^2 r^2 dr \approx \Lambda_{\rm ff}(T_{\rm i}) \frac{M_{\rm i}\rho_{\rm i}}{(\mu_{\rm e} m_H)^2}$$

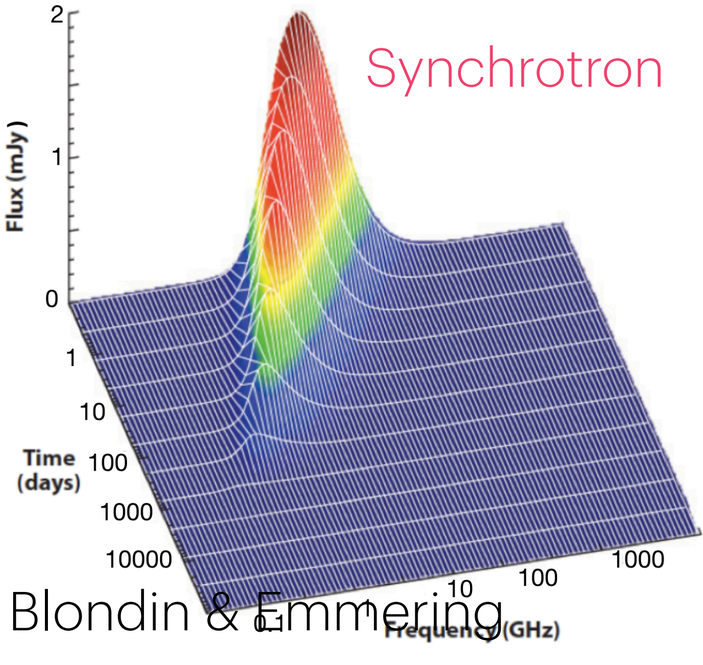
- Luminosity ~ density^2
- Observational evidence (Schlegel+95, Immler+2002, Dwarkadas+2012)

CS Interaction - Radio emission

- Magnetic field amplification at the contact discontinuity
- Acceleration of electrons in the forward shock
- Non-thermal Synchrotron forward shock emission
- Radio emission from the fastest ejecta

Image Credit: PC





Chevalier, Blondin & Emmering

Circumstellar interaction - a note

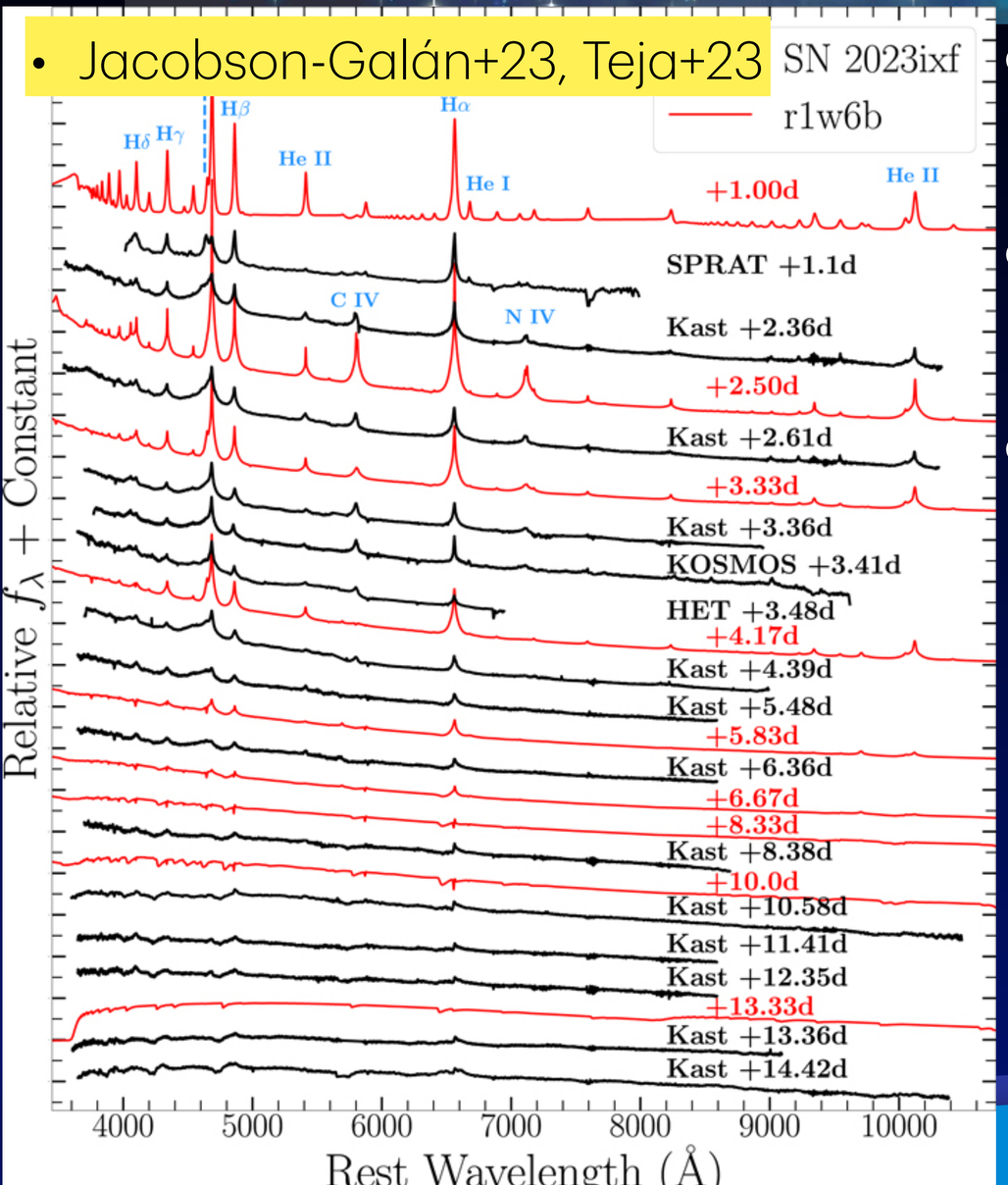
- Flash sets the boundary conditions - compact CSM
- Optical - reprocessed X-rays, thermalize UV, reshape optical spectra, mixed with radioactivity
- X-ray - absorption, reprocessing, inverse-Compton, radiative vs adiabatic physics
- Radio - whether the shocks are truly coupling to the circumstellar medium. **Most direct and least ambiguous tracer of circumstellar interaction**

CSM and Circumstellar interaction - a note

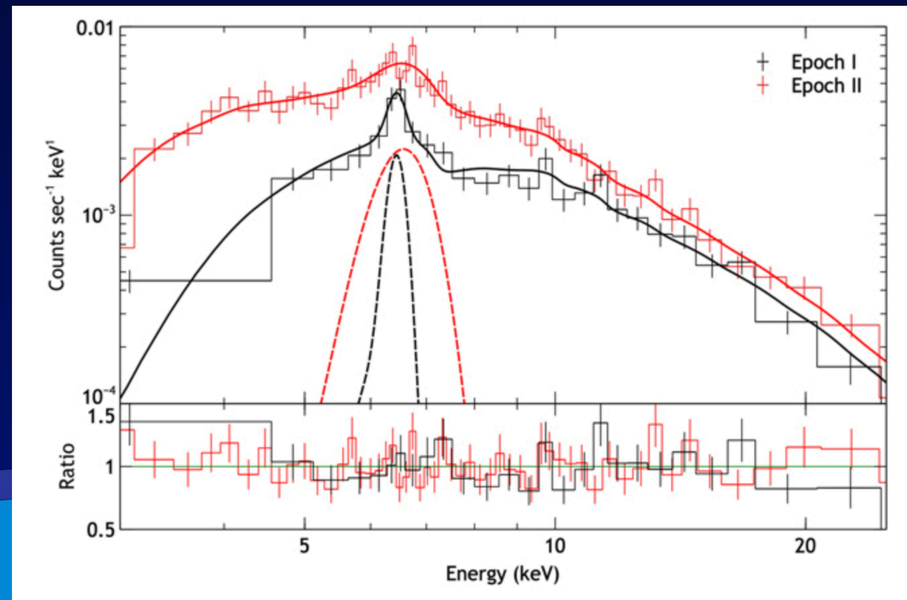
- Explosion → flash ionization → CS interaction onset → long-term interaction
  10^{14}-10^{15}cm 10^{15}-10^{16}cm 10^{16}-10^{18}cm
- Flash ionization only
  → small amount of nearby CSM, quickly exhausted
- Flash ionization + strong CS interaction
  → dense, radially extended CSM
- No flash ionization, but late CS interaction
  → inner region relatively clean, dense CSM farther out (decades–centuries old mass loss)

SN 2023ixf - flash features as well as X-rays

- Jacobson-Galán+23, Teja+23



- Flash ionization - probes optically thin inner CSM, X-rays generally absorbed
- SN 2023ixf - flash ionization (Jacobson-Galán+23, Teja+23)
- X-ray detection on day 4 - Moderate CSM (Grefenstette+23)



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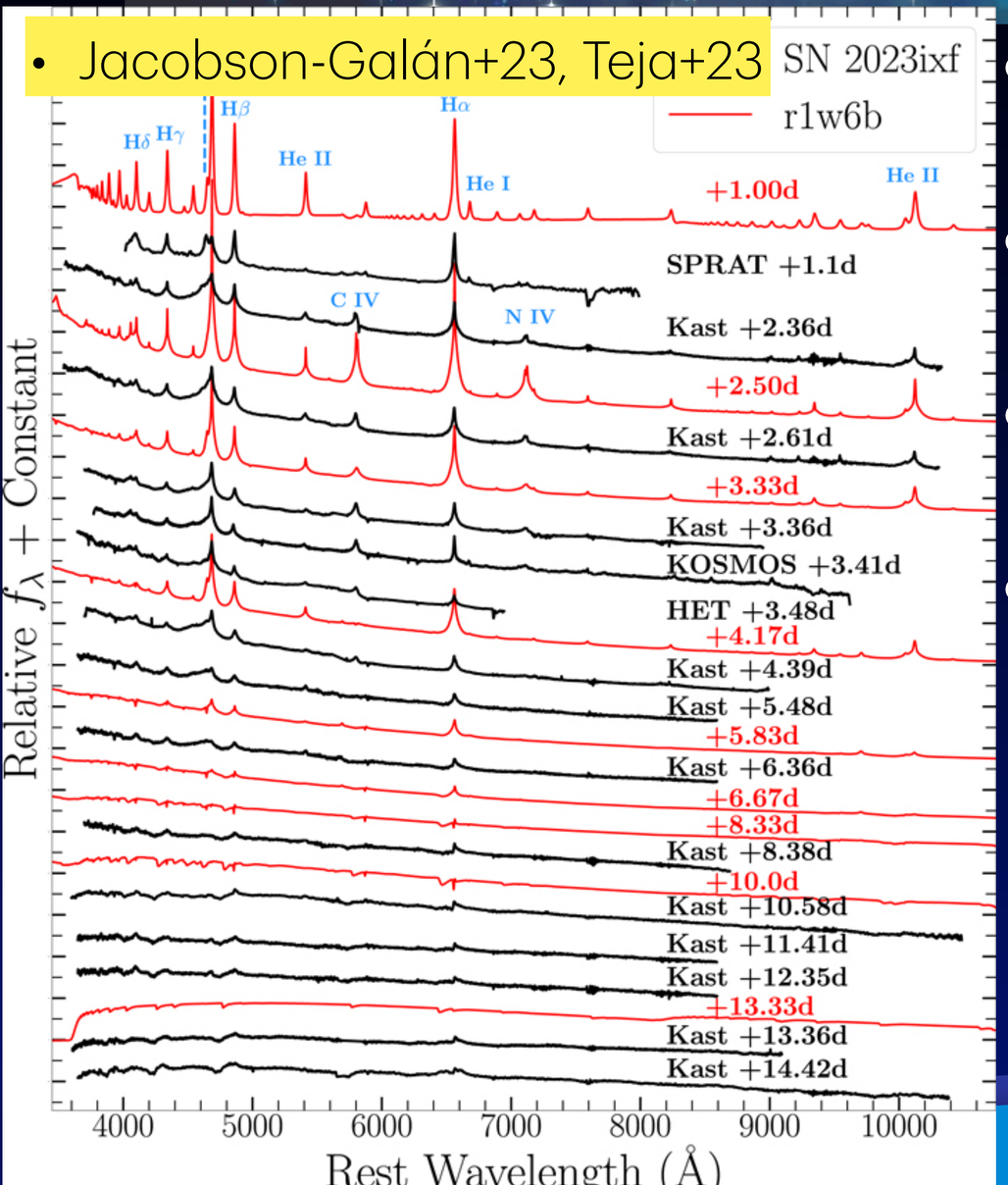

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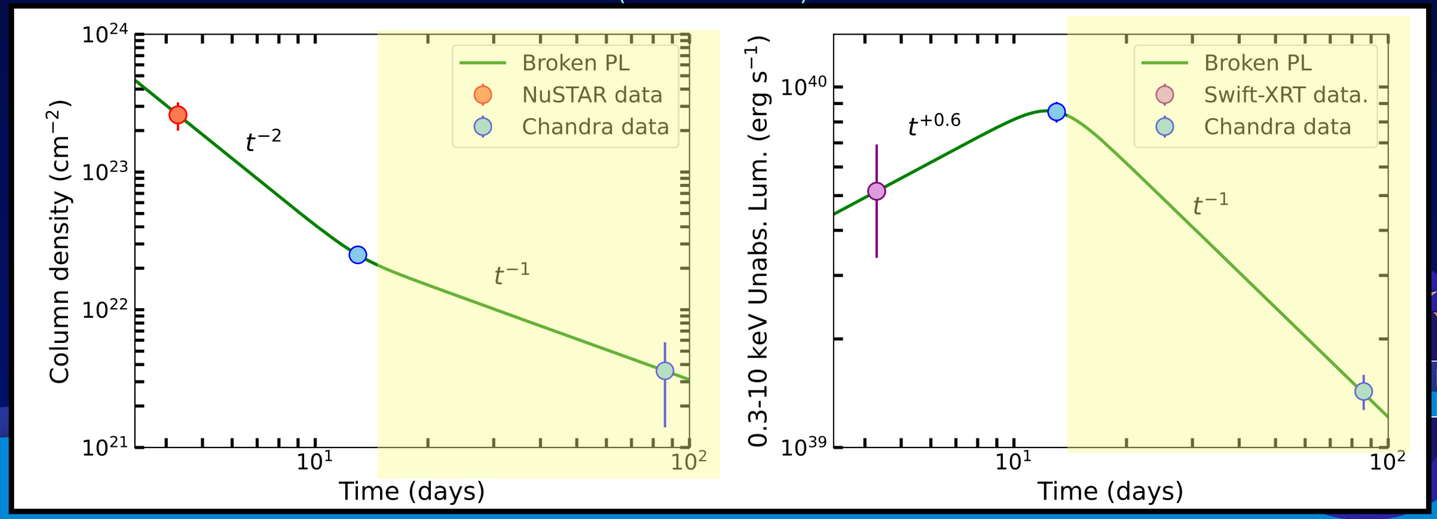
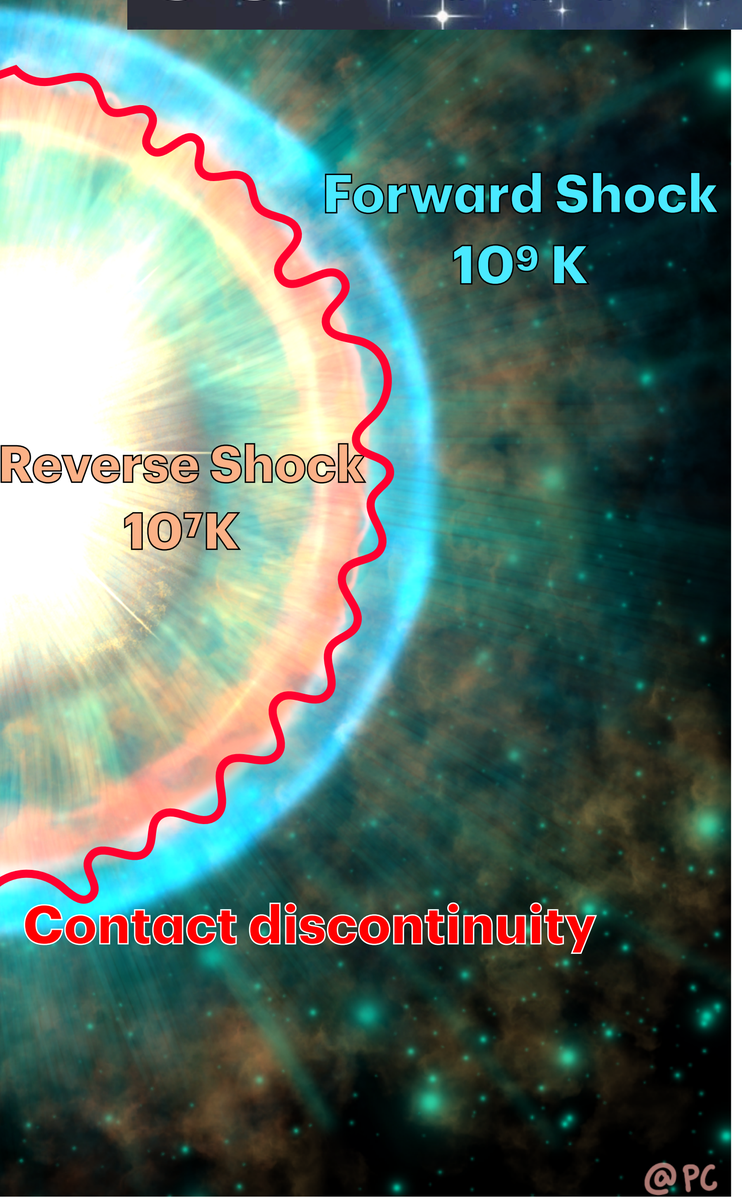
- X-ray detection on day 4 - Moderate CSM (Grefenstette+23)
- Late time data consistent with constant mass-loss rate and standard 1/R2 CSM (PC+24)



CS interaction in X-rays



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- Observational evidence (Schlegel+95, Immler+2002, Dwarkadas+2012)

X-ray emission - circumstellar interaction

Reverse shock radiative

- Cooling time ~

  Chevalier, Fransson 2017

$$t_{\rm cool} = \frac{605}{(n-3)(n-4)(n-2)^{3.34}} \left(\frac{V_{\rm ej}}{10^4\ {\rm km\ s^{-1}}}\right)^{5.34} \left(\frac{\dot{M}_{-5}}{u_{w1}}\right)^{-1} \left(\frac{t}{\rm days}\right)^{2} {\rm days},$$

- Radiative reverse shock

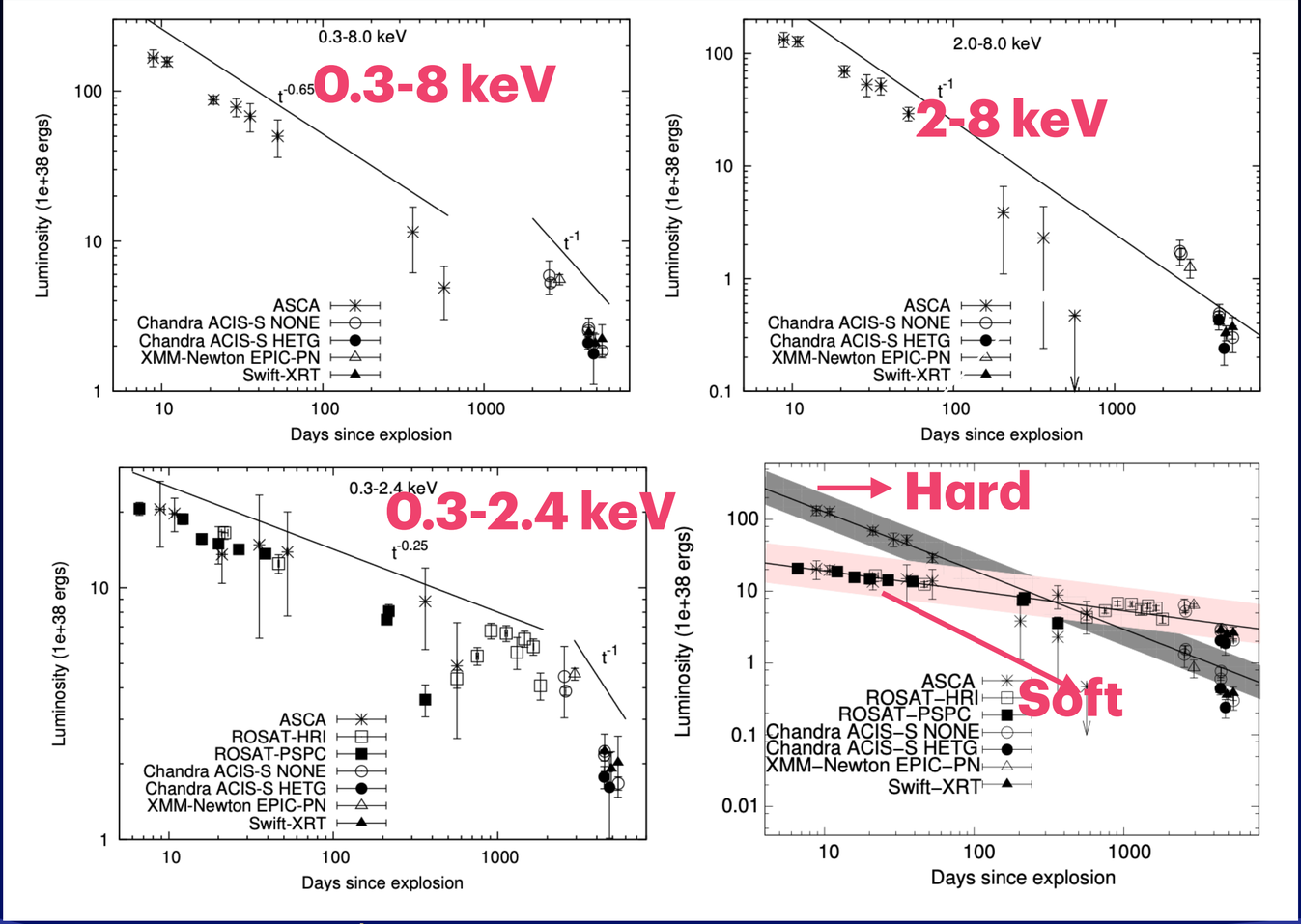
$$L_{\rm rev} = 4\pi R_{\rm s}^2 \frac{1}{2} \rho_{\rm ej} V_{\rm rev}^3$$

Luminosity ~ density

- SN 1993J - Radiative Reverse Shock - Fransson+96

X-ray emission - circumstellar interaction

Reverse shock radiative - SN 1993J

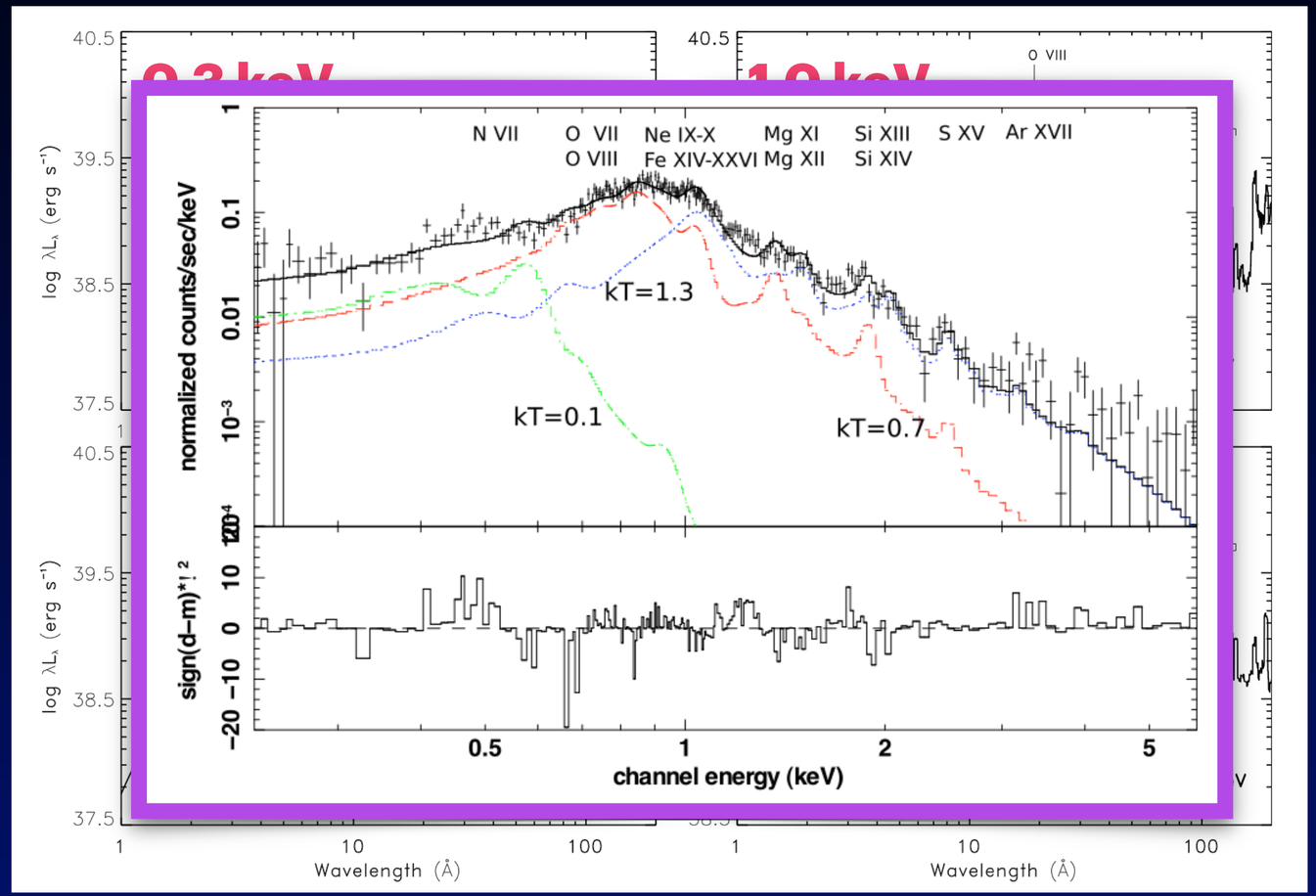


- Reverse shock radiative up to ~ 5 years after explosion and adiabatic after that (PC+2009)
- Consistent with SN 1993J modeling (Nomoto & Suzuki)

