Broadband non-thermal emission as an effective probe of progenitor origins of core-collapse SNRs

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Publications:
ApJ 925, 193 (2022) arXiv:2111.09534
ApJL 919, L16 (2021) arXiv:2109.04032

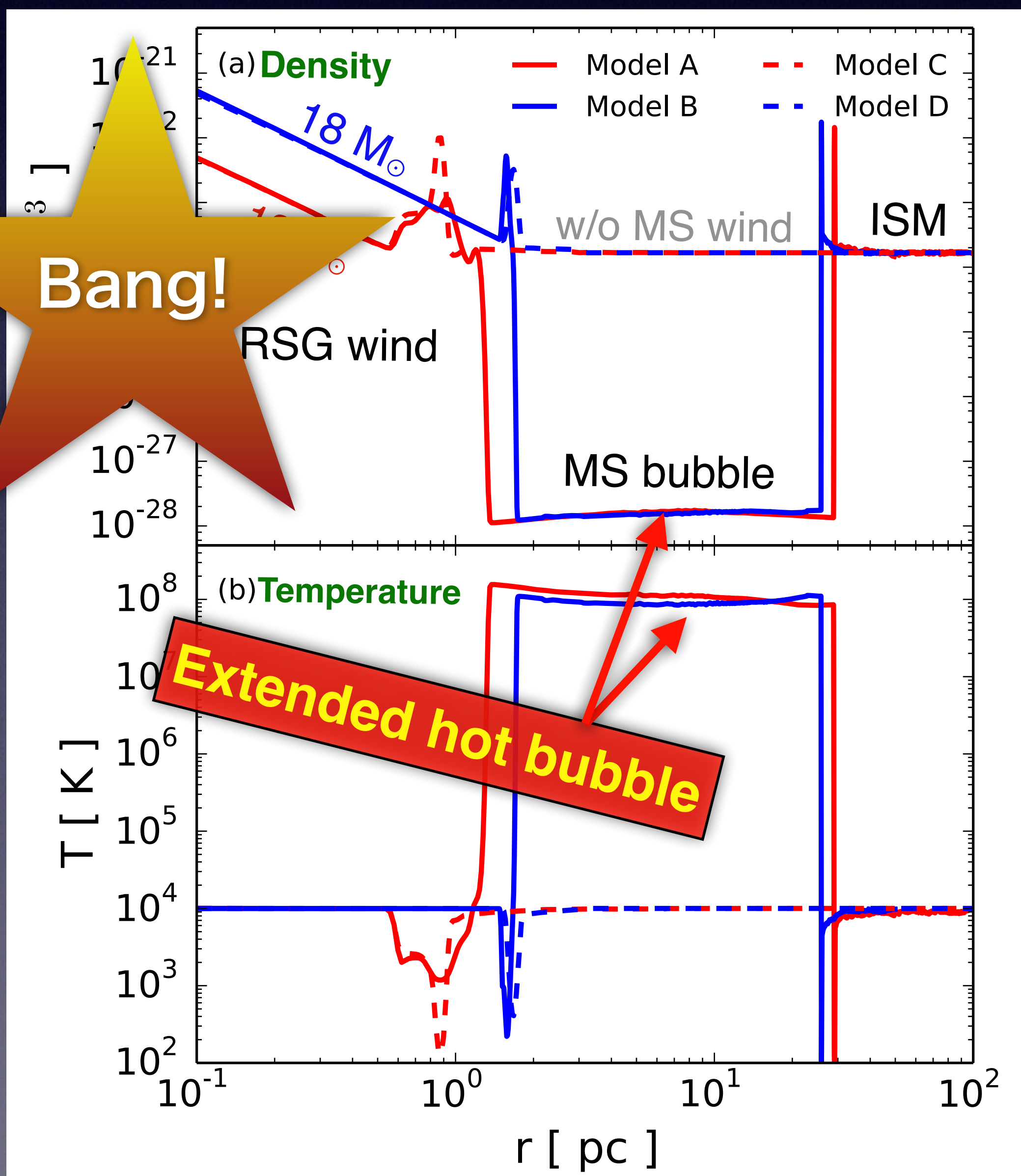
Summary

- Linking a SNR to its progenitor star is no trivial task
  - So far: historic events, light echoes, abundance ratios from thermal lines, morphological asymmetries (power ratios), CCOs/PWNe, Fe-K centroid, etc…
- We explored a new potential way to supplement this list using **non-thermal emission**
  - Given it mainly comes from shock interaction with surrounding circumstellar environment (CSM)
  - **Shock-CSM emission acts as time machine** to probe pre-SN mass loss activities
- We developed CR-hydro + CSM models for RSG-like ("Type II") and stripped ("Type Ib/c") progenitors. **Main results**:
  - **Non-thermal light curves** are **highly distinctive among CCSNR types**
  - Large impact on **observability of SNRs** of different types at different ages
  - Observed **diversity of SNR gamma-ray spectra** most likely dictated by CSM environment & SN type, instead of being an age-sequence

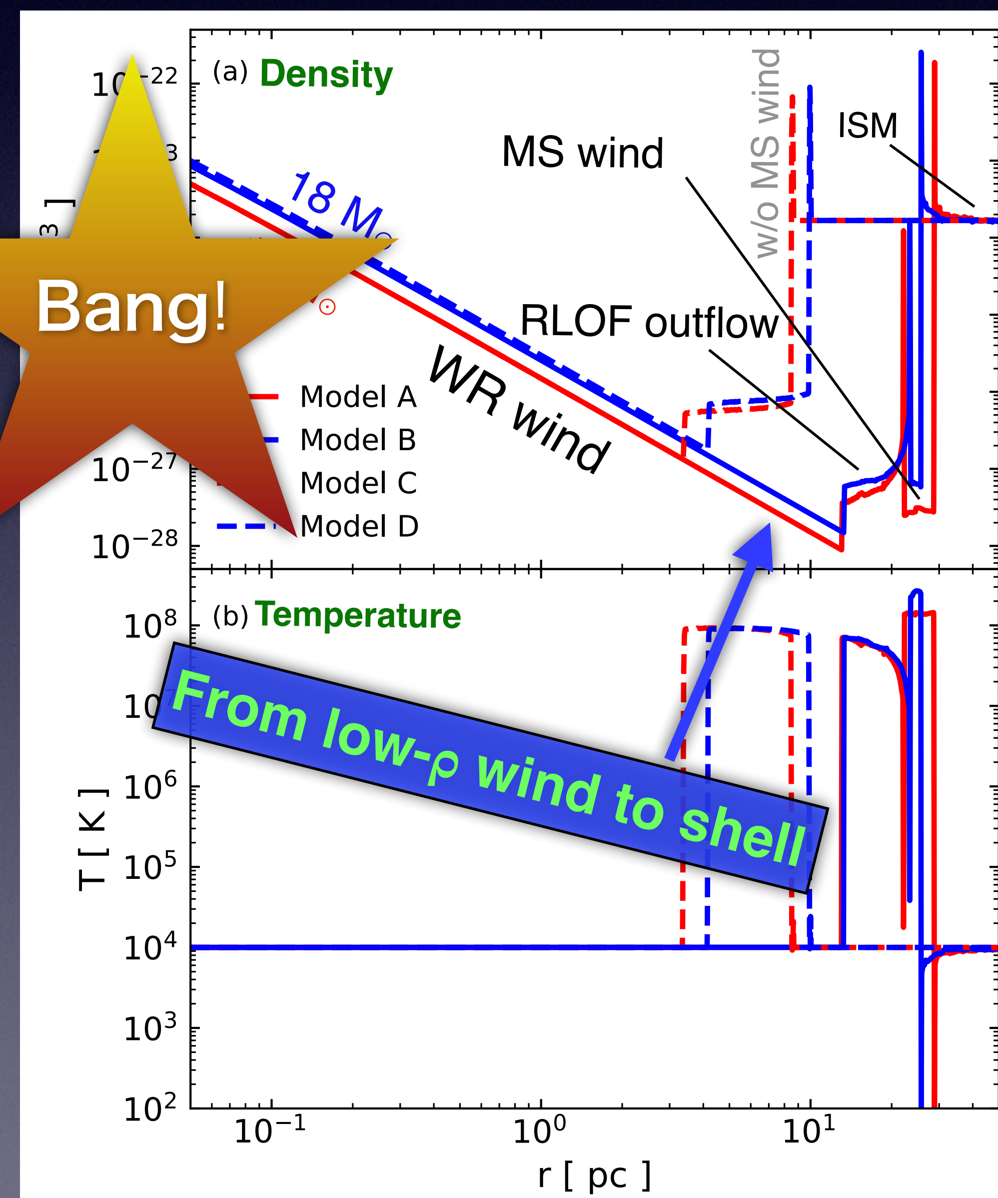
CSM models

- **1-D hydro models of CSM** for **Type-II (RSG-like)** and **Ib/c (stripped WR w/ RLOF)** progenitors
- Explored **different mass loss histories** for each (see papers for detailed episodes)

