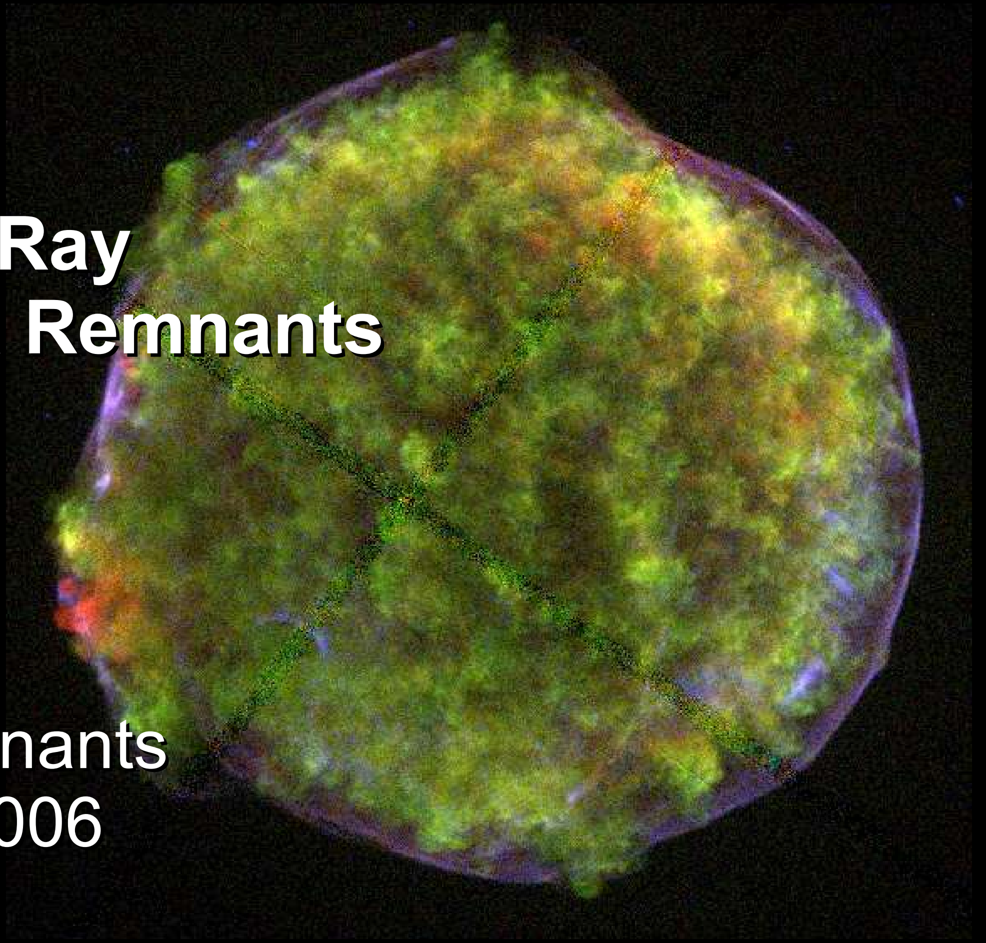
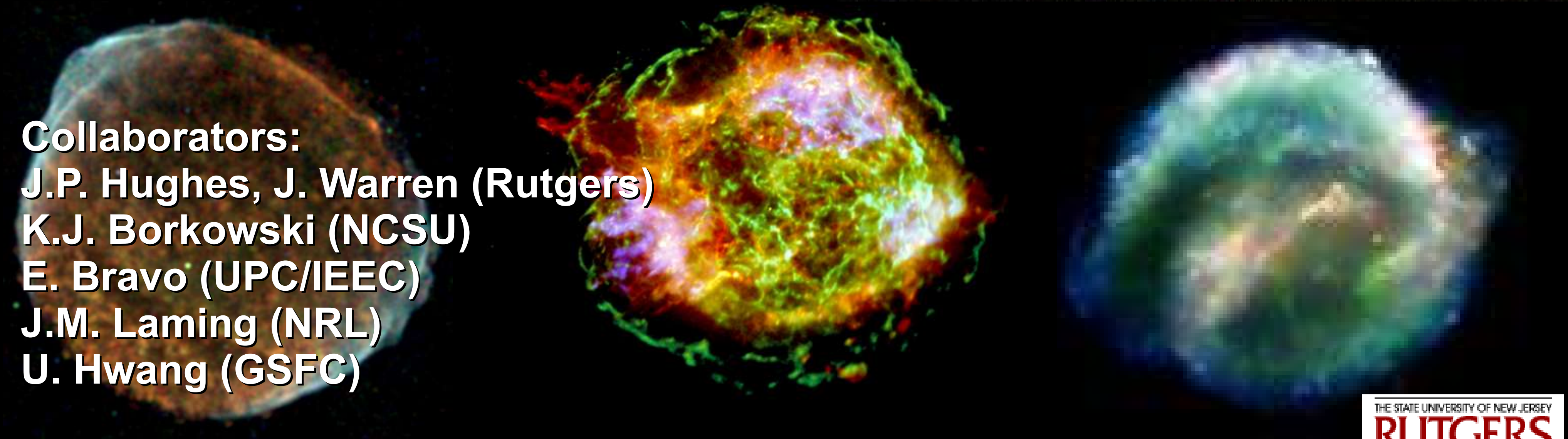
How To Build a Time Machine: Interfacing Hydrodynamics, Ionization Calculations and X-Ray Spectral Codes for Supernova Remnants



Carles Badenes
(Rutgers University)

KITP Meeting – SN and GRB Remnants
Santa Barbara, CA, February 10 2006



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OUTLINE

GOAL: Use the excellent X-ray observations of young SNRs provided by *Chandra* and *XMM-Newton* to learn about the physics of SN explosions.

- What is the best way to do this? Is there a simple approach?
- The need for hydrodynamic (HD) simulations coupled to nonequilibrium ionization (NEI) calculations.
- Levels of sophistication in HD+NEI schemes. Tools of the trade.
- Some considerations on the generation (and use) of synthetic X-ray spectra.
- The Time Machine in Action: results for the Tycho SNR and prospects for the Cas A VLP data.

ONE PROBLEM, TWO APPROACHES

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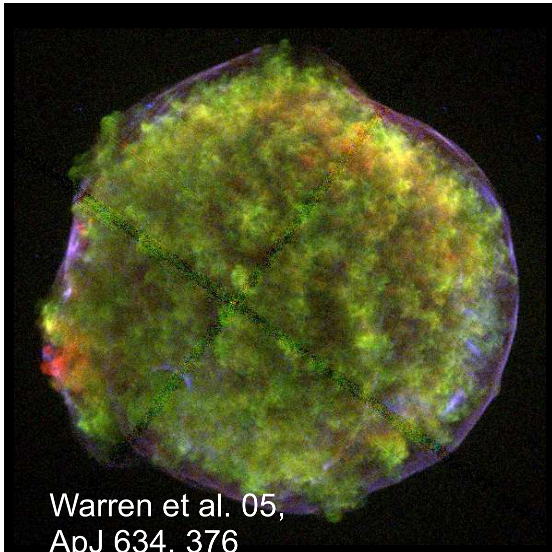
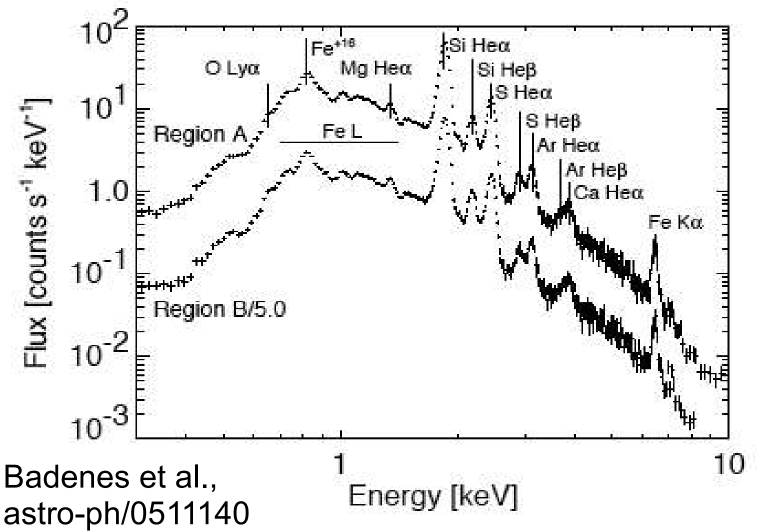
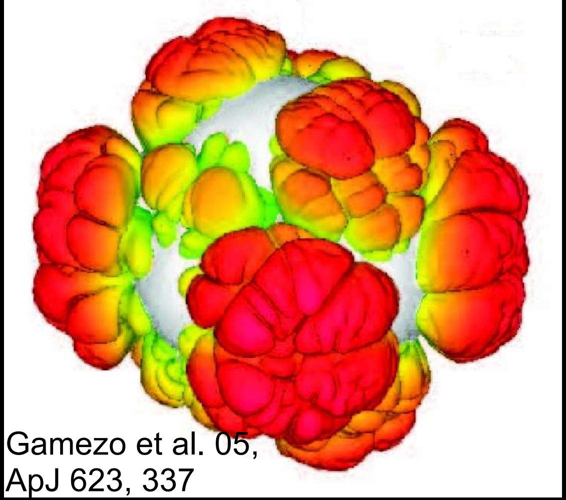


