The Persistence of Memory:
What Supernova Remnants Can Tell Us about Type Ia Supernova Progenitors

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Harvard CfA Colloquium
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with **Hiroya Yamaguchi** (NASA/UMd), **Dan Patnaude** (CfA), **Eduardo Bravo** (UPC), **Pat Slane** (CfA), **Sangwook Park** (UTA), and others

Artistic Motivation

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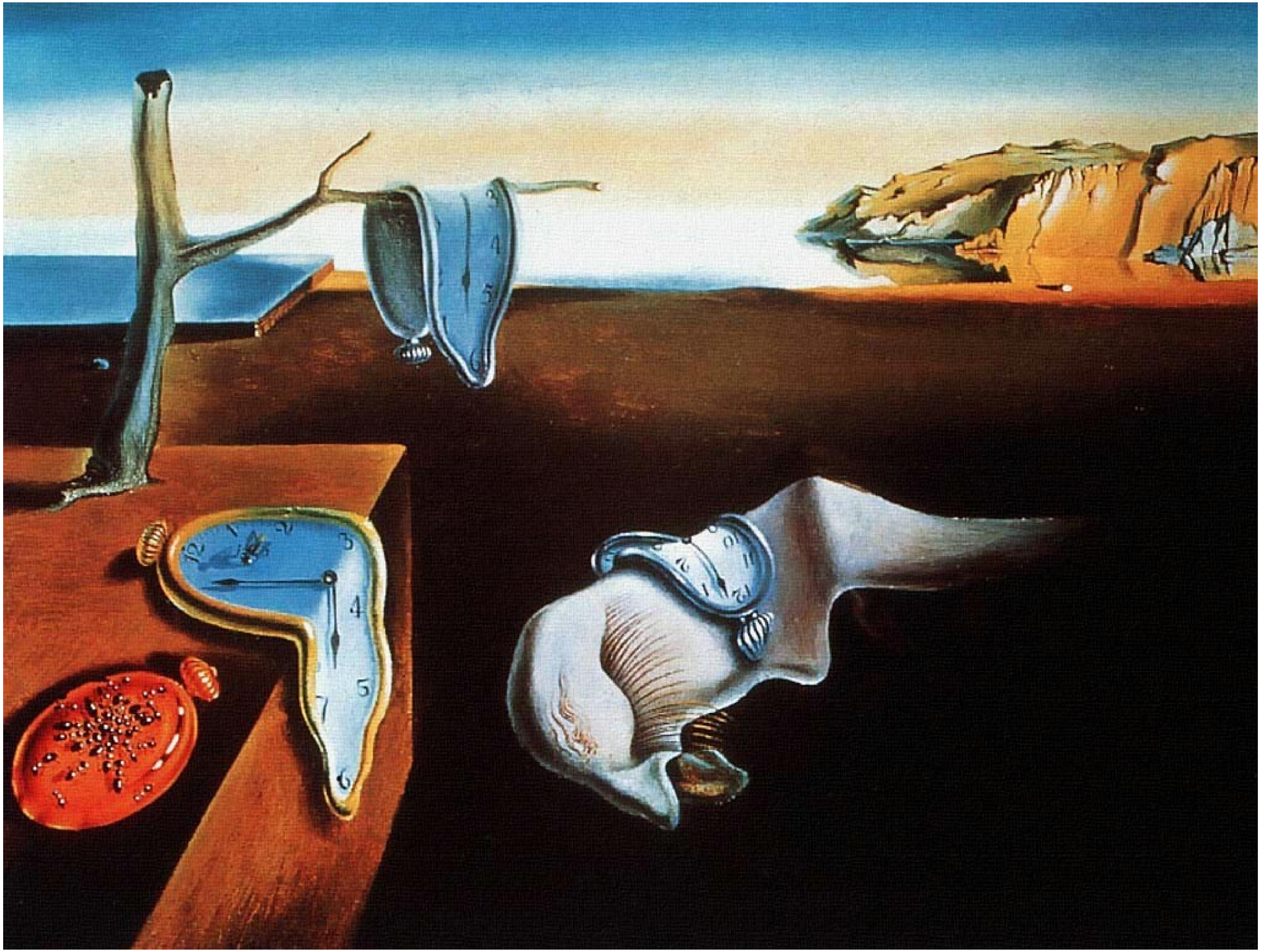

The Persistence of Memory

Salvador Dalí
(1931, MoMA)

Scientific Motivation

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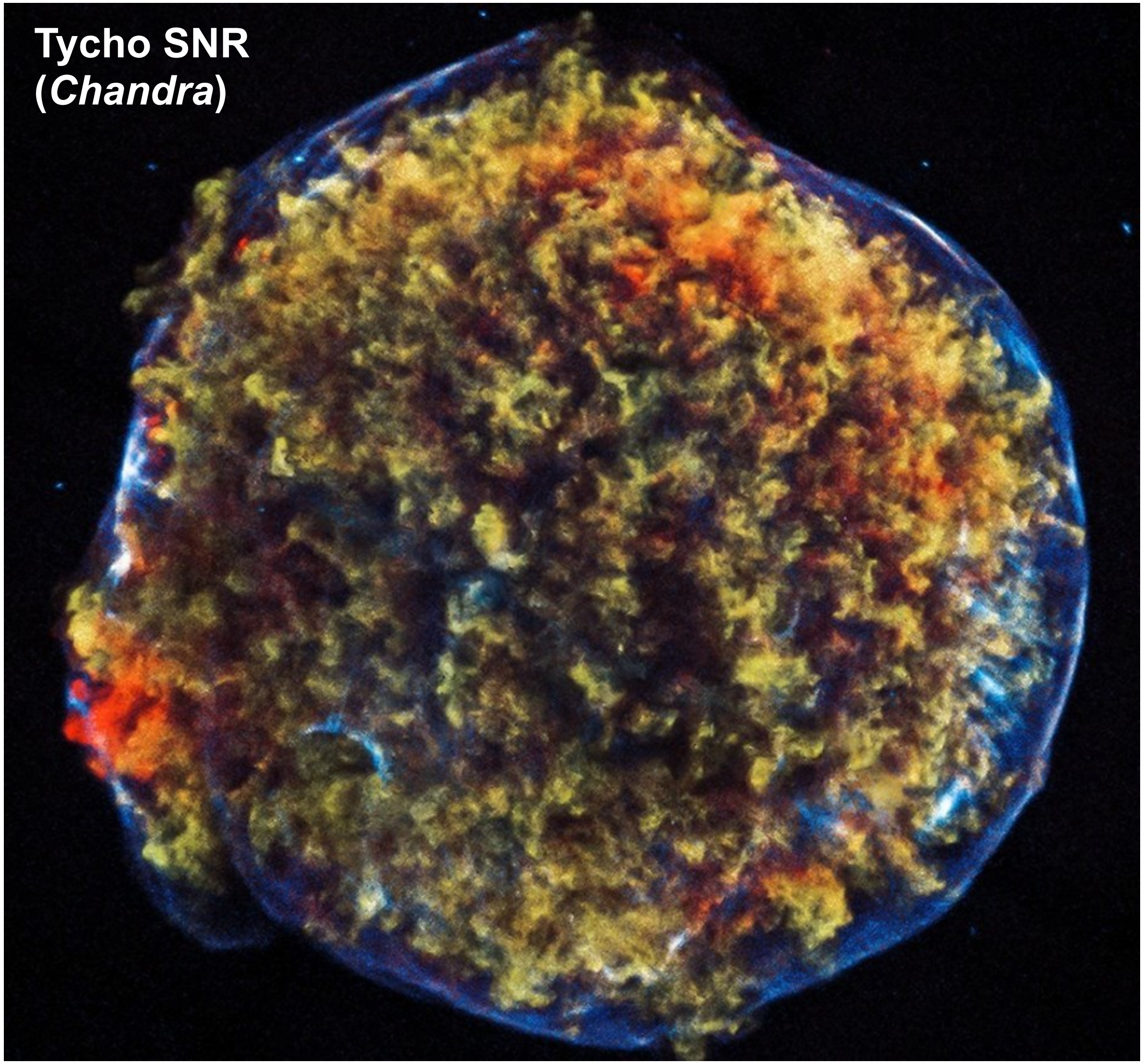
SN Ia progenitors remain unidentified

Supernova Remnants (SNRs) ⇒ different perspective on SNe

SNRs remember their birth events.

- **SN-CSM Interaction:** progenitor stellar evolution.
- **Stable Fe-peak elements:** progenitor mass.



Introduction:
SN Ia Progenitors

Supernova Types

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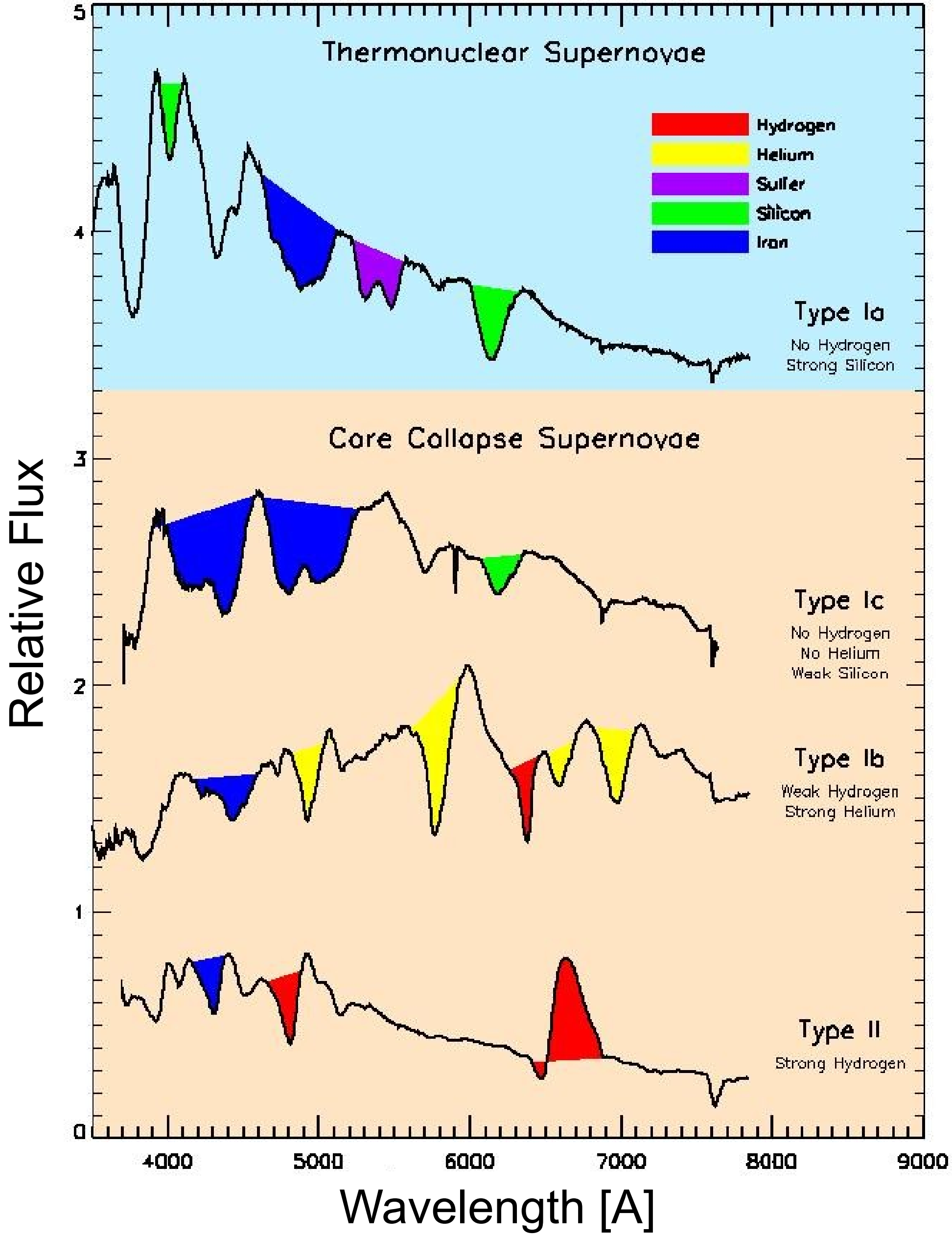


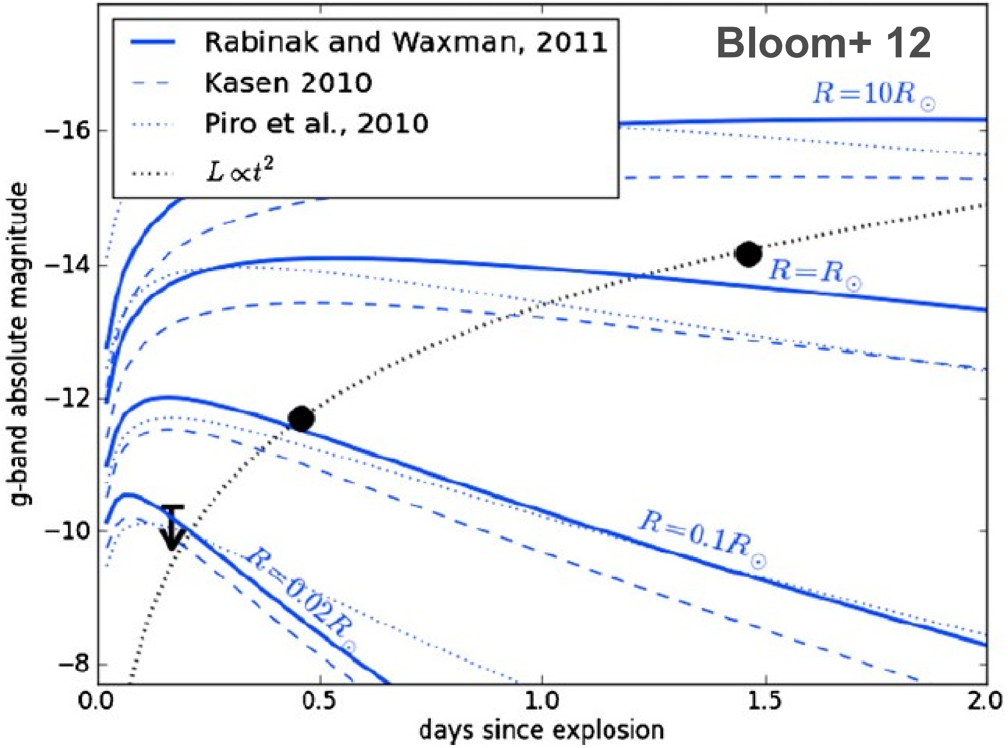
SNe are rare optical transients (t ~ months) with peak magnitudes that rival their host galaxies

- **Types** (optical spectra):
  - **Type I**: no H (**Ia**: Si, **Ib**: He, **Ic**: neither).
  - **Type II**: Strong H.
- **Core collapse** SNe (II, Ib, Ic): massive stars ($M \geq 8M_{\odot}$), several progenitors identified.
- **Thermonuclear** SNe (Ia).

SN Ia: What We Know

No SN Ia progenitors detected so far. Best constraints: pre-explosion *HST* images of nearby SNe. **Progenitors must be:**

- **Small:** early light curve of SN2011fe requires R < 0.02 $R_\odot$ ⇒ C/O WD [Nugent + 11, Bloom+ 12].
- **Faint:** SN2011fe limits rule out some accreting WDs, most RGs, and MS stars larger than ~4 $M_\odot$ [Li+ 11, Kelly+ 14].
- **H-poor:** ≲0.01 $M_\odot$ [Leonard 07, Lundqvist+15].



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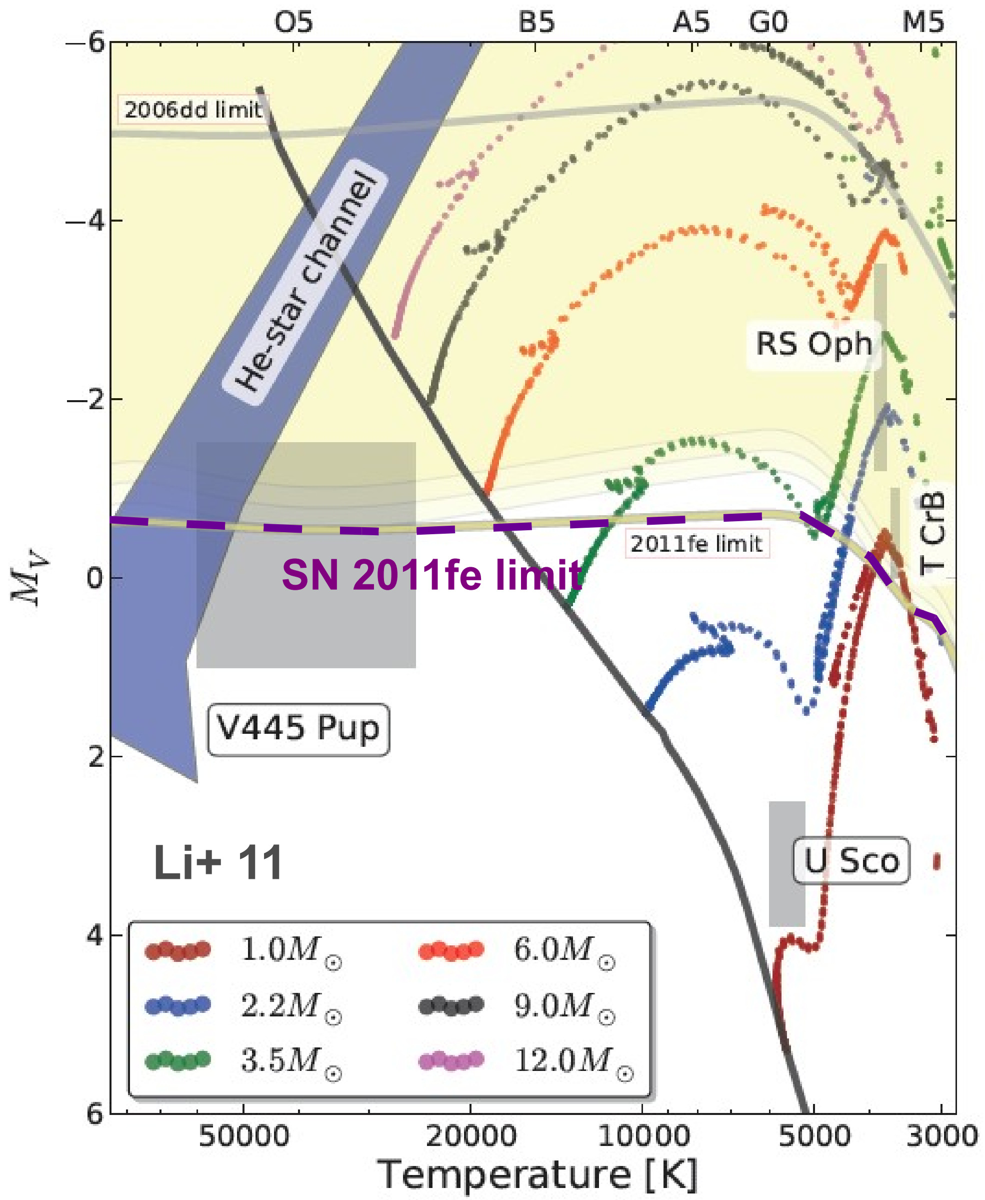

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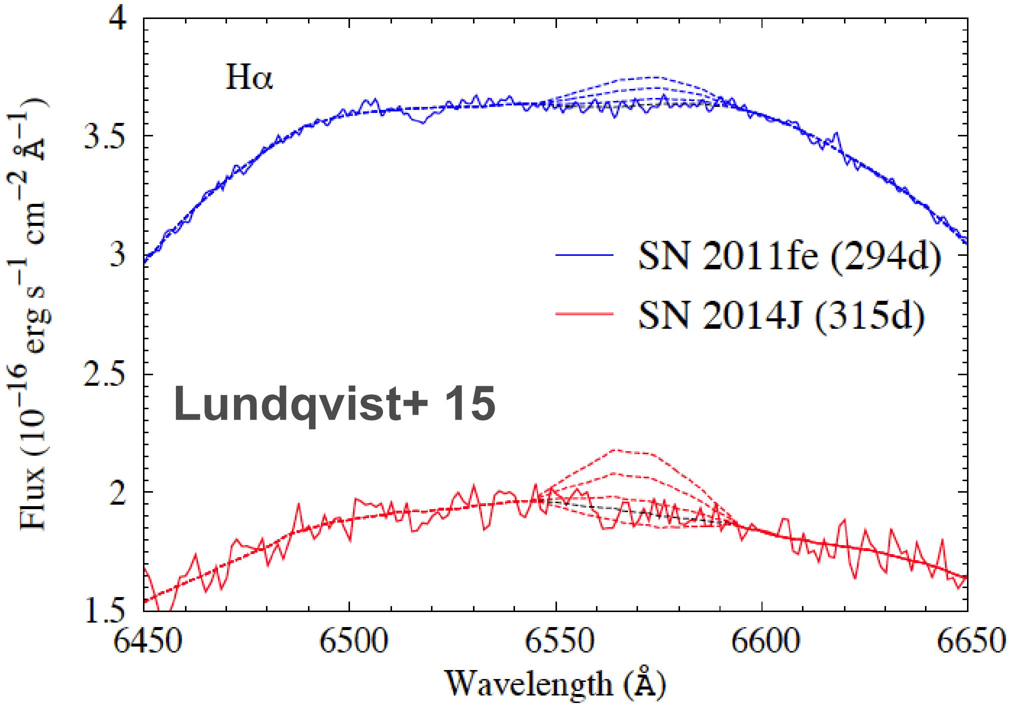

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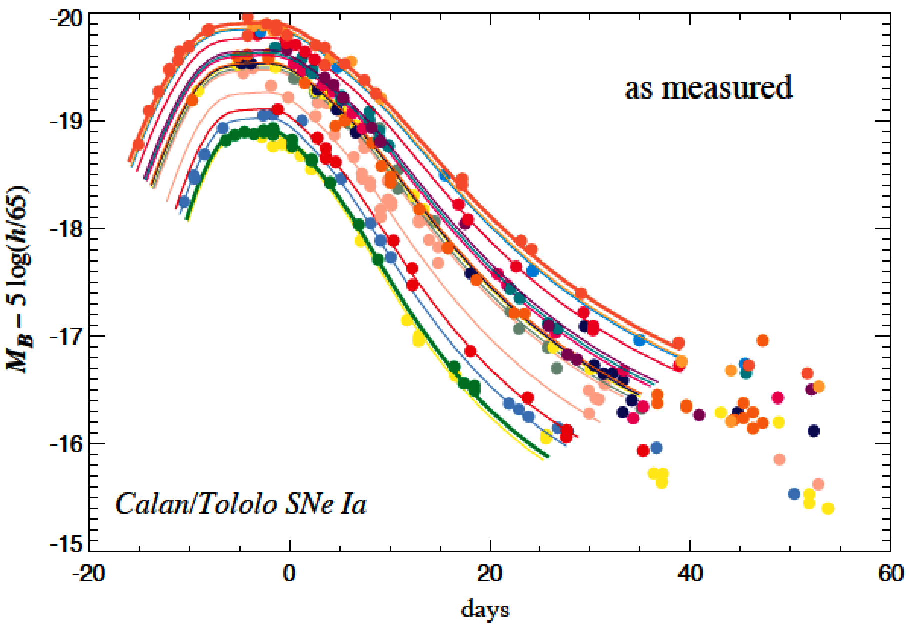

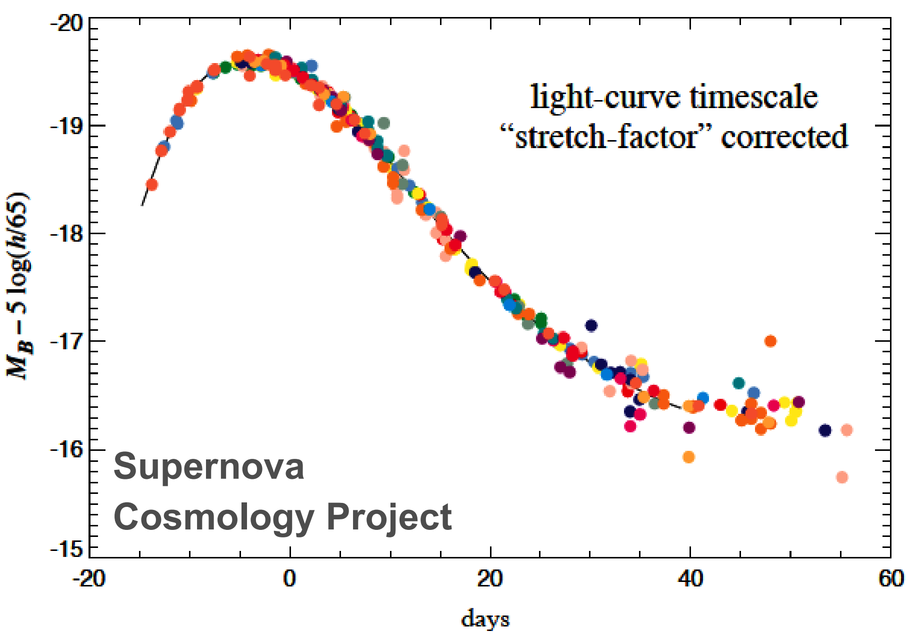

SN Ia are thermonuclear explosions of C+O white dwarfs prompted by accretion in a binary system

- **Fundamentals are well understood:** no H in spectra, energy budget, light curve decay.
- **Key details remain obscure:** explosion mechanism, **progenitor systems**.
- **Strikingly uniform events** ⇒ LC width / luminosity relation (^{56}Ni mass) ⇒ Cosmology.

