The Riddle of Steel:
On neutrons and Type Ia SNe

Carles Badenes
University of Pittsburgh

SNRs 2016 - Chania
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with **Héctor Martínez-Rodríguez** (Pitt)**, Hiroya Yamaguchi** (NASA/UMd),
Dan Patnaude (CfA), **Eduardo Bravo** (UPC), **Sangwook Park** (UTA), and others

The Riddle of Steel

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- 'Conan the Barbarian': To get reliable steel, different impurities are added to iron and carbon to make it soft or hard. These include Si, S, and Mn.

- Manganese (^{55}Mn) is a n-rich element. **The synthesis of n-rich isotopes in SN Ia explosions provides a unique window into SN Ia physics**.

- These n-rich isotopes are **best observed in SNRs** (long half-lives, cleanly separated lines, ability to see all shocked ejecta, no need for radiative transfer).

- Key issues: neutronization, SN Ia progenitors, metallicity, C simmering. Will also discuss CSM interaction in SN Ia.

SN Ia Progenitor Scenarios

Single Degenerate

WD+star

Slow **accretion** ⇒ mass growth ⇒ M_{Ch} explosion

Double Degenerate

WD+WD

GW emission ⇒ **merger or collision** ⇒ explosion

Core Degenerate

WD+AGB nucleus

Common envelope ⇒ **merger** ⇒ explosion

References: Wang & Hang 12; Maoz+14; Hachisu+ 96; Iben & Tutukov 84; Webbink 84; Kashi & Soker 11, many talks here

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"What's in a name? That which we call a rose by any other name would smell as sweet."

- W. Shakespeare

Core Degenerate

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SN Ia Progenitor Scenarios

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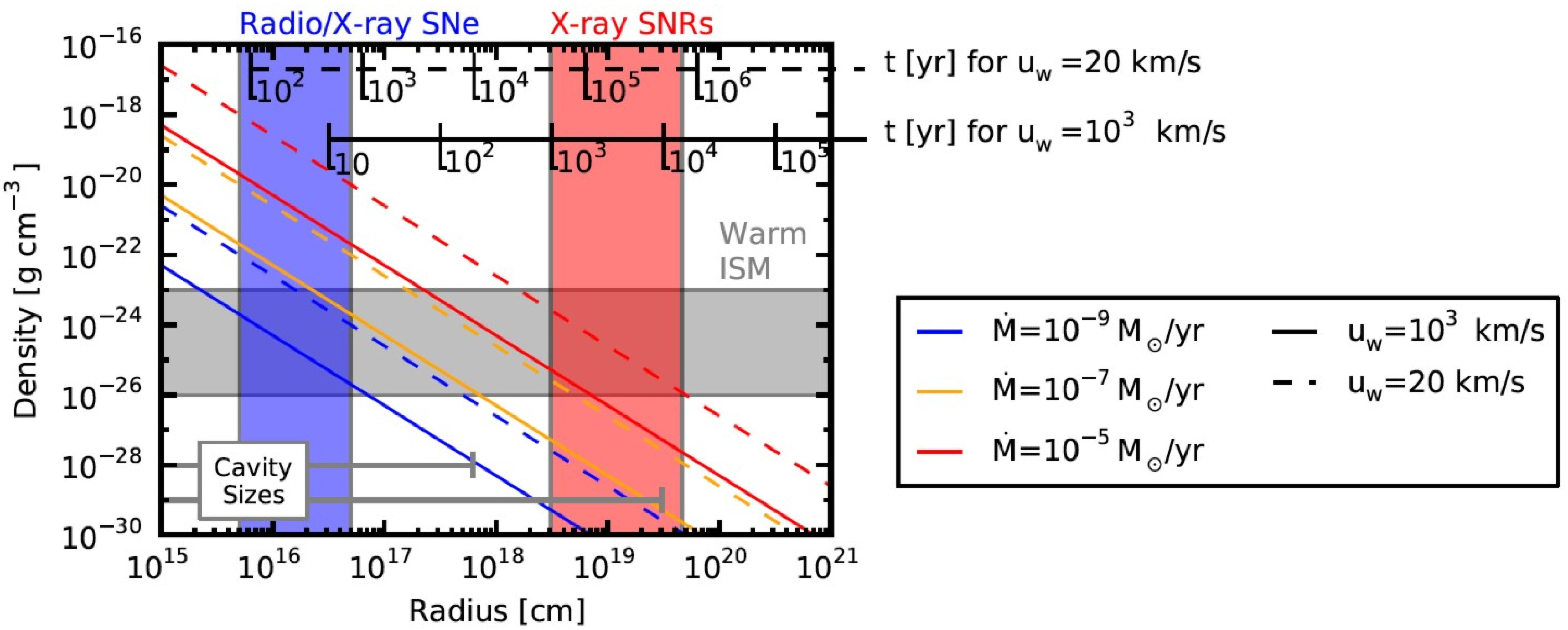
Simple expectations:

Accretors should explode close to M_{Ch} and have some CSM

Mergers and collisions should not necessarily explode close to M_{Ch} and have CSM

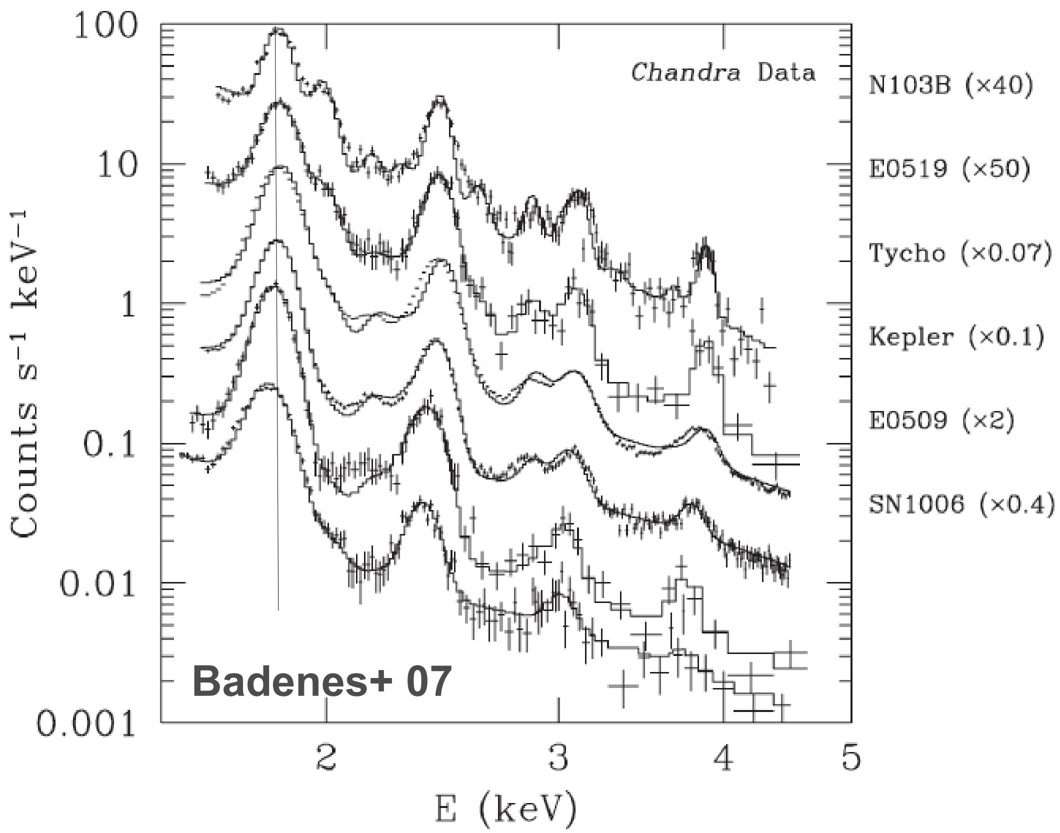
References: Wang & Hang 12; Maoz+14; Hachisu+ 96; Iben & Tutukov 84; Webbink 84; Kashi & Soker 11, many talks here

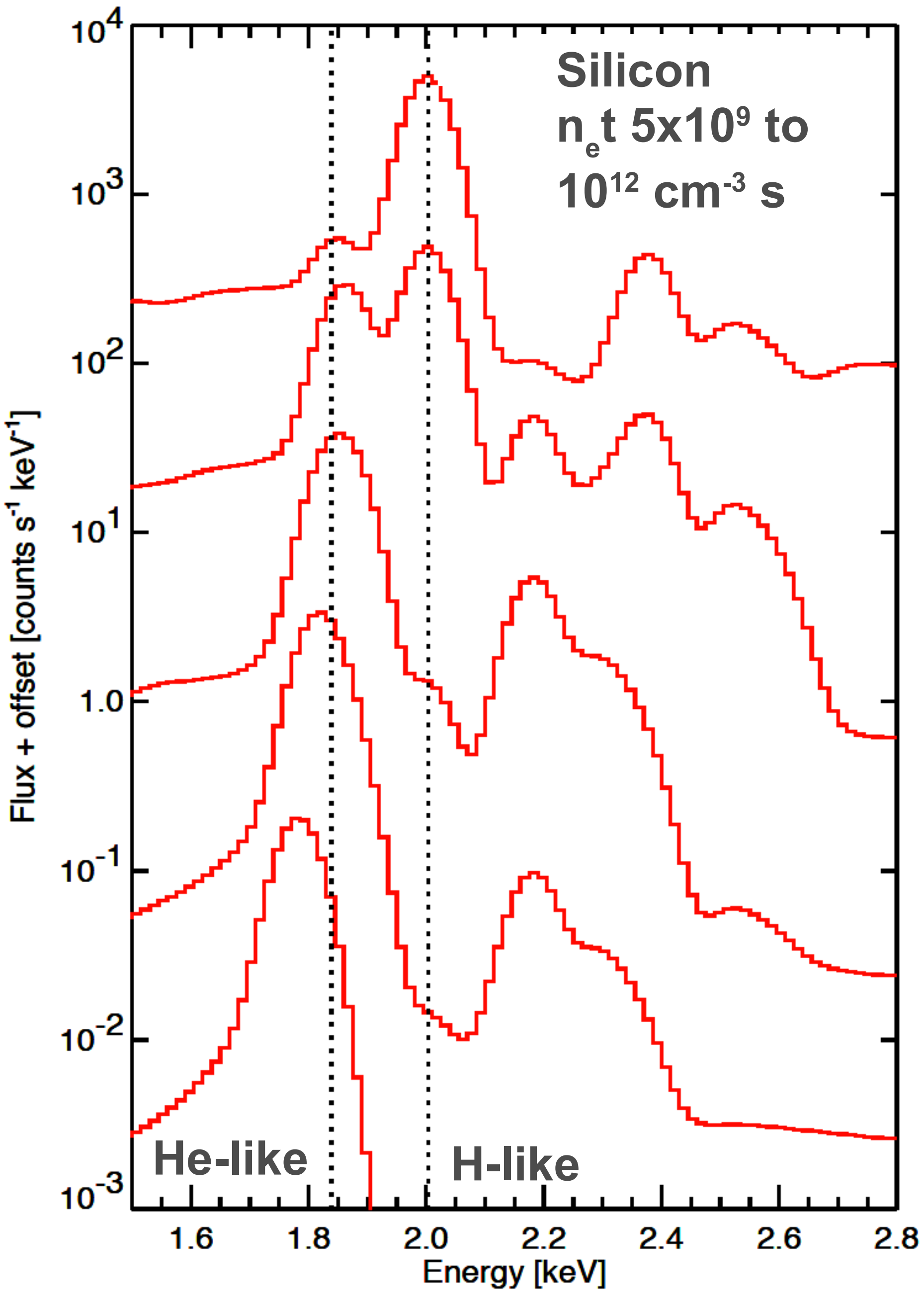
- **Fast vs. slow outflows** [Koo & McKee 92] ⇒ **Cavities vs. $\rho = A/r^2$** .
- **SNe** ⇒ Follow-up (radio/X-ray) probes to ~ 100 AU.
- **SNRs ⇒ spatial (and temporal) scales relevant for stellar evolution** of SN progenitors ($t \lesssim \tau_{KH}$).
- **Can only probe dynamical interaction!**



CSM Interaction in SNRs

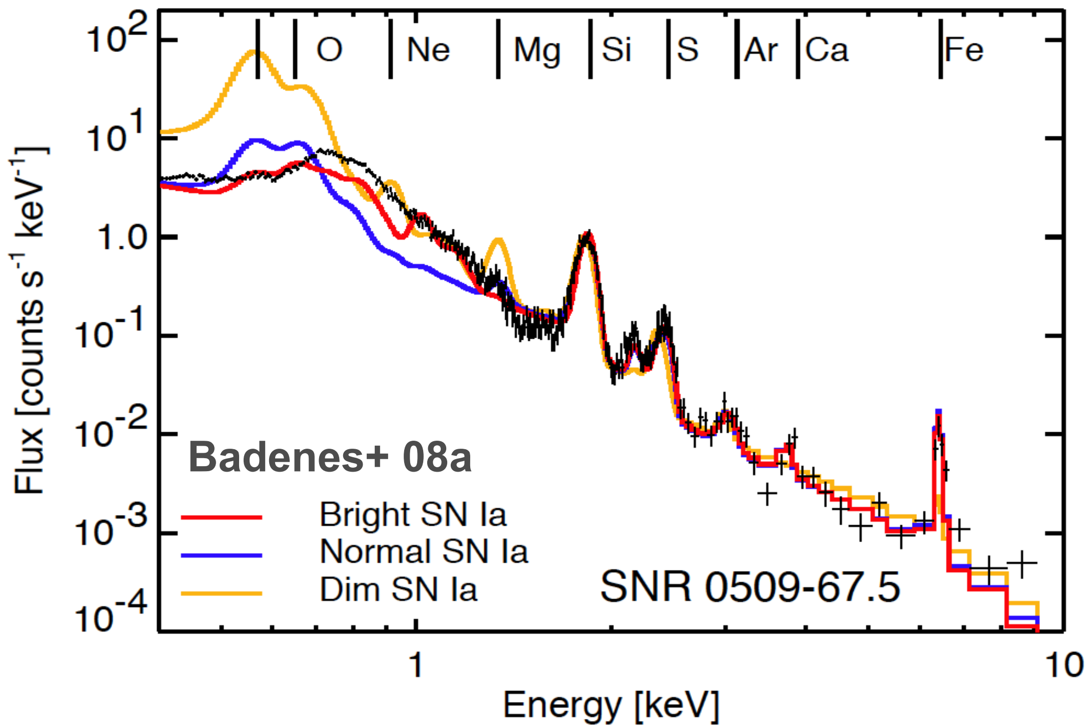
- **X-ray spectra ⇒ AM structure constraints.** NEI plasma: ionization timescale (**$n_e t$**) [Badenes+ 07].
- **High $n_e t$ ⇒ high centroid energy and line flux.**