Warren et al. 05,
ApJ 634, 376

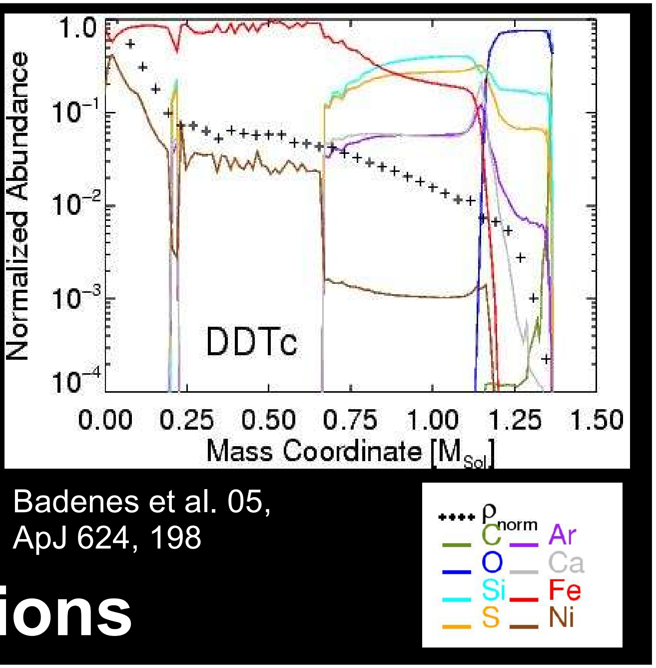


Badenes et al.,
astro-ph/0511140

X-Ray Observations of SNRs



Gamezo et al. 05,
ApJ 623, 337



Badenes et al. 05,
ApJ 624, 198

Theory of SN Explosions

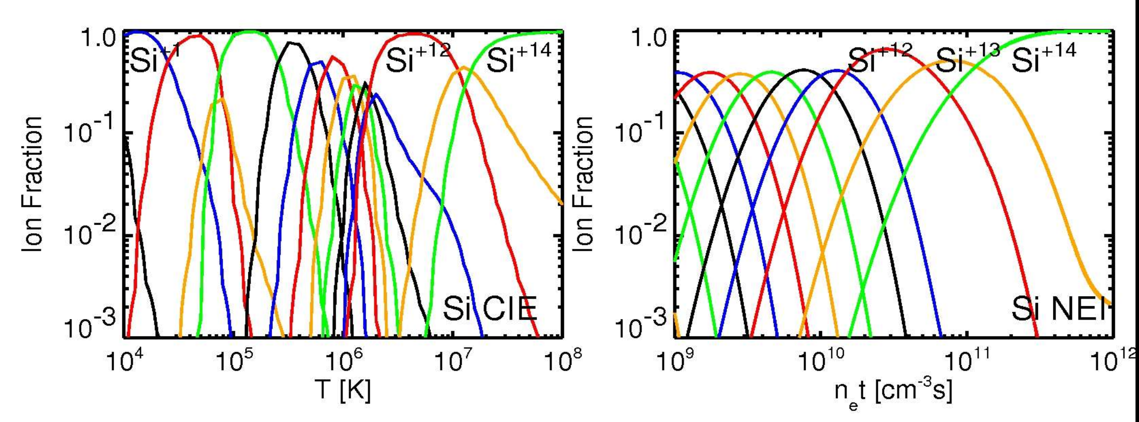
Observational: Analyze the X-ray observations, attempt to extract physical parameters, and relate them to the theory of SN explosions.

Theoretical: Start from the theory of SN explosions and attempt to 'predict' the X-ray observations of SNRs.

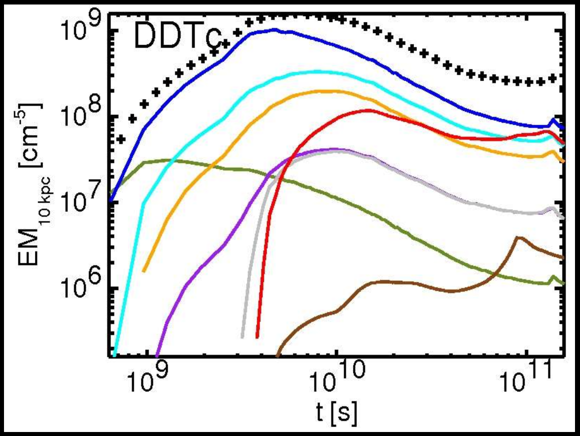
THE FAILURE OF SIMPLE MODELS (I)

- We are dealing with **transient plasmas**. The X-ray spectrum is tied to the hydrodynamic evolution through the nonequilibrium ionization processes.

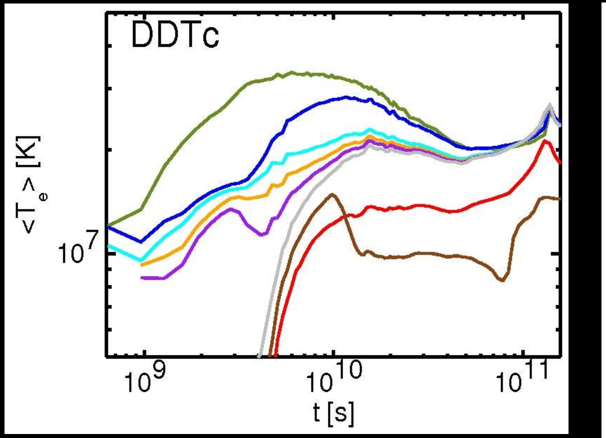
Collisional Ionization Equilibrium (CIE, left) vs. Nonequilibrium Ionization (NEI, right) for Si



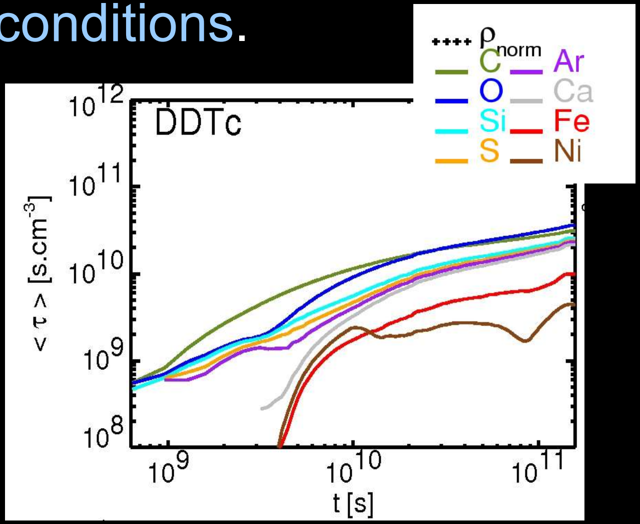
- For the **shocked ejecta** in a young SNR, the plasma is chemically inhomogeneous. Since there is a distribution of temperatures and ionization timescales, different elements emit under different conditions.



