Challenges in Nuclear Astrophysics

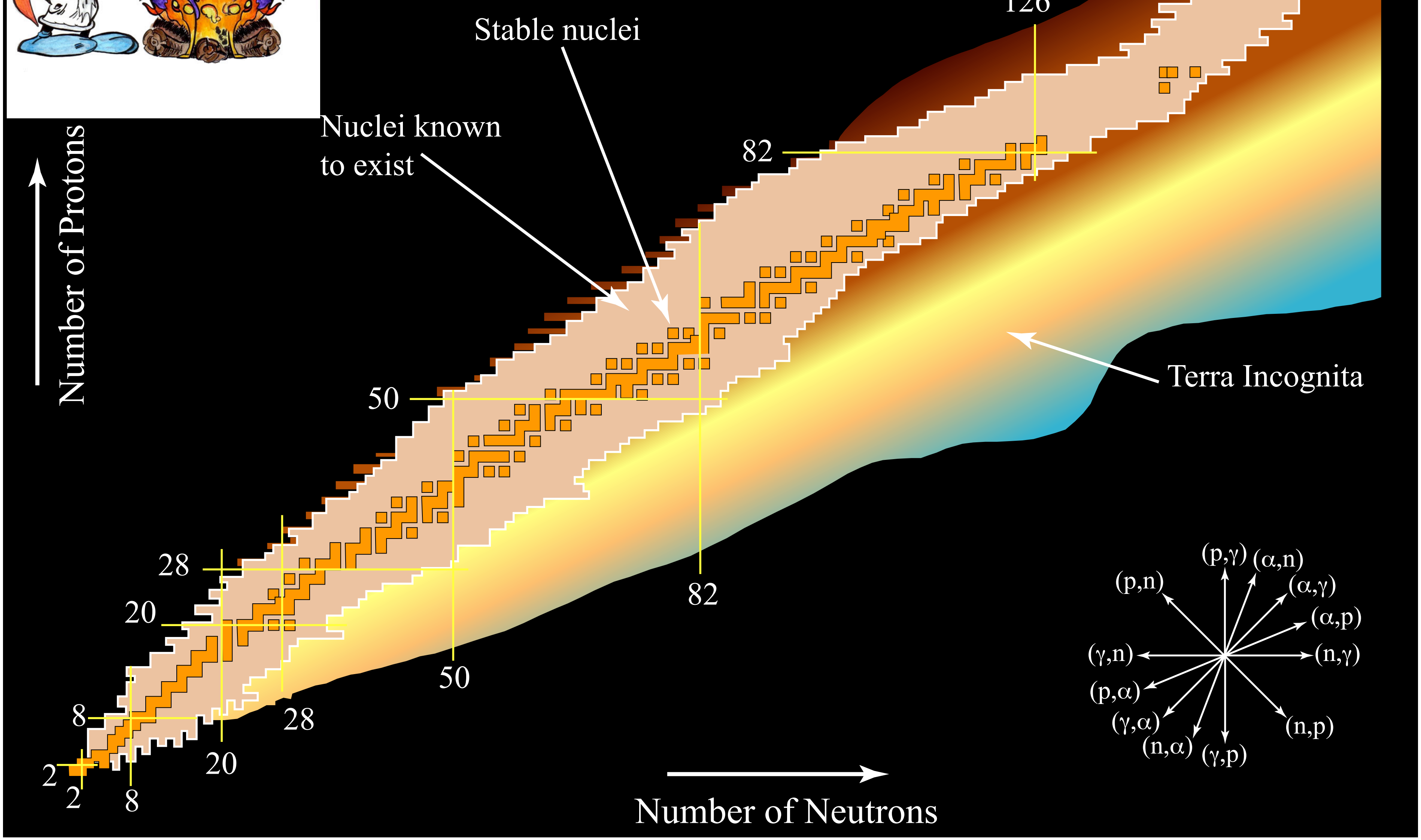
A.B. Balantekin

5th International Conference on

"COLLECTIVE MOTION IN NUCLEI UNDER EXTREME CONDITIONS"

COMEX5

How do you cook elements around us?



How do you cook elements around us?

How do you cook elements around us?

Pop III stars
(very big and very
metal poor)

How do you cook elements around us?

How do you cook elements around us?

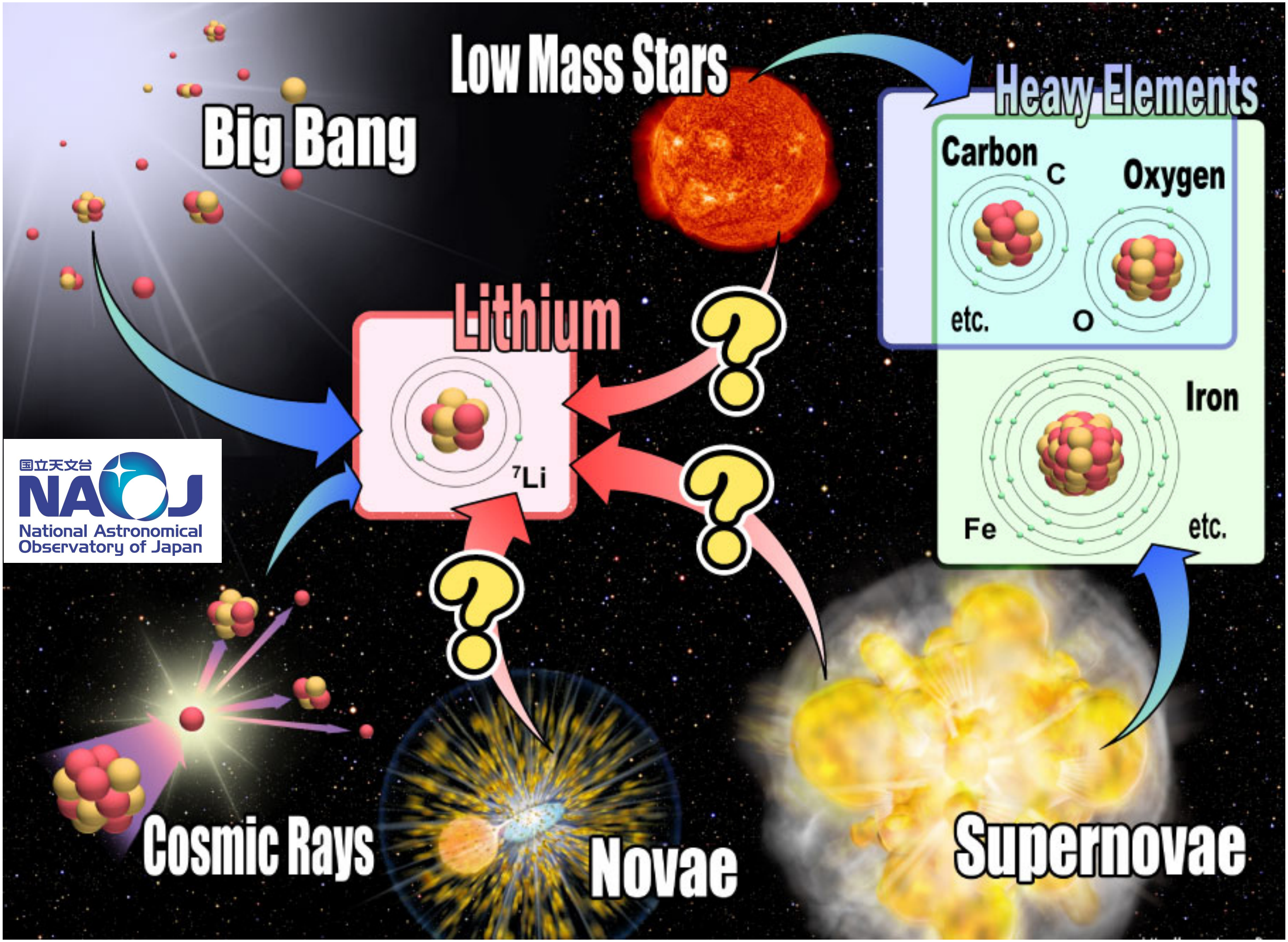
How do you cook elements around us?

How do you cook elements around us?

Some go supernova, producing U, Eu,Th… via the r-process

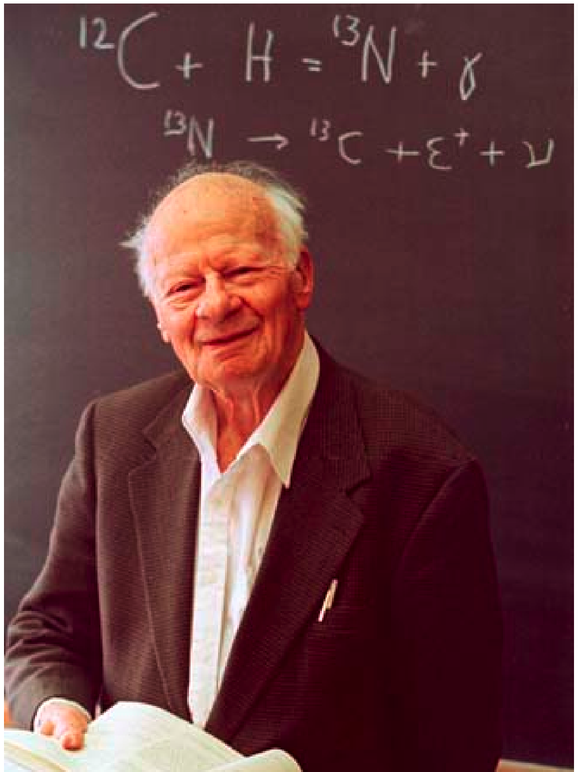
Pop II stars (metal poor)

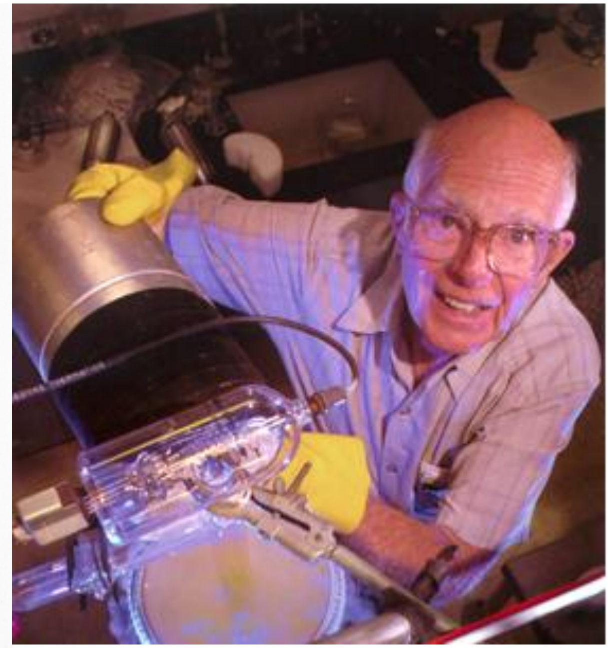
AGB stars produce Ba, La, Y,…. via the s-process



Big Bang
Low Mass Stars
Heavy Elements
Carbon
C
Oxygen
etc.
O
Lithium
^{7}Li
Iron
Fe
etc.
国立天文台
NAOJ
National Astronomical Observatory of Japan
Cosmic Rays
Novae
Supernovae

Let us start with the Sun, the closest star!

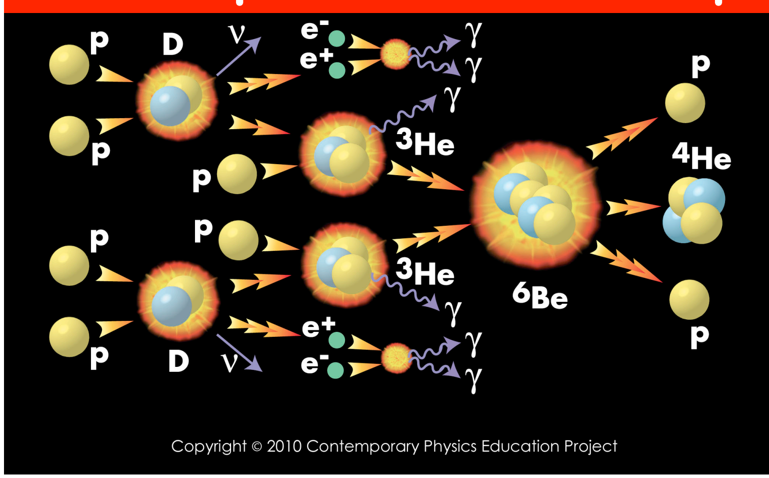


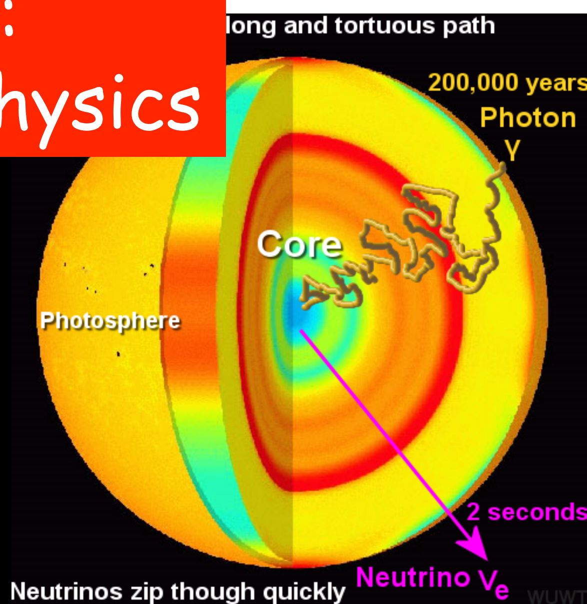


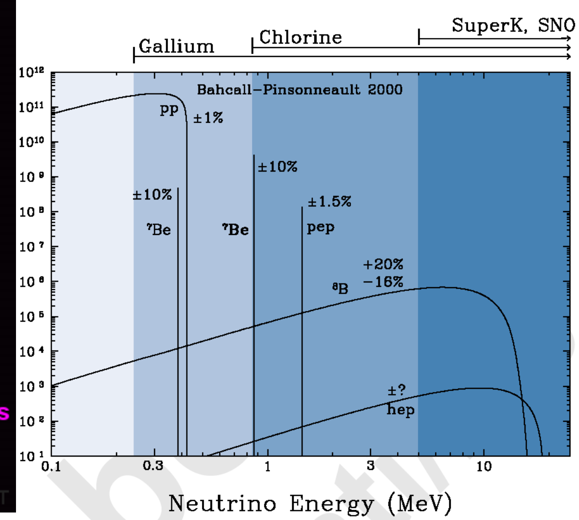
“...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation..”

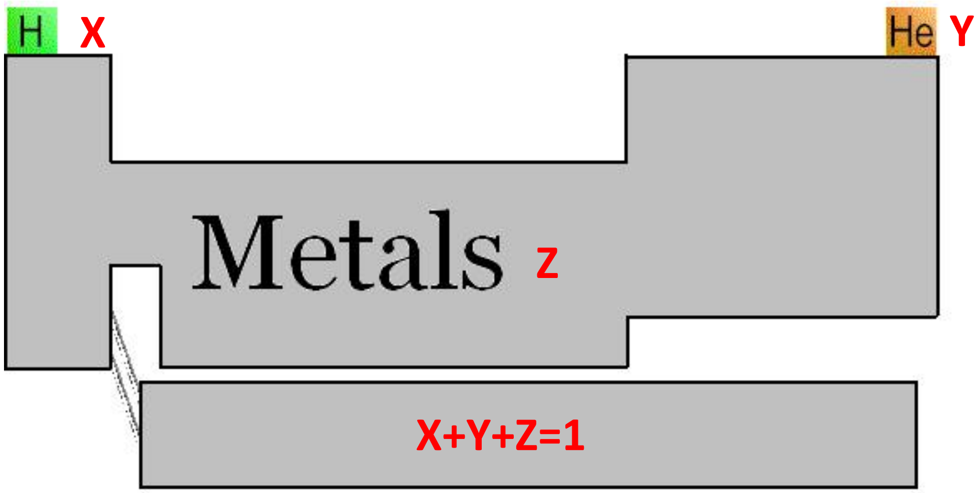
Bahcall and Davis, 1964

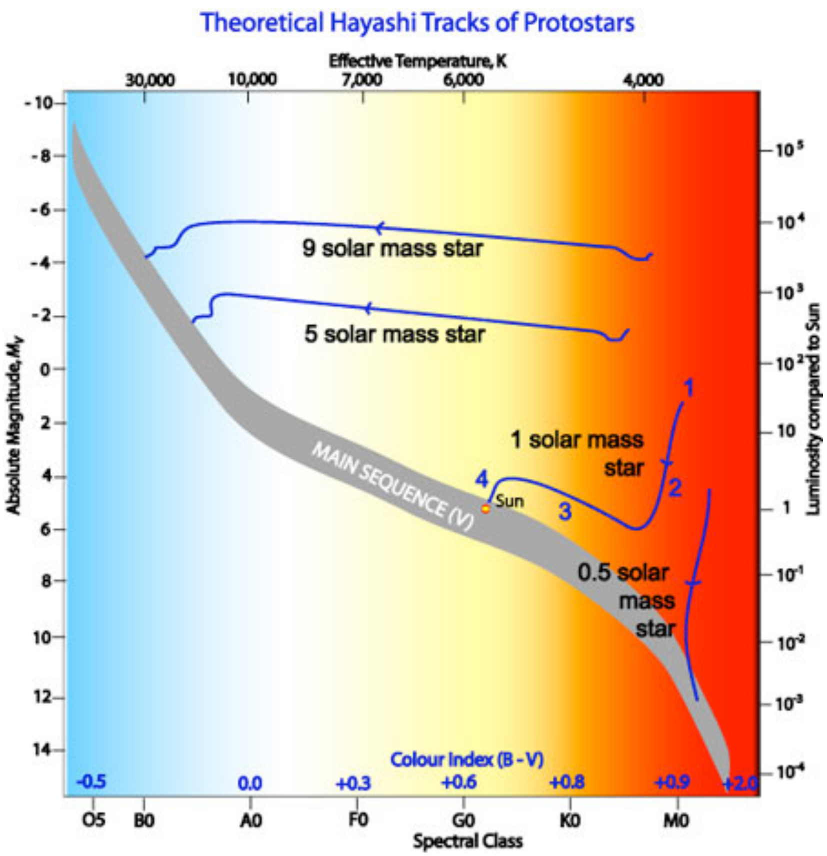
Solar Neutrinos: Triumph of nuclear physics











