Constraints on the progenitors from radio and X-ray observations of core collapse supernovae

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Supernovae in dense environments

- All supernovae have medium around them- circumstellar medium (CSM).
- Normal supernovae - medium not so effective to alter the spectra and light curves of SNe.
- Supernovae in dense medium are the ones, where density of the CSM plays important role.The narrow lines from the CSM show up on the SN spectra.
- Shock breakout (shock breaking free from the photosphere) will happen at the CSM rather than at the surface (Chevalier & Irwin 2011, Balberg & Loab 2011)

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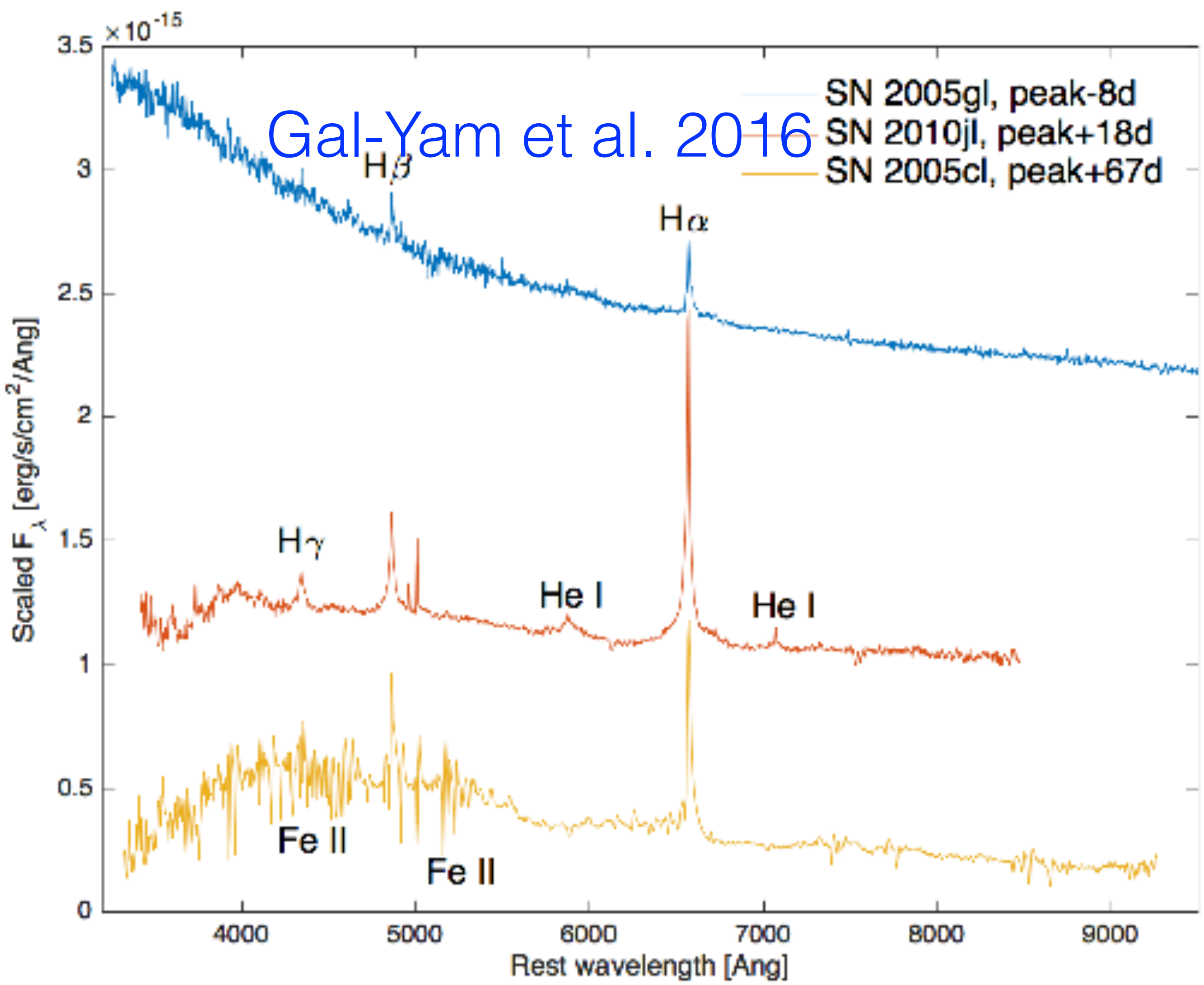

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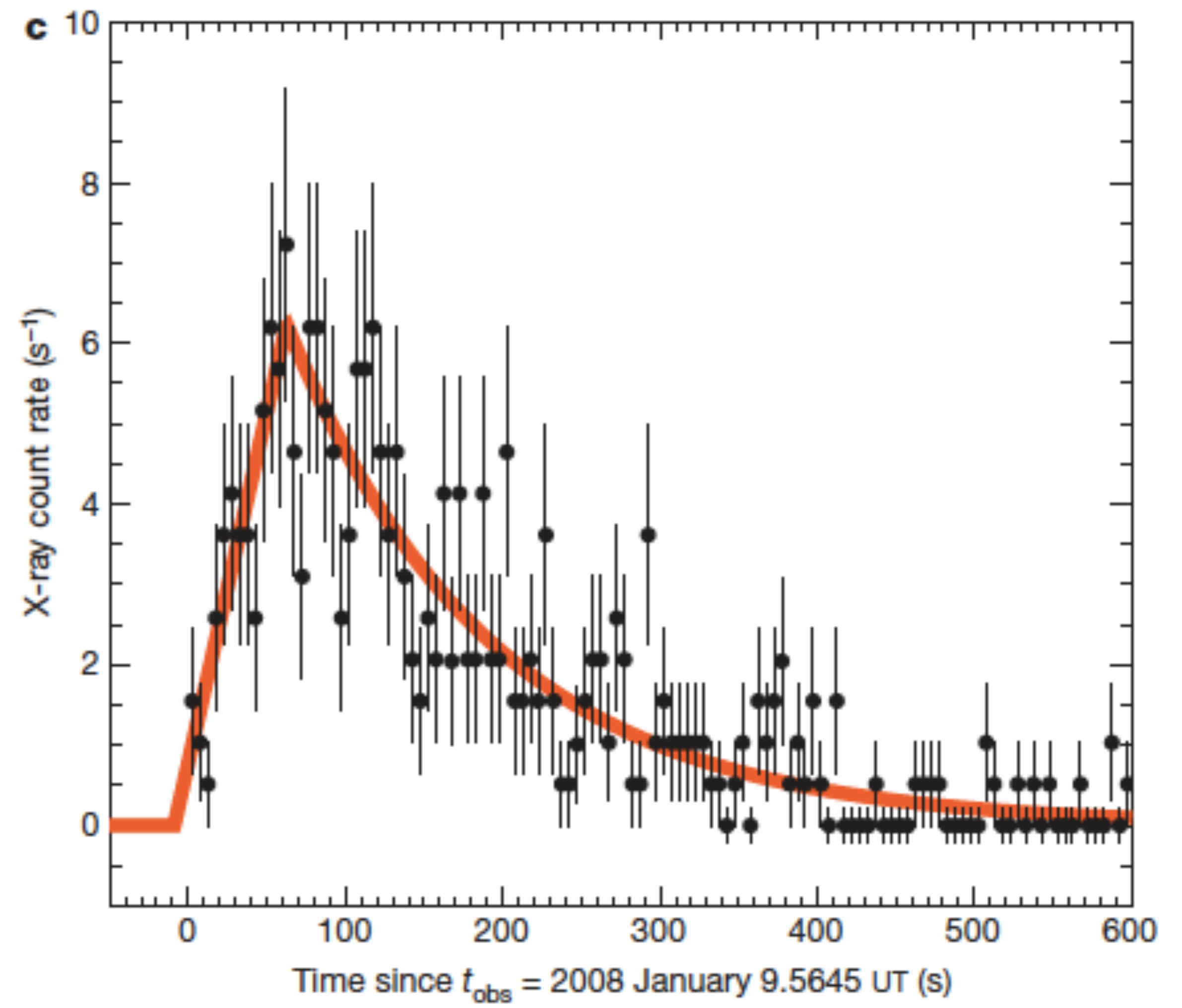

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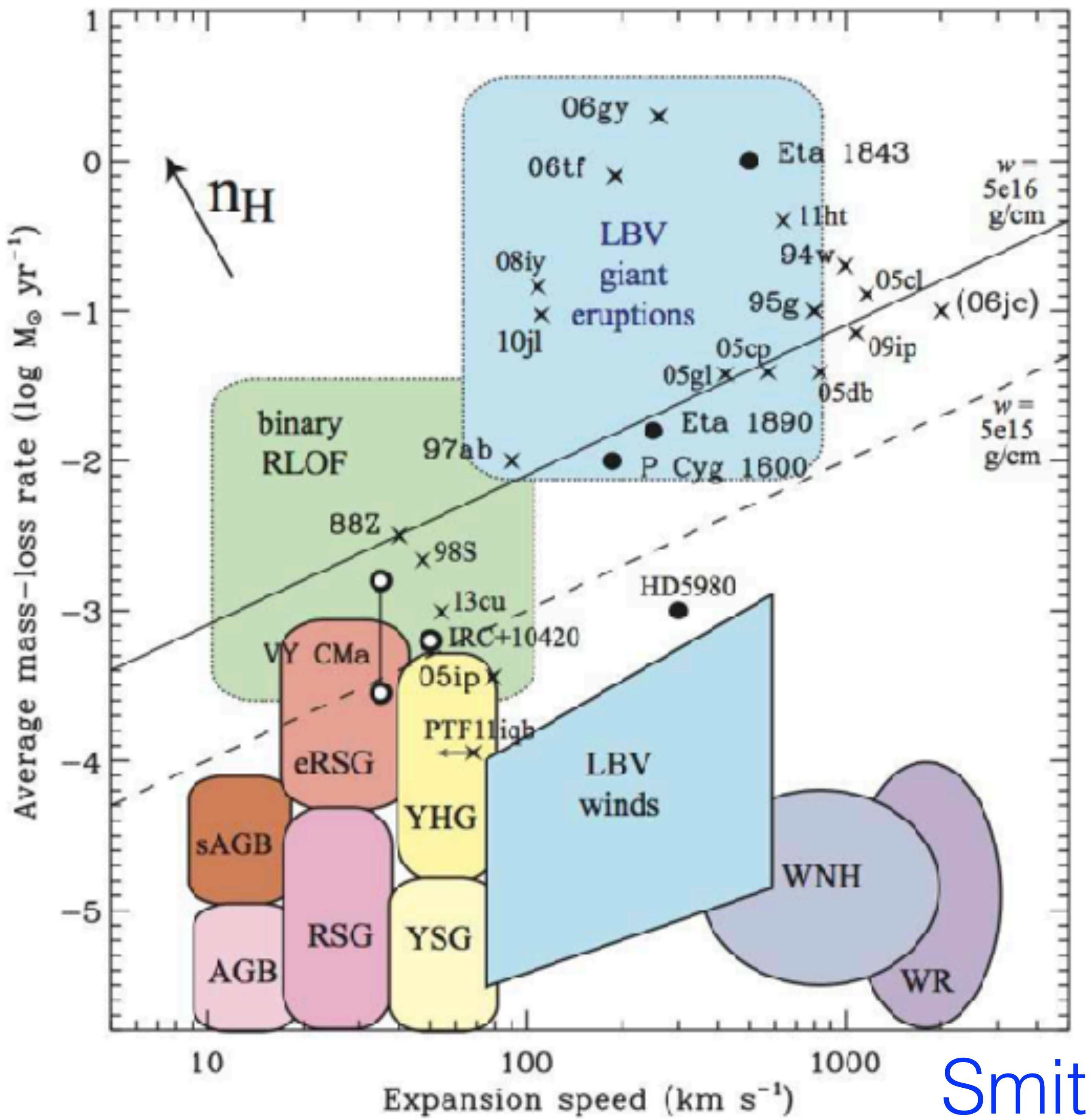
SN IIn ejecta-CSM interaction

- Extra strong CSM-ejecta interaction lead to radiative shock early on.
- In SN IIn ejecta Kinetic Energy is transferred to radiation energy, within a few days to decades
- Duration of CSM interaction is determined mainly by the duration and speed of the pre-SN mass loss, not by the intrinsic properties of the explosion (Smith 2016).

Type IIN supernovae

- Optical light curves powered by CSM. Hence diversity depending upon external density factor! Not an intrinsic class of supernovae
- Brighter than other CCSNe in optical due to this extra source of energy
- All but one superluminous supernovae II ($M_v < -21$)are Type IIn
- Highest redshift SN IIN z=2.36 (Cooke et al 2009). Highest redshift Superluminous SN z=3.9 (Cooke et al. 2012).
- Mass loss rates 10^{-2}-10^{-1} $M_\odot$ yr^{-1} (Smith 2014, 2016).
- SLSNe- If explained by CSM, $n \sim 10^{10}$ cm^{-3}, $M_{CSM}=35$ $M_\odot$.

Progenitor models of SN IIN

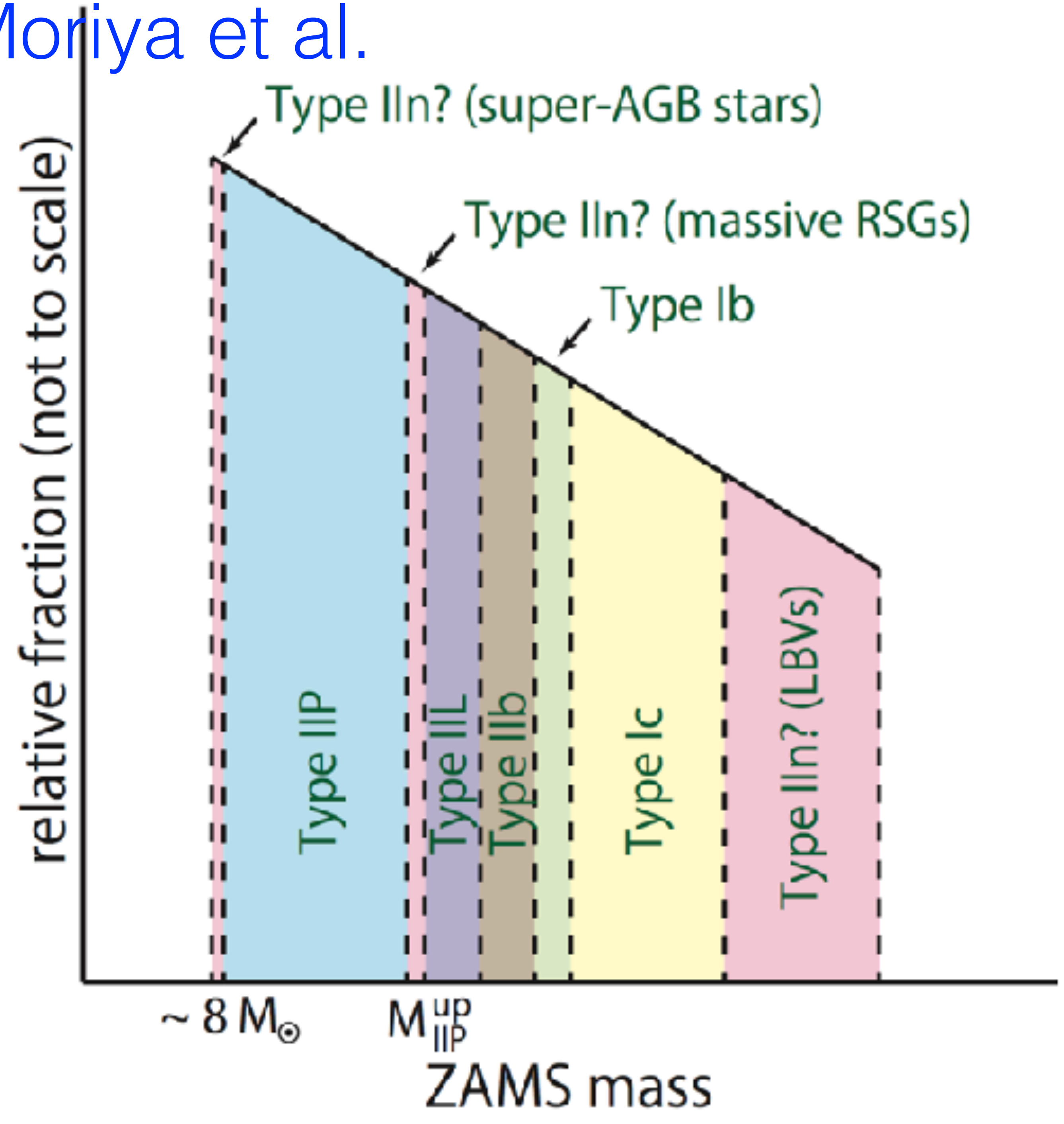


Smith et al 2014, 2016

Progenitor models of SN IIN

- 8-10 $M_\odot$ - Electron capture SNe (not upto Fe formation)- high density electron capture. E.g. SN 2008S (Botticella et al. 2009). But Moriya et al. in semi-analytic modeling rules out.
- 17-25 $M_\odot$ - massive RSG with high mass loss (SN 1998S, SN 1995N etc)
- >35 $M_\odot$ - (2005gl Gal-Yam et al. 2007), 2009ip, 2010jl? Luminous Blue Variables (LBV) progenitors

Moriya et al.