PC+2009

X-ray emission - circumstellar interaction

Reverse shock radiative - SN 1993J

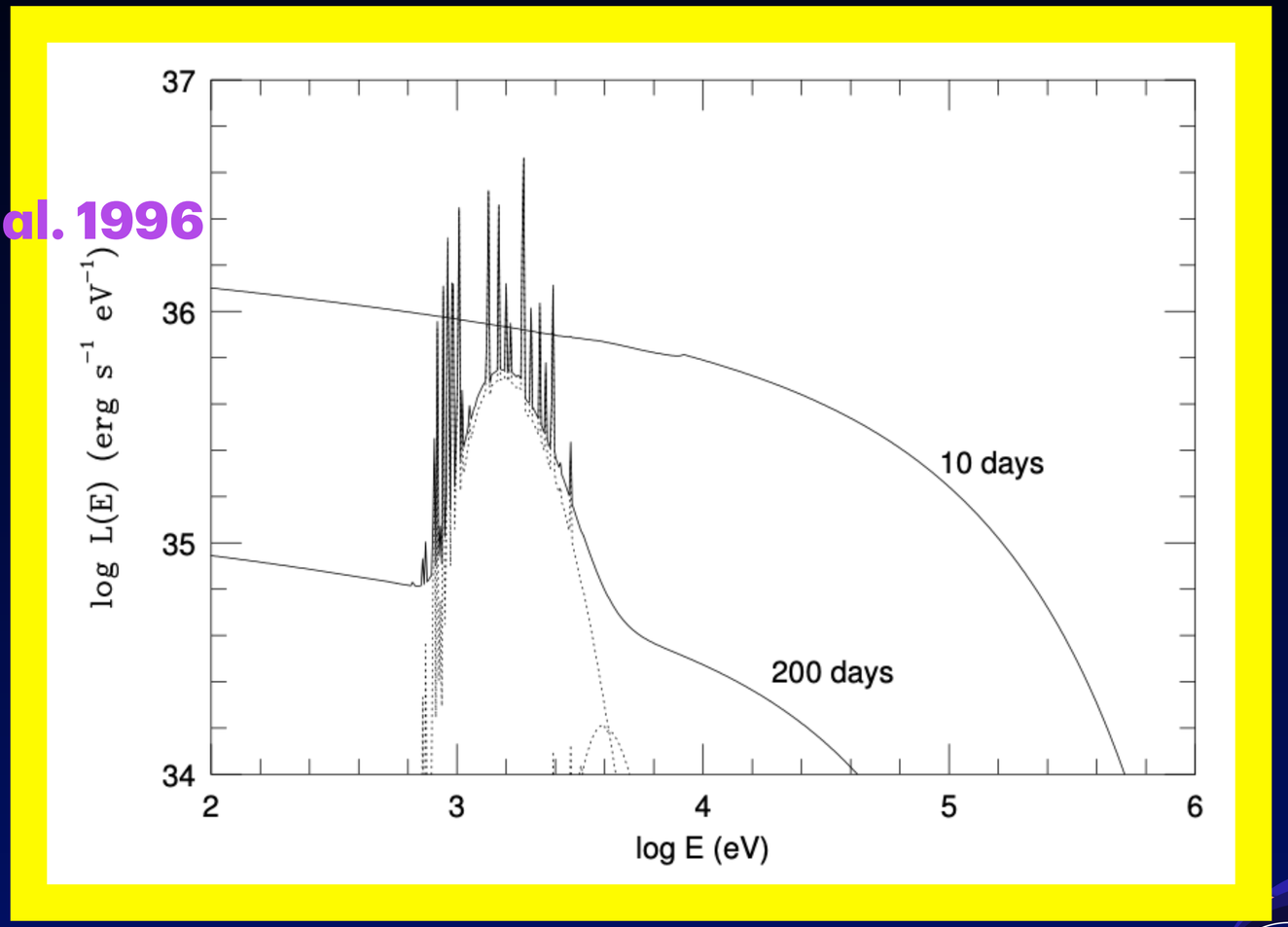


- Reverse shock radiative up to ~ 5 years after explosion and adiabatic after that (PC+2009)
- Consistent with SN 1993J modeling (Nomoto & Suzuki)
- SIngle temperature model invalid (Nymark et al. 2006)
- Demonstrated multi-temperature model in SN 1993J (Nymark, PC, Fransson 2006)

Nymark et al. 2006, Nymark, PC, Fransson+2009

X-ray emission - circumstellar interaction

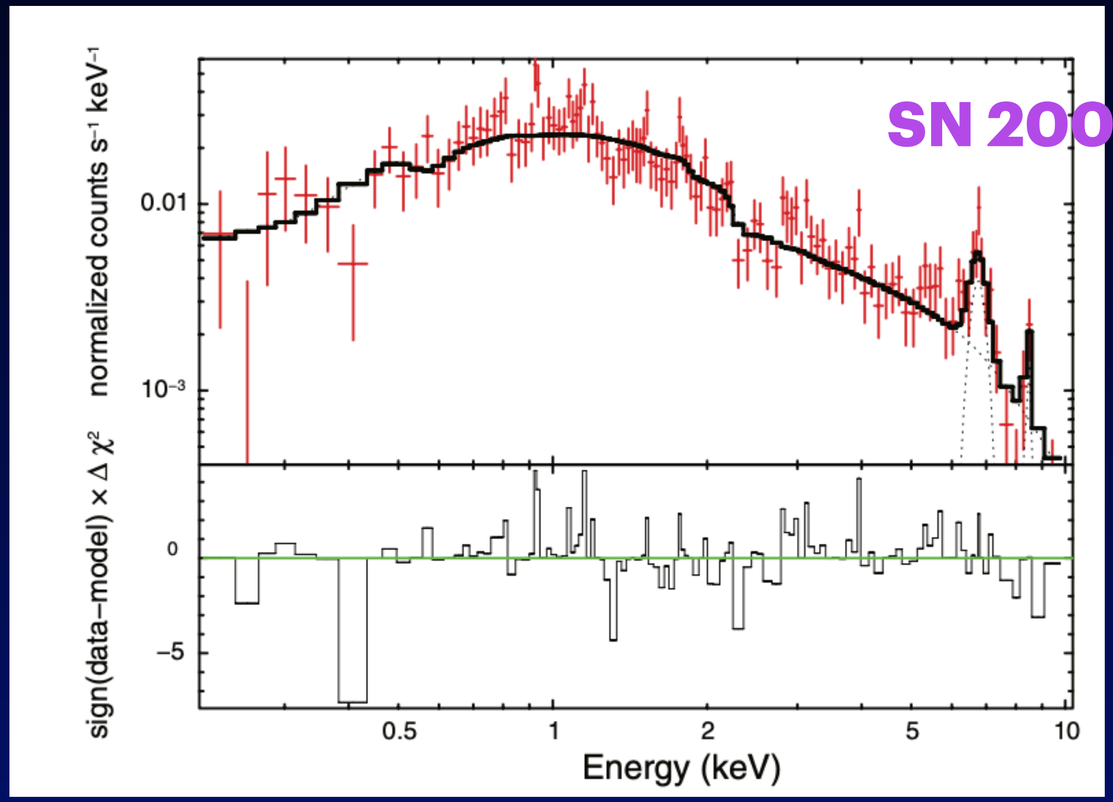
Fransson et al. 1996



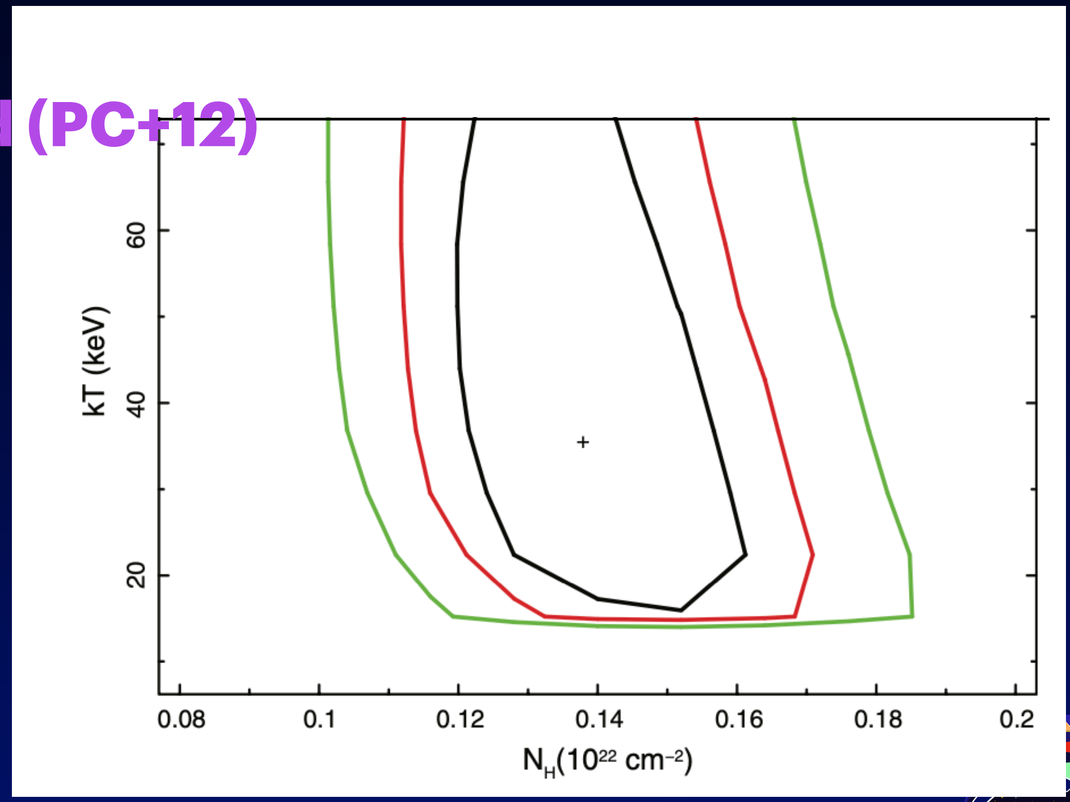
X-ray emission - circumstellar interaction

Hard X-rays

- Chandra/XMM energy range 0.3-10 keV



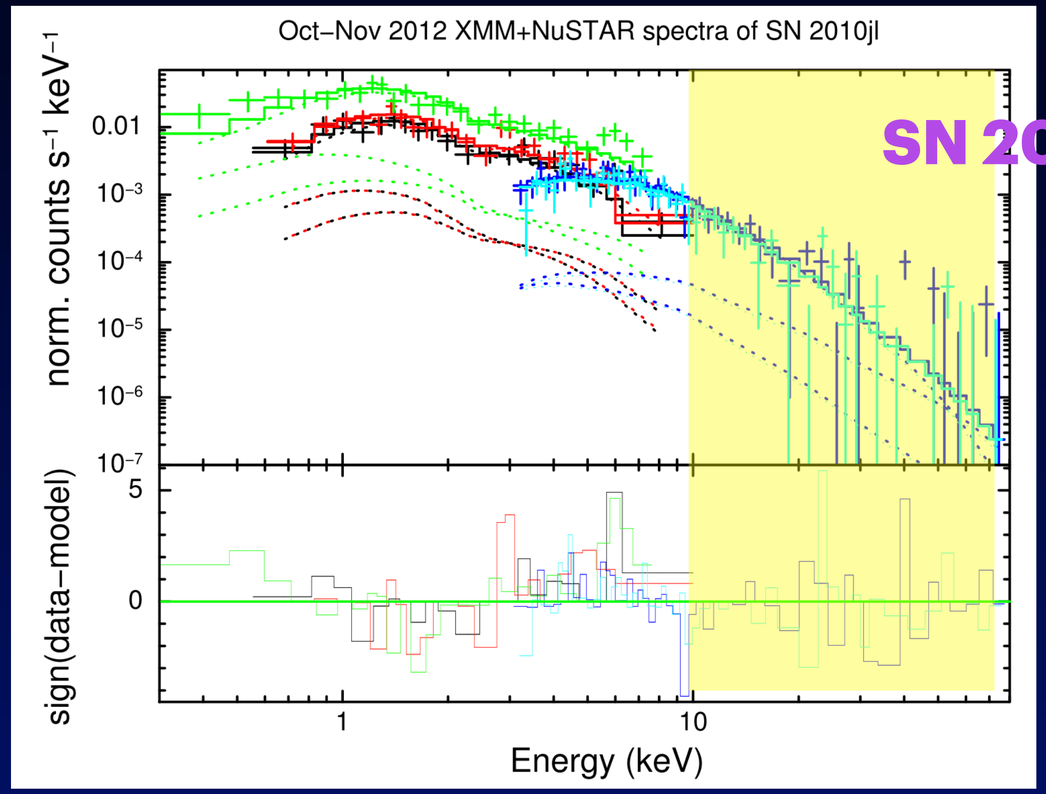
SN 2006jd (PC+12)



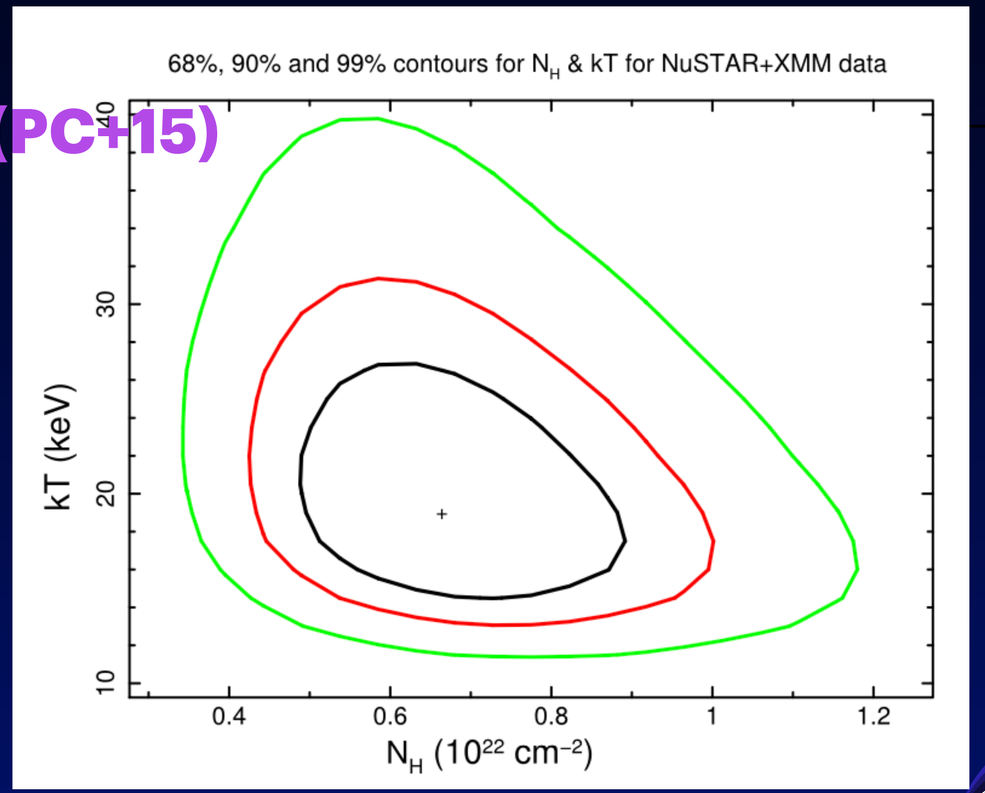
X-ray emission - circumstellar interaction

Hard X-rays

- NuSTAR revolutionary

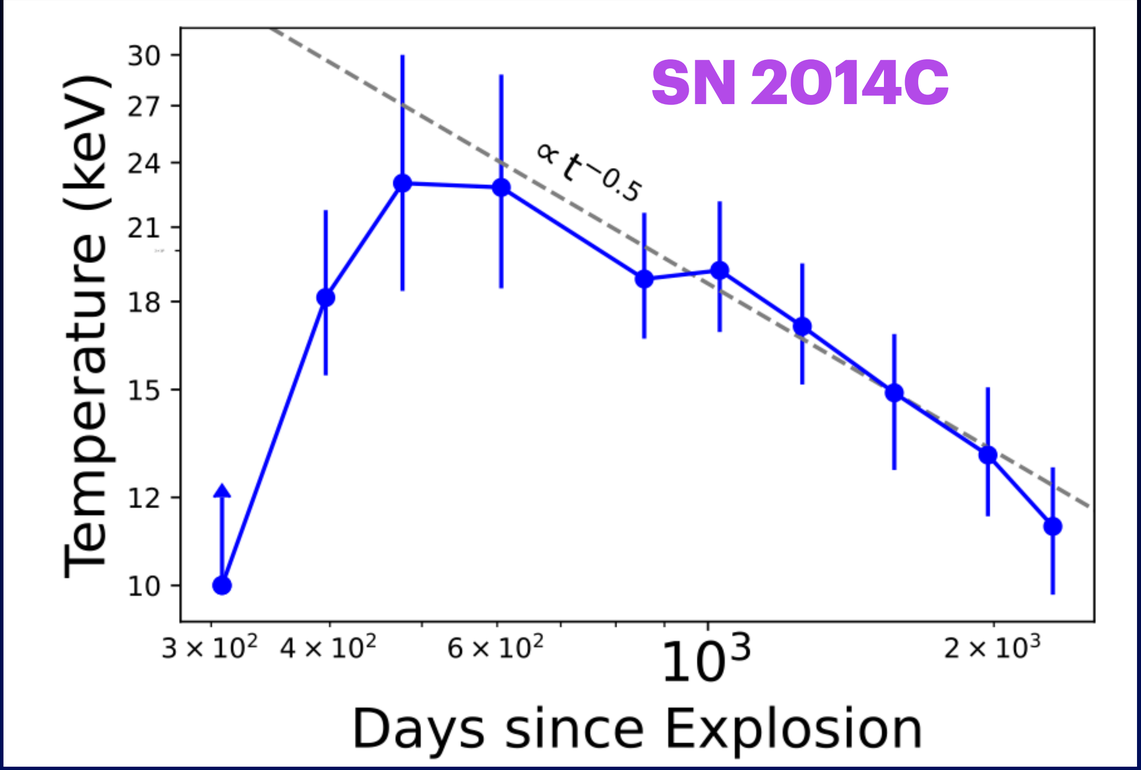


SN 2010jl (PC+15)



X-ray emission - circumstellar interaction

Hard X-rays

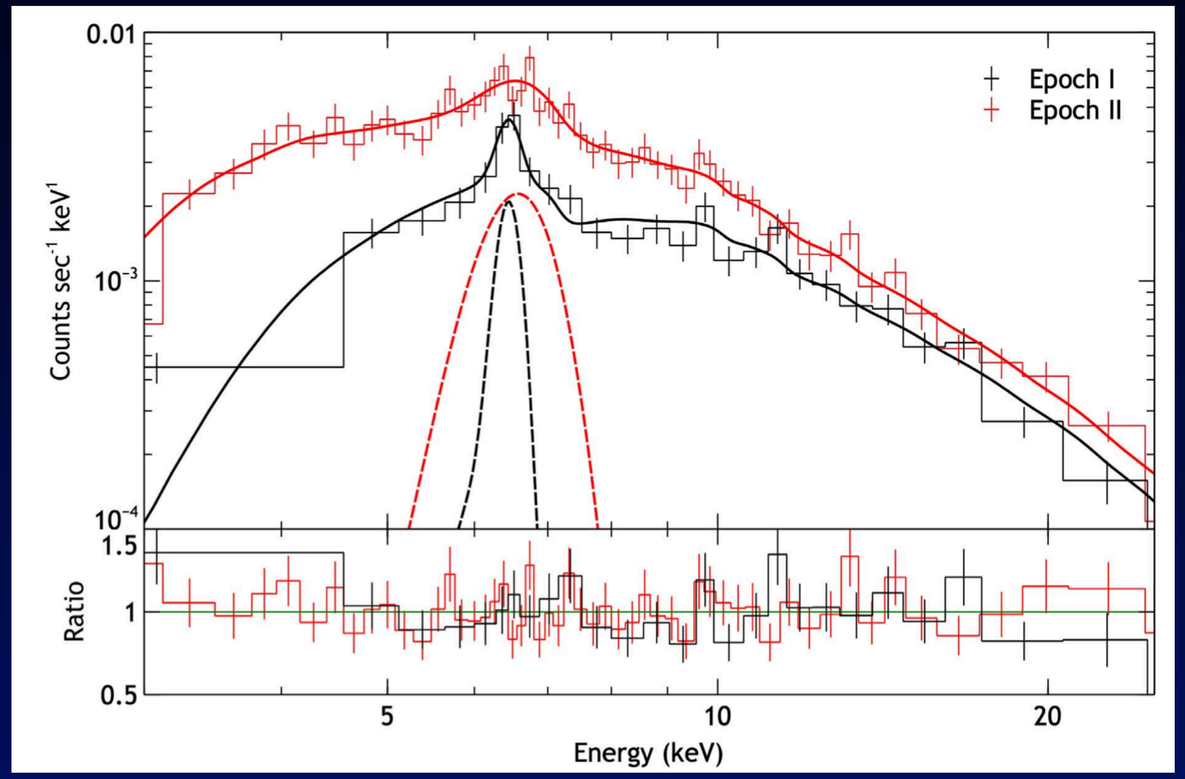


- NuSTAR revolutionary
- Temperature evolution of SN 2014C (Brethauer+22)

- Brethauer+22

X-ray emission - circumstellar interaction

Hard X-rays

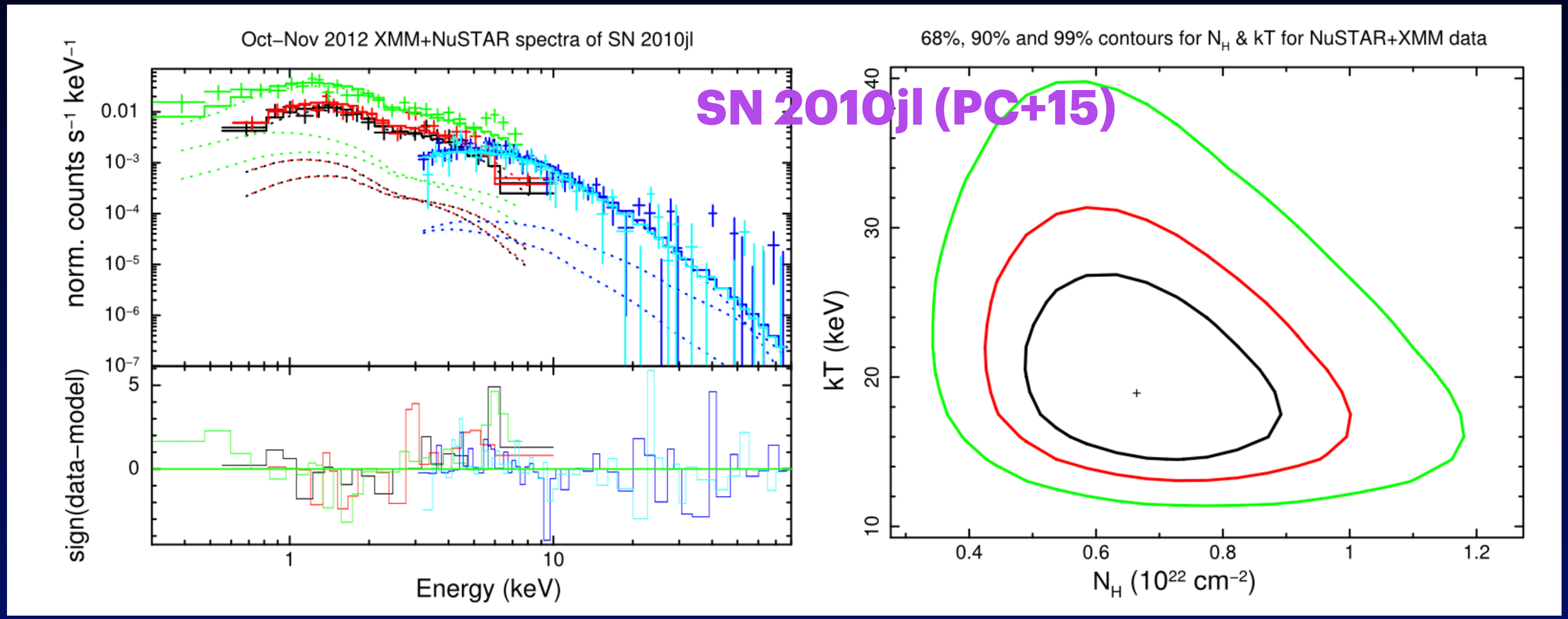


SN 2023ixf - Grefenstette+23

- NuSTAR revolutionary
- Temperature evolution of SN 2014C (Brethauer+22)
- SN 2023ixf - hard X-rays (Grefenstette+23)
- Adiabatic forward shock (PC+23)
- Cooling time - larger for forward shock

