The Synergy between Nuclear Physics and Astrophysics

A.B. Balantekin

University of Wisconsin &

東北大学 大学院理学研究科 物理学専攻

Currently there is a revolution going on in astrophysics and cosmology!

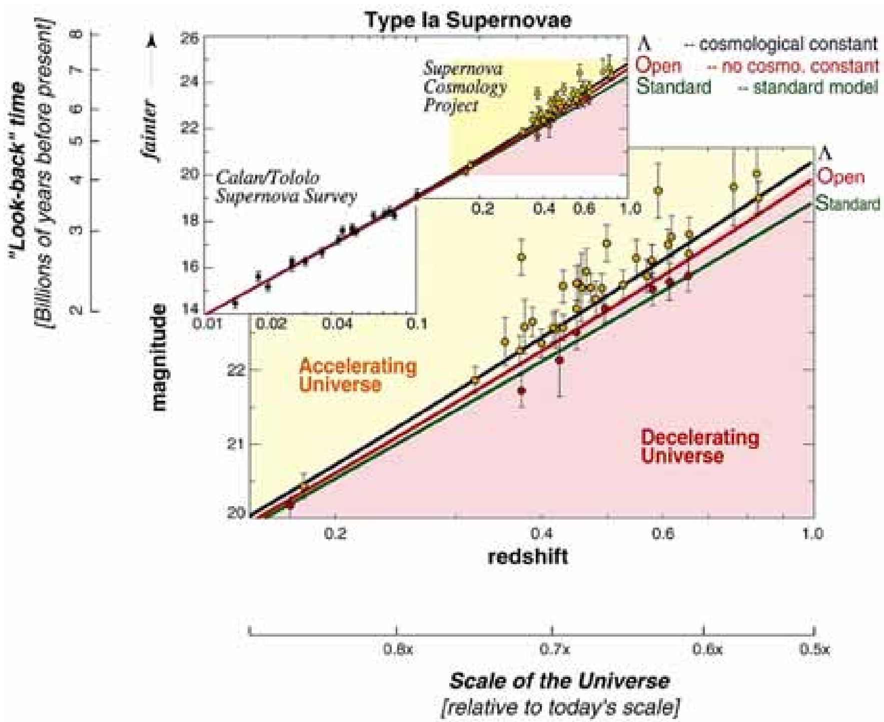
Until the 20th century astronomy was traditionally concentrated on phenomena where the microphysics was atomic and molecular physics.

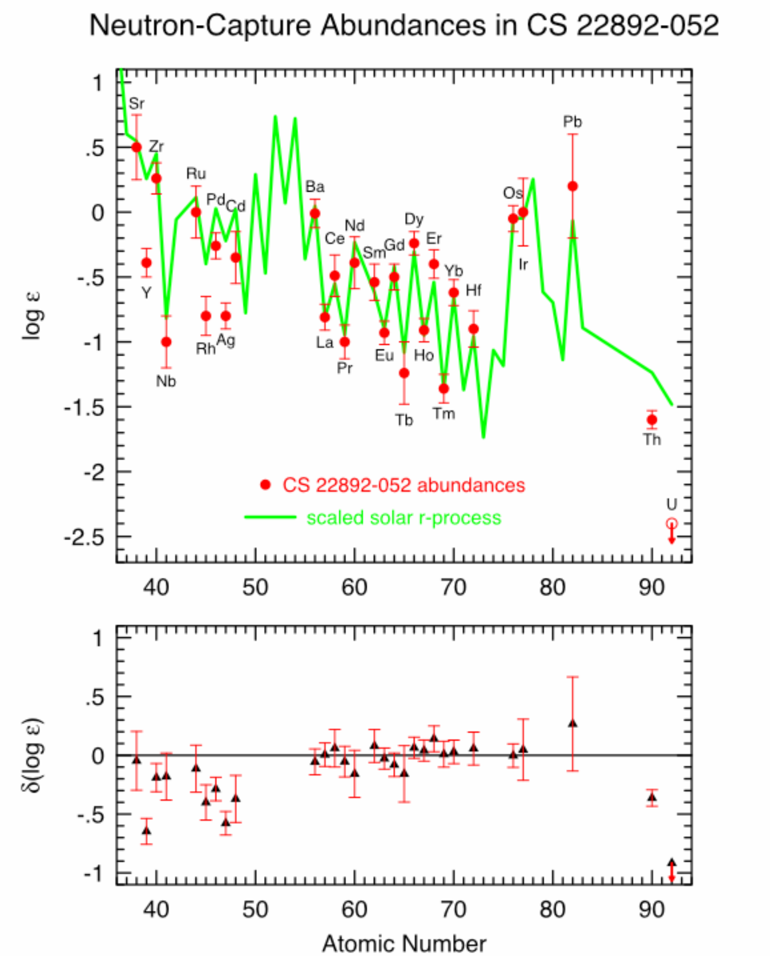
This approach was very successful. For example helium was discovered for the first time at the solar spectra by examining absorption lines.

In 20th century we started looking up at the heavens using probes well-beyond the near-visible light spectrum. For example using radar-based technology we discovered pulsars.

Today a revolution is going on…….

Powerful Earth-based telescopes:

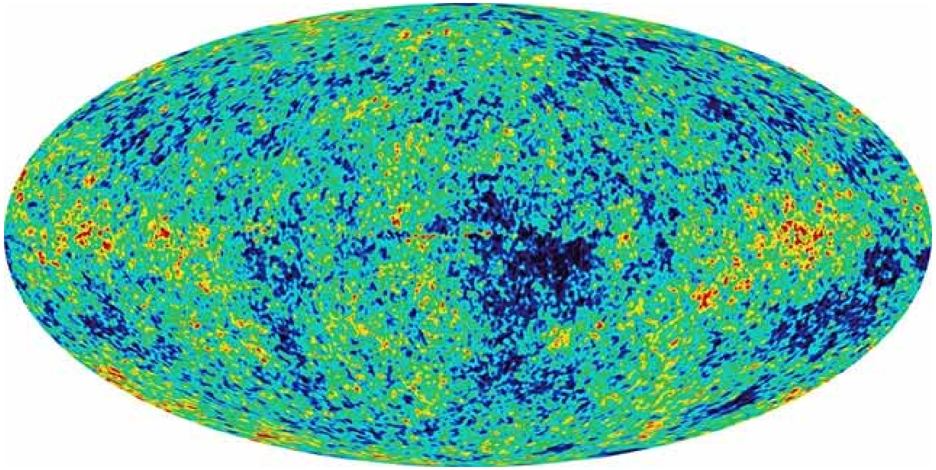




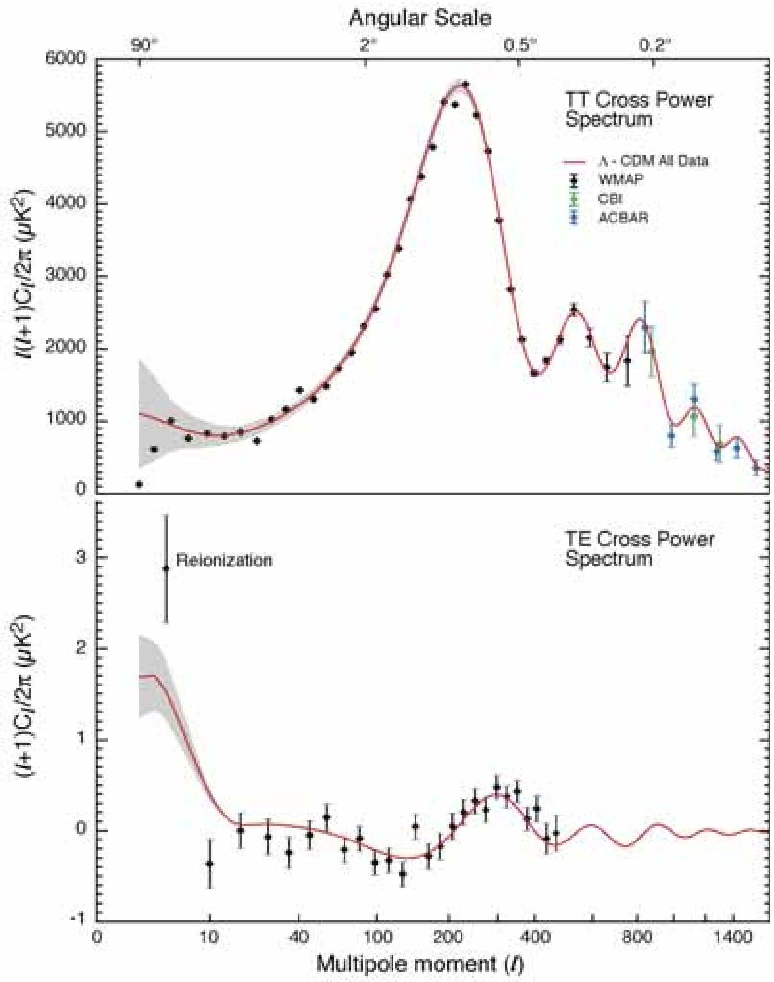
Today a revolution is going on.......

