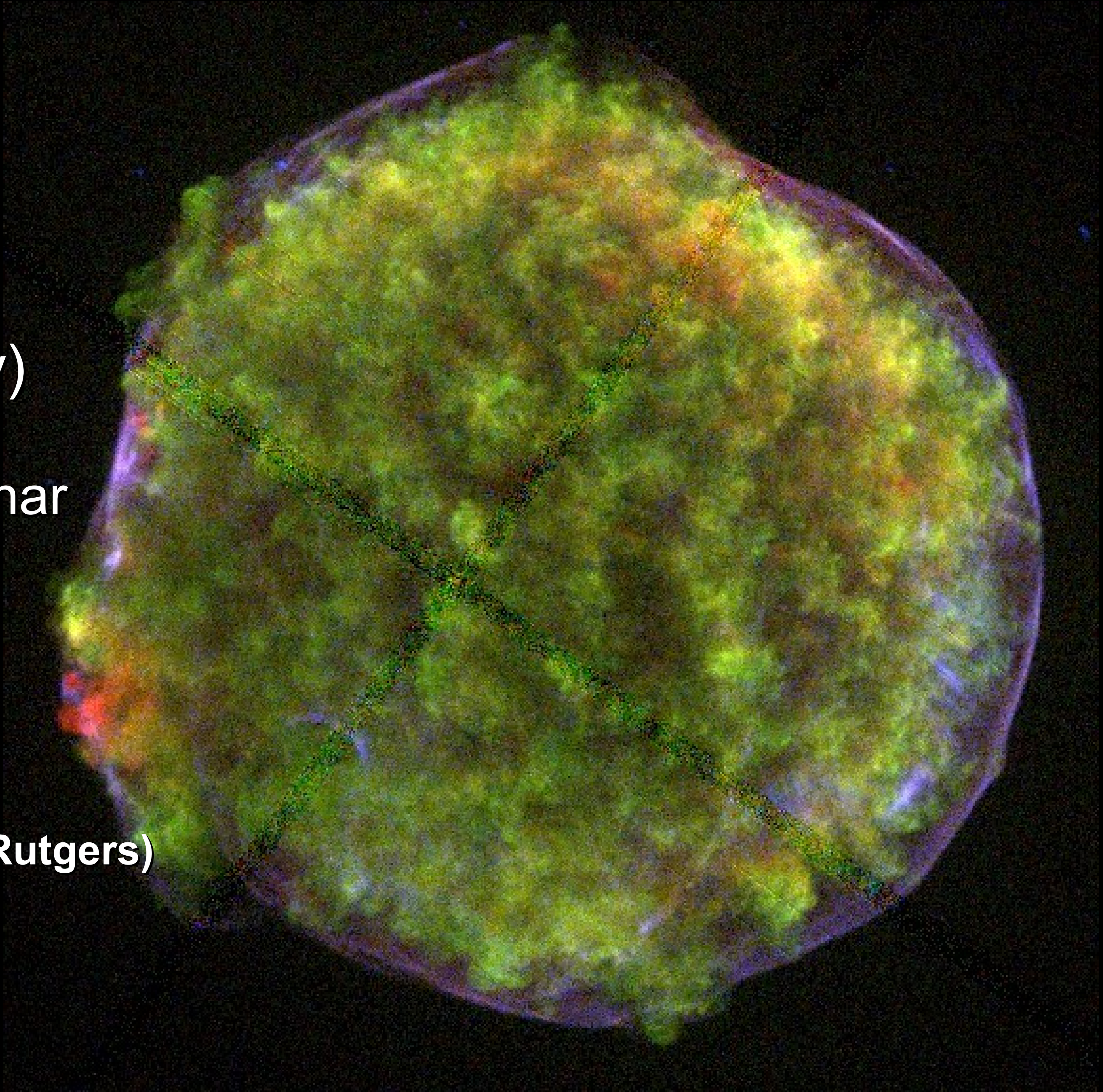
A Different Look at Type Ia Supernovae



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Princeton ISM Seminar
November 27 2006

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OUTLINE

The (X-ray) observations of young Supernova Remnants (SNRs) can reveal a wealth of information about the progenitor systems of Type Ia Supernovae (SNe) and the physics of the explosions.

- Type Ia SNe: What we know and what we don't know about the 'cosmic yardsticks'. Type Ia progenitors and explosion mechanisms.
- Young SNRs: Dynamics, non-equilibrium ionization, and X-ray emission from the shocked ejecta.
- Constraints on the explosion mechanism of SN1572 from the X-ray Spectrum of the Tycho SNR.
- Constraints on the progenitor systems from the circumstellar interaction in Type Ia SNRs.

TYPE Ia SNe: What We Know

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. 1995, PASP 107, 1019; Branch & Khokhlov 1995, Phys. Rep. 265, 53; Hillebrandt & Niemeyer 2000, ARA&A 38, 191.

- Energy budget:

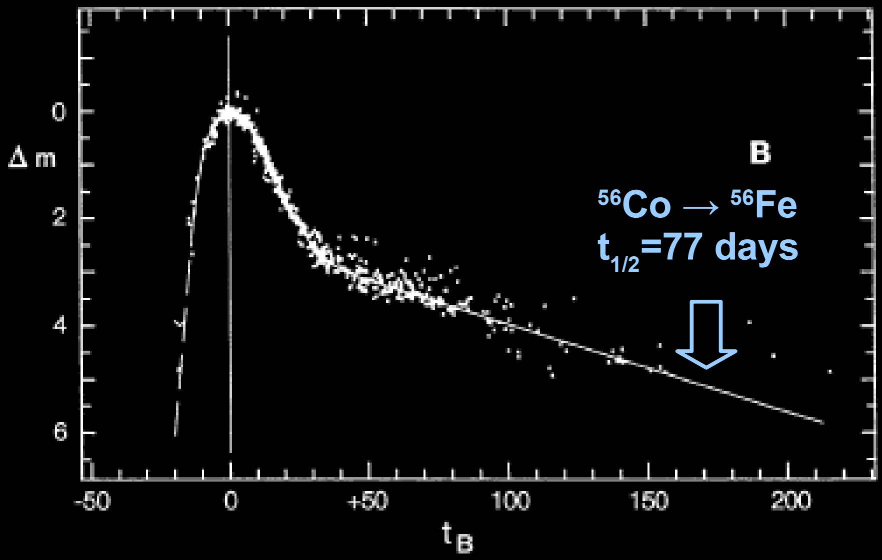
$$M_{WD} {}^{*} E_{[12C + 16O \Rightarrow 56Ni]} \approx E_{bind,WD} + E_{k,SN}$$

- Optical spectra:

  Type Ia ⇒ no H lines, Si^{+1} feature at ~ 6100 Å.

- Rate of light curve decline:

  $^{56}Ni \Rightarrow {}^{56}Co \Rightarrow {}^{56}Fe$ decay chain.

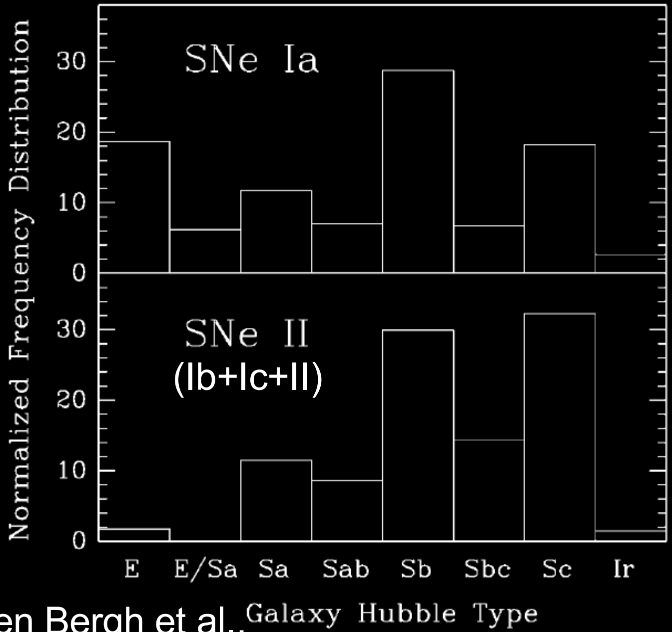


$^{56}Co \rightarrow {}^{56}Fe$
$t_{1/2}$=77 days

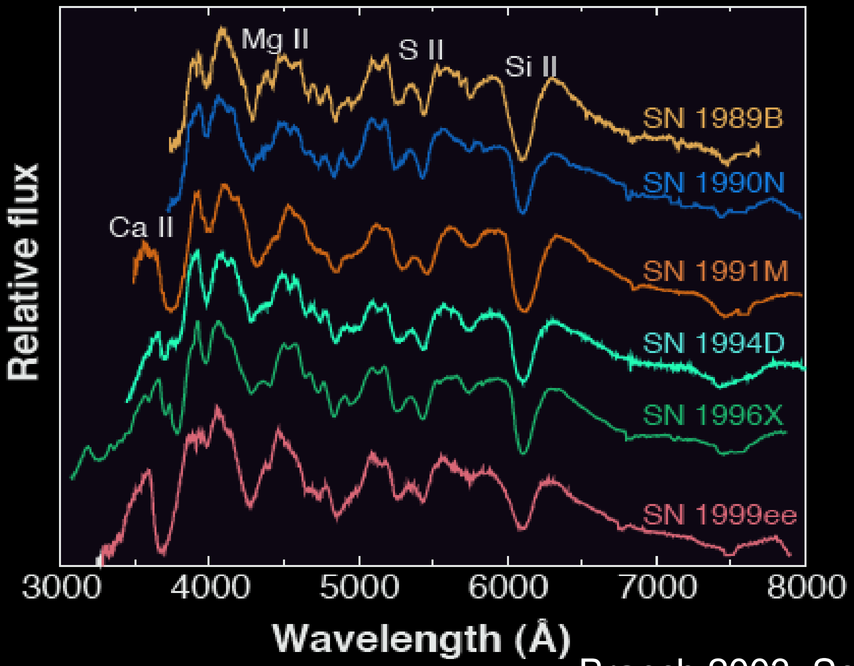
Branch & Tammann 1992, ARA&A 30, 359

TYPE Ia SNe: What We Know

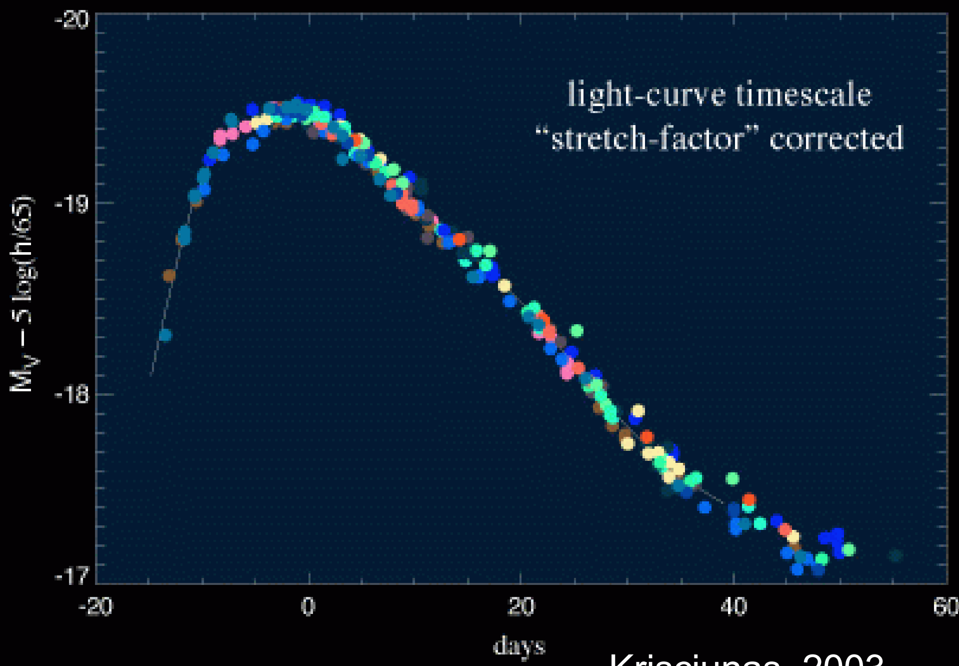
- Type Ia SNe are the only SNe observed in elliptical galaxies: progenitors not (necessarily) associated with recent stellar formation. [Two progenitor populations?].
- Striking uniformity of observational properties (spectra, light curves, peak magnitudes) ⇒ Use as 'standardizable' candles in cosmology. [Many peculiar objects]



van den Bergh et al., 2005, PASP 117, 773



Branch 2003, Sci 299, 53



Krisciunas, 2003

TYPE Ia SNe: What We Don't Know

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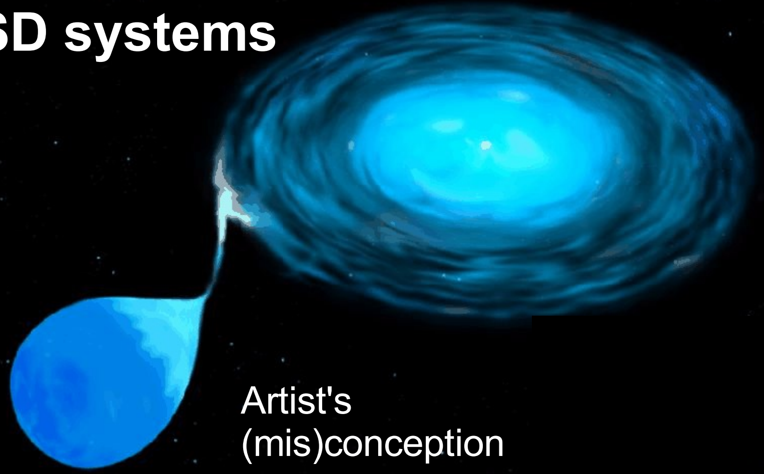
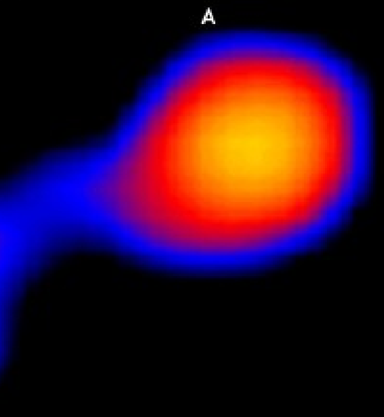
- The progenitor systems of Type Ia SNe have never been identified.
  - What is the nature of the WD companion?
    - Another WD: Double Degenerate (DD) systems. [Explosion is uncertain – BUT 'Champagne Supernova' [Howell et al. 06, Nat 443, 308]].
    - A normal star: Single Degenerate (SD) systems. [Preferred by theorists].
  - How does the WD grow to ~1.38 $M_\odot$ in SD systems?