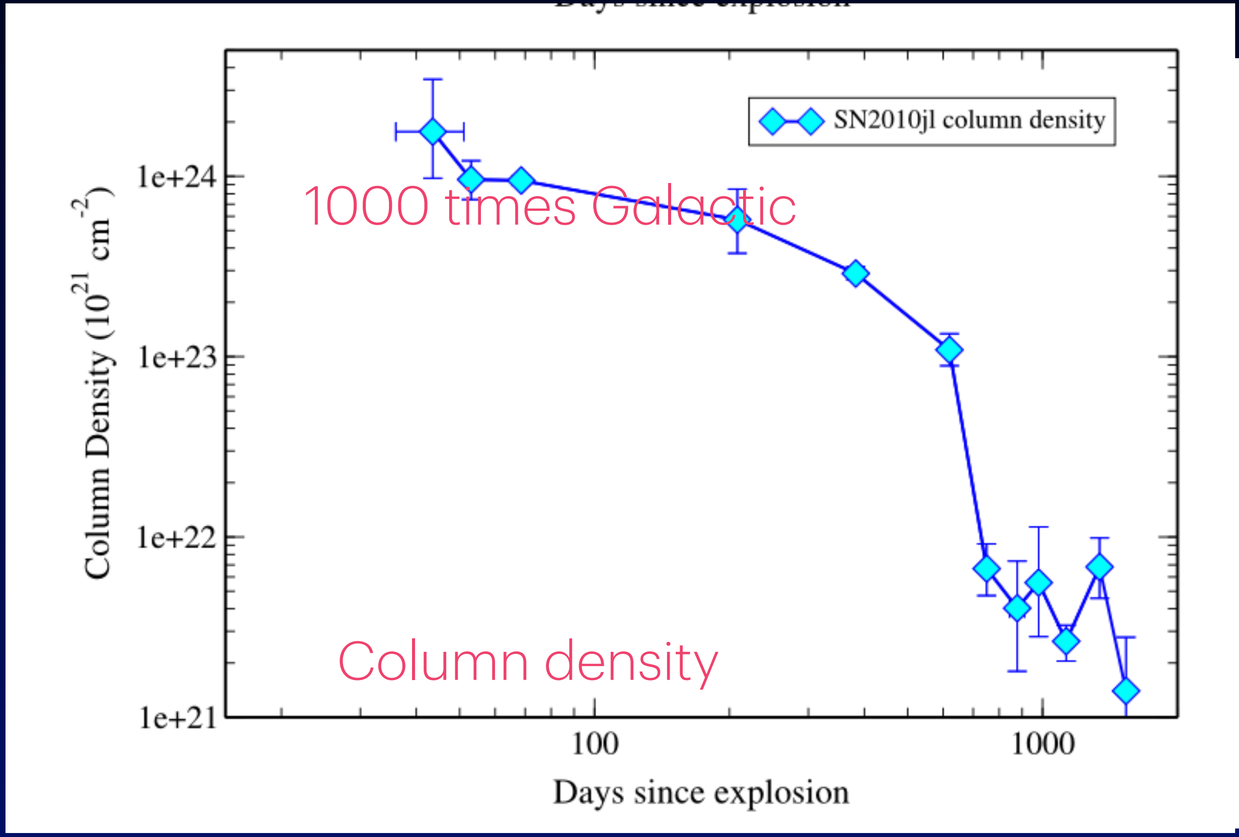
X-ray emission - circumstellar interaction

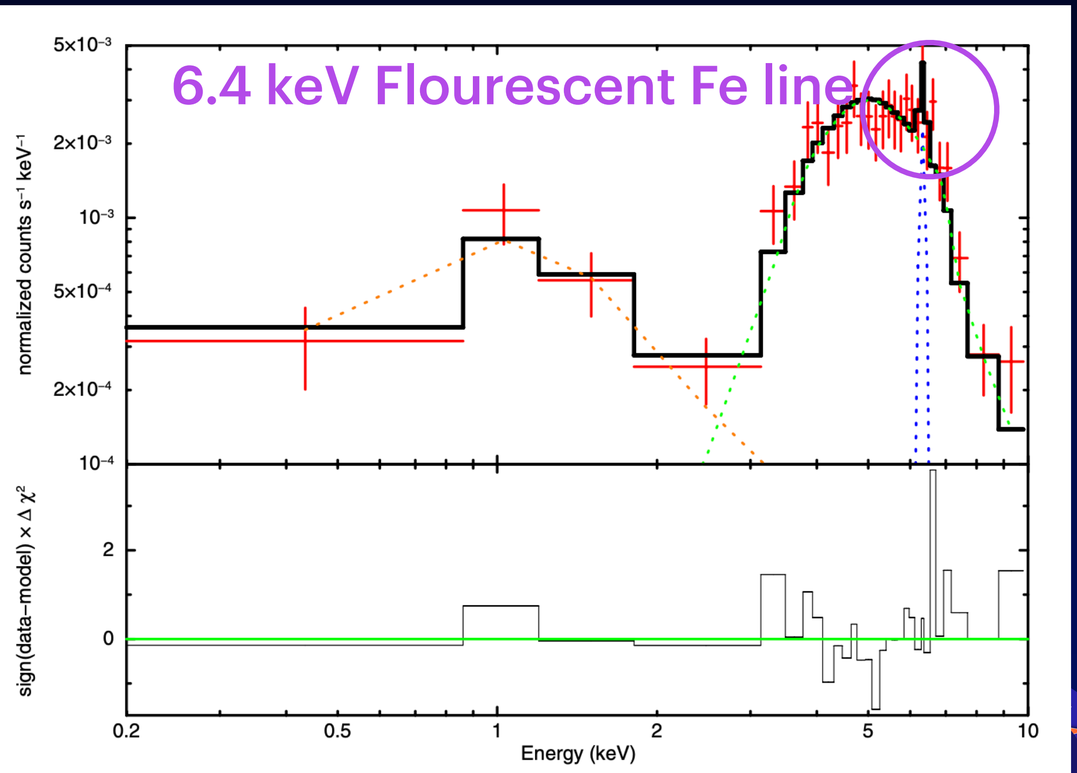
Hard X-rays - radiative forward shock (PC+18, PC+15, PC+12)



X-ray emission - circumstellar interaction

Hard X-rays - radiative forward shock (PC+18, PC+15, PC+12)

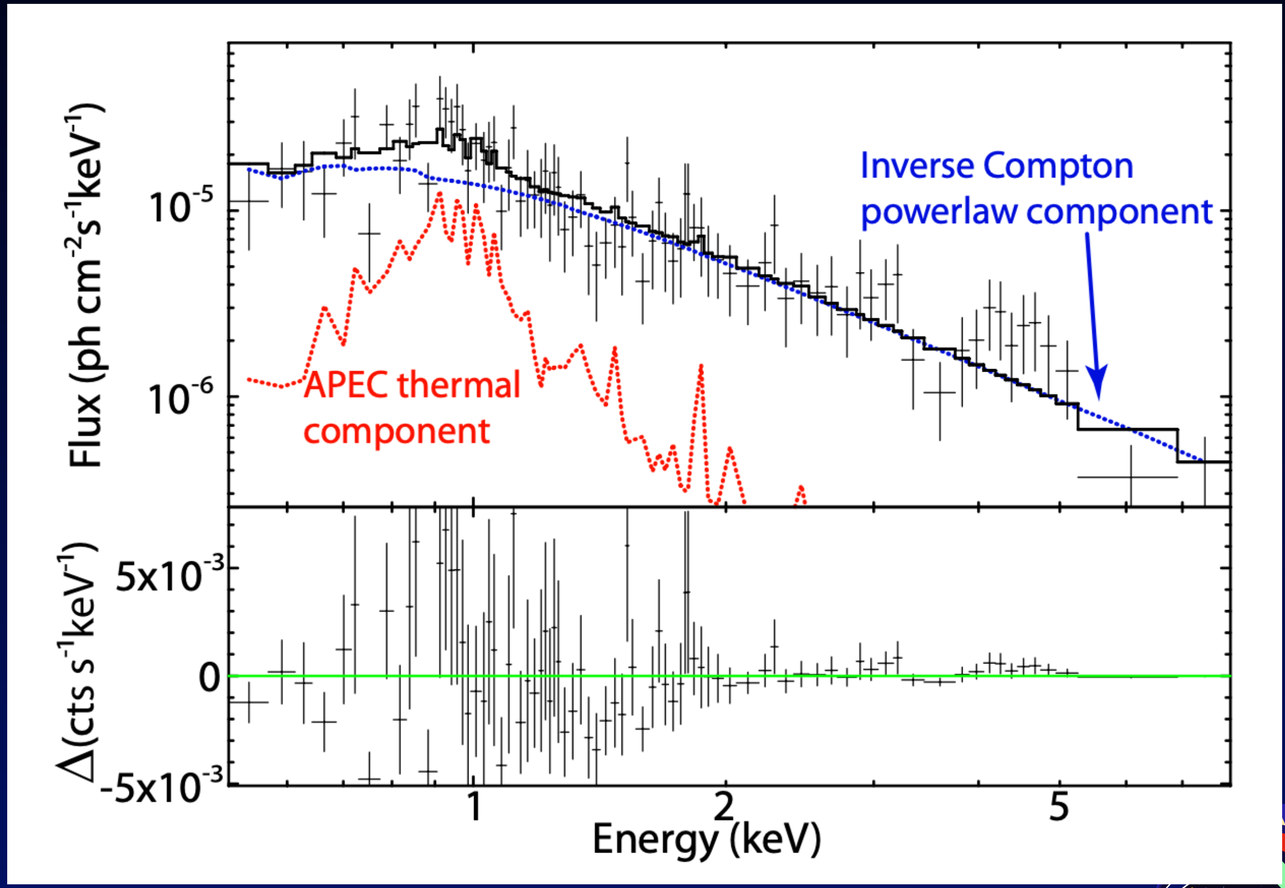




X-ray emission- Circumstellar interaction

Non-thermal X-rays

- Inverse Compton component of X-rays
- Usually in type Ib/c supernovae with large ejecta speeds
- Usually in Type IIP supernovae with large supply of photons
- See Chakraborty+12, 13, Soderberg+11, Margutti+12 etc.

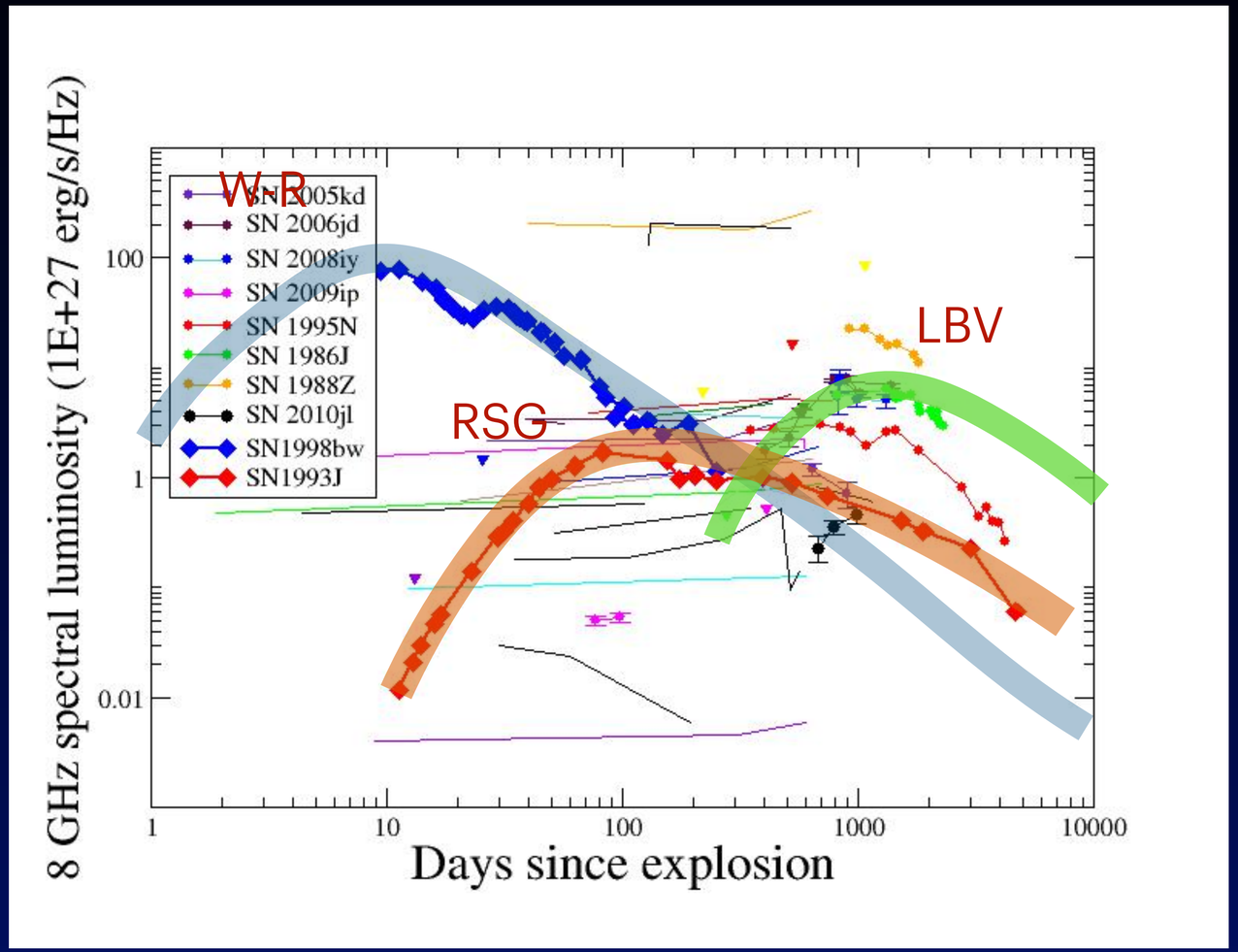


Chakraborty,...PC...2012

Radio emission

CSM ~10^{15}-10^{17}cm

Image Credit: PC

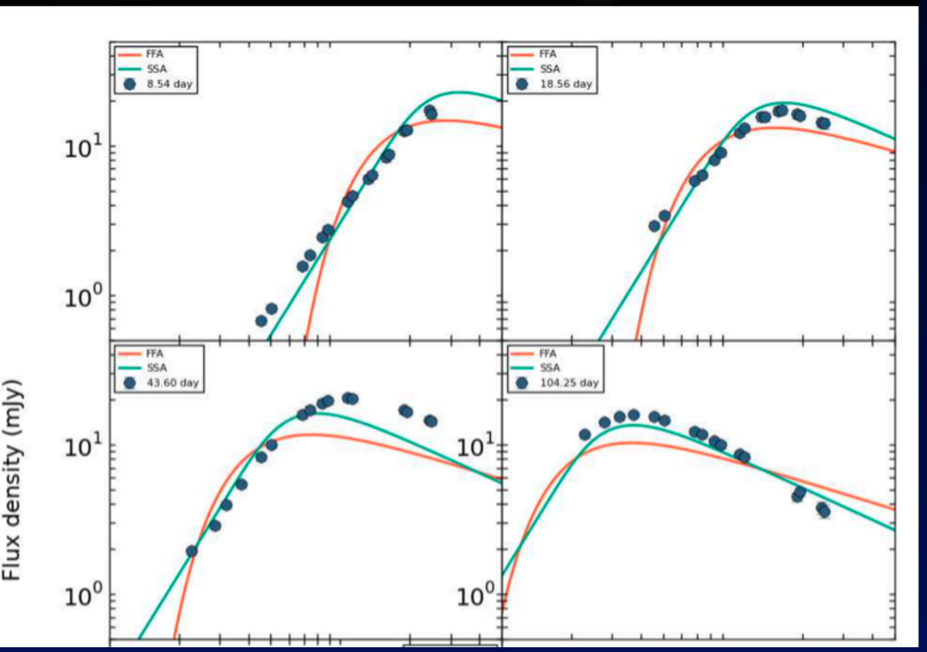


PC 2018, 2025, Bietenholz et al. 2021, Weiler et al. 2007

CSM ~10^{15}-10^{17}cm

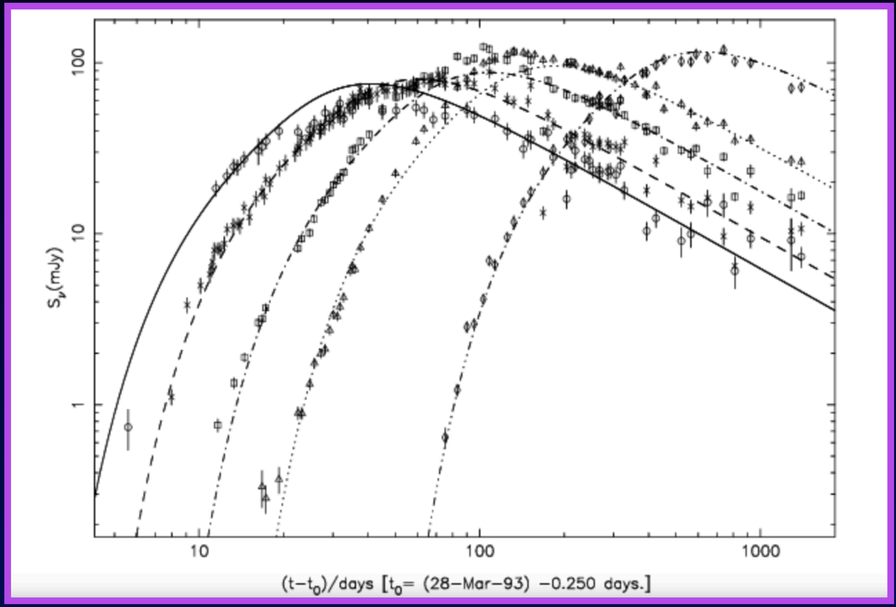
Absorption of Radio emission

- Synchrotron emission
- Synchrotron self-absorption (fast ejecta, low mass-loss rate, Ib/Ic,IIb etc. see Nayana, PC+,2022, 2023)
  - Magnetic field, size etc



Nayana,PC+22

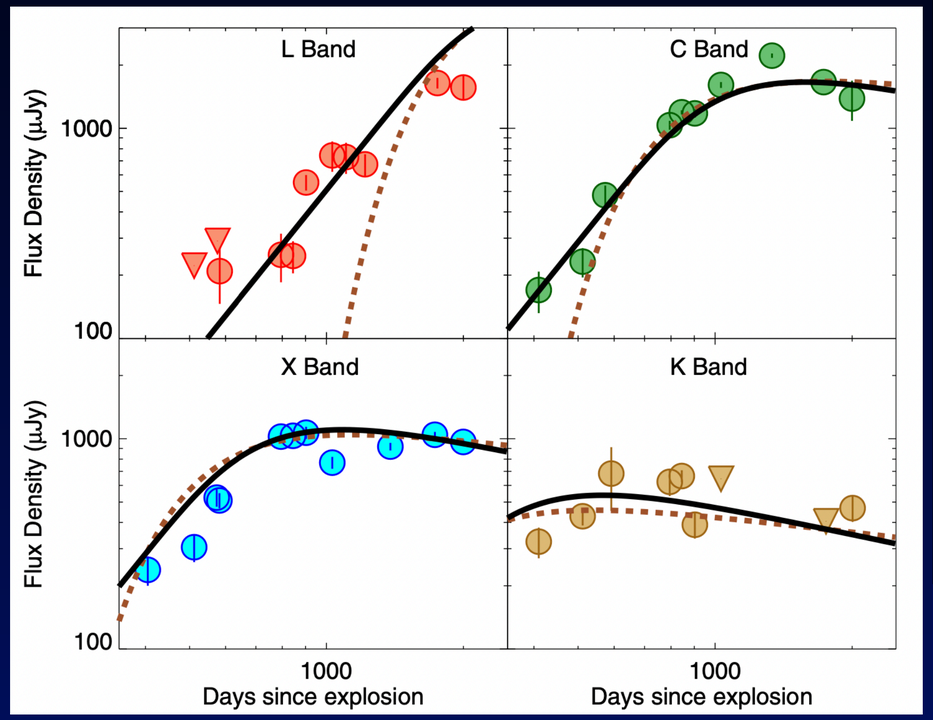
Absorption of Radio emission



Weiler+02

- Synchrotron emission
- Synchrotron self-absorption (fast ejecta, low mass-loss rate, Ib/Ic,IIb etc. see Nayana, PC+,2022, 2023)
  - Magnetic field, size etc
- Free-free absorption (slow ejecta, large mass-loss rate)
  - Density of the medium, mass-loss rate

Absorption of Radio emission



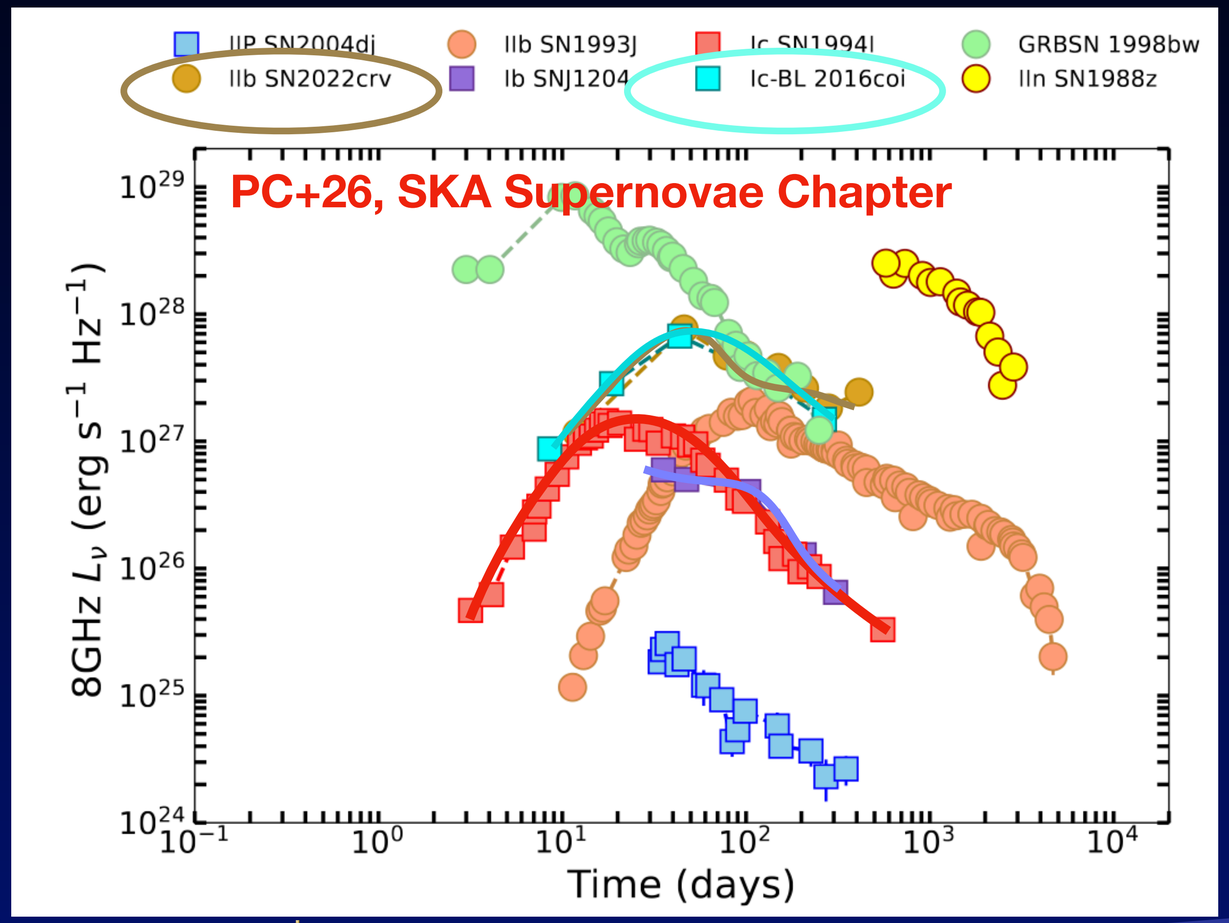
- Synchrotron emission
- Synchrotron self-absorption (fast ejecta, low mass-loss rate, Ib/Ic,IIb etc. see Nayana, PC+,2022, 2023)
  - Magnetic field, size etc
- Free-free absorption (slow ejecta, large mass-loss rate)
  - Density of the medium, mass-loss rate
- Internal free-free absorption (radiative shock, cool dense shell, mixing of cool gas)

PC+12, PC+18, Baer-way, PC 2025

$$M_a \approx 2 \times 10^{-8}\, T_4^{5/2} M_\odot$$

PC+12

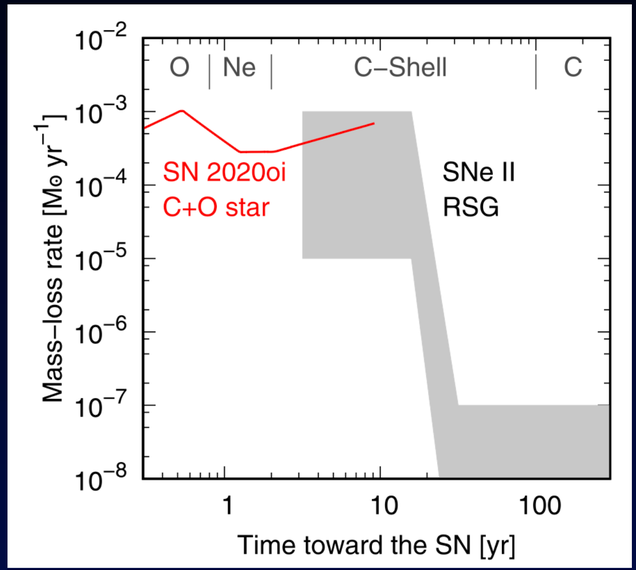
Absorption of Radio emission

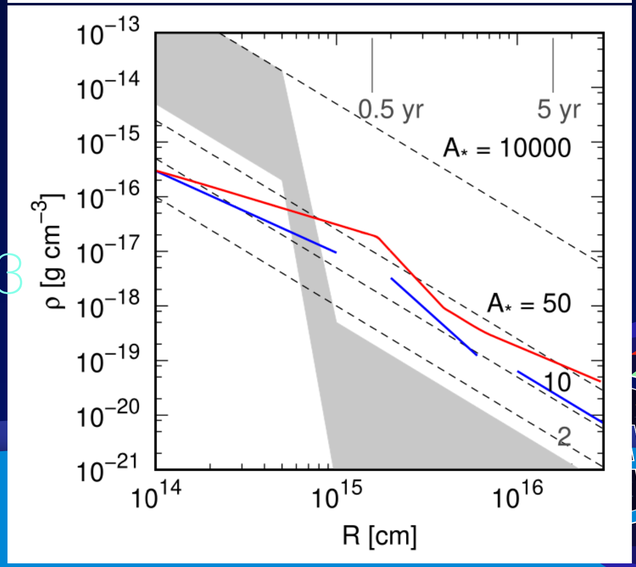


- Degeneracy in physical parameters
- Early peak due to high velocity (derived from SSA) can mimic the early peak due to low density CSM (derived from FFA)
- True understanding to physical environments about supernovae

