Harvard-Smithsonian
Center for Astrophysics

Connecting Remnants to Explosions and Their Progenitors

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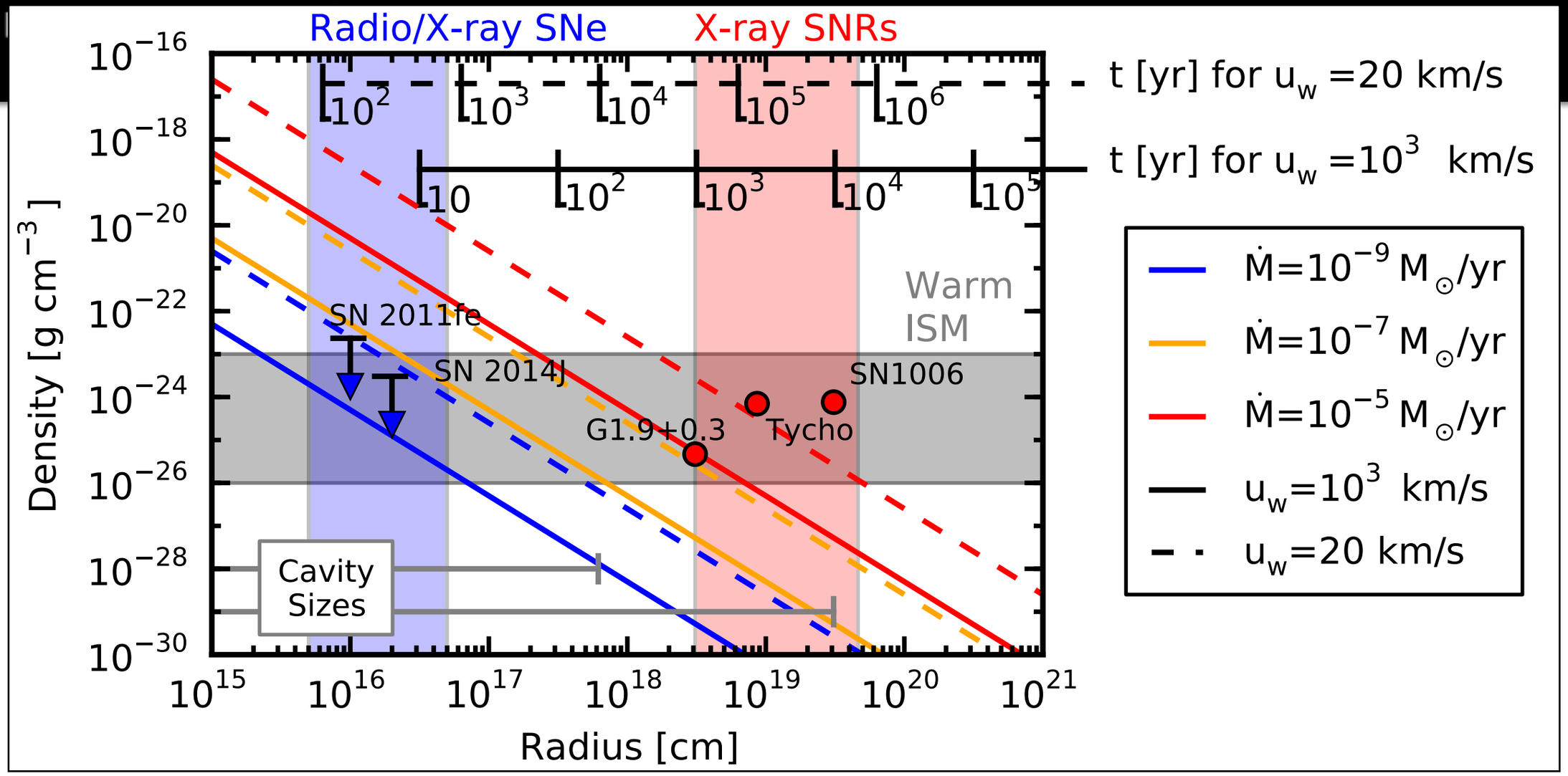
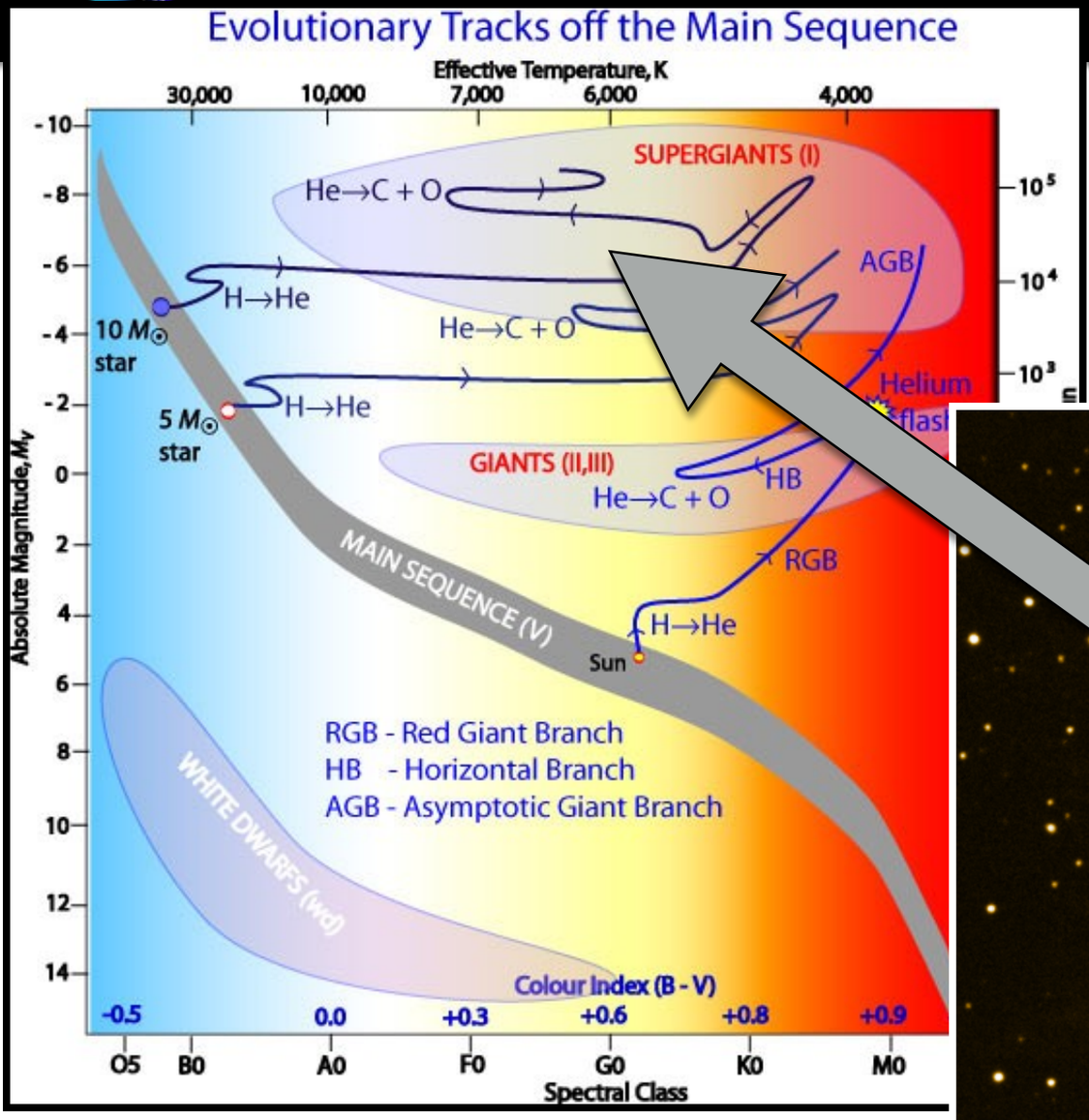
Shigehiro Nagataki (RIKEN)



SNR Evolution vs CSM Properties for fast and slow outflows (Patnaude & Badenes 2017; Springer Handbook of Supernovae)

- SNe probe the last 50-100 years of progenitor evolution
- SNR sample a much earlier phase of evolution, but late evolution can definitely impact what we observe today, and how we interpret it



Example HR Diagram with massive star evolution (credit: J. Imamura)

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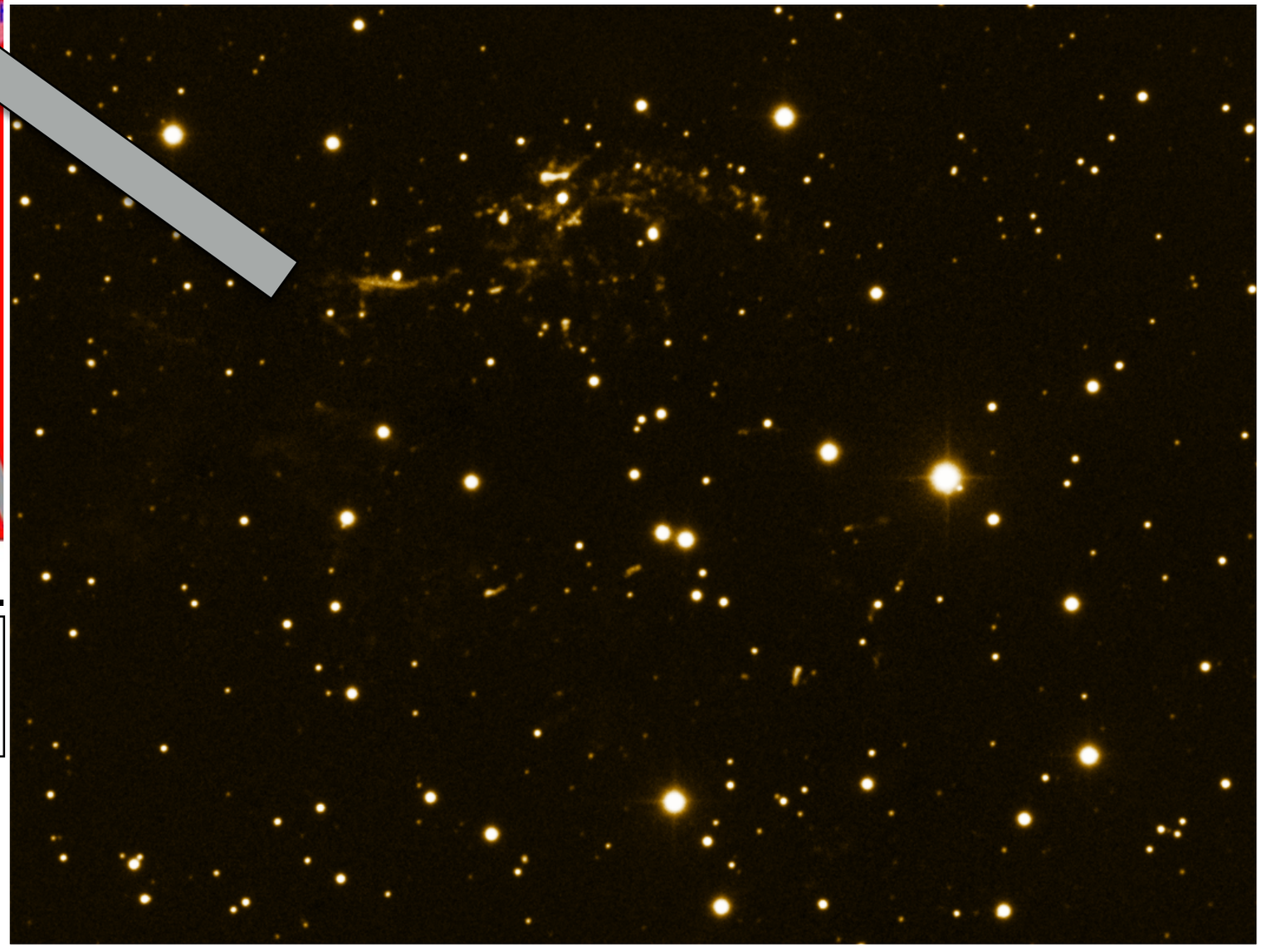

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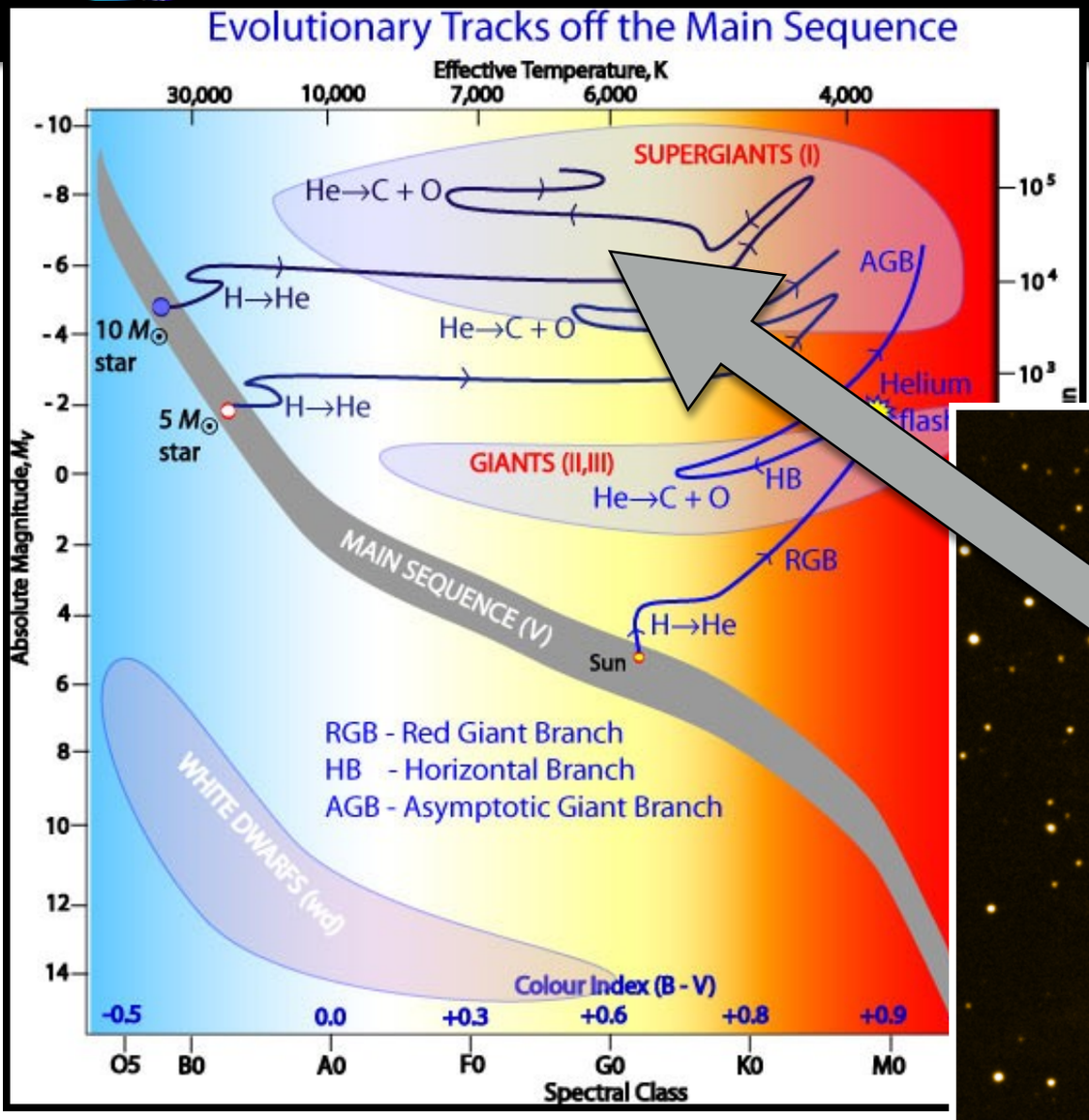

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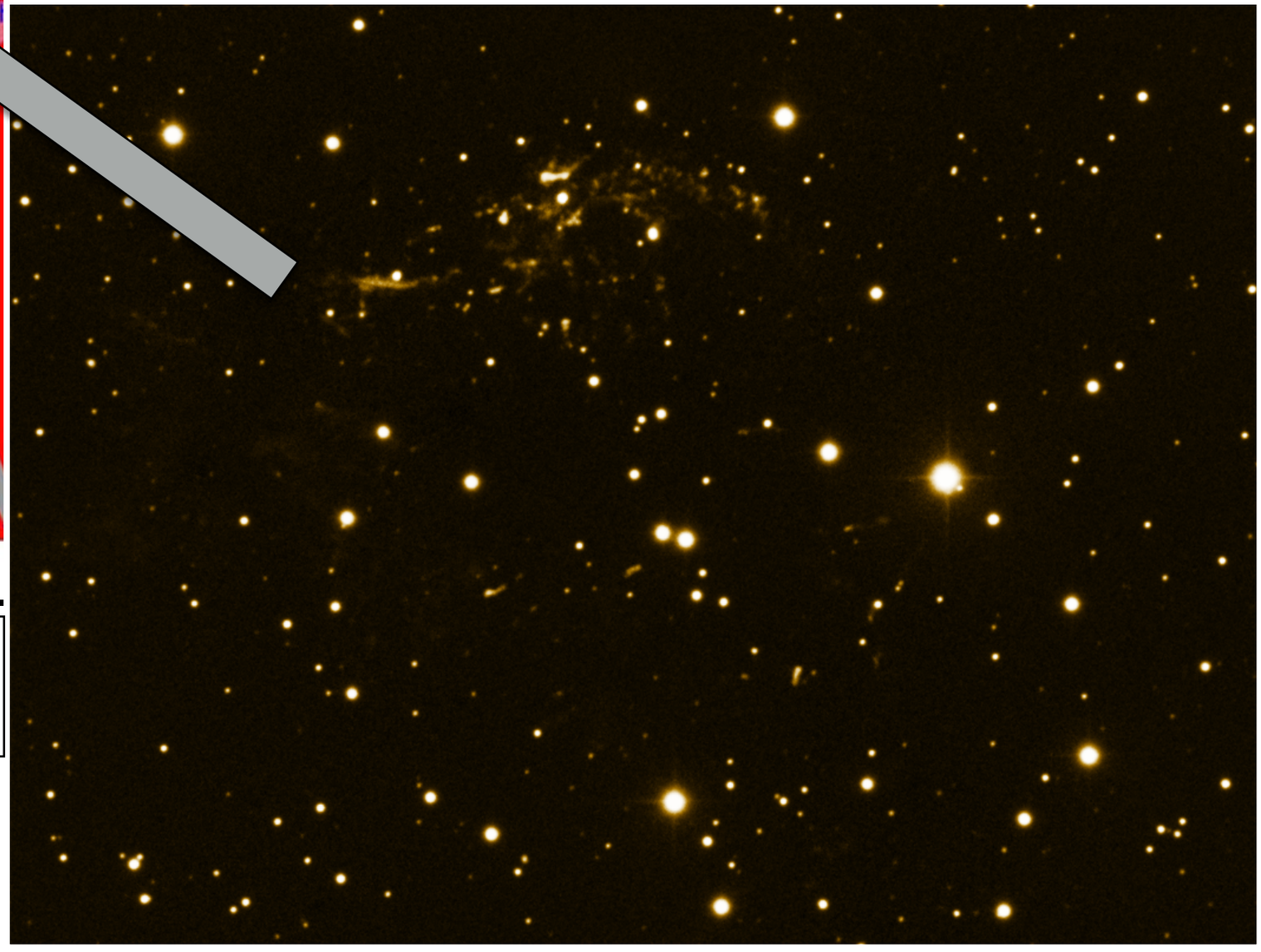

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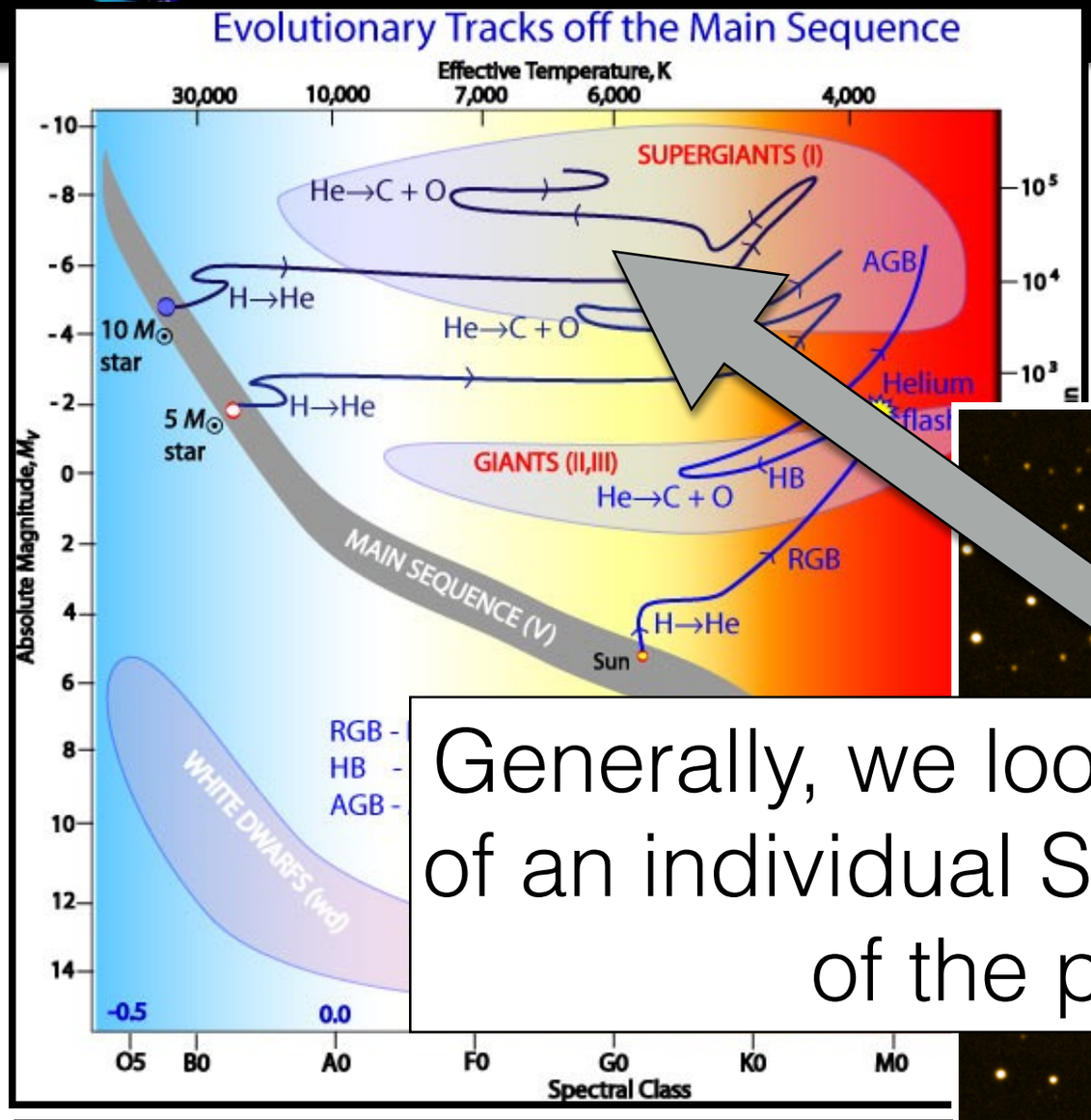