⇒ SD systems with 'accretion winds'.

SD systems

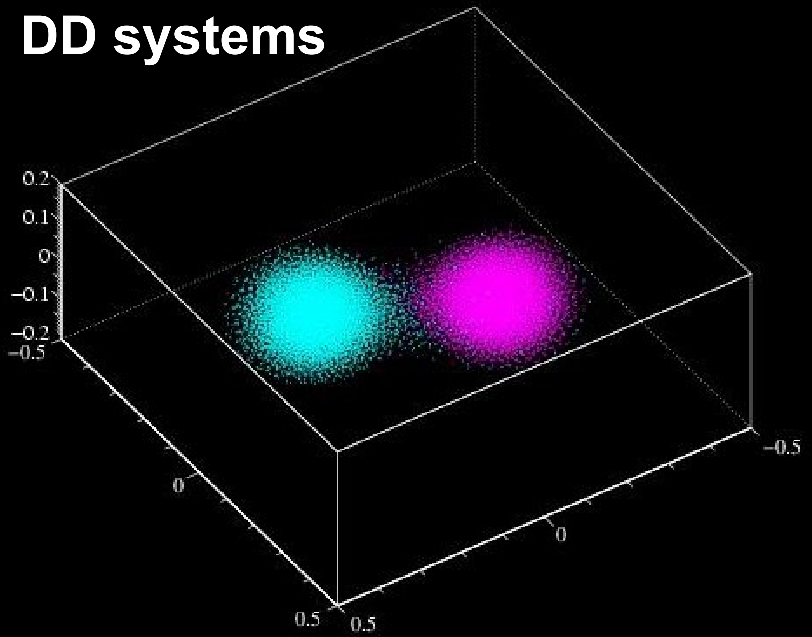


Artist's (mis)conception



Real thing: *Chandra* image of Mira (o Ceti) Karovska et al. 2005, ApJ 623, L137

DD systems



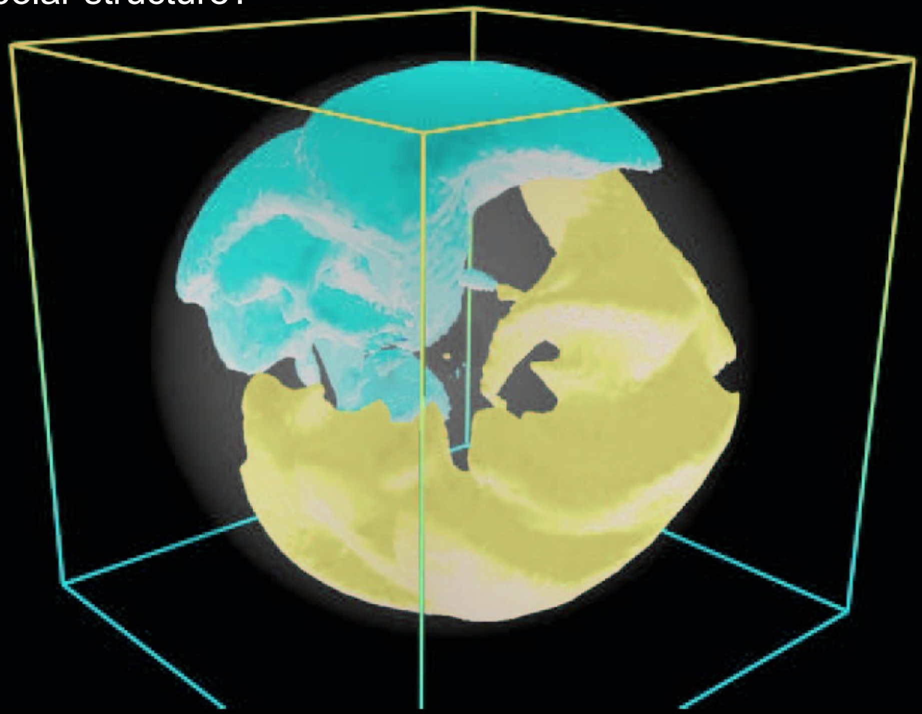
Guerrero et al. 2004, A&A 413, 257

TYPE Ia SNe: What We Don't Know

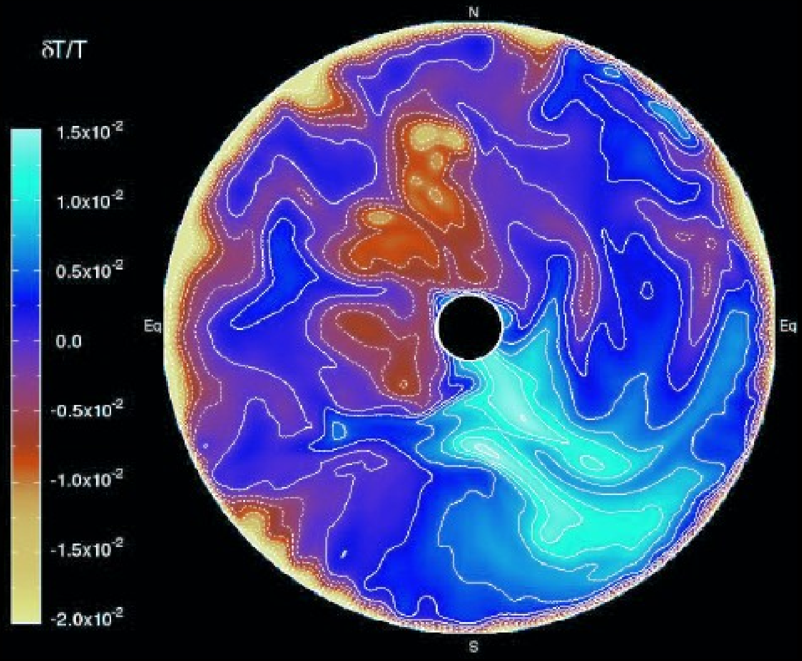
- Ignition of the thermonuclear runaway.
  - At ~1.38 $M_\odot$ the WD starts to 'smolder' ⇒ convection and turbulence.
  - Very challenging problem. EXTREME conditions: Ra~10^{25}; Re~10^{14}.
  - How many 'hot spots', and where do they originate inside the WD?

⇒ Multi-spot, off-center ignition.

Bipolar structure?



Kuhlen et al. 2006, ApJ 640, 407



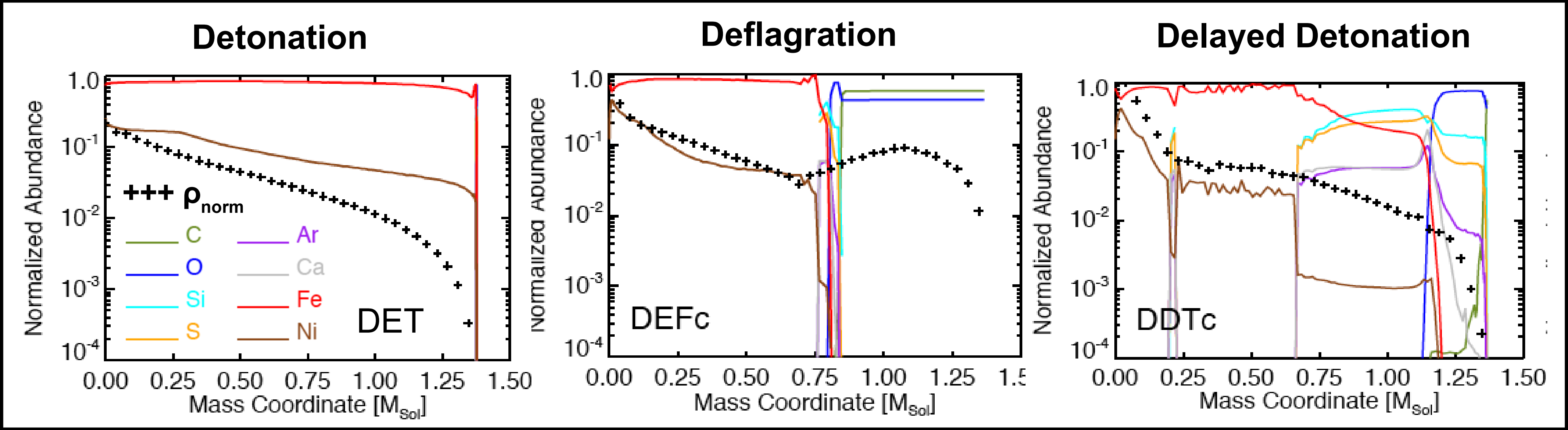
TYPE Ia SNe: What We Don't Know

- Propagation of the burning front through the WD (I):

Determines the nucleosynthesis ⇒ structure of the SN ejecta

- Supersonic (detonations). Burning at high ρ ⇒ Nuclear Statistical Equilibrium (NSE) ⇒ Fe-peak nuclei (^{56}Ni). Very energetic.
- Subsonic (deflagrations). Burning at lower ρ ⇒ departure from NSE ⇒ some intermediate mass elements (IMEs: Si, S, Ar, Ca). Flame quenches, leaving unburnt C+O. Less energetic.
- Subsonic, then supersonic (delayed detonations). Produces more IMEs and E_k than DEF. Transition to detonation imposed artificially at ρ_{tr}.

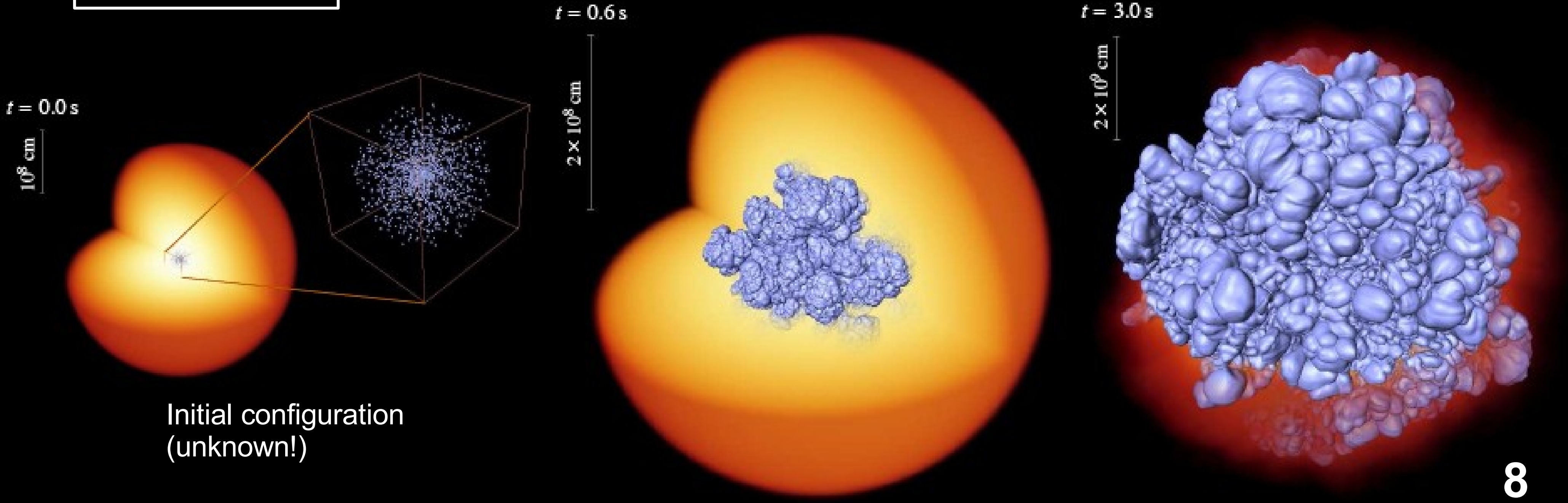
These paradigms have been explored extensively with 1D codes:



TYPE Ia SNe: What We Don't Know

- Propagation of the burning front through the WD (II):
  - Subsonic burning fronts in WDs are dynamically unstable ⇒ 3D codes.
  - 3D Deflagrations have been studied by several groups [Travaglio et al. 2004, A&A 425, 1029; Gamezo et al. 2003, Sci 299, 77; García-Senz & Bravo 2005, 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

