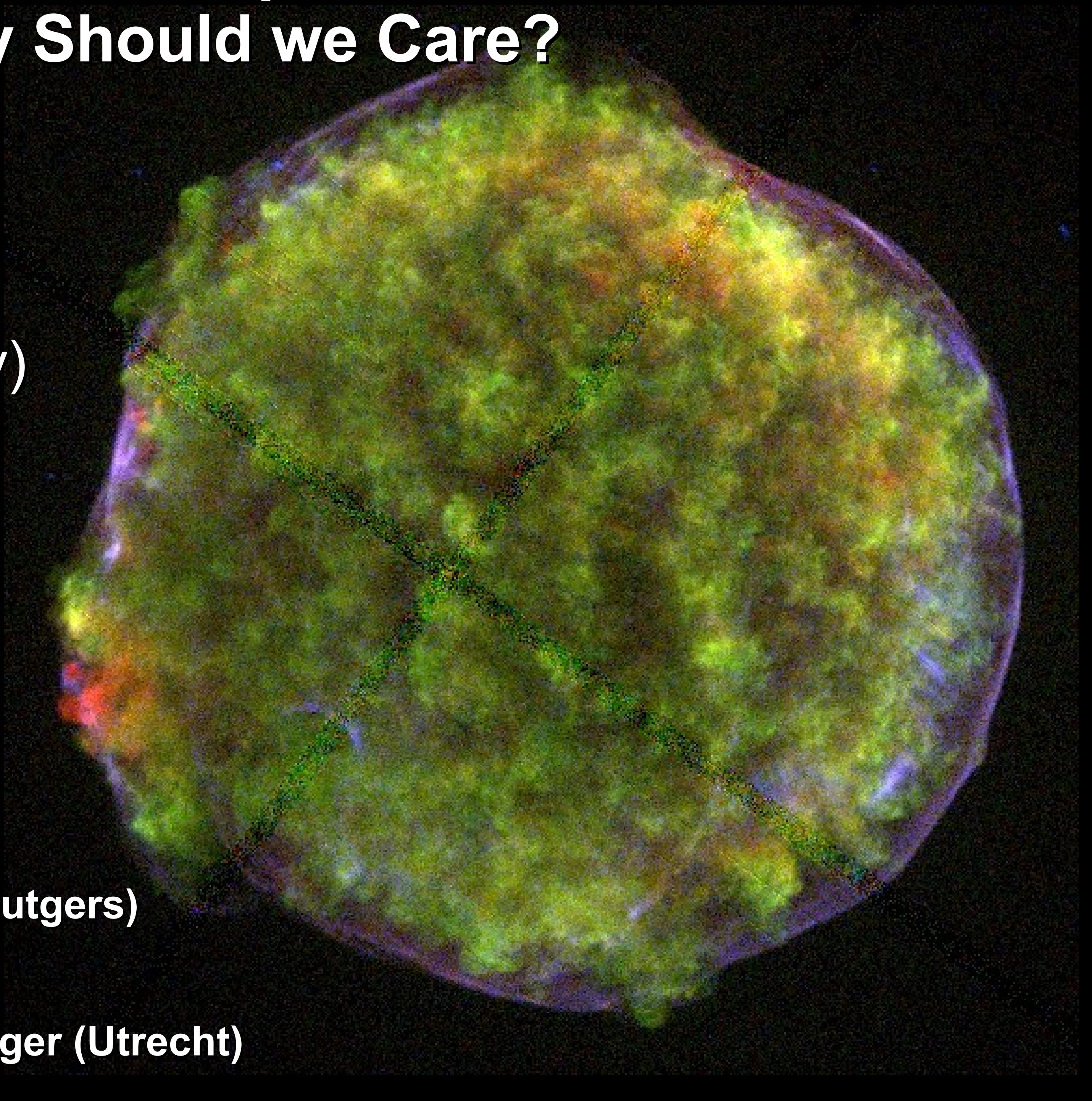
X-ray Emission from Supernova Remnants: Why Should we Care?



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AIMS AND SCOPE

- How can we know that a particular Supernova Remnant (SNR) was originated in a thermonuclear supernova explosion?
- Are the abundance determinations from the X-ray spectra of SNRs reliable? Can they be used to constrain SN explosion models?

- Overview of X-ray observations of SNRs: images and spectra.
- Interpretation of X-ray spectra: qualitative vs. quantitative arguments. The need for hydrodynamics and nonequilibrium ionization calculations.
- The Tycho SNR: constraints on SN explosion models.
- Beyond Tycho: SN1006 and Kepler.

SNRs: Light from the Ashes

Supernova Remnants (SNRs) are the result of the interaction between the SN ejecta and the surrounding ambient medium (AM) ⇒ Important clues to both the physics of the explosion and the presupernova history of the progenitor.

- Supersonic shock waves (~10^3 km.s^{-1}) heat AM and ejecta to X-ray emitting temperatures.
- Centuries after the light of the SN fades away, the ejecta are revealed once again ⇒ Light from the ashes.
- *Chandra* and *XMM-Newton* have the capability to do spatially resolved spectroscopy of extended sources.
- A number of young, ejecta-dominated SNRs in the Galaxy and the LMC are believed to be Type Ia, and have observations of excellent quality.

Chandra images of SNRs:

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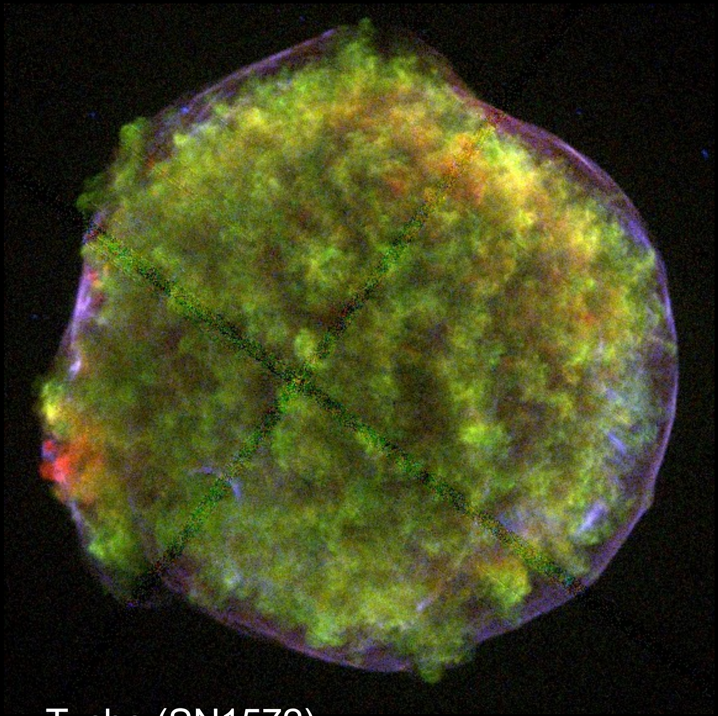
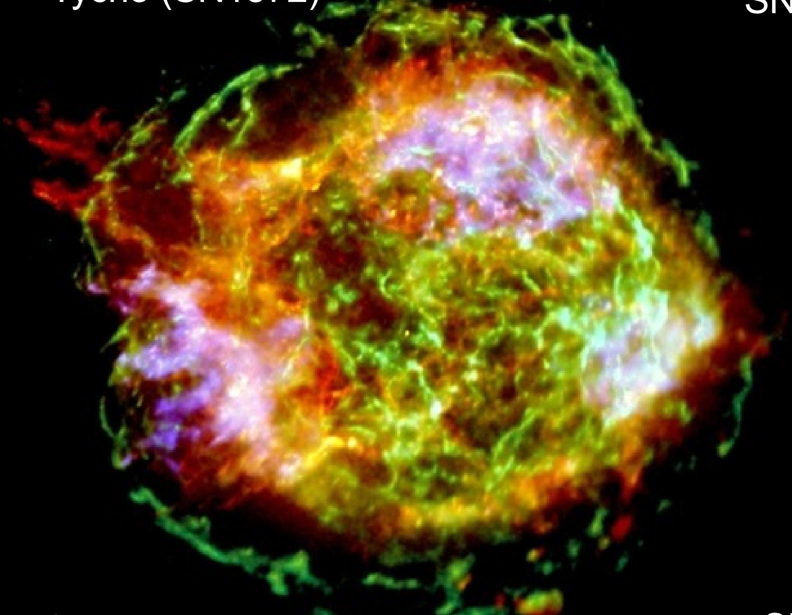
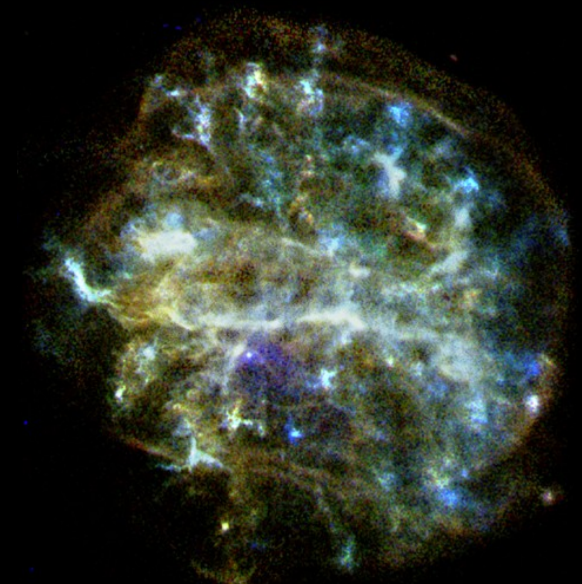


Tycho (SN1572)

SN1006



Cas A



SNR 292.0+1.8

Thermonuclear? SNRs

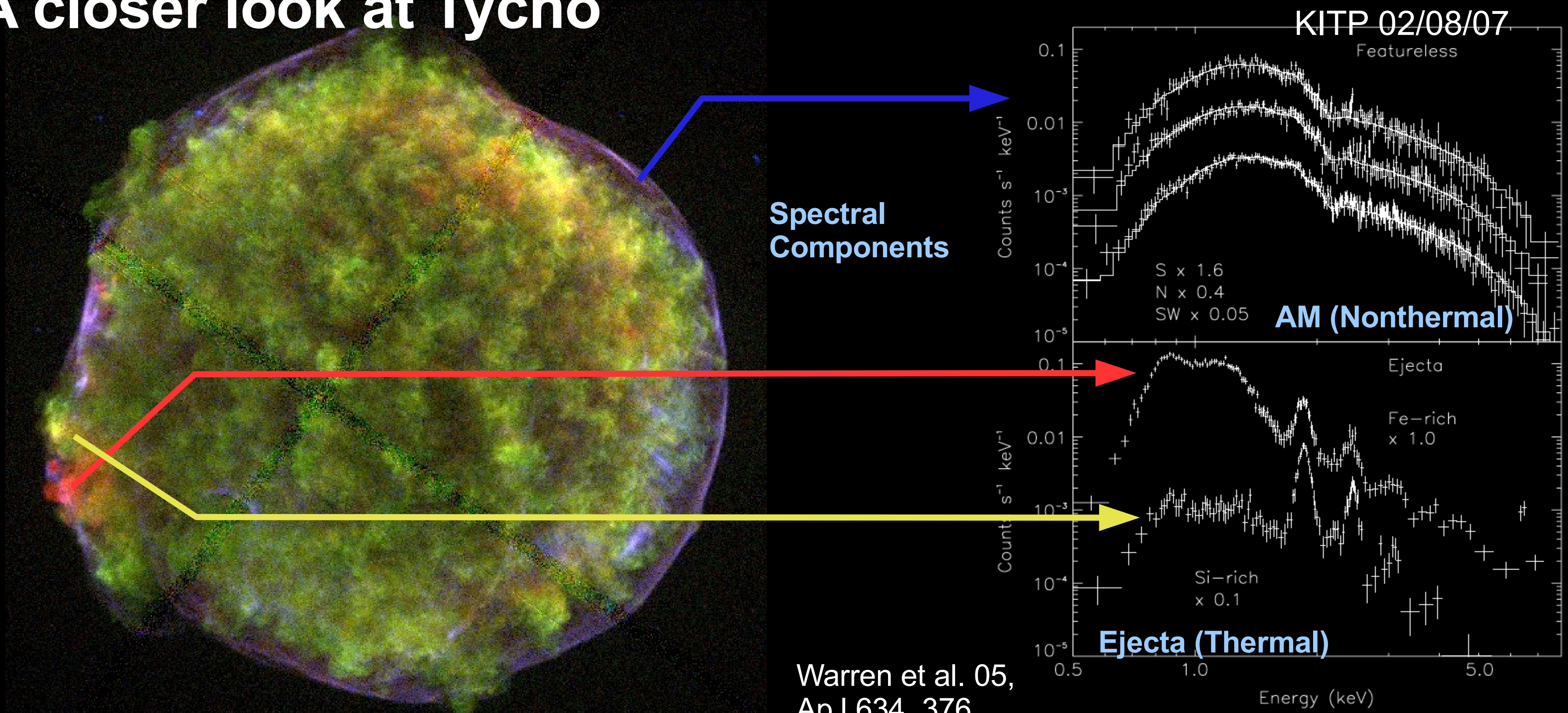
- Relatively simple ejecta structure.
- Smooth, symmetric forward shocks.
- Relatively simple SNR dynamics.

