HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

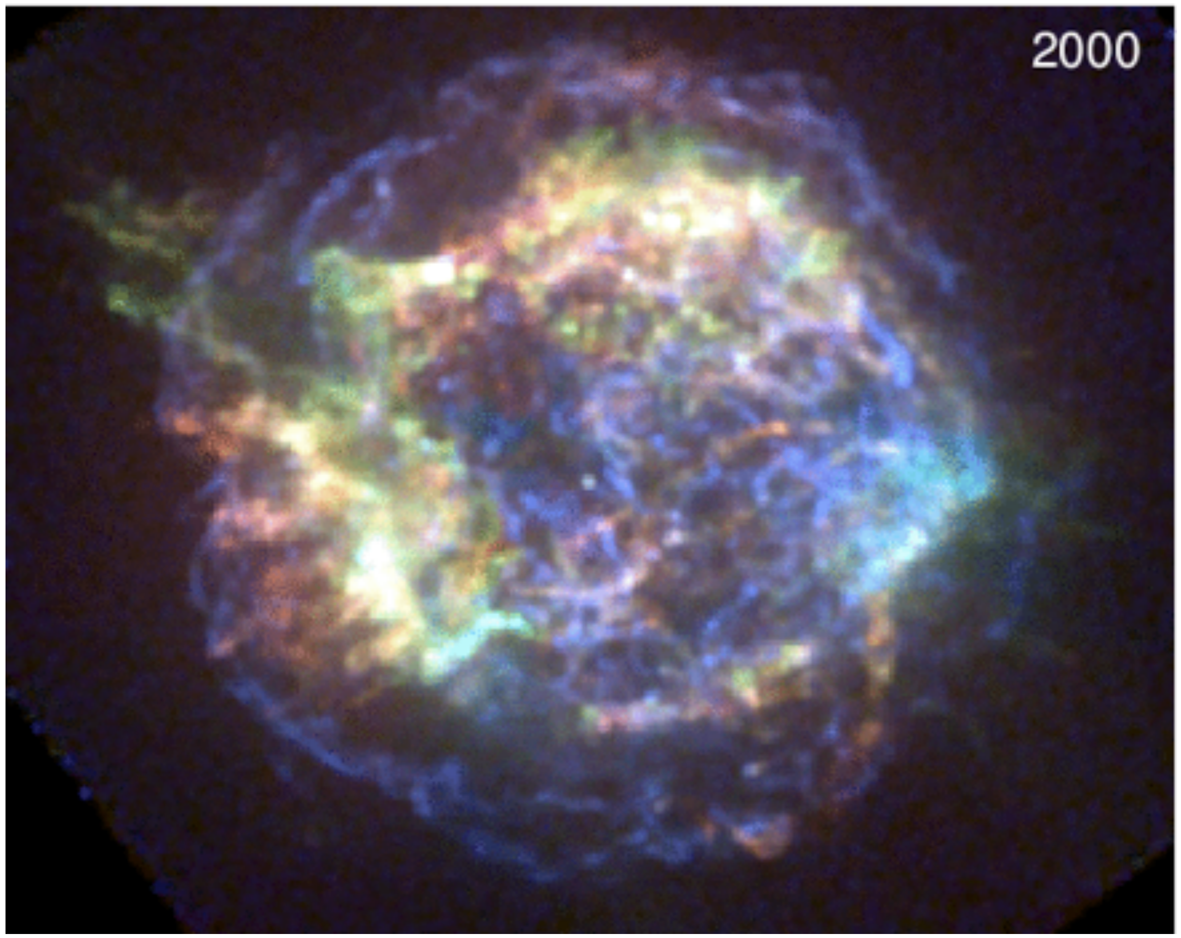
X-RAY STUDIES OF SNRS AS PROBES OF THEIR PROGENITORS

DAN PATNAUDE
(SMITHSONIAN ASTROPHYSICAL OBSERVATORY)

C. Badenes (Pitt)
H. Lee (ISAS/JAXA)
P. Slane (SAO)
D. Ellison (NCSU)
A. Heger (Monash)
R. Fesen (Dartmouth)
S. Park (UT-Arlington)
D. Milisavljevic (SAO)

Smithsonian Astrophysical Observatory

THE GOAL:

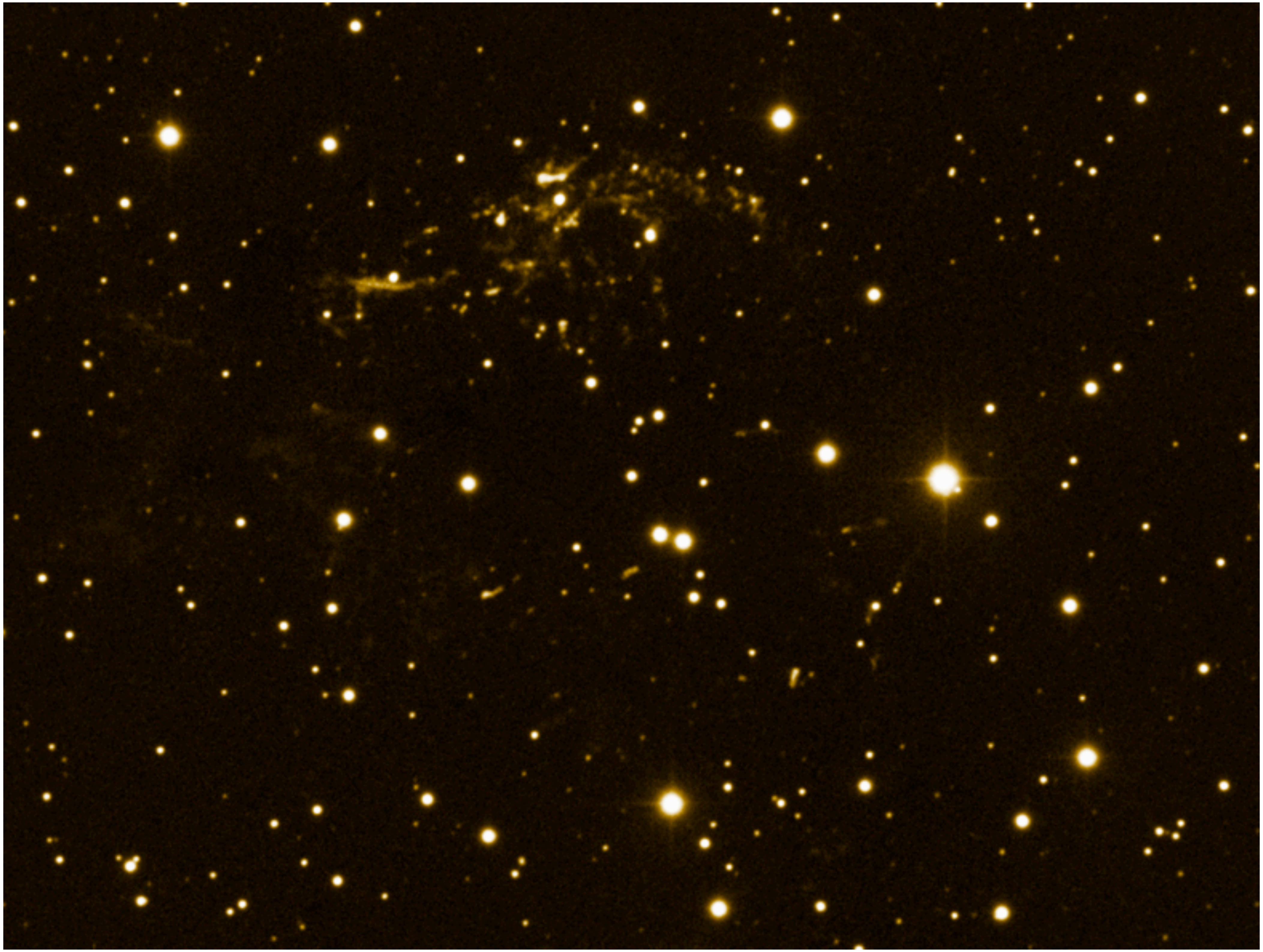


RGB movie of Cas A from 2000-2012 (Patnaude et al.)

Artist's conception of a massive star cluster

Connect a supernova remnant to some sort of progenitor

Cas A: 1951 - 2014



Derived from Patnaude & Fesen (2014)

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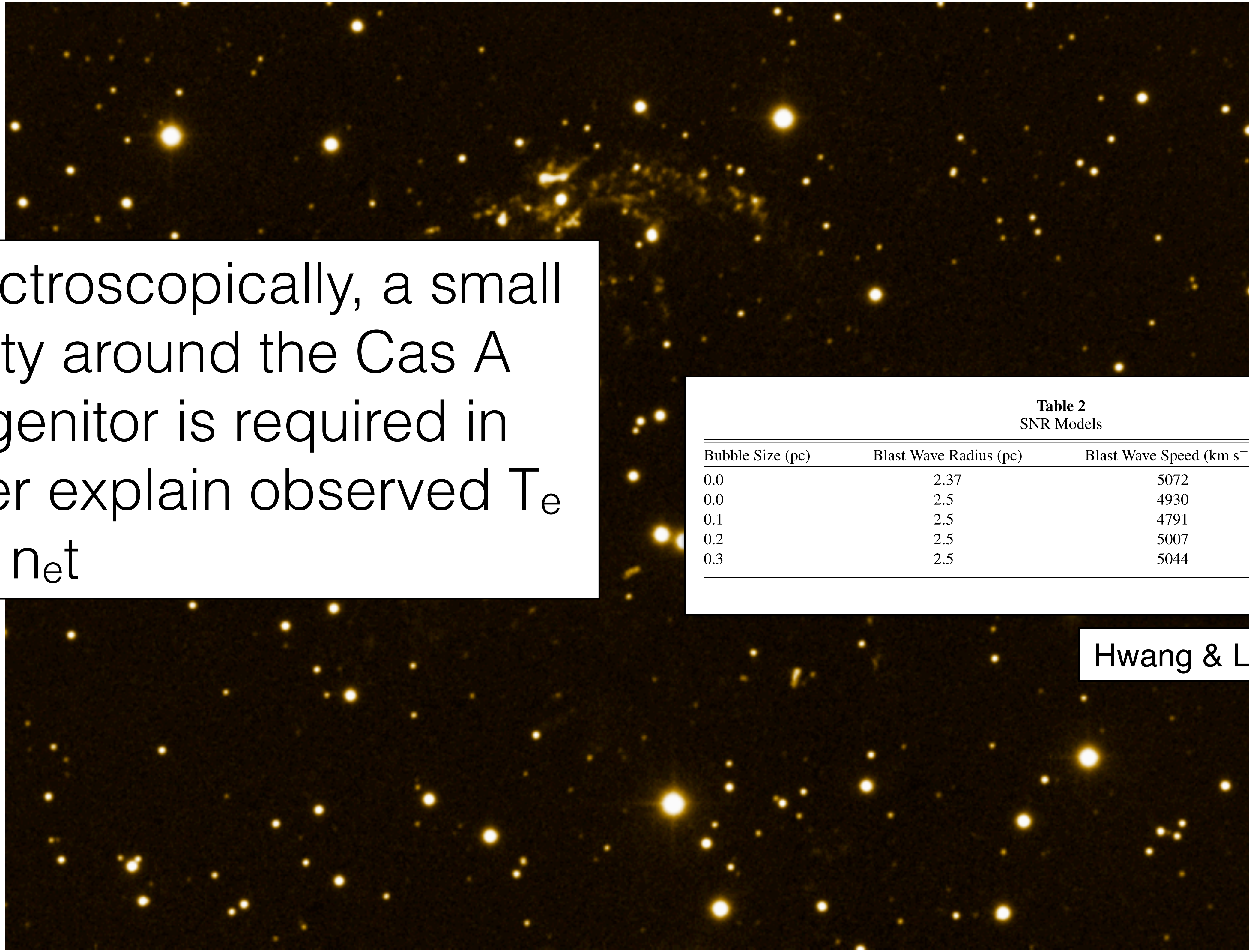


Spectroscopically, a small cavity around the Cas A progenitor is required in order explain observed T_e and $n_e t$

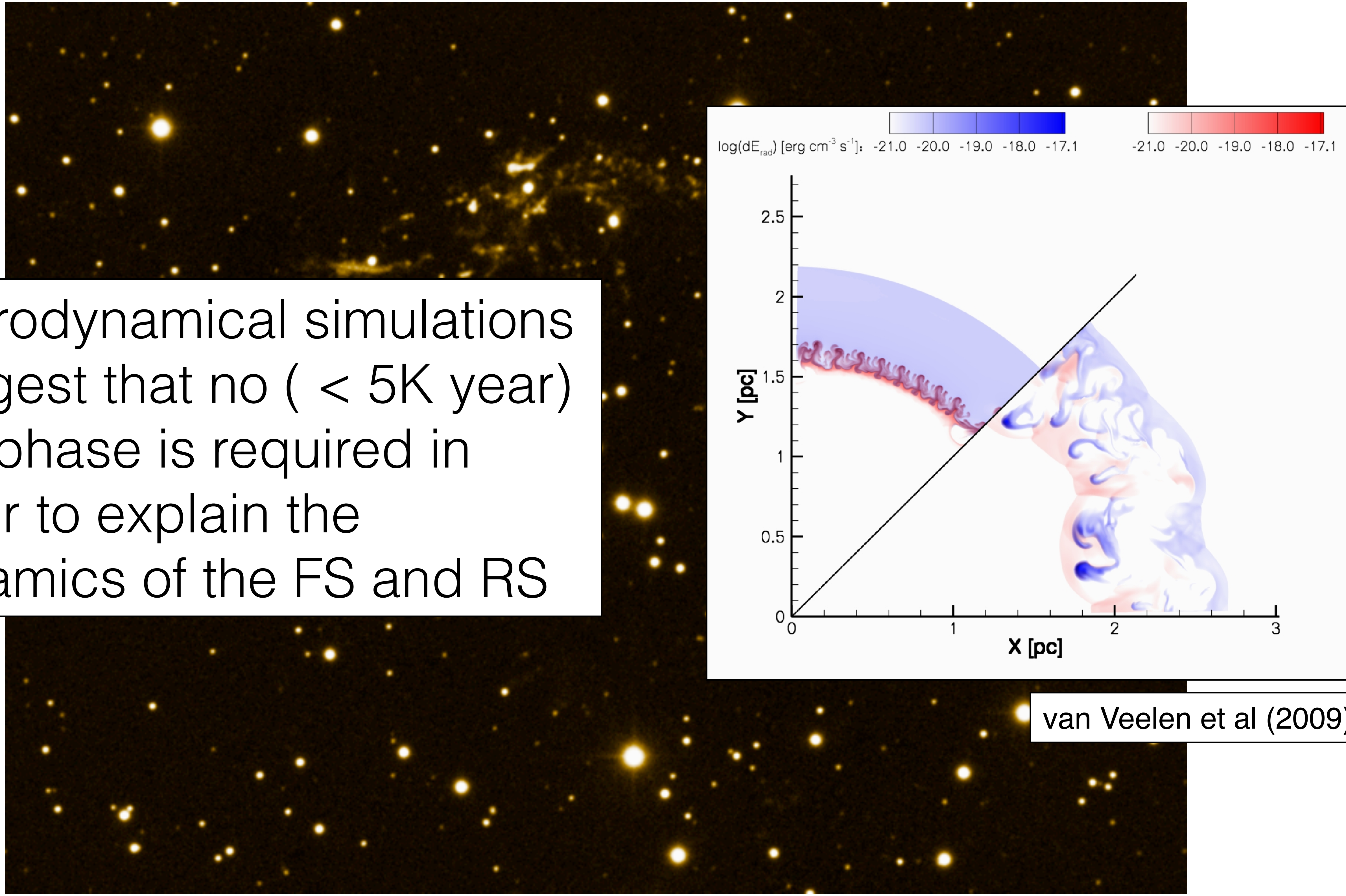
Table 2
SNR Models

Bubble Size (pc)	Blast Wave Radius (pc)	Blast Wave Speed (km s^{-1})	SNR Age (yrs)
0.0	2.37	5072	325
0.0	2.5	4930	350
0.1	2.5	4791	339
0.2	2.5	5007	331
0.3	2.5	5044	324

Hwang & Laming (2009)

Derived from Patnaude & Fesen (2014)

Cas A: 1951 - 2014

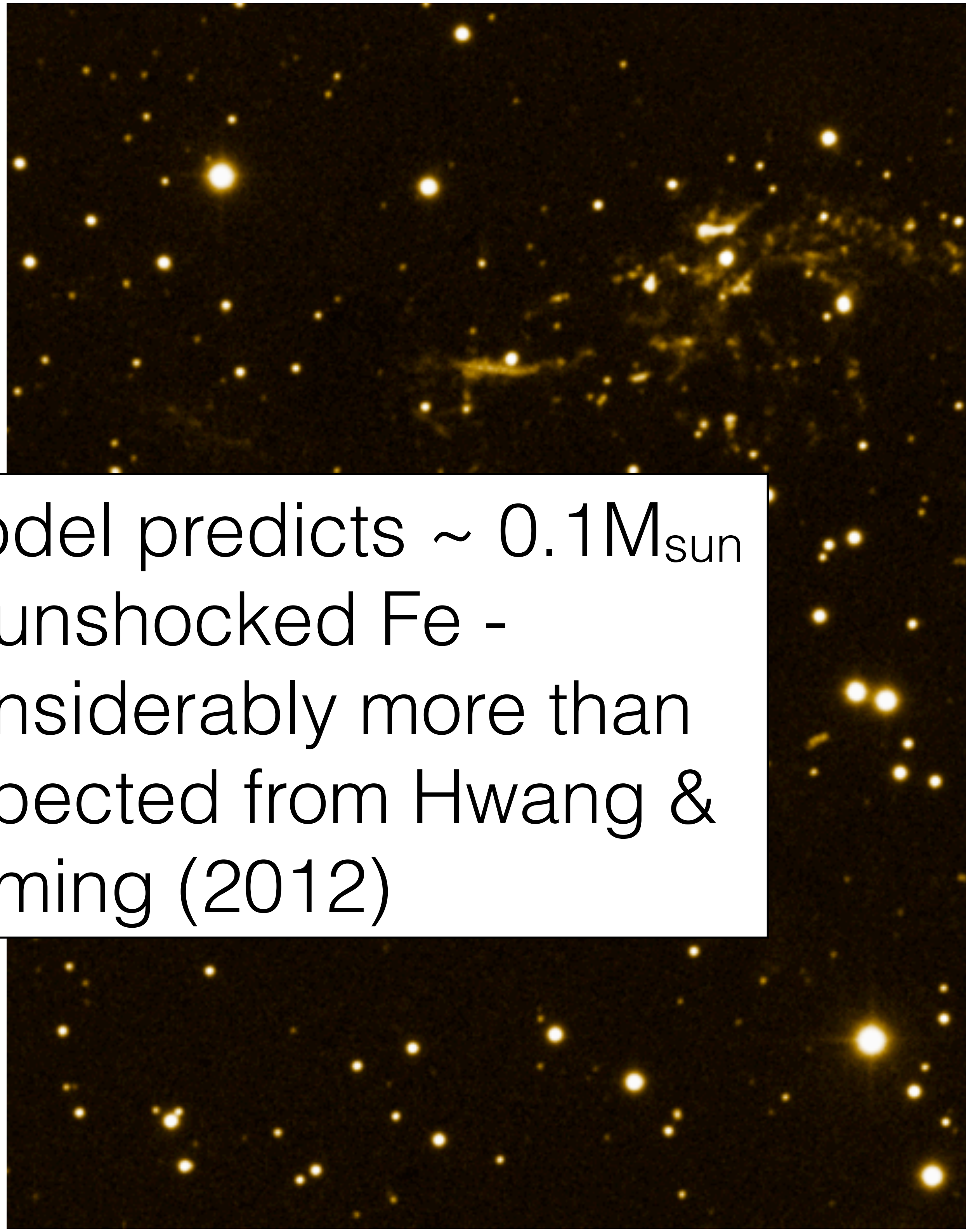


Hydrodynamical simulations suggest that no (< 5K year) WR phase is required in order to explain the dynamics of the FS and RS

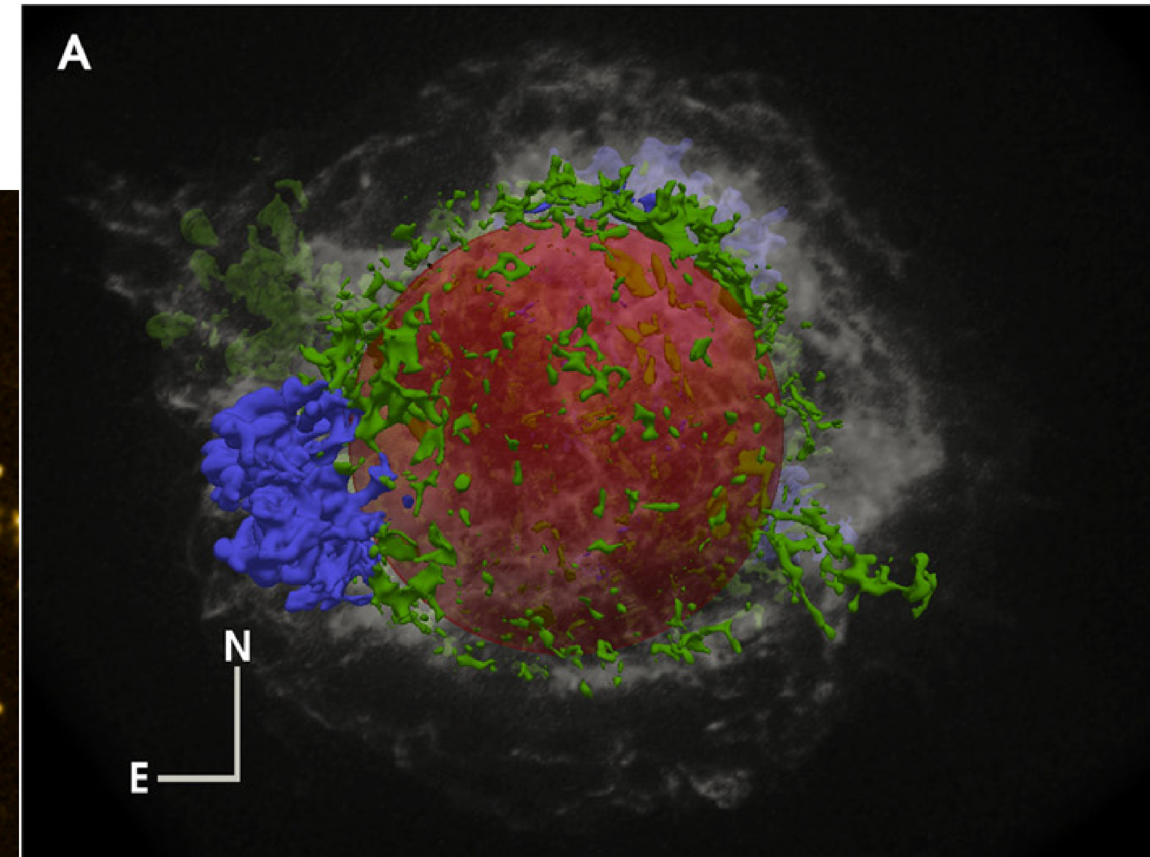
van Veelen et al (2009)