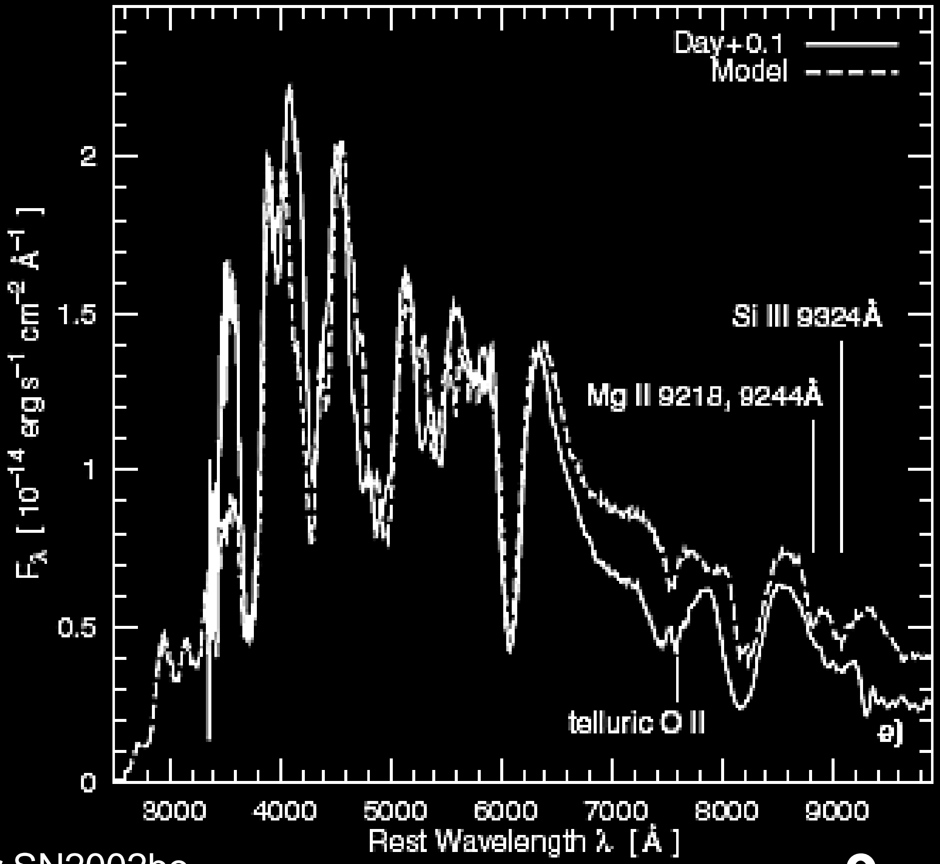


Initial configuration
(unknown!)

TYPE Ia SNe: What We Don't Know

Almost everything we know (and don't know) about Type Ia SNe comes from the study of the SNe themselves (host galaxies, spectra, light curves).

- Type Ia SNe don't tell much about their progenitor systems [stellar amnesia].
- The spectral evolution of Type Ia SNe should reveal the structure of the ejecta.
  - In practice, complex calculations are required (radiation + γ-ray transport, non-LTE conditions, time-dependent ejecta structure).
  - Common wisdom:
    - Ejecta must retain some degree of chemical stratification
    - Large scale asymmetries don't seem likely in a general case.
    - Delayed detonation models (1D) appear to work best.

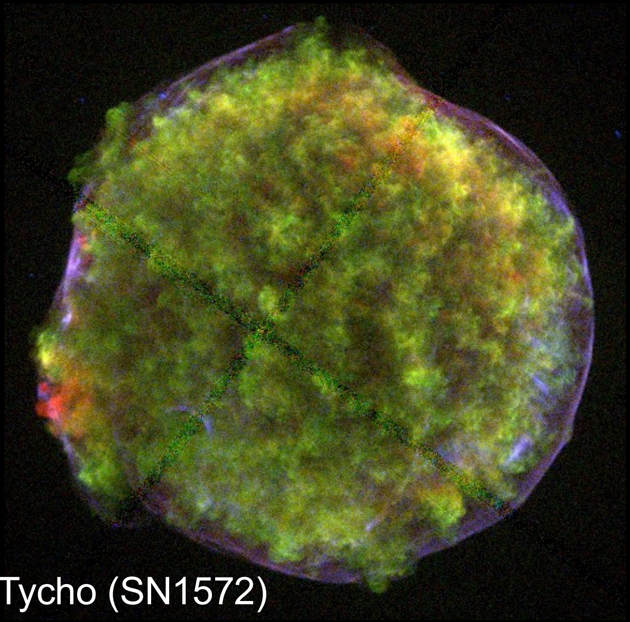


Model for SN2002bo
Stehle et al. 2005, MNRAS 360, 1231

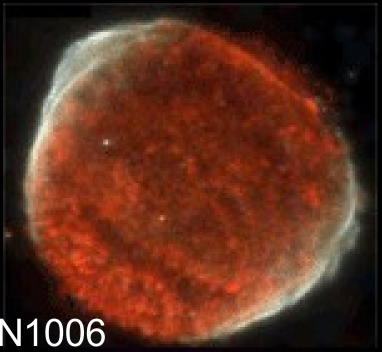
SNRs: Light from the Ashes

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.

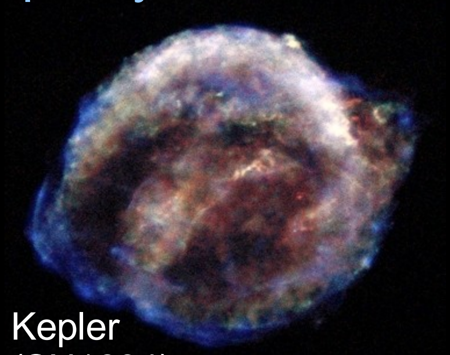
- Supersonic shock waves (~10^3 km.s^{-1}) heat AM and ejecta to X-ray emitting temperatures ⇒ centuries after the light of the SN fades away, the ejecta are revealed once again.
- A number of young, ejecta-dominated SNRs in the Galaxy and the LMC are believed to be Type Ia, and have excellent quality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



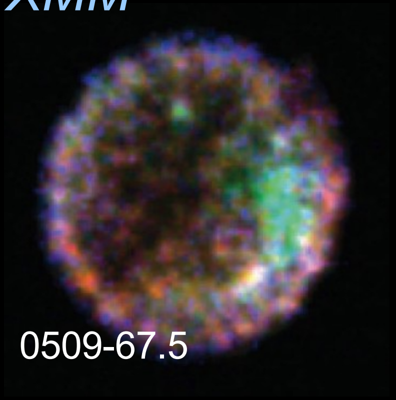
Tycho (SN1572)



SN1006



Kepler
(SN1604)



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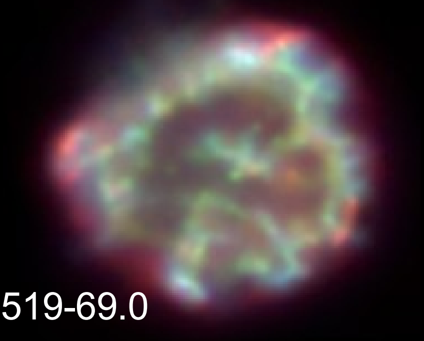

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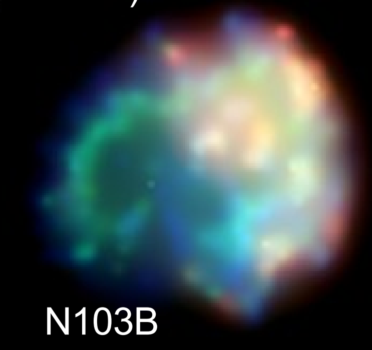

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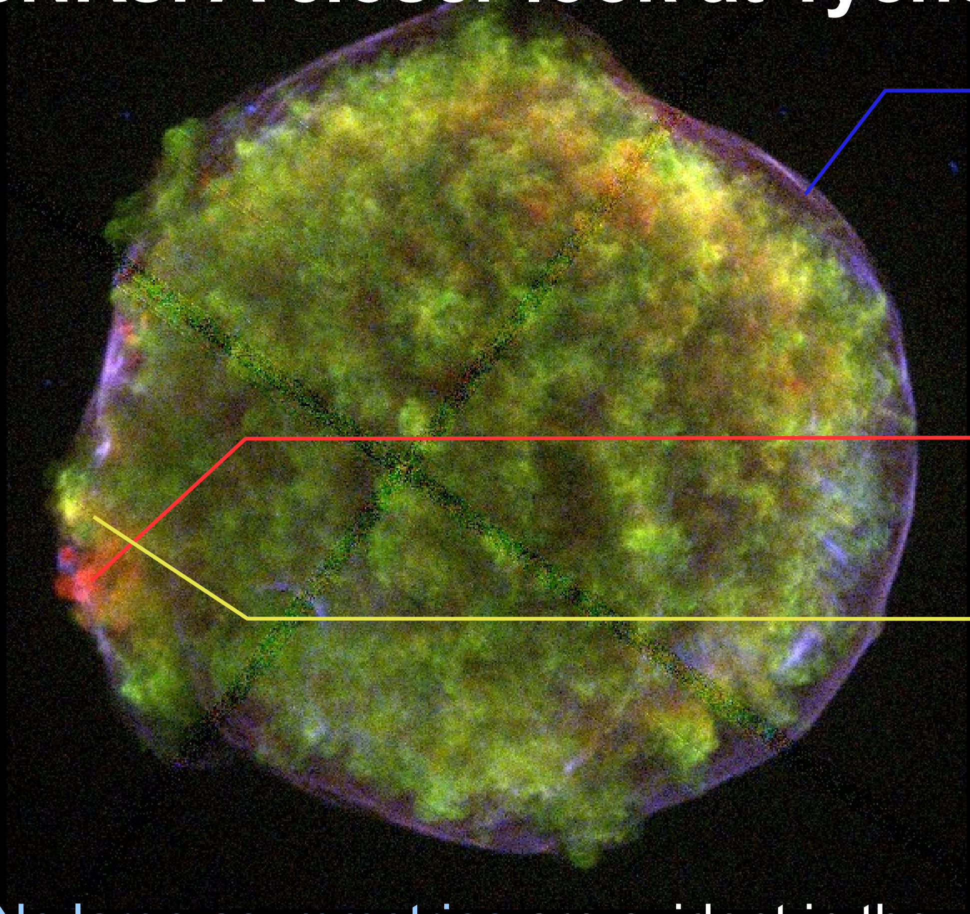
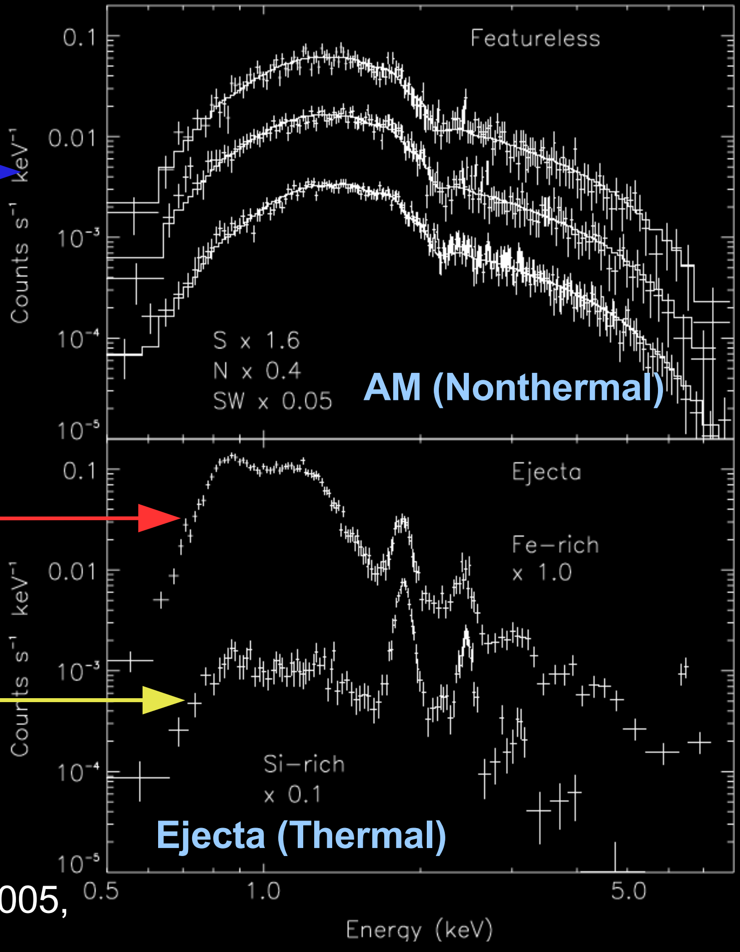
Image credits:
Chandra CXC
(J. Warren, J.P. Hughes for 0509-67.5)

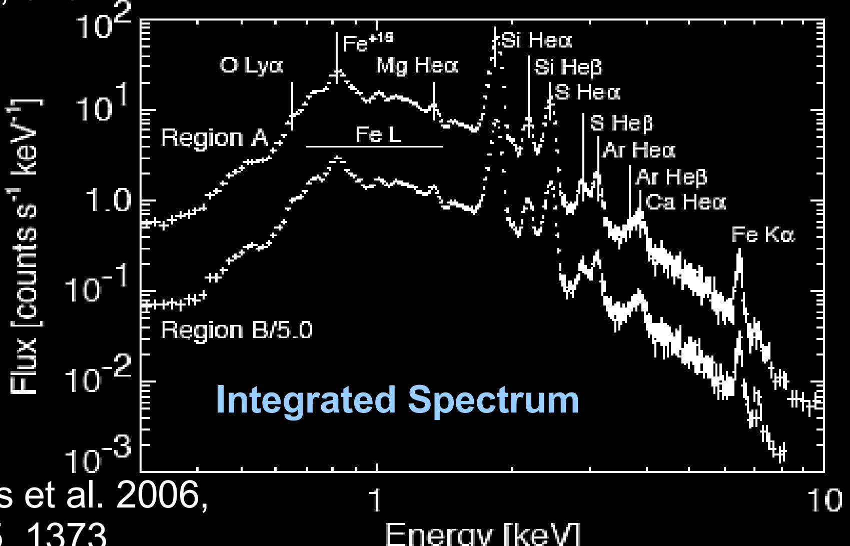
SNRs: A closer look at Tycho



Spectral Components



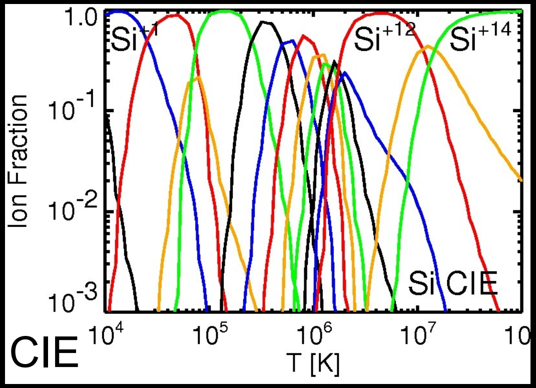
Warren et al. 2005, ApJ 634, 376



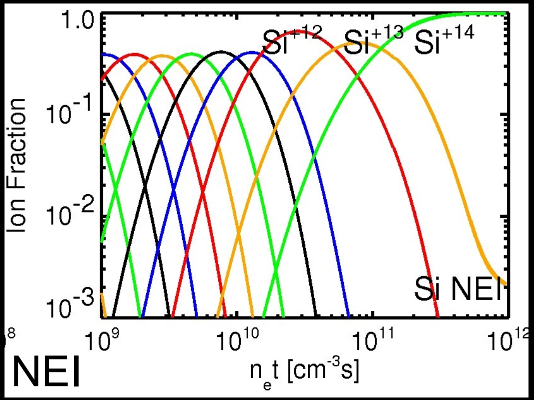
Badenes et al. 2006, ApJ 645, 1373

- 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.