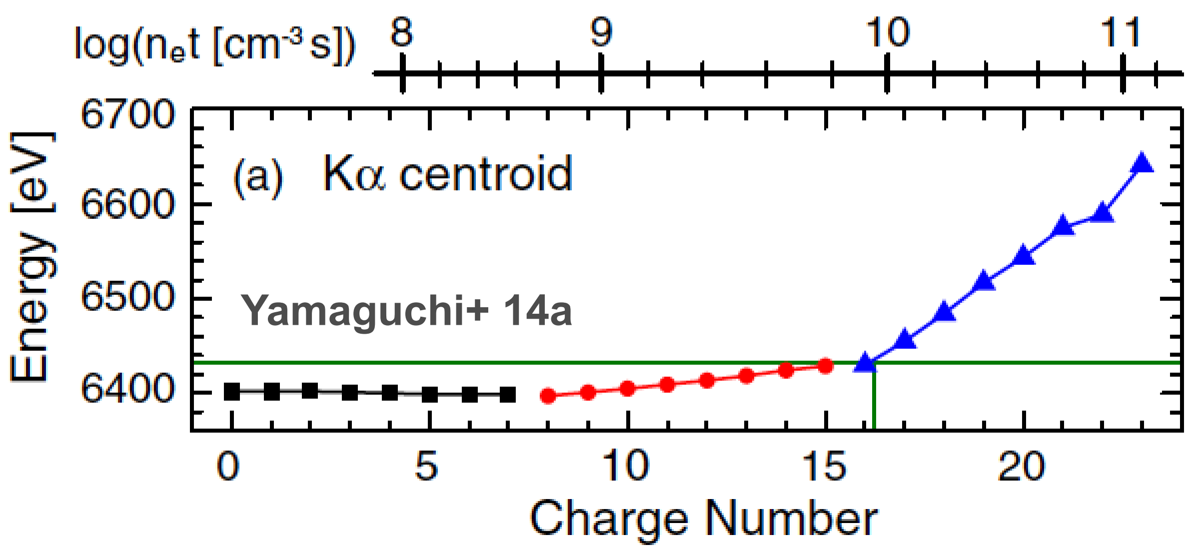




CSM Interaction in SNRs: Fe K

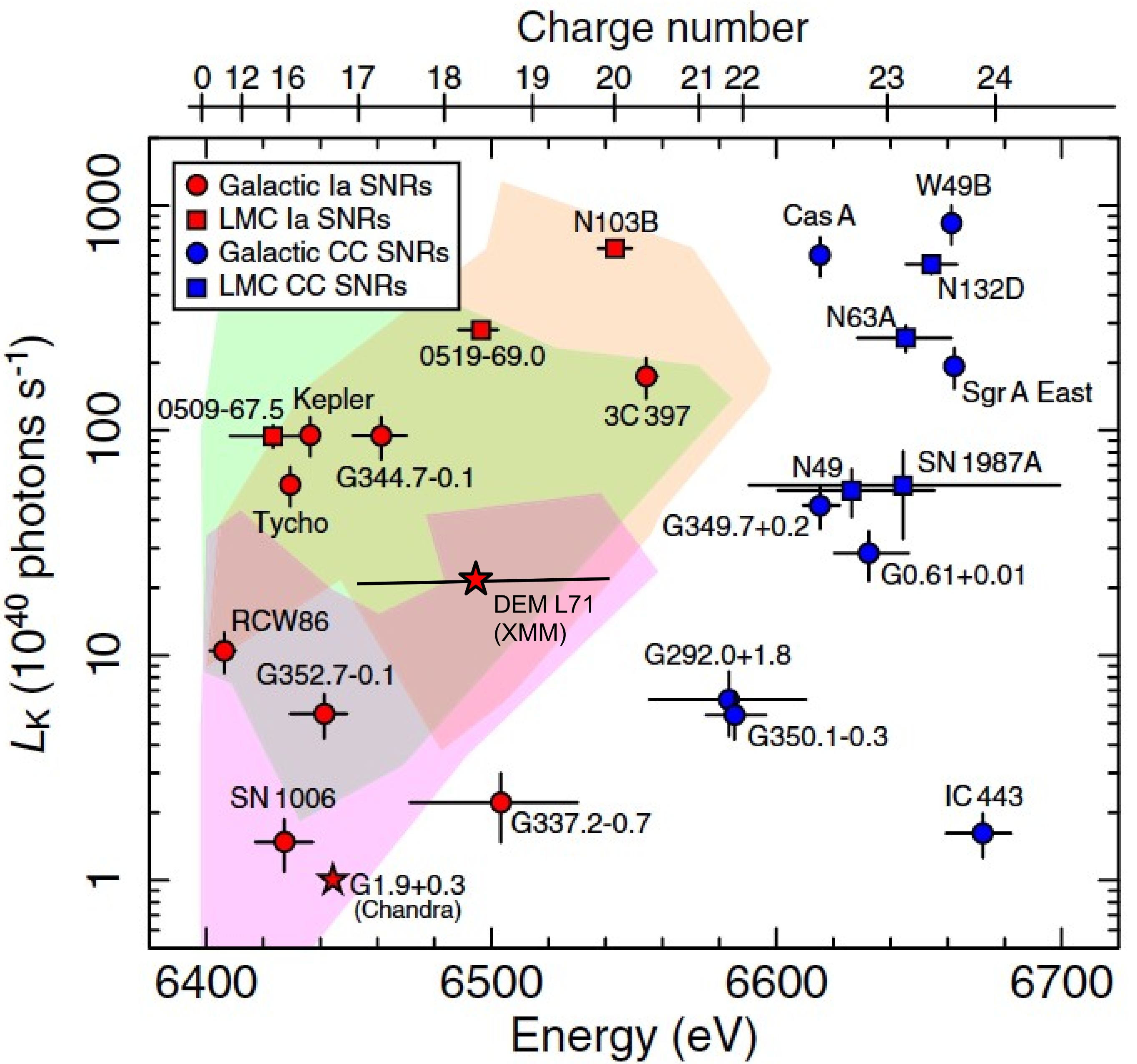
- Use **Fe Kα line blend** at ~6.5 keV as an AM density diagnostic.
- Most SNe (Ia and CC) eject some Fe ⇒ innermost layers.
- Large $n_e t$ required to fully ionize Fe ⇒ **large dynamic range in ρ_{AM}**.
- Need high effective area at 6.5 keV: ***Suzaku***.
- Details: Yamaguchi, CB+ 14b





Models vs. Data

- *Suzaku* data for 23 SNRs + *Chandra, XMM* [Yamaguchi+ 14, Borkowski+ 13, Maggi+ 16, Maggi talk, poster].
- **Evaluate stellar evolution + explosion with SNR observations**.
- **Models are required to interpret these data**.
- **Uniform AM, M_{Ch} ejecta can explain (most) Ia SNRs.**



Type Ia SNR Models

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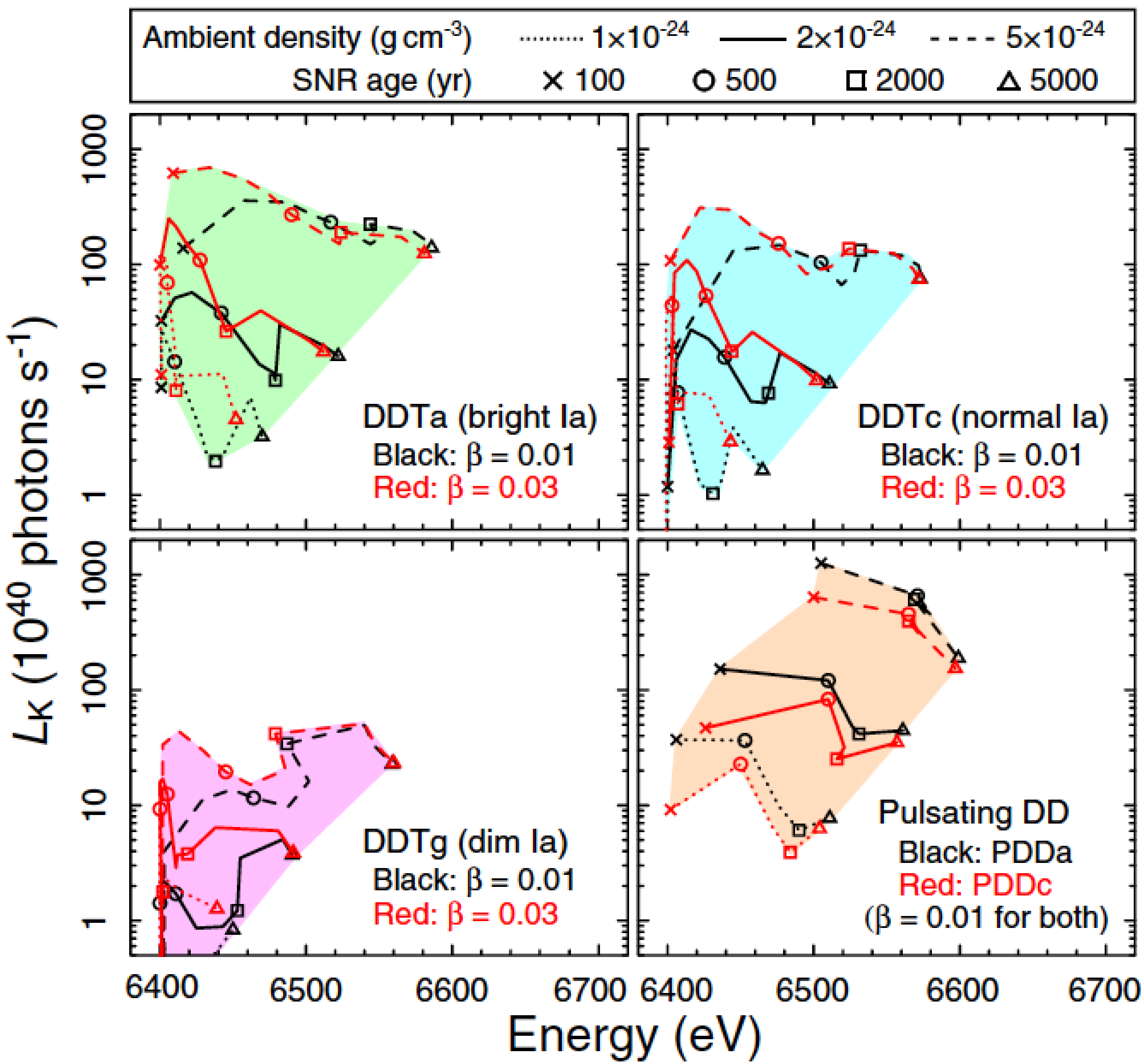
- **Type Ia SNR models:** M_{Ch} ejecta + uniform AM evolved to 5000 yr [Badenes+ 03,05,06,08a].

- **DDT** ejecta models (dim, normal, bright SN Ia) ⇒ crude (but effective) **diagnostic of SN Ia brightness!**

- Also **PDD** models ⇒ more compact ejecta.



What is going on?

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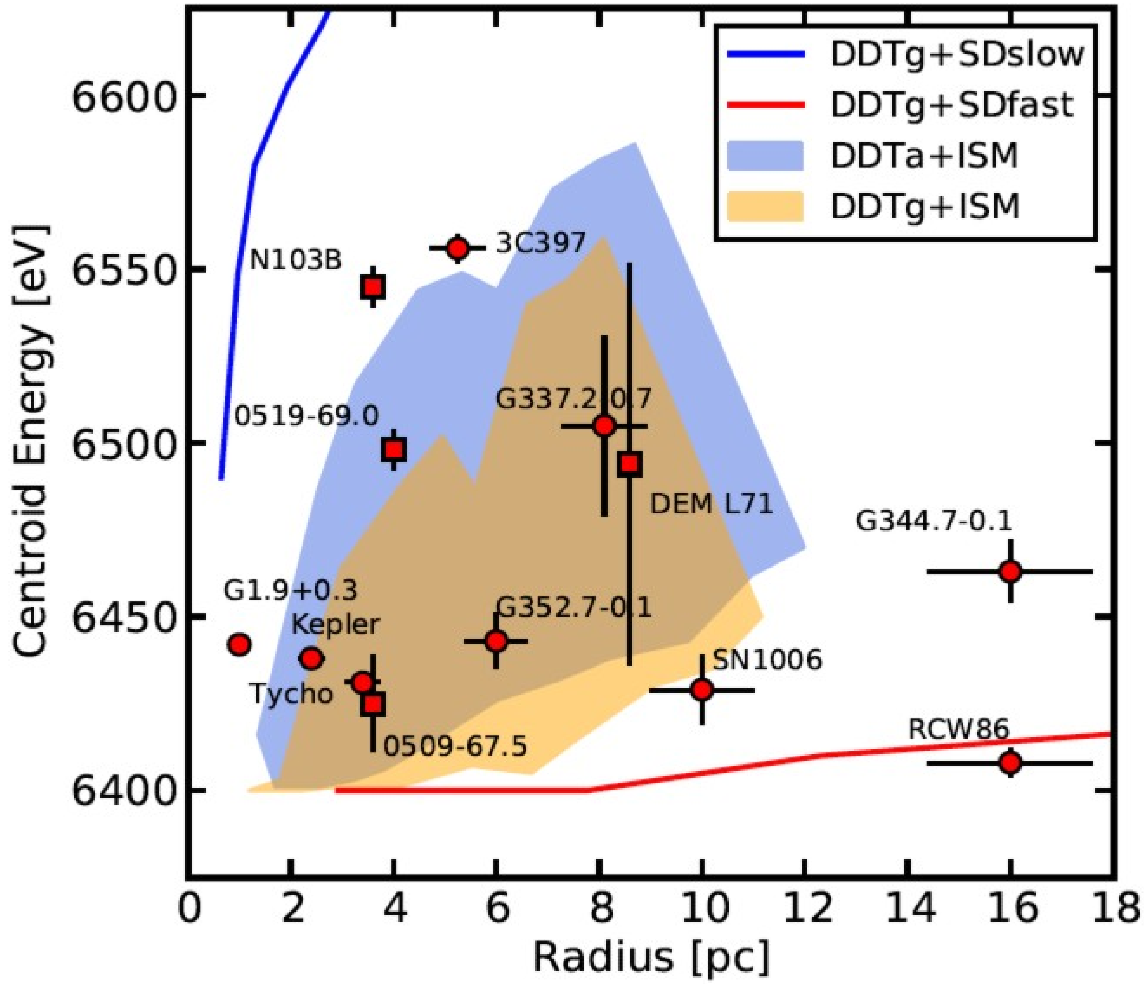
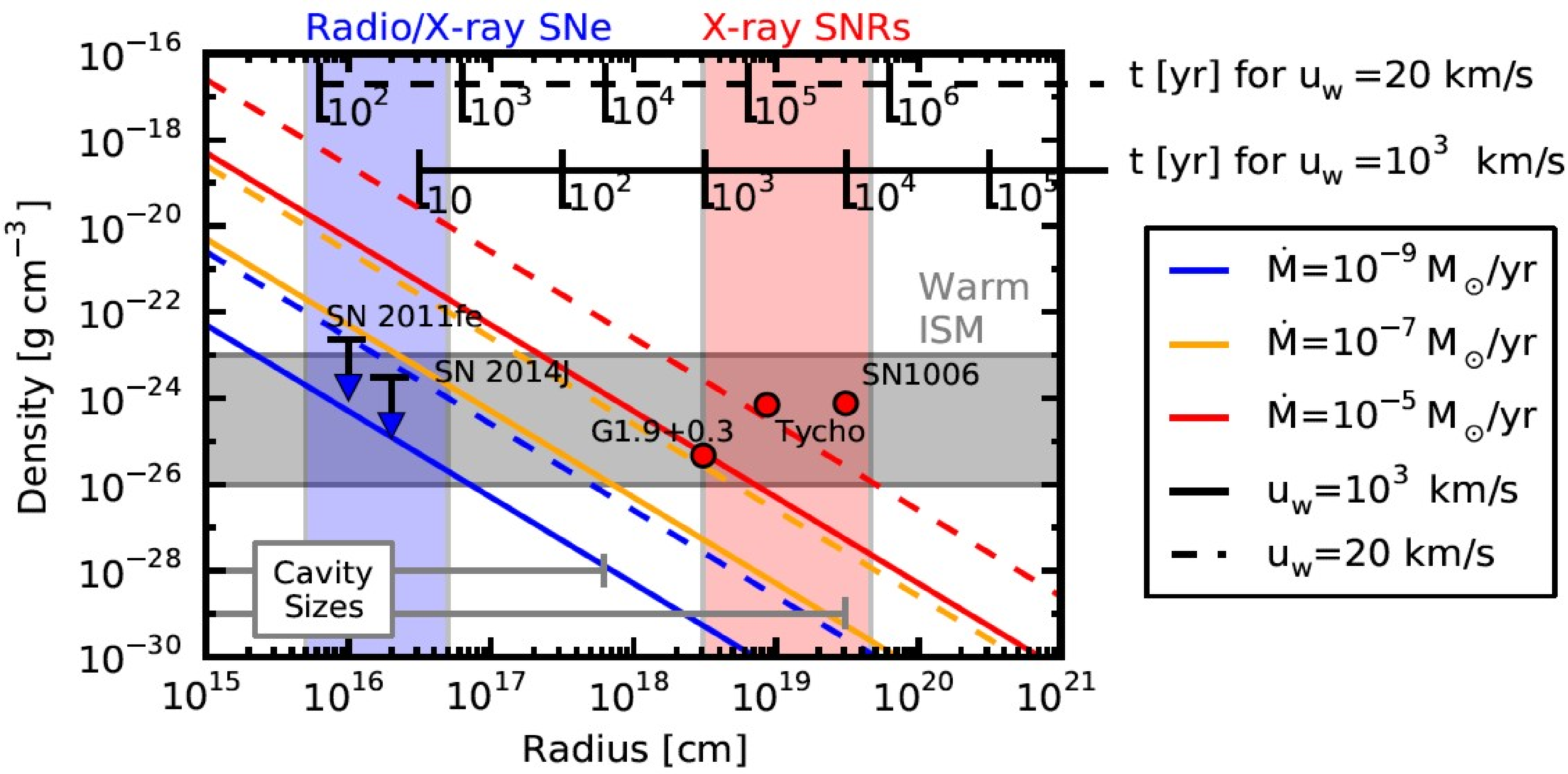
- **Different dynamics for CC and Ia SNRs**: several $M_\odot$ of CSM vs. much less, maybe no CSM at all.
- **Most Ia SNRs compatible with ISM interaction. Slow isotropic outflows active at explosion ruled out.**
- **Kepler, N103B likely have some CSM** [Patnaude+ 12, Burkey+ 12, Chiotellis+ 12, Williams+ 14].
- **RCW 86 is a cavity explosion** [Badenes+ 07, Williams+ 11, Broersen+ 14].



RCW 86 requires a fast, sustained outflow from the SN progenitor

A Step Back

- **SN Ia AM density estimates** from radio/X-ray SNe (~10d, ~0.01 pc) and SNRs (~500 yr, ~several pc) **are consistent with the warm phase of the ISM** [Badenes+ 07, Chomiuk+ 12, 16, Perez-Torres+ 14, Raymond+ 07, Slane+ 14, Borkowski+ 14]. ⇒ **'clean' mergers?**
- **Mild CSM interaction allowed**, maybe small (~0.5 pc) cavities [Patnaude+ 12, Slane+ 14], but not large ones (except for RCW86!).



