Unveiling the progenitors of young supernova via their circumstellar interaction

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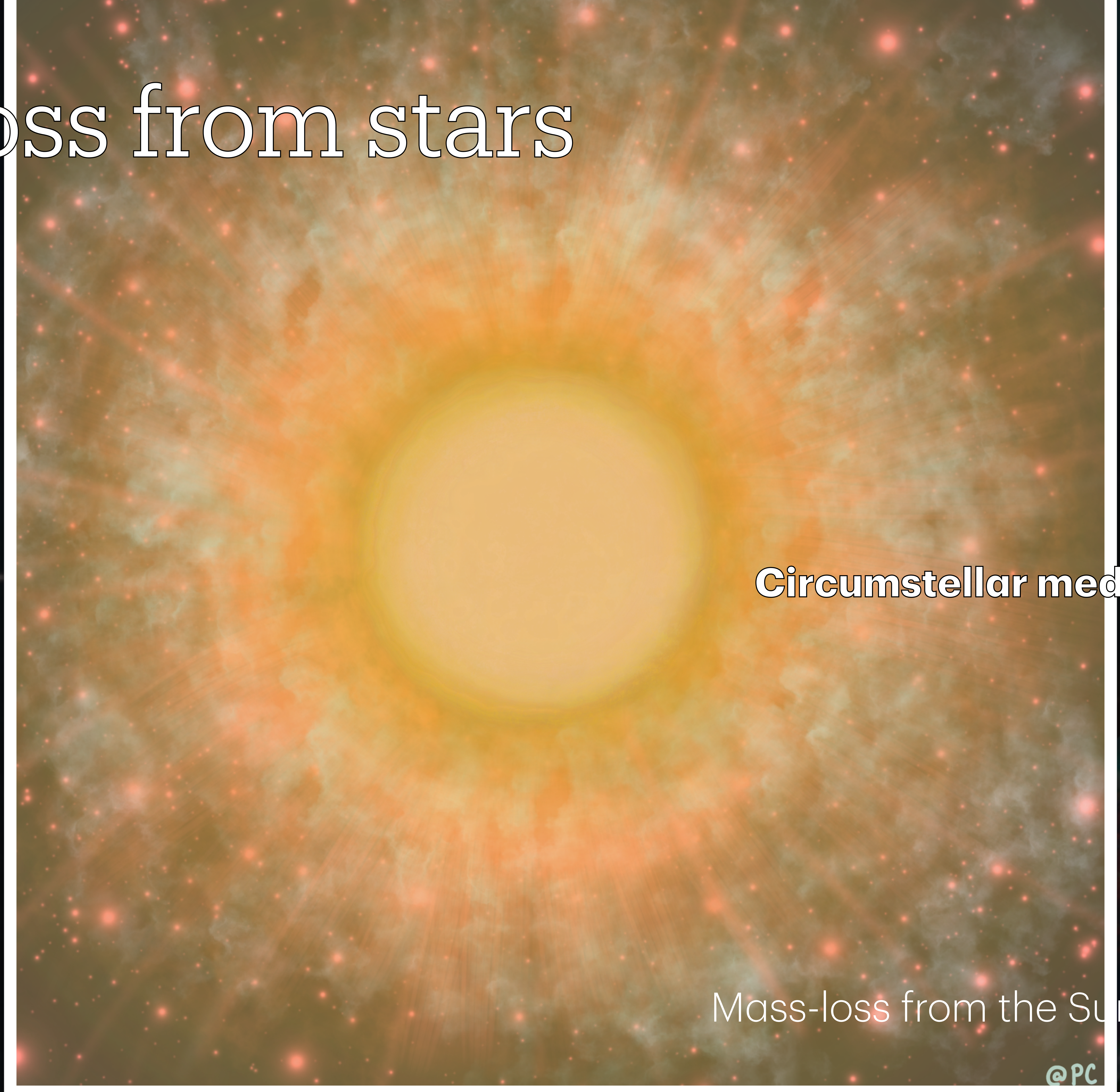
Also see the invited talks by **A. Chiotellis** and **N. Smith** on circumstellar interaction

Supernova Remnants III: An odyssey in space after stellar death, 9-15 June 2024, Chania, Crete, Greece

Circumstellar Interaction
What? Why? How?

Mass loss from stars



Circumstellar medium

Mass-loss from the Sun ~ 10^{-14} $M_\odot$/yr

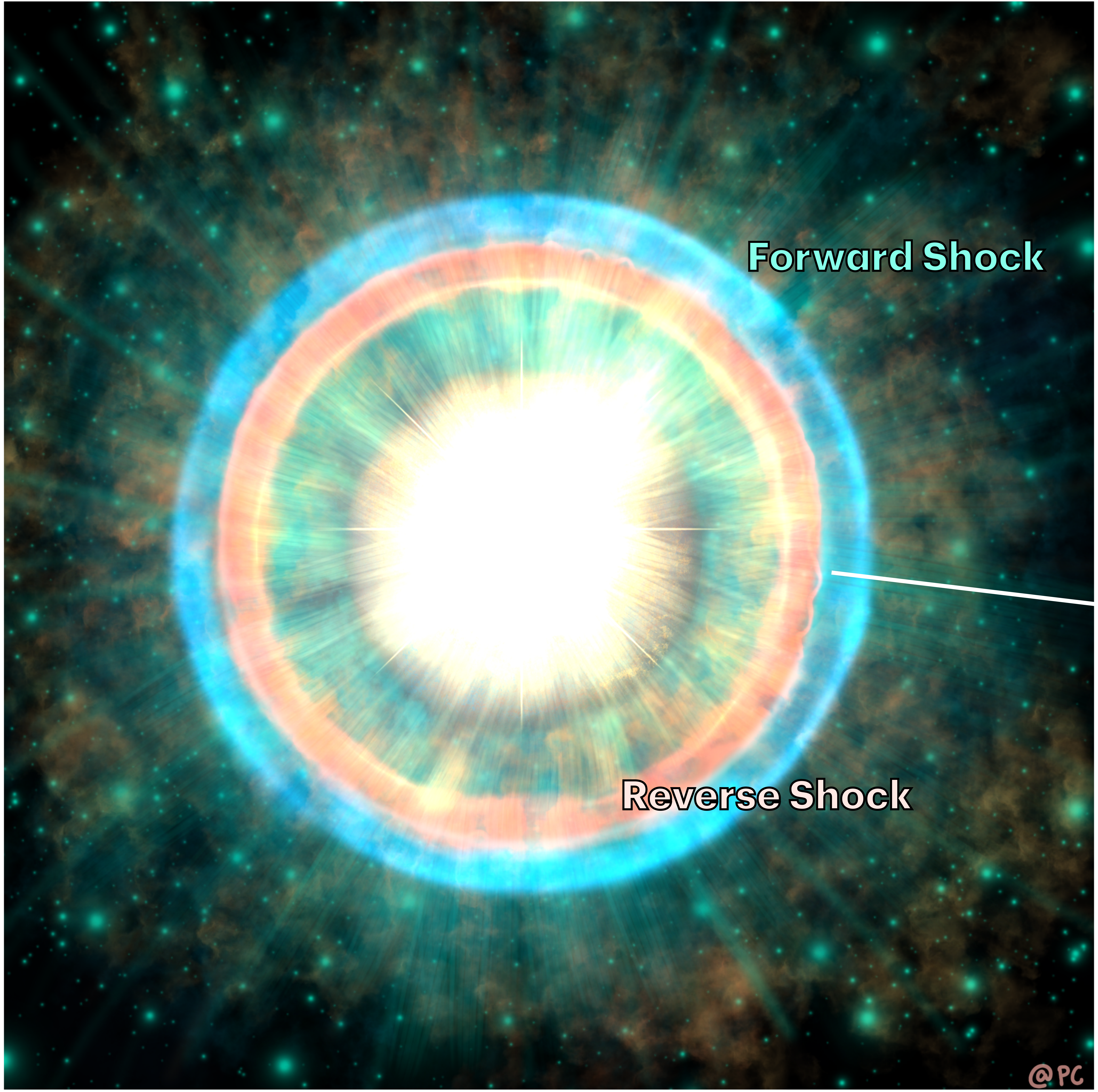
Credit: NASA/NRAO

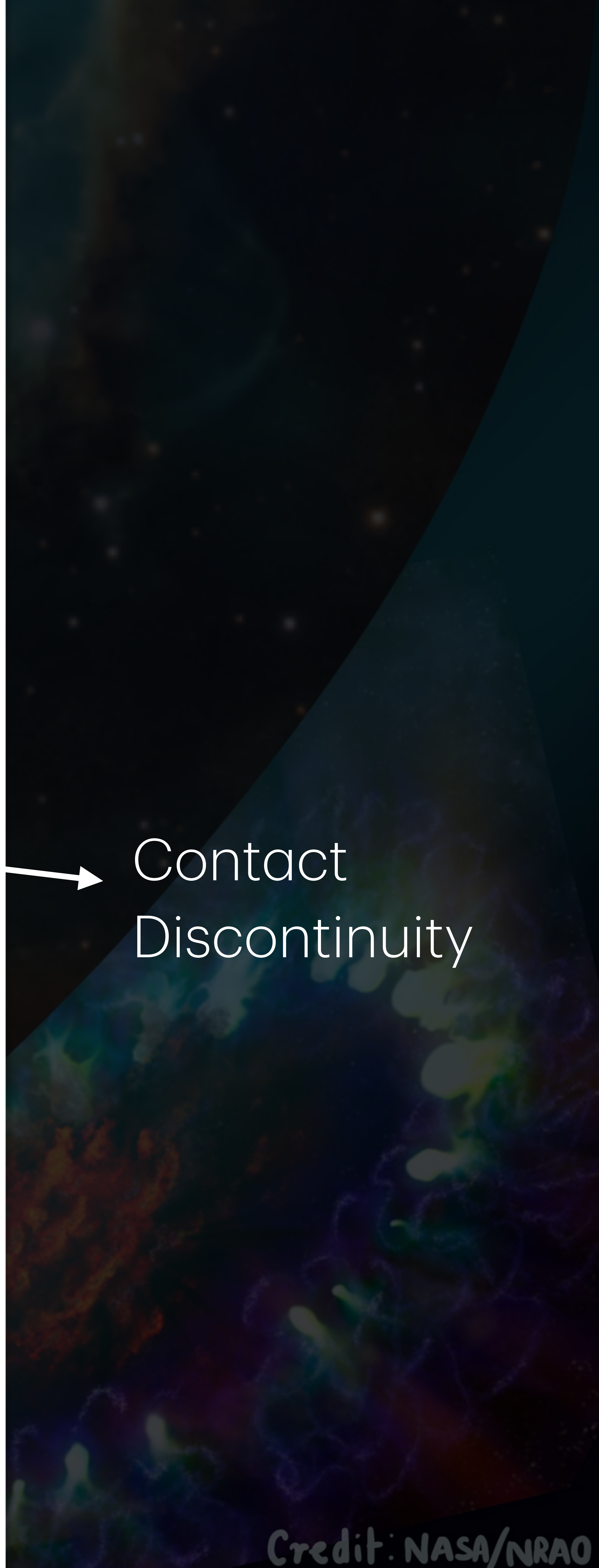
Mass loss from massive stars

Mass-loss from massive stars $10^{-5}\ M_{\odot}/yr$

Credit: NASA/NRAO

Circumstellar interaction

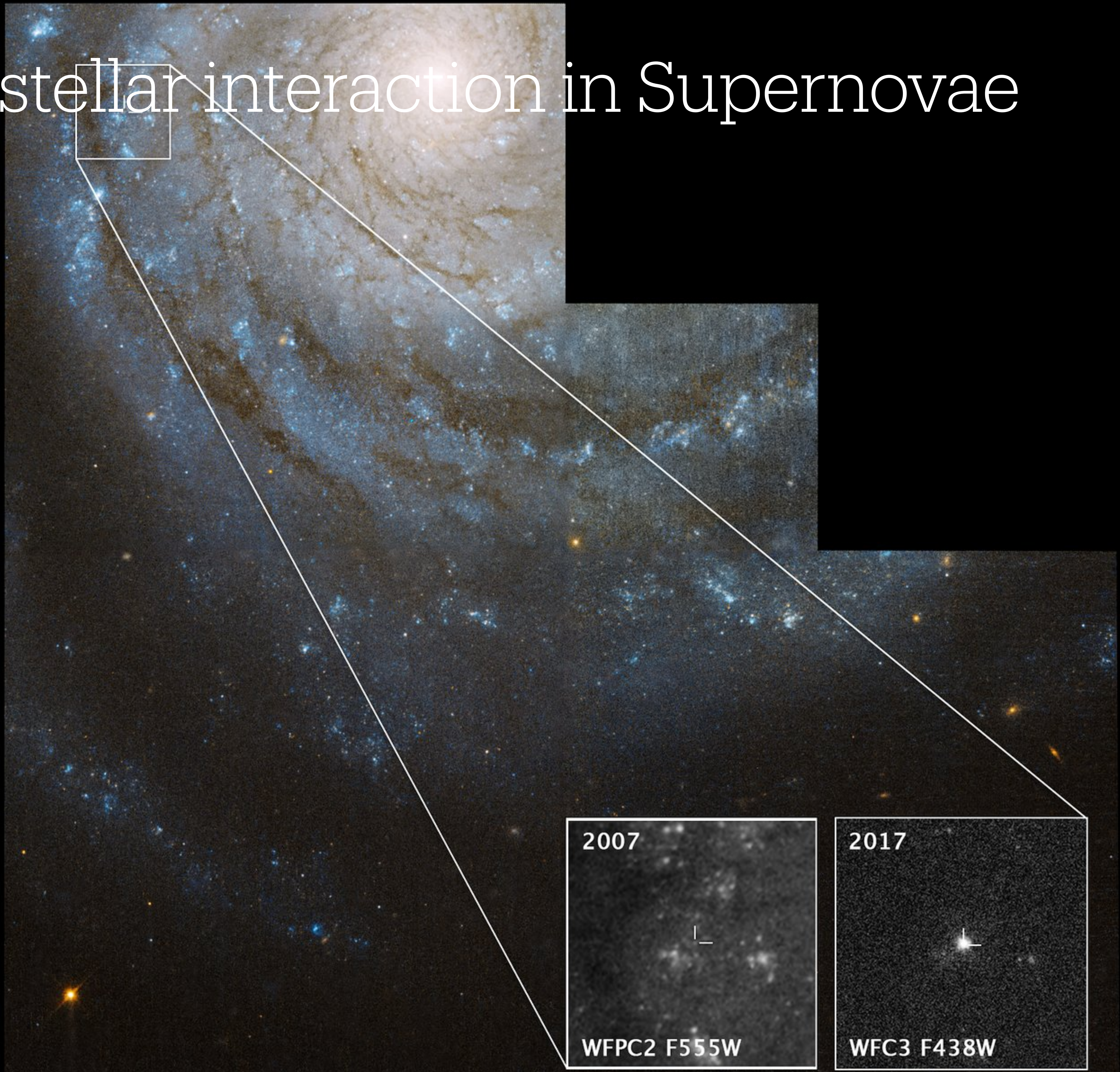





Supernove
(Core collapse)
Type I
No Hydrogen
Type II
Hydrogen
Why?
Type Ib
Helium
Type Ic
No Helium
Type IIb
Little Hydrogen
Type IIn
Narrow H emission
t=-1000 yr
Type IIP
LC plateau
Type IIL
LC linear
=0 yr
@PC
@PC
Credit: NASA/NRAO

Why do we study circumstellar interaction in Supernovae

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



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

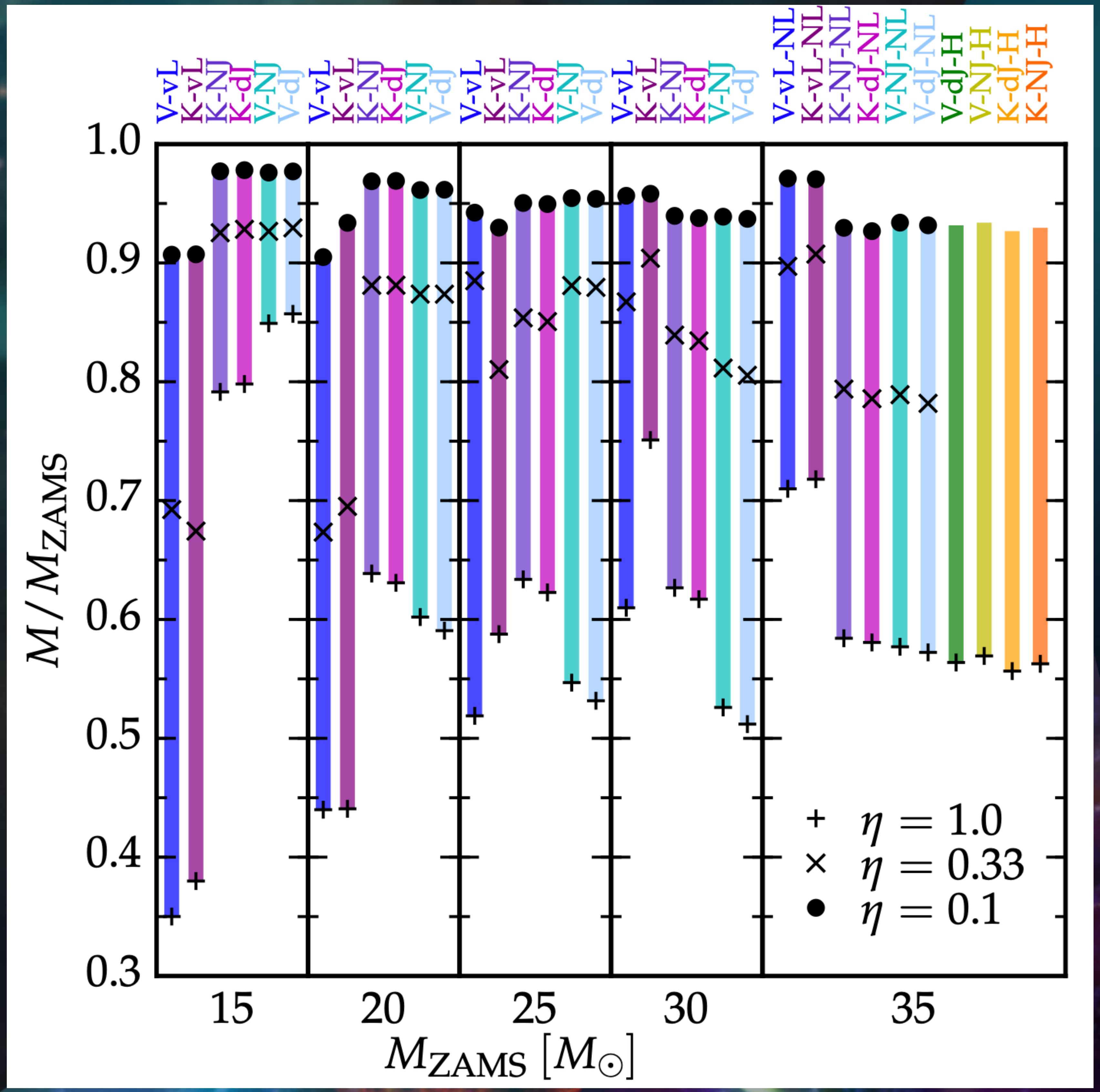
Why do we study circumstellar interaction in Supernovae

- Mapping between massive star and supernovae

- Mass-loss rate measurements

  - The initial to final mass ~ 50% uncertainty (Renzo+2017, Zapartas+2021)

  - Complexities due to binarity, magnetism, rotation, metallicity, wind clumping, asymmetry.

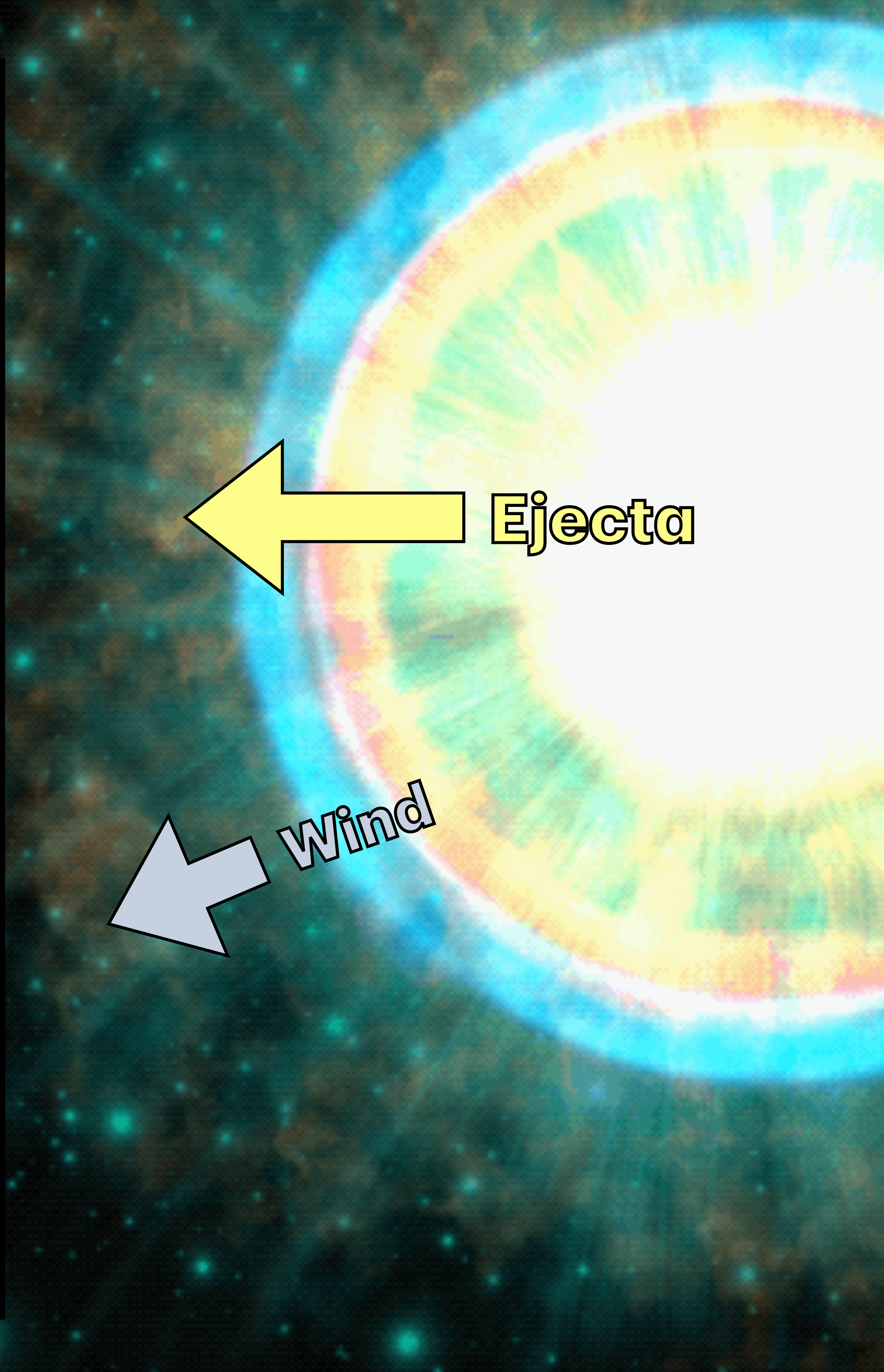


Zapartas+2021

Credit: NASA/NRAO

Evolution of supernova progenitor

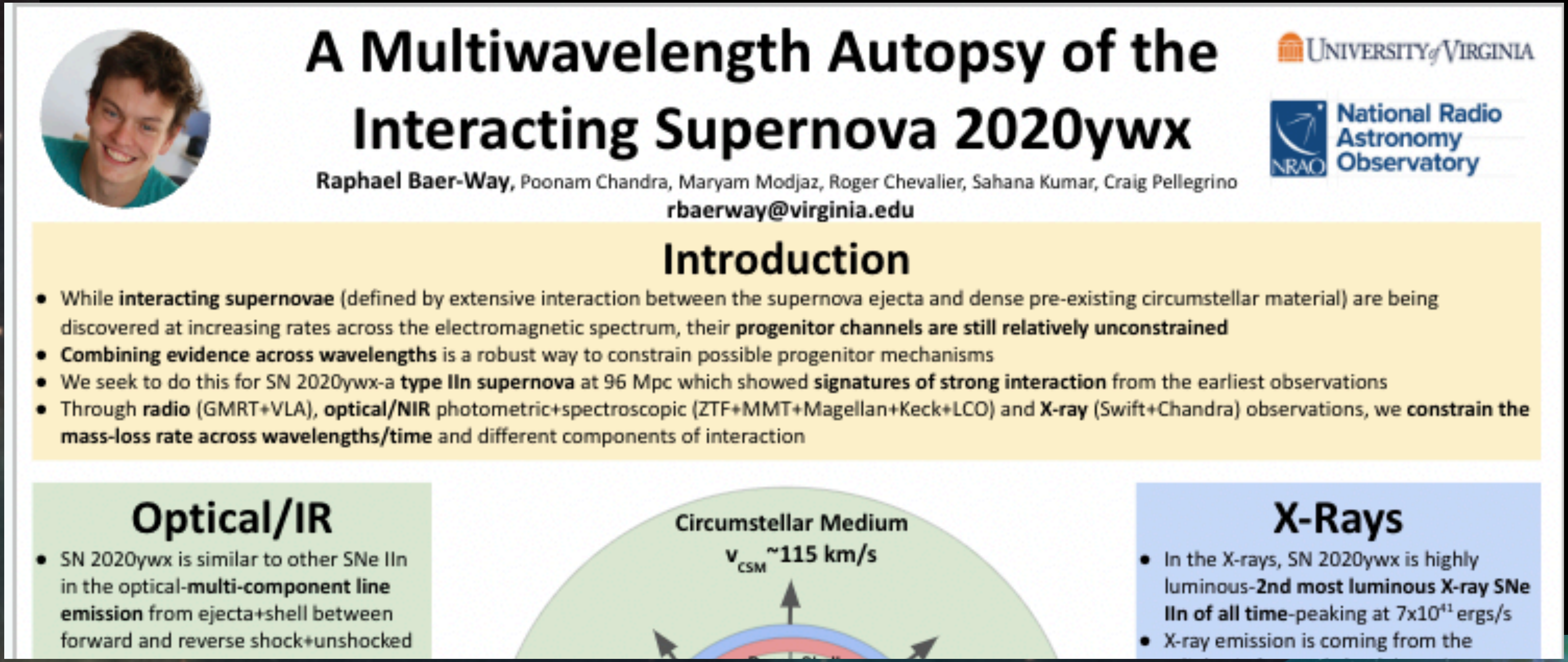
- Time Machine - Look back time= ejecta speed/wind speed
- Wind velocities and ejecta speeds different for different kinds of supernovae
  - Type IIP, ejecta speed ~10,000 km/s, wind ~10 km/s, Look back time ~1000
  - Type IIn, ejecta speed ~6000 km/s, wind ~100 km/s, look back Time ~60
  - Type Ic,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



Why do we study circumstellar interaction in Supernovae

- Multiwvelength study of circumstellar interaction in a Type Ion supernova

Please see poster and 1m talk by Raphael Baer-way



A Multiwavelength Autopsy of the Interacting Supernova 2020ywx

UNIVERSITY of VIRGINIA

NRAO National Radio Astronomy Observatory

Raphael Baer-Way, Poonam Chandra, Maryam Modjaz, Roger Chevalier, Sahana Kumar, Craig Pellegrino
rbaerway@virginia.edu

Introduction

- While **interacting supernovae** (defined by extensive interaction between the supernova ejecta and dense pre-existing circumstellar material) are being discovered at increasing rates across the electromagnetic spectrum, their **progenitor channels are still relatively unconstrained**
- **Combining evidence across wavelengths** is a robust way to constrain possible progenitor mechanisms
- We seek to do this for SN 2020ywx-a **type IIn supernova** at 96 Mpc which showed **signatures of strong interaction** from the earliest observations
- Through **radio** (GMRT+VLA), **optical/NIR** photometric+spectroscopic (ZTF+MMT+Magellan+Keck+LCO) and **X-ray** (Swift+Chandra) observations, we **constrain the mass-loss rate across wavelengths/time** and different components of interaction

Optical/IR

- SN 2020ywx is similar to other SNe IIn in the optical-**multi-component line emission** from ejecta+shell between forward and reverse shock+unshocked

Circumstellar Medium
v_{CSM} ~115 km/s

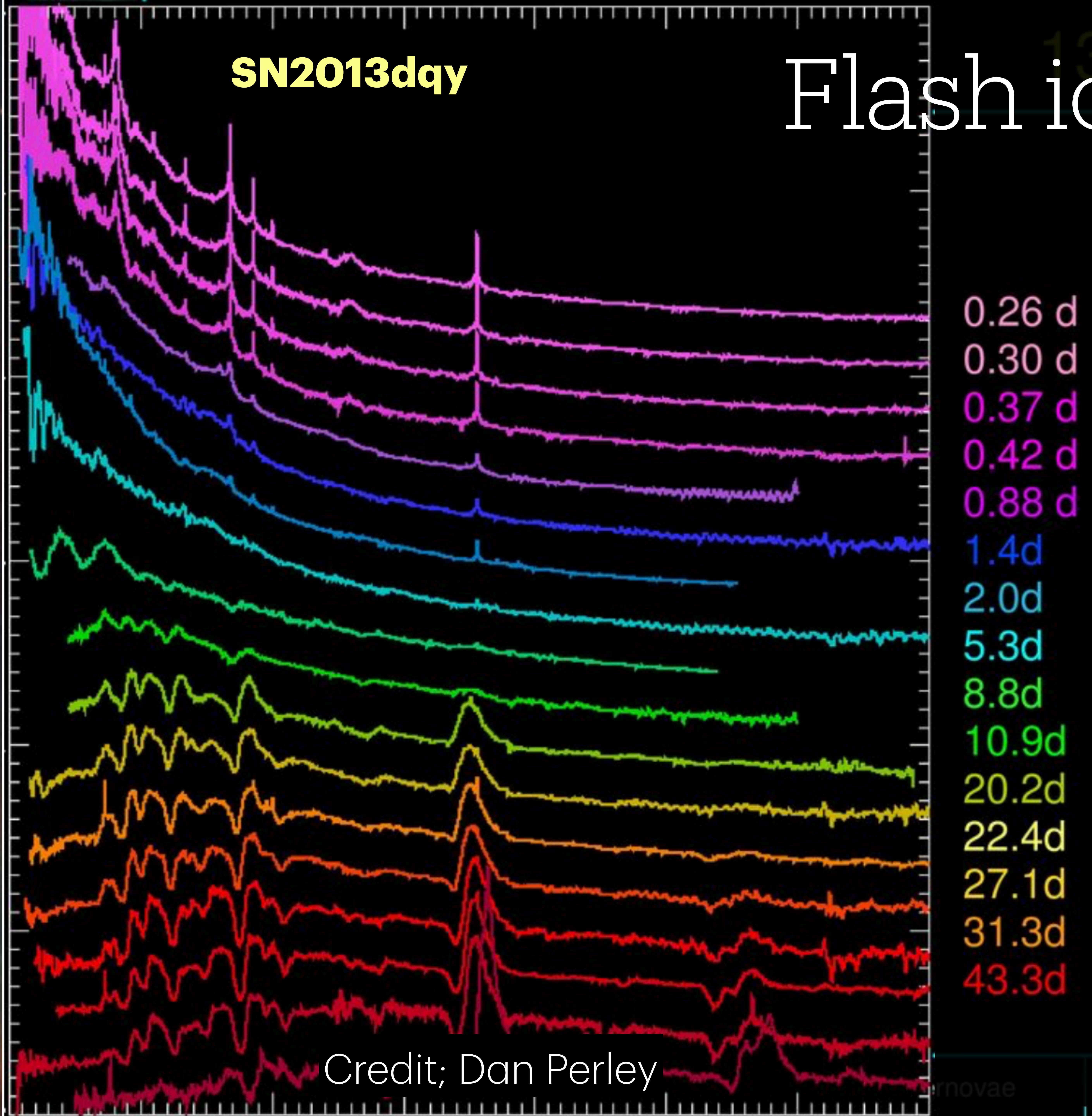
X-Rays

- In the X-rays, SN 2020ywx is highly luminous-**2nd most luminous X-ray SNe IIn of all time**-peaking at 7×10^{41} ergs/s
- X-ray emission is coming from the

