Nuclear Astrophysics - II

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Overview of Heavy Element Nucleosynthesis

process	conditions	timescale	site
S Process **n capture**	**$T \sim 10^8$ K** **$n_n \sim 10^8/cm^3$**	**10^2 - 10^6 yrs**	**Massive stars** **Low mass AGB stars**
R Process **n capture**	**$T \sim (1\text{-}2)\text{x}10^9$ K** **$n_n \sim 10^{24}$ /cm^3**	**< 1s**	**Type II Supernovae ?** **Neutron Star Mergers ?**
P Process **(γ,n),…**	**$T \sim (2\text{-}3)\text{x}10^9$ K**	**~1s**	**Type II Supernovae**

Note: neutrons are rather hard to come by in astrophysics, as the universe is proton rich and neutrons are unstable…

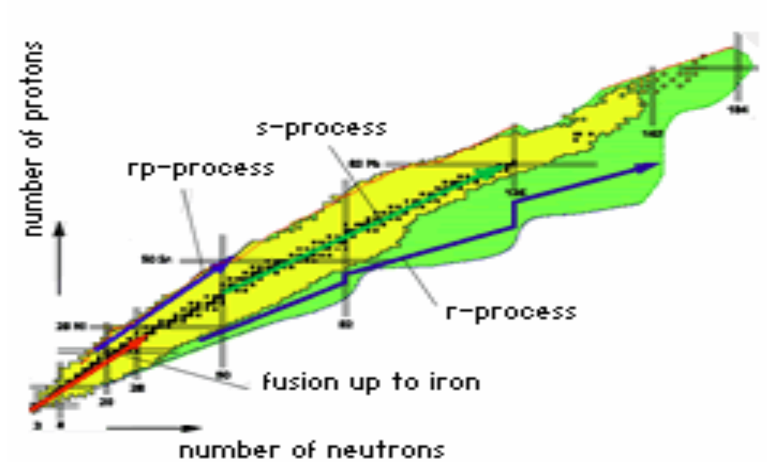
Nuclear Physics of Neutron Capture (in Heavy Nuclei)

- No Coulomb barrier ➔ large reaction rates
- Reaction rates are usually determined by many resonances
  - Statistical (Hauser-Feshbach) models are used
  - Inputs: level densities, gamma-ray strength,…
  - Nuclear structure is important
- Detailed balance ➔ photodissociation rate
  - $\lambda_\gamma = (\text{const}) \times T^{3/2} \times \exp(-S_n/kT) \times \langle\sigma v\rangle_{n\gamma}$
    where S_n is the neutron separation energy
- Direct measurement is possible for stable (or reasonably long-lived) targets
  - LANSCE, CERN-NTOF, FRANZ,…

The S Process

(slow neutron capture process)

What defines "slow" ?
— Neutron capture rate is slow compared to β decay
— The S Process thus tracks the neutron-rich edge of stability



The S Process makes half the elements heavier than iron and is critical to determining the abundances for the r-process, which makes the other half. From (NAS study) *Connecting Quarks to the Cosmos*: One of the 11 fundamental questions for the coming century is "How were the elements from iron to uranium made and ejected?"

Crucial Questions:

- **Where does the S Process take place?**
- **What are its conditions (temperature, neutron density)?**
- **How accurately can we calculate the s-process abundances?**

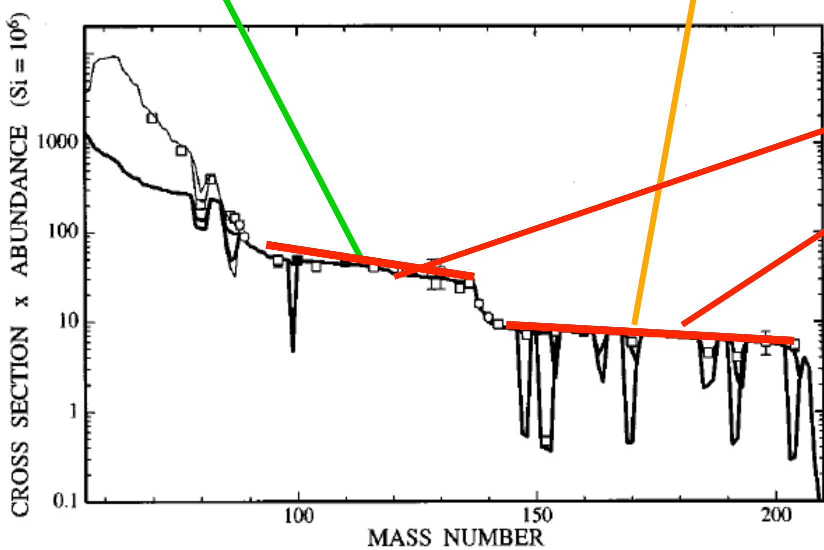
The sites of the s-process

weak s-process: core He/shell C burning in massive stars

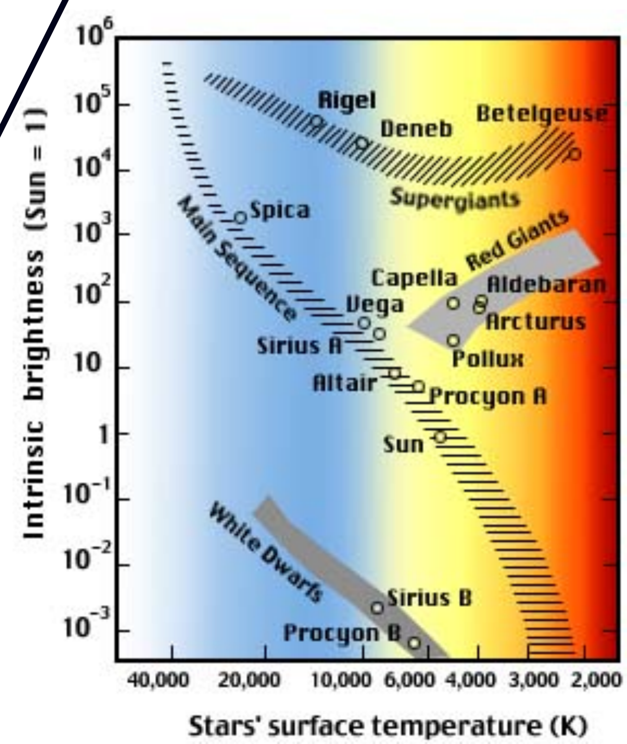
main s-process: He shell flashes in low mass Thermally Pulsing Asymptotic Giant Branch (in H-R diagram) stars

roughly steady flow

$$Y\lambda \propto Y\sigma_{(n,\gamma)} \approx \text{const}$$



Wallerstein et al. (1997)



