OPENING A NEW WINDOW ONTO THE PHYSICS OF TYPE Ia SUPERNOVAE

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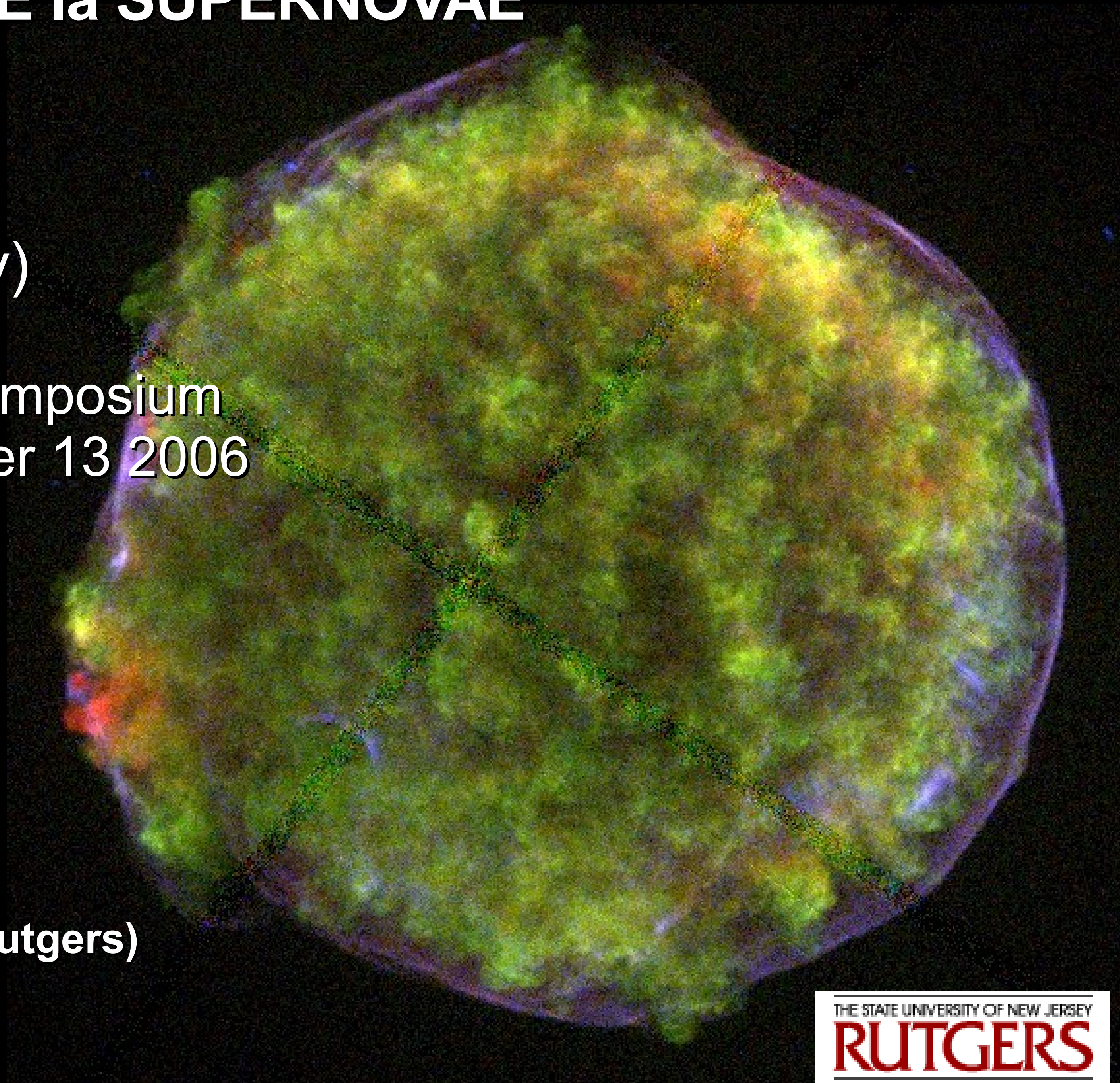

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OUTLINE

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The excellent X-ray observations of Type Ia Supernova Remnants (SNRs) provided by *Chandra* and *XMM-Newton*, together with hydrodynamic + nonequilibrium ionization (HD+NEI) modeling, can put strong, quantitative constraints on the physics of Type Ia supernovae (SNe)

- Physics of Type Ia SN explosions: still many open issues.
- From SN to SNR: challenges and techniques. HD+NEI simulations.
- **Results**:
  - Tycho SNR: only delayed detonation models can explain the fundamental properties of the X-ray emission. All other explosion paradigms fail (in particular, 3D deflagrations with well-mixed ejecta can be confidently discarded).
  - SN1006 SNR: preliminary results also suggest a delayed detonation model.
- Conclusions.

