X-ray Studies of Supernova Remnants: The Persistence of Memory

LMC image from MCELS (C. Smith et al.)

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Chandra's First Decade of Discovery

Boston, September 23 2009

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Motivation

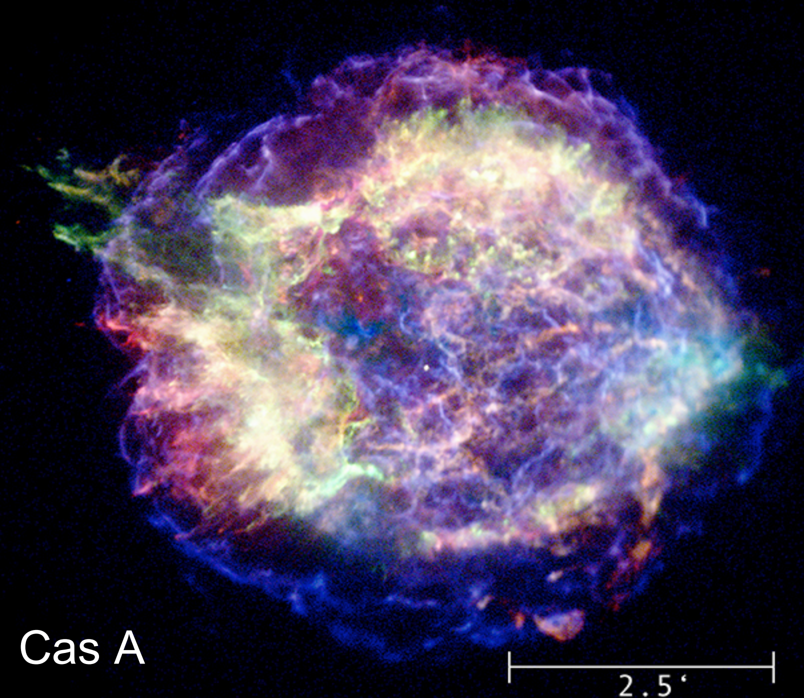
Chandra and *XMM-Newton* have radically changed our view of SNRs.

- Key new tool: **spatially resolved spectroscopy**.

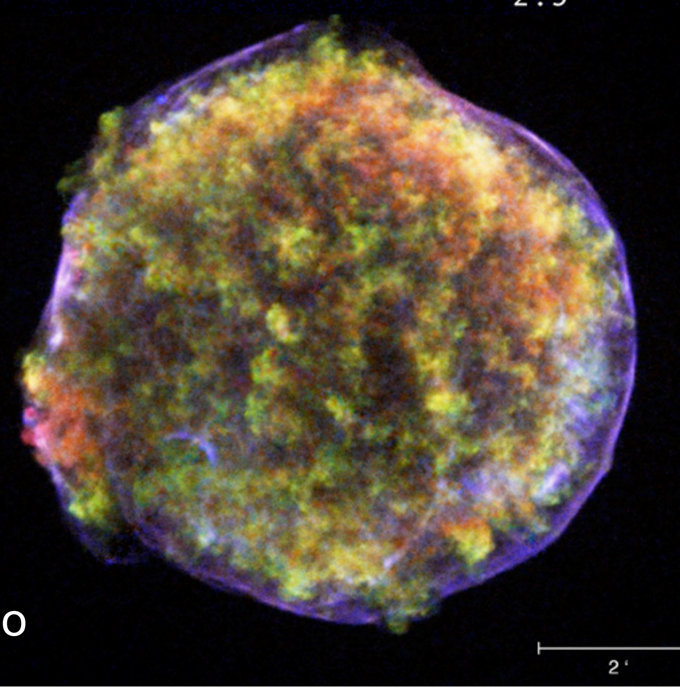
- Many exciting discoveries related to ISM and shock physics. Acceleration of CRs changes the properties of shock waves in SNRs.

- SNRs are much closer than extragalactic SNe ⇒ Unique opportunity to probe the SN phenomenon: progenitor mass loss, ejecta structure.

The data are excellent. The effort now has to concentrate on the interpretation.



Cas A



Tycho

Outline

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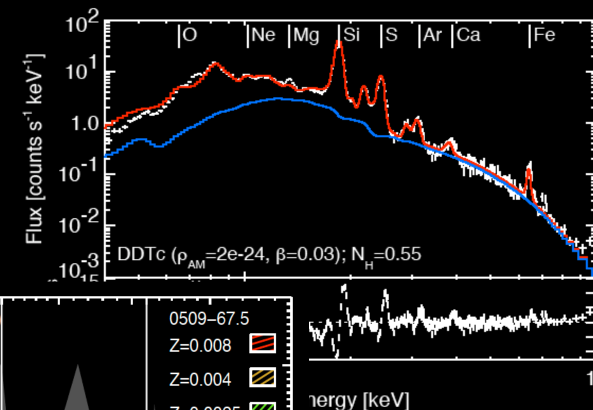
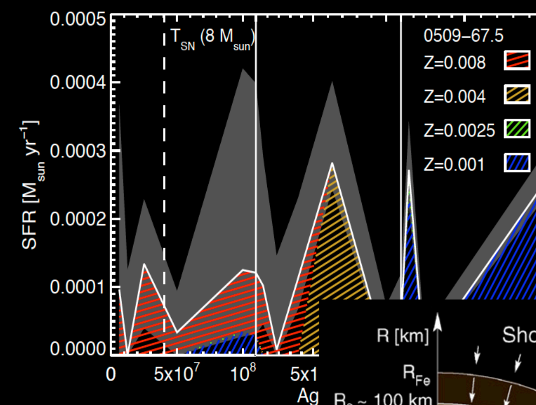
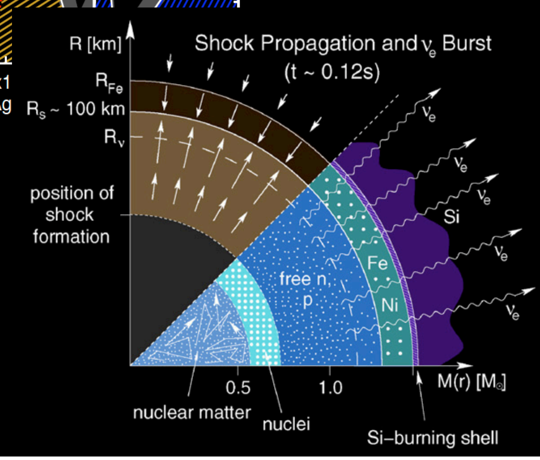
There is much we still don't know about SN explosions and their progenitors

Lack of SN observations is not the problem. In this talk, you'll hear about **the SNR approach to the SN problem**:

- Open Issues in Type Ia SNe.
  - Ejecta emission in Type Ia SNRs and comparison to SN light echoes.
  - Stellar populations around Type Ia SNRs in the LMC.
- Open issues in Core Collapse SNe.
  - Cas A as a laboratory for CC SN studies.
  - Talks by Borkowski, Lee, Park.







Type Ia SNe

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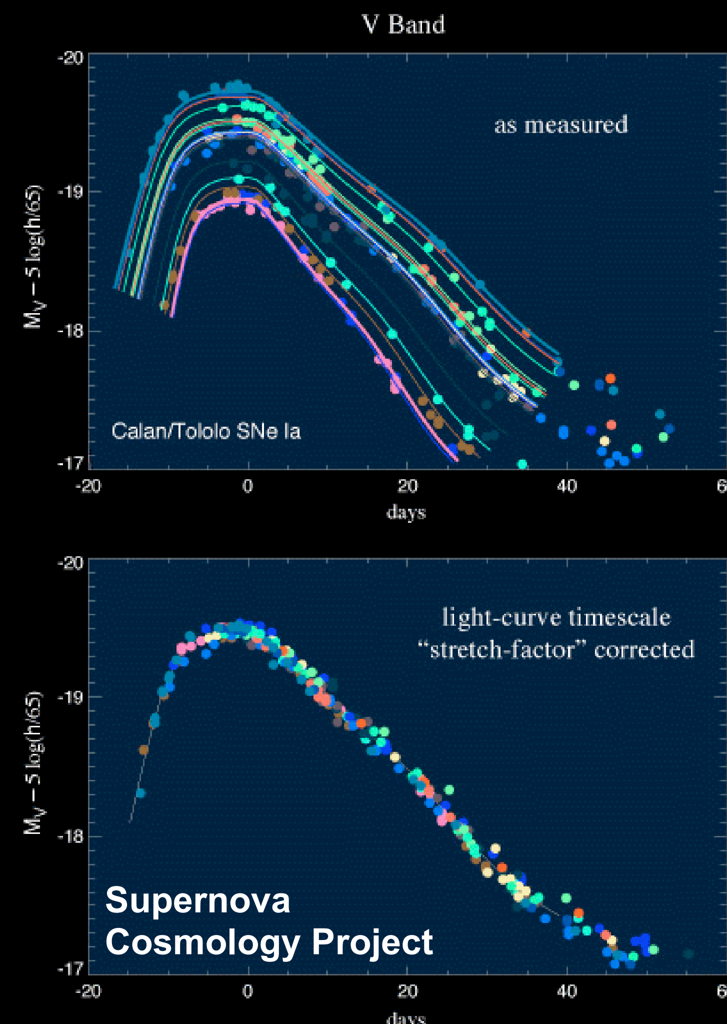
SN 1994D in
NGC 4526 (P. Challis)

Type Ia Supernovae (SNe) are the result of the thermonuclear explosion of a C+O white dwarf prompted by accretion in a binary system

REVIEWS: Branch et al. 95, PASP 107, 1019; Branch & Khokhlov 95, Phys. Rep. 265, 53; Hillebrandt & Niemeyer 00, ARA&A 38, 191.



- **Fundamentals are well understood**: energy budget, no H in spectra, rate of light curve decay.
- Some **key details remain obscure**: explosion mechanism, **progenitor systems**.
- **Light curves and spectra are strikingly uniform** ⇒ LC width / luminosity relation [Phillips 93, ApJ 4123, L105] ⇒ Cosmology.

