# Light from the Ashes: Supernovae, Supernova Remnants and X-ray Astronomy

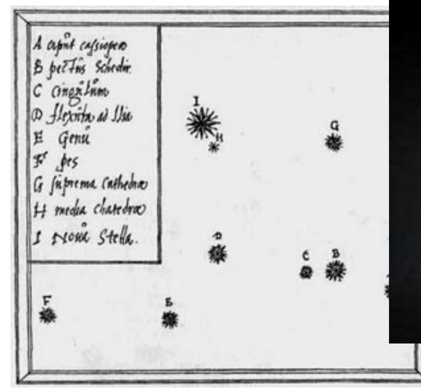
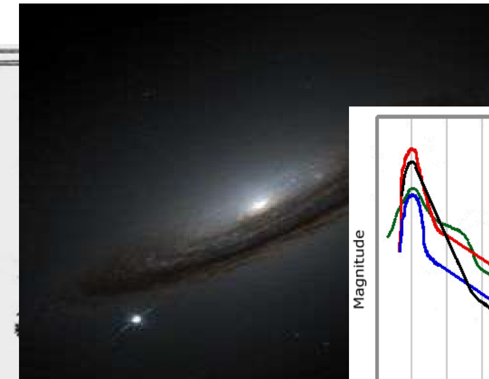
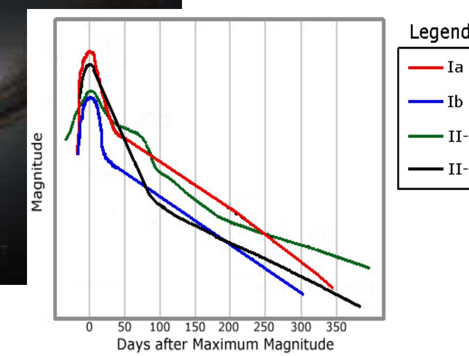
Jersey StarQuest 2005
Hope Conference Center, June 4 2005

**Carles Badenes**

The State University of New Jersey
Rutgers
Department of Physics and Astronomy

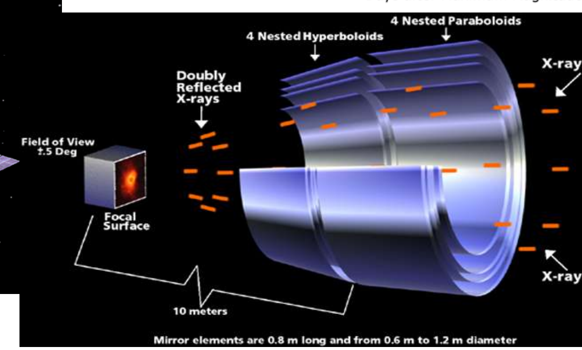
Department of Physics and Astronomy,
Rutgers, the State University of New Jersey

# Menu


## Supernovae (SNe):

- Historical Introduction
- Classification
- Astrophysical Origin
- Type Ia SNe:

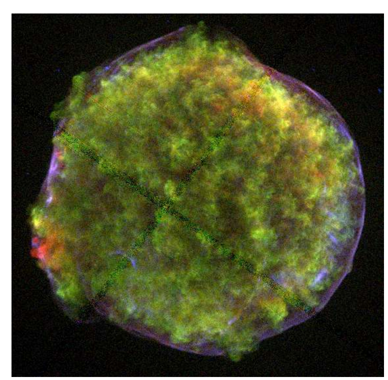
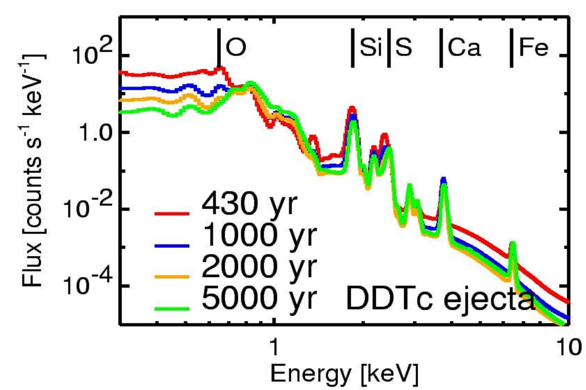




## X-ray Astronomy:

- Why X-rays?
- Tools of the trade

## Supernova Remnants (SNRs):

- From SN to SNR
- X-ray observations
- From SNR to SN
- The Tycho SNR

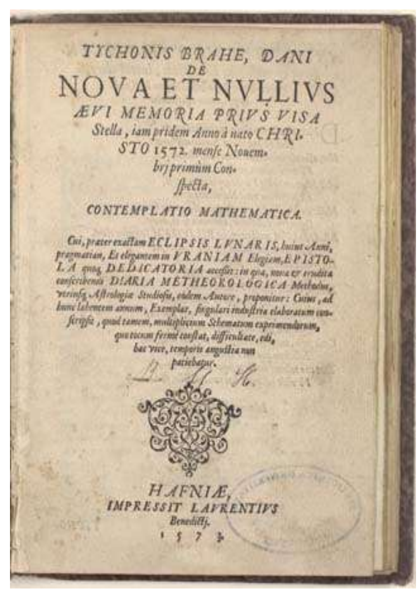



# Historical Introduction: Tycho Brahe


## Tycho Brahe (1546-1601)

- He was the first scientific astronomer, and developed many innovative instruments and techniques.
- Science (and astronomy) were very different in the 16th century. Tycho believed in astrology, and he never accepted the heliocentric model of Copernicus.
- On the night of November 11th, 1572 he discoverved a 'new star' (stella nova) in Cassiopeia. He observed it for 14 months until it disappeared.

Tycho's castle: Uraniborg

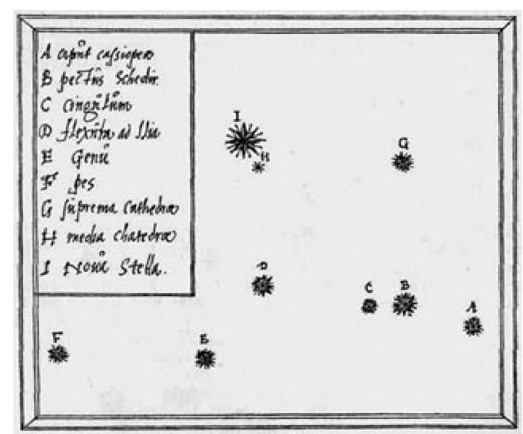


TYCHONIS BRAHE, DANI
DE
NOVA ET NVLLIVS
ÆVI MEMORIA PRIVS VISA
Stella, iam pridem Anno à nato CHRI-
STO 1572. mense Nouem-
bri primùm Con-
specta,

CONTEMPLATIO MATHEMATICA.

Cui, præter exactam ECLIPSIS LVNARIS, huius Anni, pragmatian, Et elegantem in VRANIAM Elegiam, EPISTOLA quoq; DEDICATORIA accessit: in qua, noua & erudita conscribendi DIARIA METHEOROLOGICA Methodus, vtriusq; Astrologiæ Studiosis, eidem Autore, proponitur: Cuius, ad hunc labentem annum, Exemplar, singulari industria elaboratum conscripsit, quod tamen, multiplicium Schematum exprimendorum, quæ totum fermè constat, difficultate, edi, hac vice, temporis angustia non patiebatur.

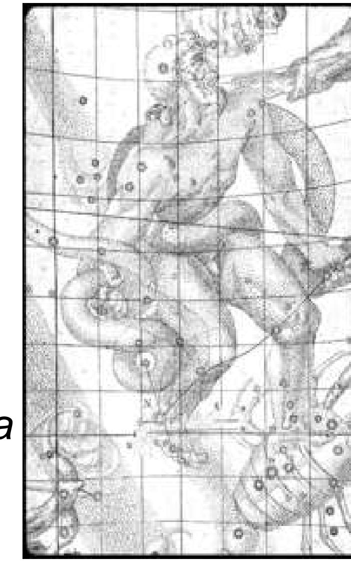
HAFNIÆ,
IMPRESSIT LAVRENTIVS
Benedictj.
1573.




Tycho's book *De Stella Nova* was published in 1573.

# Novae vs. Supernovae

- Johannes Kepler observed another 'nova' in the fall of 1604, in the constellation of Ophiuchus.
- Other historical 'bright novae' visible to the naked eye occurred in 1006, 1054 and 1181.
- With the help of telescopes and star catalogues, many more novae were discovered by astronomers.



J. Kepler: *De Stella Nova in Pede Serpentarii* (1606)

M31, the Andromeda nebula (J. Ware - APOD)

- In 1885, a 'nova' appeared in M31.
- In the 1920s, Edwin Hubble made the first realistic measurements for the distance to M31 (~700 kpc).

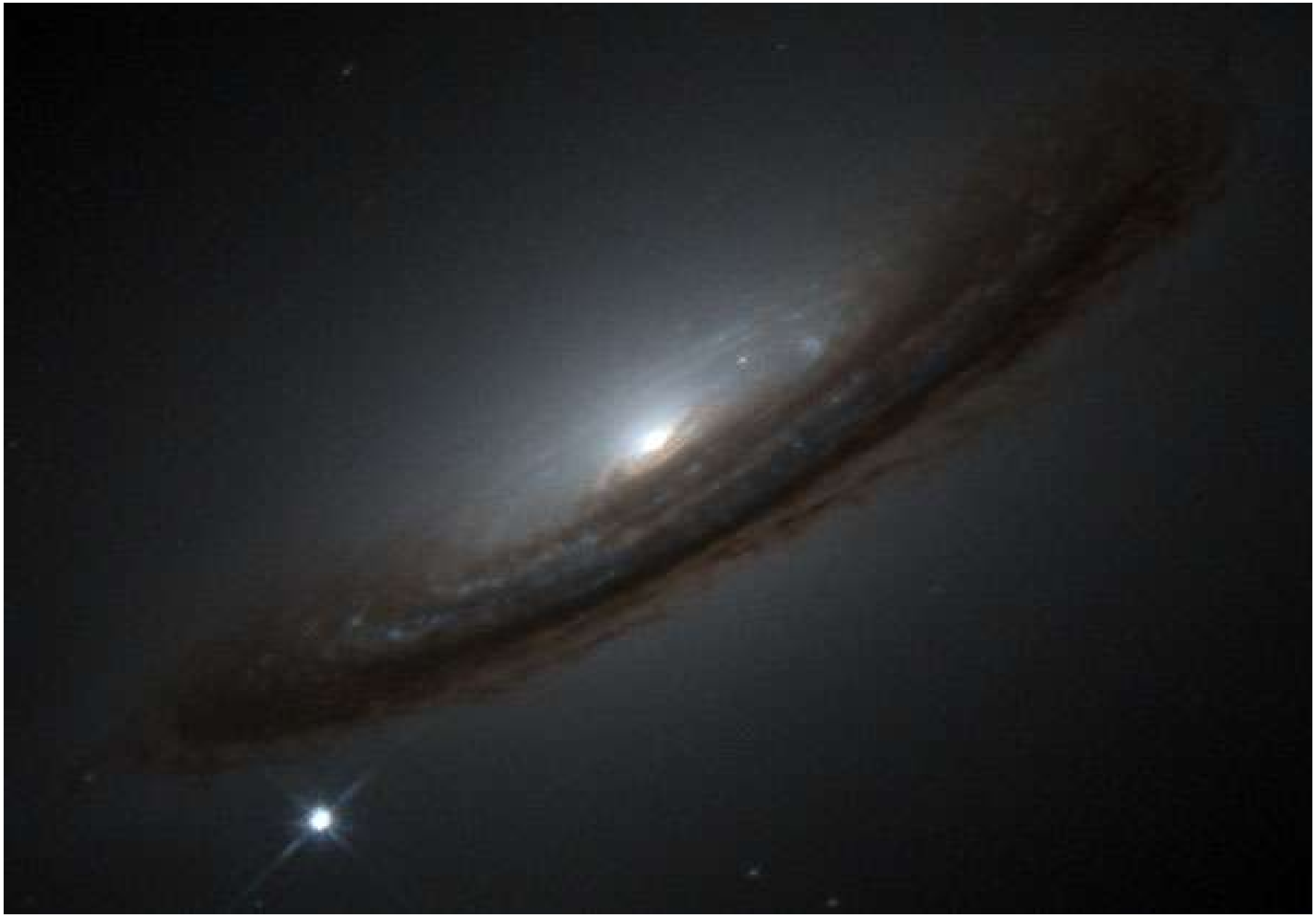
E. Hubble

- Around the same time, K. Lundmark derived a $M_v$=-15 for the 'nova' of 1885.
- In 1934, W. Baade and F. Zwicky introduced the term 'supernova'.