SSM assumption: The proto-Sun follows the convective Hayashi track ➔ zero-age Sun is homogeneous, i.e $Z_{initial} = Z_{surface\_today}$

Initial parameters: $Y_{initial}$, $Z_{initial}$, solar mixing length

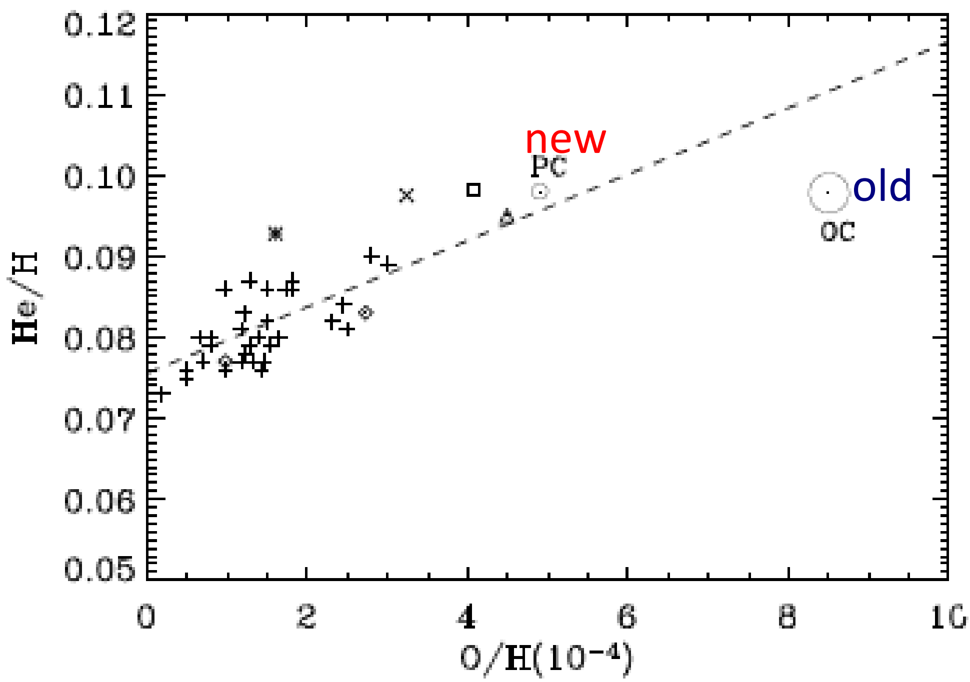
Evolve forward to today to reproduce present $R_{\odot}$, $L_{\odot}$, and $Y_{surface}$

$Z_{surface\_today}$ is deduced from photospheric absorption lines, which were recently evaluated using 3D methods. $Z_{surface\_today}$ obtained using improved methods does not match $Z_{initial}$ of the SSM!

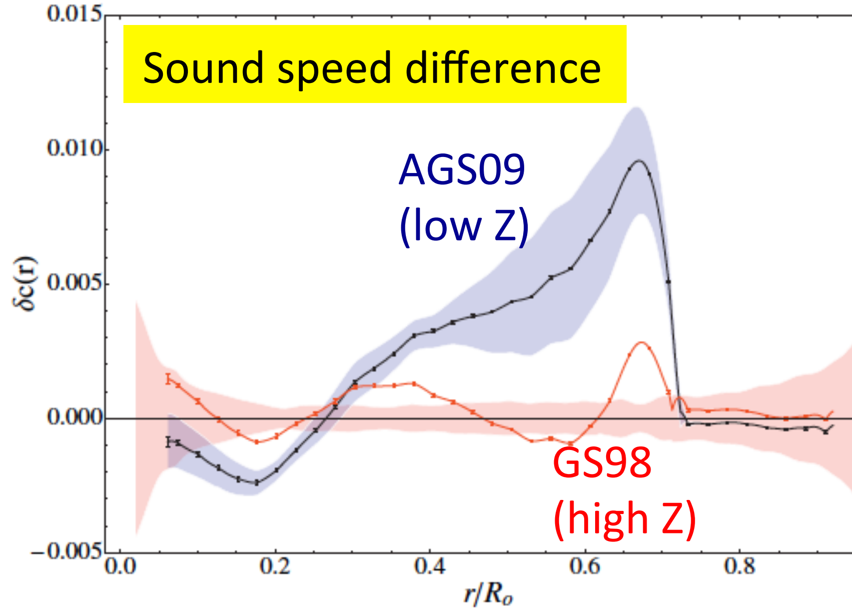
New Solar abundances:

- Asplund *et al.* (AGS09), $(Z/X)_{\odot}=0.0178$
- Grevesse and Sauvel (GS98), $(Z/X)_{\odot}=0.0229$

This fixes some old puzzles



But creates new ones!



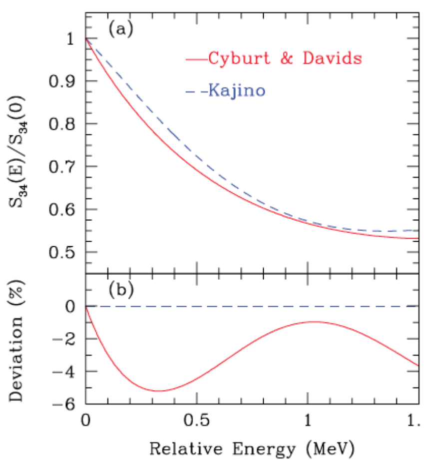
Sun is no longer an “odd” star enriched in heavy elements!

Old ^{8}B neutrino flux = 4x10^{6} cm^{-2}s^{-1}
New ^{8}B neutrino flux = 5.31x10^{6} cm^{-2}s^{-1}

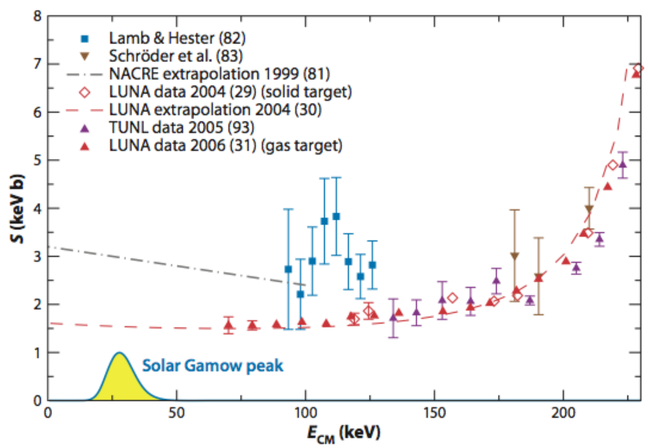
There is mismatch between the surface and the interior of the Sun!

SSM Error Budget

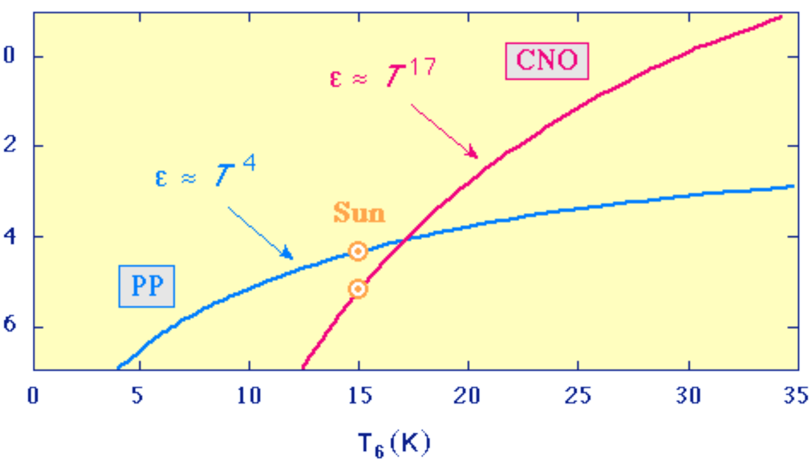
Source	Percentage Error
Diffusion coefficient of SSM	2.7%
Nuclear rates [mainly $^7Be(p,\gamma)^8B$ and $^{14}N(p,\gamma)^{15}O$]	9.9%
Neutrinos and weak interaction (mainly θ_{12})	3.2%
Other SSM input parameters	0.6%



$^3He(\alpha,\gamma)^7Be$



$^{14}N(p,\gamma)^{15}O$



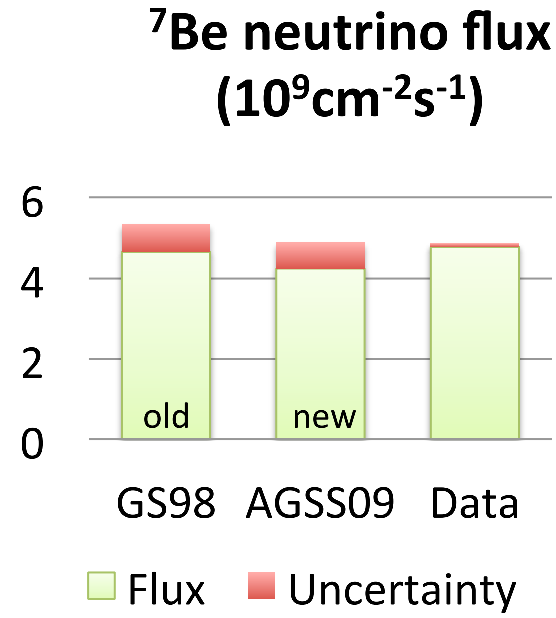
CNO Neutrinos are still not measured!

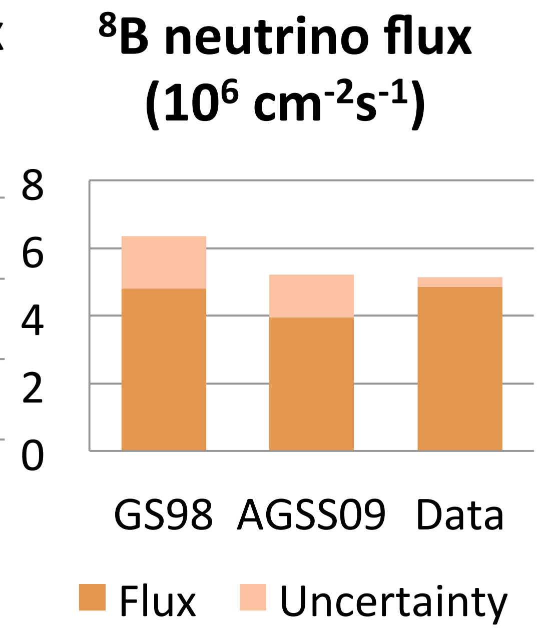
New Solar abundances:

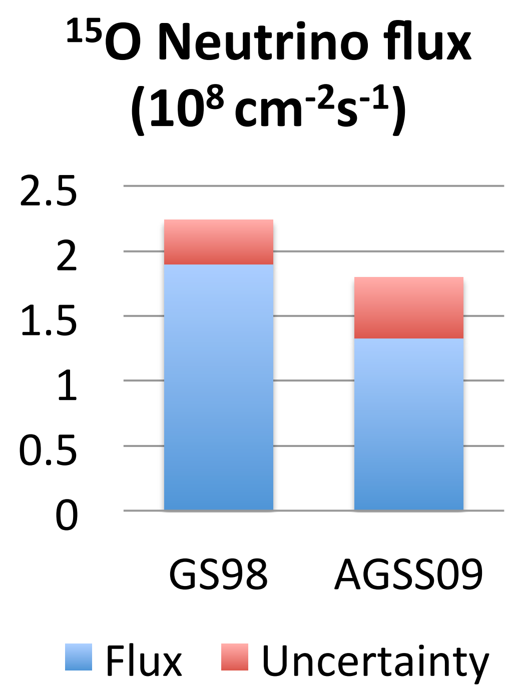
- Asplund *et al.* (AGSS09), $(Z/X)_\odot=0.0178$
- Grevesse and Sauvel (GS98), $(Z/X)_\odot=0.0229$

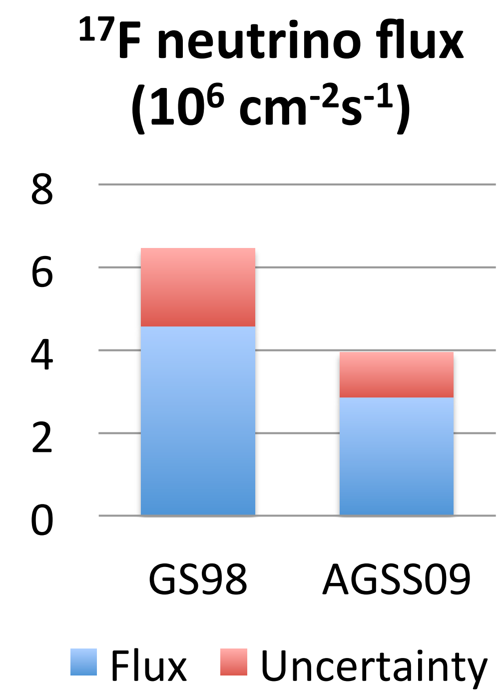
Drastically different!
Open problem in solar physics!

- New Evaluation of the nuclear reaction rates: Adelberger et al. (2011)
- New solar model calculations:Serenelli