Derived from Patnaude & Fesen (2014)

Cas A: 1951 - 2014



Model predicts ~ 0.1M_{sun} of unshocked Fe - considerably more than expected from Hwang & Laming (2012)



Orlando et al (2016)

Derived from Patnaude & Fesen (2014)

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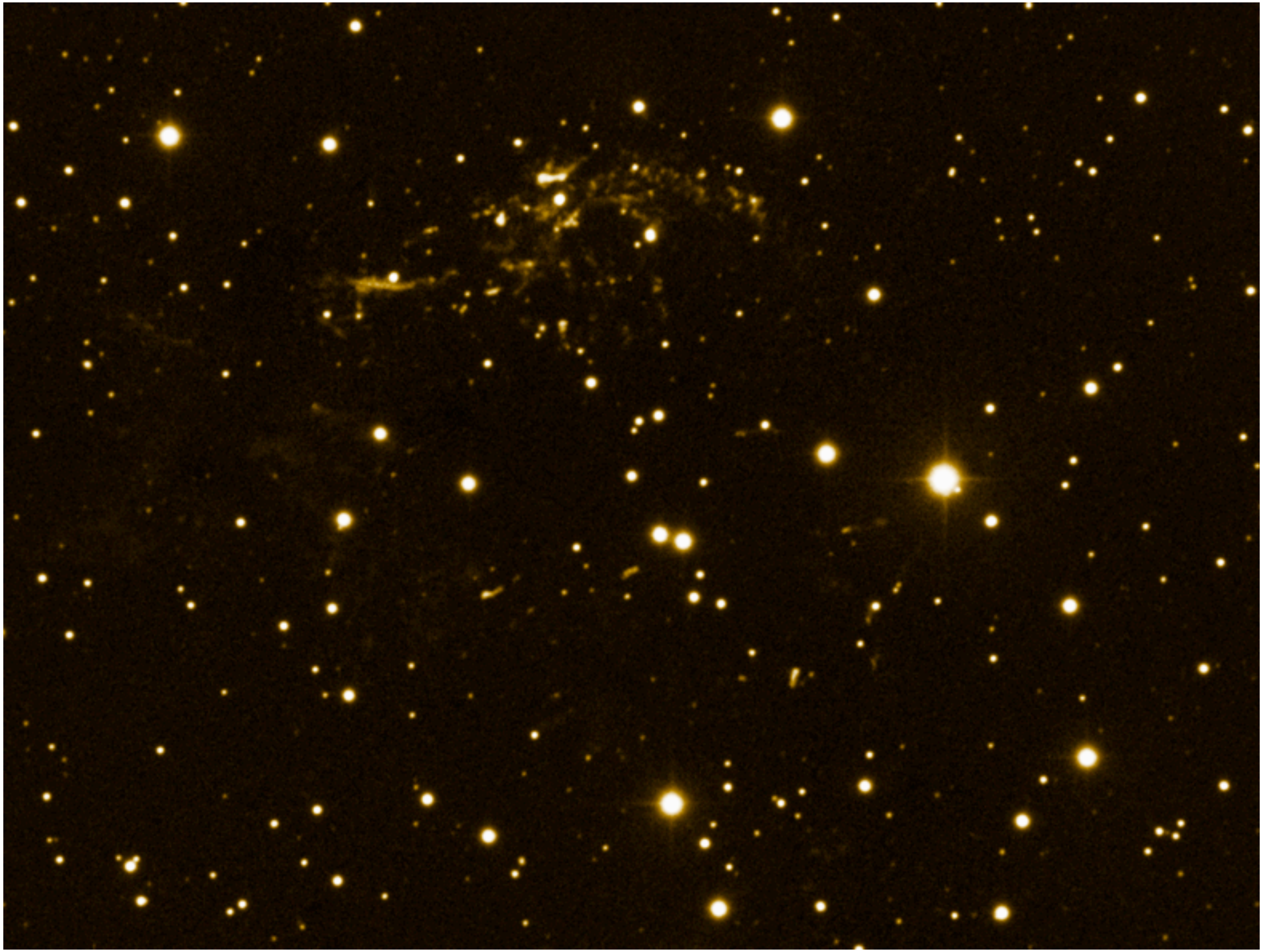
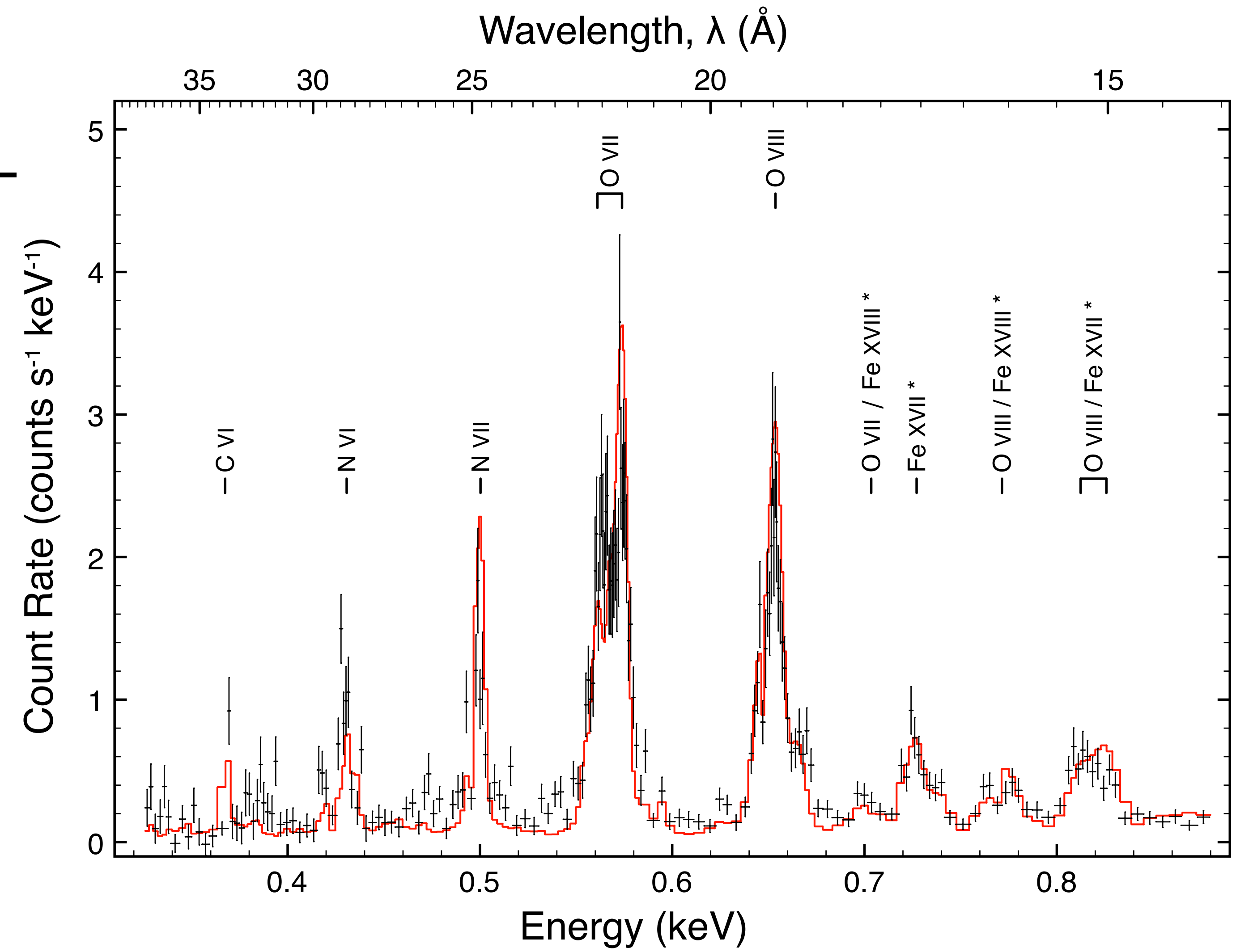
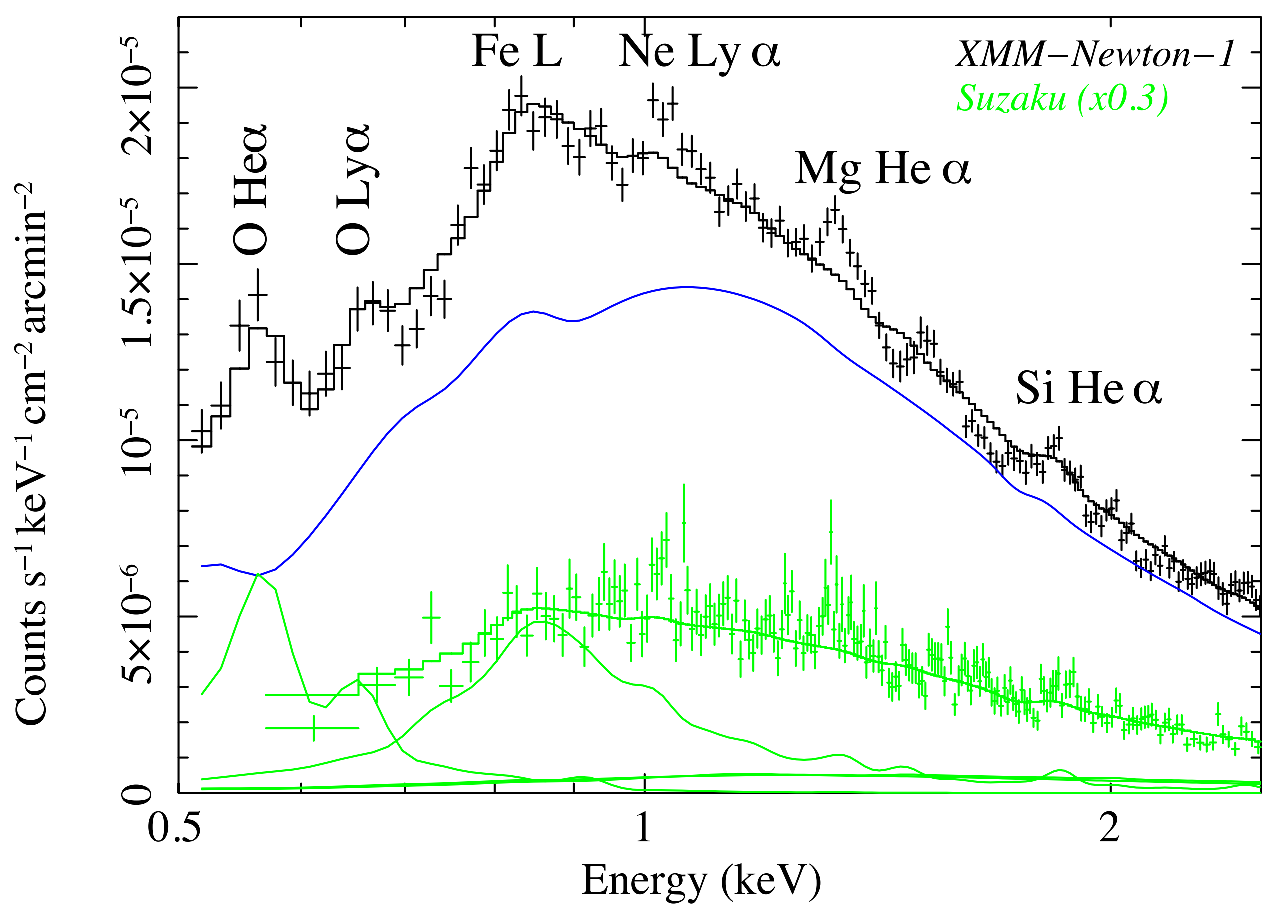


Derived from Patnaude & Fesen (2014)

G296.1-0.5:

XMM-Newton spectra reveal an excess of nitrogen and oxygen, suggestive of a WR progenitor (Castro et al. 2012)

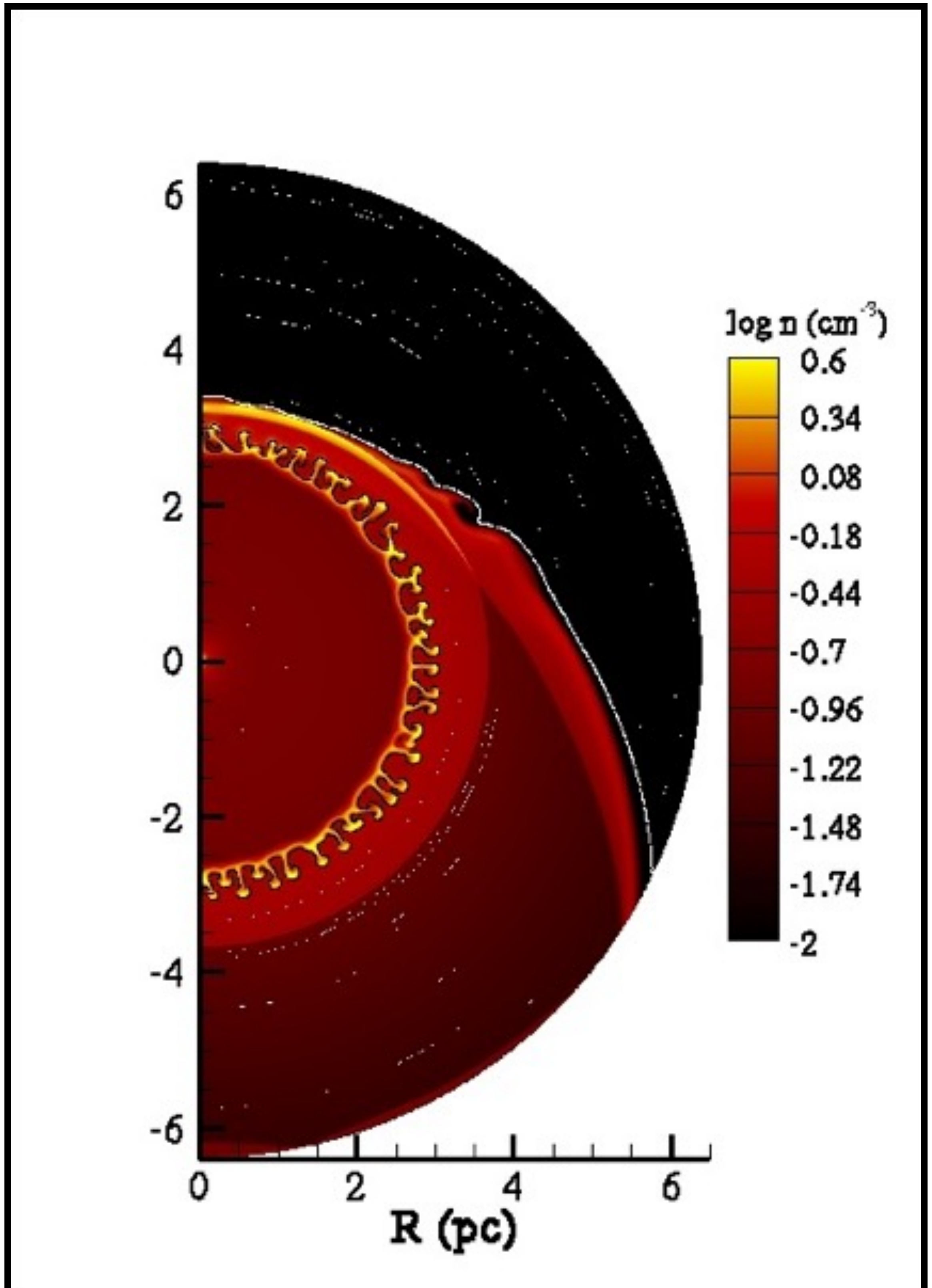




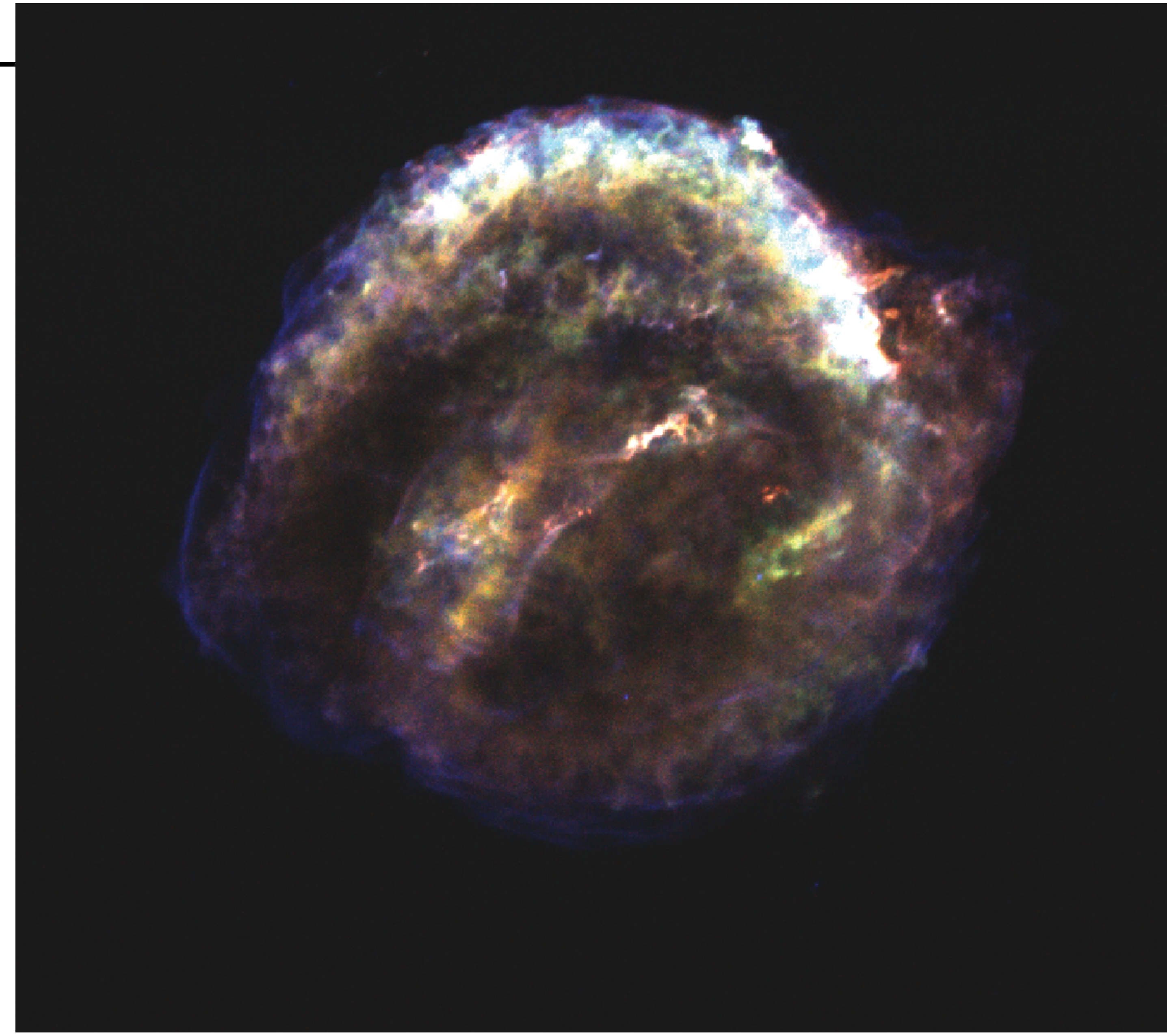
RX J1713-3946:

High shock speed relative to its age suggests that this SNR resulted from a SN Ib/c (Katsuda et al. 2015)

KEPLER'S SNR



Chiotellis et al. (2011)