SNRs: HD+NEI Simulations

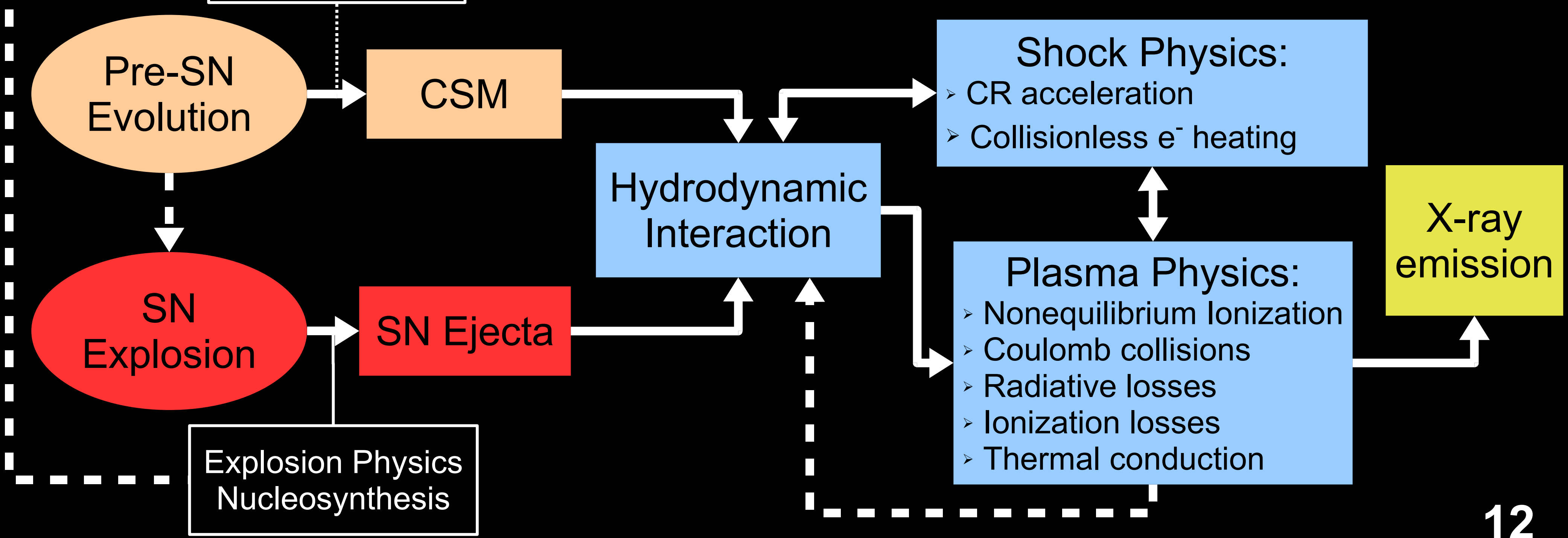


The hot plasma in SNRs is in nonequilibrium ionization (NEI) ⇒ the X-ray emission is coupled to the hydrodynamics of the SNR



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

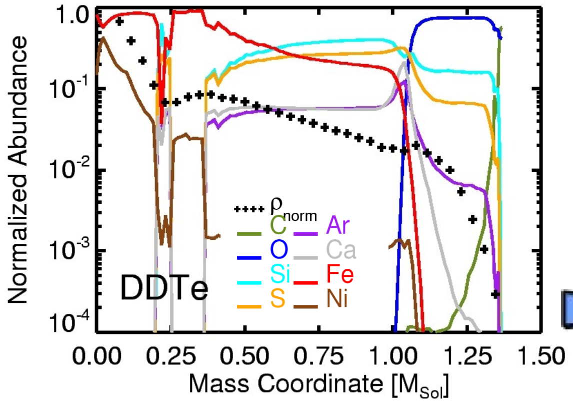
Plasma Physics:
- Nonequilibrium Ionization
- Coulomb collisions
- Radiative losses
- Ionization losses
- Thermal conduction

X-ray emission

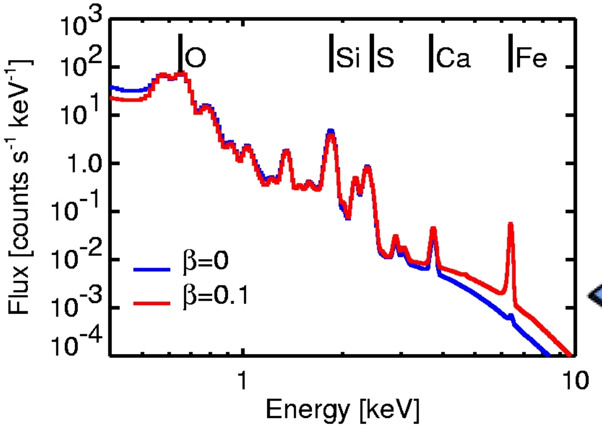
SNRs: A Practical Example

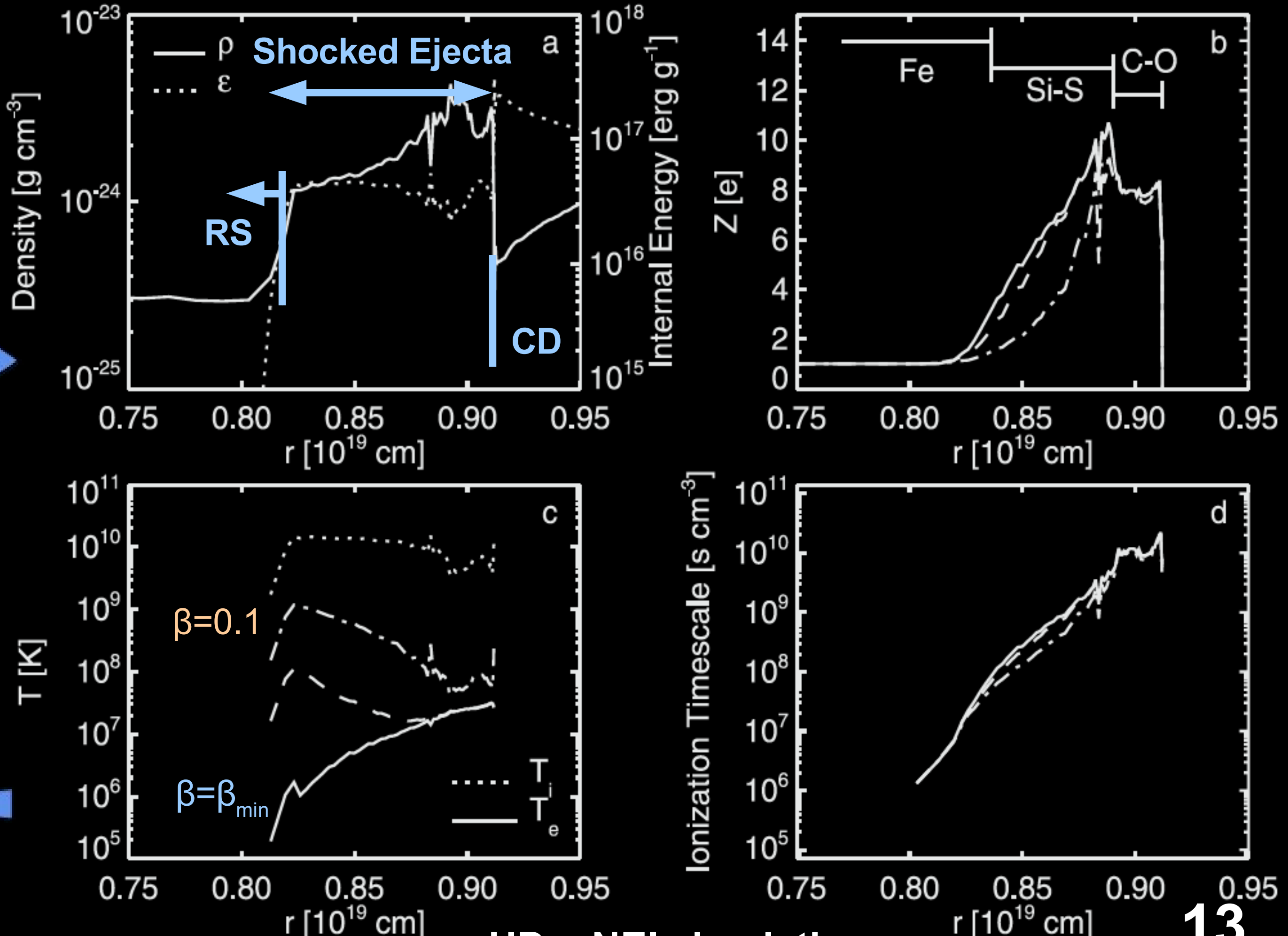
- Model DDTe (delayed detonation). 1D simulation, uniform AM.
- Parameters: AM density, $\rho_{AM}=10^{-24}$ g.cm^{-3}; SNR age, $t_{SNR}=430$ yr; amount of collisionless e$^-$ heating at the RS, $\beta[\equiv\varepsilon_{e,s}/\varepsilon_{i,s}]=\beta_{min}...0.1$.
- Different chemical elements emit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

SN Explosion model:



Synthetic X-ray spectrum:



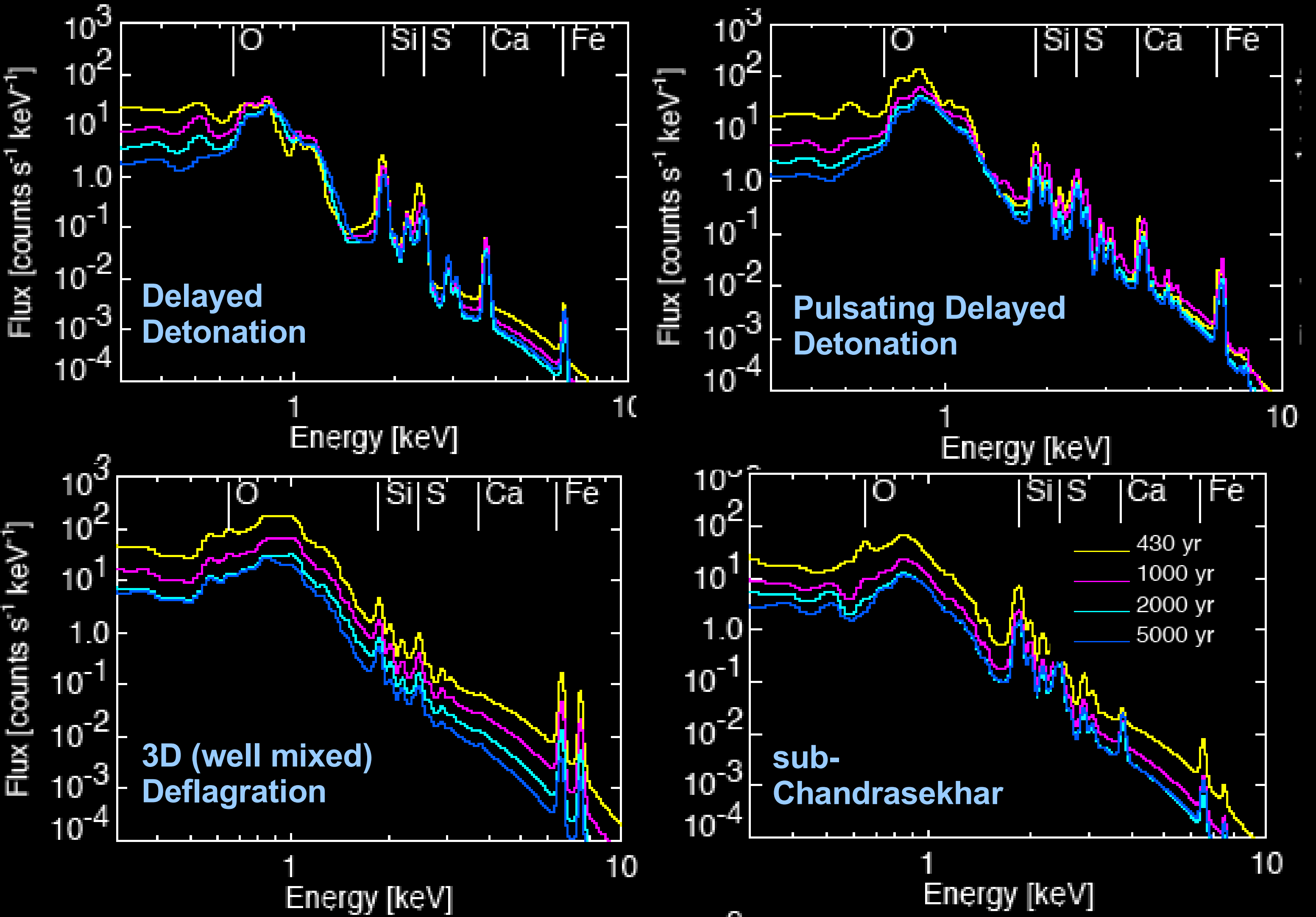


HD + NEI simulation

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 $[\rho_{AM}, t_{SNR}, \beta]$.
- More Details:
  - Badenes et al. 2003, ApJ 593, 358.
  - Badenes et al. 2005, ApJ 624, 198.



