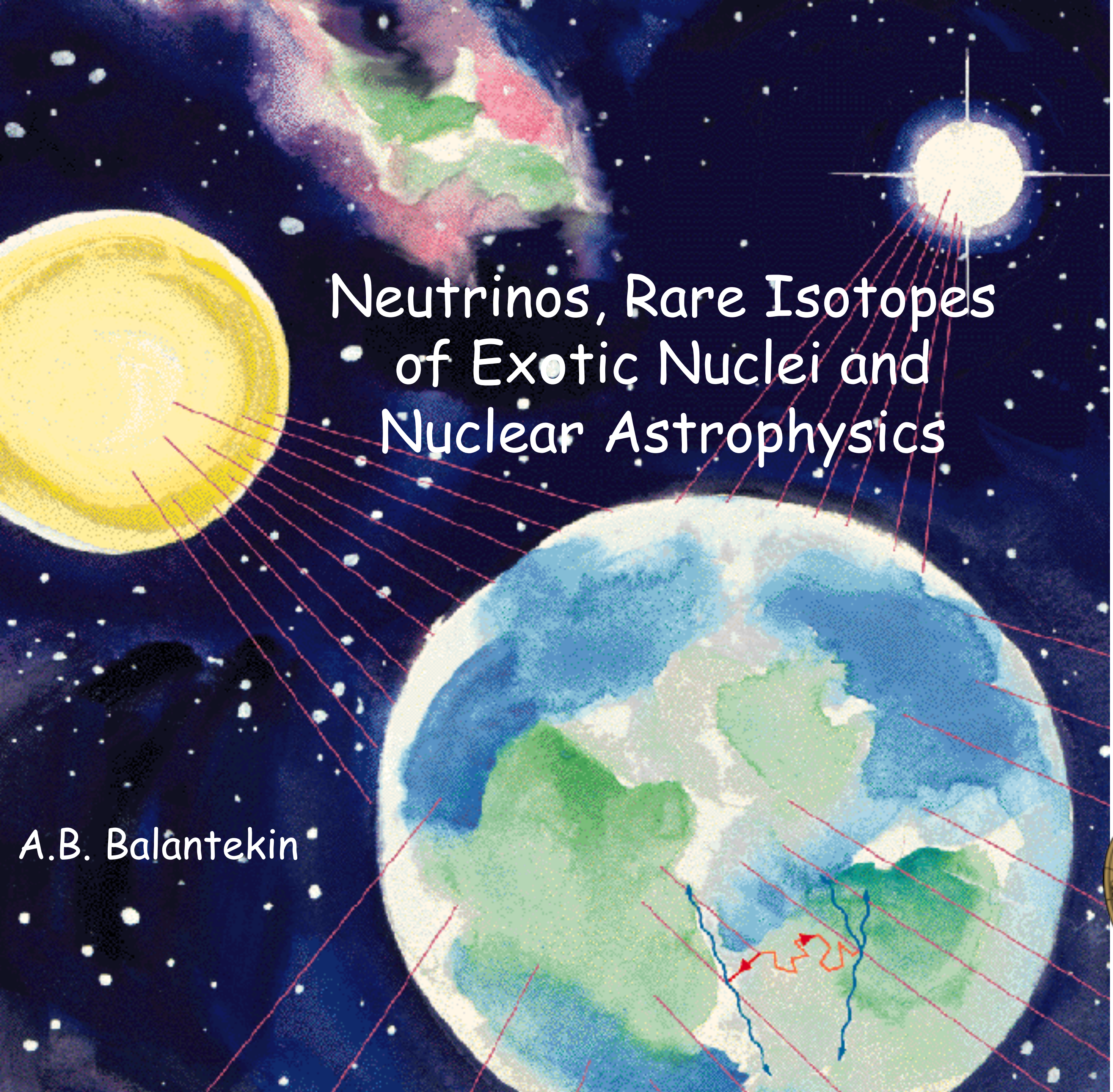
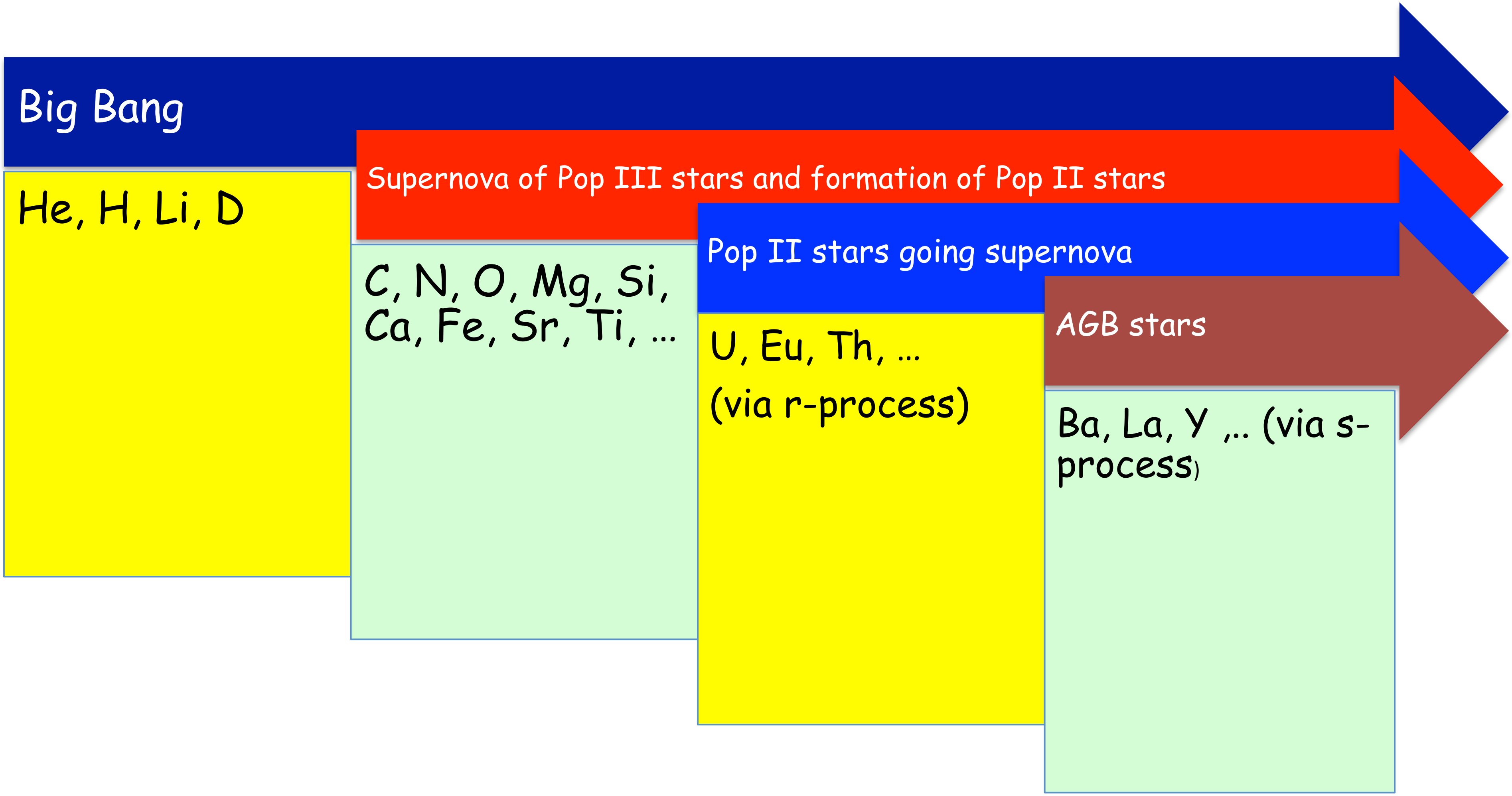


Neutrinos, Rare Isotopes of Exotic Nuclei and Nuclear Astrophysics

A.B. Balantekin

THE UNIVERSITY of WISCONSIN MADISON

Where chemical elements are made



Big Bang

He, H, Li, D

Supernova of Pop III stars and formation of Pop II stars

C, N, O, Mg, Si, Ca, Fe, Sr, Ti, …

Pop II stars going supernova

U, Eu, Th, …

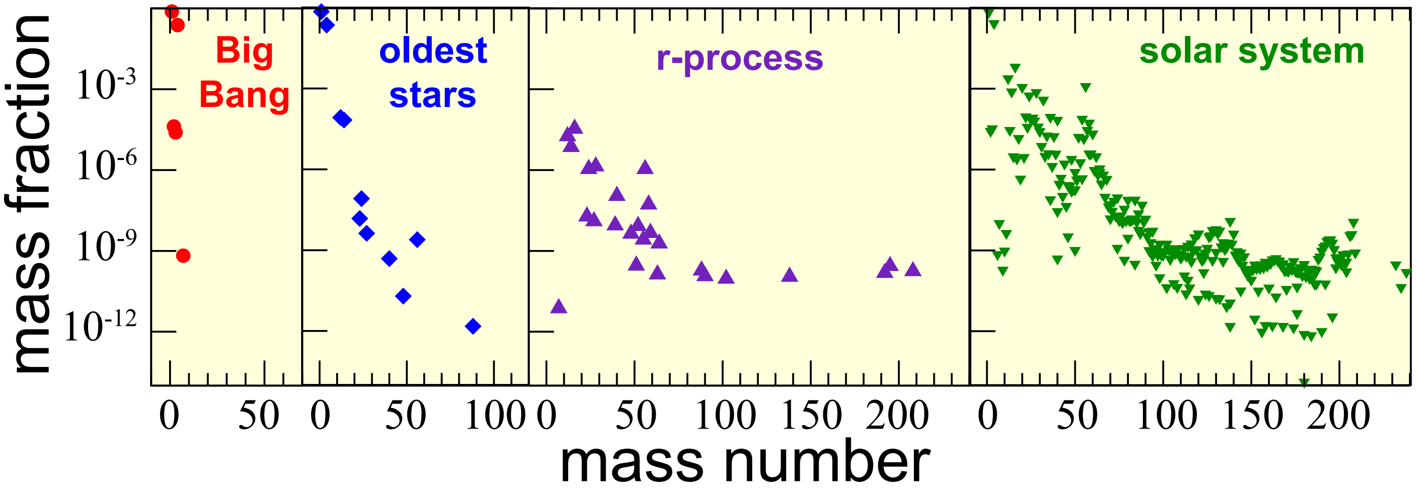
(via r-process)

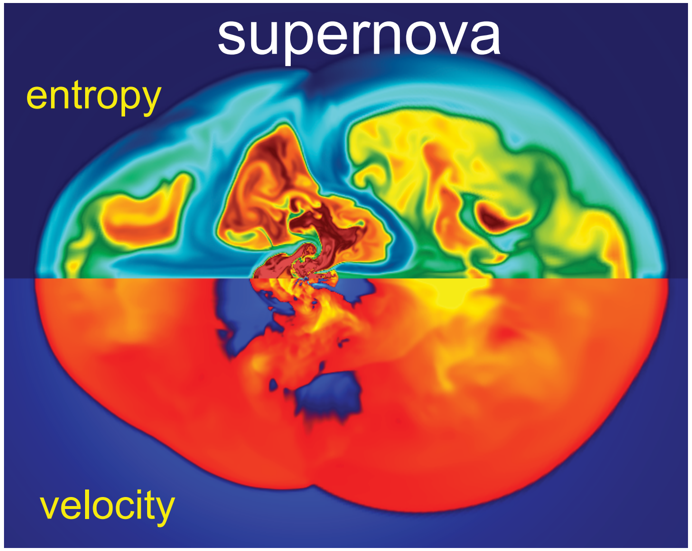
AGB stars

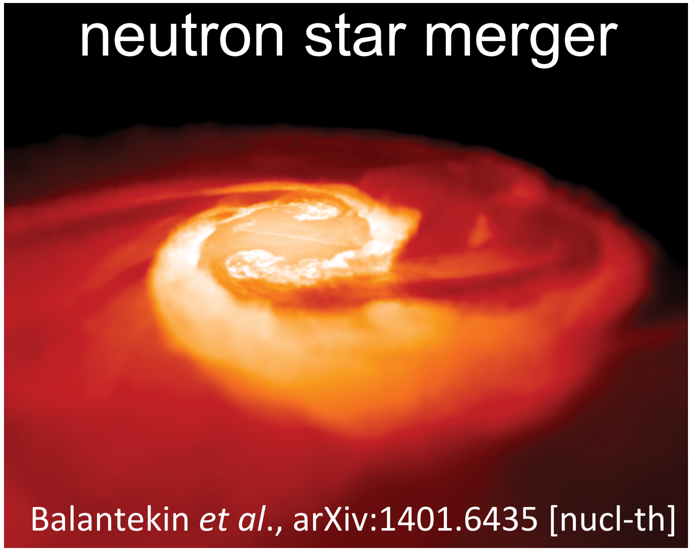
Ba, La, Y ,.. (via s-process)

Neutrinos play a crucial role in many nucleosynthesis scenarios.

The origin of elements





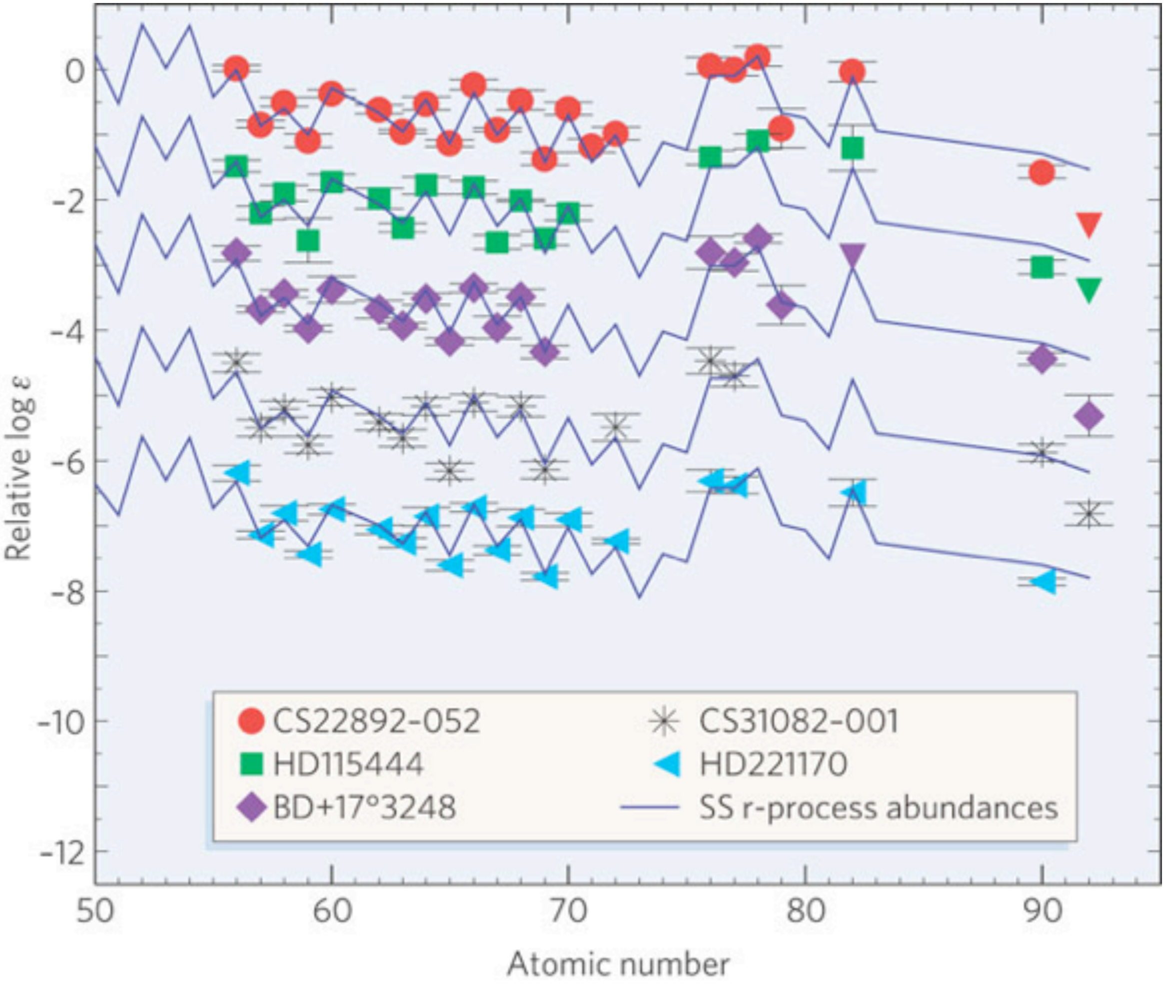


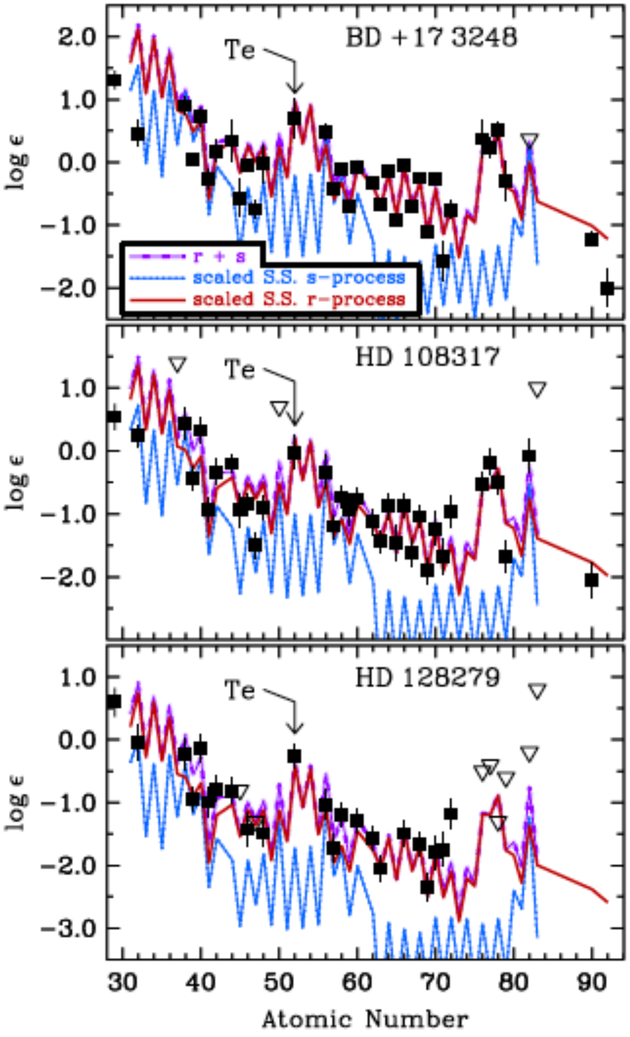
Balantekin *et al.*, arXiv:1401.6435 [nucl-th]

Possible sites for the r-process

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.

r-process nucleosynthesis



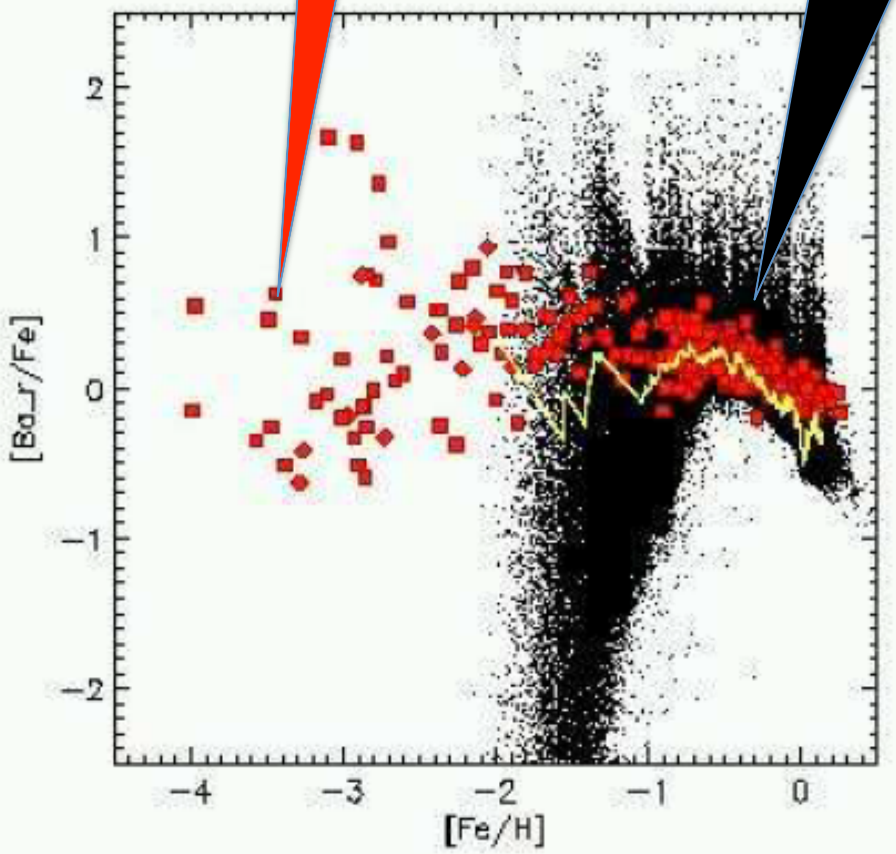


A > 100 abundance pattern fits the solar abundances well.