F. Zwicky and W. Baade

# Light from Afar

A long time ago in a galaxy far, far away...

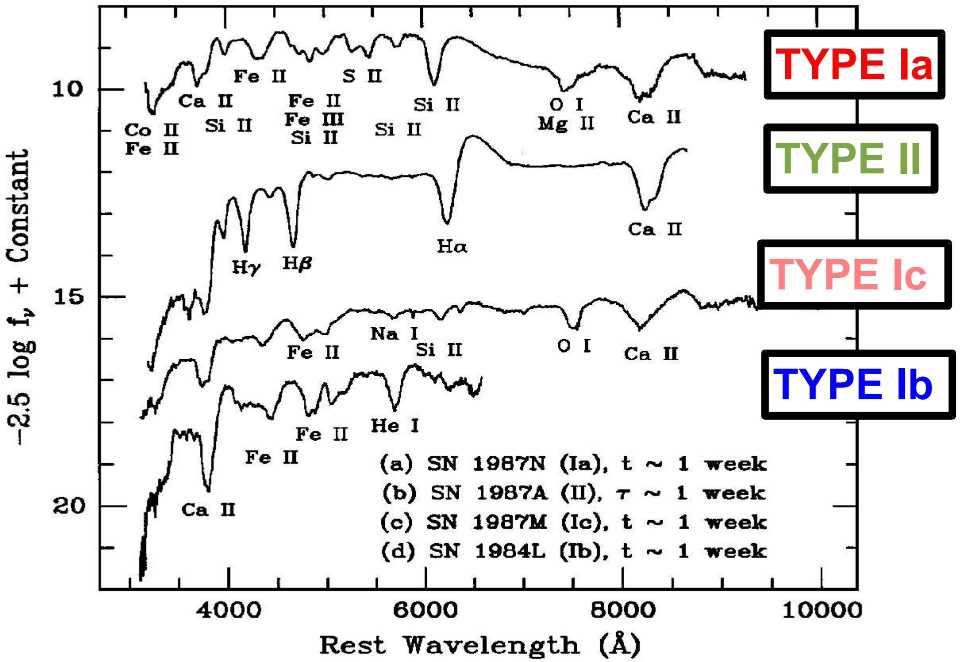


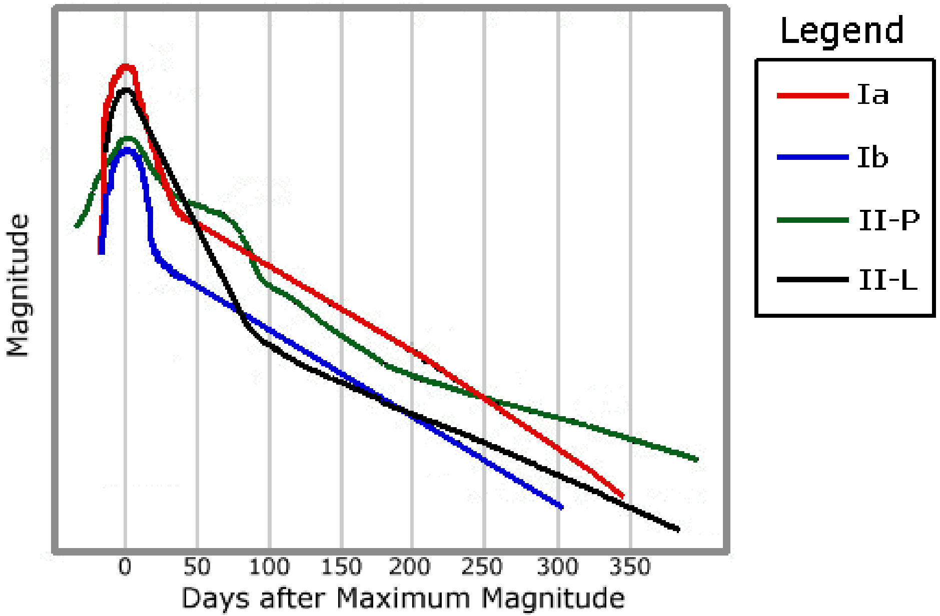
SN 1994D in NGC 4526 (P. Challis - APOD)

Supernovae are beacons that shine across the Universe.

# What is a Supernova?

- Supernovae (SNe) are bright, transient events. A typical supernova at its peak can outshine an entire galaxy!
- They are rare (1/100 yr in a galaxy like the Milky Way), but automated searches discover hundreds every year.
- SNe are classified by the properties of their optical spectra. Type II SNe have hydrogen lines, and Type Ia, Ib and Ic SNe do not. Type Ia SNe have prominent silicon lines, and Type Ib/Ic do not. The light curves are also different for each type.



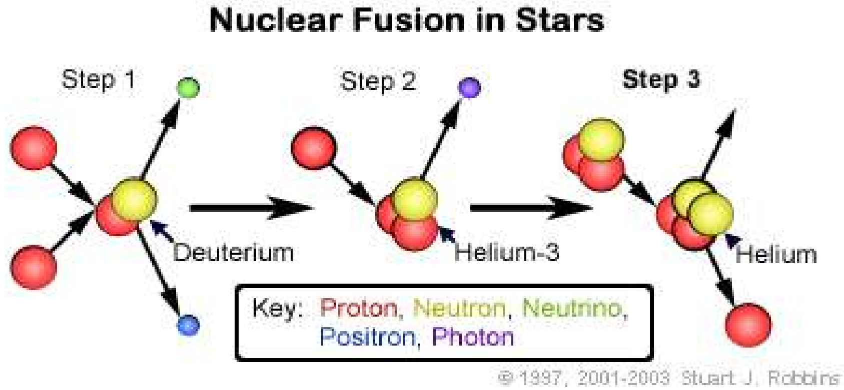

Figures: A. Filippenko

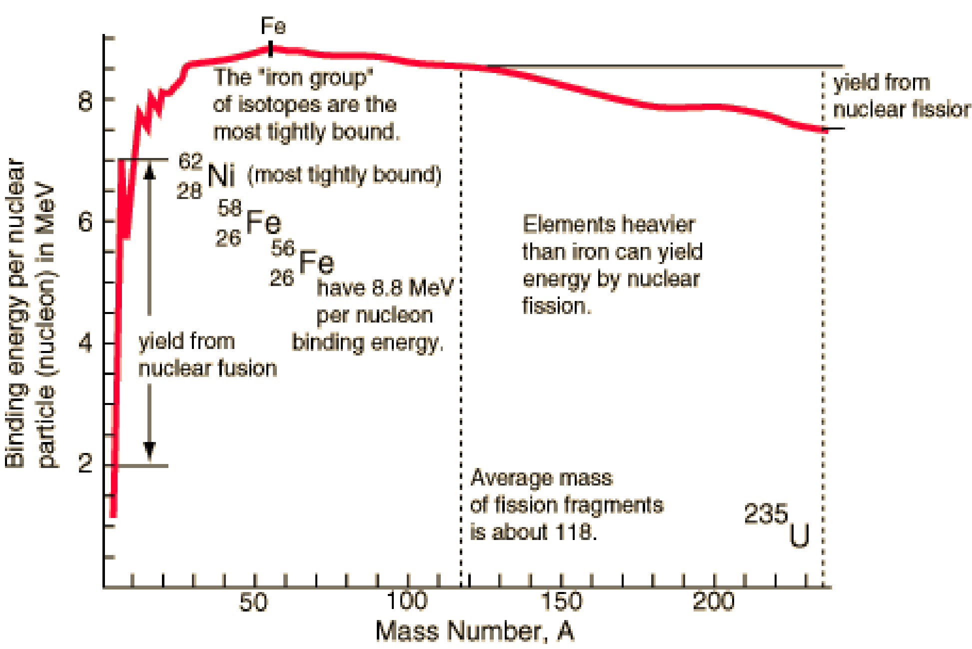
# Yes, but WHAT is a SN?

Supernovae are very violent events which release ~$10^{51}$ erg of kinetic energy (that is $5 \times 10^{28}$ megatons of TNT!). These titanic energies are associated with the late stages of stellar evolution.

STELLAR EVOLUTION 101 (a 5 min crash course):

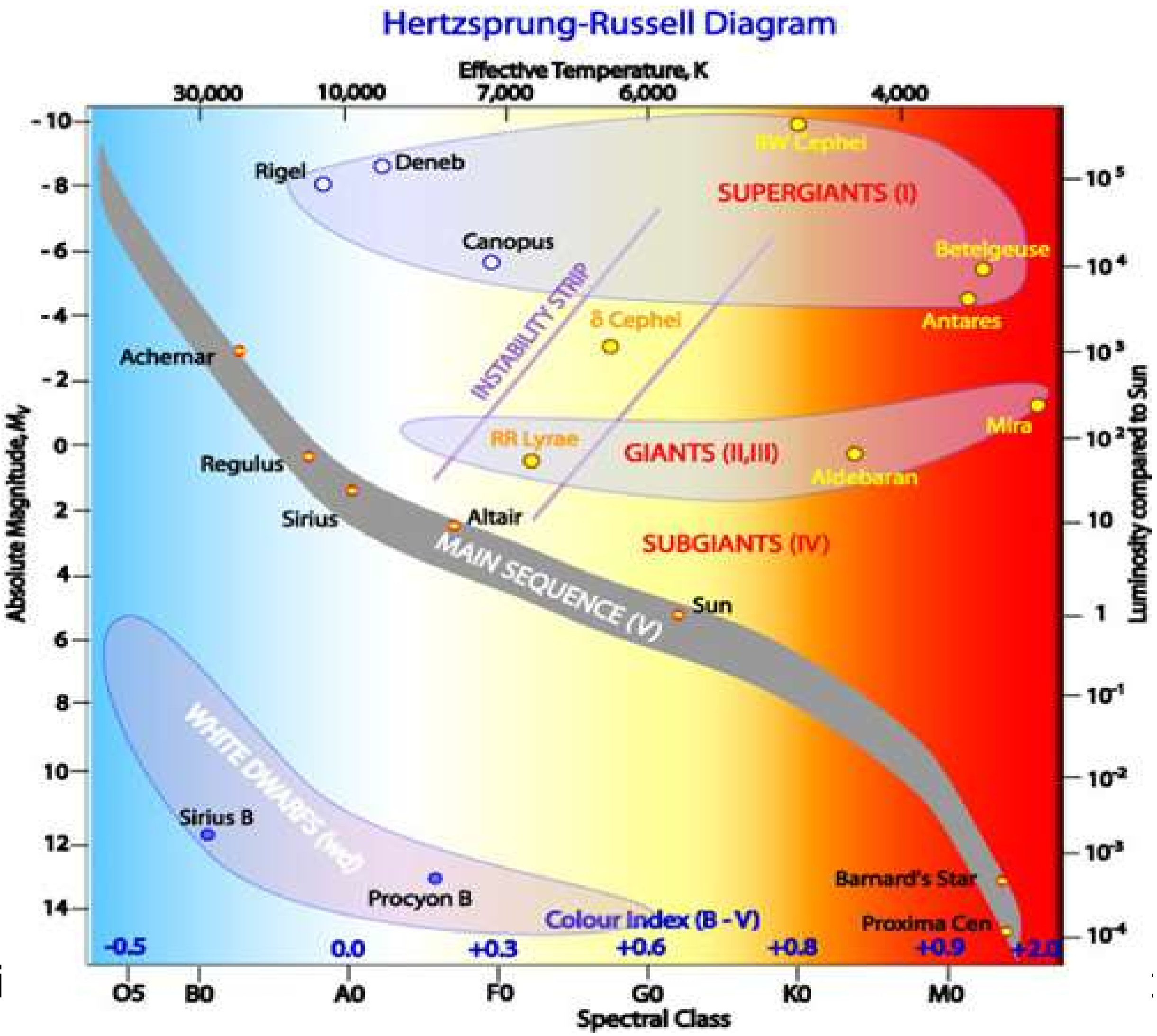
- The life of a star is the story of its fight against gravity.
- A star like our Sun counteracts gravity by burning H to He in its hot and dense interior (thermonuclear reaction - fusion).
- Larger stars burn fuel faster (their interiors are denser and hotter).
- If a star is massive enough, it can burn He into C, then C into O, and O into Si... until Fe is reached (stellar nucleosynthesis).