See IIN Progenitor models

- LBV progenitors most favourably inferred models. But LBVs are not suppose to explode as SNe but some models allow (Langer et al. 2012).
- Chevalier 2012, Common envelope in binary system. Inspiral of the compact binary.
- Anderson 2012, SN IIn progenitors come from low mass progenitors.
- Direct progenitor: SN 2005gl (Gal-Yam et al. 2007), SN 2010jl (Smith et al. 2011) have LBV progenitors (But see Fox et al. 2016)
- Ofek et al. (2014), PTF archival data for more than 16 Type IIn supernovae- more than 50% SNe IIn have precursors. However, no precursor in SNe IIn with 12 years of KAIT archival data (Bilinsky et al. 2015).

LBV progenitors

- Traditionally considered transitional phase between massive O stars and Wolf-Rayet stars

- LBVs selectively avoid cl
Tombleson (2015). Statist
stars.

- SN 2009ip, in a very isola

- Argue that LBVs product

- LBVs blue stragglers. LB
binary mass transfer, anc
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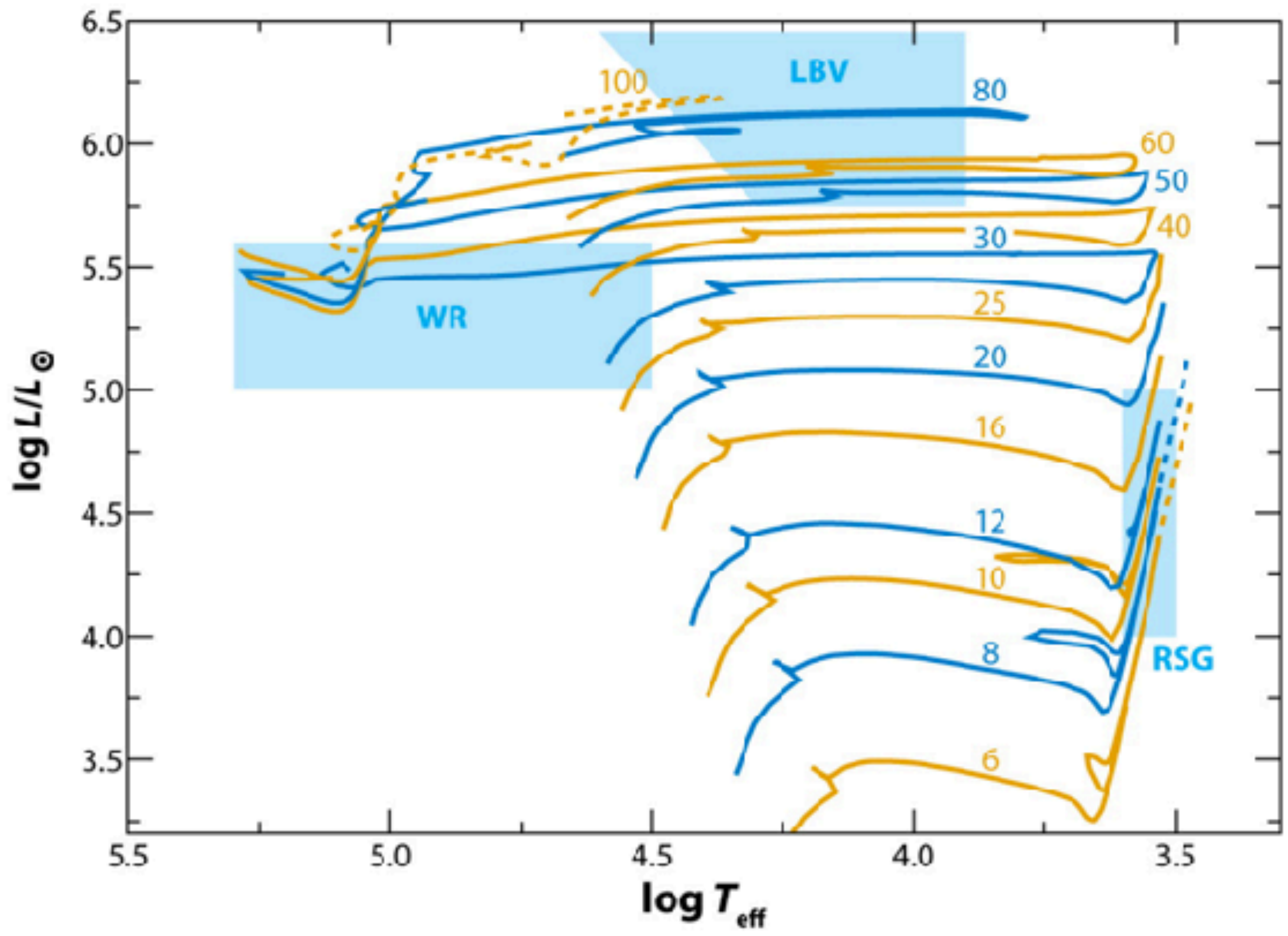
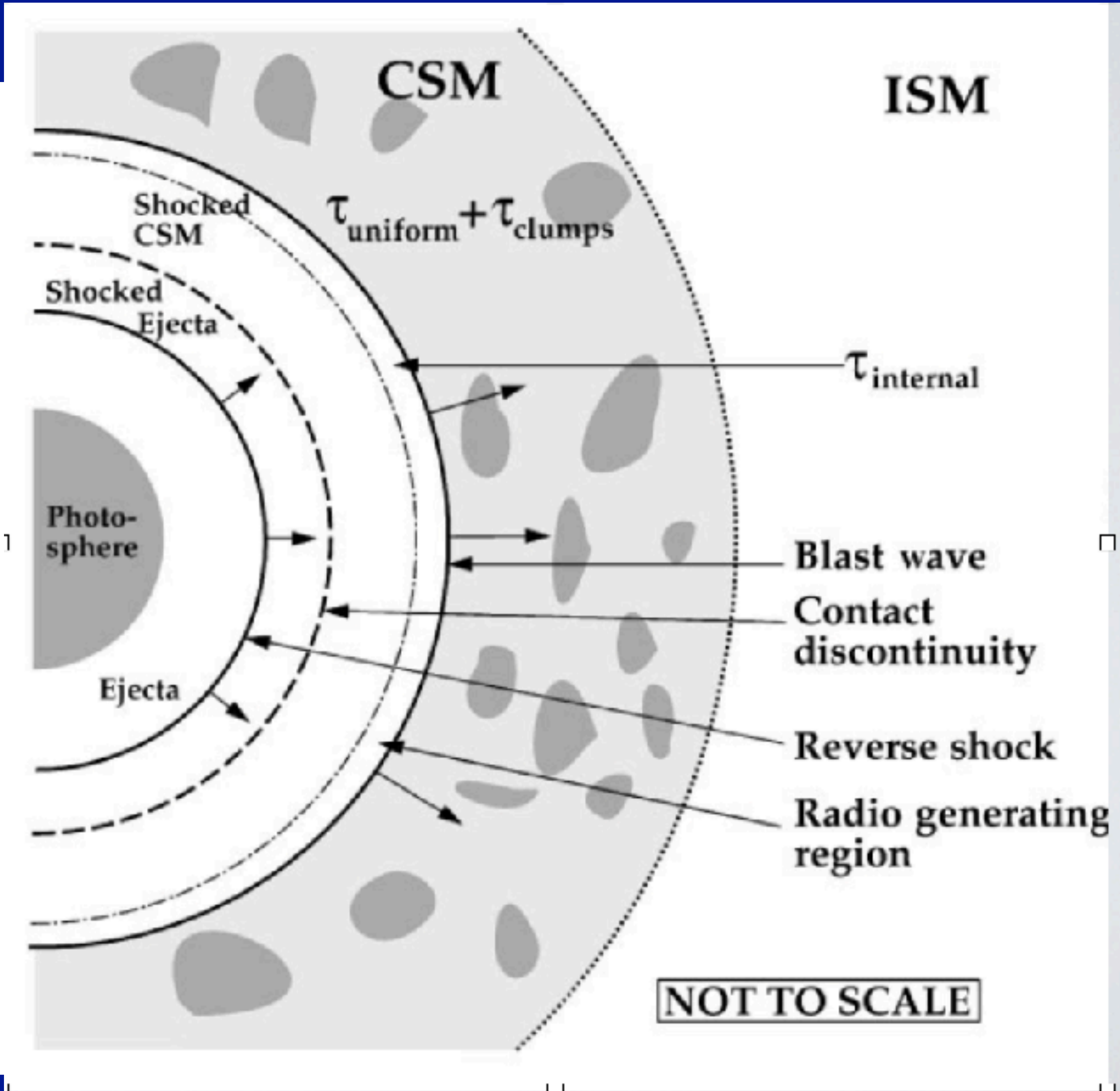


Ejecta-CSM interaction

- Synchrotron radio emission - $\dot{M}$, density
- ~1keV X-rays from 10^7 K reverse shock and ~100 keV X-rays from 10^9 K forward shock



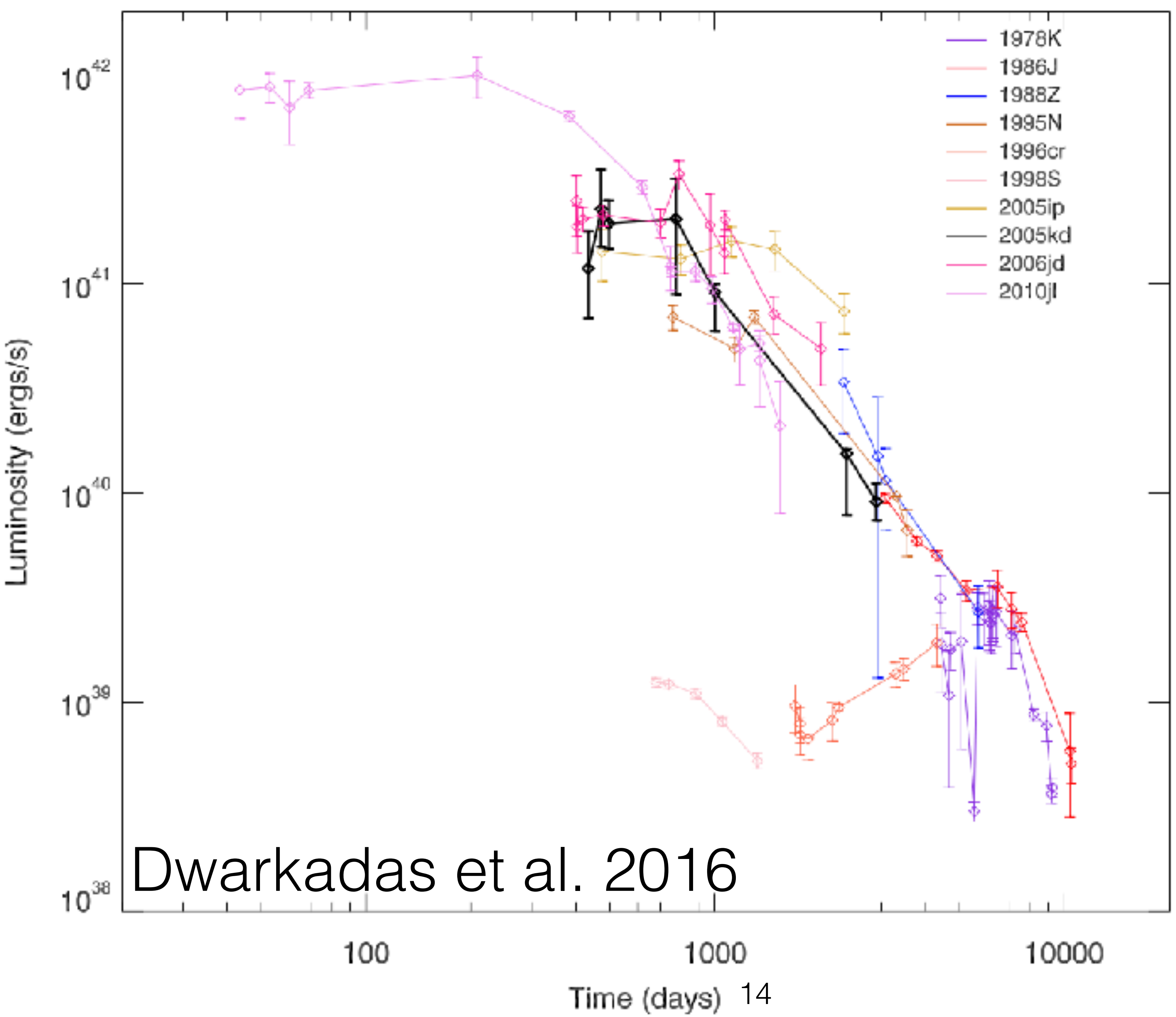
Predicting the nature of progenitors using radio and X-ray emission

- CSM is best probed by ejecta and emits in radio and X-rays
- Hence radio and X-rays are one of the best tracers of SN IIn
- Radio and X-ray light curves are extremely diverse, the diversity translate to diversity in the stellar mass loss.