SN Ia Ejecta

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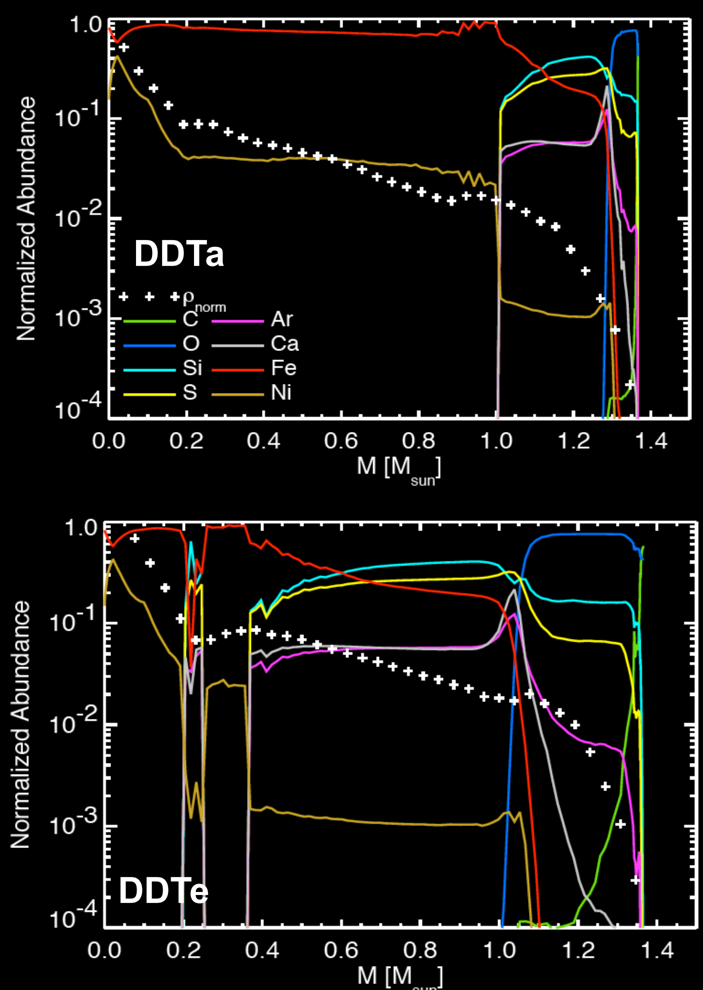
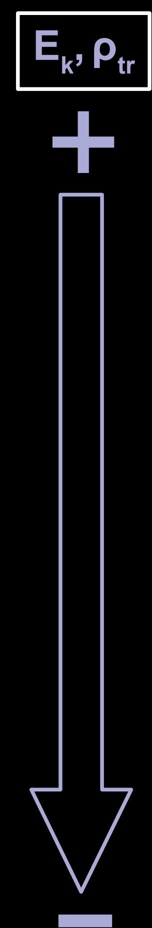
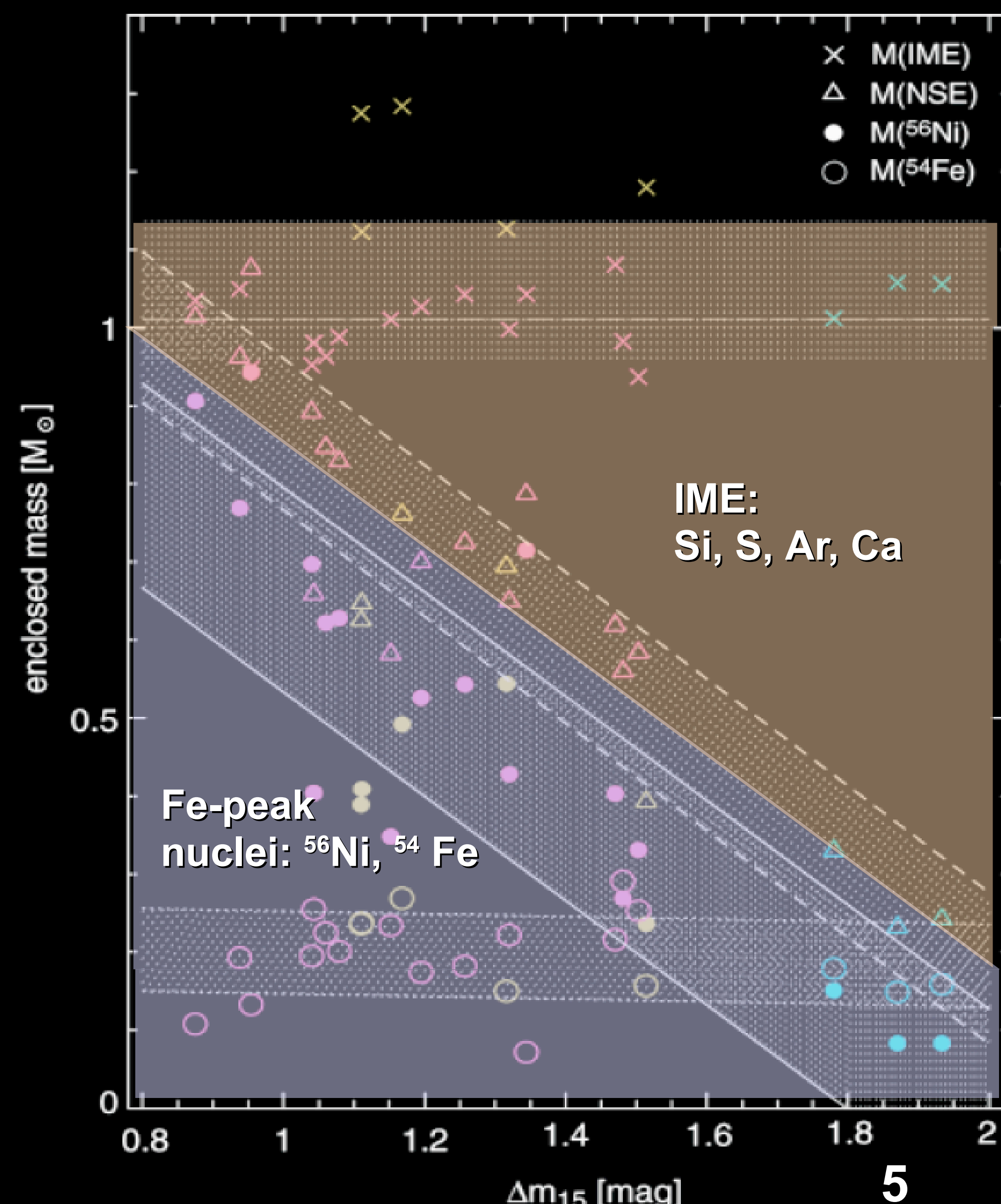
- **Phenomenological 1D delayed detonation** (DDT) models provide the best match to Type Ia SN observations.





Mazzali et al. 07, Sci 315, 825 [23 Type Ia SNe]

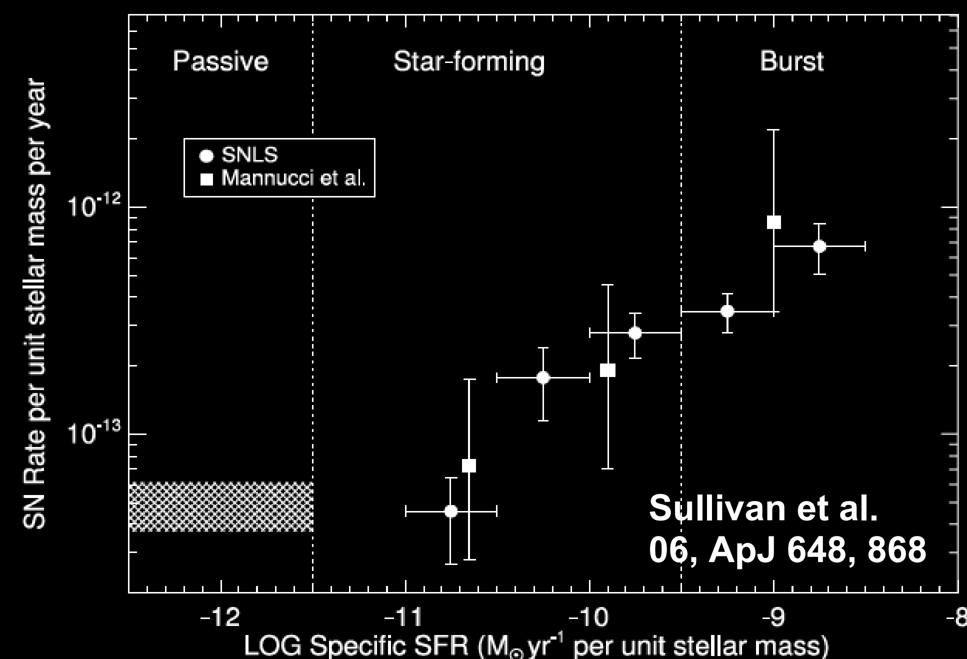


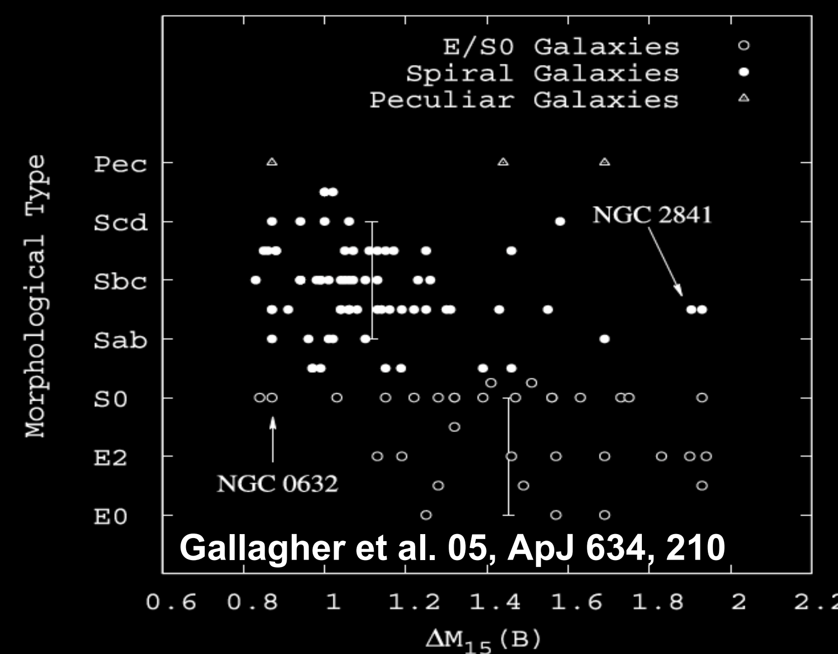
SN Ia Progenitor Systems: Observations

- Interpreted as evidence for **TWO progenitor populations**:
  - **'Prompt'** ⇒ 'younger' (~100 Myr) progenitors in star forming galaxies, SN rate ∝ star formation rate, brighter Type Ia SNe.
  - **'Delayed'** ⇒ 'older' (~Gyr) progenitors in passive galaxies, SN rate ∝ total stellar mass, dimmer Type Ia SNe.
- A+B models [Scannapieco & Bildsten 05, ApJ 629, L85]:

  $SN_{Ia} = AM_{stars} + B(dM_{stars}/dt)$

- **Both populations appear to follow the same Phillips relation!** (at least to 1st order - Howell et al. 07, ApJ 667, L37).