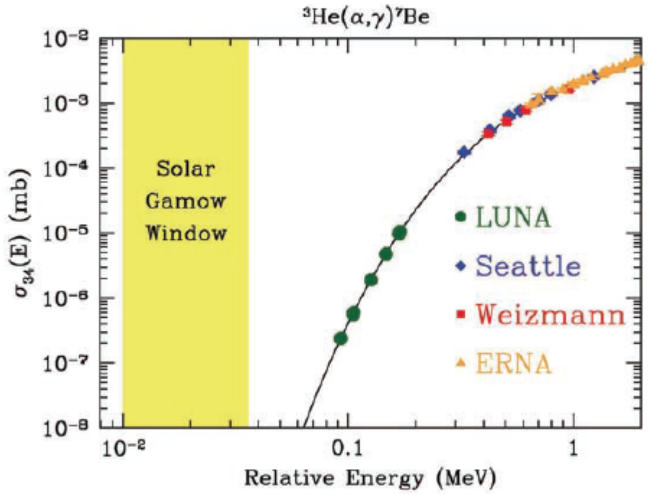


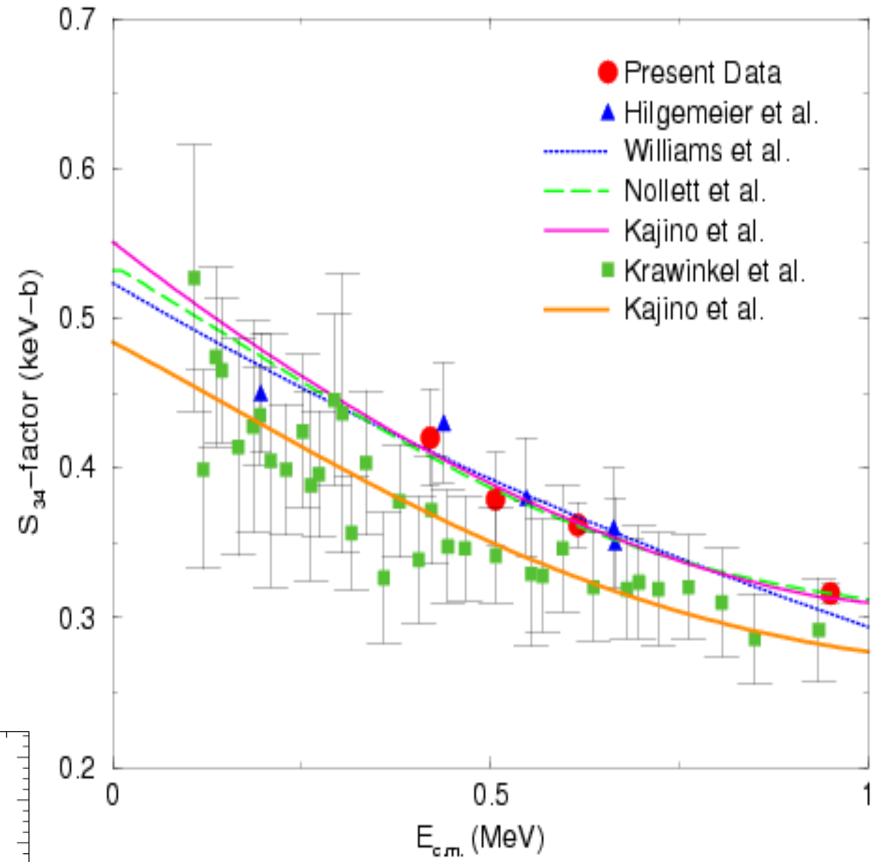


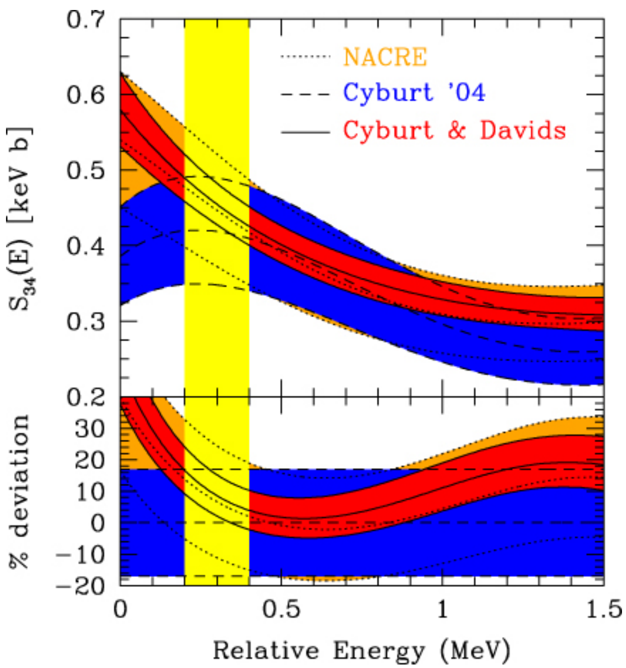


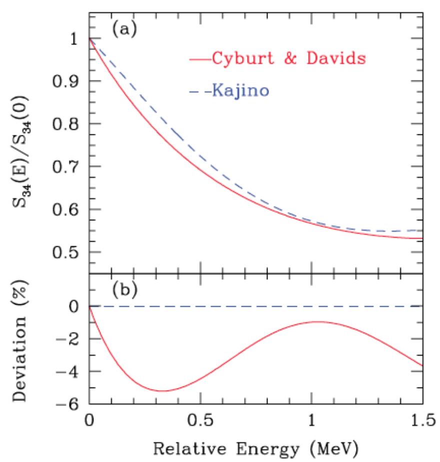


$^3He(\alpha,\gamma)^7Be$

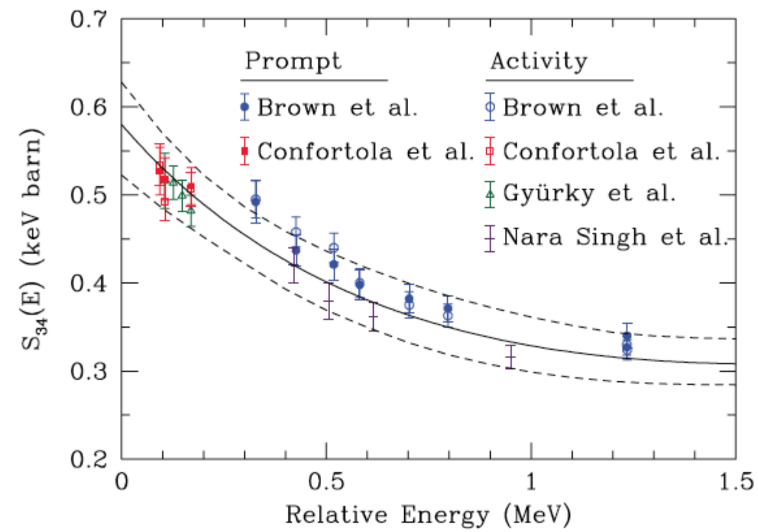




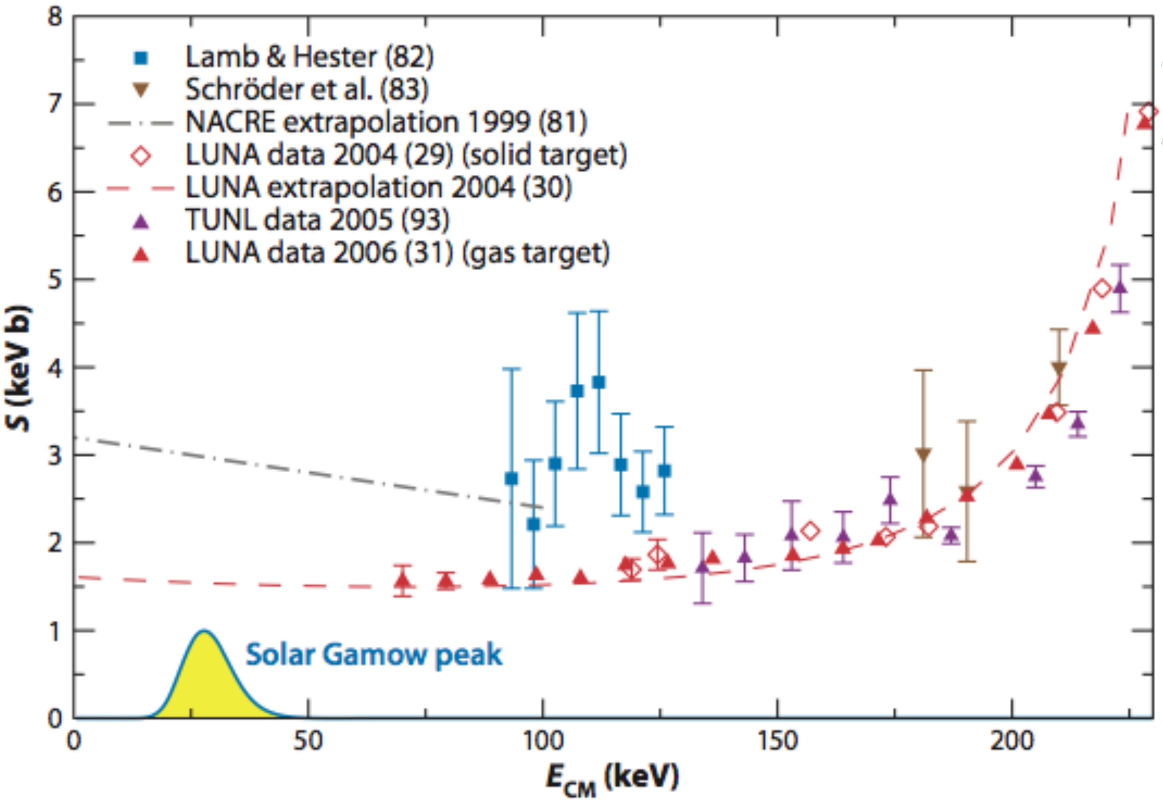


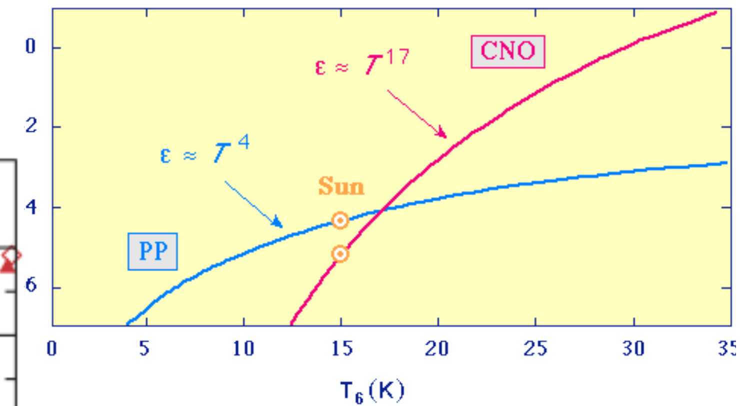


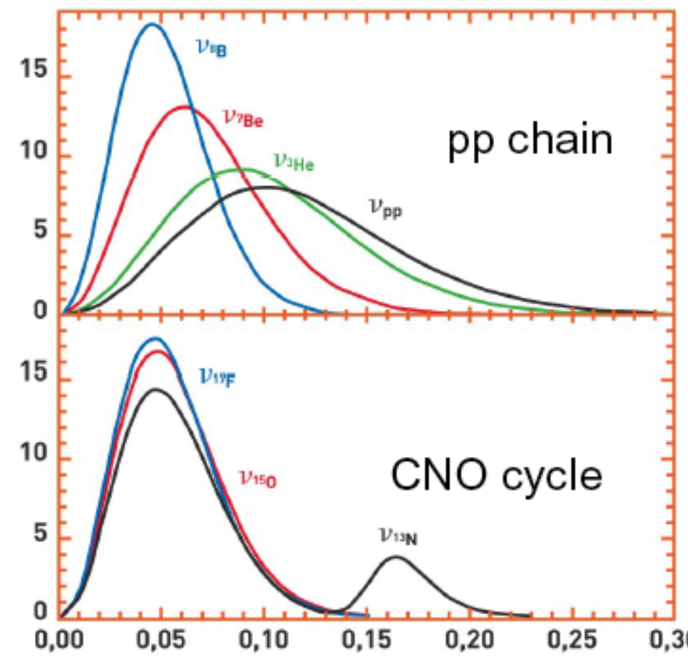
The main uncertainty for the Sun and Big-Bang nucleosynthesis