Core collapse SNRs

- Complex ejecta structure.
- Broken, asymmetric forward shocks.
- Complex SNR dynamics.

Images: Warren et al. 05, ApJ 634, 376; Hughes et al. in preparation; Hwang et al. 04, ApJ 615, L117; Hughes et al. 01, ApJ 559, L53

A closer look at Tycho

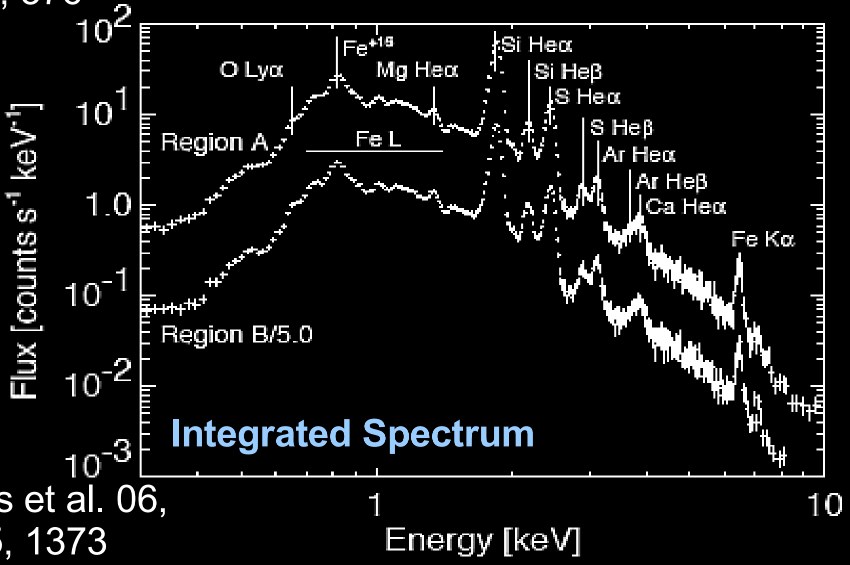


Spectral Components

AM (Nonthermal)

Ejecta (Thermal)

Warren et al. 05, ApJ 634, 376

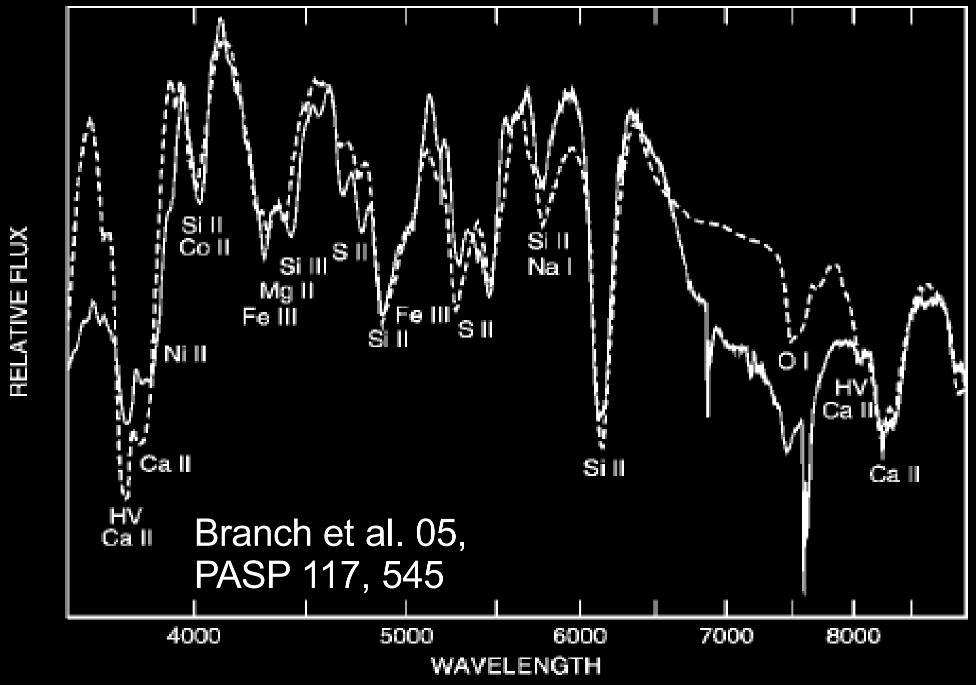


Integrated Spectrum

Badenes et al. 06, ApJ 645, 1373

- No large asymmetries are evident in the ejecta or AM.
- The AM emission is a nonthermal continuum [cosmic ray acceleration].
- The X-ray emission and dynamics of Tycho are dominated by the ejecta.

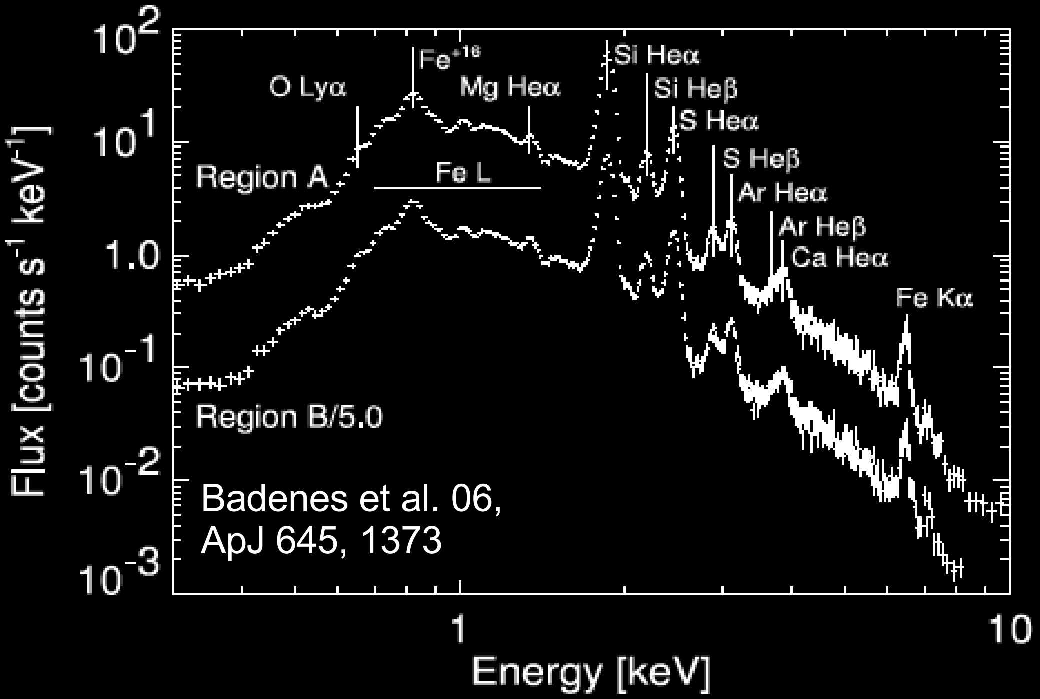
Spectra: SNe vs. SNRs



Branch et al. 05,
PASP 117, 545

SN 1994 D (day -1)

- Emission/absorption features from O, Na, Mg, Si, S, Ca, Fe, Co, Ni.
- Lines are blended (velocity). Line identification is an issue.
- Excellent statistics (for nearby SNe).
- Modeling and interpretation are challenging.



Badenes et al. 06,
ApJ 645, 1373

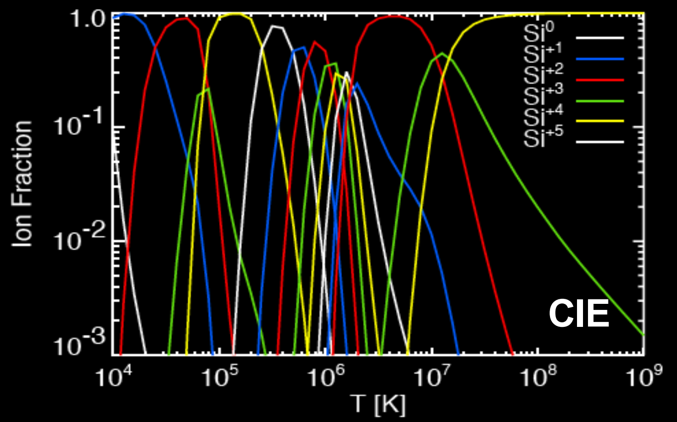
Tycho SNR (day ~22400)

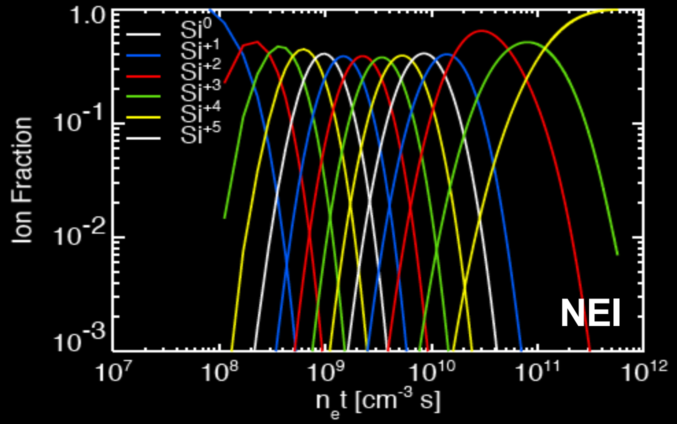
- Emission lines from O, Mg, Si, S, Ar, Ca, Fe.
- Lines are blended (resolution). Line identification is an issue.
- X-ray statistics.
- Modeling and interpretation are challenging.

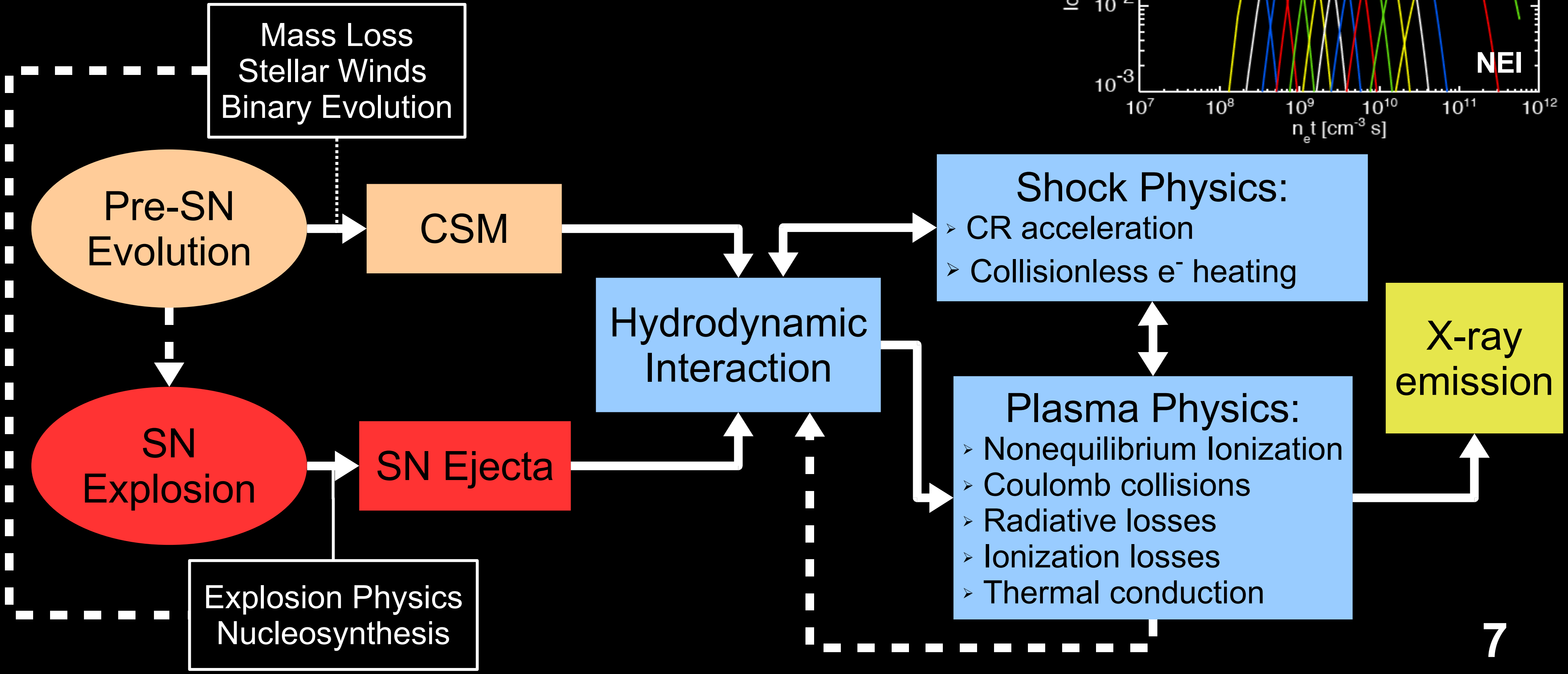
SNRs: HD+NEI Simulations

The hot plasma in SNRs is in nonequilibrium ionization (NEI) ⇒ the X-ray emission is coupled to the hydrodynamics of the SNR