CSM models for RSG-like progenitors

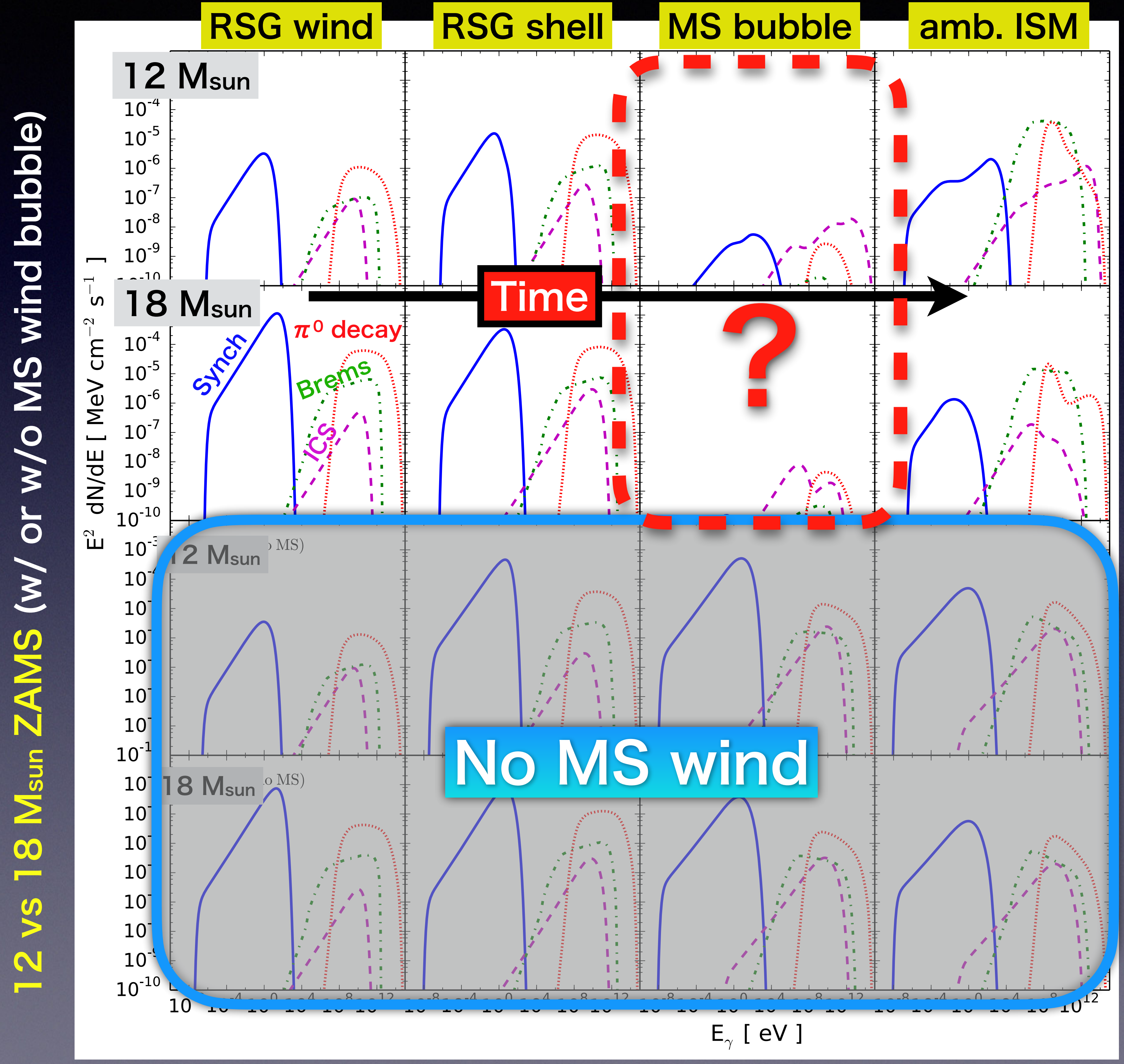


CSM model for stripped progenitors



Broadband spectral evolution

Interaction with a multi-phase CSM



Demo

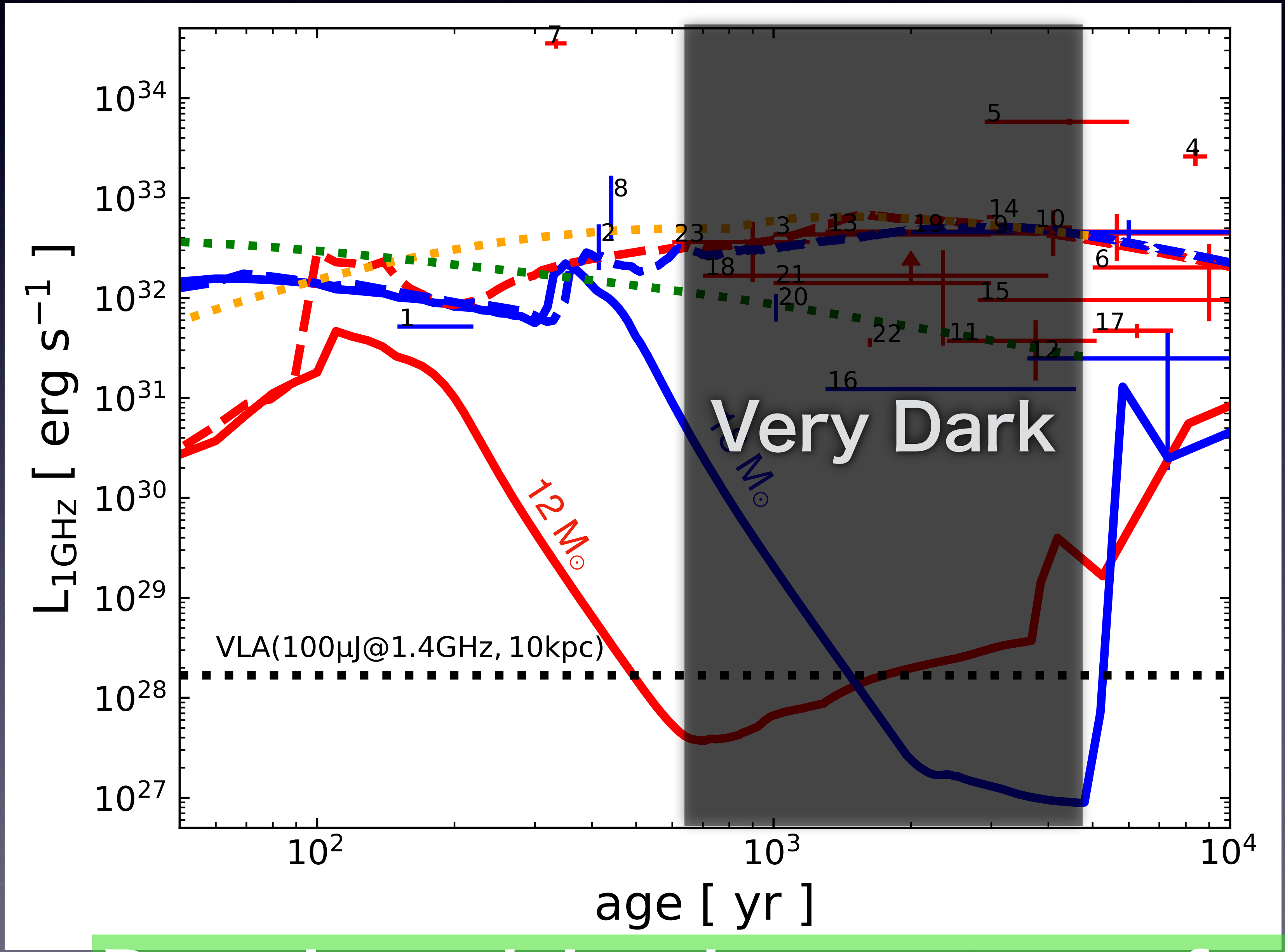
Case of Type-II explosion of a RSG

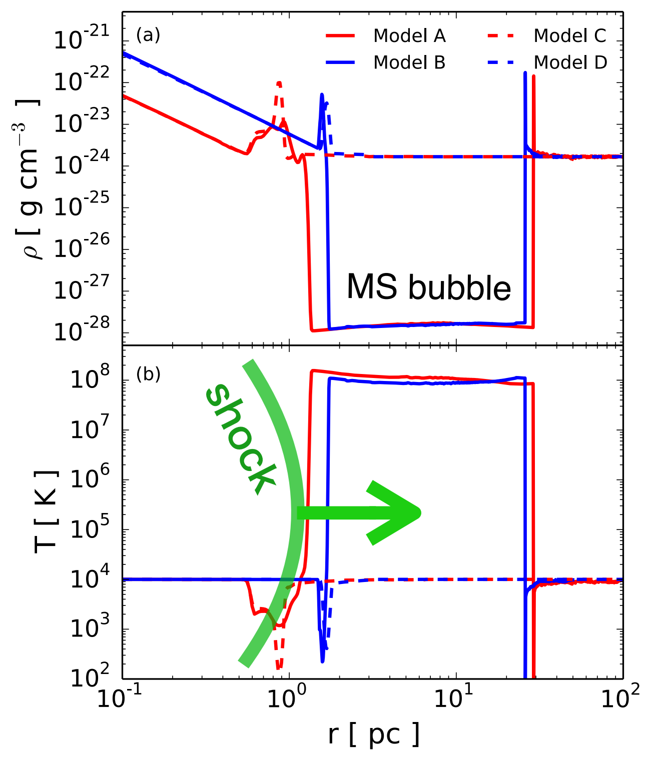
If MS phase creates an extended hot wind-blown bubble (see, e.g., V. V. Dwarkadas+ 2005 to 2023)…

DARK AGE for RSG-like SNRs is expected!