X-ray luminosity in SNe

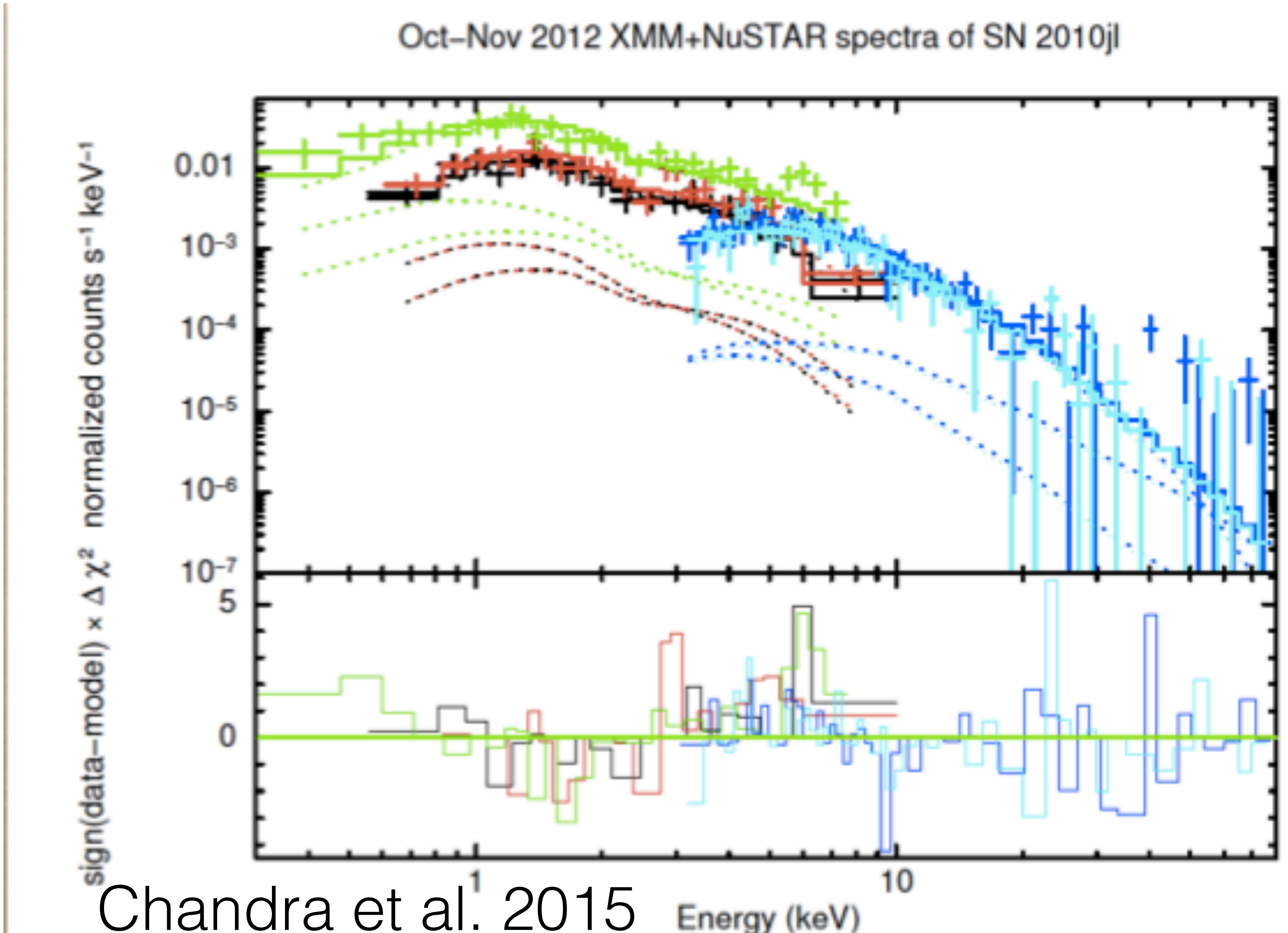
- X-ray luminosity - $L_x \sim n_e^2 V \Lambda$, electron density n_e, the emitting volume V and the cooling function Λ
- For a steady wind ($1/R^2$), expanding in $V=4\pi R^2 \Delta R$, $L_x \sim 1/t$
- For the expansion may not be completely free ($R \sim t^m$, $m<1$), Wind may not be steady $1/R^s$, $s \neq 2$, $Lx \sim t^{-(12-7s-2ns-3n)/(n-s)}$.
- But this is total X-ray luminosity, and telescopes measure in narrow X-ray range!
- Luminosity dependence flatter than 1/R (Fransson et al. 1996).

X-ray luminosity of SNe IIn



- It is clear that although there is great diversity, none of the Type IIn appears to be evolving into a steady wind with constant parameters.

Wide band X-ray observations

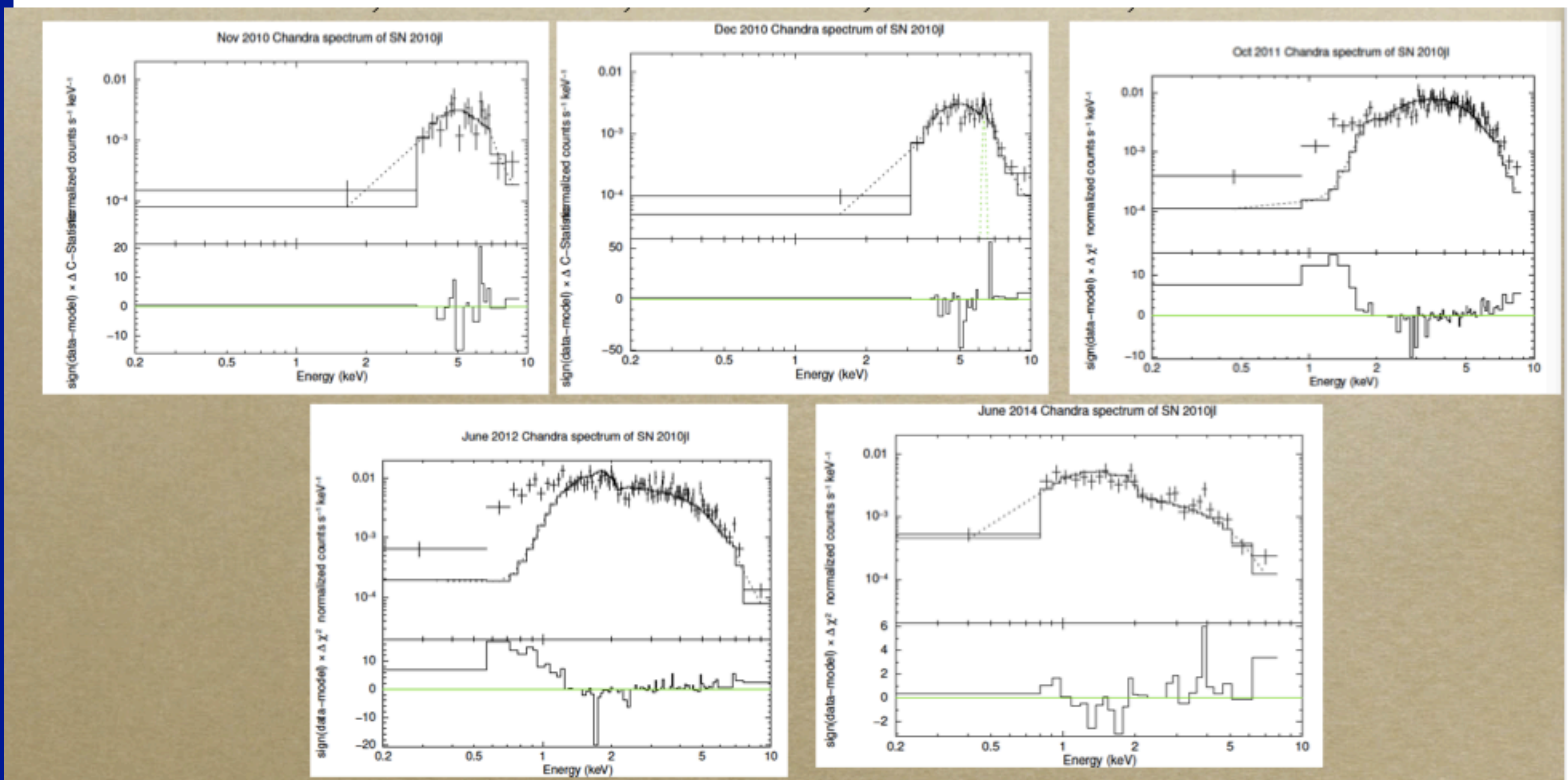


Chandra et al. 2015

X-ray emission

- Generally X-ray emission dominates from the reverse shock because density is high.
- In SNe IIN, radiation shell gets created and formation of cool shell in between, so all reverse shock X-rays absorbed.
- Forward shock itself dense enough that enough X-ray emission for a long time, e.g. 2010jl, 2006jd (Chandra et al. 2012, 2012b, 2015).

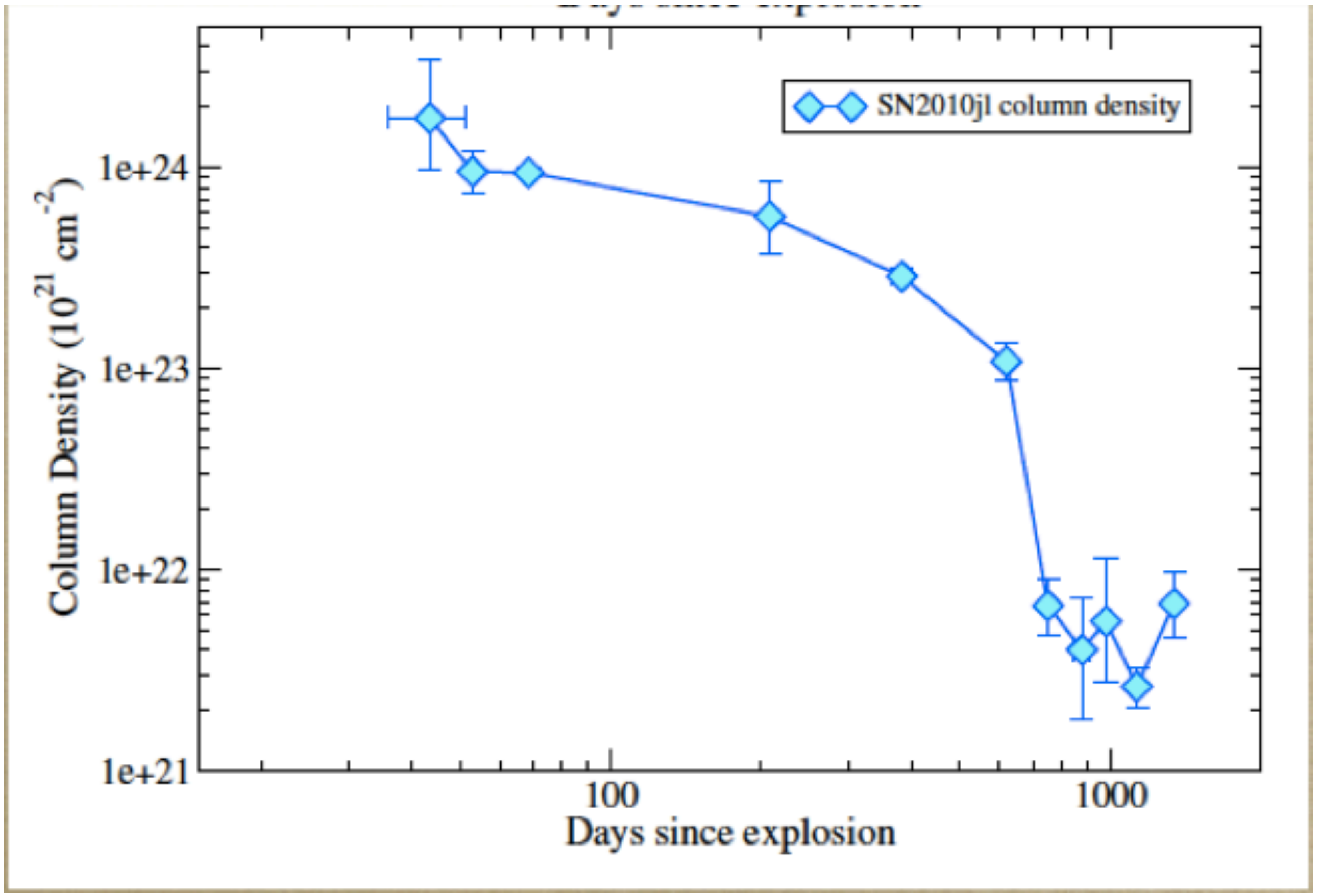
Spectra evolution in SN 2010jl



Chandra et al. 2015

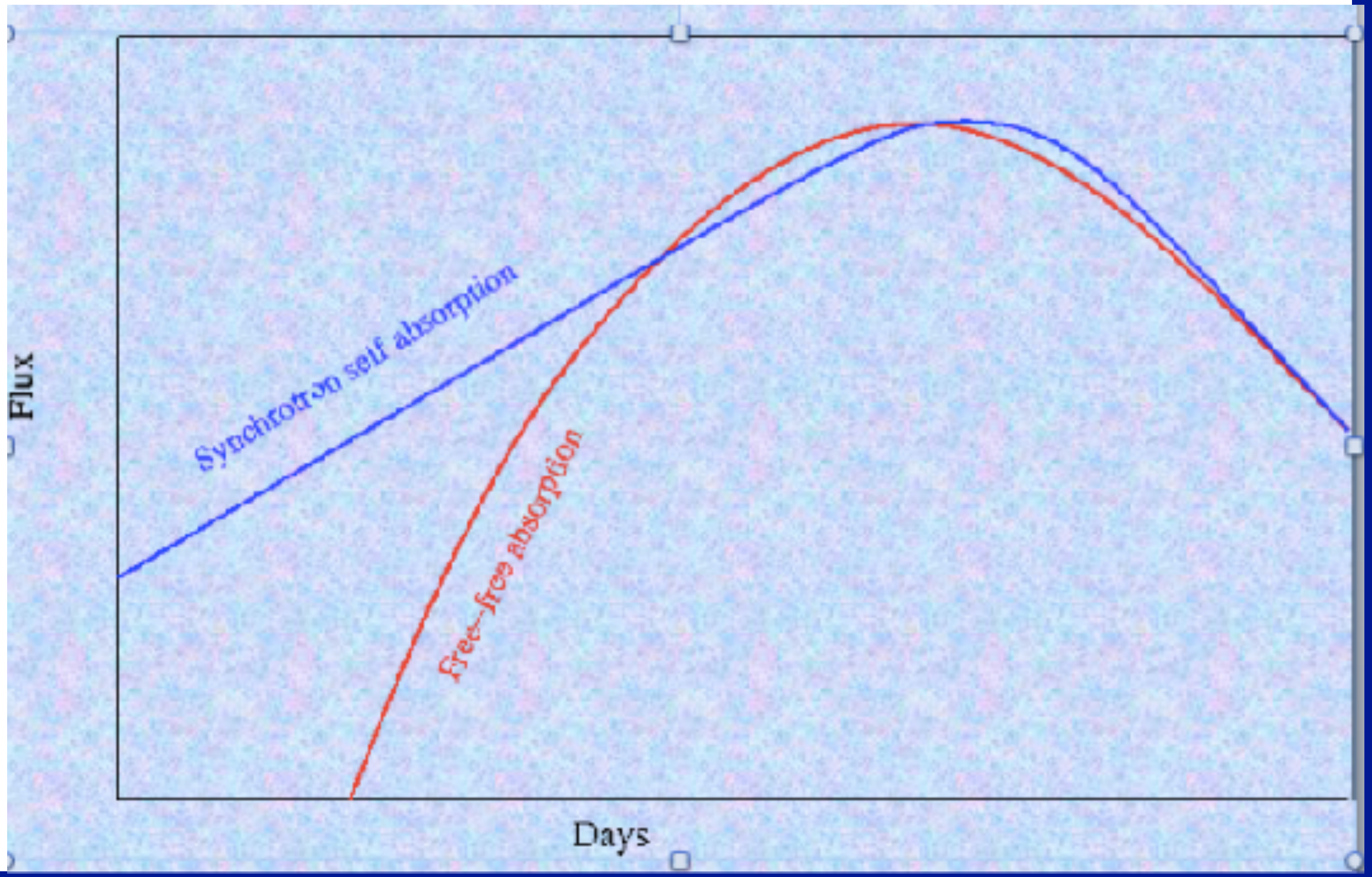
Evolution of column density in SN 2010jl