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







Mass Loss
Stellar Winds
Binary Evolution

Pre-SN Evolution

CSM

SN Explosion

SN Ejecta

Explosion Physics
Nucleosynthesis

Hydrodynamic Interaction

Shock Physics:
- CR acceleration
- Collisionless e⁻ heating

Plasma Physics:
- Nonequilibrium Ionization
- Coulomb collisions
- Radiative losses
- Ionization losses
- Thermal conduction

X-ray emission

SNRs: A Practical Example

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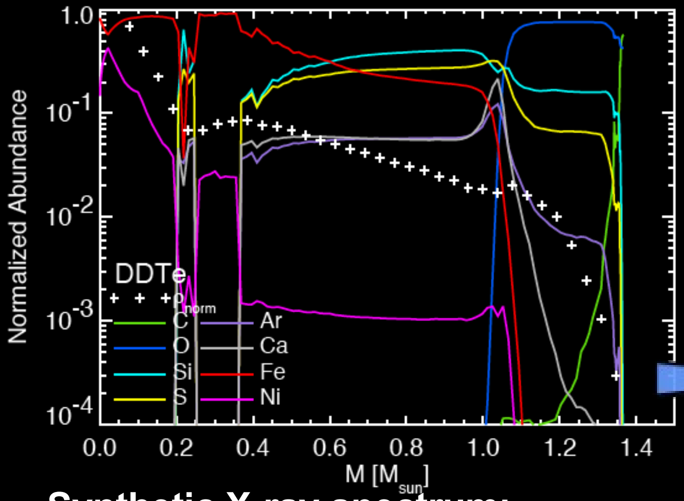
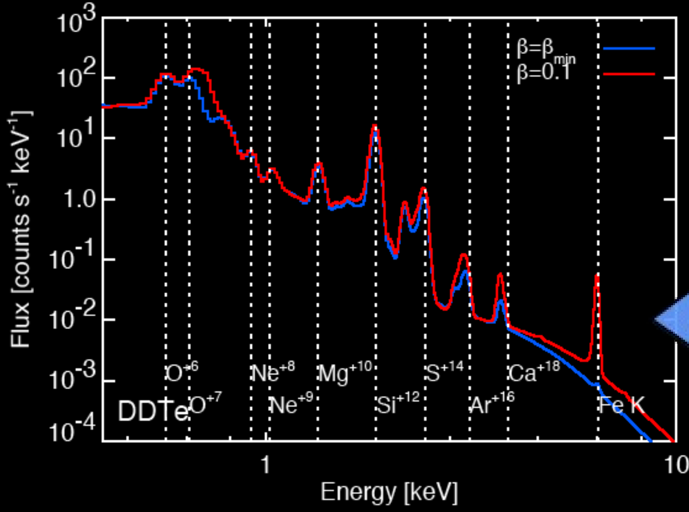
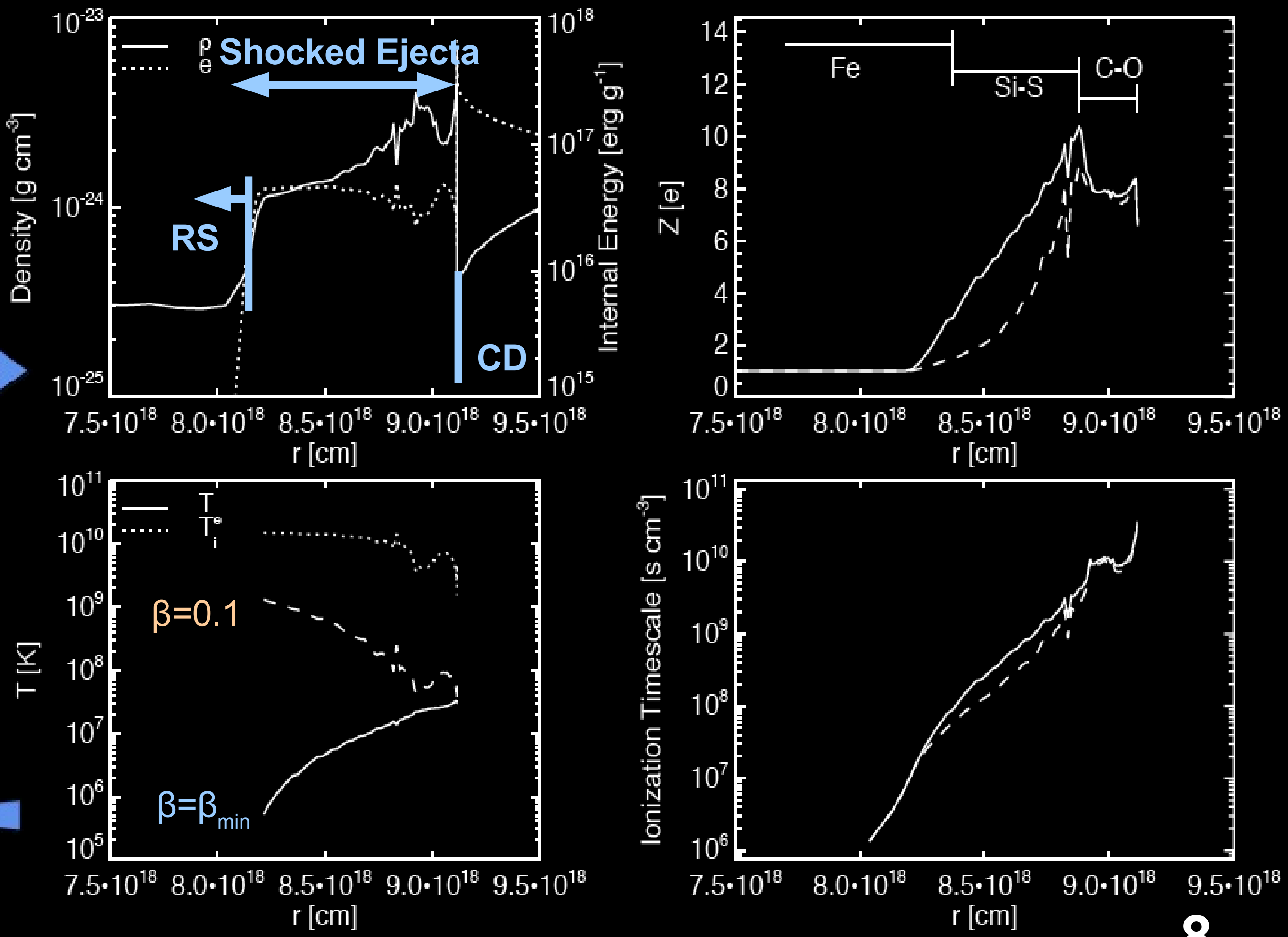
- 1D simulation, uniform AM. Radiative + ionization losses included.
- Parameters: AM density, $\rho_{AM}=10^{-24}$ g.cm^{-3}; SNR age, $t_{SNR}=430$ yr; amount of collisionless e^- heating at the RS, $\beta[\equiv\varepsilon_{e,s}/\varepsilon_{i,s}]=\beta_{min}...0.1$.
- Different chemical elements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

SN Explosion model (DDTe):



Synthetic X-ray spectrum:



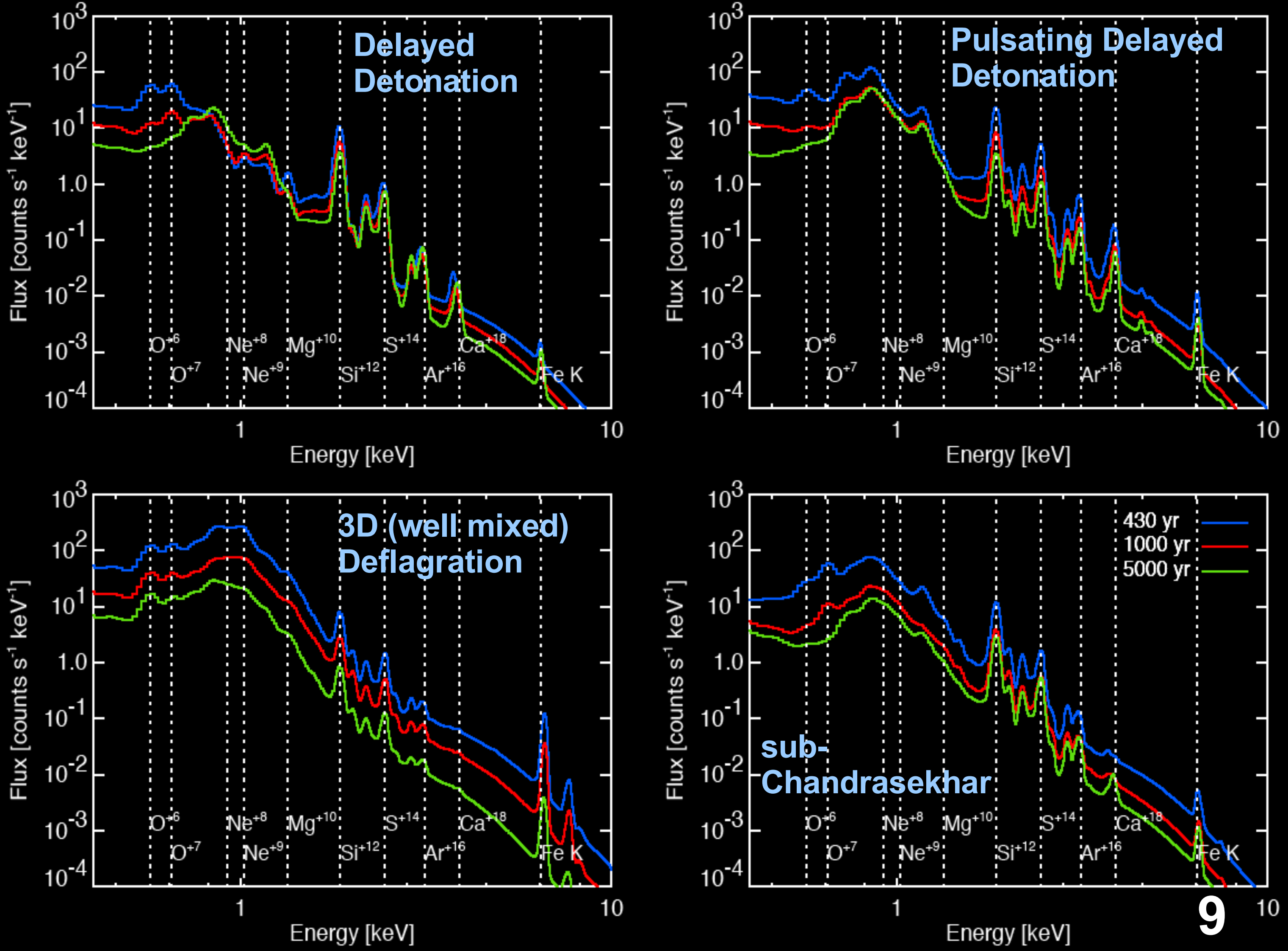


HD + NEI simulation

SNRs: Explosion mechanism vs. X-ray spectrum

HD+NEI simulations based on different Type Ia SN explosion models predict different X-ray spectra for the ejecta emission

- A grid of synthetic X-ray spectra can be created for each Type Ia SN explosion model [ρ_{AM}, t_{SNR}, β].
- More Details:
  - Badenes et al. 2003, ApJ 593, 358.
  - Badenes et al. 2005, ApJ 624, 198.