$^{14}N(p,\gamma)^{15}O$

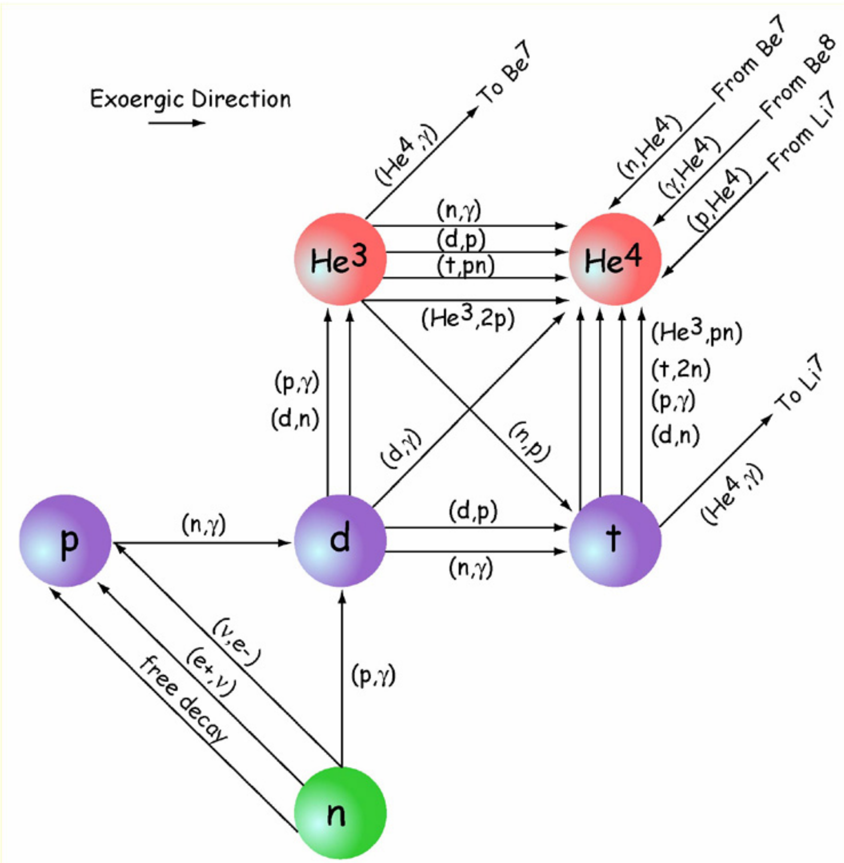


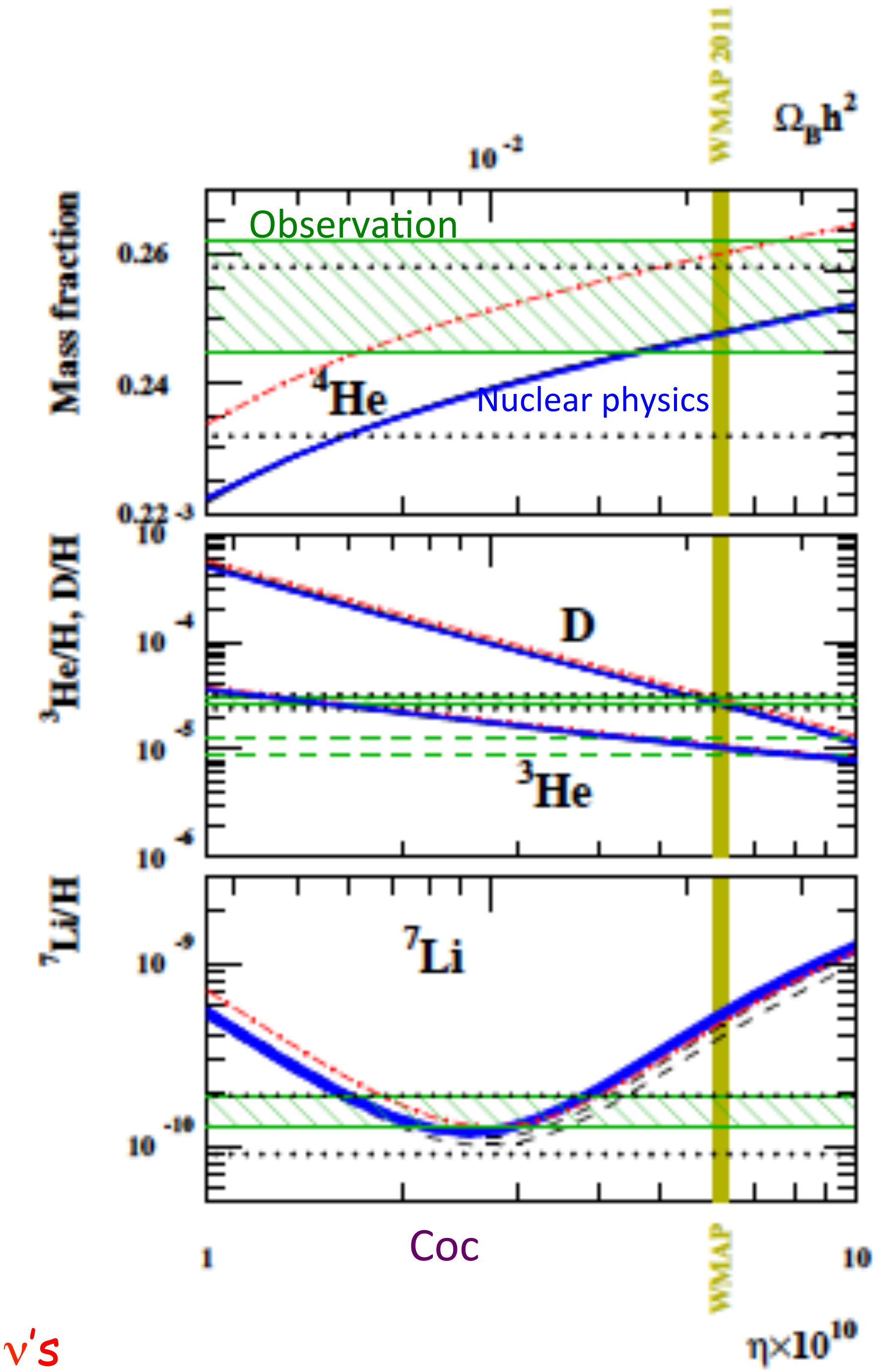




The determining reaction for the CNO burning

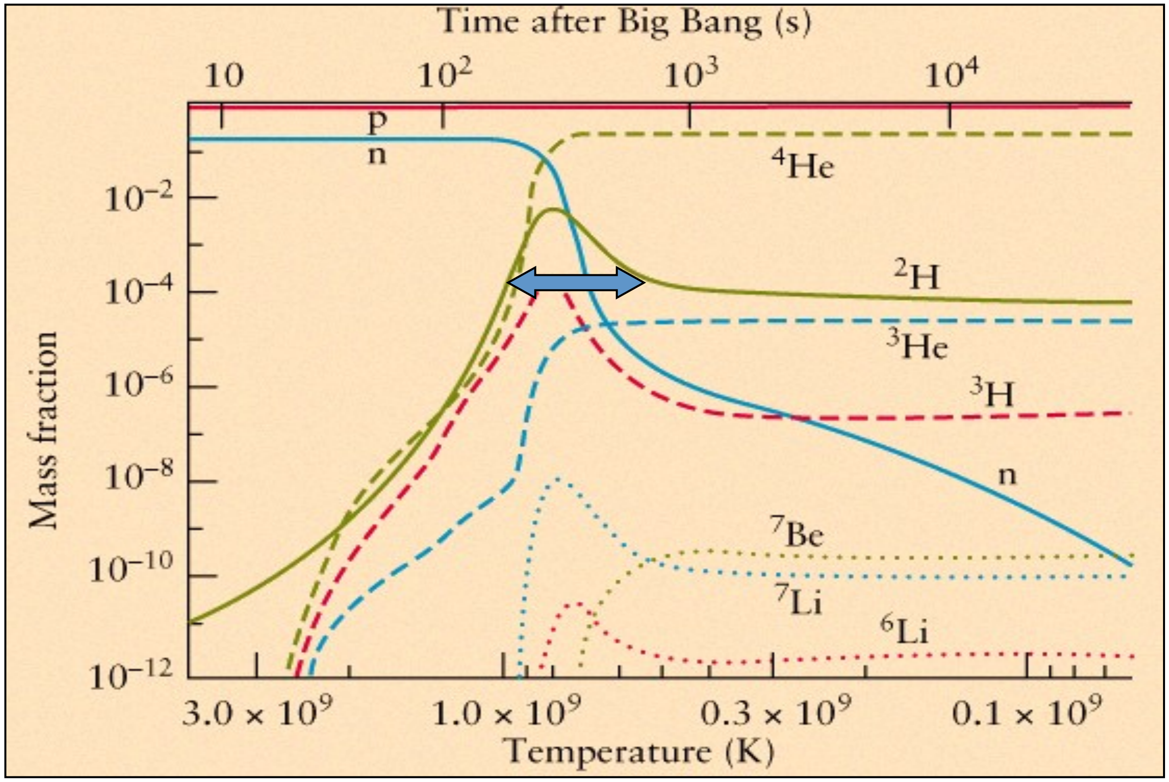
Big-bang nucleosynthesis





4 ν's

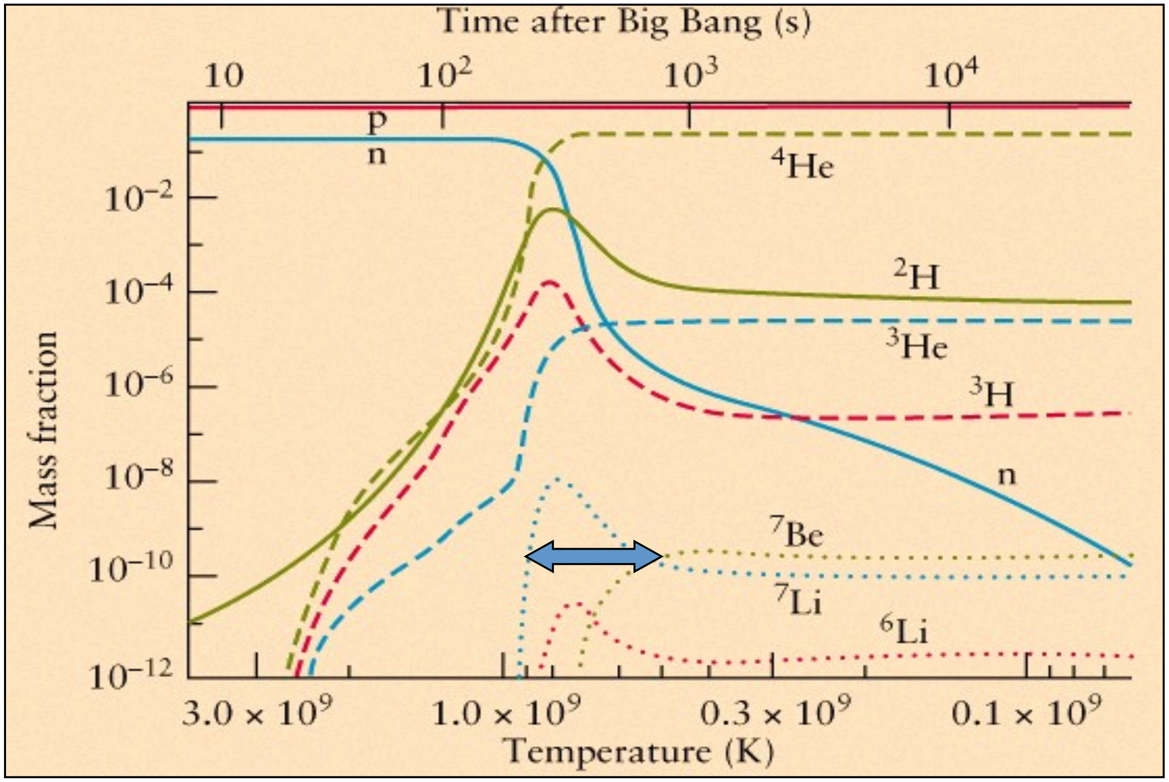
Deuterium



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

Relevant temperature ~70 keV

^7Li

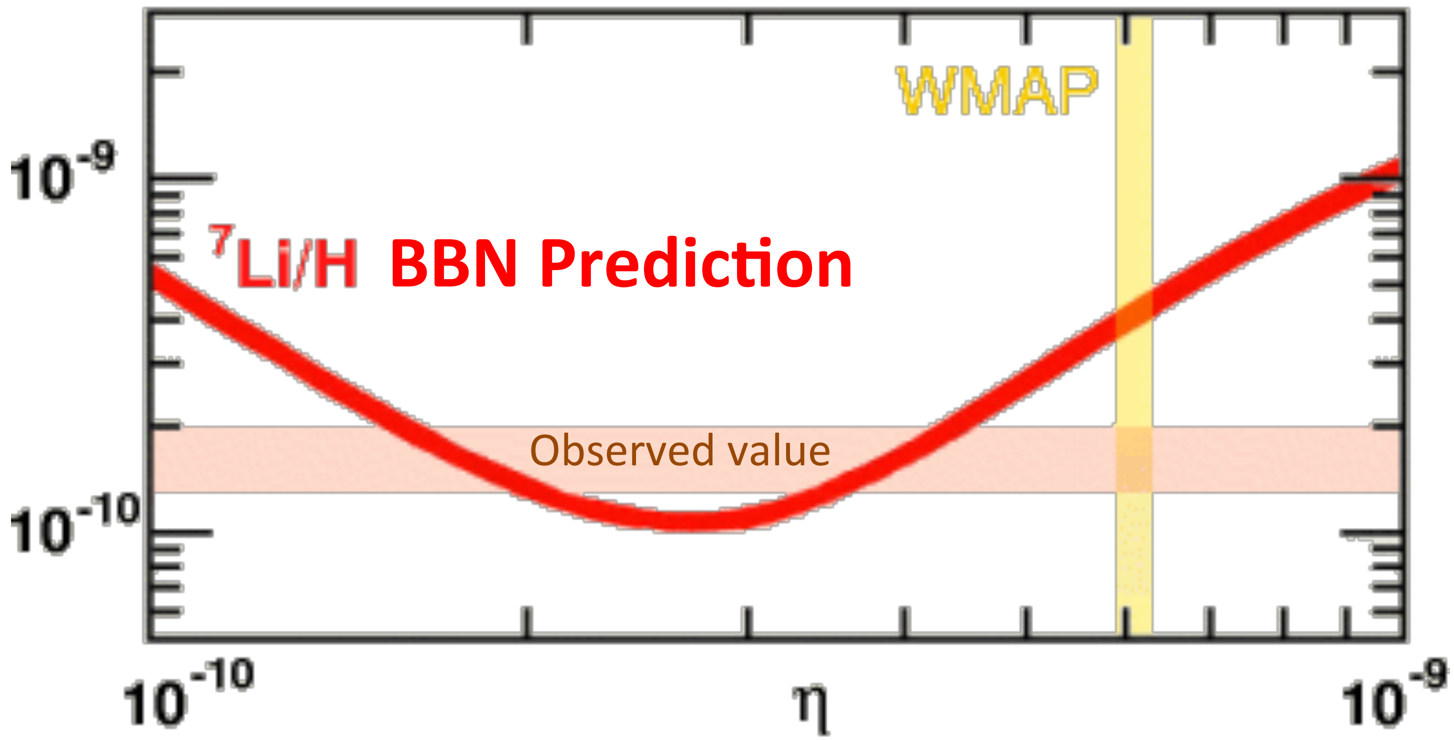


^7Li is the decay product of ^7Be

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

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

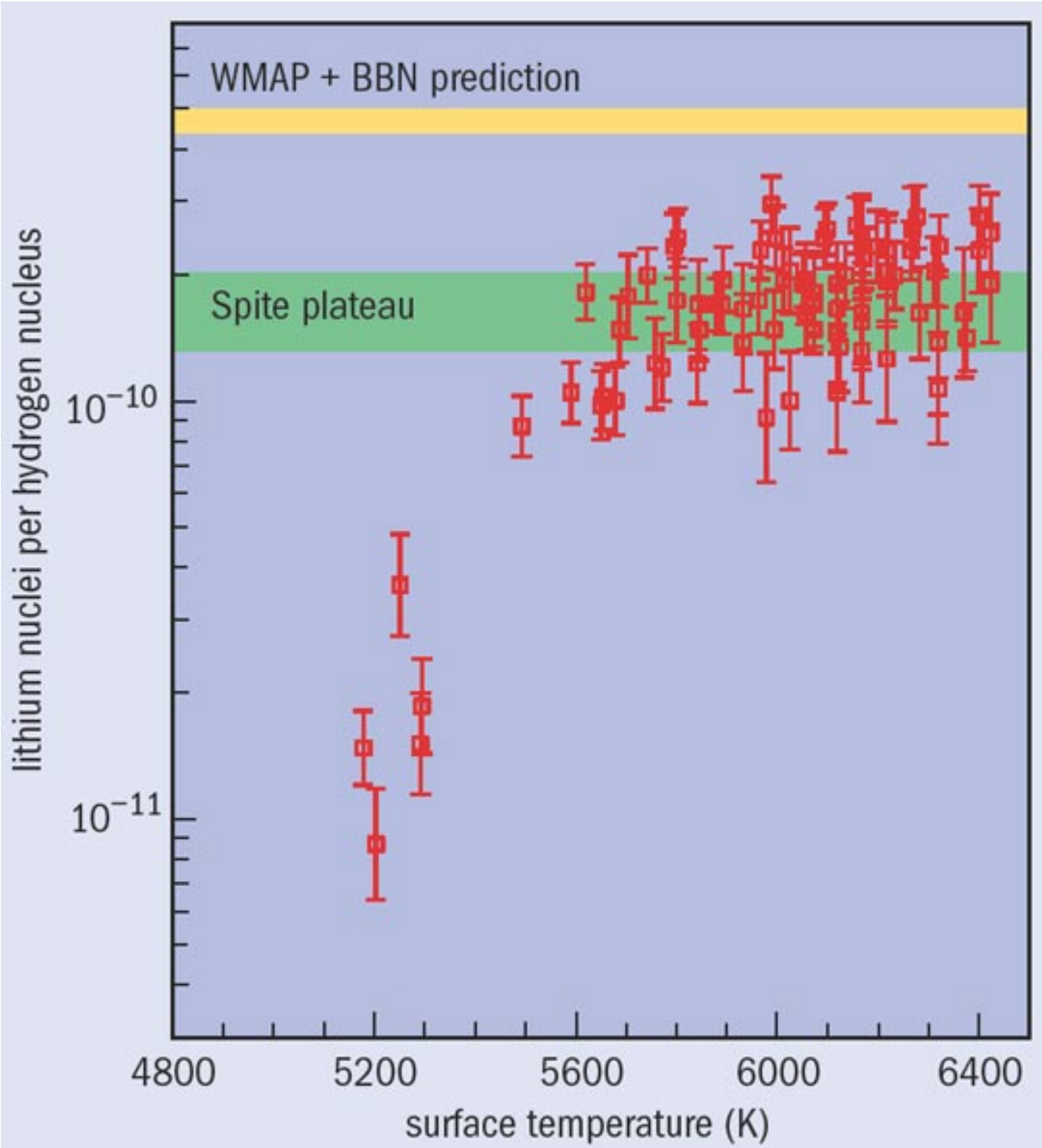
Relevant temperature ~60 keV.



- ^{7}Li produced in the Big-Bang Nucleosynthesis should dominate 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!

Comparison of Big Bang and Supernovae as Nucleosynthesis Sites

Big Bang:

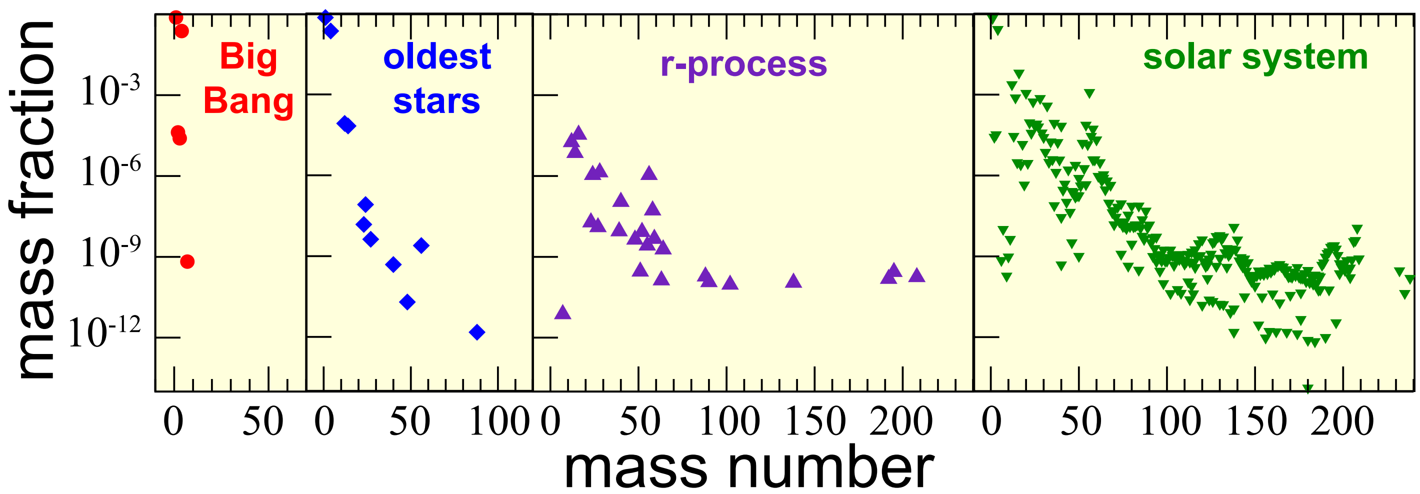
$$\frac{N_n}{N_p} = \exp\left(-\frac{m_n - m_p}{T}\right) << 1$$

Supernovae:

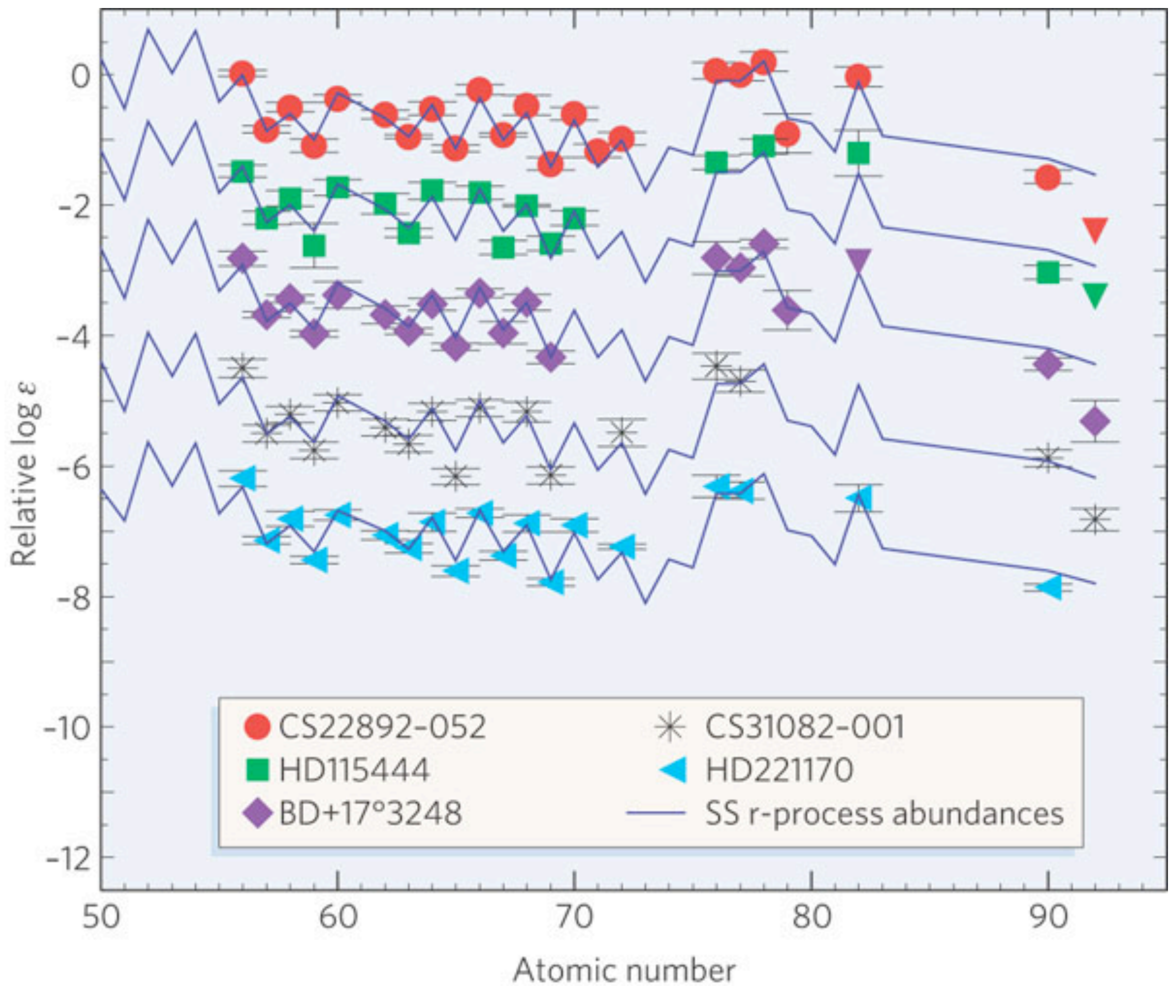
$$\frac{N_n}{N_p} >> 1$$

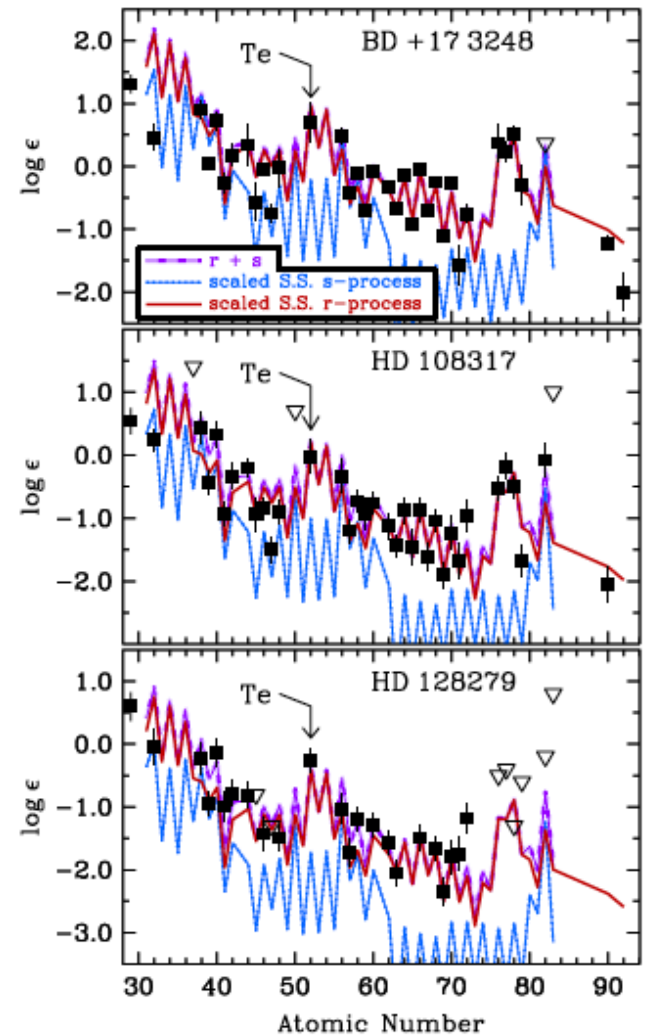
The Early Universe and Core-collapse Supernovae are isospin mirrors of one another. You can think of them as components of an isospin doublet!