Satellite-based observations:

WMAP results:

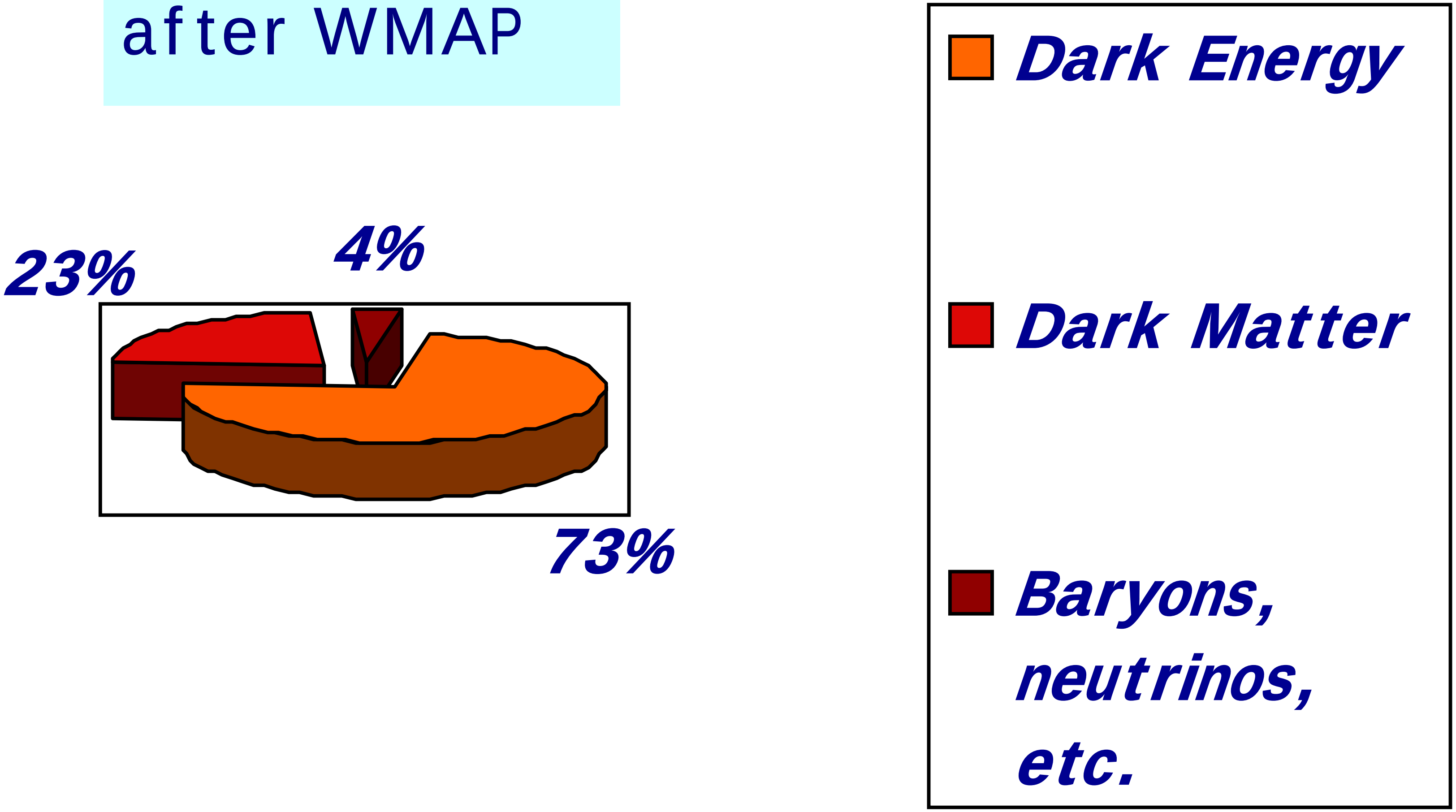


Dark Blue = -200 μK   Red = +200 μK



WMAP

Universe today after WMAP

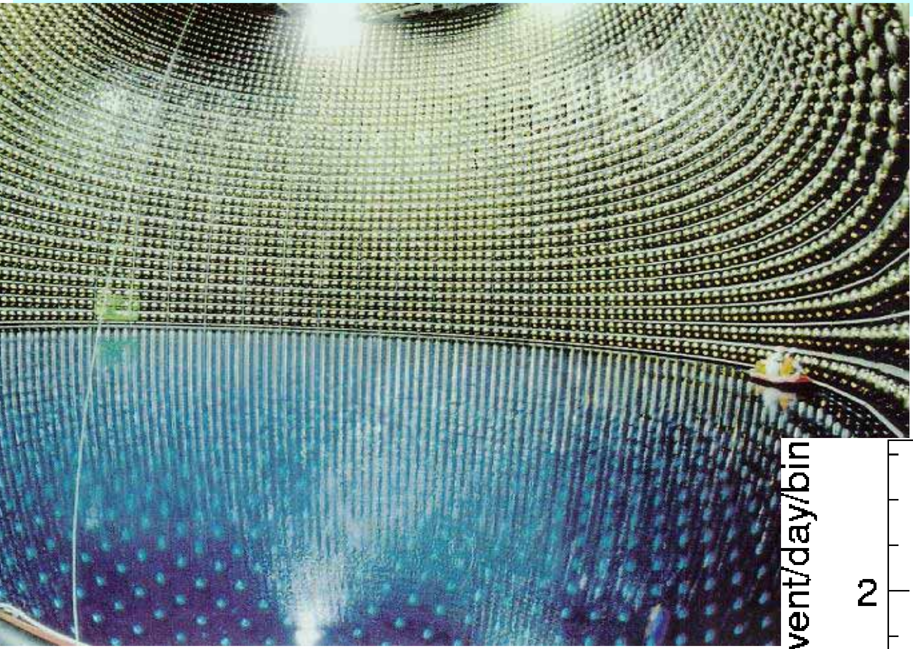


The new view of the universe - the
Earth is not only the center of the Universe

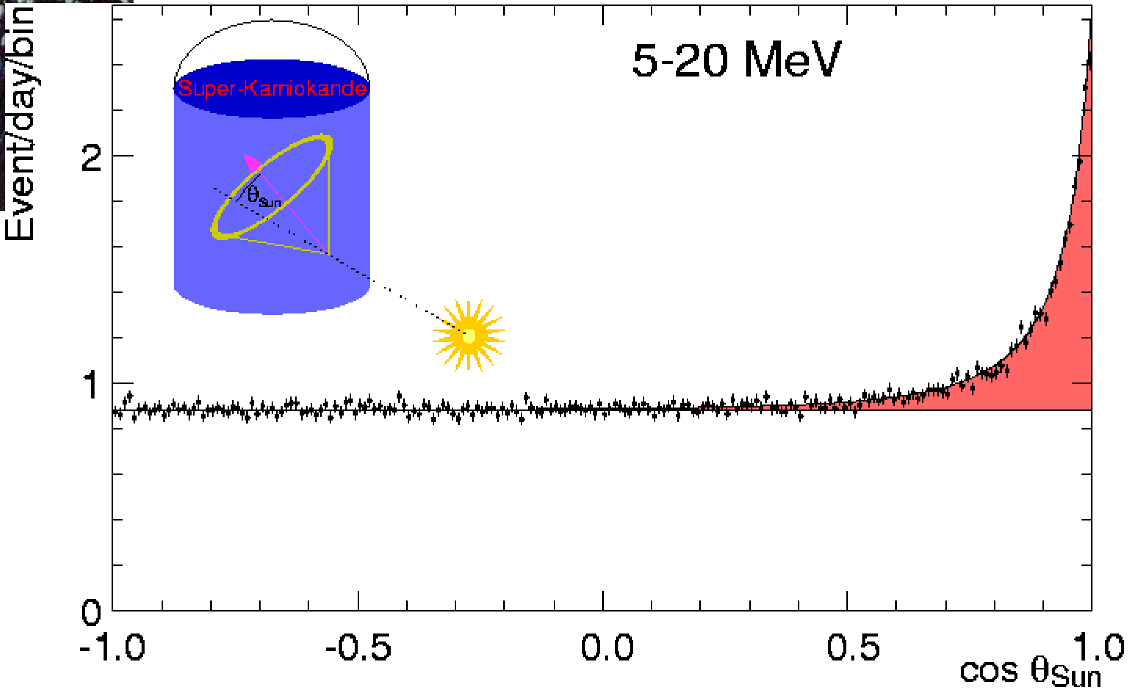
... it is even unlike most of the rest of the Universe -
which is dark matter (30%) and dark energy (66%)

Today a revolution is going on.......

