The Supernova Remnant View of SN Ia Progenitors

Carles Badenes
University of Pittsburgh

FOE 2015, NCSU
June 4, 2015

with **H. Yamaguchi** (NASA/UMd), **E. Bravo** (UPC), **D. Patnaude** (CfA), **S. Park** (UTA), **P. Slane** (CfA), **B. Williams** (NASA), and others

Motivation

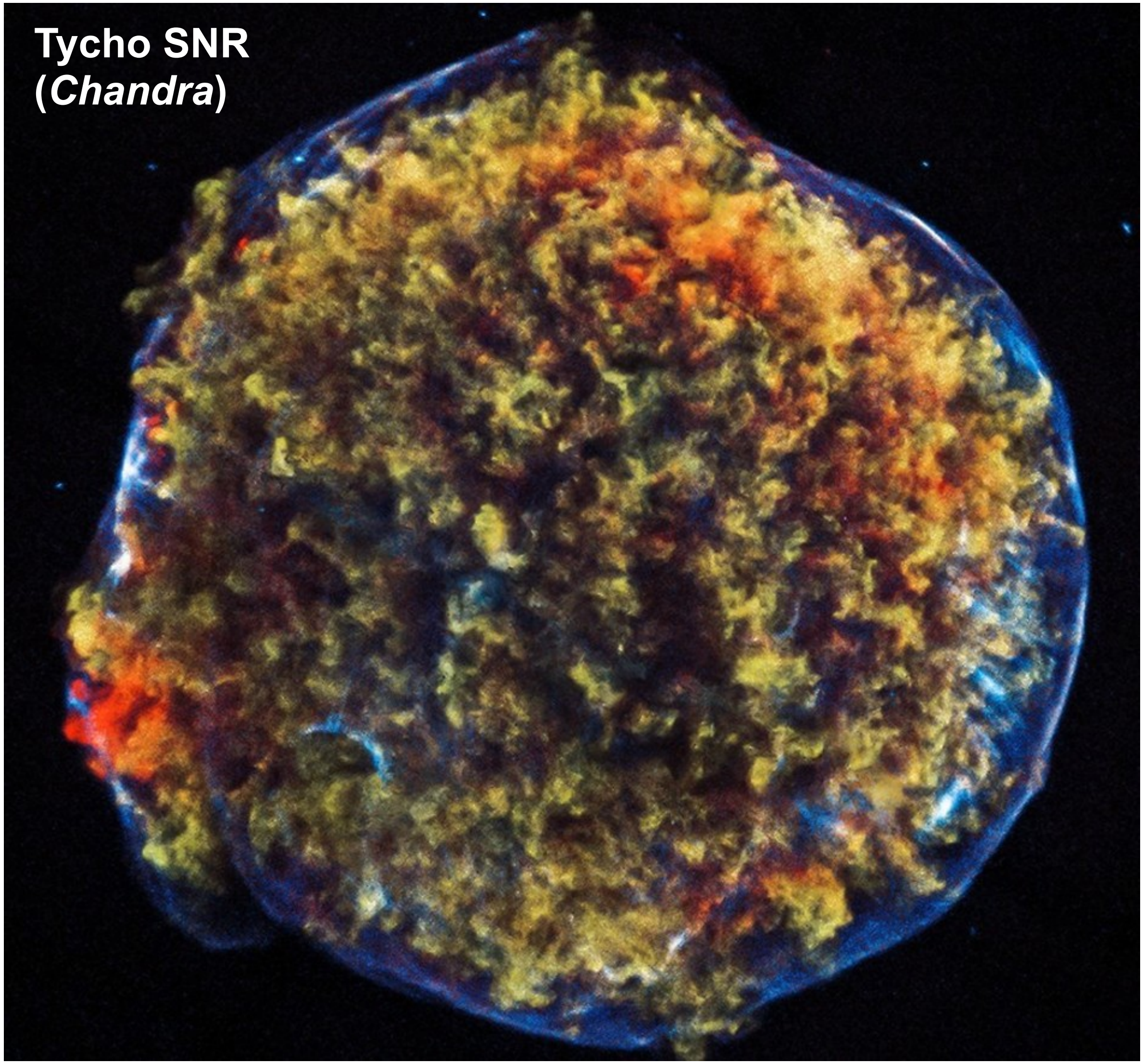
Carles Badenes
FOE 04/06/15

SN Ia progenitors remain unidentified

Supernova Remnants (SNRs) ⇒ different perspective on SNe

SNRs remember their birth events.

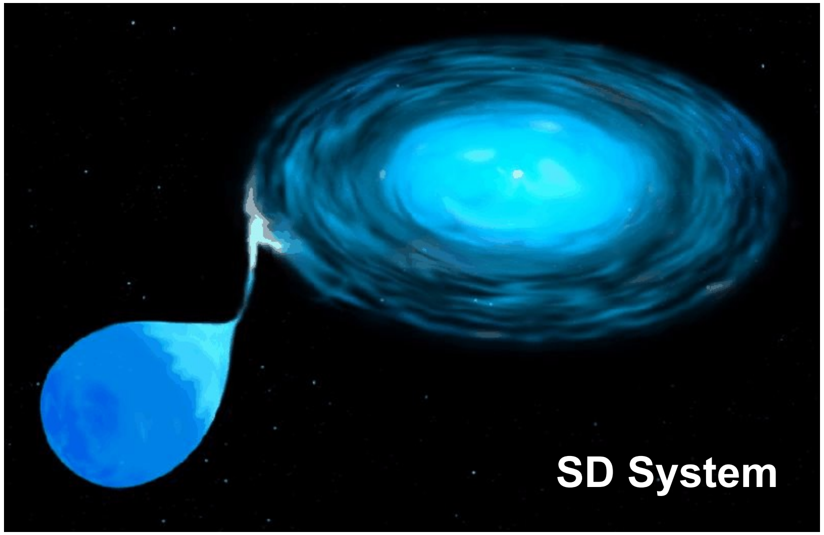
- **SN-CSM Interaction:** progenitor stellar evolution.
- **n-rich Fe-peak elements:** progenitor mass.



Single vs. Double Degenerate SN Ia

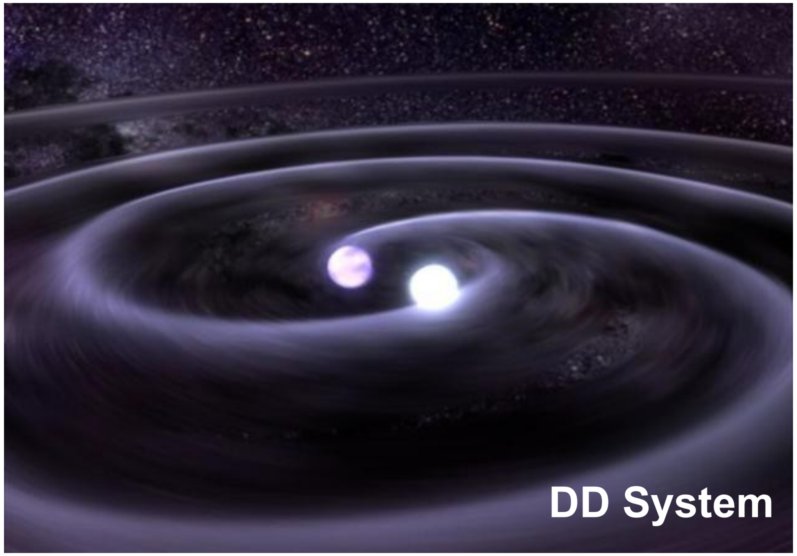
Single Degenerate (SD): WD+non-degenerate star.

- 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.

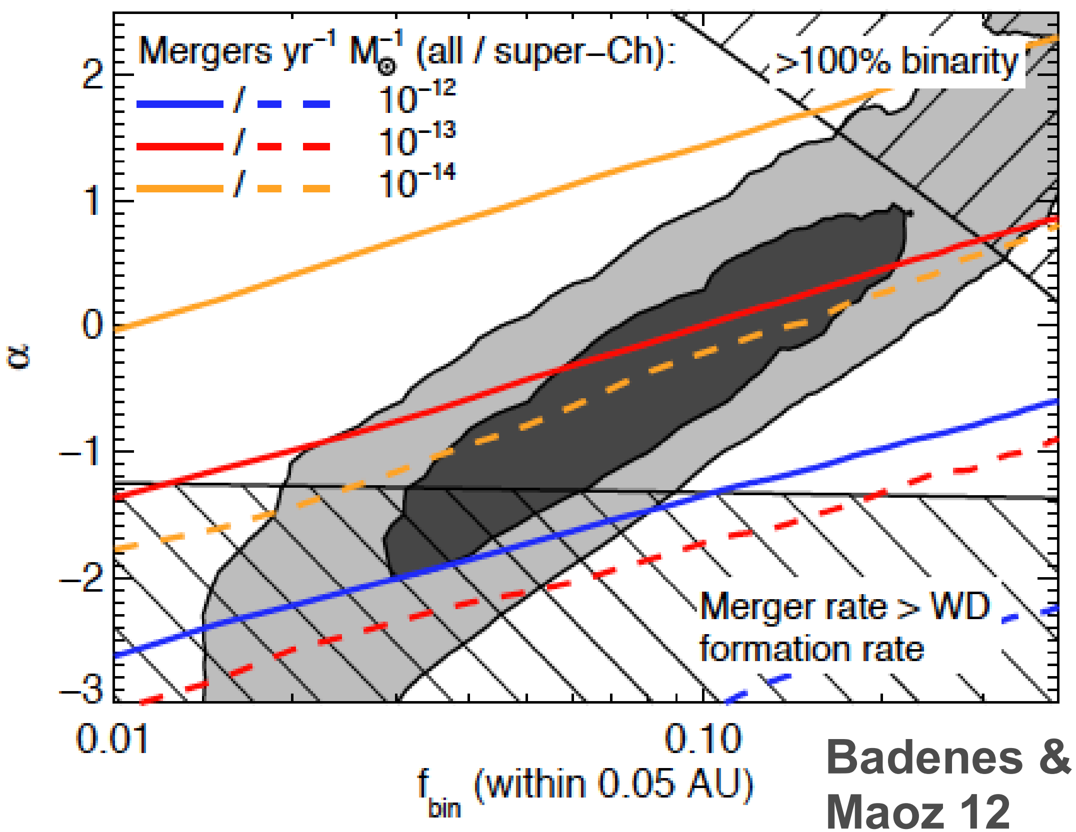
- GW emission ⇒ merging/collision ⇒ **explosion not necessarily near M_{Ch}** [Iben & Tutukov 84, Webbink 84, Sim+ 10, van Kerkwijk+ 10].
- **Not much CSM** expected (WDs are evolved objects).



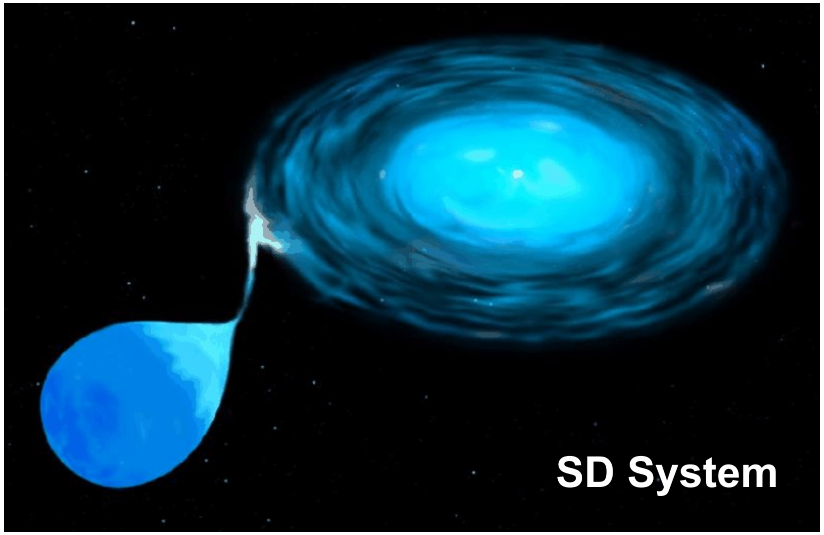
From FOE 2013

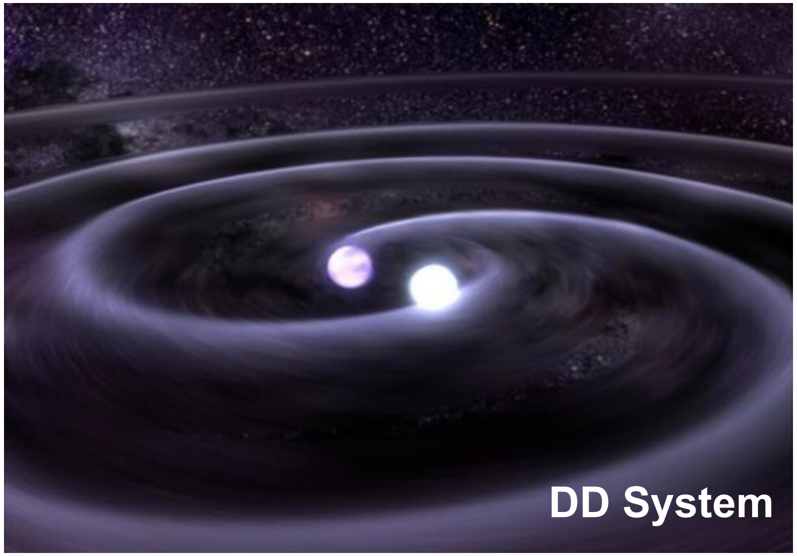
Carles Badenes
FOE 04/06/15

FOE 2013: DD vs. SD debate. I argued that most SN Ia were DD. **WD+WD merger rate in the Milky Way ~ SN Ia rate in Sbc spirals** [Badenes & Maoz 12].

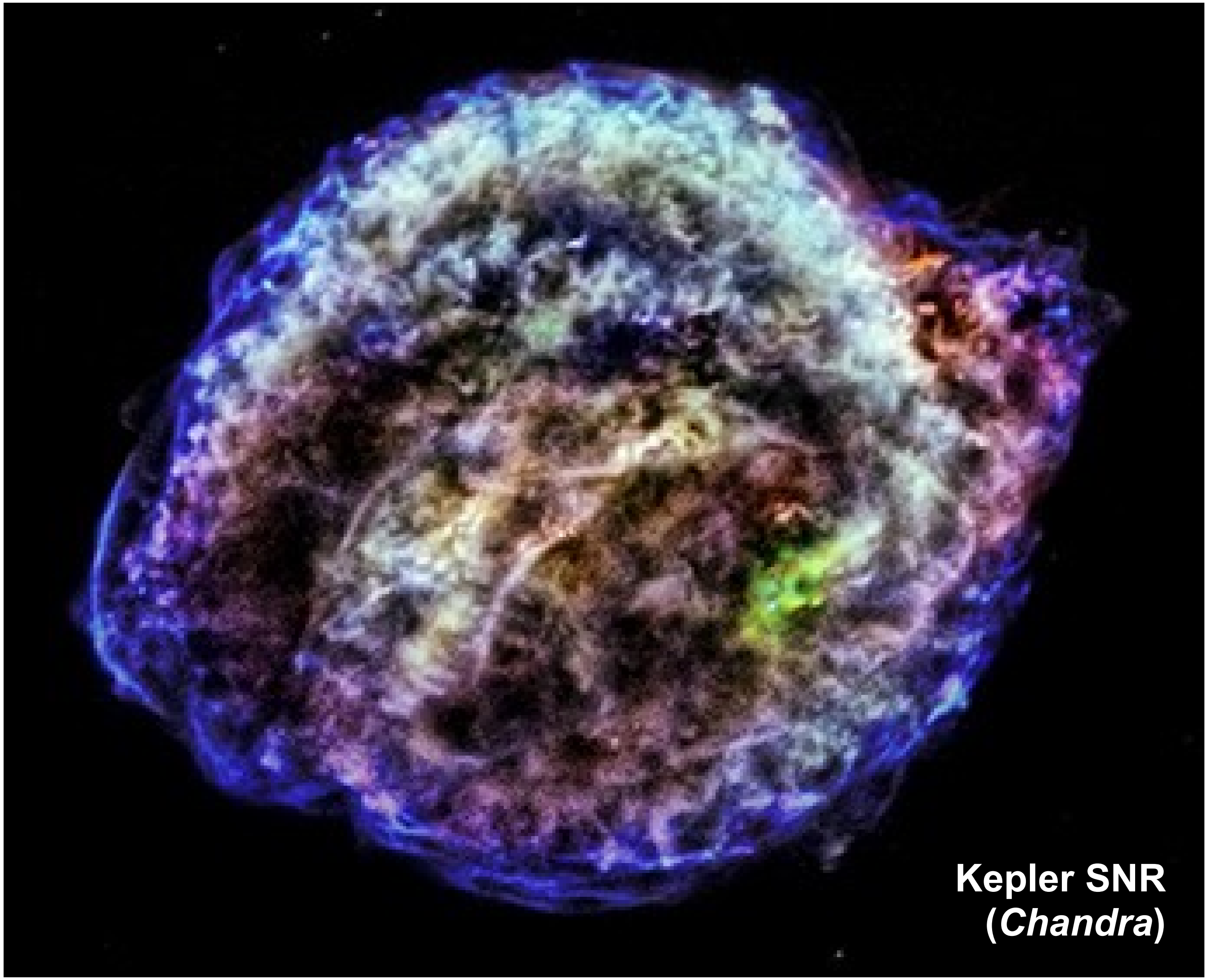


Badenes & Maoz 12





CSM Interaction in Type Ia SNRs

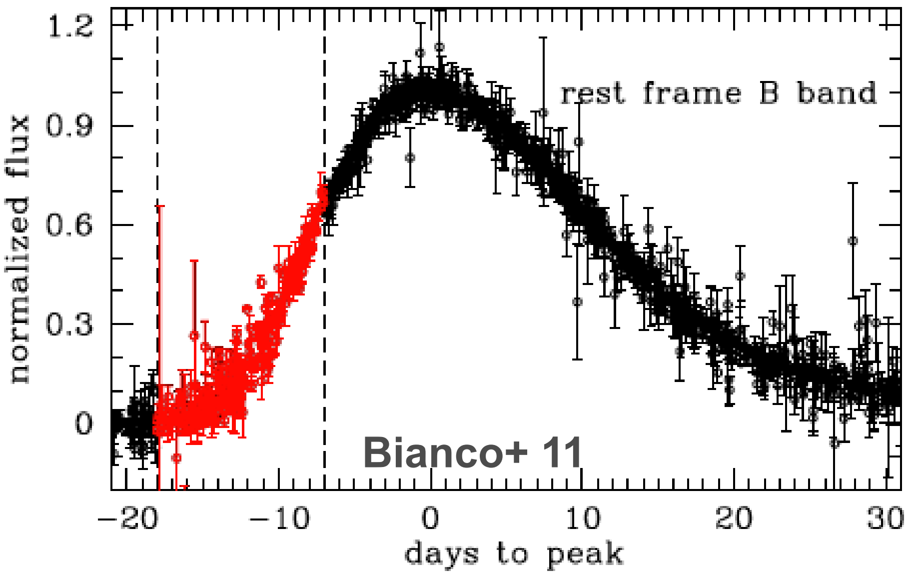


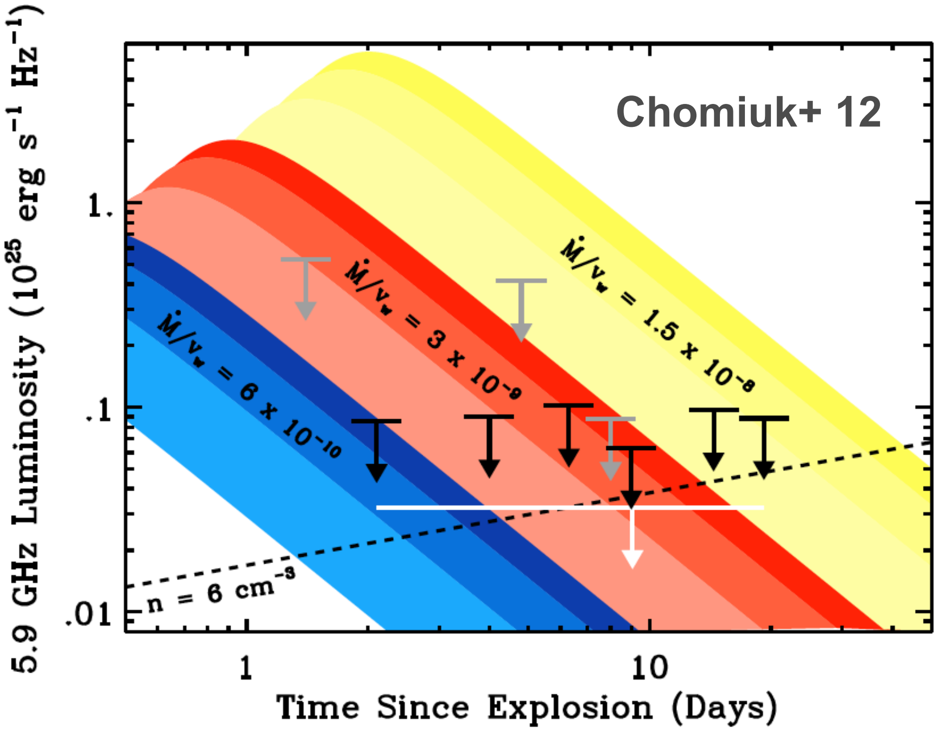
CSM Interaction in SN Ia

Carles Badenes
FOE 04/06/15

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].