REVIEWS: Branch & Khokhlov 95; Hillebrandt & Niemeyer 00, Maoz+ 14

Single vs. Double Degenerate SN Ia

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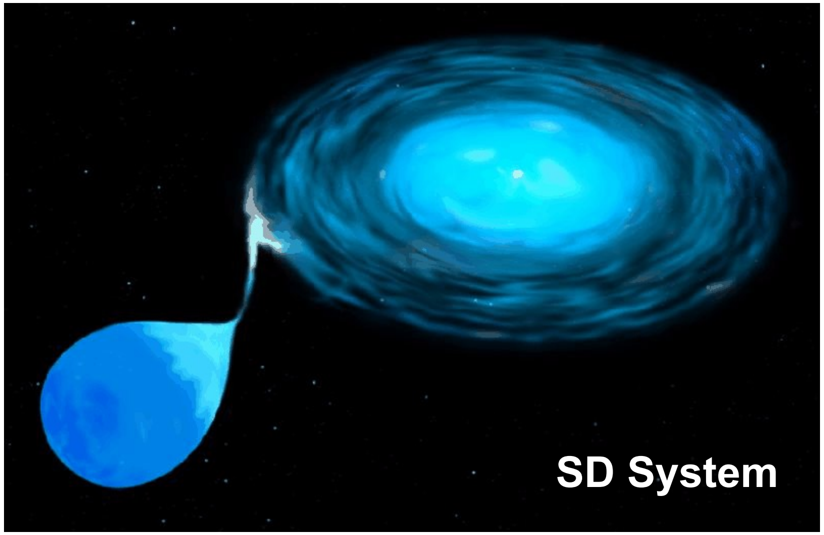
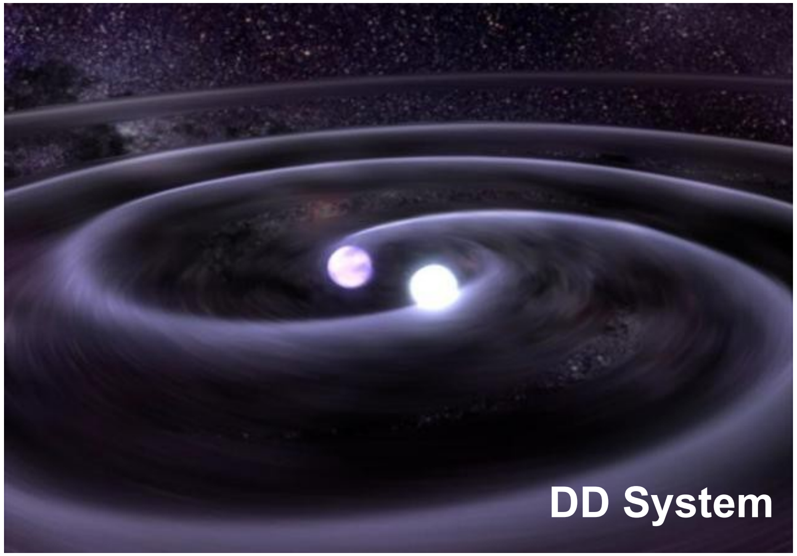
Single Degenerate (SD):

- WD+non-degenerate star.
- Slow accretion ⇒ mass growth ⇒ explosion near M_{Ch} [Hachisu+ 96].
- Some CSM expected (accretion cannot be 100% efficient) [Han & Podsiadlowski 04].



Double Degenerate (DD):

- WD+WD.
- GW emission ⇒ merging/collision ⇒ explosion, not necessarily near M_{Ch} [Iben & Tutukov 84, Webbink 84, Sim+ 10, van Kerkwijk+ 10].
- Not much CSM expected.



Clues to SN Ia Progenitors

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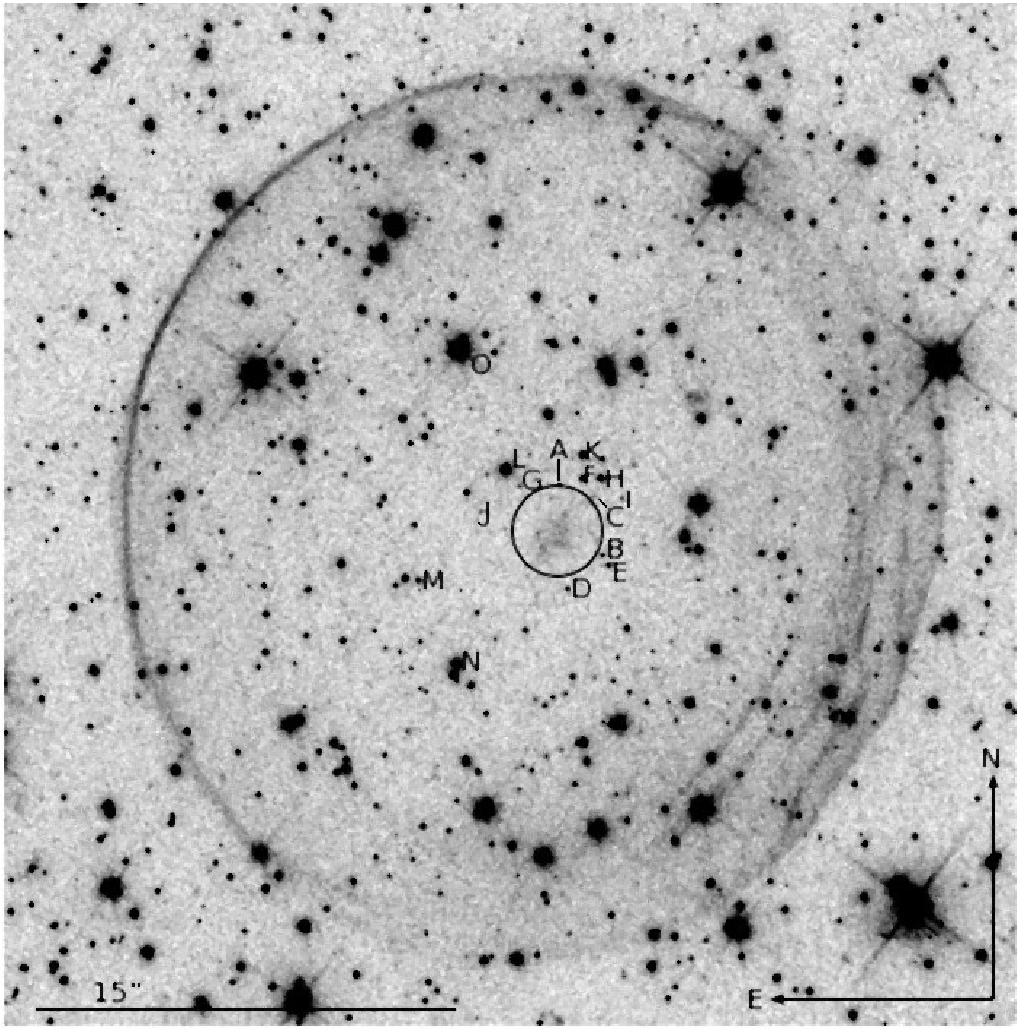
- **Surviving companion searches in SNRs** ⇒ Upper limits or ambiguous results [Ruiz-Lapuente+ 04, Kerzendorf+ 09, Schaefer & Pagnotta 12, Gonzalez-Hernandez+ 12] ⇒ DD.

- **SN Ia delay time distribution (DTD)** behaves like 1/t and has power at ~10 Gyr [Maoz & Mannucci 11, Maoz+ 14] ⇒ DD.

- **WD+WD merger rate ~ SN Ia rate** in the Milky Way; most mergers are sub-Ch [Badenes & Maoz 12] ⇒ DD.

SNR 0509-67.5



Schaefer & Pagnotta 12

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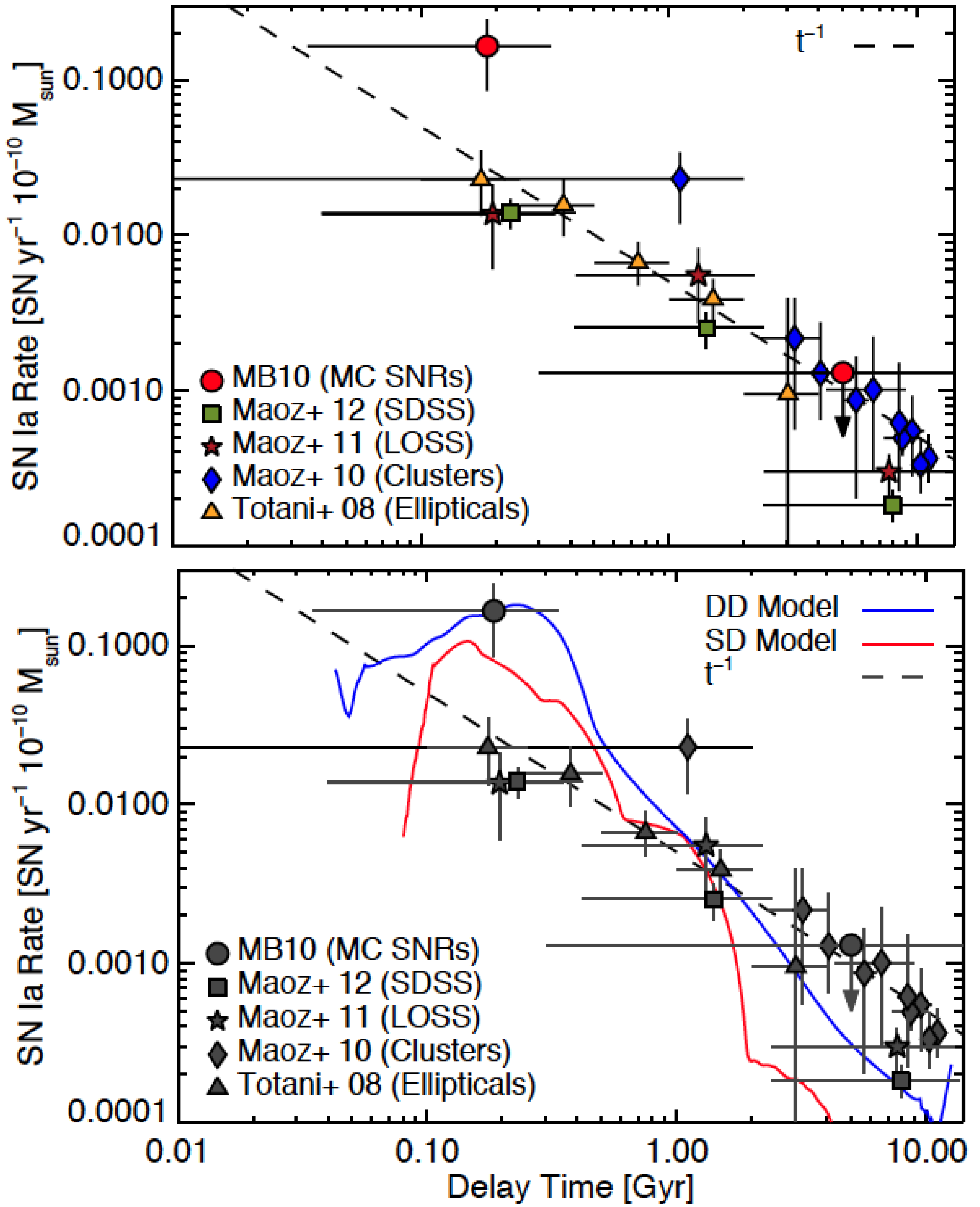

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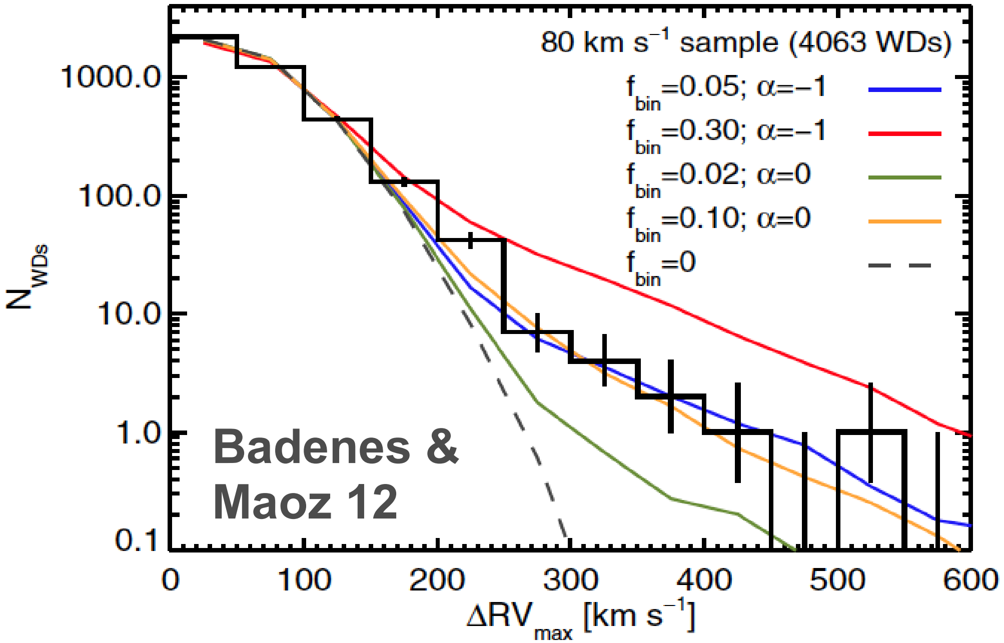

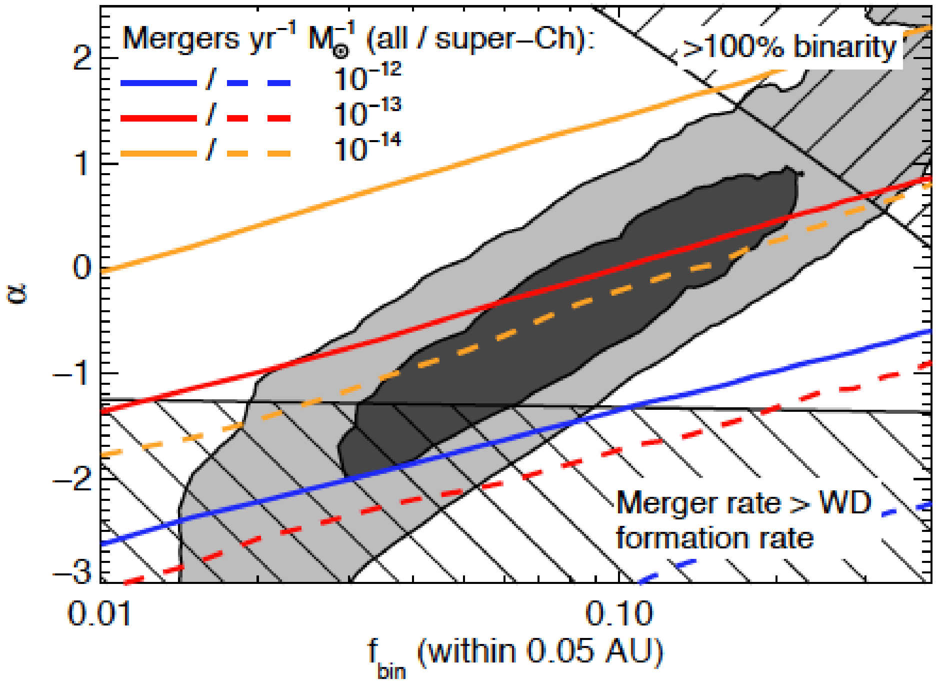

Clues to SN Ia Progenitors

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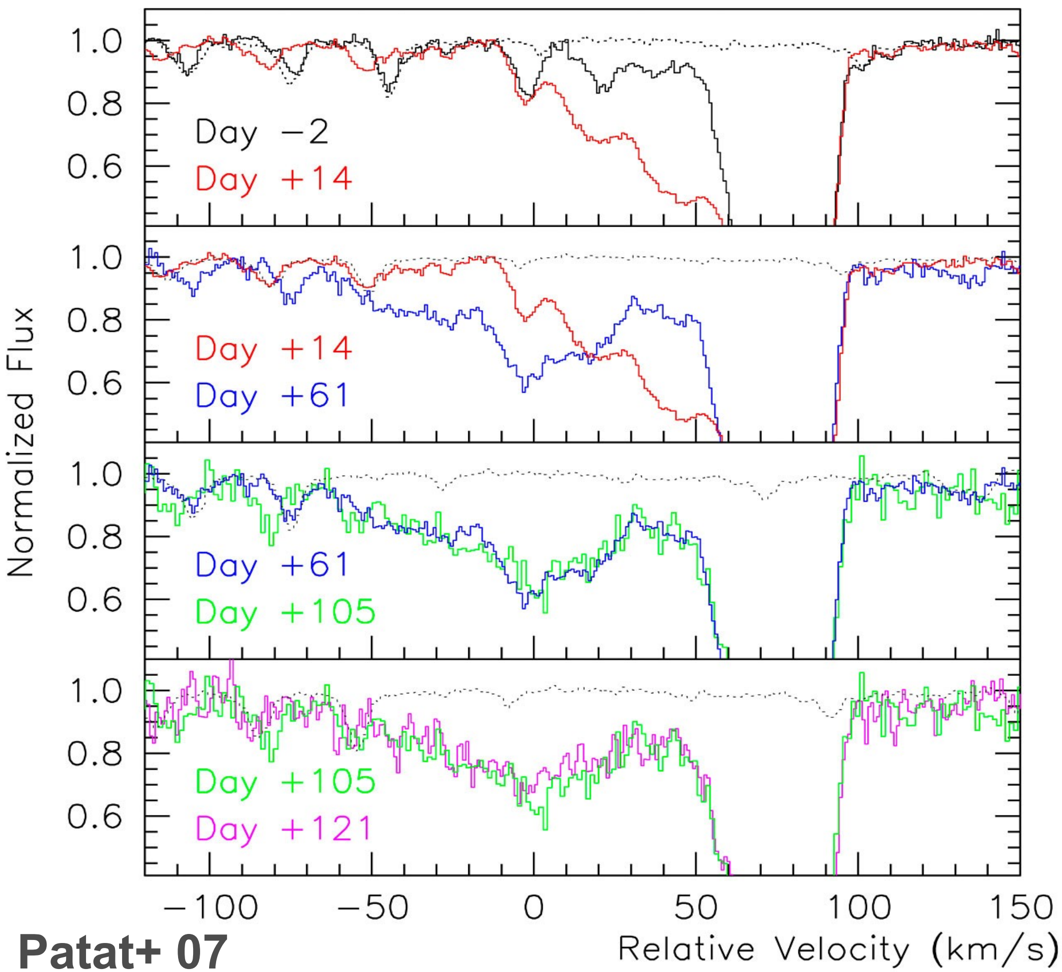
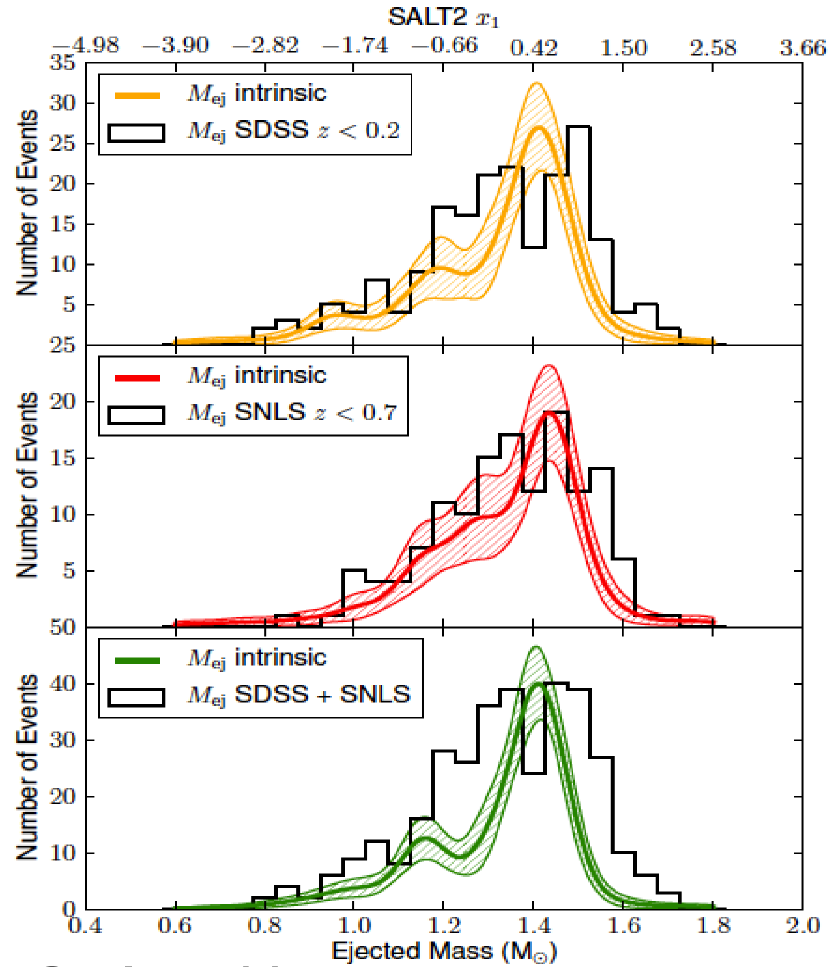
- **Blueshifted variable absorption** in SN Ia [Patat+ 07, Sternberg + 11, Dilday + 12] ⇒ SD? DD? [Moore & Bildsten 12, Soker+ 13, Raskin & Kasen 13].
- **Distribution of M_{ej}** ⇒ both M_{Ch} and sub-Ch [Scalzo+ 14] ⇒ mixture?