The Physics of Type Ia SNe: Ejecta Structure

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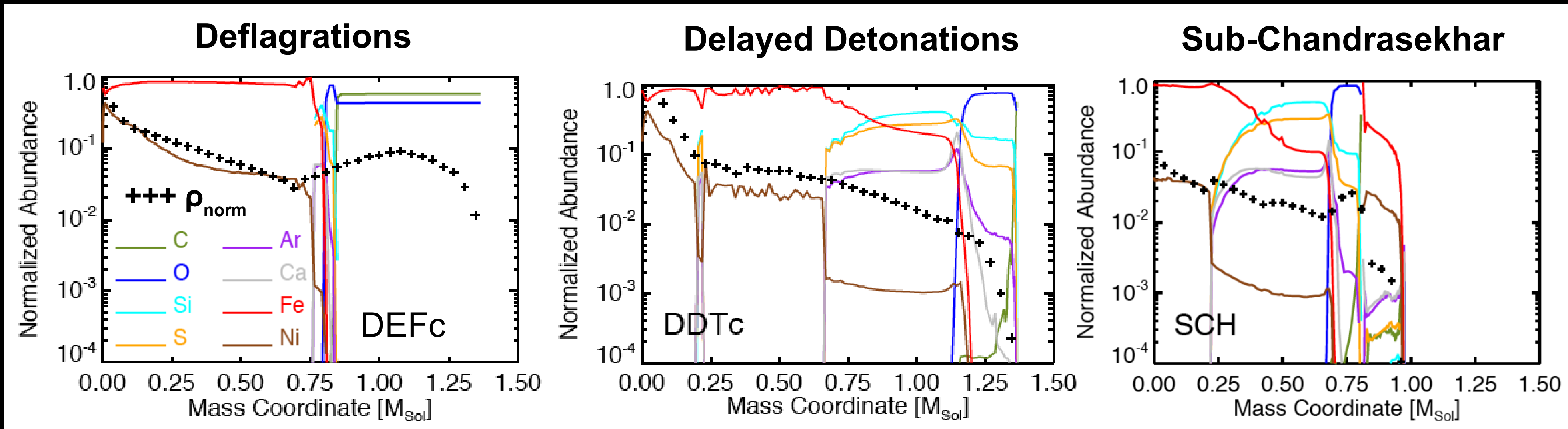
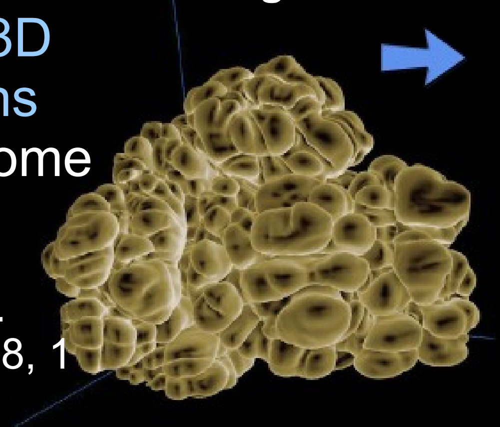
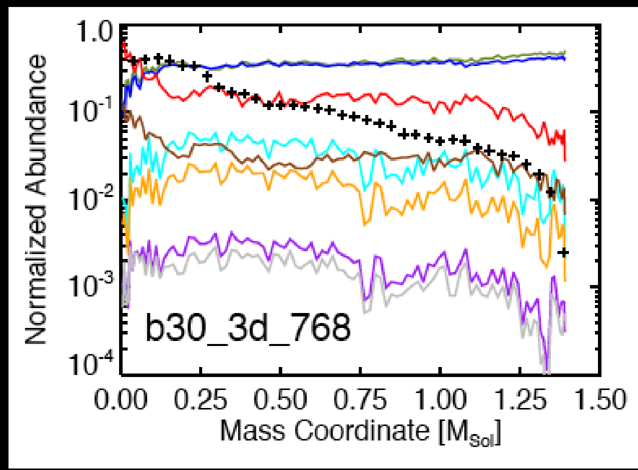
- Thermonuclear explosion of a C+O WD in a binary system (but many important details are still obscure).
- Type Ia SNe: $\boxed{\text{ejecta structure} \rightleftarrows \text{physics of the explosion.}}$
- This relationship has been explored extensively with 1D codes:



- More recently, 3D simulations have become available:

3D Deflagrations





Roepke et al. 2006 A&A 448, 1

Other 3D models are being explored: GCD [Plewa et al. 2004, ApJ 612, L37], PRD [Bravo & García-Senz 2006 ApJ 642, L157]

SNRs: Light From The Ashes

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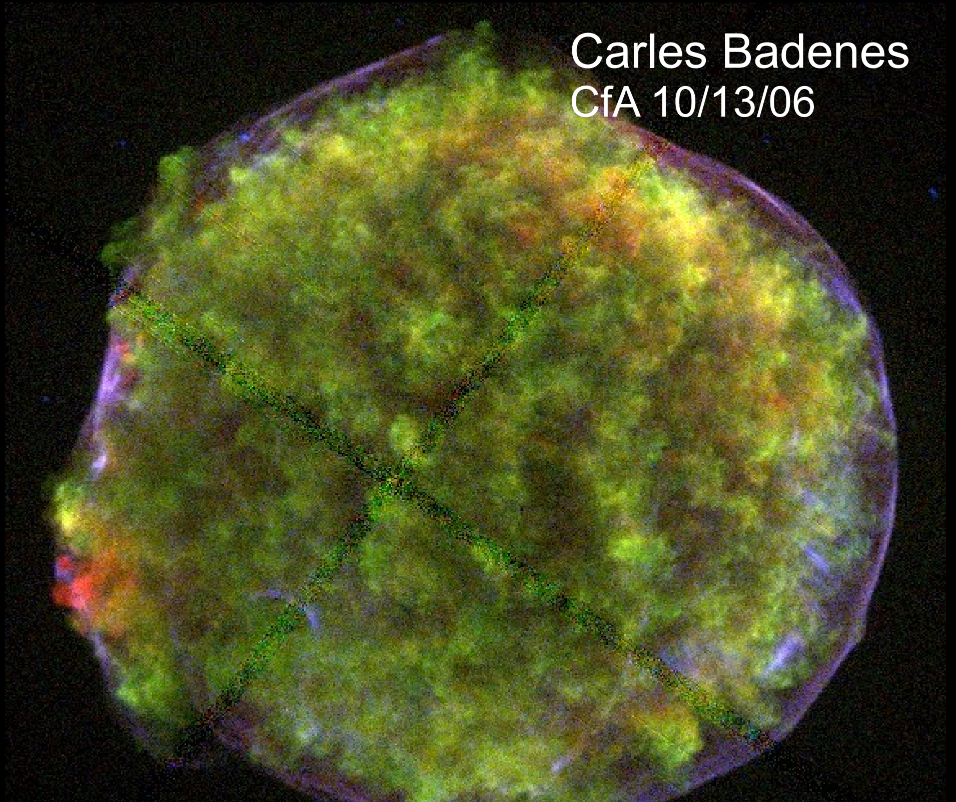
- Supernova Remnants (SNRs): ⇒ interaction between SN ejecta and the surrounding ambient medium (AM).

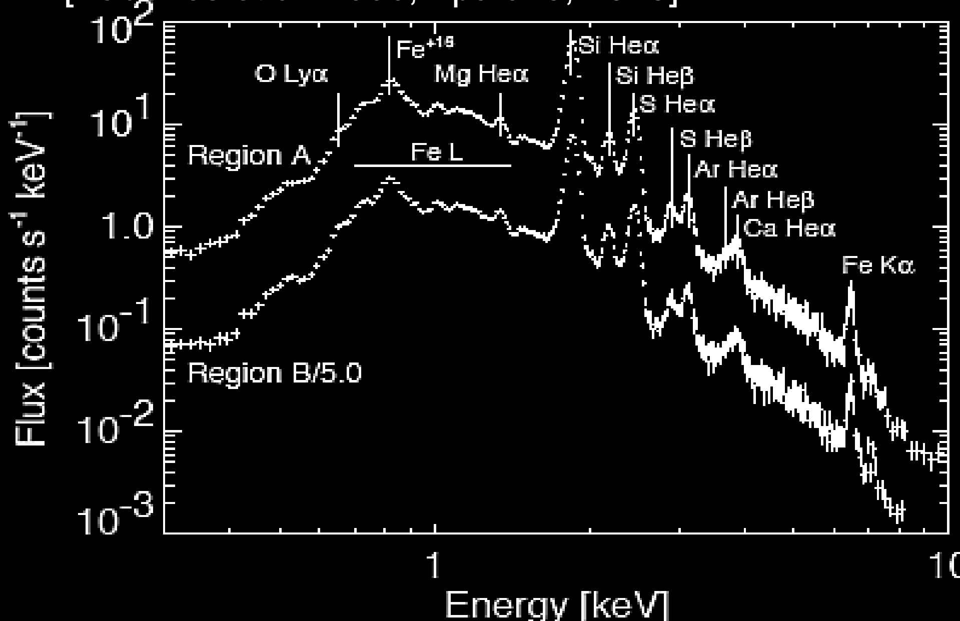
- Supersonic shock waves (~10^3 km.s^{-1}) heat AM and ejecta to X-ray emitting temperatures ⇒ centuries after the light of the SN fades away, the ejecta are revealed once again.

