# Neutrino properties and their astrophysical consequences

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# What do we know about neutrinos

- There are three different "active" flavors of neutrinos which interact with ordinary matter primarily via weak interactions. The states which participate in these interactions are linear combinations of mass eigenstates. The electromagnetic interactions of these active flavors are also non-vanishing, but seems to be strongly suppressed. .

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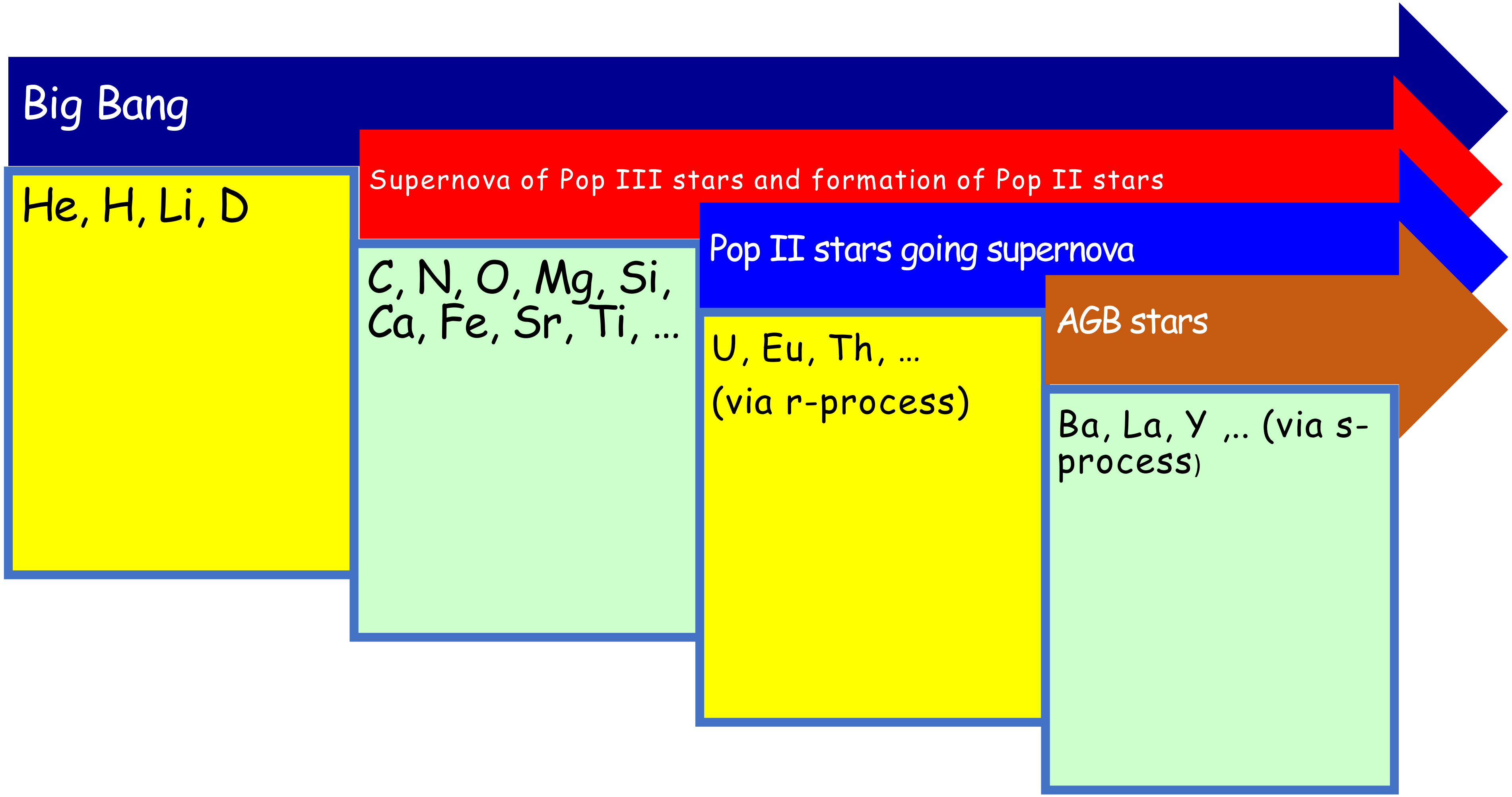
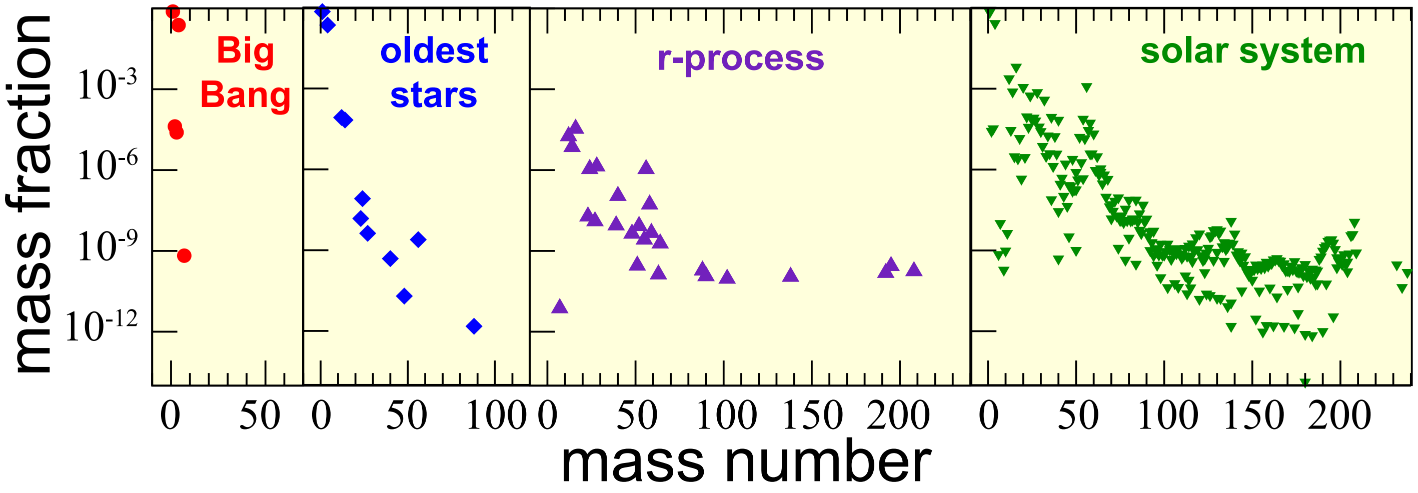
- There are hints of existence of additional neutral leptonic states which mix with the active flavors, but no conclusive evidence.
- There are a very large number of neutrinos leftover form the Big Bang. At least two of these flavors are cold, i.e., non-relativistic.
- Since all of the neutrino interactions are feeble, they can carry energy and entropy over astronomical distances. They can efficiently cool celestial objects and control the isospin in environments where elements are created.

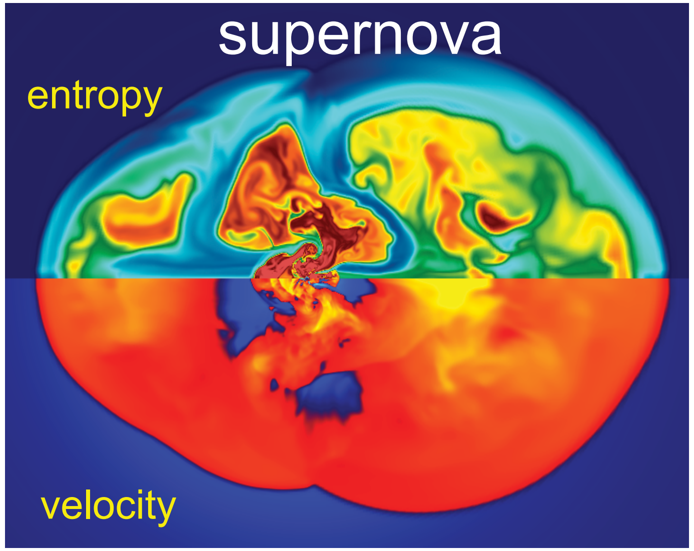
# Where chemical elements are made

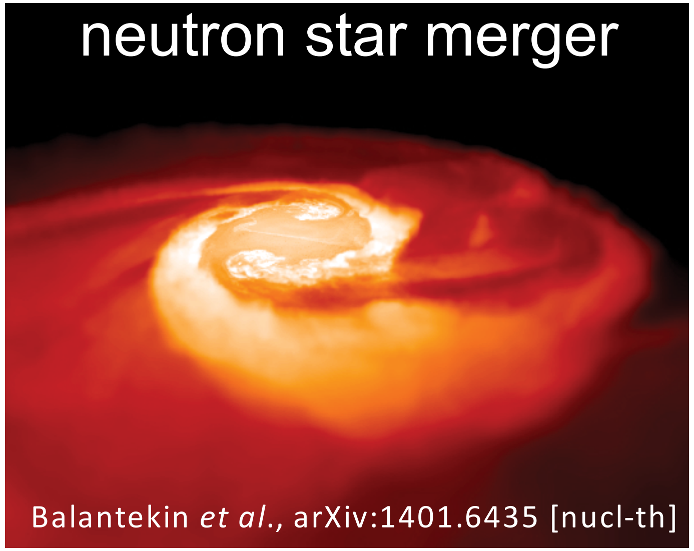



Neutrinos play a crucial role in many nucleosynthesis scenarios.

