Dead Men Do Tell Tales:

What Supernova Remnants Say About Type Ia Supernova Progenitors

STScI/JHU, Baltimore
February 4, 2026

Carles Badenes
University of Pittsburgh / PITT PACC



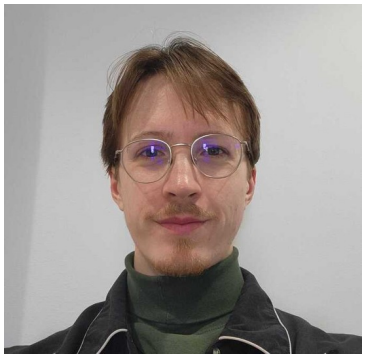


University of Pittsburgh

Research Group @ U Pitt:

- Graduate Students: **Travis Court** (⇒UNC Asheville) Tori Bonidie, Cullen Abelson.
- Undergraduate Students: **Peri Schindelheim** (⇒ Columbia).
- Postdoc: Rachel Patton.







Main Collaborators (on this research):

- Herman Lee (U.Kyoto), Dan Patnaude (Harvard/CfA), Dan Maoz (TAU), Lluís Galbany (ICE/IEEC), Guillermo García-Segura (UNAM), Eduardo Bravo (UPC).

Funding:

University of Pittsburgh

PITTPACC · PITTSBURGH PARTICLE PHYSICS ASTROPHYSICS COSMOLOGY CENTER

NSF

NASA

Outline

Carles Badenes
JHU 02/04/26

- **SN Ia progenitors**: binary pathways and explosion physics. Delay times, dM/dt, and M_{WD}.

- **SNRs**: the dead man's tale. X-ray spectra of SNRs ⇒ AM density, yields (n-rich nuclei).

- **Conclusions**: from SNRs back to SNe. Constraints on dM/dt and M_{WD}.



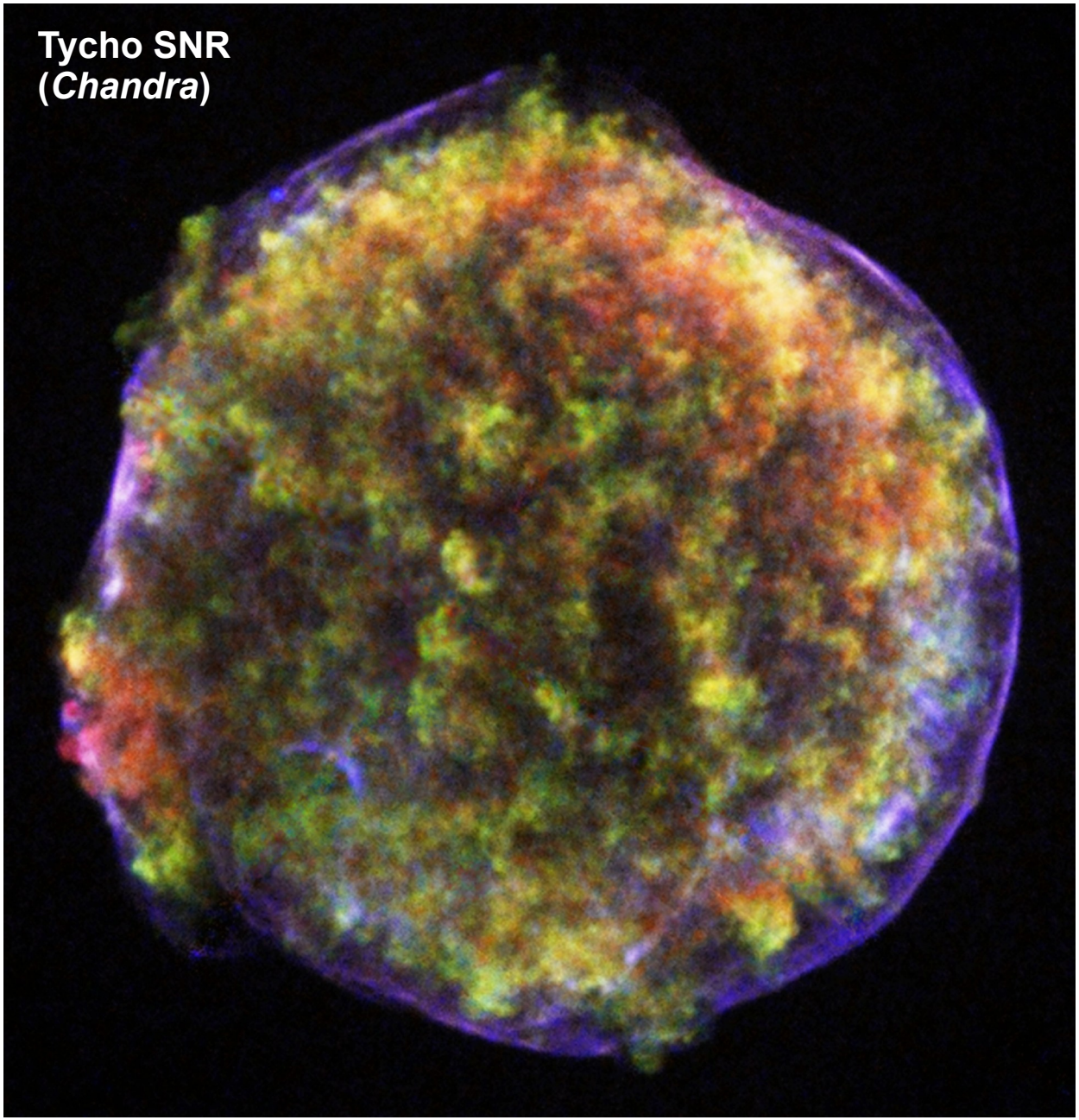
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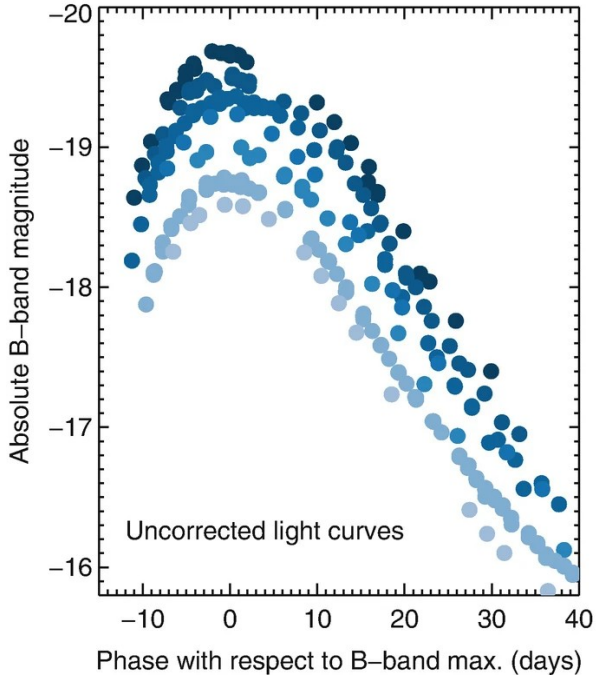
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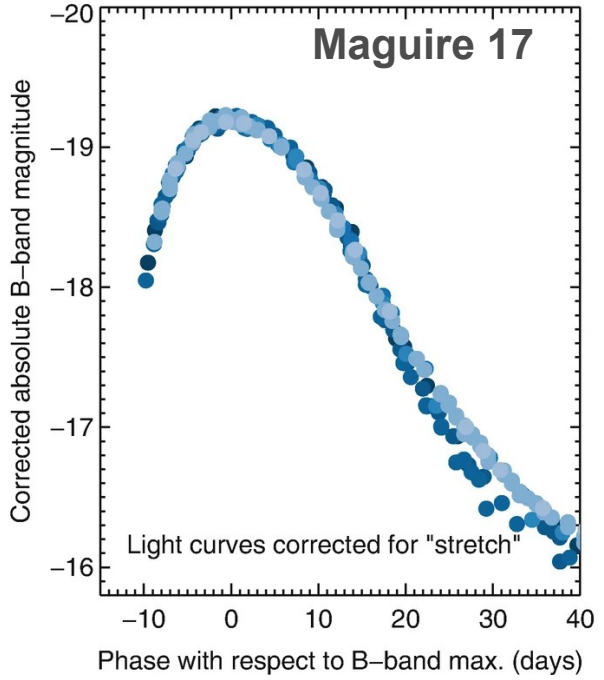
- **SN Ia** ⇒ cosmology, stellar feedback, chemical enrichment...

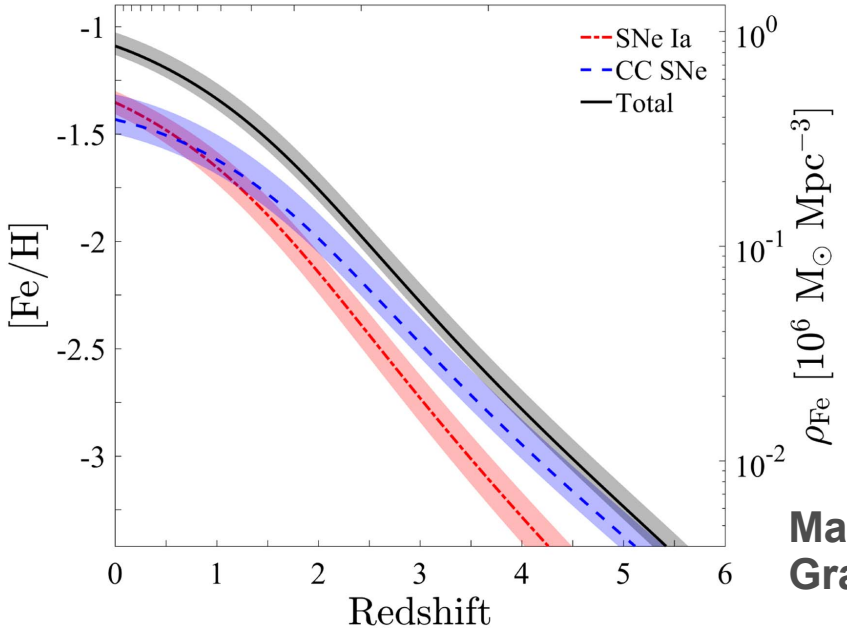
- **Diversity** in TN SNe ⇒ multiple progenitor channels. 'Normal' SN Ia dominate local rate.

- **Baseline scenario ⇒ TN runaway in a massive C+O WD**. Binary pathways? Explosion mechanism?

Reviews: Wang & Han 12; Maoz+14; Handbook of SNe, Liu+23, Seitenzahl & Ruiter 25.







Maoz & Graur 17

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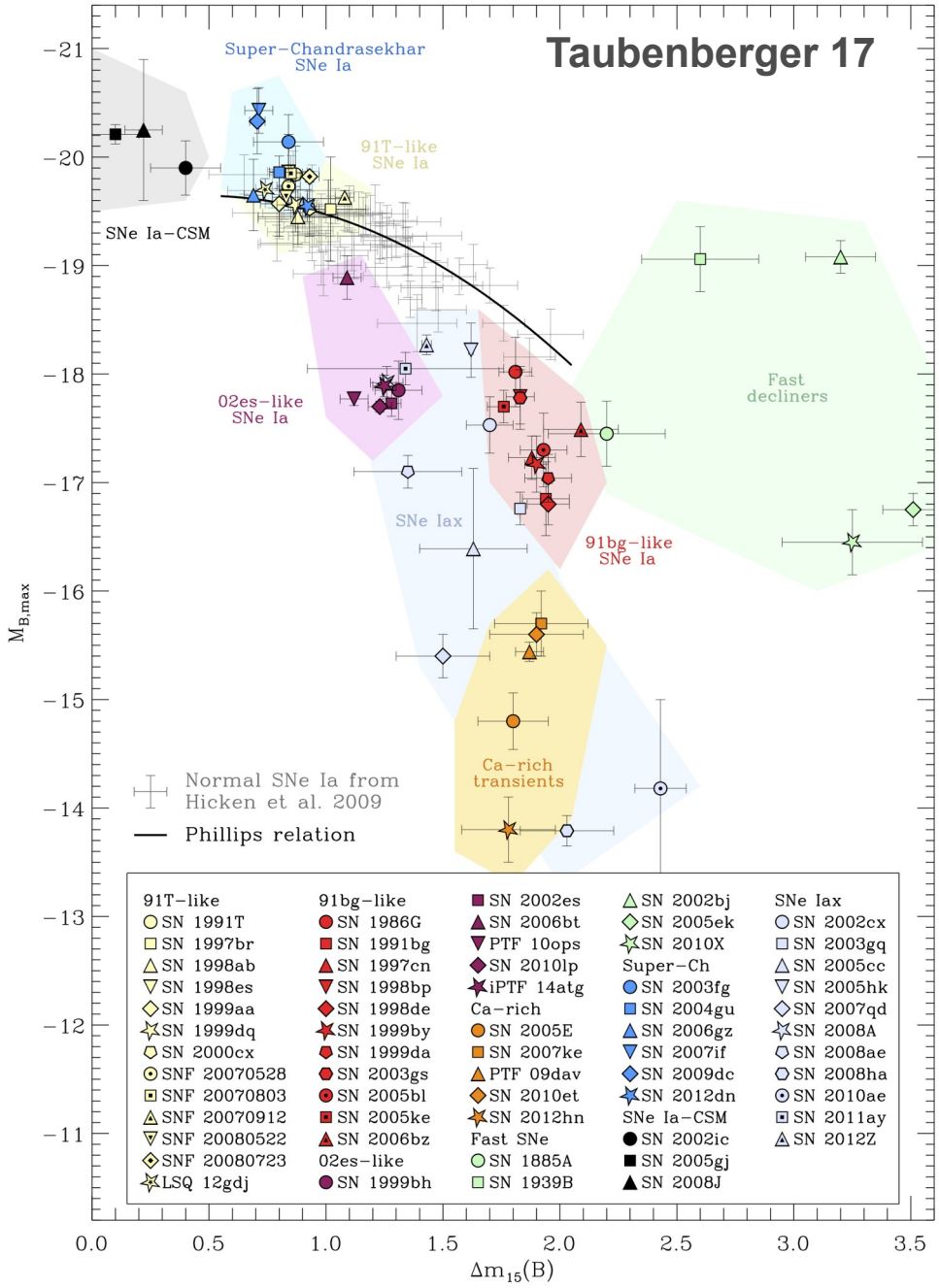
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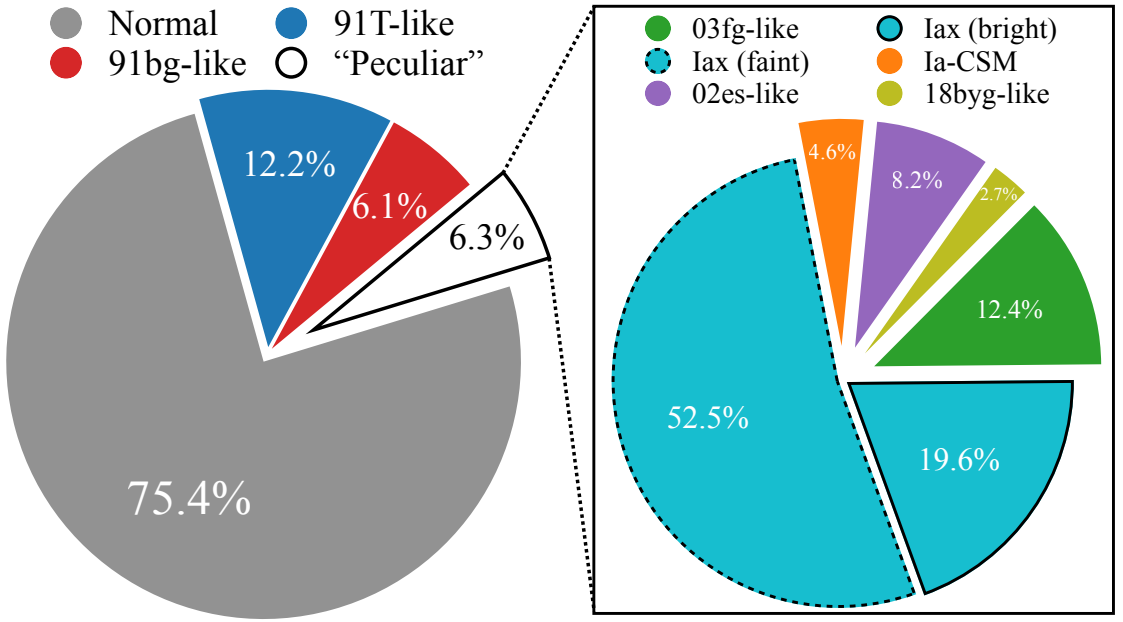
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Dimitriadis+ 25 (ZTF)

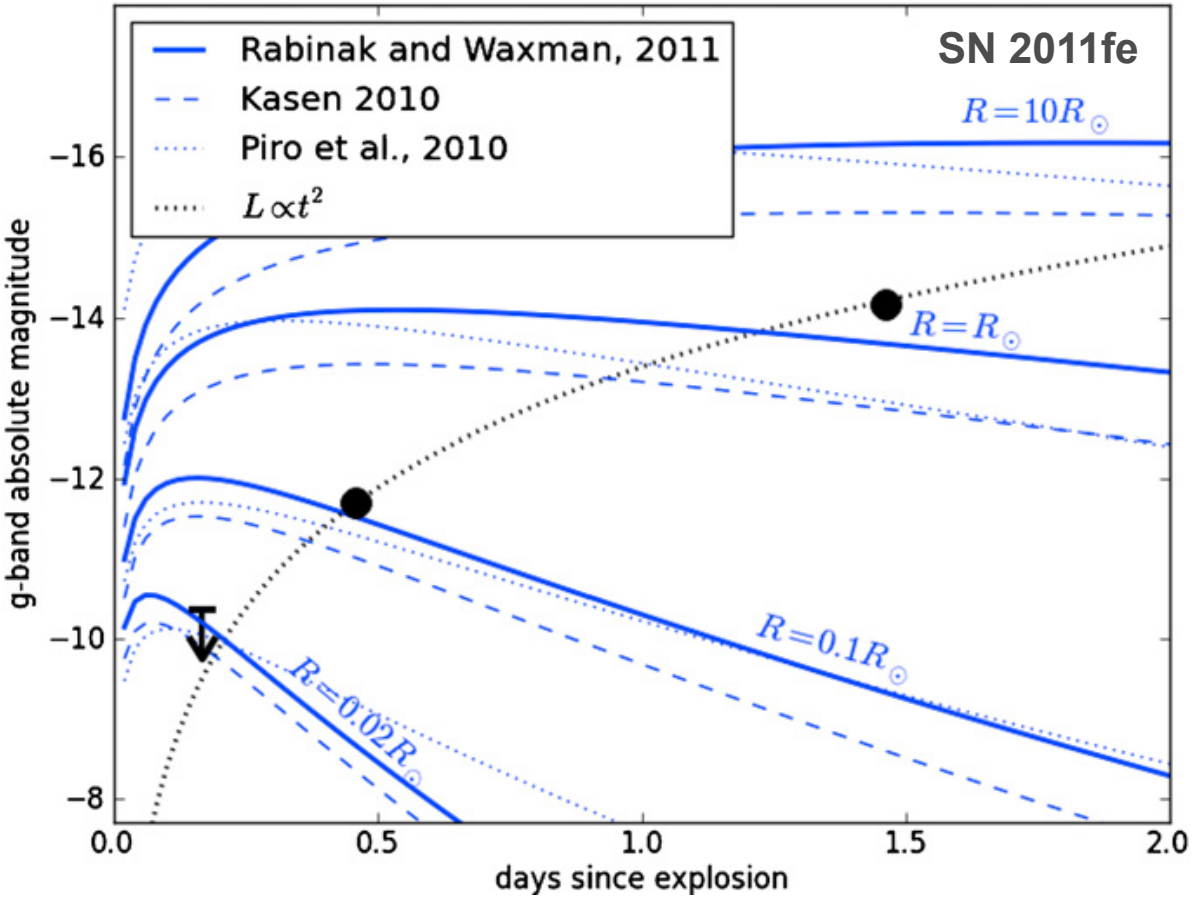


SN Ia: What To Blow Up

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- **Observations**: H-poor WD explosions. WD binaries are faint ⇒ no progenitor detections ⇒ indirect constraints.
Delay time distribution: ~1/t, wide range of t.

- **Theory**: binary stellar evolution is complicated. Multiple pathways to WD explosions. Companions: WDs, stripped stars, MS, RG, AGB. (SD/DD). CEE likely involved. Mass loss ⇔ mode and timescale of accretion.



Bloom+ 12

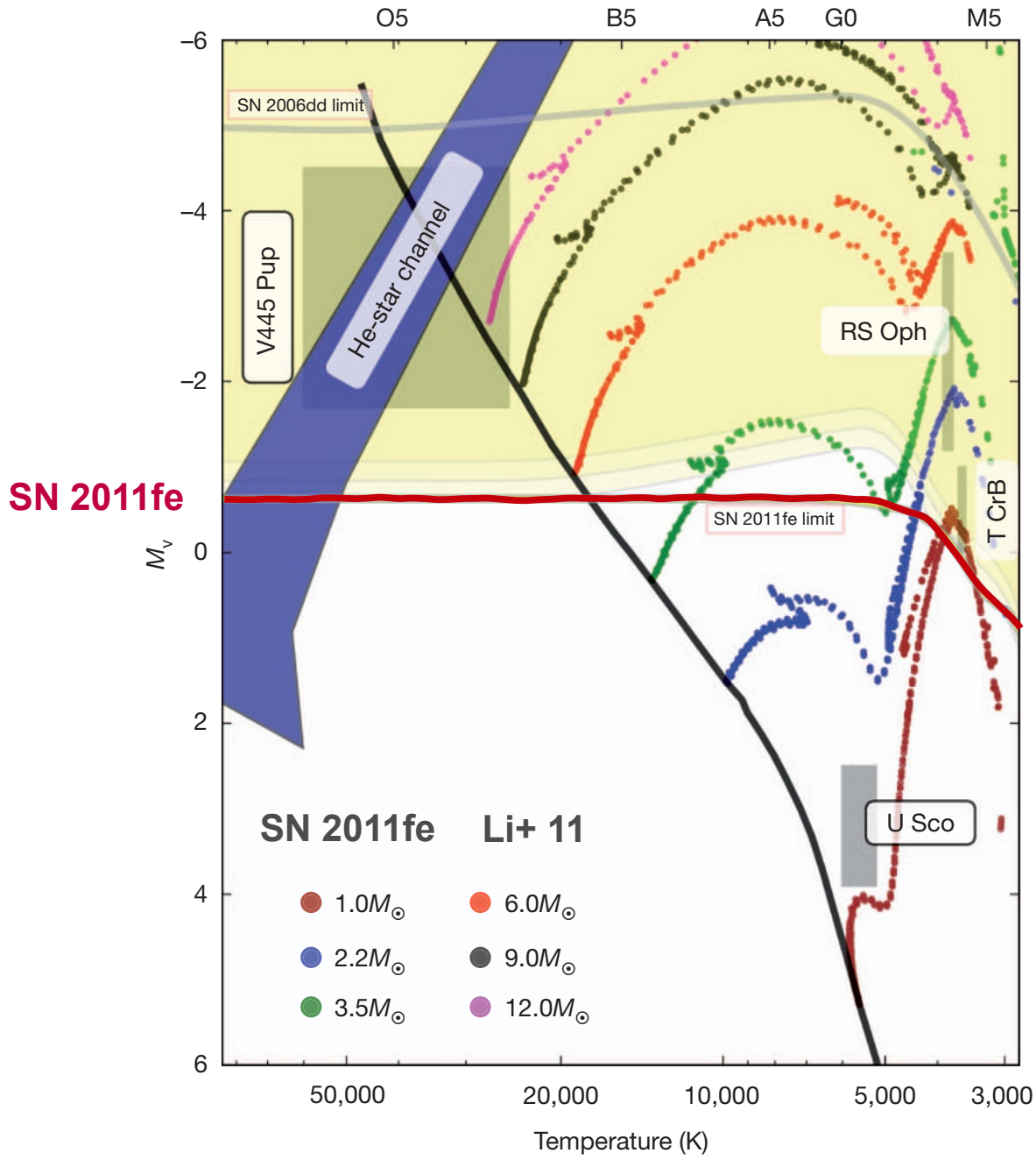
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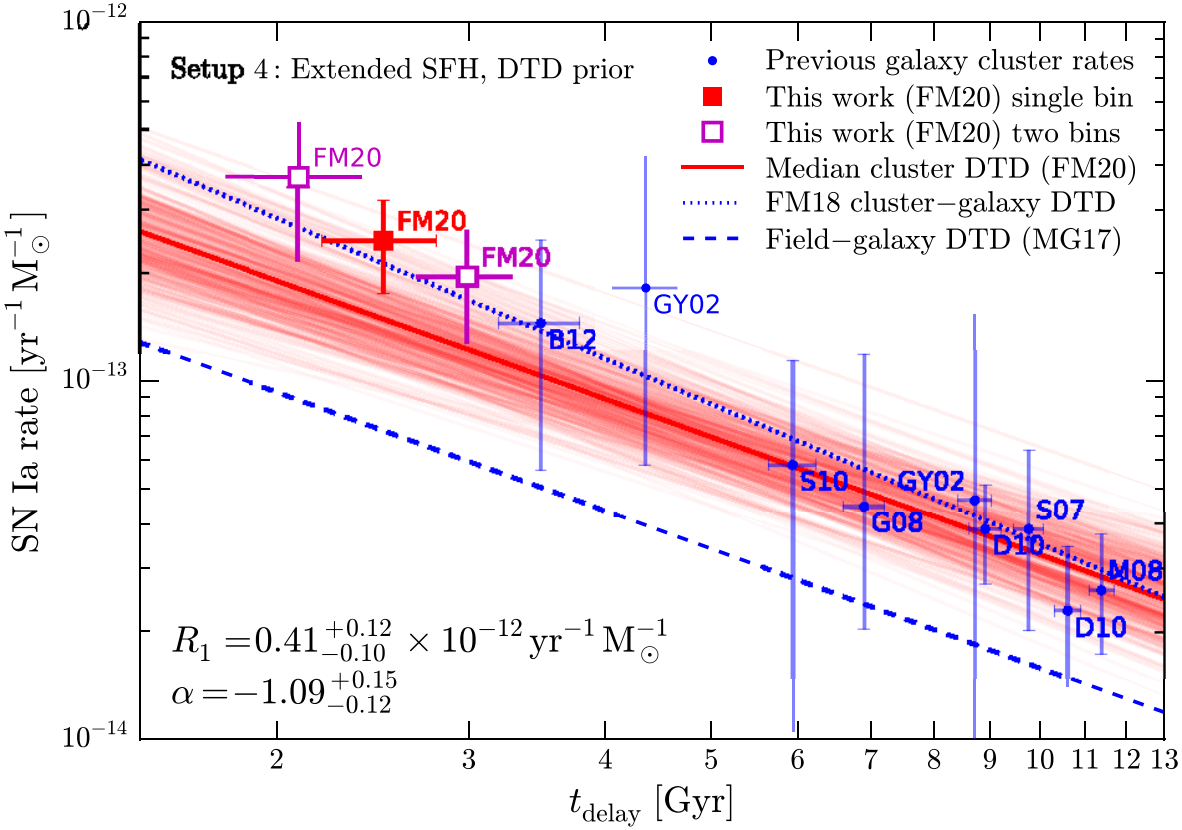
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Freundlich & Maoz 21

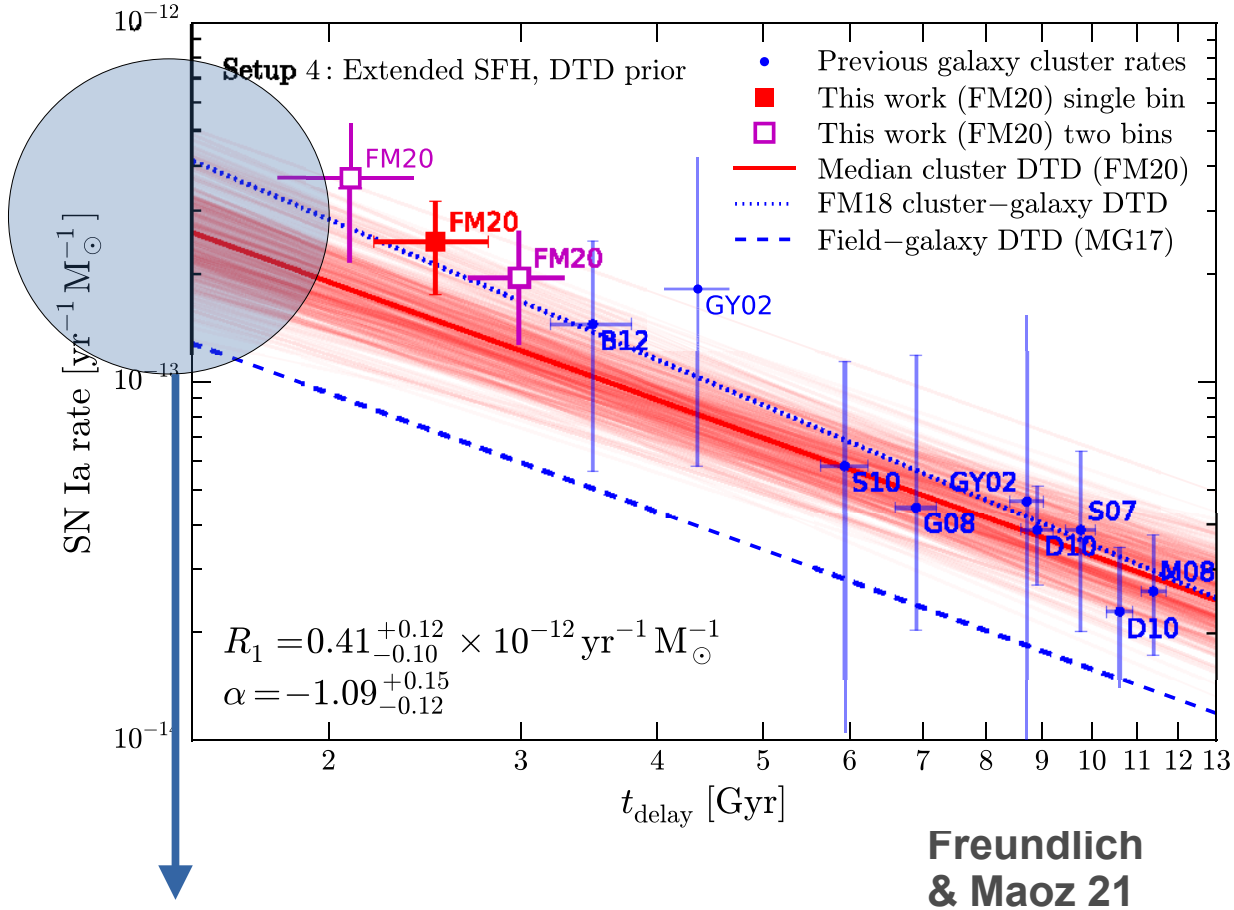
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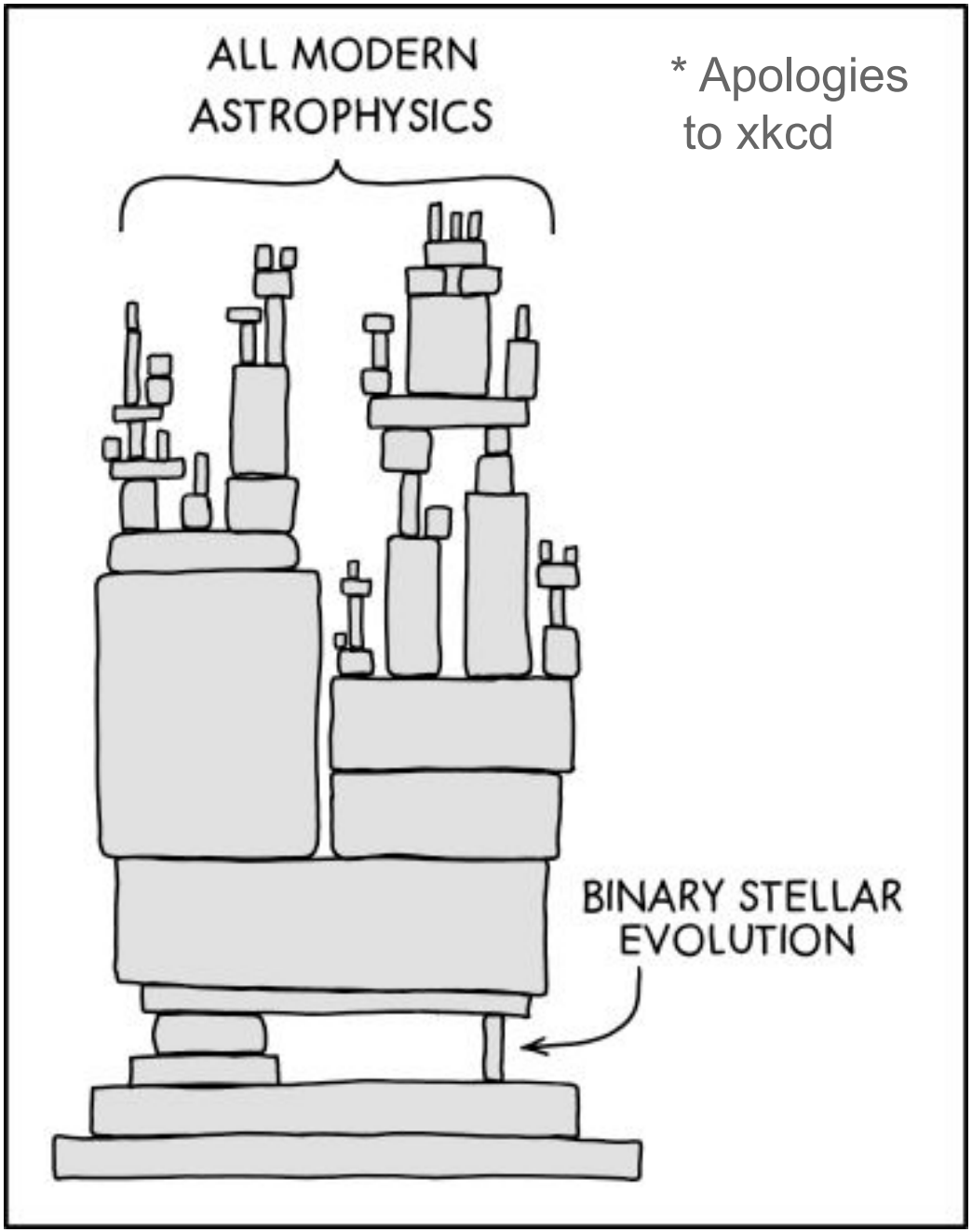
Watch this space

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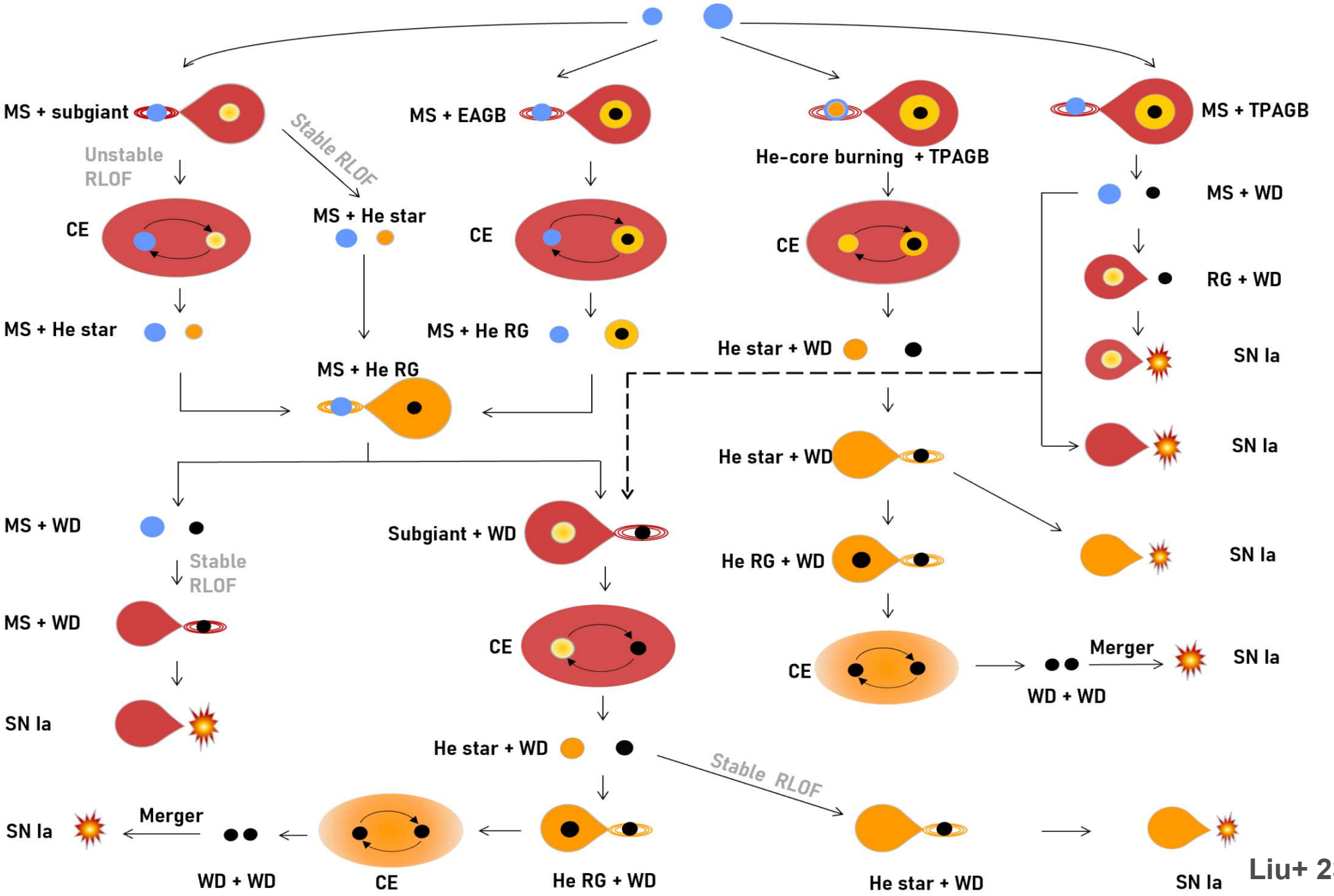
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* Apologies to xkcd

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Liu+ 23

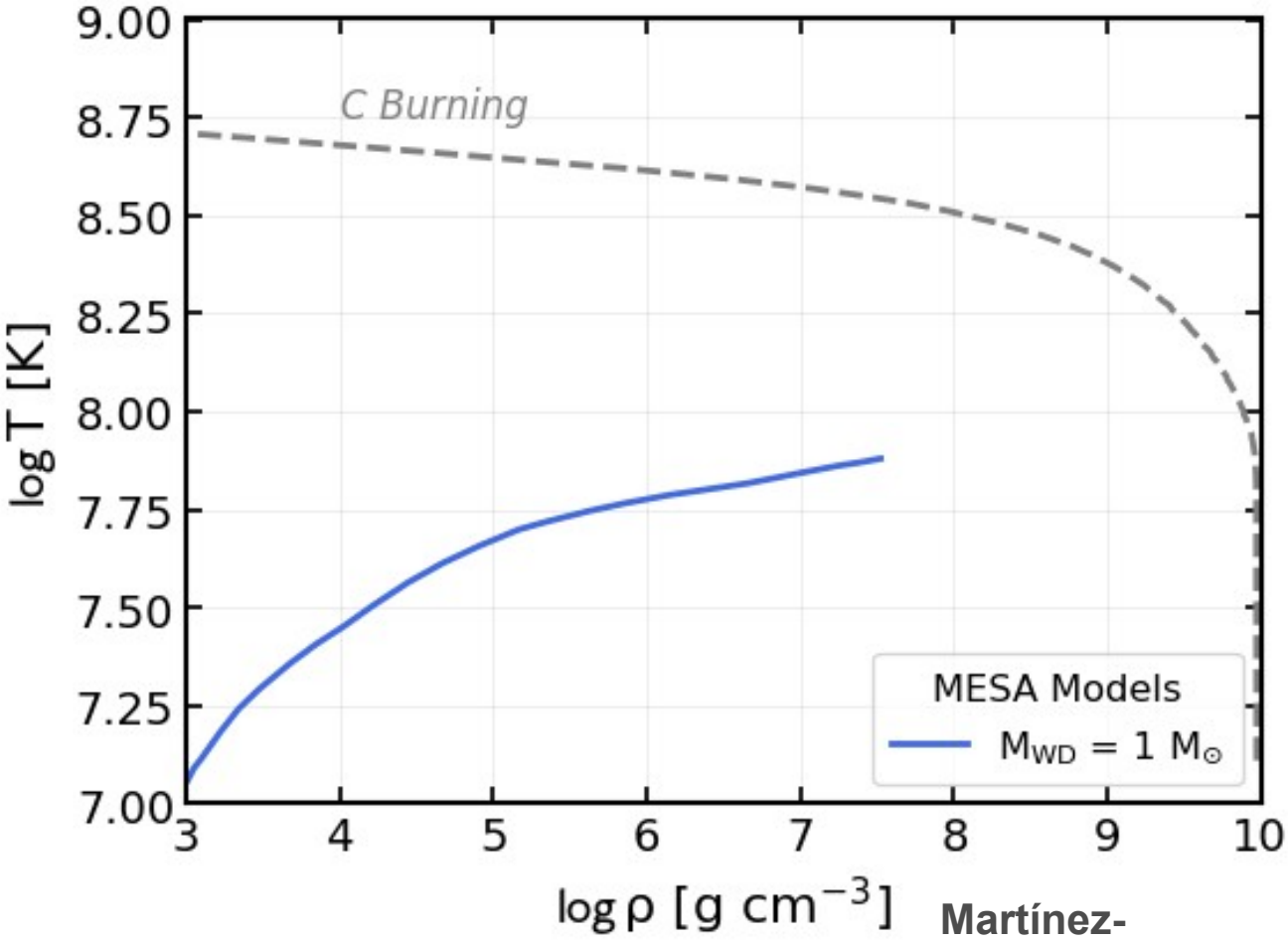
SN Ia: How To Blow Up

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- Single WDs are stable ⇒ **C ignition?** Collisions, mergers, and accretors.