- *Chandra* and *XMM* provide observations of excellent quality ⇒

- The dynamics and X-ray emission of young SNRs (Tycho, SN1006, Kepler, Cas A) are dominated by SN ejecta.



Tycho's SNR. Top: *Chandra* image [Warren et al. 2005, ApJ 634, 376]. Bottom: *XMM* spectrum [Badenes et al. 2006, ApJ 645, 1373]



There is a lot of information about the structure of the SN ejecta in the X-ray emission of the SNR, but it needs to be properly analyzed and interpreted

From SN explosion to SNR (I)

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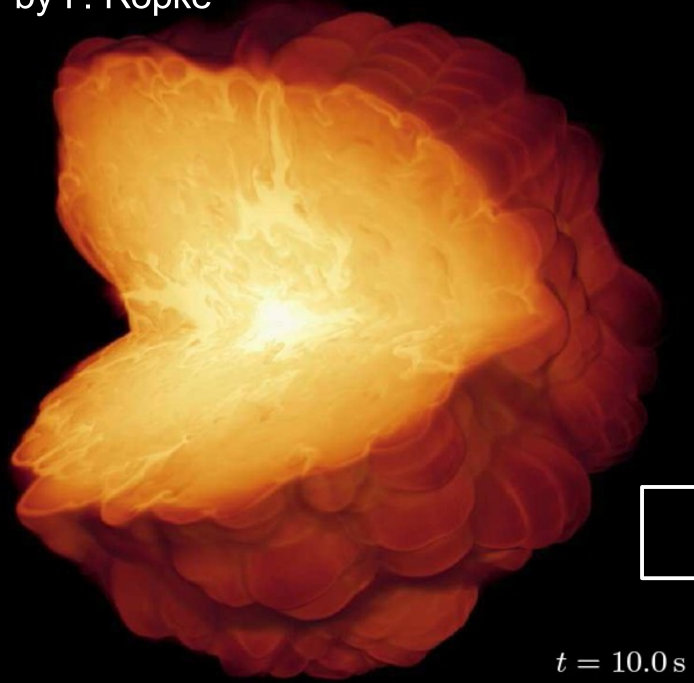
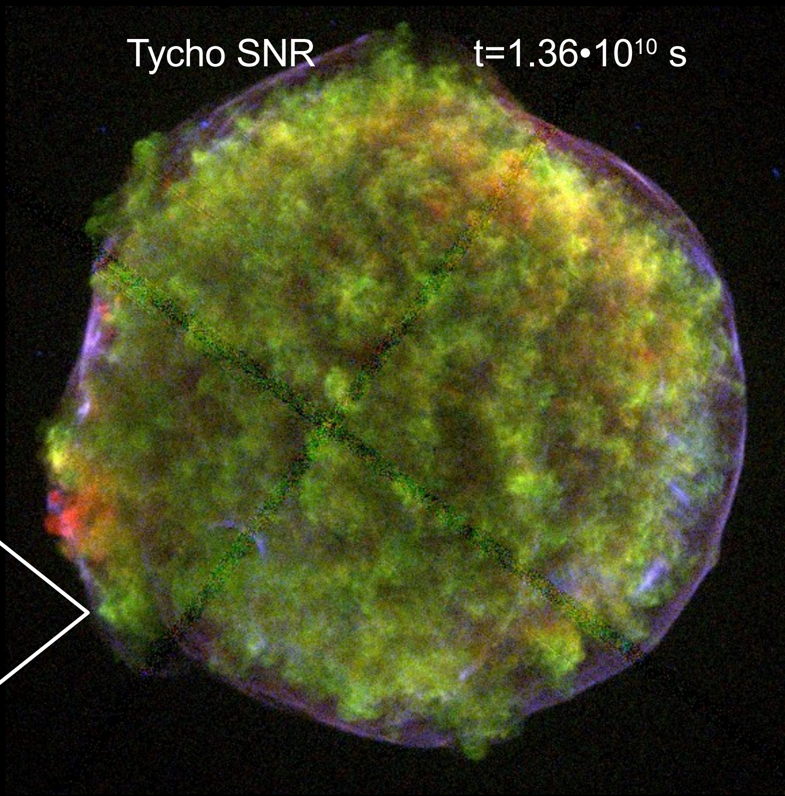
3D Type Ia SN model
by F. Röpke

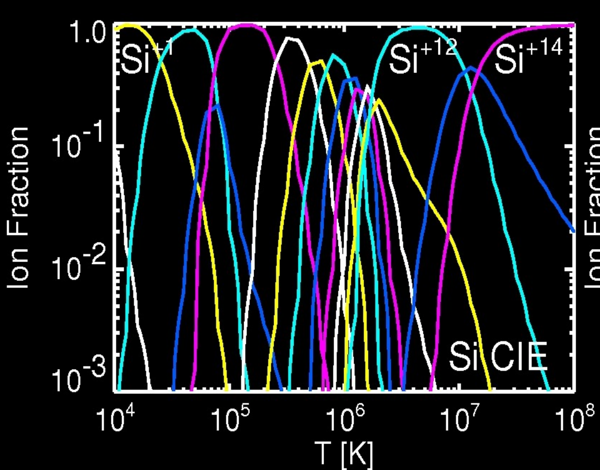
t=10 s

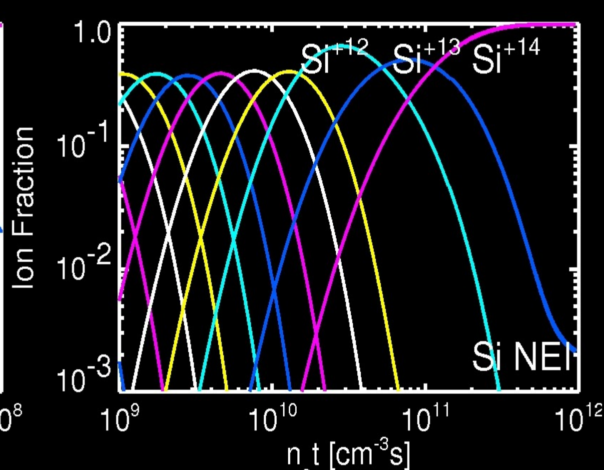


Hydrodynamics
Nonequilibrium Ionization
X-ray emission

9 decades in time!







