The significance of neutrino cross-sections for astrophysics

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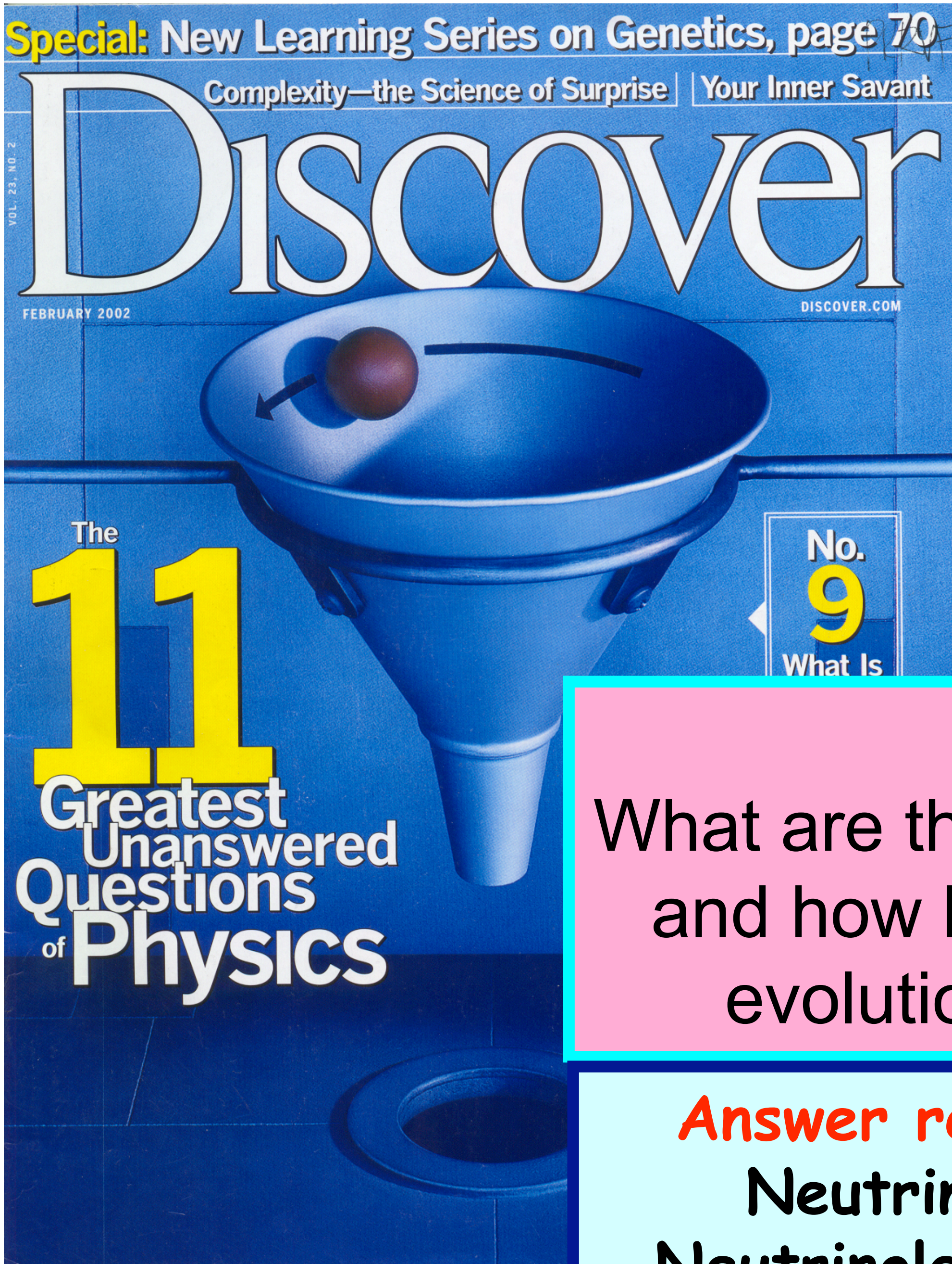
Sitges, Barcelona



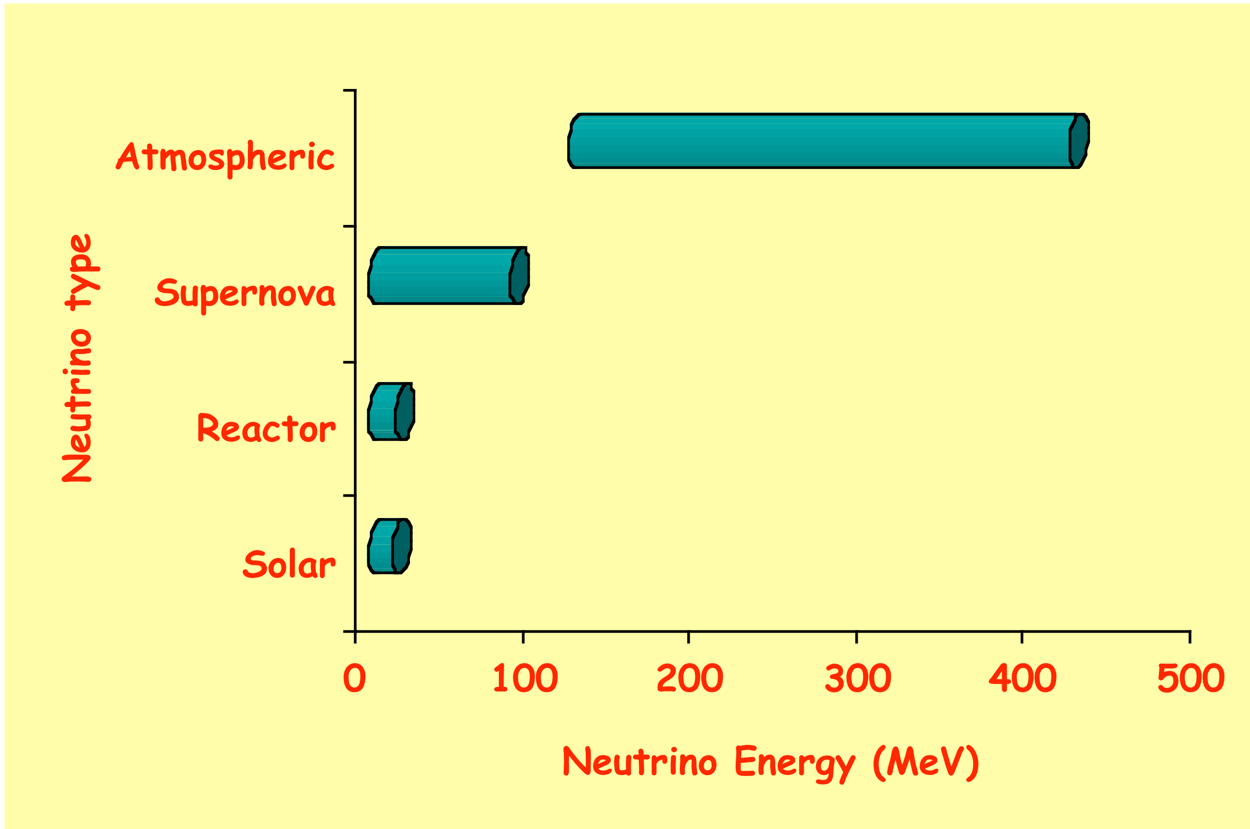
U.S. National Academy of Sciences Report "Connecting Quarks with the Cosmos: Eleven Science Questions For the New Century"

Question 5

What are the masses of neutrinos, and how have they shaped the evolution of the Universe?

Answer requires knowing about

Neutrino Interactions and Neutrinoless Double Beta Decay



Low-energy non-accelerator neutrinos so far observed

What part of the neutrino sky did we actually observe so far?

- Below 100 MeV: Solar neutrinos (SuperK, SNO, SAGE, Gallex, Homestake); neutrinos from SN1987A (Kamioka,IMB,Baksan); tail of atmospheric neutrinos.
- Up to 1 TeV: Atmospheric neutrinos (SuperK, others...).
- Above 1 TeV: Atmospheric neutrinos (Amanda); future data from Icecube.
- Very high energies: Only upper limits in neutrino fluxes

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- We had already seen neutrinos from two (and only two) such objects: A main-sequence star (the Sun) and a core-collapse supernova (SN1987A).

Applications of ν-nucleus interactions

Theory and applications of Detector Response: Detectors for solar, atmospheric, accelerator, and reactor neutrinos.

Input into astrophysics: Neutrino reactions in core-collapse supernovae, supernova nucleosynthesis, gamma-ray burst nucleosynthesis.

Tests of nuclear structure calculations: Shell Model, effective field theories.

Fundamental physics at low energies: e.g. determining proton strange form factors.

How can the neutrino cross-sections be calculated?

Low Energy (0 < E <~200 MeV)	**Non-relativistic many-body theories (Shell Model, RPA); effective field theory**	Solar and supernova neutrinos
Intermediate E (~200 MeV < E < ~200 GeV)	**Relativistic; hadronic ⇒ partonic d.o.f, superscaling ideas; quasielastic and resonance regime**	Atmospheric neutrinos
High Energy (~200 GeV < E < EeV)	**Deep-inelastic scattering, partonic d.o.f., x-scaling**	Atmospheric ν's, neutrinos from point sources, …

An approach from the first principles: Using effective field theory for low-energy neutrino-deuteron scattering

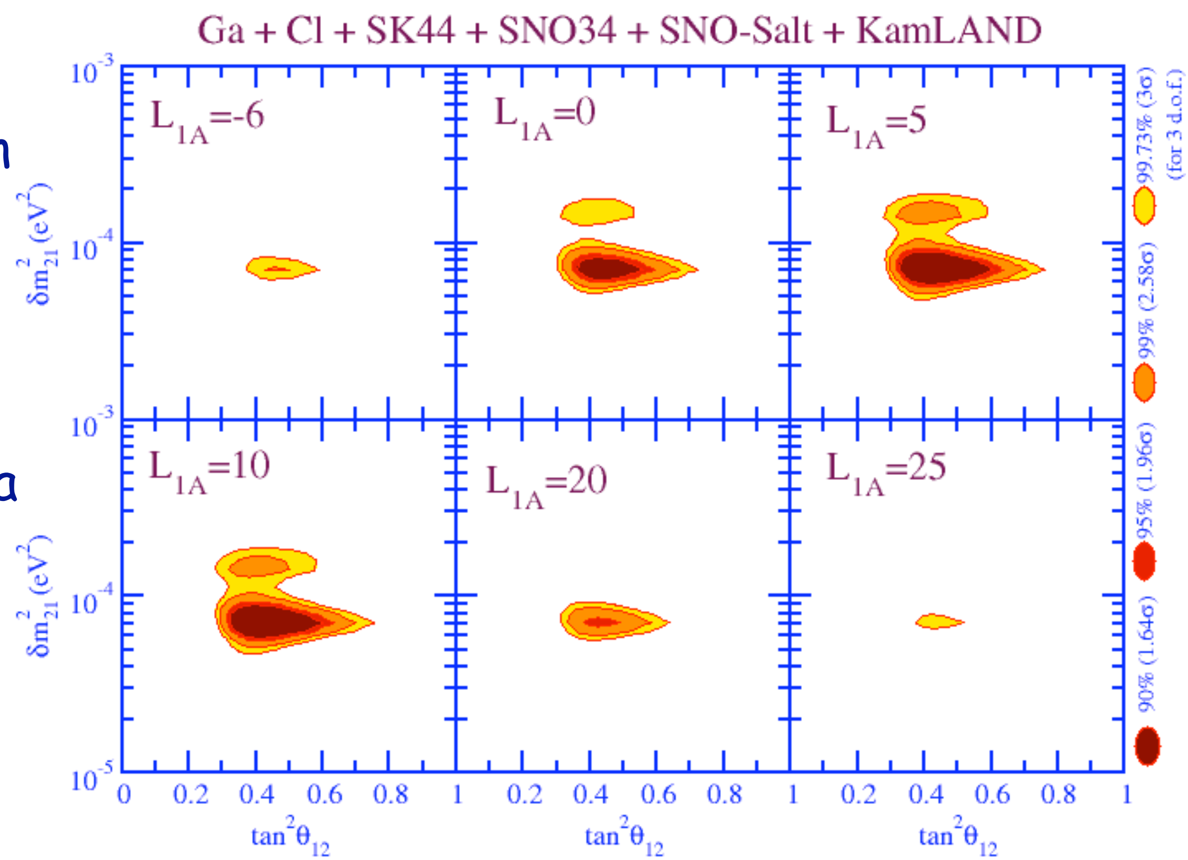
Butler, Chen

Below the pion threshold $^3S_1 \rightarrow {}^3S_0$ transition dominates and one only needs the coefficient of the two-body counter term, L_{1A} (isovector two-body axial current)