Radio light curve for Type-II

1.4 GHz continuum radio light curve of a RSG-like SNR



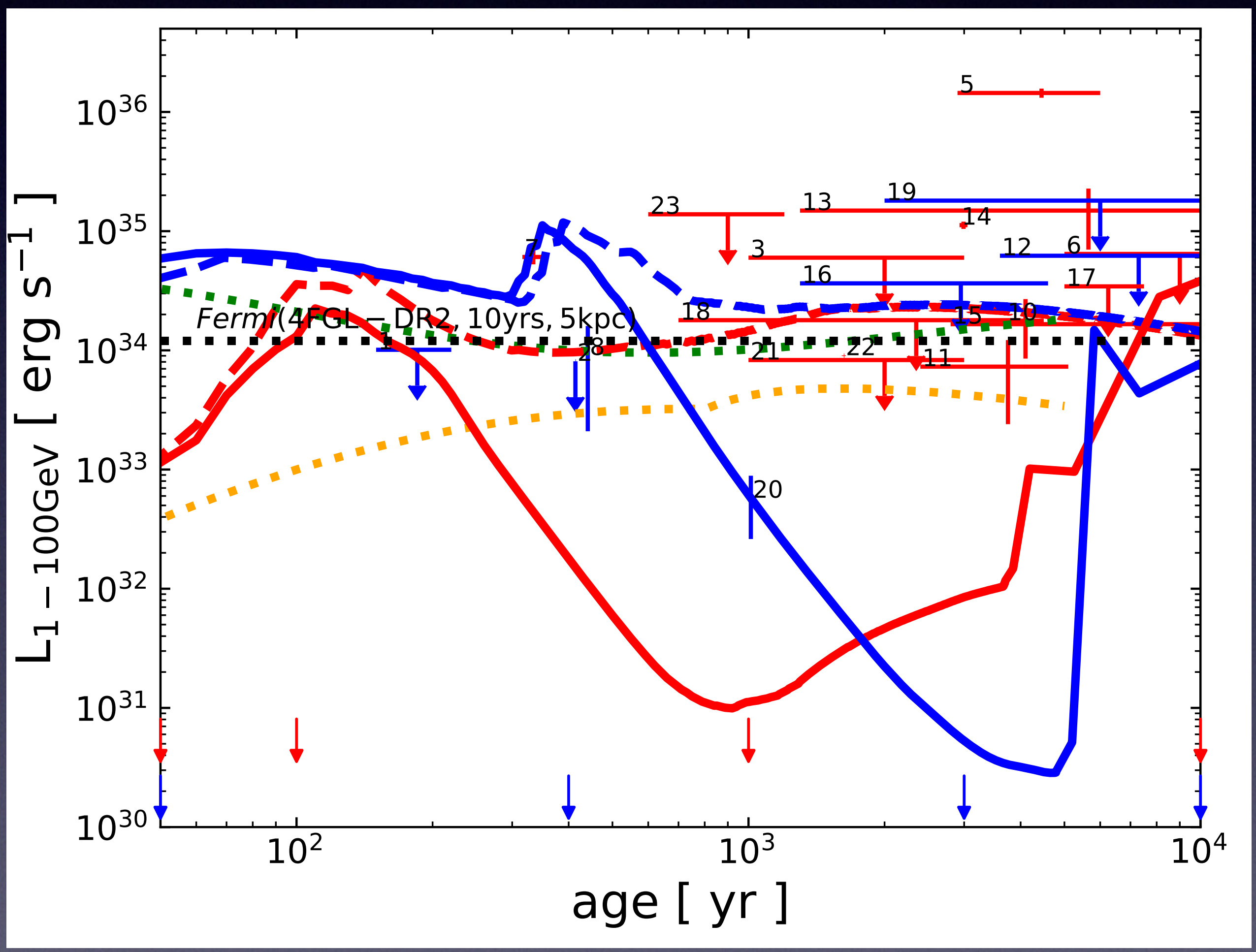


Shock runs into hot MS bubble
→ M_S drops
→ L_{radio} drops

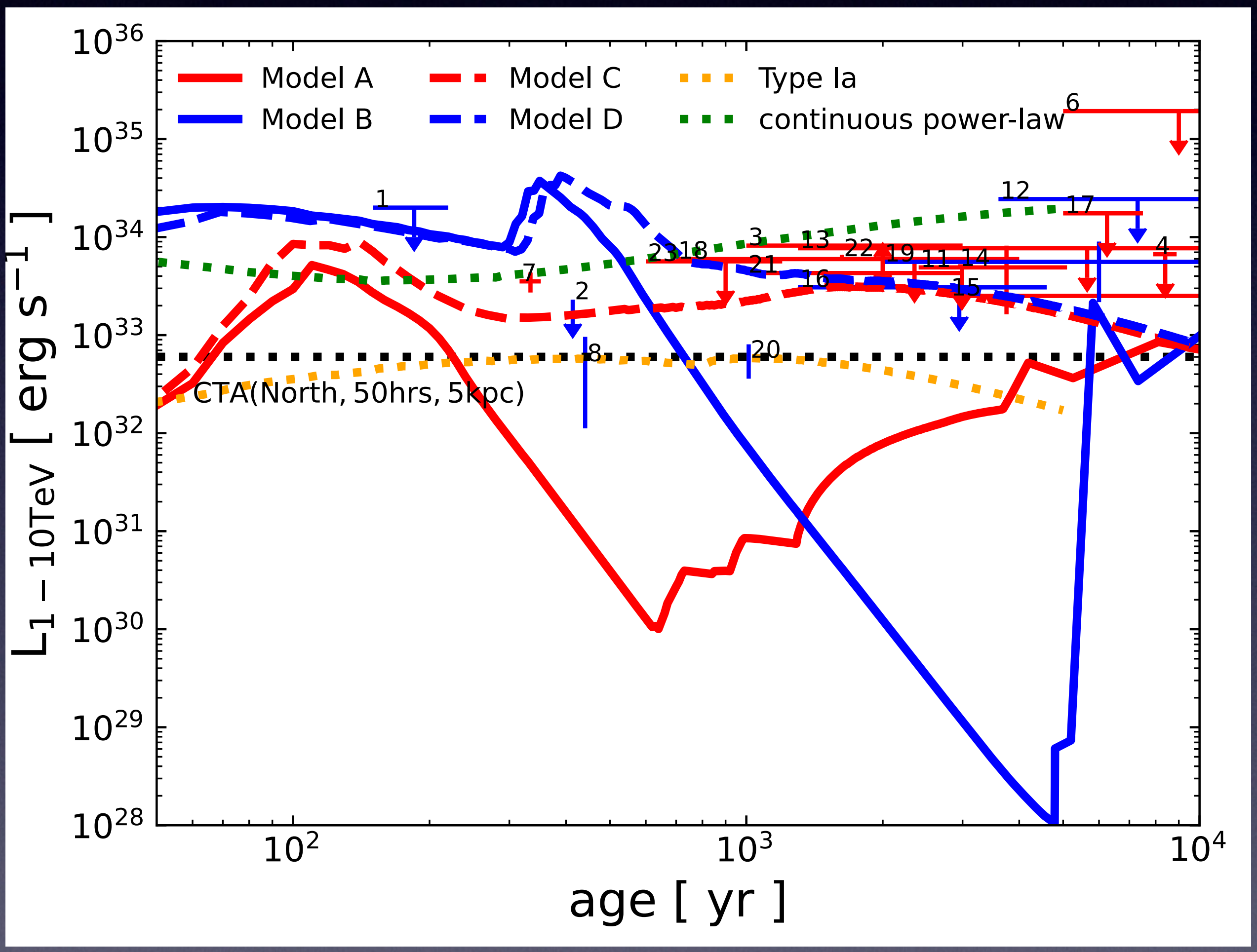
Does it explain why we got so few Type-II remnants in MW of a few 1000 yrs old?