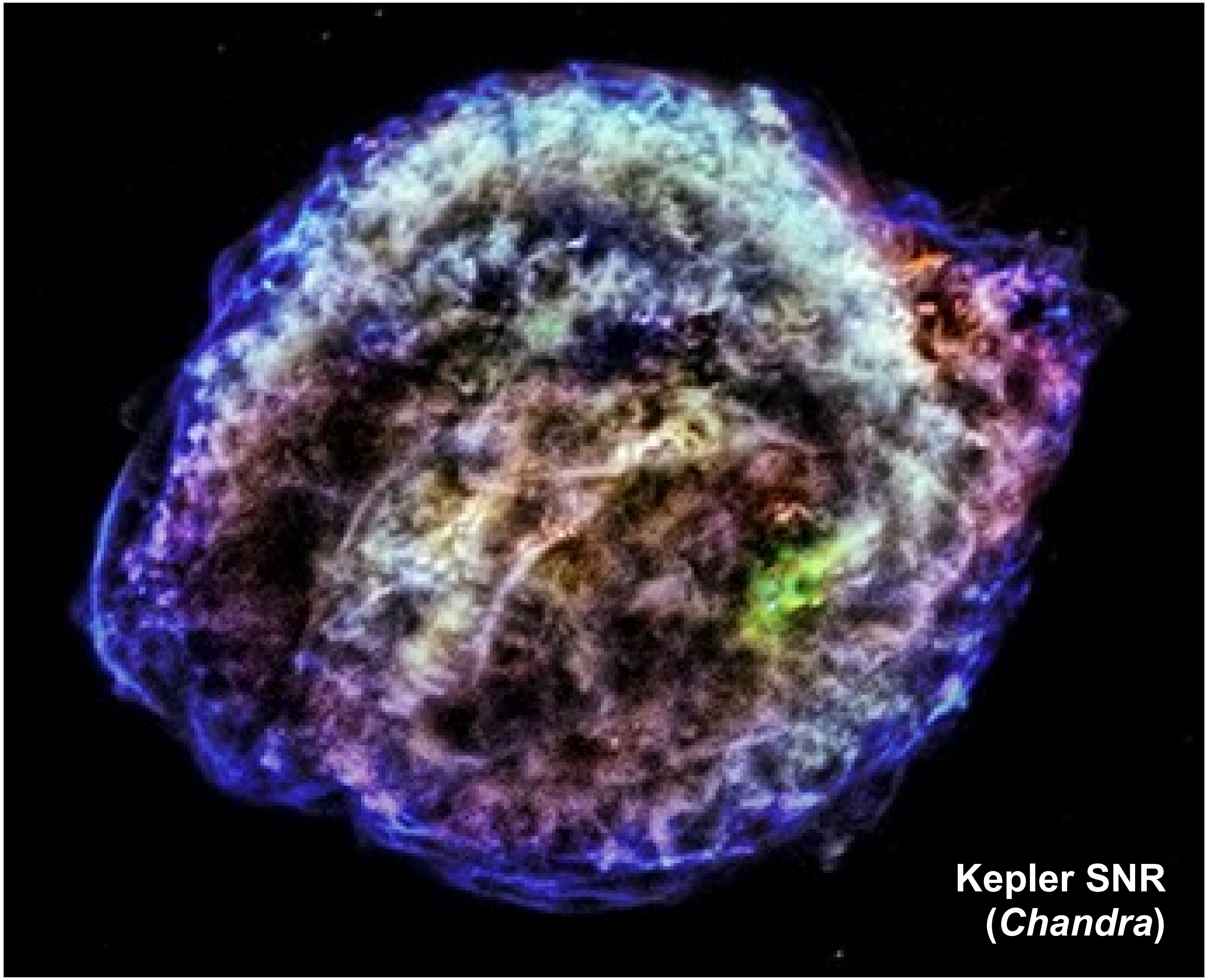


Patat+ 07



Scalzo+ 14

CSM Interaction in Type Ia SNRs



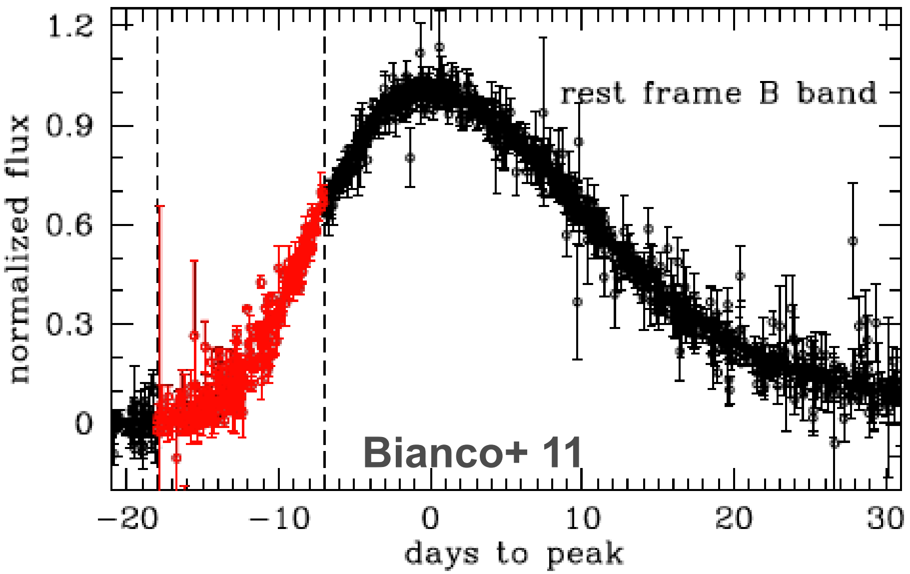
CSM Interaction in SN Ia

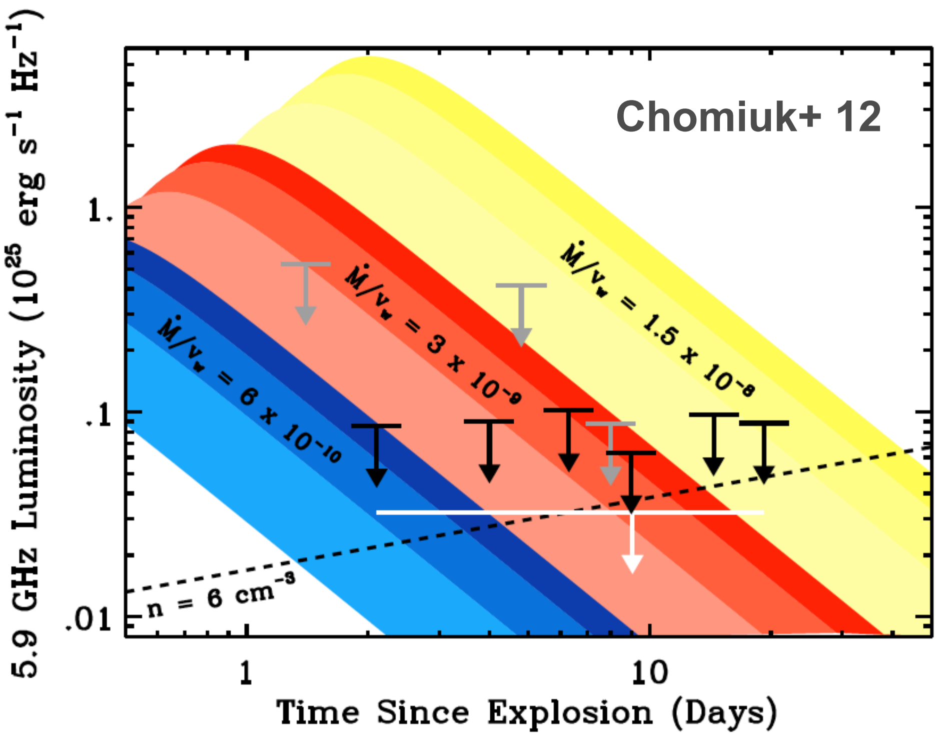
Most SN Ia show **no signs of dynamical interaction with CSM** ⇒ small dM/dt from progenitor.

- **Early times (~1 d)**: no extended envelope or accretion disk in optical light curves [Hayden+ 10; Bianco+ 11].

- **Intermediate times (~10 d)**: no radio or X-ray detections ⇒ (dM/dt)/v < 10^{-9} $M_\odot$ yr^{-1} (100 km s^{-1})$^{-1}$ [Chomiuk+ 12, Margutti+ 12, Perez-Torres+ 14].

- **Late times (~500 yr)**: (Most) Type Ia SNRs consistent with a uniform ISM [Badenes+ 06, 07, 08a].





CSM Interaction in SNRs

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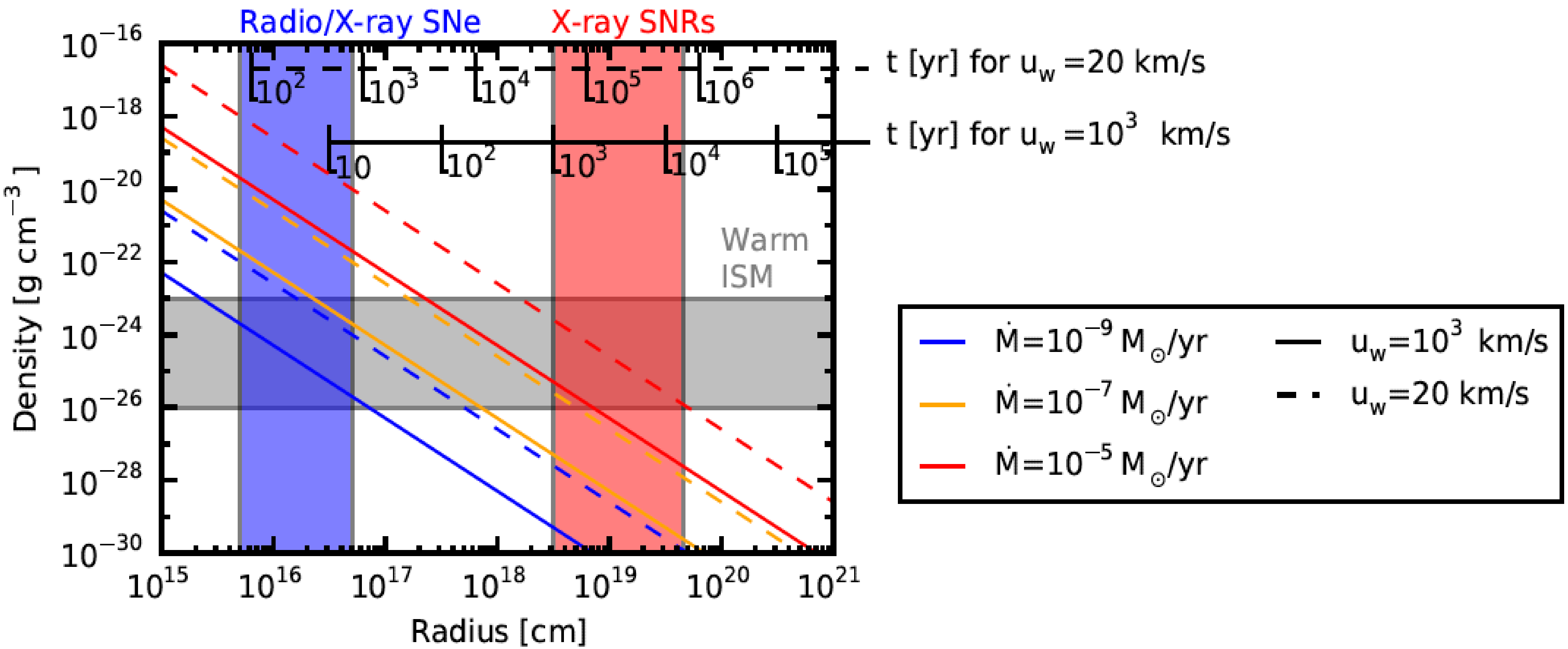
- **SNRs ⇒ spatial (and temporal) scales relevant for stellar evolution** of SN progenitors ($t \lesssim \tau_{KH}$).
- **Can only probe dynamical interaction**: CSM that can slow down SN ejecta.



CSM Interaction in SNRs

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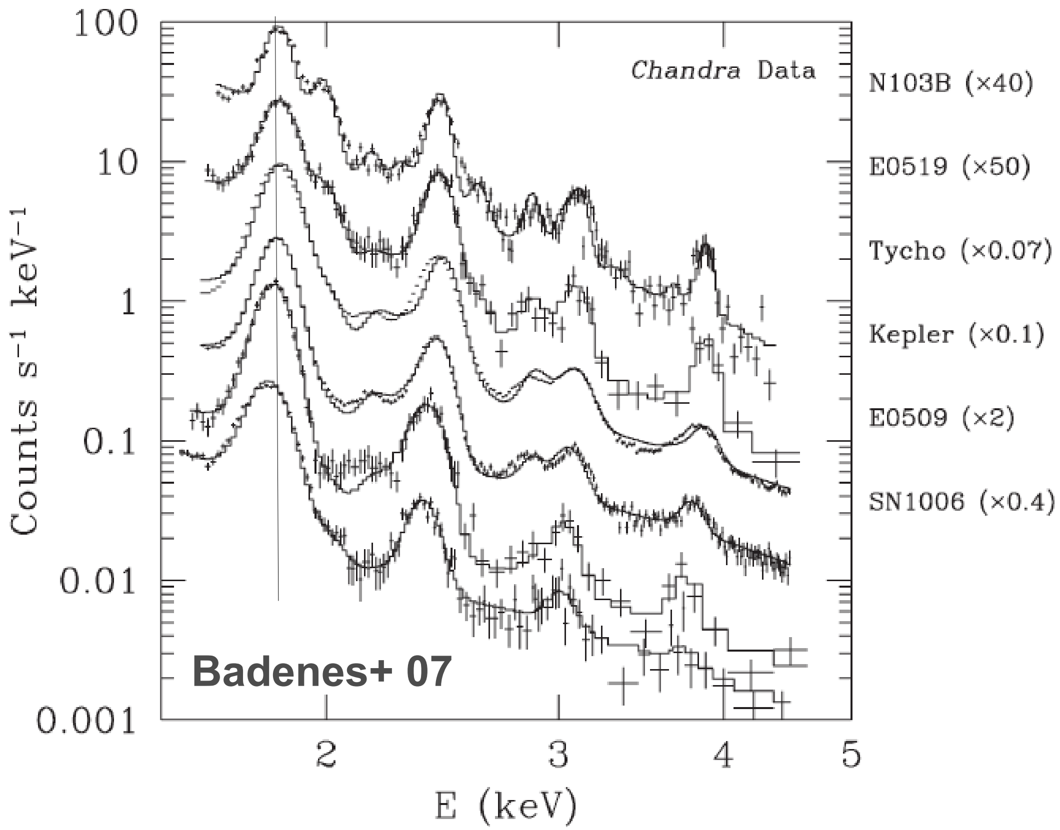
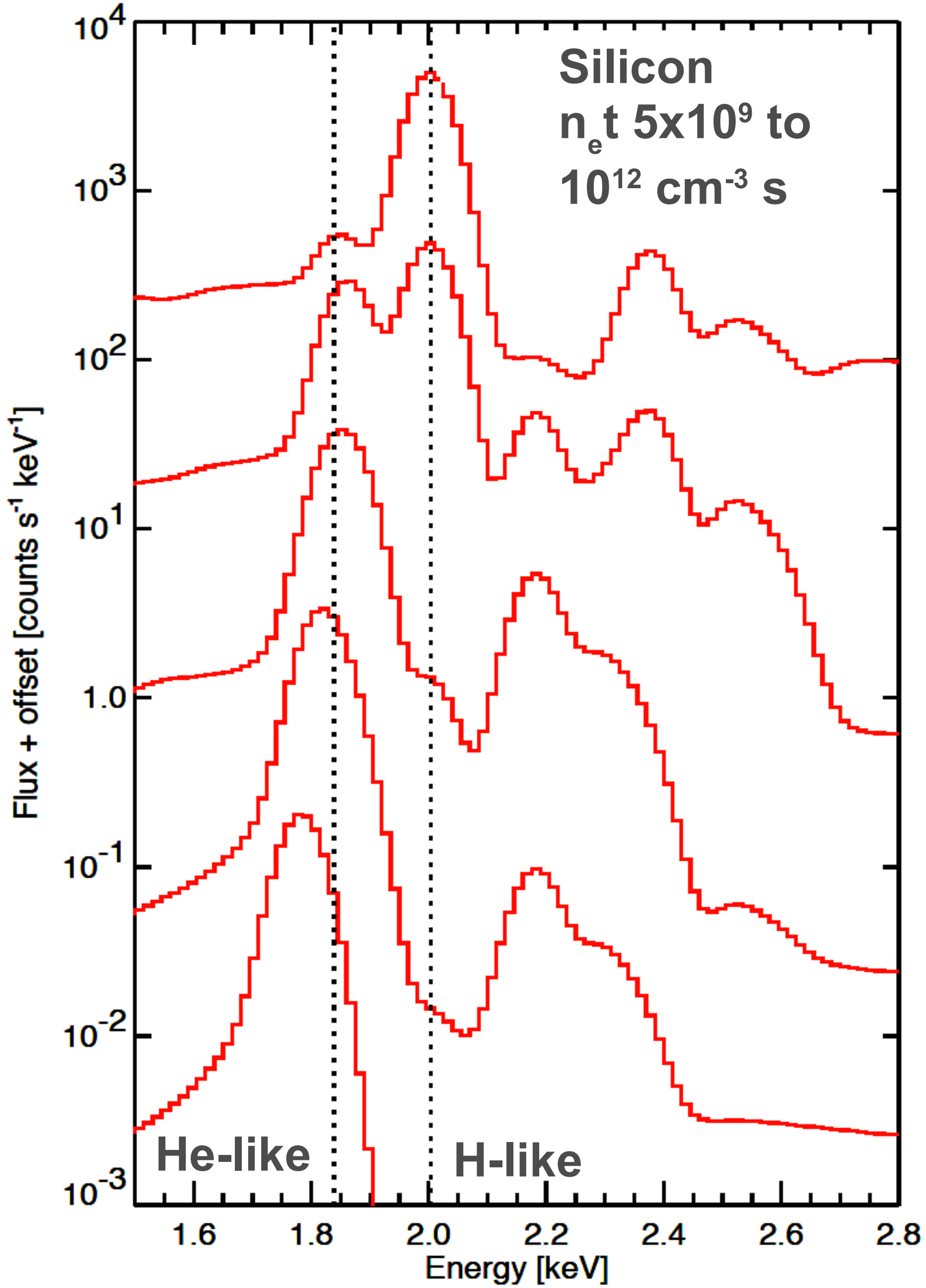
- **X-ray spectra ⇒ AM density constraints.** NEI plasma: ionization timescale (**$n_e t$**) [Badenes+ 07].
- High $n_e t$ ⇒ high centroid energy and line flux.





CSM Interaction in SNRs: Fe K

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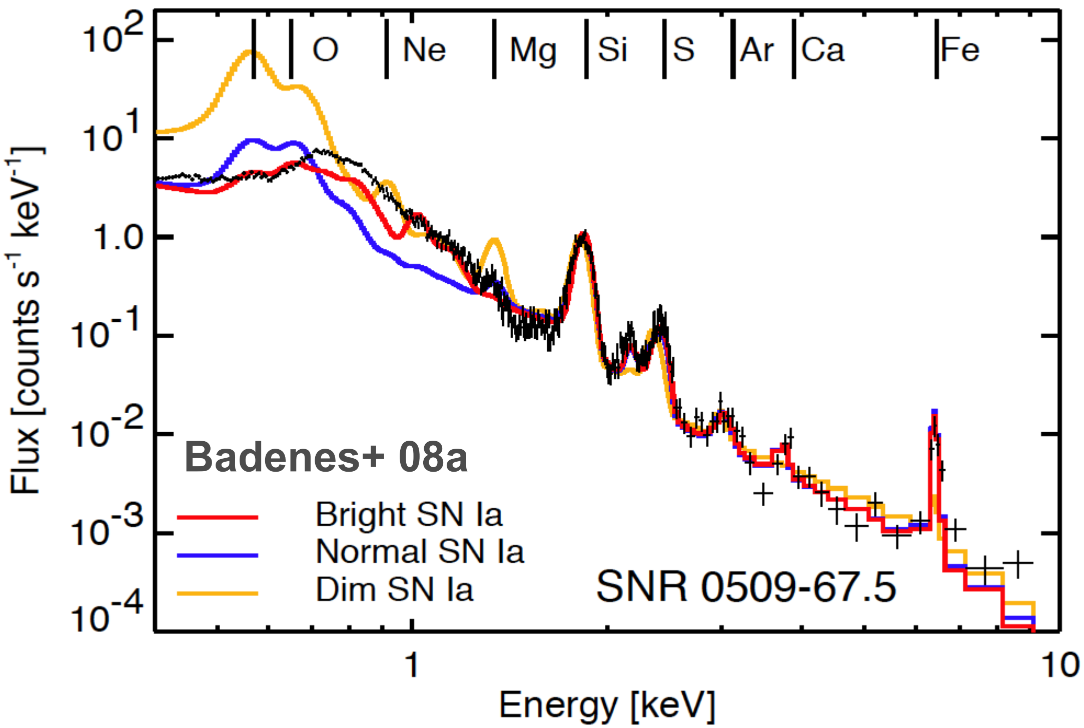
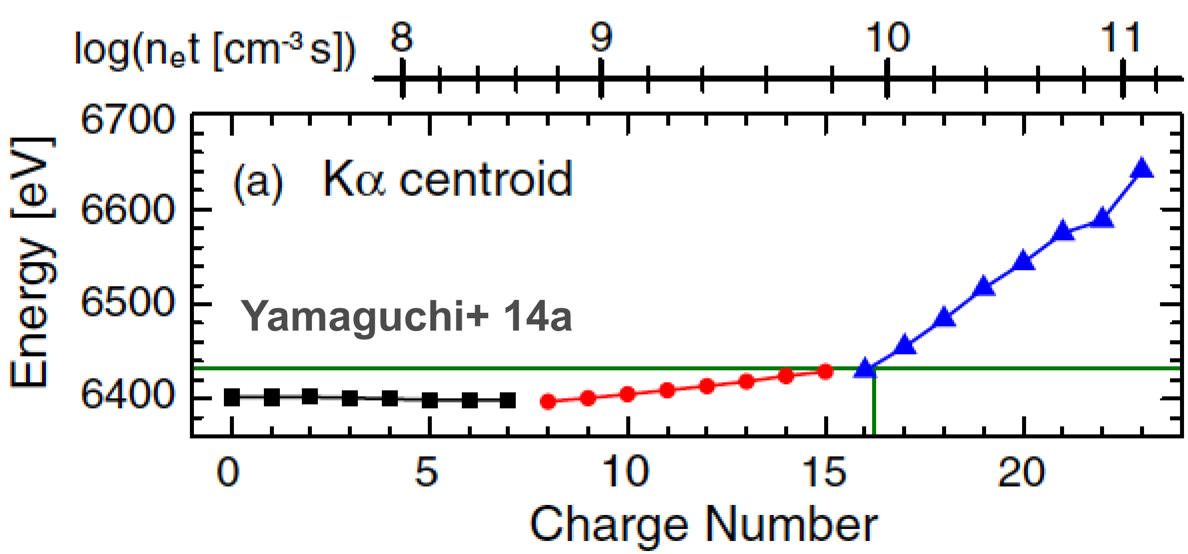
- Use **Fe Kα line blend** at ~6.5 keV as an AM density diagnostic.
- Most SNe (Ia and CC) eject some Fe ⇒ innermost layers.
- Large n_et required to fully ionize Fe ⇒ **large dynamic range in ρ_{AM}**.
- Need high effective area at 6.5 keV: ***Suzaku***.
- Details: Yamaguchi, CB+ 14b





Fe K Emission in SNRs

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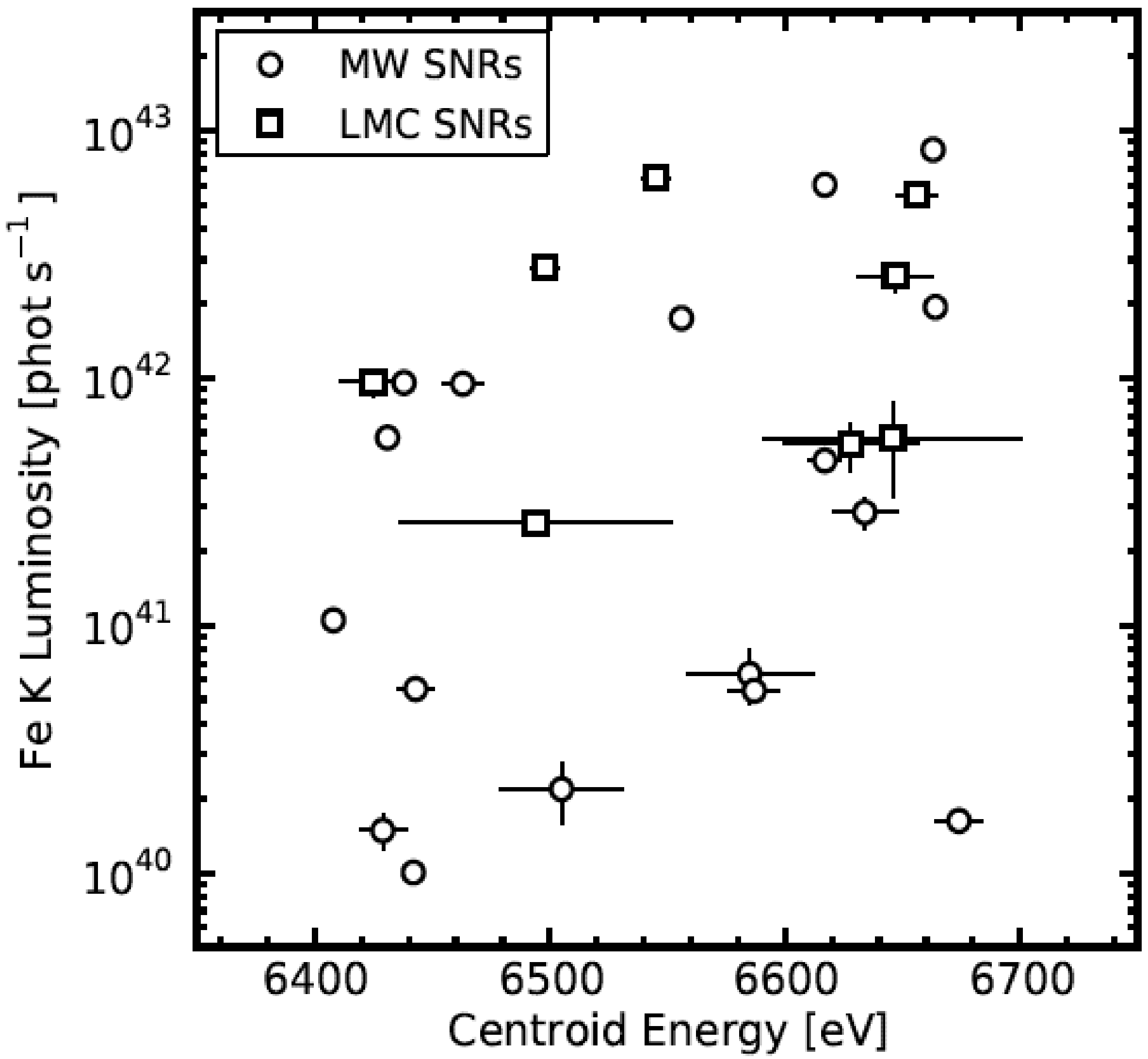
- **24 SNRs** (22 *Suzaku*, +1 *Chandra* [Borkowski+ 13], +1 *XMM* [Maggi+ in prep.]).

