# Observations and Theory of Supernova Explosions and their Remnants

CAP Congress June 15, 2015

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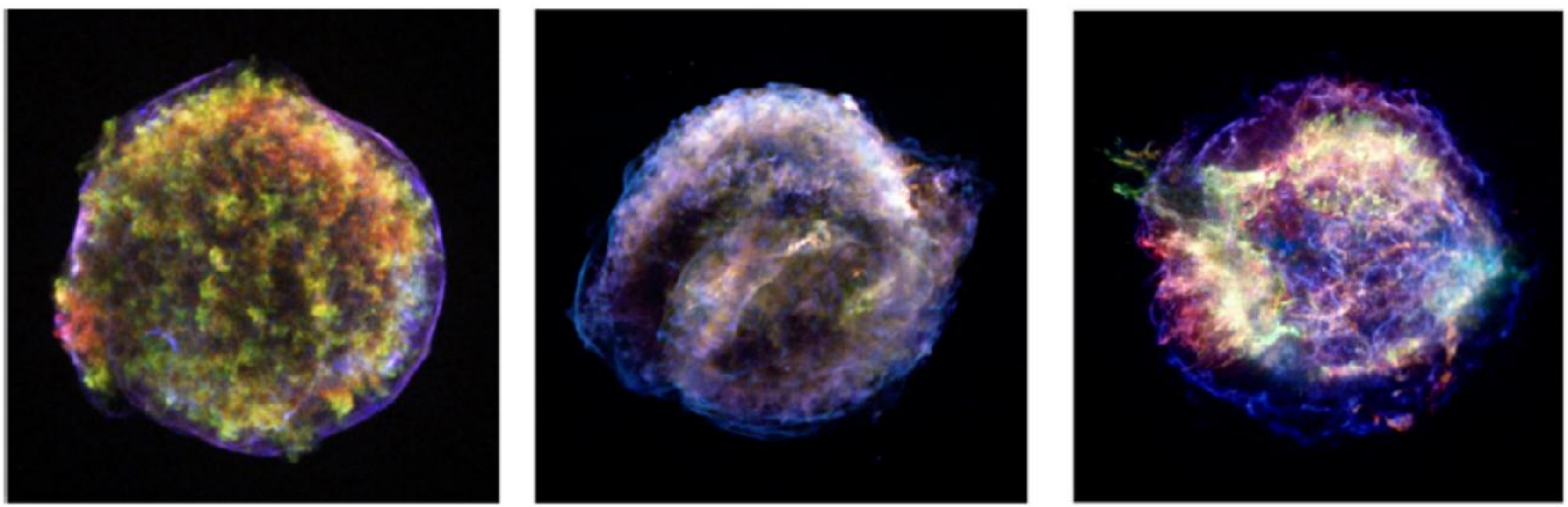
# Overview

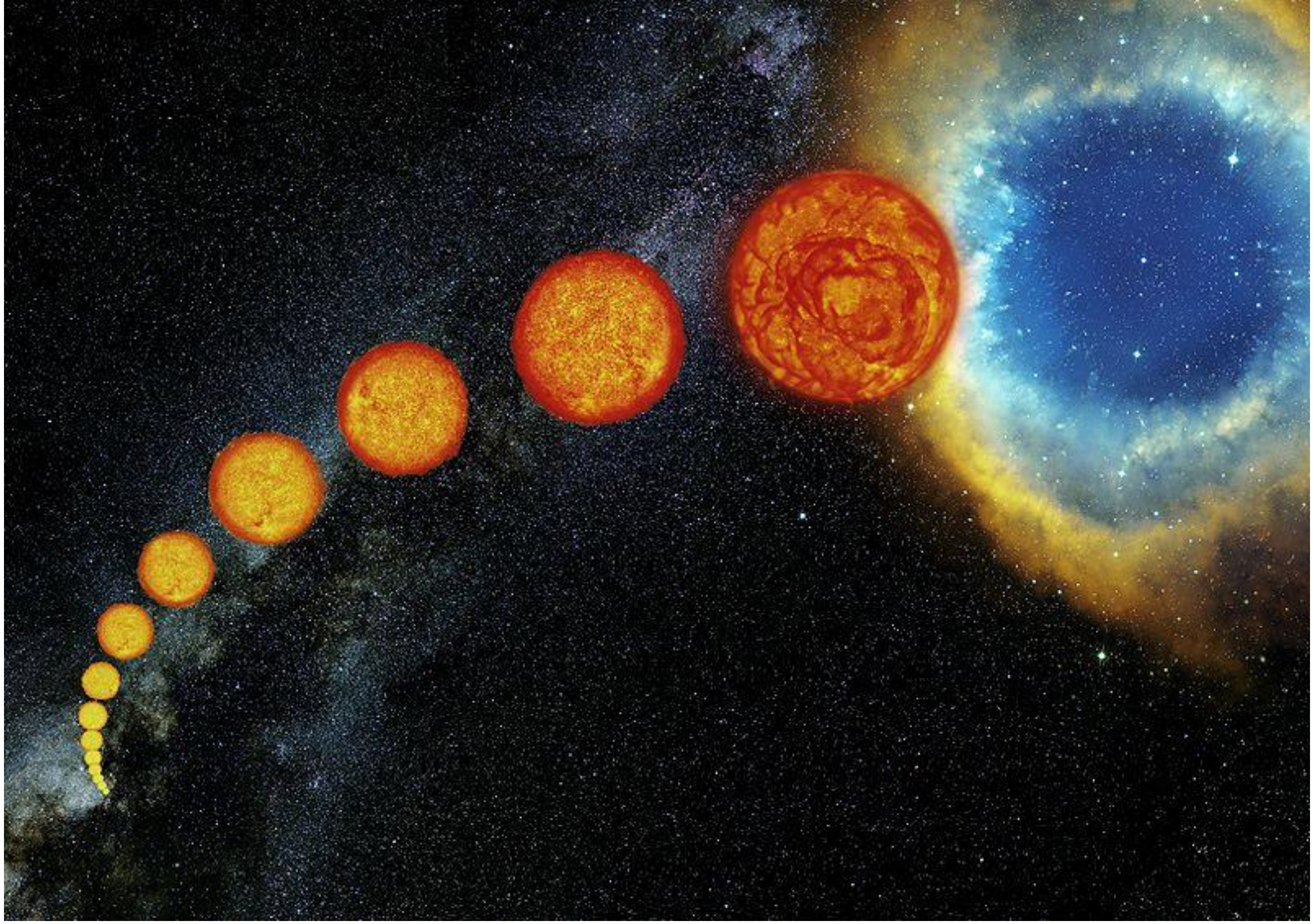
- The life/death of massive stars
- The supernova event (Type II)
- Supernova remnants
- Cosmic ray acceleration
- Research here at U Calgary



X-ray images of supernova remnants Tycho, Kepler and Cas A

# Our Sun

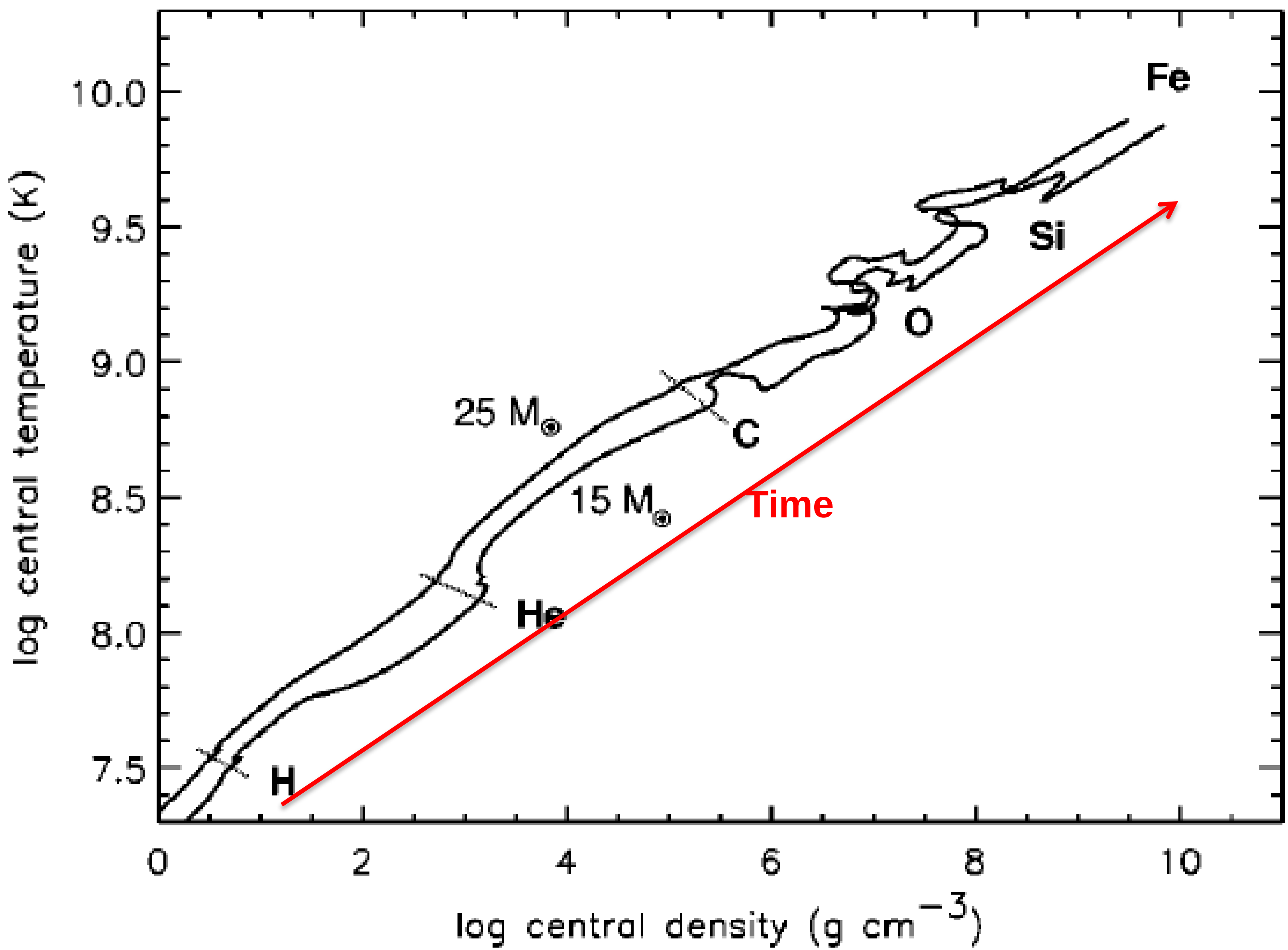
(L=3.8x10$^{27}$ W,
R=0.7 million km)