SN Ia Progenitor Systems: Theory

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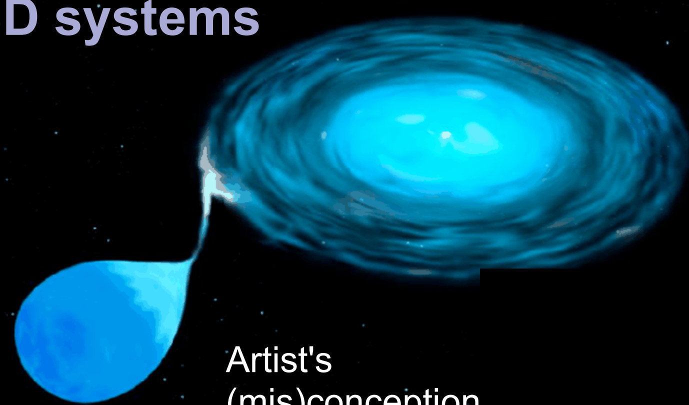
Depending on the nature of the **WD companion:**

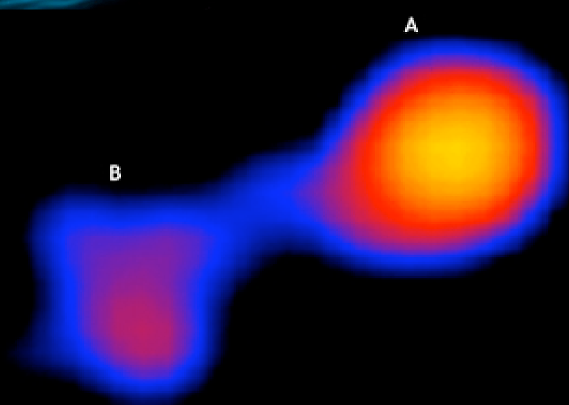
- A normal star: **Single Degenerate** (SD) systems. Many known examples of WD+star binaries [Parthasarathy et al. 07, NewAR 51, 524]. **Problem: getting the WD to M_{Ch}.**
- Another WD: **Double Degenerate** (DD) systems. Surprising lack of known examples [Napiwotzki et al 05, C.P.]. **Problem: explosion or collapse?**

A critical reappraisal of our ideas about SN Ia progenitors may be in order [Maoz 08 MNRAS 384, 267]

SD systems

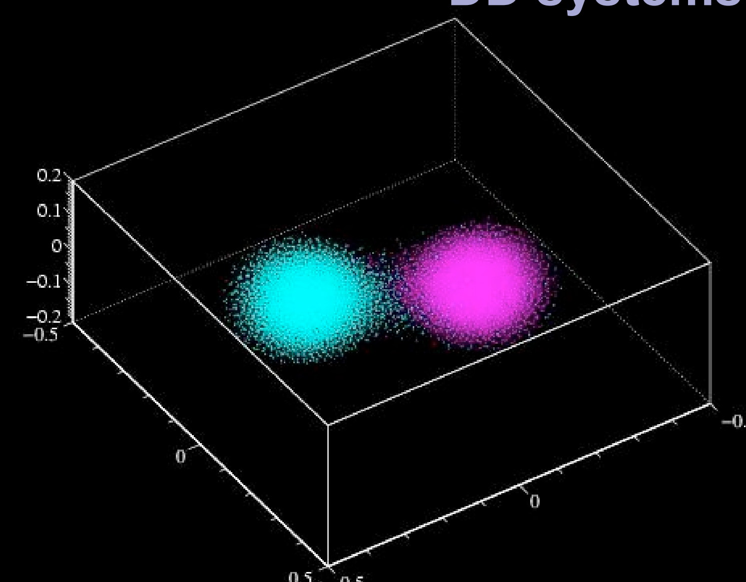


Artist's (mis)conception



Real thing: *Chandra* image of Mira (o Ceti) Karovska et al. 05, ApJ 623, L137

DD systems



Guerrero et al. 04, A&A 413, 257

Type Ia SNRs: Tycho

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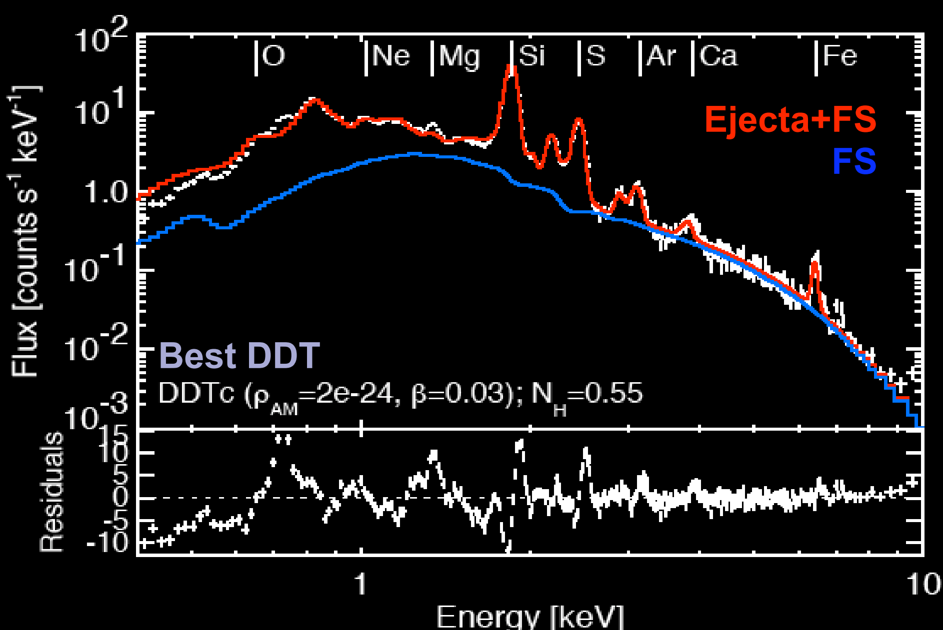
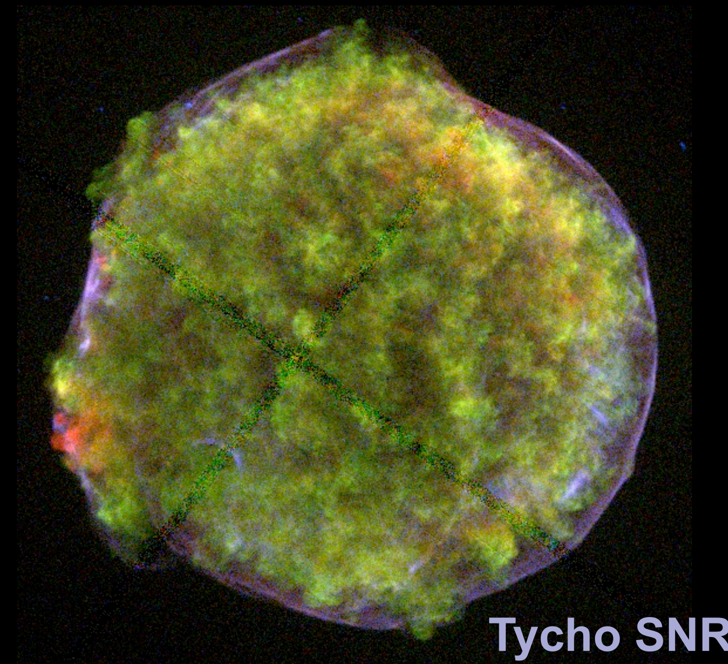
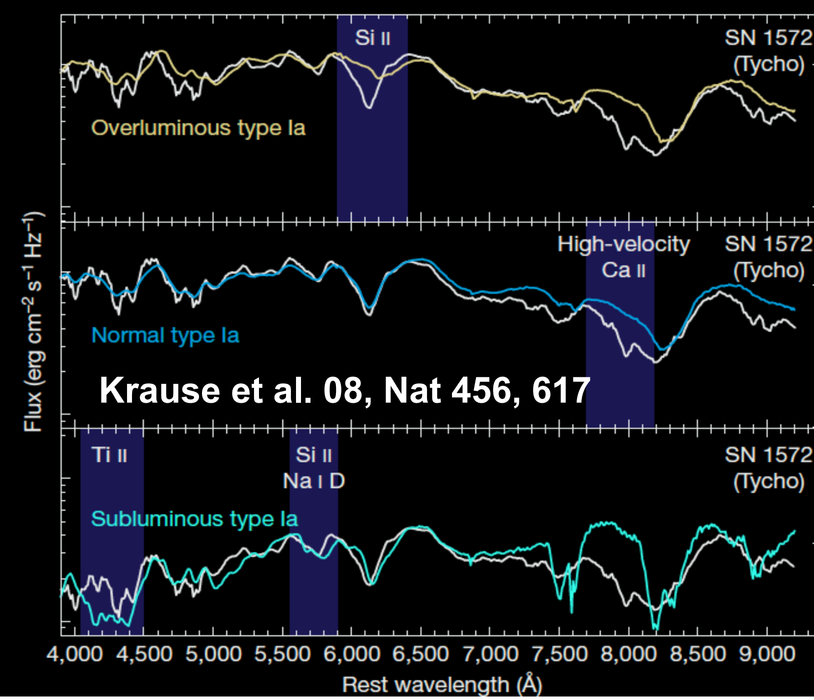
The **X-ray spectra from SNRs** can be used to **type (Ia/CC)** objects and **estimate the peak brightness** (M_{56Ni}) of SN Ia.

[Badenes et al. 03 ApJ 593, 358; 05 ApJ 624, 198.]

- **Must model spectra + dynamics**; M_{56Ni} estimate based on 1D DDT models.
- **Tycho SNR: M_{56Ni}=0.74 $M_\odot$** [Badenes et al. 06, ApJ 645, 1373]. Later confirmed by light echo spectroscopy [Krause et al. 08, Nat 456, 617].