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Steps Forward

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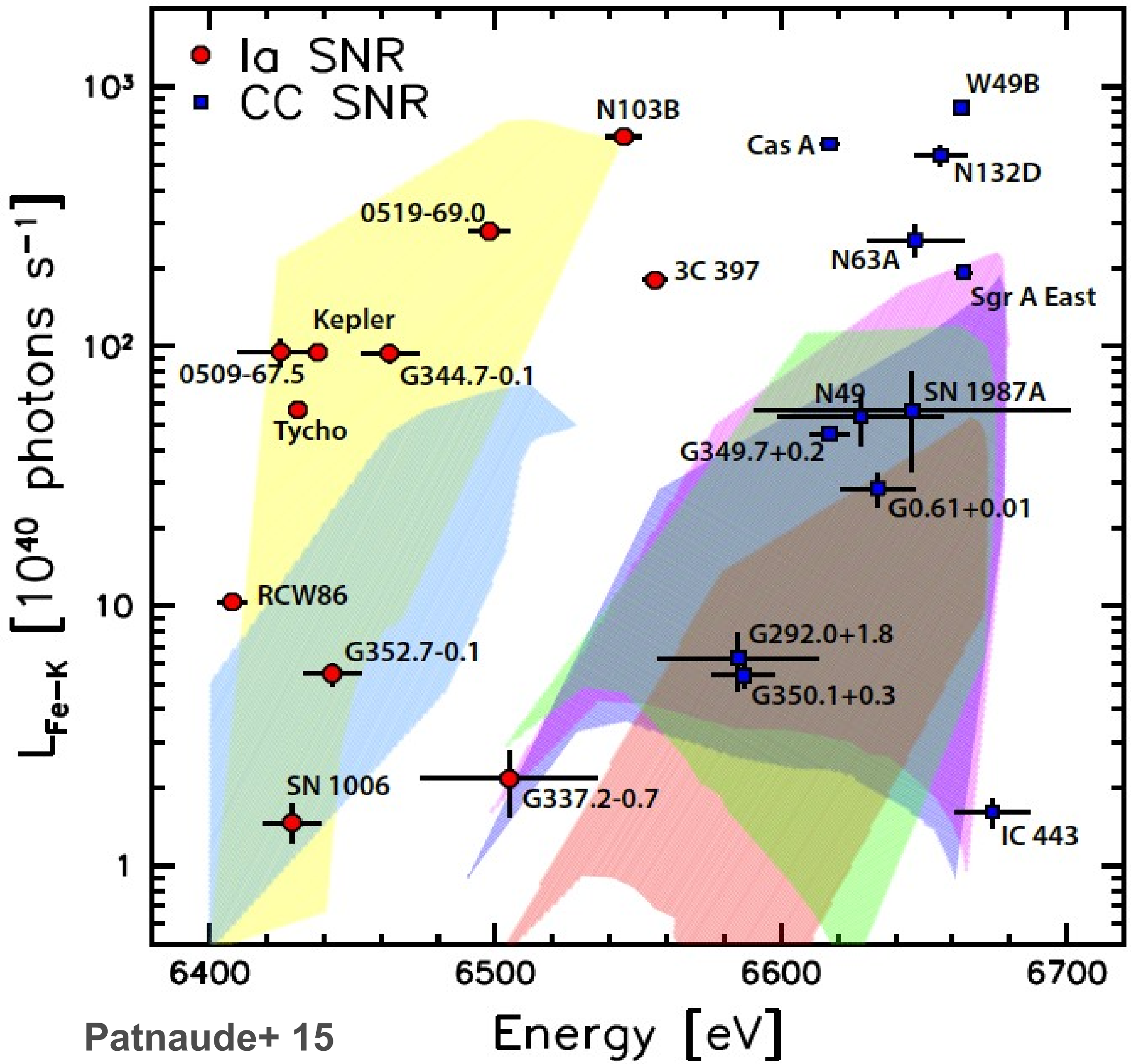
- **Expand the model grid for Type Ia SNRs**: CSM interaction, sub-Chandra explosions (Matt Schell's thesis).
- **Improve the model physics**: CR-modified dynamics [Lee+ 14].
- **CC SNR models**. Evaluate SN and progenitor models at the same time [Patnaude+15, Patnaude talk].



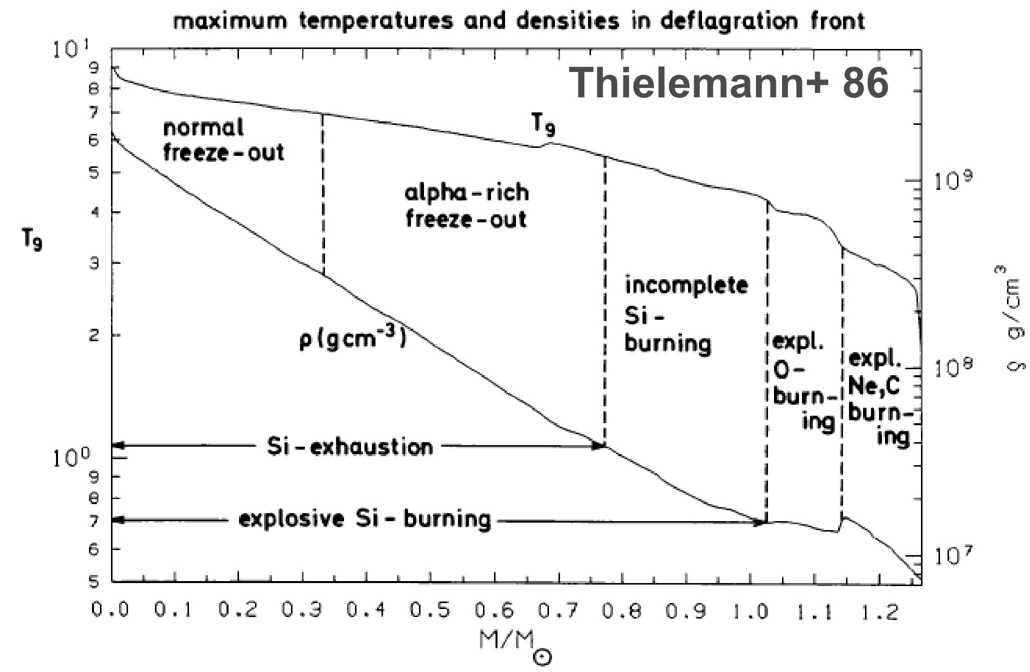
Patnaude+ 15

- **Burning regimes in SN Ia:** Explosive O burning, exp. Si burning, NSE, n-NSE ⇒ Si, S, Ar, Ca, Fe [Thielemann+ 86].

- **How are the n-rich isotopes** (^{55}**Mn,**^{60}**Ni, ...**) **produced?** CO WDs have no neutron excess! Whence do neutrons come from?

- Neutron excess η:

$$\eta = 1 - 2Y_e = \sum_i \frac{N_i - Z_i}{A_i} X_i$$



^{12}C ⇒ η = 0

^{18}O ⇒ η = 0

SN Ia Neutronization

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Neutron excess in Type Ia SNe:

- **Progenitor metallicity:** CNO cycle bottleneck is $^{14}N(\alpha,\gamma) \Rightarrow$ hydrostatic He-burning $\Rightarrow$ ^{22}Ne. Then, $\eta = 0.101xZ$ [Timmes+ 03, Badenes+ 08].
- **Carbon simmering:** C fusion before TN runaway $\Rightarrow$ convective core. Weak interactions $\Rightarrow \eta$ [Bildsten & Piro 08, Martínez-Rodríguez + 16]. **Requires slow accretion and $M_{WD}=M_{Ch}$!!**
- **n-NSE:** During explosion, e-captures in NSE at high densities $\Rightarrow \eta$ (in Fe-peak yields). **Requires $M_{WD}=M_{Ch}$!!**

$^{12}C \Rightarrow \eta = 0$

$^{18}O \Rightarrow \eta = 0$

$^{22}Ne \Rightarrow \eta \Leftrightarrow Z$

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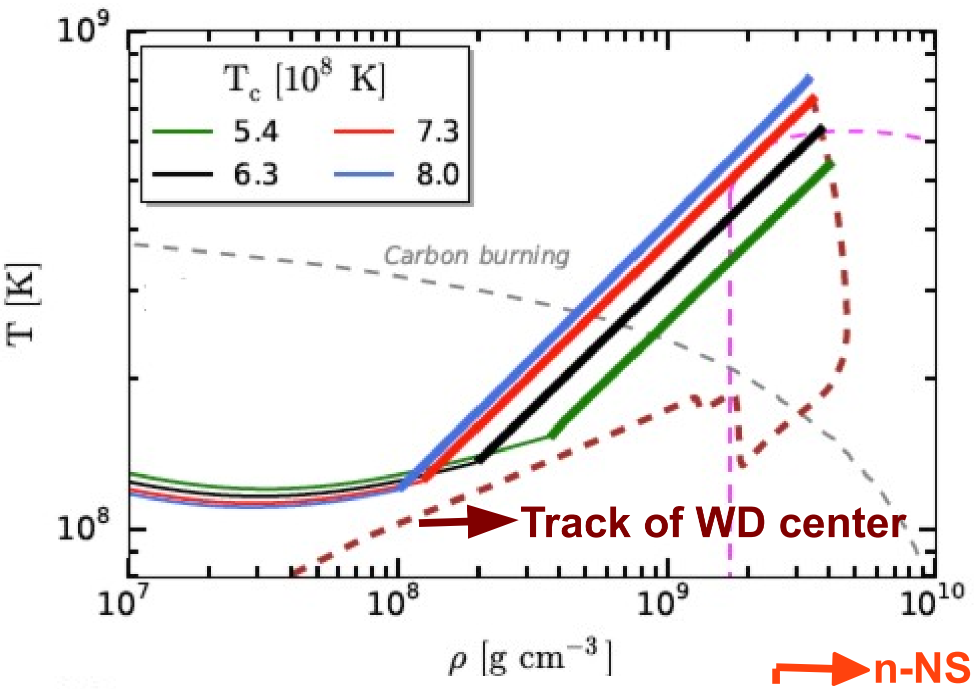

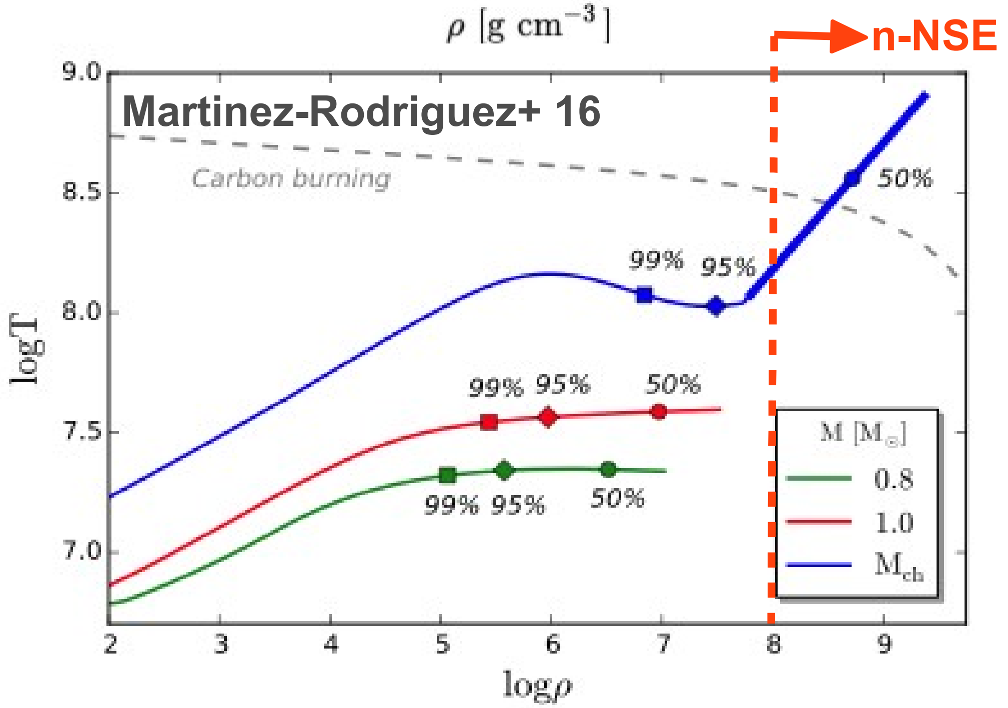

Neutron-Rich Isotopes in SN Ia

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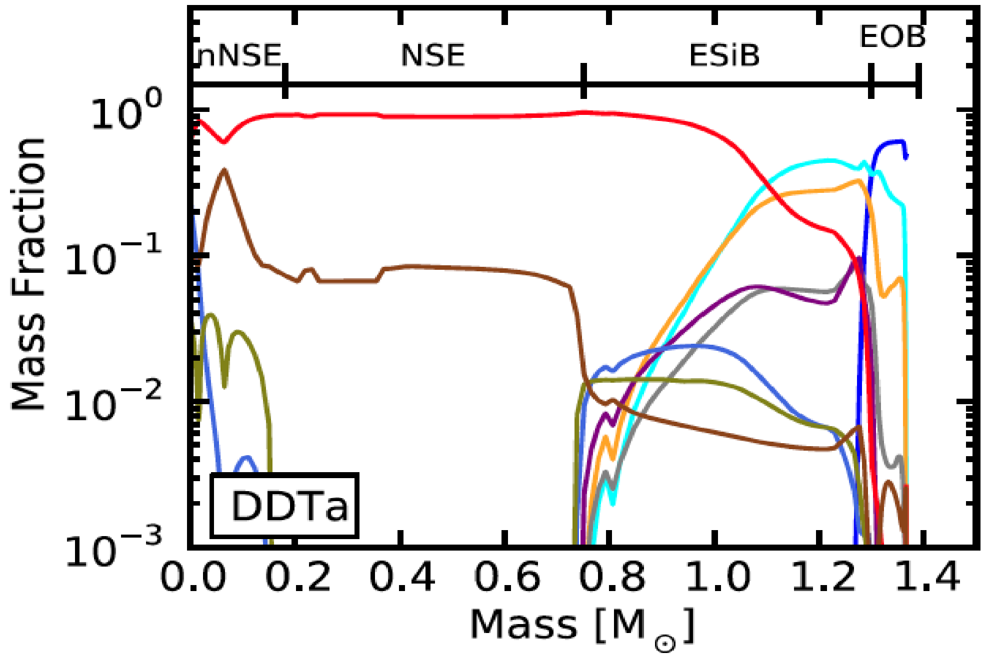
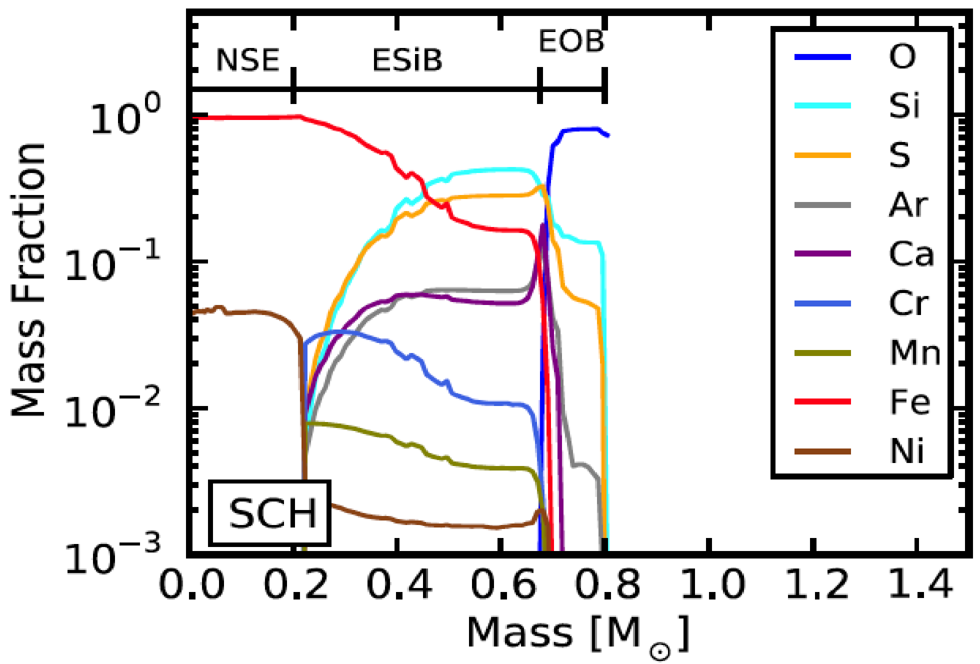
- **M_{Ch} DDT explosions** (standard SN Ia models) [Khokhlov 91]. One parameter (ρ_{tr}) ⇒ ^{56}Ni yield (SN Ia brightness).
- **Sub-Ch explosions** also viable [Sim+ 10]. One parameter (M_{WD}) ⇒ ^{56}Ni yield.
- **Sub-Ch models do not reach n-NSE ⇒ smaller yield of neutronized species** (**Mn, Ni**).
- **Tentative association:**
  - **M_{Ch} DDT ⇔ SD ⇔ High Mn, Ni**
  - **Sub-Ch ⇔ DD ⇔ Low Mn, Ni**





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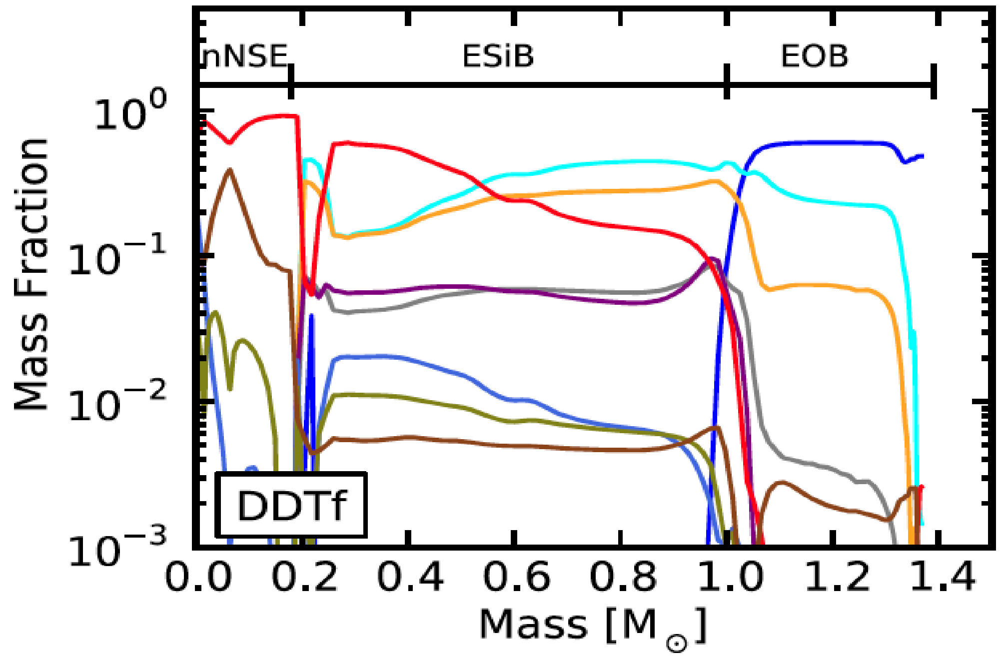