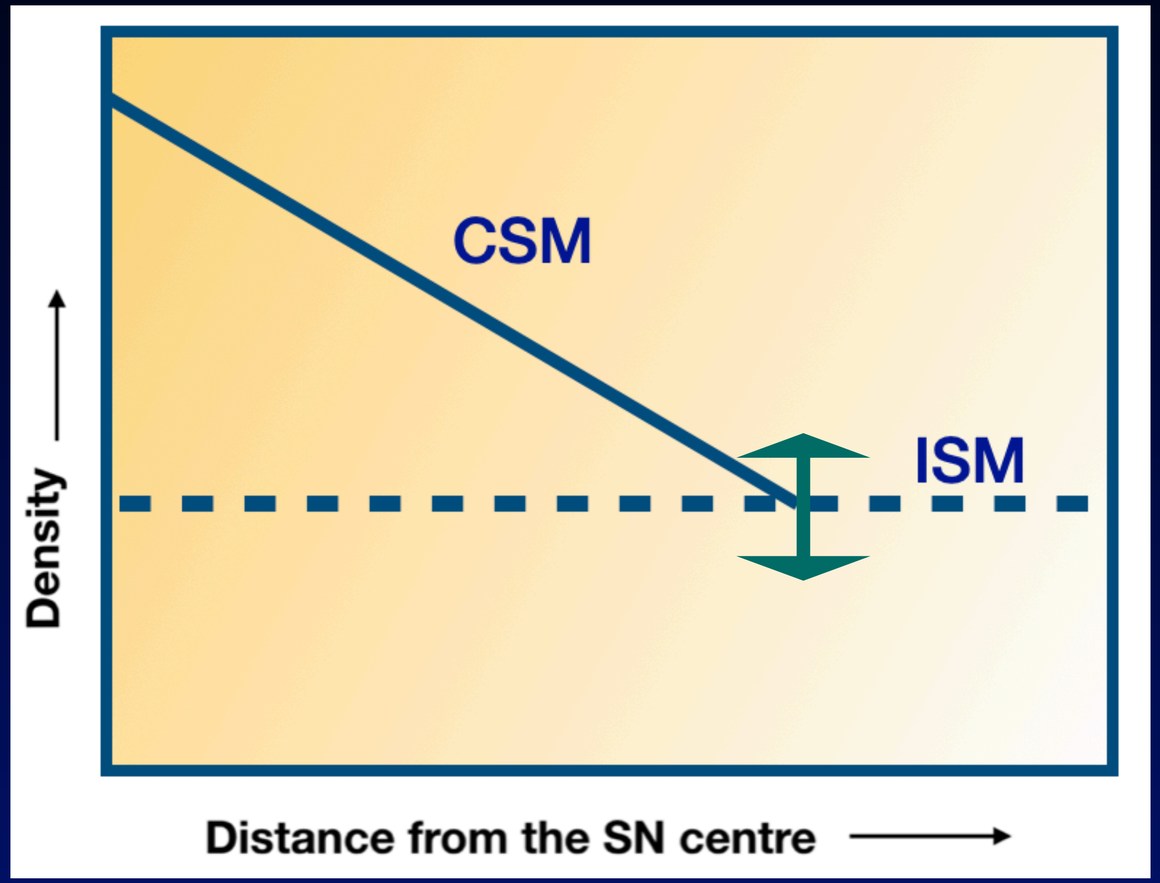
Compact CSM - also seen in ALMA mm bands

- Radio absorption SSA - $F_\nu \propto R^2 B^{-1/2} \nu^{5/2}$, $B \propto \rho_{\rm CSM}^{1/2}$, $F_\nu \propto \rho_{\rm CSM}^{-1/4}$
- Radio absorption FFA - $\tau_{\rm ff} \propto \rho_{\rm CSM}^2$, $F_\nu \approx F_{\nu,intrinsic} e^{-\tau_{\rm ff}}$
- Optically thin flux - $F_\nu \propto \rho_{\rm CSM}^{(p+5)/4}$
- Early studies possible with ALMA
- SN 2020oi (Ic) - Maeda, PC+21
- SN 2018ivc (IIL->IIb)- Maeda, PC+23, Maeda, Michiyama, pc+23
- SN 2020oi - enhanced mass-loss seen - Maeda, PC+21





Extent of CSM - radio observations



- Late time radio emission in various supernovae
- VLASS - Stroh et al. 2021- 19 supernovae - up to 40 years old
- ASKAP - Rose et al. 2024 - 7 rebrightening SNe - oldest 30 years old
- Extent of the CSM - how long mass-loss rate

Extent of CSM - implications of binary

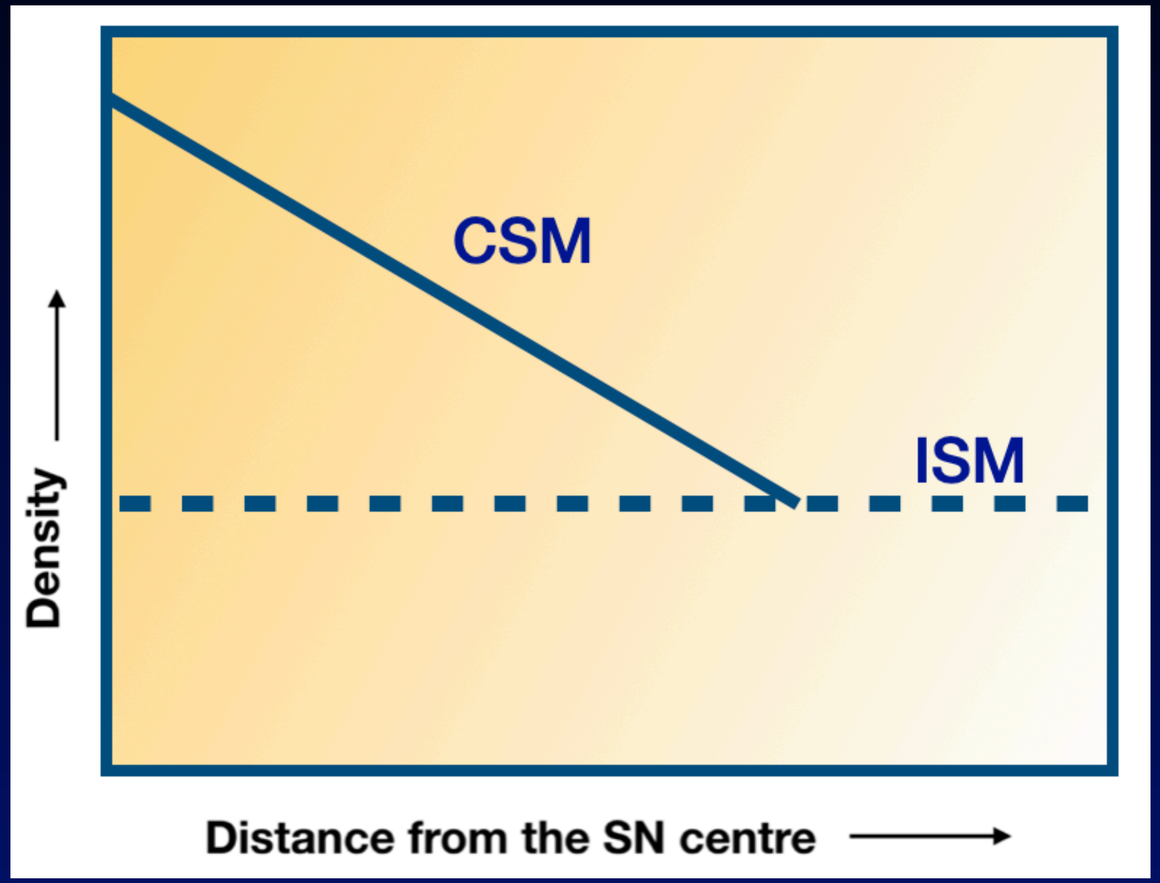
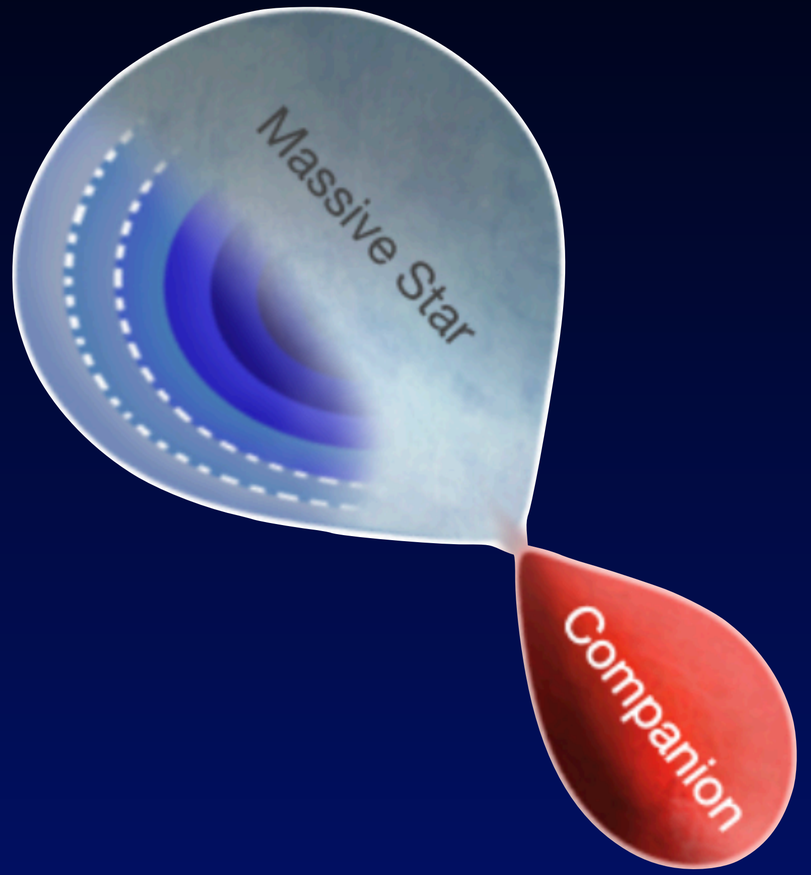
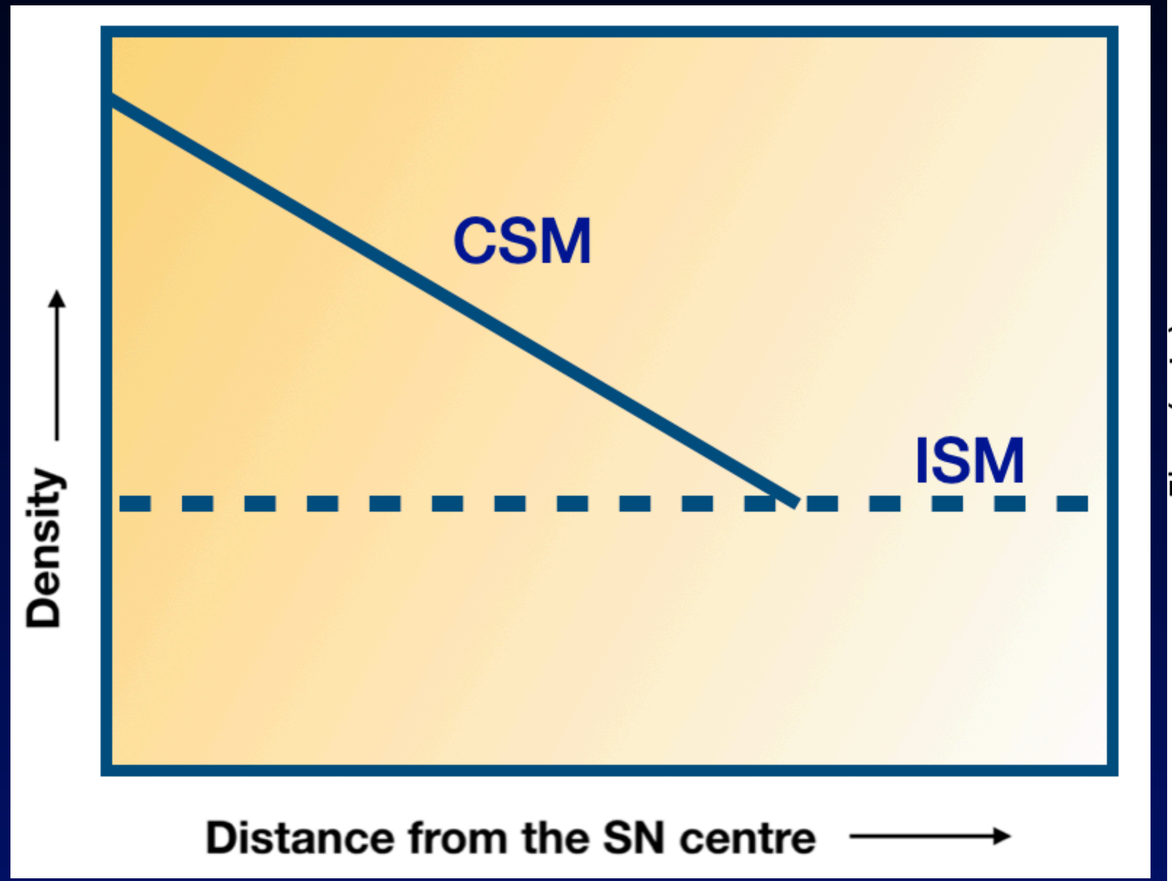
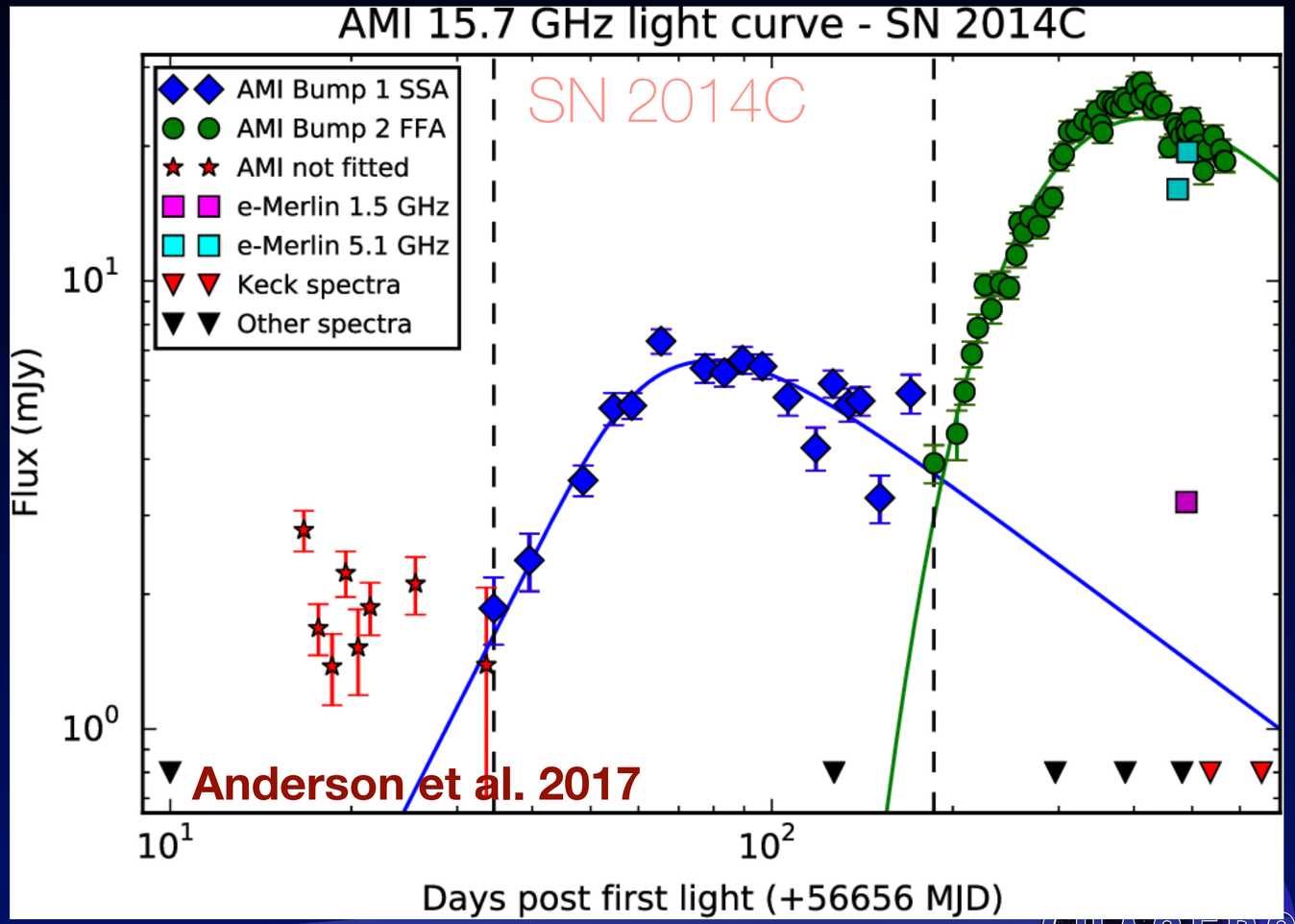


Image Credit:PC

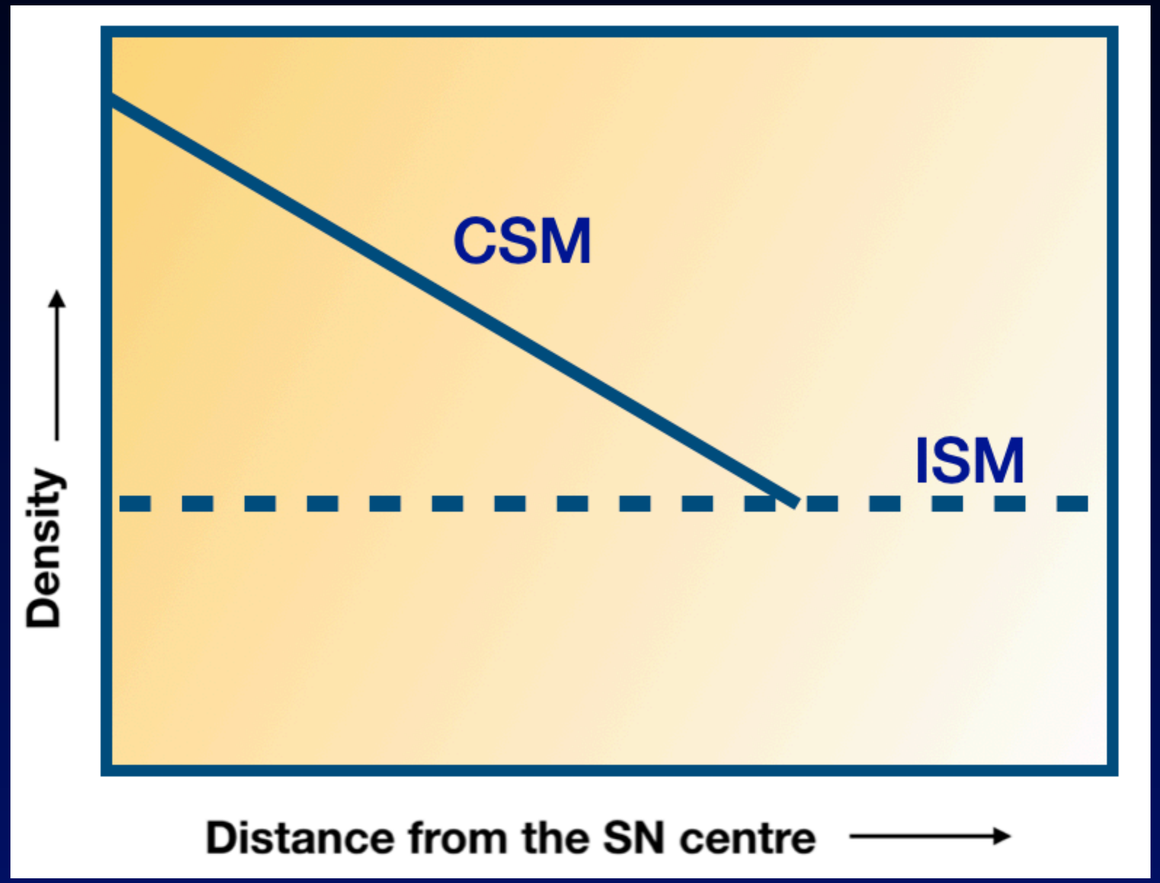


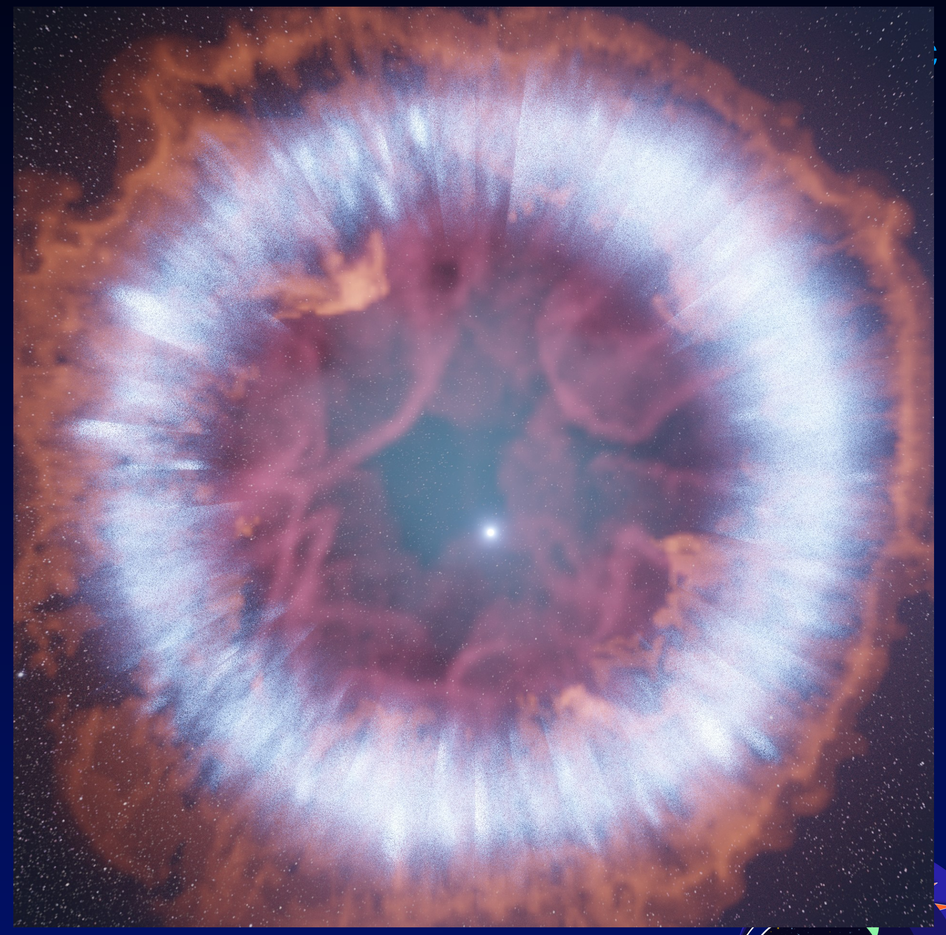
Extent of CSM - implications of binary





Extent of CSM - implications of binary

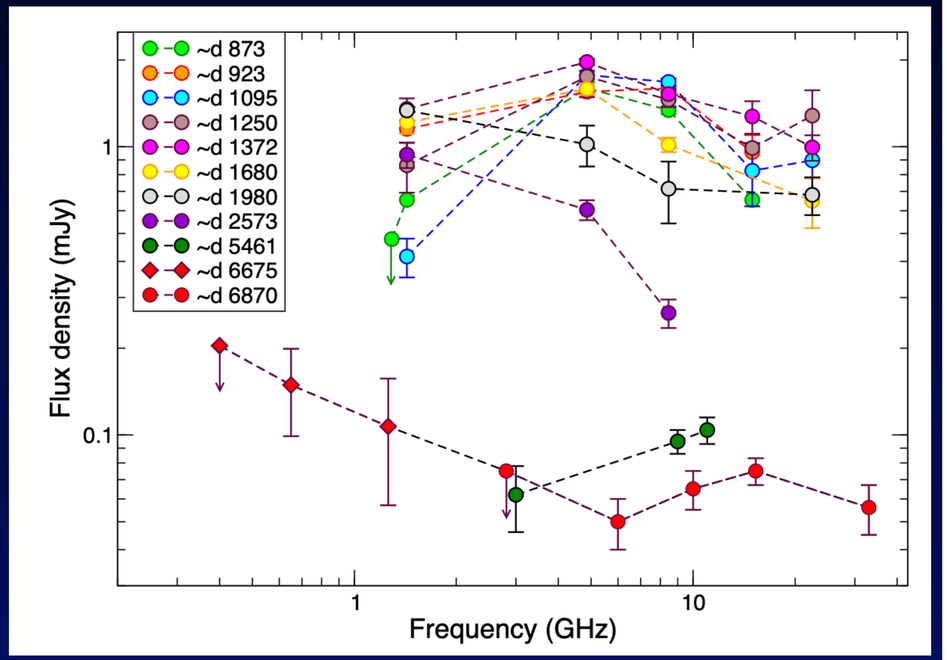


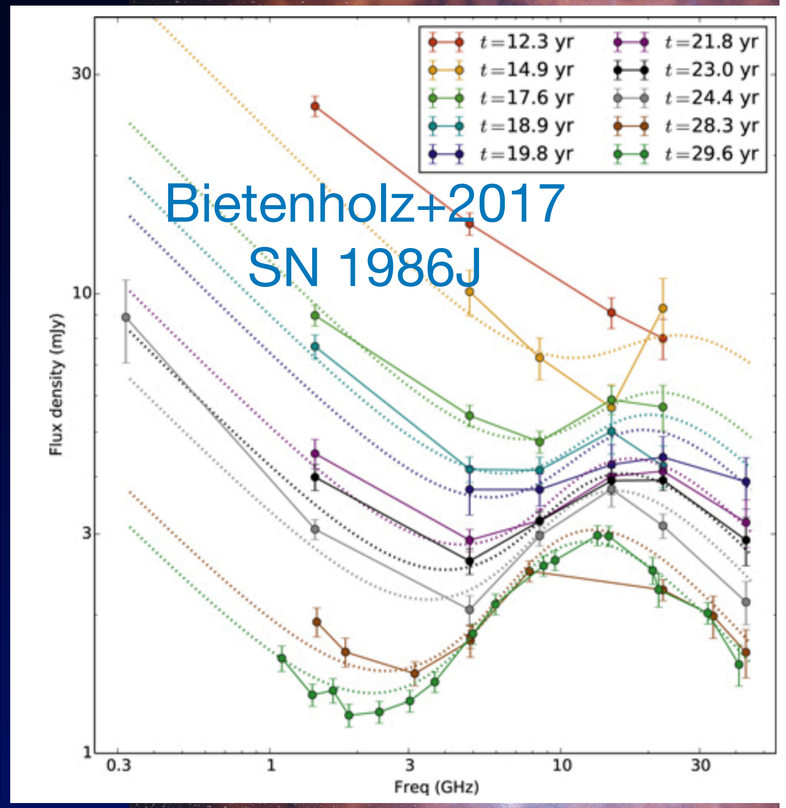


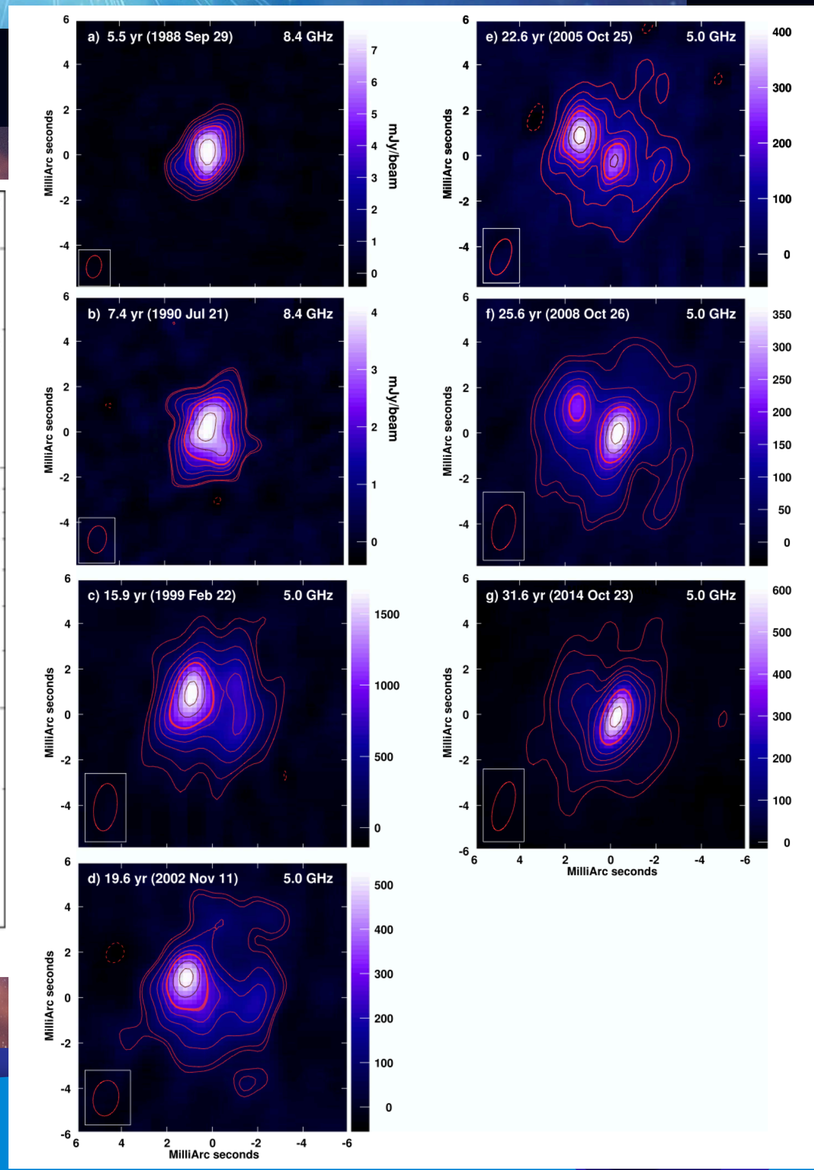
Credit: ALMA (ESO/NAOJ/NRAO), K. Maeda et al.

