X-Ray and Gamma-Ray Emission from CCSNe

Comparison of 3D Neutrino-driven Explosions With SN 1987A

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Origin of the emission

- During the first few hundred days after the explosion, SNe emit X-rays and gamma-rays.
- The emission originates from the radioactive decay, primarily from the ^{56}Ni → ^{56}Co → ^{56}Fe chain.
- We use self-consistent 3D neutrino-driven SN explosion models (Table 1) to compute this high-energy emission (Fig. 1).
- Comparisons with observations of SN 1987A constrain the progenitors and explosion simulations.

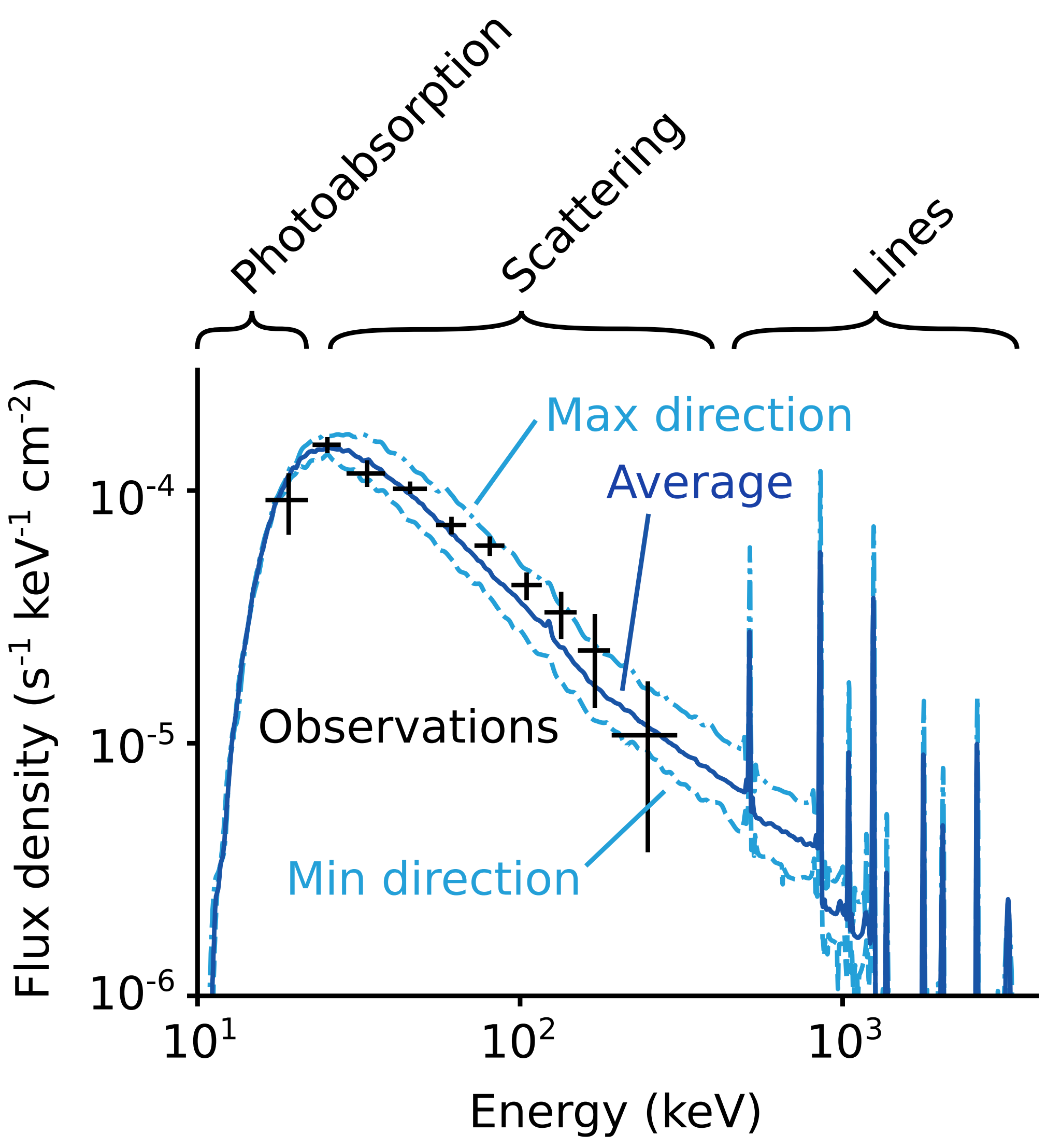

Fig. 1 B15 spectra at 300 days

General high-energy properties of CCSNe

- The observed emission is viewing-angle dependent because of the 3D ejecta asymmetries (Fig. 3). Typical flux level variations are a factor of a few.
- The spectra are characterized by a low-energy photoabsorption cutoff, a Compton scattering continuum, and direct radioactive line emission (Fig. 1).
- The progenitor envelope metallicity determines the low-energy cutoff (Fig. 4).
- The differences among H-rich progenitors are primarily driven by the varying level of mixing of ^{56}Ni.
- Stripped-envelope SNe evolve faster and are more luminous.

Early hard X-ray emission constrains progenitor models

Why are we not observing the high-energy emission?

- We find that *NuSTAR* should be able to detect (non-)stripped SNe out to distances of (3)10 Mpc (Fig. 5).
- This implies that a CCSN should be detectable by *NuSTAR* every three years and that the most likely candidates are stripped-envelope SNe.
- *INTEGRAL* is expected to detect the 847 keV ^{56}Co line out to (0.2)2 Mpc.