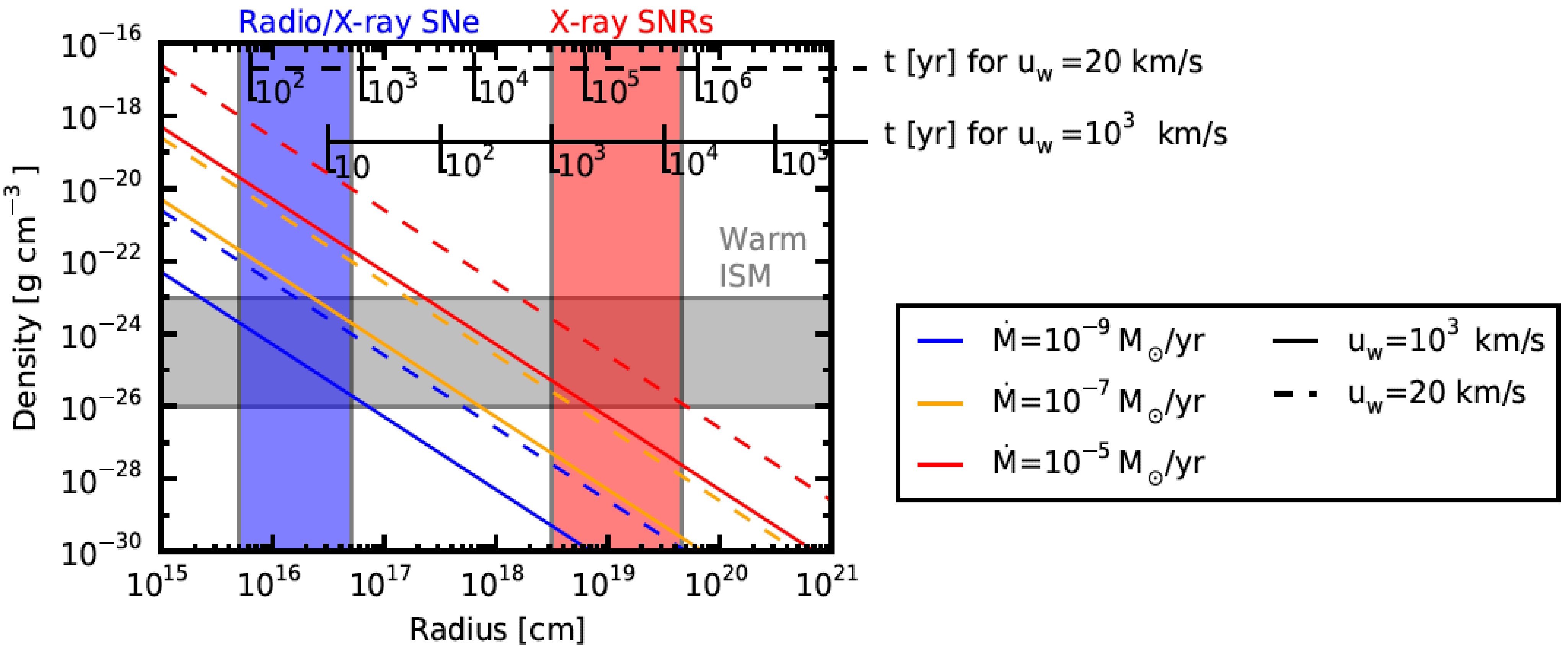




CSM Interaction in SNRs

Carles Badenes
FOE 04/06/15

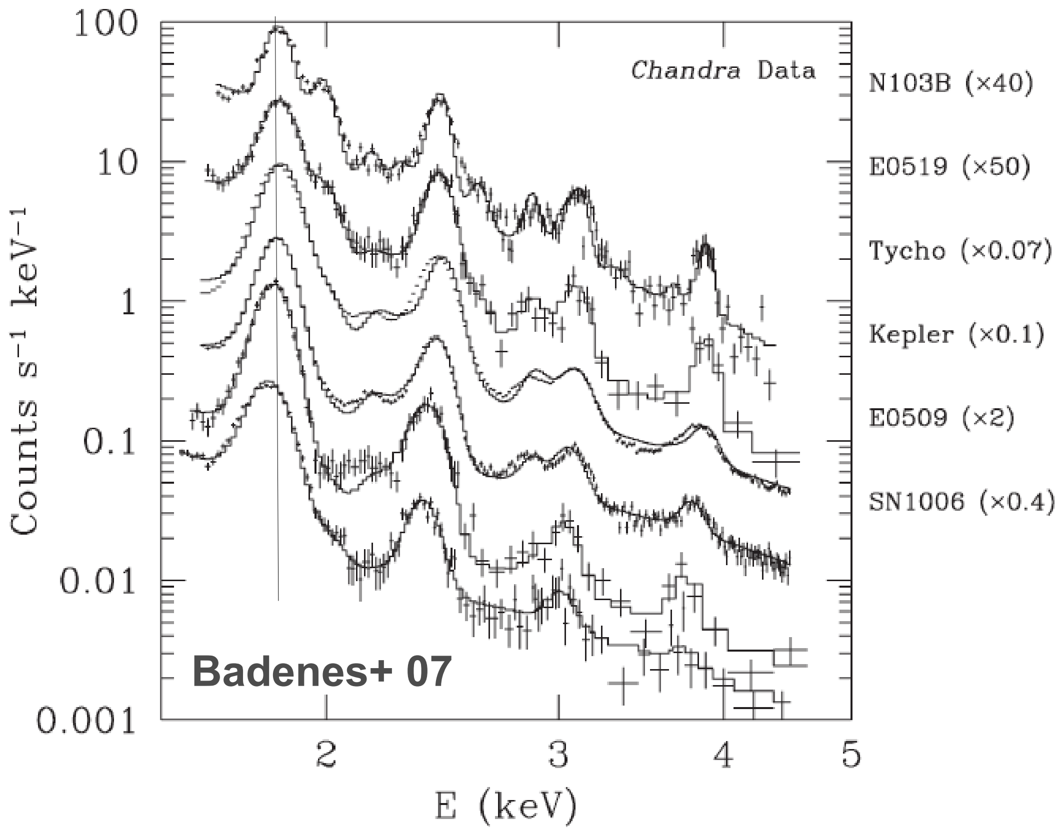
- **SNRs ⇒ spatial (and temporal) scales relevant for stellar evolution** of SN progenitors ($t \lesssim \tau_{KH}$).
- **Can only probe dynamical interaction**: CSM that can slow down SN ejecta.

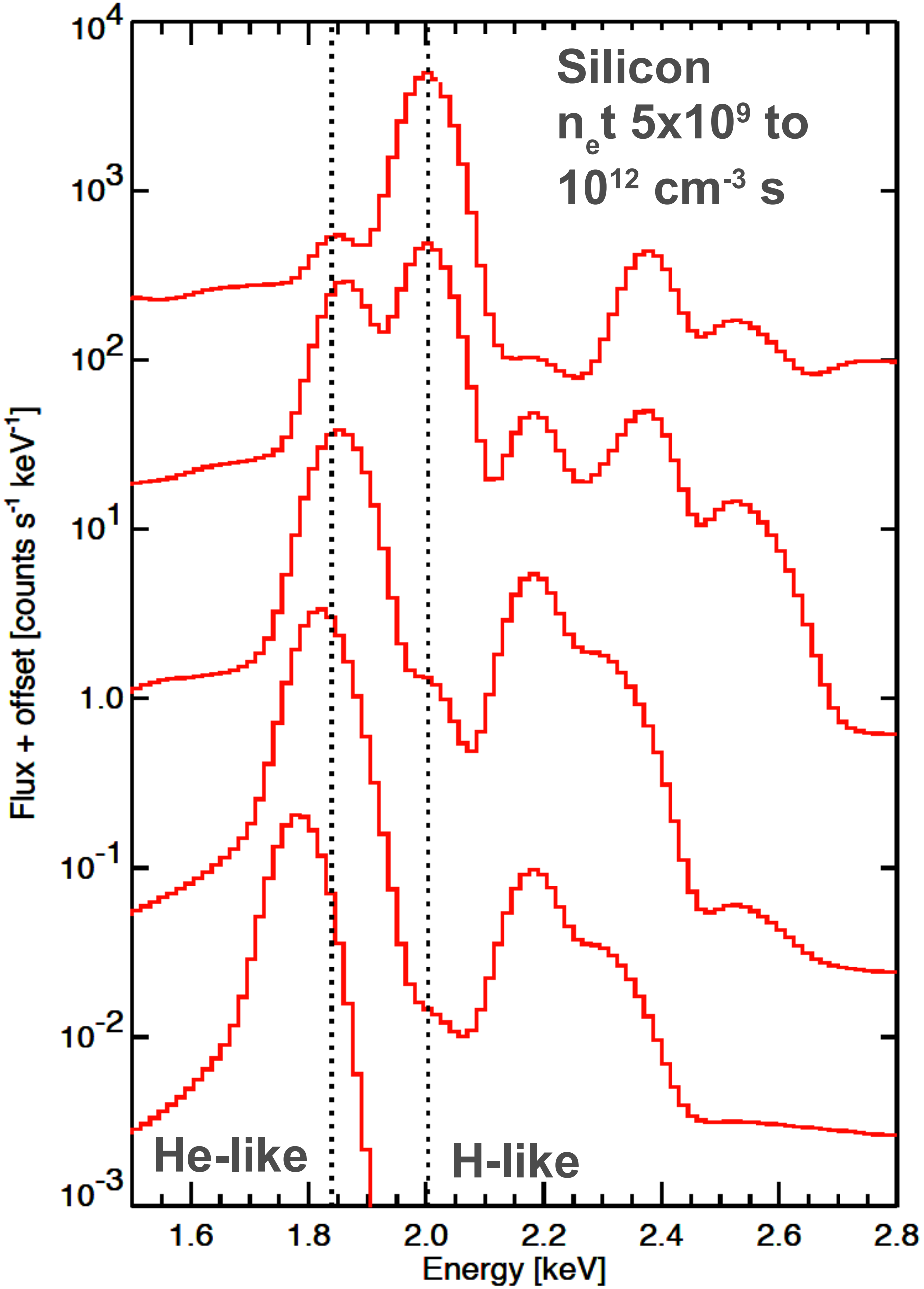


CSM Interaction in SNRs

Carles Badenes
FOE 04/06/15

- **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.

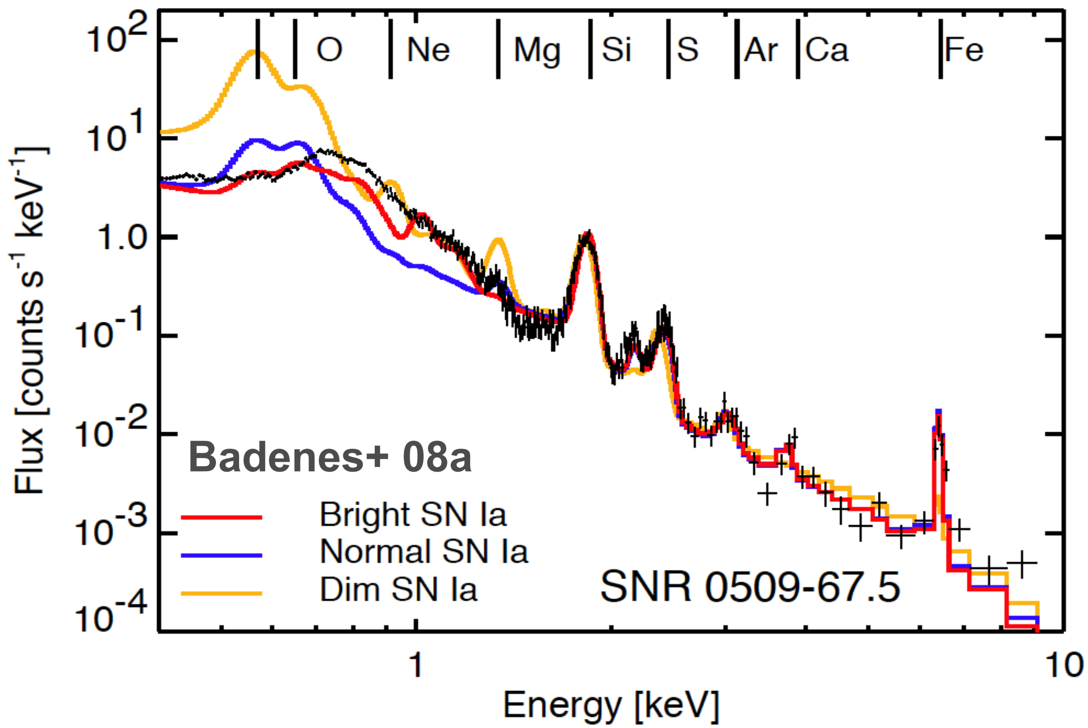


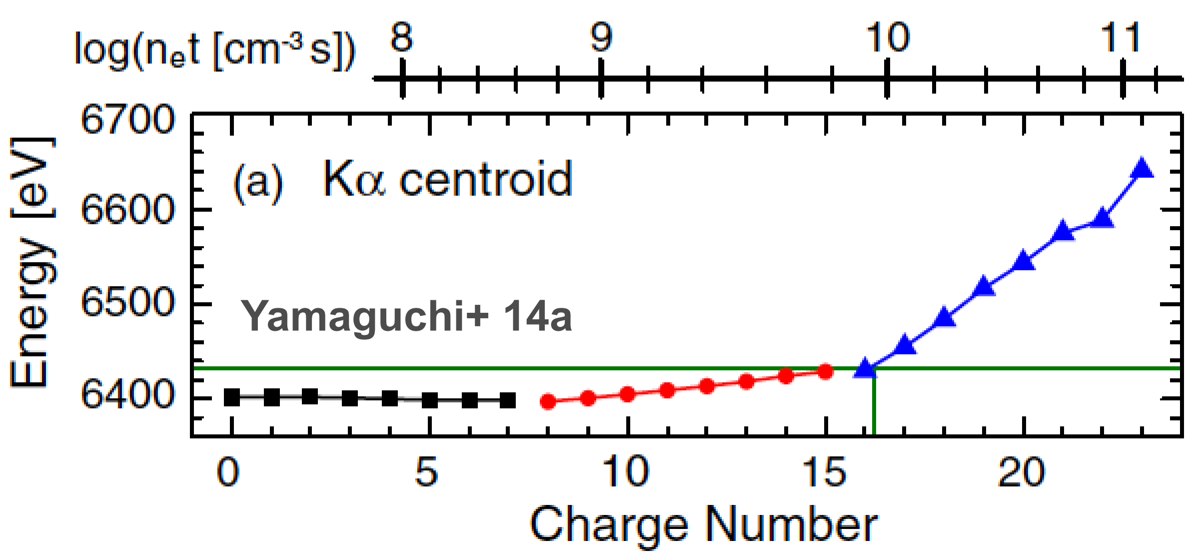


CSM Interaction in SNRs: Fe K

Carles Badenes
FOE 04/06/15

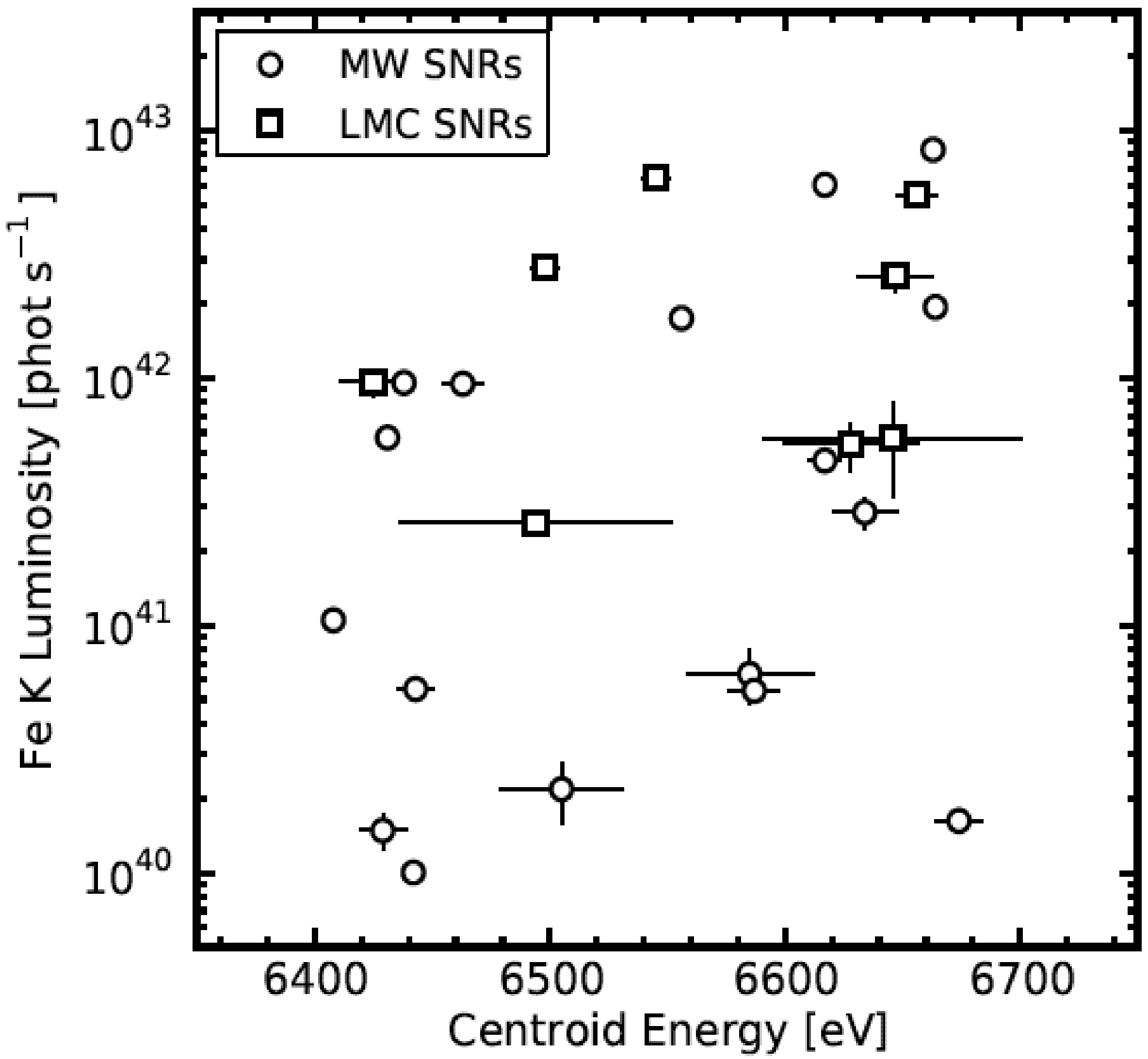
- Use **Fe Kα line blend** at ~6.5 keV as an integrated AM density diagnostic.
- Most SNe (Ia and CC) eject some Fe ⇒ innermost layers.
- Large $n_e t$ required to fully ionize Fe ⇒ **large dynamic range in ρ_{AM}**.
- Need high effective area at 6.5 keV: ***Suzaku***.
- Details: Yamaguchi, CB+ 14b





