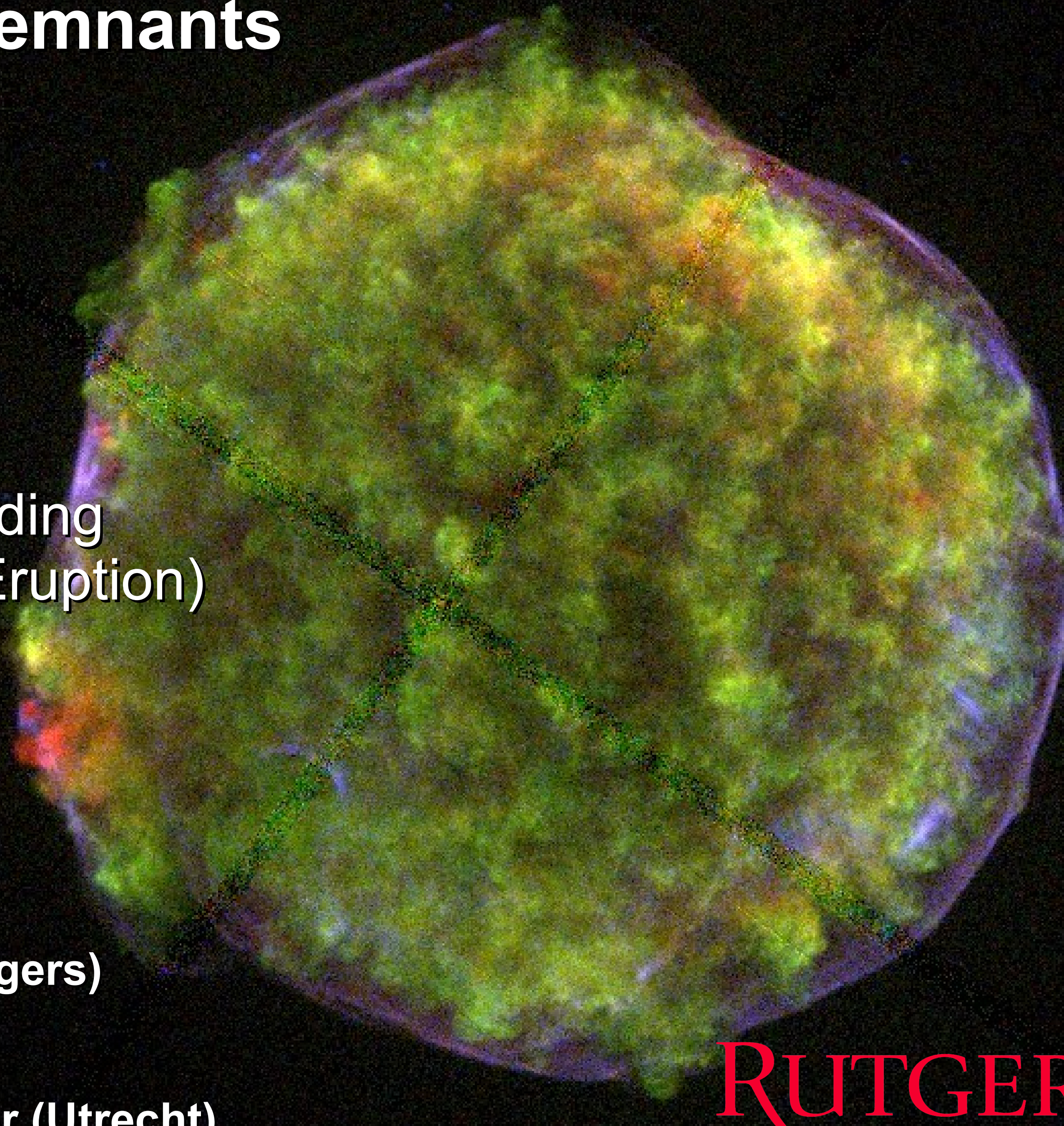
# What has been learned about Type Ia SNe from their Remnants



**Carles Badenes**
(Rutgers University)

KITP – Paths to Exploding Stars (Accretion and Eruption)
March 22, 2007

**Collaborators:**
**J.P. Hughes, J. Warren (Rutgers)**
**K.J. Borkowski (NCSU)**
**E. Bravo (UPC/IEEC)**
**U. Hwang (NASA), N. Langer (Utrecht)**

RUTGERS
UNIVERSITY

# SNRs: Light from the Ashes

Carles Badenes
KITP 03/22/07

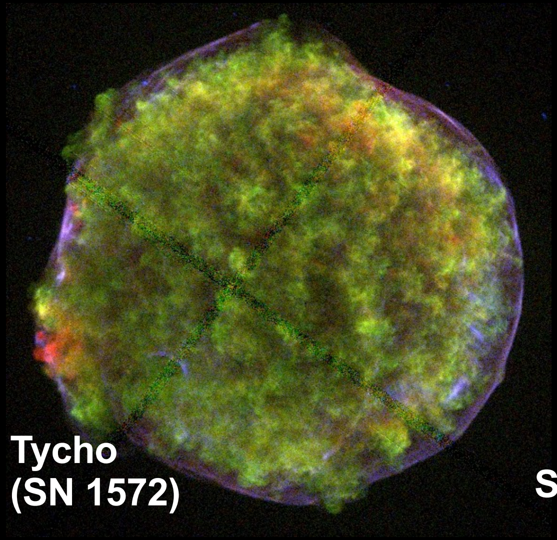
Supernova Remnants (SNRs) are the result of the interaction between the SN ejecta and the surrounding ambient medium (AM)

⇒ Imprint of both the physics of the explosion and the presupernova evolution of the (Type Ia) SN progenitor.

- Supersonic shock waves (~$10^3$ km.s$^{-1}$) heat AM and ejecta to X-ray emitting temperatures ⇒ Light from the ashes.

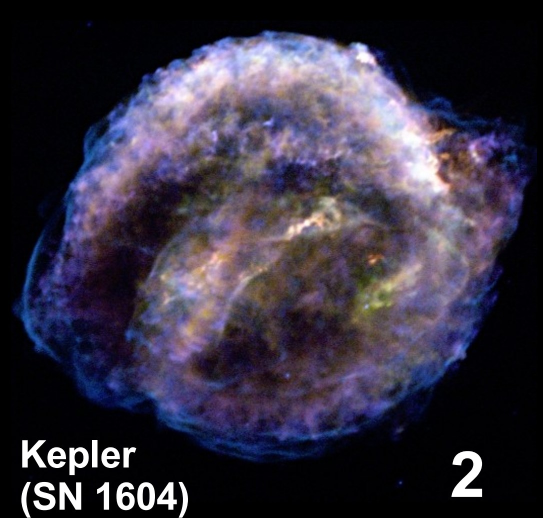
- A number of young, ejecta-dominated SNRs in the Galaxy and the LMC are Type Ia, and have observations of excellent quality (spatially resolved spectroscopy ⇔ *Chandra* and *XMM-Newton*).

**Historical Type Ia SNRs in the Galaxy:**



**Tycho (SN 1572)**

**SN 1006**



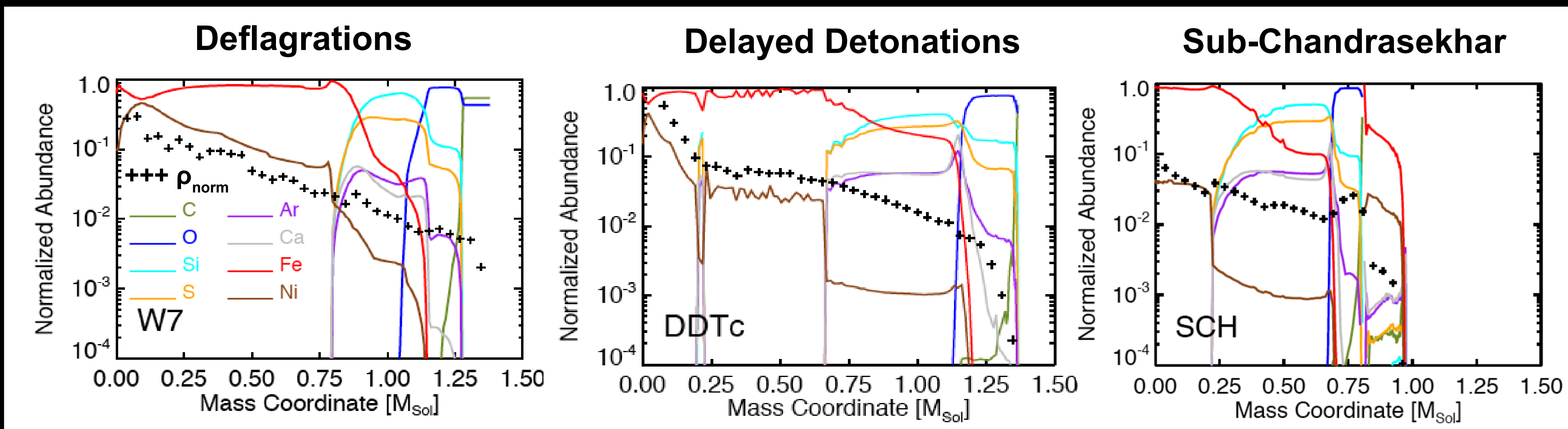
**Kepler (SN 1604)**

Image Credits:
Warren et al. 05, ApJ 634, 376
Hughes et al. 07, in prep.
Reynolds et al. 07, in prep.

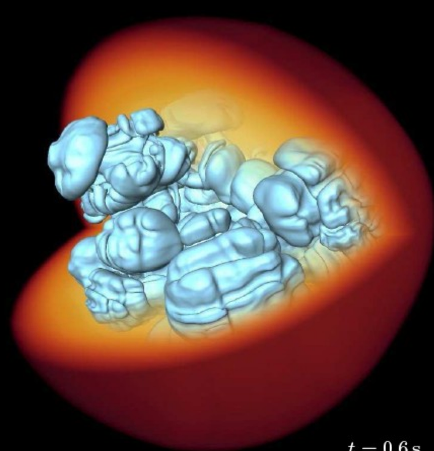
# Physics of Type Ia SNe: Ejecta Structure

Carles Badenes
KITP 03/22/07

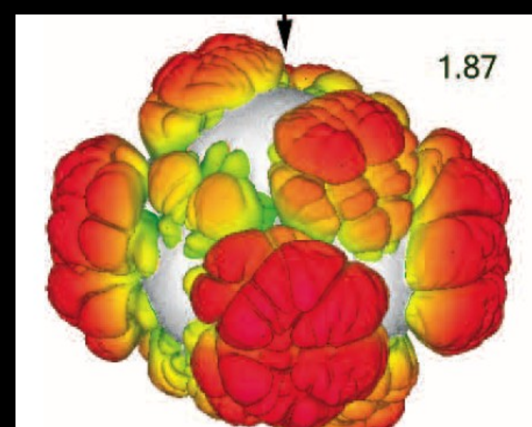
- Thermonuclear explosion of a C+O WD in a binary system (but many important details are still obscure).
- Type Ia SNe: ejecta structure ⇄ physics of the explosion.
- This relationship has been explored extensively with 1D codes:



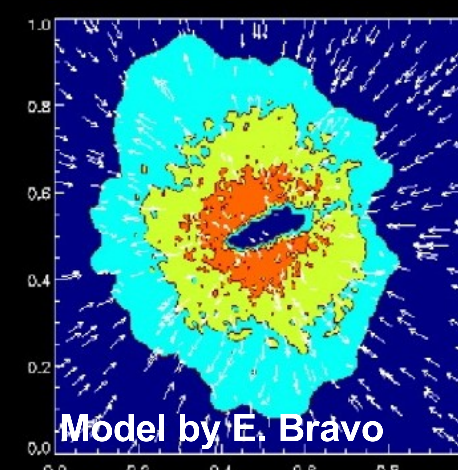

- More recently, 3D simulations have become available (morning talks)