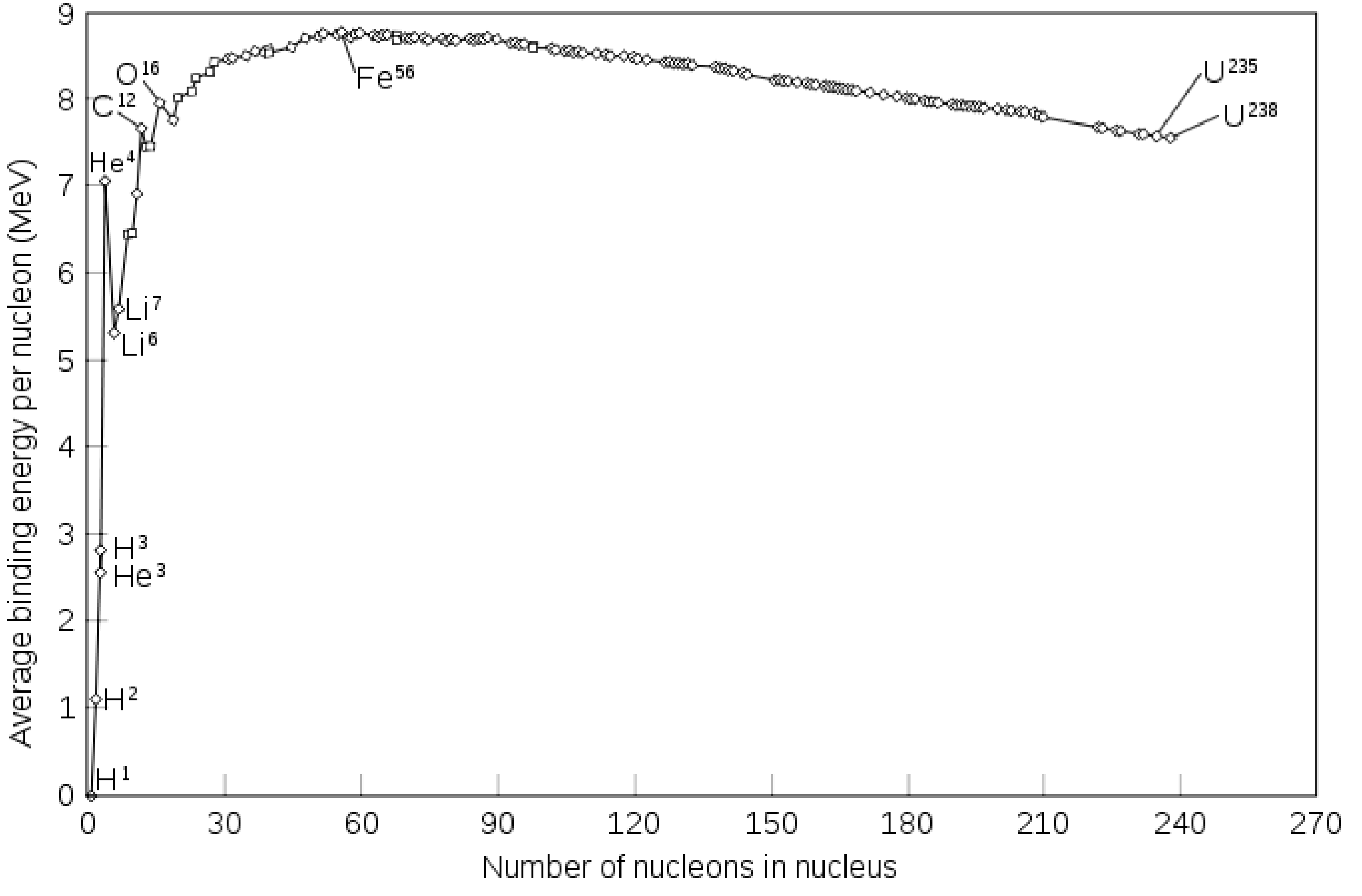


Beginning: 5 Gyr ago, start H burning (Main Sequence) 30% fainter

- Now: middle aged: still H-burning in the core
- +4 Gyr: change to Red giant (H shell burning and He burning)
- The END (+3 Gyr): Rapid mass loss, transition to a hot white dwarf inside a planetary nebula

25 $M_{sun}$ star: Increase of central density and central temperature with time (Woosley et al 2002)



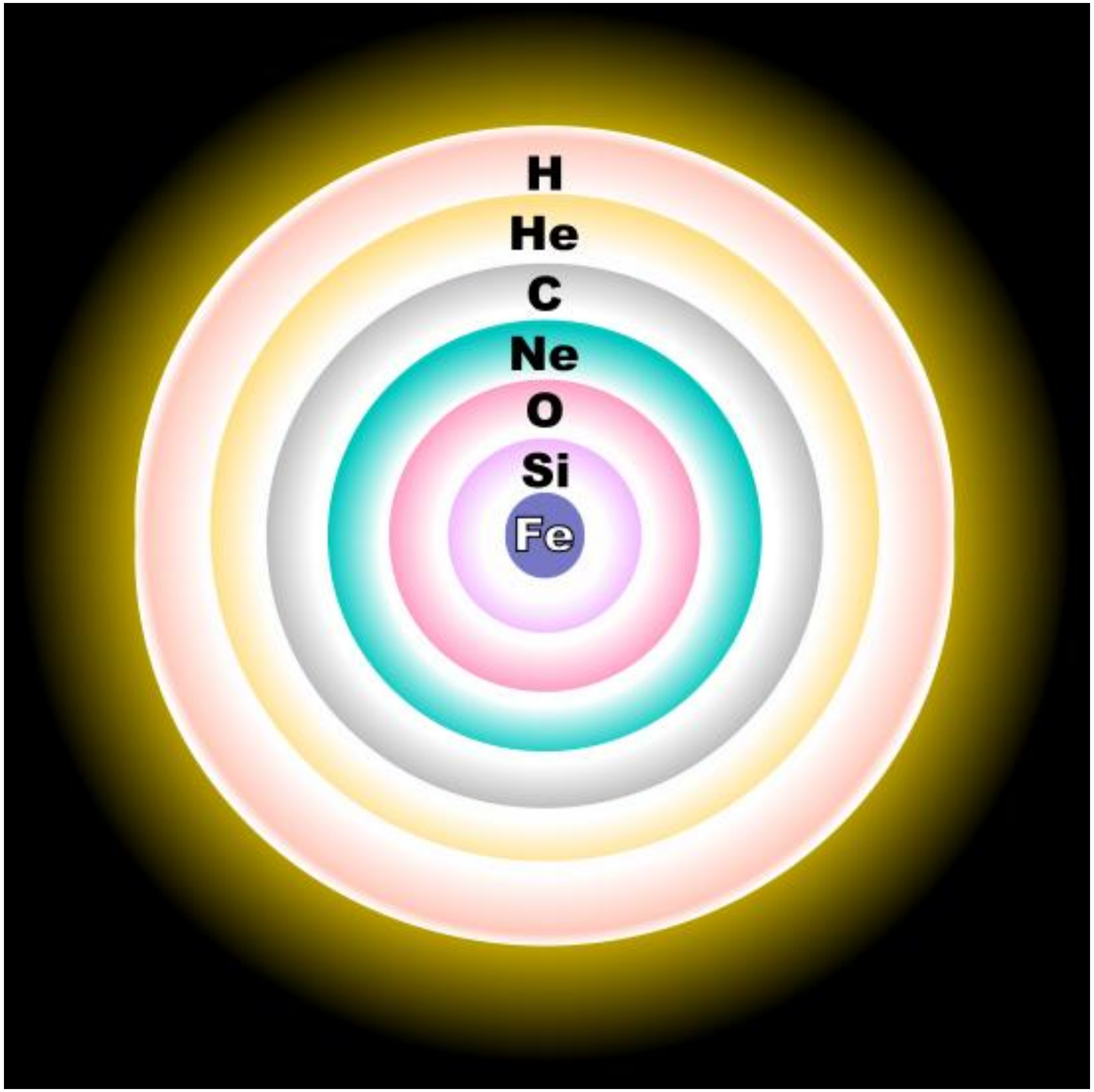



- Nuclear binding energy per nucleon vs atomic mass number A
- Iron is the most bound nucleus