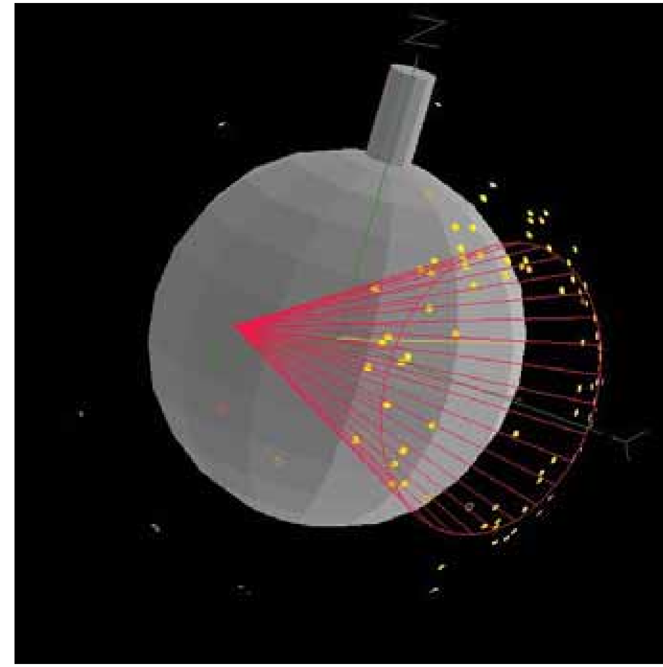
Looking at the Sun with neutrino observatories:

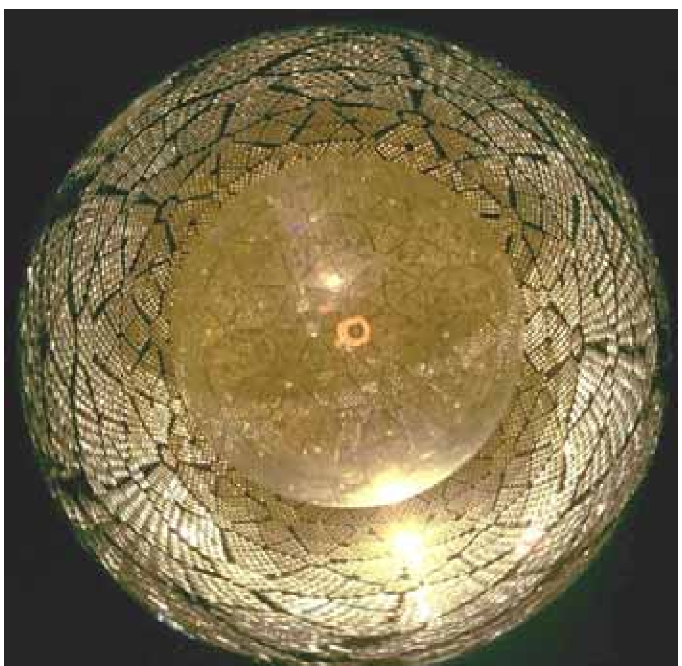


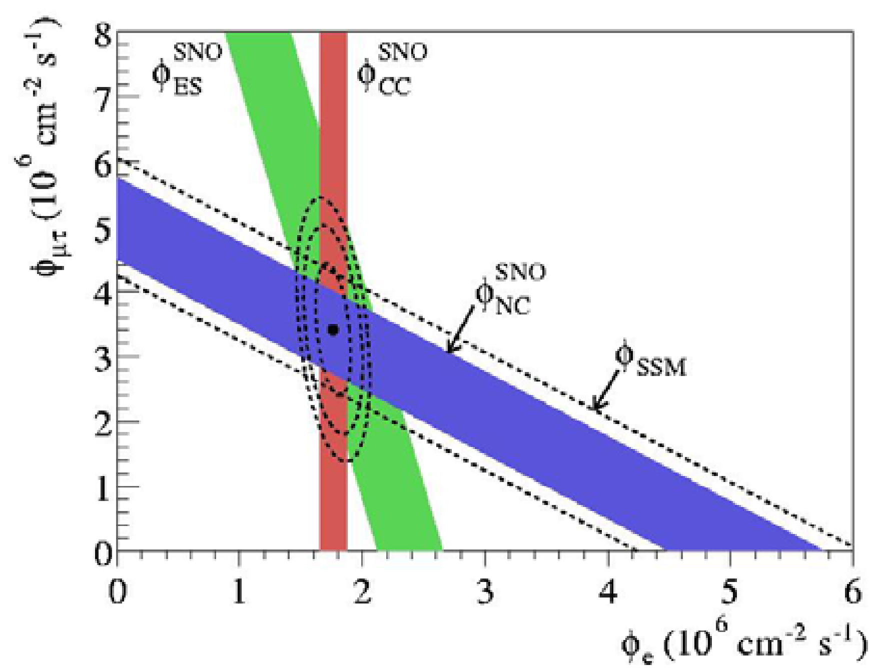
SuperKamiokande



Sudbury Neutrino Observatory







This new astrophysics and cosmology is looking at phenomena where the microphysics is markedly different from that of traditional astronomy. This microphysics is controlled by nuclear and particle physics!

The very high precision of these abundant data require:

- A much better (and more precise) understanding of the underlying nuclear physics.
- Understanding nuclear physics in entirely new environments, e.g. dense media and very high electromagnetic fields.

Nuclear physics is indispensable in understanding the Universe!

Two examples:

1. Screening of nuclear reactions (both in the laboratory and the stars).

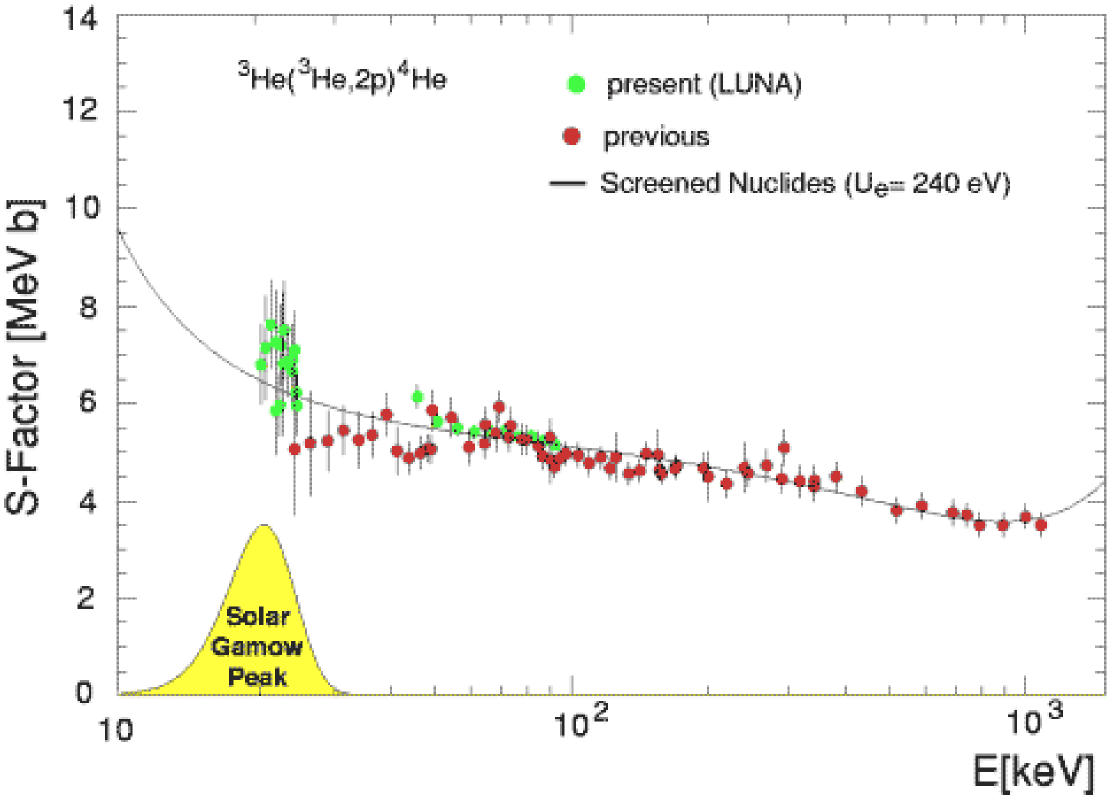
2. Neutrino-induced fission in dense media (e.g. core-collapse supernovae).