Model by F. Röpke



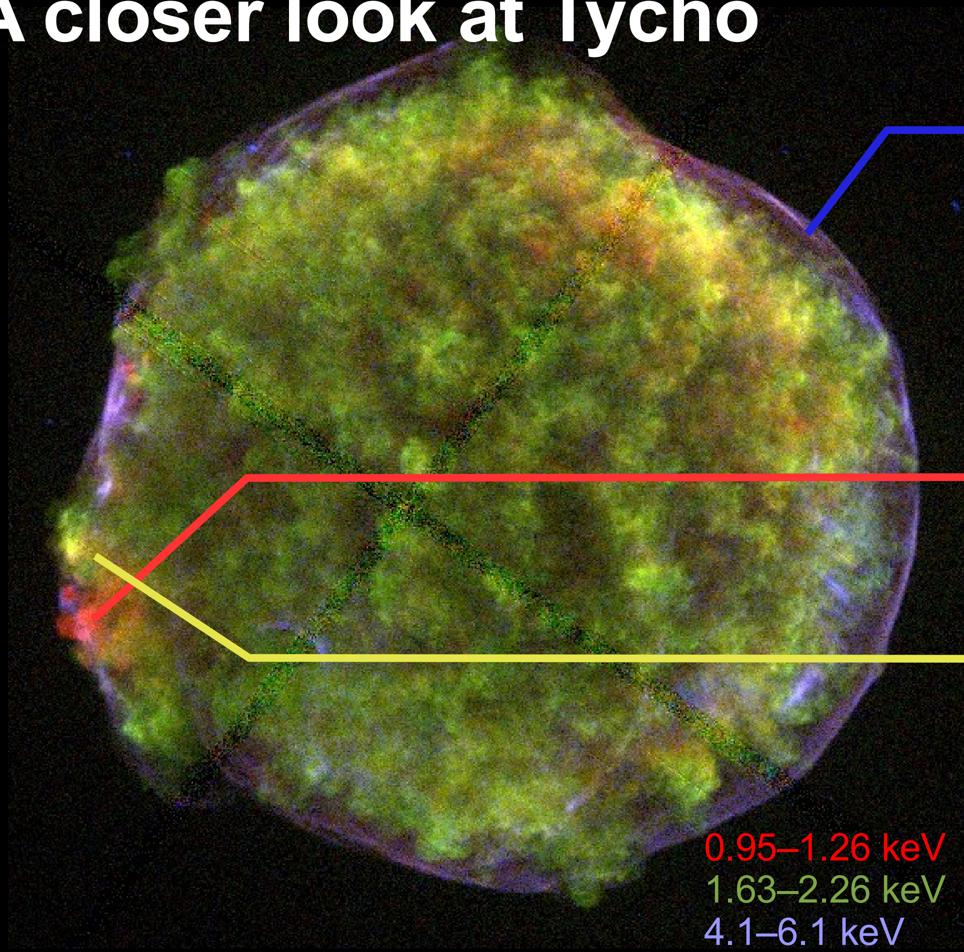

Model by V. Gamezo



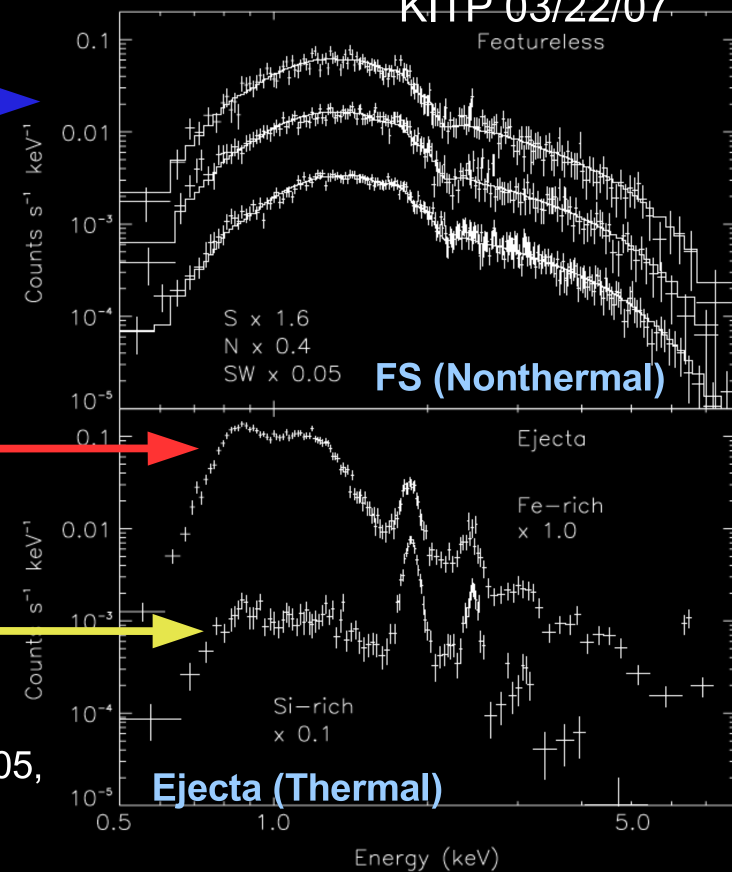
Model by E. Bravo

# A closer look at Tycho

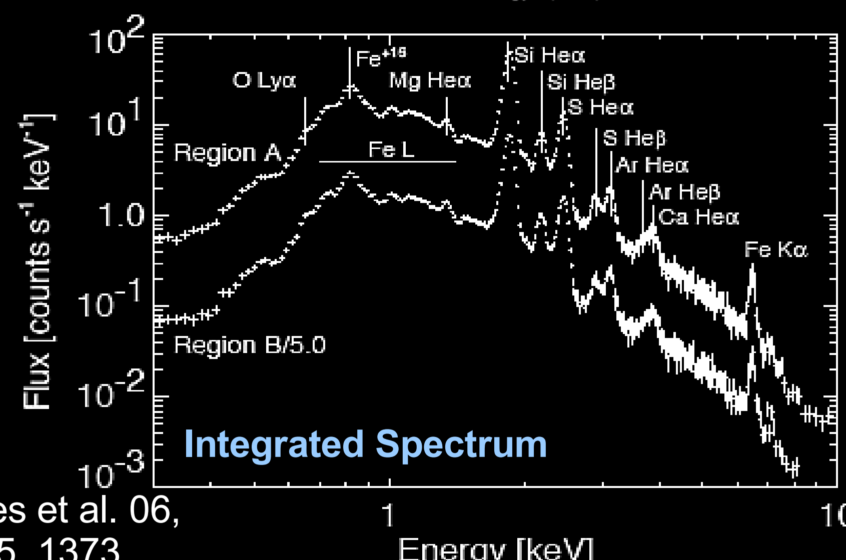
Carles Badenes
KITP 03/22/07




Spectral Components




Warren et al. 05, ApJ 634, 376




Badenes et al. 06, ApJ 645, 1373

X-ray emission has 2 components:

- **FS:** nonthermal continuum [cosmic ray acceleration].
- **Ejecta:** thermal, line-rich (dominates X-rays, dynamics)

No large asymmetries are evident in the ejecta or AM.

# SNRs: HD+NEI Simulations

Carles Badenes
KITP 03/22/07

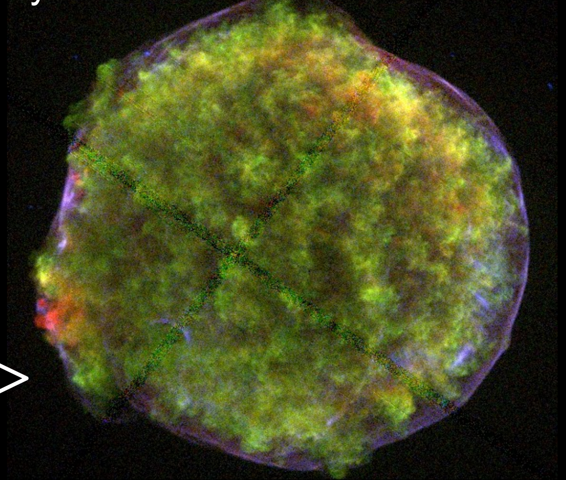
Type Ia SN model
(F. Röpke)

t=10 s


**Hydrodynamics**
**NEI**
**X-ray emission**

9 decades in time!

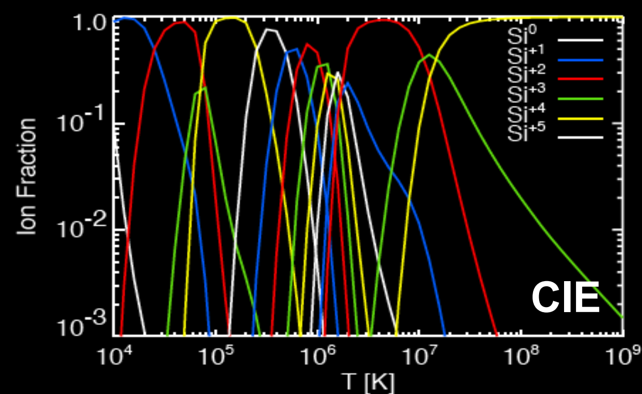
Tycho SNR    $t=1.36 \cdot 10^{10}$ s

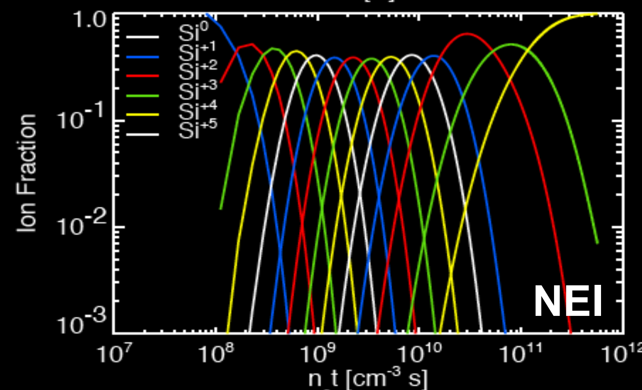


In SNRs, plasma is in **nonequilibrium ionization** ⇒

**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. Let. 30, 737; Badenes et al. 05 ApJ 624, 198].



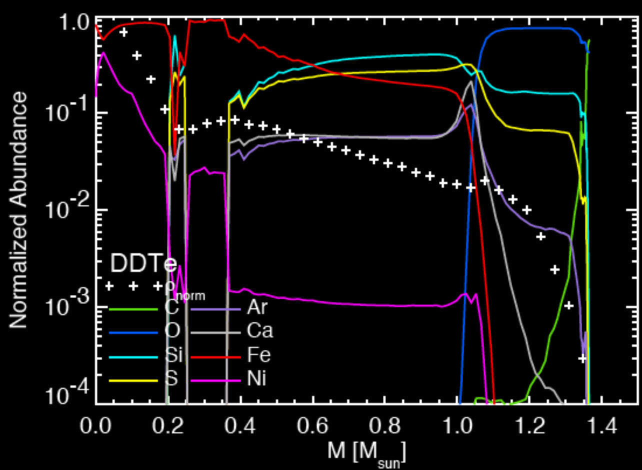

Our understanding of some of these processes is not complete ⇒ models must be incomplete!

# SNRs: A Practical Example

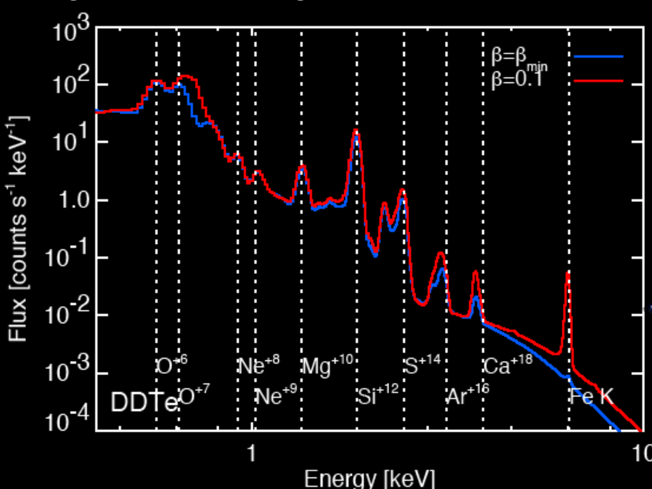
Carles Badenes
KITP 03/22/07

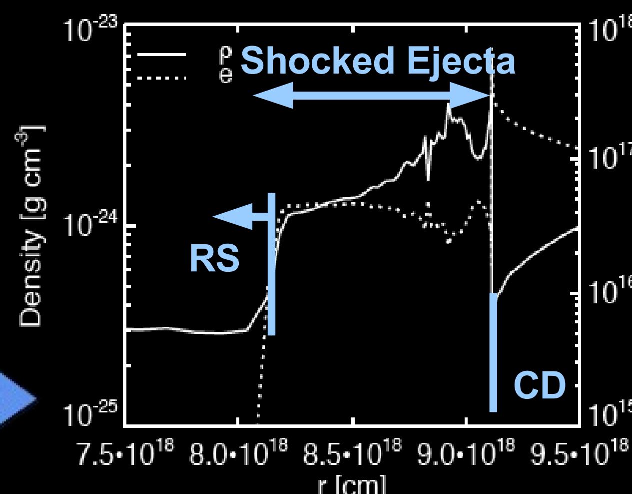
- 1D simulation, uniform AM. Radiative + ionization losses included.
- Parameters: AM density, $\rho_{AM}=10^{-24}$ g.cm$^{-3}$; SNR age, $t_{SNR}$=430 yr; amount of collisionless $e^-$ heating at the RS, $\beta[\equiv\varepsilon_{e,s}/\varepsilon_{i,s}]=\beta_{min}...0.1$.
- Different chemical elements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