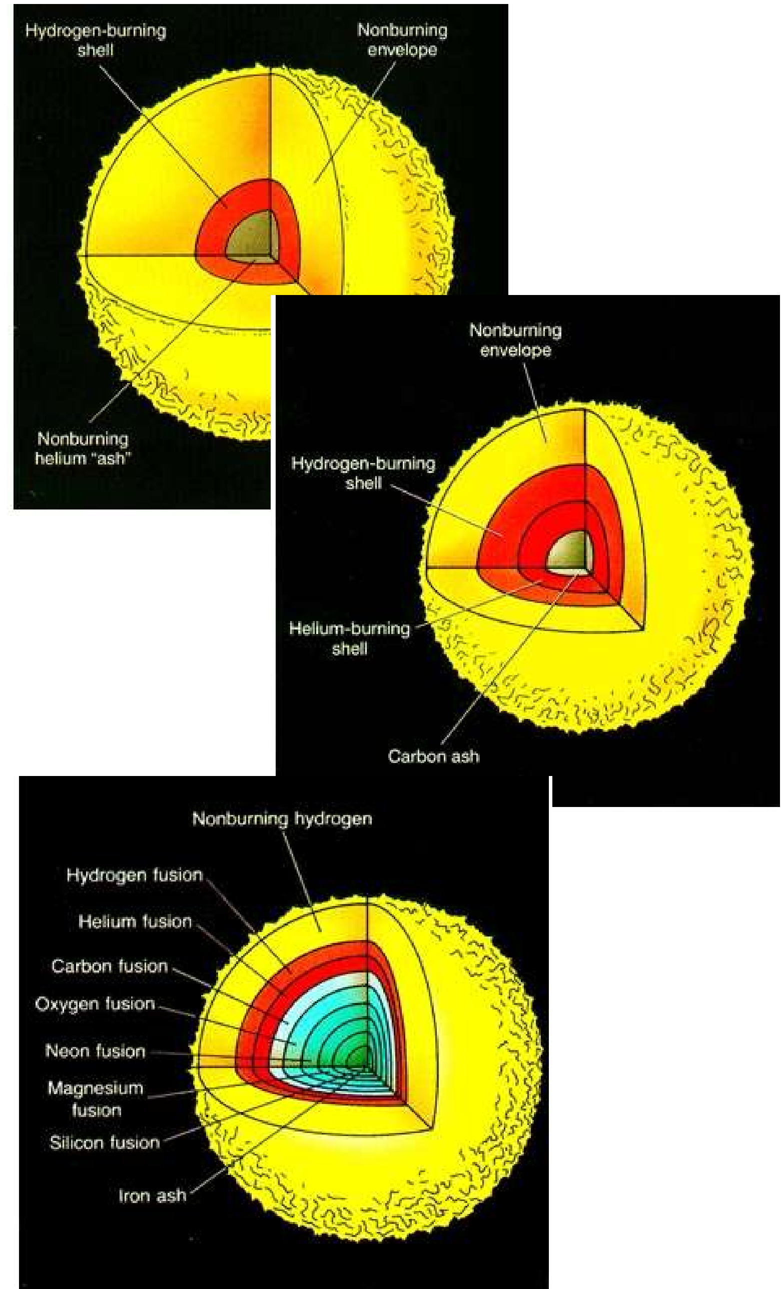


# Massive Stars: SNe of Type II, Ib, Ic

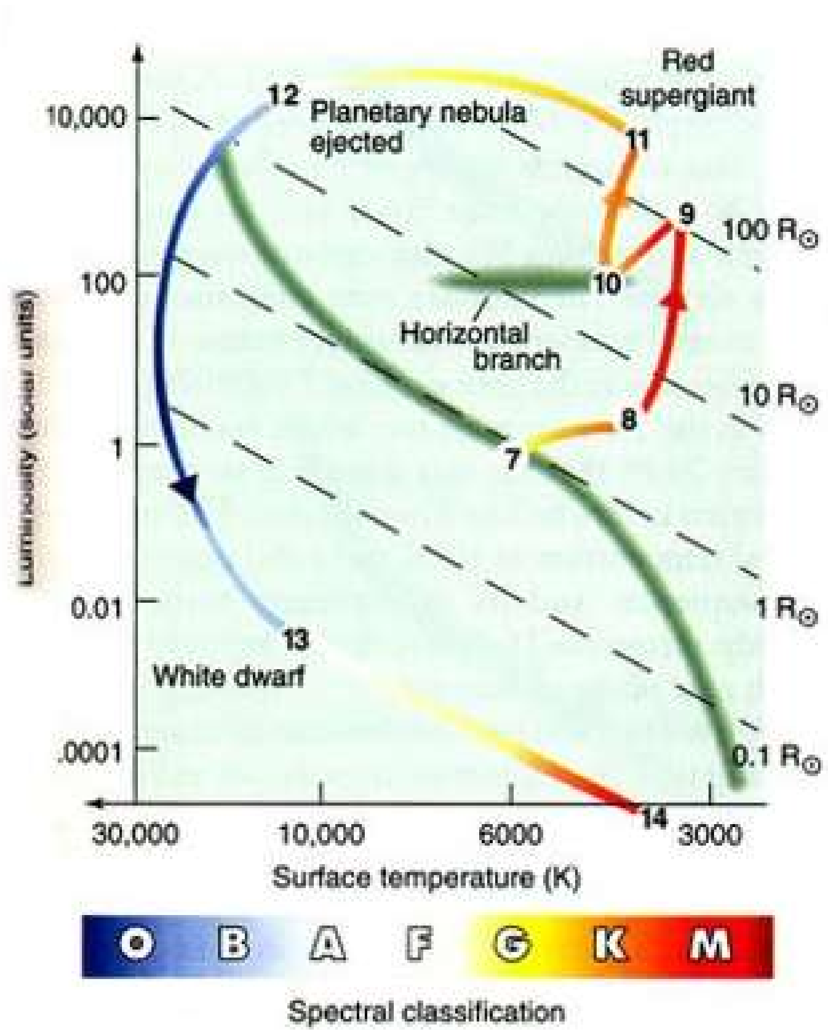
A massive star moves through the HR diagram in its path to doom, and finally dies in a supernova explosion of Type II, Ib or Ic. These SNe leave behind a black hole or a neutron star.



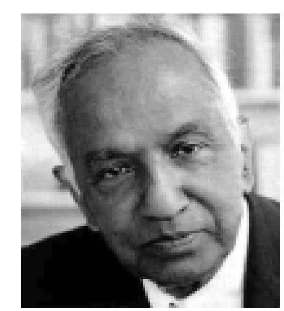
# Not-so-massive Stars: White Dwarfs

A star like our Sun is not massive enough to burn elements beyond C and O. When its fuel is exhausted, it sheds its outer layers as a planetary nebula and then it contracts... until it becomes a White Dwarf (WD).




The Helix Planetary Nebula (C. O'Dell - APOD)

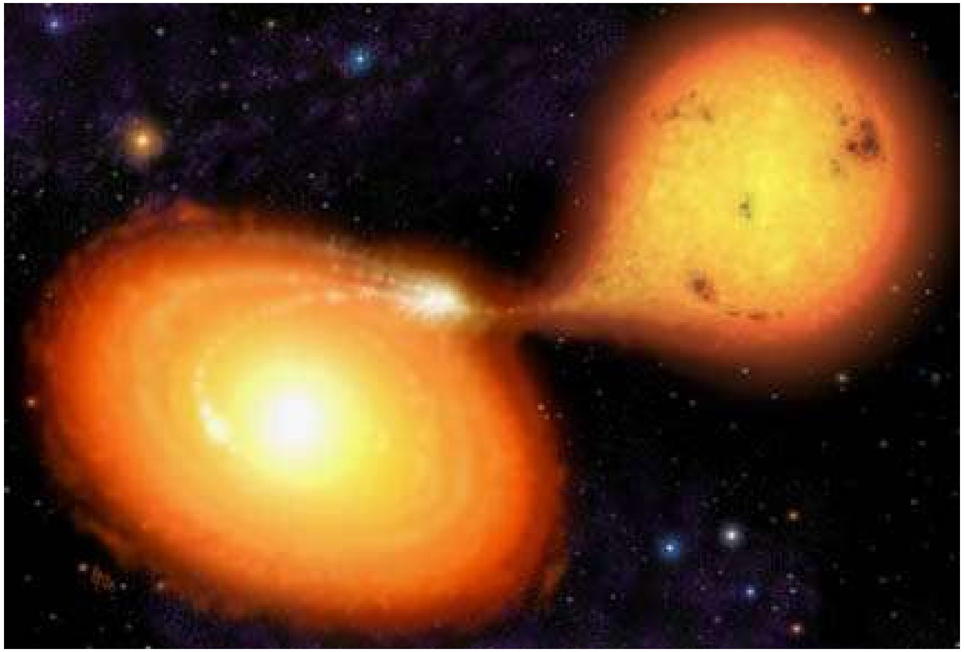
WDs are dead stars. They counteract gravity through electron degeneracy pressure. This only works if the mass of the WD is less than 1.4 $M_{sol}$ (the Chandrasekhar limit).