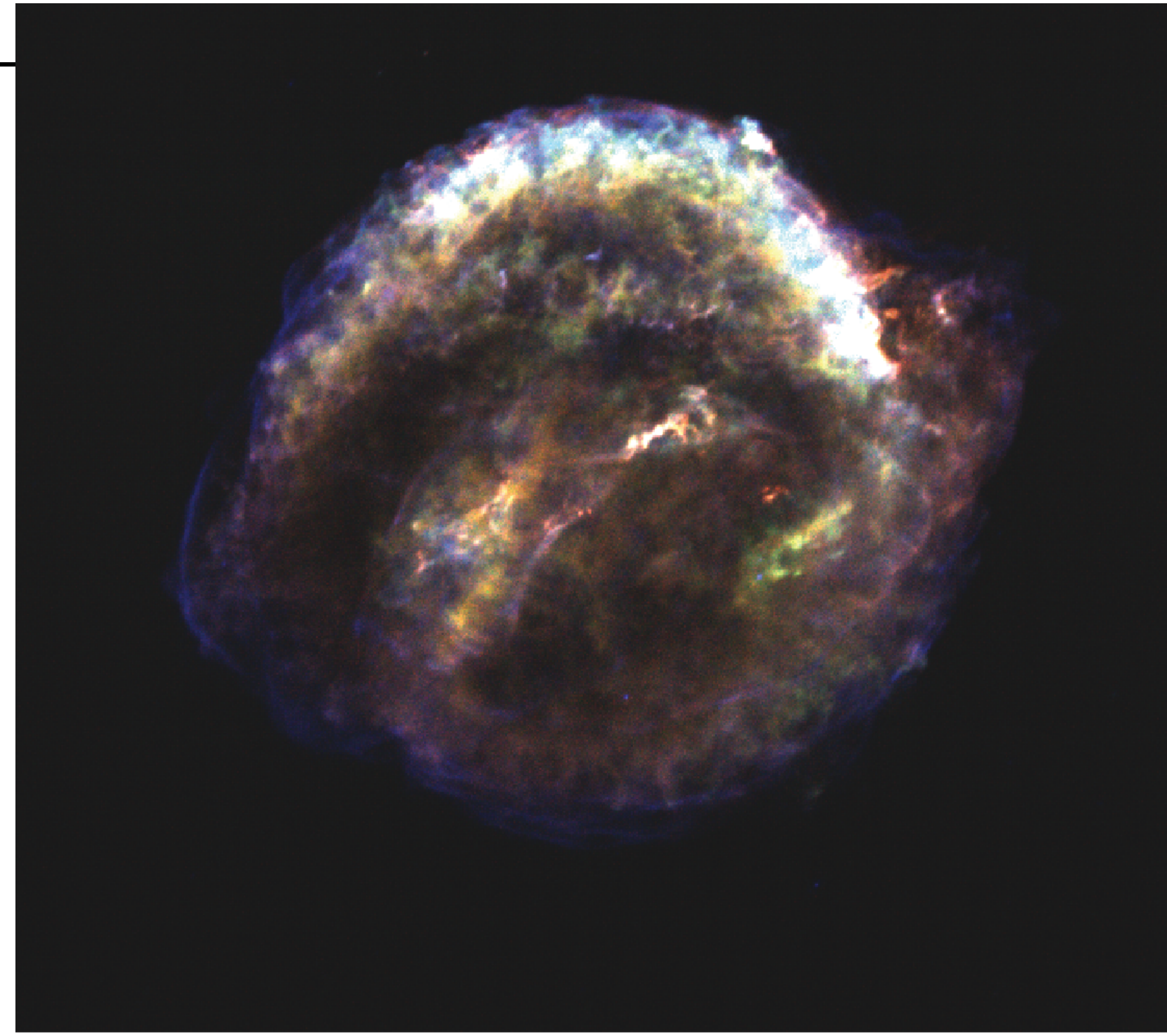
Patnaude et al. (2012) ApJ 756, 6

Morphology is well modeled as a SN expanding into a dense wind from an AGB companion

Kepler's SNR

Morphology and position above Galactic plane suggests a systemic velocity of ~ 200 km s^{-1}, into an ISM with $n_{amb} \sim 10^{-3}$ - 10^{-4} cm^{-3}

$$\dot{M} = 3.15 \times 10^{-7} \frac{n_{amb} u_*^2}{v_{wind}} \left(\frac{r_0}{\mathrm{pc}} \right)^2$$

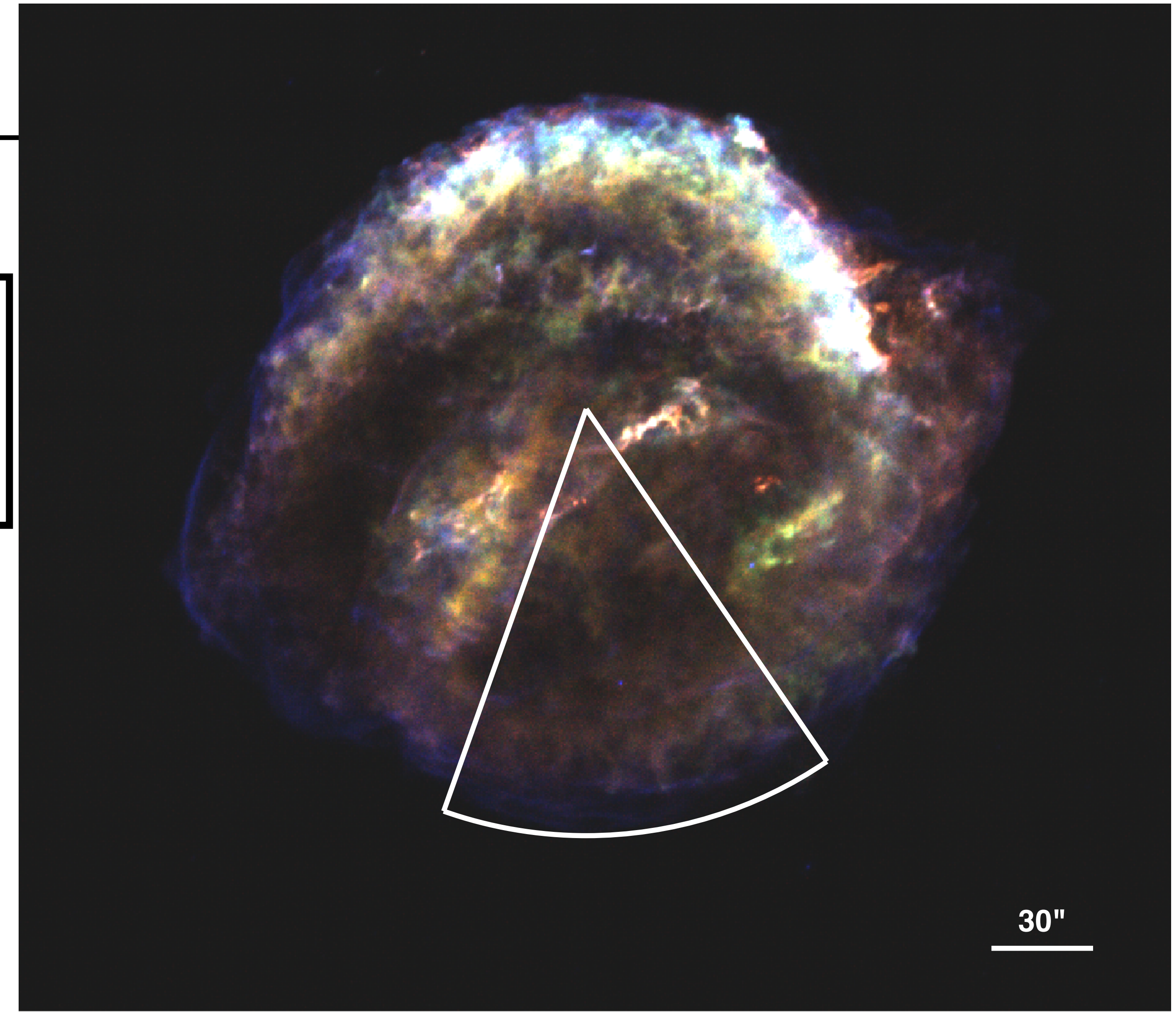


Patnaude et al. (2012) ApJ 756, 6

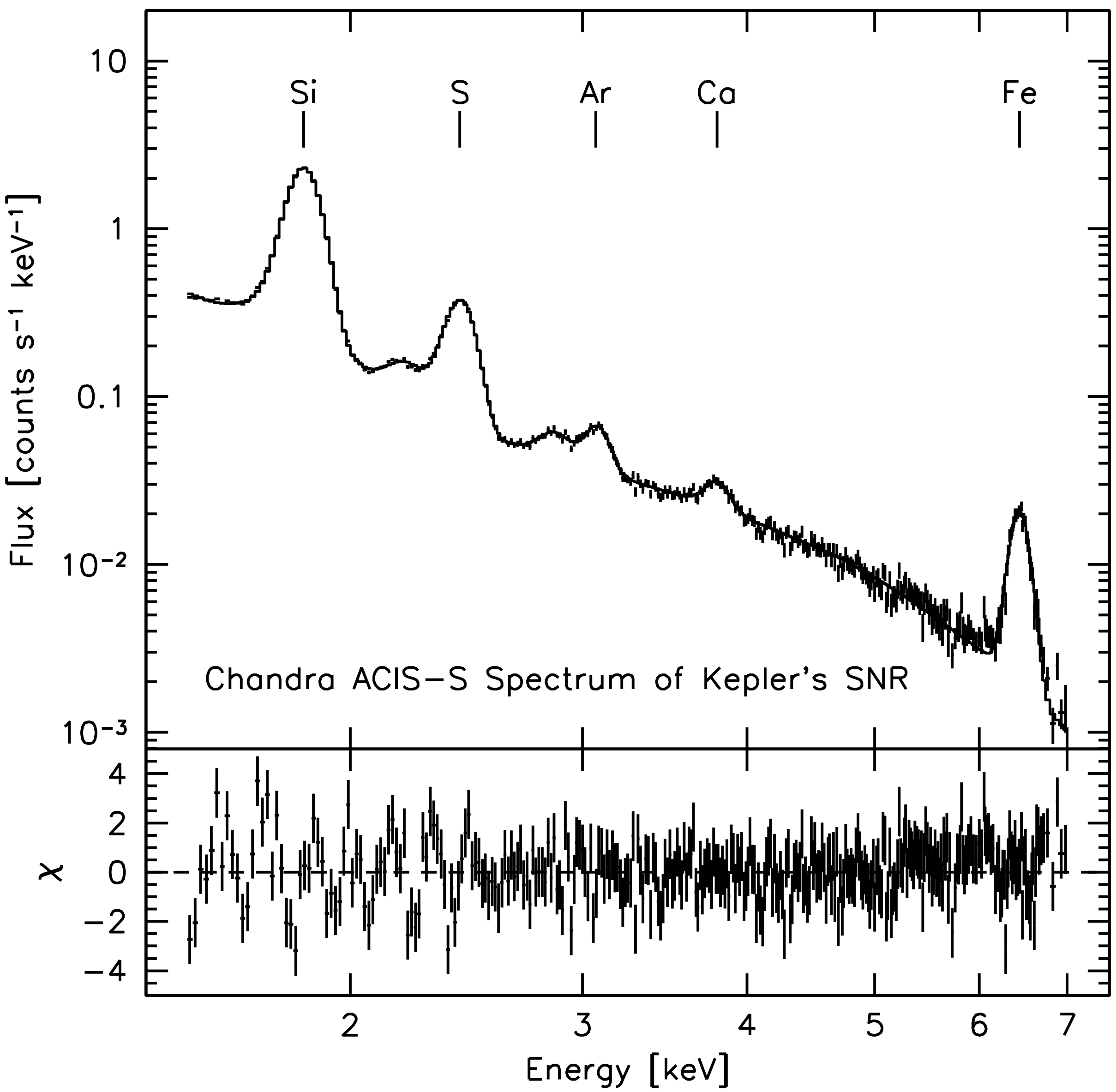
Uncertainty in distance leads to a stagnation radius of r_0 = 2-4 pc

$$\dot{M} = 10^{-5} - 10^{-6}\, \mathrm{M}_\odot\, \mathrm{yr}^{-1}$$

KEPLER'S SNR



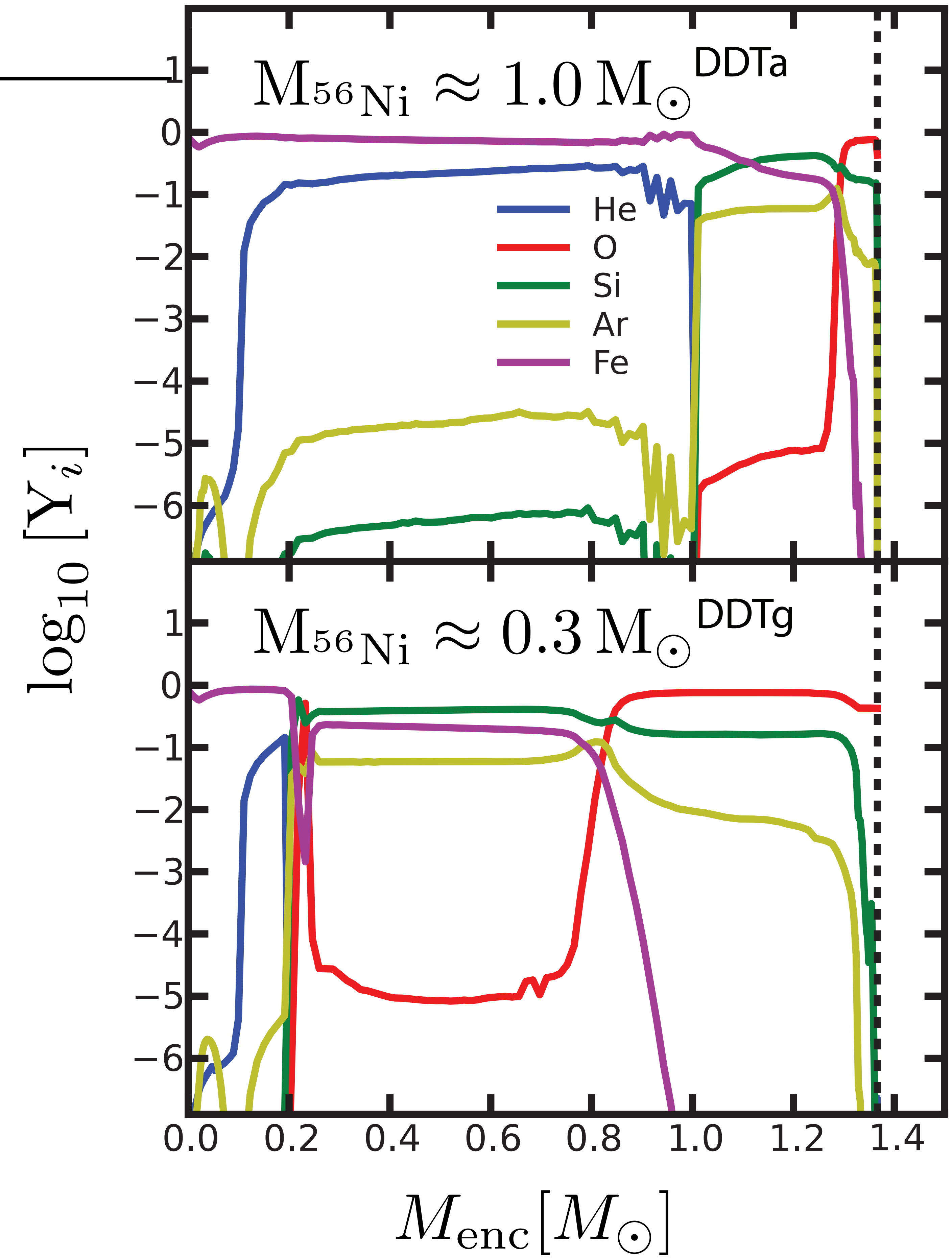
Use progenitor parameters derived from north to model X-ray emission and dynamics of south



Line fluxes (10^{-5} photons cm^{-2} s^{-1})	
Si Kα[b]	49.9 ± 0.20
Si XIV Lyα	$<4.70 \pm 0.47$
Si Kβ	5.64 ± 0.30
S Kα	13.5 ± 0.30
Ar Kα	1.19 ± 0.16
Ca Kα	0.38 ± 0.07
Fe Kα	3.84 ± 0.14
Line centroids (keV)	
Si Kα	$1.848^{+0.003}_{-0.002}$
Si Kβ	$2.190^{+0.004}_{-0.003}$
S Kα	$2.425^{+0.007}_{-0.006}$
Ar Kα	$3.077^{+0.005}_{-0.006}$
Ca Kα	$3.799^{+0.010}_{-0.010}$
Fe Kα	$6.450^{+0.010}_{-0.008}$

KEPLER'S SNR

Model SNR ejecta with Type Ia DDT models (1.4M_{sun} C+O WD) evolving into an isotropic wind with parameters determined from CSM interaction



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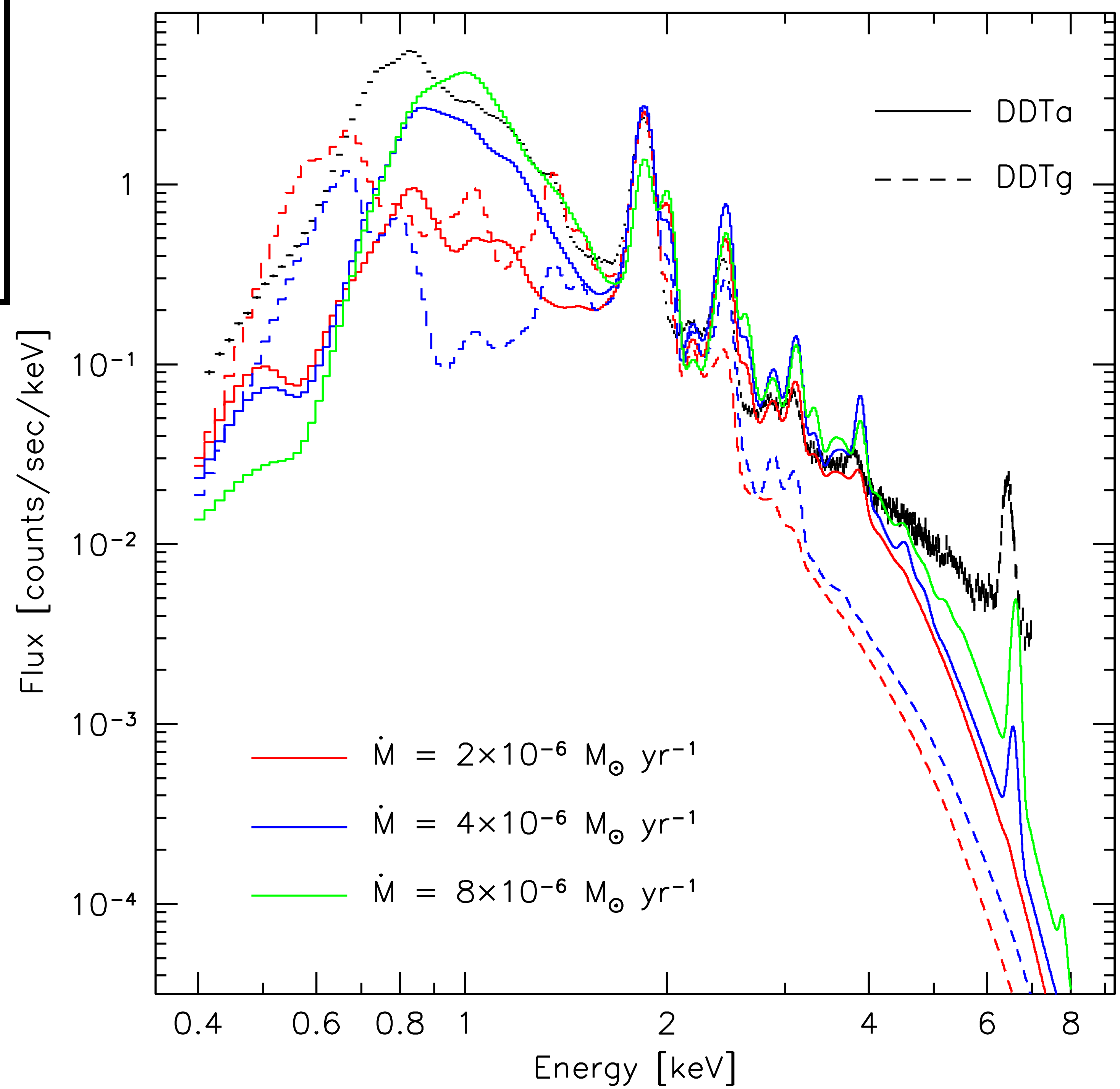
Use ejecta abundances and internal energy of shocked material to compute X-ray spectrum



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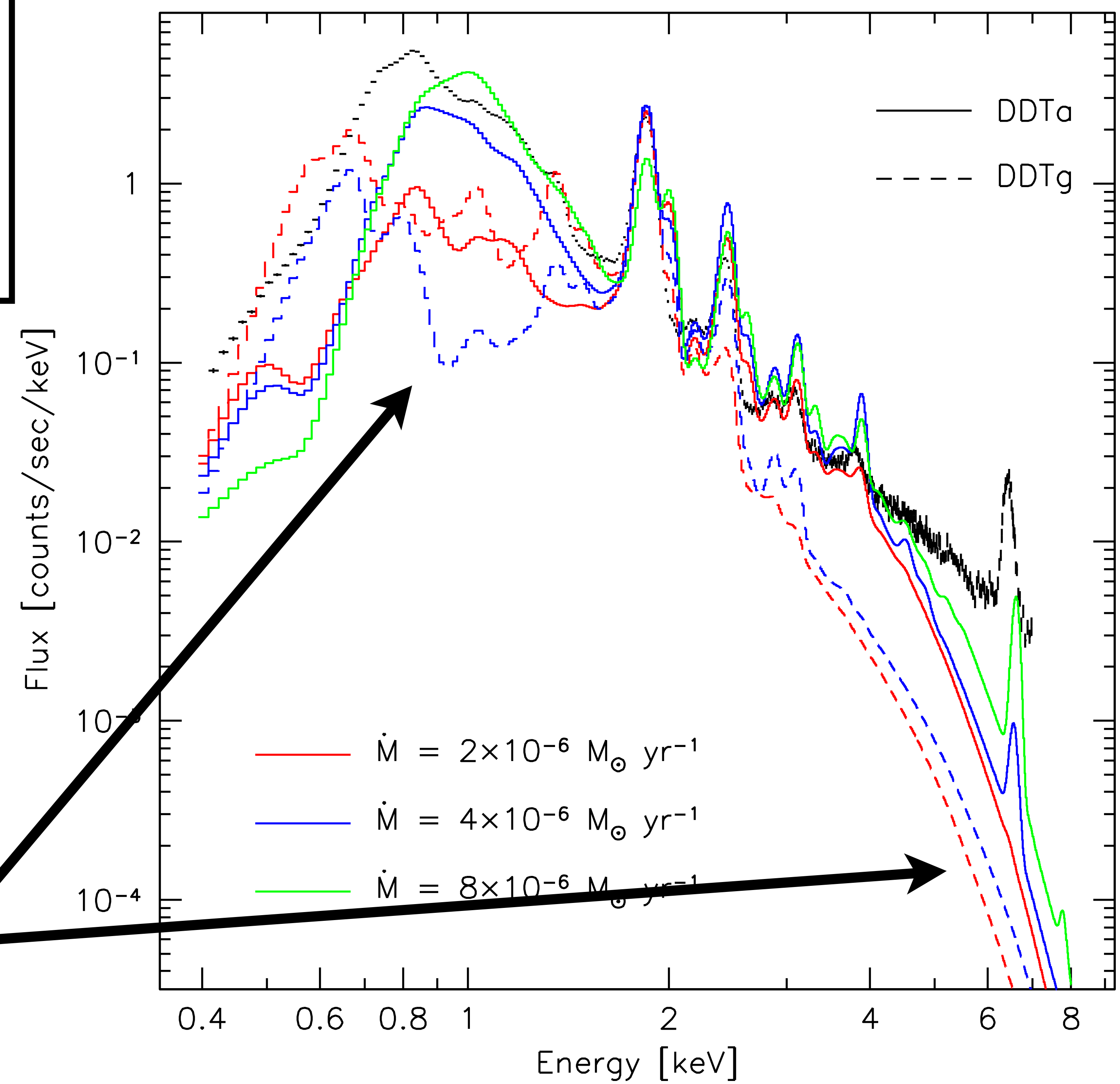
Lack of Fe emission from DDTg models rules these models out for Kepler