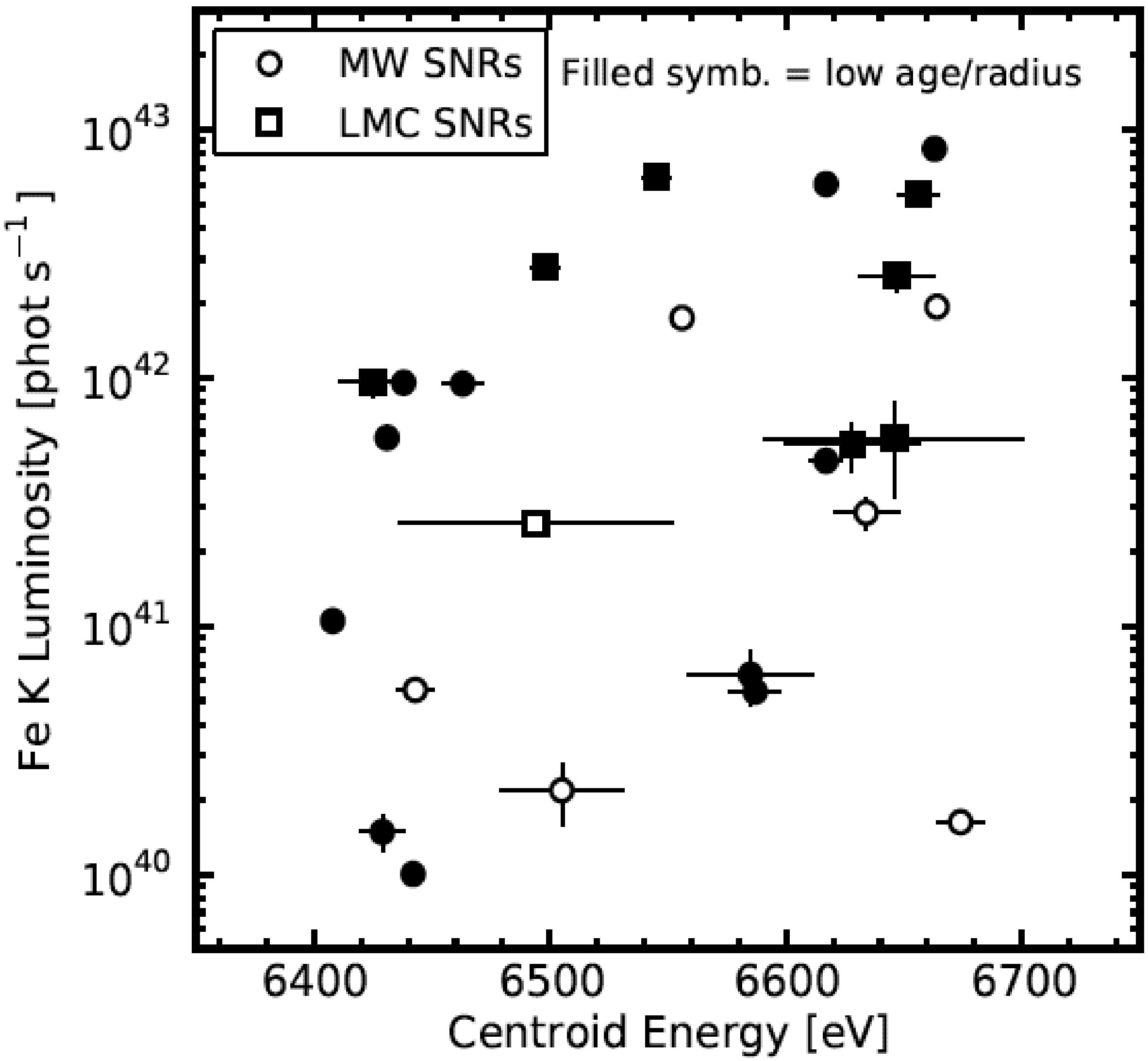
Fe K Emission in SNRs

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



Fe K Emission in SNRs

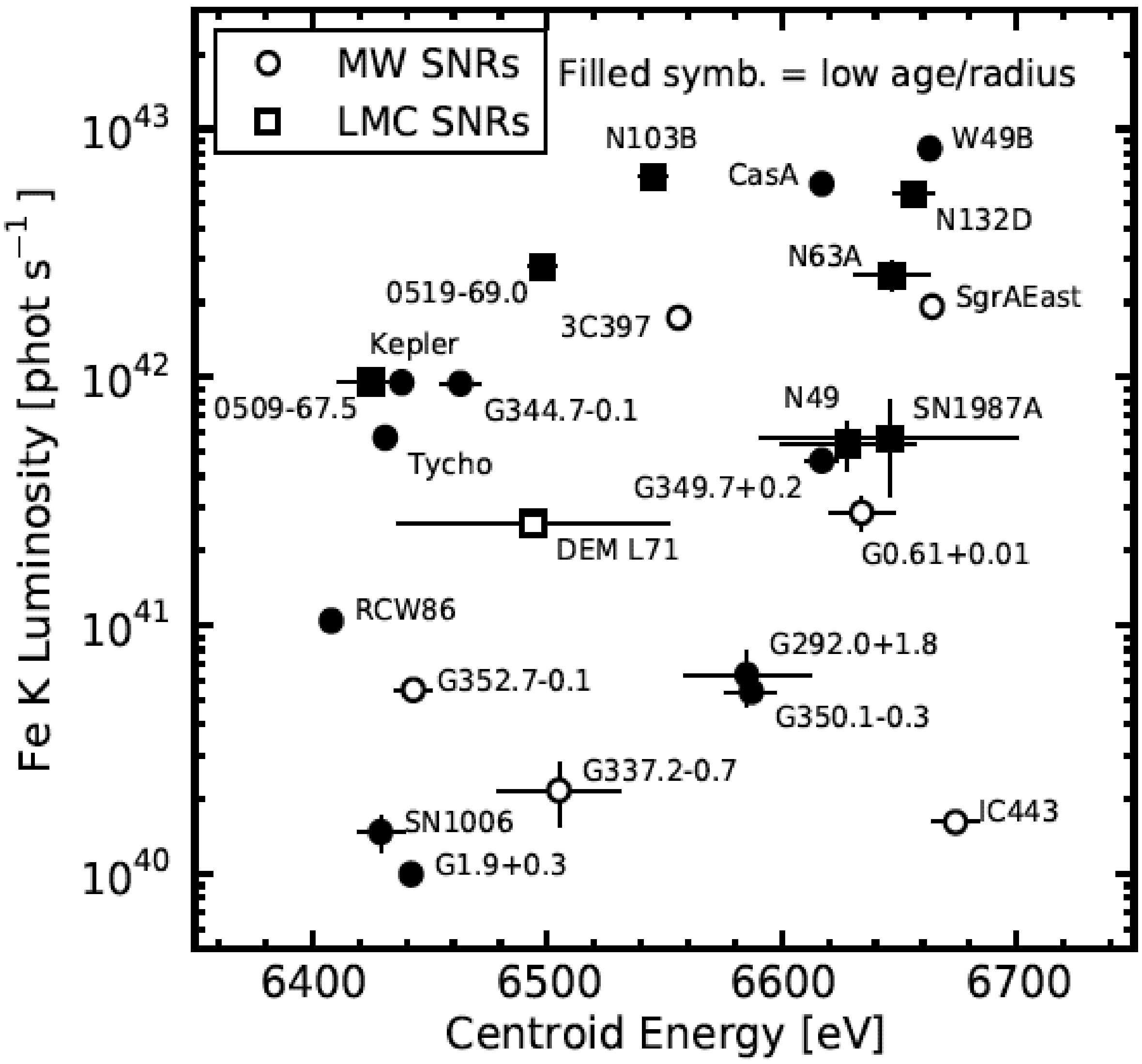
- **24 SNRs** (22 *Suzaku*, +1 *Chandra* [Borkowski+ 13], +1 *XMM* [Maggi+ in prep.]).
- Account for dynamically old/young SNRs ⇒ **bimodal distribution** in FeK centroid/luminosity.



Fe K Emission in SNRs

Carles Badenes
FOE 04/06/15

- **24 SNRs** (22 *Suzaku*, +1 *Chandra* [Borkowski+ 13], +1 *XMM* [Maggi+ in prep.]).
- Account for dynamically old/young SNRs ⇒ **bimodal distribution** in FeK centroid/luminosity.
- **Ia/CC SNRs ⇔ low/high FeK centroids**.



Fe K Emission in SNRs

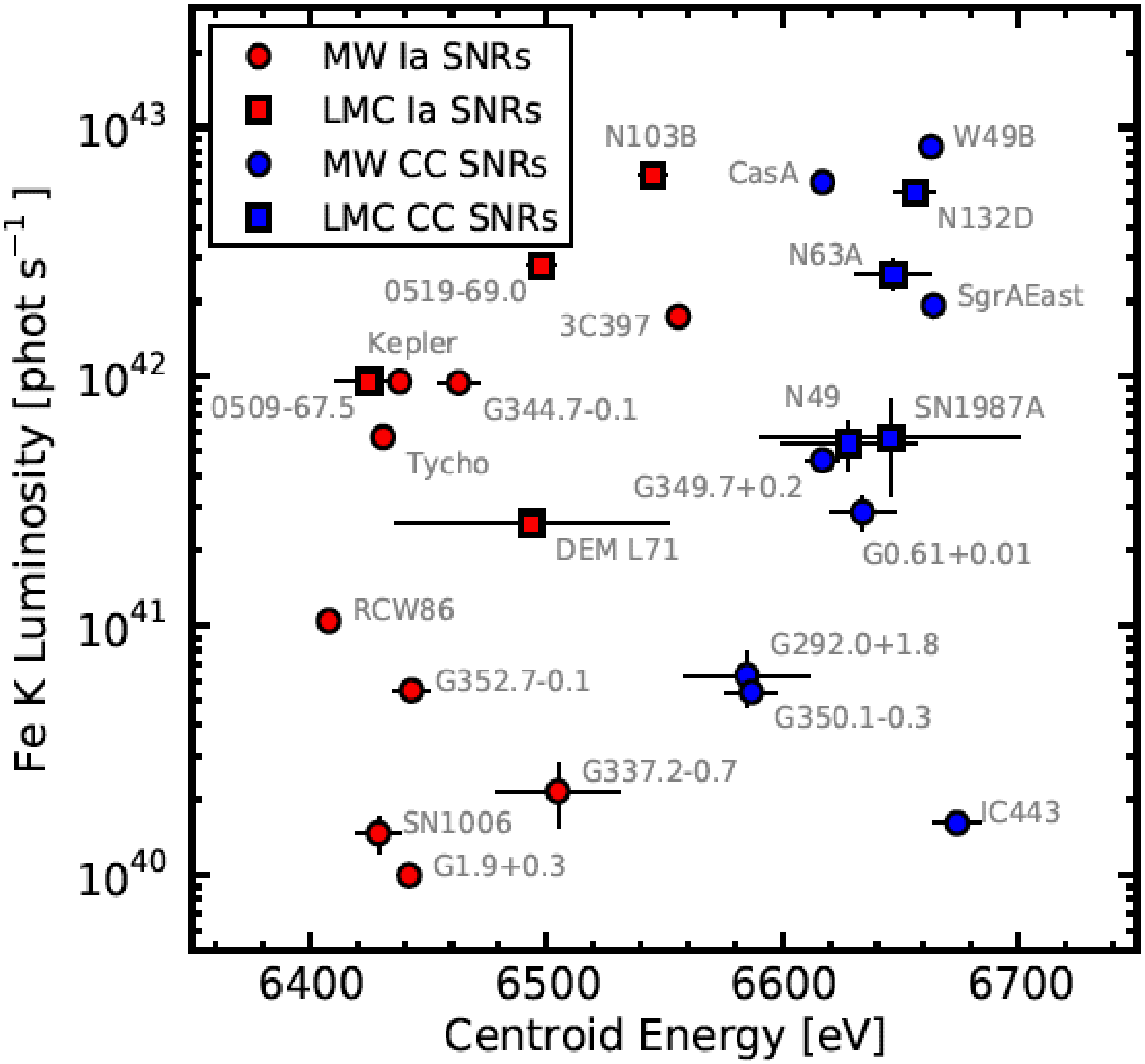
- **24 SNRs** (22 *Suzaku*, +1 *Chandra* [Borkowski+ 13], +1 *XMM* [Maggi+ in prep.]).

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

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

- **CSM interaction!**

- New method to classify SNRs + quantify CSM interaction.

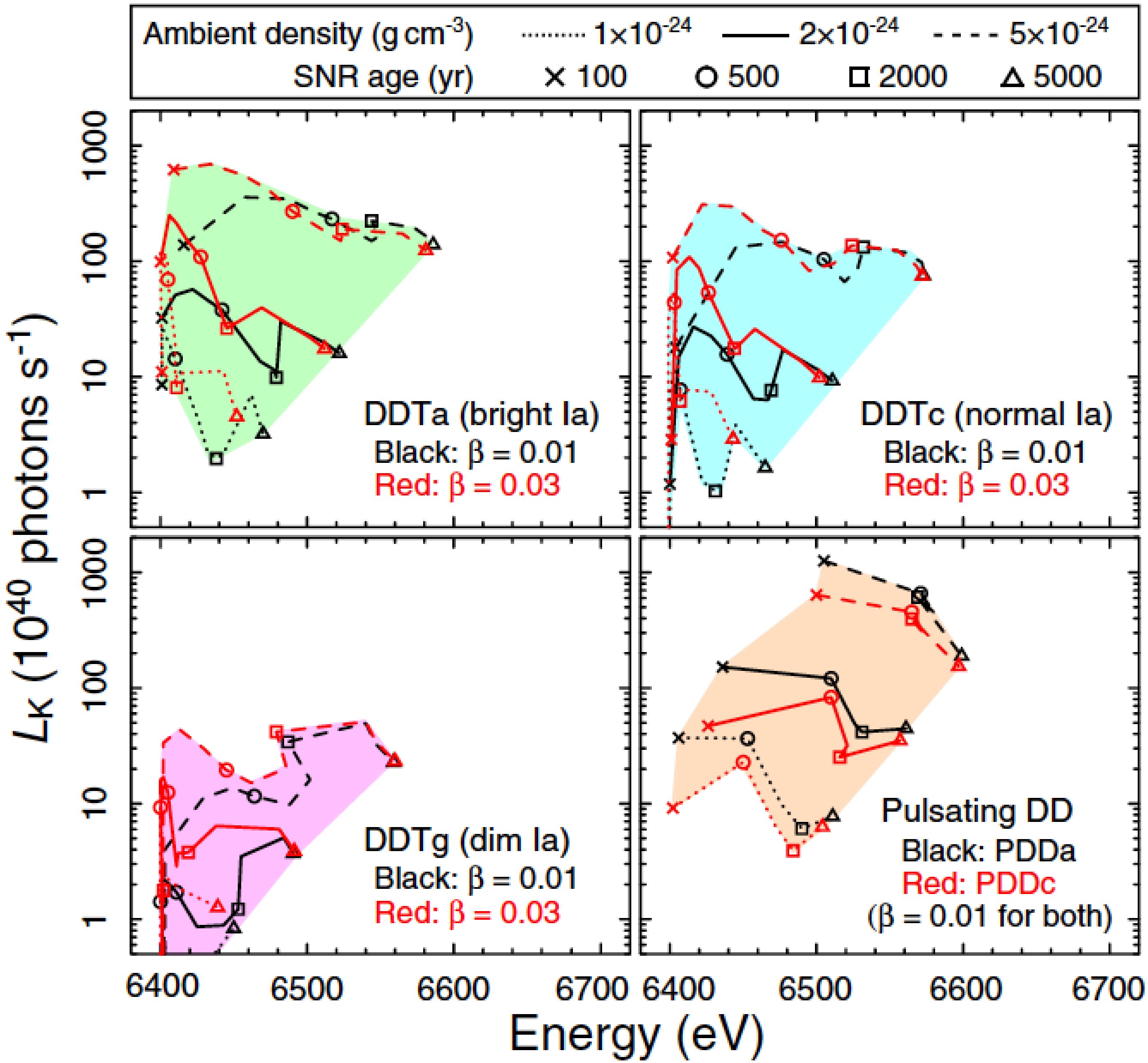


Type Ia SNR Models

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

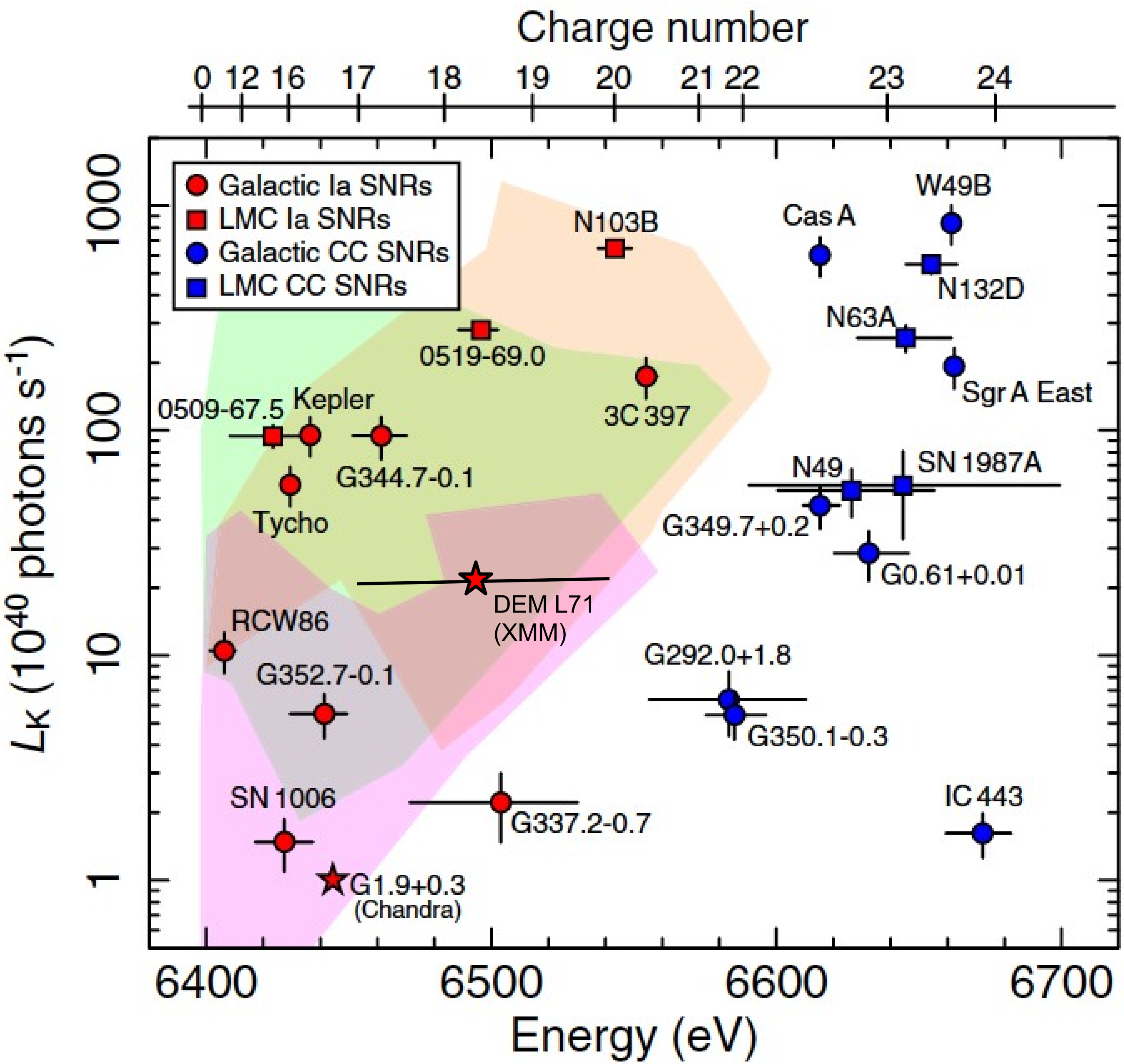
- **DDT** ejecta models (dim, normal, bright SN Ia) ⇒ crude (but effective) **diagnostic of SN Ia brightness!**

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



Models vs. Data

- **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**.

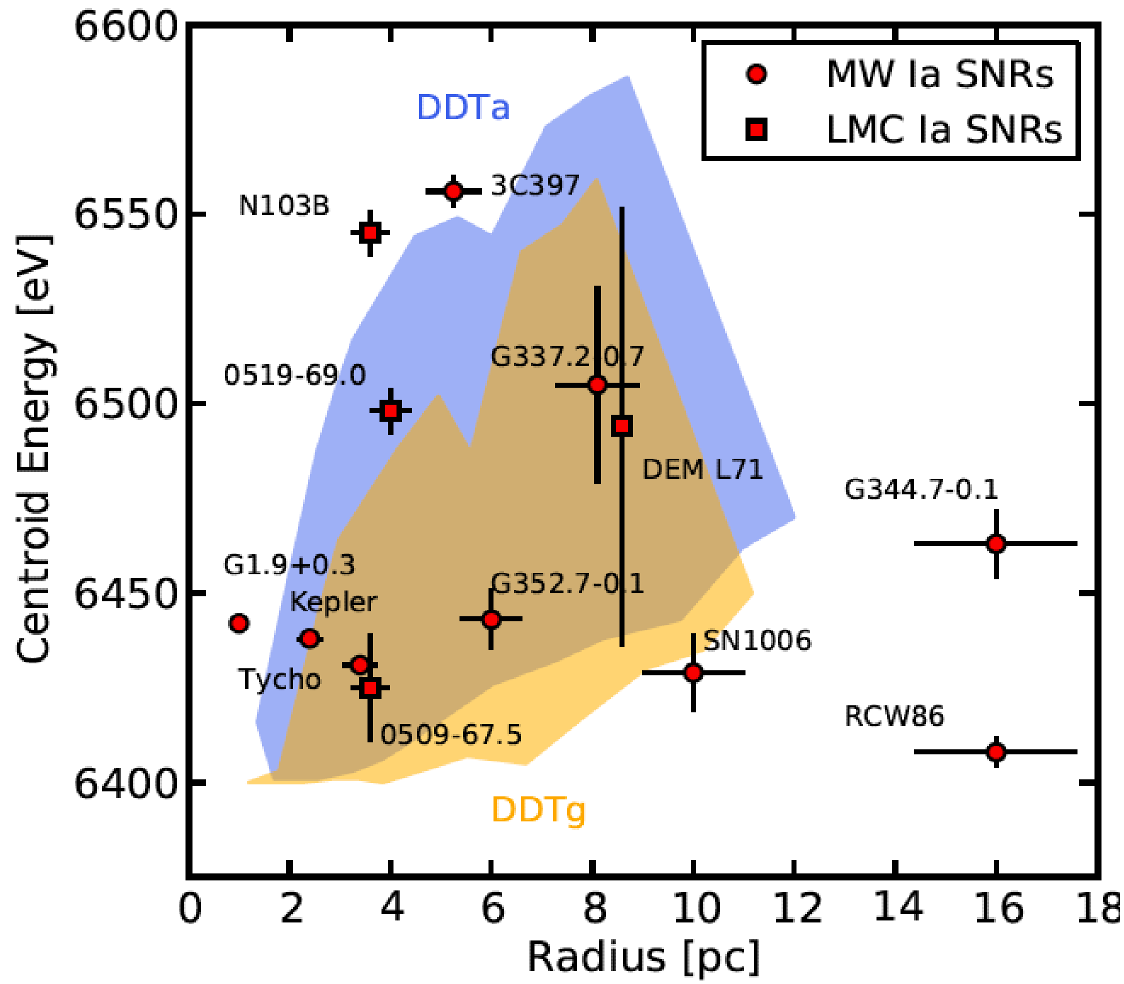


What is going on?