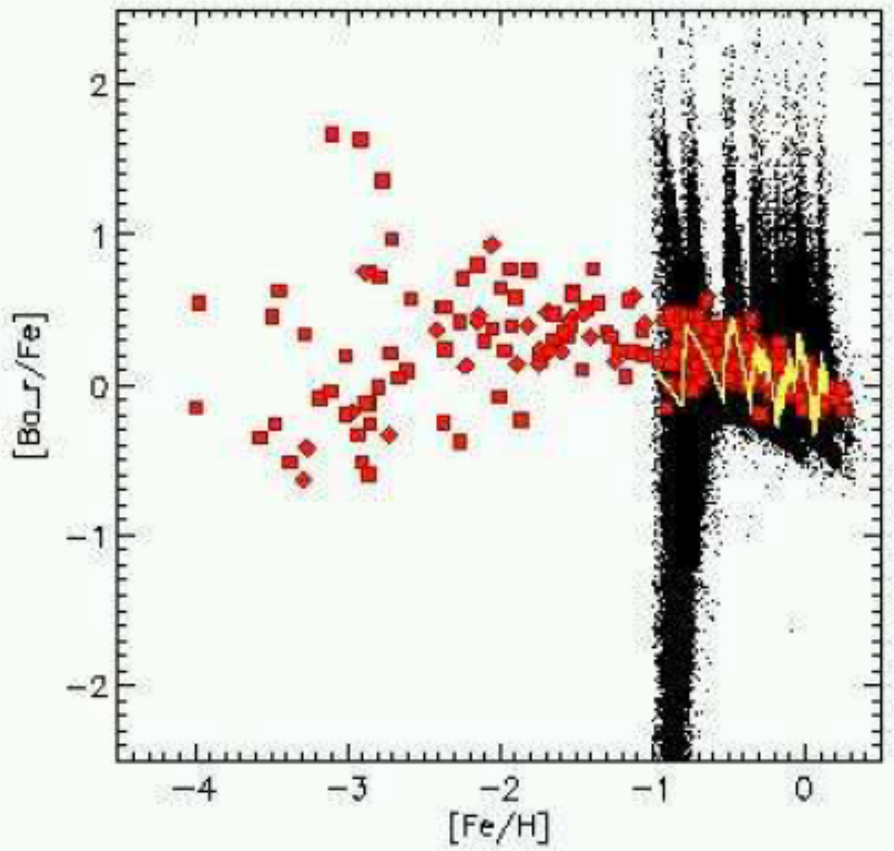
Roederer *et al.*, Ap. J. Lett. **747**, L8 (2012) observations

Model calculations for neutron-star mergers

Coalescence timescale = 1 Myr



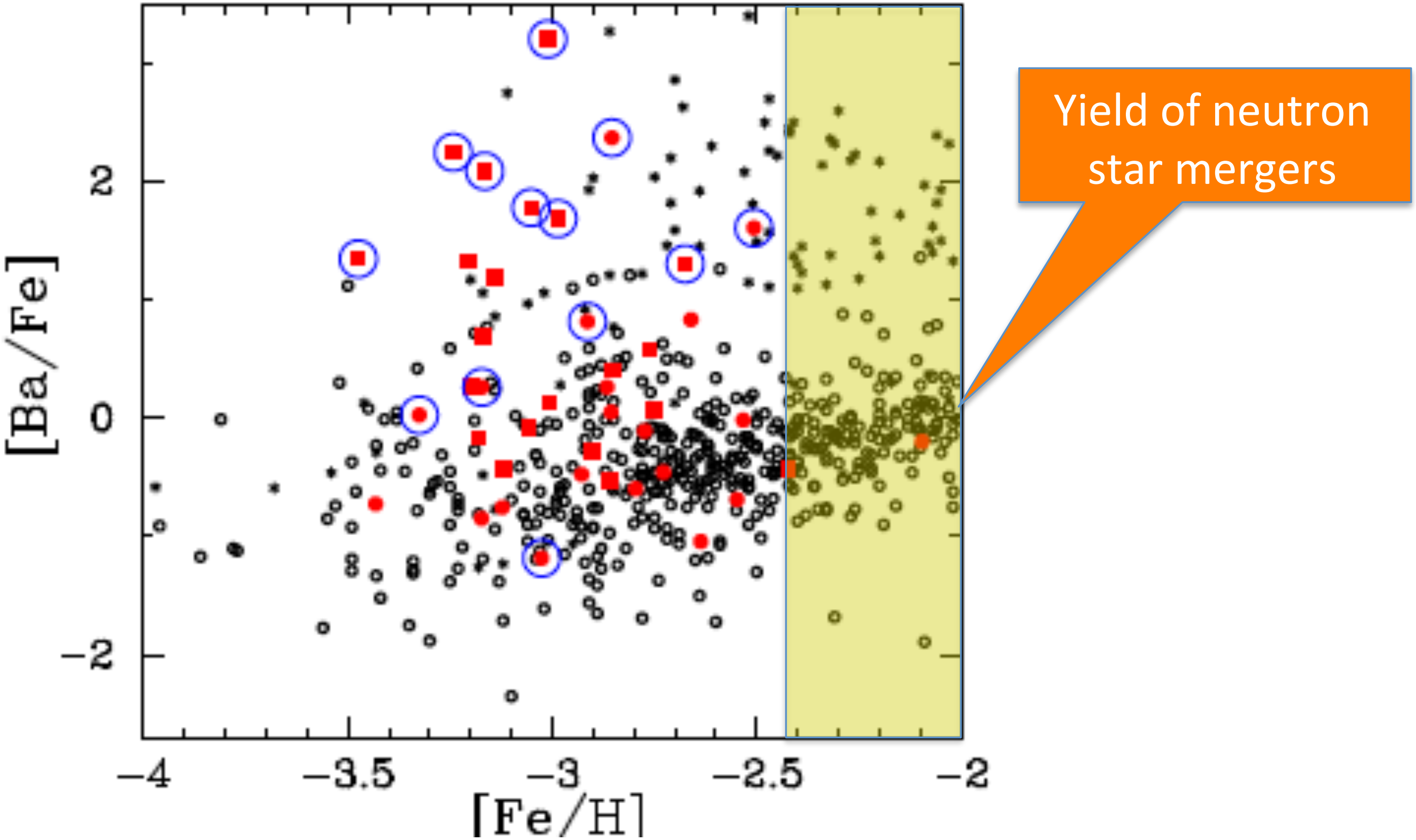
Average merger rate = 20/Myr



Average merger rate = 2/Myr

Star formation rate?

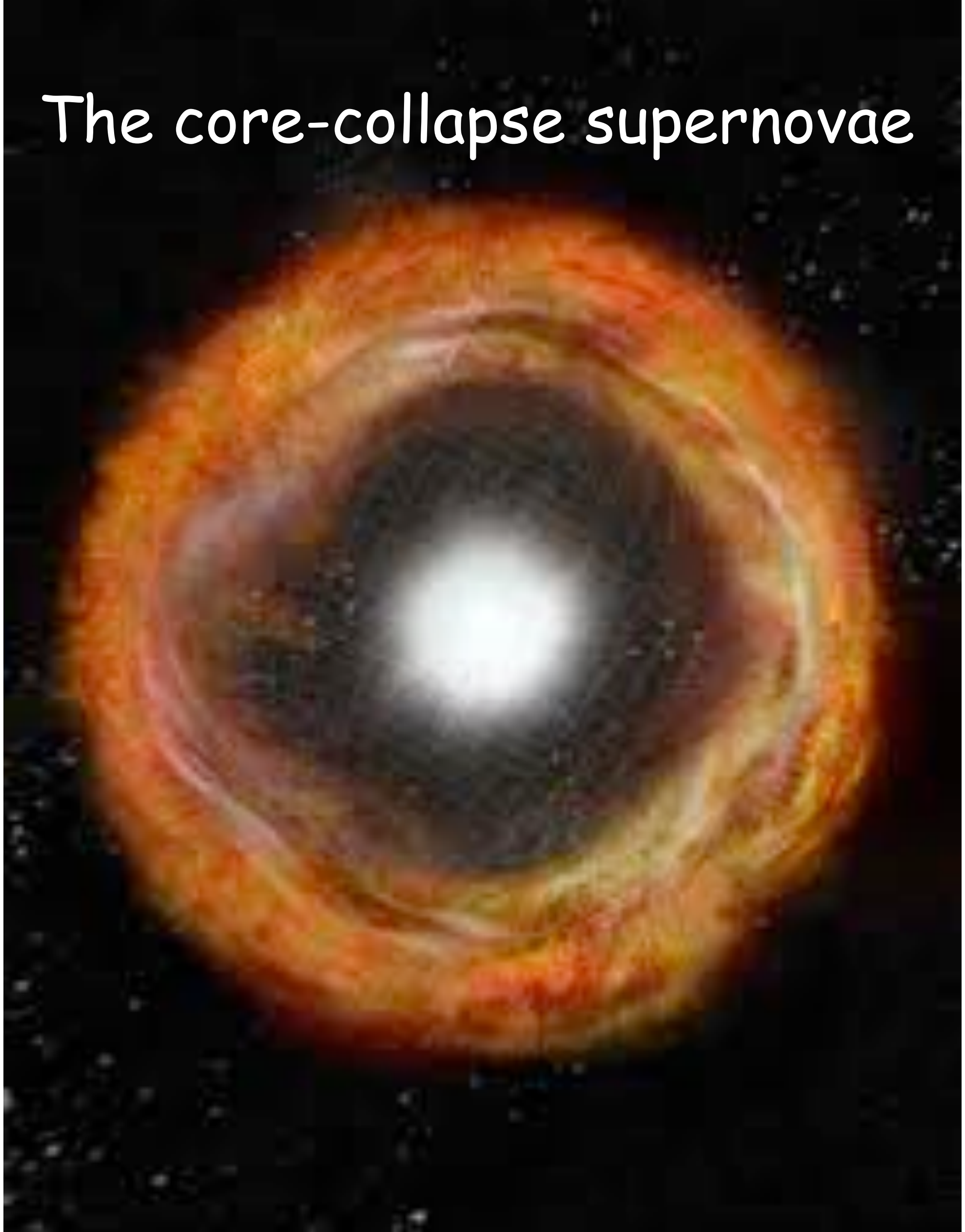
Argast *et al.*, A&A, **416**, 997 (2003)



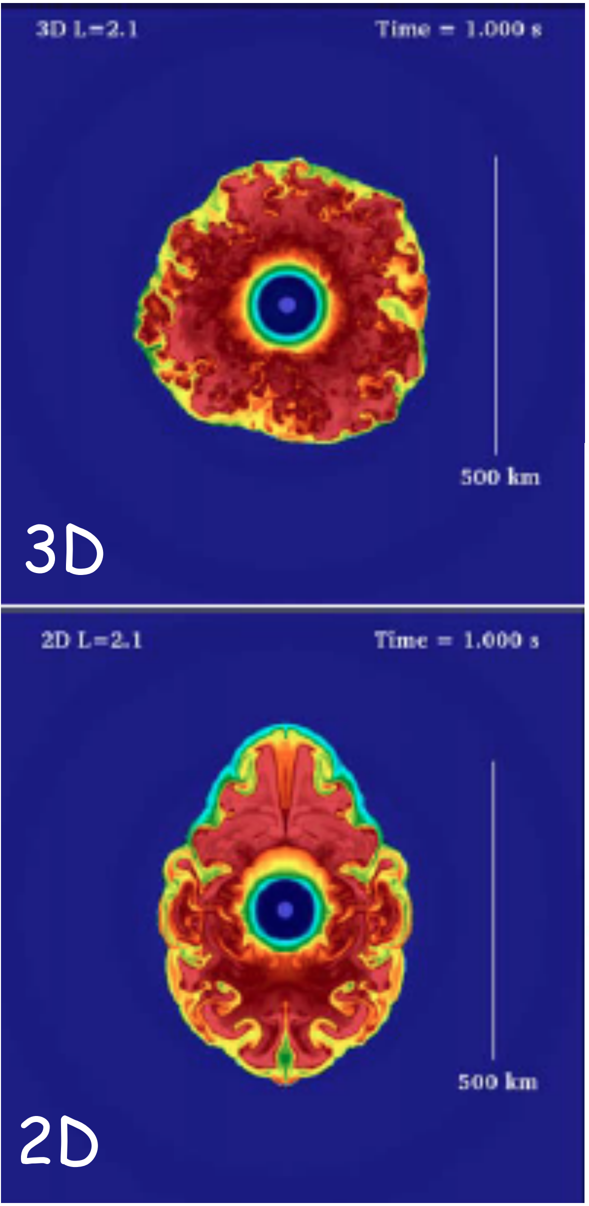
Yield of neutron star mergers

SDSS Data from Aoki *et al.*, arXiv: 1210.1946 [astro-ph.SR]

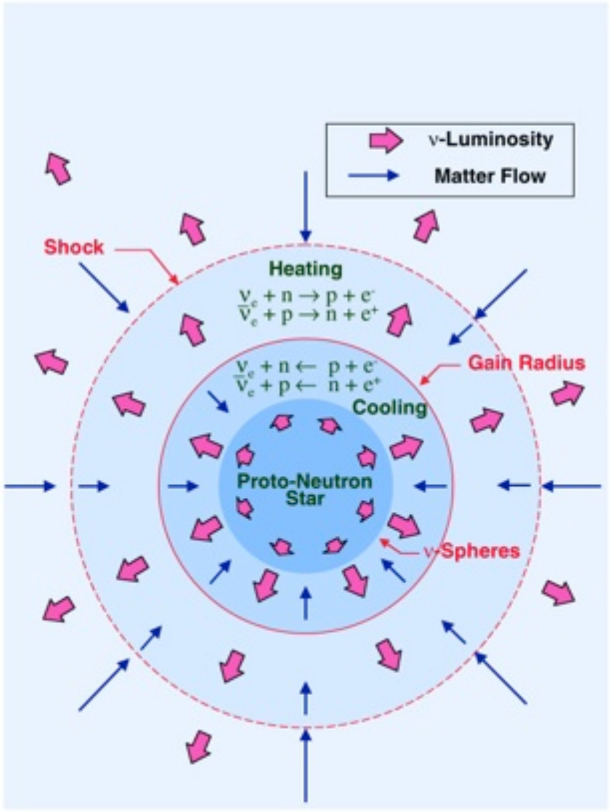
The core-collapse supernovae



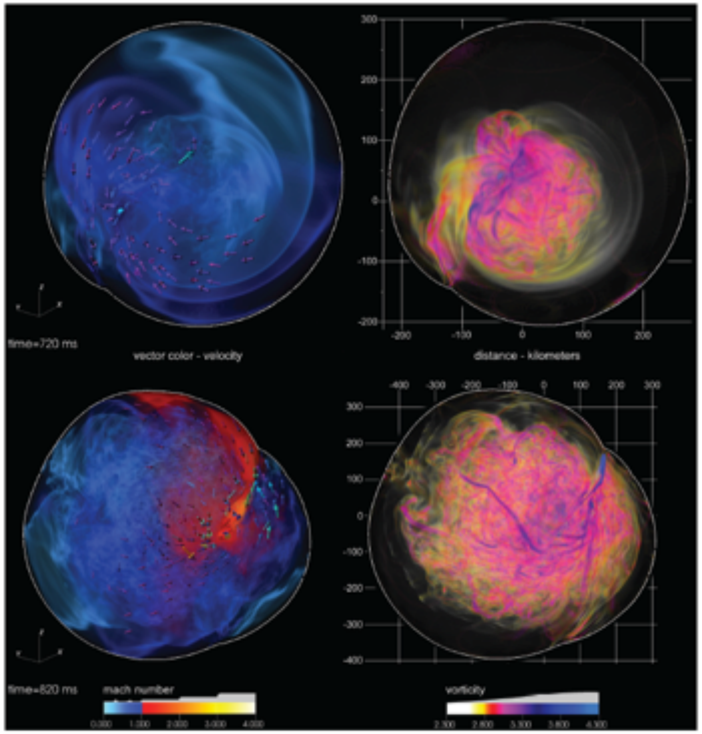
Development of 2D and 3D models for core-collapse supernovae: Complex interplay between turbulence, neutrino physics and thermonuclear reactions.