- **Near-M_{Ch}**. Accrete >0.2 $M_\odot$, slow (~t_{KH}) or fast (~t_{dyn}) ⇒ WD close to M_{Ch} without AIC. Simmering phase.

- **Sub-M_{Ch}**. Surface layer ignition (probably He) ⇒ converging shock ⇒ core ignition (double detonation). $M_{WD} > 0.8\ M_\odot$.



Martínez-Rodríguez+ 16

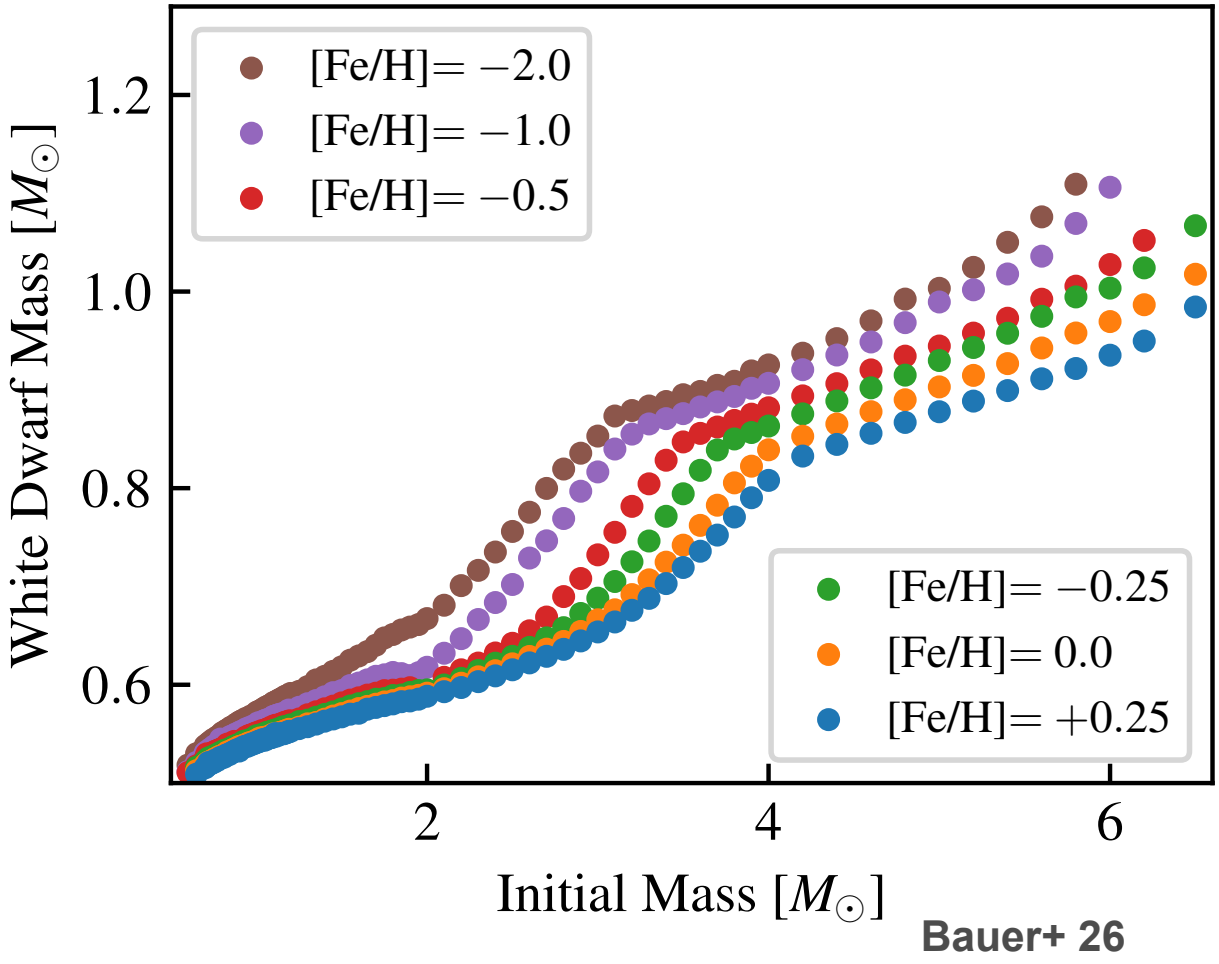
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Bauer+ 26

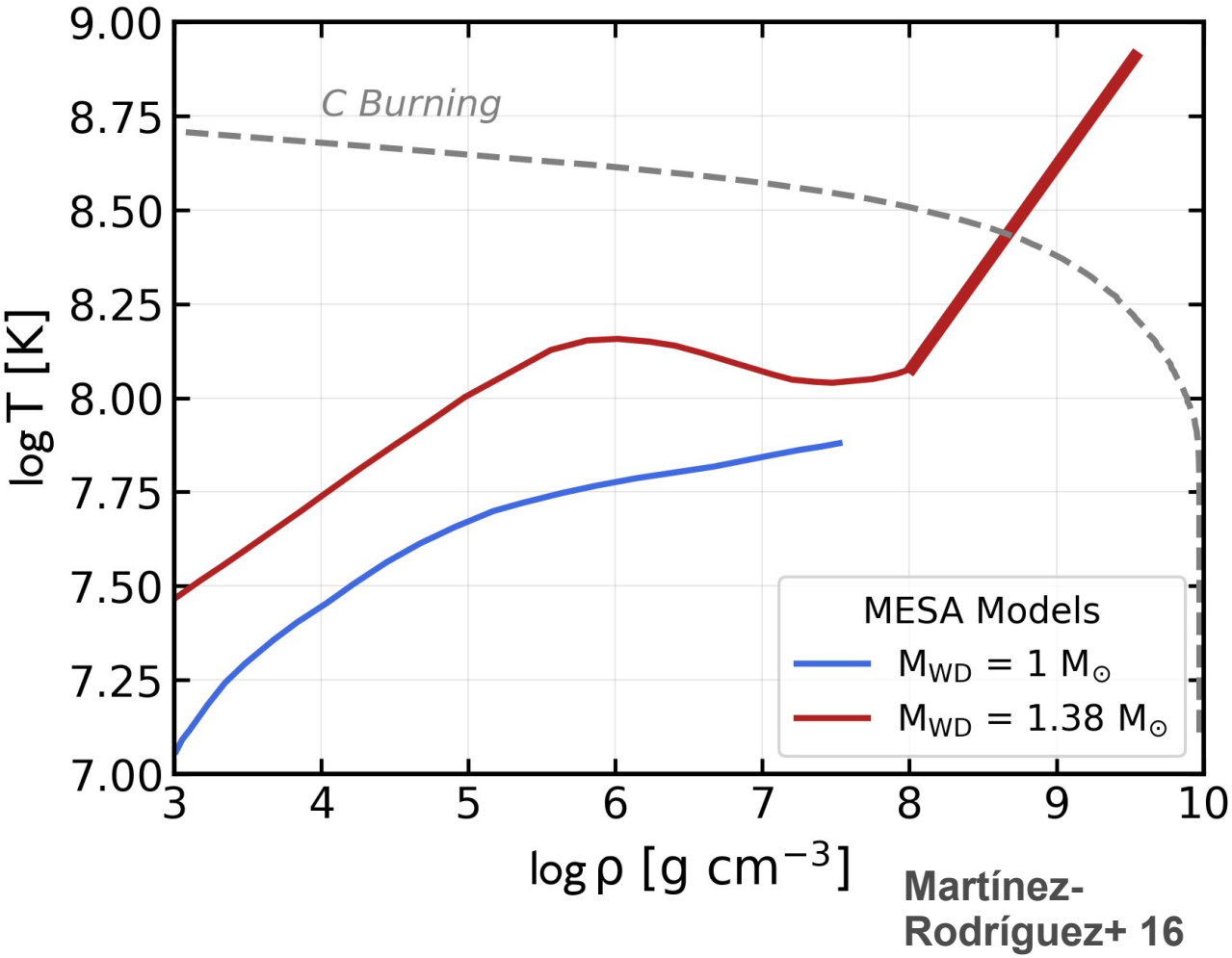
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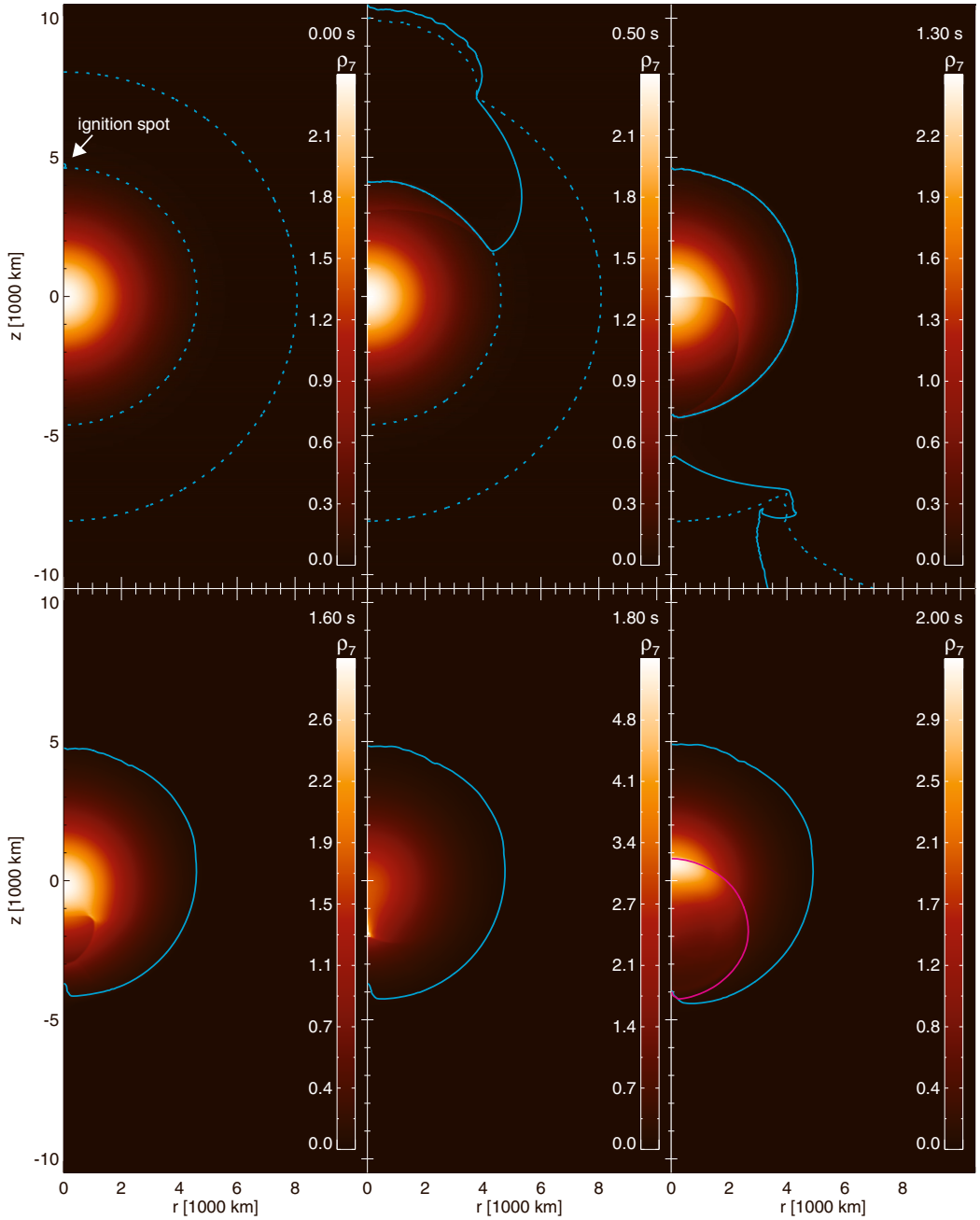
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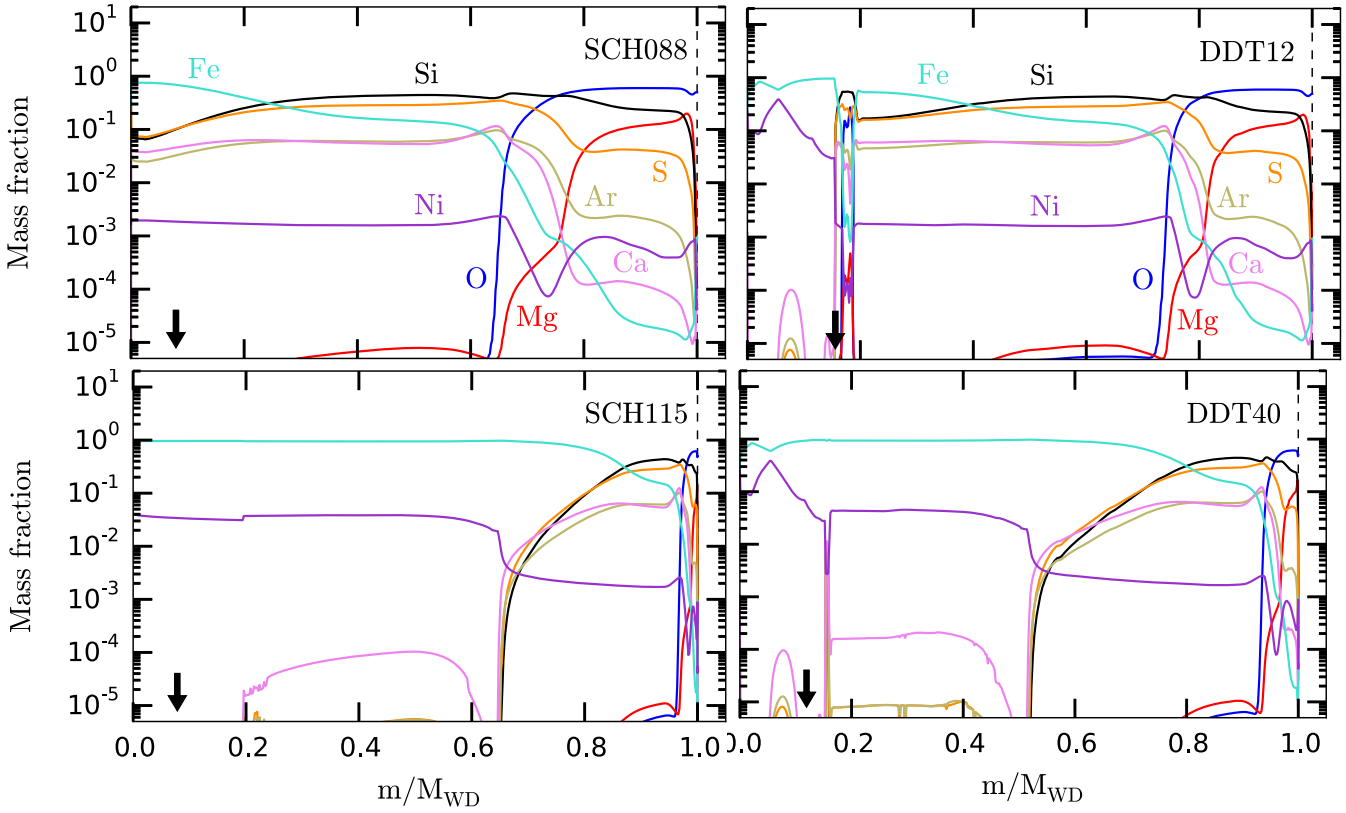


Fink+ 10

SN Ia: How To Blow Up

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- **M_{Ch} vs. sub-M_{Ch}** ⇒ similar ejecta profiles (Fe-peak/IMEs).
- **n-rich elements** (Mn, stable Ni) ⇒ WD mass.
- C+O WD ⇒ ^{12}C, ^{16}O ⇒ η = 0. Whence η?
  - Progenitor: Z⇒^{22}Ne, up to ~$Z_{\odot}$.
  - Explosion: n-rich NSE, simmering (require M_{Ch}).
- Several lines of evidence ⇒ **mixture of WD masses**.

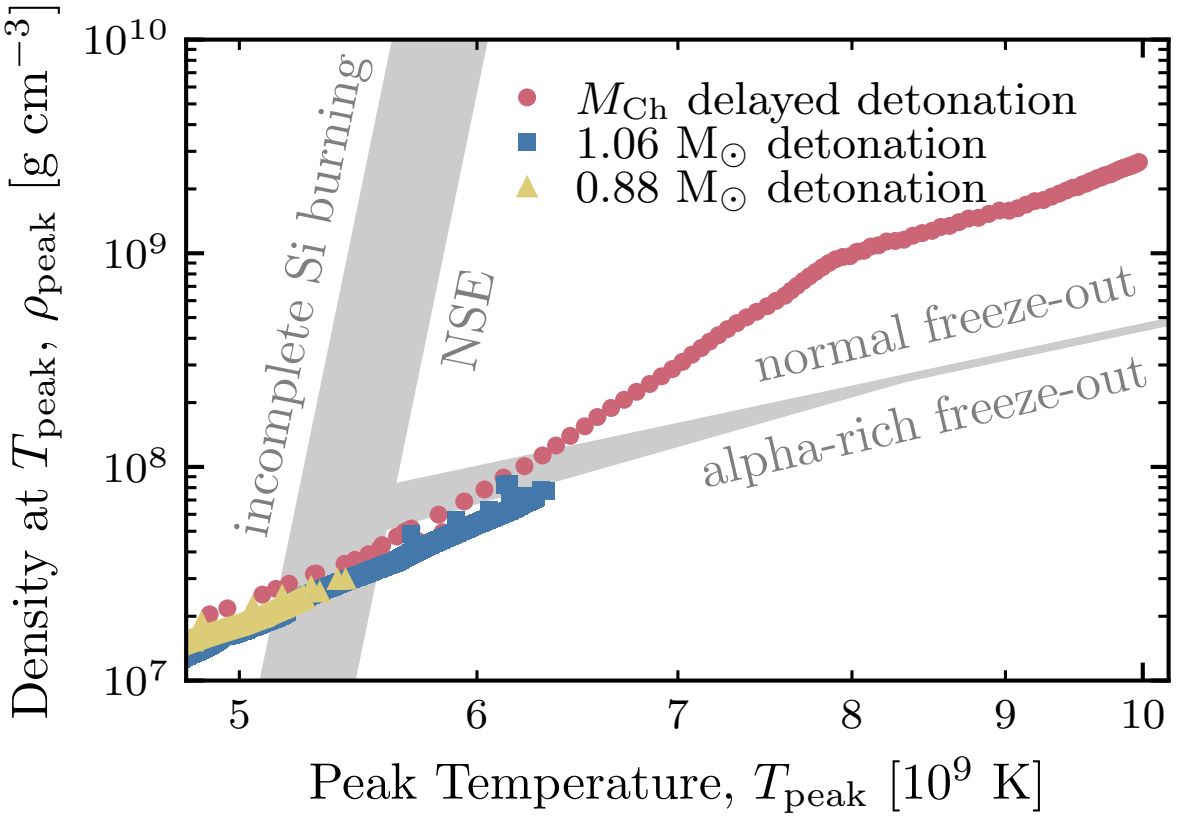


Martínez-Rodríguez+ 18

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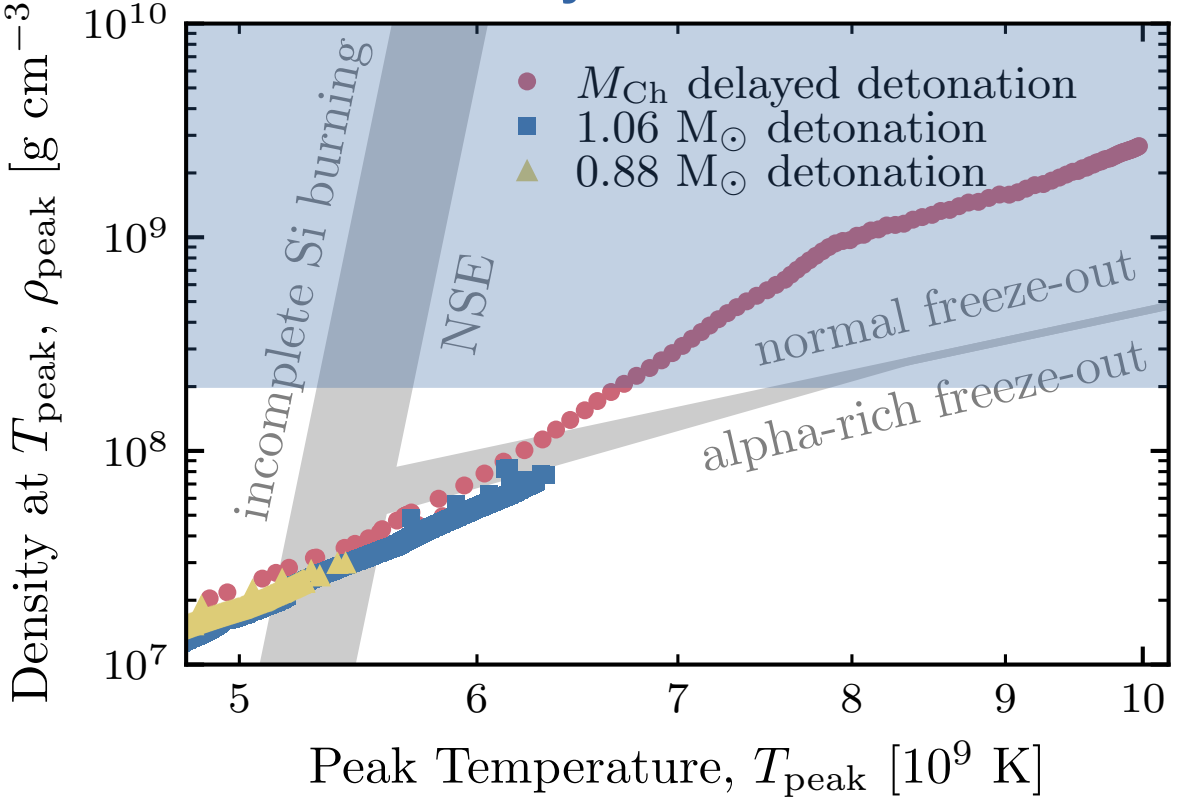
Blondin+ 22

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n-rich Nucleosynthesis

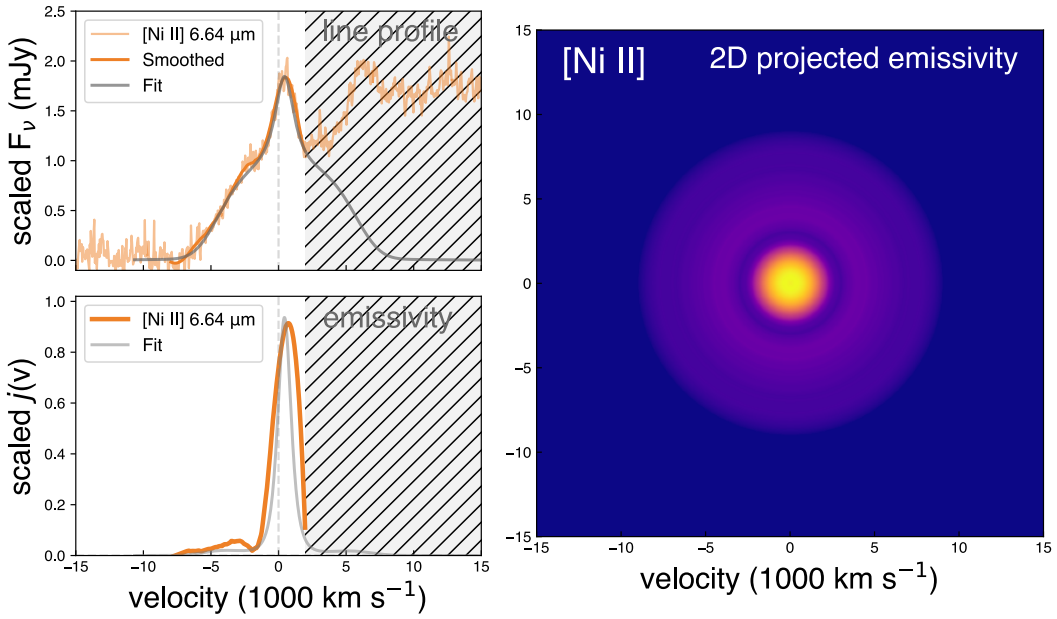


Blondin+ 22

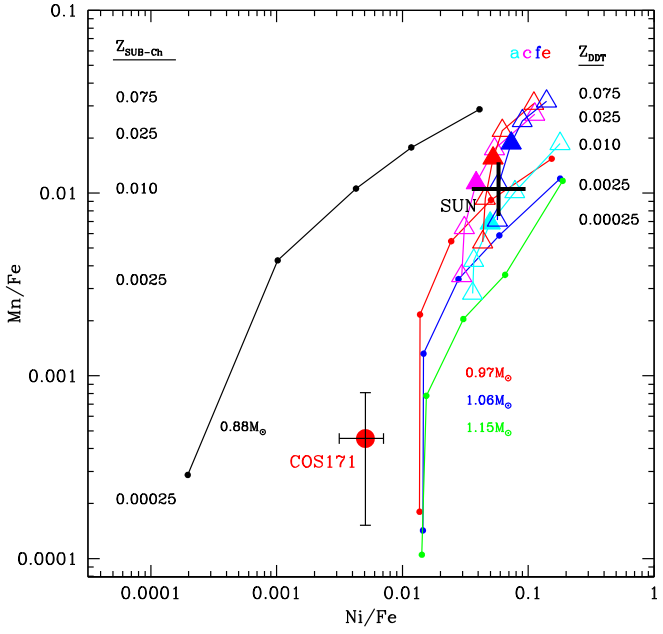
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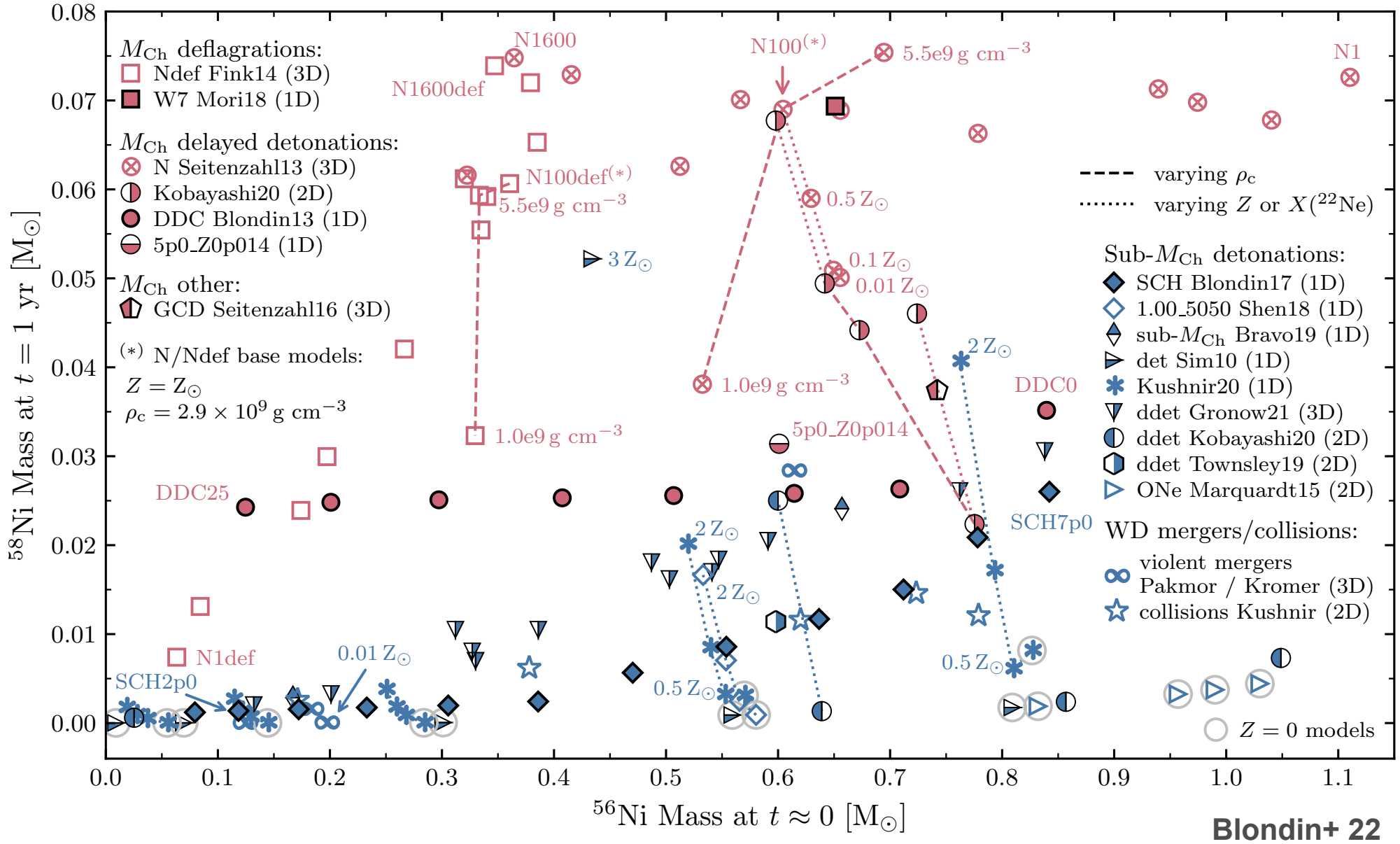
Kwok+ 26
(SN 2024gy, JWST)



McWilliam+ 18
(UMi DSph)

SN Ia: How To Blow Up

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Blondin+ 22

SN Ia: Summary

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(Normal) SN Ia are thermonuclear explosions of massive C+O white dwarfs prompted by accretion in a binary system

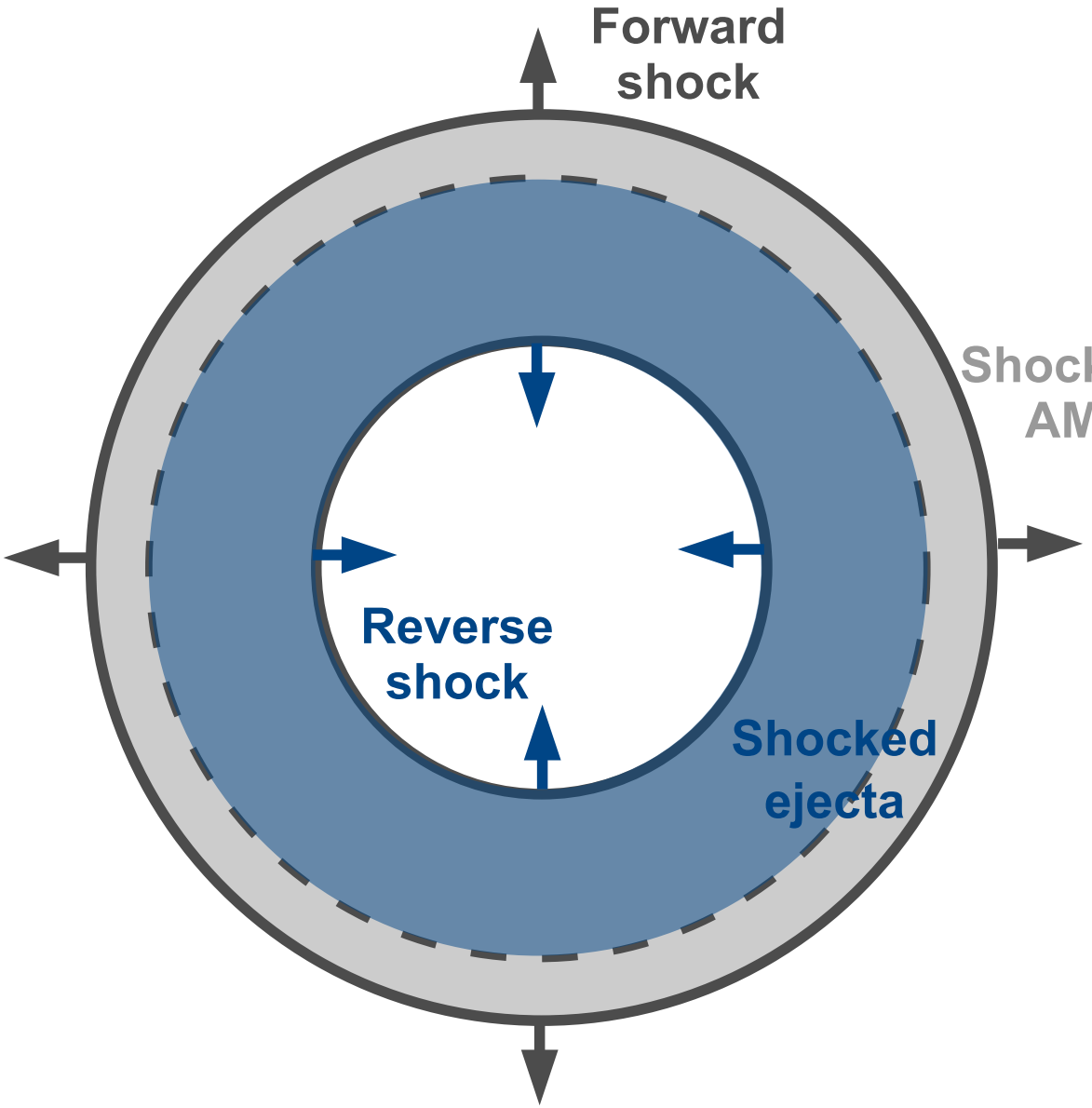
- **Many binary pathways to SN Ia** ⇒ Are the progenitors losing mass before the explosion? How, and how much? Slow vs. rapid accretion.

- **Several ways to blow up a WD** ⇒ Are the exploding WDs near-M_{Ch} or sub-M_{Ch}?

- These two questions are likely related!

Supernova Remnants (SNRs)

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- **SNR = SN + ambient medium (AM) interaction**.

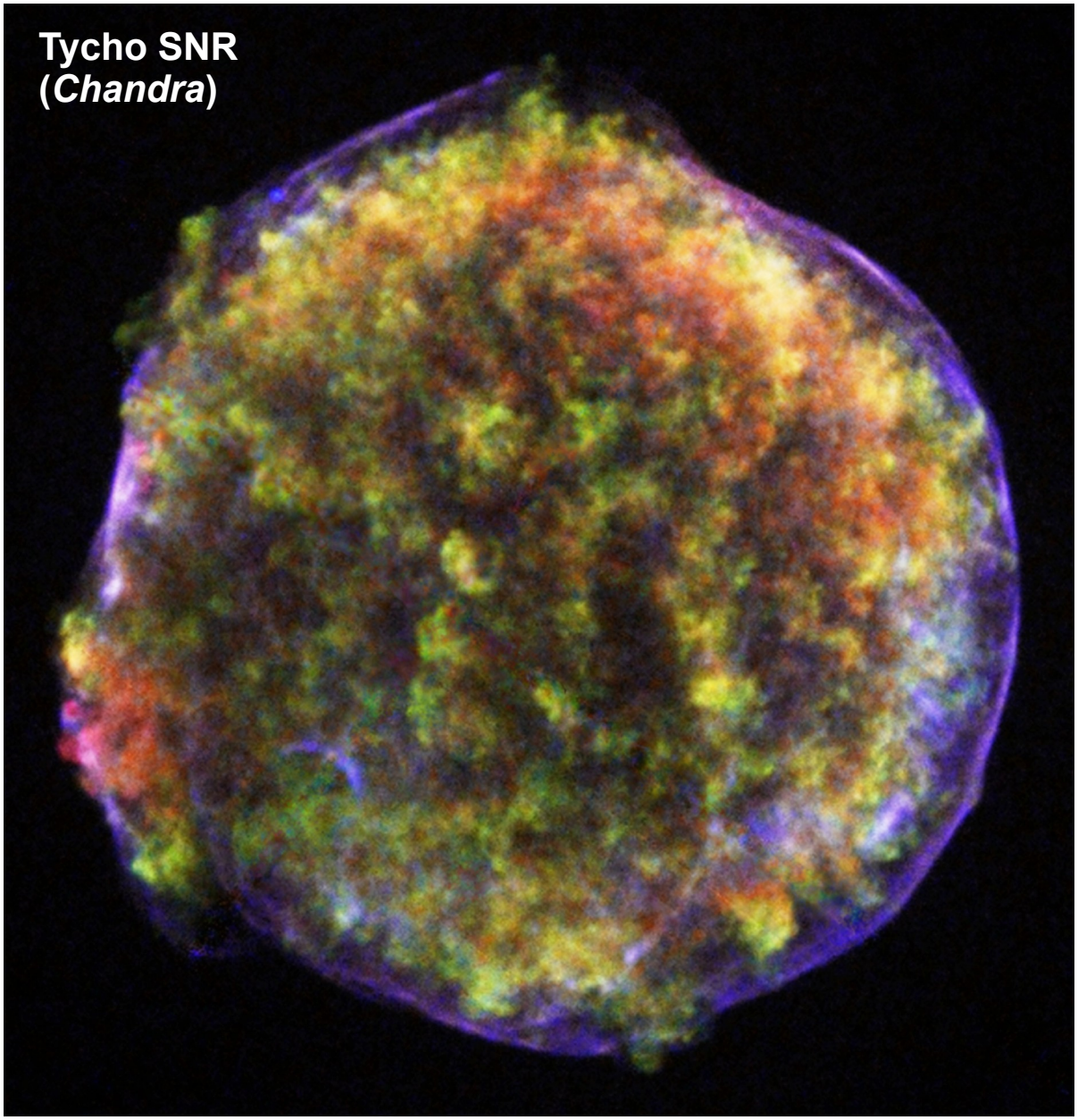
- Collisionless shocks, v~5000 km/s ⇒ **X-ray** temperatures (~1 keV).

- Forward shock moves out (ISM/CSM), reverse shock moves in (SN ejecta).

- X-ray spectrum has **prominent lines from shocked SN ejecta**.