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

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

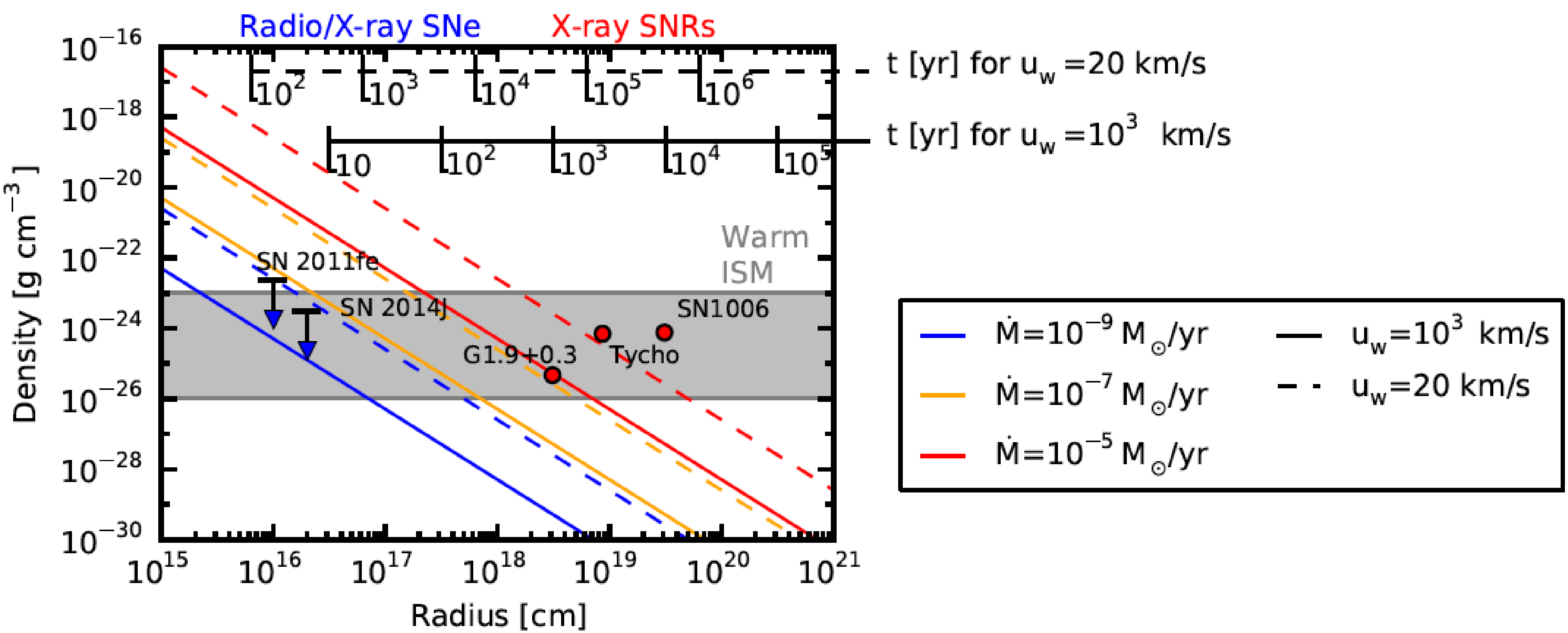
- **RCW 86** (and possibly G344.7-0.1) are **cavity explosions** [Badenes+ 07, Williams+ 11, Broersen+ 14].



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

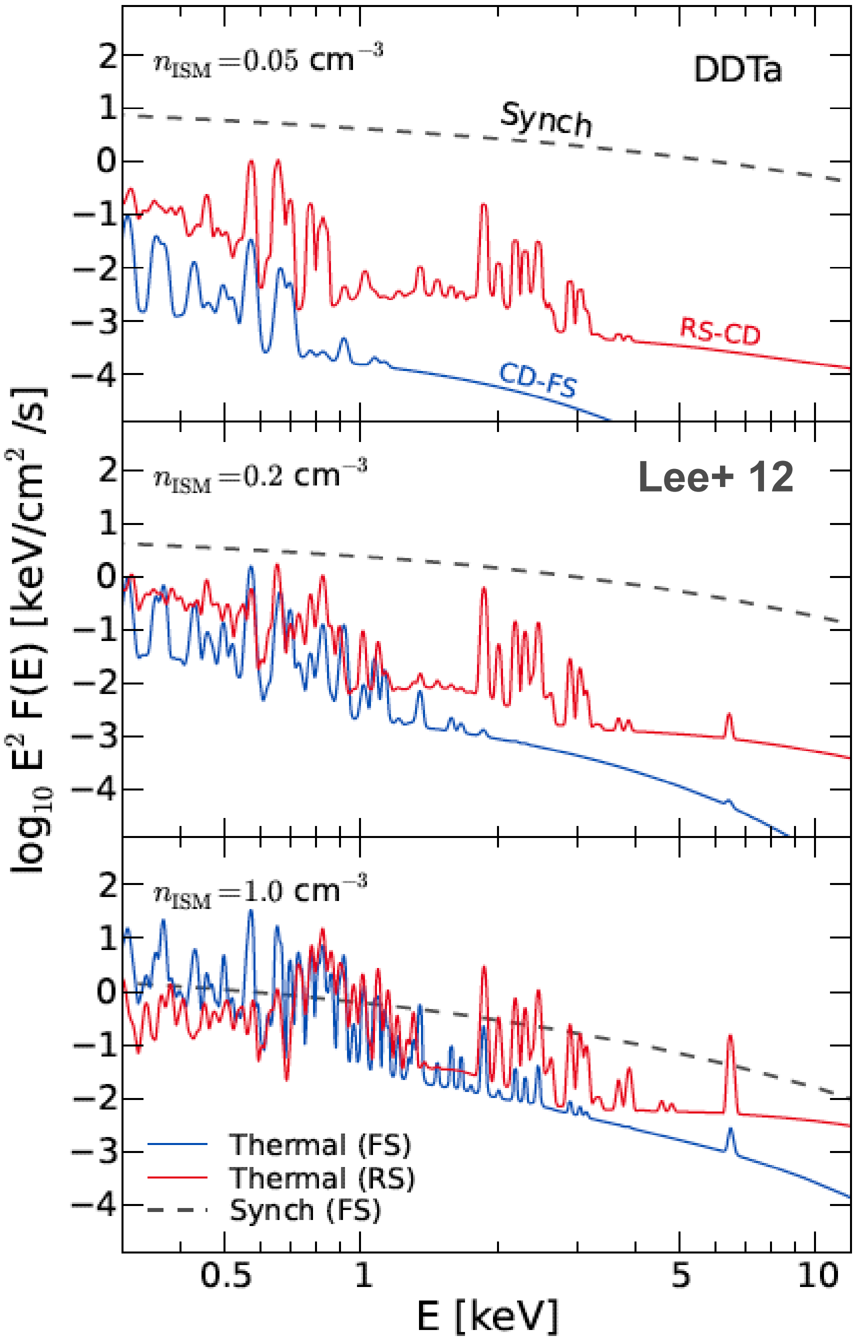
A Step Back

- **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.



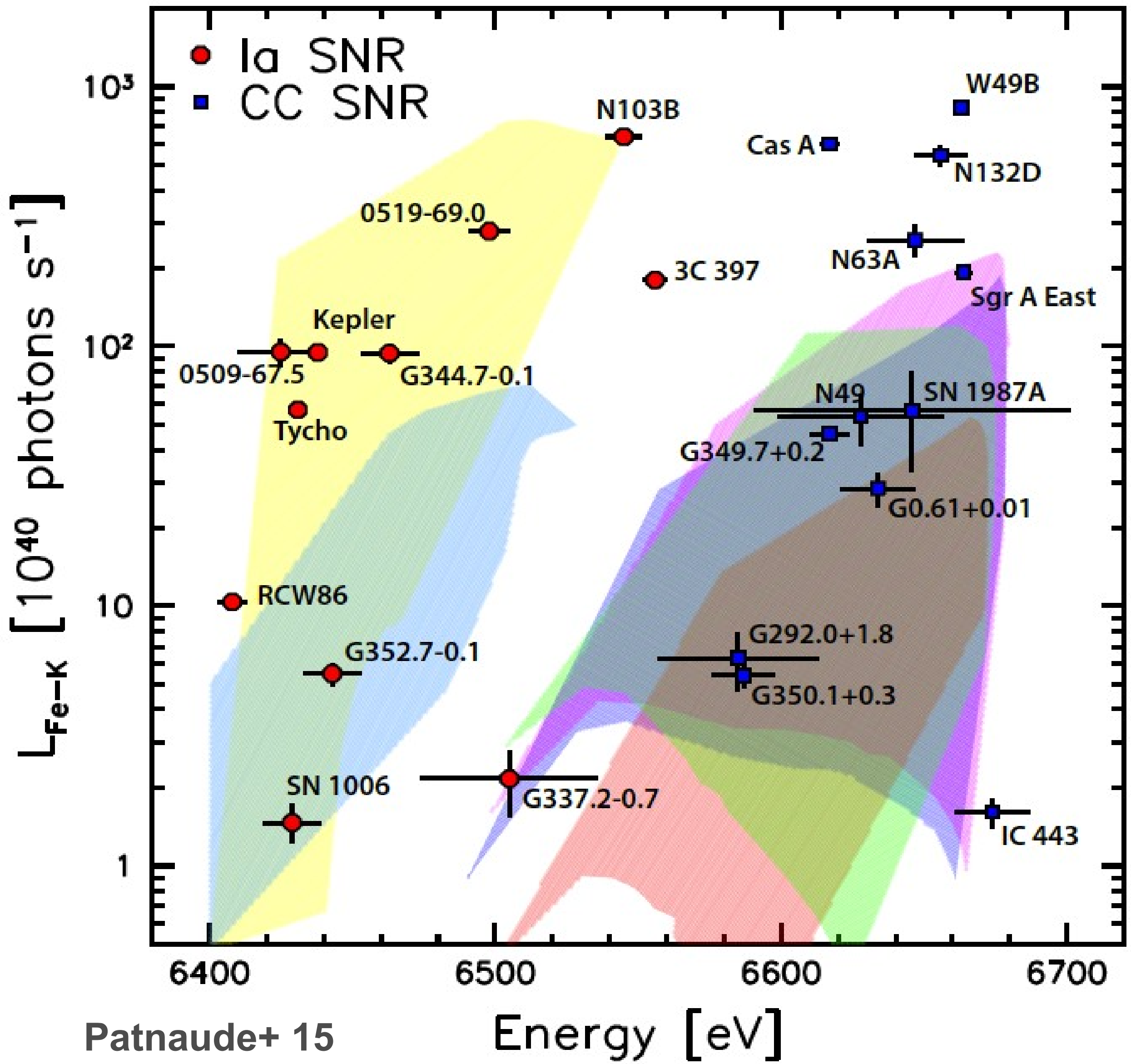
Steps Forward

- **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 2016 ⇒ Revolution in X-ray observations of SNRs.



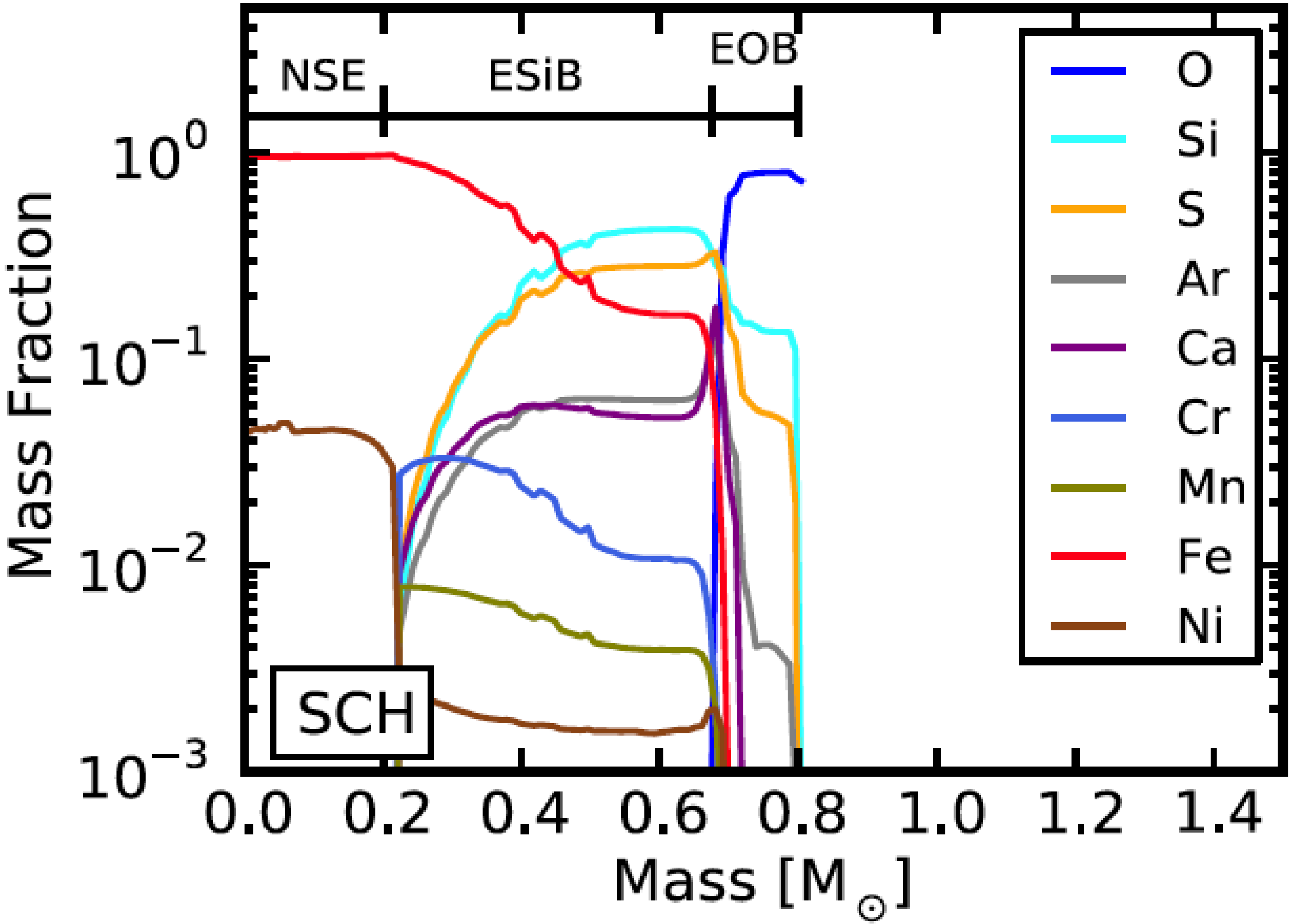
Steps Forward

- **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 2016 ⇒ Revolution in X-ray observations of SNRs.



Patnaude+ 15

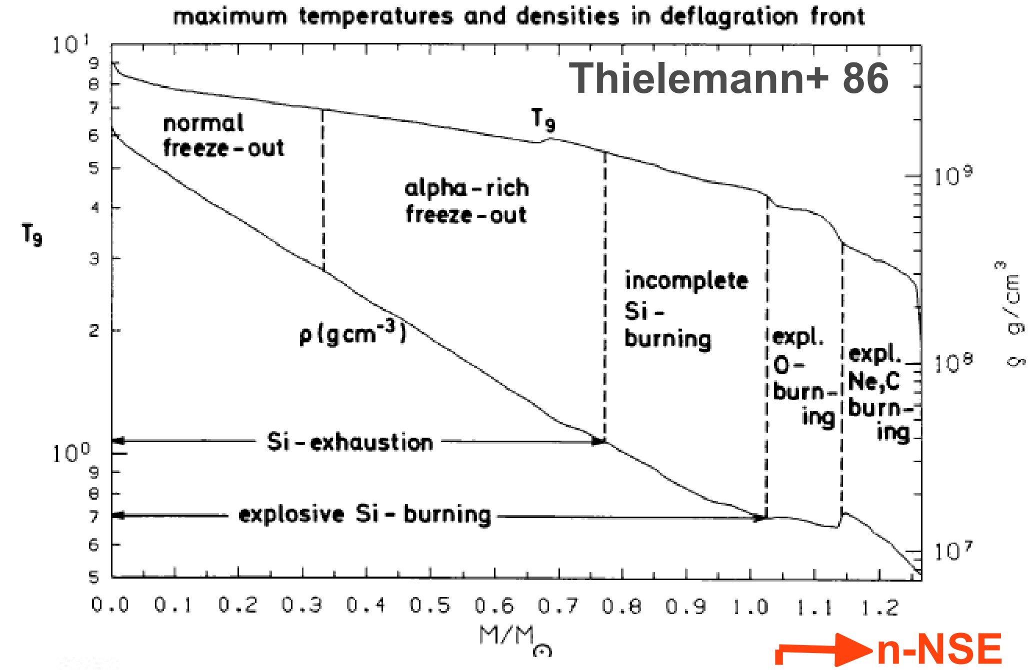
Secondary Fe-peak Elements in Type Ia SNRs

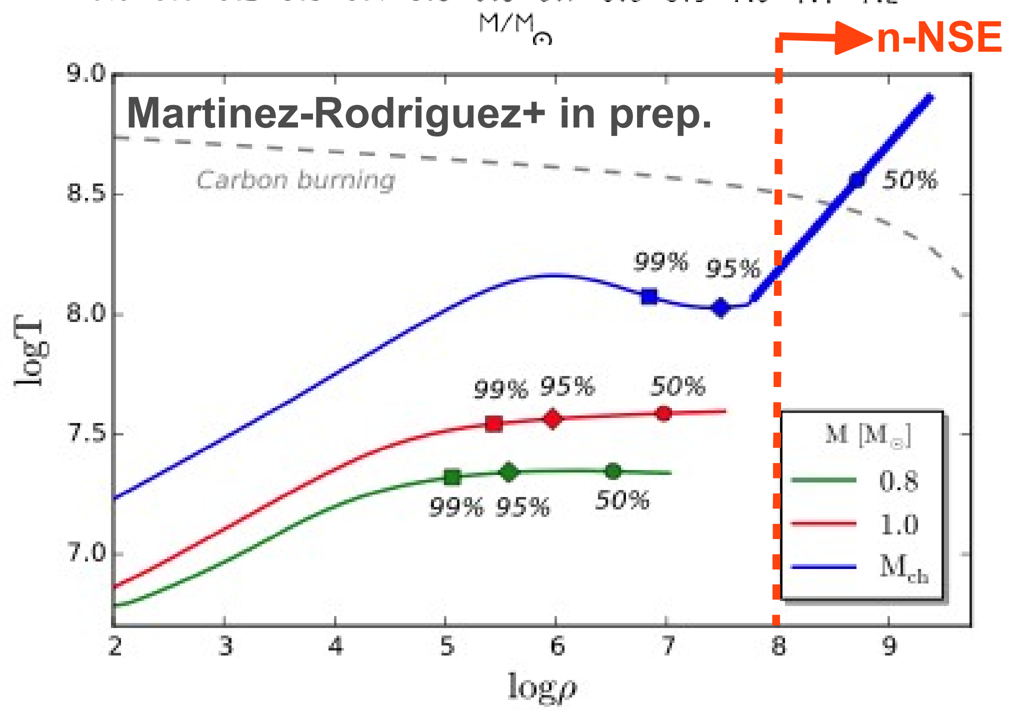


SN Ia Nucleosynthesis 101

Carles Badenes
FOE 04/06/15

- **Burning regimes in SN Ia:** Exp. O burning, exp. Si burning, NSE, n-NSE ⇒ Si, S, Ar, Ca, Fe [Thielemann+ 86, Seitenzahl talk].
- **What about n-rich isotopes (**^{55}**Mn,** ^{60}**Ni, ...)?** CO WDs have no neutron excess! Whence n?
  - **Progenitor metallicity**. CNO bottleneck is $^{14}N(\alpha,\gamma) \Rightarrow {}^{22}Ne \Rightarrow$ n-excess = 0.1xZ [Timmes+ 03, Badenes+ 08].
  - **n-NSE** (NSE at high densities). **Requires $M_{WD} \sim M_{Ch}$!!**
  - **C-simmering**. This is complicated [Piro & Bildsten 08].