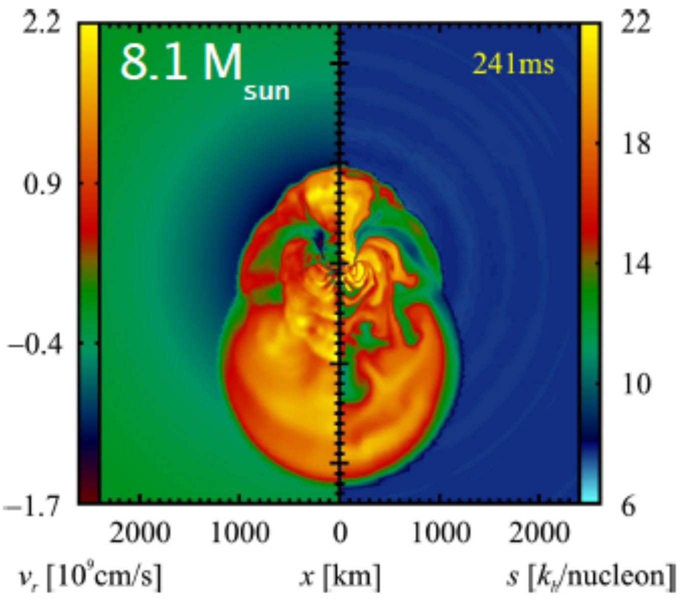


Princeton



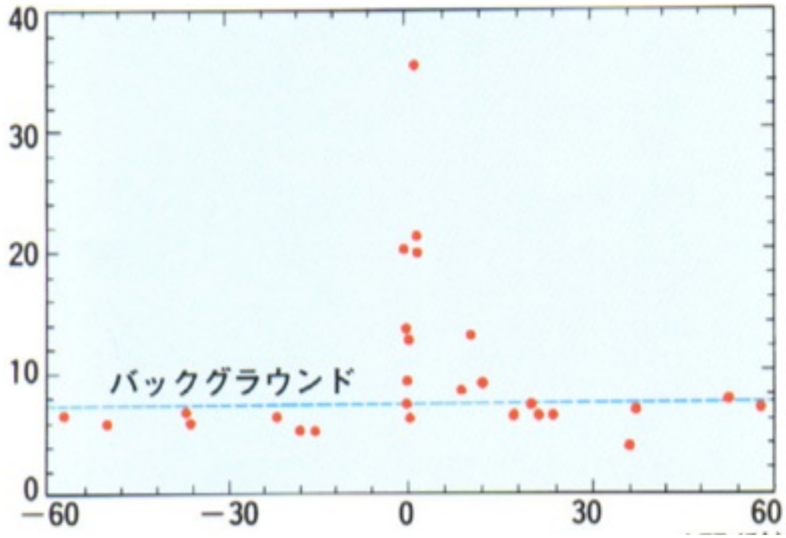
ORNL/UT





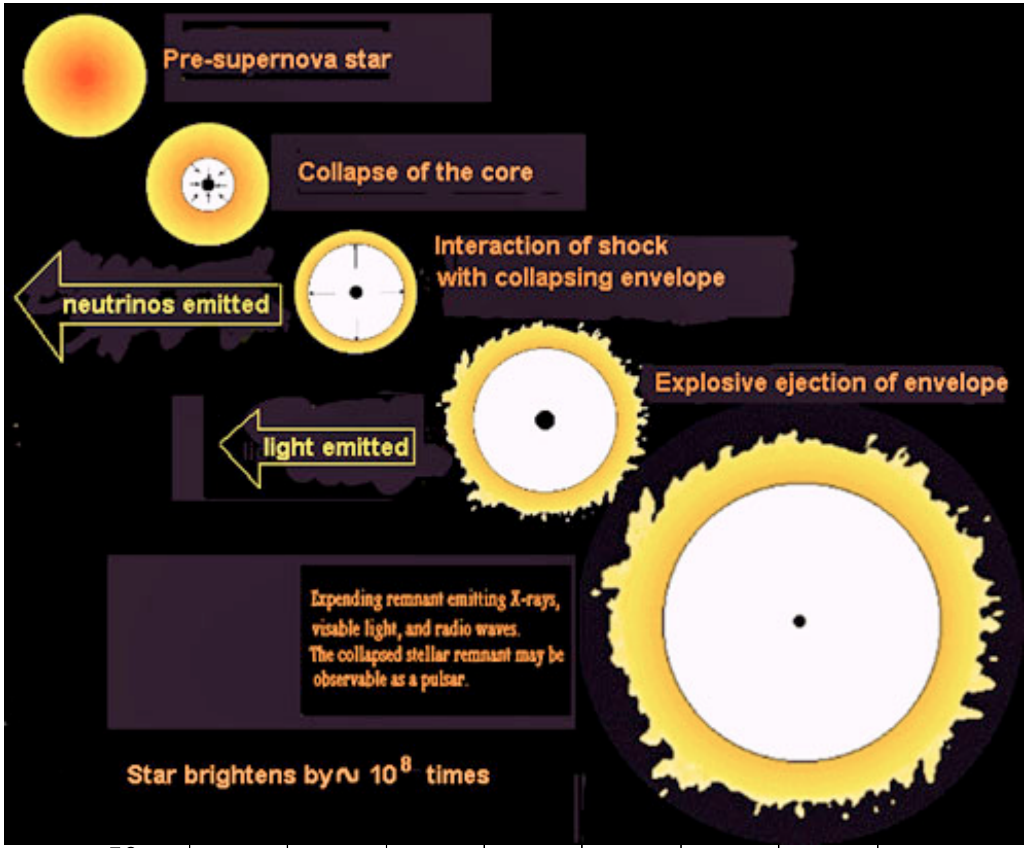
Munich

Neutrinos from core-collapse supernovae



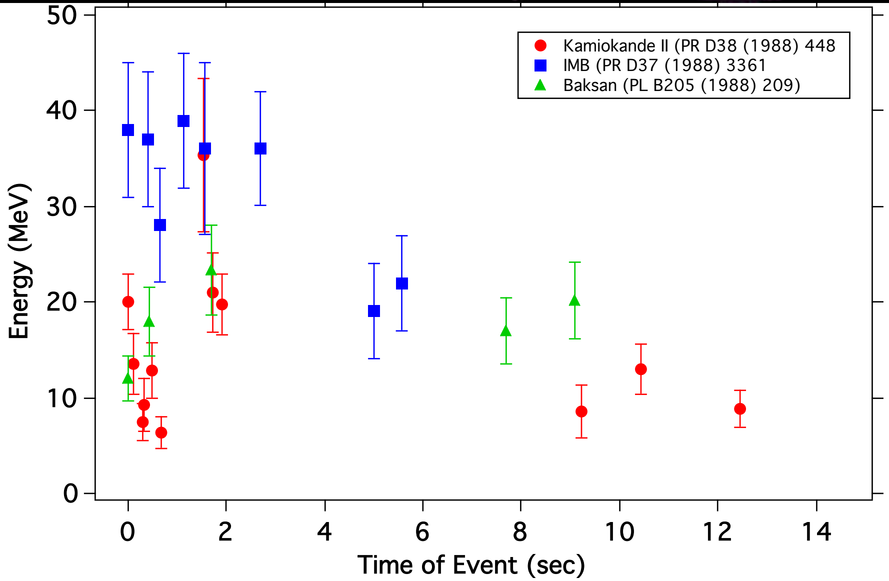
- $M_{prog} \geq 8\ M_{sun} \Rightarrow \Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV

- 99% of the energy is carried away by neutrinos and antineutrinos with $10 \lesssim E_\nu \lesssim 30$ MeV $\Rightarrow 10^{58}$ neutrinos



Expending remnant emitting X-rays, visable light, and radio waves. The collapsed stellar remnant may be observable as a pulsar.

Star brightens by $\sim 10^8$ times



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

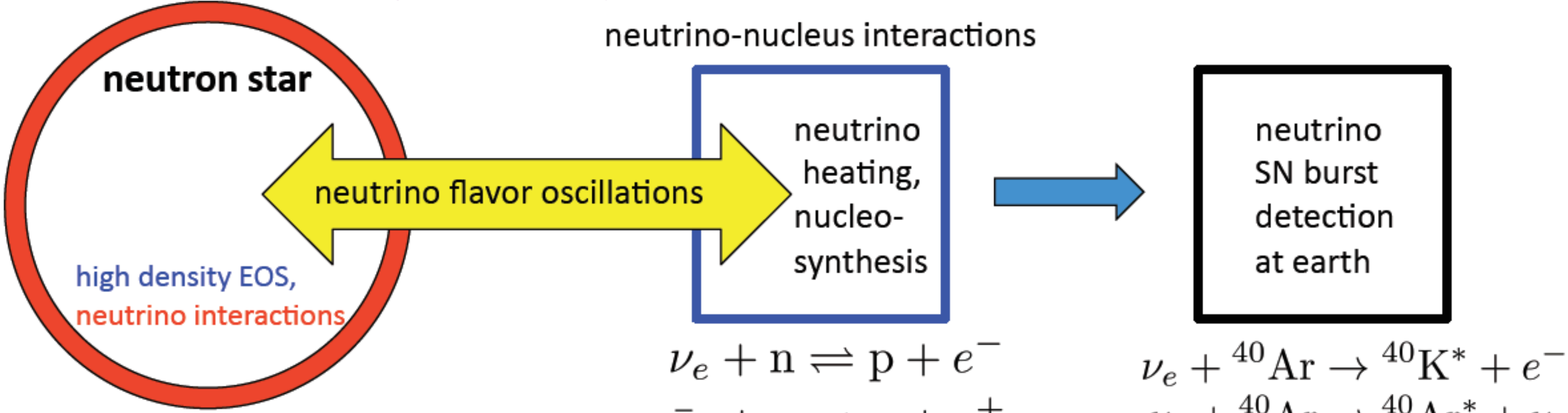
$$\boxed{E_{grav} \cong \frac{3}{5}\frac{GM_{ns}^2}{R_{ns}} \approx 3\times 10^{53} ergs \left(\frac{M_{ns}}{1.4M_{sun}}\right)^2 \left(\frac{10km}{R_{ns}}\right)}$$

Neutrino diffusion time, τ_ν ~ 2-10 s

$$\boxed{L_\nu \approx \frac{GM_{ns}^2}{6R_{ns}}\frac{1}{\tau_\nu} \approx 4\times 10^{51} ergs/s}$$

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)



neutron star

high density EOS,

neutrino interactions

neutrino flavor oscillations

neutrino-nucleus interactions

neutrino heating, nucleosynthesis

neutrino SN burst detection at earth

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

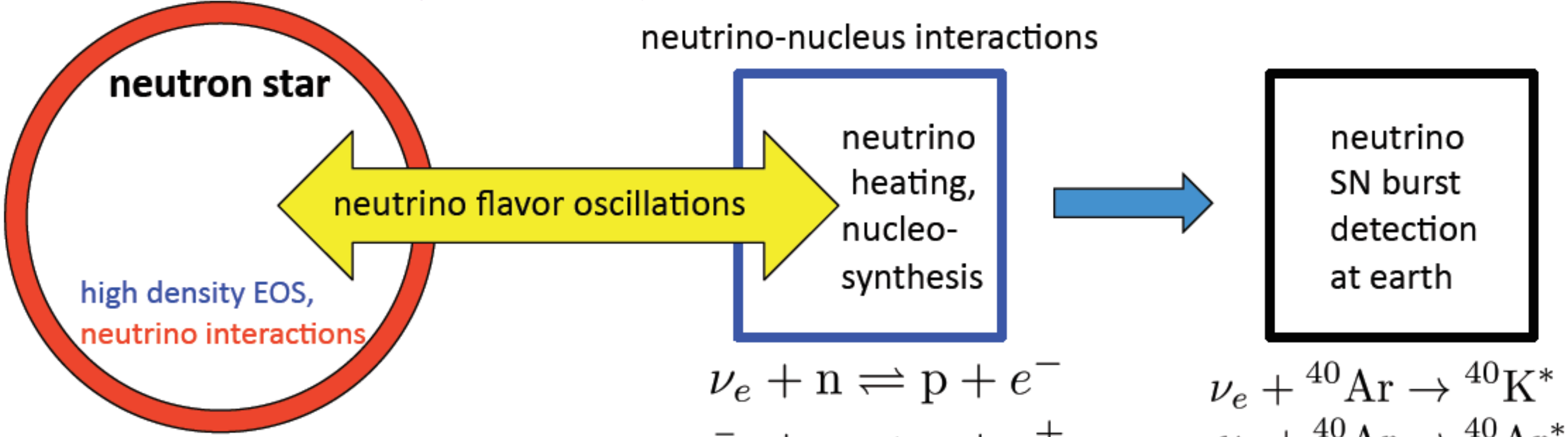
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

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

$$\nu_x + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Ar}^* + \nu_x$$

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)



neutrino-nucleus interactions

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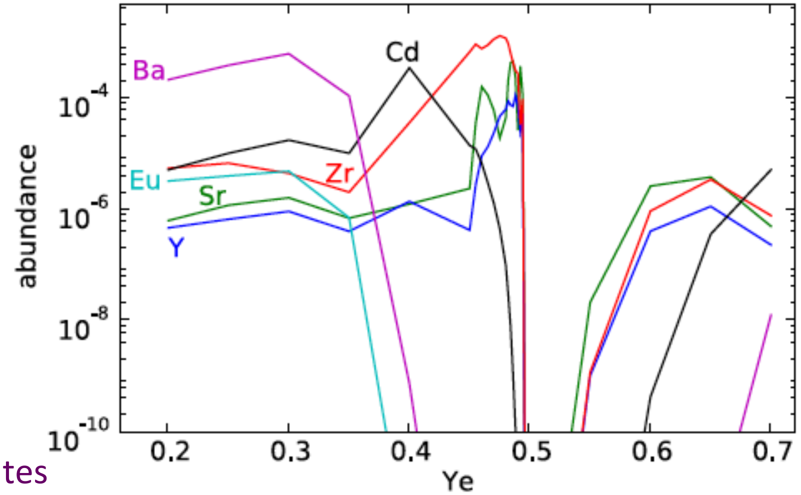
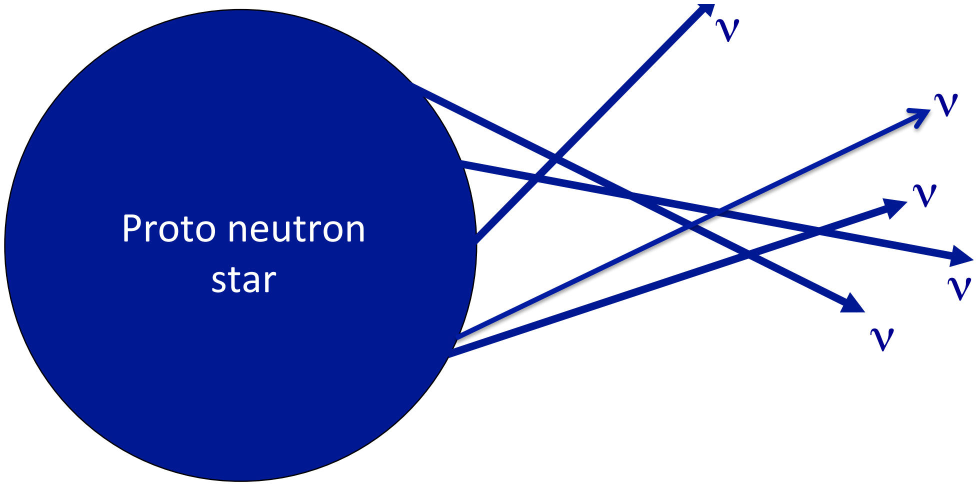
$$\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{Ar}^* + \nu_x$$

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



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”).

Many neutrino system

This is the only many-body system driven by the weak interactions:

Table: Many-body systems

Nuclei	Strong	at most ∼250 particles
Condensed matter	E&M	at most N_A particles
ν**'s in SN**	Weak	$\sim 10^{58}$particles

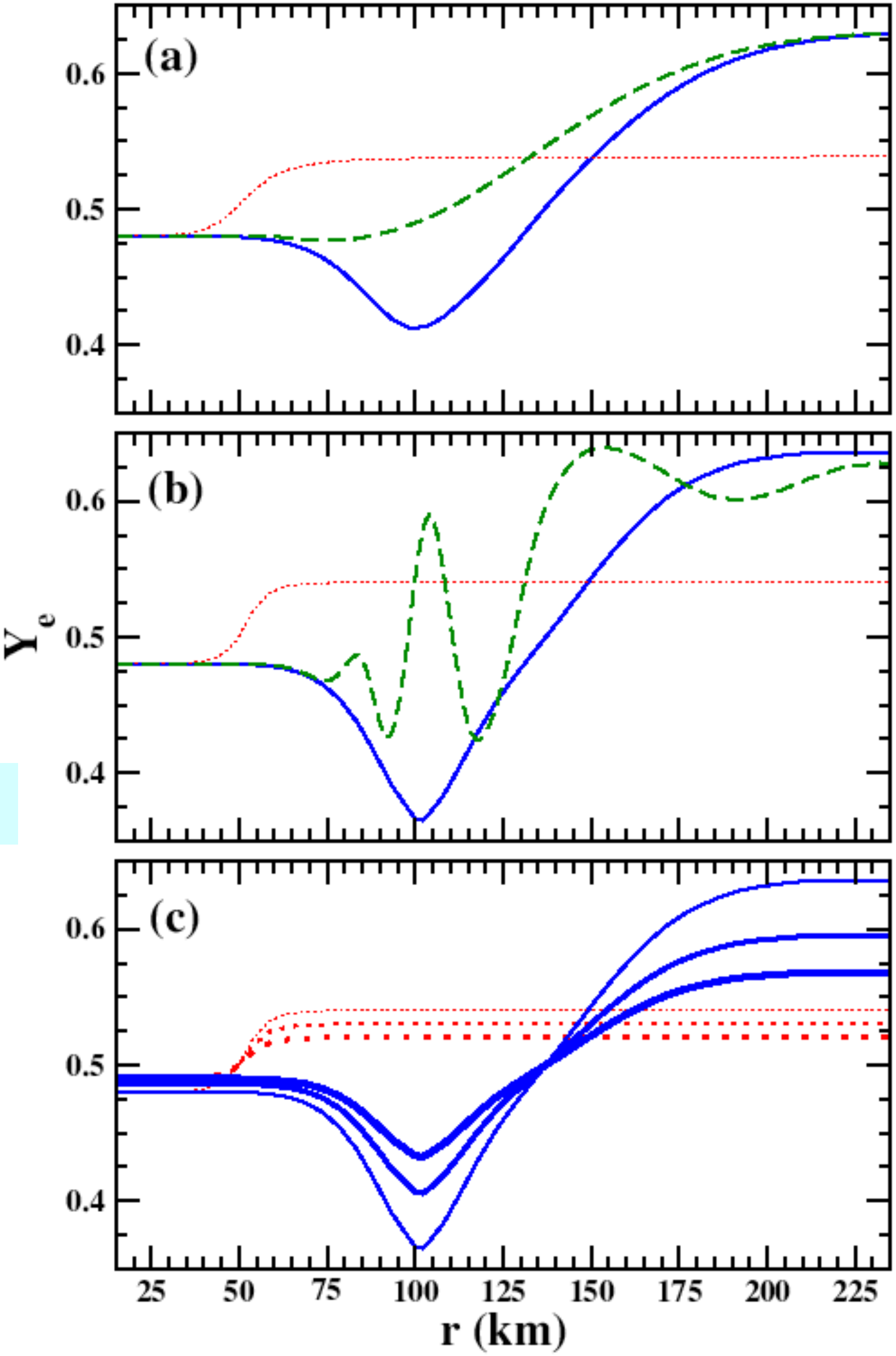
Astrophysical extremes allow us to test physics that cannot be tested elsewhere!