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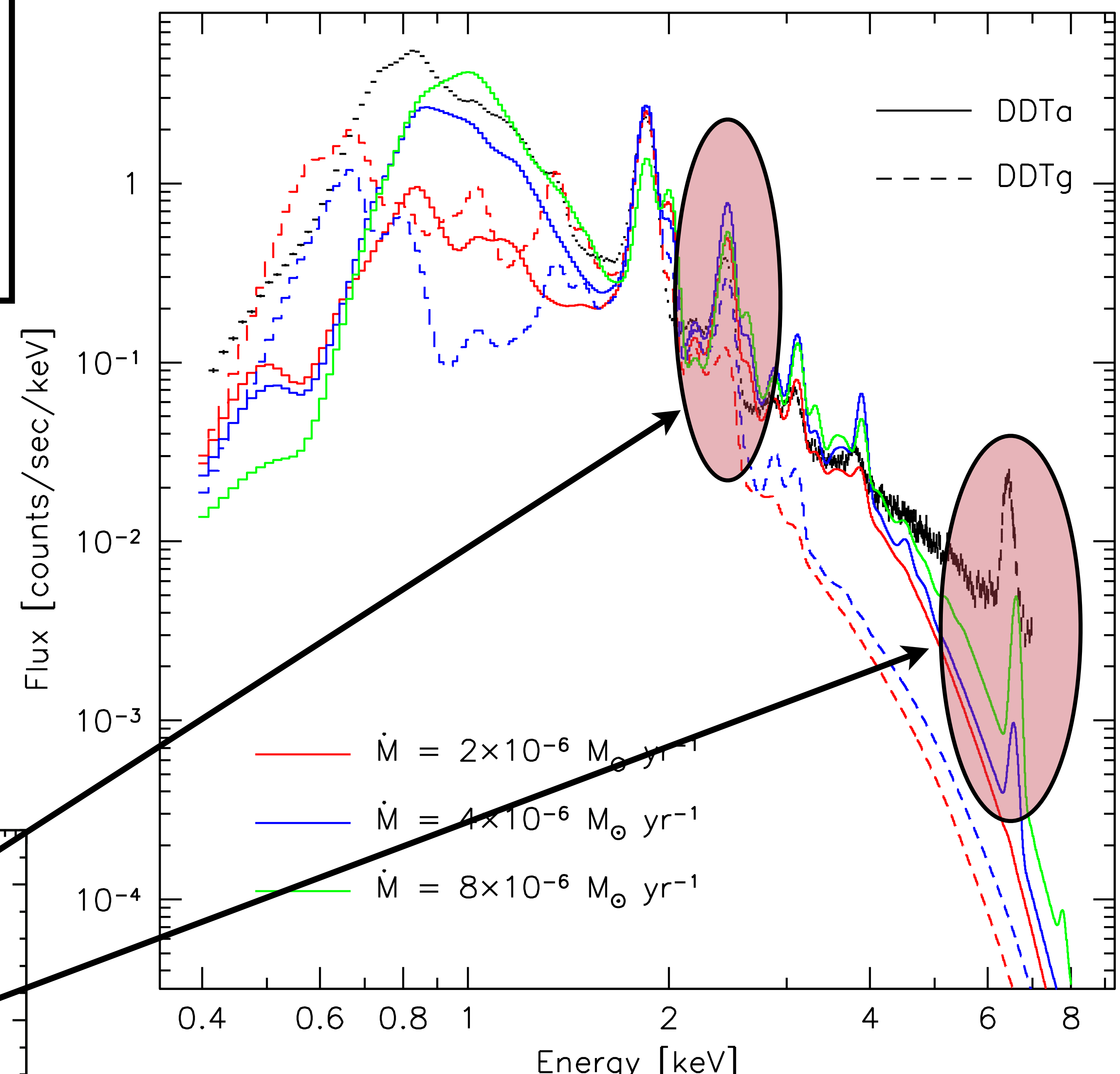
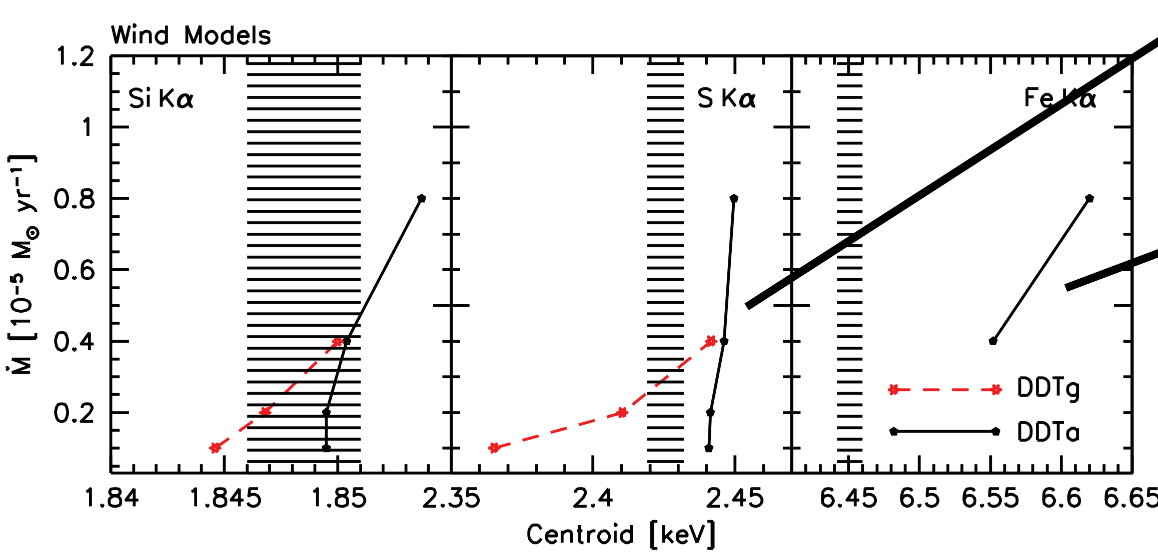


Line Centroids:



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Model SNR ejecta with Type Ia DDT models (1.4M_{sun} C+O WD) evolving into an isotropic wind with parameters determined from CSM interaction

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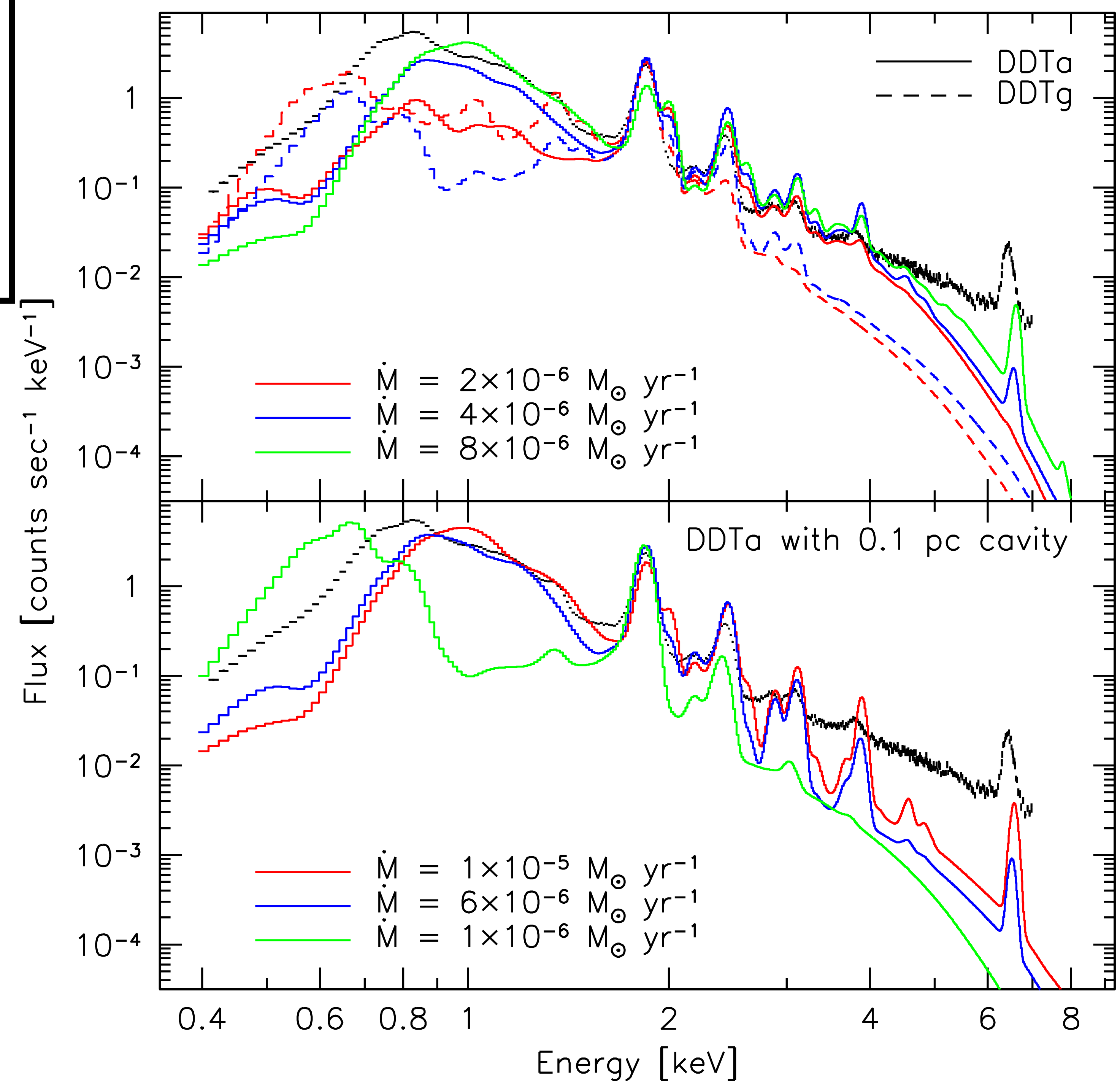
Introduce a fiducial cavity of size ~ 10^{17} cm and density ~ 0.1 cm^{-3} around DDTa models



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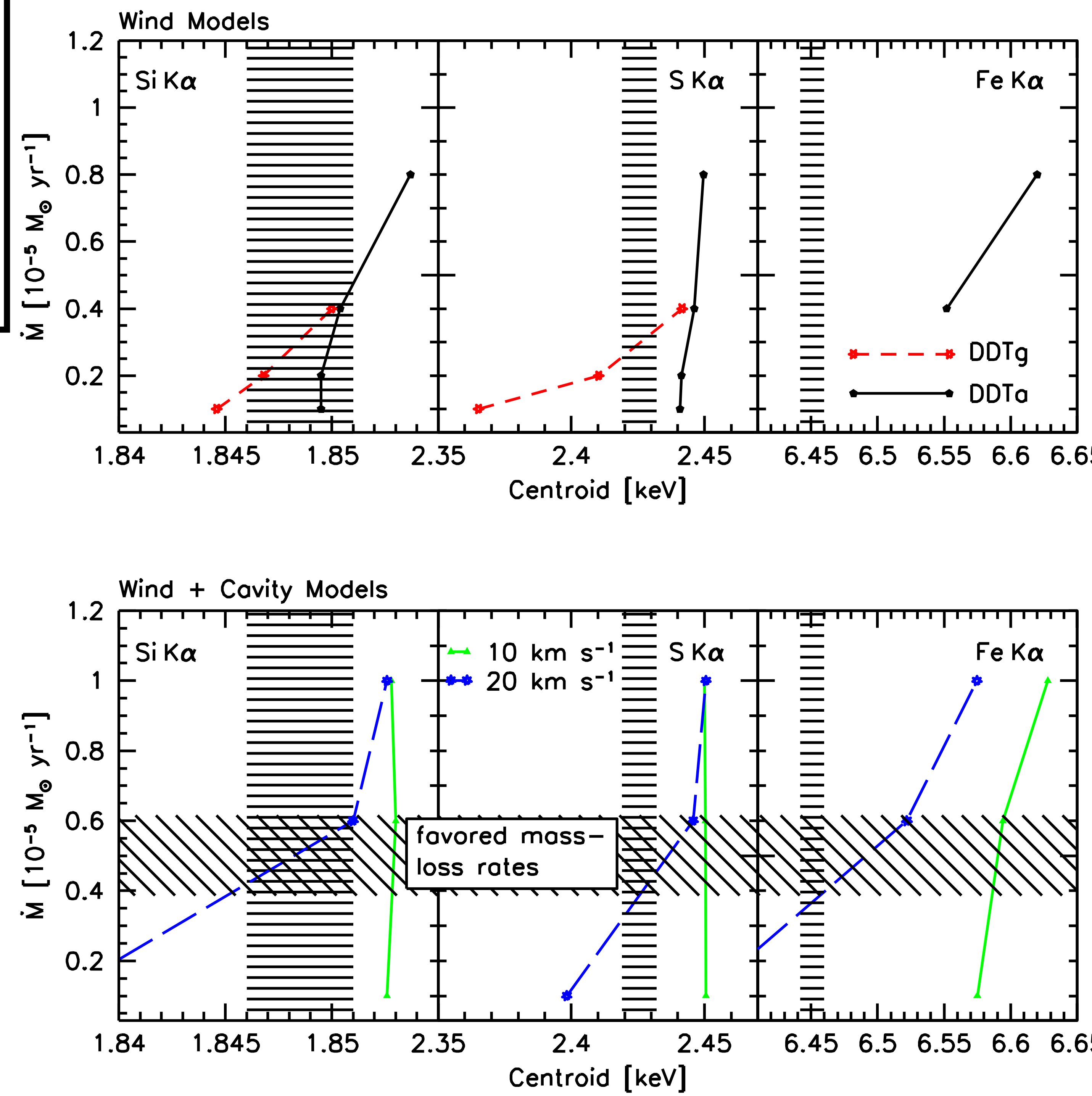

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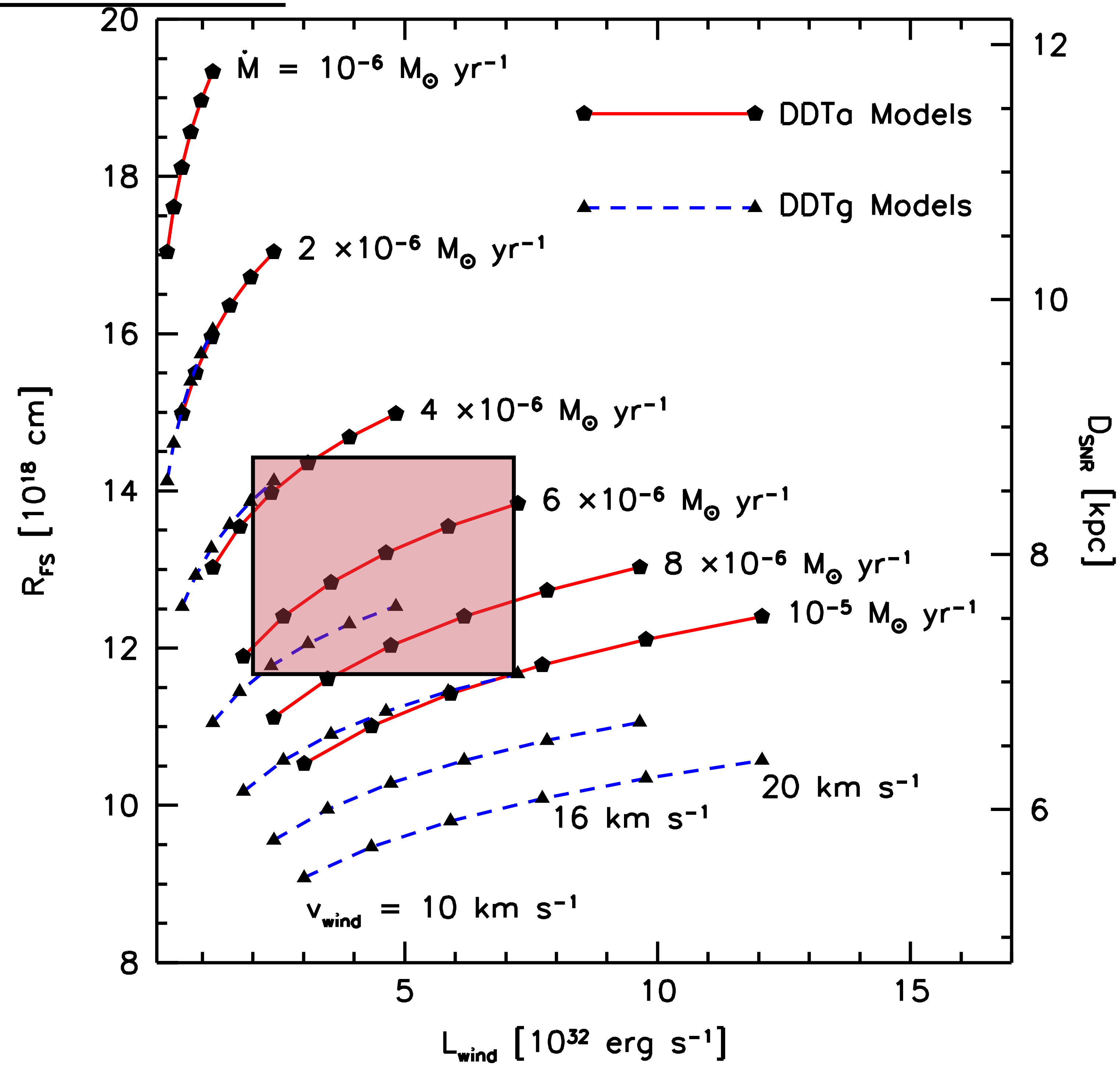

