Neutrino Oscillations in Extreme Astrophysical Laboratories: Insights from GRBs

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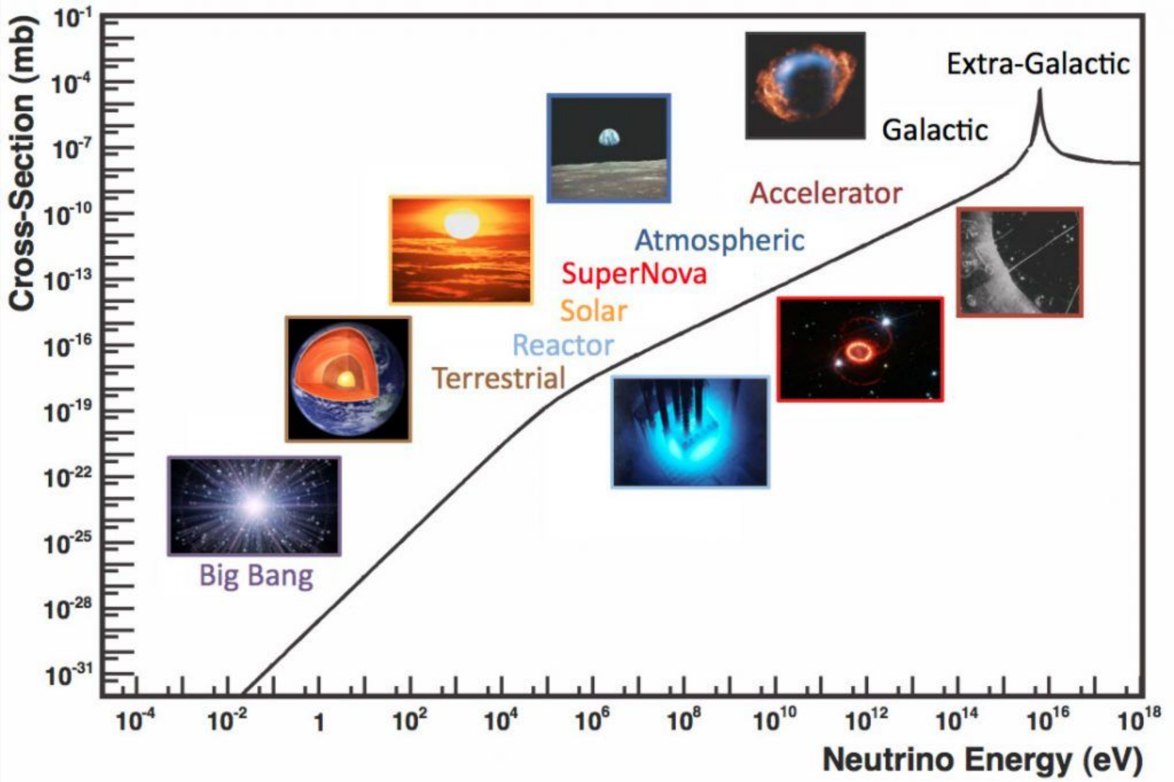
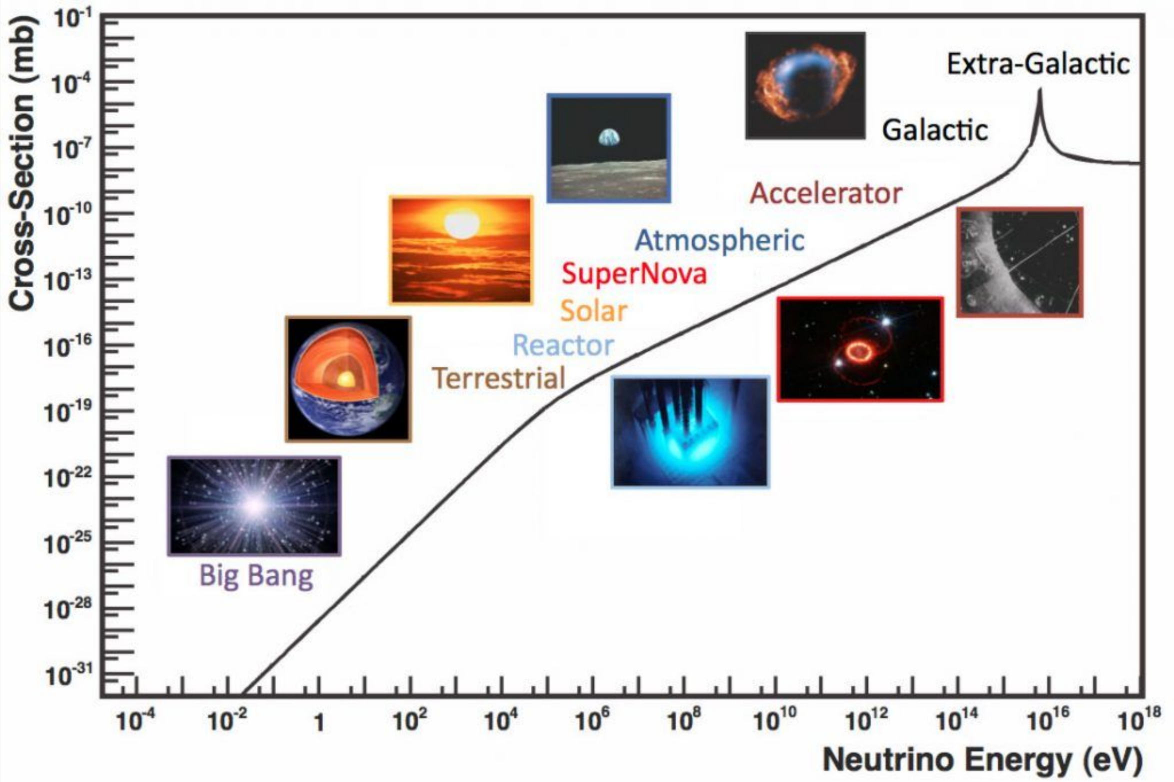