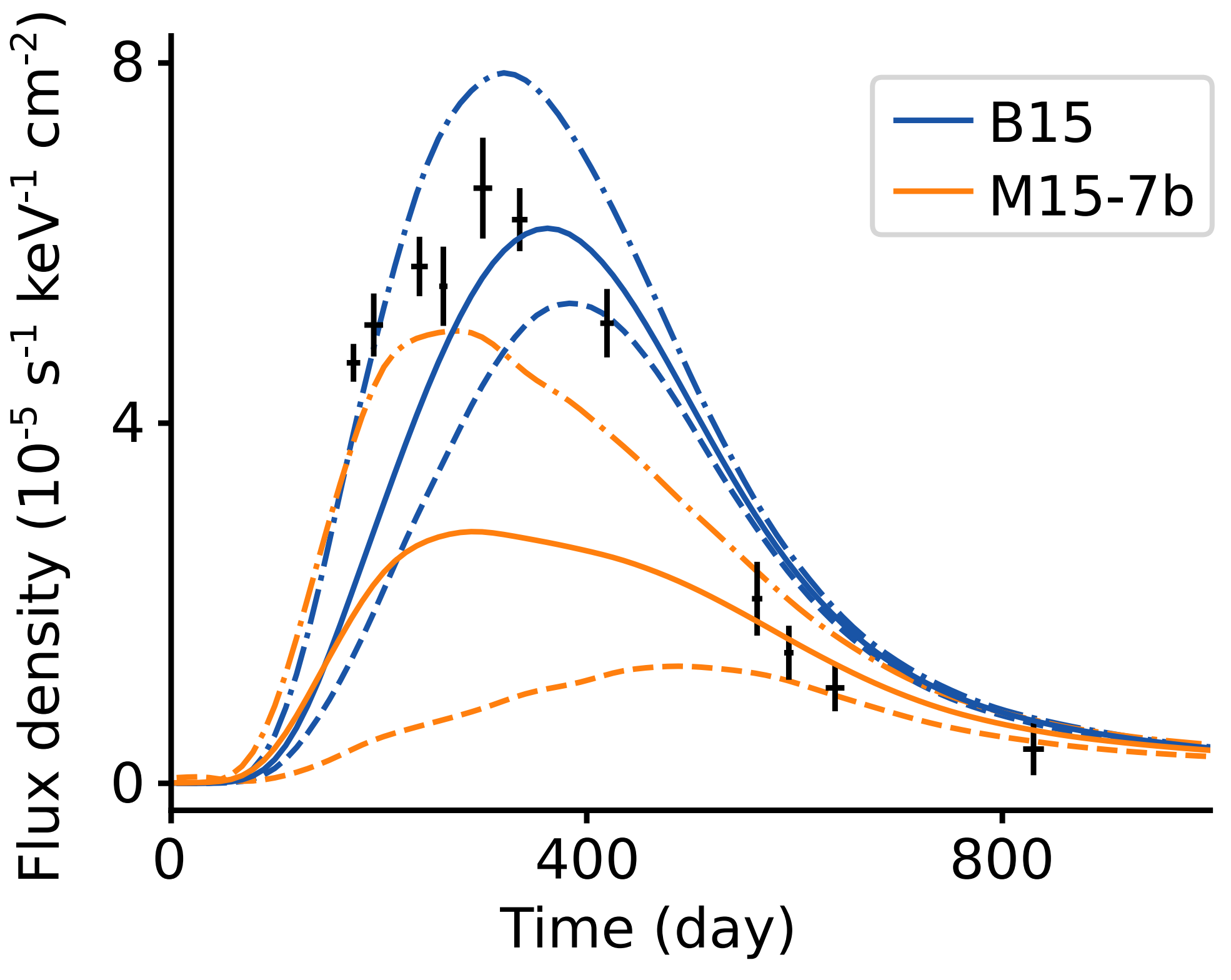

Fig. 2 45-105 keV continuum light curves

Constraints from SN 1987A

- B15 is a single-star blue supergiant and M15-7b is the result of a binary merger (Fig. 2).
- Only B15 and M15-7b, out of eight SN 1987A models, are capable of reproducing the most relevant observational high-energy properties (Fig. 6).
- Our self-consistent models suggest that neutrino-driven explosions are able to produce, in principle, sufficient mixing.
- The remaining discrepancies for B15 and M15-7b can be remedied by minor changes to the explosion dynamics.
- These discrepancies are not problems of neutrino-driven explosions, but provide insight to refine the progenitor models.

Name	Type	Mass ($M_\odot$)	Energy (10^{51} erg)
B15	BSG	14.2	1.43
N20	BSG	14.3	1.72
L15	RSG	13.7	1.71
W15	RSG	14.0	1.45
IIb	He core	3.7	1.52
M15–7b	Merger	19.5	1.43
M16–7b	Merger	20.5	1.41

Table 1 Basic properties of the models. Four additional merger models are not shown. They have similar basic characteristics as the two mergers that are shown.

References for the models
Menon, A., & Heger, A. 2017, MNRAS, 469, 4649
Wongwathanarat, A., Janka, H.-Th., & Müller, E. 2013, A&A, 552, A126
Wongwathanarat, A., Müller, E., & Janka, H.-Th. 2015, A&A, 577, A48