Emission Measure



Electron Temperature



Ionization Timescale

THE FAILURE OF SIMPLE MODELS (II)

- The observational approach is often based on **simple spectral models** with variable abundances (e.g., vnei, vgnei, vpshock in XSPEC [Borkowski et al. 2001, ApJ 548, 820]). These models are not adequate for ejecta emission in general:
  - Chemically homogeneous plasma.
  - Simplified (i.e. plane) shock geometry.
  - Electron pool dominated by H, He (i.e. 'solar' plasma).

- Even if a given model fits the data, the fitted parameters (T_e, $n_e t$, abundances) are very hard to interpret [Rakowski et al. 2006, ApJ submitted].

- Simple models can be used to gain some understanding of small regions, but the dynamic evolution of the entire SNR needs to be taken into account in order to interpret the results [Laming & Hwang 2003, ApJ 597, 347; Hwang & Laming 2003, ApJ 597, 362].

The **ONLY** way to understand the X-ray emission from the shocked ejecta in young SNRs **GLOBALLY** is through hydrodynamic (HD) simulations coupled to nonequilibrium ionization (NEI) calculations and an X-ray emission code.

HD+NEI SIMULATIONS FOR YOUNG SNRs

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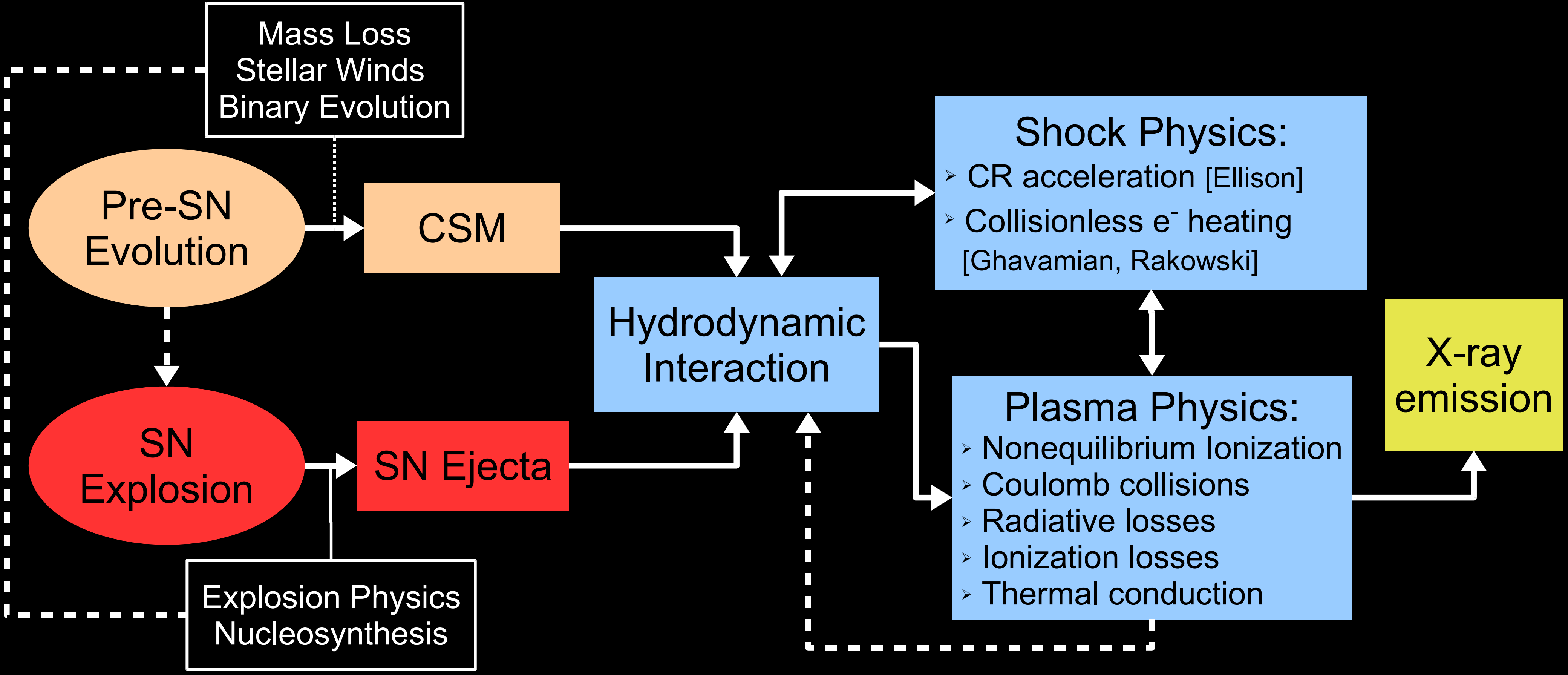

Mass Loss
Stellar Winds
Binary Evolution

Pre-SN Evolution

CSM

SN Explosion

SN Ejecta

Explosion Physics
Nucleosynthesis

Hydrodynamic Interaction

Shock Physics:
- CR acceleration [Ellison]
- Collisionless e^- heating [Ghavamian, Rakowski]

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

X-ray emission

- This is every bit as complex as it seems (it is a very 'unclean' problem).
- Our theoretical understanding of young SNRs is not complete (so the simulations MUST be incomplete). Approximations are often necessary.
- It is crucial to identify which approximations are reasonable for each object.

HYDRODYNAMIC CODES

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- **There is no 'universal HD code'.**
- All of them are designed to integrate the Euler equations. →
- There are IMPORTANT differences.

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0$$

Mass

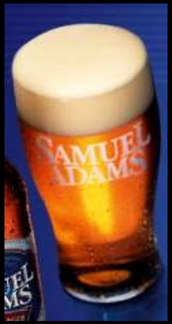
$$\frac{\partial (\rho \vec{u})}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u} \vec{u}) + \vec{\nabla} p = 0$$

Momentum

$$\frac{\partial (\rho E)}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u} E + \vec{u} p) = 0$$

Energy

- LAGRANGIAN codes: The mesh is fixed to the material
  - Good for composition-dependent processes (nucleosynthesis, ionization, radiative cooling,...).



A pint of lager

- EULERIAN codes: The mesh is NOT fixed to the material
  - Good for spatial accuracy. Multi-D codes are usually Eulerian.

A pint of ale

Publicly available codes:

- VH-1 [J.Blondin, http://wonka.physics.ncsu.edu/pub/VH-1]
- ZEUS [J.Stone, http://www.astro.princeton.edu/~jstone/zeus.html]
- FLASH [U.Chicago, http://flash.uchicago.edu]

↓

- Less painful/powerful

+ More painful/powerful

NEI CALCULATIONS

Badenes et al. 03, ApJ 593, 358
(adapted from Hamilton & Sarazin)

$$-\frac{d\varepsilon_i/\varepsilon}{dt} = \frac{d\varepsilon_e/\varepsilon}{dt} = \frac{1}{\rho\varepsilon}\frac{2^{5/2}\pi^{1/2}e^4 n_e n_i \overline{Z}^2 \ln\Lambda}{m_e \overline{A} m_u k^{1/2}}\frac{(T_i - T_e)}{(T_i/\overline{A}m_u + T_e/m_e)^{3/2}}\,, \qquad (1)$$

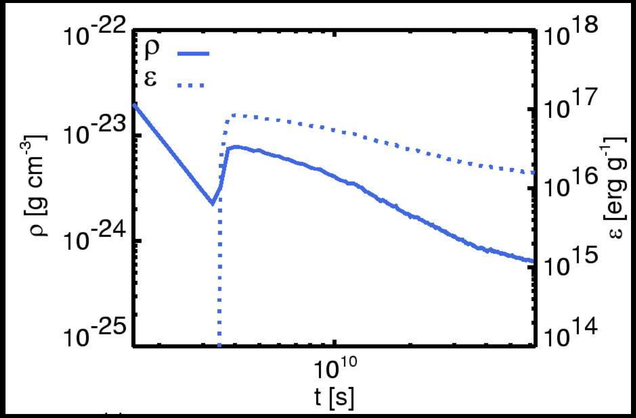
$$\frac{df_{X^q}}{dt} = \frac{\overline{Z}\rho}{\overline{A}m_u}\left[I_{X^{q-1}}f_{X^{q-1}} + R_{X^{q+1}}f_{X^{q+1}} - (I_{X^q} + R_{X^q})f_{X^q}\right]\,, \qquad (2)$$