Equilibrium electron fraction with the inclusion of νν interactions

L^{51} = 0.001, 0.1, 50

Balantekin and Yuksel

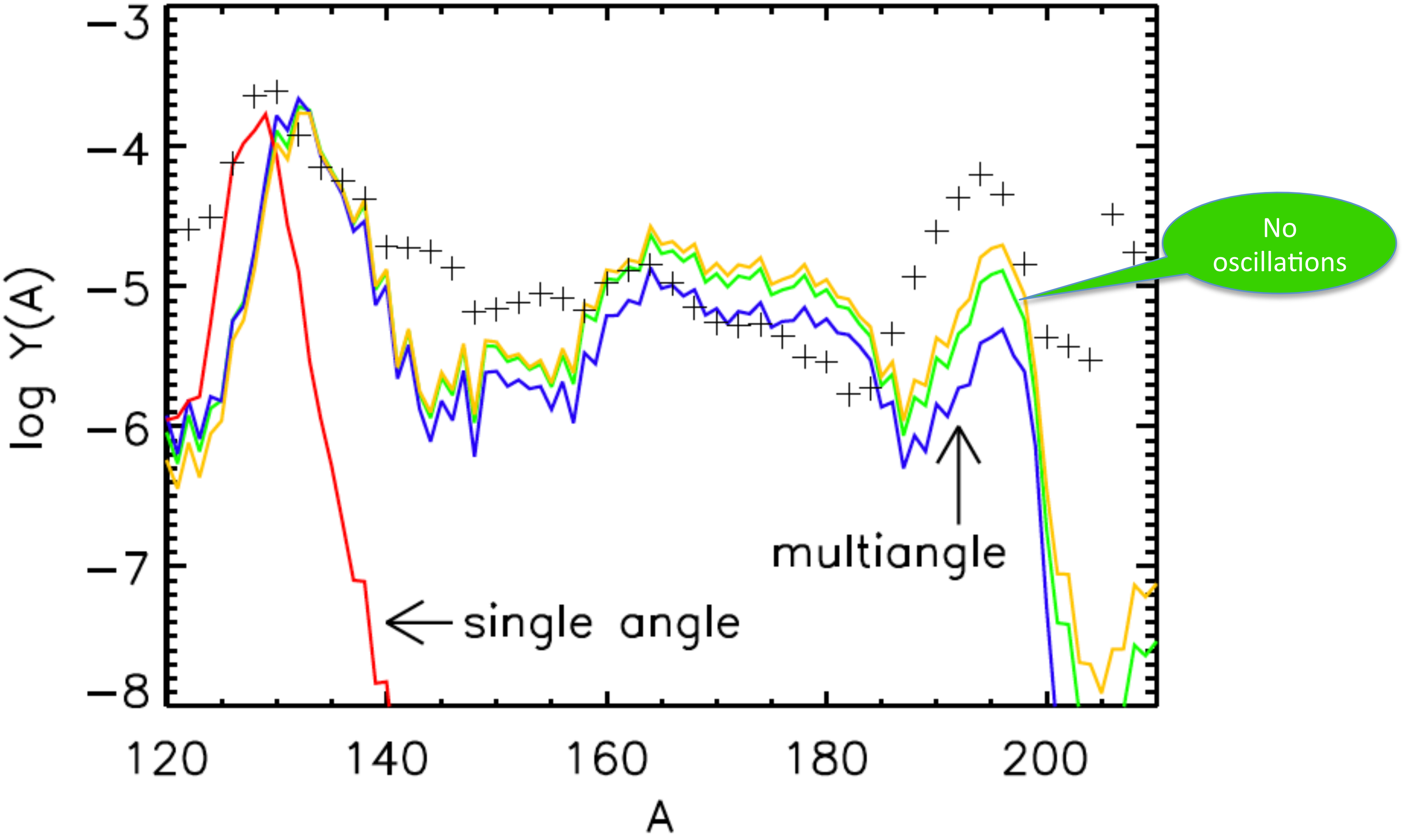
X_α= 0, 0.3, 0.5 (thin, medium, thick lines)



θ_{13}~π/10

θ_{13}~π/20

θ_{13}~π/20 with α effect



No oscillations

Duan, Friedland, McLaughlin, Surman

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)

$$\boxed{Y_e = \frac{\lambda_n}{\lambda_p + \lambda_n} + \frac{1}{2}\frac{\lambda_p - \lambda_n}{\lambda_p + \lambda_n} X_\alpha}$$

If alpha particles are present

$$\boxed{Y_e^{(0)} = \frac{1}{1 + \lambda_{\bar{\nu}_e}/\lambda_{\nu_e}}}$$

If alpha particles are absent

$$\boxed{Y_e = Y_e^{(0)} + \left(\frac{1}{2} - Y_e^{(0)}\right) X_\alpha}$$

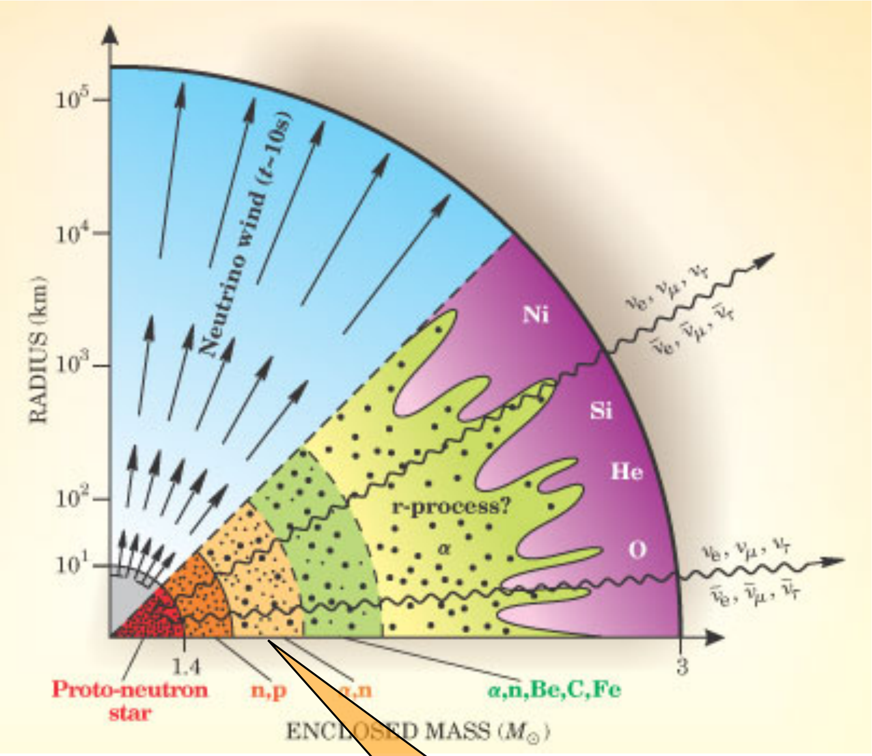
If $Y_e^{(0)} < 1/2$, non-zero X_α increases Y_e.

If $Y_e^{(0)} > 1/2$, non-zero X_α decreases Y_e.

→

Non-zero X_α pushes Y_e to 1/2

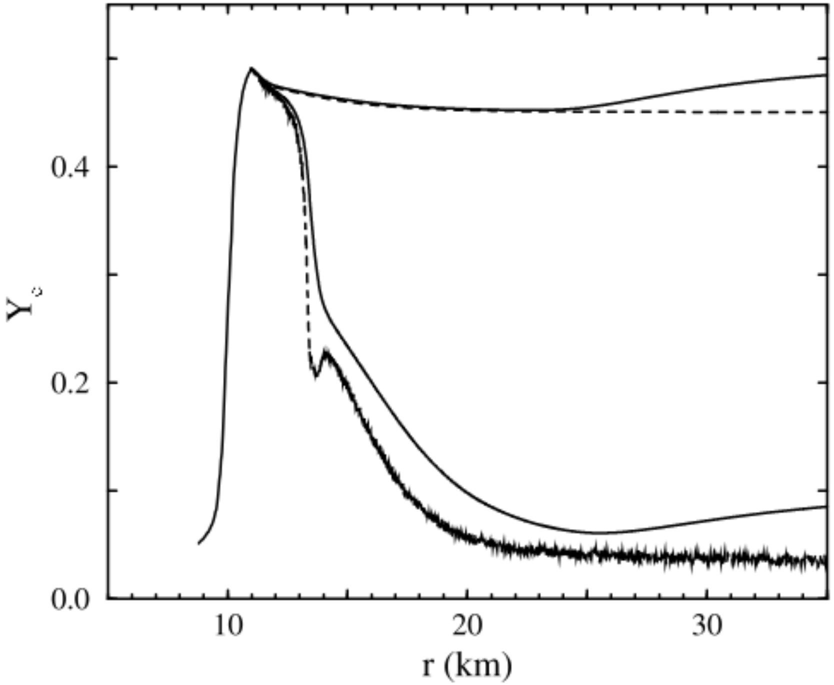
Alpha effect

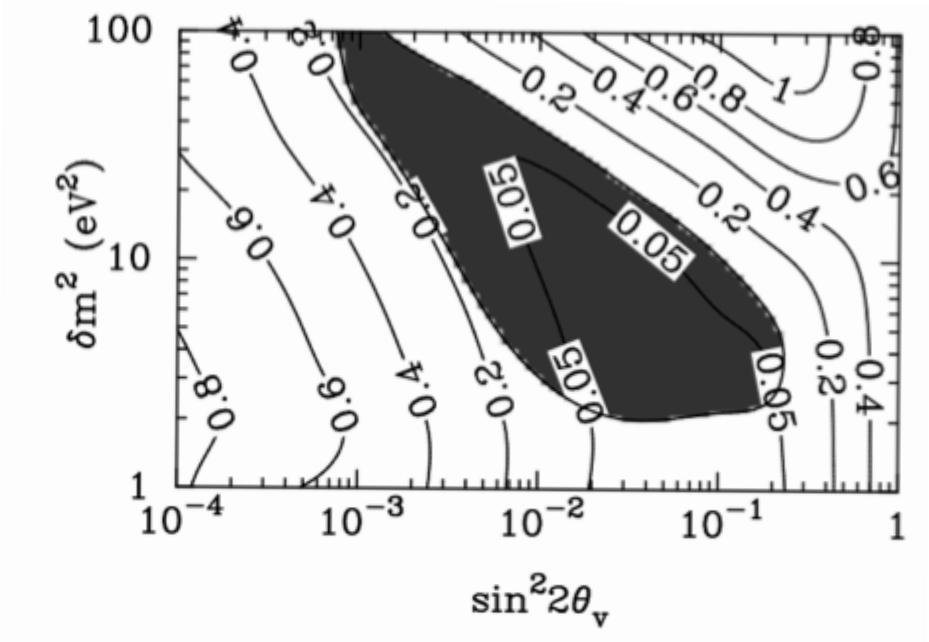


Alpha effect

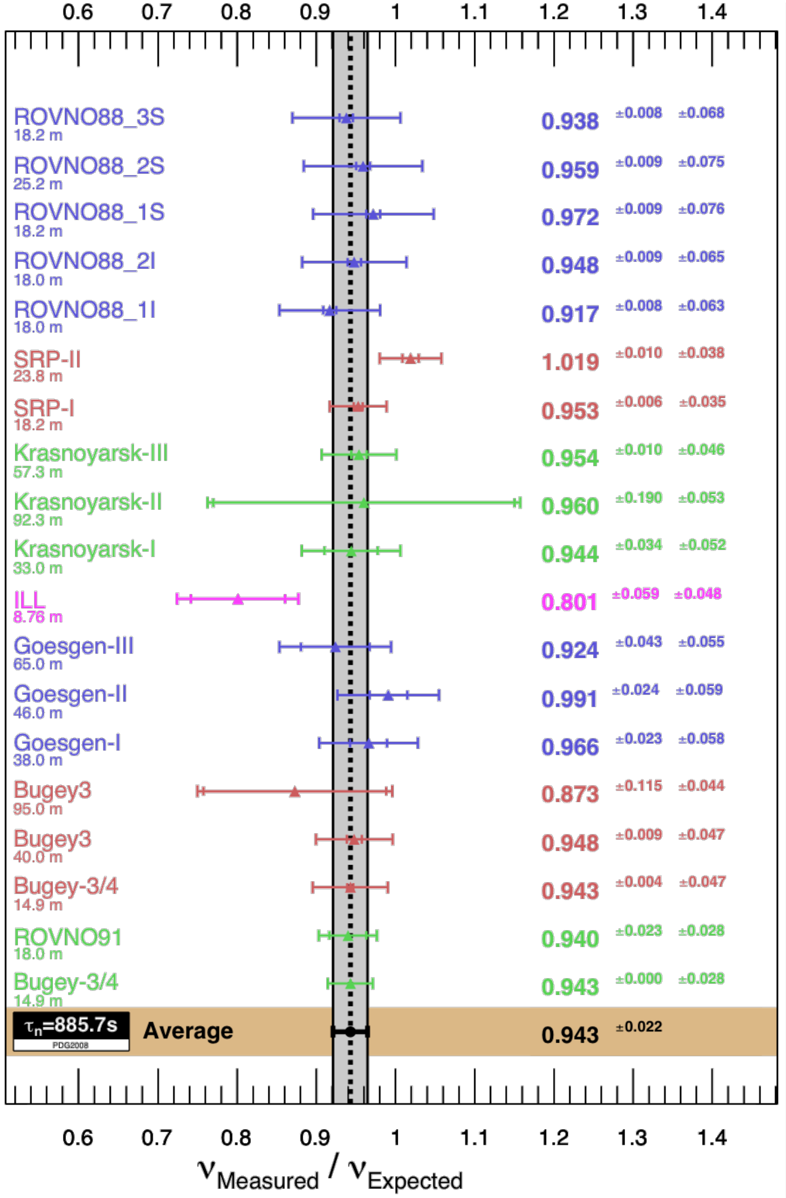
Active-sterile mixing

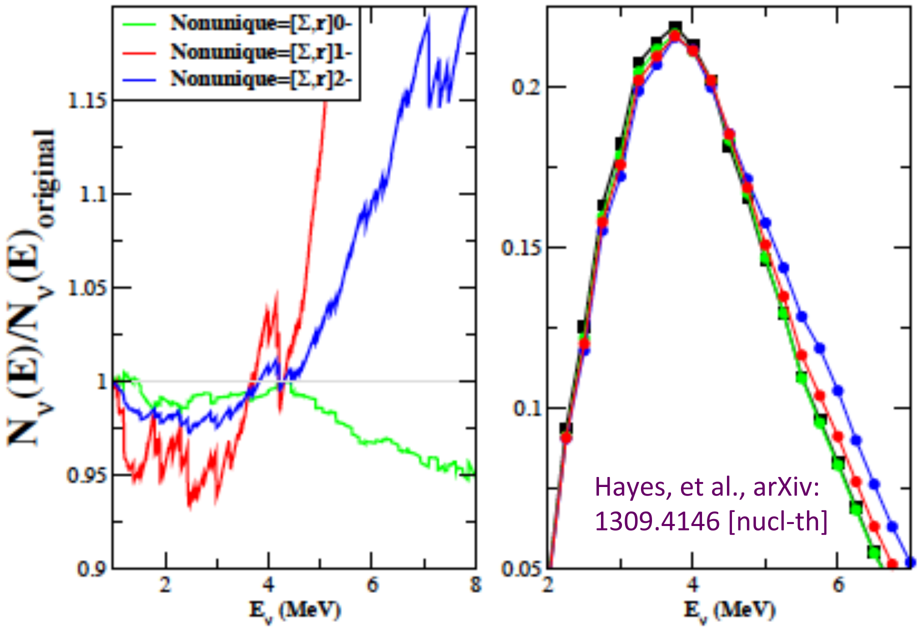
McLaughlin, Fetter, Balantekin, Fuller, Astropart. Phys., 18, 433 (2003)



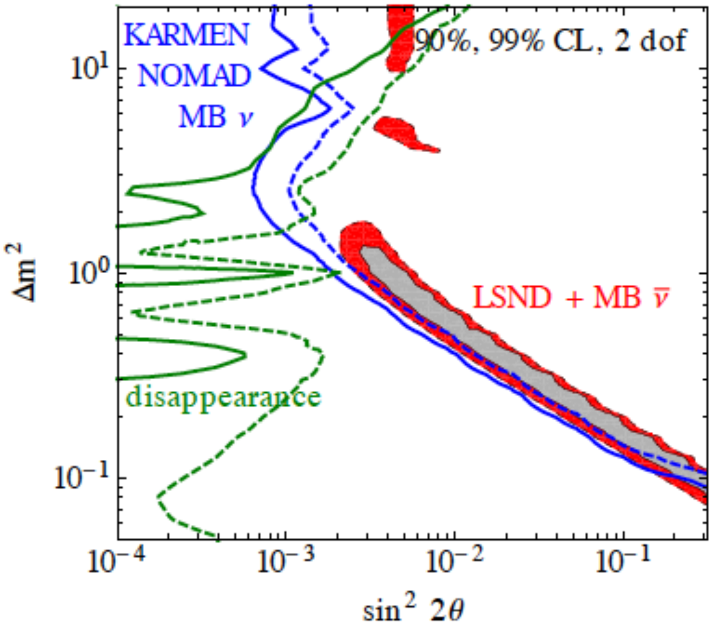


Does the reactor-flux anomaly imply active-sterile neutrino mixing?