Type Ia SNRs: Tycho

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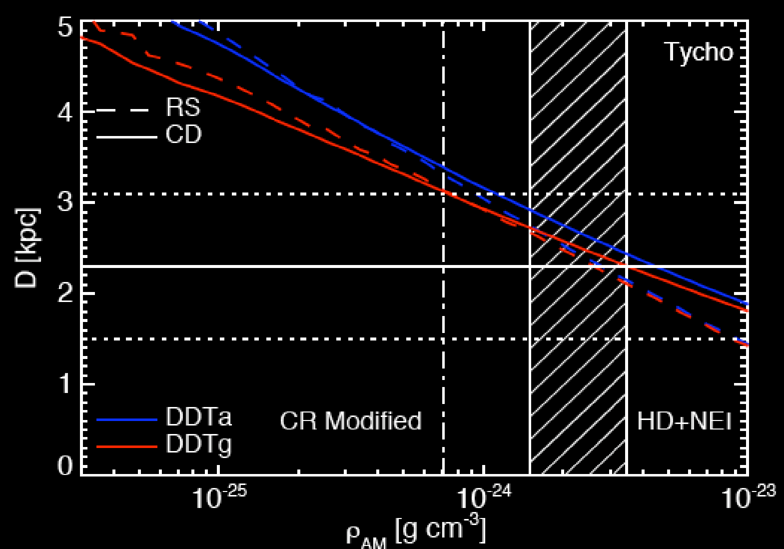
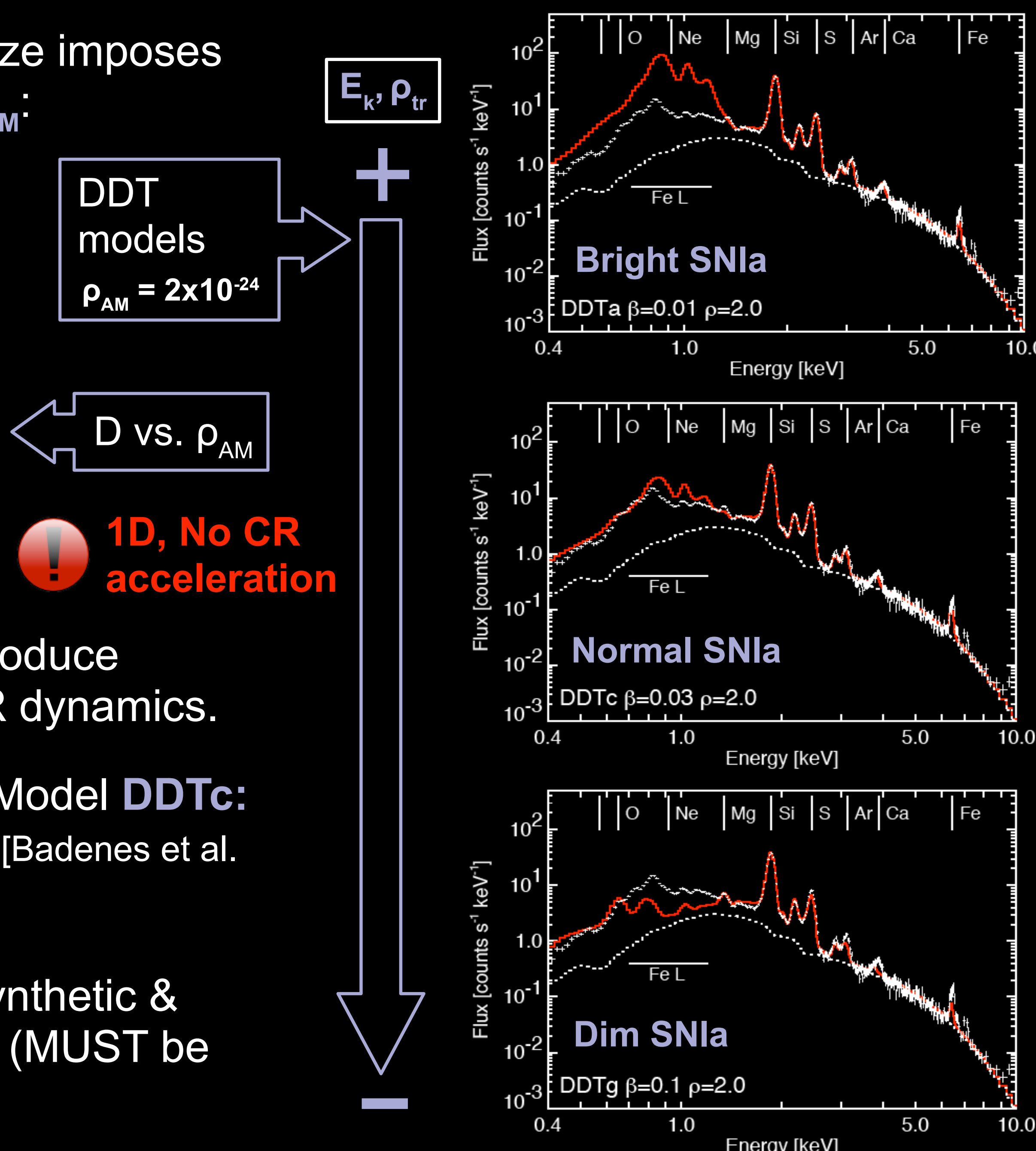
Age is known (SN1572). SNR size imposes a **correlation between D and ρ_{AM}**:



- Only **DDT models** at can reproduce BOTH X-ray spectrum and SNR dynamics.

- Mildly energetic explosion ⇒ Model **DDTc: E_k=1.2x10^{51} erg; M_{56Ni}=0.74 $M_\odot$** [Badenes et al. 06, ApJ 645, 1373].

- WARNING: Comparison of synthetic & observed spectra is NOT trivial! (MUST be quantitative).



Type Ia SNRs: SNR 0509-67.5

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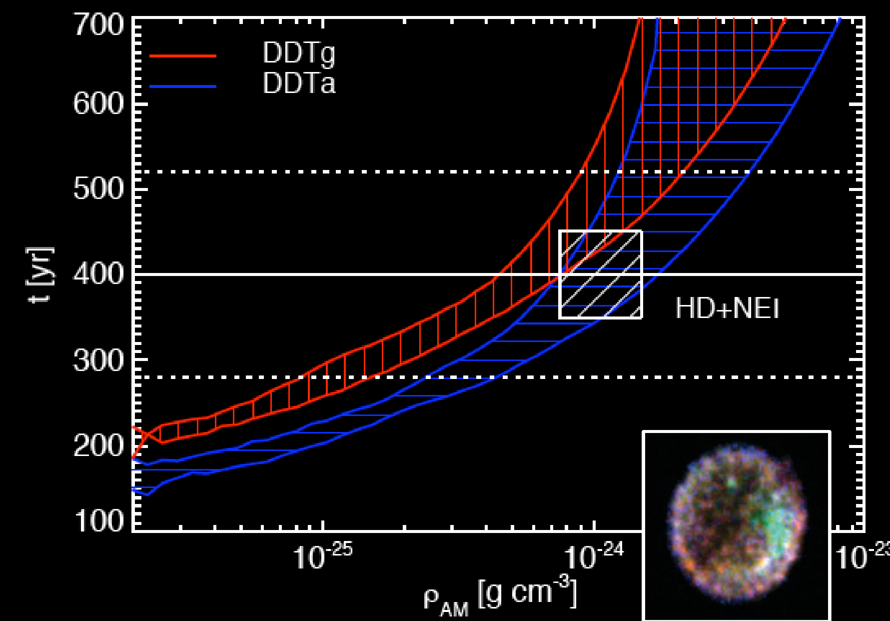
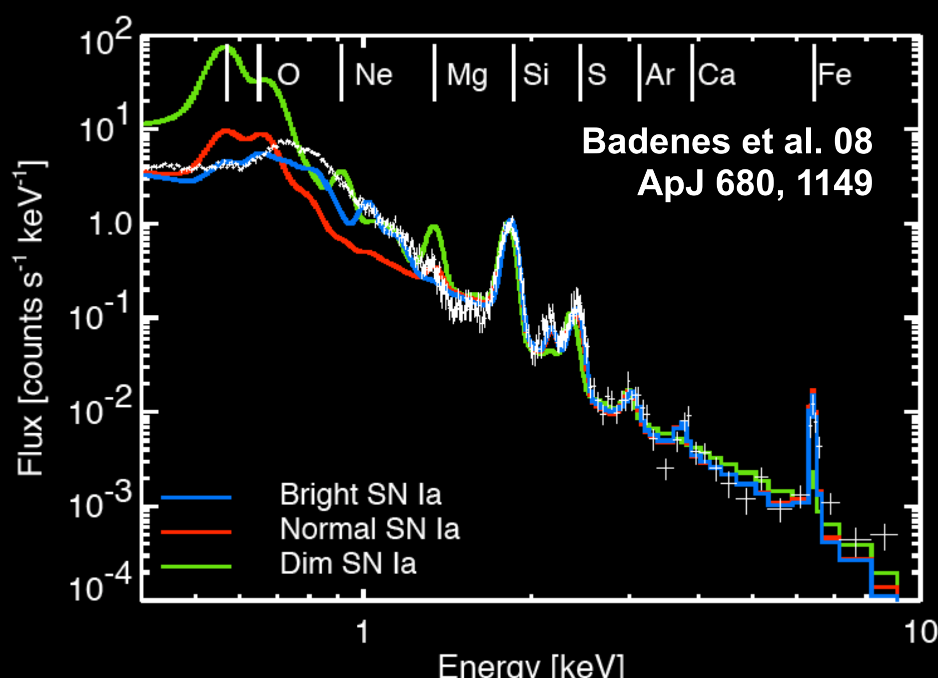
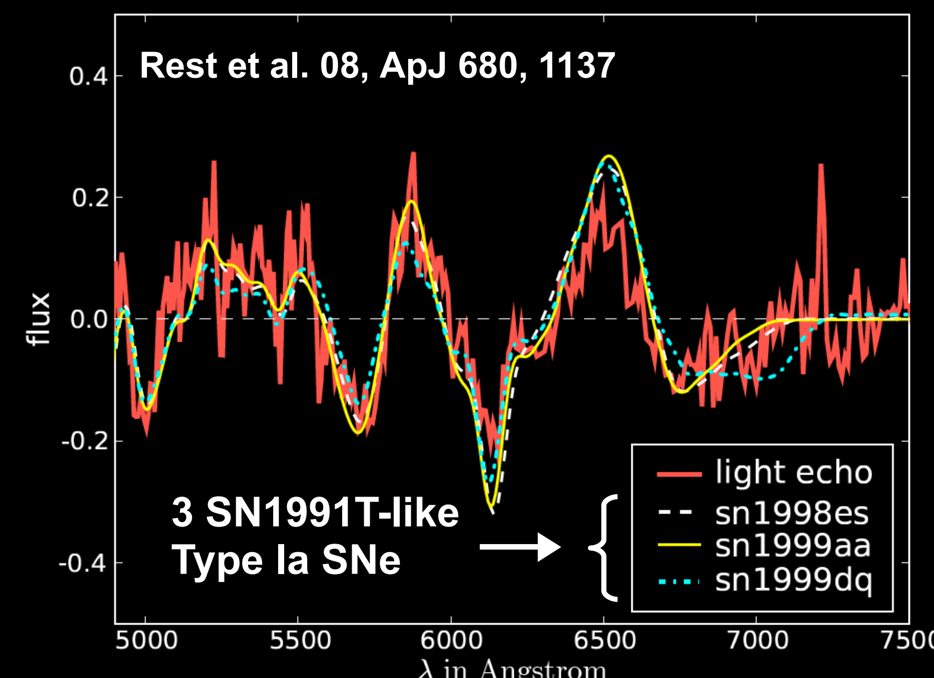
- Method can be applied to any young, X-ray bright, ejecta-dominated Type Ia SNR. Need at least a good estimate of the age.

- **SNR 0509-67.5** in the LMC ⇒ M_{56Ni}=0.97 $M_\odot$ [Badenes et al. 08, ApJ 680, 1149]. Also confirmed by the light echo [Rest et al. 08, ApJ 680, 1137].