- Scatter plot?



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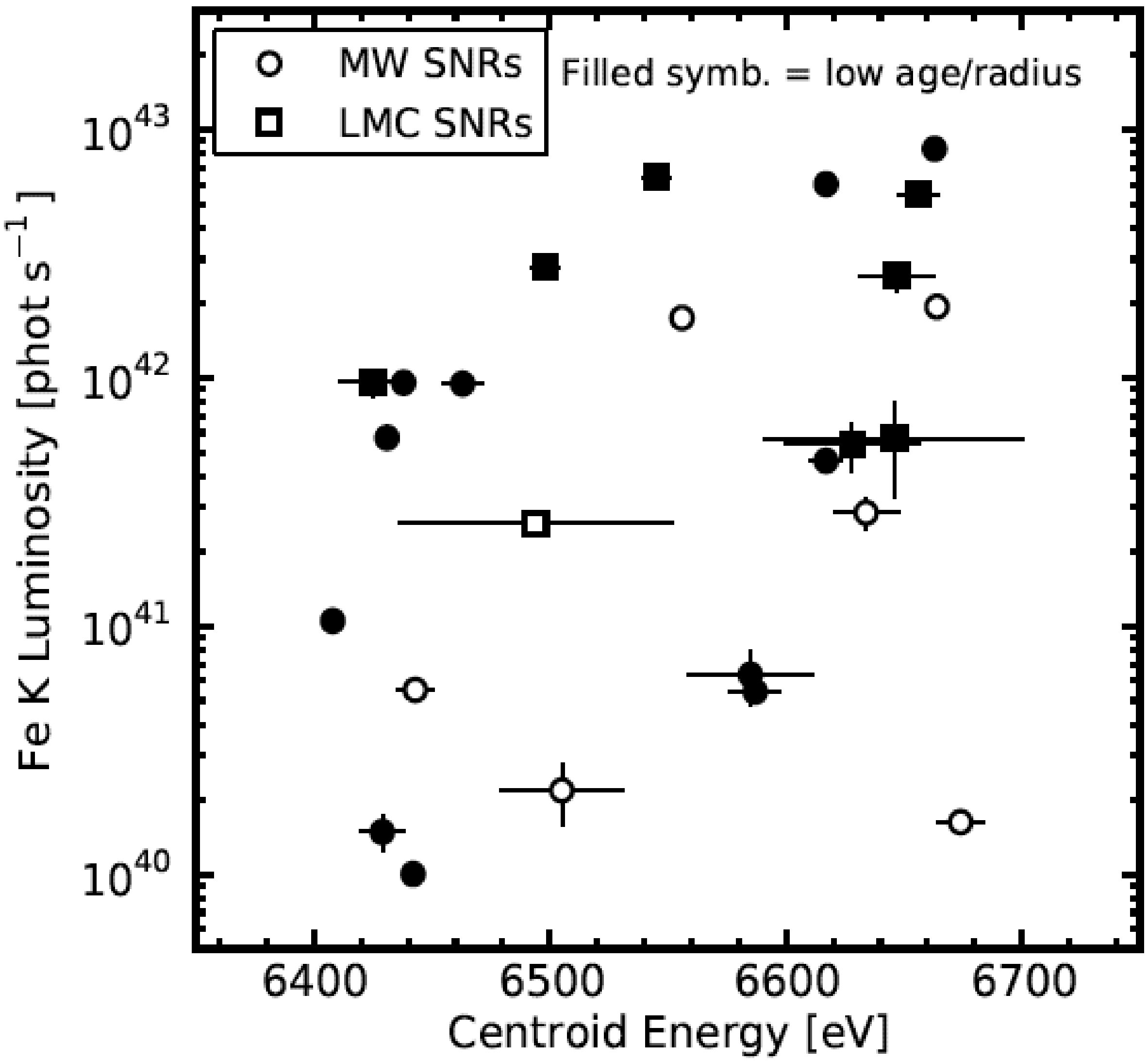
- Account for dynamically old/young SNRs ⇒ **bimodal distribution** in FeK centroid/luminosity.



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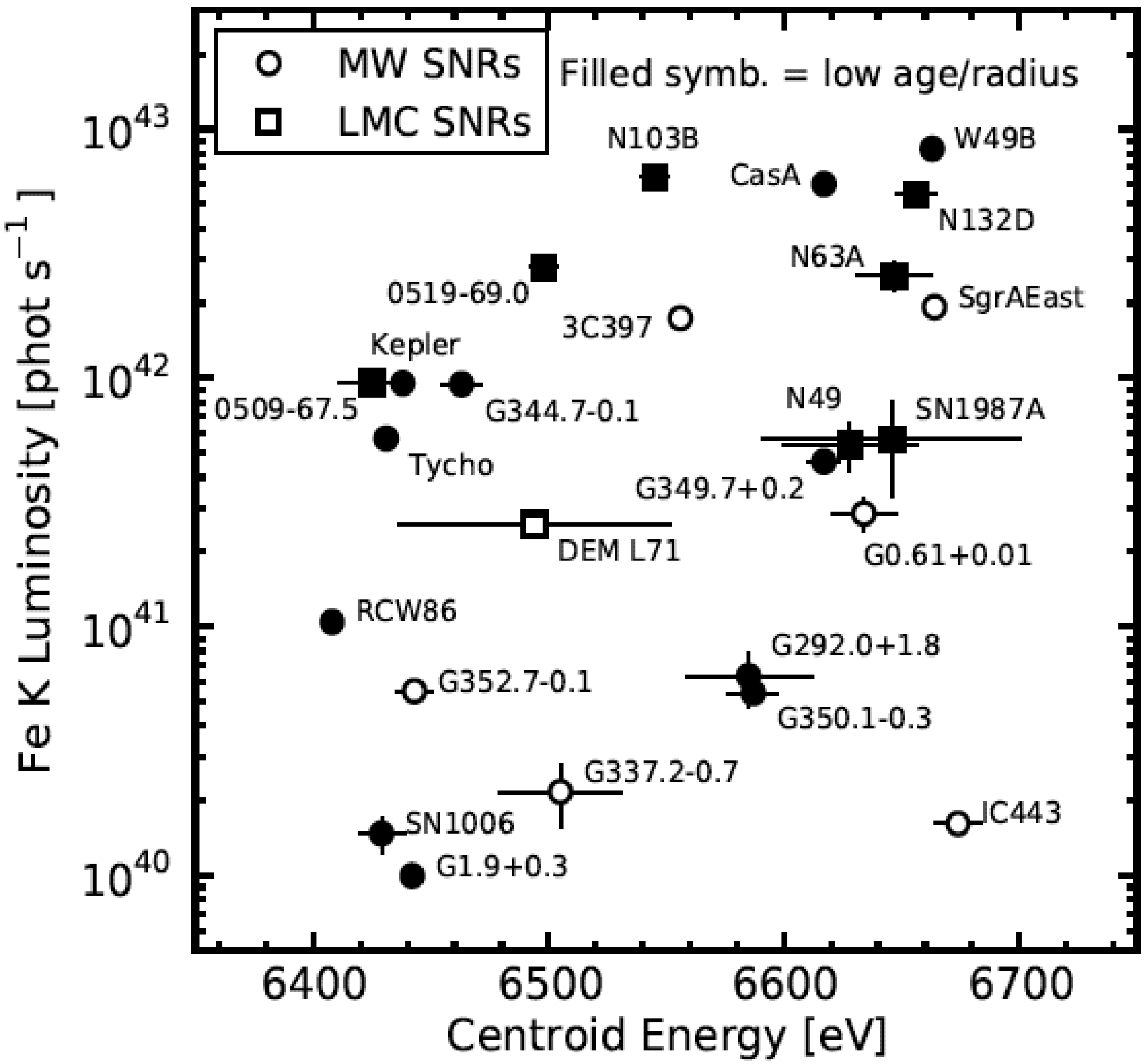
- **Ia/CC SNRs ⇔ low/high FeK centroids**.



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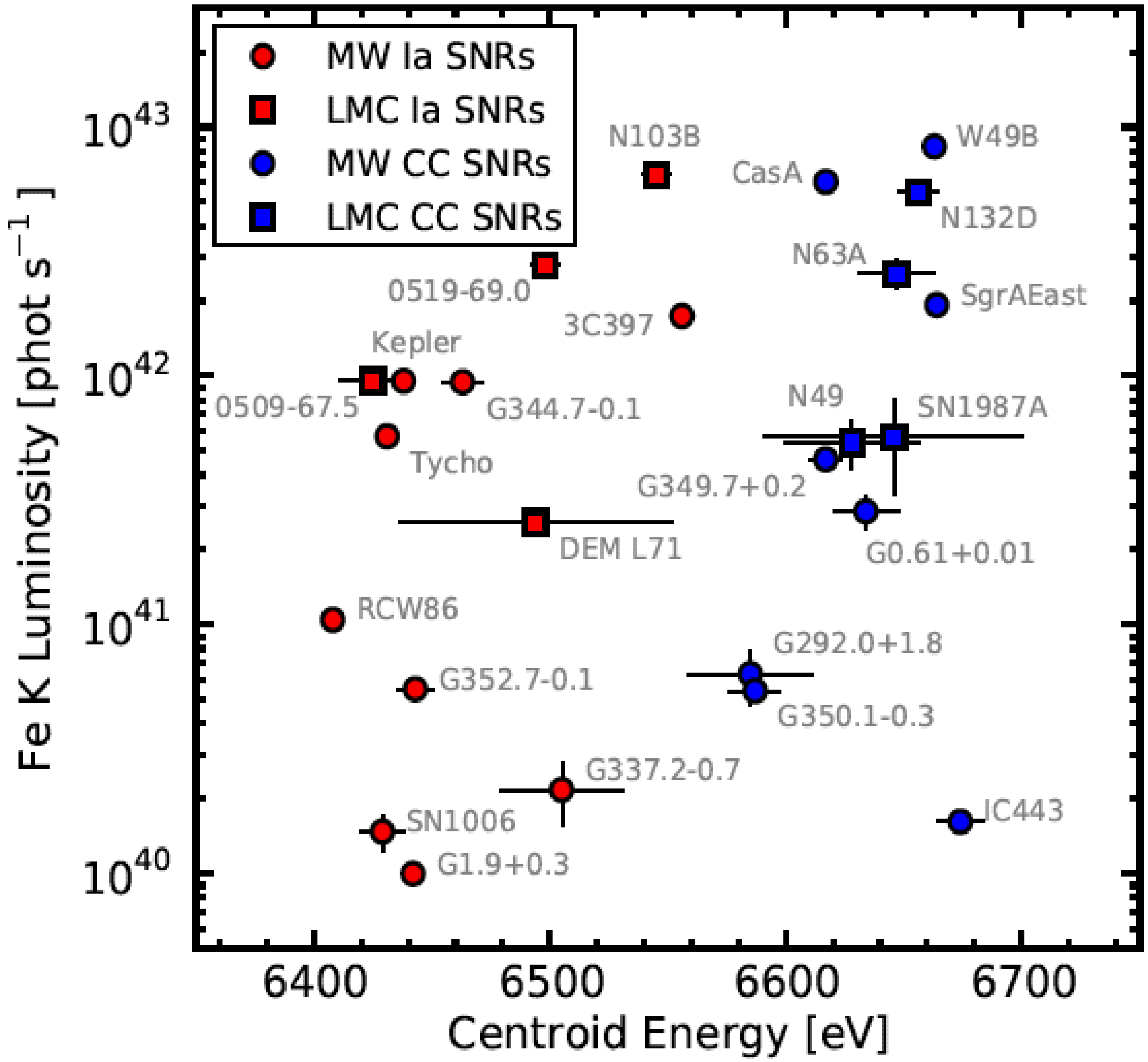
- **Ia/CC SNRs ⇔ low/high FeK centroids**.

- **CSM interaction!**

- New method to classify SNRs + quantify CSM interaction.



Type Ia SNR Models

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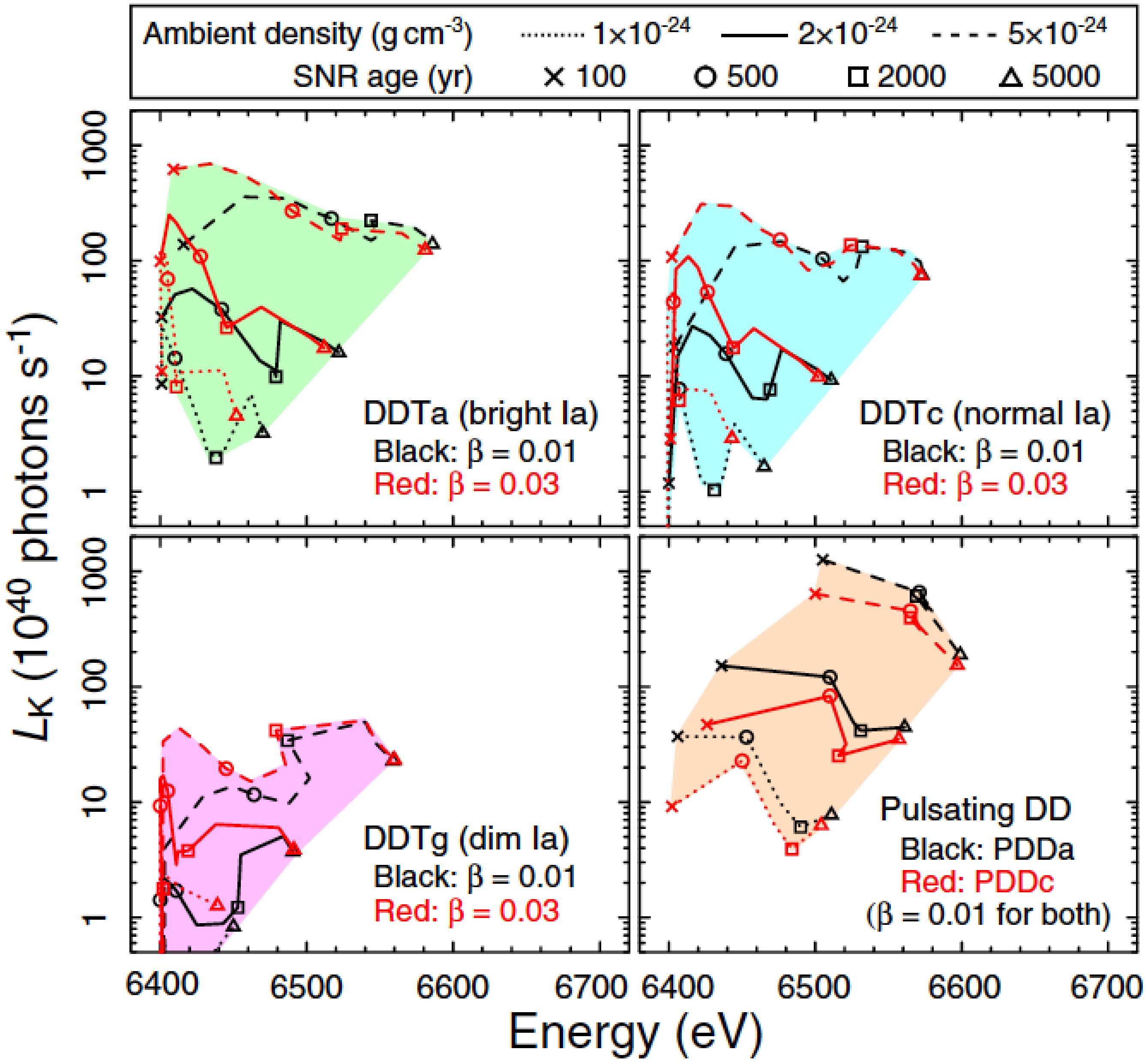
- **Type Ia SNR models:** M_{Ch} ejecta + uniform AM evolved to 5000 yr [Badenes+ 03,05,06,08a].

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

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



Models vs. Data

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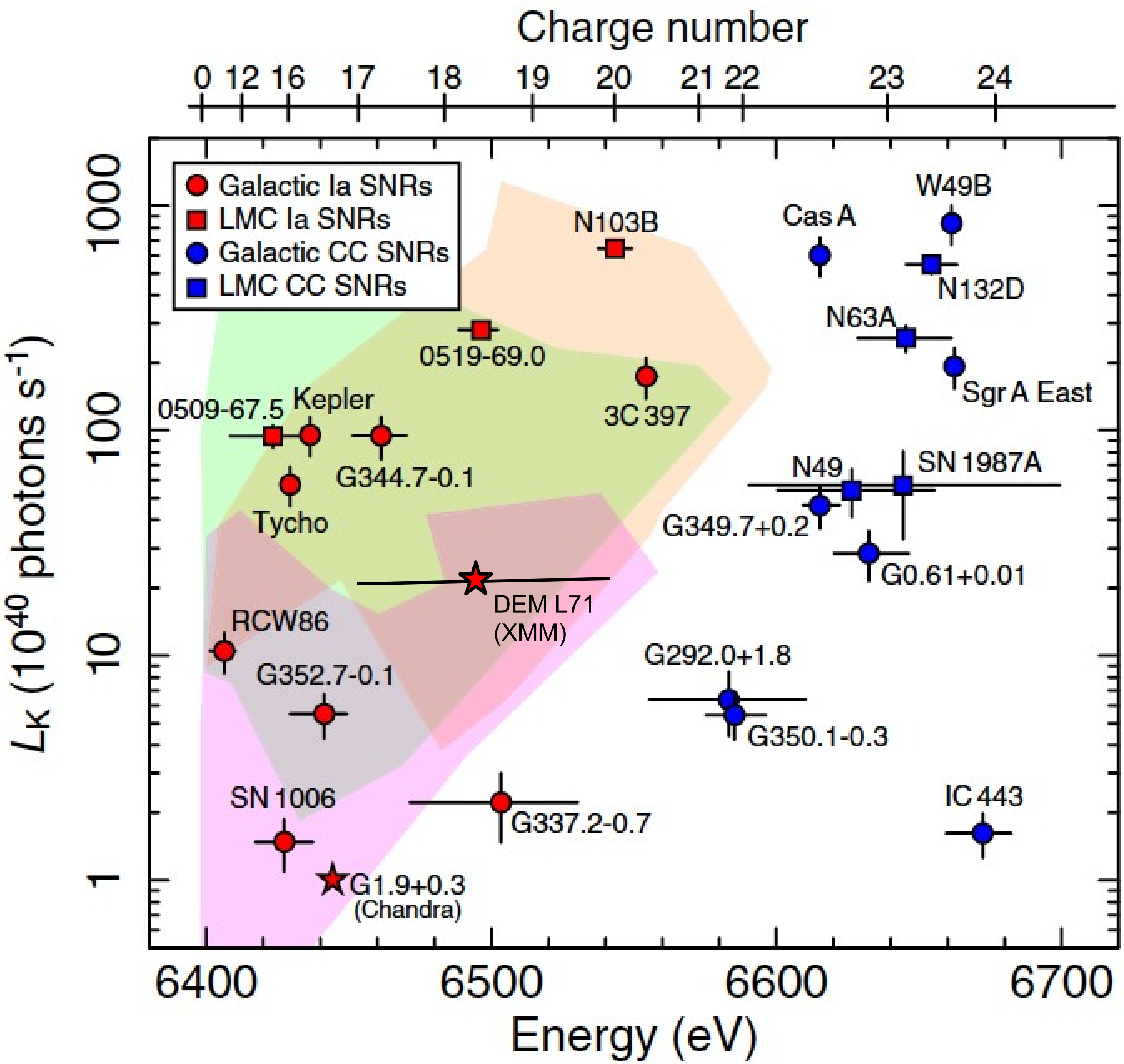
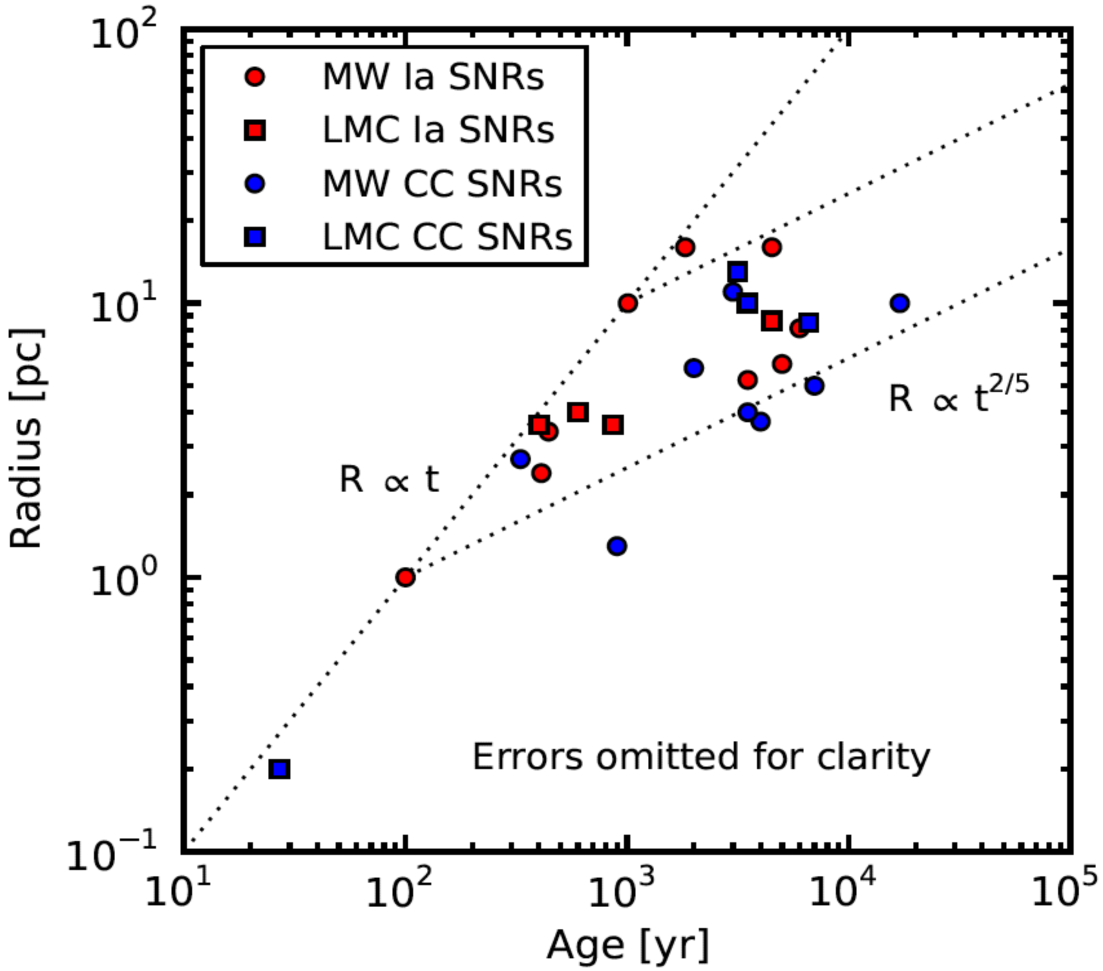
- **Uniform AM, M_{Ch} ejecta can explain (most) Ia SNRs.**
- N103B requires PDD model, maybe CSM interaction [Williams+ 14].
- **Evaluate stellar evolution + explosion with SNR observations**.
- **Models are required to interpret these data**.



What is going on?

- **Different dynamics for CC and Ia SNRs**: several $M_\odot$ of CSM vs. much less, maybe none ⇒ later transition to Sedov.