The origin of elements



r-process nucleosynthesis

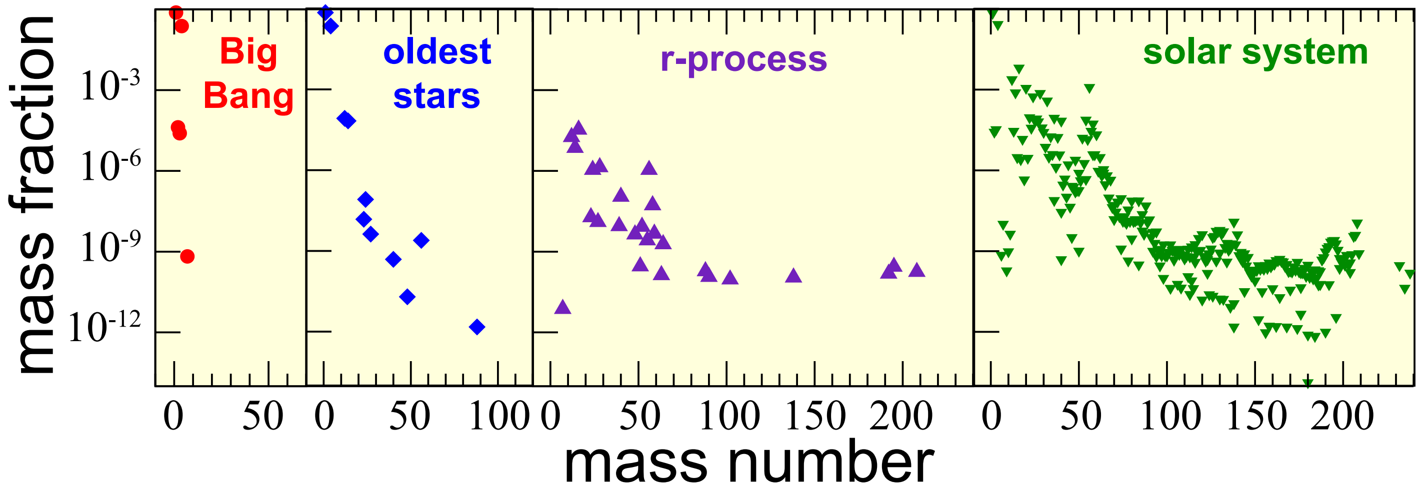


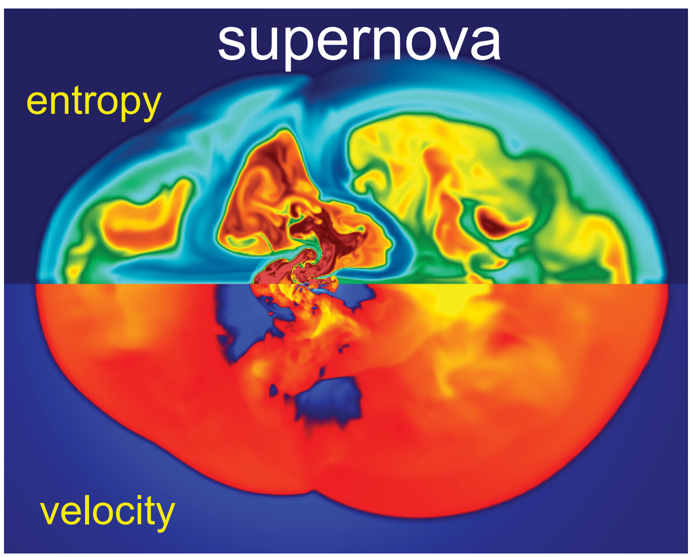


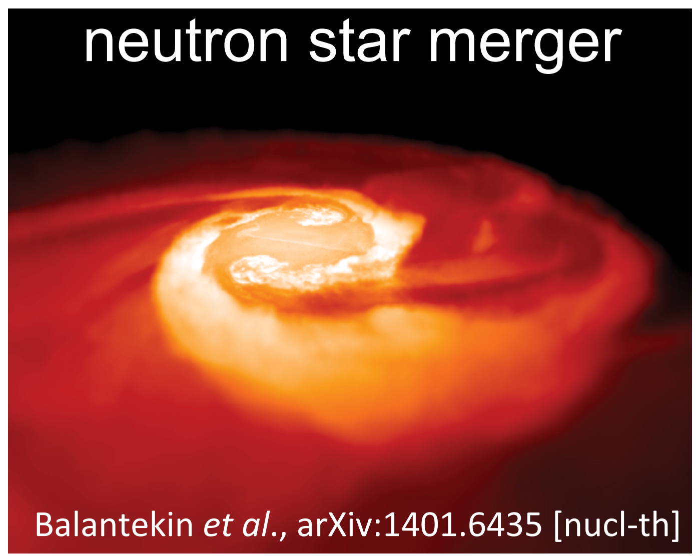
Roederer *et al.*, Ap. J. Lett. **747**, L8 (2012)

A > 100 abundance pattern fits the solar abundances well.

The origin of elements

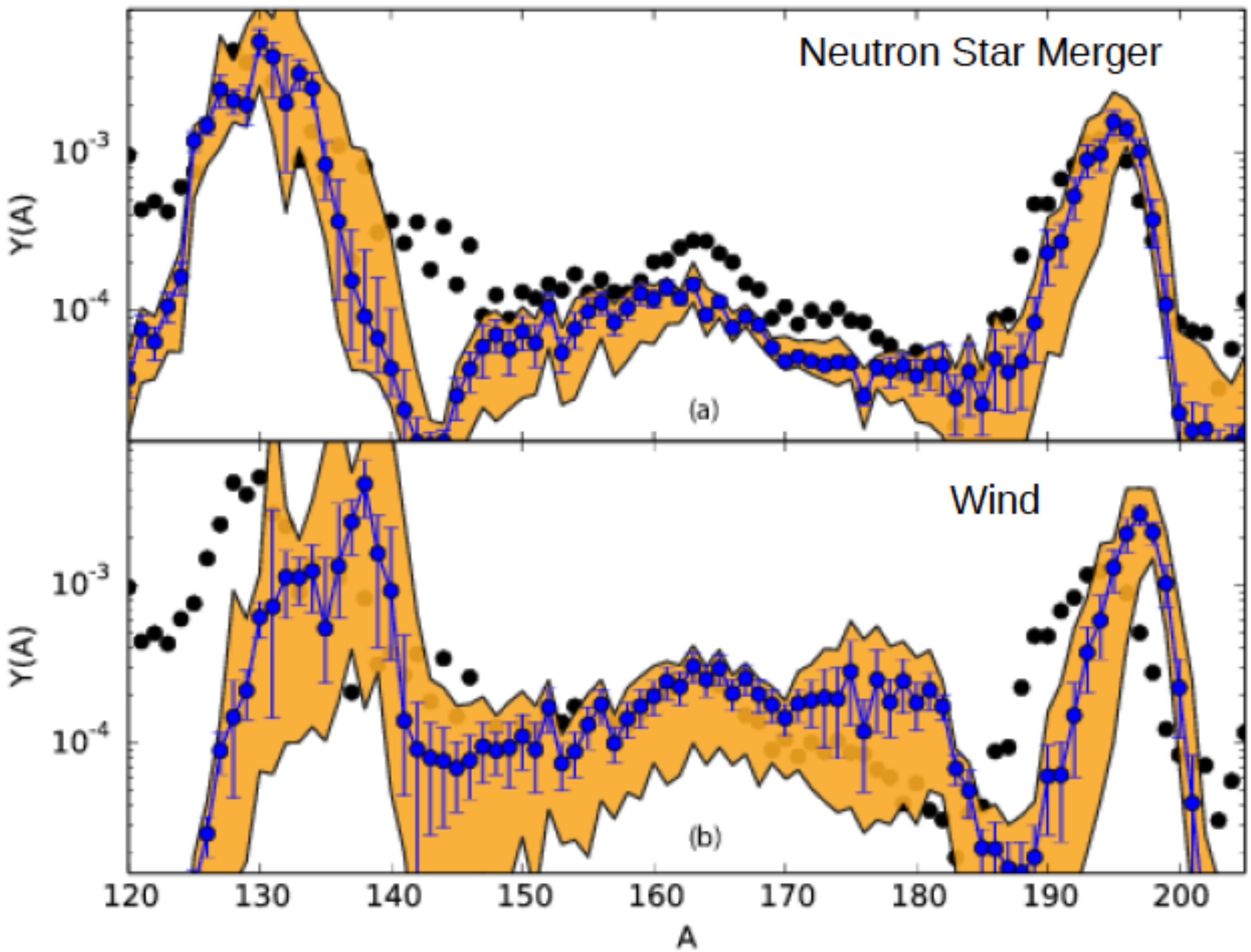






Possible sites for the r-process

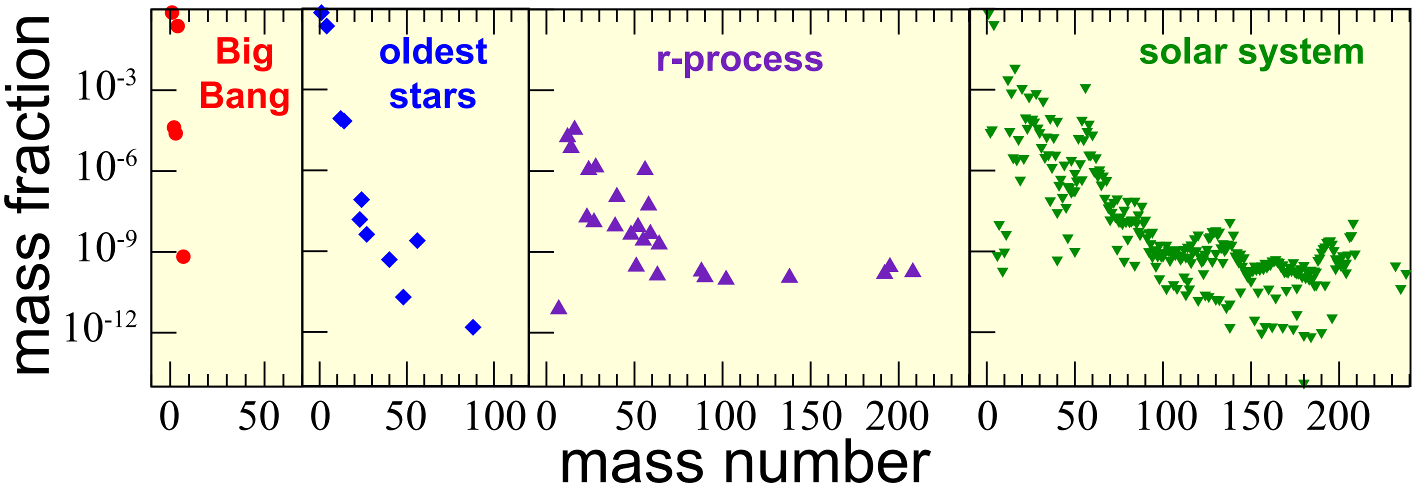
Estimated Final Abundances With Uncertainties

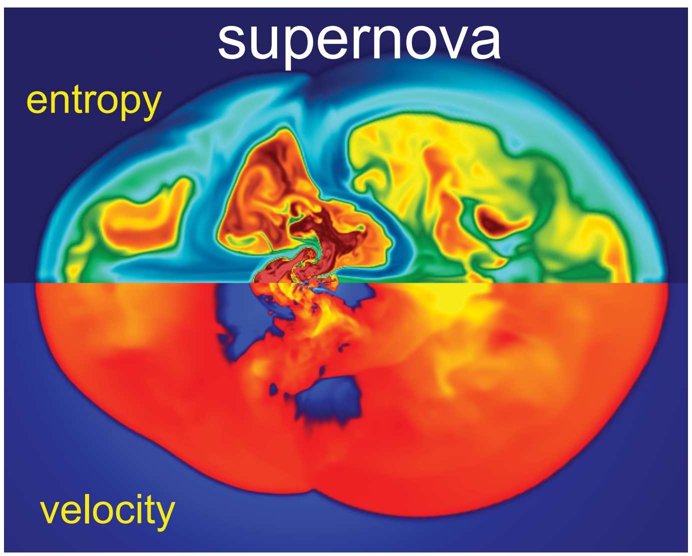


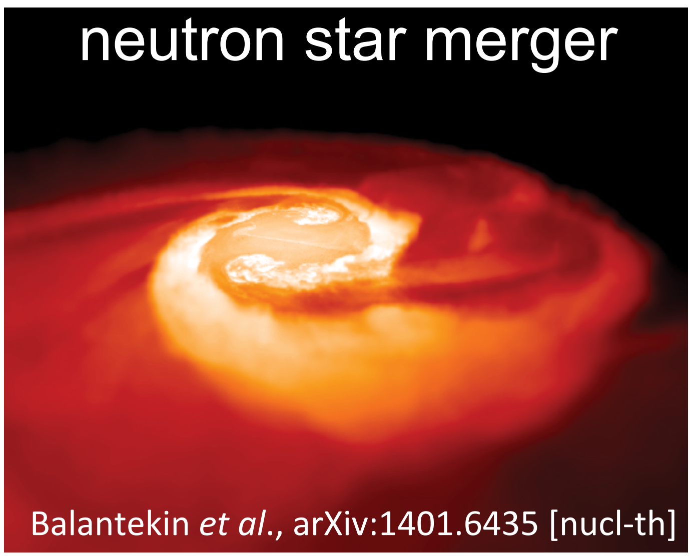
Variations in masses of N~82 and N~126 nuclei of +/- 1 MeV

Mumpower et al. (in prep)

The origin of elements



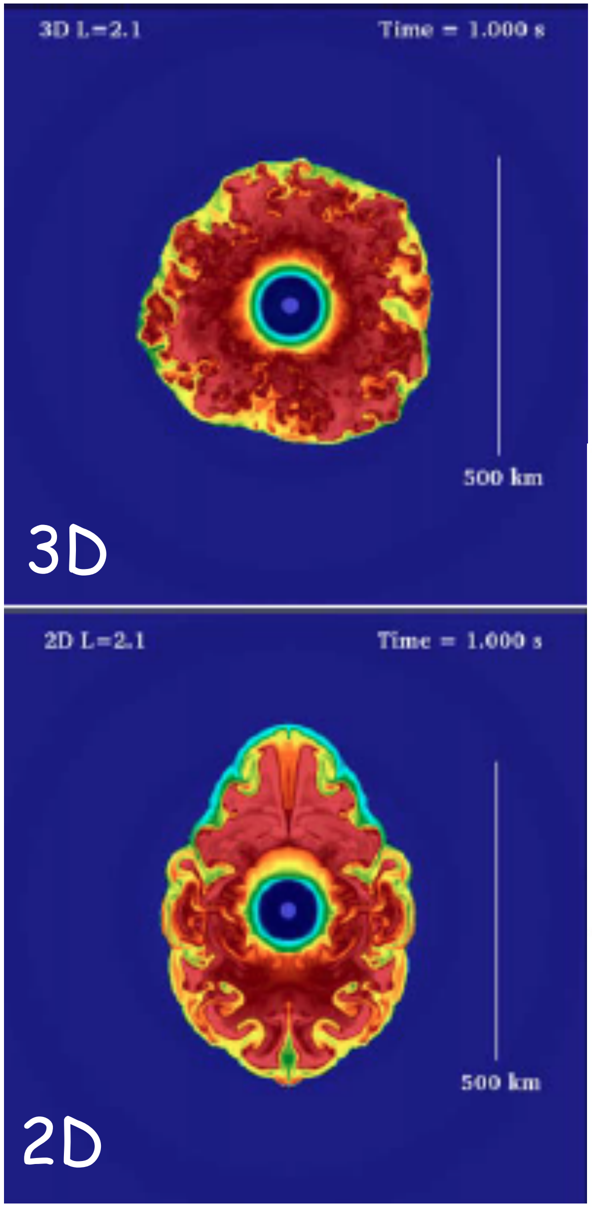




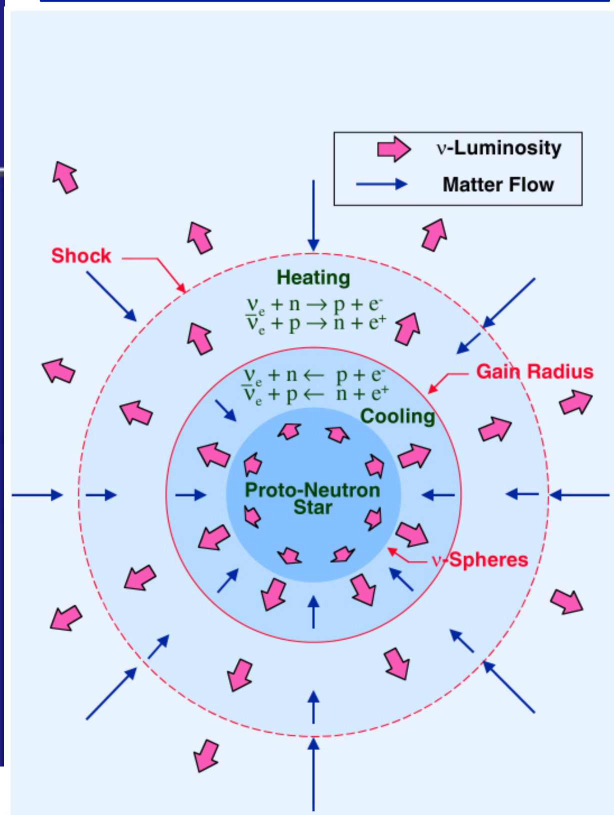
Neutrinos not only play a crucial role in the dynamics of these sites, but they also control the value of the electron fraction, the parameter determining the yields of the r-process.

Possible sites for the r-process

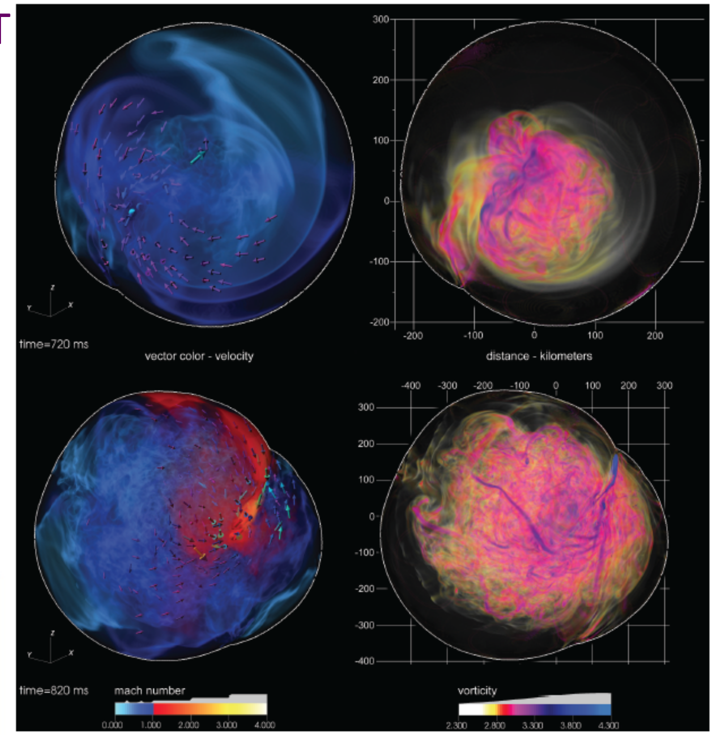
Development of 2D and 3D models for core-collapse supernovae: Complex interplay between turbulence, neutrino physics and thermonuclear reactions.