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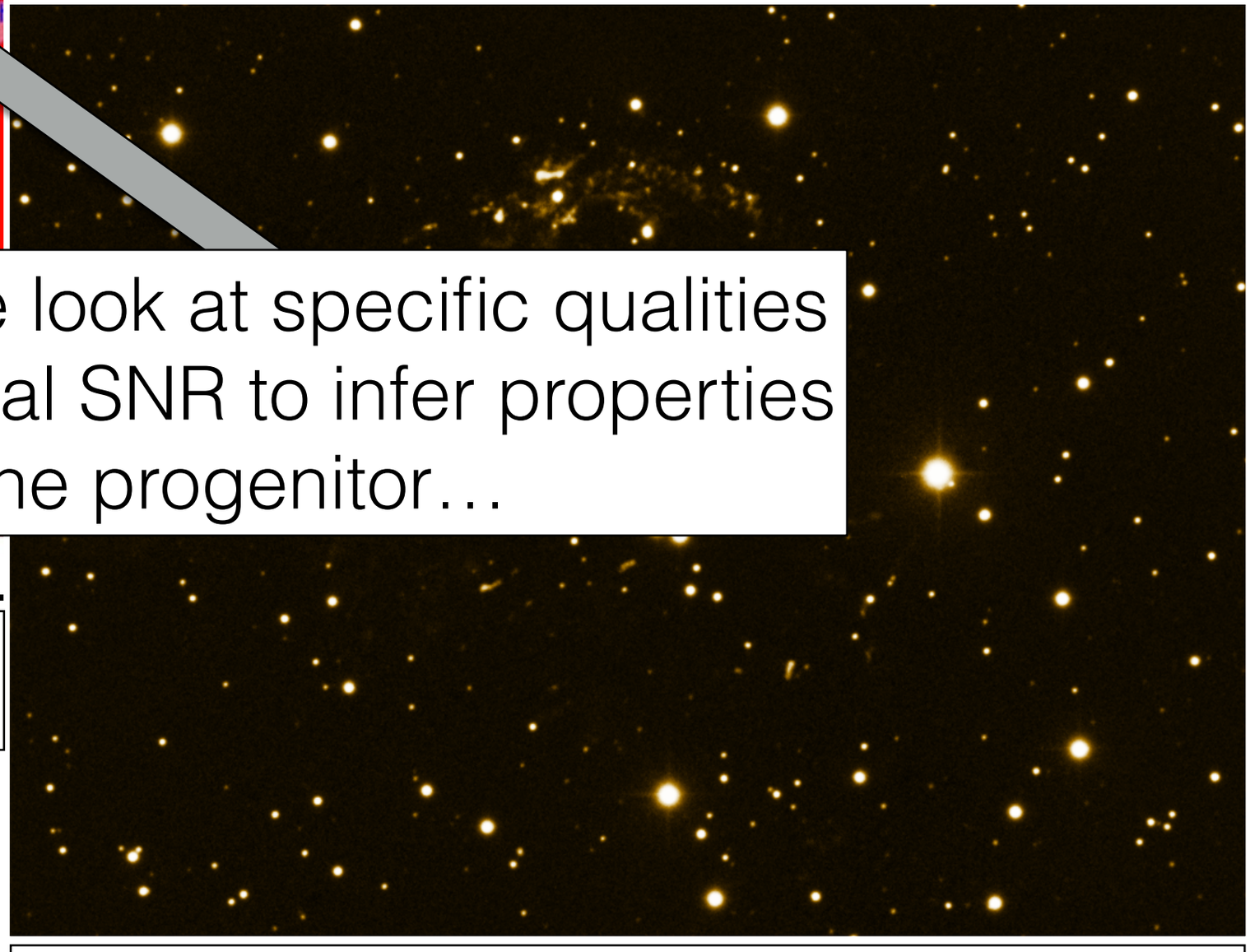

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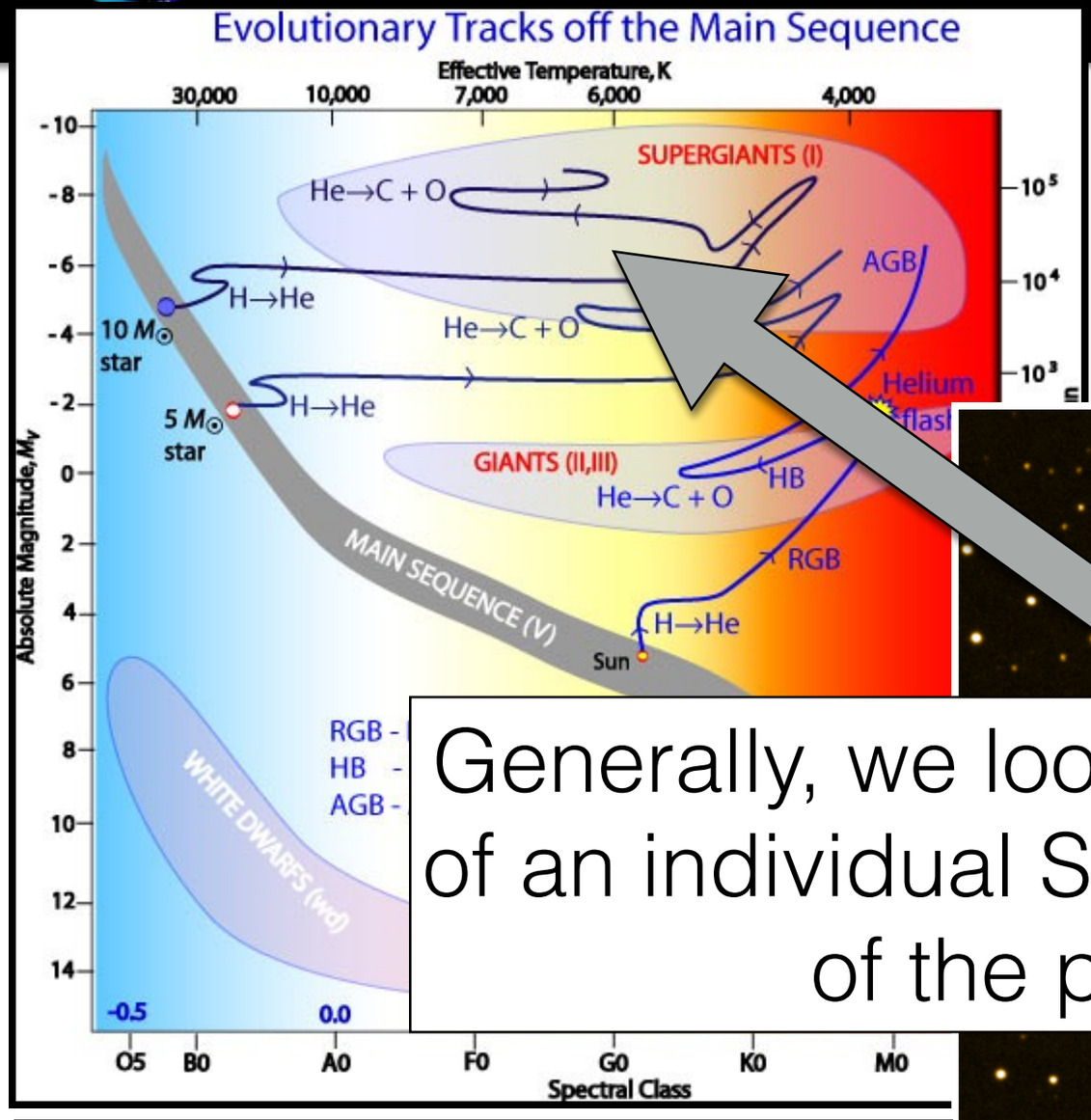

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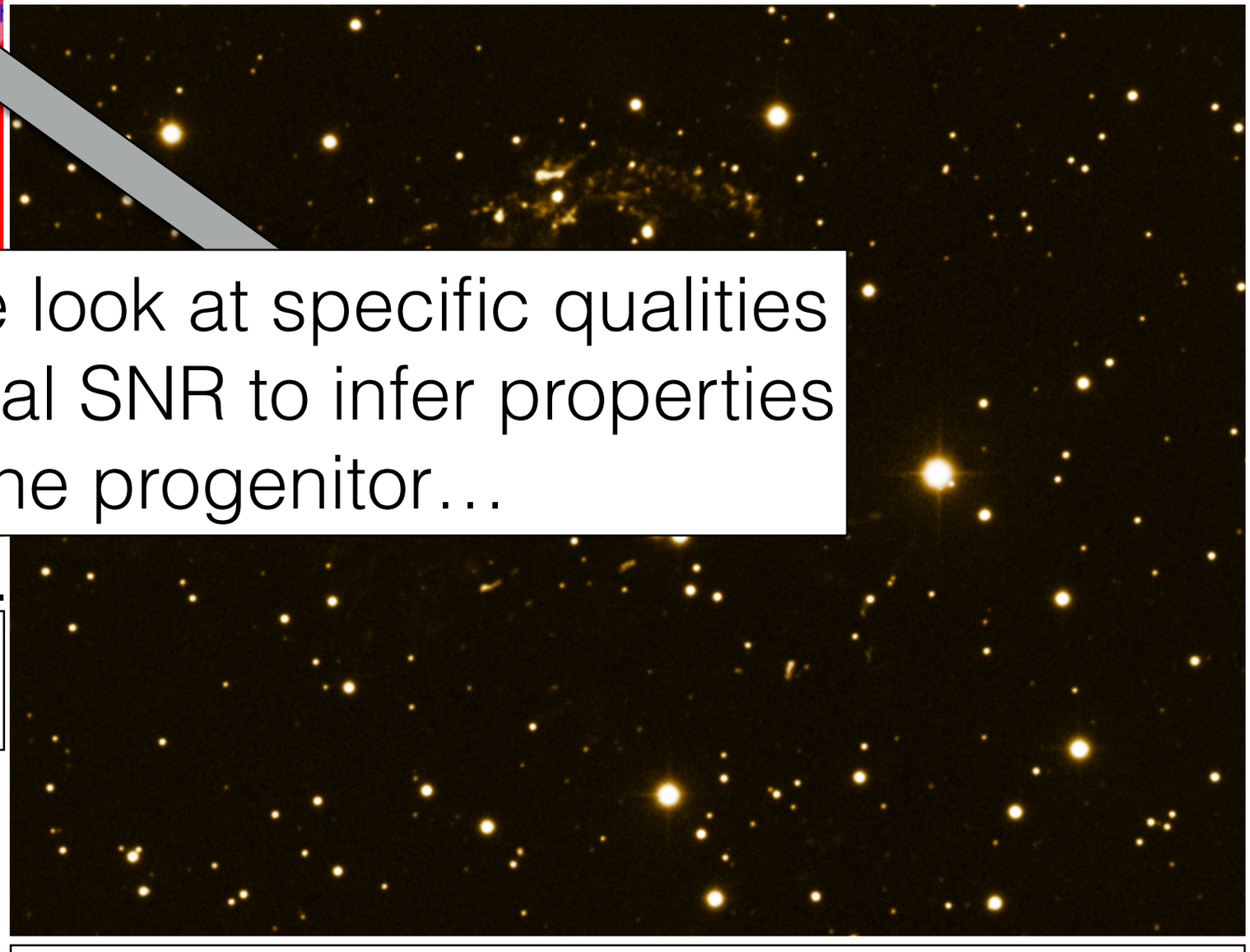

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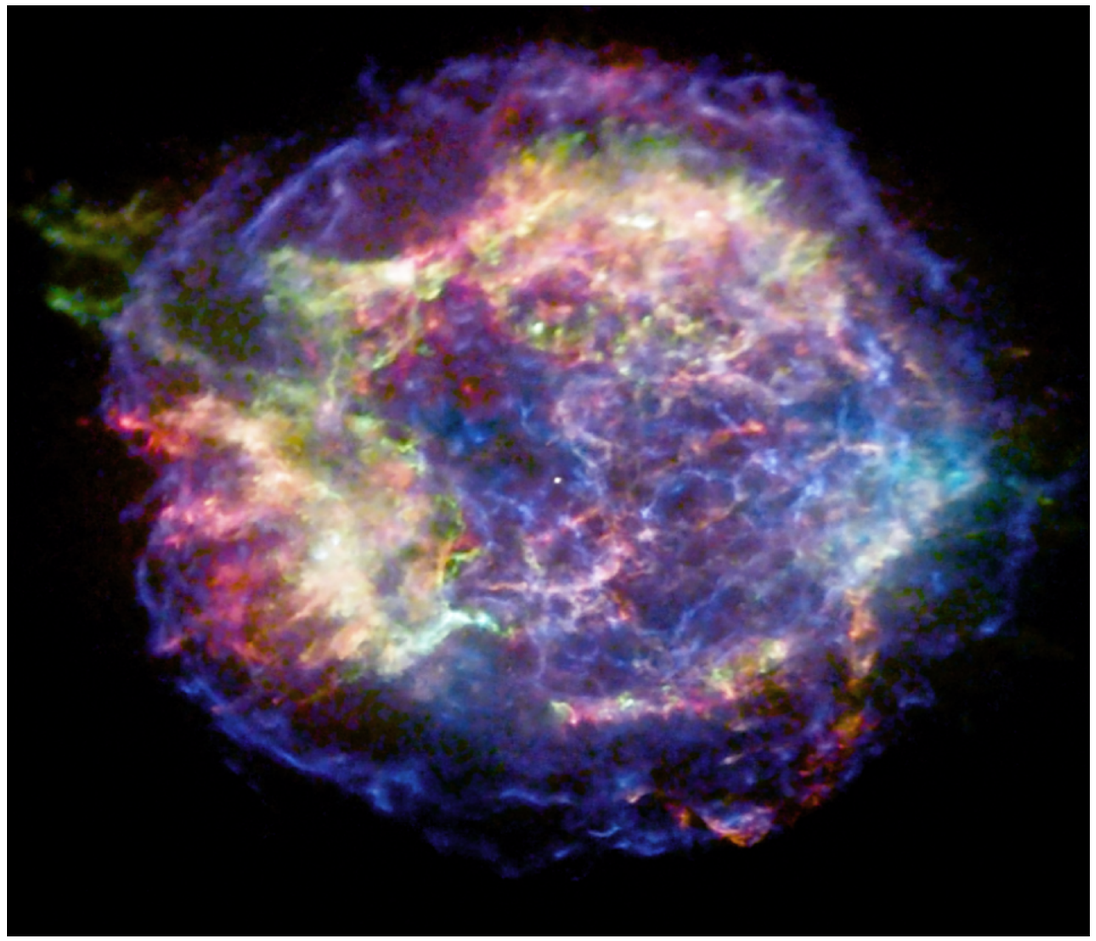
Cas A:

- Youngest known Galactic CC SNR



Chandra RGB image of Cas A

Cas A:

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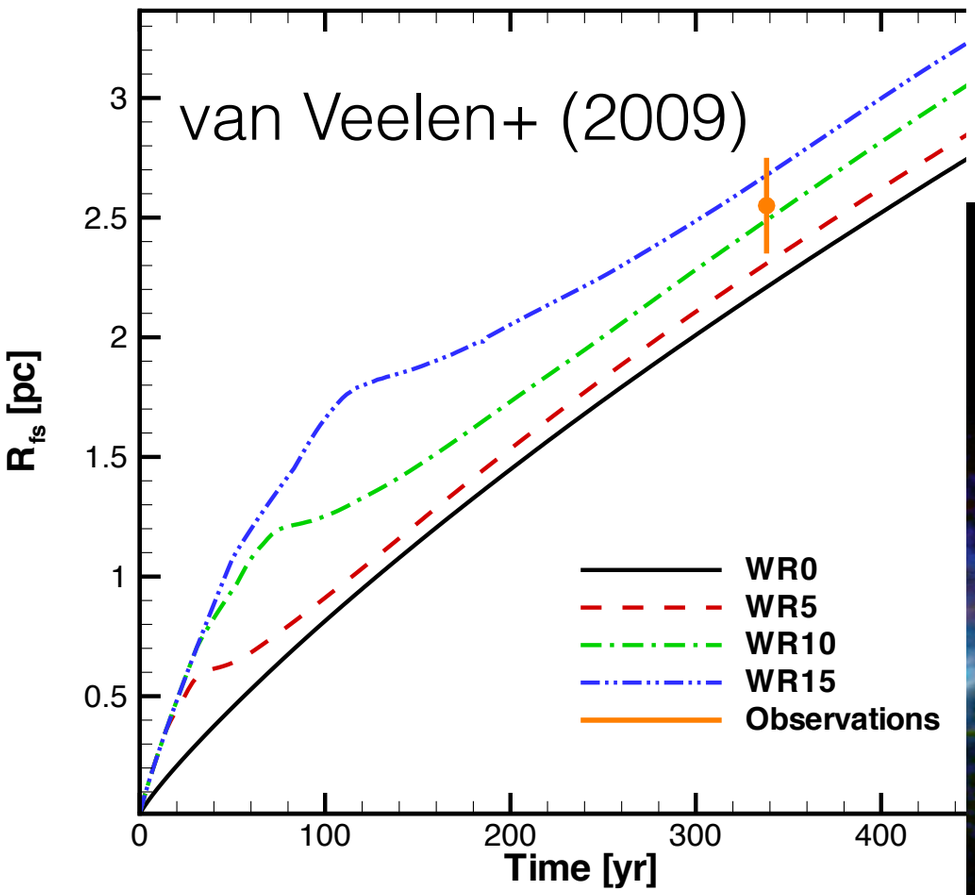
  - Cas A progenitor likely went through a short (< 10kyr) W-R phase



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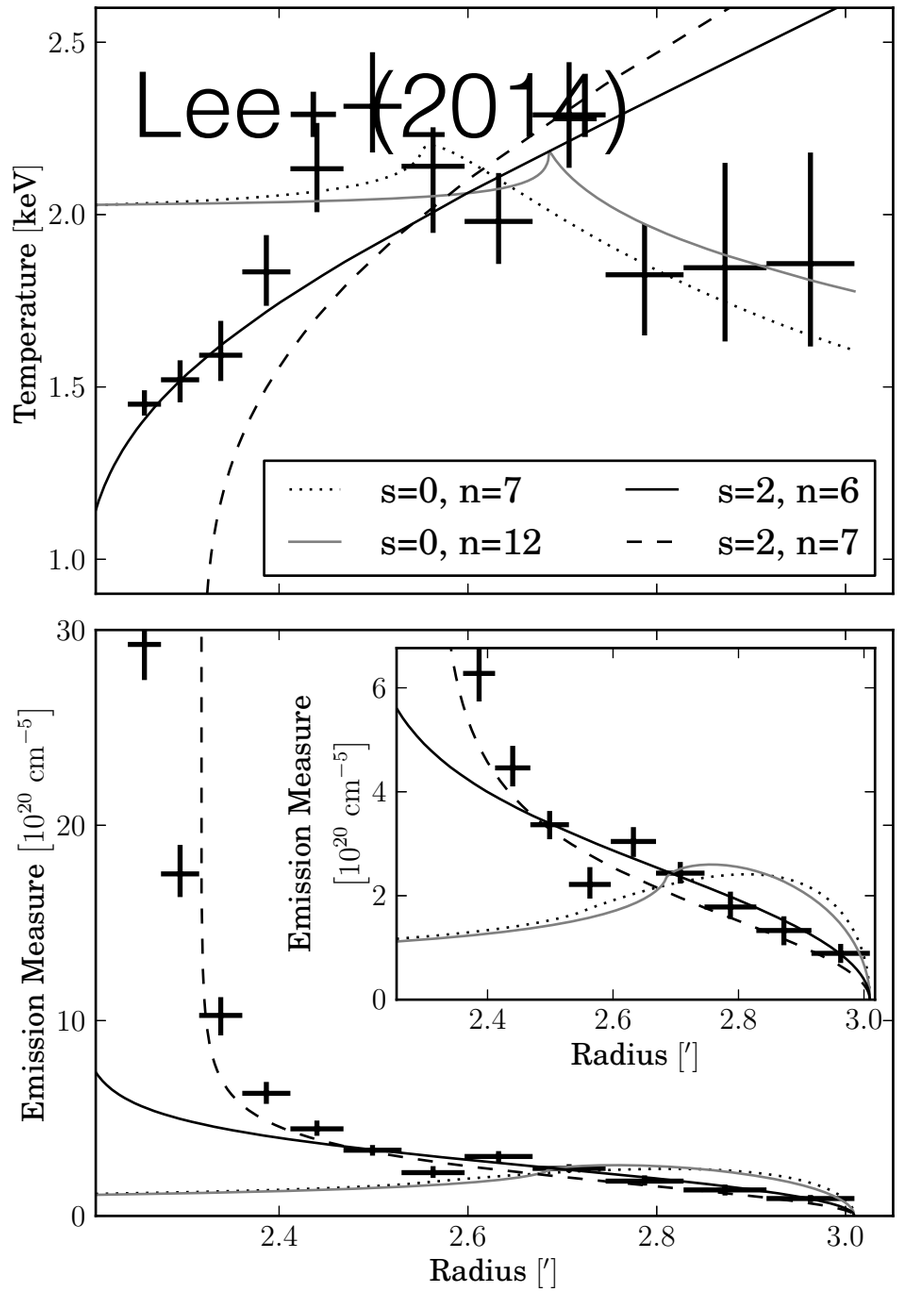

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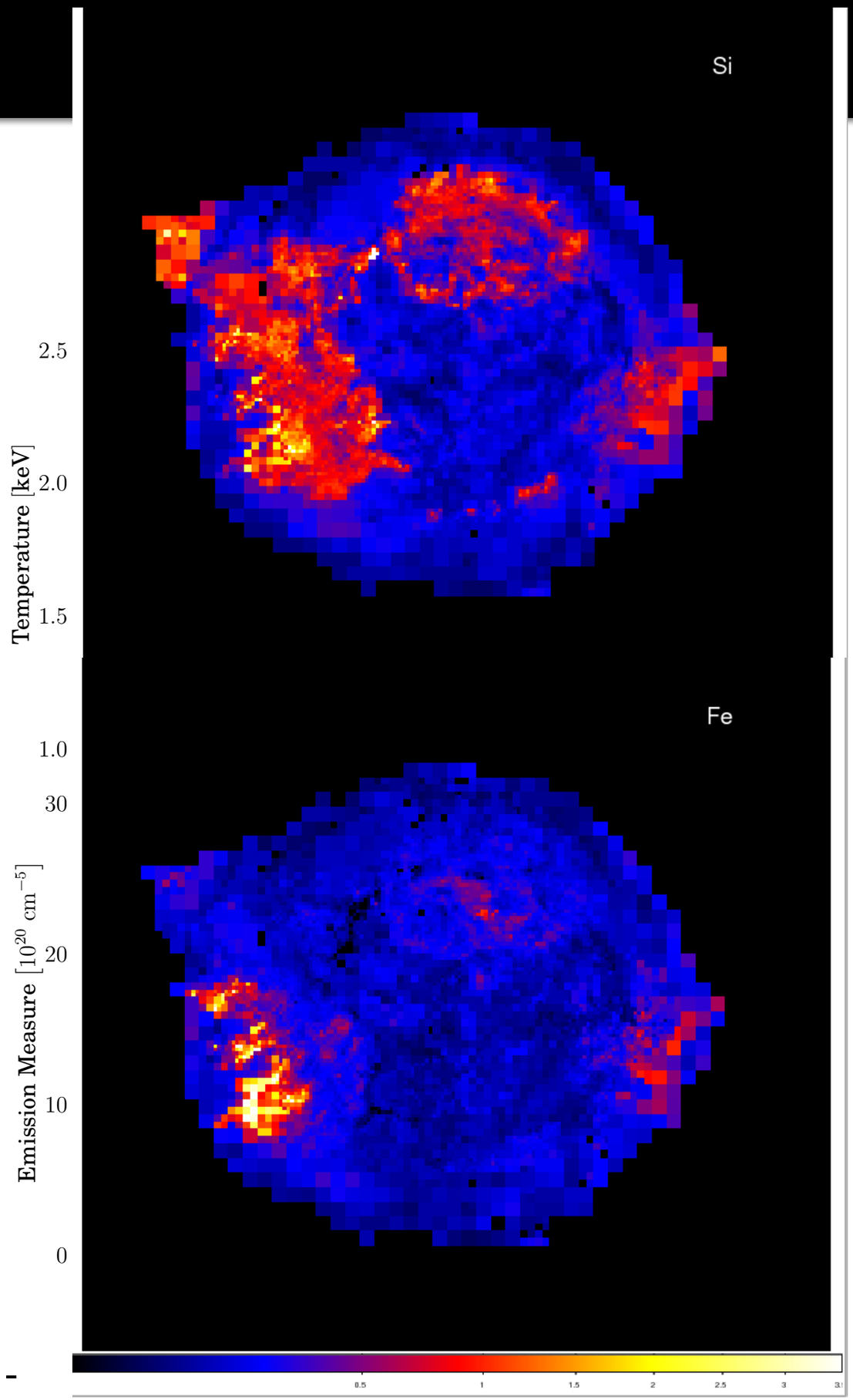
  - Measured abundances constrain nucleosynthesis during stellar evolution and core-collapse