TYCHO: Evidence for Cosmic Ray Acceleration

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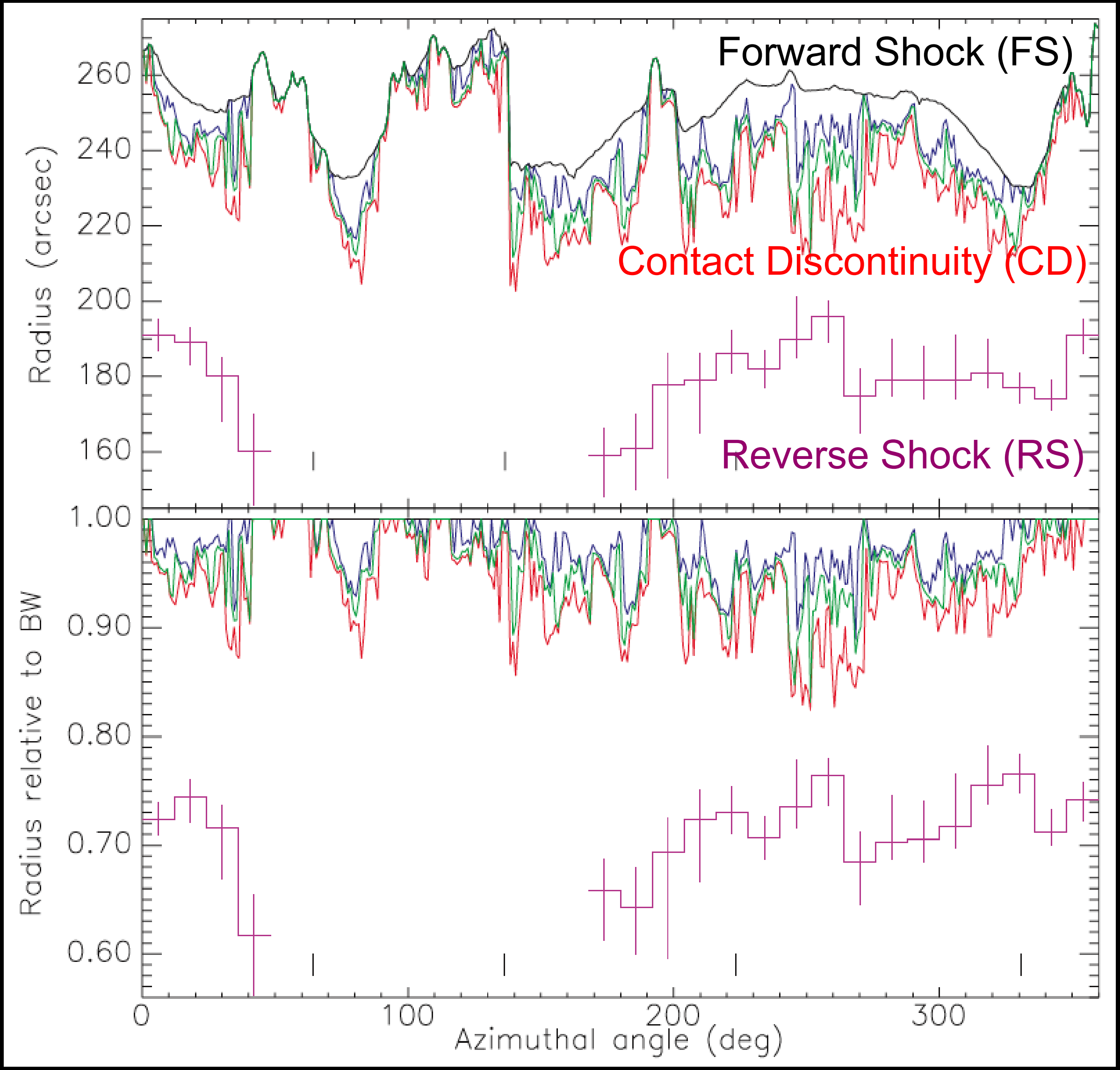
- FS is very close to CD ($R_{CD} \simeq 0.93 R_{FS}$) ⇒ Cosmic Rays are being accelerated at the FS [Warren et al. 2005, ApJ 634, 376].
- CR-modified dynamics cannot be studied with γ=5/3 hydro [Ellison et al. 2004, A&A 413, 189].
- RS is NOT accelerating CRs:
  - Not close to CD.
  - Traced by hot Fe Kα
- CR acceleration at the FS does not appear to disturb the dynamics of the shocked ejecta [Blondin & Ellison 2001, ApJ 560, 244].

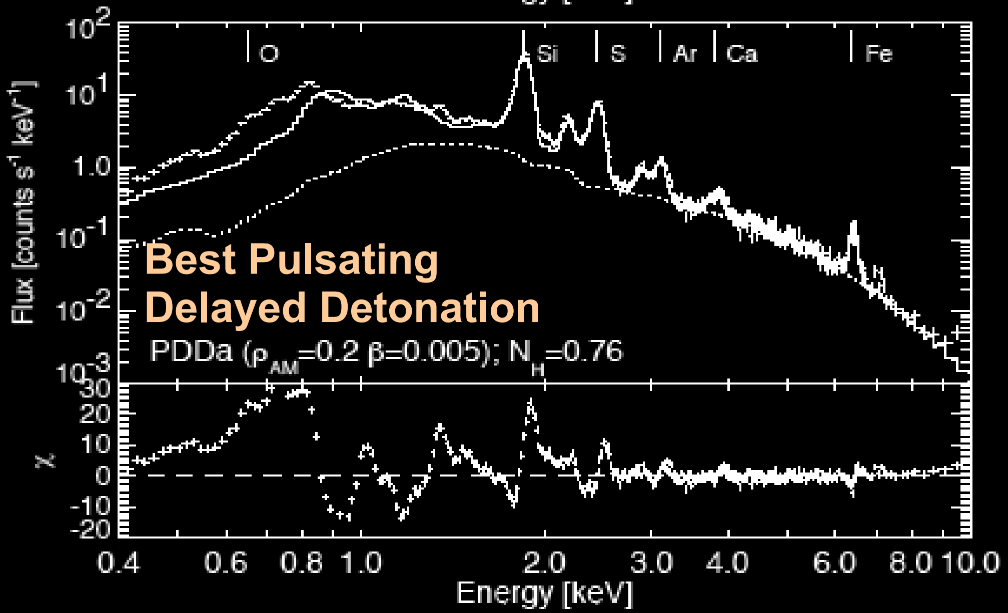
⇒ γ=5/3 HD+NEI models seem appropriate for the shocked ejecta



Warren et al. 2005, ApJ 634, 376

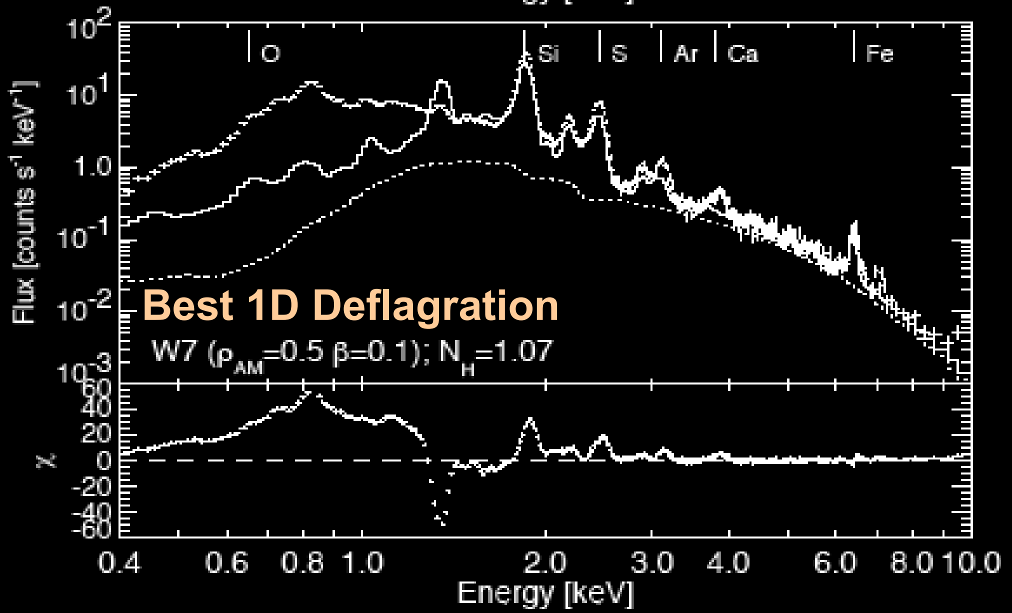
TYCHO: Models vs. Data – The Losers

- The age of Tycho is known (434 yr) ⇒ only ρ_{AM} and β can be varied.
- AM emission: $\Gamma=2.72$ power law [Fink et al. 1994 A&A 283, 635]; $N_H \sim 0.6\times10^{22}$ cm^{-2}.