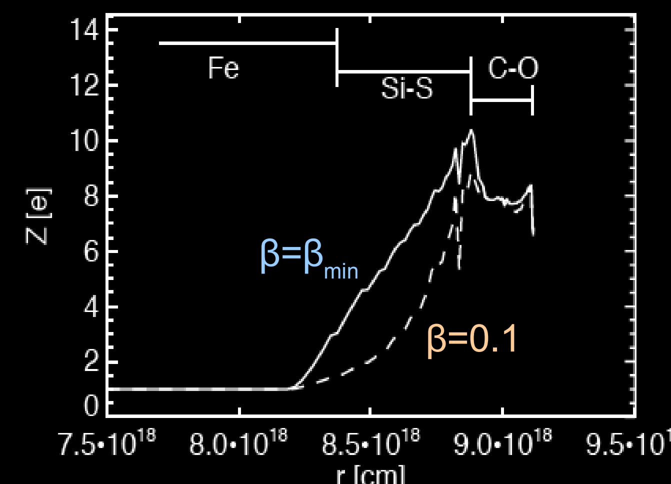
**SN Explosion model (DDTe):**

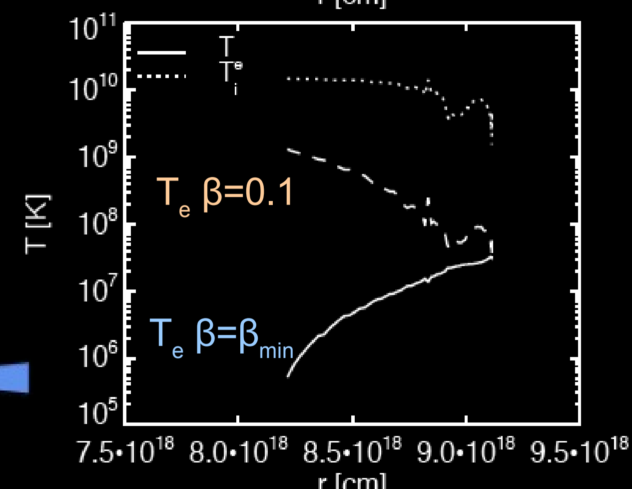


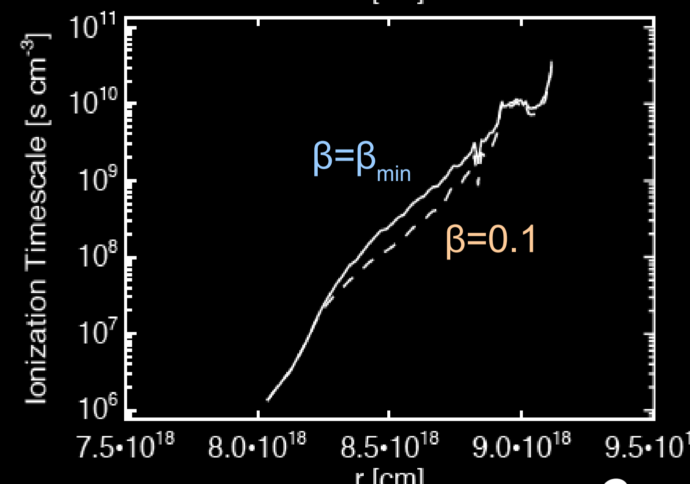

**Synthetic X-ray spectrum:**



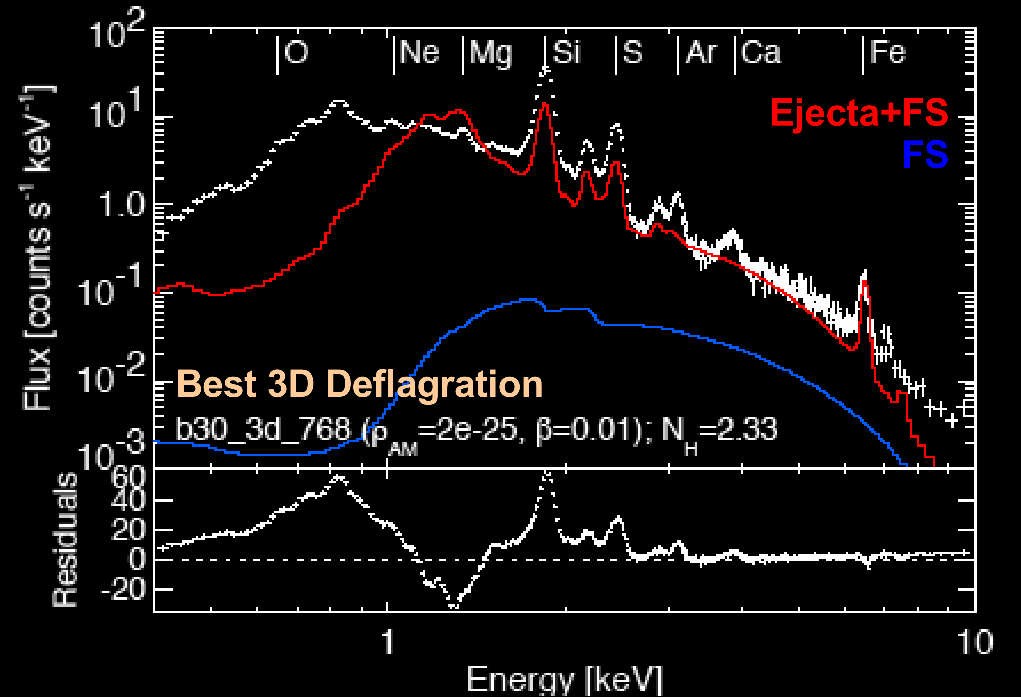



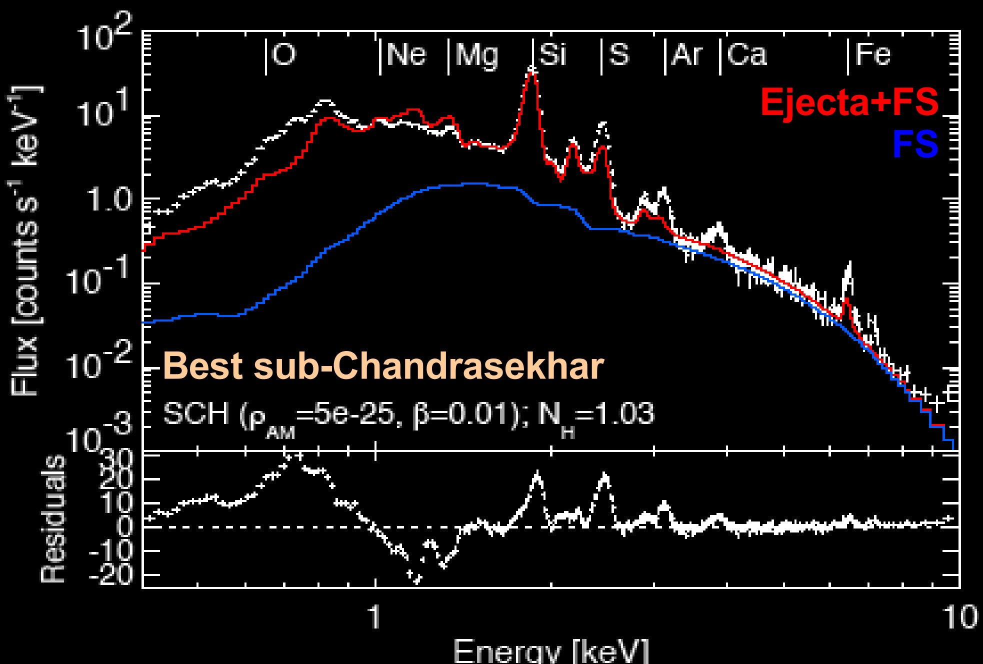

**HD + NEI simulation**

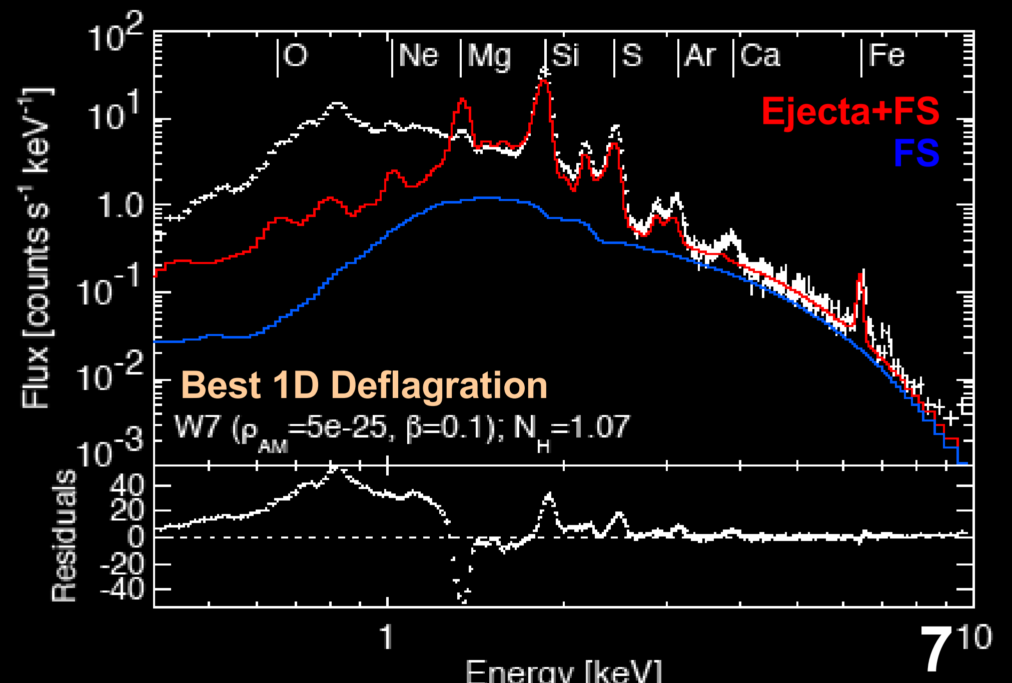
# Tycho: Models vs. Data (I)

Carles Badenes
KITP 03/22/07

- Ejecta models: t=435 yr ⇒ only $\rho_{AM}$ and β can be varied.
- Forward shock: Γ=2.72 power law, $F_{pwl}$=7.4-8.9 phot.cm$^{-2}$s$^{-1}$keV$^{-1}$ [Fink et al. 94 A&A 283,635].
- Only normalization and $N_H$ are fitted!
- $N_H$~0.6x10$^{22}$ cm$^{-2}$ [Hwang et al. 02 ApJ 581, 1101].
- Most models don't do very well...