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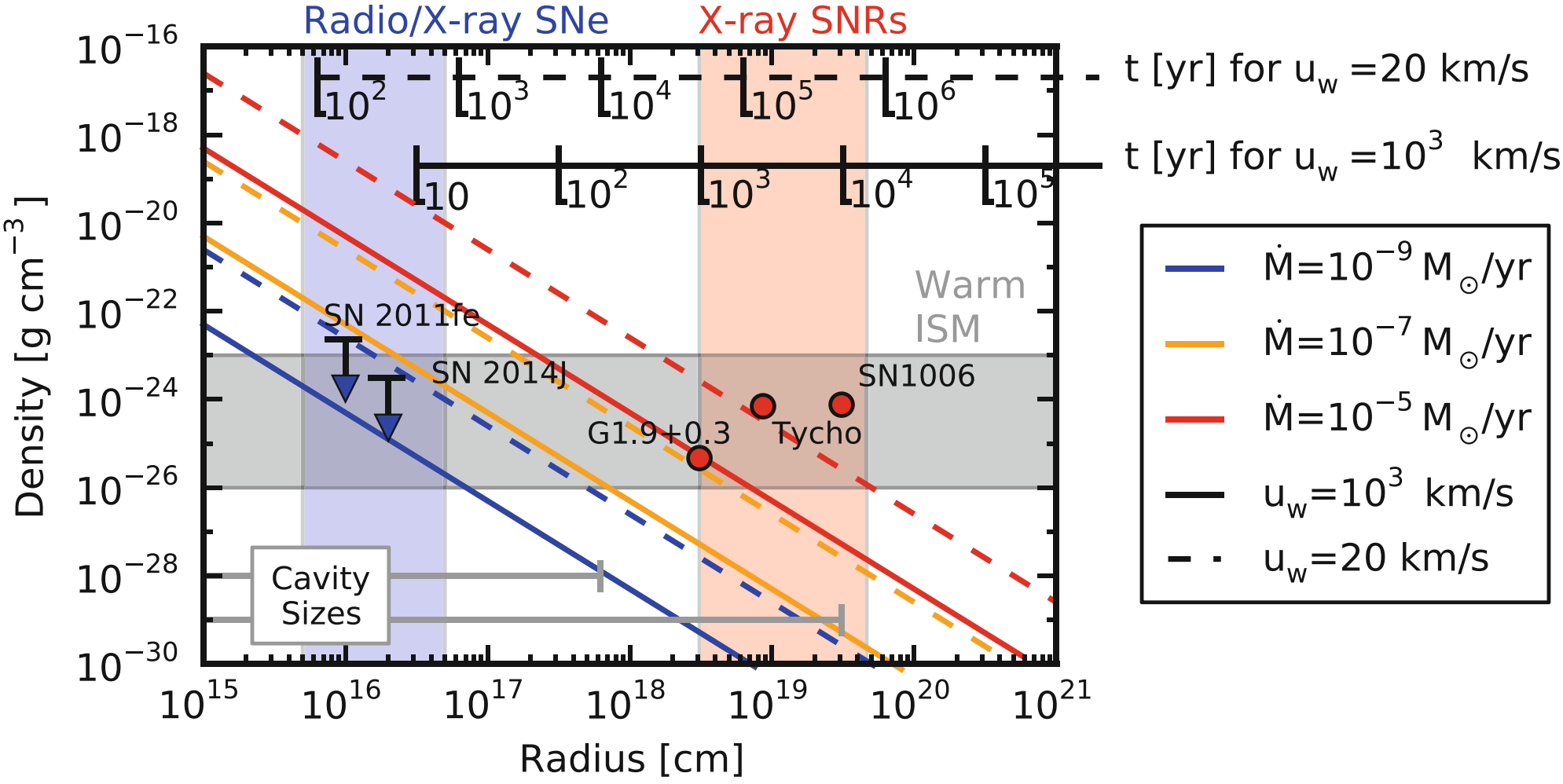
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SNRs and Progenitor mass loss

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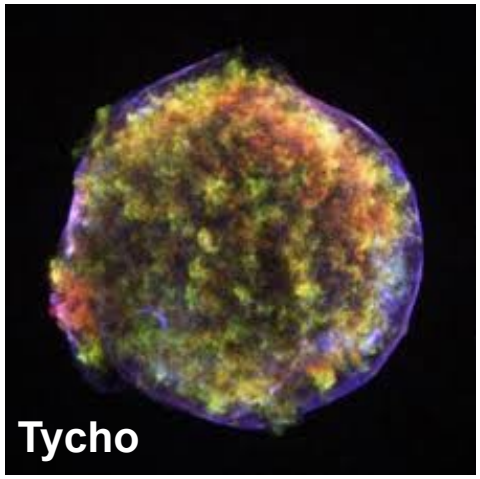
- **SN Ia progenitor ⇒ dM/dt ⇒ AM**. SNR (radii, ages, $n_e t$) ⇒ AM on ~pc scales ($t_{dM/dt}$~10^3-10^6 yr) ⇔ binary stellar evolution.
- **SN Ia progenitor dM/dt from bulk SNR dynamics**.

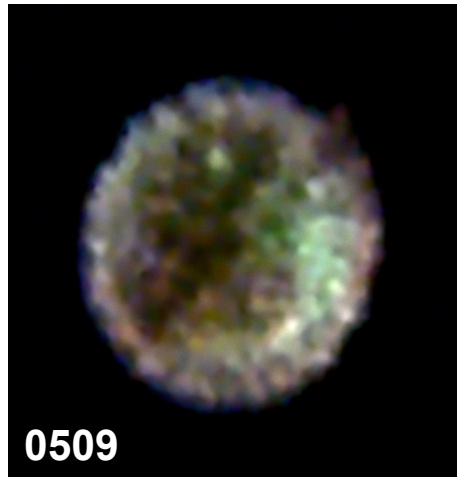


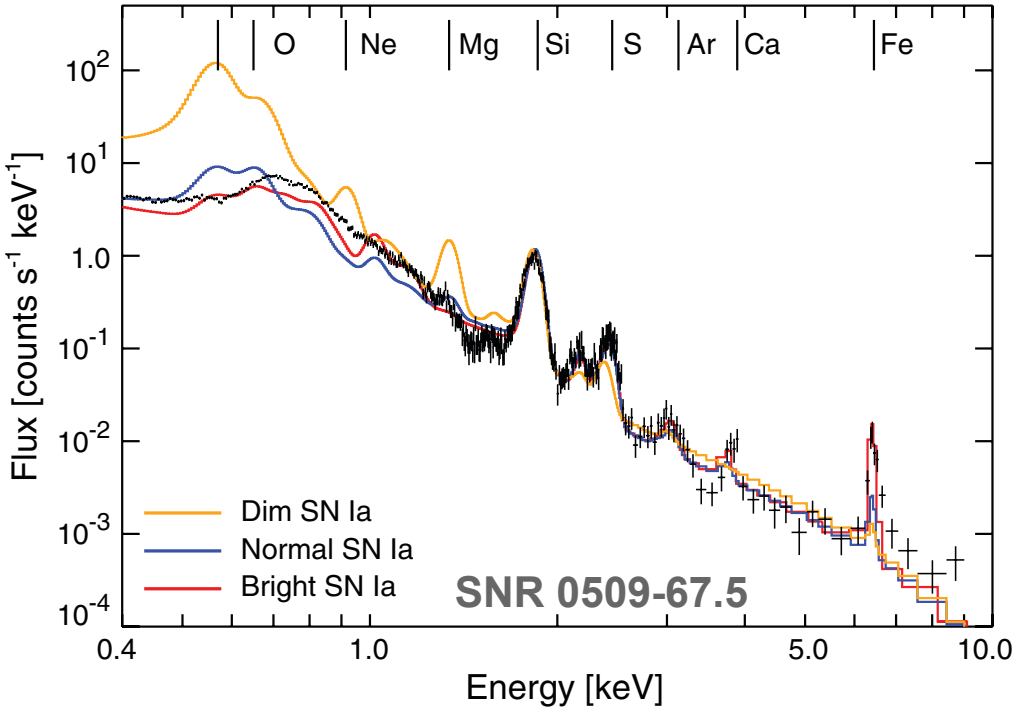
Data: X-ray Spectra of SNRs

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- **X-ray bright SNRs** in the MW and LMC: X-ray spectra, ages, radii.
- **NEI** (non-equilibrium ionization): collisional ionization proceeds faster at higher ρ.
- **Fe Kα centroid ⇔ $n_e t$ ⇔ ρ_{AM}.**
- CC SNRs have higher Fe Kα centroids than Type Ia SNRs [Yamaguchi+ 14].
- **SNR models** (NEI+HD) can put quantitative **constraints on ρ_{AM} around SN progenitors** [Badenes+ 07, Patnaude+ 15,17, Jacovich+ 21, 23, Martinez-Rodriguez+ 18, Court+ 24,26].



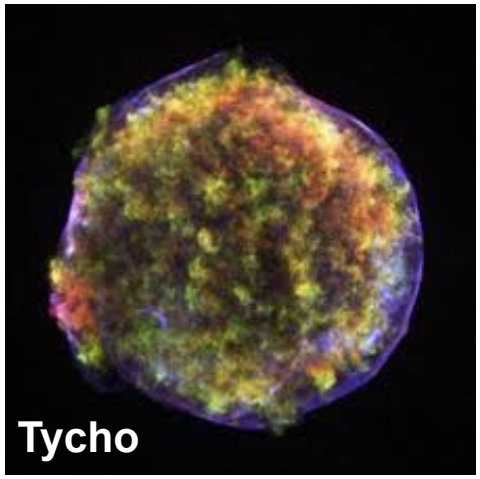


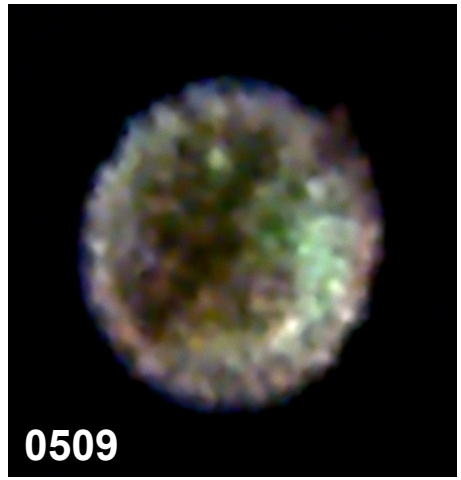


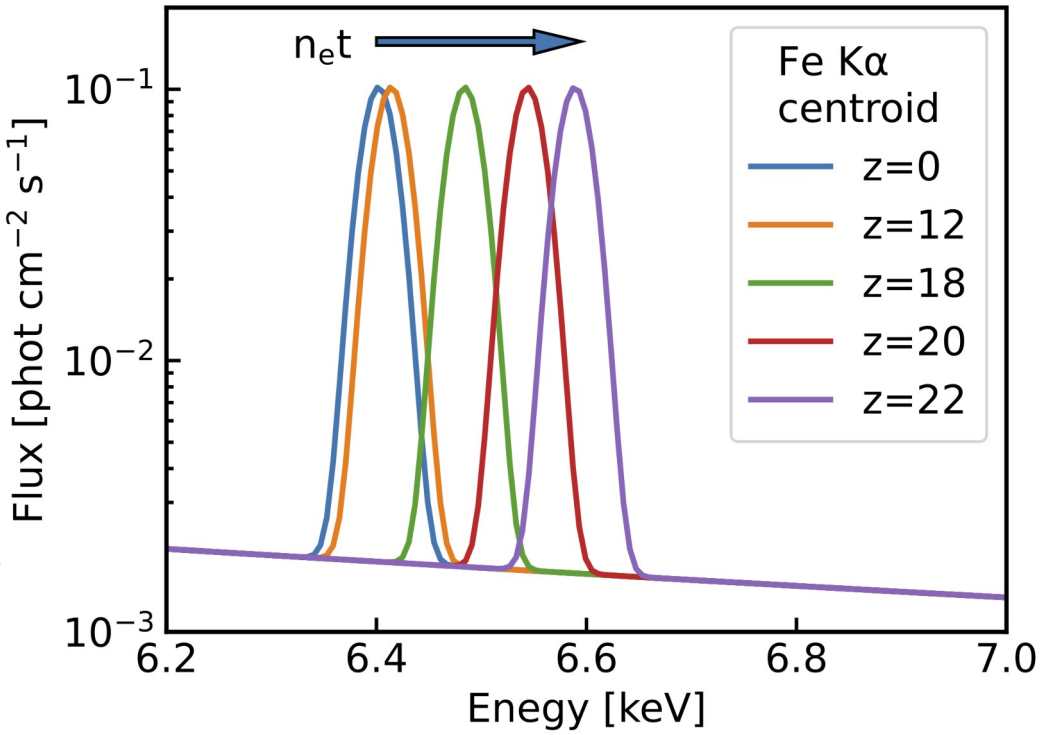
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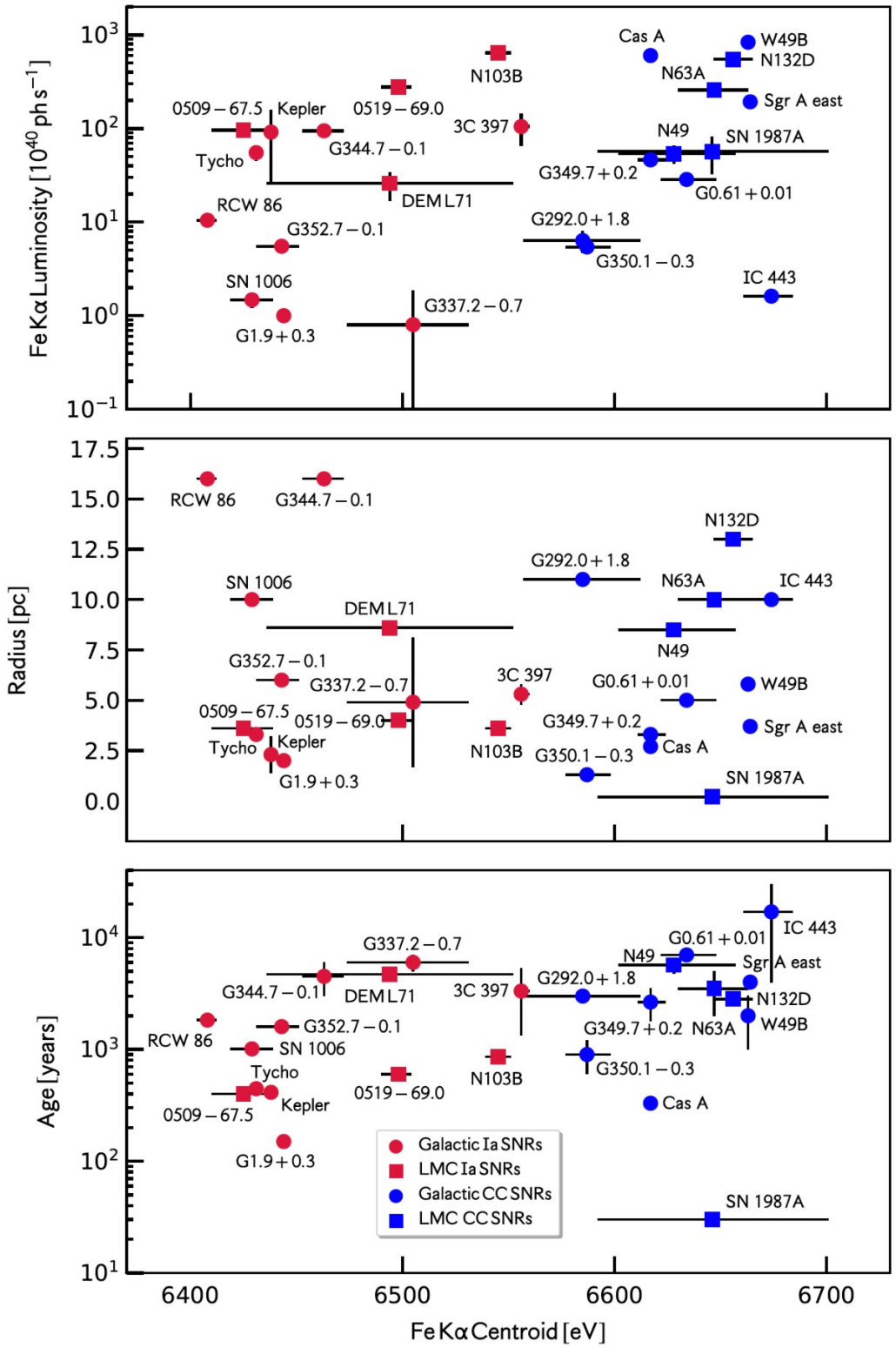






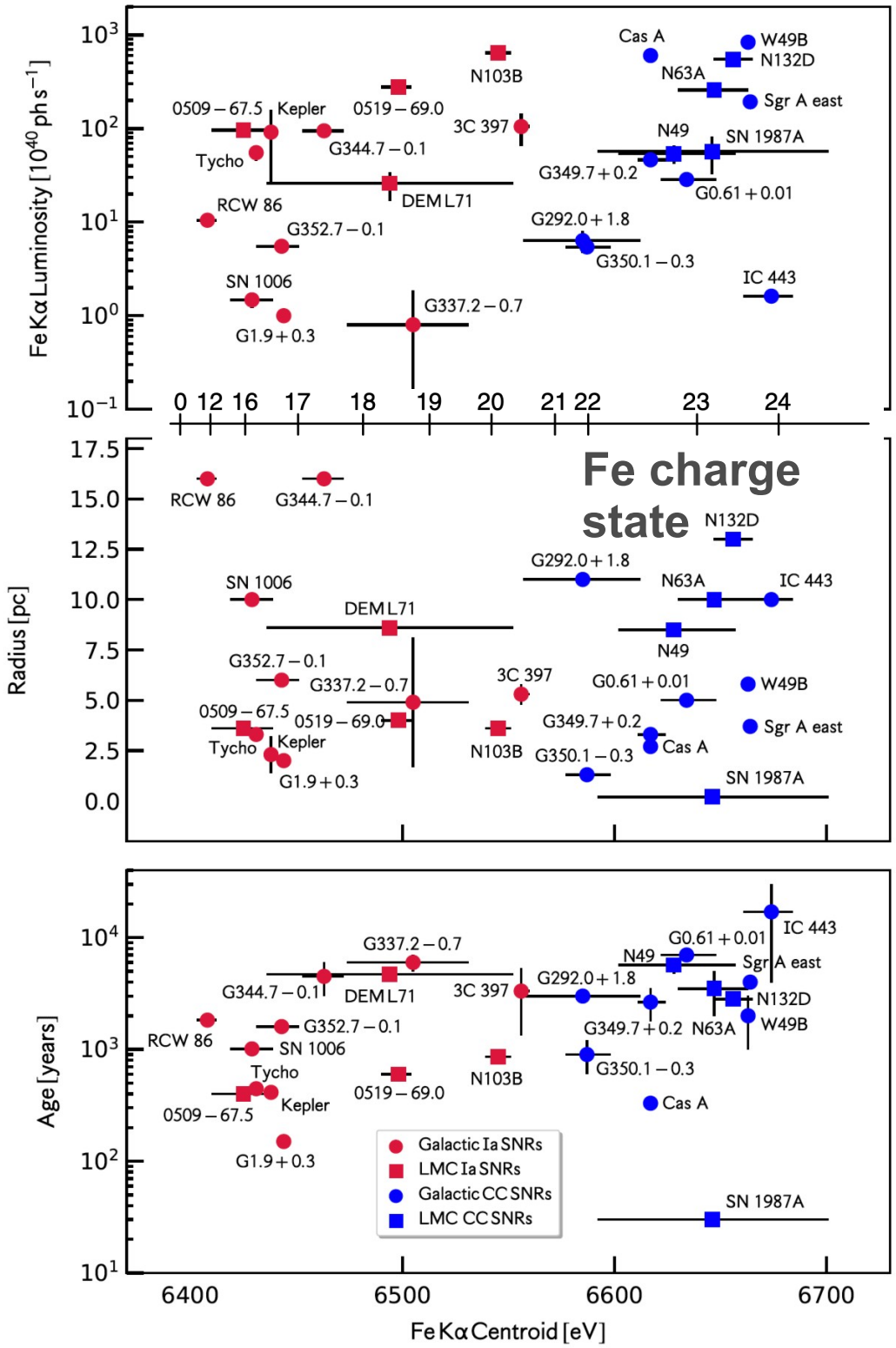
Data

- **X-ray bright SNRs** in the MW and LMC: X-ray spectra, ages, radii.
- **NEI** (non-equilibrium ionization): collisional ionization proceeds faster at higher ρ.
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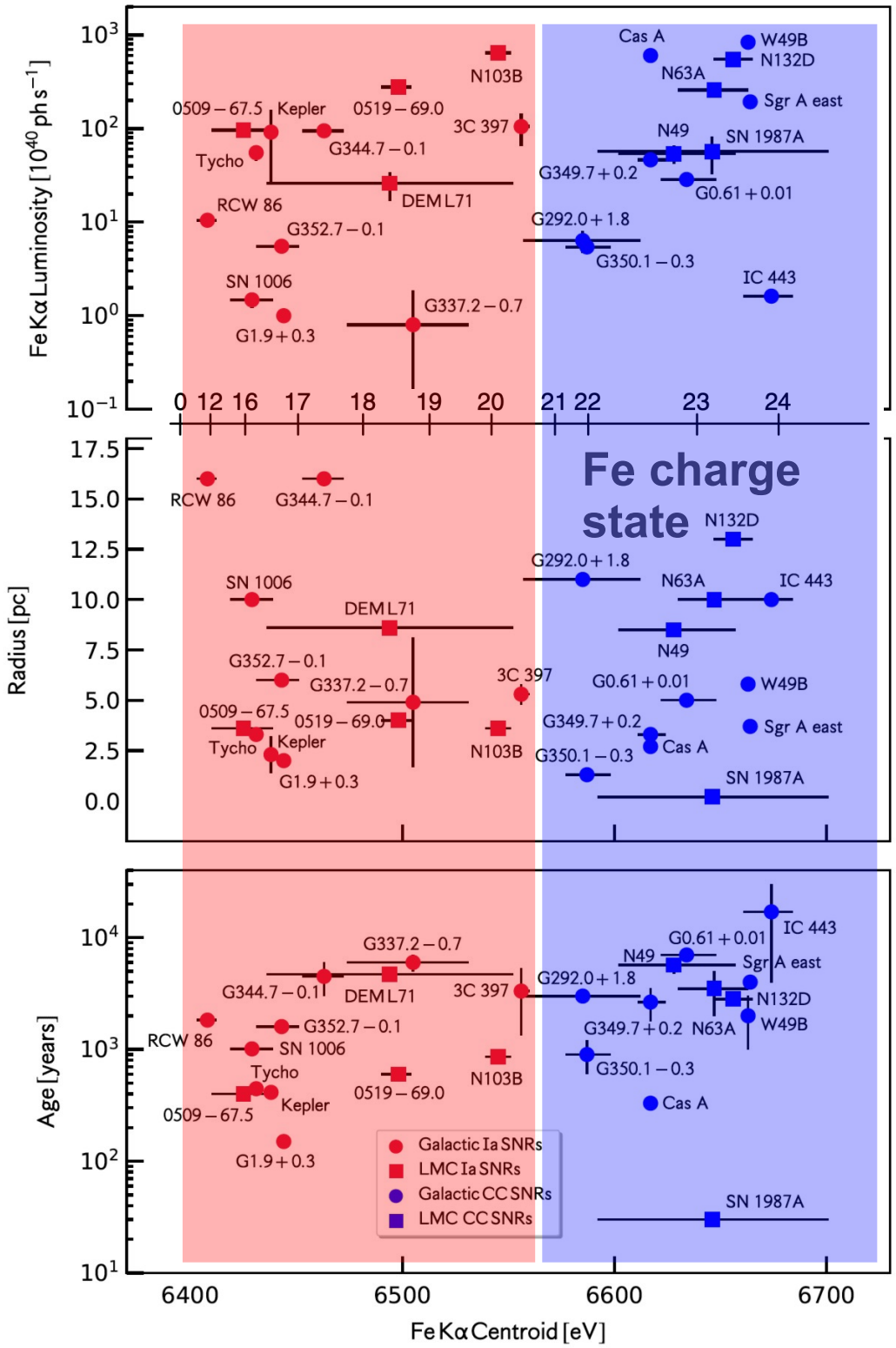
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Data

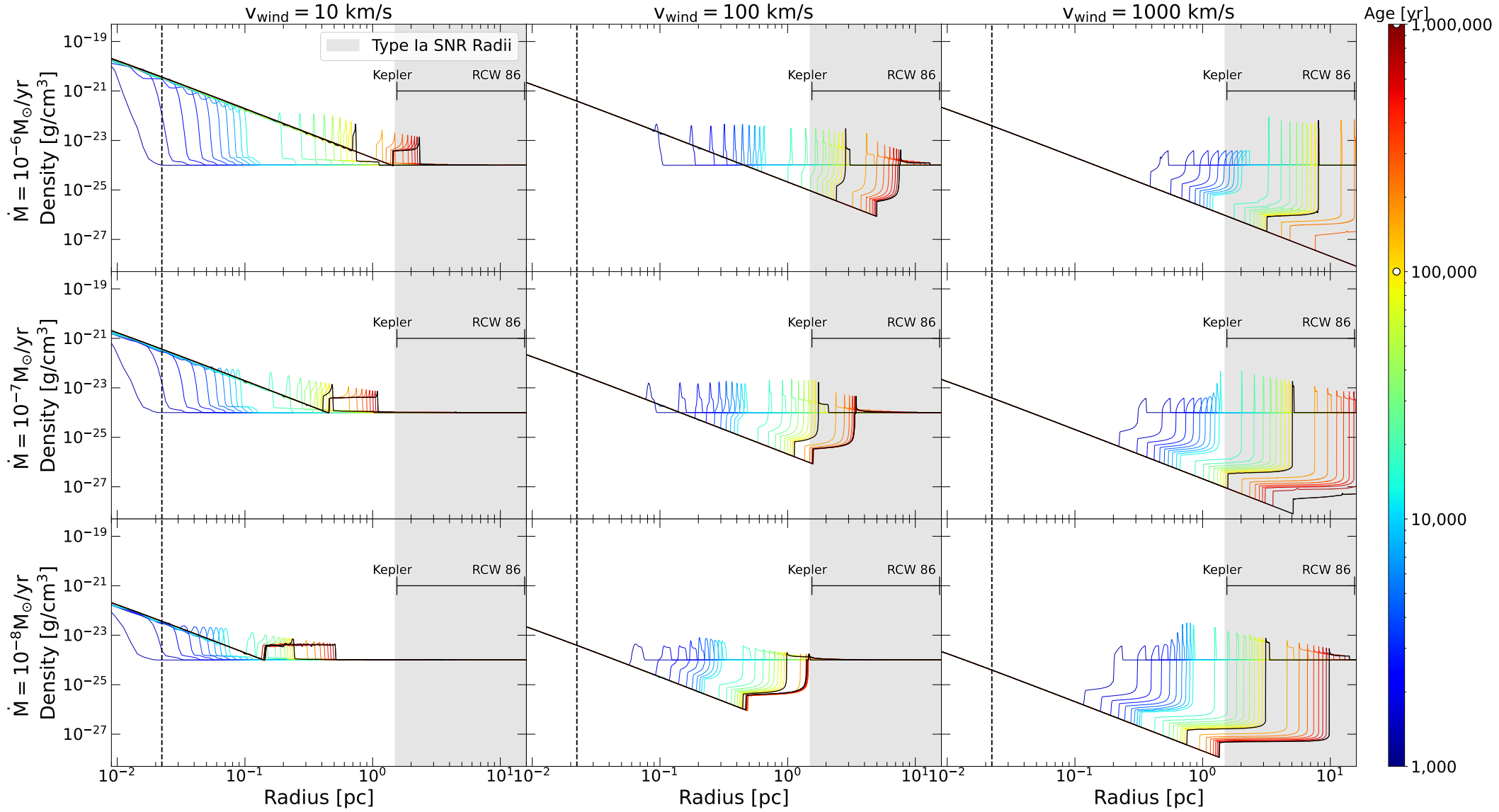
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CSM Models: Isotropic Outflows

Carles Badenes
JHU 02/04/26

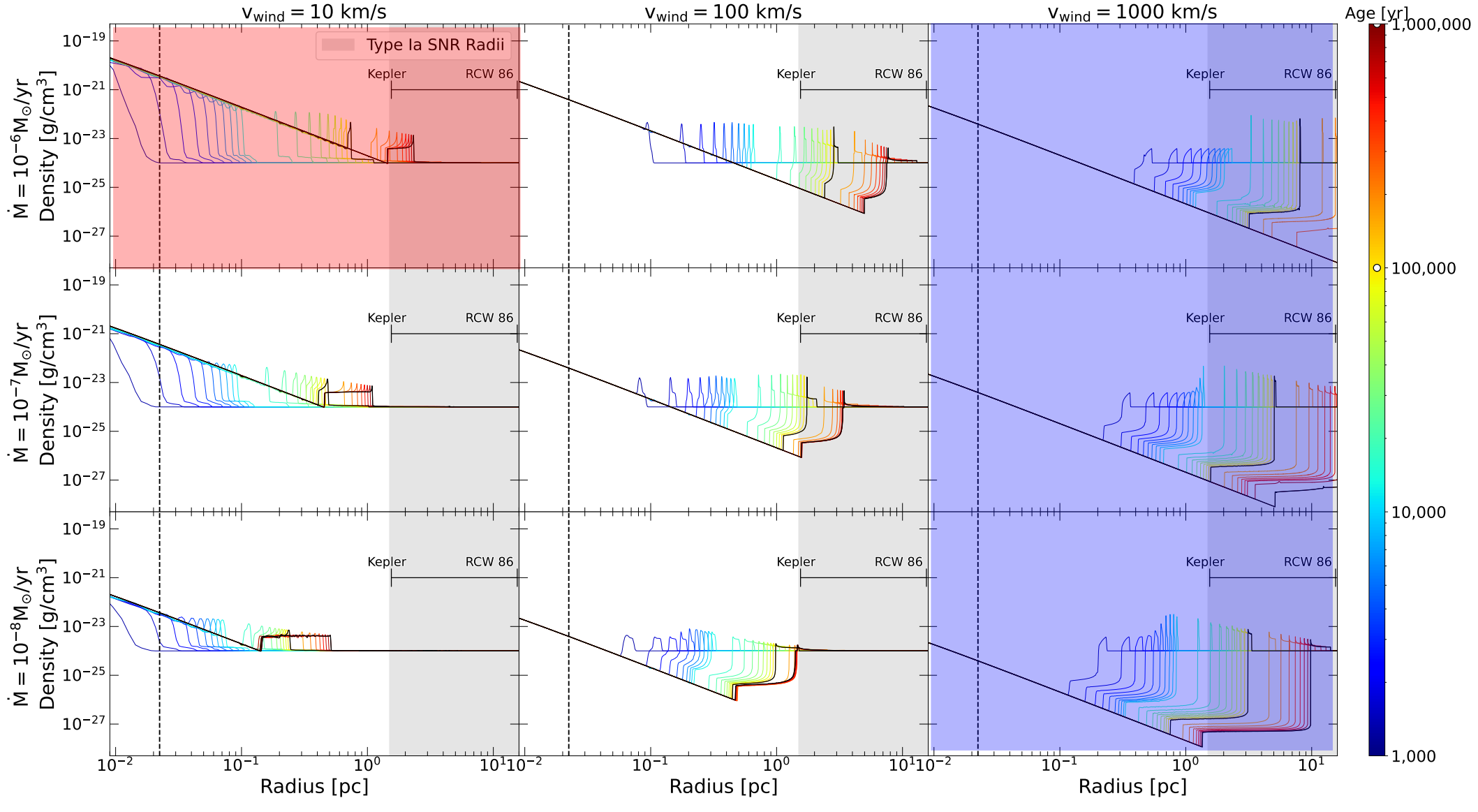
- **Isotropic outflows**: **dM/dt** [10^{-8},10^{-7},10^{-6} $M_\odot$/yr], **v_{wind}** [10, 100, 1000 km/s], **t_{wind}** [10^5,10^6 yr] ⇒ **CSM** (fast/slow outflows [Koo & McKee 92])



CSM Models: Isotropic Outflows

Carles Badenes
JHU 02/04/26

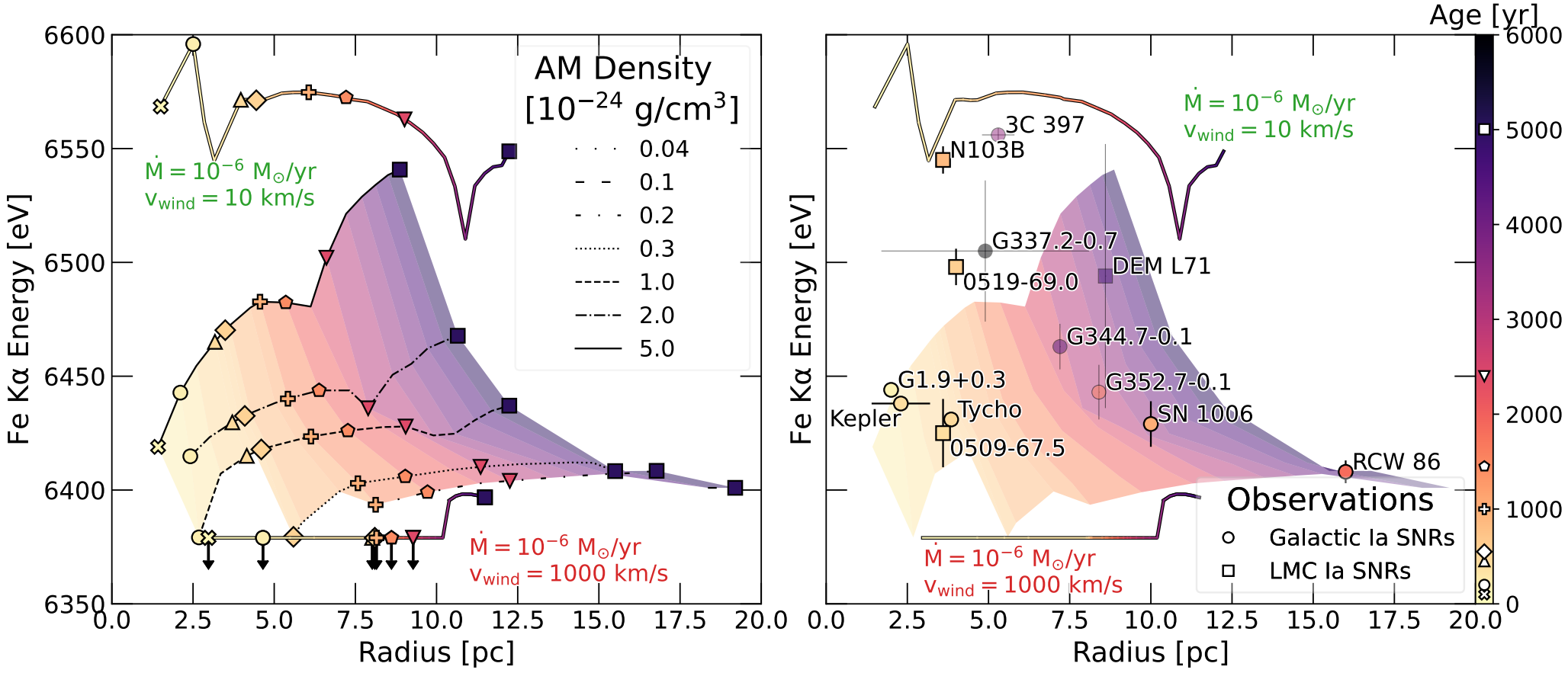
- dM/dt ≳10^{-6} $M_\odot$/yr + v_{wind} ~10 km/s ⇒ **dense CSM**.
- v_{wind} ≳1000 km/s ⇒ **large low ρ cavities**.