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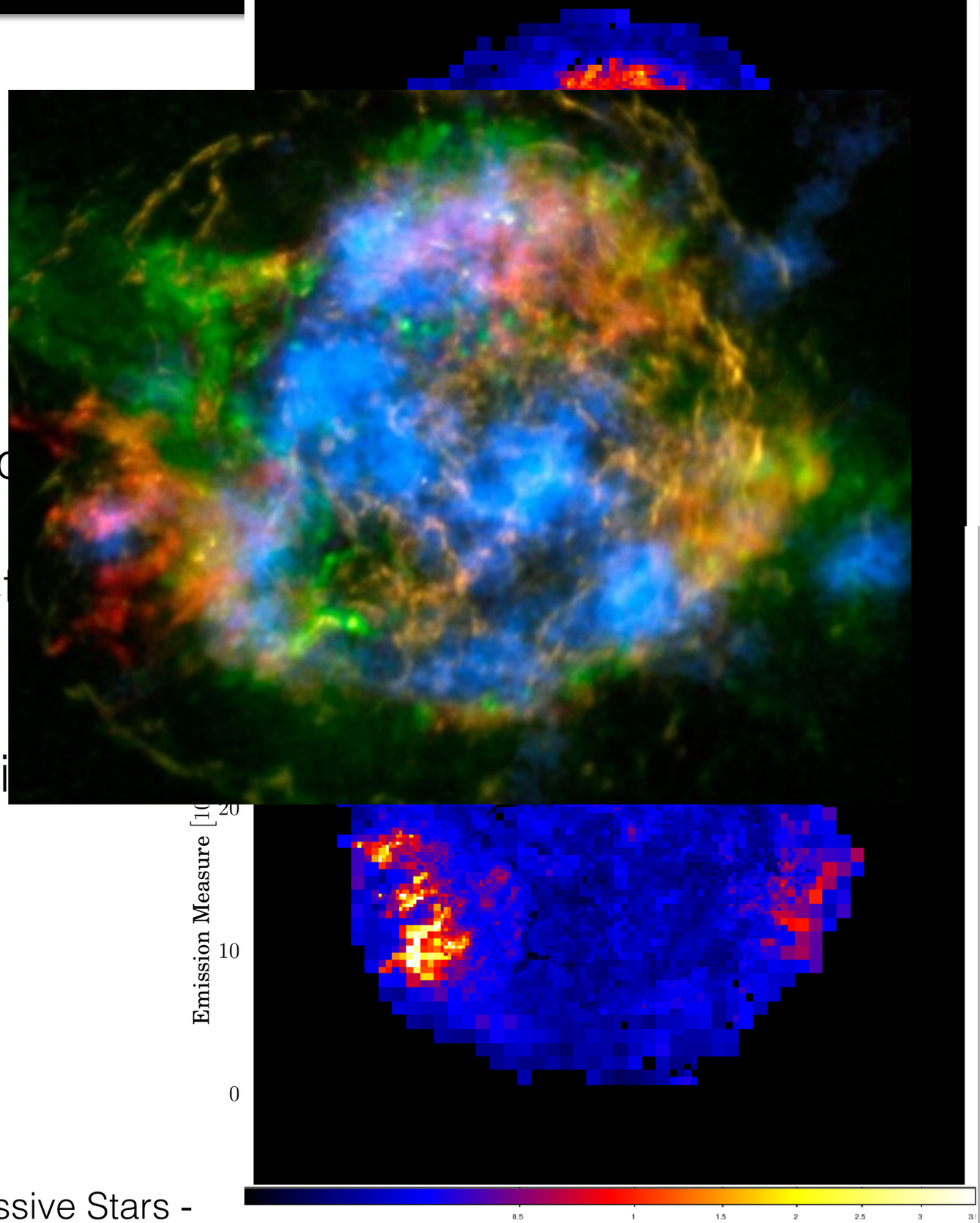
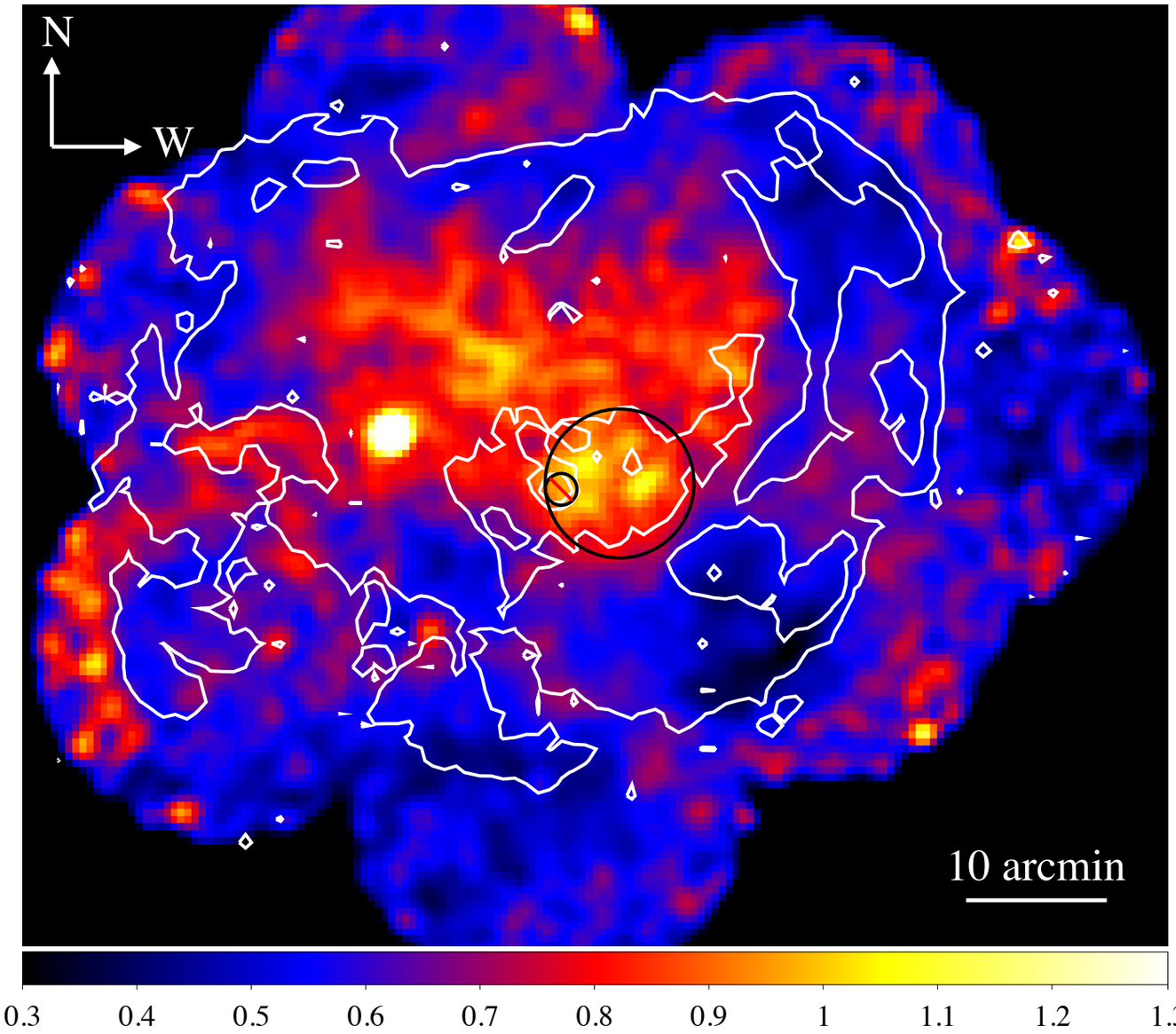


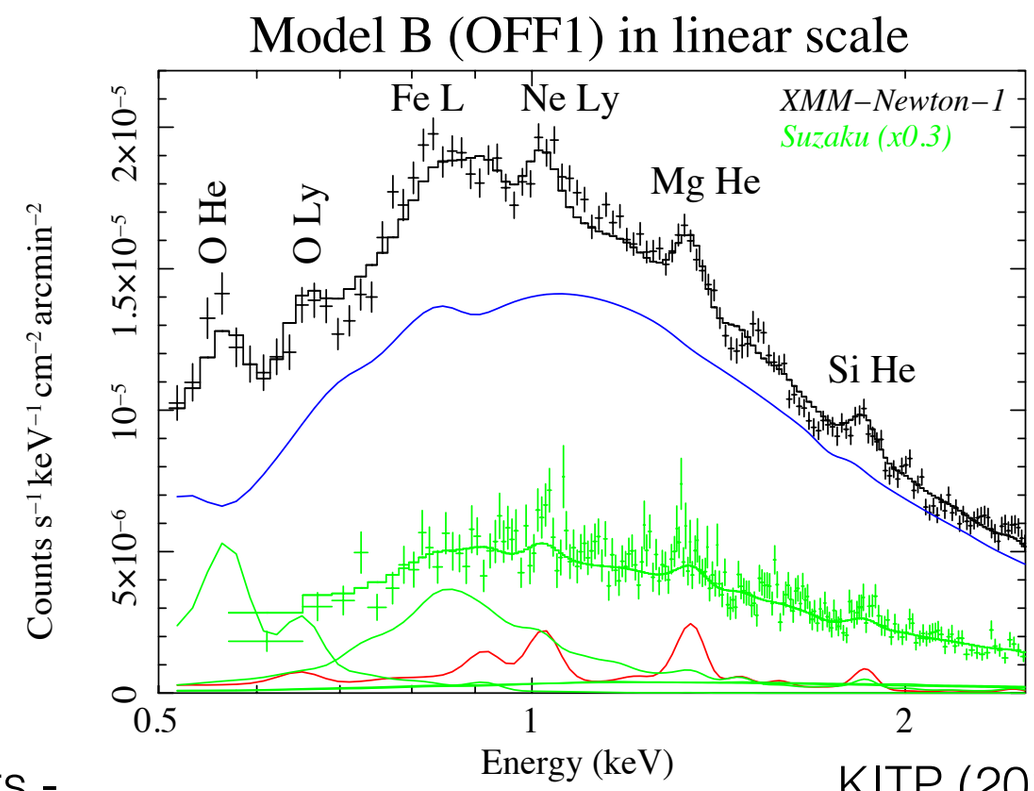
RX J1713-3946:



XMM-Newton image of RX J1713 with CO radio contours overlaid (Katsuda et al. 2015)

Thermal emission suggests:

- blastwave expanding in a low density cavity
- abundances infer a low mass (< 20 M_{sun})
- Progenitor likely lost much of its mass through binary interaction



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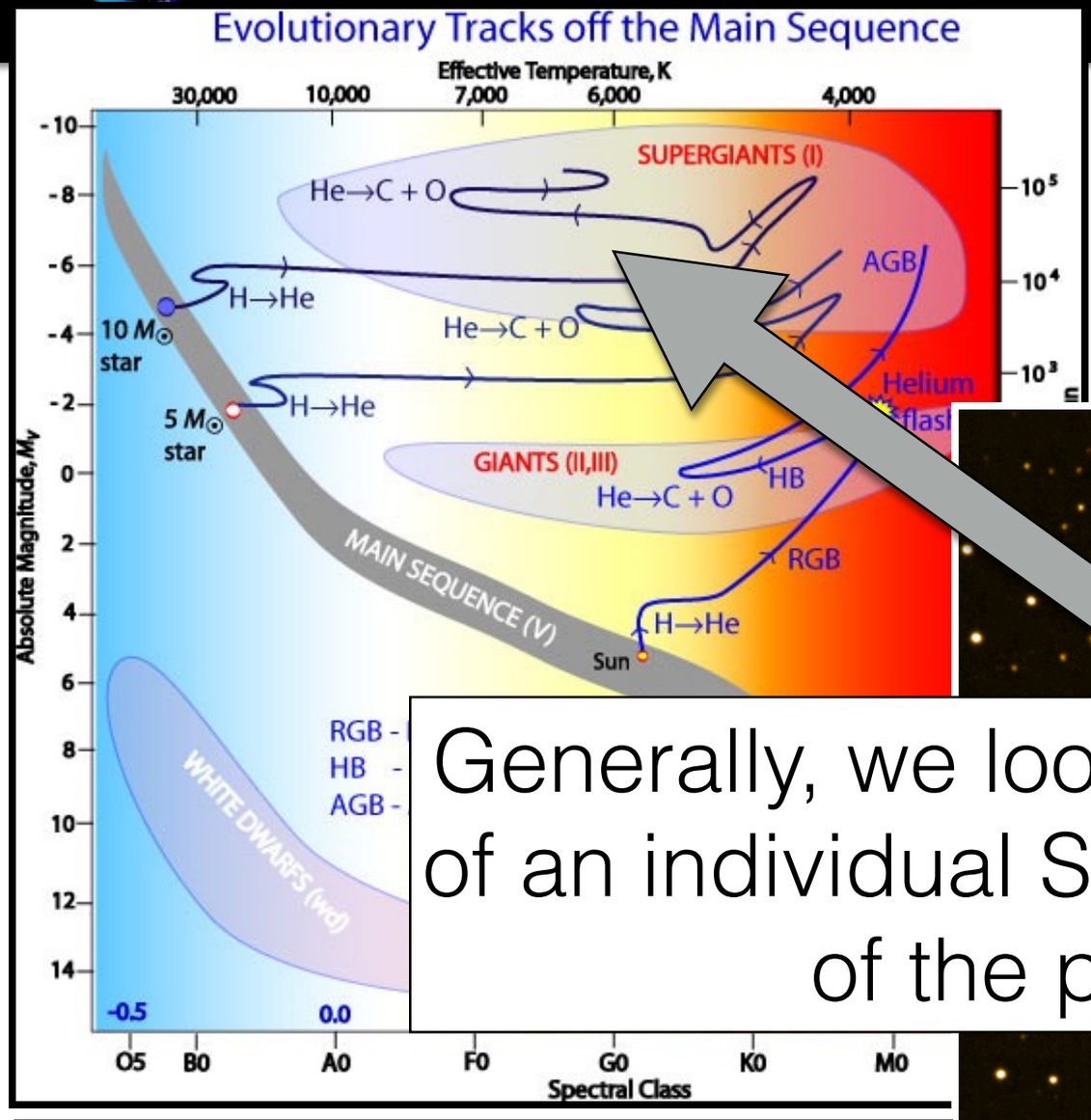

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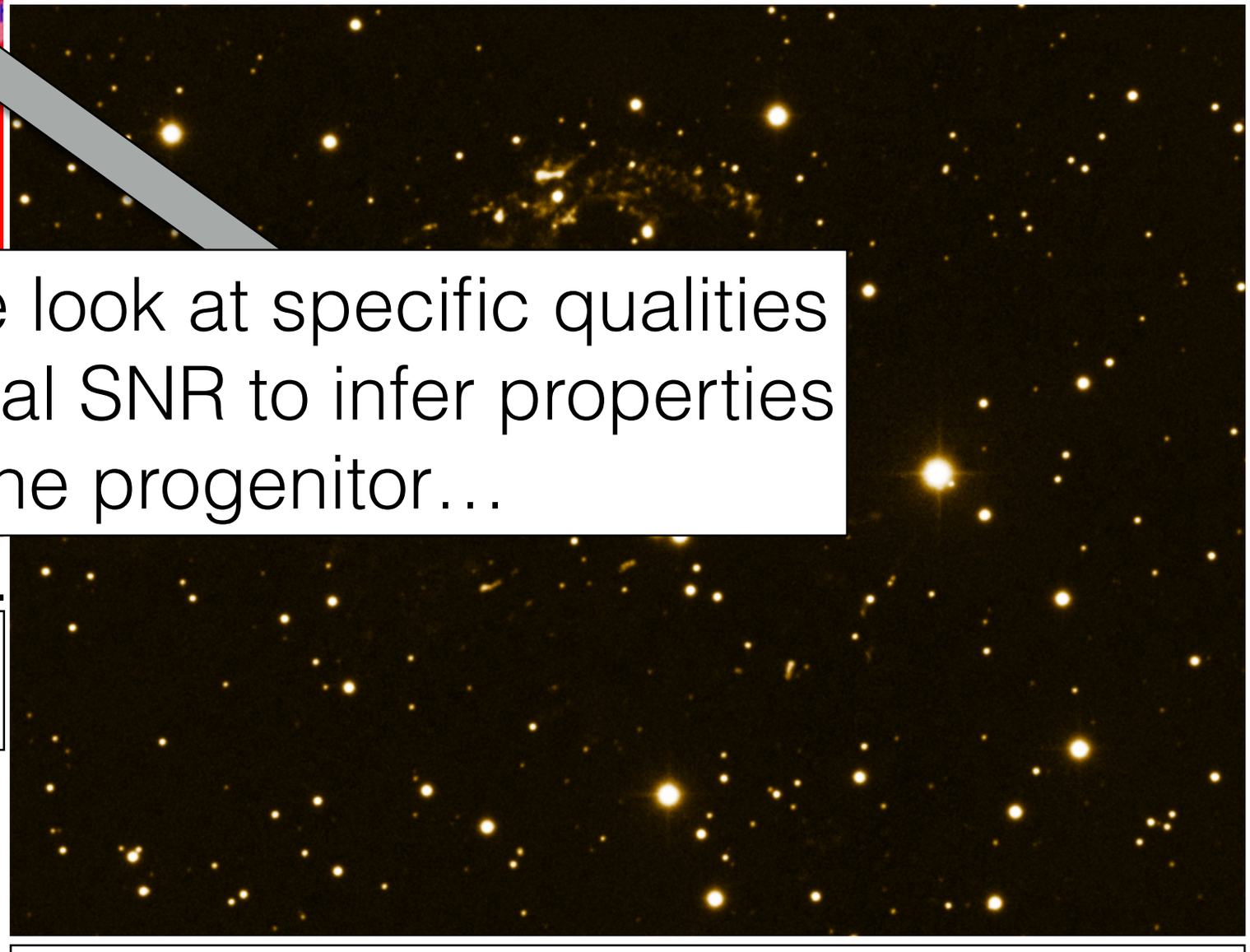

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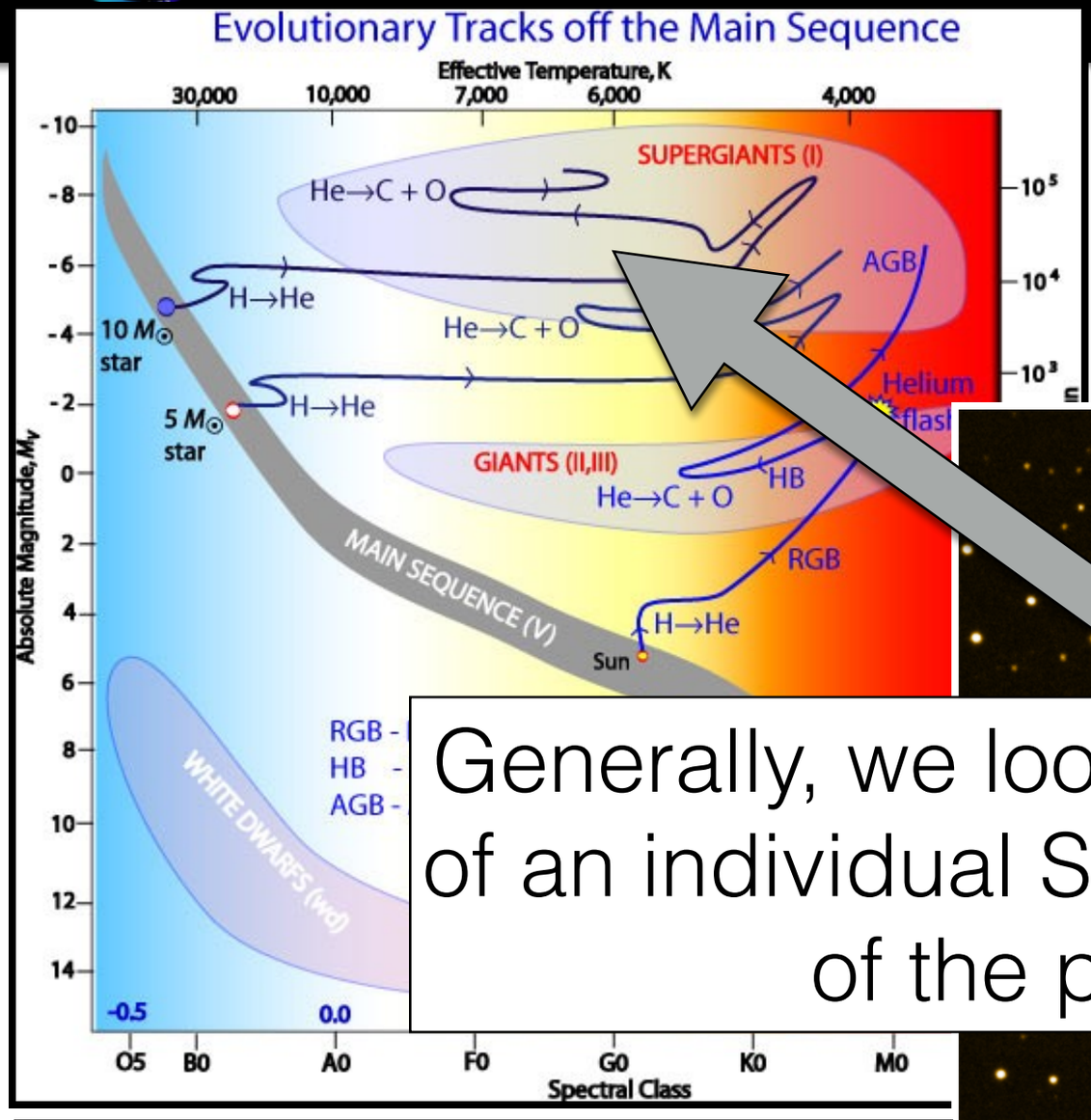

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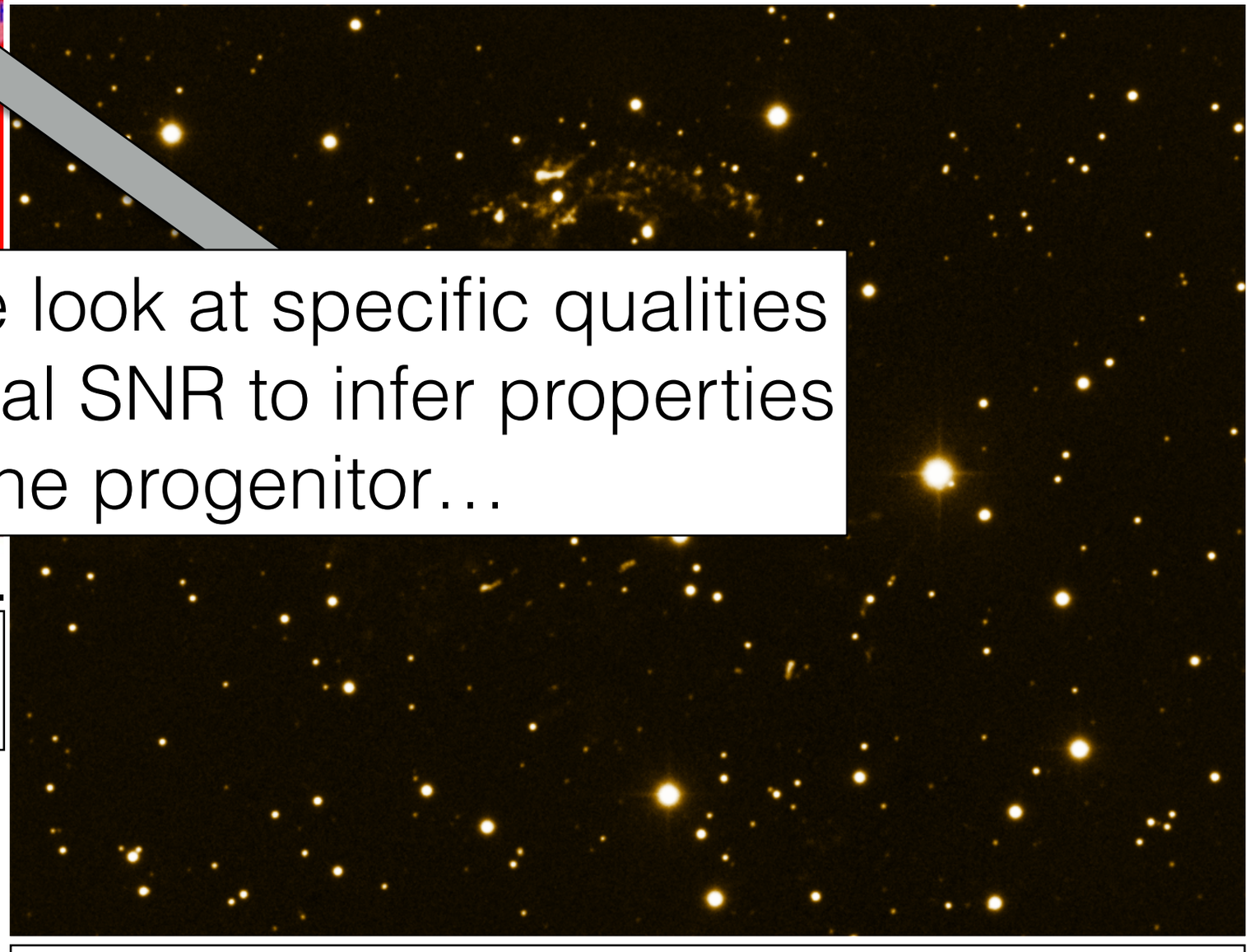