Clues to the progenitor- late time

- SN 2001em - VLA, ChandraXO, PC+2020



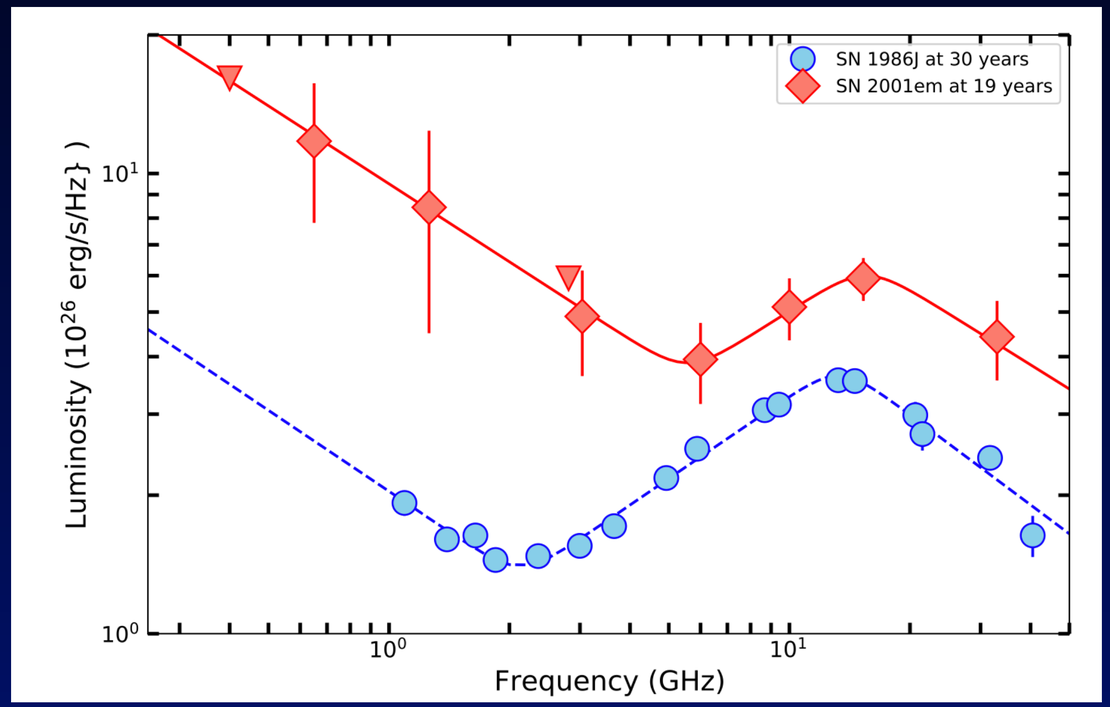


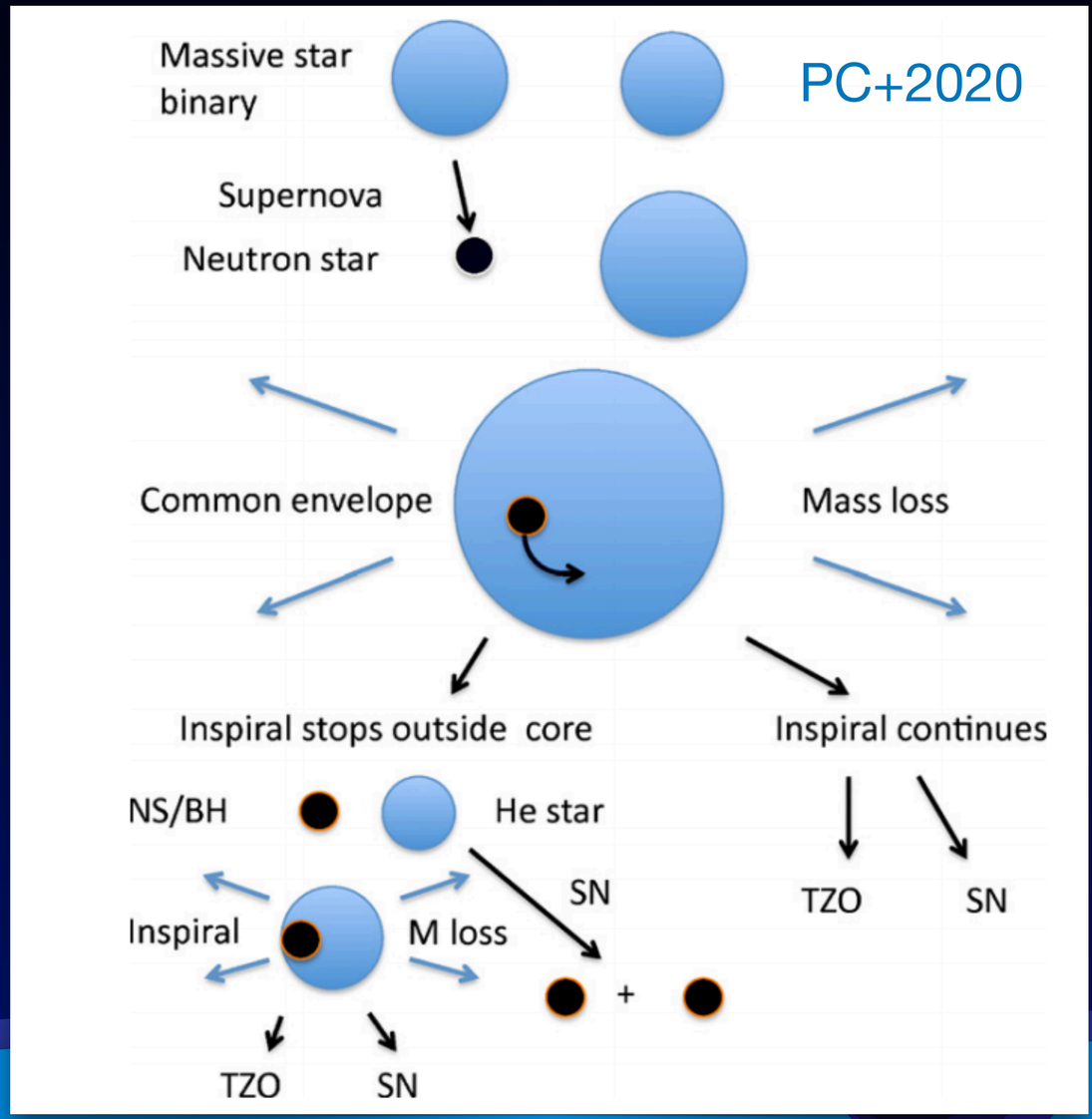


Clues to the progenitor- late time

Bietenholz+2017
SN 1986J

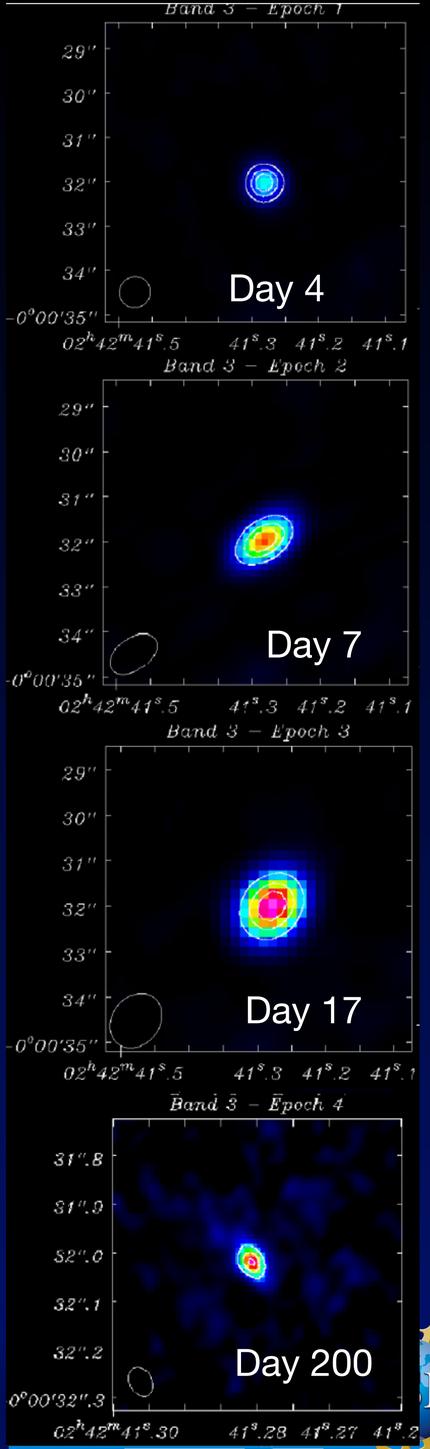
PC+2020



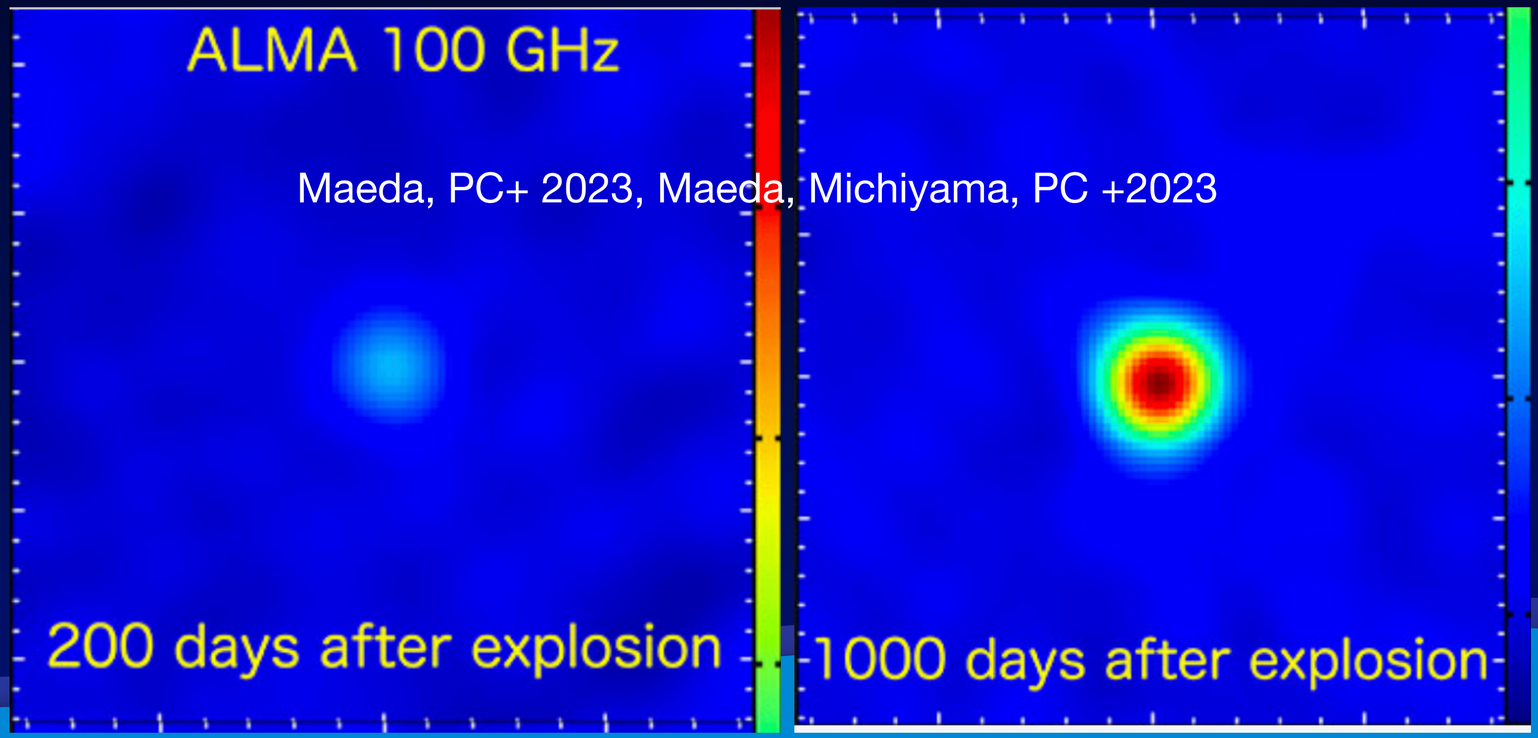


PC+2020

Binarity in Supernovae

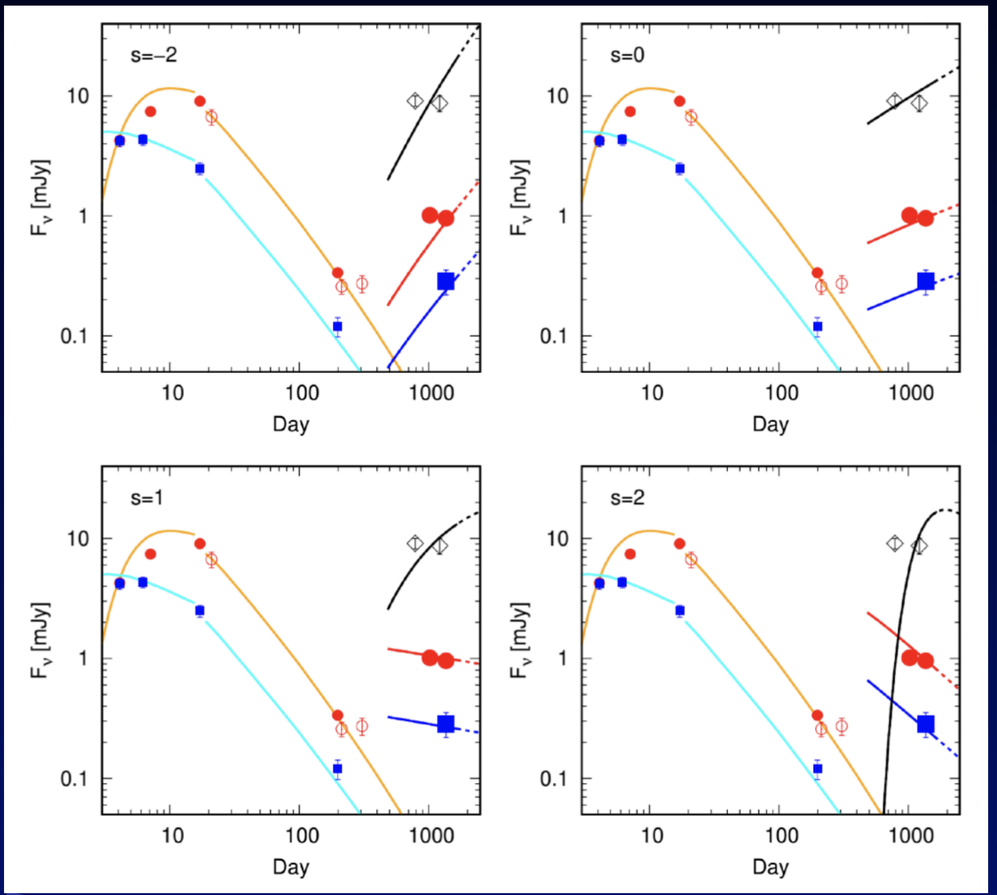


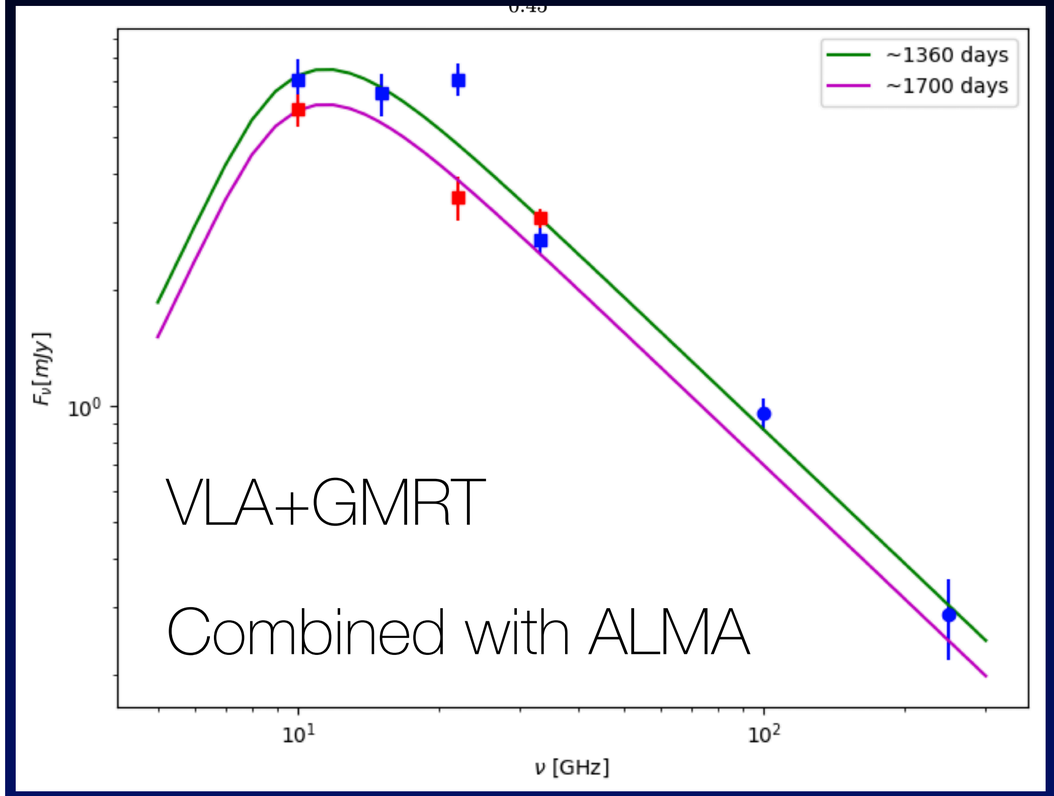
- ALMA infant supernovae program
- SN 2018ivc - Day 4 - 200 (Maeda, PC+2023a)
- A supernova with just a hint of Hydrogen in the spectrum