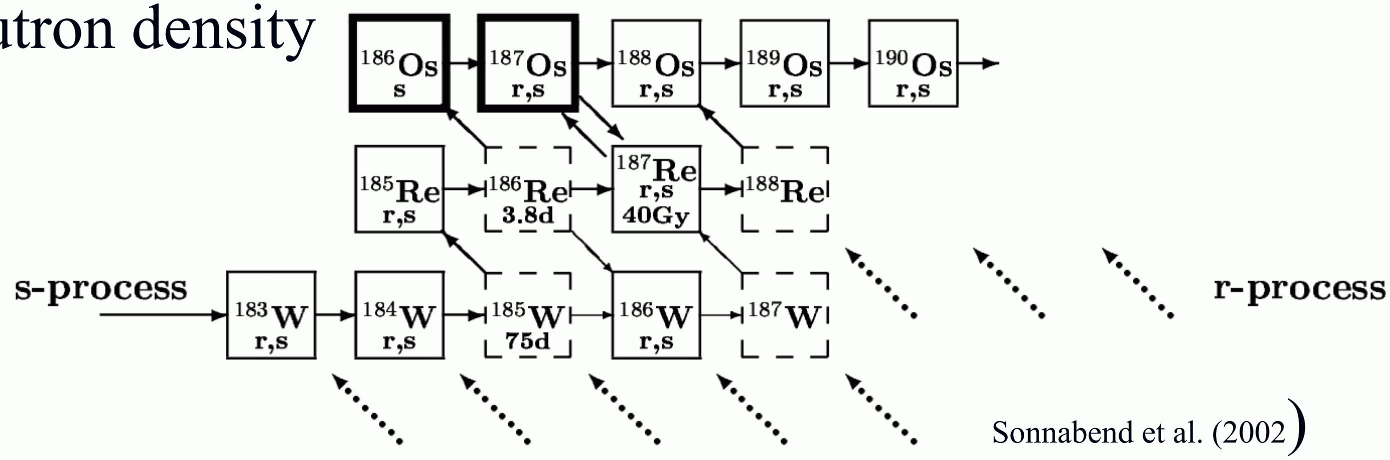
Can calculate s-process abundances accurately if neutron capture cross sections are known

More on the S-Process

- Iron and other pre-existing nuclei serve as "seeds"
- Main S-Process
  - Low-mass thermally-pulsing AGB stars (1.5-3 solar masses)
  - $^{13}C(\alpha,n)$ neutron source
  - requires mixing with hydrogen shell
  - $T \sim 1.5 \times 10^8$ K
- Weak S-Process
  - Core helium (and shell carbon) burning
  - $^{22}Ne(\alpha,n)$ neutron source
  - $T \sim 3.0 \times 10^8$ K

Current S-Process Issues

• Branch Points (**β**-decay rate comparable to neutron-capture rate) are sensitive to the dynamical conditions and can provide information about temperature and/or neutron density



Sonnabend et al. (2002)

• What is the temperature? (T~3 x 10^8 K   kT~20 keV)
• What is the neutron density? (~3 x 10^8 n/cm^3)

• What is the rate of $^{13}C(\alpha,n)$?
• What is the rate of $^{22}Ne(\alpha,n)$?

neutron sources

The R-Process

- Many heavy nuclei cannot be made by the S-process!
- T = (1-2)×10^9 K
- density ~ 300 g/cm^2 , ~half neutrons
- neutron capture timescale ~ μs

"R-Process Residuals"
For the solar system
Kaeppeler, Beer and
Wisshak (1989)