Models vs. Observations

Carles Badenes
JHU 02/04/26

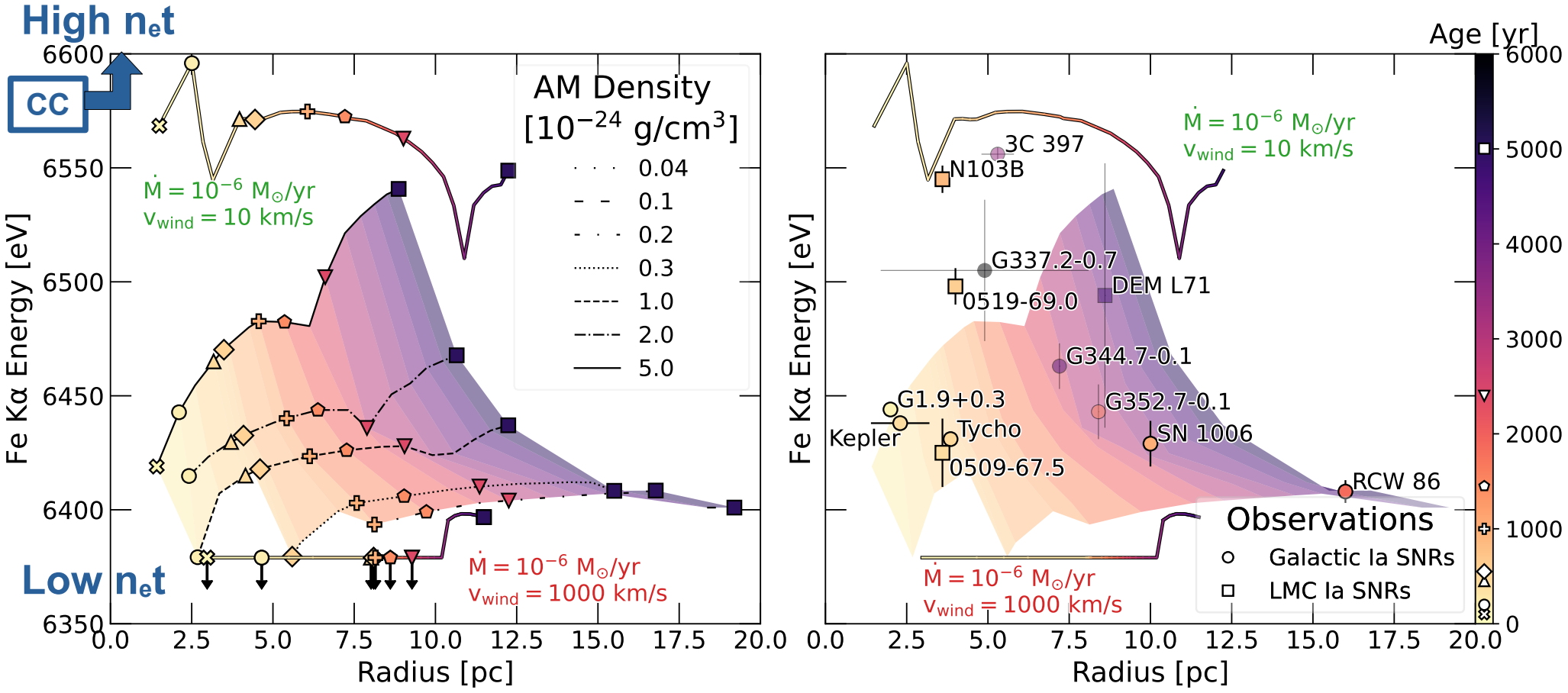
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Models vs. Observations

Carles Badenes
JHU 02/04/26

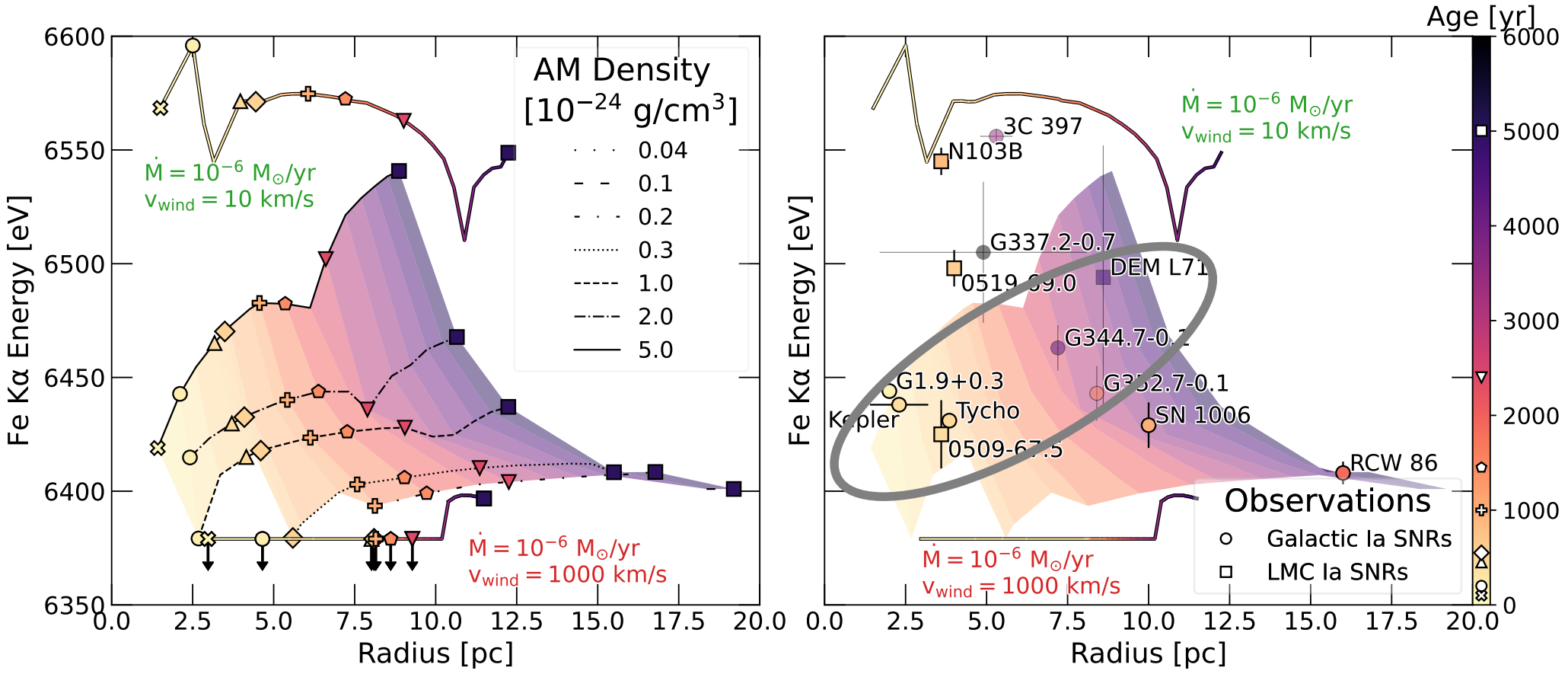
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Models vs. Observations

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JHU 02/04/26

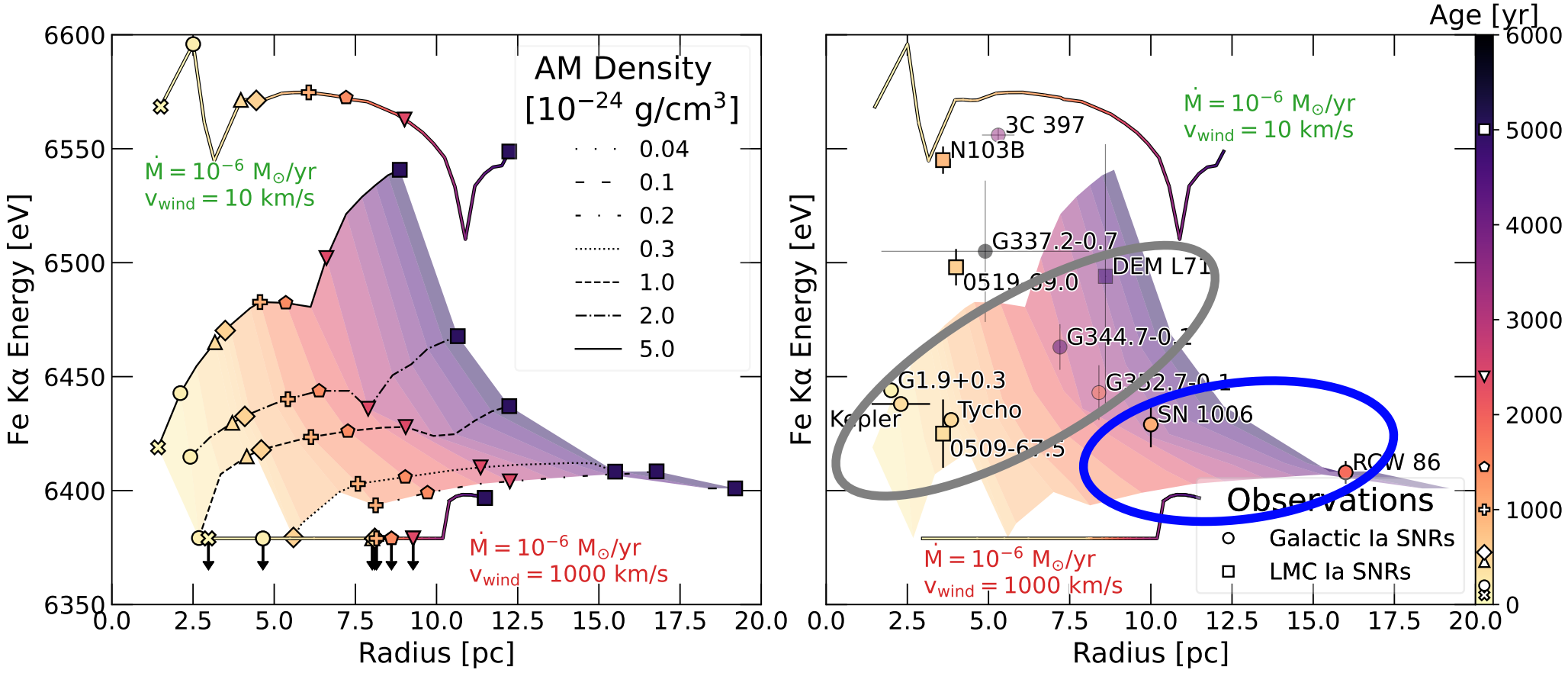
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JHU 02/04/26

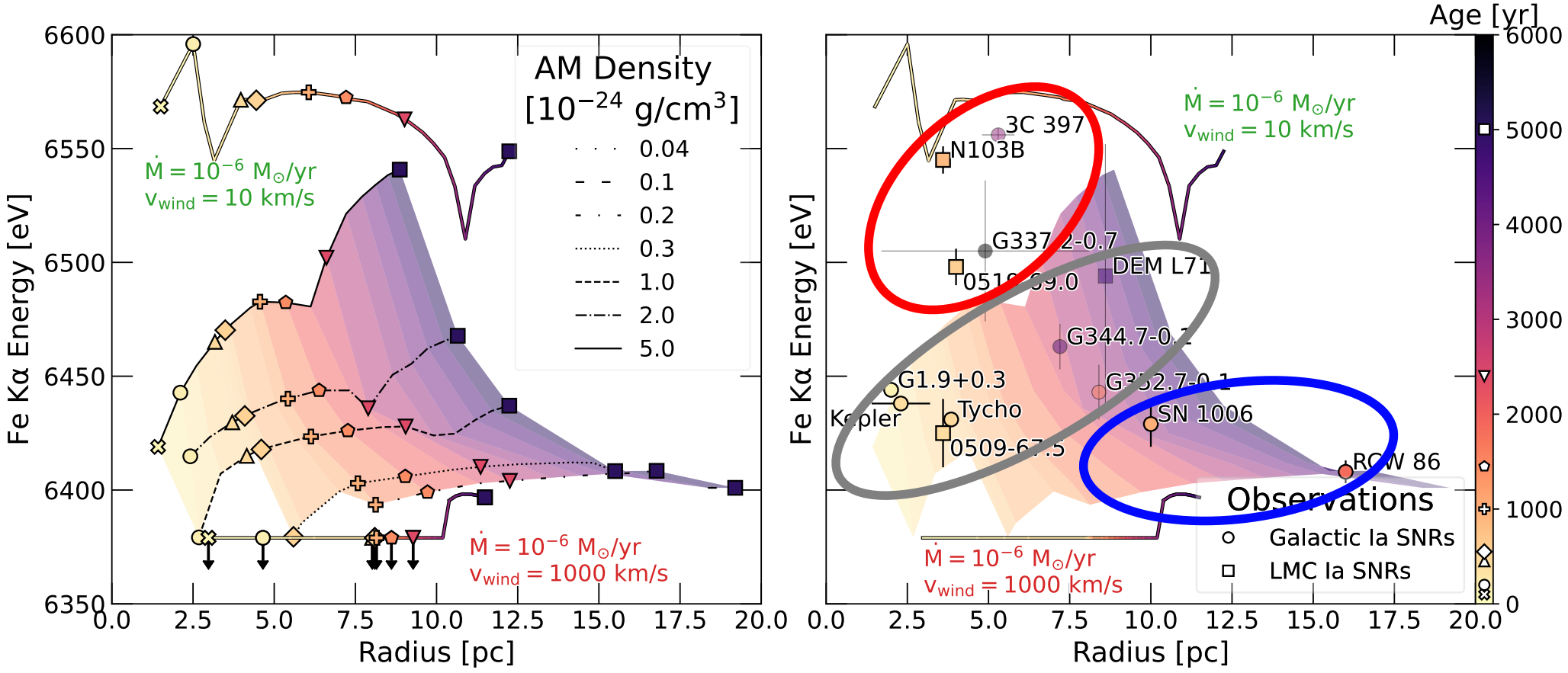
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JHU 02/04/26

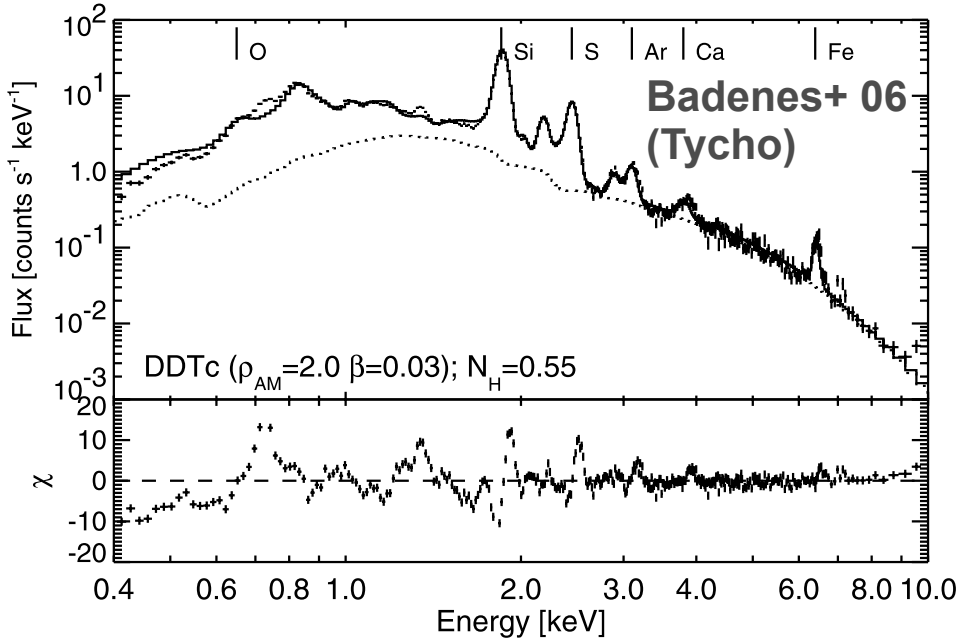
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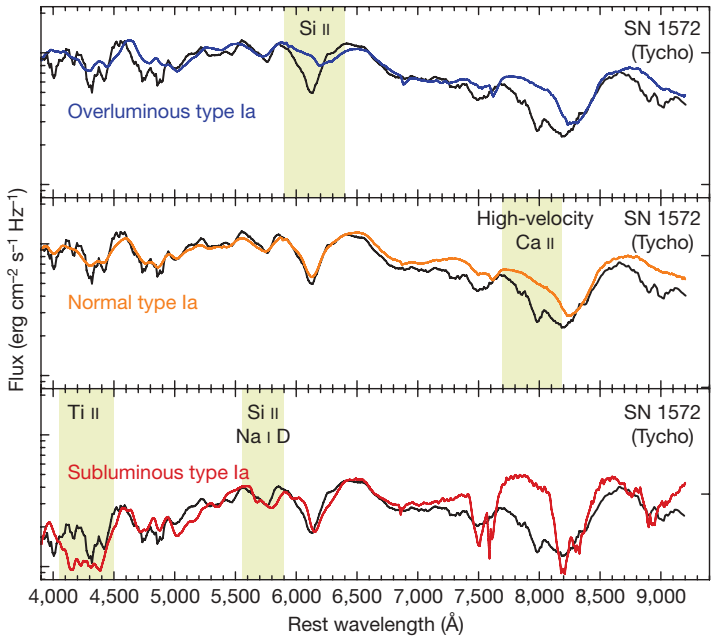


The Dead Man's Tale

Carles Badenes
JHU 02/04/26

- **~55% (7/13) of SN Ia progenitors do not strongly modify AM on ~pc scales:** G1.9+0.3, 0509, Kepler, Tycho, G344, G352, DEM L 71.
- dM/dt ≲ 10^{-7} M⊙/yr, v_{wind} ≲ 100 km/s (for t_{wind}~10^5 yr); ≲ 10 km/s (for t_{wind}~10^6 yr).
- **Tycho** ⇒ normal SN Ia [Badenes+ 06, Krause+ 08].
- **0509** ⇒ luminous 91T-like SN Ia [Rest+ 08, Badenes+ 08], likely double detonation in a sub-Ch WD [Das+ 25].
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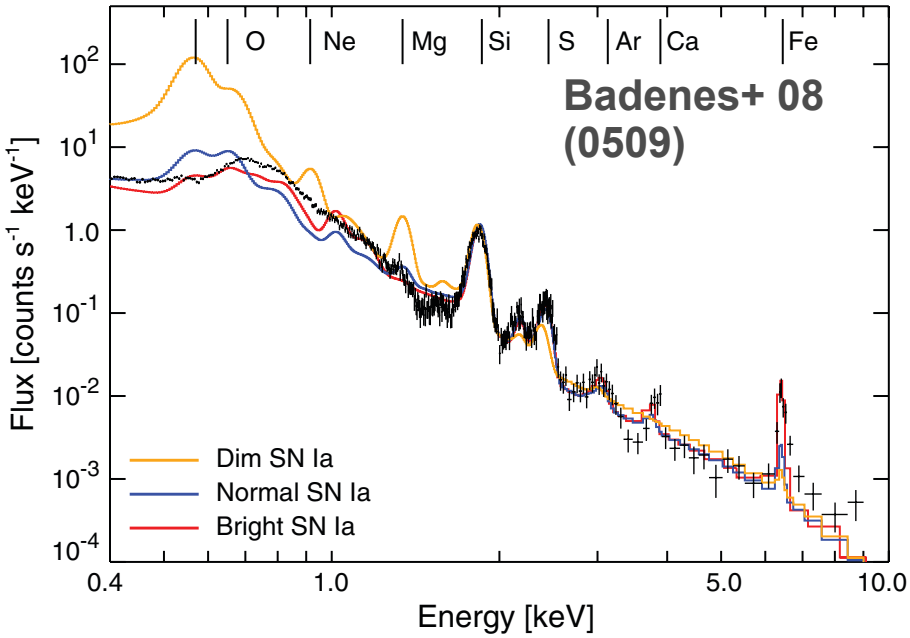


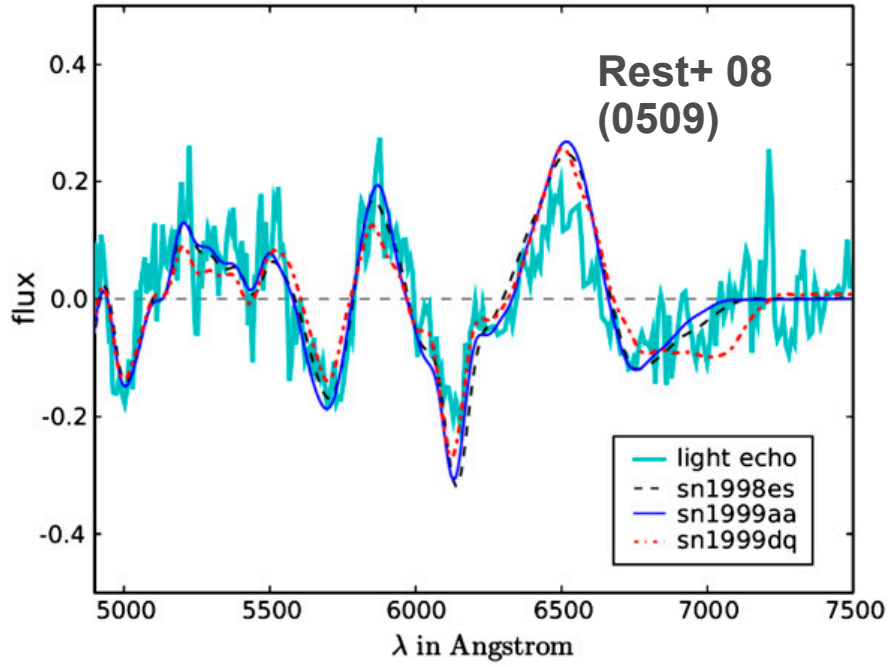
Krause+ 08 (Tycho)

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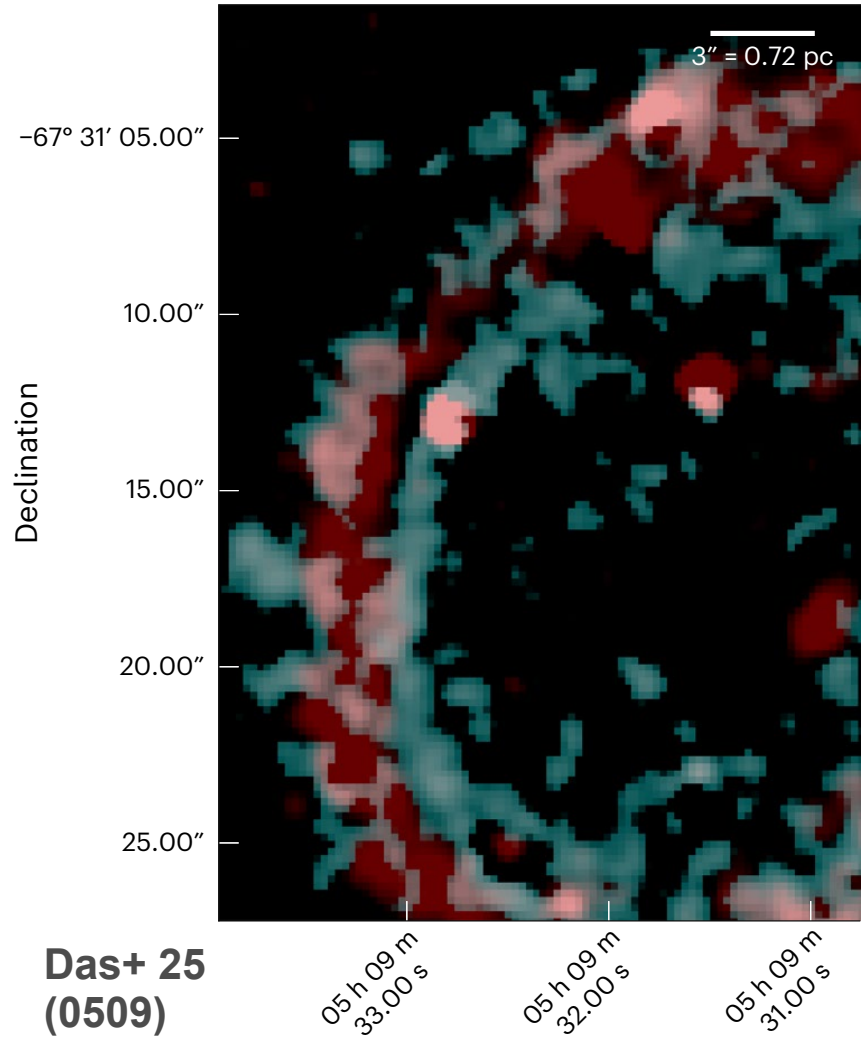




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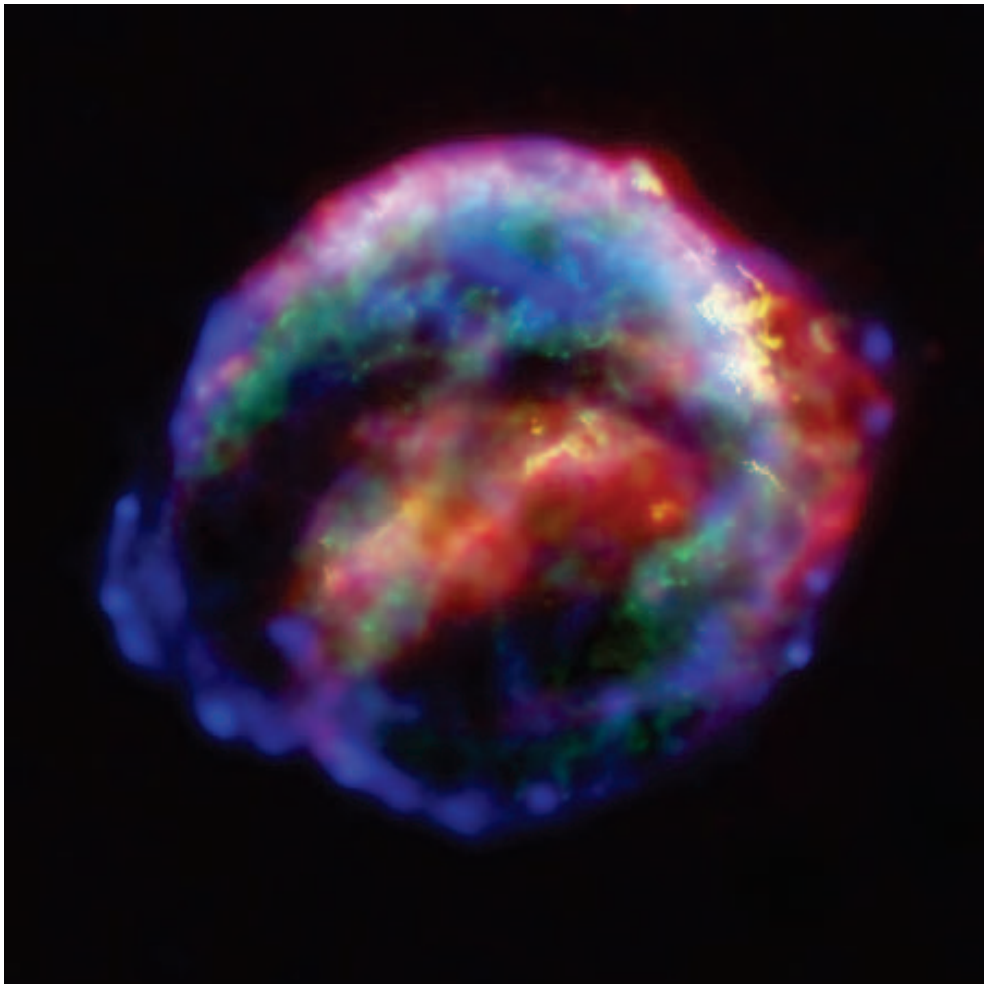


Das+ 25 (0509)

The Dead Man's Tale

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JHU 02/04/26

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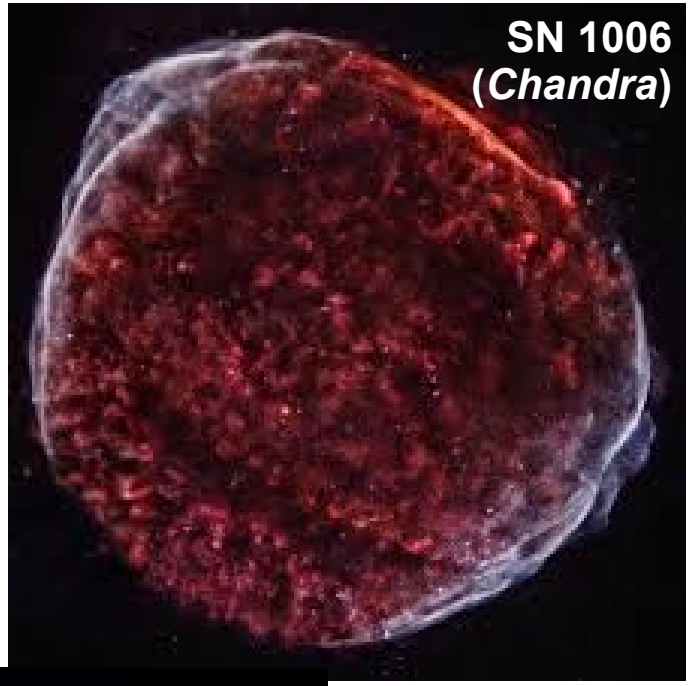


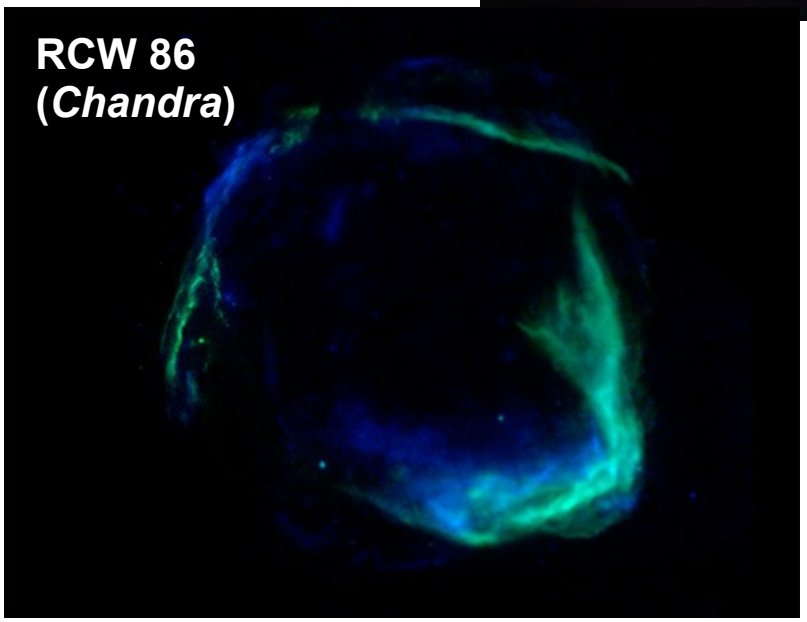
Blair+ 07 (Kepler)

The Dead Man's Tale

Carles Badenes
JHU 02/04/26

- **~15% (2/13) of SN Ia progenitors excavate large low ρ cavities**: SN1006, RCW 86.
- $v_{wind} \gtrsim 1000$ km/s [Vink+ 06, Badenes+ 07, Williams+ 11].
- Accretion winds from WD surface or accretion disk? [Hachisu+96].
- These two SNRs have spectra dominated by synchrotron emission.

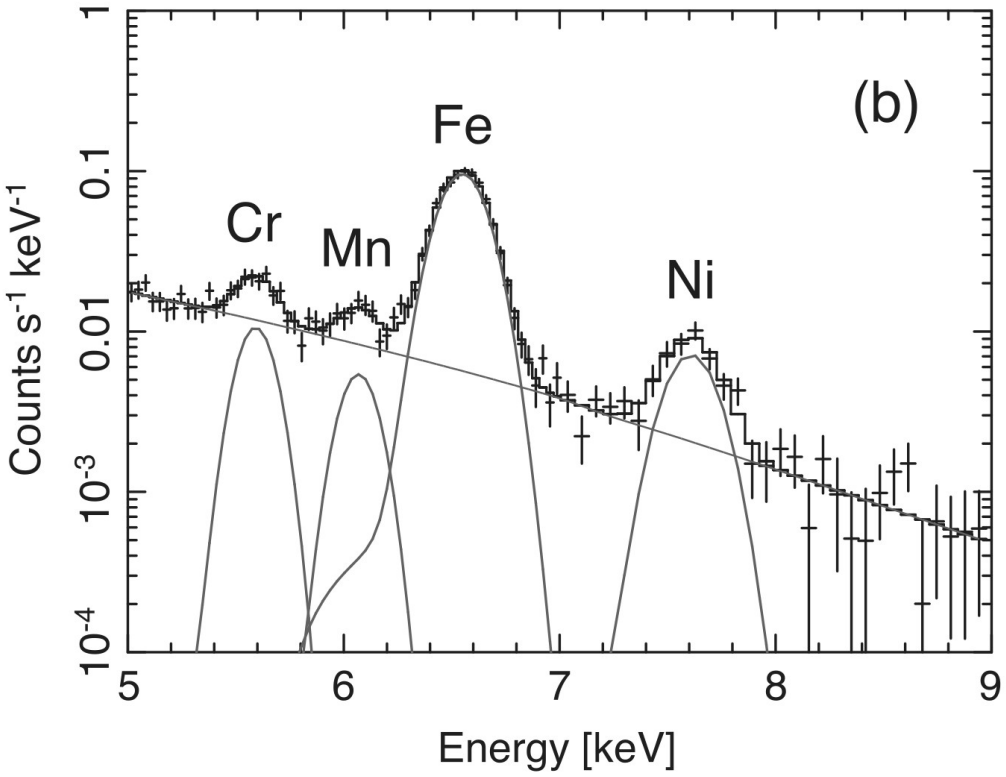




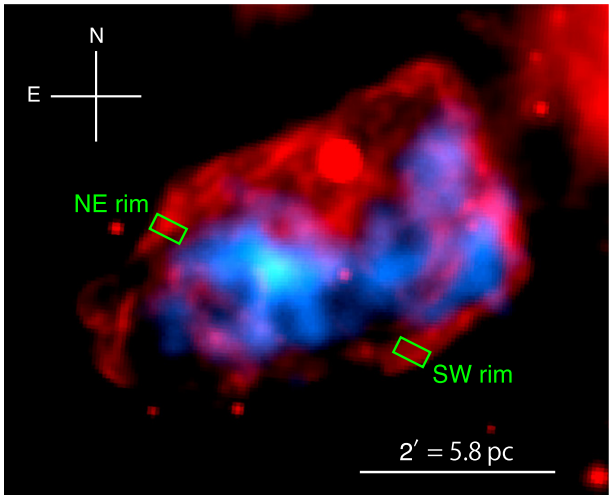
The Dead Man's Tale

Carles Badenes
JHU 02/04/26

- **~30% (4/13) of SN Ia progenitors have dense CSM**: N103B, 3C397, 0519, G337.
- dM/dt ≳ 10^{-6} $M_\odot$/yr, v_{wind} ~10 km/s.
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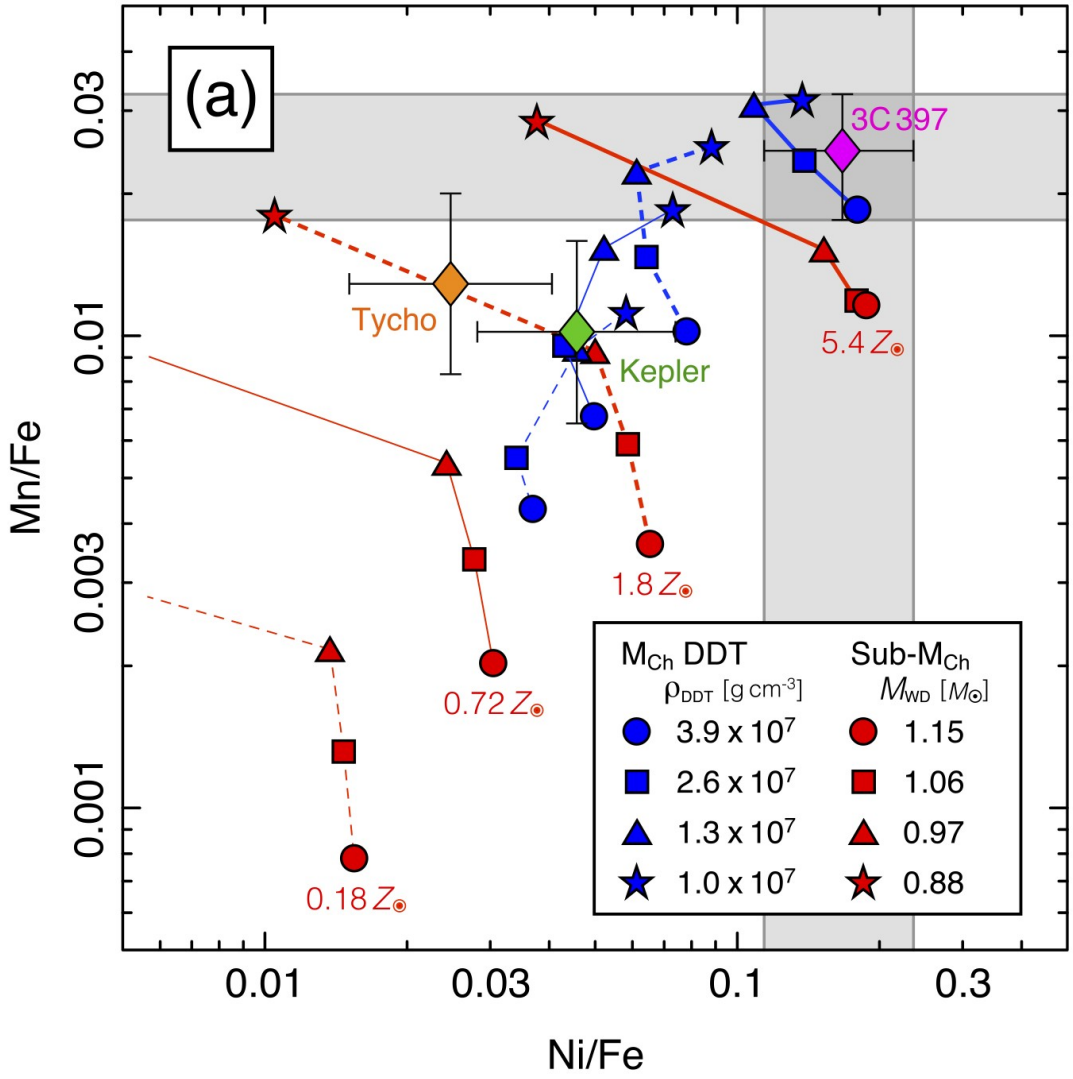
Yamaguchi+ 15
(3C 397)



The Dead Man's Tale

Carles Badenes
JHU 02/04/26

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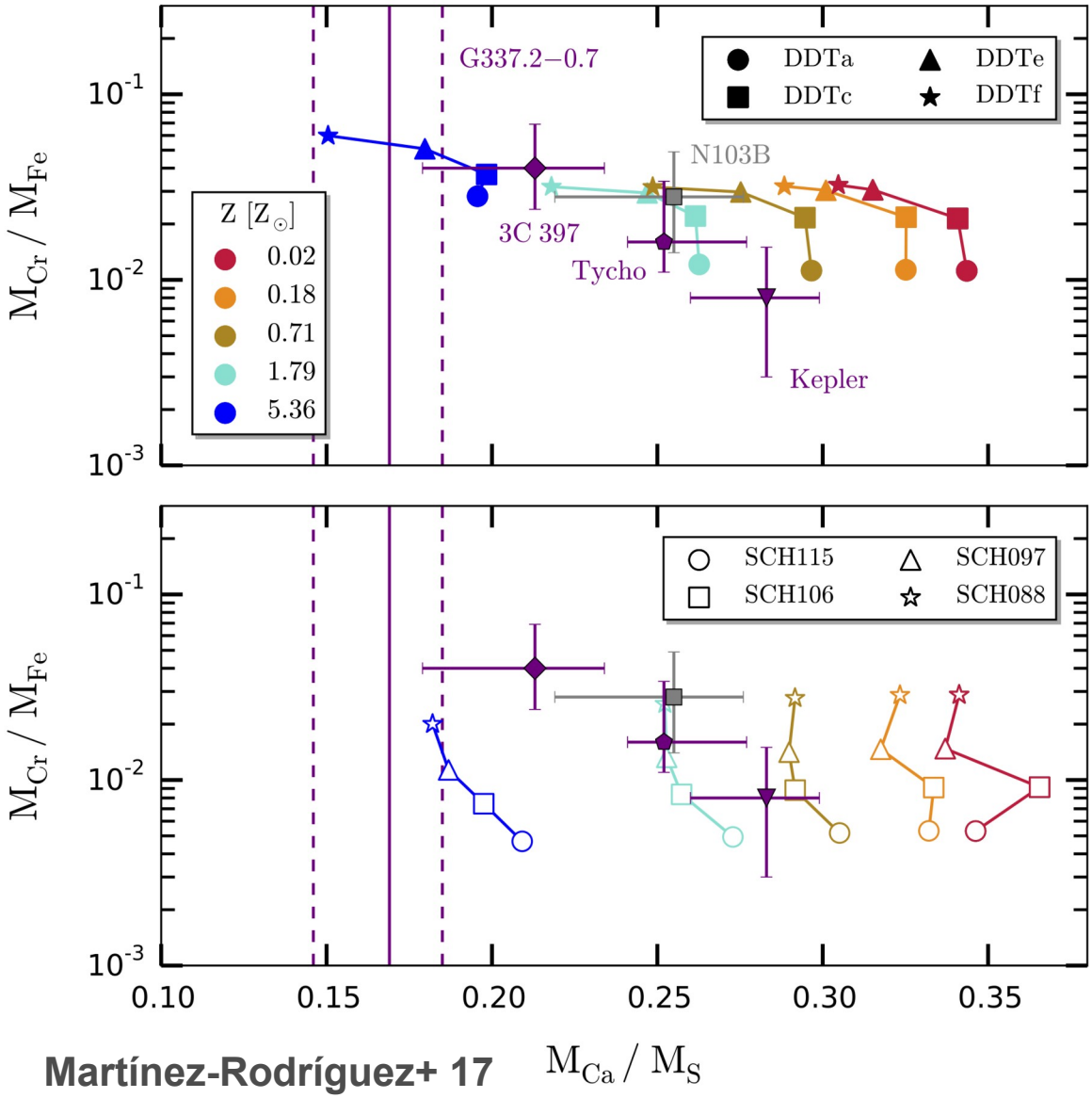


Yamaguchi+ 15
(3C 397)

The Dead Man's Tale

Carles Badenes
JHU 02/04/26

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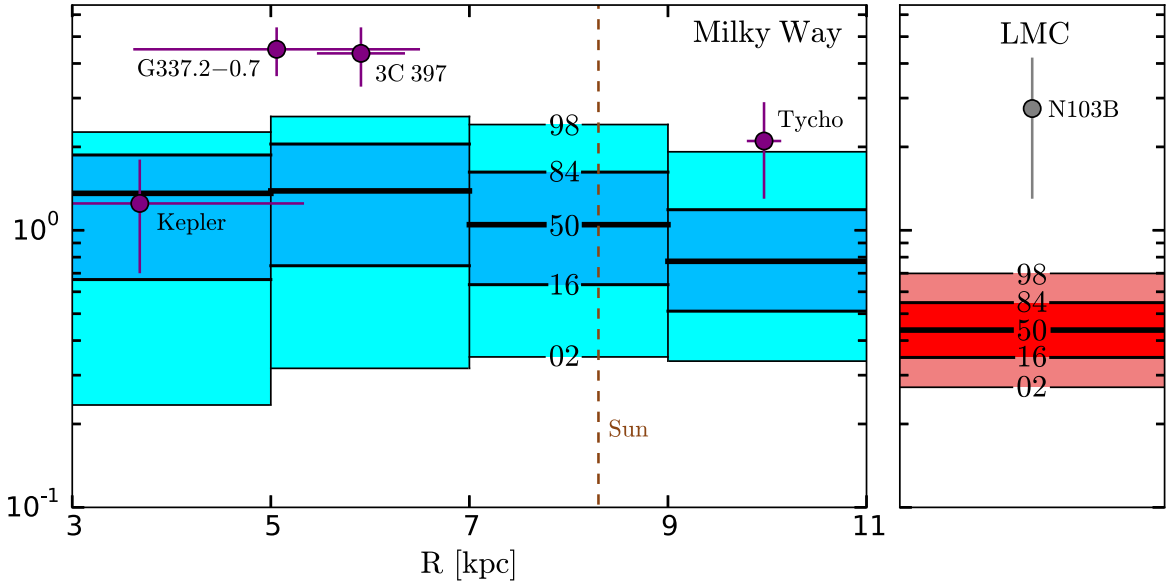