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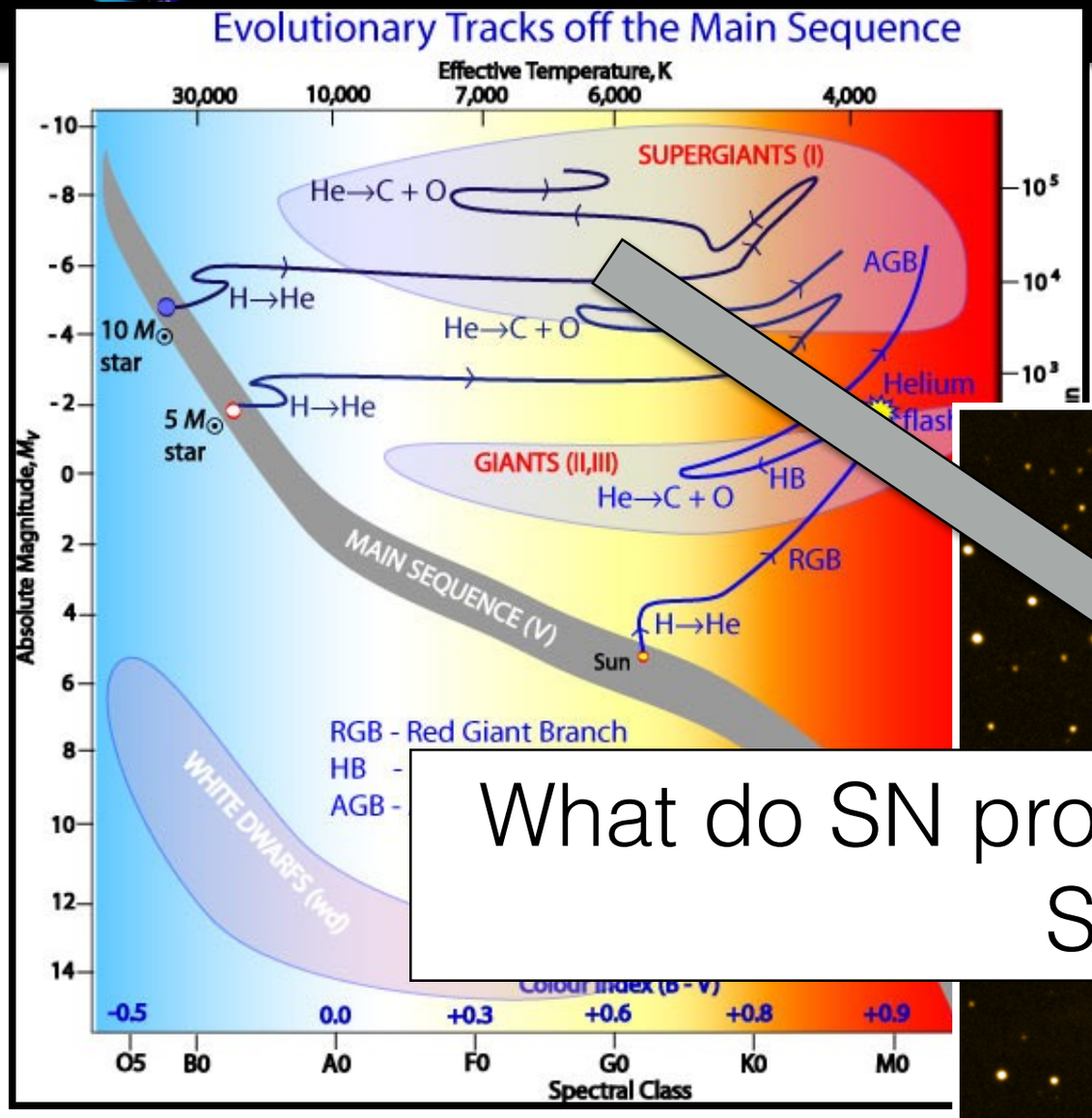

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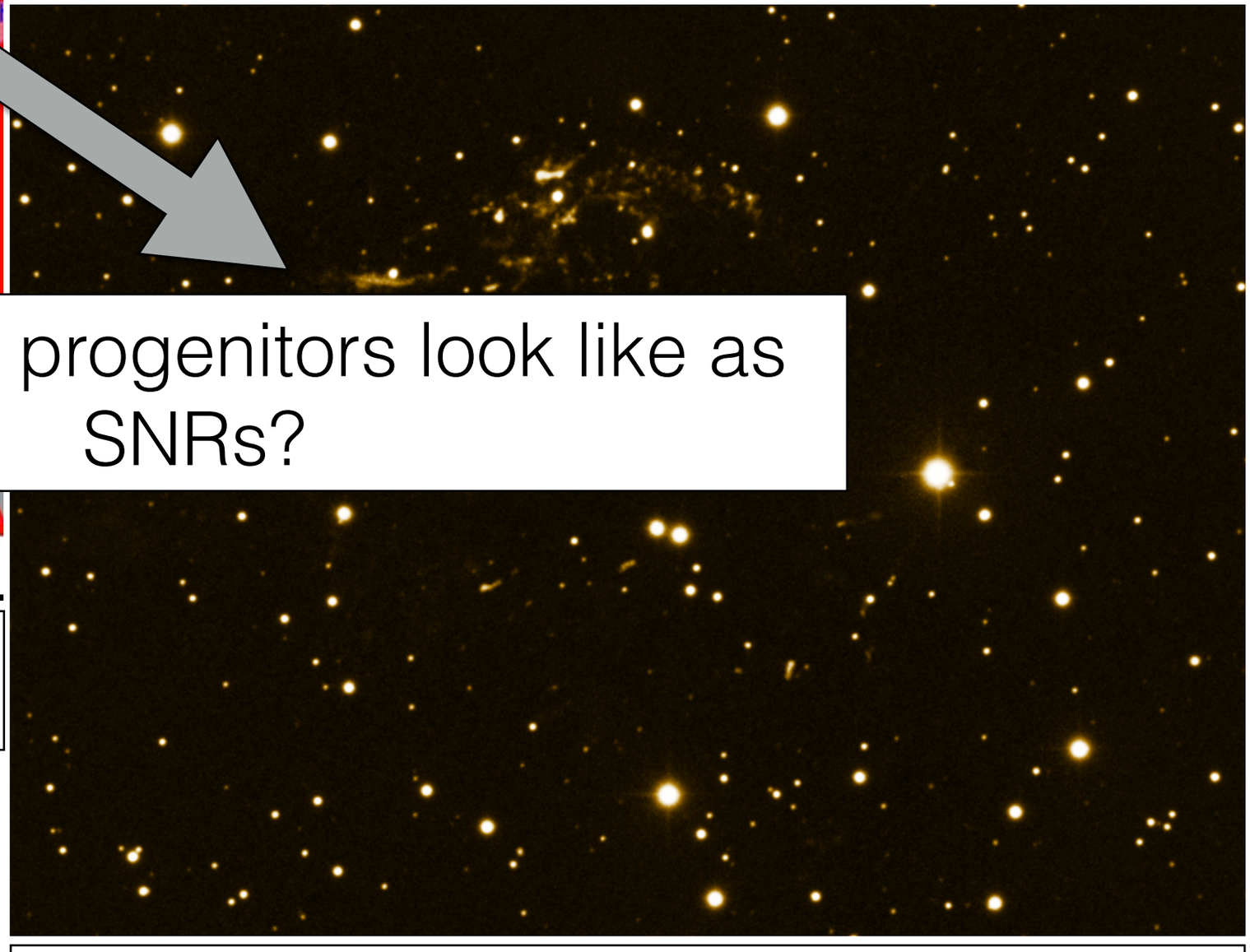
What do SN progenitors look like as SNRs?



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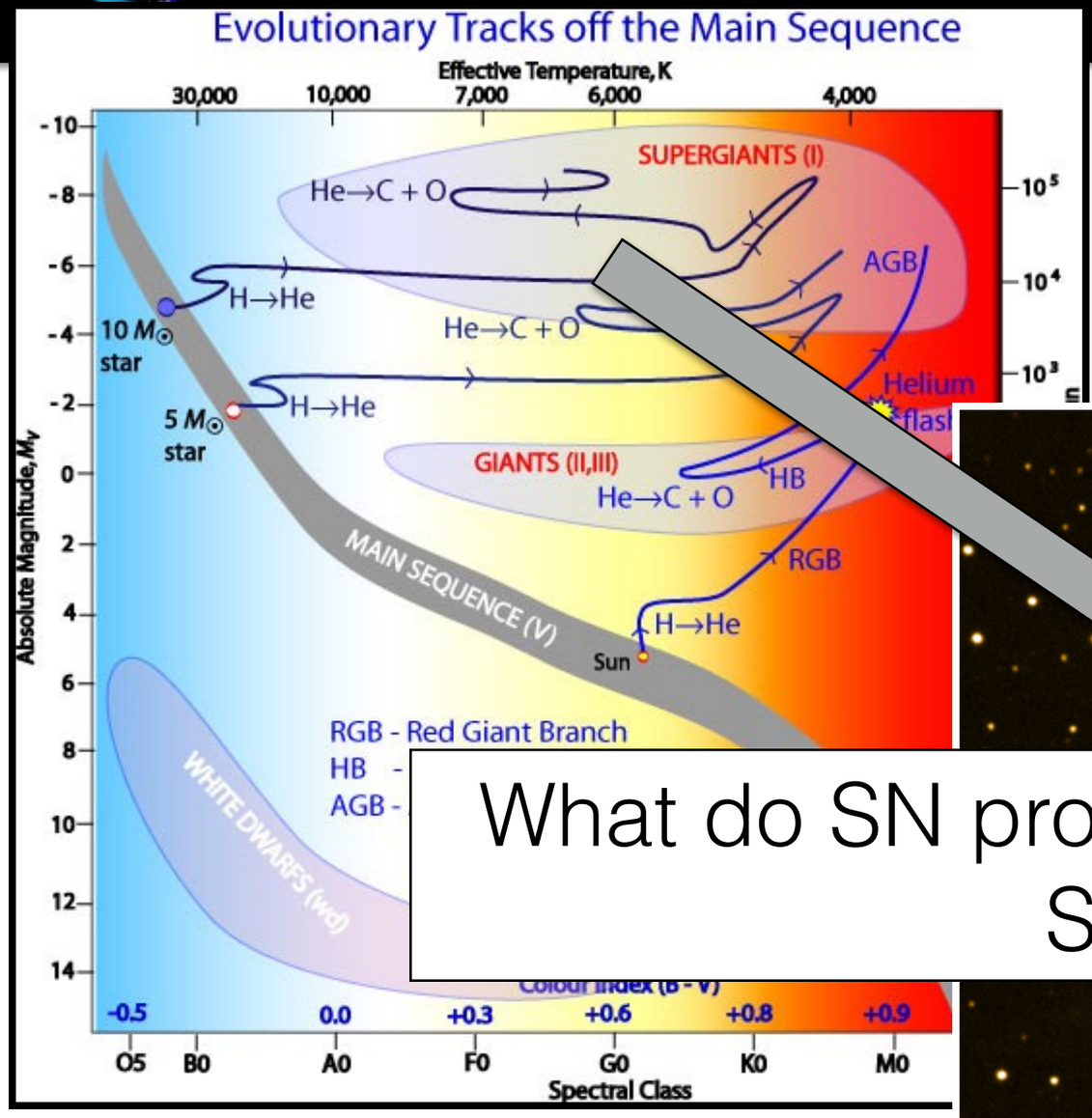

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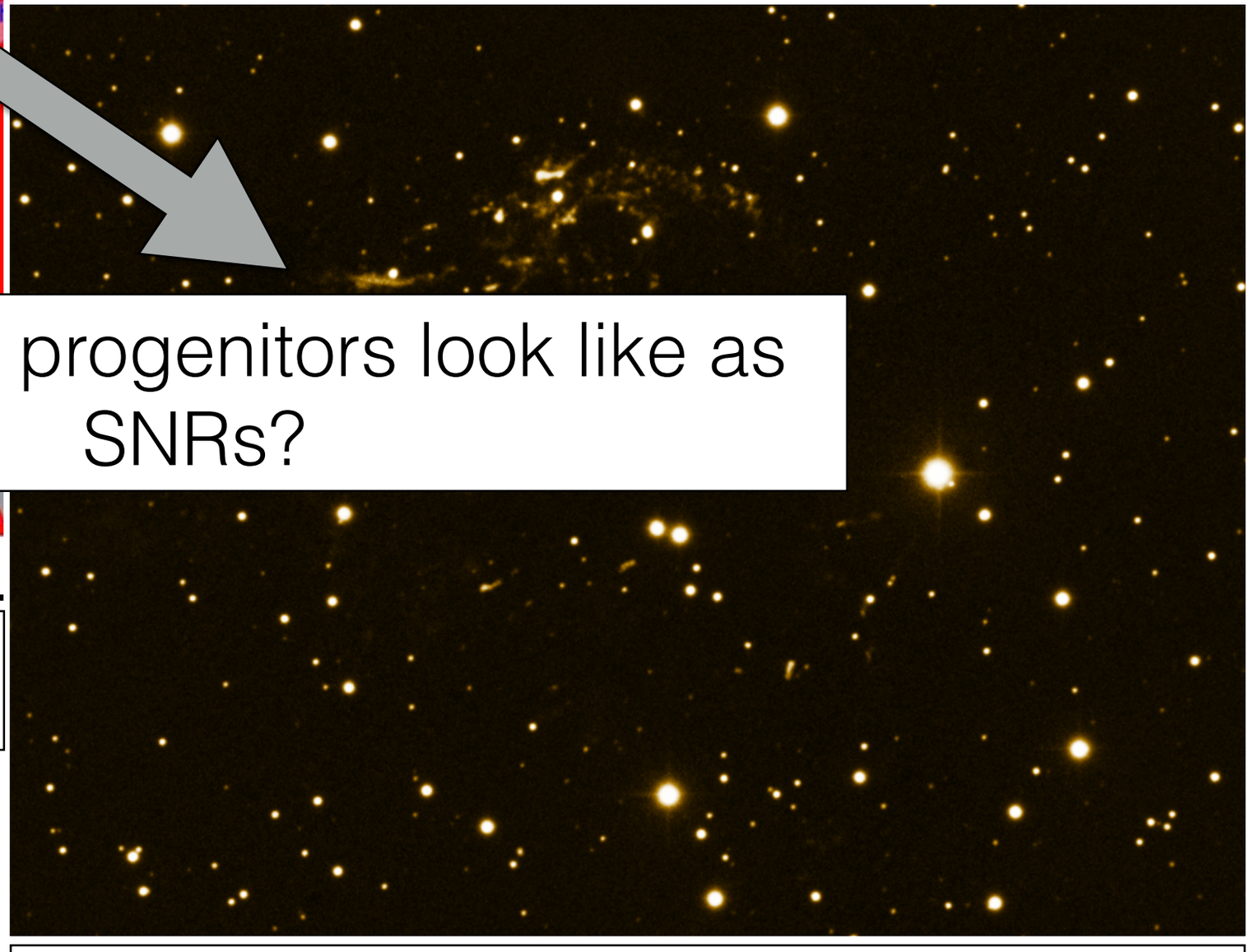

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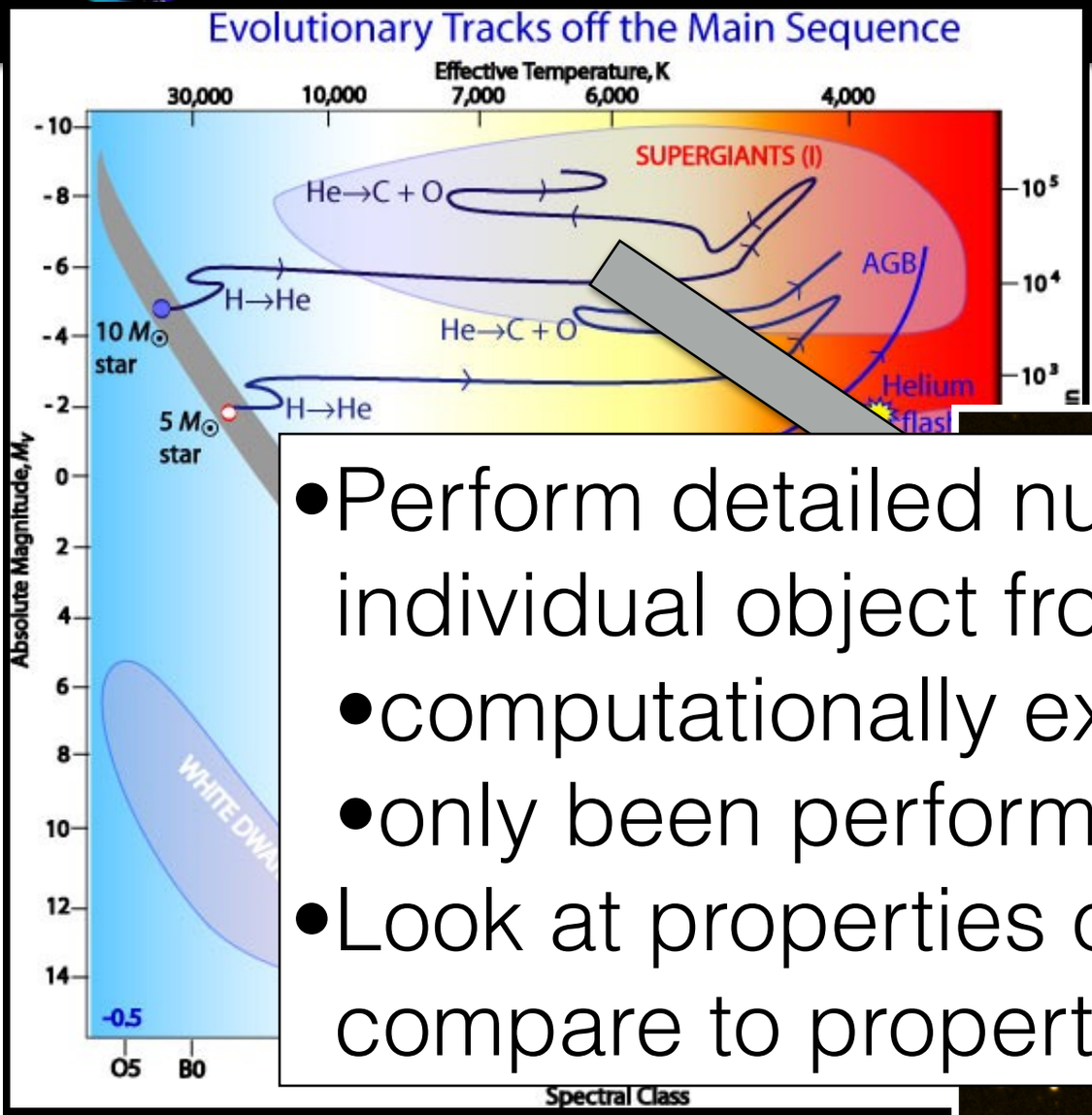

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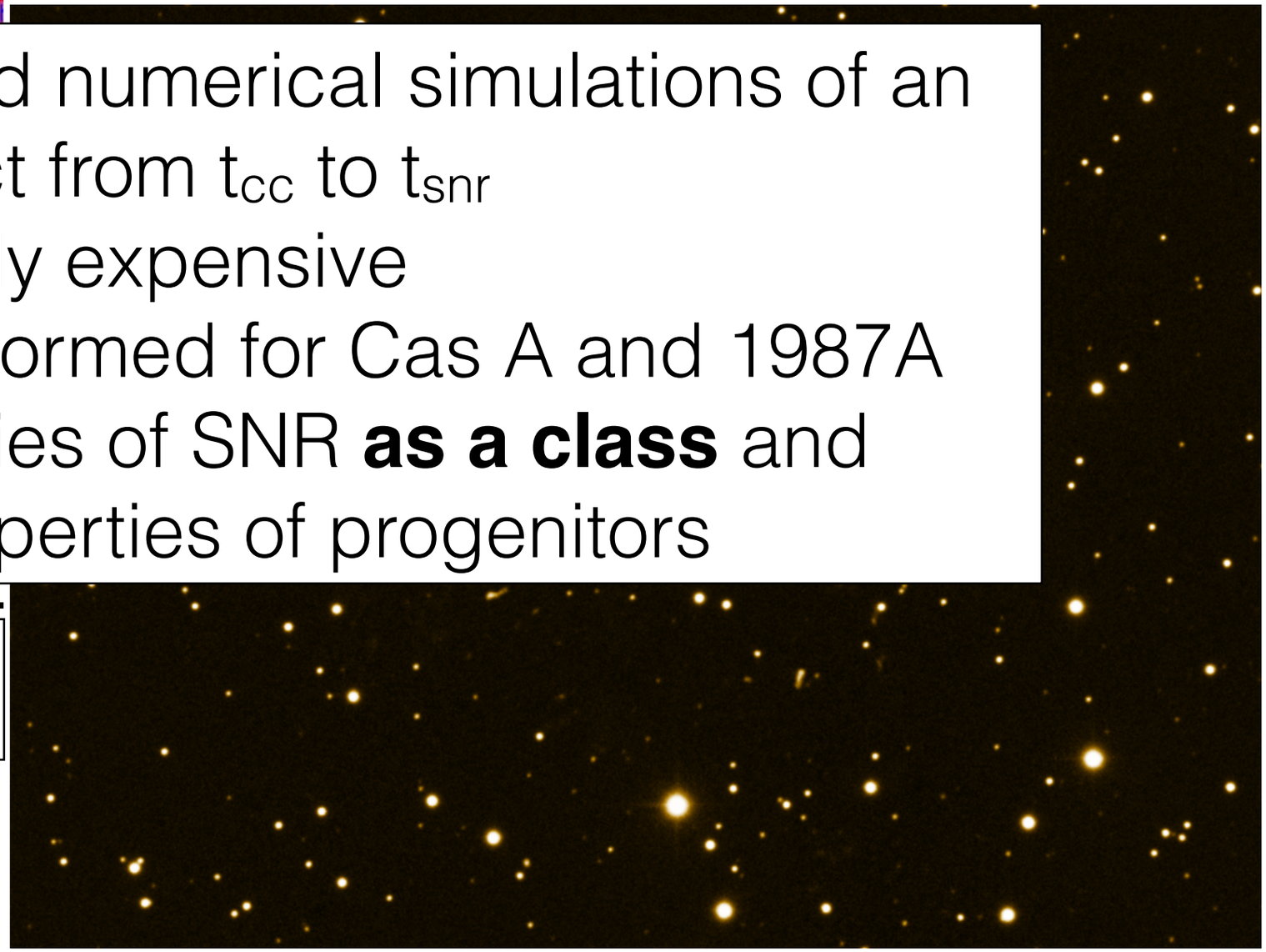
Goal is to connect a supernova remnant back to a progenitor

- Perform detailed numerical simulations of an individual object from t_{cc} to t_{snr}
  - computationally expensive
  - only been performed for Cas A and 1987A
- Look at properties of SNR **as a class** and compare to properties of progenitors