L_{1A} can be obtained by comparing the cross section $\sigma(E) = \sigma_0(E) + L_{1A}\, \sigma_1(E)$ with cross-section calculated using other approaches or measured experimentally.

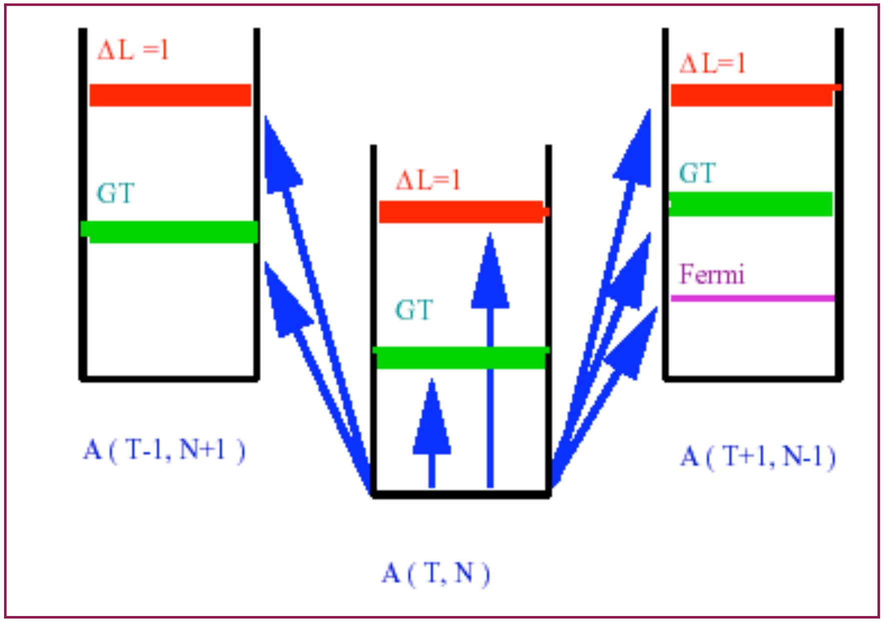
(e.g. use solar neutrinos as a source)

Difficult to go beyond two-body systems!



A.B. Balantekin and H. Yuksel

For SN the question is to find out what happens when a 50 MeV neutrino hits a nucleus? Where is the strength? What is g_A/g_V?



At the lowest energies Shell Model is the best approach. Gamow-Teller strength is quenched in the Shell Model:

Nucleus	^{128}Sn	^{130}Sn	^{132}Sb	^{132}Te	^{133}Te
Transition	$0^+ \to 1^+$	$0^+ \to 1^+$	$4^+ \to 3,4,5^+$	$0^+ \to 1^+$	$\frac{3}{2}^+ \to \frac{1}{2},\frac{3}{2},\frac{5}{2}^+$
$T_{1/2}$exp.	59.07m	3.72m	2.79m	3.2d	12.5m
$T_{1/2}$calc. (0.74)	32.21m	2.47m	1.56m	1.73d	6.42m
Renorm.	0.54	0.6	0.55	0.54	0.53

Beta-decay rates from Nowacki

As the incoming neutrino energy increases, the contribution of the states which are not well-known increase, including first- and even second-forbidden transitions.

At higher energies where the rate is sensitive to total strength and the energy of giant resonances there is a tendency to use RPA.

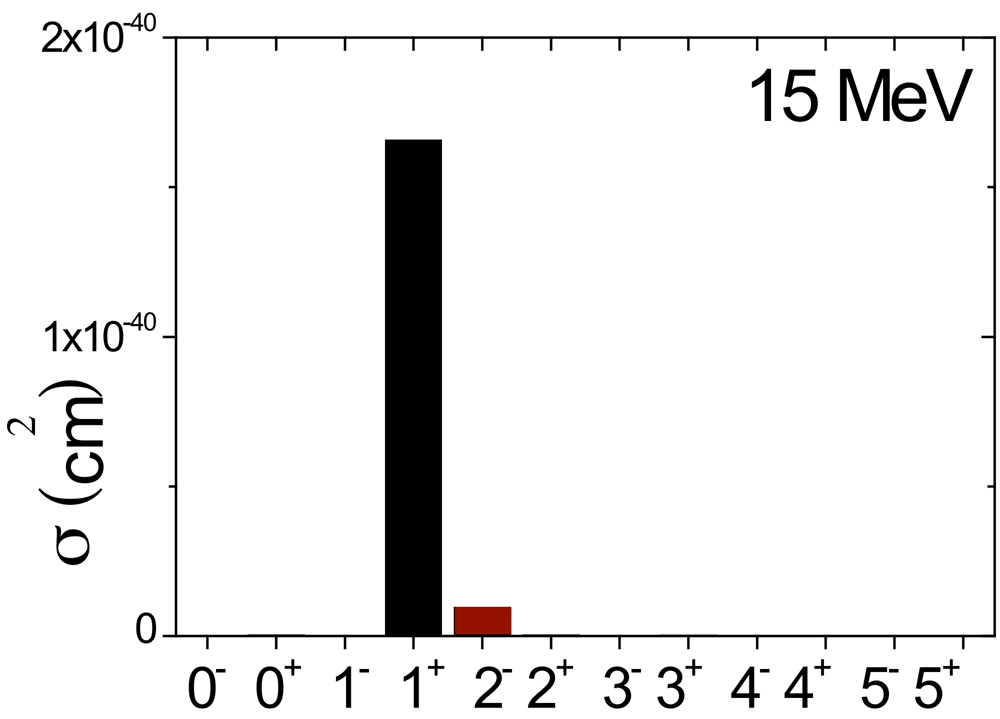
However some theoretical difficulties with RPA remain!

Example:

States once can excite in the reaction

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

as a function of the neutrino energy



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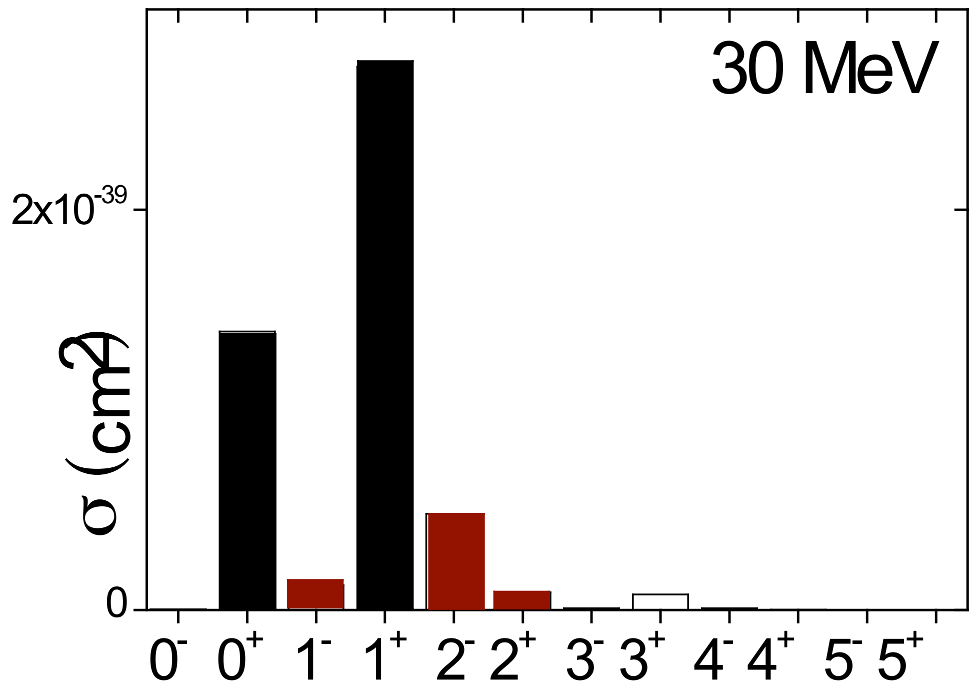

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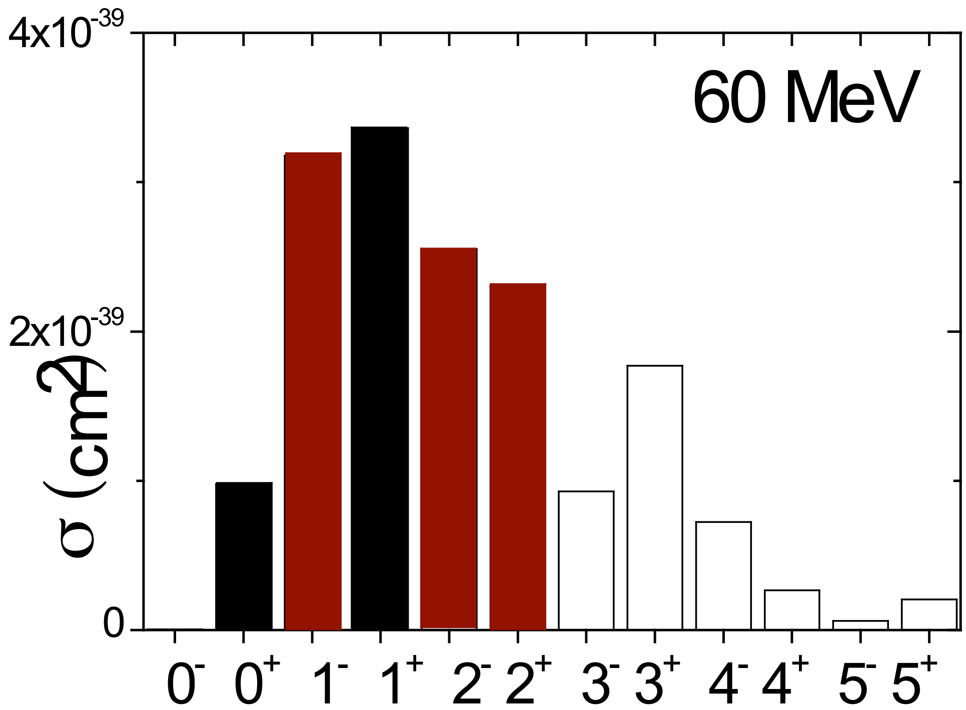


