The Persistence of Memory

or how the X-ray Spectra of Supernova Remnants Reveal the Brightness of their Parent Supernovae

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Wunch Talk
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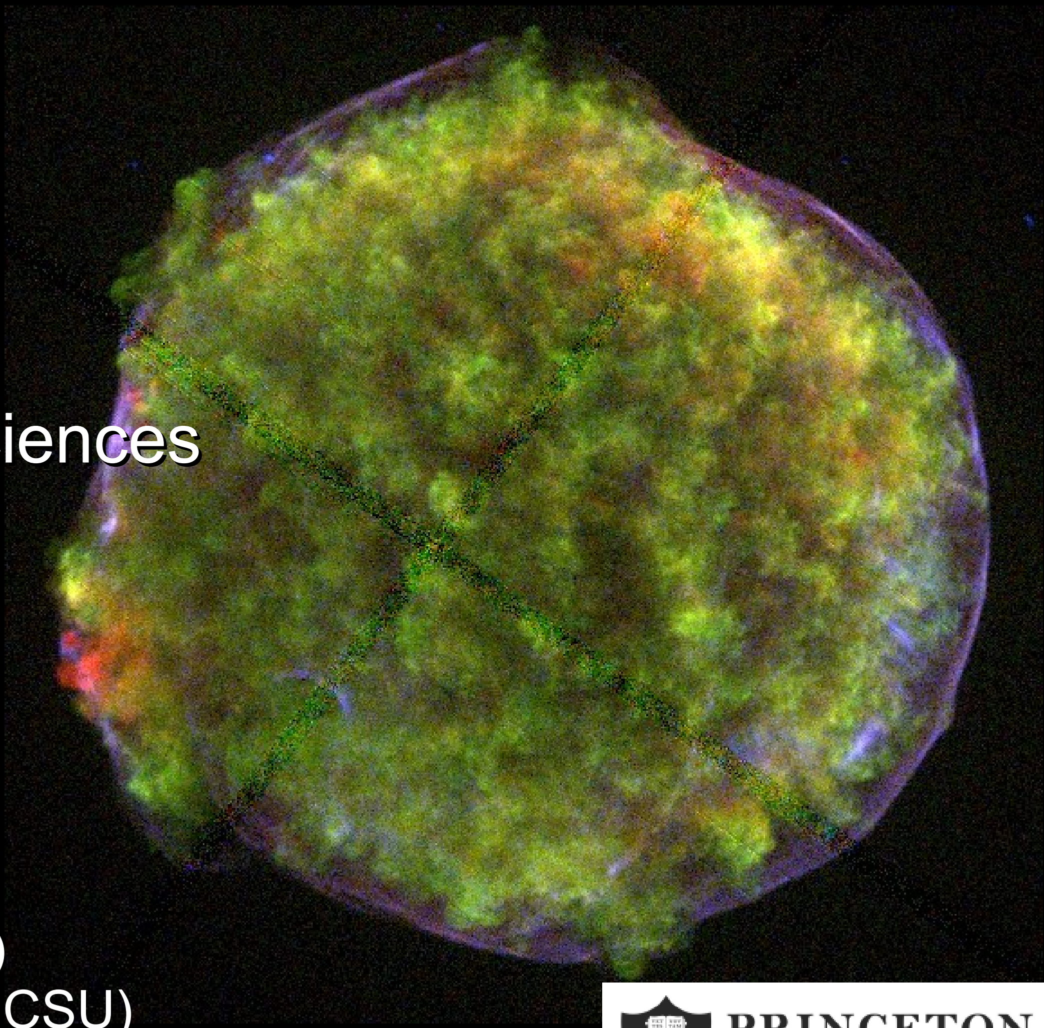
Princeton, January 30 2008



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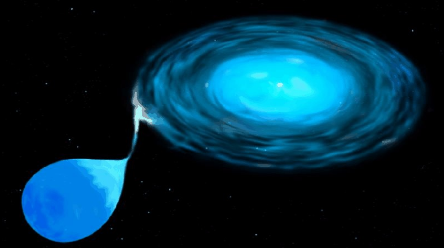
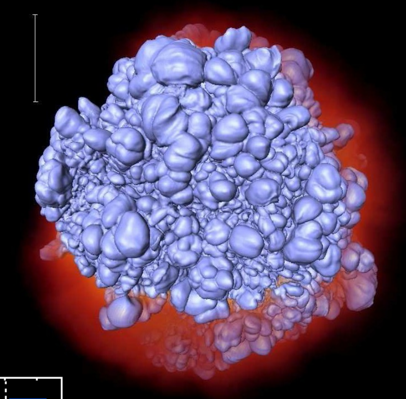
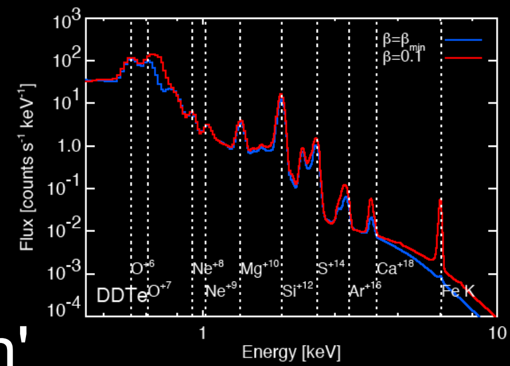
Outline

- **Type Ia Supernovae: Open issues.** Progenitor systems, explosion mechanisms.

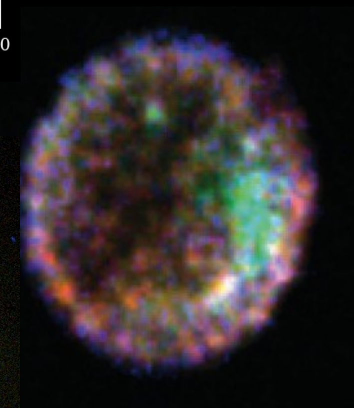




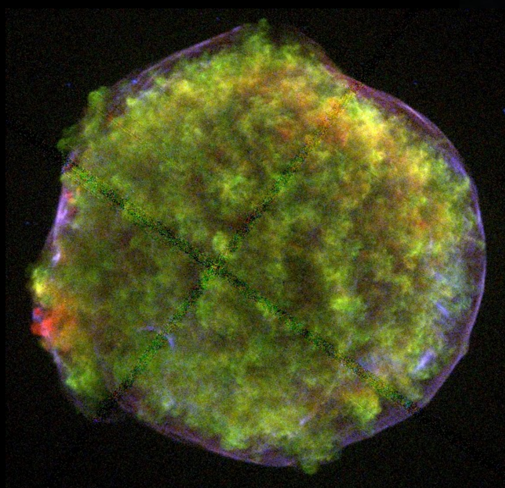
- **X-ray emission from Supernova Remnants.** HD+NEI simulations.



- **Two Practical examples: SNR 0509-67.5 and Tycho.** Light echoes from a 400yr old SN in the LMC as a 'calibration' of HD+NEI simulations.



- **Young SNRs as probes of Type Ia progenitors.**



- **Why SNRs are Important: The Persistence of Memory.**

Type Ia SNe

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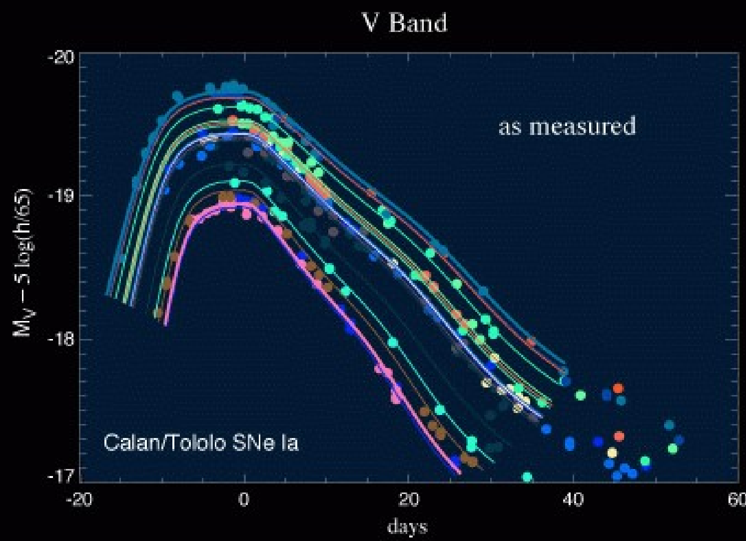
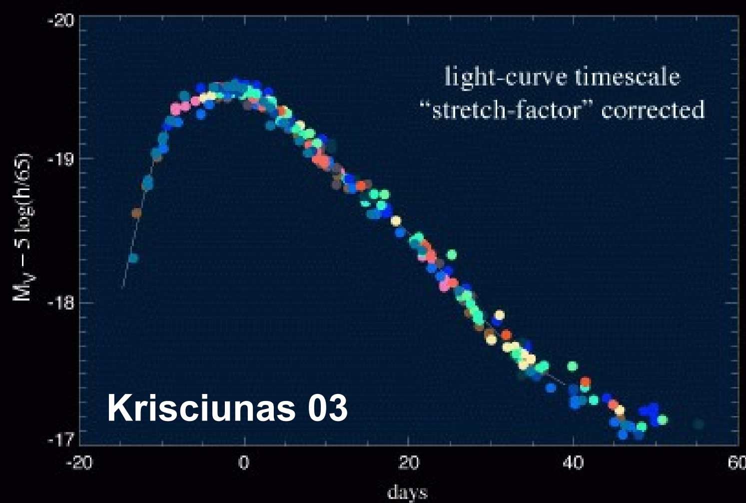
Type Ia Supernovae (SNe) are the result of the thermonuclear explosion of a C+O white dwarf prompted by accretion in a binary system

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**: progenitor systems, explosion mechanism.
- **Light curves and spectra are strikingly uniform** ⇒ LC width / luminosity relation [Phillips 93, ApJ 4123, L105] ⇒ Cosmology.

Progenitor Systems

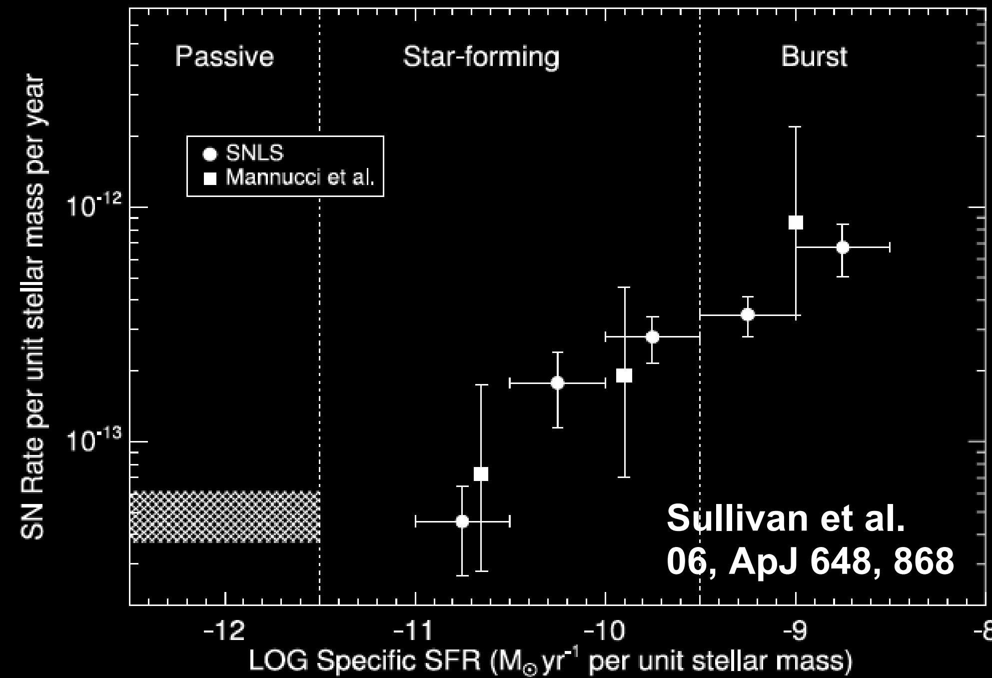
- **Type Ia SNe are the ONLY SNe observed in elliptical galaxies** ⇒ progenitors not necessarily associated with recent stellar formation.

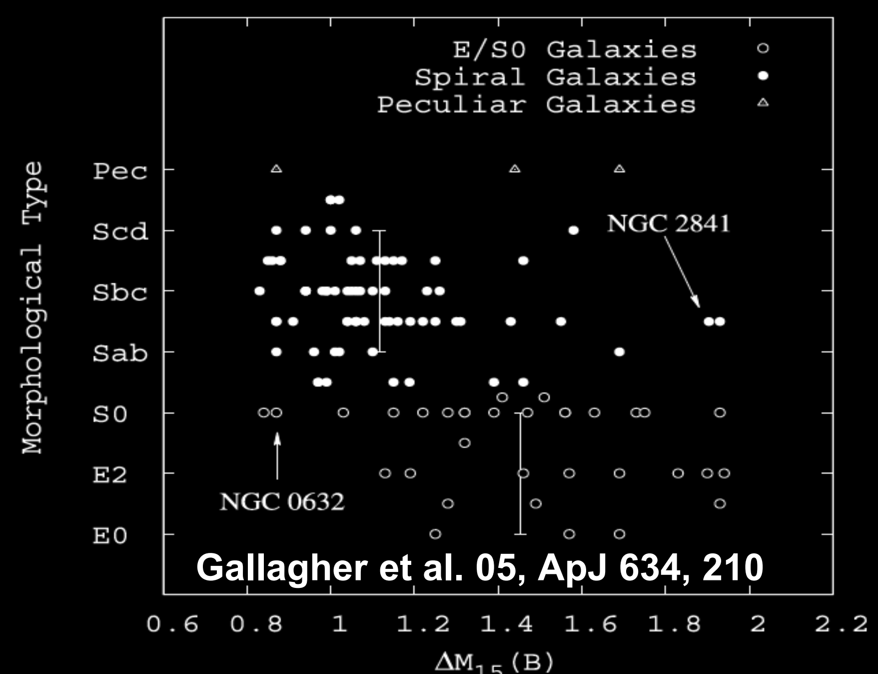
- Evidence for **TWO progenitor populations**: A+B models [Scannapieco & Bildsten 05, ApJ 629, L85]:

  - **'Prompt'** ⇒ 'younger' progenitors, rate ∝ star formation rate, brighter Type Ia SNe.

  - **'Delayed'** ⇒ 'older' progenitors, rate ∝ total stellar mass, dimmer Type Ia SNe.

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



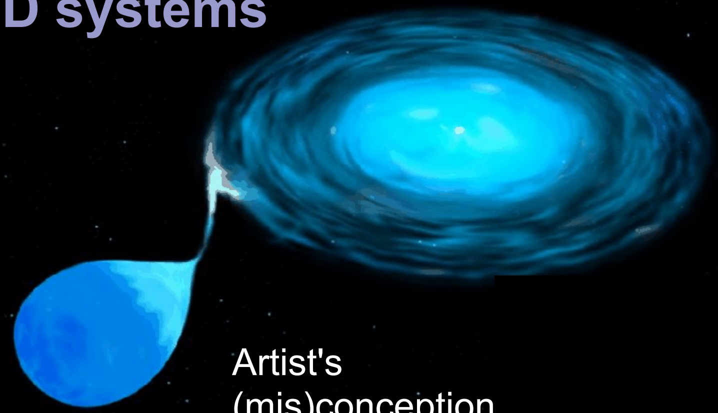


Theoretical Scenarios for Progenitors

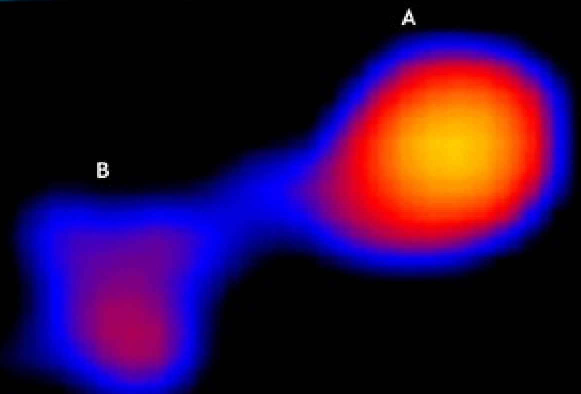
Depending on the nature of the **WD companion:**

- A normal star: **Single Degenerate** (SD) systems. Many known examples of WD binaries [Parthasarathy et al. 07, NewAR 51, 524]. WD explodes close to Chandrasekhar limit (**SD-Ch**) or some time before attaining it (**SD-SubCh**).
- Another WD: **Double Degenerate** (DD) systems. Surprising lack of known examples [Napiwotzki et al 05, C.P.]. Explosion is uncertain [Guerrero et al. 04, A&A 413, 257] BUT Super-CH Type Ia [Howell et al. 06, Nat 443, 308; Hicken et al. 07, ApJ 669, L17].

SD systems

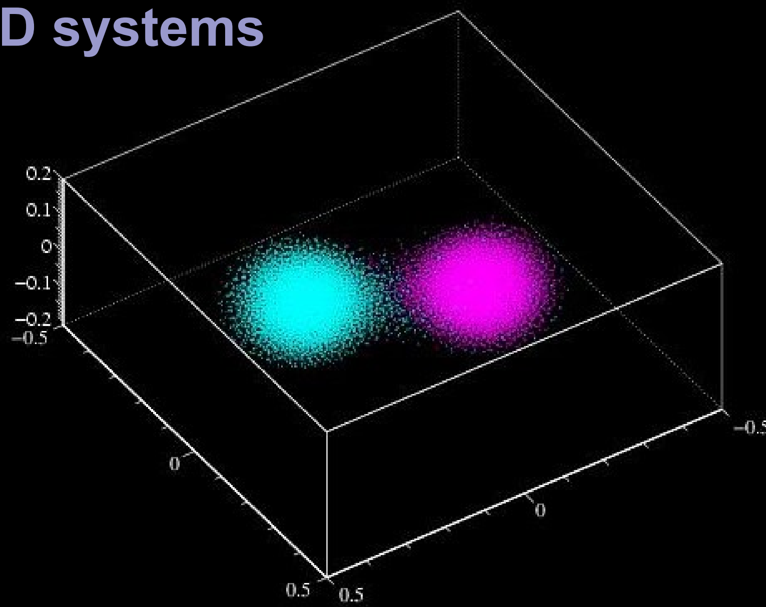


Artist's (mis)conception



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

Explosion Mechanisms: 1D Models

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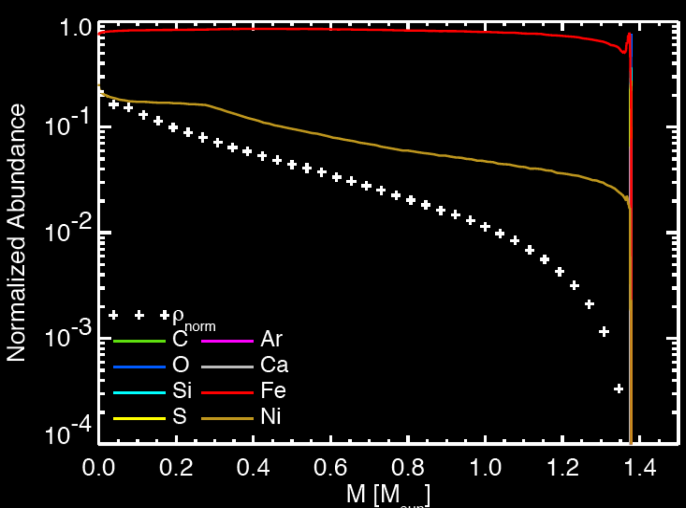
The mode of propagation of the burning front through the WD determines the nucleosynthesis ⇒ structure of the SN ejecta

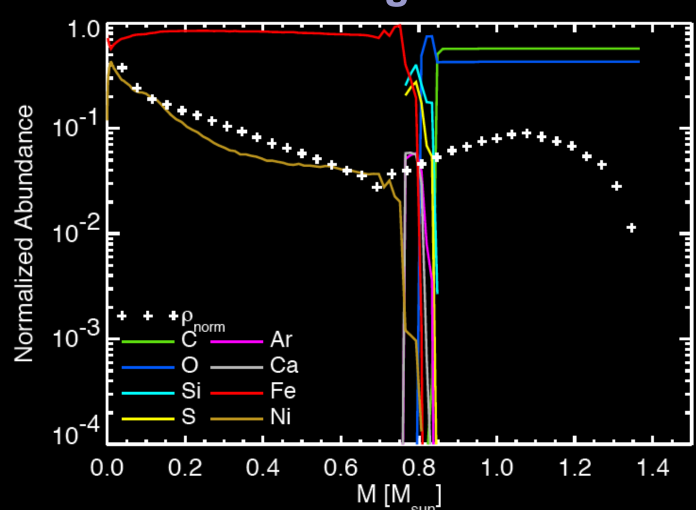
- **Supersonic** (**detonations**). Burning at high T ⇒ NSE ⇒ Fe-peak nuclei (^{56}Ni). Very energetic.
- **Subsonic** (**deflagrations**). Burning at lower T ⇒ departure from NSE ⇒ IMEs: Si, S, Ar, Ca. Flame quenches ⇒ unburnt C+O. Less energetic.
- **Subsonic, then supersonic** (**delayed detonations**). More IMEs and E_k than DEF. Transition to detonation imposed artificially at ρ_{tr}.