Same thing for gamma-rays

GeV band



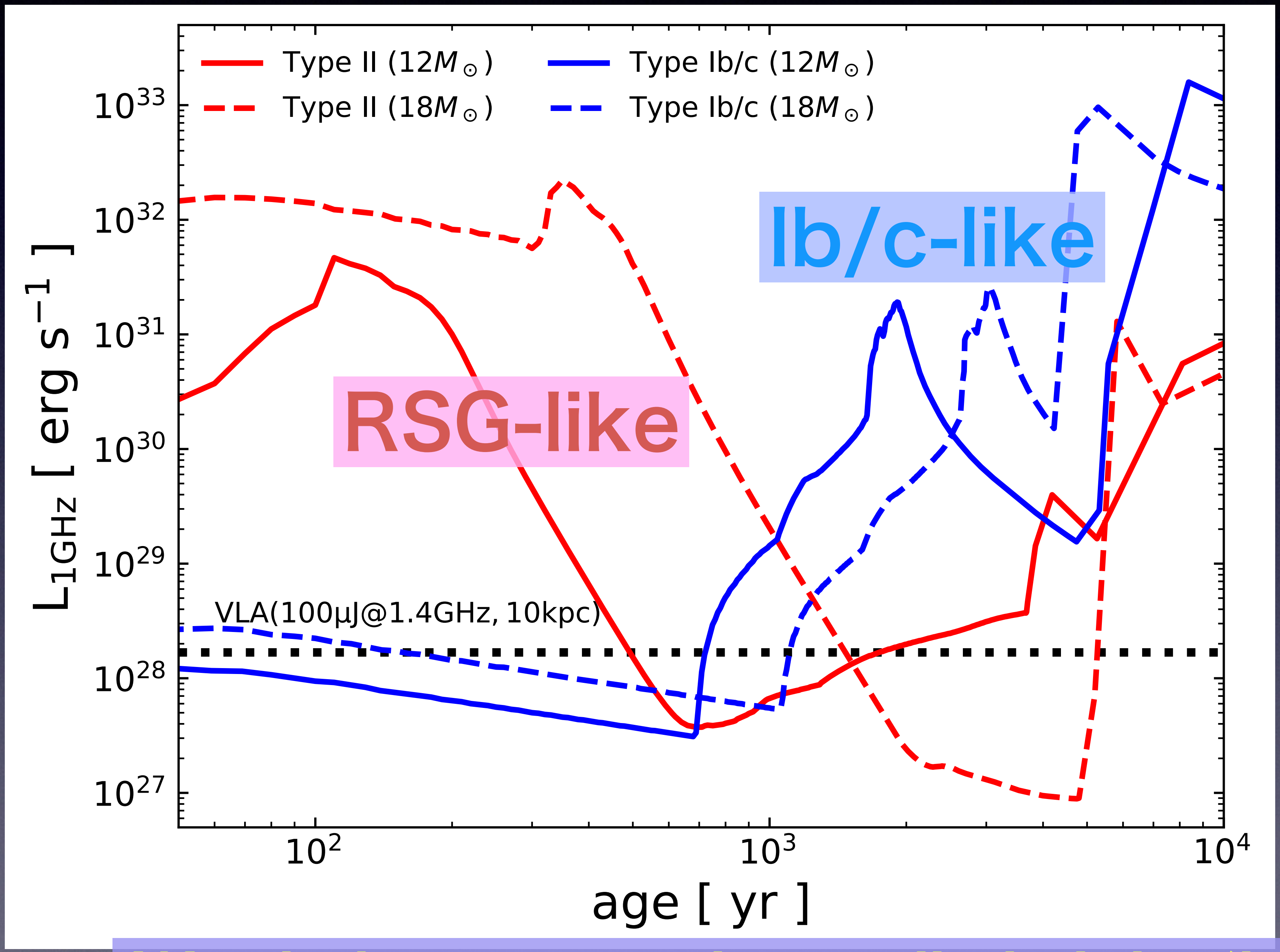
TeV band



Timing & span of dark age and light curve shape depend on detailed mass loss history (M_{ZAMS} etc…), but trend stays the same

How about the stripped folks?

1.4 GHz continuum radio light curve

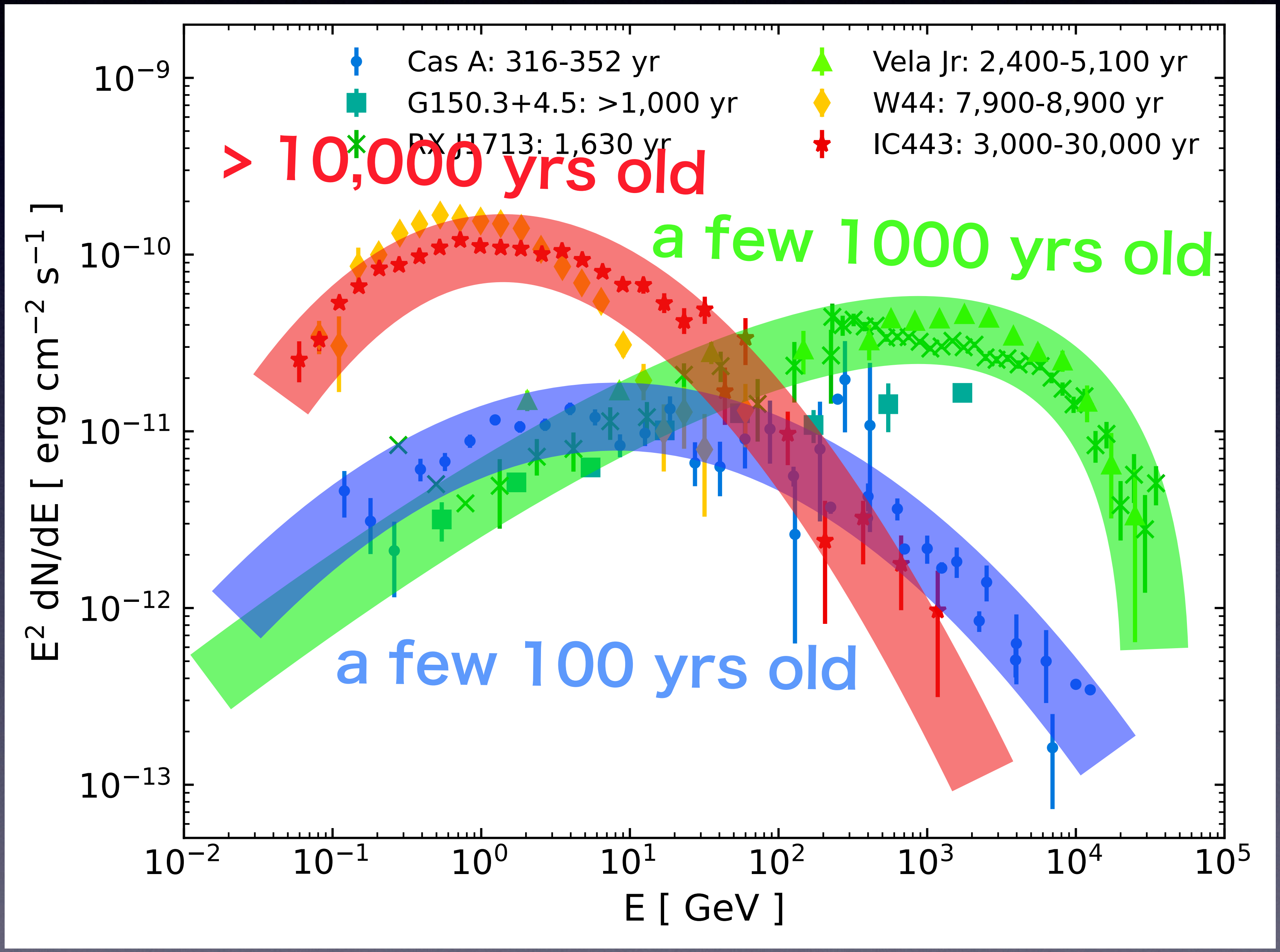


Explosion of stripped WR stars in binaries → shock propagates from thin WR wind to dense wind-blown shell

Evolution is **from faint to bright**, i.e., **exactly the opposite to Type-II SNRs**!

