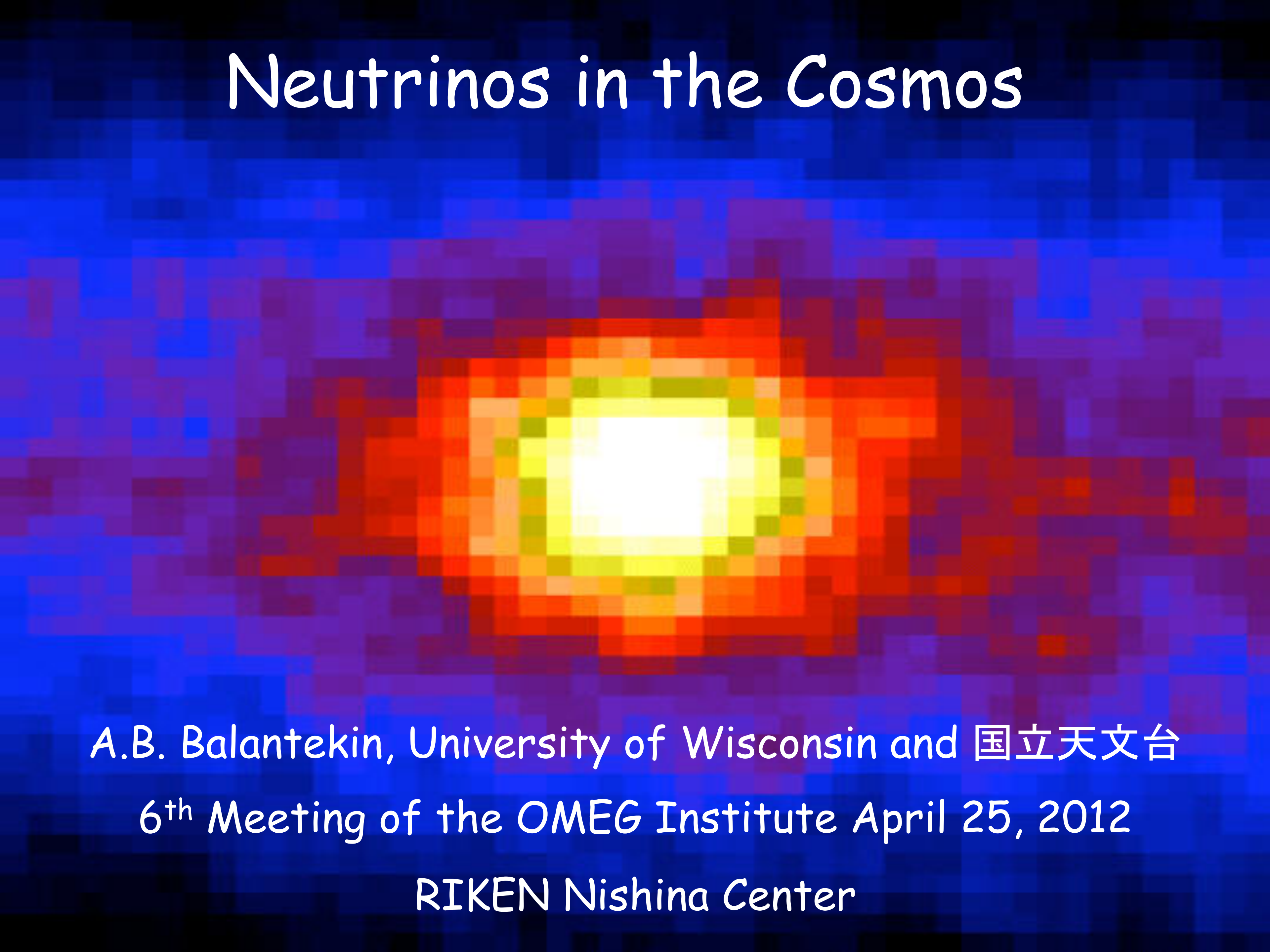
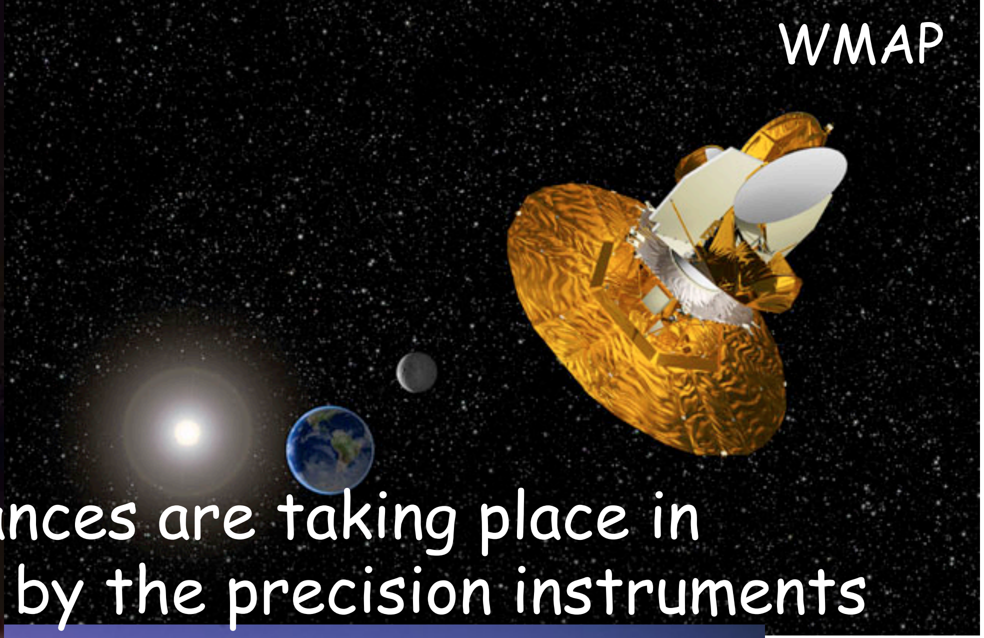
Neutrinos in the Cosmos



A.B. Balantekin, University of Wisconsin and 国立天文台

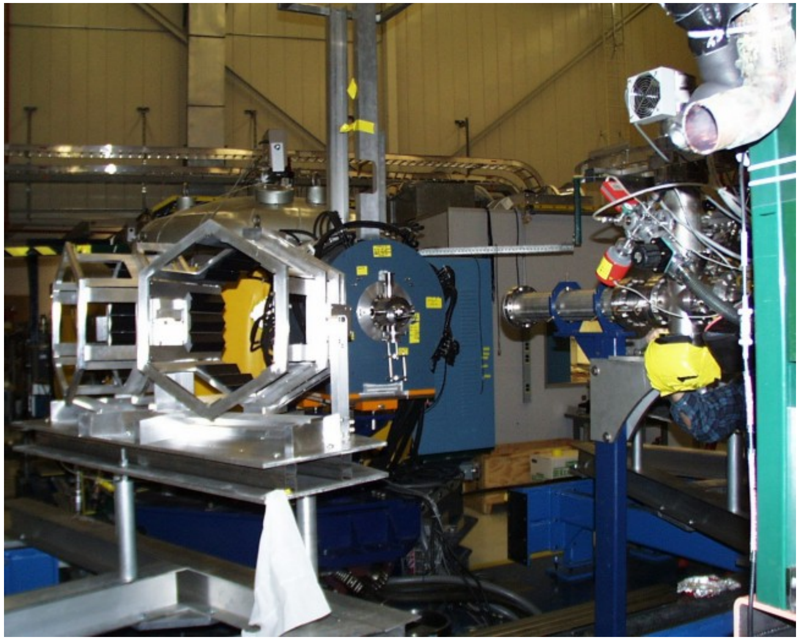
6th Meeting of the OMEG Institute April 25, 2012

RIKEN Nishina Center

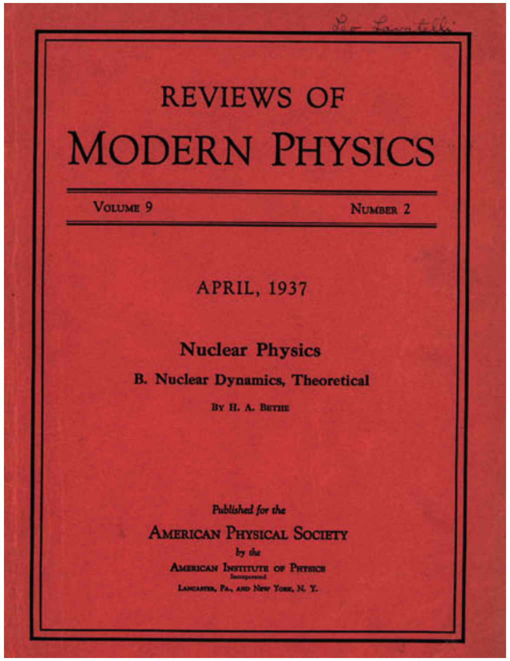


Revolutionary advances are taking place in astrophysics motivated by the precision instruments

..and state of the art nuclear physics facilities



How Stars Shine?



REVIEWS OF

MODERN PHYSICS

VOLUME 9 NUMBER 2

APRIL, 1937

Nuclear Physics

B. Nuclear Dynamics, Theoretical

BY H. A. BETHE

Published for the

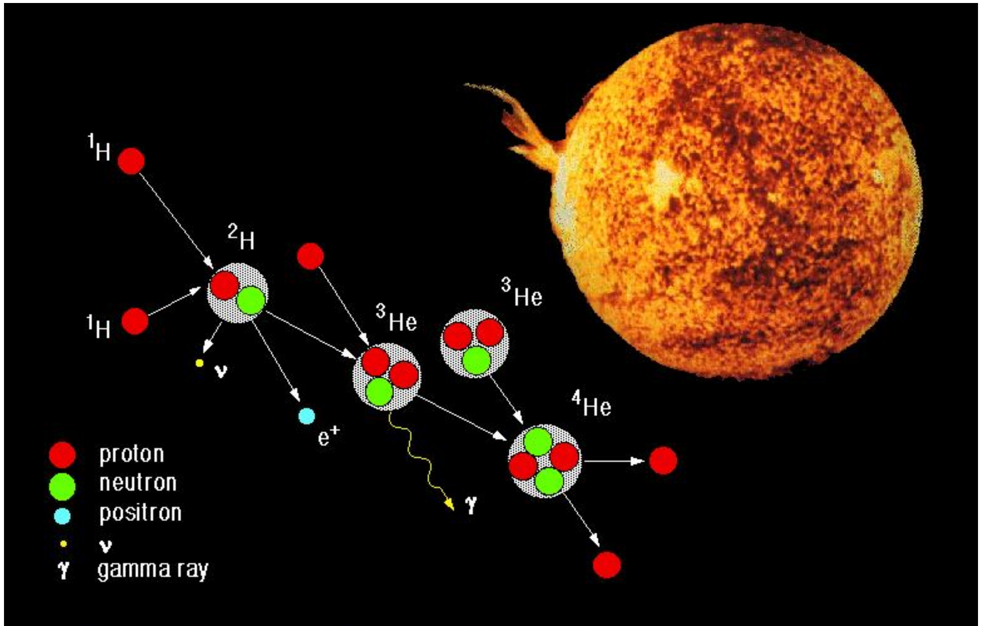
AMERICAN PHYSICAL SOCIETY

by the

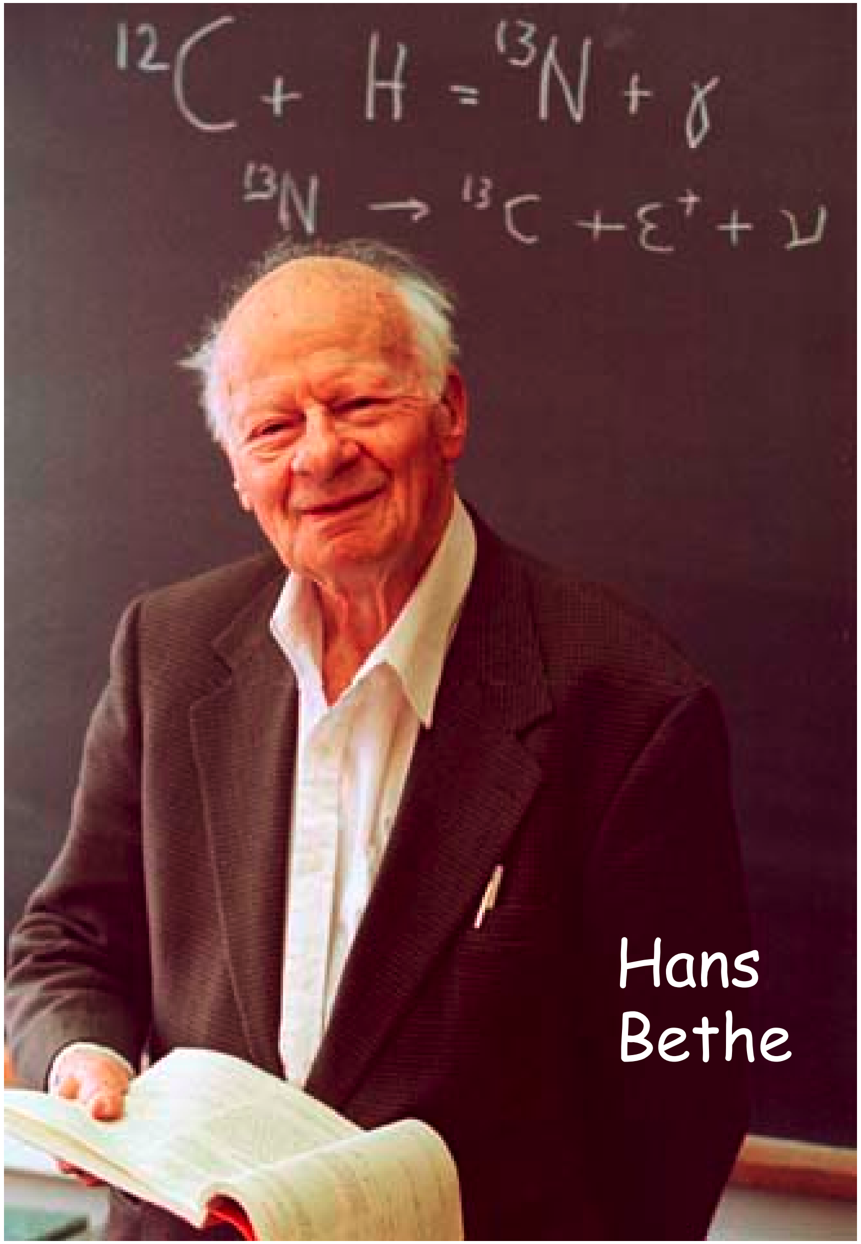
AMERICAN INSTITUTE OF PHYSICS

Incorporated

LANCASTER, PA., AND NEW YORK, N. Y.

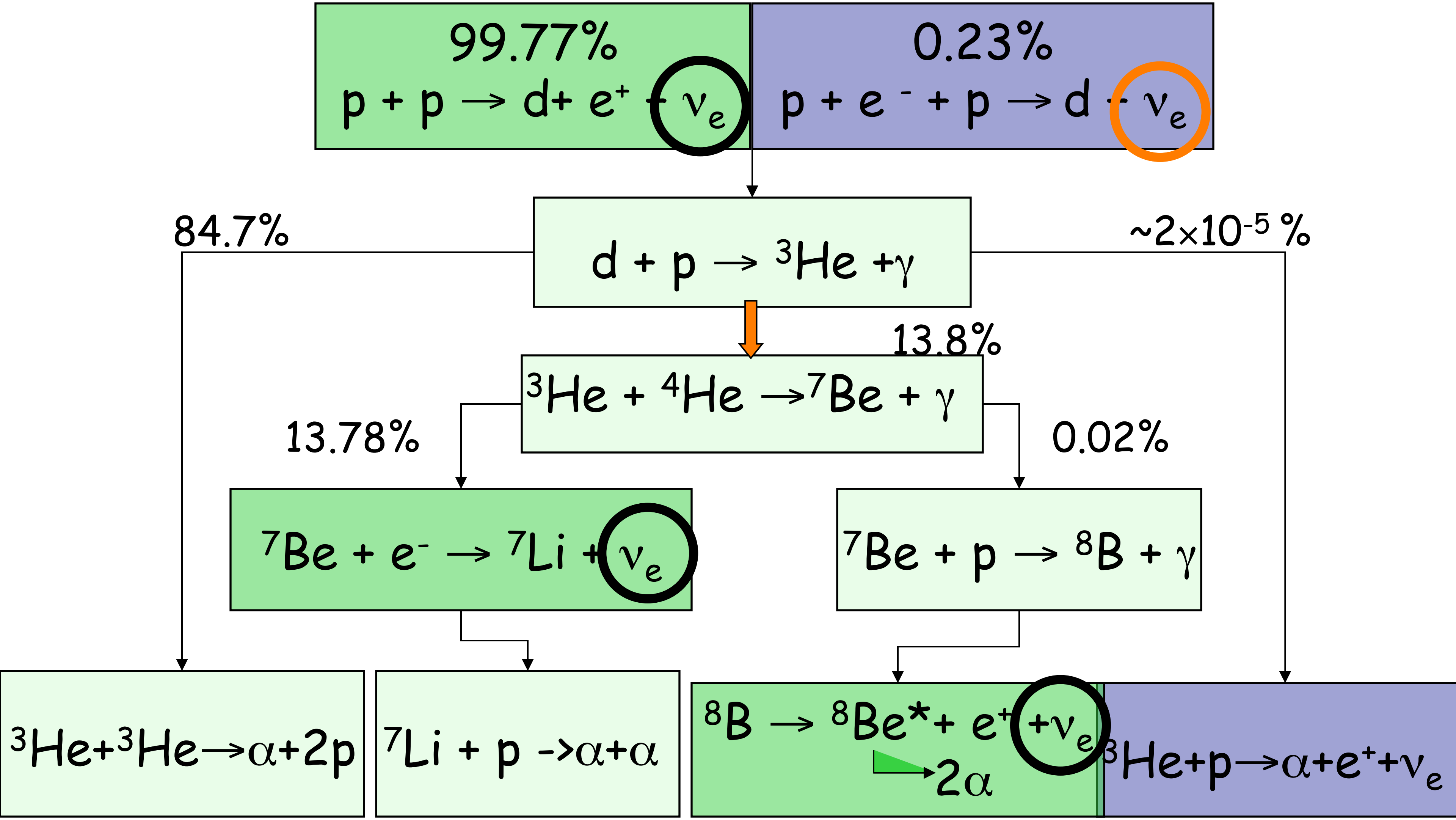


Solar Nuclear Fusion Reactions via the Proton-Proton Chain



Hans Bethe

Nuclear reaction network in the Sun



99.77%

$p + p \rightarrow d + e^+ + \nu_e$

0.23%

$p + e^- + p \rightarrow d + \nu_e$

$d + p \rightarrow {}^3He + \gamma$

84.7%

~2×10⁻⁵ %

13.8%

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

13.78%

0.02%

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^3He + {}^3He \rightarrow \alpha + 2p$

${}^7Li + p \rightarrow \alpha + \alpha$

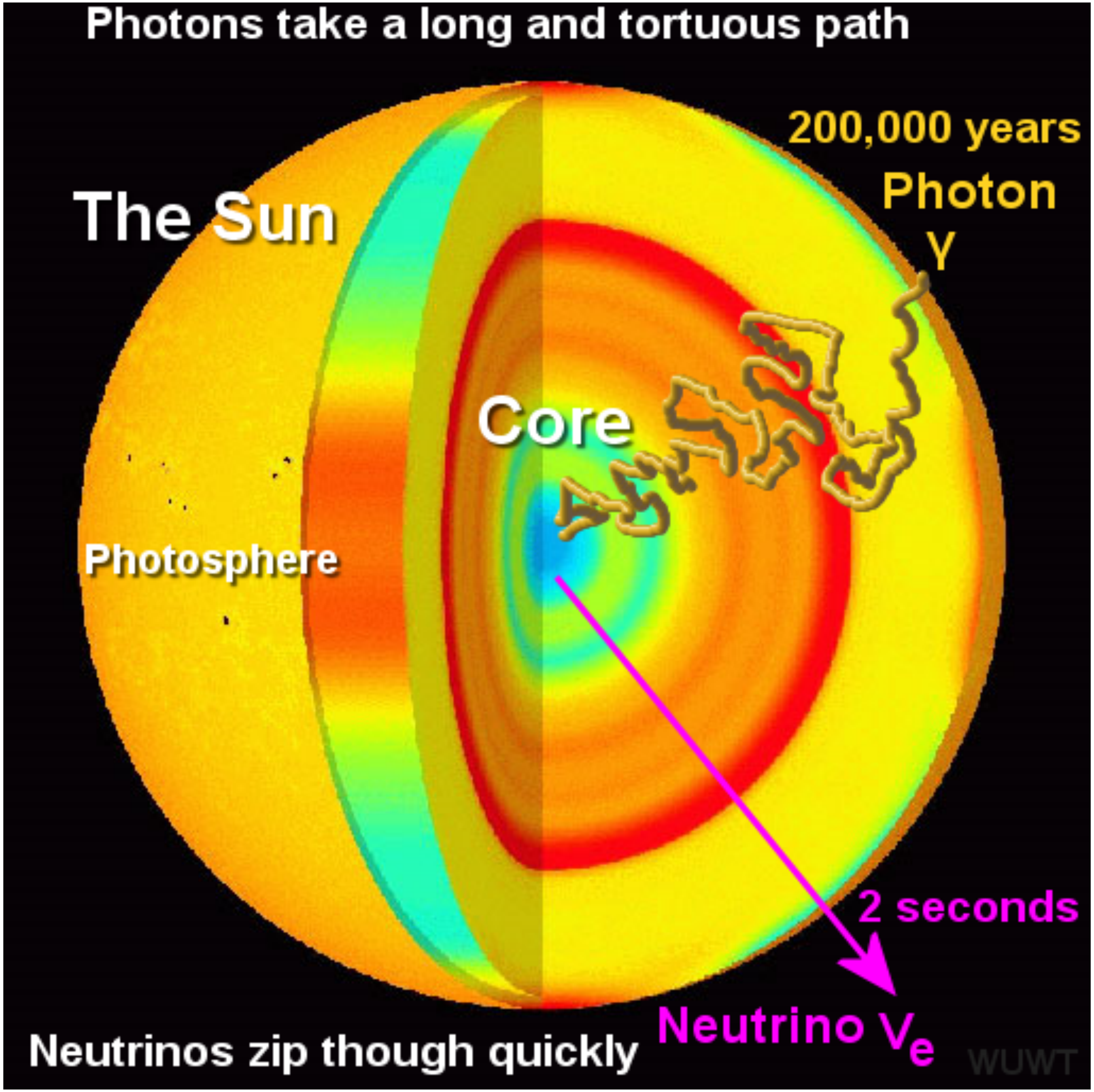
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$\rightarrow 2\alpha$

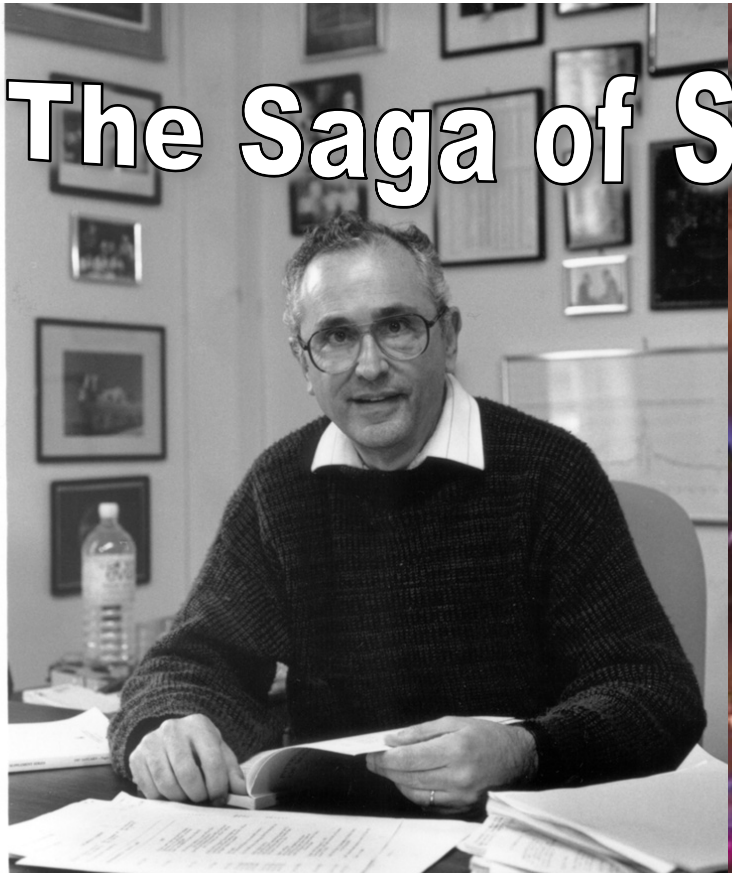
${}^3He + p \rightarrow \alpha + e^+ + \nu_e$

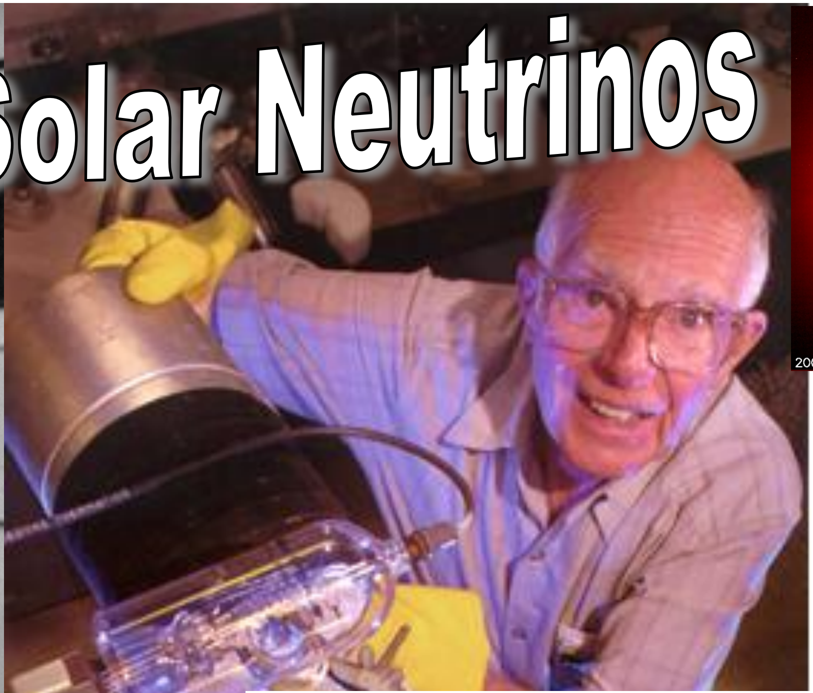
Three paths leading to neutrinos are called pp-I, pp-II and pp-III chains, respectively.

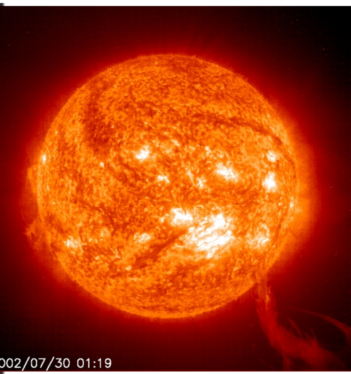
Neutrinos interact only weakly. 15 trillion solar neutrinos go through your body every second, yet energetic ones (E > 5 MeV) interact once in every 30 years inside your body! So they zip through the Sun, yet retain the memory of nuclear fusion reactions that produced them.