# The origin of elements



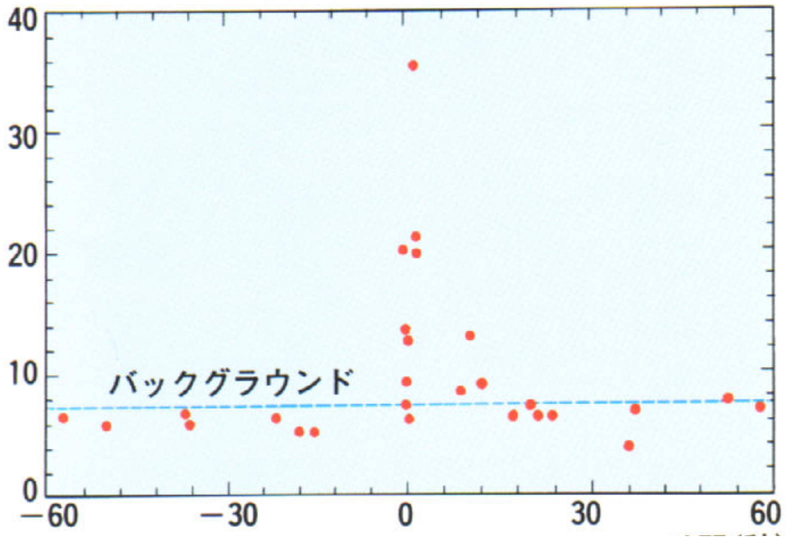



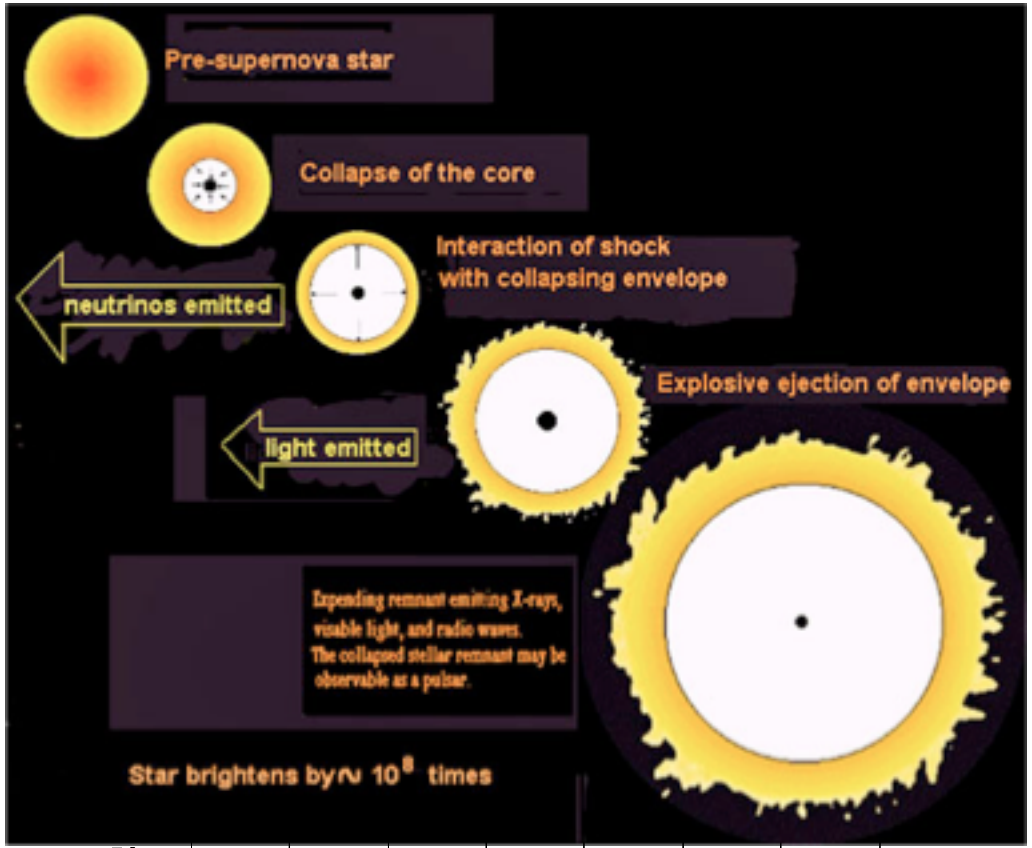



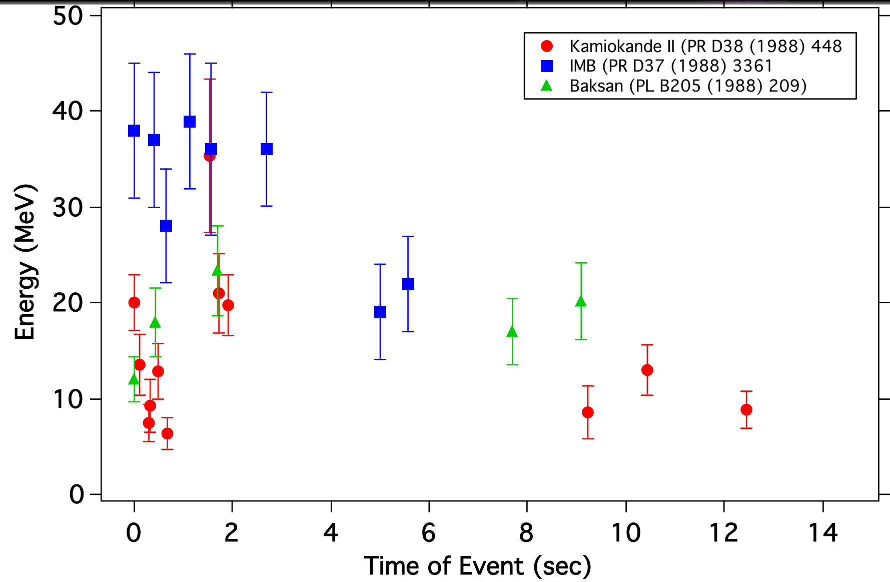

Neutrinos not only play a crucial role in the dynamics of these sites, but they also control the value of the electron fraction, the parameter determining the yields of the r-process.

Possible sites for the r-process

# Neutrinos from core-collapse supernovae



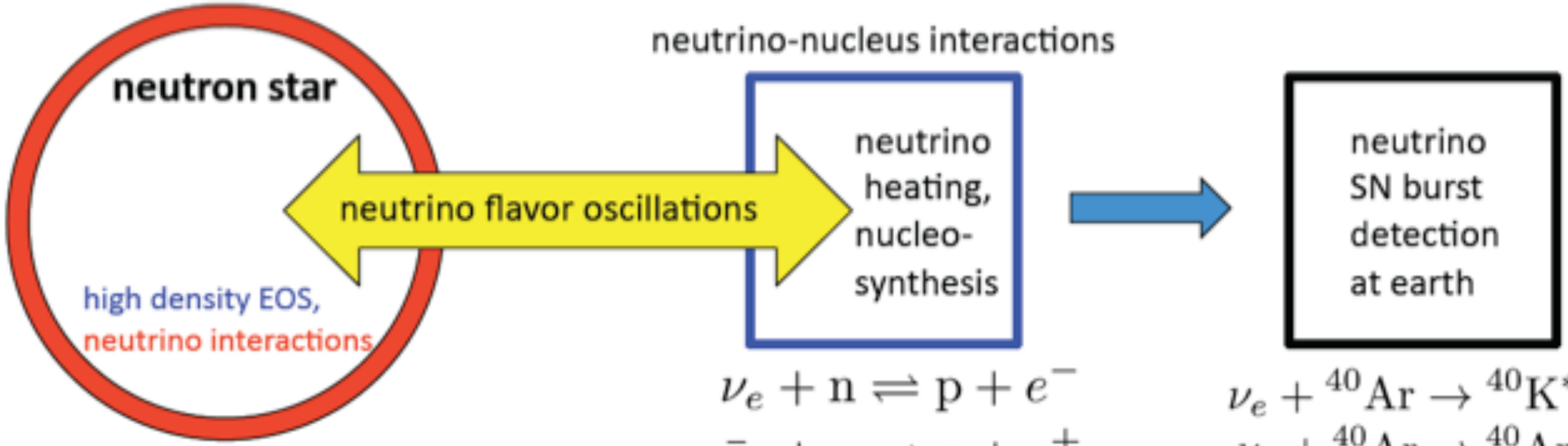




- $M_{prog} \geq 8\ M_{sun} \Rightarrow \Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV

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

# Understanding a core-collapse supernova and the nucleosynthesis it may host requires answers to a variety of questions!

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

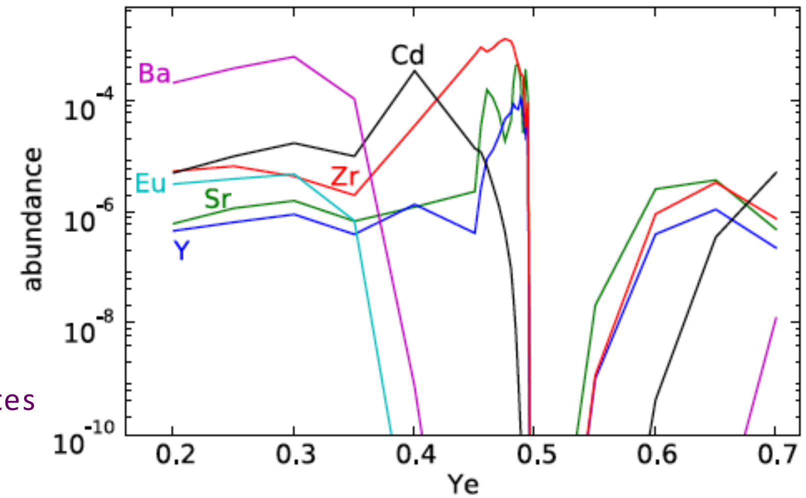



$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

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

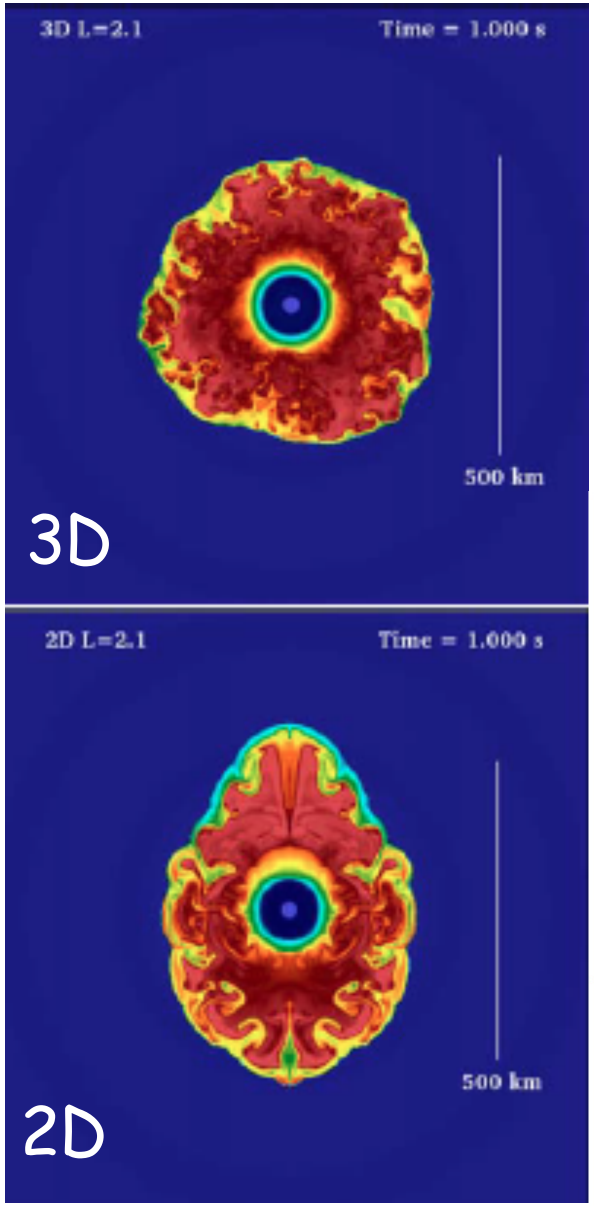
$$Y_e = \frac{N_p}{N_p + N_n} = \frac{1}{1 + \lambda_p / \lambda_n}$$