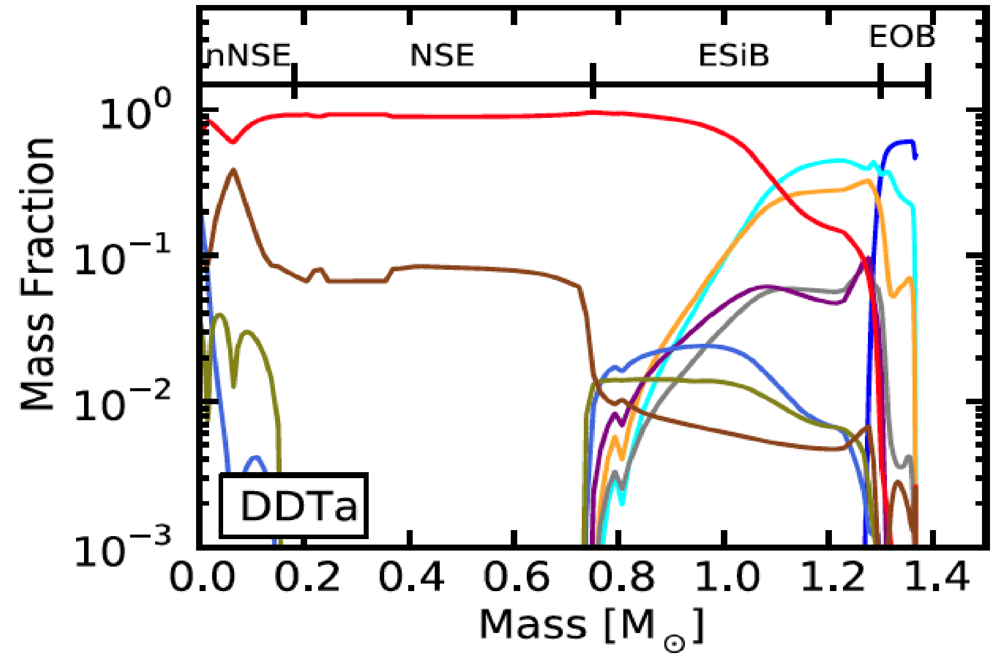


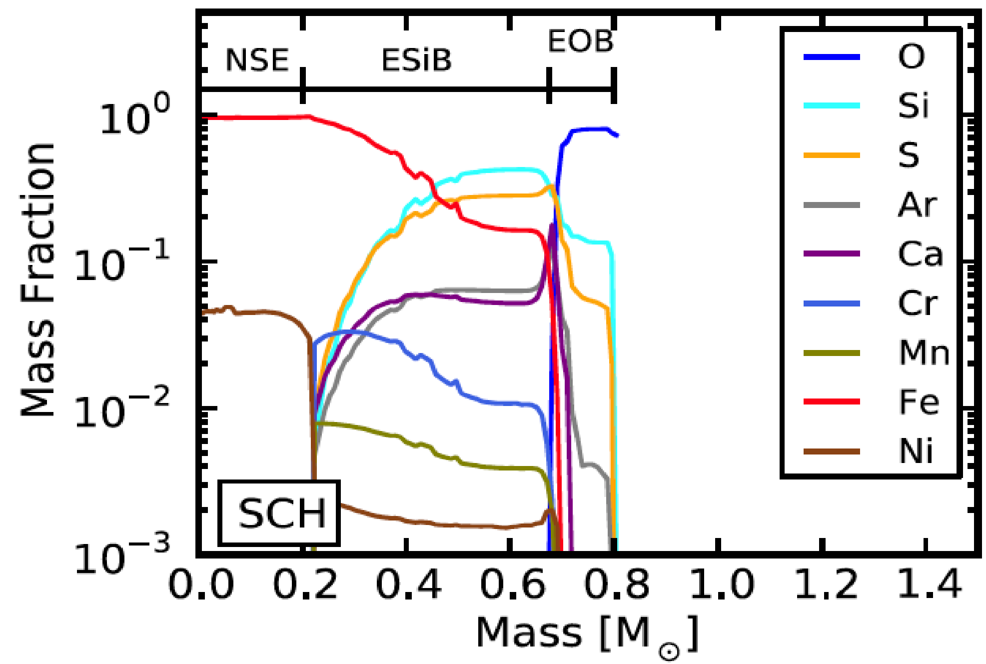


Secondary Fe-peak Elements

Carles Badenes
FOE 04/06/15

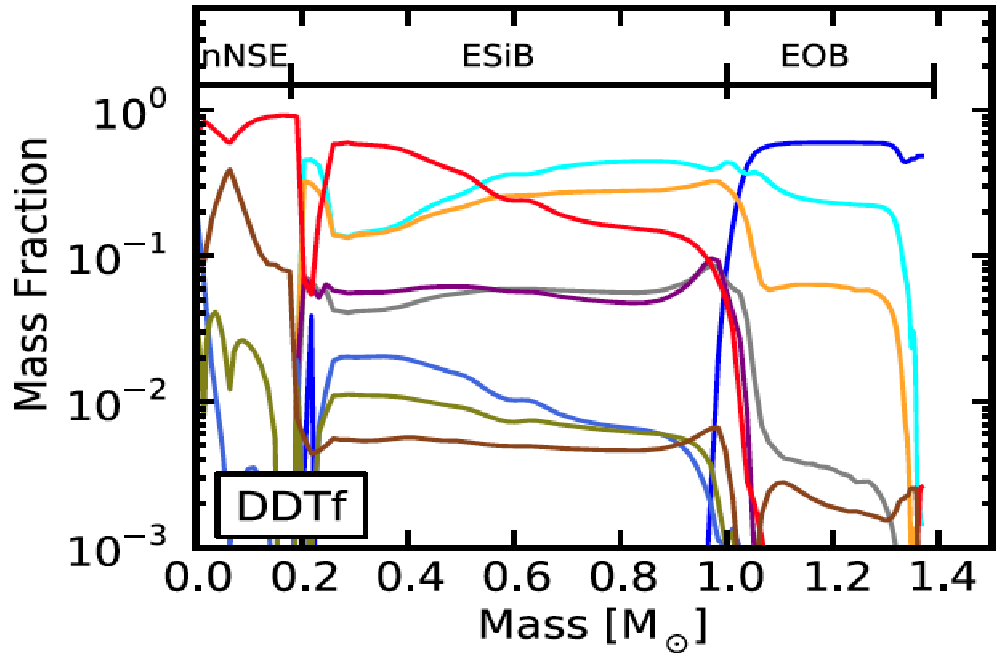
- **M_{Ch} DDT explosions** (standard SN Ia models) [Khokhlov 91]. One parameter (ρ_{tr}) ⇒ ^{56}Ni yield (SN Ia brightness).
- **Sub-Ch explosions** also viable [Sim+ 10]. One parameter (M_{WD}) ⇒ ^{56}Ni yield.
- **Sub-Ch models do not reach n-NSE ⇒ smaller yield of neutronized species** (**Mn, Ni**).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

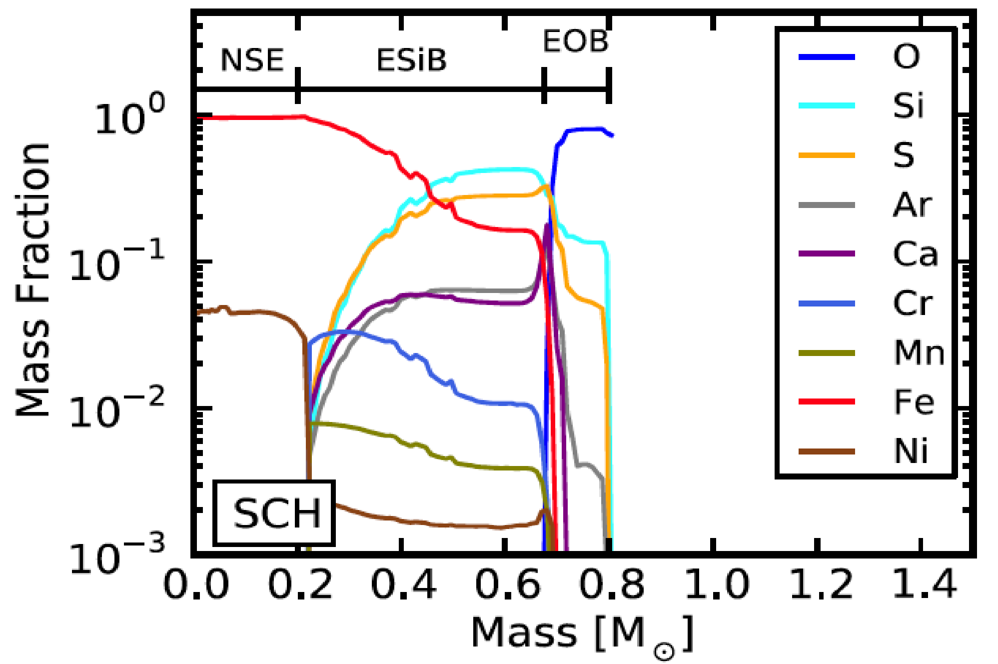




Secondary Fe-peak Elements

- **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**
  - **Sub-Ch ⇔ DD**



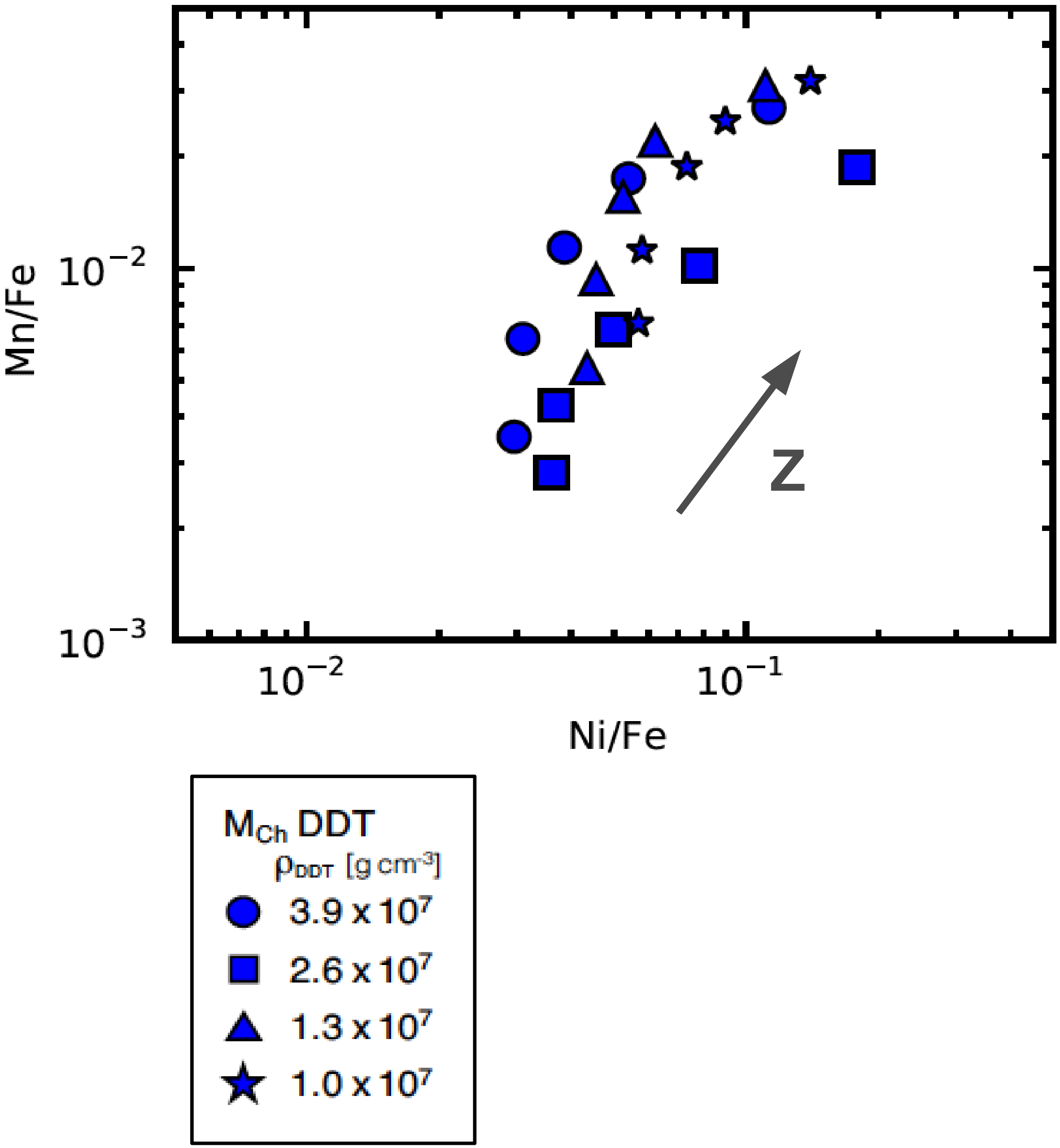


Secondary Fe-peak Elements

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

- Diagnostic mass ratios: $\mathbf{M_{Ni}/M_{Fe}}$ and $\mathbf{M_{Mn}/M_{Fe}}$ $\Rightarrow$ discriminate Ch and Sub-Ch explosions!

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



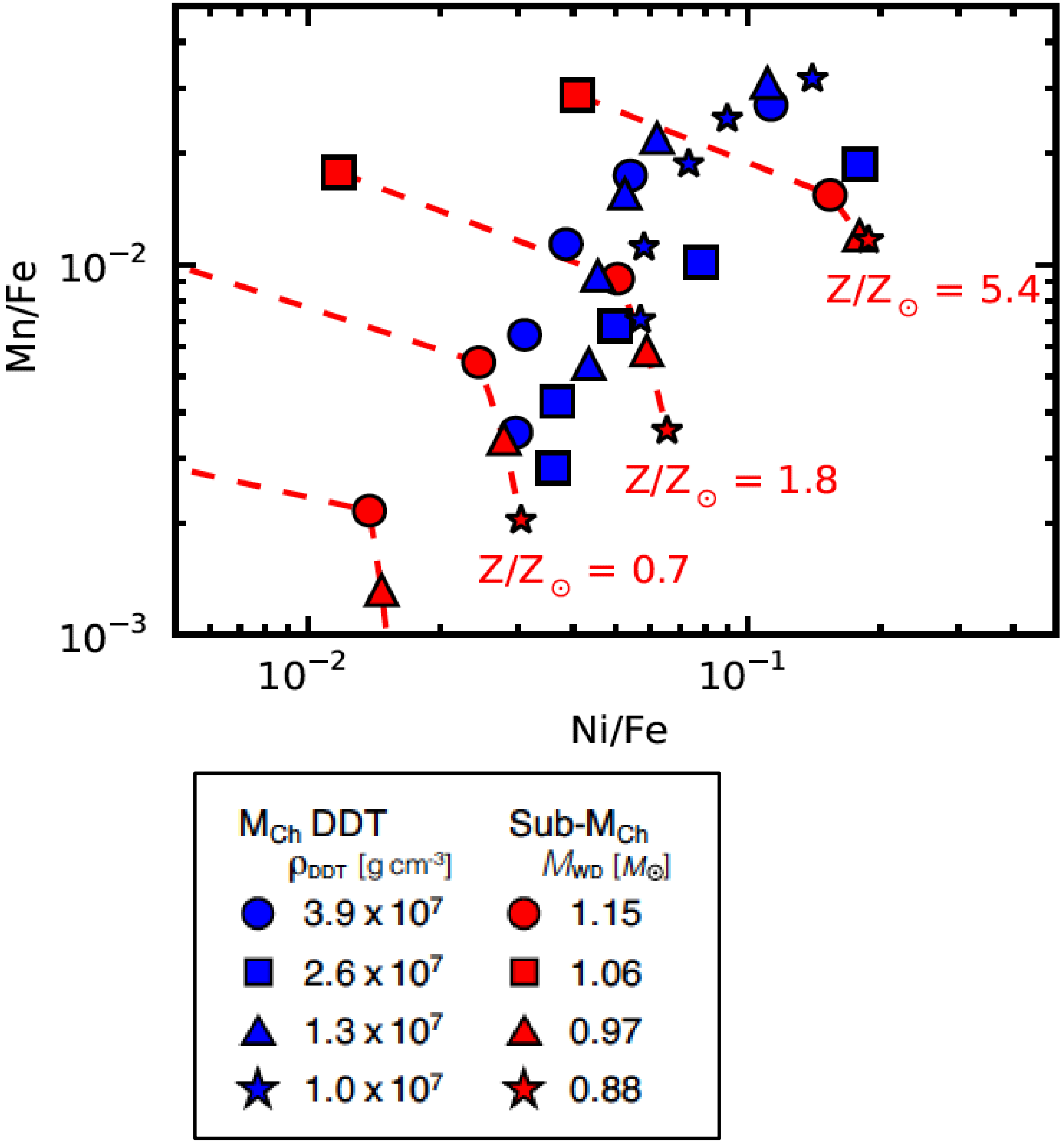
Secondary Fe-peak Elements

Carles Badenes
FOE 04/06/15

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

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

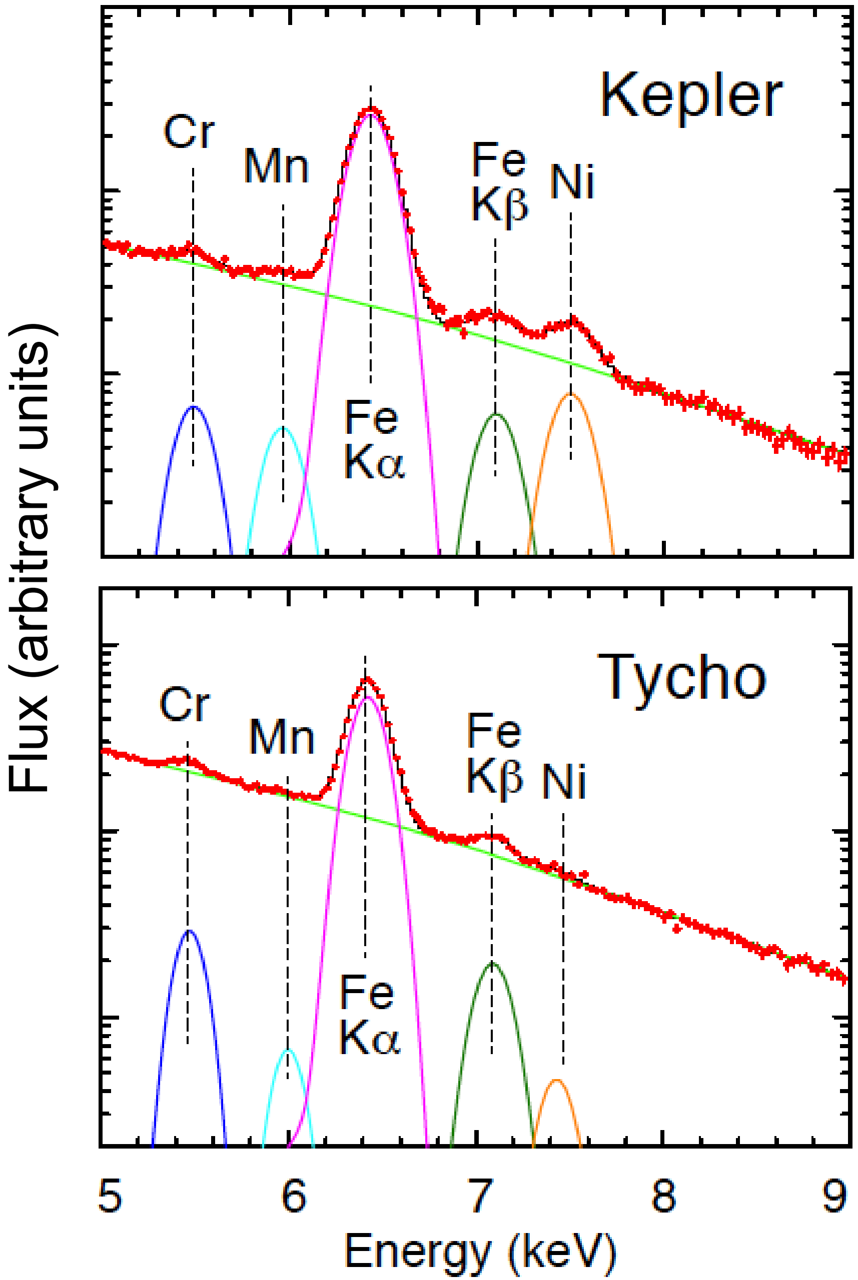
- Mn and Ni are hard to observe in the optical [Maeda+ 10, Seitenzahl+ 13].



Secondary Fe-peak Elements

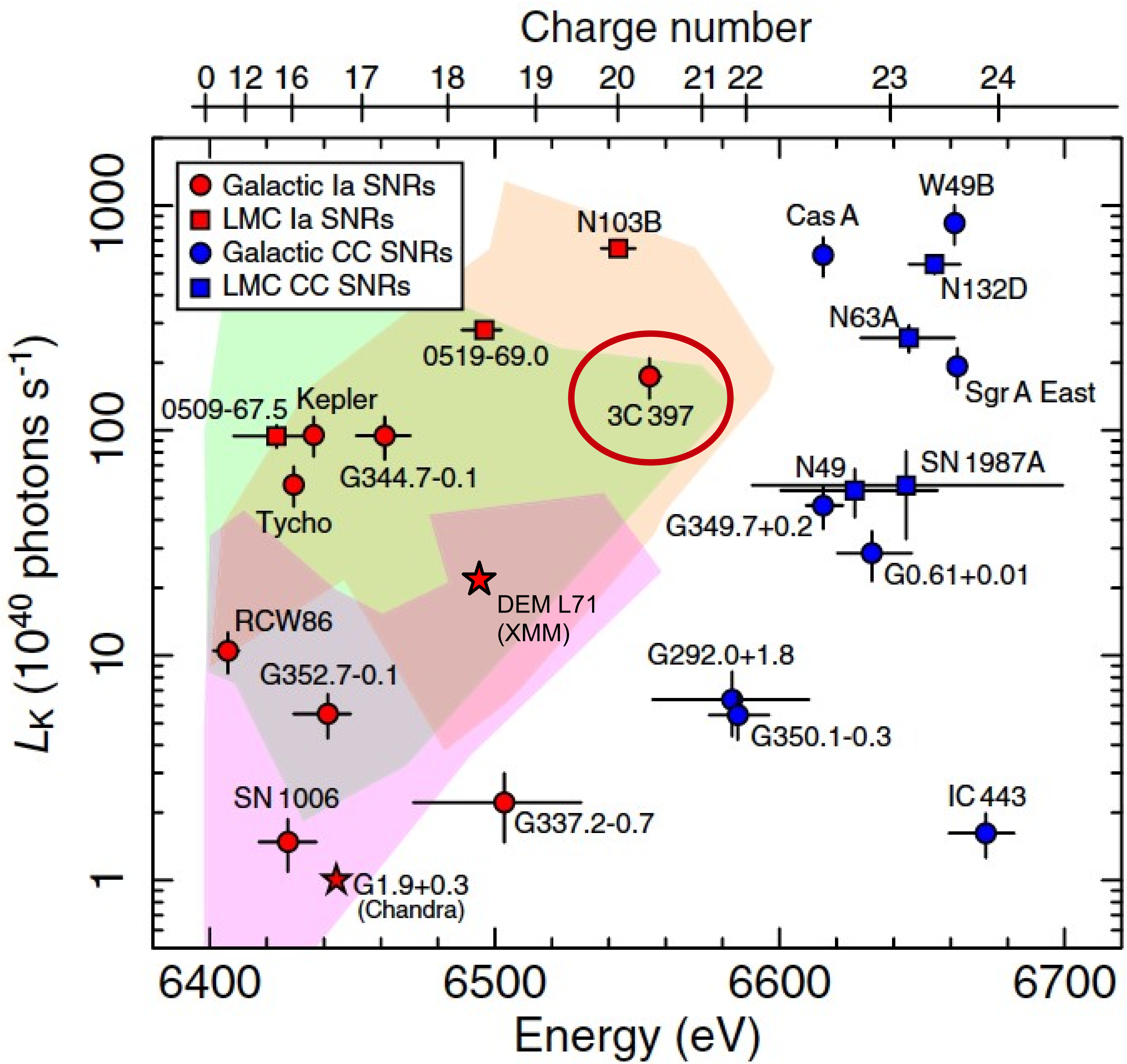
- ***Suzaku*** can detect Cr, Mn, and Ni lines in SNRs: Tycho, Kepler, ... [Tamagawa+ 08, Park+ 13,Yang+ 13].