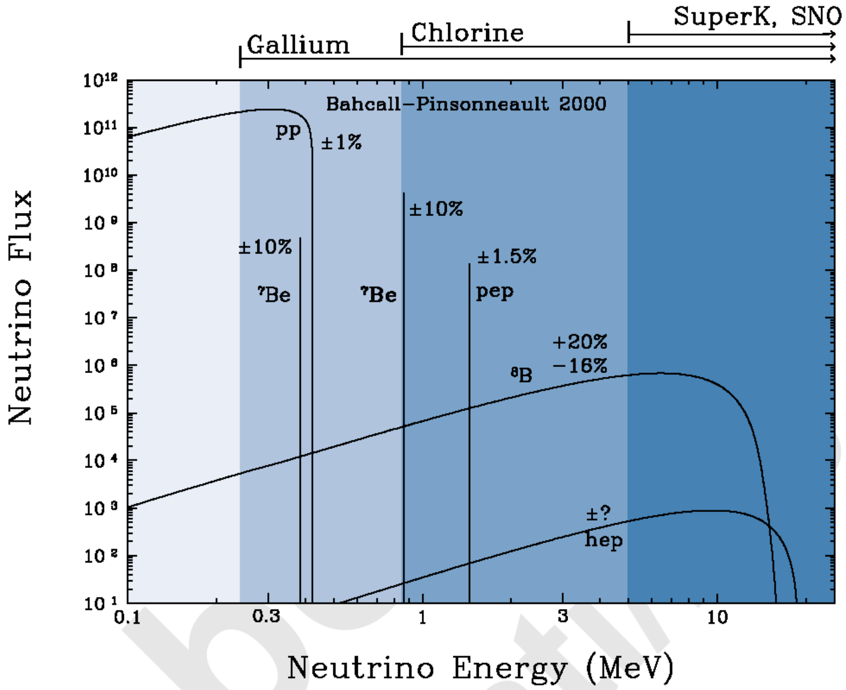
The Saga of Solar Neutrinos





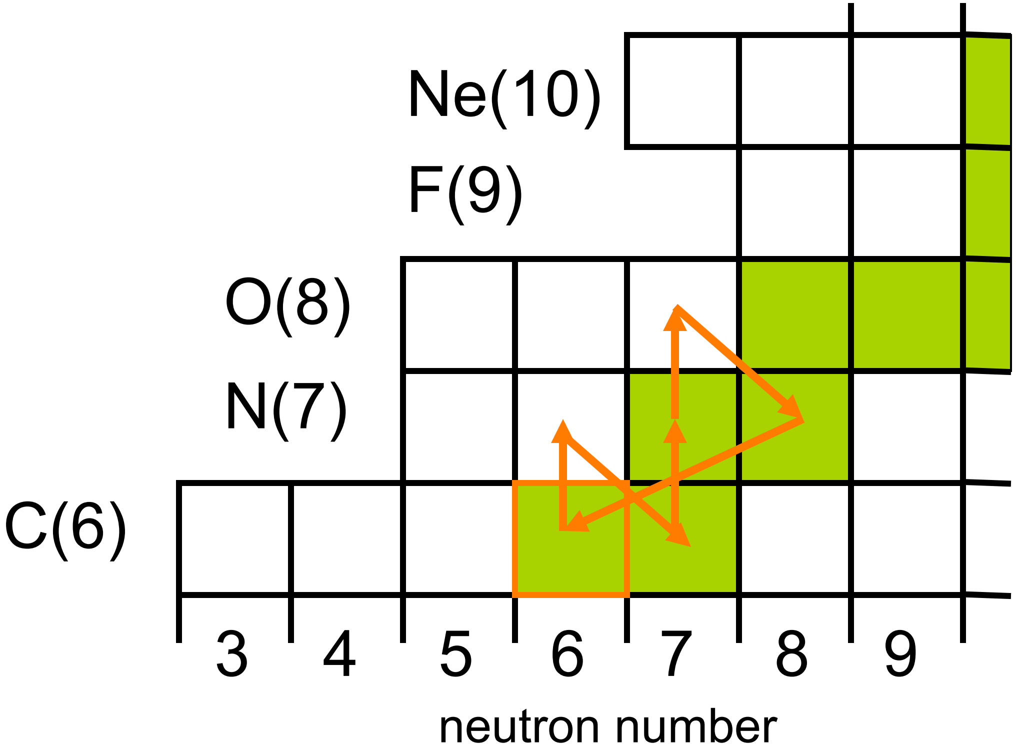


2002/07/30 01:19



> "...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation.."
>
> Bahcall and Davis, 1964

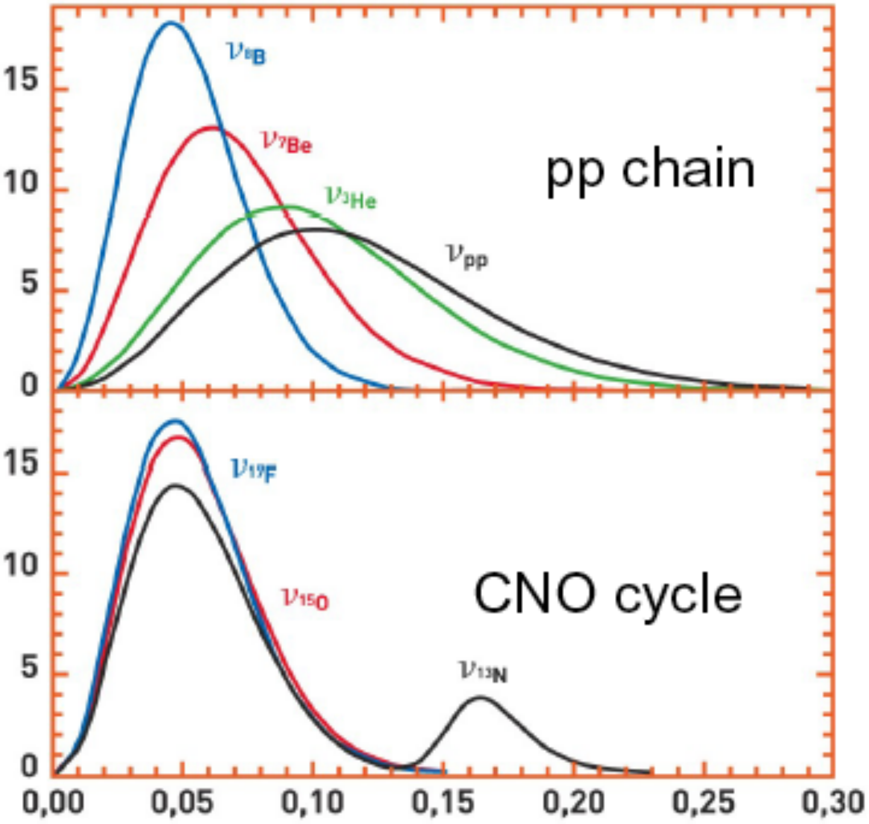
The CNO cycle

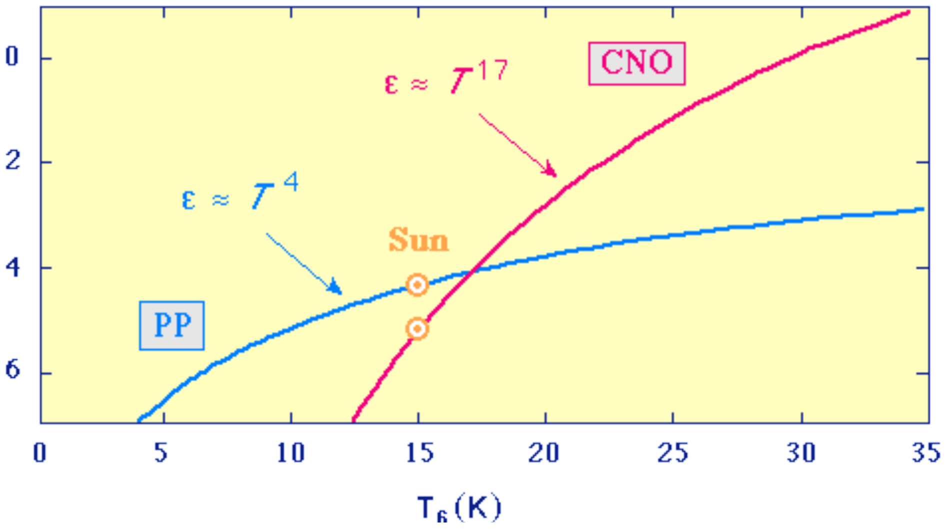


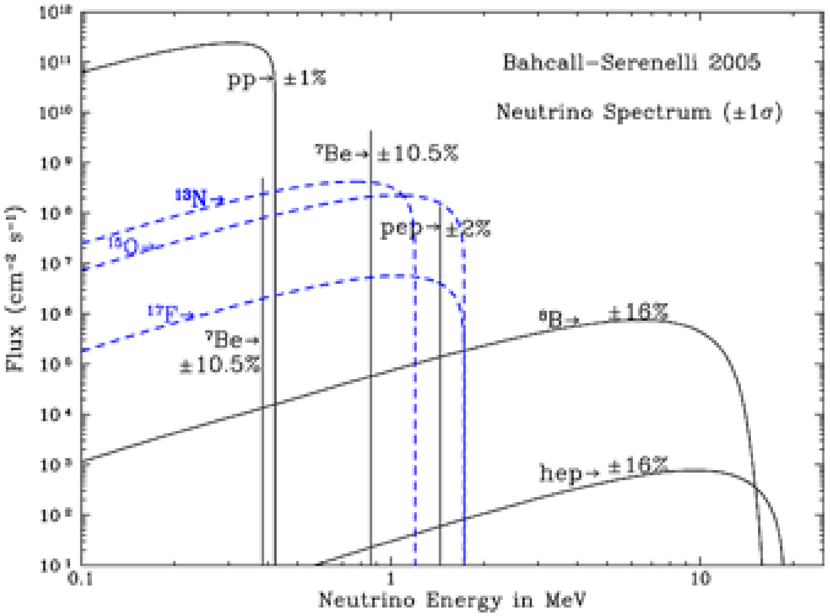
$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(p,\gamma)^{14}N\ (p,\gamma)^{15}O\ (\beta^+)^{15}N(p,\alpha)^{12}C$

Net effect: $4p \rightarrow \alpha + 2e^+ + 2\nu_e$

How much does the CNO cycle contribute in the Sun?







In SSM CNO cycle contribute about 0.8% of the neutrino flux. Data are consistent with this. A more precise measurement of the CNO contribution will provide a test of SSM.

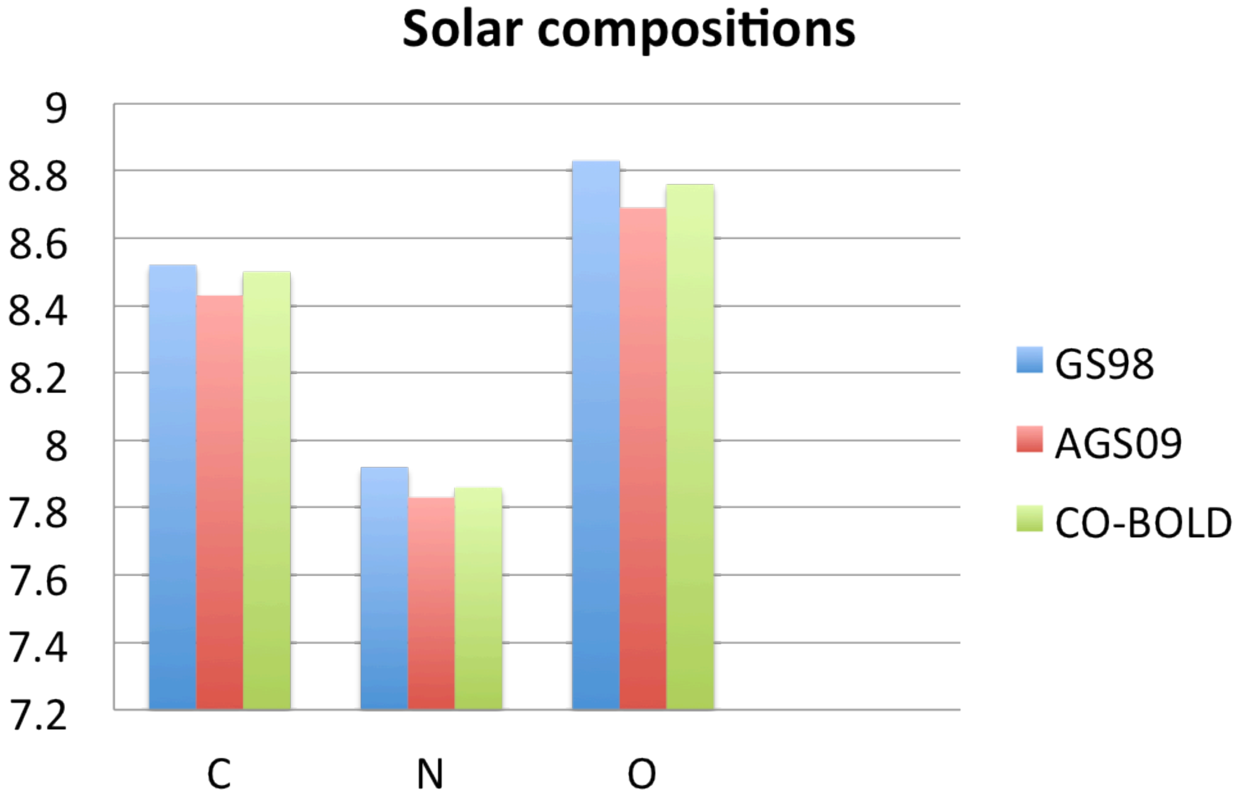
New Solar abundances:

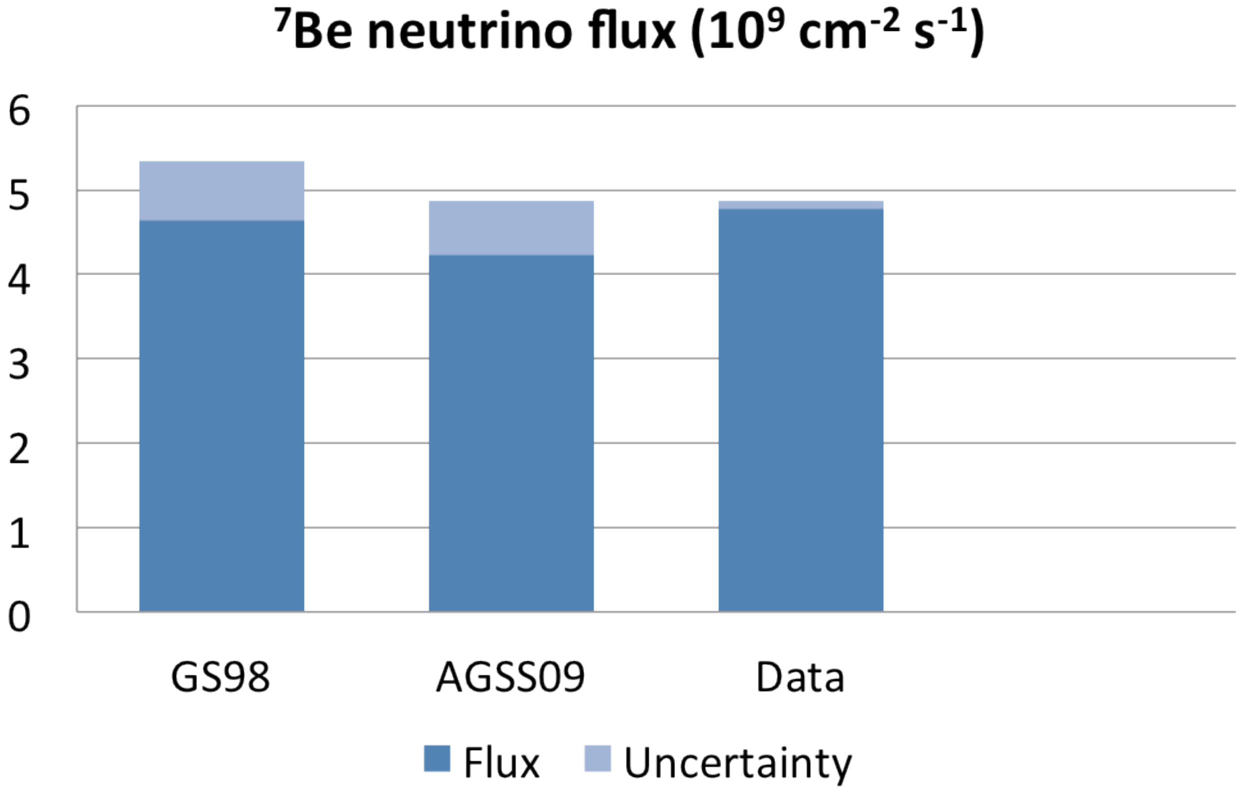
- Asplund *et al.* (AGSS09), $(Z/X)_\odot$=0.0178
- Grevesse and Sauvel (GS98), $(Z/X)_\odot$=0.0229

Drastically different!
Open problem in solar physics!

New Evaluation of the nuclear reaction rates:
Adelberger et al. (2011)

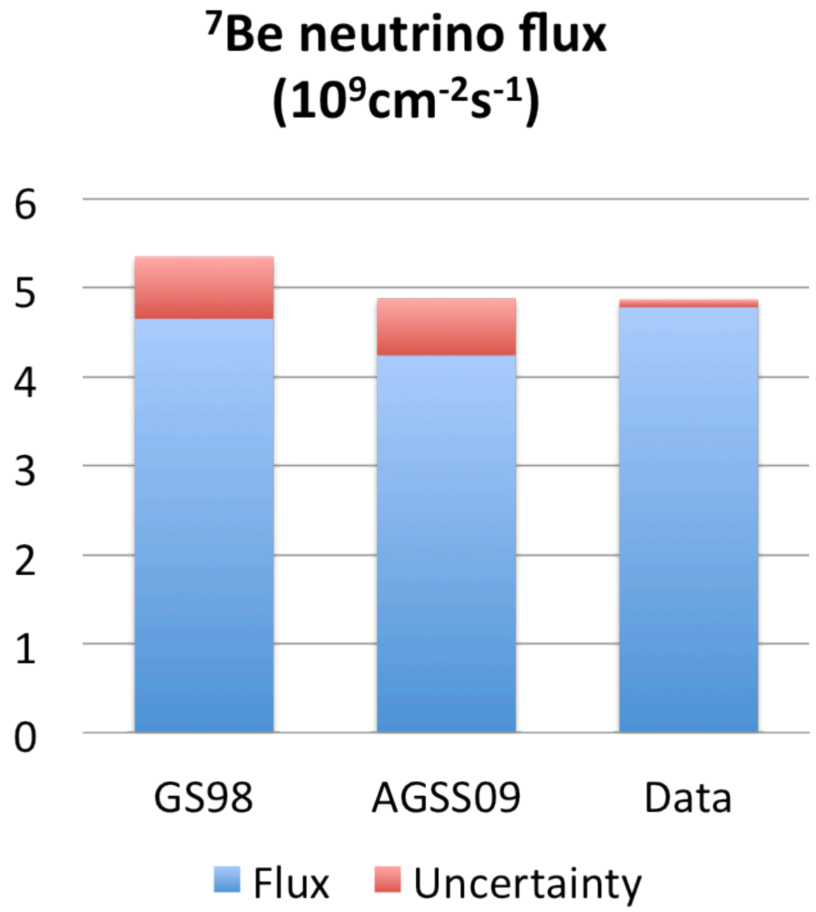
New solar model calculations:
Serenelli


Solar compositions
9
8.8
8.6
8.4
8.2
8
7.8
7.6
7.4
7.2
C
N
O
GS98
AGS09
CO-BOLD

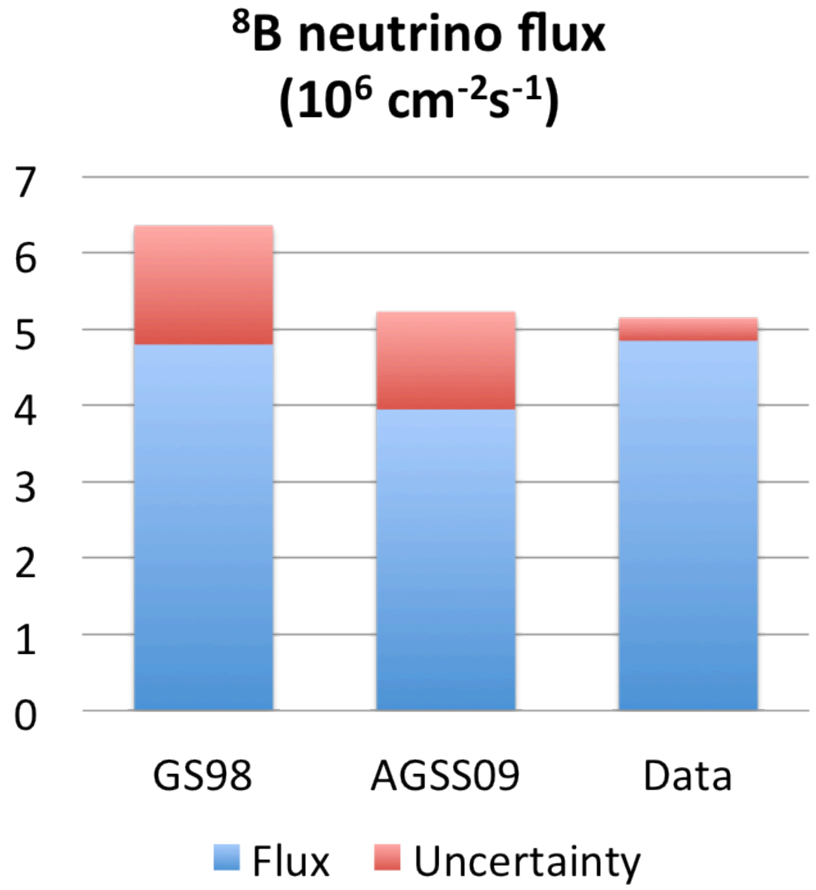


^{7}Be neutrino flux (10^9 cm^{-2} s^{-1})

Measured neutrino fluxes from the pp-chain cannot distinguish between different abundances:

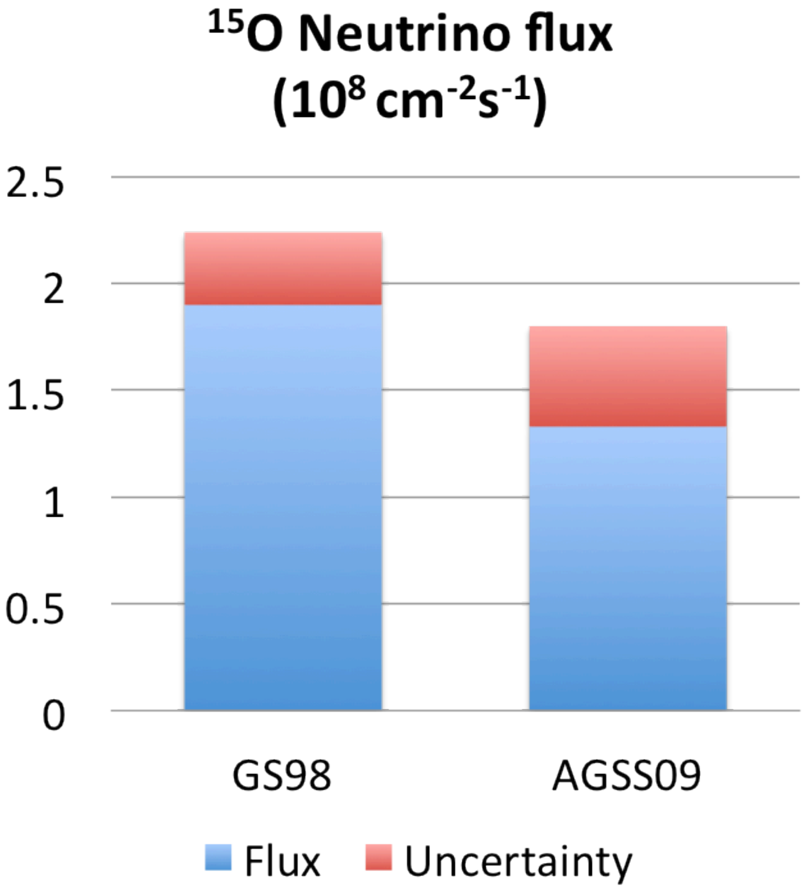


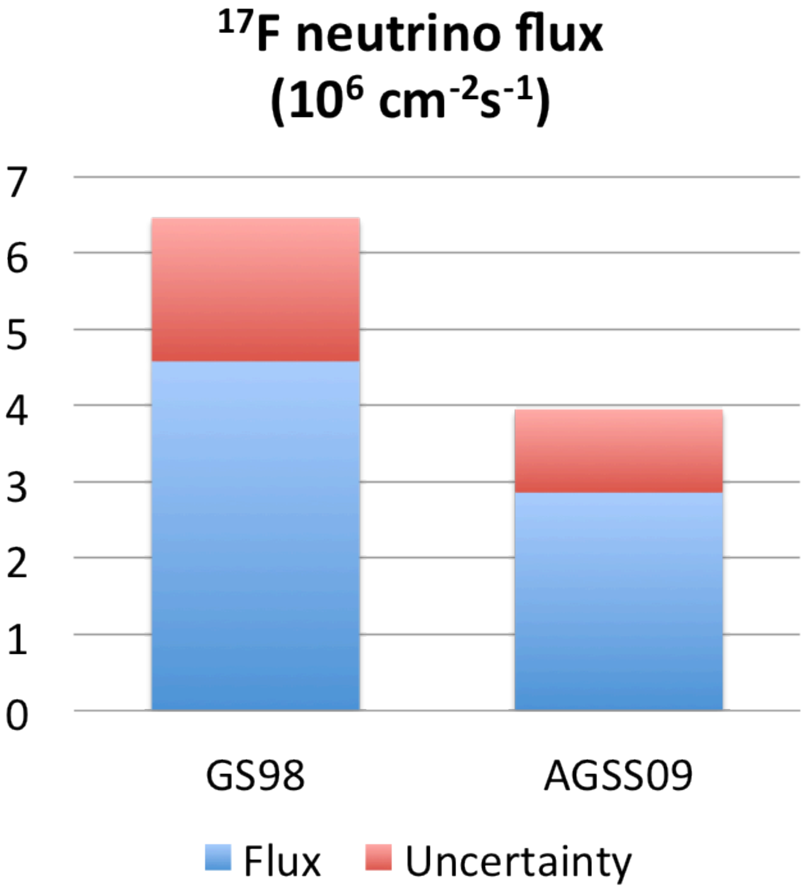
^{7}Be neutrino flux (10^9cm^{-2}s^{-1})



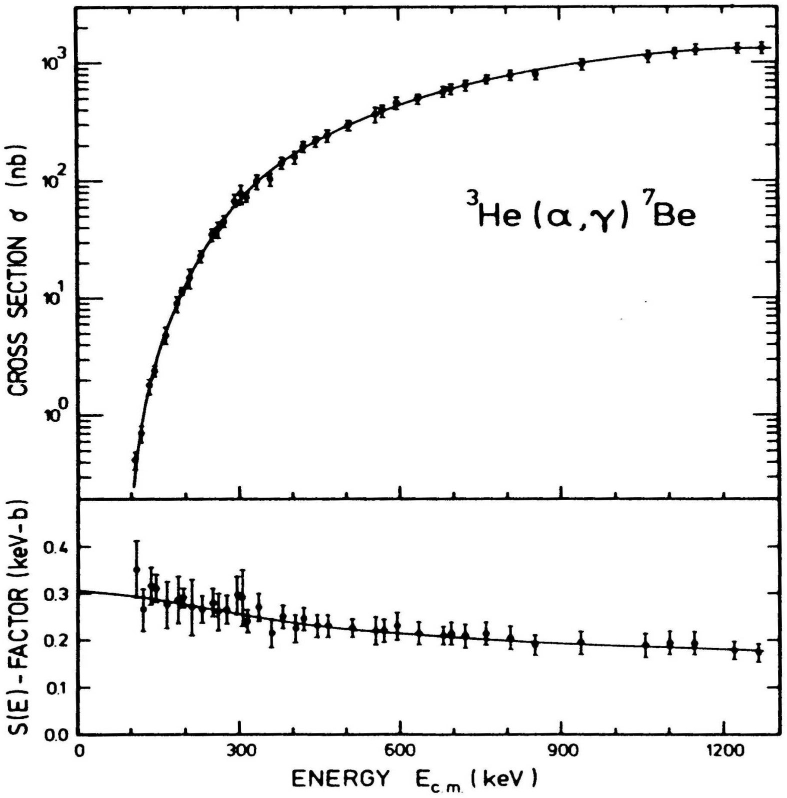
^{8}B neutrino flux (10^6 cm^{-2}s^{-1})

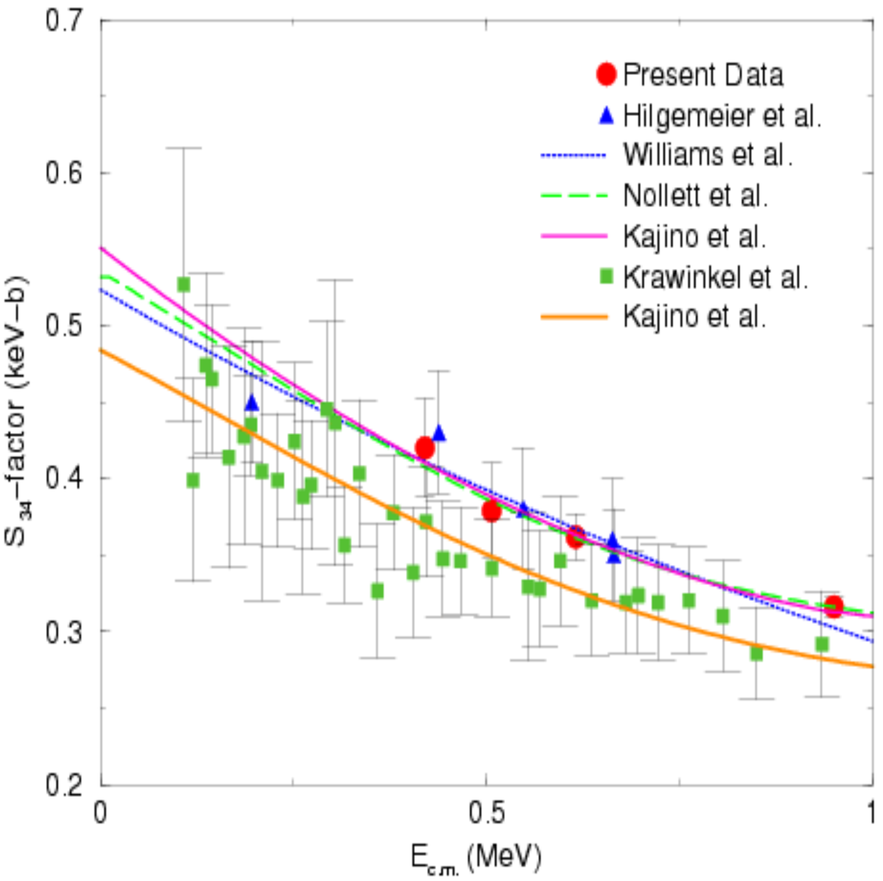
But a future measurement of the CNO-chain neutrino fluxes may distinguish between different abundances:





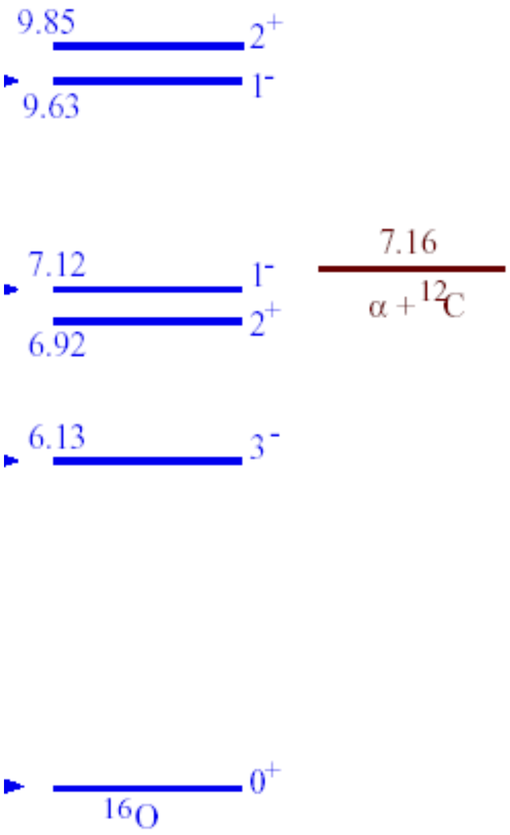
Three important reactions in nuclear astrophysics: I. $^{3}He(\alpha,\gamma)^{7}Be$

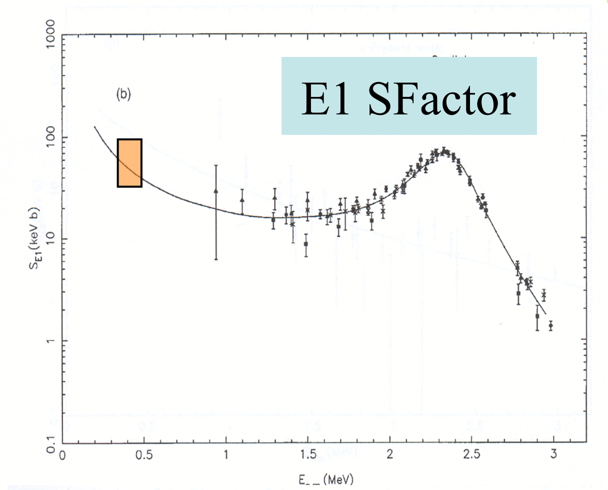


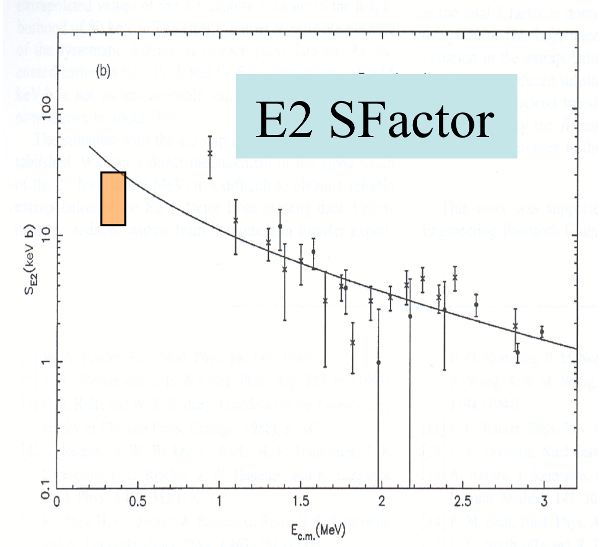


The main uncertainty for the Sun and big-bang nucleosynthesis

Three important reactions in nuclear astrophysics: II. $^{12}C(\alpha,\gamma)^{16}O$

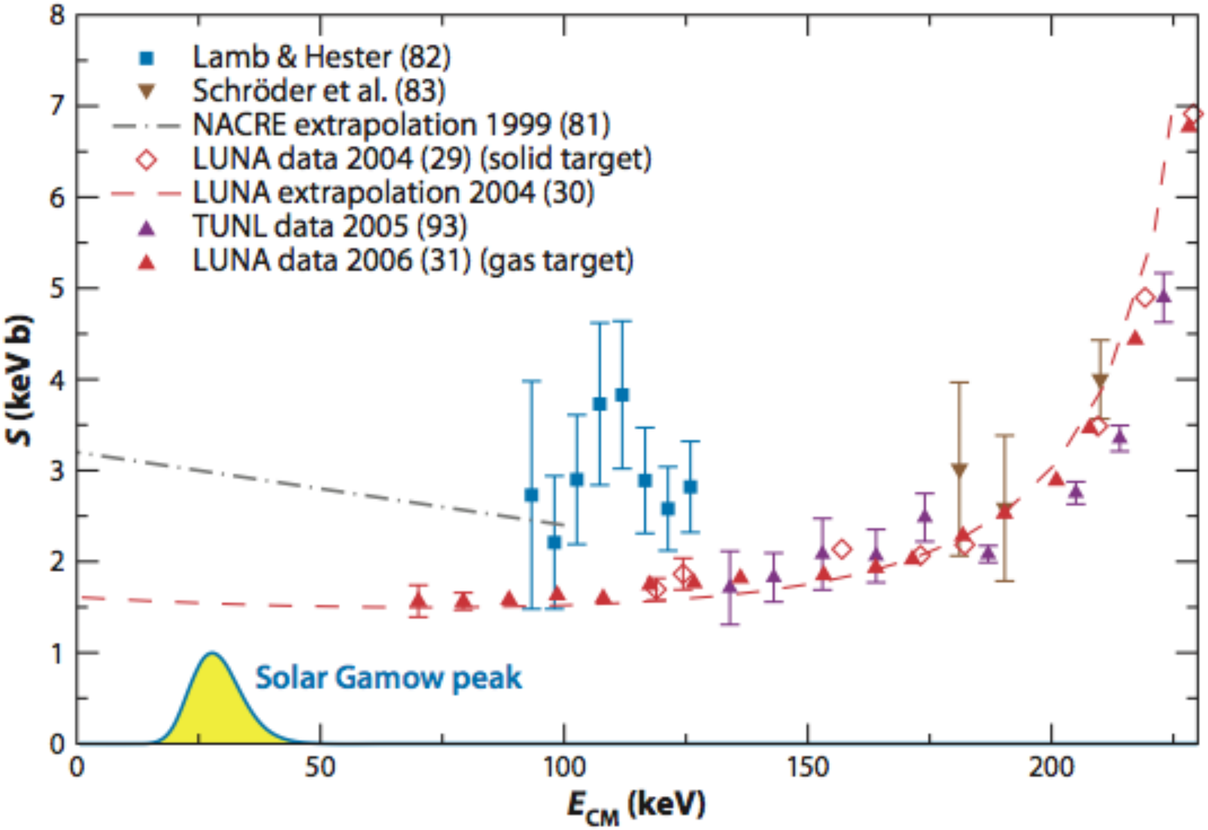






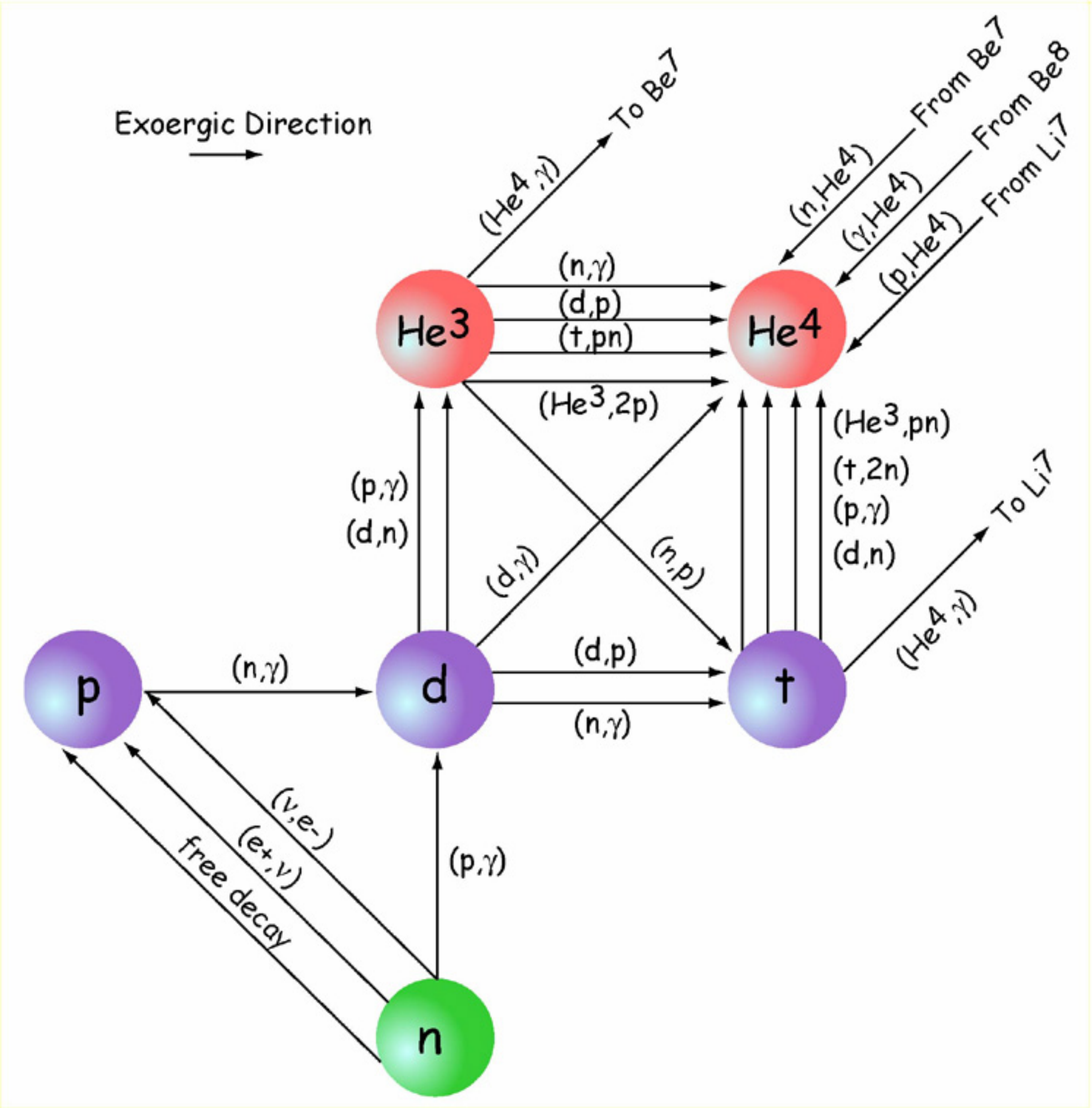
The determining quantity of the C/O ratio (*i.e.* life)in the Universe

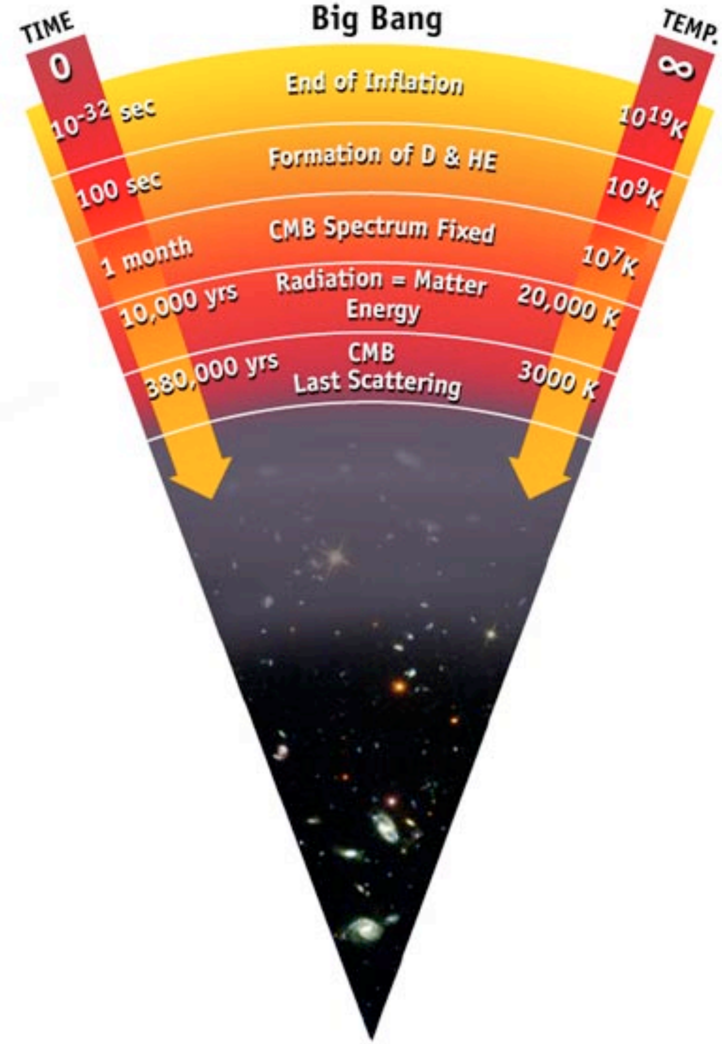
Three important reactions in nuclear astrophysics: III. $^{14}N(p,\gamma)^{15}O$



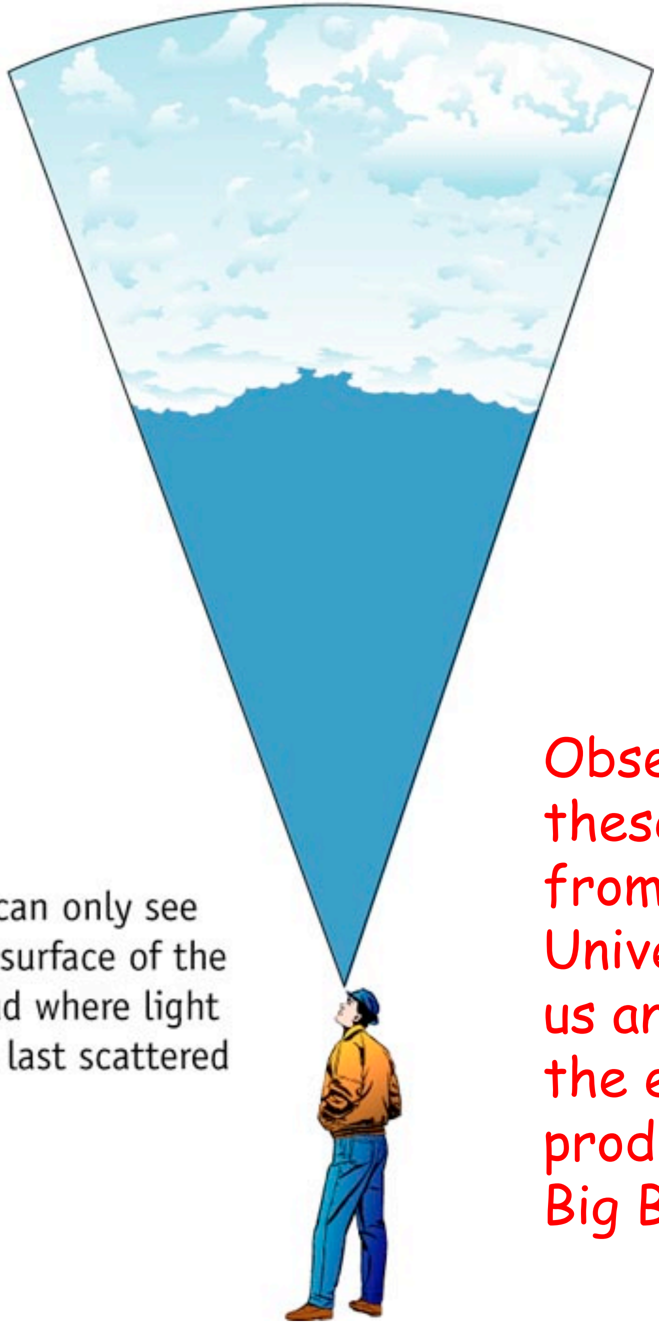
The determining reaction for the CNO burning

Big-bang nucleosynthesis



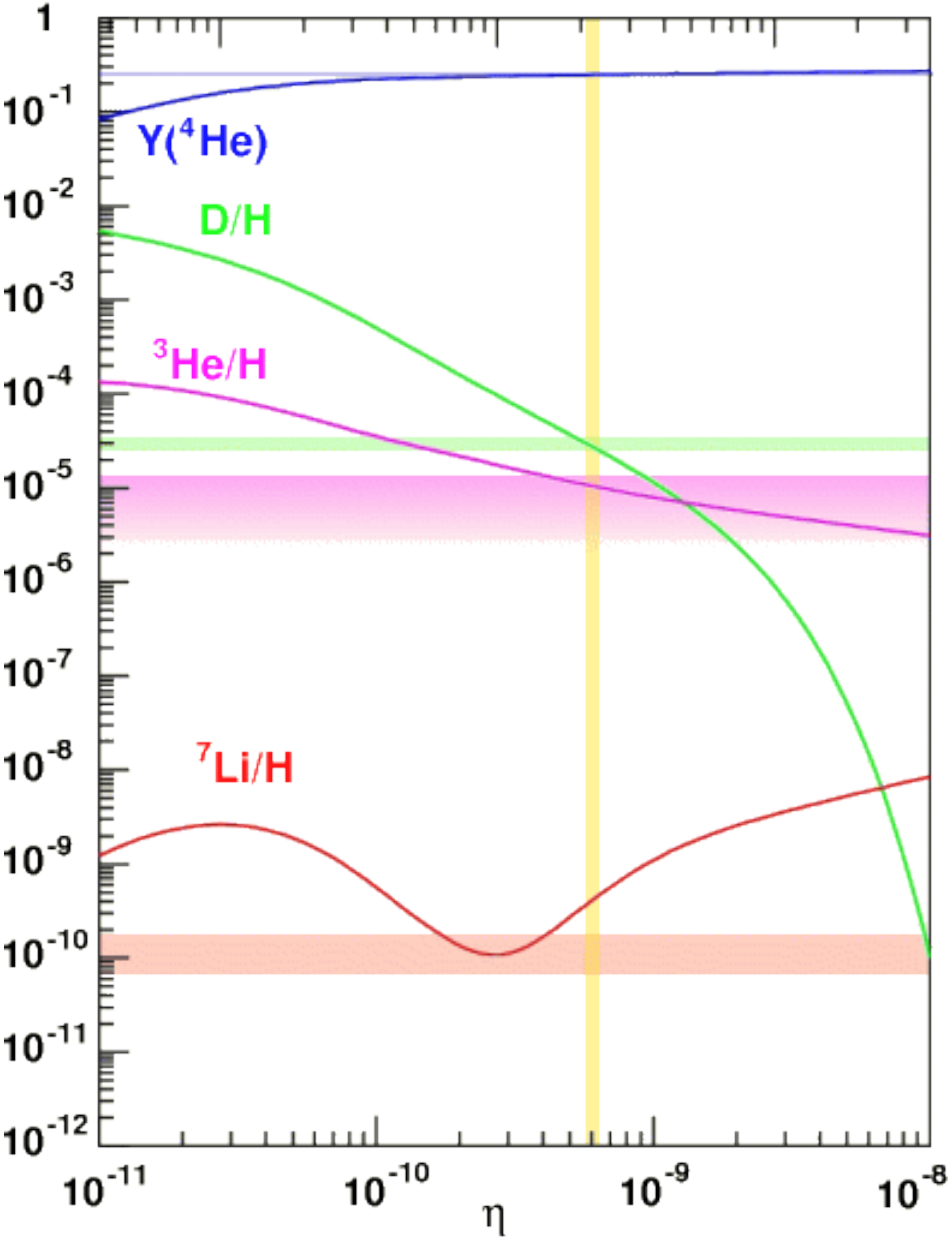


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



We can only see the surface of the cloud where light was last scattered

Observation of these photons from the Early Universe provides us an estimate of the elements produced in the Big Bang!

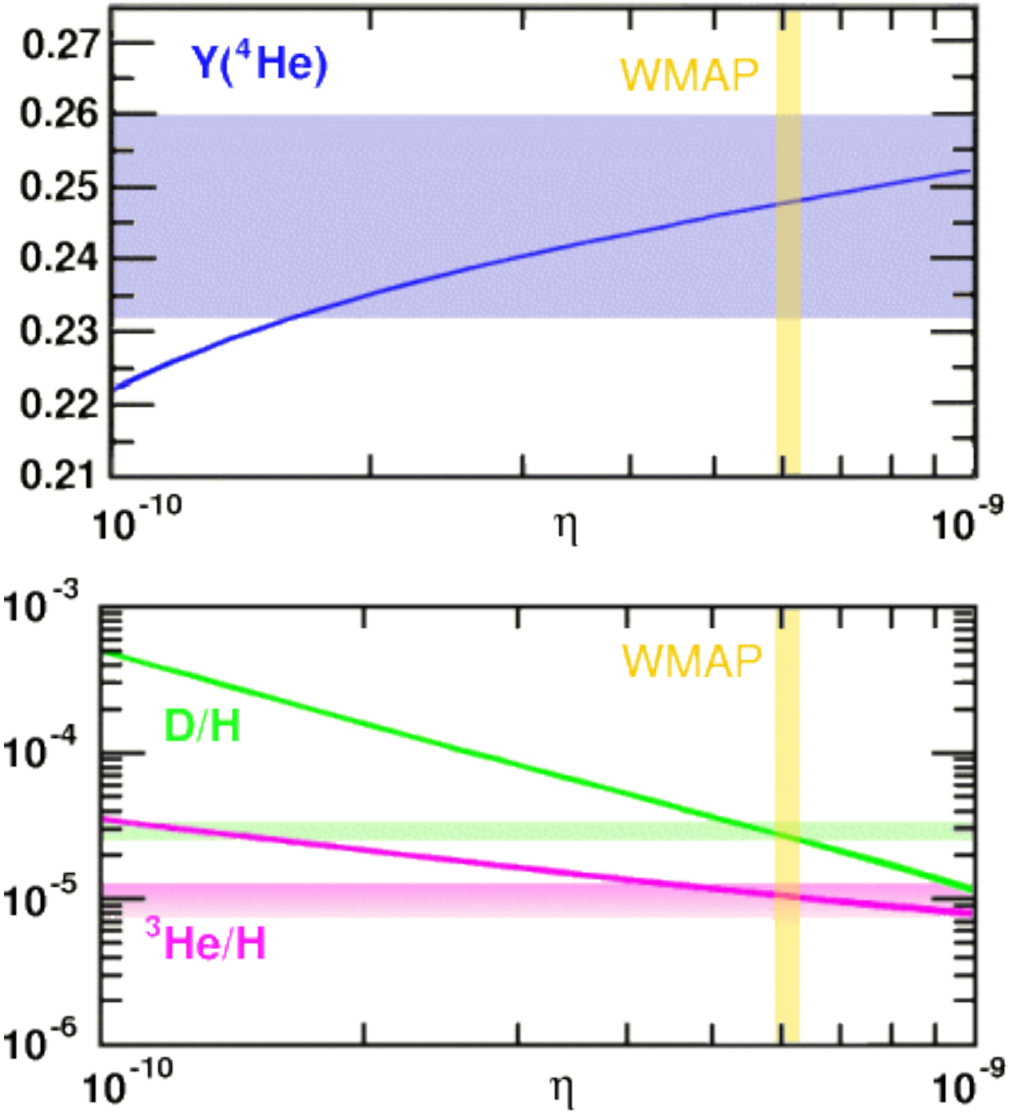

1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$Y(^4He)$
D/H
$^3He/H$
$^7Li/H$
10^{-11}
10^{-10}
10^{-9}
10^{-8}
η

Most of the primordial abundances are consistent with the baryon density inferred from CMB.

CMB probes universe at $t \approx 4\ 10^5$ yrs; $z \approx 10^3$ $T \approx 0.3$ eV

^{4}He production probes $t \approx 1$s; $z \approx 10^9$ $T \approx 1$ MeV

D production probes $t \approx 100$ s $z \approx 10^8$ $T \approx 0.1$ MeV



^{4}He equilibrium abundance

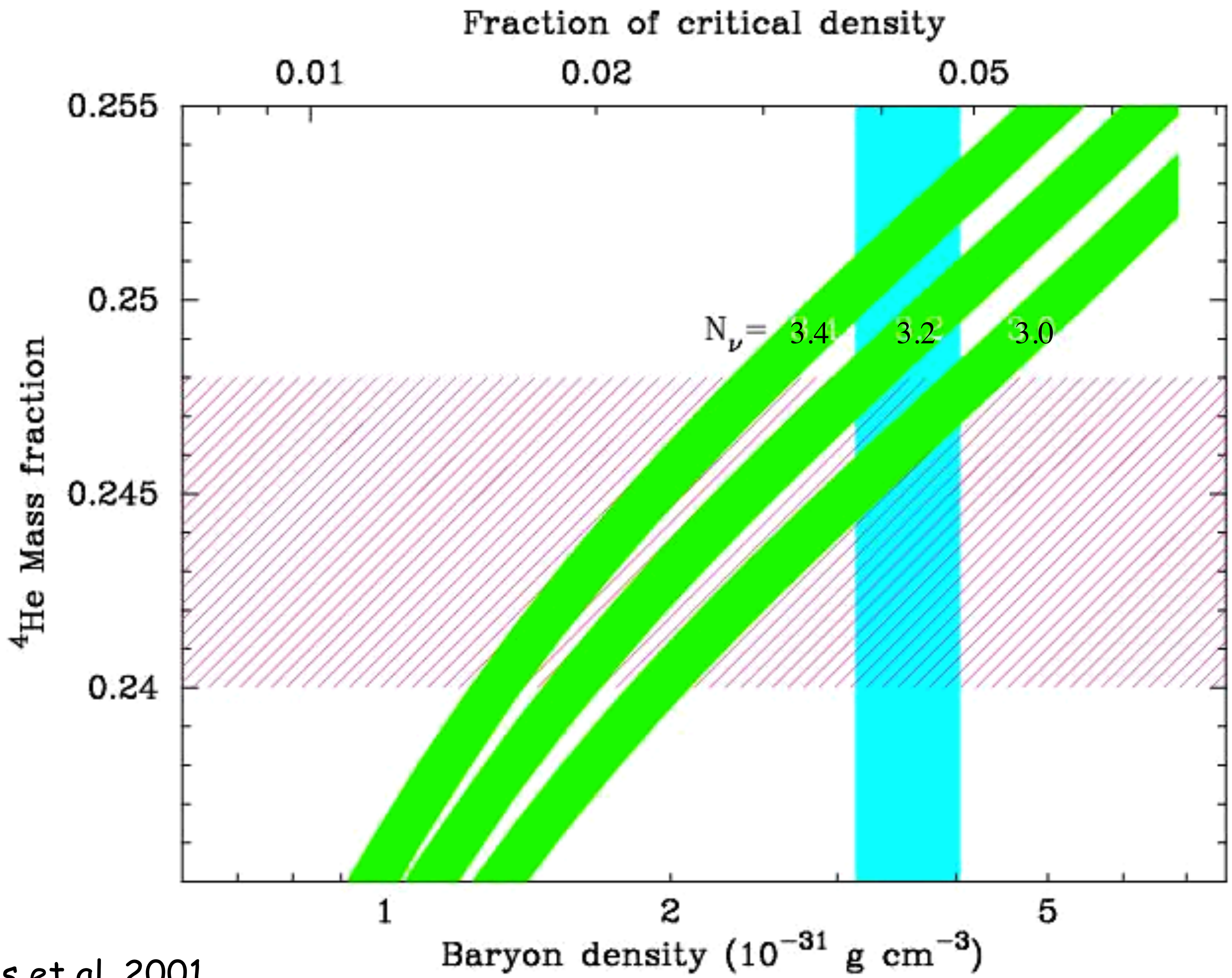
$$Y_\alpha = \frac{4\,(N_n/2)}{N_n + N_p}$$

He mass fraction

$$(N_n/N_p) = \exp(-\Delta m/T)$$

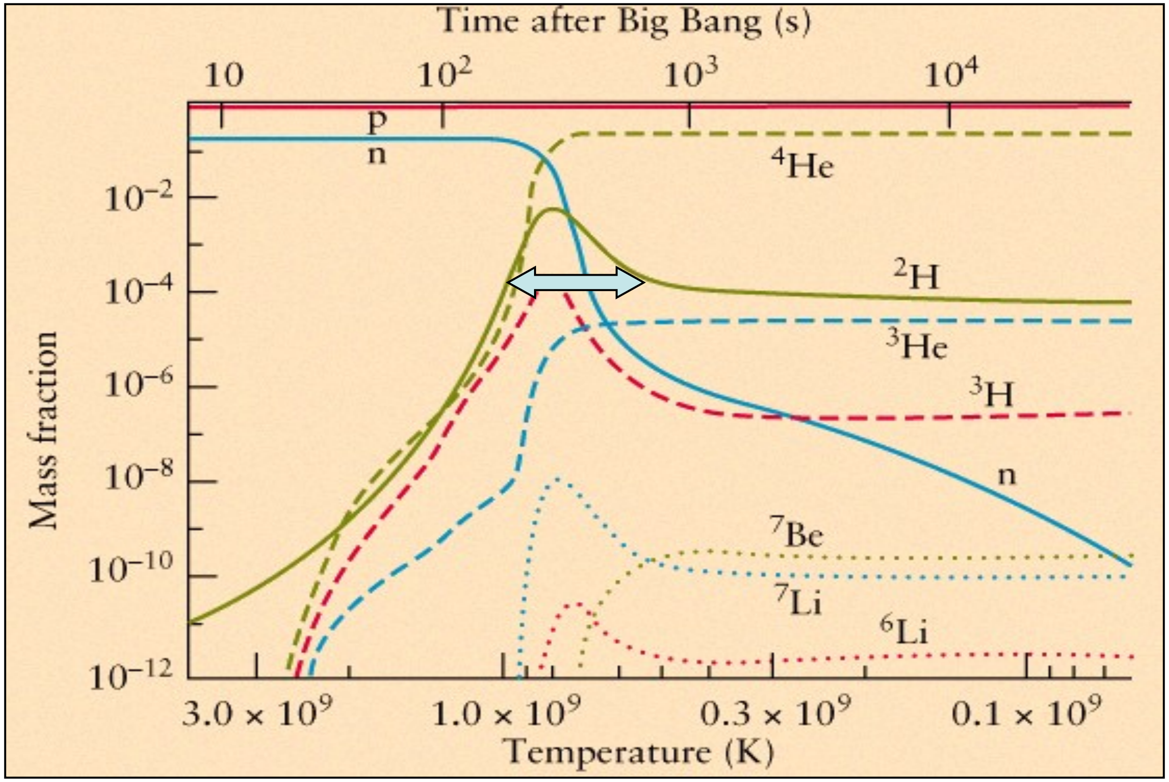
neutron-proton mass difference

Freeze-out temperature (depends on N_ν)