Arcones and Montes

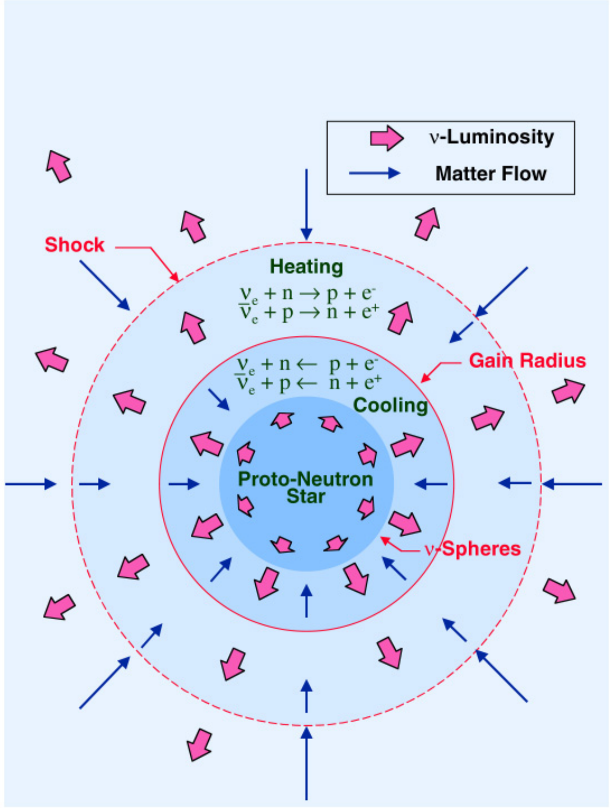


# Impact on supernova physics?

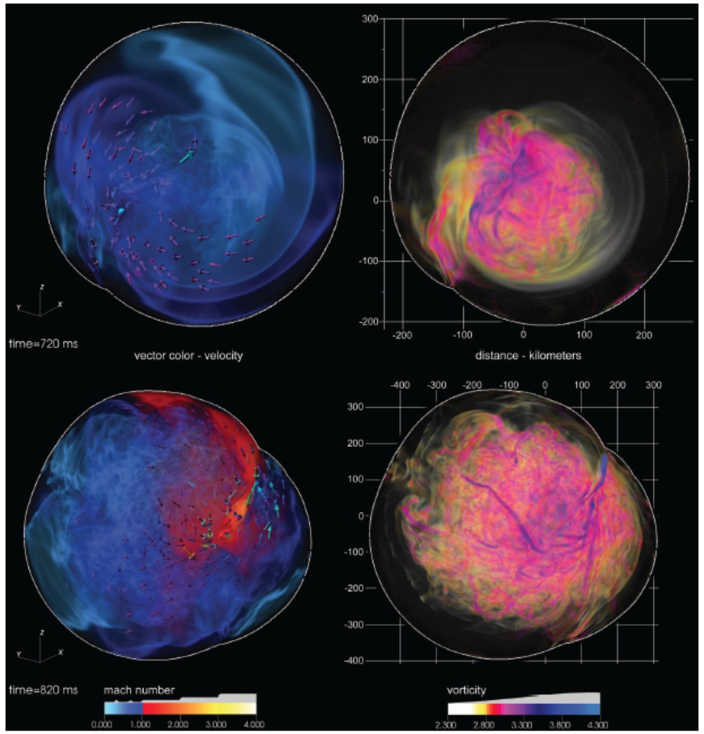
Development of 2D and 3D models for core-collapse supernovae: Complex interplay between turbulence, neutrino physics and thermonuclear reactions.

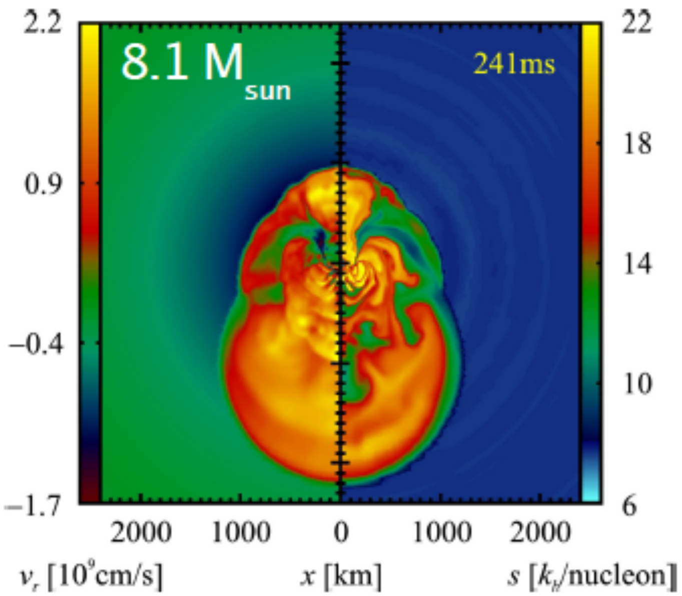



Princeton

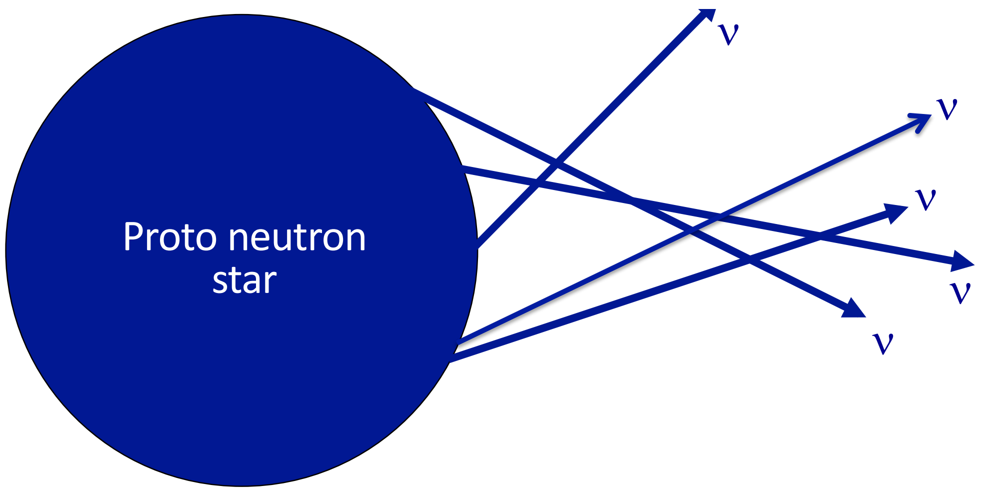



ORNL/UT




Munich




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!

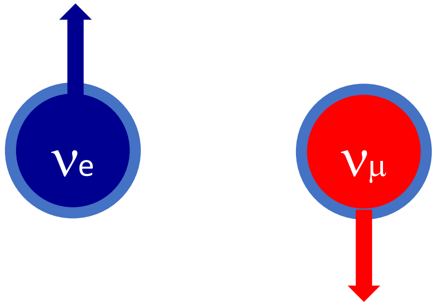
This necessitates including the effects of $\nu\nu$ interactions!

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

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").

## Neutrino flavor isospin

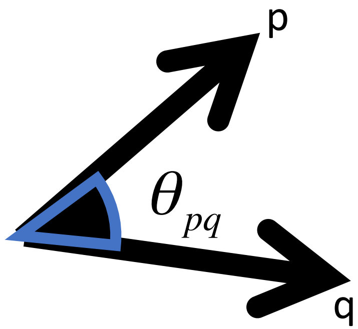



$$\hat{J}_+ = a_e^\dagger a_\mu \qquad \hat{J}_- = a_\mu^\dagger a_e$$

$$\hat{J}_0 = \frac{1}{2}\left(a_e^\dagger a_e - a_\mu^\dagger a_\mu\right)$$

These operators can be written in either mass or flavor basis

$$\hat{H}_{\nu\nu} = \frac{\sqrt{2}G_F}{V}\int dp\, dq\left(1-\cos\theta_{pq}\right)\vec{\mathbf{J}}_p \cdot \vec{\mathbf{J}}_q$$




$$\hat{H} = \int dp\left(\frac{\delta m^2}{2E}\vec{\mathbf{B}}\cdot\vec{\mathbf{J}}_p - \sqrt{2}G_F N_e \mathbf{J}_p^0\right) + \frac{\sqrt{2}G_F}{V}\int dp\, dq\left(1-\cos\theta_{pq}\right)\vec{\mathbf{J}}_p \cdot \vec{\mathbf{J}}_q$$

$$\vec{\mathbf{B}} = \left(\sin 2\theta,\ 0, -\cos 2\theta\right)$$

# What is the mean-field approximation?

$$\left[\hat{O}_1, \hat{O}_2\right] \cong 0$$

$$\hat{O}_1\hat{O}_2 \approx \hat{O}_1\left\langle \hat{O}_2 \right\rangle + \left\langle \hat{O}_1 \right\rangle \hat{O}_2 - \left\langle \hat{O}_1\hat{O}_2 \right\rangle$$

Expectation values should be calculated with a state $\left|\Psi\right\rangle$ chosen to satisfy:

$$\left\langle \hat{O}_1\hat{O}_2 \right\rangle = \left\langle \hat{O}_1 \right\rangle \left\langle \hat{O}_2 \right\rangle$$