2 Maxwellian populations (ions/electrons)

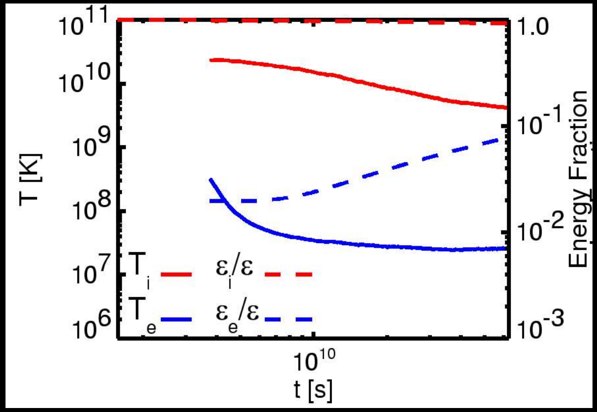
→ Internal Energy Exchange
(Elastic Collisions)

→ Ionization and Recombination
(Inelastic Collisions)

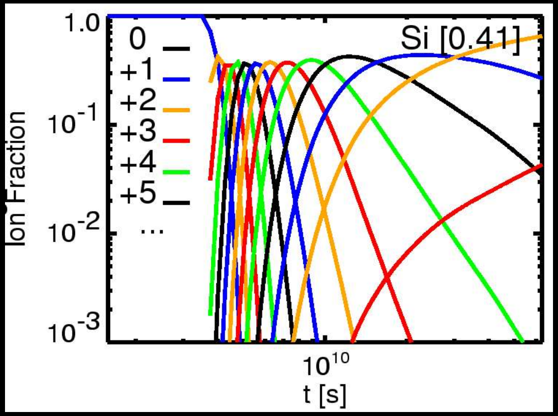
- Input from HD: ρ, ε.
- The equations are coupled (in SN ejecta, *Z* (#e$^-$/ion) changes with time).
- The equations are stiff [Press et al. 94, pp. 734-737]: (semi-)implicit scheme.



HD Evolution



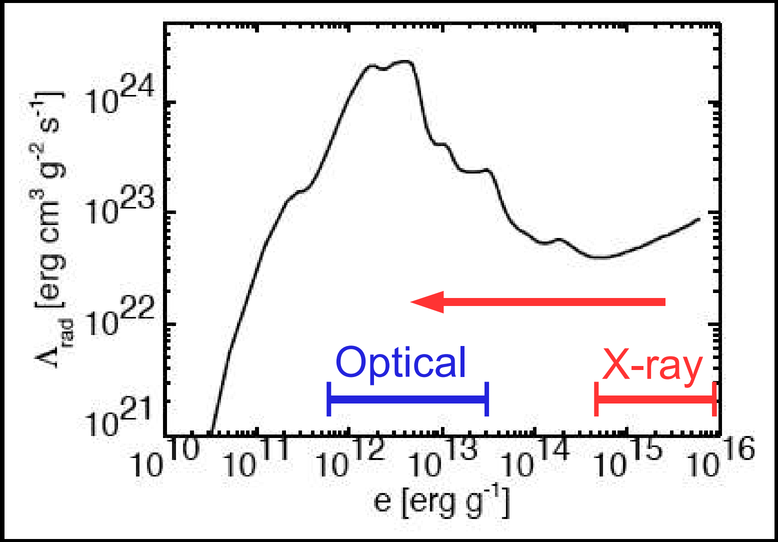
$T_{i,e}$, $\varepsilon_{i,e}/\varepsilon$ Evolution



Ionization (Si)

FEEDBACK PROCESSES

- **Radiative Losses:**
  - Affect dense material (shocked early on, strong CSM interaction).
  - Strongly dependent on ionization state and chemical composition.
  - Runaway process (X-ray → Optical).
- **Ionization Losses:**
  - Behave essentially like radiative losses.

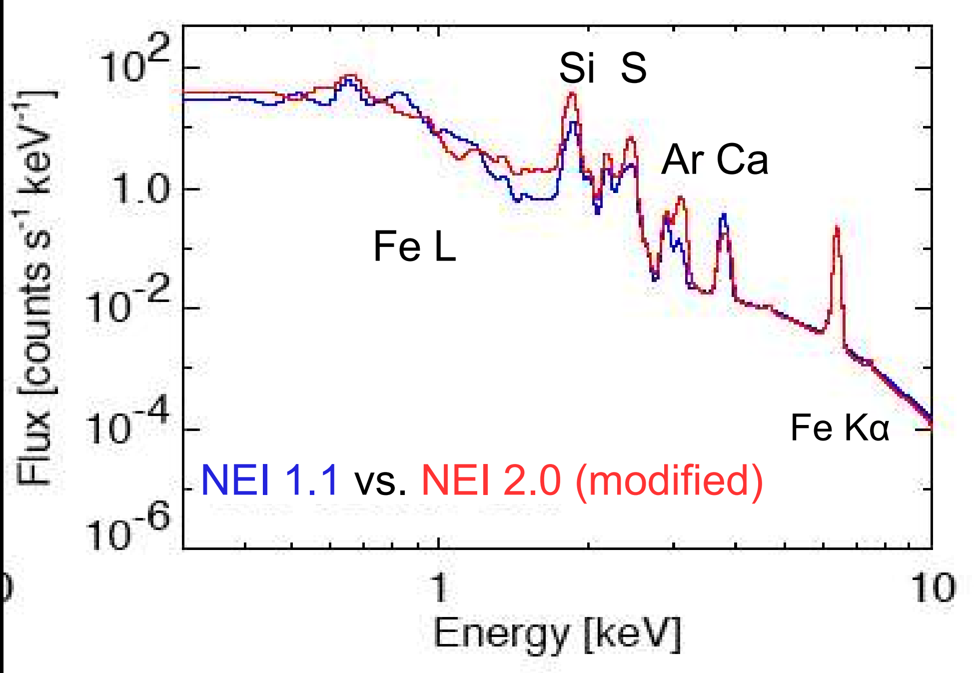


Cooling curve (solar plasma, CIE)
Sutherland & Dopita 93, ApJS 88, 253

- **Thermal conduction:**
  - Very complex process. Strongly dependent on magnetic field distribution and density inhomogeneities in the shocked plasma [Velázquez et al. 04, ApJ 601, 885].
  - Model predictions are hard to reconcile with the morphology of young SNRs [Bedogni & D'Ercole 88, A&A 190, 320].
  - In some cases, the observations rule out efficient thermal conduction due to the presence of strong temperature gradients.

SYNTHETIC X-RAY SPECTRA

- Once the HD and NEI calculations are done, it is relatively simple to calculate synthetic X-ray spectra.
- This can be done directly in XSPEC (thanks to K.J. Borkowski and R. Smith).
- WARNING:
  - Atomic data for NEI plasmas are incomplete.
    - He and H-like ions SHOULD be OK for most elements.
    - Lower ionization stages are a liability.
    - Fe L is a nightmare.
    - BE CONSERVATIVE.



  - Comparing synthetic spectra and data **quantitatively** is not trivial.