Chandra et al. 2015



Radio Observations

- Synchrotron emission
- External free-free absorption
- Synchrotron Self Absorption

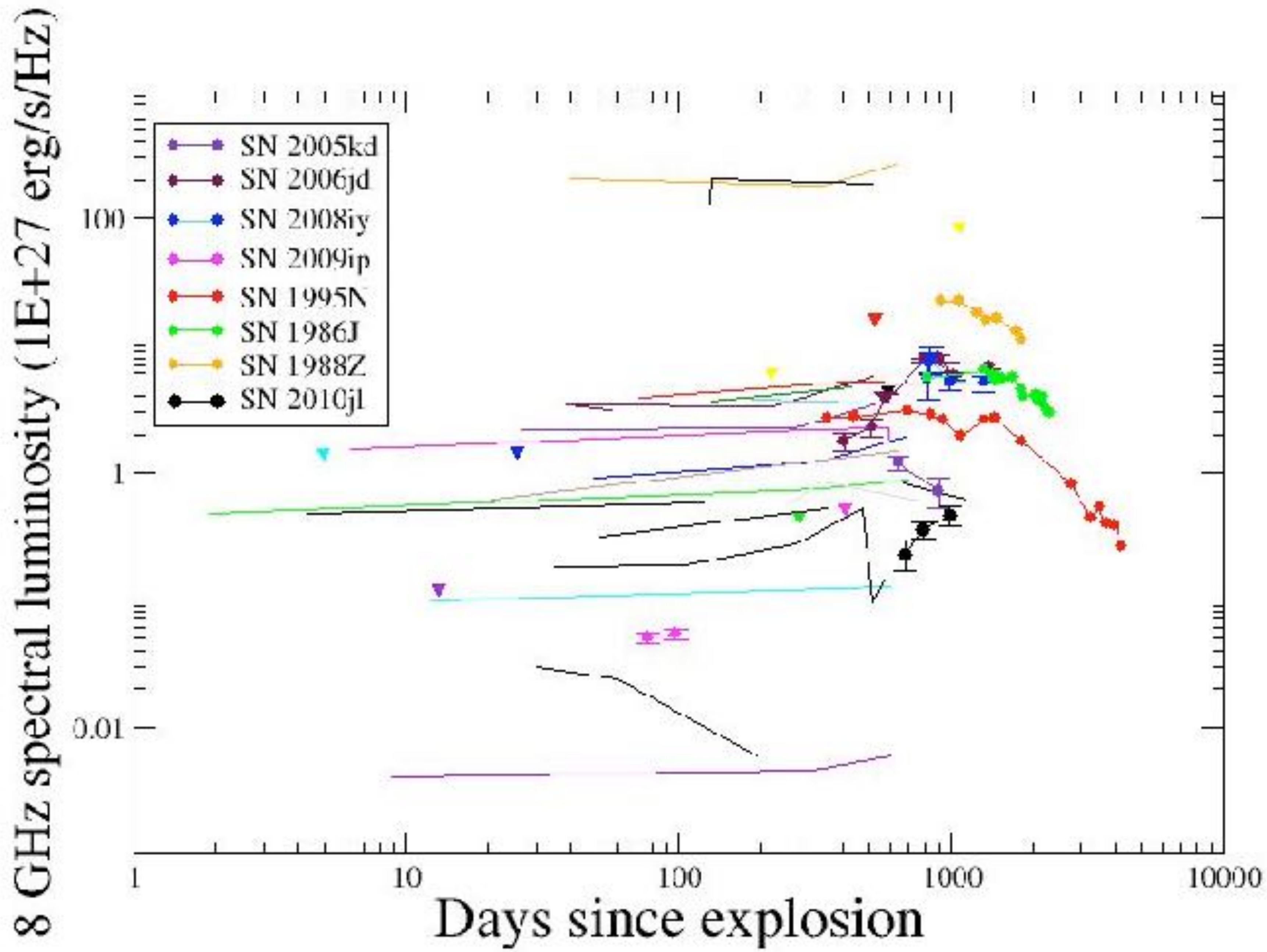


Radio observations statistics

- Around 398 IIn supernovae (a fraction other too)- rare <10%
- Includes 12 SLSNe ($M_V < -21$) . 32 SN IIn with ($M_V < -20$)
- Only 154 SNe IIn were looked in radio bands (99% with the VLA/ EVLA/JVLA, **Weiler, van Dyk, PC, Chevalier, Soderberg, Chugai, Fransson).**
- Only ~24 are detected (PS1-10acl, SN2010jl, PTF11iqb, SN1994W, DES12S2a, SN2012hk, SN2015bh, SN2014G, SN2010mc, SN1986J, SN2009kr, SN1995N, SN2013gc, SN1978K, SN1996cr, CSS100217:102913+404220, SN2007nx, SN2014C, SN19988Z, SN2006jd, SN2008iy, SN1998S, 2005kd, SN 2014ab)
- Low detection rate ~10%

Delayed Radio Turn On

PC et al. to be submitted



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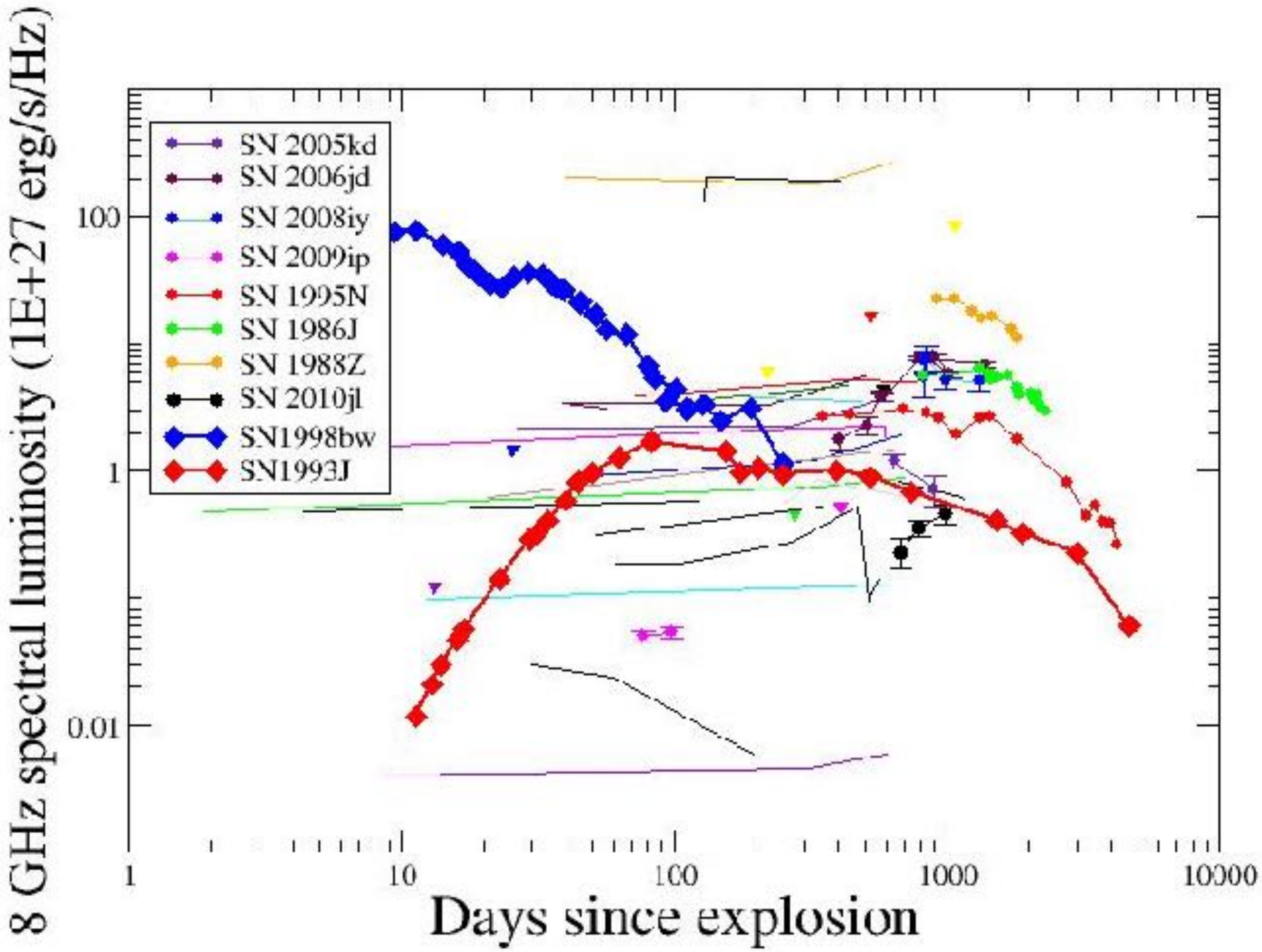
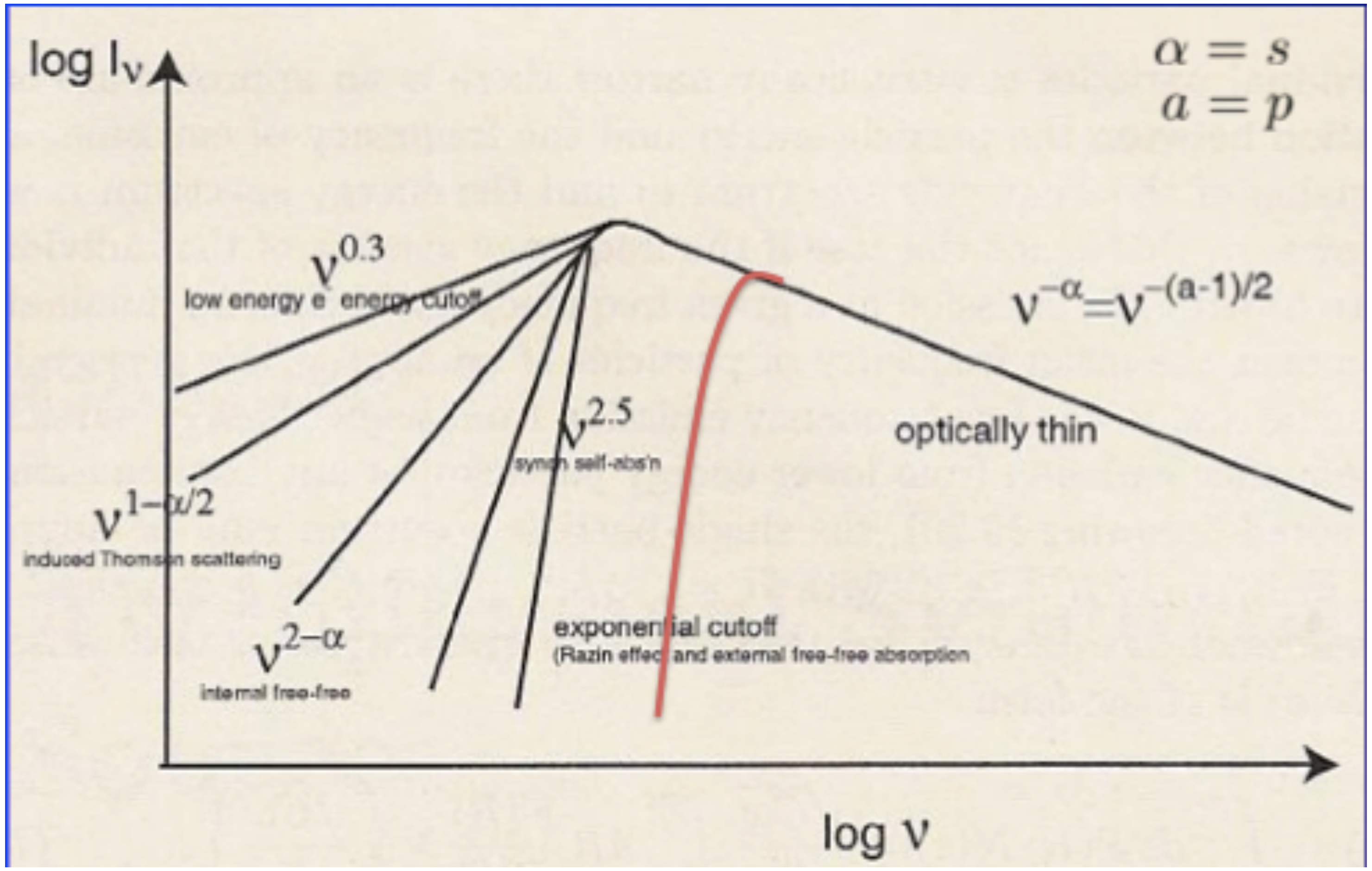


Late Turn On

- Intrinsically weak or too much absorption.
- The low detection rate may be a consequence of late turn on, e.g. SN 2010jl (PC et al. 2015)
- Microscopic parameters may have crucial role to play too

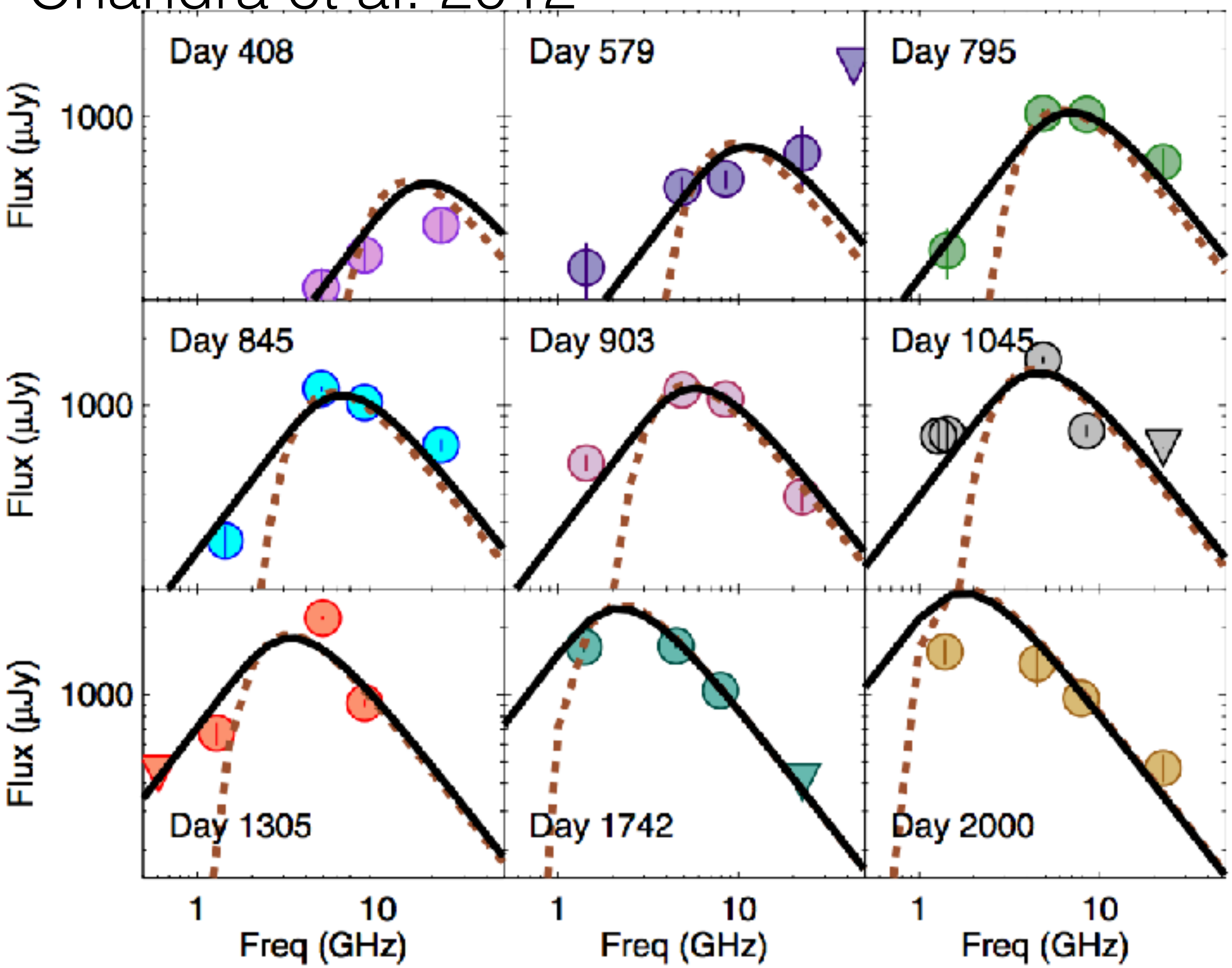


SN IIN internal absorption

- Generally radio is either free-free absorbed by ionised CSM or synchrotron self absorbed.
- In SN IIN, due to high density radiative cooling of dense gas in the shocked region- mixing of cool gas in emitting stoked region
- Internal free-free absorption SN 2006jd (Chandra et al. 2012), SN 1986J (Weiler et al. 1990) and SN 1988Z (van Dyk et al. 1993; Williams et al. 2002). Weiler et al. (1990)
- Modest amount of cool gas (~10^4K) i.e.$10^{-8} M_{\odot}$ can explain internal absorption
- The low gas column density inferred along the line of sight to the emission region.