This reduces the two-body problem to a one-body problem:

$$a^\dagger a^\dagger a a \Rightarrow \left\langle a^\dagger a \right\rangle a^\dagger a + \left\langle a^\dagger a^\dagger \right\rangle a a + \text{h.c.}$$

$$\hat{H}_{\nu\nu} = \frac{\sqrt{2}G_F}{V} \int dp\, dq \left(1 - \cos\theta_{pq}\right) \vec{\mathbf{J}}_p \cdot \vec{\mathbf{J}}_q \cong \frac{\sqrt{2}G_F}{V} \int dp\, dq \left(1 - \cos\theta_{pq}\right) \left\langle \vec{\mathbf{J}}_p \right\rangle \cdot \vec{\mathbf{J}}_q$$

# But one can go beyond the mean field approximation!

Single-angle approximation Hamiltonian:

$$H = \sum_p \frac{\delta m^2}{2p} J_p^0 + 2\mu \sum_{\substack{p,\,q \\ p \neq q}} \mathbf{J}_p \bullet \mathbf{J}_q$$

$$\mu = \frac{G_F}{\sqrt{2}V} \langle 1 - \cos\Theta \rangle$$

Eigenstates:

$$|x_i\rangle = \prod_{i=1}^N \sum_k \frac{J_k^\dagger}{\left(\delta m^2/2k\right) - x_i} |0\rangle$$

$$-\frac{1}{2\mu} - \sum_k \frac{j_k}{\left(\delta m^2/2k\right) - x_i} = \sum_{j \neq i} \frac{1}{x_i - x_j}$$

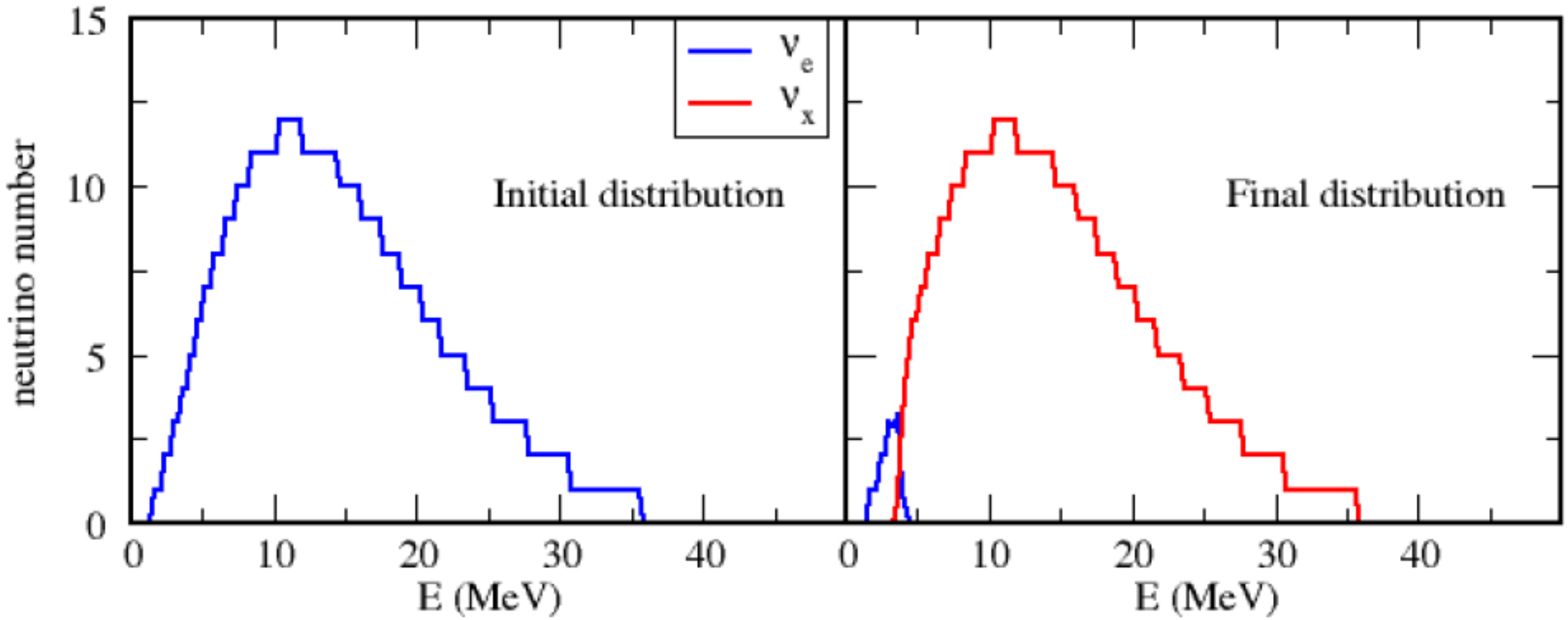
Bethe ansatz equations

Invariants:

$$h_p = J_p^0 + 2\mu \sum_{\substack{p,\,q \\ p \neq q}} \frac{\mathbf{J}_p \bullet \mathbf{J}_q}{\delta m^2 \left( \frac{1}{p} - \frac{1}{q} \right)}$$

Pehlivan, ABB, Kajino, & Yoshida
Phys. Rev. D 84, 065008 (2011)

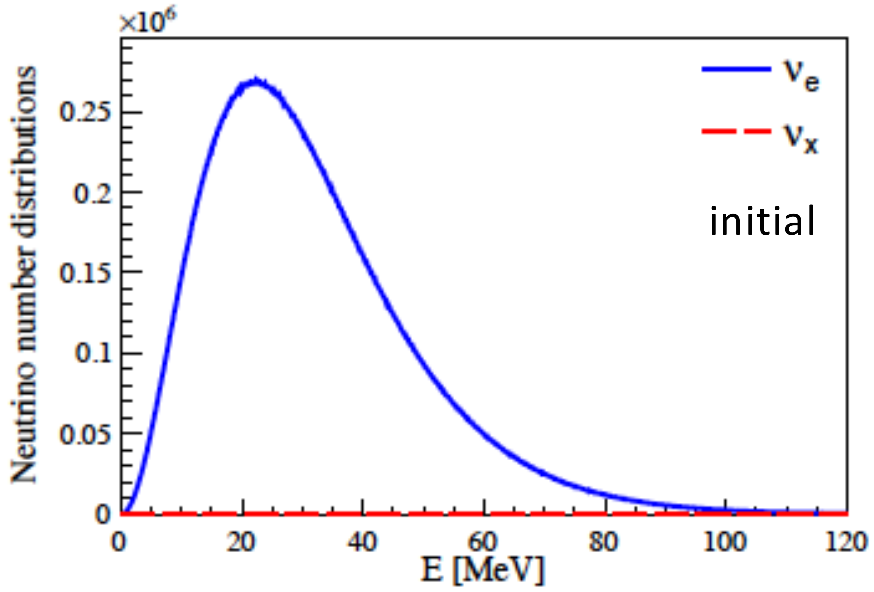
# Away from the mean-field: First adiabatic solution of the *exact* many-body Hamiltonian

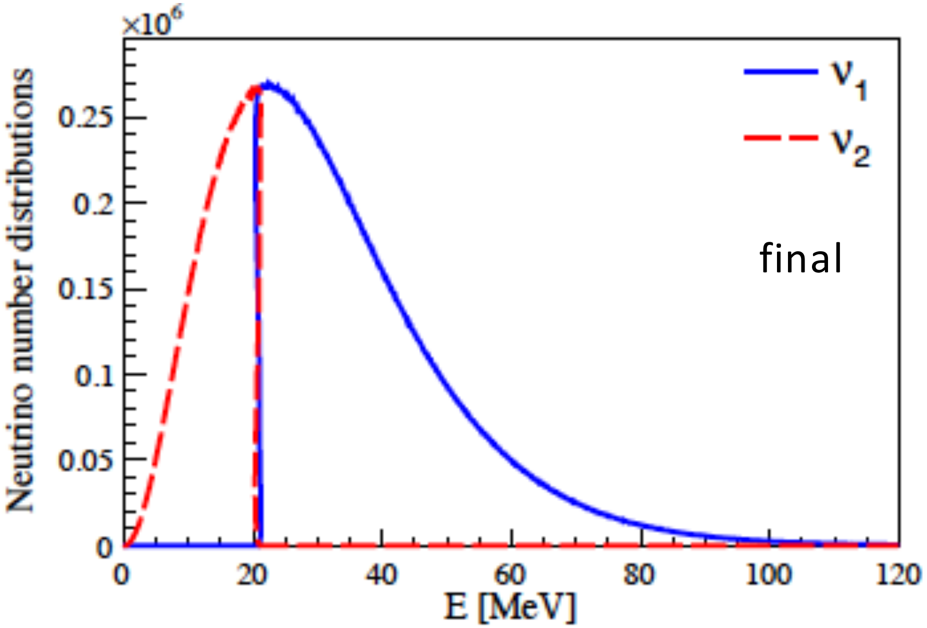



- Solutions of the Bethe ansatz equations for 250 neutrinos. Same behavior as the mean-field.
- Two flavors only
- Inverted hierarchy, no matter effect