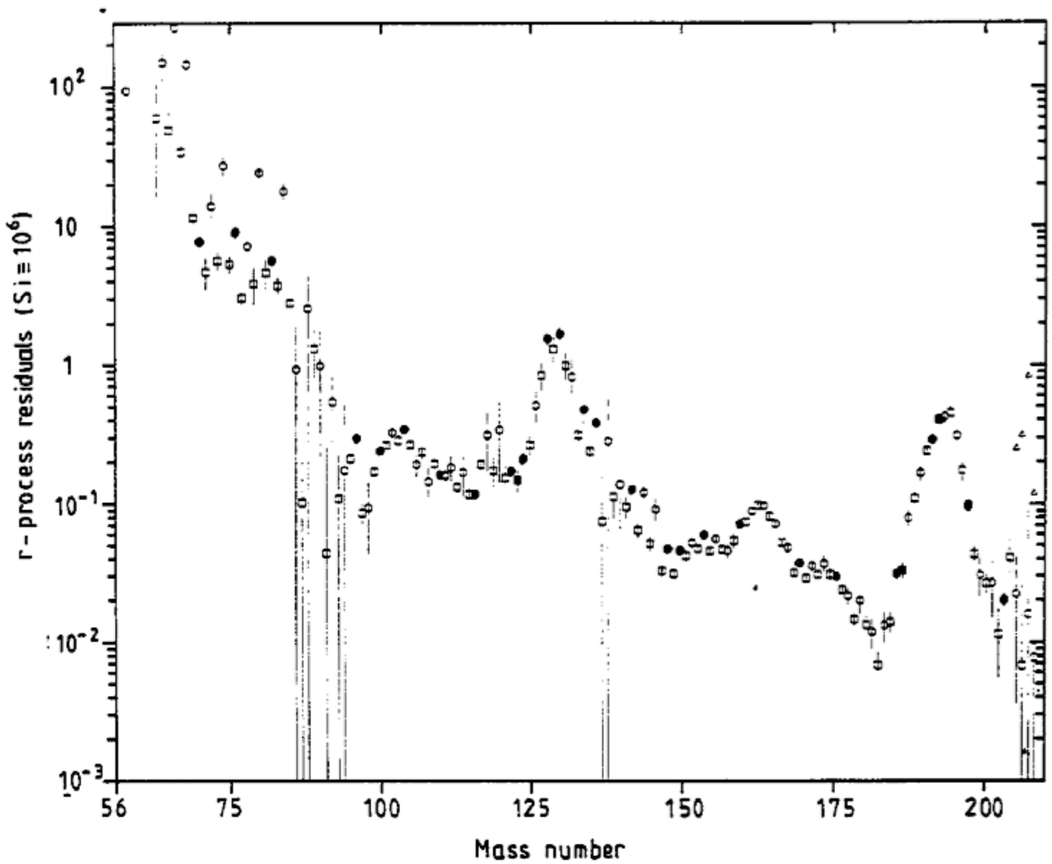
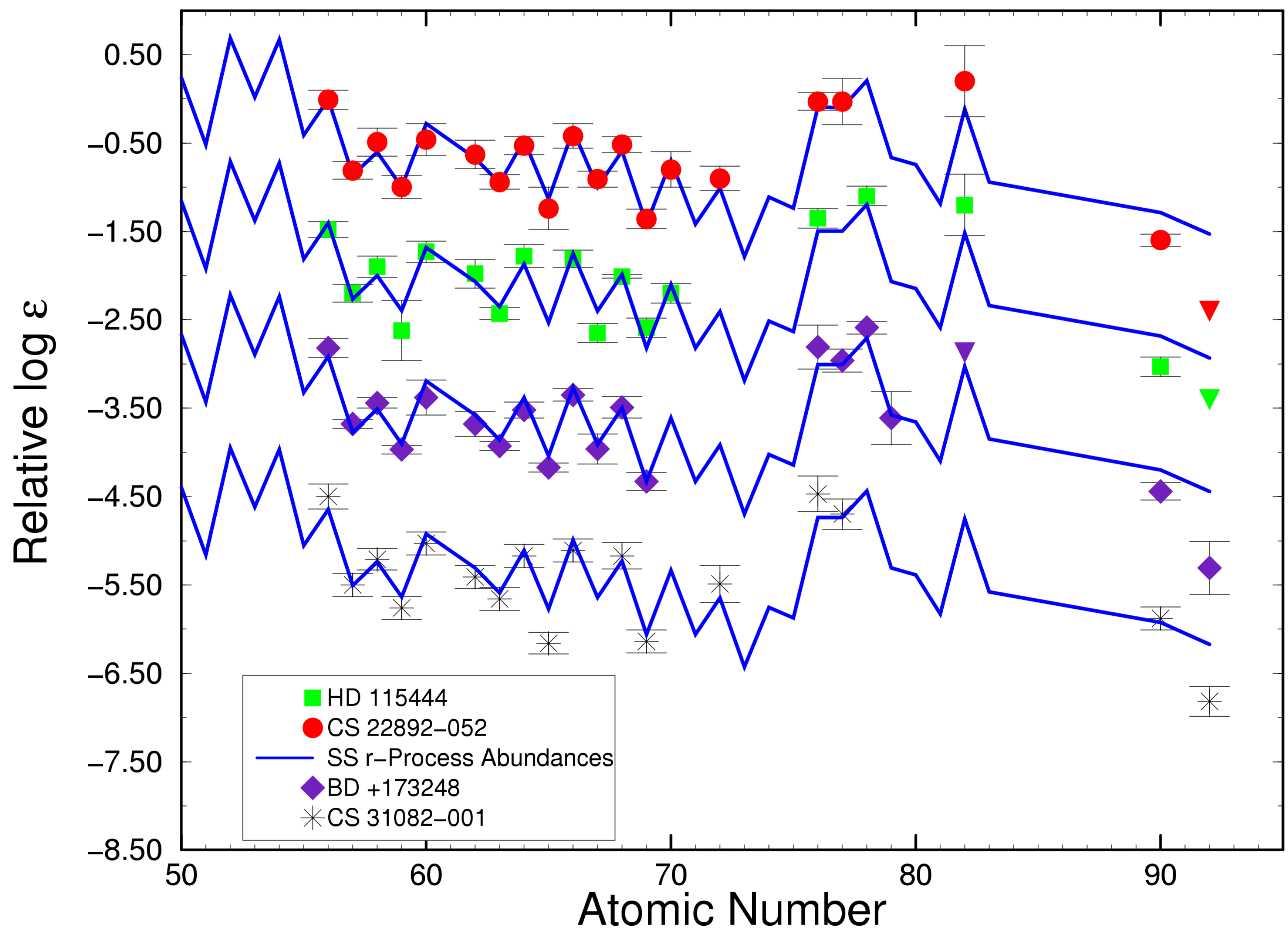