These paradigms have been explored extensively with 1D codes:

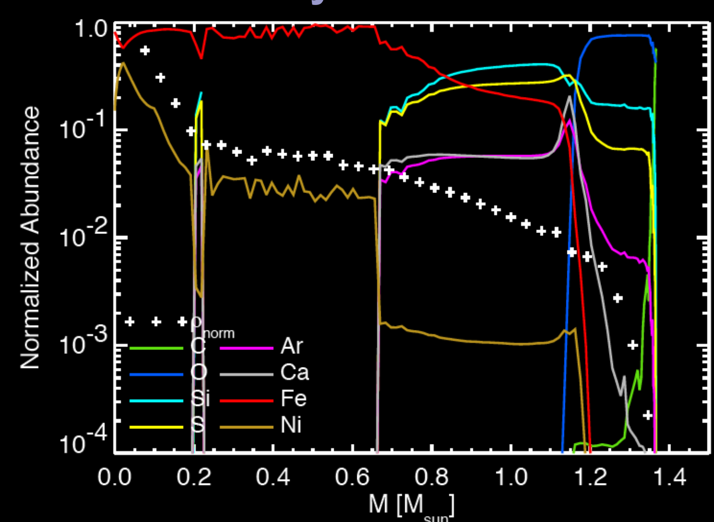
Detonation



Deflagration



Delayed Detonation



Explosion Mechanisms: 3D Models

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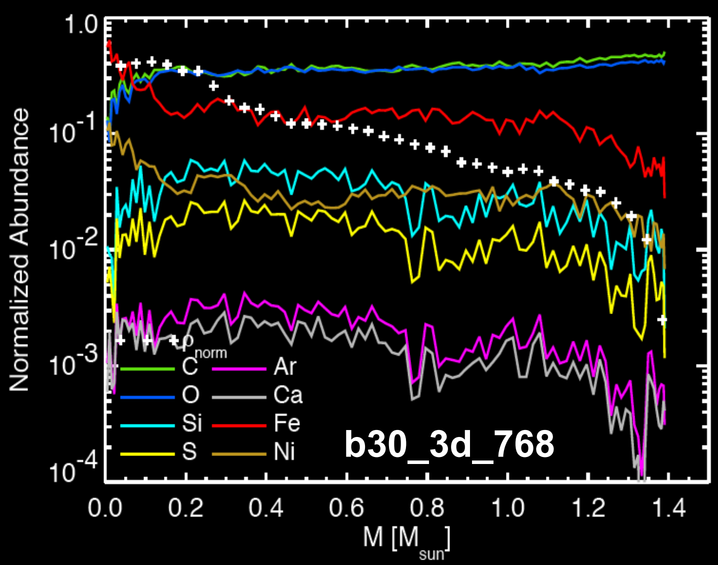
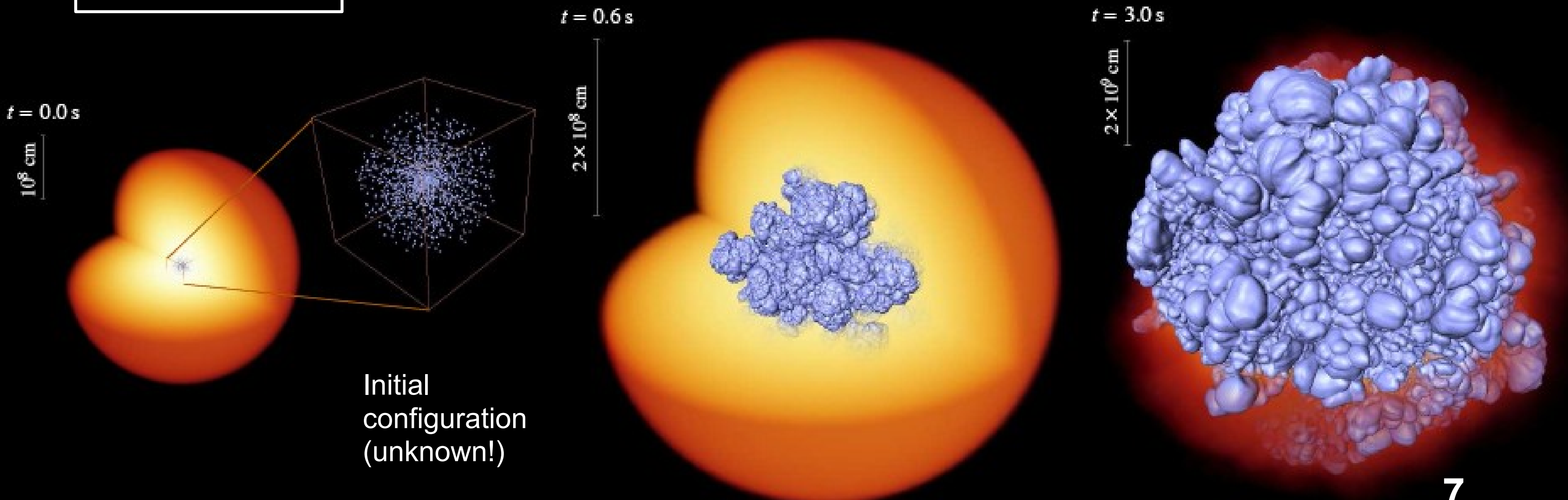
- Subsonic burning fronts in WDs are dynamically unstable ⇒ 3D codes. [Travaglio et al. 04, A&A 425, 1029; Gamezo et al. 03, Sci 299, 77; García-Senz & Bravo 05, A&A 430, 585].

- Explosion is dominated by turbulence and buoyancy ⇒ **well-mixed ejecta** (fuel and ashes), low E_k (~50% of WD remains unburnt), low yield of IMEs.



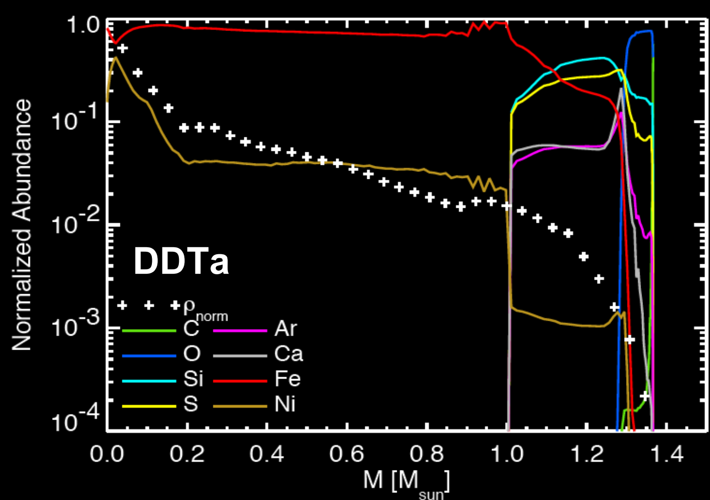
3D Deflagration
Model by F. Röpke

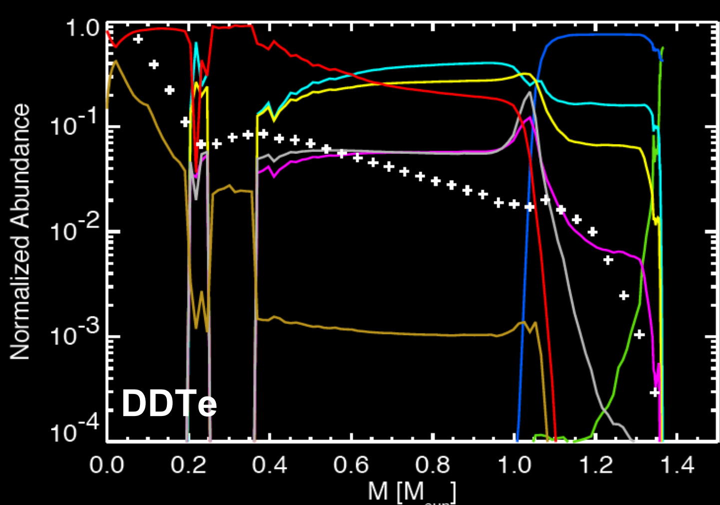


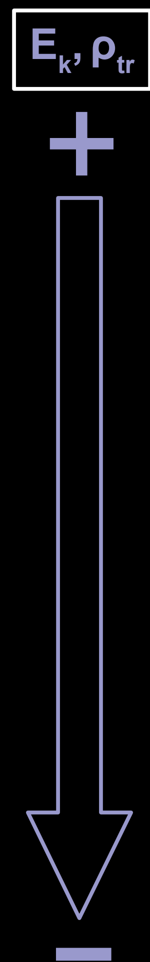
Initial configuration (unknown!)

The Success of Delayed Detonations

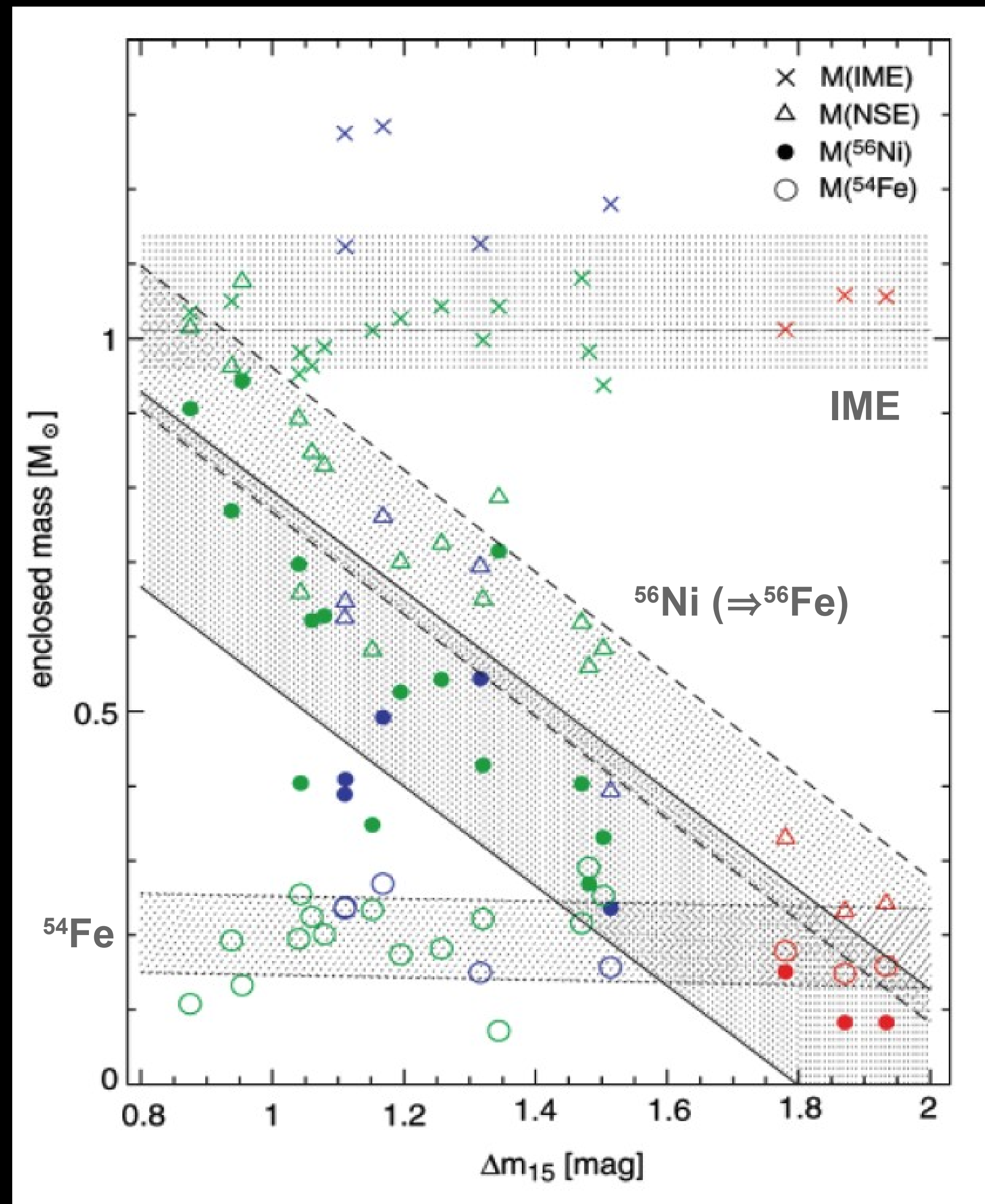
- Phenomenological 1D **delayed detonation** (DDT) models provide the best match to Type Ia SN observations.







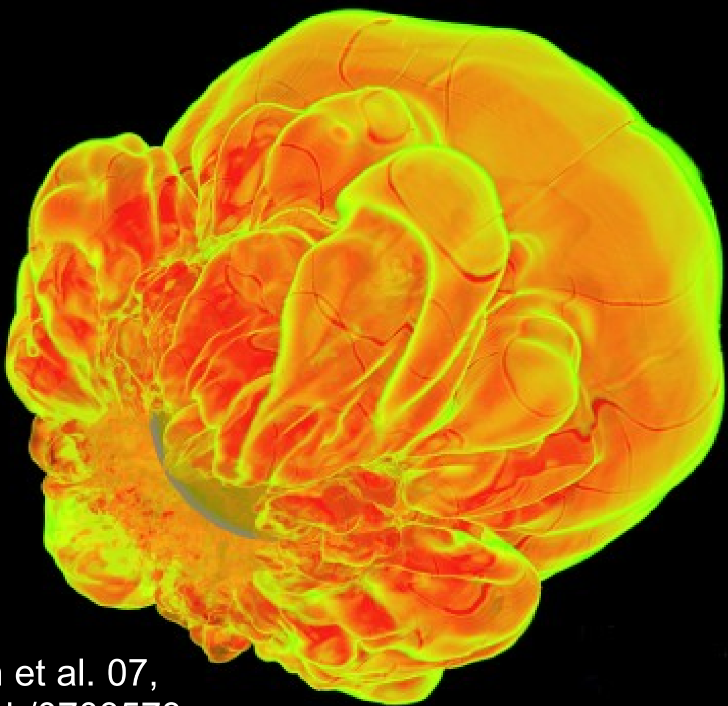
Mazzali et al. 07, Sci 315, 825 [23 Type Ia SNe]



Explosion Mechanisms: 3D Models

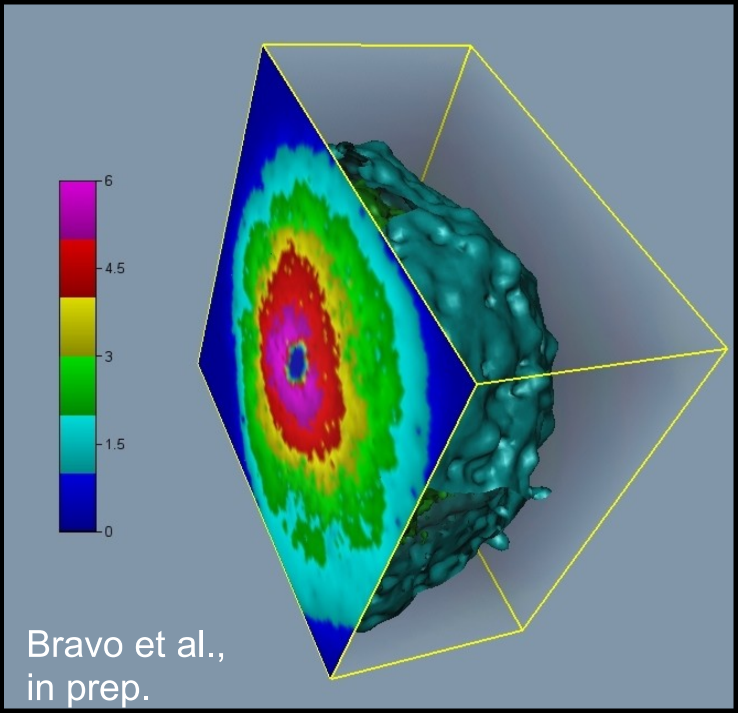
- Ongoing efforts to model the **deflagration to detonation transition** in a self-consistant way using 3D codes:

Gravitationally Confined Detonations
[Plewa et al. 04 ApJ 612, L37]



Jordan et al. 07,
astro-ph/0703573

Pulsating Reverse Detonations
[Bravo & García-Senz 06 ApJ 642, L157]



Large scale full-star models have limitations. Most theoretical calculations start from similar initial conditions (~M_{Ch} CO WD). What about sub-Ch models?

How Much Fe in Type Ia SNe?