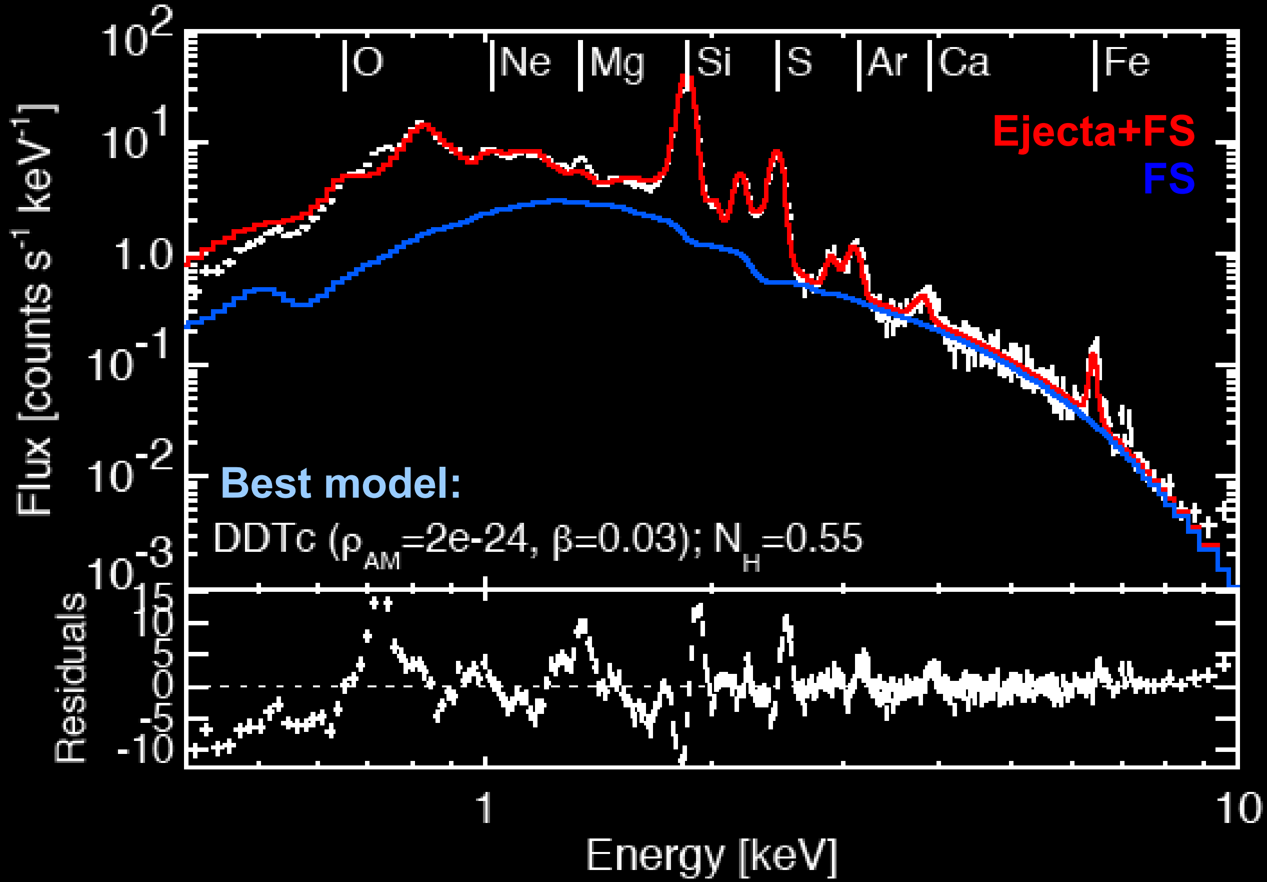



# Tycho: Models vs. Data (II)

Carles Badenes
KITP 03/22/07

- 1D Delayed detonations work! ⇒ **DDTc** ($\rho_{AM}$=2x10$^{-24}$ g.cm$^{-3}$, β=0.03).
- Reproduces ALL the fundamental lines from Si, S, Ar, Ca, Fe. $N_H$ (0.55x10$^{22}$ cm$^{-2}$) and $F_{pwl}$ (8.1 phot.cm$^{-2}$s$^{-1}$keV$^{-1}$) within tolerances.
- Model also reproduces:
  - SNR dimensions
  - Expansion velocity of the shocked ejecta
  - Radial profiles of line emission (qualitative)
- Adjustment is very good, but not perfect!

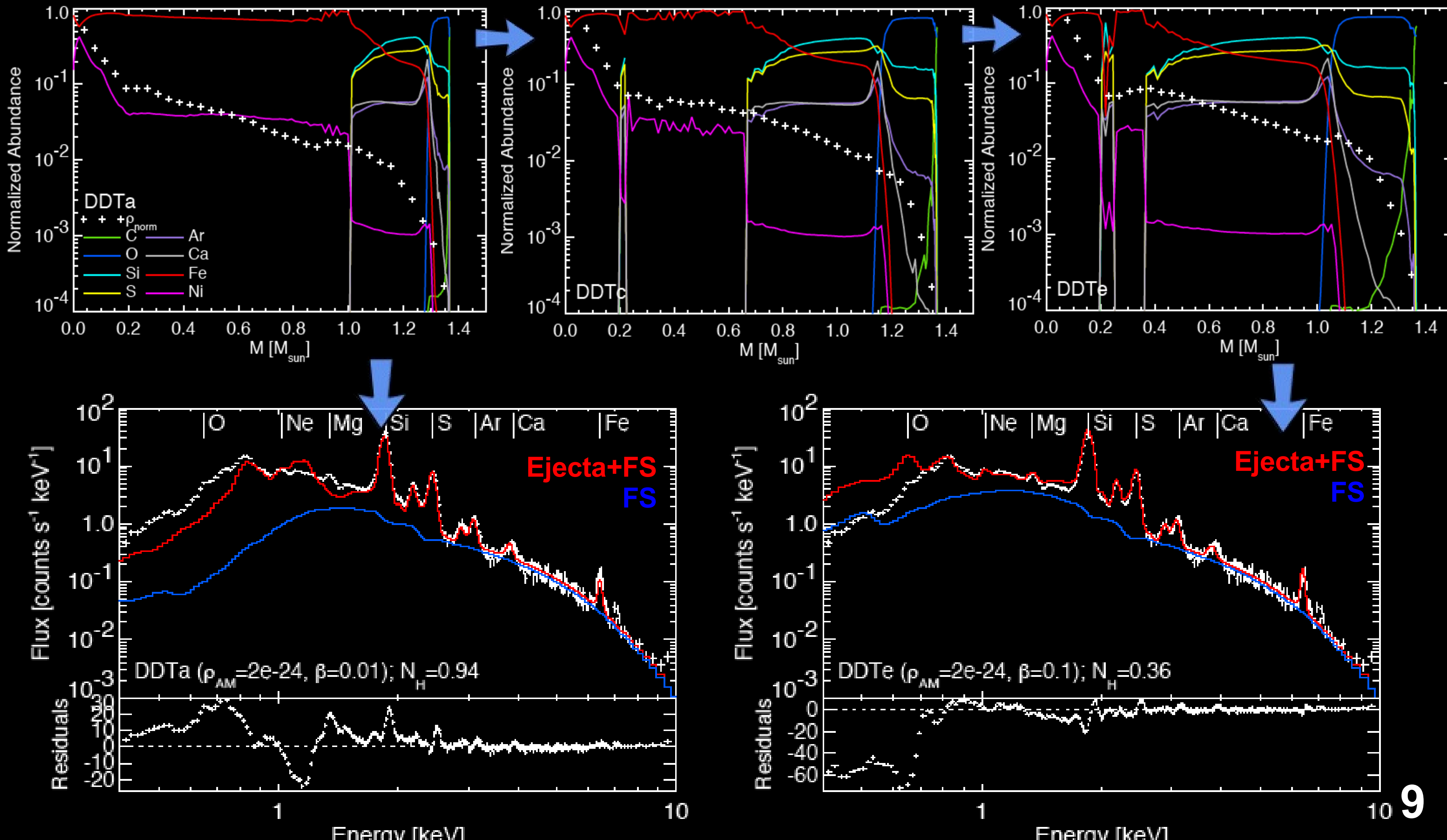



**Model DDTc**: $E_k$=1.16·10$^{51}$ erg; $\rho_{tr}$=2.2x10$^7$ g cm$^{-3}$
Yields [$M_\odot$] Fe: 0.8, O: 0.12, Si:0.17, S:0.13, Ar:0.033, Ca: 0.038

# Tycho: Models vs. Data (III)

Carles Badenes
KITP 03/22/07

➢ Other delayed detonations are also successful. E<1keV emission ⇒ strong constraints on the amount of Fe-peak elements and O synthesized in the explosion ⇒ $\rho_{tr}[10^7 \text{ g cm}^{-3}]$: DDTa (3.9) → DDTc (2.2) → DDTe (1.3)



# Things Learned About SN Ia Explosions:

Carles Badenes
KITP 03/22/07

- HD+NEI models are not complete (1D, no CR acceleration), but the fundamental physical processes that affect the ejecta emission are included.

- **Tycho** ⇒ 1D delayed detonation models can reproduce the X-ray emission from the SN ejecta. Other models do not work: Pulsating delayed detonations, 1D Deflagrations, sub-Chandrasekhar explosions, 3D Deflagrations (with well-mixed ejecta).

- X-ray spectra AND SNR dynamics **MUST** form a consistent picture.

- These results agree with (but are completely independent of!) those obtained from Type Ia SN spectra.

- Future work: Other Type Ia SNRs (SN 1006, Kepler - see poster). New explosion models.

- Some aspects of Type Ia SN explosions can **ONLY** be studied through SNRs. *Chandra* can resolve the spatial structure of the ejecta!

More details: Badenes et al. 2006, ApJ 645, 1373

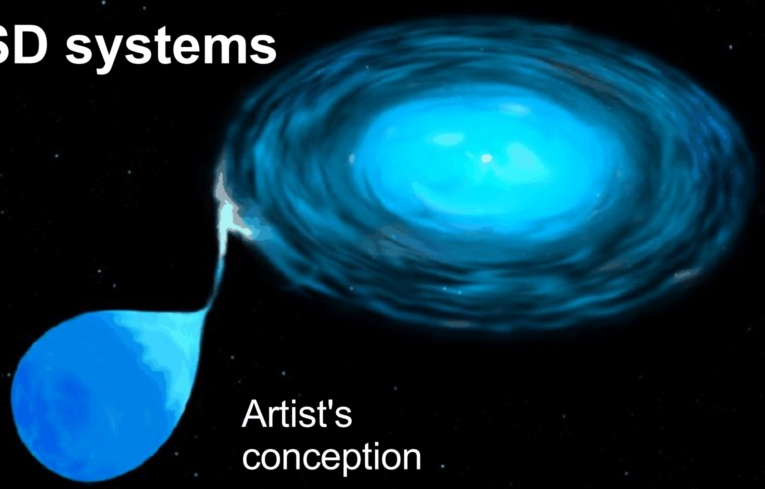
# SN Ia Progenitors

Carles Badenes
KITP 03/22/07

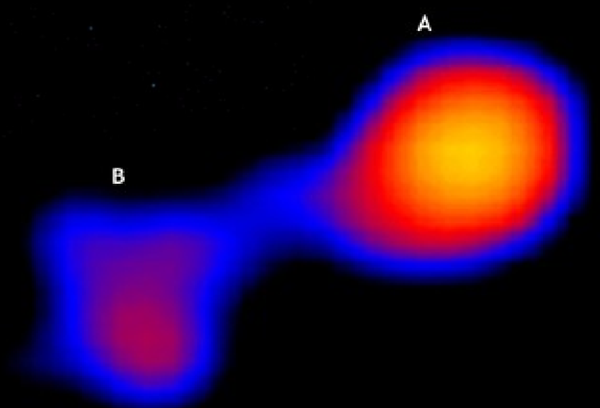
The dynamics and X-ray emission of SNRs are affected by the structure of the ambient medium (AM) ⇒ Imprint of the Progenitor?

- **SD Progenitors**: Most candidate systems experience some kind of pre-SN mass loss.
- **DD Progenitors**: If final spiral-in is due to gravitational wave emission, pre-SN evolution should be mass conservative.