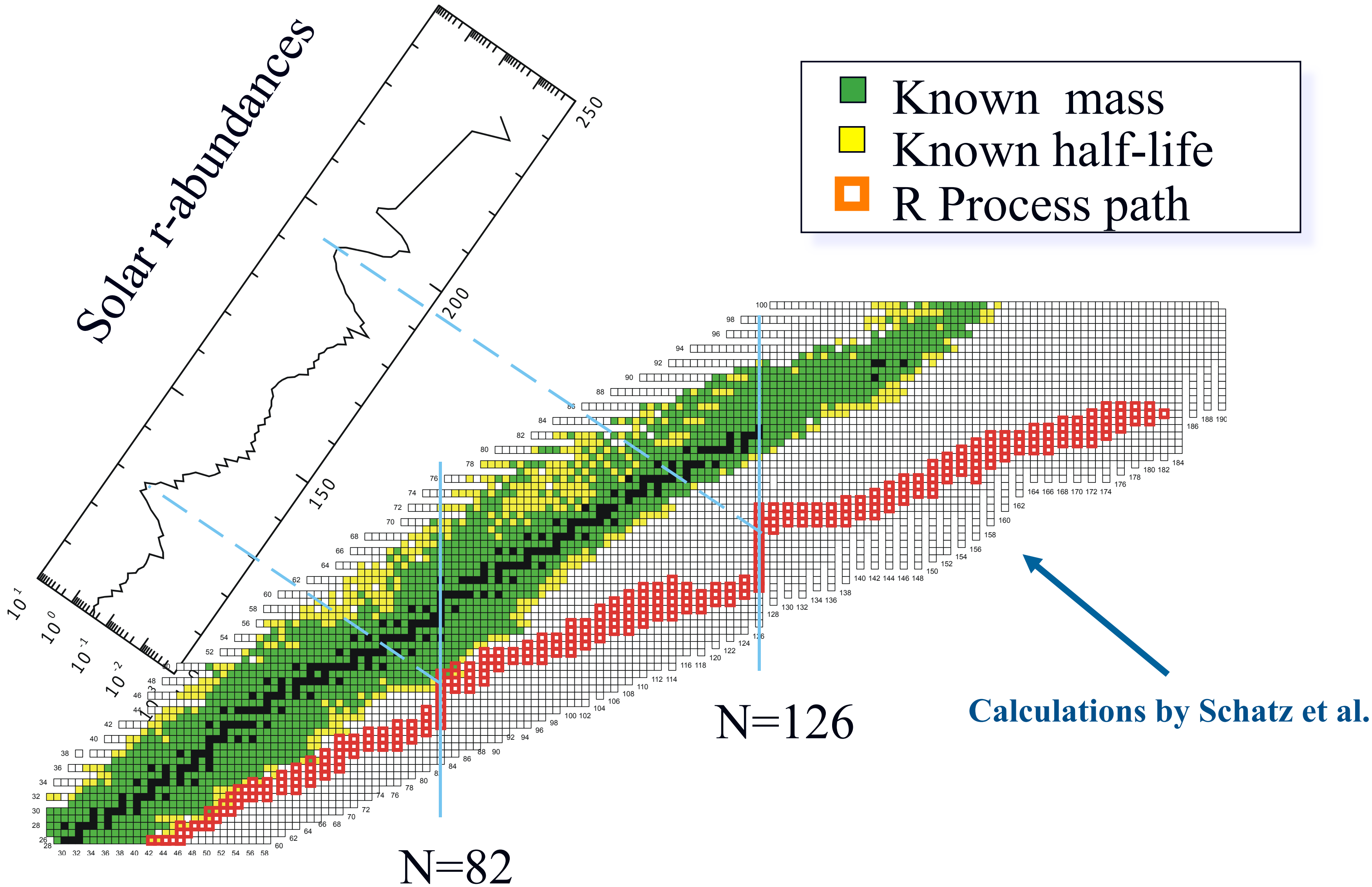
Figure 20. r-Process yields: the distribution of r-only isotopes (full points) and the abundances obtained by subtraction of s-process abundances from solar values (open symbols).