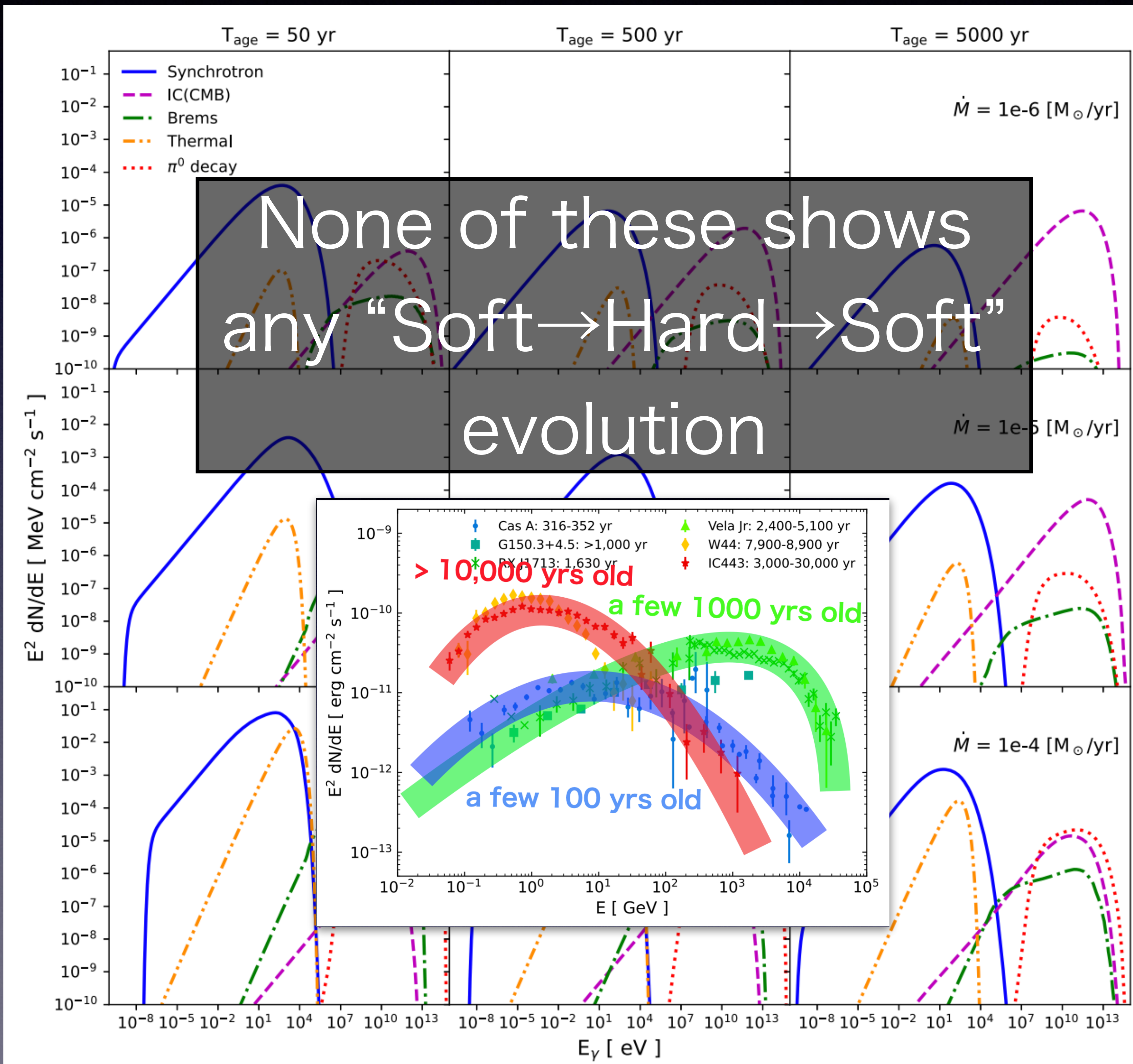
We do know non-thermally bright (but thermally faint) SNRs of a few 1000 yrs old!

Diversity of gamma-ray spectra in CC SNRs



Tempting to link with an age-sequence (spectral evolution) of CC SNRs

But we know any single time evolution model just doesn't work



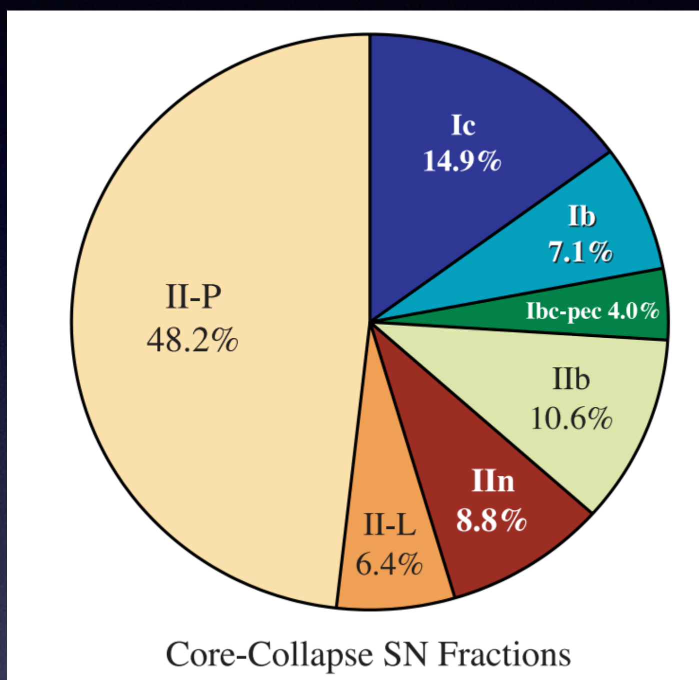
Examples of broadband non-thermal SED evolution models in a simple r^{-2} stellar wind

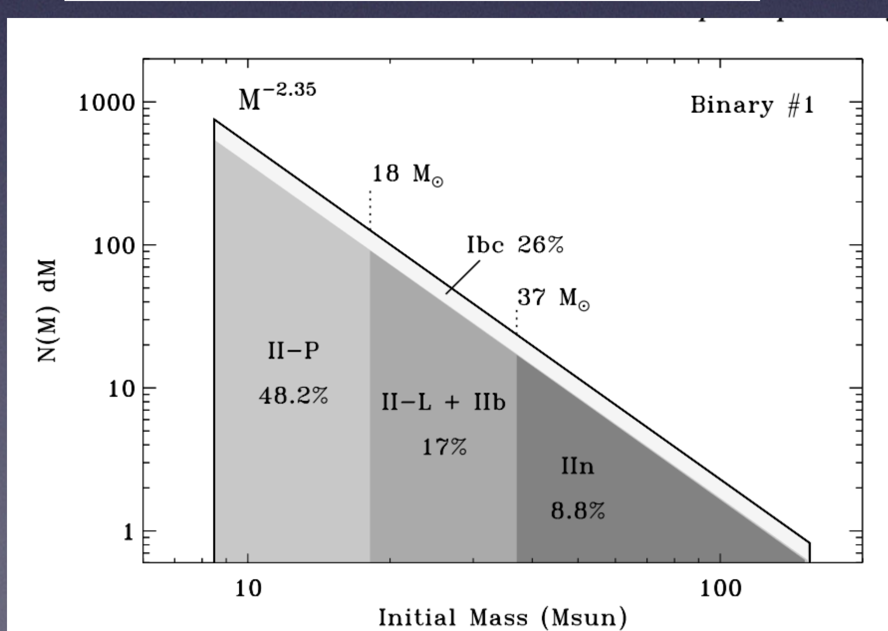
None of these can explain the observed spectral "evolution"

So maybe it is just NOT a spectral "evolution" at all!

Yasuda & HL, ApJ 876, 27 (2019)