Lazauskas and Volpe, Nucl.Phys.A792,219,2007

States

as a rgy

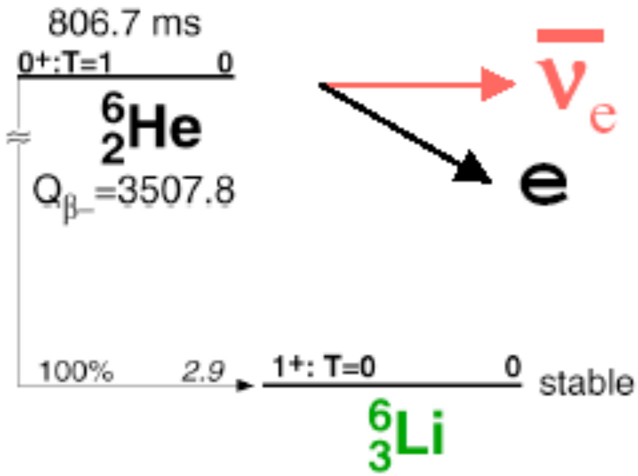
4

2

To experimentally study neutrino cross-sections at astrophysically relevant low-energies (i.e. to measure the spin-isospin response of the nuclei) one needs neutrinos with varying energies !

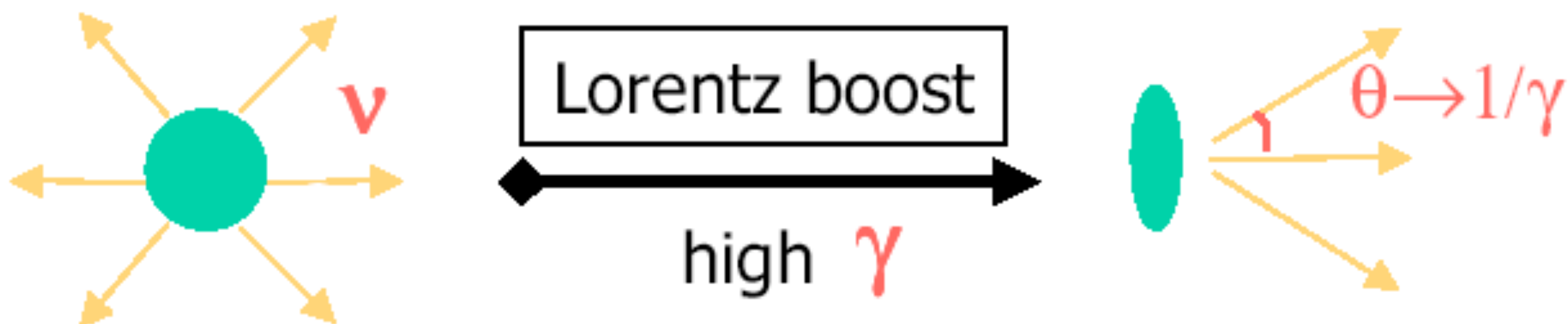
Lazauskas and Volpe, Nucl.Phys.A792,219,2007

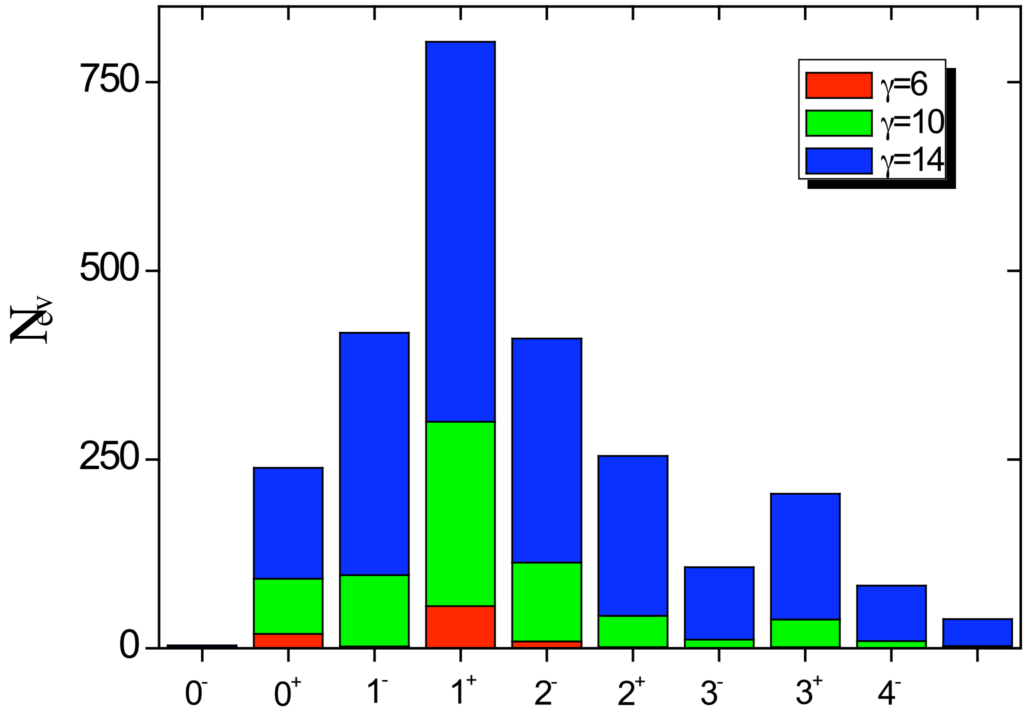
Beta-beam concept



Advantages:

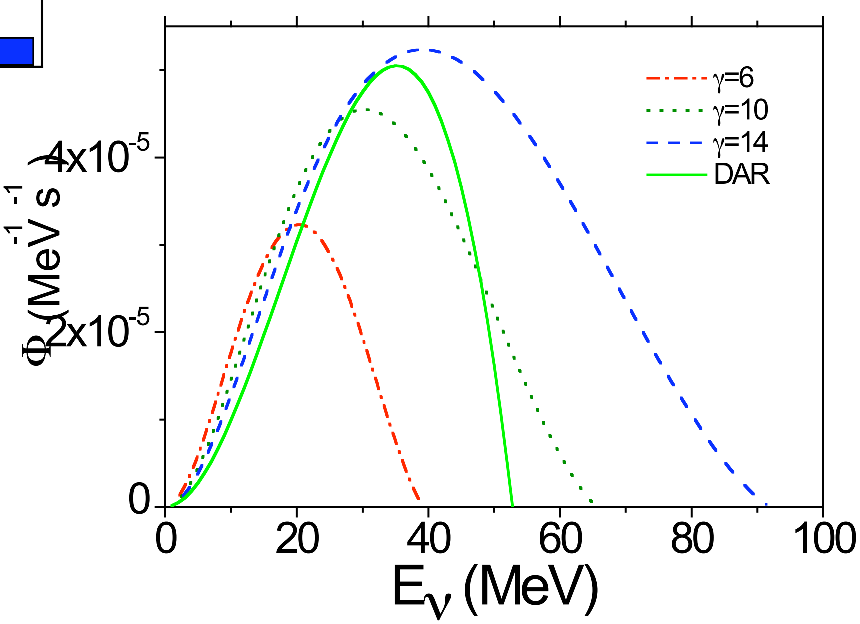
- Can be done at a facility studying exotic nuclei with radioactive beams
- Pure beams of a single neutrino flavor
- Well-known spectra
- Strong collimation at higher energies





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

With low-energy beta-beams it would be possible to do a systematic study of spin-isospin response of nuclei!



Lazauskas and Volpe, Nucl.Phys.A792,219,2007

The weak-magnetism contribution to the cross-section for the reaction

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

Weak hadronic current

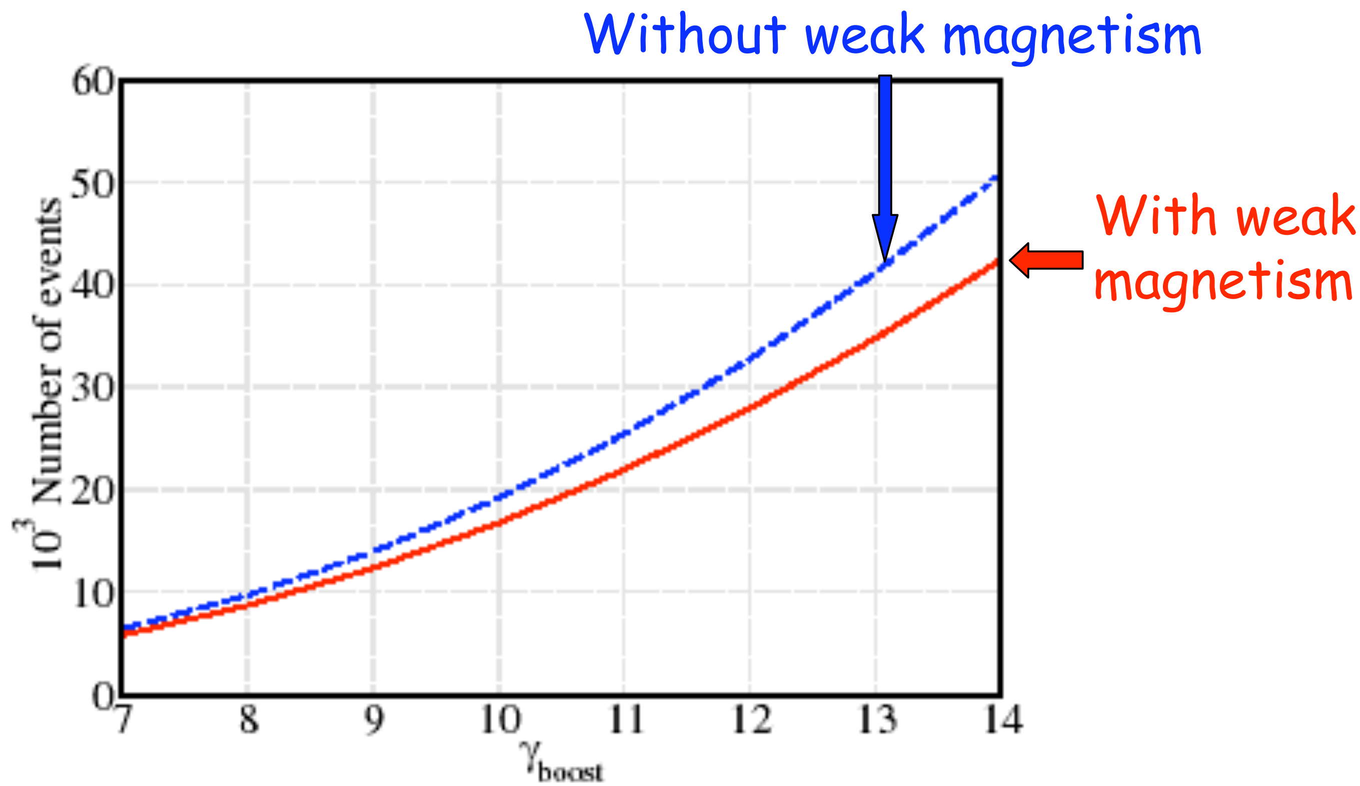
$$\boxed{\frac{G_F \cos\theta_C}{\sqrt{2}} \left\{ \overline{u}_n \left[\gamma_\alpha (f_1 - g_1 \gamma_5) + \sigma_{\alpha\beta} k^\beta (f_2 + g_2 \gamma_5) + k_\alpha (f_3 + g_3 \gamma_5) \right] u_p \right\}}$$