r–Process Abundances in Halo Stars

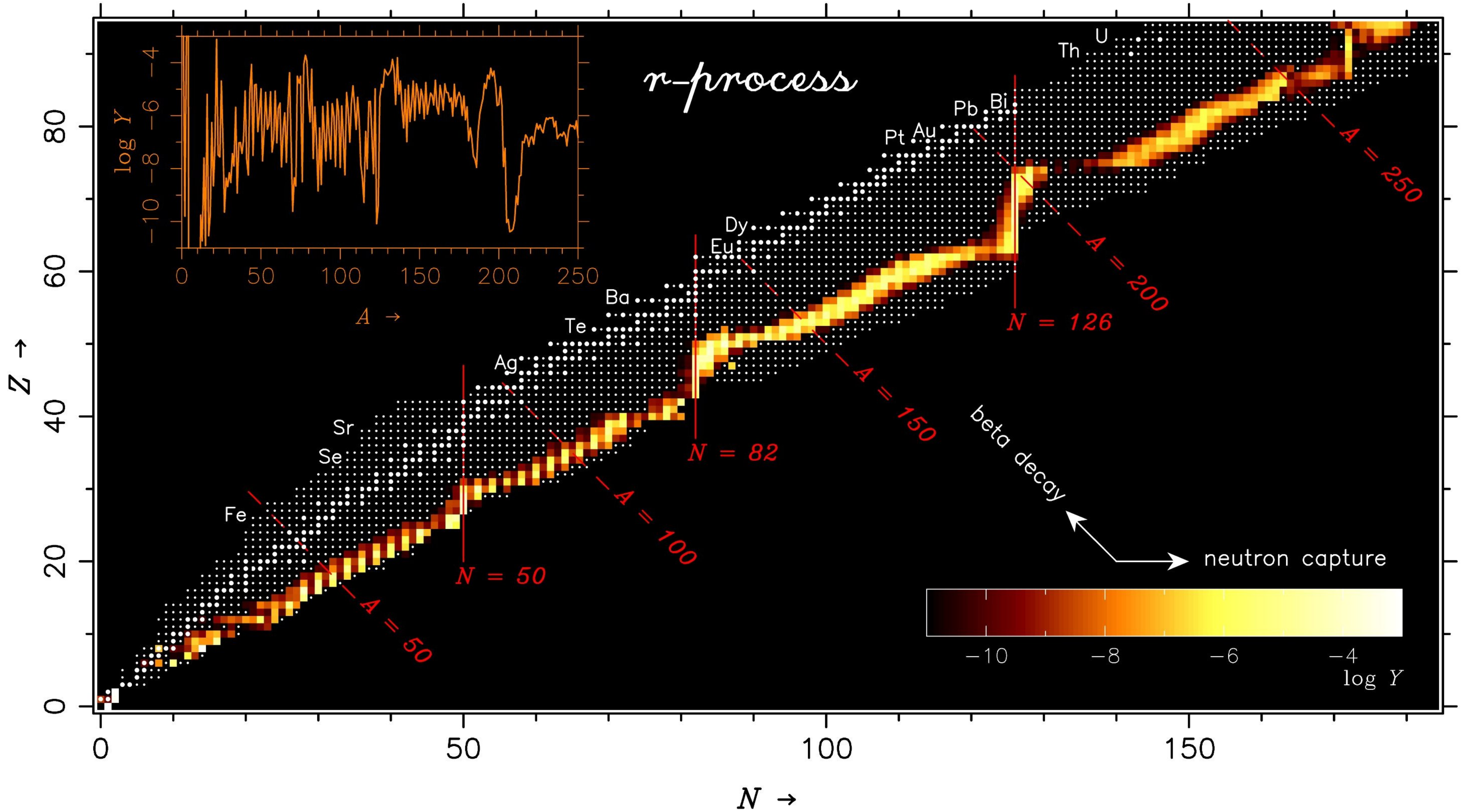


Cowan, Sneden, and Truran

R Process Path



Another Calculation

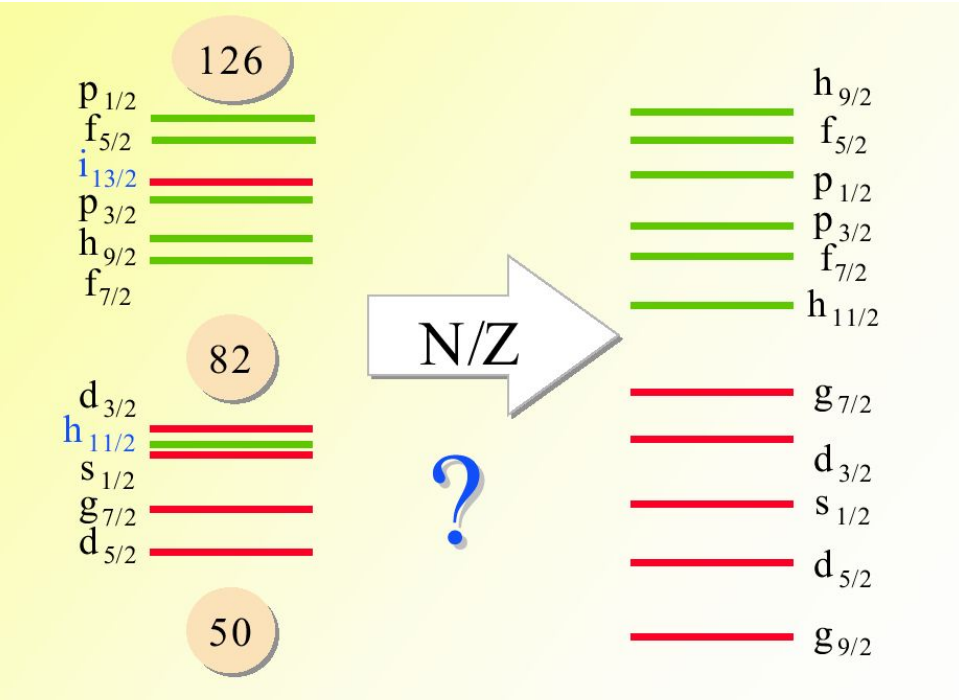


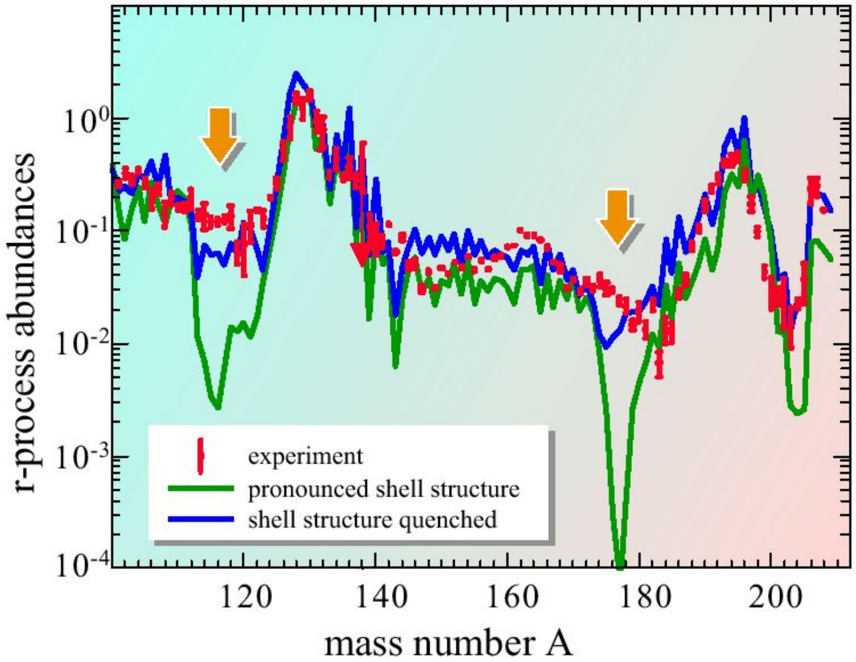
(S. Wanajo calculation)

Shell Structure and the R Process

line of stability

R-Process Nuclei





Nuclear Physics in the R Process

Quantity	Effect
neutron separation energy	• **Path**
β-decay half-lives	• **abundance pattern** • **timescale**
β-delayed neutron emission	• **final abundance pattern**
fission	• **endpoint** • **abundance pattern ?** • **degree of fission cycling**
σ (neutron capture)	• **final abundance pattern (freezeout)**

Effect of Cross Sections on the R Process

Surman, Beun, McLaughlin, and Hix PRC 79, 045809 (2009)

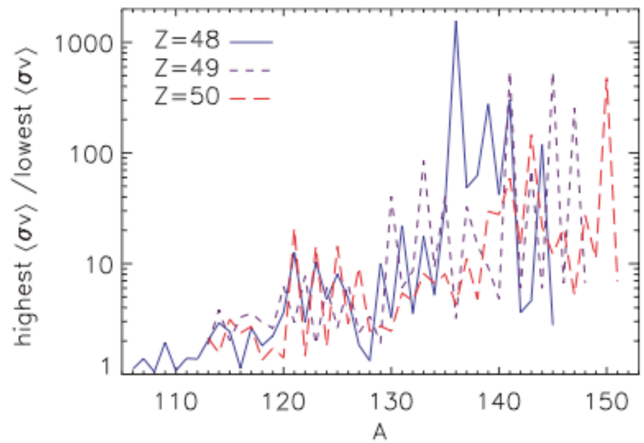


FIG. 1. (Color online) Shows the ratio of the highest neutron capture cross section to the lowest of three sets of neutron capture rates [23–25] at $T_9 = 1$ for isotopes of cadmium (solid line), indium (short dashes), and tin (long dashes).