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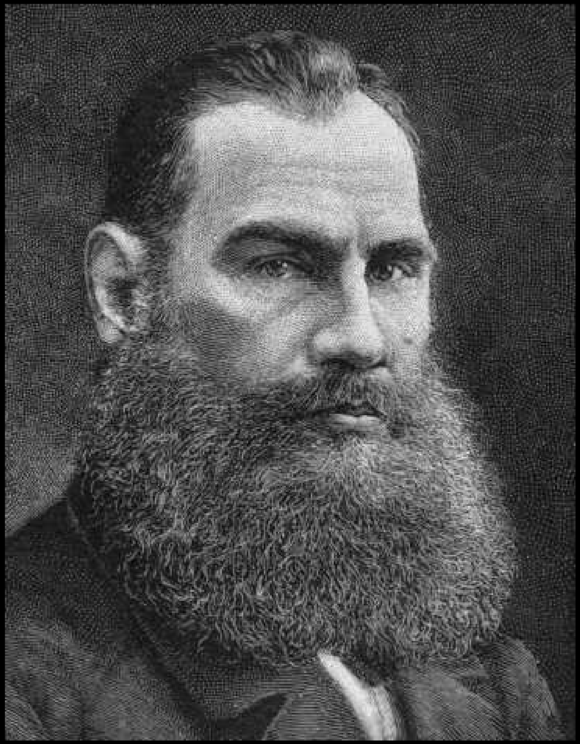
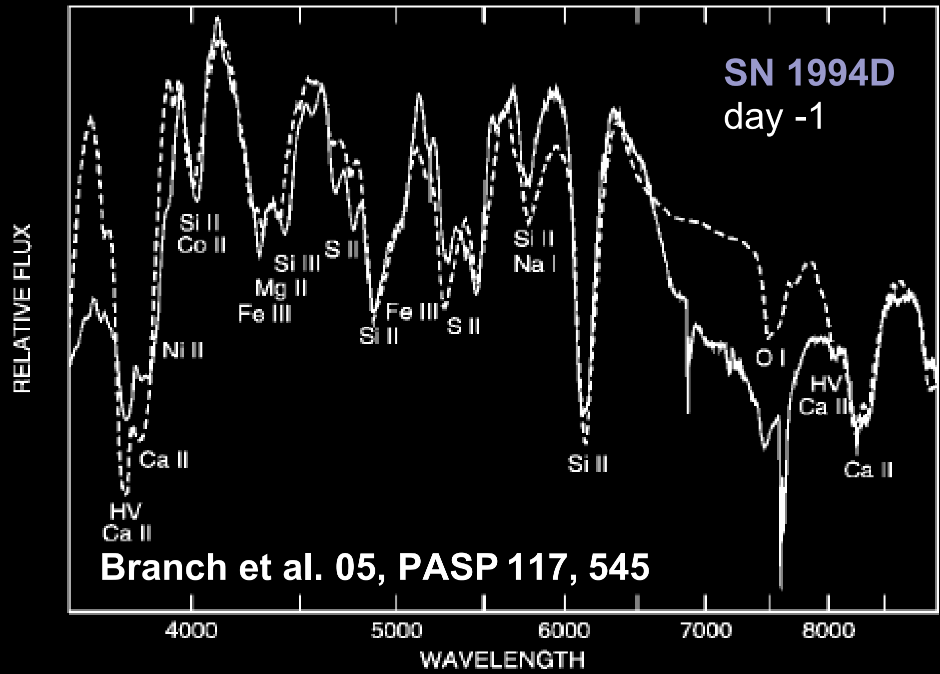
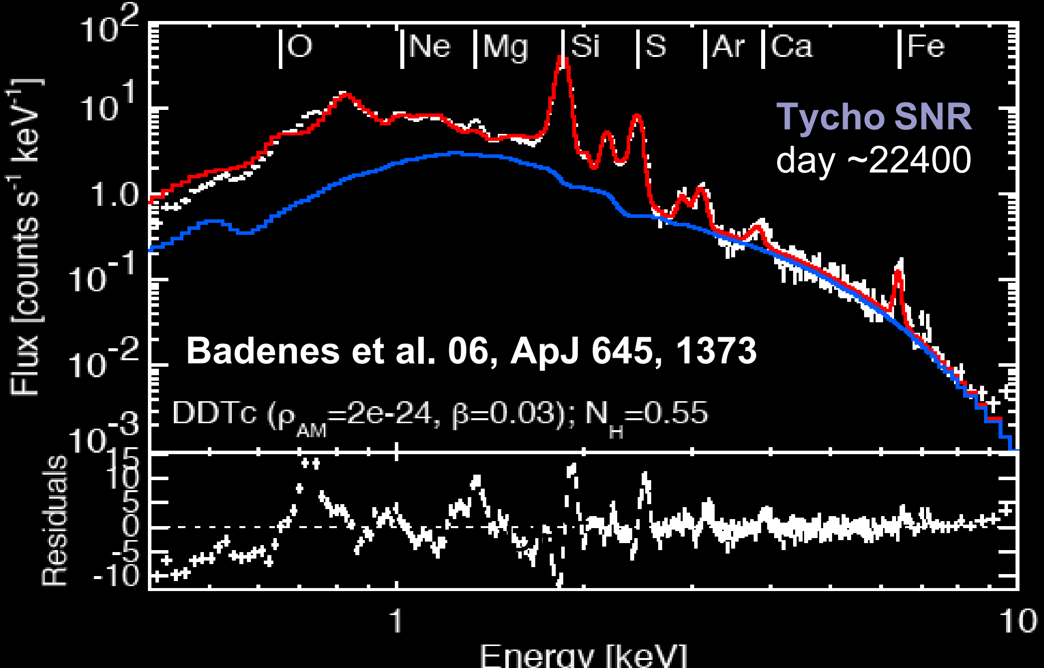


Yes, it will be a long time before people learn what I know. How much of iron and other metal there is in the sun and the stars is easy to find out, but anything that exposes our swinishness is difficult, terribly difficult!

Lev Nikolayevich Tolstoy (1828-1910), *The Kreutzer Sonata*
Thanks to Martin Laming for the quote!

Probing the SN Ejecta





Two ways to probe SN ejecta:

- **SN light curves & spectra (optical/IR/UV)**:
  - Blended emission/absorption features from O, Na, Mg, Si, S, Ca, Co, Fe, Ni.
  - Spectral modeling and interpretation are challenging.
- **SNR spectra (X-ray)**:
  - Blended emission lines from O, Ne, Mg, Si, S, Ar, Ca, and Fe.
  - Spectral modeling and interpretation are challenging.

Calibration has been impossible... until now.

HD+NEI Simulations for SNRs

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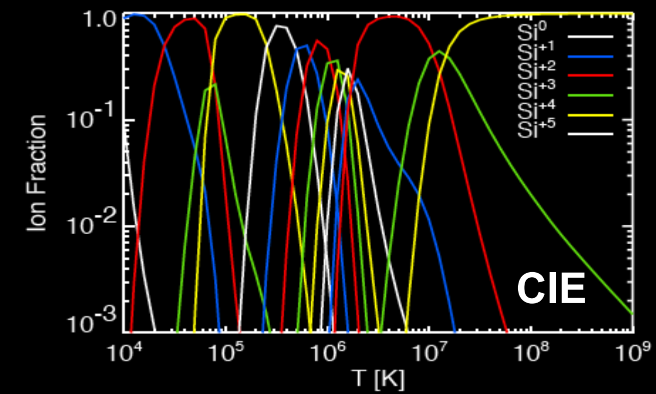
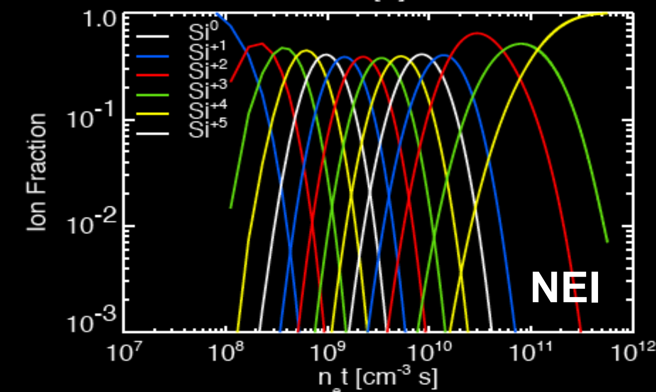
In SNRs, plasma is in **nonequilibrium ionization** ⇒

X-ray emission is coupled to the hydrodynamics

→ **HD+NEI simulations**: Hydrodynamics, NEI, physics of collisionless shocks, electron-ion coupling, radiative + ionization losses, ... [Hamilton & Sarazin 84 ApJ 287, 282; Badenes et al. 03 ApJ 593, 358; Sorokina et al. 04, Ast. Lett 30, 737; Badenes et al. 05 ApJ 624, 198].

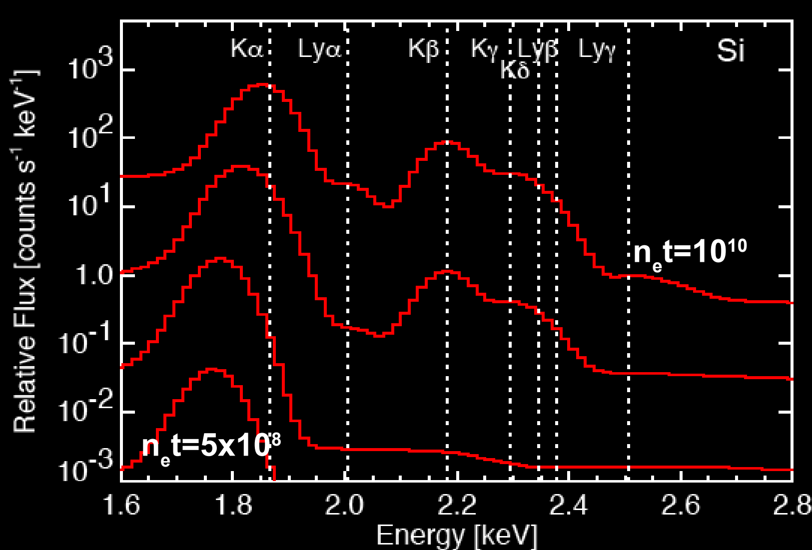


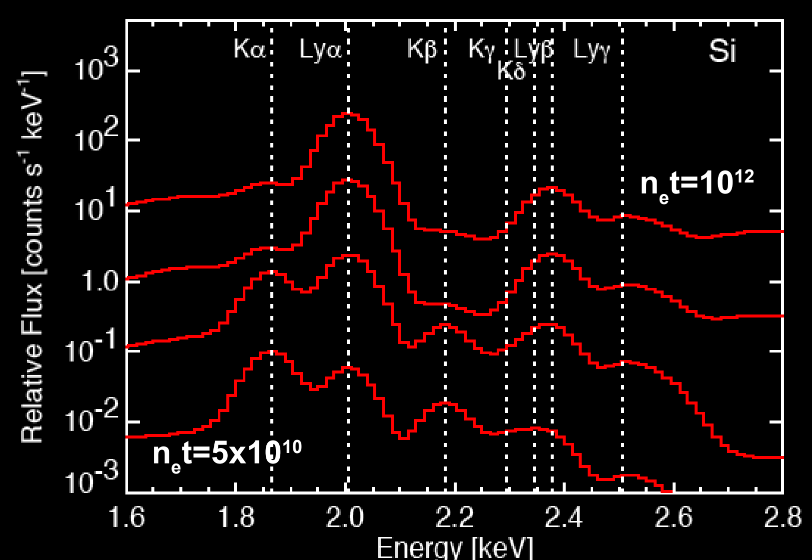


Our understanding of some of these processes is not complete ⇒ models must be incomplete!

An example of NEI X-ray emission for Si:

$n_e t$ from 5×10^8 cm^{-3}s to 10^{12} cm^{-3}s





HD+NEI Simulations for SNRs

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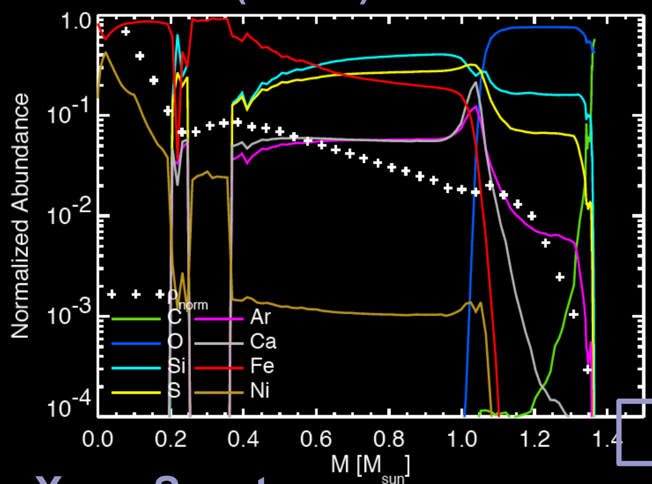
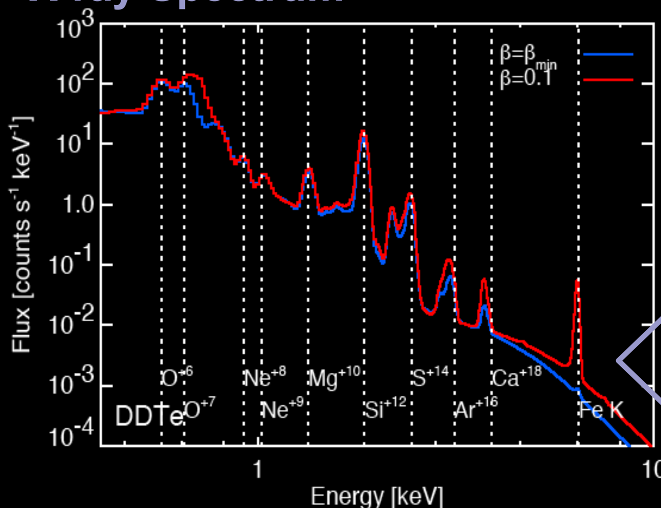
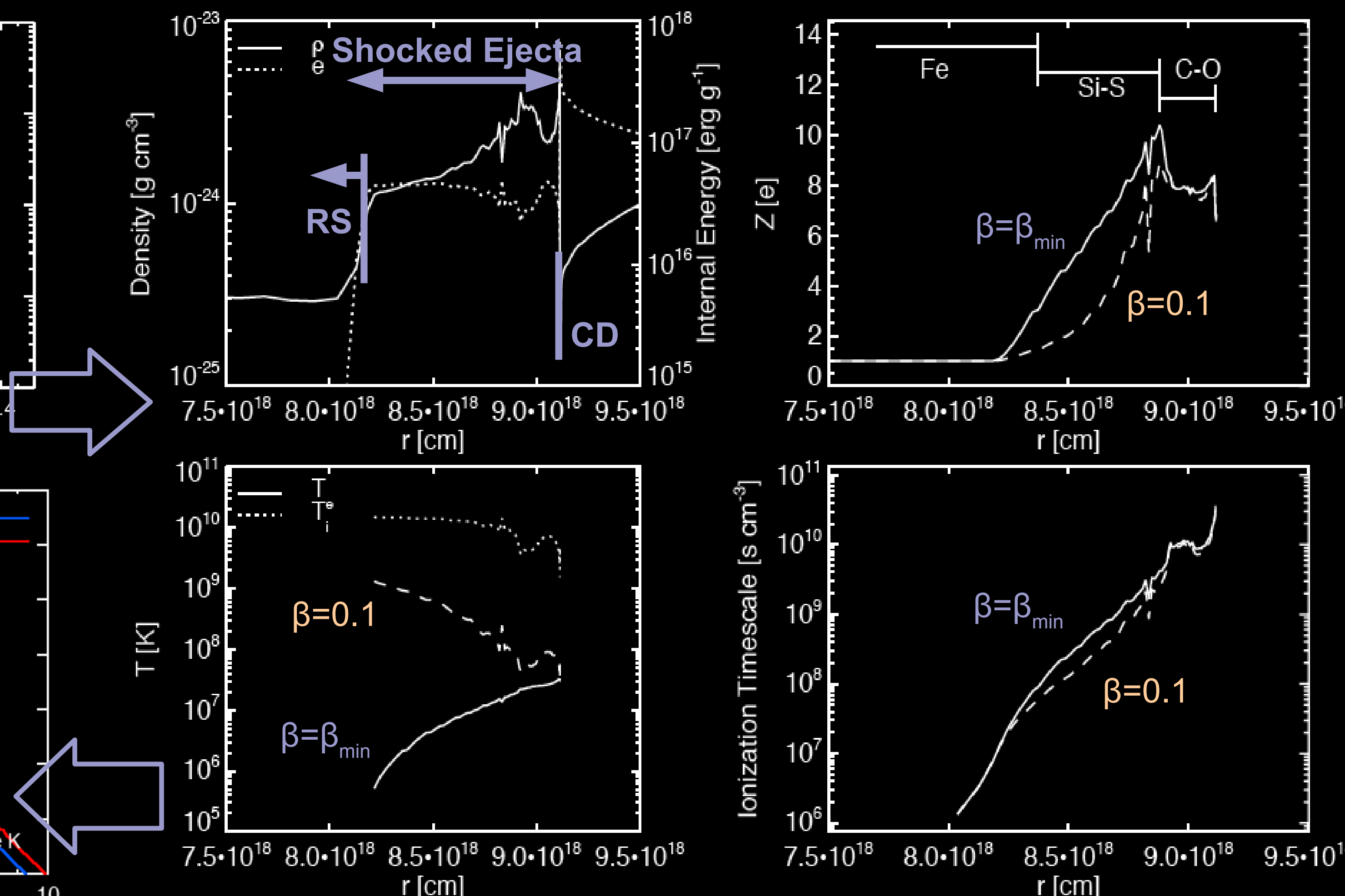
- **1D simulations, uniform AM**. Radiative + ionization losses included.
- **Parameters:** AM density, $\rho_{AM}=10^{-24}$ g.cm^{-3}; SNR age, t_{SNR}=430 yr; amount of collisionless e^- heating at the RS, $\beta[\equiv\varepsilon_{e,s}/\varepsilon_{i,s}]=\beta_{min}...0.1$.

SN model (DDTe)



X-ray Spectrum





Light Echoes in the LMC

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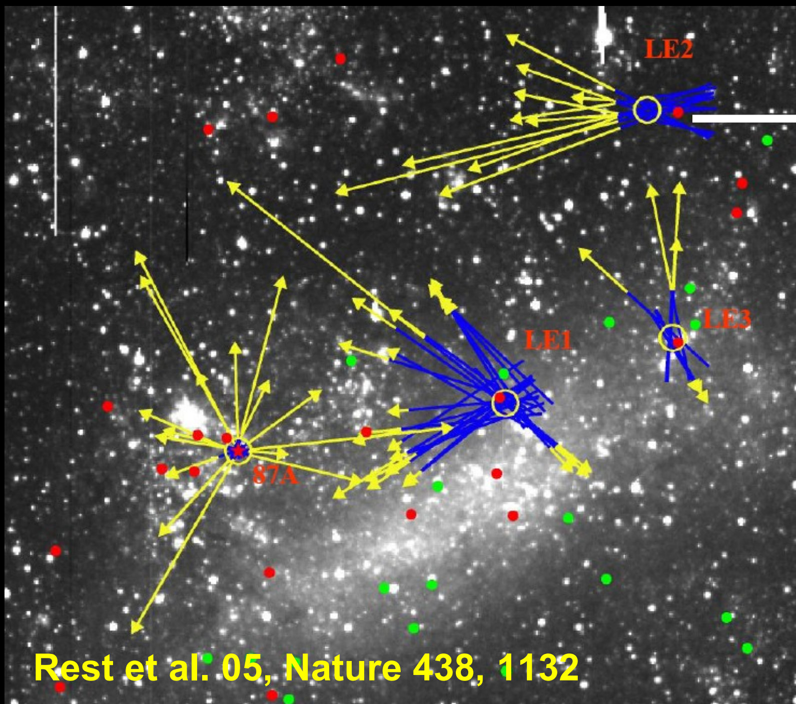

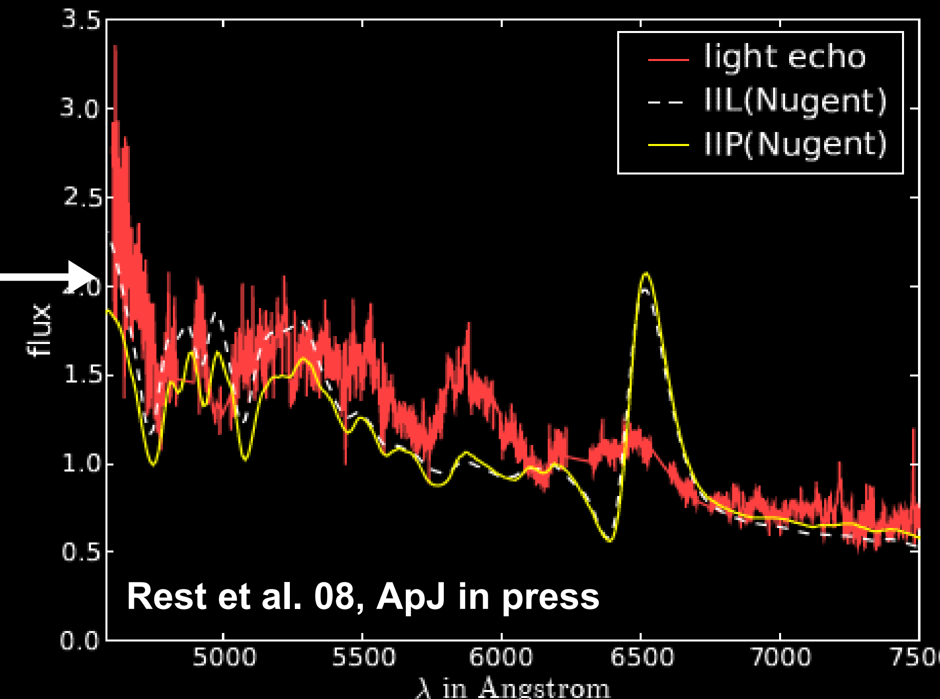

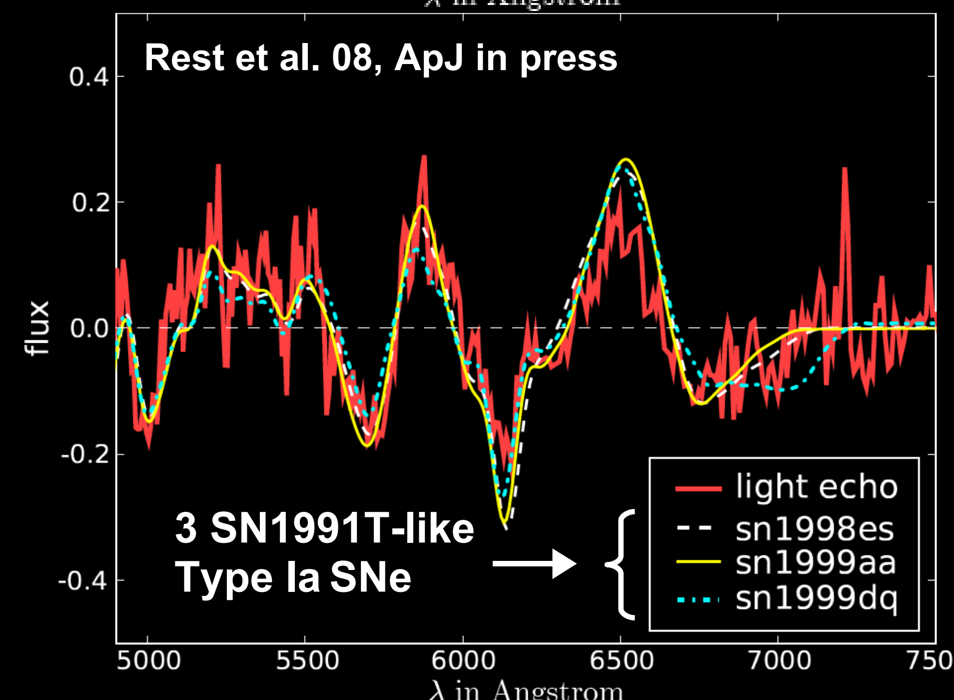

- SuperMACHO team found **Light echoes associated with three young Type Ia SNRs** in the LMC $\Rightarrow$ age estimates.
- **Spectroscopy of LE2** (SNR 0509-67.5):
  - Definitely **NOT a Type II SN**.
  - SNID yields very good matches for **bright, SN1991T-like Type Ias** $\Rightarrow$ lots of ^{56}Ni, less IMEs.