Cosmic Ray Acceleration at the Forward Shock of Tycho

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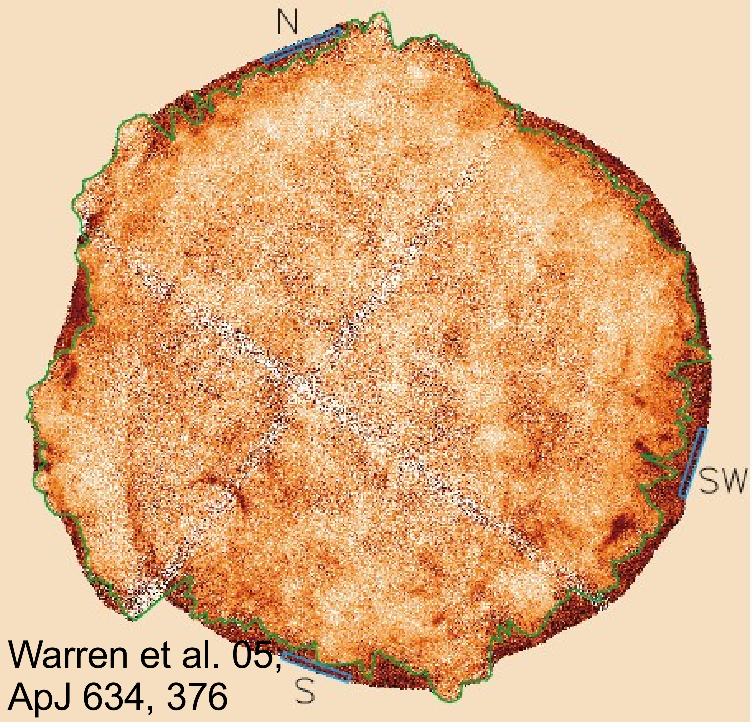
- FS is very close to CD ($R_{CD} \simeq 0.93 R_{FS}$) ⇒ Cosmic Rays are being accelerated at the FS [Warren et al. 05, ApJ 634, 376].

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

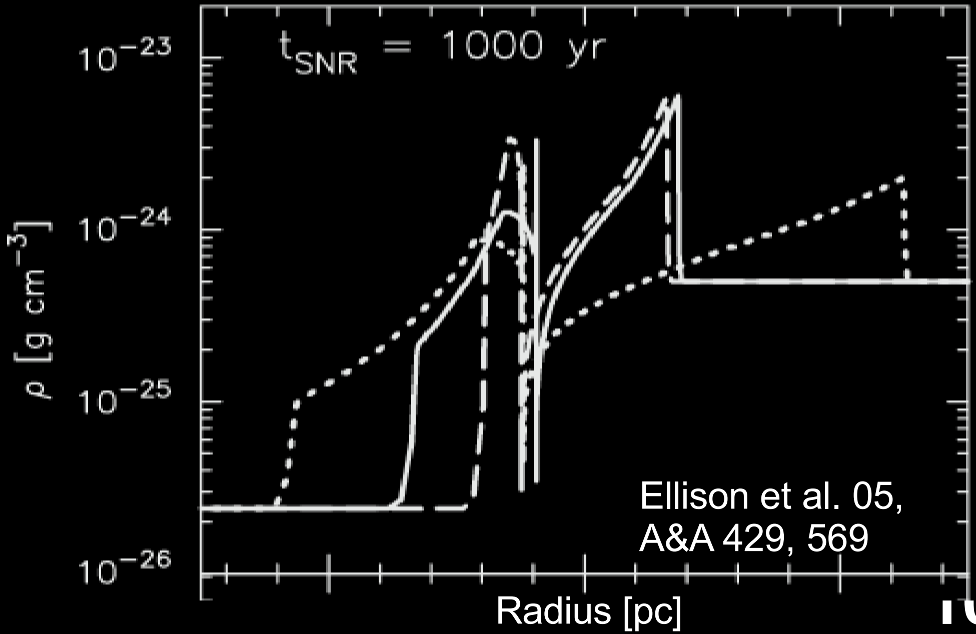
- RS is NOT accelerating CRs:
  - Not close to CD.
  - Traced by hot Fe Kα

- CR acceleration at the FS does not appear to disturb the dynamics of the shocked ejecta [Blondin & Ellison 01, ApJ 560, 244].

⇒ $\gamma=5/3$ HD+NEI models seem appropriate for the shocked ejecta



Warren et al. 05, ApJ 634, 376



Ellison et al. 05, A&A 429, 569

Models vs. Data – The Losers

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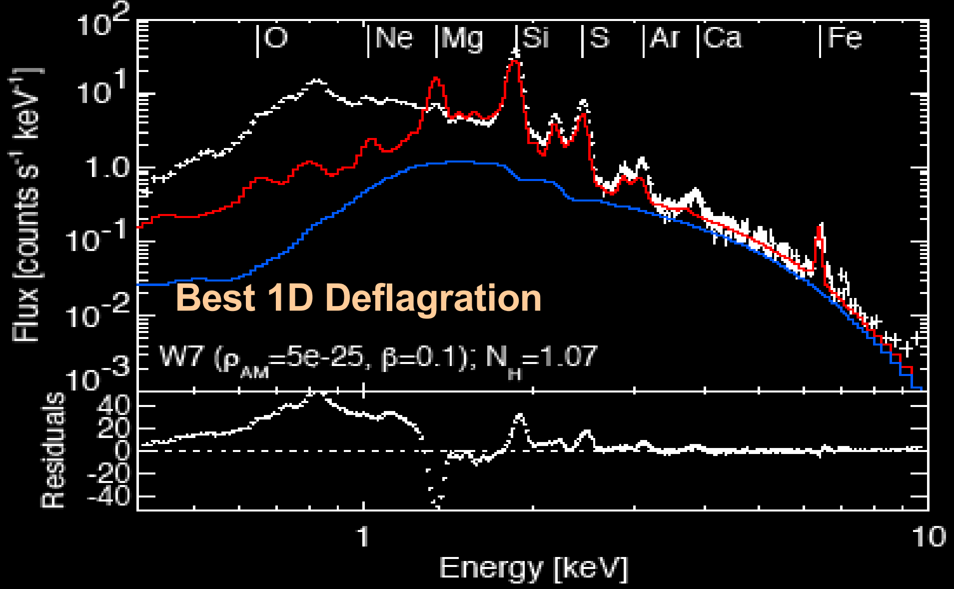
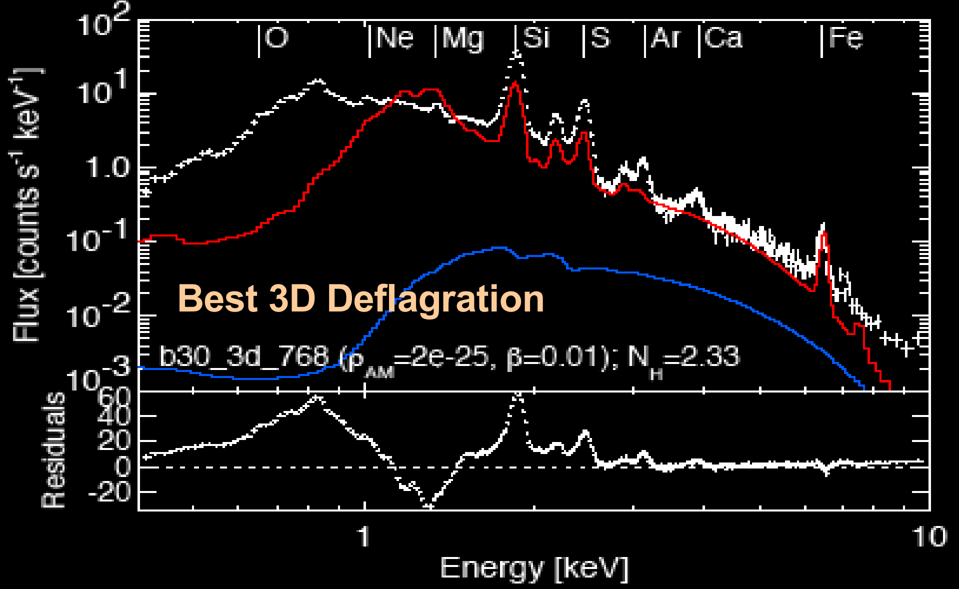
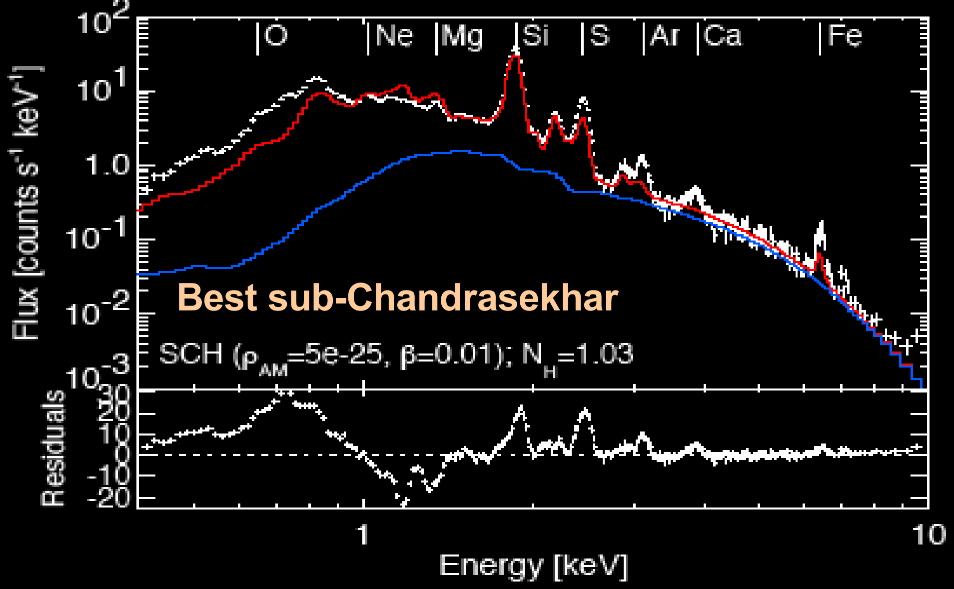
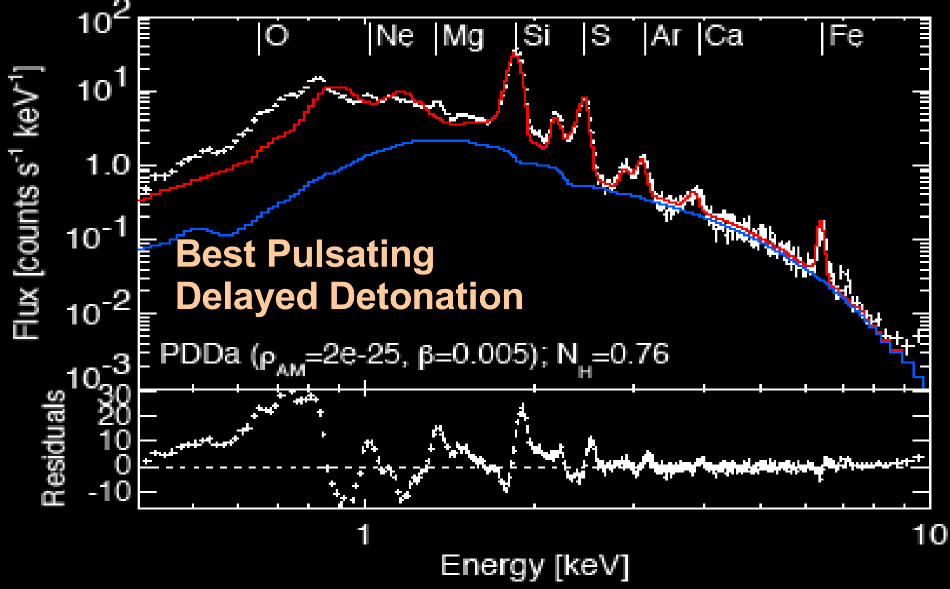
- The age of Tycho is known (435 yr) ⇒ only ρ_{AM} and β can be varied.
- FS: $\Gamma=2.72$ power law, $F=7.4\text{-}8.9$ photons.cm^{-2}s^{-1}keV^{-1} [Fink et al. 94 A&A 283,635].
- $N_H \sim 0.6\times10^{22}$ cm^{-2}.