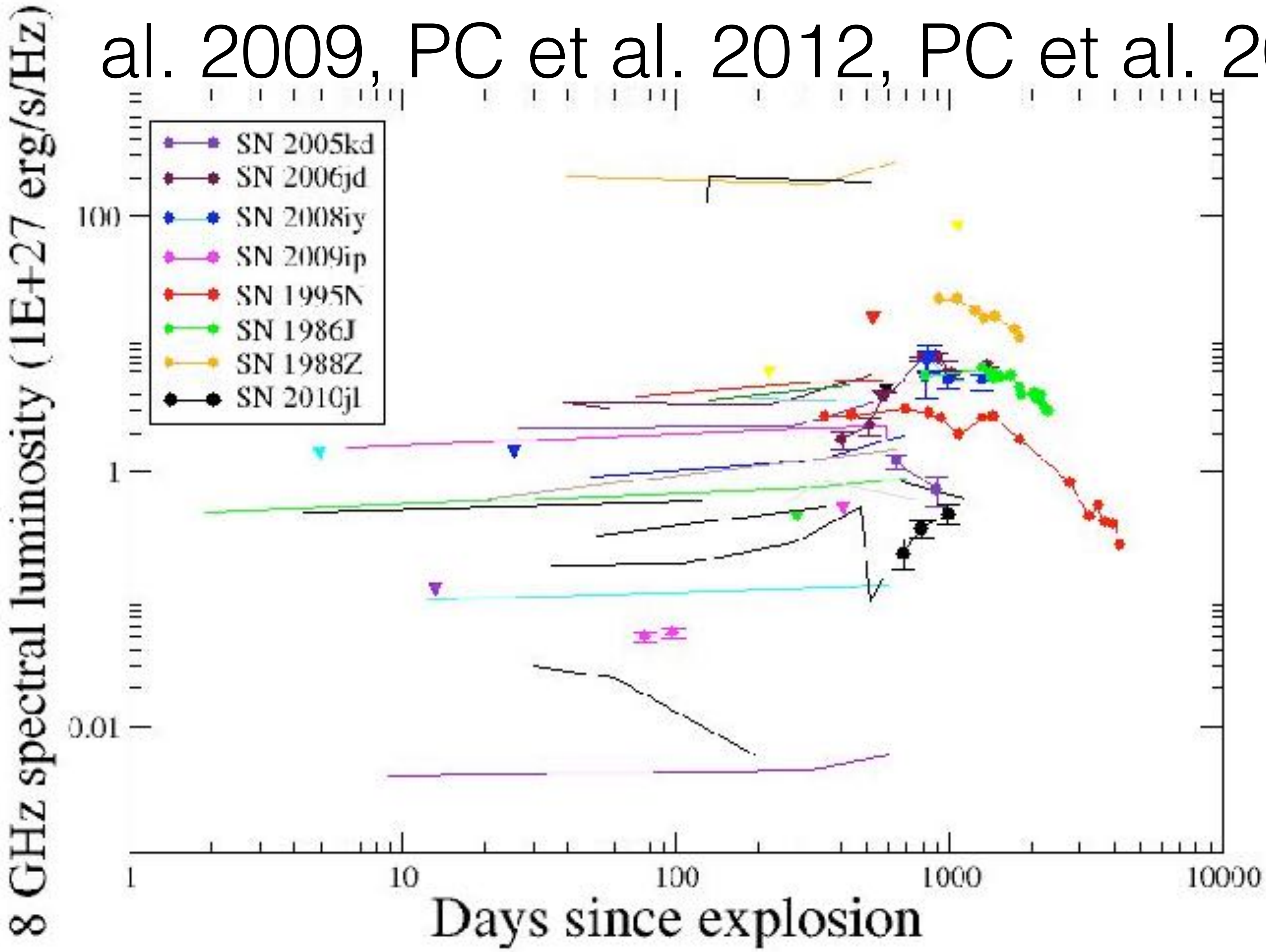
Internal absorption in SN 2006jd

Chandra et al. 2012



Diverse radio luminosities

Dwarkadas et al. 2016, Dwarkadas and Gruszko 2012, PC et al. 2009, PC et al. 2012, PC et al. 2015, to be submitted



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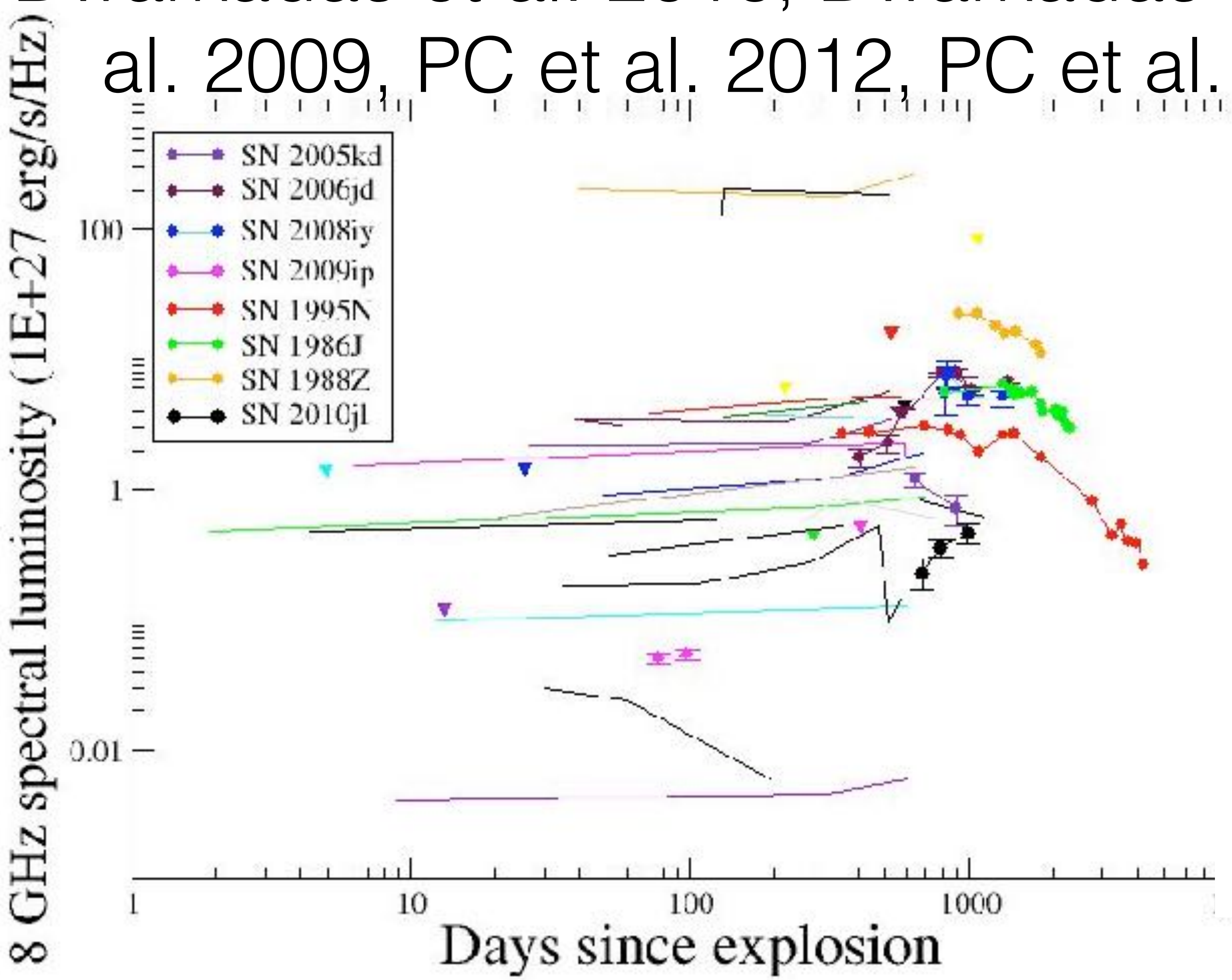
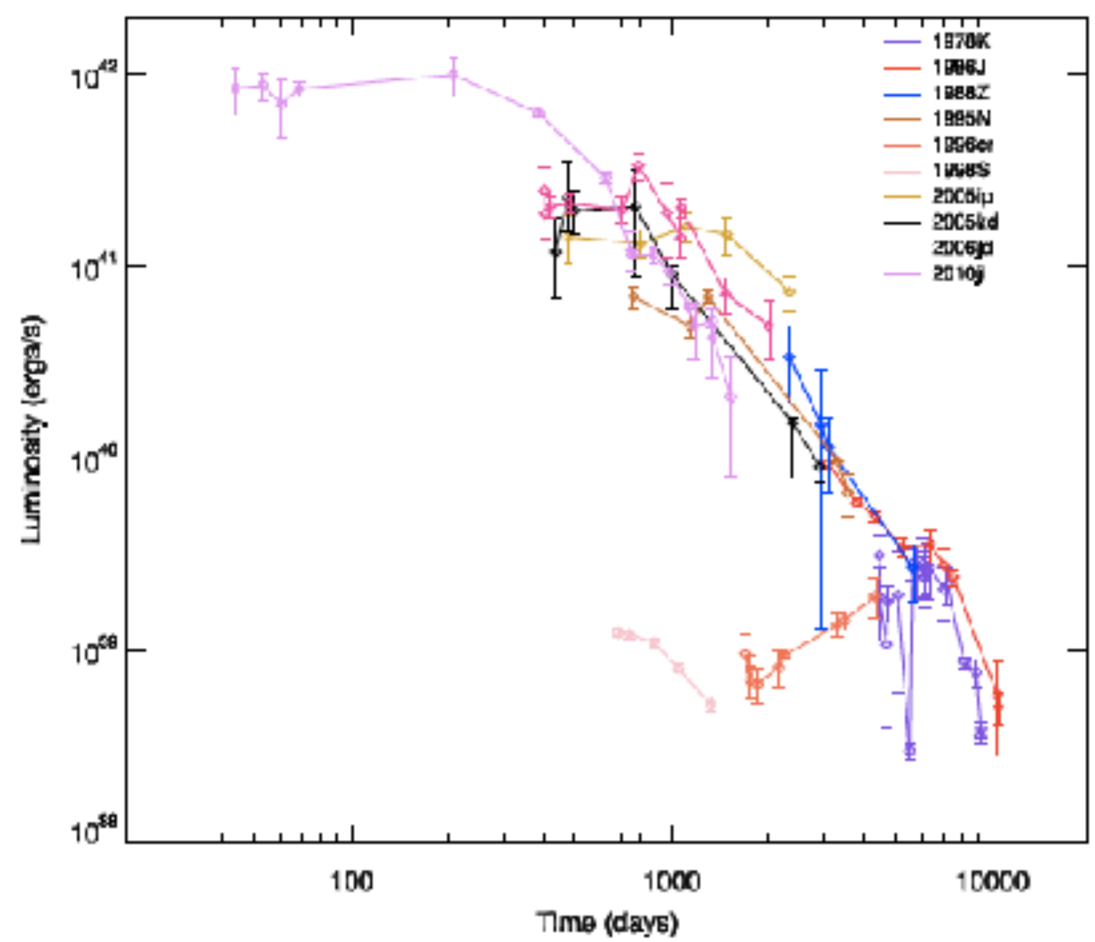
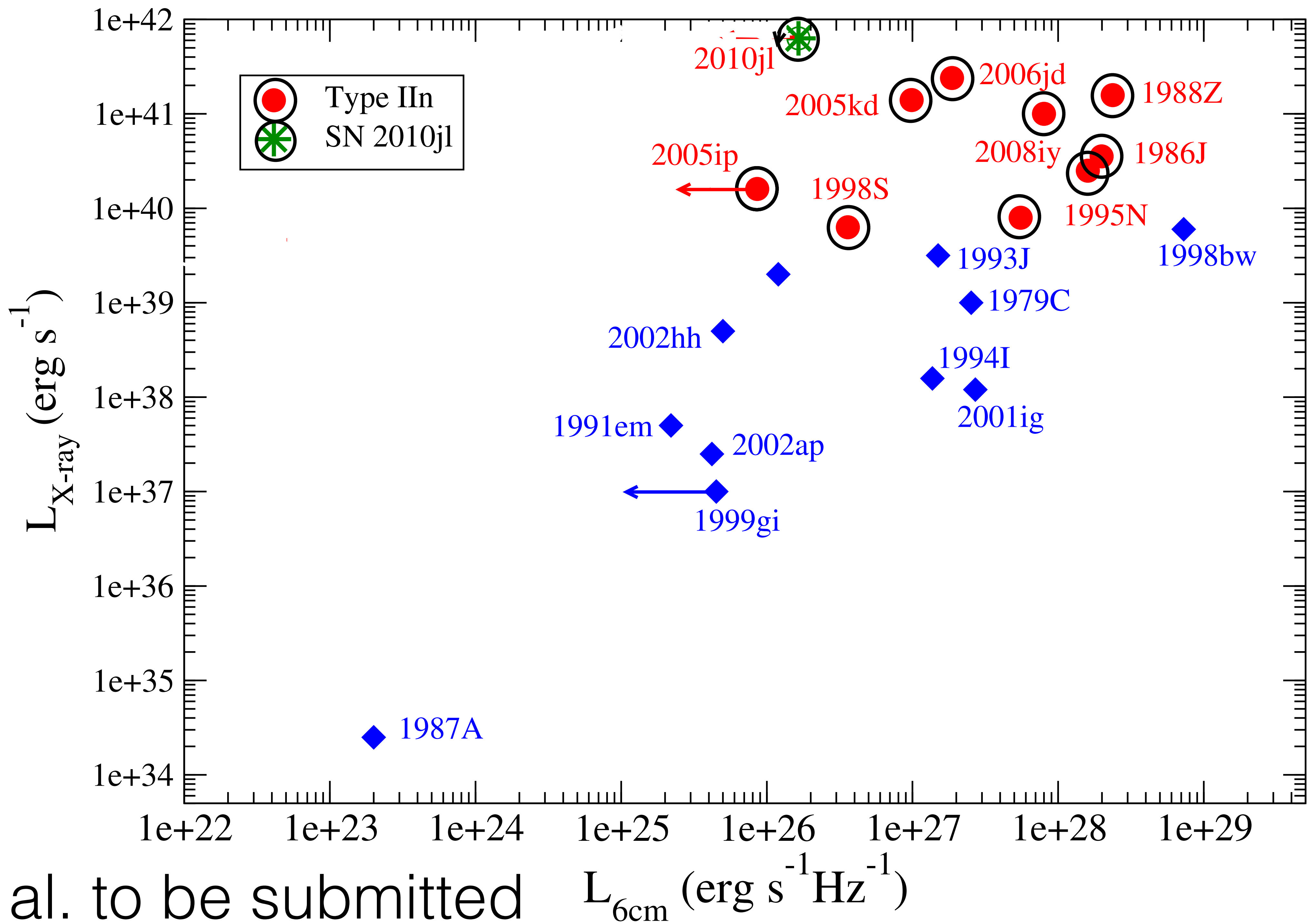