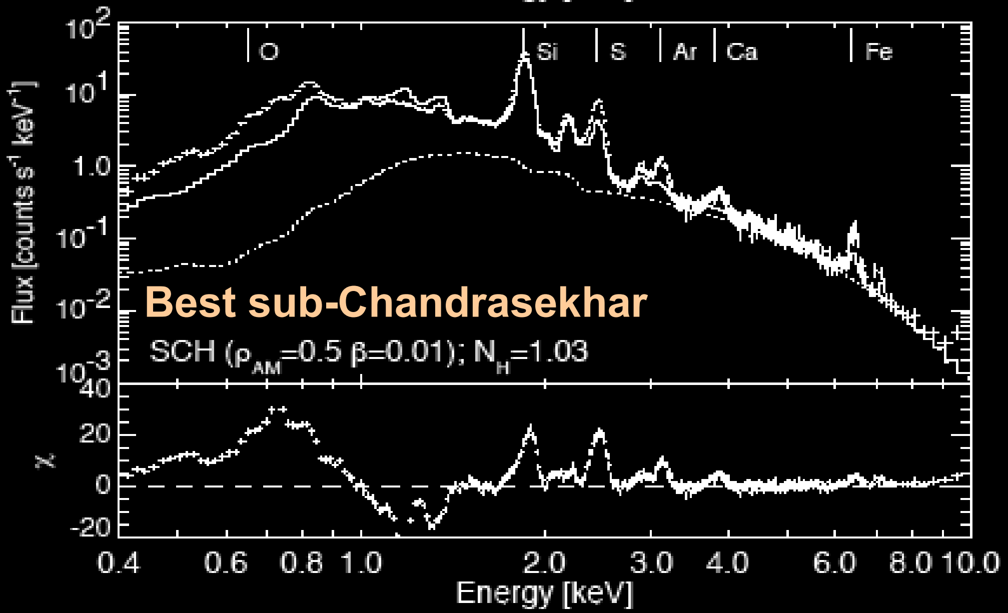
Best Pulsating Delayed Detonation

PDDa (ρ_{AM}=0.2 β=0.005); N_H=0.76



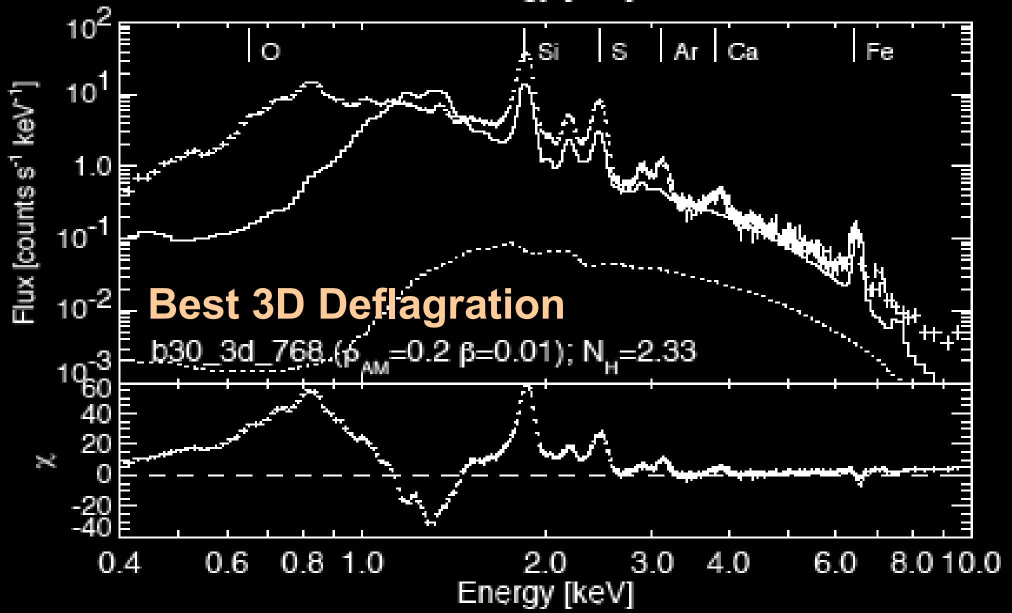
Best 1D Deflagration

W7 (ρ_{AM}=0.5 β=0.1); N_H=1.07



Best sub-Chandrasekhar

SCH (ρ_{AM}=0.5 β=0.01); N_H=1.03



Best 3D Deflagration

b30_3d_768 (ρ_{AM}=0.2 β=0.01); N_H=2.33

TYCHO: Models vs. Data – The Winner

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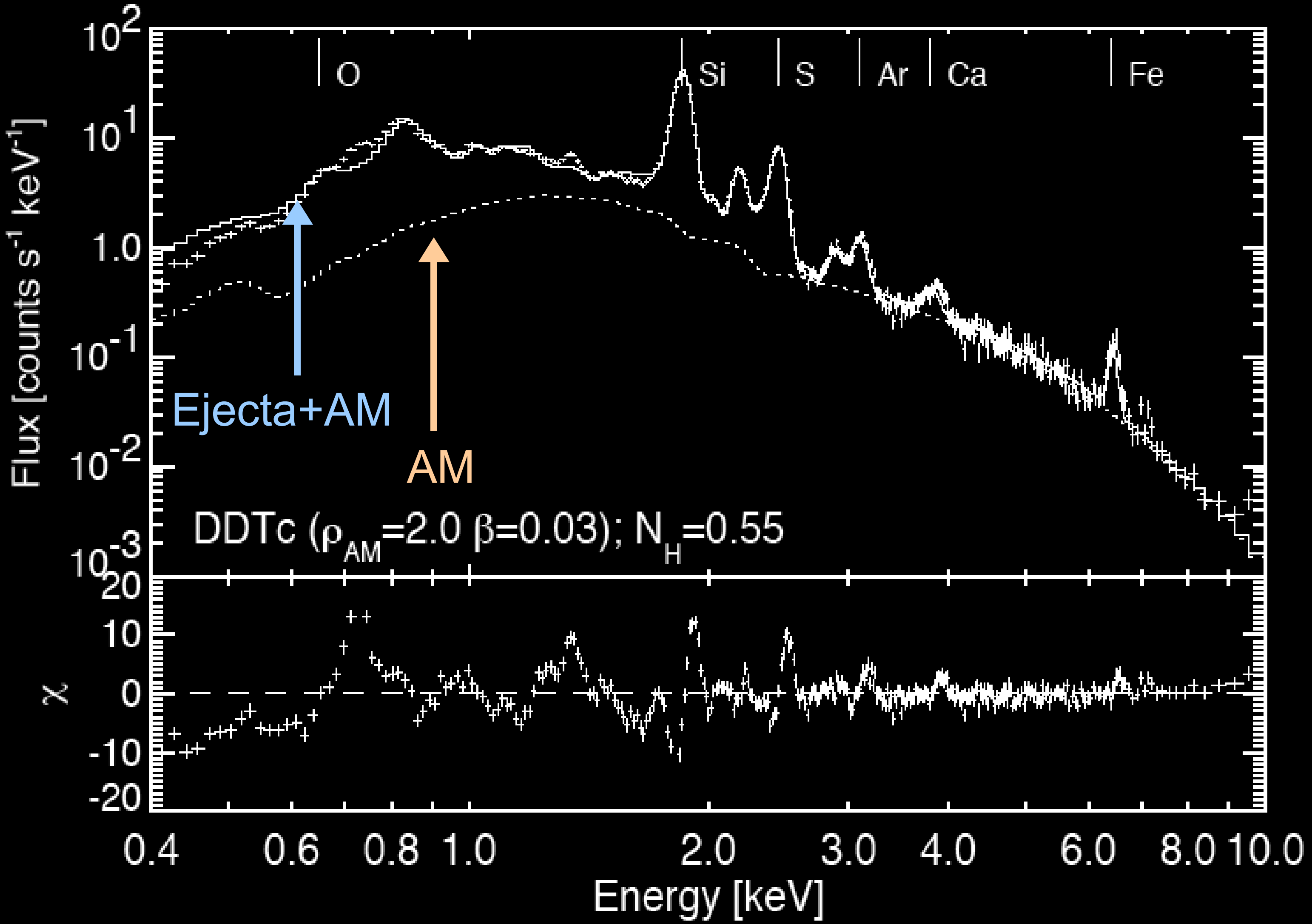
- Most Type Ia SN explosion models don't work very well. 1D Delayed detonations are the only exception.
- Best model: **DDTc** (ρ_{AM}=2x10^{-24} g.cm^{-3}, β=0.03).

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.



TYCHO: Constraints on the explosion mechanism

- For the Tycho SNR, only 1D delayed detonation models can reproduce the thermal X-ray emission from the shocked SN ejecta.
- All other explosion paradigms FAIL: Pulsating delayed detonations, 1D Deflagrations, sub-Chandrasekhar explosions and 3D Deflagrations.
- Spectra AND dynamics form a consistent picture.
- These results agree with (but are completely independent of!) those obtained from optical Type Ia SN spectra.
- 1D HD+NEI models have proven successful for this object, but they have limitations!

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

SN Ia Progenitors: Open issues

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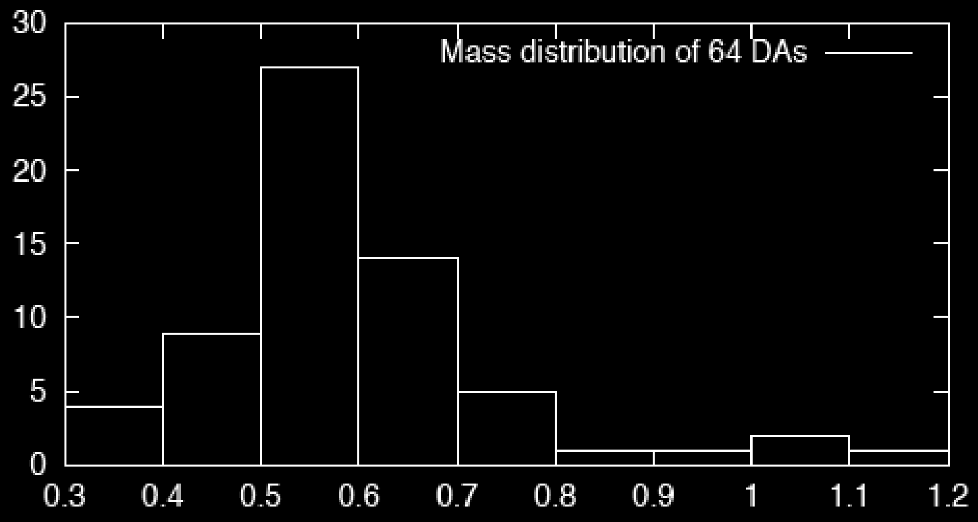
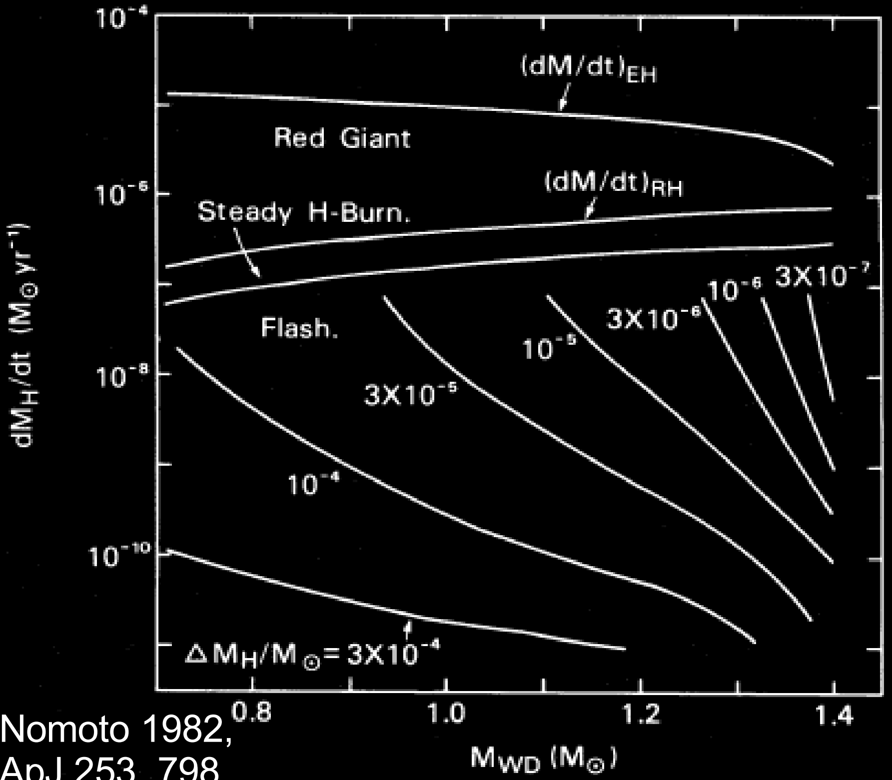
Princeton 11/27/06

- Single degenerate binary systems are the preferred candidates for Type Ia SN progenitors [Branch et al. 1995, PASP 107, 1019].

- **Their viability has not been proved!**
  - $M_{WD} \sim 0.6\ M_\odot$ and always $< 1.2\ M_\odot \Rightarrow$ Need to accrete at least $0.2\ M_\odot$.
  - The H-rich matter from the companion must burn to C and O under degenerate conditions ⇒ dM/dt has to be fine-tuned.



Homeier et al. 1998, A&A 338, 563



Nomoto 1982, ApJ 253, 798

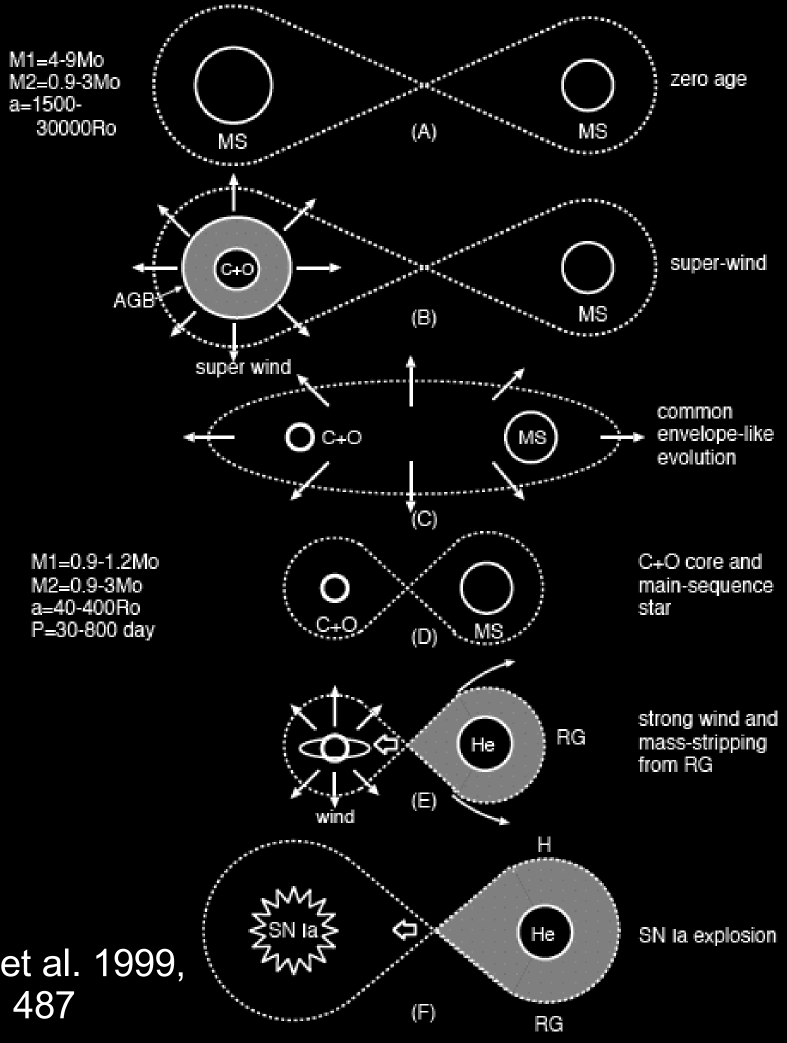
SN Ia Progenitors: Accretion Winds

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.