Understanding the progenitor -Binarity in supernovae progenitors

Maeda, Michiyama , PC+2023b





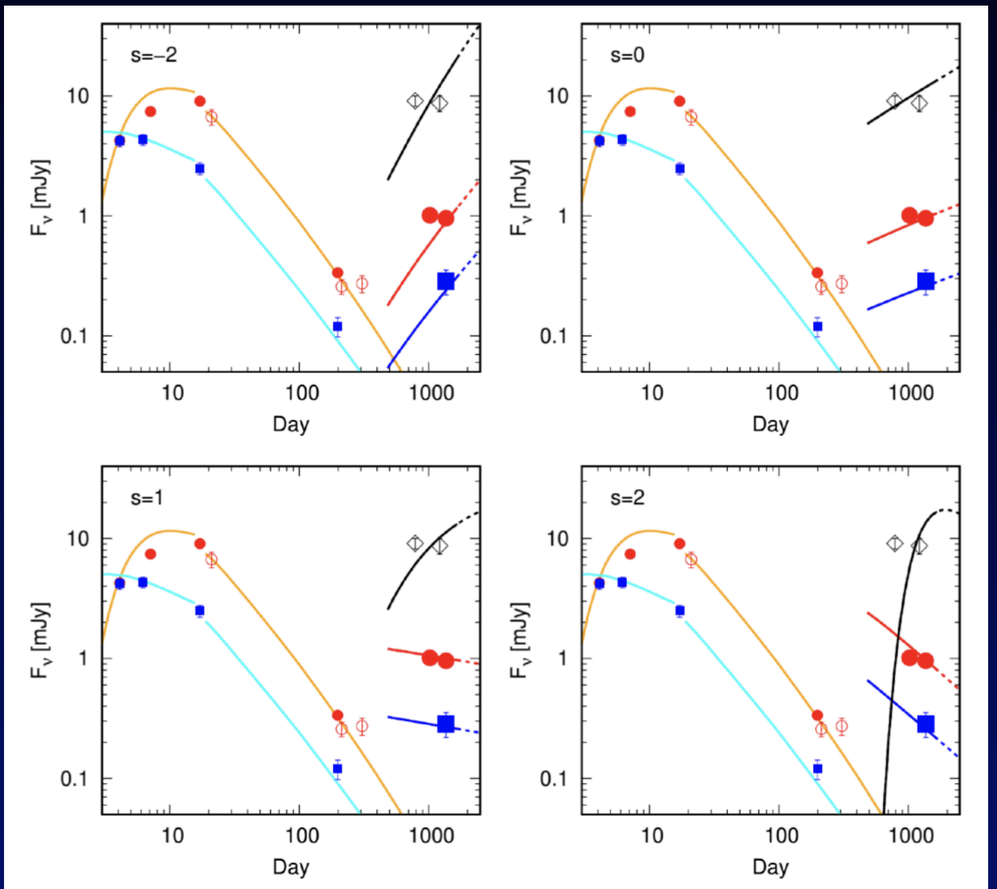
Annika Deutsch

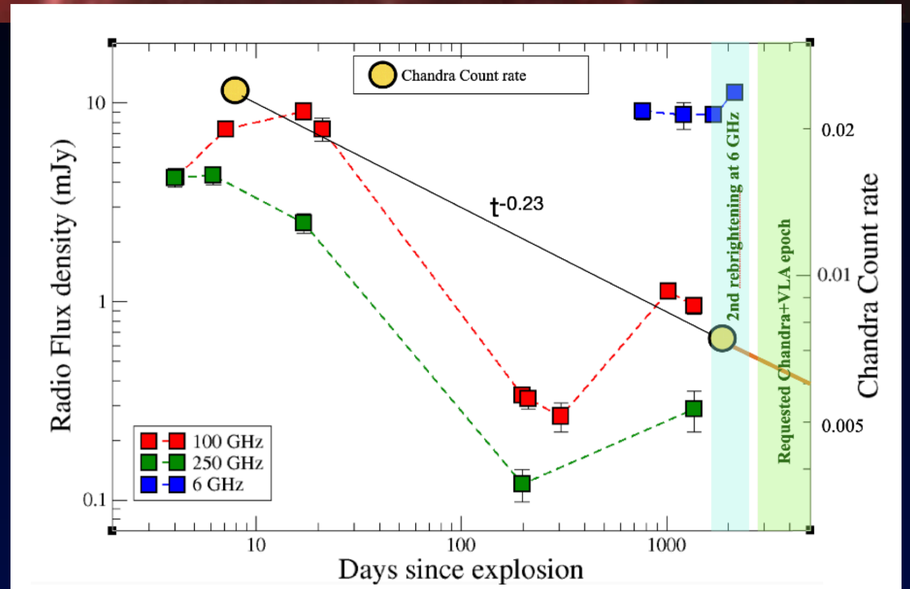
Multiwavelength

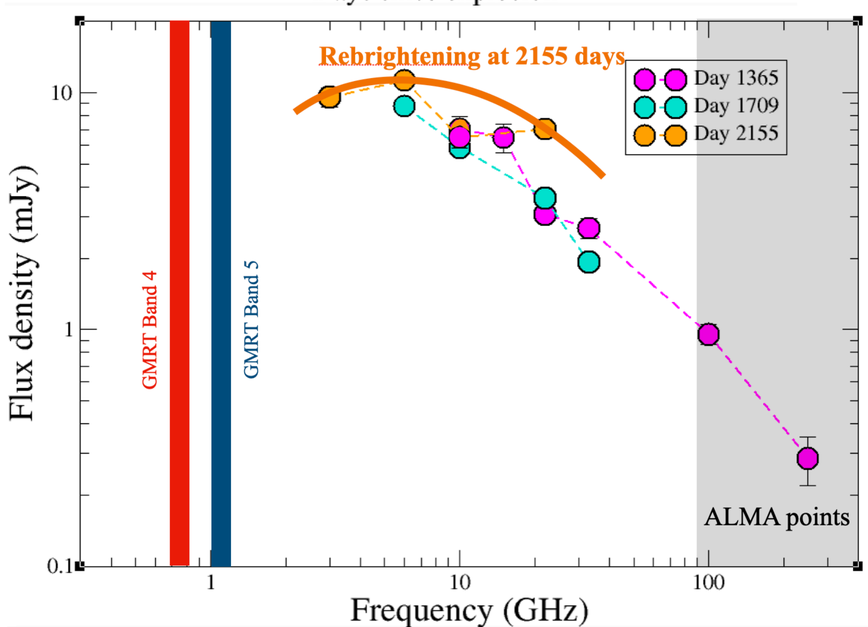
Study, X-ray, IR, radio

Understanding the progenitor -Binarity in supernovae progenitors

Maeda, Michiyama , PC+2023b







Annika Deutsch

Multiwavelength

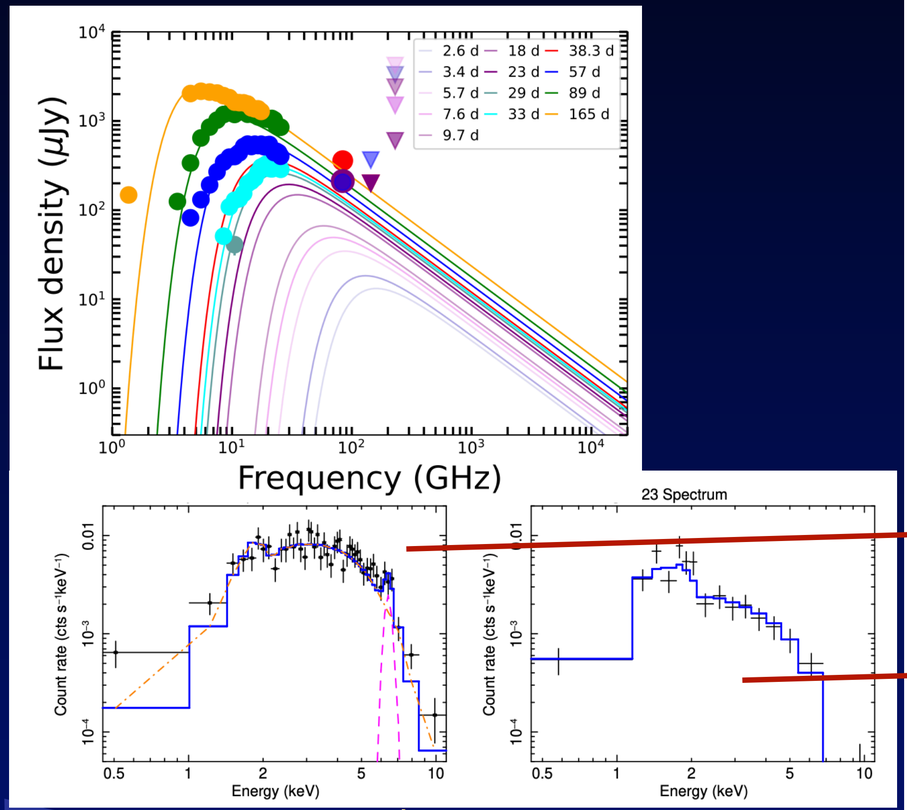
Study, X-ray, IR, radio

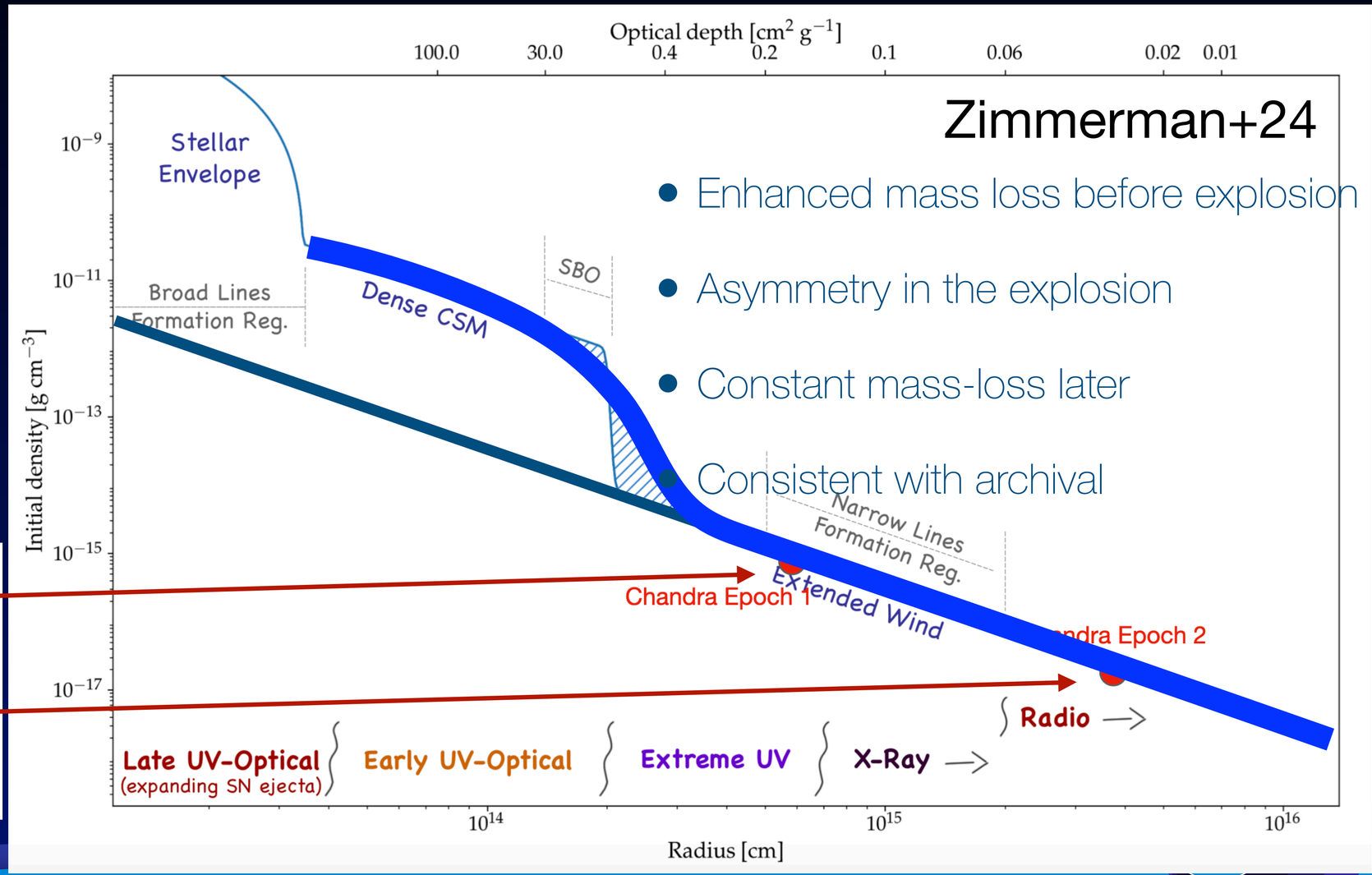
Circumstellar interaction across supernovae

Multiwavelength study. SN 2023ixf

VLA+GMRT+Chandra+XMM+NuSTAR- SN 2023ixf

PC+2024, Nayana….PC+2024,
Berger+2023, Zimmermann 2023



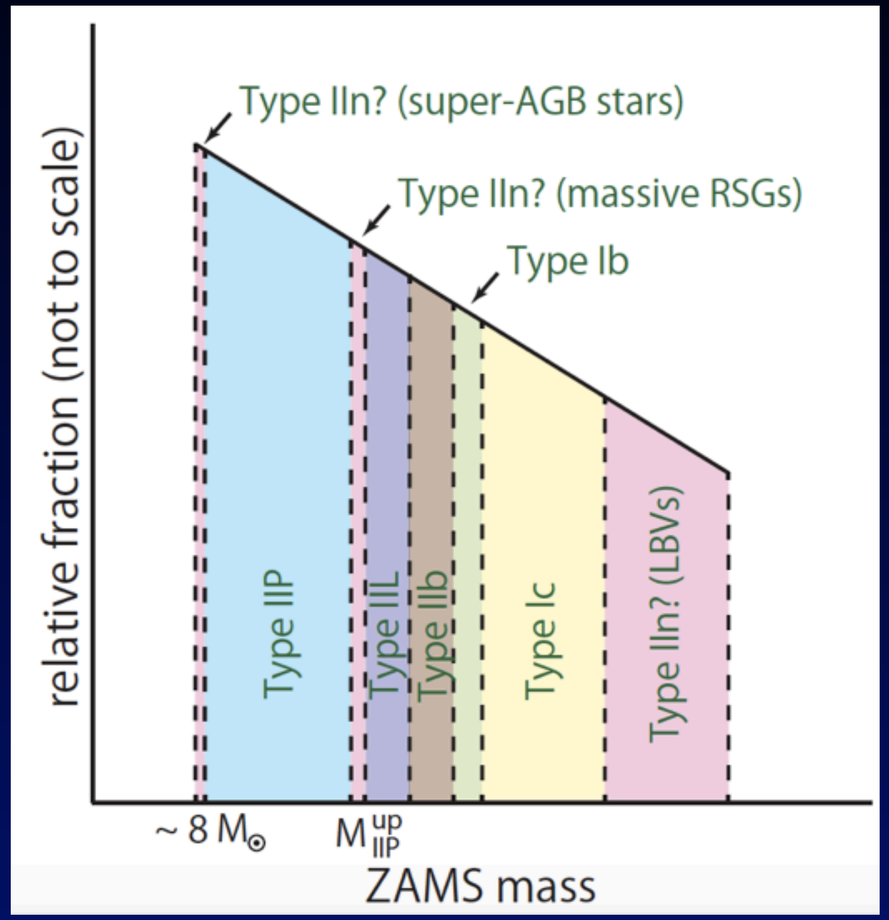


Zimmerman+24

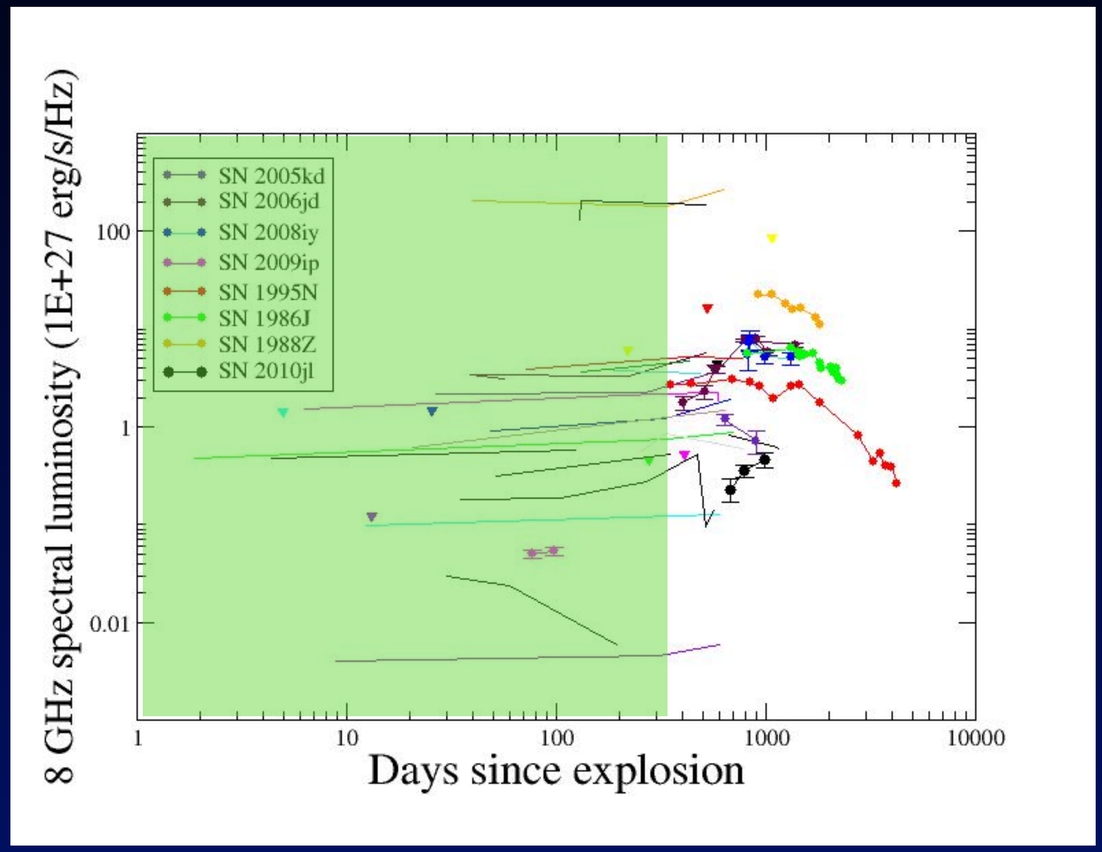
- Enhanced mass loss before explosion
- Asymmetry in the explosion
- Constant mass-loss later
- Consistent with archival

Progenitors of IIn supernovae

Moriya+2012



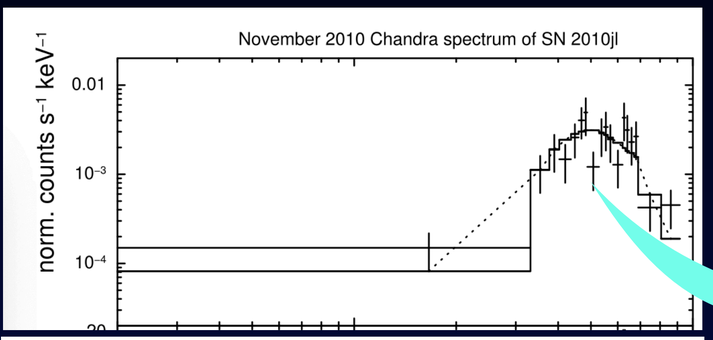
PC 2018, 2025

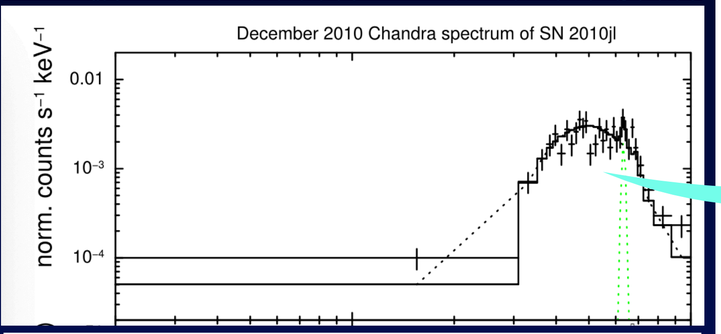


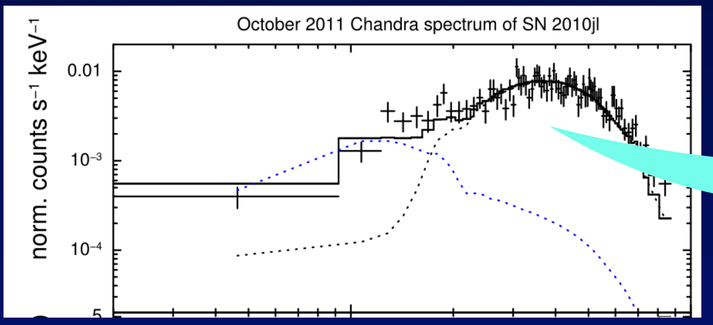
CSM ~10^{15}-10^{16}cm

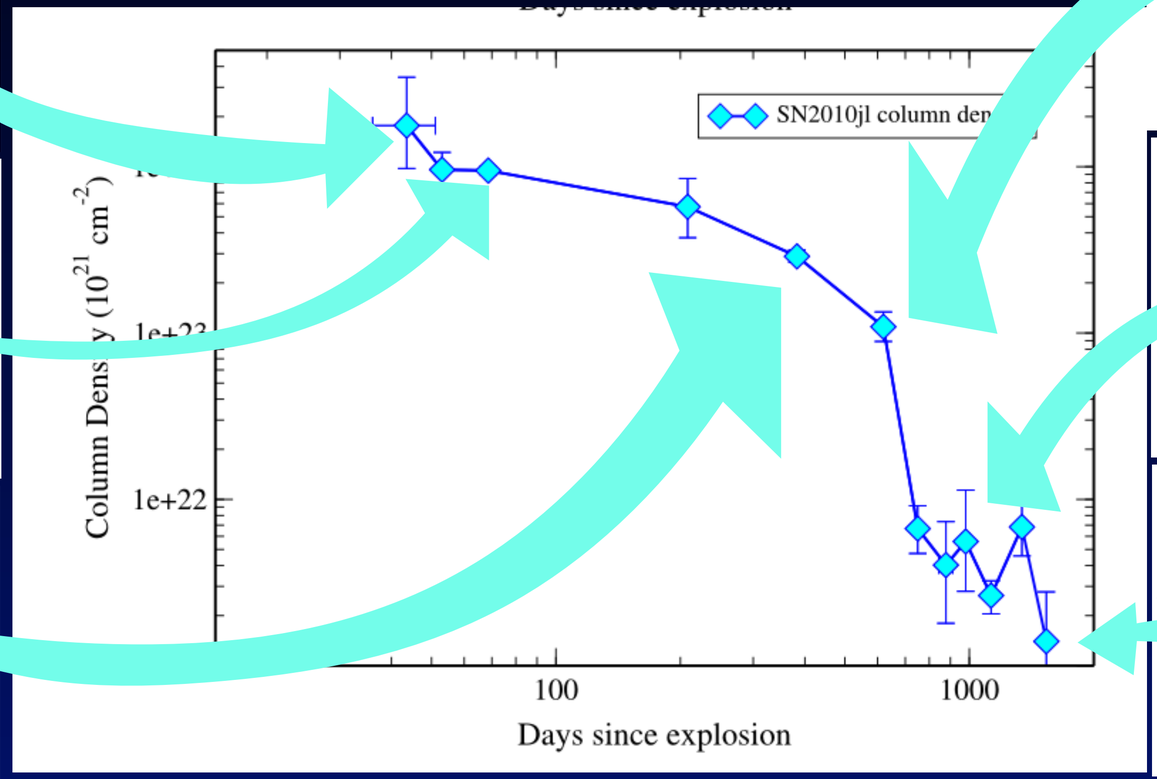
X-ray emission - Evolving CSM

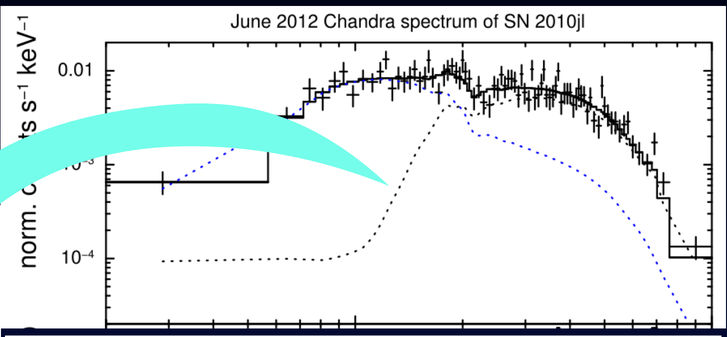
SN 2010jl PC+2015, enhanced mass loss for last 300 years