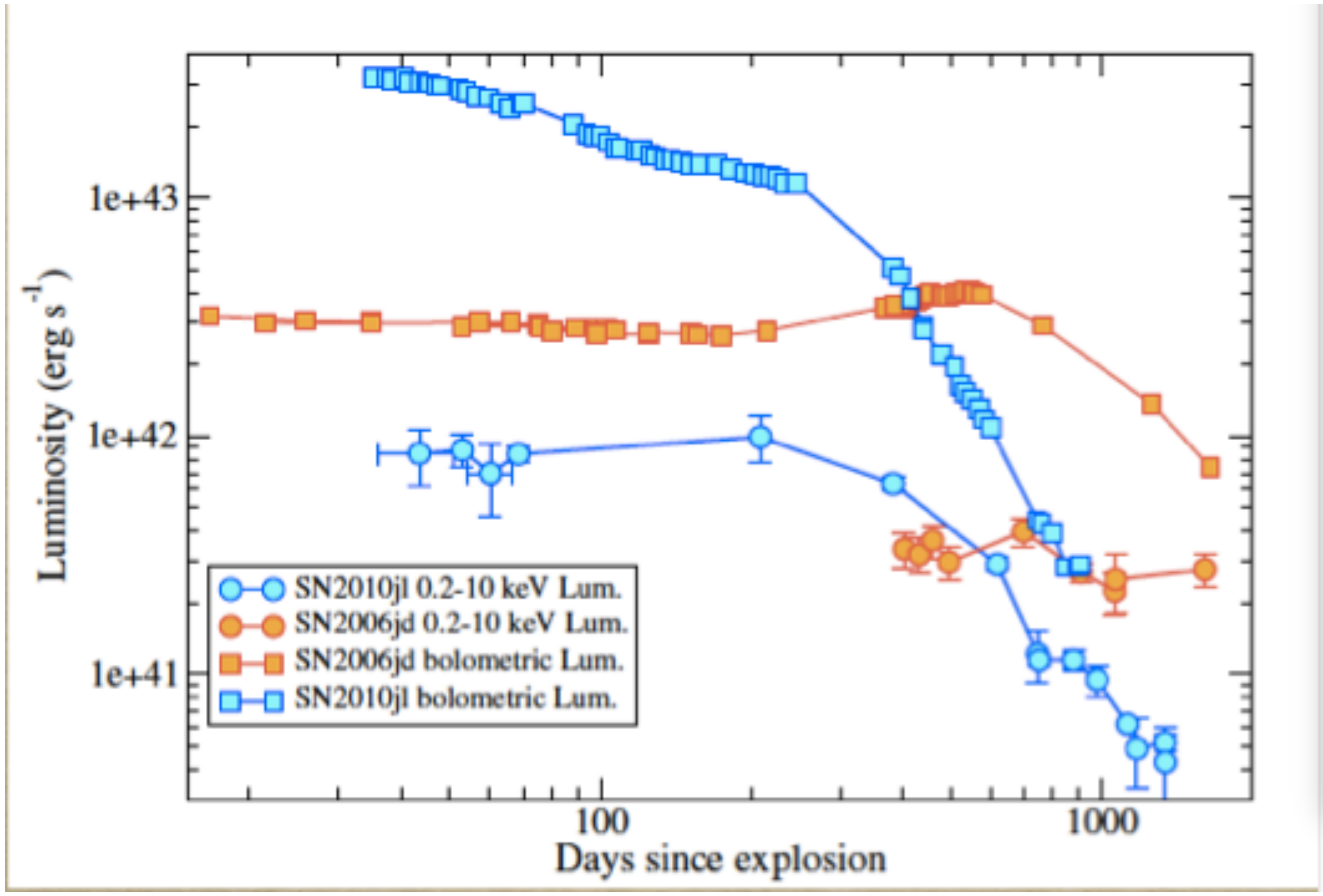
High X-ray luminosities, diverse radio luminosities



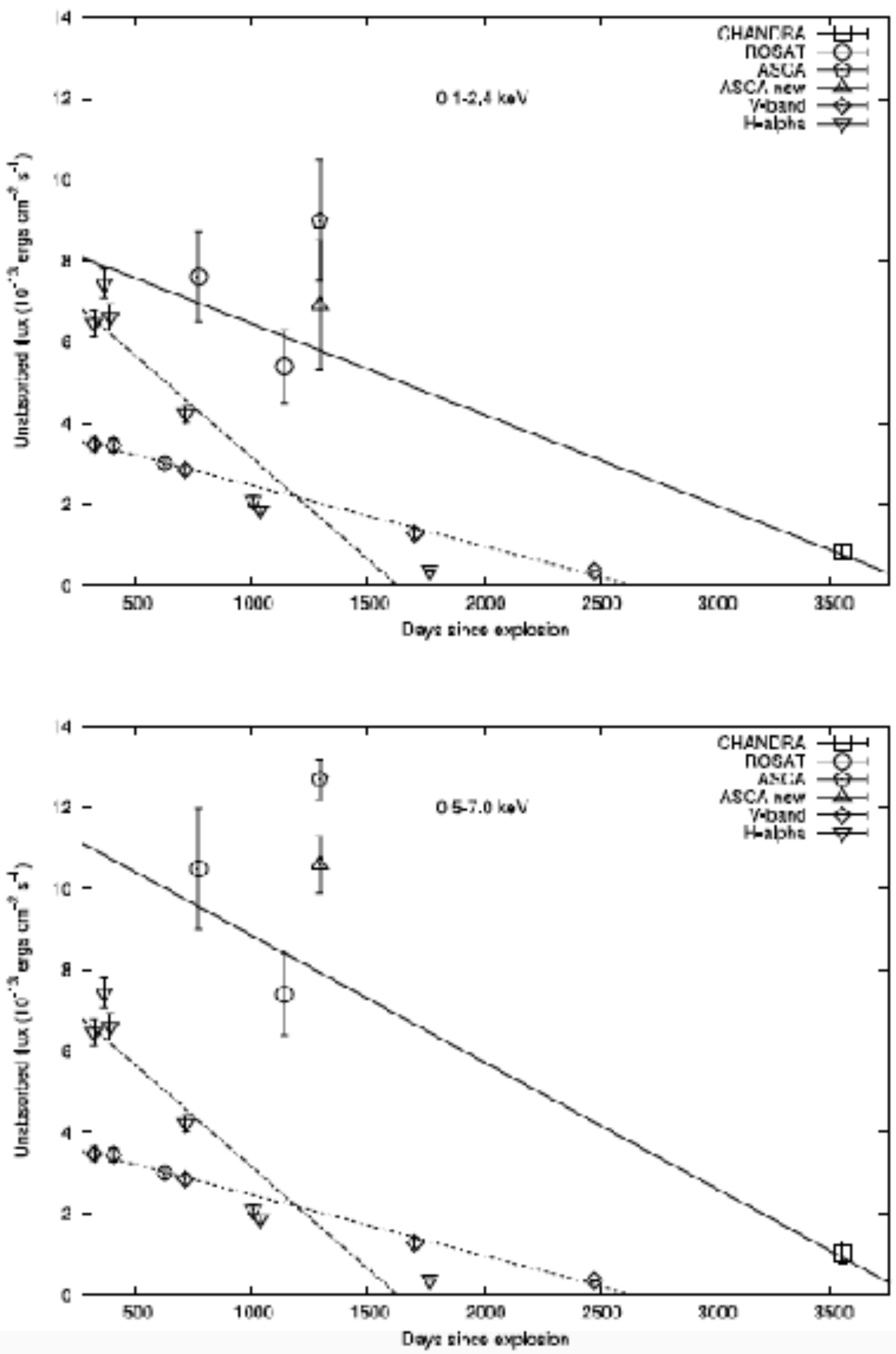
PC et al. to be submitted

Late time follow up

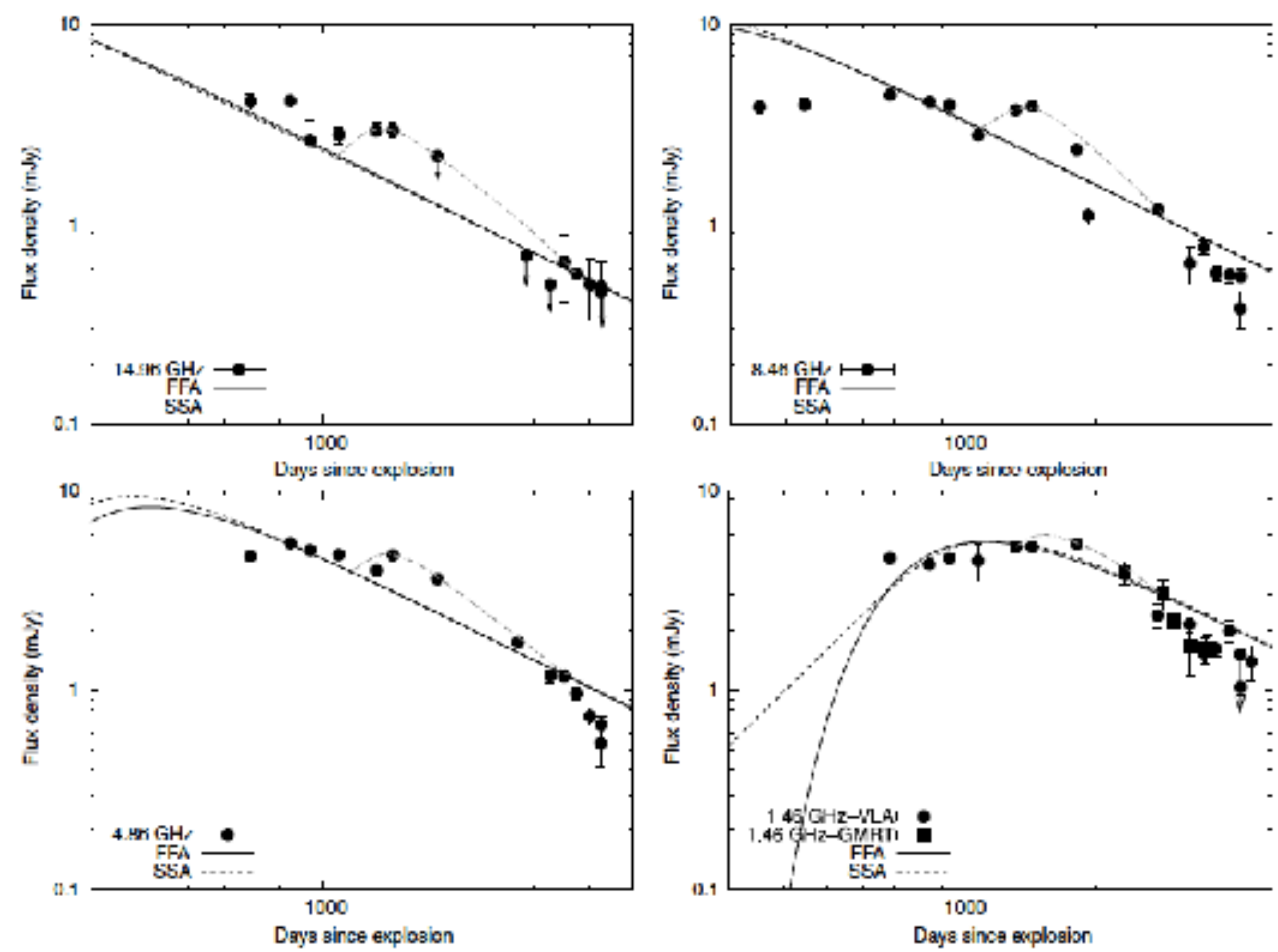
- Late time follow up crucial to probe earlier precursor history or change in mass loss



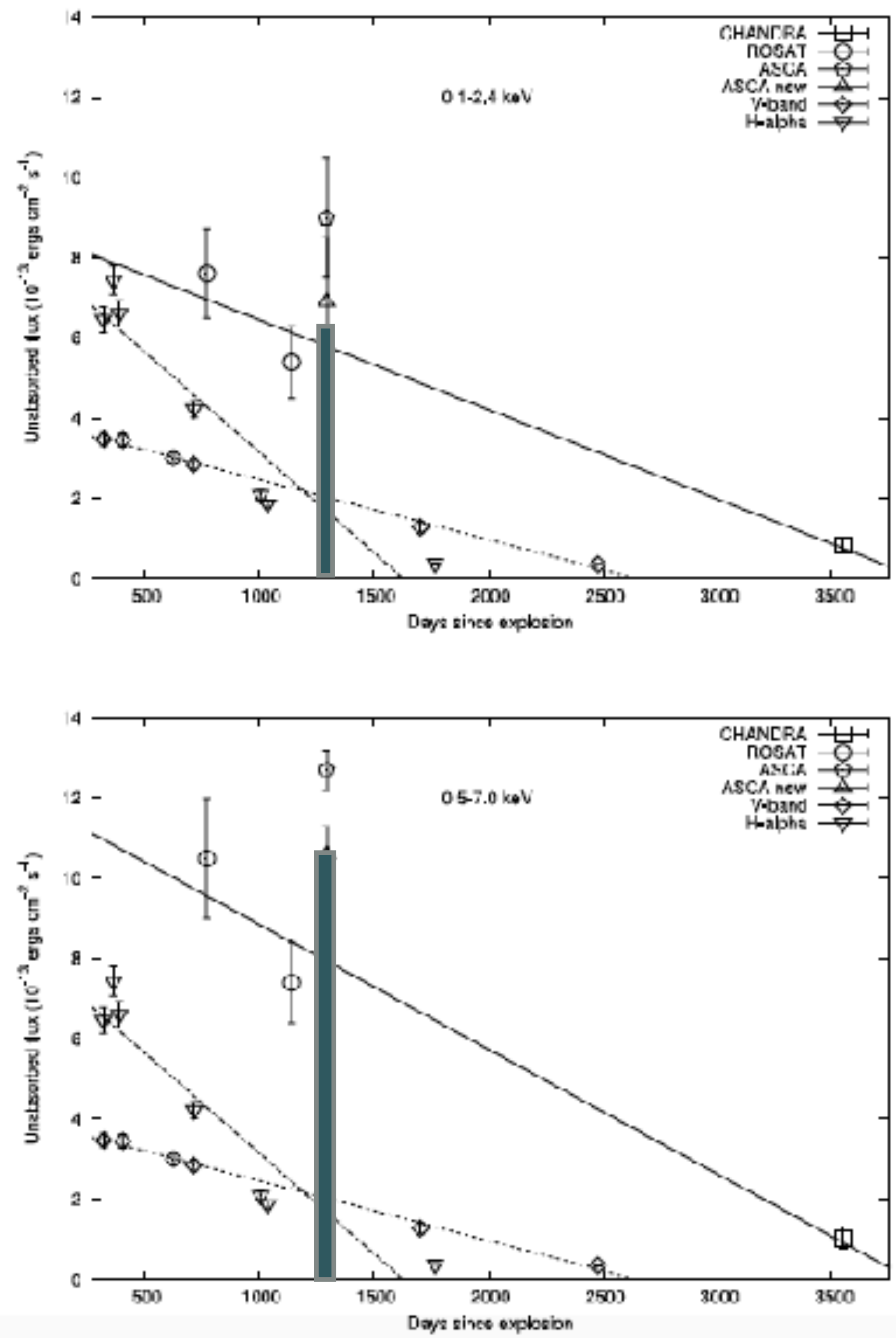
Evidence for increased density? SN1995N



PC, Schlegel, Ray et al. 2005, PC, Chevalier, Chugai et al. 2009, PC et al. to be submitted