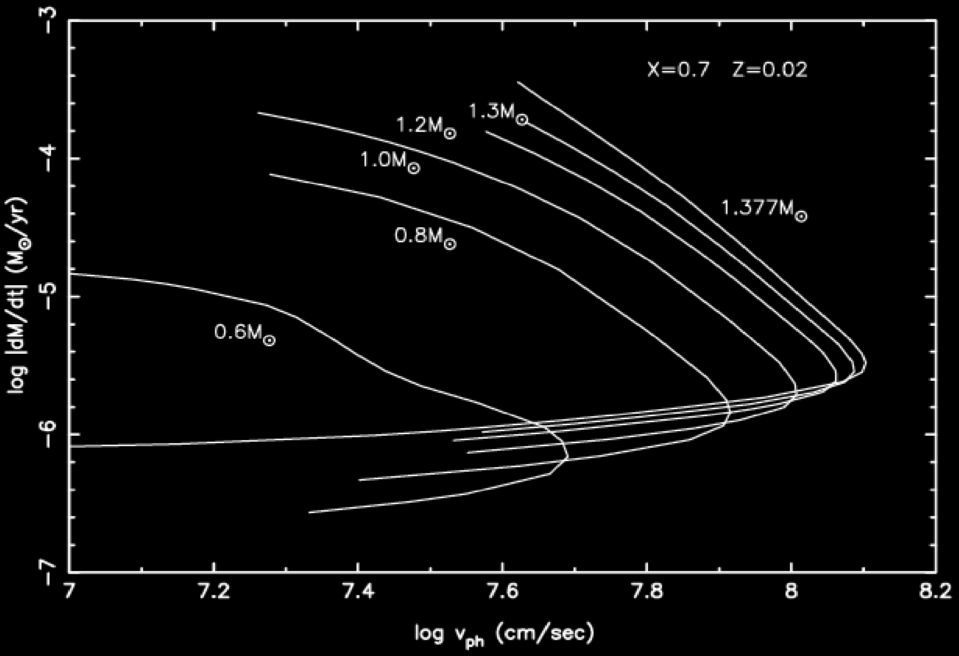
- **Essential** for the evolution of Type Ia progenitors in the SD channel (only way to avoid a common envelope phase).
- The details of the binary evolution can be quite complex. [Li & van den Heuvel 1997, A&A 322, L9; Hachisu et al. 1999, ApJ 519, 314; Hachisu et al. 1999, ApJ 522, 487; Langer et al. 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].



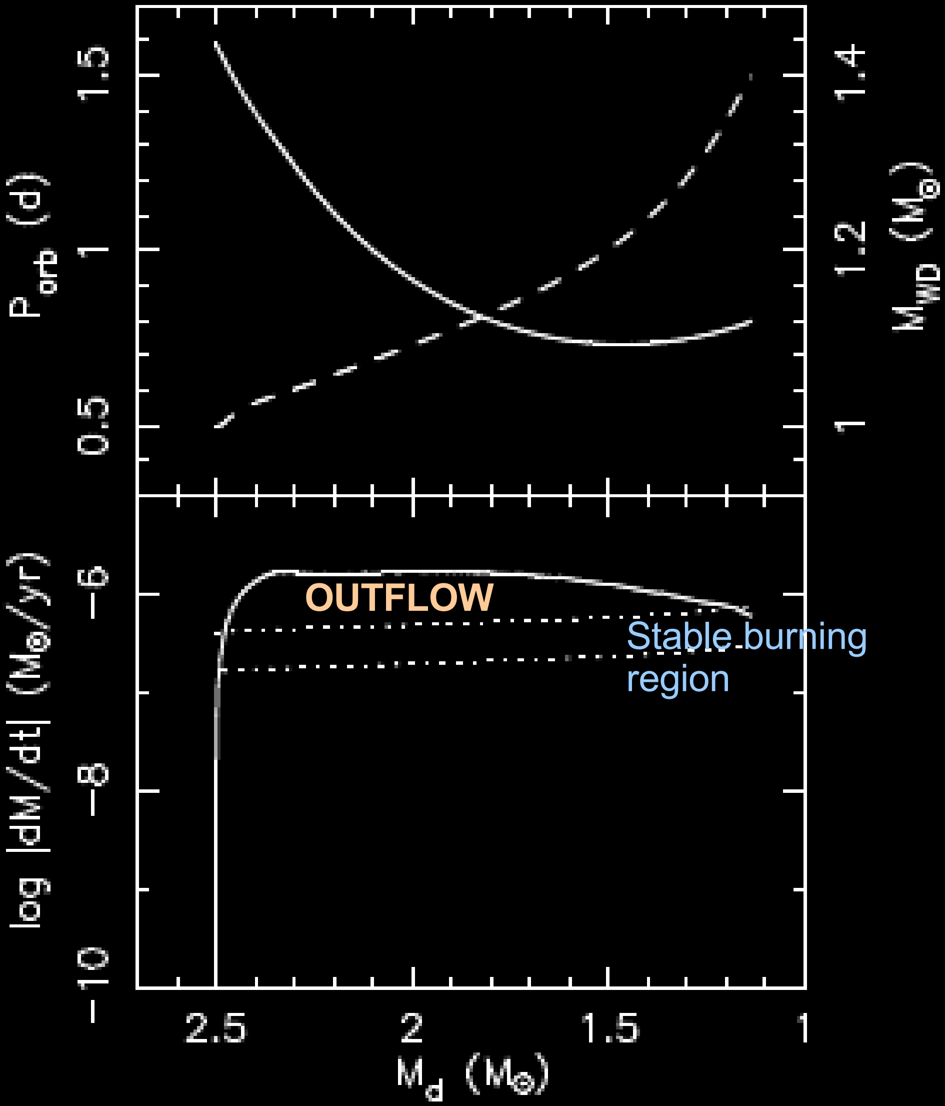
Hachisu et al. 1999, ApJ 522, 487

SN Ia Progenitors: Accretion Wind Outflows

- Part of the material accreted from the companion is not burnt at the WD surface. It escapes the binary system as an 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



OUTFLOW

Stable burning region

Li & van den Heuvel 1997 A&A 322, L9

SN Ia Progenitors: Observational Evidence for Accretion Winds

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Princeton 11/27/06

- Two variable sources have been successfully modeled using accretion winds: RXJ0513.9-6951 [Hachisu & Kato 2003, ApJ 590, 445] and V Sagittae [Hachisu & Kato 2003, ApJ 598, 527]. These sources have fast (bipolar?) outflows.

- Some connection between supersoft X-ray sources and Type Ia SN progenitors has been proposed [Li & van den Heuvel 1997, A&A 322, L9], but the details are not clear.

- Type Ia SNe themselves show little (no?) evidence for CSM interaction:

  - They are not detected in radio [Panagia et al. 2006, ApJ 646, 369] or X-rays [Immler et al. 2006 ApJ 648, L119].

  - Traces of low-velocity H have never been found in spectroscopically normal Type Ia SNe [Mattila et al. 2005, A&A 443, 649]. The interpretation of freak objects like SN2002ic [Hamuy et al. 2003, Nat 424, 651] or SN2005gj [Alderling et al. 2006, ApJ 650, 510] is complex.

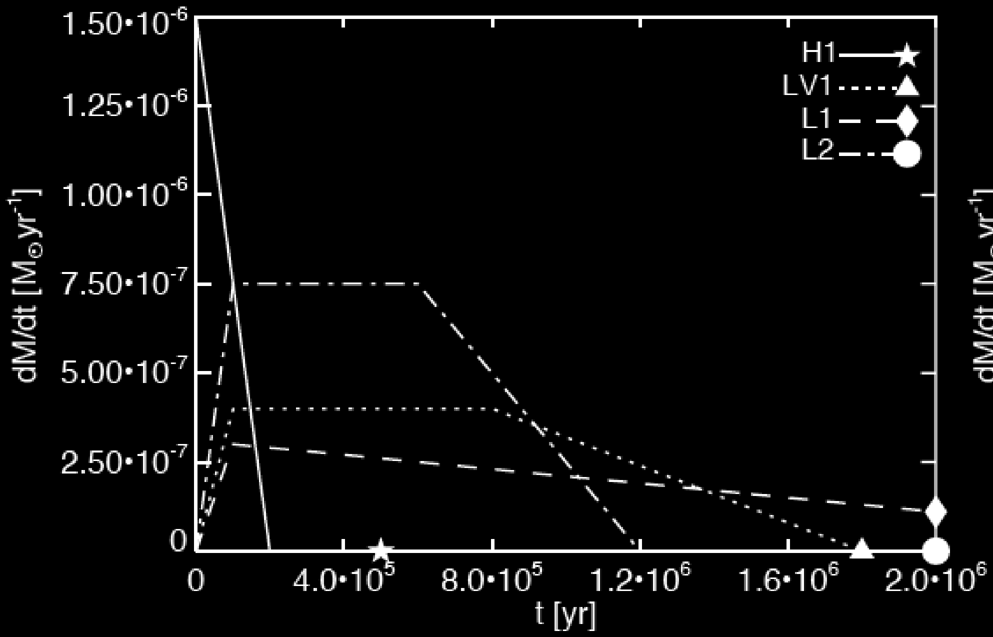
  - Light echoes from SN1991T and SN1998bu [Patat et al. 2006, MNRAS 369, 1949] and SN1995E [Quinn et al. 2006, ApJ 652, 512] ⇒ Detached CSM shells?

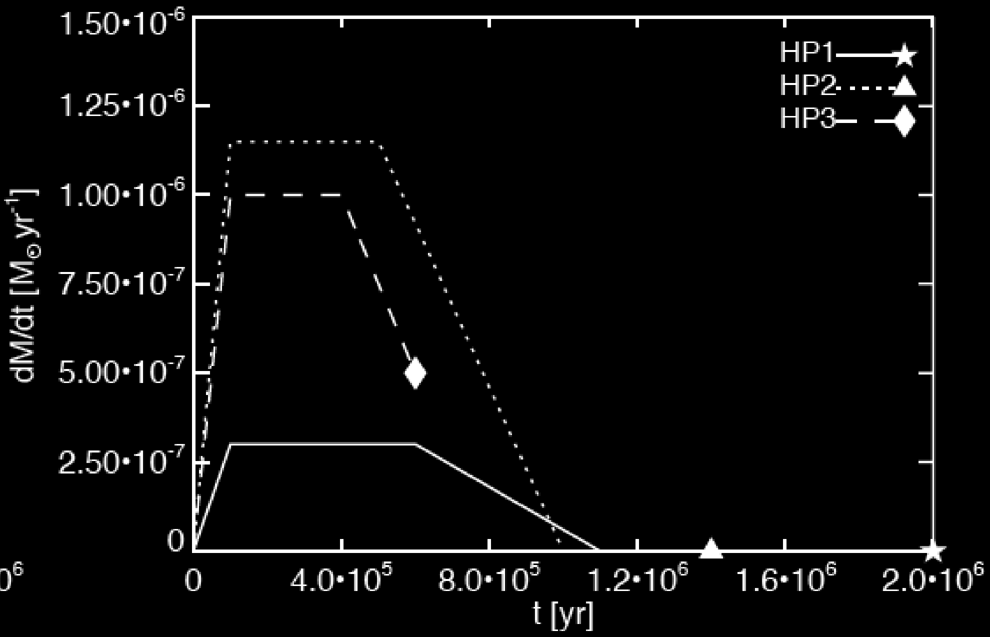
SN Ia Progenitors: Modeling Accretion Wind Outflows

- 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)