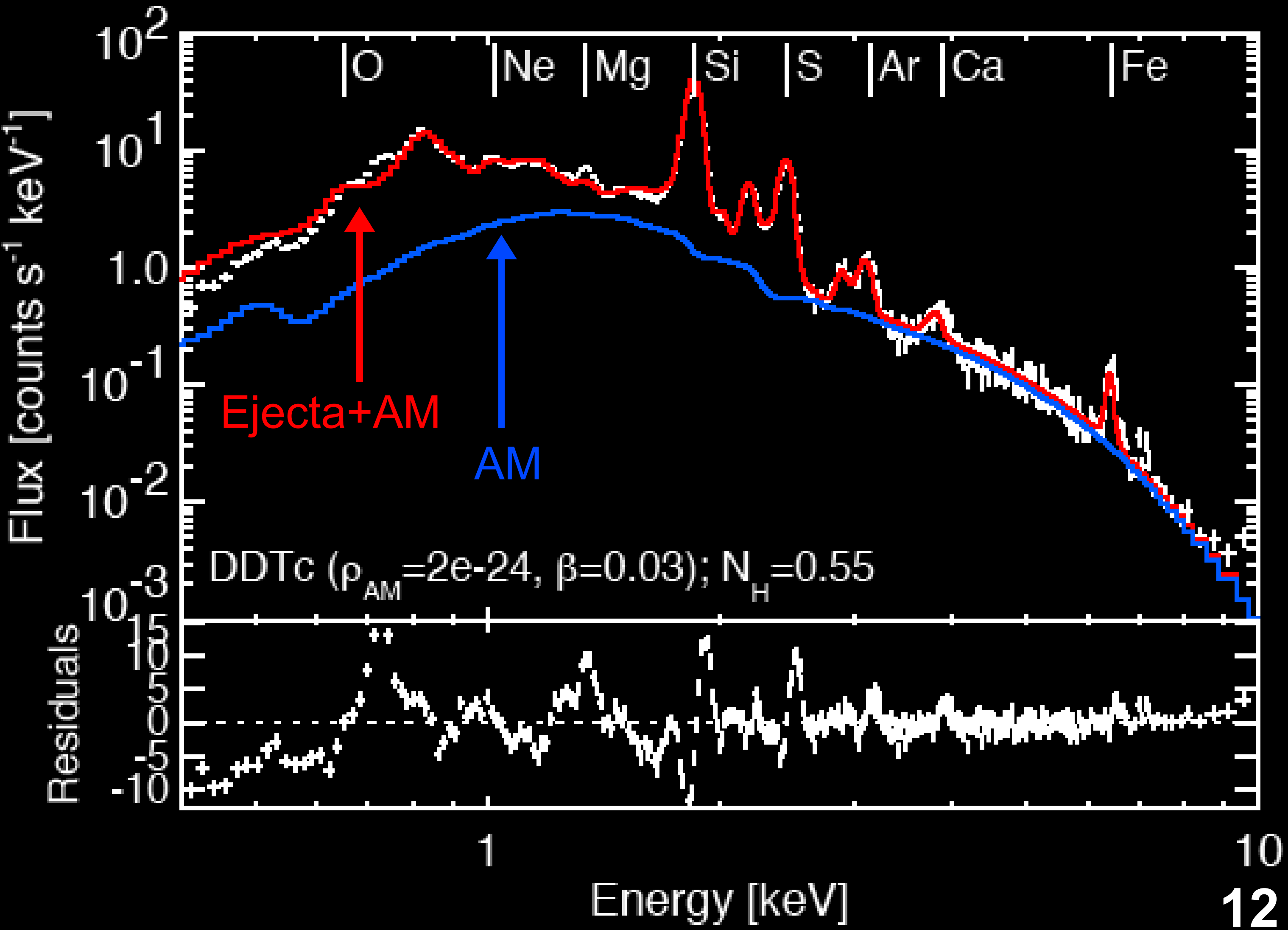


Models vs. Data – The Winner

- Most Type Ia SN explosion models don't work very well. 1D Delayed detonations are the only exception.
- Best model: **DDTc** (ρ_{AM}=2x10^{-24} g.cm^{-3}, β=0.03).

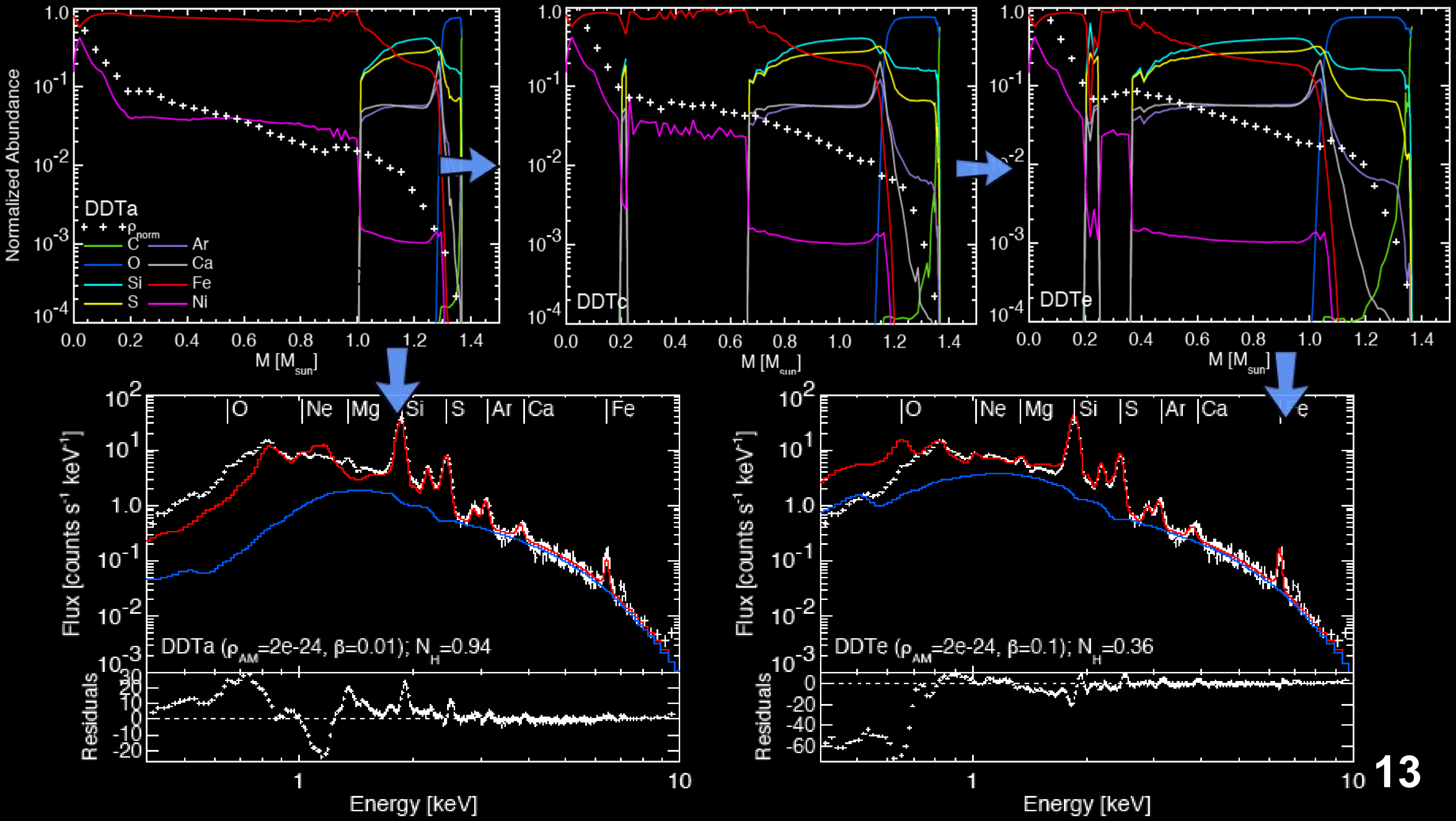
Things to note:

- Only N_H and the normalizations are fitted.
- The ejecta model reproduces the emission from ALL elements: O, Si, S, Ar, Ca, and Fe.
- Fit is very good, but not perfect.
- Continuum is mostly nonthermal AM emission.



Models vs. Data – The Winner's Close Relatives

- Other delayed detonations are also successful. E<1keV emission ⇒ strong constraints on the amount of ^{56}Ni and O synthesized in the explosion ⇒ ρ_{tr}.



Conclusions

- 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. Best model: DDTc (E_k=1.16·10^{51} erg; Yields (in $M_\odot$) Fe: 0.8, O: 0.12, Si:0.17, S:0.13, Ar:0.033, Ca: 0.038). All other explosion paradigms FAIL: Pulsating delayed detonations, 1D Deflagrations, sub-Chandrasekhar explosions and 3D Deflagrations.

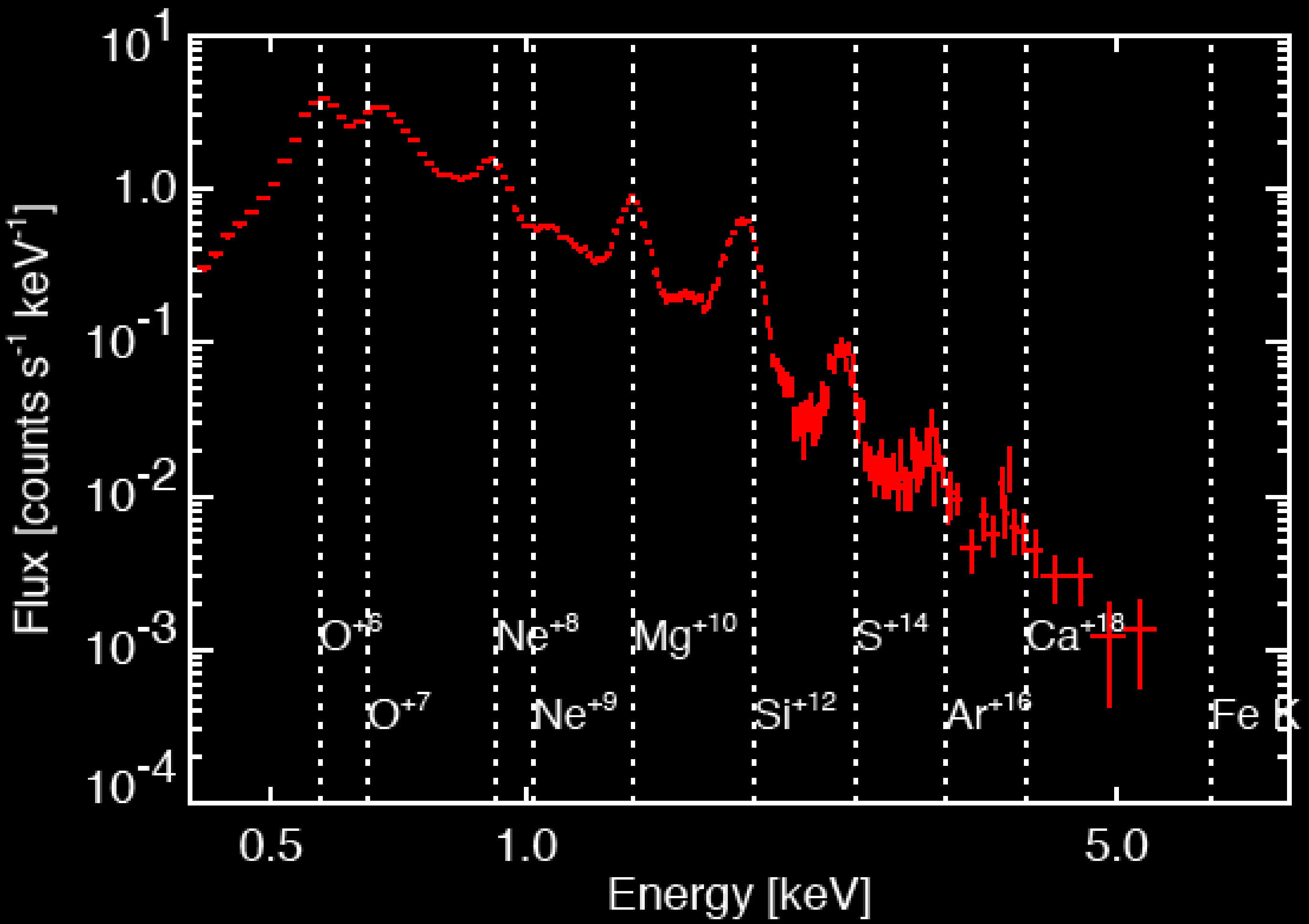
- X-ray spectra AND SNR dynamics **MUST** form a consistent picture.

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

- Some aspects of Type Ia SN explosions can **ONLY** be studied through SNRs!