- Low ρ plasma in SNRs is in Nonequilibrium Ionization (NEI).
- Hydrodynamic evolution and X-ray emission are coupled by the NEI processes! [Badenes et al. 2003, ApJ 593, 358; 2005, ApJ 624, 198]

From SN explosion to SNR (II)

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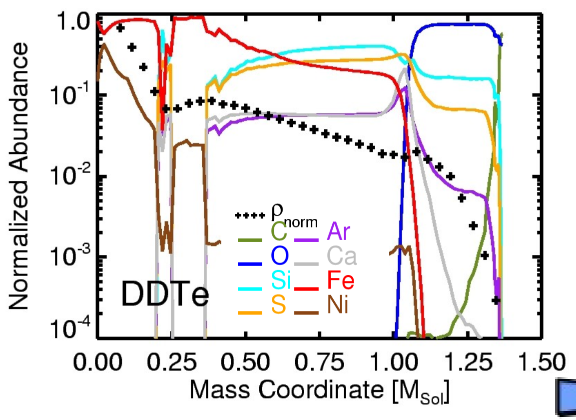
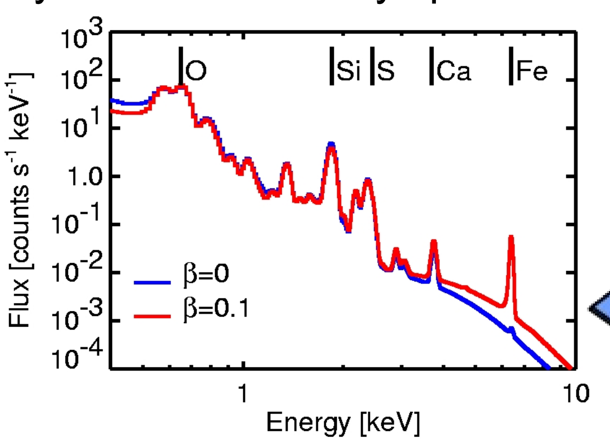
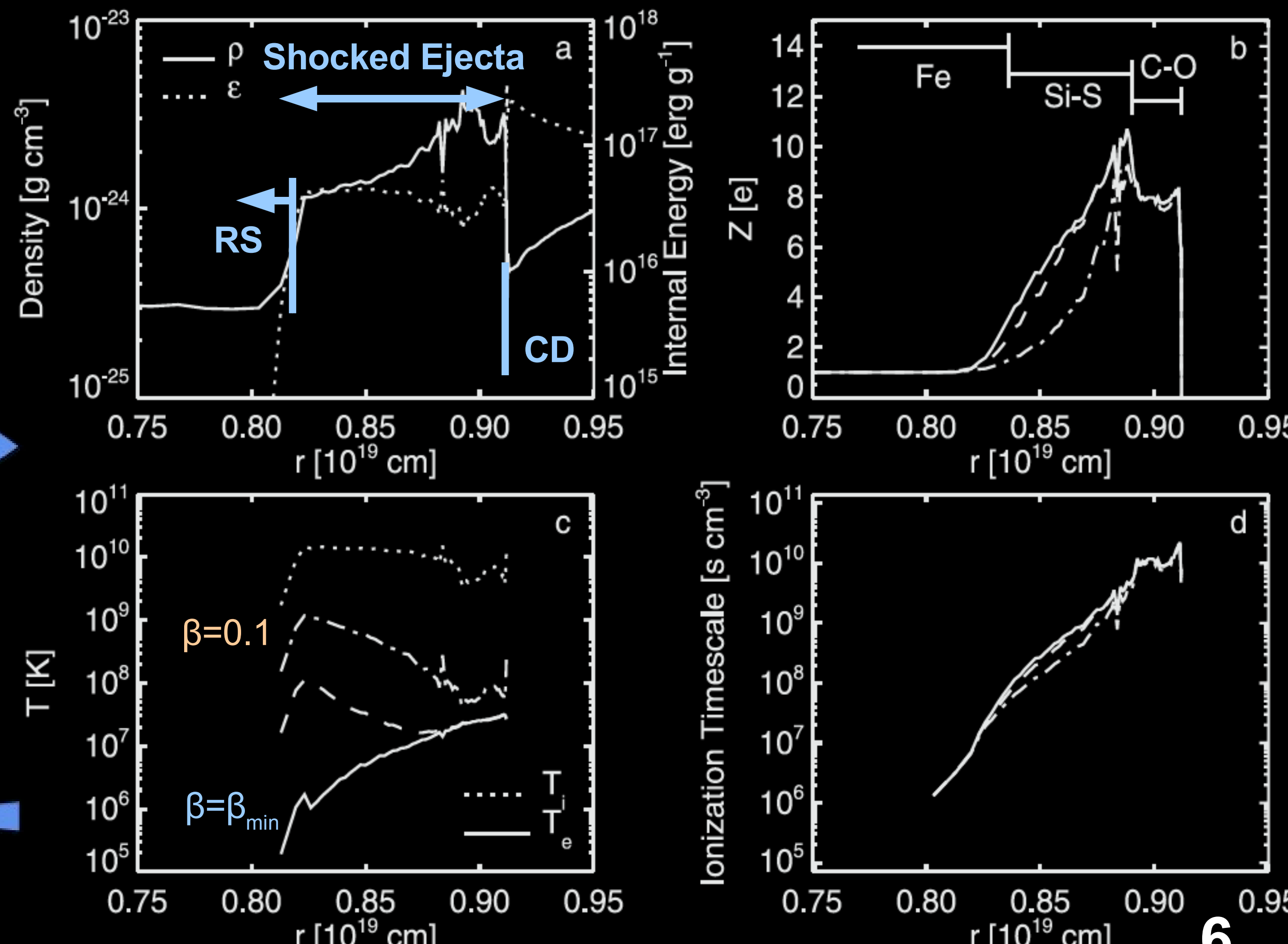
- Complete hydro + nonequilibrium ionization simulation in 1D, uniform AM.
- Parameters: AM density, $\rho_{AM}=10^{-24}$ g.cm^{-3}; SNR age, $t_{SNR}=430$ yr; amount of collisionless e$^-$ heating at the RS, $\beta[\equiv\varepsilon_{e,s}/\varepsilon_{i,s}]=\beta_{min}...0.1$.
- Different chemical elements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