Burles et al. 2001

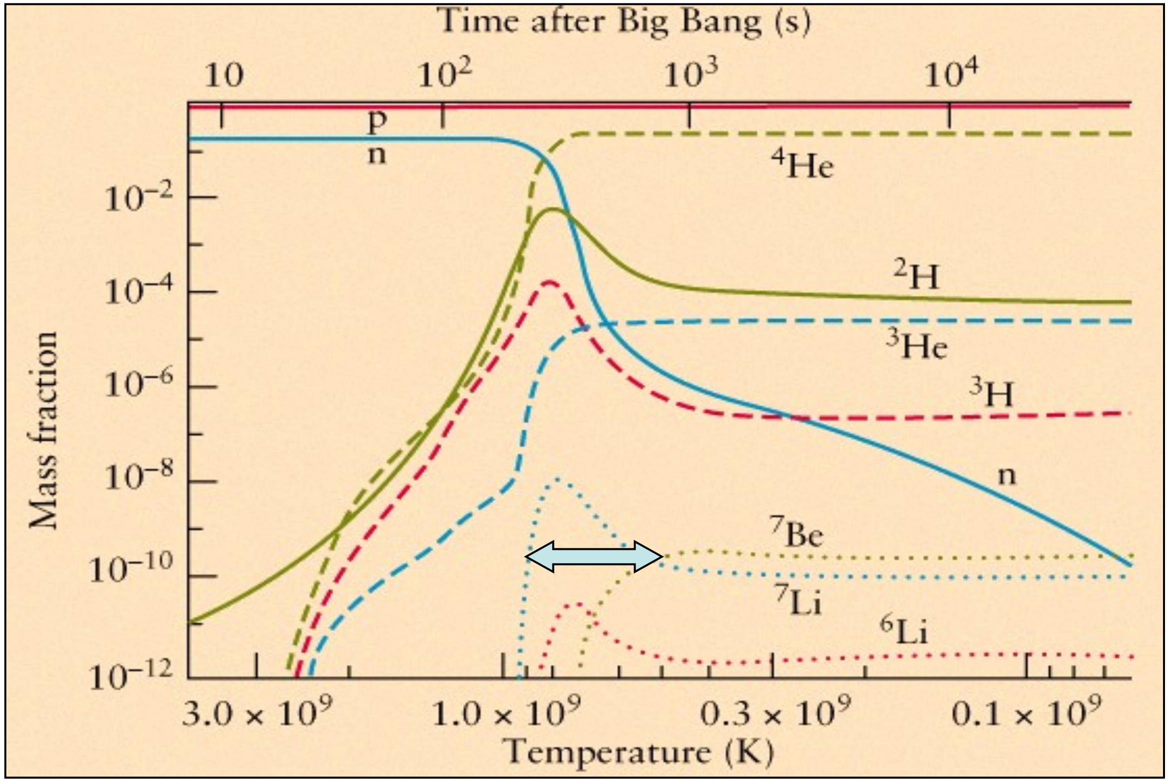
Deuterium



D is produced by $p+n \rightarrow d+\gamma$ and destroyed (mainly) by $p+d \rightarrow {}^3He + \gamma$

Relevant temperature ~70 keV

^{7}Li



^{7}Li is the decay product of ^{7}Be

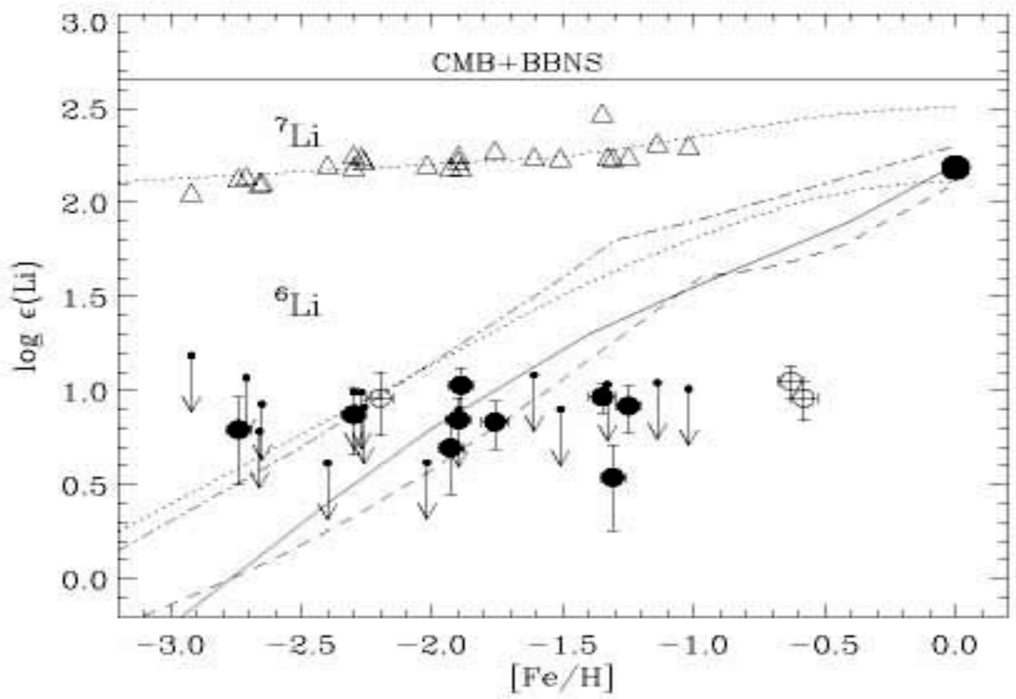
At high η ^{7}Be is mainly produced by $^3\text{He}+^4\text{He} \rightarrow {}^7\text{Be}+\gamma$

It is destroyed by $n+{}^7\text{Be} \rightarrow {}^7\text{Li}+p$ and at later times by electron capture.

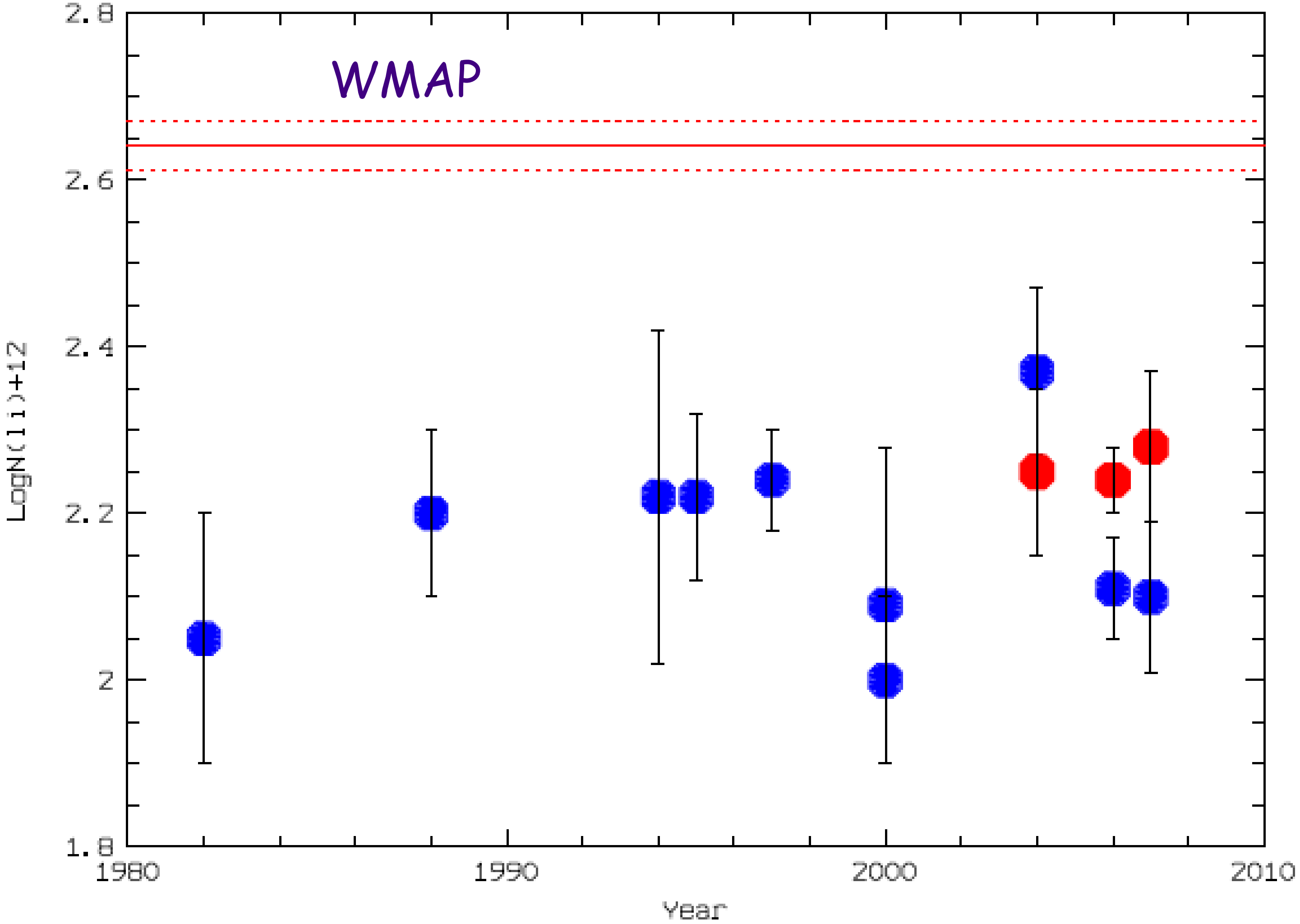
Relevant temperature ~60 keV.

Is there a problem with the big-bang nucleosynthesis?

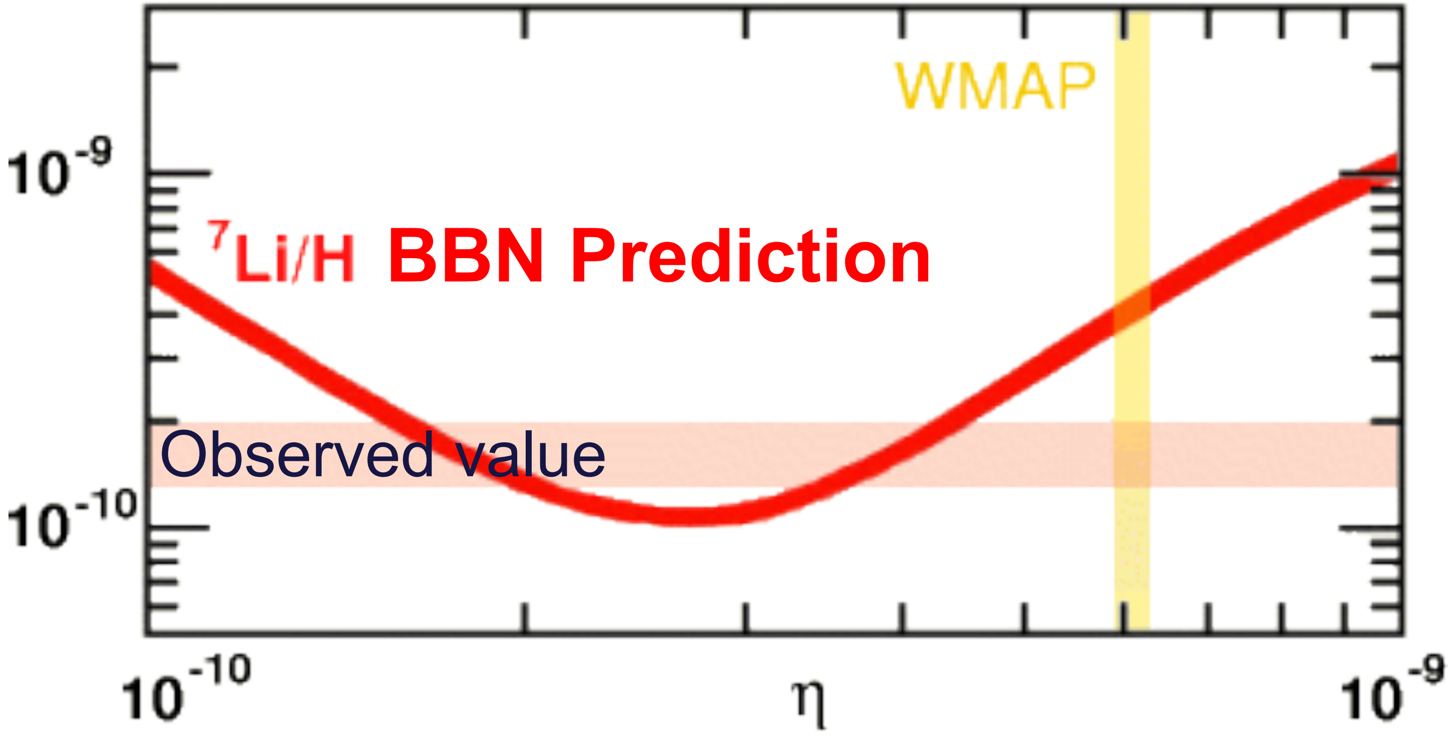
- WMAP observations of D and ^{4}He are in good agreement with BBN predictions but nuclear physics predicts a higher ^{7}Li abundance (by a factor of 2 or 3) than what is observed. What can we do to reduce the abundance of ^{7}Li and ^{7}Be while keeping ^{6}Li within observational limits?



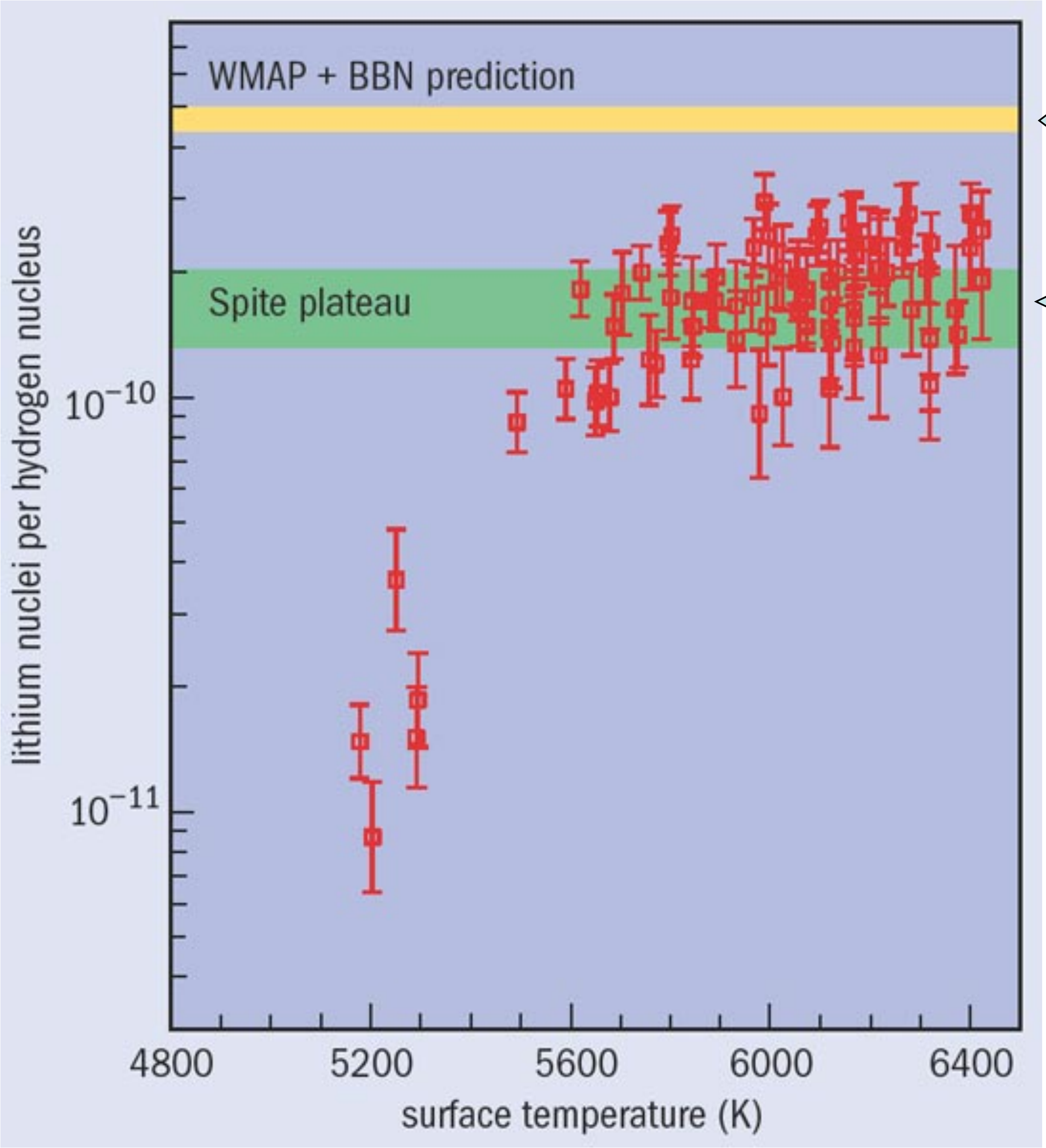
Asplund *et al.*



Molaro, 2007



- ^{7}Li produced in the Big-Bang Nucleosynthesis dominates the observed ^{7}Li abundance.
- In 1982 Spite and Spite observed that low-metallicity halo stars exhibit a plateau of ^{7}Li abundance indicating its primordial origin.
- But WMAP observations imply 2~3 times more ^{7}Li than that is observed in halo stars!

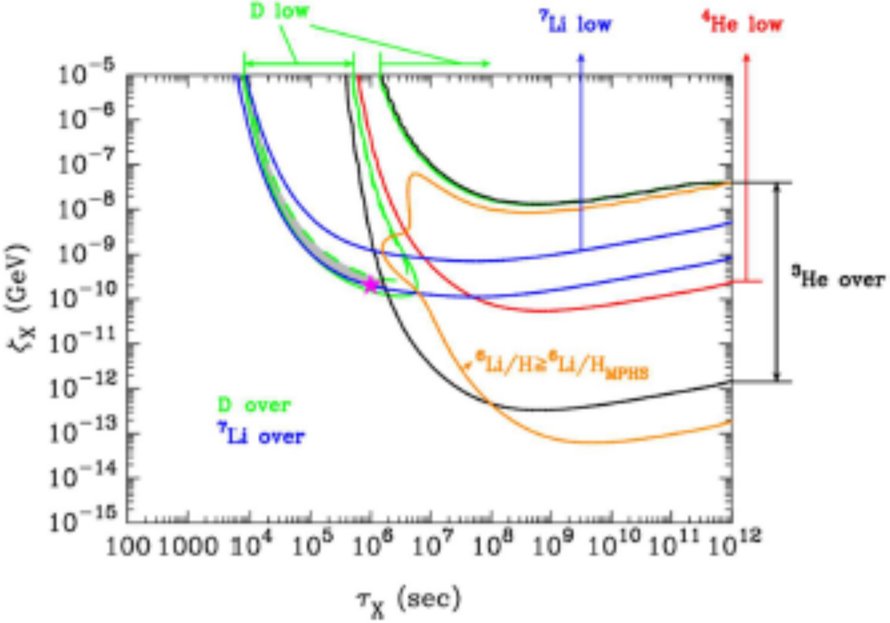


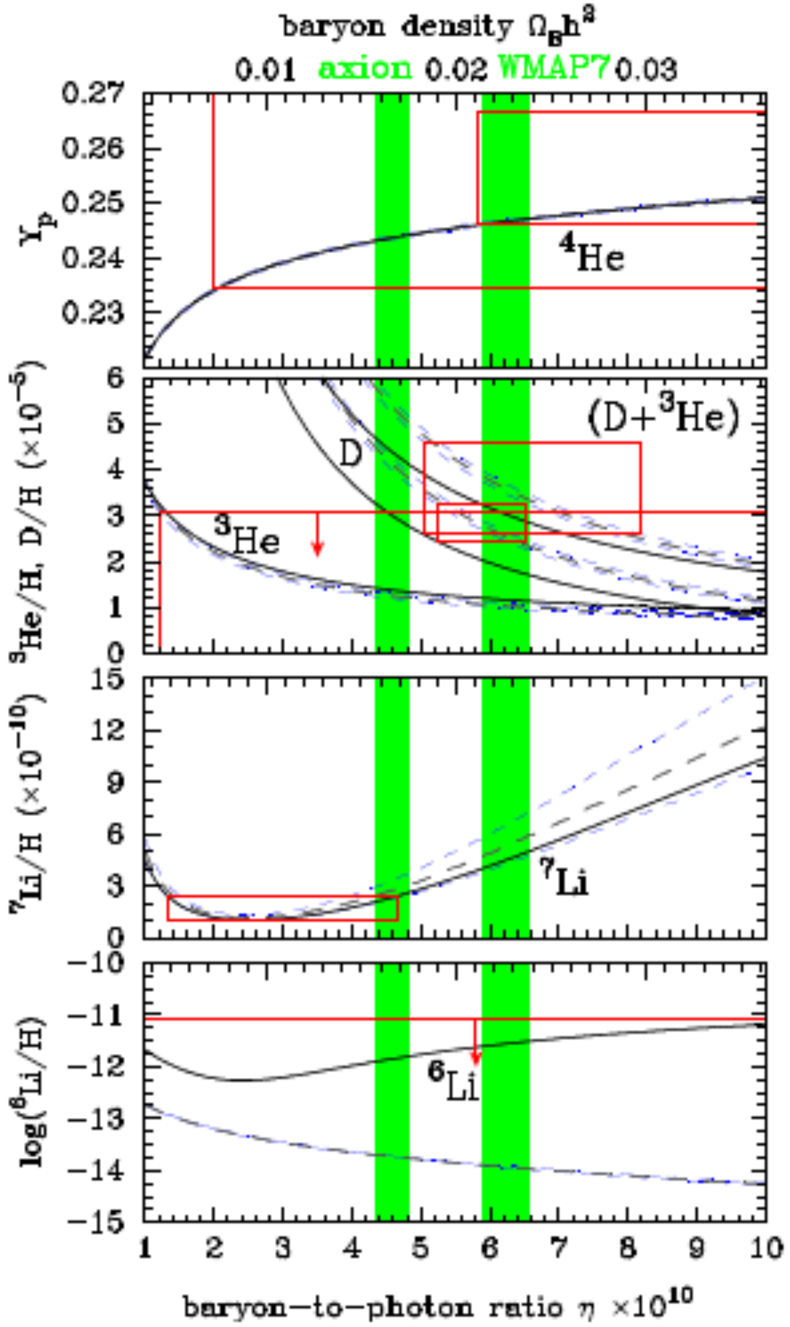
^{7}Li needed to be consistent with the microwave photon observations

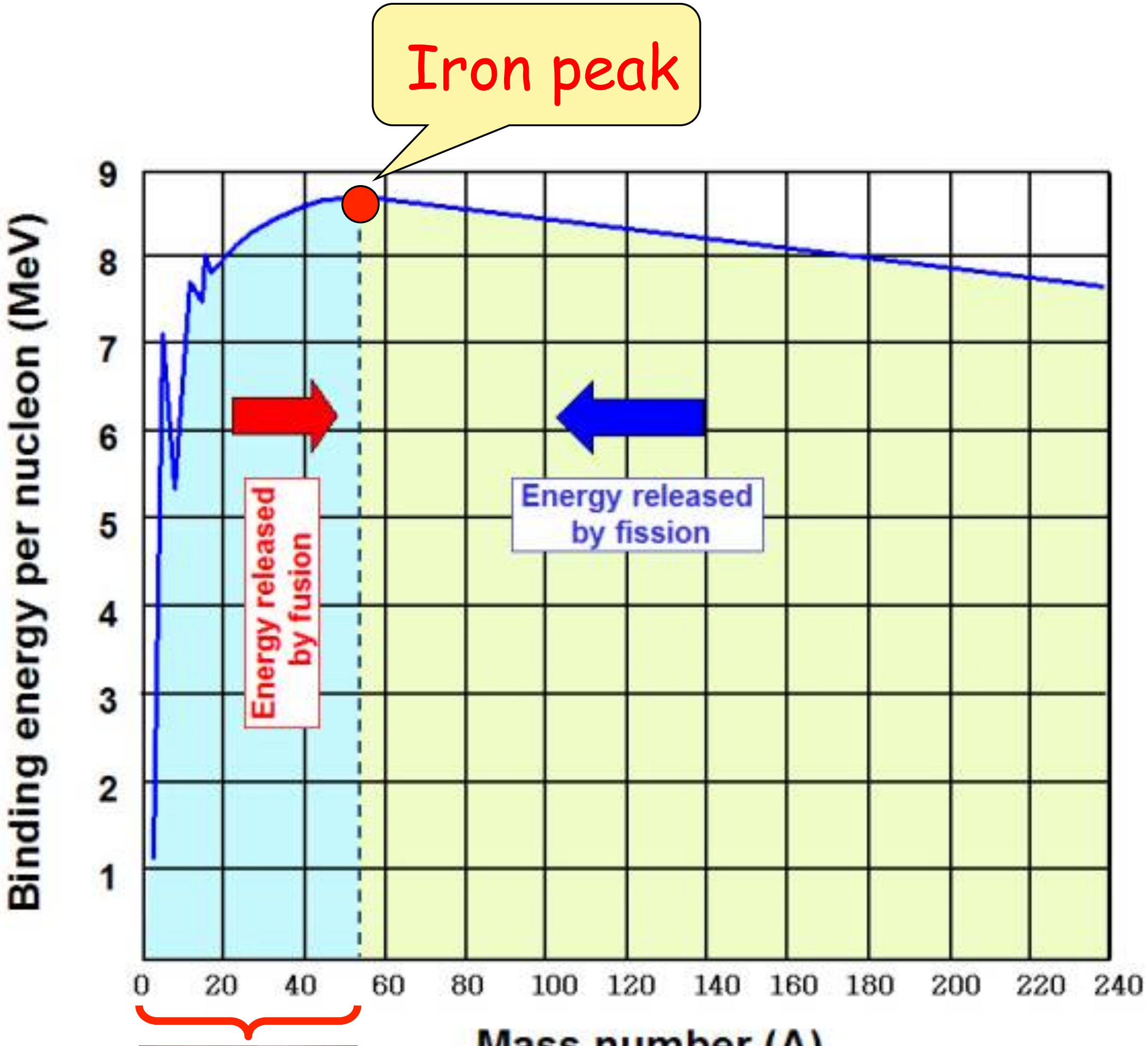
^{7}Li observed in old halo stars

^{7}Li is made in the Early Universe. But still much work needs to be done!

- One possibility: Axion BEC causes photons to lose energy: Erken, *et al.*, *PRL* **108**, 061304 (2012).
- But this creates a problem with the deuterium abundance.
- Solution: Introduce particles that decay into non-thermal photons. Kusakabe, Balantekin, Kajino and Pehlivan, arXiv: 1202.5603 [astro-ph.CO].