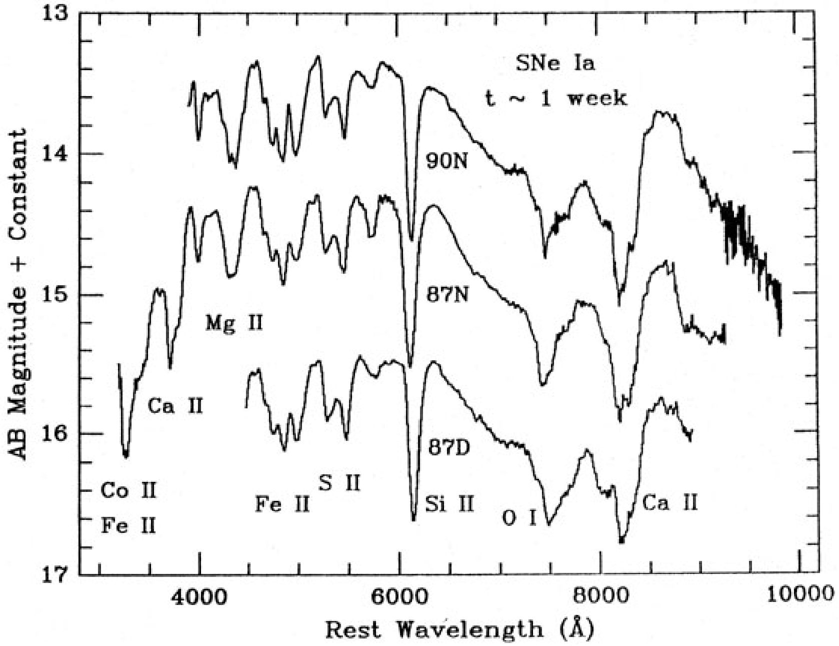
S. Chandrasekhar

# WDs in Binary Systems: Type Ia SNe

- An isolated WD is stable: if left alone, it will just cool and fade away. But WDs in close binary systems can accrete mass from their companions until they exceed the Chandrasekhar limit. This leads to a Type Ia SN.
- (Almost) all the progenitors of Type Ia SNe are C+O WD of 1.4 $M_{sol}$. This makes their light curves and spectra very uniform.



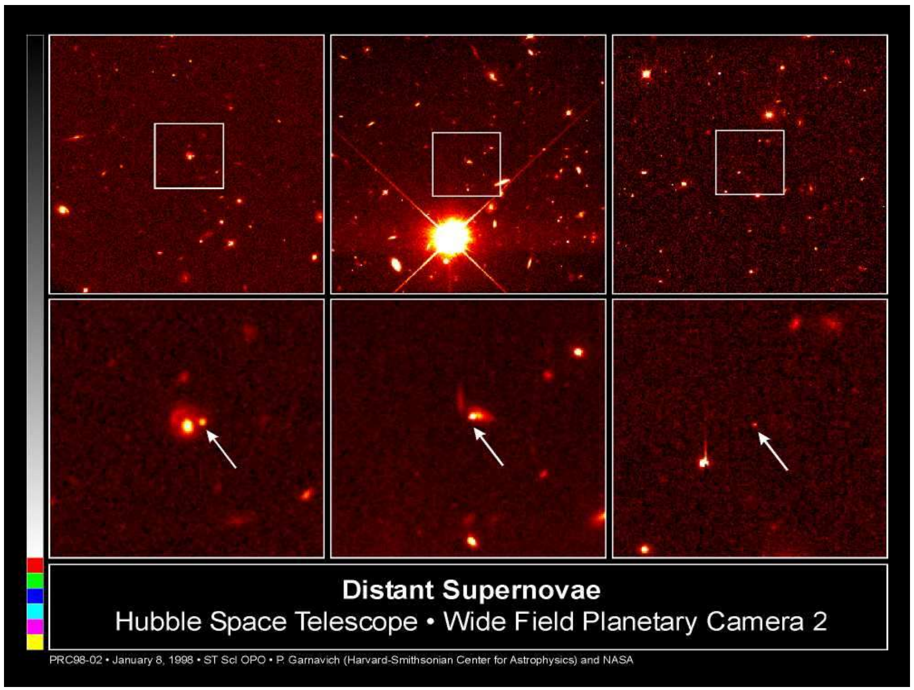
A WD in a close binary system accreting matter from its companion.

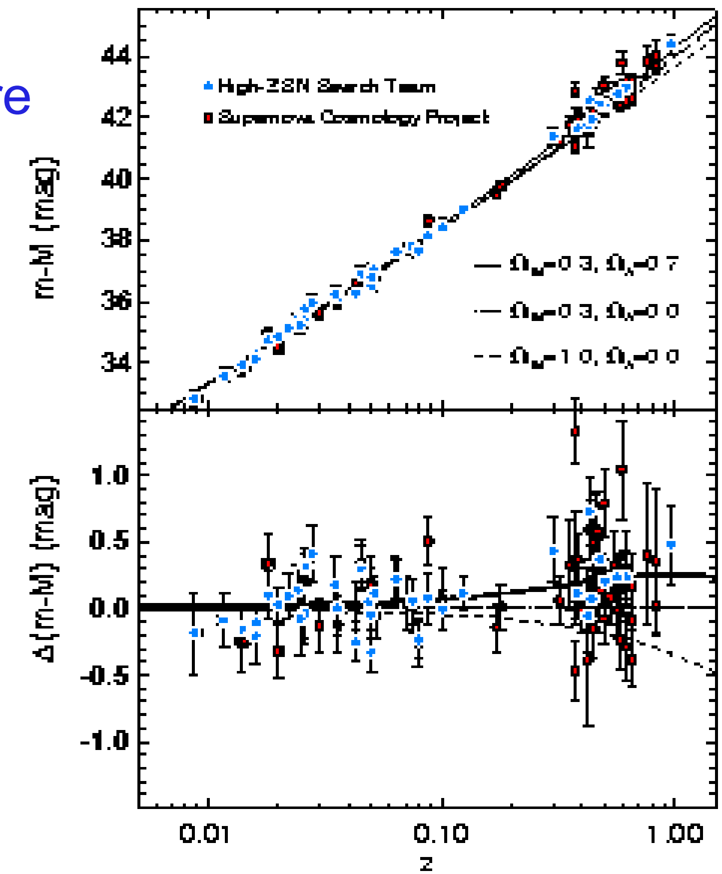



The spectra of 3 Type Ia SNe 1 week after maximum (A. Filippenko).

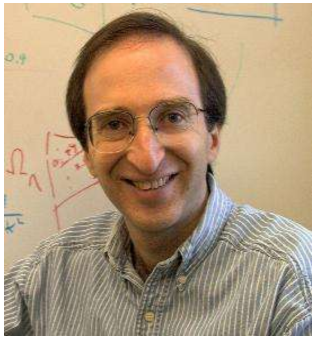
# The Importance of Type Ia SNe

- The uniformity in the light curves of Type Ia SNe allows to use them as standard candles to measure distances in the Universe.
- Using this technique, 2 groups of reserchers (A. Riess et al.; S. Perlmutter et al.) revolutionized cosmology in 1998 with the astonishing discovery that the expansion of the universe is accelerating.



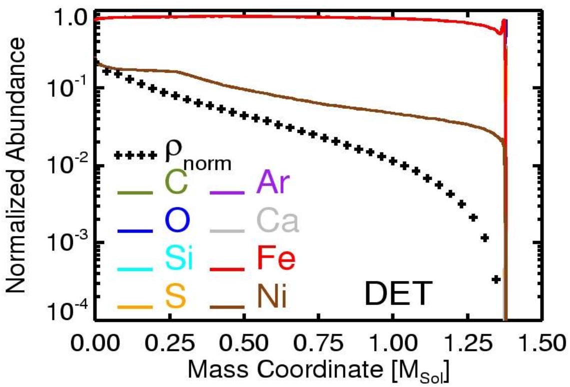

The results from Type Ia SNe at high redshift have changed our picture of the Universe

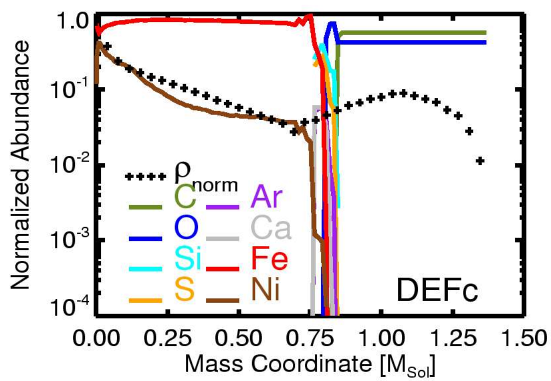


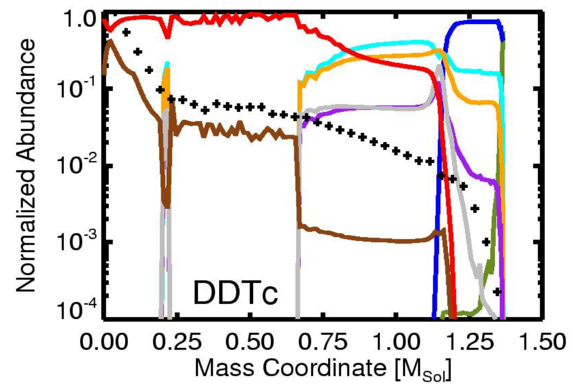
Saul Perlmutter and Adam Riess

# An Embarrassing Problem

Fundamental details of the explosion mechanism of Type Ia SNe are not understood. The propagation of the burning front through the WD could be supersonic (detonations), subsonic (deflagrations), or a mixture of both (delayed detonations).

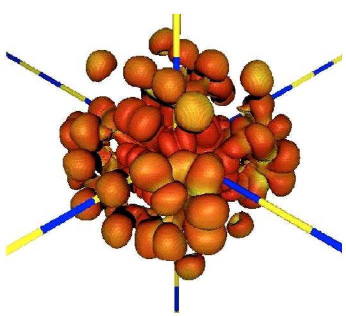


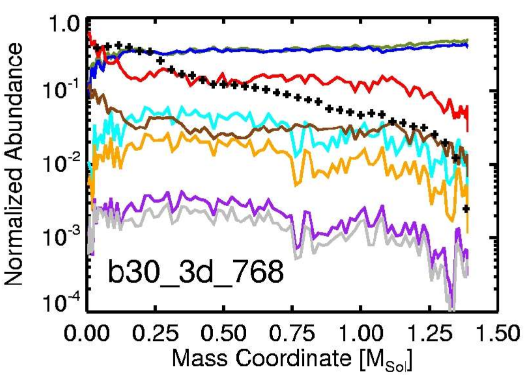




Each model makes different predictions for the structure of the supernova ejecta – but which one is right? Optical observations of Type Ia SNe have not been able to disentangle this problem.

Recent 3D simulations predict a high degree of mixing in the ejecta.