For these models $R_{FS} \sim (L_W)^{2/5}$

Best fit models imply SN 1991T-like event

Patnaude et al. (2012) ApJ 756, 6

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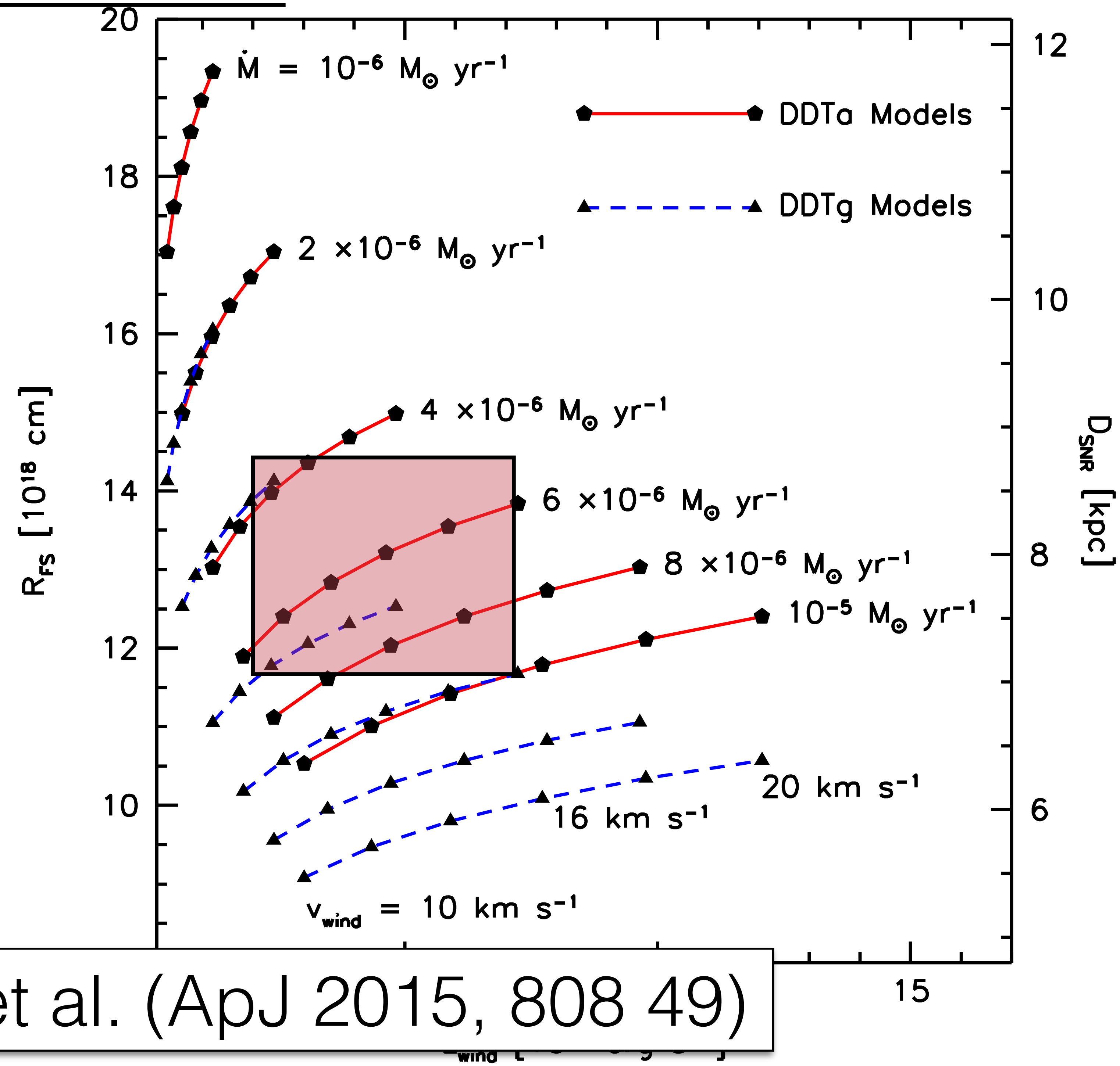
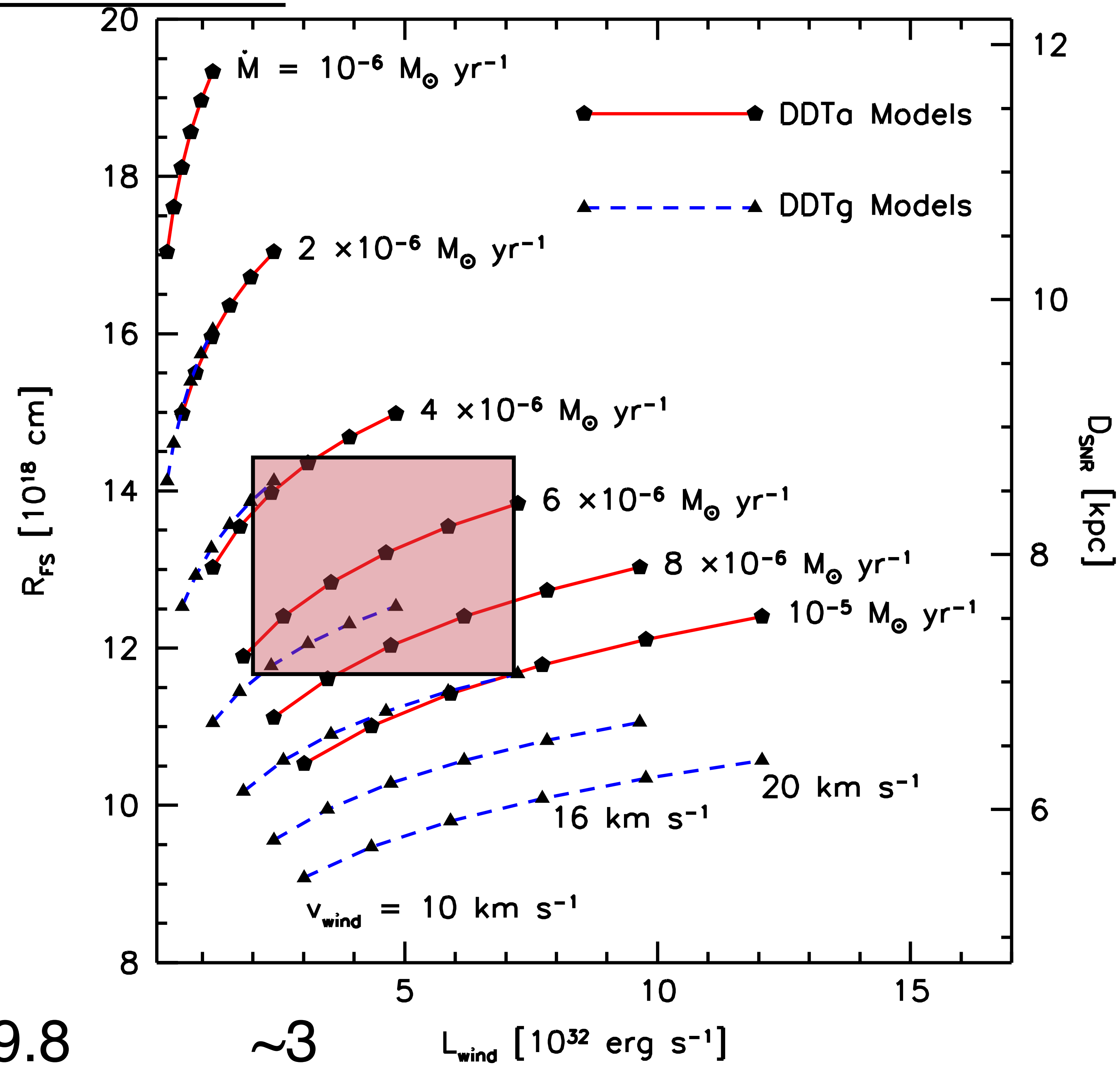


see also Katsuda et al. (ApJ 2015, 808 49)

Patnaude et al. (2012) ApJ 756, 6

Kepler's SNR



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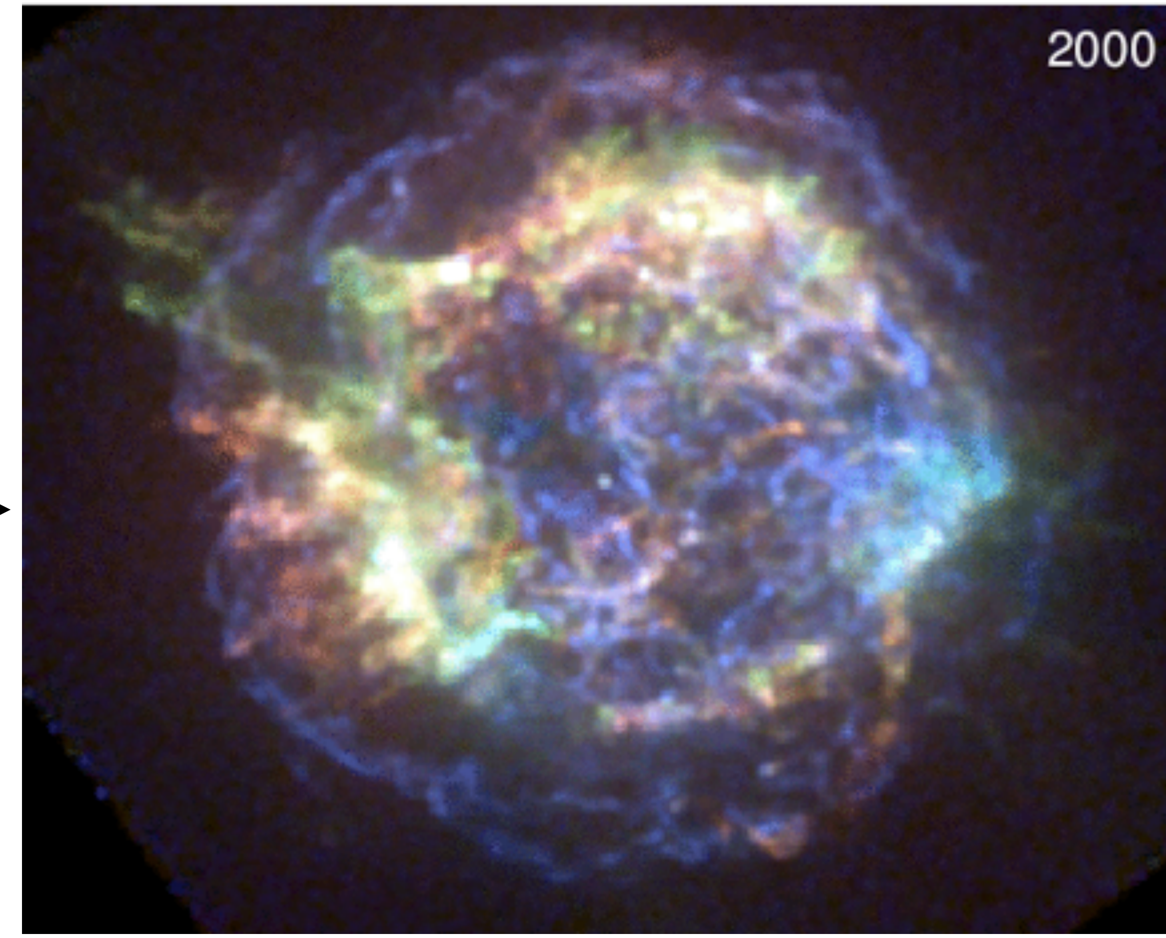
Best fit models imply SN 1991T-like event

$$\log_{10}\left(\frac{D}{1\mathrm{pc}}\right) = \frac{1}{5}\left(\underset{-2.5}{m} - \underset{-19.8}{M} + 5 - \underset{\sim 3}{A_v}\right)$$

$\Rightarrow D_{SNR} \approx 7$ kpc

THE GOAL:

Artist's conception of a massive star cluster

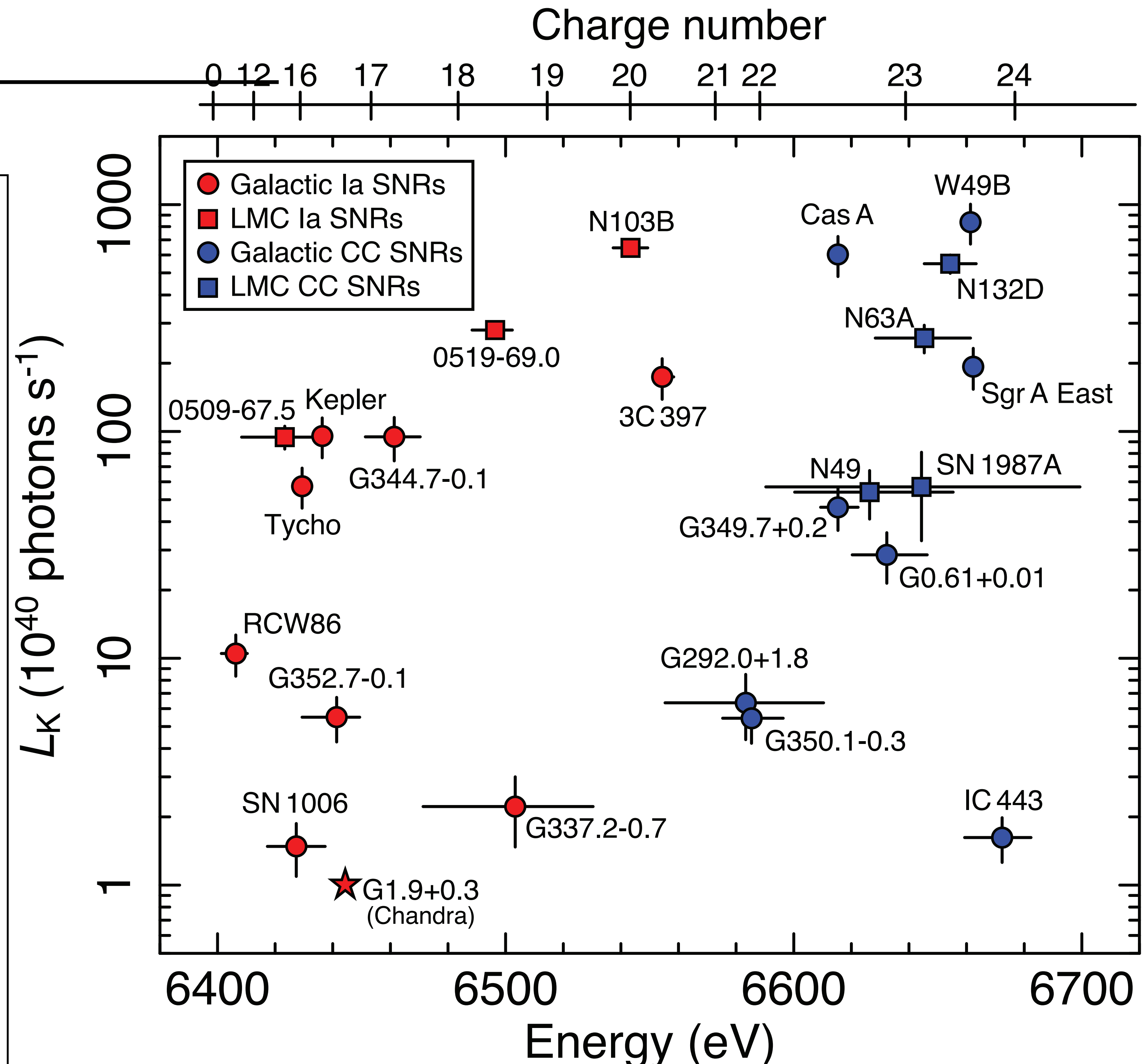


RGB movie of Cas A from 2000-2012 (Patnaude et al.)

Do progenitor models produce the bulk observables of supernova remnants?

Bulk Properties

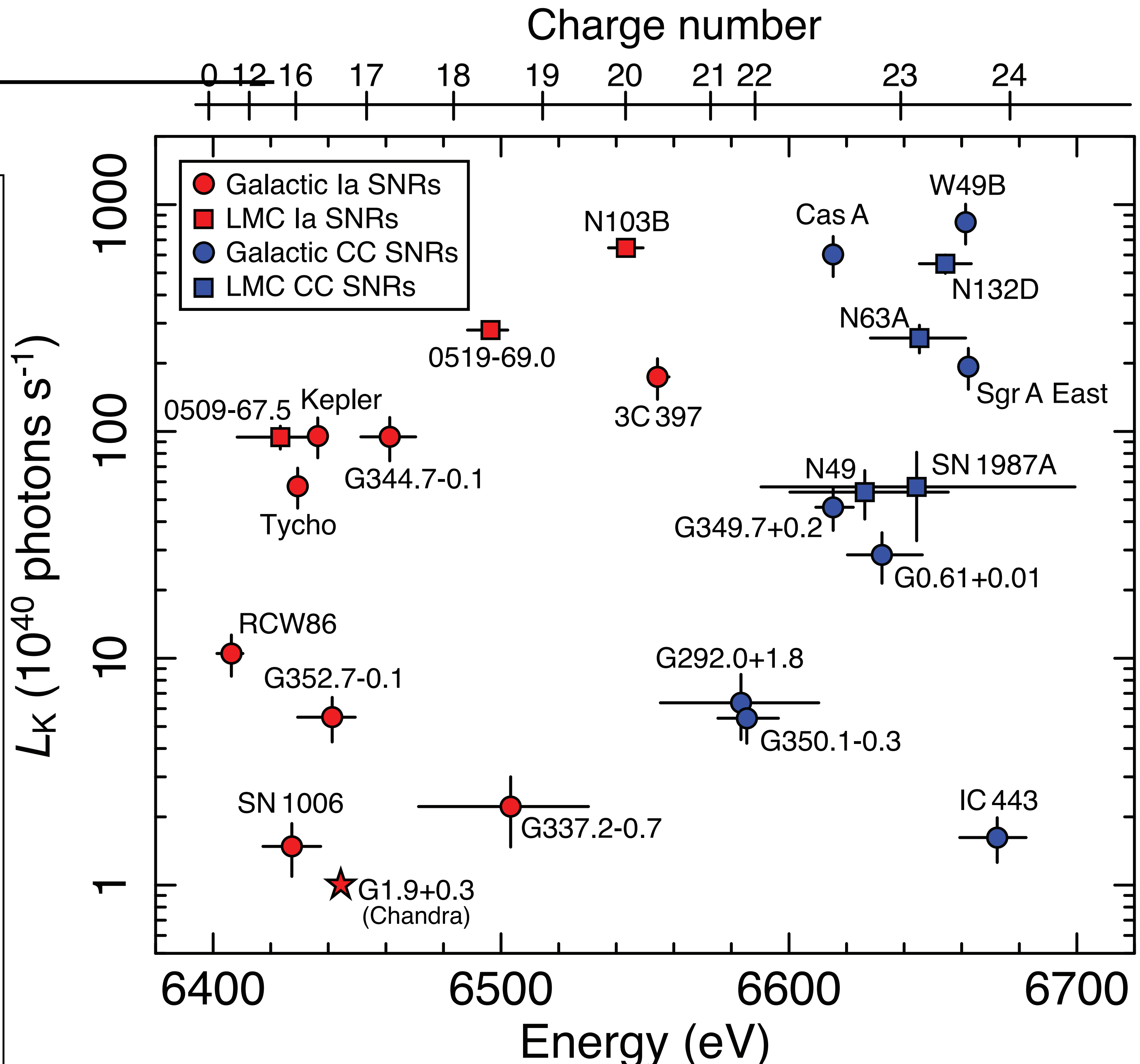
- Spectral qualities
  - line centroids
  - line ratios
  - luminosites
- Dynamical qualities
  - expansion velocity
  - remnant size
- Environment



Yamaguchi et al. (2014)

Bulk Properties

- Spectral qualities
  - Line luminosities are uniformly distributed across both Ia and CC types
  - Line centroids show a clear bifurcation between SN types



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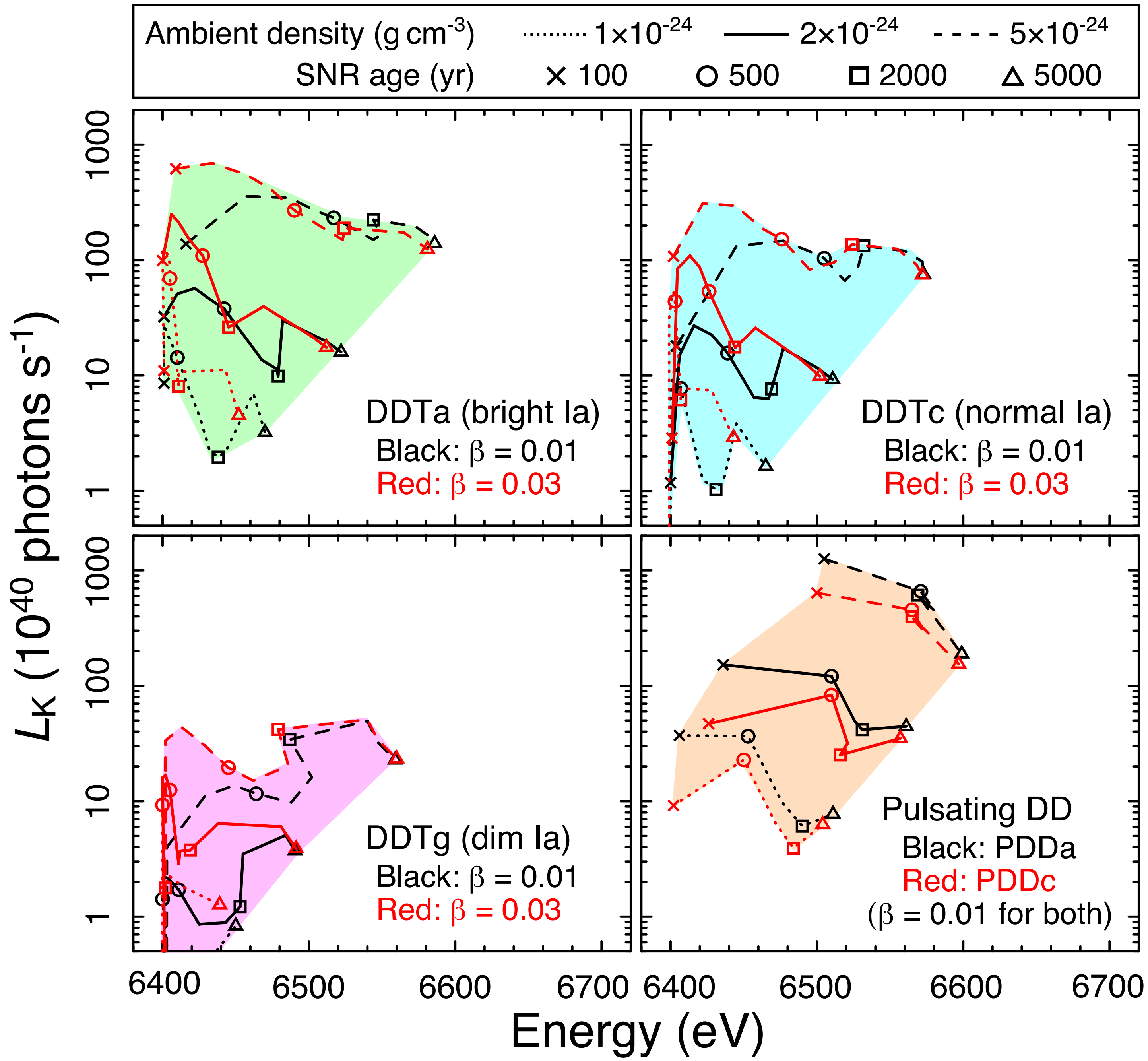