SNR 0509-67.5: Spectrum and Dynamics

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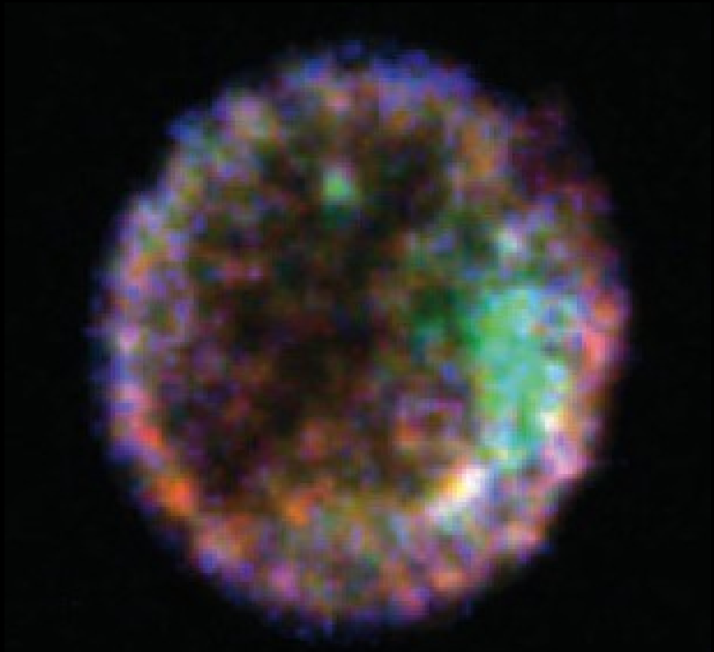
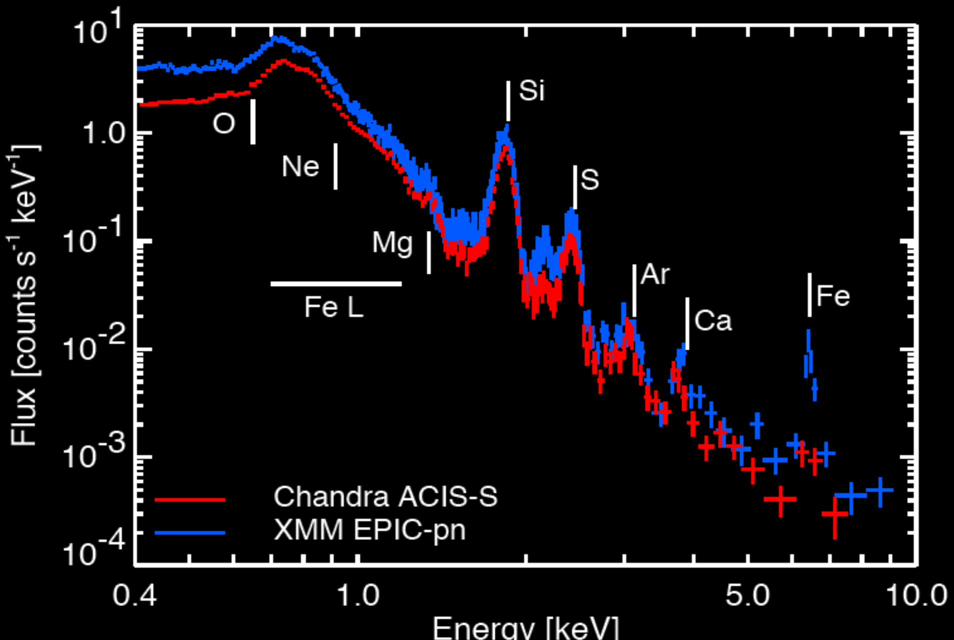
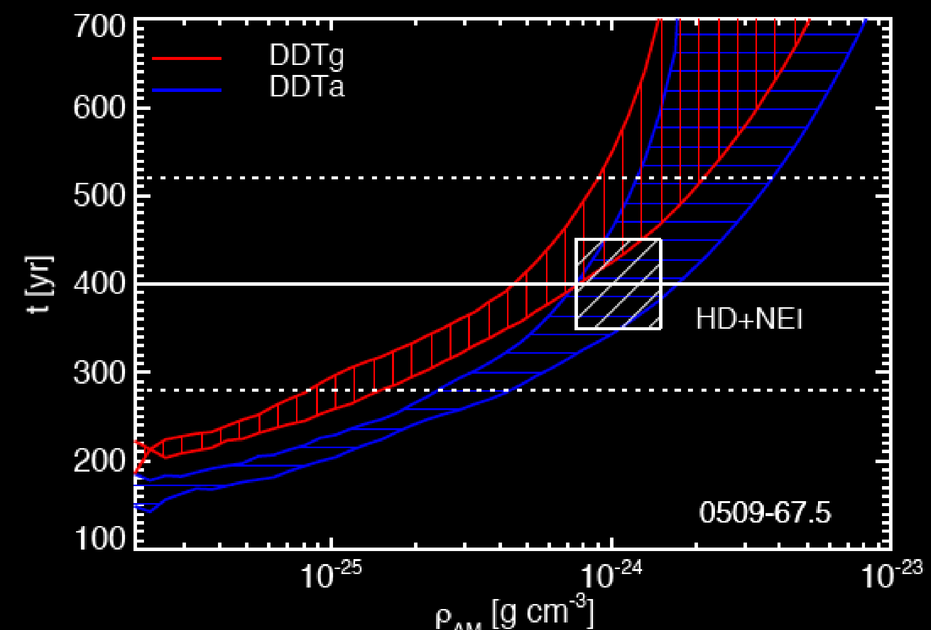


Warren & Hughes 04, ApJ 608, 261

- **0509-67.5** was known to be a **young Type Ia SNR** ⇔ Fe-rich, O-poor spectrum [Hughes et al. 95, ApJ 444 L81, Warren & Hughes 04, ApJ 608, 261].

- Known distance to the LMC (50 kpc) + angular radius (15.1'') + age estimate from the LE (400±120 yr) ⇒ **STRONG CONSTRAINTS ON THE SNR DYNAMICS**.





Badenes et al. 08, ApJ in press

SNR 0509-67.5: Models vs. Data

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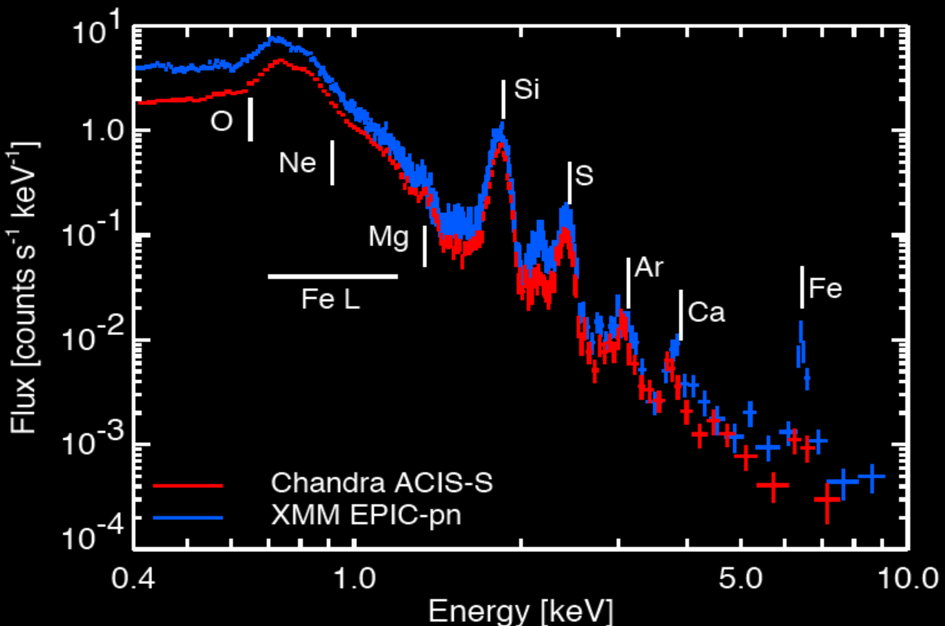
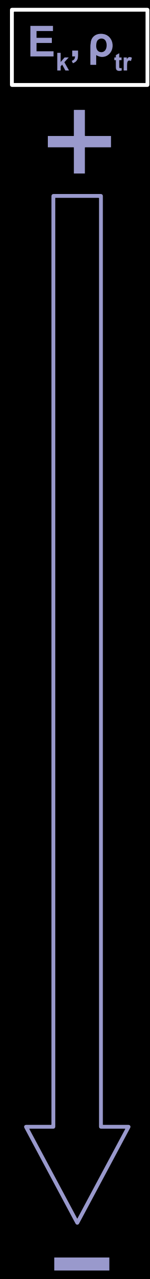
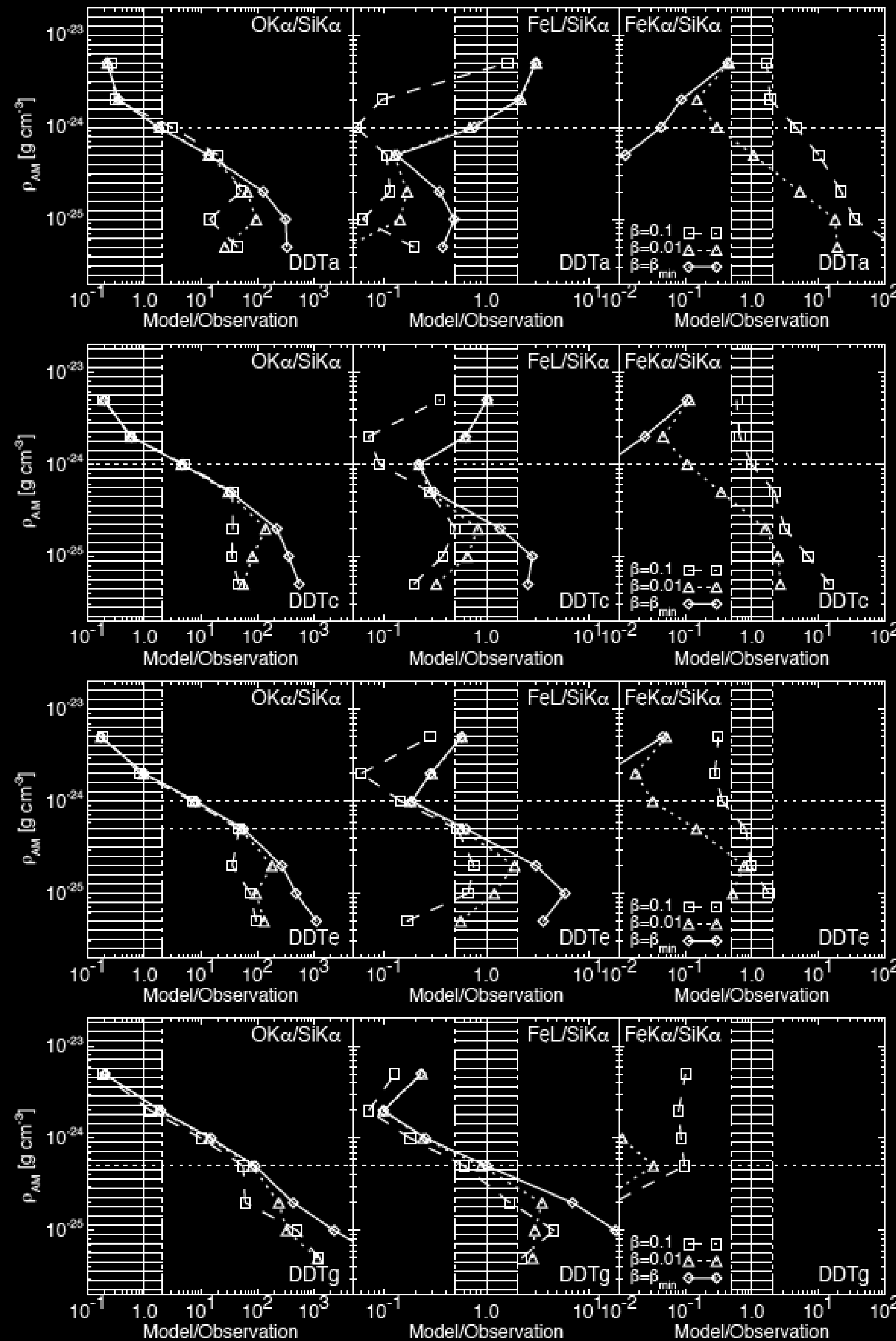
- Comparing models and data is NOT trivial.
- It is **CRUCIAL to select parameters that can be determined reliably in BOTH models and observations**.
- Fundamental flux ratios:

O Kα/Si Kα
Fe L/Si Kα
Fe Kα/Si Kα







SNR 0509-67.5: Born Under a Bright Star

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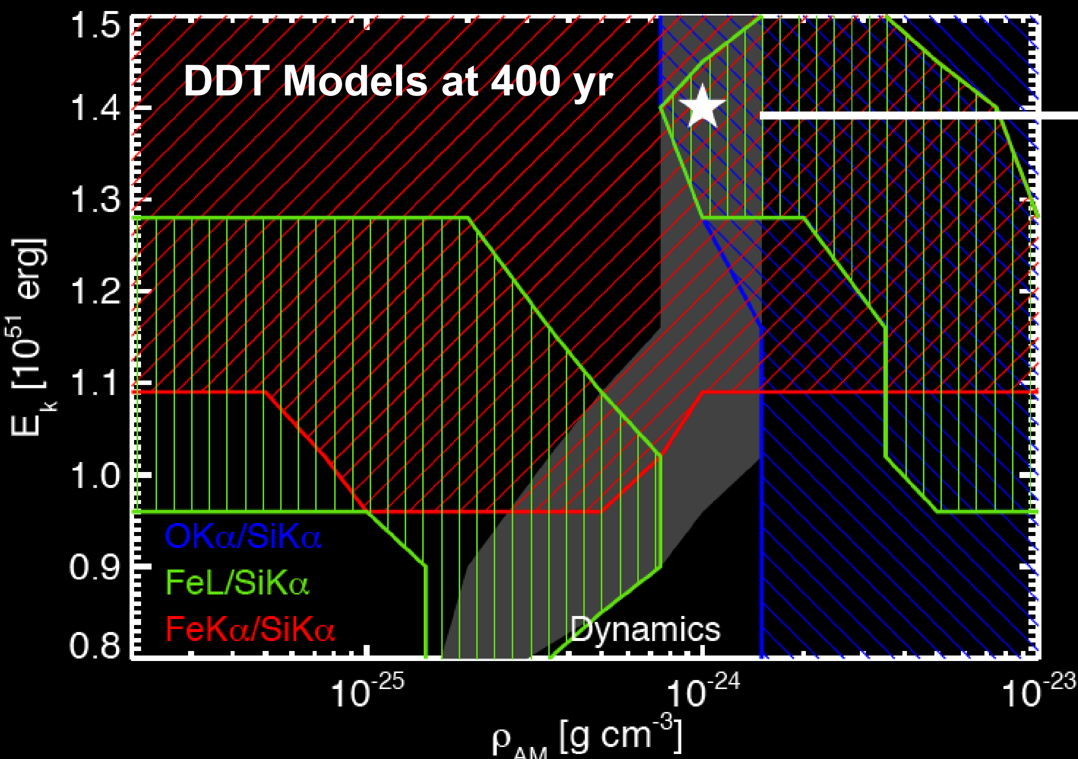
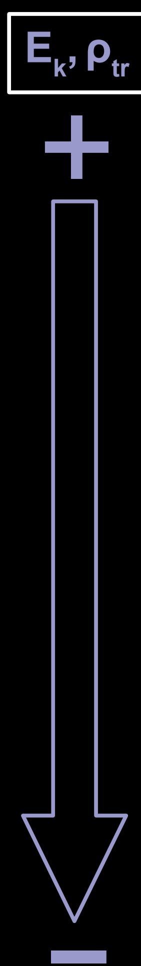
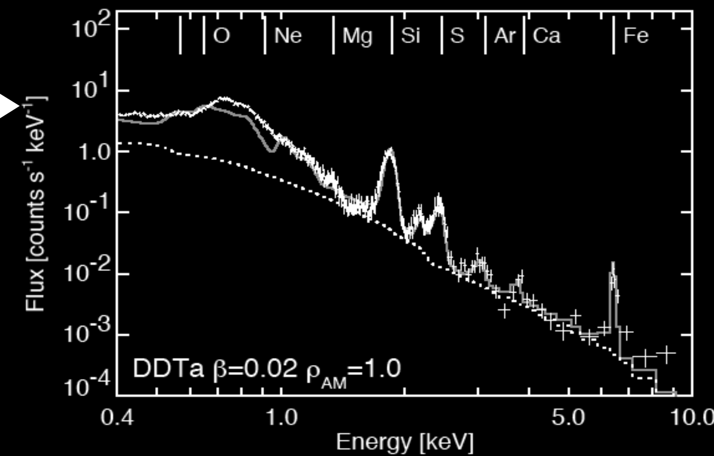
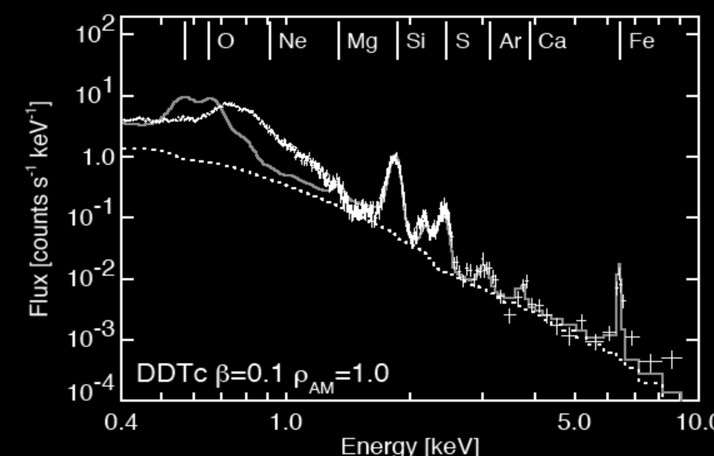


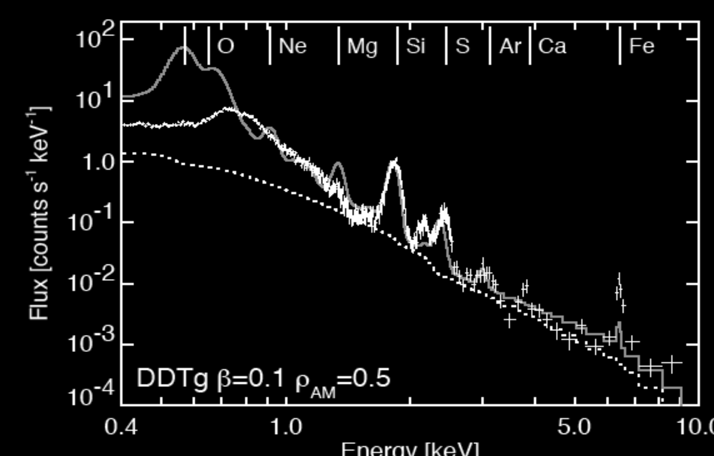
DDTa

$\rho_{AM}=10^{-24}$
$\beta=0.02$









- At t=400 yr, only a **highly energetic DDT model** can reproduce both the X-ray emission (**O Kα**, **Fe L**, **Fe Kα**) and SNR dynamics ⇒ **DDTa: $E_k=1.4\times10^{51}$ erg; $M_{56Ni}=0.97\ M_\odot$**.
- Other explosion models (SCH, DEF) can't reproduce the X-ray spectrum. Models at higher or lower ages don't work well.