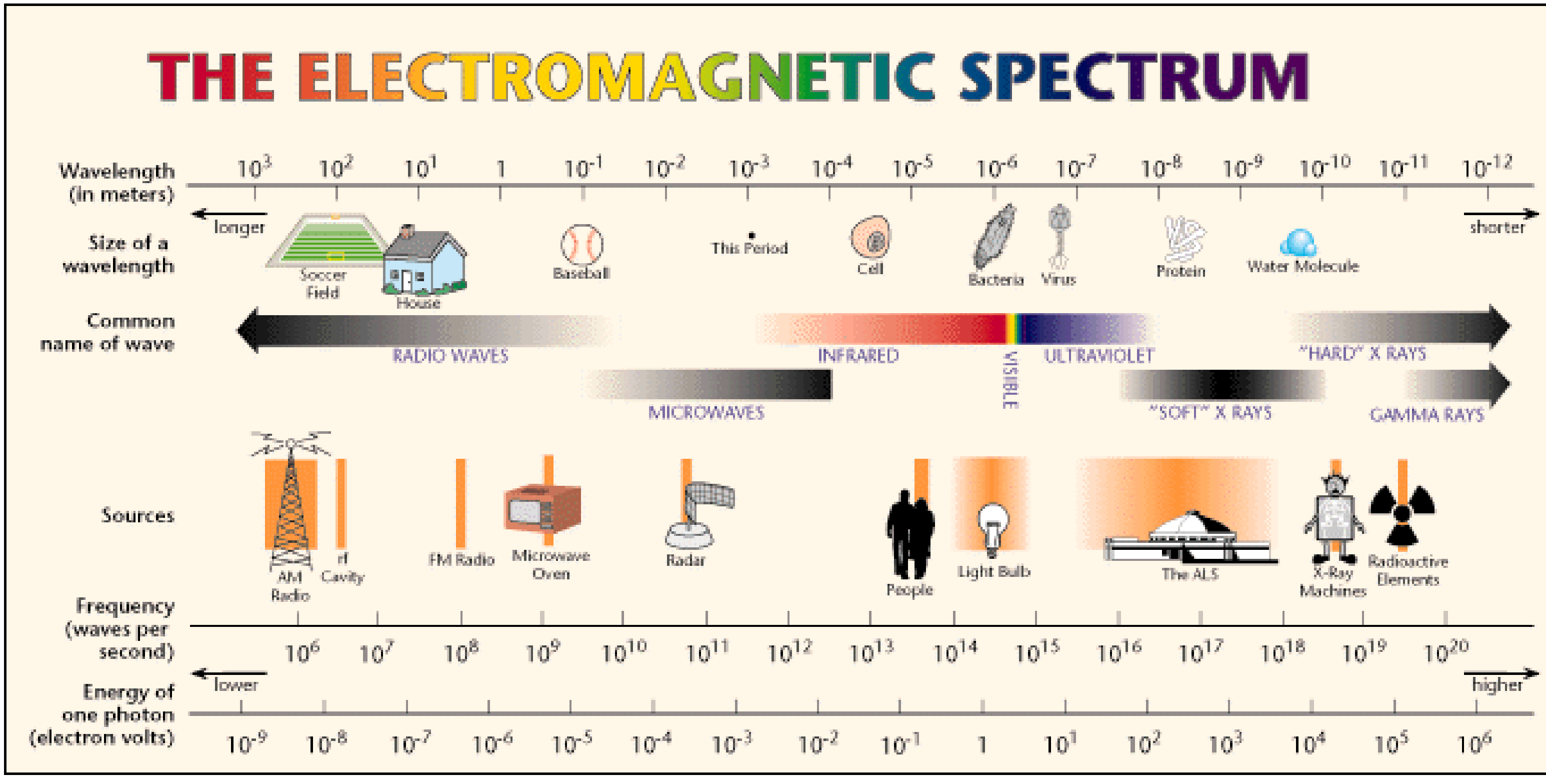




# X-ray Astronomy

X-rays are electromagnetic waves – just like visible light, but much more energetic.

Right: the EM spectrum

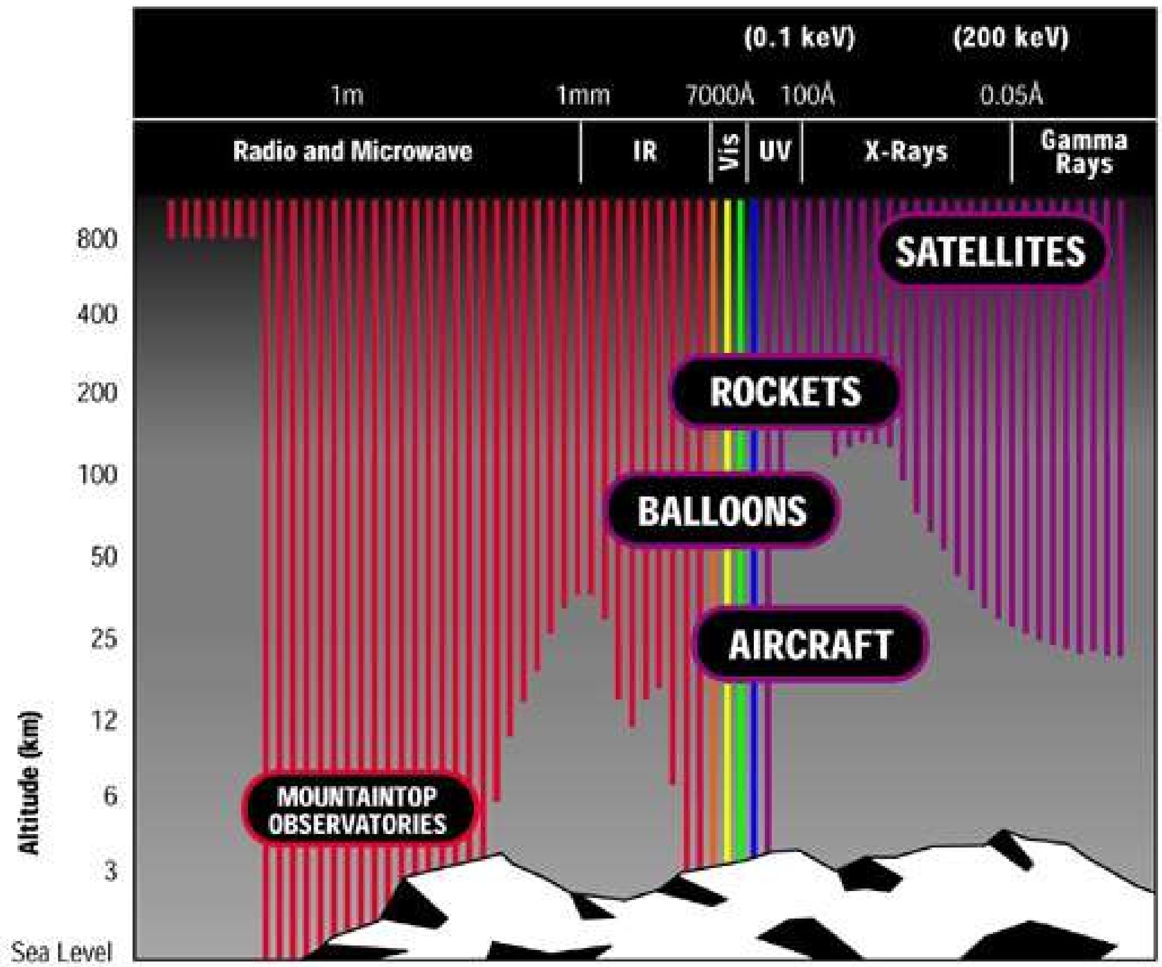


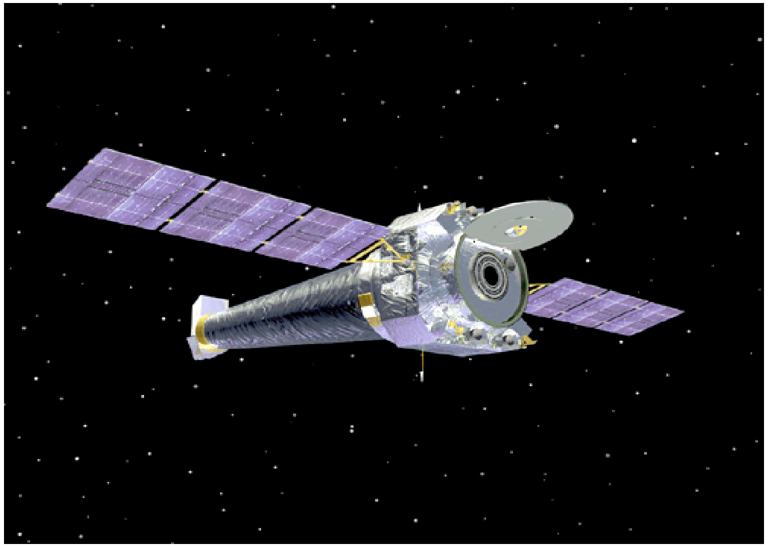

Below: The first X-ray photograph taken by Röntgen

The use of X-rays in astronomy has allowed us to 'see' a whole range of phenomena that are invisible in the optical. In particular, we have access to the radiation emitted by objects that are VERY HOT.

# X-ray Telescopes

Since our atmosphere is opaque to X-rays, X-ray astronomy has to be done with satellites like NASA's *Chandra* and ESA's *XMM-Newton*.



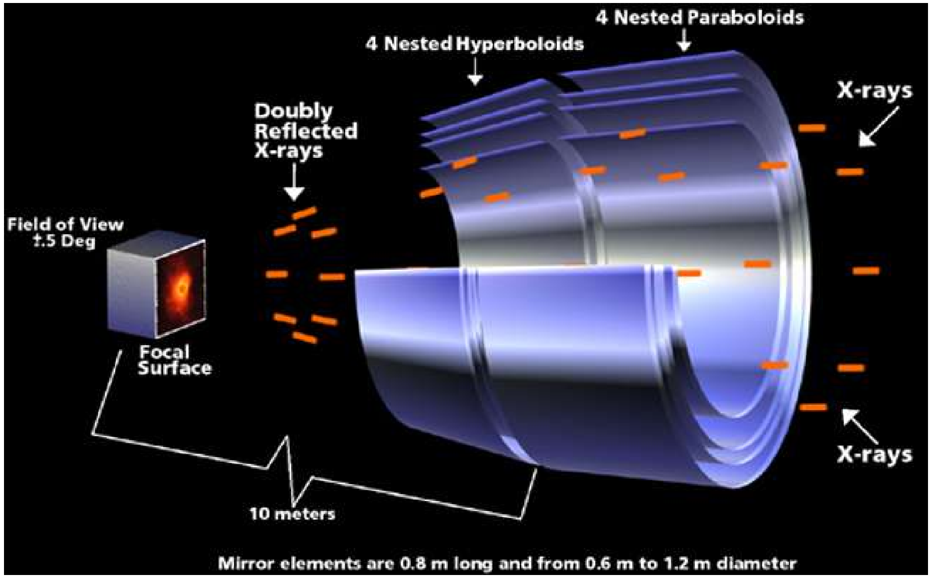
The two major X-ray observatories, *Chandra* (top) and *XMM-Newton* (bottom)

# How Does *Chandra* Work?

An X-ray telescope is essentially like an optical one: it is built to concentrate light.

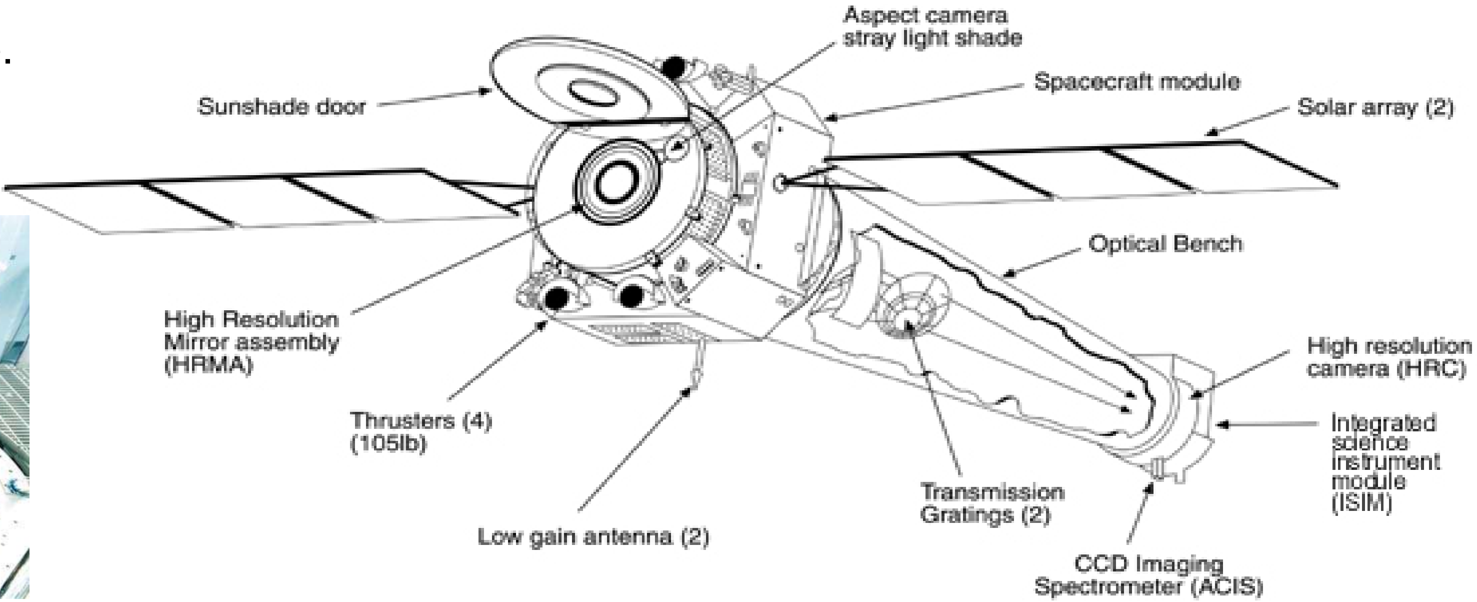
The differences are in the methods of concentration and detection:

- The mirrors work at grazing incidence.
- The CCD detectors are sensitive to X-rays.