The Conserved Vector Current (CVC) hypothesis:

$$\boxed{\lim_{q^2 \to 0} f_1(q^2) = 1 \; ; \qquad \lim_{q^2 \to 0} f_2(q^2) = \frac{\mu_p - \mu_n}{2 m_N} \; ; \qquad f_3(q^2) = 0}$$

Weak magnetism

Weak magnetism contributions may increase the antineutrino mean free path in a supernova Horowitz



Expected number of events at a low-energy beta-beam over a year for antineutrino-proton scattering using a Water Cerenkov detector

Balantekin, de Jesus, Lazauskas, Volpe, 2006

Neutrino-electron scattering

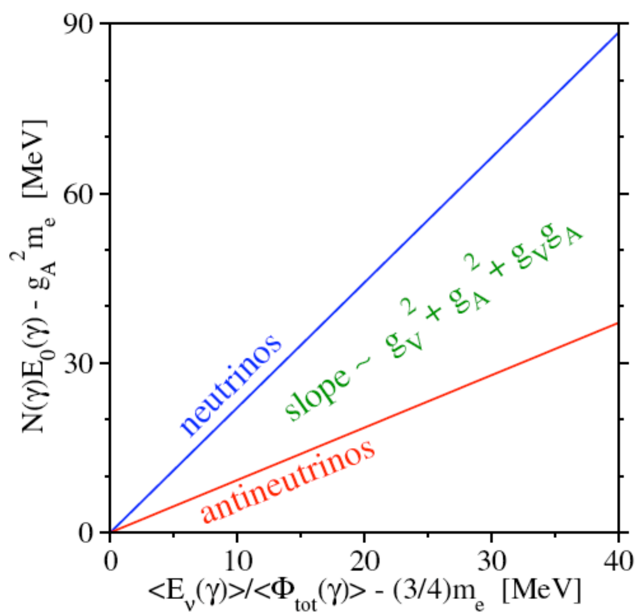
$$\frac{d\sigma_{(\nu,e)}}{dT_e} \sim \left(g_V^2 + g_A^2\right) + \left(g_V^2 - g_A^2\right)\left(1 - \frac{T_e}{E_\nu}\right)^2 + \cdots$$

$$g_V = 1/2 + 2\sin^2\theta_W + \cdots \qquad g_A = \pm 1/2 + \cdots$$

Averaging over the beta-beam flux, $\langle \phi \rangle$, gives

$$\langle \sigma_{(\nu,e)} \rangle \sim -g_V\left(g_V + g_A\right) m_e \langle \phi_\nu \rangle + \frac{4}{3}\left(g_V^2 + g_A^2 + g_V g_A\right)\langle E_\nu \rangle$$

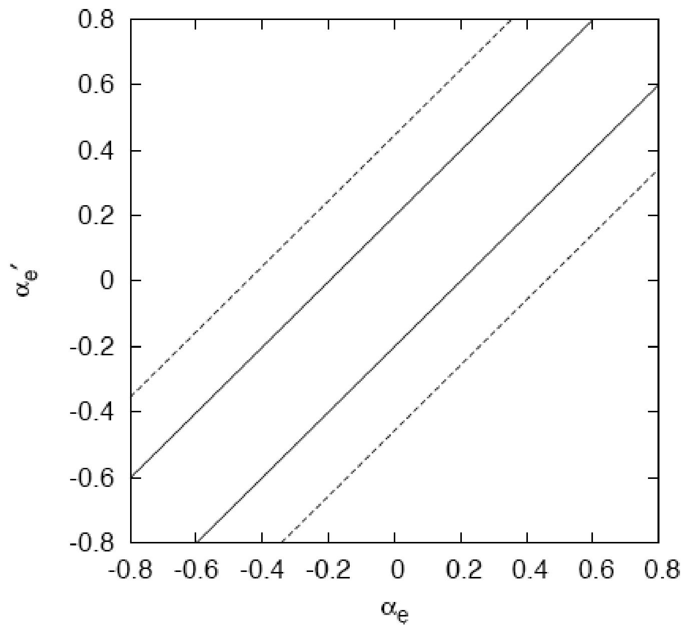
Balantekin, J.H. de Jesus and C. Volpe, Phys. Lett. B **634**, 180 (2006)



Testing flavor universality in ν neutral-current scattering

$$\sigma(\nu_e e^- \to \nu_e e^-) = \frac{G_F^2 E_\nu^2 m_e}{\pi(2E_\nu + m_e)^3}\left[\frac{16}{3}({g''_A}^2 + {g''_V}^2 + g''_A g''_V)E_\nu^2 + 4m_e(2{g''_A}^2 + {g''_V}^2 + g''_A g''_V)E_\nu + m_e^2(3{g''_A}^2 + {g''_V}^2)\right]$$

$$\begin{aligned}
g''_{A(V)} &= \left(1 + \frac{v^2}{\Lambda^2}(-\alpha_e + \alpha'_e)\right) g'_{A(V)} + \left(1 + \frac{2v^2}{\Lambda^2}\alpha'_e\right)^2, \\
g'_{A(V)} &= g_{A(V)} - \frac{v^2}{2\Lambda^2}(\alpha_e + \alpha'_e), \\
g_A &= -\frac{1}{2}, \quad g_V = -\frac{1}{2} + 2\sin^2\theta_W,
\end{aligned}$$



Balantekin, Sahin and Sahin, 2009

γ = 530

Solar Neutrinos-Open Questions:

- Can we test the relation between solar photon and neutrino luminosities? Is there a subdominant neutrino source?
- Does the Sun entirely work via the pp-chain? What is the contribution from the CNO cycle?
- Does the neutrino have a magnetic moment? If so, does it effect solar neutrino flux? Are there solar antineutrinos?
- Can we use neutrinos to measure solar properties such as density scale height?
- Can we use solar neutrinos to do physics beyond both the Standard Model of the Sun and the Standard Model of particle physics? Are the signatures for such physics generic?
- Once we are done with the solar nuclear fusion neutrinos, can we ever detect solar plasma neutrinos?

Solar Neutrinos-Open Questions:

• C … between solar pho … lumi …

• Does … contrib …

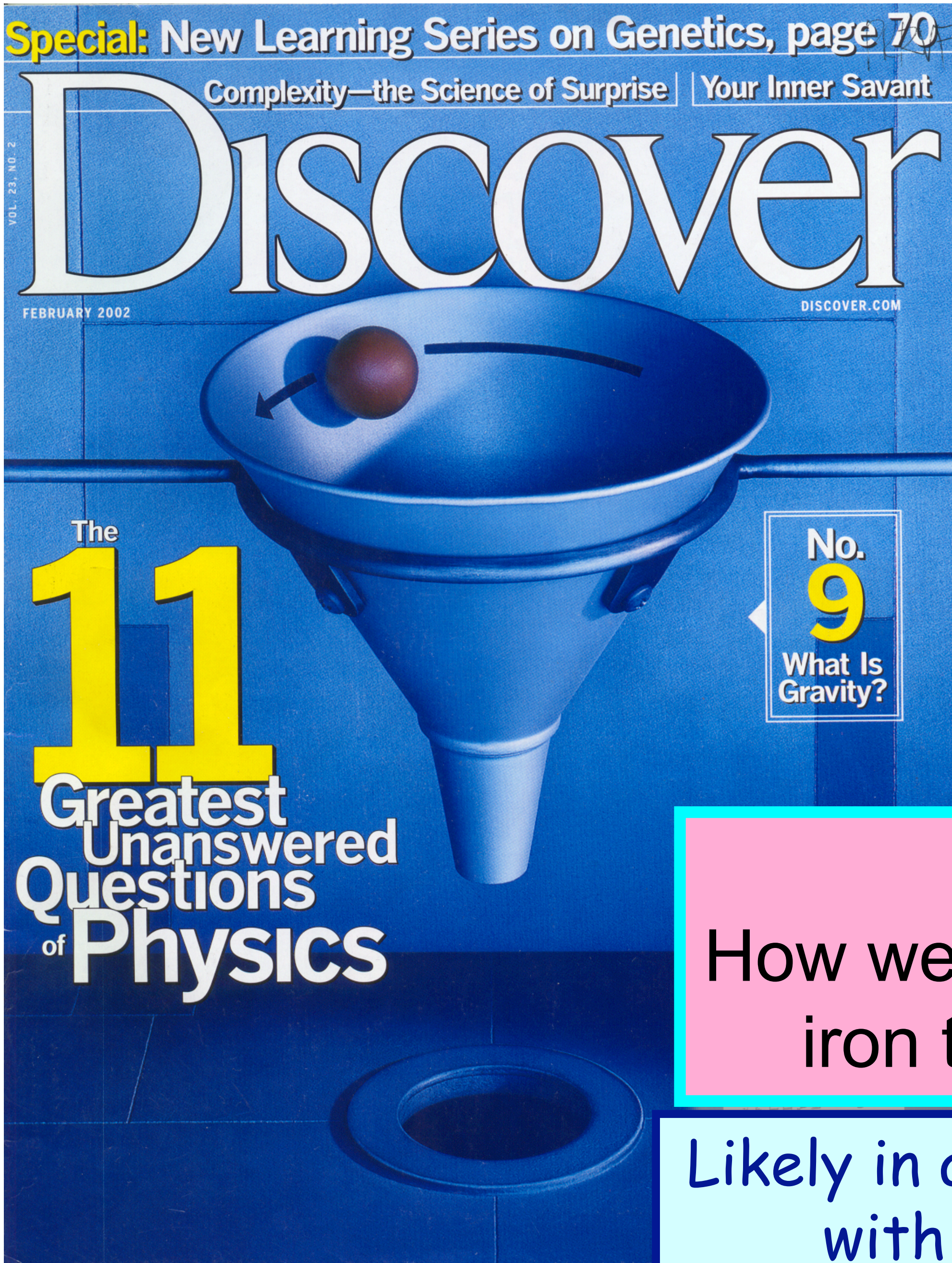
• Does th … fect solar ne …

• Can … scal …

• C … Model of the Sun … physics? Are the signatures for suc …

All these questions require knowledge of either production or detection cross sections for neutrinos!

• Once we are done with the solar nuclear fusion neutrinos, can we ever detect solar plasma neutrinos?