APPLICATION TO THE TYCHO SNR

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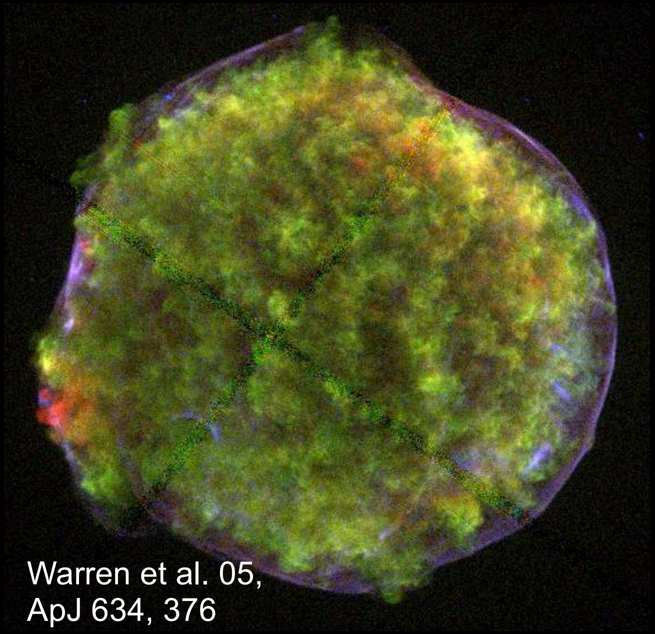
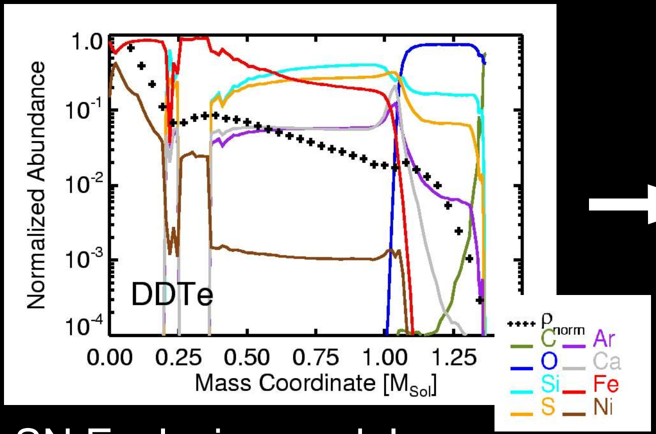


Warren et al. 05,
ApJ 634, 376

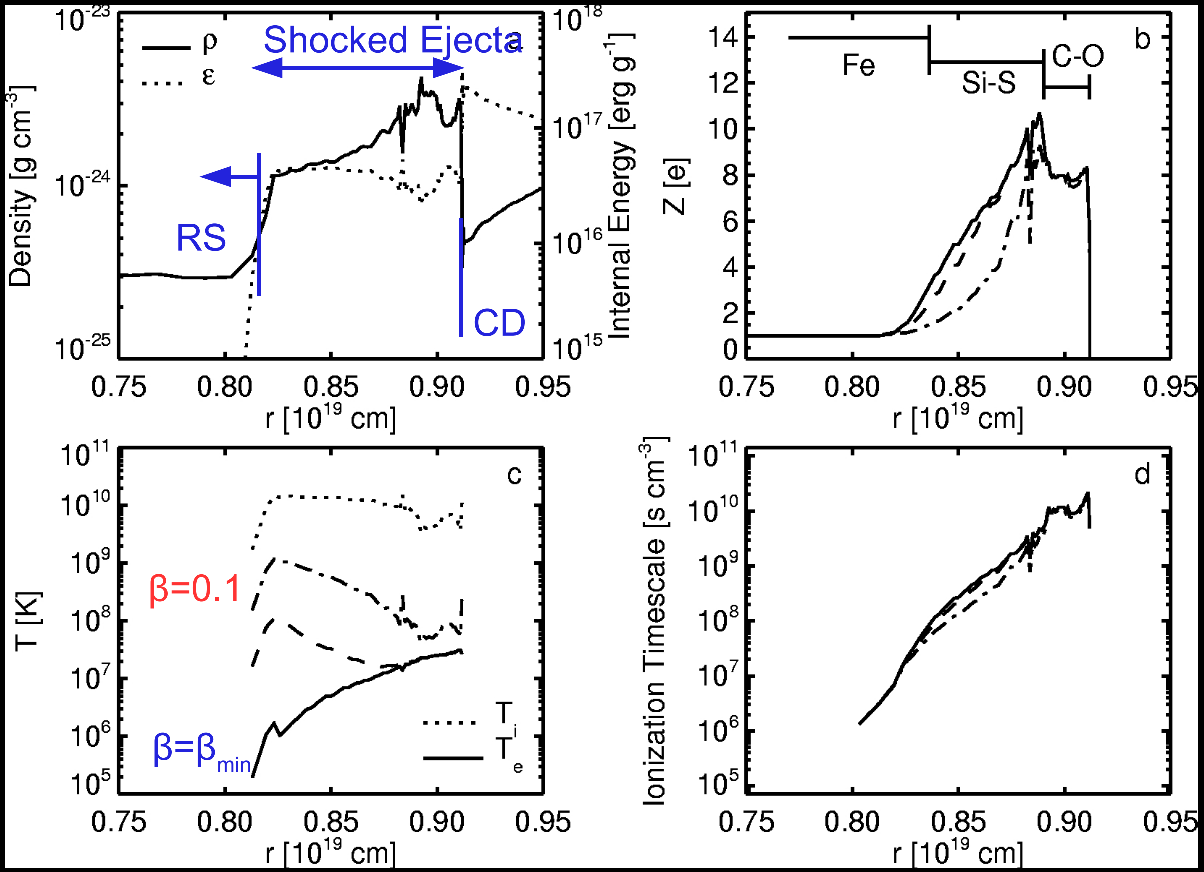
- **Reasonable approximations**
  - Type Ia SN: Type Ia SN models; constant AM density (W half) [Badenes & Bravo 01, 556, L41].
  - No radiative or ionization losses. No optically-emitting ejecta [Smith et al. 91, ApJ 375, 652]. This NEEDS to be verified in the models!
  - No thermal conduction: Fe K peaks interior to Fe L [Hwang & Gotthelf 97, ApJ 475, 665].
- **Not-so-reasonable approximations**
  - HD simulations without Cosmic Ray acceleration: OK for the shocked ejecta, but outrageously wrong for the forward shock [Warren et al. 05, ApJ 634, 376].
  - HD simulations with spherical symmetry: dynamic instabilities at the contact discontinuity probably won't have a dramatic effect on the spatially integrated X-ray emission. [HD code: 1D Lagrangian].
- For details: Badenes et al., astro-ph/0511140.

A PRACTICAL EXAMPLE: MODEL DDTe

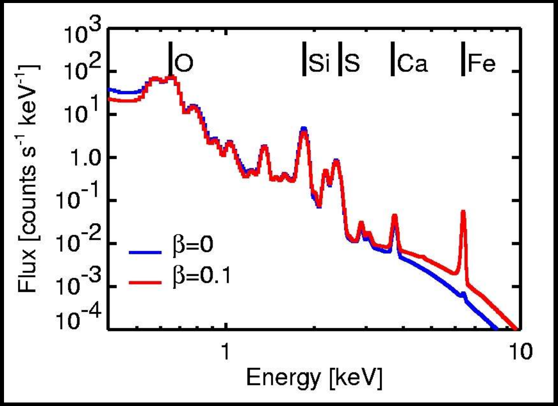
- Model DDTe (delayed detonation). Interaction with a uniform AM.
- Parameters: $\rho_{AM}=10^{-24}$ g.cm^{-3}; t=430 yr; $\beta[\equiv\varepsilon_{e,s}/\varepsilon_{i,s}]=\beta_{min}...0.1$.
- X-ray spectrum and SN model are TIED TOGETHER through the HD+NEI simulation. Different elements emit under different conditions.