Martínez-Rodríguez+ 17

The Dead Man's Tale

Carles Badenes
JHU 02/04/26

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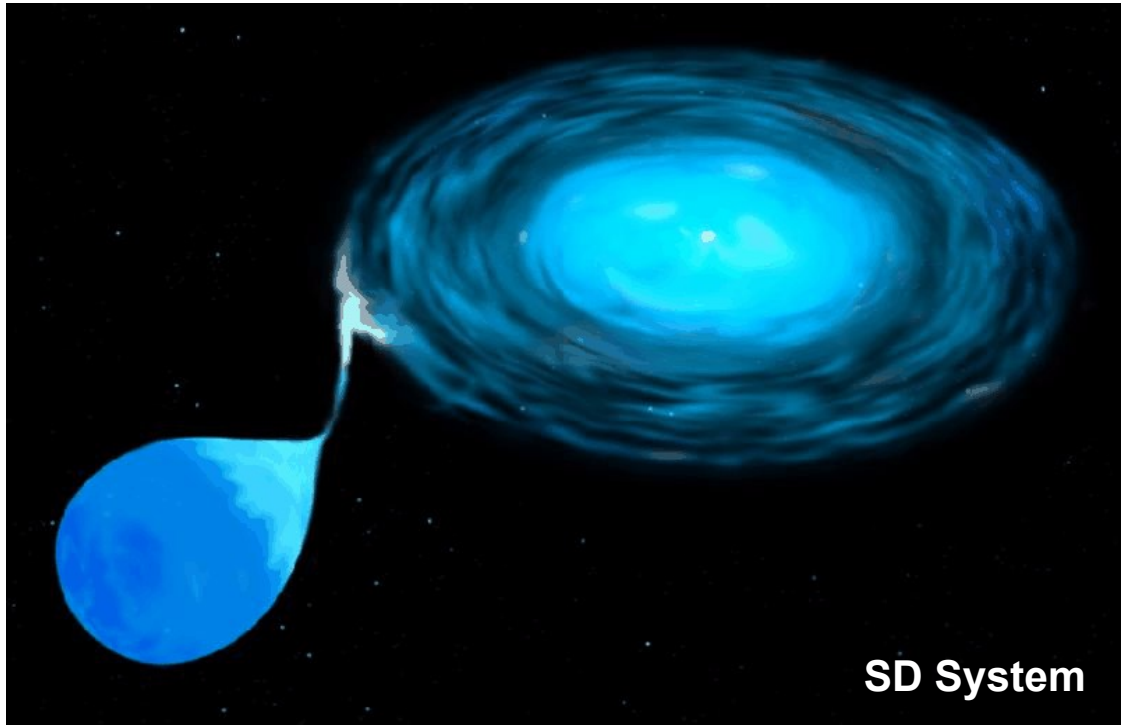


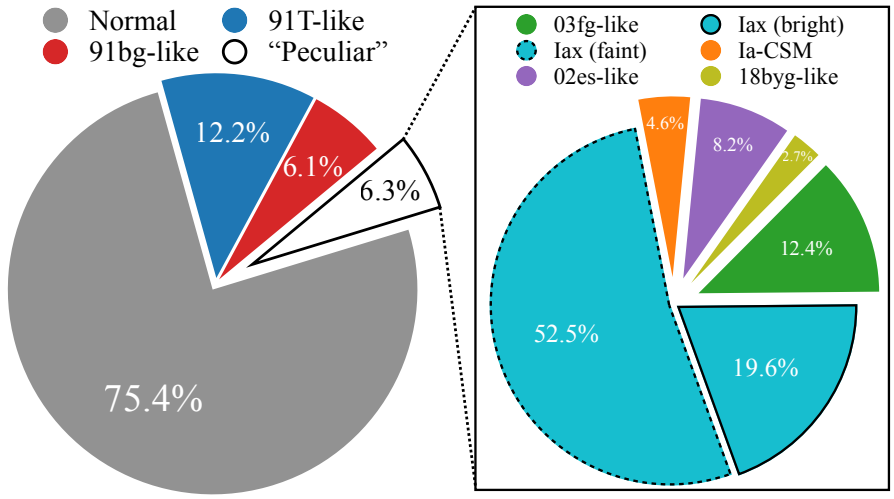
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The Dead Man's Tale

Carles Badenes
JHU 02/04/26

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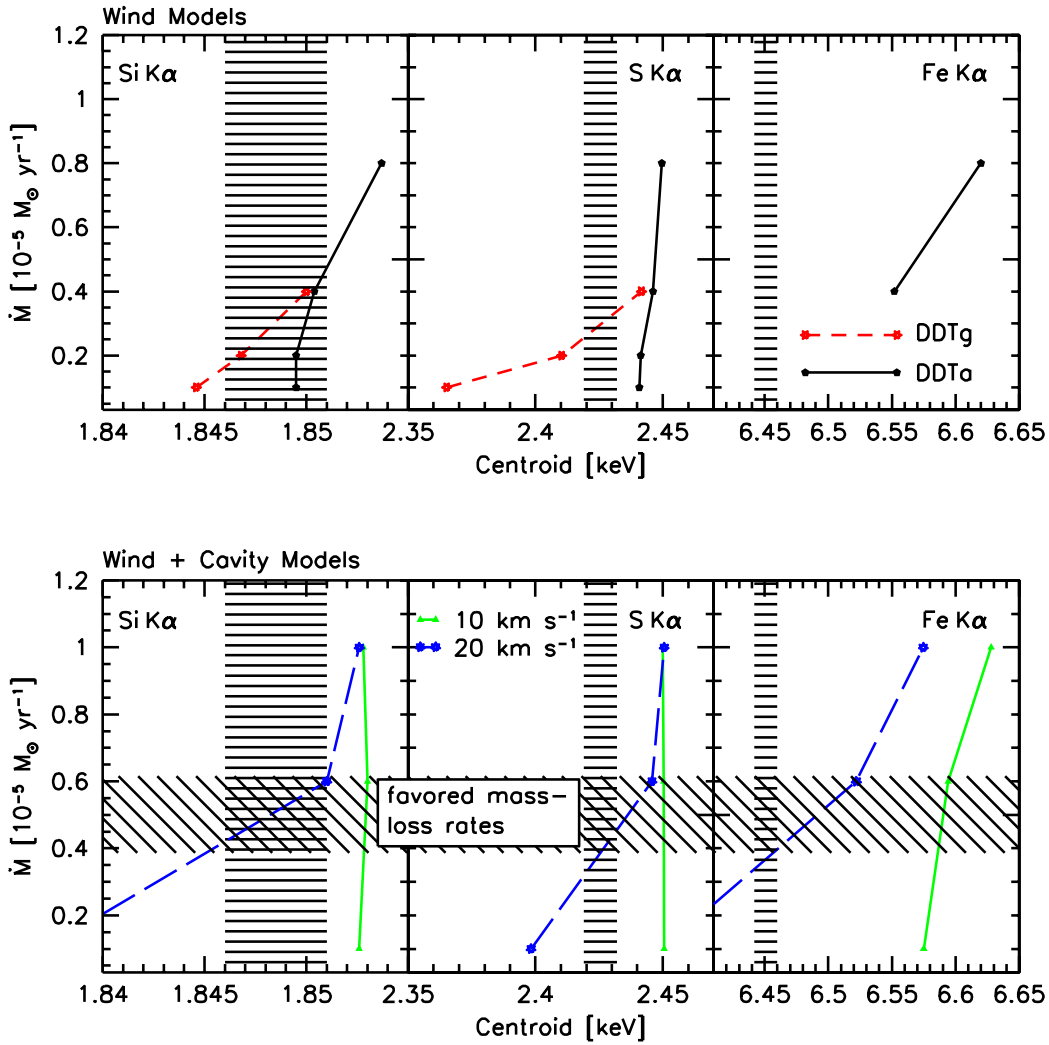


Dimitriadis+ 25 (ZTF)

The Dead Man's Tale

Carles Badenes
JHU 02/04/26

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- Small (~0.03 pc) **cavities** embedded in winds ⇒ Kepler [Patnaude+ 12]. Others?
- **Planetary Nebulae**: SN Ia after CEE [Kashi & Soker 11]. Too dense, but t_{Delay}~10^4 yr might work [Court+ 24] ⇒ 0519 [Schindelheim+ 24]. Others?
- The parameter space for progenitor mass loss is vast.
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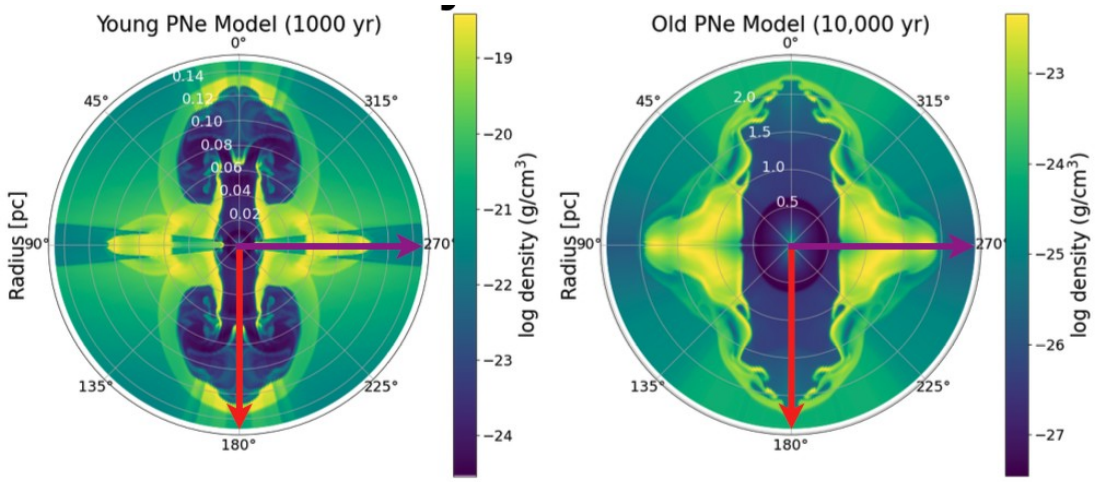


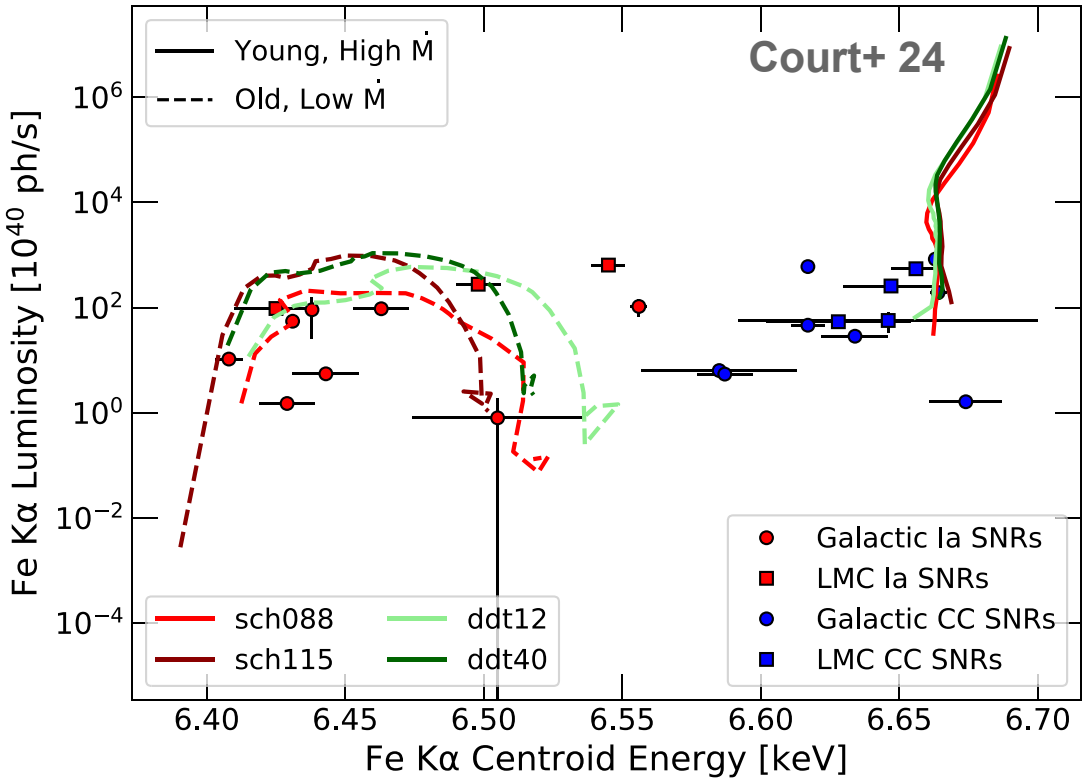
Patnaude+ 12 (Kepler)

The Dead Man's Tale

Carles Badenes
JHU 02/04/26

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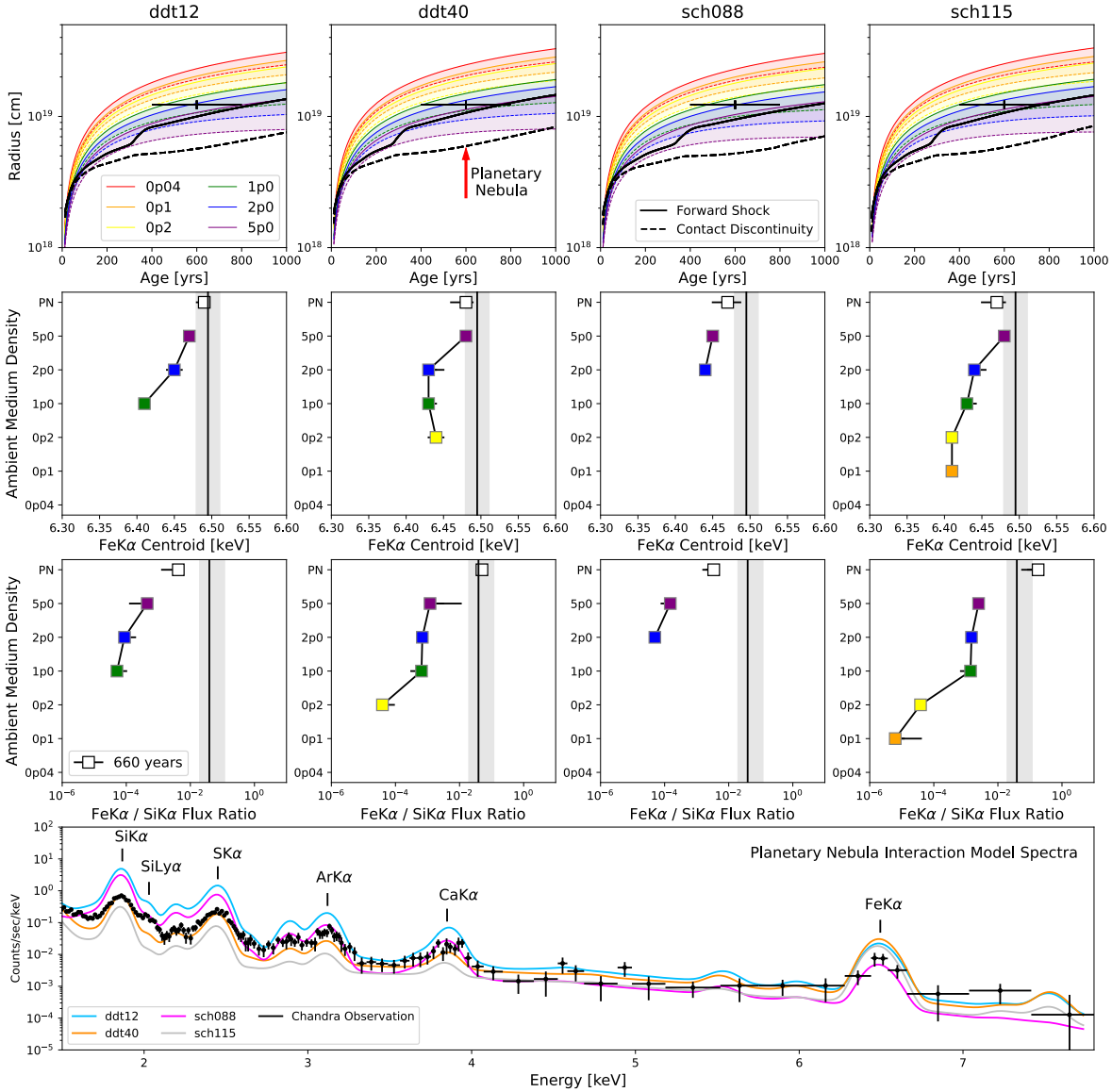




The Dead Man's Tale

Carles Badenes
JHU 02/04/26

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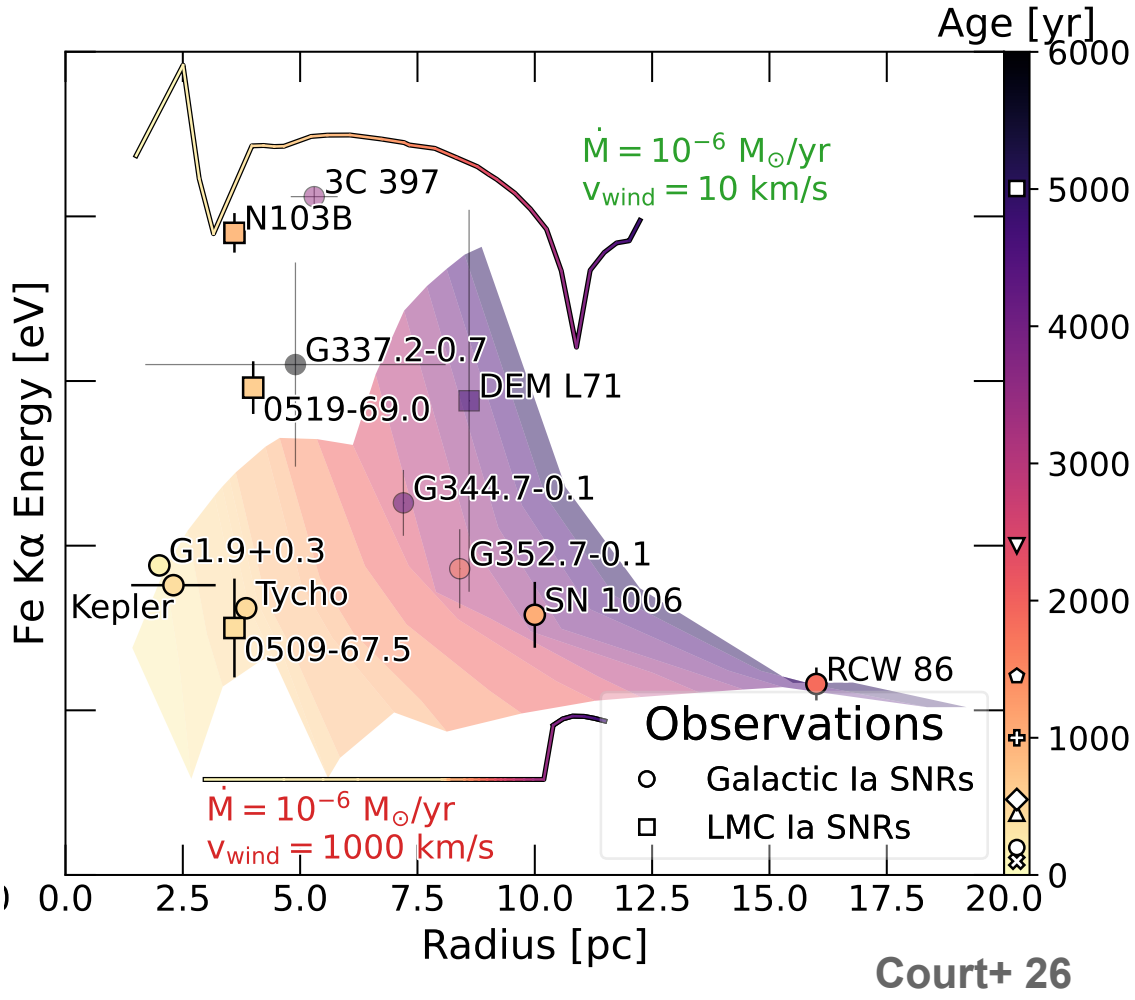


Schindelheim+ 24

The Dead Man's Tale

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Do Type Ia Supernovae Explode inside Planetary Nebulae?

Travis Court[1,2], Carles Badenes[1,2], Shiu-Hang Lee[3], Daniel Patnaude[4], Guillermo García-Segura[5], and Eduardo Bravo[6]
[1] Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara Street, Pittsburgh, PA 15260, USA
[2] Pittsburgh Particle Physics, Astrophysics, and Cosmology Center (PITT PACC), University of Pittsburgh, Pittsburgh, PA 15260, USA
[3] Department of Astronomy, Kyoto University Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan
[4] Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA
[5] Instituto de Astronomía, Universidad Nacional Autónoma de México, Km. 107 Carr. Tijuana-Ensenada, 22860, Ensenada, B.C., Mexico
[6] Departamento de Física Teórica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain
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A Classification Scheme for X-Ray-bright Type Ia Supernova Remnants Based on Their Circumstellar Interaction

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Conclusions

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- X-ray bright SNRs probe the AM of SN progenitors to ~pc scales.

- SN Ia: multiple progenitor channels.

- Many (most?) SN Ia progenitors do not strongly modify their AM ⇒ no dense CSM, no large cavities. This includes normal SN Ia (Tycho) and luminous 91T-like SN Ia (0509 ⇒ double detonation?).

- A few SN Ia explode in large low-density cavities excavated by fast, sustained progenitor outflows.

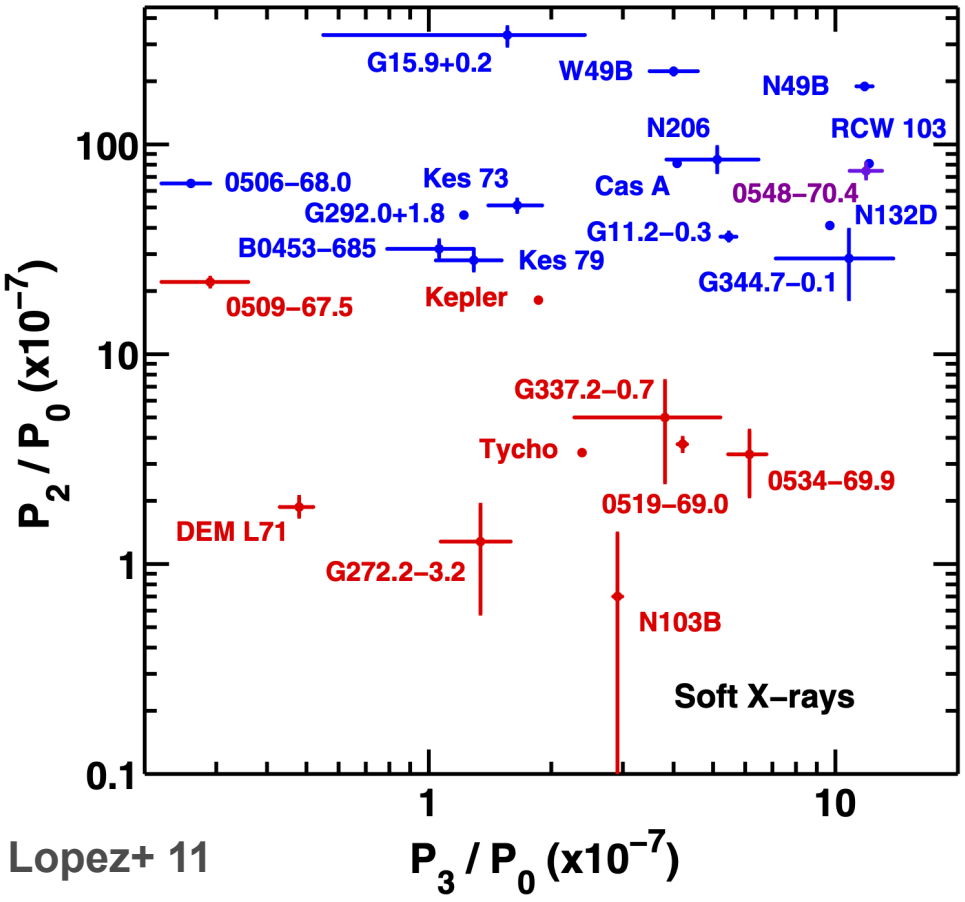
- Some SN Ia interact with dense CSM. This includes likely near-M_{Ch} explosions (3C397, N103B, G337) in younger stellar populations (N103B). SD systems? Post-CE cocoons? SN Ia-CSM?

- Implications for binary evolution of SN Ia progenitors.

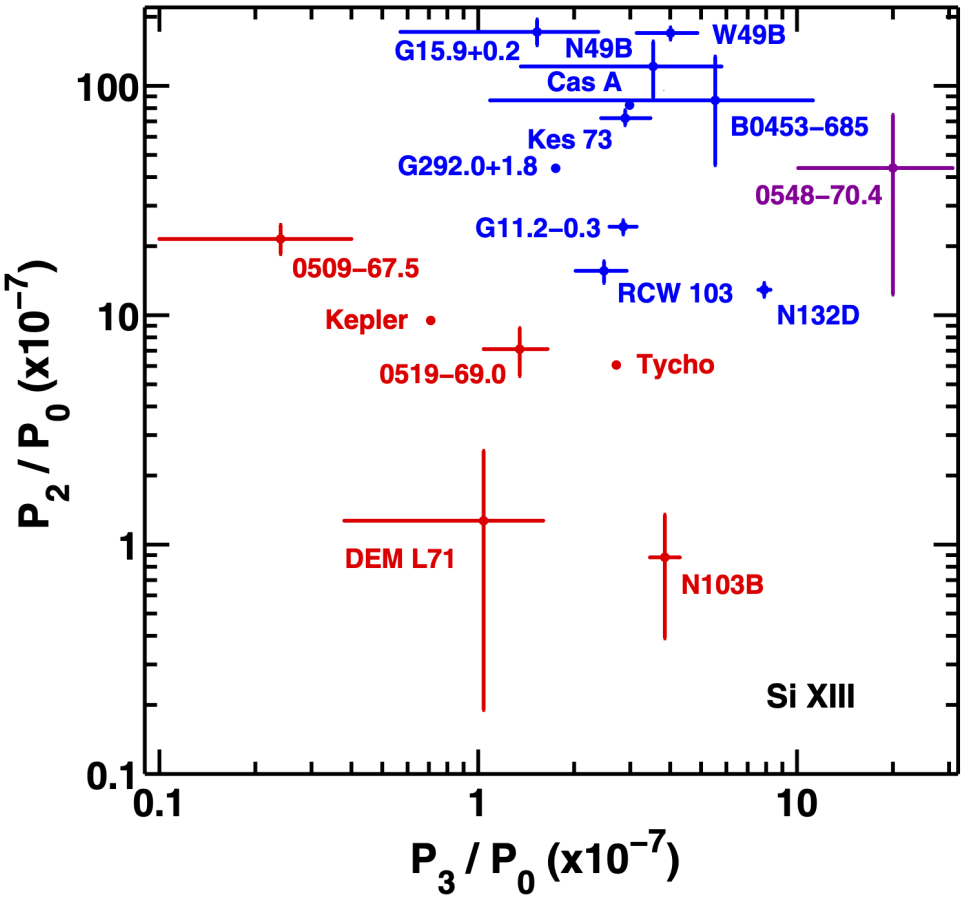
The Way Forward

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- As you all know, SNe (and SNRs!) are not 1D objects.



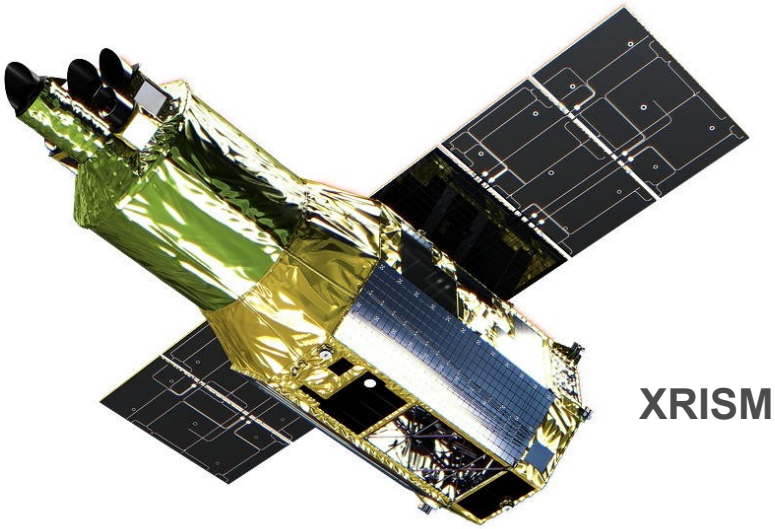
Lopez+ 11



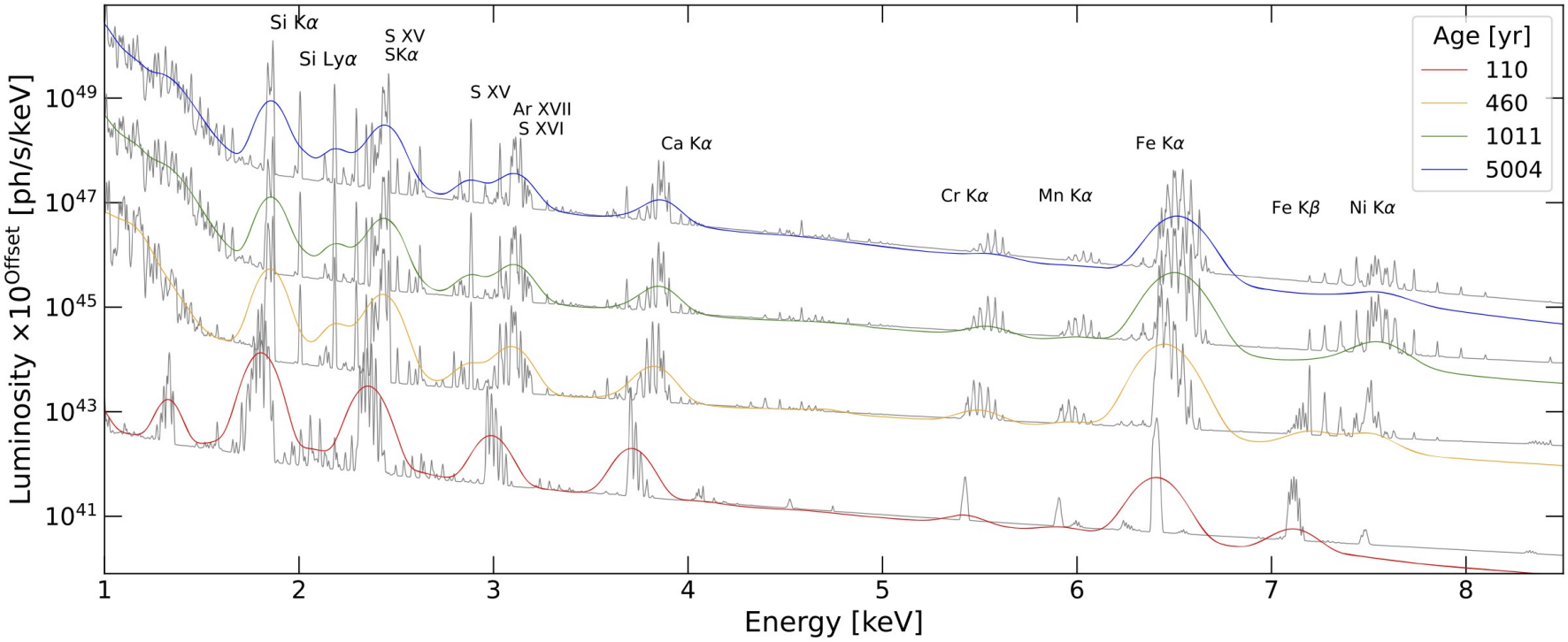
The Way Forward

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- **XRISM** will help! Superb spectral resolution ⇒ kinematics.



XRISM

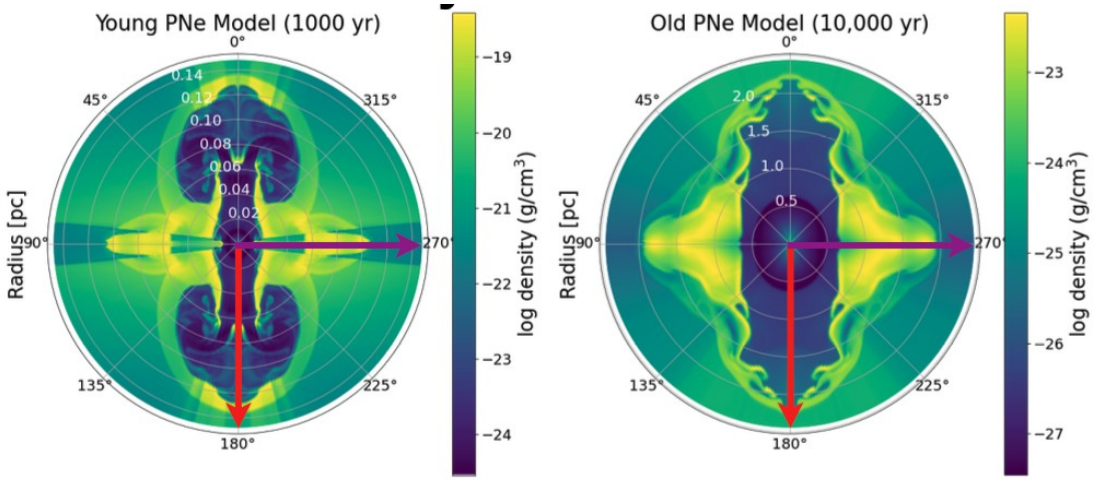


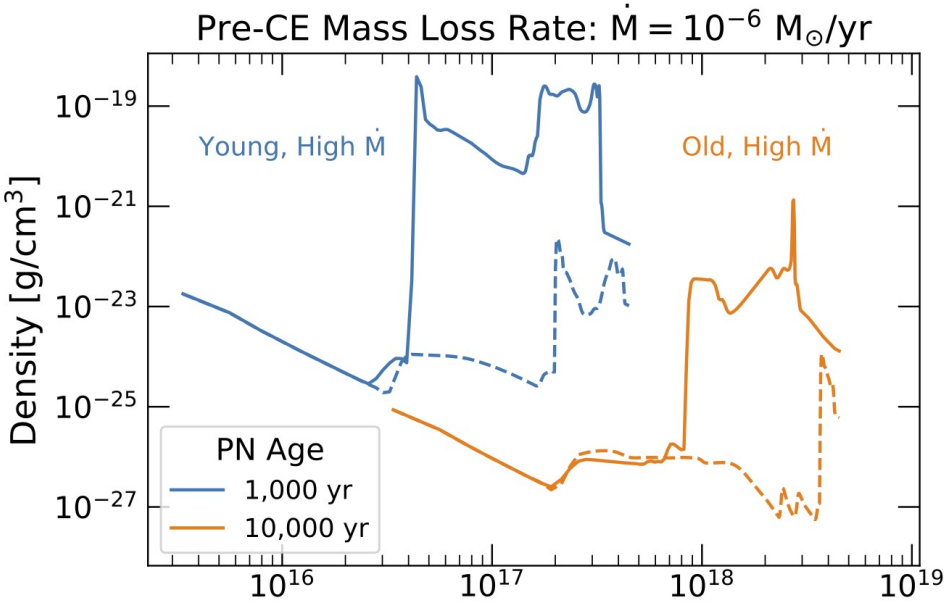
Court+ 23

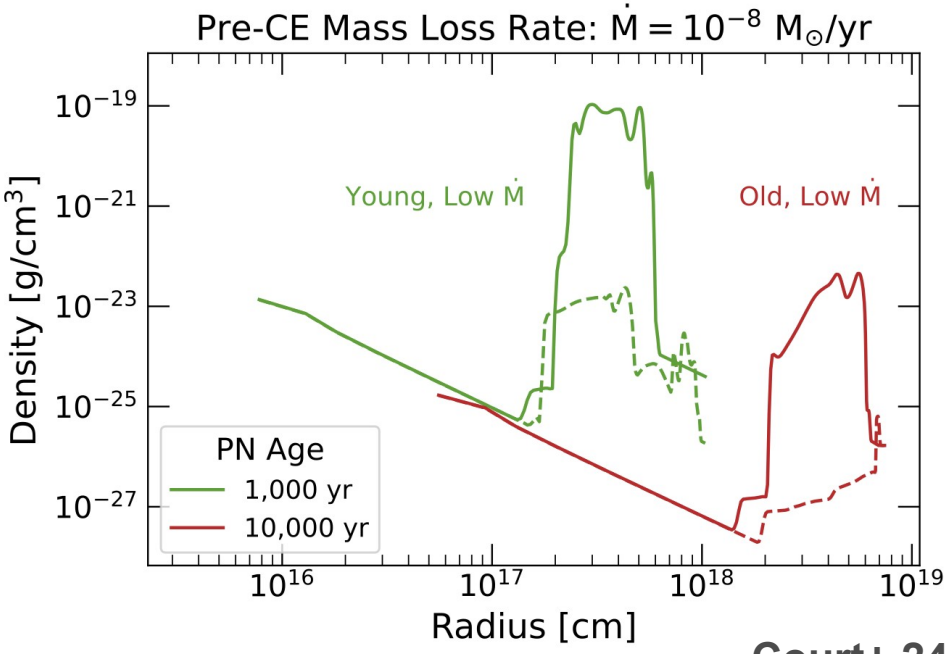
Models: SNIPs

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- **SN Ia inside a post-CE cocoon** (PN) [Kashi & Soker 11] ⇒ evolve SNR inside PN models [García-Segura+ 18].
- Equatorial/Polar profiles bracket AM interaction (EM$\propto\rho^2$ favors eq.)
- In most cases, **$n_e t$ is too high**, unless the delay between CE episode and SN is ≳ 10,000 yr [Court+ 24]. Good match to SNR 0519-69.0.