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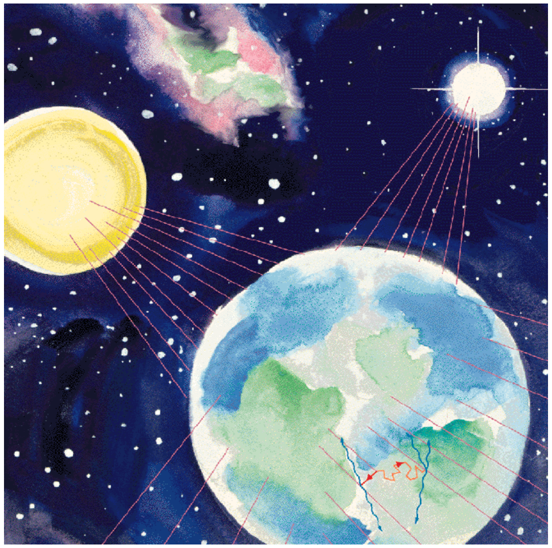
Question 10

How were the elements from iron to uranium made ?

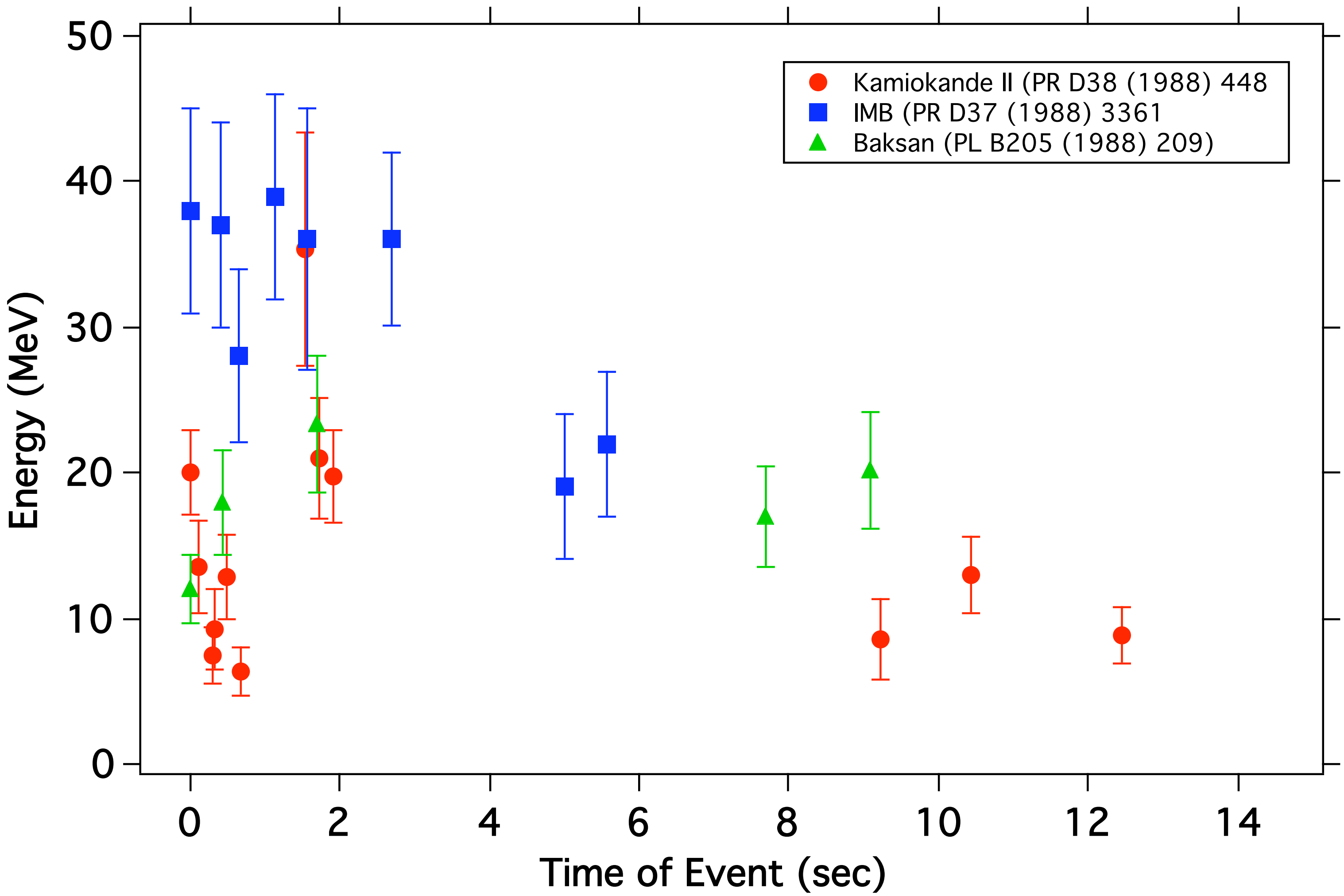
Likely in a core-collapse supernova with the aid of neutrinos

Neutrinos from core-collapse supernovae



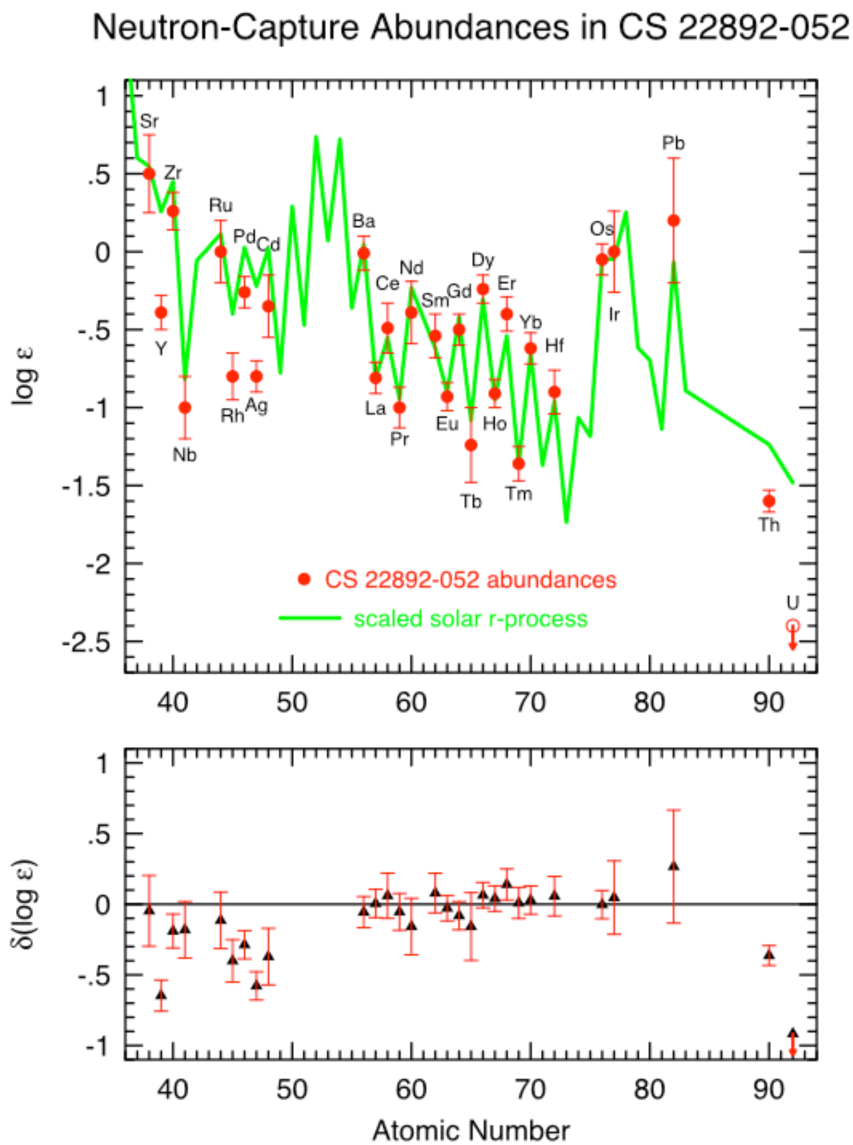
- $M_{prog} \geq 8\ M_{Sun}$
- $\Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV
- 99% of the energy is carried away by neutrinos and antineutrinos with $10 \leq E_\nu \leq 30$ MeV
- 10^{58} Neutrinos!

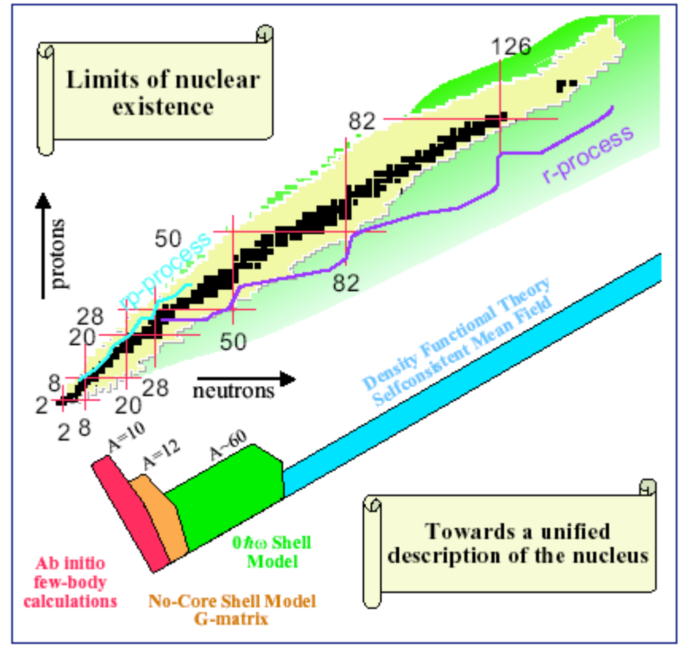
Neutrinos from SN1987A



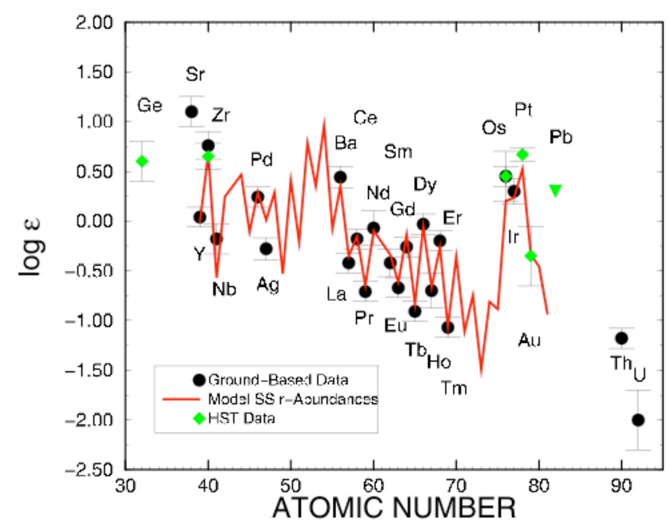
Observed r-process abundances

[Fe/H] ≈ -3.1





A > 100 abundance pattern fits the solar abundances well.