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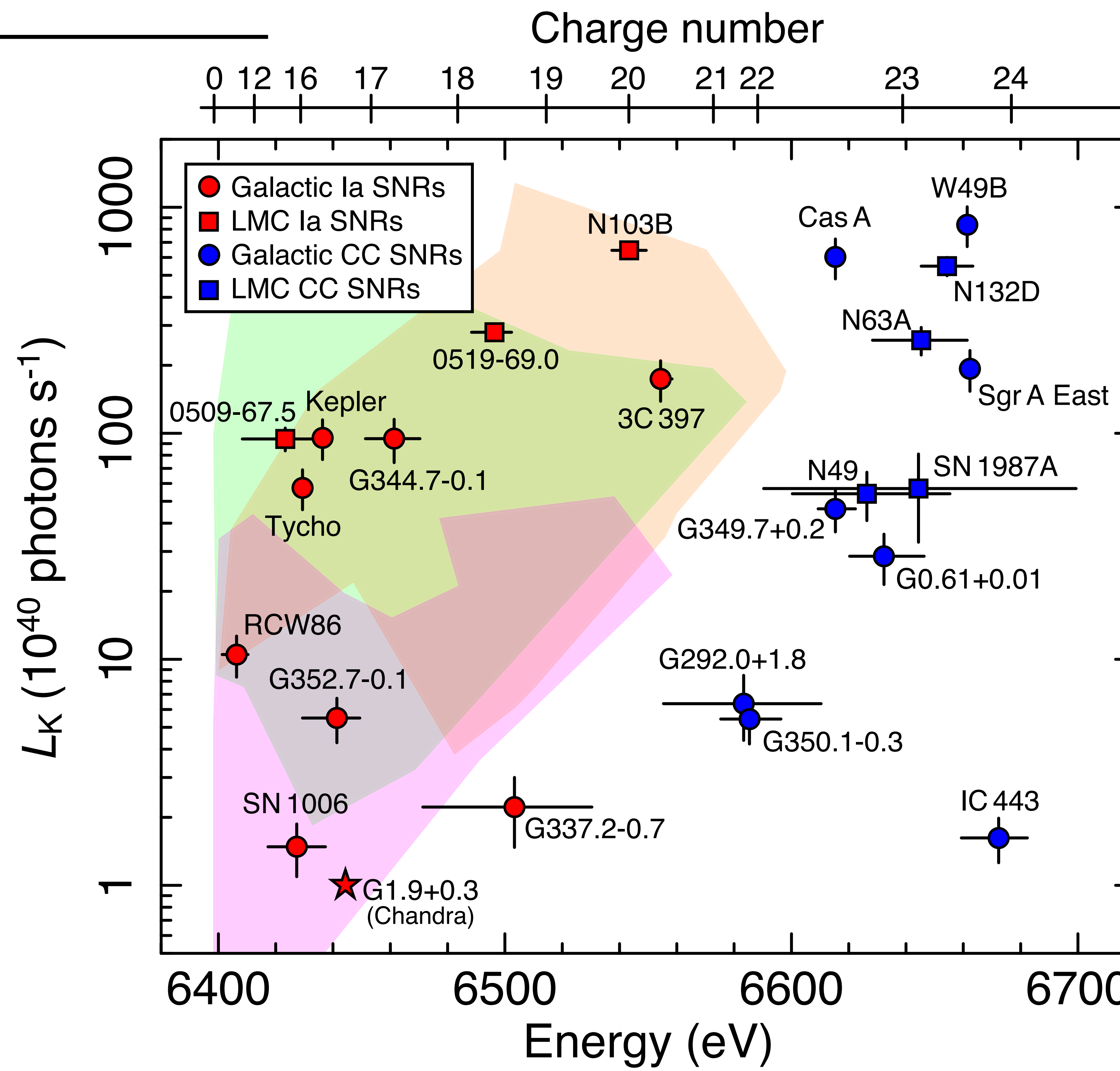

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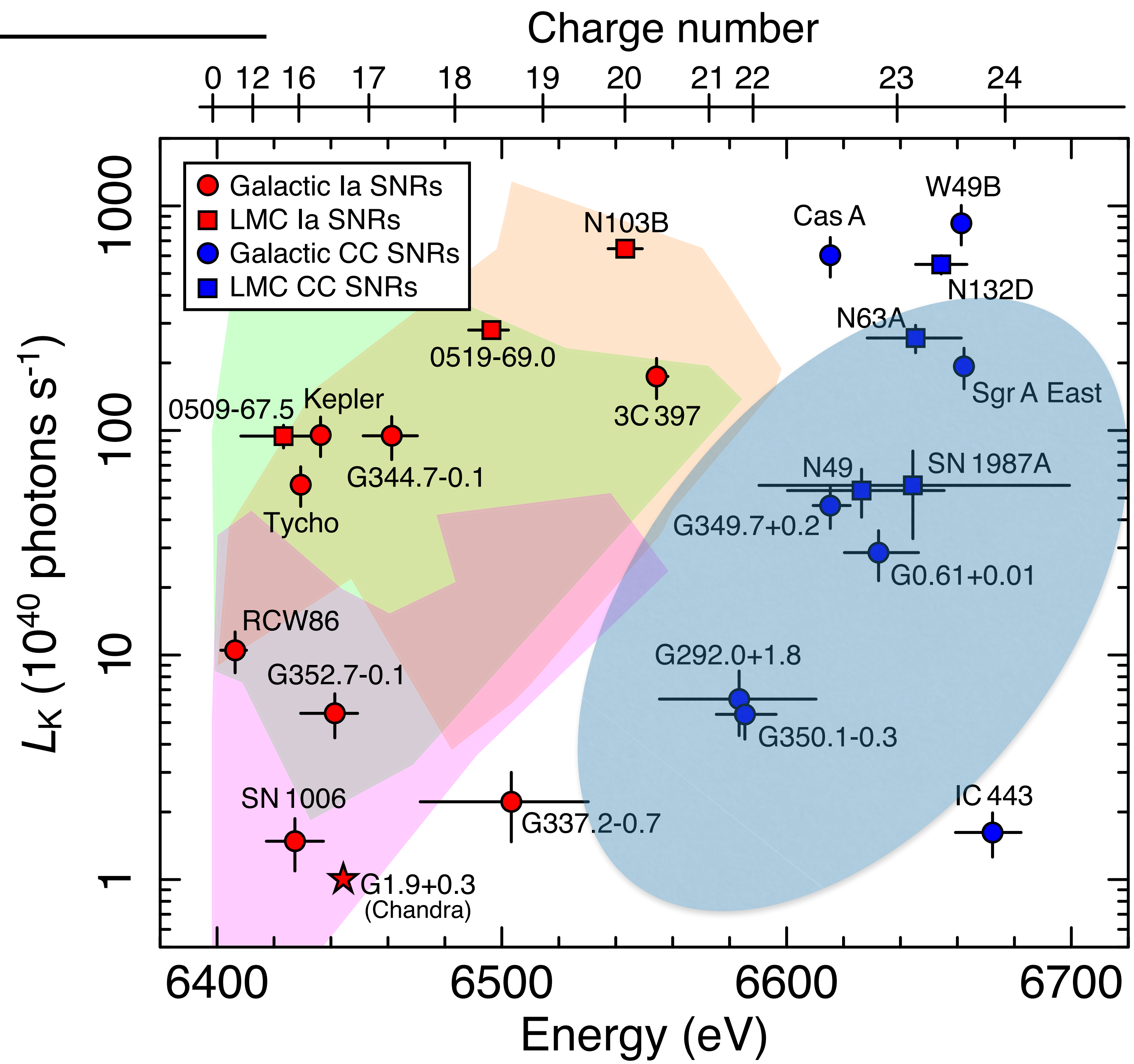


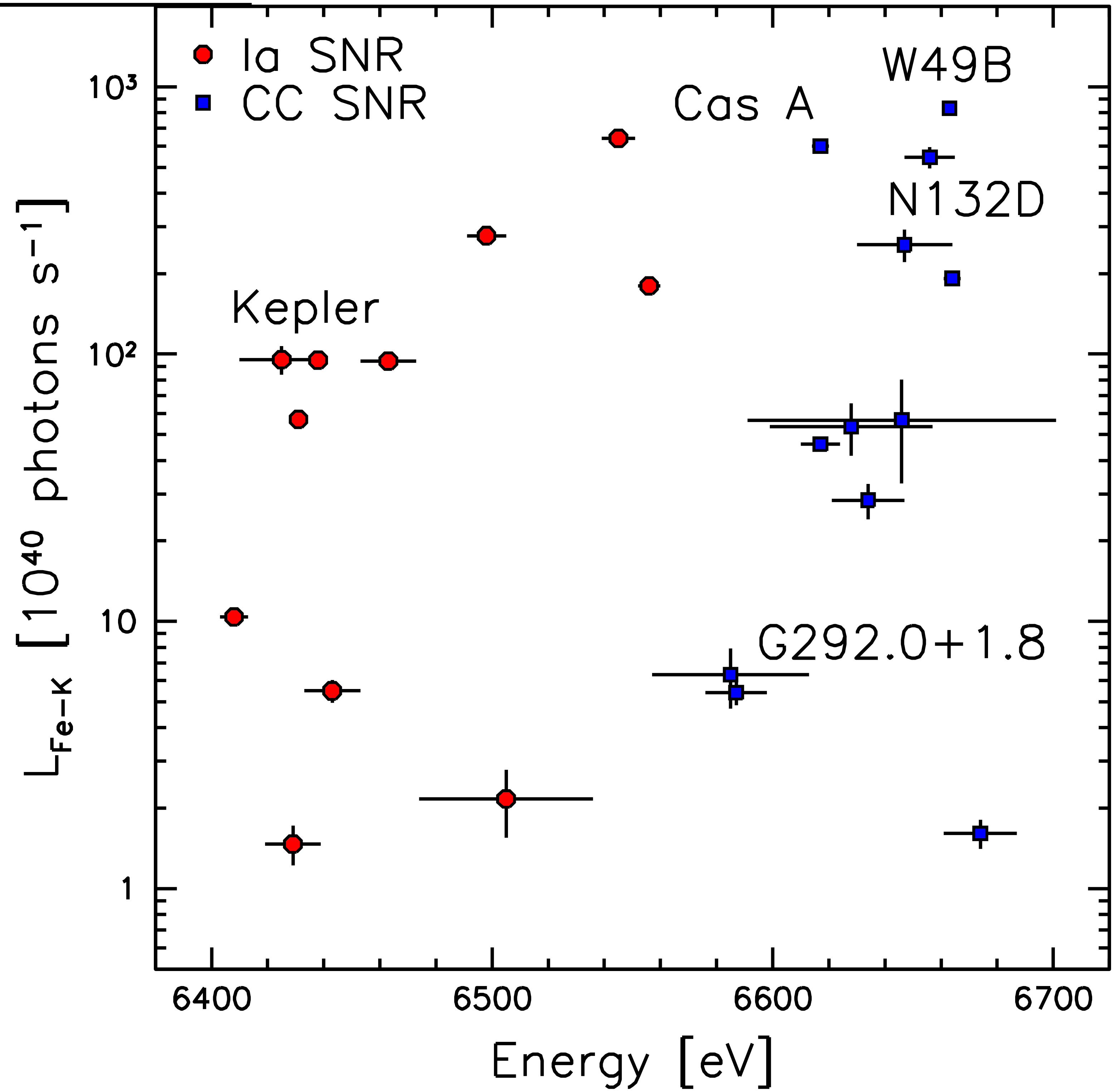
Yamaguchi et al. (2014)

Model Ingredients

- Progenitor and Supernova Model
  - use KEPLER code (e.g., Heger & Woosley) for stellar evolution and piston driven explosion
  - standard r^{-2} circumstellar environment
- Supernova Remnant Model
  - ChN cosmic-ray hydrodynamics code (see talk by Herman Lee)

What about CCSNe?

- Can simulate SNe dynamics to ages of SNRs for a range of CSM parameters
- Ia's (DDTa & DDTg):
    - $n_0 = 0.1 - 3.0\ cm^{-3}$
- CCSNe (S12D, S25D, 1987A, & 1993J):
    - $M_{dot} = 1\text{-}2{\times}10^{-5}\ M_{sun}\ yr^{-1}$
    - $v_w = 10\text{-}20\ km\ s^{-1}$
- Use Ia models as a sanity check



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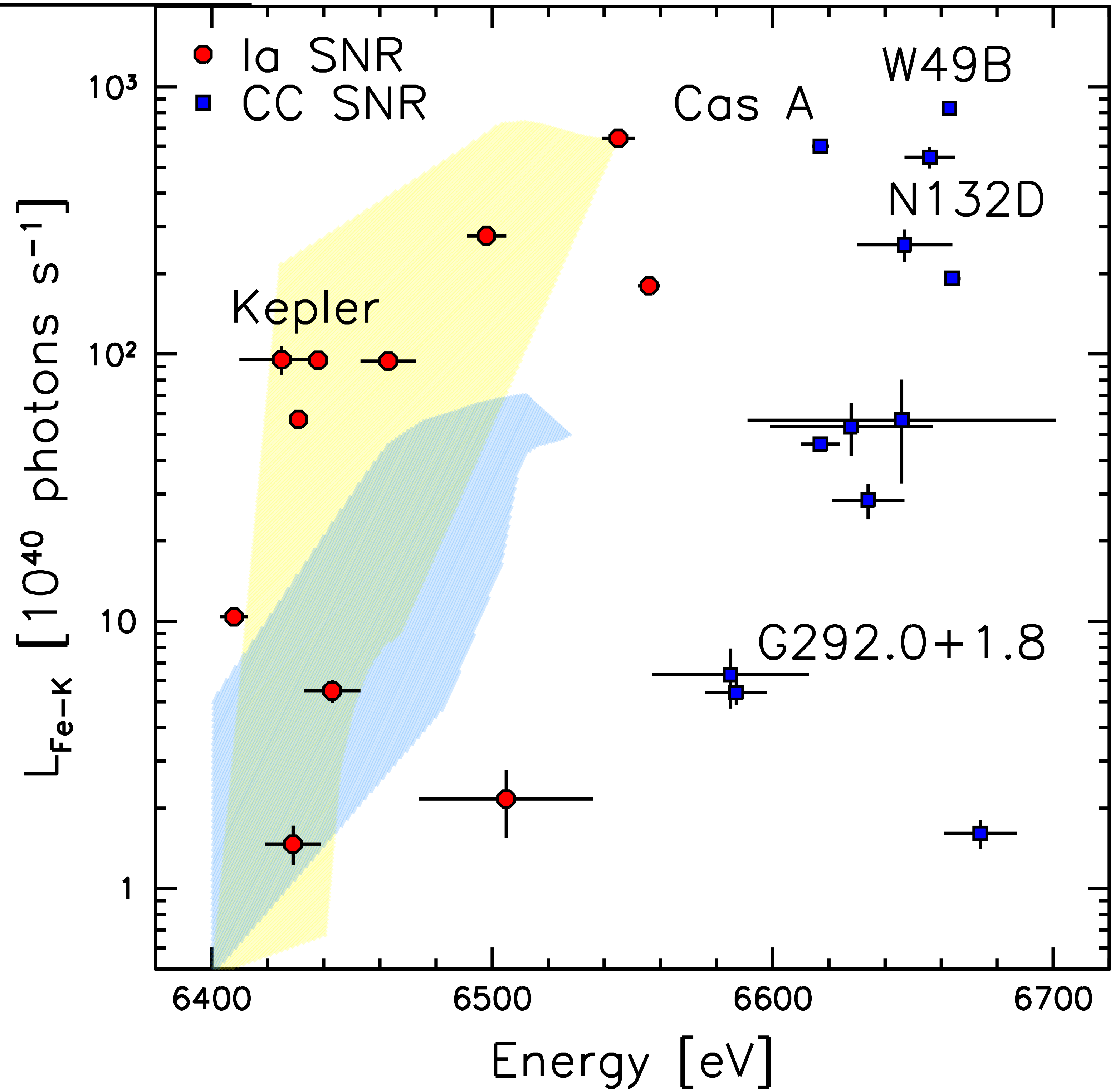

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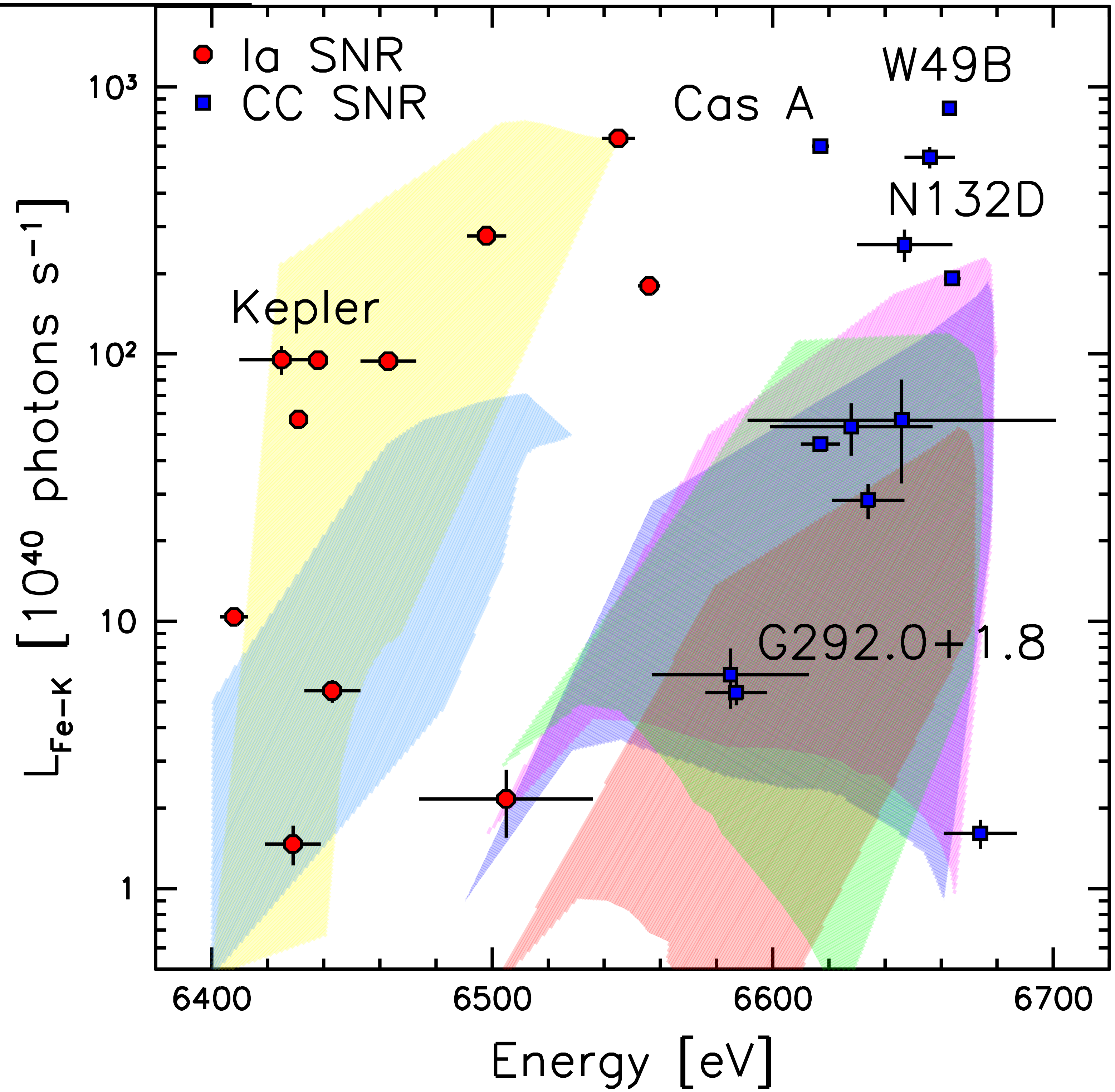
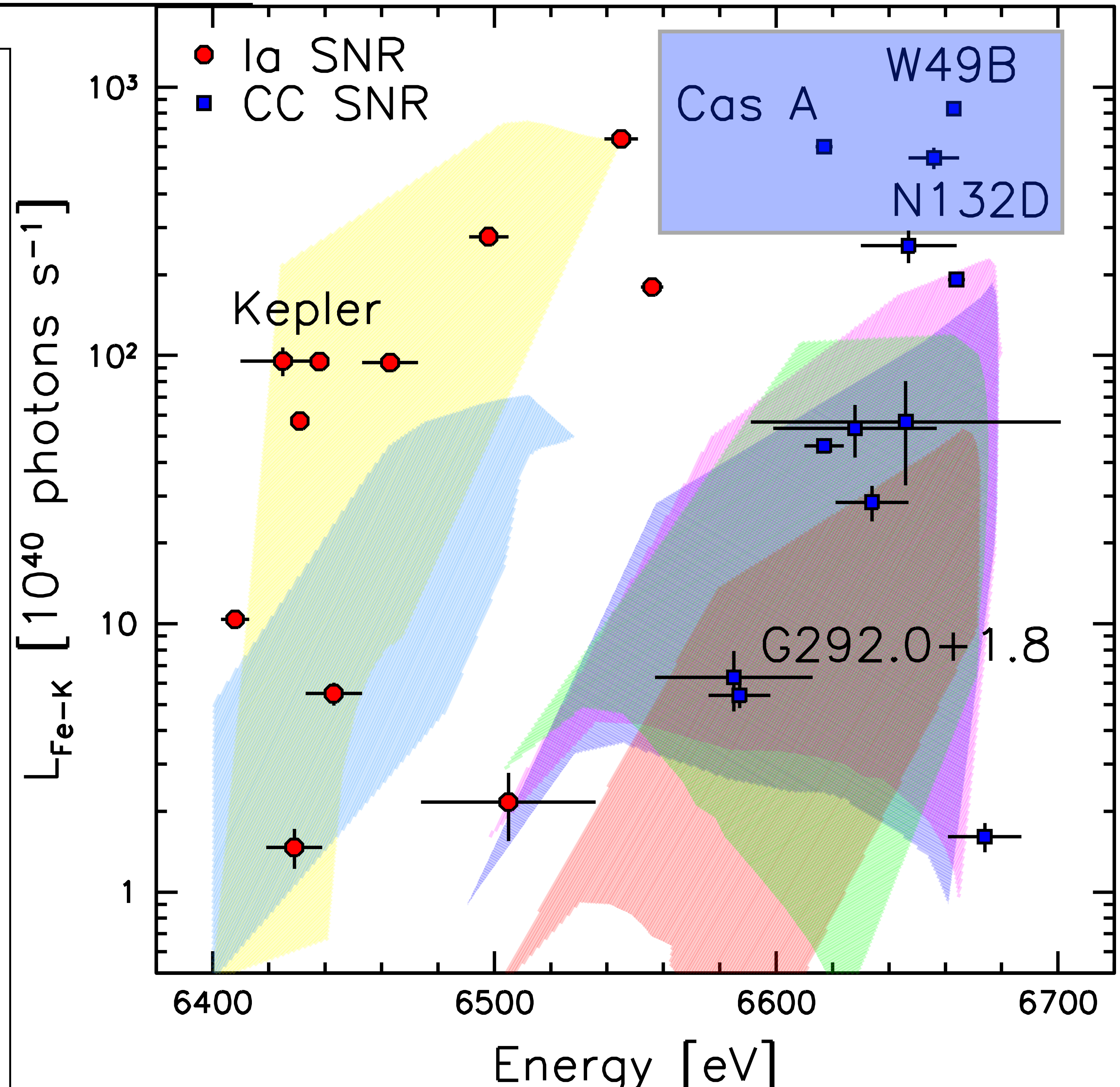


Patnaude et al. (2015)

What about CCSNe?