**SD systems**

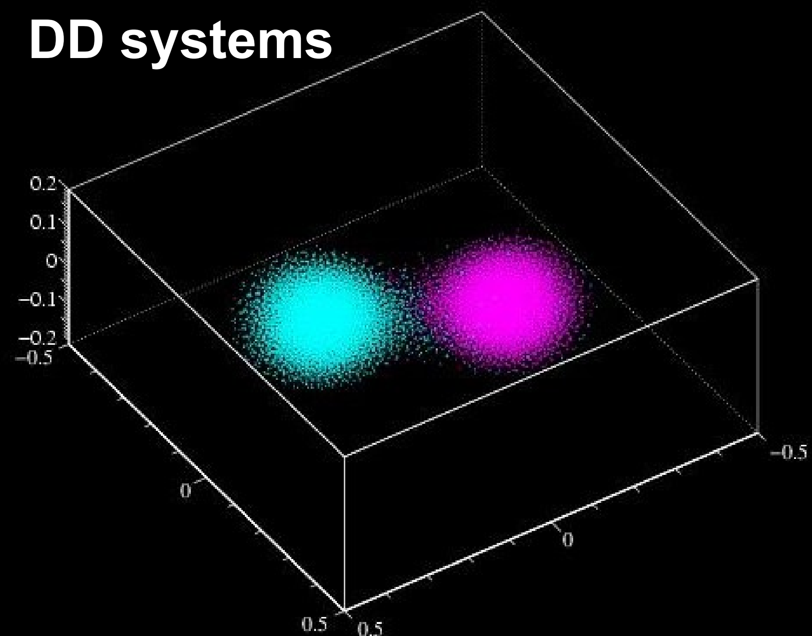


Artist's conception




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

# SN Ia Progenitors: Accretion Winds

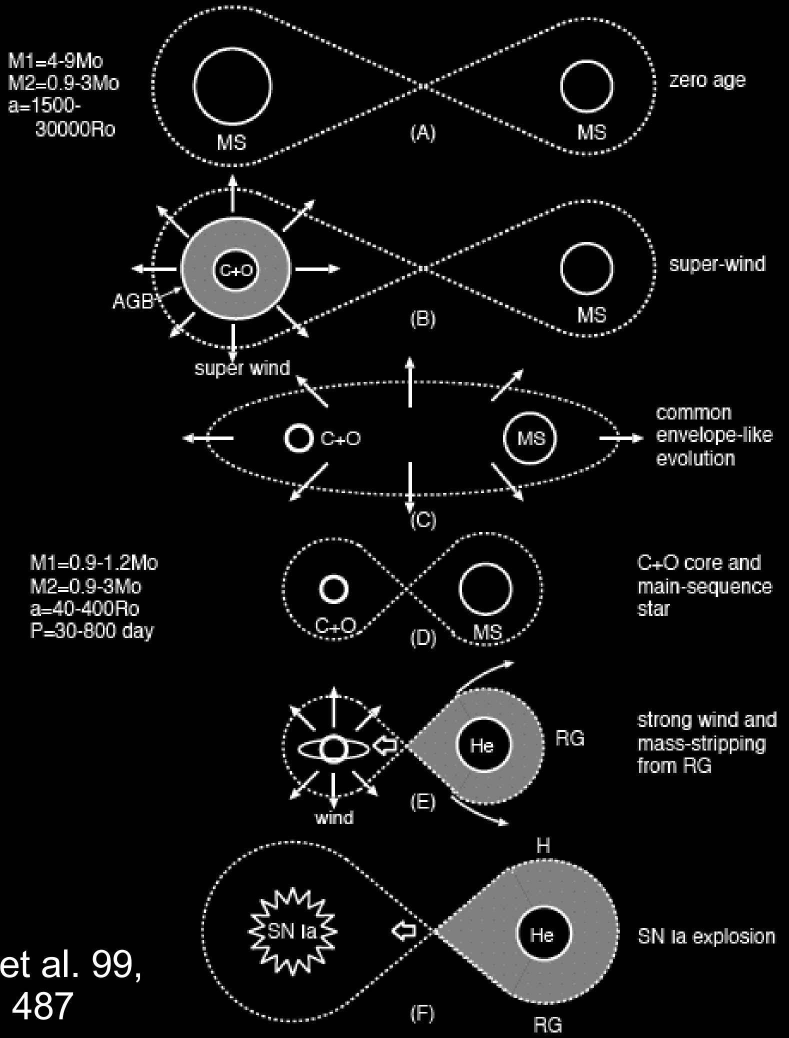
Carles Badenes
KITP 03/22/07

**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. [Li & van den Heuvel 97 A&A 322, L29; Langer et al. 00, A&A 362, 1046; Han & Podsiadlowski 04, MNRAS 350, 1301].
- 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].



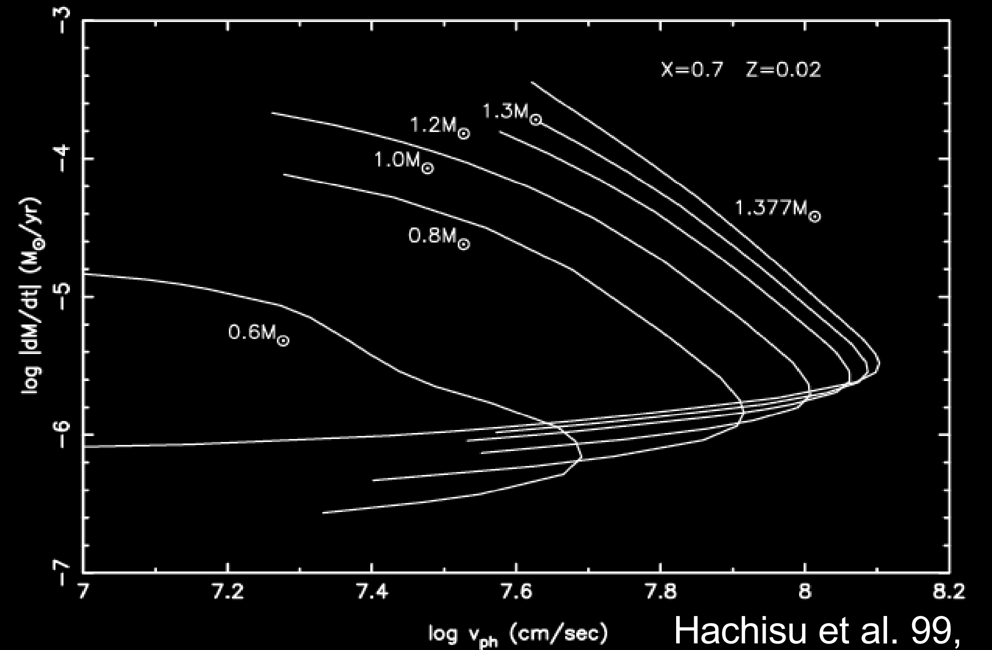

Hachisu et al. 99, ApJ 522, 487

Carles Badenes
KITP 03/22/07

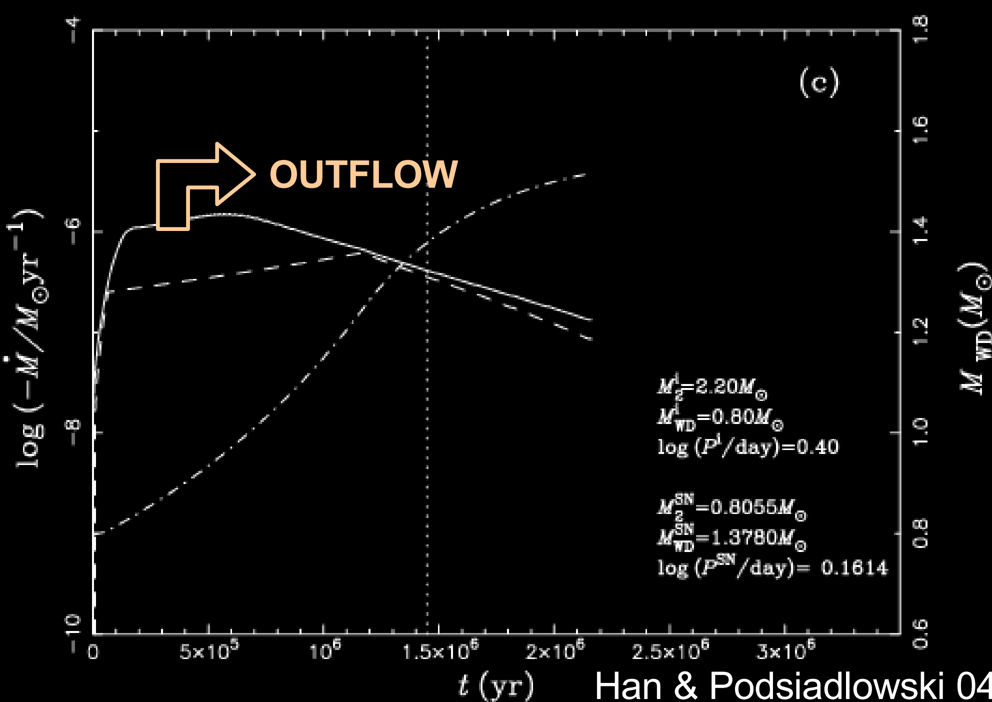
# SN Ia Progenitors: Accretion Wind Outflows

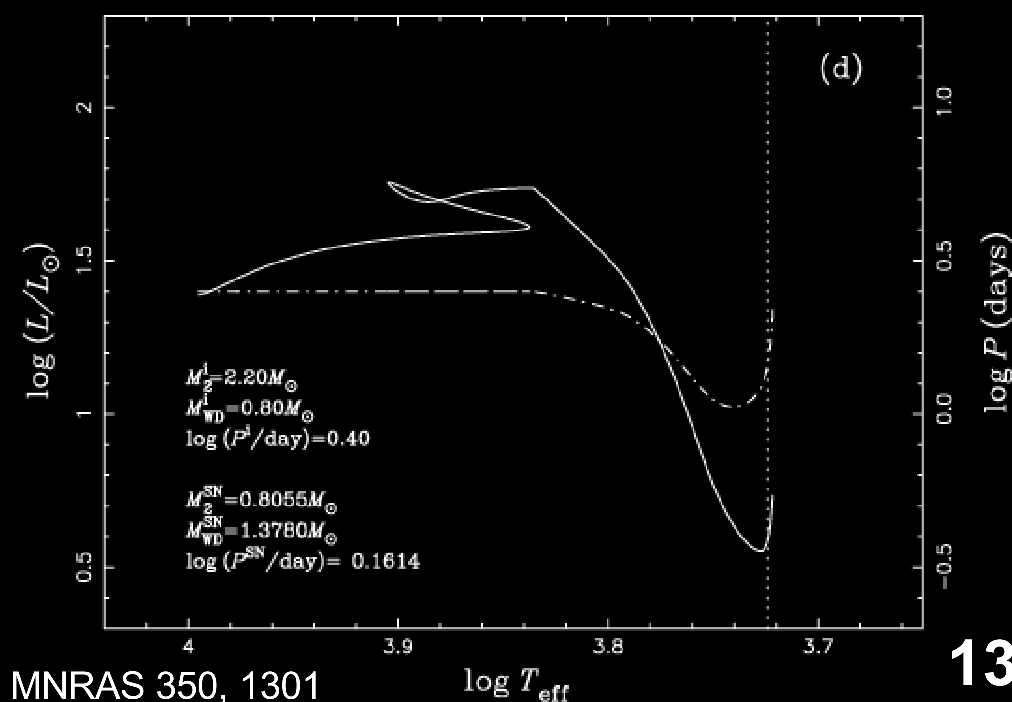
- Part of the material accreted from the companion is not burnt at the WD surface. It escapes the binary system as a fast accretion wind outflow.

- Typical 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 $s^{-1}$.




Hachisu et al. 99, ApJ 522, 487




Han & Podsiadlowski 04 MNRAS 350, 1301

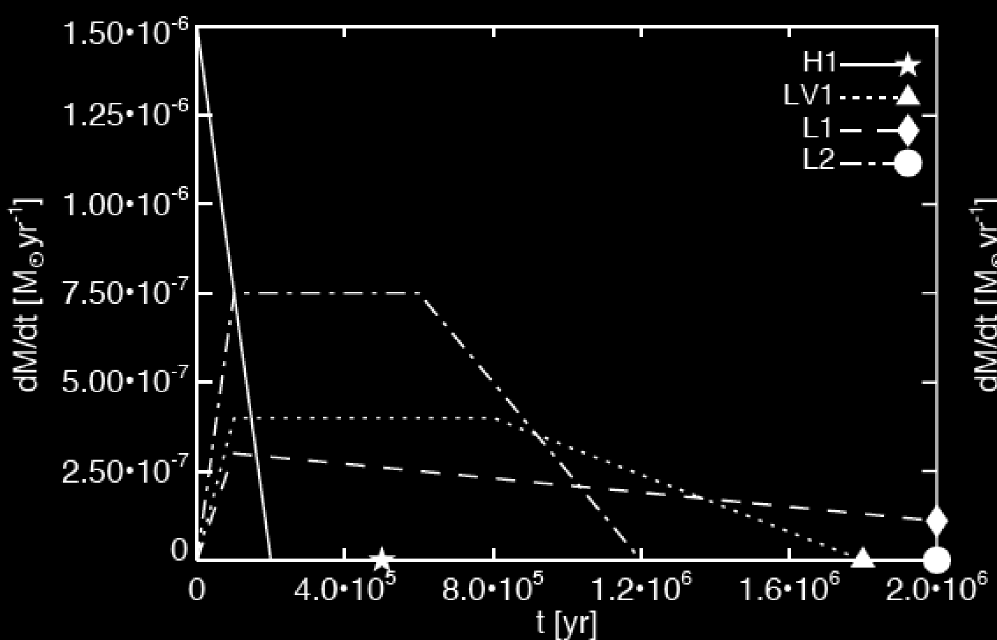
# SN Ia Progenitors: Modeling Accretion Wind Outflows