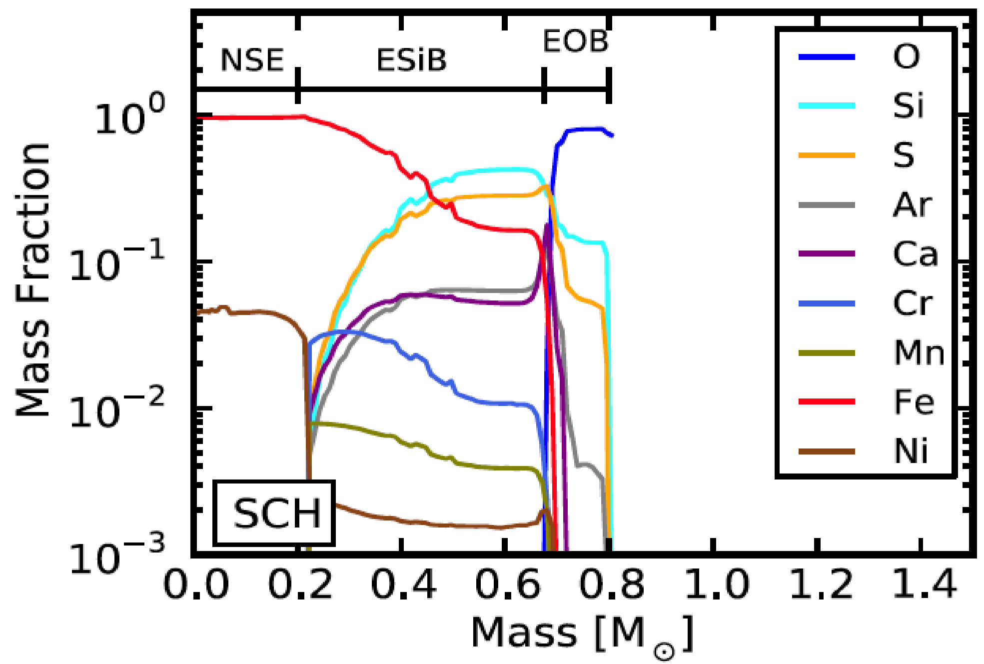

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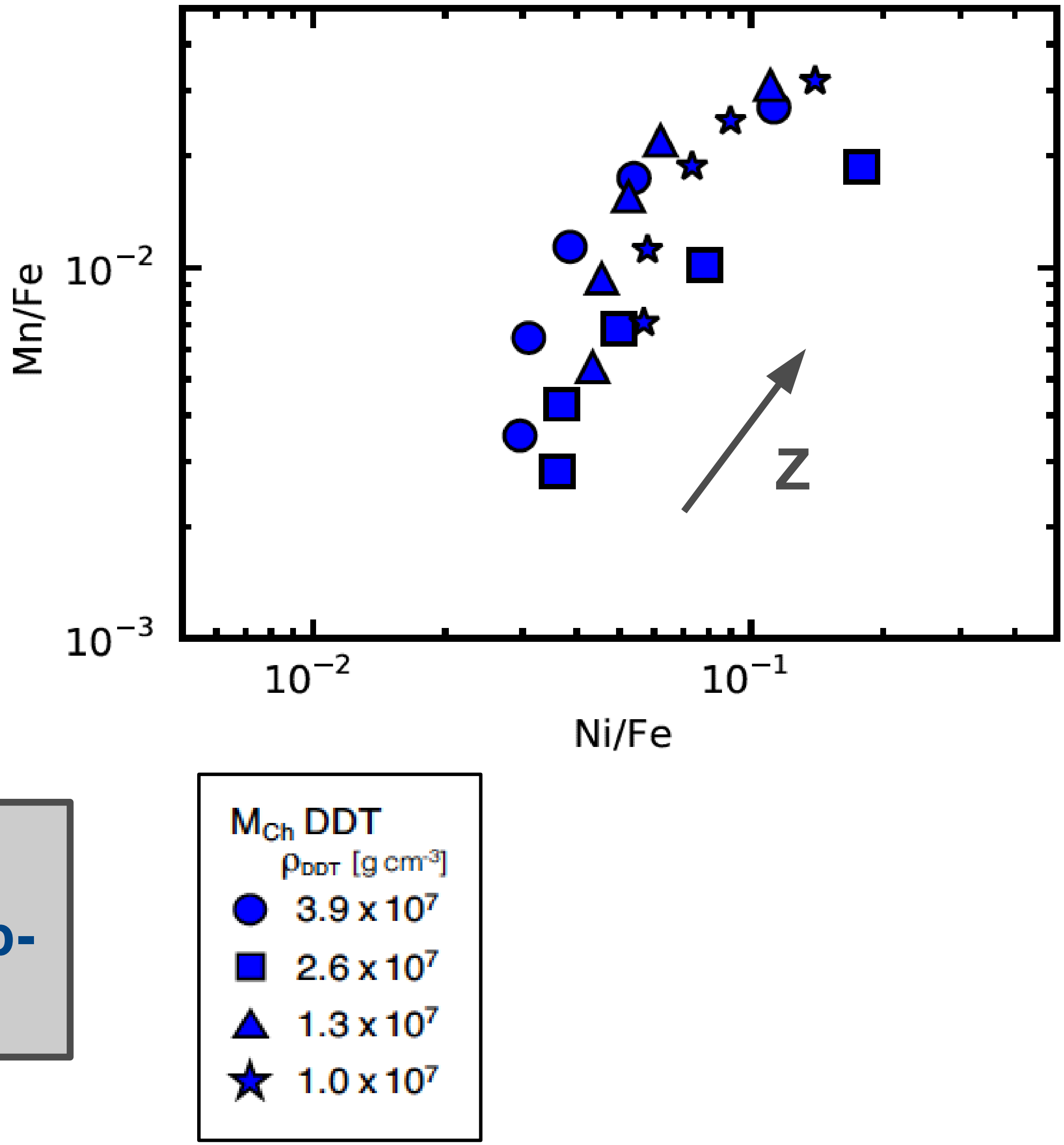
- Yield of neutronized species: **n-NSE + progenitor metallicity** [Timmes+ 03, Badenes+ 08b].

- Mn and Ni are hard to observe in the optical [Maeda+ 10, Seitenzahl+ 13].

- Diagnostic mass ratios for SNRs: $\mathbf{M_{Ni}/M_{Fe}}$ and $\mathbf{M_{Mn}/M_{Fe}}$



$\mathbf{M_{Ni}/M_{Fe}}$ and $\mathbf{M_{Mn}/M_{Fe}}$ can discriminate Ch and Sub-Ch SN Ia progenitors

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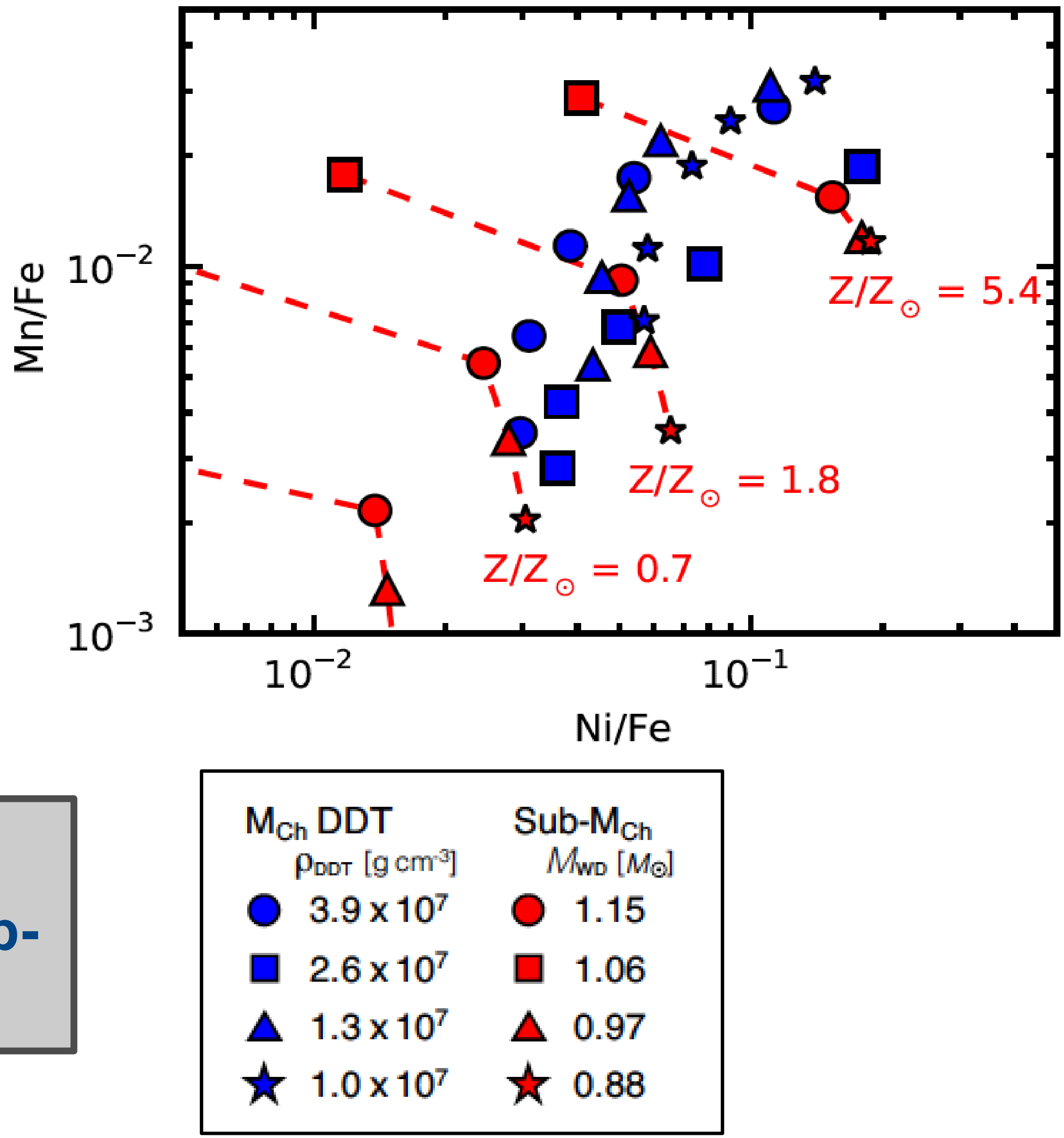

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SNR 3C397

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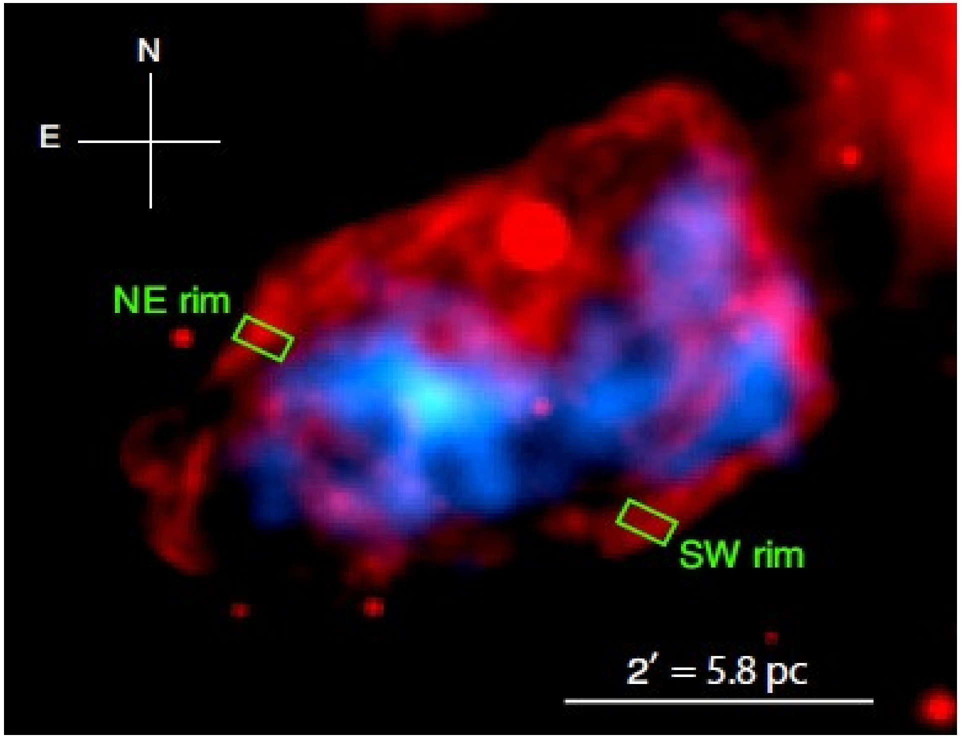
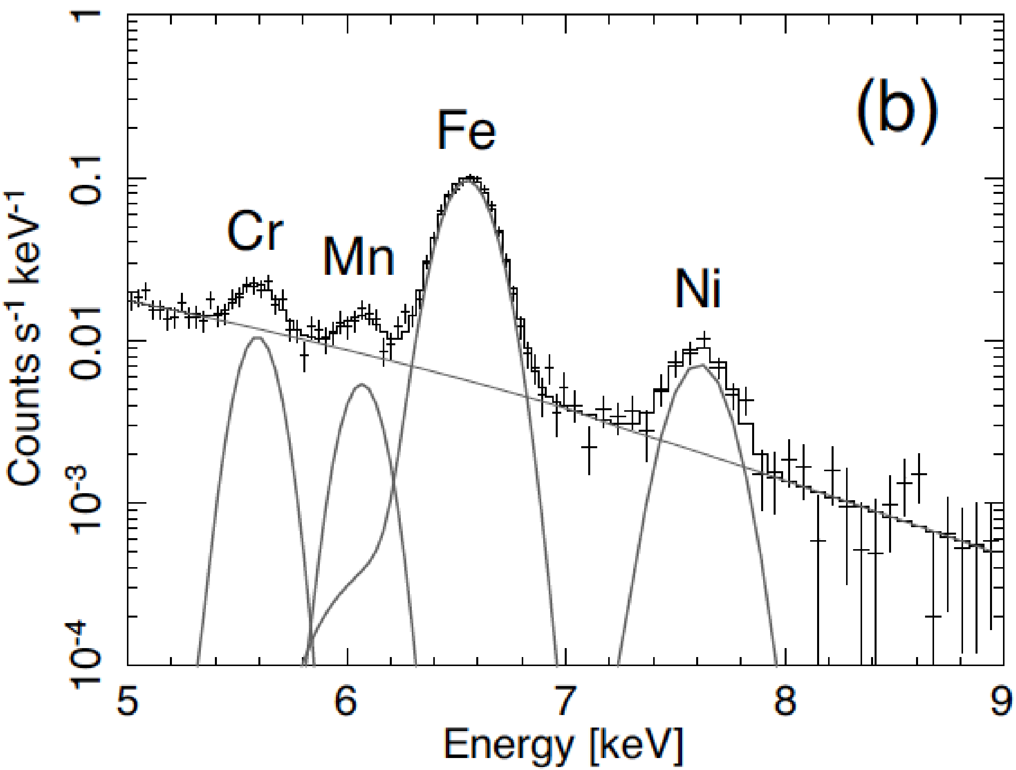
- 3C397 is an evolved Type Ia SNR at D~10 kpc [Safi-Harb+ 05, Williams talk].
- Consistent dynamical model (IR+X-ray) ⇒ **RS has thermalized all the SN ejecta**.
- Extraordinary X-ray spectrum! **Very strong Ni and Mn emission**.