# Burning Timescales (for 25 solar mass star)

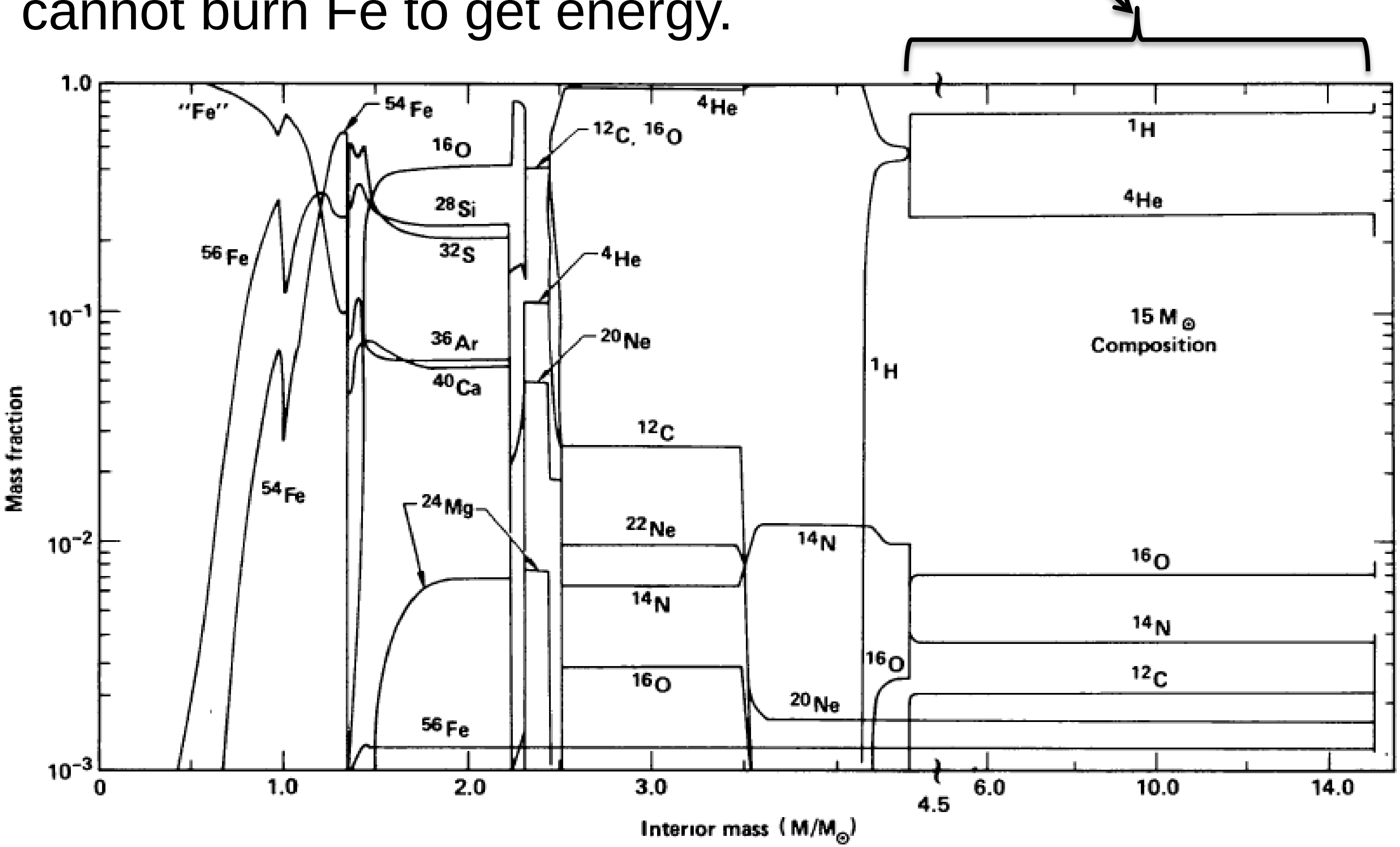
- H burning into He: CNO cycle.
- Net energy release of 27 MeV per He.
- The H-burning lifetime is 6 million years. (vs. 9 Gyr for the sun)
- He burning into C: triple-alpha process.
- Net energy release of 7 MeV per C.
- He burning lasts 600,000 yr.
- C burning produces O, Ne, Mg.
- Neutrino energy losses become important and speed up the burning. C burning takes about 200 years.
- In 1-2 years the star burns its neon.
- O burning lasts about 6 months
- Si burning lasts about 1 day.

1. Creation of elements in "steady" nuclear burning




Onion-shell structure for a massive star near the end of its life (last day):
(not to scale)

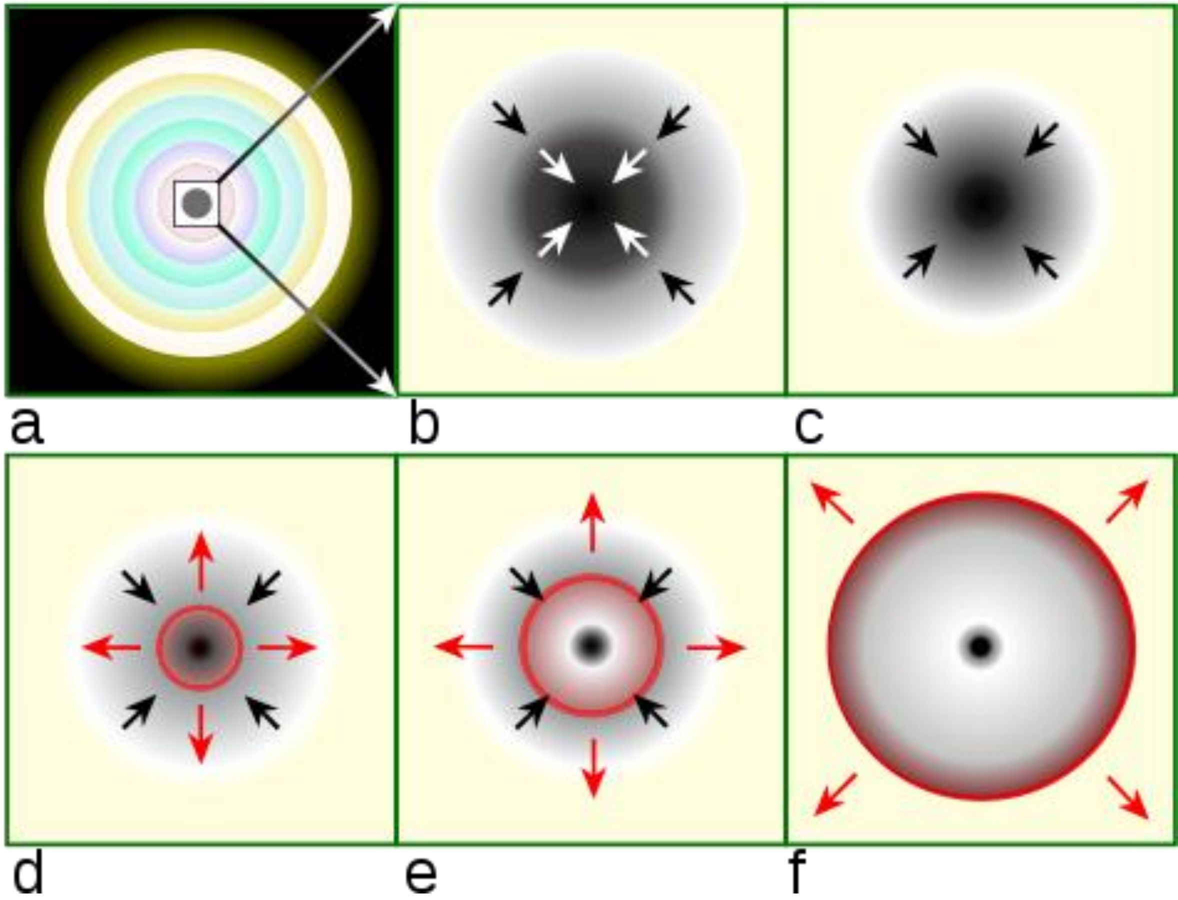
“Onion-shell” structure:
The composition at any point is a mixture.
The star is at the end of its life, cannot burn Fe to get energy.



# The Supernova(SN) explosion

- What happens after Si burning?
- SN are highly energetic ($10^{44}$J= $10^{52}$erg of kinetic energy)
- SN from massive stars: energy from gravitational collapse of the stellar core. These give Type II, Ib, Ic SN
- Type Ia SN: energy from explosive thermonuclear burning of a white dwarf
- Discuss massive star SN here

# How the explosion happens




- Time sequence of events:
- (a) nuclear burning ends
- in the Fe core
- (b) core loses pressure
- and collapses.
- (c) matter in the core is compressed into neutrons.
- (d) core reaches nuclear density ($10^{14}$ g/cm$^3$), ending collapse and causing an outward-propagating shock.
- (e) the shock is stopped by infalling matter, but re-energized by input from neutrinos at t~1-2s
- (f) The surrounding material is blasted away, leaving behind a neutron star or black.