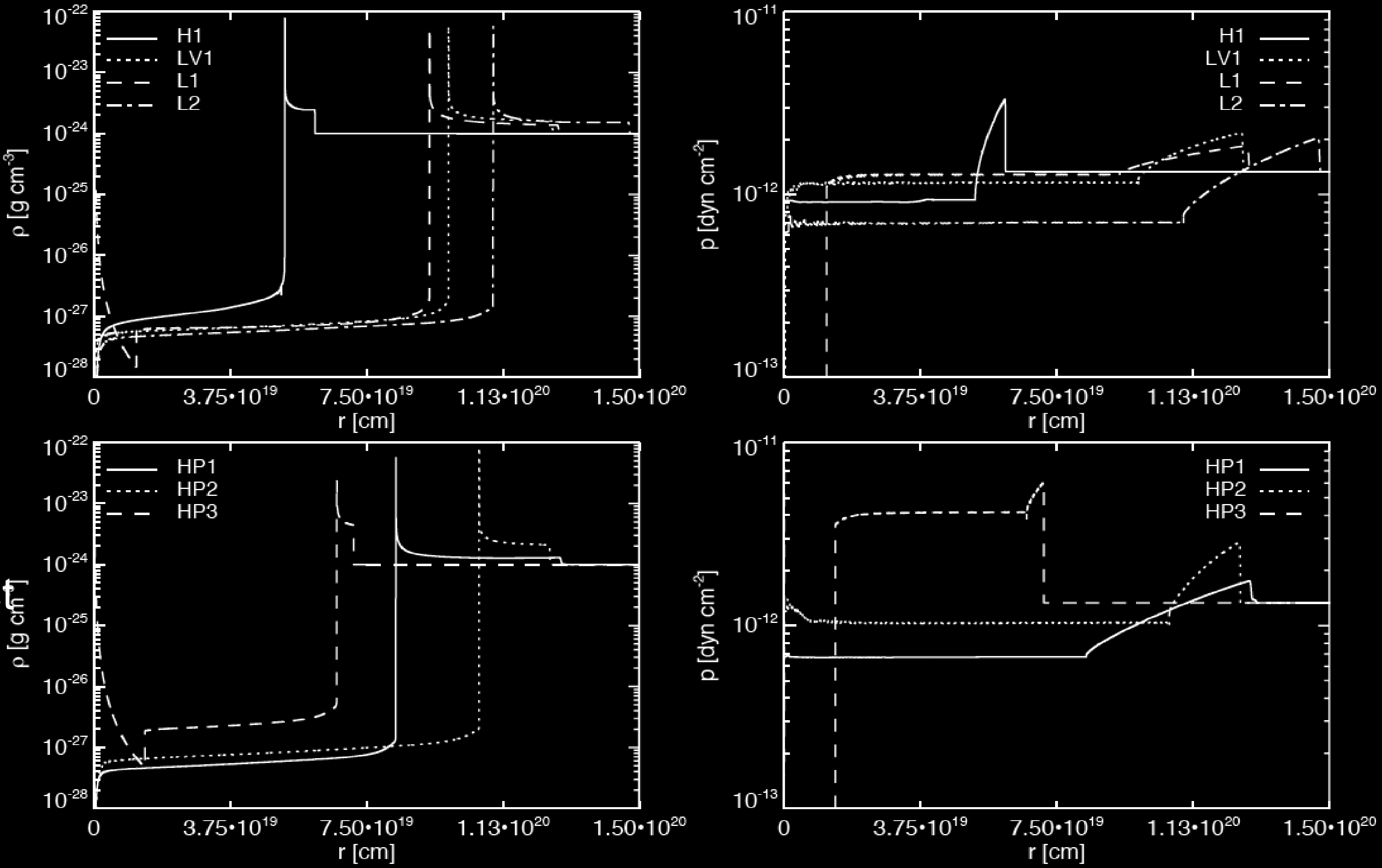


SN Ia Progenitors: Sculpting the CSM

- 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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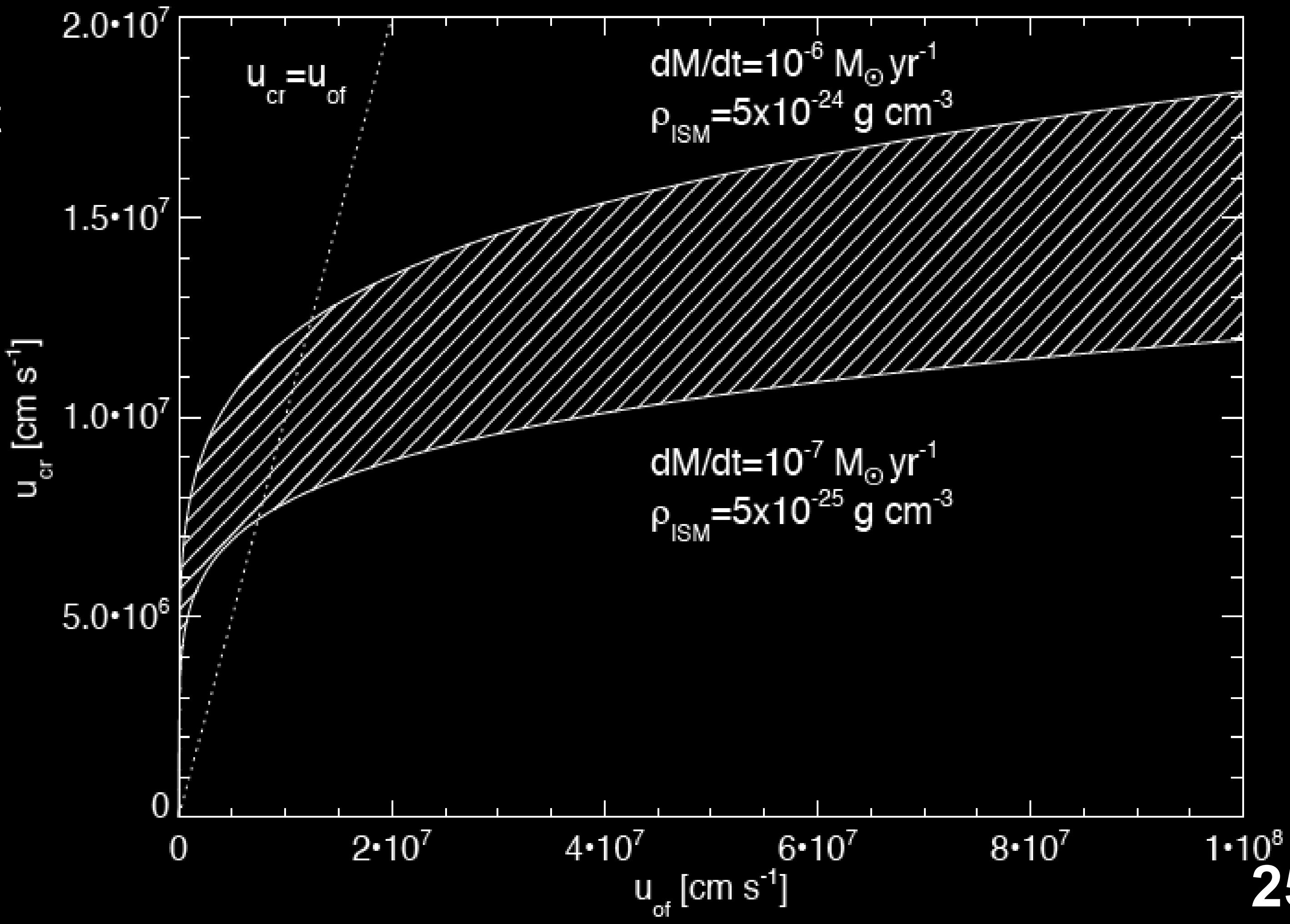
Princeton 11/27/06

- 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.

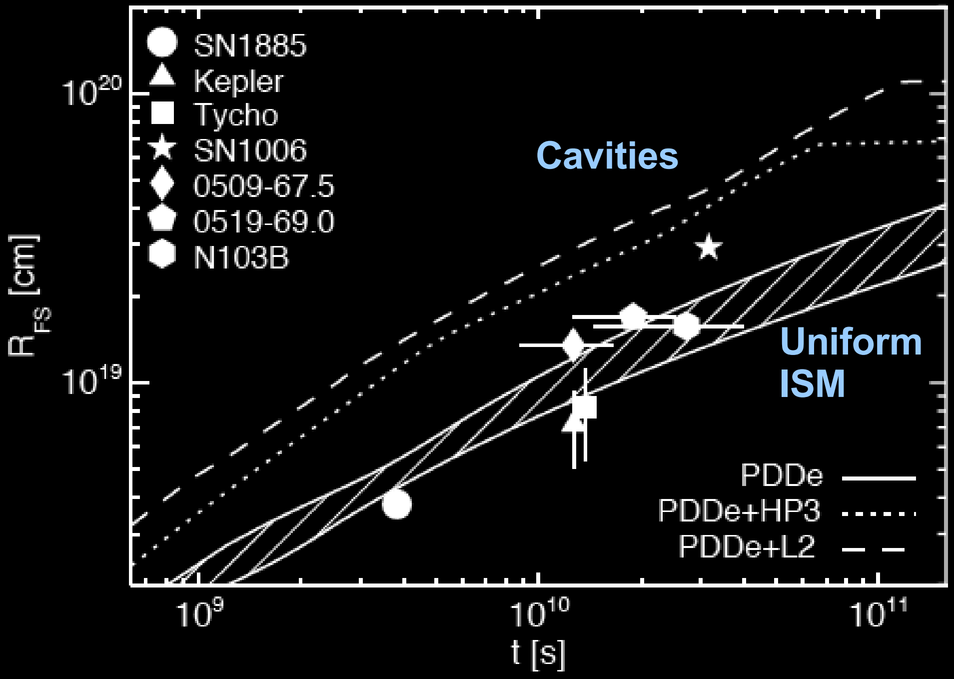


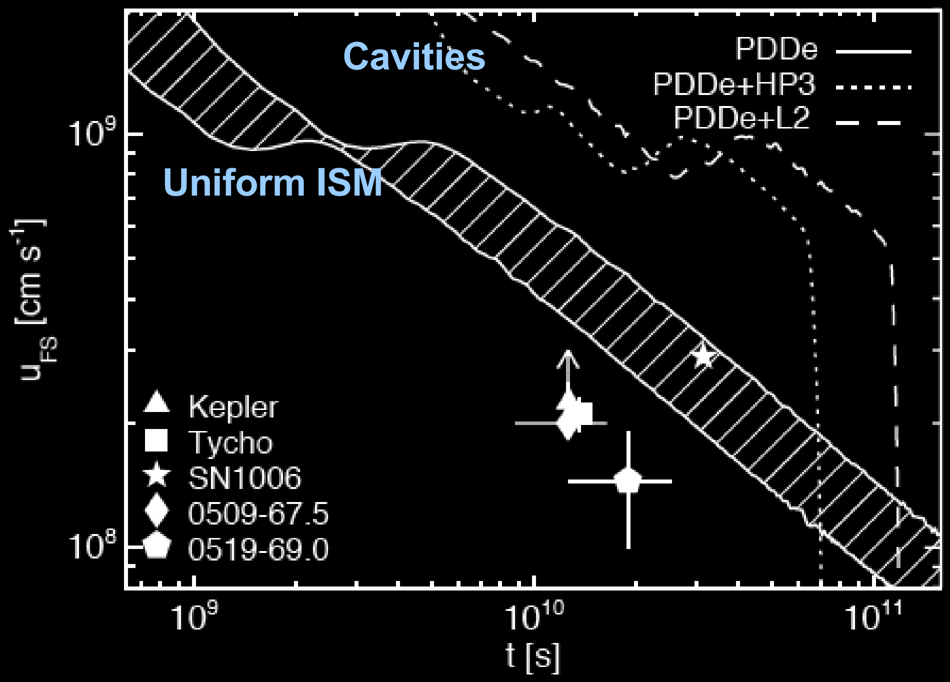
SN Ia Progenitors: Constraints from SNR dynamics

- 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, SN1006) + LMC Type Ia SNRs with good age estimates [Rest et al. 2005, Nat. 438, 1132] (0509-67.5, 0519-69.0, N103B).

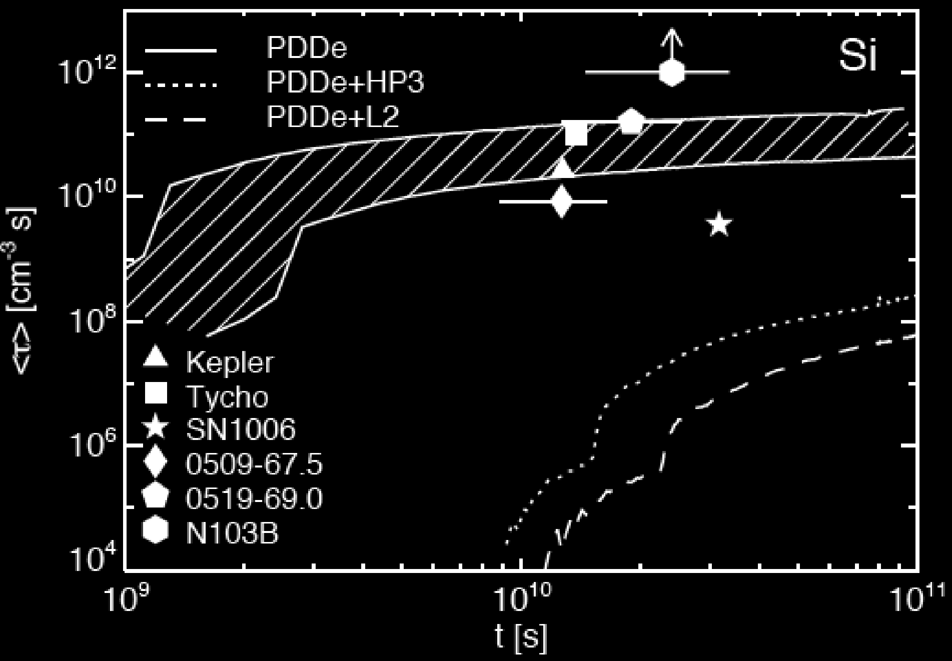
- The existence of large cavities around Type Ia SN progenitors is inconsistent with the observations:

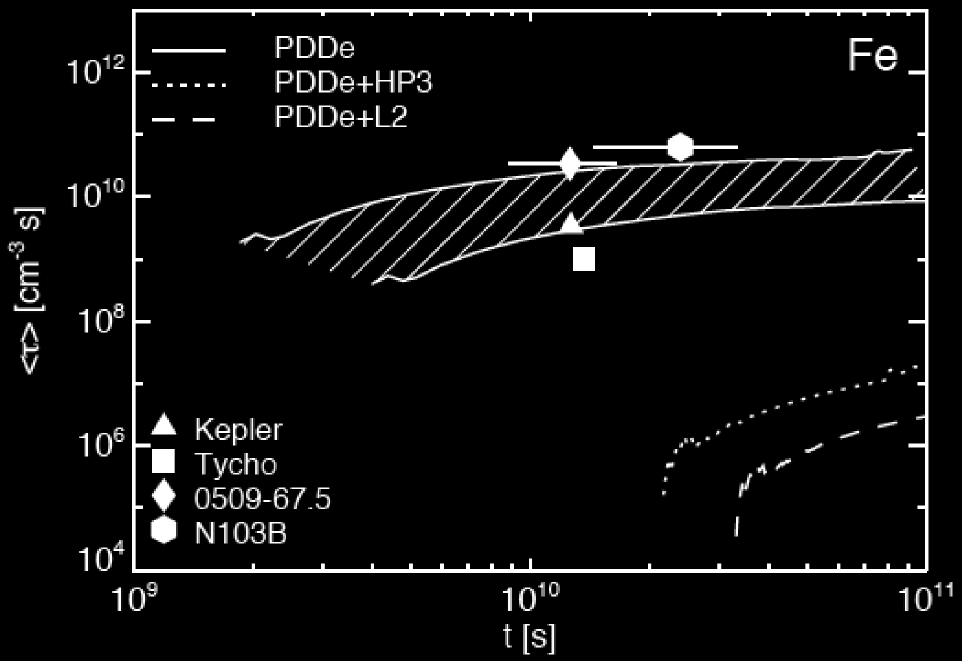




SN Ia Progenitors: Constraints from ejecta emission in the SNR

- 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

- 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., in preparation