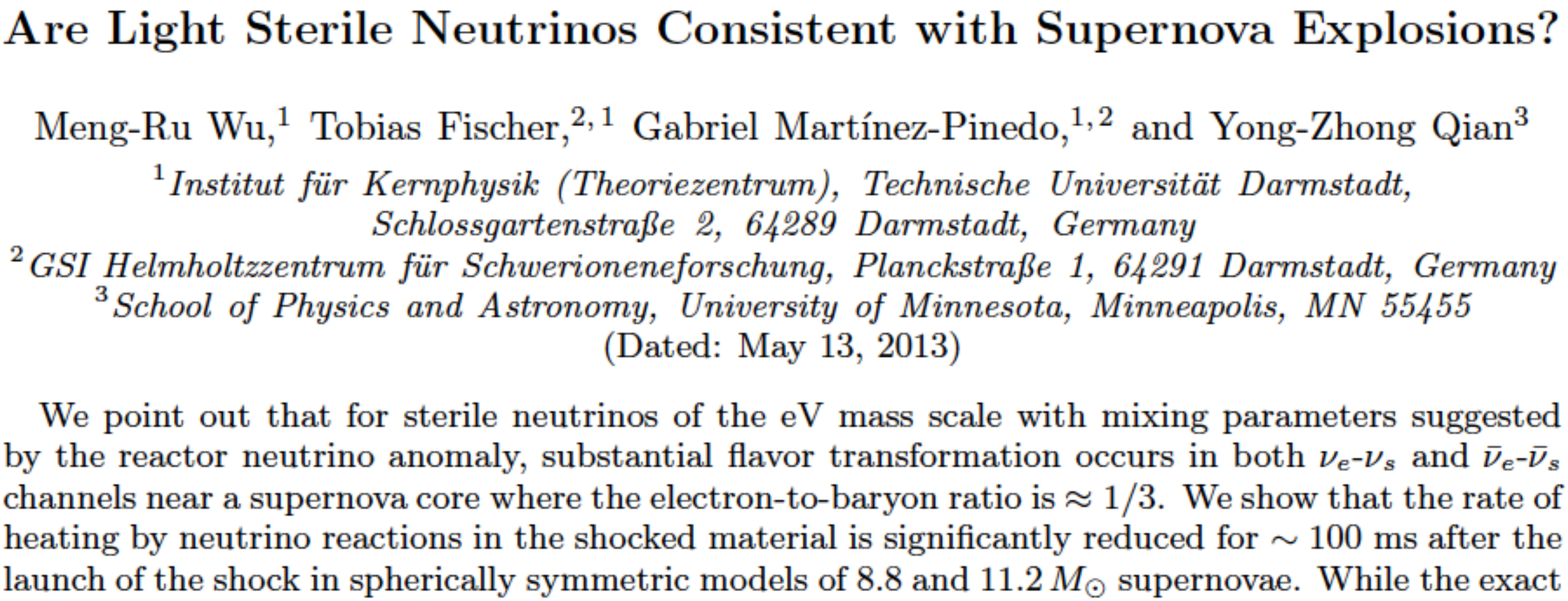




Hayes, et al., arXiv: 1309.4146 [nucl-th]



Can we know the reactor neutrino flux ever as well as we need?

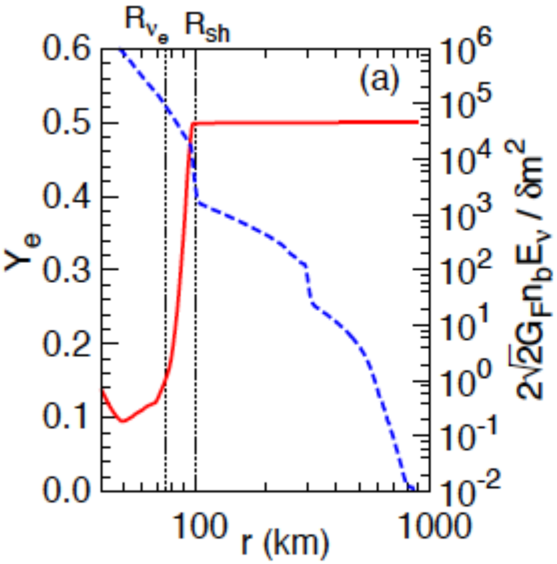


Are Light Sterile Neutrinos Consistent with Supernova Explosions?

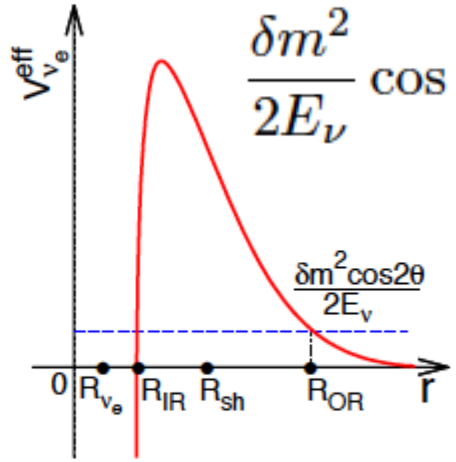
Meng-Ru Wu,[1] Tobias Fischer,[2,1] Gabriel Martínez-Pinedo,[1,2] and Yong-Zhong Qian[3]
[1] *Institut für Kernphysik (Theoriezentrum), Technische Universität Darmstadt, Schlossgartenstraße 2, 64289 Darmstadt, Germany*
[2] *GSI Helmholtzzentrum für Schwerioneneforschung, Planckstraße 1, 64291 Darmstadt, Germany*
[3] *School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455*

(Dated: May 13, 2013)

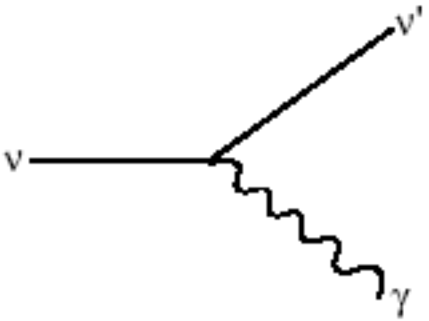
We point out that for sterile neutrinos of the eV mass scale with mixing parameters suggested by the reactor neutrino anomaly, substantial flavor transformation occurs in both ν_e-ν_s and $\bar{\nu}_e$-$\bar{\nu}_s$ channels near a supernova core where the electron-to-baryon ratio is $\approx 1/3$. We show that the rate of heating by neutrino reactions in the shocked material is significantly reduced for ~ 100 ms after the launch of the shock in spherically symmetric models of 8.8 and $11.2\,M_\odot$ supernovae. While the exact



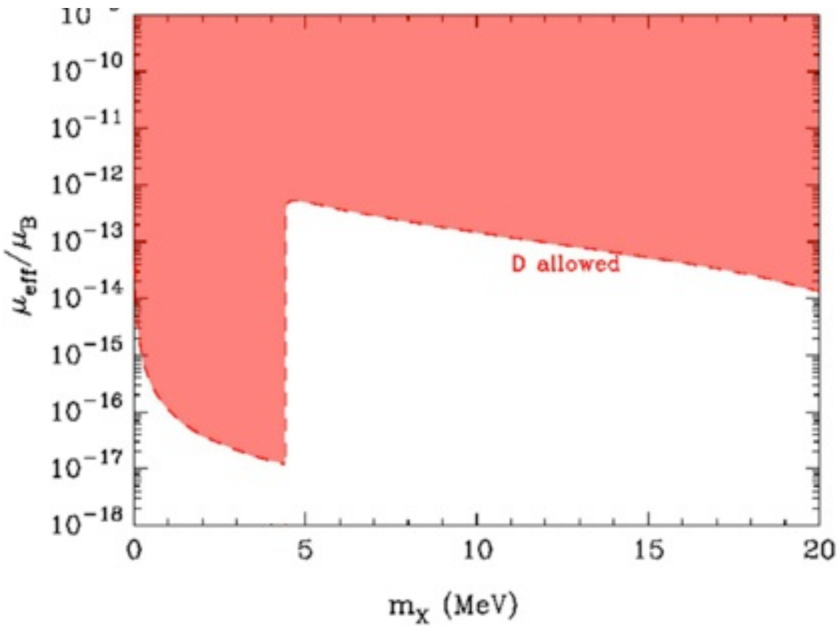
$$\frac{\delta m^2}{2E_\nu}\cos 2\theta = \frac{3\sqrt{2}}{2} G_F n_b \left(Y_e - \frac{1}{3}\right) = V_{\nu_e}^{\rm eff}$$

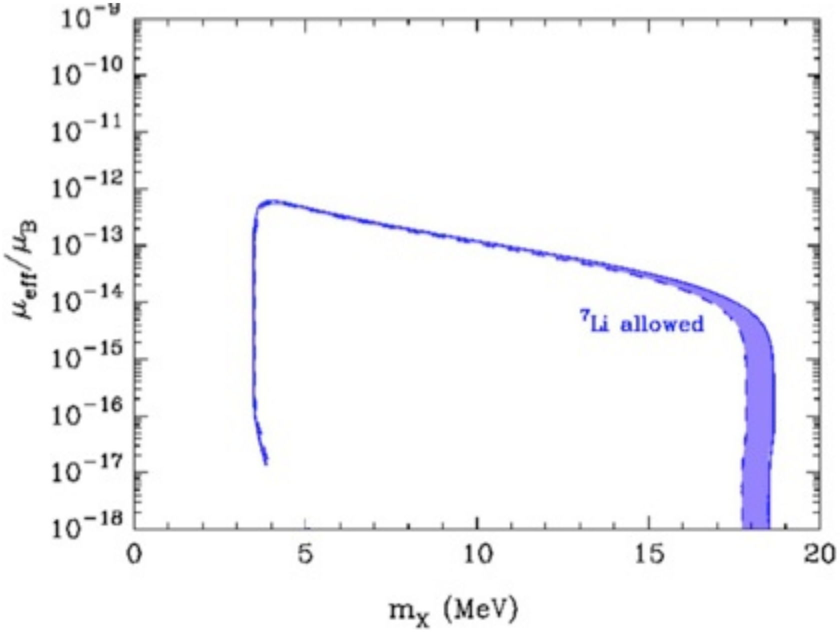


Sterile neutrino decay and Big Bang Nucleosynthesis



$$\Gamma_{i\to j} = \frac{|\mu|^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i}\right)^3 = 5.308\, s^{-1}\left(\frac{\mu_{eff}}{\mu_B}\right)^2\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{eV}\right)^3$$





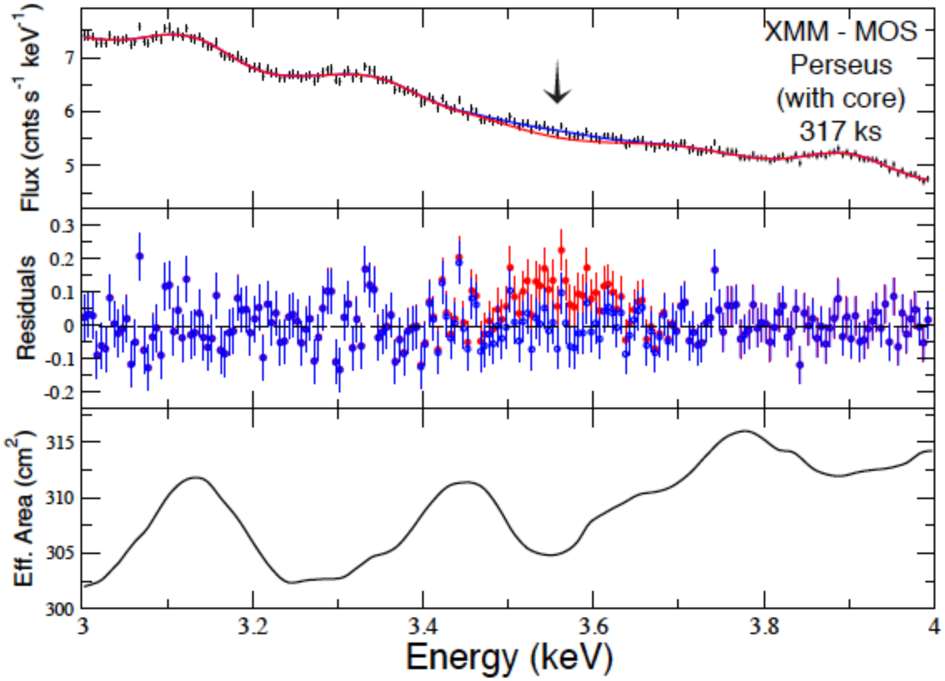
Kusakabe, A.B.B., Kajino, and Pehlivan, Phys. Rev. D 87, 085045 (2013)

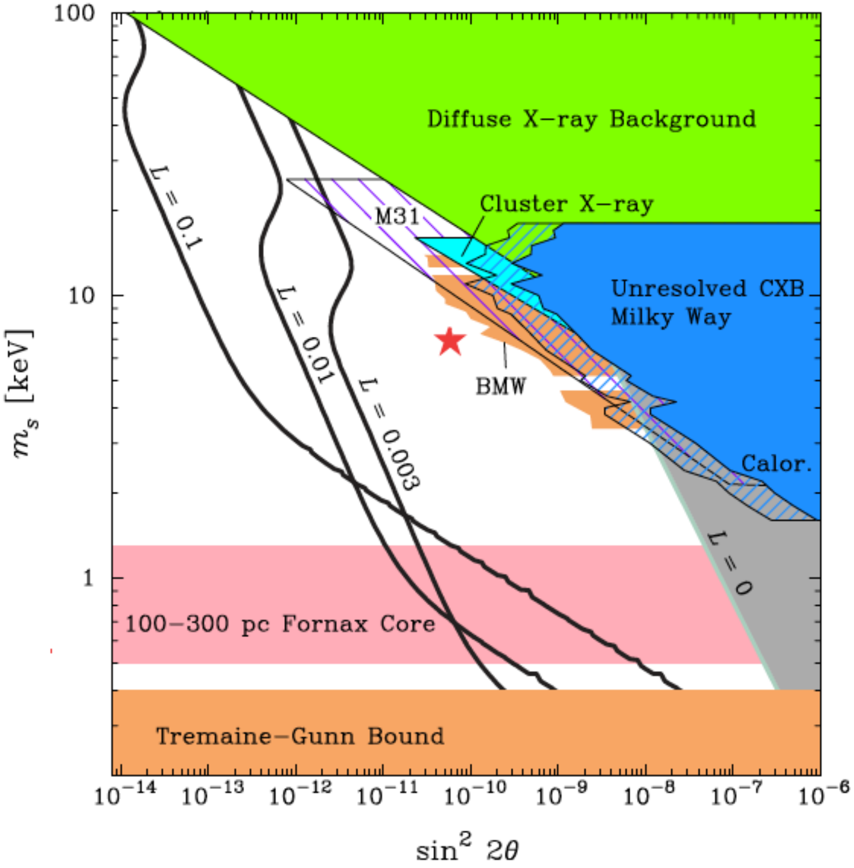
Submitted to ApJ, 2014 February 10
Preprint typeset using LaTeX style emulateapj v. 04/17/13

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Submitted to ApJ, 2014 February 10



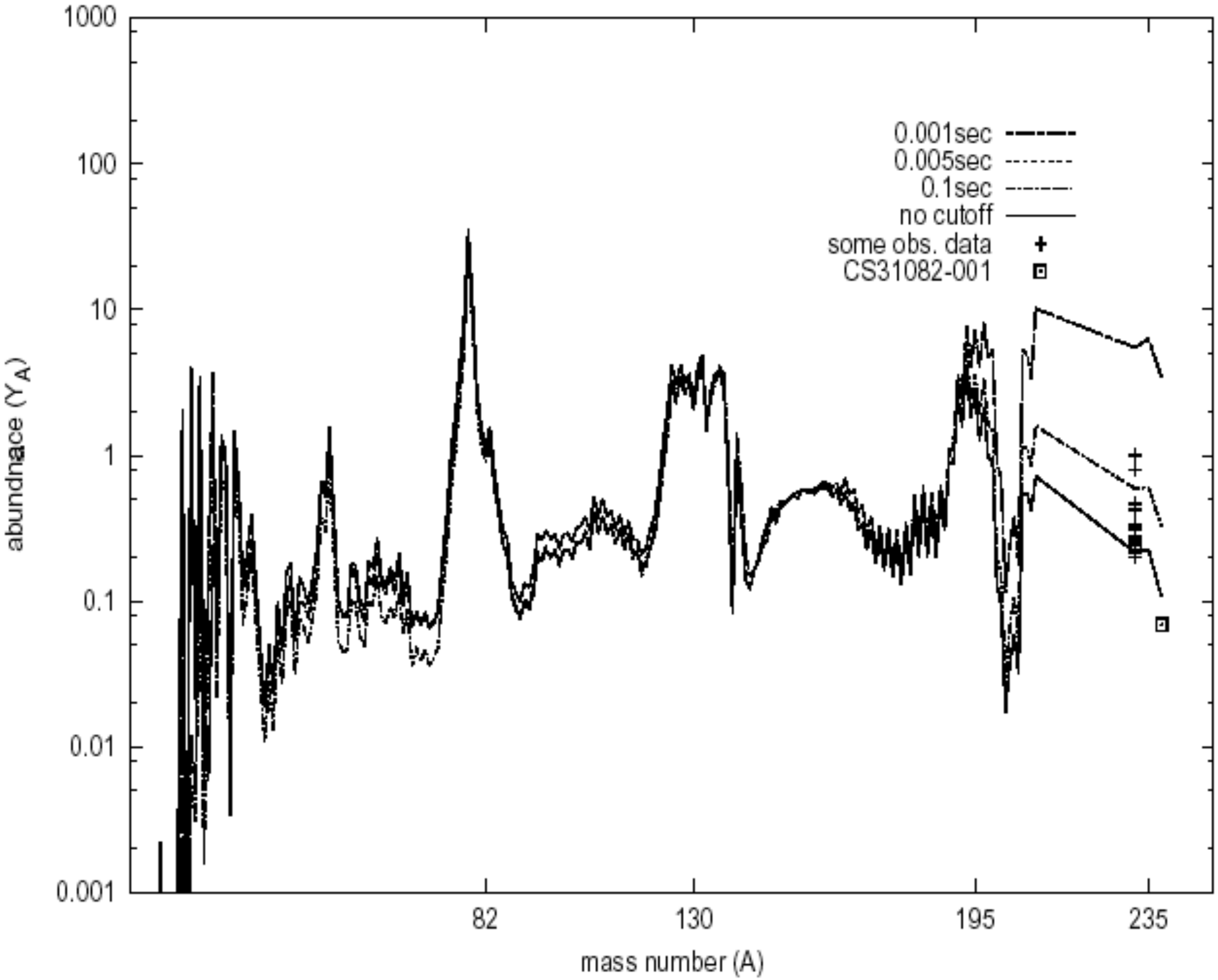


See also : arXiv:1204.5477 [hep-ph],
F. Bezrukov, A. Kartavtsev, M. Lindner

Sterile neutrino mass	How it asserts itself	What does it solve?
~ 1 eV	Mixing with active flavors	Reactor anomaly, IceCube data
~ 7 keV	Electromagnetic decay	Gammas rays from the galactic centers
~ 4-5 MeV	Electromagnetic decay	^{7}Li problem in BBN

Are we cooking up a separate magic potion for each malady?