Because… we should expect a mix of different things



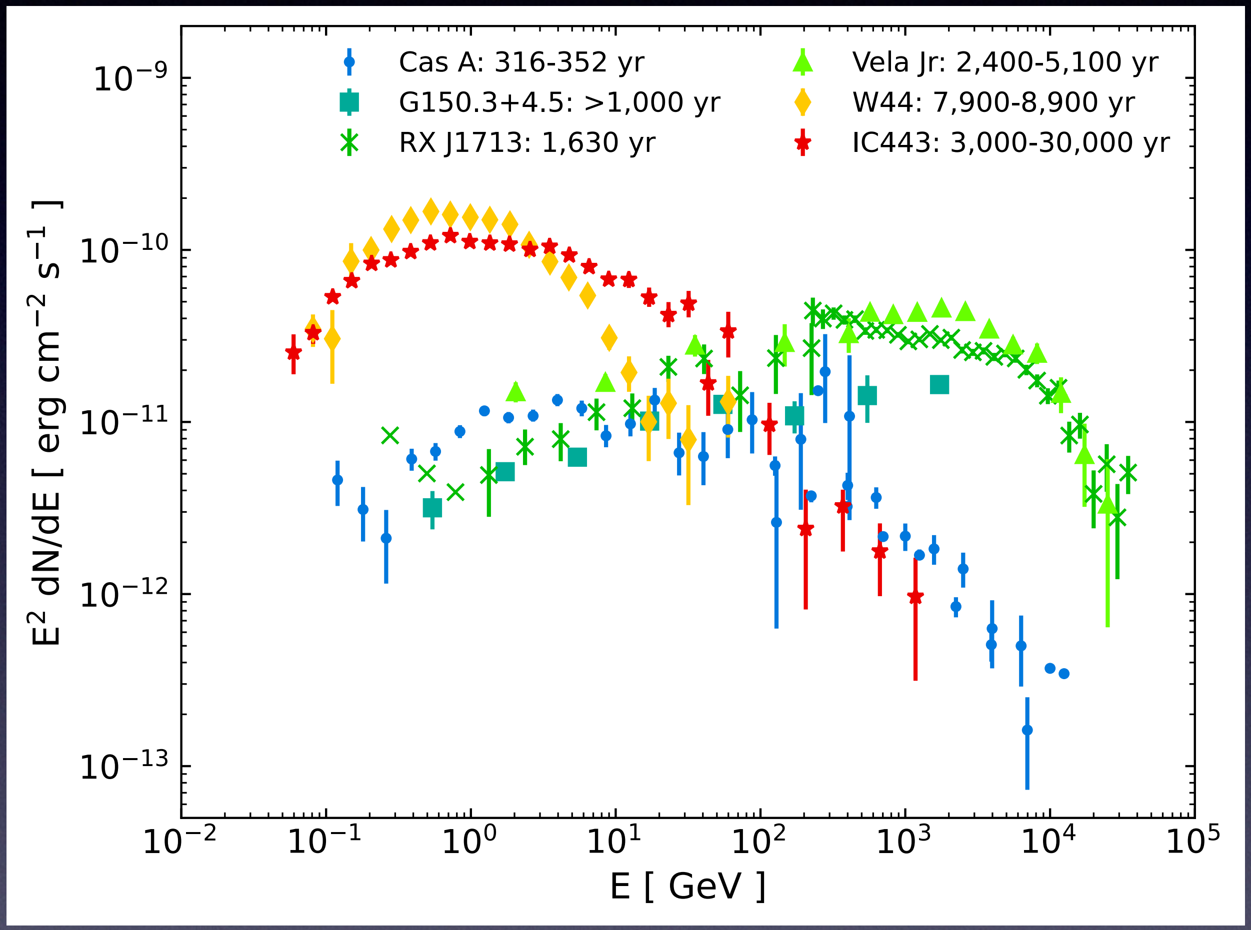


Nathan Smith+ (2011)

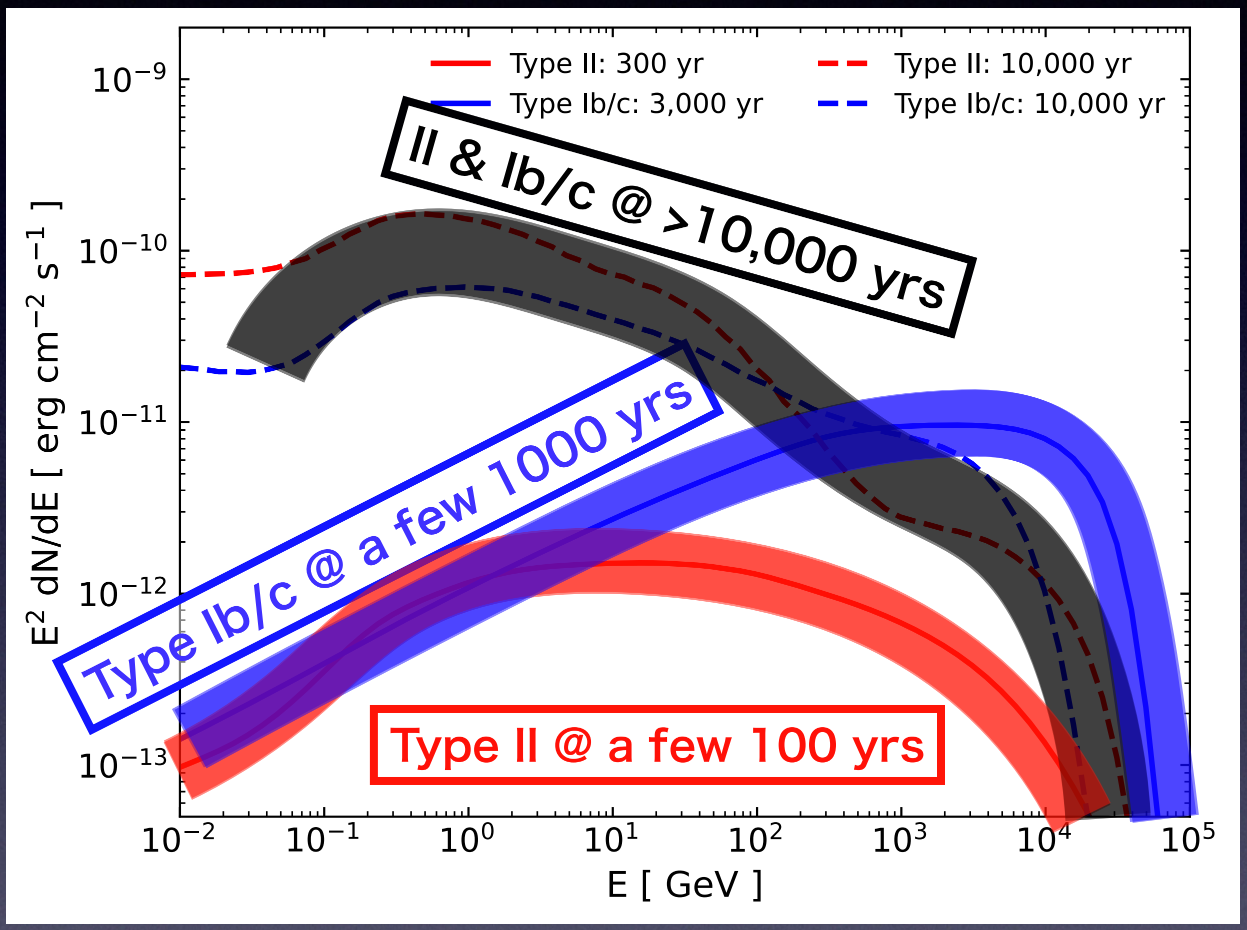
- We know SESNe compose a large (~1/3) fraction of CCSNe
- We should expect a mixed contribution of **both** RSG-like and stripped-envelope progenitors to the SNR population
- The observed spectral samples (in gamma-ray or not) should then reflect this mixed population as well!