SN 1995N



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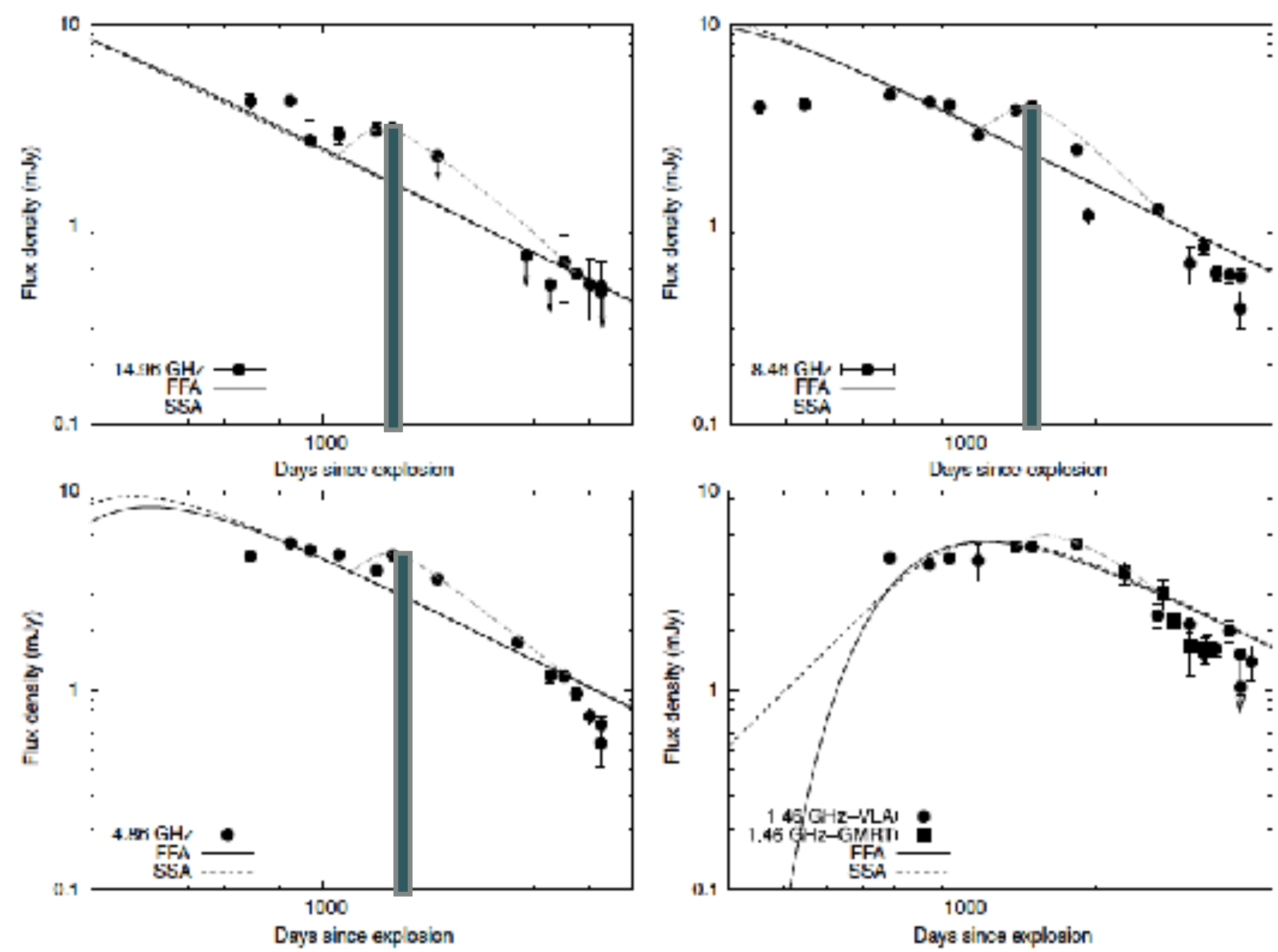
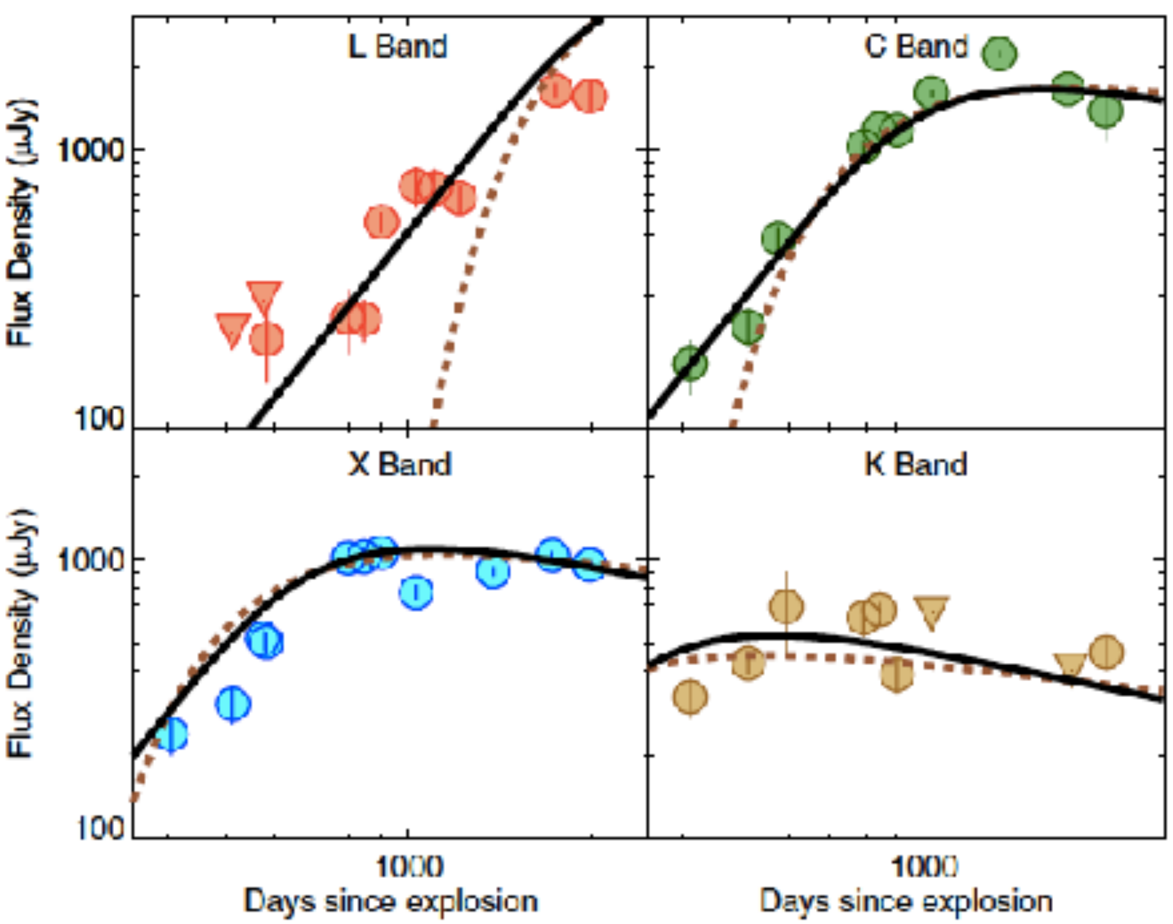
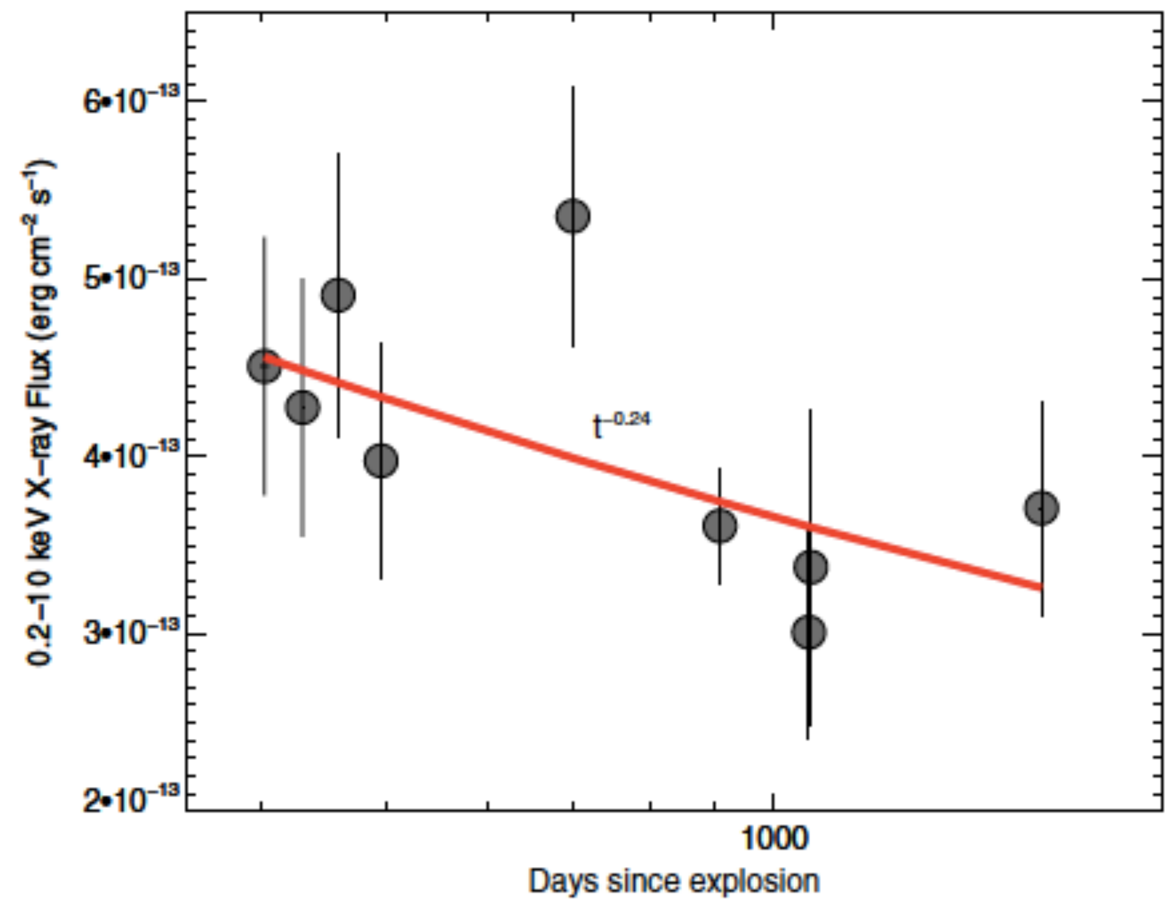


SN 2006jd - Episodic mass loss?





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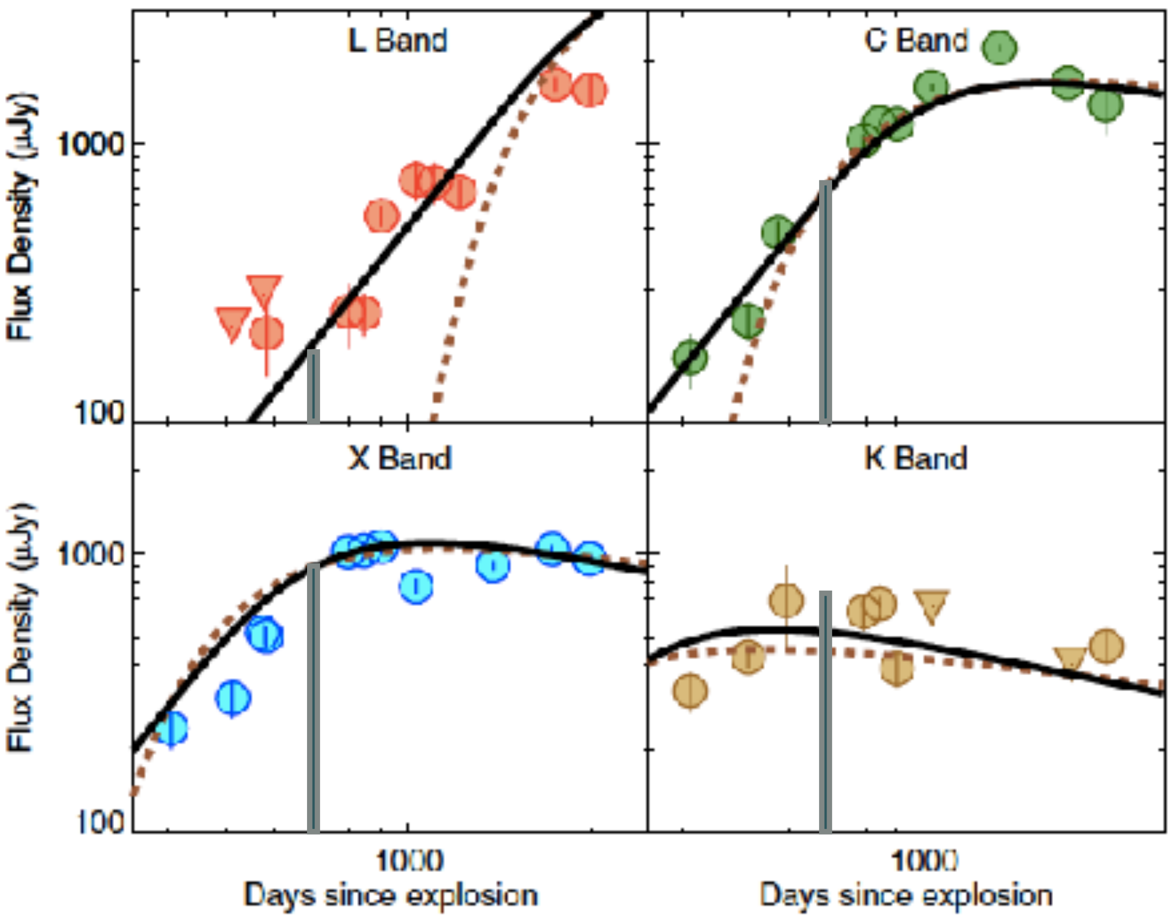