- Majority of CCSNR are consistent with CCSNe models
- Outliers can be explained
  - Cas A: overturned ejecta
  - W49B: Energetic, jet-driven explosion
  - N132D/IC443: Interacting with large amounts of MC material



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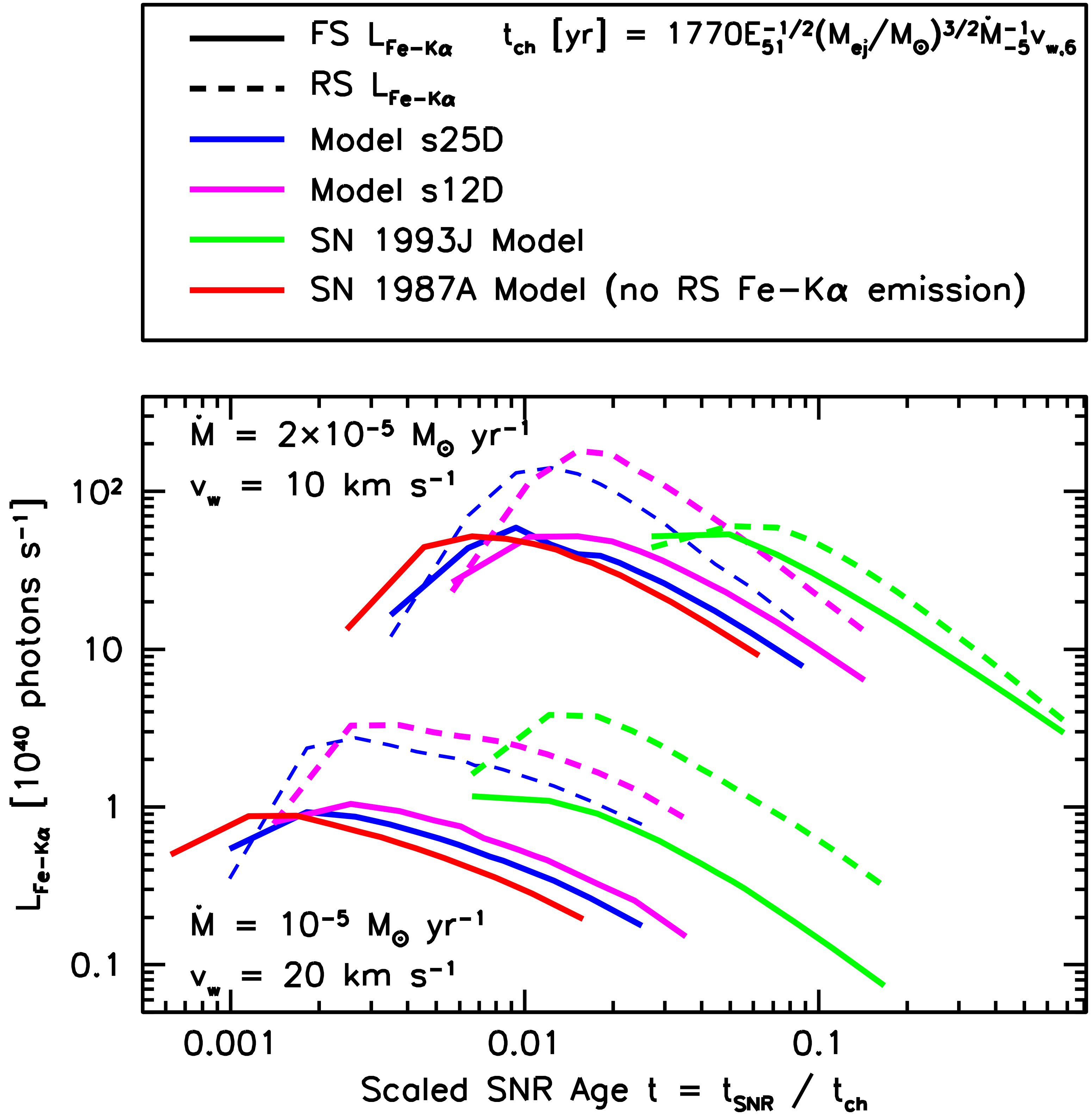
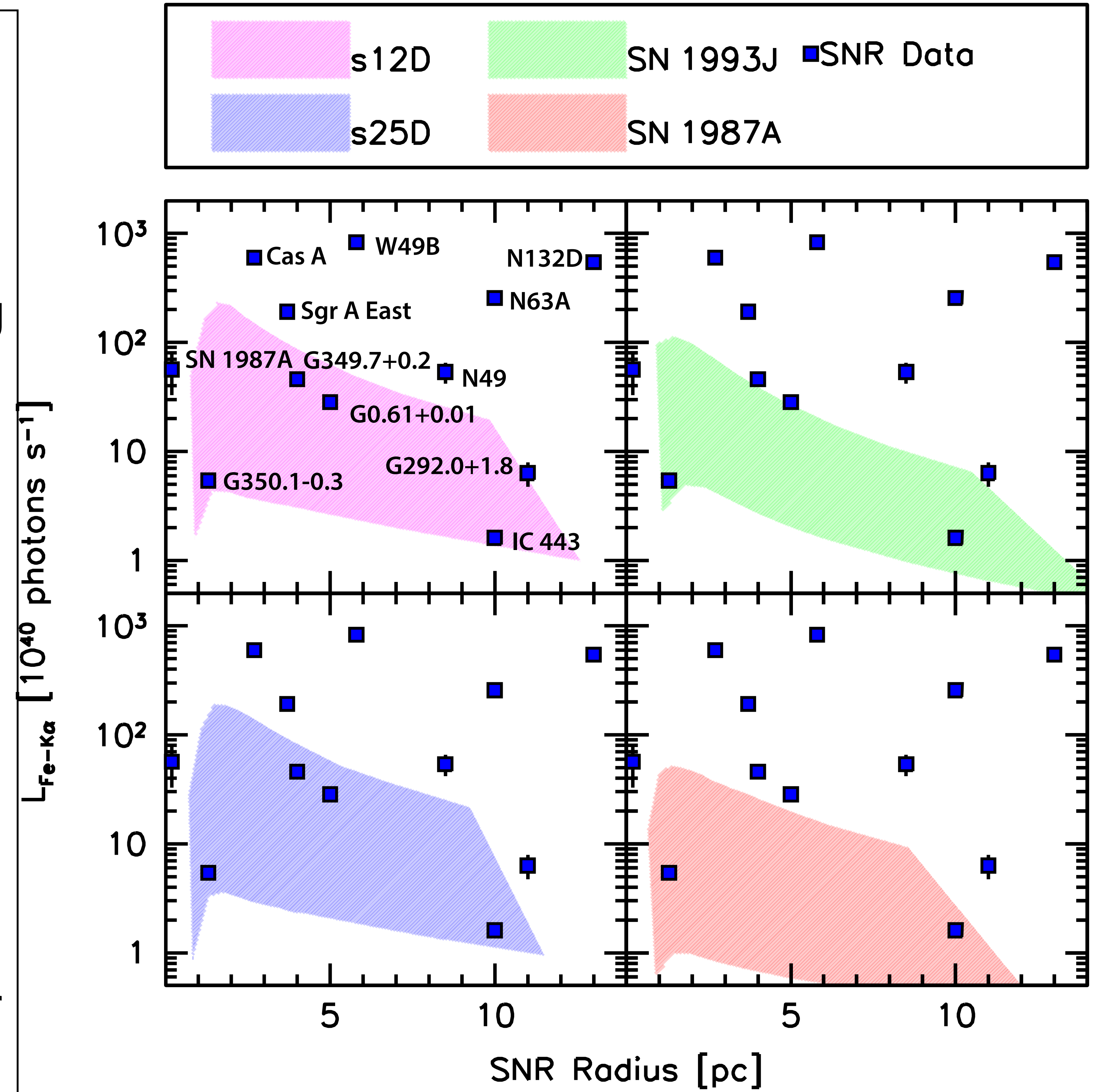


Patnaude et al. (2015)

WHAT ABOUT CCSNE?

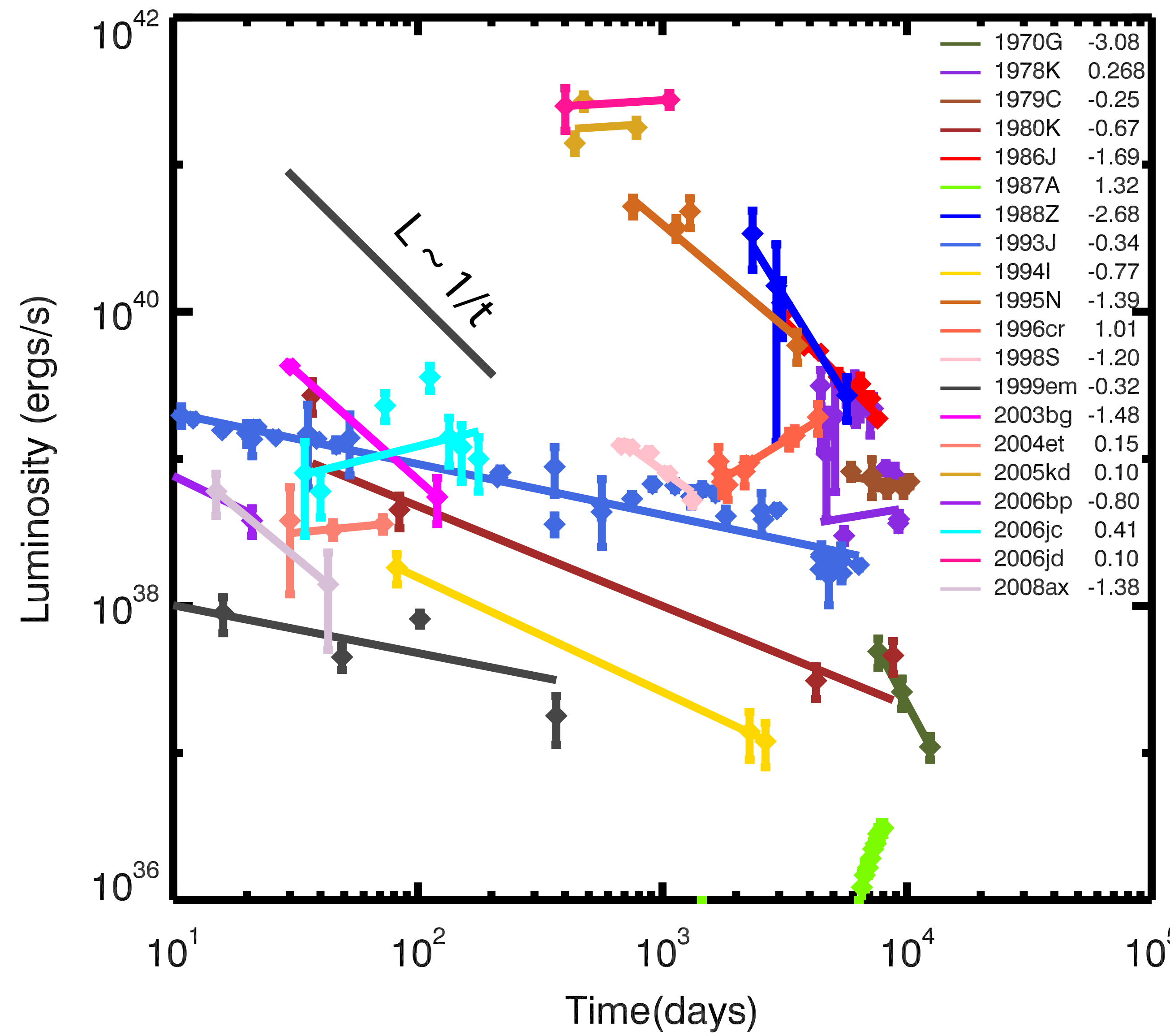
- Modeled SNR radii are consistent with observed radii in SNR, but generally the Fe-K luminosity vs radius shows that the models are underestimating $L_{Fe\text{-}K}$
- $R_b \propto \dot{M}^{-(1/(n-s))}$
- $L_X \propto \dot{M}^2$
    - Large increases in $\dot{M}$ result in an increase in L_X without significantly changing R_b
- Several SNe show evidence for eruptive pre-SN mass loss (e.g., SN 2009ip)



Patnaude et al. (2015)

X-RAY LIGHT CURVES OF SNE

- Isotropic mass loss implies a steady decline in the X-ray luminosity
- X-ray light curves show strong evidence for departures from steady mass loss
- see poster by V. Dwarkadas (S1.5) for more details



Dwarkadas & Gruszko (2012)

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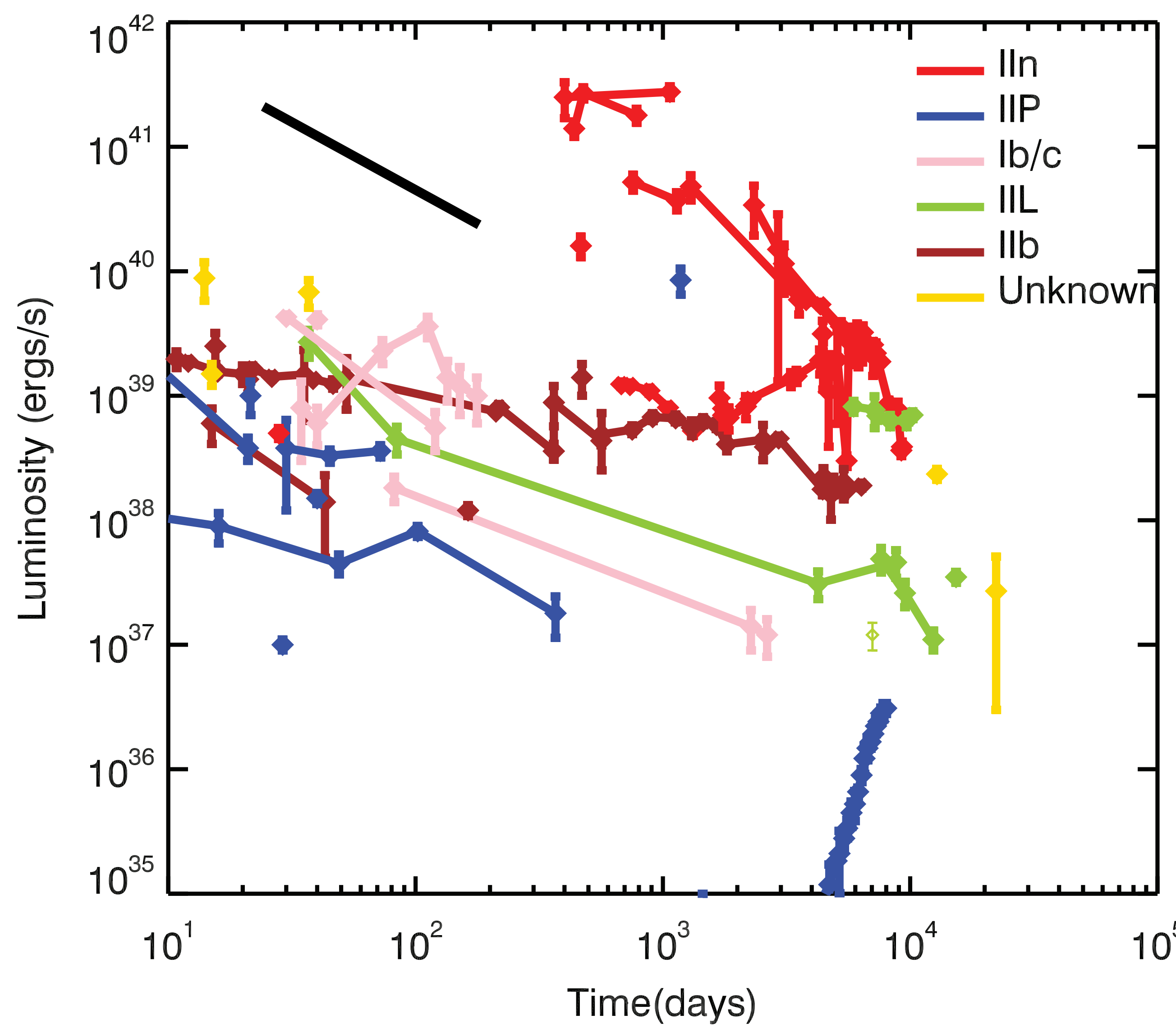
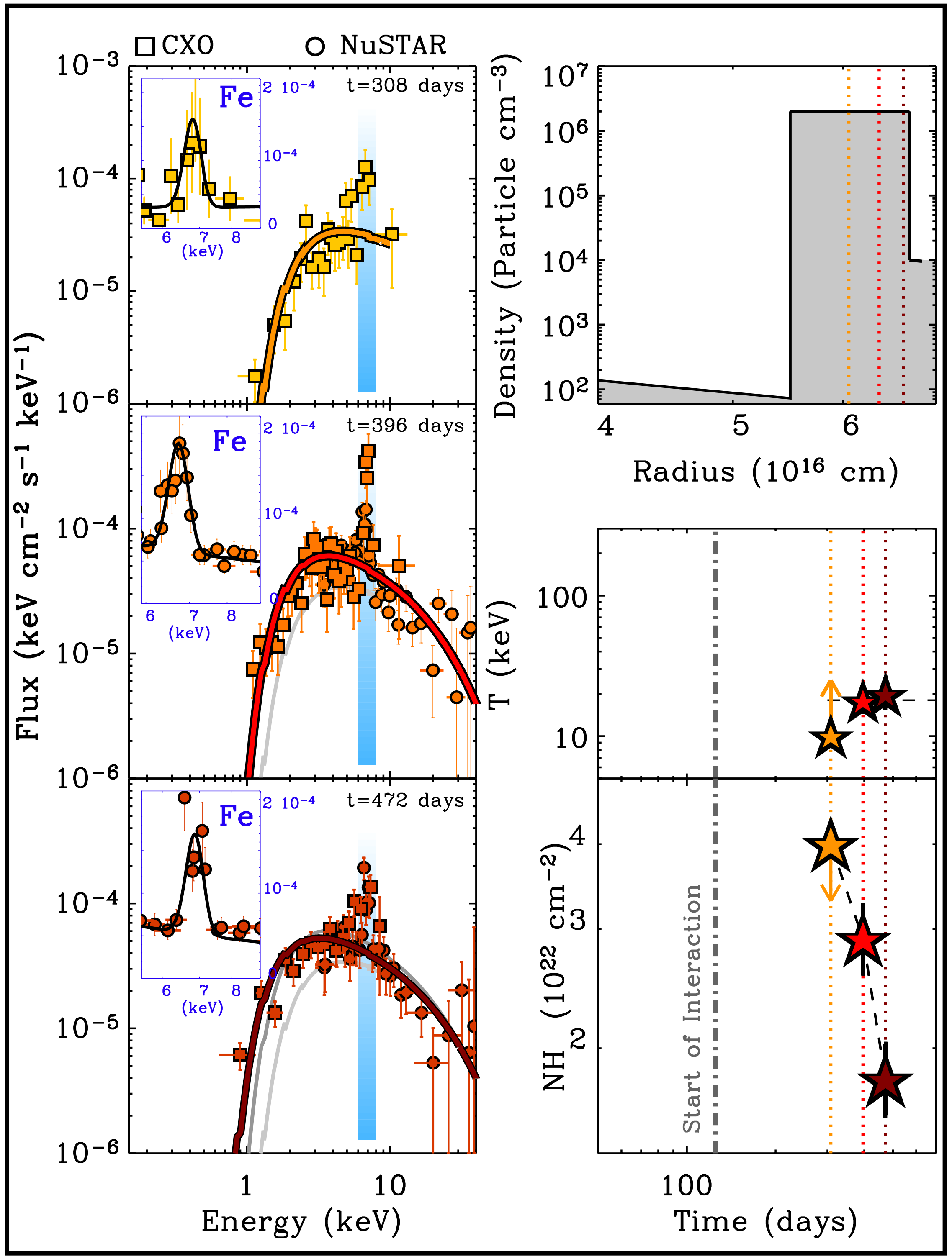
- see poster by V. Dwarkadas (S1.5) for more details
- Light curves argue for long term monitoring of X-ray SNe to probe CSM properties



Dwarkadas & Gruszko (2012)

LOOK TO SNE TO UNDERSTAND MASS LOSS



SN 2014C transitioned from a Ib to a IIn ~ 1 year after explosion. The transition was driven by the interaction between the blast wave and a dense CSM shell ejected from the progenitor ~ 500 yr before CC

Margutti et al (2016)