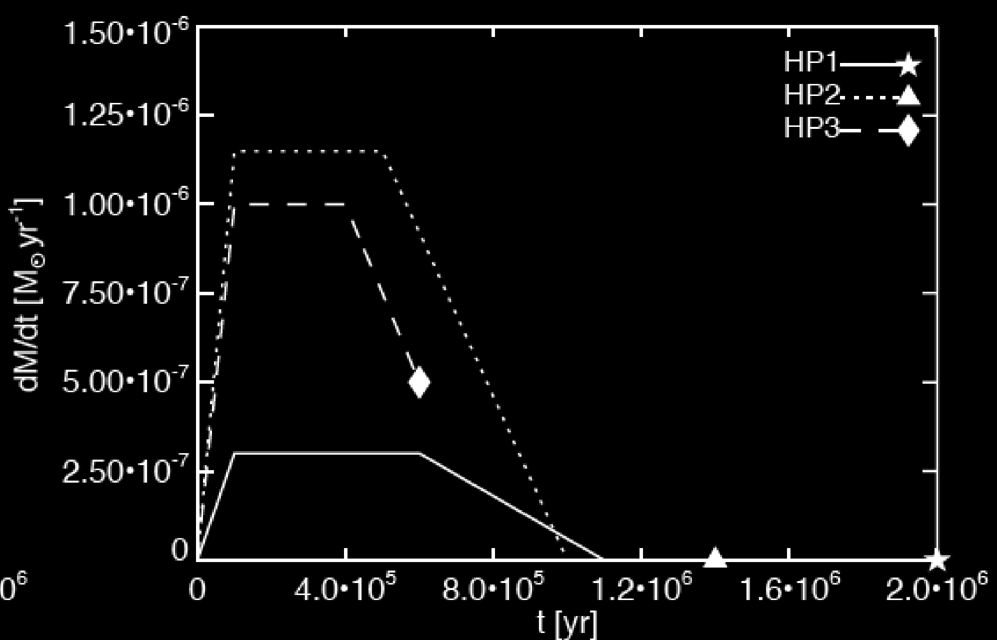
Carles Badenes
KITP 03/22/07

- Different authors make similar predictions for the outflows from Type Ia progenitors.
- The behavior of the outflows can be approximated with simple models:

| Model Name | $M_{of}$ ($M_\odot$) | $t_{SN}$ (yr) | Binary System Parameters $M_{WD,0}$ ($M_\odot$) | $M_{D,0}$ ($M_\odot$) | $P_0$ (days) | Reference |
|---|---|---|---|---|---|---|
| H1 | 0.15 | $5.0 \times 10^5$ | 1.0 | 2.0 | 2.0 | 1 (Fig. 7) |
| LV1 | 0.50 | $1.8 \times 10^6$ | 1.0 | 2.5 | 1.6 | 2 (Fig. 1) |
| HP1 | 0.24 | $2.0 \times 10^6$ | 0.75 | 2.0 | 1.58 | 3 (Fig. 1a) |
| HP2 | 0.80 | $1.4 \times 10^6$ | 0.8 | 2.2 | 2.50 | 3 (Fig. 1c) |
| HP3 | 0.50 | $6.0 \times 10^5$ | 1.0 | 2.4 | 3.98 | 3 (Fig. 1e) |
| L1 | 0.40 | $2.0 \times 10^6$ | 1.0 | 2.3 | 1.74 | 4 (Model 2, Fig.7) |
| L2 | 0.64 | $2.0 \times 10^6$ | 0.8 | 2.1 | 1.53 | 4,5 (Model 31, Fig. 36 in ref. 5) |

References. — (1): Hachisu et al. (1999b); (2): Li & van den Heuvel (1997); (3): Han & Podsiadlowski (2004); (4): Langer et al. (2000); (5): Deutschmann (1998)



# SN Ia Progenitors: Shaping the CSM (I)

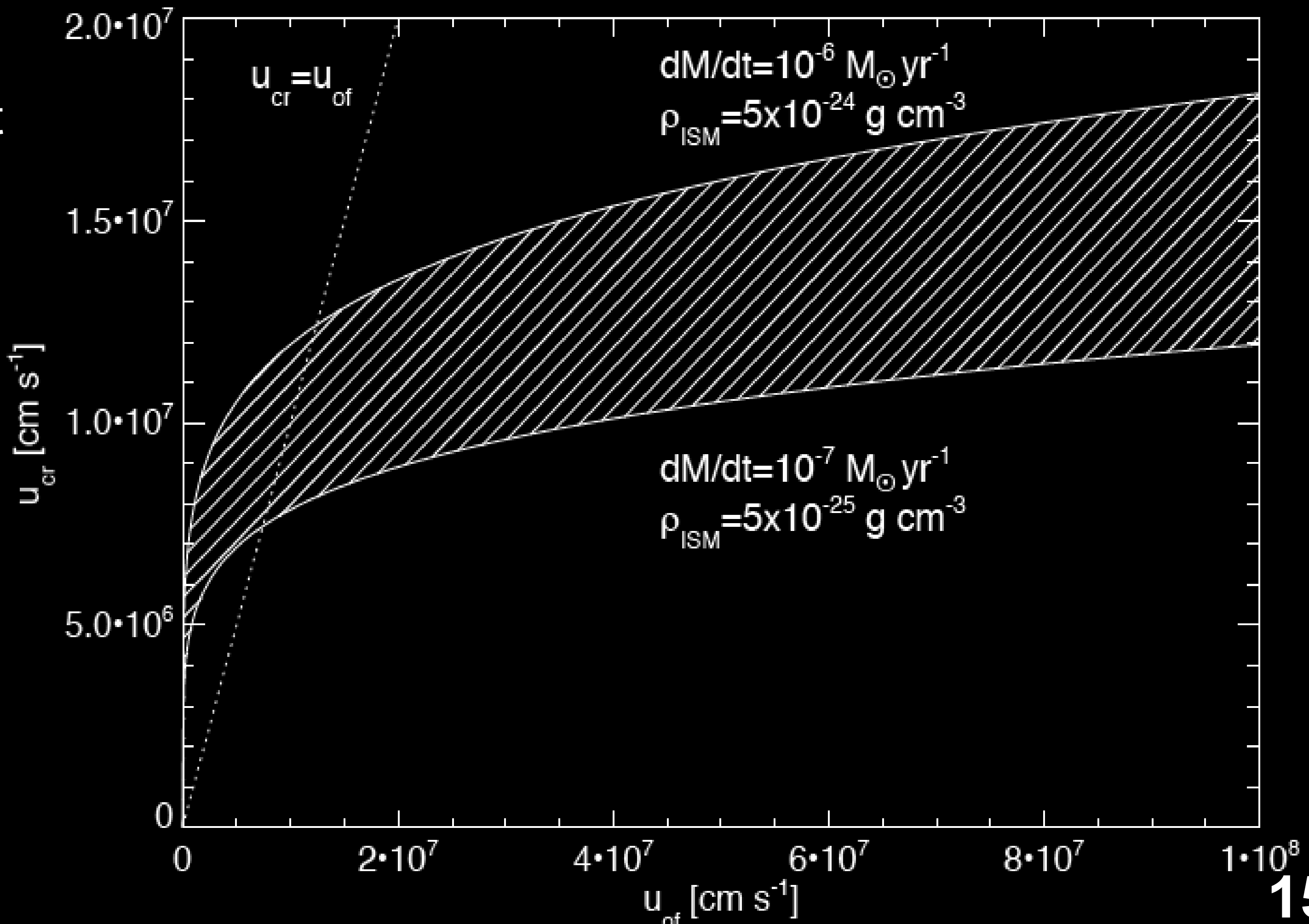
Carles Badenes
KITP 03/22/07

- Outflows into the ISM: wind cavities.
- Properties of the cavity determined by outflow velocity $u_{of}$ ⇔ critical limit $u_{cr}$ [Koo & McKee 92, ApJ 388, 93]:

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

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

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



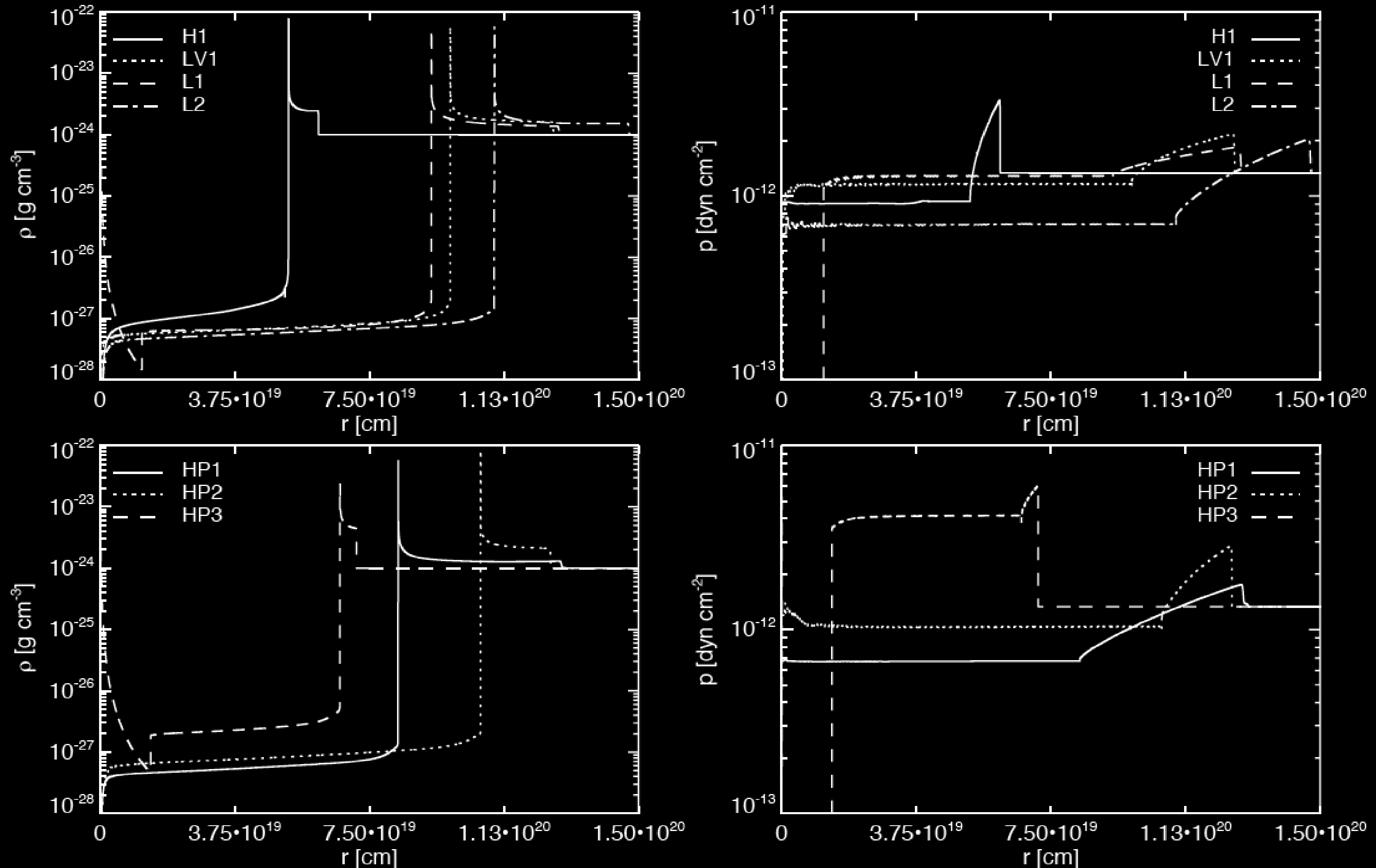
# SN Ia Progenitors: Shaping the CSM (II)

Carles Badenes
KITP 03/22/07

- When these fast, continuous outflows expand into the warm ISM, they excavate **large** (~$10^{20}$ cm) **interstellar bubbles** around the Type Ia progenitors.
- Variations in $\rho_{ISM}$ and $p_{ISM}$ do not affect the bubbles significantly.