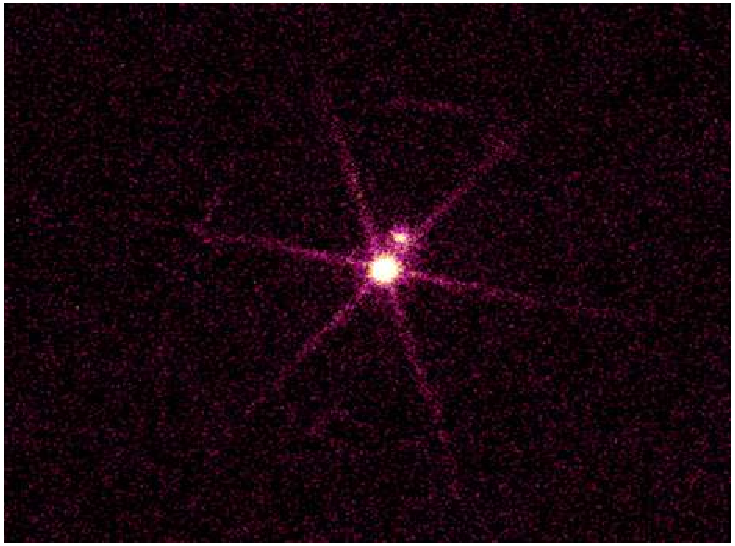

Images: *Chandra* web site.

The *Chandra* mirrors.



# X-ray observations by *Chandra*

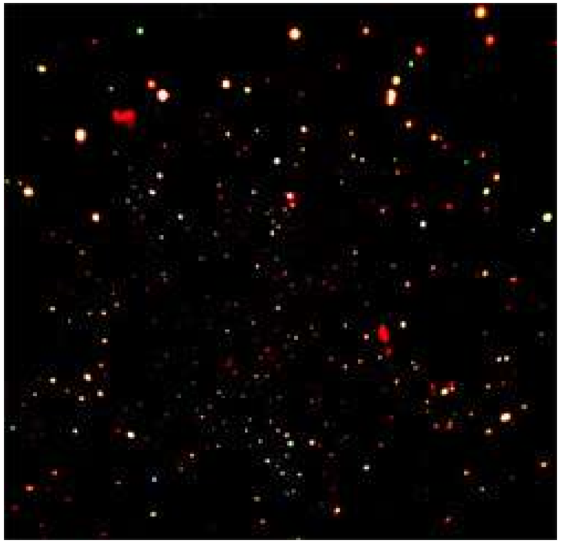

The Crab Nebula in visible light (left) and X-rays (right)



Sirius A and Sirius B

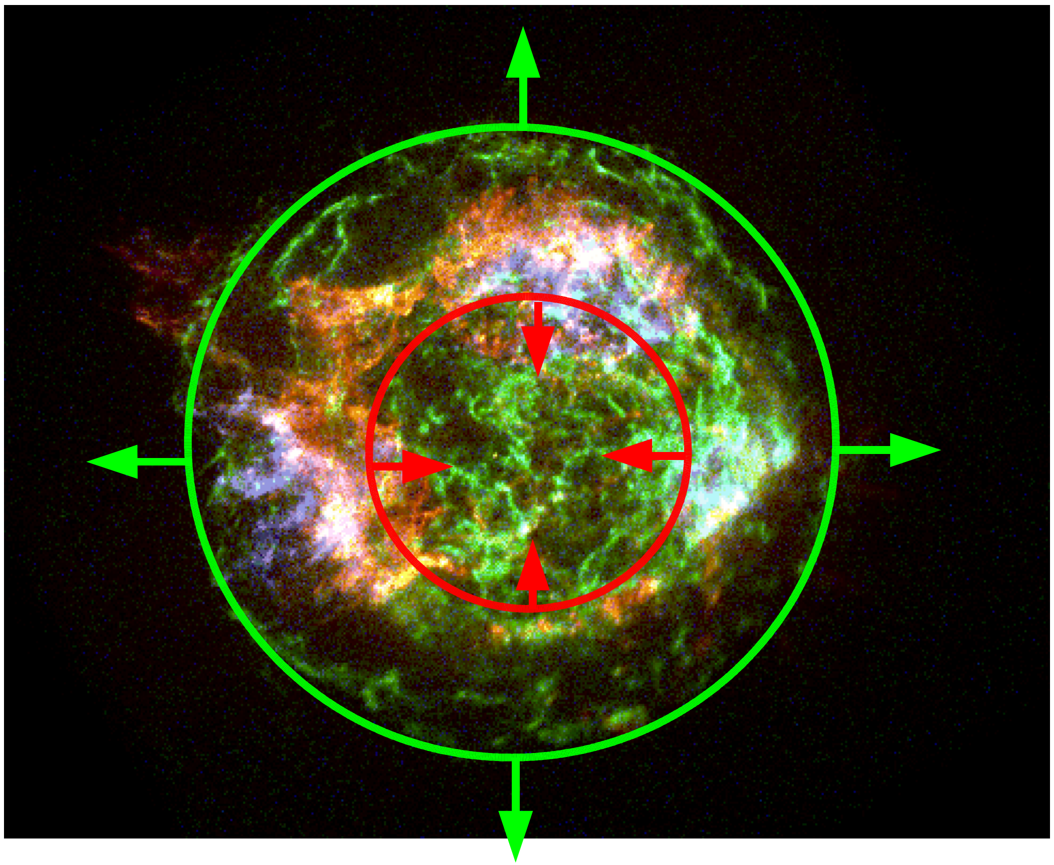
The Galactic center, including Sagittarius A* (mosaic is 400x900 ly)

The *Chandra* Deep Field



# From SN to Supernova Remnant

Supernova remnants (SNRs) are the result of the interaction between the ejecta produced in a supernova explosion and the ambient medium (AM) that surrounds the SN progenitor system.



Cas A, the youngest Galactic SNR [Hwang et al., 2004, ApJ 615, L117]

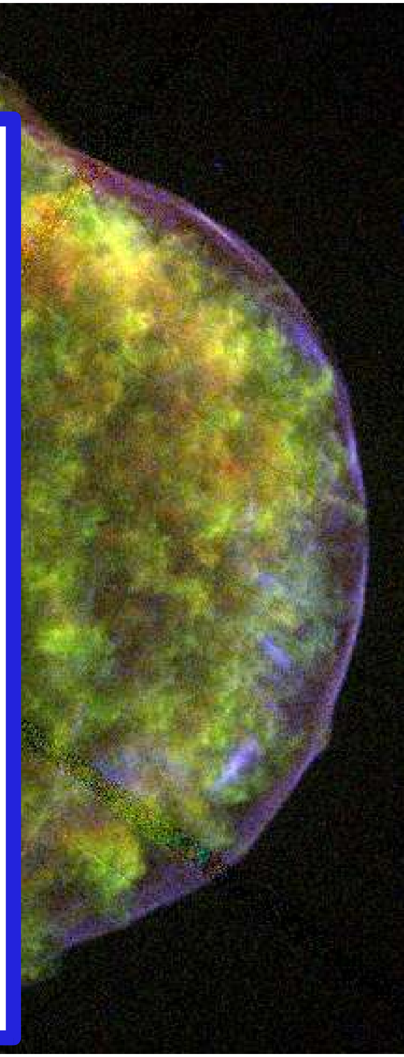
- The expansion of the SN ejecta into the AM drives two supersonic shock waves: a forward shock that heats, compresses and accelerates the AM and a reverse shock that heats, compresses and decelerates the ejecta.
- These shock waves travel at several thousand $km \cdot s^{-1}$, and heat the material to X-ray emitting temperatures.
- Hundreds of years after the optical emission from the SN fades away, the reverse shock reveals the ejecta again.

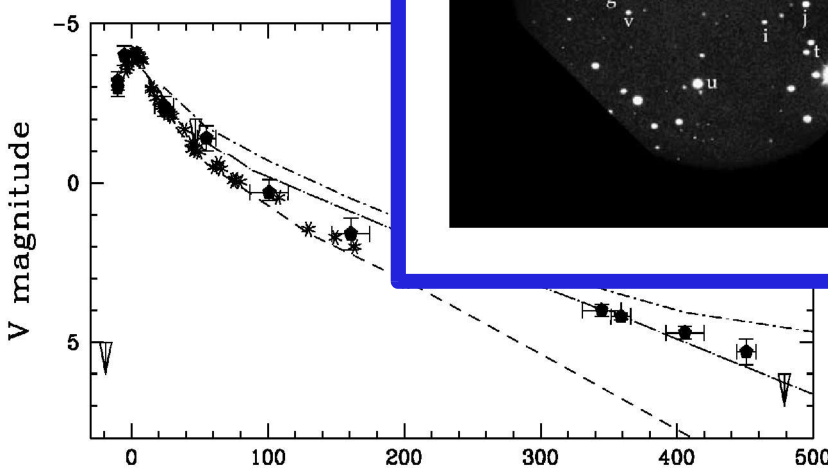
# The Tycho SNR

The Tycho SNR is the remnant of the supernova that Tycho Brahe observed in 157
wide, and one o
ray sources in th
that SN 1572 wa

- No black hole
has been found

- Tycho's obser
are so good tha
reconstruct the

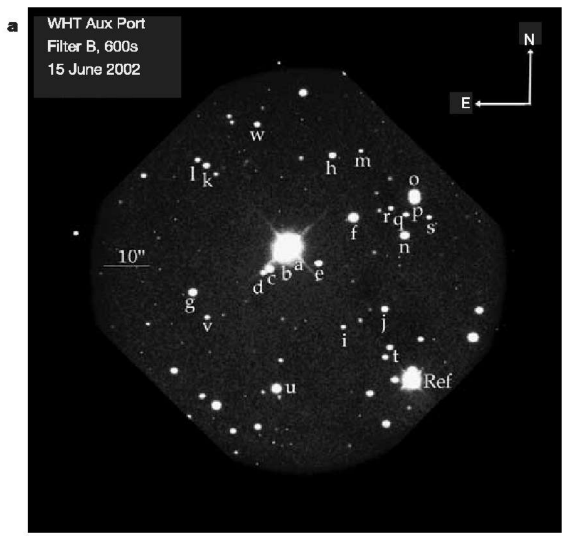


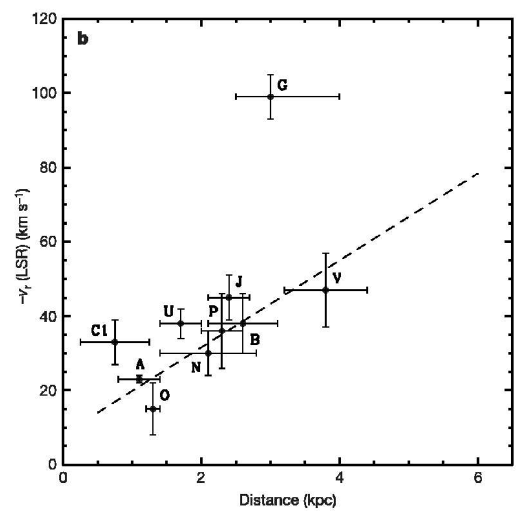



**The Daily Chronicle**

## Stellar Murderer Caught on the Run!

Ruiz-Lapuente et al. 2004, Nature, 431, 1069.