Fusion in astrophysical settings

Key issues:

- Stellar Screening
- Laboratory Screening

  Adelberger, et al. 1998



Laboratory Electron Screening

- Adiabatic approximation: Constant energy shift to the Coulomb potential.

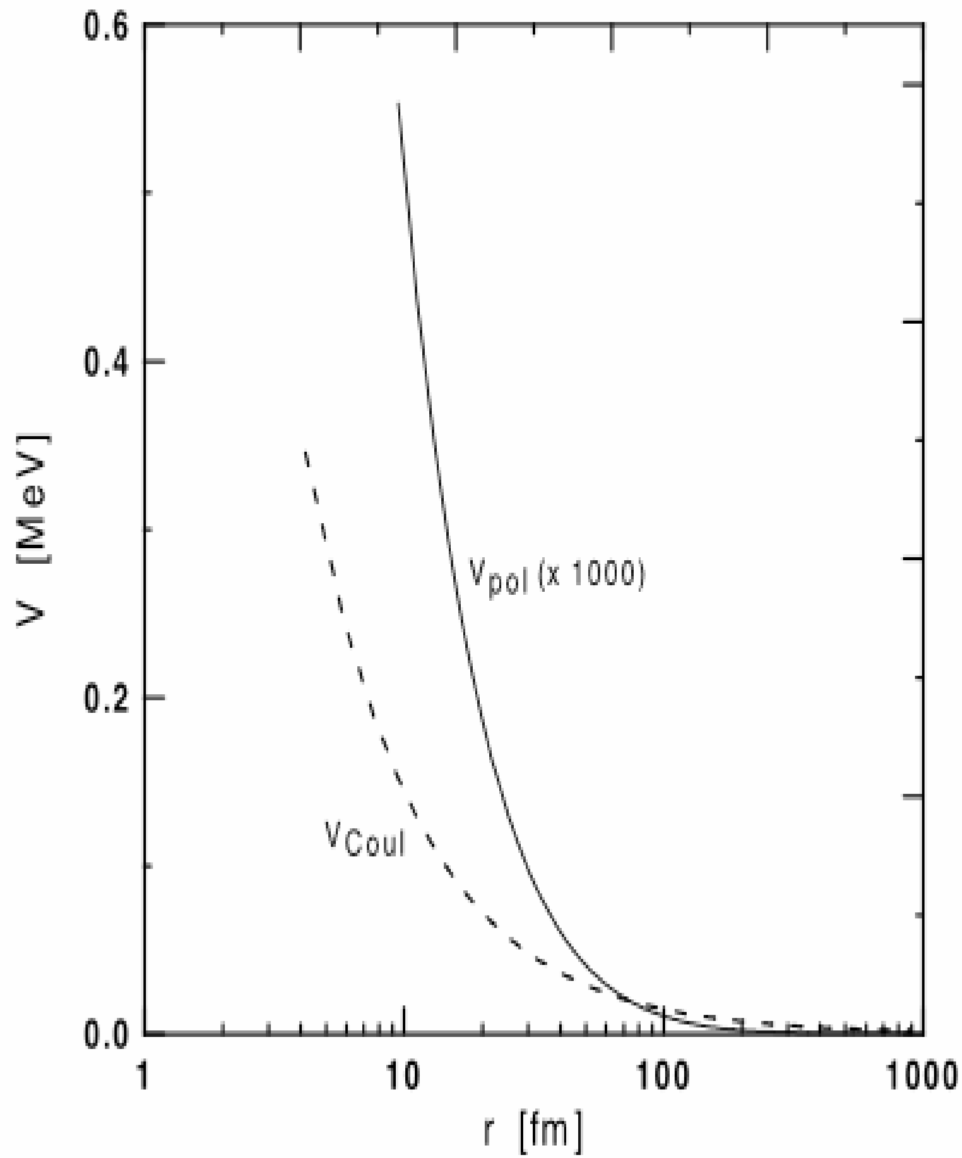
  Langanke et al.

- Data requires even larger shifts.
- Puzzle: Adiabatic approximation typically overpredicts. ($\rightarrow$ excluded physics?)

Laboratory screening

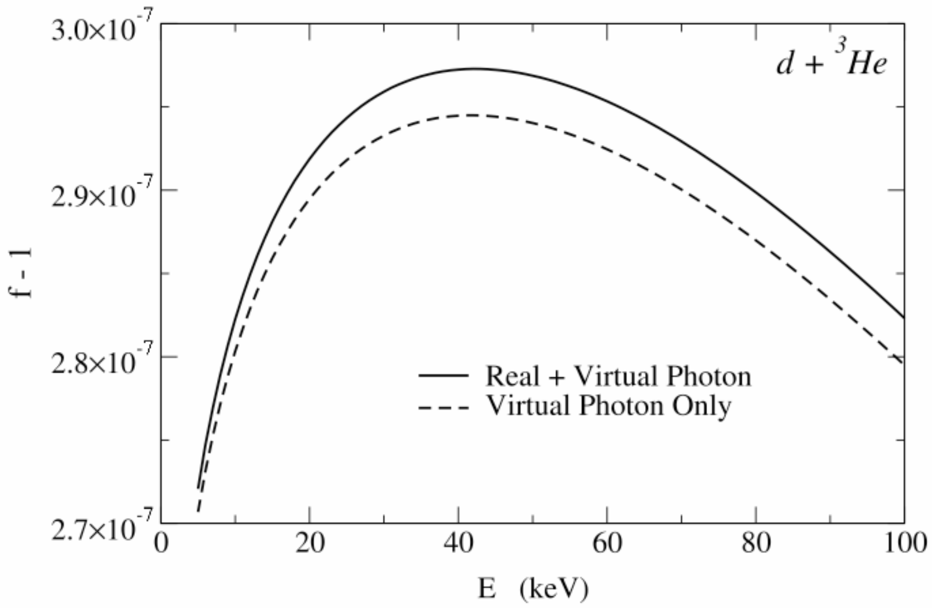
Other Effects (vacuum polarization,relativity, Bremsstrahlung and atomic polarization) are very small.