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



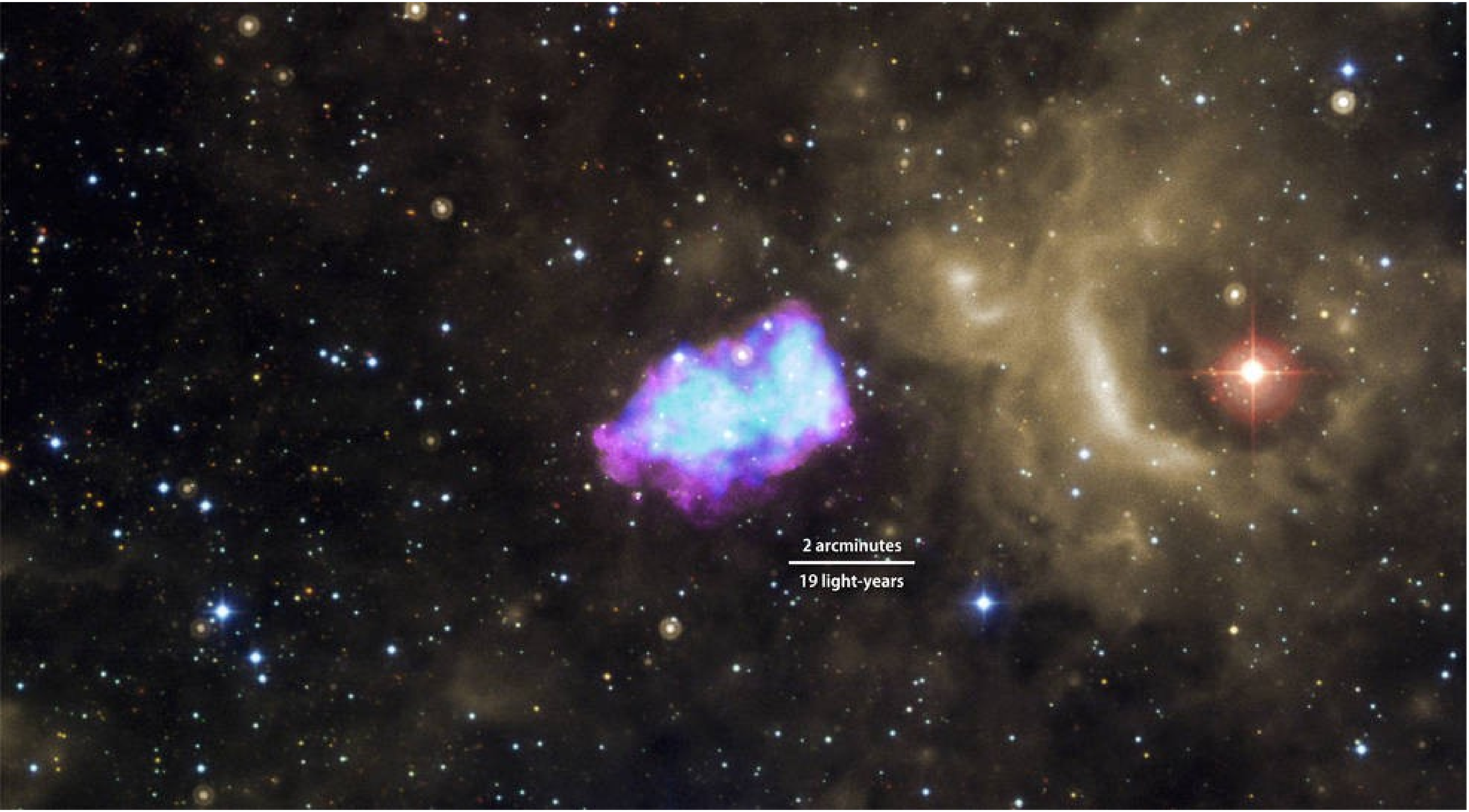
Secondary Fe-peak Elements

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



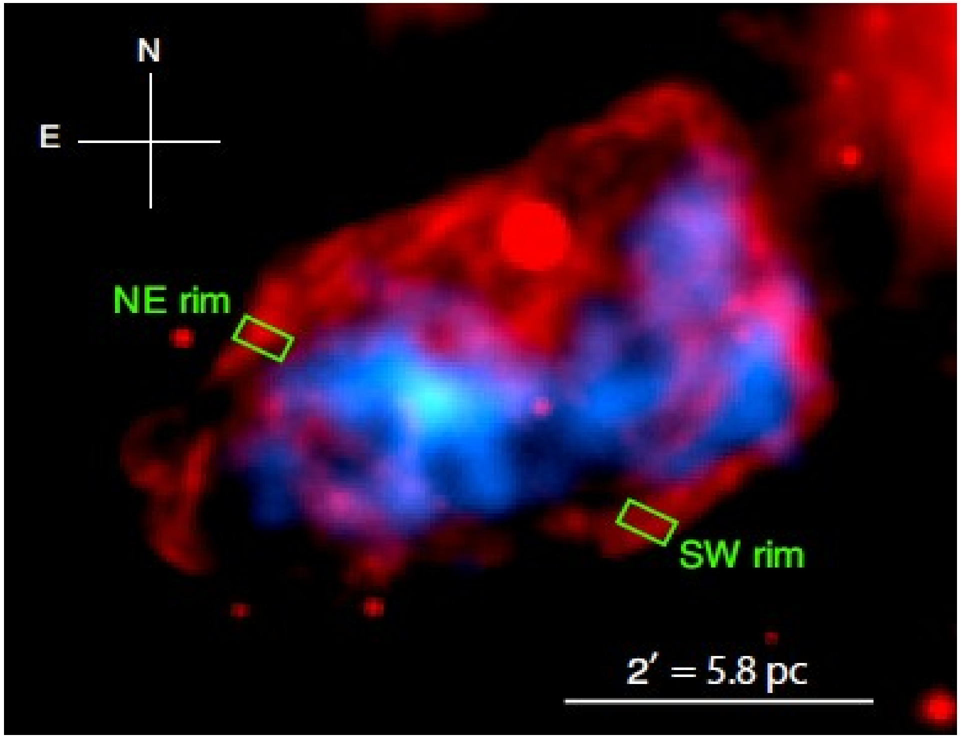
SNR 3C397

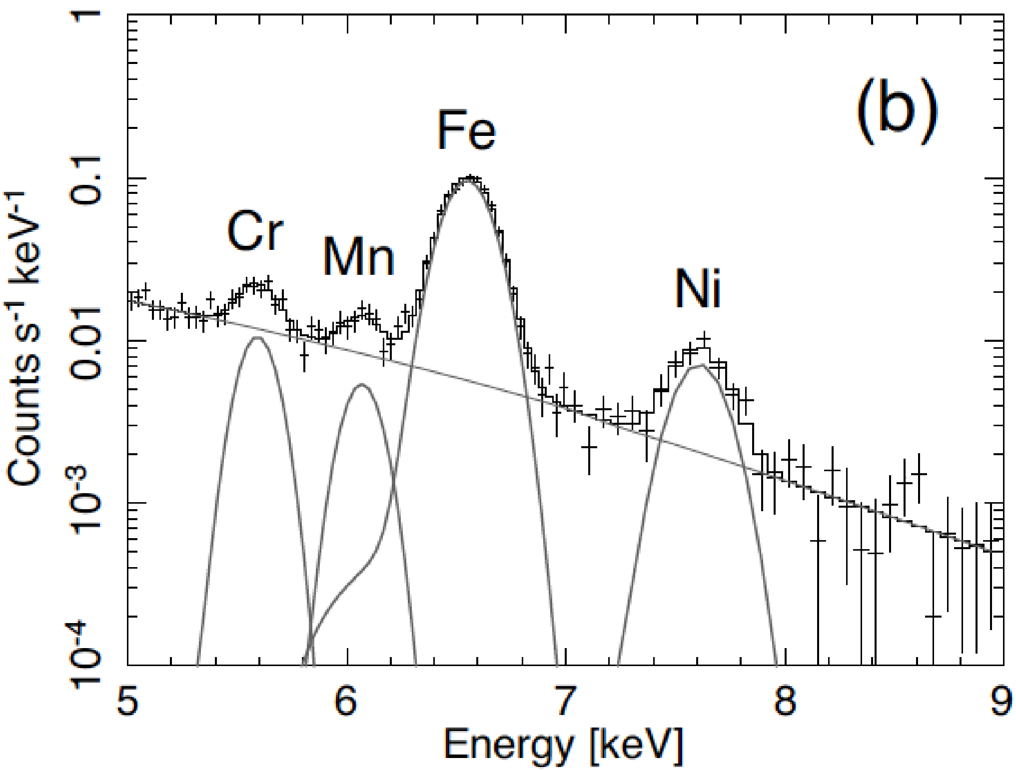
Carles Badenes
FOE 04/06/15



SNR 3C397

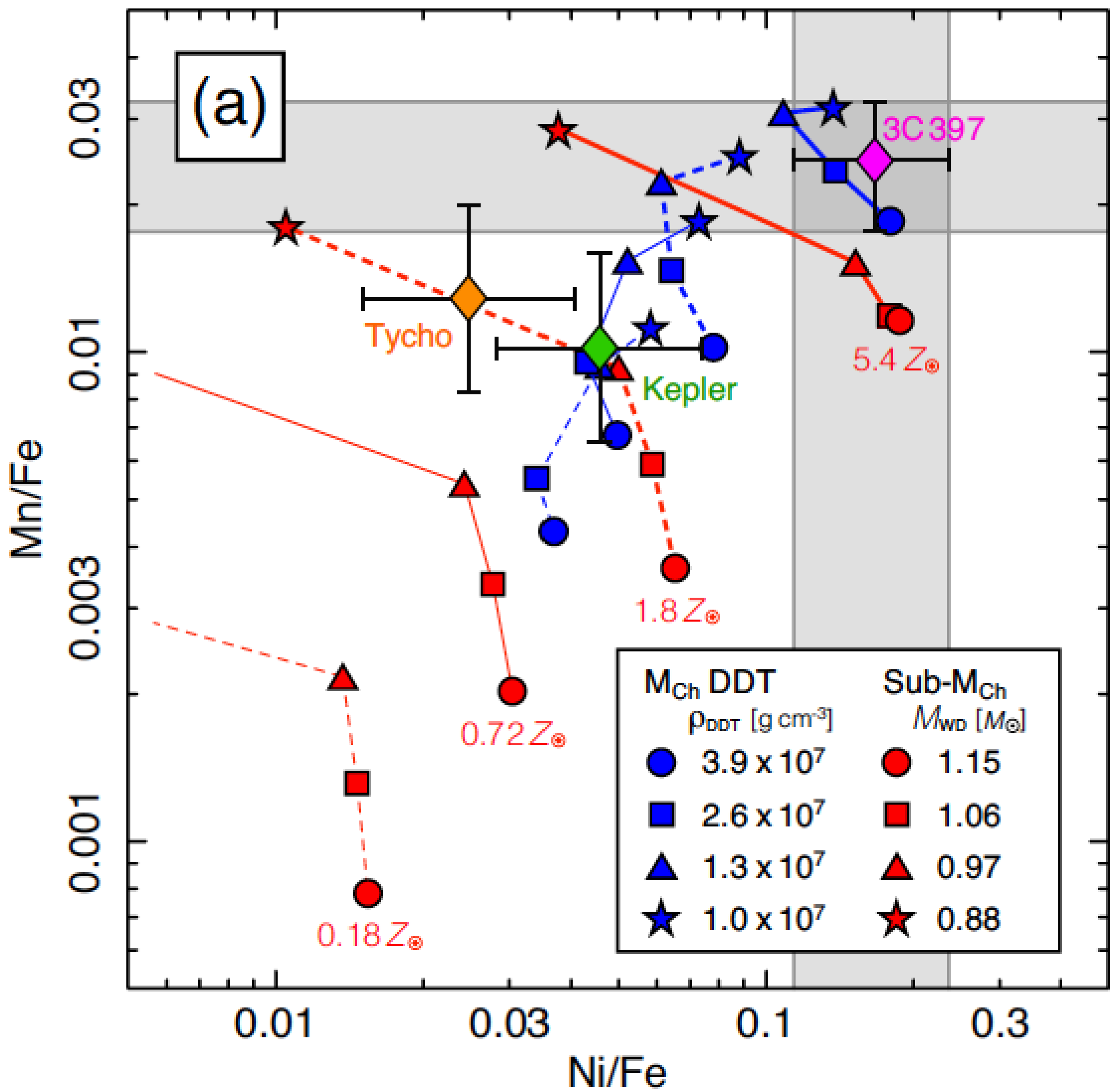
- 3C397 is an evolved Type Ia SNR at D~10 kpc [Safi-Harb+ 05].
- Consistent dynamical model (IR+X-ray) ⇒ **RS has thermalized all the SN ejecta**.
- Extraordinary X-ray spectrum! **Very strong Ni and Mn emission**.





SNR 3C397

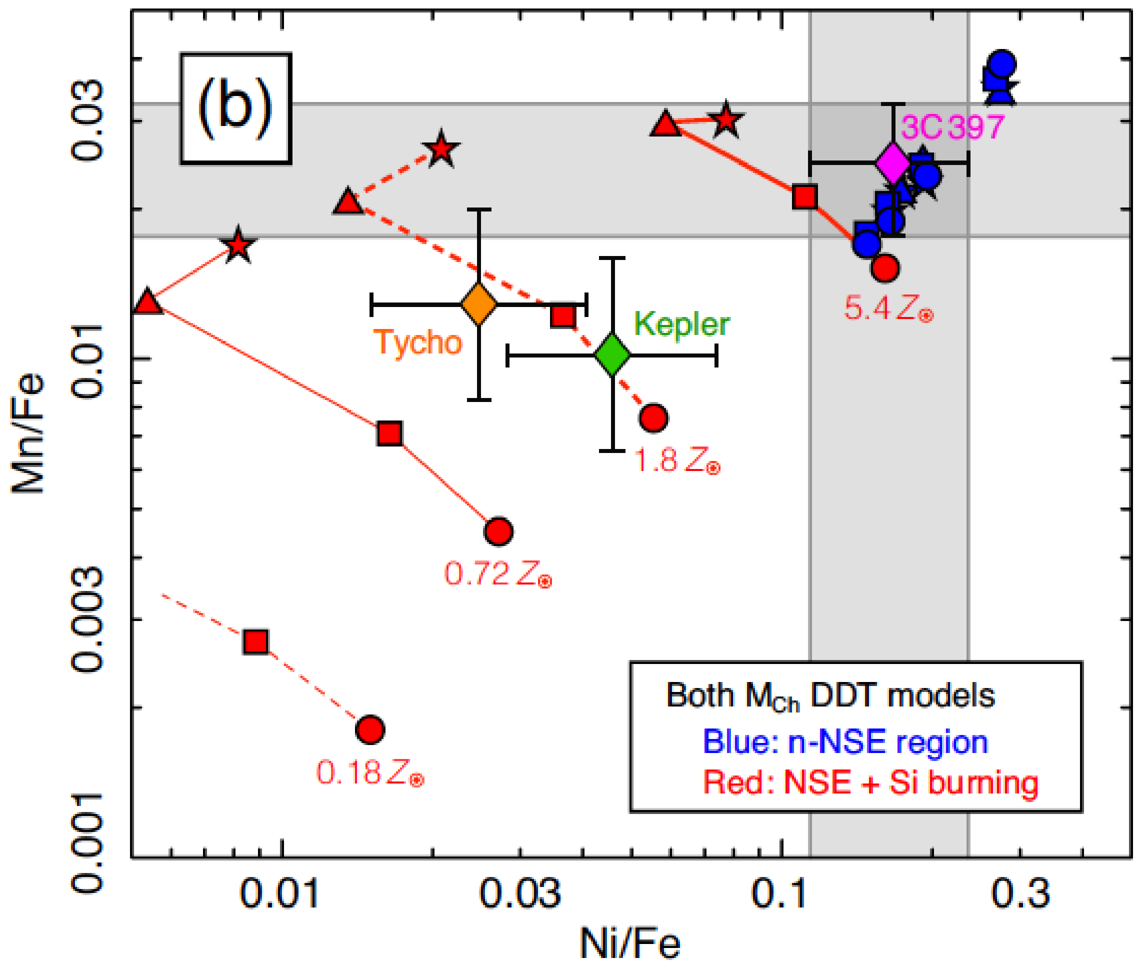
- Model line emission with updated atomic data (AtomDB, Foster+) ⇒ **M_{Ni}/M_{Fe}~0.2; M_{Mn}/M_{Fe}~0.03**.
- **Sub-Ch models do not work**, or require unreasonable progenitor metallicities (>5$Z_{\odot}$).
- **M_{Ni}/M_{Fe} and M_{Mn}/M_{Fe} require n-NSE material ⇒ Chandrasekhar-mass progenitor.**
- Details: Yamaguchi, CB + 15 [arXiv:1502:04255]



SNR 3C397

Carles Badenes
FOE 04/06/15

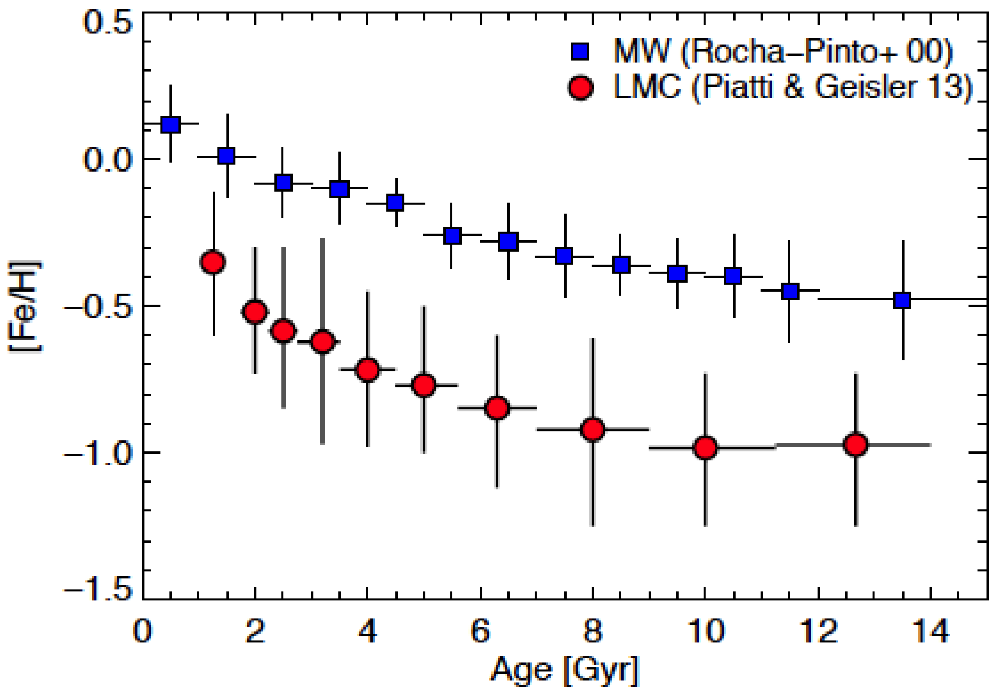
- Model line emission with updated atomic data (AtomDB, Foster+) ⇒ **M_{Ni}/M_{Fe}~0.2; M_{Mn}/M_{Fe}~0.03**.
- **Sub-Ch models do not work**, or require unreasonable progenitor metallicities (>5$Z_{\odot}$).
- **M_{Ni}/M_{Fe} and M_{Mn}/M_{Fe} require n-NSE material ⇒ Chandrasekhar-mass progenitor.**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

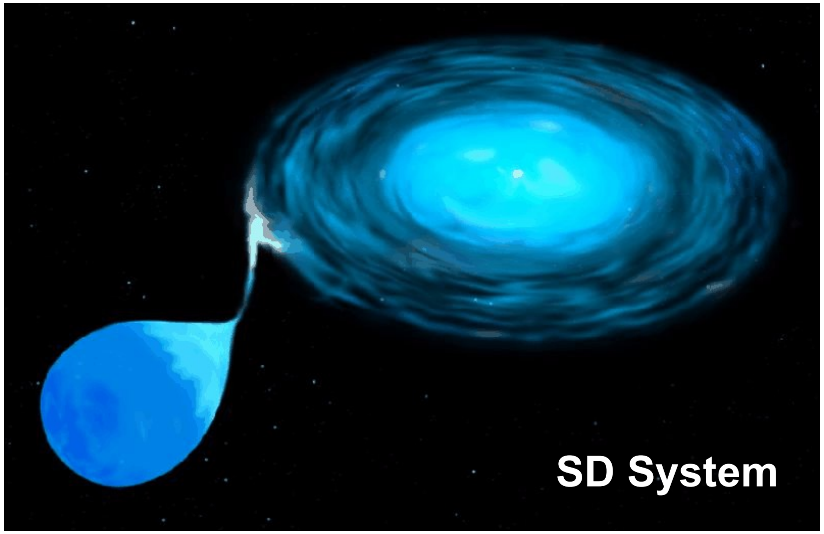


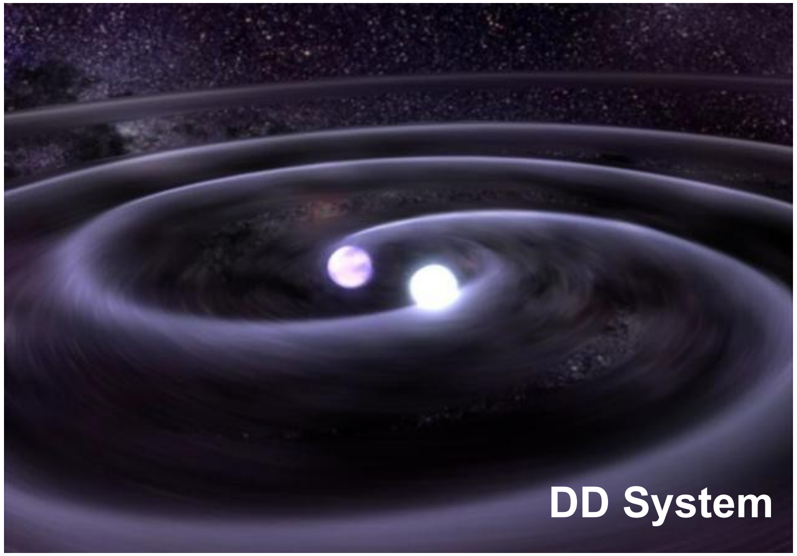
SNR 3C397

- Could the progenitor of SNR 3C397 be a VERY metal-rich sub-Ch WD? Extremely unlikely.

- **Evidence for some M_{Ch} SN Ia progenitors is now growing** [Seitenzahl+ 13, Scalzo+ 14].