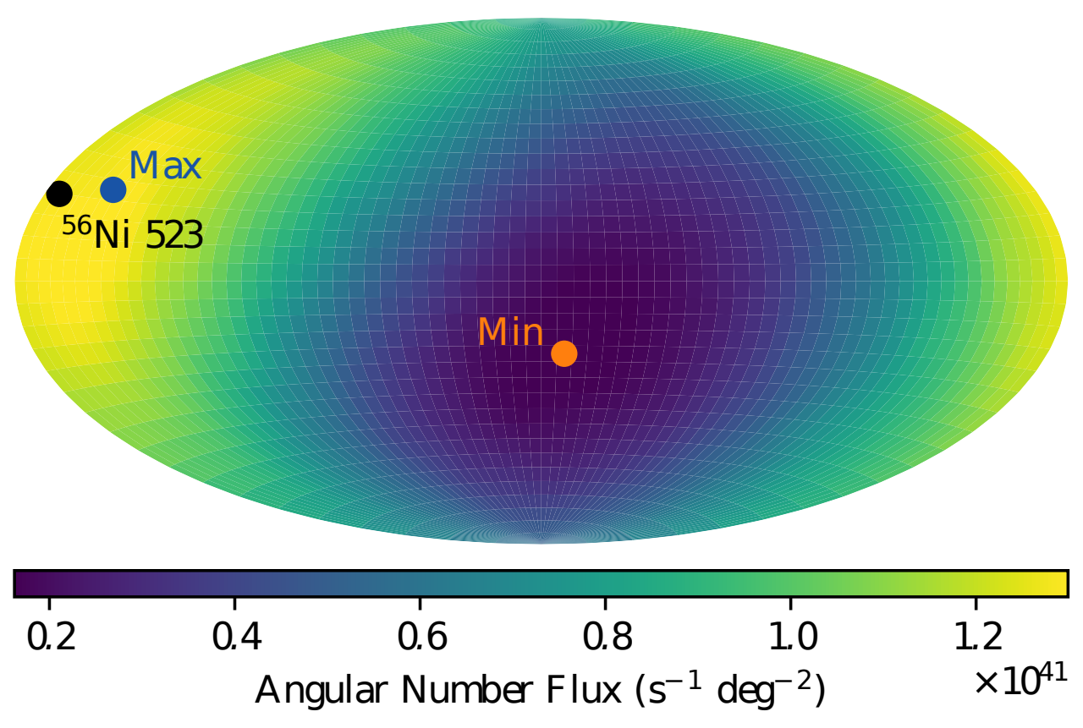

Fig. 3 Spherical equal-area Hammer projection of the escaping photons for the M15-7b model at 300 d. The points show the direction of the ^{56}Ni center of mass (black), minimum flux (orange), and maximum flux (blue). The number for the ^{56}Ni center of mass is the radial velocity in units of km s^{-1}.