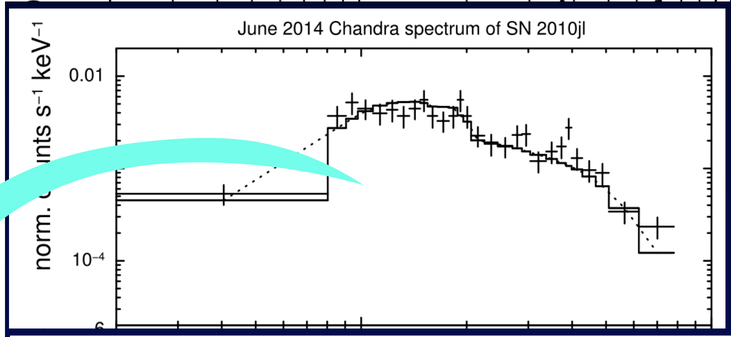


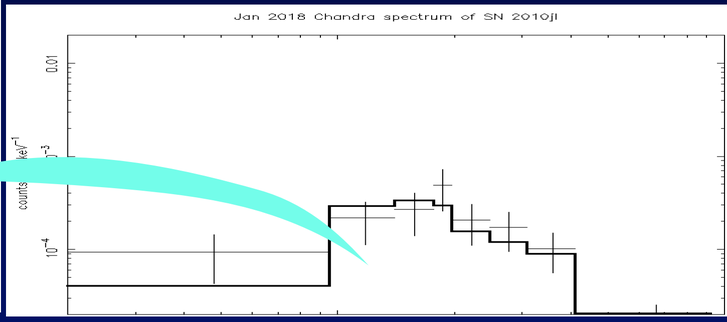








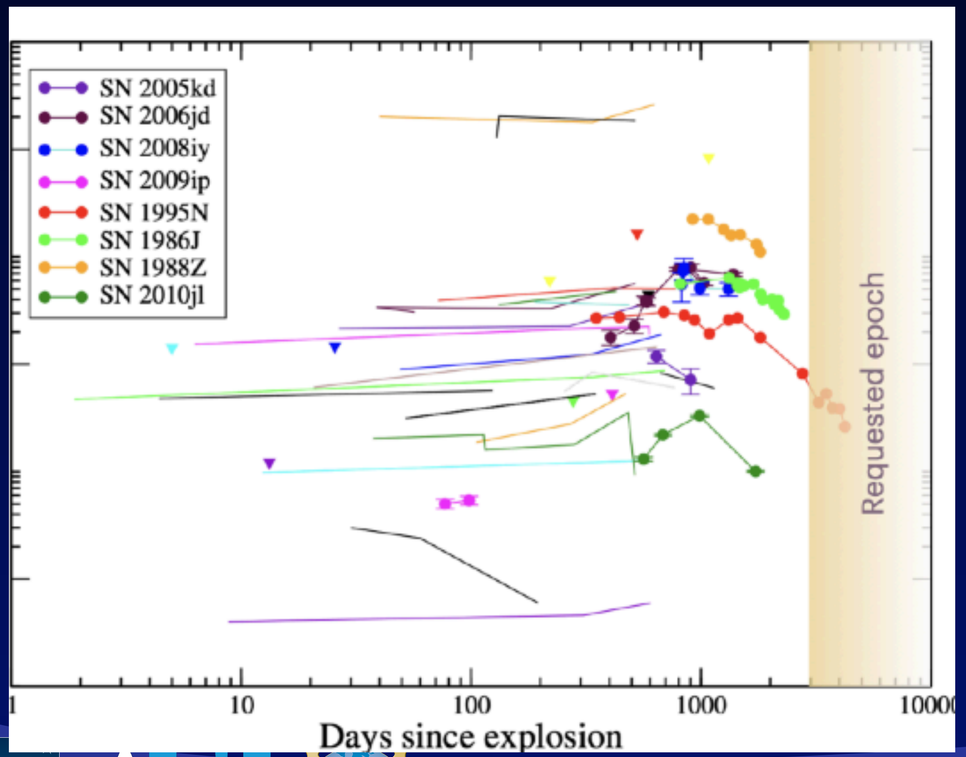


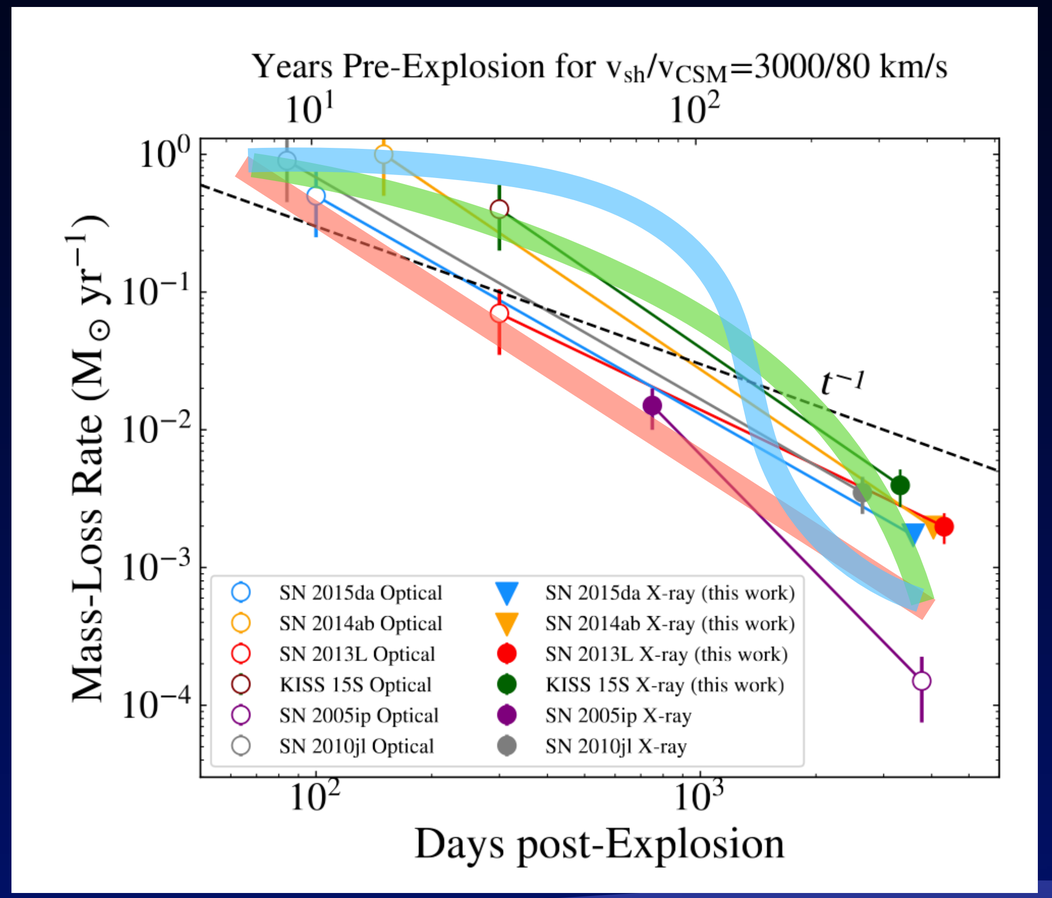


Late time studies - >3000 d

Four interacting supernovae: VLA+GMRT+Chandra, **Hillenkamp, Baer-way, PC+2026**

arXiv:2601.19891





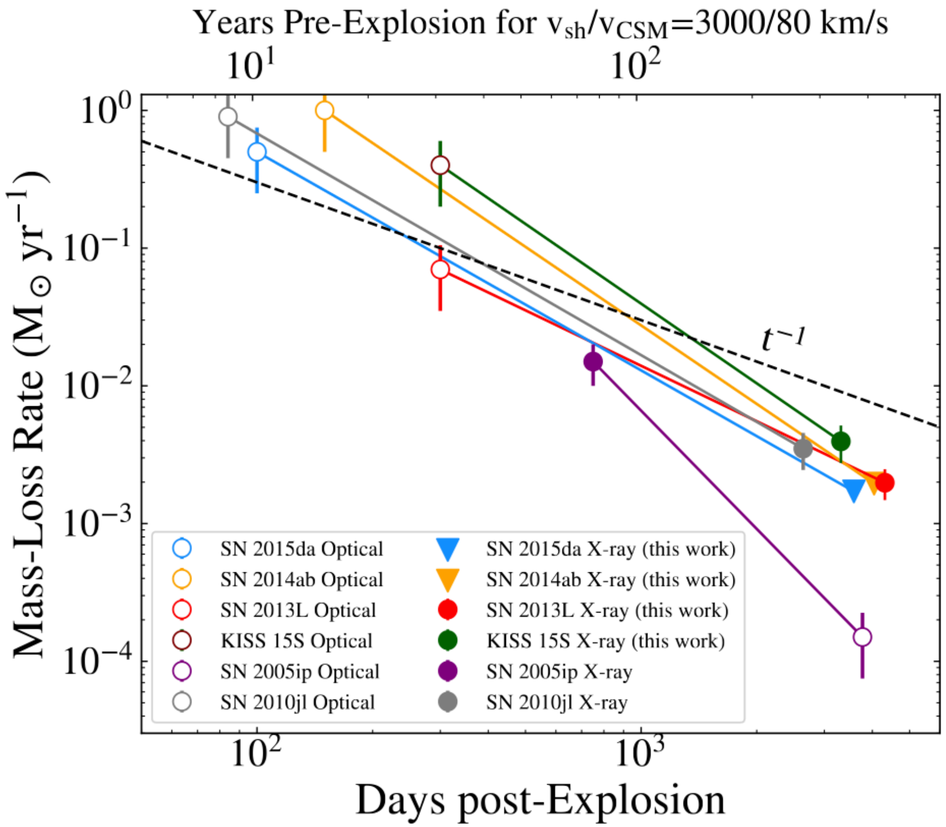
Eliza Hillenkamp

Raphael Baer-way

Late time studies - highly interacting supernovae

Four interacting supernovae: VLA+GMRT+Chandra, **Hillenkamp, Baer-way, PC+2026**

arXiv:2601.19891



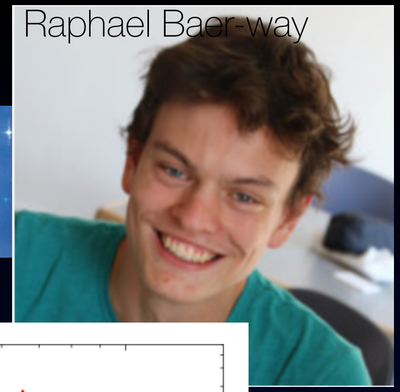
- 2013L, 2014ab, 2015da, KISS15s - Chandra, VLA, GMRT > 3000 d
- 2 orders lower mass-loss rate than previous
- A rapidly evolving progenitor process over the last centuries pre-explosion.