The blast wave causes nuclear burning as it propagates through the star (~few million km radius)

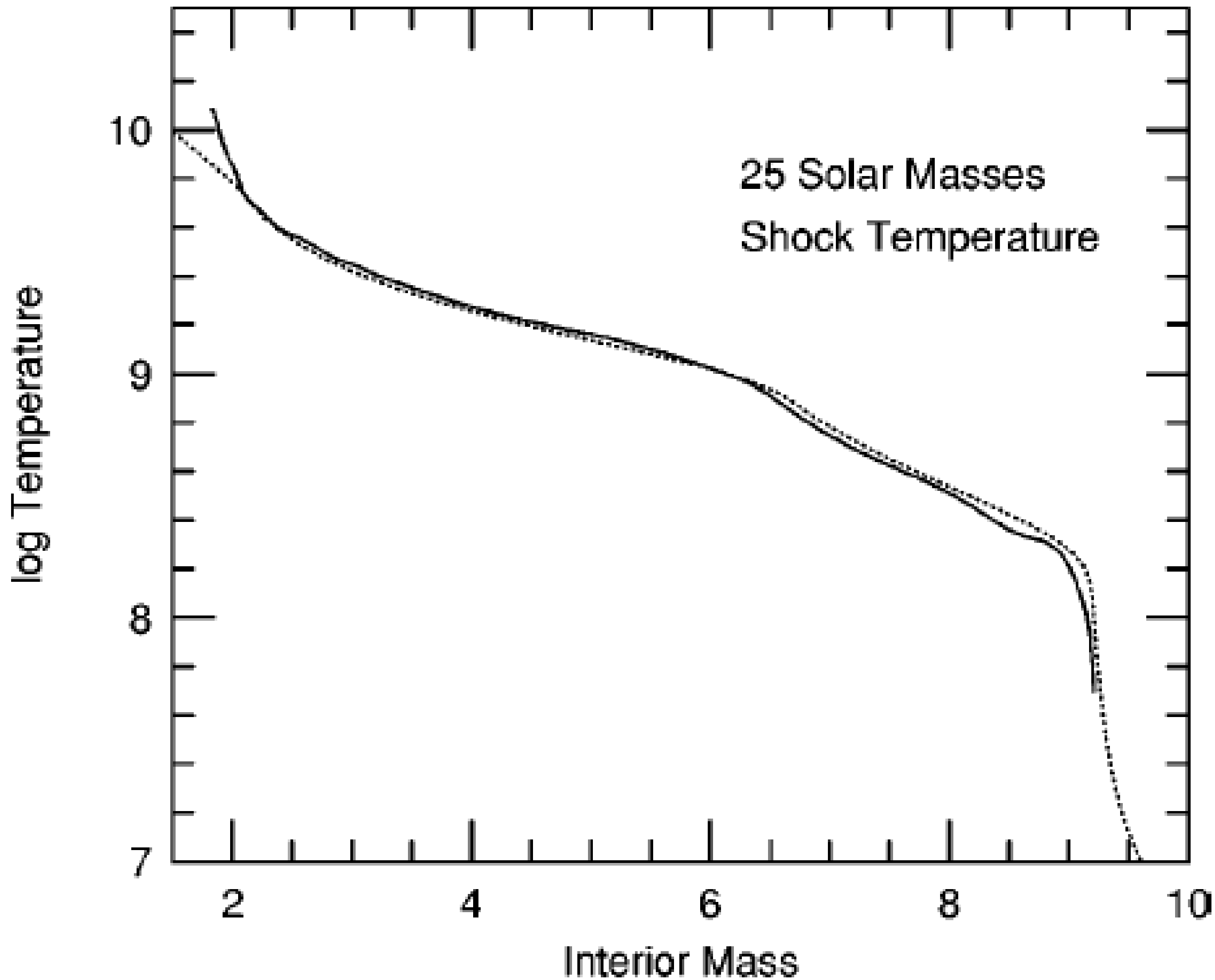
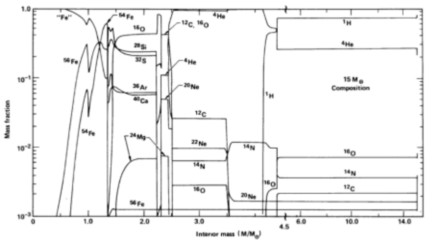
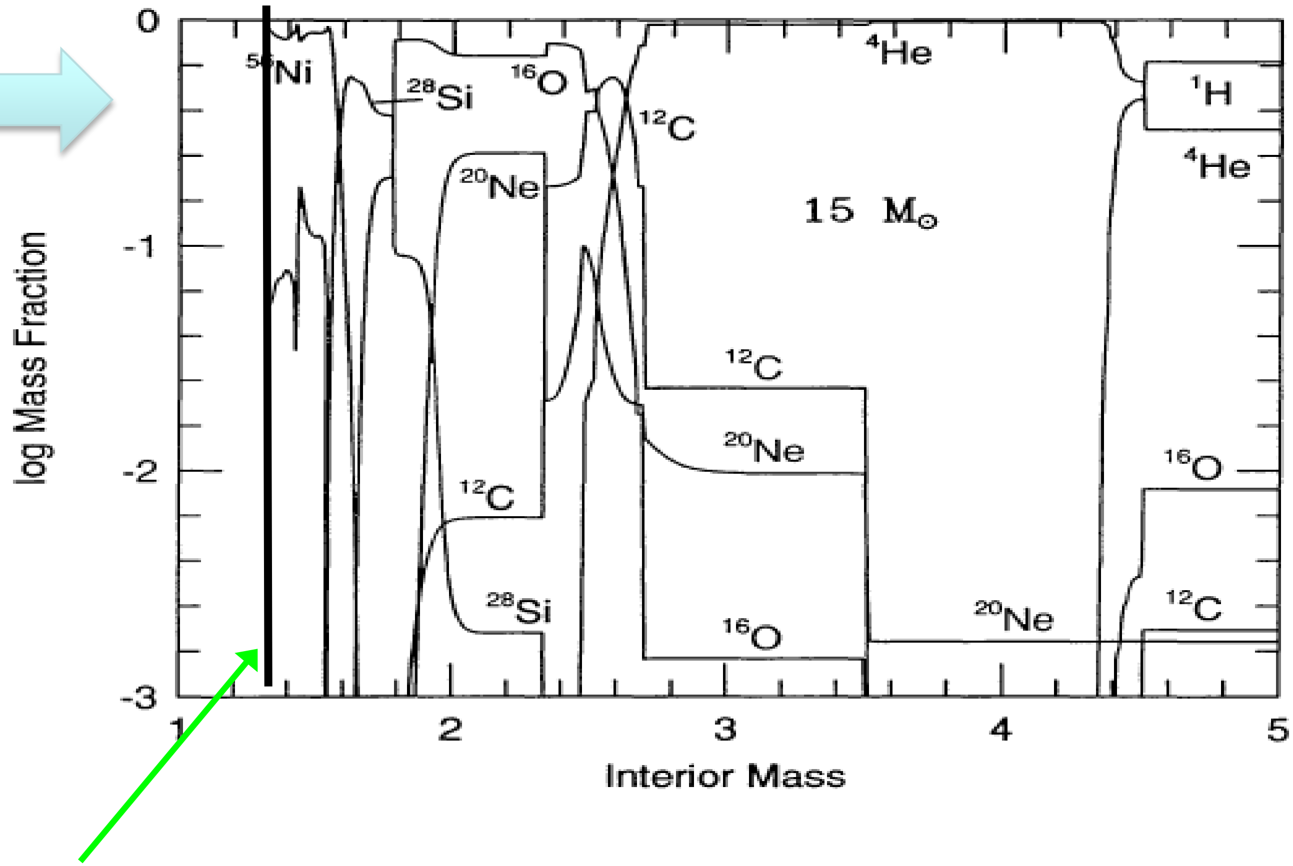



FIG. 26. Shock temperature as a function of mass for a $25M_\odot$ supernova of final kinetic energy at infinity of $1.2\times10^{51}$ erg.

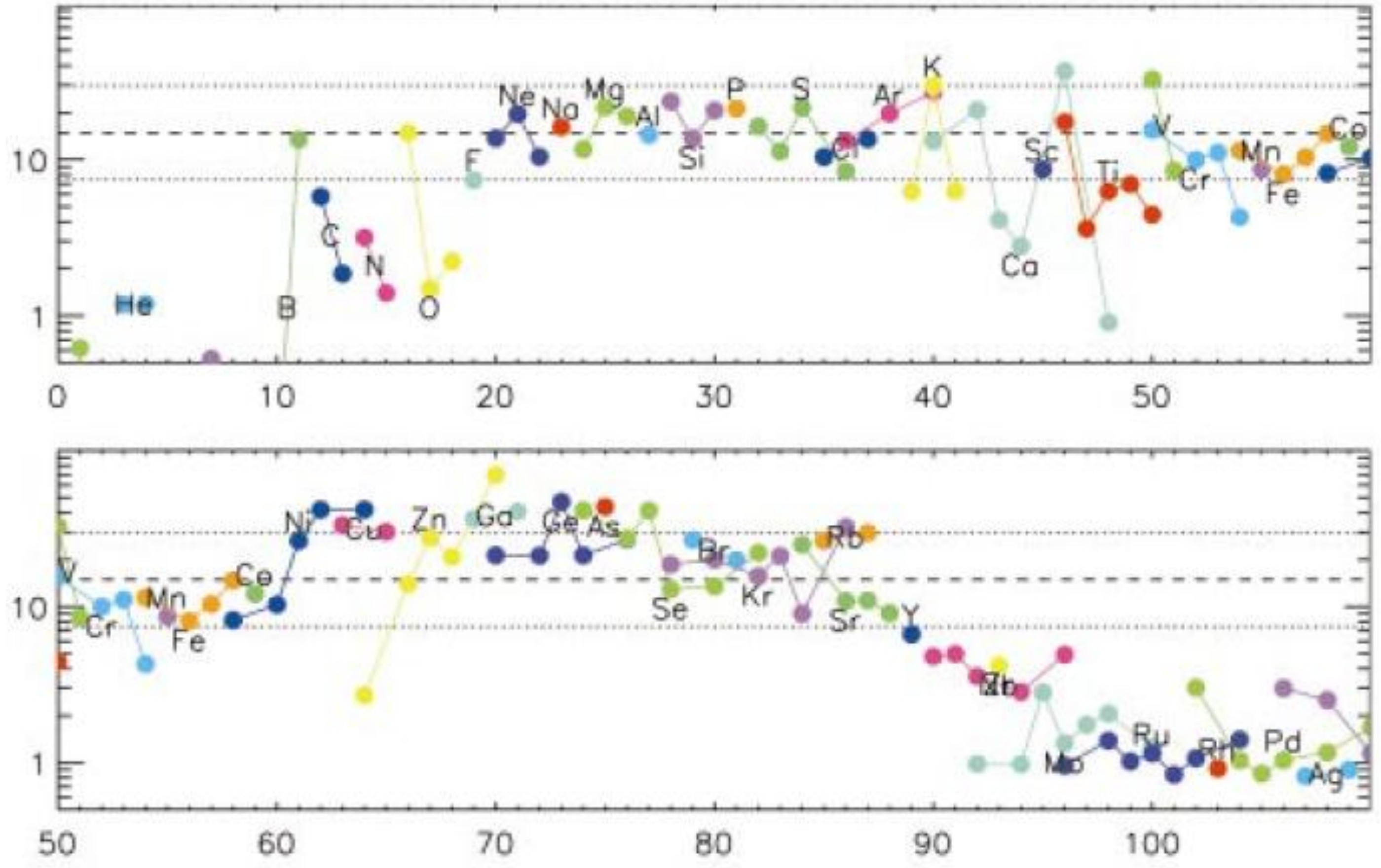





2. Nuclear processing by the explosion shock

Elements below the "mass cut" line are trapped by gravity in the compact object

The shock converts the elements above the mass cut into nuclear products which are expelled.