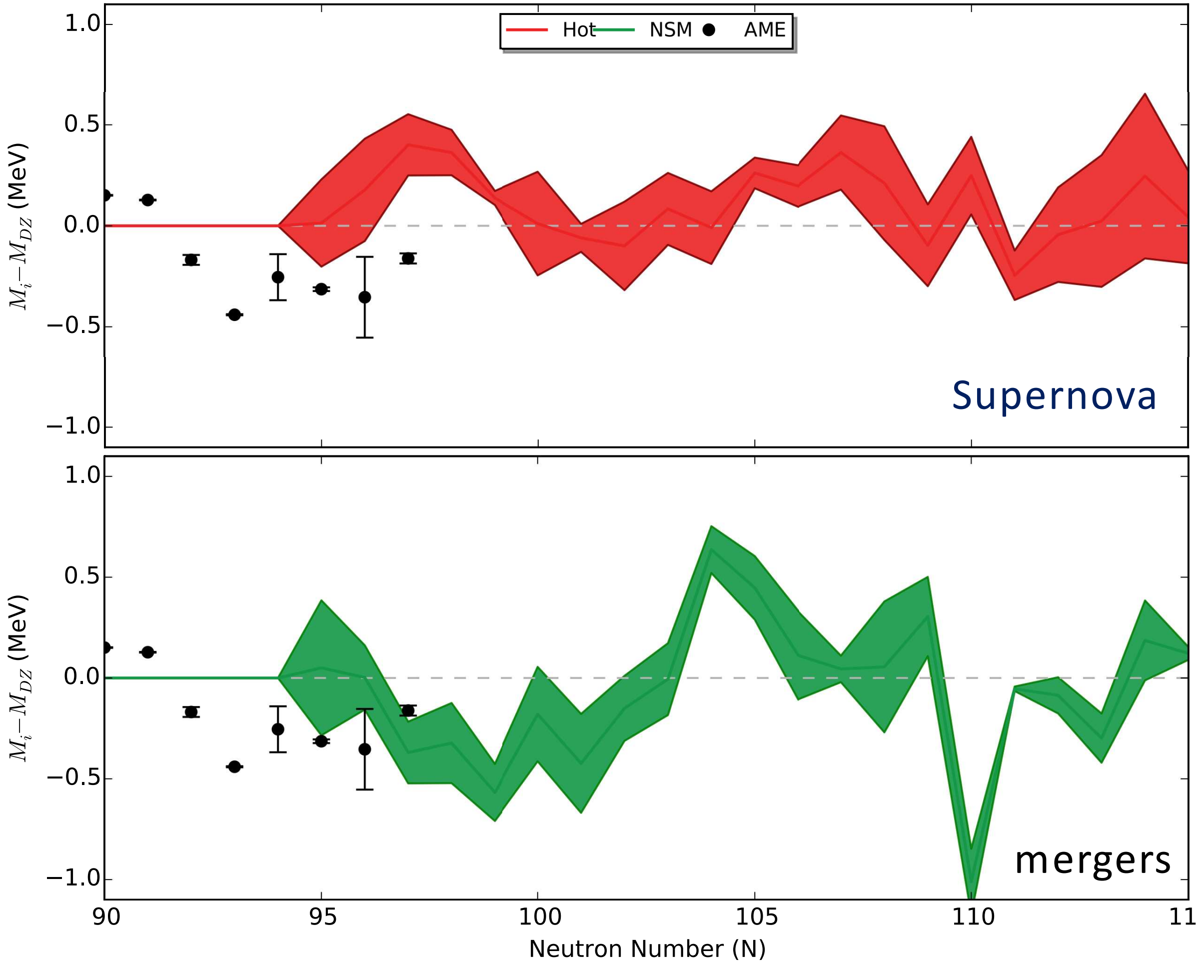
2015

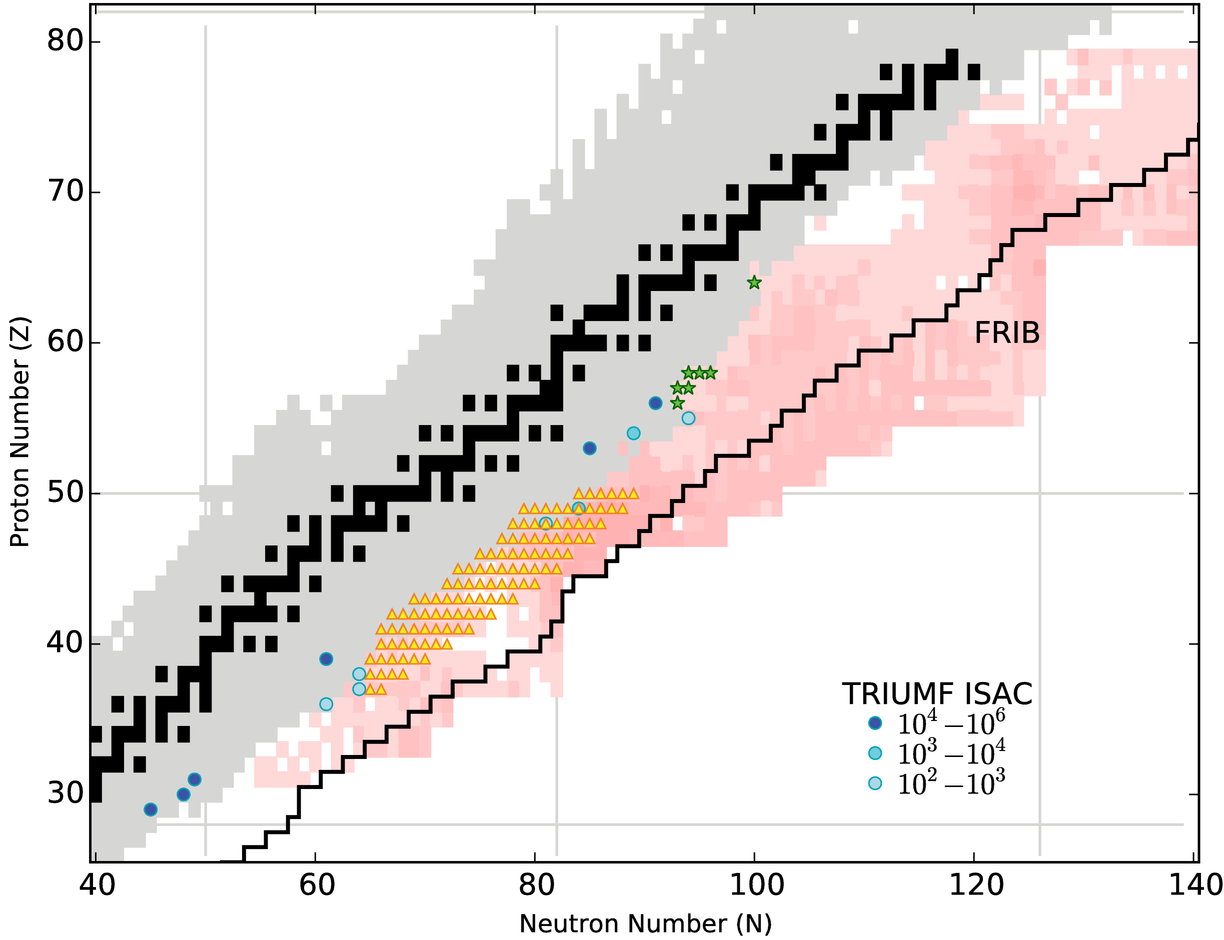
Adiabatic evolution of an initial thermal distribution (T = 10 MeV) of electron neutrinos. $10^8$ neutrinos distributed over 1200 energy bins with solar neutrino parameters and normal hierarchy.