CSM configuration at the time of the SN explosion:

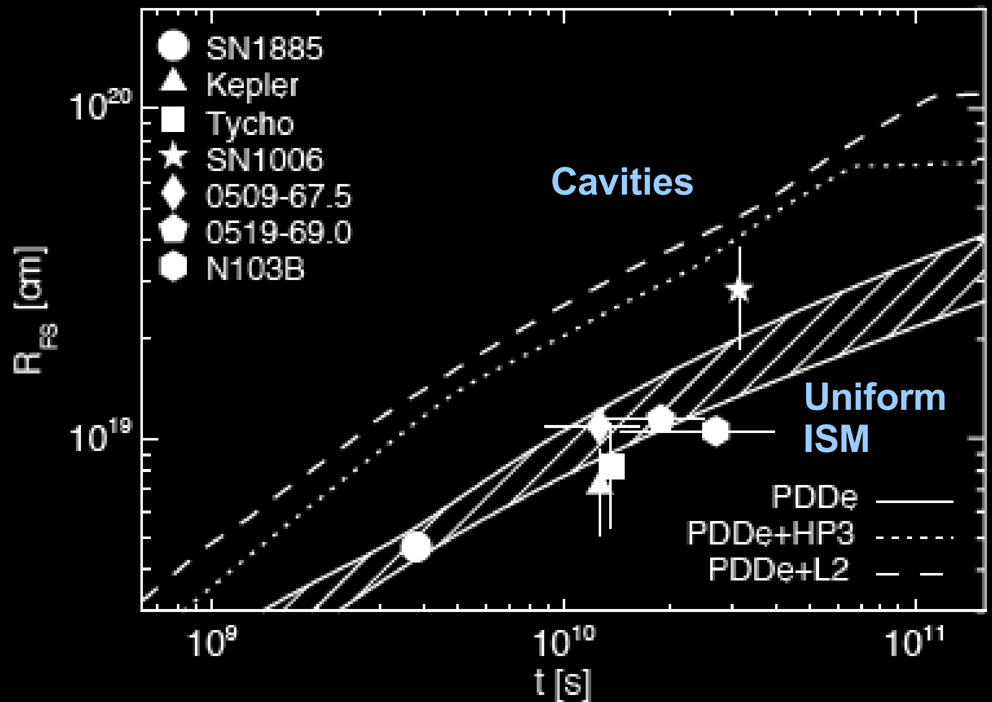
Note that most bubbles are pressure-confined!

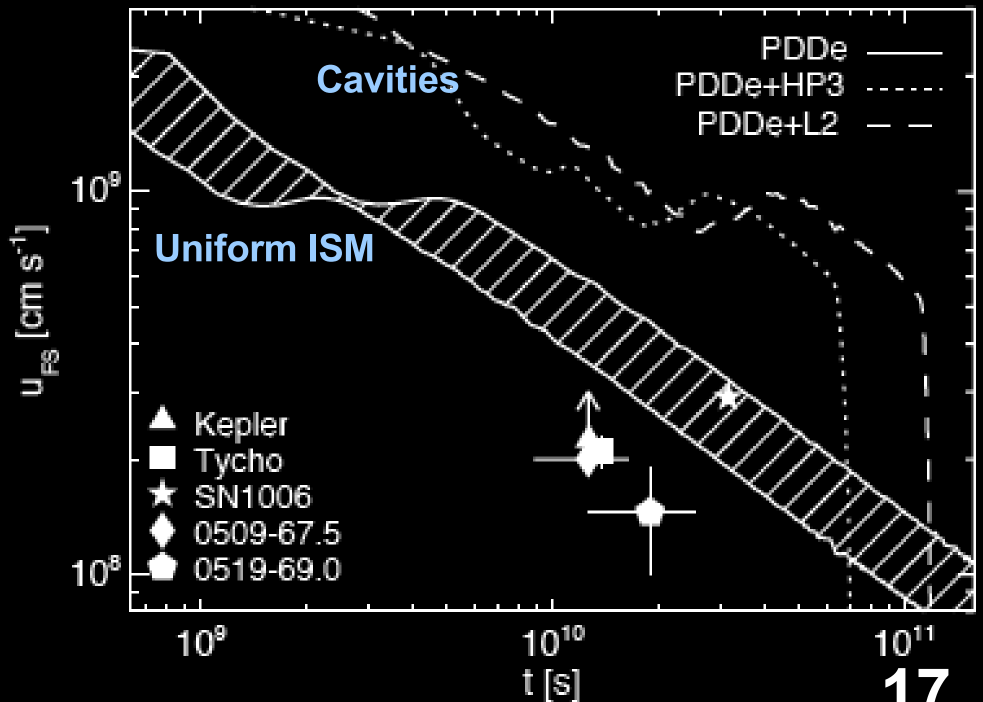


# SN Ia Progenitors: Constraints from SNR dynamics

Carles Badenes
KITP 03/22/07

- We can compare the dynamics of SNR models evolving inside accretion wind-blown bubbles with the fundamental properties of known Type Ia SNRs.
- Object sample: historical Type Ia SNRs (SN 1885, Kepler, Tycho, SN 1006) + LMC Type Ia SNRs with good age estimates [Rest et al. 05, Nat. 438, 1132] (0509-67.5, 0519-69.0, N103B).
- The existence of large cavities around Type Ia SN progenitors is inconsistent with the observations:



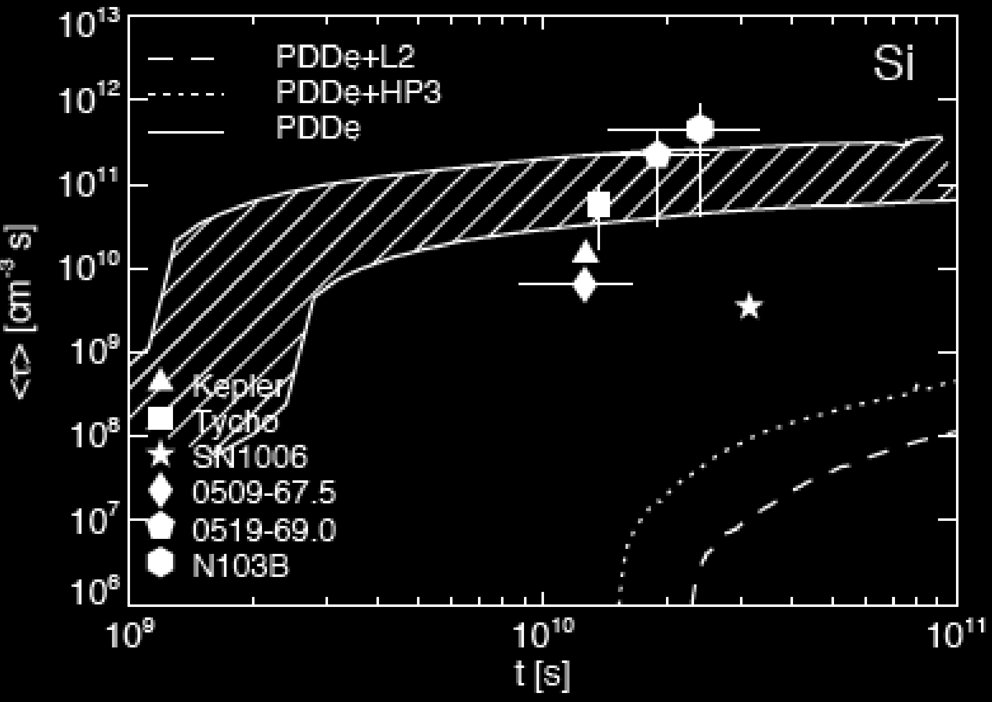
# SN Ia Progenitors: Constraints from ejecta emission in the SNR

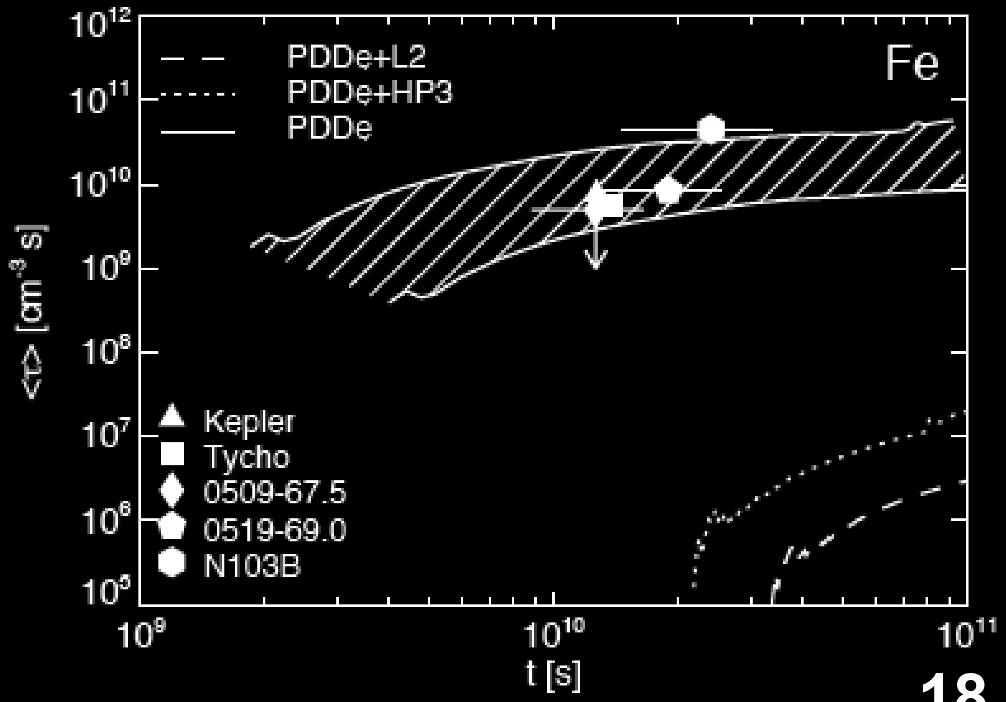
Carles Badenes
KITP 03/22/07

- A similar comparison can be done based on the spectral properties of the X-ray emission from the shocked SN ejecta.

- In SNR models evolving inside large cavities, the SN ejecta expand to very low densities before any significant interaction can take place.

- These models are characterized by low values for the ionization timescales of Si and Fe in the shocked ejecta:

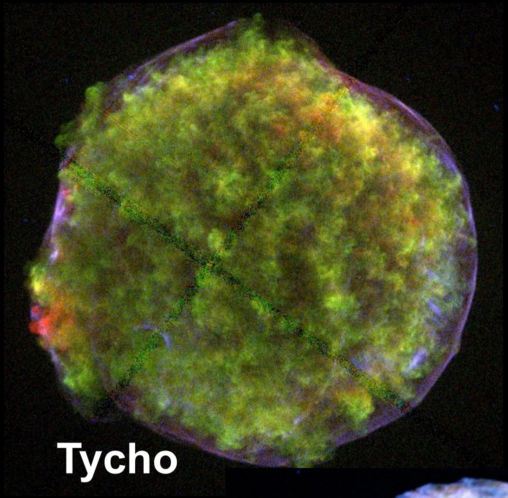


# Progenitor Imprints in Type Ia SNRs?

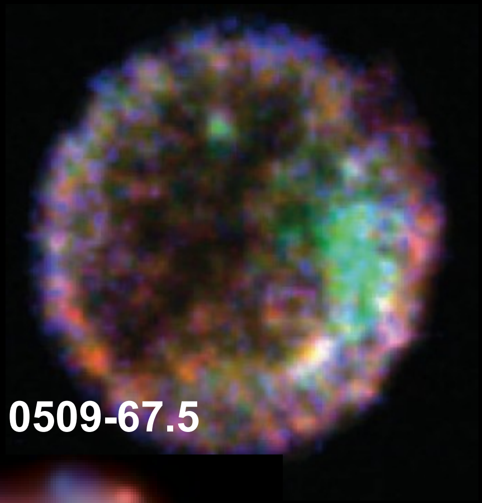
Carles Badenes
KITP 03/22/07

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



Tycho

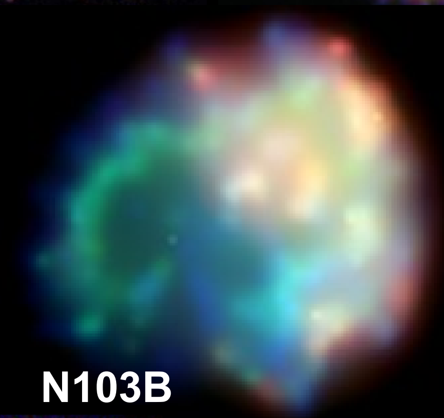
SN 1006



0509-67.5

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

Kepler

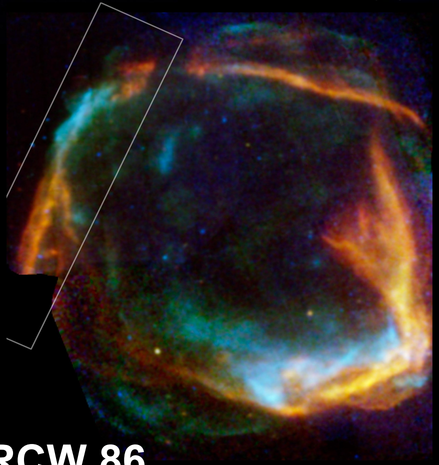


N103B

There **might** be a population of Type Ia SNRs interacting with accretion wind bubbles!