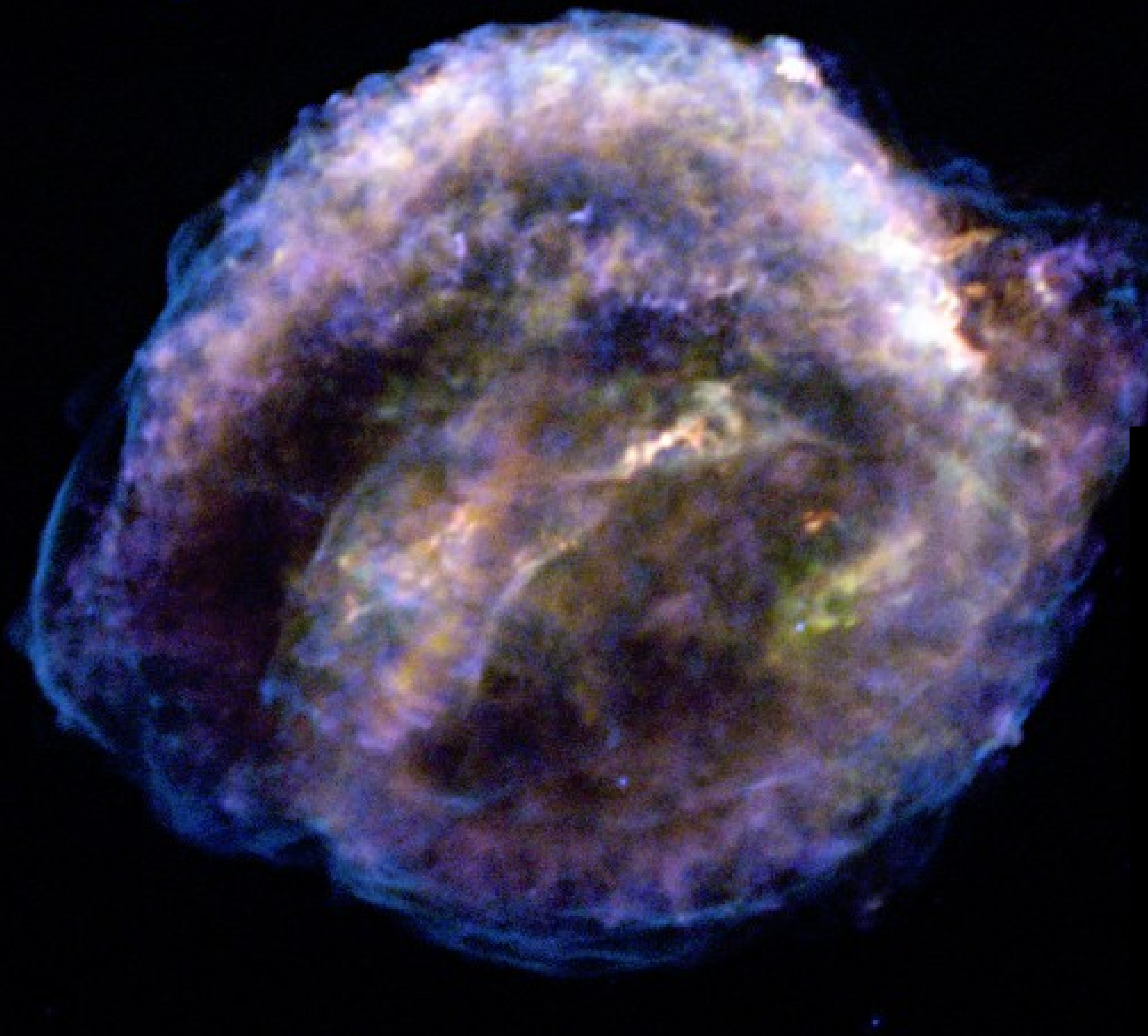
More details: Badenes et al. 2006, ApJ 645, 1373

SN1006: A younger Type Ia SNR



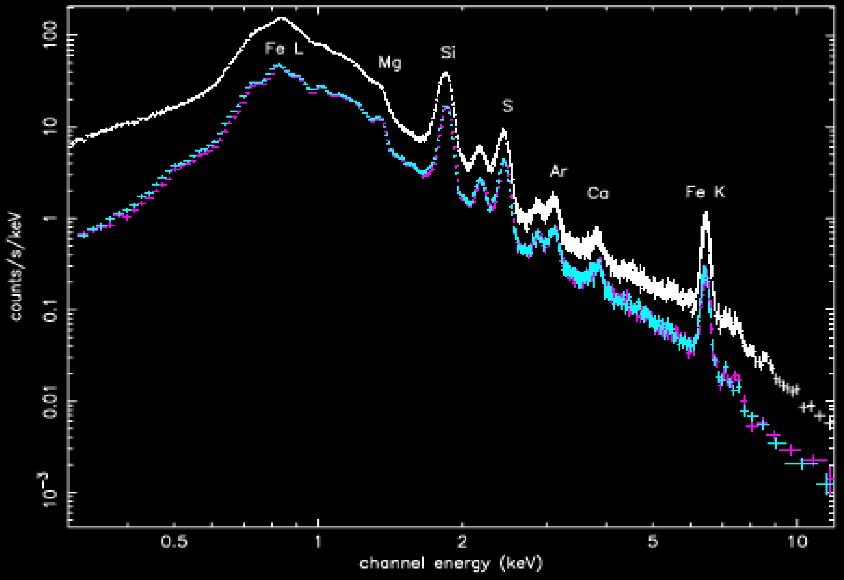
- Very low density AM ⇒ Dynamically younger than Tycho!
- The thermal spectrum shows O, Ne, Mg, Si, S, Ar and Ca. No Fe!
- Work in progress, but DDT models appear to work much better than others.

Kepler: A Type Ia SNR with CSM Interaction



Chandra image from a deep (750 ks) exposure
[Reynolds et al., in preparation]

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 in the NW.
- The progenitor of this Type Ia SN modified its CSM!

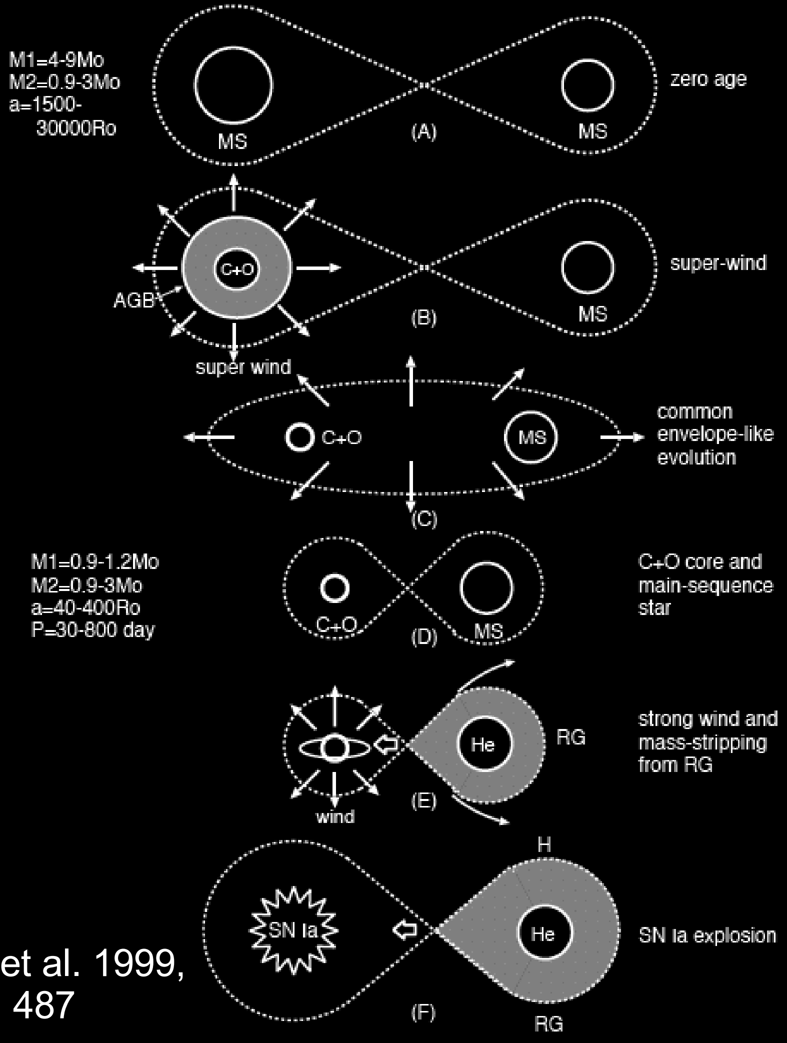
SN Ia Progenitors: Accretion Winds

Accretion Winds

(Hachisu et al. 1996, 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 1997, A&A 322, L9; Hachisu et al. 1999, ApJ 519, 314; Hachisu et al. 1999, ApJ 522, 487; Langer et al. 2000, A&A 362, 1046; Han & Podsiadlowski 2004, MNRAS 350, 1301].
- The viability of the accretion wind mechanism is debated. Some authors claim that a H-accreting WD **cannot** grow to 1.38 $M_\odot$ [Cassisi et al. 1998, ApJ 496, 376].



Hachisu et al. 1999, ApJ 522, 487

SN Ia Progenitors: Accretion Wind Outflows

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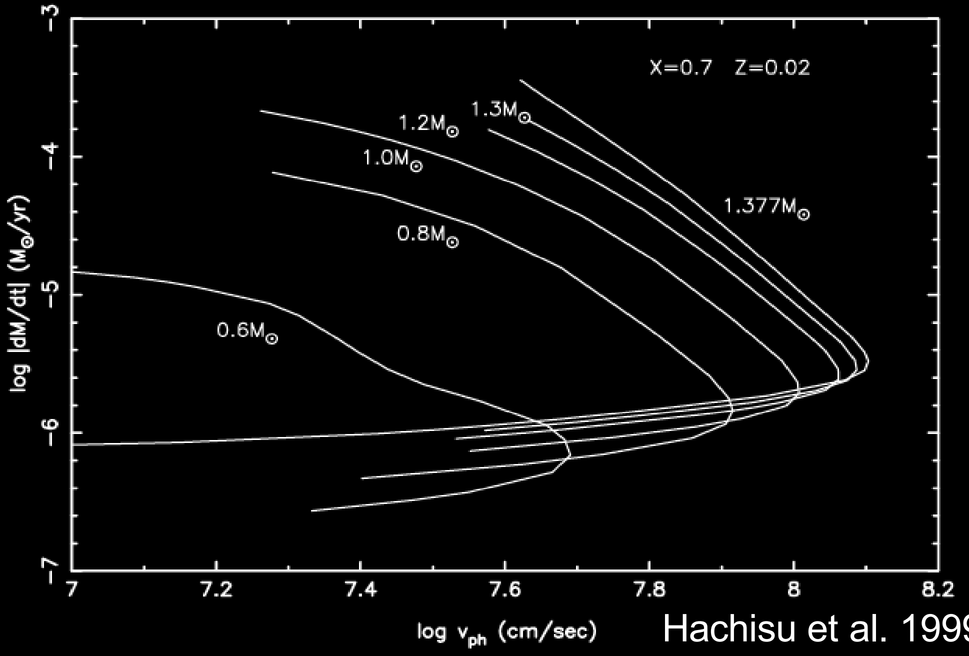
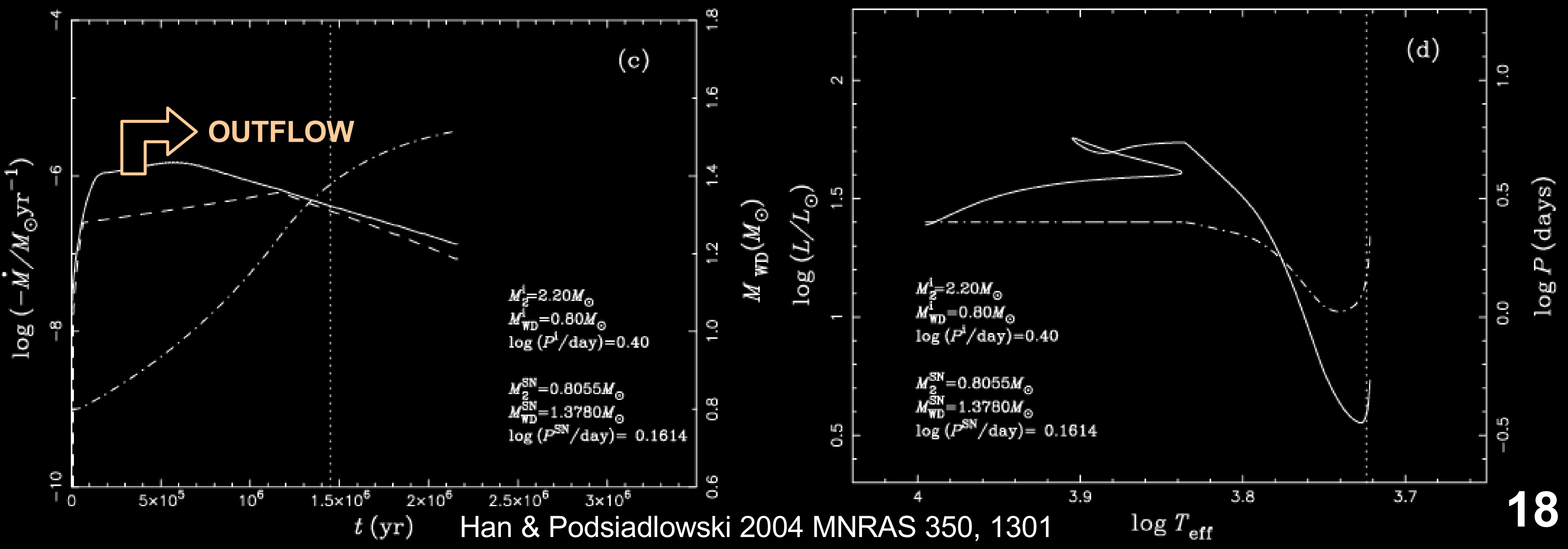
- Part of the material accreted from the companion is not burnt at the WD surface. It escapes the binary system as a fast accretion wind outflow.
- Typical scales:
  - $dM/dt_{of} \sim 10^{-7}$ to $10^{-6}\ M_{\odot}yr^{-1}$.
  - $t_{of} \sim 10^{6}$ yr.
  - $u_{of} \sim 10^{3}$ km s^{-1}.