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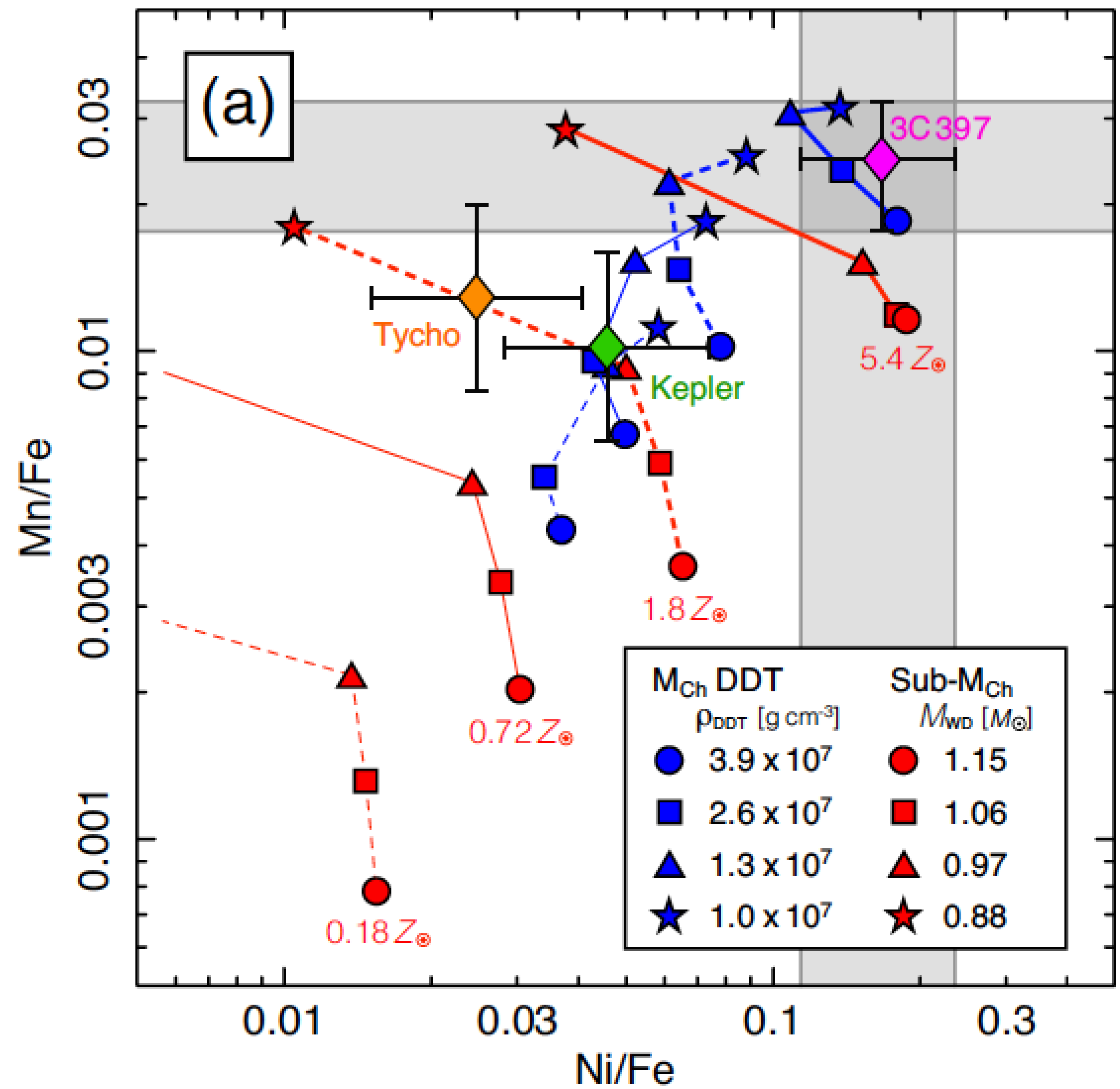
- Model line emission with updated atomic data (AtomDB, Foster+) ⇒ **M_{Ni}/M_{Fe}~0.2; M_{Mn}/M_{Fe}~0.03**.
- **Sub-Ch models do not work**, or require unreasonable progenitor metallicities (>5$Z_{\odot}$).
- **M_{Ni}/M_{Fe} and M_{Mn}/M_{Fe} require n-NSE material ⇒ Chandrasekhar-mass progenitor.**
- Details: Yamaguchi, CB + 15 ApJ 801, L31.



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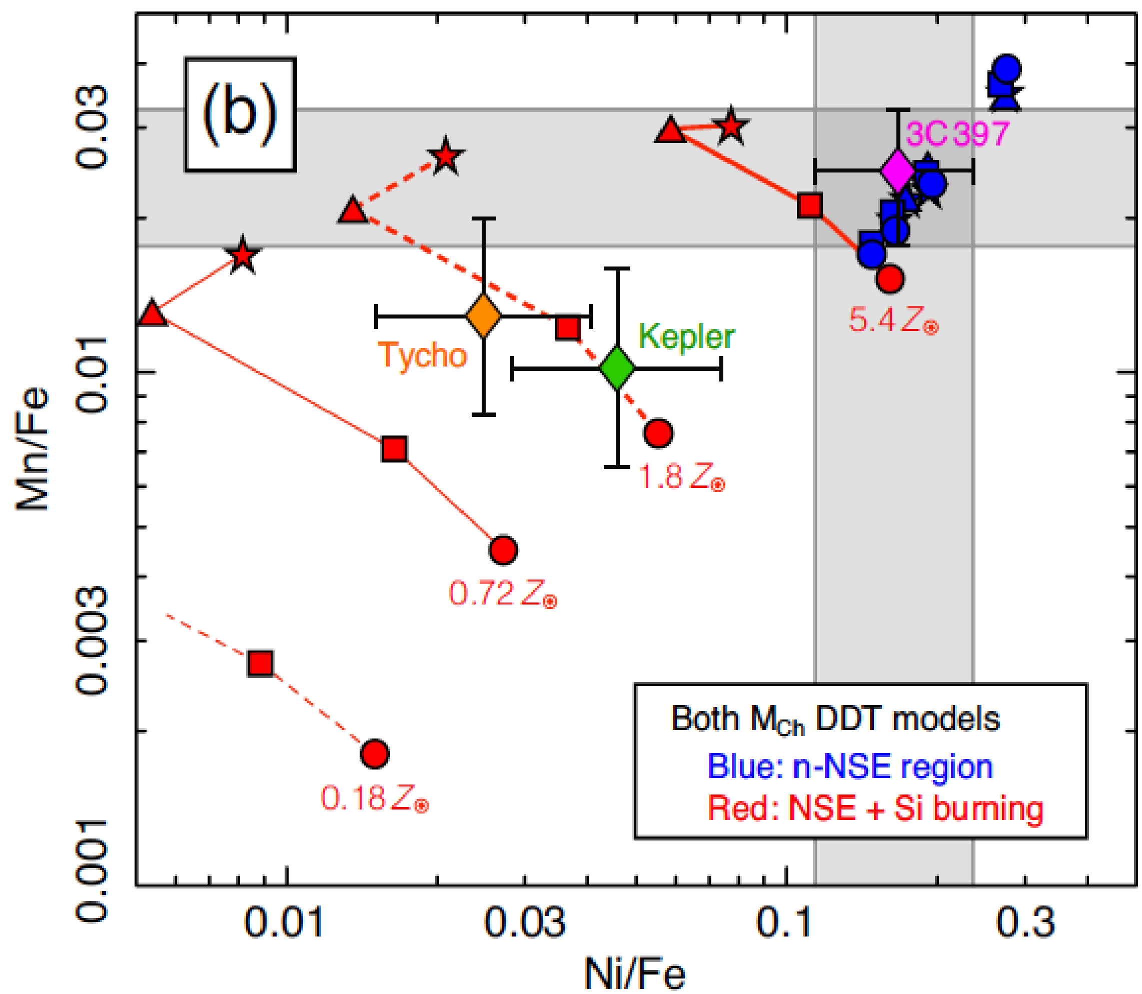


Beyond Ni and Mn

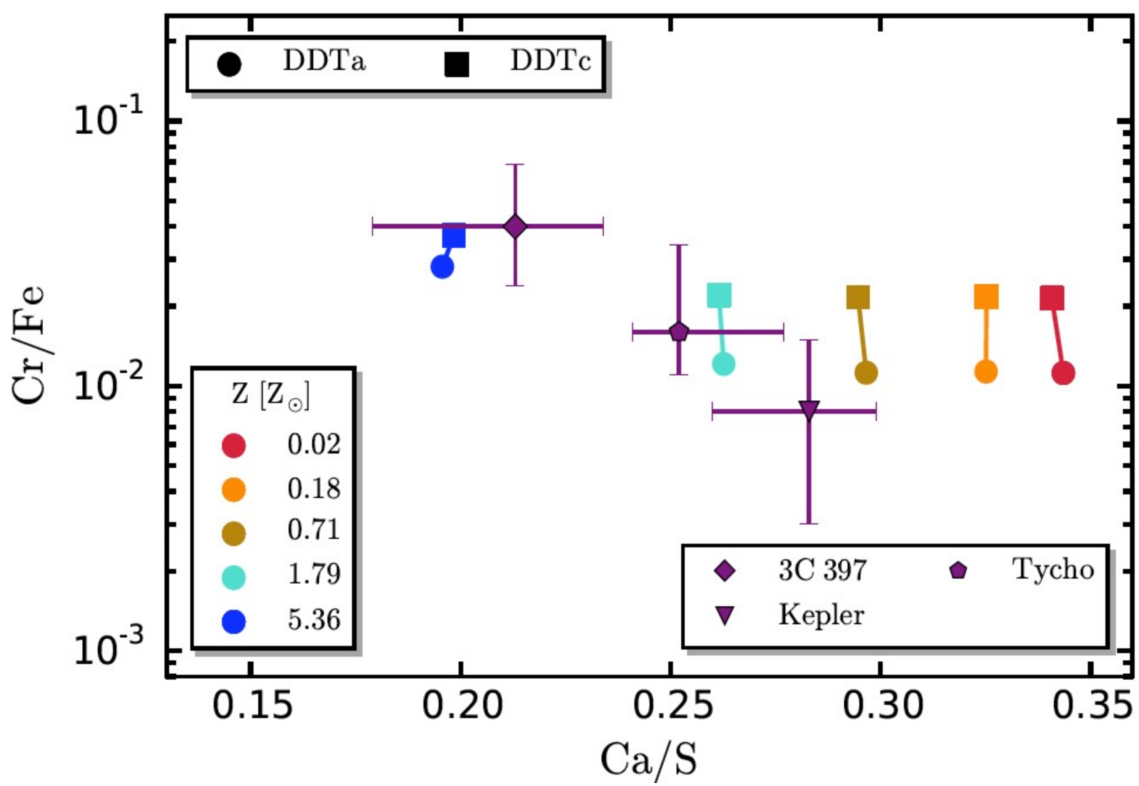
- Progenitor metallicity (η) for Tycho, Kepler, and 3C397 from Mn and Ni lines: solar or super-solar [Badenes +08, Park+ 13, Yamaguchi+ 15].

- **Ca yield also depends on η** [De +14, Miles+ 16], unaffected by n-NSE!!!

- Measure η in more SNRs, including those in the LMC! Work by Héctor Martínez-Rodríguez in prep.

- For Tycho, Kepler, and 3C397, we recover the high values of η.

Normal and energetic SN Ia models (subenergetic ruled out by Fe K centroids [Yamaguchi+ 14])



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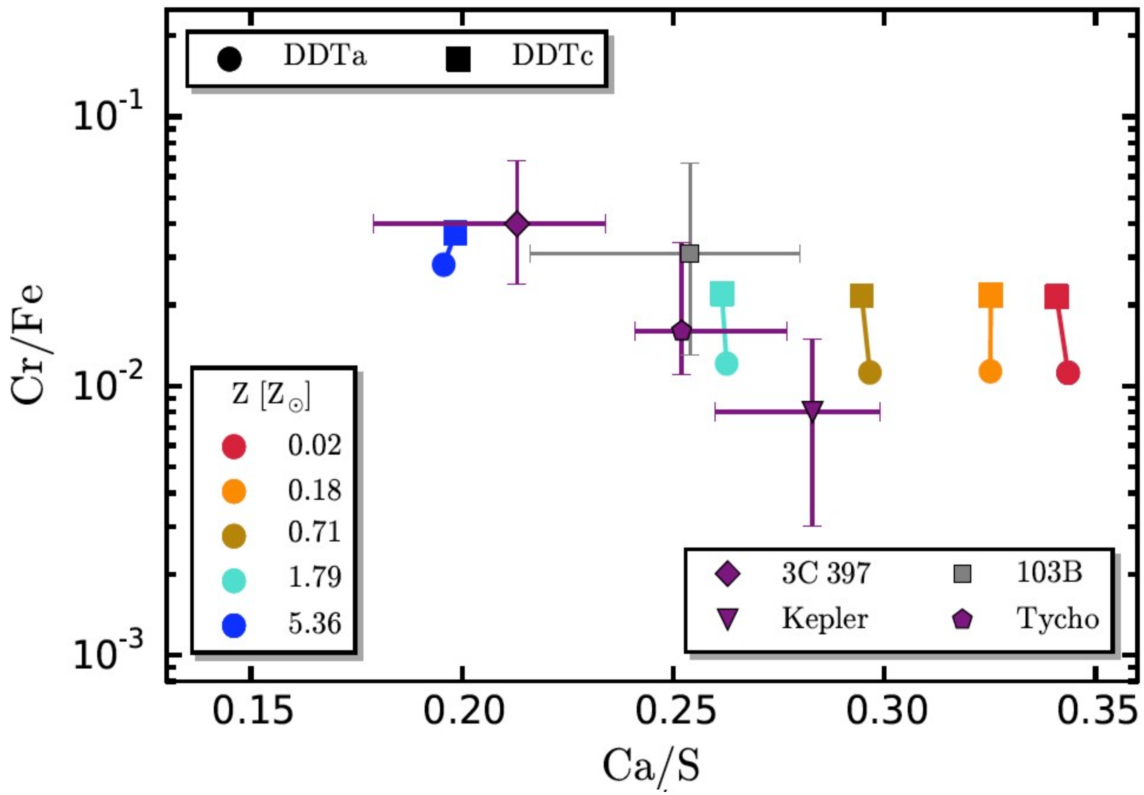
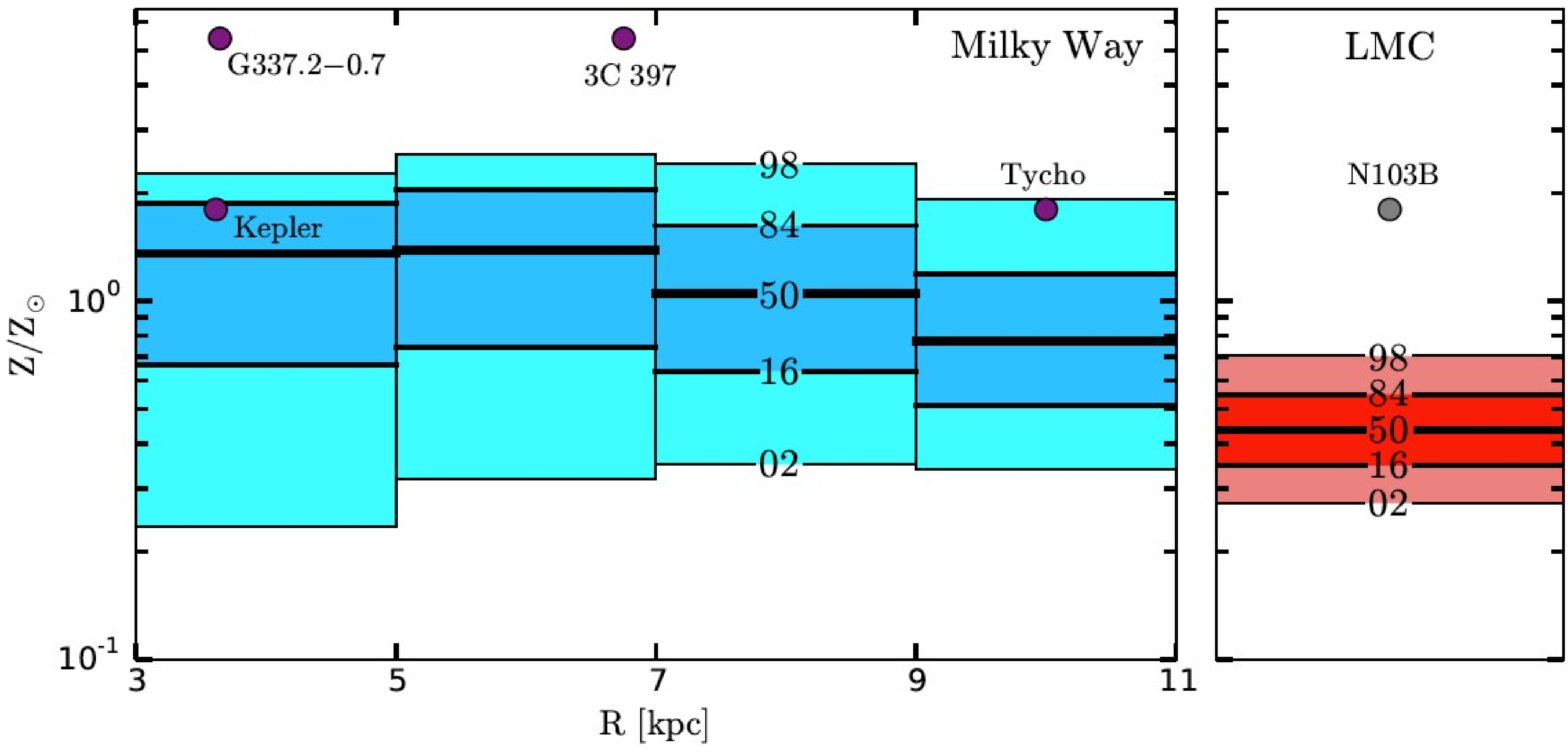
Very high η for 3C397 & N103B!!!



Neutronization from metallicity?