SNR 0509-67.5 as a 'Rosetta Stone'

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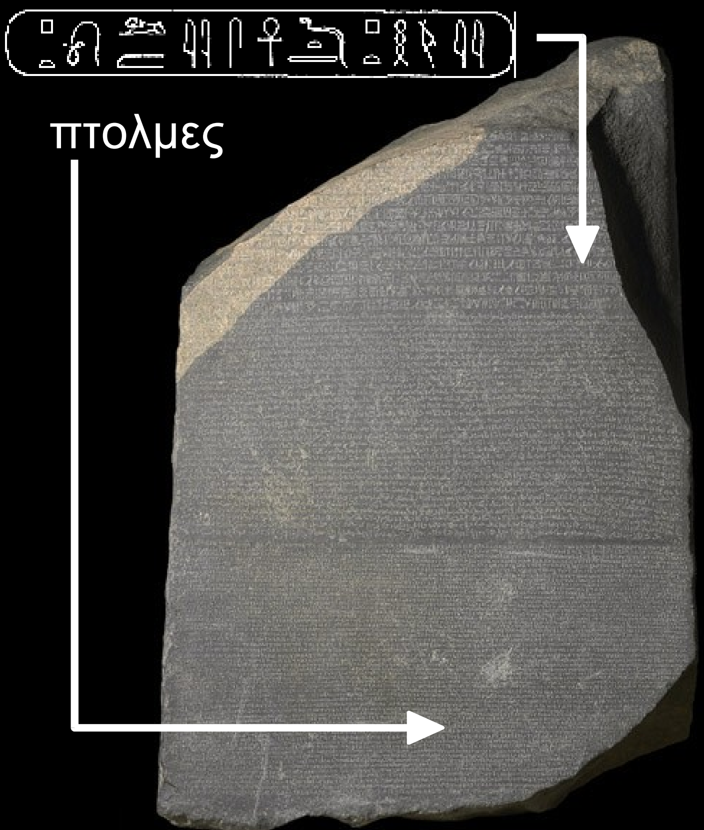
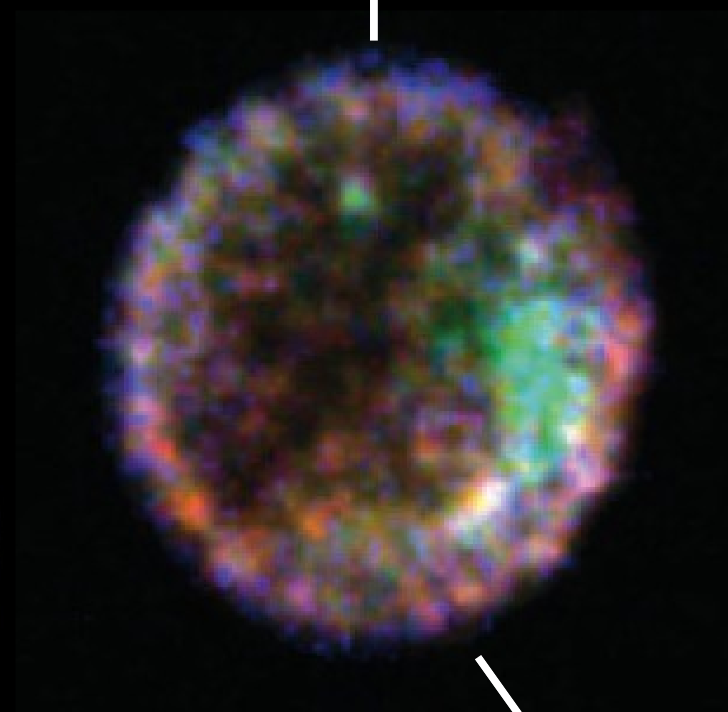
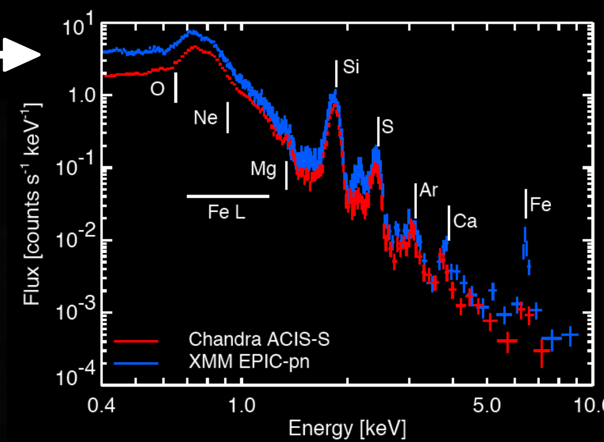
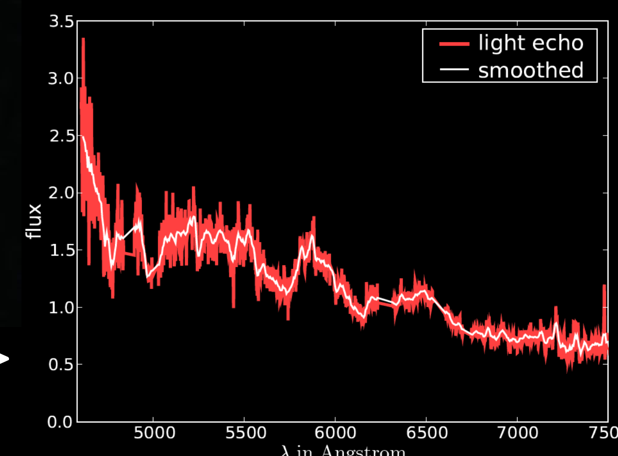


The Rosetta Stone
(British Museum)



SNR 0509-67.5
(Large Magellanic Cloud)





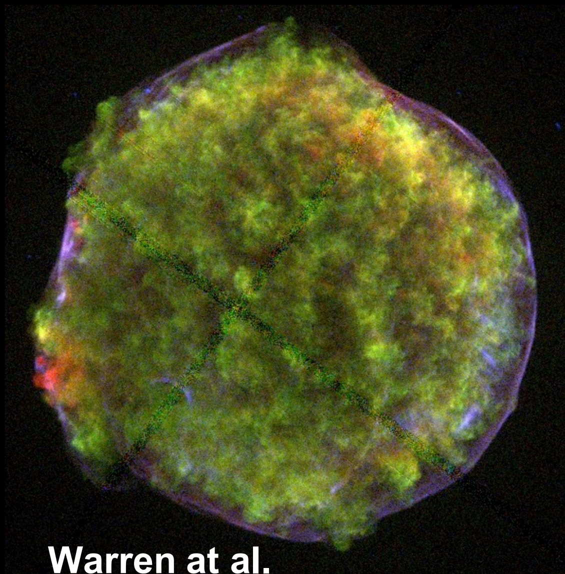
- **SNR 0509-67.5** is the only object (so far) where we can study **both** the **light of a Type Ia SN** and the **X-ray spectrum of its SNR**.

BOTH AGREE ⇒ energetic (SN1991T-like) explosion with a high ^{56}Ni yield

[Rest et al. 08, ApJ in press; Badenes et al. 08, ApJ in press]

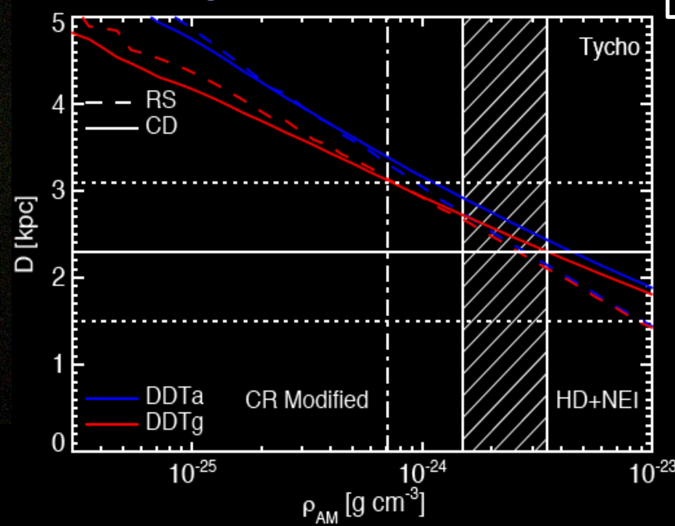
Tycho: Born Under a Not-so-Bright Star

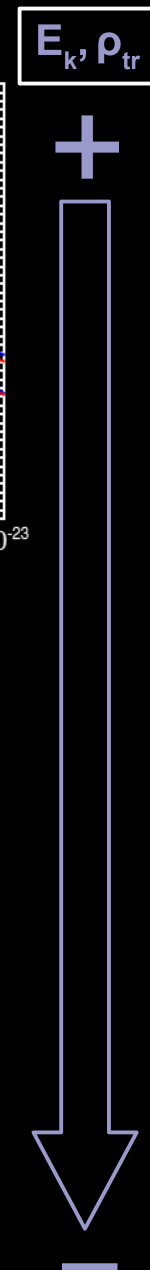
Carles Badenes
Wunch 01/30/08

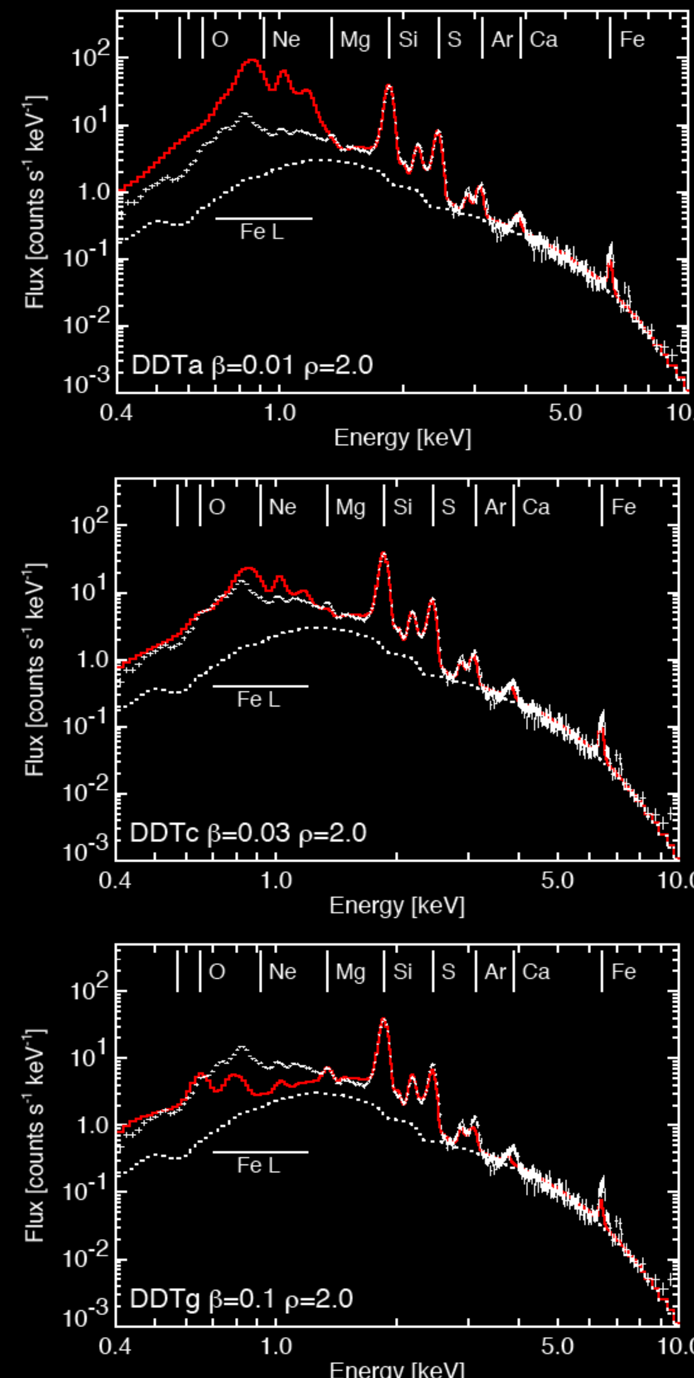


Warren at al.
05 ApJ 634, 376

SNR Dynamics:



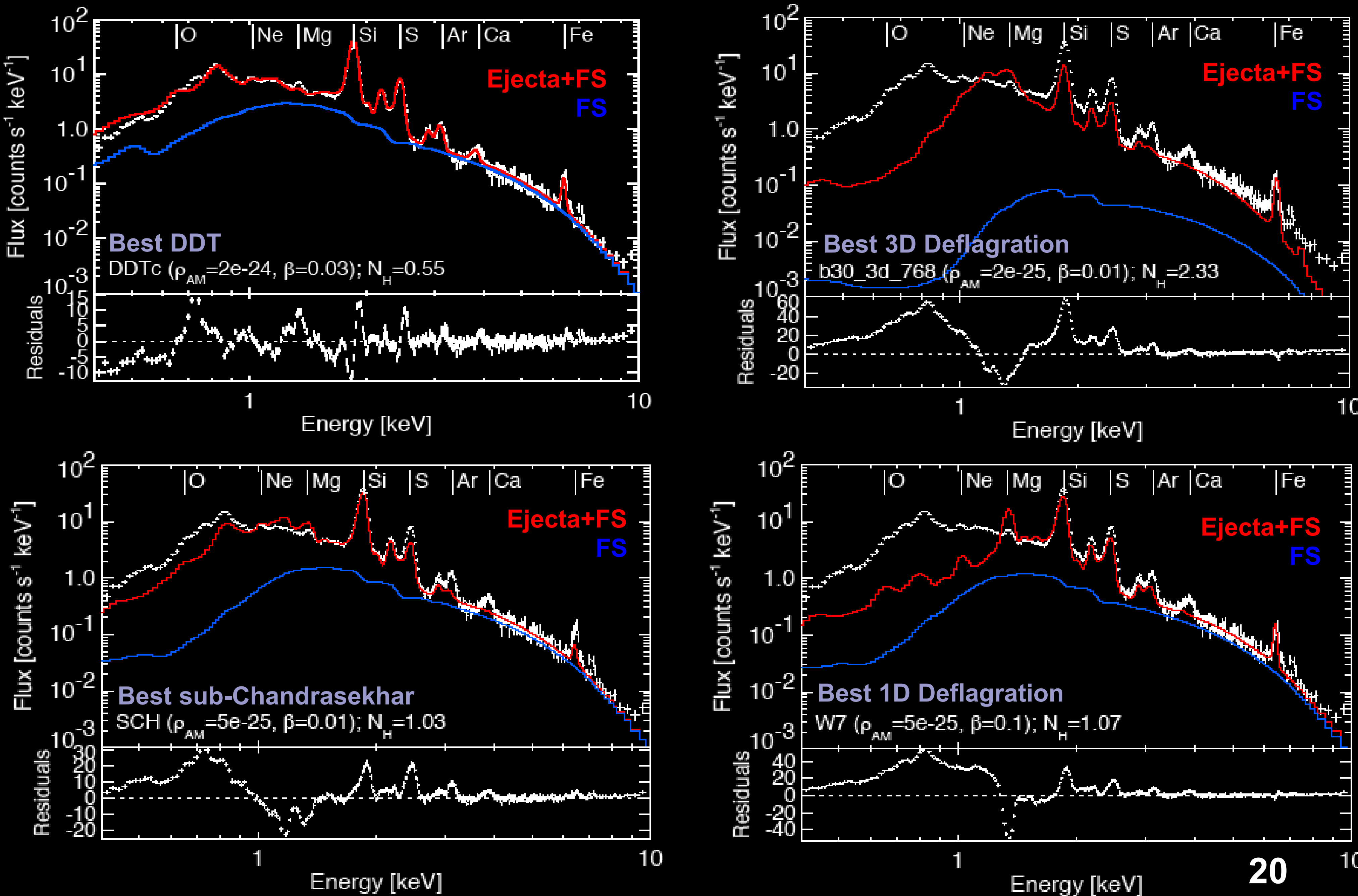




- The same models can be applied to **other Type Ia SNRs**: Tycho, Kepler, SN1006 ...
- **Tycho** [Badenes et al. 06, ApJ 645, 1373]:
  - Only **DDT models** can reproduce BOTH the X-ray spectrum and the SNR dynamics.
  - Mildly energetic explosion ⇒ Model **DDTc: E_k=1.2x10^{51} erg; M_{56Ni}=0.74 $M_{\odot}$**.

What about other models?

Carles Badenes
Wunch 01/30/08



Summary of SNRs and Explosion Physics

- ***Chandra*** **and** ***XMM-Newton*** **observations of young SNRs open a new window onto the physics of Type Ia SN explosions**. Constraints on the ejecta structure are completely independent from SN light curves and spectra.
- **X-ray spectra and SNR dynamics MUST form a consistent picture**.
- **0509-67.5**: Unique object where both techniques can be compared (thanks to SuperMACHO!) ⇒ very good agreement **DDTa: E_k=1.4x10^{51} erg; M_{56Ni}=0.97 $M_\odot$**.
- **Tycho**: **DDTc: E_k=1.2x10^{51} erg; M_{56Ni}=0.74 $M_\odot$**.
- These results agree with the SN spectra ⇒ **Type Ia sequence is well reproduced by 1D DDT models (ρ_{tr})**.