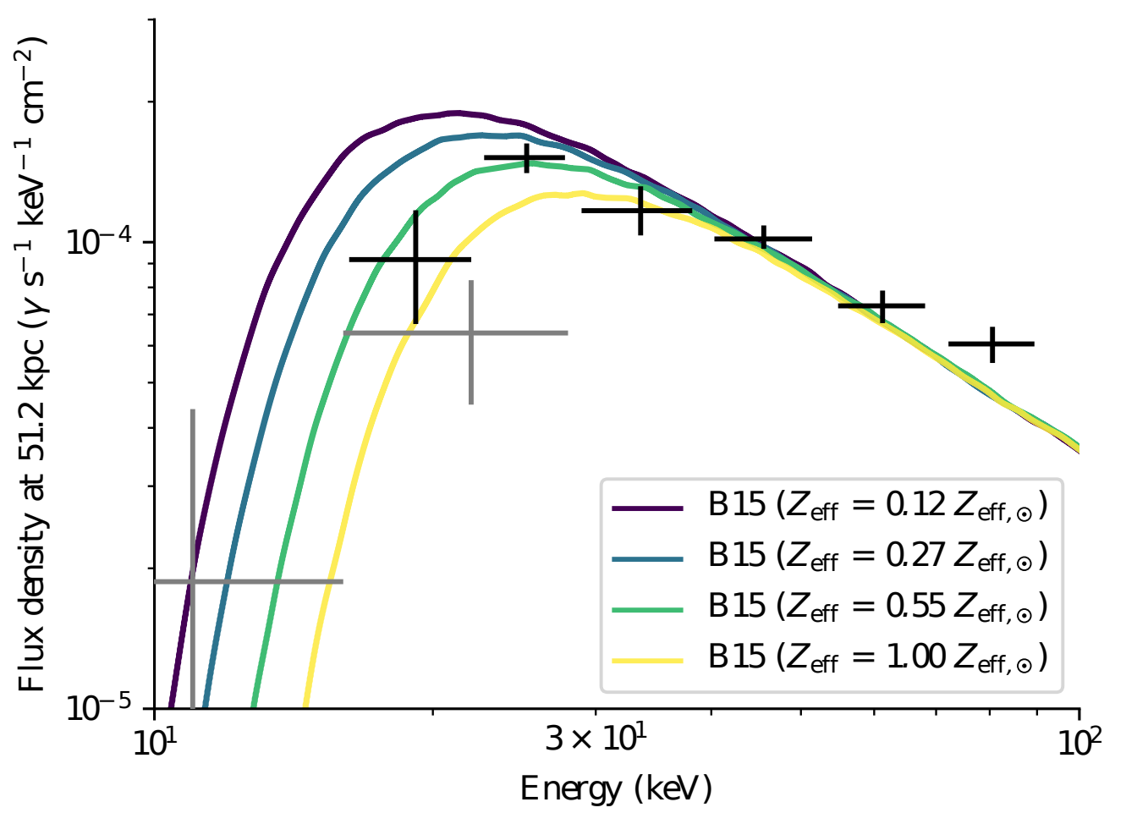

Fig. 4 Spectra at 300 d for the B15 model at four different metallicities. This shows how increasing metallicity (primarily Fe abundance) of the progenitor envelope affects the low-energy photoabsorption cutoff. The 0.55 $Z_{\rm eff,\odot}$ line is for LMC abundances. Overplotted are the observed HEXE spectrum at 320 d (black crosses), and the *Ginga* bands at 300 d (gray crosses).