Wide range of products caused by the wide range of burning density and temperature.

In the outer parts of the star, the shock is too cool to cause nuclear burning

# What happens after explosion: the supernova remnant (SNR)

A SN gradually turns into a SNR

- **SN: kinetic energy of ~$10^{51}$erg** (10 billion yr worth of the Sun's power output)
- 1 to 10 solar masses of elements ejected at speeds of 5000 km/s (the "ejecta")
- The ejecta cools rapidly from expansion
- **The ejecta hits the surrounding gas and heats it** to ~40 million K (4 keV)
- **The hot gas expands with a shock wave at its outer edge**, reaching a size of ~1-2 light years in 100 yr
- The shock wave slows down, reaching 100 km/s after 20000 yr
- (1 lt-yr=$9.5 \times 10^{12}$ km)

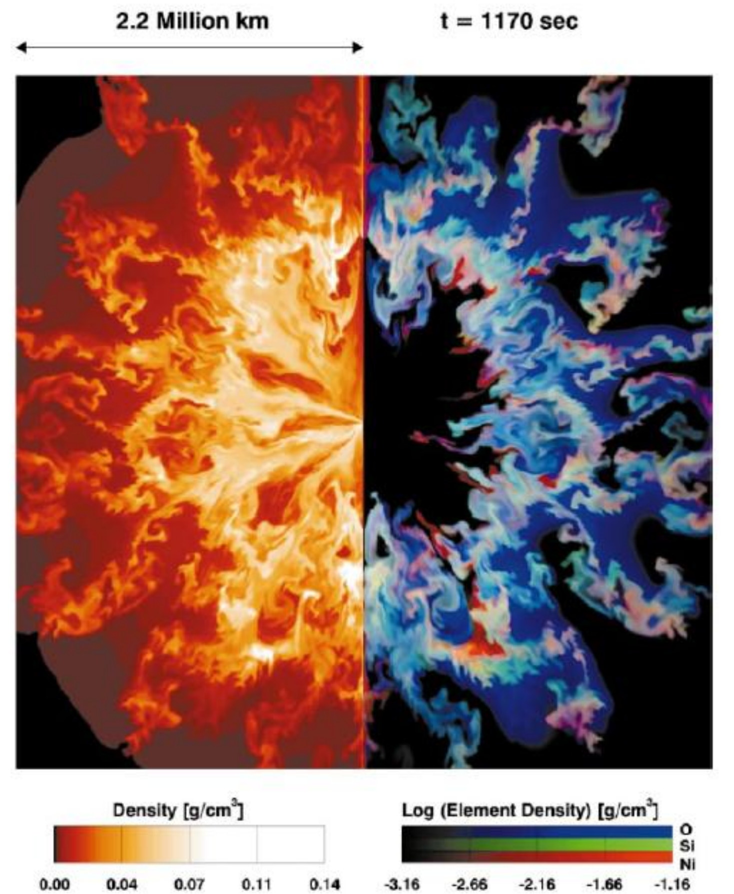
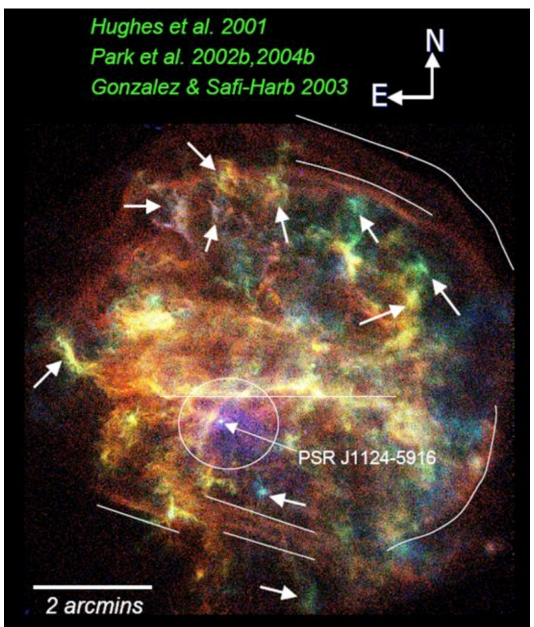


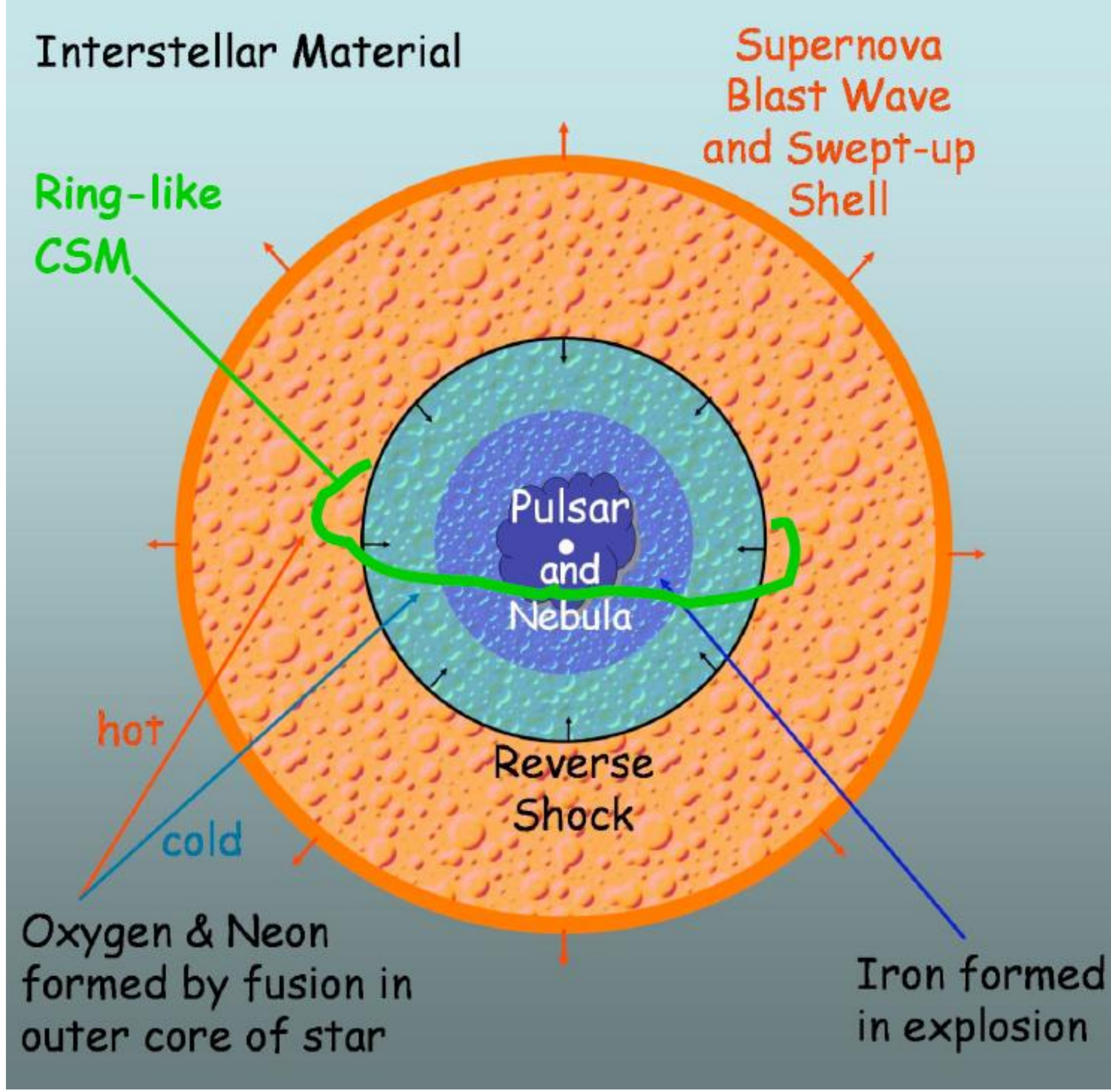

FIG. 24. Mixing in the explosion of a $15M_{\odot}$ red supergiant. From Kifonidis *et al.*, 2000 [Color].

# Implications of SNRs

- A SNR heats interstellar (ISM) gas and accelerates cosmic rays.
- The ISM compression and subsequent cooling drives the next generation of star/planet formation.
- A SNR can reveal the evolution history, nucleo-synthesis, and explosion mechanism of the progenitor star.
- SNRs are a laboratory for the study of the shock physics, chemical composition, thermal states, density structure, and the particle acceleration in the ISM.