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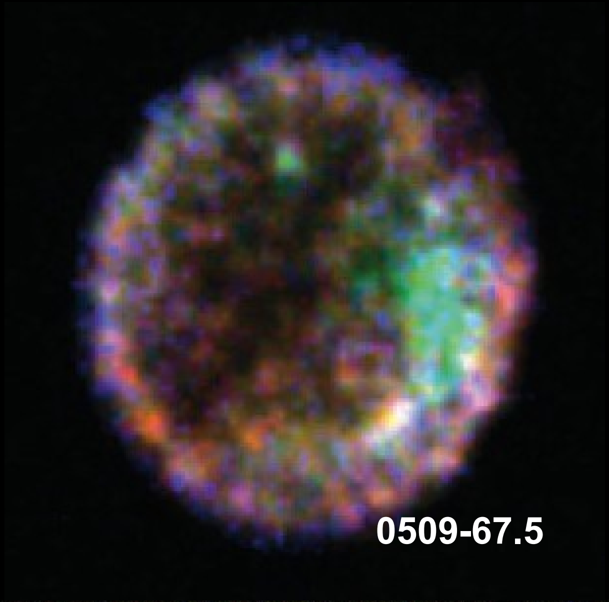
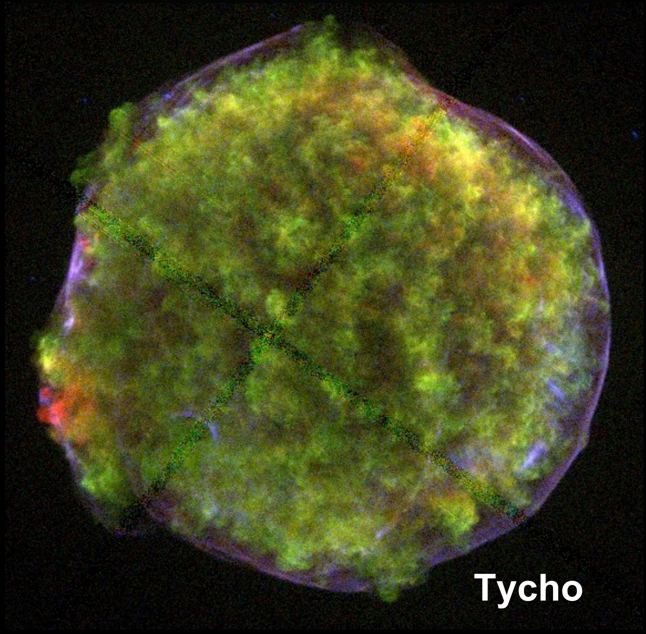


0509-67.5



Tycho

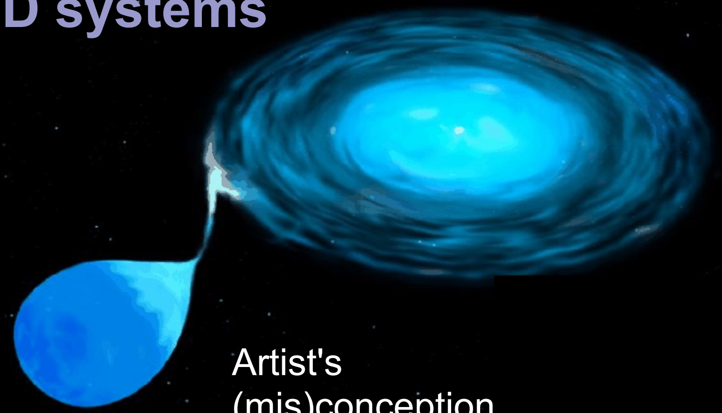
Badenes et al. 06, ApJ 645, 1373
Badenes et al. 08, ApJ in press

Theoretical Scenarios for Progenitors

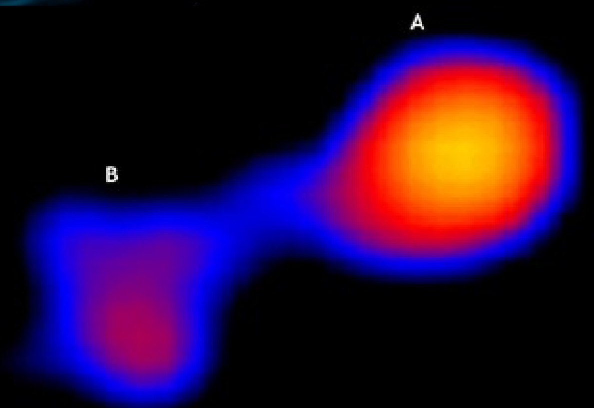
Depending on the nature of the **WD companion:**

- A normal star: **Single Degenerate** (SD) systems. Many known examples of WD binaries [Parthasarathy et al. 07, NewAR 51, 524]. WD explodes close to Chandrasekhar limit (**SD-Ch**) or some time before attaining it (**SD-SubCh**).
- Another WD: **Double Degenerate** (DD) systems. Surprising lack of known examples [Napiwotzki et al 05, C.P.]. Explosion is uncertain [Guerrero et al. 04, A&A 413, 257] BUT Super-CH Type Ia [Howell et al. 06, Nat 443, 308; Hicken et al. 07, ApJ 669, L17].

SD systems

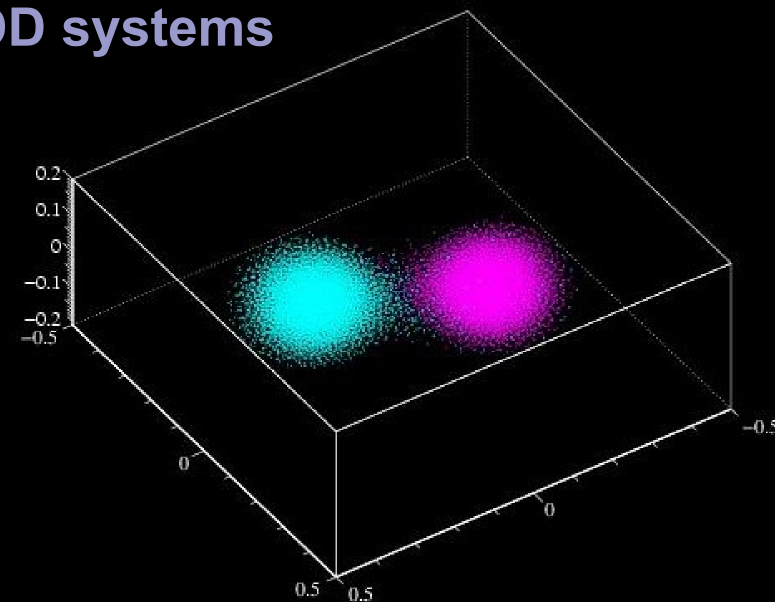


Artist's (mis)conception



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

Open issues in SD Type Ia Progenitors

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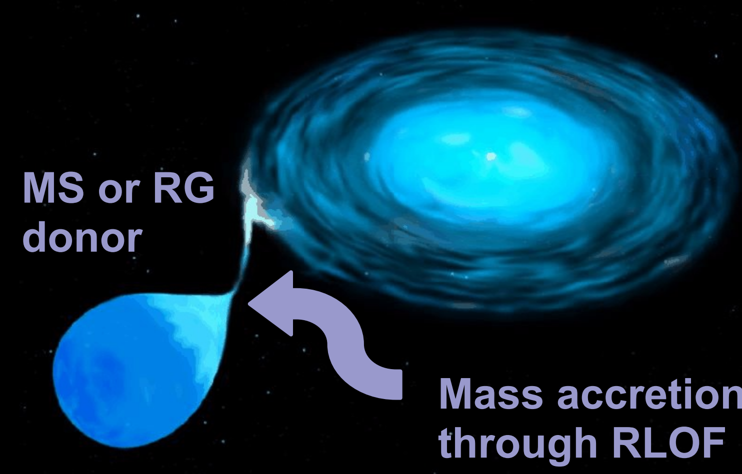
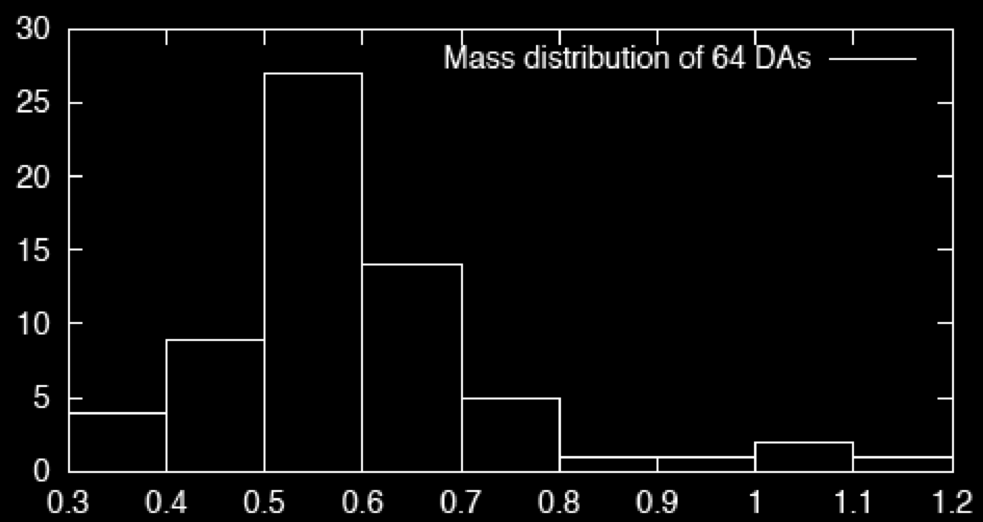
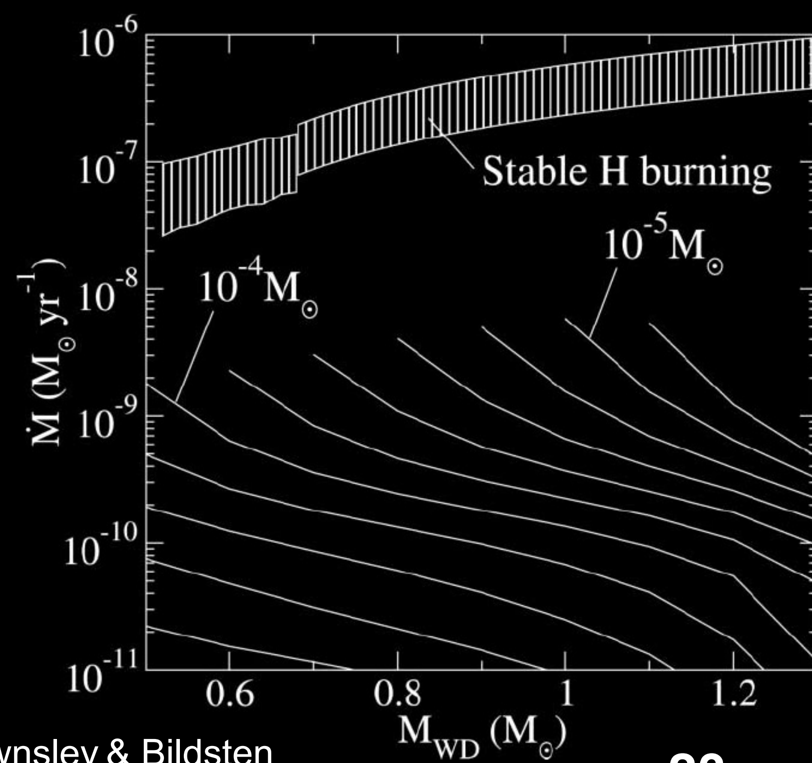
- **The viability of SD systems as Type Ia progenitors has not been proved!**
  - $M_{WD} \sim 0.6\ M_\odot$ and always $< 1.2\ M_\odot \Rightarrow$ Need to accrete at least $0.2\ M_\odot$ to reach $1.38\ M_\odot$.
  - H-rich matter from the companion must burn to C and O **QUIETLY** $\Rightarrow$ dM/dt has to be fine-tuned.





Homeier et al. 98, A&A 338, 563



Townsley & Bildsten 05 ApJ 628, 395

SD Type Ia Progenitors: Accretion Winds

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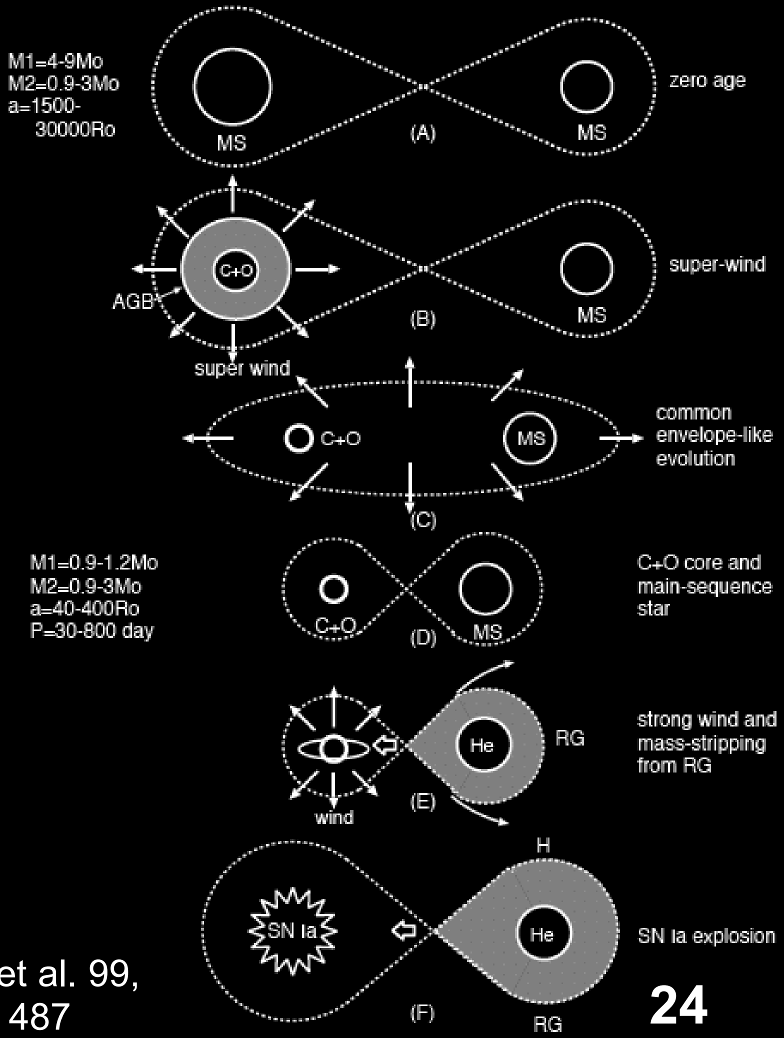
Accretion Winds
(Hachisu et al. 96, ApJ 470, L97)
The luminosity from the WD surface drives a fast, optically thick outflow that gets rid of the excess material.

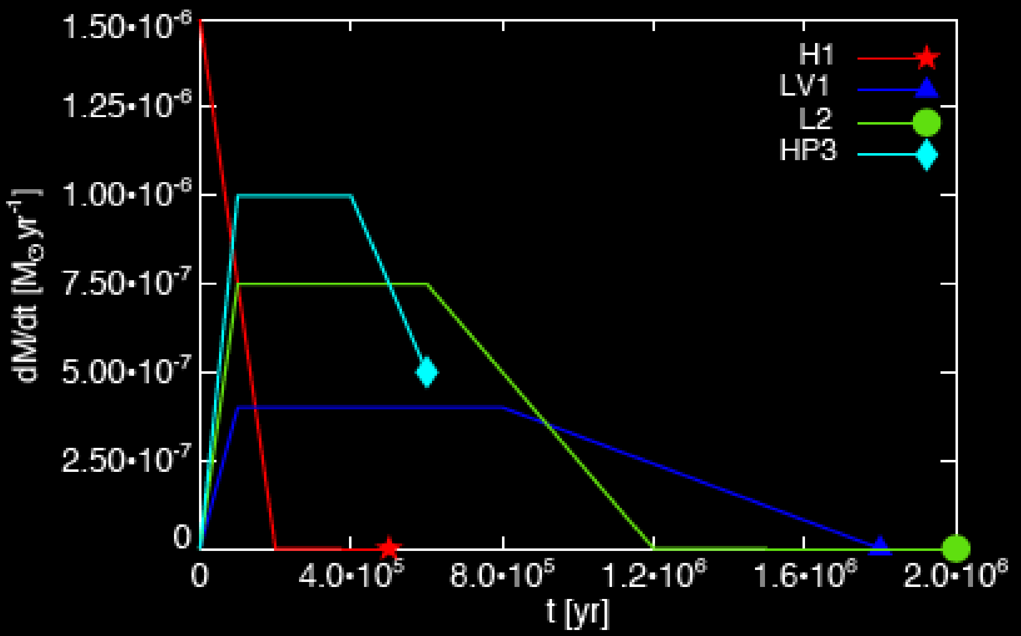
- **Essential** for the evolution of Type Ia progenitors in the SD channel (only way to avoid a common envelope phase).
- The details of the binary evolution can be quite complex.
- RXJ0513.9-6951 and V Sge are systems with active accretion winds [Hachisu & Kato 03, ApJ 590, 445; ApJ 598, 527].
- Some authors claim that a H-accreting WD **cannot** grow to 1.38 $M_{\odot}$ [Cassisi et al. 98, ApJ 496, 376].

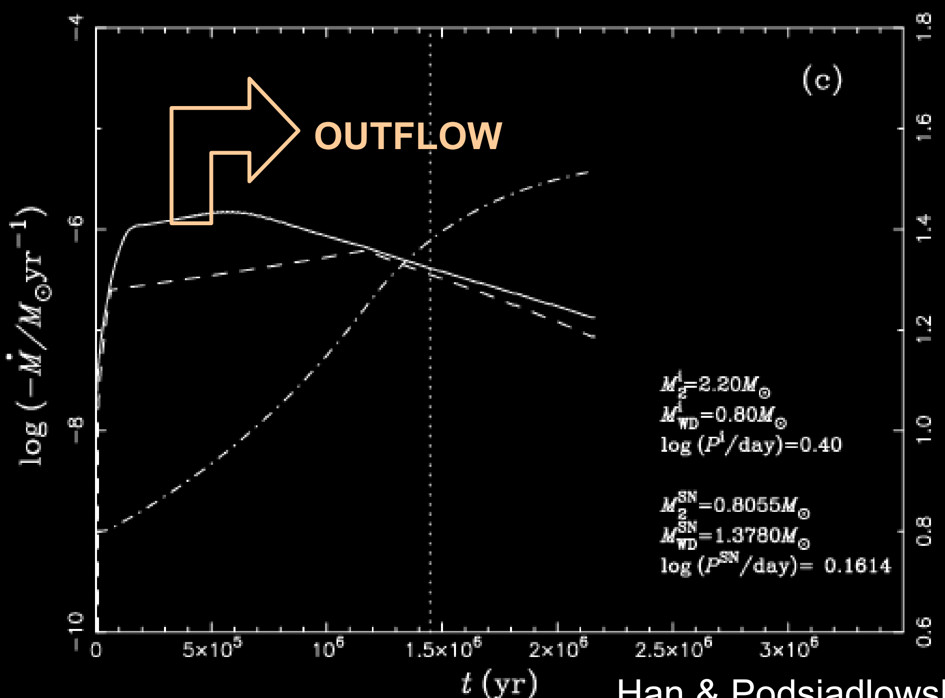


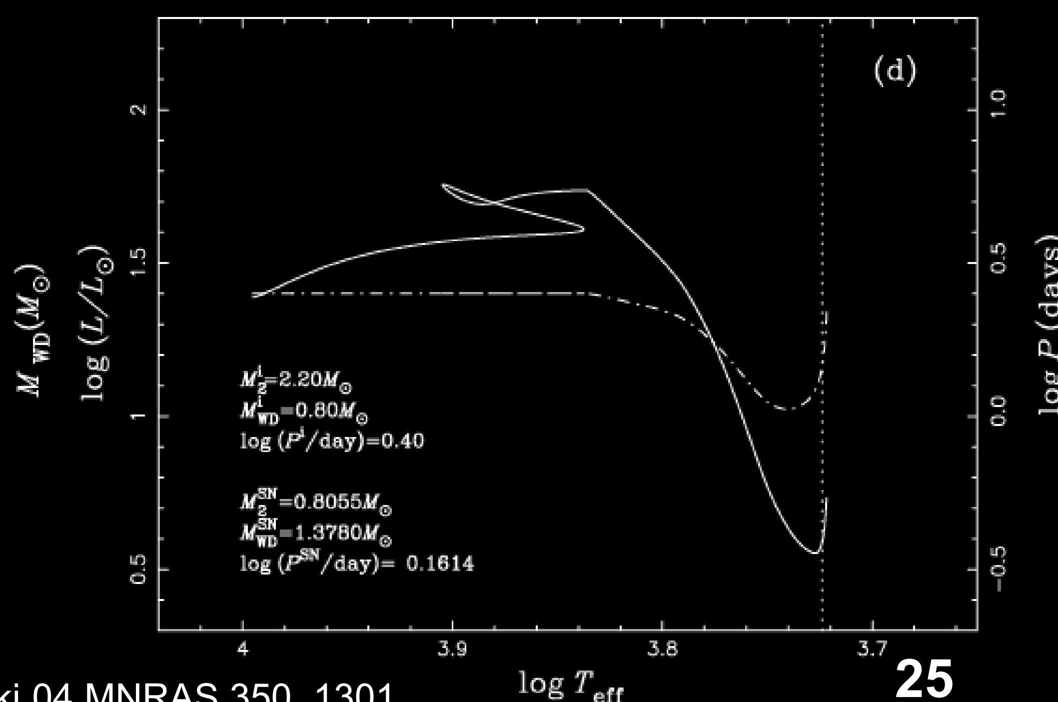
Hachisu et al. 99, ApJ 522, 487

SD Type Ia Progenitors: Accretion Winds

- All **evolutionary studies** of SD Type Ia progenitors include accretion wind outflows [Langer et al. 00, A&A 362, 1046; Han & Podsiadlowski 04, MNRAS 350, 1301, etc.].
- **Typical outflow scales:**
  - $dM/dt_{of} \sim 10^{-7}$ to $10^{-6}\ M_{\odot} yr^{-1}$.
  - $t_{of} \sim 10^{6}$ yr.
  - $u_{of} \sim 10^{3}$ km s^{-1}.
- **How does this shape the CSM?**