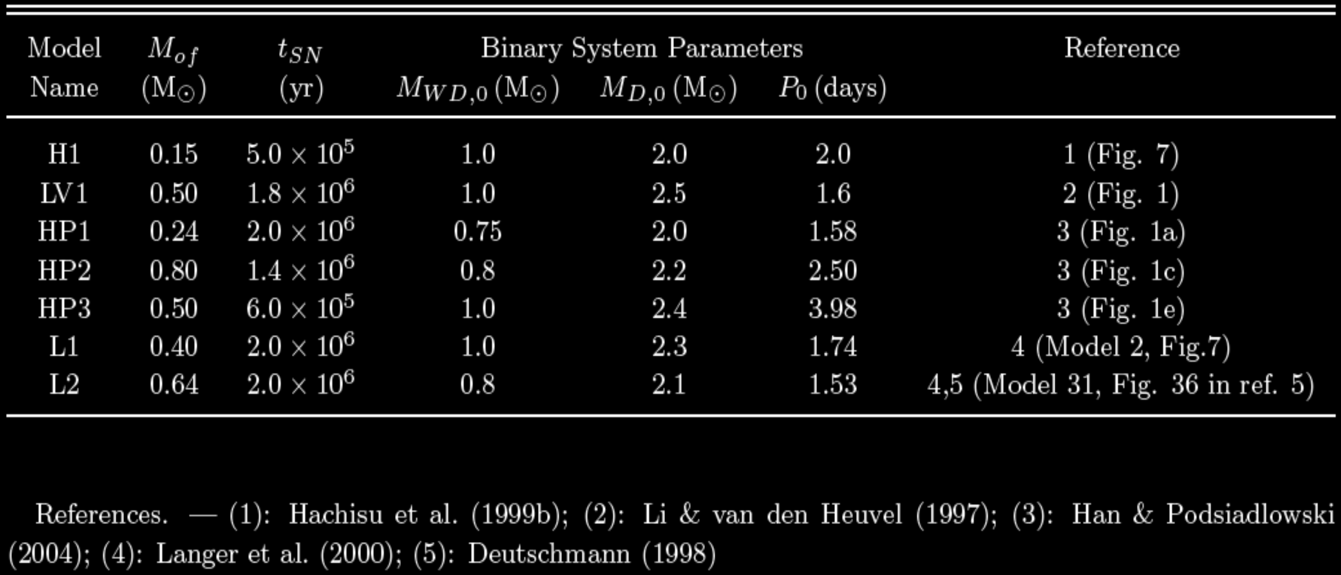
Hachisu et al. 1999, ApJ 522, 487



Han & Podsiadlowski 2004 MNRAS 350, 1301

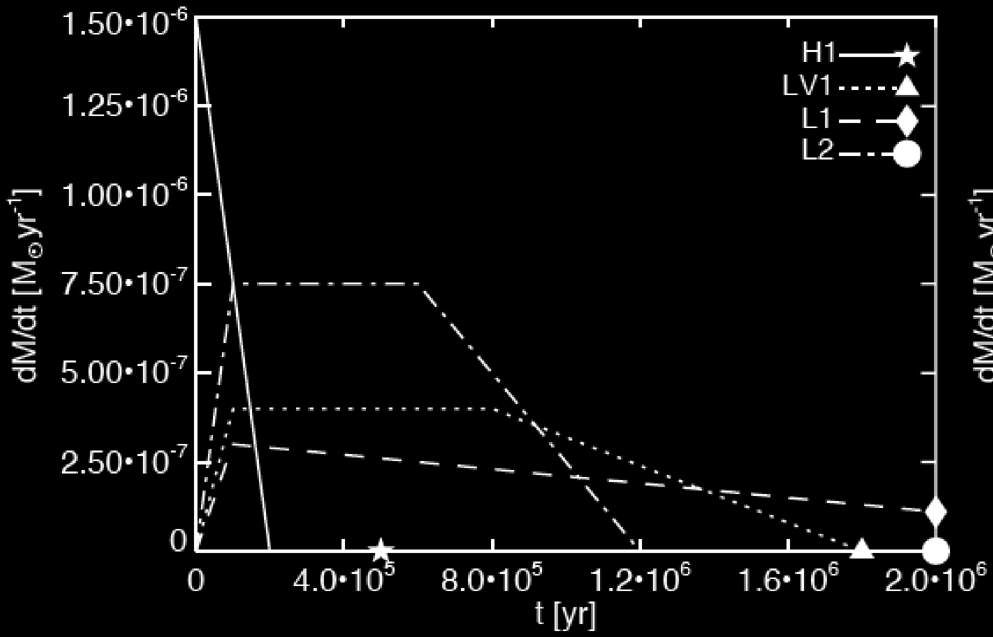
SN Ia Progenitors: Modeling Accretion Wind Outflows

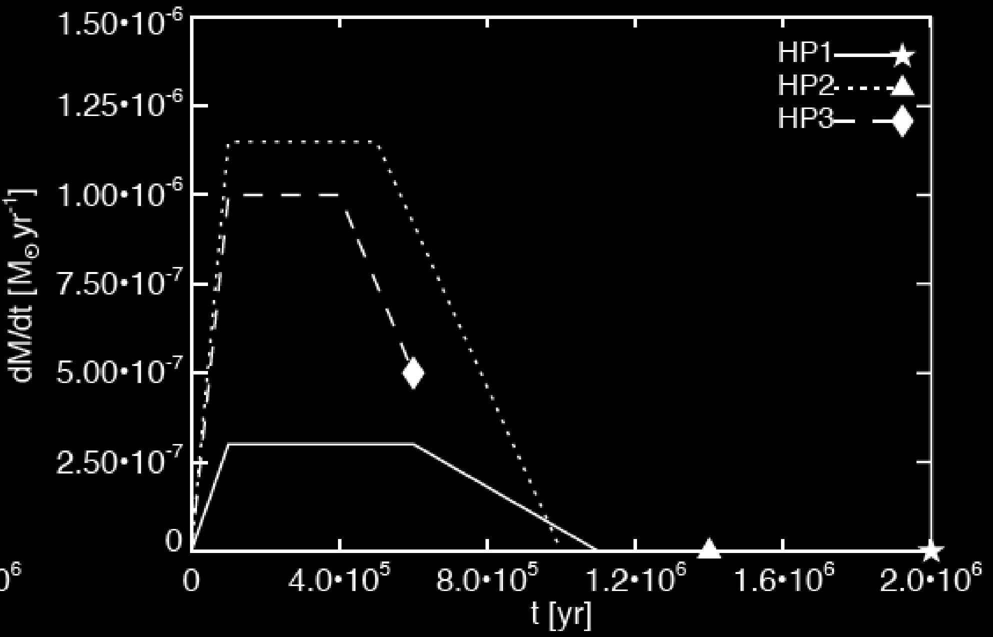
- Different authors make similar predictions for the outflows from Type Ia progenitors.
- The behavior of the outflows can be approximated with simple models:



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	5.0×10^5	1.0	2.0	2.0	1 (Fig. 7)
LV1	0.50	1.8×10^6	1.0	2.5	1.6	2 (Fig. 1)
HP1	0.24	2.0×10^6	0.75	2.0	1.58	3 (Fig. 1a)
HP2	0.80	1.4×10^6	0.8	2.2	2.50	3 (Fig. 1c)
HP3	0.50	6.0×10^5	1.0	2.4	3.98	3 (Fig. 1e)
L1	0.40	2.0×10^6	1.0	2.3	1.74	4 (Model 2, Fig.7)
L2	0.64	2.0×10^6	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)



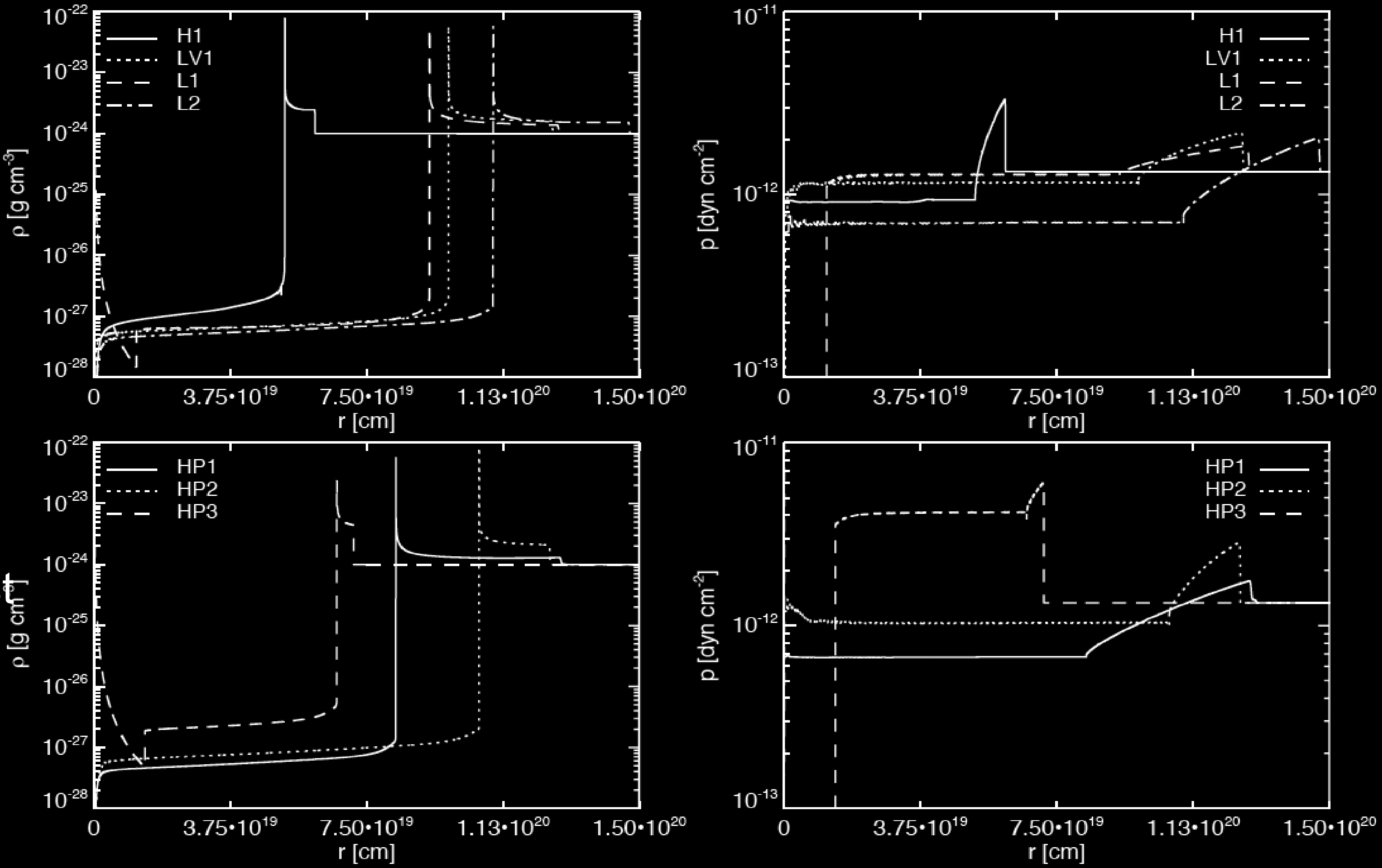


SN Ia Progenitors: Sculpting the CSM

- 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 ρ_{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: Sculpting the CSM