SN Explosion model



HD + NEI simulation



Synthetic X-ray spectrum

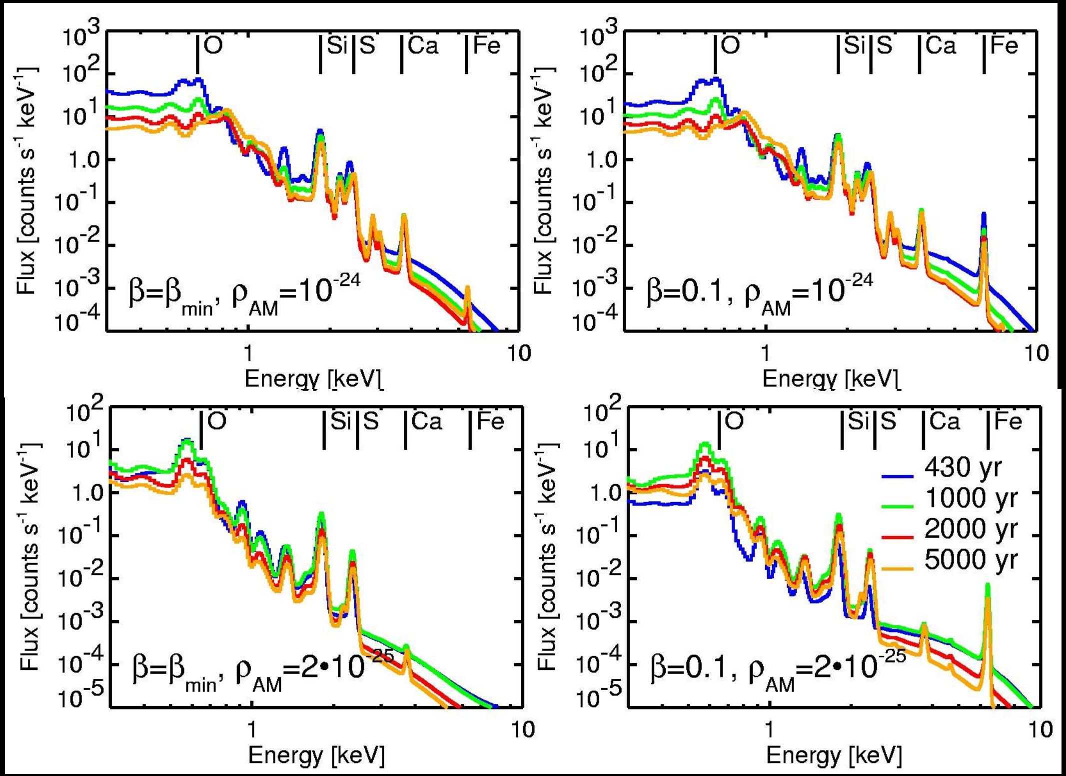
THE GRID OF SYNTHETIC SPECTRA

- For each Type Ia SN explosion model, three parameters determine the X-ray spectrum from the shocked ejecta: the age of the SNR (t_{SNR}), the AM density (ρ_{AM}) and the amount of collisionless electron heating at the reverse shock (β).

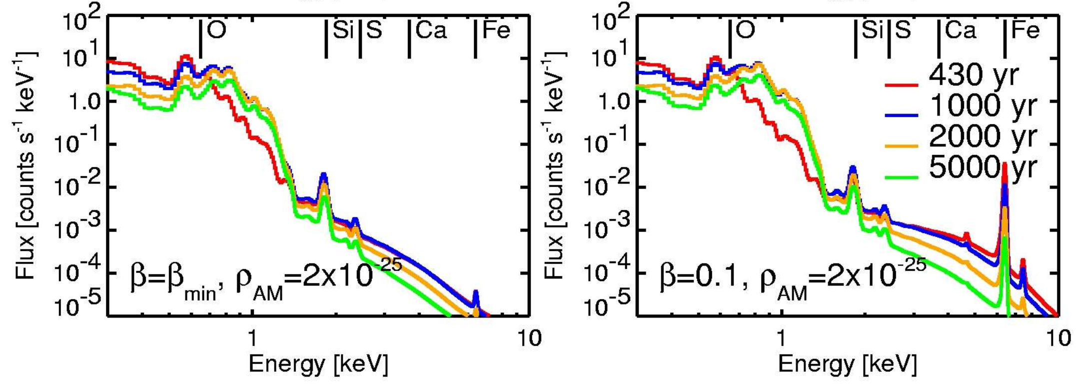
- We have considered 32 Type Ia SN explosion models: deflagrations (including W7), delayed detonations, pulsating delayed detonations, sub-Chandrasekhar explosions, 1D averages of 3D deflagrations, ...

- The spectra for different explosion models are very different from each other.

Model DDTe (t_{SNR}, ρ_{AM}, β):



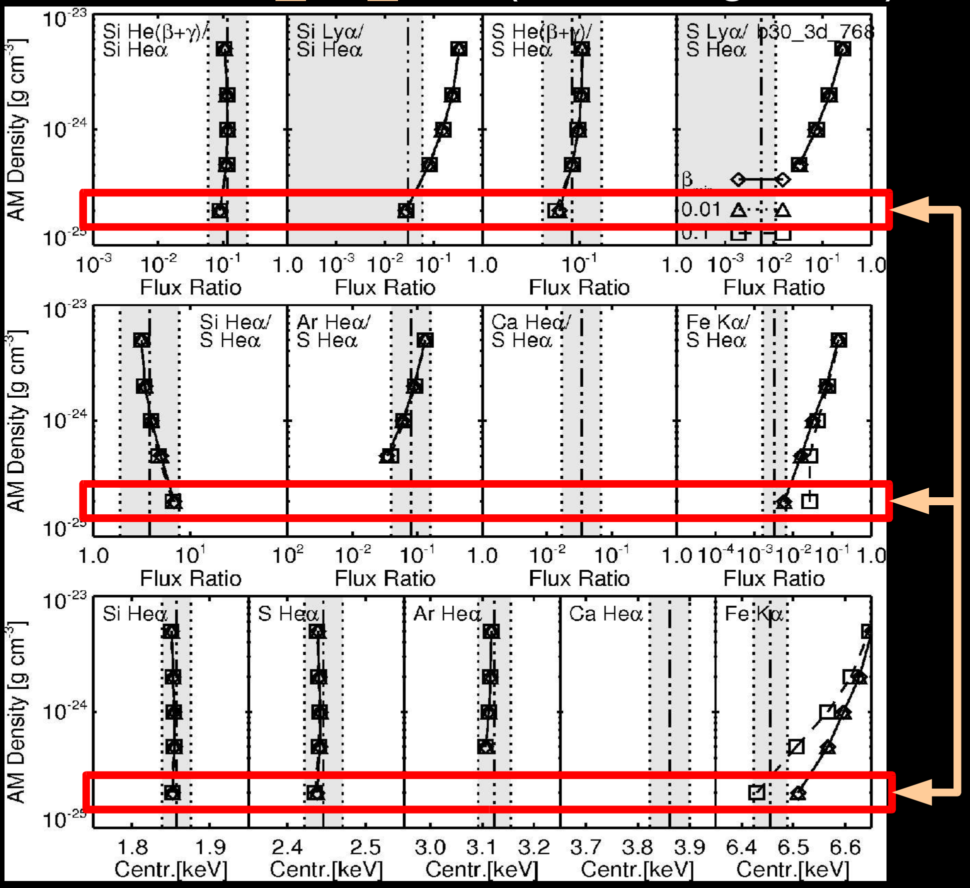
Model B30U (t_{SNR}, ρ_{AM}, β):