Han & Podsiadlowski 04 MNRAS 350, 1301

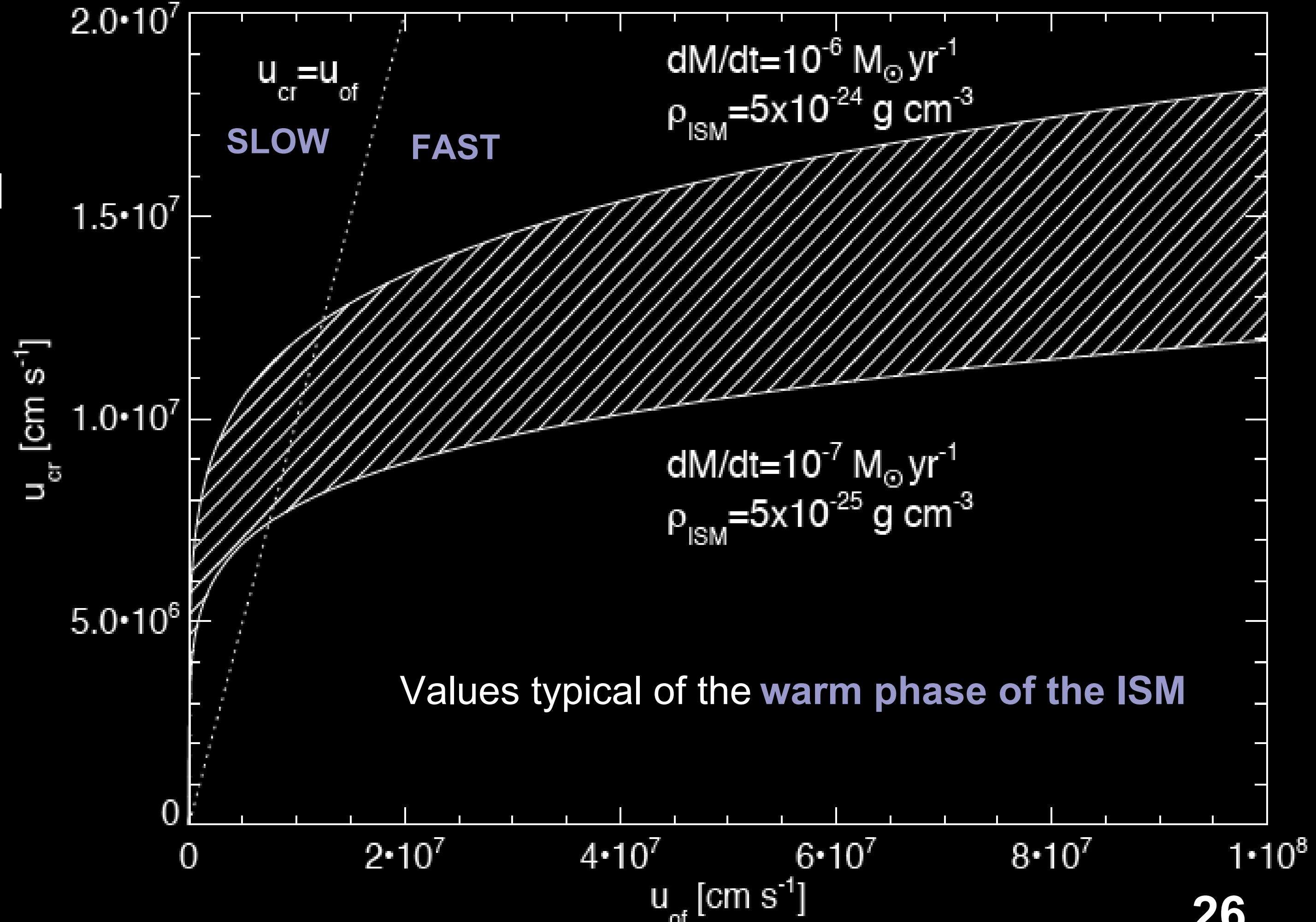
Sculpting the CSM

• Outflows into the ISM: theory of stellar winds [Koo & McKee 92, ApJ 388, 93] $\Rightarrow$ **critical outflow velocity u_{cr}**.

$$u_{cr} = 10^4 \left[\frac{\dot{M}_{of} u_{of}^2}{2} \frac{\rho_{ISM}}{\mu_H} \right]^{1/11}$$

$u_{of} > u_{cr} \Rightarrow$ fast
Radiative losses do not affect the shocked outflow. Cavity is energy-driven.

$u_{of} < u_{cr} \Rightarrow$ slow
Radiative losses affect the shocked outflow. Cavity is momentum-driven.



Shaping the CSM

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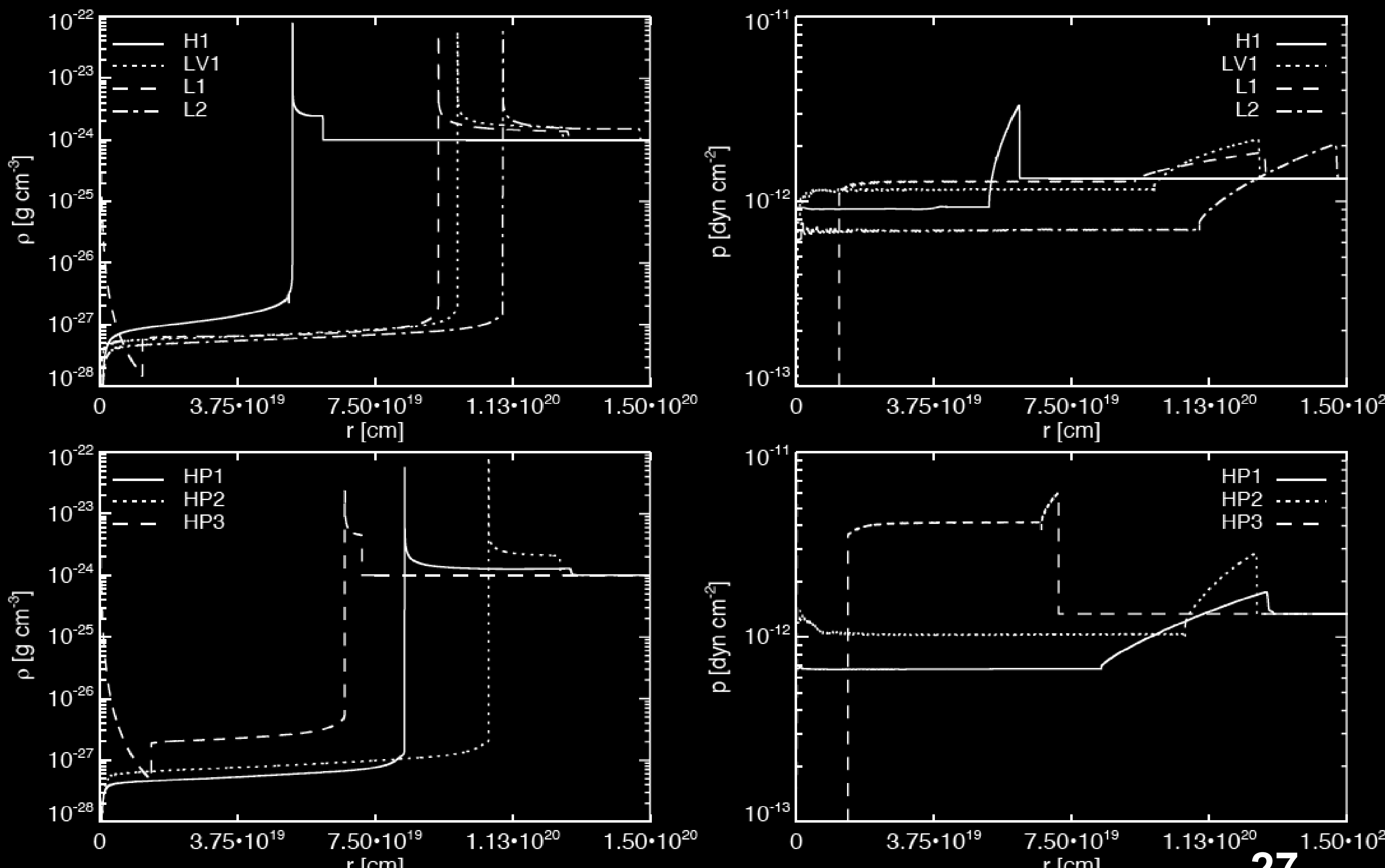
Wunch 01/30/08

- Fast, continuous accretion wind outflows expanding into the warm phase of the ISM excavate **large (~10^{20} cm) energy-driven cavities** (interstellar bubbles).
- Reasonable **variations of ρ_{ISM} and p_{ISM}** do not affect the cavities.

CSM configuration at the time of the SN explosion:

Note that most bubbles are pressure-confined!



SNRs in the CSM: Radii and Velocities

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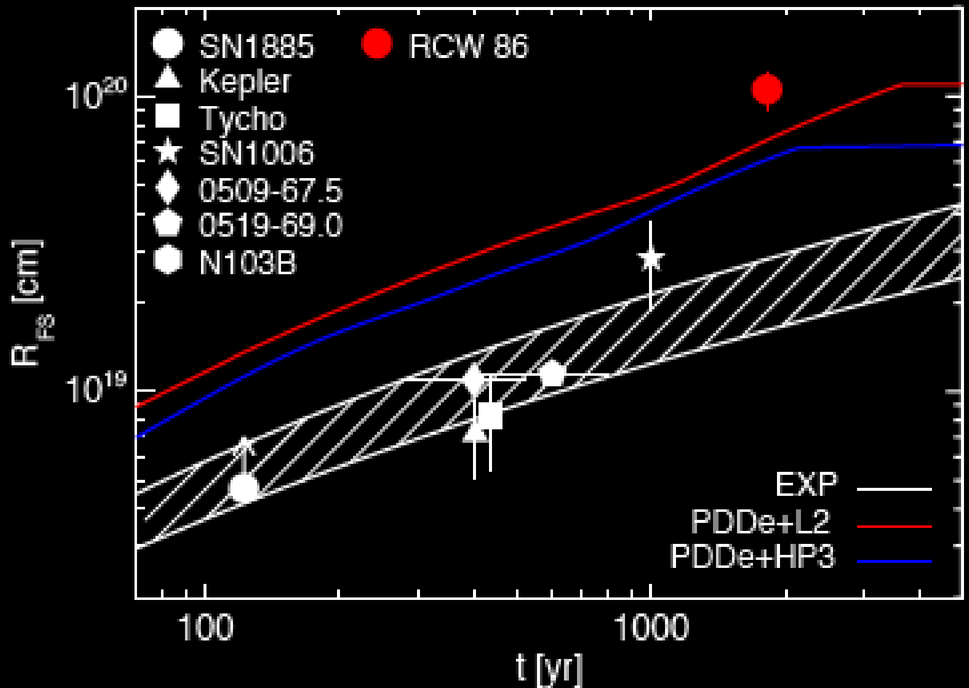
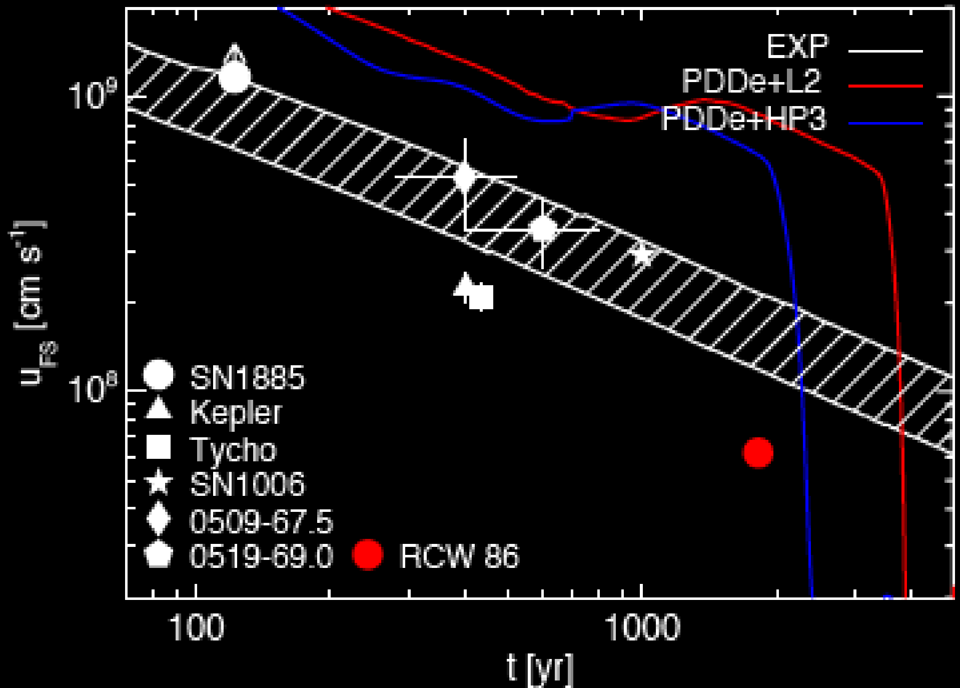
- The dynamics (FS radii and velocities) of SNR models expanding into accretion wind cavities are very different from the canonical uniform ISM interaction.
- **Models**: EXP+ISM (E_k=0.8 .. 1.4 foe; $\rho_{ISM}=5\times10^{-25}$ .. 5×10^{-24} g cm^{-3}); SNRs in accretion wind cavities (PDDe+L2, PDDe+HP3).
- **Data**: SNRs with reliable age estimates: historical (SN1885, Kepler, Tycho, SN1006), light echoes (0509-67.5, 0519-69.0, N103B) + RCW 86 (IF Type Ia SNR of SN185)



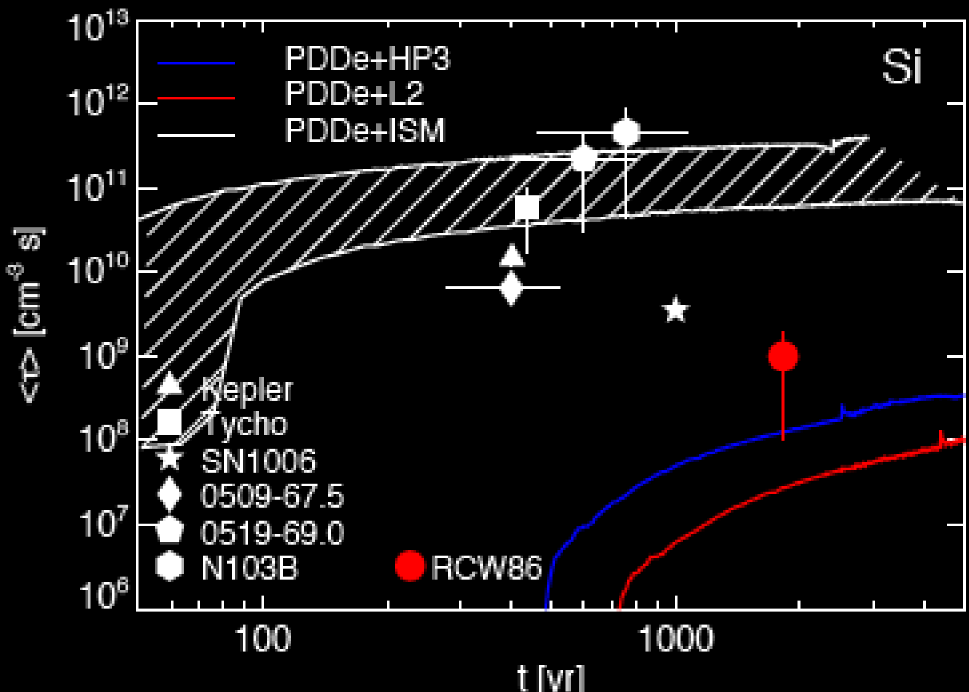


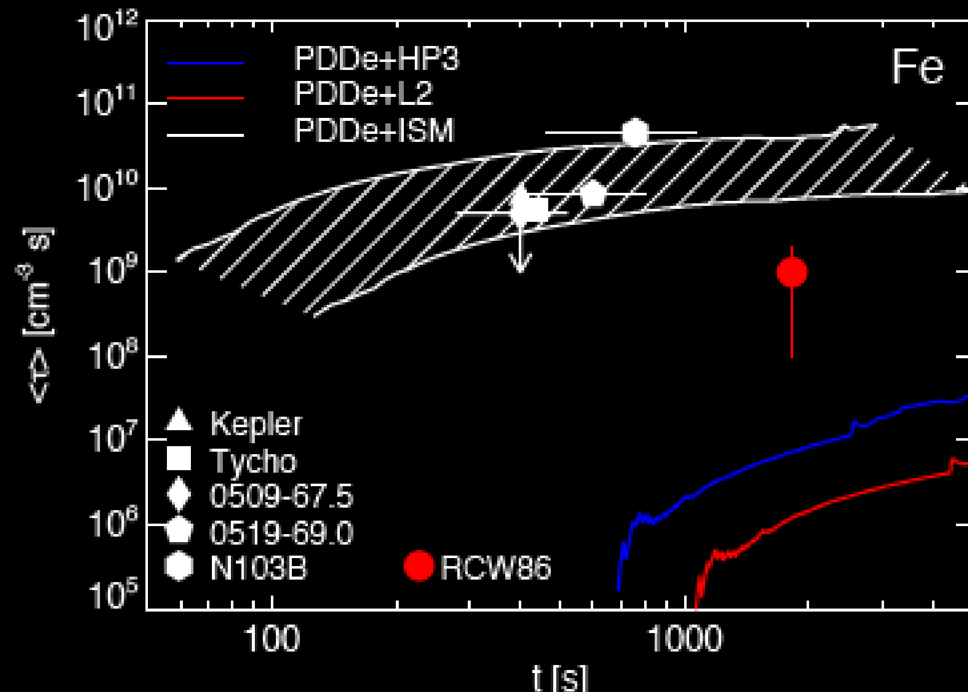
⇒ **Most SNRs are compatible with a uniform ISM** (not RCW 86)

SNRs in the CSM: Ionization Timescales

Carles Badenes
Wunch 01/30/08

- A similar comparison can be performed using the **ionization timescale of the shocked ejecta**. Models: PDDe+ISM (ρ_{ISM}=5x10^{-25} .. 5x10^{-24} g cm^{-3}); PDDe+L2; PDDe+HP3.
- In SNR models evolving inside large cavities, the SN ejecta expand to very low densities before any significant interaction can take place ⇒ low values for the ionization timescales of Si and Fe in the shocked ejecta.
- Spectral properties constrain the CSM structure independently of the dynamics.



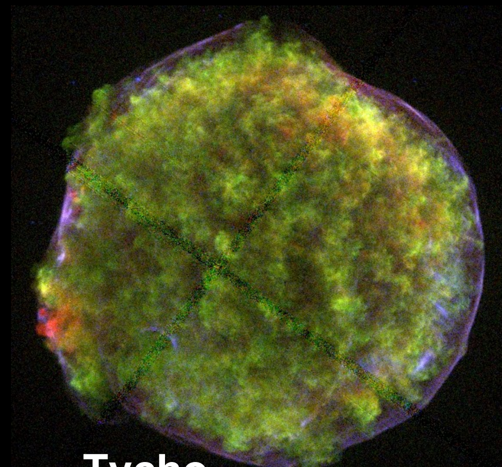


⇒ **Most SNRs are compatible with a uniform ISM**, albeit with a larger spread (issues w/ PDDe). RCW 86 is again closest to the cavity models.