Credit: NASA/NRAO


How?
Credit: NASA/NRAO

Flash ionization



Credit; Dan Perley

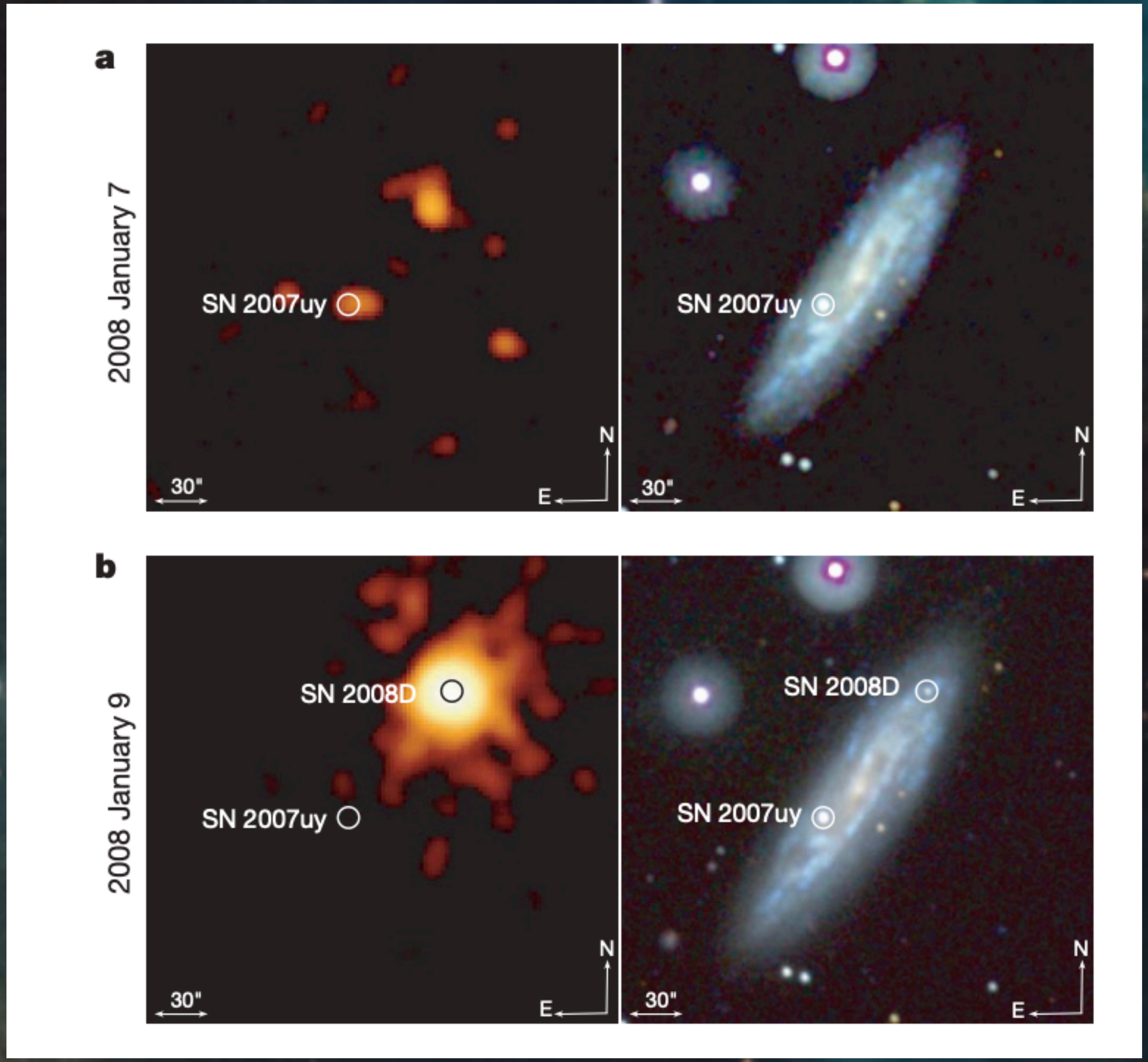
- Observations of supernovae within hours of days

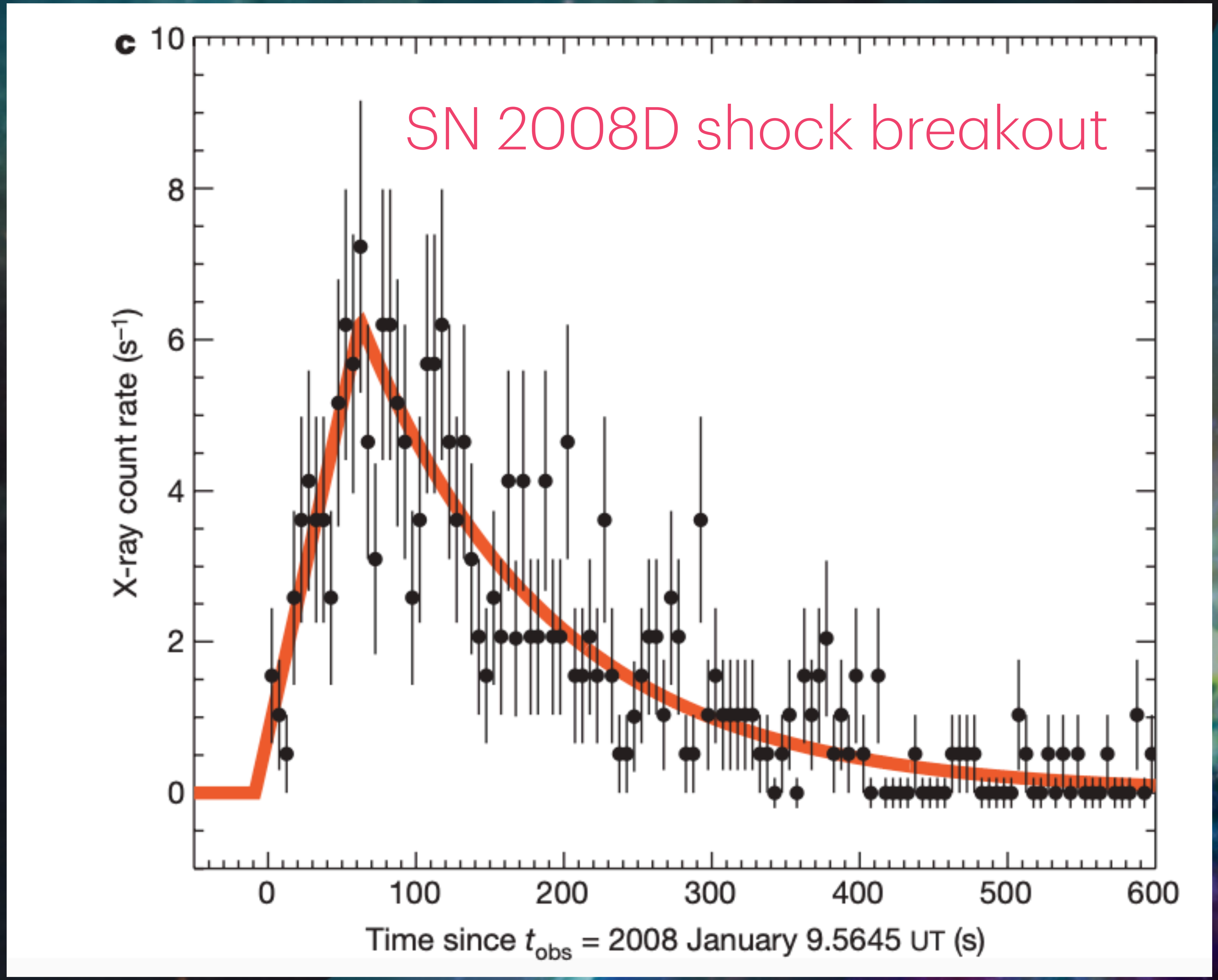
- Number of narrow emission lines from highly ionized species - flash ionization

- Ionization of CSM at shock breakout - earliest traces of CSM (Gal-Yam et al. 2014, Khazov et al. 2016, Kochanek 2019)

Flash ionization

Shock breakout - SN 2008D

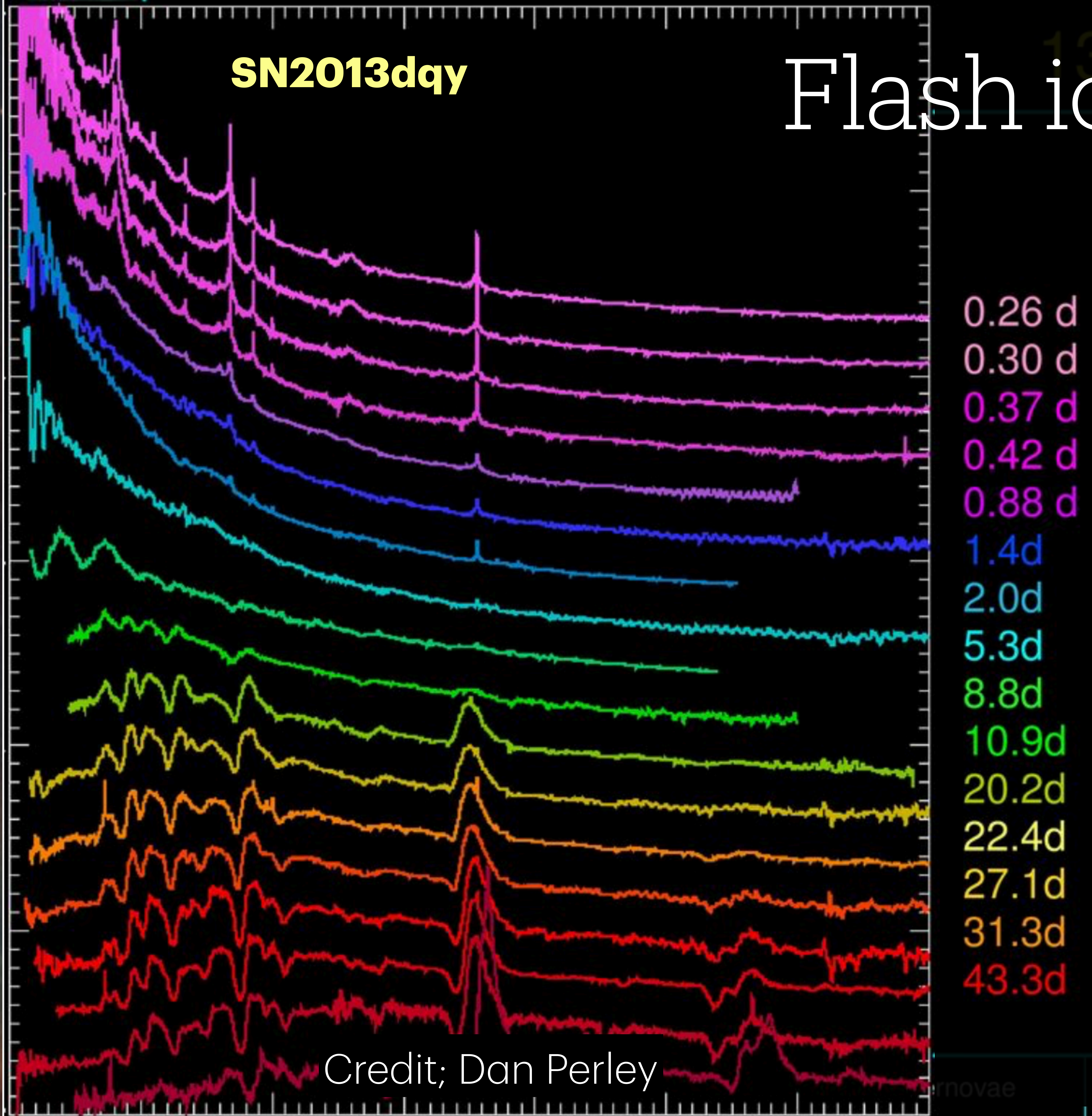




Soderberg,...PC... 2008

Credit: NASA/NRAO

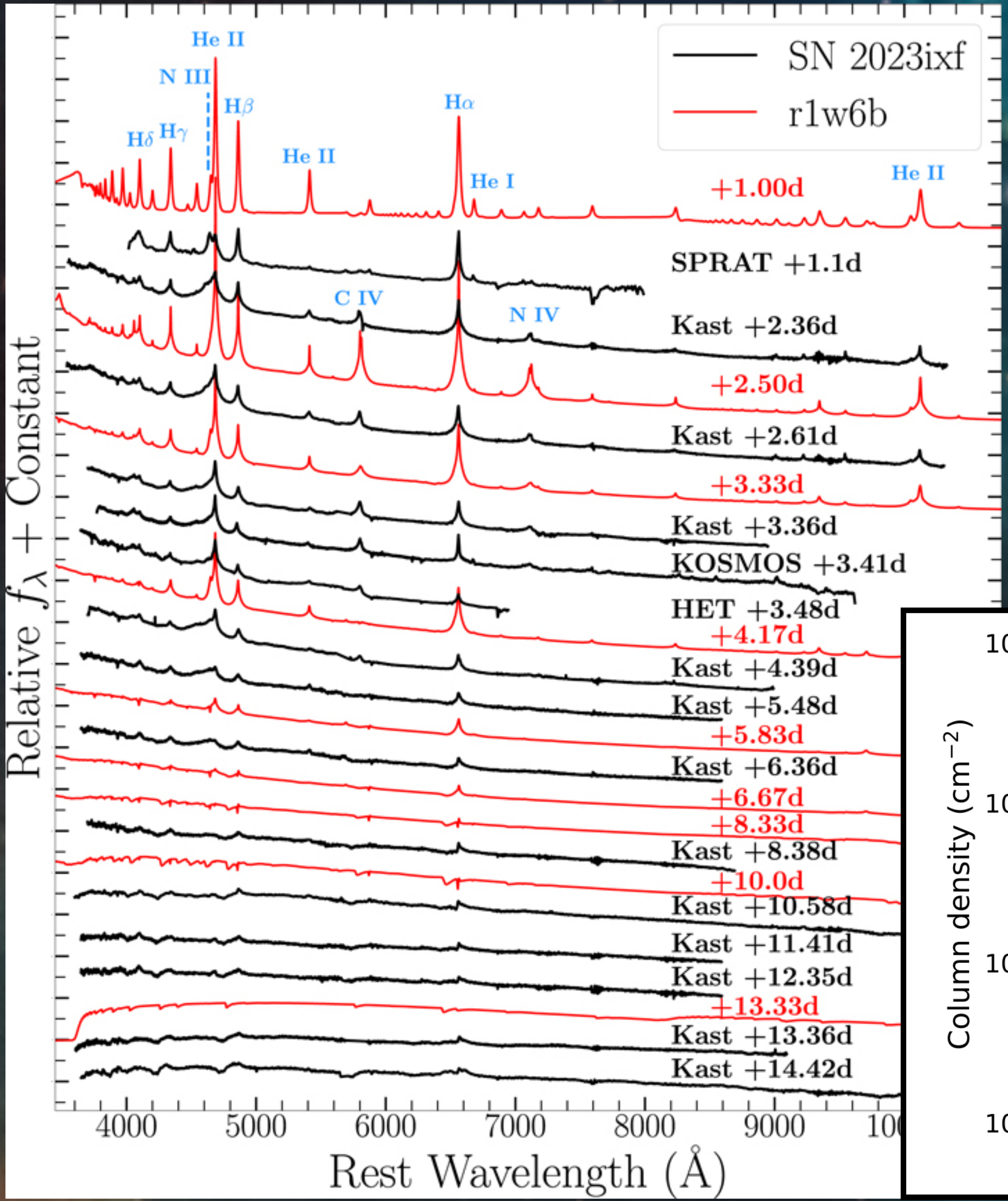
Flash ionization



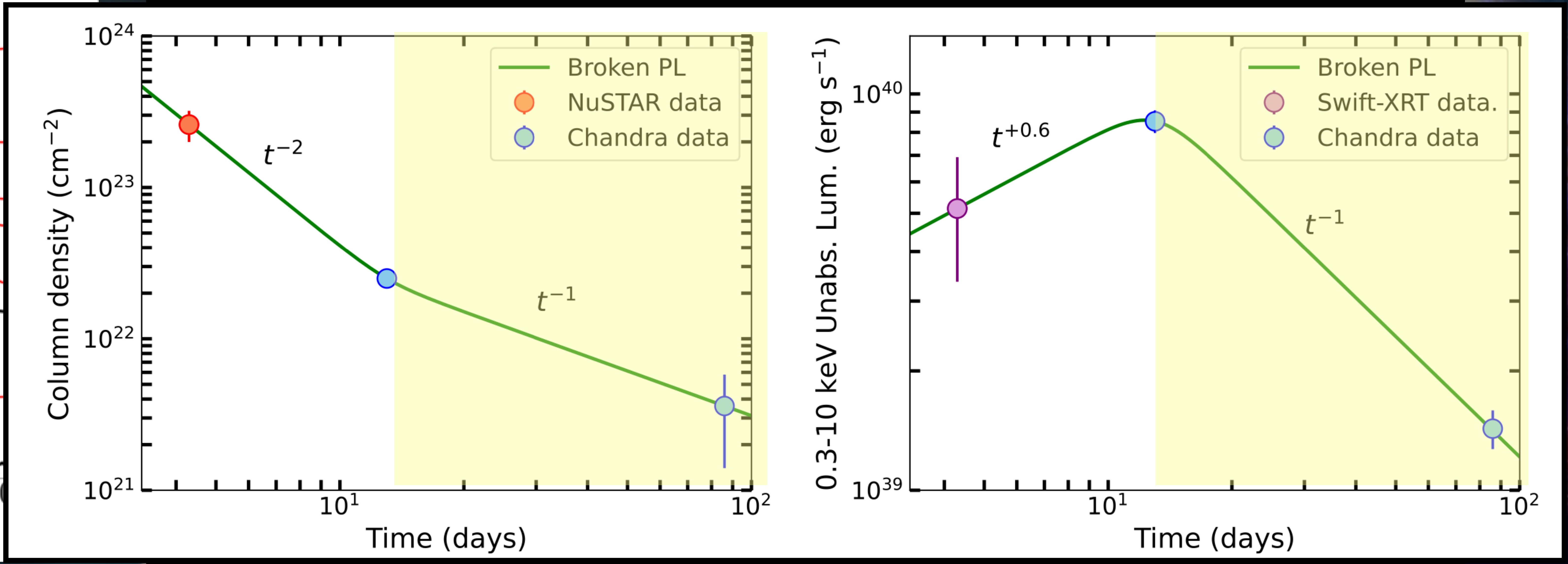
Credit; Dan Perley

- Observations of supernovae within hours of 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)
- Disappear within few days - confined CSM (Khazov+16)
- Mass loss rate ~ 10^{-3} $M_\odot$ yr^{-1}. Denser CSM extending to <10^{15} cm
- Type IIP iPTF13dqy (SN 2013fs, Yaron et al. 2017). Several ZTF supernovae (Bruch+23, Perley+19)
- Binarity less probable, gravity waves instabilities (Shiode, Quataert)

Flash ionization



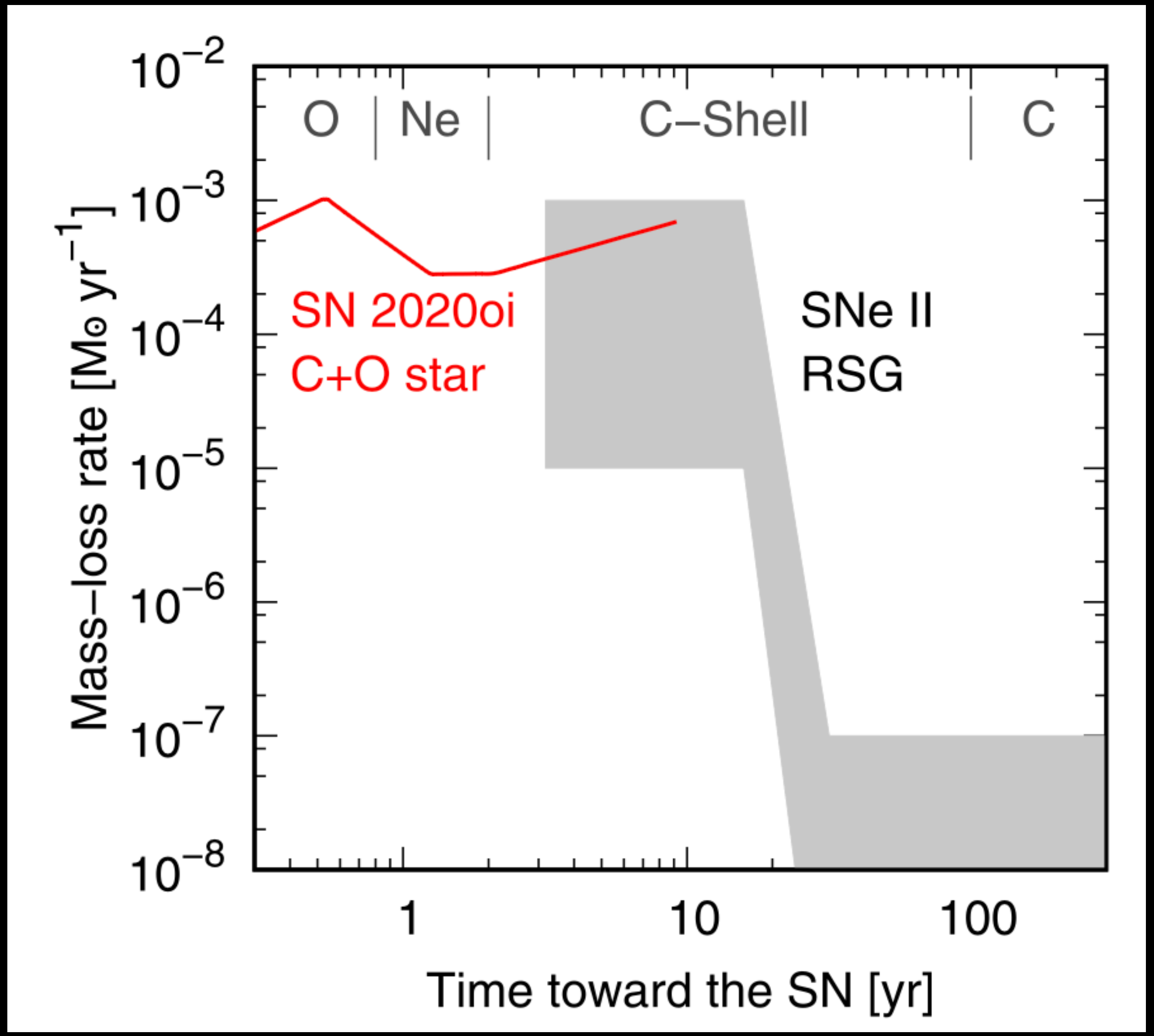
- SN 2023ixf - flash ionization (Jacobson-Galán+23, Teja+23)
- Standard evolution at later time - X-ray data (PC+24)
- From X-rays Mass loss rate ~ 6.5X10^{-5} M$_\odot$/yr (PC+24, Grefenstette+23)

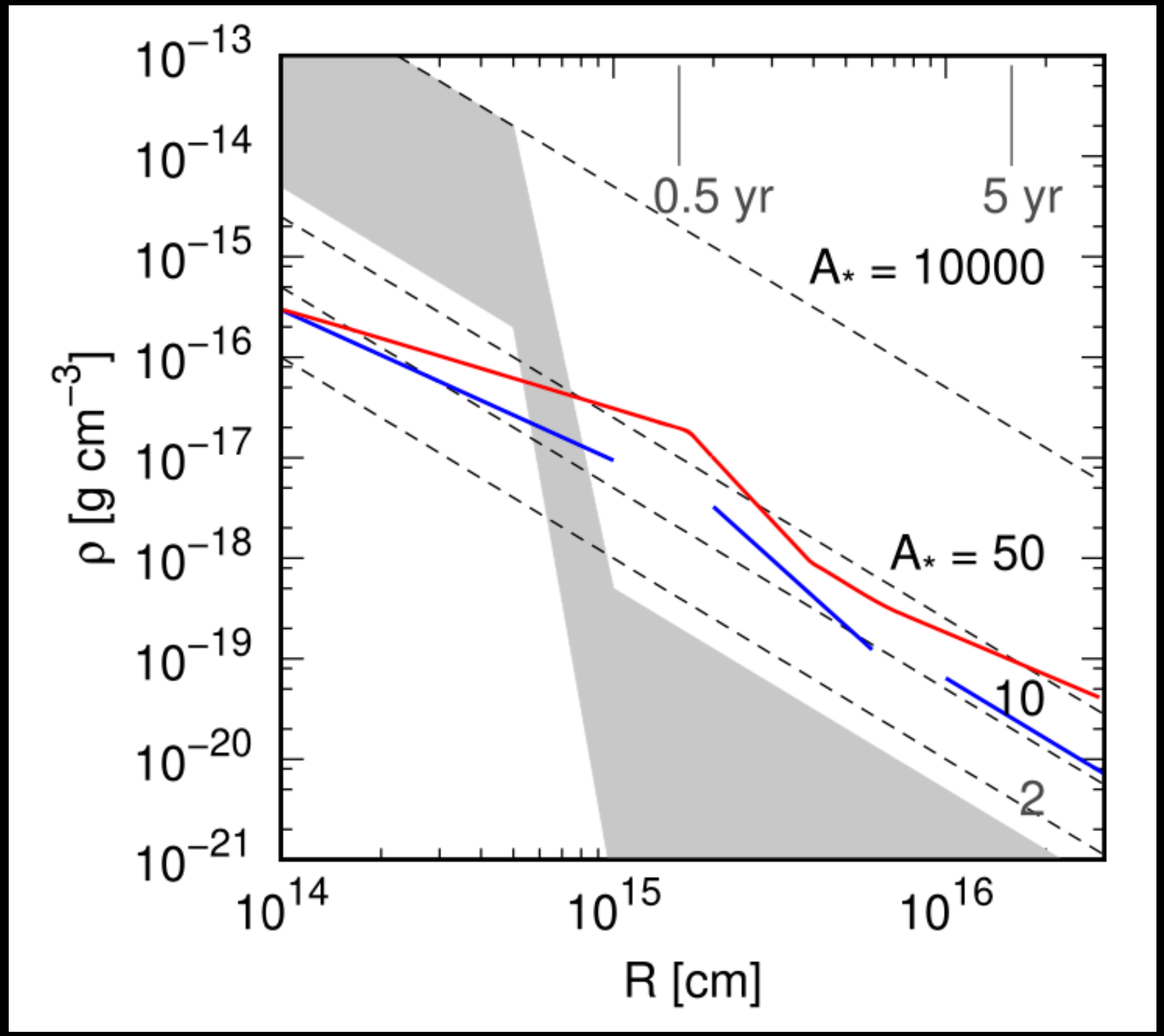


Credit: NASA/NRAO

Dense CSM- also seen in other bands

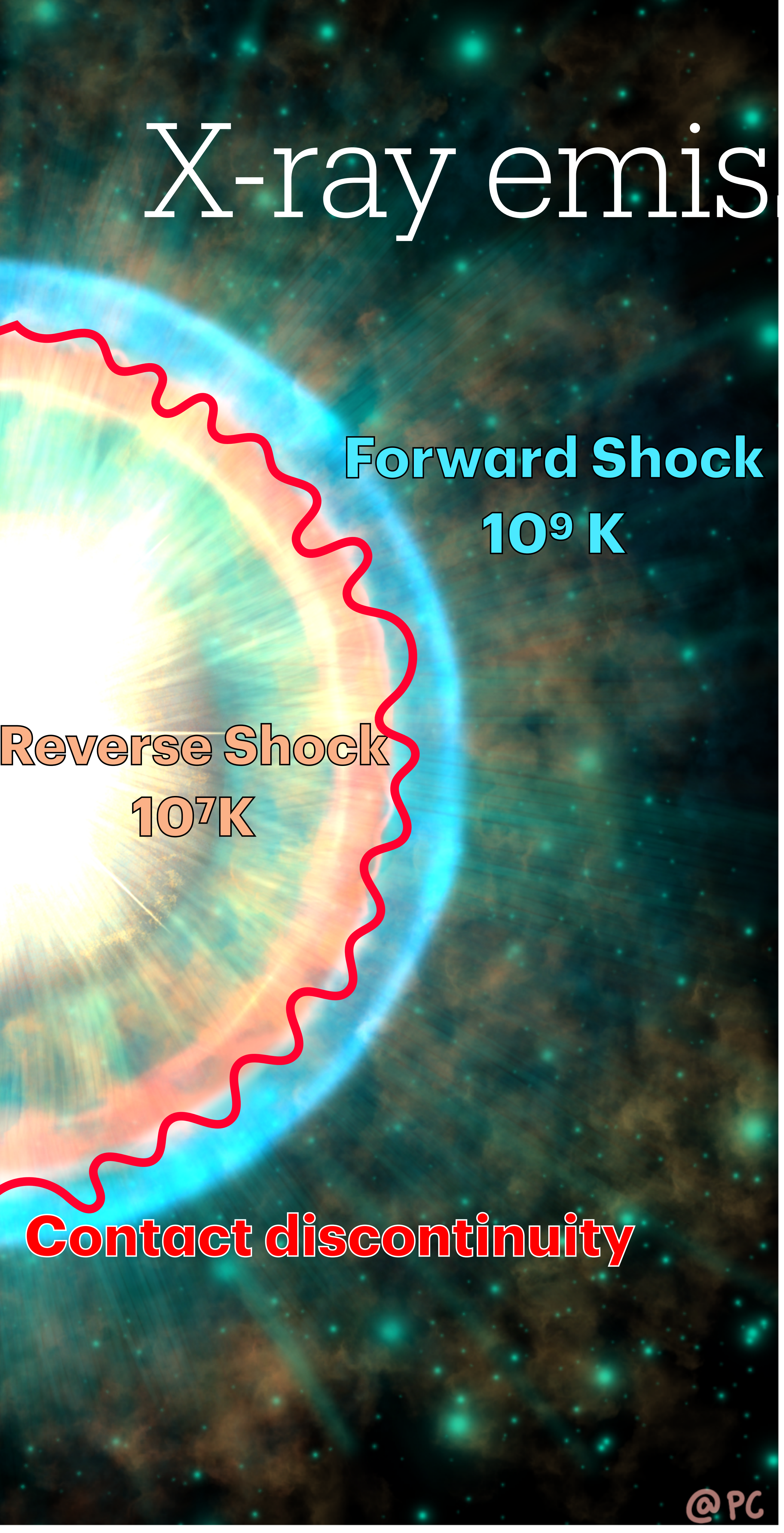
- Enhanced mass-loss rates also seen in ALMA mm data (Maeda, PC+21, Maeda, PC+23, Maeda, Michiyama, pc+23)