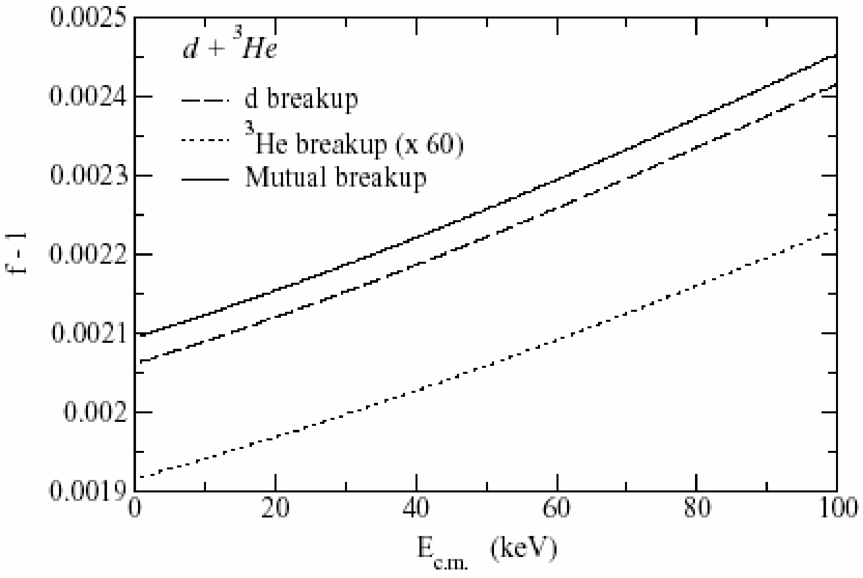
Balantekin, Bertulani, Hussein, 1997

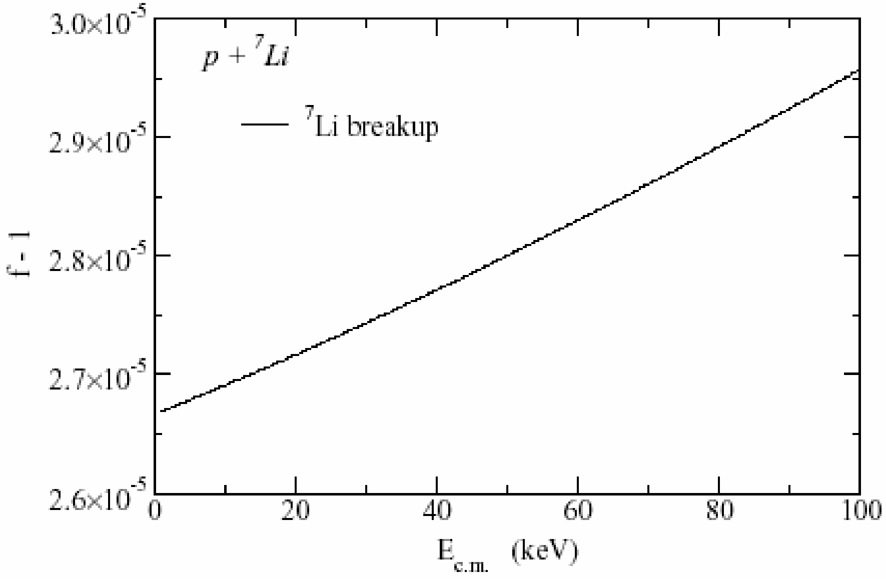


Electromagnetic Effects in Tunneling

- Suggestion: Virtual photon emission during tunneling may increase probability Flambaum and Zelevinsky, 1999
- Radiation field can be eliminated using the path integral formalism. Enhancement is extremely small.⇒ Discrepancy in screening is still a puzzle Hagino and Balantekin, 2002.



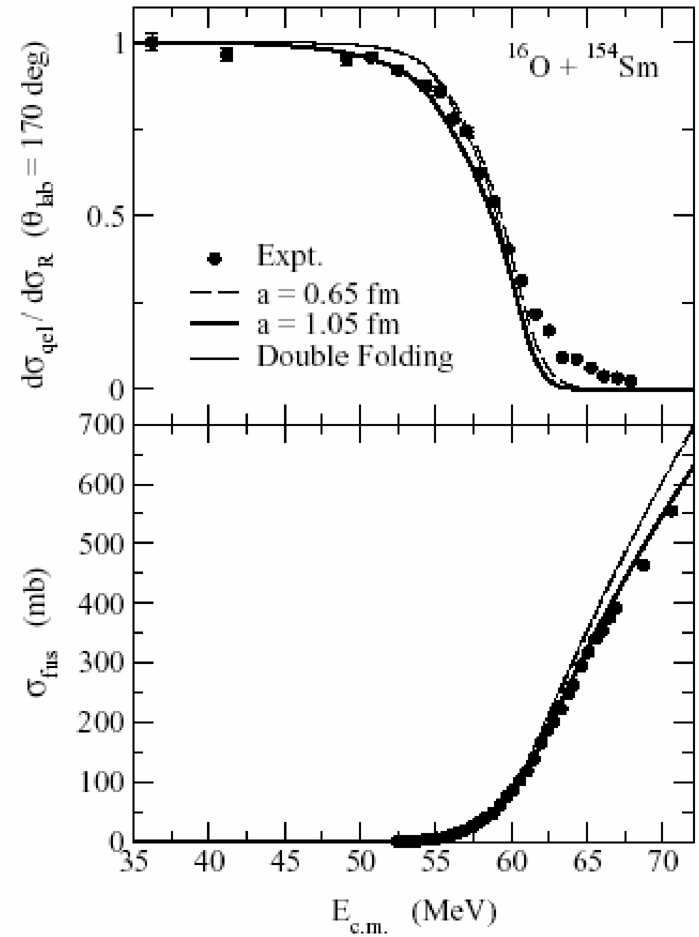




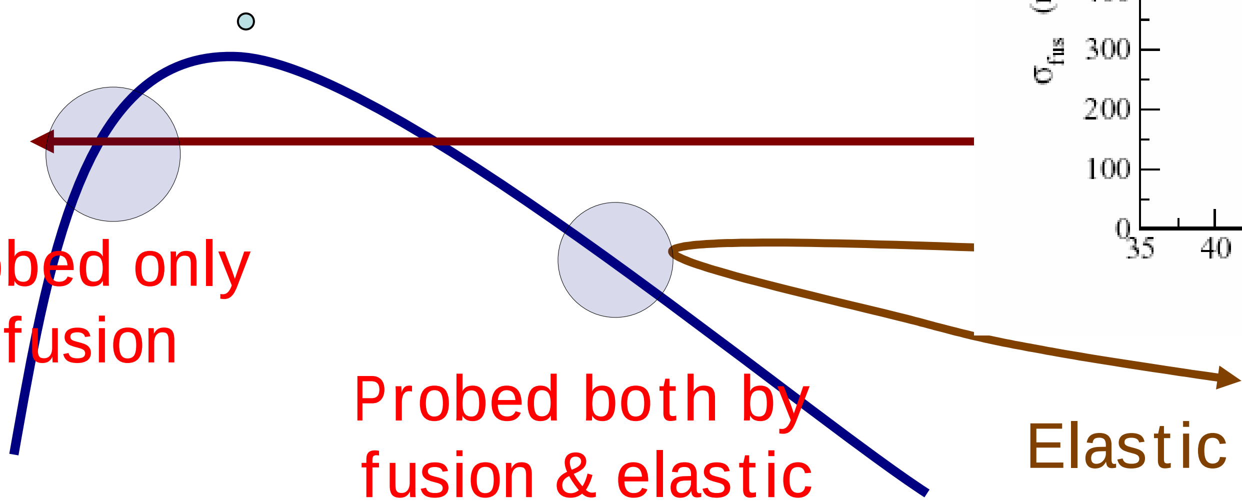
Enhancement of the probability due to deuteron breakup is also too small