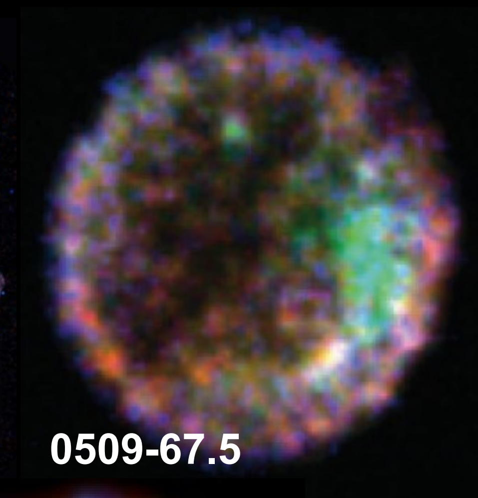
Summary of SNRs and Progenitor Systems

Carles Badenes
Wunch 01/30/08

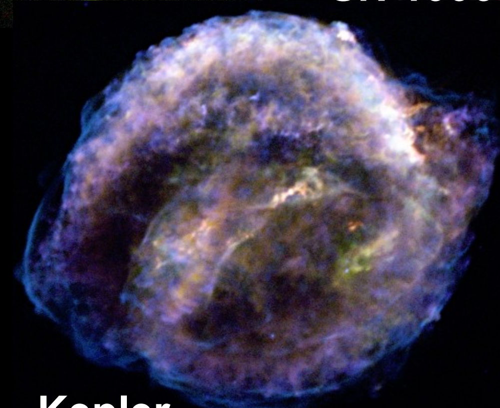
Most Type Ia SNRs show **no evidence for CSM interaction**

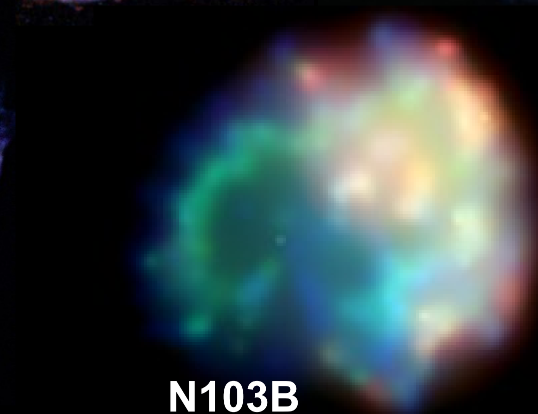

Tycho


SN 1006

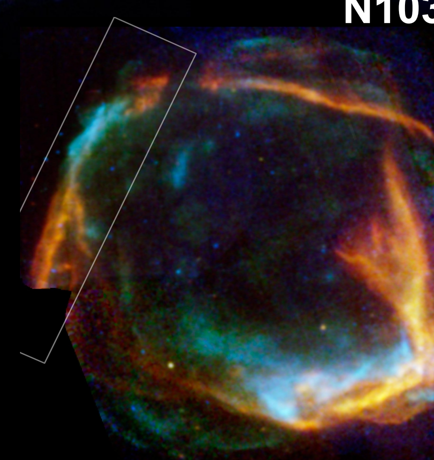

0509-67.5

A few (two!) Type Ia SNRs show **evidence for some kind of CSM interaction** (probably not accretion winds!)


Kepler


N103B

❗ There **might** be a population of Type Ia SNRs interacting with accretion wind bubbles! ⇒ RCW 86 (IF Type Ia SNR of SN 185)


RCW 86

Badenes et al. 07, ApJ 662, 472

Image Credits: Warren et al. 05, ApJ 634, 376; Hughes et al., in prep.; Warren & Hughes 04, ApJ 608, 261; Reynolds et al. 07, ApJ 668, L135; Lewis et al. 03, ApJ 582, 770; Vink et al. 06, ApJ 648, L33

Summary of SNRs and Explosion Physics

Carles Badenes
Wunch 01/30/08

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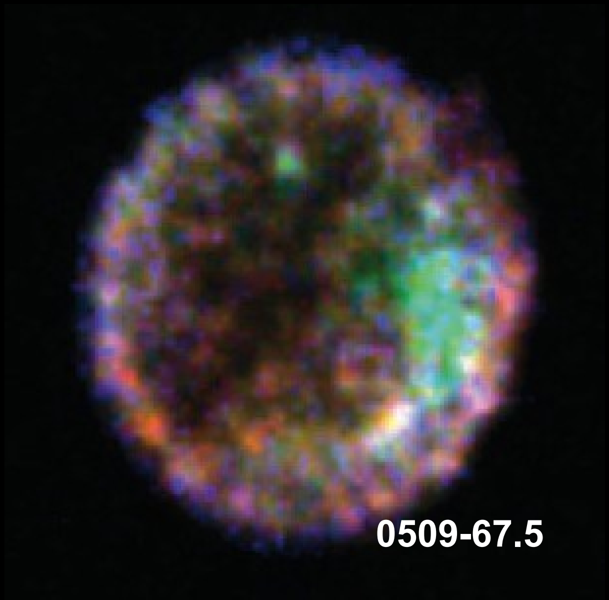
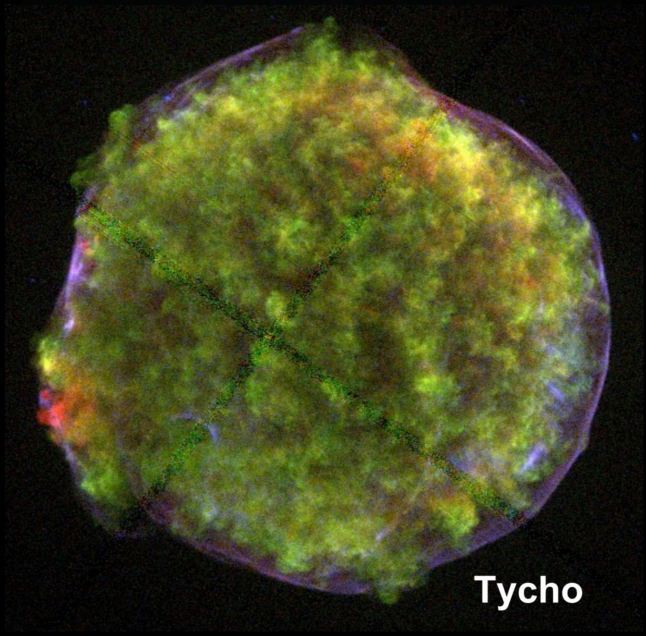
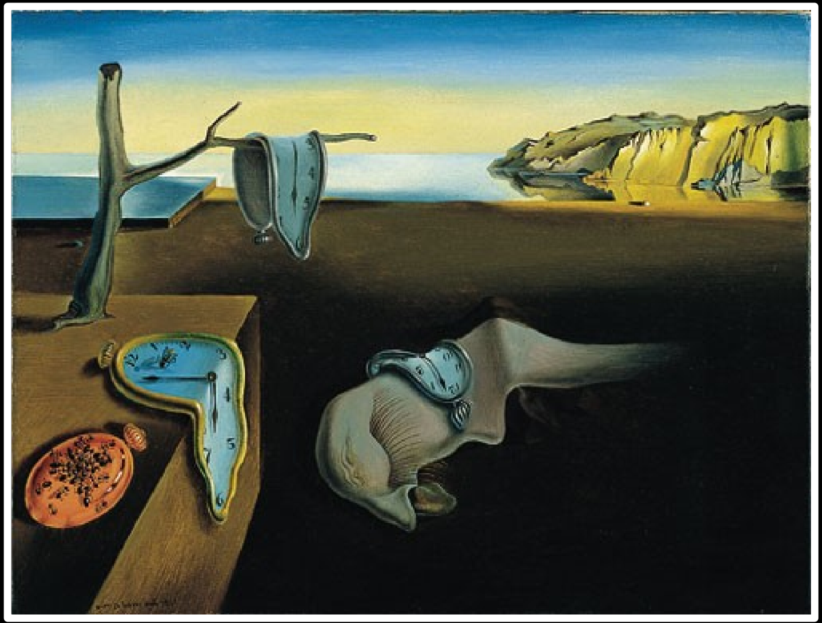
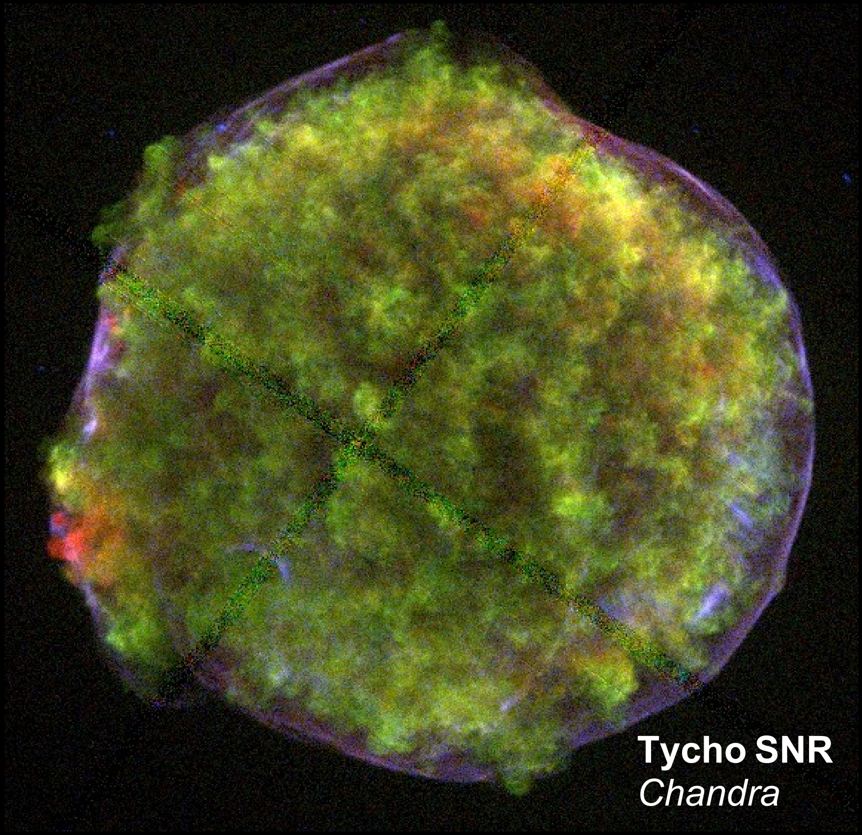




Badenes et al. 06, ApJ 645, 1373
Badenes et al. 07, ApJ in press



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**: Identifying the SNRs from dim/bright SNe allows us to study the immediate environment of putative 'delayed' and 'prompt' progenitors.

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

A Few Words On The Kepler SNR

Carles Badenes
Wunch 01/30/08

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.

• Is it possible to ignite a thermonuclear runaway in the degenerate C+O core of a massive star? ⇒ Type I.5 SN [Iben & Renzini 83 ARA&A 21, 271] (many problems - what about H?)

• More complex multiple-star progenitor?

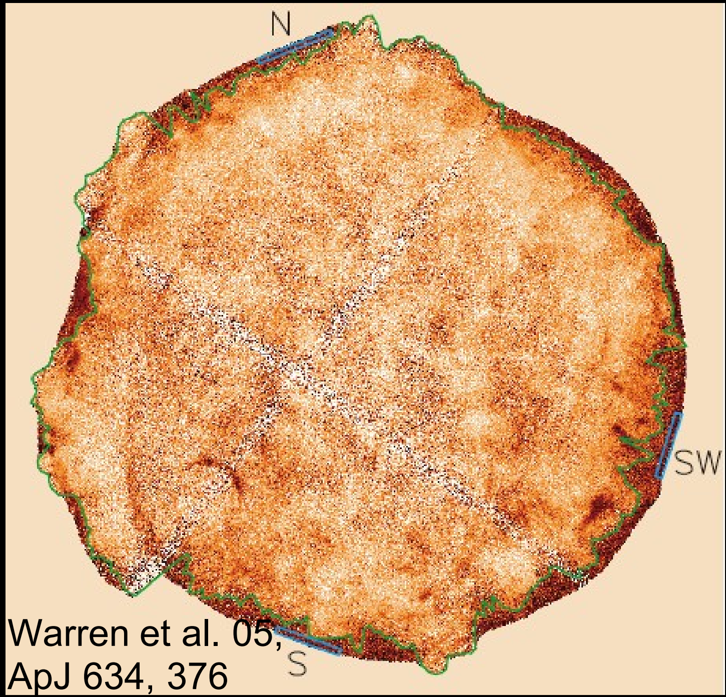
• Is this the nearest example of the 'prompt' channel to Type Ia SNe?

Cosmic Ray Acceleration at SNR Shocks

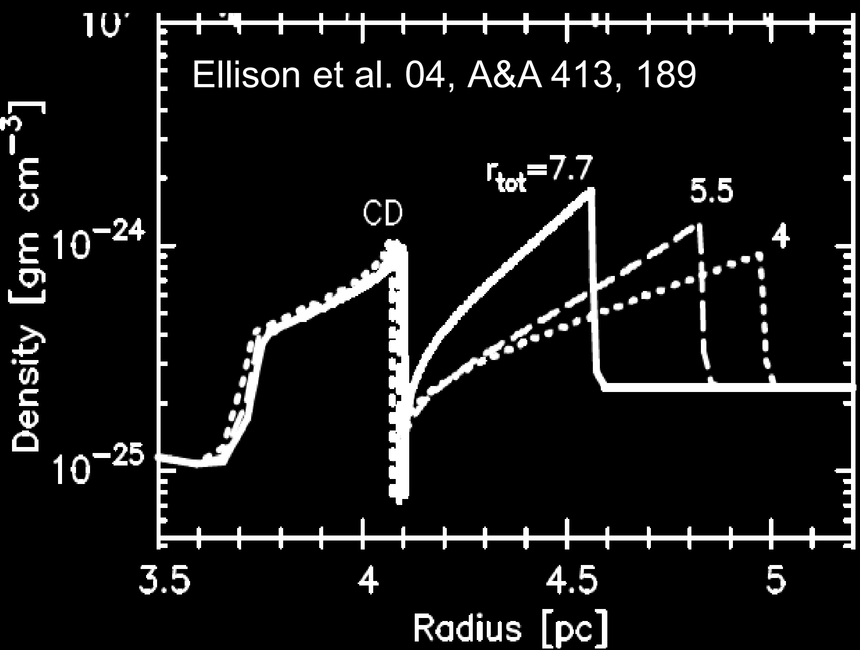
Carles Badenes
Wunch 01/30/08

- FS in Tycho is very close to CD ($R_{CD} \simeq 0.93 R_{FS}$) $\Rightarrow$ **Cosmic Rays are being accelerated at the FS** [Warren et al. 05, ApJ 634, 376; Cassam-Chenaï et al. 07, ApJ 665, 315].
- CR-modified dynamics cannot be studied with γ=5/3 hydro [Ellison et al. 04, A&A 413, 189].
- **RS is NOT accelerating CRs**:
  - Not close to CD.
  - Traced by hot Fe Kα
- **CR acceleration at the FS does not disturb the dynamics of the shocked ejecta** [Ellison et al. 07, ApJ 661, 879].

$\Rightarrow$ γ=5/3 HD+NEI models are appropriate for the shocked ejecta

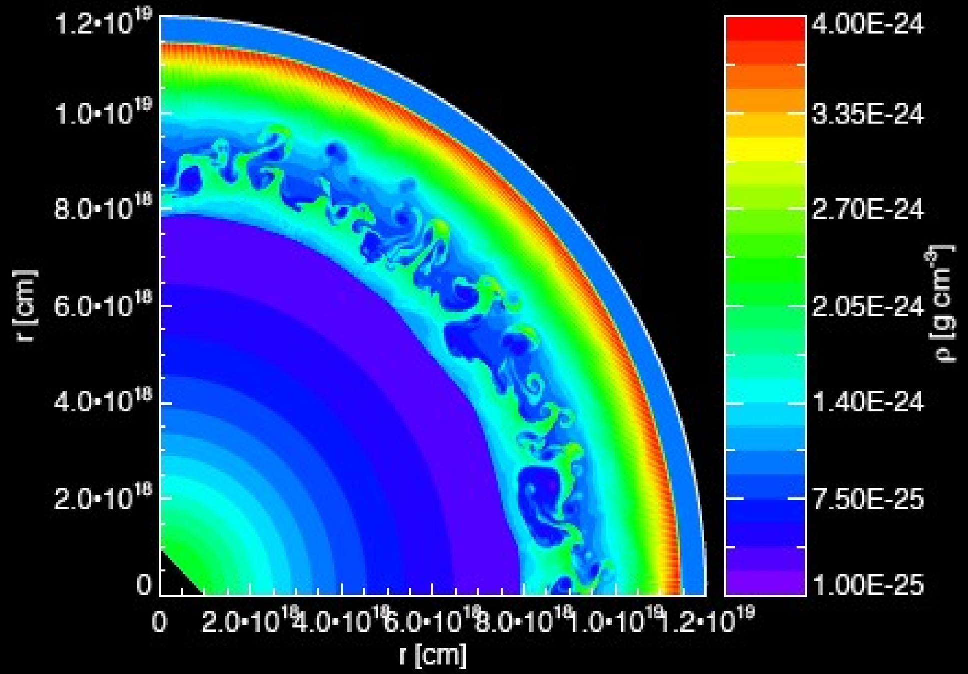


Warren et al. 05, ApJ 634, 376

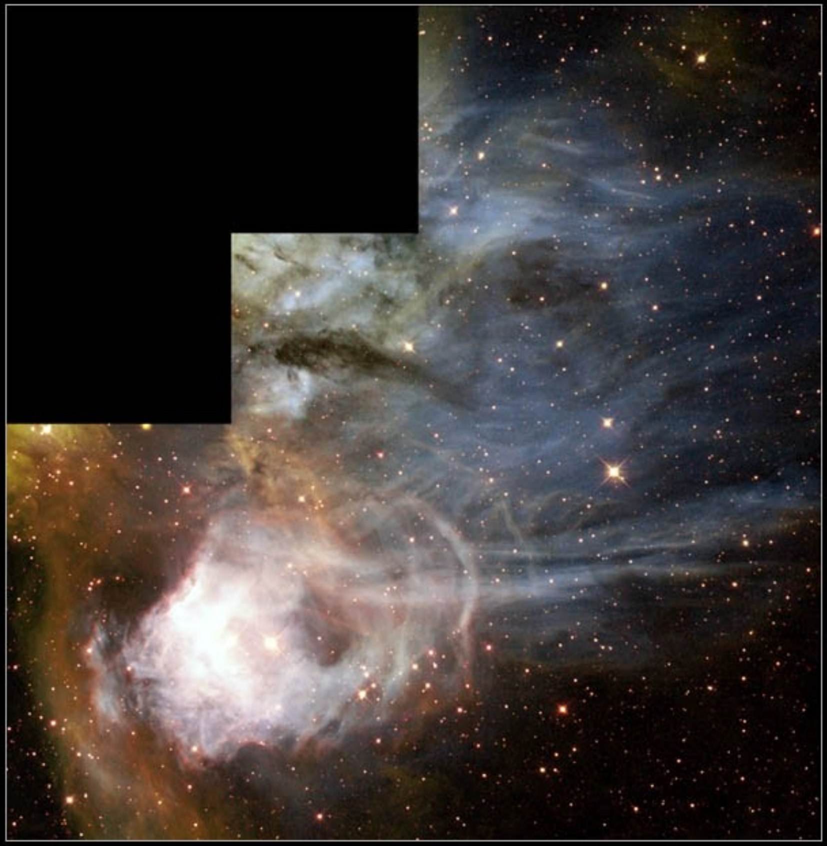


The way ahead

• Multi-D HD+NEI simulations are necessary to interpret the spatially resolved spectroscopy from Chandra ⇒



N44C in the Large Magellanic Cloud



Hubble Heritage

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC02-12

• In-situ studies of the stellar population around nearby SNRs originated from dim/bright SNe can constrain the 'prompt' and 'delayed' progenitor populations.