Life stages of a core-collapse supernova

1. Collapse and bounce epoch. $S/k \approx 1$
2. Shock-reheating epoch. $S/k \approx 40$
3. Hot-bubble epoch. $S/k \approx 75$ to 500?

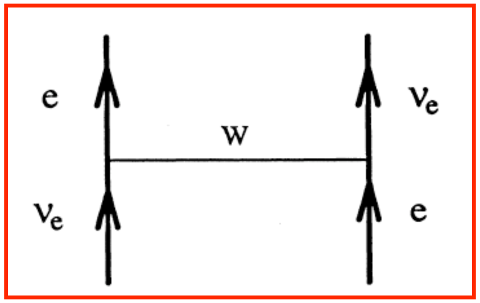
Possible site of r-process nucleosynthesis

MSW effect

In vacuum: $E^2 = p^2 + m^2$

In a potential: $(E-\Phi)^2 = p^2 + m^2 \Rightarrow E^2 = p^2 + m_{eff}^2,\ m_{eff}^2 \approx m^2 + 2E\Phi$

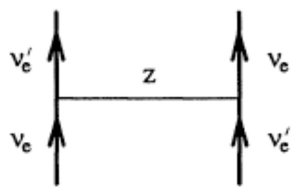
The potential is provided by the coherent forward scattering of ν_e's off the electrons in dense matter.

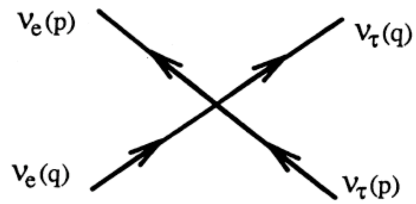


There is a similar term with Z-exchange. But since it is the same for all neutrino flavors, it does not contribute to phase differences *unless* we invoke a sterile neutrino.

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_e\\ \psi_x\end{pmatrix} = \begin{pmatrix} -\frac{\delta m^2}{4p}\cos 2\theta + \frac{1}{\sqrt{2}}G_F N_e & \frac{\delta m^2}{4p}\sin 2\theta \\ \frac{\delta m^2}{4p}\sin 2\theta & \frac{\delta m^2}{4p}\cos 2\theta - \frac{1}{\sqrt{2}}G_F N_e \end{pmatrix}\begin{pmatrix}\psi_e\\ \psi_x\end{pmatrix}$$

If the neutrino density itself is also very high then one has to consider the effects of neutrinos scattering off other neutrinos. This is the case for a core-collapse supernova.





In core-collapse supernovae particle abundances are the isospin-mirror of the abundances for Big-bang nucleosynthesis!

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

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

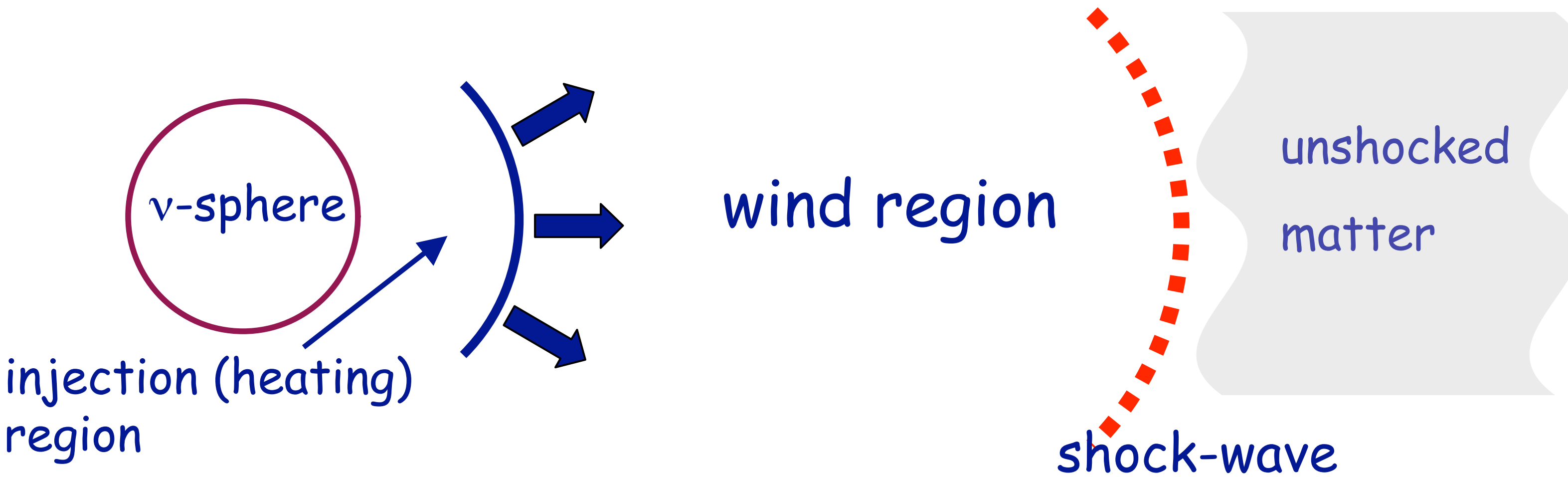
This makes core-collapse supernovae an ideal site for r-process nucleosynthesis which requires a lot of neutrons!

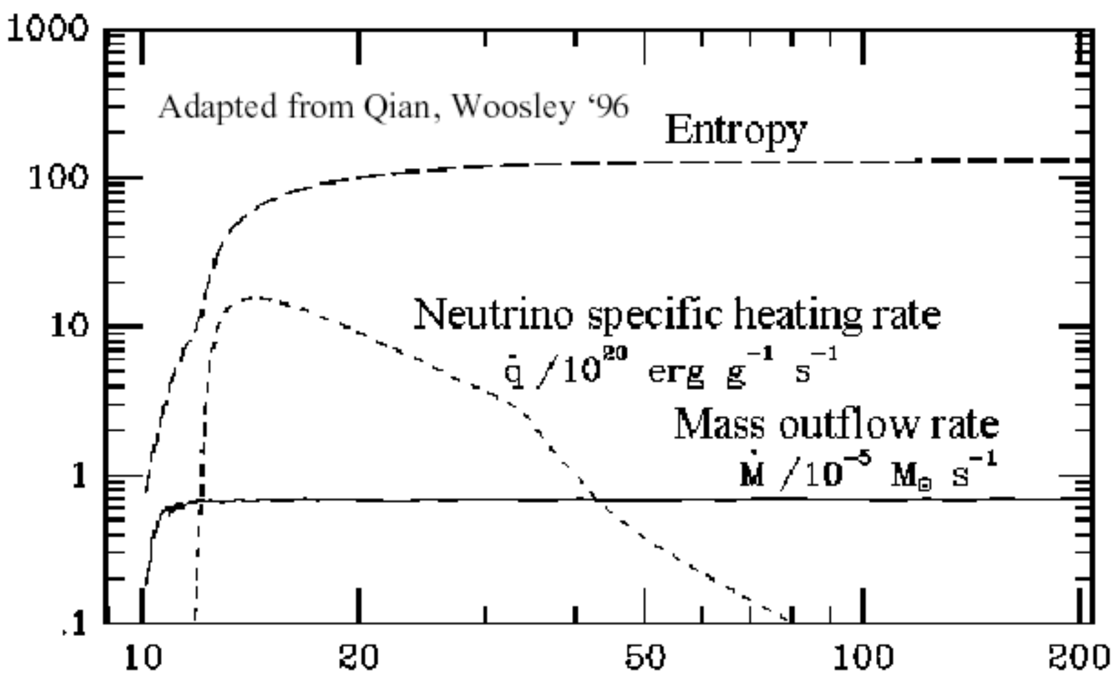
Yields of r-process nucleosynthesis are determined by neutron-to-proton ratio, n/p

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 (and measure!) neutrino-nucleon as well as neutrino-nucleus 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 completely understood, but may have significant impact on r-process nucleosynthesis.

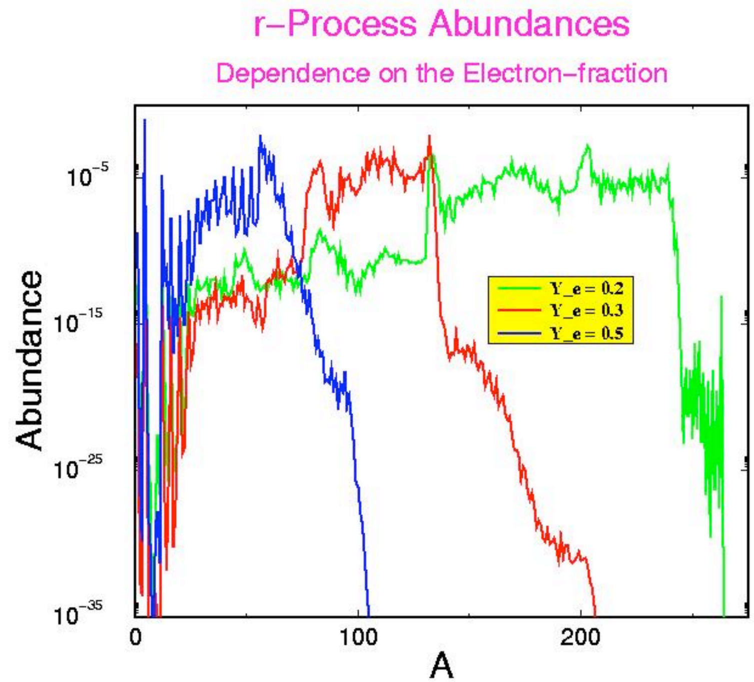
Neutrino-driven wind in post-core bounce supernova





Mass outflow rate in the wind region is approximately constant

Electron Fraction



$Y_e = (n_{e^-} - n_{e^+}) / n_{baryons}$

λ = reaction rate

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

$\lambda_p = \lambda_{\overline{\nu e}} + \lambda_{e-}$
proton loss rate

$\lambda_n = \lambda_{\nu e} + \lambda_{e+}$
neutron loss rate

X_α alpha fraction

Weak freeze-out radius: where neutron-to-proton conversion rate is less than the outflow rate