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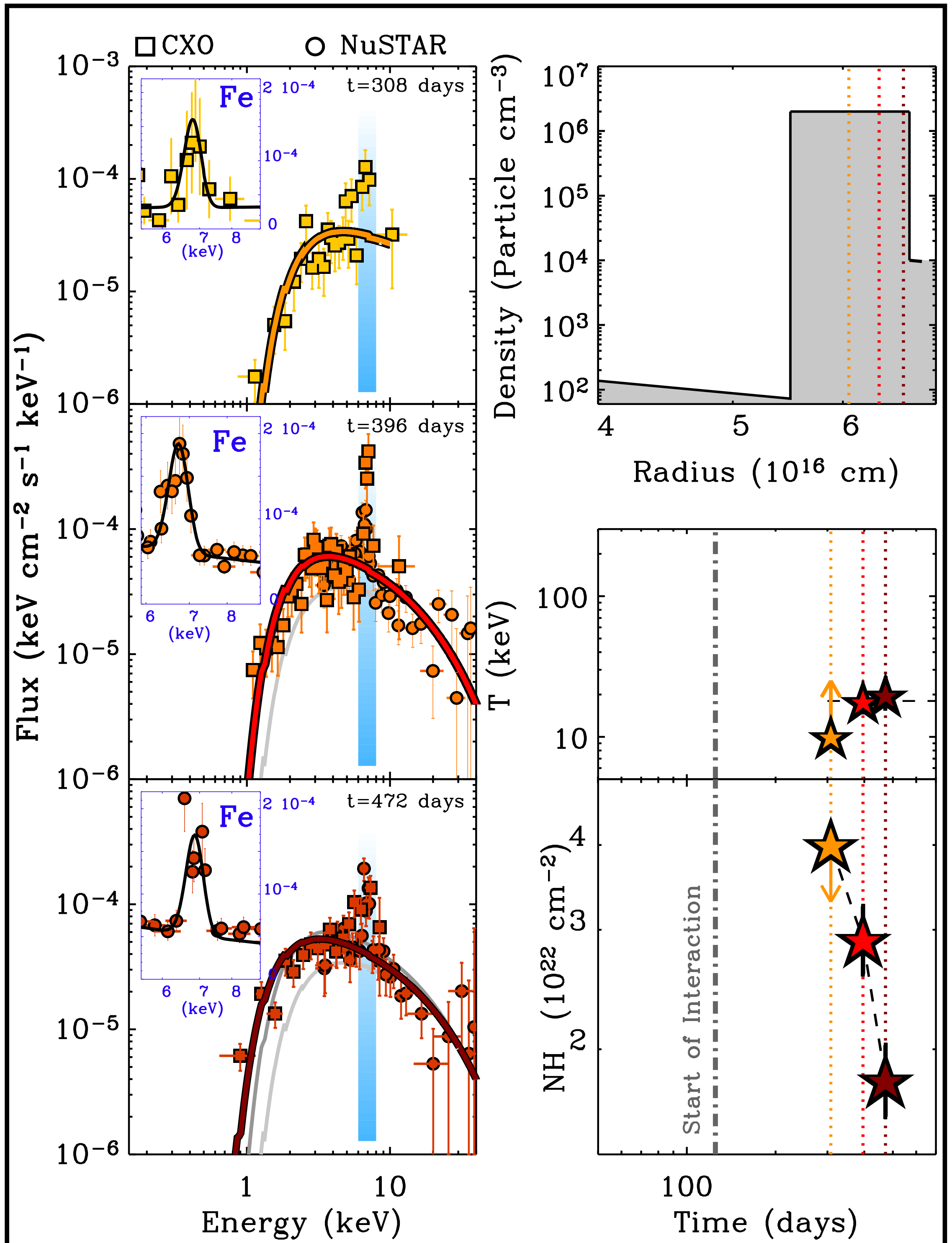

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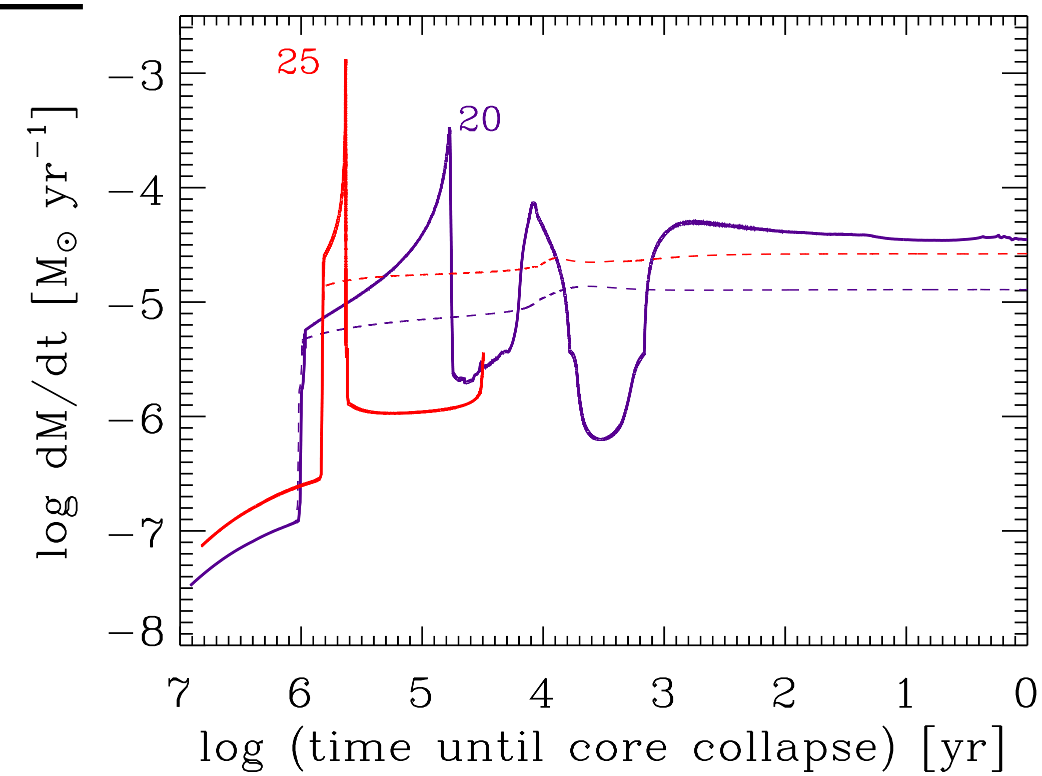
Other SNe show evidence for episodic mass loss prior to core collapse (2009ip; 2010mc; 2001em)

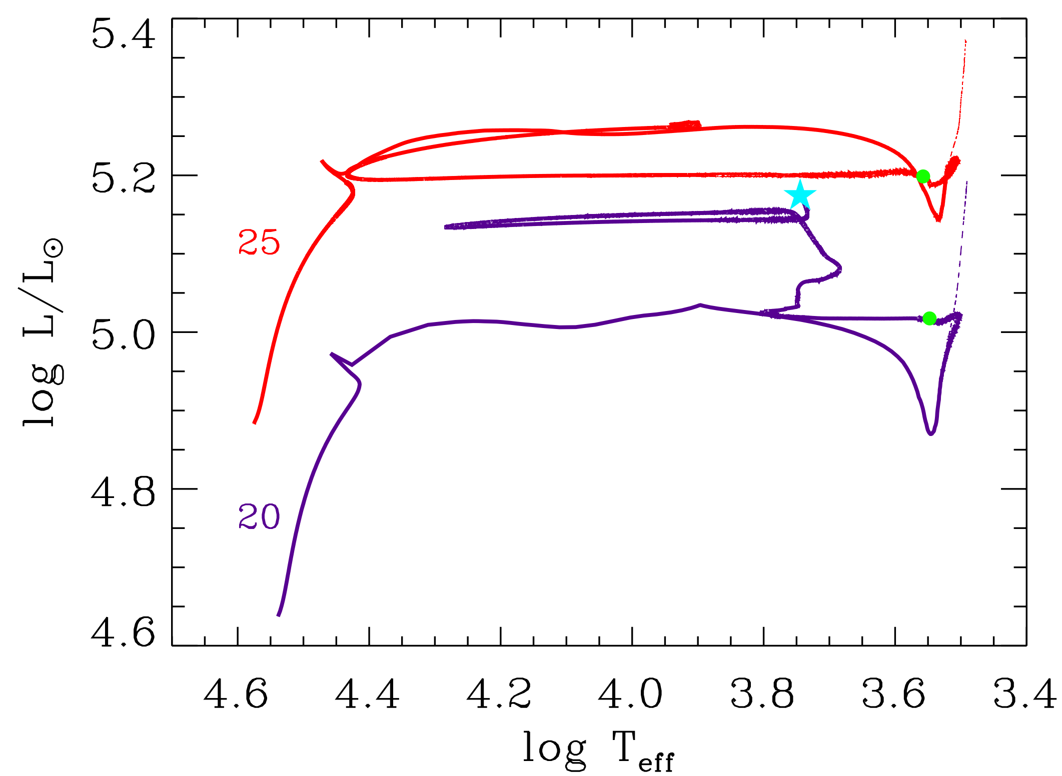
Margutti et al (2016)

MECHANISMS FOR ENHANCED MASS LOSS

Pulsational driven super-winds can enhance mass loss in early stages of massive star evolution

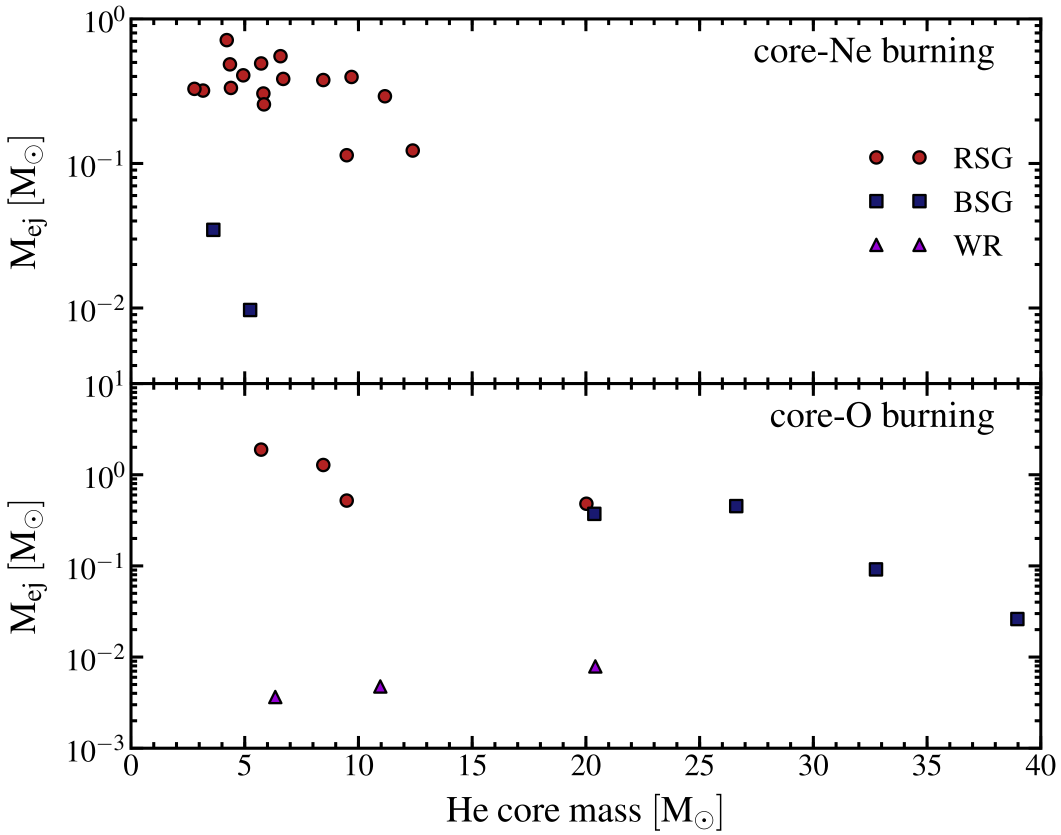
Mass loss prior to core collapse is not enhanced and the PDSW cannot explain enhanced CSM interaction in SNe

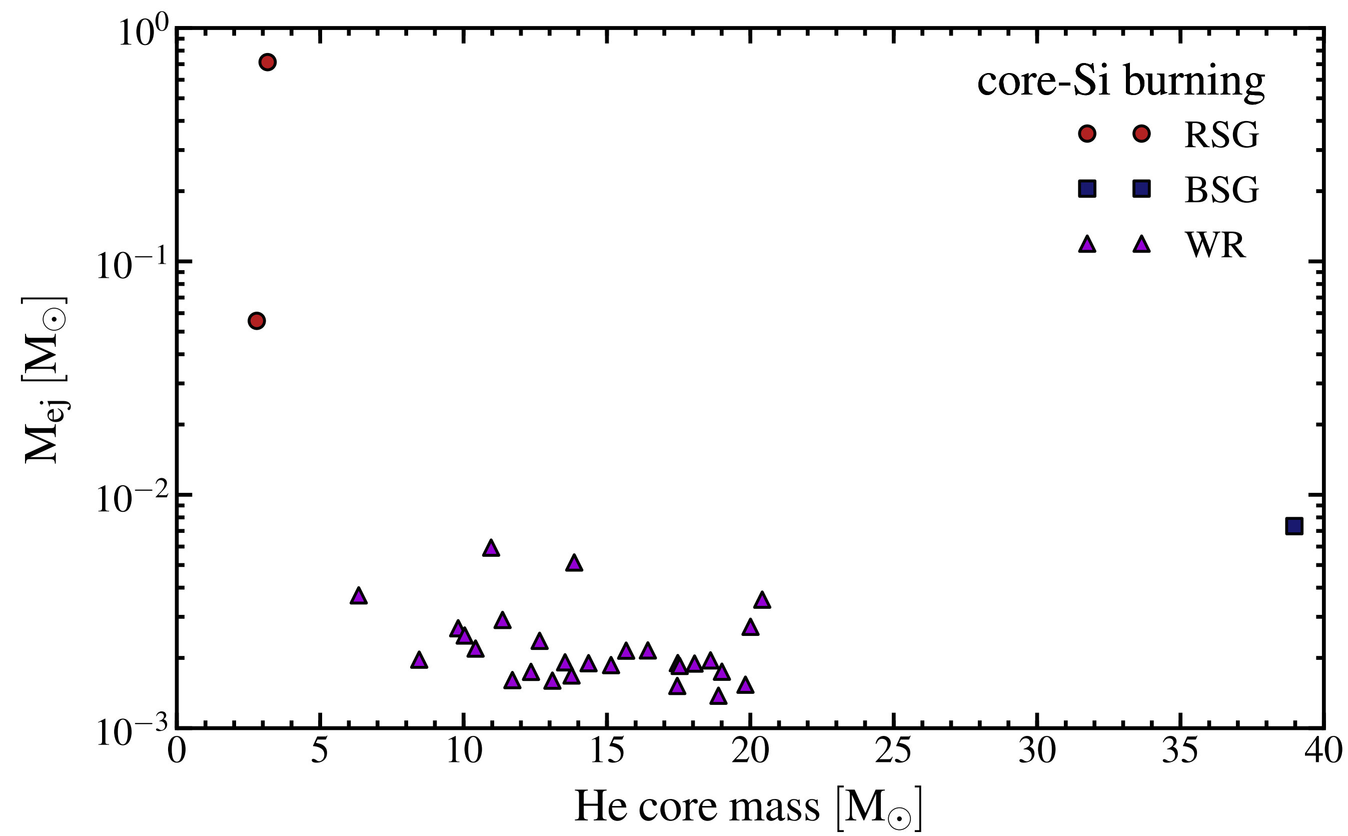


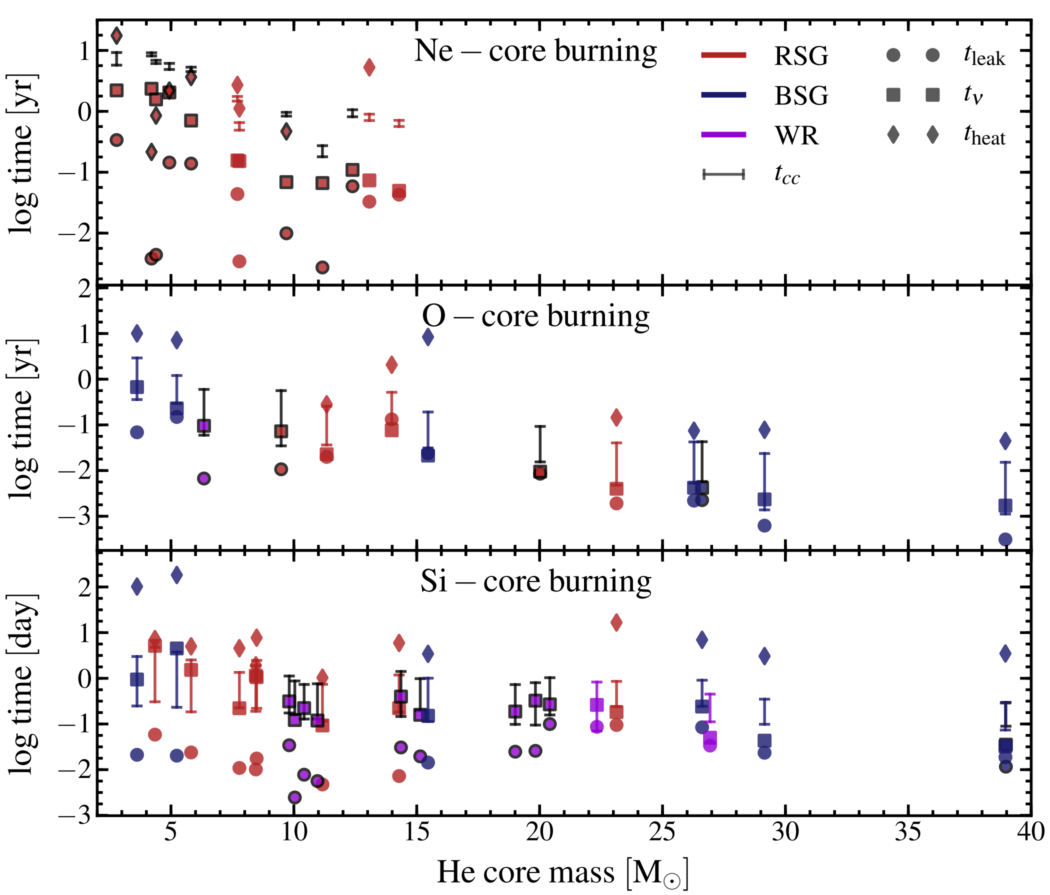


Yoon & Cantiello (2010)

Mechanisms for enhanced mass loss



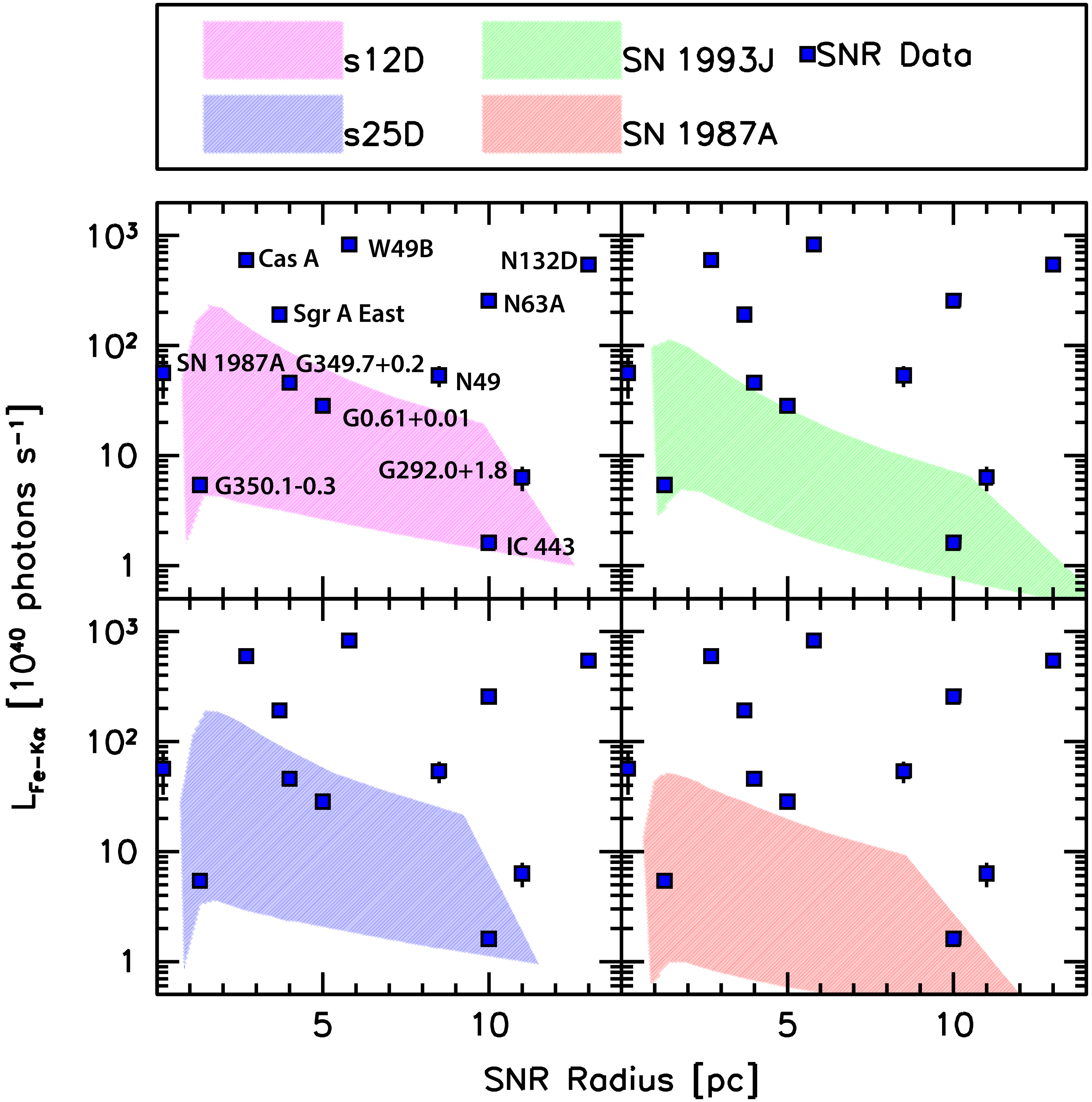




Convection driven instabilities can lead to the ejection of envelope material with masses 10^{-2} - 10^{-1} M_{sun} a few years before CC (Shiode & Quataert; 2014)

MECHANISMS FOR ENHANCED MASS LOSS

Episodic mass loss prior to core-collapse may lead to increased ionization and higher line luminosities at much later times



CONCLUSIONS

- Models should encode both the dynamics and spectral properties of the SNR
- Kepler’s SNR is the result of a 1991T-like event
- Models for core-collapse supernova progenitors can broadly reproduce Fe-K line emission and luminosity
    - Episodic mass-loss from convection driven instabilities may explain observed enhanced Fe-K emission

Meeting Announcement

Deadline for regular conference registration ($280 USD) is Thu, June 30, 2016.
Late registration ($330 USD) will be open until Fri, July 15th, 2016.

http:cxc.harvard.edu/cdo/next_decade2016/