- Lake Wobegon effect ⇒ need to compare to Milky Way and LMC metallicity distributions [Hayden+ 15, Piatti & Gleiser 12].
- **There must be some extraneous (non-metallicity) source of neutrons** ⇒ simmering? **Requires $M_{WD}=M_{Ch}$!**



Summary

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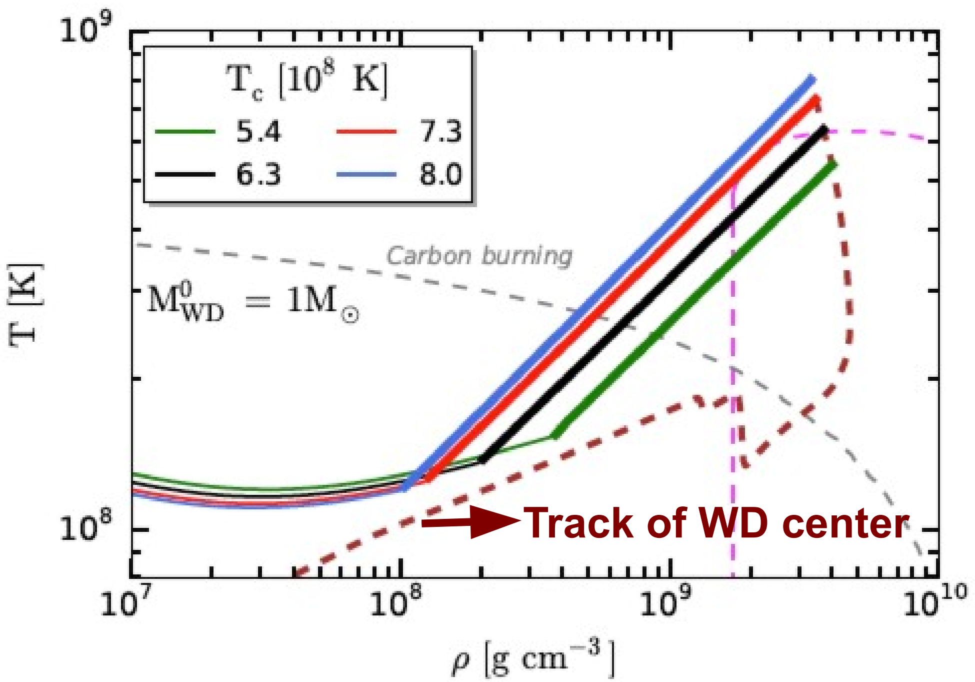
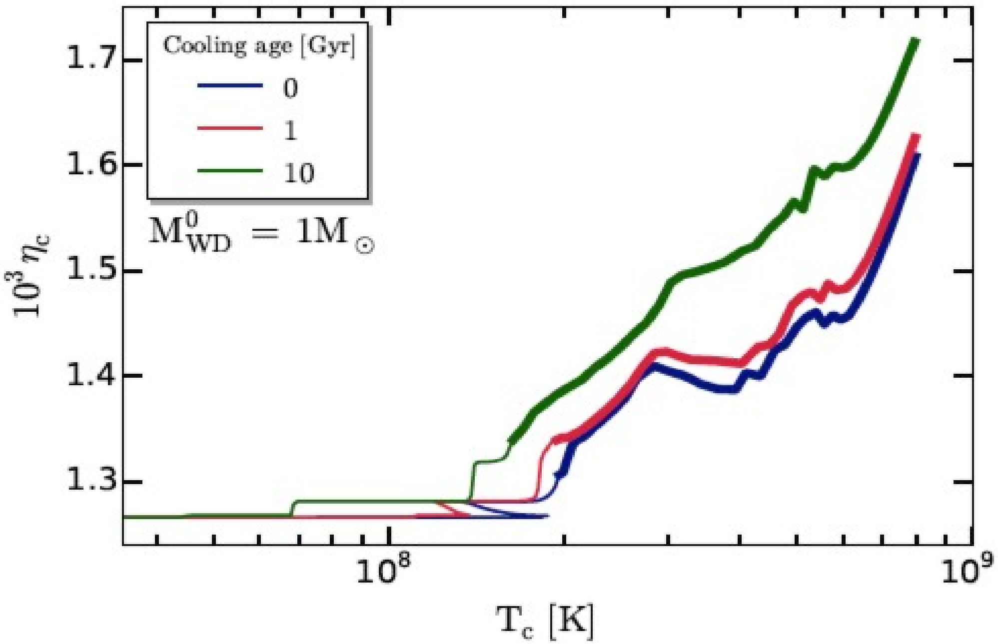
- **Fe K line ⇒ CC/Ia + quantitative test for progenitor evolution. Most Ia SNRs compatible with little or no CSM ⇒ mergers?**
- **RCW 86 ⇒ fast, continuous pre-SN outflow ⇒ accretor?**
- **SNR 3C397 ⇒ prominent Mn and Ni emission ⇒ M_{Ch} progenitor ⇒ accretor?**
- **High neutron excess in 3C397 and N103B cannot be attributed to metallicity ⇒ slow (~kyr) pre-explosion accretion phase (simmering) ⇒ accretor?**
- **Other measurements show a preference for merger** scenario (missing companions, DTD, WD merger rate).

SN Ia in star-forming galaxies probably come from a mixture of mergers and accretors

Yes, but...

- Recent study of C simmering in accreting WDs with MESA **limits η from simmering to ~1/3$Z_\odot$** [Martínez-Rodríguez + 16].
- Not enough to reproduce observed η, but models are simple. Longer simmering timescale? Additional cooling from axions?
- **Simmering remains the only viable candidate for the origin of the neutron excess seen in the Ca/S measurements of SNRs! ⇒ progenitors must accrete slowly before they explode!**





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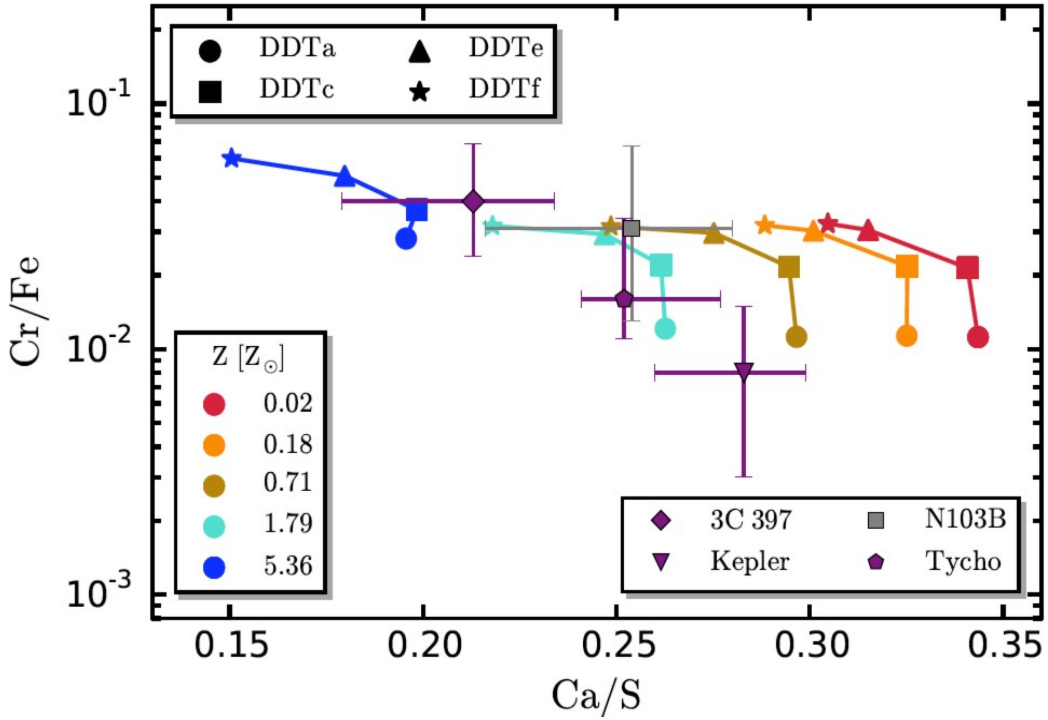

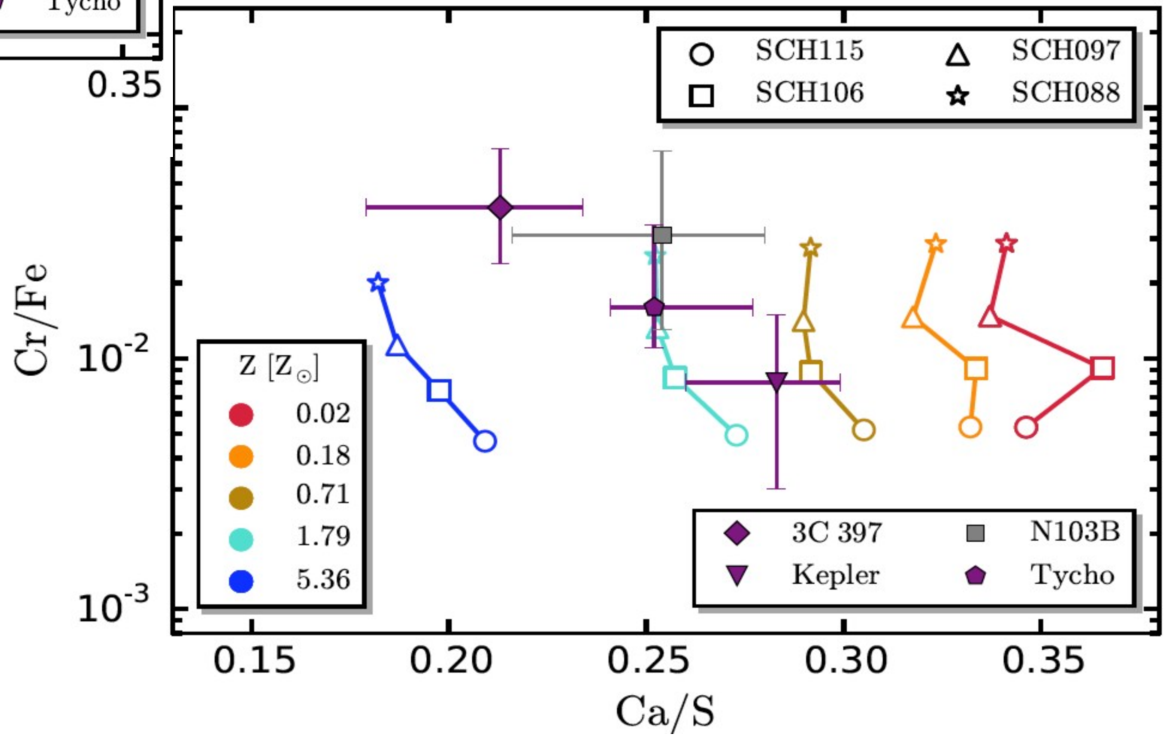

Type Ia SNRs and cavities

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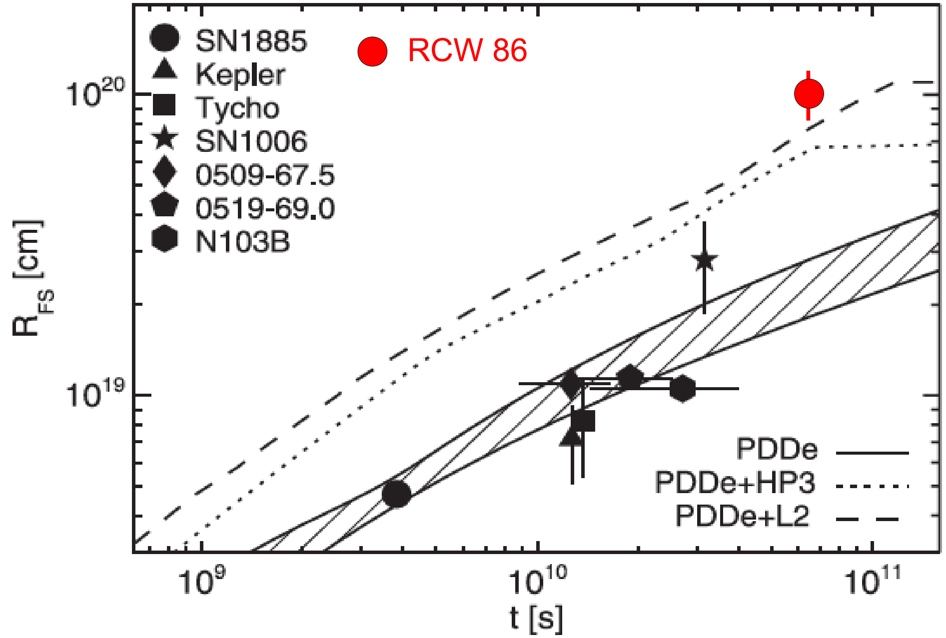
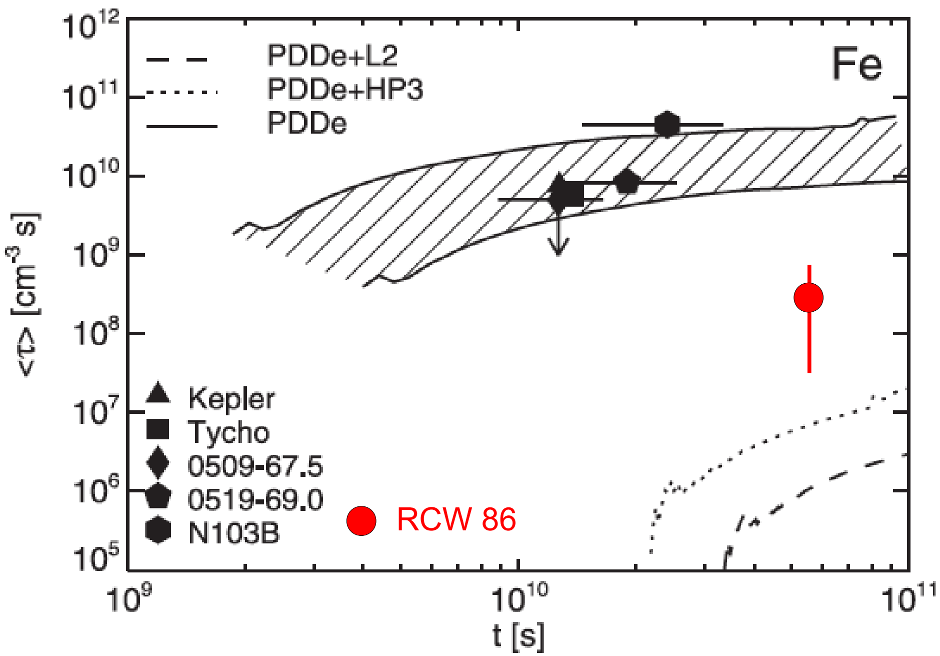
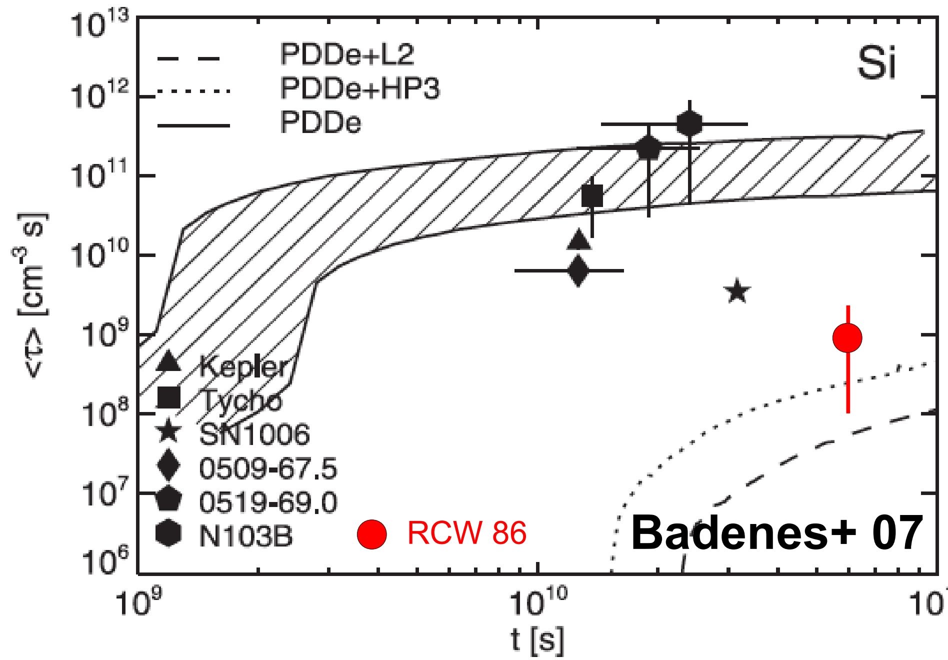
- **Radii and $n_e t$ of Type Ia SNRs** with known ages are **consistent with uniform ambient medium interaction** [Badenes+ 07].

- '**Accretion winds**' in SD progenitor models [Hachisu+ 96] excavate **large cavities** [Koo & McKee 92] that lead to **large SNR radii and low $n_e t$**.

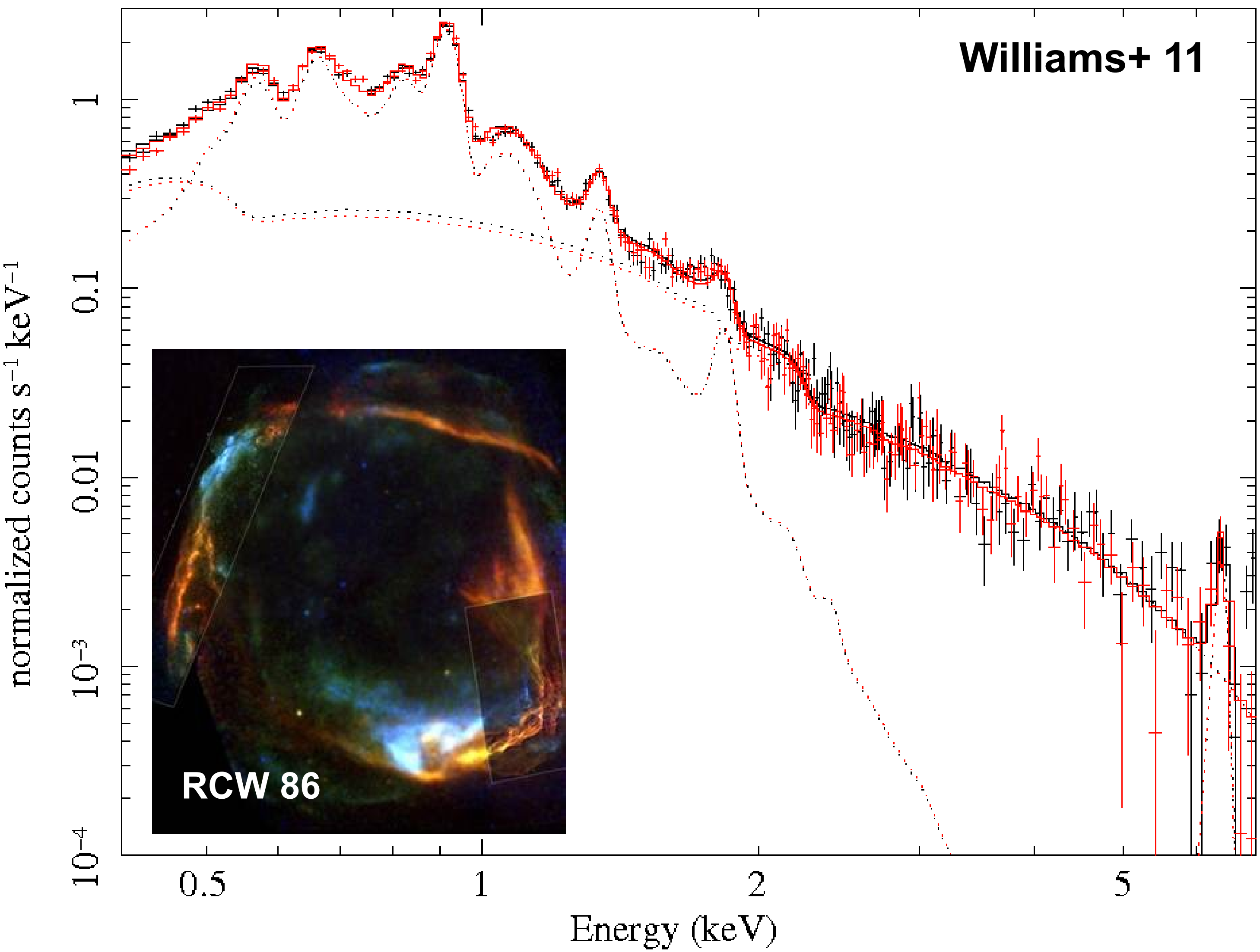






More on RCW 86

- **RCW 86** is large (~25 pc), with well defined borders, low $n_e t$, bright Fe, and no compact remnant [Williams+ 11].
- **IF SNR of SN 185 AD ⇒ cavity explosion** [Vink+ 97].
- **IF Ia SNR ⇒ fast, sustained outflow** from the progenitor ⇒ **SD** [Badenes+ 07, Williams +11].
- A light echo or detailed HD+NEI models would be very nice!