$dY_e/dt = 0$

$dY_e/dt = 0$

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

If alpha particles are present

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

If alpha particles are absent

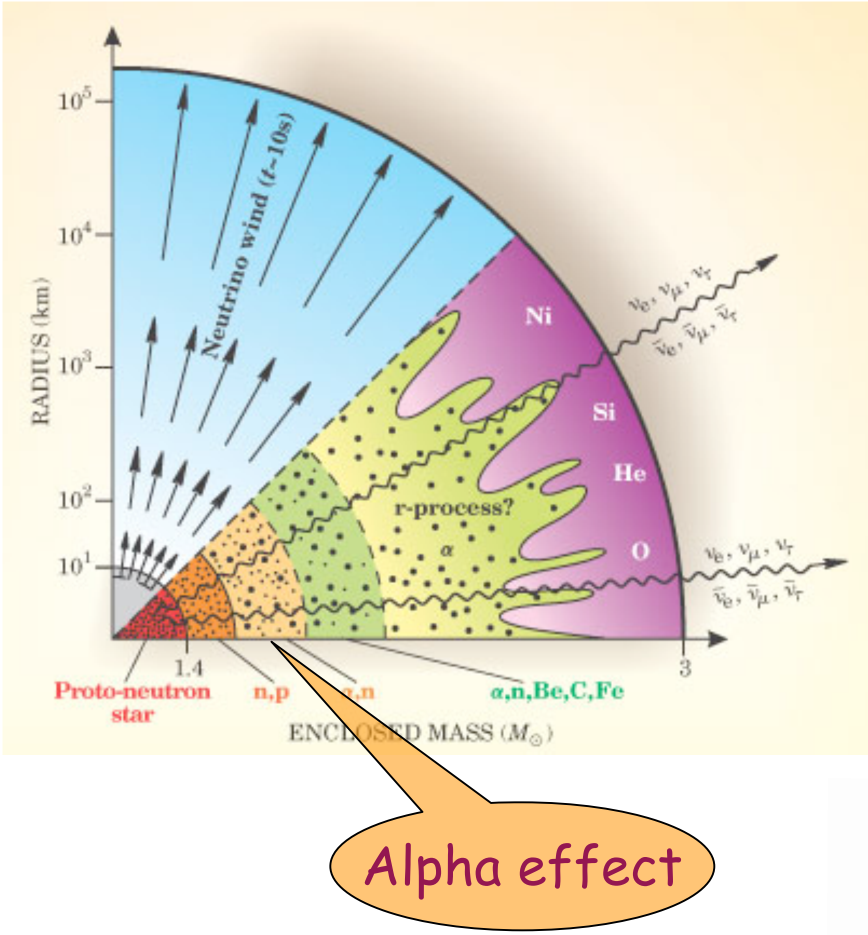
$$Y_e = Y_e^{(0)} + \left(\frac{1}{2} - Y_e^{(0)}\right) X_\alpha$$

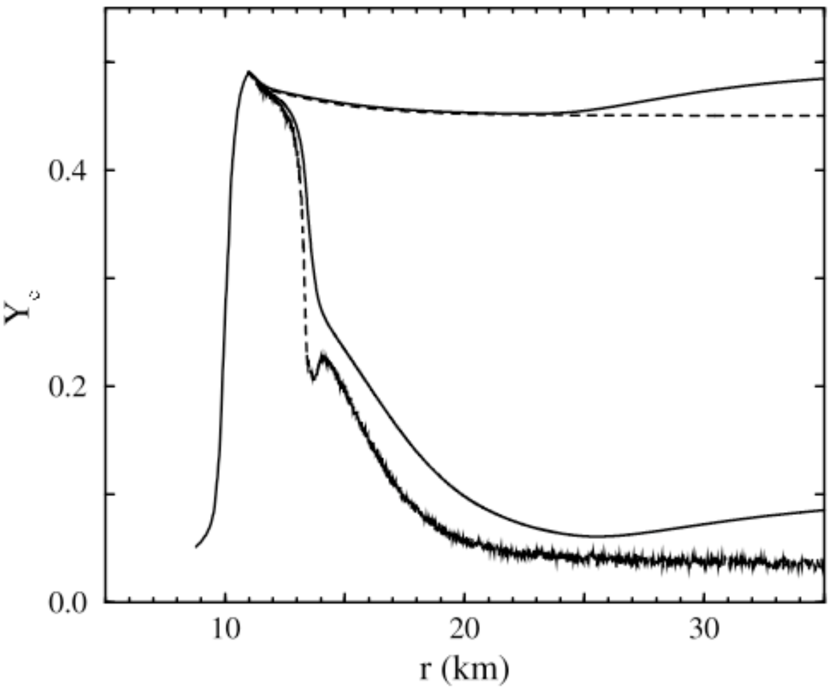
If $Y_e^{(0)} < 1/2$, non-zero X_α increases Y_e.
If $Y_e^{(0)} > 1/2$, non-zero X_α decreases Y_e.

Non-zero X_α pushes Y_e to 1/2

Alpha effect

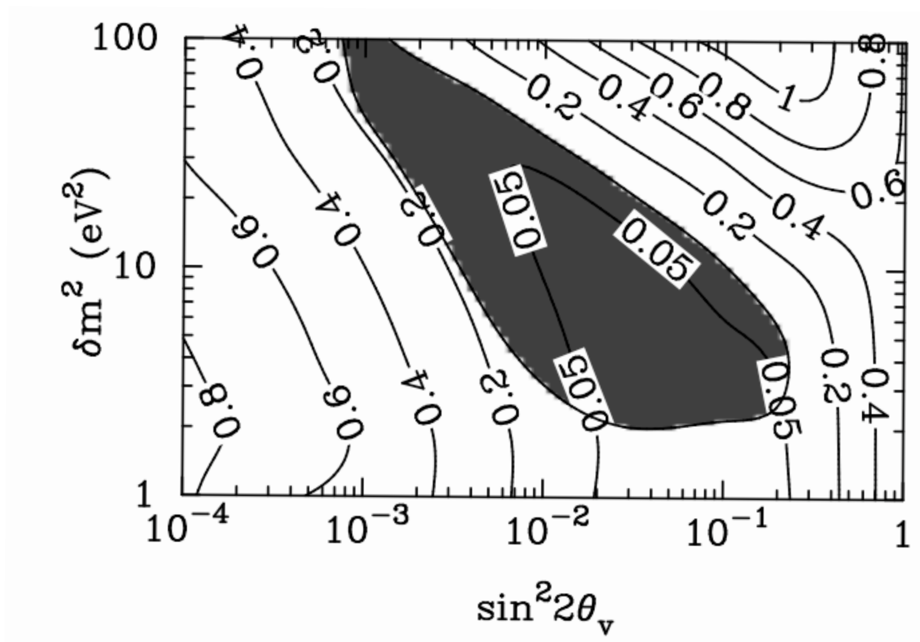
Fuller, McLaughlin, Meyer





Active-sterile mixing

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



Can neutrino magnetic moment help with the alpha problem?

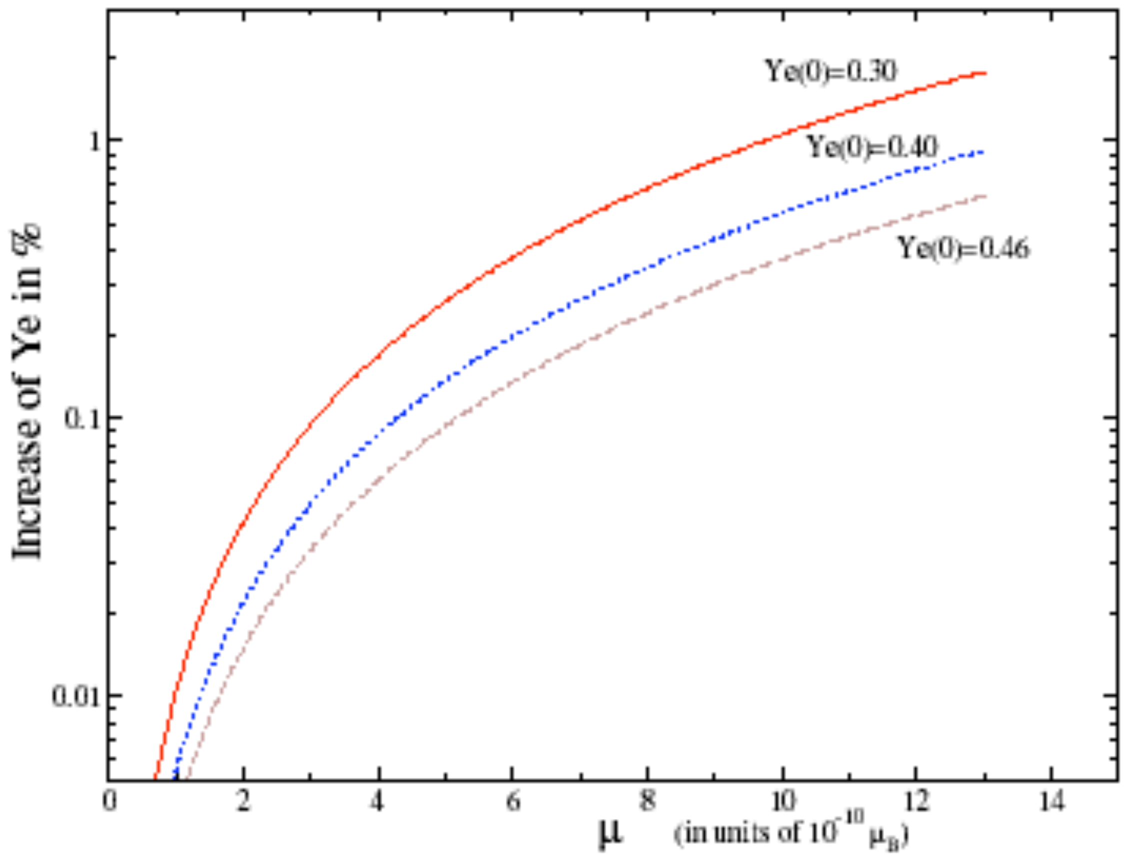
No!

For Dirac neutrinos

$\nu_{eL} \rightarrow$ sterile states

Both neutrinos and antineutrinos are reduced and the electron fraction increases!

Balantekin, Volpe, Welzel, JCAP 09 (2007).



4 km away from the neutron star surface

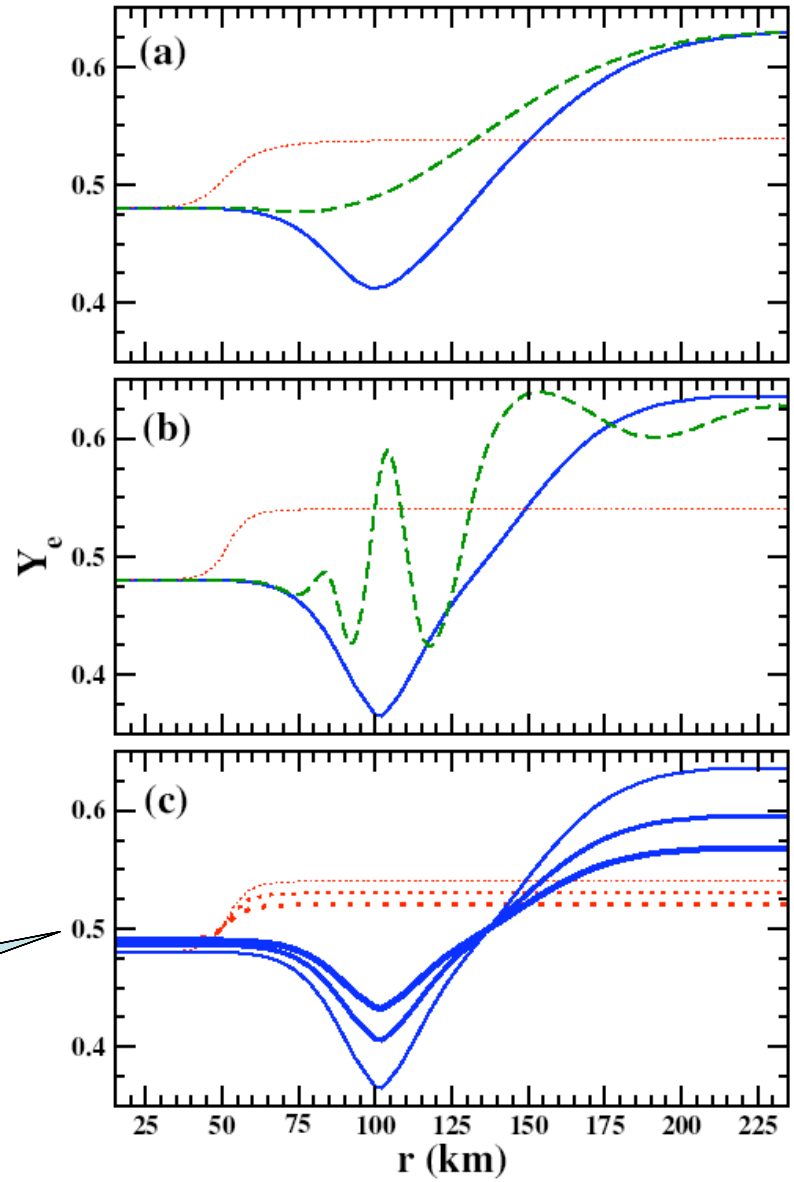
But…

One finds large-scale, collective flavor oscillations deep in the supernova envelope, which is sensitive to the value of θ_{13}.