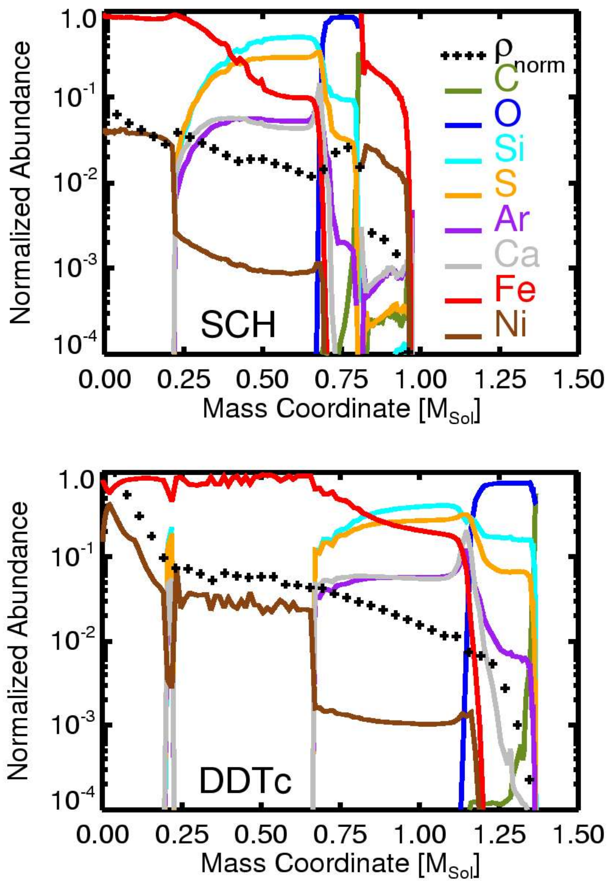

Left: The light curve of SN1572, from Ruiz-Lapuente 2004, ApJ, 612, 357

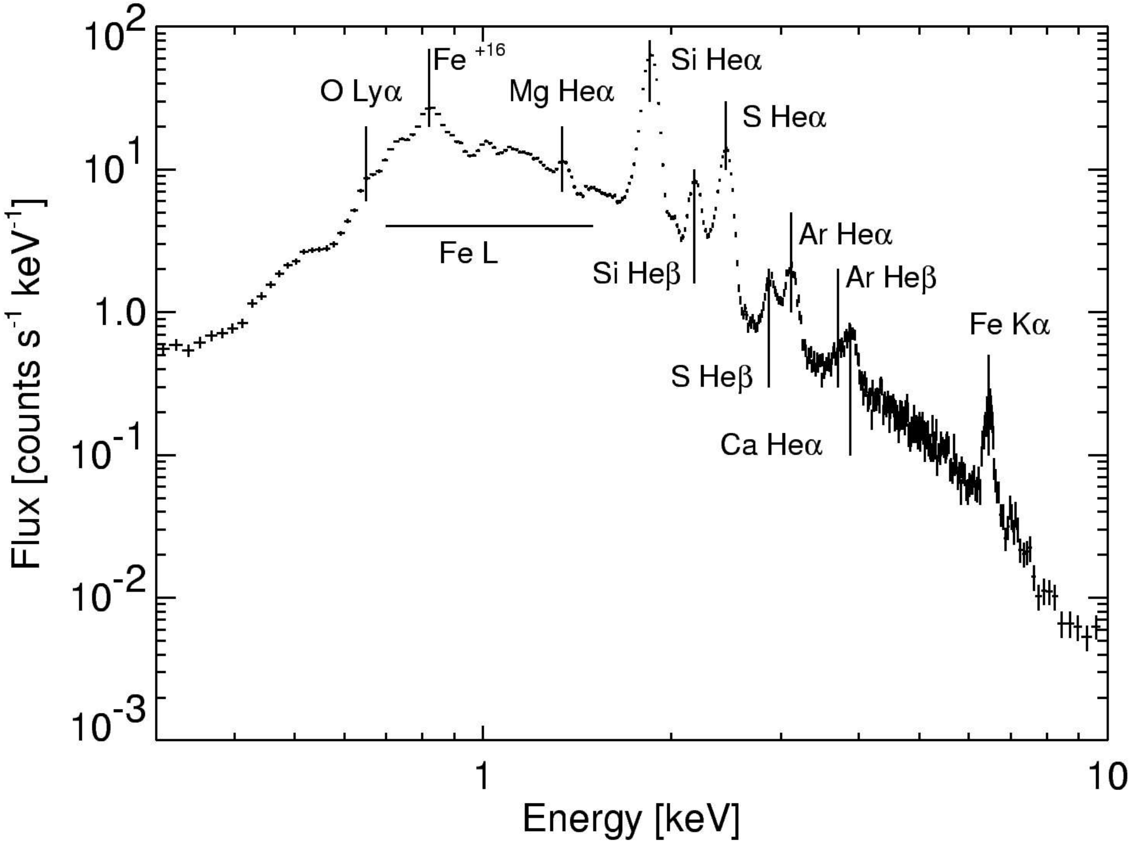
Top: *Chandra* 'true color' image [Warren et al. 2005, ApJ, submitted].

# The Tycho SNR: X-ray Spectrum

The X-ray spectrum of the Tycho SNR observed by *XMM-Newton* bears the imprint of all the chemical elements synthesized in Type Ia SN explosions: O, Si, S, Ar, Ca and Fe.

Can these observations be used to constrain Type Ia explosion models?



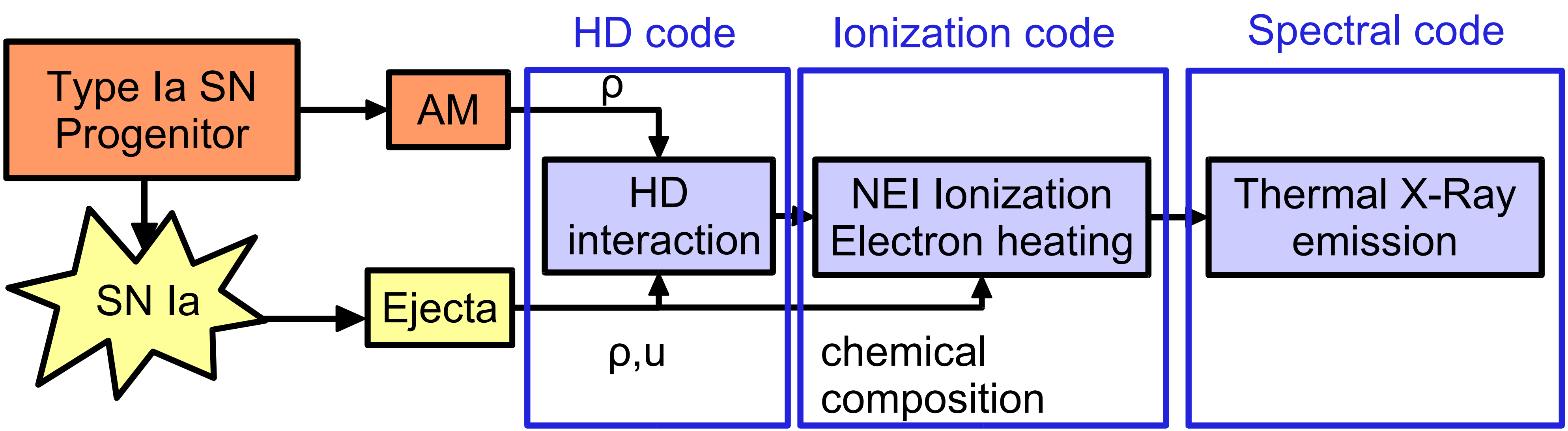



# Models for the X-ray Spectrum

The X-ray emission from the shocked ejecta in Type Ia SNRs can be used to constrain the physics of Type Ia SN explosions.

- Badenes et al. 2003, ApJ 593, 358
- Badenes et al. 2005, ApJ 624, 128
- Badenes 2004, Ph D Thesis

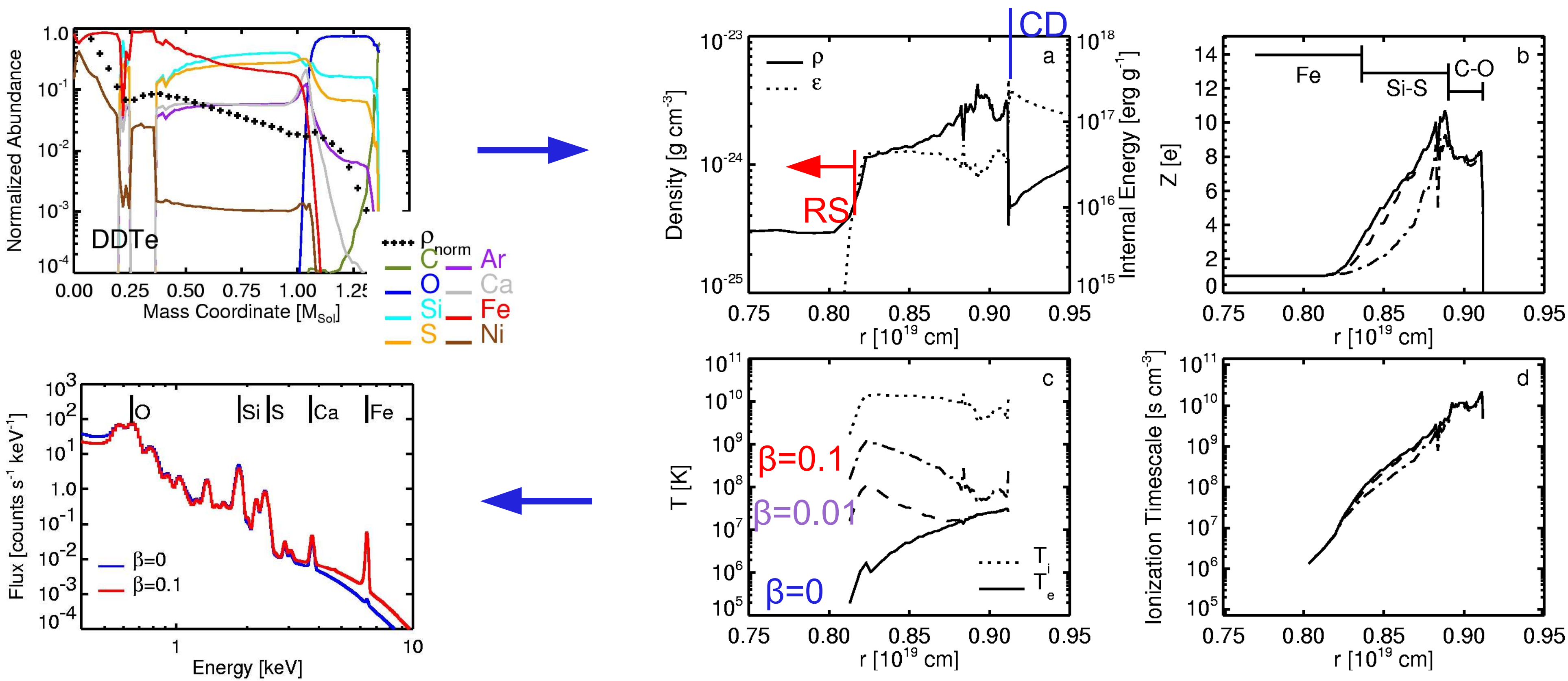
In order to go from a model of a Type Ia explosion to a model for the X-ray emission of the SNR, we have to simulate the evolution of the SNR. The basic ingredients are:



# From SN to SNR: A Delayed Detonation

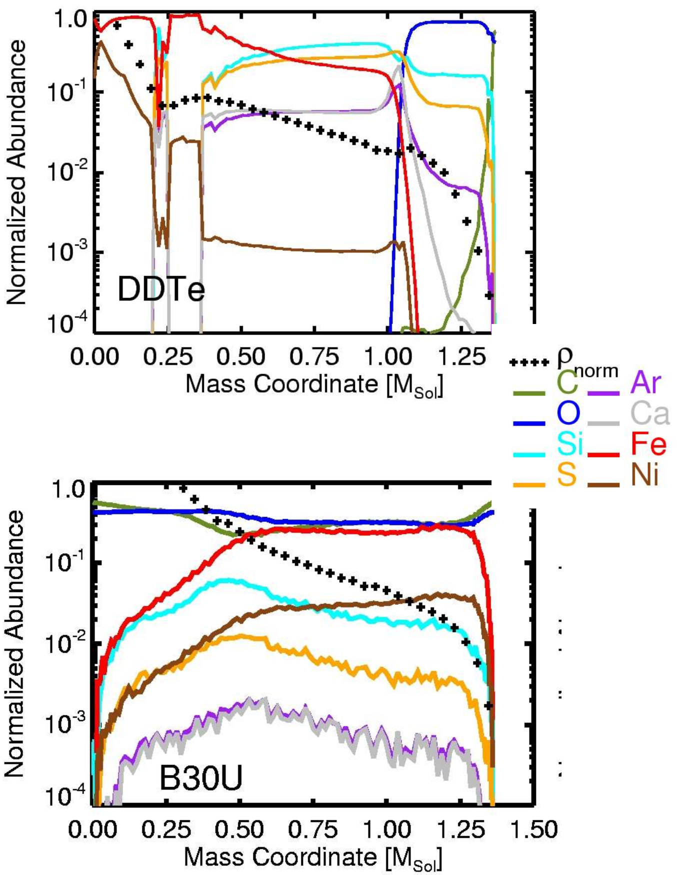
The X-ray spectrum from the shocked ejecta is determined by the hydrodynamic interaction with the AM, the ionization and heating processes in the plasma and the composition of the ejecta.

The shocked ejecta of model DDTe, 430 yr after the explosion, interacting with a uniform AM of $\rho_{AM}=10^{-24}\ g\cdot cm^{-3}$ :

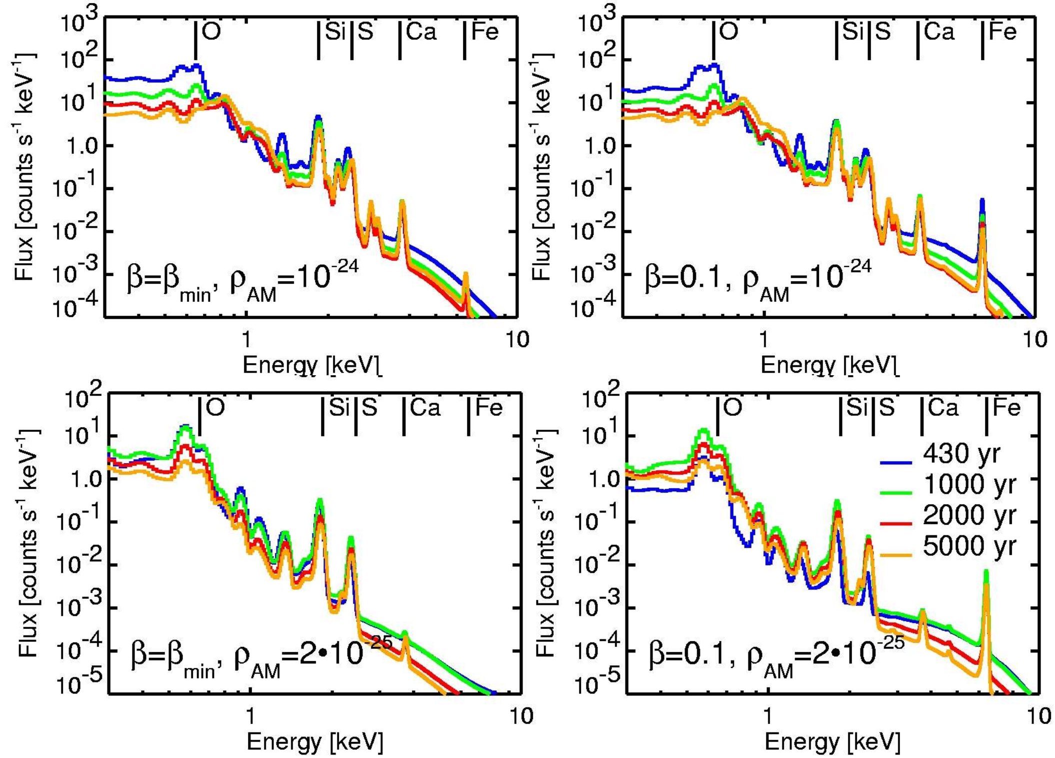


# A Grid of Synthetic Spectra

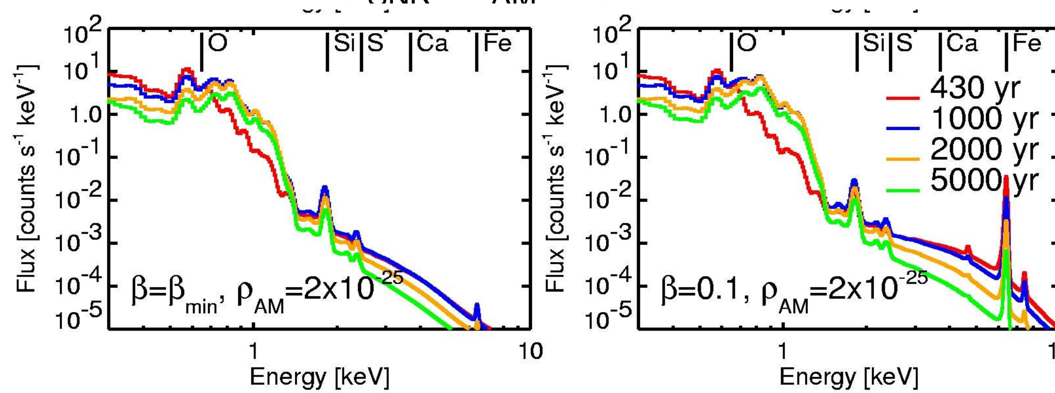
For each Type Ia SN explosion models, a suite of 'synthetic' X-ray spectra for the SNR is generated.




Model DDTe ($t_{SNR}$, $\rho_{AM}$, $\beta$):

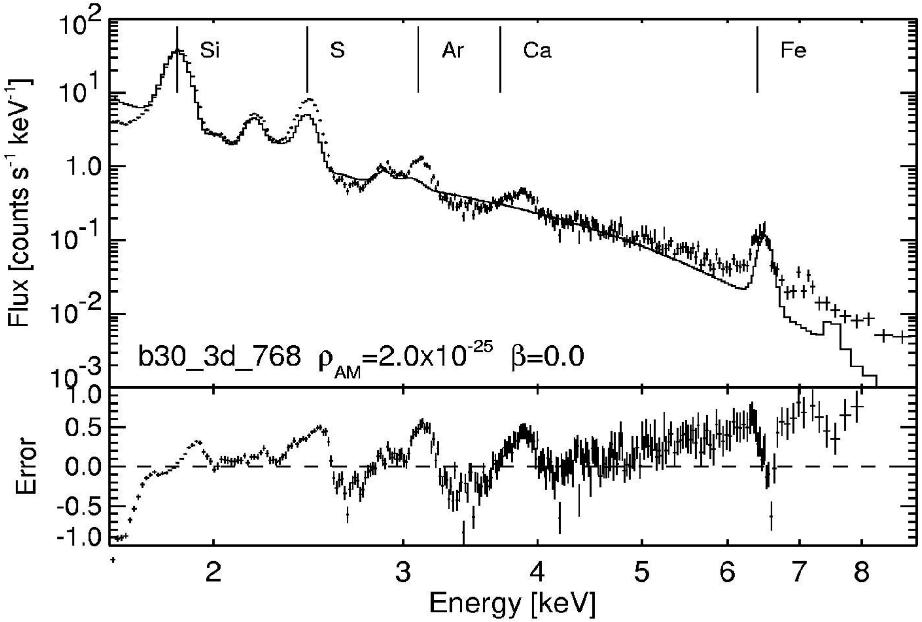


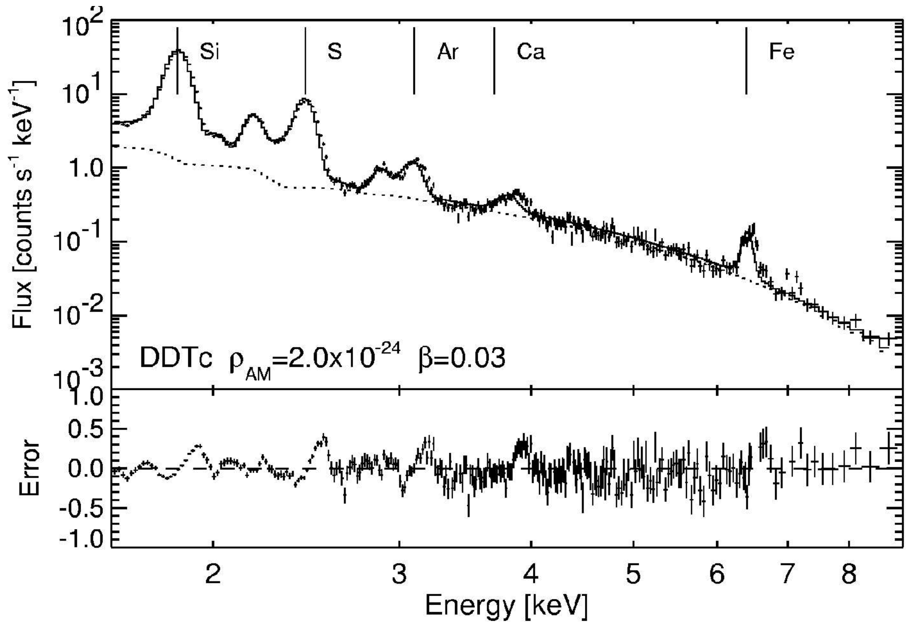

Model B30U ($t_{SNR}$, $\rho_{AM}$, $\beta$):



# Models vs. Observations

The comparison between the synthetic models and the observed spectrum is the crucial step. It is not enough to get a good match – the parameters used to generate the model have to make physical sense!




The model on the left is a 3D deflagration with well-mixed ejecta, the model on the right is a delayed detonation with stratified ejecta.

**These models and the X-ray observations of SNRs have helped us to learn more about Type Ia SN explosions.**

# The SN – SNR Connection