Credit: NASA/NRAO

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

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

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

Credit: NASA/NRAO

X-ray emission - circumstellar interaction

Reverse shock radiative

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

  Chevalier, Fransson 2017

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

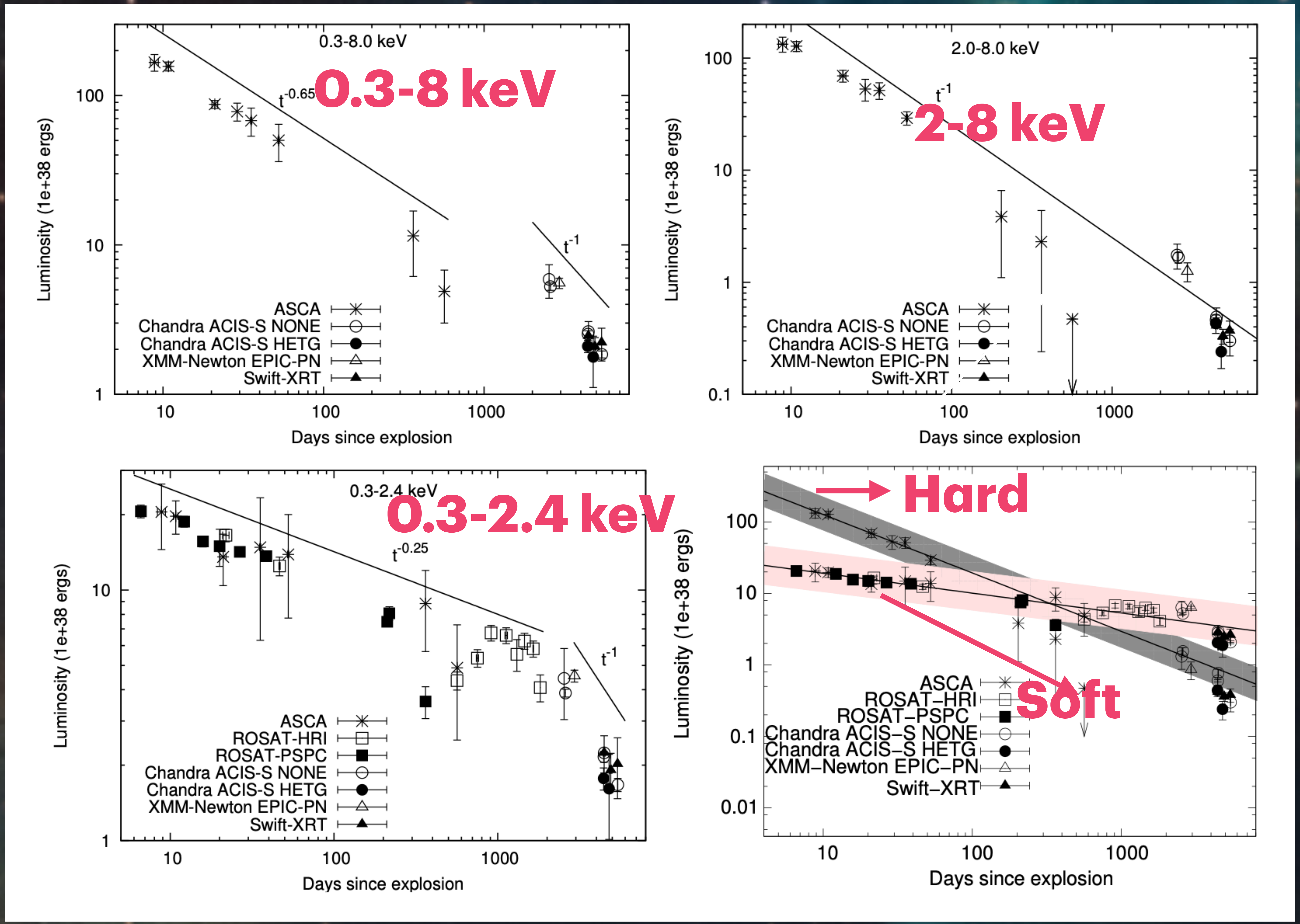
  Luminosity ~ density

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

Credit: NASA/NRAO

X-ray emission - circumstellar interaction

Reverse shock radiative - SN 1993J



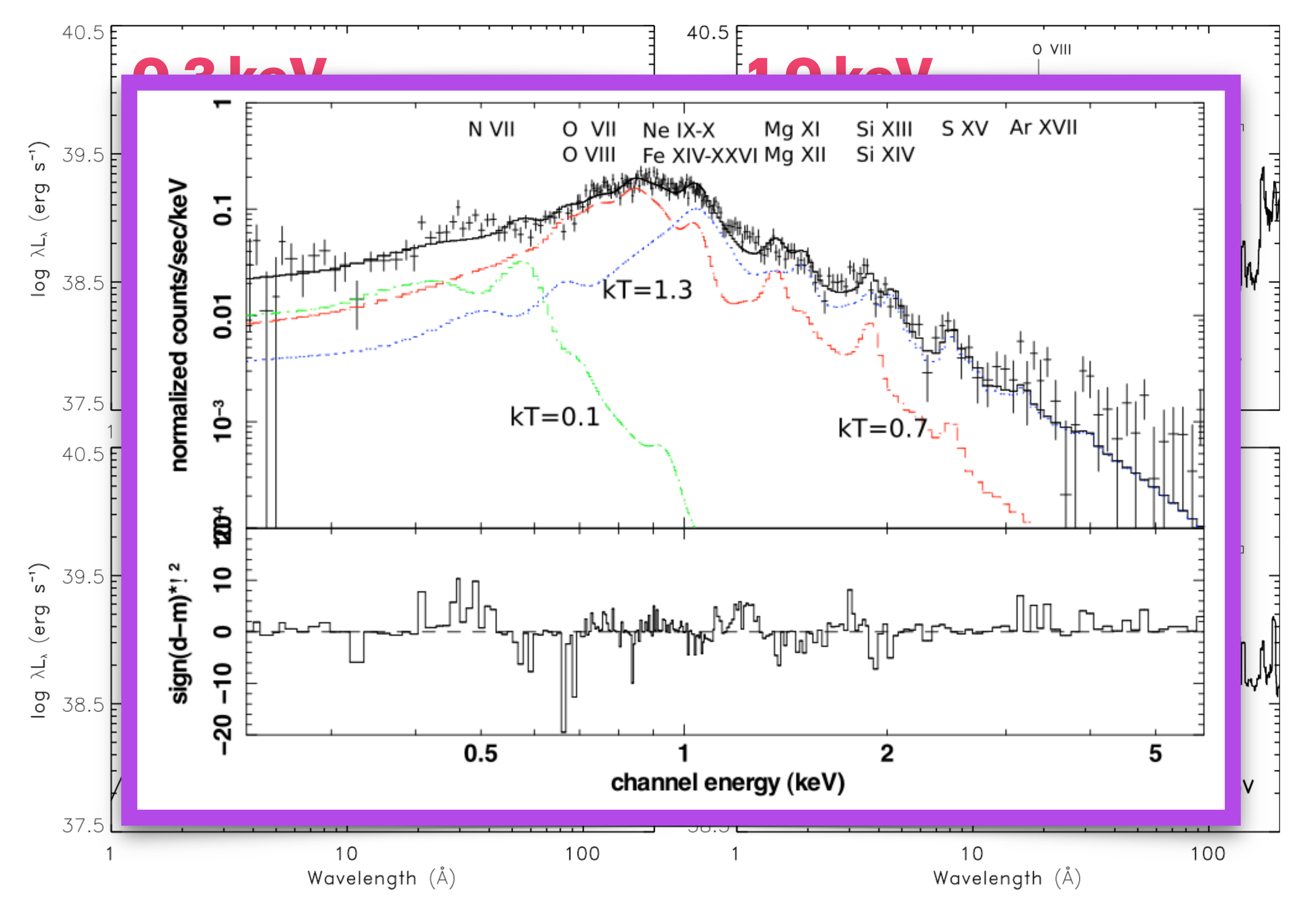
PC+2009

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

Credit: NASA/NRAO

X-ray emission - circumstellar interaction

Reverse shock radiative - SN 1993J

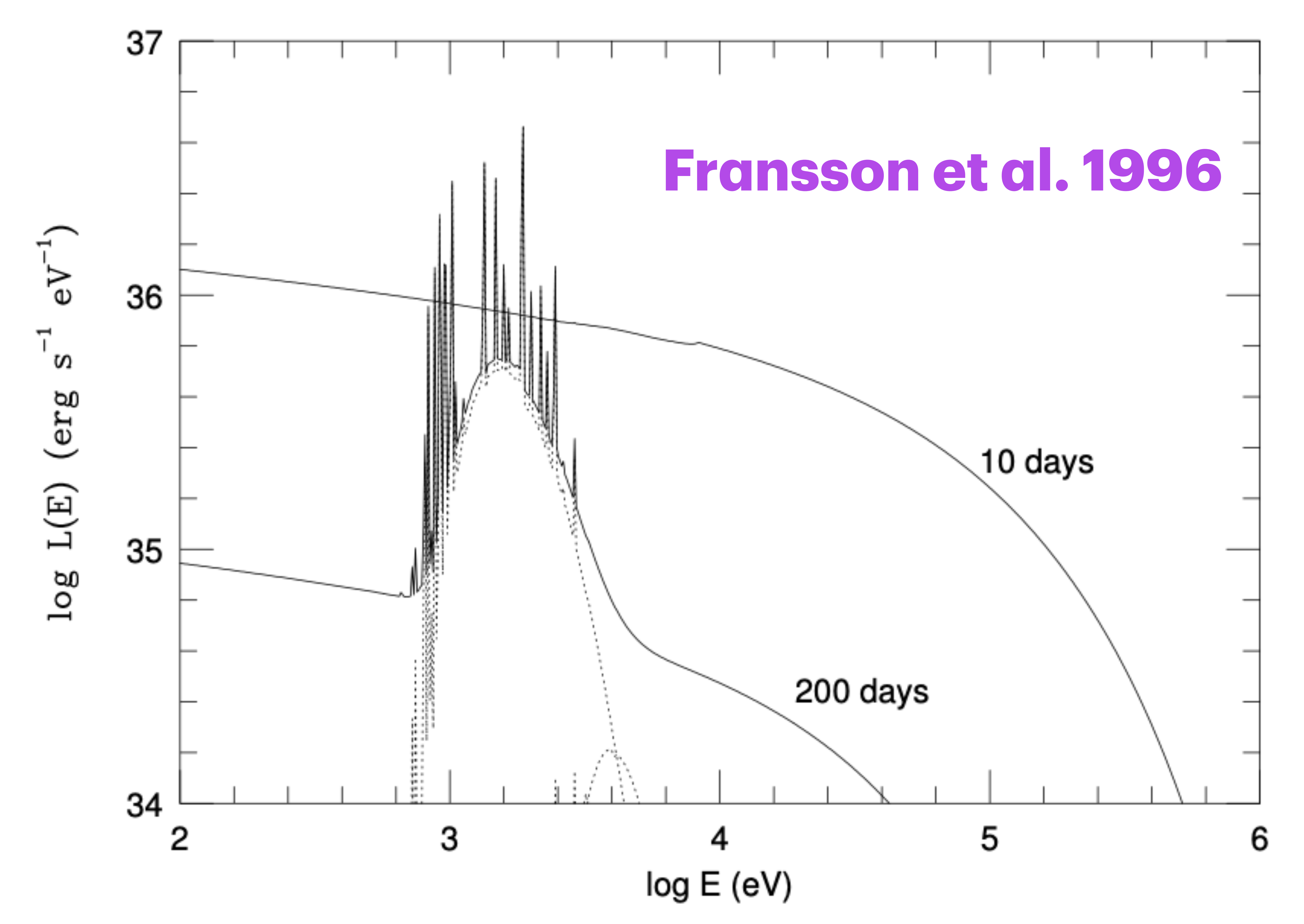


Nymark et al. 2006, Nymark, PC, Fransson+2009

- 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)

Credit: NASA/NRAO

X-ray emission - circumstellar interaction



Fransson et al. 1996

- Reverse shock radiative up to ~ 5 years after explosion and adiabatic after that (PC+2009)
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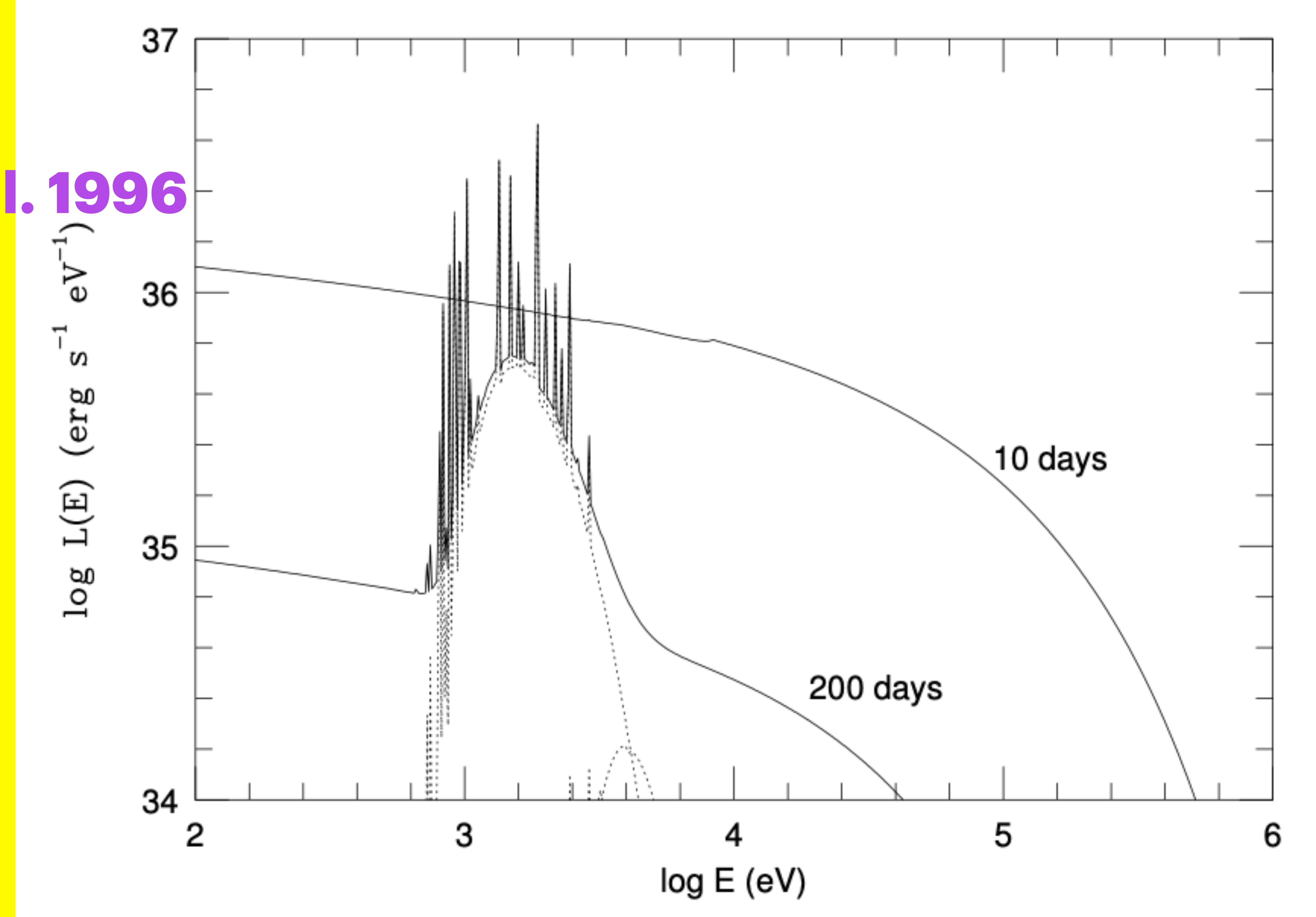
Credit: NASA/NRAO

sion - circumstellar interaction

Fransson et al. 1996

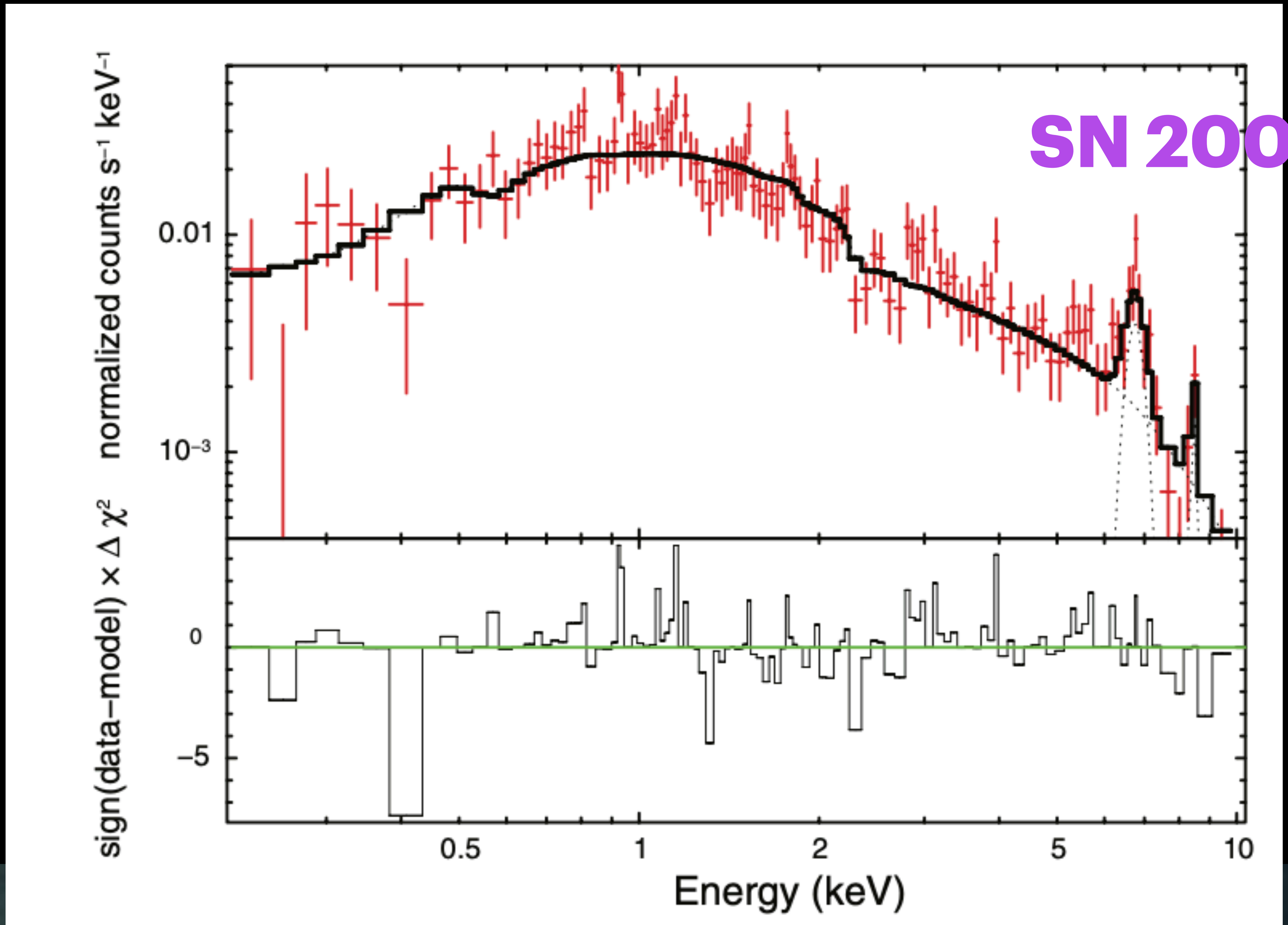


Credit: NASA/NRAO

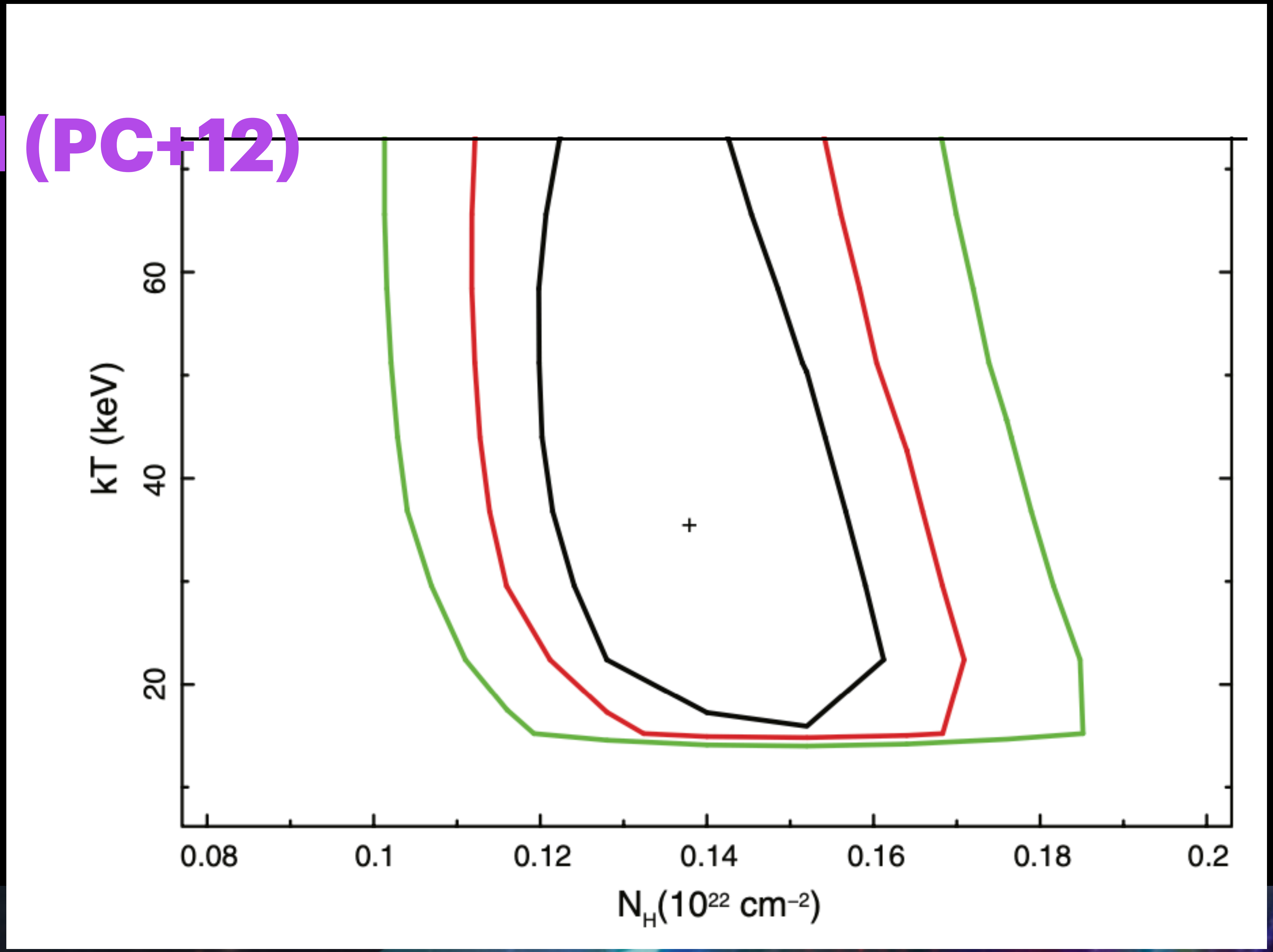
X-ray emission - circumstellar interaction

Hard X-rays

- Chandra/XMM energy range 0.3-10 keV



SN 2006jd (PC+12)

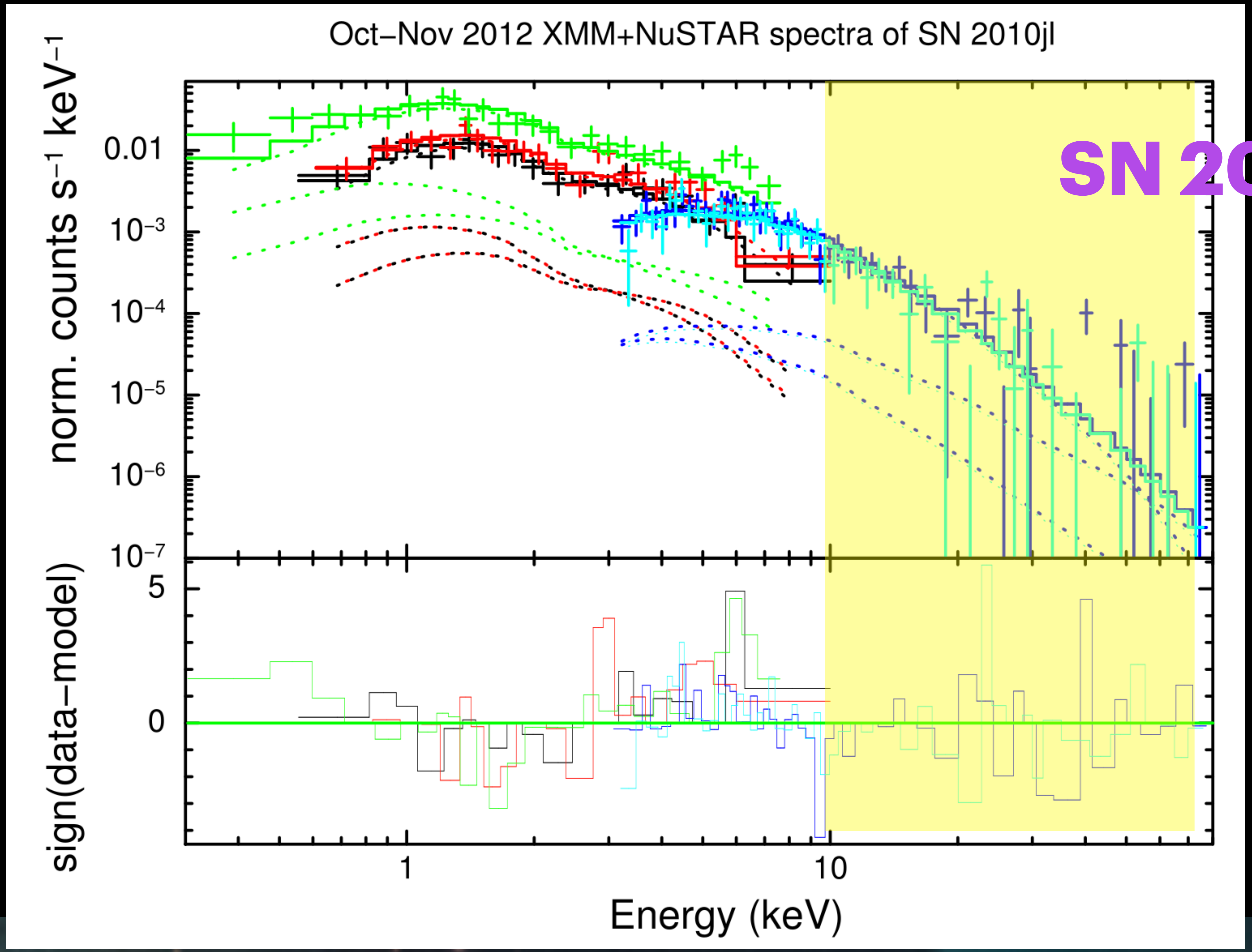


Credit: NASA/NRAO

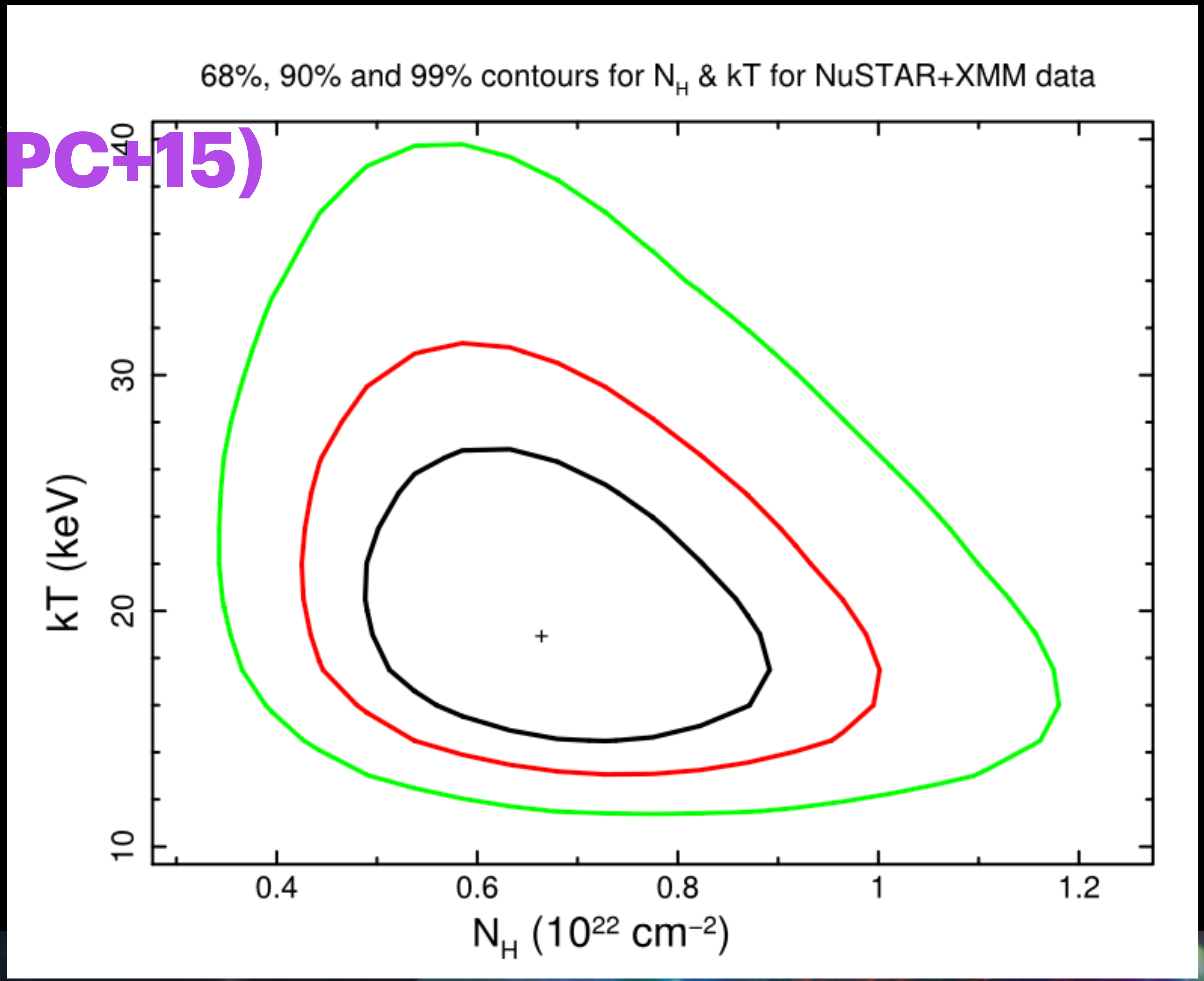
X-ray emission - circumstellar interaction

Hard X-rays

- NuSTAR revolutionary



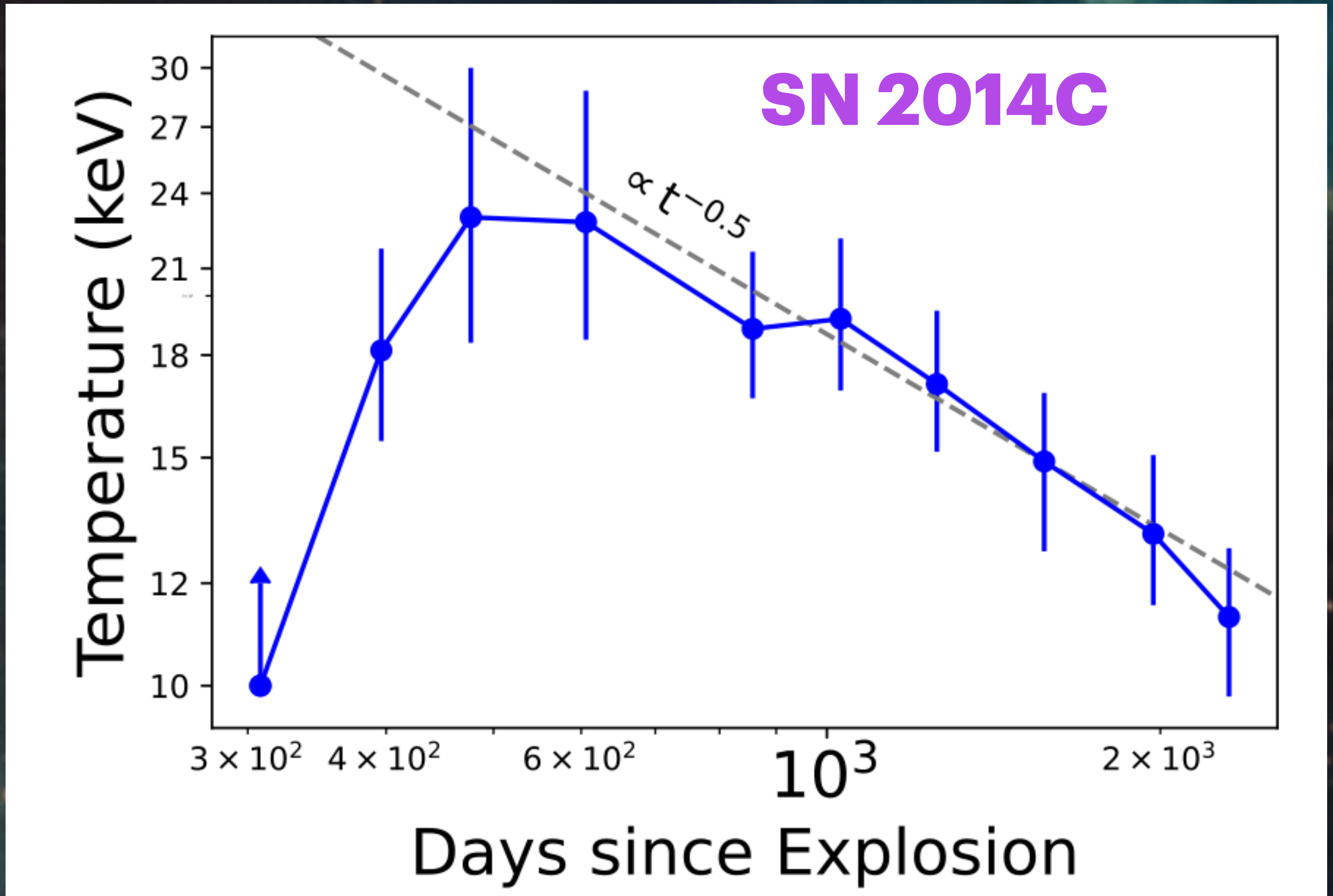
SN 2010jl (PC+15)