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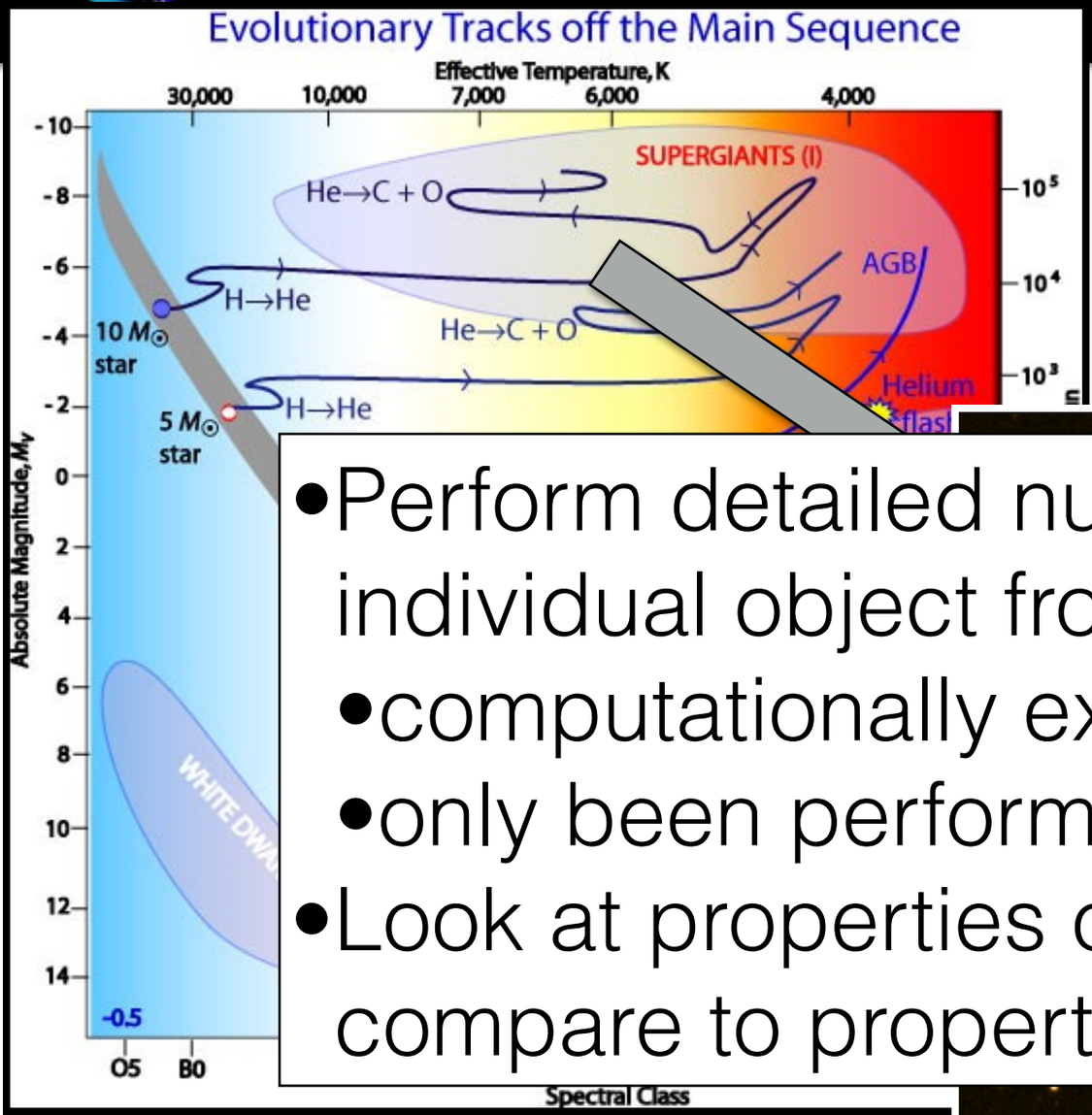

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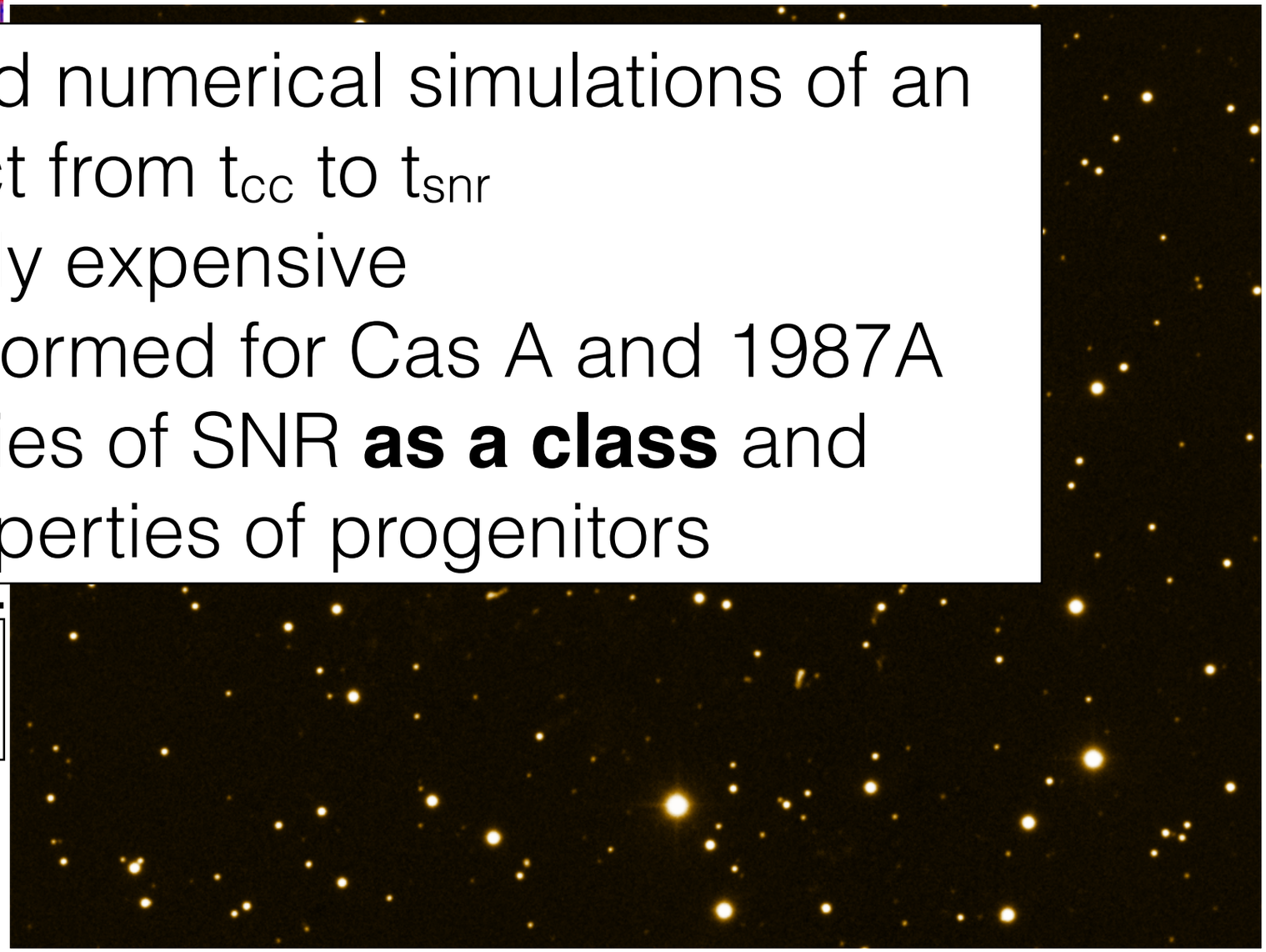


Evolution of Cas A (from Patnaude & Fesen; 2014)

Bulk SNR Properties

- Dynamical:
  - Age
  - Size
  - V_{shock}
- Spectral:
  - line centroids
  - line ratios
  - line fluxes

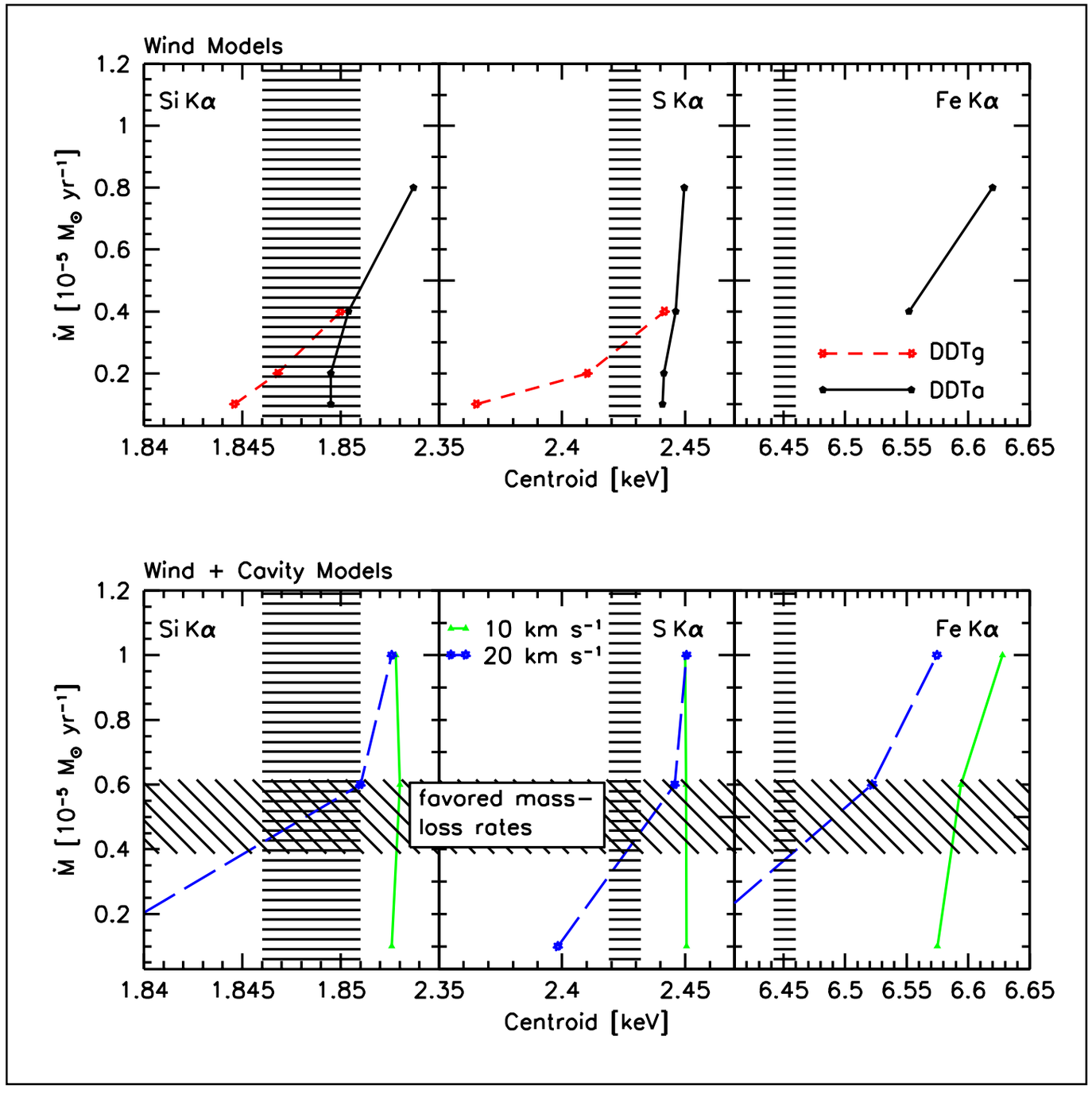
List of the SNRs Where Fe Kα Emission is Detected[a]

Name[b]	Obs. ID	Exposure (ks)	Energy (eV)	Photon Flux (10^{-5} cm^{-2} s^{-1})	N_H[c] (10^{22} cm^{-2})	Distance (kpc)	Radius (pc)	Age (yr)
Type Ia SNRs and Candidates								
Kepler	5050920[1–7]0	574	6438 ± 1	34.6 ± 0.2	0.5	4.8	2.4	410
3C 397†	505008010	69	6556^{+4}_{-3}	13.7 ± 0.4	3.0	10.3	10.5	1500–5500
Tycho*	5030850[1,2]0	416	6431 ± 1	61.0 ± 0.4	0.7	2.8	3.4	442
RCW 86†	(See notes)	378	6408^{+4}_{-5}	14.0 ± 0.7	0.3	2.5	16	1829
SN 1006*	(See notes)	317	6429 ± 10	2.55 ± 0.43	0.07	2.2	10	1008
G337.2–0.7	507068010	304	6505^{+26}_{-31}	0.21 ± 0.06	4.0	9.3	8.1	5000–7000
G344.7–0.1†	501011010	42	6463^{+9}_{-10}	4.03 ± 0.33	5.0	14	16	3000–6000
G352.7–0.1†	506052010	202	6443^{+8}_{-12}	0.82 ± 0.08	2.6	7.5	6.0	∼5000
N103B†	804039010	224	6545 ± 6	2.15 ± 0.10	0.06	50	3.6	∼860
0509–67.5*	5080720[1,2]0	329	6425^{+14}_{-15}	0.32 ± 0.04	0.05	50	3.6	∼400
0519–69.0*	806026010	348	6498^{+6}_{-8}	0.93 ± 0.05	0.06	50	4.0	∼600
Core-collapse SNRs and Candidates								
Sgr A East*	(See notes)	88	6664 ± 3	22.3 ± 1.0	10	8.5	3.7	∼4000
G0.61+0.01†	100037060	77	6634^{+14}_{-12}	3.3 ± 0.5	16	8.5	5.0	∼7000
W49B	50308[4,5]010	114	6663 ± 1	109 ± 1	5.0	8.0	5.8	1000–3000
Cas A*	100043020	7	6617^{+3}_{-2}	435 ± 9	2.0	3.4	2.7	310–350
IC 443	5070150[1–4]0	368	6674^{+10}_{-13}	6.01 ± 0.59	0.6	1.5	10	4000–30000
G292.0+1.8*	506062010	44	6585^{+27}_{-28}	1.38 ± 0.35	0.5	6.2	11	∼3000
G349.7+0.2	506064010	160	6617^{+7}_{-6}	2.92 ± 0.18	7.0	11.5	4.0	∼3500
G350.1–0.3*	506065010	70	6587^{+11}_{-10}	2.24 ± 0.23	3.7	4.5	1.3	∼900
N49†	807007010	185	6628^{+29}_{-26}	0.18 ± 0.04	0.06	50	8.5	∼6600
N63A	508071010	82	6647^{+16}_{-17}	0.86 ± 0.12	0.06	50	10	2000–5000
N132D	(See notes)	86	6656 ± 9	1.83 ± 0.17	0.06	50	13	∼3150
SN 1987A*	707020010	81	6646^{+55}_{-54}	0.19 ± 0.08	0.06	50	0.2	27

Yamaguchi et al. (2014)

- Dynamical:
  - Age
  - Size
  - v_{shock}
- Spectral:
  - line centroids
  - line ratios
  - line fluxes

Progenitor evolution makes precise statements about the observed properties of a SNR 100-1000 years after the SN



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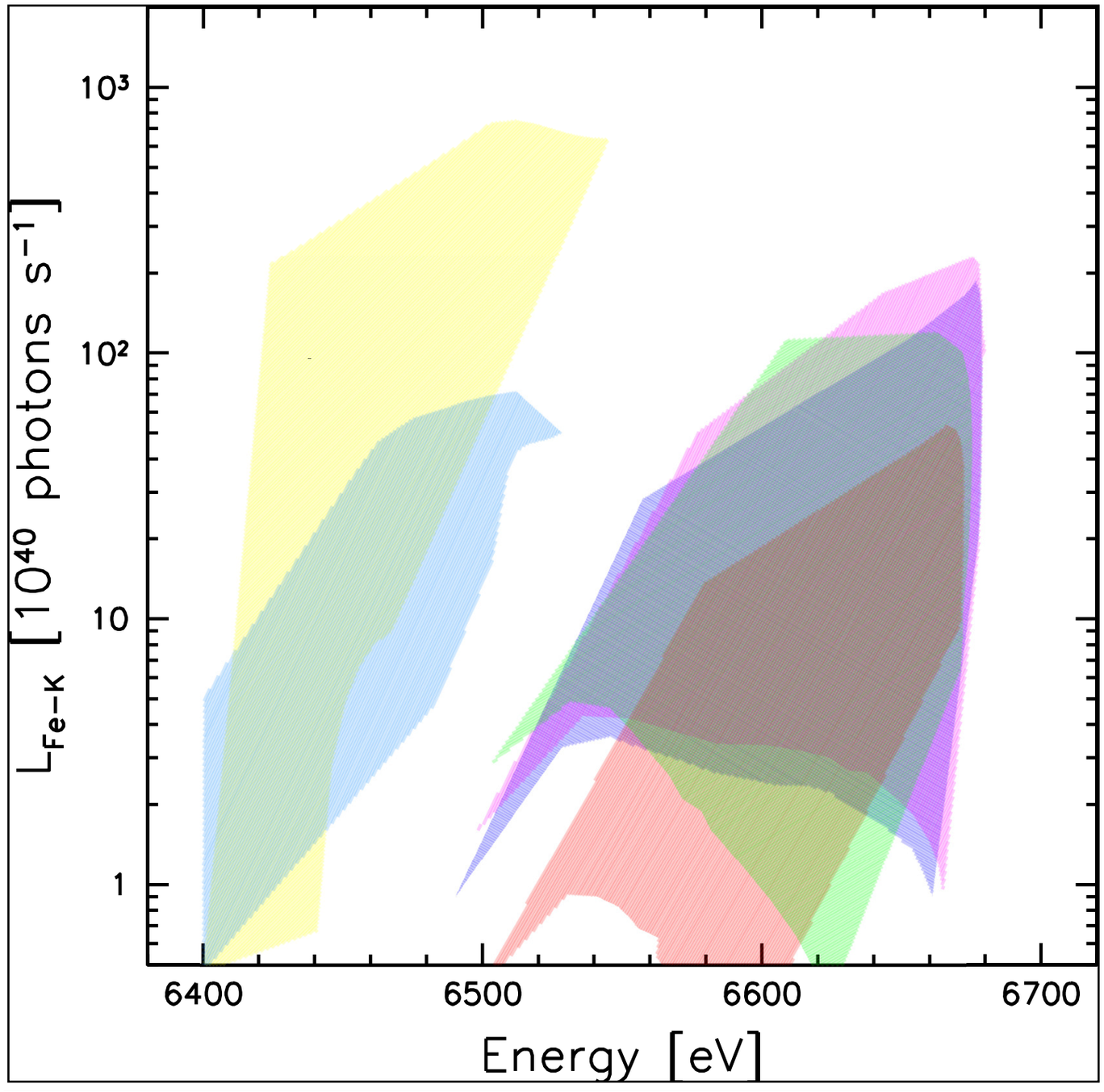

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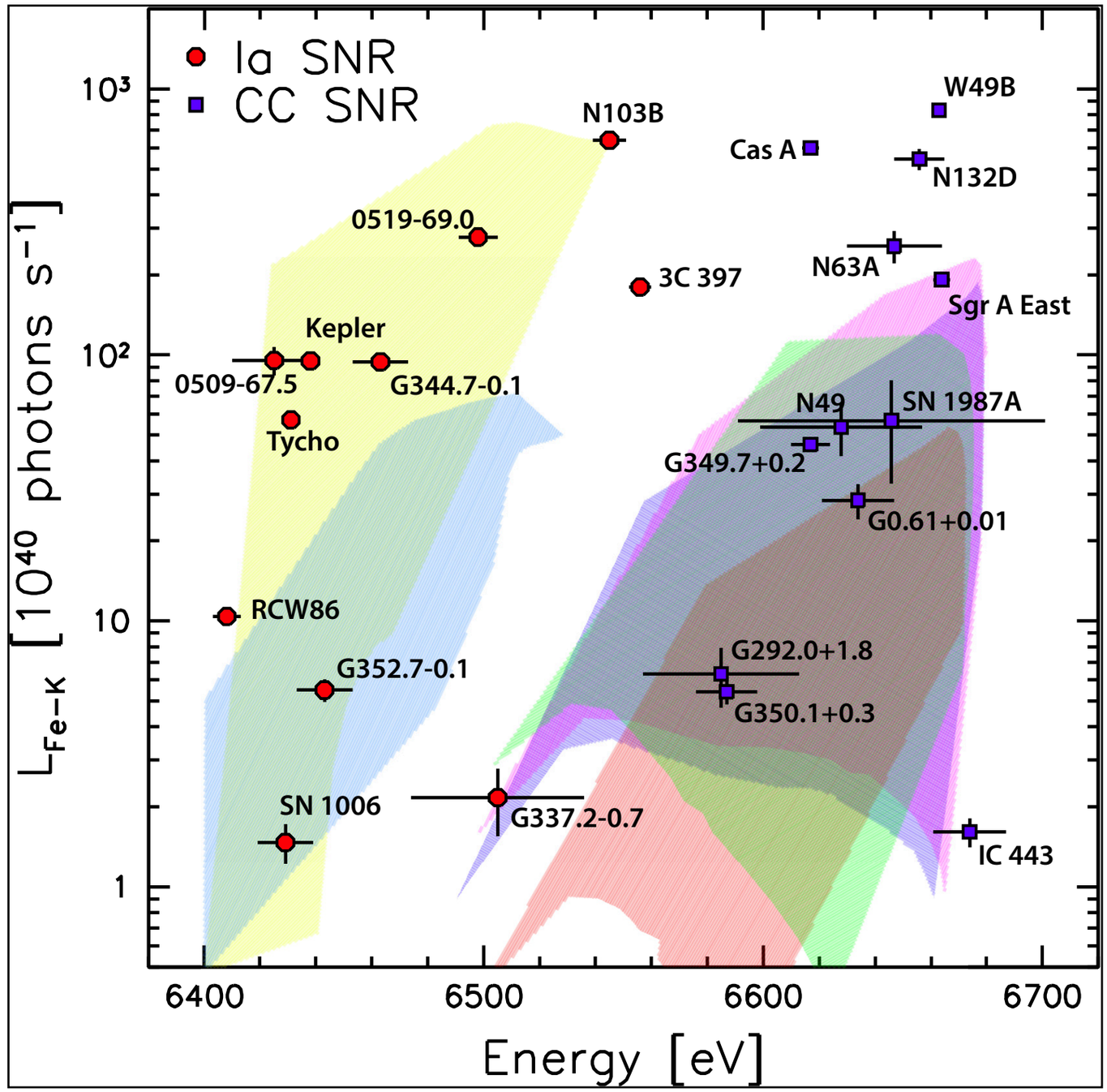
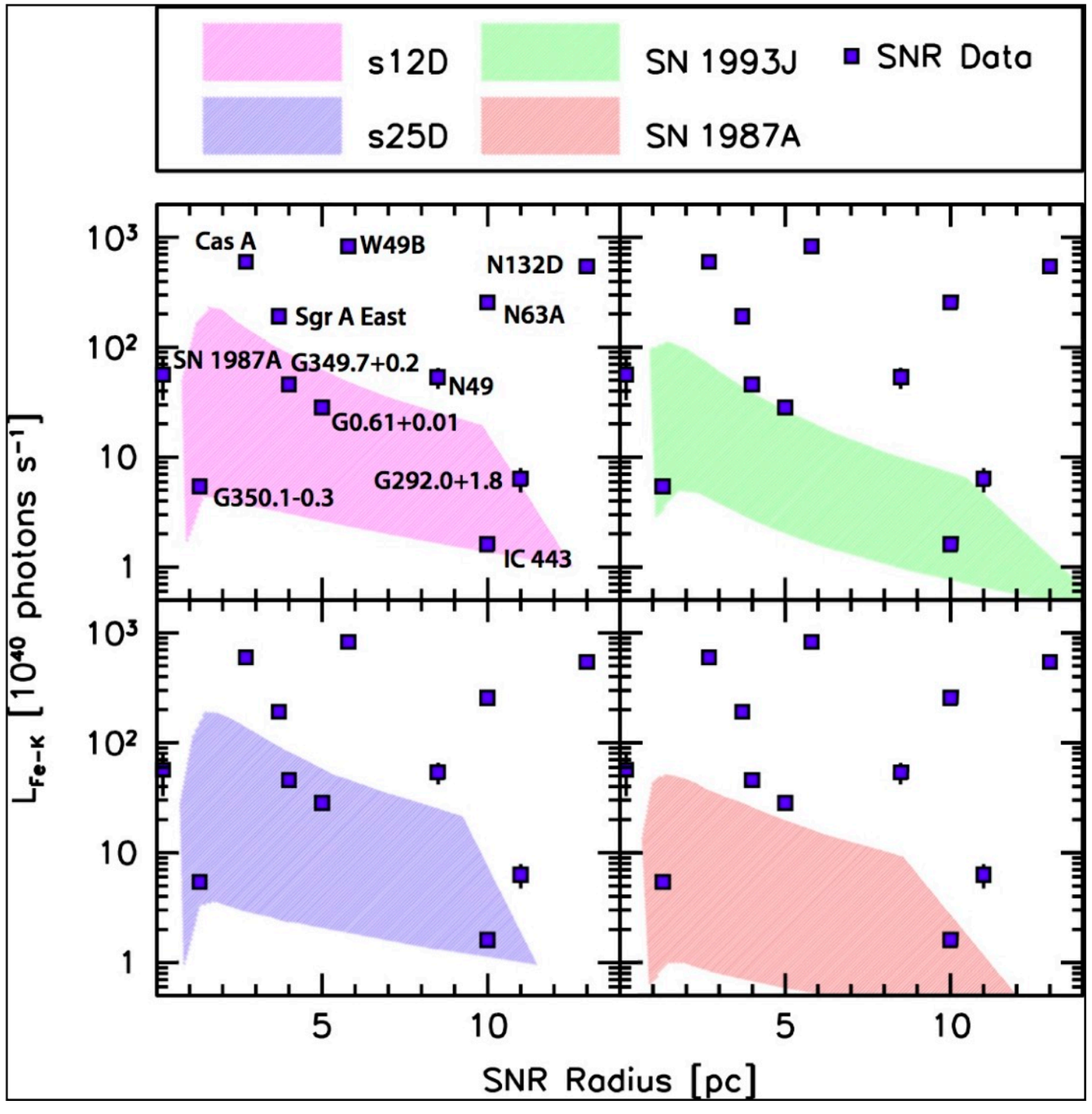
When the same principles are applied to a host of SNR and SN progenitor models, there is broad agreement, but …