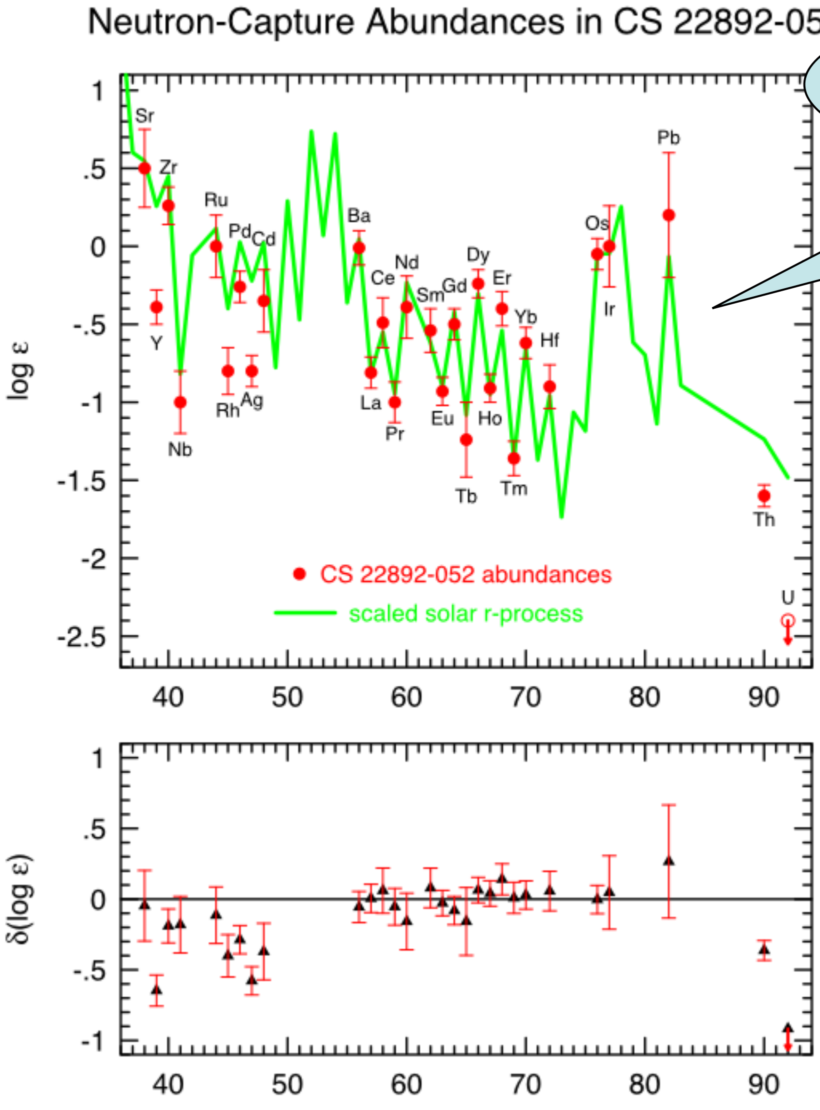




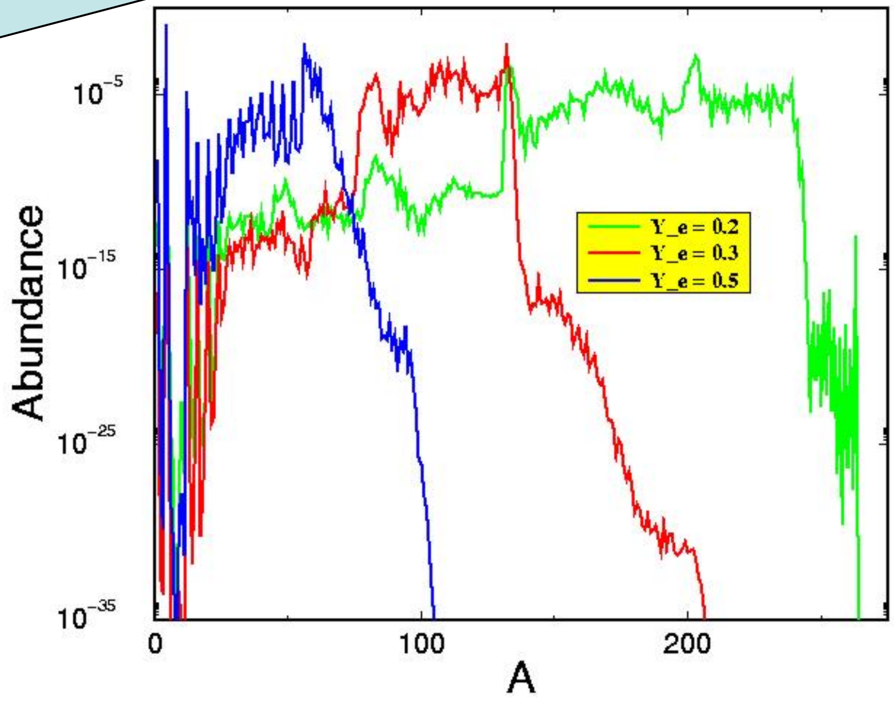
to produce these nuclei another process besides fusion is needed

One way to produce most of the elements heavier than iron is via rapid neutron capture (r-process)

[Fe/H] ≈ -3.1

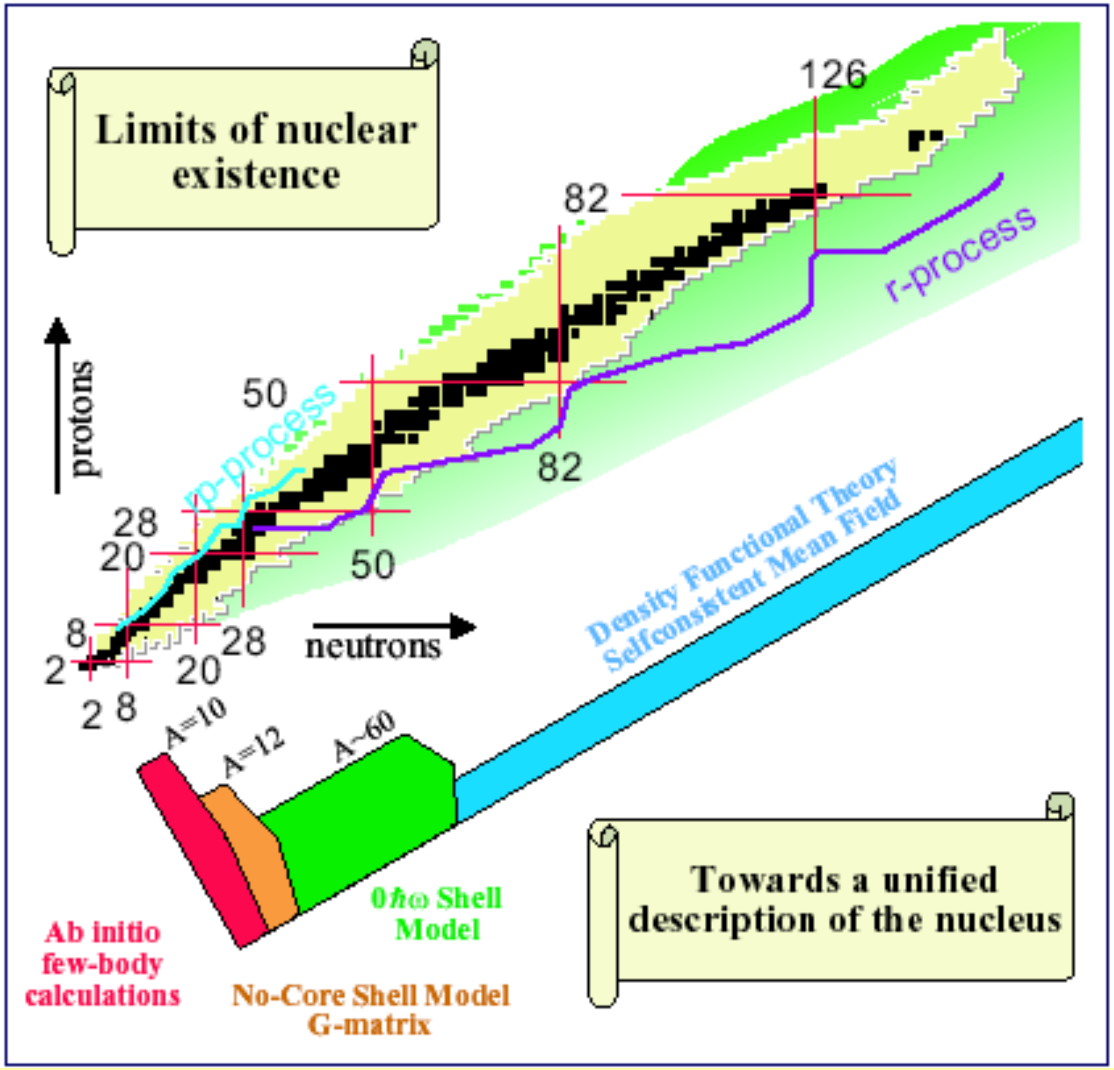


A > 100 abundance pattern fits the solar abundances well



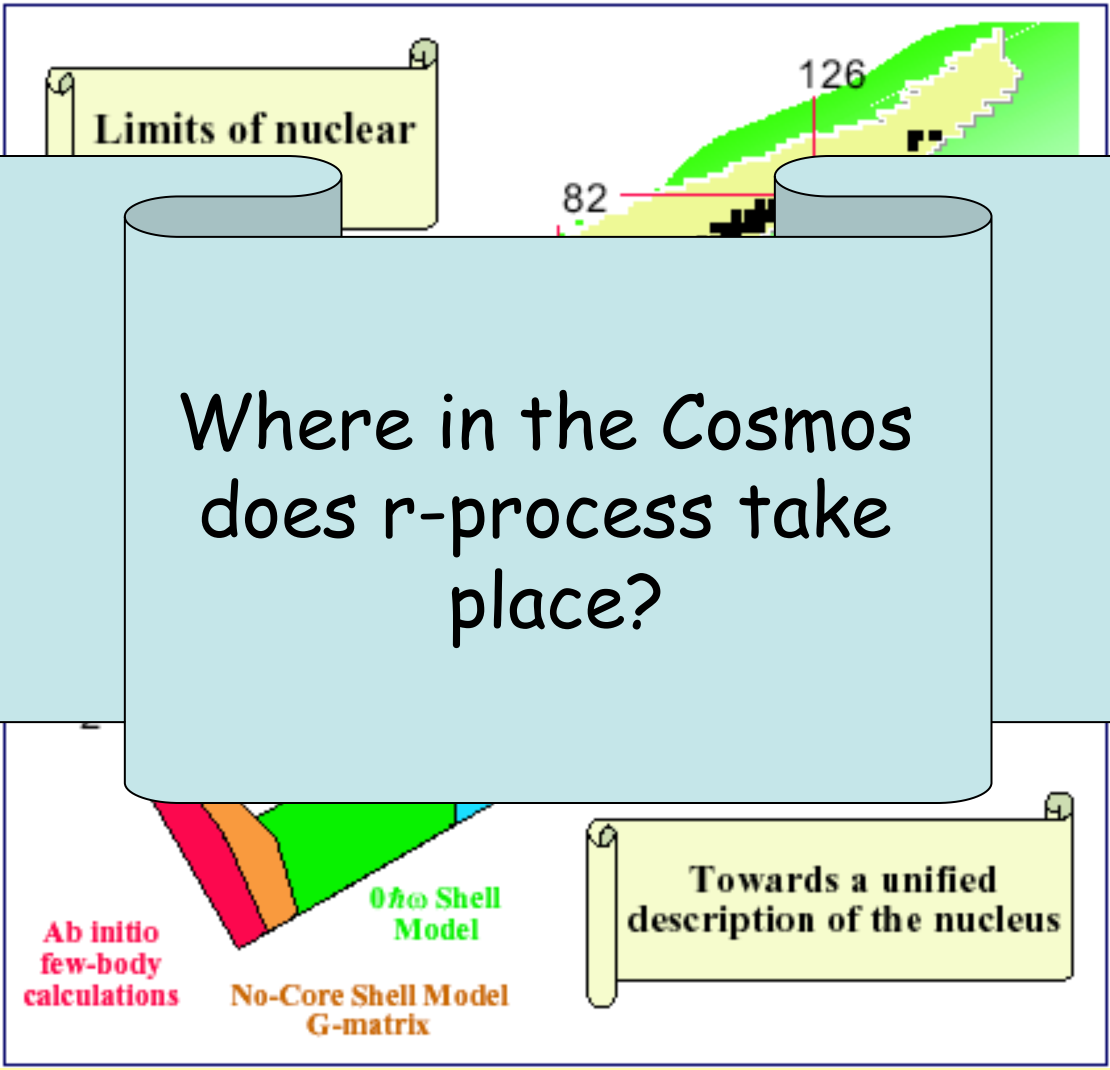
r-process abundances should depend very strongly on electron fraction Meyer

To understand the r-process one needs to first understand beta-decays of nuclei both at and far-from stability:



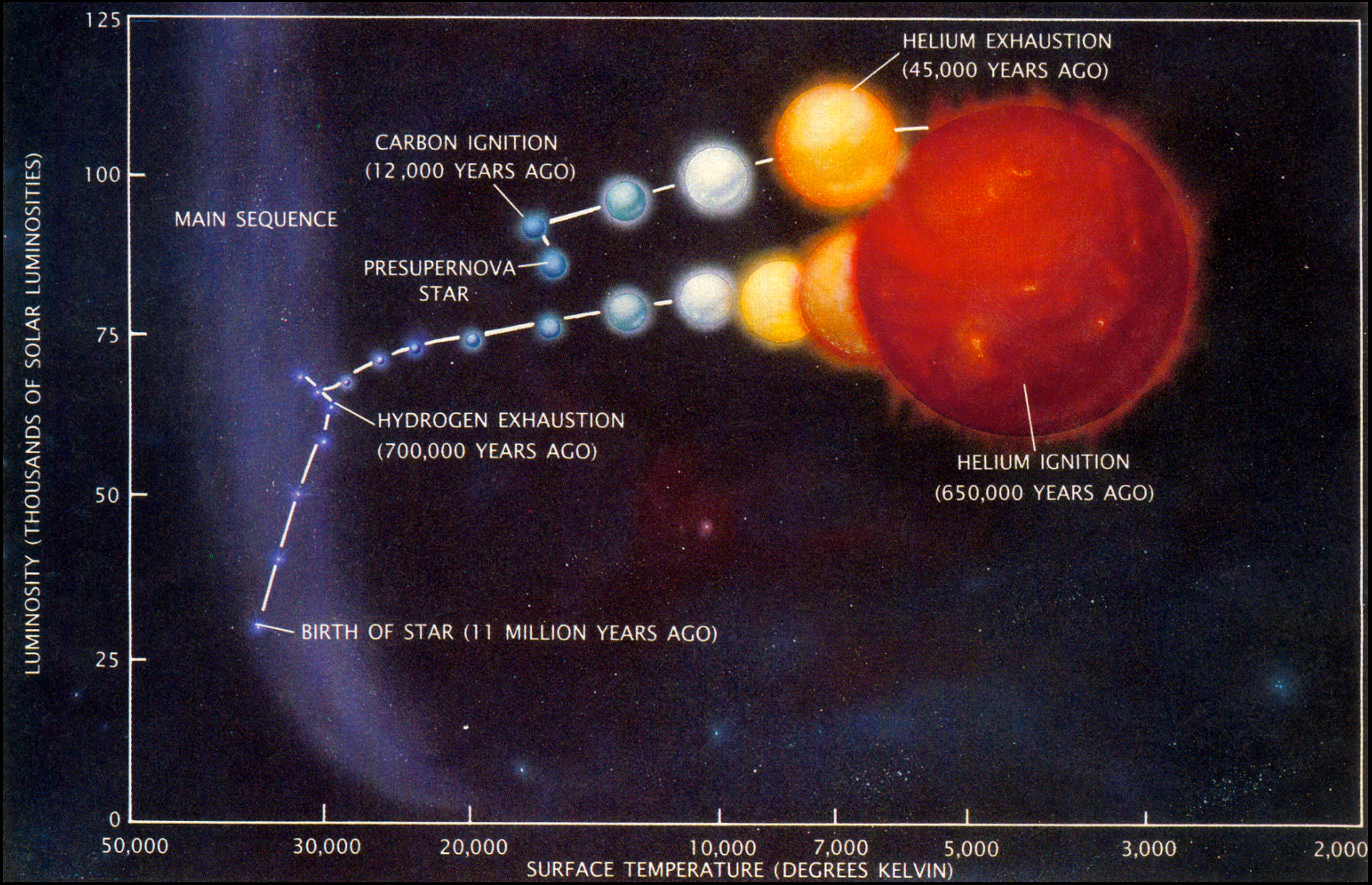
Understanding the spin-isospin response of a broad range of nuclei to a variety of probes is crucial for astrophysics applications!

To understand the r-process one needs to first understand beta-decays of nuclei both at and far-from stability:

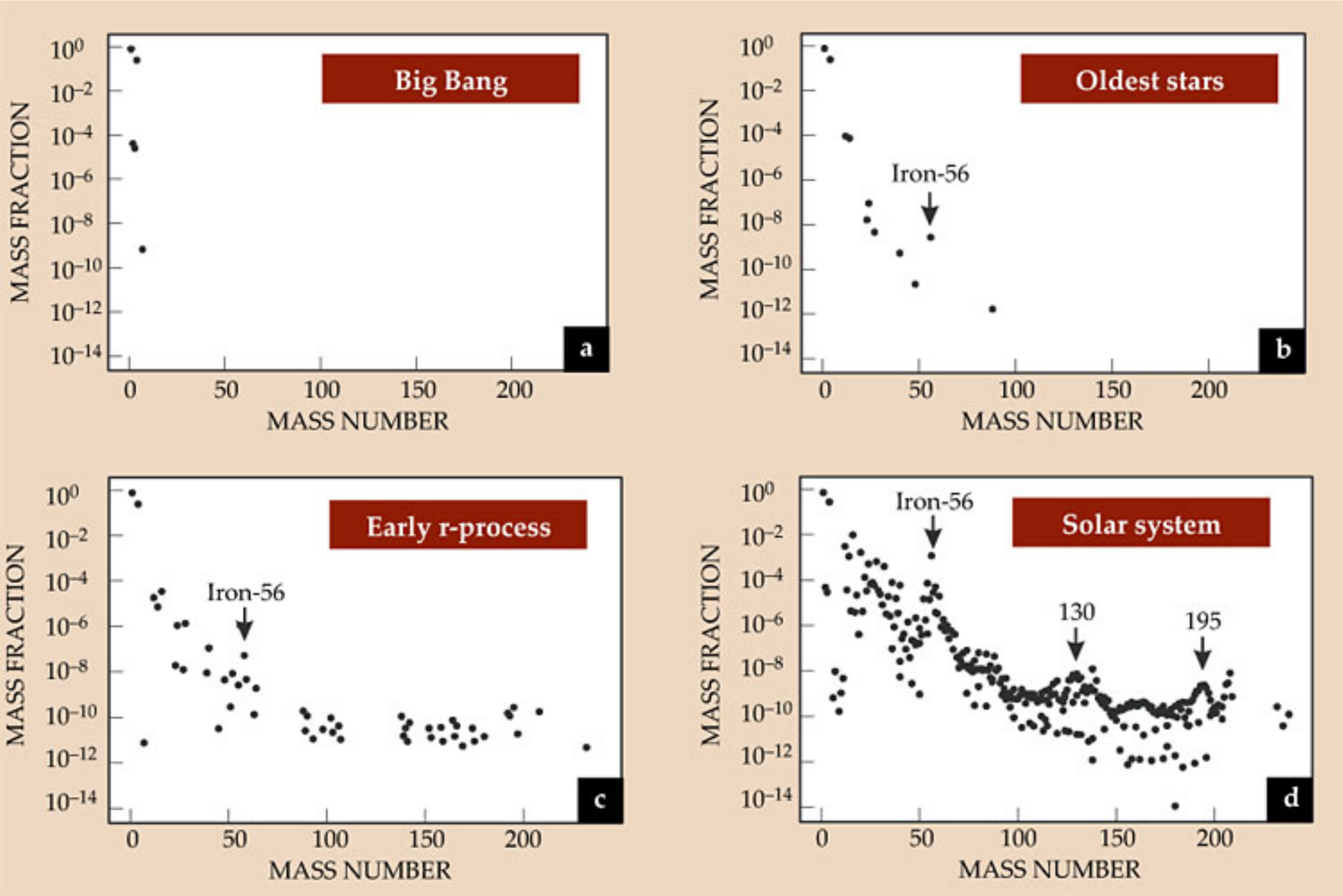


Where in the Cosmos does r-process take place?

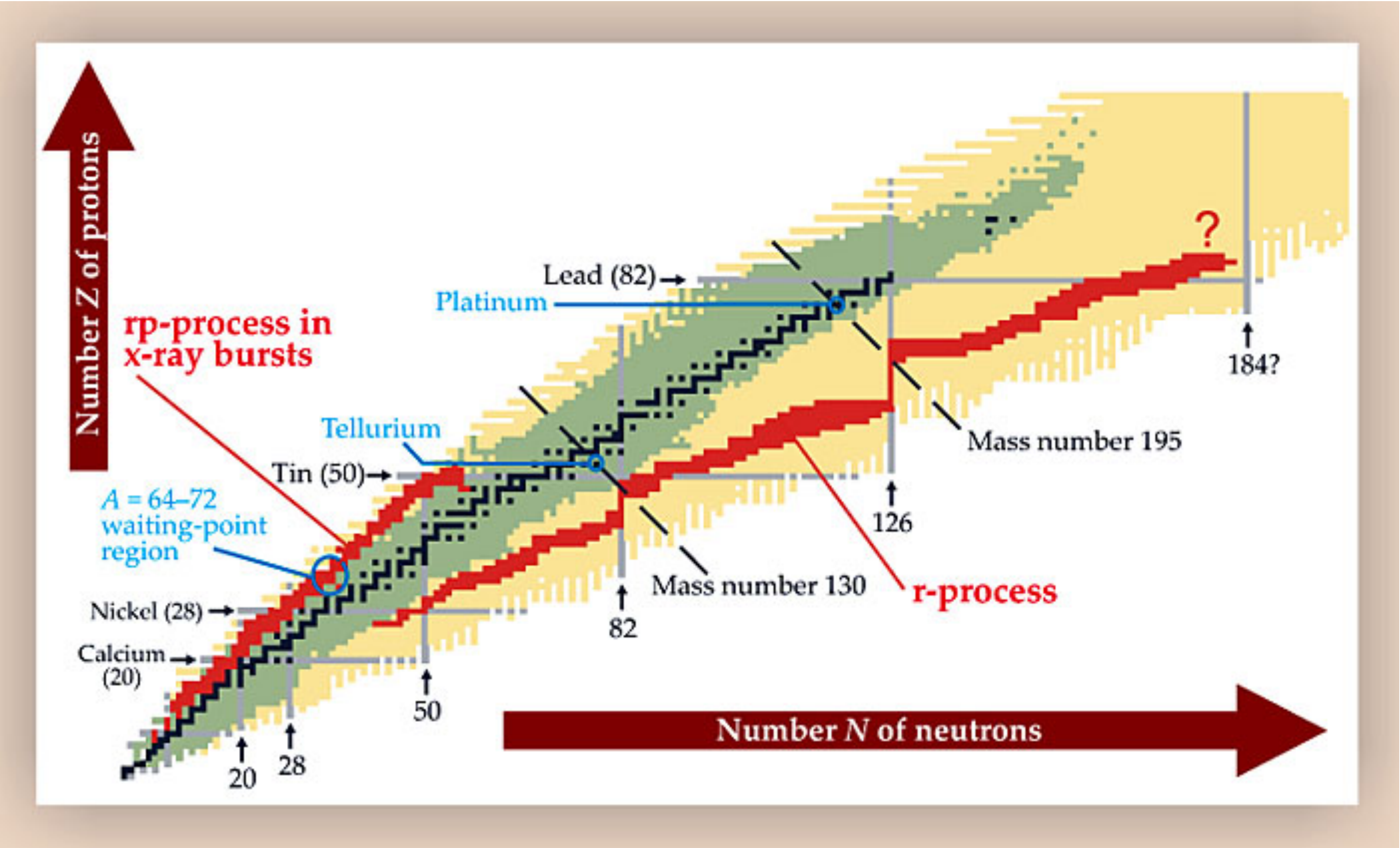
Understanding the spin-isospin response of a broad range of nuclei to a variety of probes is crucial for astrophysics applications!



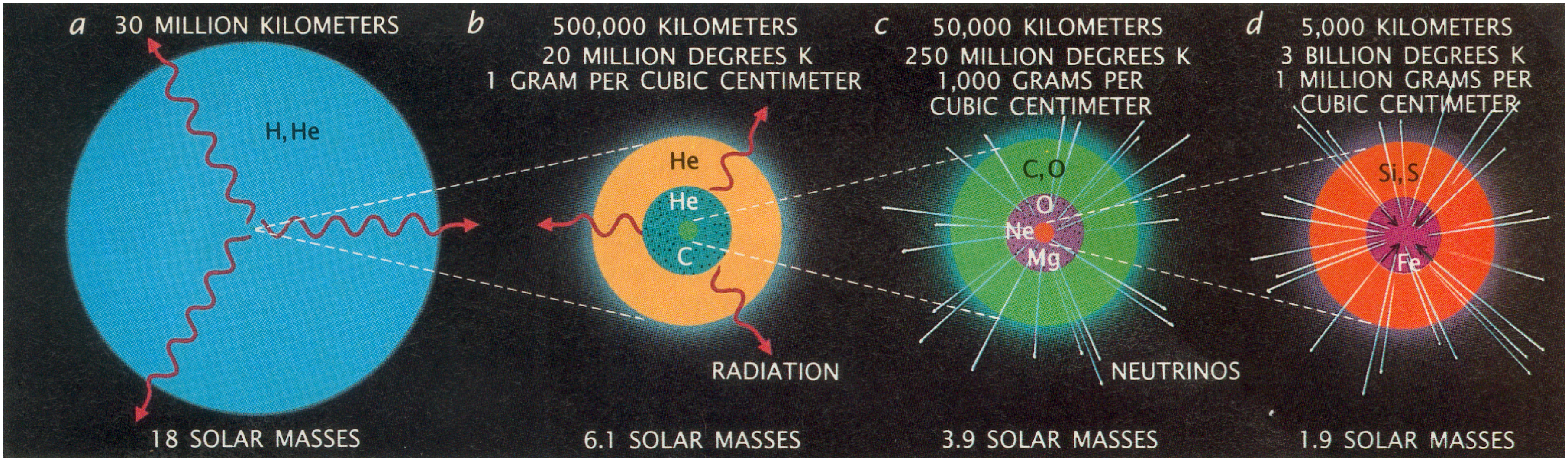
Weaver & Woosley, ***Sci Am***, **1987**