Summary

THE ASTROPHYSICAL JOURNAL LETTERS, 785:L27 (5pp), 2014 April 20 doi:10.1088/2041-8205/785/2/L27
© 2014. The American Astronomical Society. All rights reserved. Printed in the U.S.A.

DISCRIMINATING THE PROGENITOR TYPE OF SUPERNOVA REMNANTS WITH IRON K-SHELL EMISSION

HIROYA YAMAGUCHI[1,2,3], CARLES BADENES[4], ROBERT PETRE[1], TOSHIO NAKANO[5], DANIEL CASTRO[6], TERUAKI ENOTO[1,7], JUNKO S. HIRAGA[5], JOHN P. HUGHES[8], YOSHITOMO MAEDA[9], MASAYOSHI NOBUKAWA[10], SAMAR SAFI-HARB[11,12], PATRICK O. SLANE[3], RANDALL K. SMITH[3], AND HIROYUKI UCHIDA[10]

THE ASTROPHYSICAL JOURNAL LETTERS, 801:L31 (6pp), 2015 March 10 doi:10.1088/2041-8205/801/2/L31
© 2015. The American Astronomical Society. All rights reserved.

A CHANDRASEKHAR MASS PROGENITOR FOR THE TYPE Ia SUPERNOVA REMNANT 3C 397 FROM THE ENHANCED ABUNDANCES OF NICKEL AND MANGANESE

HIROYA YAMAGUCHI[1,2,3], CARLES BADENES[4], ADAM R. FOSTER[3], EDUARDO BRAVO[5], BRIAN J. WILLIAMS[1], KEIICHI MAEDA[6,7], MASAYOSHI NOBUKAWA[8], KRISTOFFER A. ERIKSEN[9], NANCY S. BRICKHOUSE[3], ROBERT PETRE[1], AND KATSUJI KOYAMA[8,10]

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

Summary

- **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).

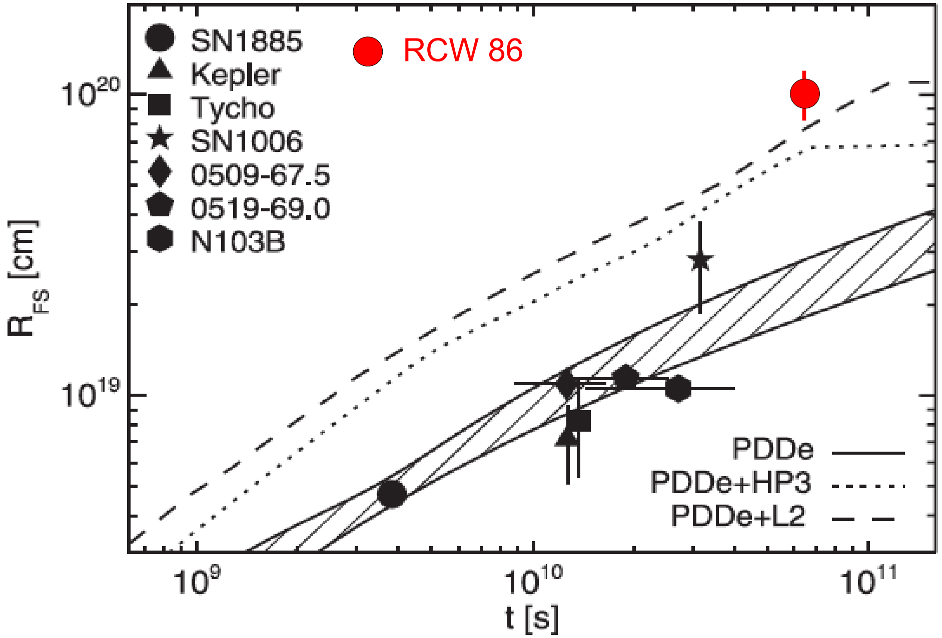
SN Ia in star-forming galaxies probably come from a mixture of SD and DD progenitors

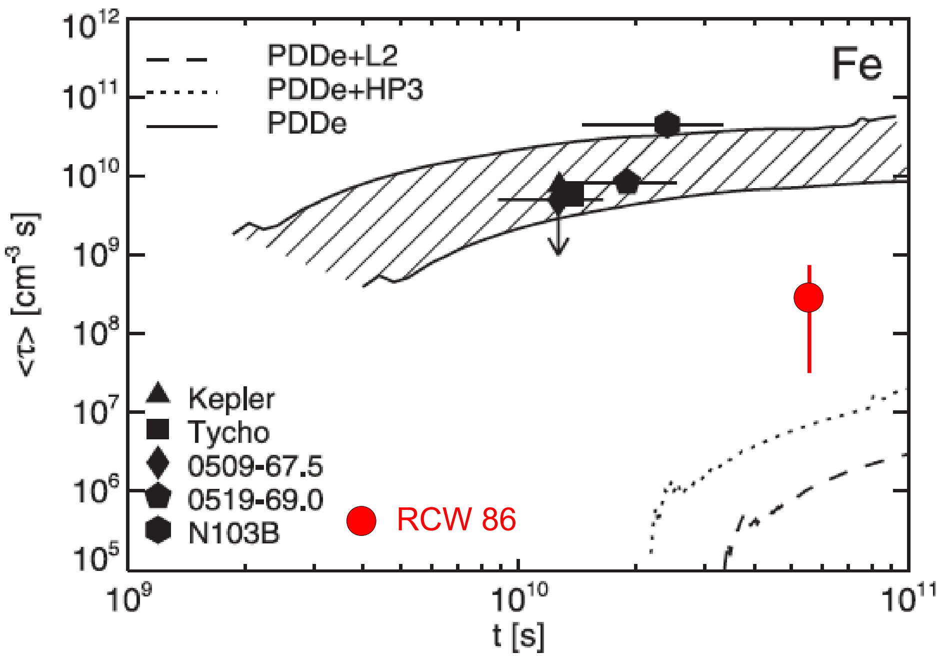
Type Ia SNRs and cavities

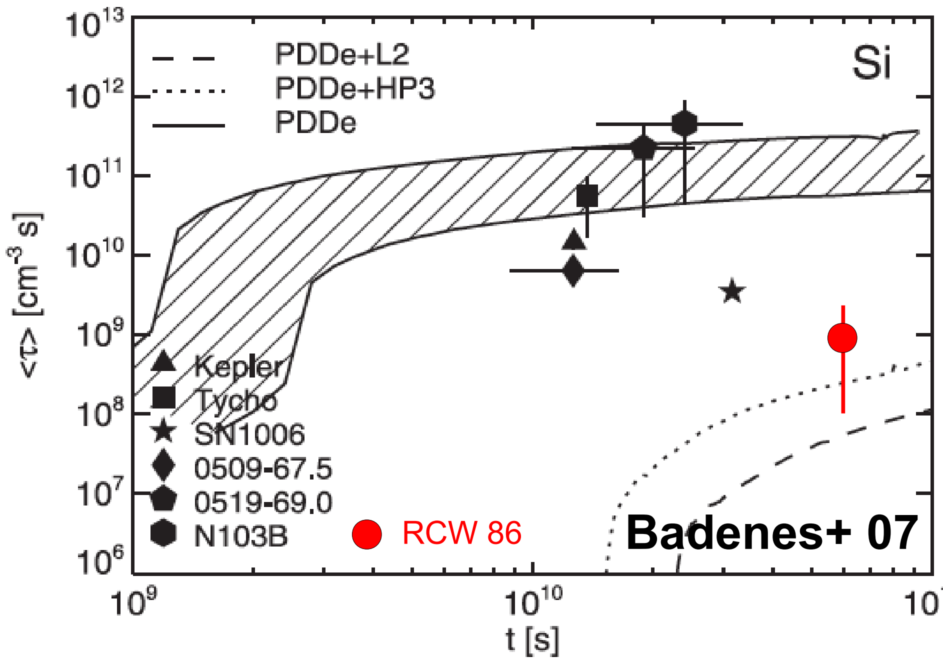
Carles Badenes
FOE 04/06/15

- **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 $n_e t$**.



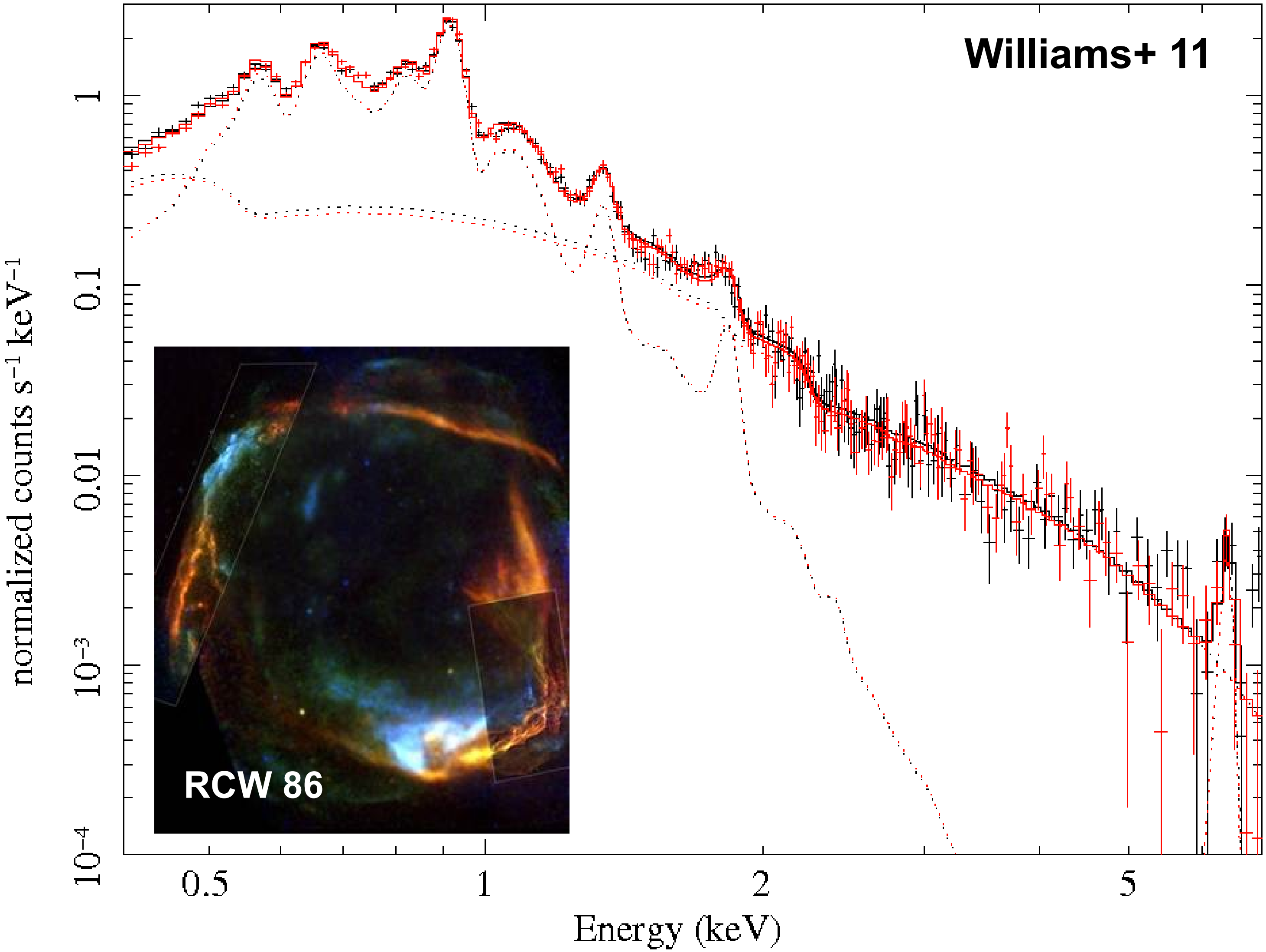




More on RCW 86

Carles Badenes
FOE 04/06/15

- **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?

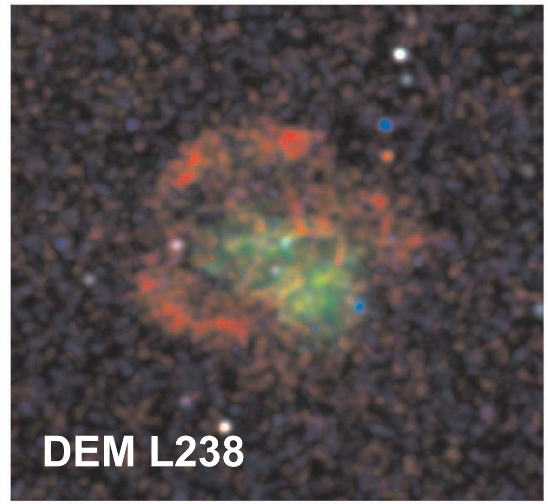
Carles Badenes
FOE 04/06/15

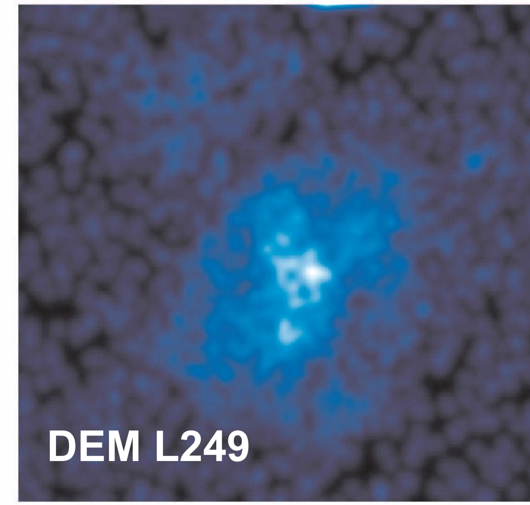
- **RCW 86** might not be the only example of Type Ia SN in a cavity.

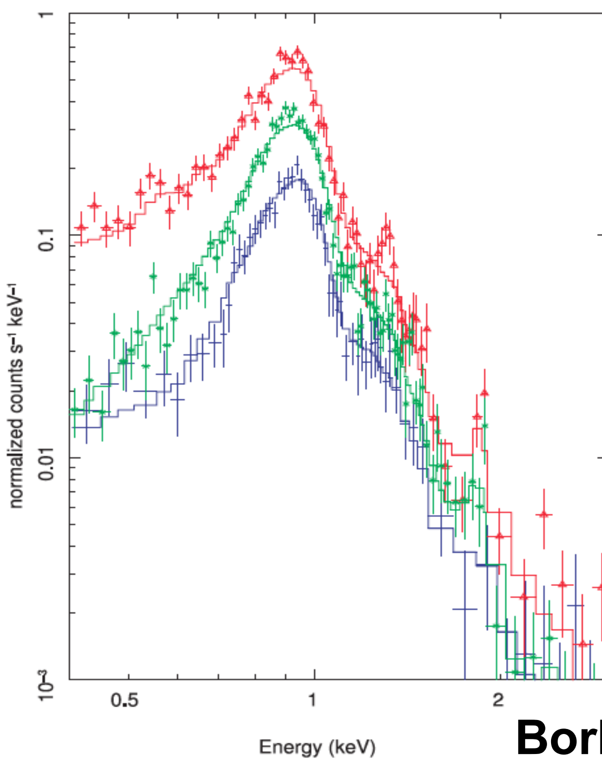
- **DEM L238** and **DEM L249**, two middle-aged SNRs in the LMC have Fe-rich spectra and low $n_e t$.

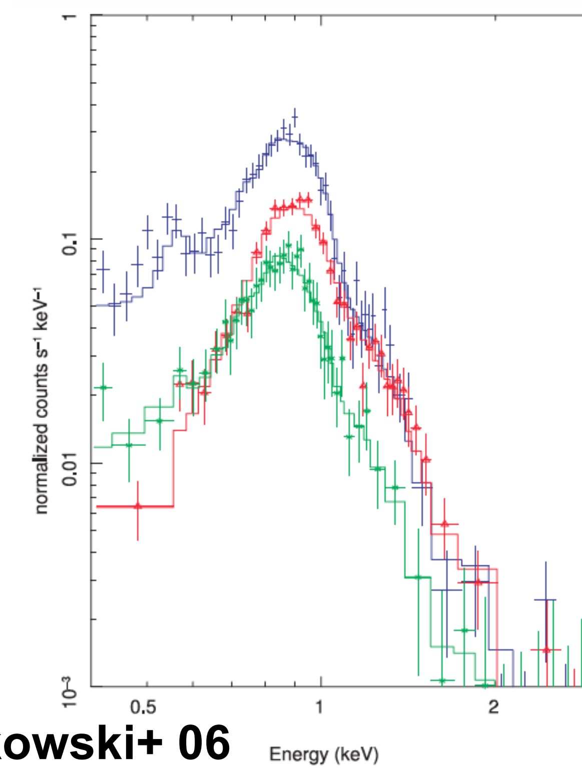
- **IF Type Ia SNRs**, they might also be **cavity explosions** [Borkowski+ 06].