Prototype of a SNR from a massive star



# Cosmic-ray acceleration in supernova remnants

- Average CR lifetime 16 Myr
- Implied CR energy source $10^{48}$erg/yr
- SN rate is 2-3 per century, ~10% of SN kinetic energy needs to go into CRs
- Particle acceleration theory: several percent of the SN explosion energy is given to CRs (Blandford and Eichler 1987)
- **CRs escape the SNR during acceleration process and propagate in the interstellar medium to create the diffuse CRs in the Galaxy**

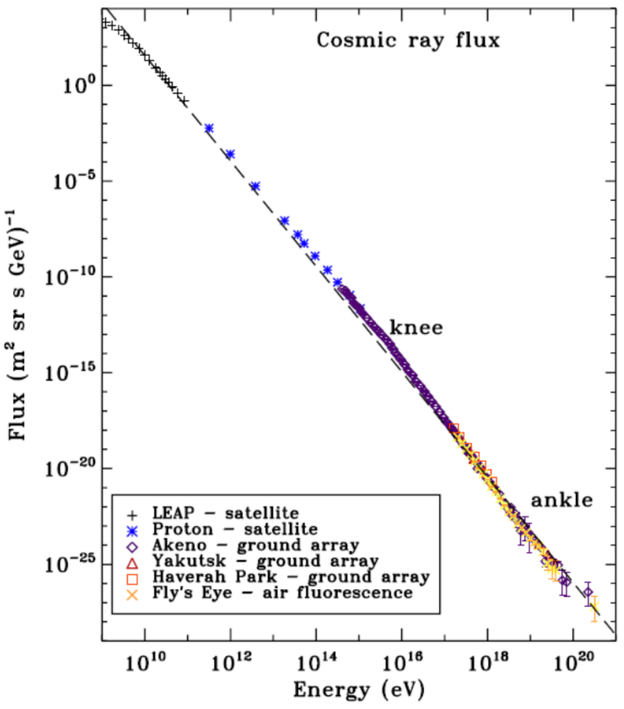


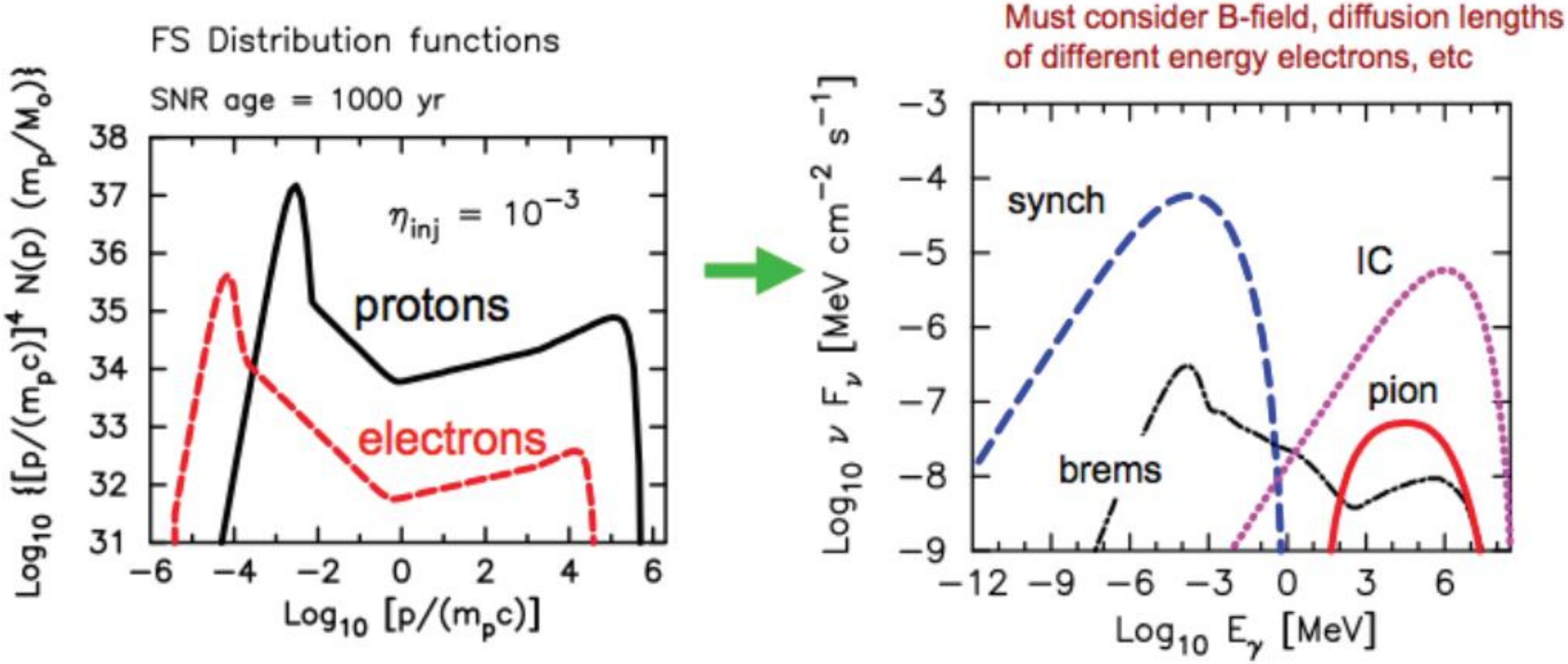

**Figure 1.1:** Cosmic-ray energy spectrum, as obtained by several experiments. Note the slight bends at $3 \times 10^{15}$ and $10^{18}$ eV; also known as the 'knee' and the 'ankle' of the spectrum respectively (data compiled by J. Swordy, courtesy to Klara Schure).

# Fermi diffusive shock acceleration

- First idea was the second order Fermi process (Fermi 1949): CR gain energy from elastic collisions with magnetic field structures in motion (second order in u/c)
- **First order Fermi process (diffusive shock acceleration or DSA), occurs in association with blast waves** (Krymsky 1977, Axford et al 1977)
- CR diffusion back and forth across a strong shock produces a fractional energy gain ~u/c on each crossing with probability of escape $(1 - u/c)^m$ after m shock crossings
- **Fermi DSA acceleration gives a power-law particle spectrum $N(p)=c\ p^{-3r/(r-1)+2} = c\ p^{-\Gamma}$ . For compression ratio r=4, Γ=2.**
- Non-linear shock modification results in a concave spectrum of accelerated particles (Berezhko & Ellison 1999): high-energy end is flatter than $E^{-2}$ spectrum and low-energy end is steeper spectra

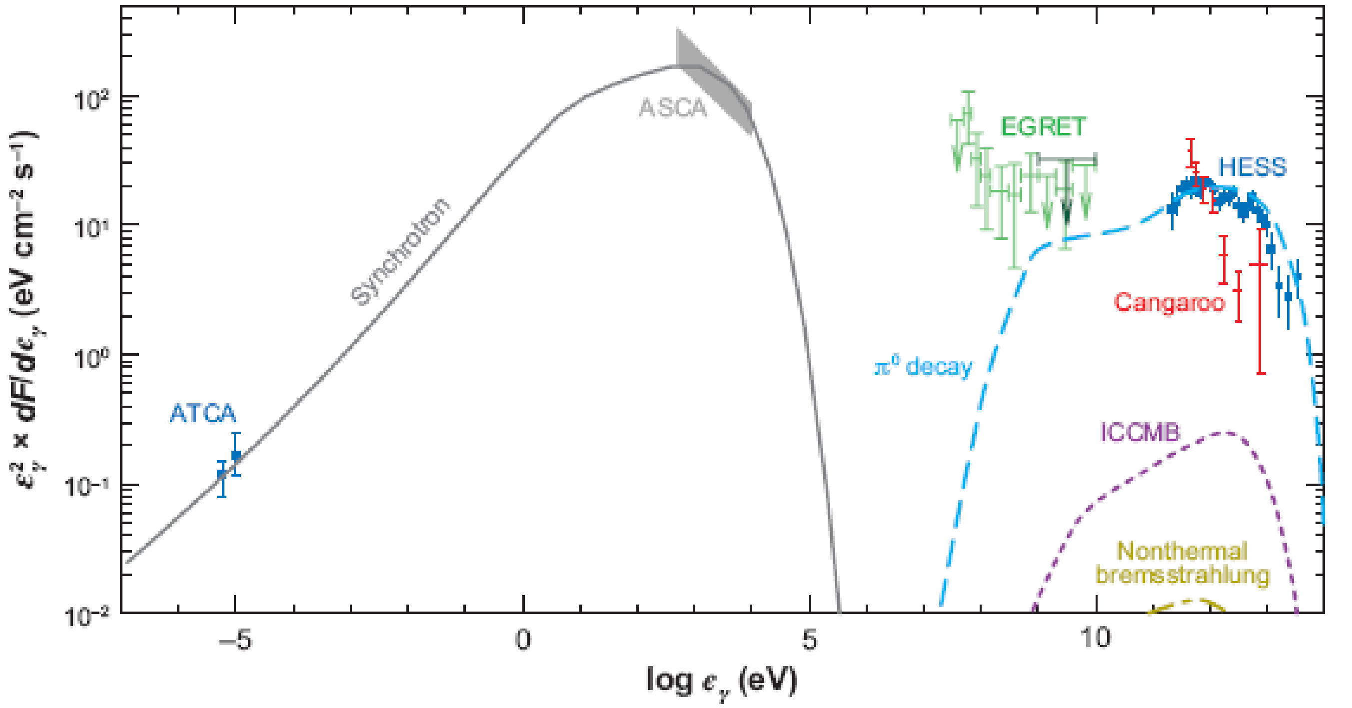
# Photon emission from SNR accelerated particles