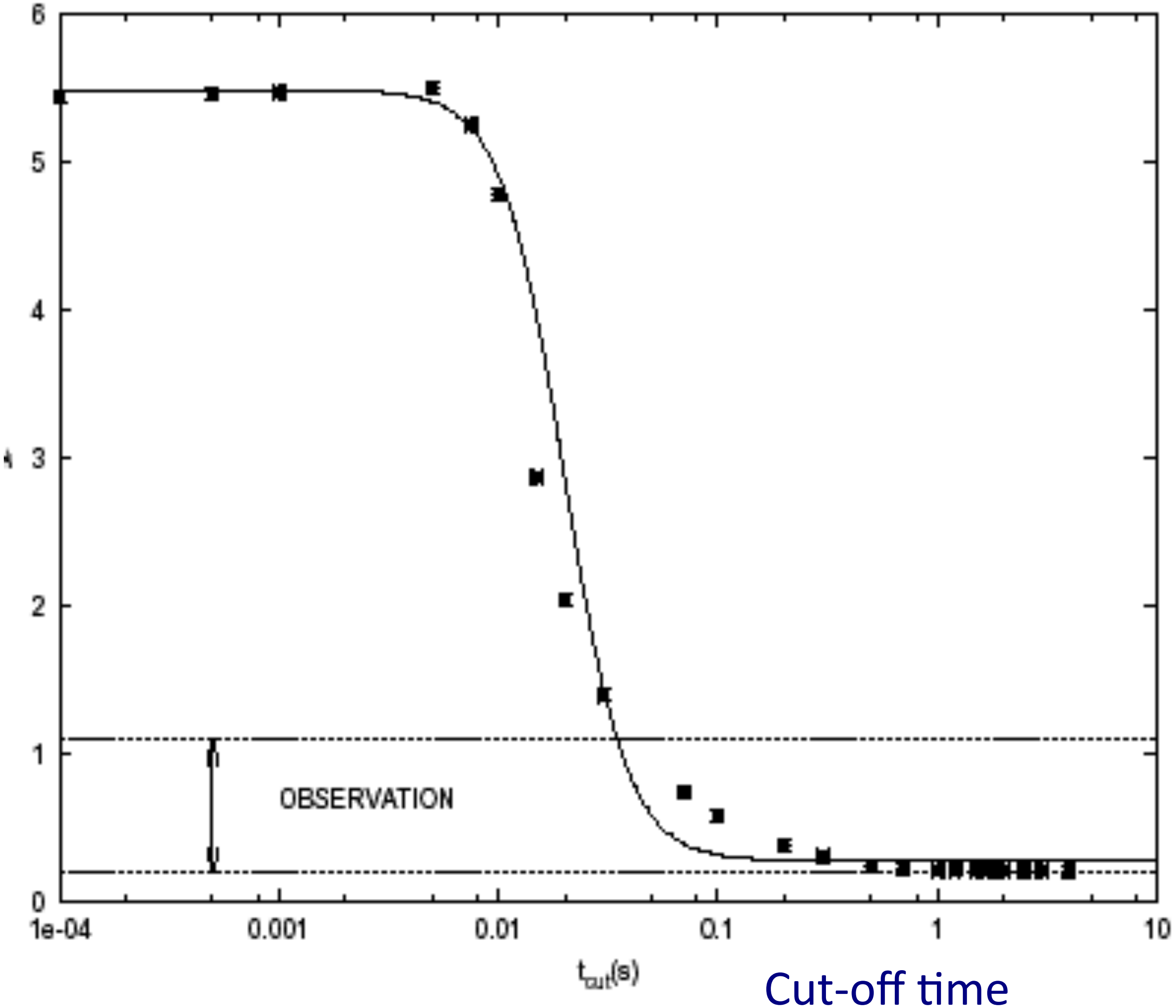
Black hole or neutron star?



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

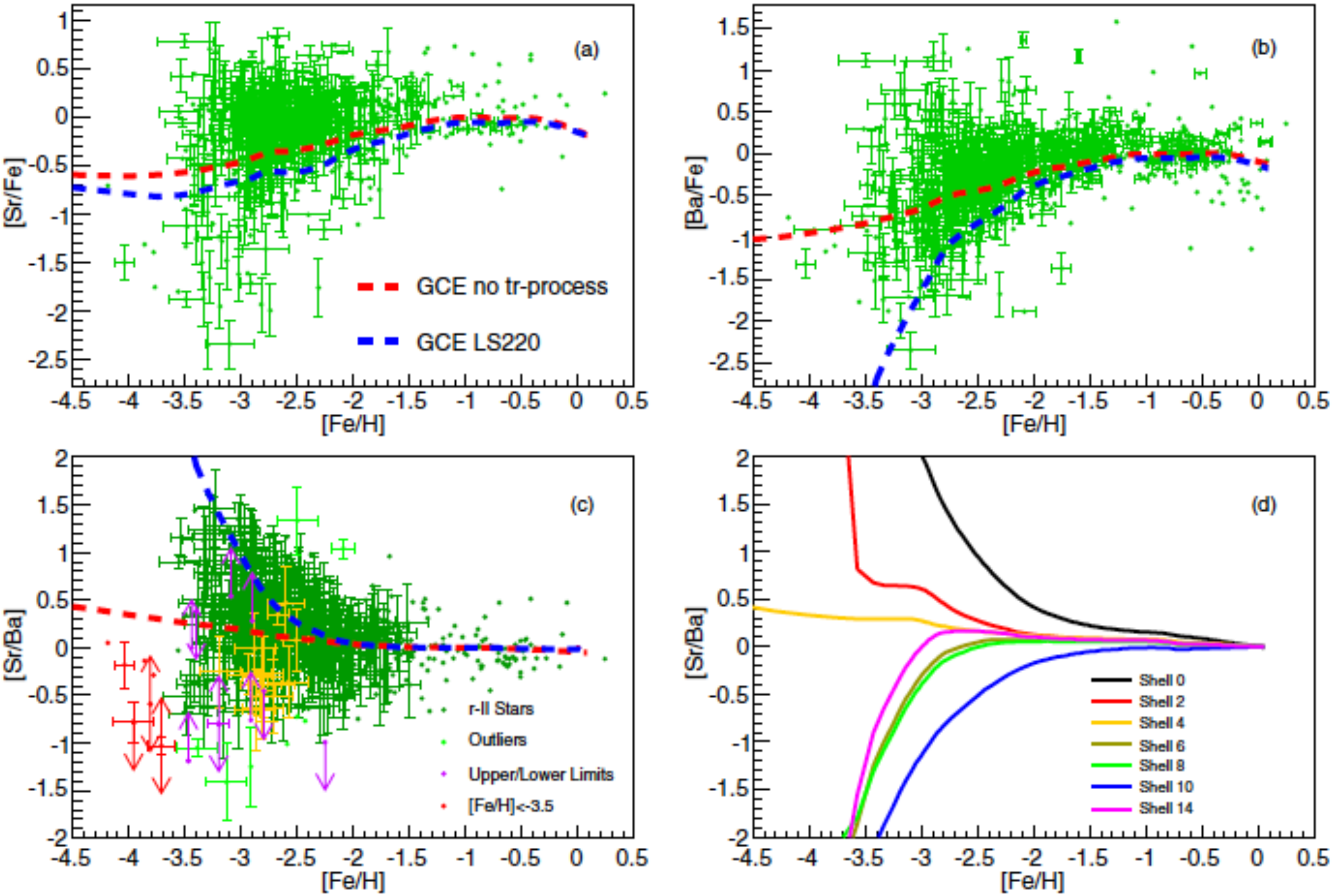
Black hole or neutron star?

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



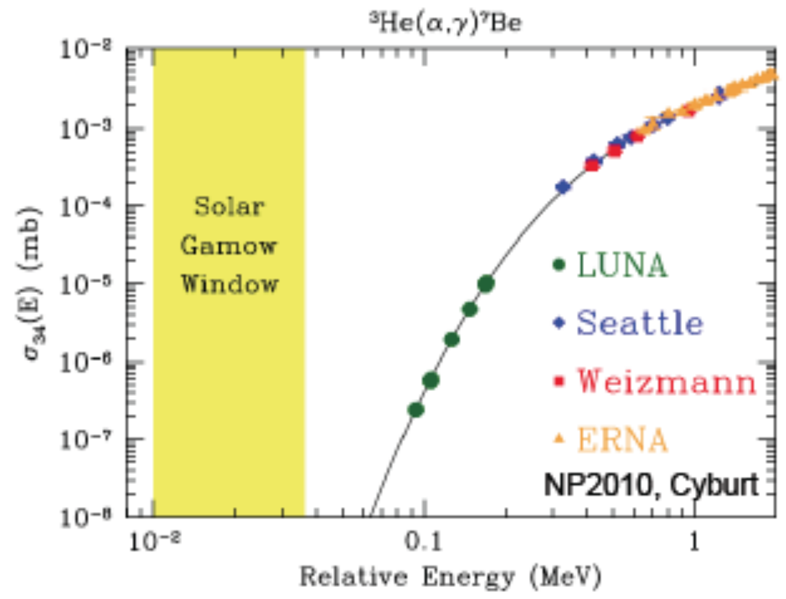
Cut-off time

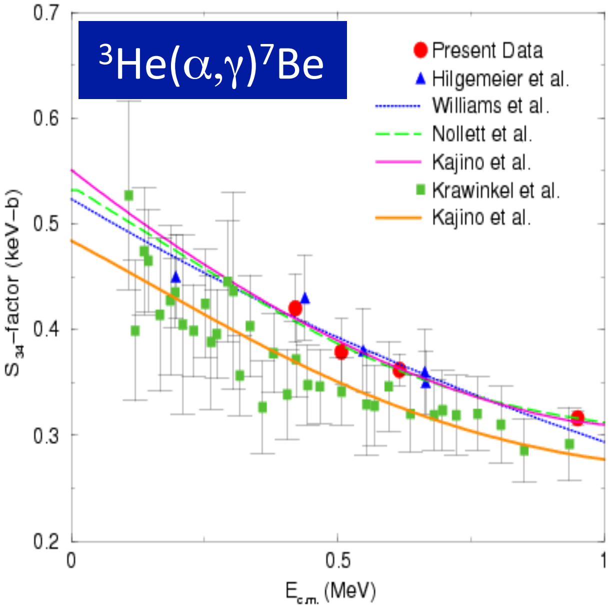
Truncated r-process

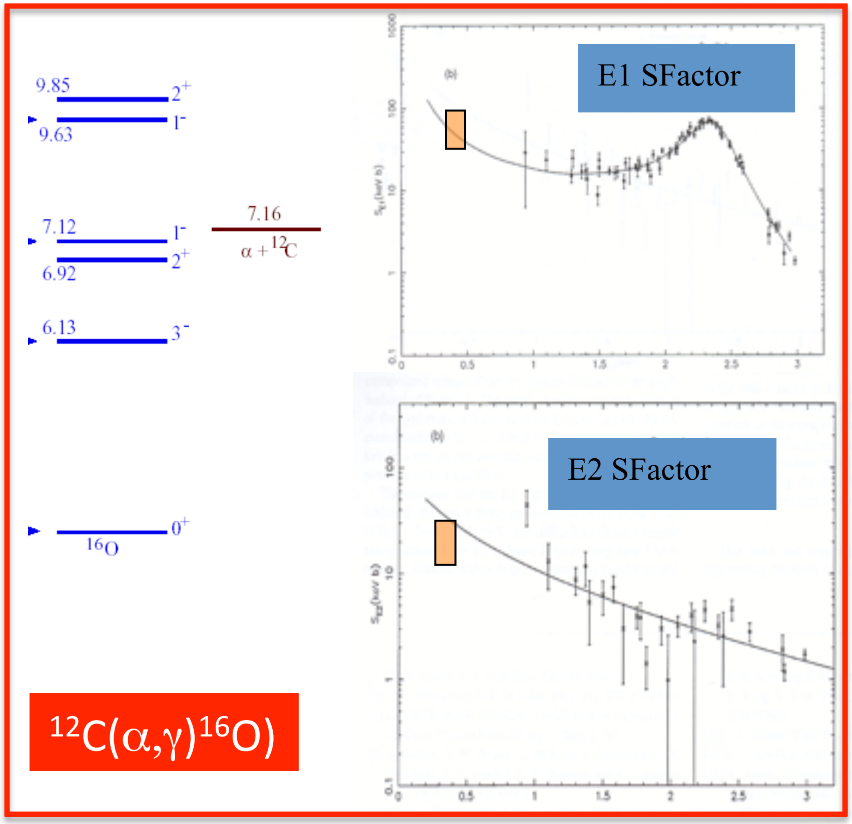


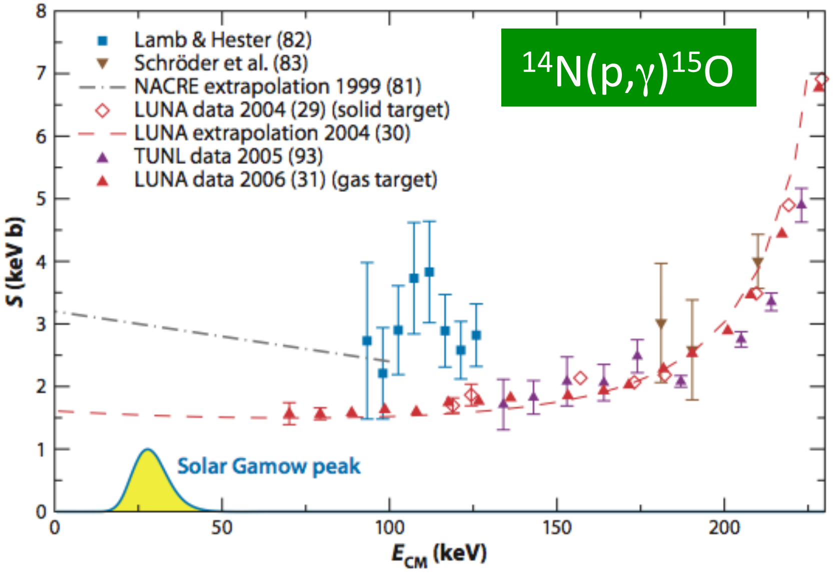
Aoki *et al.*, APL **766**, L13 (2013

Three important "stable-beam" reactions for astrophysics

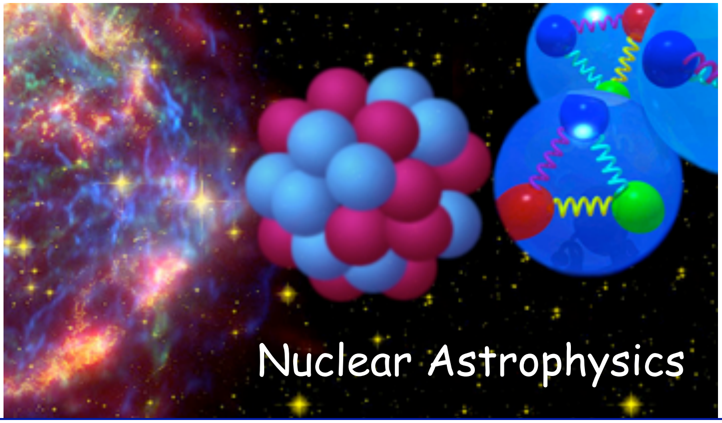






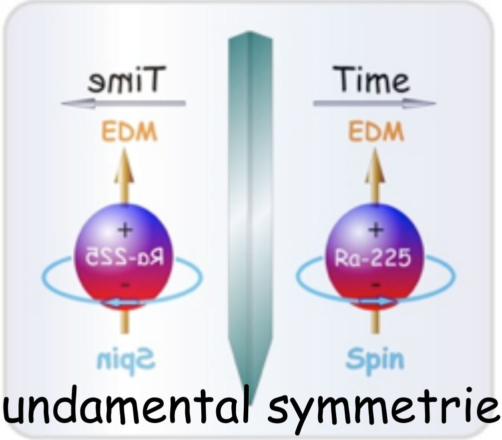


Which science drives physics with rare isotopes?



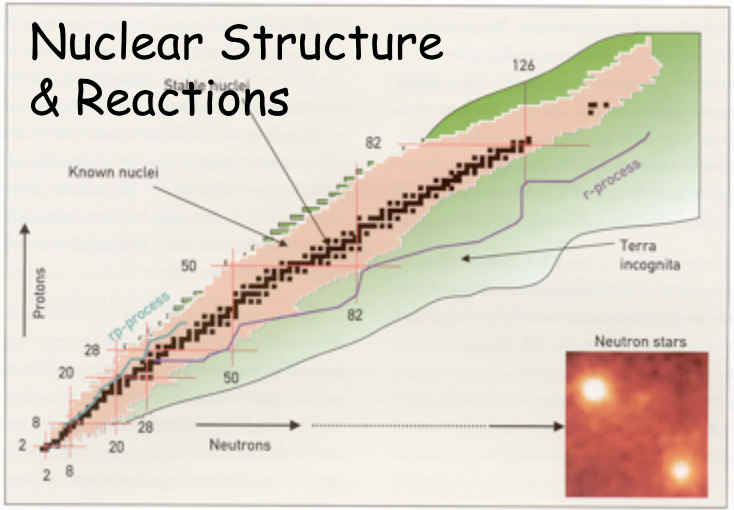
Nuclear Astrophysics

Origin of new elements, rare isotopes powering stellar explosions, neutron star crust



Fundamental symmetries

Use of rare isotopes as laboratories where symmetry violations are amplified.



Nuclear Structure & Reactions

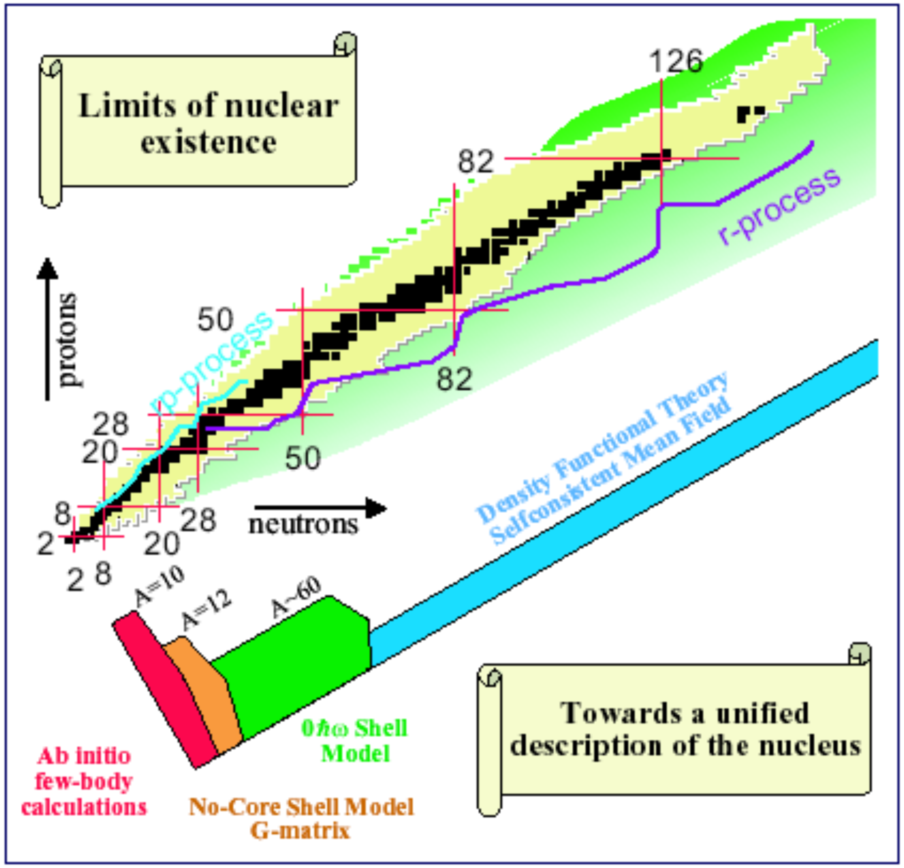
Limits of existence: what makes nuclei stable? New shapes, new collective behavior.