Patnaude et al. (2015)

Poor correlation between simulated and measured dynamics



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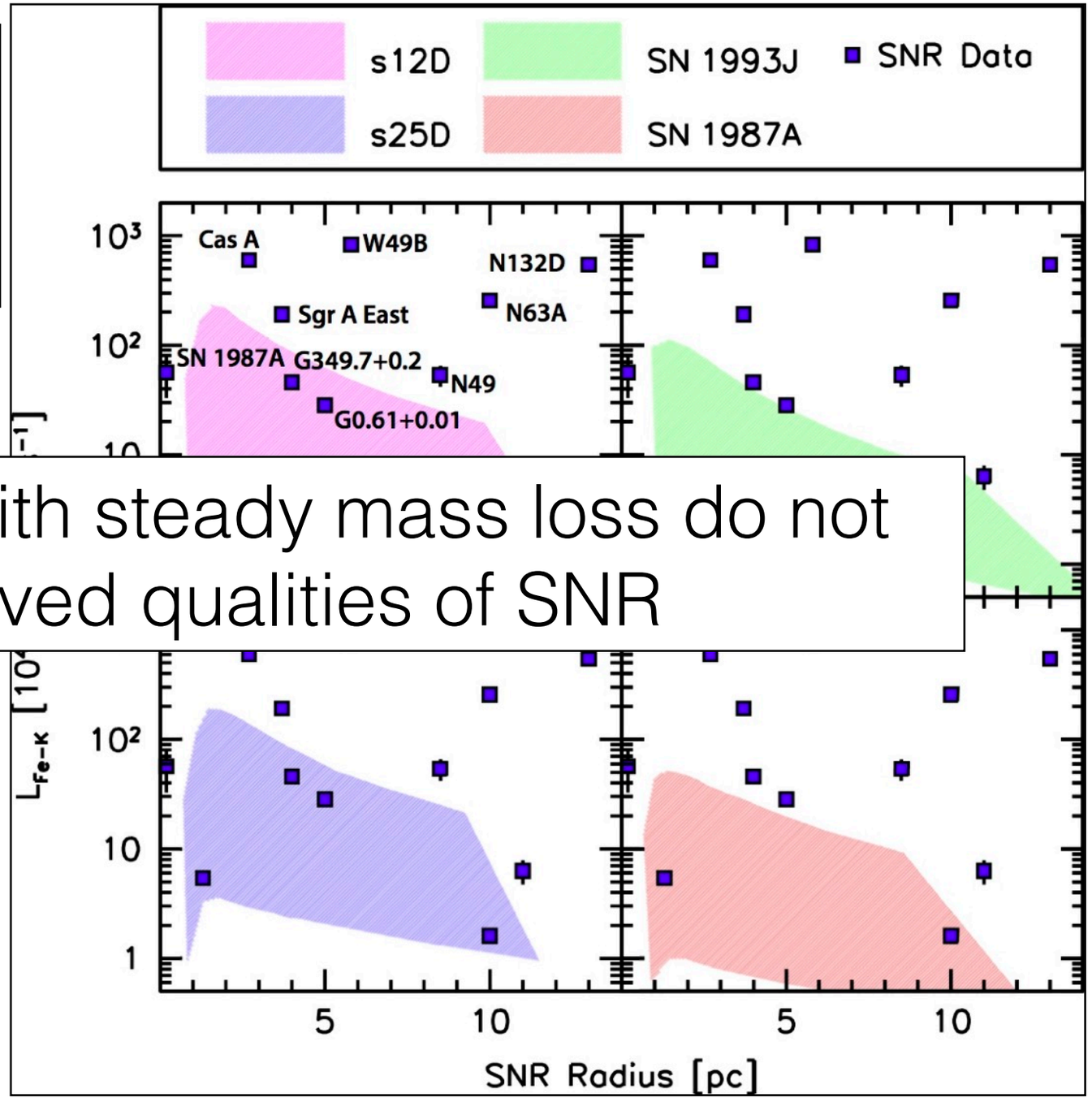

Progenitor models with steady mass loss do not explain observed qualities of SNR

Patnaude et al. (2015)

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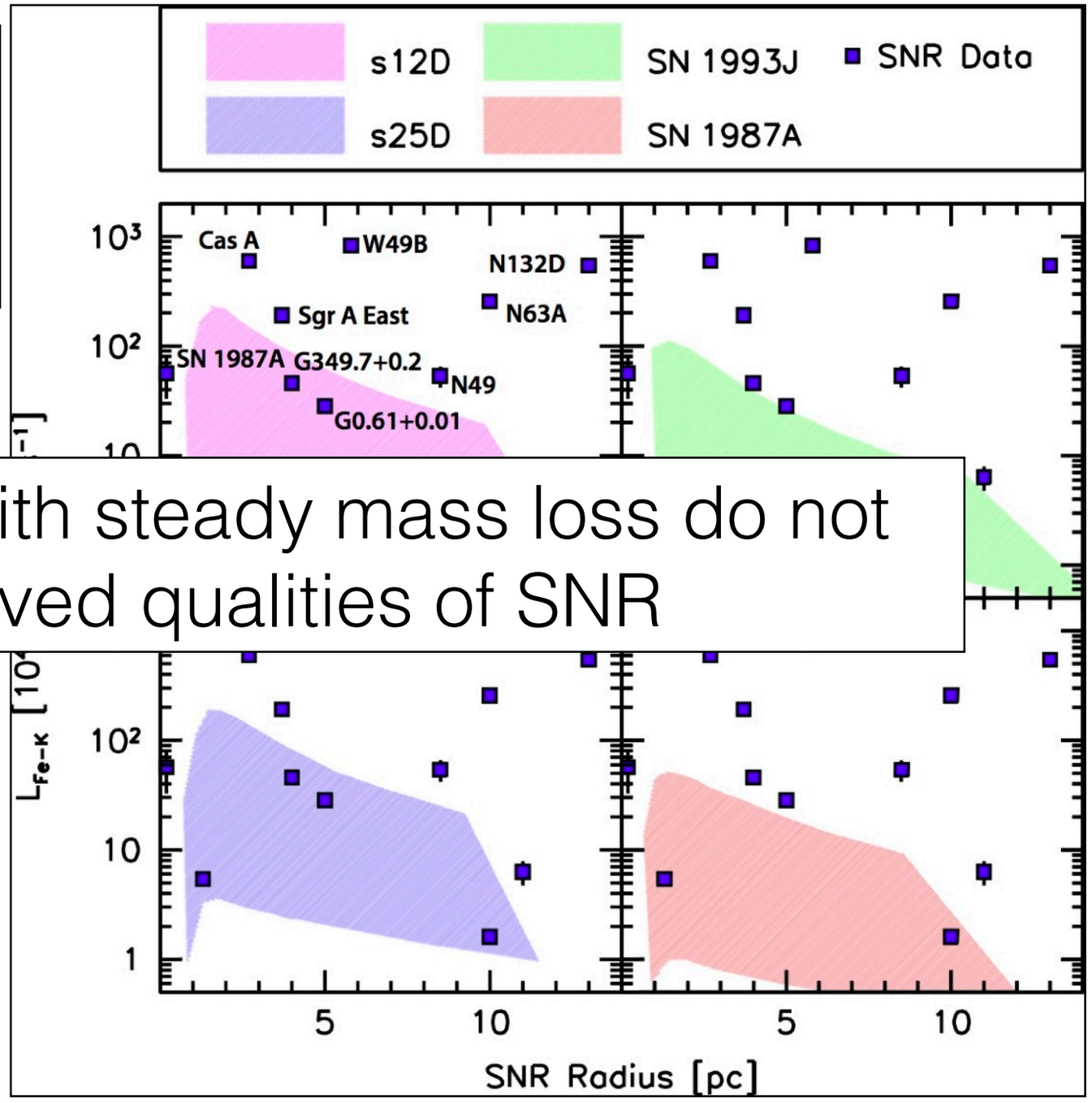

Progenitor models with steady mass loss do not explain observed qualities of SNR

$$R_b \propto \left[\frac{Ag^n}{q}\right]^{1/(n-s)} t^{\frac{n-3}{n-s}}$$

$$L_X \propto q^2 \qquad q = \dot{M}/(4\pi v_w)$$

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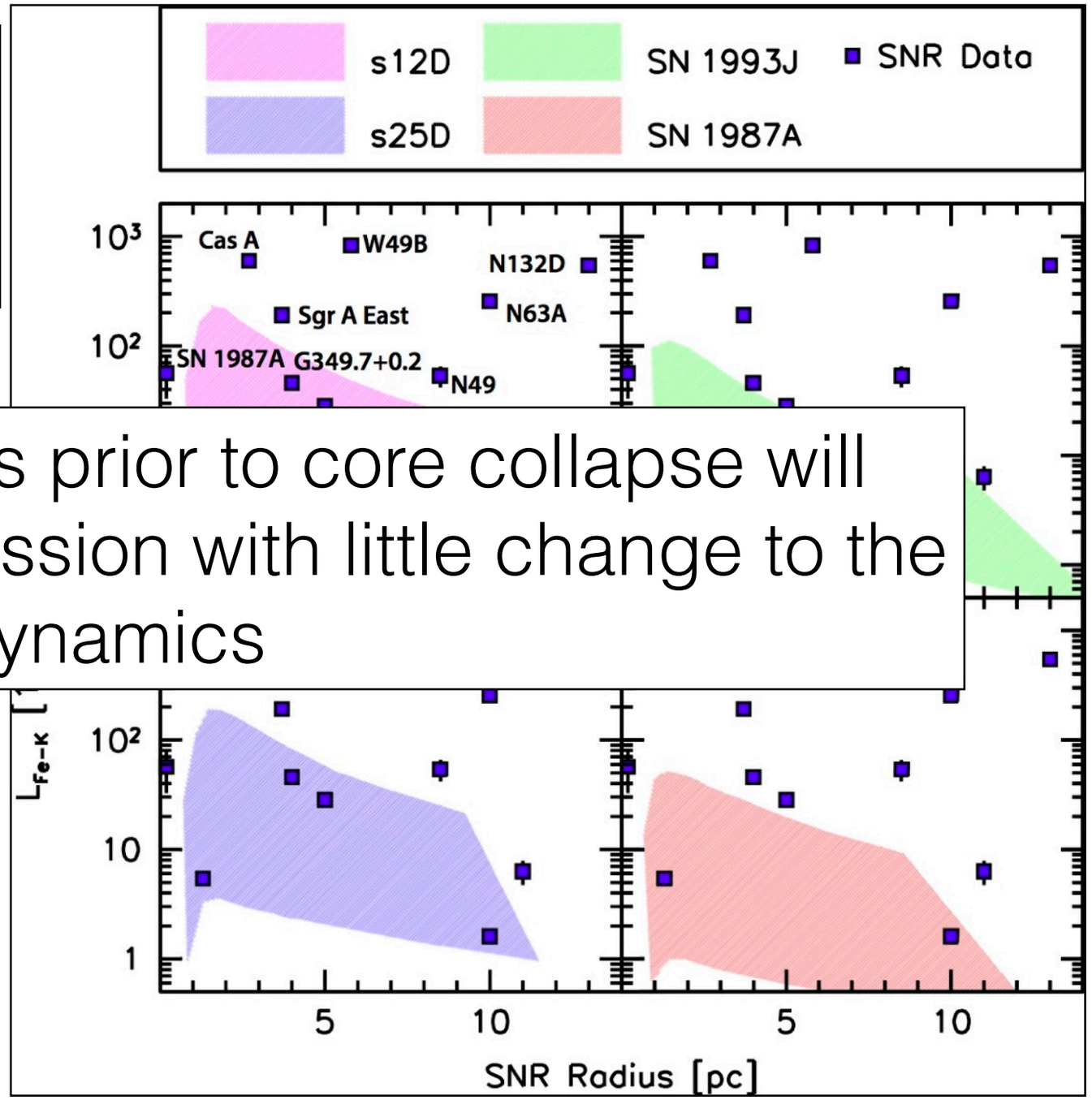

Enhanced mass loss prior to core collapse will increase the X-ray emission with little change to the dynamics

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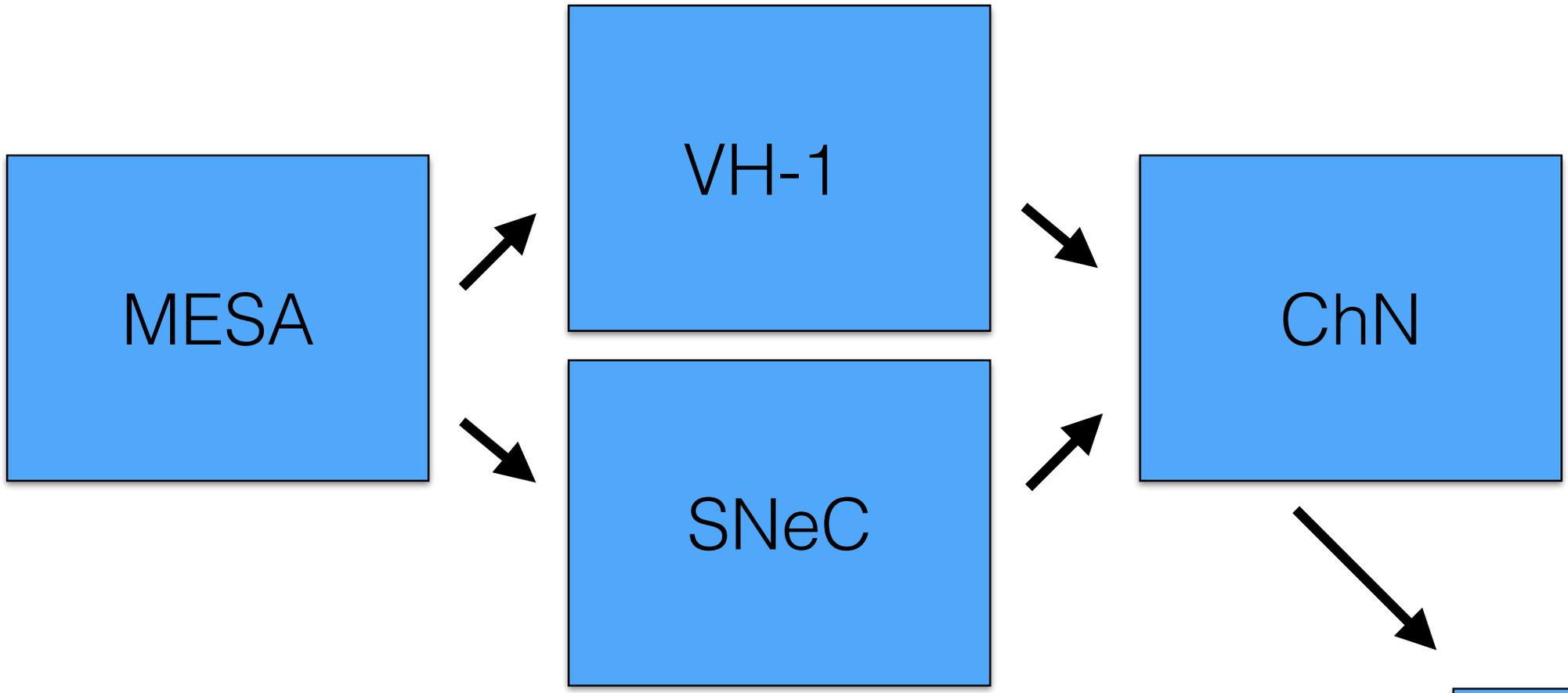
Models from other groups

ChN

Observables

Models from Patnaude et al. (2015) explored a limited parameter space in progenitor evolution



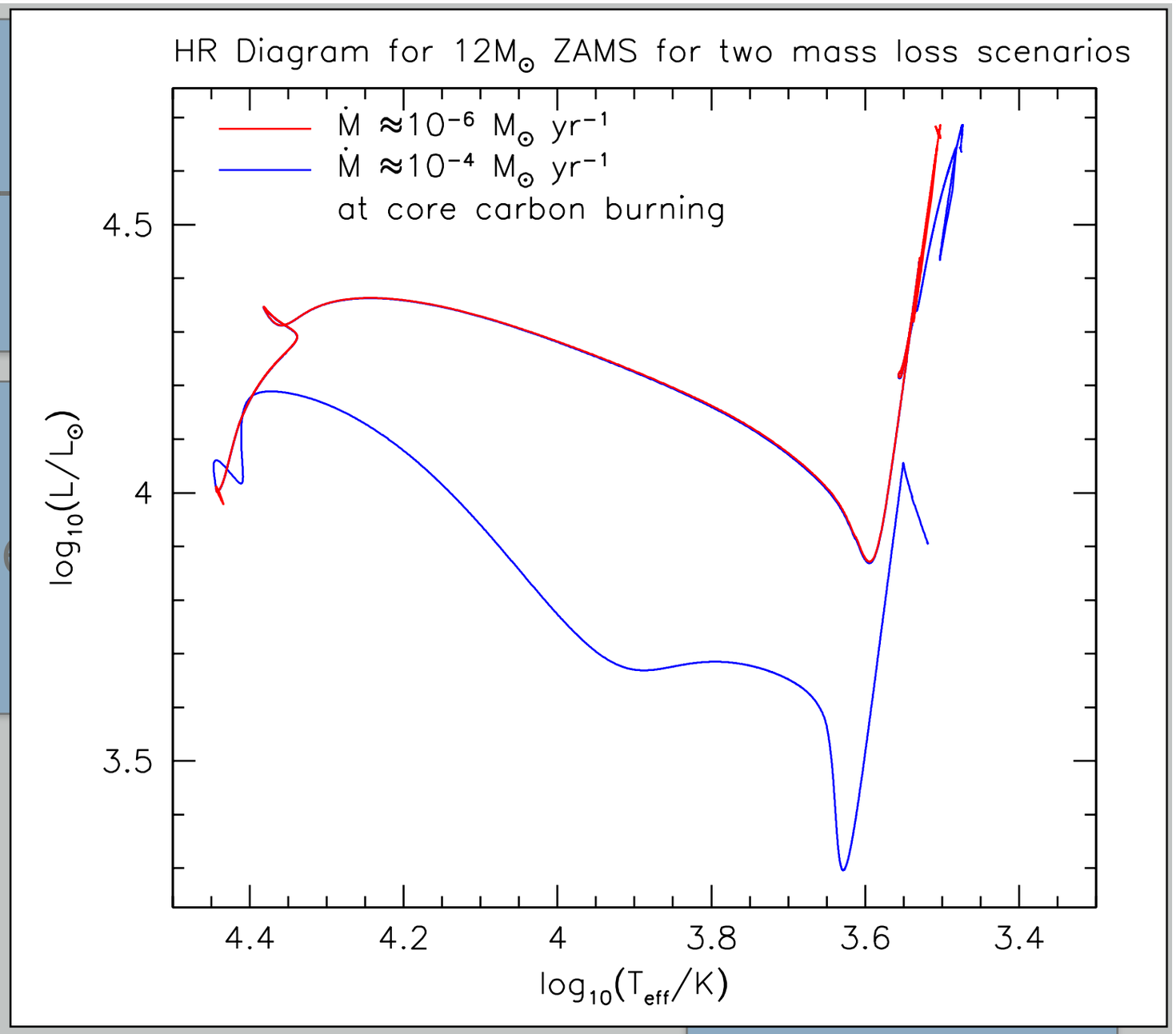
We can explore a much larger parameter space by generating our own progenitor models … also allows us to explore variations in CSM as determined by progenitor evolution

MESA

VH-

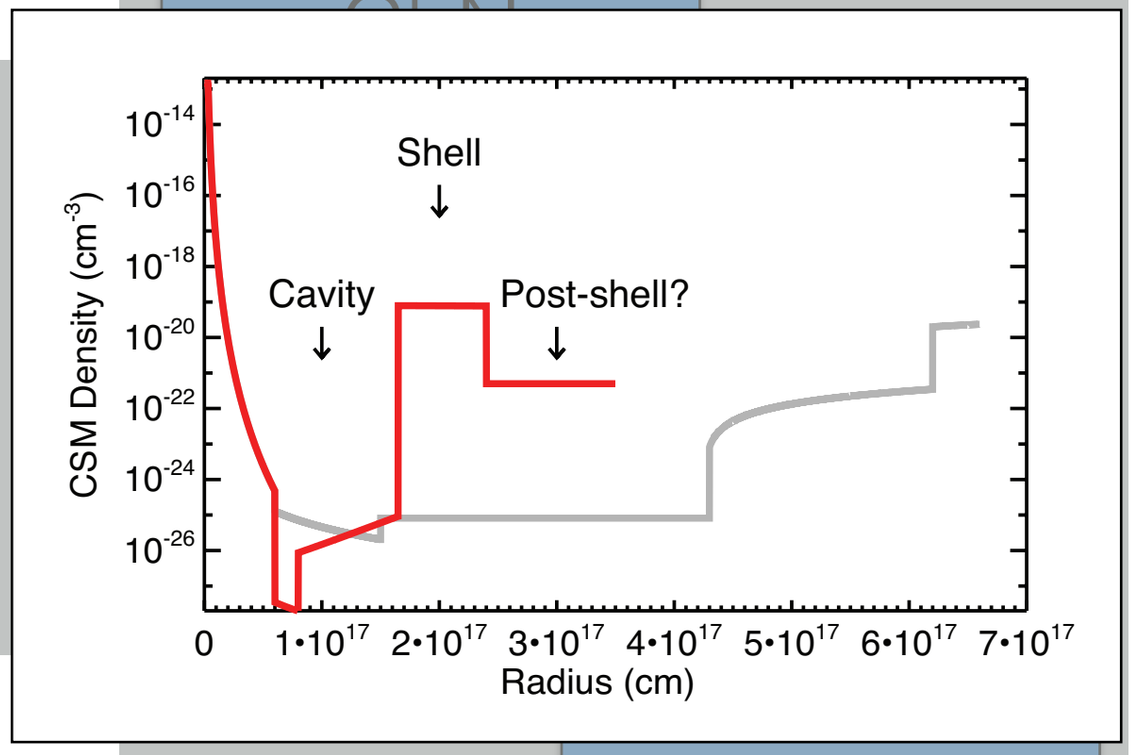
SN

- Simulate stellar evolution to CC
- Assume a range of parameters for mass loss, rotation, etc.,