Credit: NASA/NRAO

X-ray emission - circumstellar interaction

Hard X-rays



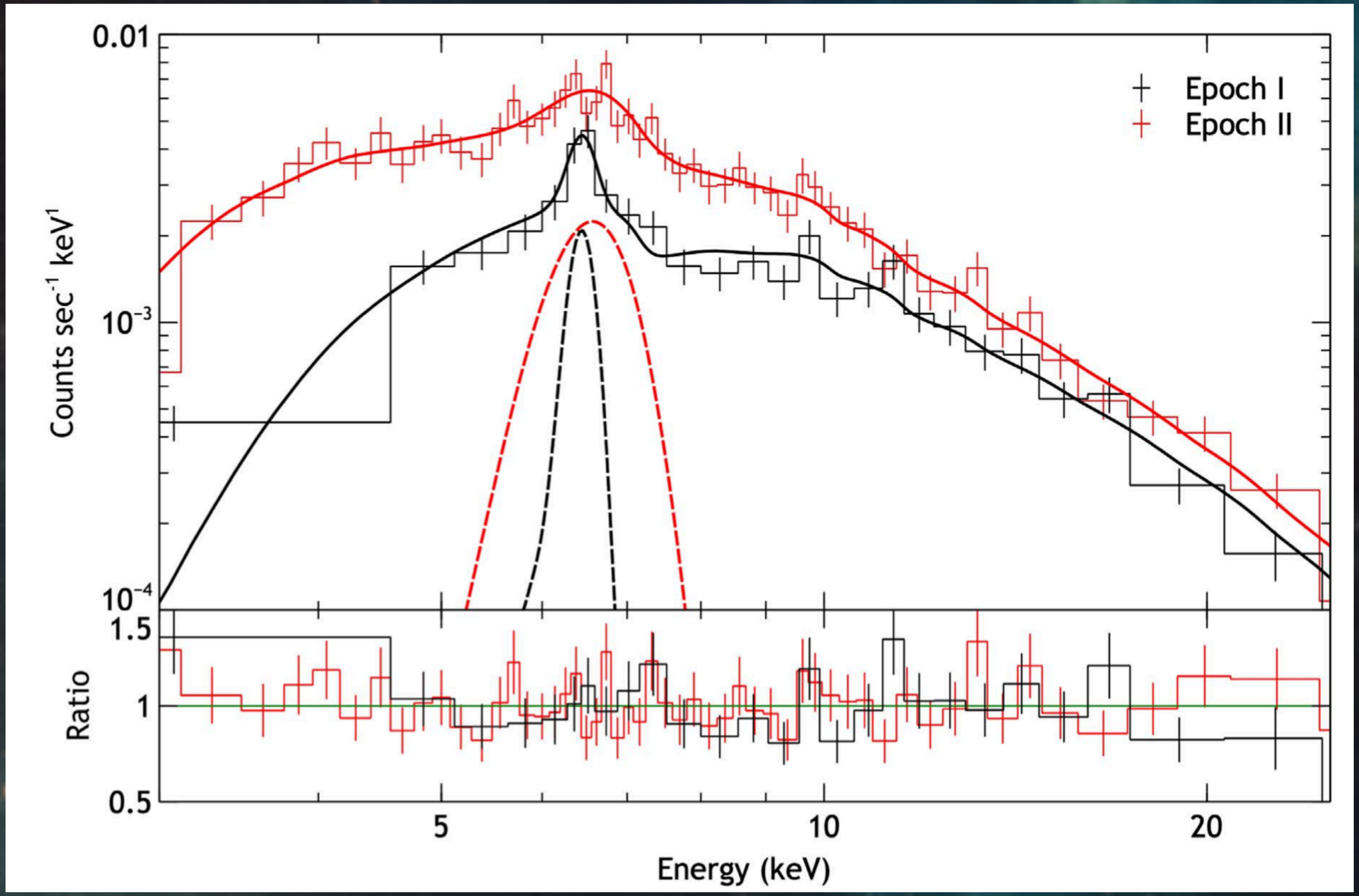
- Brethauer+22

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

Credit: NASA/NRAO

X-ray emission - circumstellar interaction

Hard X-rays



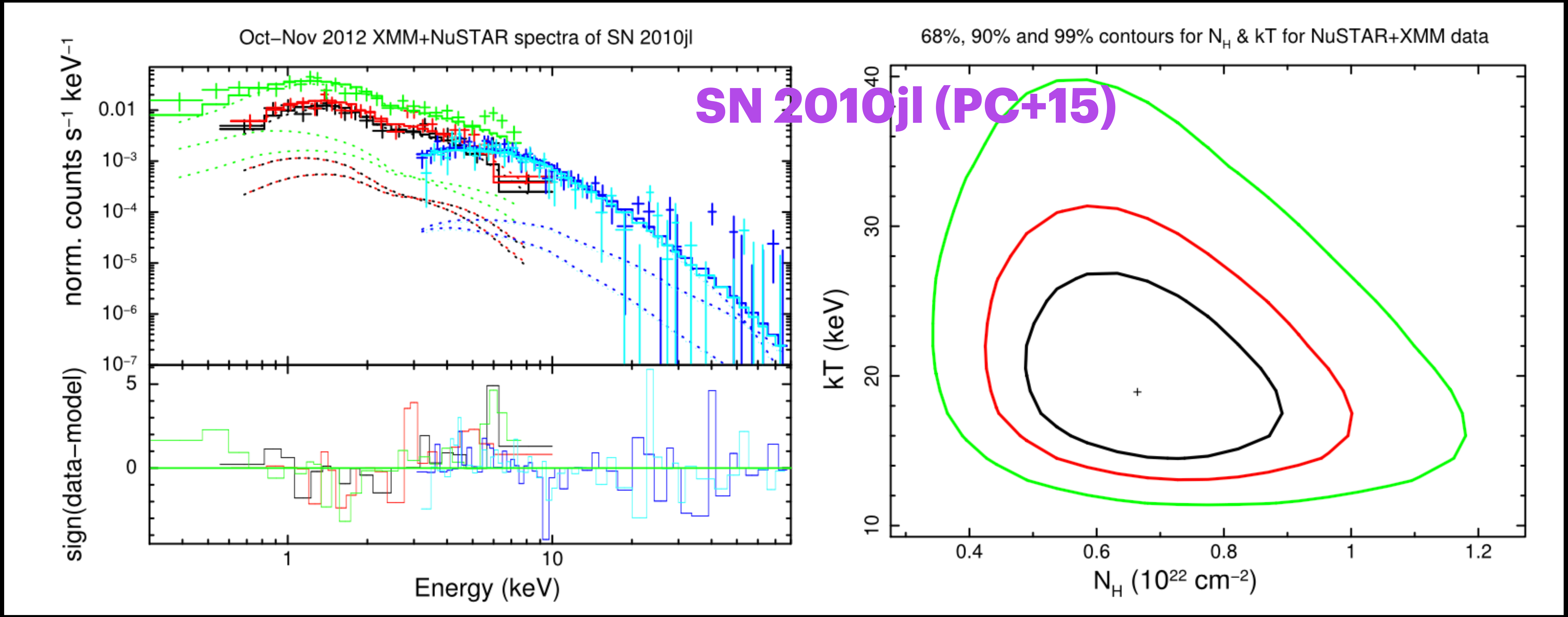
SN 2023ixf - Grefenstette+23

- 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

Credit: NASA/NRAO

X-ray emission - circumstellar interaction

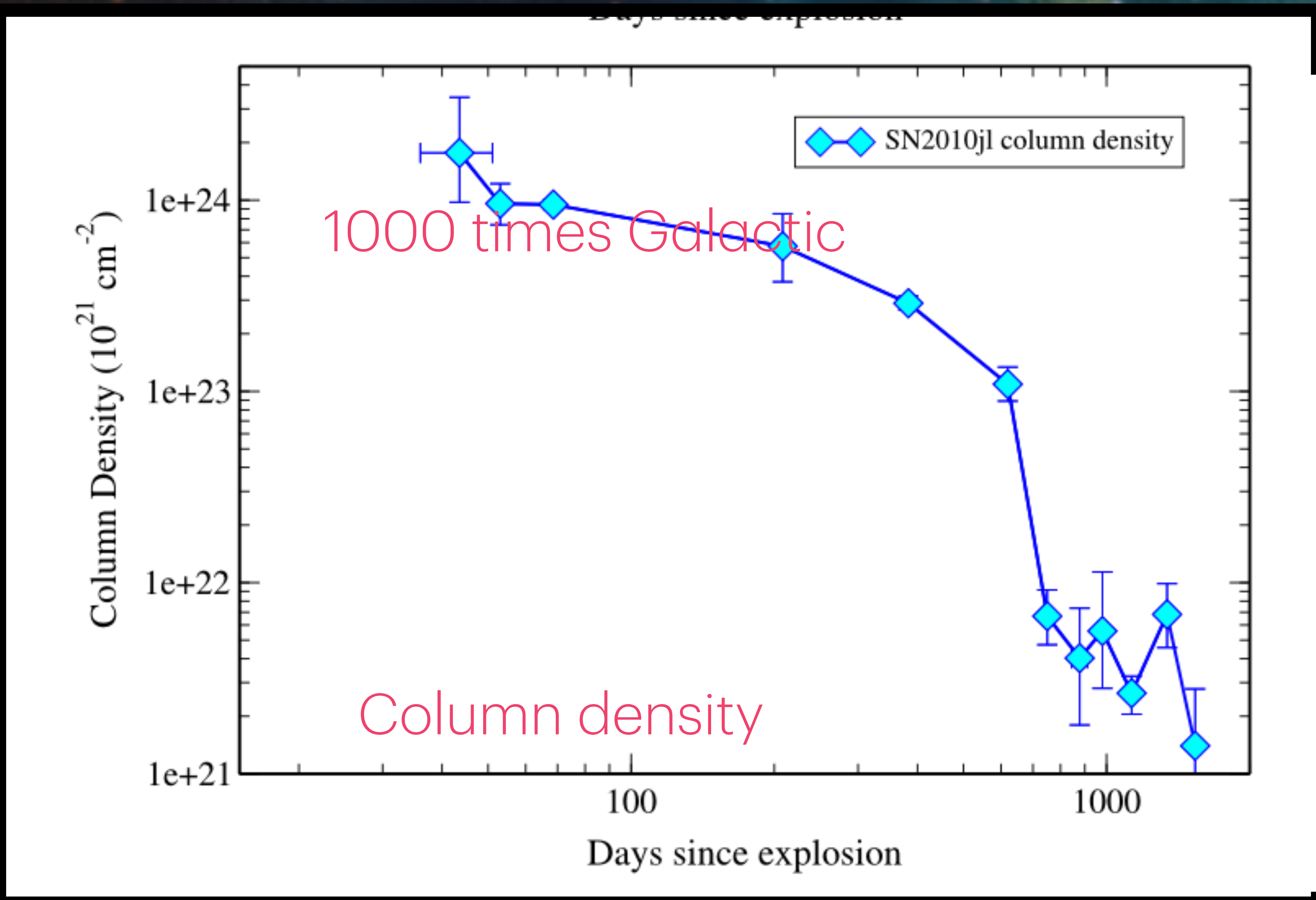
Hard X-rays - radiative forward shock (PC+18, PC+15, PC+12)

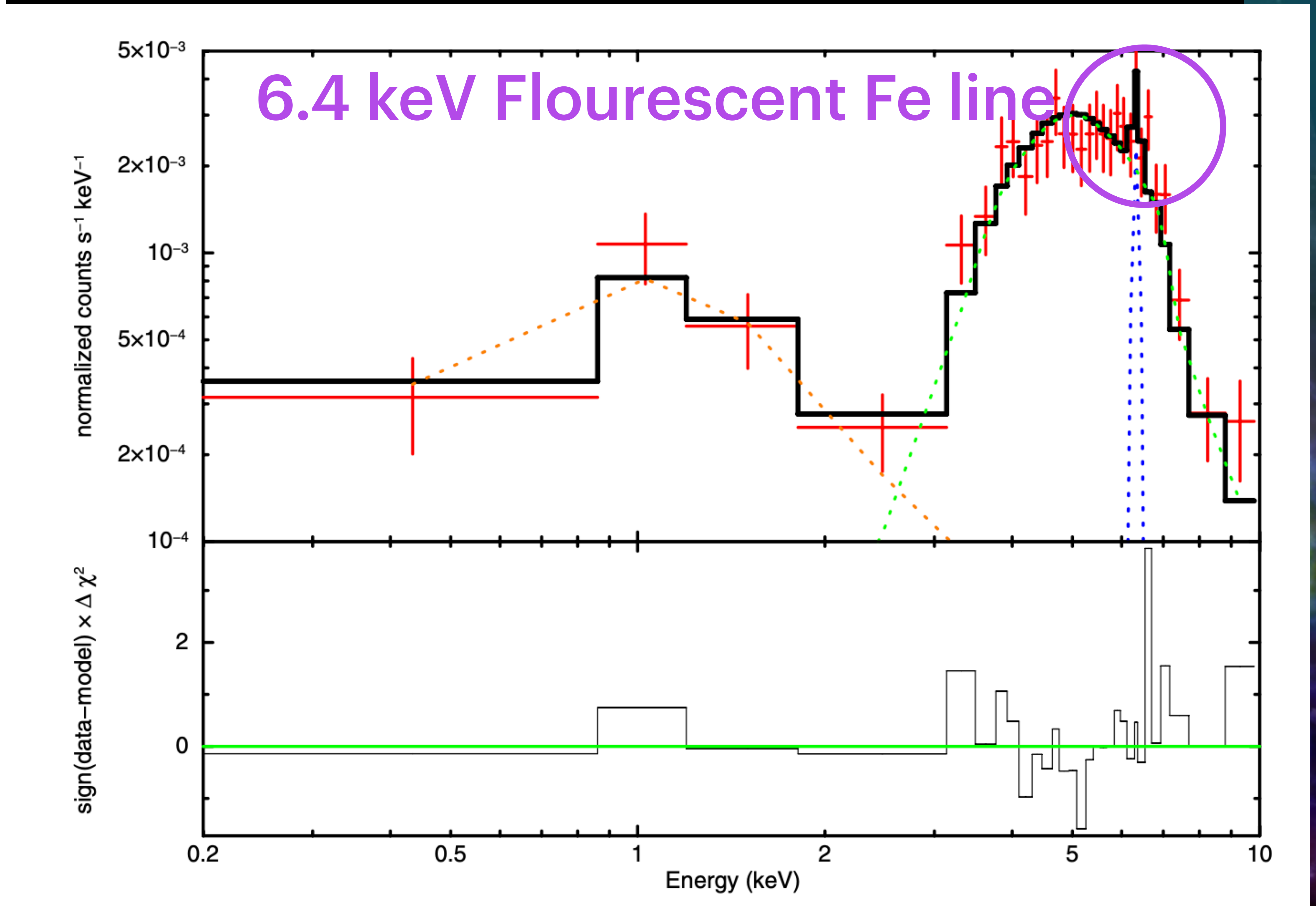


Credit: NASA/NRAO

X-ray emission - circumstellar interaction

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



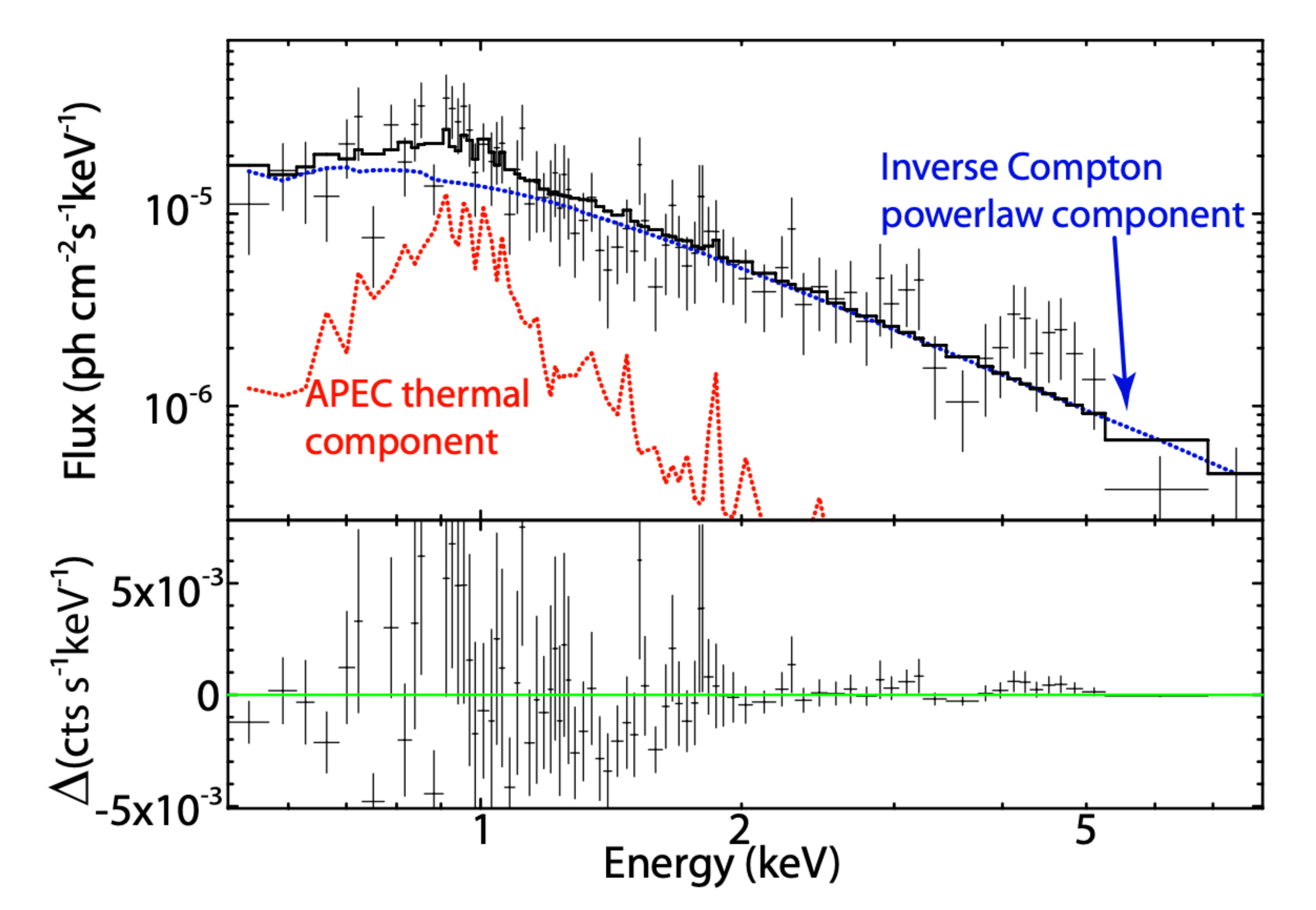


Credit: NASA/NRAO

X-ray emission- Circumstellar interaction

Non-thermal X-rays

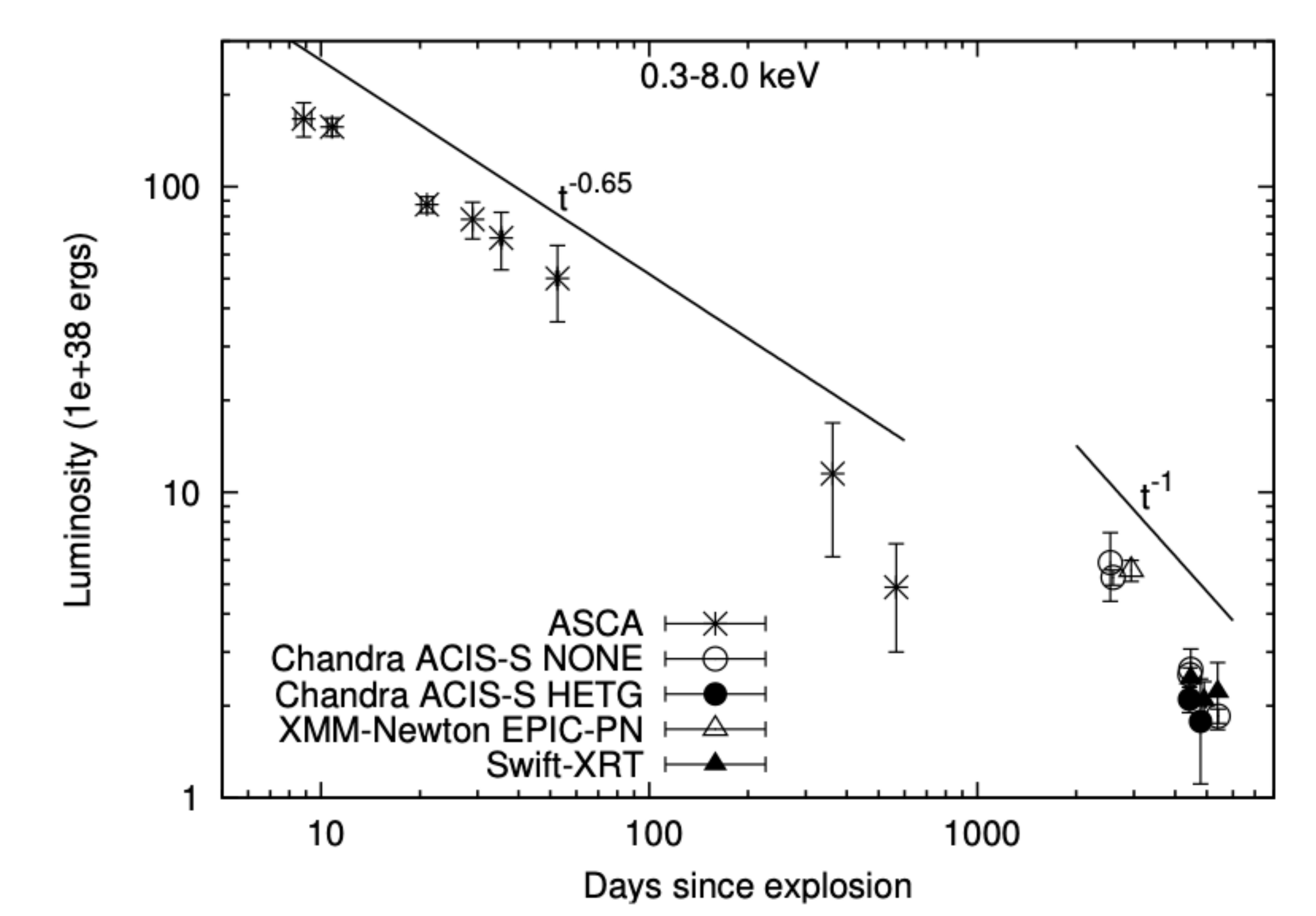
- Inverse Compton component of X-rays
- Usually in type Ib/c supernovae with large ejecta speeds
- Usually in Type IIP supernovae with large supply of photons
- See Chakraborty+12, 13, Soderberg+11, Margutti+12 etc.