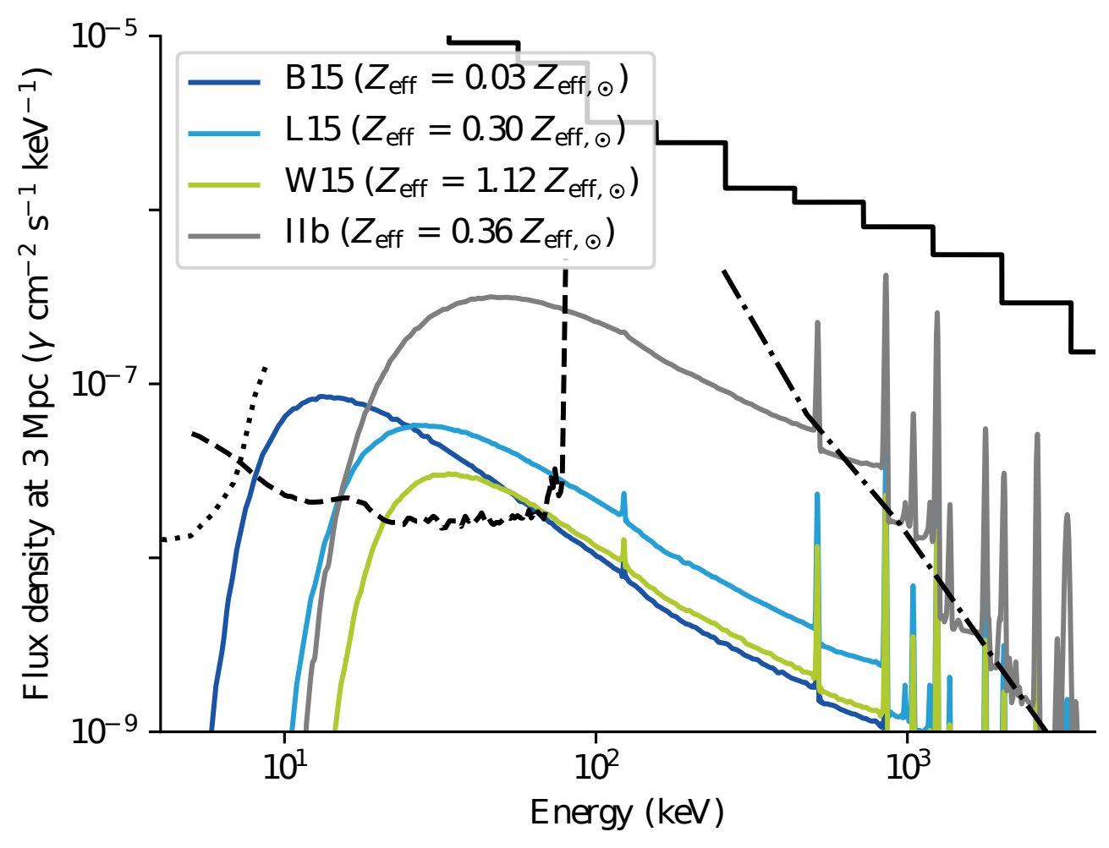

Fig. 5 Predicted continua scaled to 3 Mpc and the detection sensitivities of *Chandra* (dotted black line), *NuSTAR* (dashed black line), *INTEGRAL* (solid black line), and *e-ASTROGAM* (dash-dotted black line). The spectra are at a time of 300 d for the non-stripped models and 100 d for the IIb model. Sensitivities are given