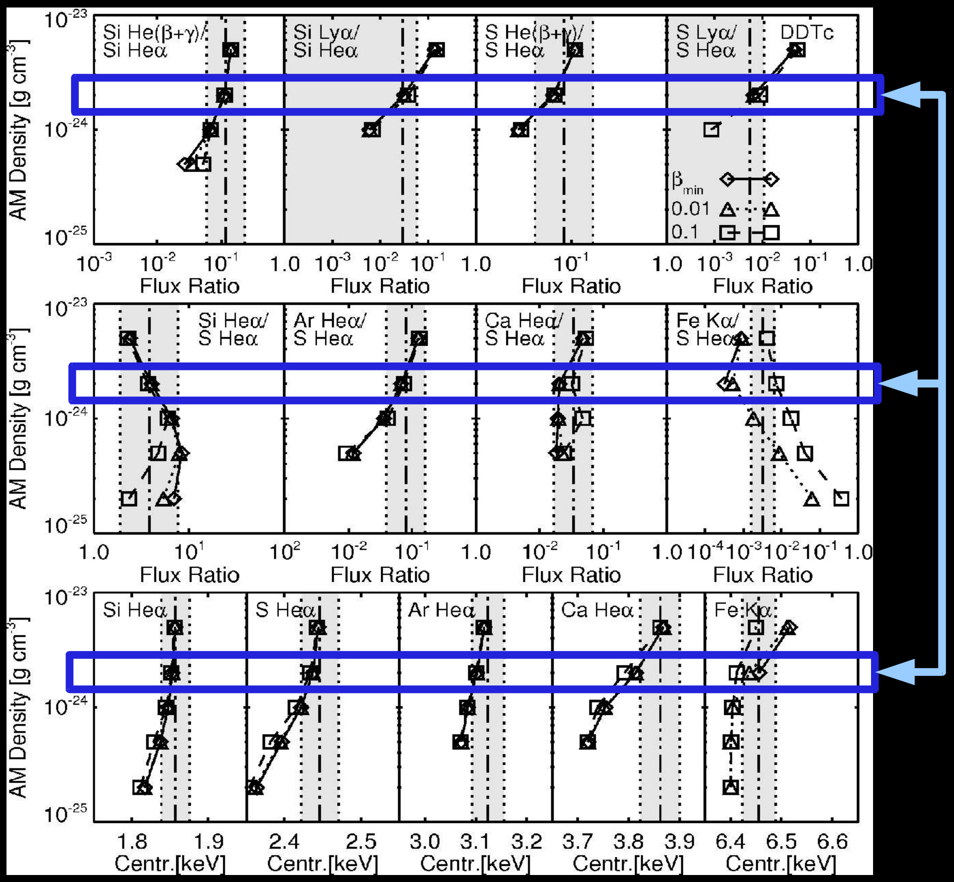
REDUCING THE PARAMETER SPACE

- 13 diagnostic quantities (8 line flux ratios and 5 line centroids).
- Only ρ_{AM} and β can be varied for a given Type Ia SN model (t_{SNR}=433 yr).
- Delayed detonations turn out to be the most successful paradigm.

Model **b30_3d_768** (3D deflagration)



Model **DDTc** (delayed detonation)



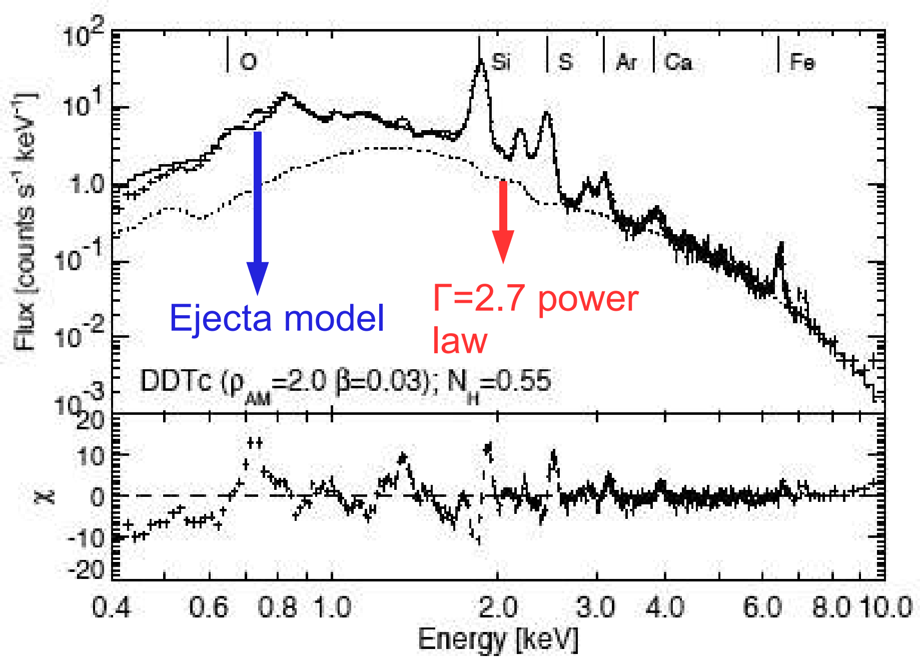
→ ρ_{AM}=2.10^{-25} g.cm^{-3} β=0.01

→ ρ_{AM}=2.10^{-24} g.cm^{-3} β=0.03

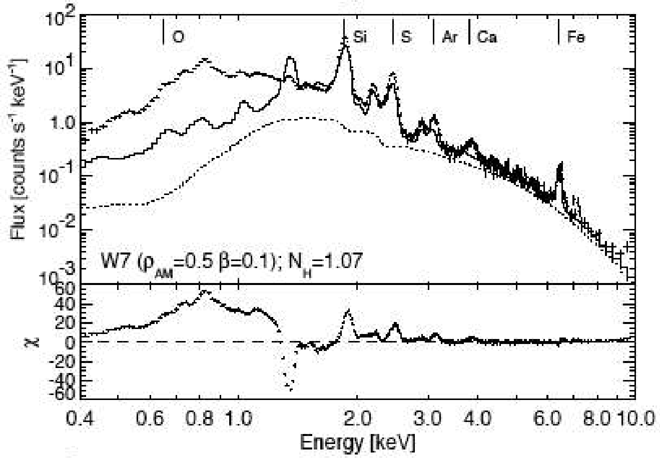
THE TIME MACHINE IN ACTION: THE EXPLOSION MECHANISM OF SN 1572

- Only delayed detonation models can explain the fundamental properties of the X-ray emission from *all* the elements in the shocked ejecta: O, Si, S, Ar, Ca, Fe.

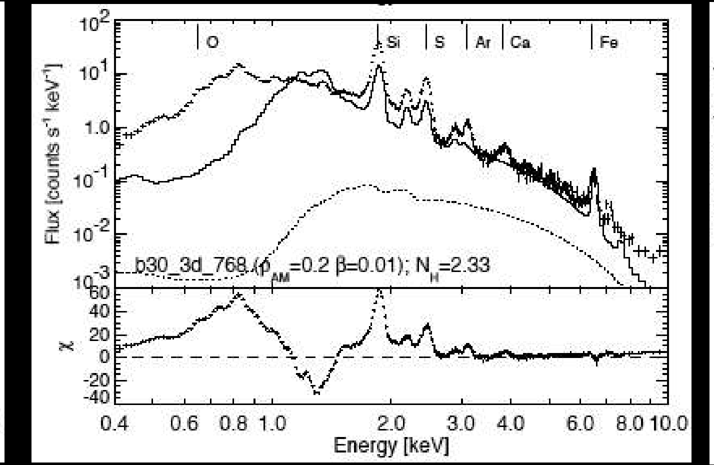
- The best model requires the correct amount of interstellar absorption and nonthermal flux from the forward shock, and matches the measured position of the reverse shock and velocity of the shocked ejecta.



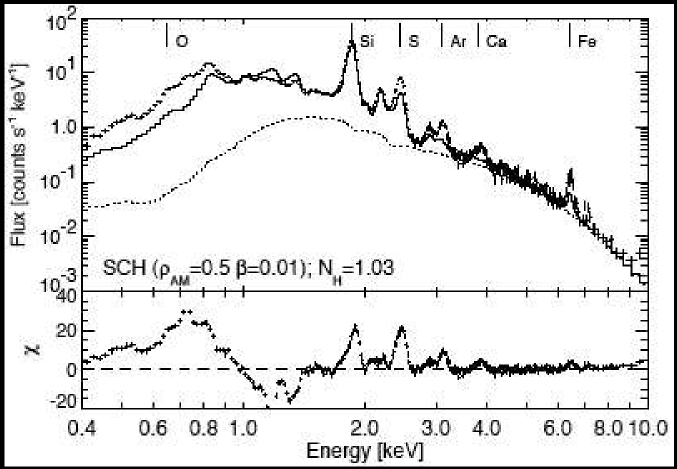
Delayed Detonation



1D Deflagration



3D Deflagration



Sub-Chandrasekhar Explosion

THERMONUCLEAR vs. CORE-COLLAPSE SUPERNOVA REMNANTS (I)