Hagino, Hussein, Balantekin, 2003

Hagino, Takehi, Balantekin, and Takigawa; nucl-th/0412044



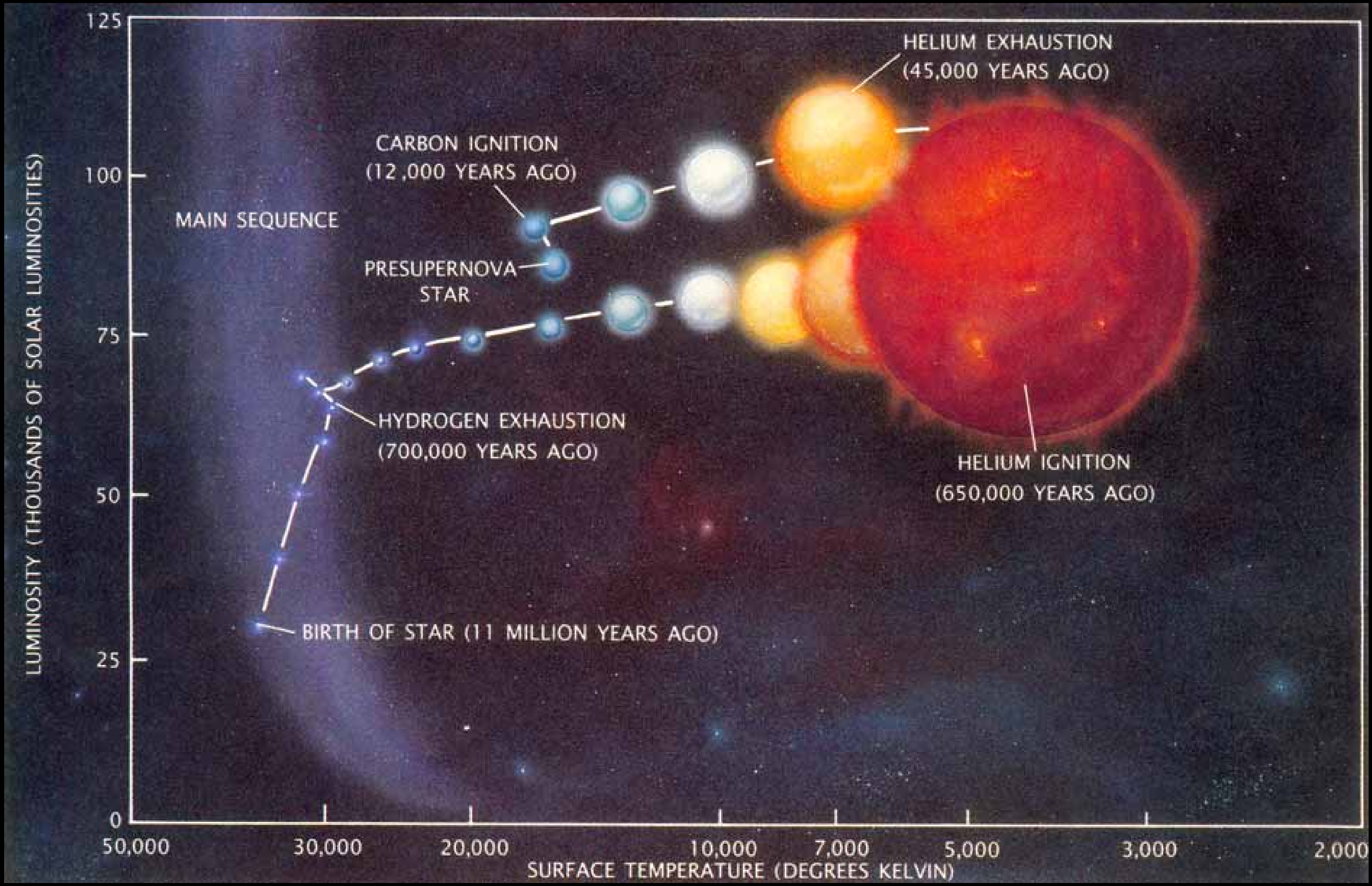
Fusion



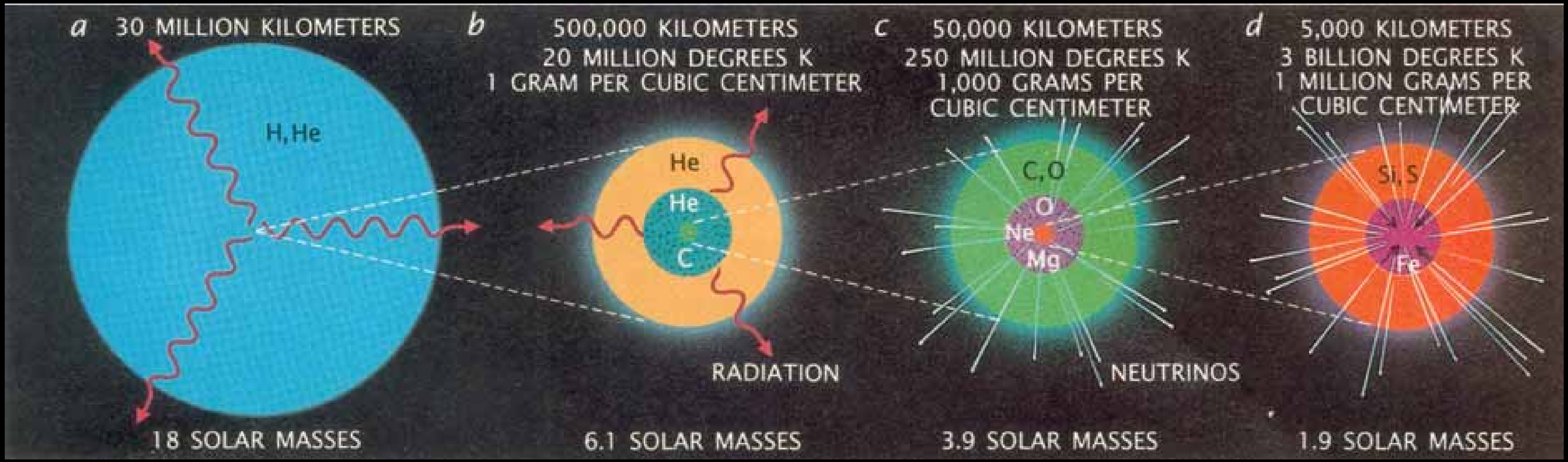
Probed only by fusion

Probed both by fusion & elastic scattering

Elastic scattering



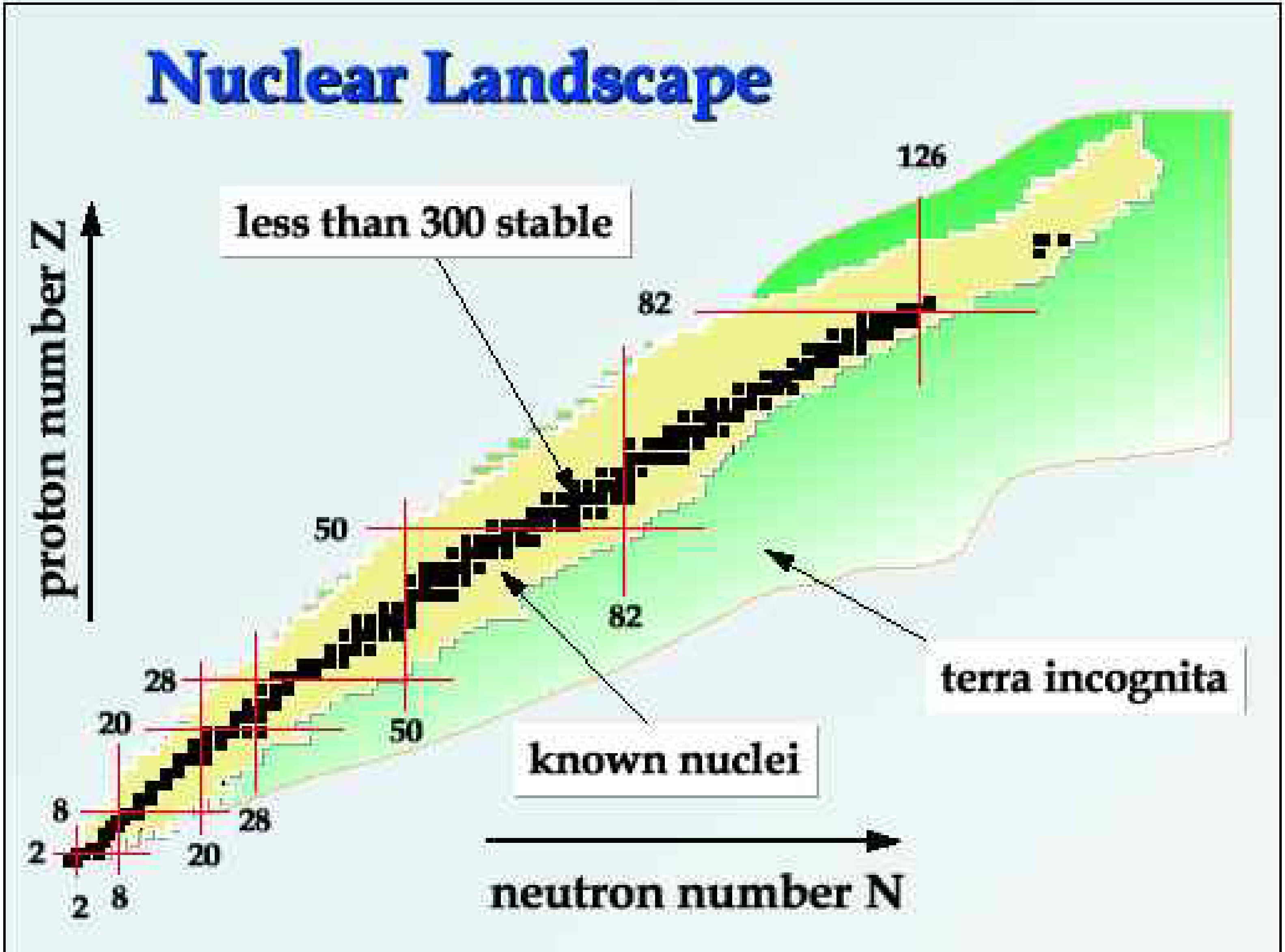
Weaver & Woosley, ***Sci Am***, **1987**