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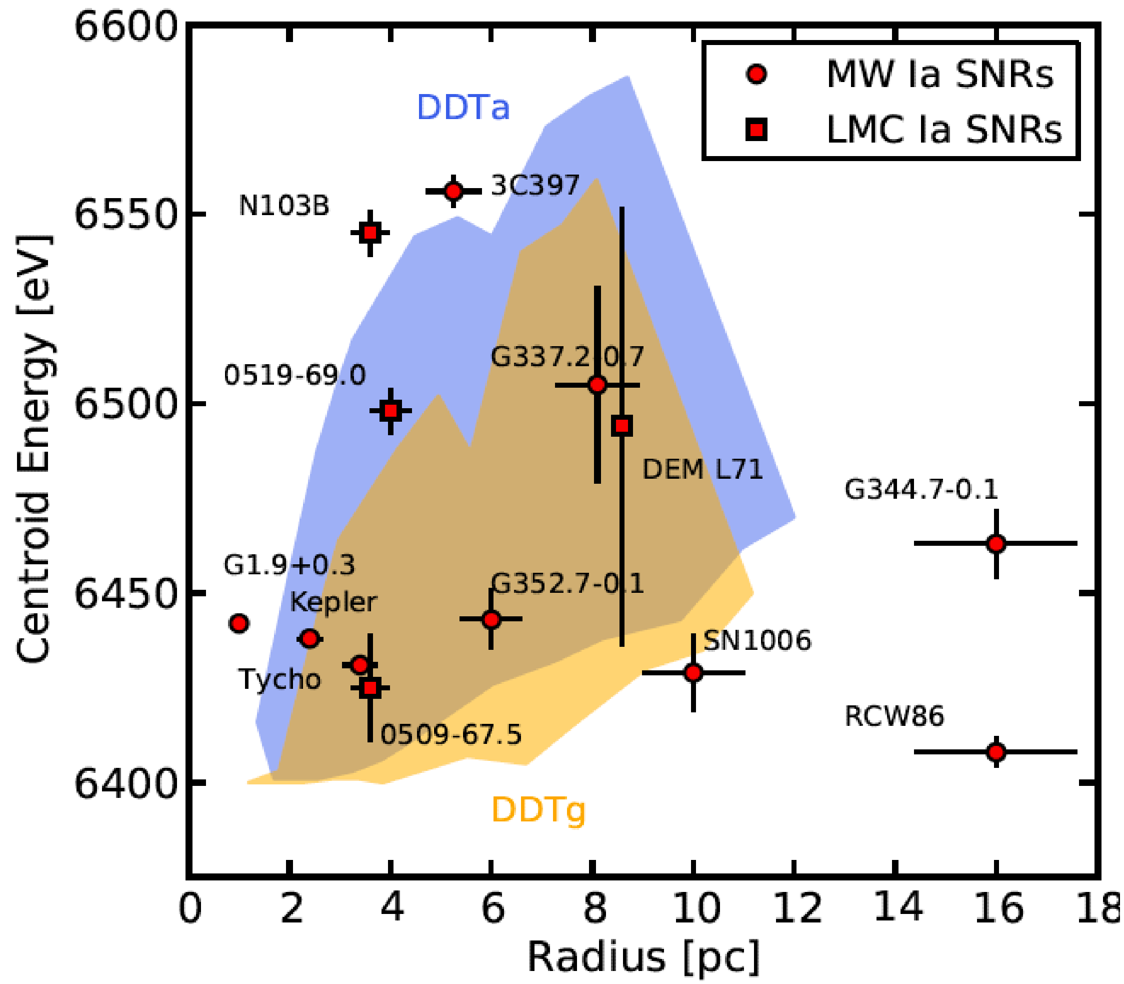
- **Kepler, N103B might have some CSM** [Patnaude+ 12, Burkey+ 12, Chiotellis+ 12, Williams+ 14].

- **RCW 86** (and possibly G344.7-0.1) are **cavity explosions** [Badenes+ 07, Williams+ 11, Broersen+ 14].



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

A Step Back

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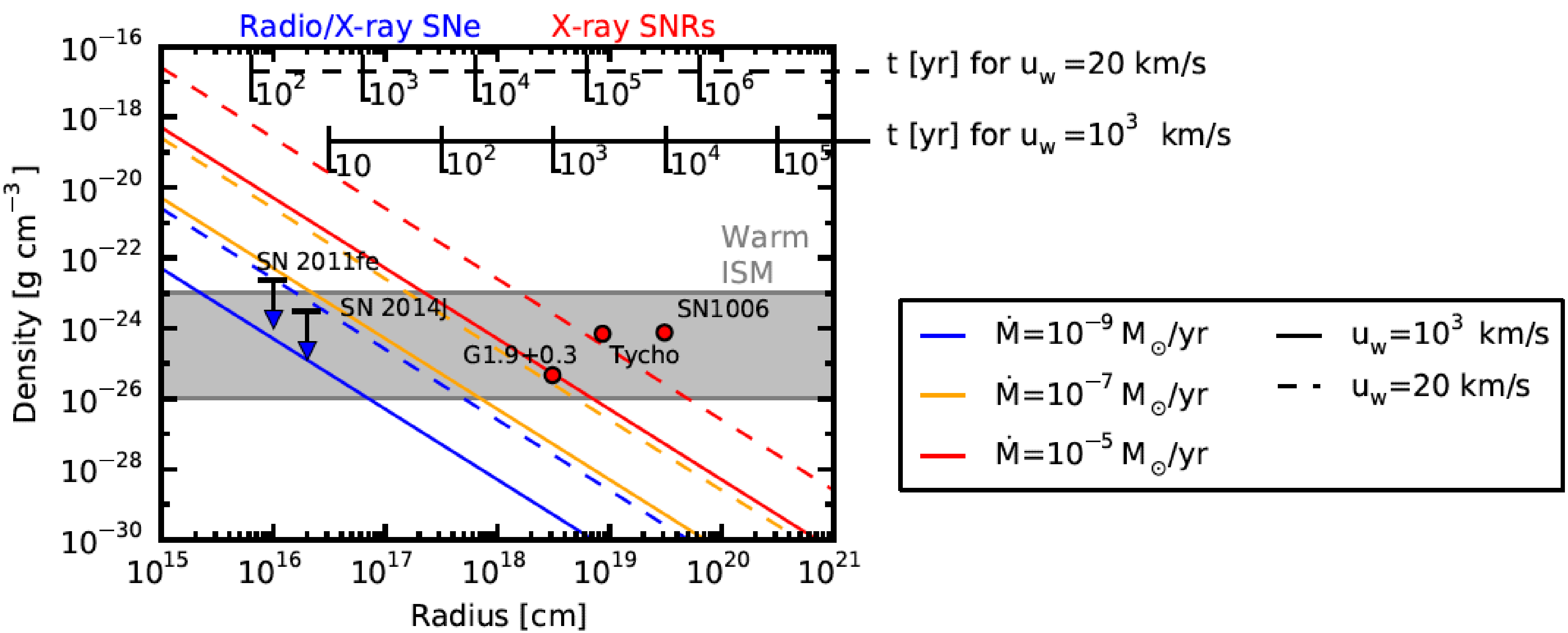
- **SN Ia AM density estimates** from radio/X-ray SNe (~10d, ~0.01 pc) and SNRs (~500 yr, ~several pc) **are consistent with the warm phase of the ISM** [Chomiuk+12 Perez-Torres+ 14, Raymond+ 07, Slane+ 14, Borkowski+ 14]. Mild CSM interaction is allowed, probably also small (~0.5 pc) cavities around the progenitor.



Steps Forward

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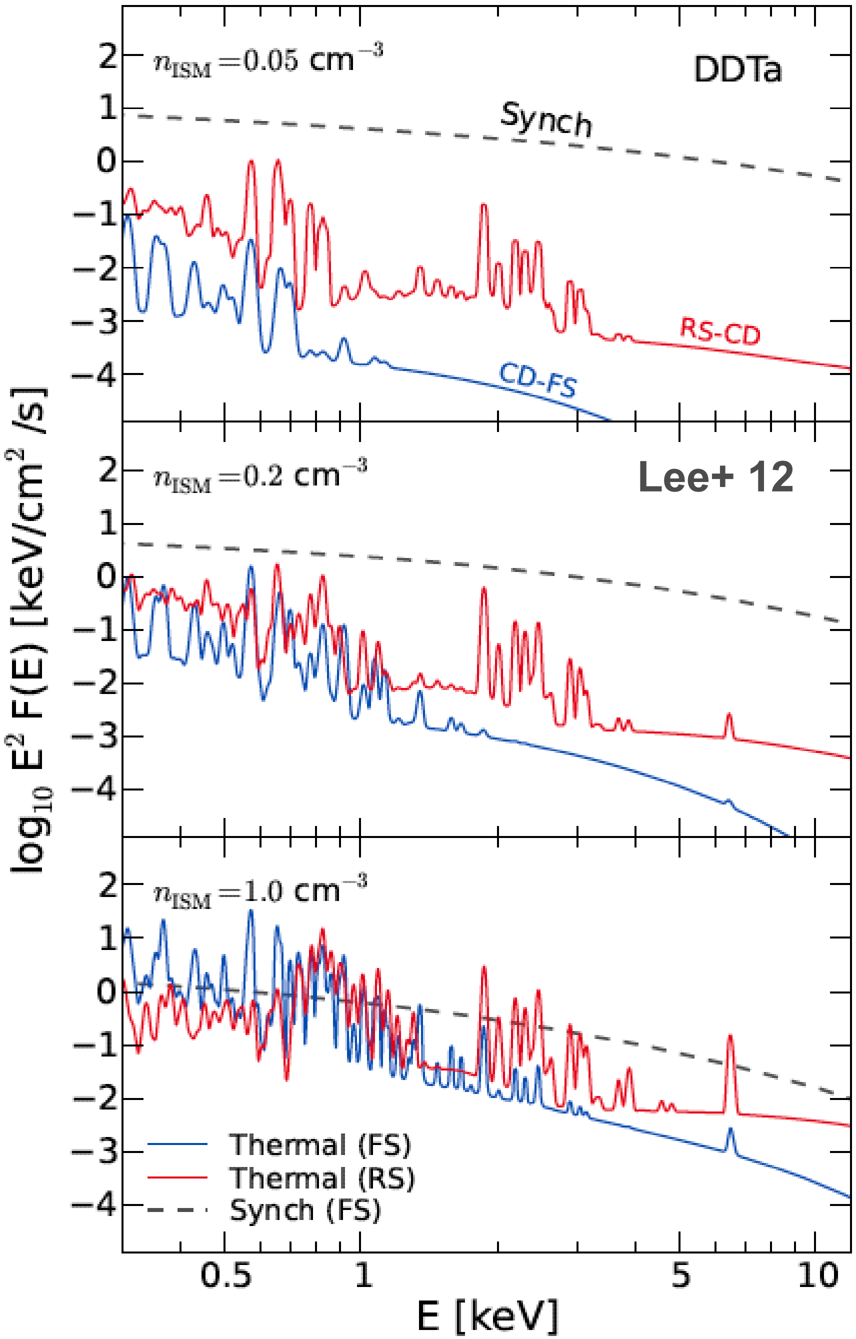
- **Expand the model grid for Type Ia SNRs**: CSM interaction, sub-Chandra explosions (Matt Schell's thesis).
- **Improve the model physics**: CR-modified dynamics [Lee+ 14].
- **CC SNR models**. Evaluate SN and progenitor models at the same time [Patnaude+15].
- ***Astro-H*** scheduled for launch in 2015 ⇒ Revolution in X-ray observations of SNRs.



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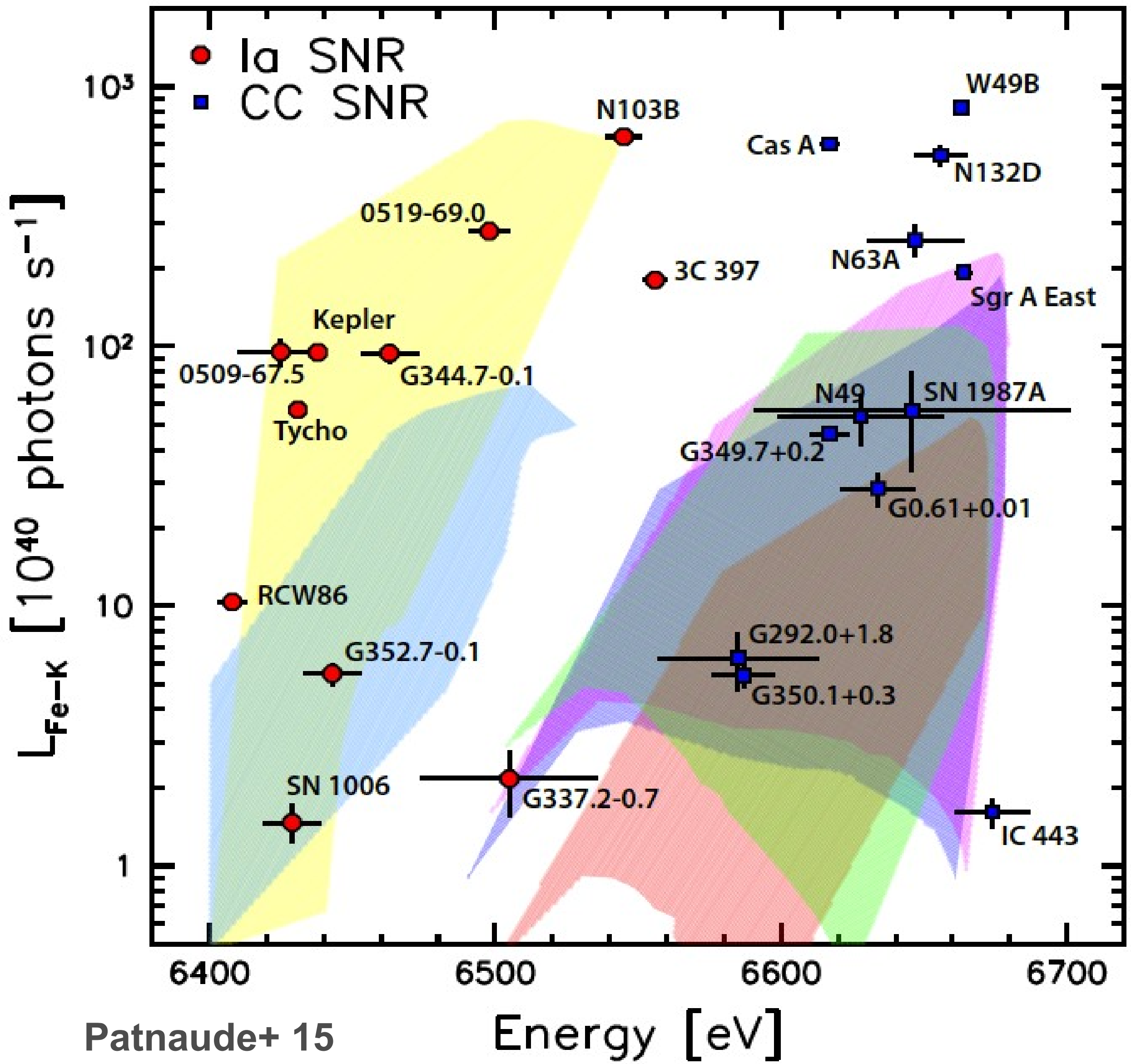
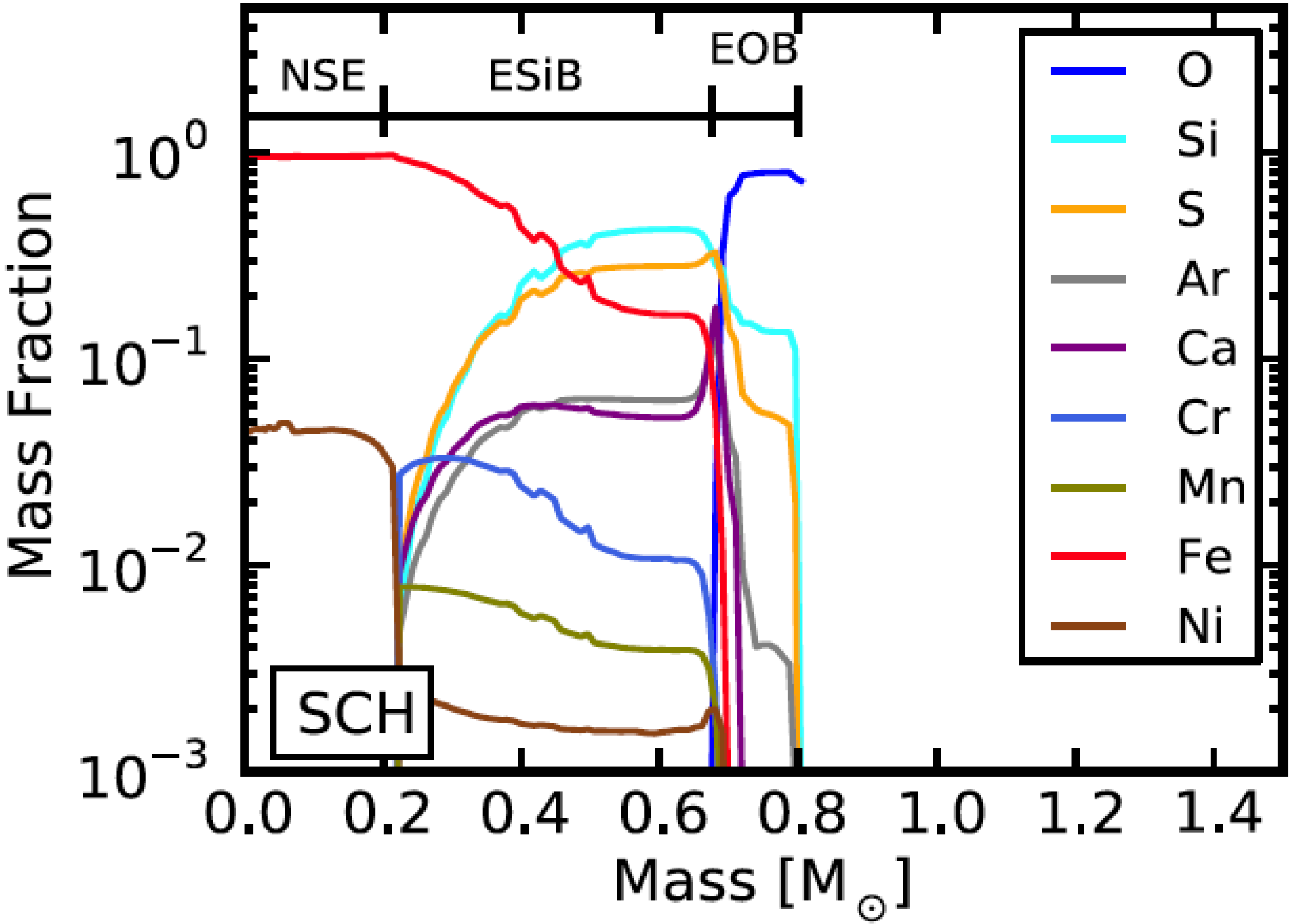


Patnaude+ 15

Secondary Fe-peak Elements in Type Ia SNRs



Secondary Fe-peak Elements

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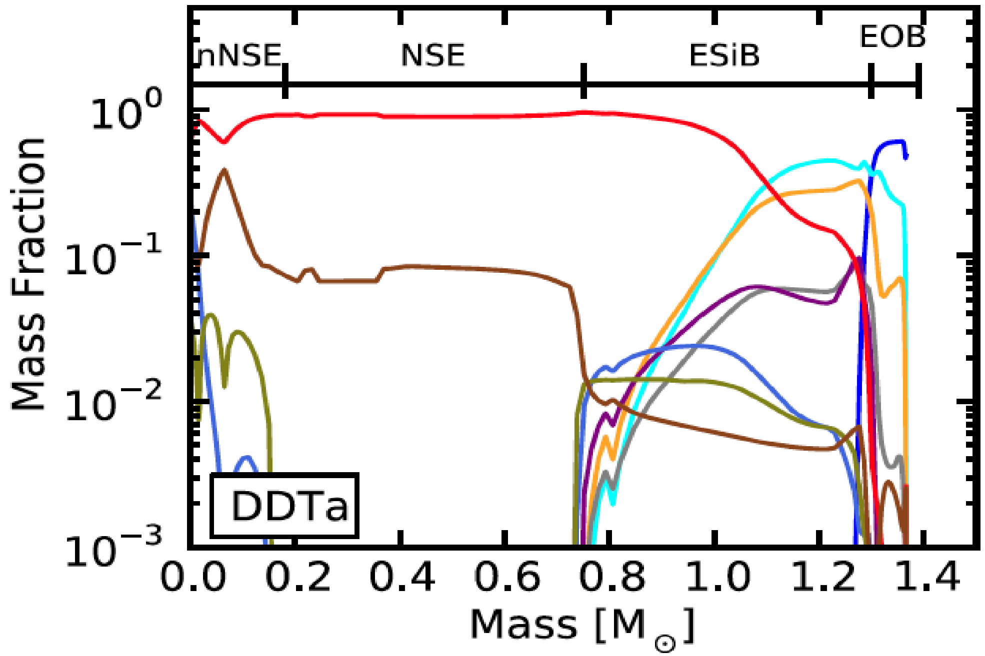
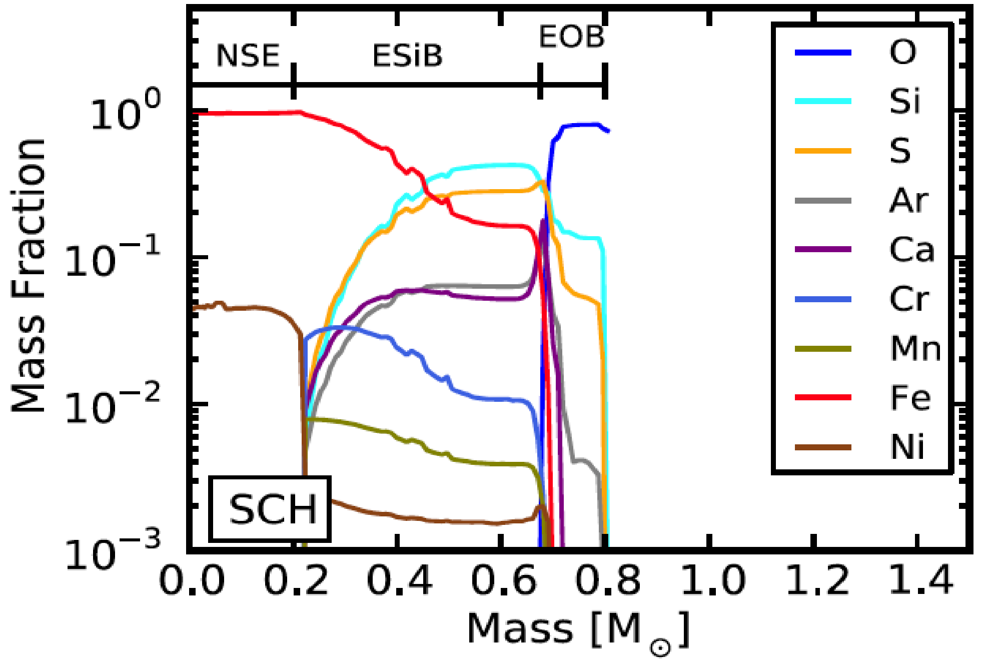
- Standard models: **M_{Ch} DDT explosions** [Khokhlov 91]. One parameter (ρ_{tr}) ⇒ ^{56}Ni yield (SN Ia brightness).

- **Burning regimes:** Exp. O burning, exp. Si burning, NSE, n-NSE.

- **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**).