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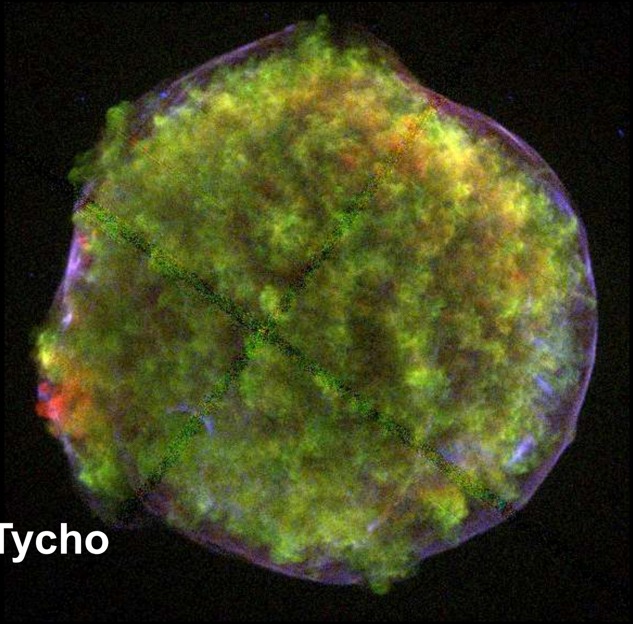
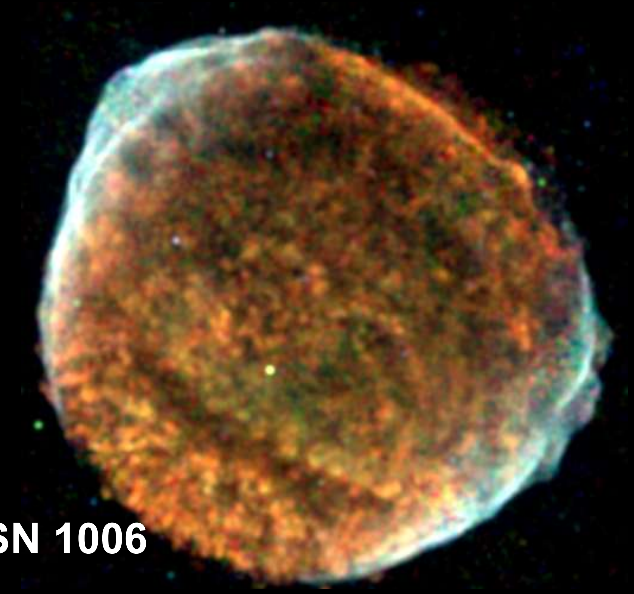


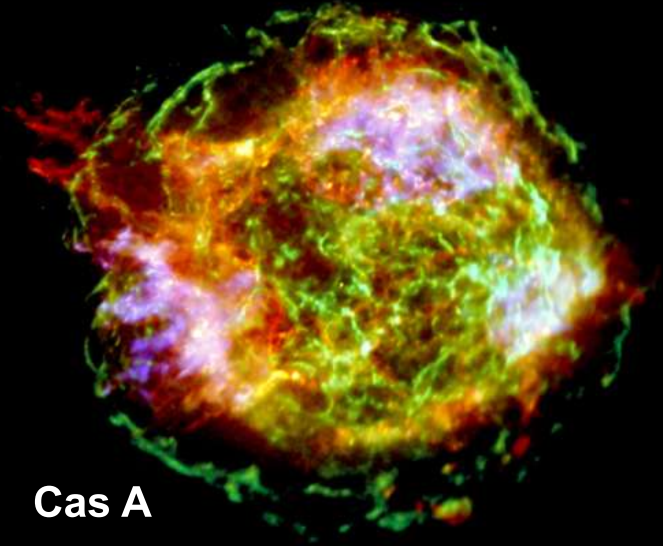
Tycho



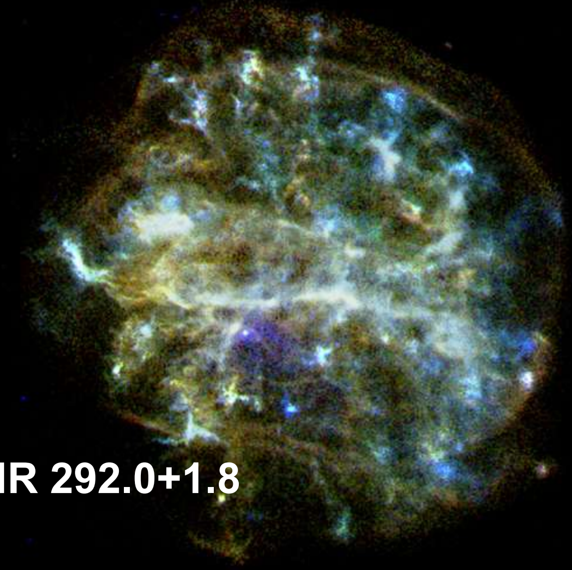
SN 1006

Thermonuclear SNe:

- Straightforward explosions.
- Relatively simple SNR dynamics.



Cas A



SNR 292.0+1.8

Core collapse SNe:

- More complex explosions.
- More 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

THERMONUCLEAR vs. CORE-COLLAPSE SUPERNOVA REMNANTS (II)

Core-collapse SNRs are more challenging than thermonuclear SNRs.

- Core collapse SNe are not so well understood:
  - Theoretical models STILL do not explode [A.Burrows].
  - Parameter space is considerably larger [Blondin, Janka].
  - Relationship between explosion physics and ejecta structure is less direct. In particular, nucleosynthesis is NOT instrumental for the explosion [Hungerford].
- The SNR dynamics are more complex:
  - Ejecta are more turbulent and anisotropic [Wang, Nomoto].
  - Progenitors strongly modify their circumstellar medium [Immler]. SNR evolution in this CSM can be dramatically different [Dwarkadas].

WHAT IS NEEDED FOR Cas A? (IN LIEU OF CONCLUSIONS)

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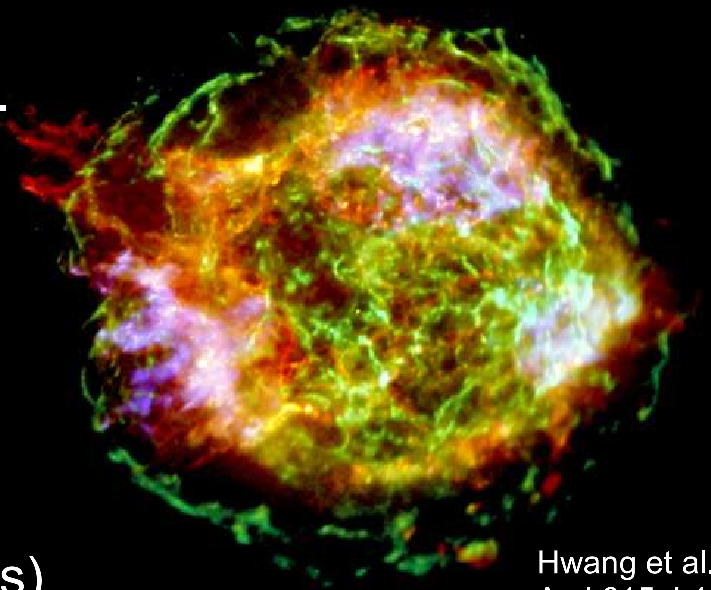
- There are strong asymmetries in the ejecta:
  - Abundance pattern [Hughes et al. 00, ApJ 528, L113].
  - Jet-counterjet [Vink, Laming].

→ multi-D HD+NEI simulations

- There is conspicuous optical emission from radiatively cooled ejecta [Morse et al. 04, ApJ 614,727].

→ Radiative cooling (simplified cooling curves)



Hwang et al. 04, ApJ 615, L117

- ✓ This is a very complex problem. The technical aspects of the simulations will be crucial.
- ✓ The initial configuration will require a lot of attention [Young].
- ✓ A global approach might not be the best choice at first.
- ✓ However, ONLY HD+NEI simulations can lead to a reasonably complete understanding of the ejecta emission in Cas A.

IN CASE ANYBODY ASKS...

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