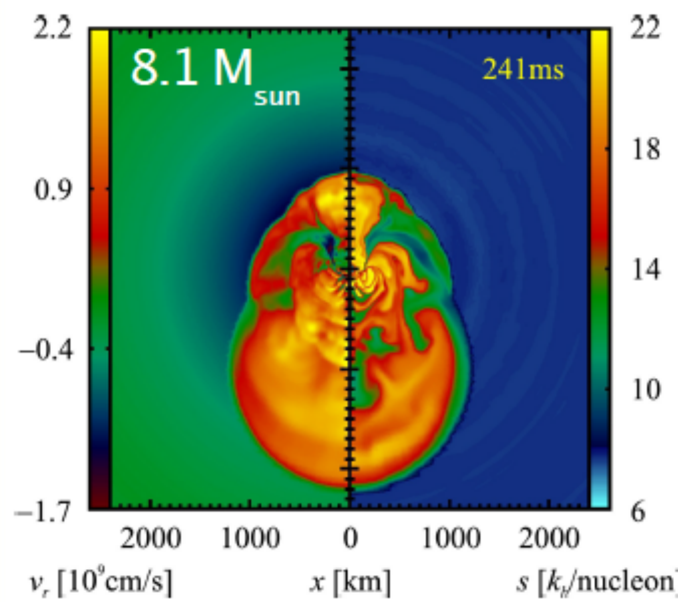


Princeton



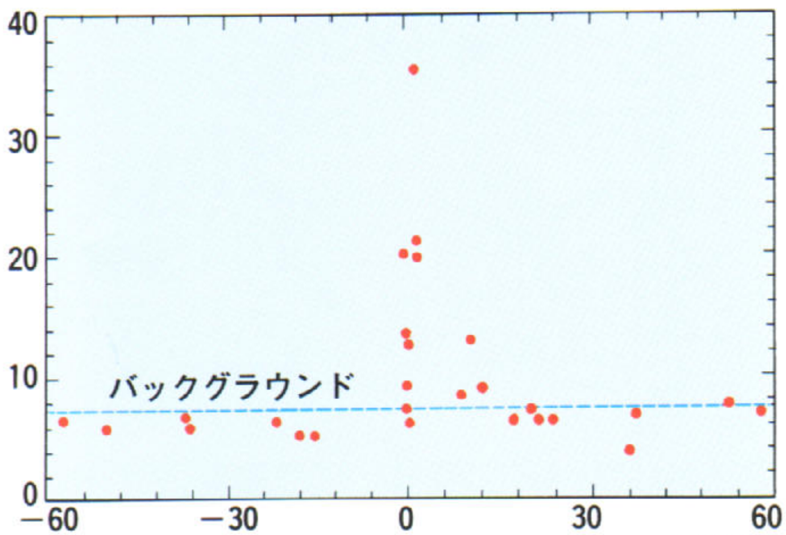
ORNL/UT



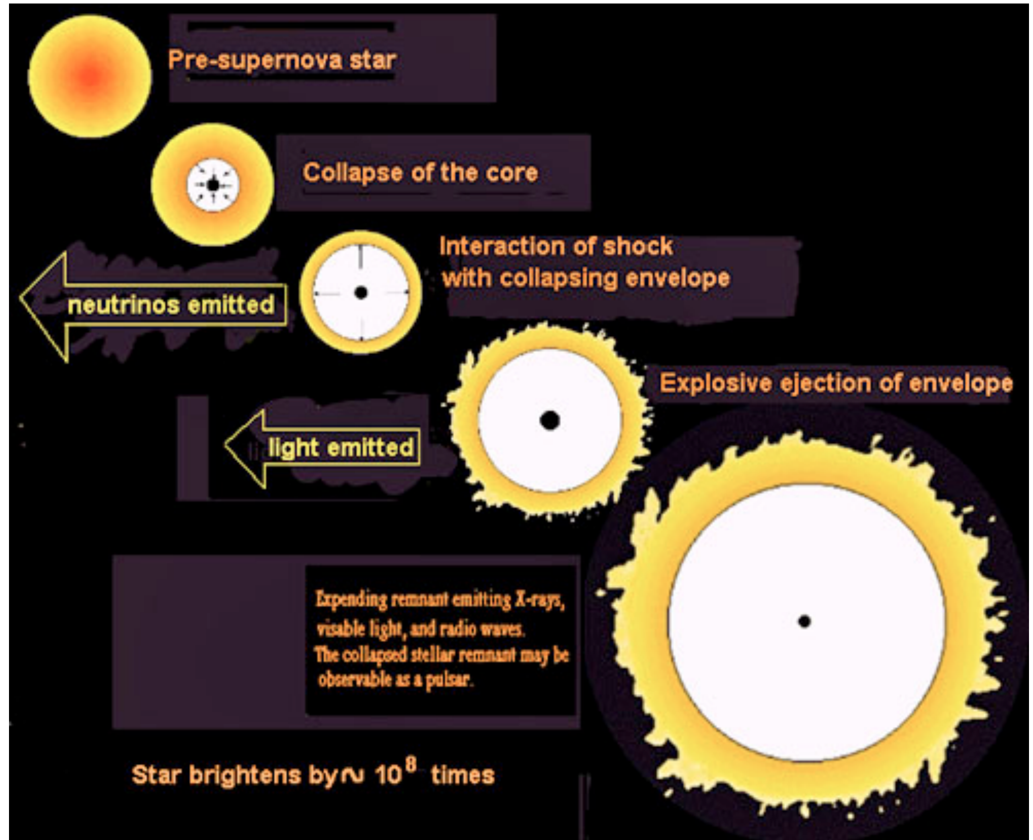


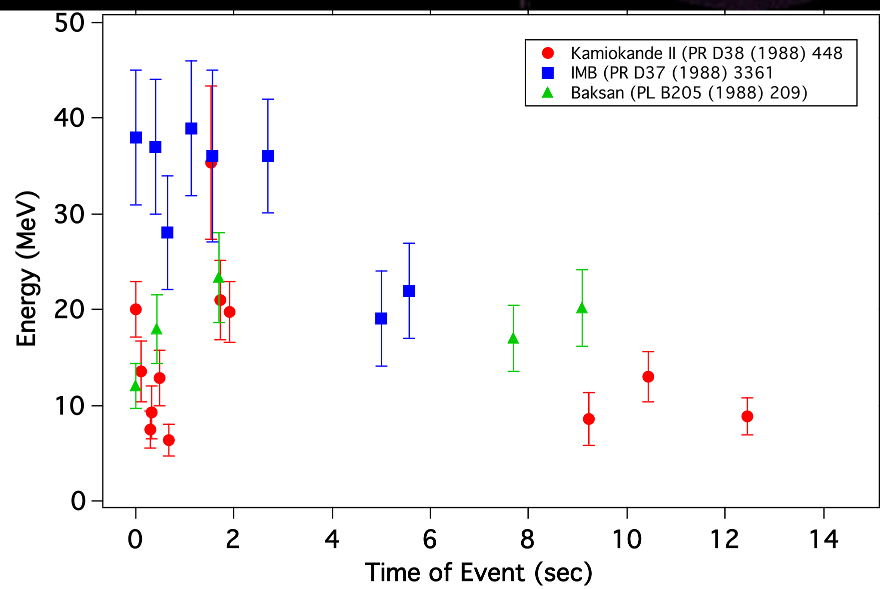
Munich

Neutrinos from core-collapse supernovae



- $M_{prog} \geq 8\ M_{sun} \Rightarrow \Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV
- 99% of the energy is carried away by neutrinos and antineutrinos with $10 \leq E_\nu \leq 30$ MeV $\Rightarrow 10^{58}$ neutrinos





Neutrinos dominate the energetics of core-collapse SN

Explosion only 1% of total energy

Total optical and kinetic energy = 10^{51} ergs

Total energy carried by neutrinos = 10^{53} ergs

10% of star's rest mass

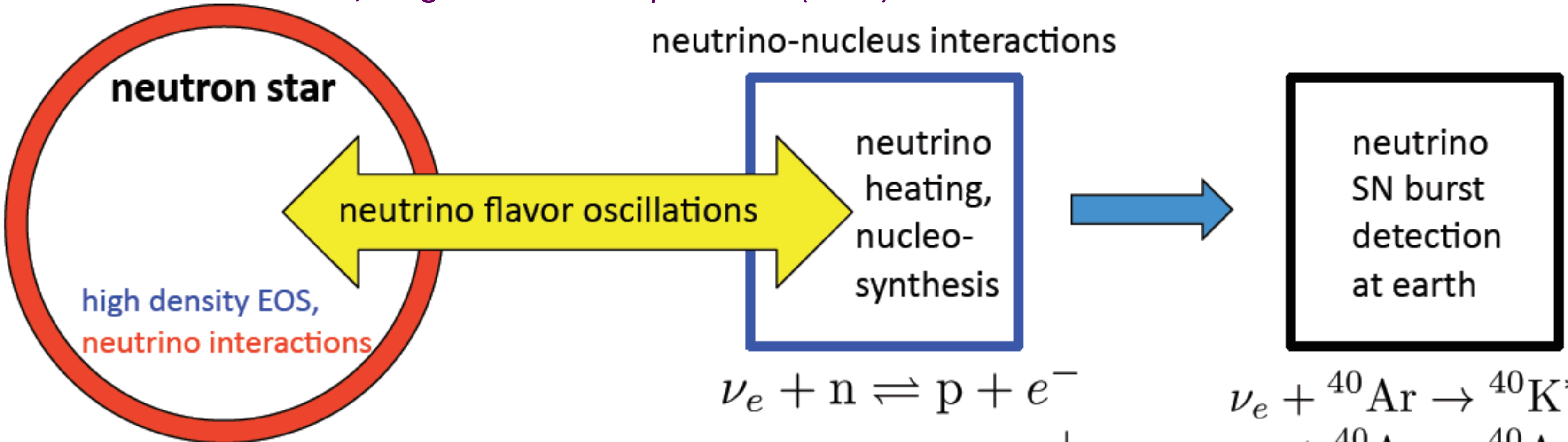
$$E_{grav} \cong \frac{3}{5}\frac{GM_{ns}^{2}}{R_{ns}} \approx 3\times10^{53} ergs\left(\frac{M_{ns}}{1.4M_{sun}}\right)^{2}\left(\frac{10km}{R_{ns}}\right)$$

Neutrino diffusion time, τ_ν ~ 2-10 s

$$L_\nu \approx \frac{GM_{ns}^{2}}{6R_{ns}}\frac{1}{\tau_\nu} \approx 4\times10^{51} ergs/s$$

For example understanding a core-collapse supernova requires answers to a variety of questions some of which need to be answered by nuclear physics, both theoretically and experimentally.

Balantekin and Fuller, Prog. Part. Nucl. Phys. **71** 162 (2013)



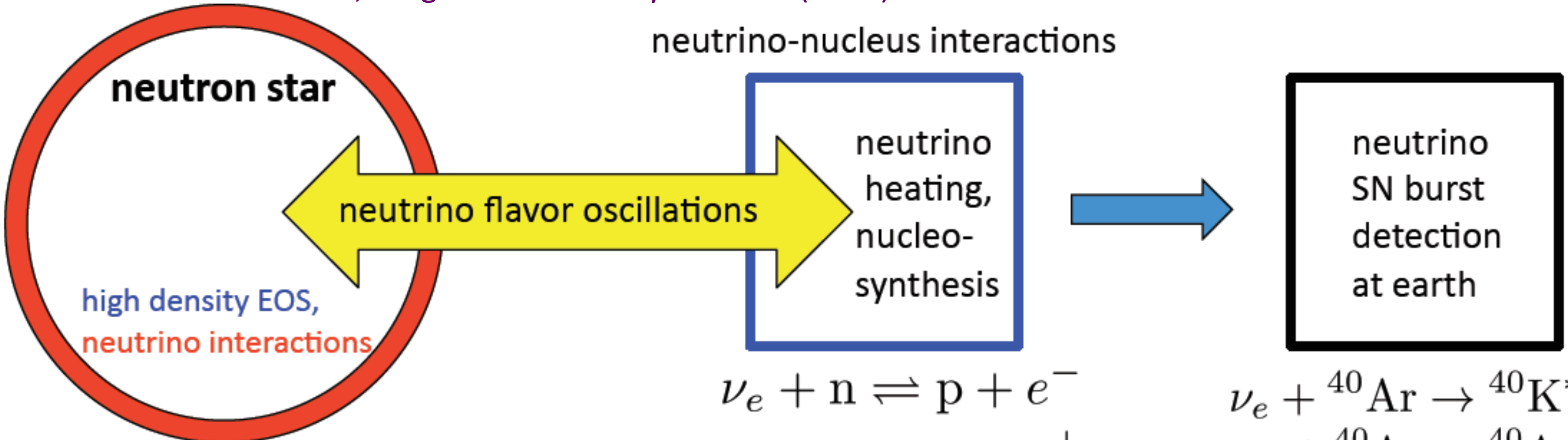
$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

$$\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{Ar}^* + \nu_x$$

If we want to catch a supernova with neutrinos we'd better know what neutrinos do inside a supernova.

For example understanding a core-collapse supernova requires answers to a variety of questions some of which need to be answered by nuclear physics, both theoretically and experimentally.

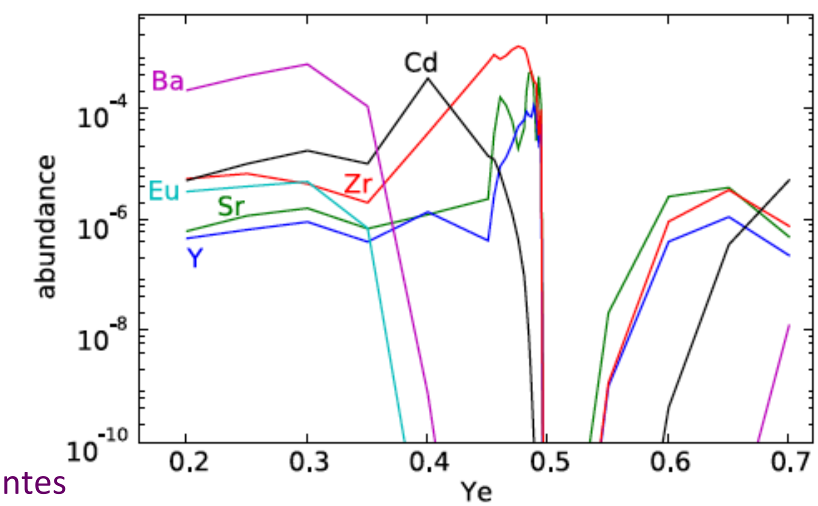
Balantekin and Fuller, Prog. Part. Nucl. Phys. **71** 162 (2013)



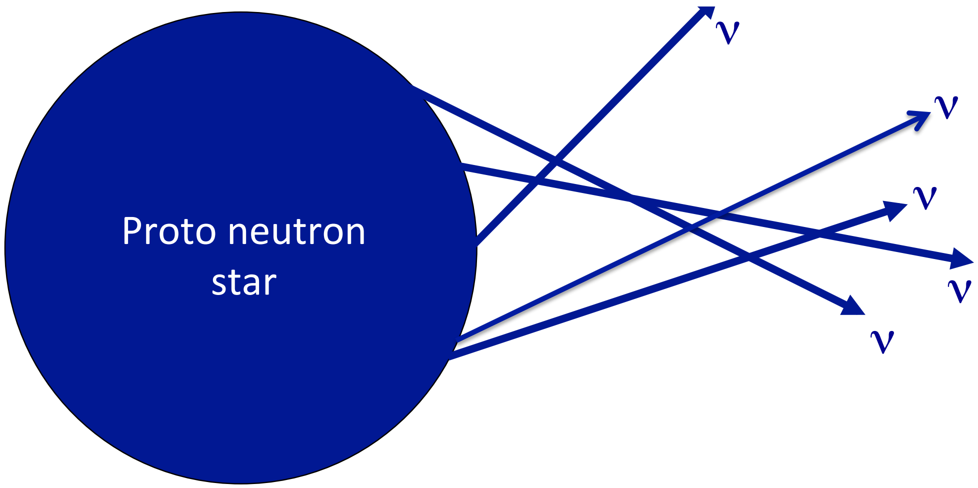
$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

$$\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{Ar}^* + \nu_x$$

$$Y_e = \frac{N_p}{N_p + N_n} = \frac{1}{1 + \lambda_p / \lambda_n}$$



Arcones and Montes



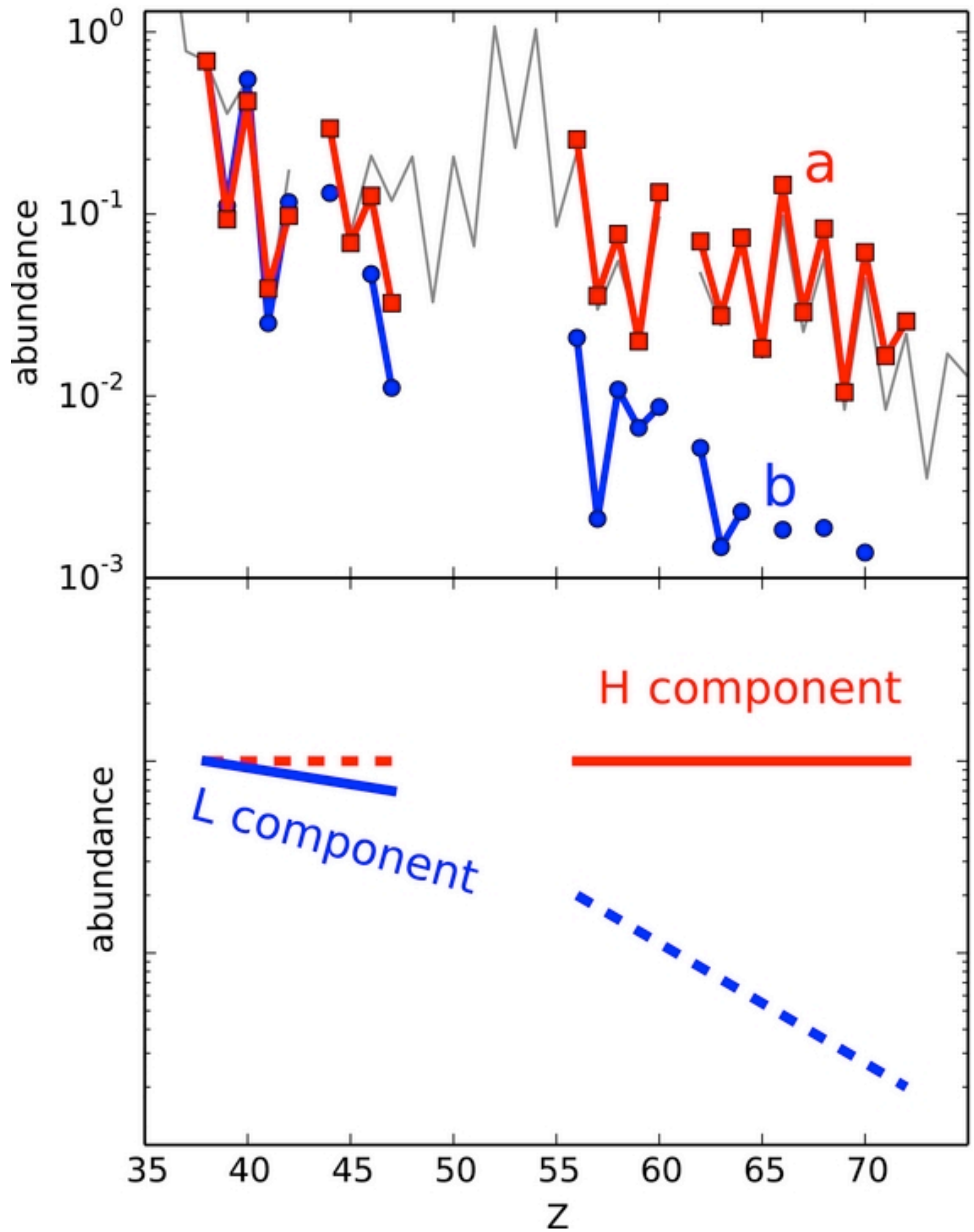
Energy released in a core-collapse SN: $\Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV
99% of this energy is carried away by neutrinos and antineutrinos!
~ 10^{58} Neutrinos!
This necessitates including the effects of $\nu\nu$ interactions!