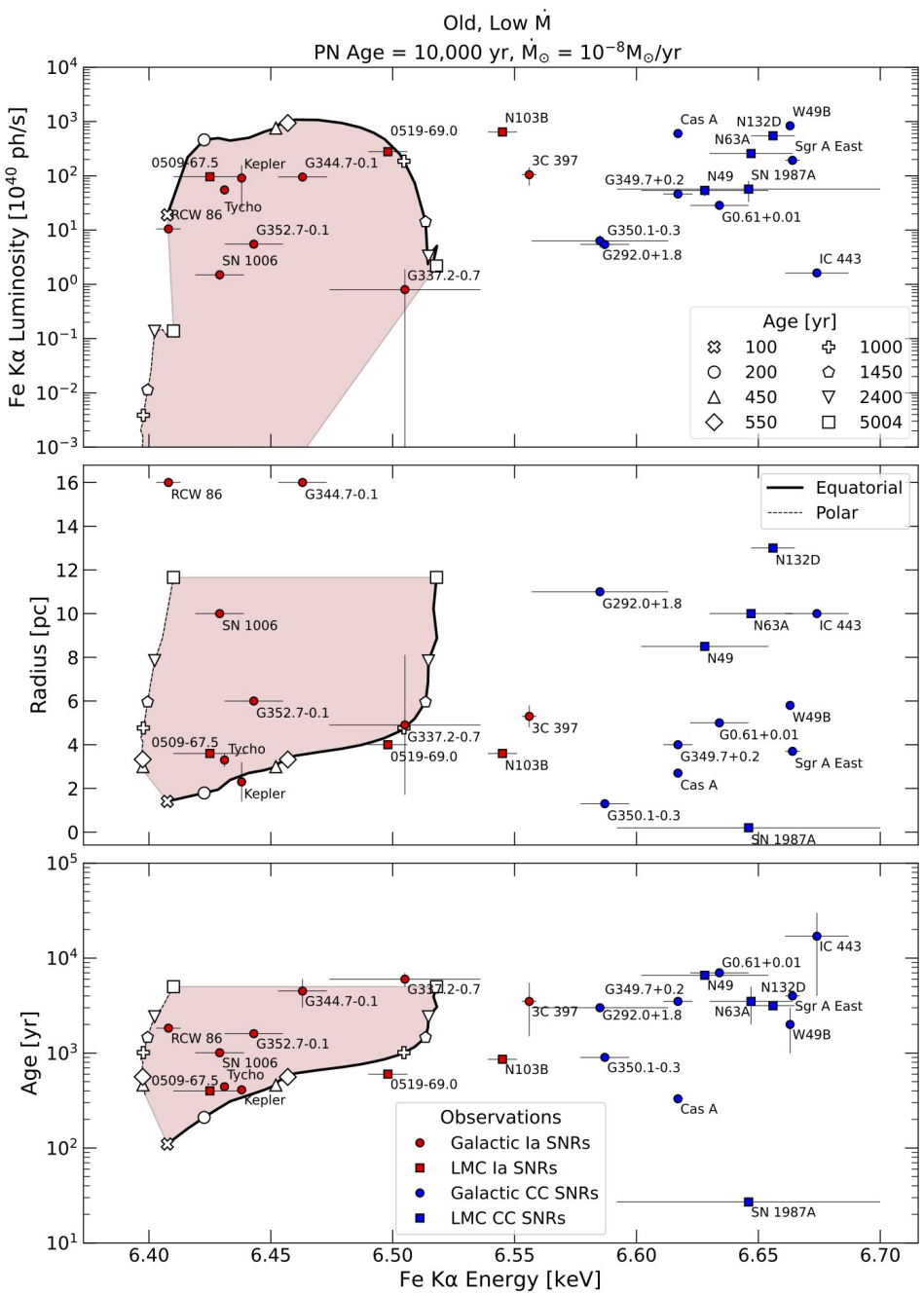


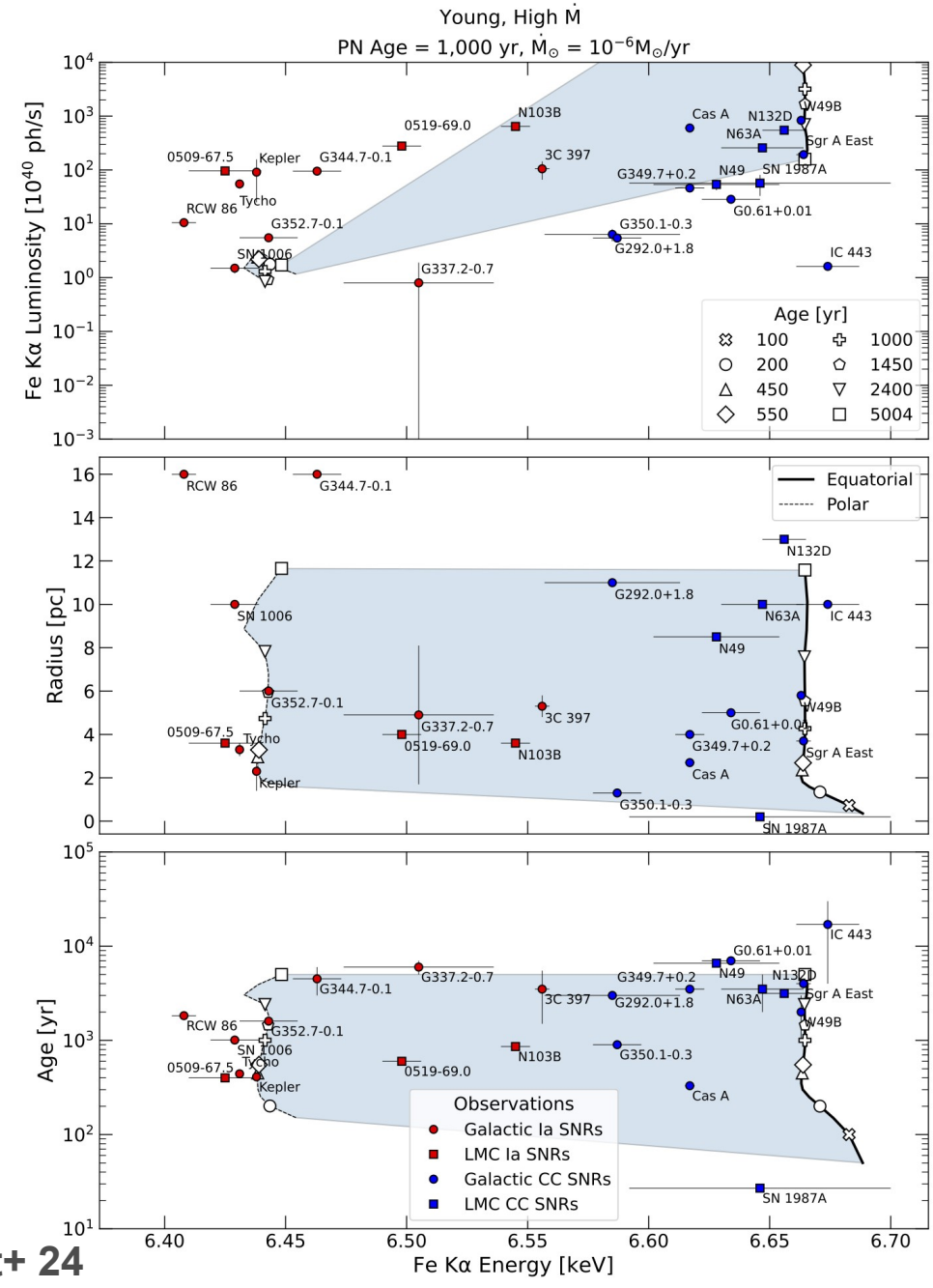


Court+ 24

Models: SNIPs

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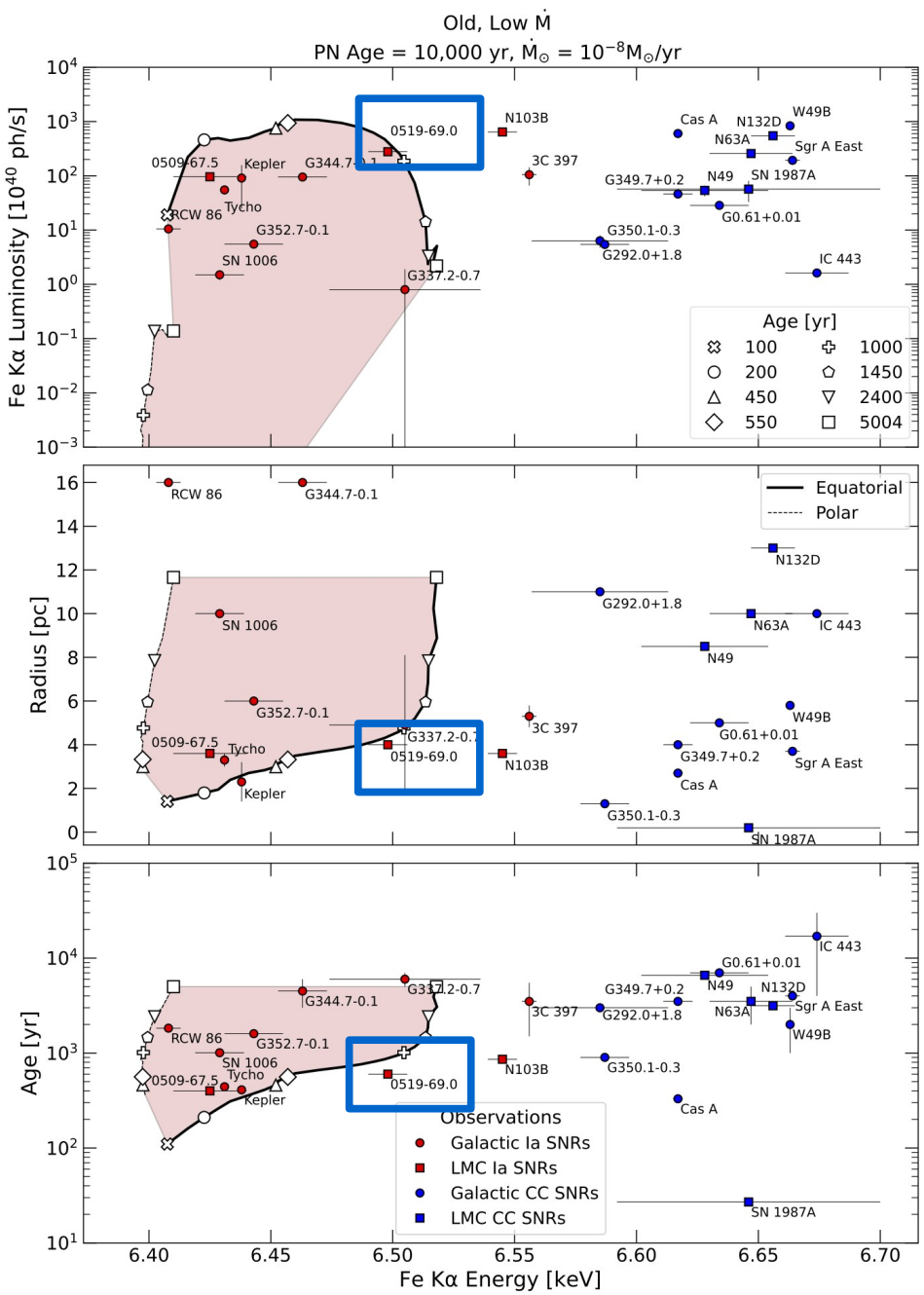


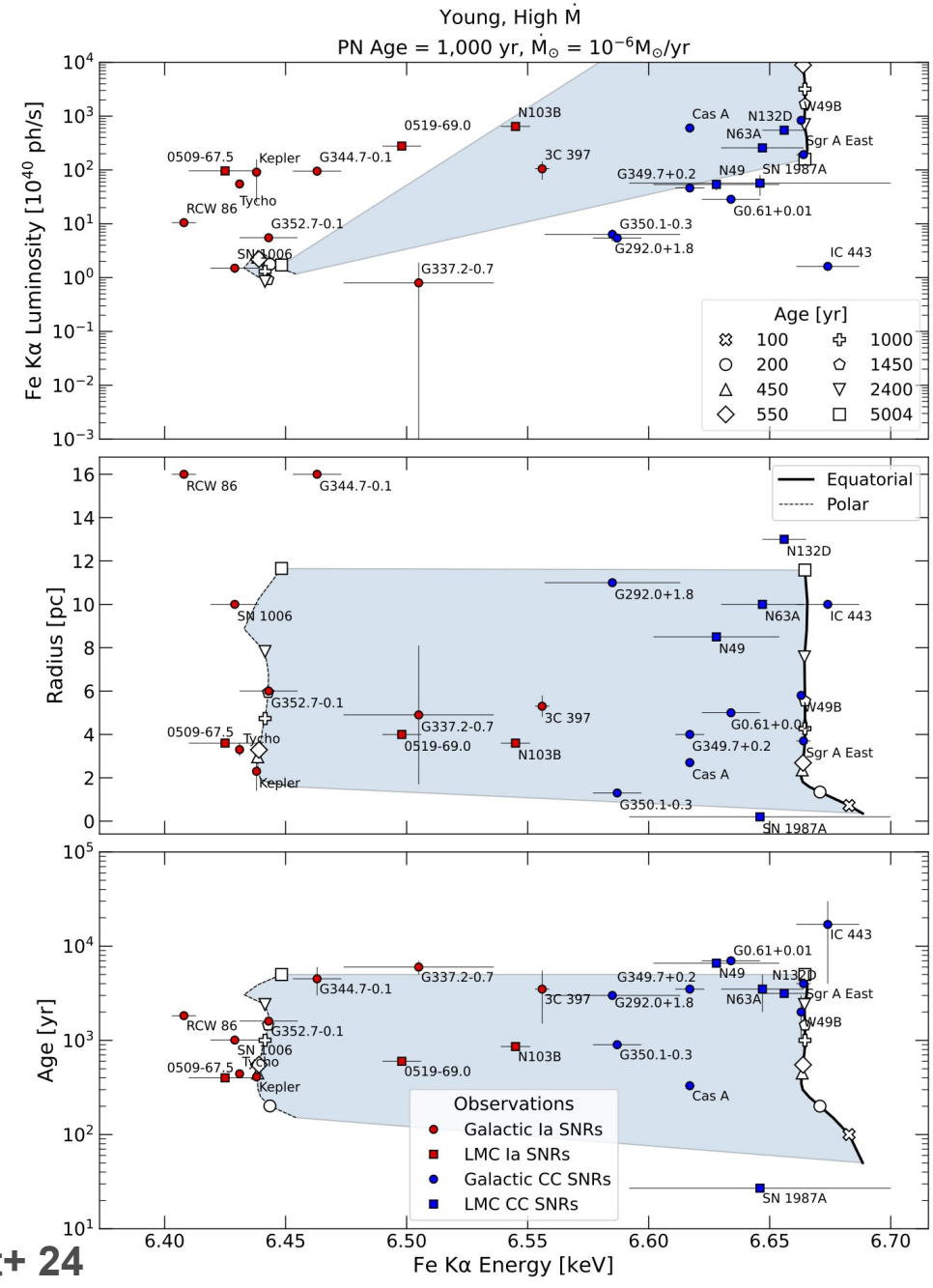


Court+ 24

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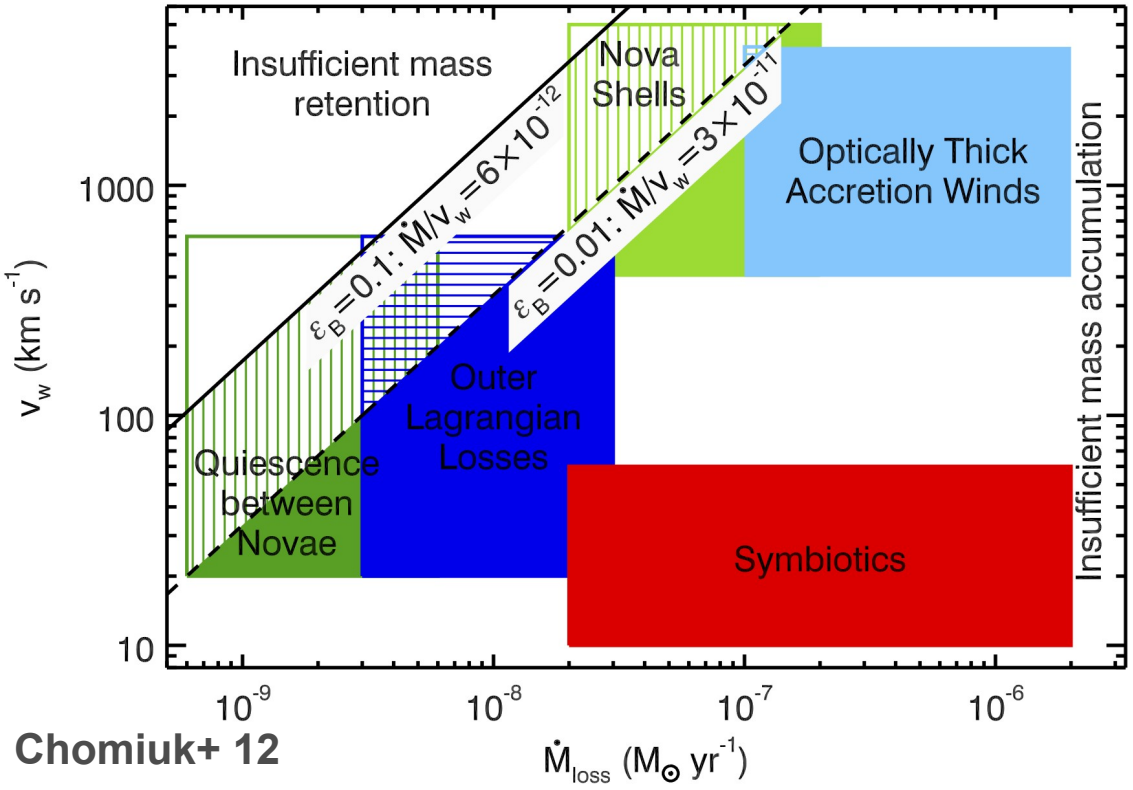


Court+ 24

AM Interaction in SNRs

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- **Pre-SN mass loss** (dM/dt, v_w): fast and slow outflows. Sustained fast outflows ⇒ large energy-driven cavities. Slow outflows ⇒ dense CSM [Koo & McKee 92a,b, Badenes+ 07, Patnaude & Badenes 17].
- **Episodic outflows** ⇒ shells [Wood-Vasey & Sokoloski 06, Darnley+ 19].
- **Common Envelope** cocoon + ionization ⇒ PN [Kashi & Soker 11; Ilkov & Soker 12; Tsebrenko & Soker 13,15; García-Segura+ 18, Court+ 24].



Chomiuk+ 12

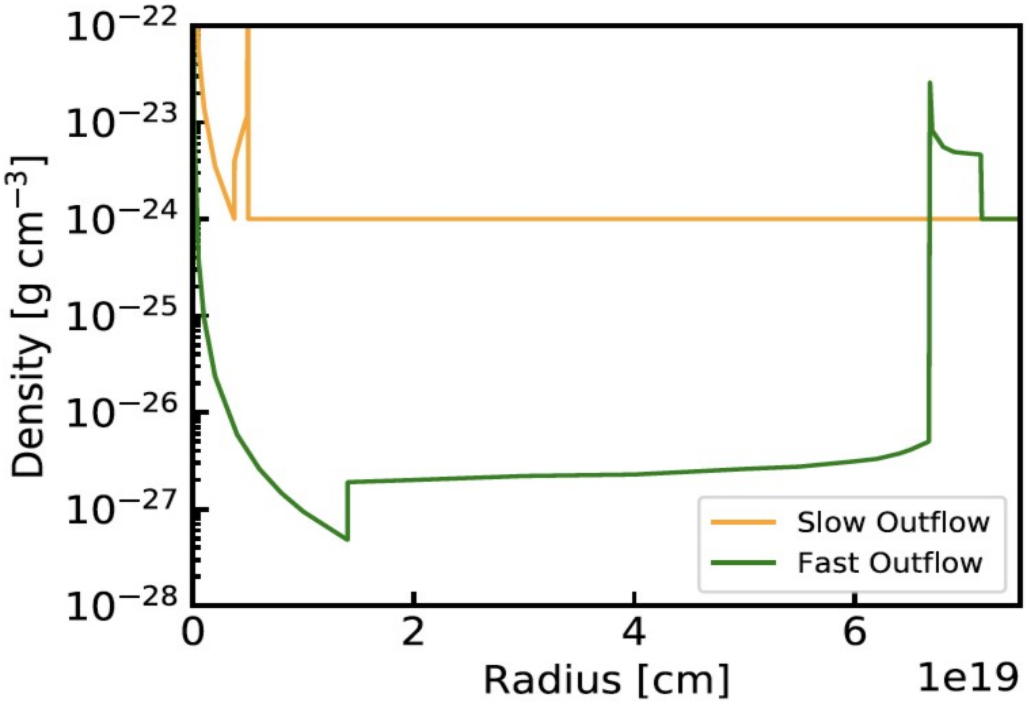
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References: Seaquist & Taylor 90; Patat+ 18; Chen+ 11; Deufel+ 99; Williams+ 08; Huang & Yu 96; Hachisu+ 96, 99; Cowley+ 98; Murray 02; Wood-Vasey & Sokoloski 06; Darnley+ 19 ...

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Badenes+ 07

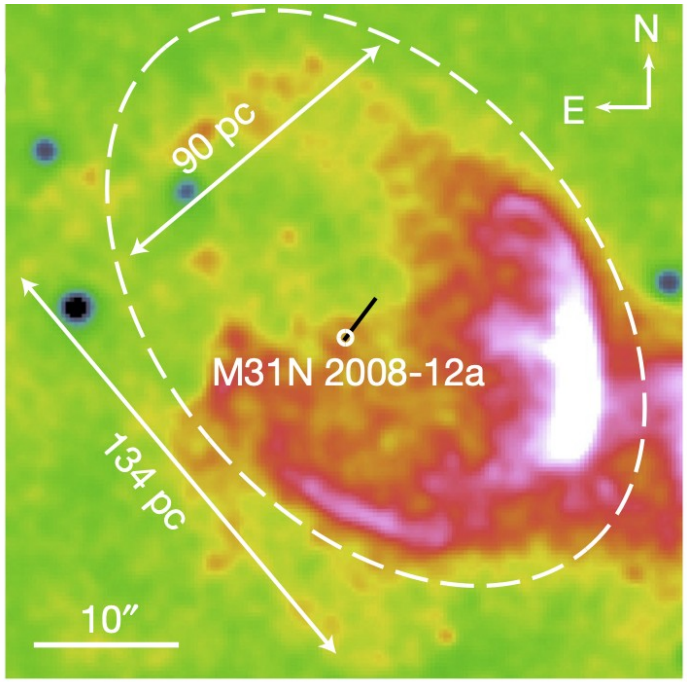
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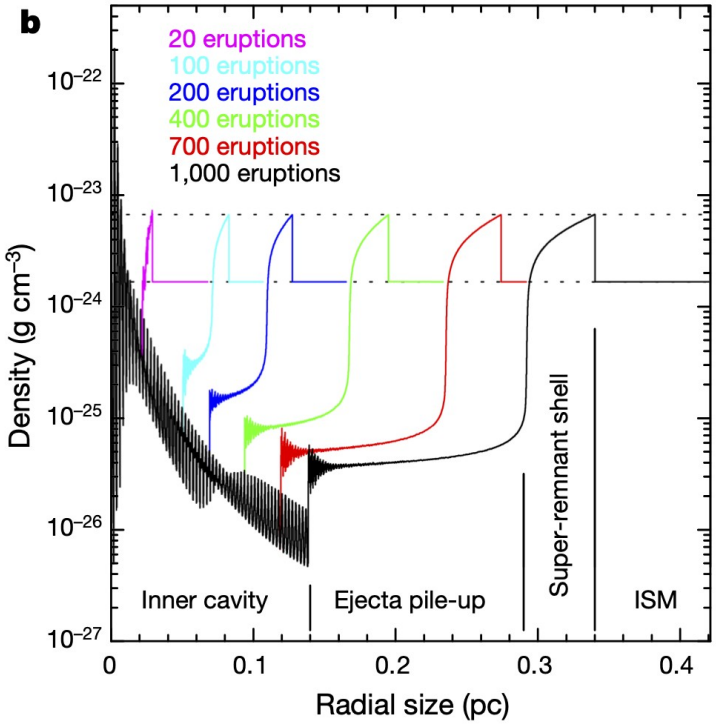
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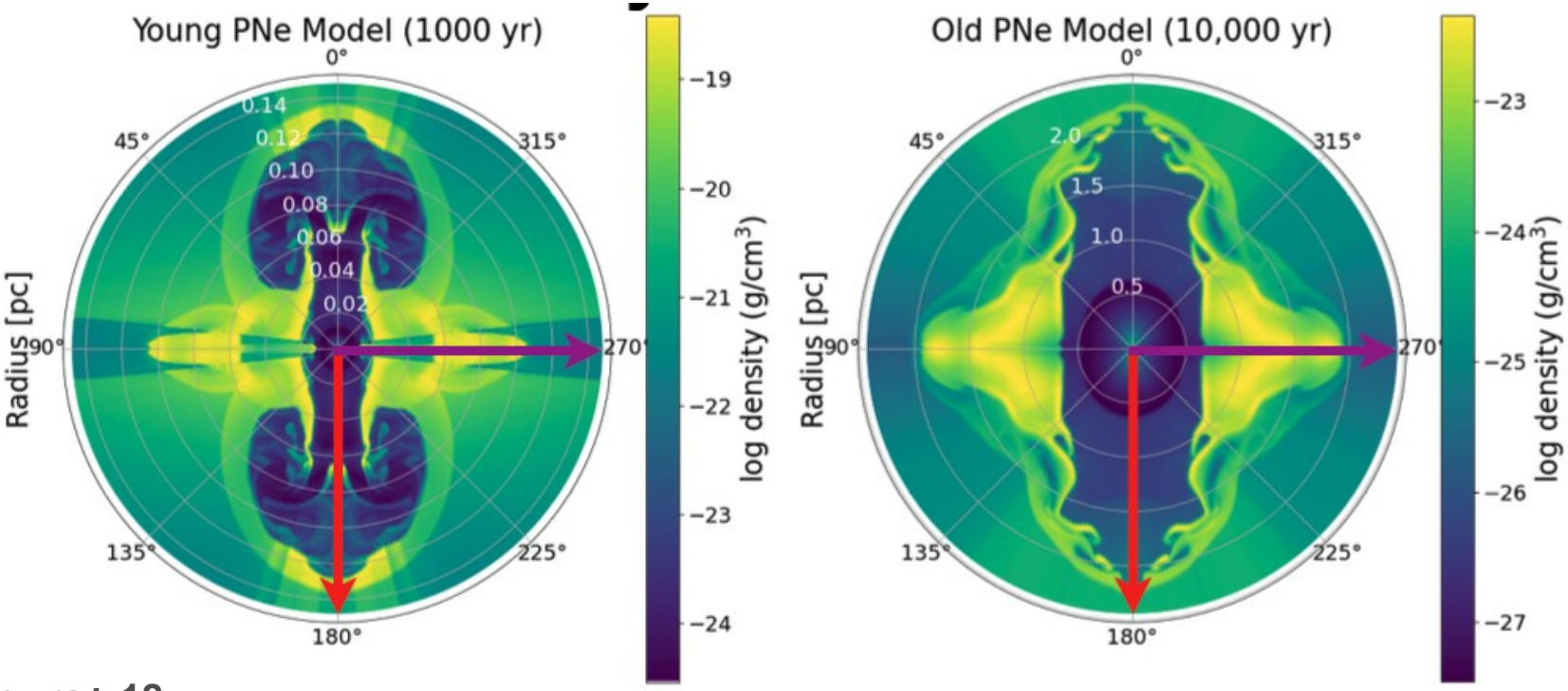


Darnley+ 19

AM Interaction in SNRs

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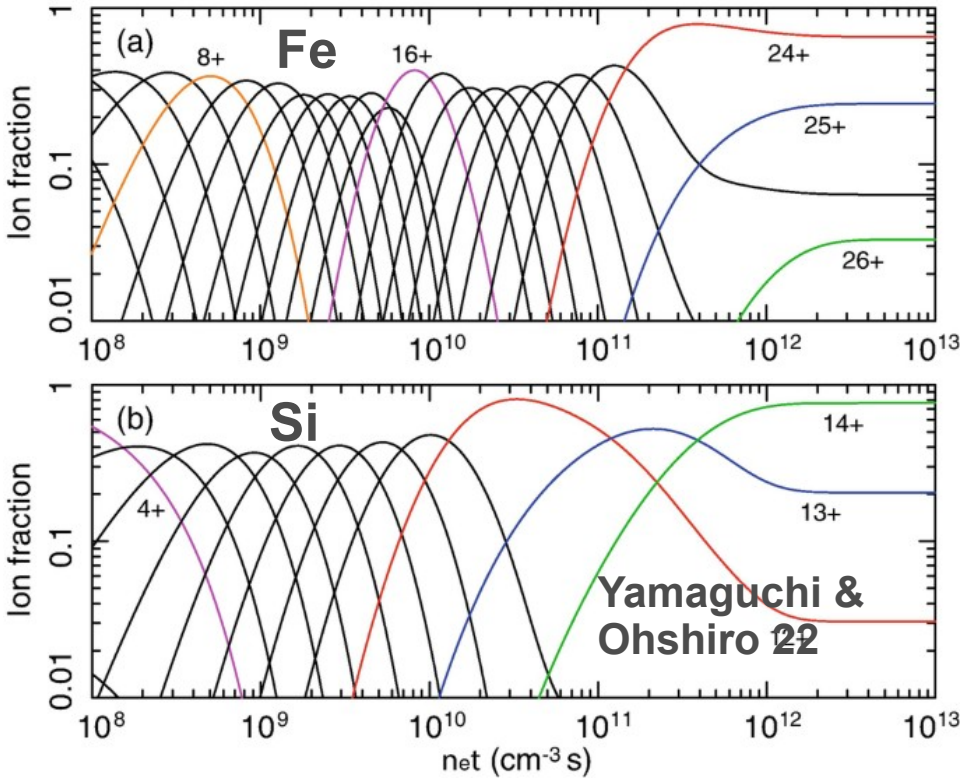


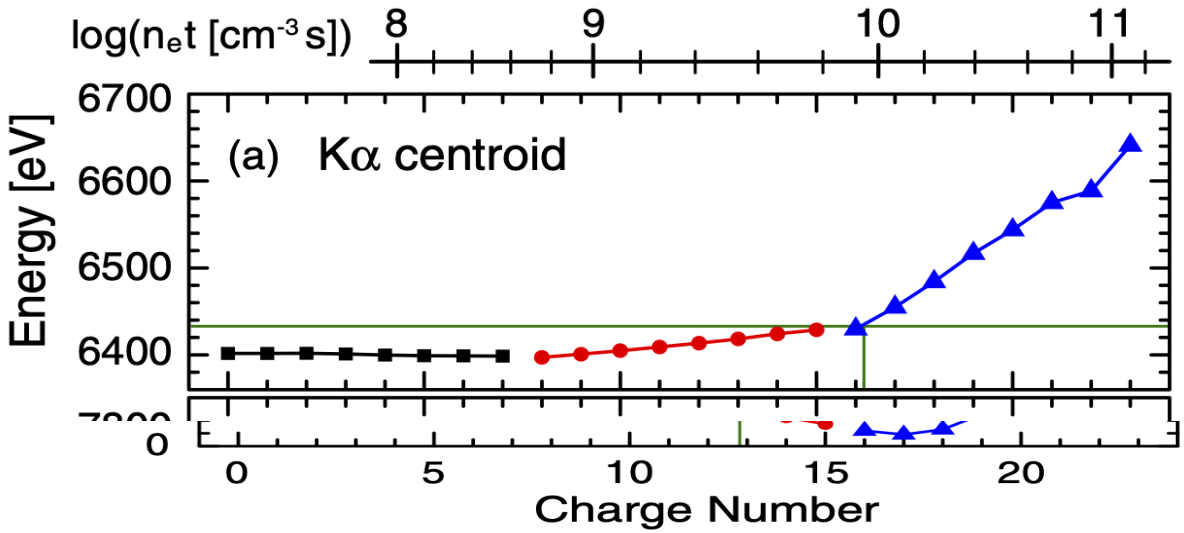
Garcia-Segura+ 18

AM Interaction and SNR spectra

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- **X-ray spectra of SNRs ⇔ AM structure.** NEI plasma: ionization timescale (**$n_e t$**).
- **Dense AM ⇒ high $n_e t$ ⇒ high centroid energies and line fluxes.**
- **Fe Kα line blend** at ~6.5 keV as an AM density diagnostic ⇒ large $n_e t$ to fully ionize Fe ⇒ **large dynamic range in ρ_{AM}**.
- Details: Yamaguchi+ 14b, Patnaude & Badenes 17, Martínez-Rodríguez+ 18, Court+ 24.

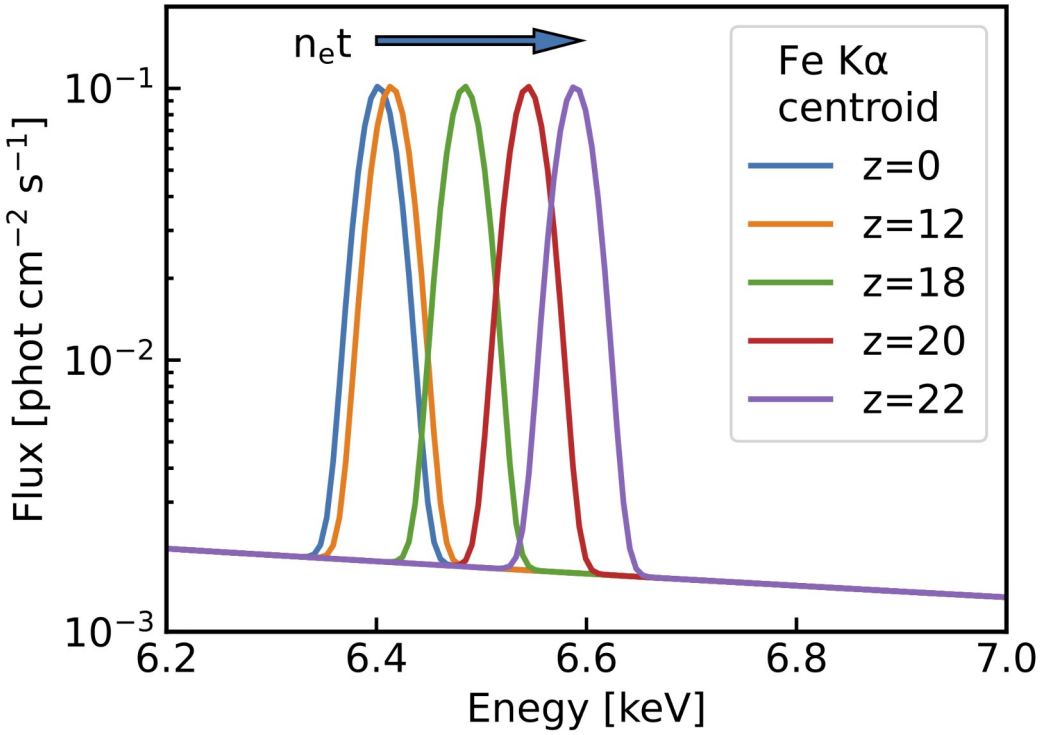


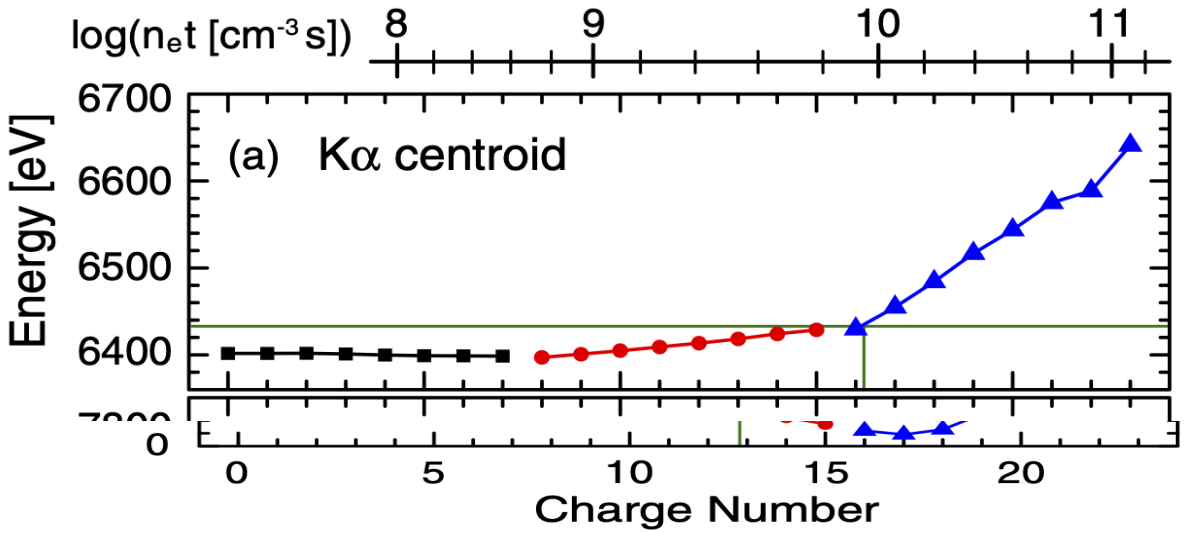


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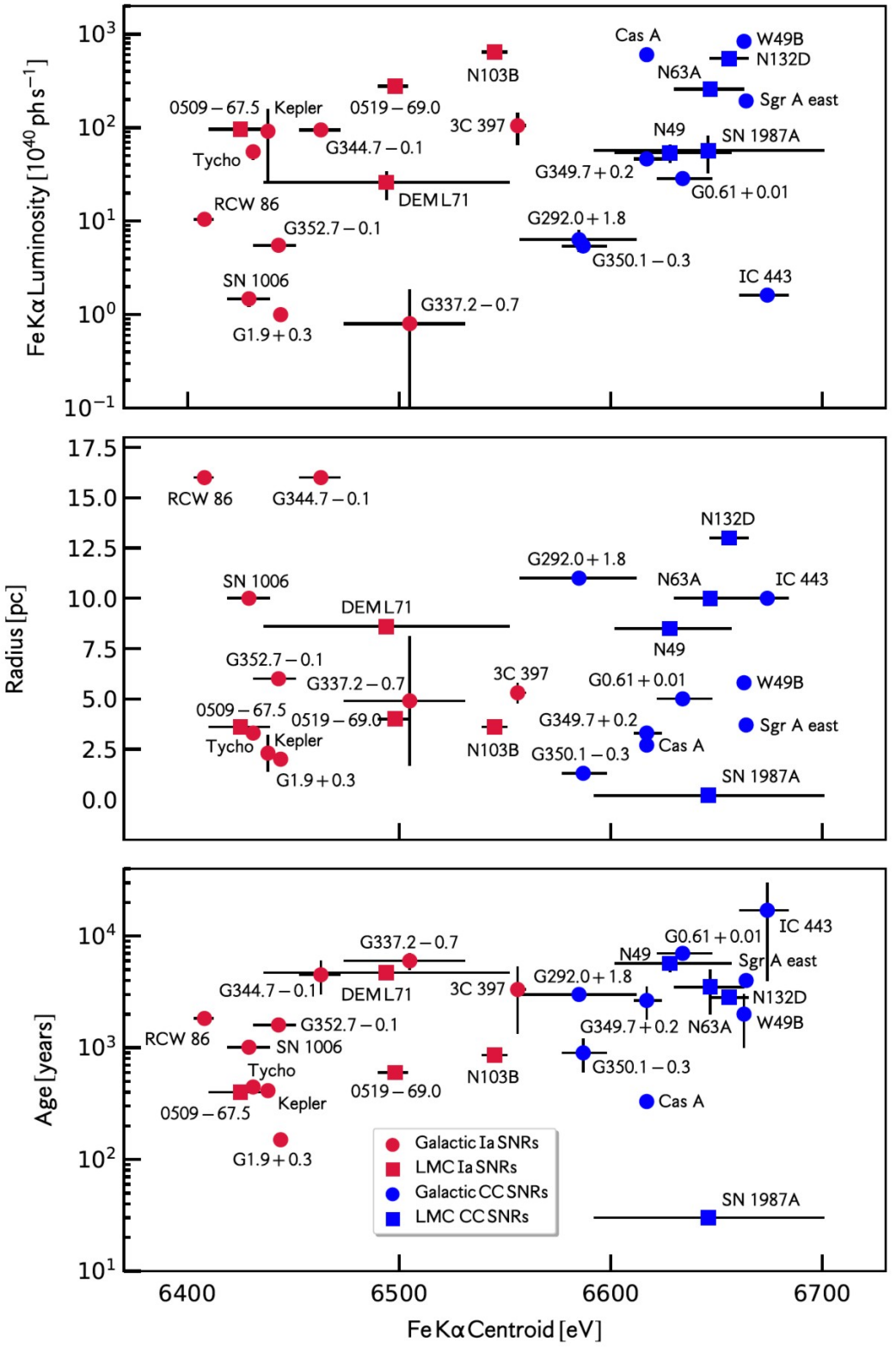
SNRs in Bulk

- **25 MW & LMC SNRs** with good Fe Kα centroids (*Chandra, Suzaku, XMM*) [Yamaguchi+ 14, Borkowski+ 13, Maggi+ 16, M-R+ 18, Siegel+ 21].

- **Bulk properties:** Fe Kα centroid, Fe Kα luminosity, radius, age.

- **Typing:** a few secure cases (SNe, LEs, NSs), many likely ones (X-ray spectra).

- **A pattern emerges**: Ia SNRs below ~6.55 keV, CC SNRs above [Yamaguchi+ 14].