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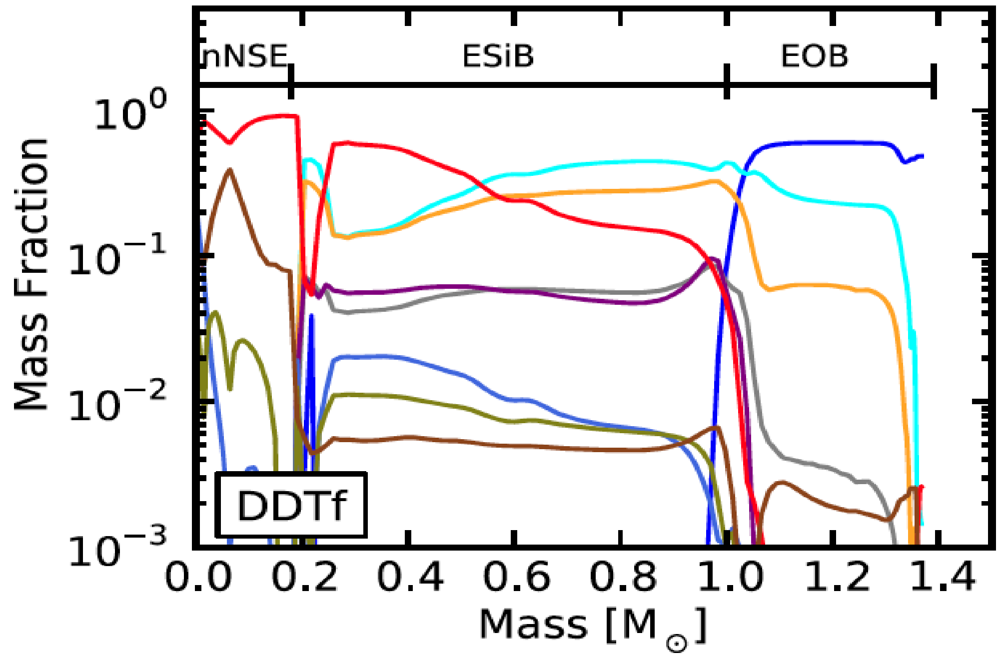

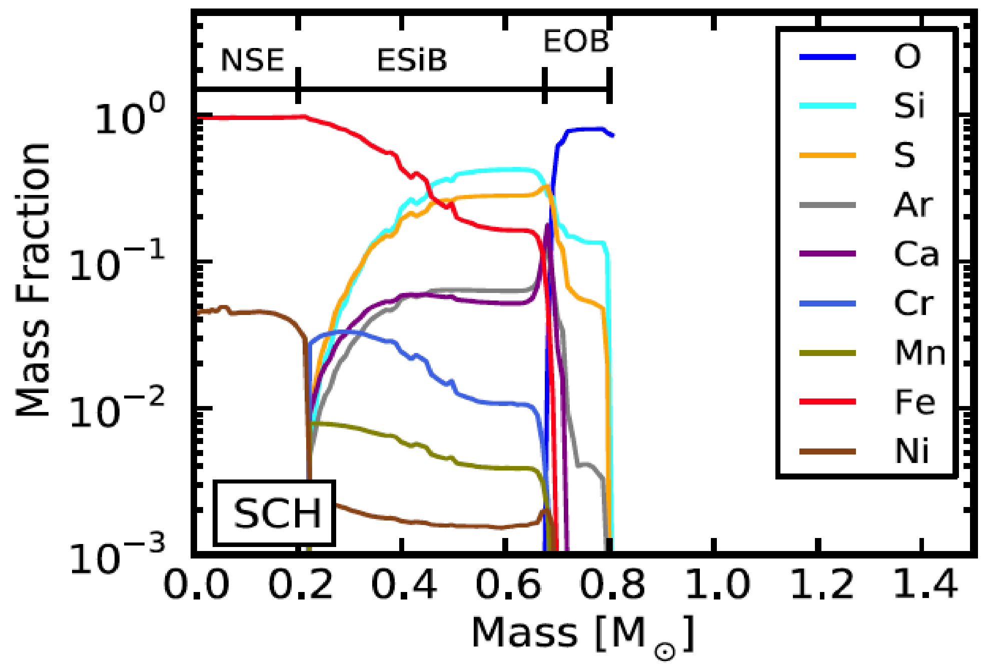

Secondary Fe-peak Elements

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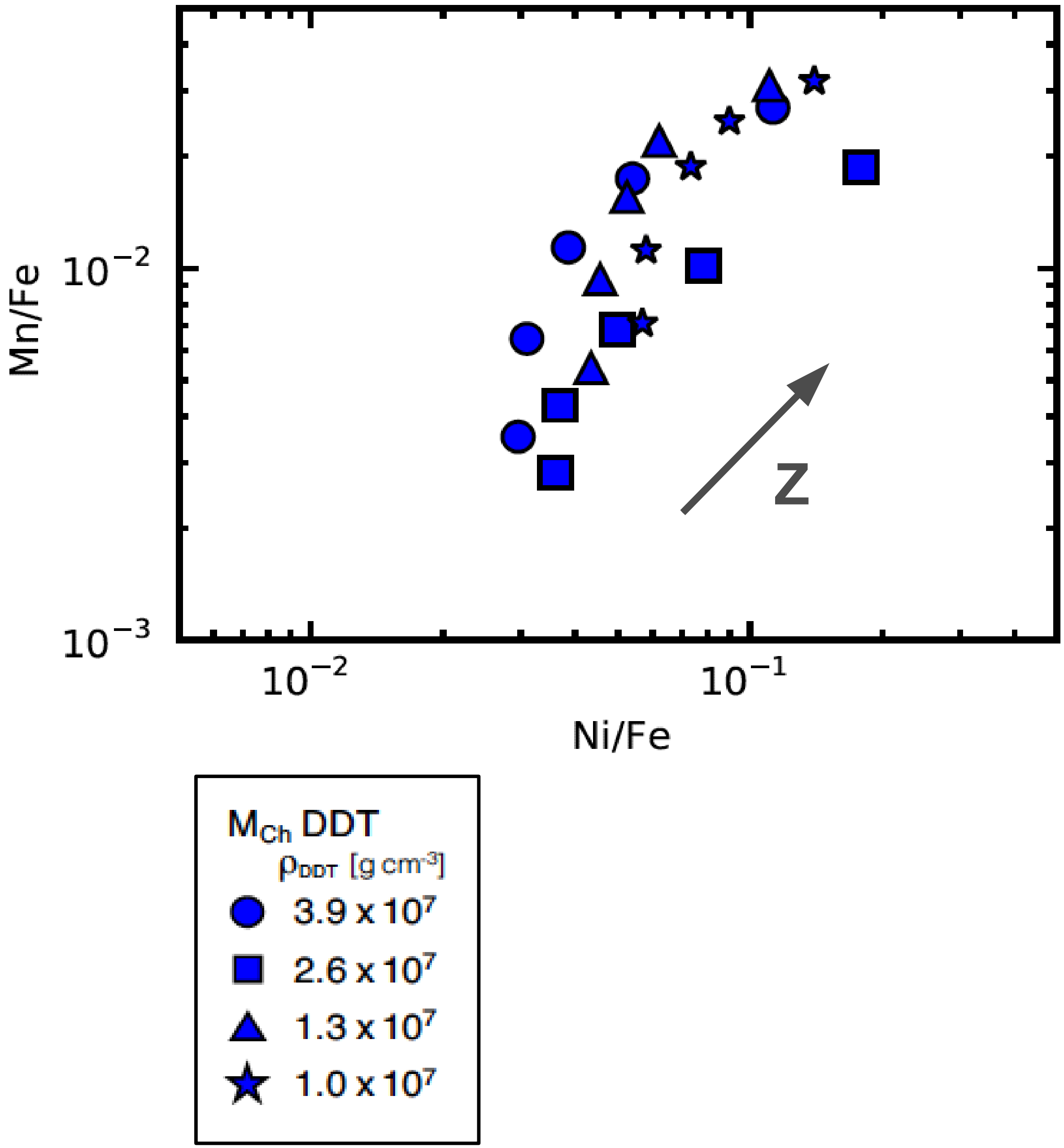
- Yield of neutronized species: **n-NSE + progenitor metallicity** (^{14}N from CNO becomes ^{22}Ne) [Timmes+ 03, Badenes+ 08b].

- Diagnostic mass ratios: **M_{Ni}/M_{Fe}** and **M_{Mn}/M_{Fe}** ⇒ discriminate Ch and Sub-Ch explosions!

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



Secondary Fe-peak Elements

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- Yield of neutronized species: **n-NSE + progenitor metallicity** (^{14}N from CNO becomes ^{22}Ne) [Timmes+ 03, Badenes+ 08b].
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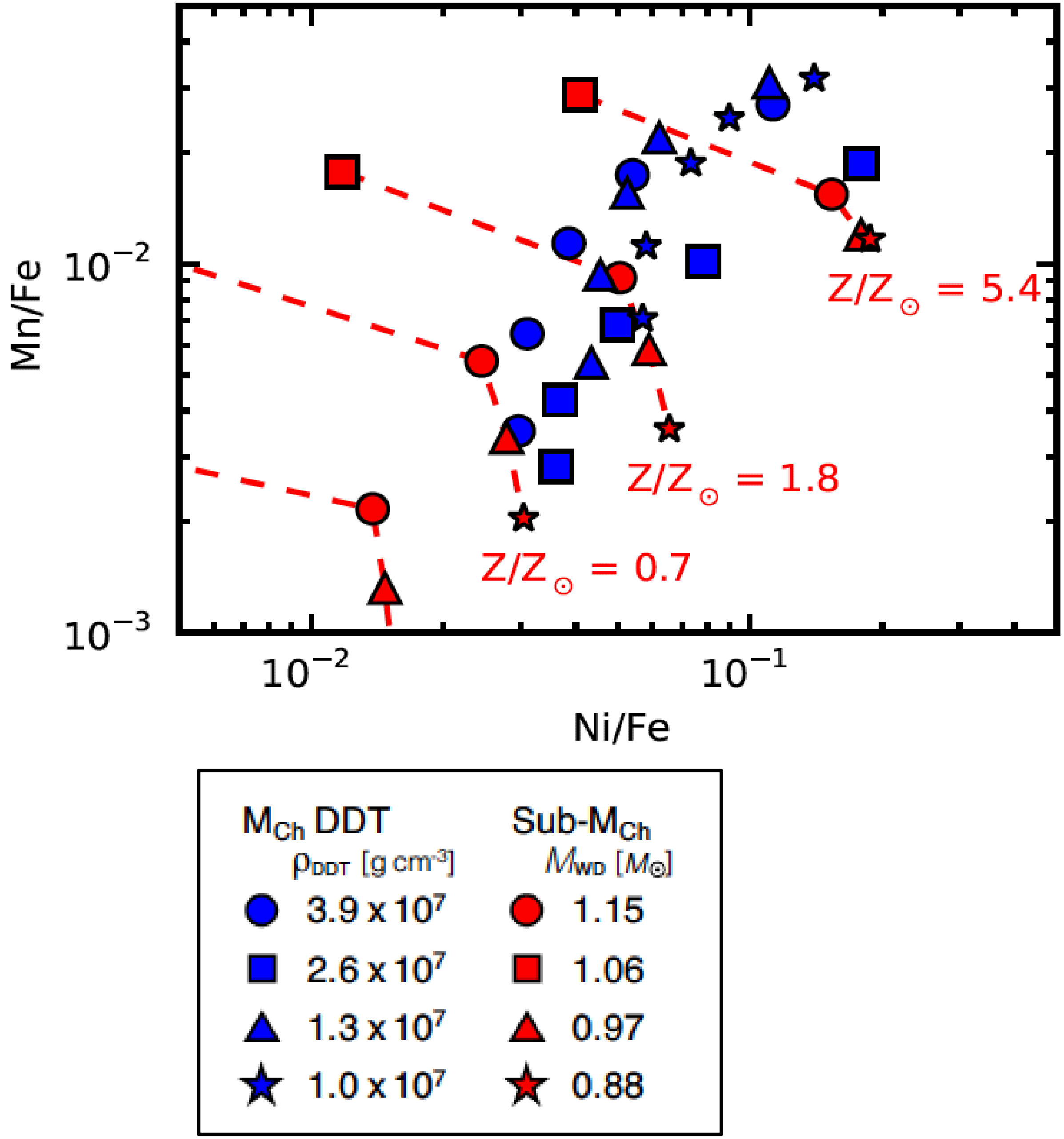

Secondary Fe-peak Elements

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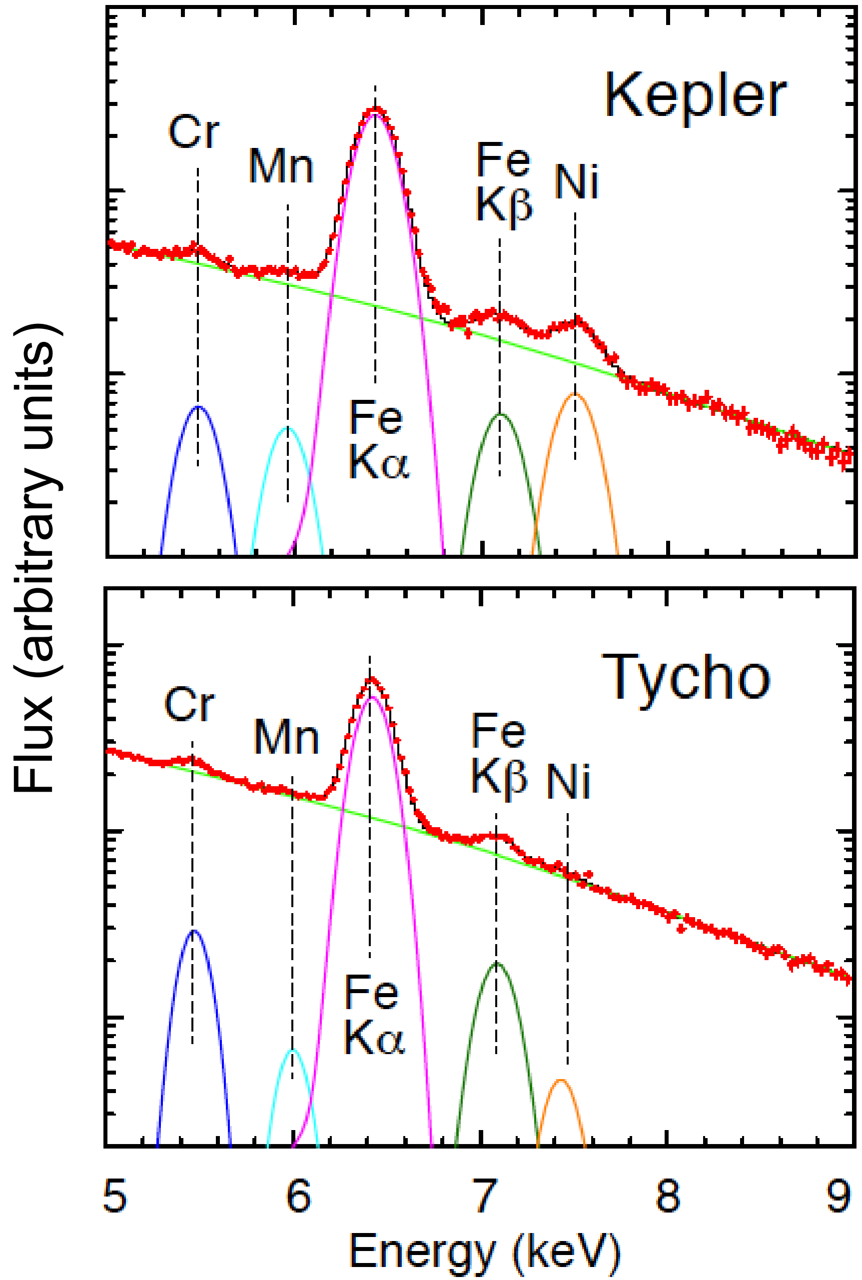
- ***Suzaku*** can detect Cr, Mn, and Ni lines in SNRs: Tycho, Kepler, ... [Tamagawa+ 08, Park+ 13,Yang+ 13].

- In young objects, **RS has not reached n-NSE** region ⇒ progenitor metallicity [Badenes+ 08b, Park+ 13].



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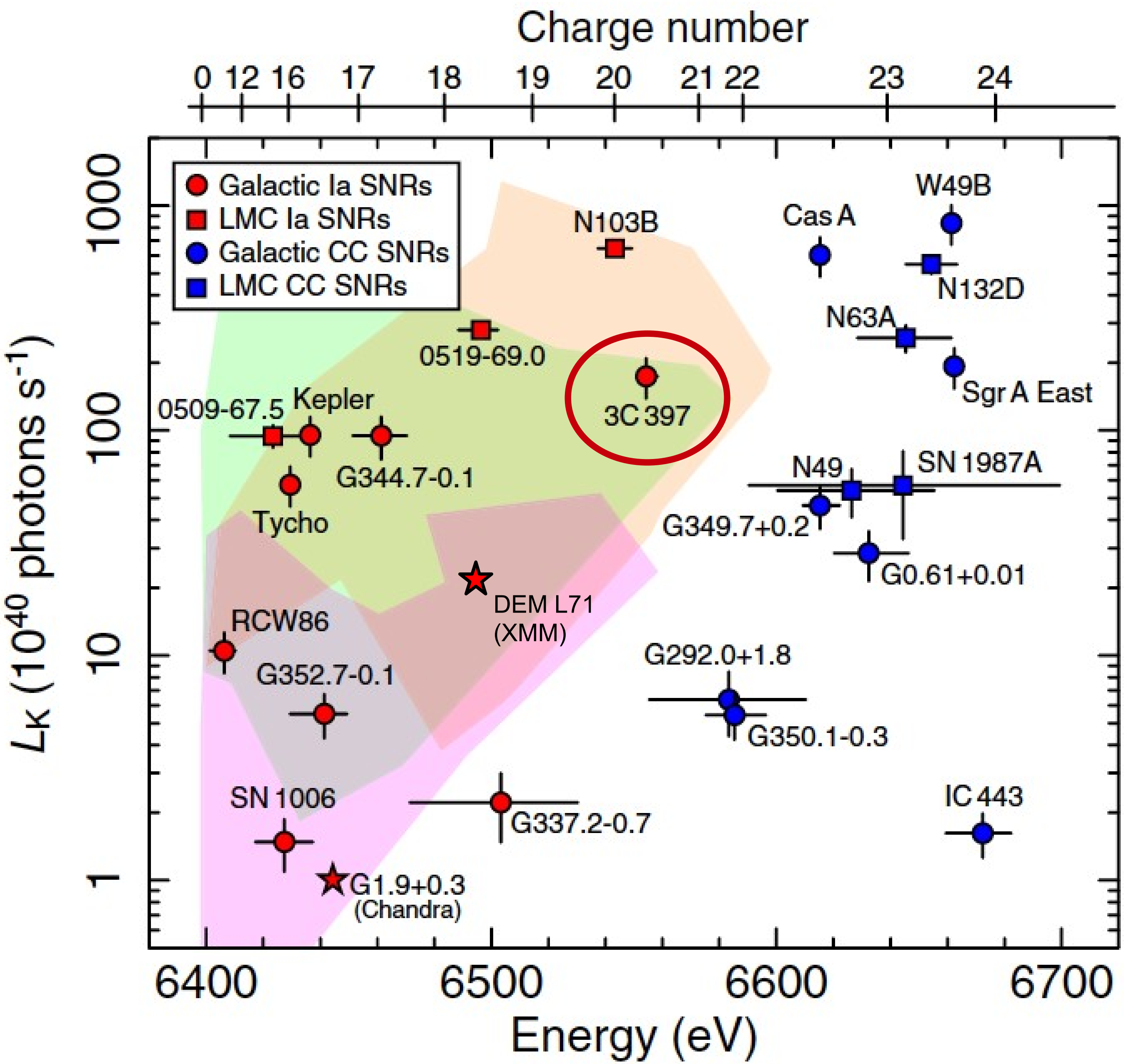
- Need an **evolved SNR with lots of Fe** ⇒**SNR 3C397**!



SNR 3C397

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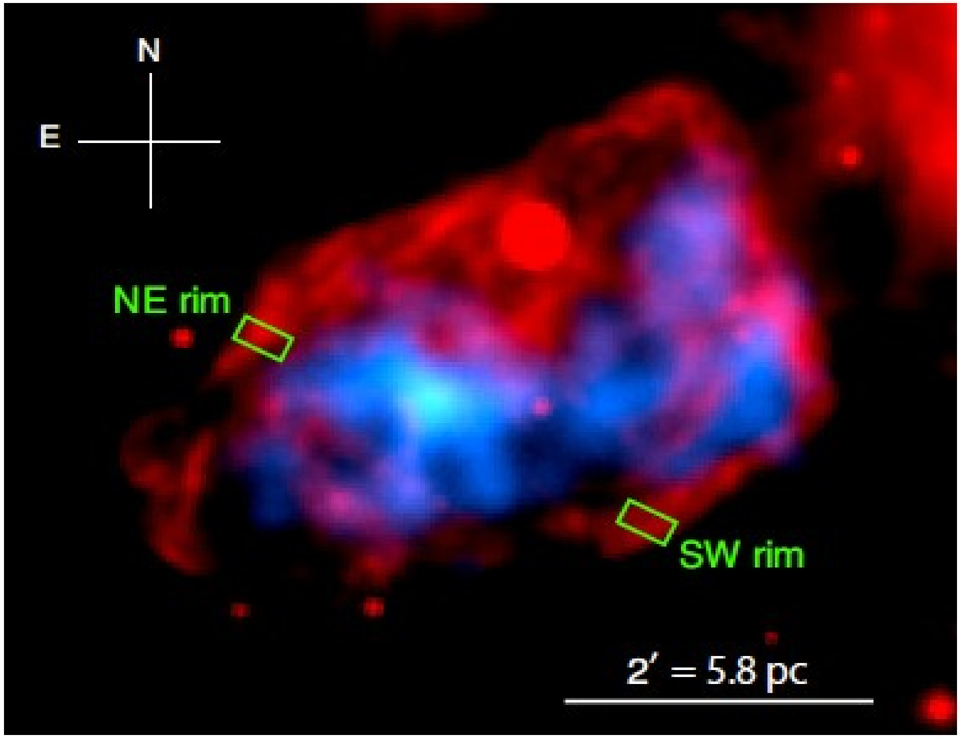
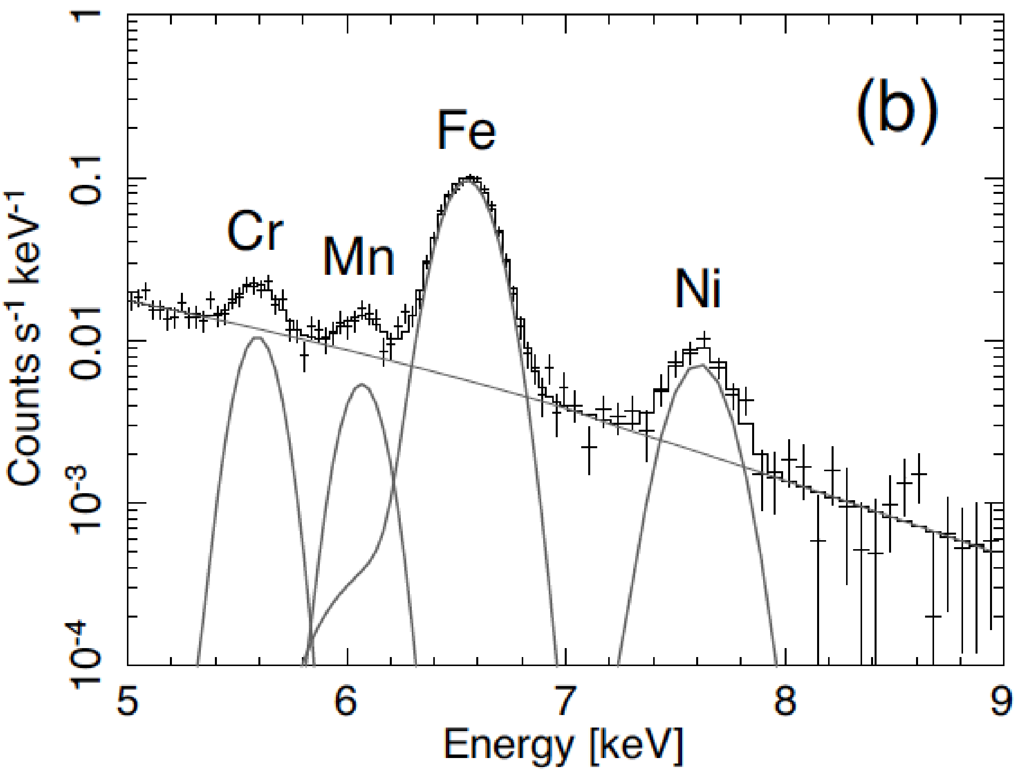
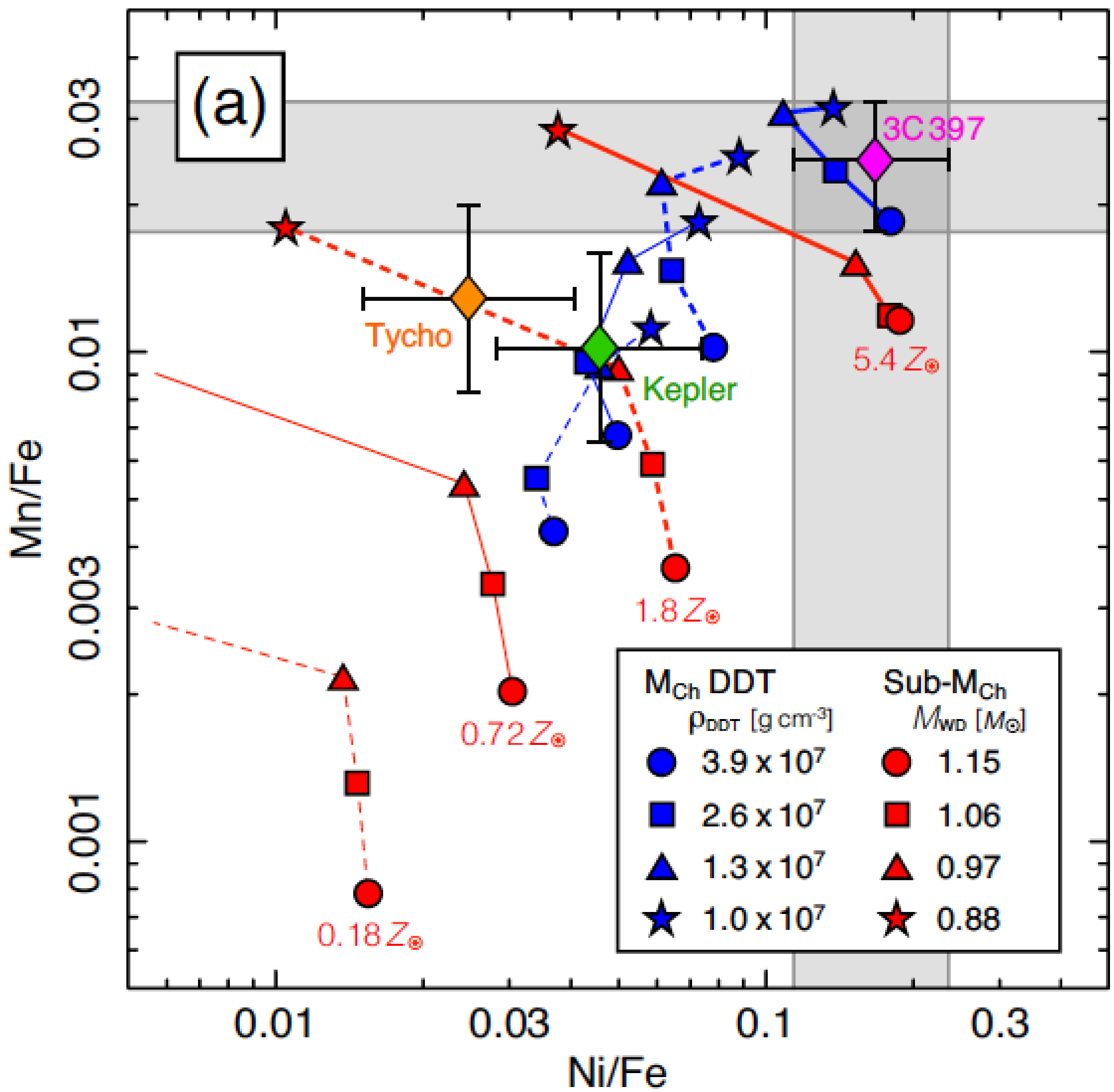
- 3C397 is an evolved Galactic SNR at D~10 kpc [Safi-Harb+ 05].
- Consistent dynamical model (IR+X-ray) ⇒ **RS has thermalized all the SN ejecta**.
- Extraordinary X-ray spectrum! **Very strong Ni and Mn emission**.