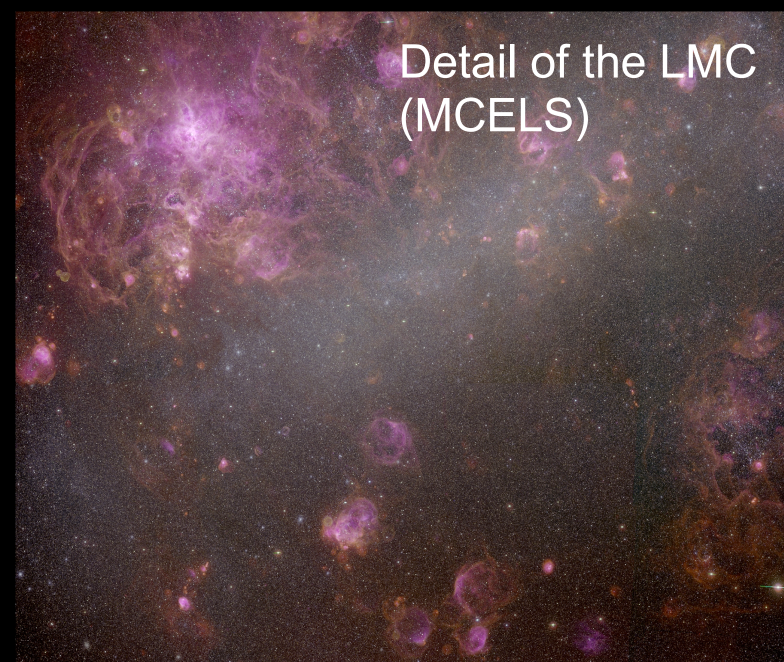




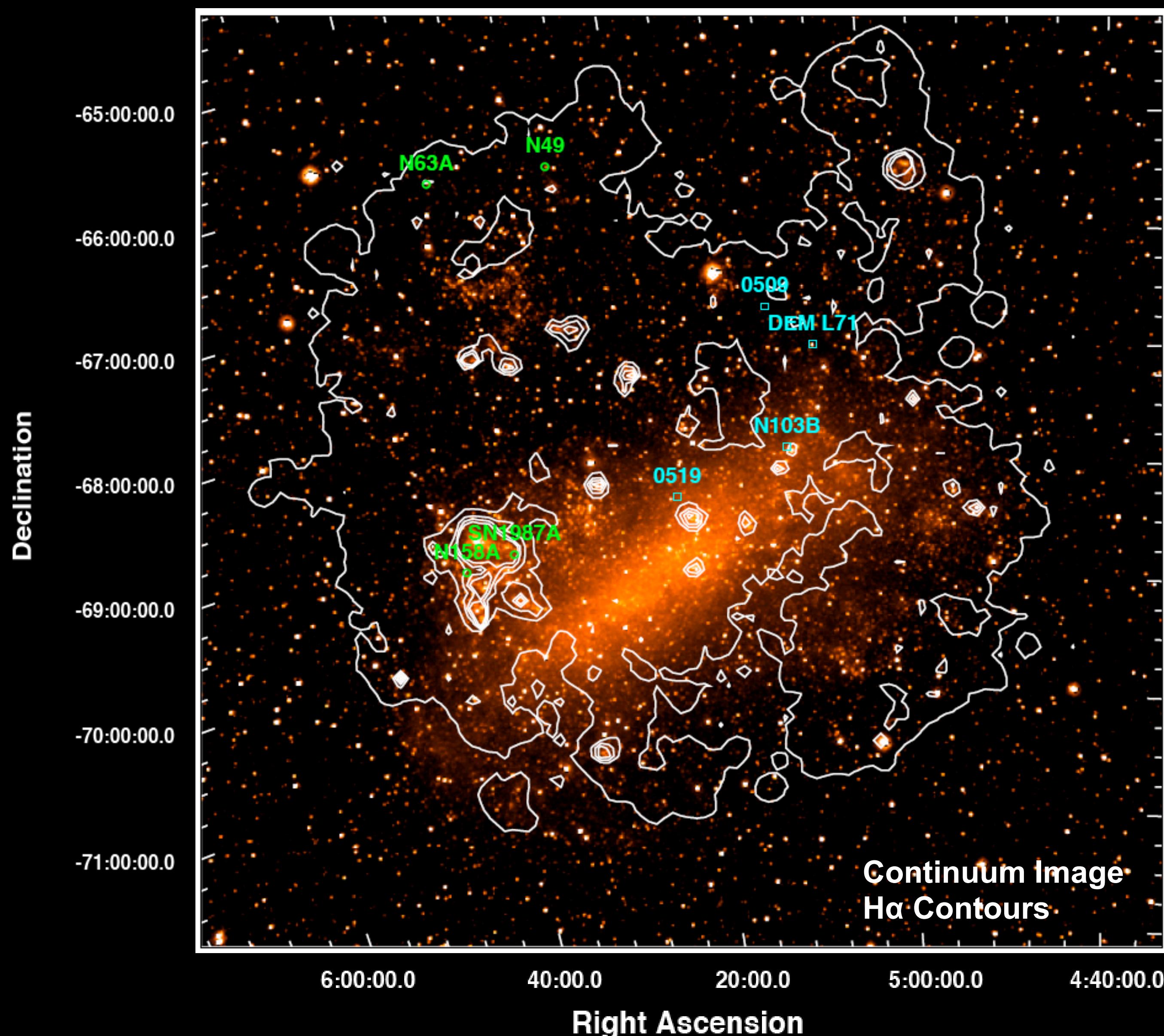
Why Study Type Ia SNRs?

- Much of what we know about **Type Ia SN progenitors** comes from studies of the **stellar populations in their host galaxies** ⇒ **metallicities, ages, SFRs, SFHs**. Issues:
  - **Unresolved stellar populations** ⇒ luminosity weighted spectra/SED.
  - **Measurements are not local** ⇒ age and metallicity gradients.
- Can we use **resolved stellar populations at the location of Type Ia SN progenitors**?
  - **YES!** ⇒ Star Formation History (SFH) maps for the LMC [Harris & Zaritsky 09, arXiv:0908.1422] and SMC [Harris & zaritsky 04, AJ 127, 1531].
  - What about the SNe? ⇒ **Use Supernova Remnants!**

Typical Ia SN hosts (SDSS)



Type Ia SNRs in the LMC



CC SNRs: N158A, SN1987A, N63A, N49

Type Ia SNRs: 0519-69.0, N103B, DEM L71, 0509-67.5

- 47 known SNRs in the LMC [Williams et al. 99, ApJS 123, 467].
- Avoid mistyping ⇒ young SNRs (ejecta-dominated or with a compact object).
- Four objects: DEM L71, 0509-67.5, 0519-69.0, N103B
- Three w/ light echoes (0509-67.5, 0519-69.0, N103B) [Rest et al. 05, Nat 438, 1132].

SFHs of the CC SNRs

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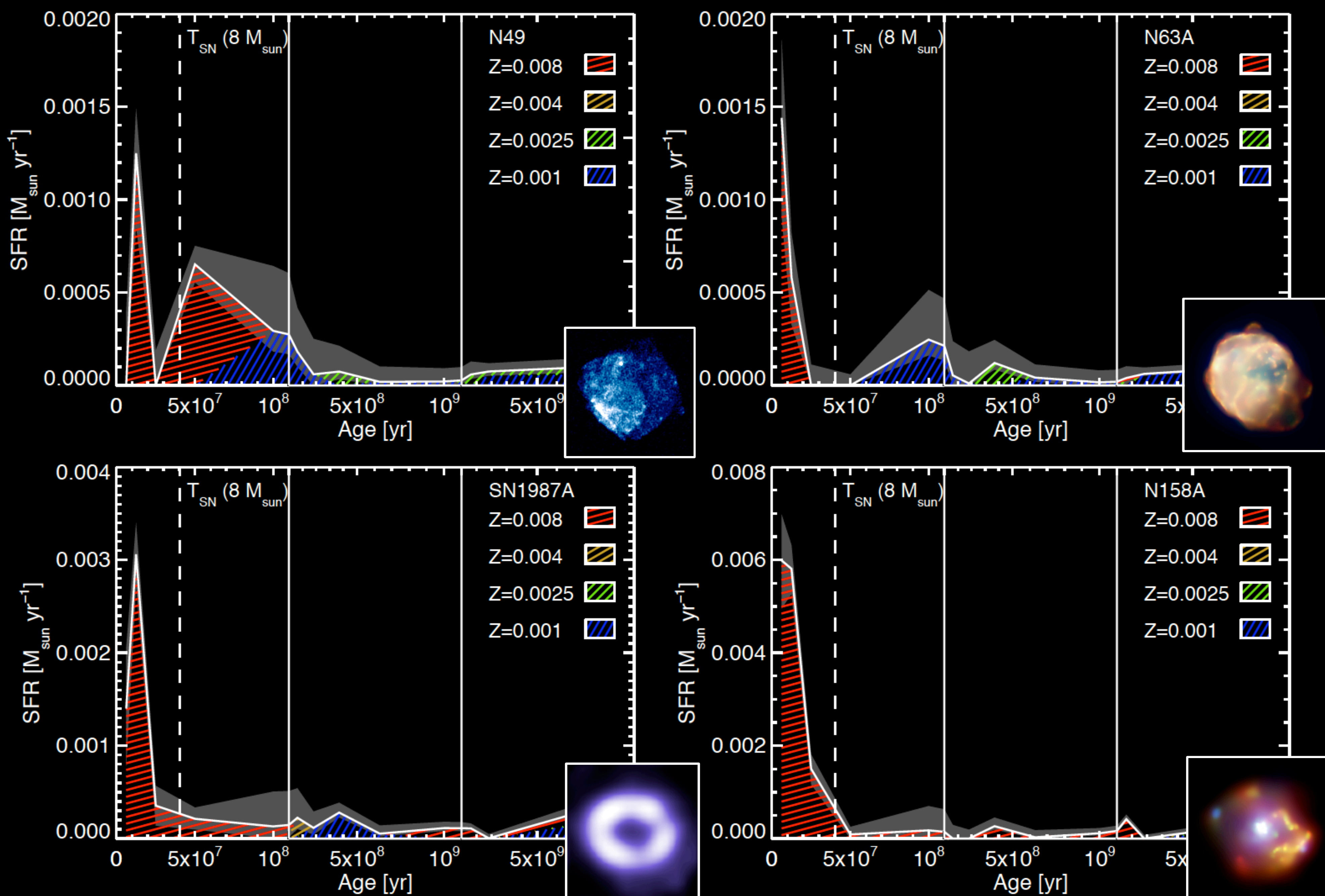