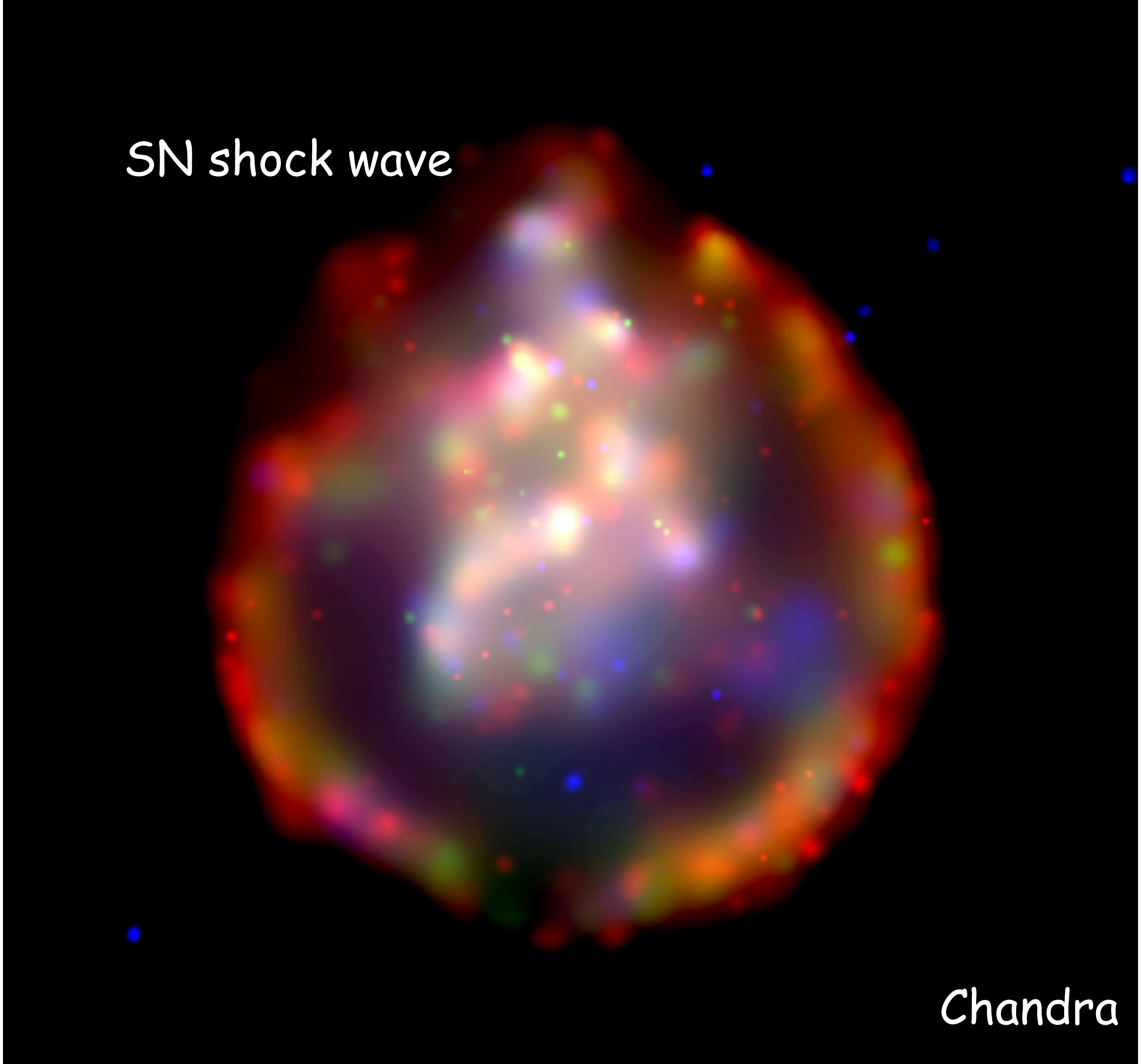


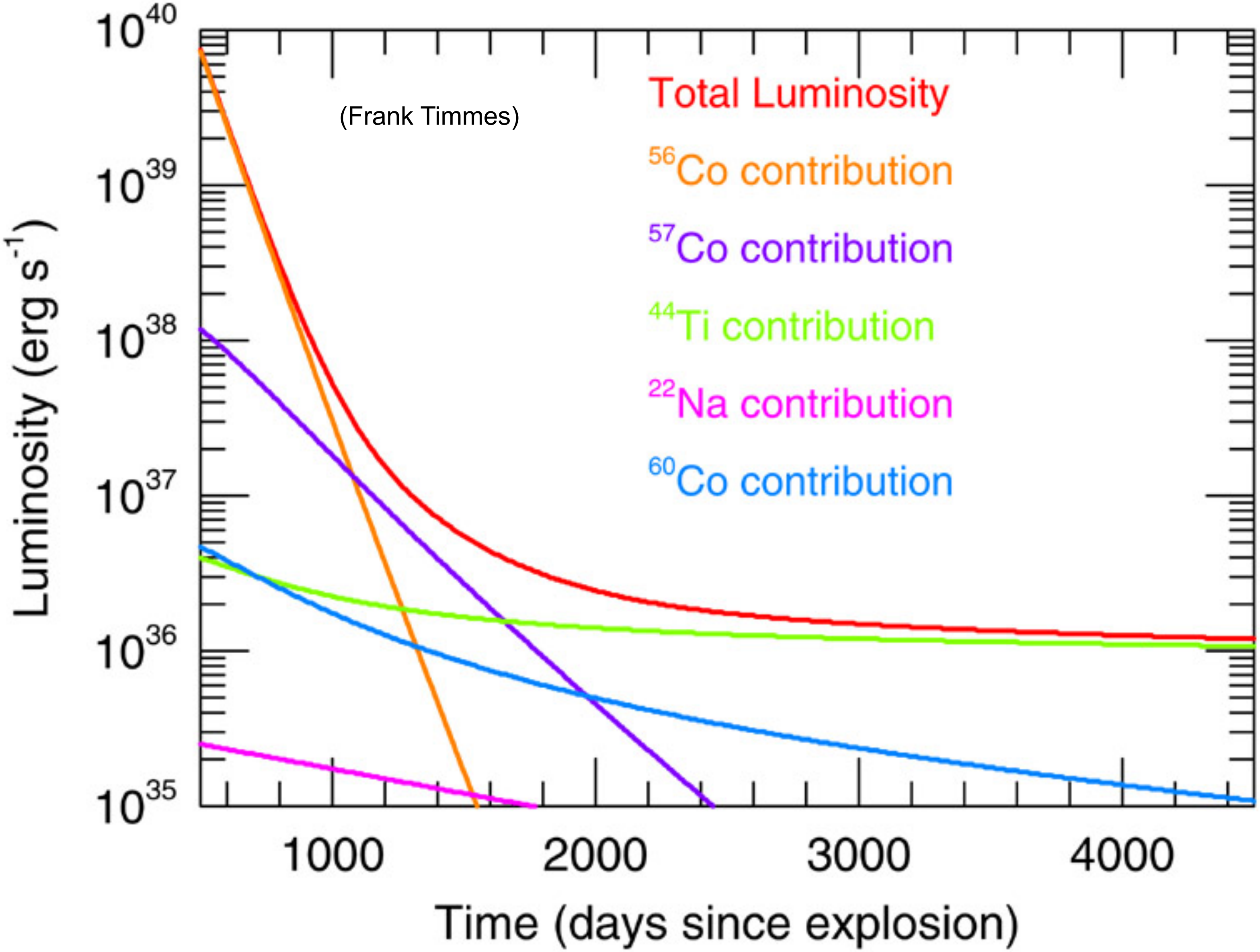
From H. Schatz



From H. Schatz

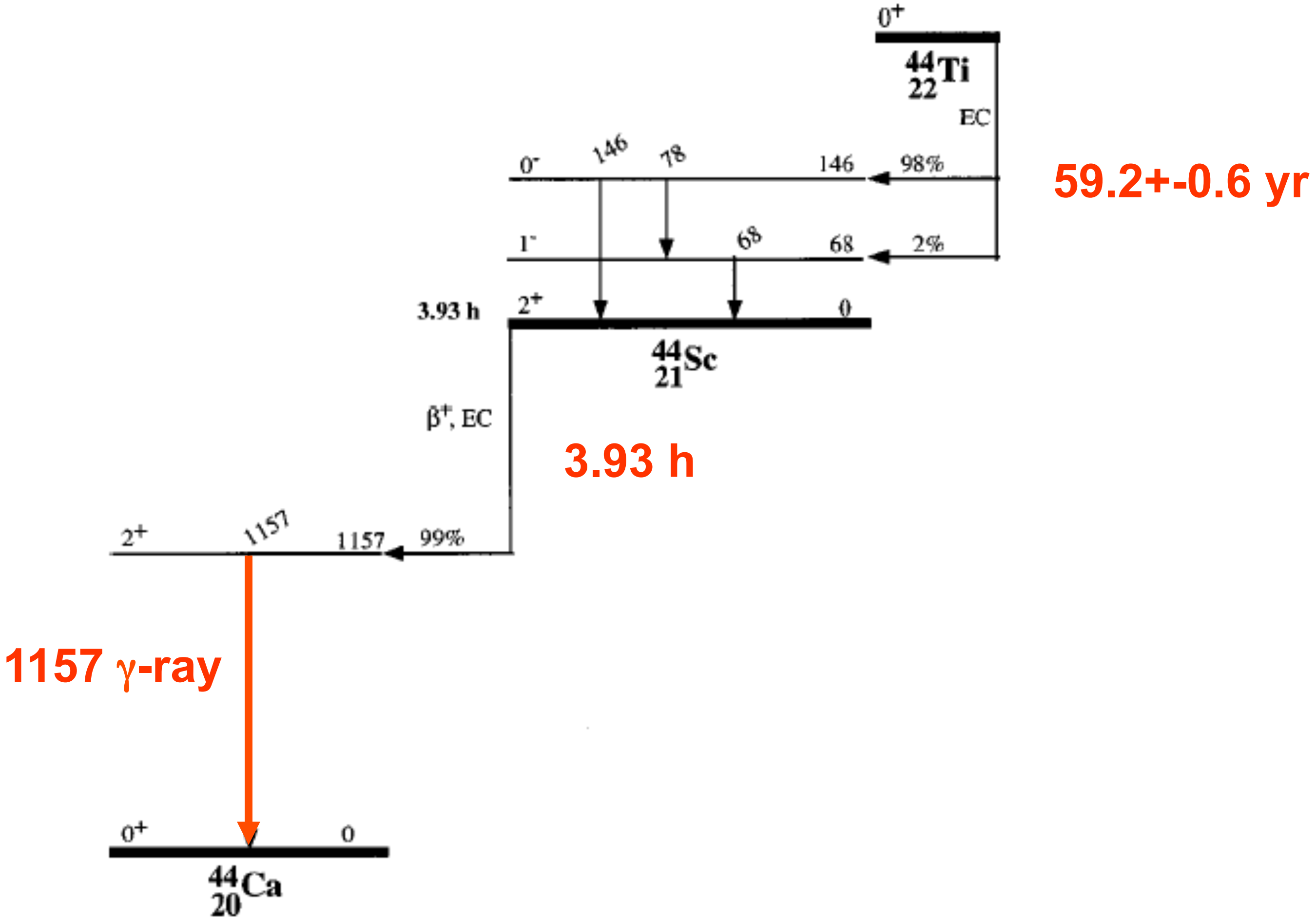
a
30 MILLION KILOMETERS
H, He
18 SOLAR MASSES
b
500,000 KILOMETERS
20 MILLION DEGREES K
1 GRAM PER CUBIC CENTIMETER
He
He
C
RADIATION
6.1 SOLAR MASSES
c
50,000 KILOMETERS
250 MILLION DEGREES K
1,000 GRAMS PER
CUBIC CENTIMETER
C, O
O
Ne
Mg
NEUTRINOS
3.9 SOLAR MASSES
d
5,000 KILOMETERS
3 BILLION DEGREES K
1 MILLION GRAMS PER
CUBIC CENTIMETER
Si, S
Fe
1.9 SOLAR MASSES


SN shock wave
Chandra



(Frank Timmes)

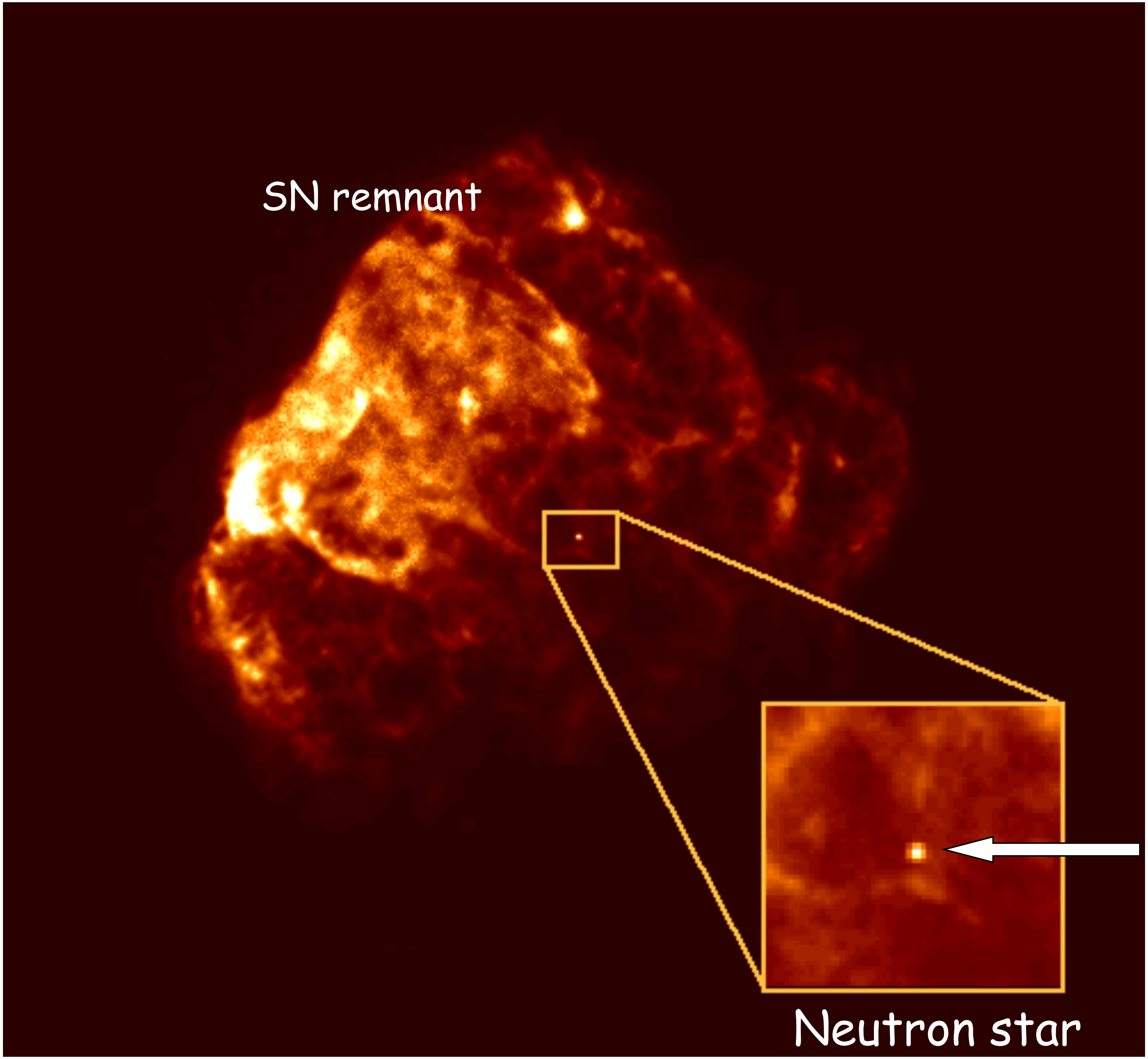
44Ti



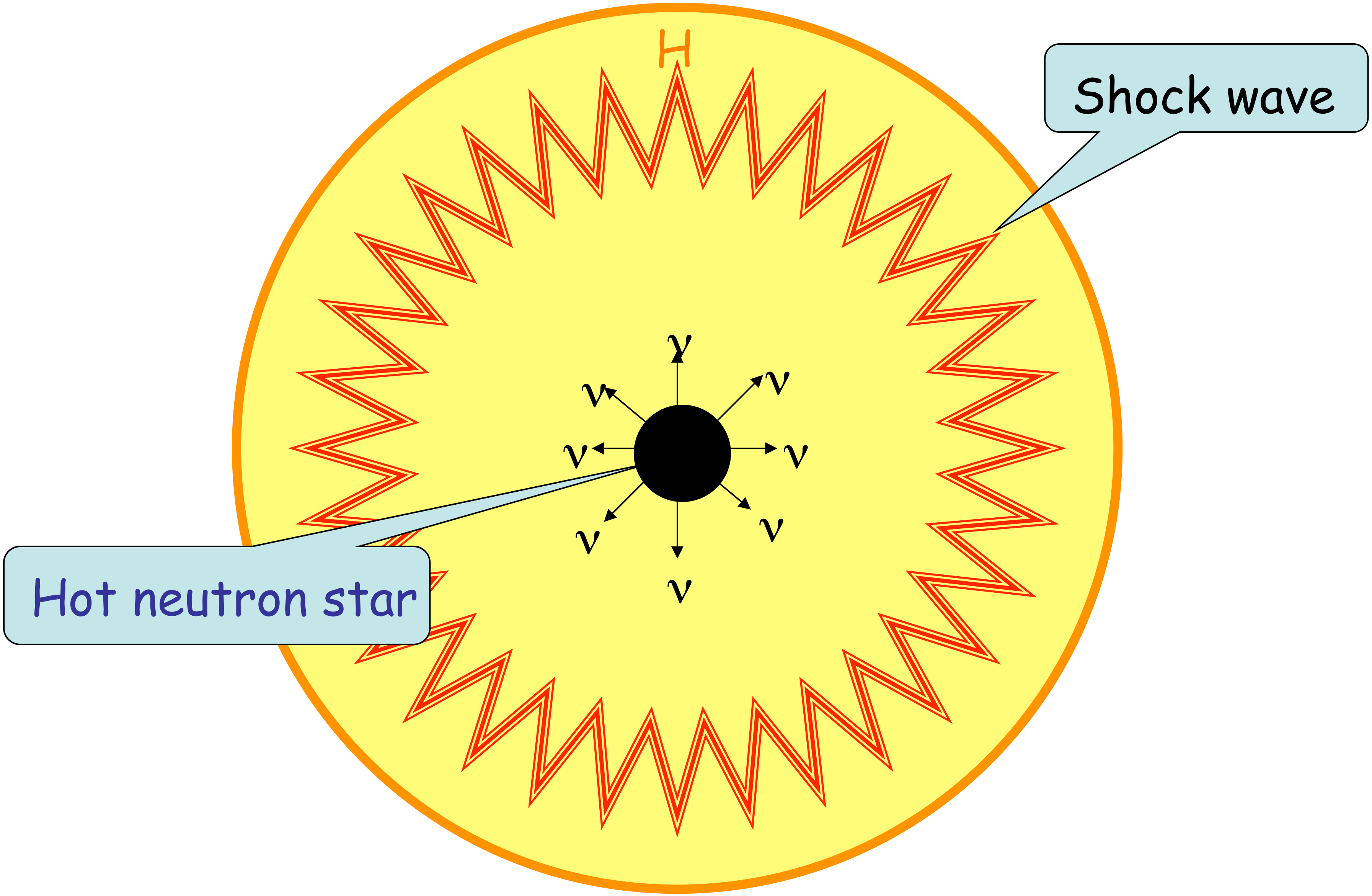
59.2+-0.6 yr

3.93 h

1157 γ-ray

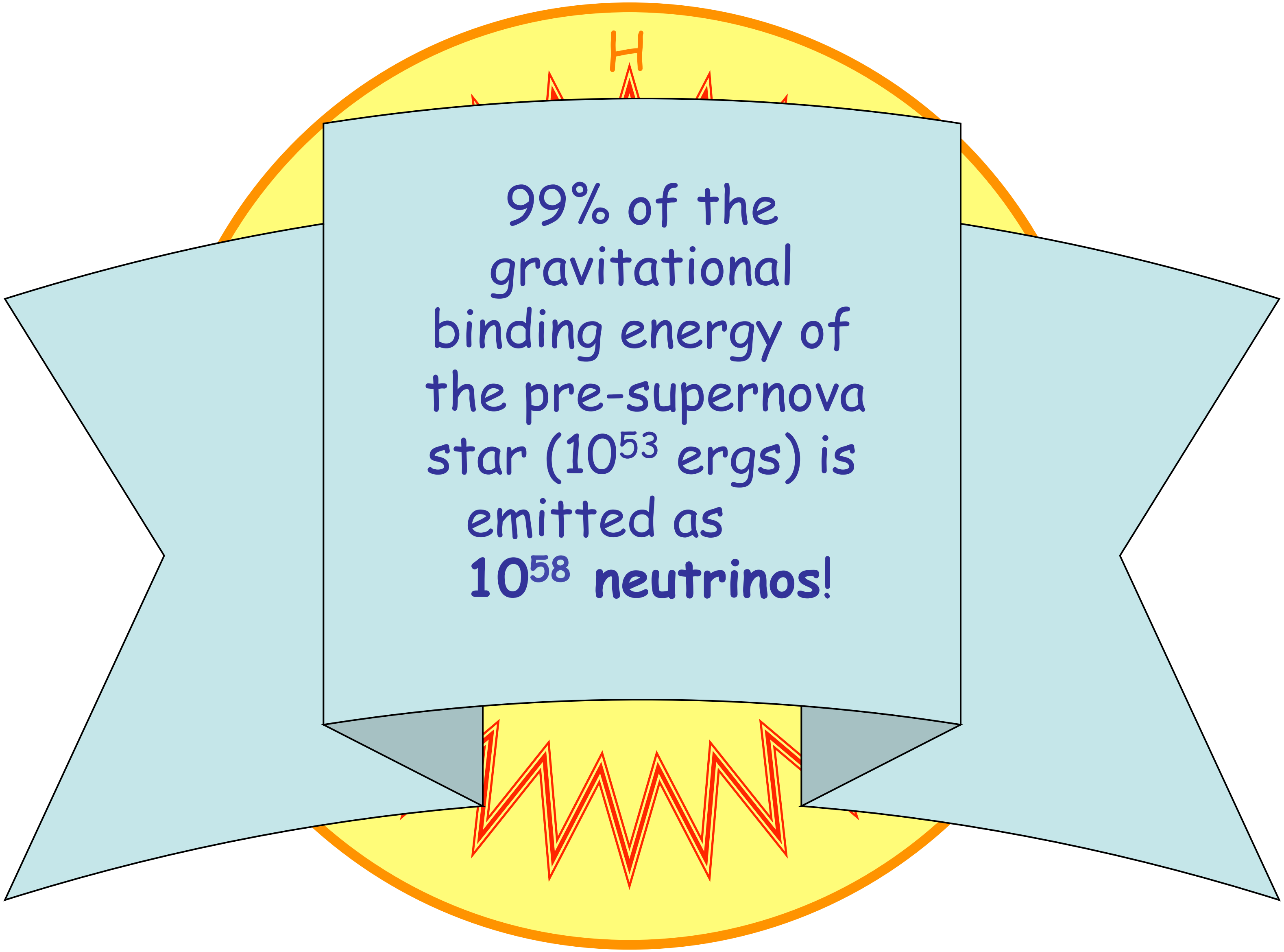


99% of the gravitational binding energy of the star

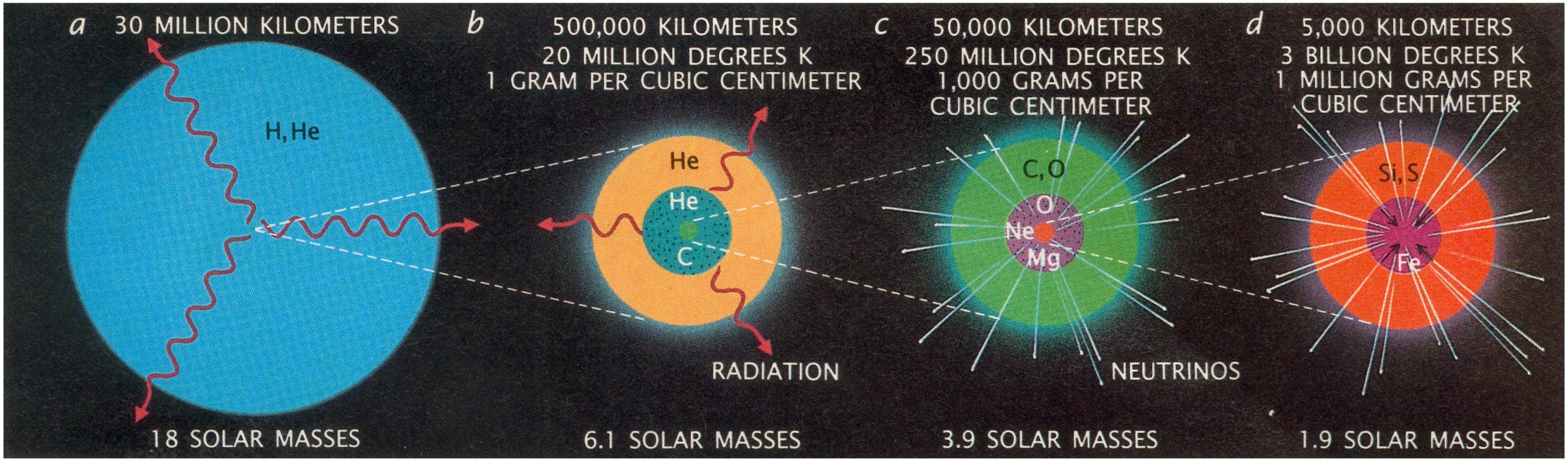


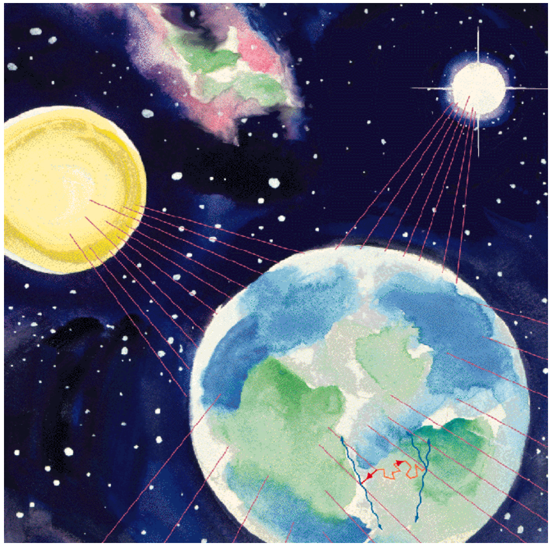
Shock wave

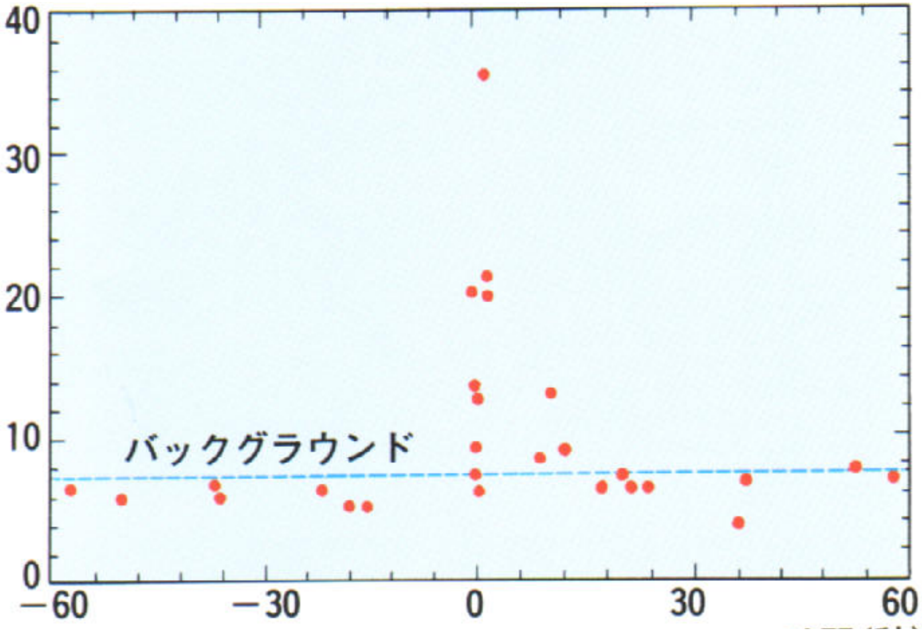
Hot neutron star



99% of the gravitational binding energy of the pre-supernova star (10^{53} ergs) is emitted as **10^{58} neutrinos**!


a
30 MILLION KILOMETERS
H, He
18 SOLAR MASSES
b
500,000 KILOMETERS
20 MILLION DEGREES K
1 GRAM PER CUBIC CENTIMETER
He
He
C
RADIATION
6.1 SOLAR MASSES
c
50,000 KILOMETERS
250 MILLION DEGREES K
1,000 GRAMS PER
CUBIC CENTIMETER
C, O
O
Ne
Mg
NEUTRINOS
3.9 SOLAR MASSES
d
5,000 KILOMETERS
3 BILLION DEGREES K
1 MILLION GRAMS PER
CUBIC CENTIMETER
Si, S
Fe
1.9 SOLAR MASSES




40
30
20
10
0
バックグラウンド
−60
−30
0
30
60

Yields of r-process nucleosynthesis are determined by neutron-to-proton ratio, n/p

Interactions of the neutrinos and antineutrinos streaming out of the core both with nucleons and seed nuclei determine the n/p ratio. ❶ Hence it is crucial to understand neutrino-nucleon cross-sections.

Before these neutrinos reach the r-process region they undergo matter-enhanced neutrino oscillations.

The MSW Effect

In vacuum: $E^2 = \mathbf{p}^2 + m^2$

In matter:

$(E - V)^2 = (\mathbf{p} - \mathbf{A})^2 + m^2$

$\Rightarrow E^2 = \mathbf{p}^2 + m^2_{\text{eff}}$

V $\propto$ background density

$\mathbf{A} \propto \mathbf{J}_{\text{background}}$ (currents) or

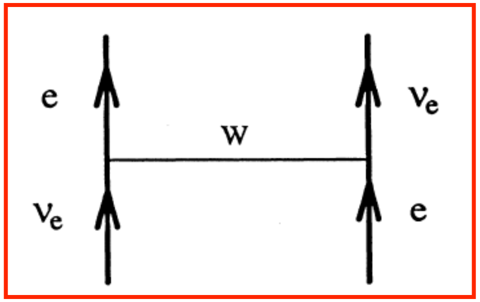
$\mathbf{A} \propto \mathbf{S}_{\text{background}}$ (spin)

In the limit of static, charge-neutral, and unpolarized background

V$\propto N_e$ and $\mathbf{A} = 0$

$\Rightarrow m^2_{\text{eff}} = m^2 + 2EV + \mathcal{O}(V^2)$

The potential is provided by the coherent forward scattering of ν_e's off the electrons in dense matter



There is a similar term with Z-exchange. But since it is the same for all neutrino flavors, it does not contribute to phase differences *unless* we invoke a sterile neutrino.

Yields of r-process nucleosynthesis are determined by neutron-to-proton ratio, n/p

Interactions of the neutrinos and antineutrinos streaming out of the core both with nucleons and seed nuclei determine the n/p ratio. ❶ Hence it is crucial to understand neutrino-nucleon cross-sections.

Before these neutrinos reach the r-process region they undergo matter-enhanced neutrino oscillations as well as coherently scatter over other neutrinos. ❷ Many-body behavior of this neutrino gas is not well understood, but may have significant impact on r-process nucleosynthesis.

Recall that nucleosynthesis in core-collapse supernovae occurs in conditions which are the isospin-mirror of the conditions for Big-bang nucleosynthesis!