Source: neutrinos.fnal.gov/types/energies

Neutrino sources

- Stars
- Atmosphere
- Accelerators
- Nuclear reactors
- Extragalactic sources:

  AGN, SN, GRB, CCO, etc.



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GRB's progenitors

Neutrino oscillation

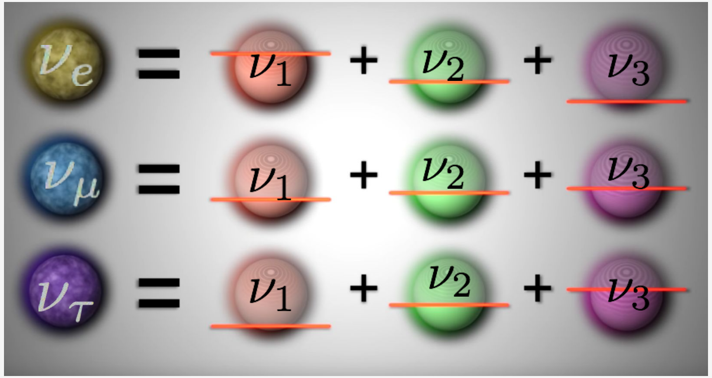
- Neutrinos comes in three flavors
- Each flavor is a superposition of the mass eigenstates

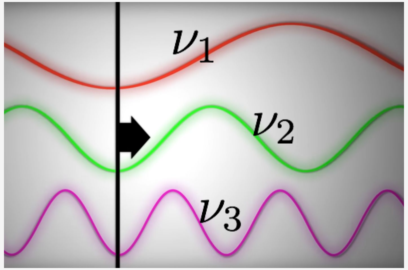
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}\,|\nu_i\rangle\,; \quad \alpha = e, \mu, \tau$$

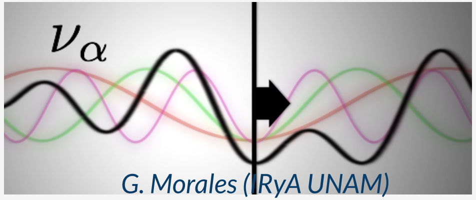
- Nine allowed transitions; Six independent
- Neutrinos are relativistic particles