SN Explosion model:



Synthetic SNR X-ray spectrum:





HD + NEI simulation

Tycho SNR: Evidence for Cosmic Ray Acceleration

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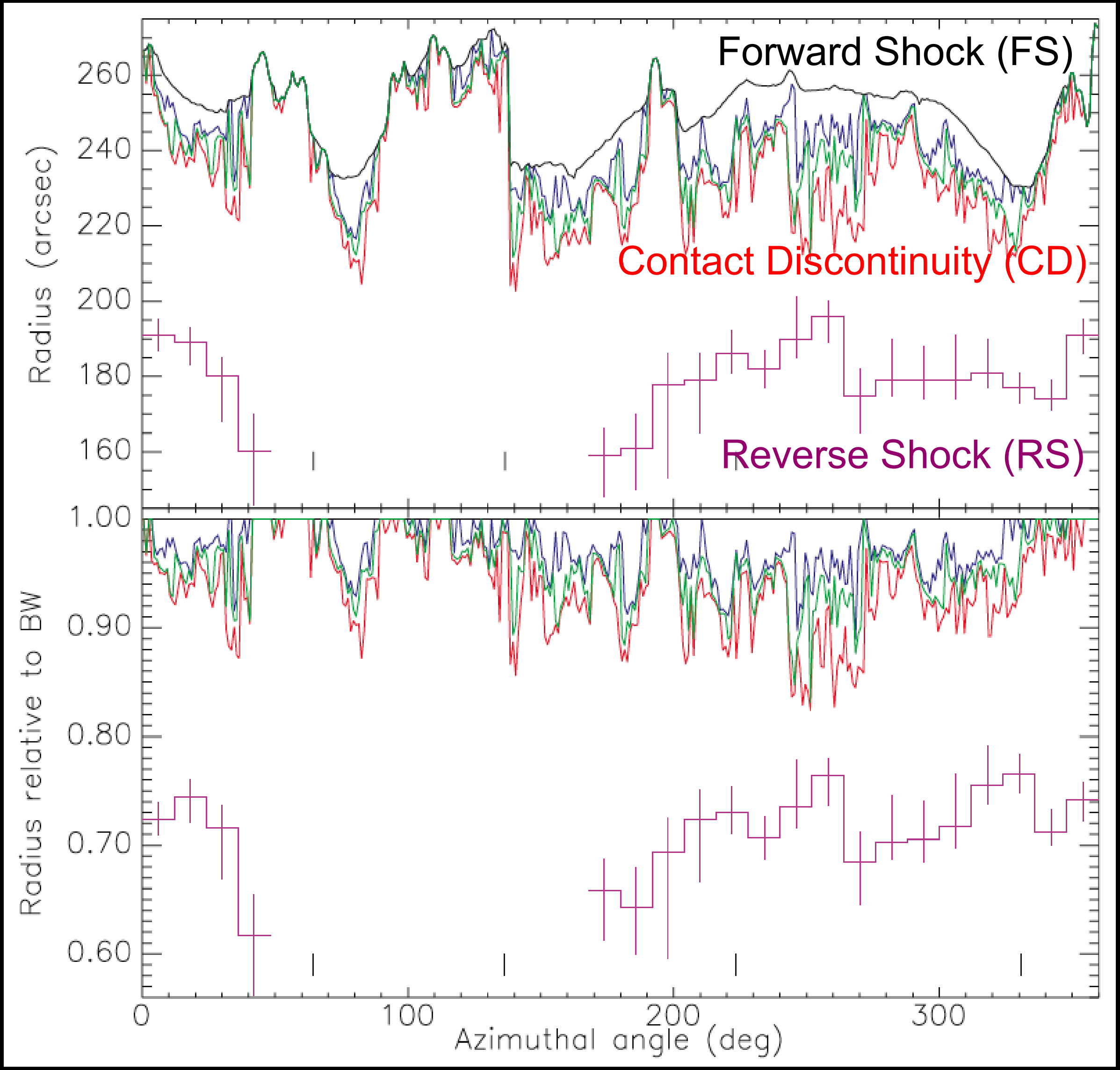
- FS is very close to CD ($R_{CD} \simeq 0.93 R_{FS}$) ⇒ Cosmic Rays are being accelerated at the FS [Warren et al. 2005, ApJ 634, 376].
- CR-modified dynamics cannot be studied with standard hydro [Ellison et al. 2004, A&A 413, 189].
- RS is NOT accelerating CRs:
  - Not close to CD.
  - Traced by hot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