Nuclear applications

Materials, medical physics, reactors,..

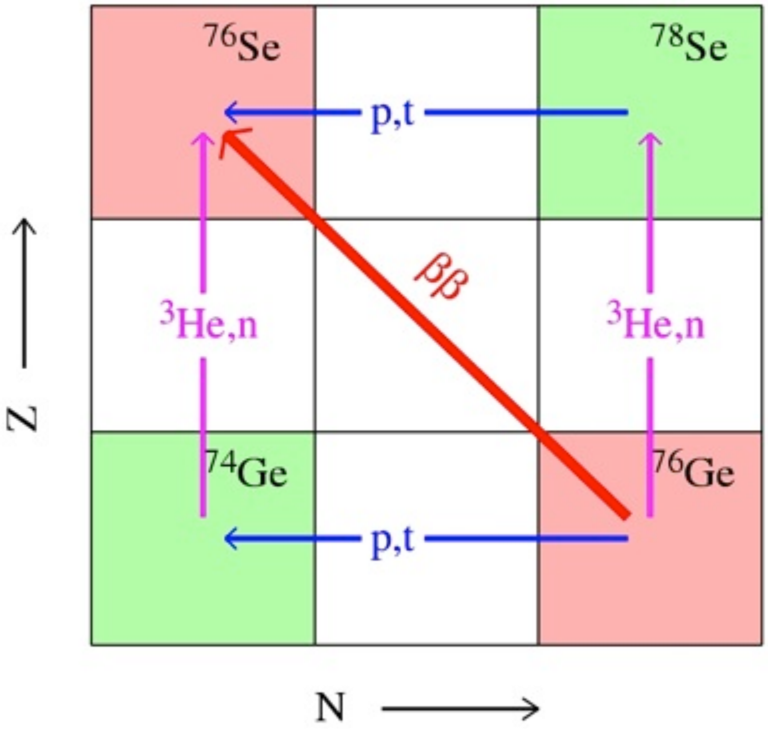
Part of the research program with exotic beams: to better understand the r-process. One needs to first learn beta-decays of nuclei both at and far-from stability:

- We need half-lifes at the r-process ladders (N=50, 82, 126) where abundances peak (⇐ direct measurements).
- We need accurate values of initial and final state energies (⇐ direct measurements).
- Spin-isospin response: Matrix elements of the Gamow-Teller operator $\sigma.\tau$ between the initial and final states (measurements either with inverse kinematics or with beta-beams where RIB's are used to produce the beam).

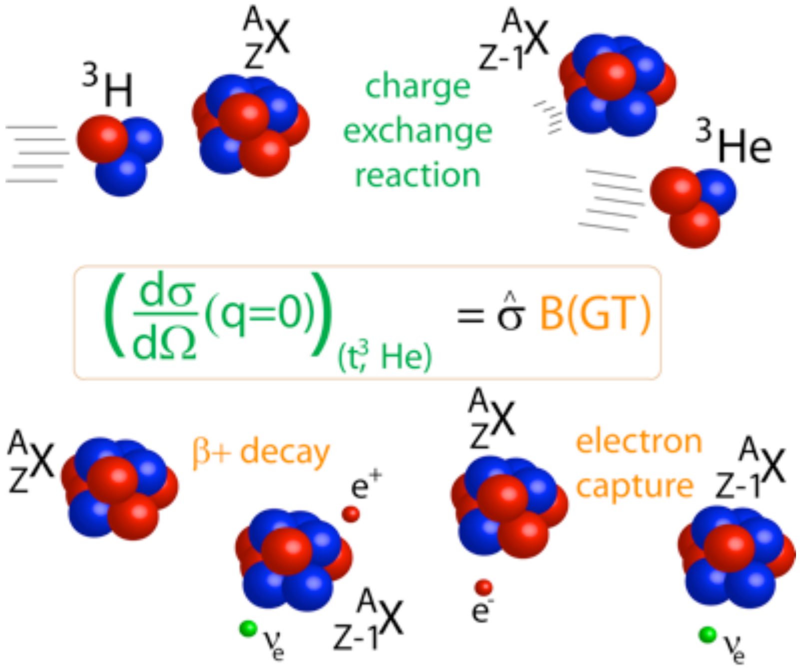


Understanding the spin-isospin response of a broad range of nuclei to a variety of probes is crucial for astrophysics applications!

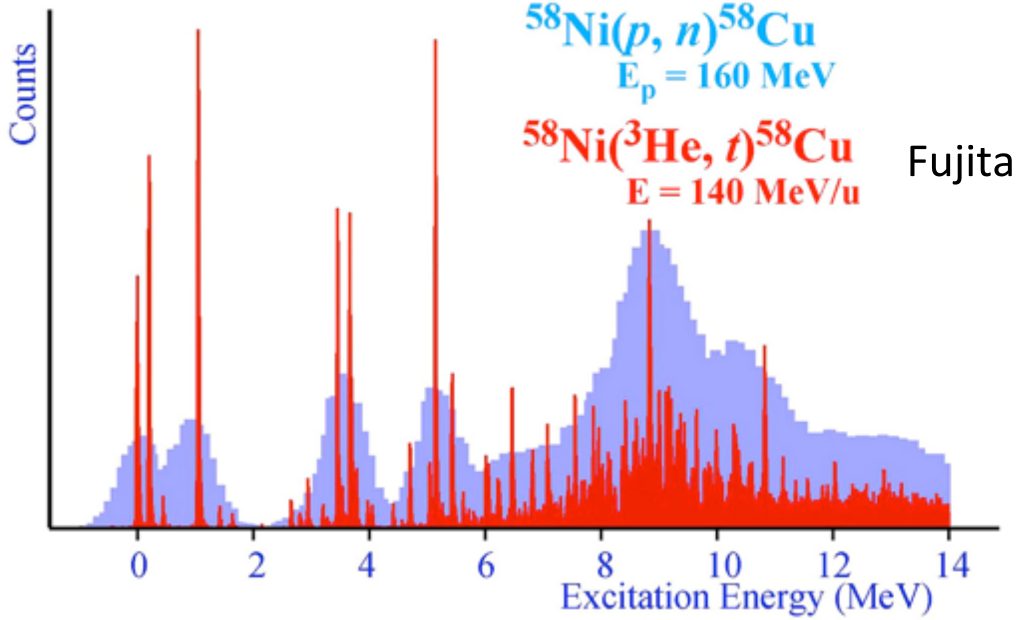
Charge-exchange reaction experiments both with direct and inverse kinematics will help. Recently there have been significant developments in this area.



Schiffer

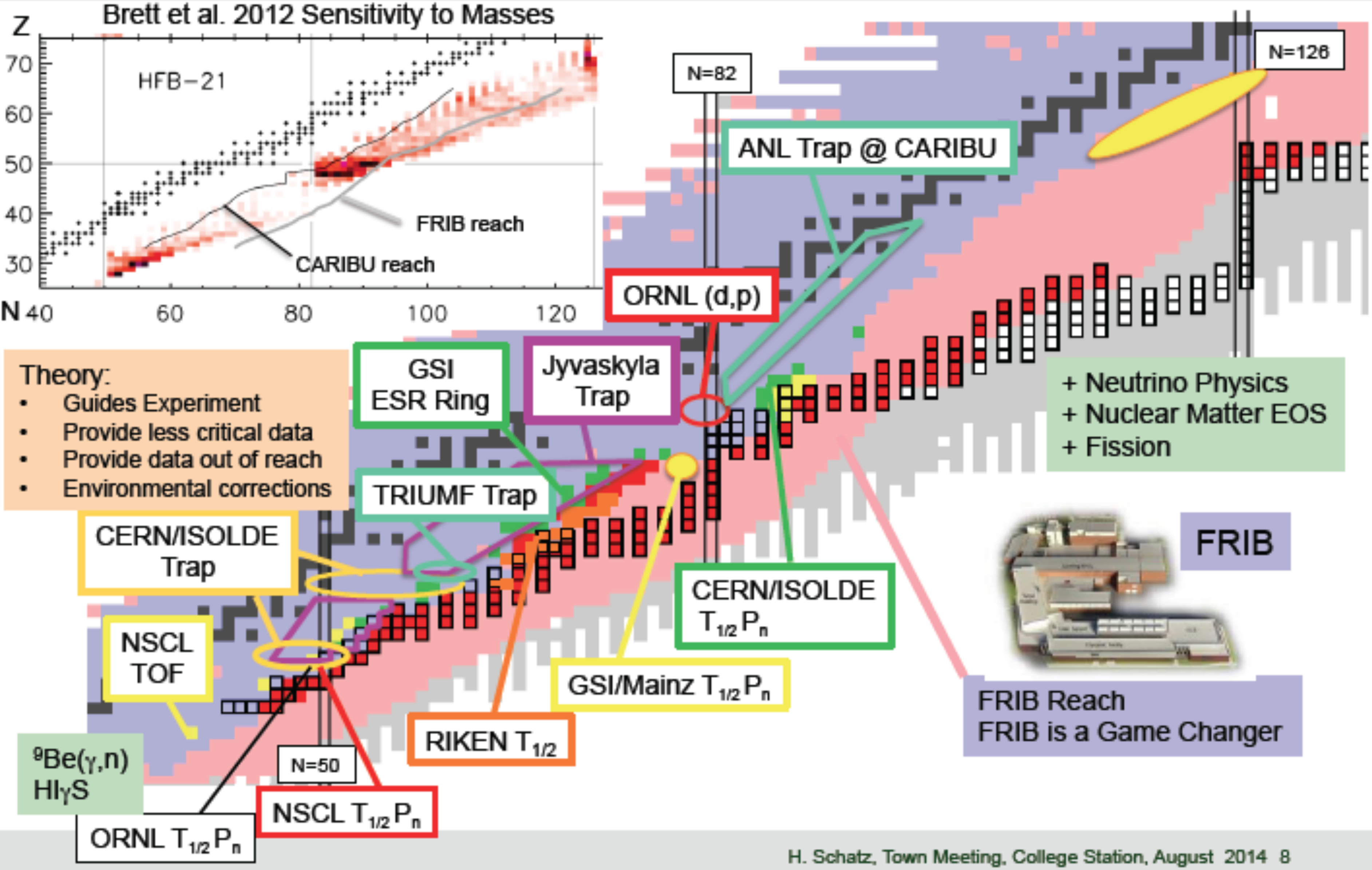


Zegers



Fujita

The Quest for r-process Nuclear Physics



Theory:

- Guides Experiment
- Provide less critical data
- Provide data out of reach
- Environmental corrections

ANL Trap @ CARIBU

ORNL (d,p)

GSI ESR Ring

Jyvaskyla Trap

TRIUMF Trap

CERN/ISOLDE Trap

NSCL TOF

^{9}Be(γ,n) HIγS

ORNL $T_{1/2}$ P_n

NSCL $T_{1/2}$ P_n

RIKEN $T_{1/2}$

GSI/Mainz $T_{1/2}$ P_n

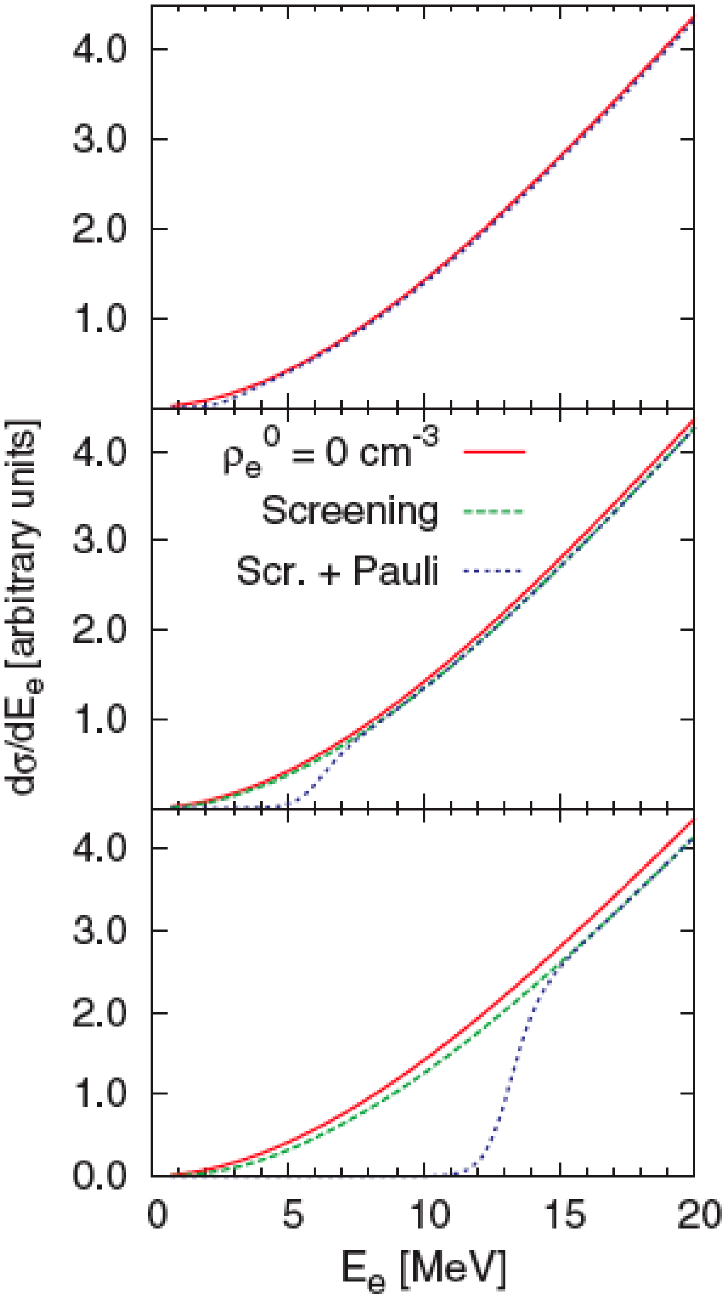
CERN/ISOLDE $T_{1/2}$ P_n

+ Neutrino Physics
+ Nuclear Matter EOS
+ Fission

FRIB Reach
FRIB is a Game Changer

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.