RCW 86 [Vink et al. 06 ApJ 648, L33]:

- Cavity SNR
- Type Ia?
- SNR of SN 185 AD?



RCW 86

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

# Things Learned About SN Ia Progenitors:



- Accretion winds are an essential mechanism to make the SD progenitors of Type Ia SNe viable.

- Fast accretion winds lead to large cavities around the Type Ia progenitors. Cavities are driven by mechanical luminosity ⇒ bipolar and/or episodic outflows, thermal conduction, etc. are unlikely to change this.

- The existence of such cavities is incompatible with the fundamental properties (forward shock dynamics, X-ray emission) of known Type Ia SNRs: Tycho, SN1006, Kepler, 0509-67.5, 0519-69.0, N103B.

- A population of Type Ia SNRs expanding into accretion wind blown cavities cannot be discarded (RCW 86?).

More details: Badenes et al., ApJ, in press [astro-ph/0703321]

# Cosmic Ray Acceleration at the Forward Shock of Tycho

Carles Badenes
KITP 03/22/07

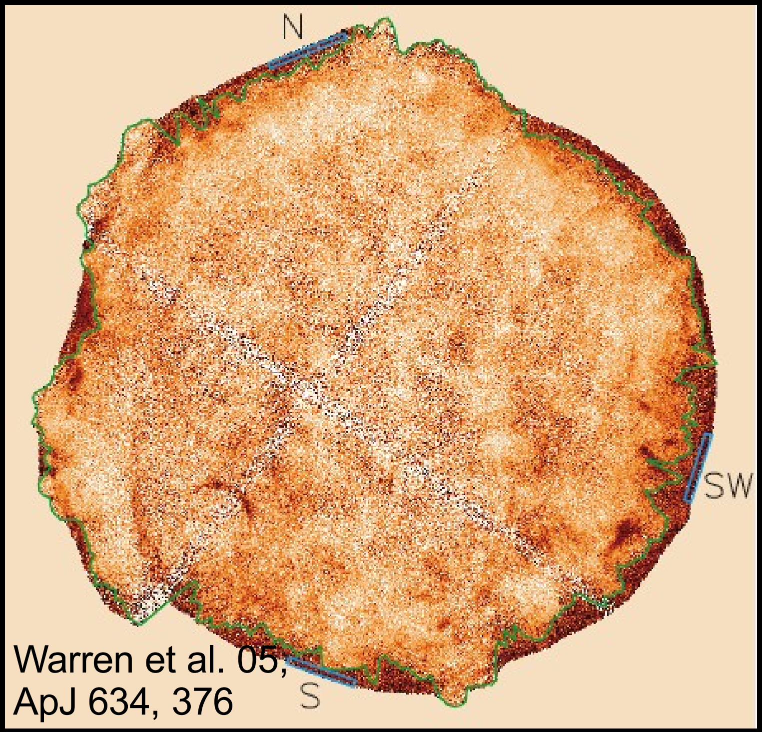
- FS is very close to CD ($R_{CD} \simeq 0.93 R_{FS}$) ⇒ Cosmic Rays are being accelerated at the FS [Warren et al. 05, ApJ 634, 376].

- CR-modified dynamics cannot be studied with γ=5/3 hydro [Ellison et al. 04, A&A 413, 189].

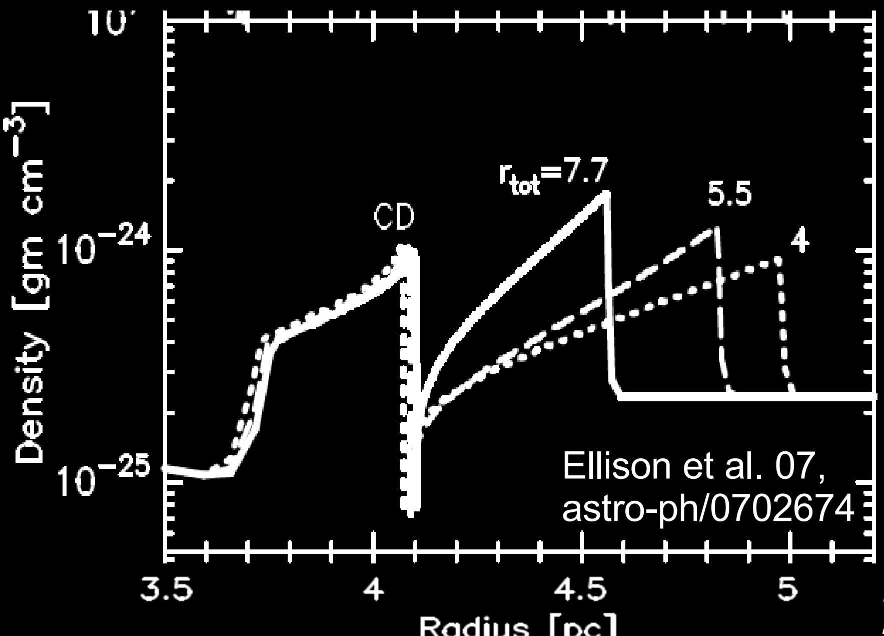
- RS is NOT accelerating CRs:
  - Not close to CD.
  - Traced by hot Fe Kα

- CR acceleration at the FS does not disturb the dynamics of the shocked ejecta [Ellison et al. 07, astro-ph/0702647].

⇒ γ=5/3 HD+NEI models are appropriate for the shocked ejecta



Warren et al. 05, ApJ 634, 376

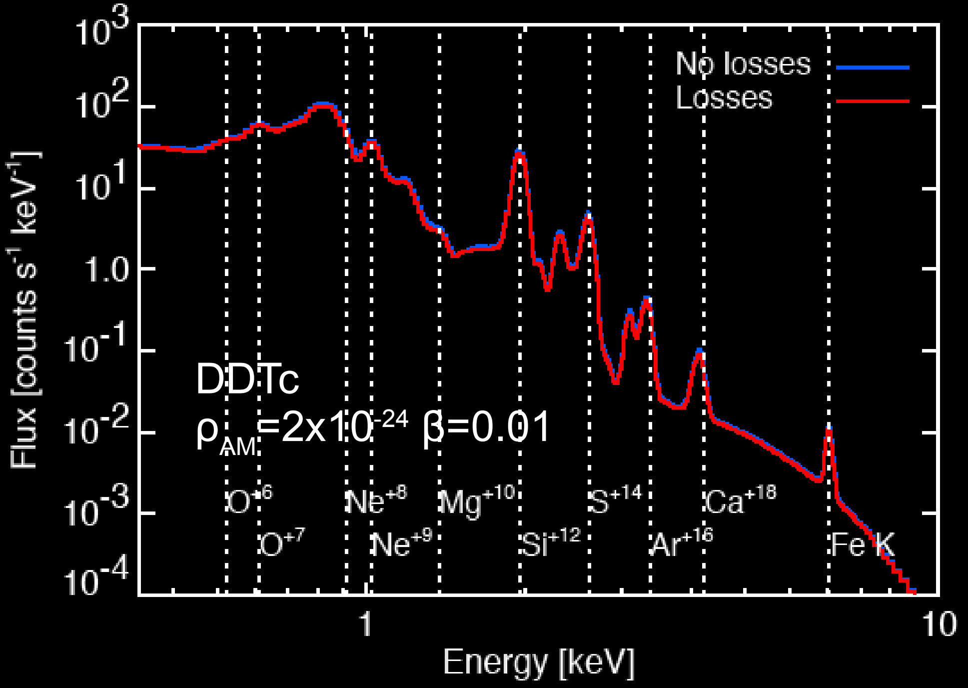


Ellison et al. 07, astro-ph/0702674

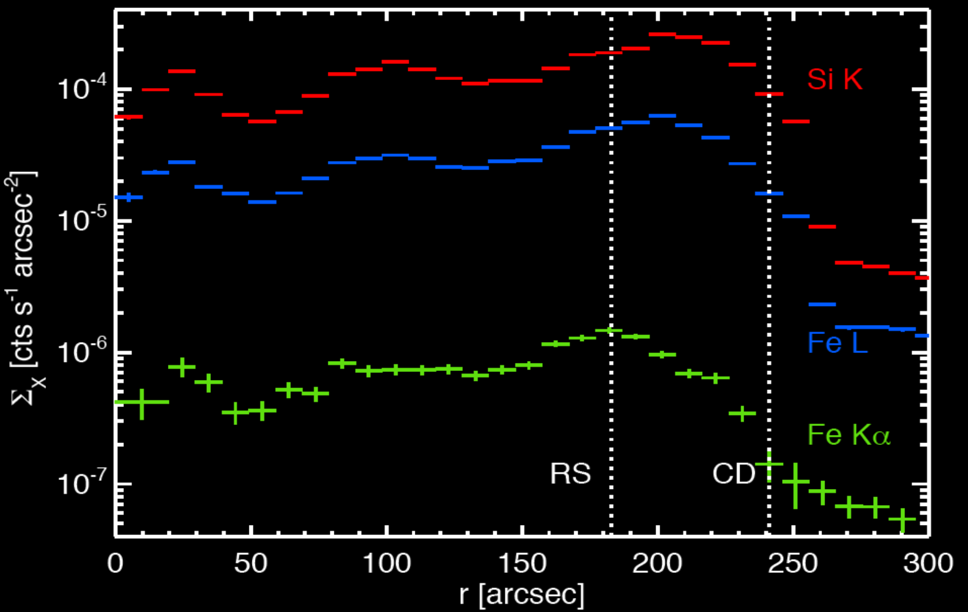
# Radiative and Ionization Losses, Thermal Conduction

Carles Badenes
KITP 03/22/07

- Radiative and ionization losses have very little impact on the X-ray spectrum from the shocked ejecta for models that are appropriate for Tycho's SNR ($\rho_{AM} \lesssim 5 \times 10^{-24}$ g cm$^{-3}$), provided the ejecta density profile is reasonable (~exponential). [Badenes et al. 03 ApJ 593, 358; Sorokina et al. 04, Ast. Let. 30, 737; Badenes et al. 05 ApJ 624, 198].




- Thermal conduction cannot be efficient in Tycho (or Kepler), because the spatial morphology of Fe K and Fe L emission requires the presence of a temperature gradient (consistent with $\beta \neq 0$ at the RS).

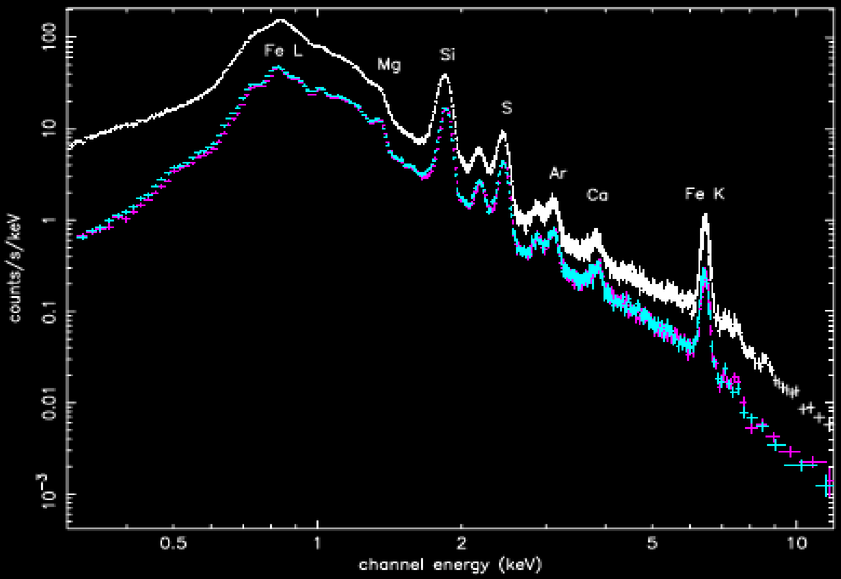


# Kepler: A Type Ia SNR with CSM Interaction

Carles Badenes
KITP 03/22/07

*Chandra* image from a deep (750 ks) exposure
[Reynolds et al., in prep. - See poster]

*XMM-Newton* spectrum
[Cassam-Chenai et al. 04, A&A 414, 545]




- Kepler has Fe-rich ejecta with almost no O emission.
- Optical observations show slow-moving, dense knots of material.
- The progenitor of this Type Ia SN modified its CSM!