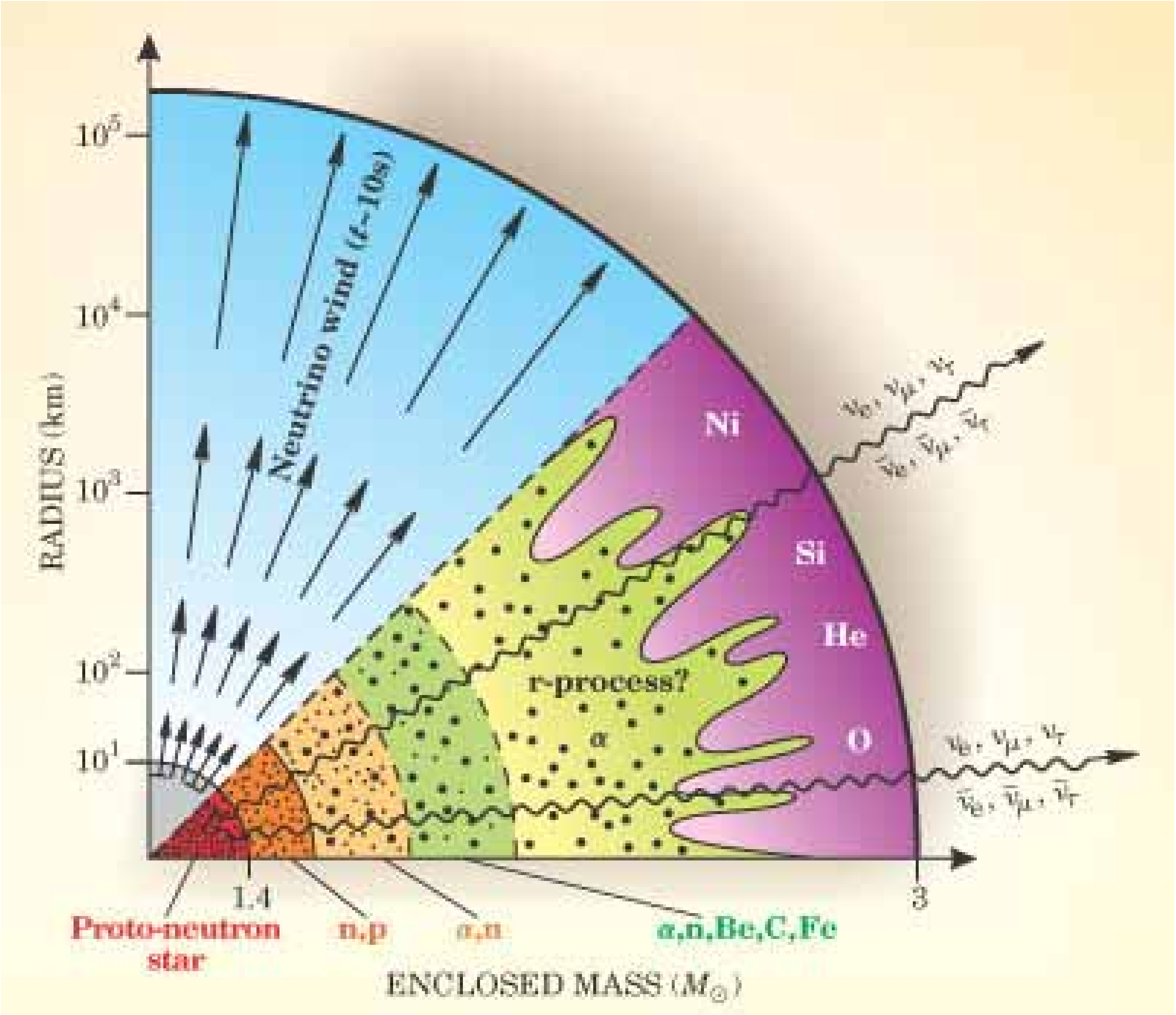
Weaver & Woosley, ***Sci Am***, **1987**

Neutrinos from core-collapse supernovae

- $M_{prog} \geq 8\ M_{Sun}$
- $\Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV
- 99% of the energy is carried away by neutrinos and antineutrinos with $10 \leq E_{\nu} \leq 30$ MeV
- 10^{59} Neutrinos!



Nuclear Landscape
proton number Z
neutron number N
less than 300 stable
known nuclei
terra incognita
126
82
82
50
50
28
28
20
20
8
8
2
2

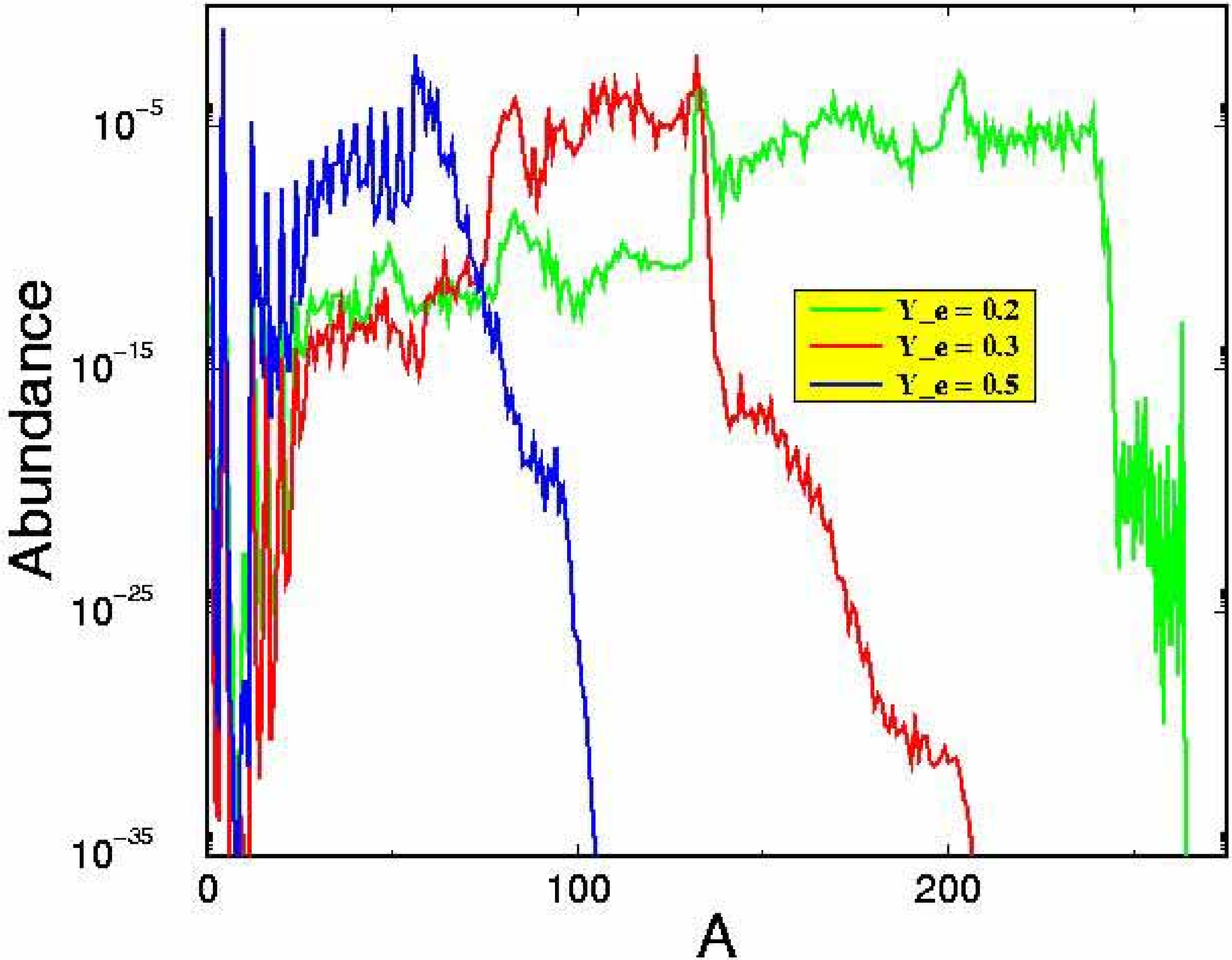


RADIUS (km)
10⁵
10⁴
10³
10²
10¹
Neutrino wind (t~10s)
Ni
Si
He
O
r-process?
α
ν_e, ν_μ, ν_τ
$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
ν_e, ν_μ, ν_τ
$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
1.4
3
Proto-neutron star
n,p
α,n
α,n,Be,C,Fe
ENCLOSED MASS ($M_\odot$)