⇒ standard HD+NEI models seem appropriate for the shocked ejecta



Warren et al. 2005, ApJ 634, 376

Tycho SNR: Models vs. Data – The Winner

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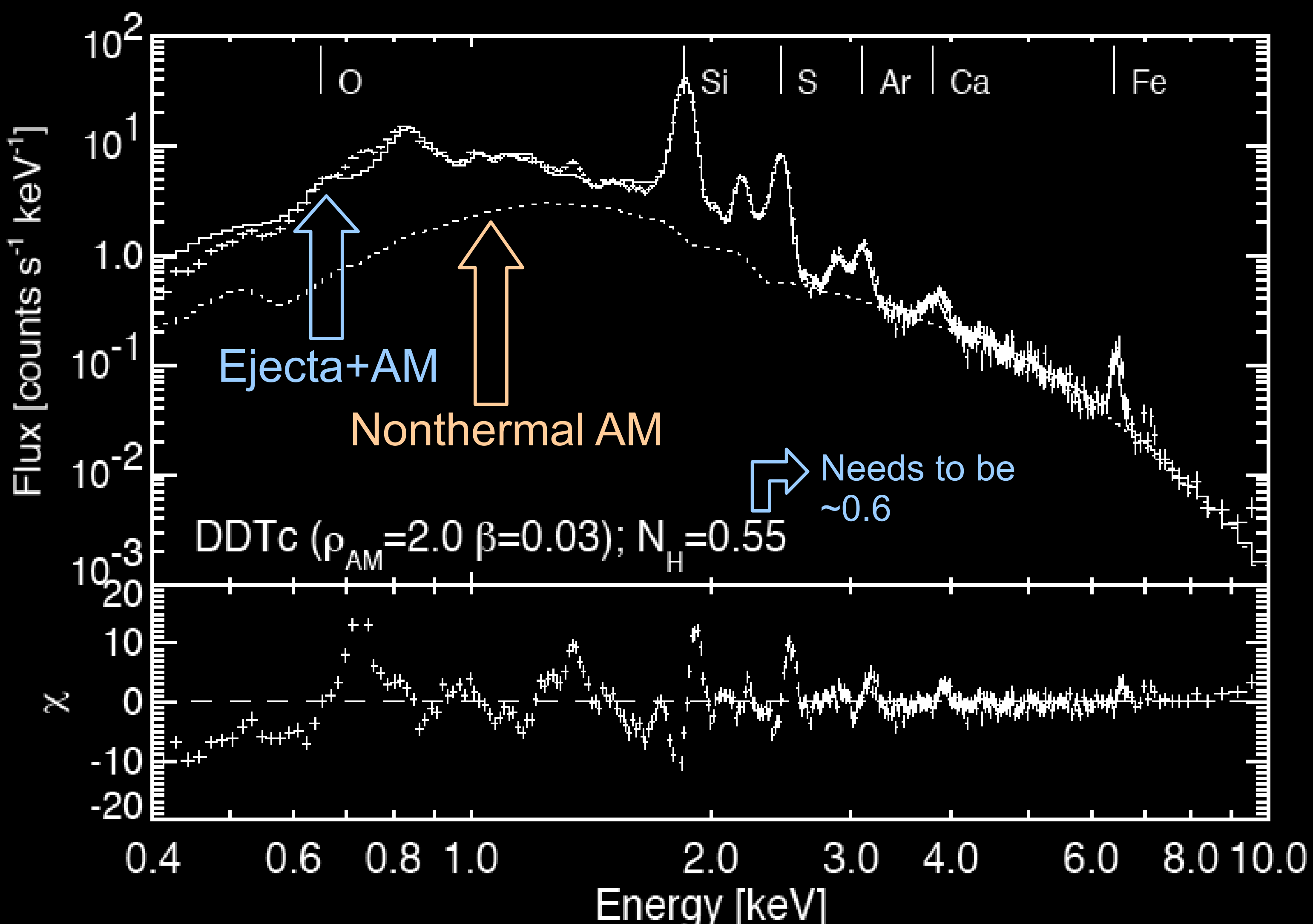
- Compare ejecta emission to observed spectrum ⇒ add AM emission: Power law with $\Gamma=2.72$ [Fink et al. 1994 A&A 283, 635].
- Best model: **DDTc** (1D delayed detonation), $\rho_{AM}=2\times10^{-24}$ g.cm^{-3}, $\beta=0.03$.

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 SNR: Models vs. Data – The Winner's Close Relatives

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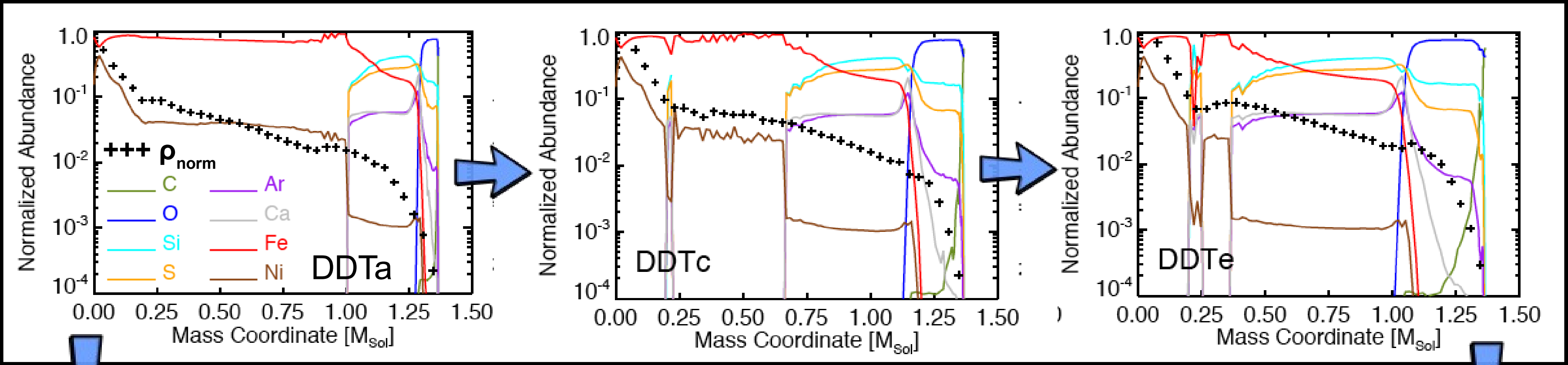
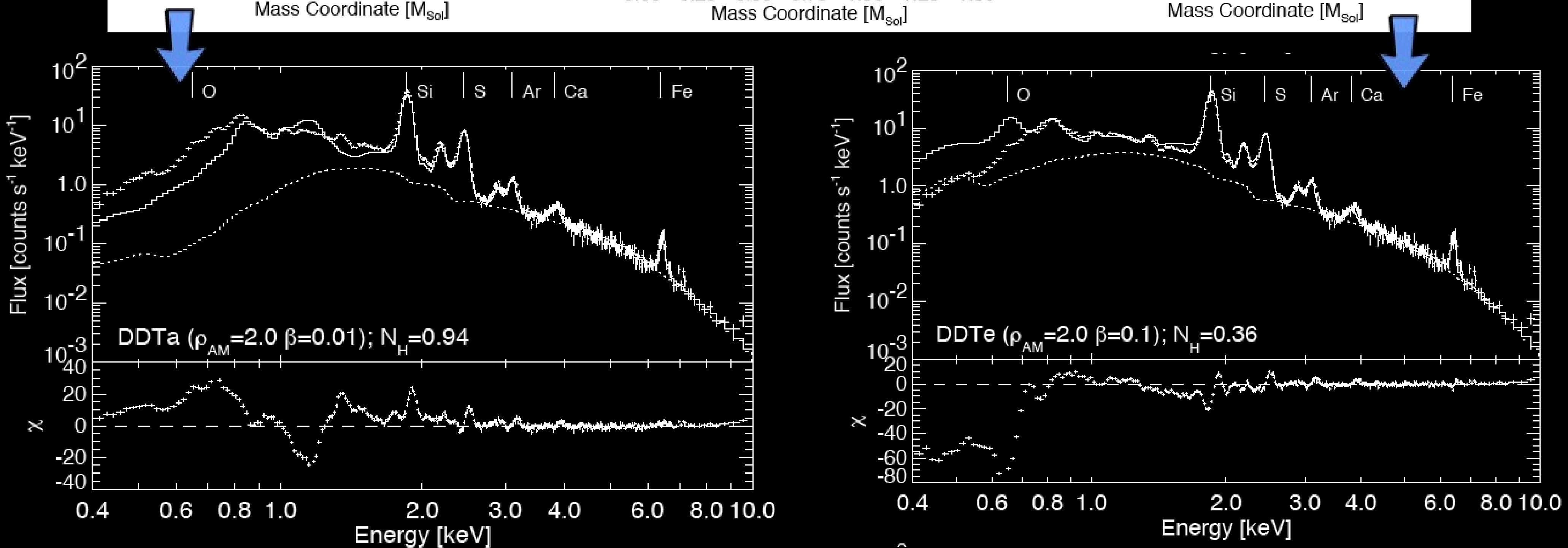
- Other delayed detonations are also successful at high energies (E>1keV).
- Low-energy (E<1keV) emission ⇒ strong constraints on the amount of ^{56}Ni and O synthesized in the explosion ⇒ ρ_{tr}.