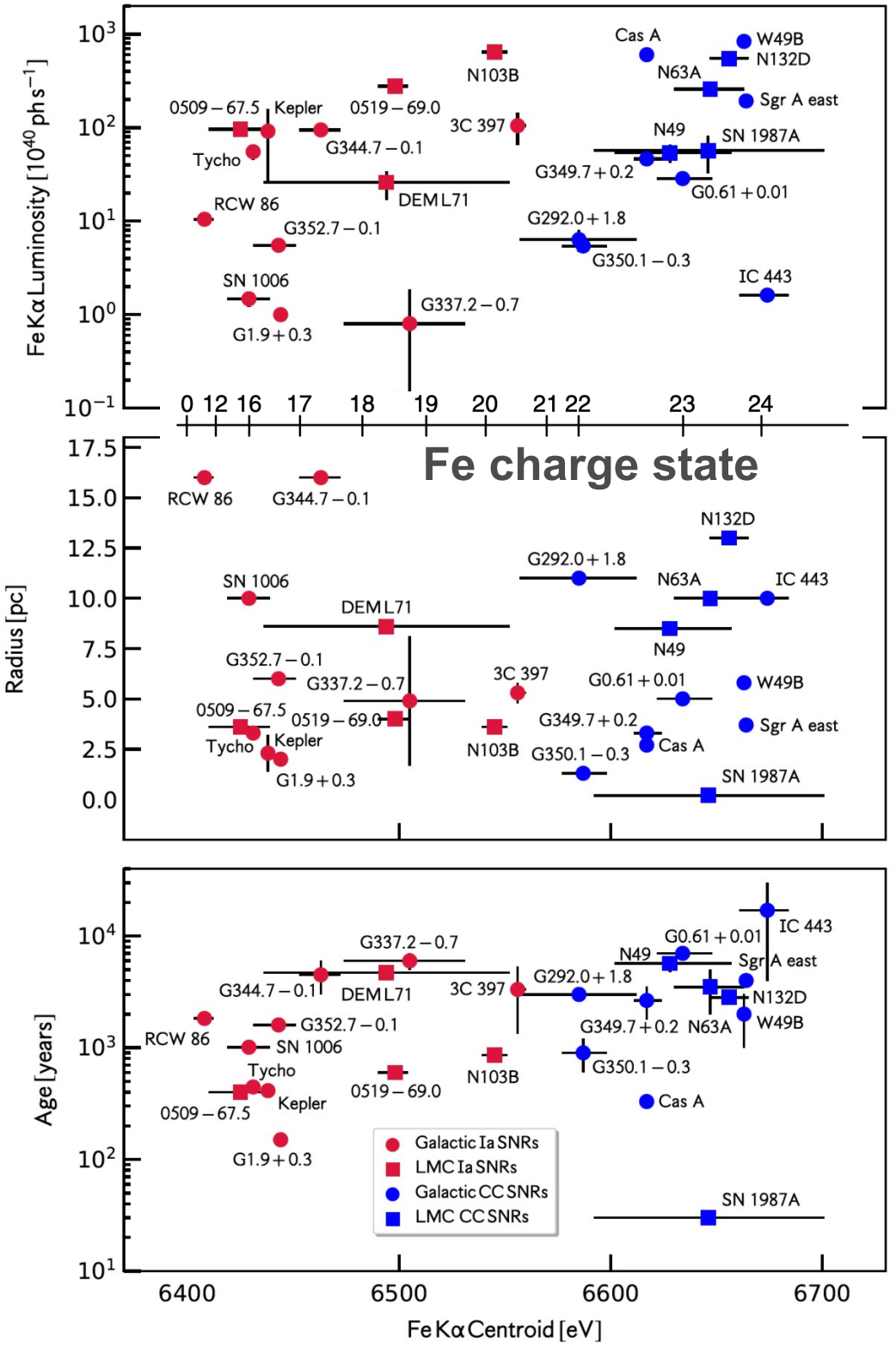
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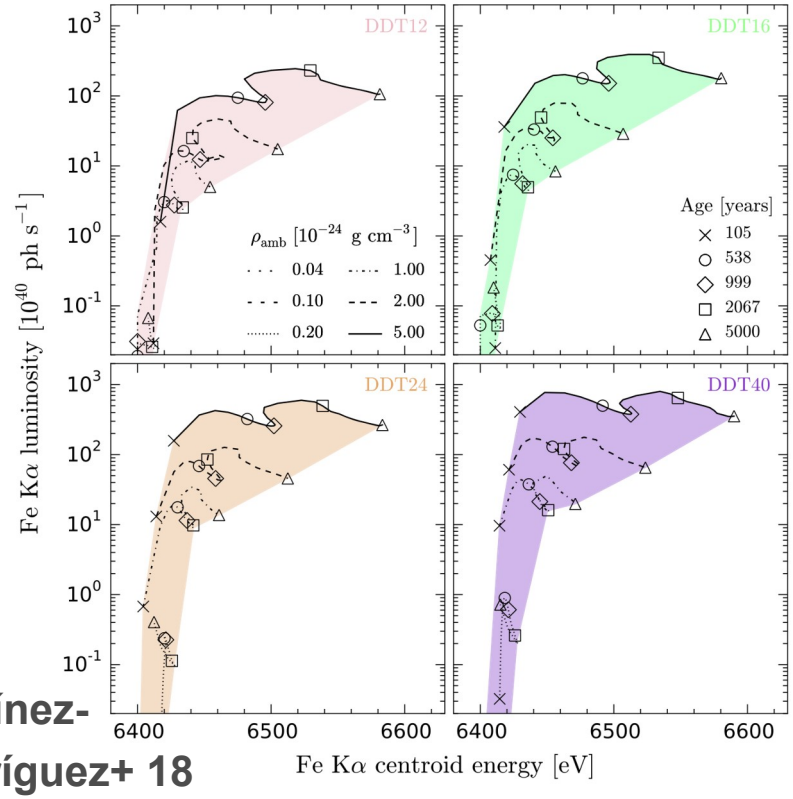
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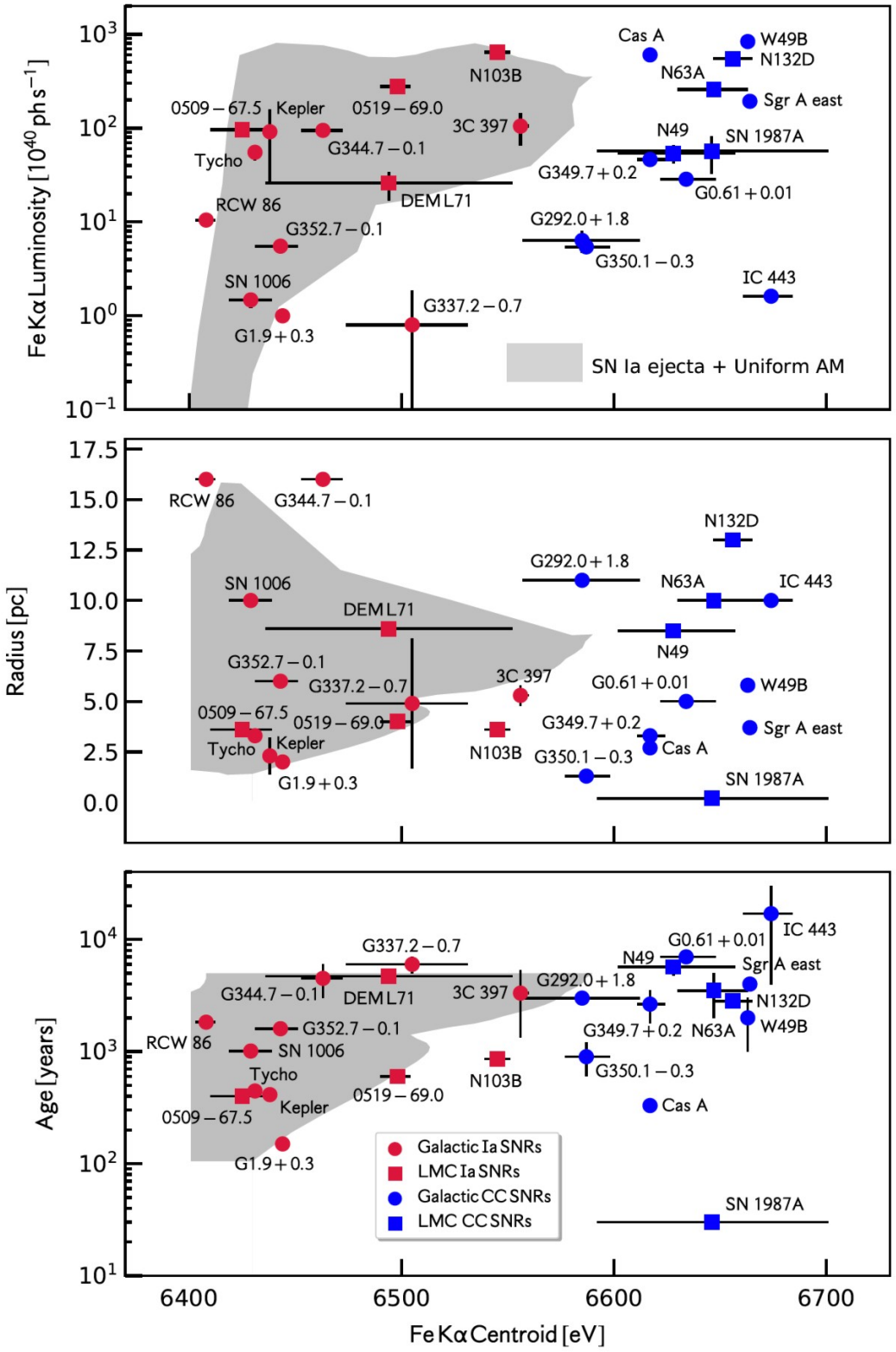


Models: Uniform AM

- **Constraints on AM** ⇒ HD+NEI models [Badenes+ 03,05,06, Patnaude+ 15,17, Jacovich+ 21,23, Court+ 24].
- **Uniform AM works quite well for most Ia SNRs** [Badenes+ 07, Yamaguchi+ 14, M-R+ 18]. **This does not imply there is no CSM!**

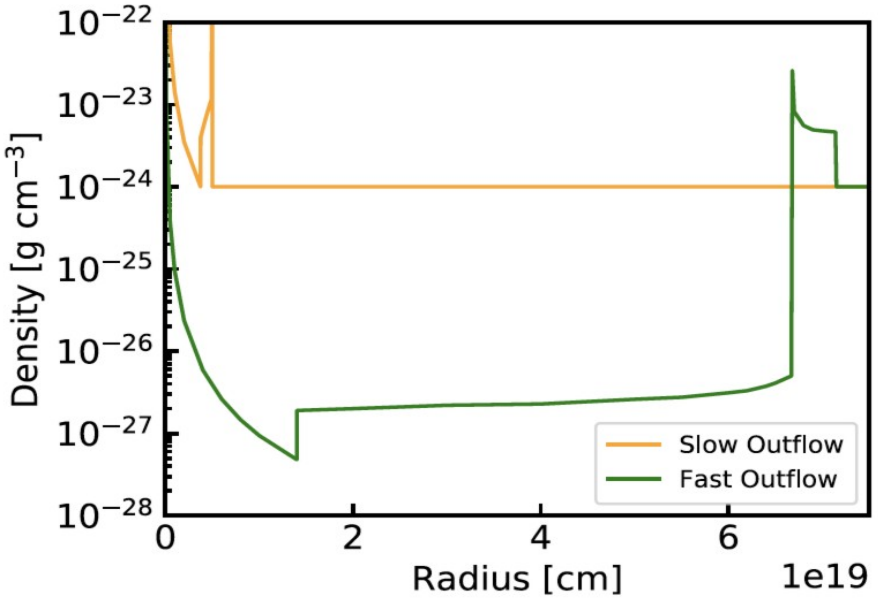


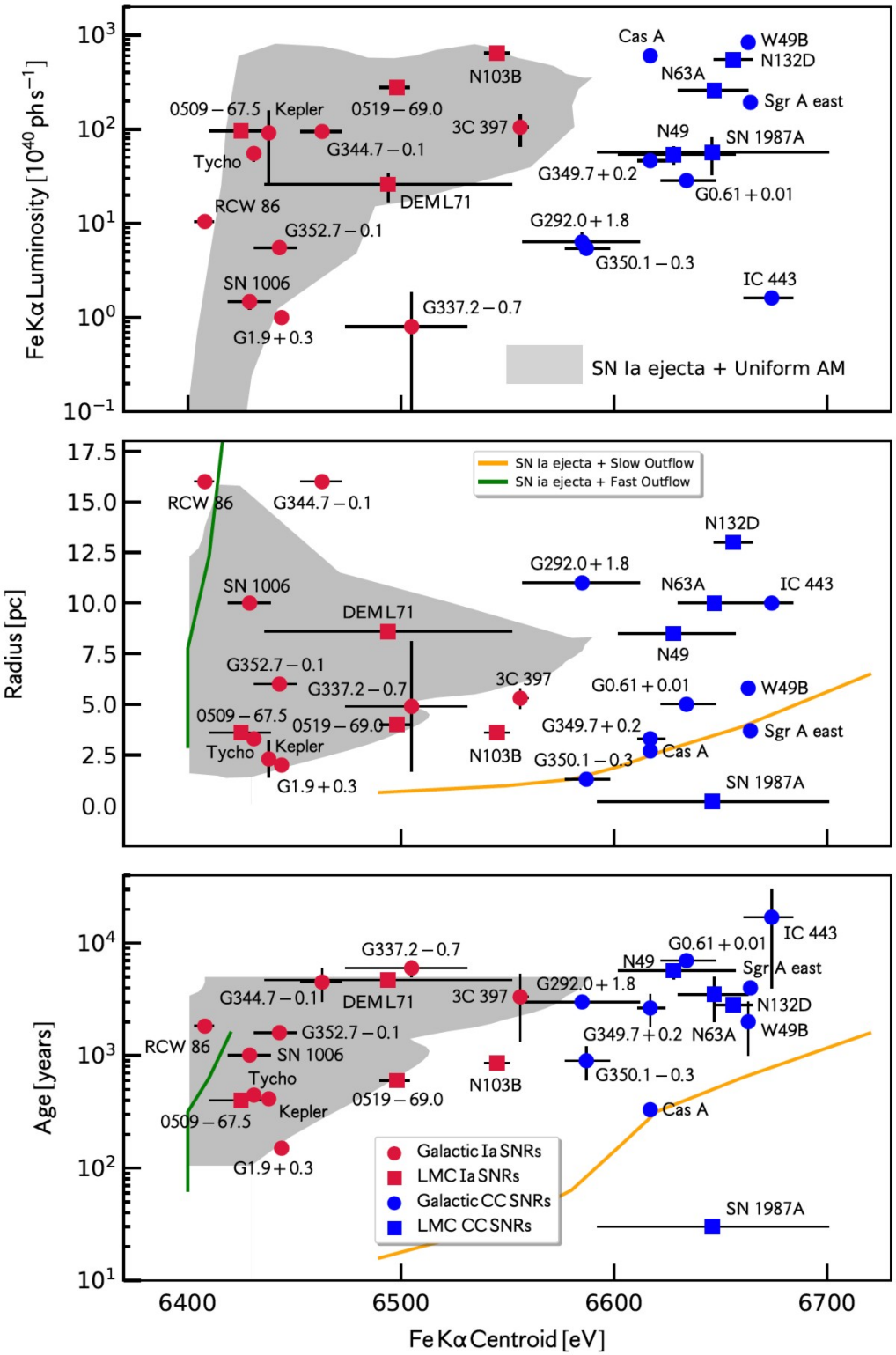
Martínez-Rodríguez+ 18



Models: CSM

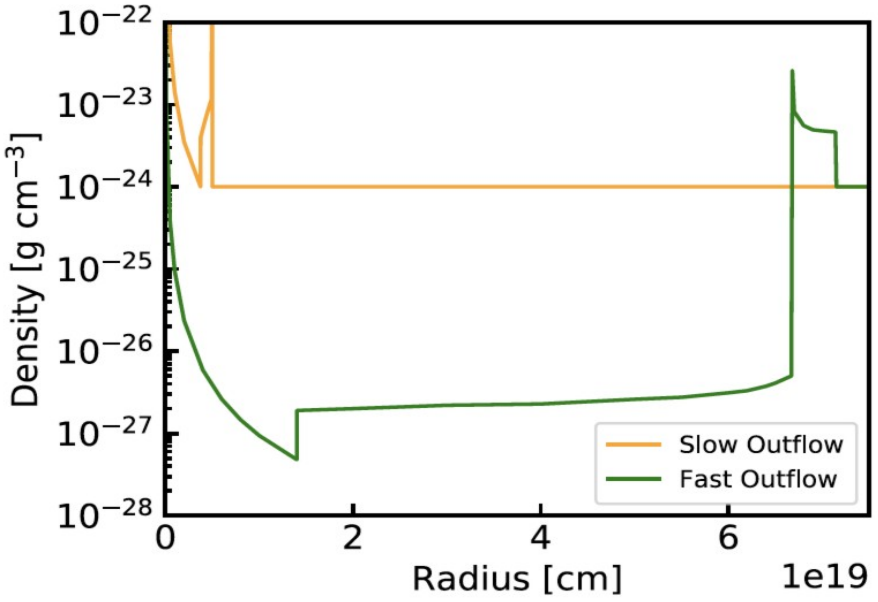
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- **Slow/dense outflows** (e.g., AGB winds) can be ruled out in most cases.

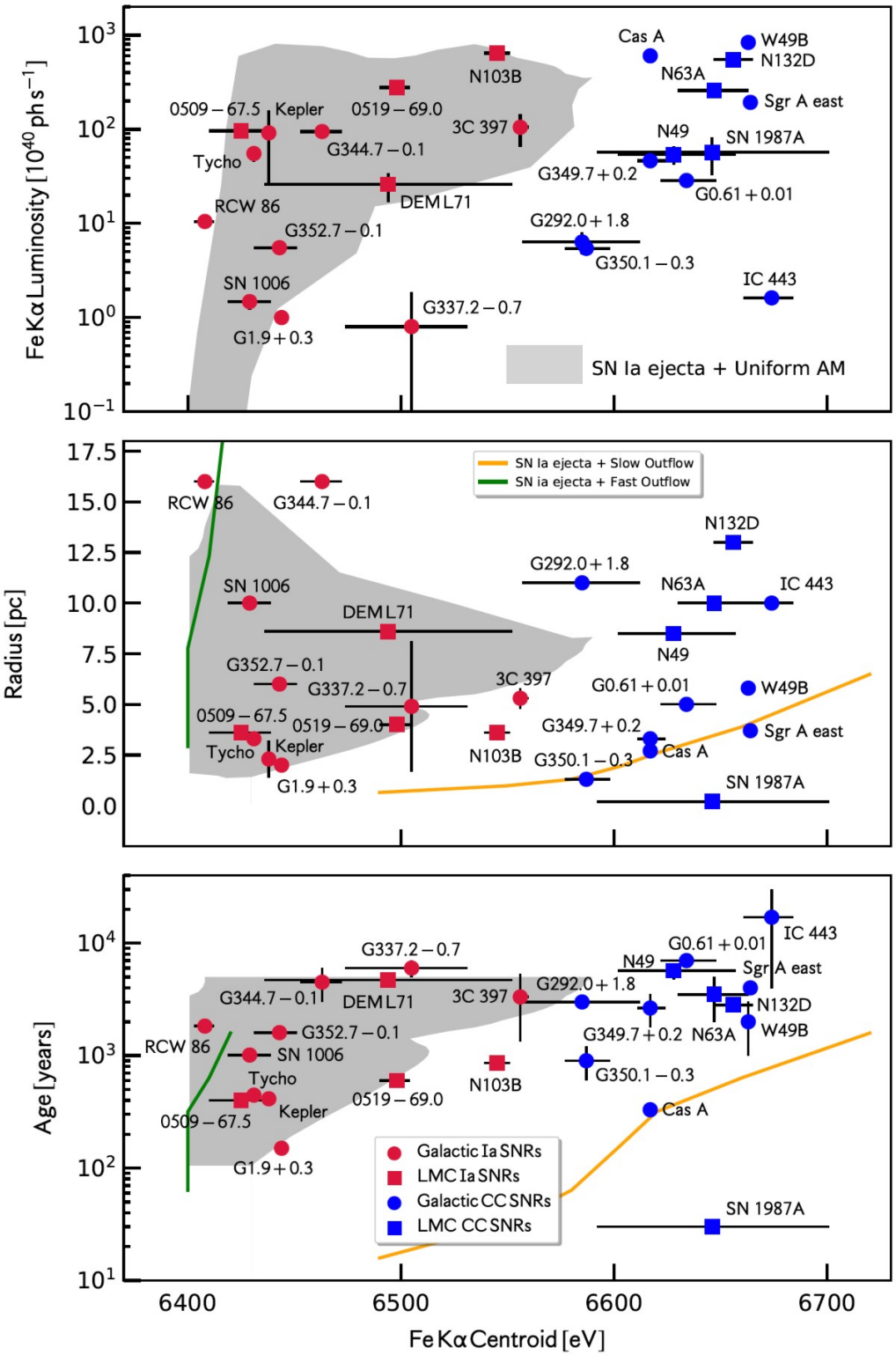




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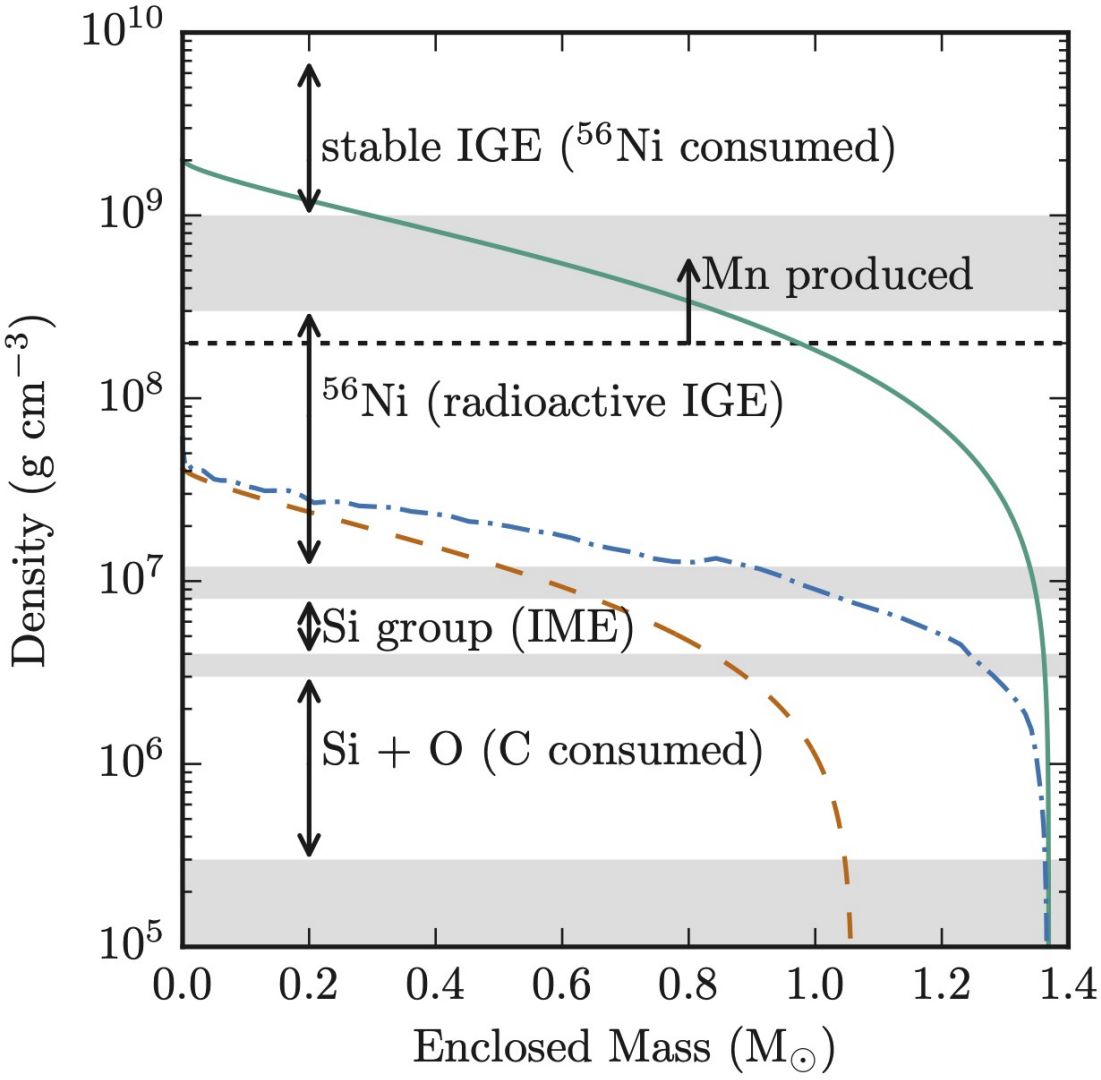




Neutronization in SNRs

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- **Mn, Ni, and Ca** lines in SNRs can constrain **neutronization** (η) in SN Ia.
- Inferred **η is high**, both from Fe-peak elements and Ca/S [Badenes+ 08b, Park+ 13, M-R+ 17, H-A+ 23] ⇒ **Neutron source not tied to Z**.
- **Physical interpretation is controversial**: near-Ch progenitors [Yamaguchi+ 14, M-R+ 17] or not [Shen+ 18].
- Ca/S in SNRs ⇒ **^{12}C+^{16}O rate attenuated by ~90%**! [M-R+17, Bravo+19, H-A+ 23].



Seitenzahl & Townsley 17

Neutronization in SNRs

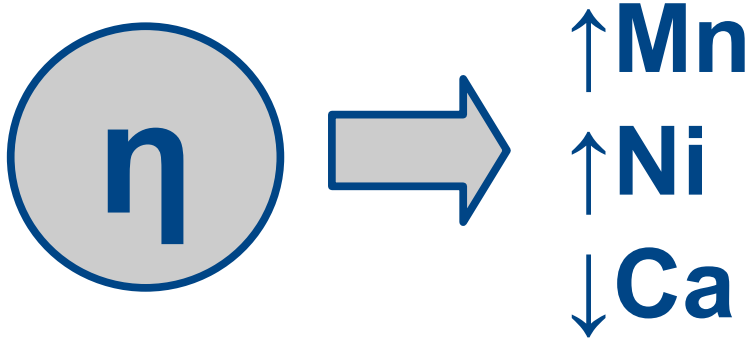
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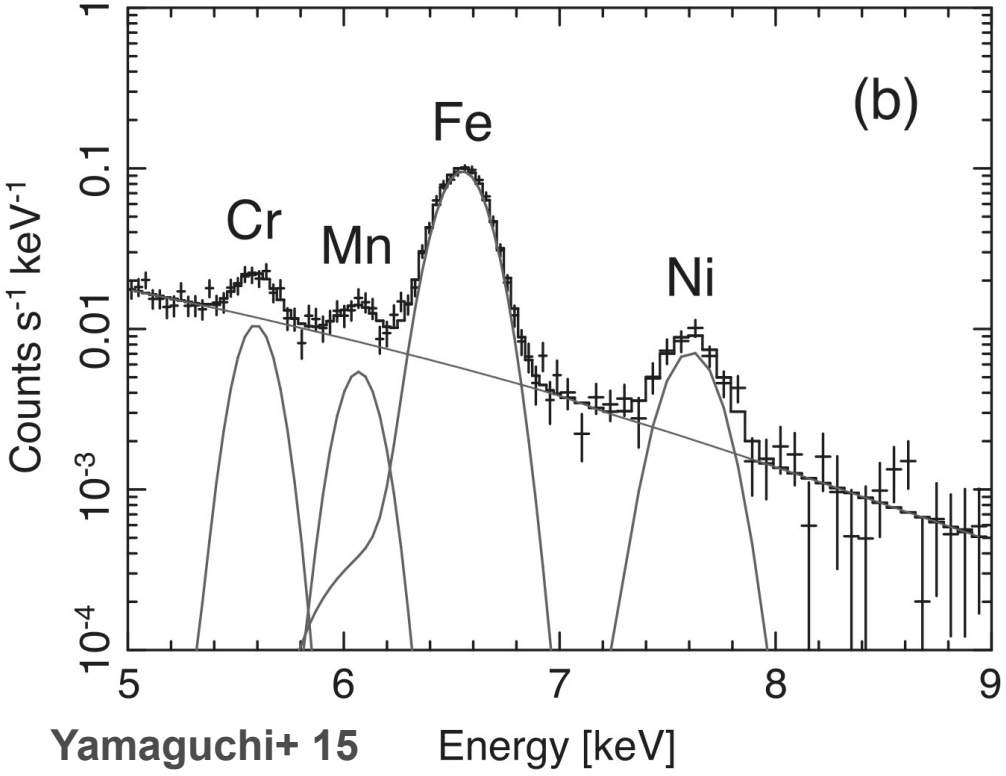
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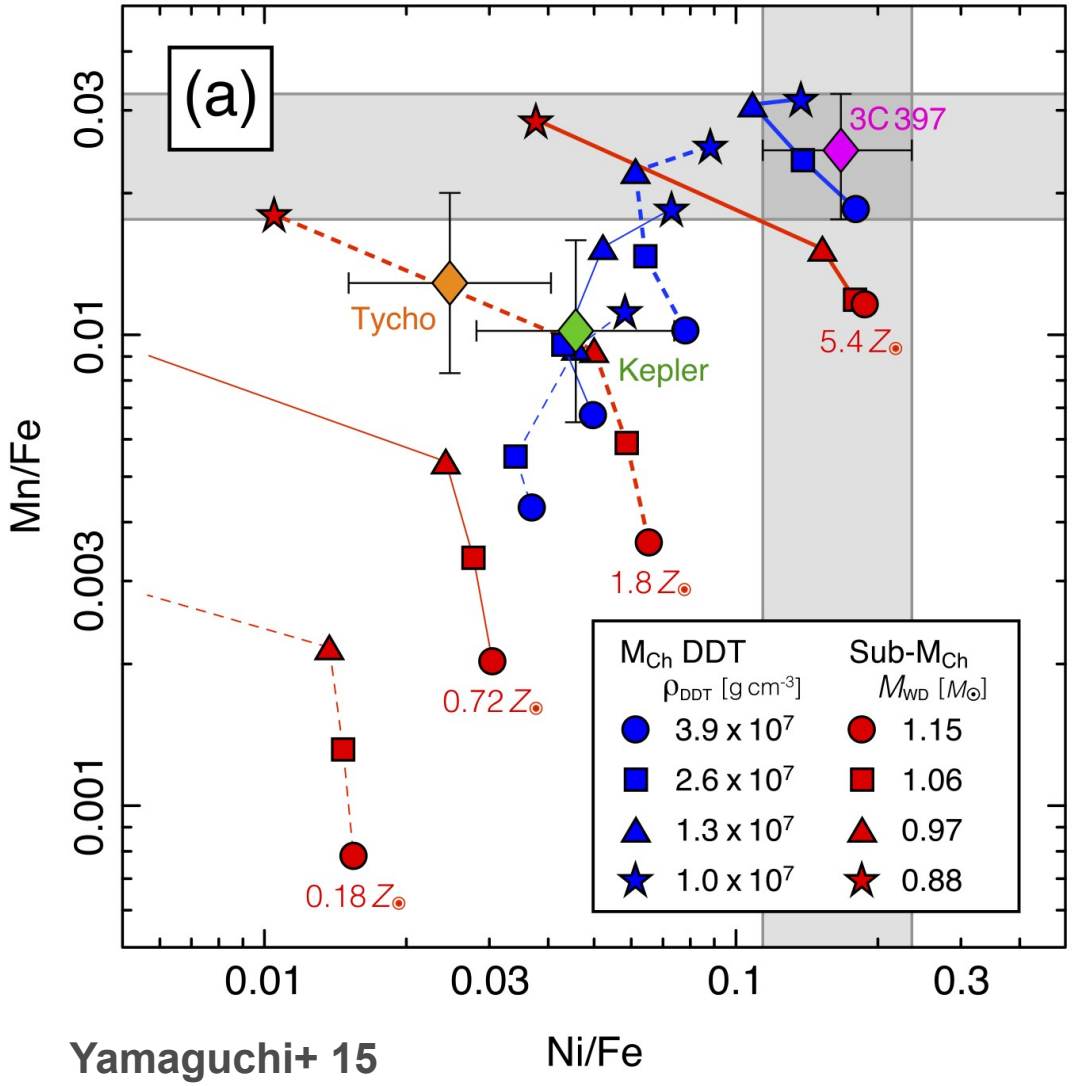
References: Timmes+ 03, De+ 14



Neutronization in SNRs

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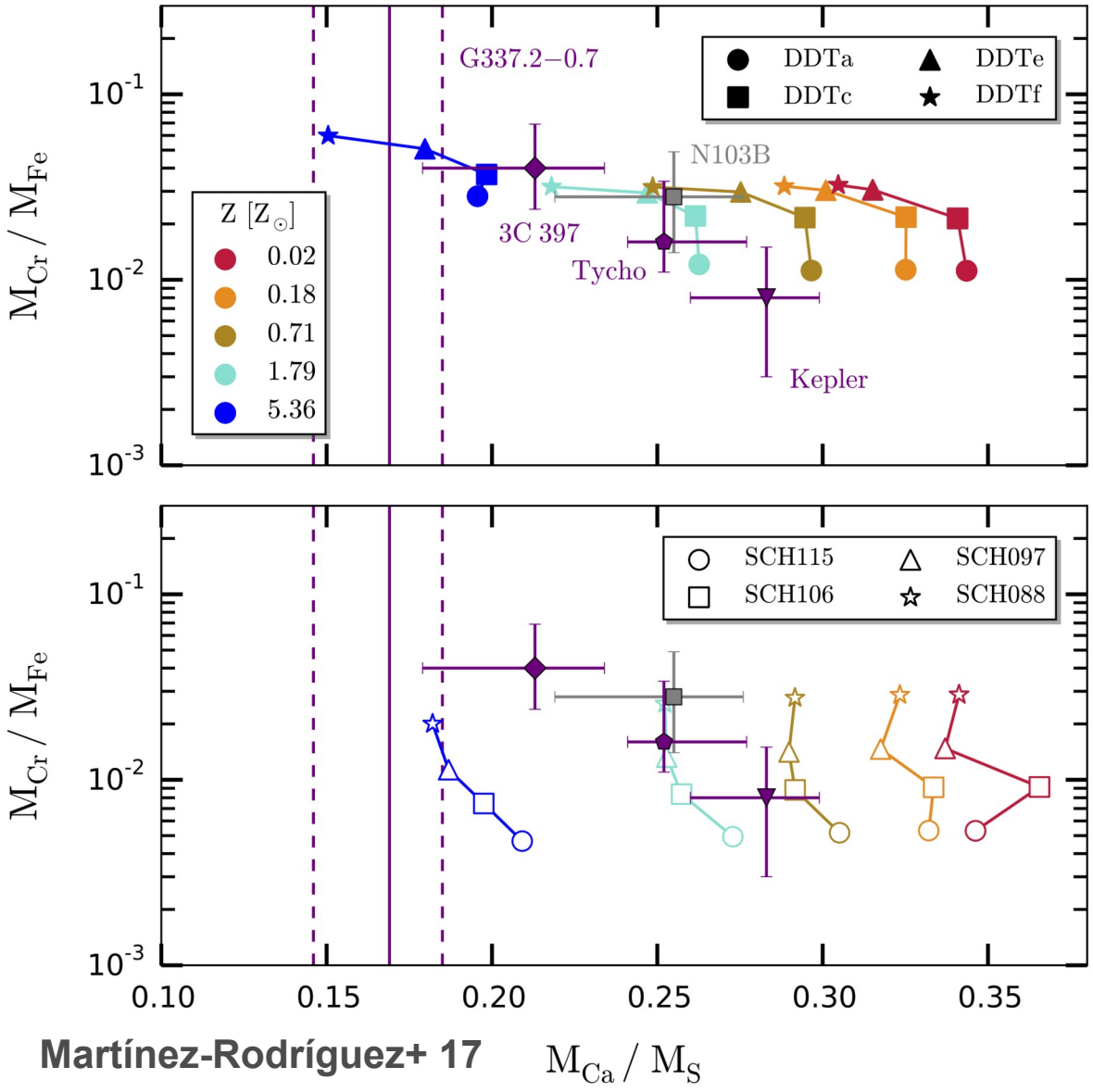
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- Ca/S in SNRs ⇒ **^{12}C+^{16}O rate attenuated by ~90%**! [M-R+17, Bravo+19, H-A+ 23].