Fuller, Qian, Raffelt, Duan, Sigl, Balantekin, Pehlivan, Carlson,….

ν luminosity:
L^{51} = 0.001, 0.1, 50

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



$\theta_{13} \sim \pi/10$

$\theta_{13} \sim \pi/20$

$\theta_{13} \sim \pi/20$
with α effect

Balantekin and Yuksel, New J. Phys. 7, 51 (2005)

- Core-collapse supernovae indeed emit neutrinos. It would nice to see a second one besides SN1987A.

- If you measure the neutrino spectra you learn a lot about the supernova mechanism. We need the time-dependence (neutronization burst, black-hole vs. neutron-star) and the flavor content of the neutrino spectra as well as the average energy and time-integrated luminosity (to understand the neutron star).

- Ability to observe supernovae in nearby galaxies would greatly improve the statistics.

- Diffuse supernova neutrinos give us a handle on the star-formation rate.

- Astrophysical extremes allow testing neutrino properties in ways that cannot be done elsewhere, e.g. ν-ν effect as an "emergent phenomenon".

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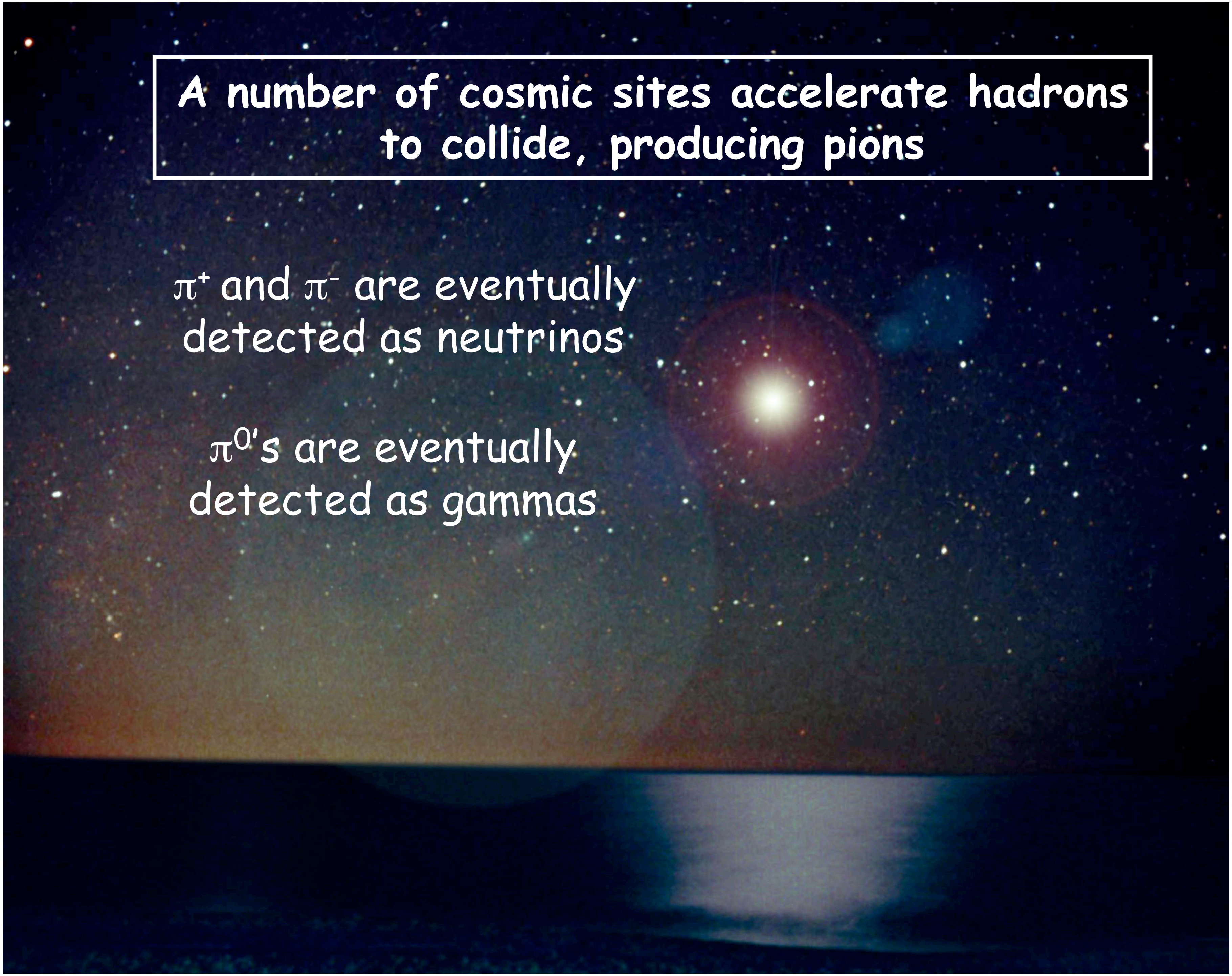
All of this also requires a detailed understanding of neutrino interactions!

• Ability t… laxies would greatly im…

• Diffuse s… pernova neu… le on the star-formation rate.

• Astrophysical extremes allow testing neutrino properties in ways that cannot be done elsewhere, e.g. ν-ν effect as an "emergent phenomenon".



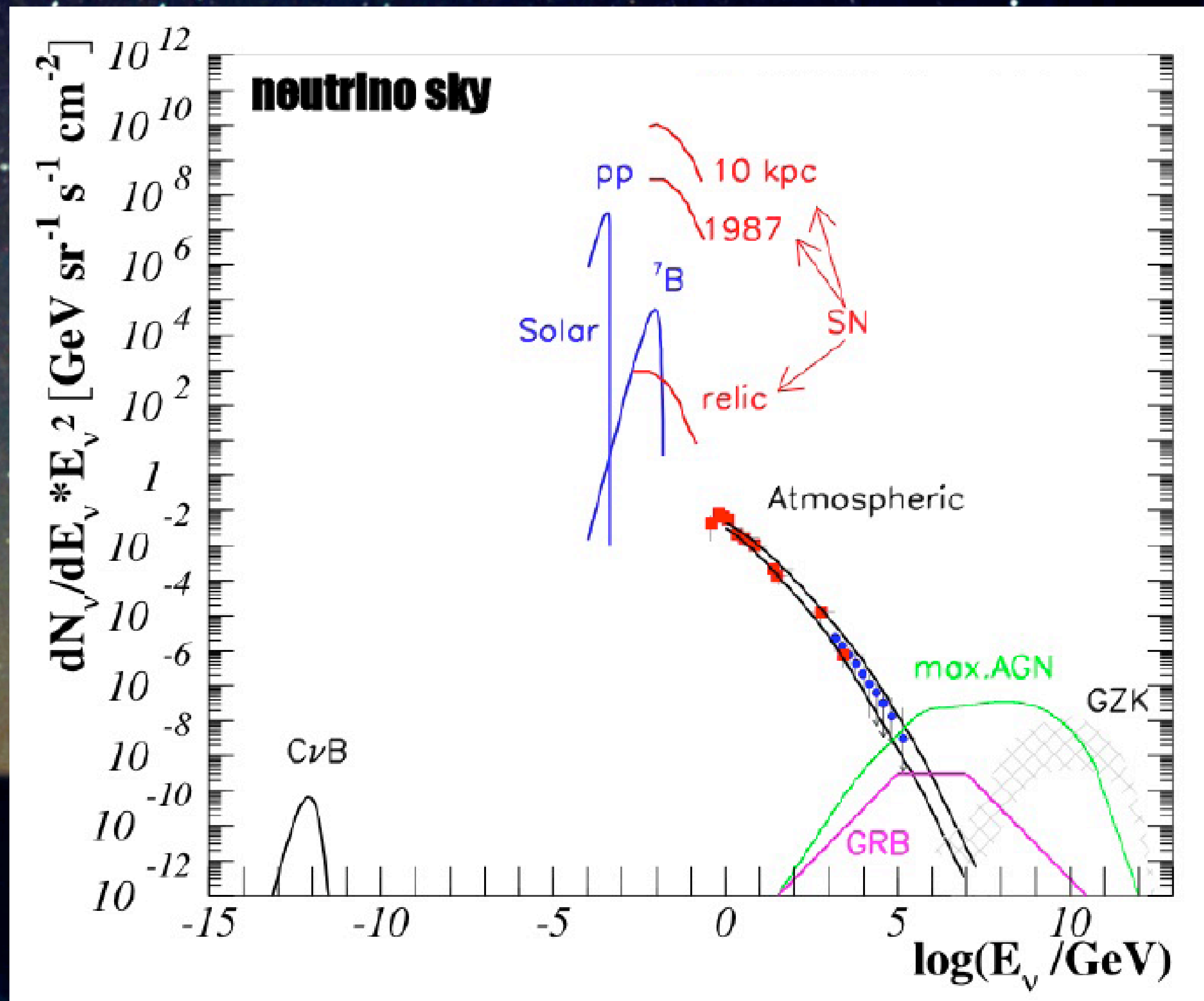
A number of cosmic sites accelerate hadrons to collide, producing pions

π^+ and π^- are eventually detected as neutrinos

π^0's are eventually detected as gammas

A number of cosmic sites accelerate hadrons to collide, producing pions.

π^+ and π^- are eventually detected as neutrinos



Assessment of such cosmic neutrino sources requires understanding neutrino interactions at exceedingly high energies!

Conclusions

•Neutrino cross sections are often a crucial input in understanding a broad range of phenomena ranging from stellar evolution to core-collapse supernovae and gamma-ray bursts.

•Understanding neutrino interactions from very low to very high energies are often crucial in interpreting the data from a variety of astrophysical sources.

• At low energies (supernova and tail of atmospheric neutrinos) calculational tools are still being developed. At very high energies physics beyond the Standard Model is very likely to contribute.

• At astrophysical sites novel forms of neutrino interactions may emerge such as collective behavior driven by neutrino-neutrino interactions.