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







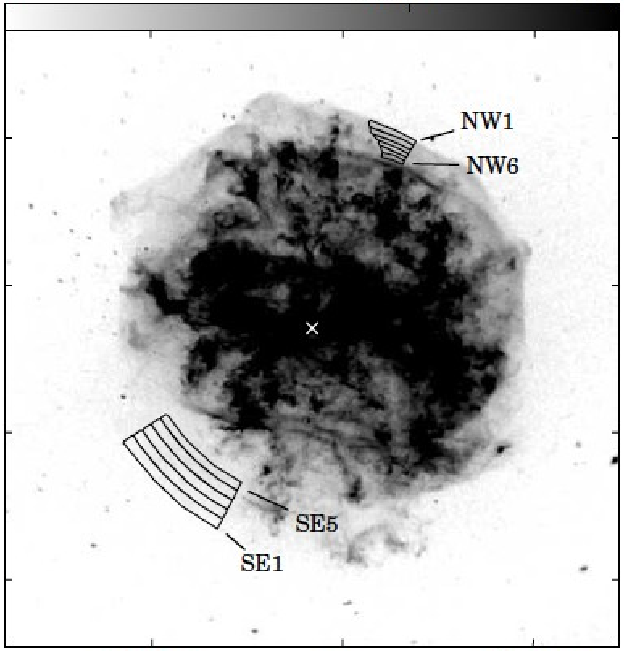


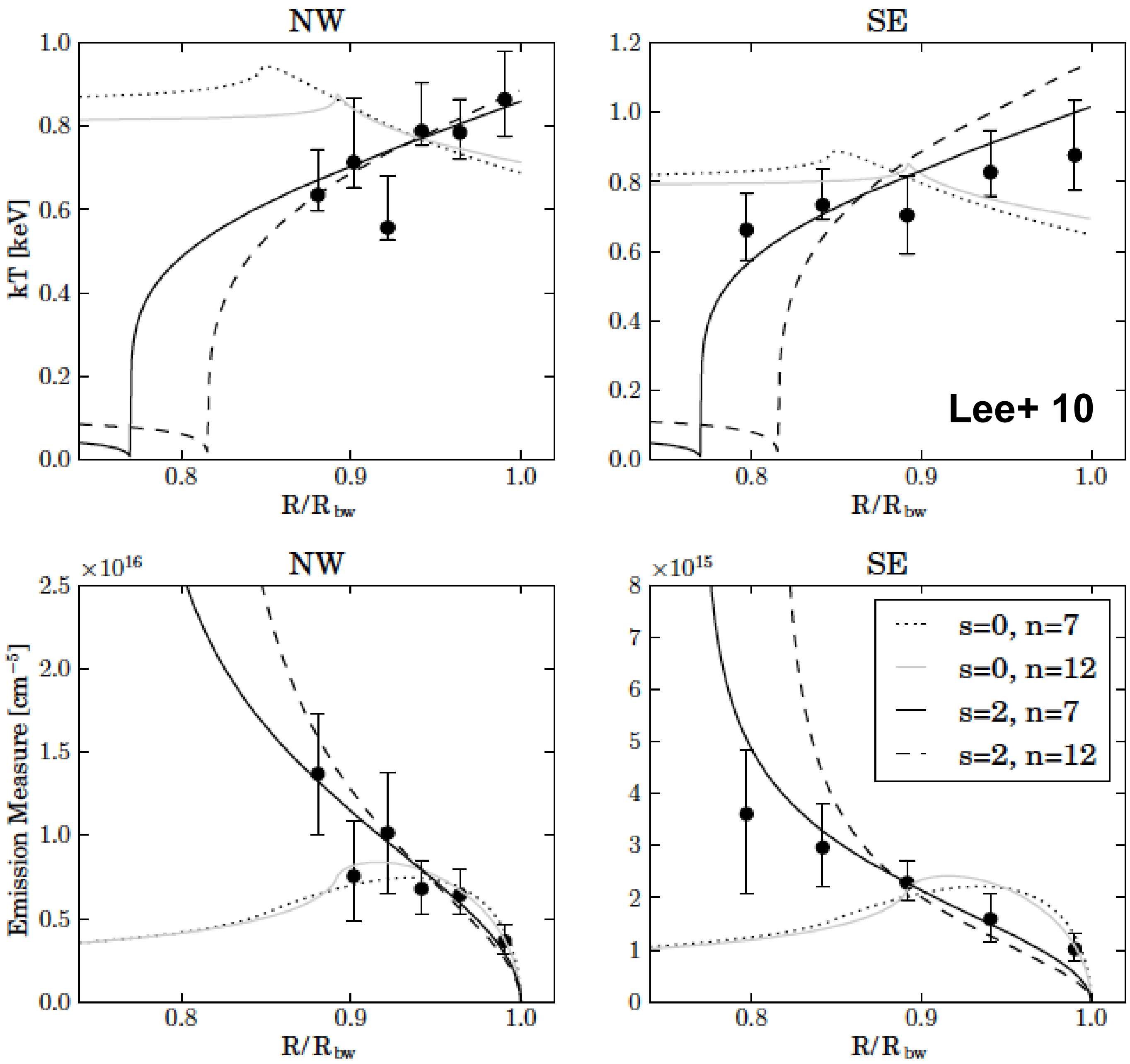
Borkowski+ 06

CSM in CC SNRs

Carles Badenes
FOE 04/06/15

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

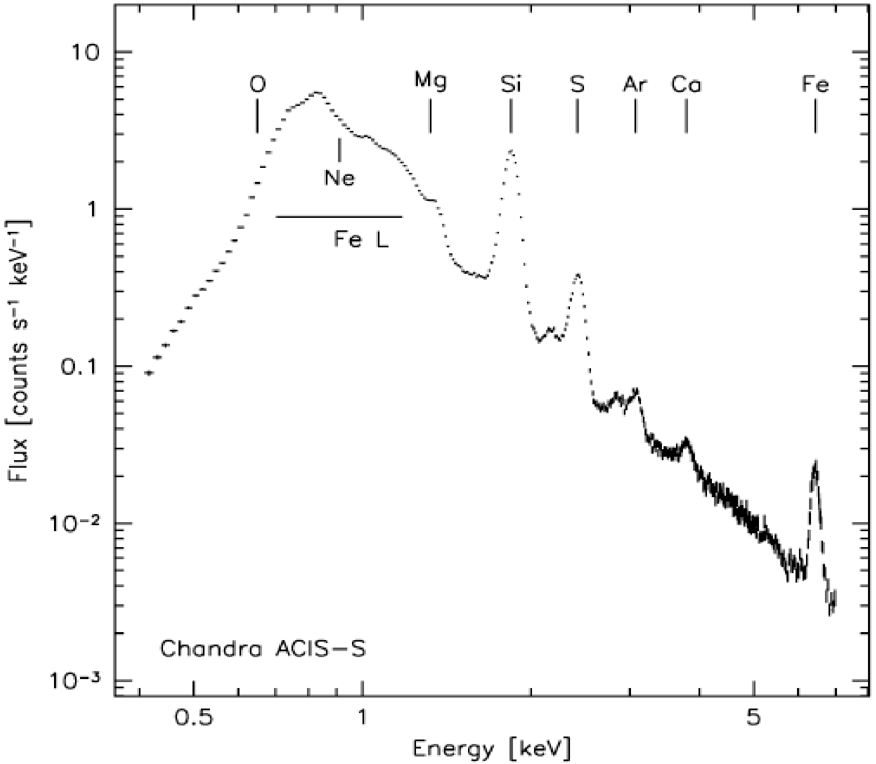


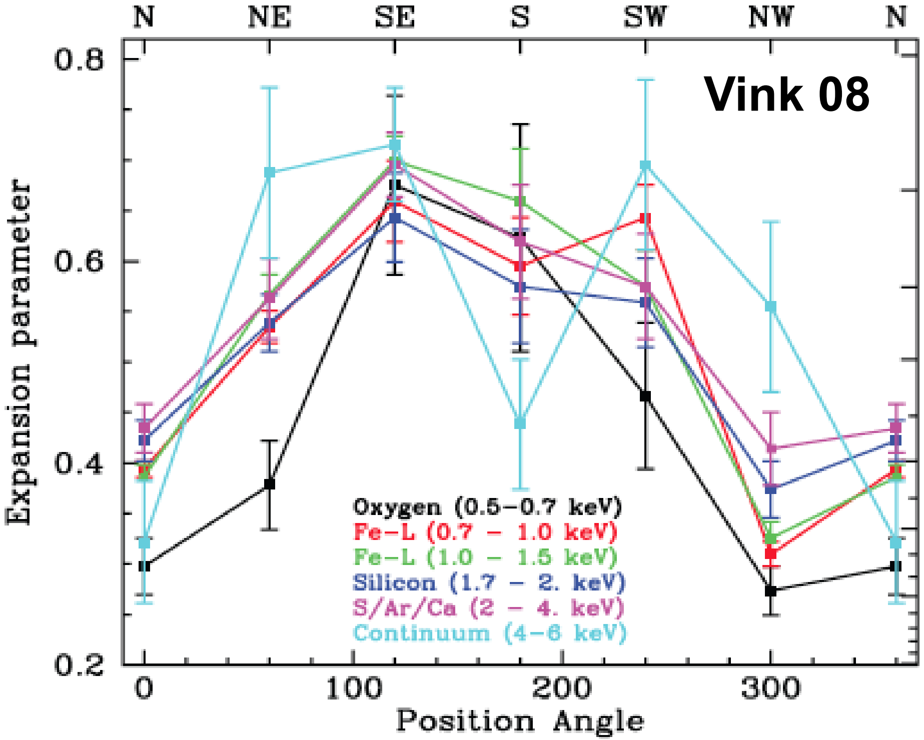


CSM Interaction: Kepler SNR

- **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).

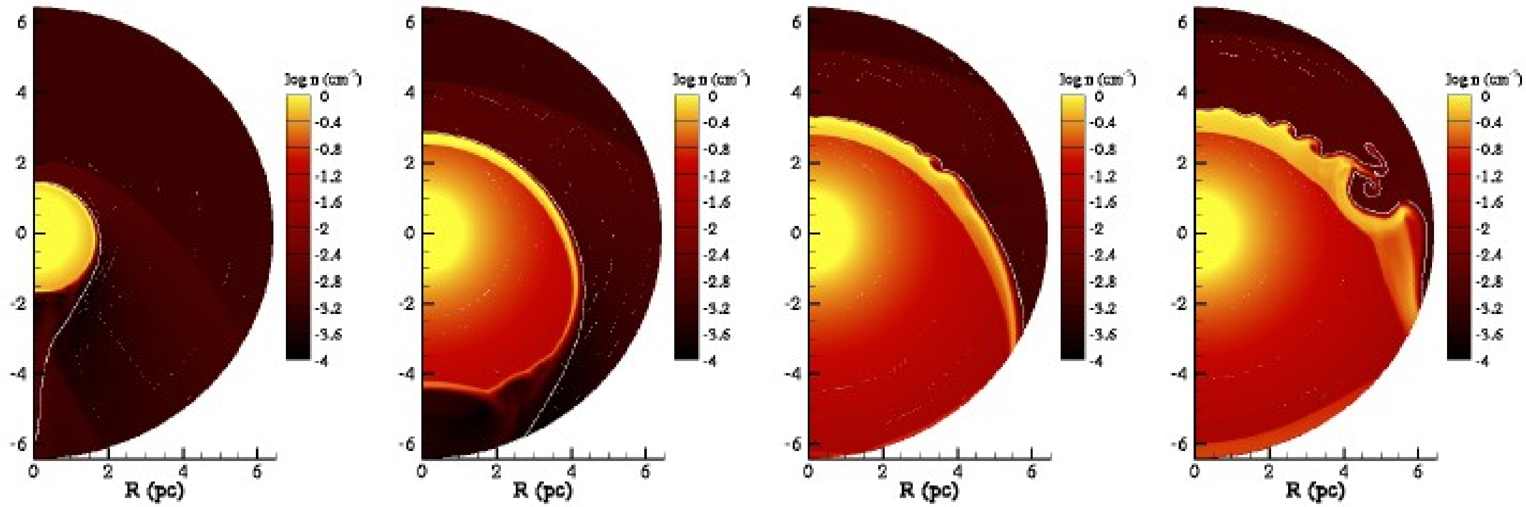


Fig. 4. The evolution of the wind bubble of model A. The snapshots from left to right correspond to the times 0.10 Myr, 0.29 Myr, 0.38 Myr and 0.57 Myr.

Chiotellis+ 12

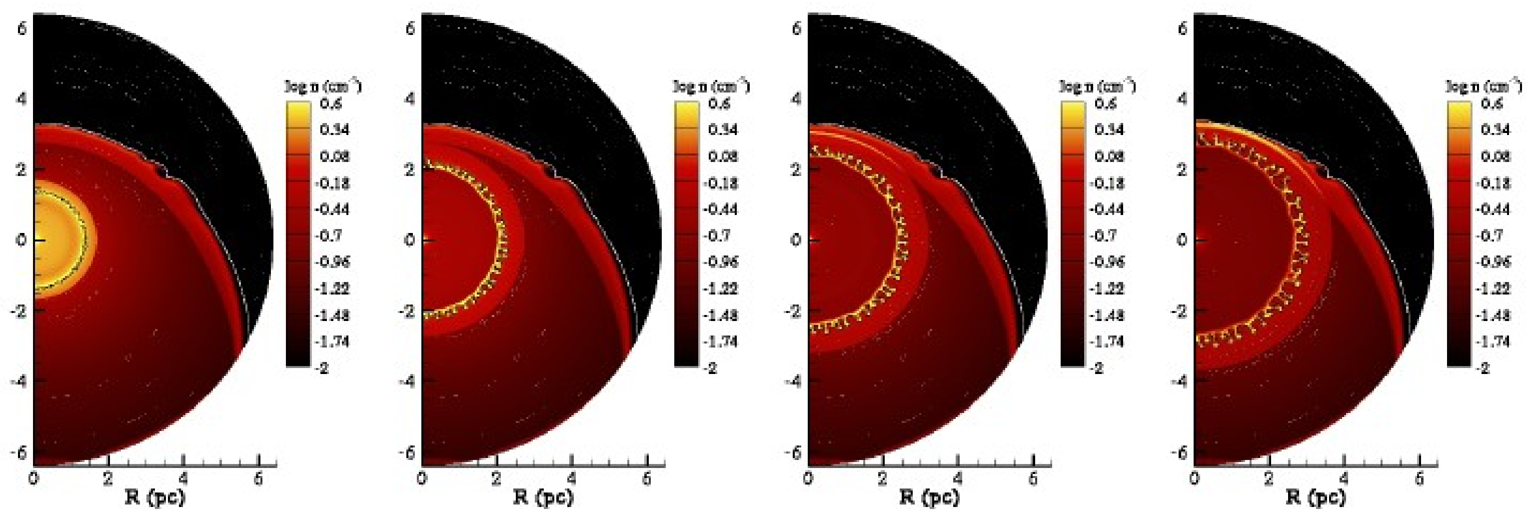
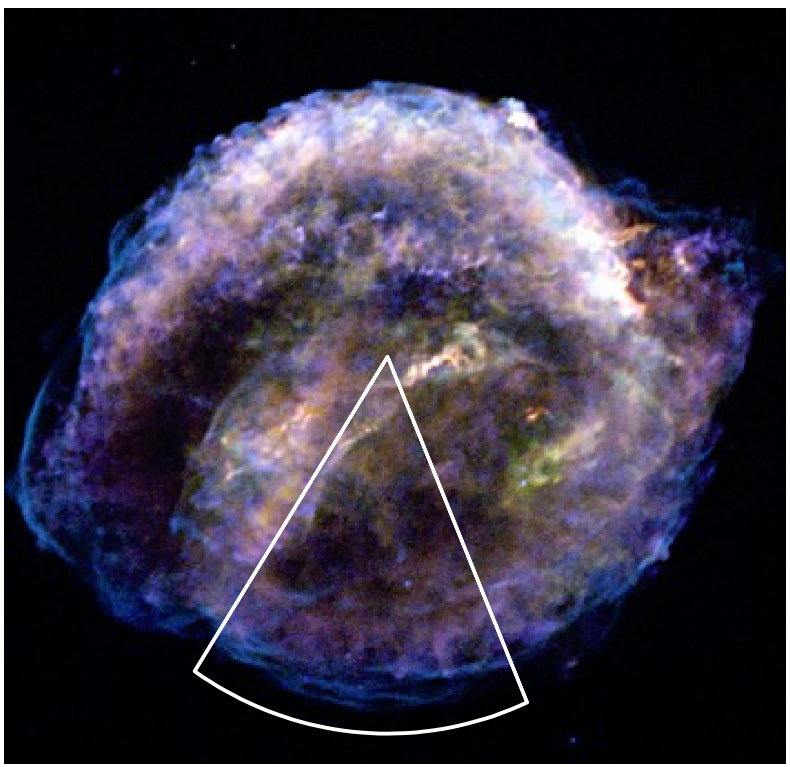
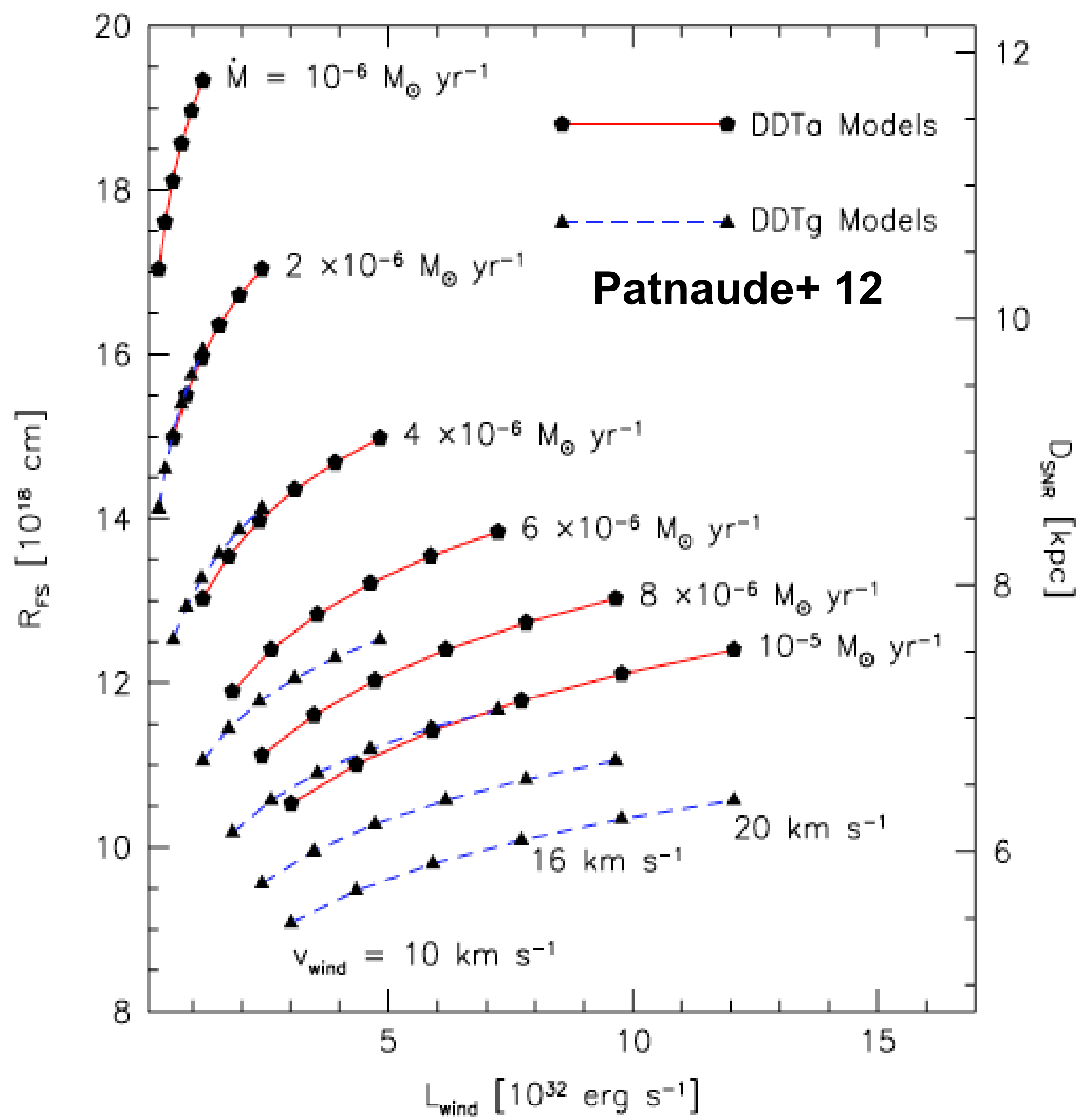


Fig. 5. SNR evolution of model A. The snapshots from left to right correspond to the times 158 yr, 285 yr, 349 yr and 412 yr.

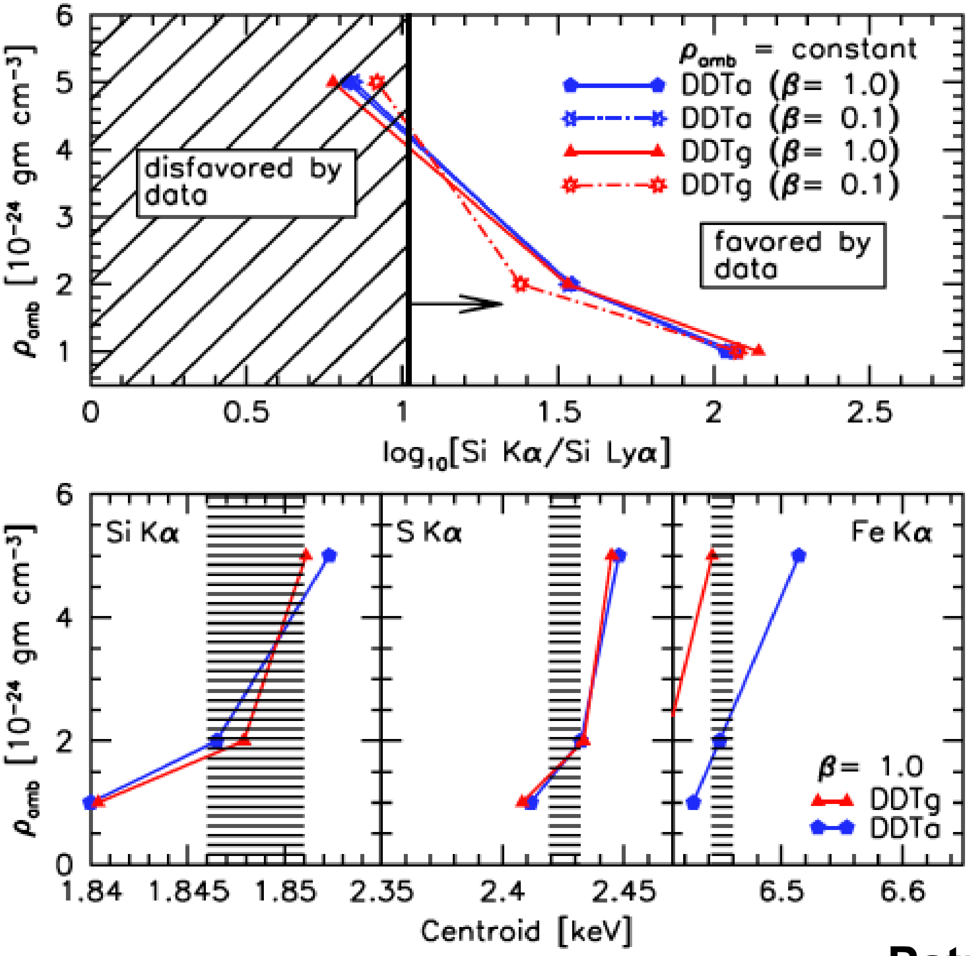
CSM Interaction: Kepler SNR

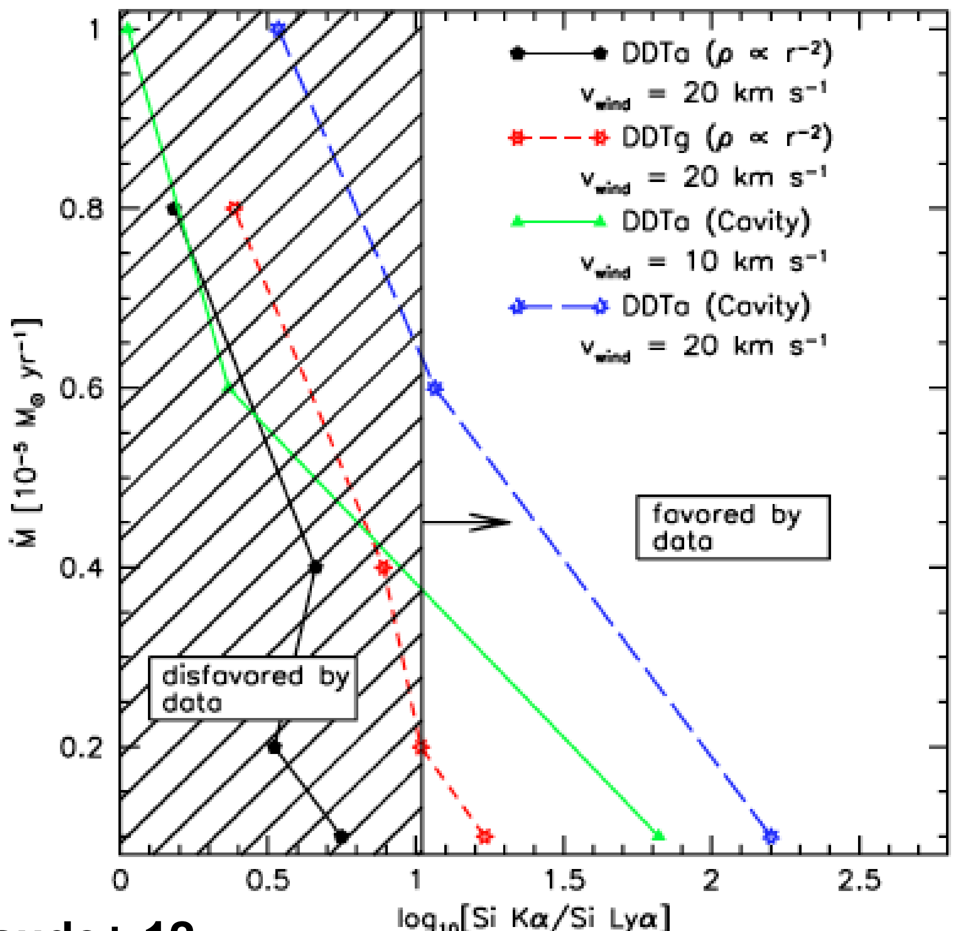
- HD+NEI models in the S, where the ejecta should be interacting with the pristine CSM from the progenitor ⇒ **constrain both M_{56Ni} and pre-SN dM/dt** [Patnaude+ 12].





- HD+NEI models **rule out a standard ρ ∝ 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} ~ 1 $M_\odot$**).





Patnaude+ 12