Tycho SNR: Models vs. Data – The Losers

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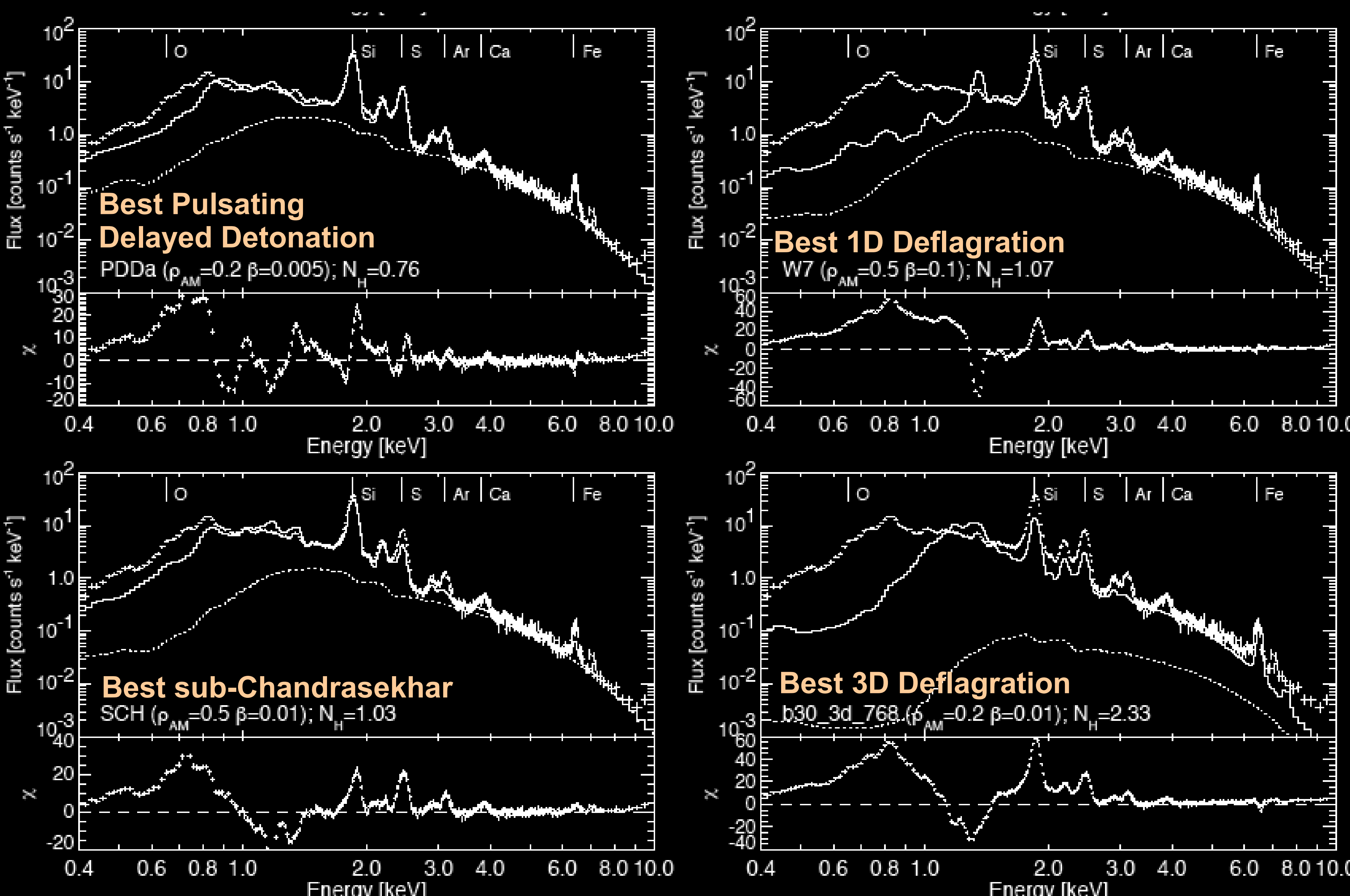
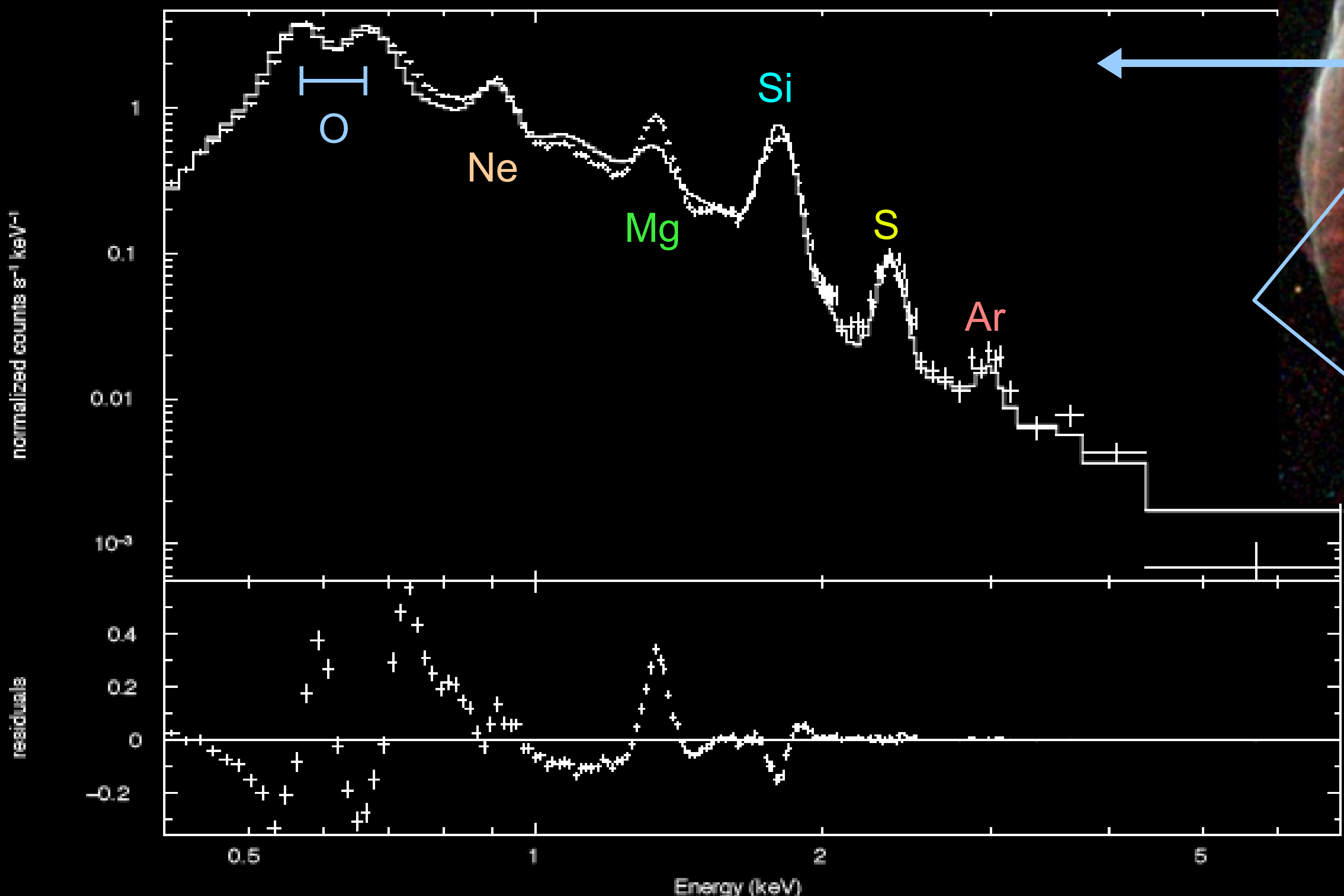
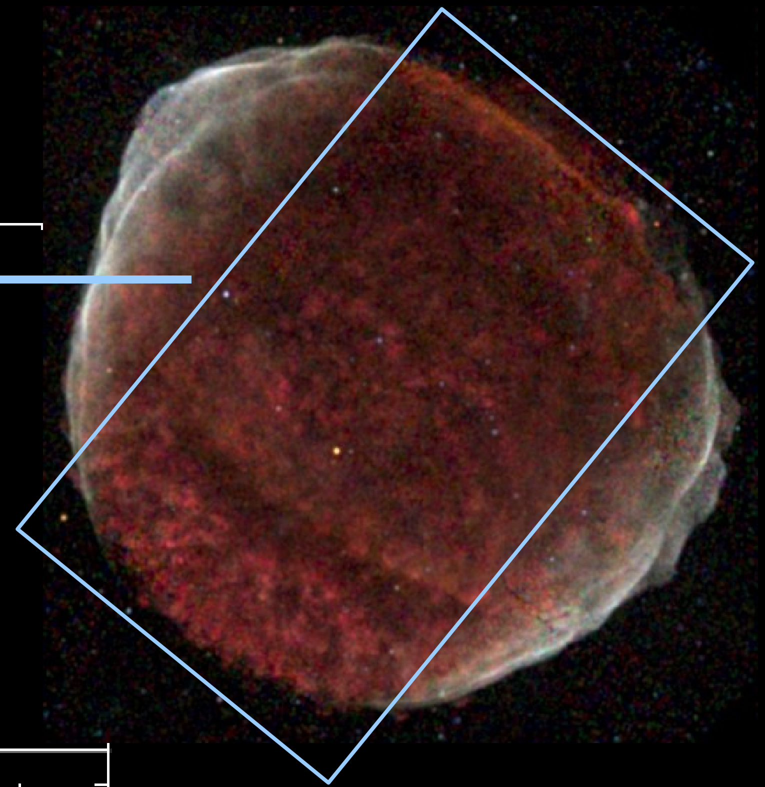
- All models that are NOT delayed detonations FAIL:



SN1006 SNR: Also a DDT?





SN 1006 SNR. Top: *Chandra* image [Hughes et al. in prep.]. Left: *Chandra* spectrum [Badenes et al. in prep.]

- The thermal X-ray emission in SN1006 is also dominated by ejecta.
- Model DDTe (ρ_{AM}=2x10^{-25} g.cm^{-3}, β=0.1) + powerlaw + absorption.
- Work in progress, but DDT models are the only ones that work well so far...

Looking back, looking ahead

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- **So far:**
  - 1D HD+NEI models without CR acceleration can reproduce the fundamental properties of the spatially integrated X-ray emission from SN ejecta in Tycho and SN1006.
  - Direct link to explosion physics. For Tycho, model DDTc: $E_k=1.16\cdot10^{51}$ erg, $M_{Fe}=0.8\ M_\odot$, $M_O=0.12\ M_\odot$, $M_{Si}=0.17\ M_\odot$, $M_S=0.13\ M_\odot$, $M_{Ar}=0.033\ M_\odot$, $M_{Ca}=0.038\ M_\odot$.
  - Description of BOTH X-ray emission and ejecta dynamics.
  - The library of synthetic spectra is PUBLIC!
- **For the future:**
  - CR acceleration is needed to explain the dynamics of young SNRs.
  - Understanding the spatially resolved X-ray emission from the SN ejecta will require multi-D HD+NEI simulations.

CONCLUSIONS

The excellent X-ray observations of Type Ia Supernova Remnants (SNRs) provided by *Chandra* and *XMM-Newton*, together with hydrodynamic + nonequilibrium ionization (HD+NEI) modeling, can put strong, quantitative constraints on the physics of Type Ia supernovae (SNe)

- Relevance to Type Ia SNe: SNRs provide results that are completely independent from those obtained using optical light curves and spectra.

- Relevance to SNRs: understand the X-ray emission from the SN ejecta (and hence dynamics, CR acceleration, etc.).

RESULTS:

- Tycho SNR: only delayed detonation models can explain the fundamental properties of the X-ray emission. All other explosion paradigms fail (in particular, 3D deflagrations with well-mixed ejecta can be confidently discarded).

- SN1006: preliminary results also suggest a delayed detonation model.

- Gory details: Badenes et al. 2006, ApJ 645, 1373.