SFHs of the Ia SNRs

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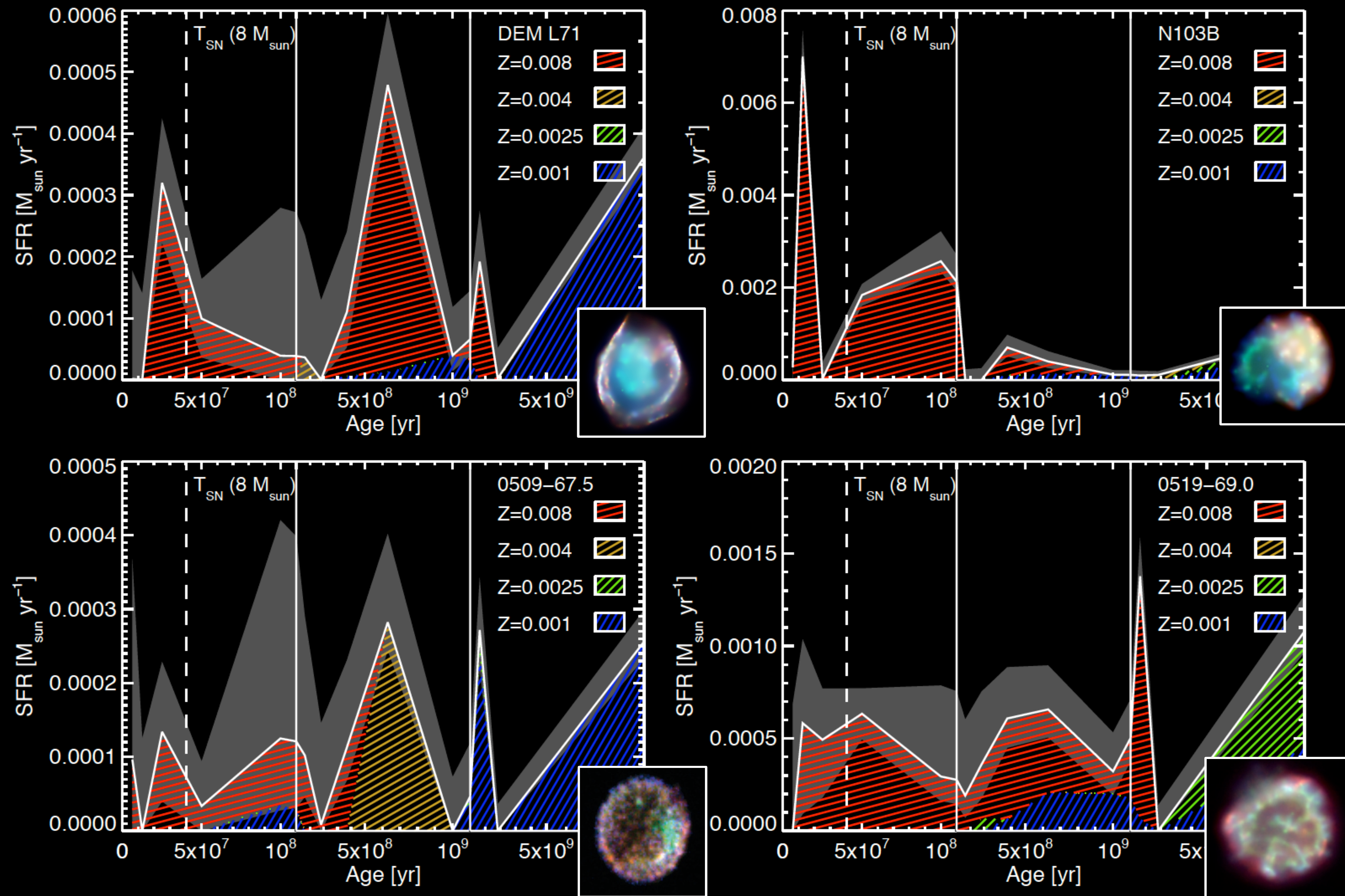

SNRs 0509-67.5 and N103B

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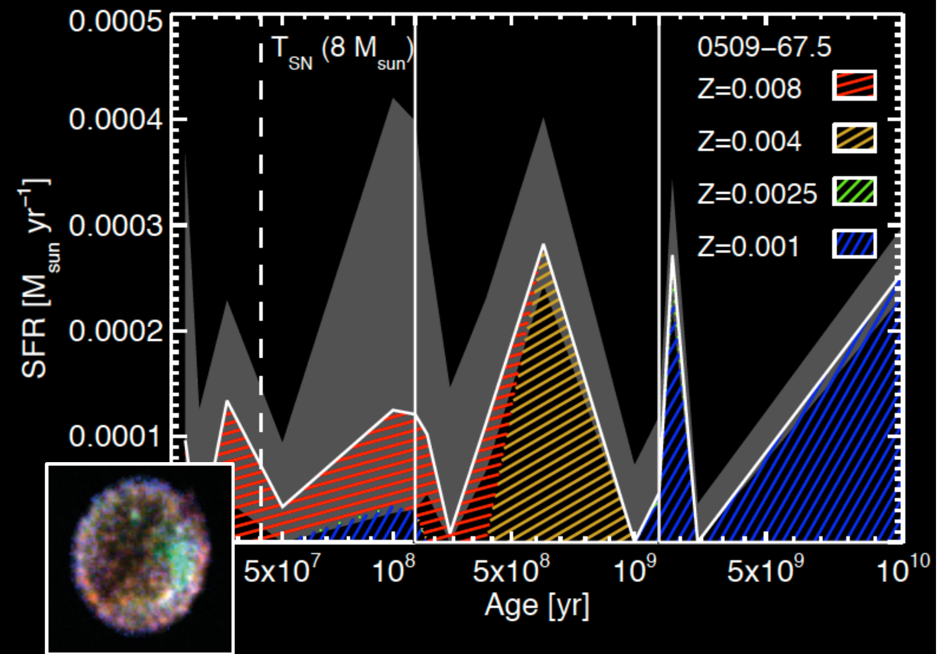
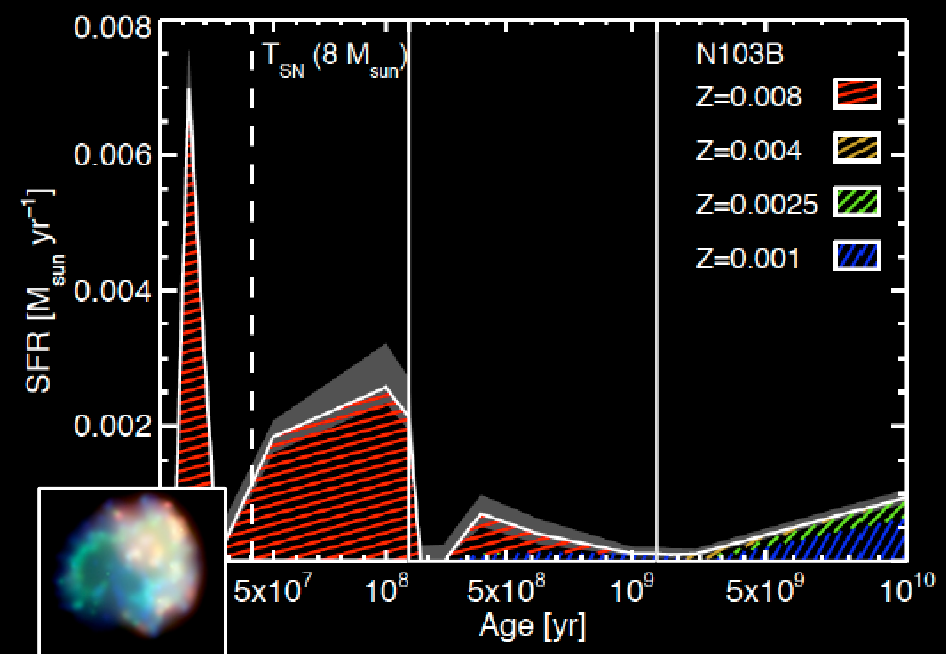
- SNR 0509-67.5 was originated by a very bright Type Ia SN (M_{56Ni}~1$M_{\odot}$). Δ_{m15}<0.9 [Rest et al. 08, ApJ 680, 1137] ⇒ M_V ~ -19.5. Yet, it is embedded in an old (7.9 Gyr) and metal-poor (Z=0.0014) stellar population.

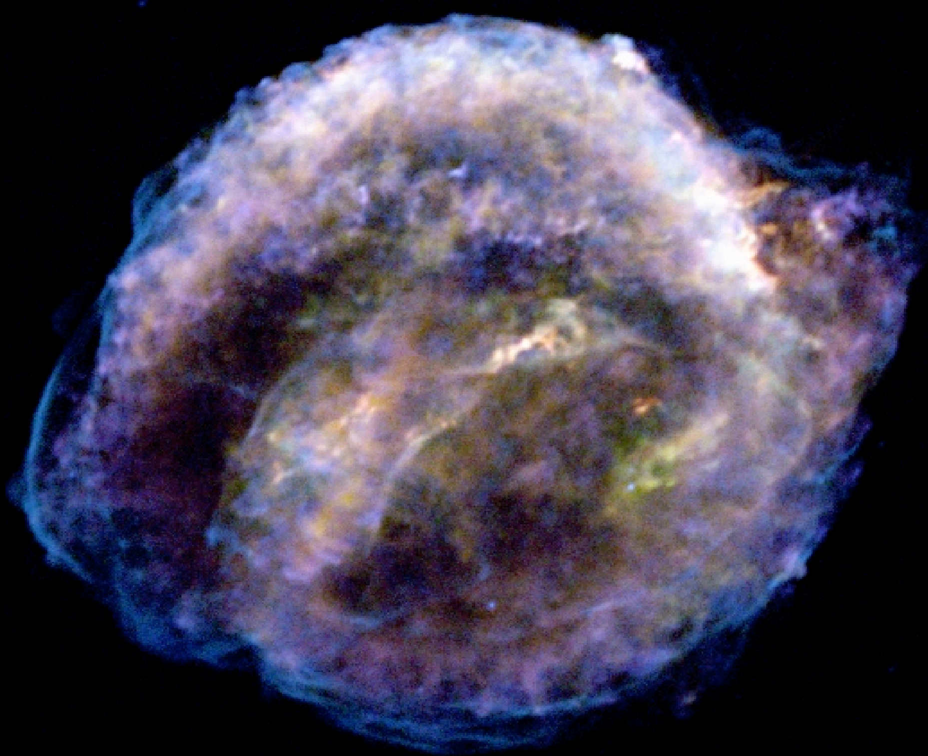


- SNR N103B, on the other hand, is associated with vigorous SF in the recent past (t<100 Myr). Its morphology shows signs of interaction [Lewis et al. 03, ApJ 582, 770]. Maybe it had a young(er), more massive progenitor that lost a large amount of mass before the explosion.



No definitive claims about the progenitors can be made from the SFHs alone!

The Kepler SNR



750 ks *Chandra* exposure [Reynolds et al. 07, ApJ 668, L135]

Kepler: A Type Ia SNR with circumstellar interaction

- Optical: dense knots (N enriched), radiative shocks. ~500 pc above the Galactic plane, high systemic velocity (>200 km.s^{-1}) ⇒ Massive runaway progenitor interacting with a bow shock CSM [Bandiera 87, ApJ 319, 885].

- X-rays: lots of Fe in the ejecta, but no detectable O. No compact object (>10^{-2} $L_{Cas\ A}$). Balmer shocks (require partially neutral CSM) ⇒ Thermonuclear SN.

- The **Kepler SNR is is a Type Ia SN expanding into N-enriched CSM**.
- Either the progenitor or the companion must have lost CNO-enriched material before the explosion.
- No detailed models for Kepler's ejecta emission + CSM interaction exist.