Janka

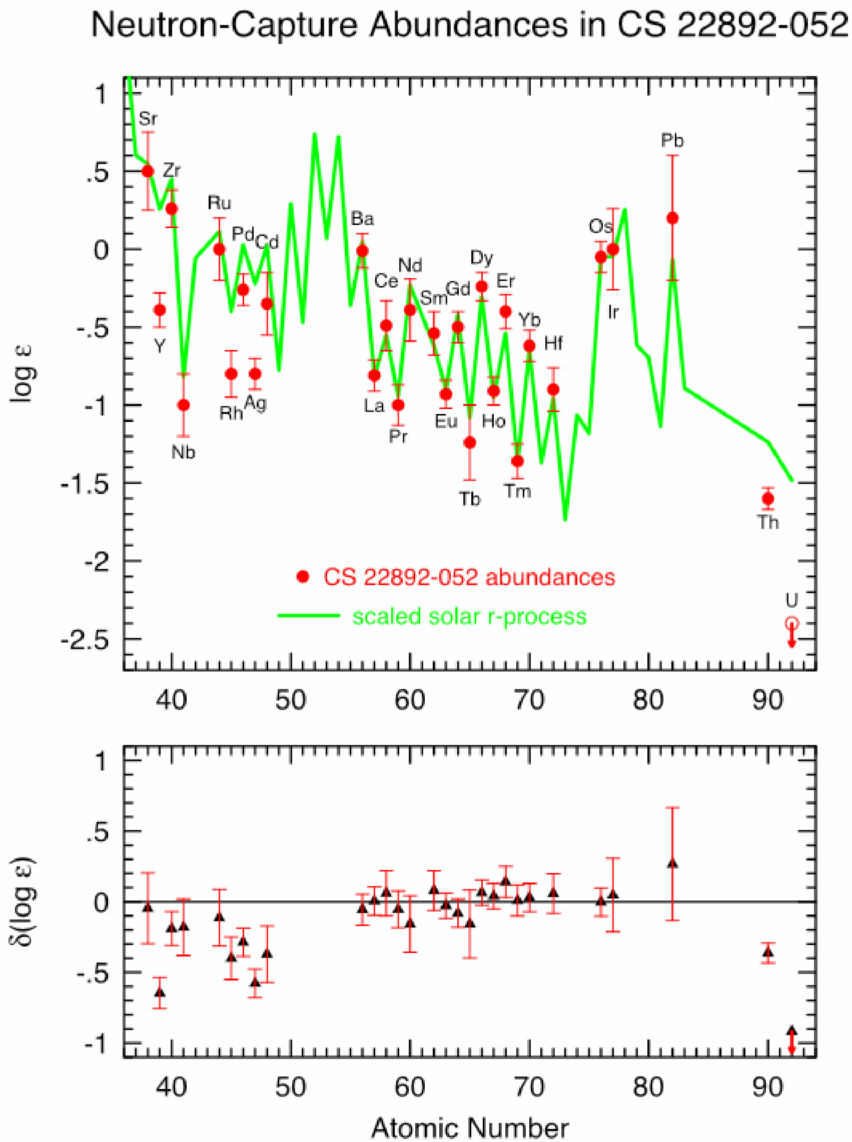
r–Process Abundances

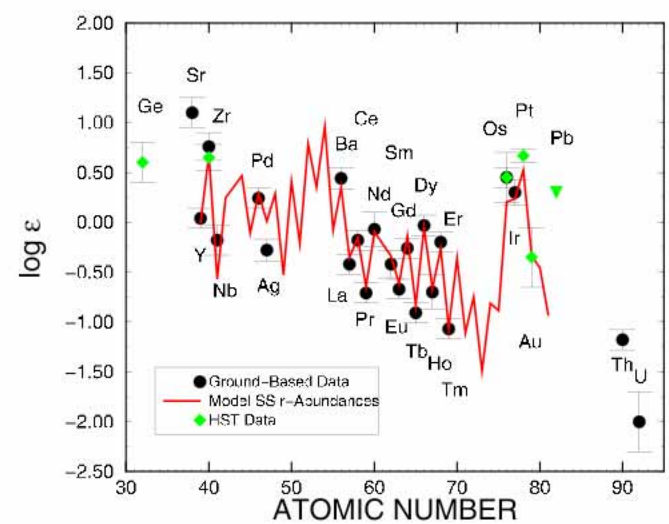
Dependence on the Electron–fraction



Meyer

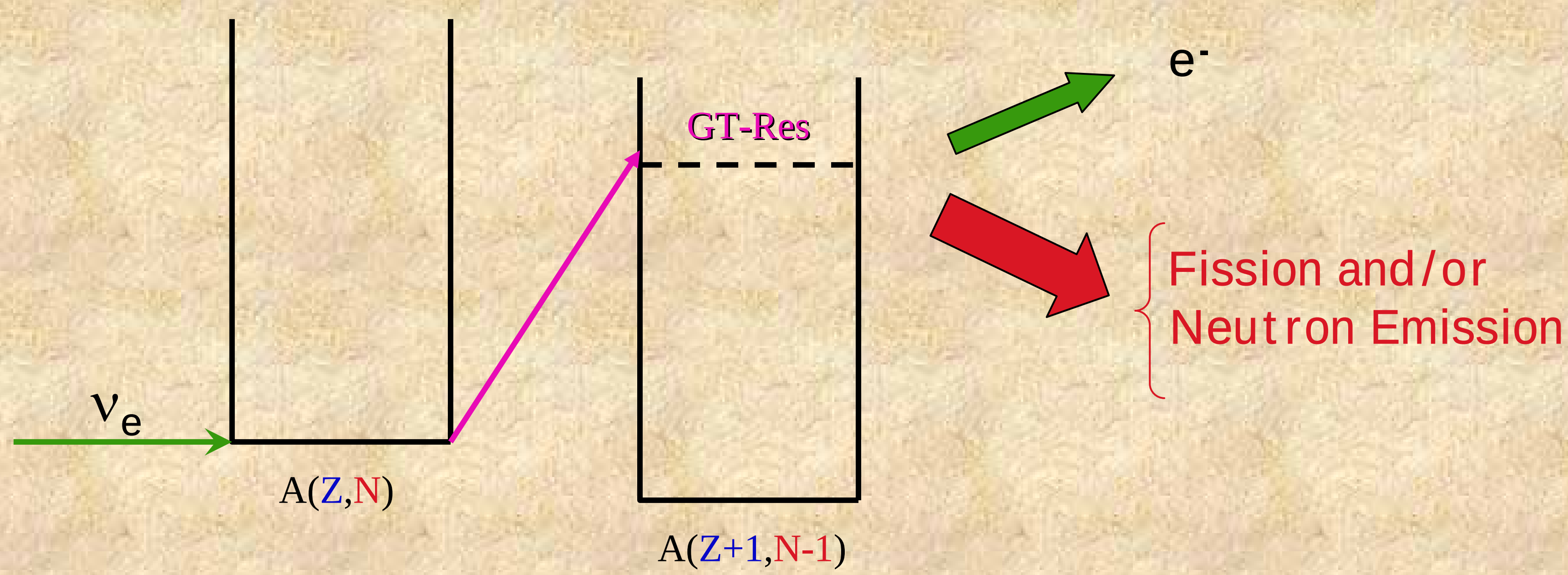
Observed r-process abundances





neutrino capture-induced fission/neutron emission

Y.-Z. Qian, ApJ 519 L103 (2002);
E. Kolbe, K. Langanke, G. M. Fuller astro-ph/0308350.



Take advantage of "nuclear coherence,"
i.e., collective Gamow-Teller and forbidden modes

$\sigma \sim 10^{-38}\,\mathrm{cm}^2$

Neutrino-induced fission in dense media

Balantekin, Hagino, Takigawa

ν-induced fission at late times in a core-collapse supernova may be very important in understanding the abundances of heavy elements.

$$\nu_e + U \rightarrow A + A' + e^- \quad \text{or} \quad \nu_x + U \rightarrow A + A' + \nu_x$$

Question: How does a nucleus fission inside a medium with high temperature and density?