Flavor states

Mass states







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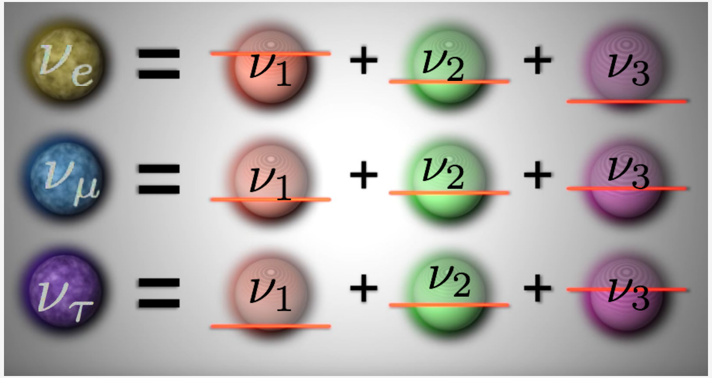
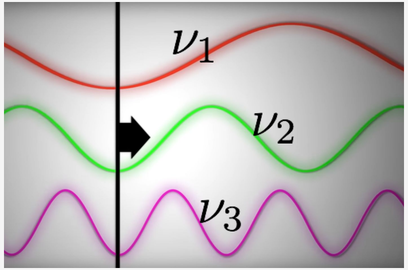
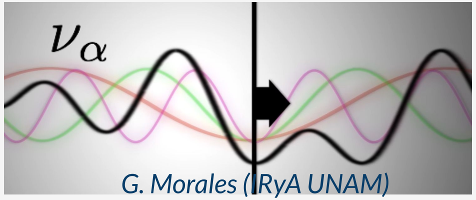
$$P_{\alpha\rightarrow\beta}(t) = |A_{\alpha\rightarrow\beta}(t)|^2 = \langle \nu_\beta | \nu_\alpha \rangle^2$$