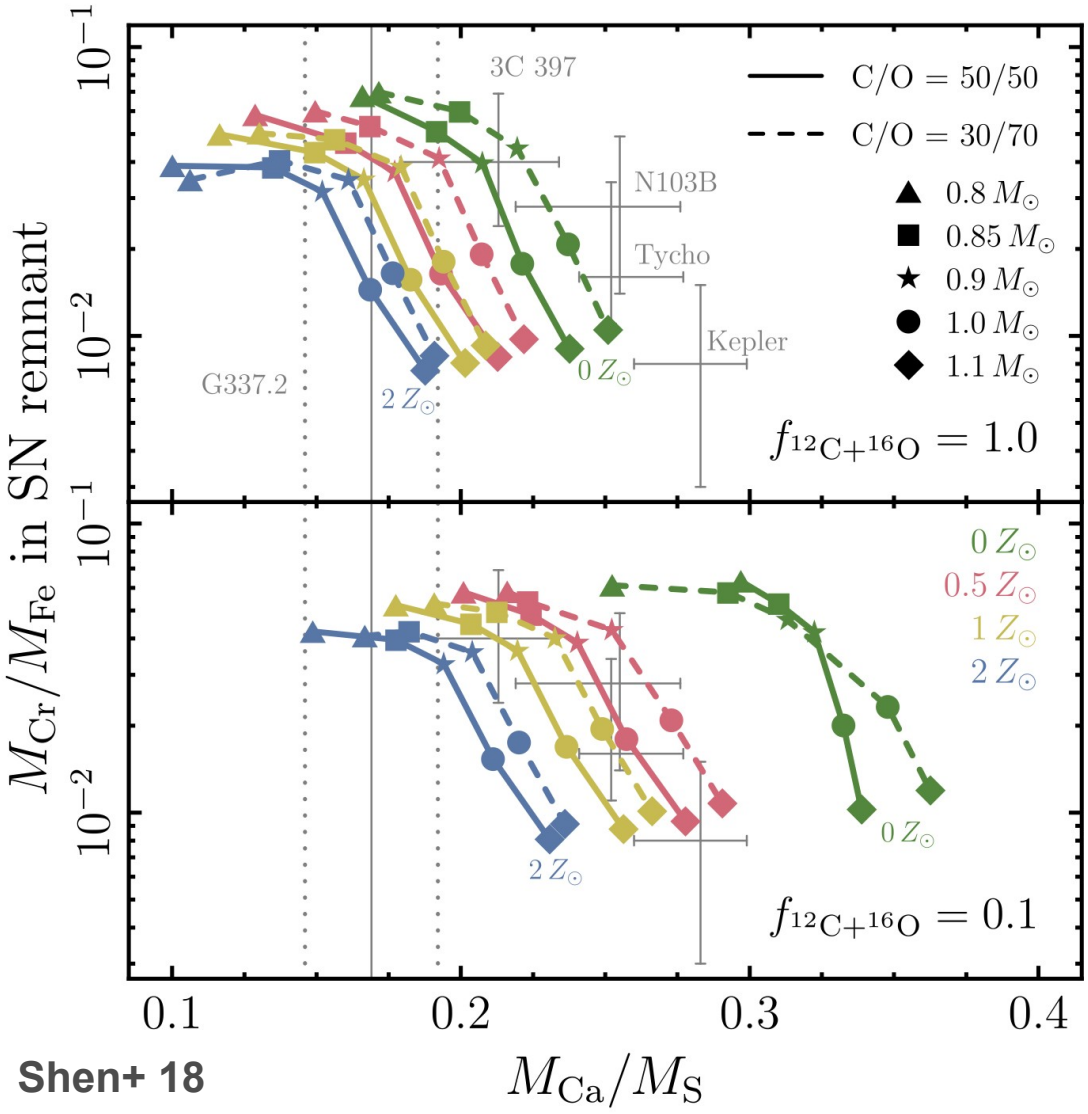


Martínez-Rodríguez+ 17

Neutronization in SNRs

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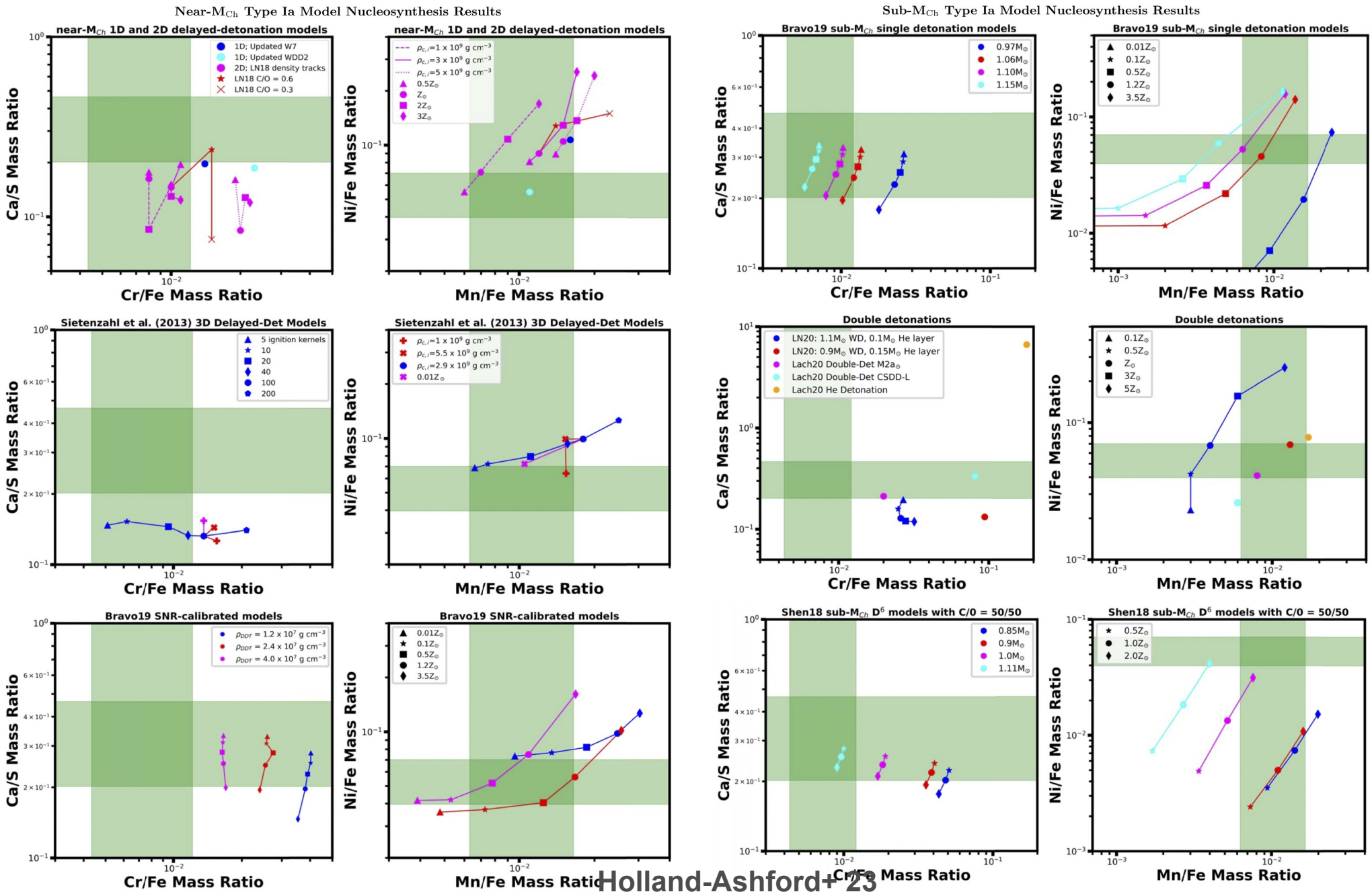
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Shen+ 18

Neutronization in SNRs

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Holland-Ashford+ 23

Conclusions

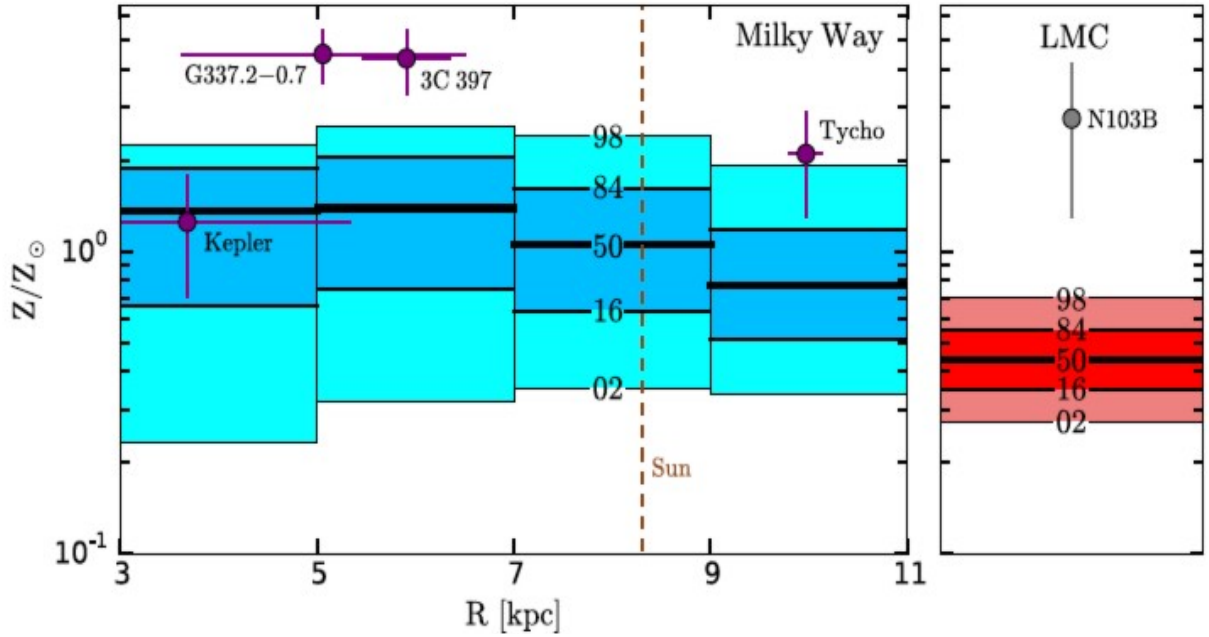
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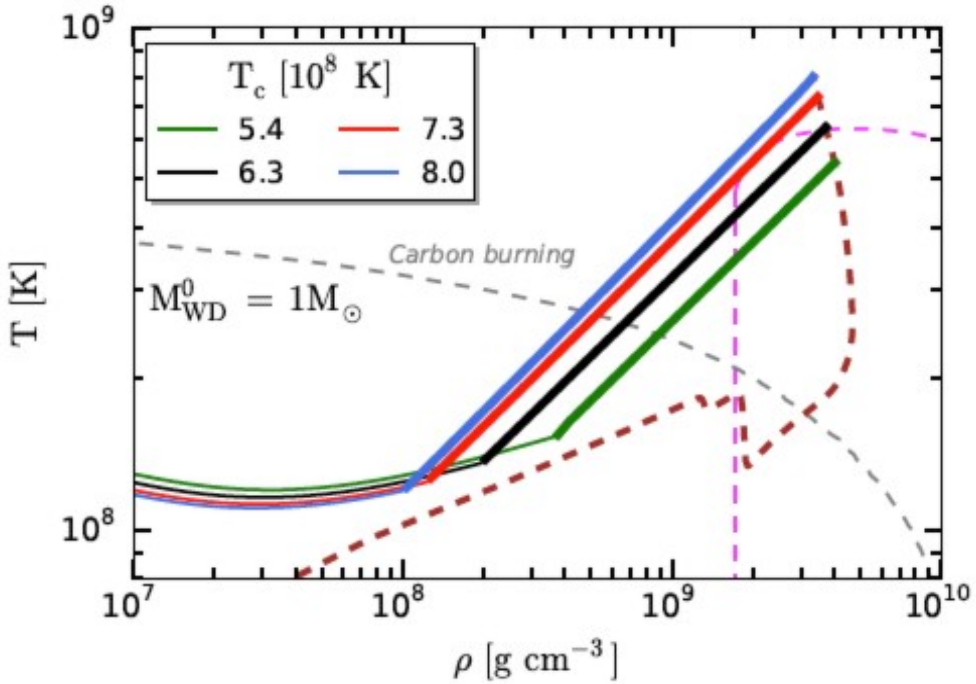
- SNRs are crucial to the SN Ia progenitor problem.
- Many Type Ia SNRs show no evidence for strongly modified AM on ~pc scales. This is hard(er) to explain with slowly accreting progenitors.
- Some Type Ia SNRs probably have CSM (RCW 86, N103B, 0519). Spectral models are necessary to constrain progenitor outflows. SNIPs might work in some cases, but $t_{delay} \gtrsim 10^4$ yr. Keep an eye out for XRISM results!
- Neutronization in Type Ia SNRs (Mn, Ni, Ca): there is likely a neutron source that is not tied to metallicity. This is hard(er) to explain with progenitors that merge or collide on dynamical timescales.

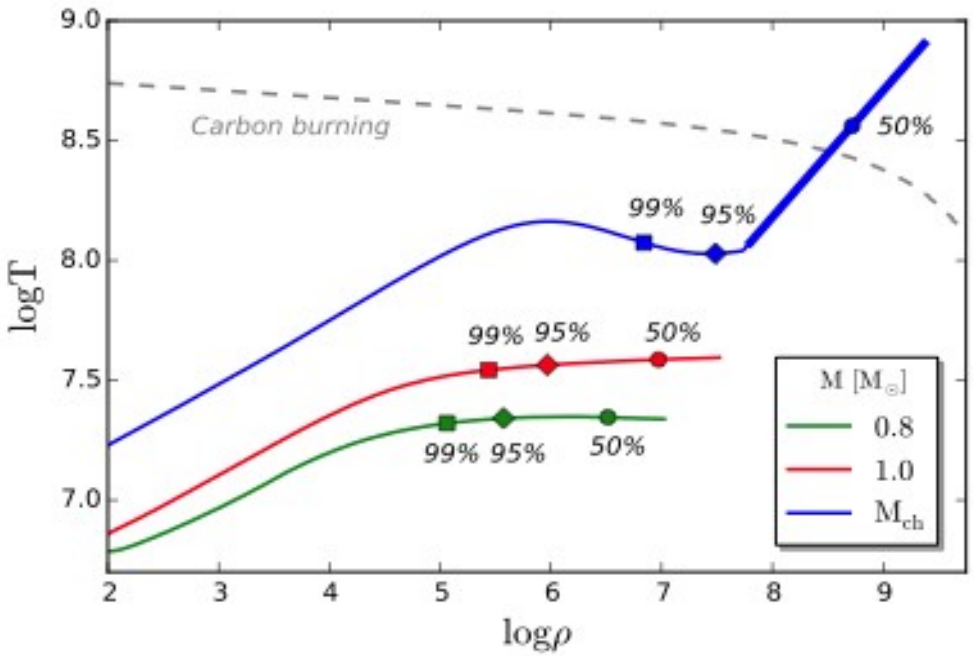
There is probably a mixture of SN Ia progenitor channels in star-forming galaxies

Extra Plots

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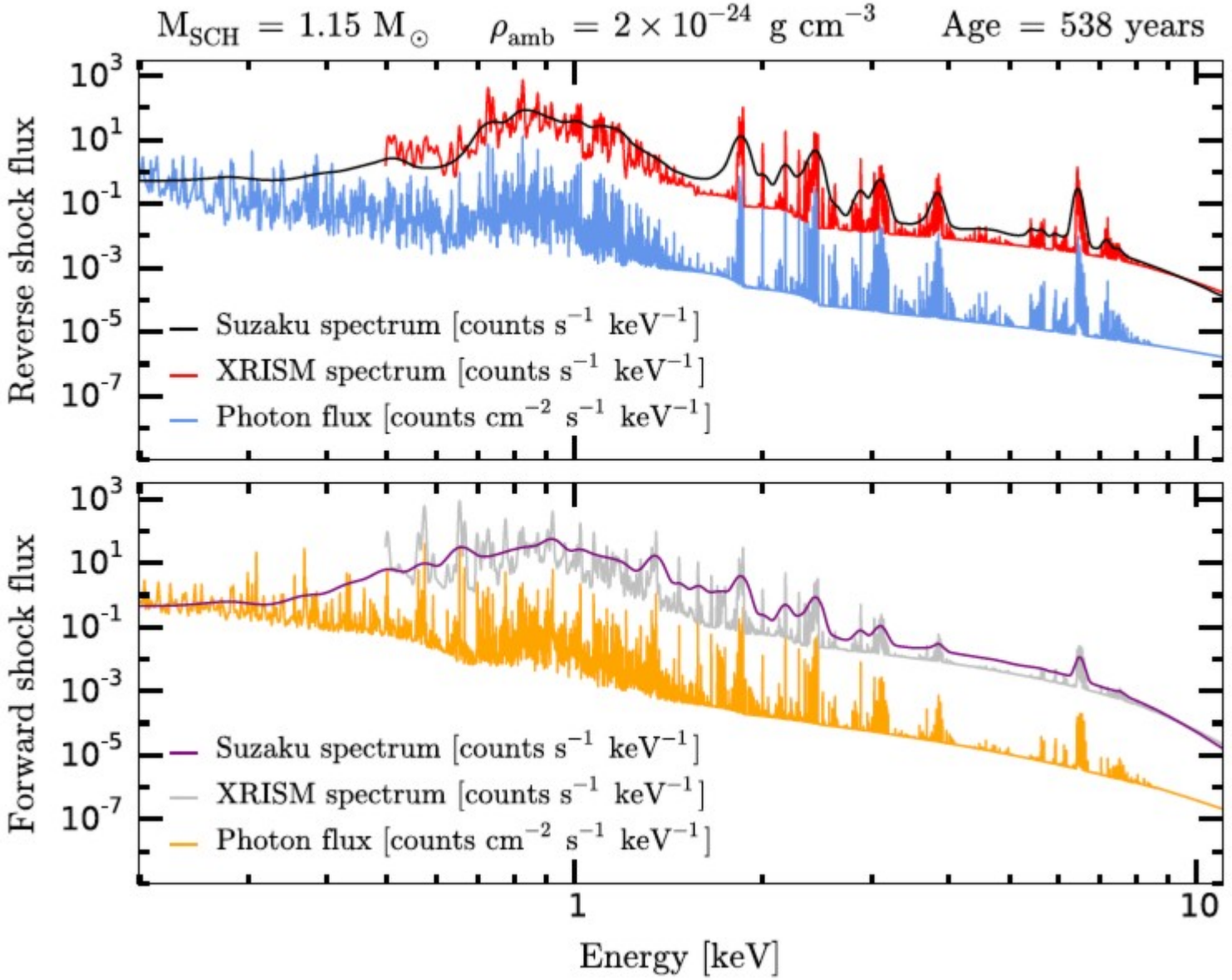






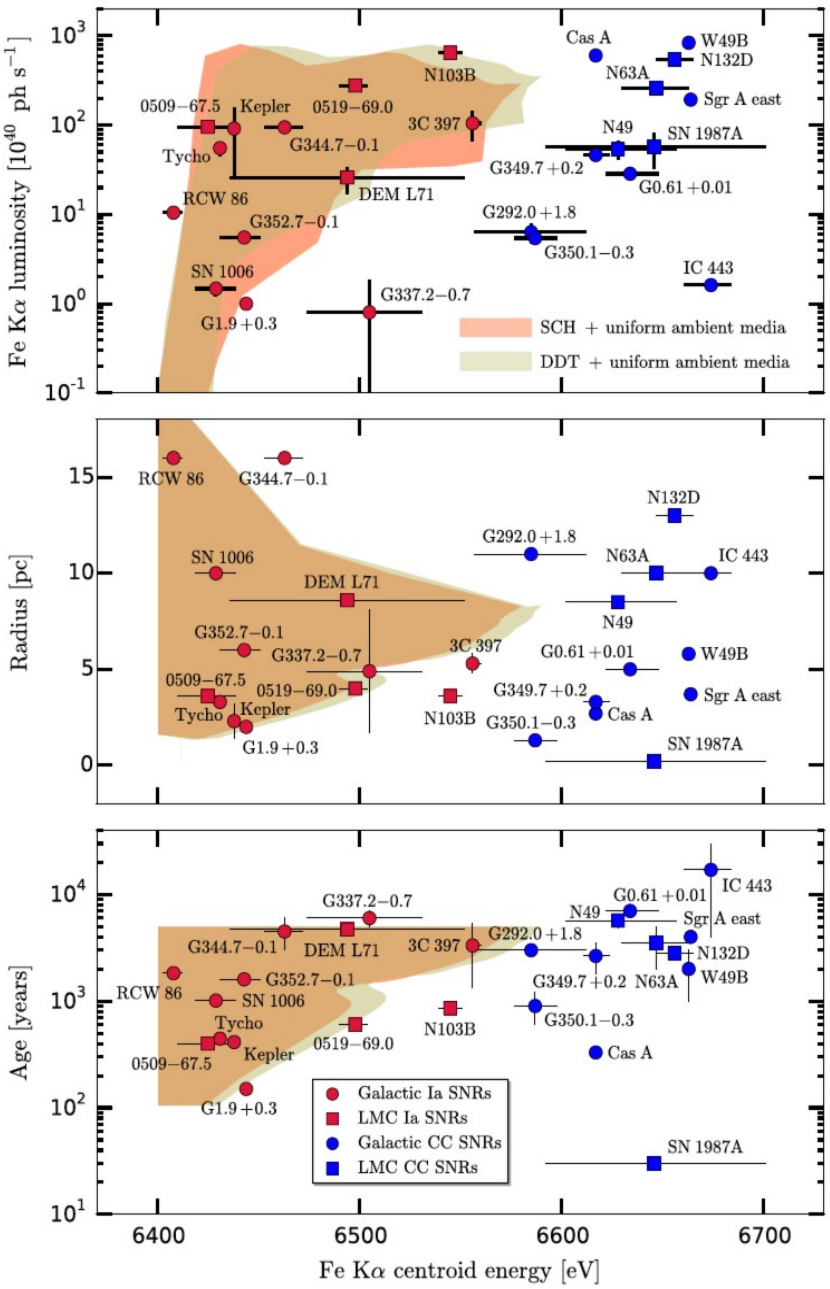
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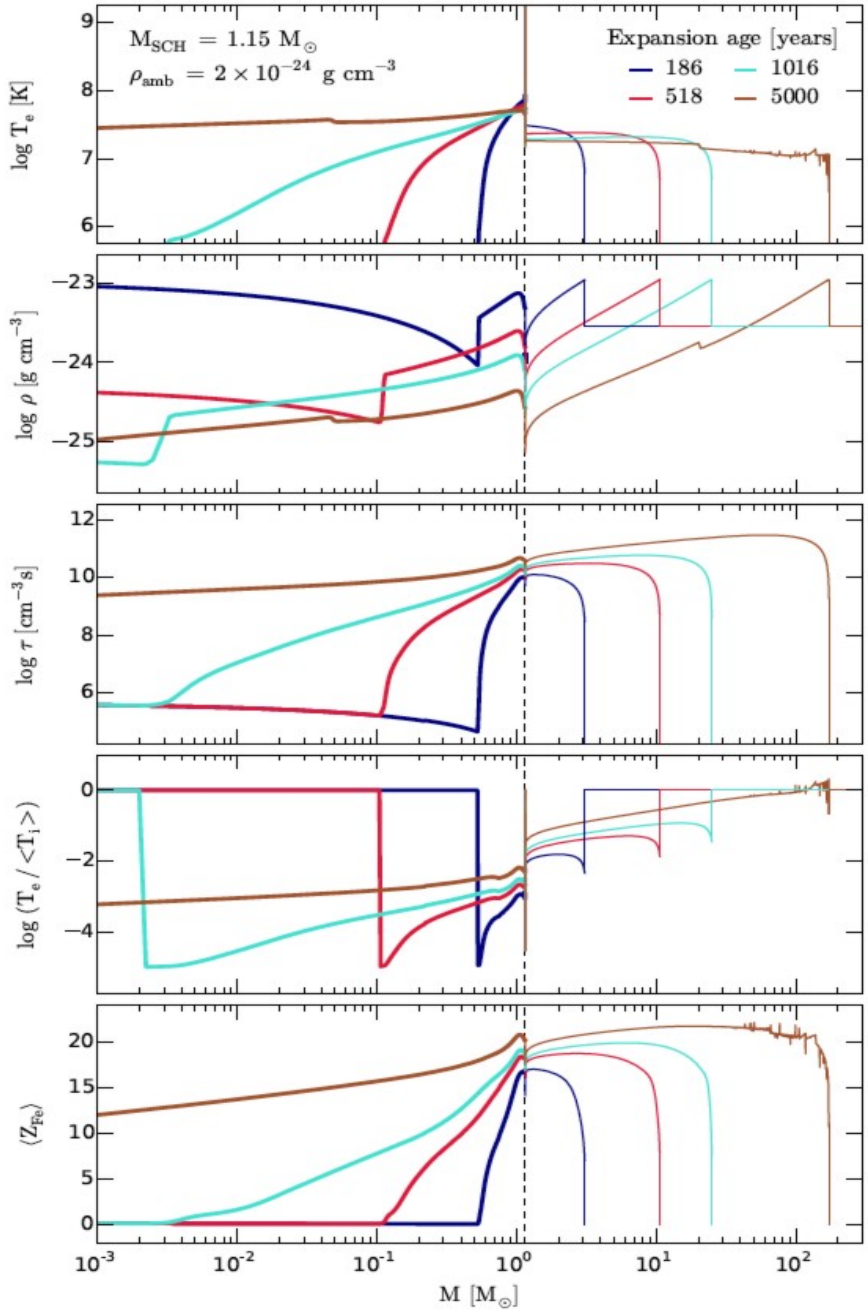
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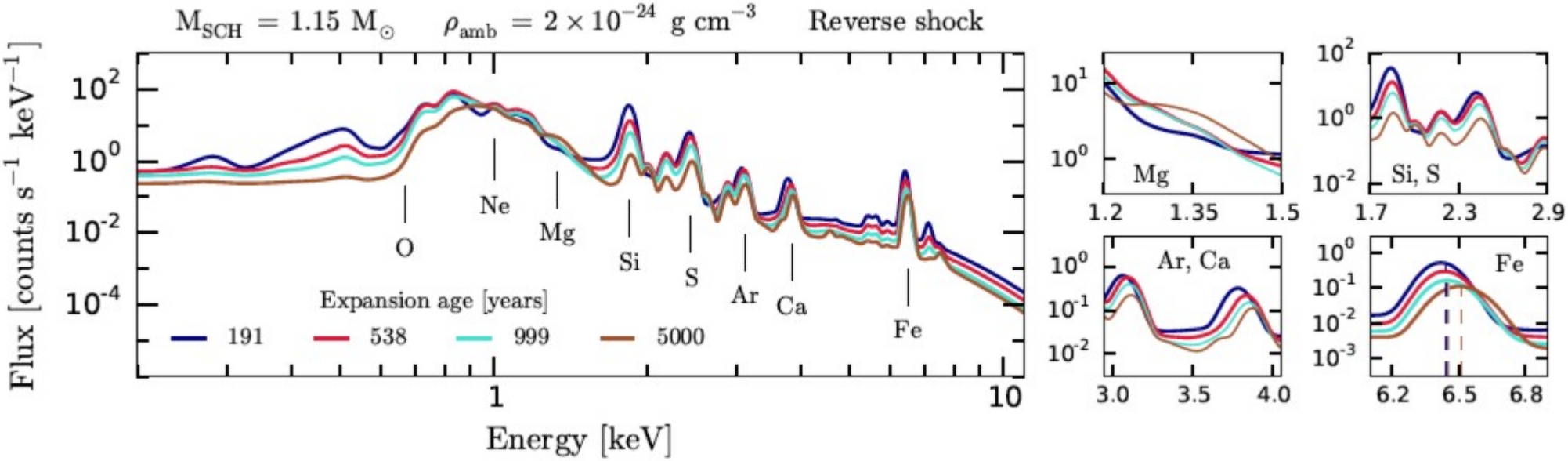
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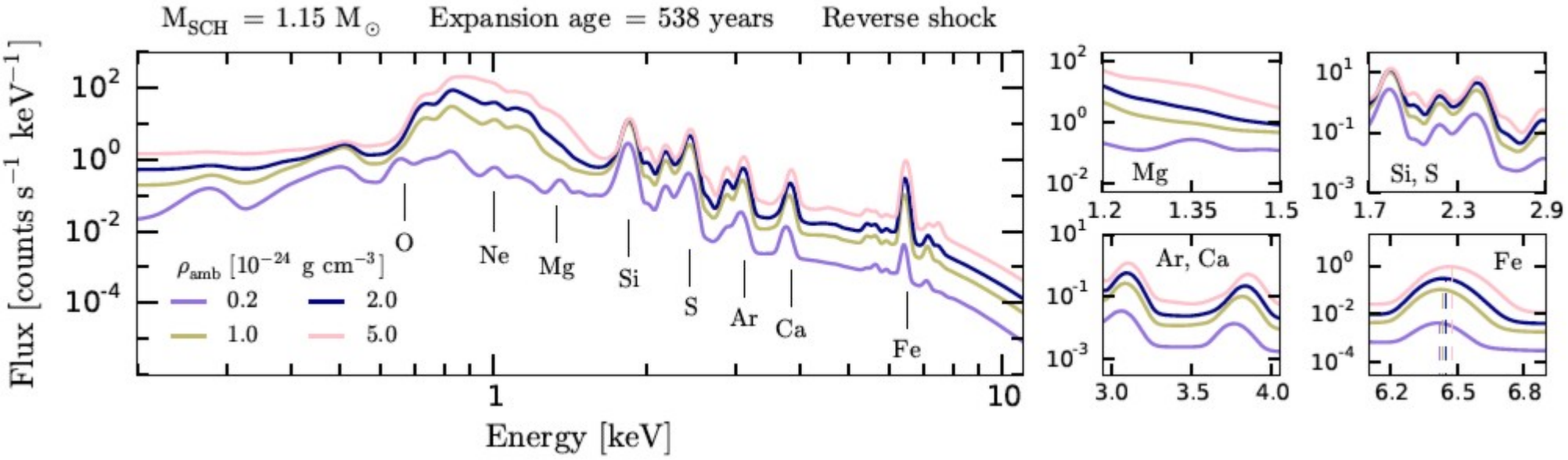




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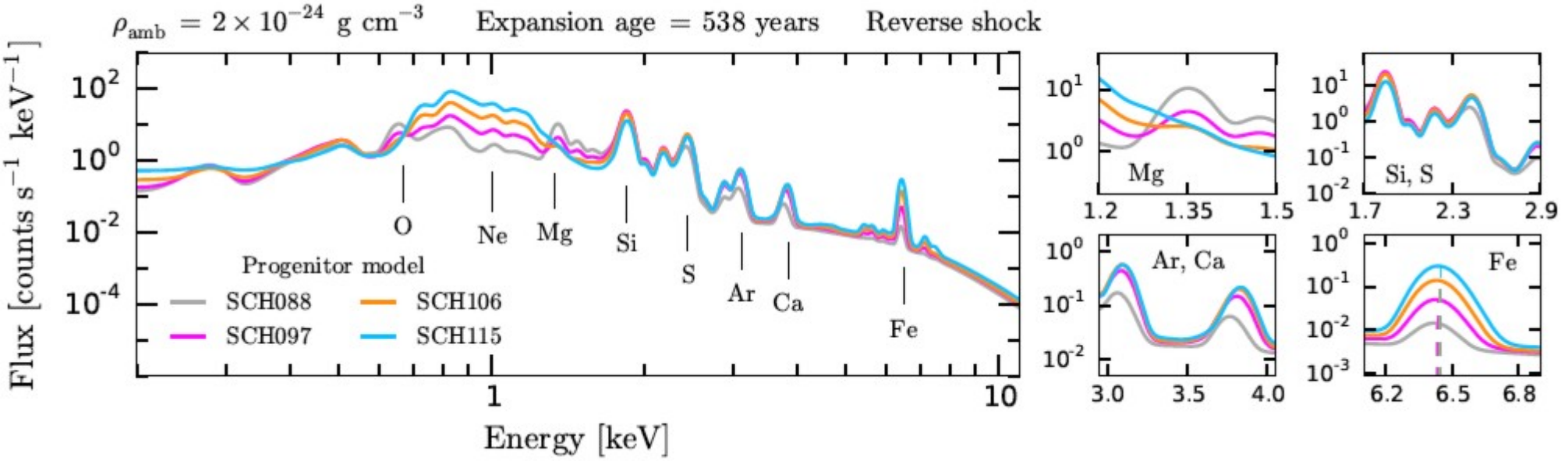
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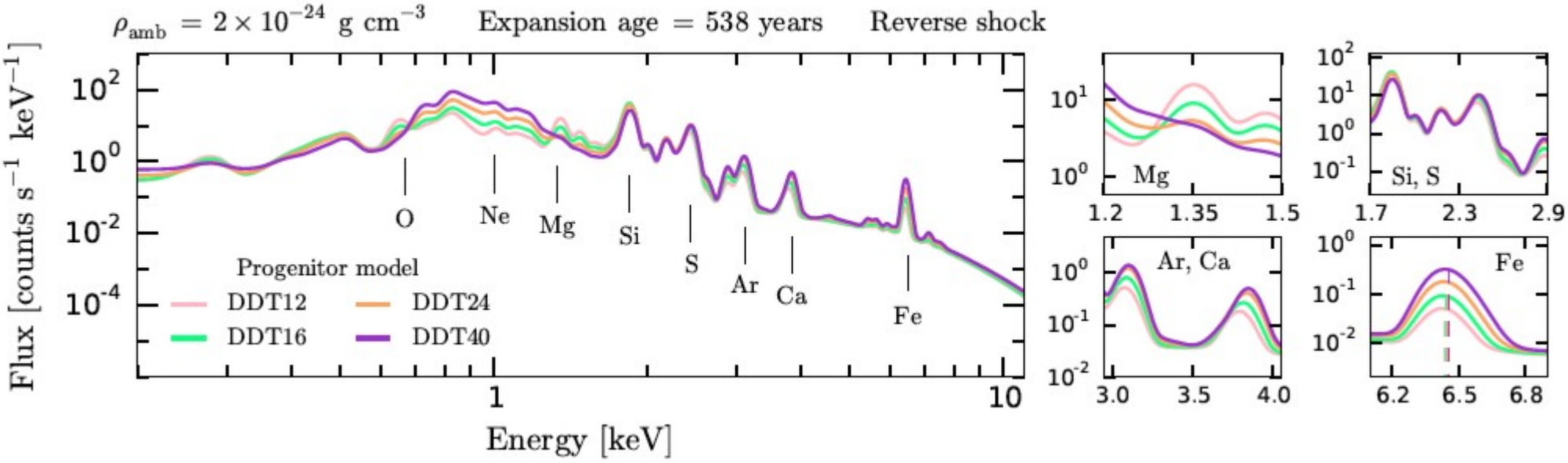




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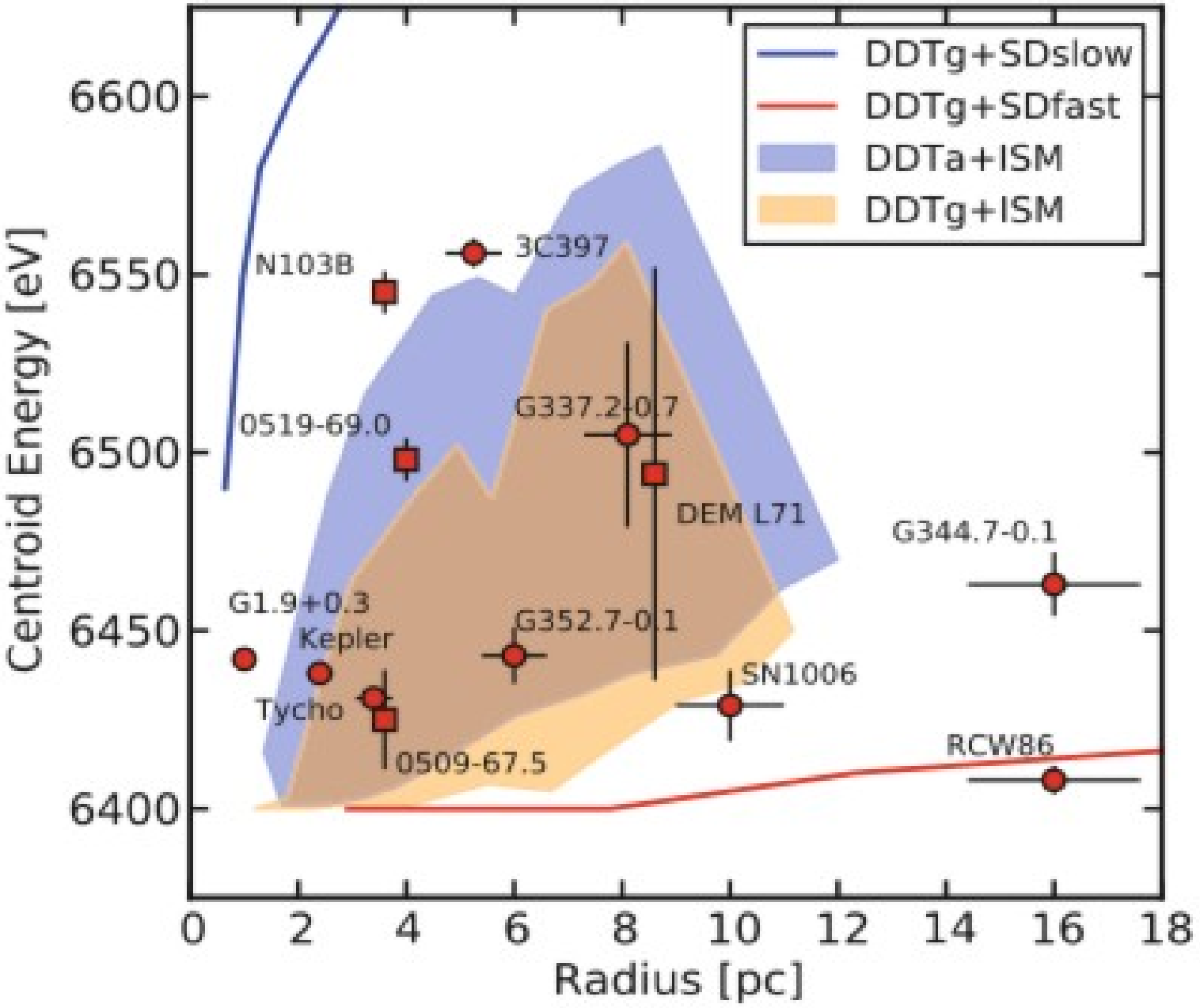
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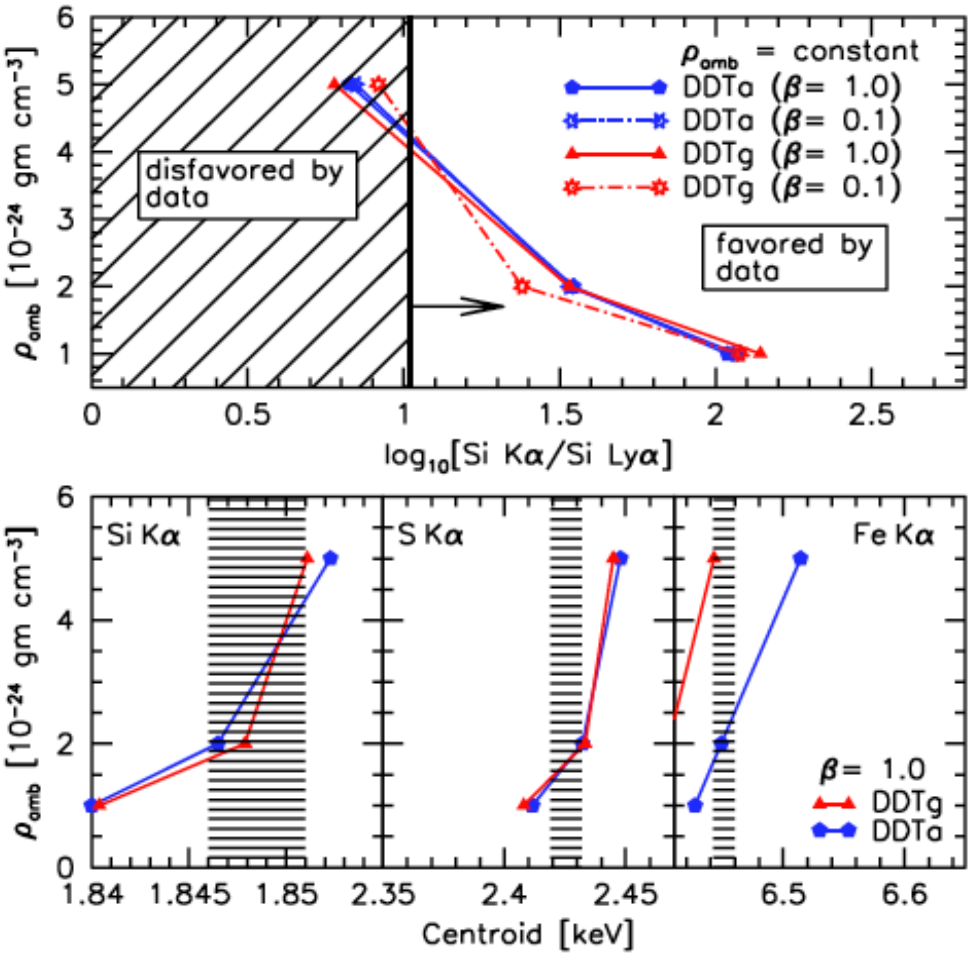
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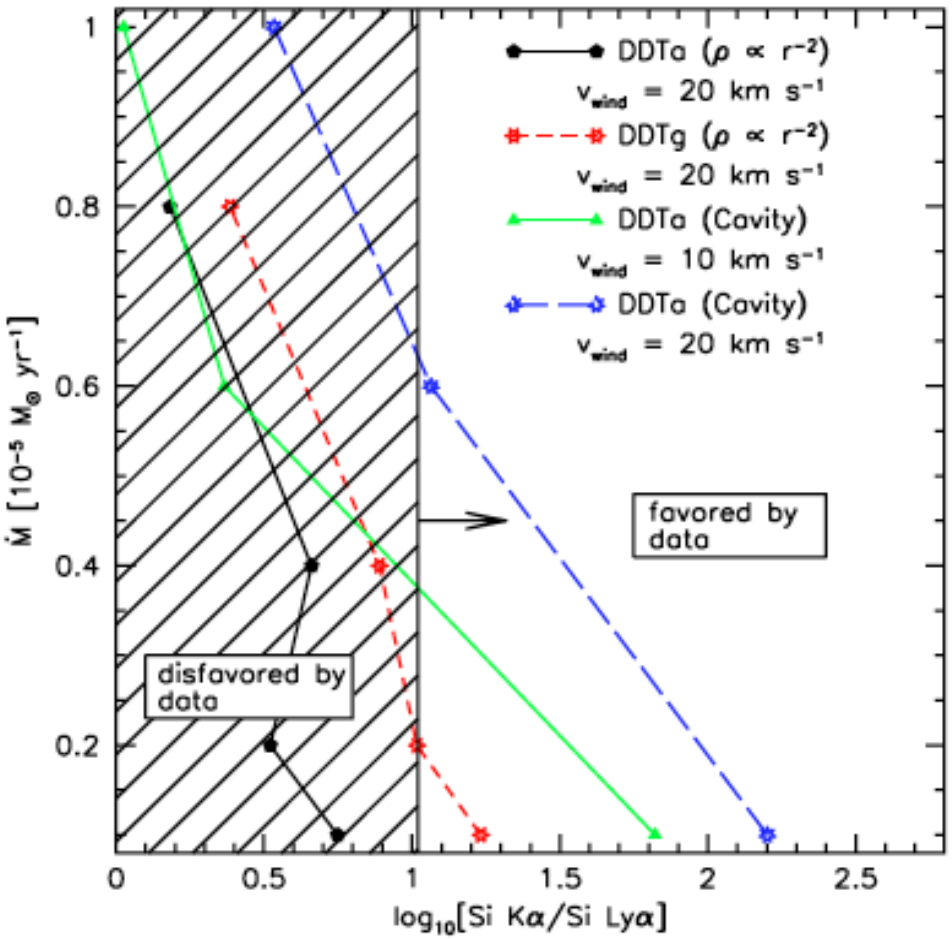
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AM Interaction in SNRs: Fe K

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- 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}**.
- Details: Yamaguchi+ 14b, Patnaude & Badenes 17, Martínez-Rodríguez+ 18, Court+ 24.
- Need high effective area at 6.5 keV: ***Suzaku***.