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

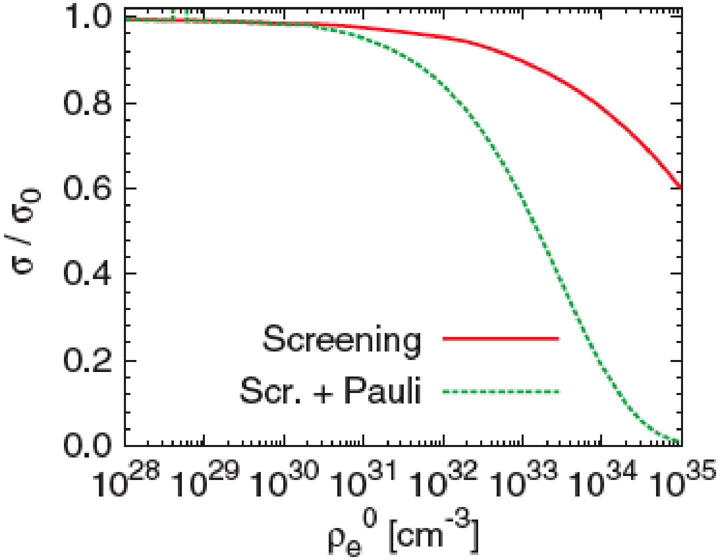


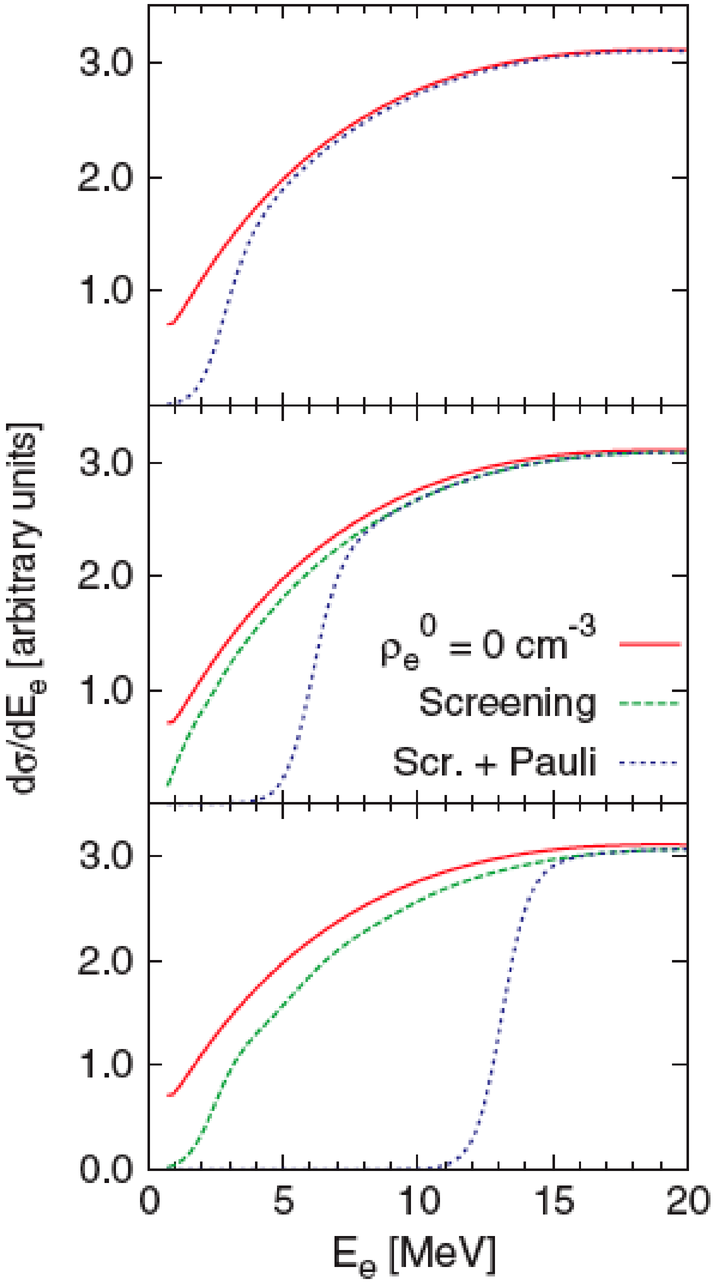
$\rho_e = 10^{32}\ \mathrm{cm}^{-3}$

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

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

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





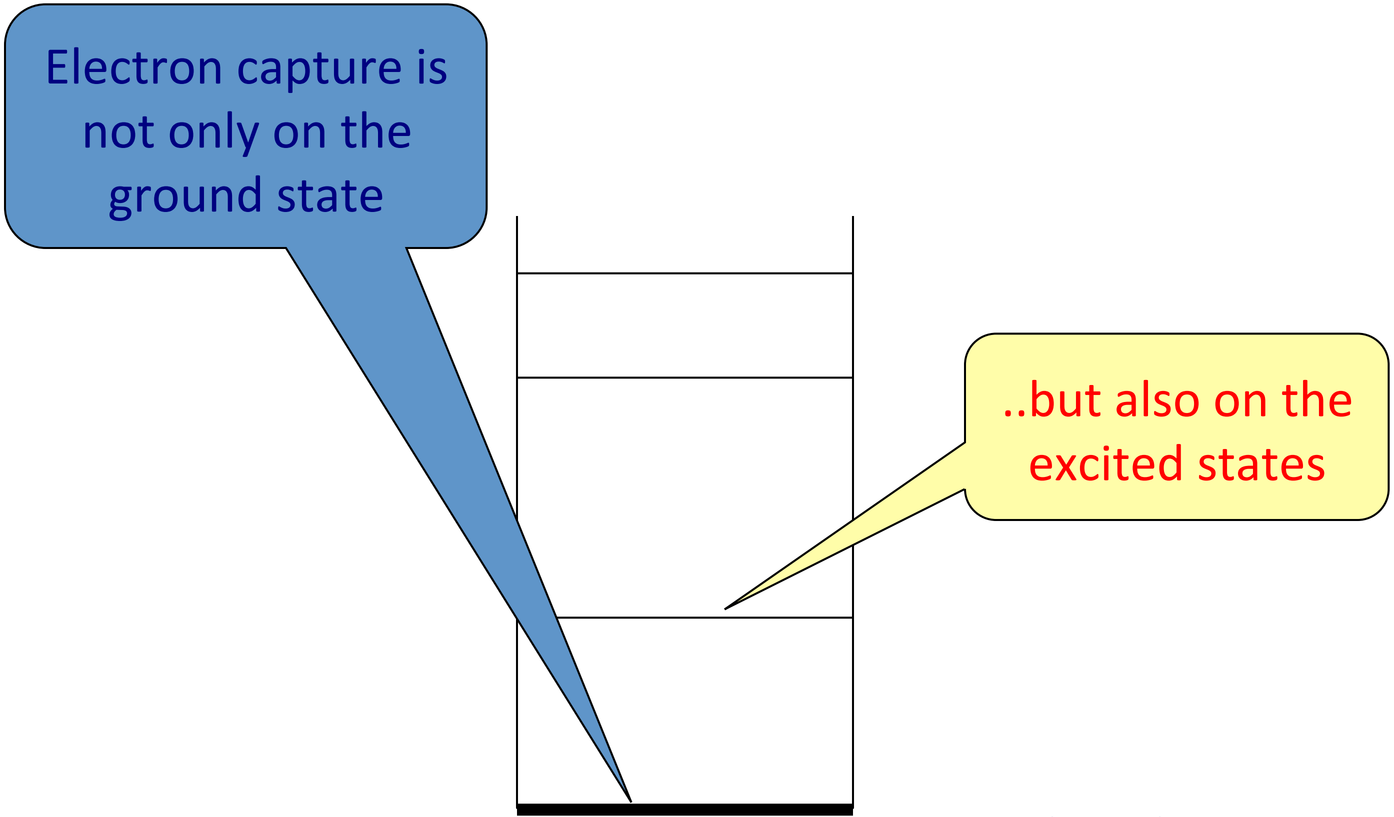
$\rho_e = 10^{32}$ cm^{-3}

$\rho_e = 10^{33}$ 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

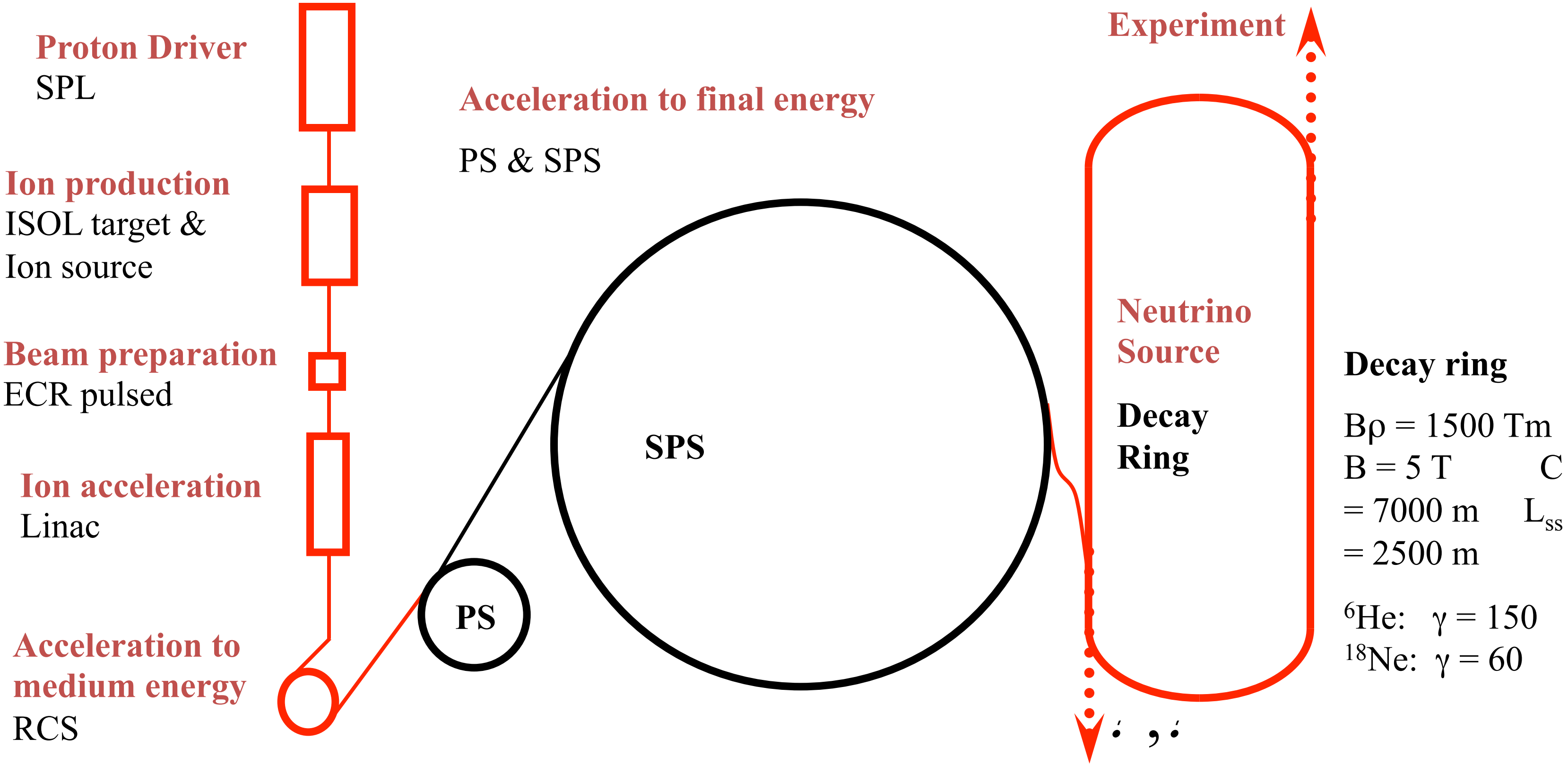
..but also on the excited states

…making theory input crucial!

The beta-beam concept

Use unstable nuclei as ν sources

Zucchelli, PLB 2002



Proton Driver
SPL

Ion production
ISOL target &
Ion source

Beam preparation
ECR pulsed

Ion acceleration
Linac

Acceleration to medium energy
RCS

Acceleration to final energy

PS & SPS

PS

SPS

Experiment

Neutrino Source

Decay Ring

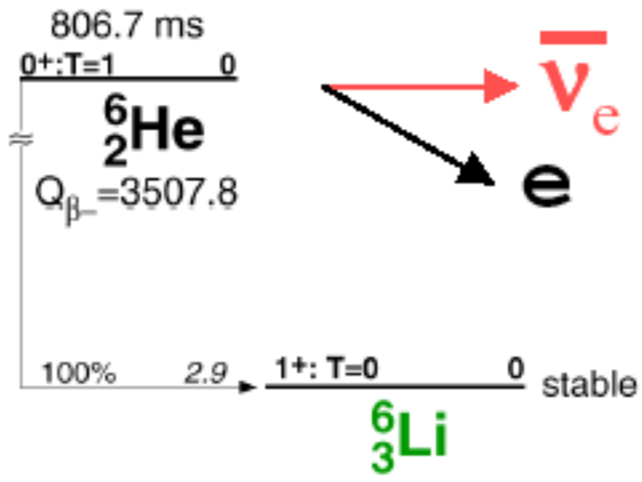
¿ , ¿

Decay ring

$B\rho = 1500$ Tm
$B = 5$ T C
$= 7000$ m L_{ss}
$= 2500$ m

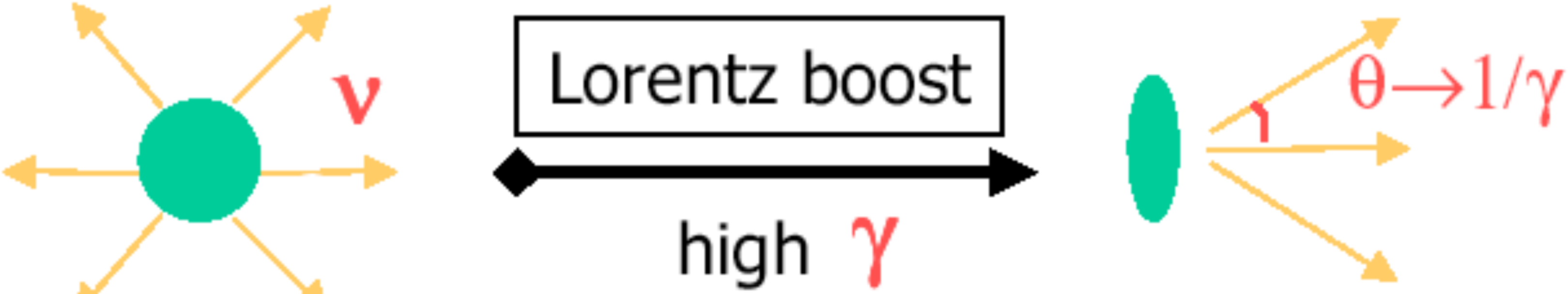
^{6}He: $\gamma = 150$
^{18}Ne: $\gamma = 60$

Beta-beam concept

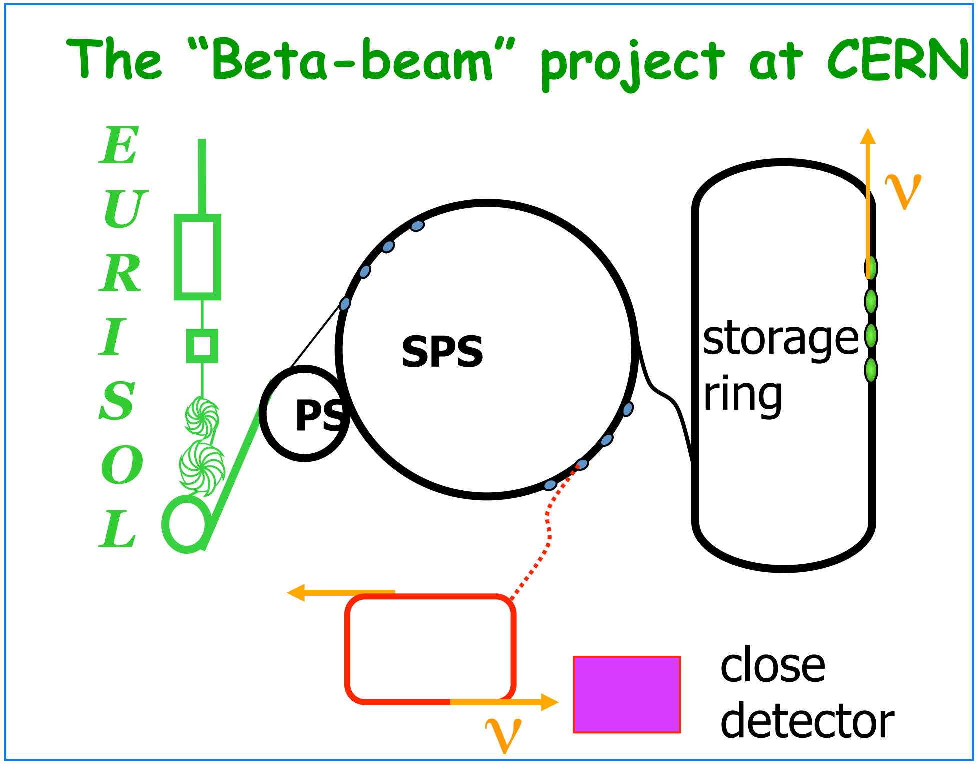


Advantages:

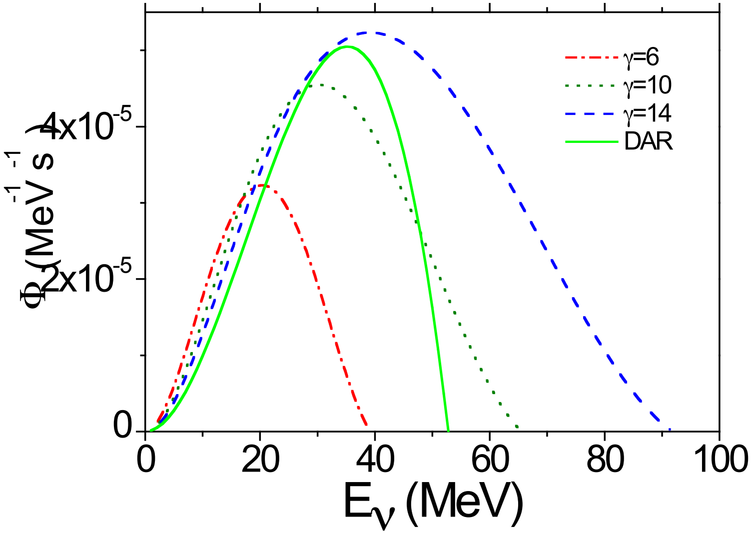
- Can be done at a facility studying exotic nuclei with radioactive beams
- Pure beams of a single neutrino flavor
- Well-known spectra
- Strong collimation at higher energies



Original low-energy beta-beam idea (Volpe, JPG 30,2004): To use the beta-beam concept to produce single-flavor low-energy neutrino beams (10 - 100 MeV with γ = 5 -14)

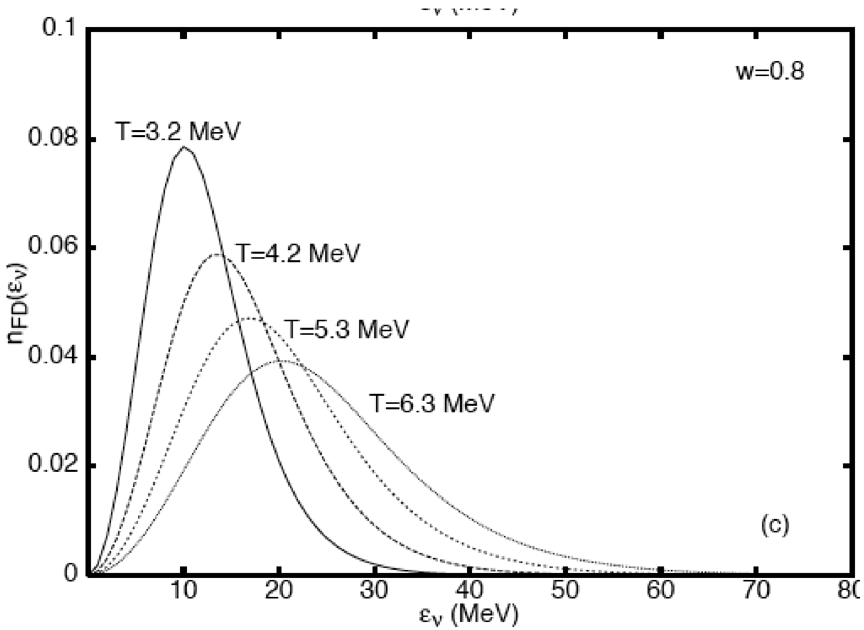


The "Beta-beam" project at CERN

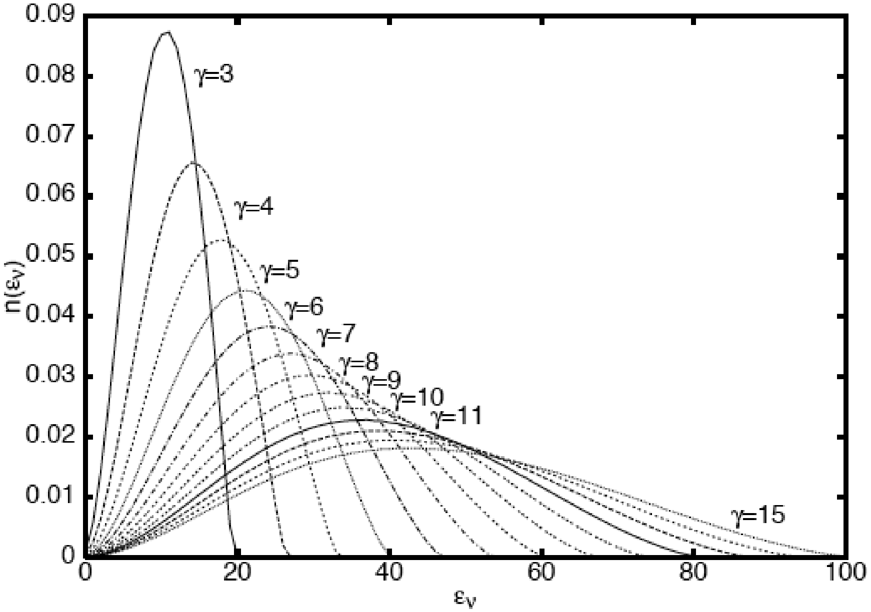


Serreau, Volpe, PRC 2004

Use beta-beams to mimic supernova neutrino spectra!



Supernova neutrino spectra



Normalized beta-beam spectra

Jachowicz, McLaughlin and Volpe, PRC 2008

Thank you very much!