Flavor states

Mass states







Neutrino oscillation

- Vacuum

$$P_{\alpha\beta}(E_\nu, L, \theta, \Delta m^2)$$

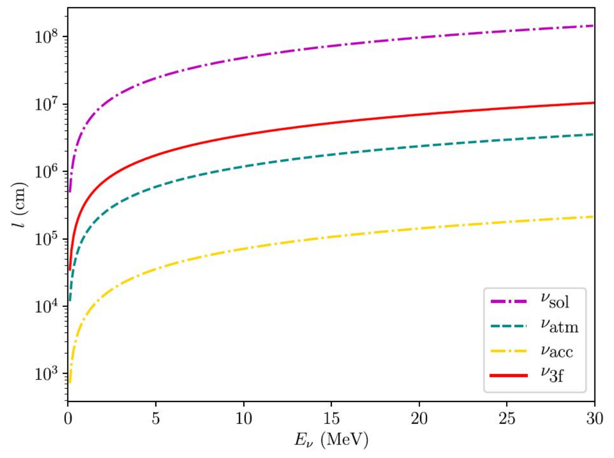
~MeV

Known in experiments

Extragalactic

$$L >> L_{\rm osc}$$

$$L_{\rm osc} = \frac{4\pi E_\nu}{\Delta m^2_{ij}}$$



Neutrino oscillation

- **Vacuum**

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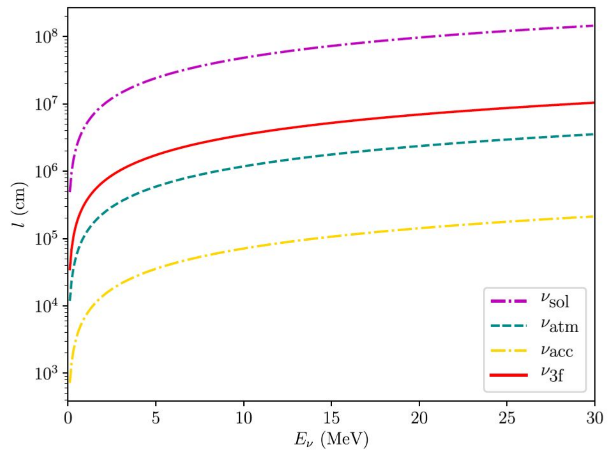
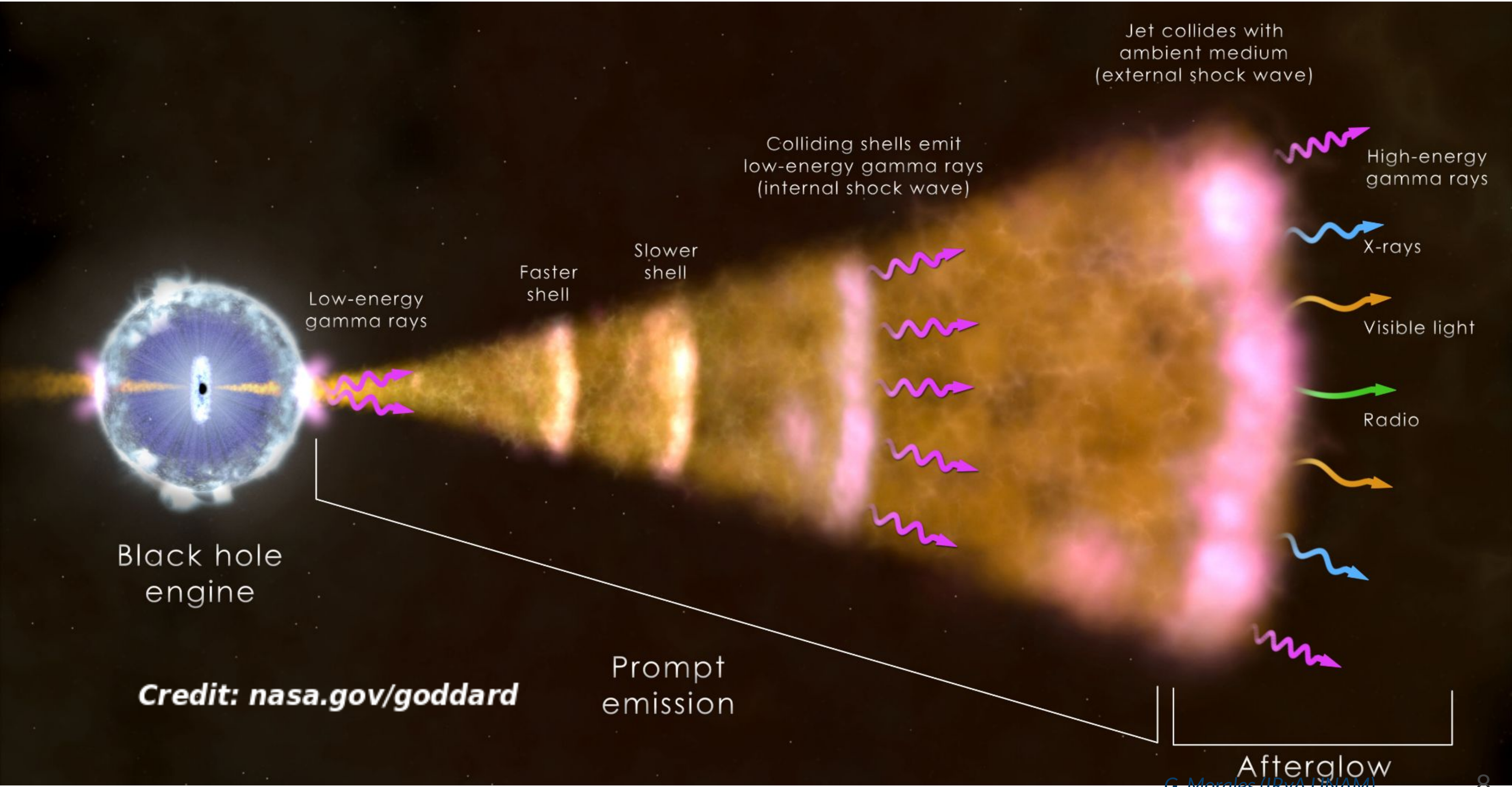


- **Matter**

$$P_{\alpha\beta}(E_\nu, L, \theta, \Delta m^2) + V_{\rm eff}$$

Medium

Hamiltonian is modified → A little bit more complicated


Jet collides with
ambient medium
(external shock wave)
Colliding shells emit
low-energy gamma rays
(internal shock wave)
High-energy
gamma rays
X-rays
Visible light
Radio
Slower
shell
Faster
shell
Low-energy
gamma rays
Black hole
engine
Credit: nasa.gov/goddard
Prompt
emission
Afterglow