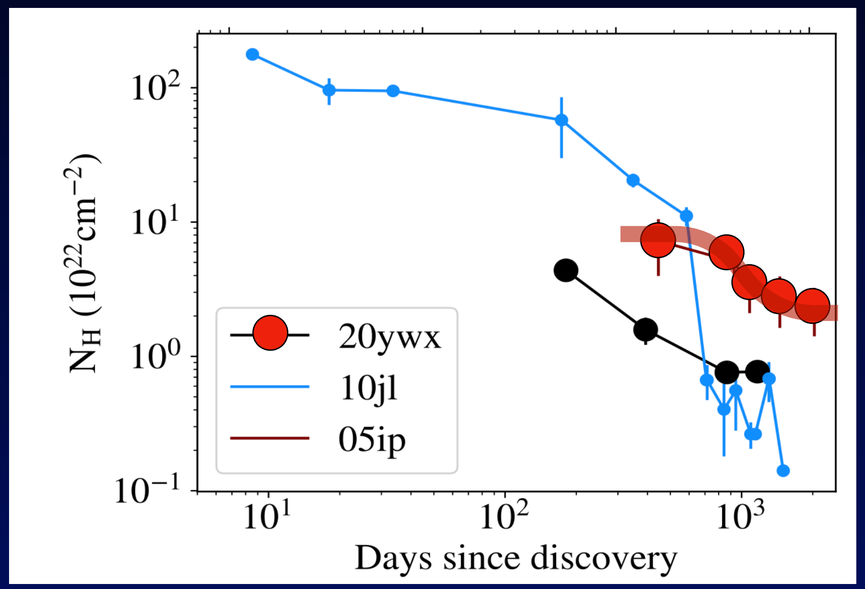
Eliza Hillenkamp

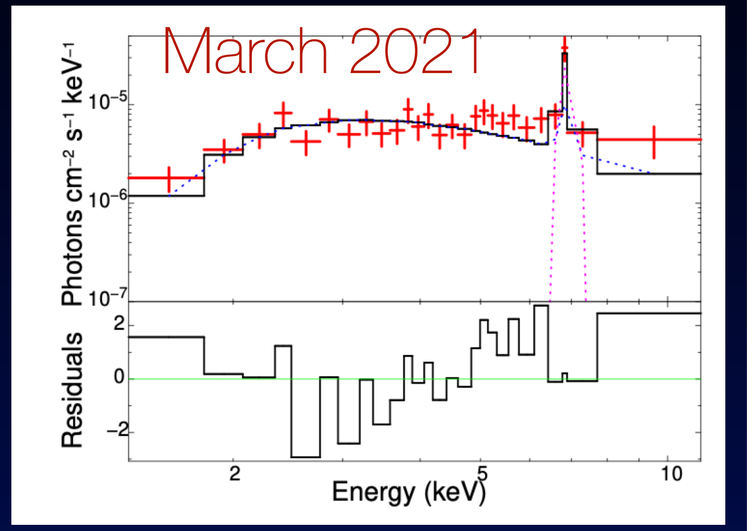
Raphael Baer-way

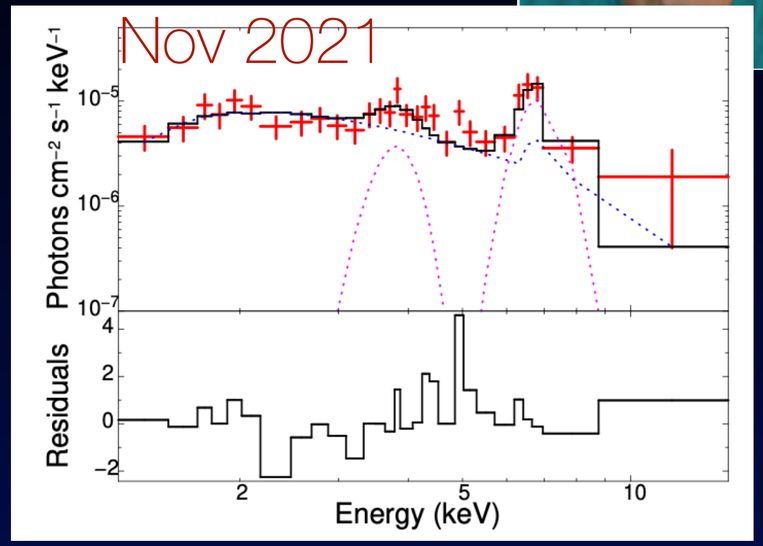
Multiwavelength studies of SN 2020ywx

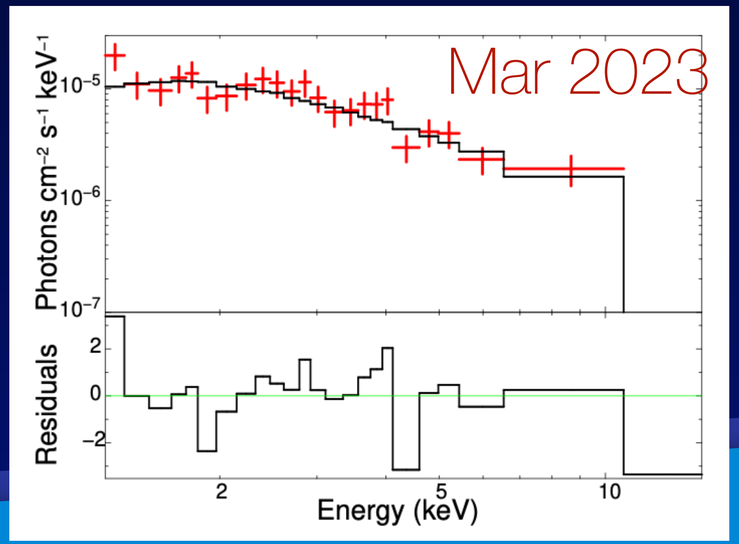
Baer-way, Chandra, Modjaz et al. 2025

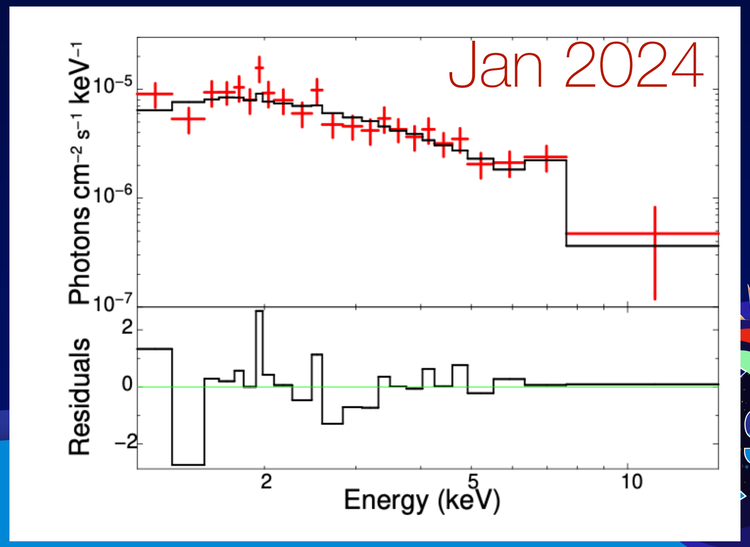






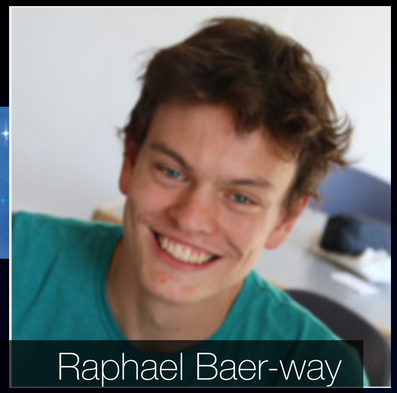


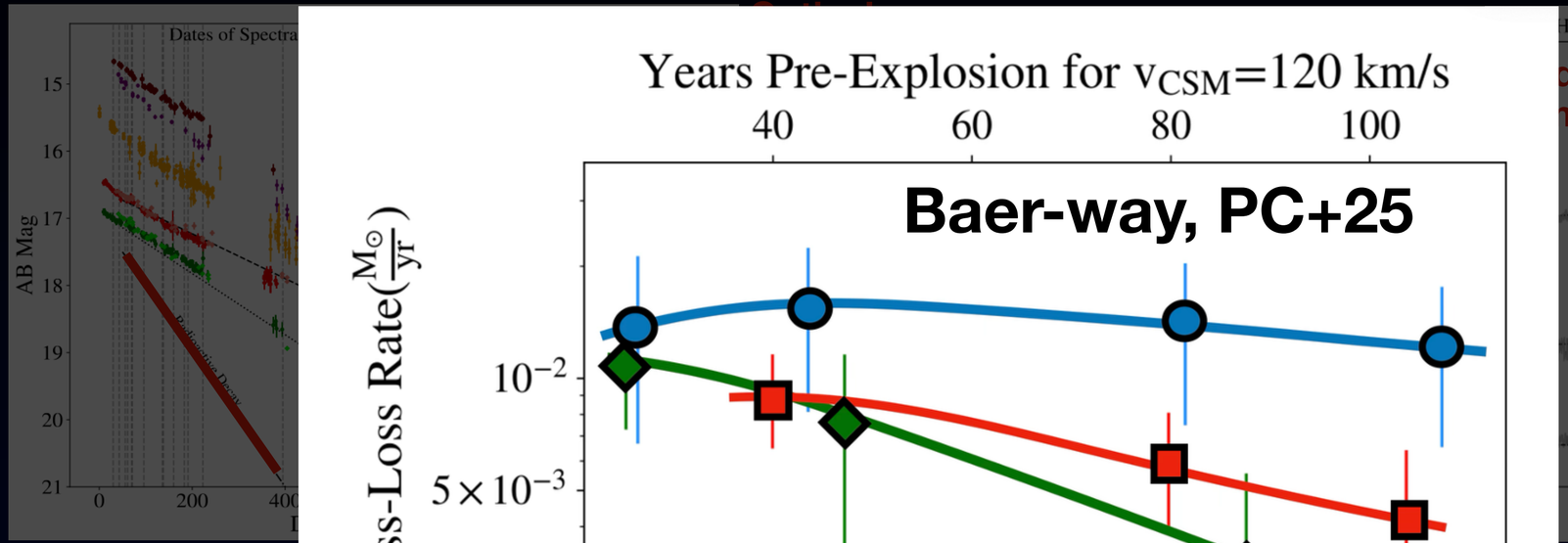


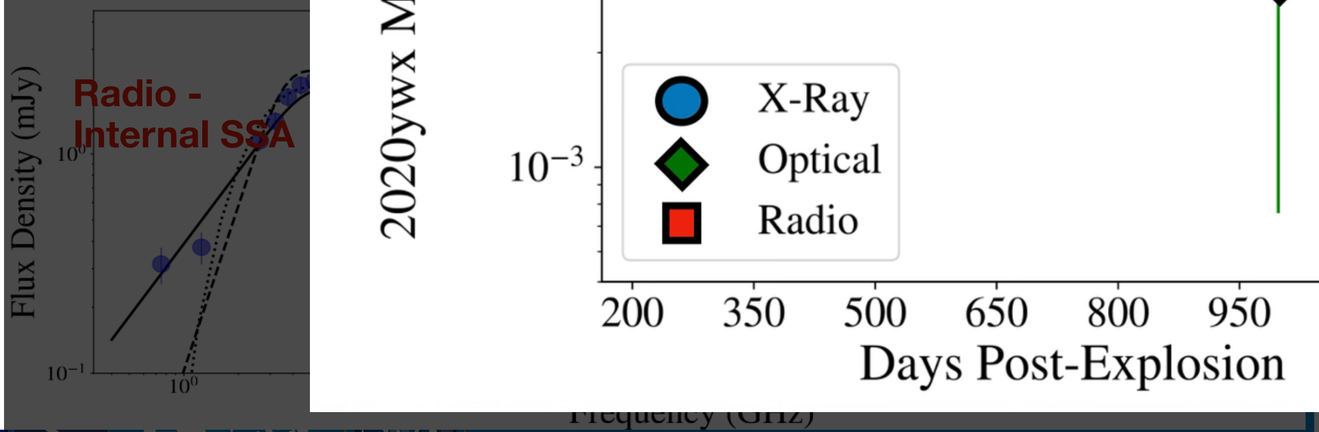


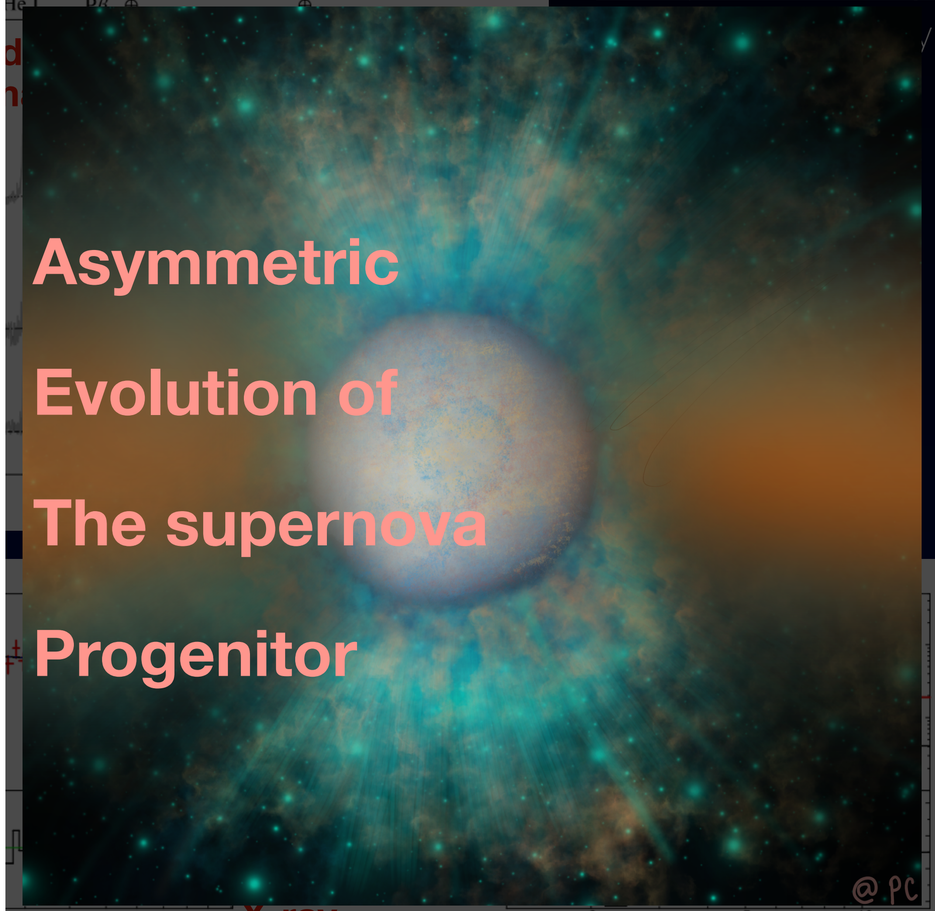
Multiwavelength studies - Asymmetry

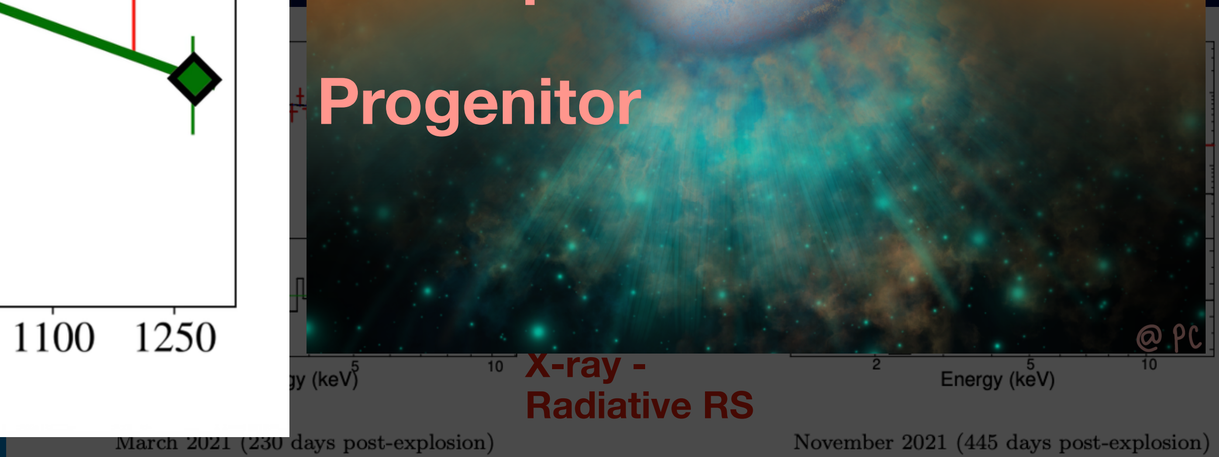
Baer-way, Chandra, Modjaz et al. 2024







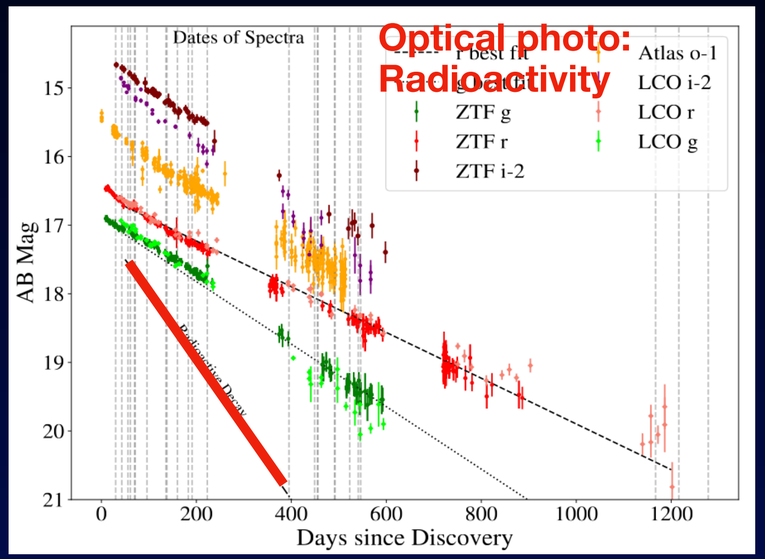


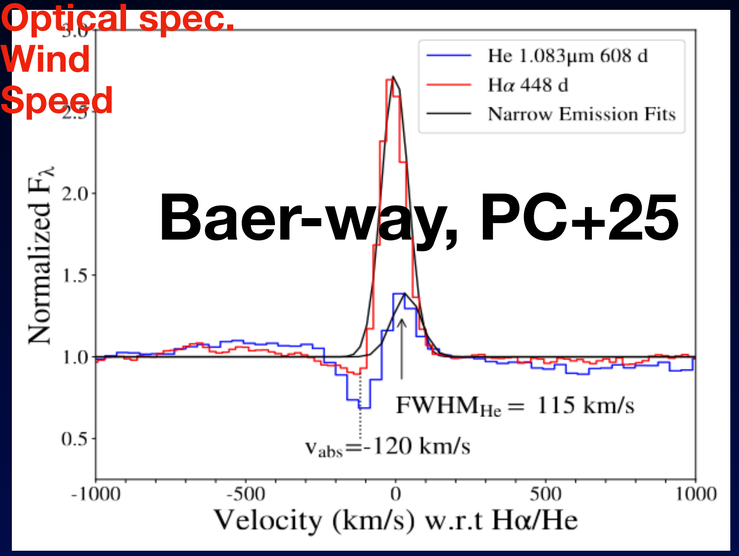


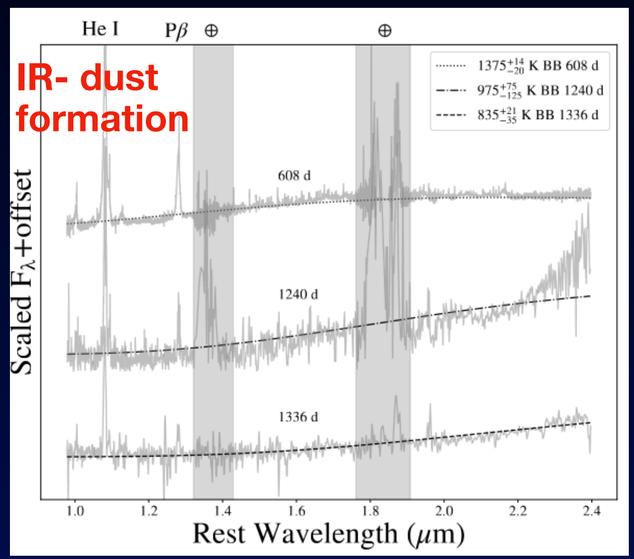
Multiwavelength studies - Asymmetry

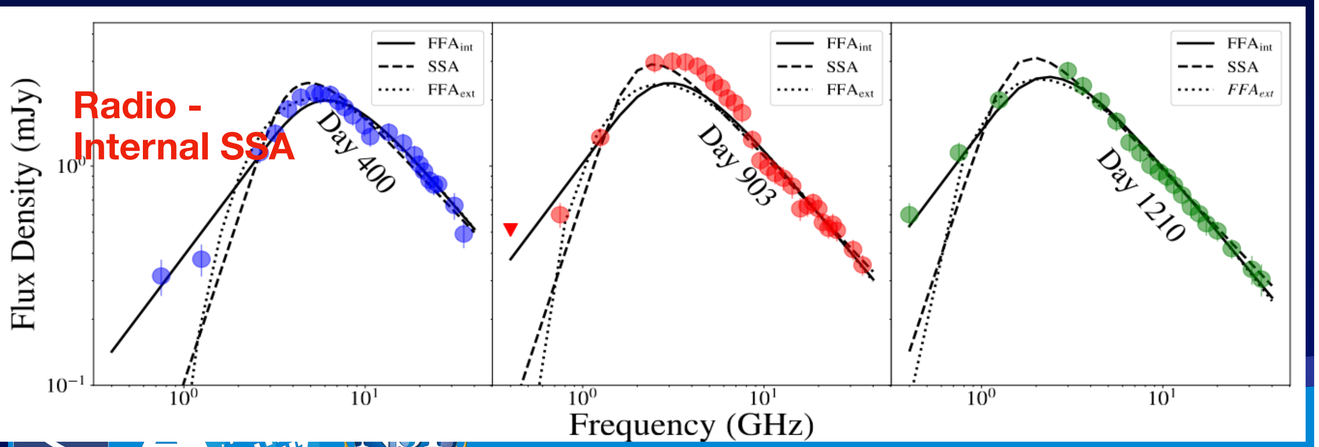
Baer-way, Chandra, Modjaz et al. 2024

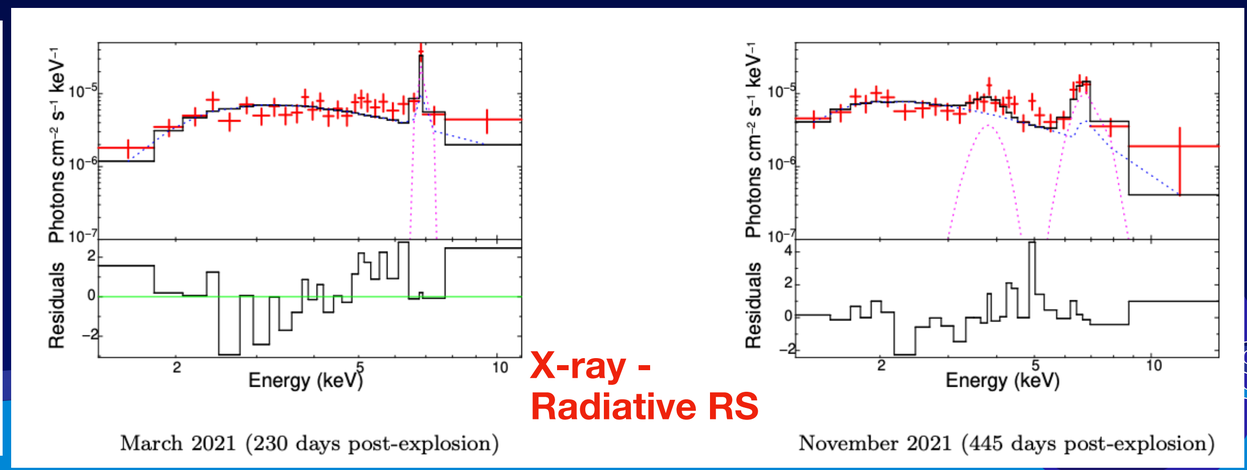
Raphael Baer-Way





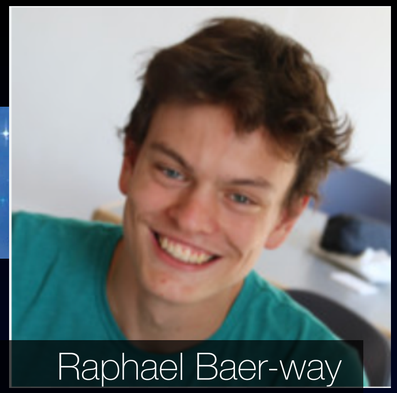


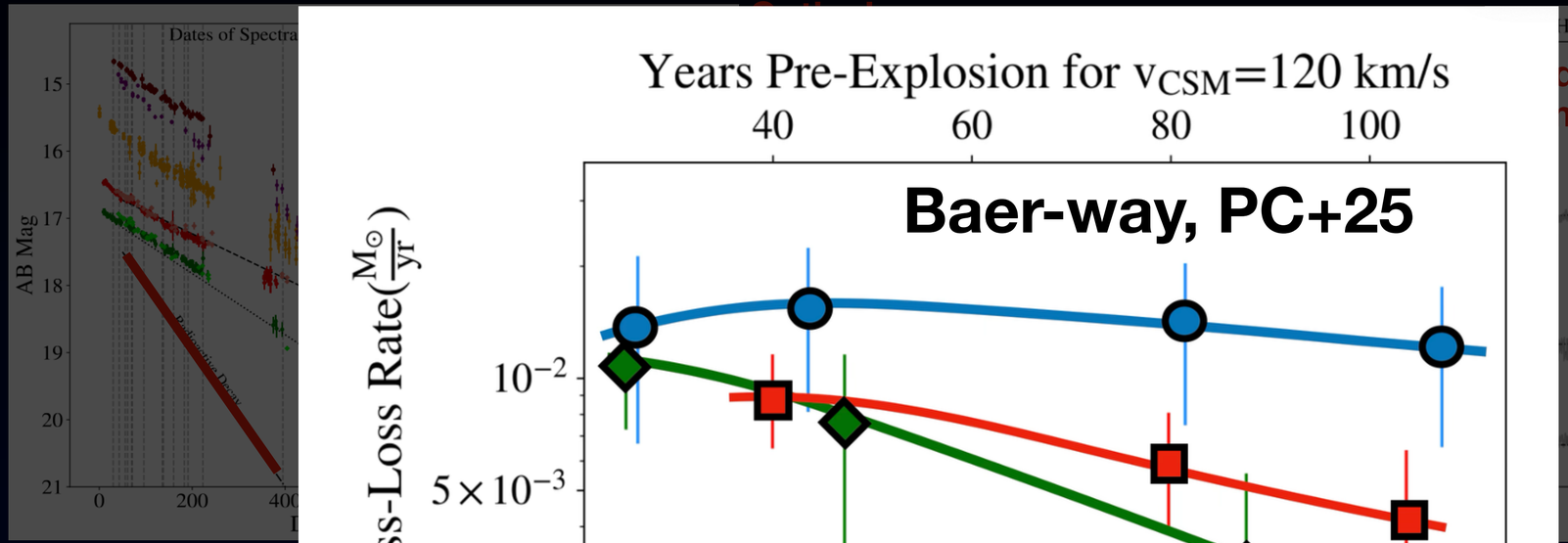


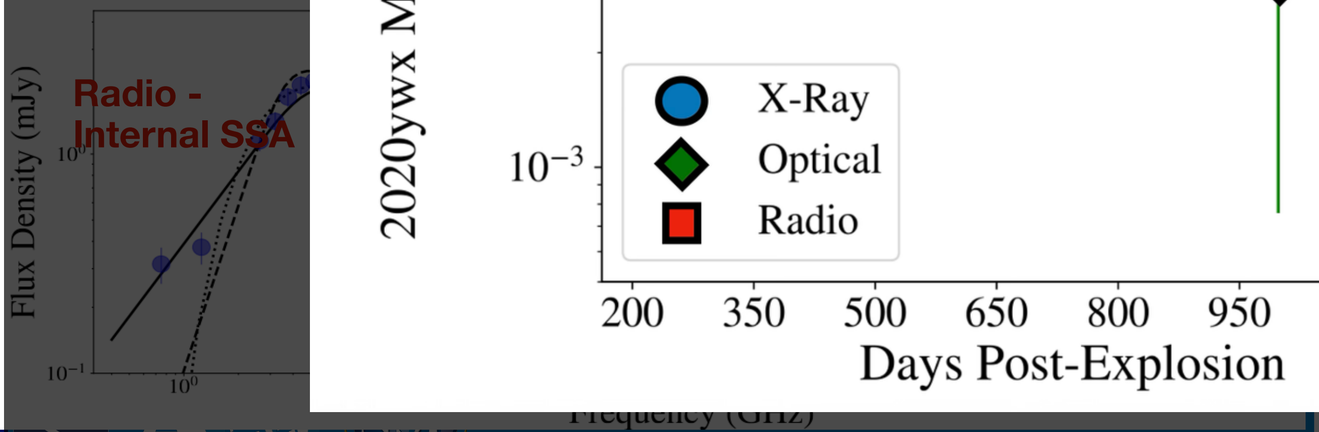


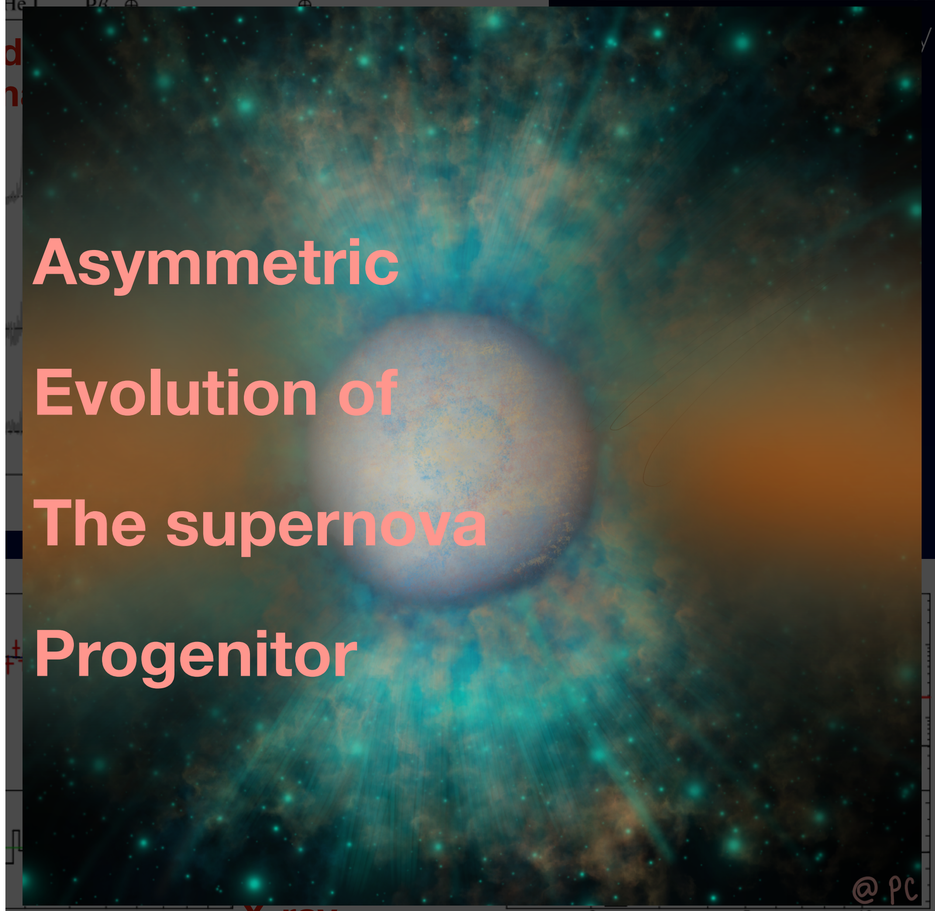
Multiwavelength studies - Asymmetry

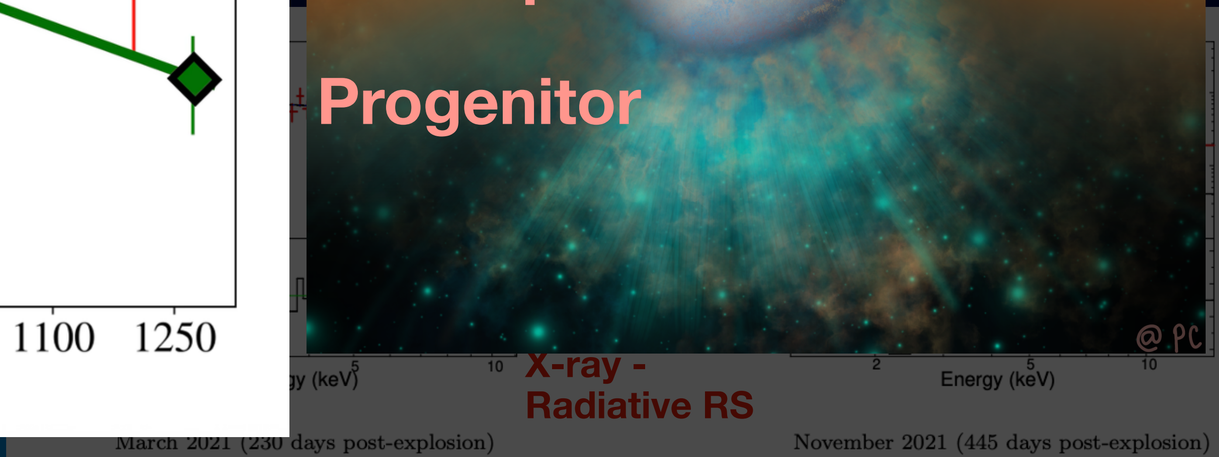
Baer-way, Chandra, Modjaz et al. 2024









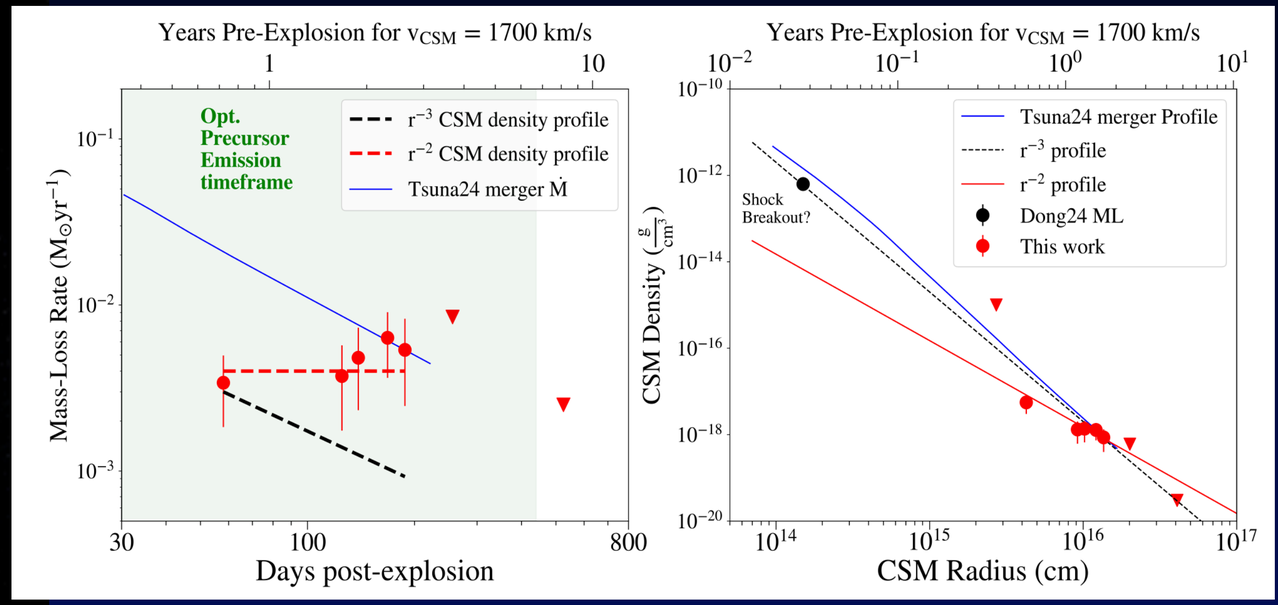


First radio emission from **Ibn** supernova - 2023fyq

Baer-way…PC..2025, Astrophysical Journal Letters, 995:L49

Raphael Baer-way

- Narrow He lines- dense CSM of Helium



- ~5x10^{-3}M$_\odot$/yr mass-loss in last 3 years
- Merger scenario

Ibn supernova 2023fyq

Credit: NRAO

CaSTs - Calcium rich supernovae

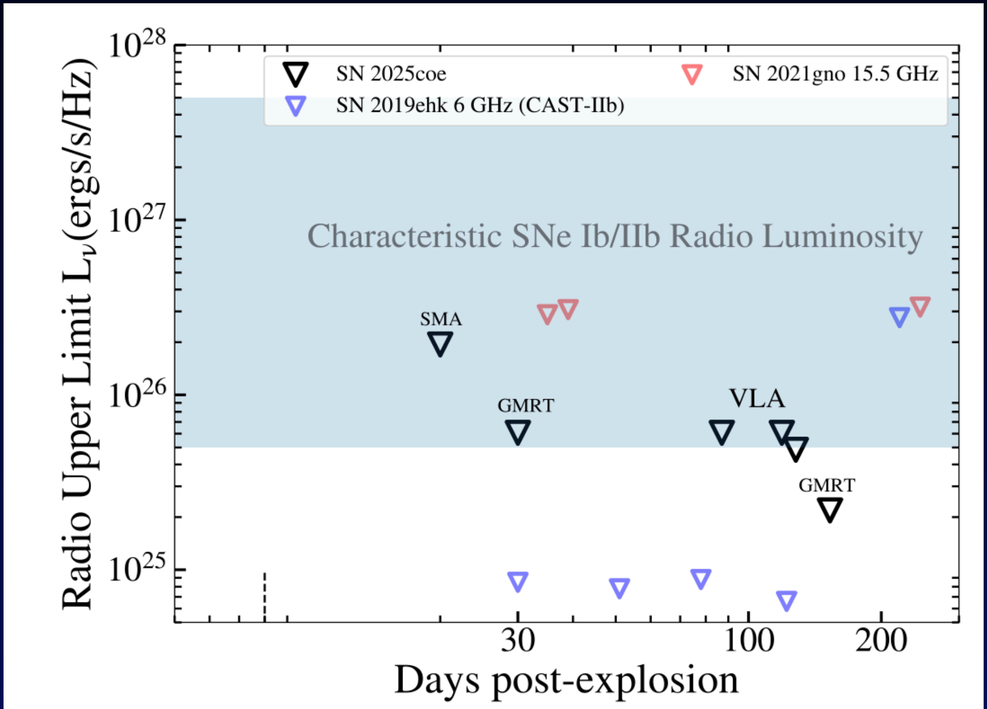
Sahana Kumar, Baer-way,…PC….arXiv:2601.19018

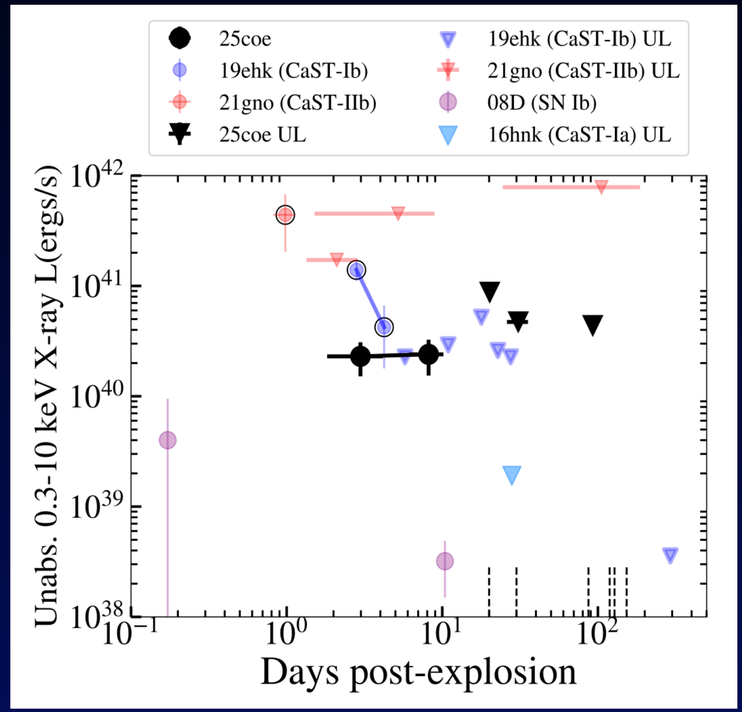
- CaSTs - strong calcium features and notably weak oxygen features
- Physical origins of CaSTs - thermonuclear or core collapse
- SN 2025coe - one of the nearest Ca-rich
- SN 2025coe shows spectral signatures characteristic of Type Ib SNe
- Radio, Xray (GMRT, VLA, SwiftXRT, optical)— third X-ray bright

[redacted]

CaSTs - Calcium rich supernovae

Sahana Kumar, Baer-way,…PC….arXiv:2601.19018

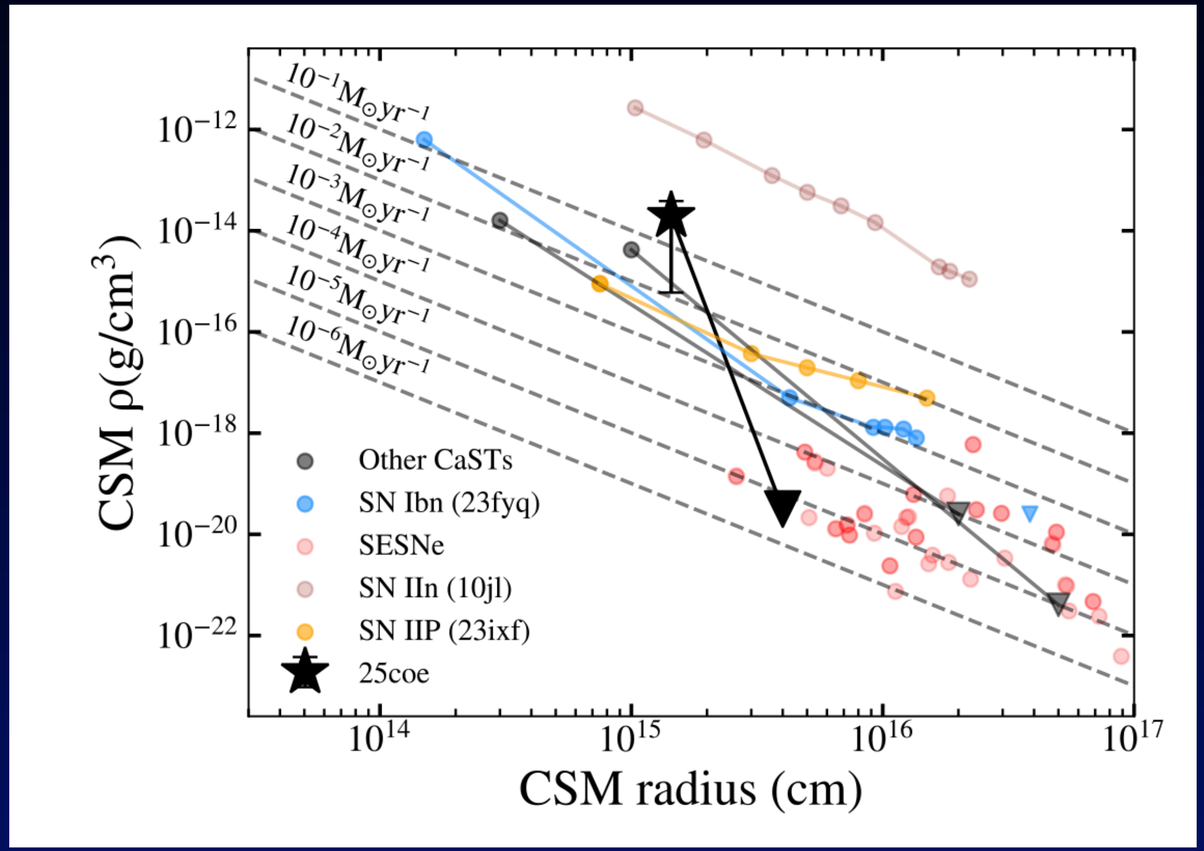




CaSTs - Calcium rich supernovae

Sahana Kumar, Baer-way,….PC….arXiv:2601.19018

- Radio to X-ray 0.12 $M_\odot$ material within >2x10^{15}cm - <4x10^{15}cm extent of CSM
- Around 0.2–0.5$M_\odot$/yr if the mass was lost directly in the last 100-200 days before the explosion



Supernovae progenitors constraints

- SNe IIn - enhanced mass-loss rate few centuries before explosion
- SNe Ibn/Icn - envelope expulsulsion years before expulsion
- SNe Ib, Ic - envelopes stripped long before explosion
- CaSTs - not known - thermonuclear vs core collapse (if thermonuclear first X-ray emitting thermonuclear supernova - **2025coe, 2019ehk, 2021gno**)
- Binarity - spiral CSM structure, asymmetry, complex CSM

Summary

- Explosion
  - ↓ Internal energy driven
- Flash Ionization
  - Radiation driven, photons at c
  - ↓
- CSI Onset
  - Shock-driven, matter at 10^4km/s
  - ↓
- Long-term Interaction
  - Sustained shock power

- Earliest signature of CSM - Flash ionization
  - Sets the inner boundary condition - independent of shock st
  - Purely radiative phenomenon
  - Samples months - years before explosion
- Circumstellar interaction as a fossil record of stellar death
  - mass-loss rates - decades to centuries before explosion
  - eruption timescales
  - binarity
  - pre-SN instability mechanisms

Summary - Observational regime

- Earliest signature of CSM - Flash ionization
  - Alert latency
  - Robotic spectroscopy
  - Classification pipelines
- Circumstellar interaction as a fossil record of stellar death
  - Early optical
  - Soft to hard X-ray
  - Early mm, early to late cm radio
  - Cadence matters more than depth
  - Optical X-ray, radio synergies

- **Early spectra → final instability in the progenitor**
- **Study lasting weeks–months → eruptive mass loss**
- **CS interaction for years → binary interaction history**

Summary - Observational regime

- Hydrogen rich supernovae - moderate long lasting CSM (Red supergiants!)
- Type IIb supernovae - common late time rebrightenings (binarity important)
- Interacting hydrogen rich supernovae - enhanced mass loss centuries before explosion (LBV kind mass eruptions)
- Interacting hydrogen poor supernovae - enhanced mass loss years before explosion (merger scenario?)
- Core-collapse CaSTs - enhanced mass loss months before explosion (weak explosion with enhanced mass loss just before death)
- **Fine tuned strategies for different class of supernovae**