**Accelerated Particles** **Observed Gamma-Rays**



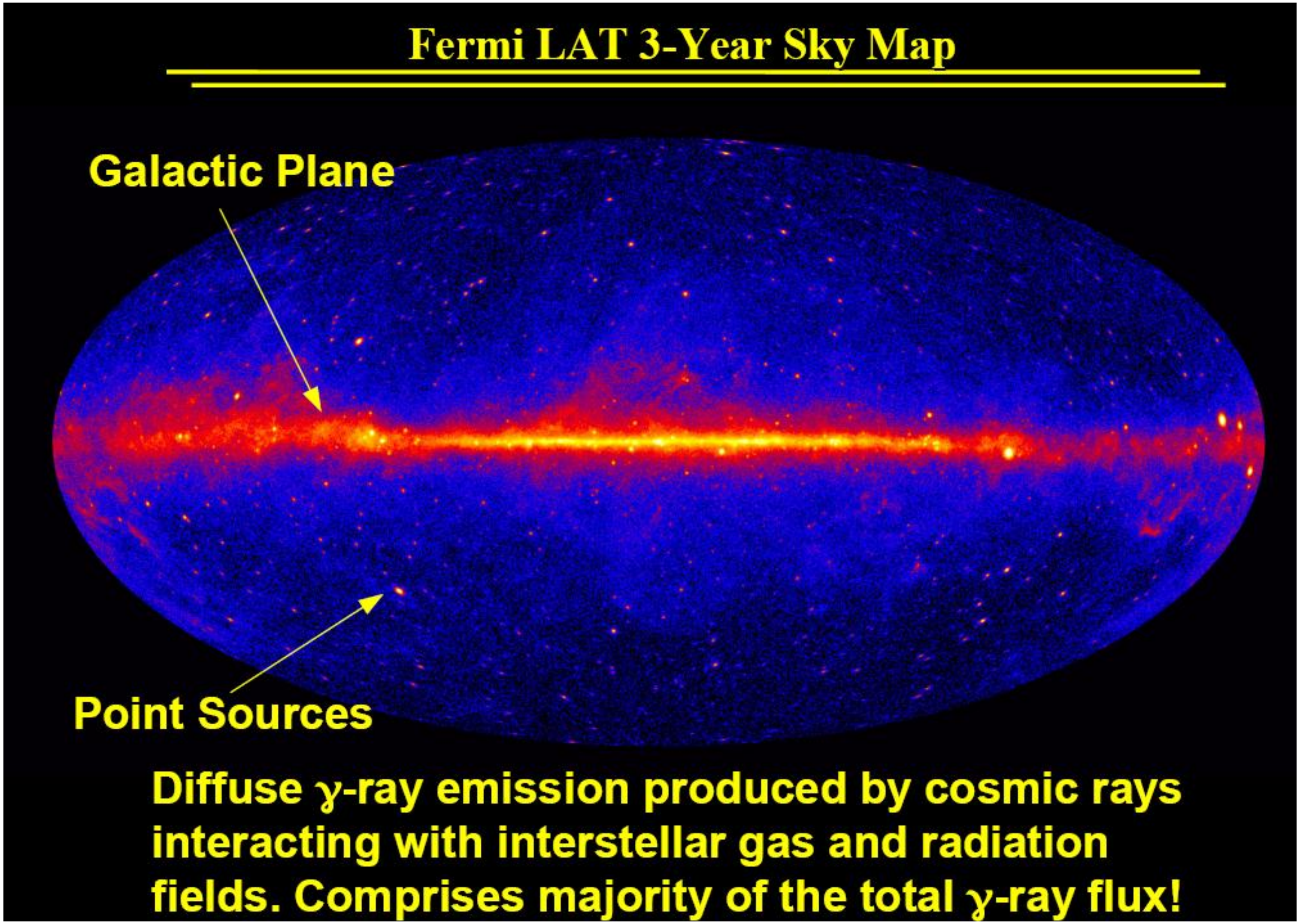

- From simulations by Ellison et al. (2009) which assume injection efficiency and non-linear diffusive shock acceleration of particles.

gamma-ray emitting SNR G347.3-0.5

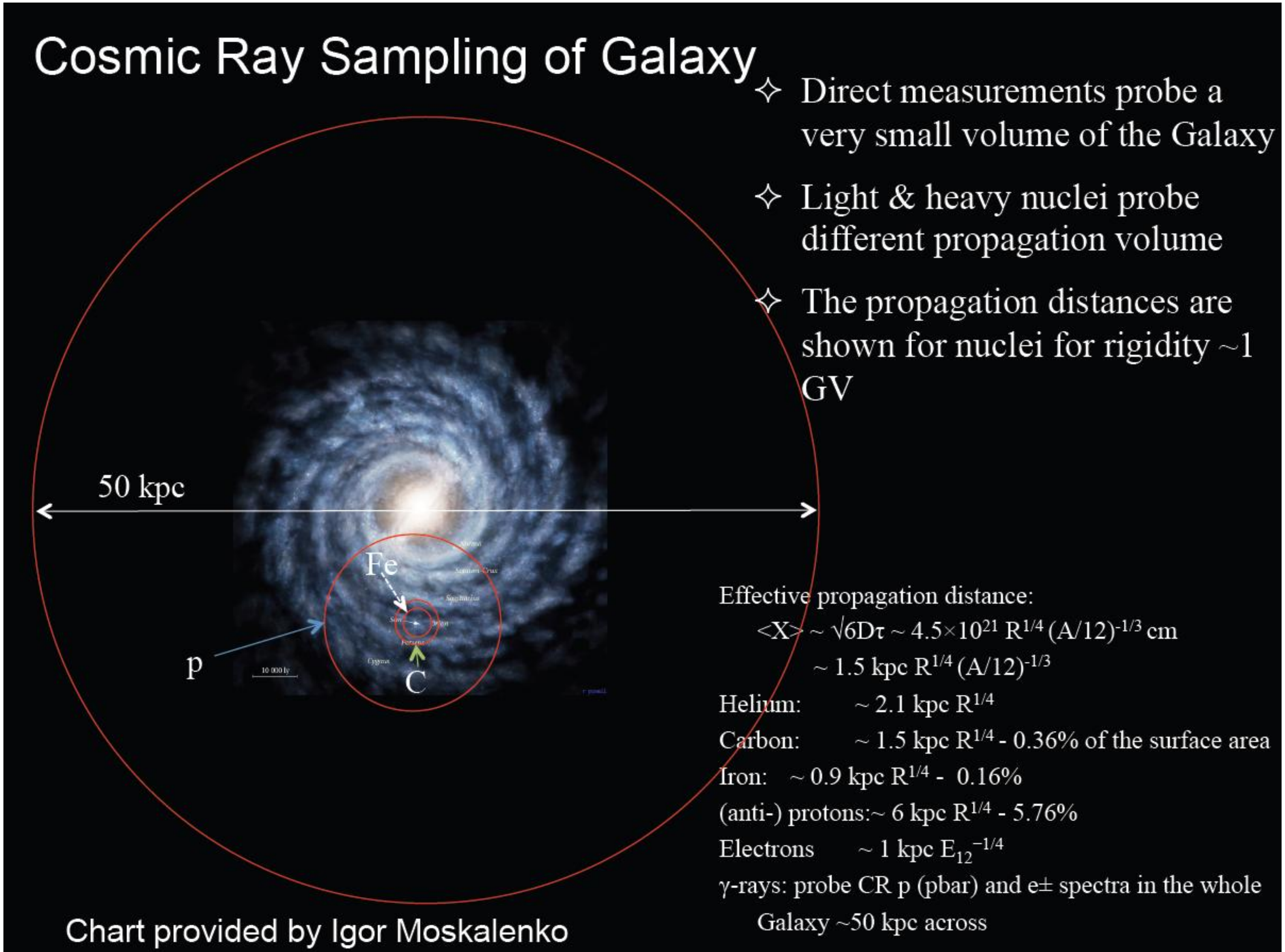



- Discovered with gamma-ray telescopes: Fermi, EGRET, HESS
- **Demonstrates existence of high energy particles (electrons, protons)**
- Particles are accelerated by the SNR shock wave
- Radio and X-ray emissions are from energetic electrons.
- **Gamma-rays from high energy protons which collide to produce pions**; the neutral pions decay to gamma-rays at $10^{10}$ to $10^{14}$ eV.

Cosmic rays produced by SNRs then propagate throughout the Galaxy



# Cosmic rays: what do we measure on Earth?



# Modeling Galactic Cosmic Rays from SNRs including propagation from sources

- Model using kinetic nonlinear theory (Berezhko & Volk, 2007)
- Esn=$10^{51}$ erg, Mej=1.4 Msun
- $10^5$ yr for active SNR age
- $\tau_{esc}$~$R^{-\mu}$ with μ=0.75