VH-1

- Simulate CSM from MESA mass loss parameters
- Include radiative cooling to produce cooled circumstellar shell
- Simulate ejected shells and clumping by assuming an appropriate filling factor

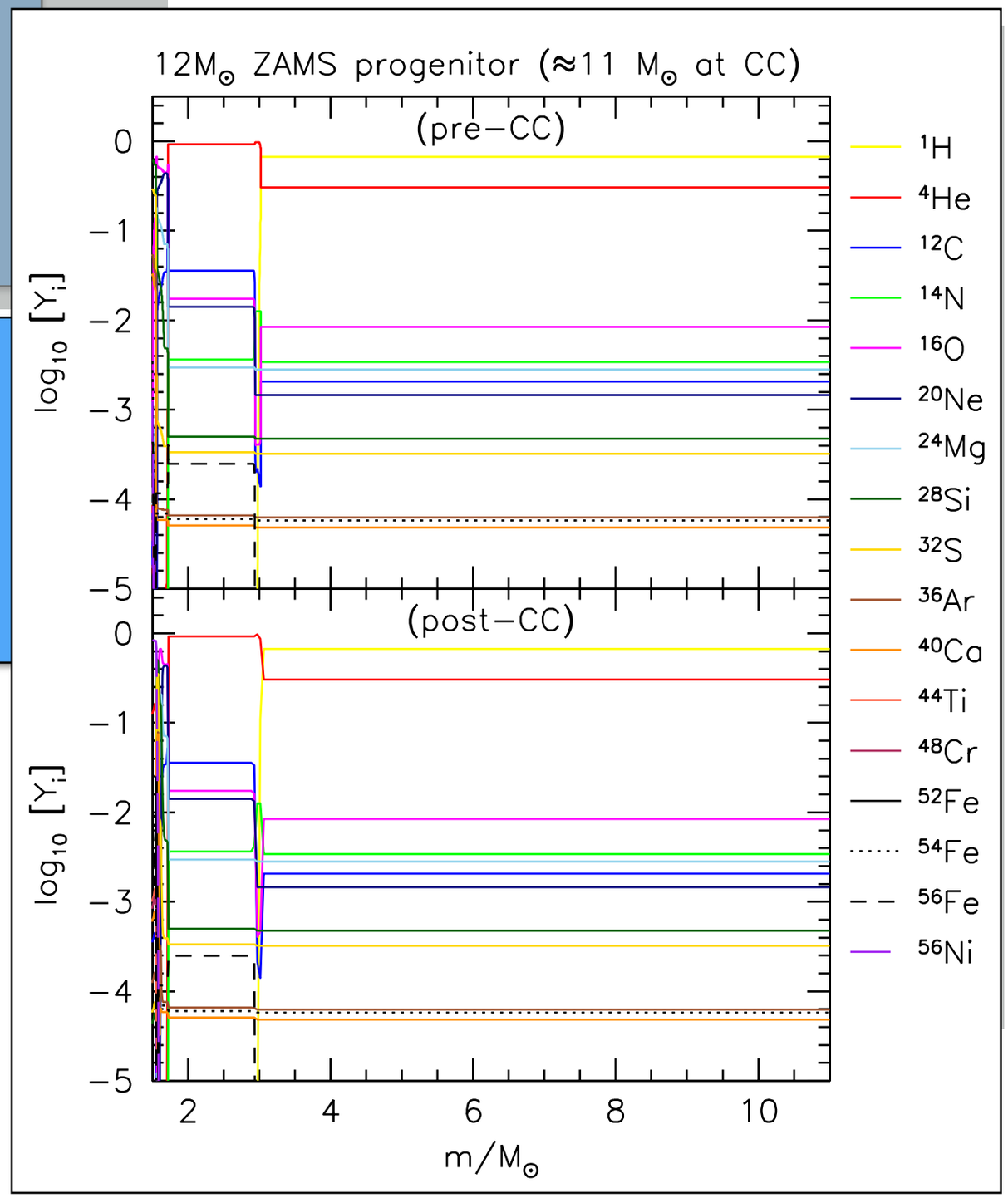


MESA

VH-1

SNeC

- Use SNeC to simulate explosion
  - Added capability to do nuclear burning
  - Added in Timmes EOS



MESA

VH-1

SNeC

- Use SNeC to simulate explosion
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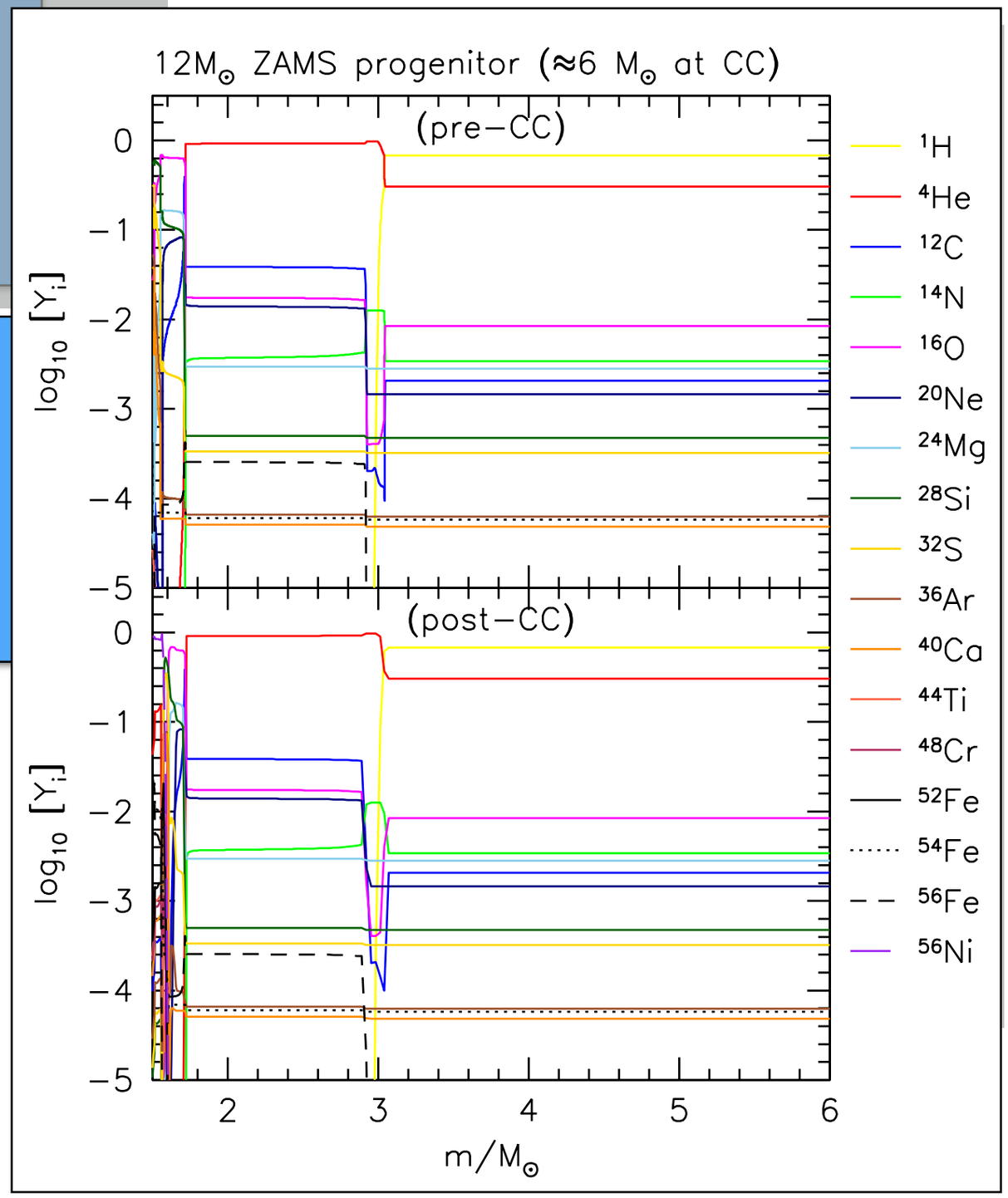

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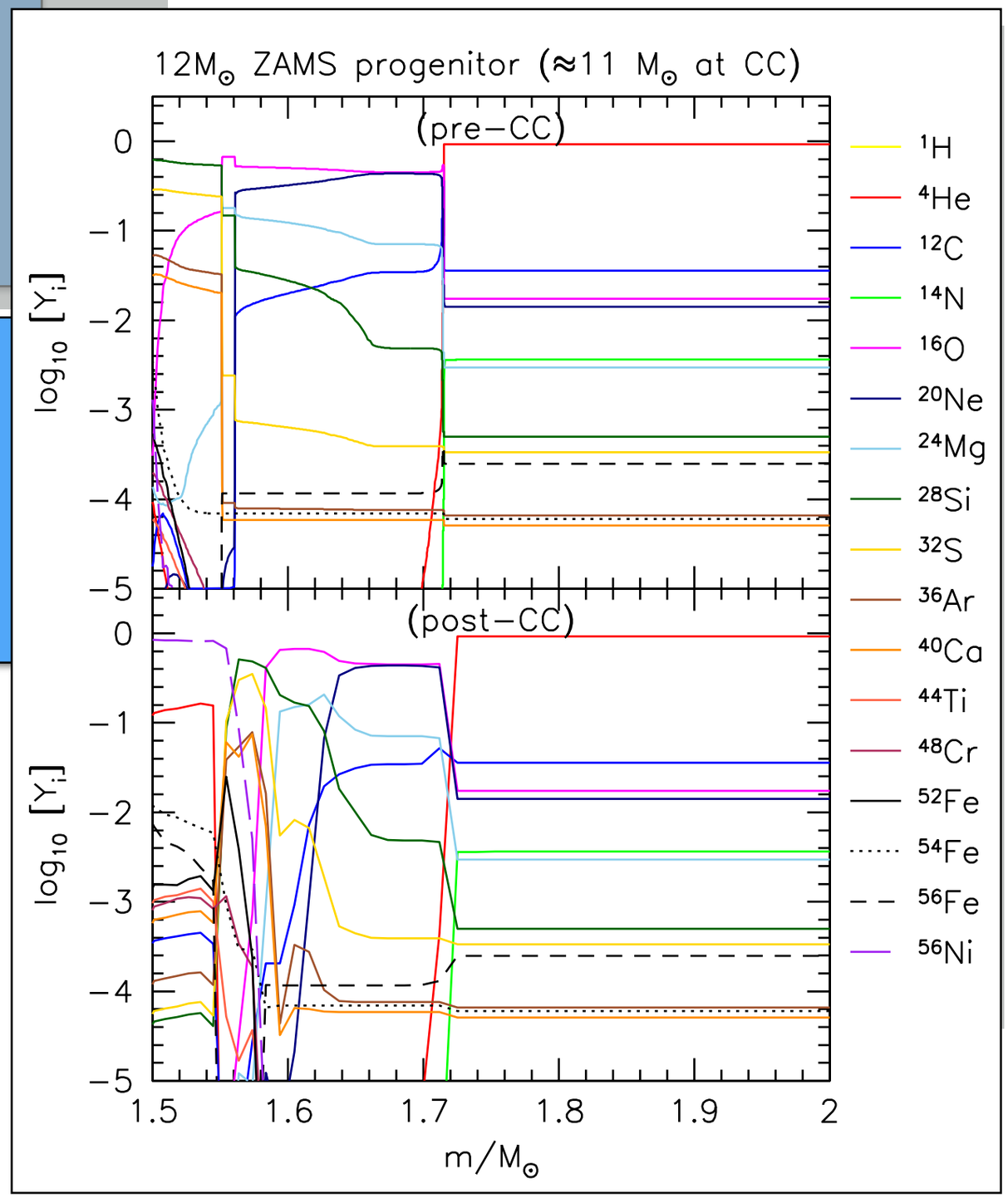

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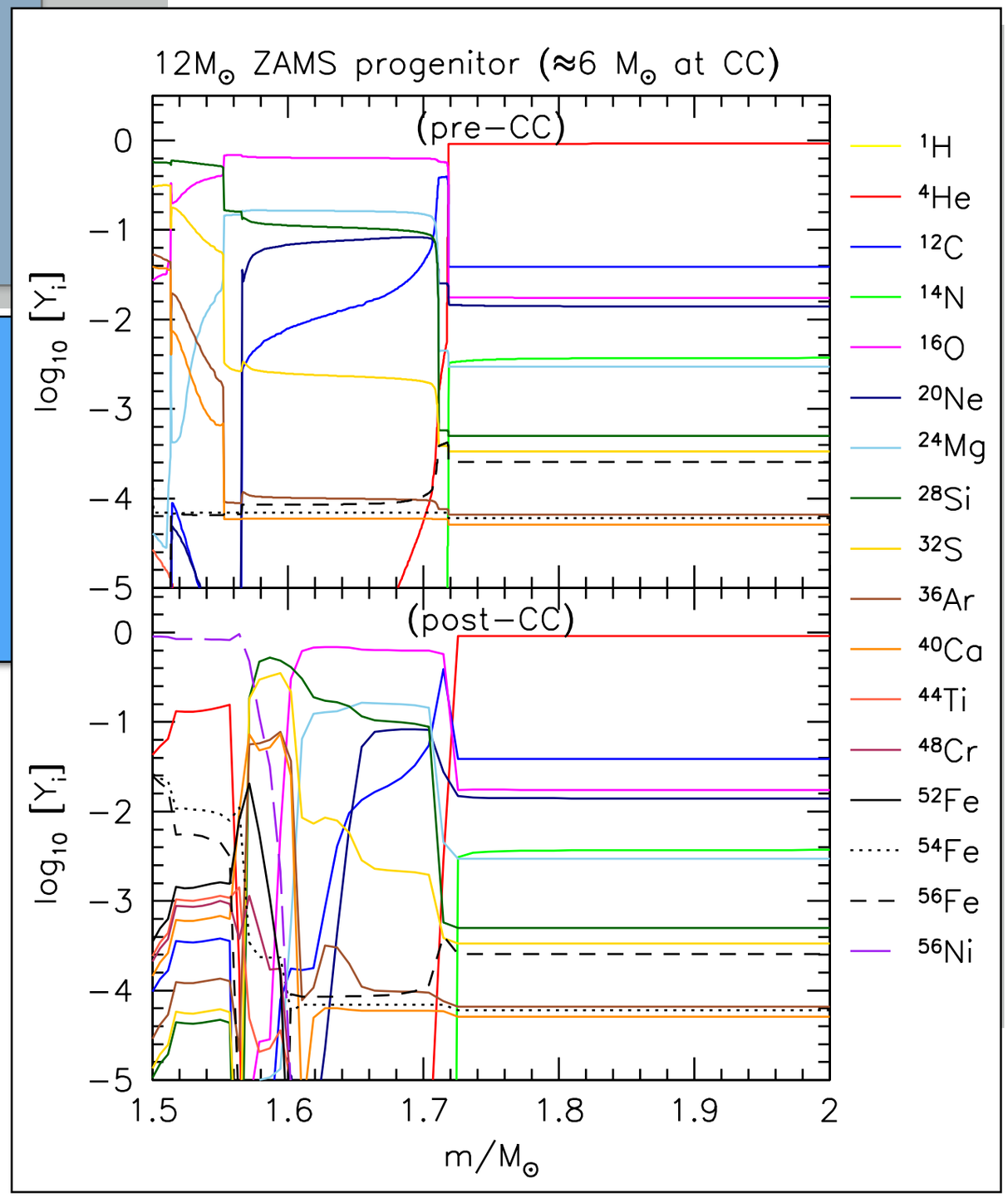
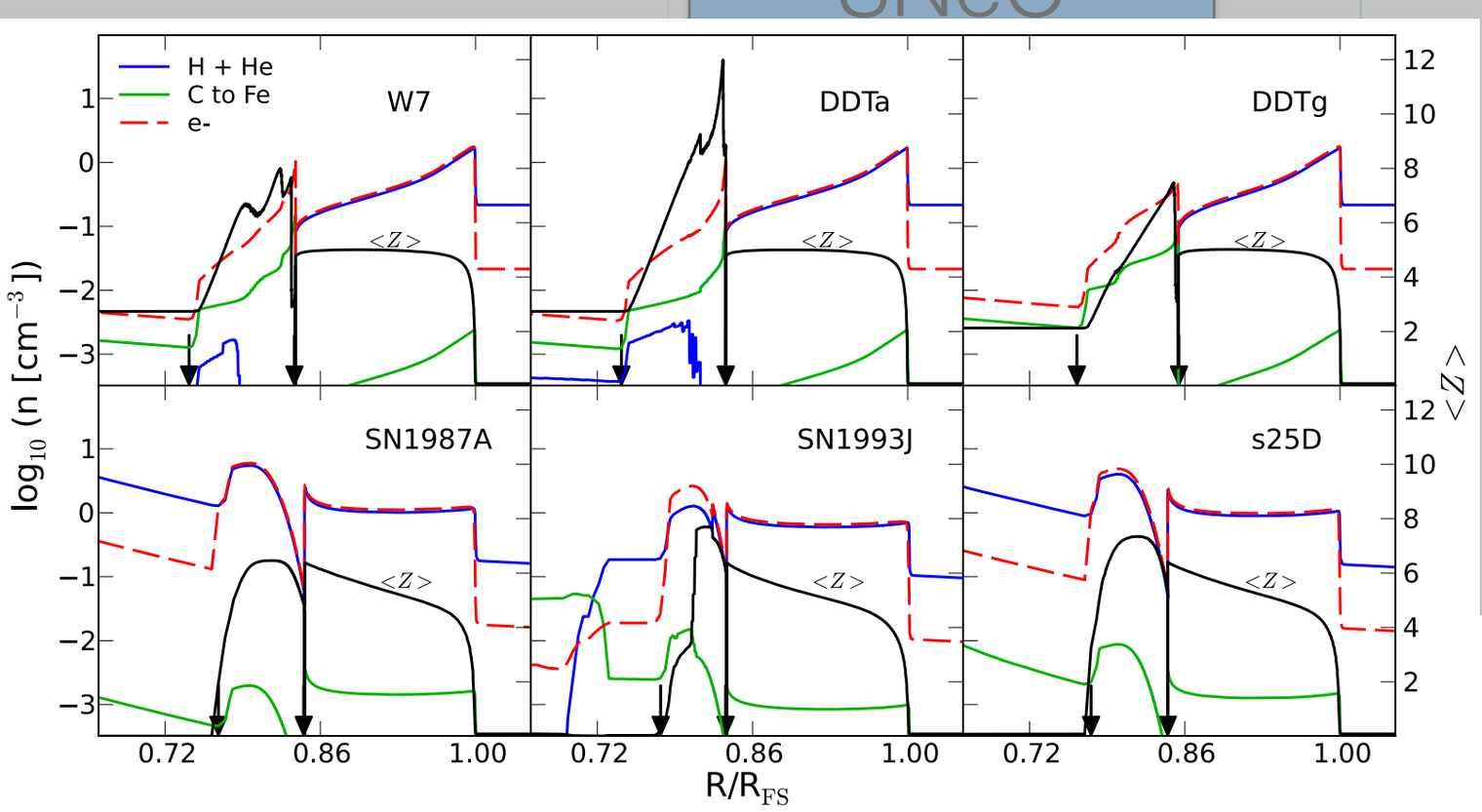
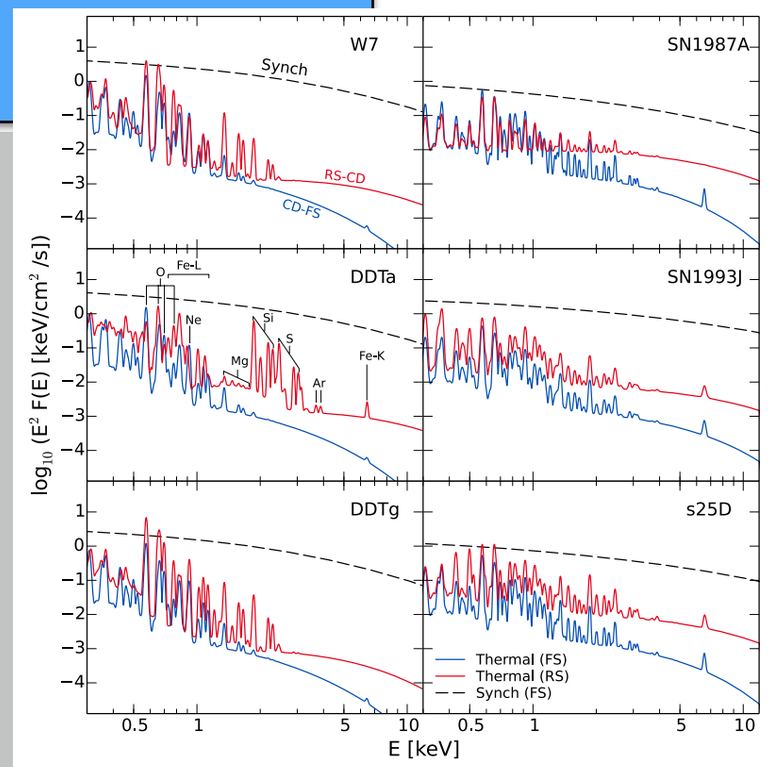


- 1D hydro code with self-consistent NL DSA and NEI
- Computes broadband thermal and nonthermal emission including effects from optical forbidden line emission