for spectral bins of $\Delta E/E = 0.5$, a detection threshold of 3σ, and an exposure time of 1 Ms.

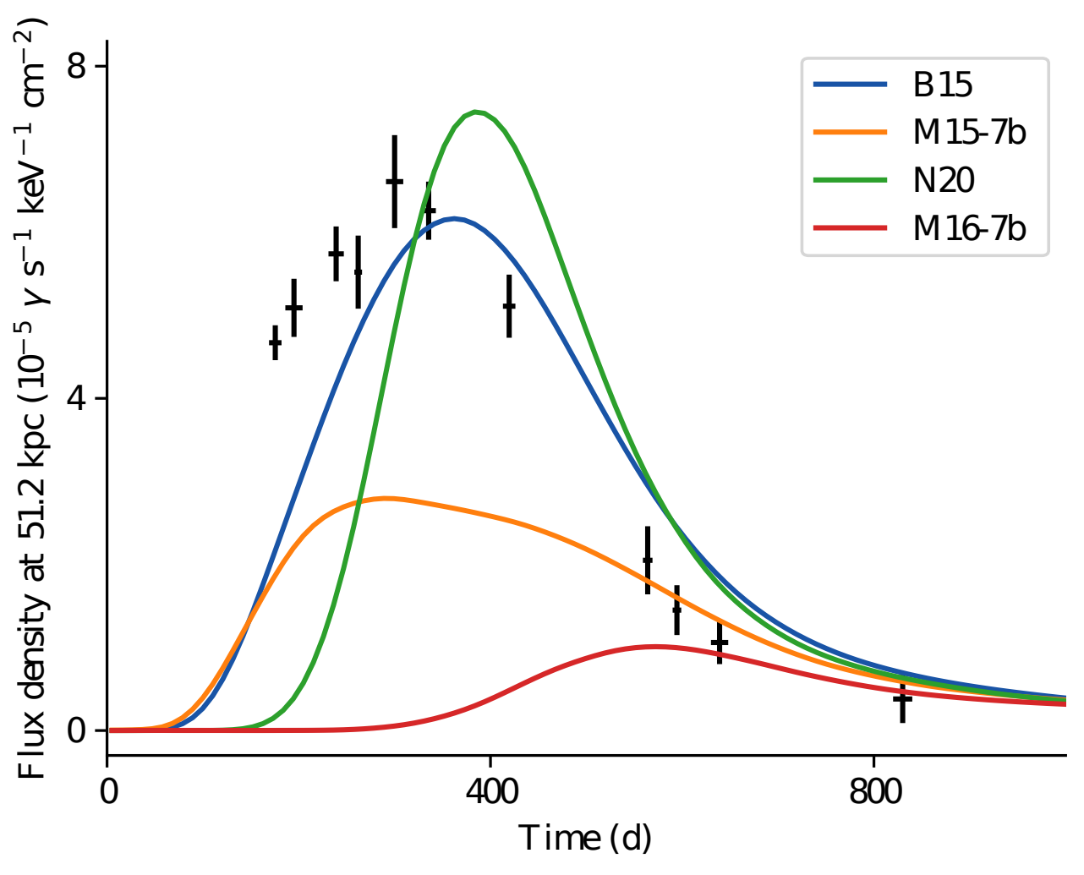

Fig. 6 Direction-averaged 45–105 keV light curves from all SN 1987A models, and HEXE SN 1987A observations (black crosses). Four additional merger models are not shown. Their properties are between those of M15-7b and M16-7b.