Core Collapse SNe

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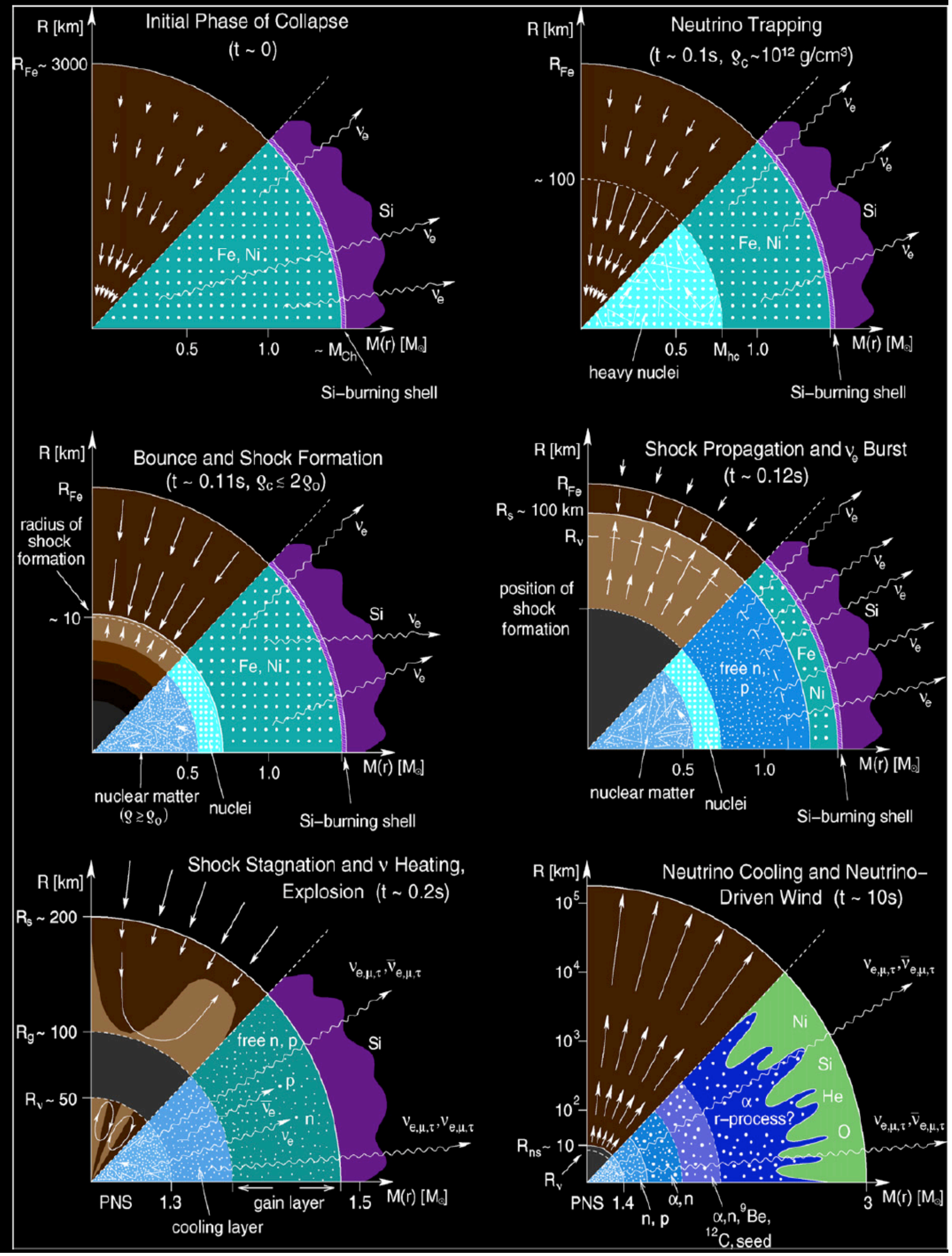
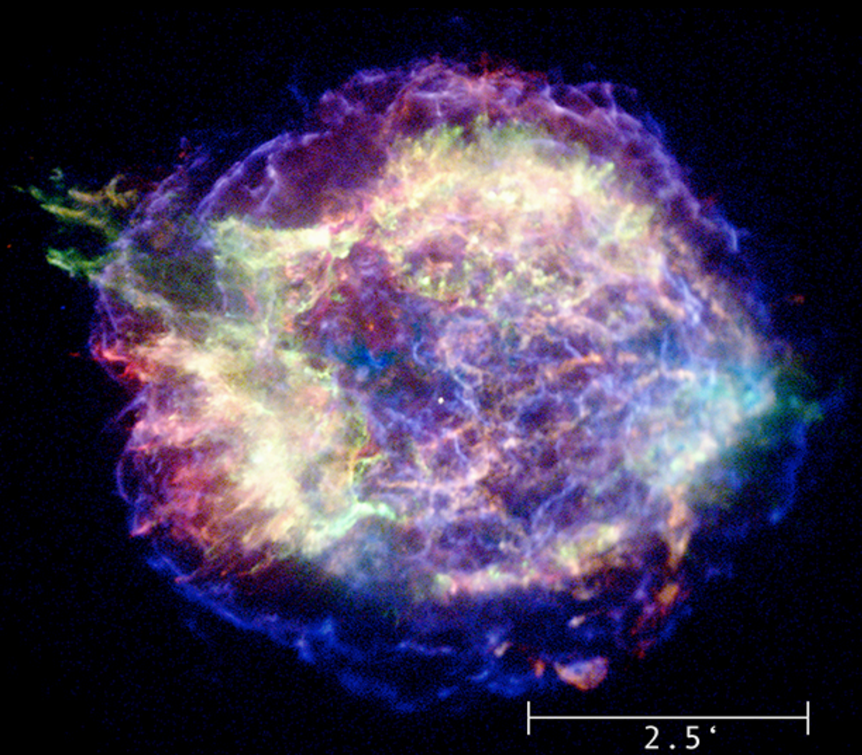
Core Collapse Supernovae (SNe) are the result of the gravitational collapse and rebound of the core of a massive star ⇒ NS or BH

- Fundamentals are reasonably well understood, but the details of the explosion mechanism are not. Much more complex than SN Ia!
- CC SN progenitors only identified for a small number of objects ⇒ many important aspects are unconstrained [Smartt, 09, ARA&A].
- CC SNRs provide vital input to stellar evolution: mass loss rates, ejecta distribution, NS kicks...



Janka et al. 07 PhysRep 442, 38

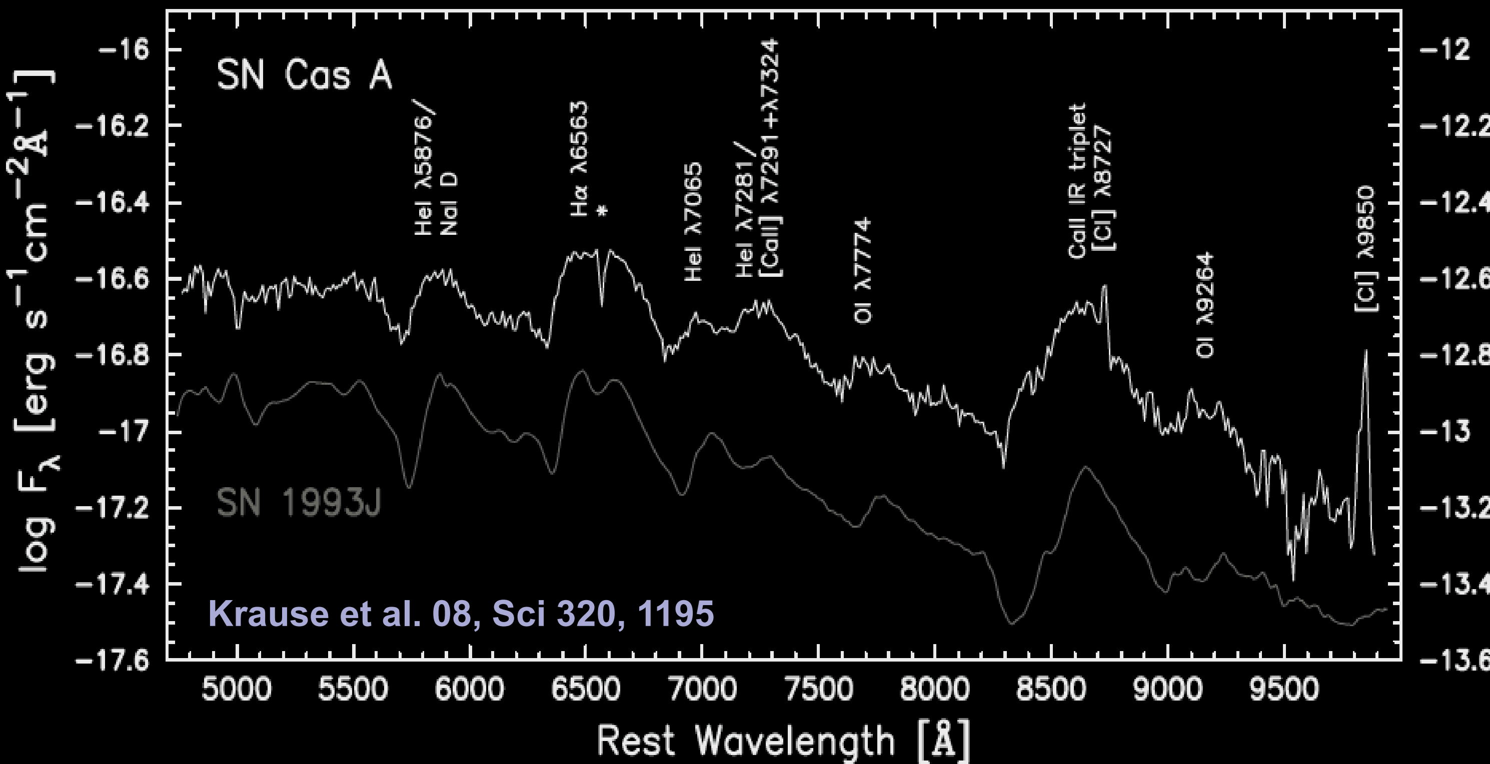
Cas A: The Poster Child of CC SNRs



- First scientific result from *Chandra*: CCO in Cas A [Tananbaum 99, IAU Circ 7246].
- First refereed paper based on *Chandra* data: ejecta overturn in Cas A [Hughes et al. 00, ApJ 528 L109].
- Superb view of the turbulent nature of the CC SN phenomenon: jet-like structure, small and large scale mixing, CCO, presence of CSM...

- The jet/counterjet structure [Hwang et al. 04, ApJ 615, L117], its energetics [Laming et al. 06, ApJ 644, 260] and its relationship with the CCO [Fesen et al. 06, ApJ 645, 283] ⇒ Not a jet-powered explosion.
- Mass loss from the progenitor and the structure of the CSM [Patnaude & Fesen 09, ApJ 697, 535, Hwang & Laming 09, ApJ 703, 883] ⇒ Dense RSG wind + cavity.
- Comparison to detailed stellar evolution calculations [Young et al. 06, ApJ 640, 891] ⇒ 15-25 $M_\odot$ progenitor w/ binary companion.