SNR 3C397

- 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 [arXiv:1502:04255]



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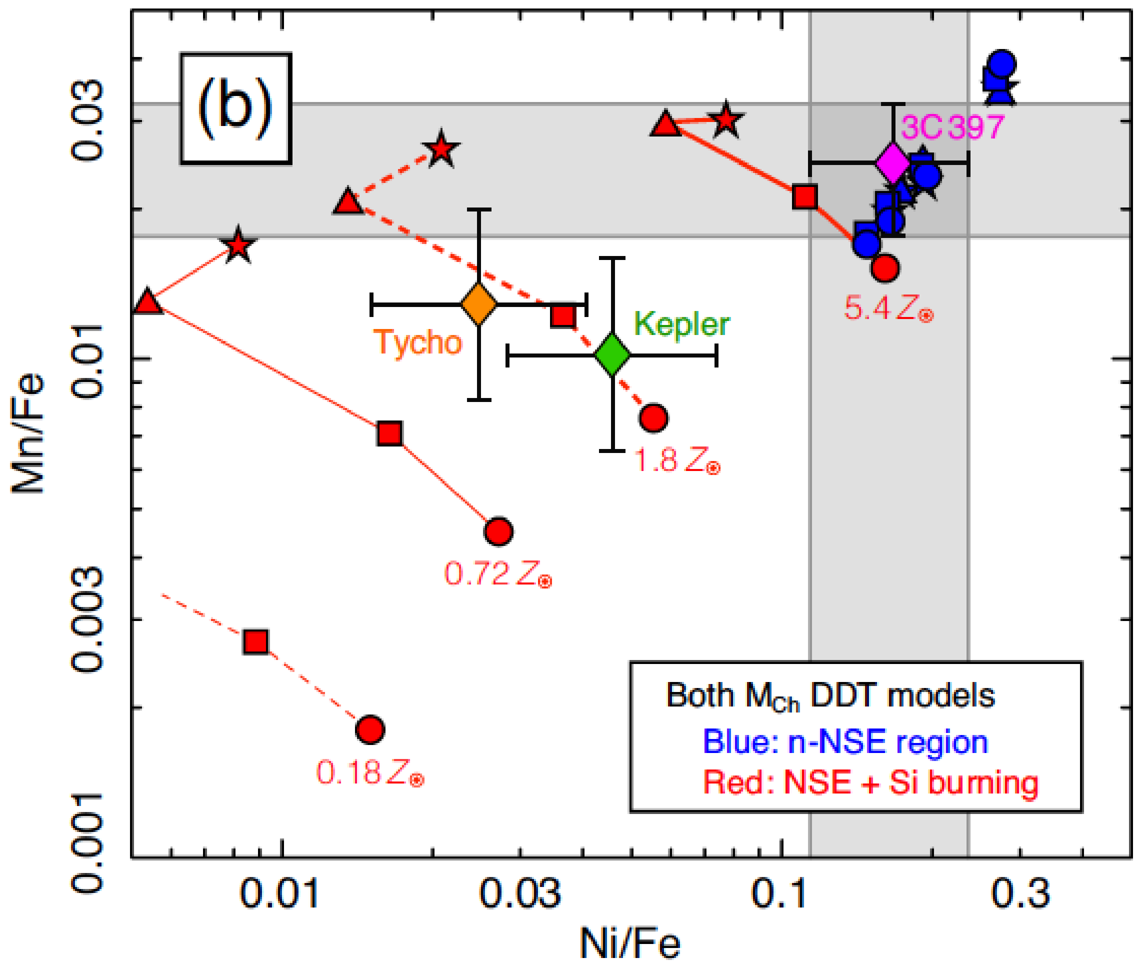

Summary

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- **Fe K line ⇒ CC/Ia SNRs + quantitative test for progenitor evolution scenarios (CSM).**
- **Dynamically, most Ia SNRs are compatible with little or no CSM.** ~M_{Ch}, uniform AM models work really well ⇒ **DD?**
- **RCW 86** (and maybe G344.7-0.1) **require fast, continuous pre-SN outflows ⇒ SD?**
- **SNR 3C397 shows prominent Mn and Ni emission ⇒ M_{Ch} progenitor ⇒ SD**.
- **Other measurements show a preference for DD** scenario (no companions, DTD, merger rate).

SN Ia in star-forming galaxies probably come from a mixture of SD and DD progenitors

Summary

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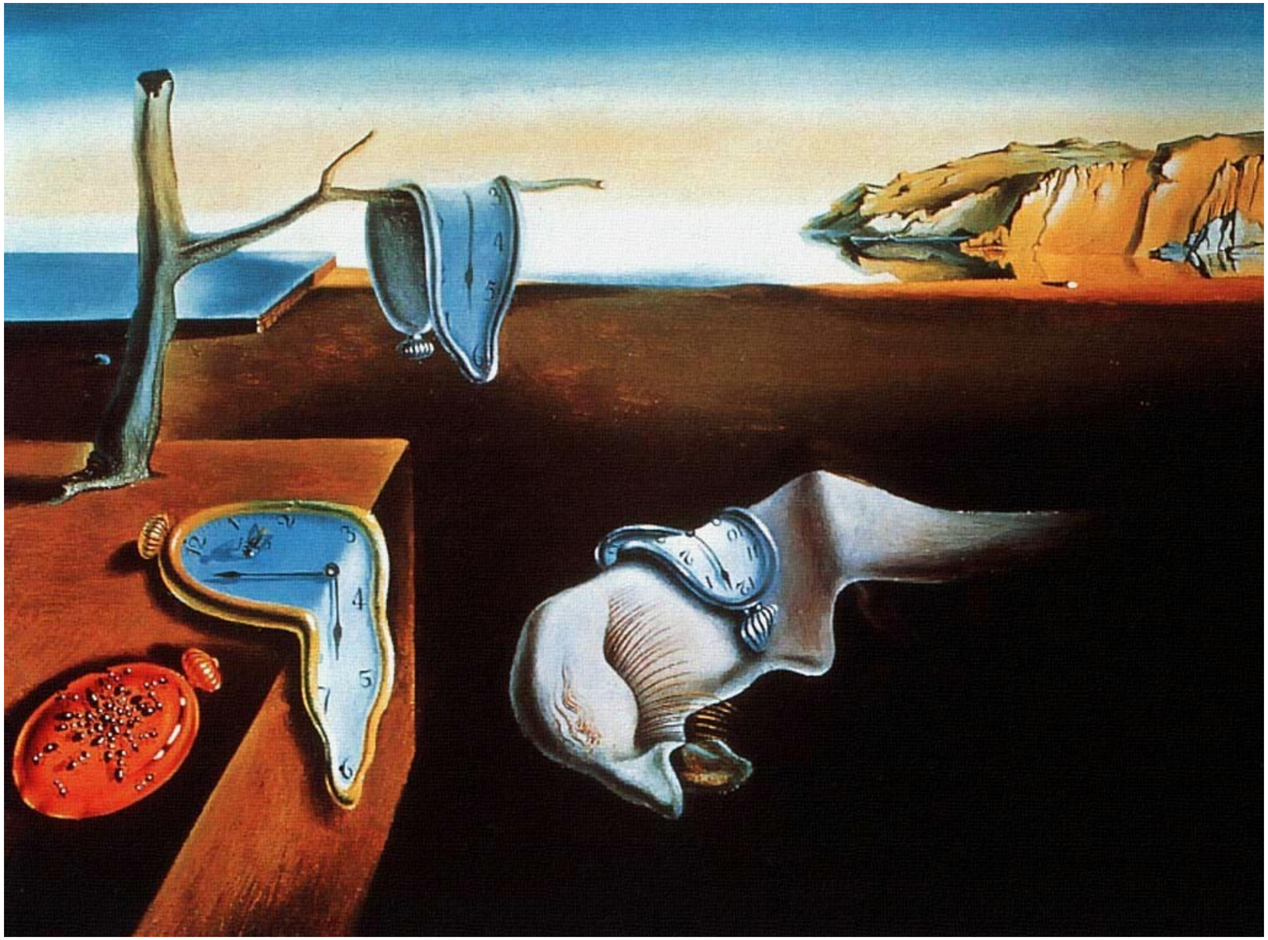

SN Ia in star-forming galaxies probably come from a mixture of SD and DD progenitors

Type Ia SNRs and cavities

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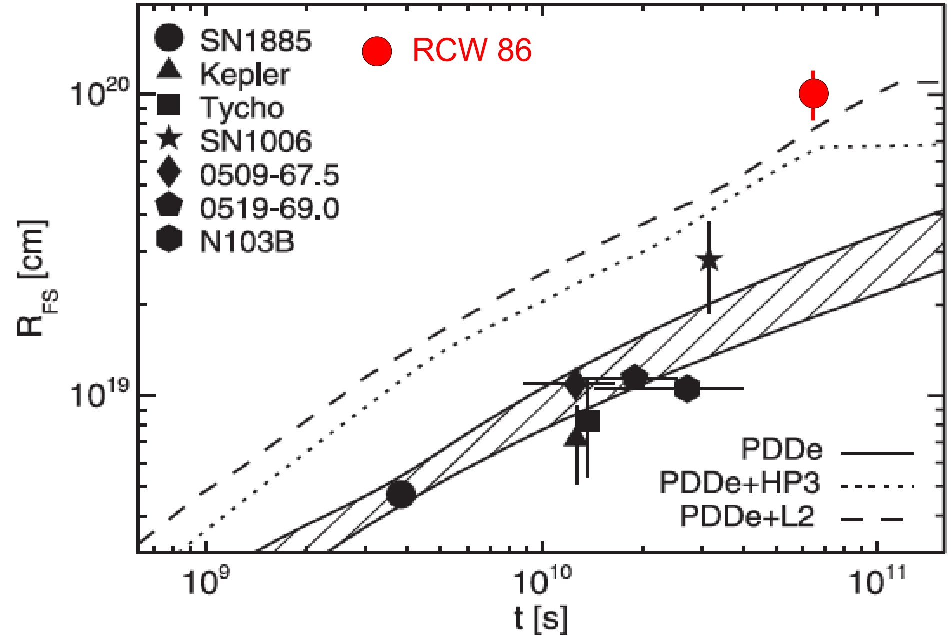
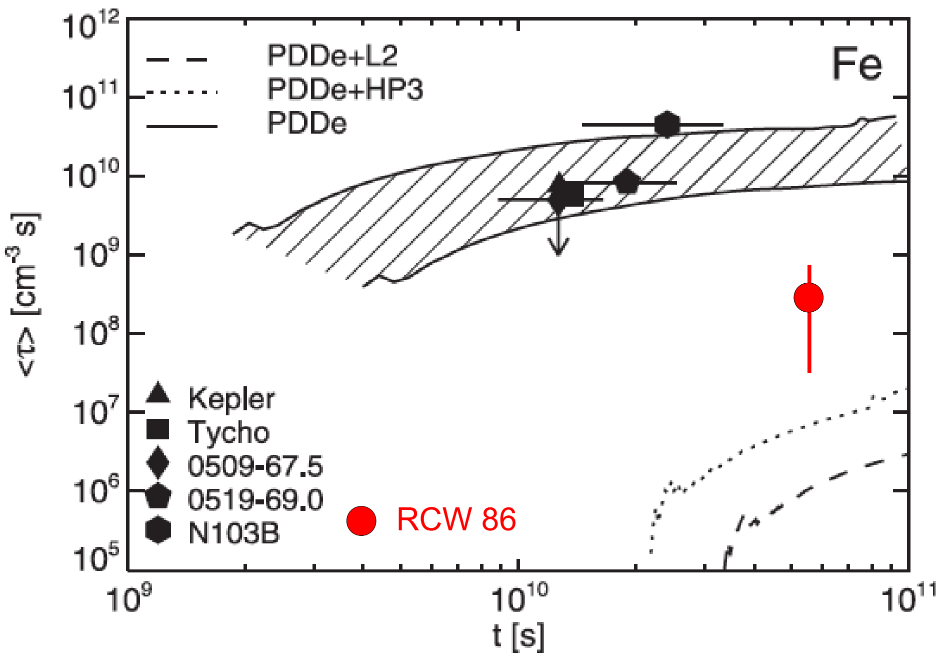
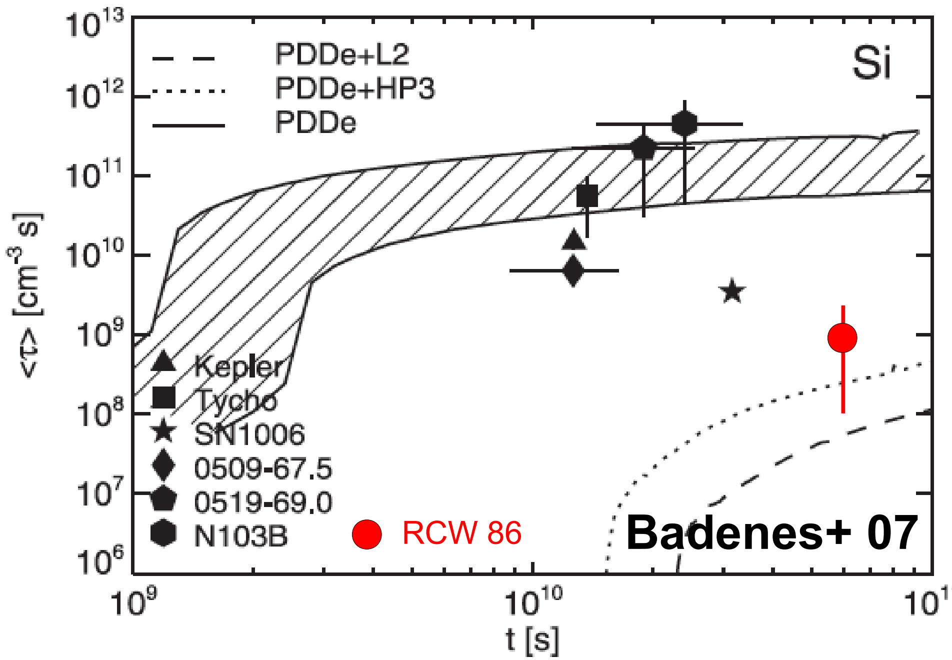
- **Radii and $n_e t$ of Type Ia SNRs** with known ages are **consistent with uniform ambient medium interaction** [Badenes+ 07].

- '**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

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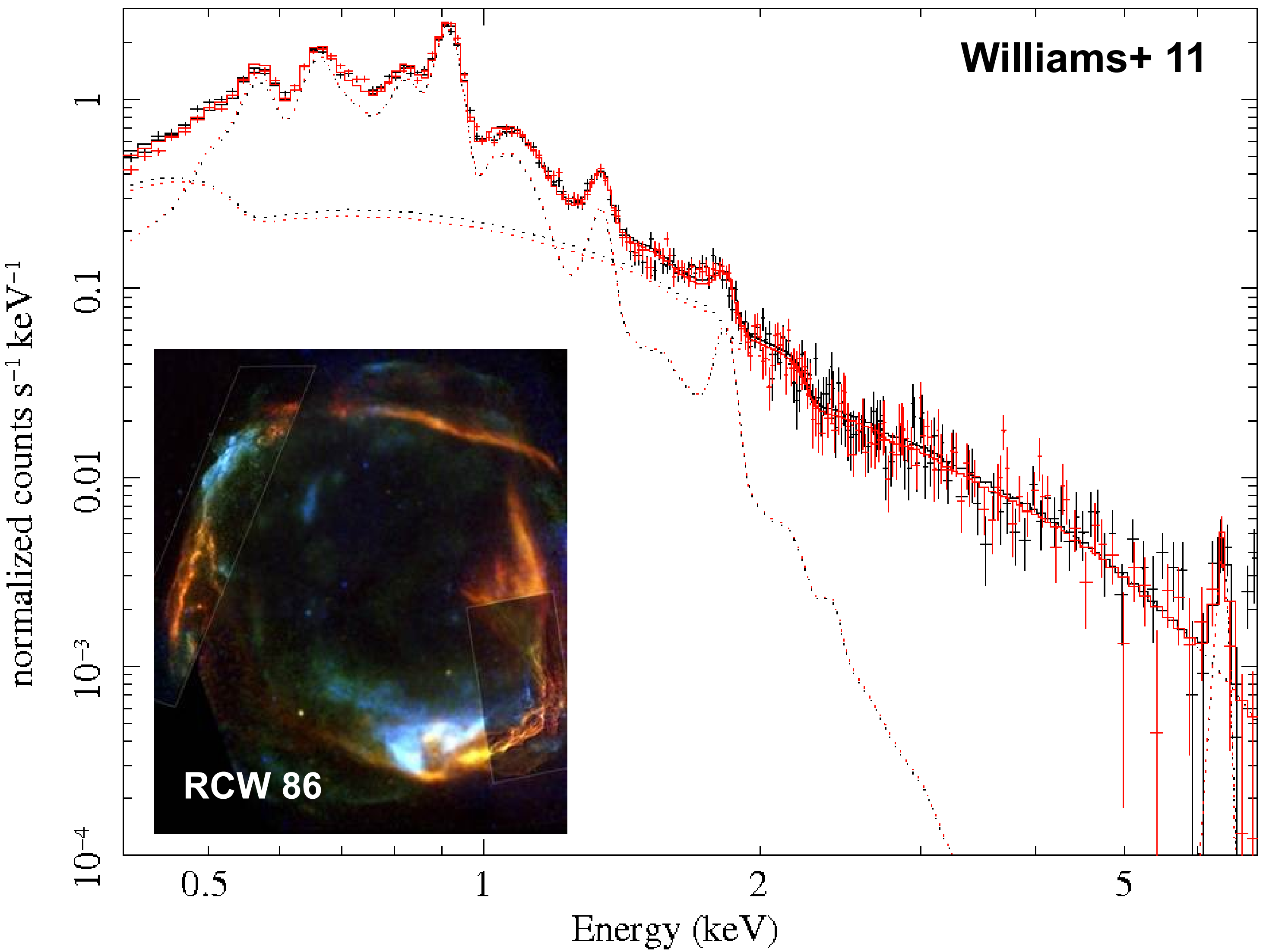
- **RCW 86** is large (~25 pc), with well defined borders, low $n_e t$, bright Fe, and no compact remnant [Williams+ 11].
- **IF SNR of SN 185 AD ⇒ cavity explosion** [Vink+ 97].
- **IF Ia SNR ⇒ fast, sustained outflow** from the progenitor ⇒ **SD** [Badenes+ 07, Williams +11].
- A light echo or detailed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



Other cavity Ia SNRs?

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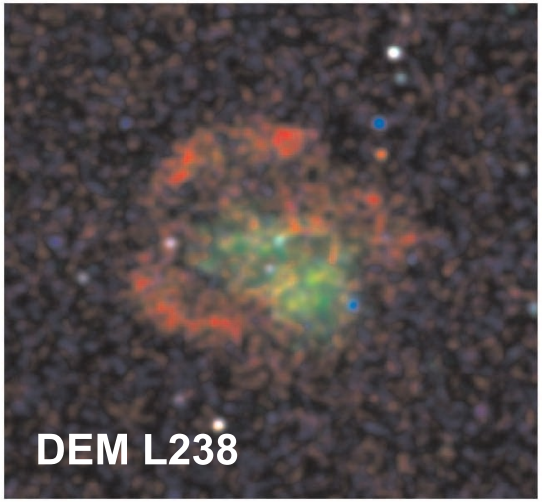
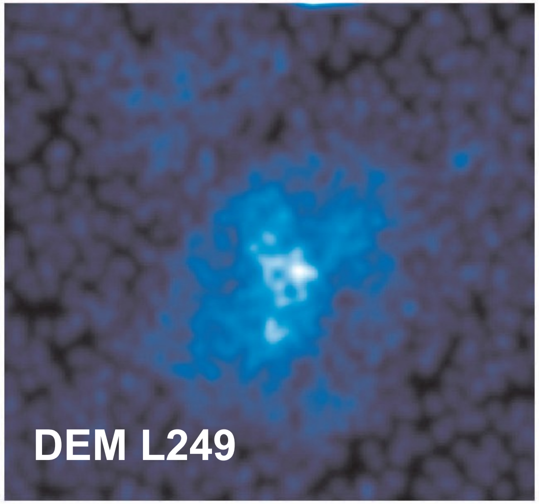
- **RCW 86** might not be the only example of Type Ia SN in a cavity.

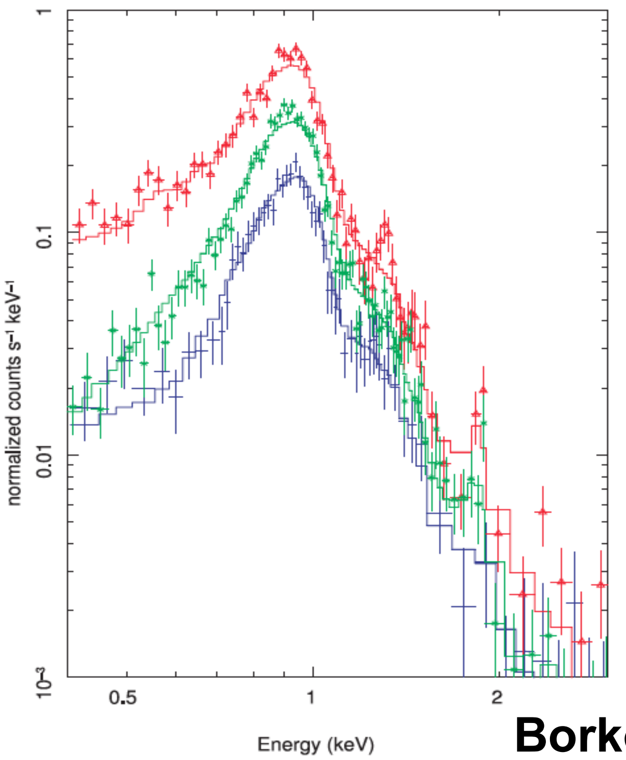
- **DEM L238** and **DEM L249**, two middle-aged SNRs in the LMC have Fe-rich spectra and low $n_e t$.

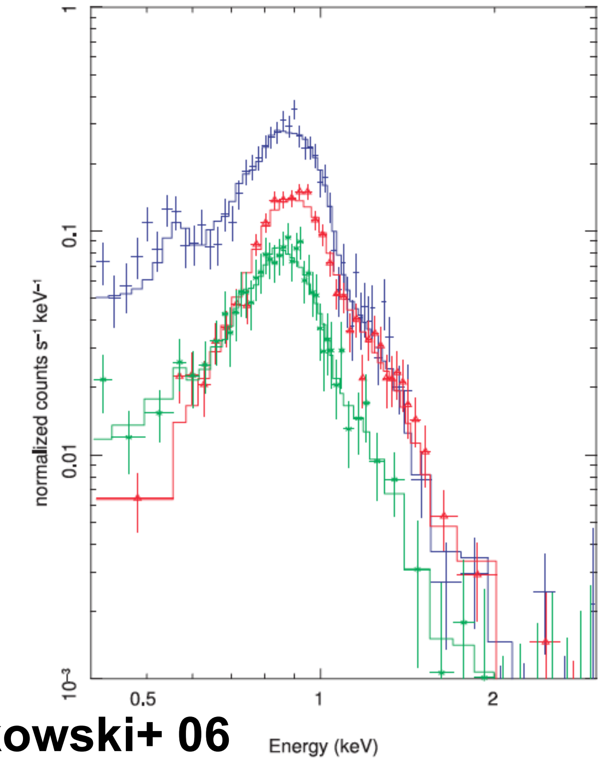
- **IF Type Ia SNRs**, they might also be **cavity explosions** [Borkowski+ 06].

- **Beware:** typing SNRs older than a few thousand years is difficult, and so is modeling their dynamic evolution!