Big-Bang: $n/p \ll 1$

Core-collapse SN: $n/p \gg 1$

Mass and Flavor States

$$a_1(\mathbf{p}, s) = \cos\theta\, a_e(\mathbf{p}, s) - \sin\theta\, a_x(\mathbf{p}, s)$$

$$a_2(\mathbf{p}, s) = \sin\theta\, a_e(\mathbf{p}, s) + \cos\theta\, a_x(\mathbf{p}, s)$$

Flavor Isospin Operators

$$\mathfrak{J}^+_{\mathbf{p},s} = a^\dagger_e(\mathbf{p}, s) a_x(\mathbf{p}, s) \ , \qquad \mathfrak{J}^-_{\mathbf{p},s} = a^\dagger_x(\mathbf{p}, s) a_e(\mathbf{p}, s) \ ,$$

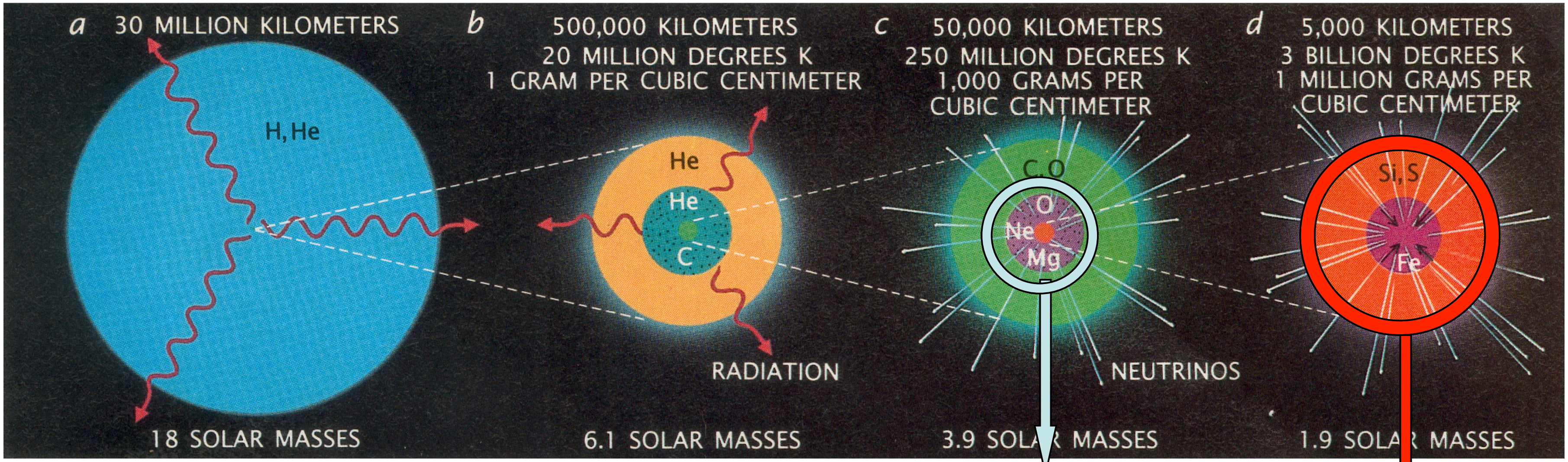
$$\mathfrak{J}^0_{\mathbf{p},s} = \frac{1}{2}\left(a^\dagger_e(\mathbf{p}, s) a_e(\mathbf{p}, s) - a^\dagger_x(\mathbf{p}, s) a_x(\mathbf{p}, s) \right)$$

$$[\mathfrak{J}^+_{\mathbf{p},s}, \mathfrak{J}^-_{\mathbf{q},r}] = 2\delta_{\mathbf{pq}}\delta_{sr}\mathfrak{J}^0_{\mathbf{p},s} \ , \qquad [\mathfrak{J}^0_{\mathbf{p},s}, \mathfrak{J}^\pm_{\mathbf{q},r}] = \pm\delta_{\mathbf{pq}}\delta_{sr}\mathfrak{J}^\pm_{\mathbf{p},s} \ ,$$

The total neutrino Hamiltonian

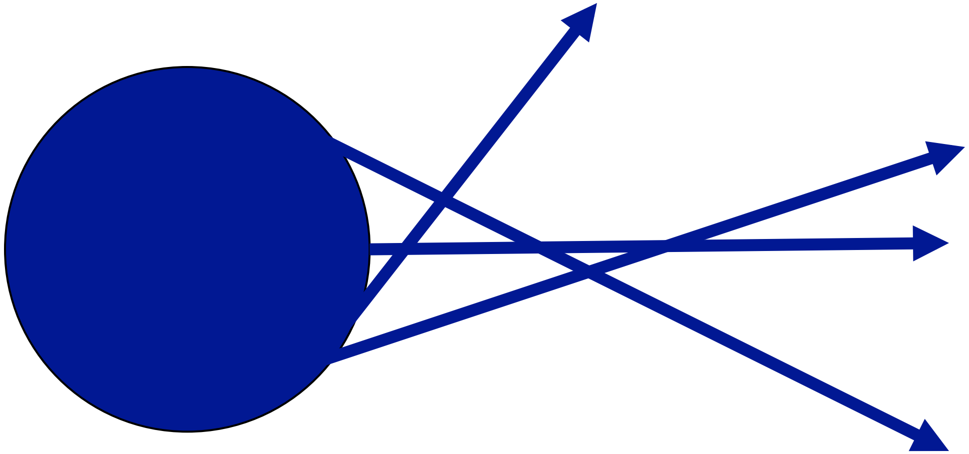
$$
\begin{aligned}
\hat{H}_{\text{total}} = H_\nu + H_{\nu\nu} &= \left(\sum_p \frac{\delta m^2}{2p} \hat{B} \cdot \vec{J}_p - \sqrt{2} G_F N_e J_p^0 \right) \\
&+ \frac{\sqrt{2} G_F}{V} \sum_{\mathbf{p},\mathbf{q}} \left(1 - \cos \vartheta_{\mathbf{pq}}\right) \vec{J}_{\mathbf{p}} \cdot \vec{J}_{\mathbf{q}}
\end{aligned}
$$

Pantaleone, Dasgupta, Fogli, Fuller, Kostelecky, McKellar, Lisi, Mirizzi, Qian, Pastor, Raffelt, Samuel, Sawyer, Sigl, Smirnov, $\cdots$



O-Ne-Mg
core-collapse,
8 to 12 $M_\odot$

Fe core-collapse,
more than 12 $M_\odot$



Both scenarios should be effected by neutrino-neutrino interactions

Invariants

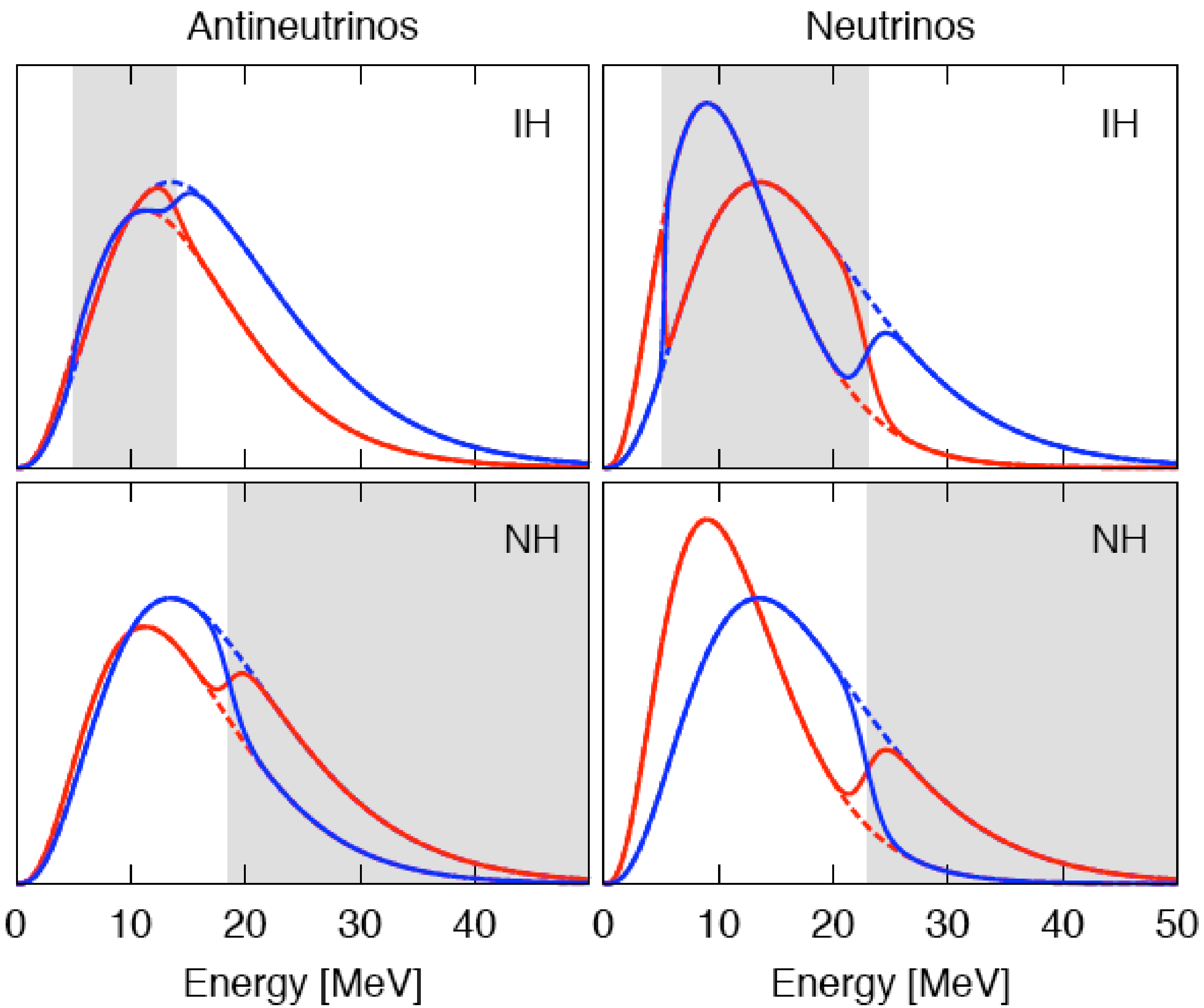
Conserved quantities for each neutrino energy mode p:

$$\hat{h}_p = \hat{B} \cdot \vec{J}_p + 2 \sum_{q(\neq p)} \frac{\vec{J}_p \cdot \vec{J}_q}{\omega_p - \omega_q} + 2 \sum_{\bar{q}} \frac{\vec{J}_p \cdot \vec{\tilde{J}}_{\bar{q}}}{\omega_p - \omega_{\bar{q}}}$$

Conserved quantity $\hat{h}_{\bar{p}}$ for each antineutrino energy mode:

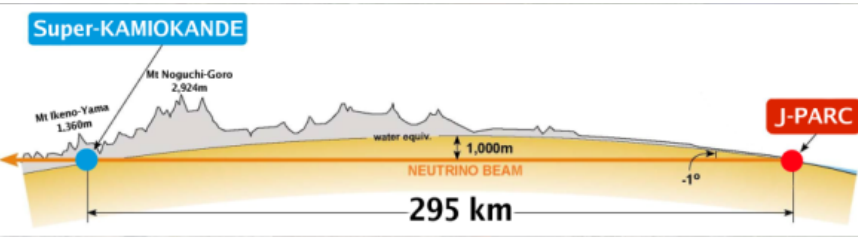
$$\hat{h}_{\bar{p}} = \hat{B} \cdot \vec{\tilde{J}}_p + 2 \sum_{\bar{q}(\neq \bar{p})} \frac{\vec{\tilde{J}}_{\bar{p}} \cdot \vec{\tilde{J}}_{\bar{q}}}{\omega_{\bar{p}} - \omega_{\bar{q}}} + 2 \sum_{q} \frac{\vec{\tilde{J}}_{\bar{p}} \cdot \vec{J}_q}{\omega_{\bar{p}} - \omega_q} \, .$$

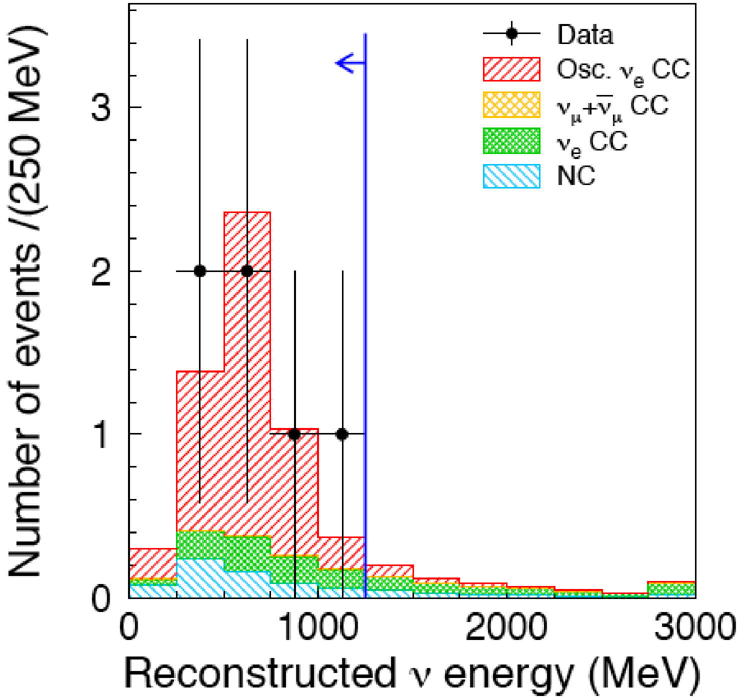
Pehlivan, Balantekin, Kajino, and T. Yoshida), Phys. Rev. D **84**, 065008 (2011)

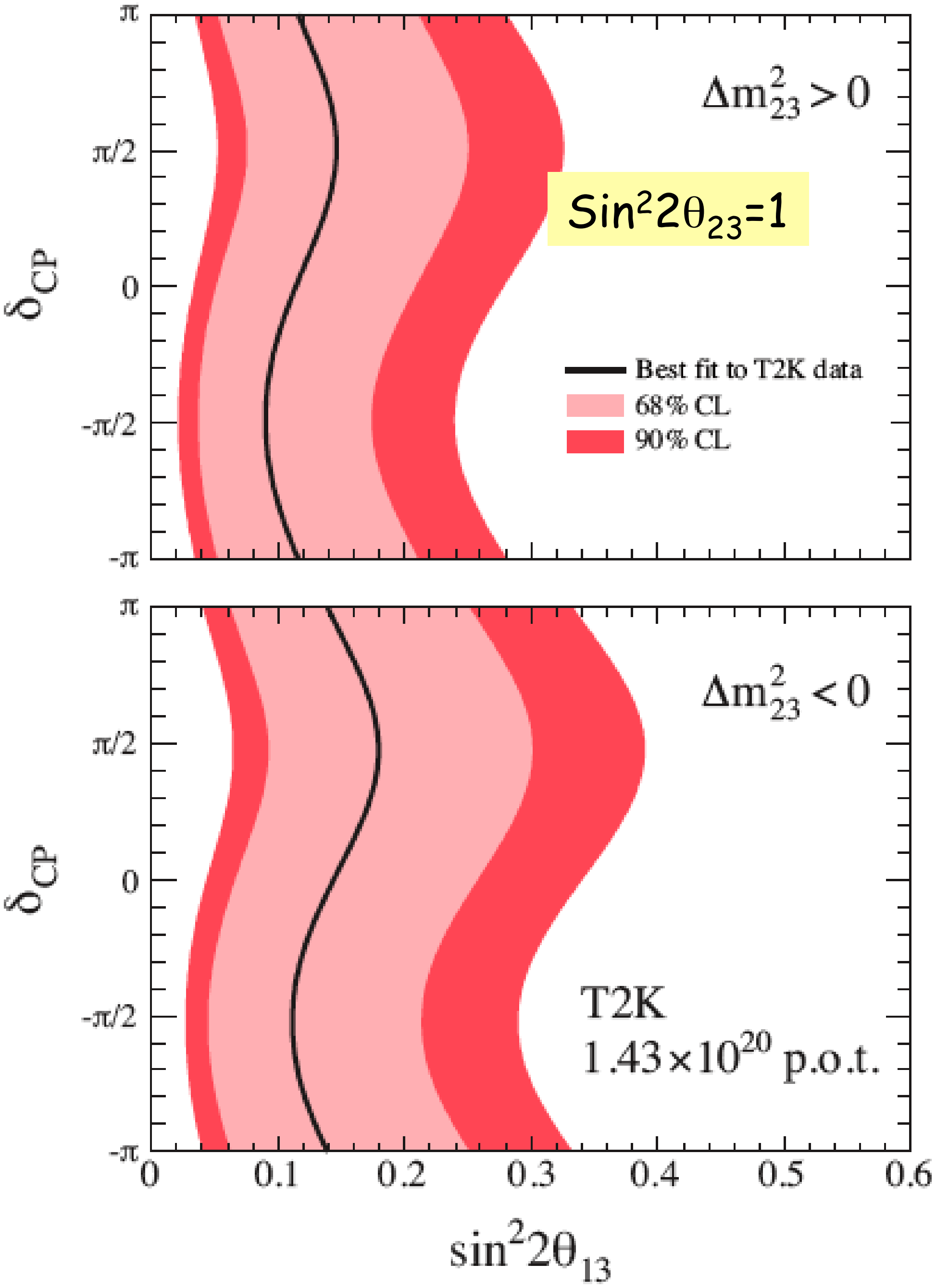


From Dasgupta and Raffelt

Recent T2K results







$\sin^2 2\theta_{23}=1$

Measuring θ_{13} with Reactor Antineutrinos

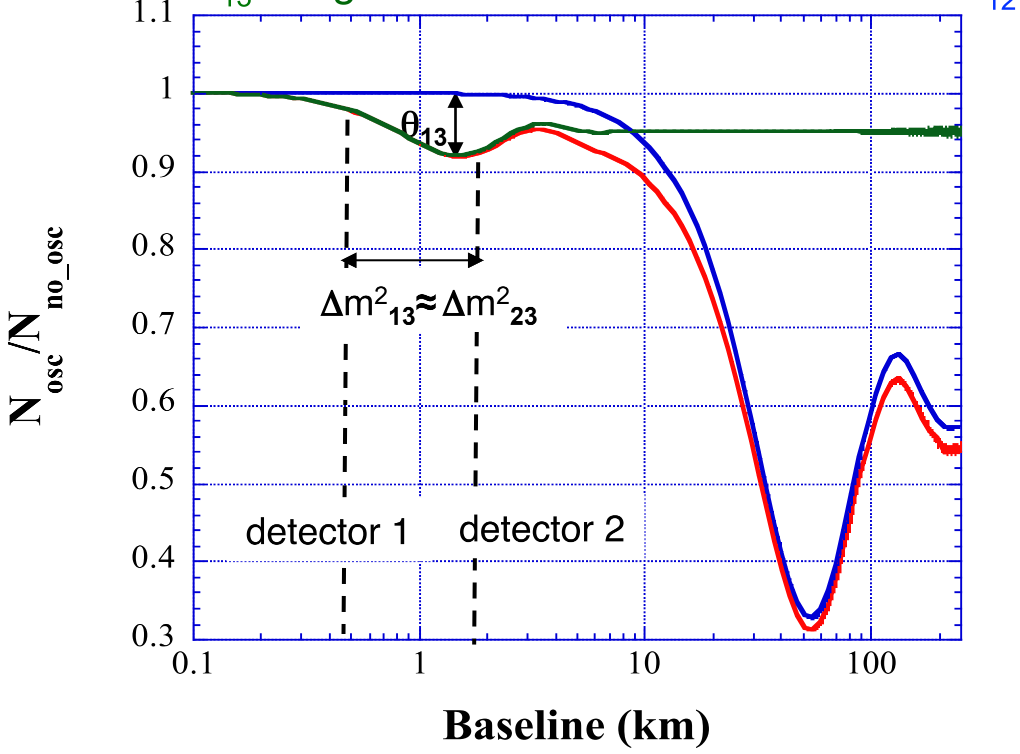
Double Chooz
Daya Bay
RENO

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

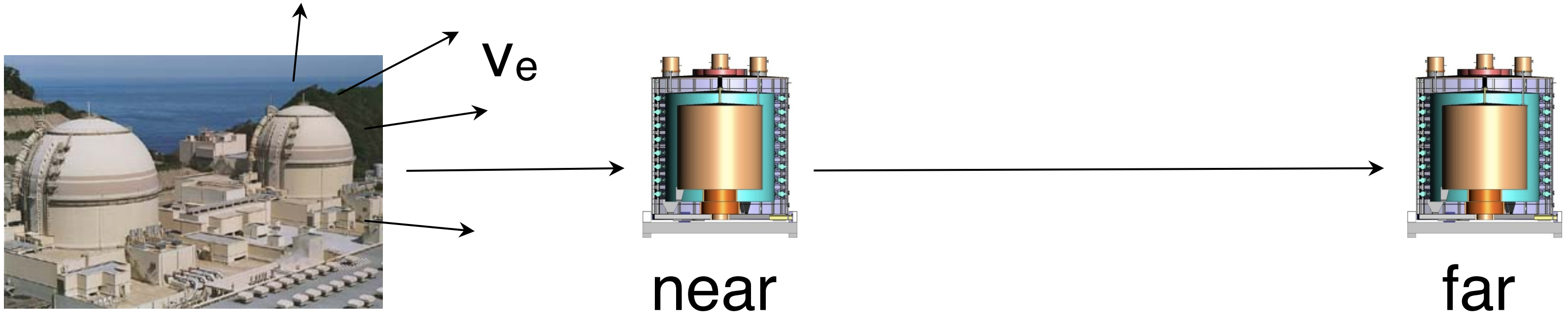
- Reactor neutrino energies are too low to produce muons. Hence this is an antineutrino disappearance experiment (also no matter effects).
- Measure ratio(s) of interaction rates in two or more detectors to cancel systematic errors.
- Those detectors will never be identical, hence one should try to control mass differences, detection efficiencies, etc.

Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}



From K. Heeger



ν_e

near

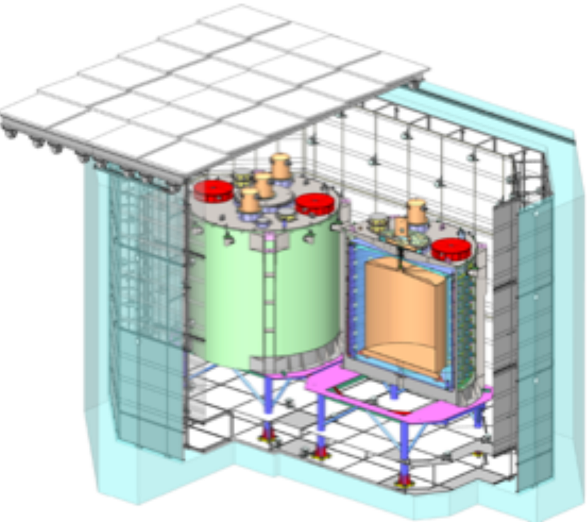
far

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\underbrace{\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]}_{\sin^2 2\theta_{13}}$$

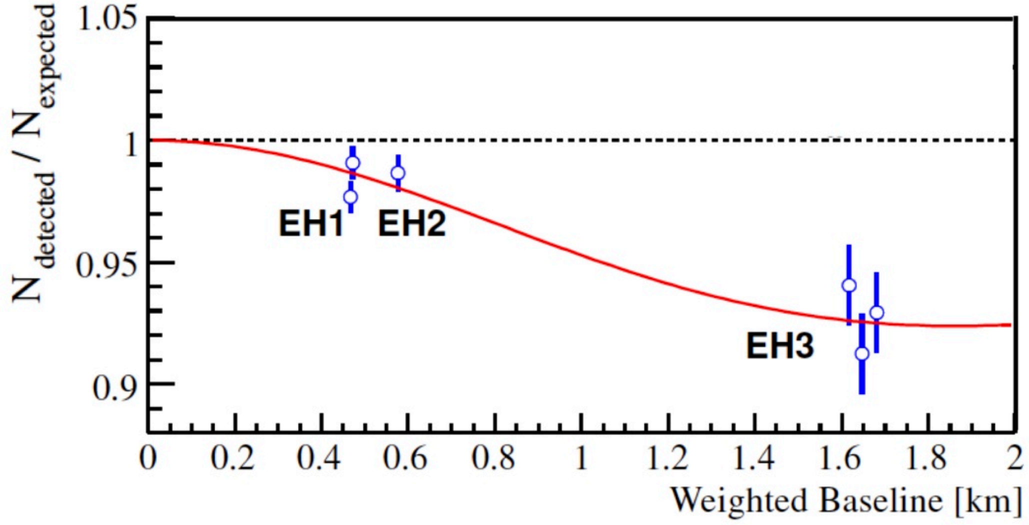
Ratio of detector masses

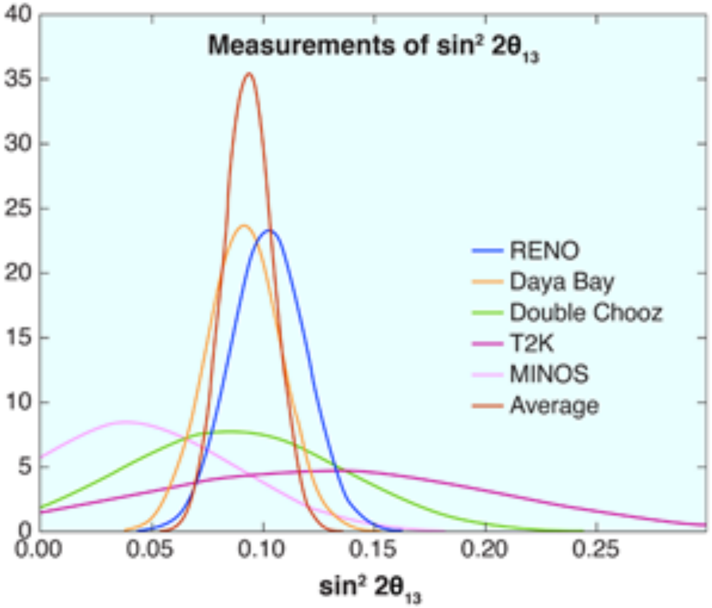
Ratio of detector efficiencies

Daya Bay θ_{13} Measurement



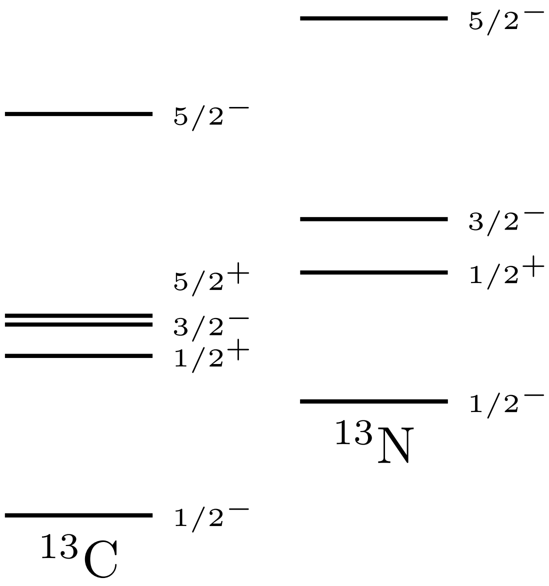
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$

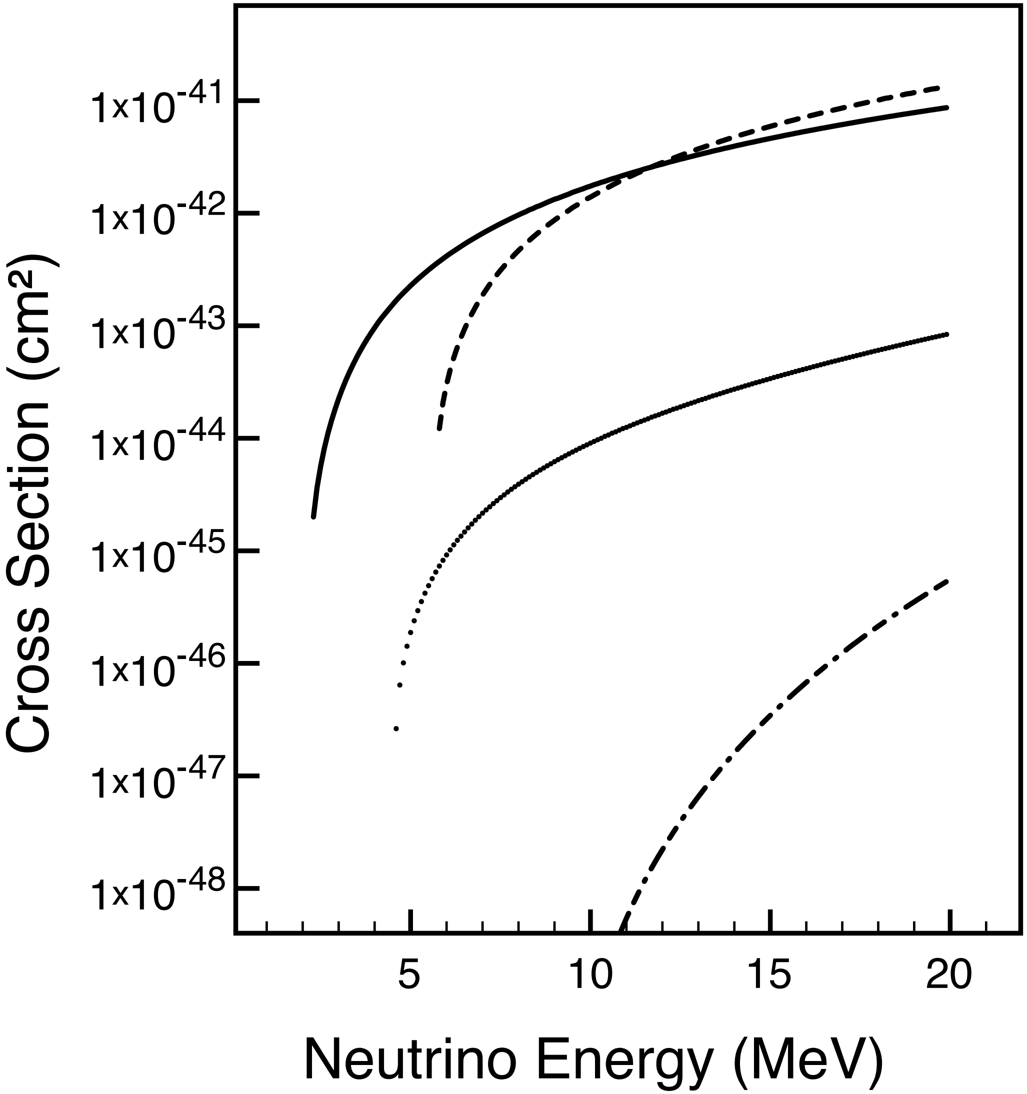




Are there electron neutrinos in the reactor flux? (a test of CPT theorem)

Suzuki, Balantekin, Kajino, arXiv:1204.4231 [nucl-th].