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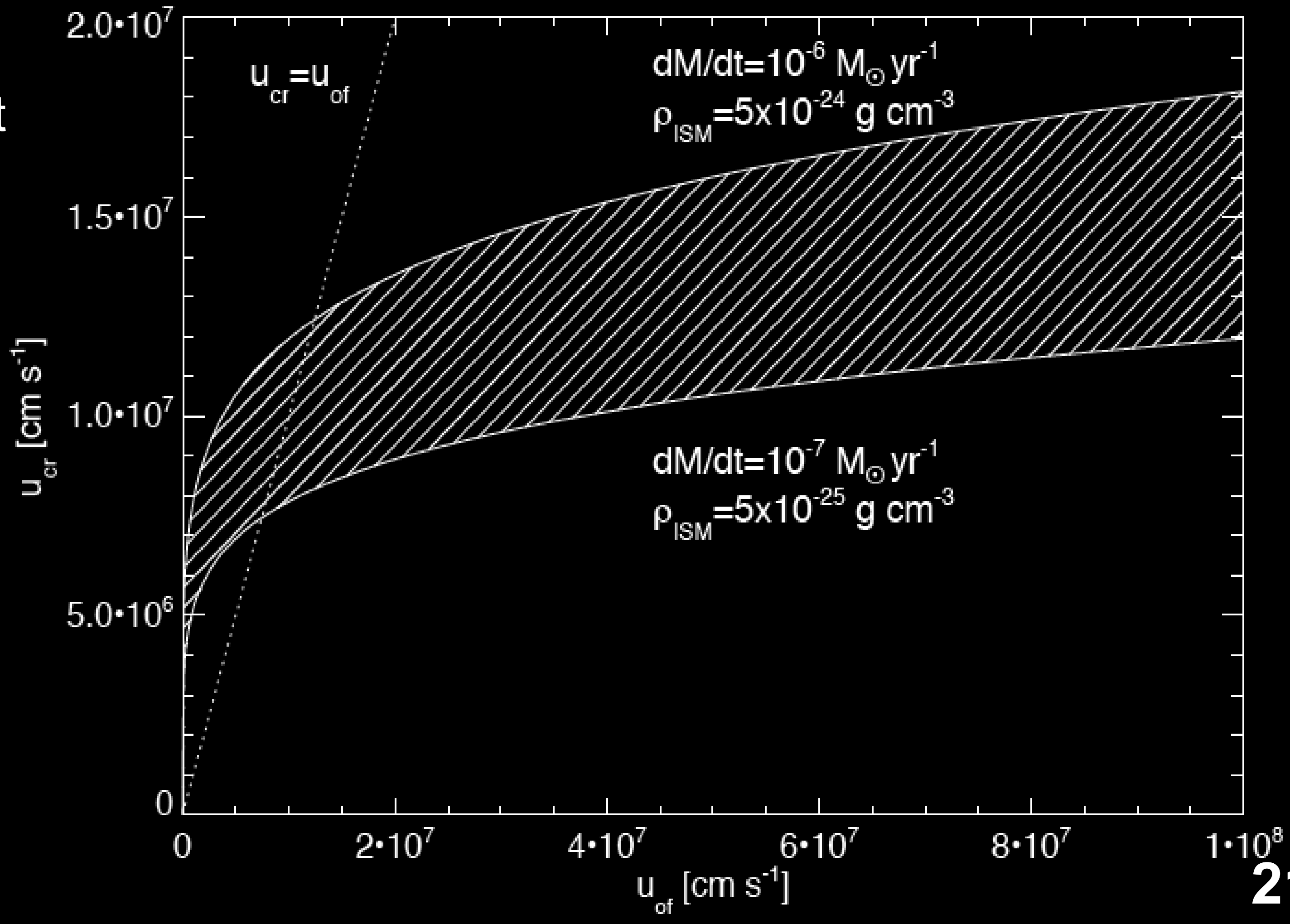
- The formation of large cavities is inevitable if u_{of} is above a critical limit u_{cr} [Koo & Mc Kee 1992, ApJ 388, 93]:

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

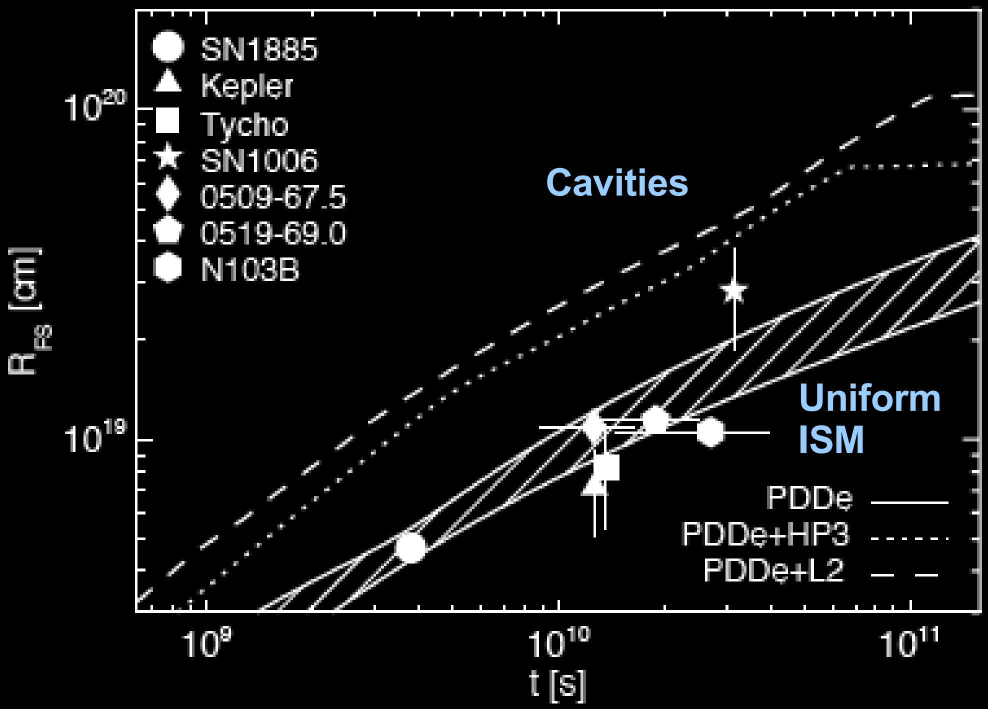
$u_{of}>u_{cr}$ ⇒
Radiative losses do not affect the shocked outflow. Cavity is energy-driven.

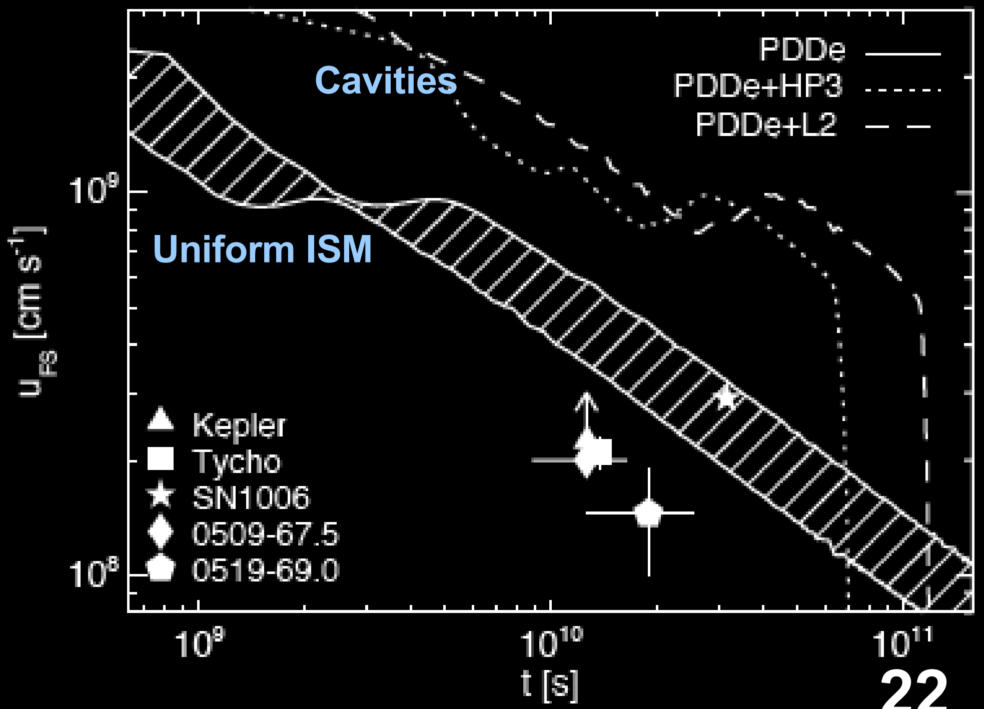
$u_{of}<u_{cr}$ ⇒
Radiative losses affect the shocked outflow. Cavity is momentum-driven.



SN Ia Progenitors: Constraints from SNR dynamics

- 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. 2005, 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

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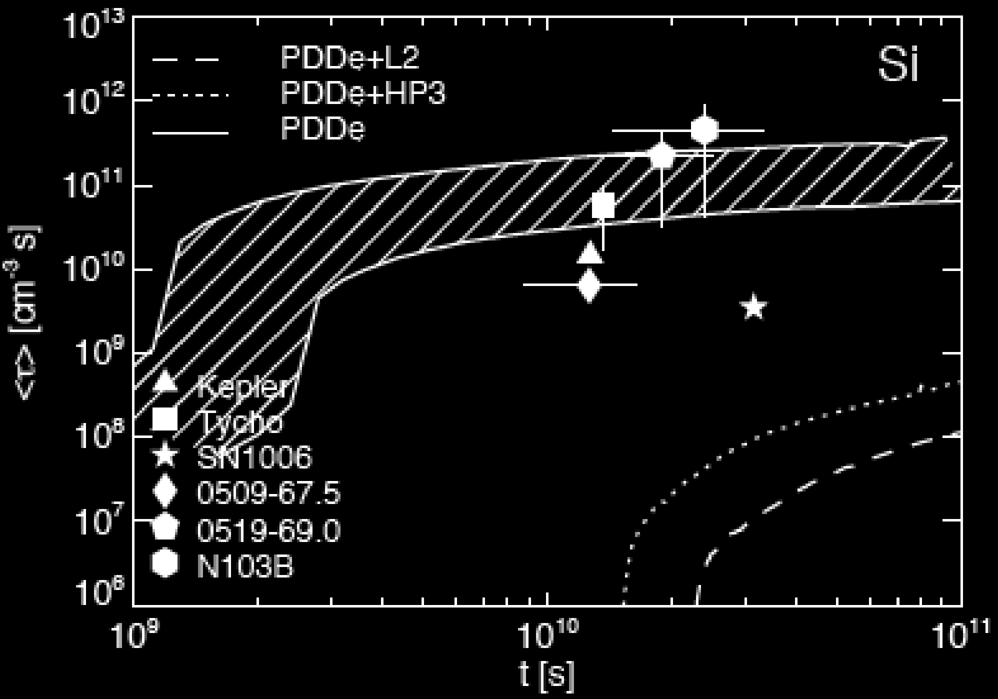
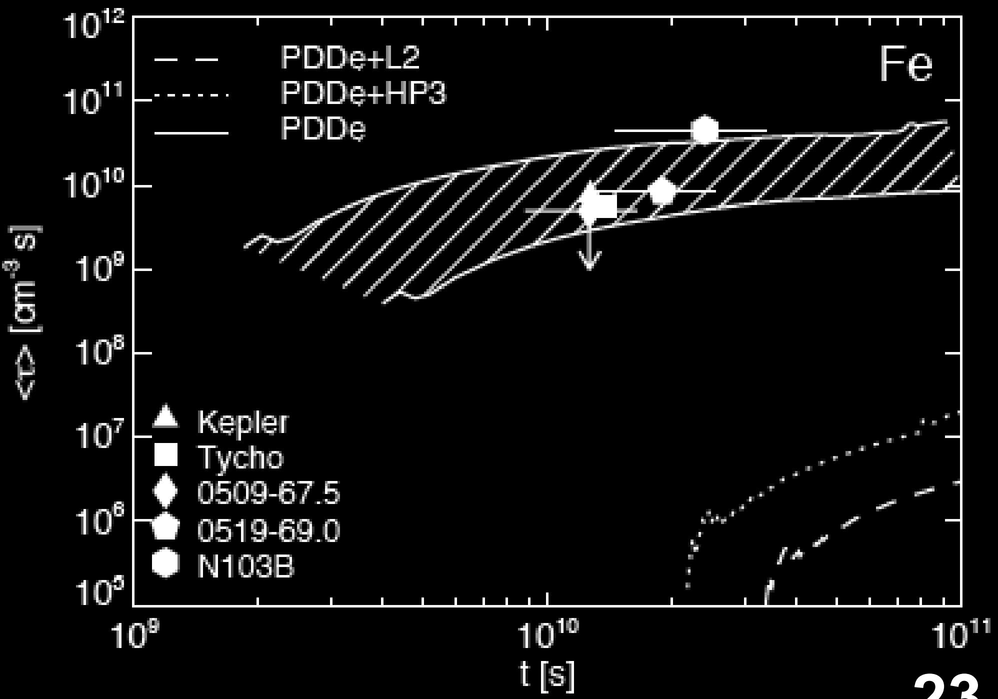
- A similar comparison can be done based on the spectral properties of the X-ray emission from the shocked SN ejecta.

- 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:





SN Ia Progenitors: Constraints from SNRs

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

- As they are postulated in the literature, these accretion winds lead to large cavities around the Type Ia progenitors.

  - Do they? 1D simulations of continuous outflows without thermal conduction.

- The existence of such cavities is incompatible with the fundamental properties (forward shock dynamics, X-ray emission) of known Type Ia SNRs in the Galaxy and the LMC.

More details: Badenes et al., ApJ, submitted