A mixed model

Observations



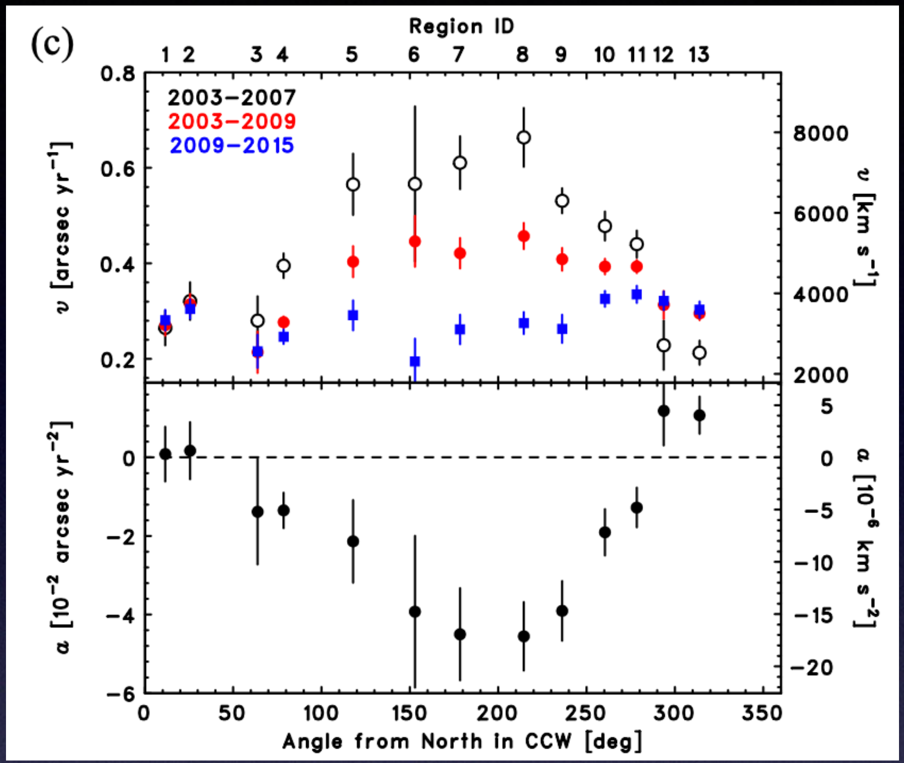
Our models



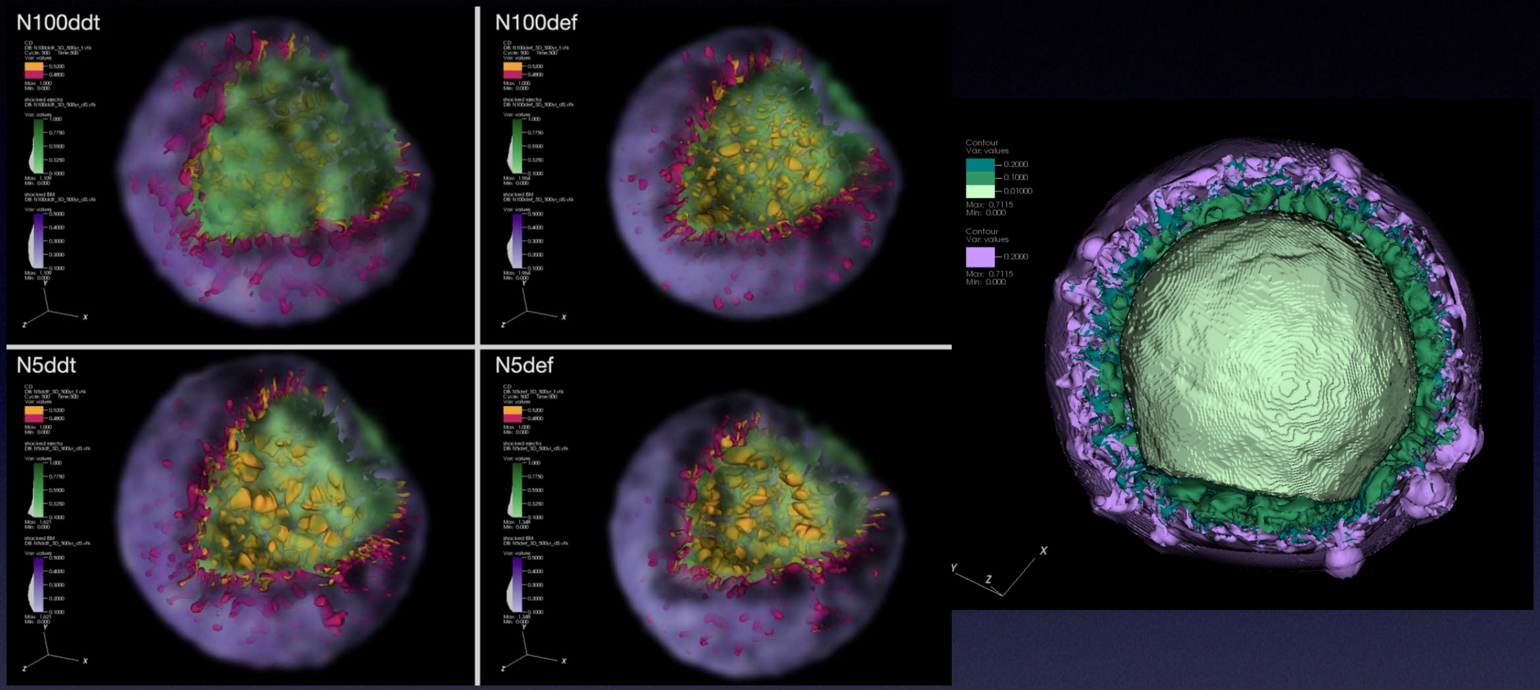
1) Type II's are bright at a few 100 yrs but darken after ~ 1,000 yrs
2) Type Ib/c's are faint at a few 100 yrs but re-brighten after ~ 1,000 yrs
3) Both types are bright at GeV after ~10,000 yrs

Qualitatively, we may be on the right track

How about Ia SNRs?



Taka Tanaka+ (poster S3.33)
Recent rapid deceleration of Tycho's shock



Gilles Ferrand (see his talk today)
3-D SNR models from various Ia progenitors

(also see **S2.7 by Travis Court** for 1-D models in wind cavities)

- Non-trivial CSM is not a trademark of only CCSNRs, **some Ia's are known to evolve in complex environments** like wind-blown cavities
- These CSM should also couple to the diversity of Ia progenitors, explosion channels and pre-SN activities, just like the CC remnants
- **Q: can we use non-thermal emission to constrain Ia progenitors?**

Things yet to do

- 3-D explosions in 3-D CSM
  - Mass loss and resulted CSM can be highly anisotropic especially in binaries, and explosions in such can be aspherical as well (see e.g., talk and **S2.18** by Salvo Orlando and **S5.18** by Dai Tateishi)
  - Shock-cloud interactions (see e.g. talk by Hidetoshi Sano)
  - In-prep: 3-D hydro models to quantify impact on the thermal and non-thermal emission
- Remnants from other CCSN subtypes / other galaxies
  - Will explore a broader parameter space for progenitor type and mass loss history to better sample the CCSNR population