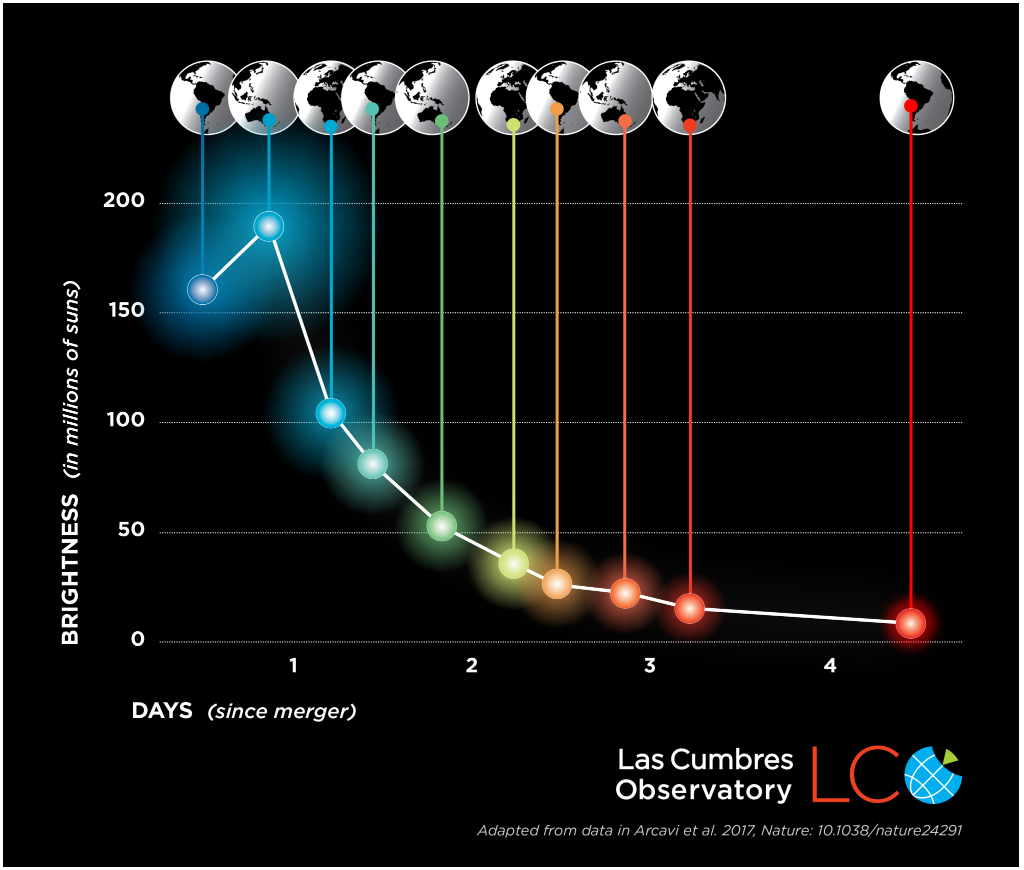




Birol, Pehlivan, Balantekin, Kajino
arXiv:1805.11767

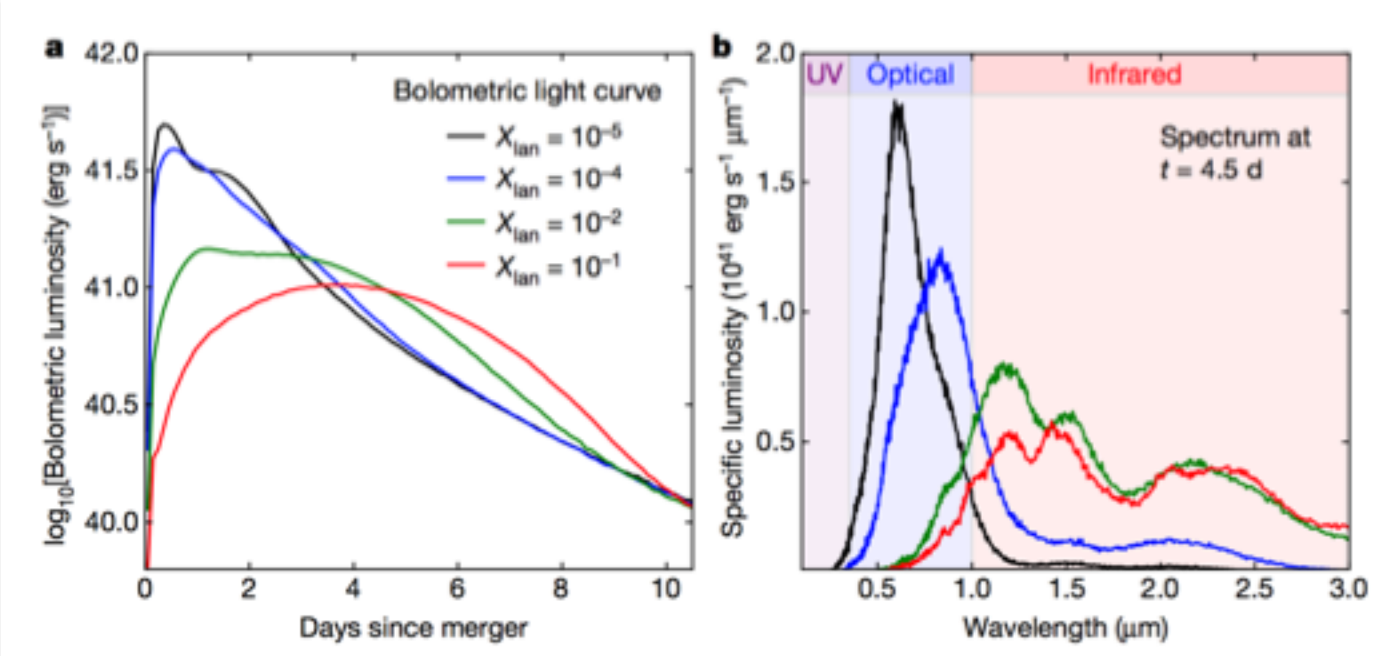



The predictions of masses required for the r-process are different for supernovae and mergers; but both are within reach of radioactive beams




# Recently observed merger event suggests lanthanides produced via r-process in this event



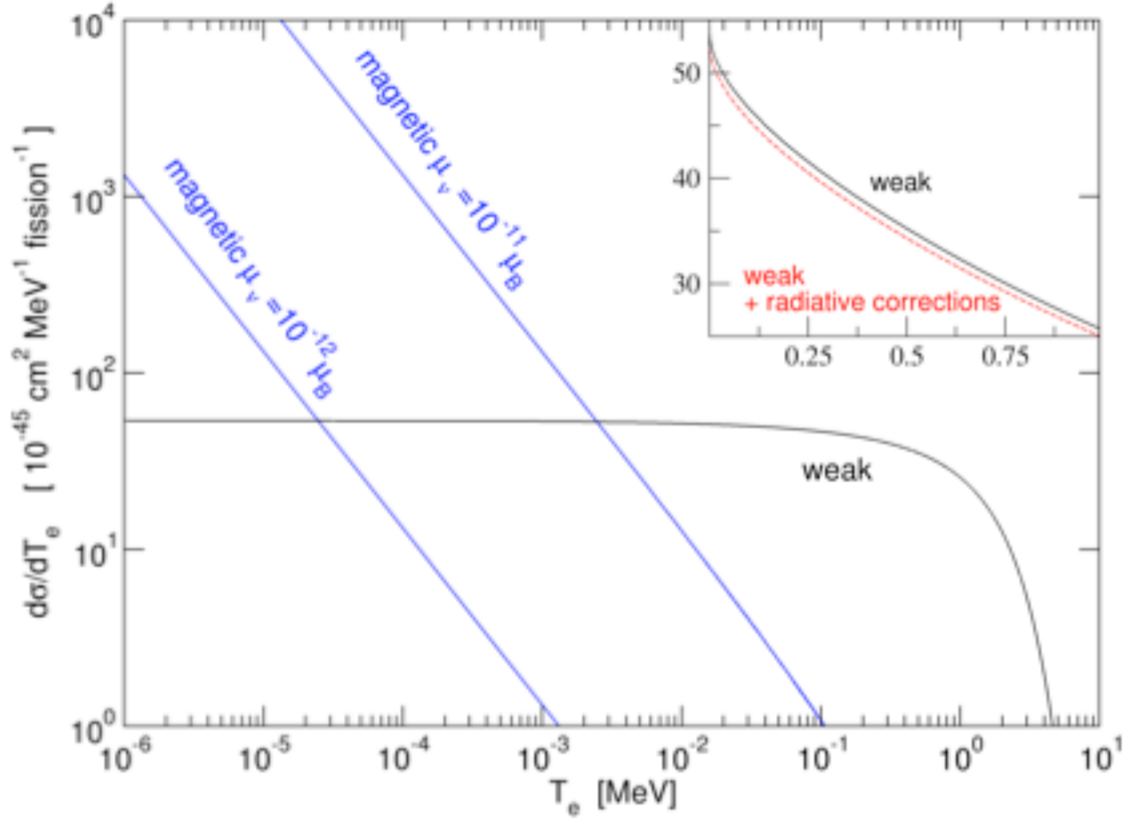

Kasen et al.

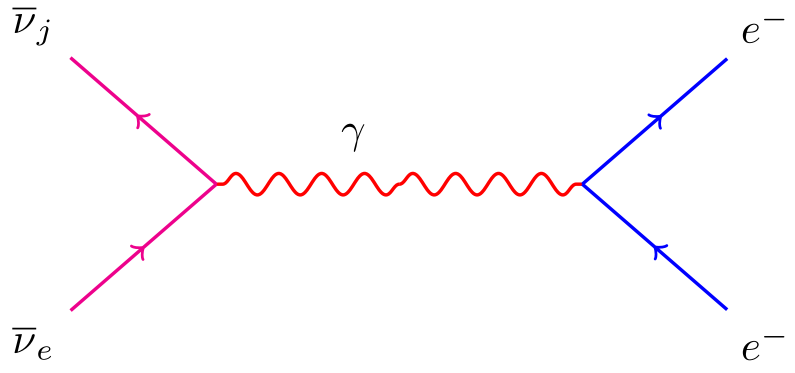
$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}\right]$$ ← weak

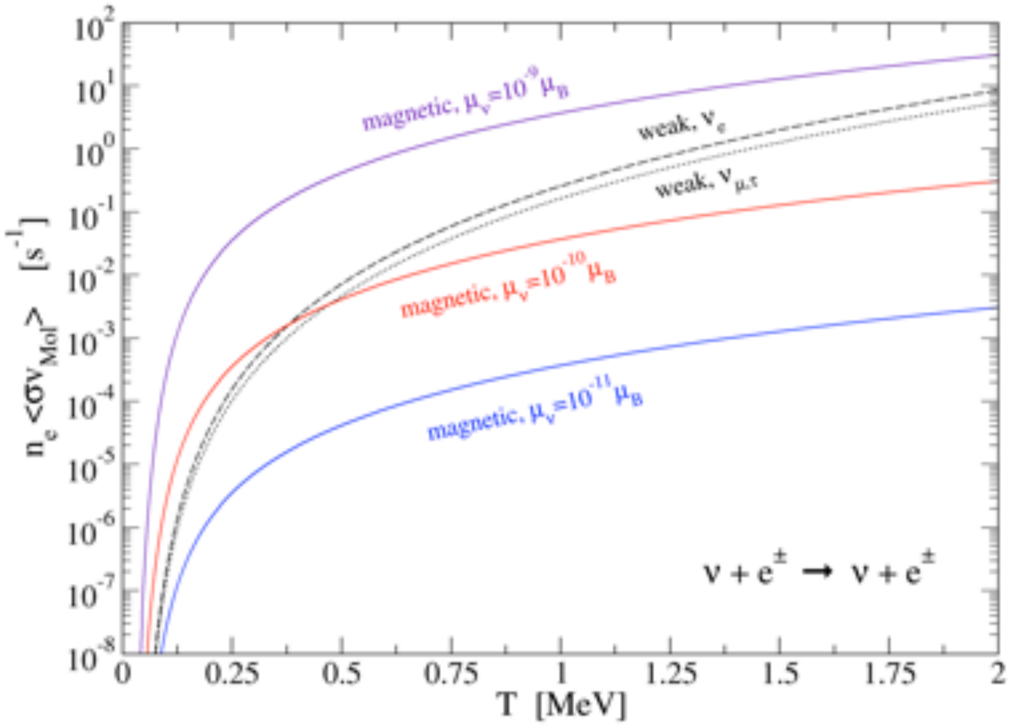
$$+ \frac{\pi\alpha^2\mu^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$ ← magnetic

$$g_\nu = 2\sin^2\theta_W + 1/2$$

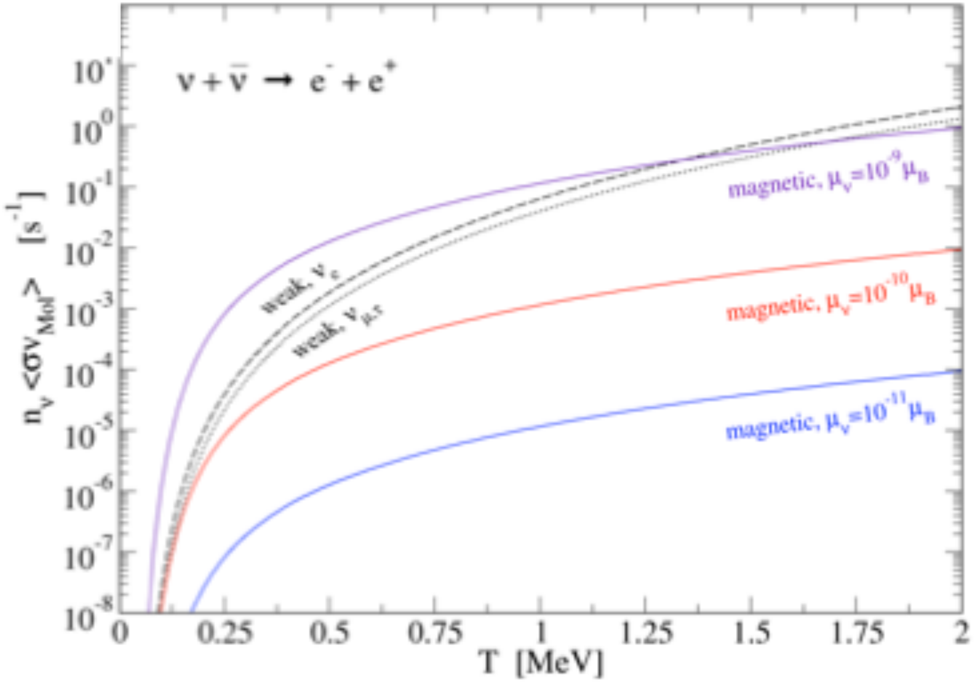
$$g_A = \begin{cases} +1/2 & \text{for electron neutrinos} \\ -1/2 & \text{for electron antineutrinos} \end{cases}$$