Other cavity Ia SNRs?

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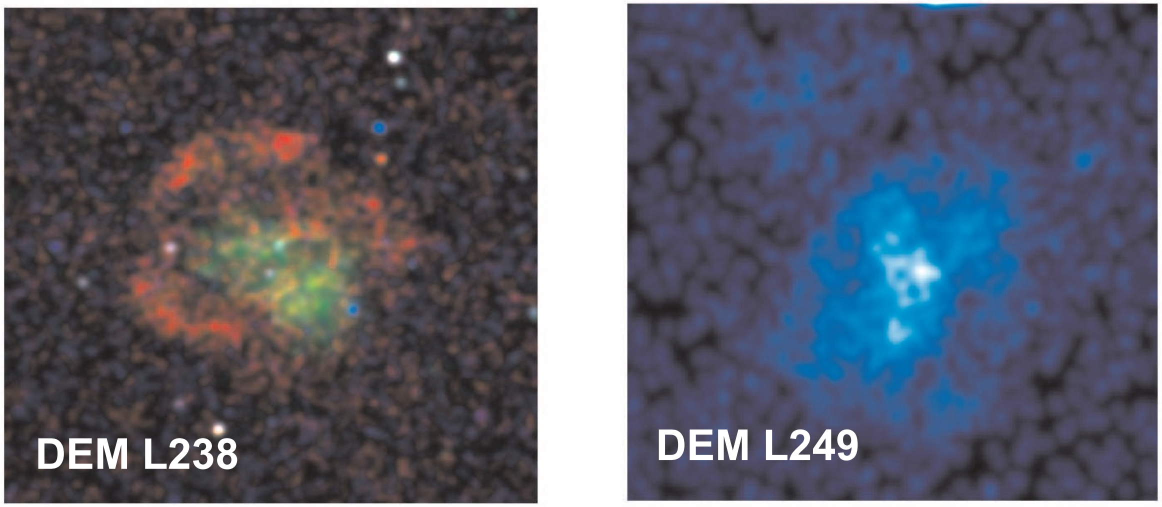
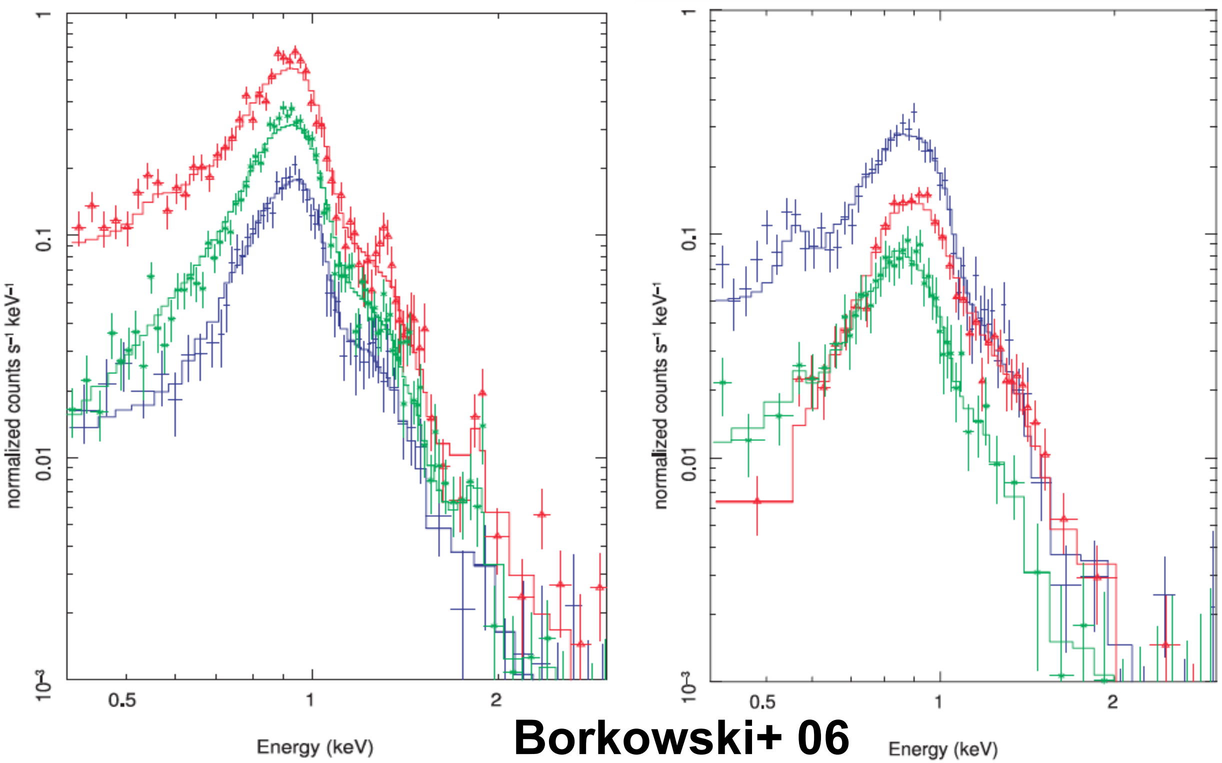
- **RCW 86** might not be the only example of Type Ia SN in a cavity.
- **DEM L238** and **DEM L249**, two middle-aged SNRs in the LMC have Fe-rich spectra and low $n_e t$.
- **IF Type Ia SNRs**, they might also be **cavity explosions** [Borkowski+ 06].
- **Beware:** typing SNRs older than a few thousand years is difficult, and so is modeling their dynamic evolution!



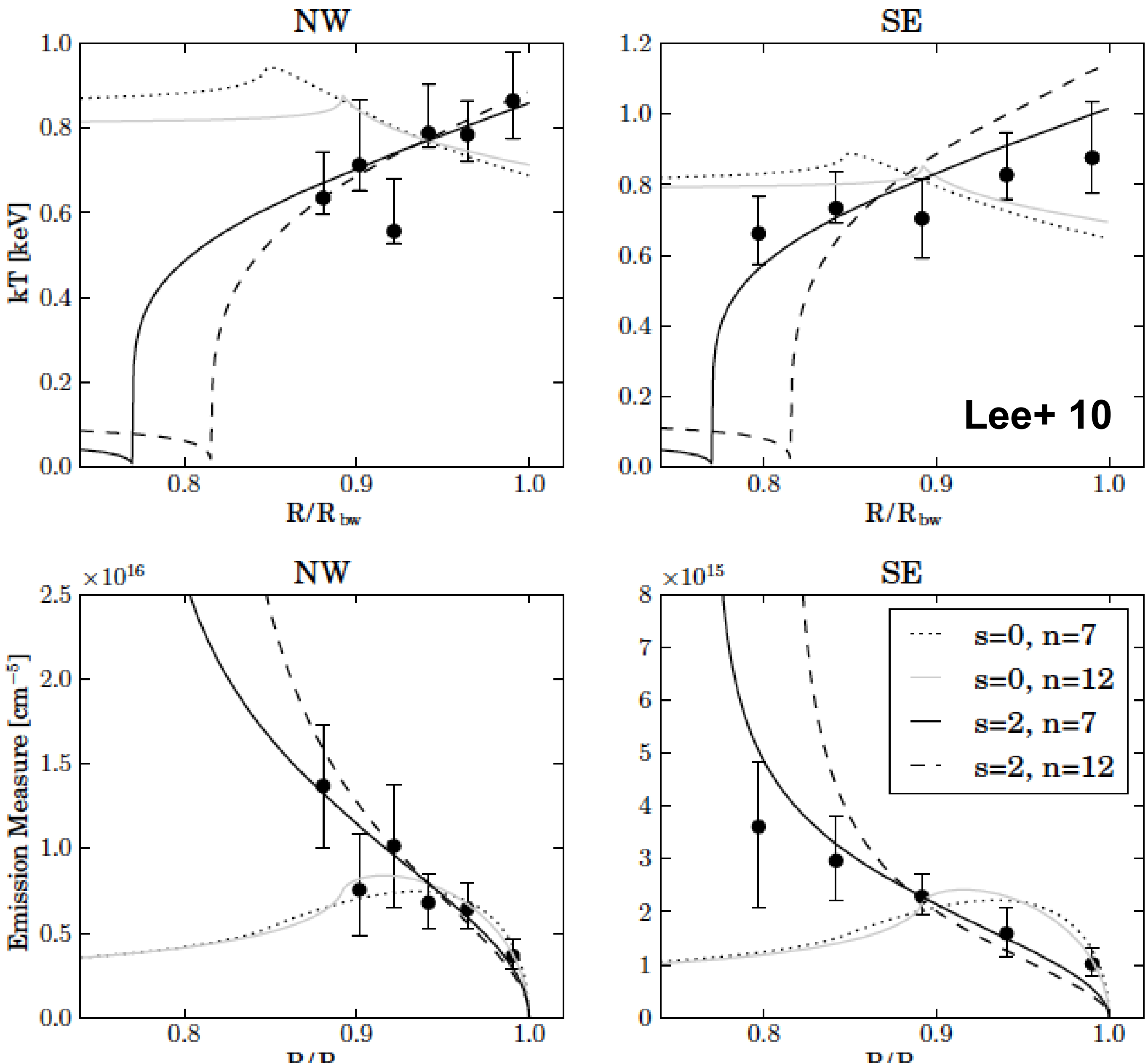


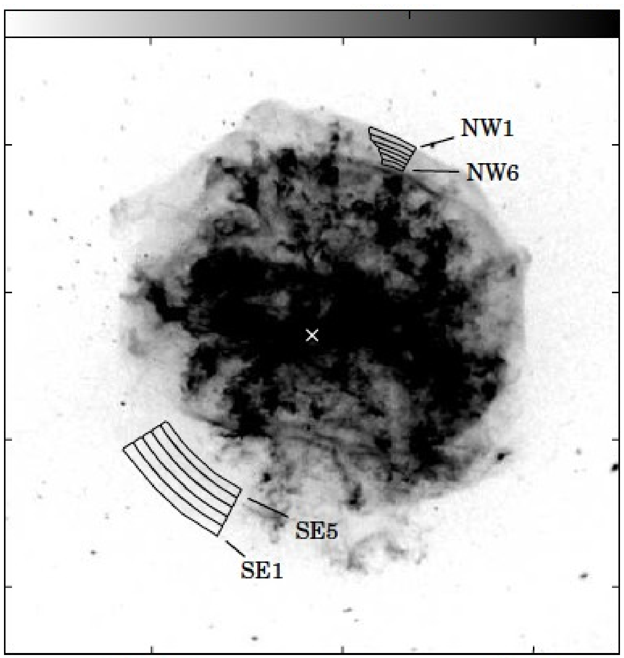
Borkowski+ 06

CSM in CC SNRs

Carles Badenes
CfA 02/19/15

- In more evolved SNRs like **G292.0+1.8, forward shock morphology can constrain ejecta and CSM density profiles** ⇒ CC SN progenitor [Lee+ 10].

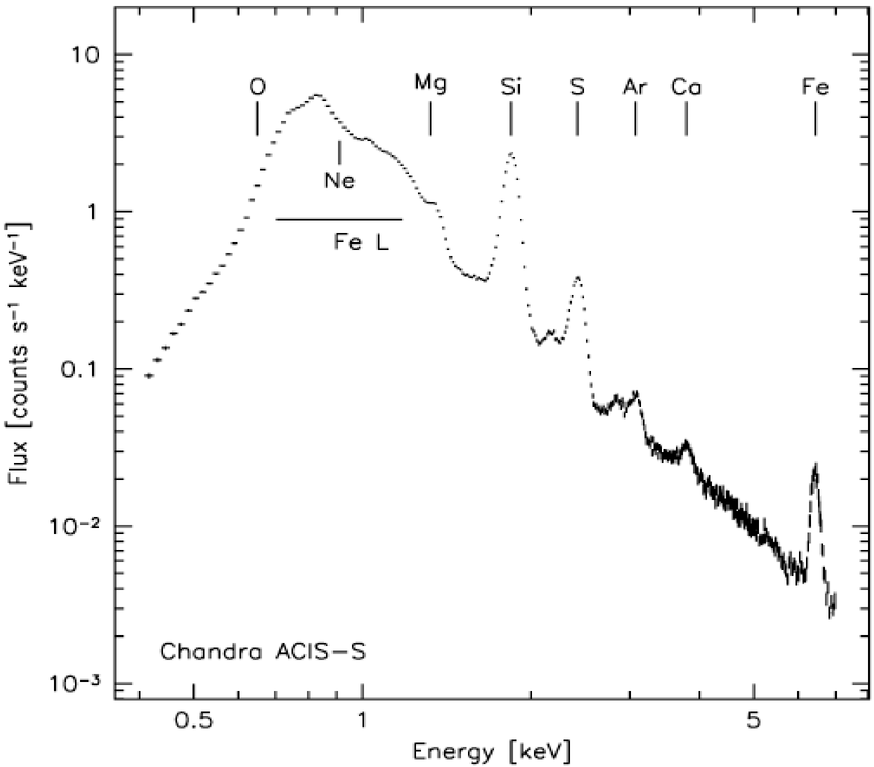


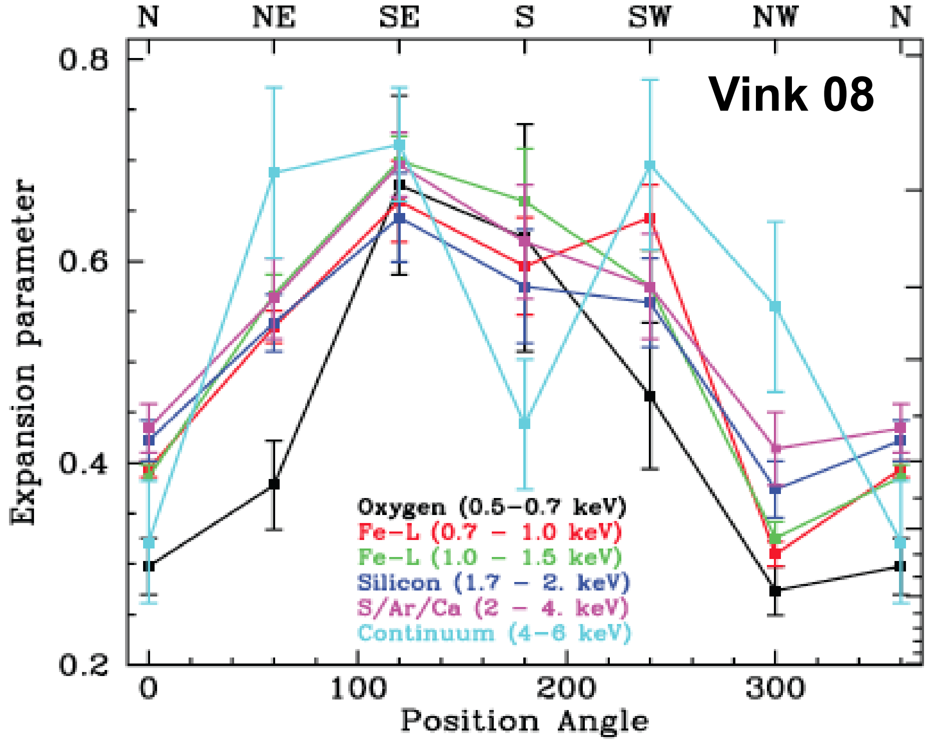


CSM Interaction: Kepler SNR

- **Kepler is unique among Type Ia SNRs** in that it shows **clear signs of a non-uniform AM** in the NW: brighter X-ray emission, larger $n_e t$, lower expansion parameters, optical N-rich emission [Blair+ 91, Reynolds+ 07, Vink 08].

- Well above Galactic plane ⇒ **CSM from a mass-losing progenitor**. A popular model posits a large relative motion wrt to the local ISM ⇒ **bow shock structure overrun by SN ejecta** [Bandiera 87, Borkowski+ 92, 94].





CSM Interaction: Kepler SNR

- Morphology (radius and N/S asymmetry) and kinematics (expansion parameters) can be reproduced by a **symbiotic model** (AGB wind ~20 km/s, moving at 250 km/s wrt ISM) [Chiotellis+ 12].