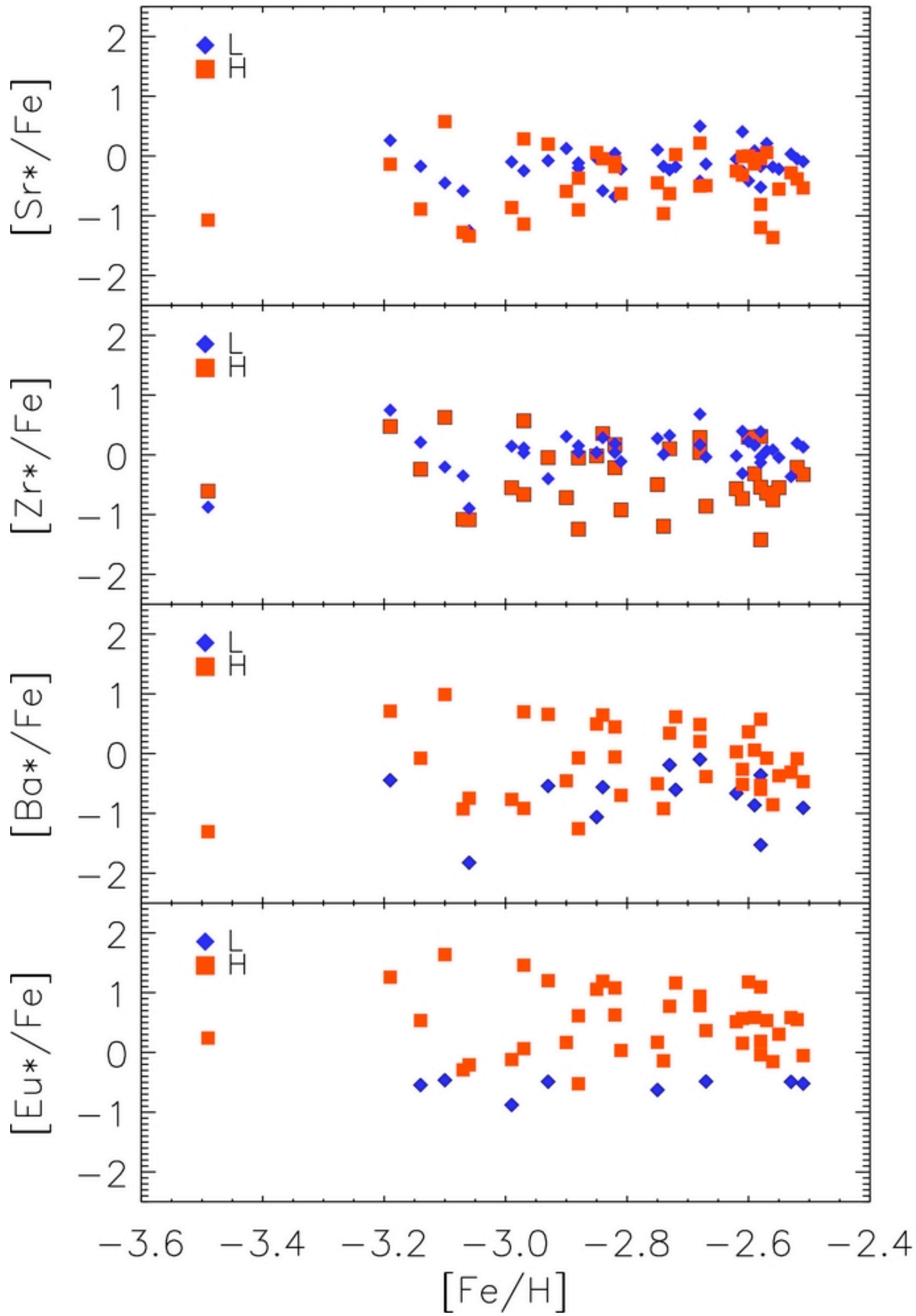
$$H = \underbrace{\sum a^{\dagger} a}_{\substack{\text{describes neutrino oscillations} \\ \text{interaction with matter (MSW effect)}}} + \underbrace{\sum (1-\cos\theta)\, a^{\dagger} a^{\dagger} a a}_{\substack{\text{describes neutrino-neutrino} \\ \text{interactions}}}$$

The second term makes the physics of a neutrino gas in a core-collapse supernova a very interesting many-body problem, driven by weak interactions.

Neutrino-neutrino interactions lead to novel collective and emergent effects, such as conserved quantities and interesting features in the neutrino energy spectra (spectral "swaps" or "splits").

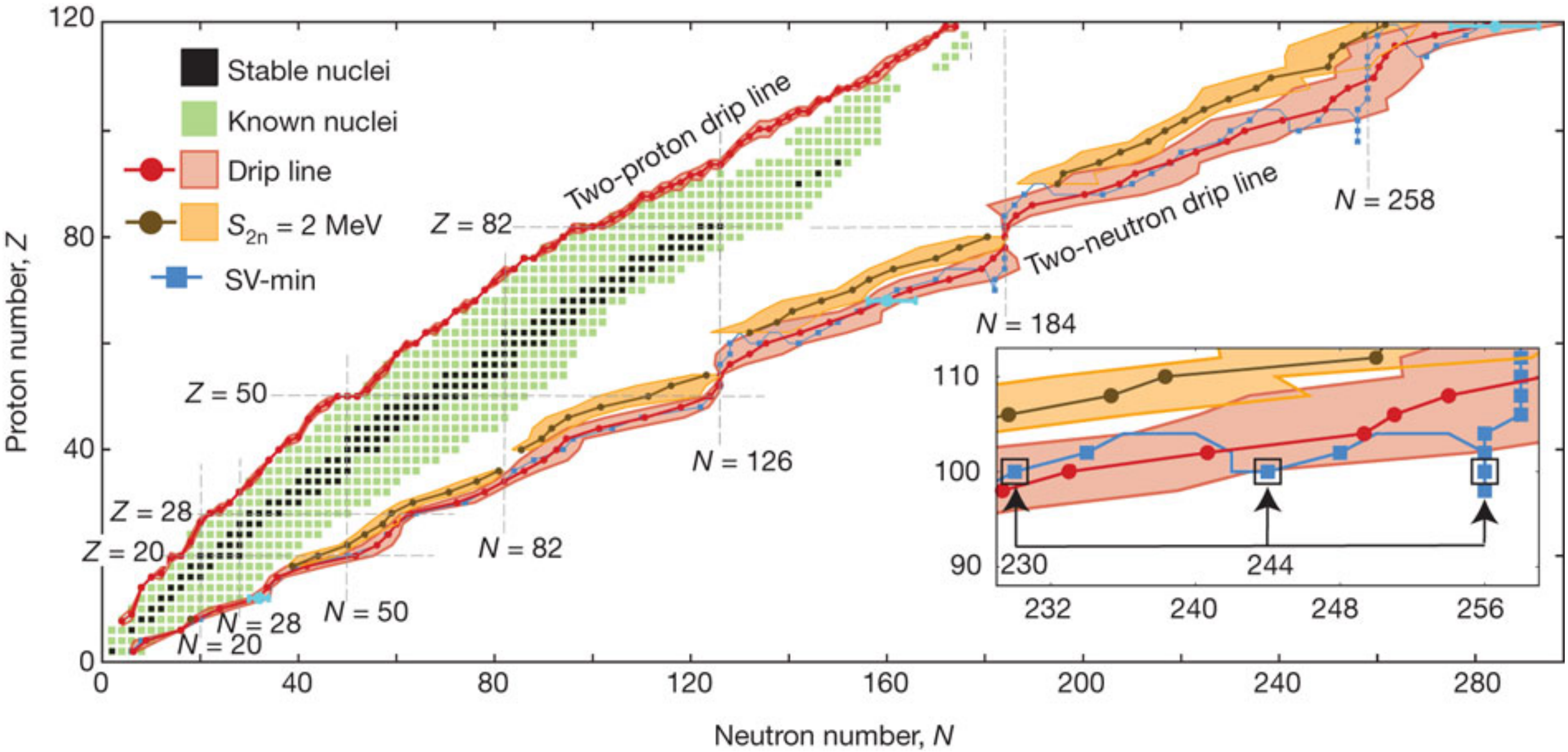
Ultra metal poor stars with high (H) and low (L) enrichment of r-process nuclei: At least two components or sites (Qian & Wasserburg)





Hansen, Montes, and Arcones, Ap.J. **797**, 2 (2014).

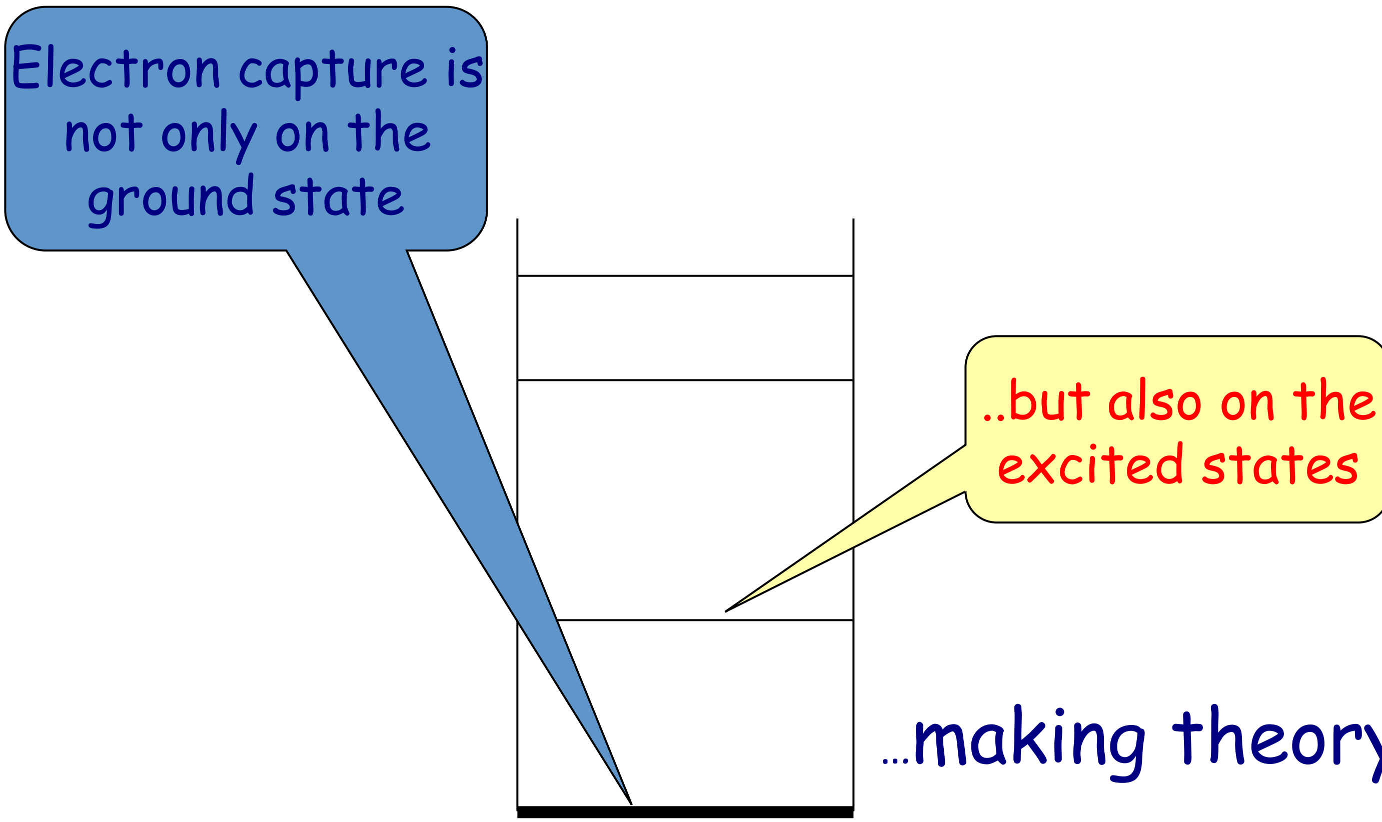
In recent years major advances in computational capabilities have pushed the boundaries of what can be calculated by microscopic *ab initio* methods in nuclear theory



J. Erler *et al. Nature* **486**, 509-512 (2012)

Theoretical Issues

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

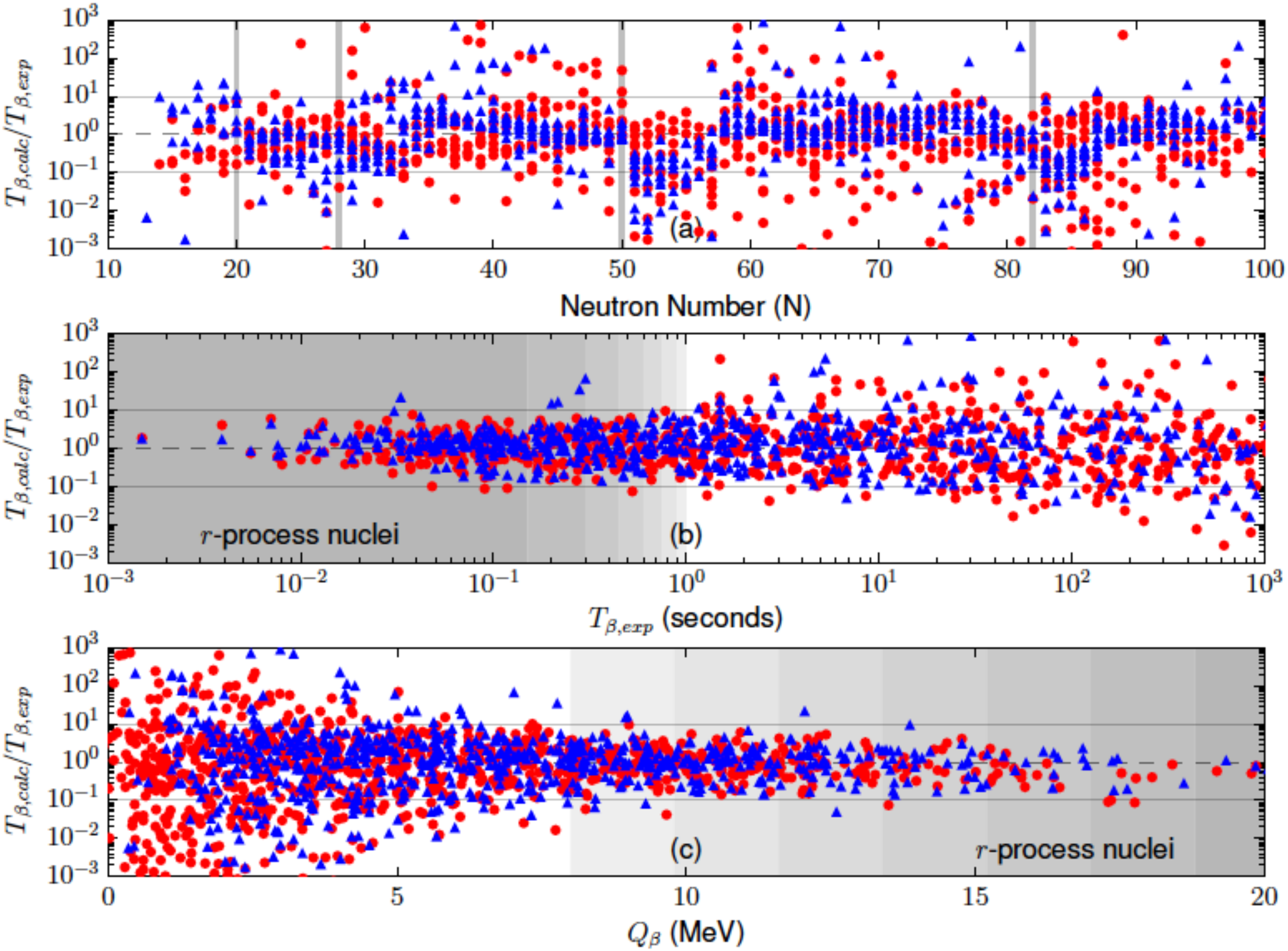


...making theory input crucial!