ChN

SNeC





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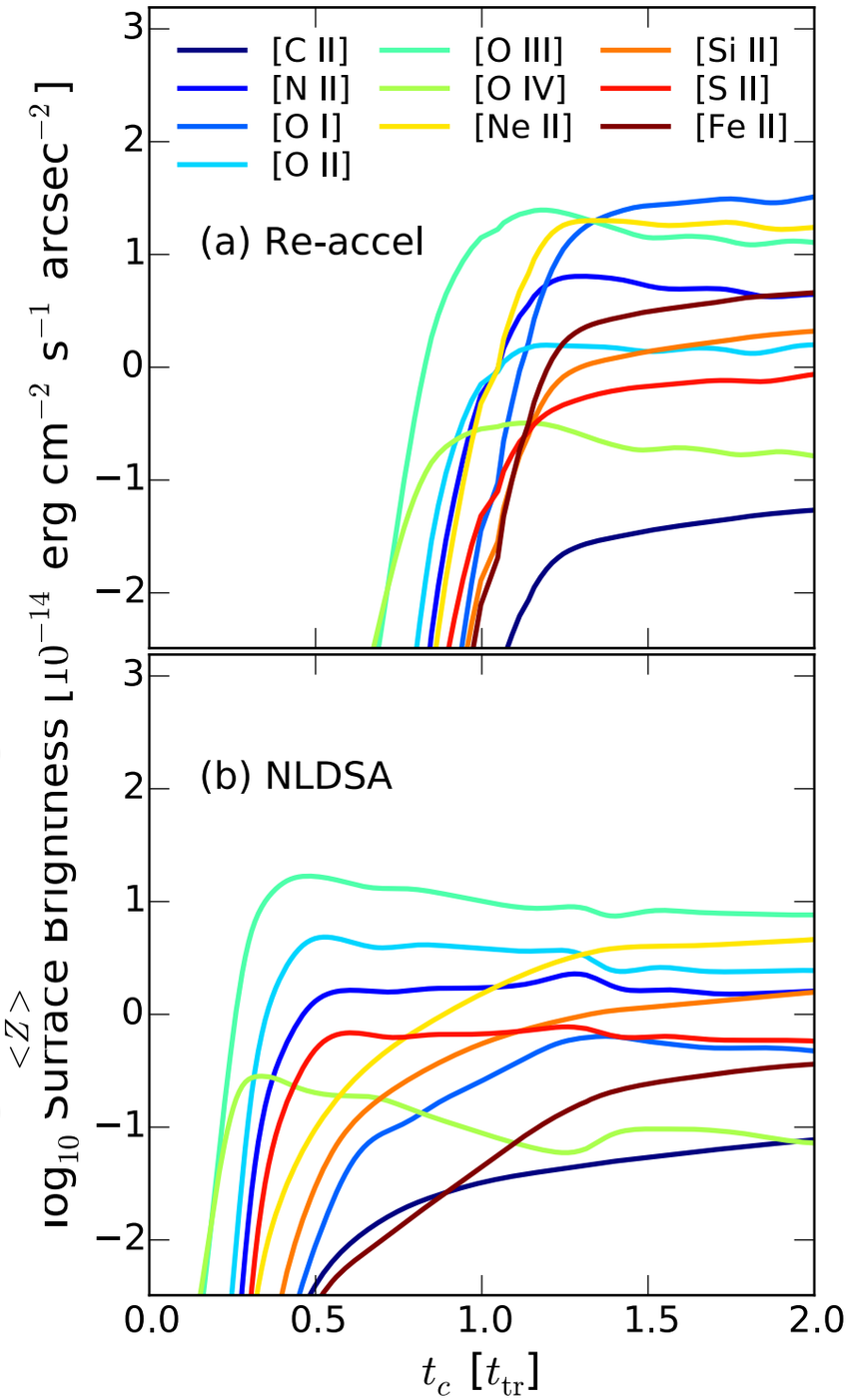
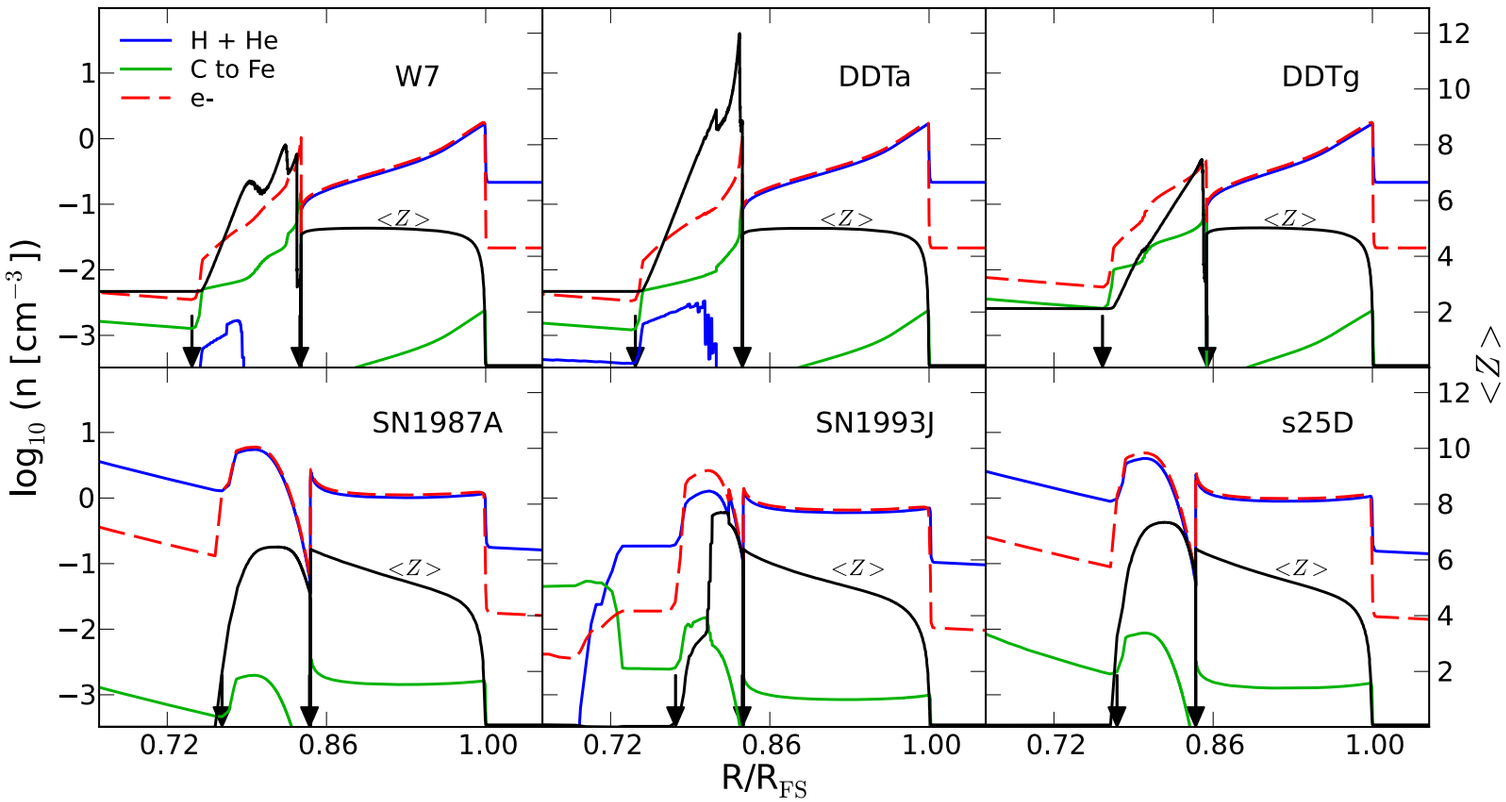
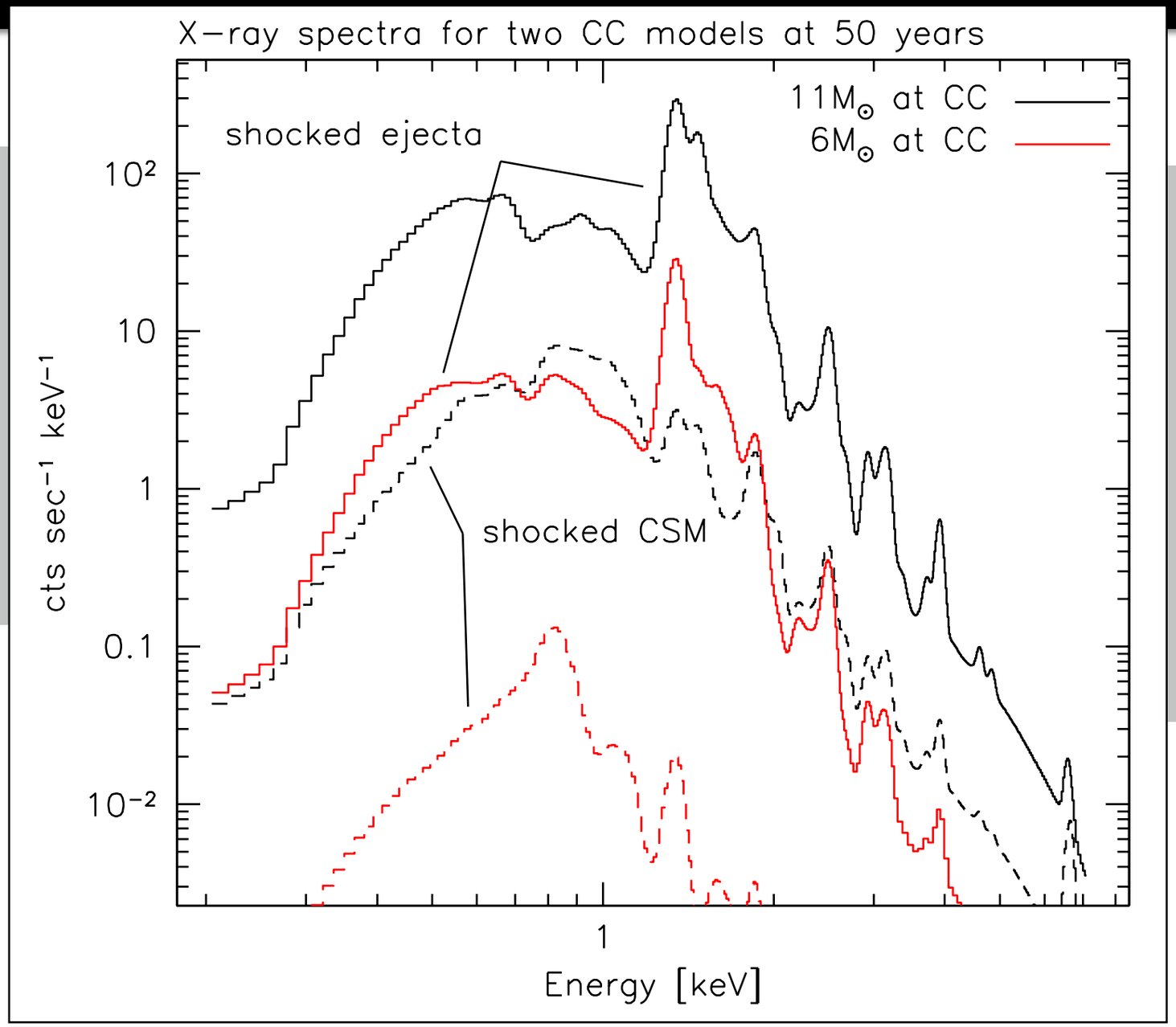


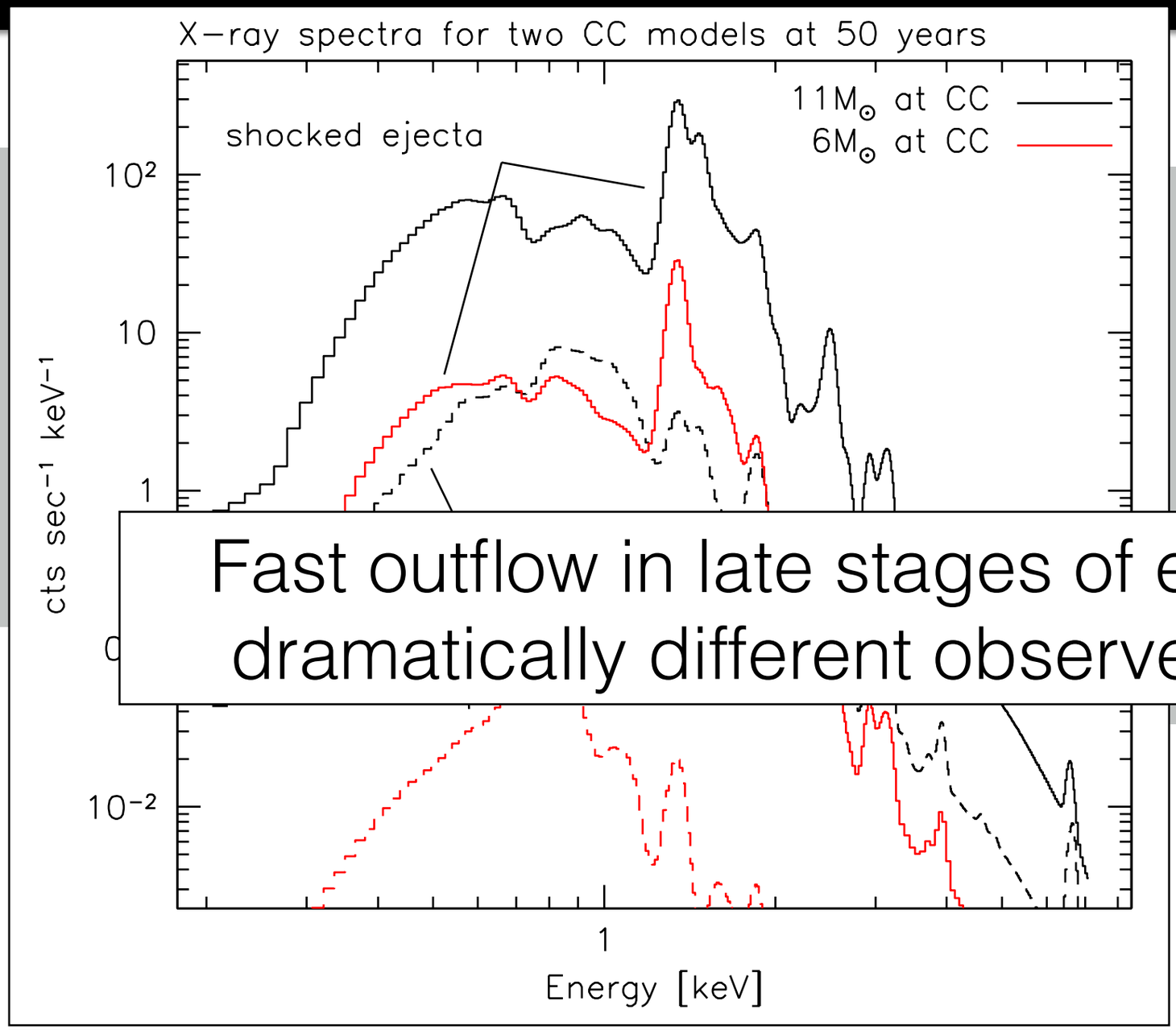




Simulated spectra convolved with X-ray CCD response function

- Line centroids
- Line ratios
- Chemical composition

Observables



Simulated spectra convolved with X-ray CCD response function

- Line centroids
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Fast outflow in late stages of evolution result in dramatically different observed X-ray spectra

Observables

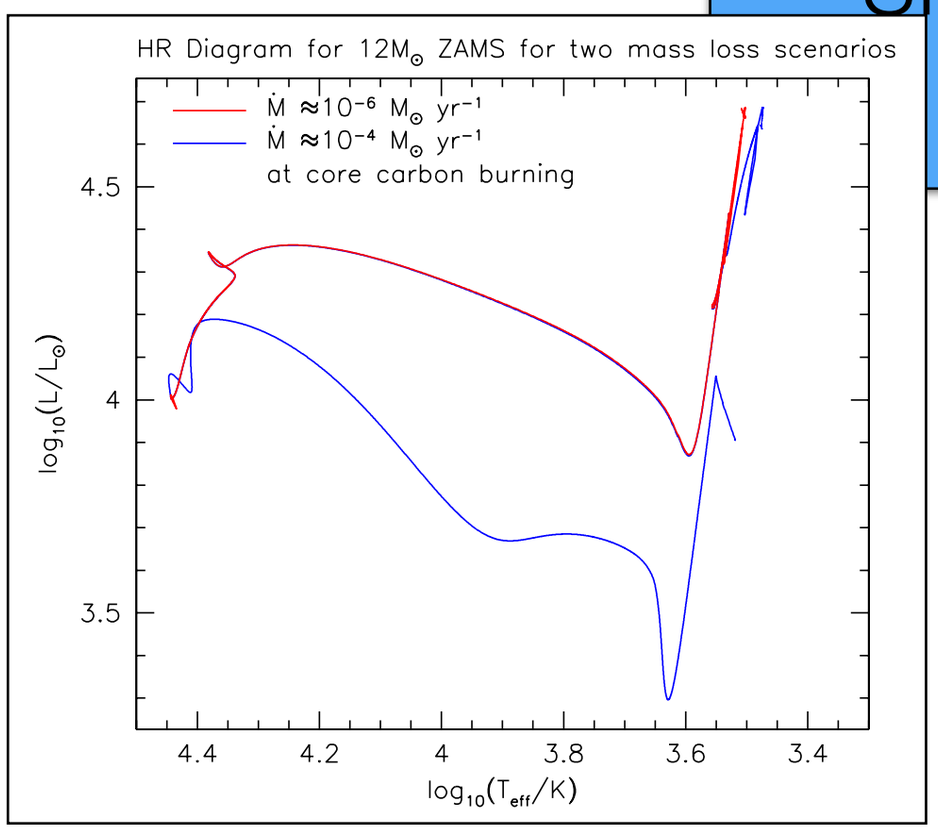
Uncertainties

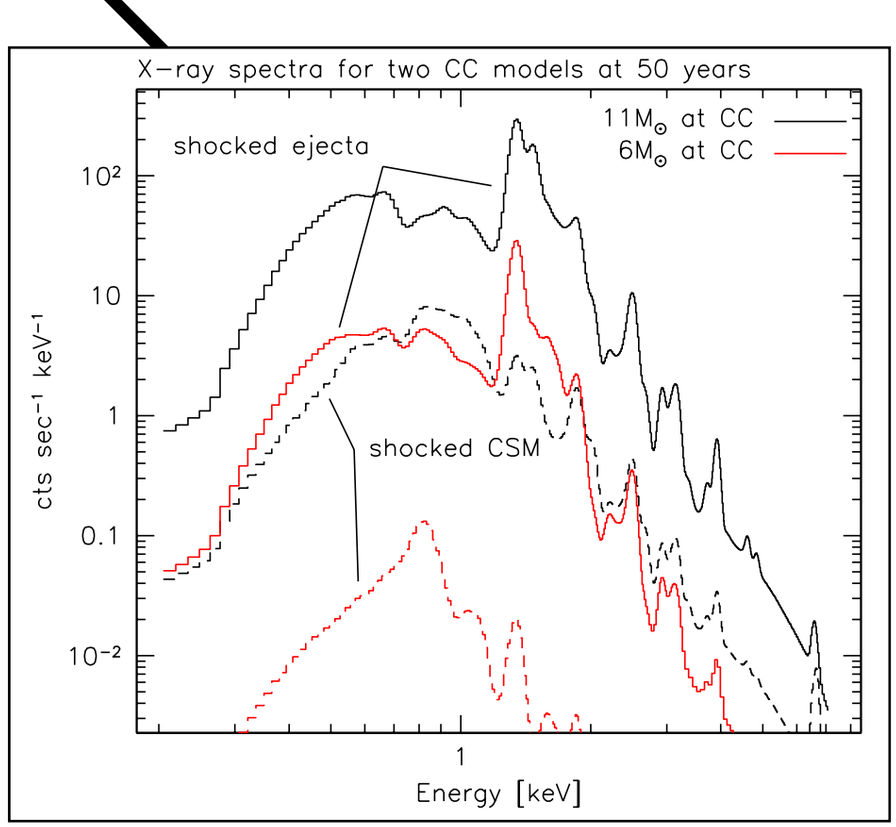
MESA

VH-1

SNeC

ChN





Uncertainties

- MESA:
  - mass loss rates
  - nuclear physics
  - rotation, binarity, etc…
- SNeC:
  - nuclear physics
  - atomic physics (opacities)
  - simple approximation to the explosion
  - choice of mass cut, etc…
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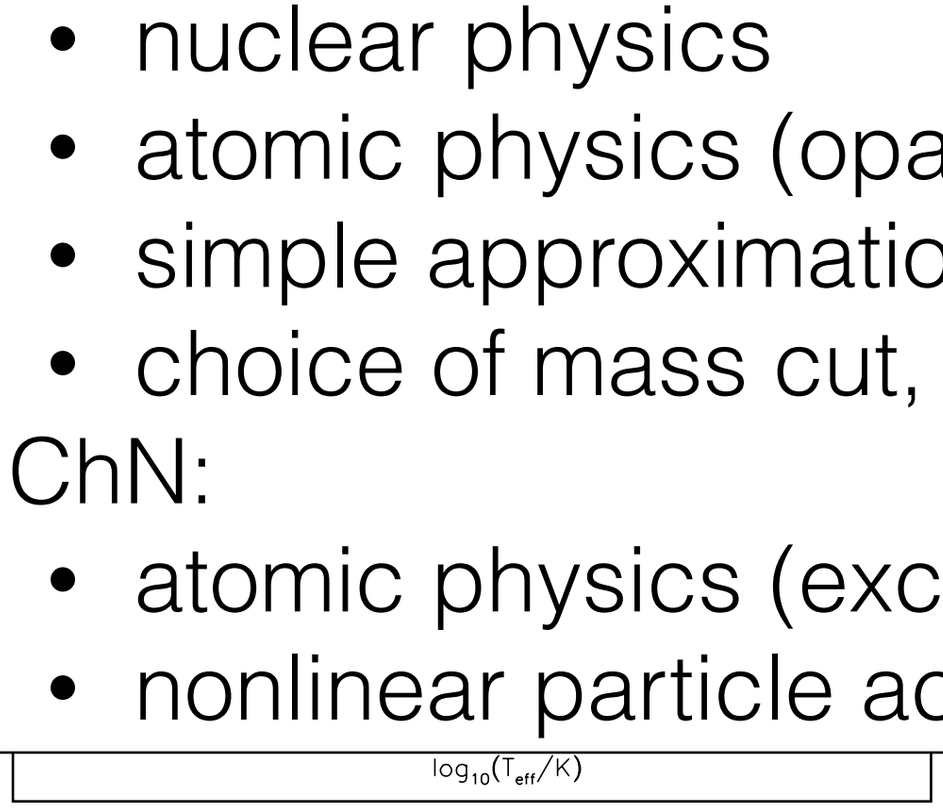
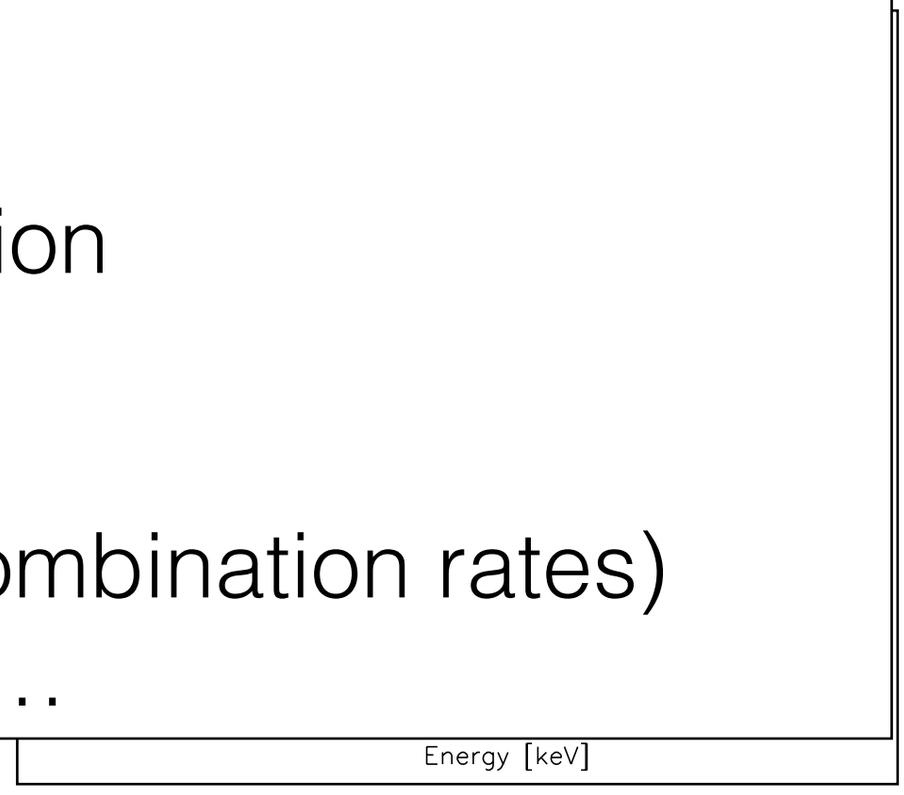
  - atomic physics (excitation and recombination rates)
  - nonlinear particle acceleration, etc…





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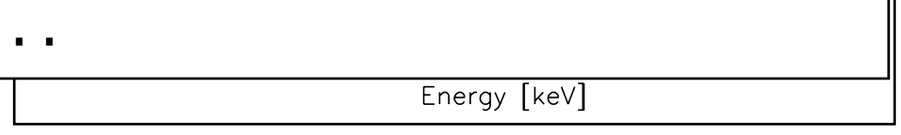
Massive parameter space to explore!



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  - **"The Role of Diffusive Shock Acceleration on Nonequilibrium Ionization in Supernova Remnants,"** Patnaude et al. (2009) ApJ, 696, 1956
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  - **"Reverse and Forward Shock X-Ray Emission in an Evolutionary Model of Supernova Remnants Undergoing Efficient Diffusive Shock Acceleration,"** Lee et al (2014) ApJ, 791, 97
- **SNeC** (a primitive code for supernova evolution):
  - **"Light Curves of Core-Collapse Supernovae with Substantial Mass Loss Using the New Open-Source Supernova Explosion Code (SNEC),"** Morozova et al. (2015) ApJ 814, 63
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- **Cas A Properties**:
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  - **"A Comparison of X-Ray and Optical Emission in Cassiopeia A,"** Patnaude & Fesen (2014) 789, 138
  - **"A Chandra X-Ray Survey of Ejecta in the Cassiopeia A Supernova Remnant,"** Hwang et al. (2012) ApJ, 736, 140
  - **"The Circumstellar Medium of Cassiopeia a Inferred from the Outer Ejecta Knot Properties,"** Hwang et al. (2009) ApJ, 703, 883
  - **"The hydrodynamics of the supernova remnant Cassiopeia A. The influence of the progenitor evolution on the velocity structure and clumping,"** van Veelen (2009) A&A, 503, 495
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- **Other**:
  - Timmes EOS & nuclear reaction networks (http://cococubed.asu.edu/code_pages/codes.shtml)
  - VH-1 (a general purpose hydrodynamics code; http://wonka.physics.ncsu.edu/pub/VH-1/)