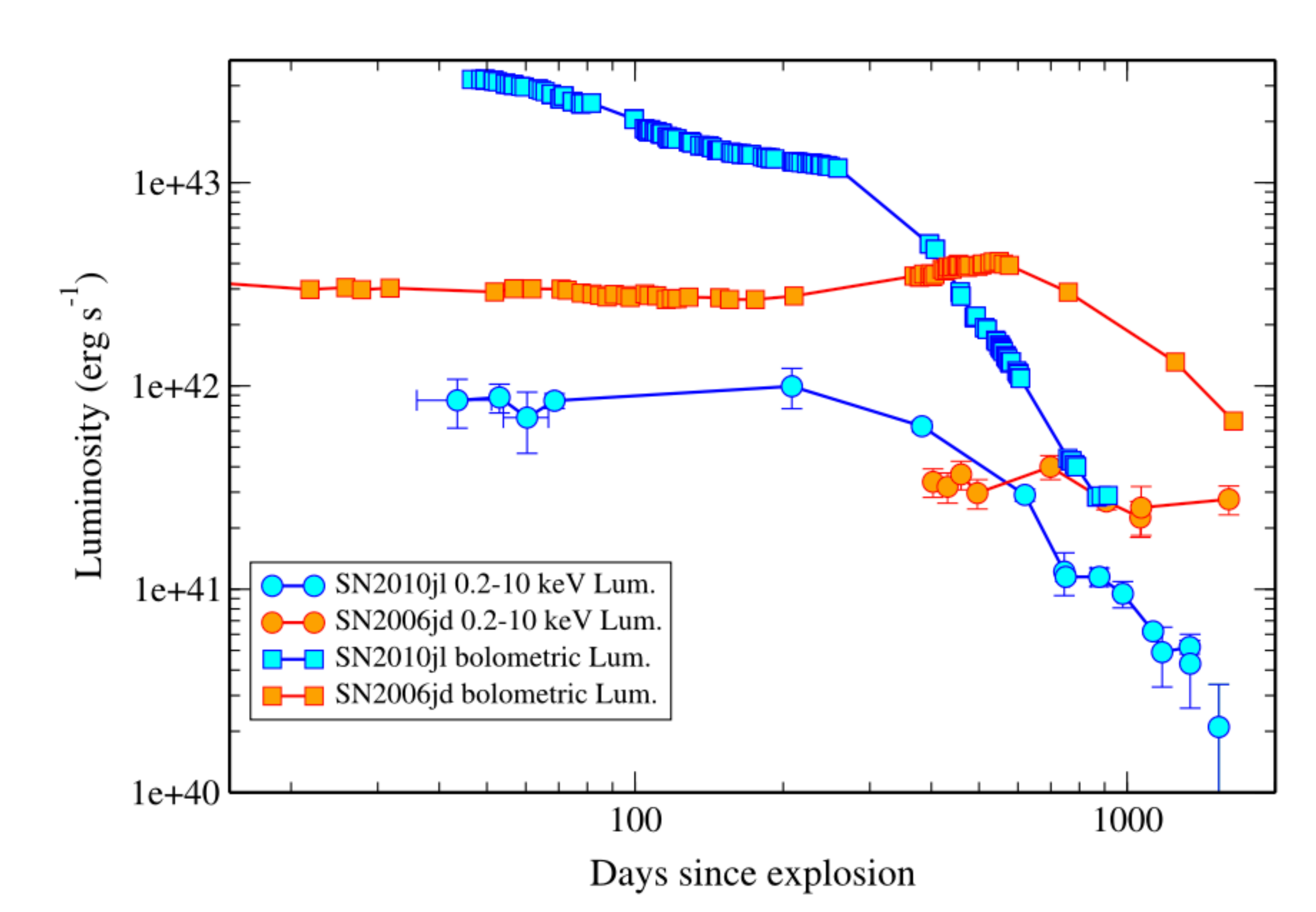


Chakraborty,...PC...2012

X-ray emission - circumstellar interaction

Picture of progenitor evolution



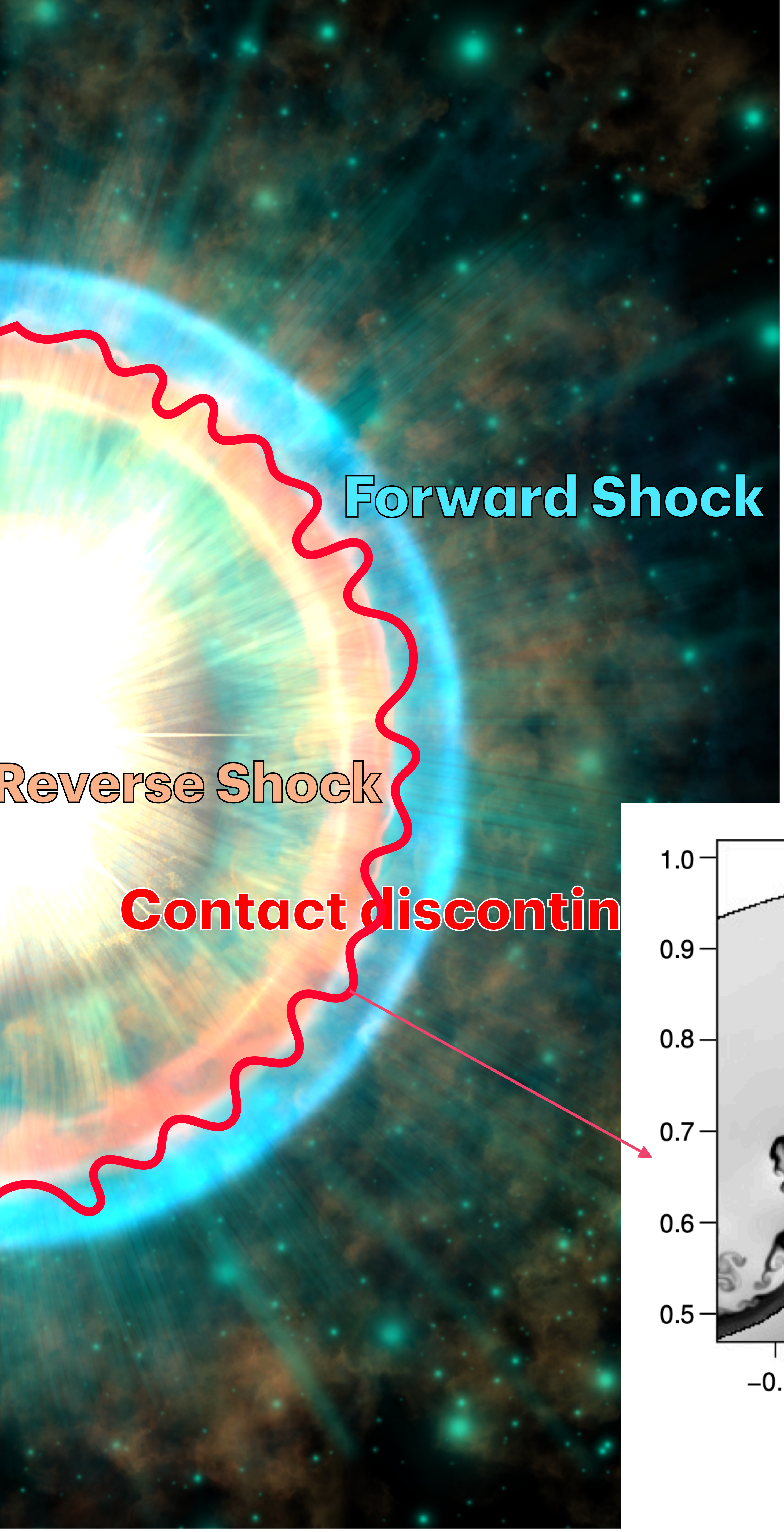


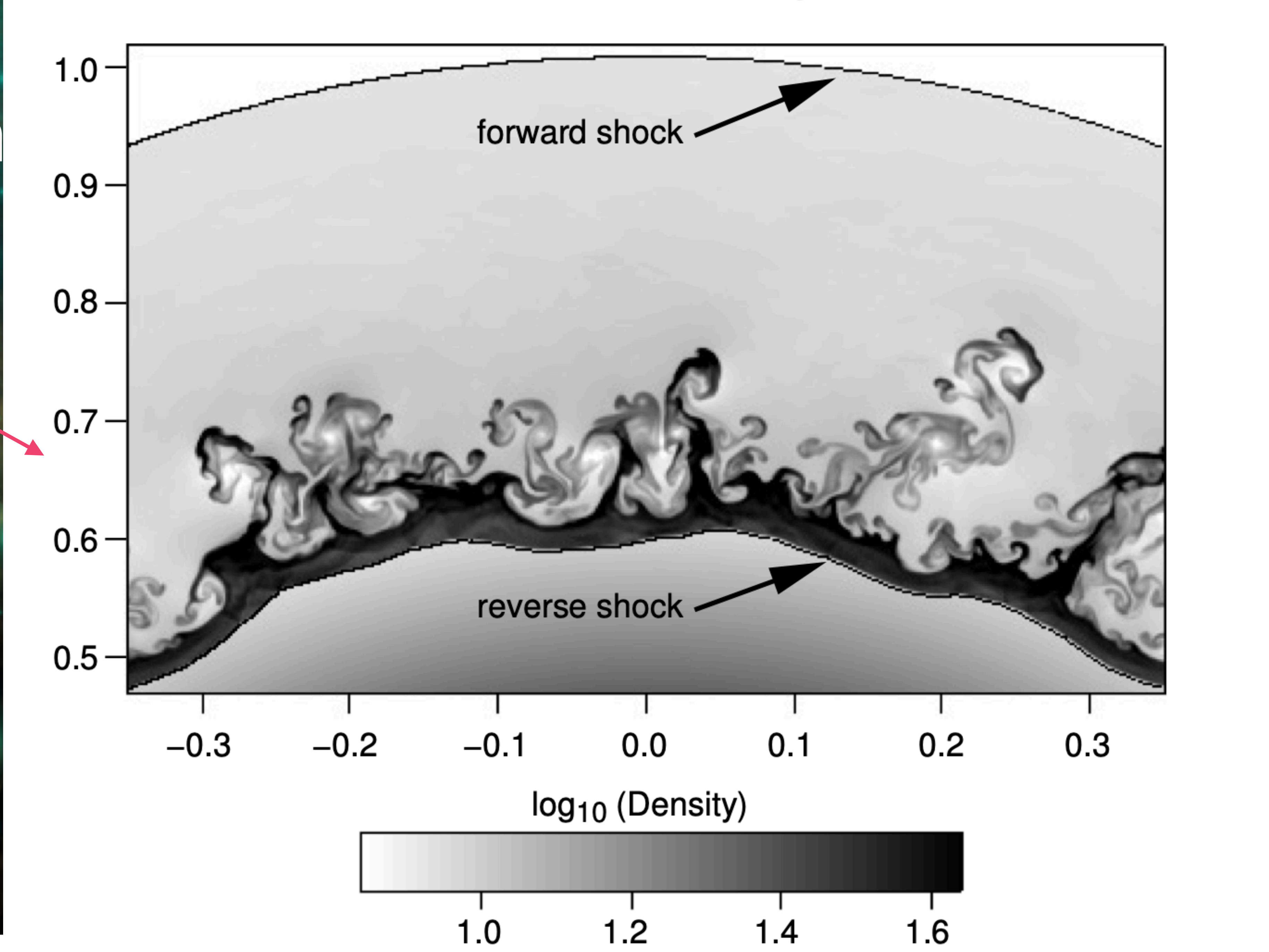
PC+09, 15, 18

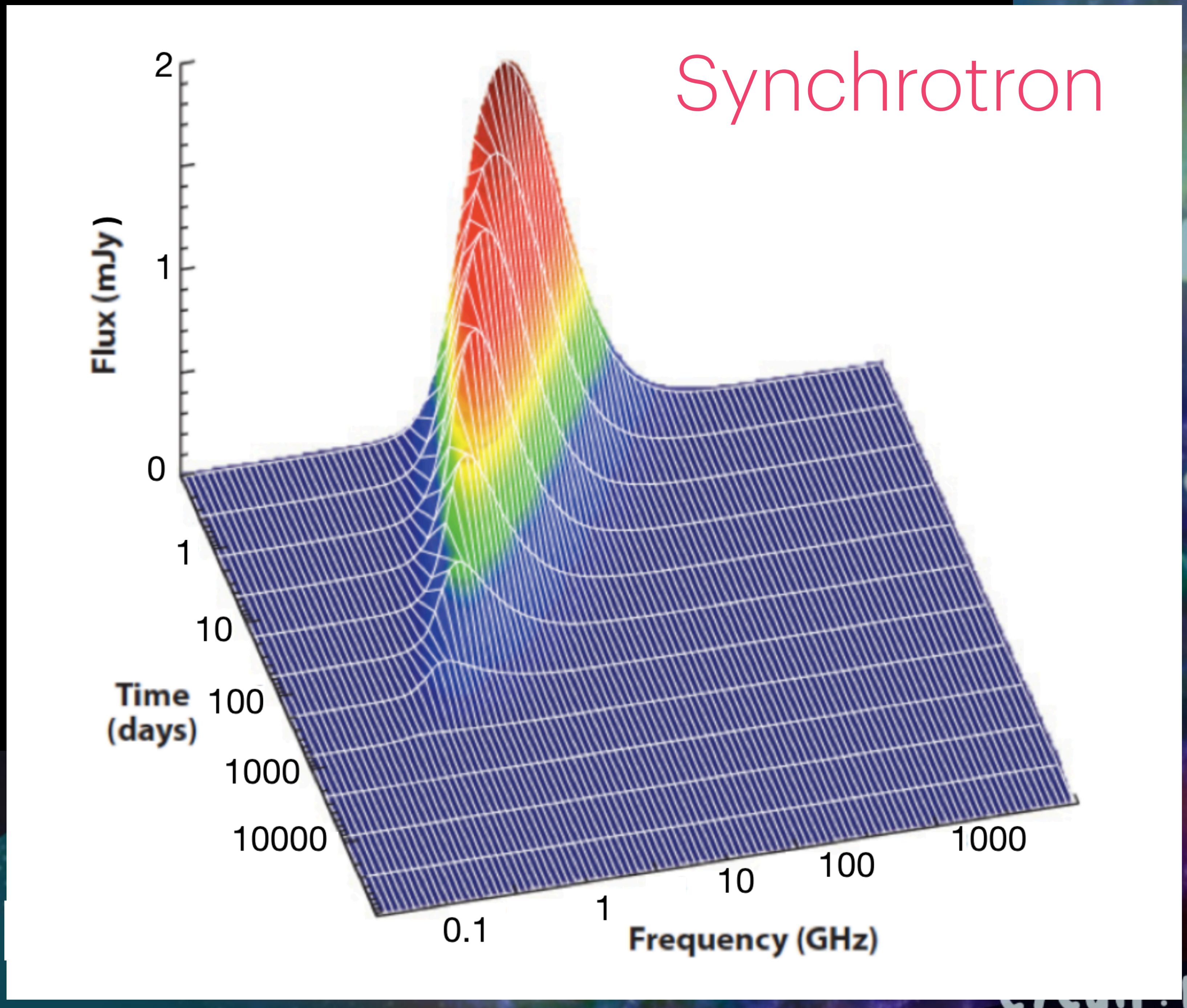
Credit: NASA/NRAO

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

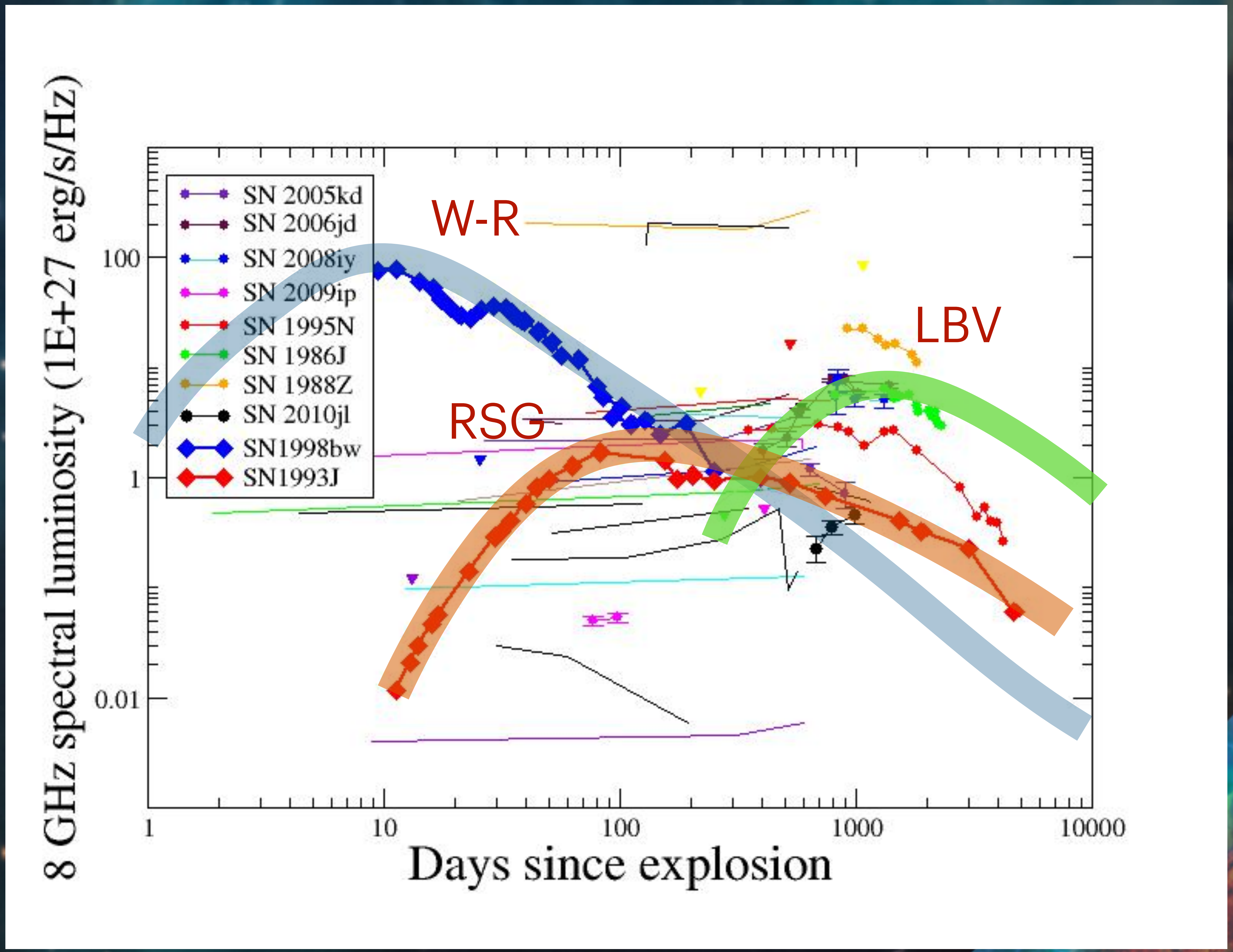






NASA/NRAO

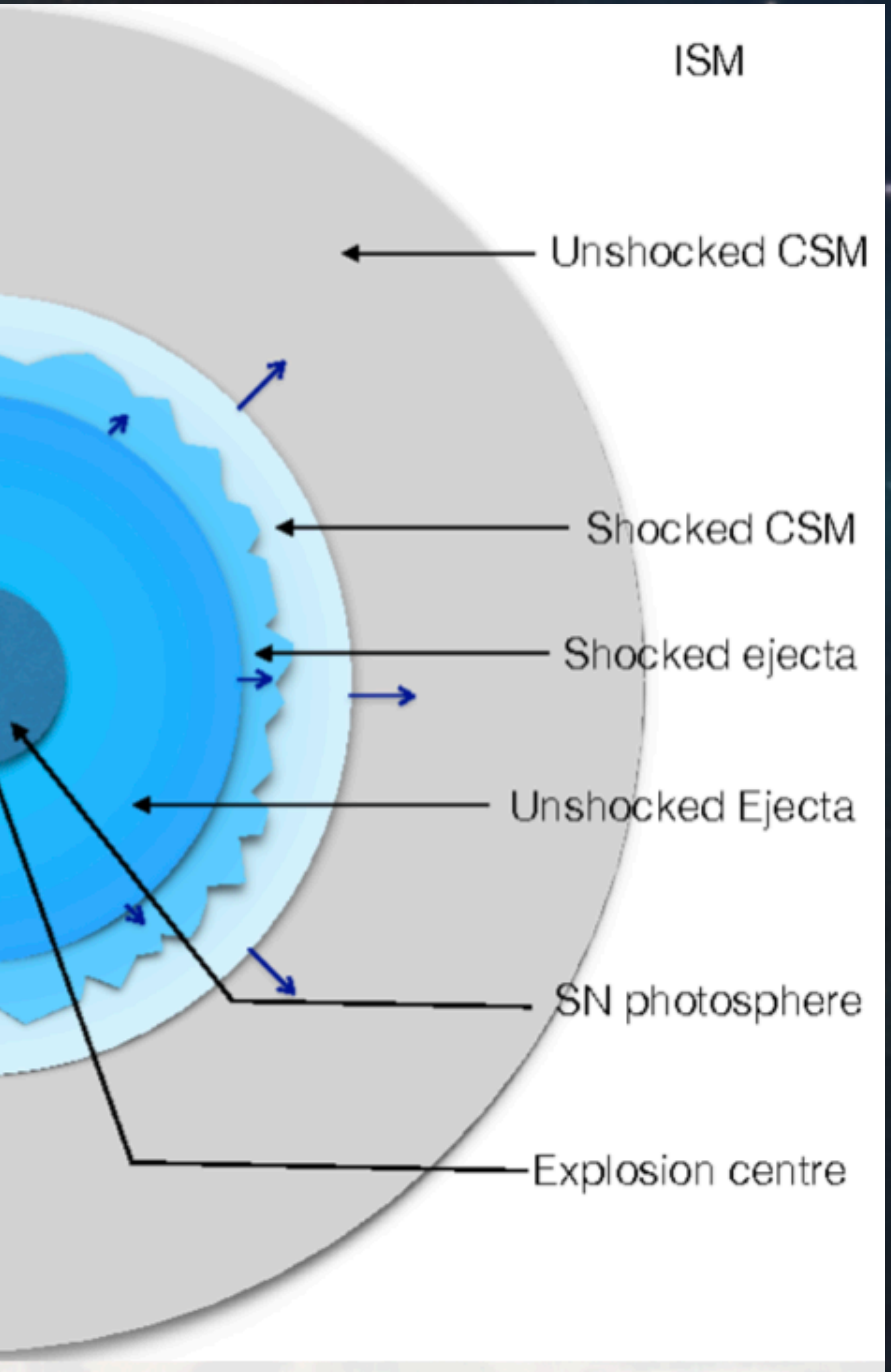
Radio emission



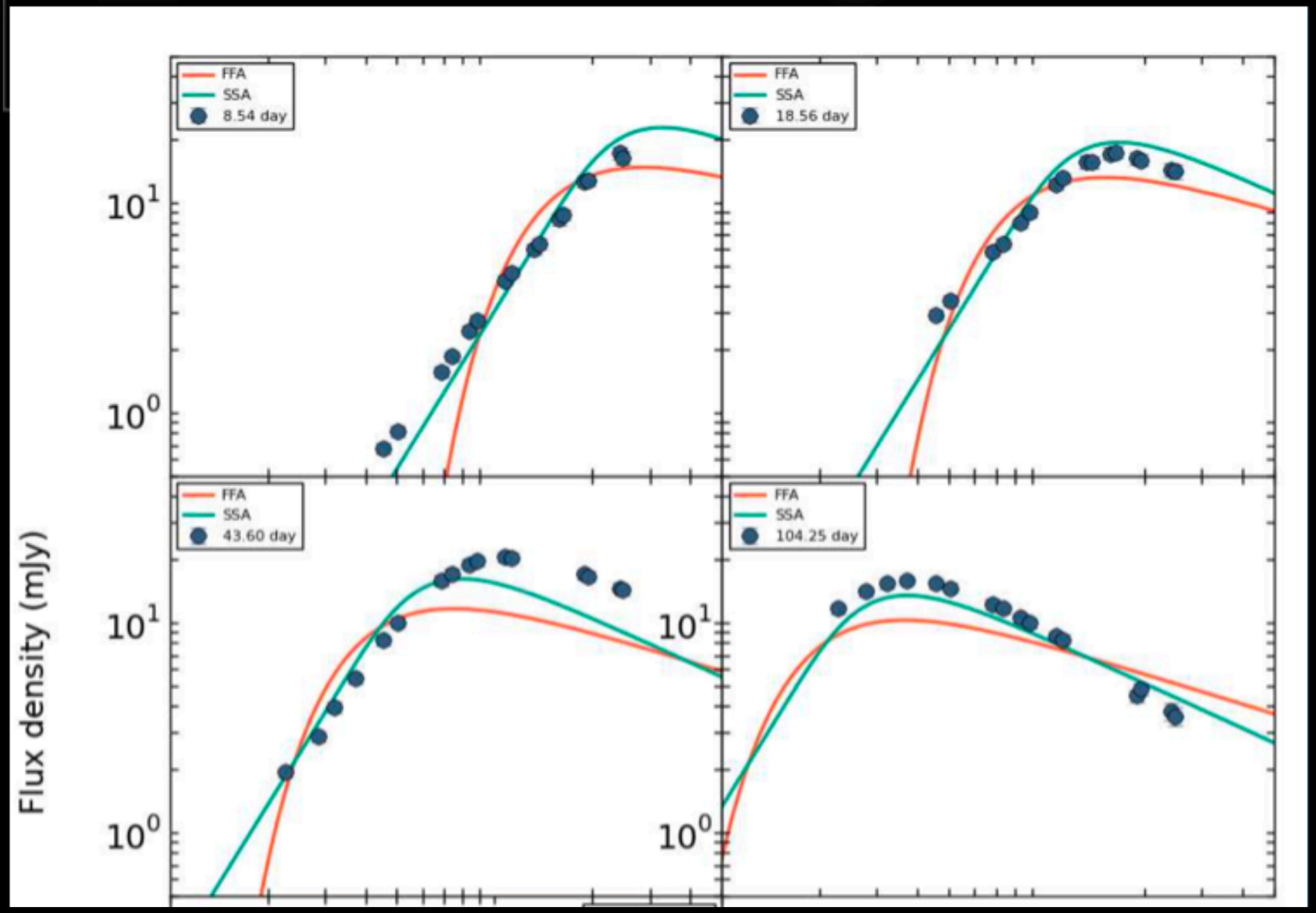
Chandra 2018, Bietenholz et al. 2021, Weiler et al. 2007

Credit: NASA/NRAO

Absorption of Radio emission



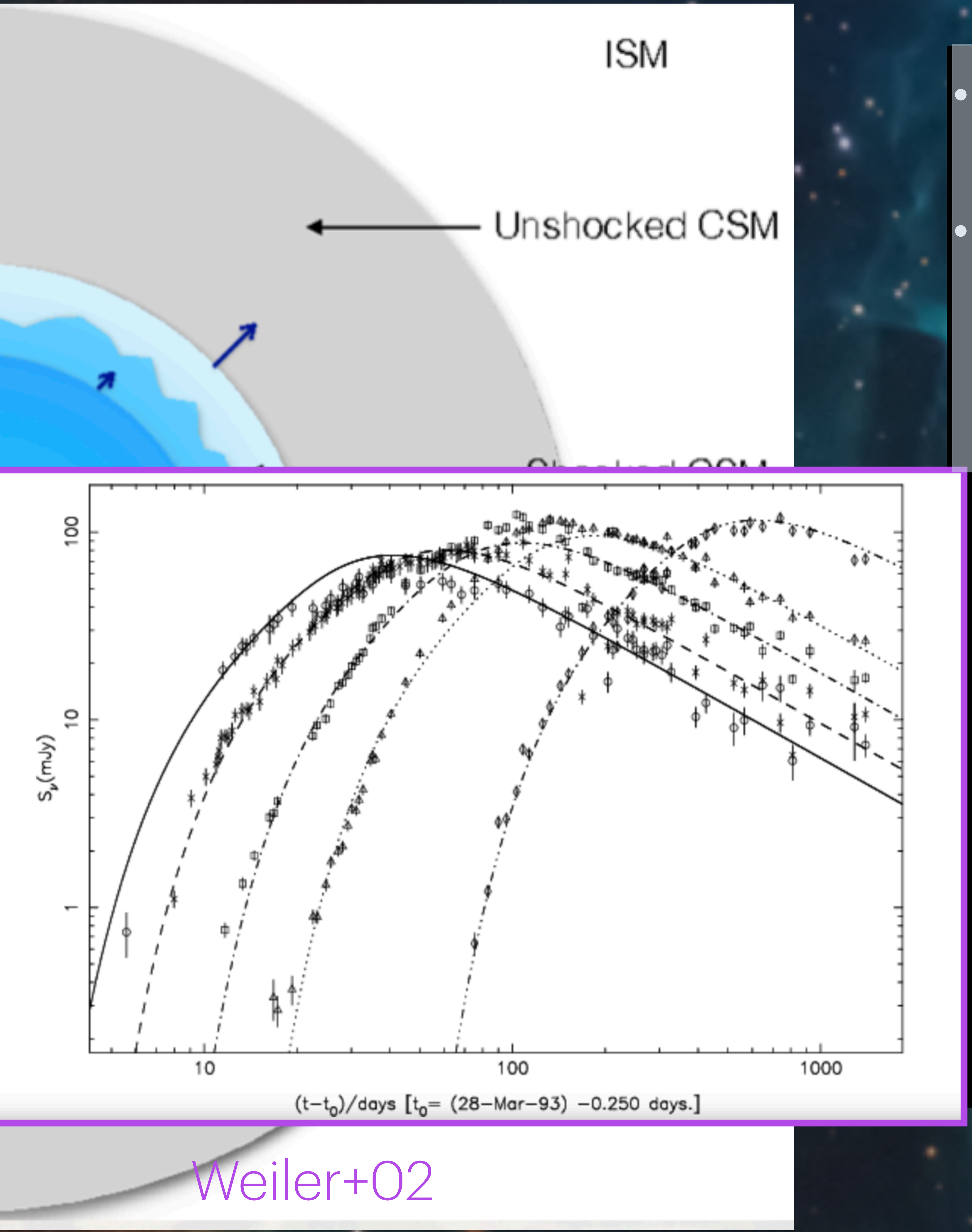
- Synchrotron emission
- Synchrotron self-absorption (fast ejecta, low mass-loss rate, Ib/Ic,IIb etc. see Nayana, PC+,2022, 2023)
  - Magnetic field, size etc



Nayana,PC+22

Credit: NASA/NRAO

Absorption of Radio emission



Weiler+02

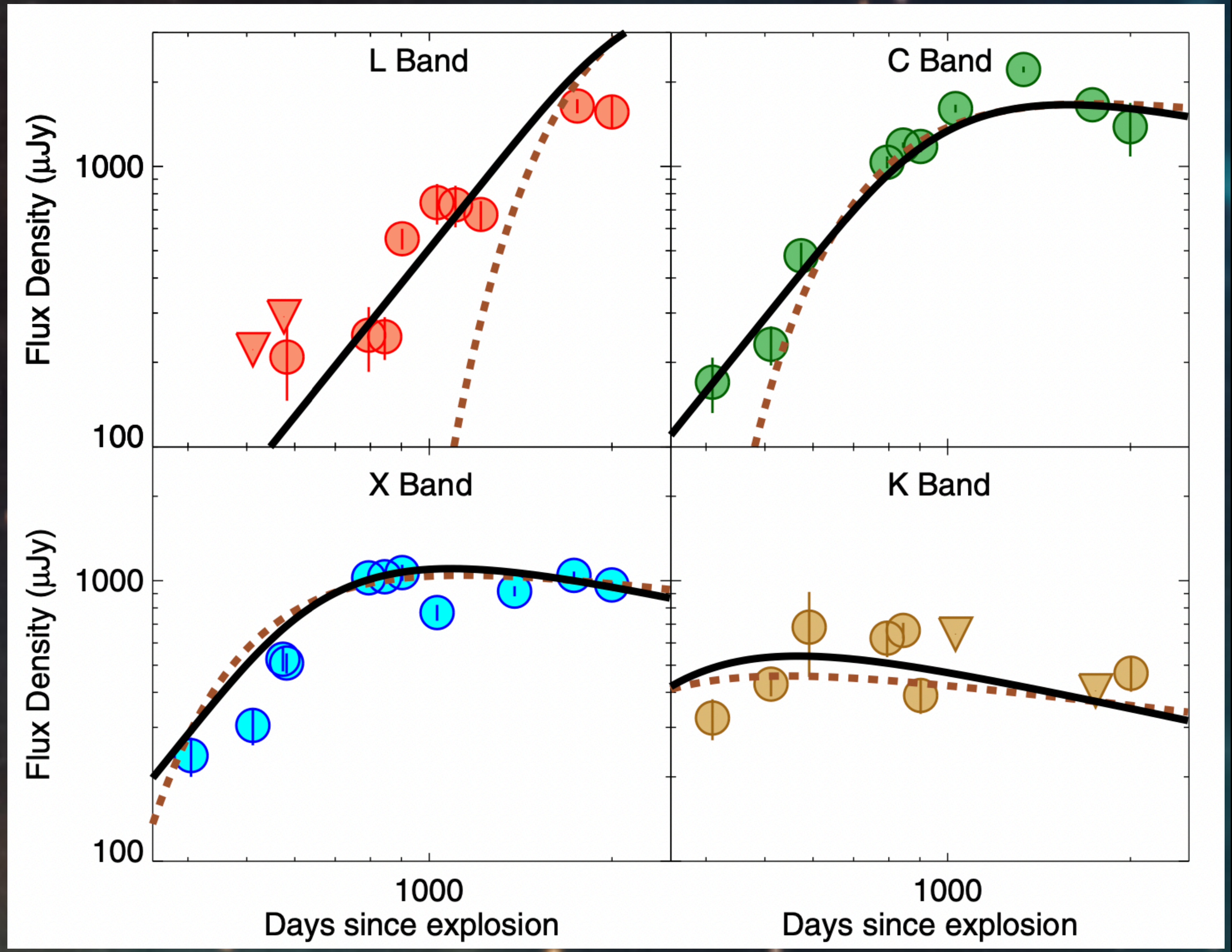
- Synchrotron emission
- Synchrotron self-absorption (fast ejecta, low mass-loss rate, Ib/Ic,IIb etc. see Nayana, PC+,2022, 2023)
  - Magnetic field, size etc

Free-free absorption (slow ejecta, large mass-loss rate)

- Density of the medium, mass-loss rate

Credit: NASA/NRAO

Absorption of Radio emission



,PC+12

InternalFFA

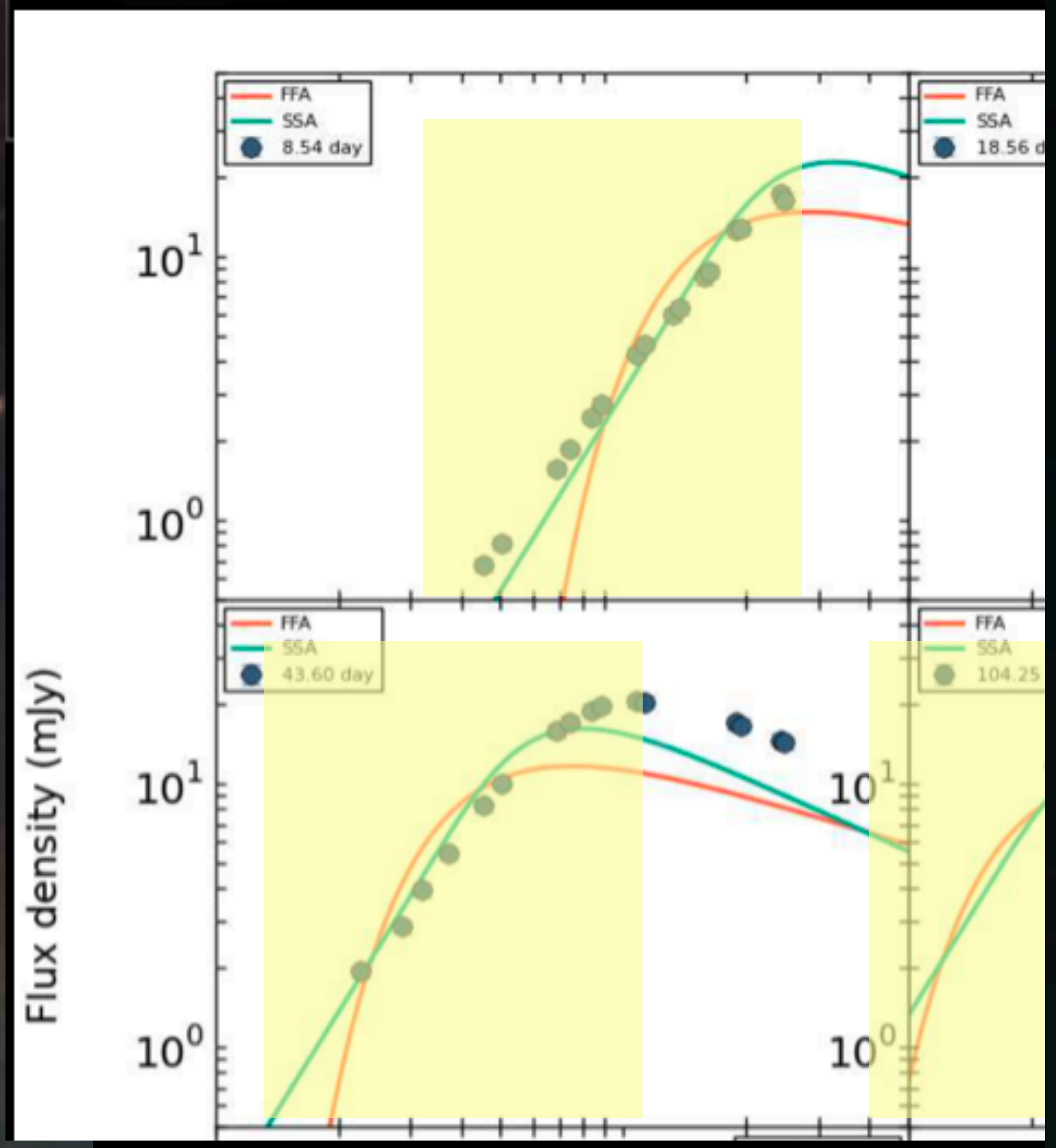
- Synchrotron emission
- Synchrotron self-absorption (fast ejecta, low mass-loss rate, Ib/Ic,IIb etc. see Nayana, PC+,2022, 2023)
  - Magnetic field, size etc
- Free-free absorption (slow ejecta, large mass-loss rate)
  - Density of the medium, mass-loss rate
- Internal free-free absorption (radiative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

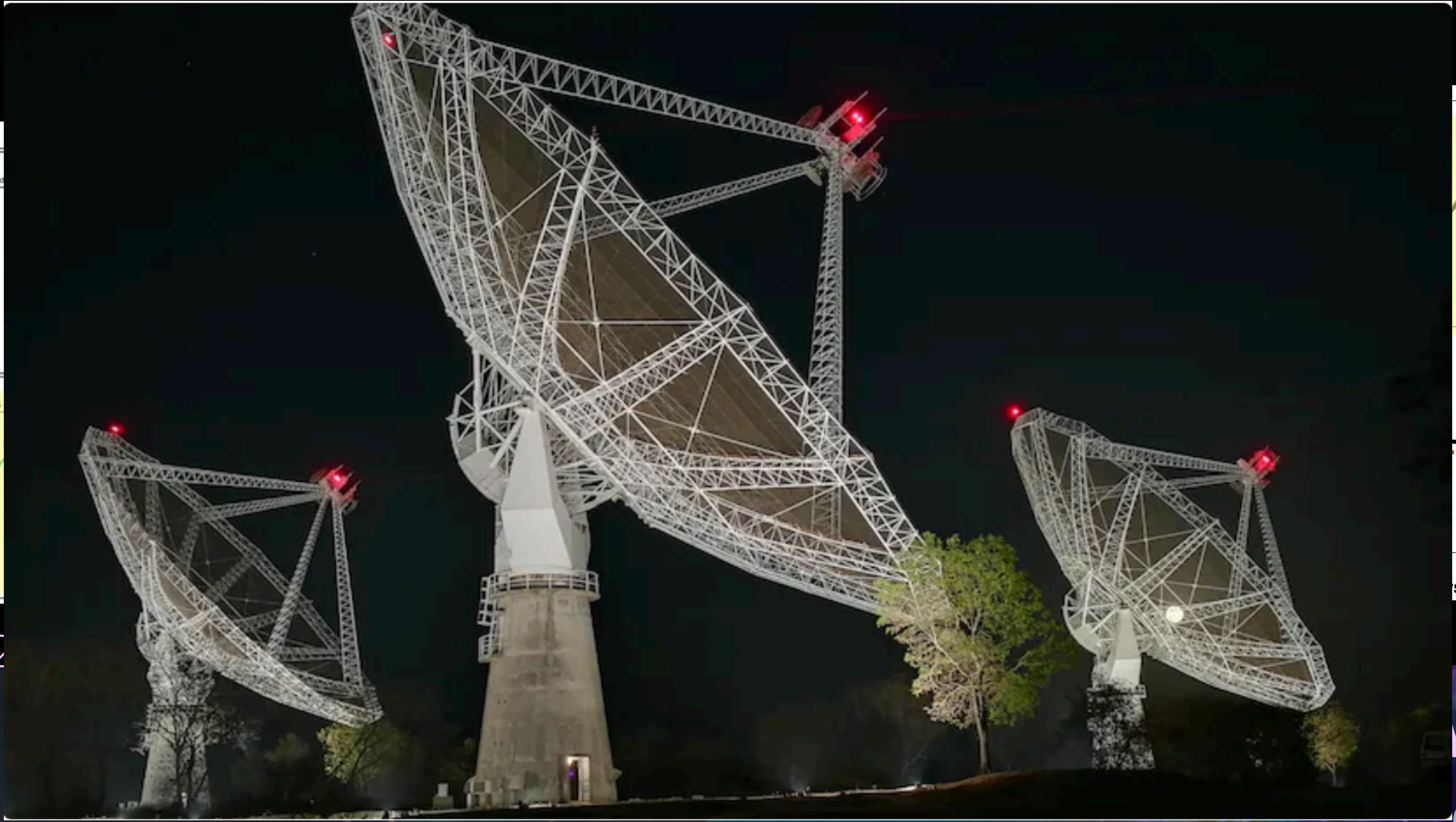
$$M_a \approx 2 \times 10^{-8}\, T_4^{5/2} M_\odot$$

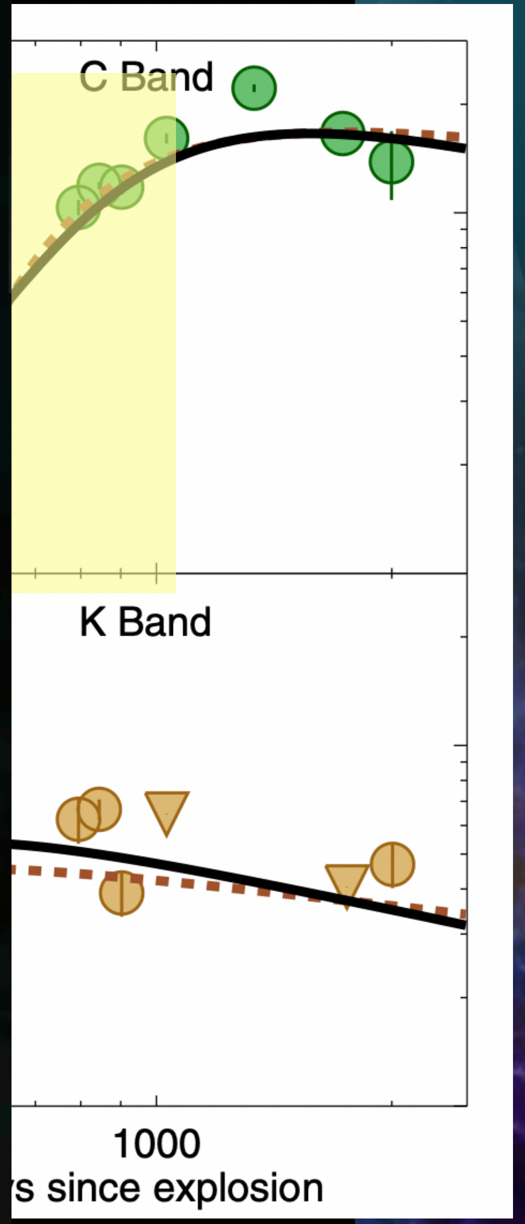
PC+12

Radio emission- low frequency observations critical

- Low frequency observations critical
- GMRT sub-GHz view of supernovae (400-1400 MHz, PC+22,18, Nayana+23,21,Thesis of A. J. Nayana)