To understand the r-process one needs, among other things, to learn beta-decays of nuclei both at and far-from stability:

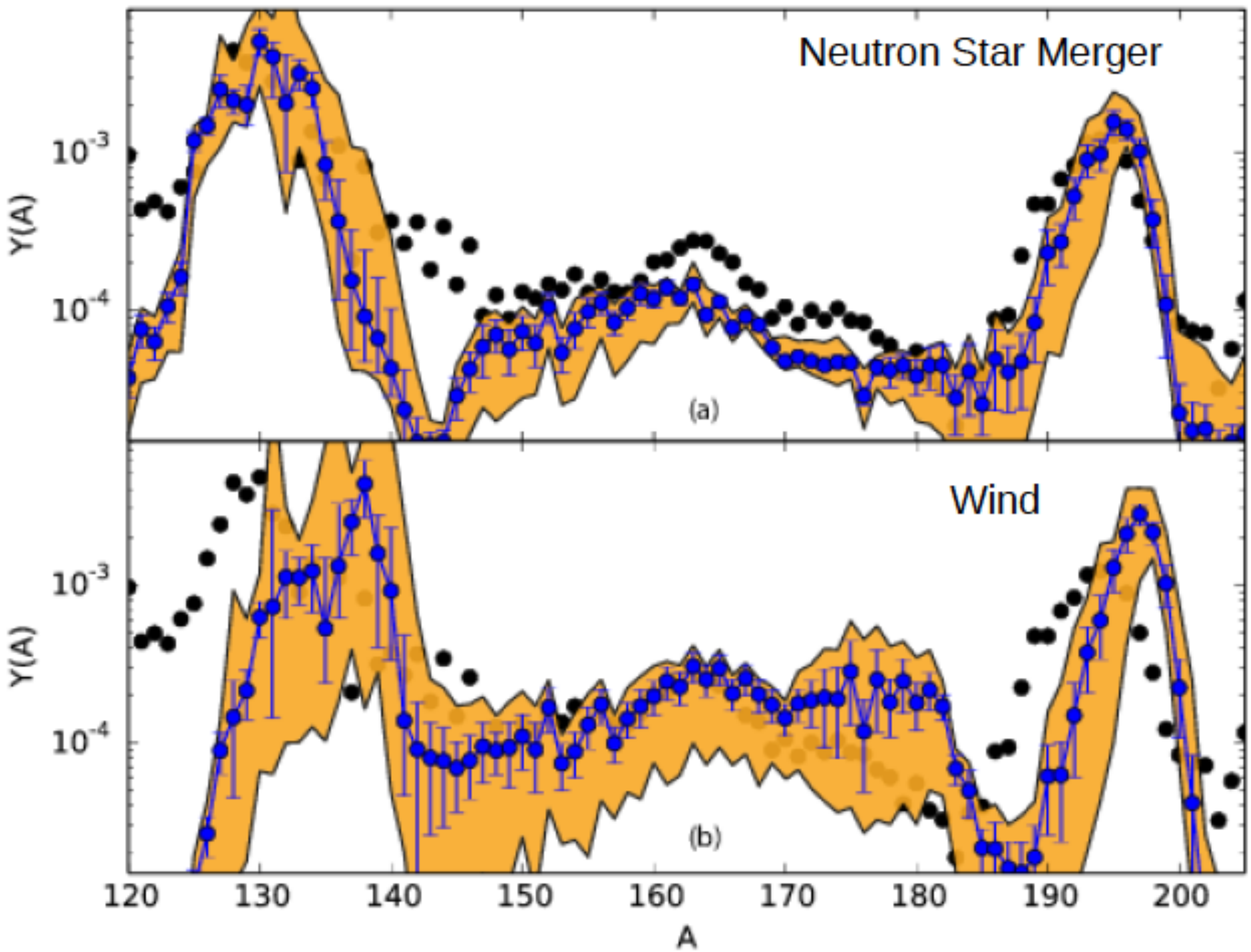
- We need half-lifes at the r-process ladders (N=50, 82, 126) where abundances peak.
- We need accurate values of initial and final state energies.
- Spin-isospin response: Matrix elements of the Gamow-Teller operator $\sigma.\tau$ (even the forbidden operators $\mathbf{r}\sigma.\tau$) between the initial and final states.

Comparison of the theoretical beta decay half-lives to the measured values



Mumpower *et al.*

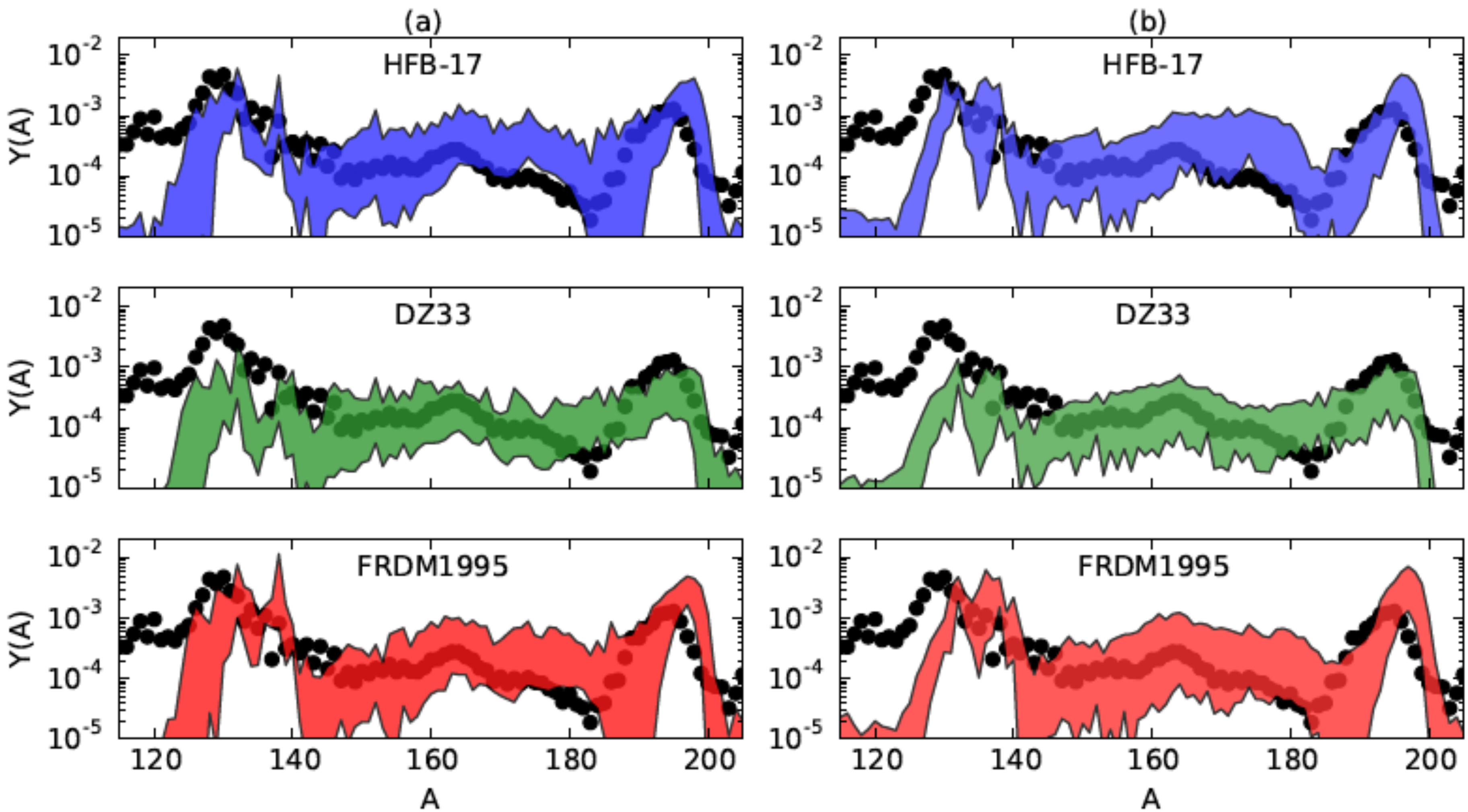
Estimated Final Abundances With Uncertainties



Variations in masses of N~82 and N~126 nuclei of +/- 1 MeV

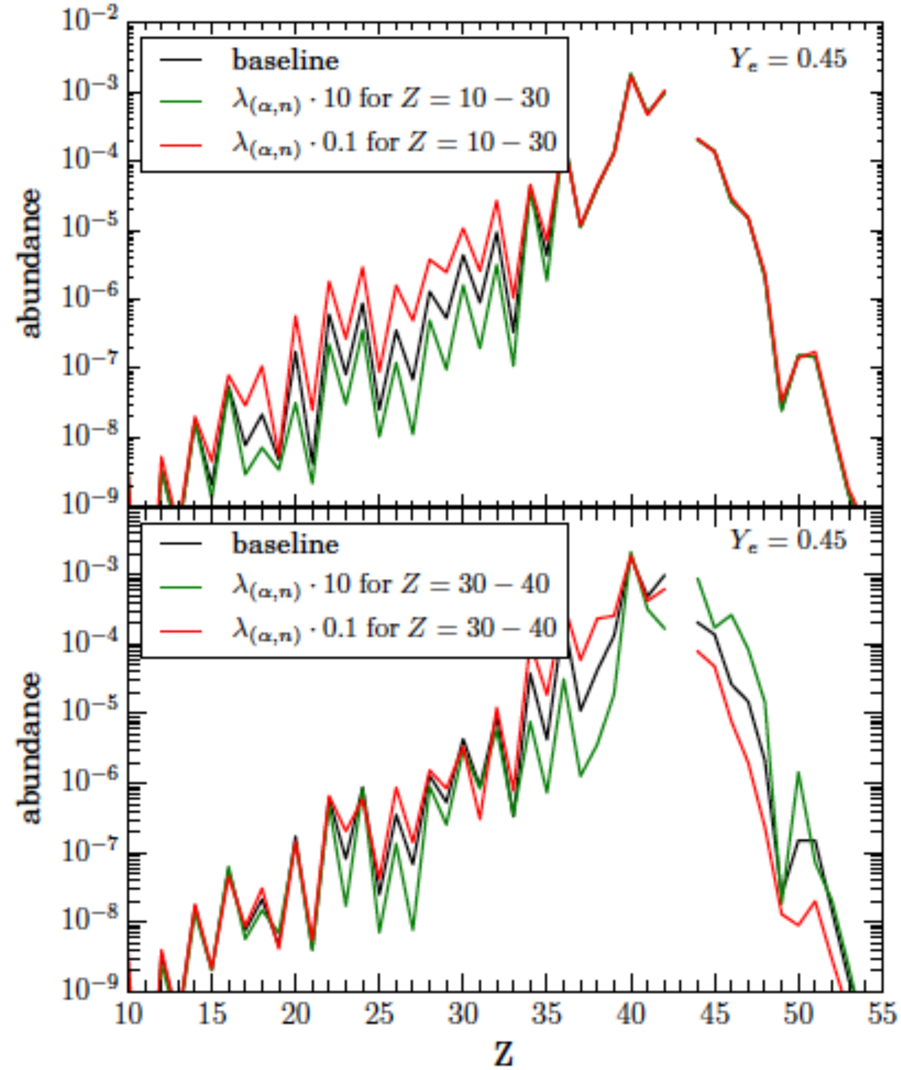
Mumpower et al. (in prep)

Variances in isotopic abundance patterns for three different nuclear mass models a) uncertain beta-decay half lives, b) uncertain neutron capture rates



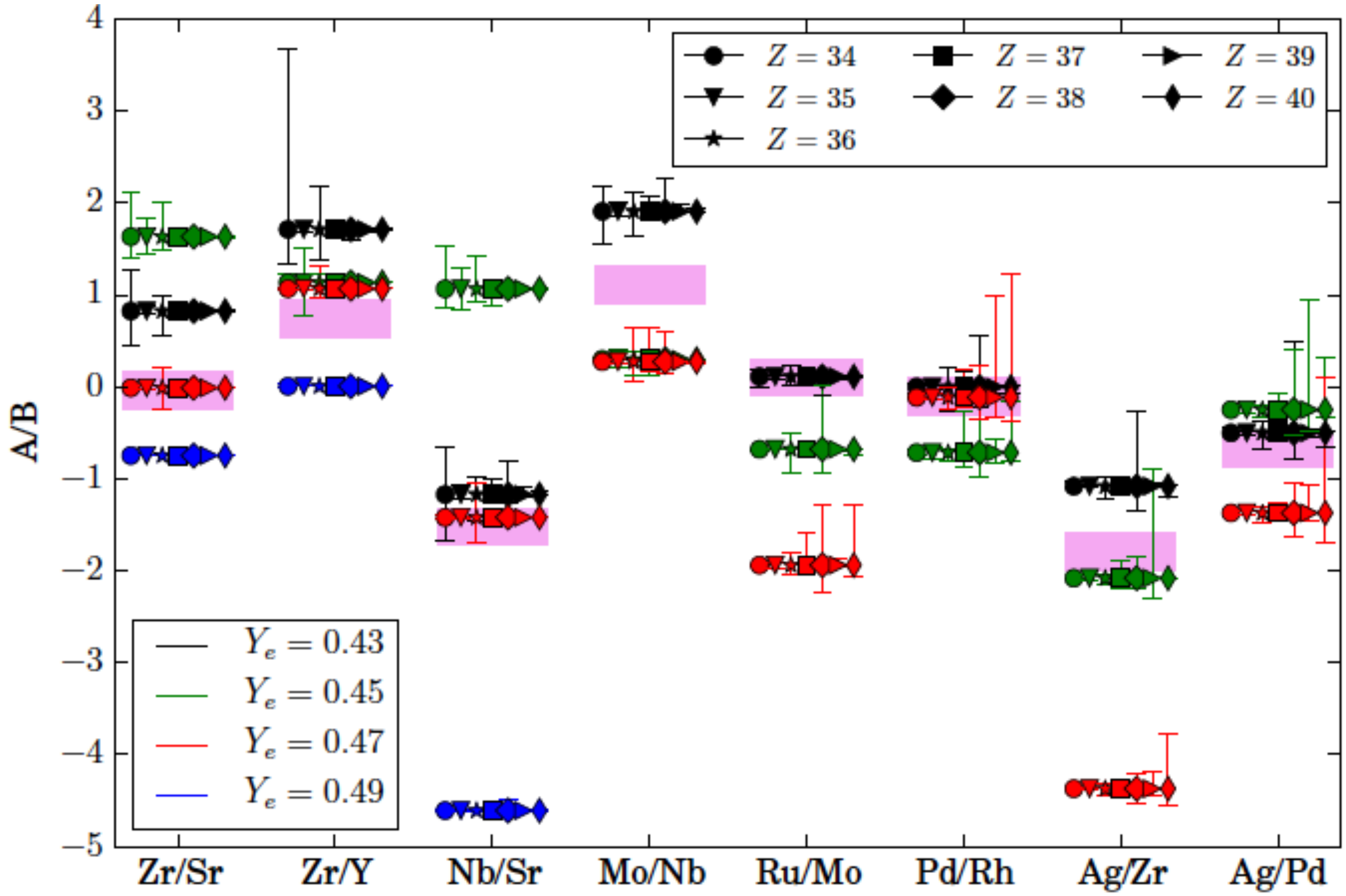
Mumpower *et al.*

Nuclear physics uncertainties: (α,n) reactions



Bliss, Arcones, et.al.

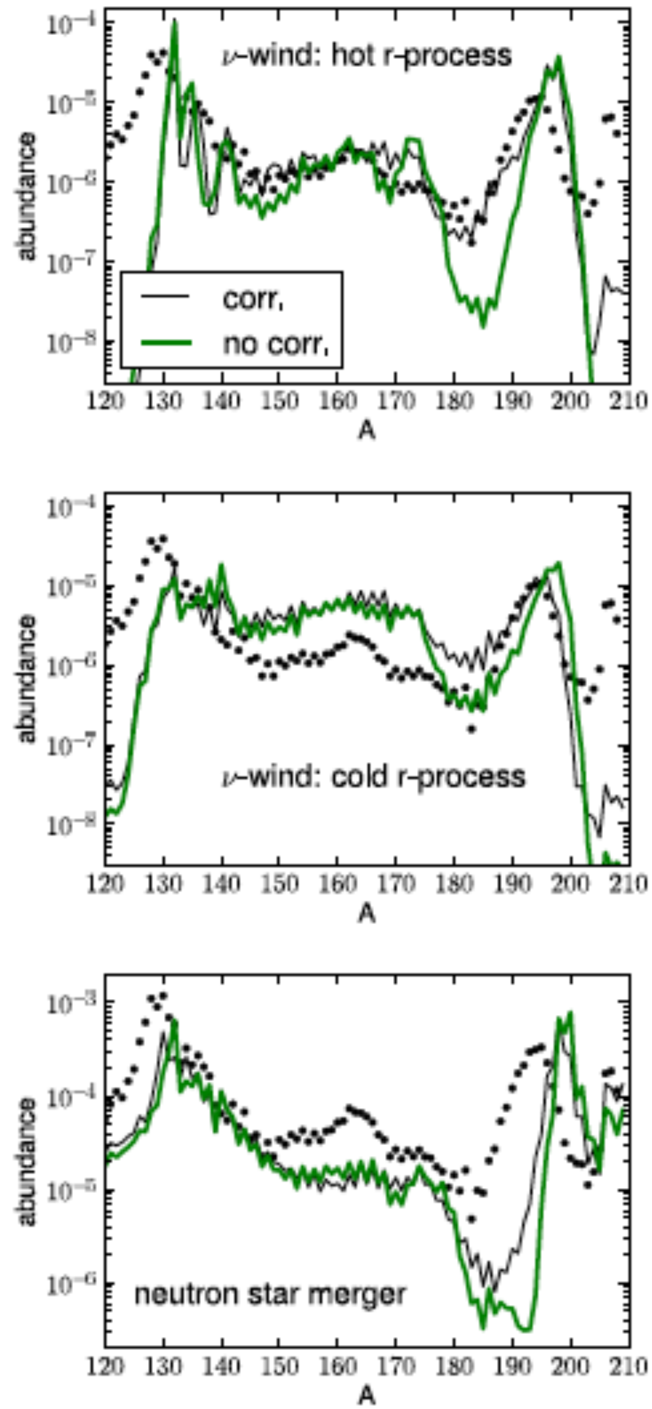
X(α,n)Y uncertainties



Bliss, Arcones, et.al.

Effect of the correlations in nuclear mass models

Arcones and Bertsch



A few concluding remarks

- Nuclear Physics input is crucial in many facets of astrophysics and cosmology.
- Despite recent remarkable advances in nuclear theory many unanswered questions remain.
- The experimental program in this quest requires both stable and exotic rare-ion beams.
- The current situation presents an opportunity for a synergistic collaboration between nuclear physicists, astronomical observers, and computational astrophysicists with big potential pay-off.


Dziękuję bardzo!
RMF