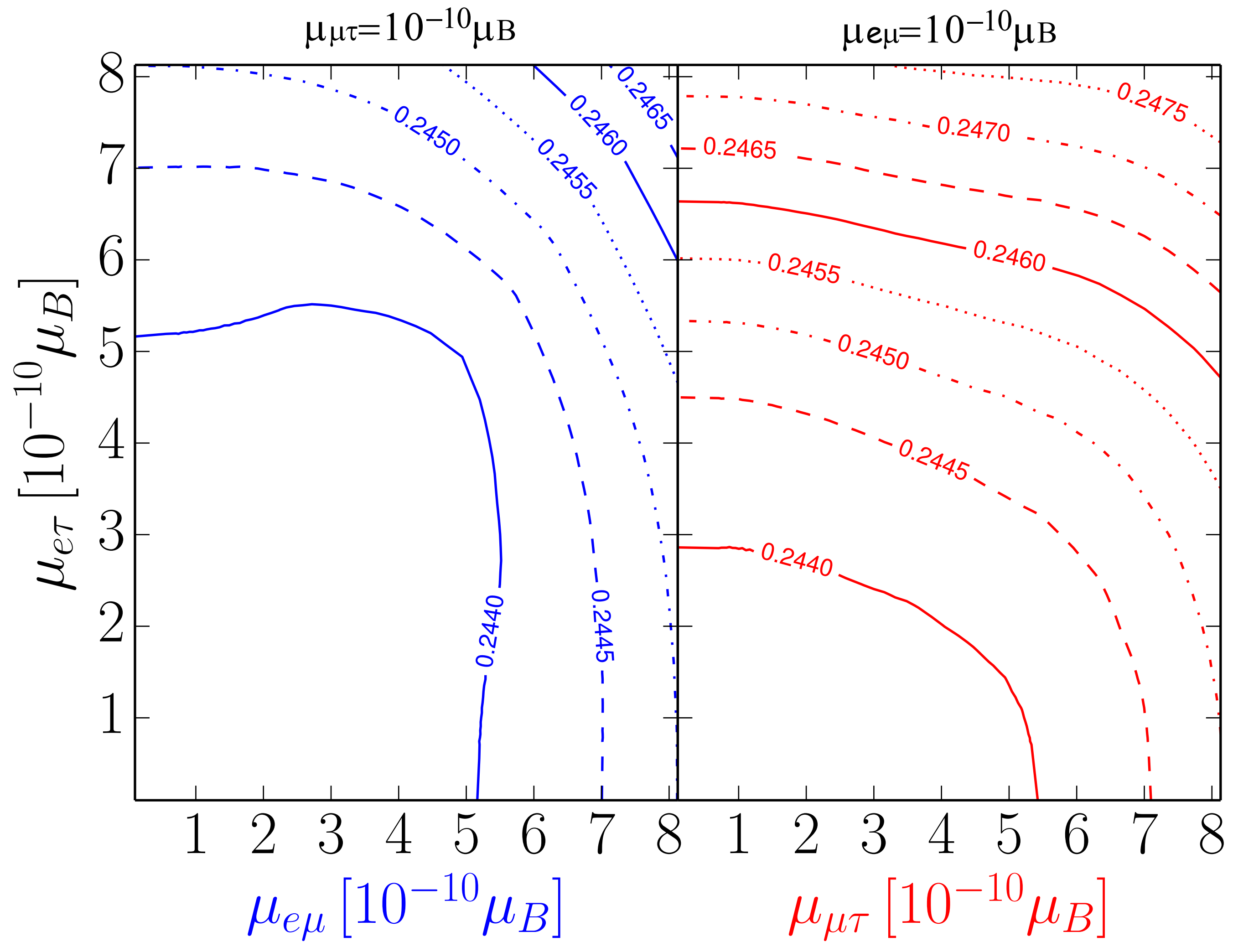



The effect of the neutrino magnetic moment on neutrino decoupling in the BBN epoch

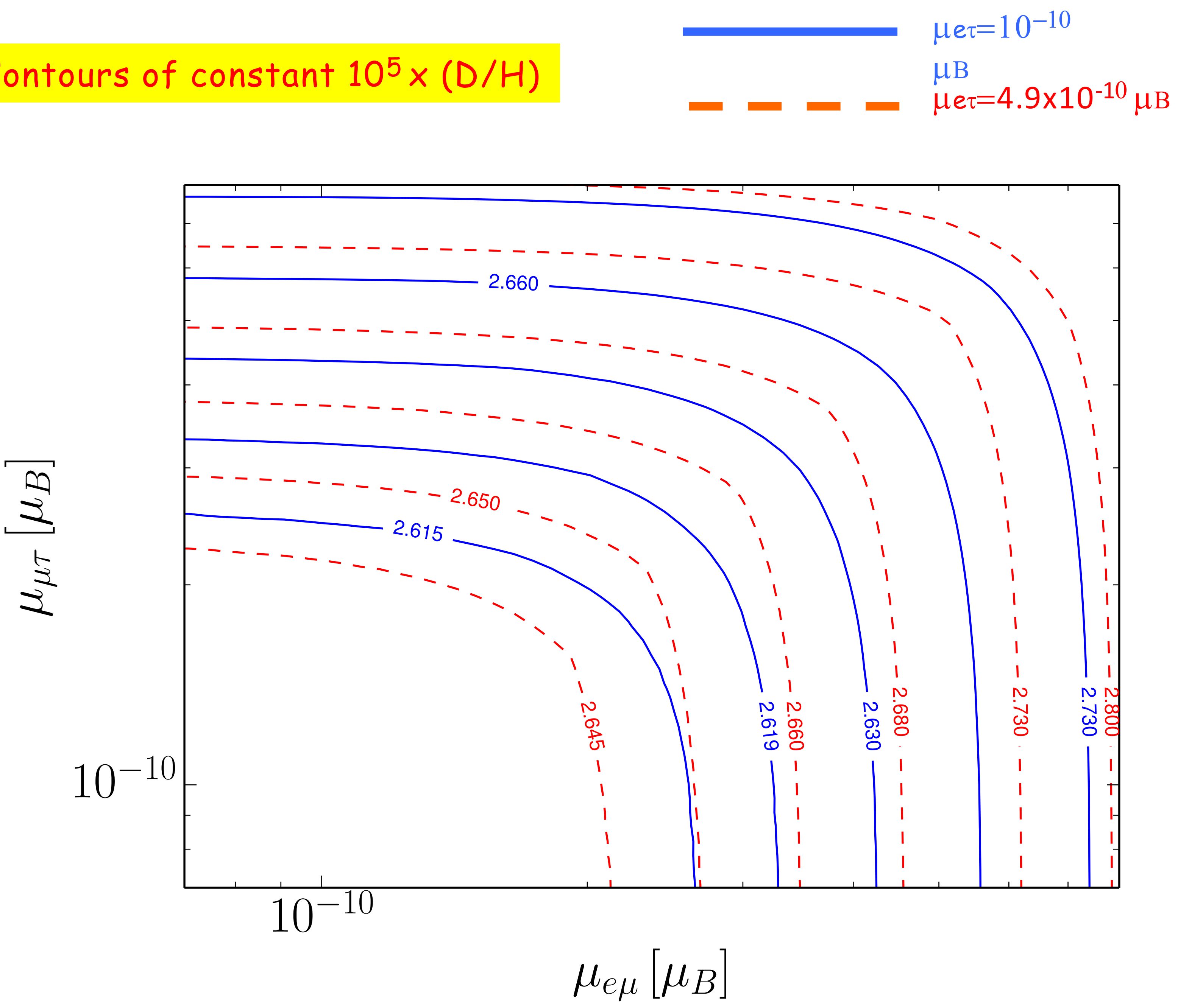



Vassh, Grohs, Balantekin, Fuller,
Phys. Rev. **D 92,** 125020 (2015)