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Appendix

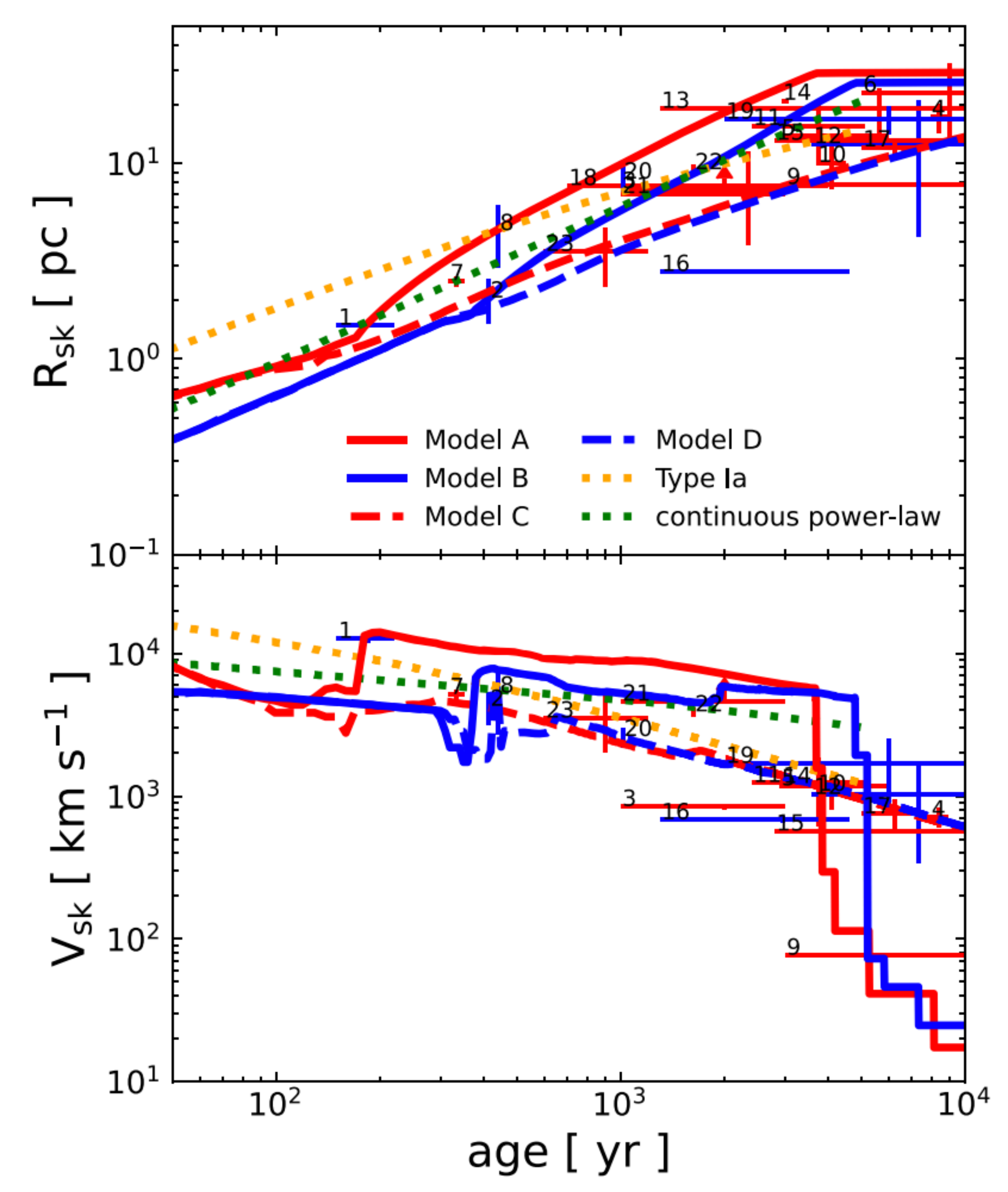
Mass loss episode - RSG-like

Table 1
Model Parameters

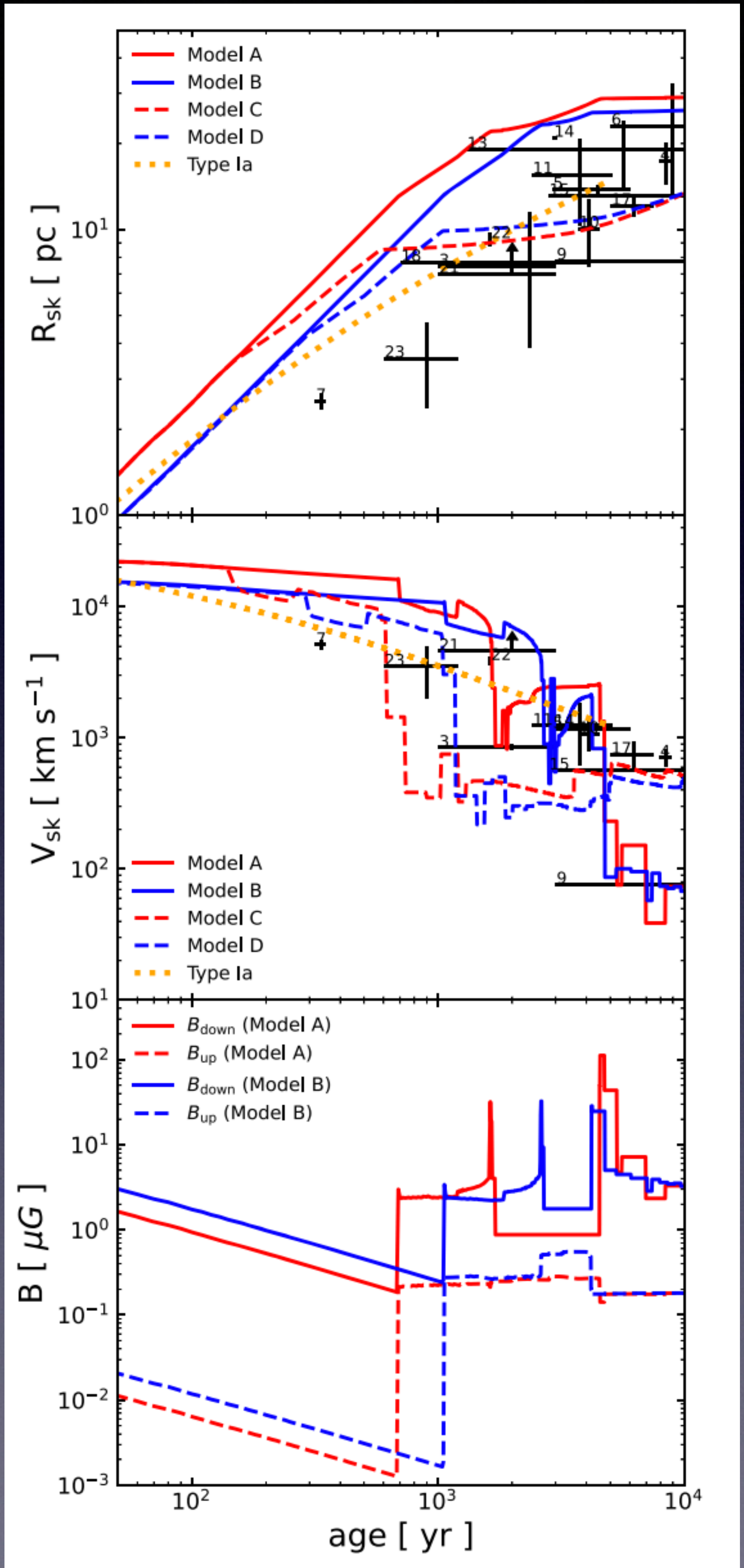
Model	$M_{\rm ZAMS}$ ($M_\odot$)	Wind Phases	$\dot{M}$ ($M_\odot$ yr^{-1})	$V_{\rm w}$ (km s^{-1})	$M_{\rm w}$ ($M_\odot$)	$\tau_{\rm phase}$ (yr)	$M_{\rm ej}$ ($M_\odot$)
A	12	MS	5.0×10^{-8}	2000	0.5	10^7	
		RSG	1.0×10^{-6}	10	0.5	5.0×10^5	9.5
B	18	MS	6.0×10^{-8}	2000	0.3	5.0×10^6	
		RSG	1.0×10^{-5}	10	2.7	2.7×10^5	13.5
C	12	RSG	1.0×10^{-6}	10	1.0	10^6	9.5
D	18	RSG	1.0×10^{-5}	10	3.0	3.0×10^5	13.5

Yasuda, HL & Maeda (2021)

Dynamics - RSG-like



Dynamics - Ib/c-like



Mass loss episode - Ib/c-like

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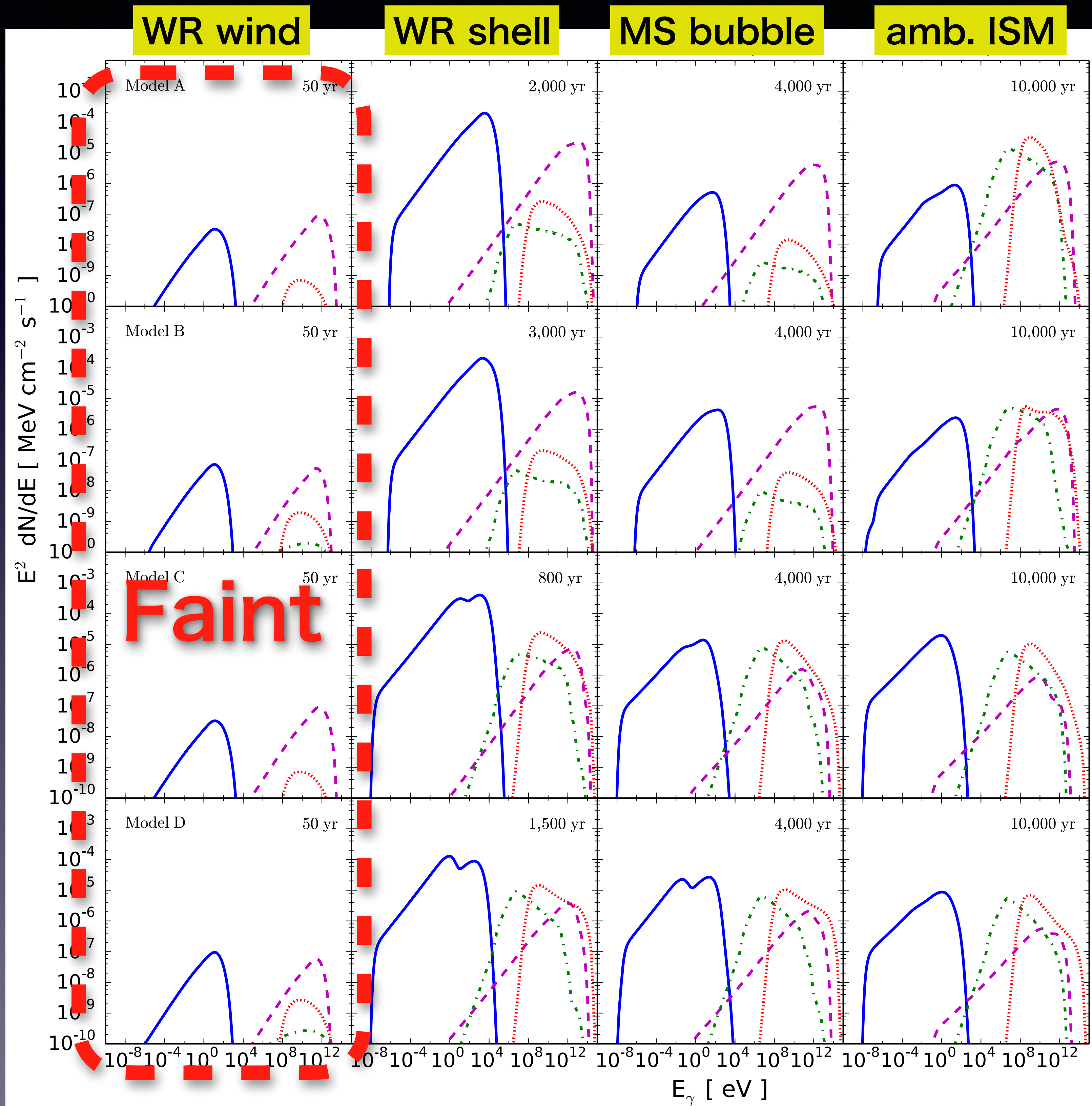
A	12	MS	5.0×10^{-8}	2000	0.5	1.0×10^{7}	
		RLOF	8.5×10^{-4}	10	8.5	1.0×10^{4}	
		W-R	5.0×10^{-6}	2000	0.5	1.0×10^{5}	1.0
B	18	MS	6.0×10^{-8}	2000	0.3	5.0×10^{6}	
		RLOF	1.27×10^{-3}	10	12.7	1.0×10^{4}	
		W-R	1.0×10^{-5}	2000	1.0	1.0×10^{5}	2.5
C	12	RLOF	9.0×10^{-4}	10	9.0	1.0×10^{4}	
		W-R	5.0×10^{-6}	2000	0.5	1.0×10^{5}	1.0
D	18	RLOF	1.3×10^{-3}	10	13.0	1.0×10^{4}	
		W-R	1.0×10^{-5}	2000	1.0	1.0×10^{5}	2.5

Note. Wind parameters and ejecta properties for a Type Ib/c SNR. The wind temperature is set to $T = 10^4$ K, SN explosion energy $E_{\rm SN} = 1.2 \times 10^{51}$ erg, power-law index of the ejecta envelope $n_{\rm ej} = 10$, and stellar remnant mass $M_{\rm rm} = 1.5\ M_\odot$ (Woosley et al. 2020) in all models. We also assume $n = 1.0$ cm^{-3} and $T = 10^4$ K for the outer ISM region.

Yasuda, HL & Maeda (2022)

SED evolution for Type-Ib/c



<u>Demo 2</u>

Case of Type-Ib/c explosion of a stripped WR star

Fast WR wind creates a low-density cavity enclosed by a termination shock and dense shell

RLOF outflow and MS bubble are compressed by WR wind pressure

Hot WR shell and MS bubble are small enough to reduce weakening of shock

pi0 vs ICS (Ib/c case)