Nayana,PC+22

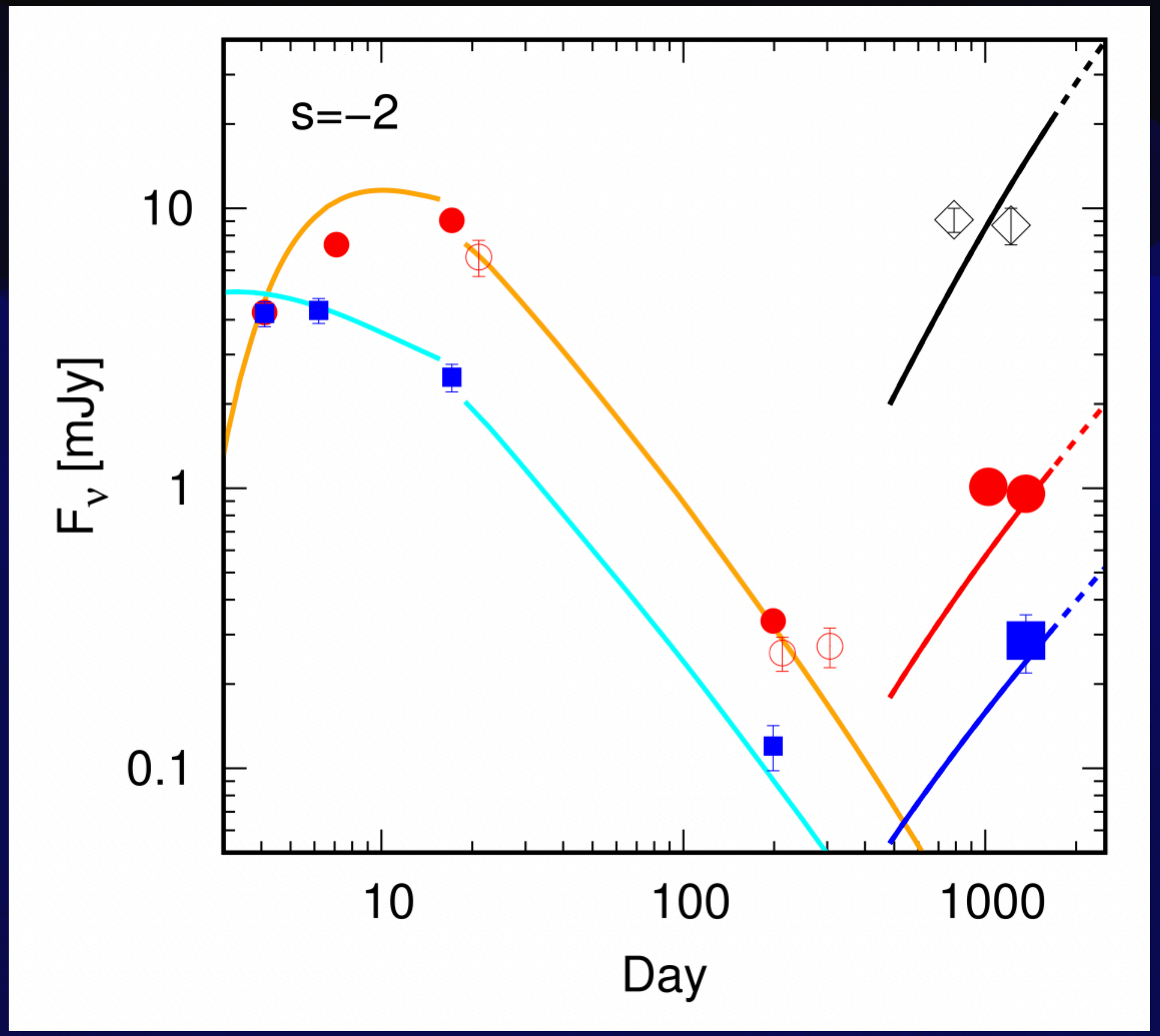
SSA

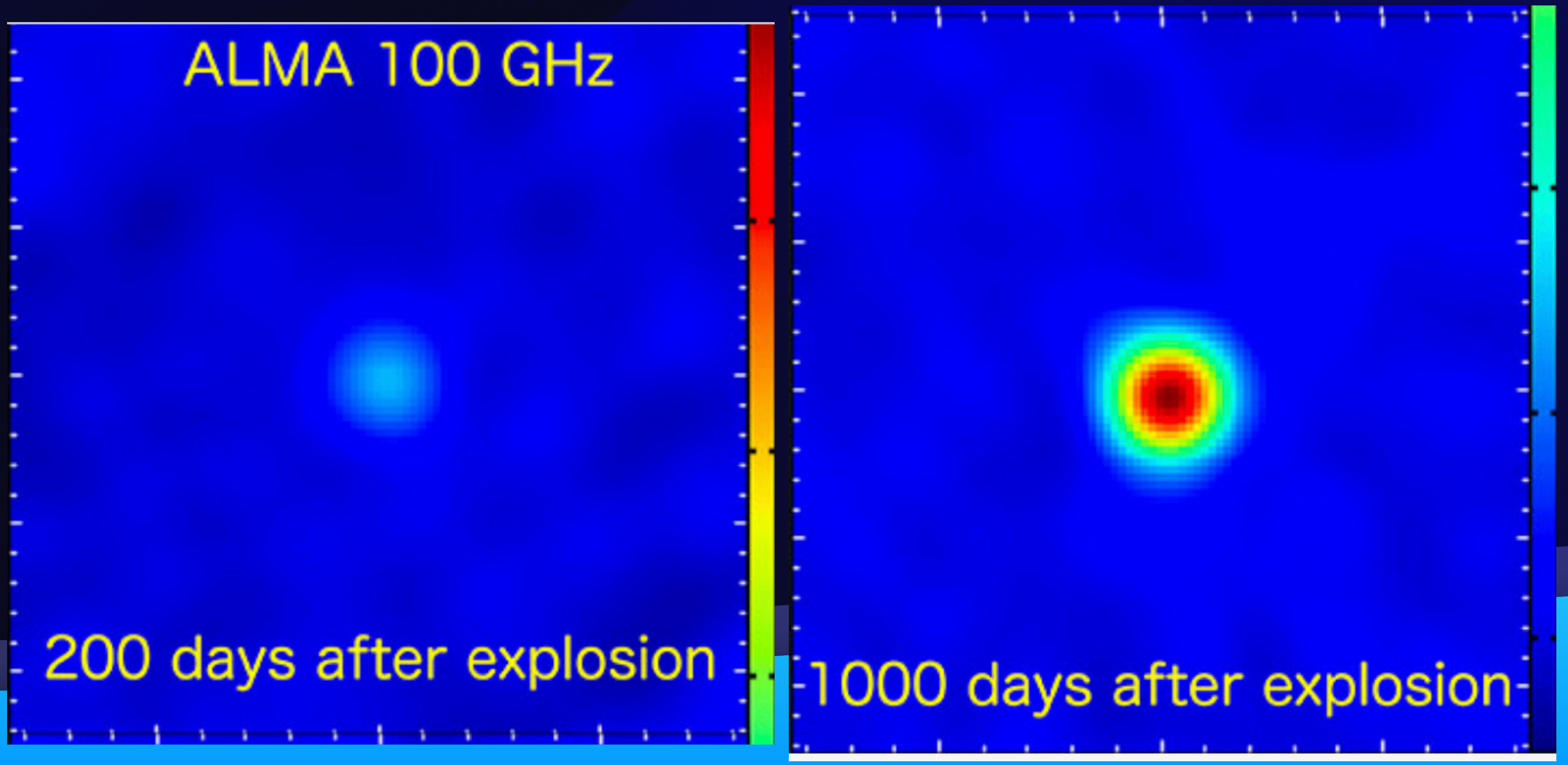
Credit: NASA/NRAO

Binarity in supernovae progenitors

Maeda, Chandra et al 2023, Maeda, Michiyama and Chandra 2023 et al., ApJ

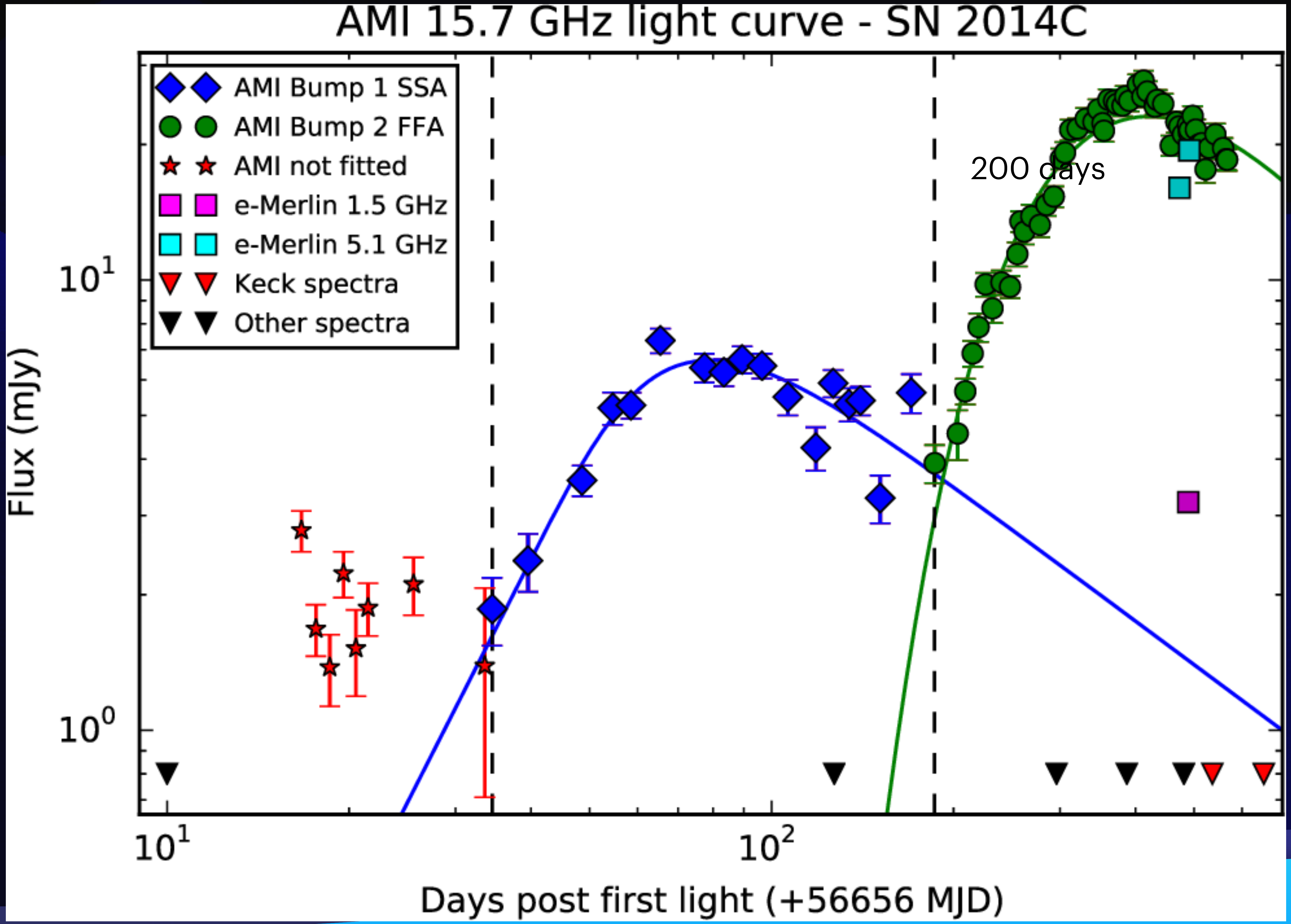
- SN 2018ivc - dimming 200 days after the initial explosion
- Rebrightening at 1000 days - ALMA data
- A large amount of CSM surrounding the exploding star at 0.1 light-years.
- Large amounts of CSM - outcome of a strong binary interaction that took place about 1500 years before the SN explosion.





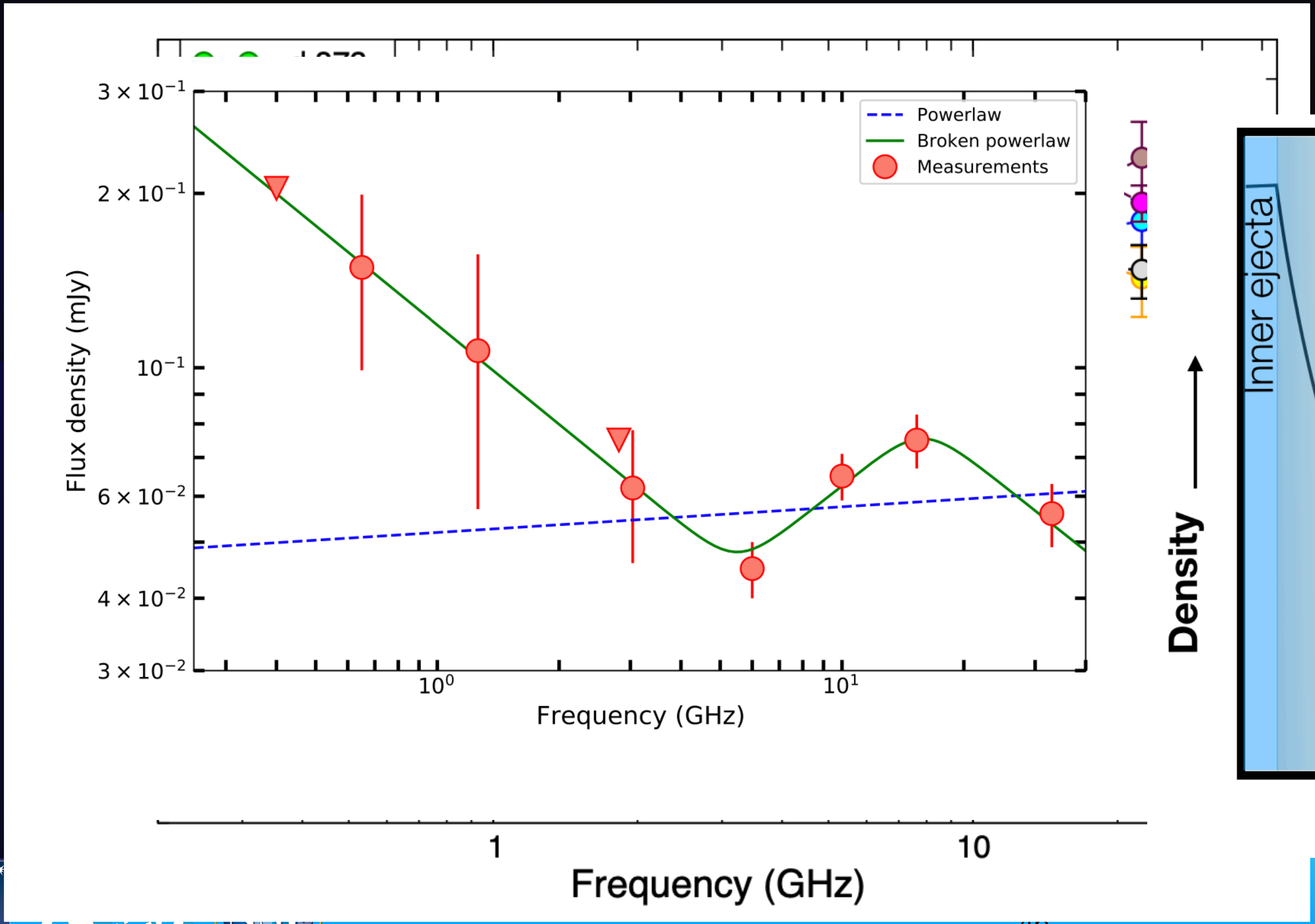
Binarity in supernovae progenitors

SN 2014C - Anderson et al. 2017

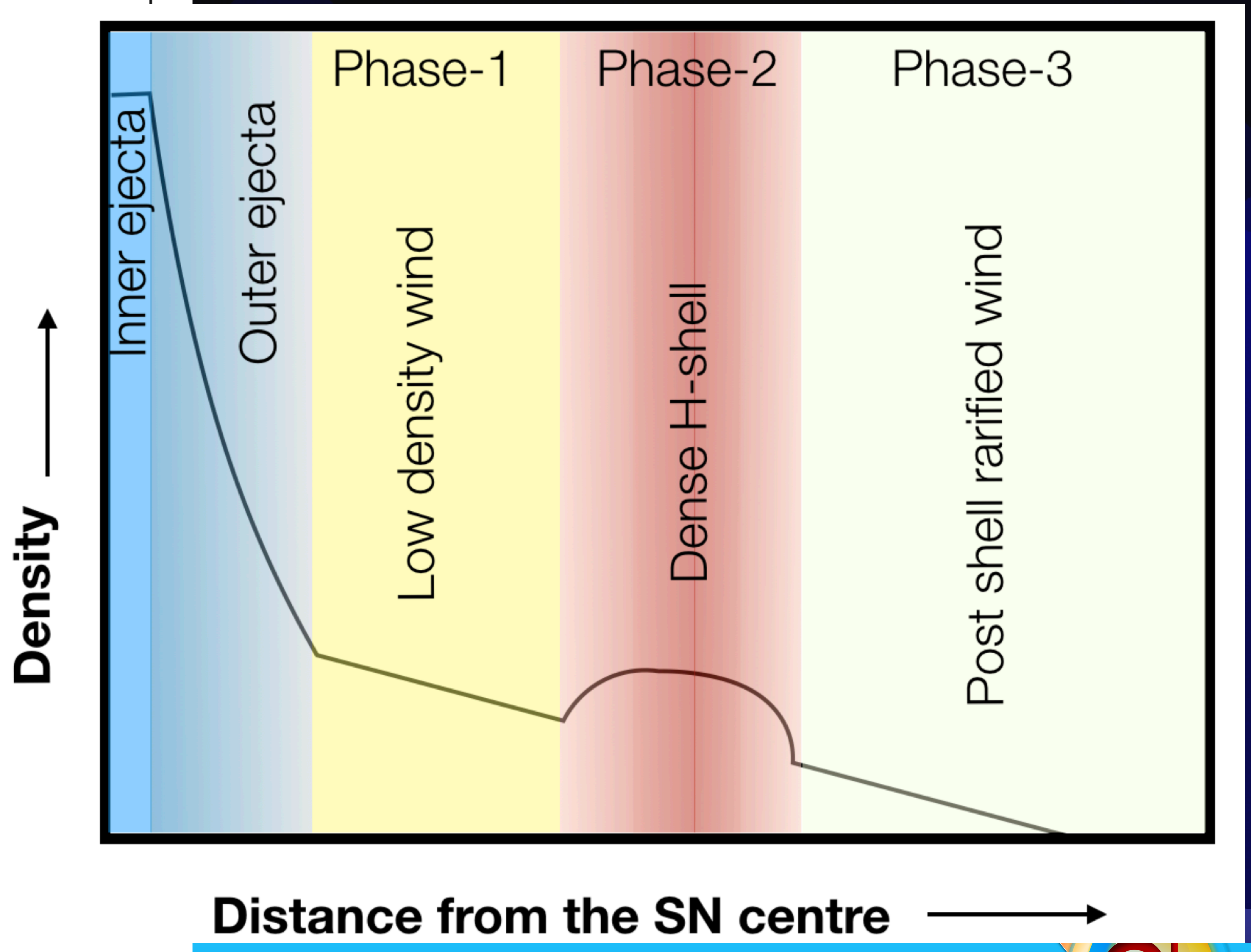


SN 2001em - binarity

PC et al. 2020, Chug, Chevalier 2006



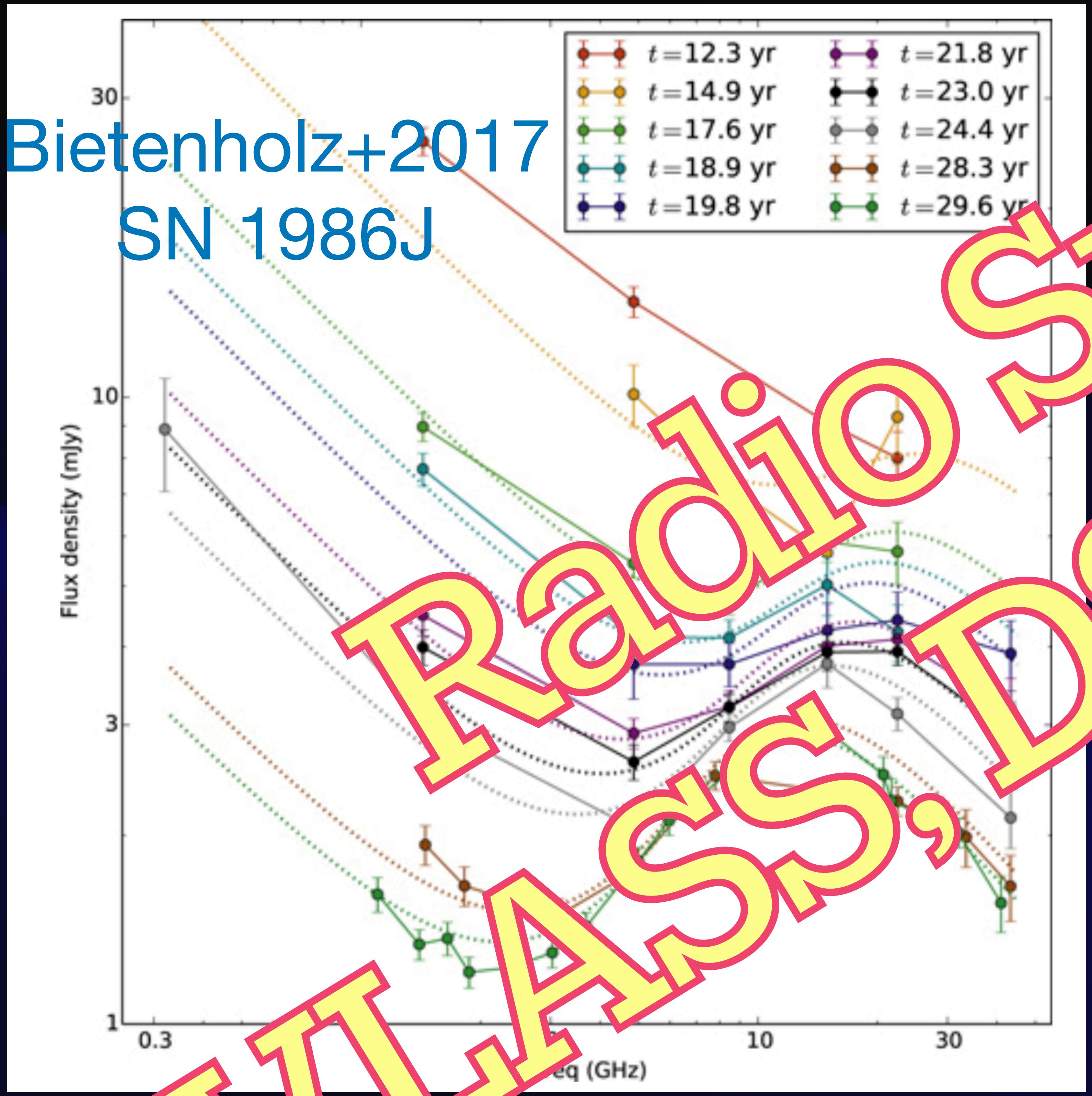
- A shell at 3 years when

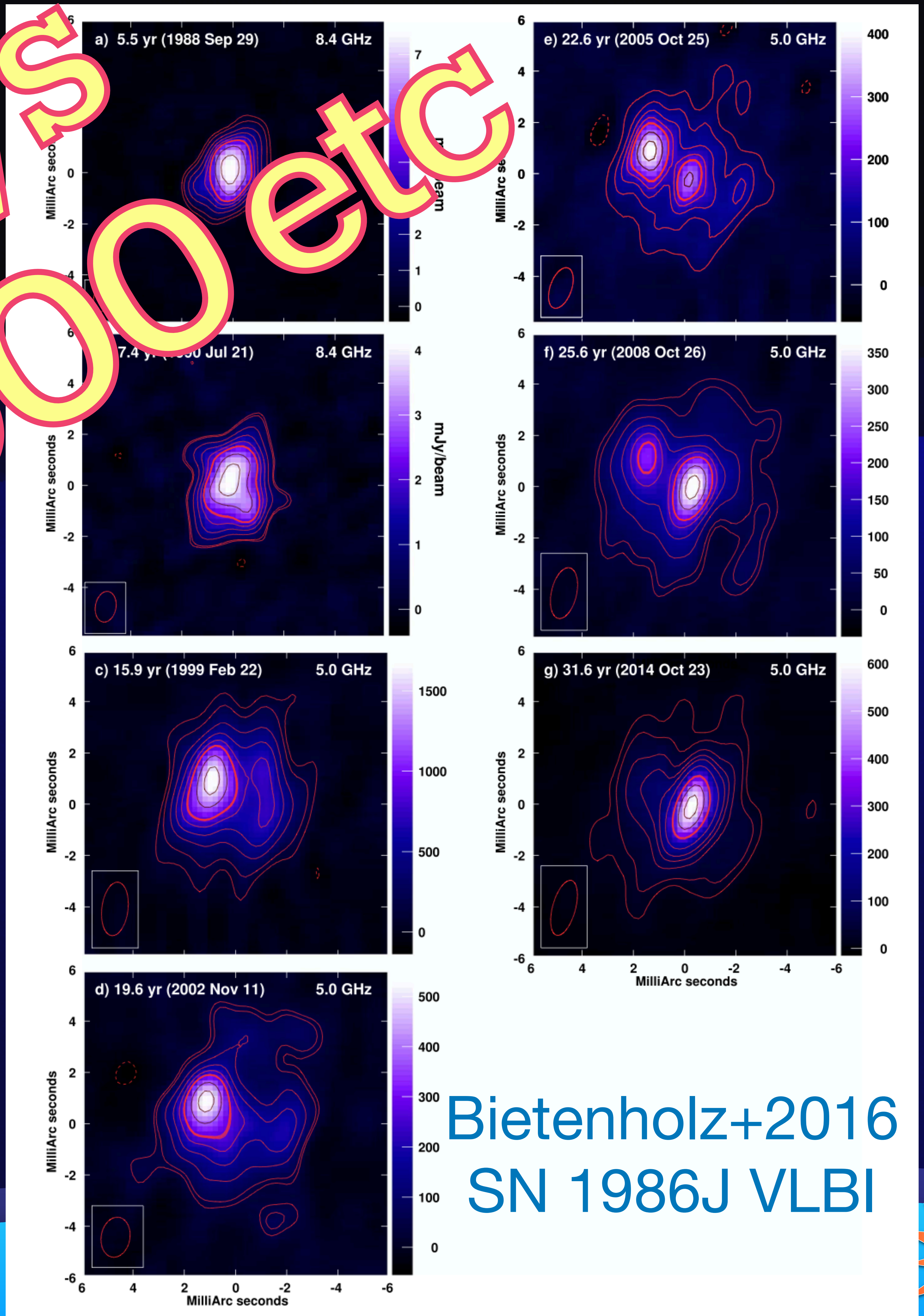


SN 2001em - binarity

SN 1986J

Radio Surveys
VLASS, DSA2000 etc



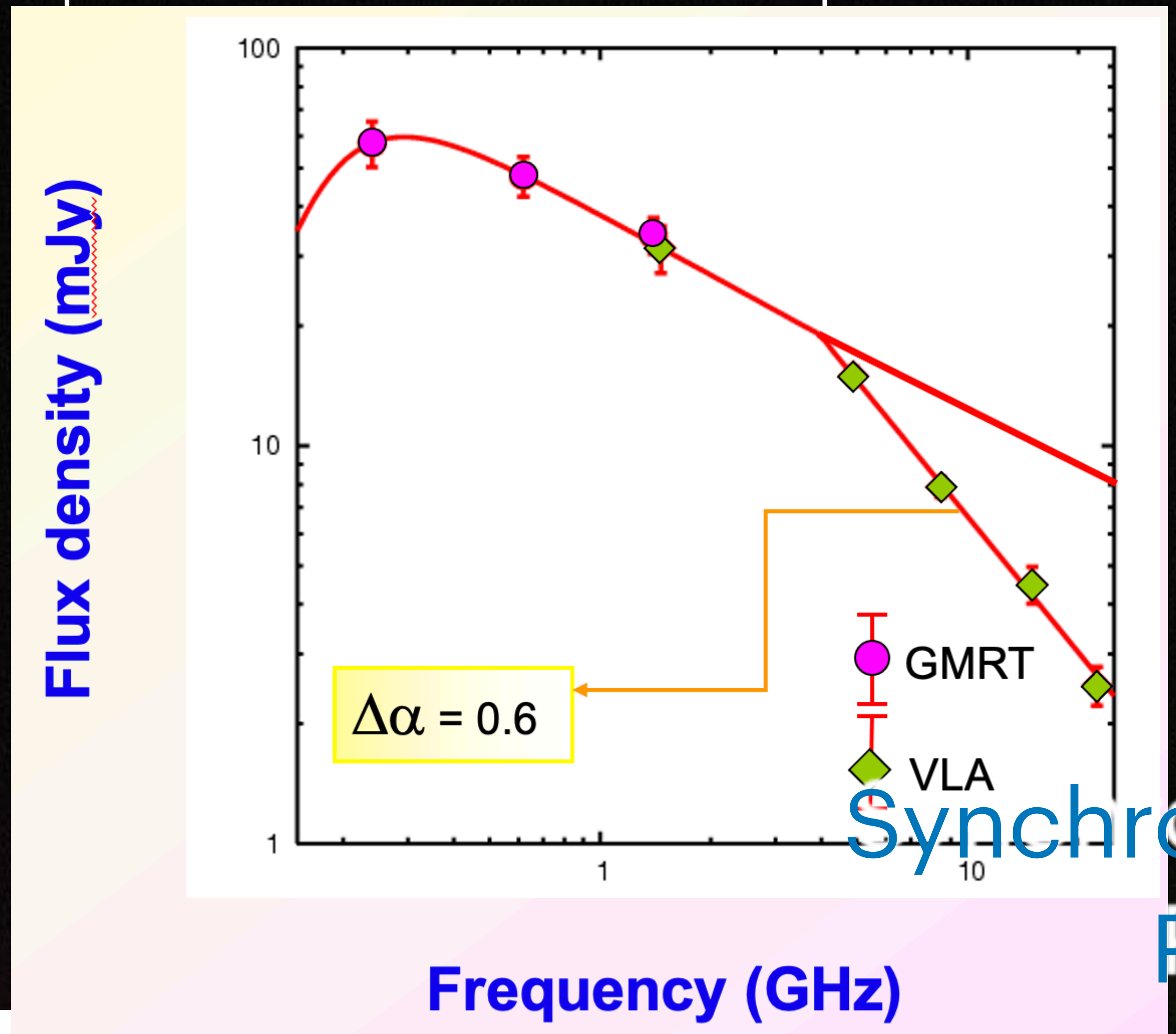


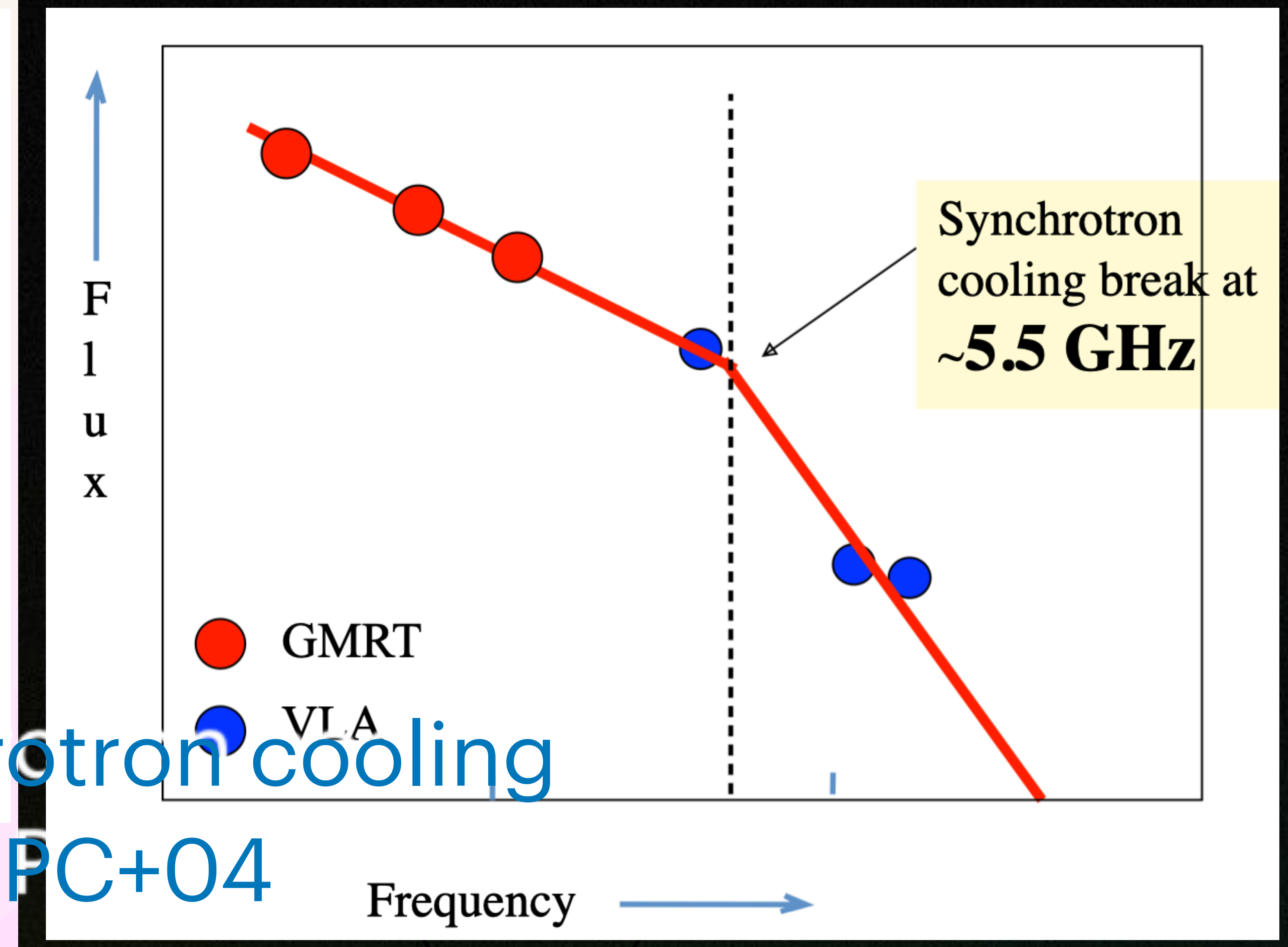
Bietenholz+2016
SN 1986J VLBI

NRAO AUI NSF e5

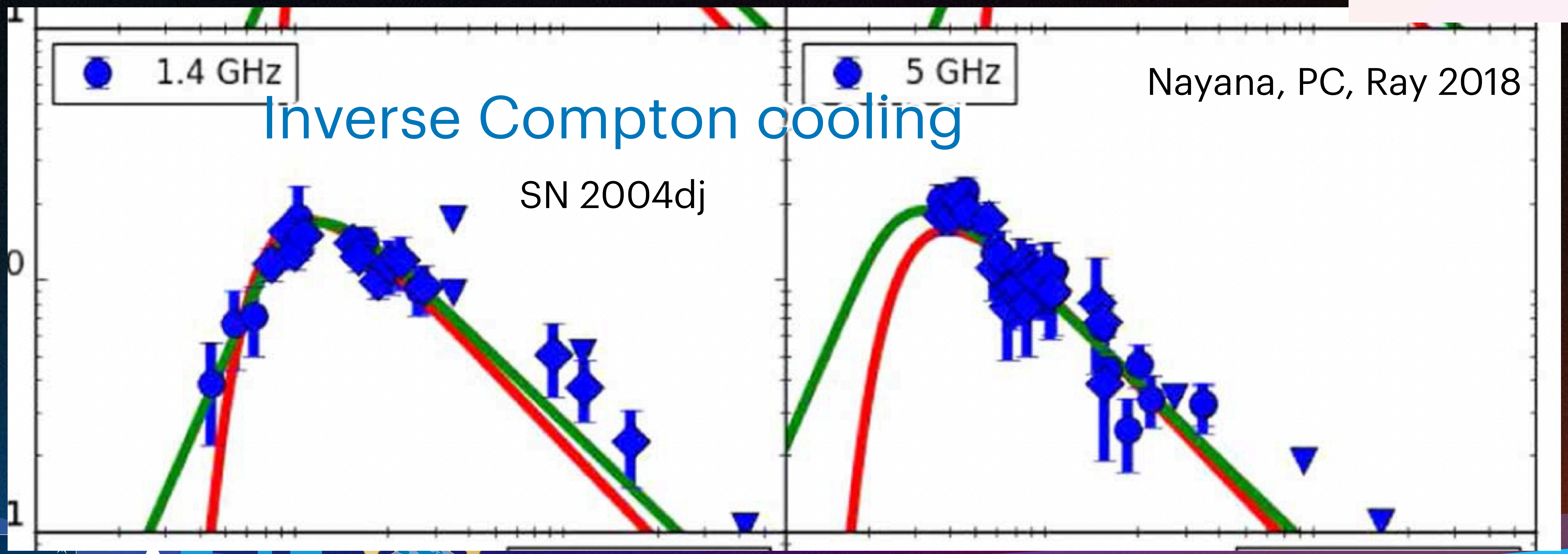
Microscopic parameters

- Radio and X-ray emission - under the equipartition assumption
- Need not be true always (e.g. PC+2004)
- Inverse Compton cooling
- Synchrotron cooling