Borkowski+ 06

CSM in CC SNRs

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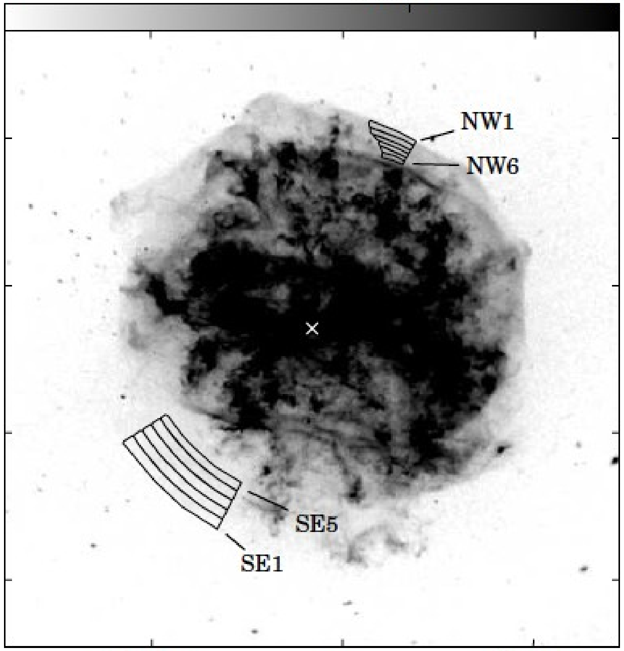
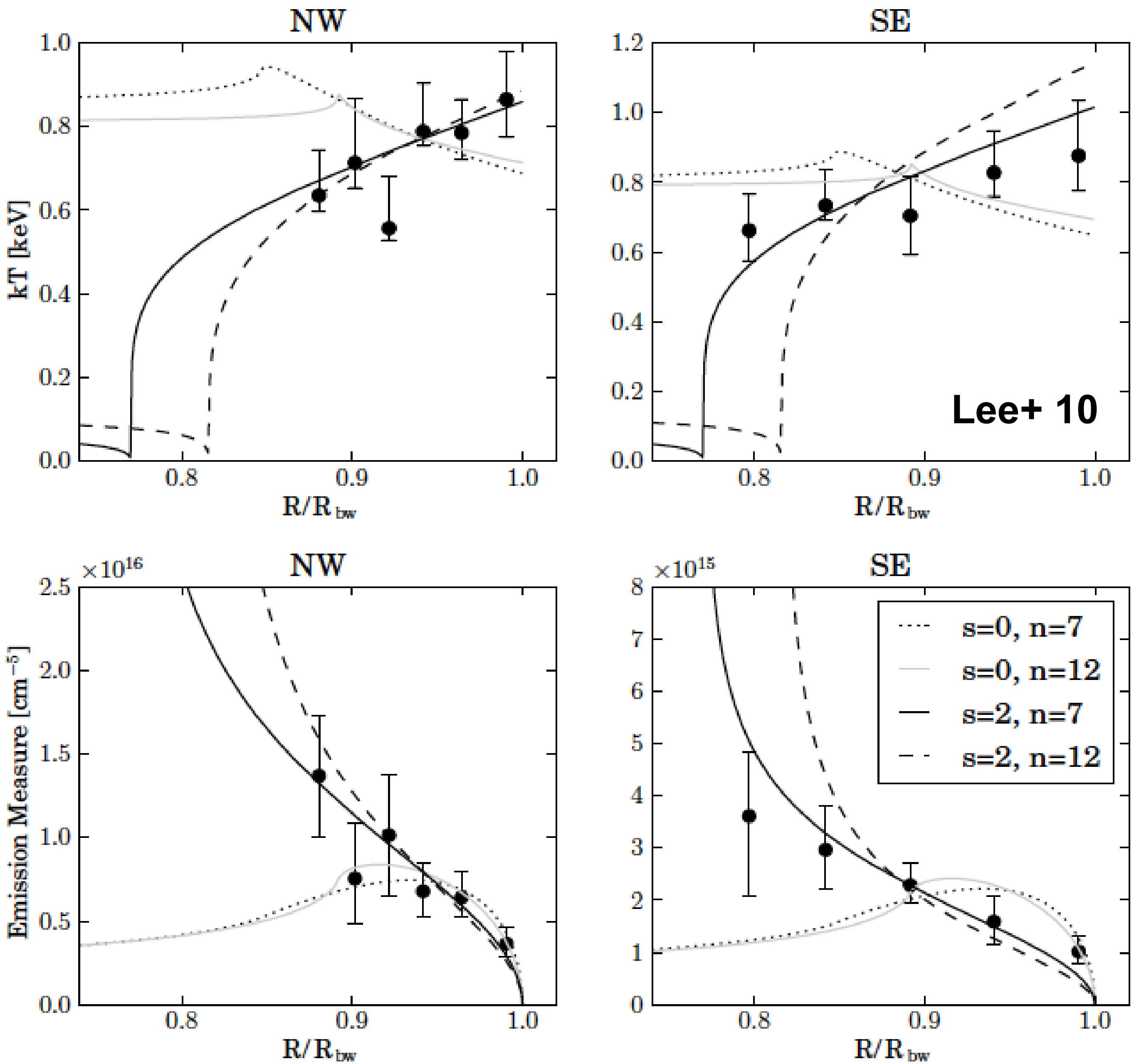
- In more evolved SNRs like **G292.0+1.8, forward shock morphology can constrain ejecta and CSM density profiles** ⇒ CC SN progenitor [Lee+ 10].

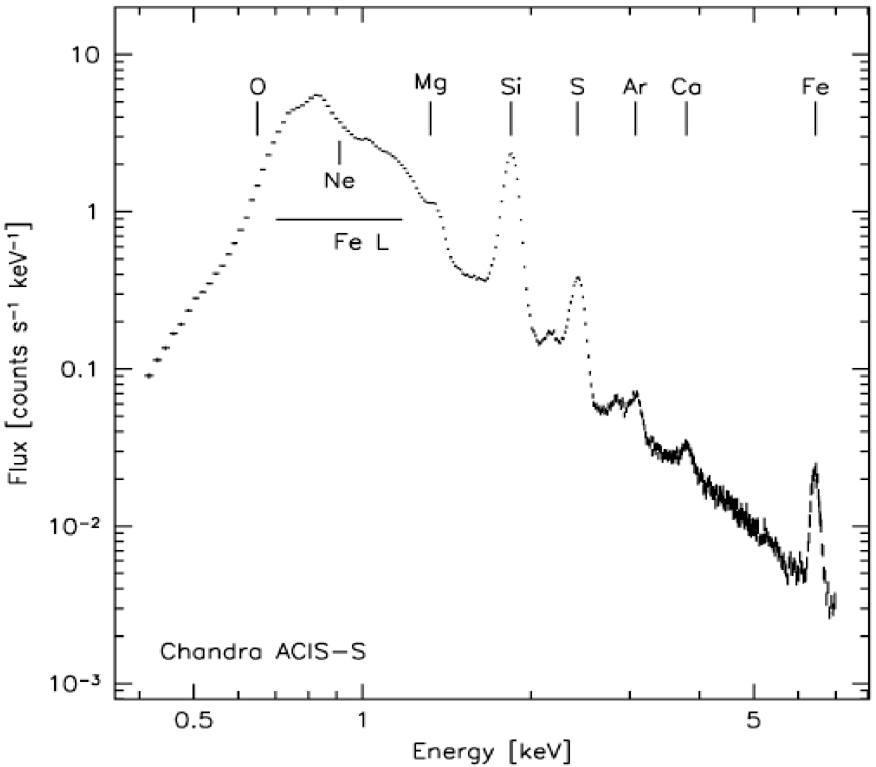


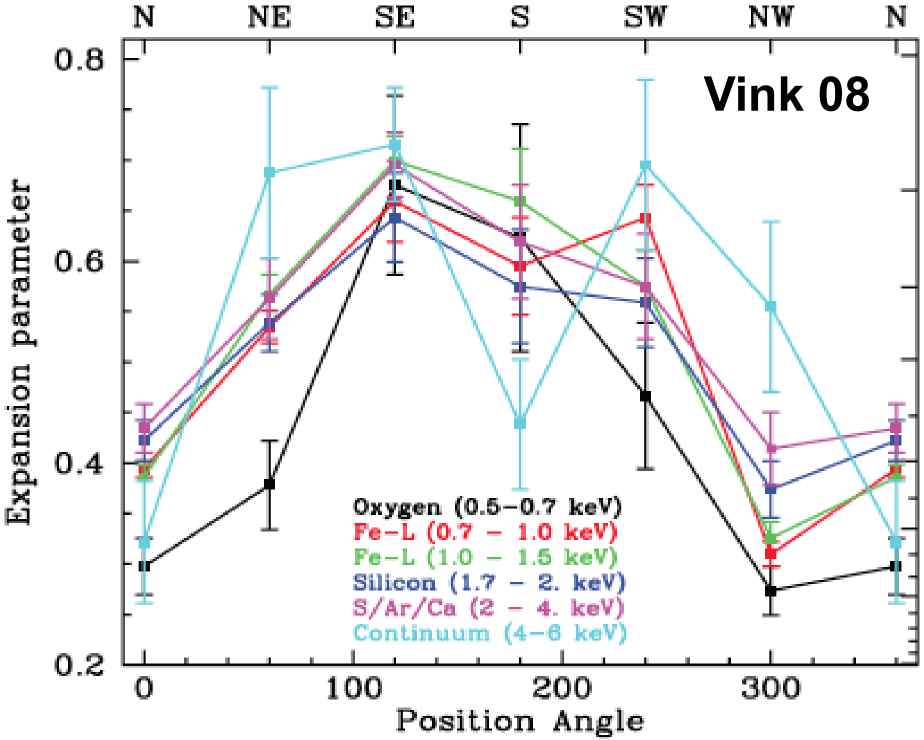


CSM Interaction: Kepler SNR

- **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~2×10^{50} erg).

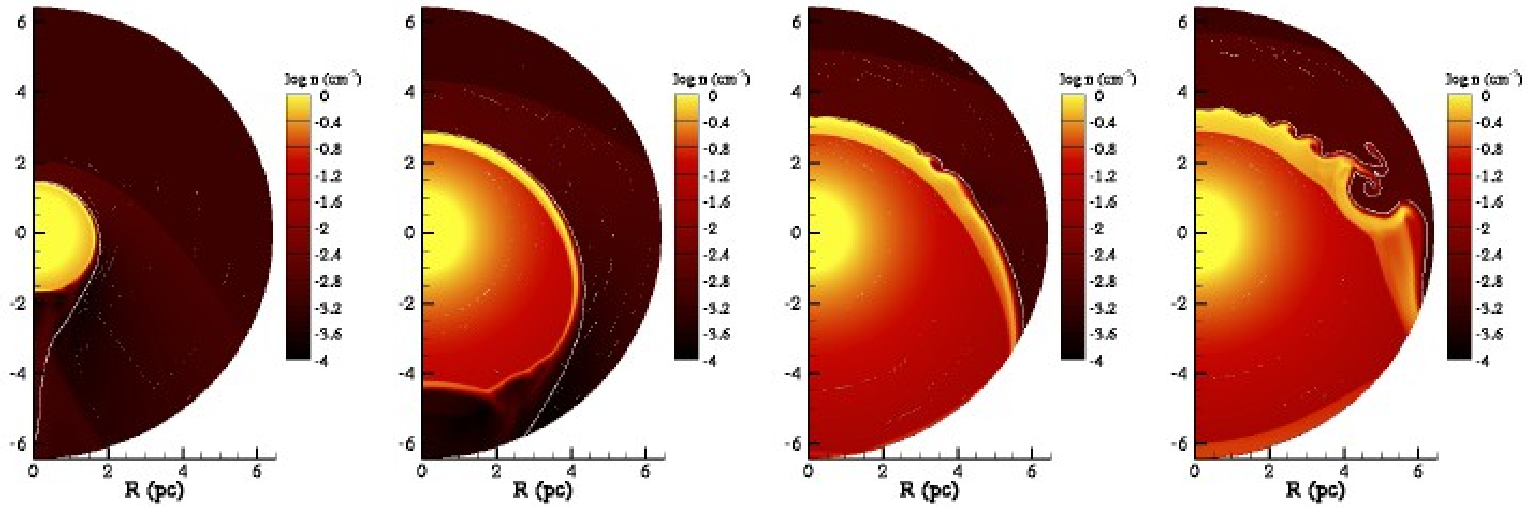


Fig. 4. The evolution of the wind bubble of model A. The snapshots from left to right correspond to the times 0.10 Myr, 0.29 Myr, 0.38 Myr and 0.57 Myr.

Chiotellis+ 12

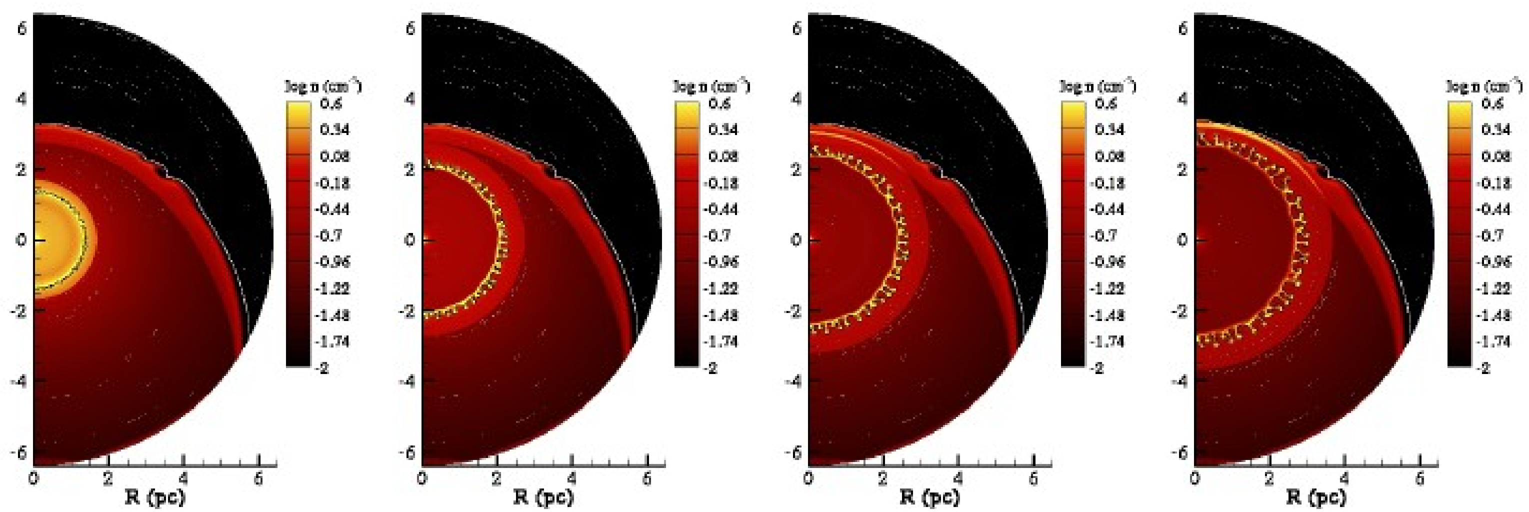
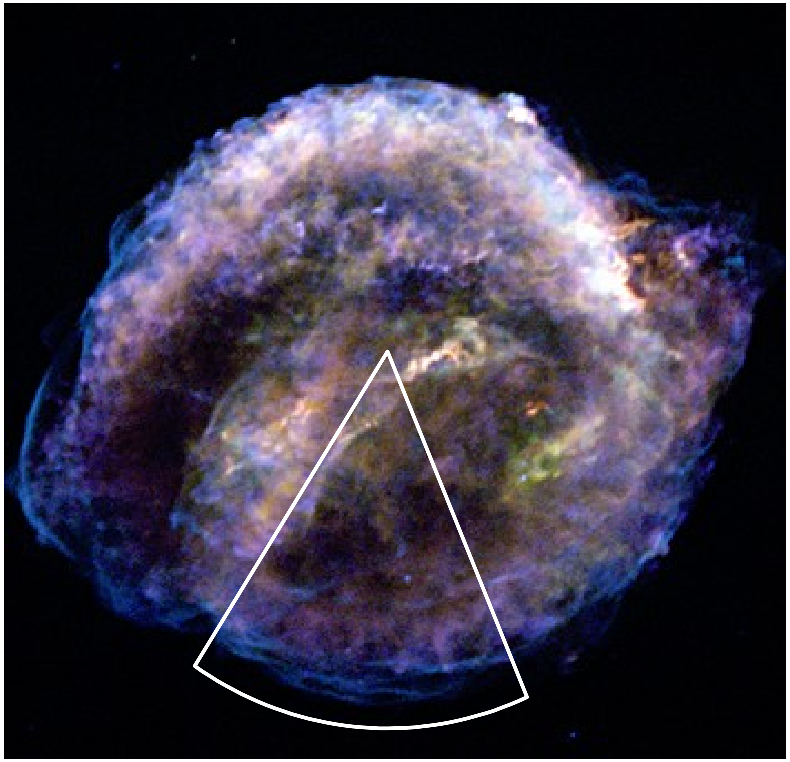
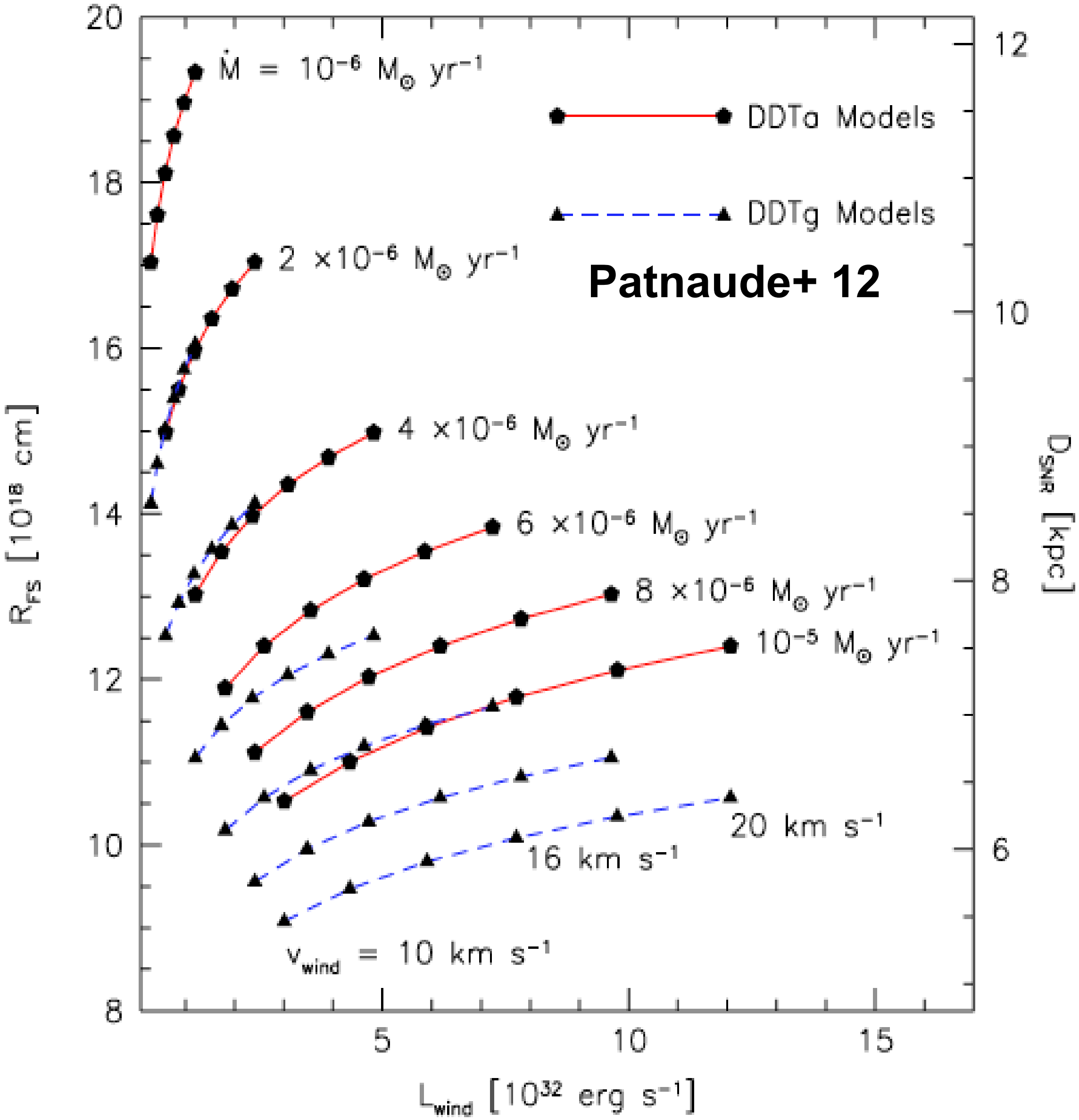


Fig. 5. SNR evolution of model A. The snapshots from left to right correspond to the times 158 yr, 285 yr, 349 yr and 412 yr.

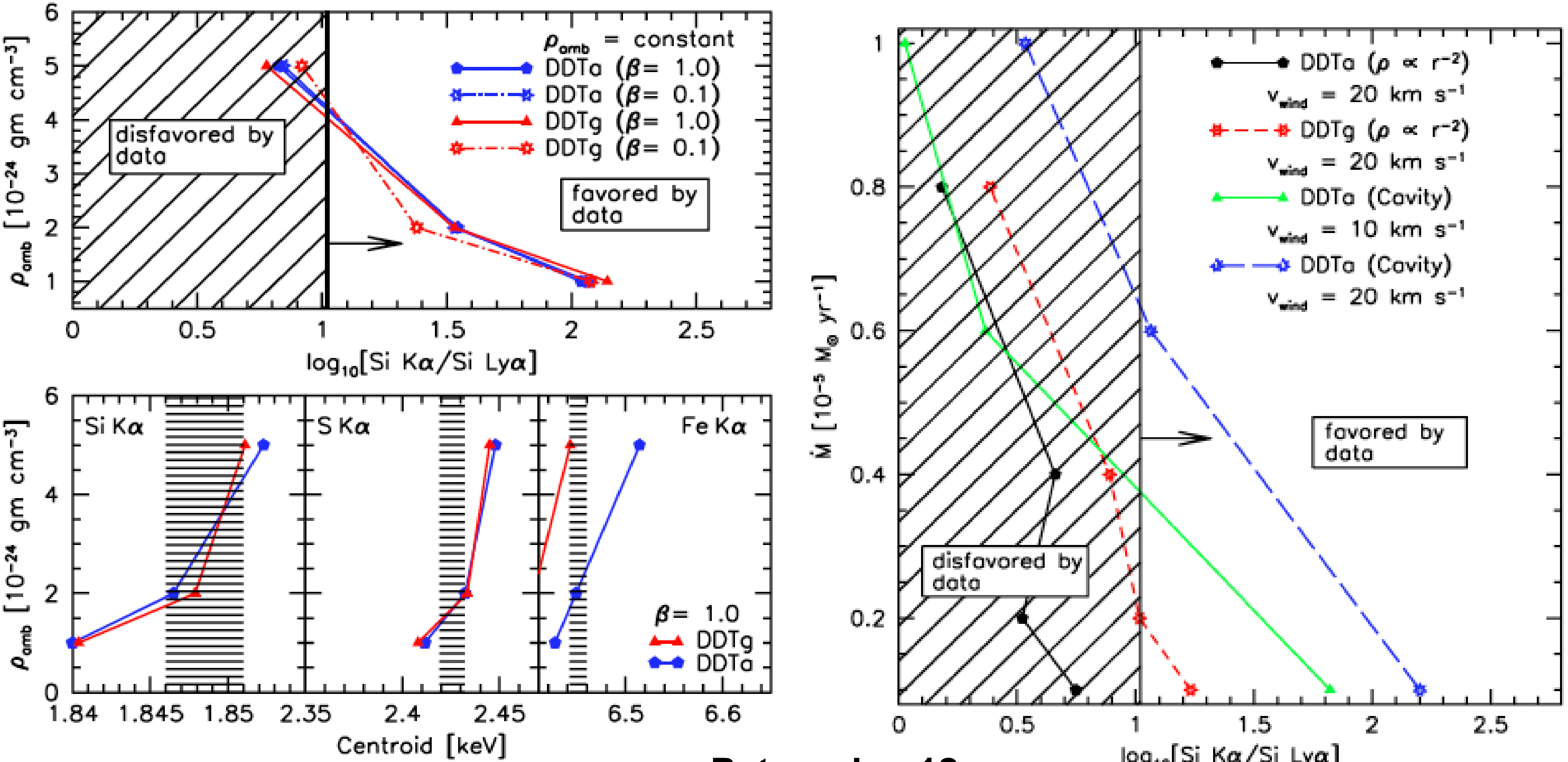
• HD+NEI models in the S, where the ejecta should be interacting with the pristine CSM from the progenitor ⇒ **constrain both M_{56Ni} and pre-SN dM/dt** [Patnaude+ 12].





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