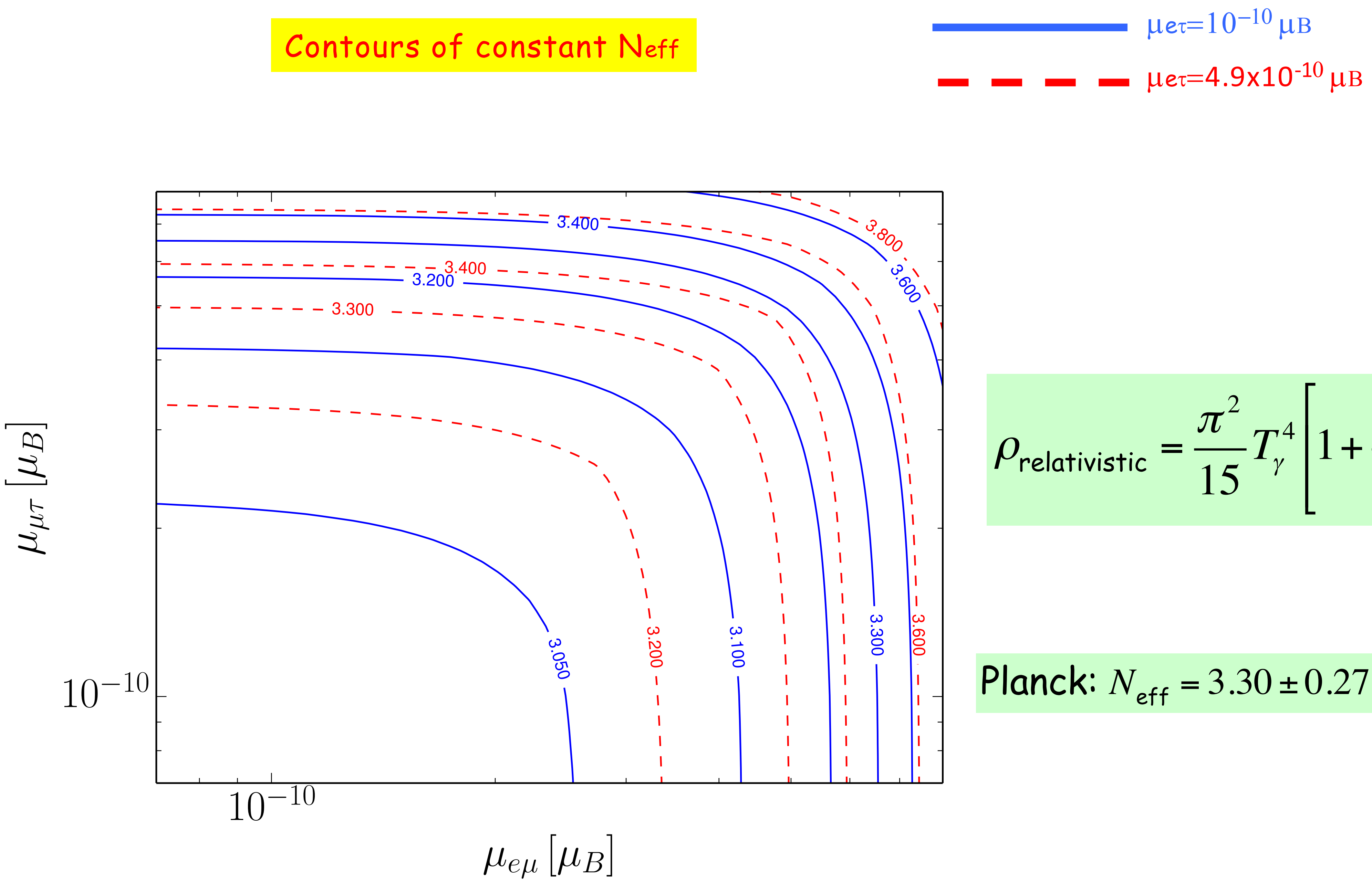
## Contours of constant $Y_P$



## Contours of constant $10^5 \times$ (D/H)



# Contours of constant Neff

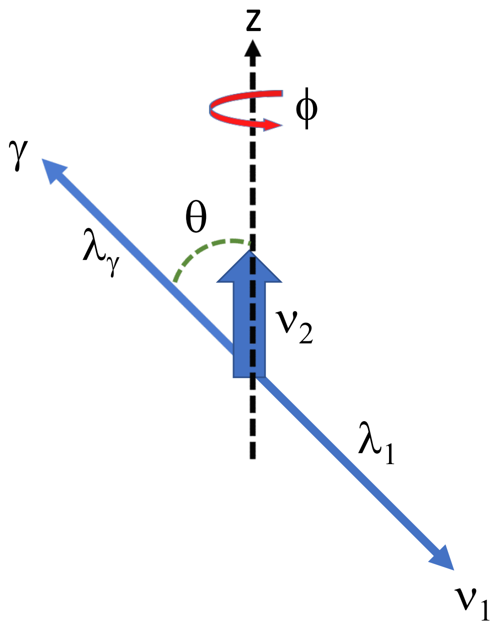



$$\rho_{\text{relativistic}} = \frac{\pi^2}{15} T_\gamma^4 \left[ 1 + \frac{7}{8} N_{\text{effective}} \left( \frac{4}{11} \right)^{4/3} \right]$$

Planck: $N_{\text{eff}} = 3.30 \pm 0.27 \quad \Rightarrow \quad \mu \leq 6 \times 10^{-10} \mu_B$

# MAJORANA NEUTRINO DECAY

$$\nu_2^{(M)} \rightarrow \nu_1^{(M)} + \gamma$$



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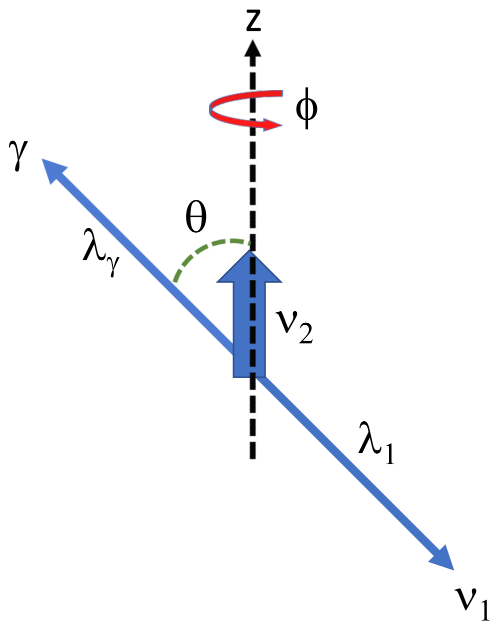


**Angular momentum conservation in helicity formalism**

$$\text{Amplitude} = D^{j*}_{m,\lambda}(\phi,\theta,-\phi)A_{\lambda_1,\lambda_\gamma}\ ,|\lambda_\gamma-\lambda_1|\le j = 1/2$$

**$\lambda_\gamma = +1 \Rightarrow \lambda_1 = +1/2$ and $\lambda = +1/2$**

$$\langle\gamma(\mathbf{p},+1)\,\nu_1(-\mathbf{p},+1/2)|H_{\rm EM}|\nu_2(0,+1/2)\rangle = d^{1/2}_{+1/2,+1/2}A_{+1,+1/2}$$

**$\lambda_\gamma = -1 \Rightarrow \lambda_1 = -1/2$ and $\lambda = -1/2$**

$$\langle\gamma(\mathbf{p},-1)\,\nu_1(-\mathbf{p},-1/2)|H_{\rm EM}|\nu_2(0,+1/2)\rangle = d^{1/2}_{+1/2,-1/2}A_{-1,-1/2}$$


A.B. Balantekin and B. Kayser, arXiv:1805.00922
A.B. Balantekin, A. De Gouvea, and B. Kayser, in prep.

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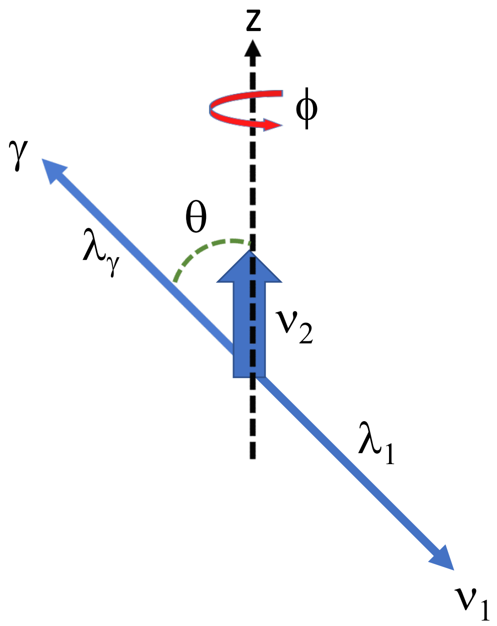


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$$\text{Amplitude} = D^{j*}_{m,\lambda}(\phi, \theta, -\phi) A_{\lambda_1, \lambda_\gamma} \;, |\lambda_\gamma - \lambda_1| \leq j = 1/2$$

+

**Impose Invariance under CPT transformation ($\zeta$)**

$$\begin{aligned} & \langle \gamma(\mathbf{p}, \lambda_\gamma)\, \nu_1(-\mathbf{p}, \lambda_1) | H_{\text{EM}} | \nu_2(0, +1/2) \rangle \\ = & \langle \zeta H_{\text{EM}} \zeta^{-1} \zeta[\nu_2(0, +1/2)] | \zeta[\gamma(\mathbf{p}, \lambda_\gamma)\, \nu_1(-\mathbf{p}, \lambda_1)] \rangle \\ = & \langle \gamma(\mathbf{p}, -\lambda_\gamma)\, \nu_1(-\mathbf{p}, -\lambda_1) | H_{\text{EM}} | \nu_2(0, -1/2) \rangle^* \end{aligned}$$

$$d^{1/2}_{+1/2,+1/2} A_{+1,+1/2} = d^{1/2}_{-1/2,-1/2} A^*_{-1,-1/2} \Rightarrow A_{+1,+1/2} = A^*_{-1,-1/2} \equiv A$$


A.B. Balantekin and B. Kayser, ArXiv: 1805.00922

A.B. Balantekin, A. De Gouvea, and B. Kayser, in prep.

**Decay rate into photons with helicity $\lambda_\gamma = +1$**

$$\frac{d\Gamma_+}{d\cos\theta} = \left(d^{1/2}_{+1/2,+1/2}\right)^2 |A_{+1,+1/2}|^2 = \cos^2\frac{\theta}{2}|A_{+1,+1/2}|^2$$

**Decay rate into photons with helicity $\lambda_\gamma = -1$**

$$\frac{d\Gamma_-}{d\cos\theta} = \left(d^{1/2}_{+1/2,-1/2}\right)^2 |A_{-1,-1/2}|^2 = \sin^2\frac{\theta}{2}|A_{-1,-1/2}|^2$$

⇓

**Total decay rate of a spin-up Majorana neutrino**

$$\frac{d\Gamma}{d\cos\theta} = \cos^2\frac{\theta}{2}|A_{+1,+1/2}|^2 + \sin^2\frac{\theta}{2}|A_{-1,-1/2}|^2 = |A|^2$$

### Total decay rate of a spin-up Majorana neutrino

$$\frac{d\Gamma}{d\cos\theta} = \cos^2\frac{\theta}{2}|A_{+1,+1/2}|^2 + \sin^2\frac{\theta}{2}|A_{-1,-1/2}|^2 = |A|^2$$

### Decay rate of Dirac Neutrino

$$\frac{d\Gamma}{d\cos\theta} \propto (1+\cos\theta)$$

This is a generic behavior. If a heavy neutrino is discovered, the angular distributions of its decays could tell us if those neutrinos are Dirac or Majorana.

A.B. Balantekin, A. De Gouvea, and B. Kayser, in prep.


감사합니다