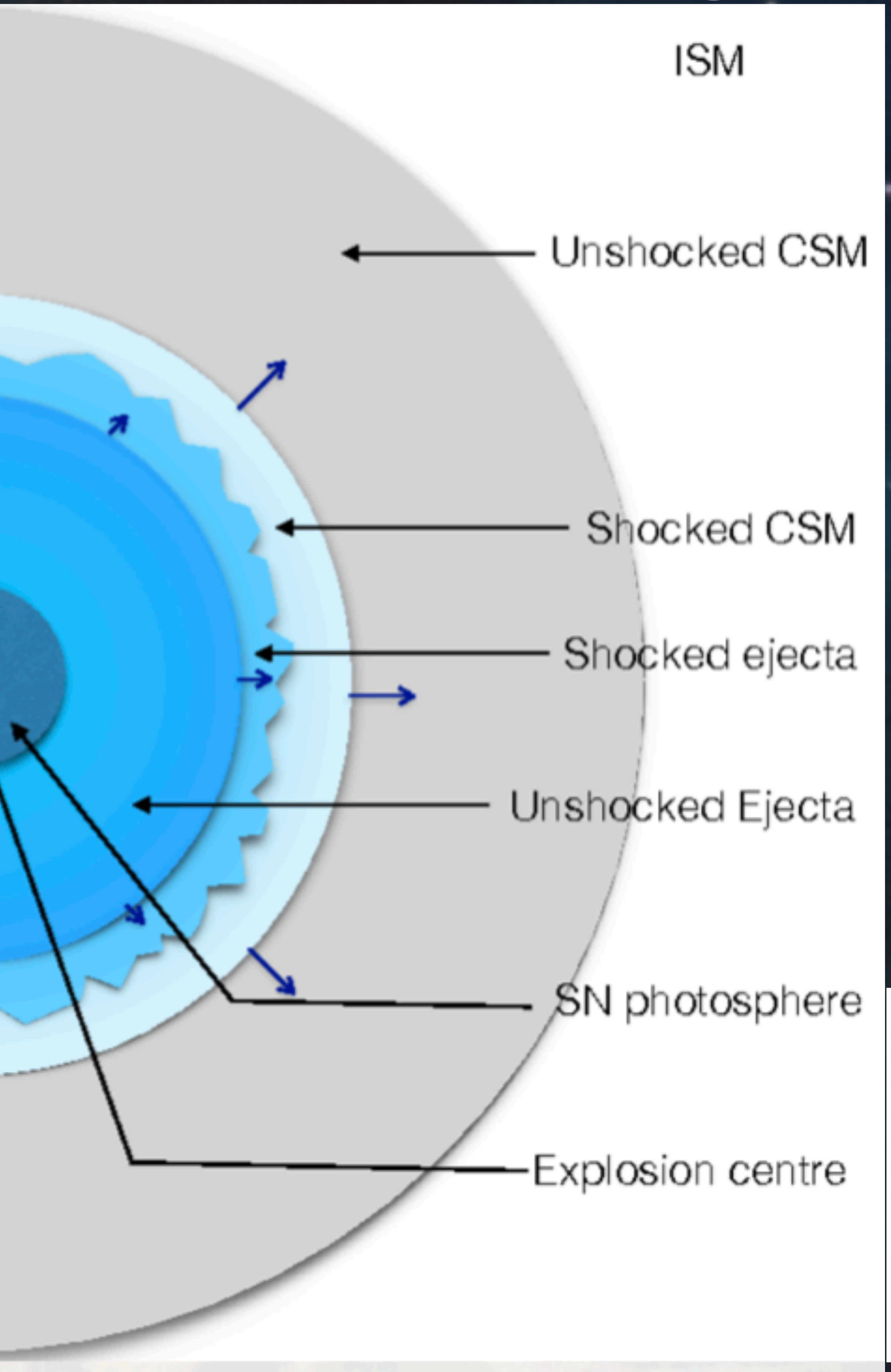
Synchrotron cooling
PC+04

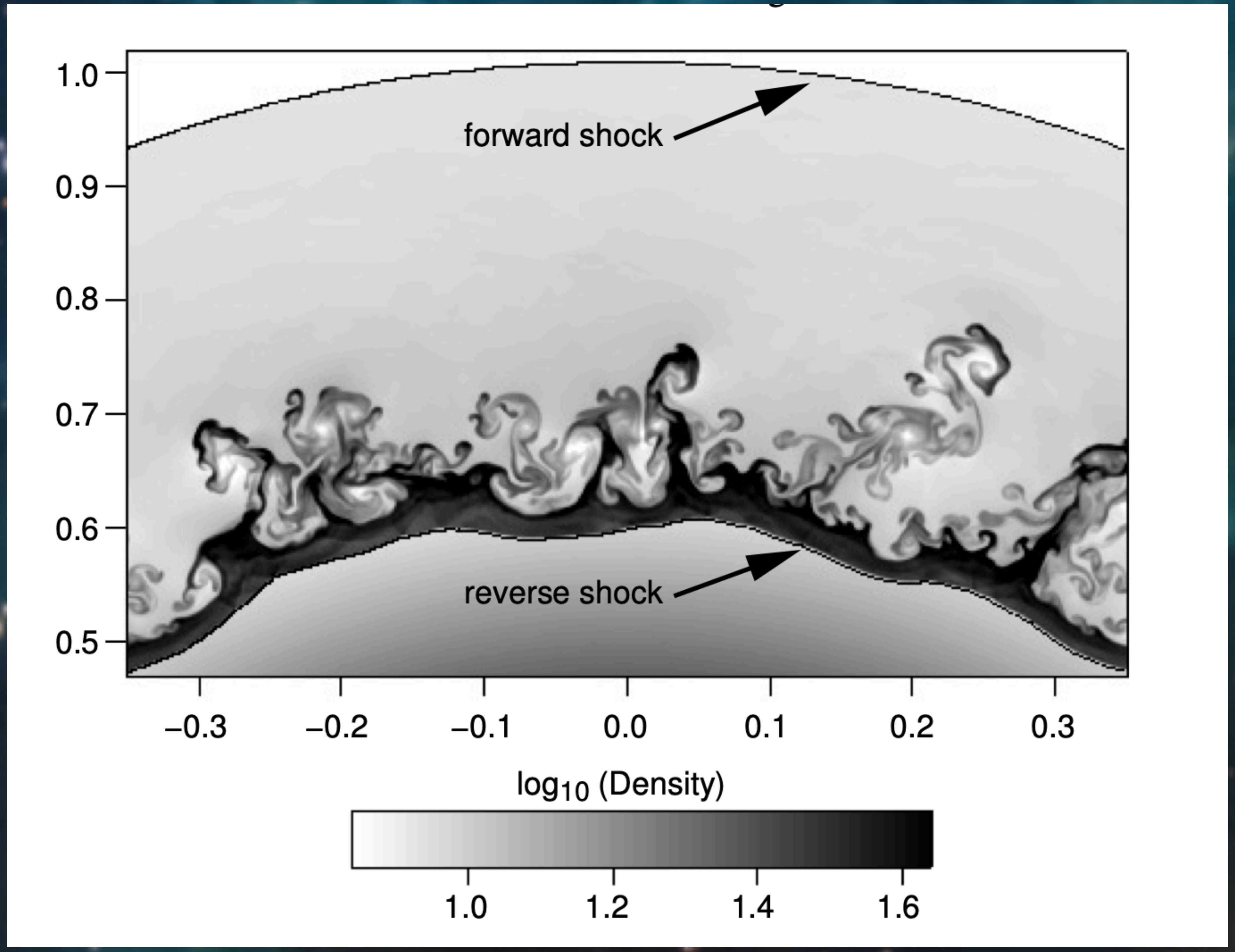


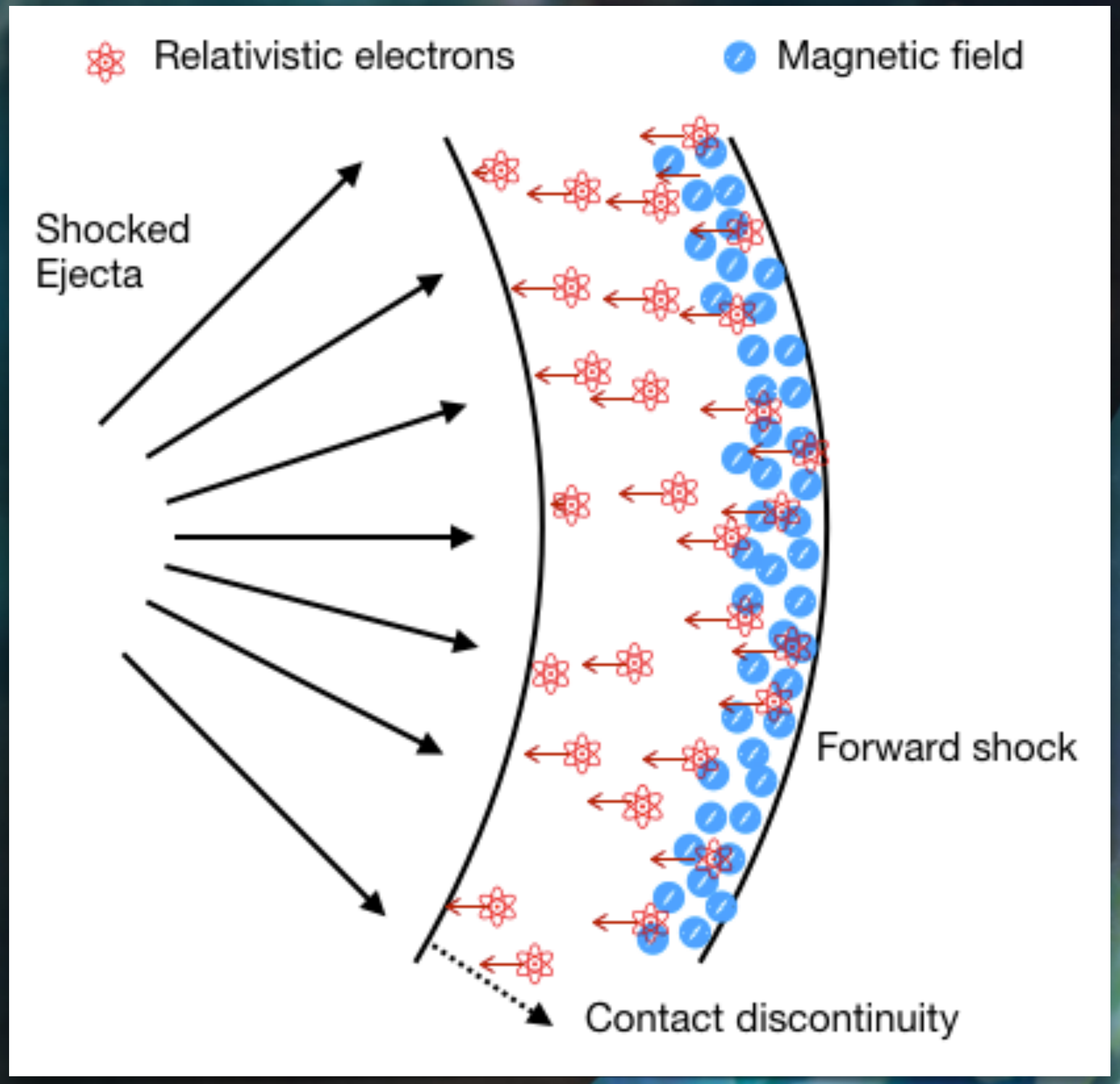
Inverse Compton cooling

Inhomogeneities in shocks

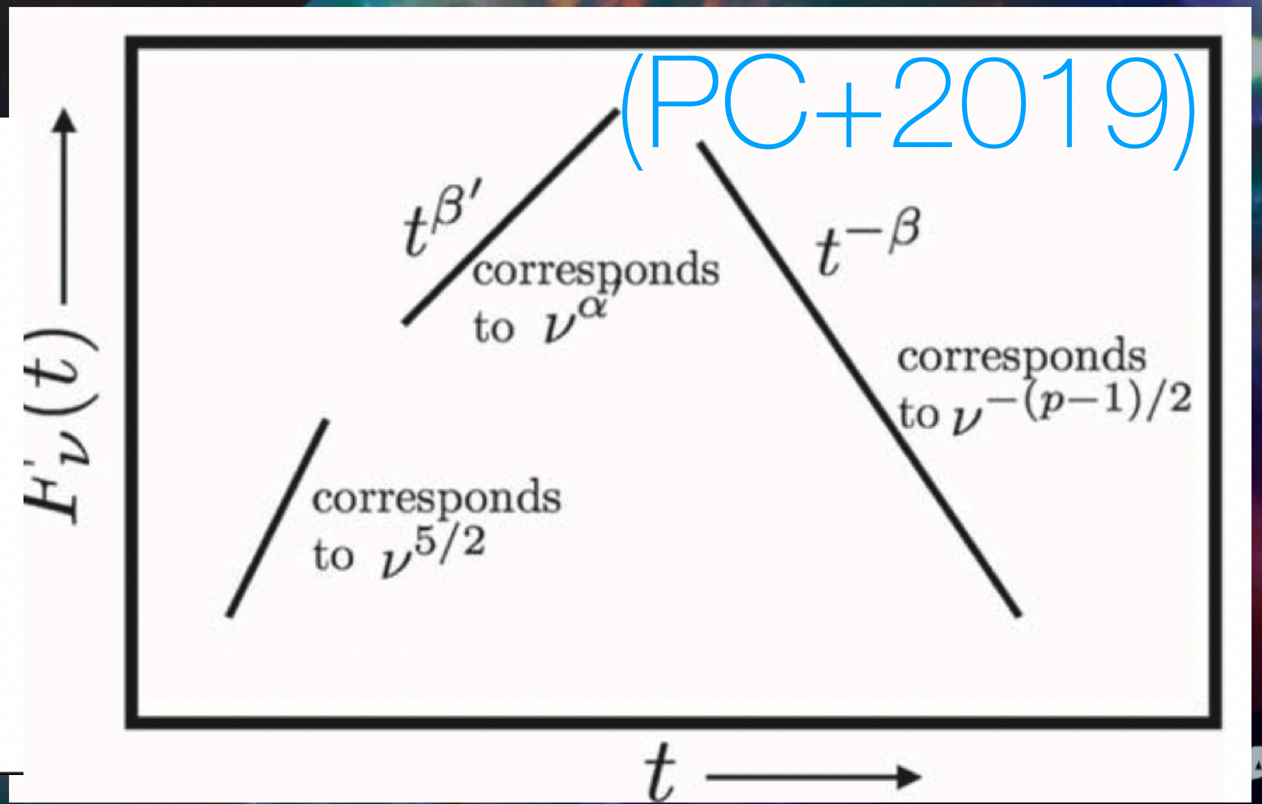
Bjornsson+13, 17, PC+19





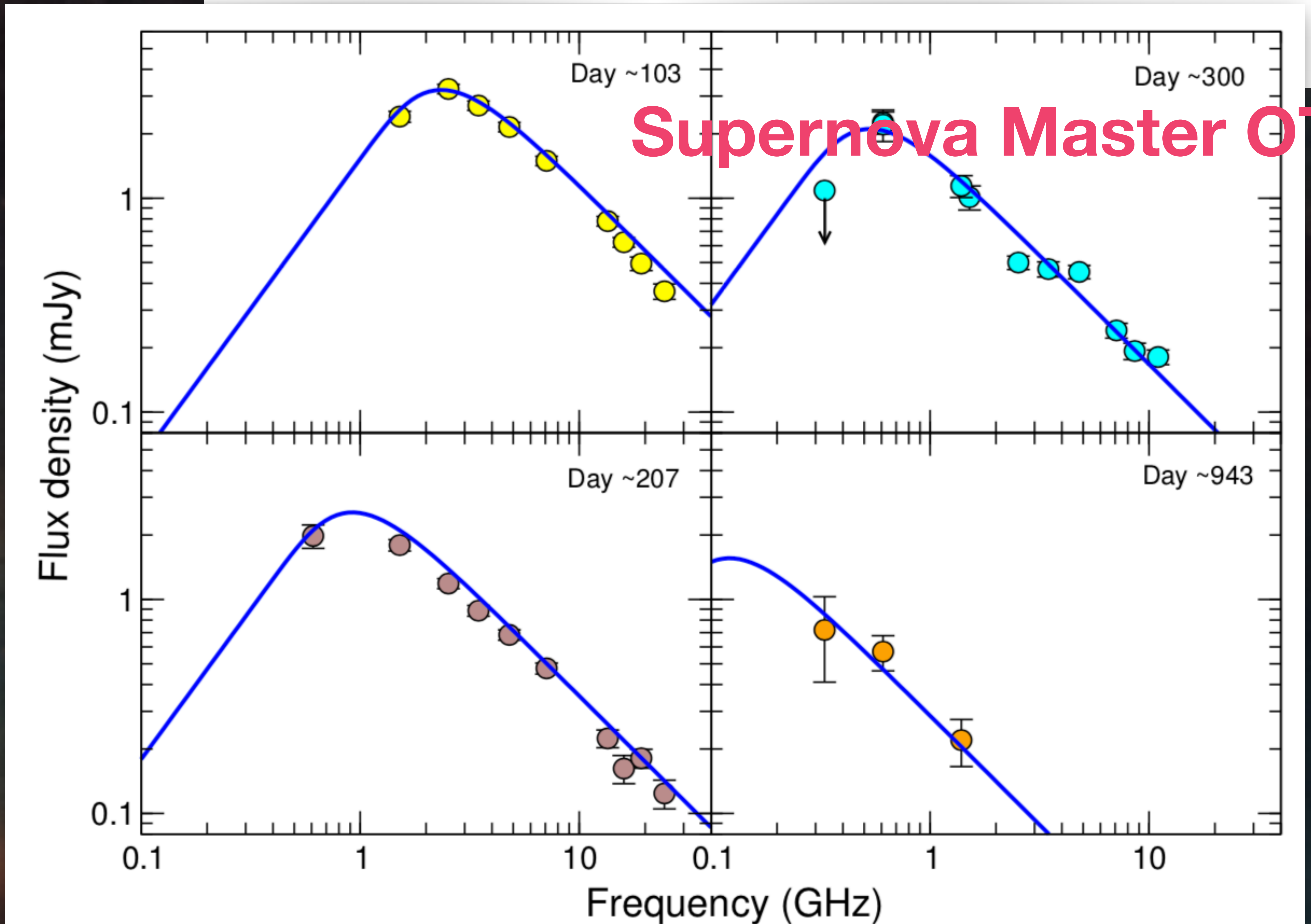


$$F(\nu) \propto \begin{cases} \nu^{\frac{5}{2}}, & \nu < \nu_{\rm abs}(B_0) \\ \nu^{\alpha'} \text{where } \alpha' = \dfrac{3p + 7 + 5\delta' - a(p+4)}{p + 2(1+\delta')}, & \nu_{\rm abs}(B_0) < \nu < \nu_{\rm abs}(B_1) \\ \nu^{\frac{-(p-1)}{2}}, & \nu > \nu_{\rm abs}(B_1). \end{cases}$$

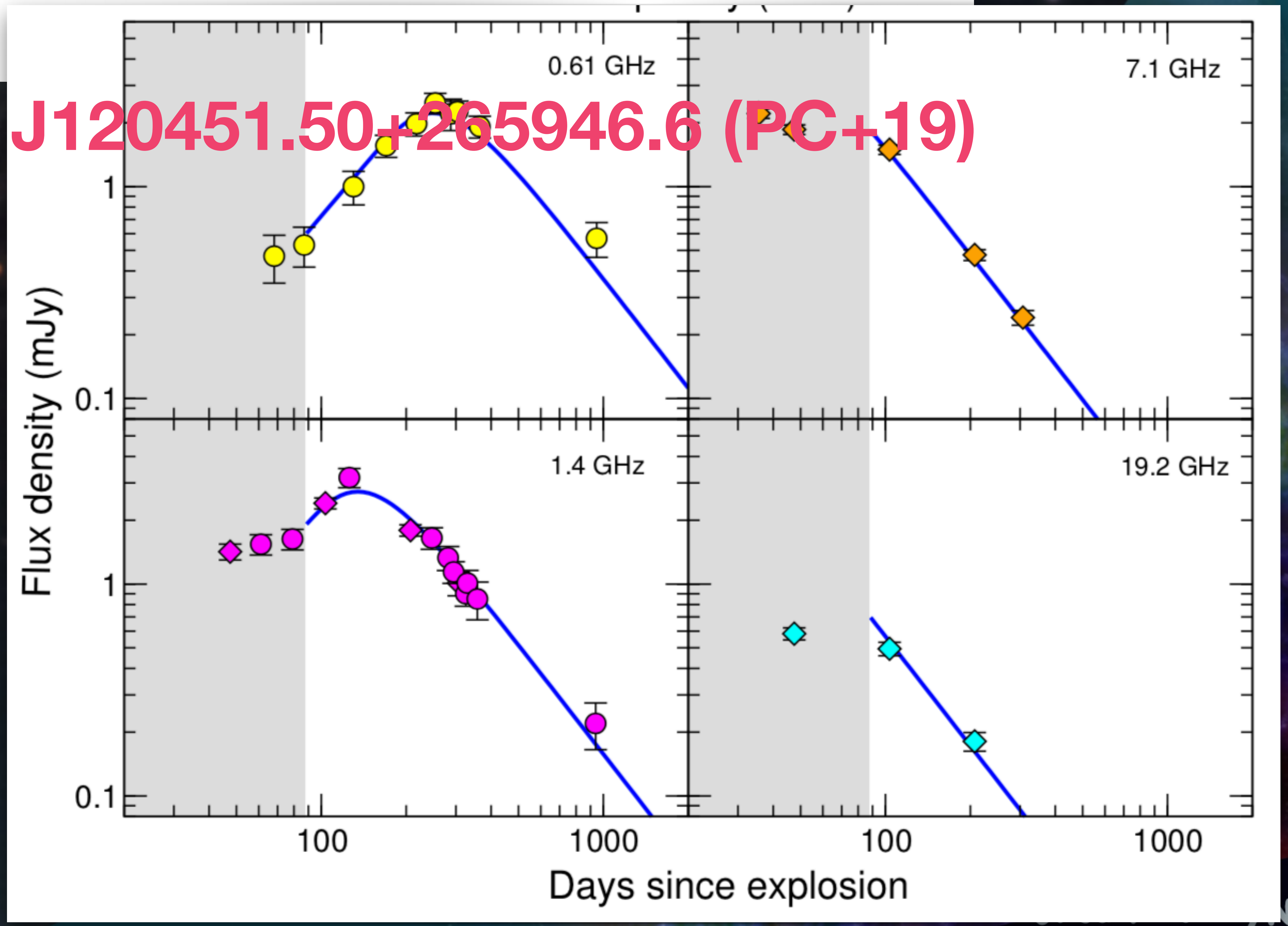


Inhomogeneities in shocks

$$(\nu) \propto \begin{cases} \nu^{\frac{5}{2}}, & \nu < \nu_{\rm abs}(B_0) \\ \nu^{\alpha'} \text{ where } \alpha' = \frac{3p+7+5\delta'-a(p+4)}{p+2(1+\delta')}, & \nu_{\rm abs}(B_0) < \nu < \nu_{\rm abs}(B_1 \\ \nu^{\frac{-(p-1)}{2}}, & \nu > \nu_{\rm abs}(B_1)\,, \end{cases}$$



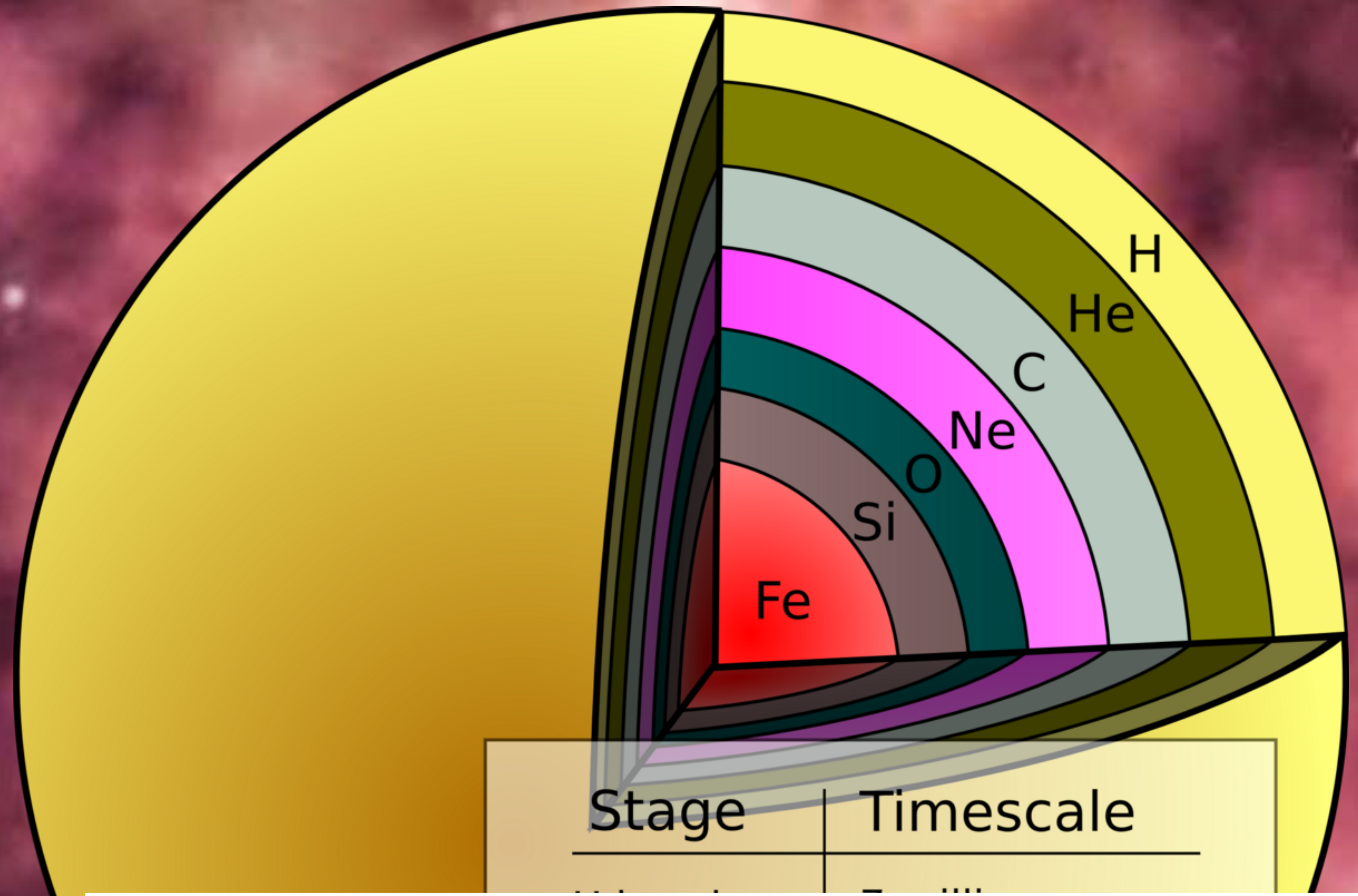
Supernova Master OT J120451.50+265946.6 (PC+19)