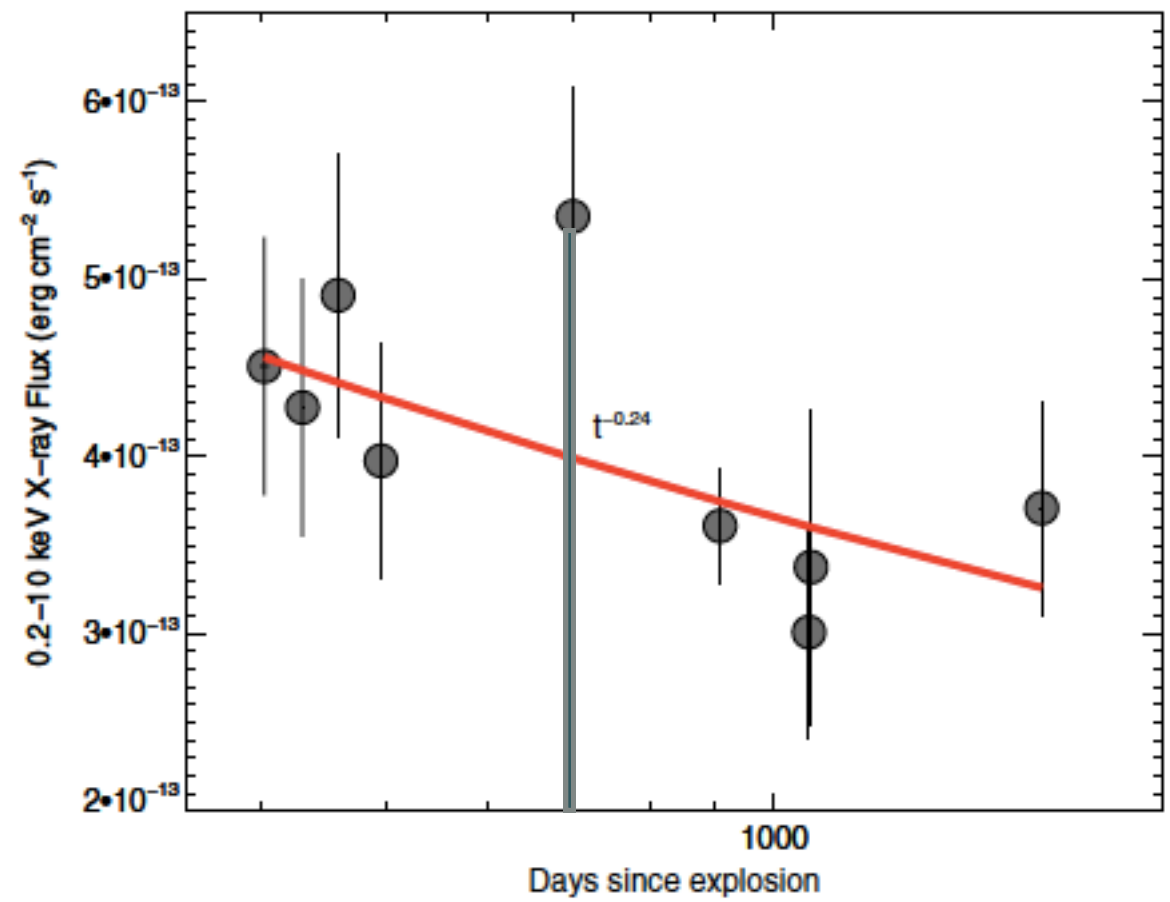

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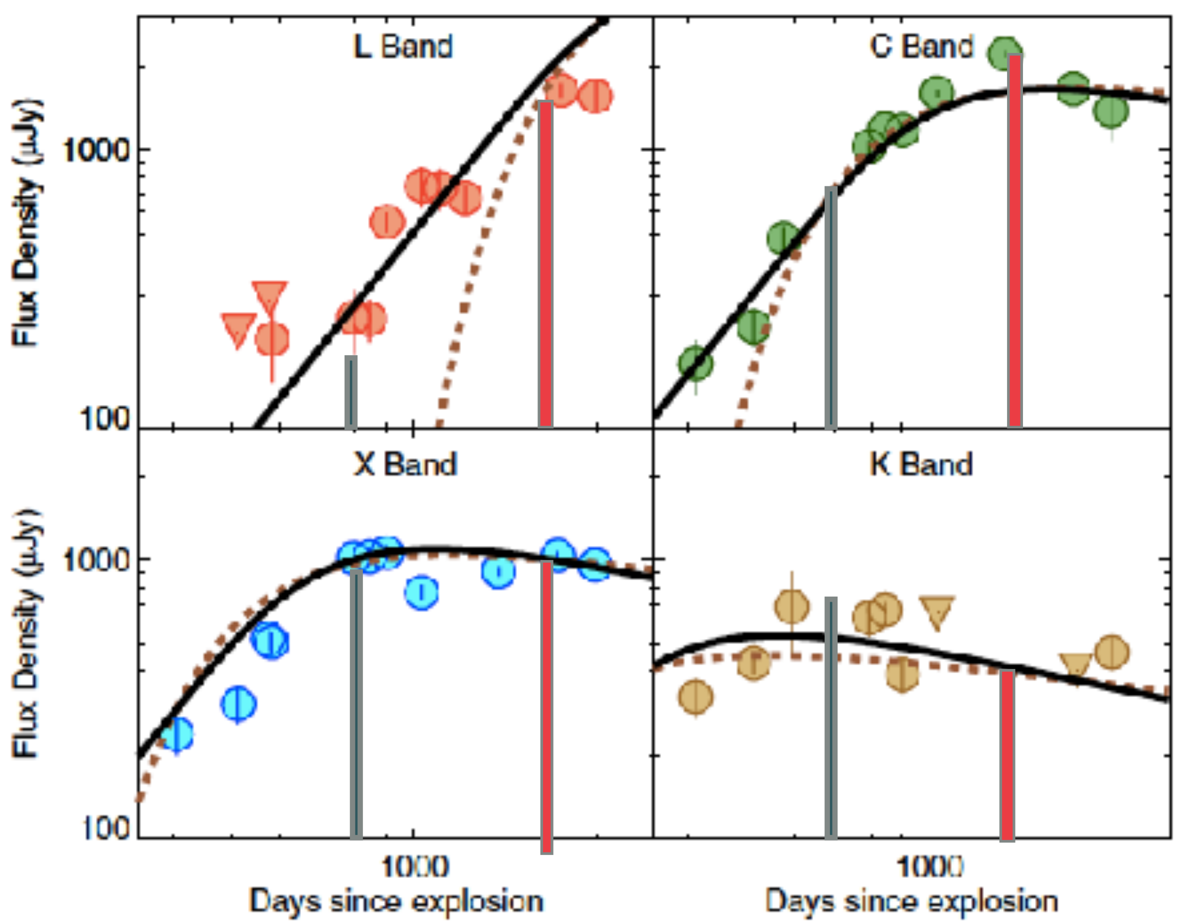
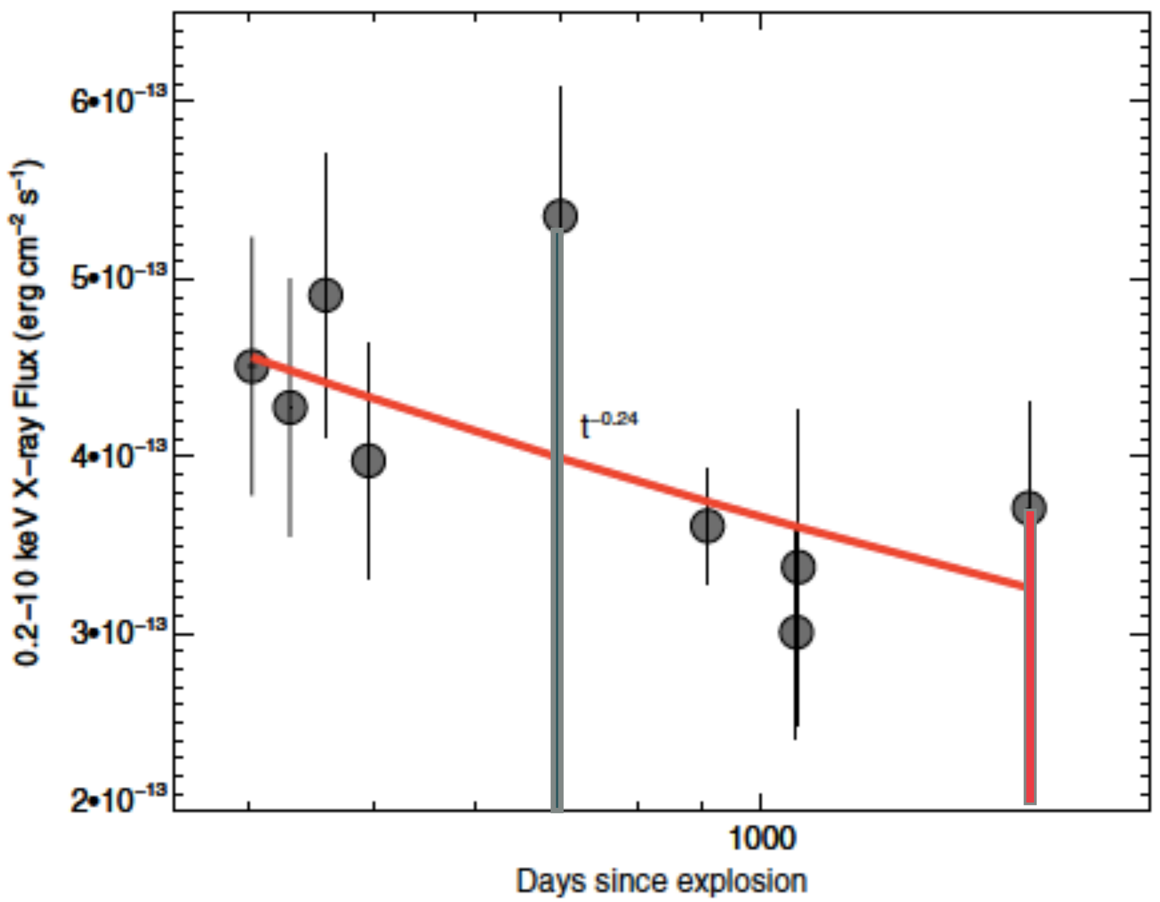




PC et al. 2012, PC et al. to be submitted

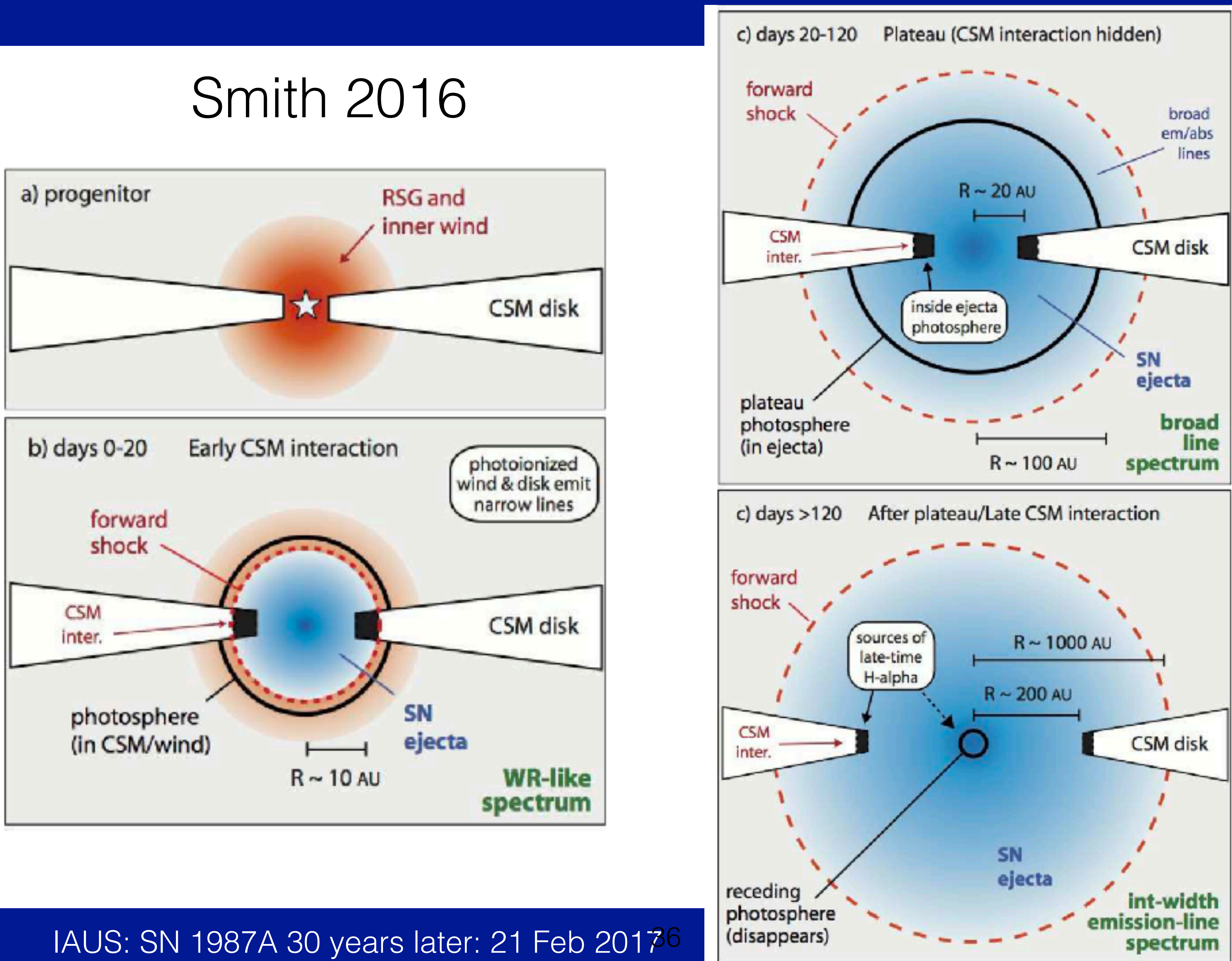
Asymmetry in the explosions

- SN 2010jl: Presence of broad emission lines in the early spectra requires electron scattering optical depth 1-3 and column density > 3×10^{24} cm^{-2} (matches with X-ray, Chandra et al. 2015). Later X-ray column density <10^{24} cm^{-2}. Indicative X-rays escape the interaction region. Suggestive of bipolar geometry (Fransson et al. , PC et al. 2015, 2012b, to be submitted)

- SN 2006jd: The X-ray luminosity implies a preshock circumstellar density ~10^6 cm^{-3} at a radius r ~ 2×10^{16} cm, but the column density inferred from the photoabsorption of X-rays along the line of sight suggests a significantly lower density. CSM column density ~10^{21} cm^{-2}. Expected column density 4×10^{22} cm^{-2}. Suggestive of asymmetry (PC et al. 2012a, 2017)

Asymmetry in the explosions

Smith 2016



Properties of SN IIN

- Detections in radio at very late times.
- Cool gas mixed into the hot gas. Internal absorption in radio bands
- X-ray emission from forward shock. Radiative reverse shock emission absorbed by cool dense shell
- Highest in X-rays but diverse in radio
- Density profiles not standard $1/R^2$
- In radio quite week, diversity

Summary

- Current models are limited to spherical models.
- Differences in wind speed, density, composition, binarity, asymmetry
- Clumping, empirical mass loss could be 3-10 times lower than the measured (Smith et al 2014)
- Binarity. More than 50% O star in binaries (Sana et al. 2012)
- Disk like CSM seen, asymmetries