Cas A: The Poster Child of CC SNRs



Krause et al. 08, Sci 320, 1195

- Detection and spectroscopy of the SN light echo [Krause et al. 08, Sci 320, 1145] ⇒ Very similar to the Type IIb SN 1993J, whose binary progenitor (K-SG w/ B-SG companion) has been detected in pre-explosion images [Maund & Smartt 09, Sci 324, 486].
- Confirms another 'prediction of the past' based on the SNR: Cas A must have been originated by a Type IIL or IIb SN [Chevalier 05, ApJ 619, 839].

New ways to look at the data

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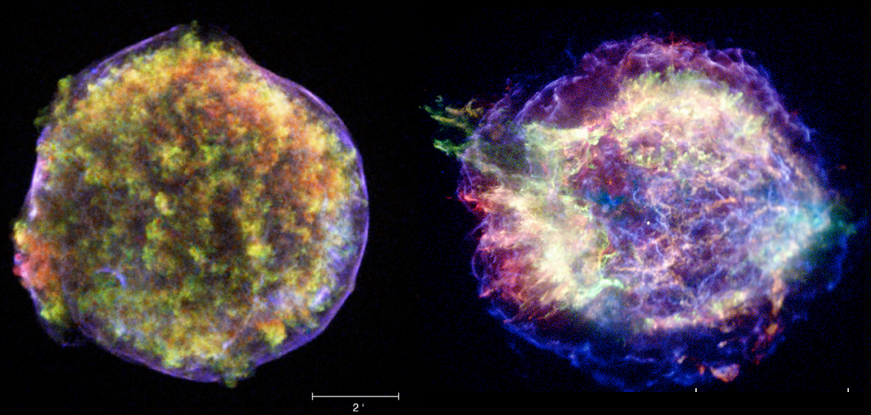
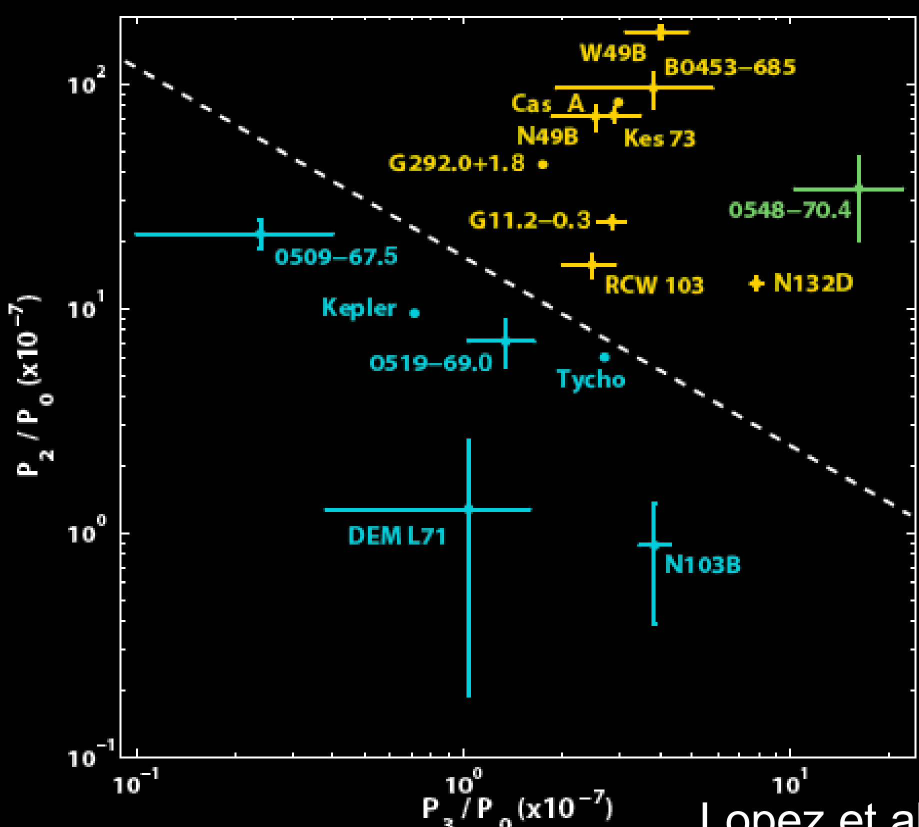
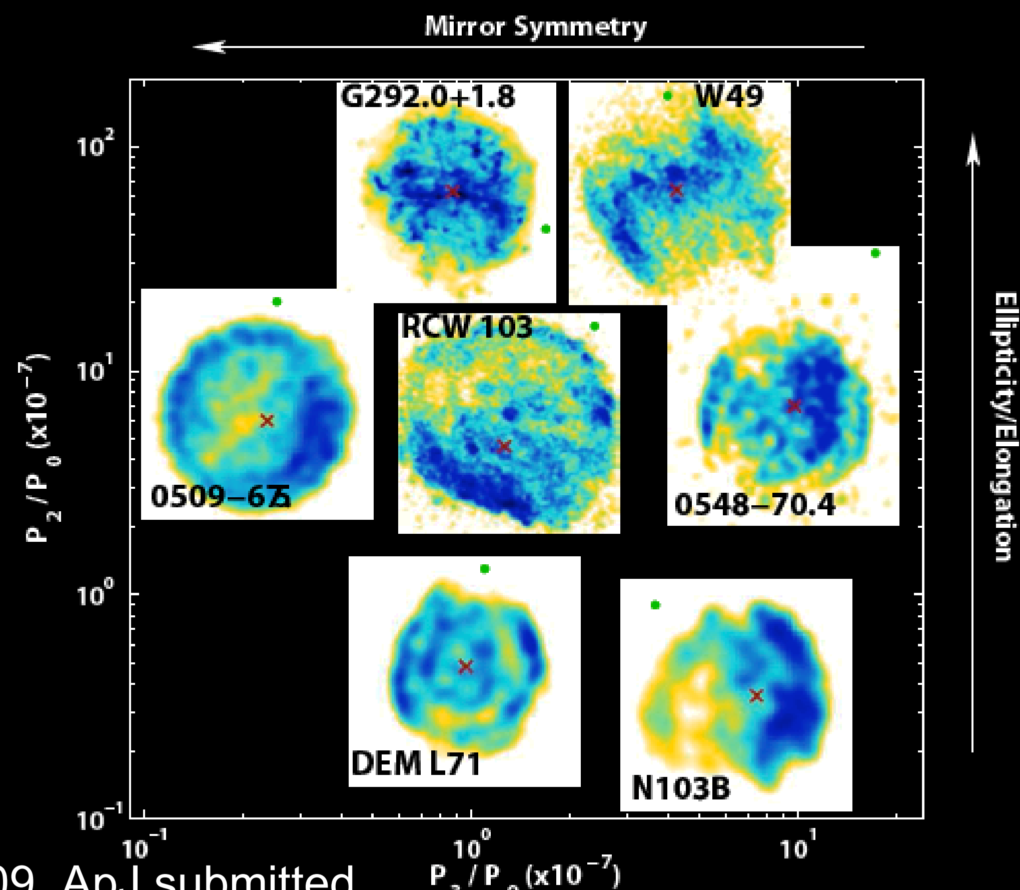


- Type Ia and CC SNe are fundamentally different phenomena.
- Lopez et al. 09 (ApJ, submitted) ⇒ Ellipticity / mirror symmetry of *Chandra* images can distinguish CC from Ia SNRs.





Lopez et al. 09, ApJ submitted

Summary and Future Challenges

X-ray observations of SNRs open a new window onto the physics of the SN explosions and the properties of their progenitor systems

- For **Type Ia SNe**, SNR studies are exceptionally well positioned to disentangle the **progenitor puzzle**.

- For **CC SNe**, SNR studies offer the best window into the mysterious **explosion mechanism**, which is inherently asymmetrical and must be studied in 3D.

Challenges for the future:

- Only a few X-ray bright, nearby SNRs. Deep observations of them will be a lasting legacy of *Chandra*.

- High quality data are useless without robust interpretation methods to extract physical information from the observations.

- We are dealing with very complex observations and equally complex theoretical models $\Rightarrow$ comparisons are highly non-trivial.

SNRs: The Persistence of Memory

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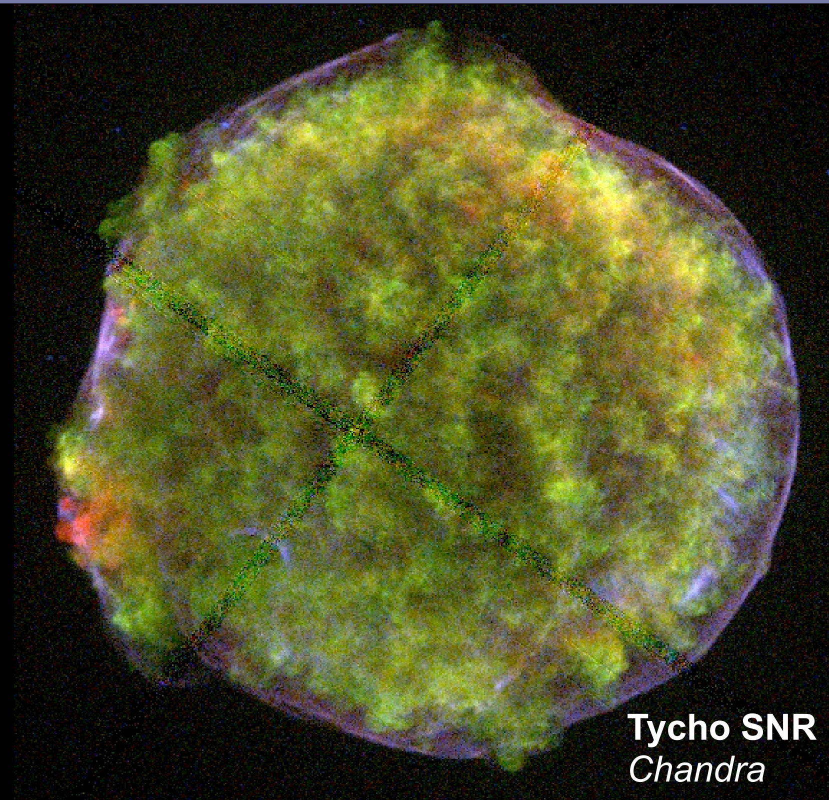
The Persistence of Memory.
Salvador Dalí (1931), now at MoMA (NYC)



Tycho SNR
Chandra

SNR observations can probe regimes that are NOT available to SNe:

- **Explosion physics**: *Chandra* can resolve the structure of the SN ejecta in Galactic SNRs (NOT equivalent to probing lines of sight!).
- **Progenitors**: We can identify the SNRs from *specific subtypes* of SNe and study the structure of the CSM and their stellar environment .

Without SNR studies, our understanding of SNe will never be complete.