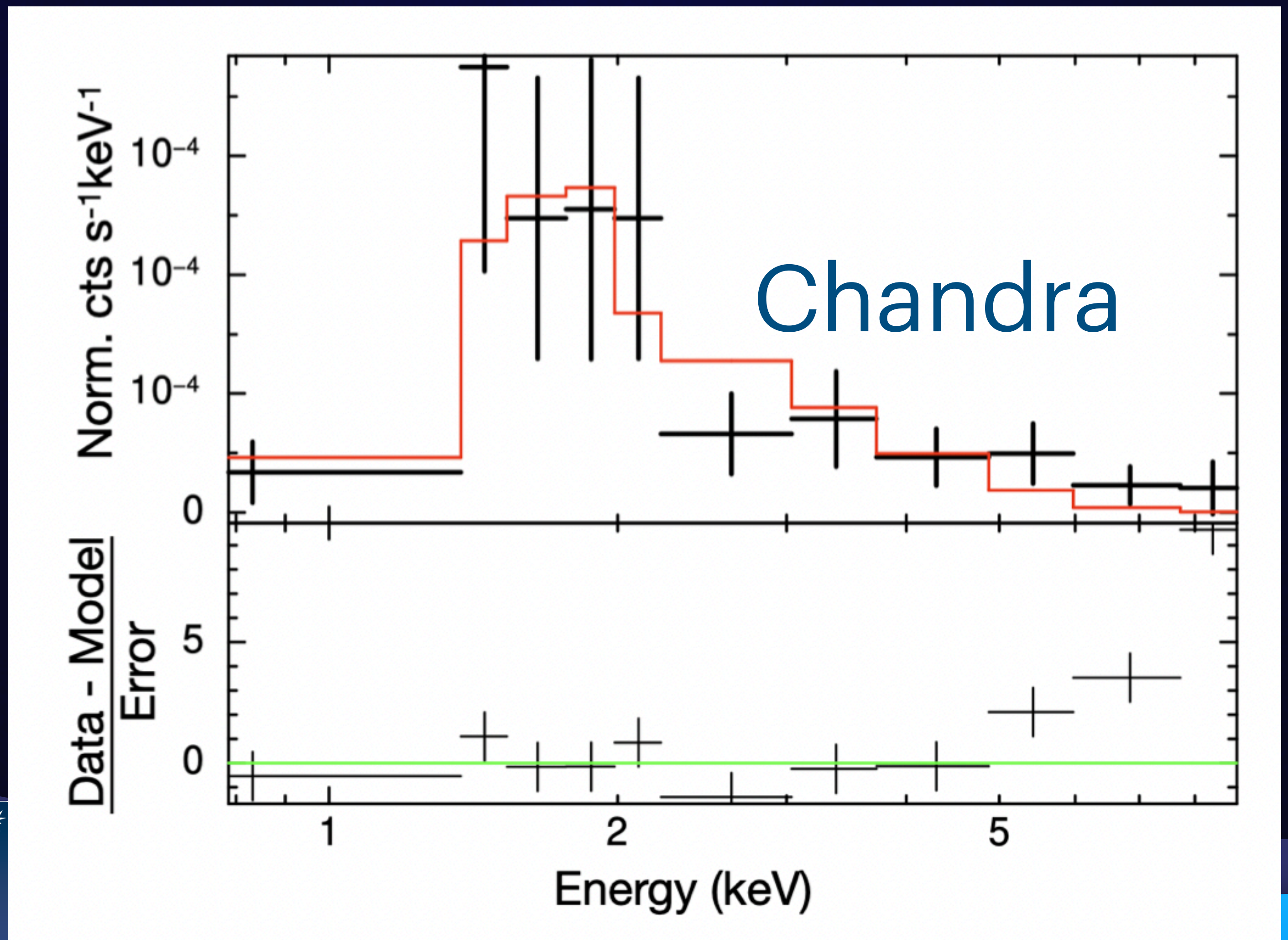


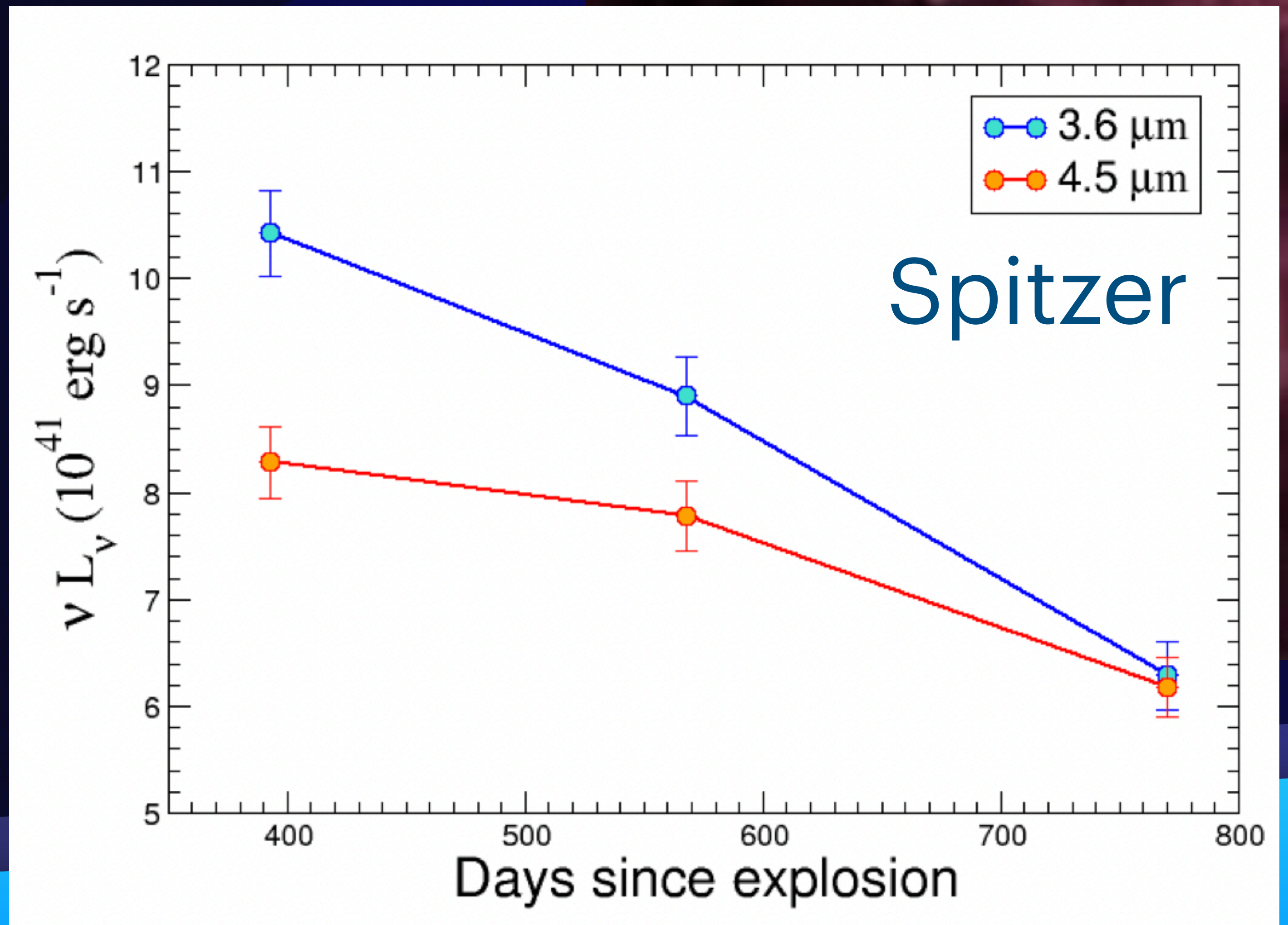
Progenitor histories via radio observations

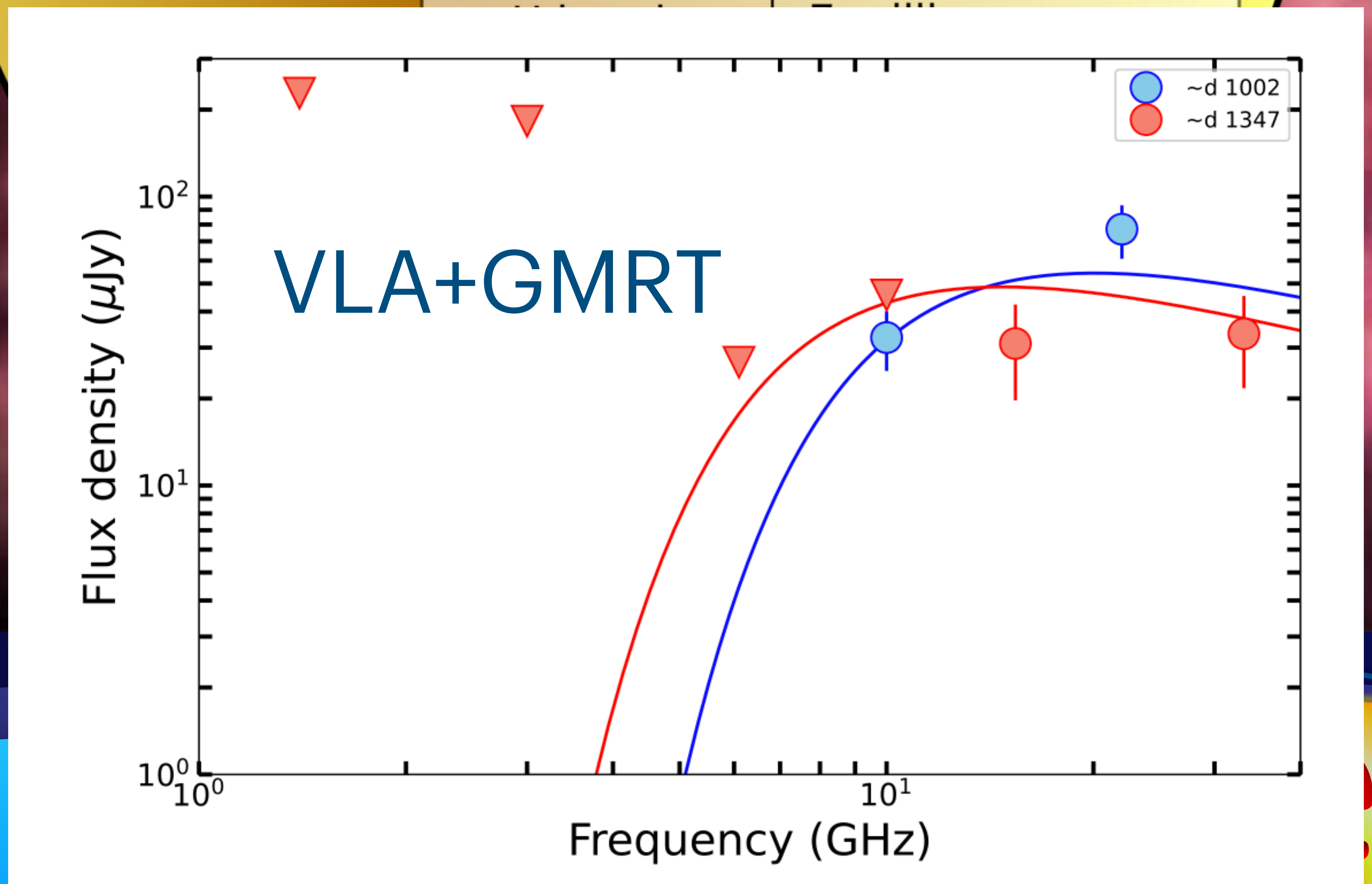
PC et al. 2023, MNRAS

- SN 2017hcc - a Type IIn SN - radio, X-ray, IR studies for 4 years
- Shock breakout - **mass loss rate 0.1 $M_\odot$/yr^{-1} at one month (80 years before the star exploded)**
- Power generated by the shock (IR) - **Few 100 days IR - 2 x 10^{-3} $M_\odot$/yr^{-1} (300 yrs before explosion)**
- Radio data - **1000 days mass loss rate 6 x 10^{-4} $M_\odot$/yr^{-1} (3000 years before explosion)**

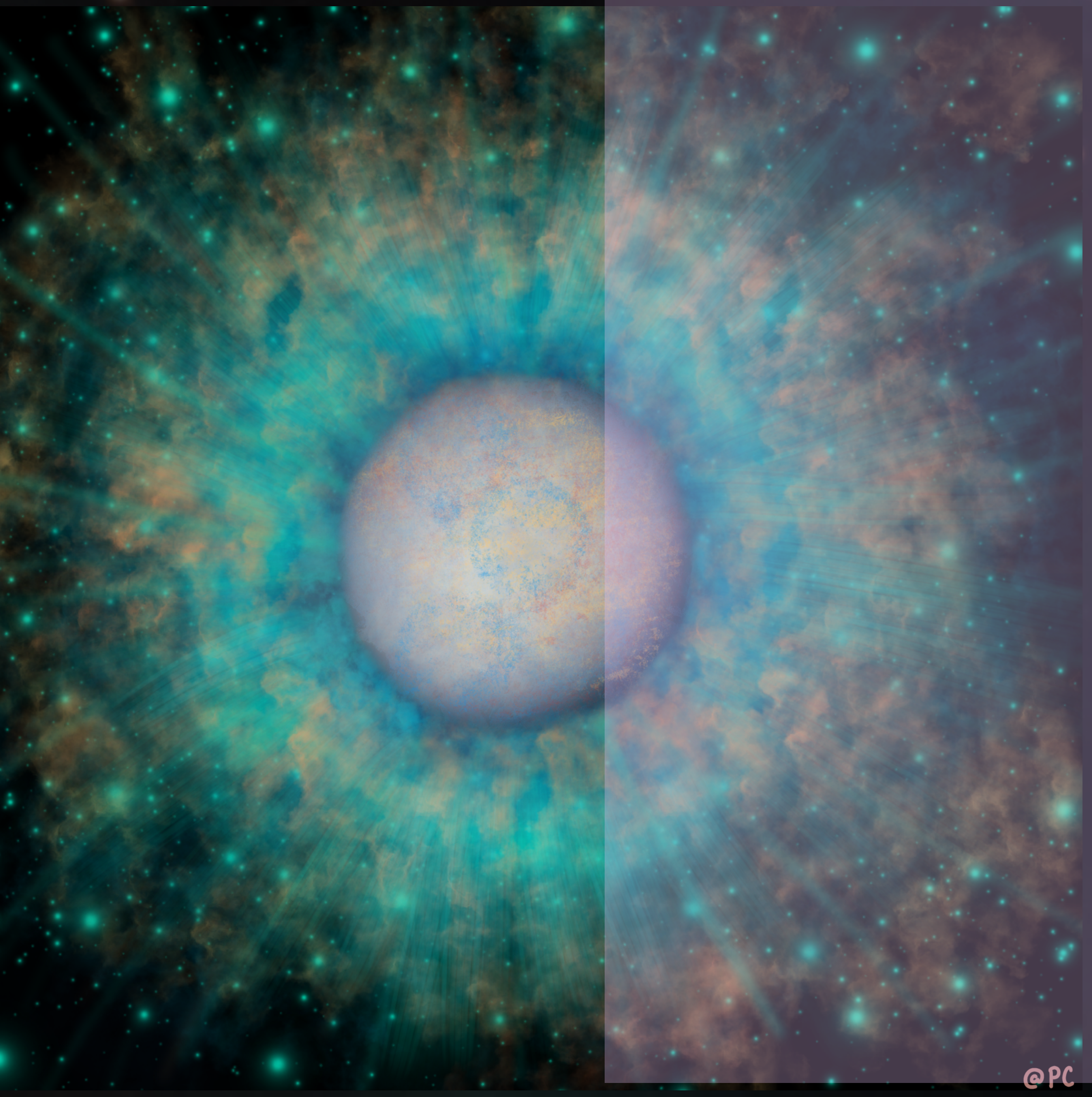




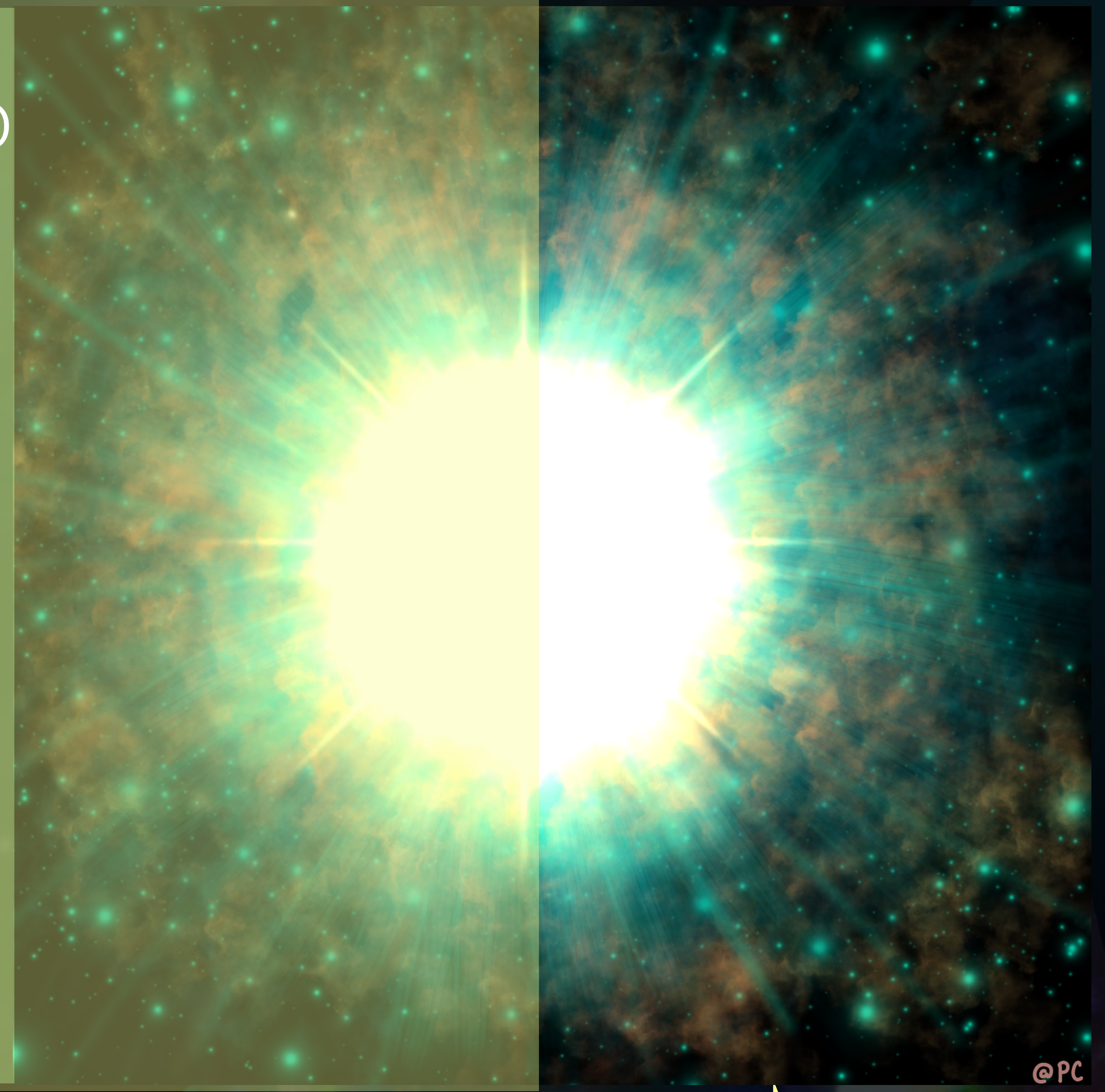




Summary



- Circumstellar interaction - Best way to build gap between stellar evolution and end products
- Flash ionization <10^{15} cm
- X-ray emission ~10^{15}-10^{16} cm
- Radio emission ~ 10^{15} - >10^{17} cm

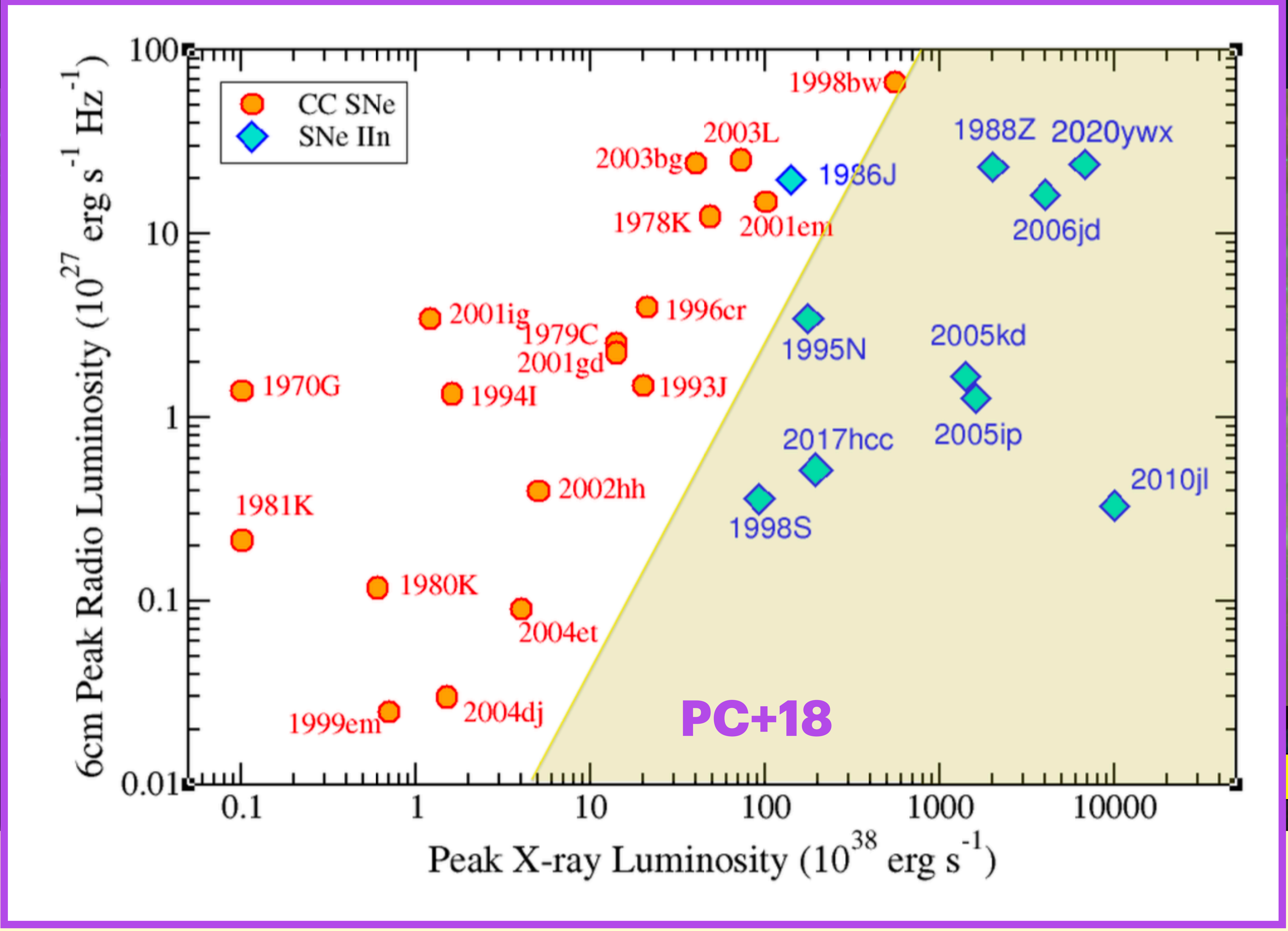


Radio **X-rays** **Flash ionization**

t=-1000 yr → t=0 yr

Credit: NASA/NRAO

Summary



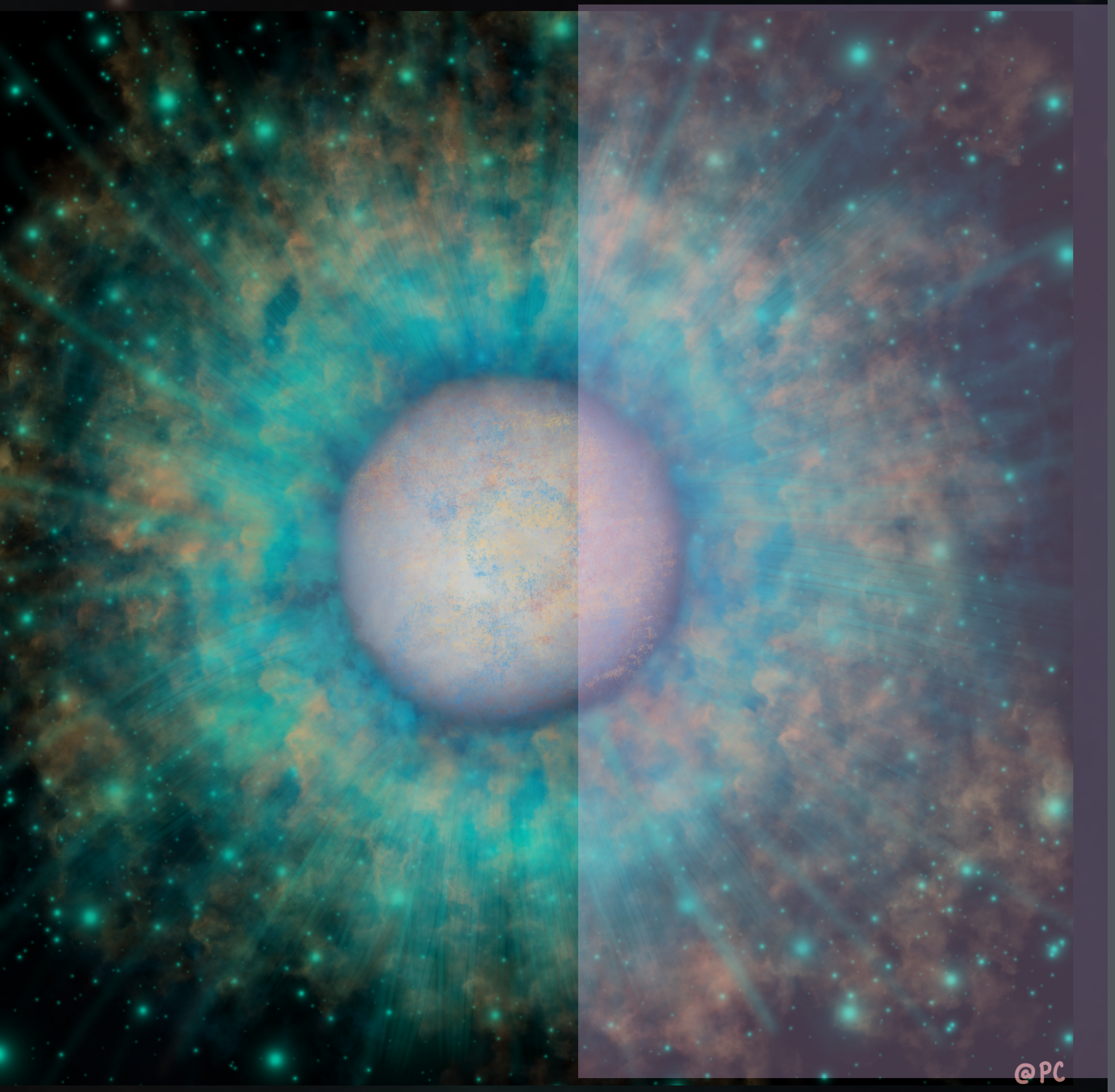
h ionization

t=-1000 yr

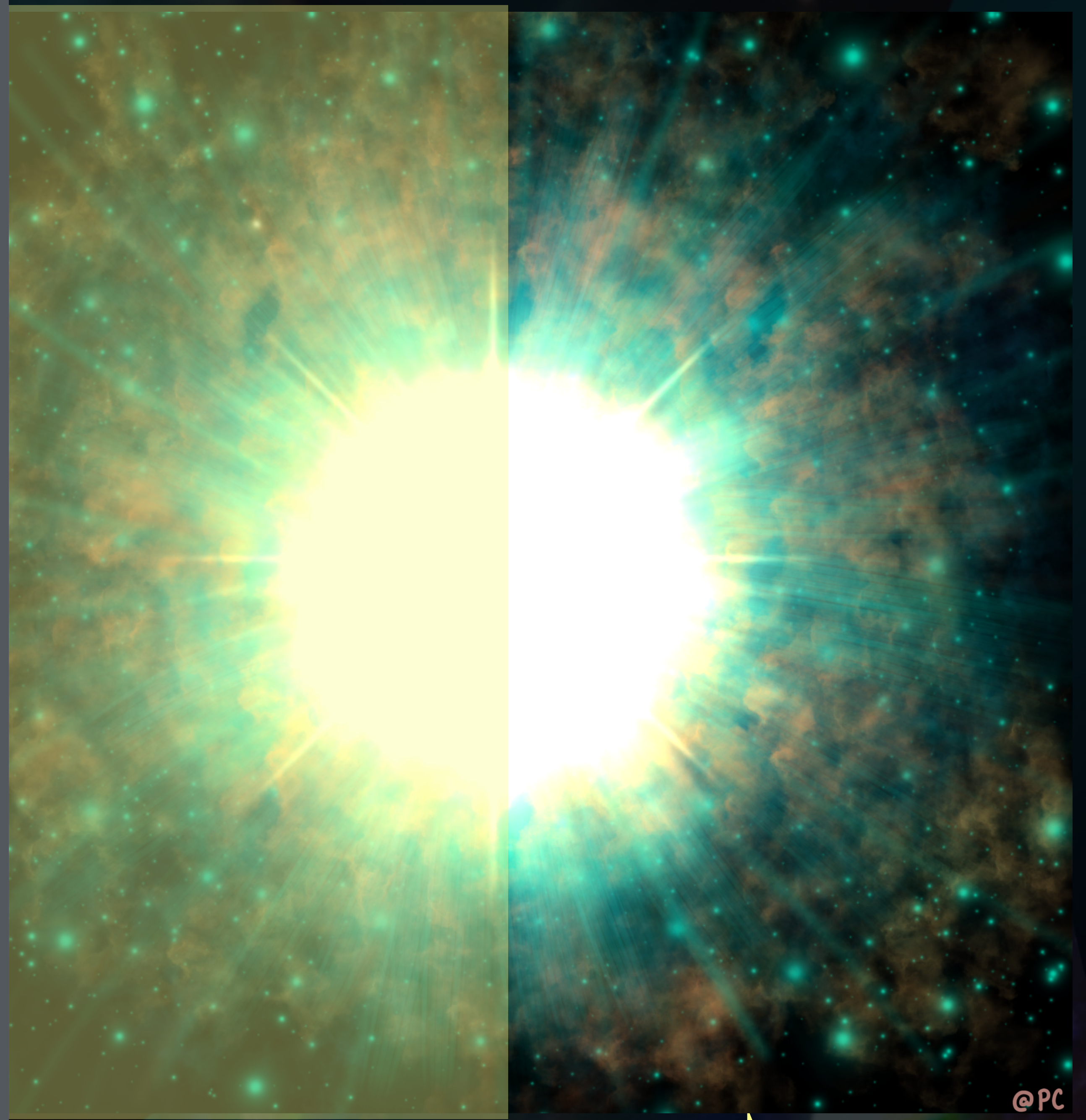
t=0 yr

Credit: NASA/NRAO

Summary



- Optical surveys capturing supernovae within hours - Young supernova Experiment, DLT40, ZTF etc
- Radio facilities
  - ALMA mm bands (>100 GHz)
  - VLA (1-40 GHz)
  - GMRT (0.4-1.4 GHz)
- X-ray facilities
  - Chandra, XMM-Newton, Swift-XRT (<10 keV)
  - NuSTAR (<100 keV)



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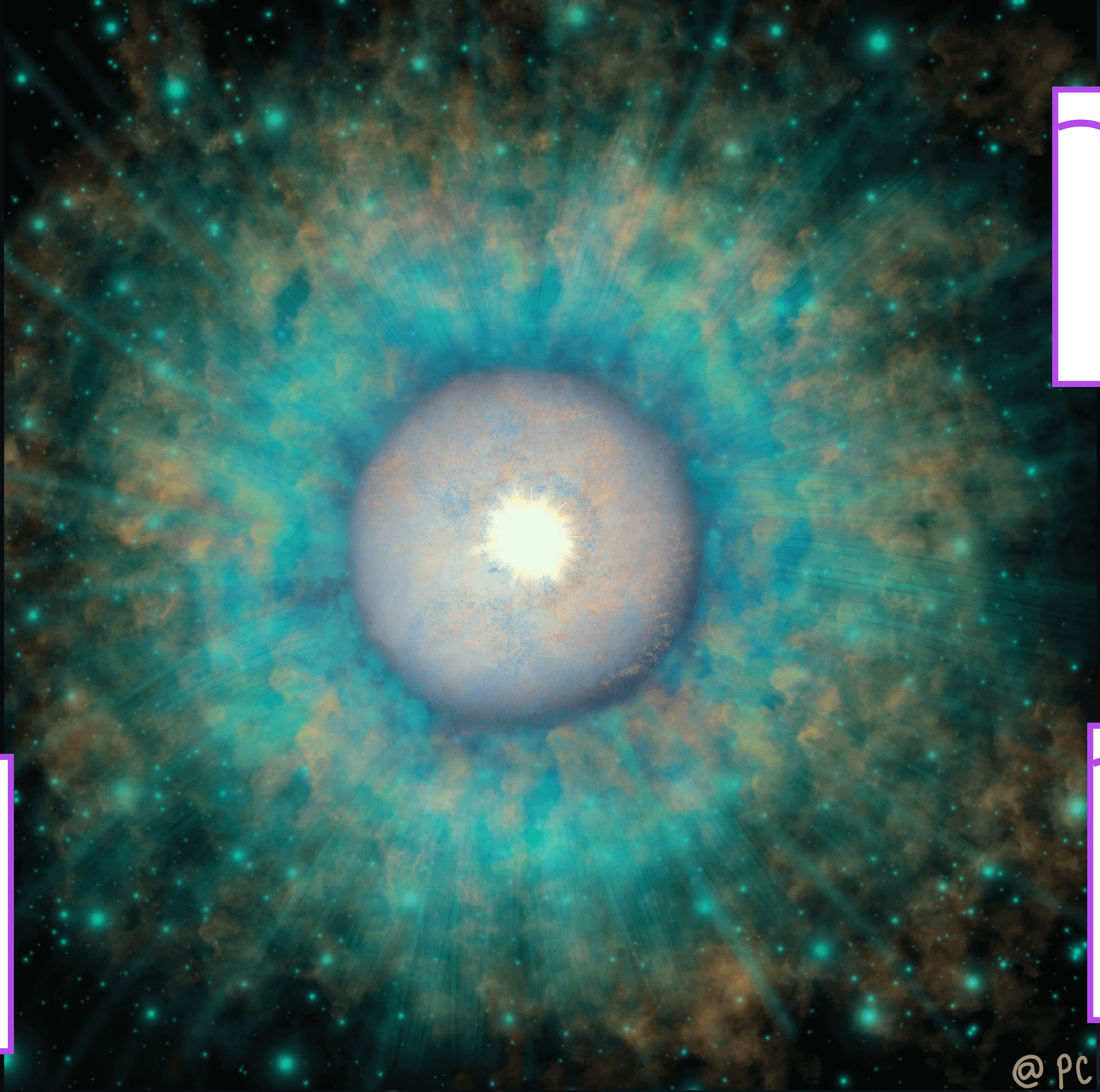
@ PC


Credit: NASA/NRAO

Asymmetry!
Thank you!
STELLAR DEATH