[23] J. J. Cowan, F.-K. Thielemann, and J. W. Truran, Phys. Rep. **208**, 267 (1991).

[24] S. Goriely (private communication, unpublished, 2000).

[25] T. Rauscher and F.-K. Thielemann, At. Data Nucl. Data Tables **75**, 1 (2000).

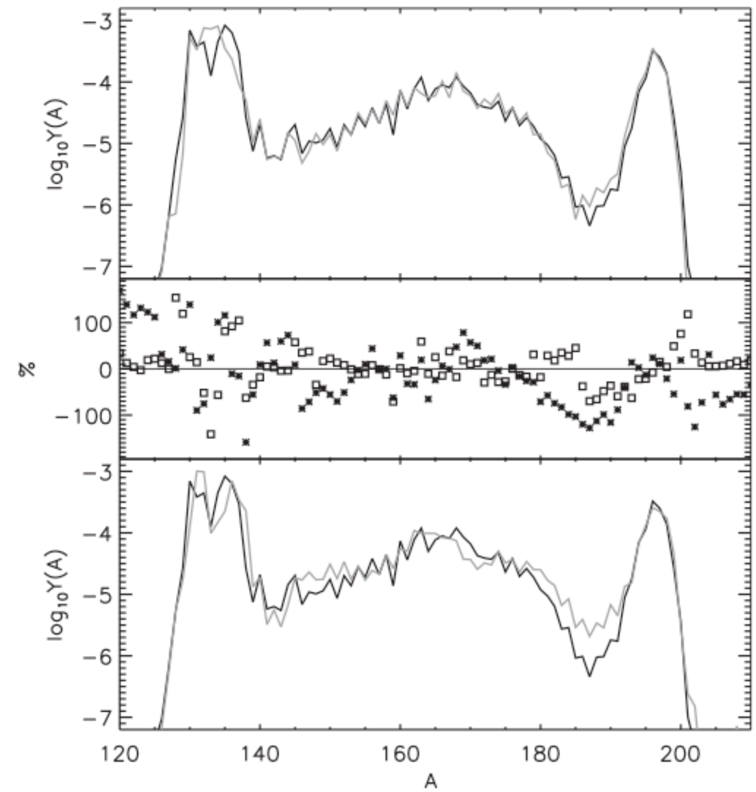
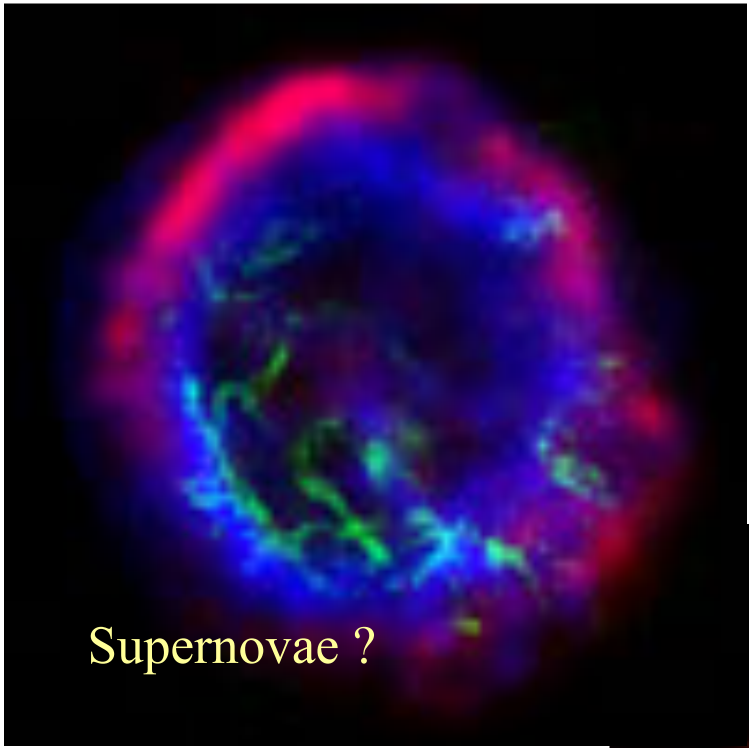
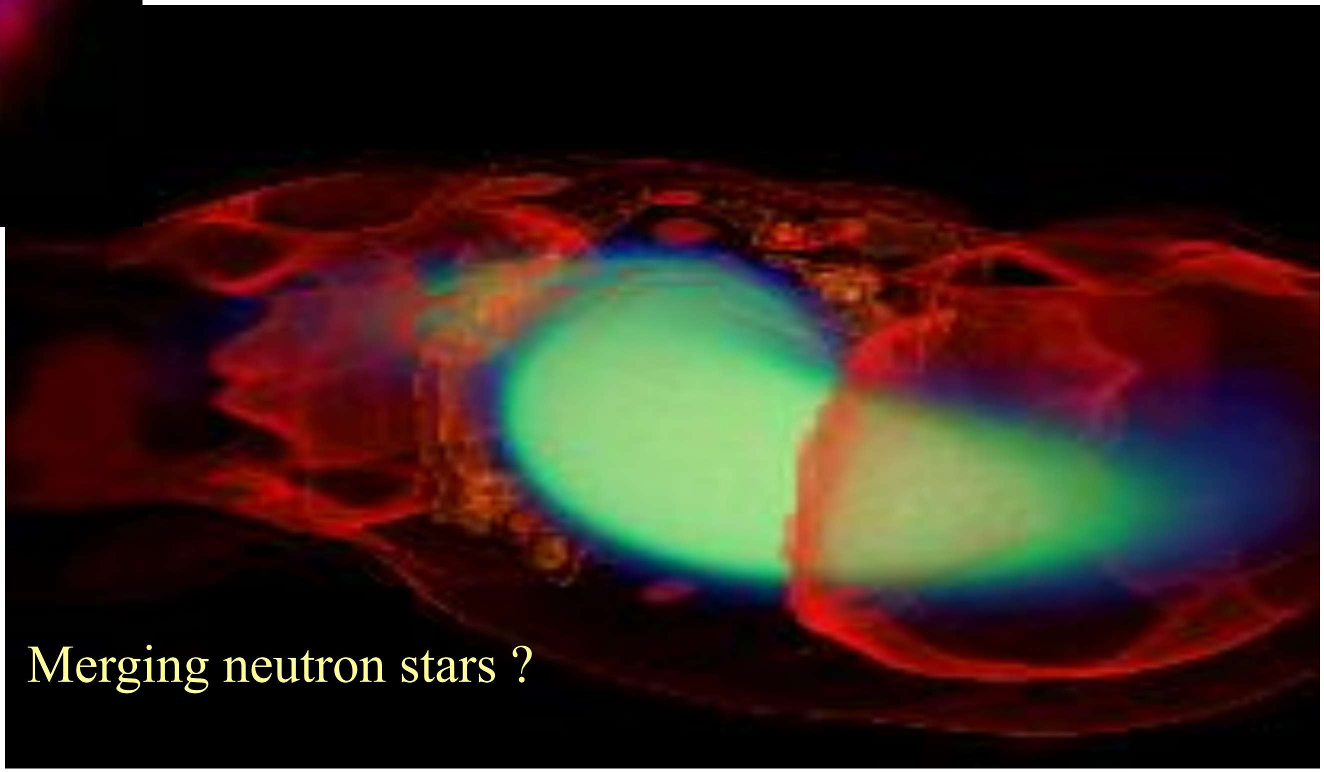