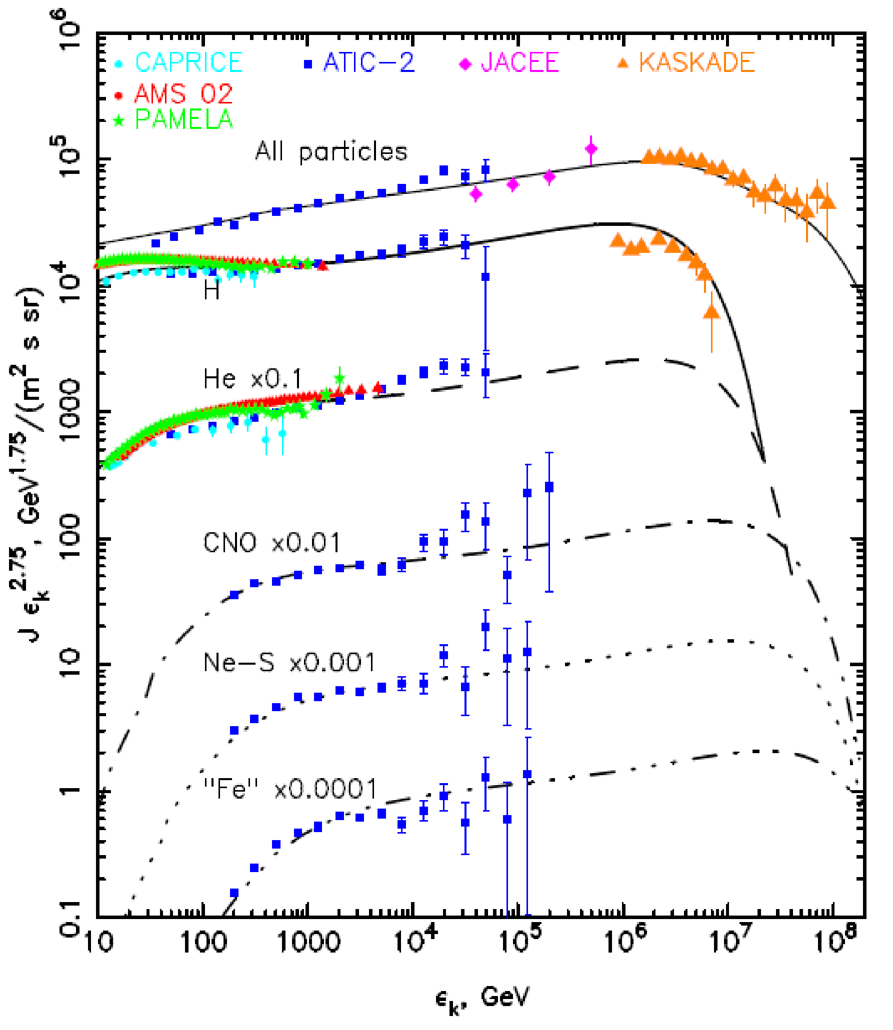
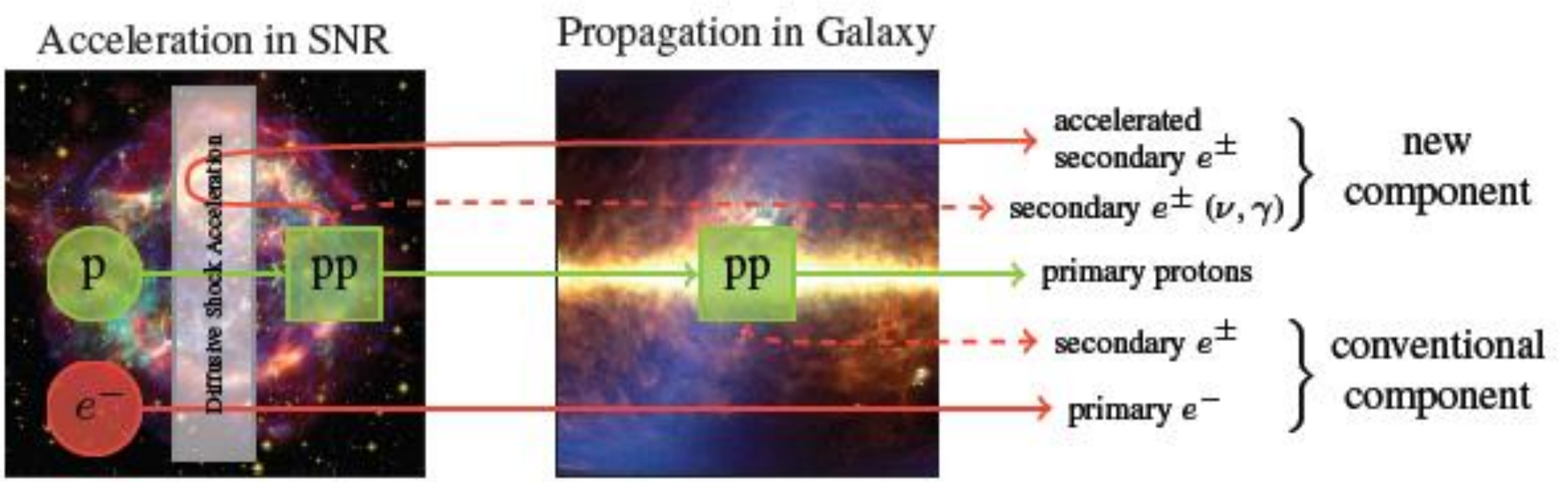


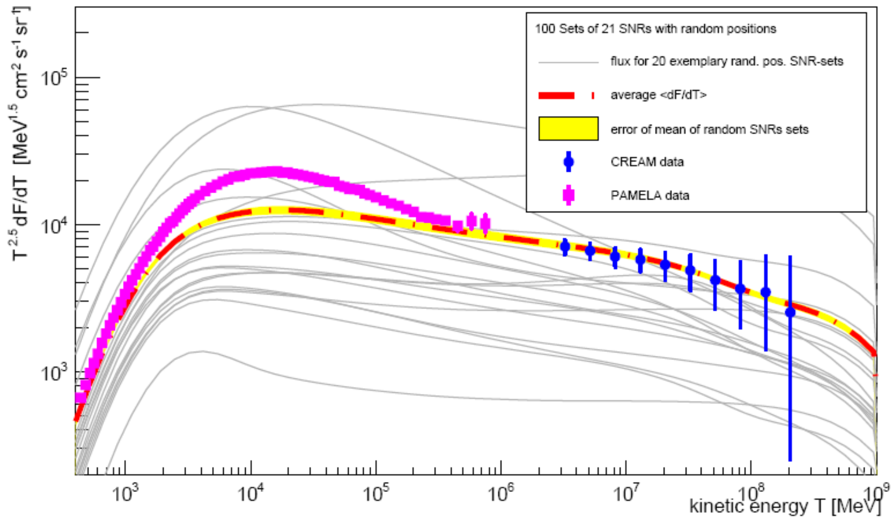

Figure 1: GCR intensities at the Solar system as a function of kinetic energy. Experimental data obtained in the CAPRICE [29], AMS 02 [30] PAMELA [31], ATIC-2 [32], JACEE [33] and KASCADE [34] experiments are shown as well. The calculated curves were normalized to the ATIC-2 data at $\epsilon_k > 1$ TeV

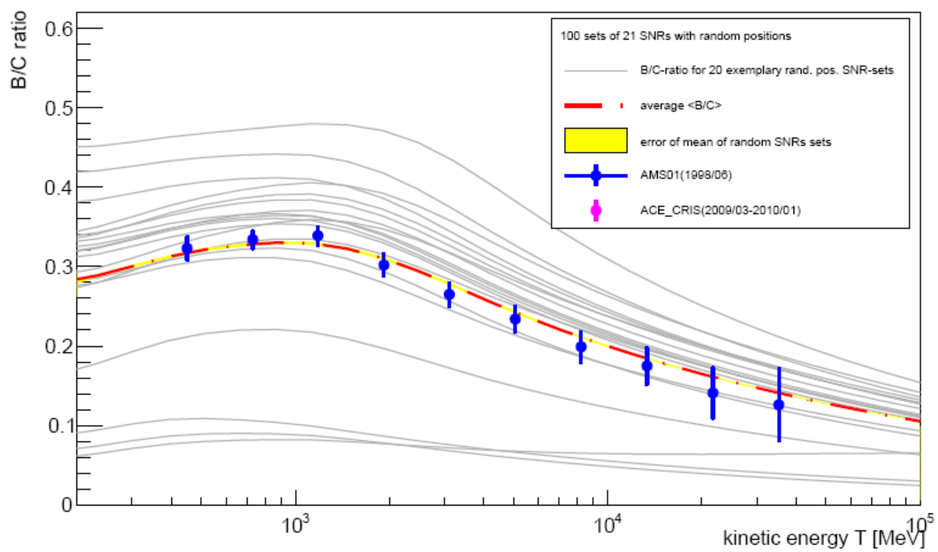
- Positrons
- positrons are created as secondaries in ISM: **SNR accelerated protons create secondary e+,e- by collisions**
- positron spectrum should be softer than electron spectrum, contrary to observation
- However **the secondary e+,e- are then accelerated by the SNR shock**.
- This results in harder e+ spectrum than primary e-



# Variance in propagation of CRs from individual SNRs
(Nierstenhoefer et al 2015)

- models of leptonic or hadronic origin of observed gamma-rays for 24 well-identified SNRs (Mandelartz & Becker 2015)
- source proton spectra ($j_p(E)$) systematically determined.
- **a single SNR is active for ~$10^4$ years, but cosmic rays diffuse in the Galaxy for ~$10^7$ years**.
- → Need to simulate the positions of sources (SNRs) as old as $10^7$ yrs and the propagation of CRs
- **Current CRs are dominated by SNRs which are long-dead**



# SNR/Compact remnant Research at UC

- Theory/modeling:
- modeling of super-luminous SN, quark novae, nucleosynthesis and spallation, magnetars- R.Ouyed, DL, N.Koning, A.Ouyed
- modeling millisecond X-ray pulsars- S.Morsink (U of A), DL

- Observations:
- X-ray spectra of SNR and X-ray binaries, radio observations of SNR, radio spectra, images, distances, physical properties, TeV emitting SNR- W.Tian (NAOC), DL, M.Abdallah, S.Ranasinghe
- XMM-Newton observations of neutron stars- N.Webb(IRAP), DL

- Experimental:
- instrument calibration, software development for ASTROSAT UV/X-ray observatory- DL, J.Postma, J.Hutchings(HIA)
- Previous projects: work with instrument and science teams for ROSAT, Spektrum X-gamma, Tenma, Ginga, HEAO-1, USA/NRL

# Summary

- Massive stars and (a some white dwarfs in binaries) explode as supernovae (SN).
- Supernovae/massive stars create all elements heavier than Li in the universe.
- A SN ejects a few solar masses at  ~5000 km/s into interstellar space, creating a SNR.
- SNR have drastic impact on the interstellar medium and accelerate cosmic rays.
- SNR can be used to study SN explosions.