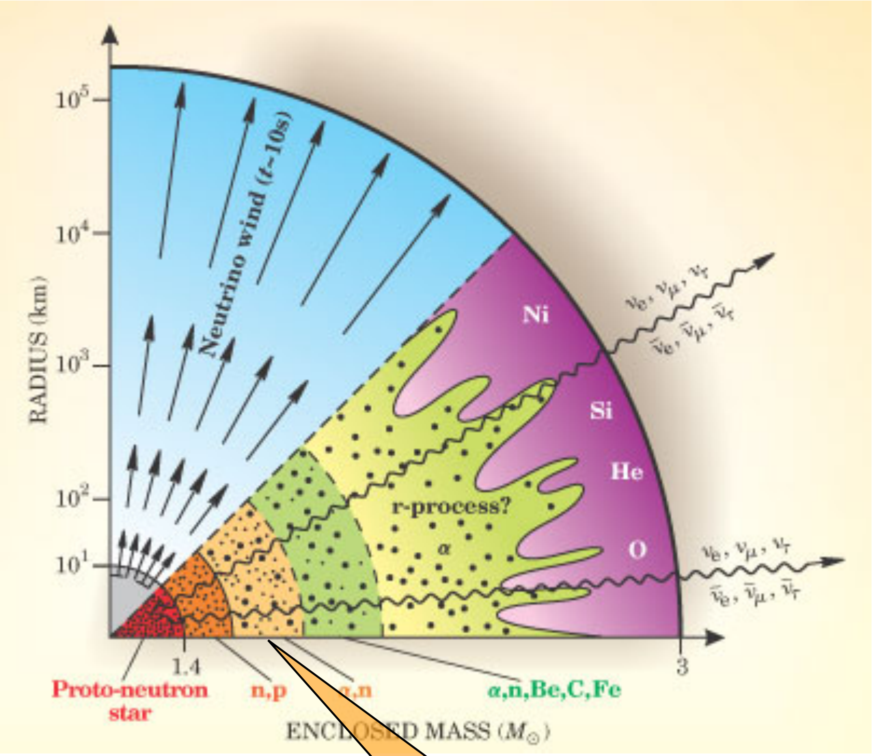
Problems with excess alpha particles (Meyer & Fuller)

- Neutrino spallation on alphas produce too many seed nuclei and too few free neutrons (wrecks the r-process at especially high entropy)
- $\nu_e + n \rightarrow p + e^-$

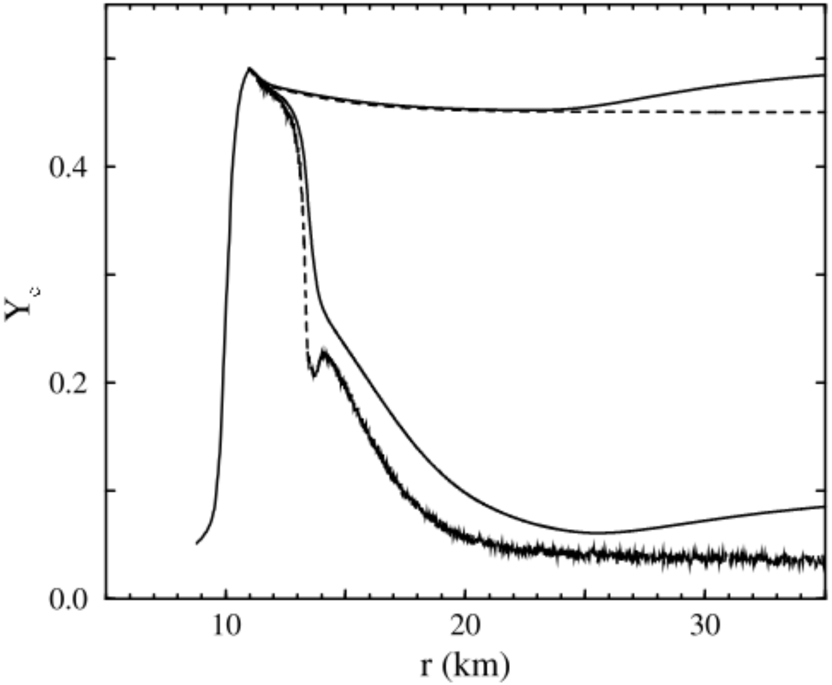
  $+ n \rightarrow d + \gamma$

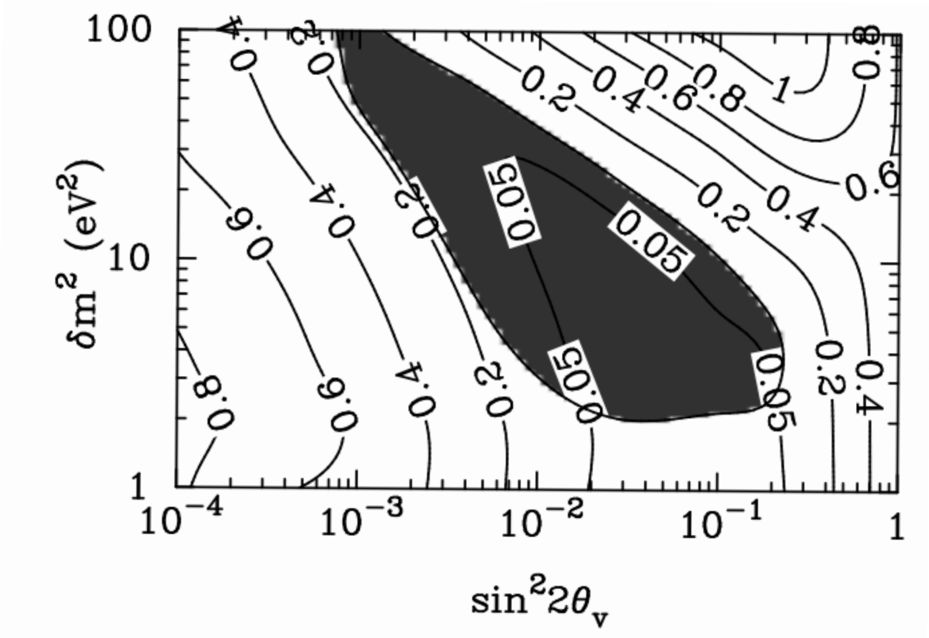
(pushes Y_e toward 0.5)

Can neutrinos help?



Alpha effect





Active-sterile mixing

McLaughlin, Fetter, Balantekin, Fuller, Astropart. Phys., 18, 433 (2003)

Various supernova and nucleosynthesis questions:

- Can supernovae produce r-process elements such as Th ($\tau_{1/2}$ = 140.5 Gy), a cosmic clock?

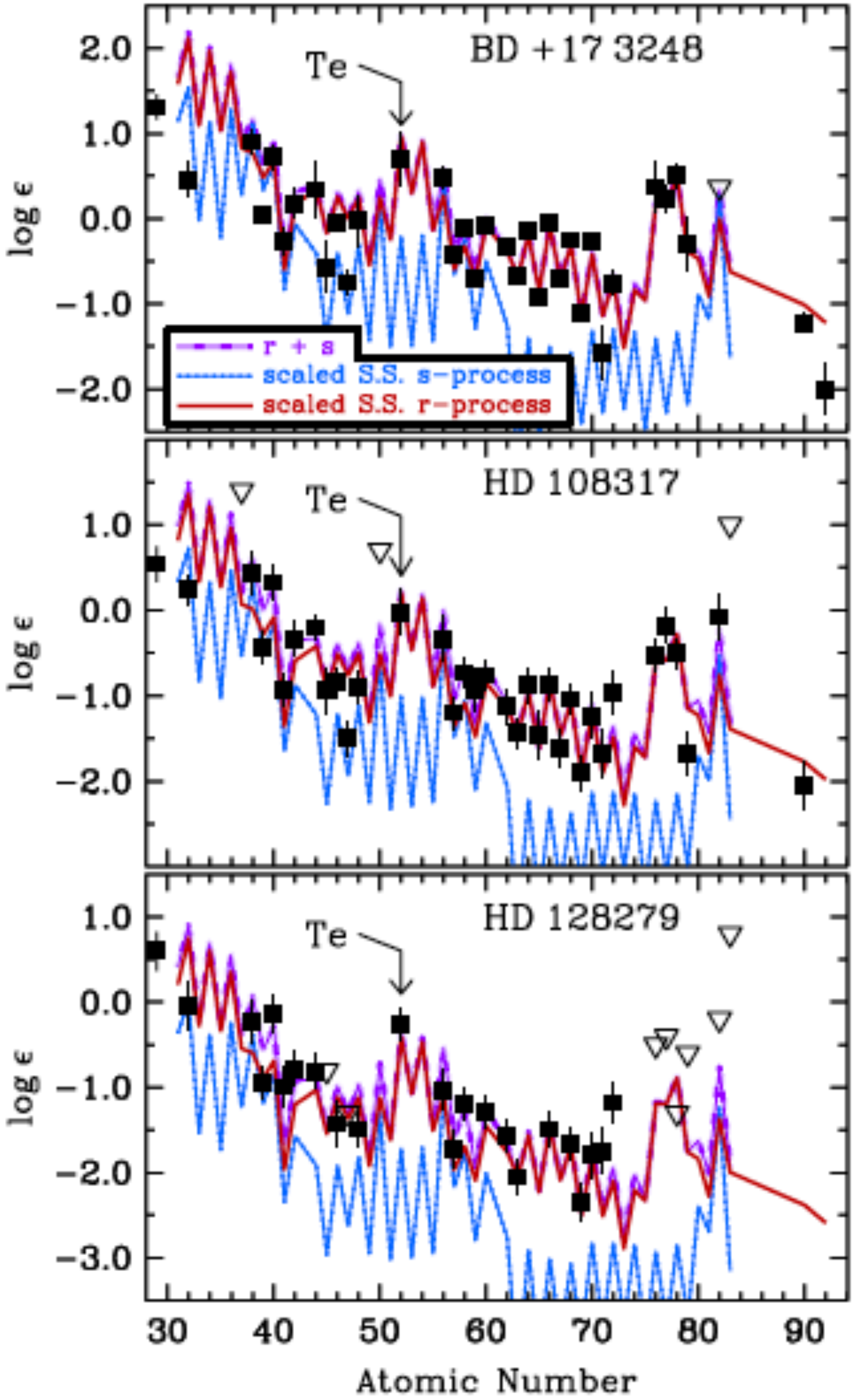
- Can we observe elements at all three r-process peaks?

- Why has a pulsar not yet been observed in the SNN1987A remnant for more than 17 years? Was a black hole formed? (Black hole = Neutrino-flux truncation).

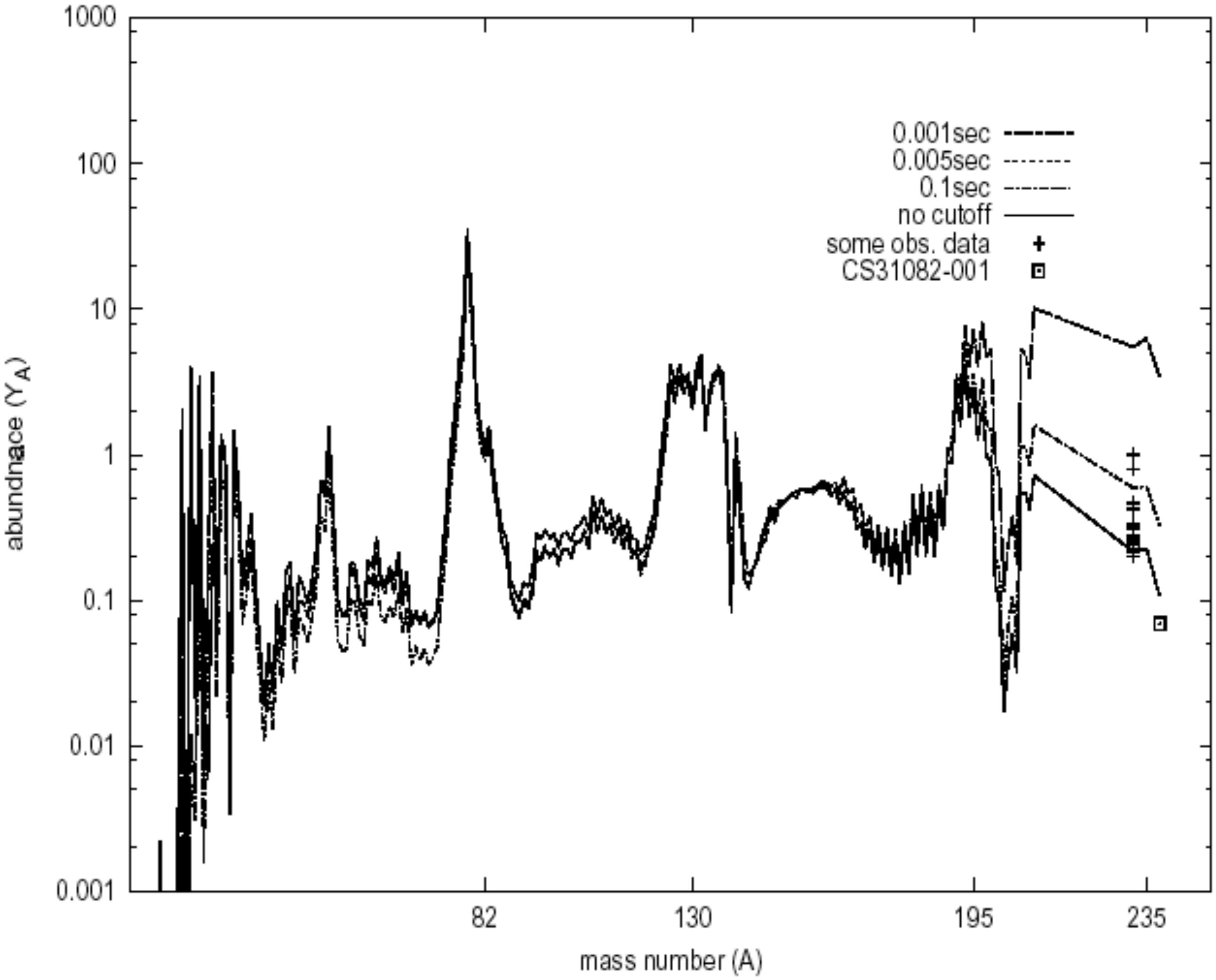
- Assuming neutrino-driven wind scenario, can we distinguish between black-hole vs. neutron-star formation from the fossil-record of r-process nucleosynthesis, without directly observing neutrinos?

- Can we observe elements at all three r-process peaks?
- Yes

Roederer *et al.*, Ap. J. Lett. **747**, L8 (2012)



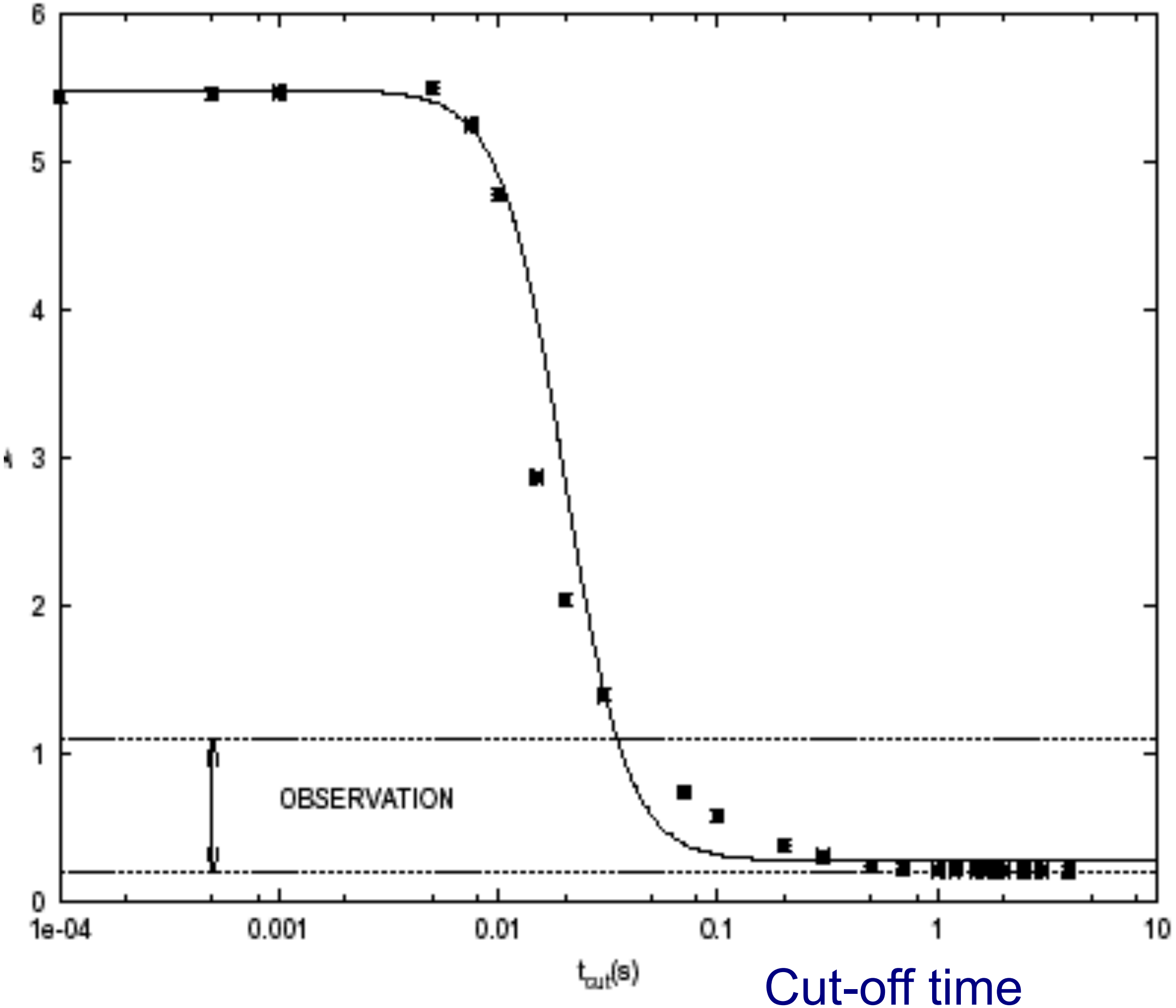
Black hole or neutron star?



Sasaqui, Kajino, Balantekin, Ap. J 634, 534 (2005)

Black hole or neutron star?

$$\frac{^{232}\mathrm{Th}}{^{151}\mathrm{Eu} + ^{153}\mathrm{Eu}}$$



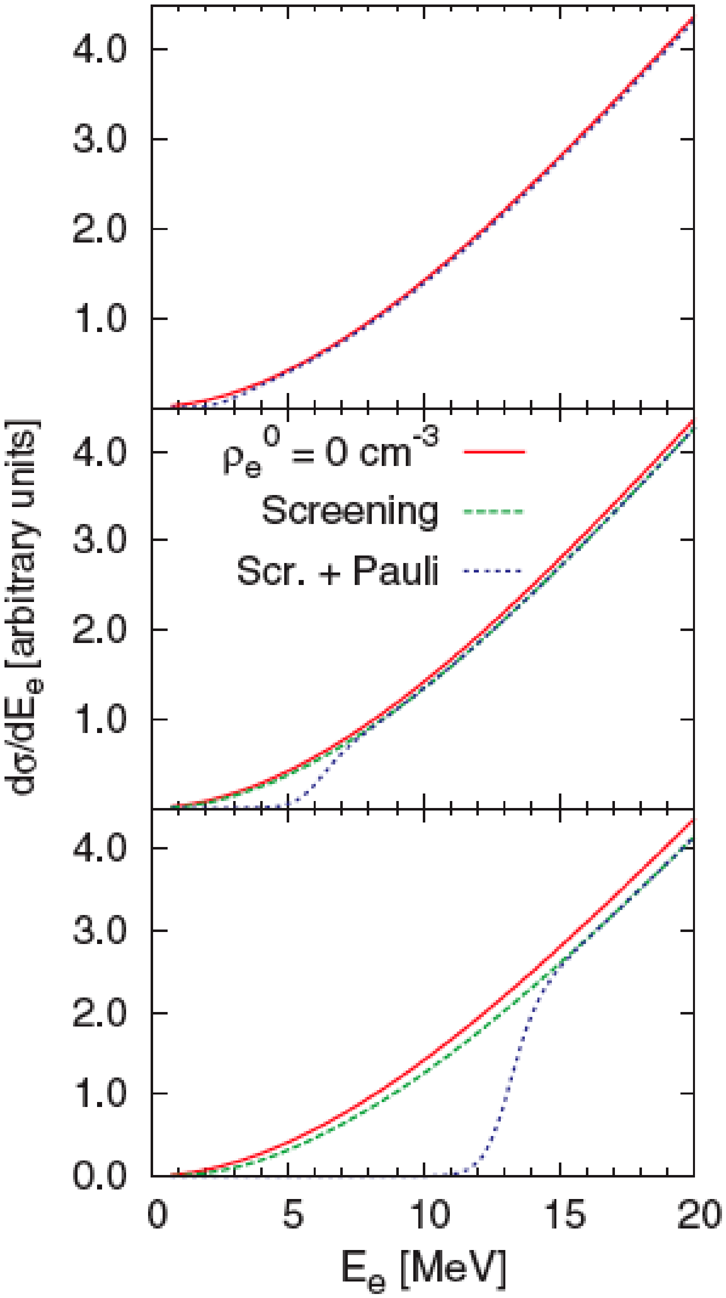
Cut-off time

Theoretical challenges

- Achieve a better understanding of the limitations of the Shell Model and (Q)RPA and exploit the complementarities of these approaches.
- Provide a robust theoretical description of capture reactions involving complex nuclei. Two key inputs are the level density and the optical potential. Reassess and improve both.
- Provide a robust theoretical description of the capture reactions leading into continuum states.
- Improve the existing codes to achieve all of the above.

In astrophysical settings additional final-state effects may come into play; for example, in a core-collapse supernova neutrino capture reactions may be influenced by the Pauli-blocking by other electrons present.

$\nu_e + {}^{56}\mathrm{Fe} \rightarrow e^- + {}^{56}\mathrm{Co}$

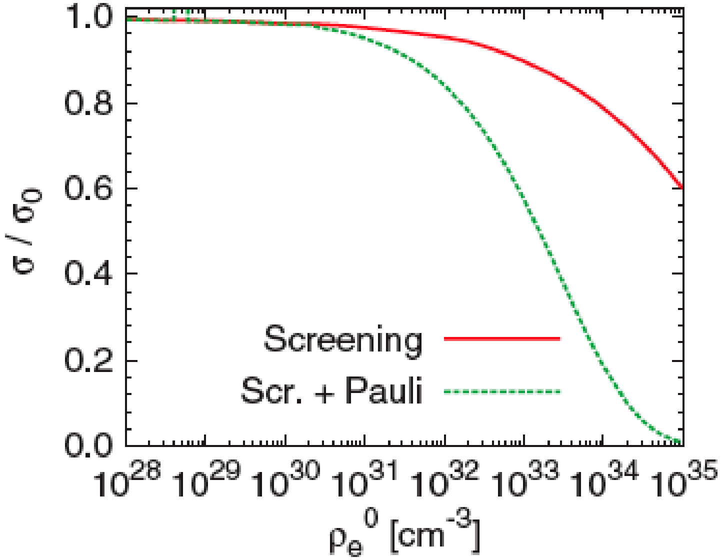


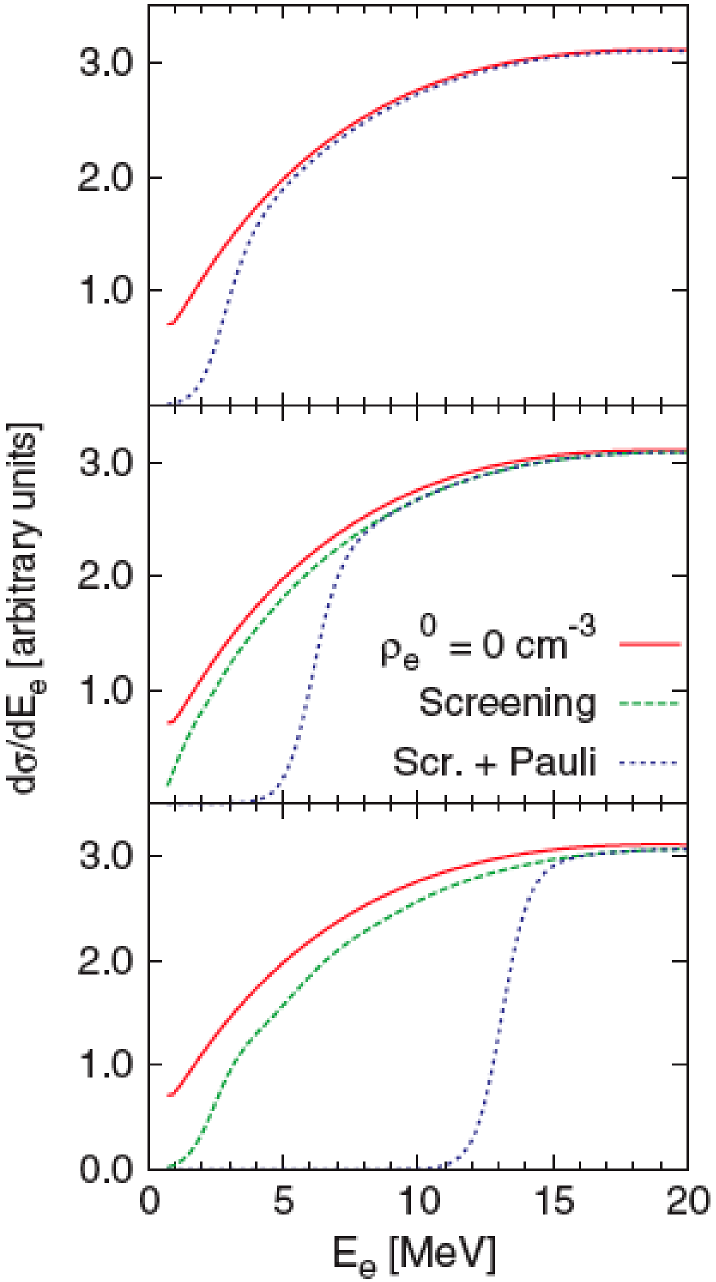
$\rho_e = 10^{32}$ cm^{-3}

$\rho_e = 10^{33}$ cm^{-3}

$\rho_e = 10^{34}$ cm^{-3}

$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}$





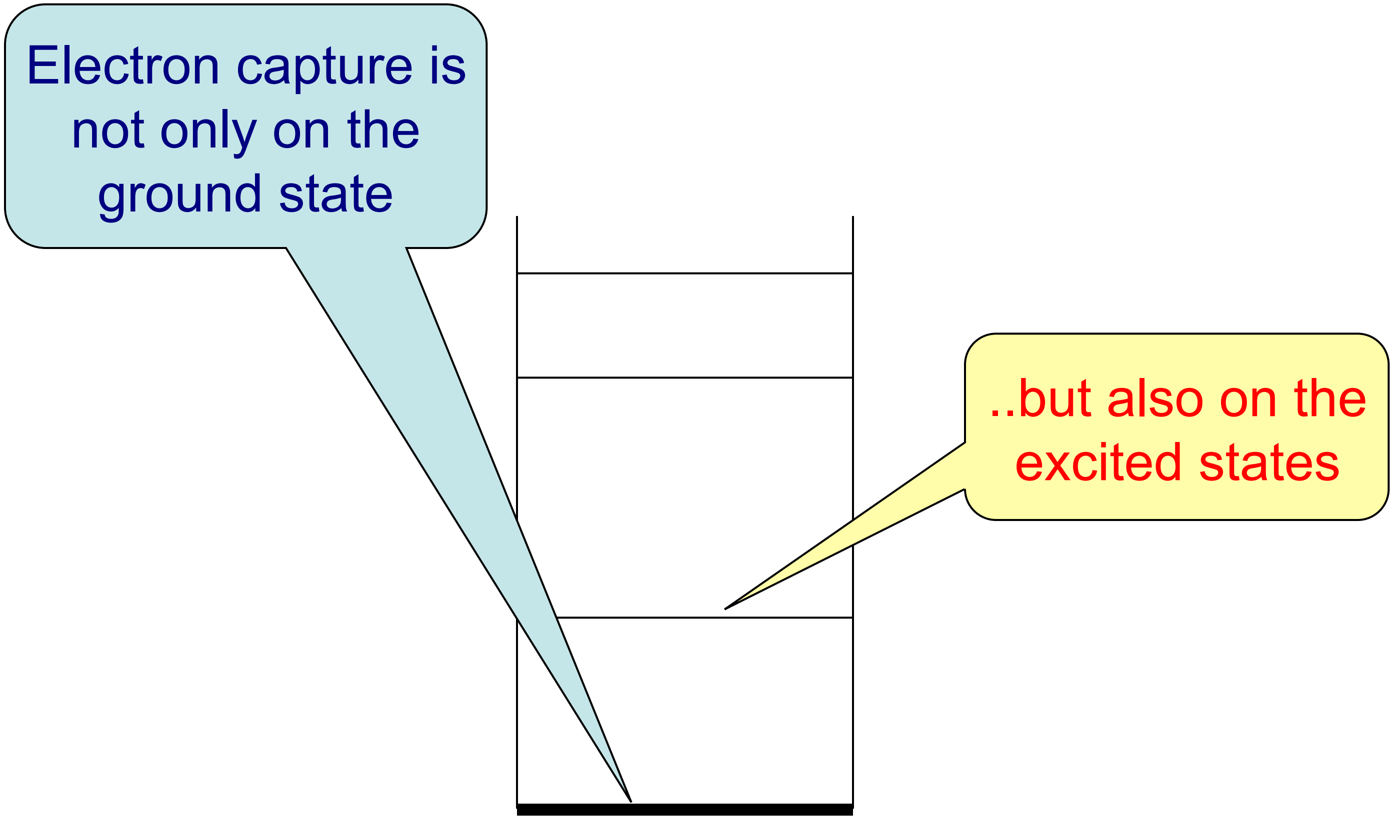
$\rho_e = 10^{32}$ cm^{-3}

$\rho_e = 10^{33}$ cm^{-3}

$\rho_e = 10^{34}$ cm^{-3}

Minato, *et al.* Phys. Rev C **75**, 045802 (2007).

A pre-supernova star is a hot place where nuclei are excited!



Electron capture is not only on the ground state

..but also on the excited states

…making theory input crucial!

Final Remarks

- Neutrinos play a crucial role in nuclear astrophysics, the quest for the origin of elements.
- To understand where the nuclei are made in the cosmos both theoretical and experimental input are necessary.
- Theory input: nuclear structure both near the ground state and higher excitations, electromagnetic and spin-isospin response to external probes
- Experimental input: Cross sections with both stable and rare isotope beams, data to calibrate calculations.