- However, this requires a **subenergetic** SN explosion (E~2x10^{50} erg).

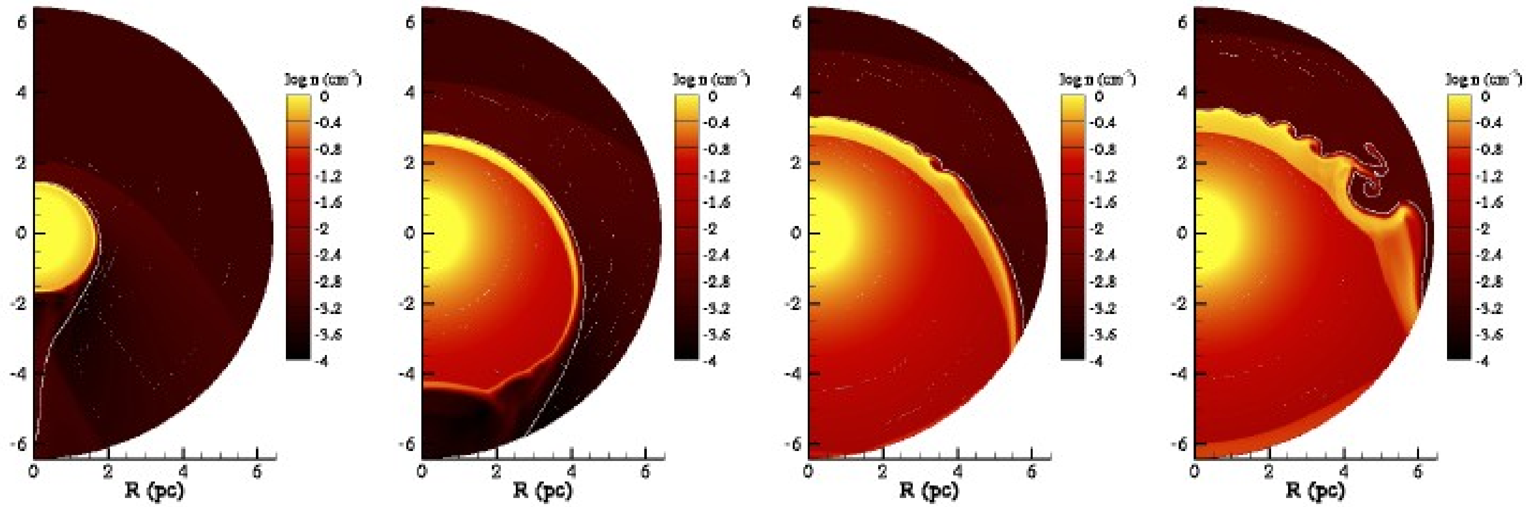


Fig. 4. The evolution of the wind bubble of model A. The snapshots from left to right correspond to the times 0.10 Myr, 0.29 Myr, 0.38 Myr and 0.57 Myr.

Chiotellis+ 12

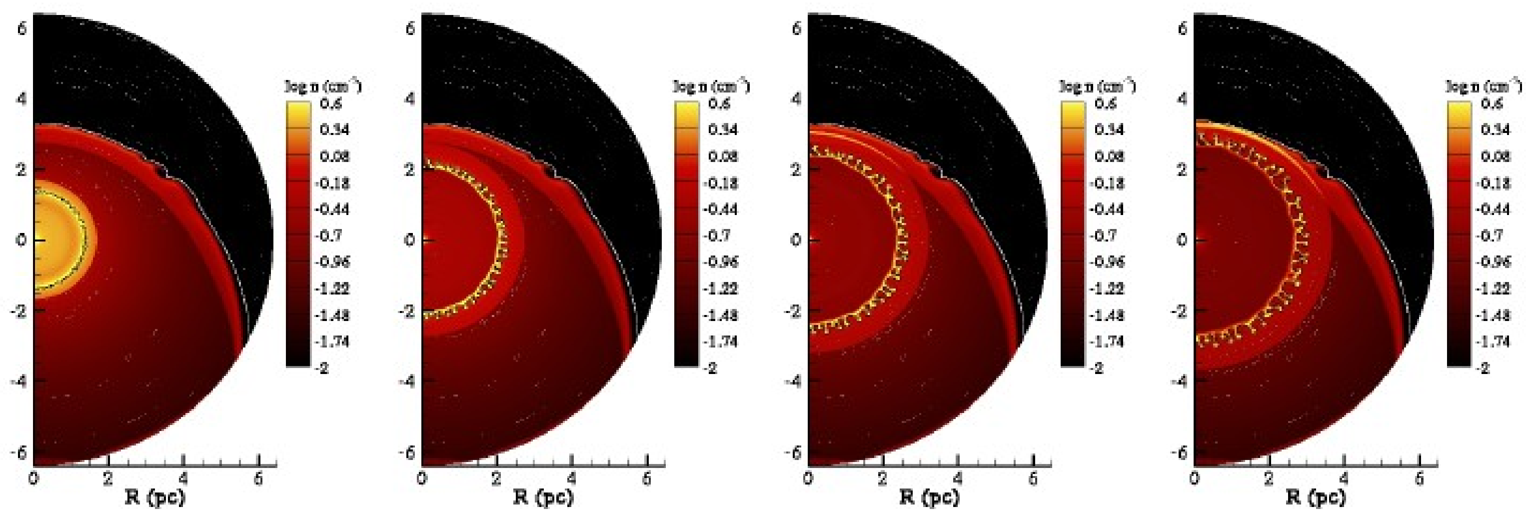
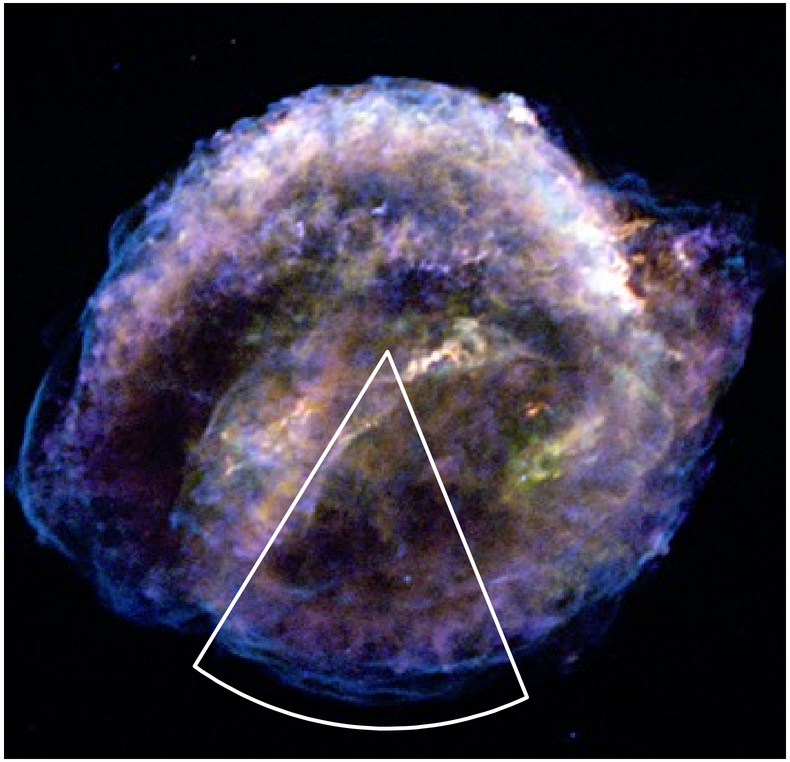
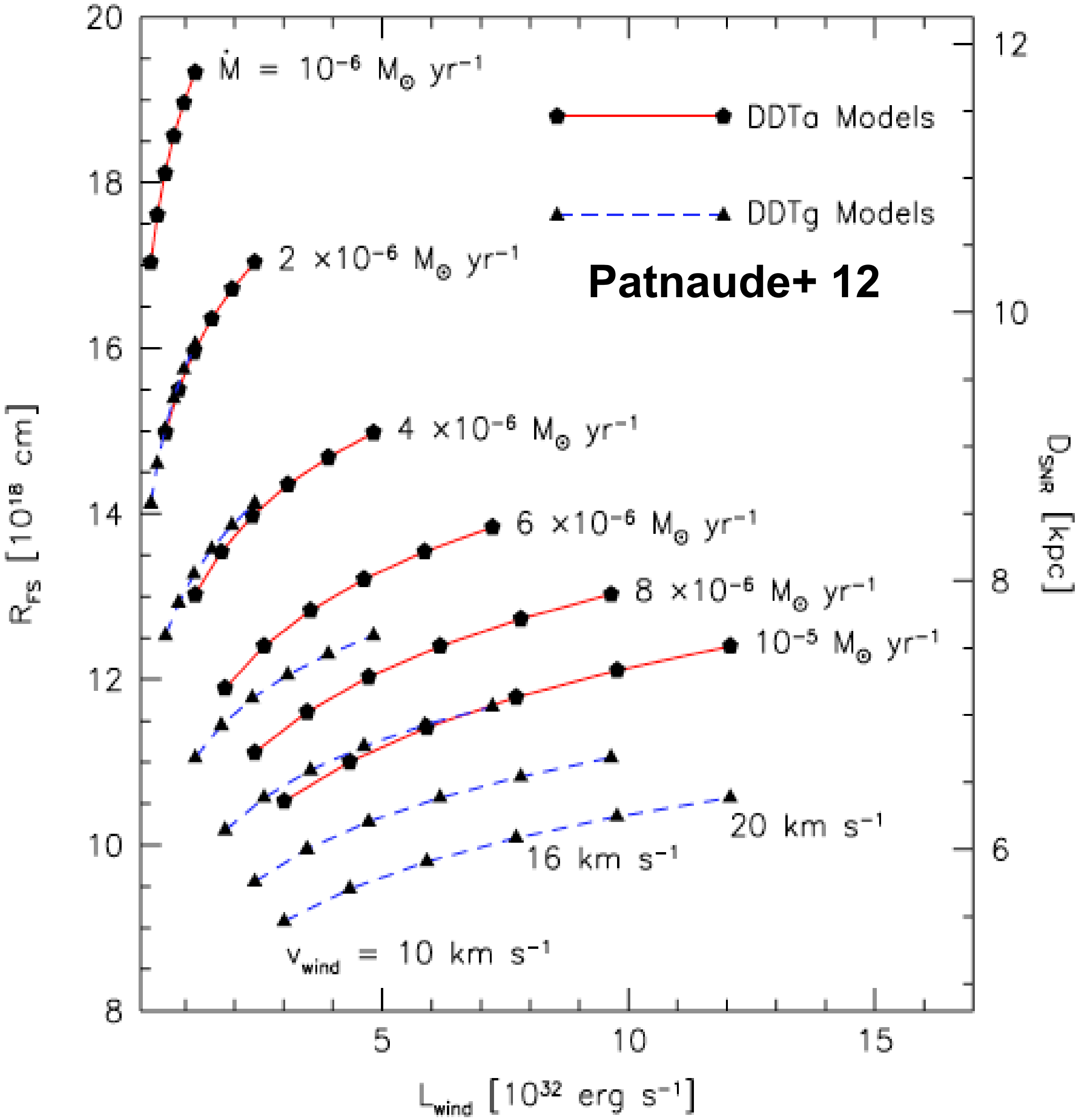


Fig. 5. SNR evolution of model A. The snapshots from left to right correspond to the times 158 yr, 285 yr, 349 yr and 412 yr.

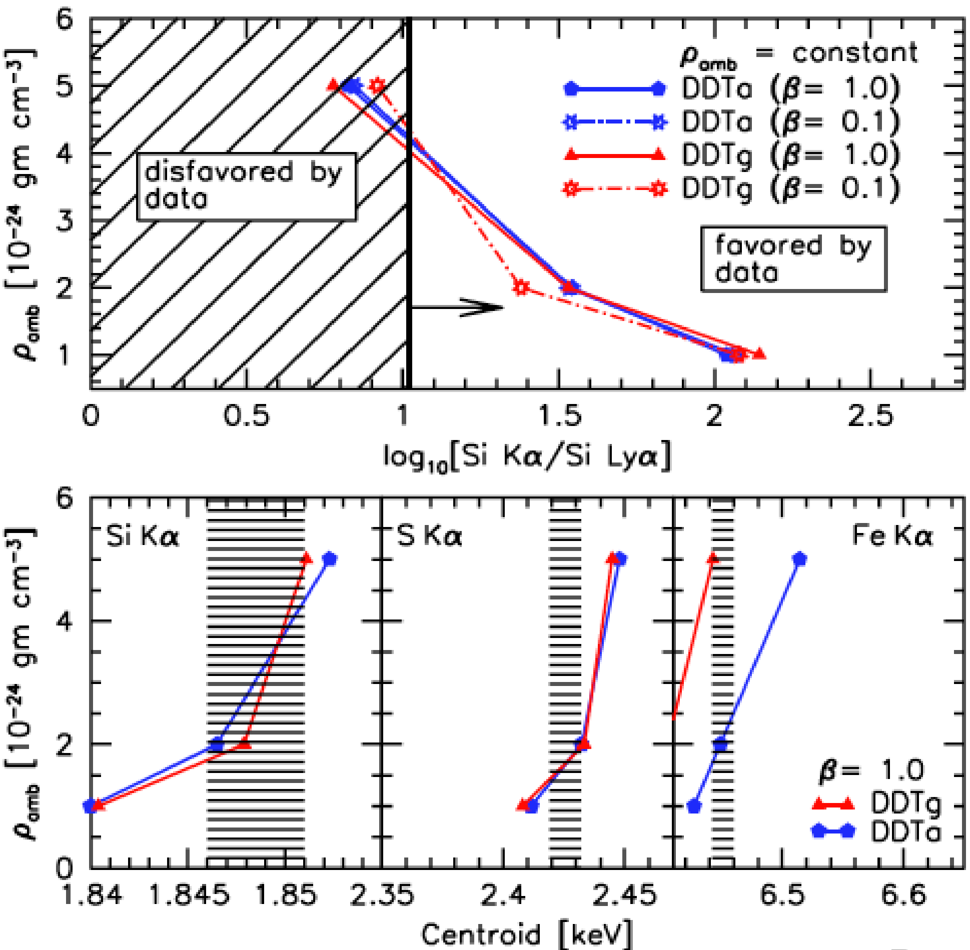
- HD+NEI models in the S, where the ejecta should be interacting with the pristine CSM from the progenitor ⇒ **constrain both M_{56Ni} and pre-SN dM/dt** [Patnaude+ 12].

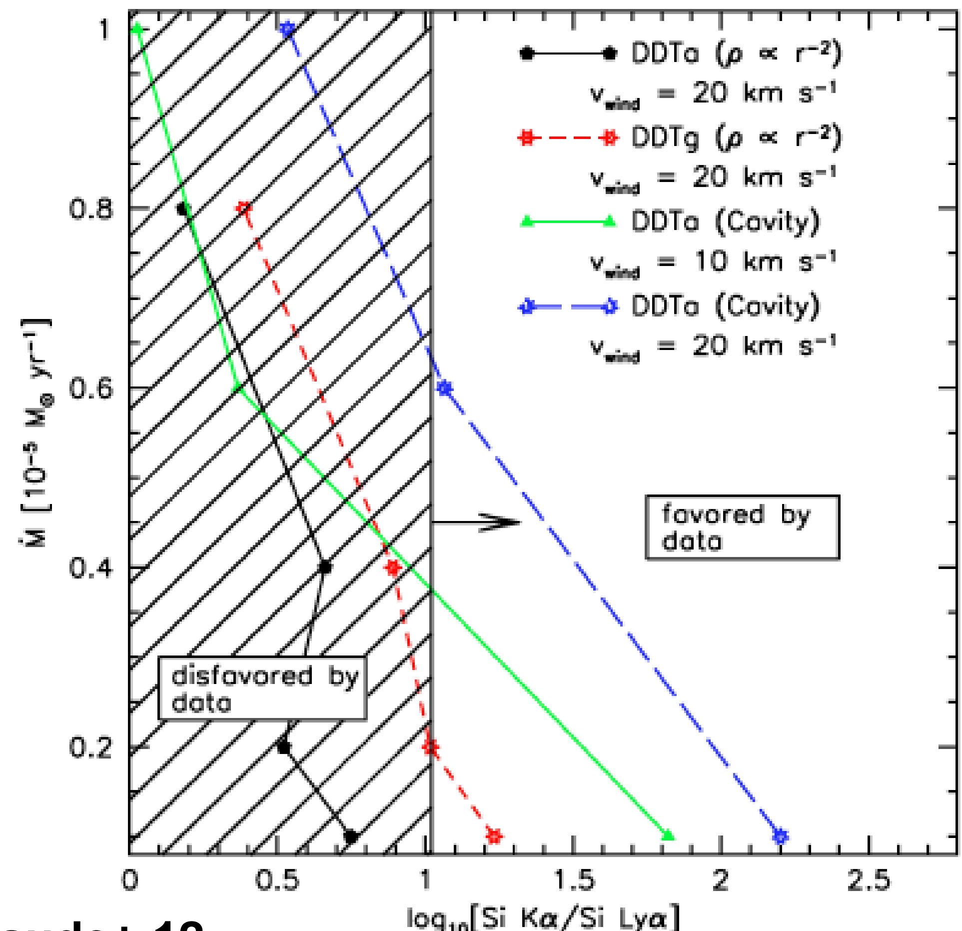




CSM Interaction: Kepler SNR

- HD+NEI models **rule out a standard $\rho \propto r^{-2}$ CSM!** (allowed by HD [Chiotellis+ 12]).
- **Small cavity + wind** works [Wood-Vasey & Sokoloski 06], but so does a **uniform AM**.
- In any case, Kepler must have been a bright SN Ia (**$M_{56Ni} \sim 1\ M_{\odot}$**).





Patnaude+ 12