FIG. 2. The bottom panel shows two different abundance patterns that were obtained using the same astrophysical conditions but different mass models. The top panel shows abundance patterns that were obtained using the same mass model but by increasing 50 neutron capture rates in the $A = 130$ peak region by a factor of 100. The middle panel shows the percentage difference in abundance for each point on the curves on the bottom panel (stars) and the top panel (squares).

Approaches to Modeling

- site-independent models
- type-II supernovae
- neutron-star mergers





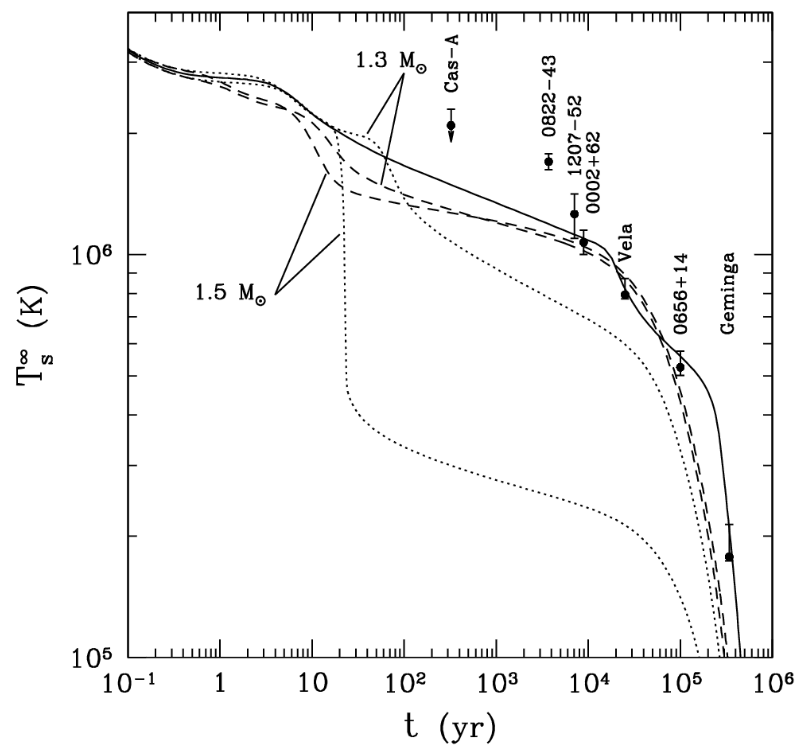
Neutron Stars

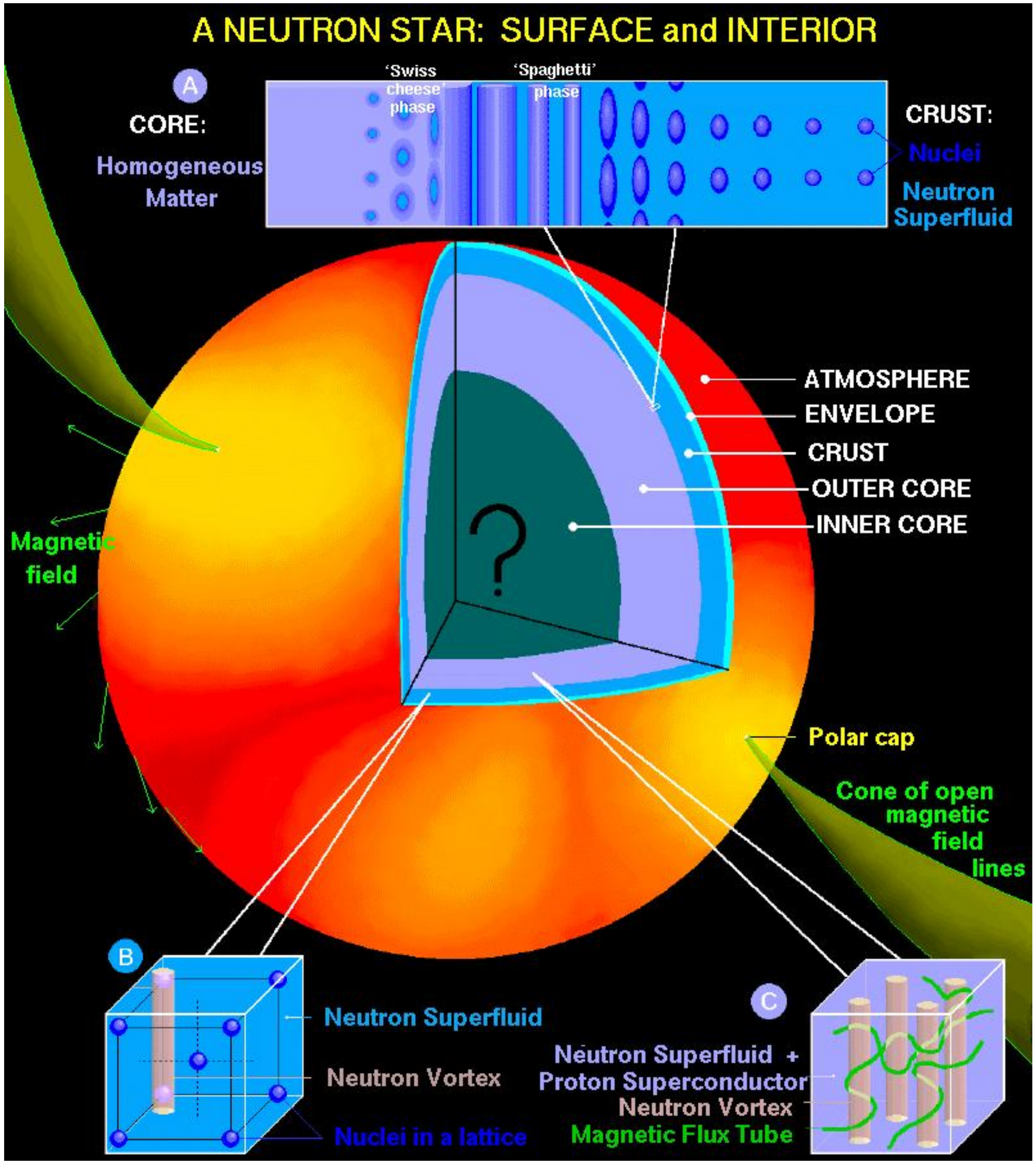
Unique astrophysical laboratories

- Thought to be primarily degenerate neutron matter
- ~ 1 solar mass with several times nuclear density

Two interesting questions:

- The equation of state ?
- Cooling mechanisms ?

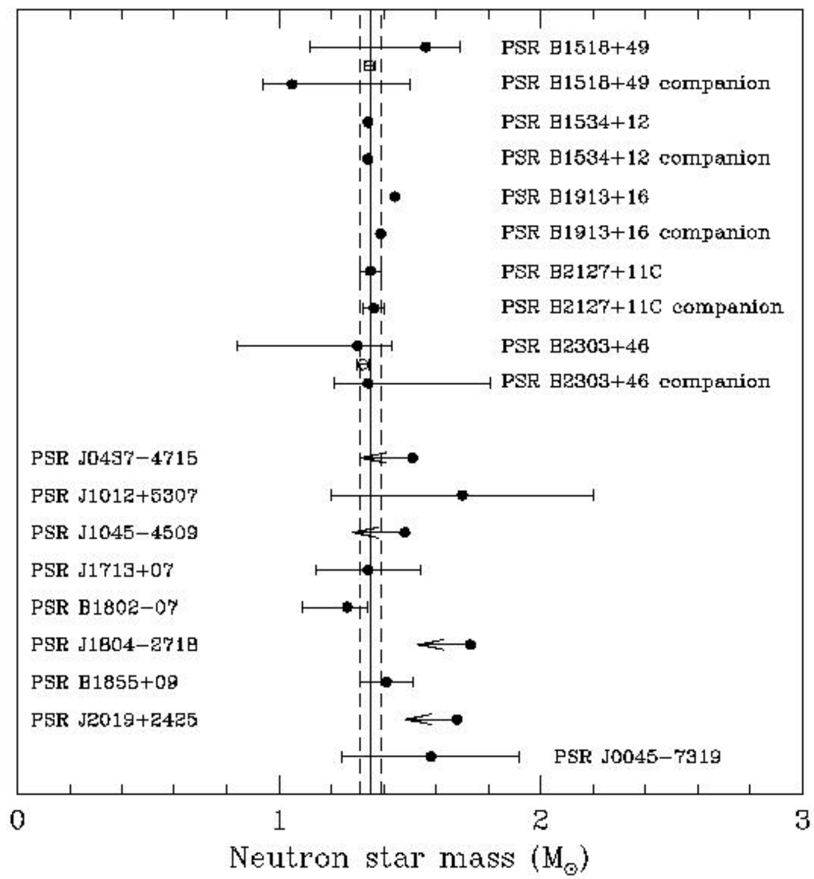



A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous
Matter
'Swiss
cheese'
phase
'Spaghetti'
phase
CRUST:
Nuclei
Neutron
Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic
field
Polar cap
Cone of open
magnetic
field
lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid +
Proton Superconductor
Neutron Vortex
Magnetic Flux Tube

(D. Page)

Neutron Star Masses and Radii

- The nuclear equation of state defines the radius for a given mass
- Radius measurements are expected in the future
- For now we have beautiful mass measurements:



Facilities

- **Radioactive ion beams**
  - **NSCL/FRIB, Argonne, TRIUMF,…**
  - **Cross section measurements**
  - **Masses**
  - **Decay properties**
  - **Transfer reactions**
  - **Spectroscopy**
- **Stable beams**
  - **University laboratories**
  - **Underground (LUNA, CASPAR)**
- **Neutron beams**
  - **S process (LANSCE,…)**
- **Wide range of experimental techniques**
  - **Low statistics RIB measurements**
  - **Precision measurements for solar neutrinos, BBN, or S process**

Summary

- **This brings us to the end of my lectures**
- **We have touched on**
  - **Overview and Reaction Rates**
  - **Big-Bang Nucleosynthesis**
  - **Stellar Evolution (particularly helium burning)**
  - **Explosive Nucleosynthesis**
  - **S-Process**
  - **R-process**
  - **Neutron Stars**
- **Thanks for listening!**