Short Gamma-Ray Bursts (sGRB)

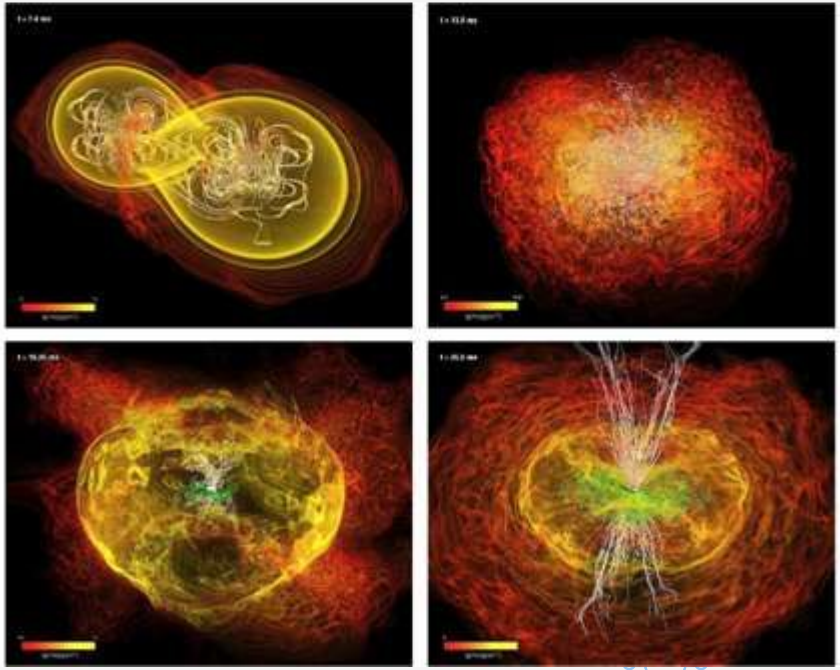
- t<2 seconds *(Kouveliotou, 1993)*
- Merger of two compact objects

BH-NS

- Moderate magnetic field
- B~10^{12} G

NS-NS

- Magnetic field could be amplified up to B~10^{16} G *(Price, 2006; Kiuchi, 2015)*



(Rezzolla, et al., 2011)

Long Gamma-Ray Bursts (LGRB)

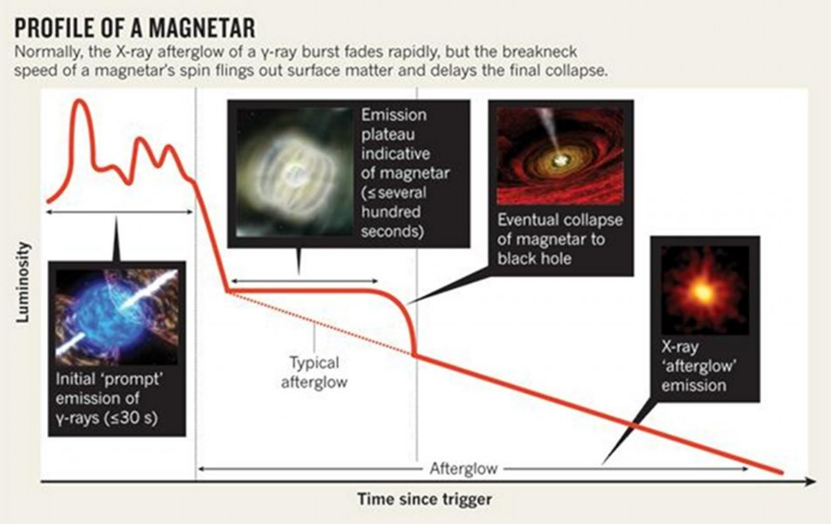
- t>2 seconds *(Kouveliotou, 1993)*
- Collapsar model

Millisecond **magnetar** model

- $B \sim 10^{15}$ G

Black-hole (**BH**)-accretion disk

- $B \sim 10^{12}$ G



Credit: NASA/Skyworks Digital

MeV-neutrino production

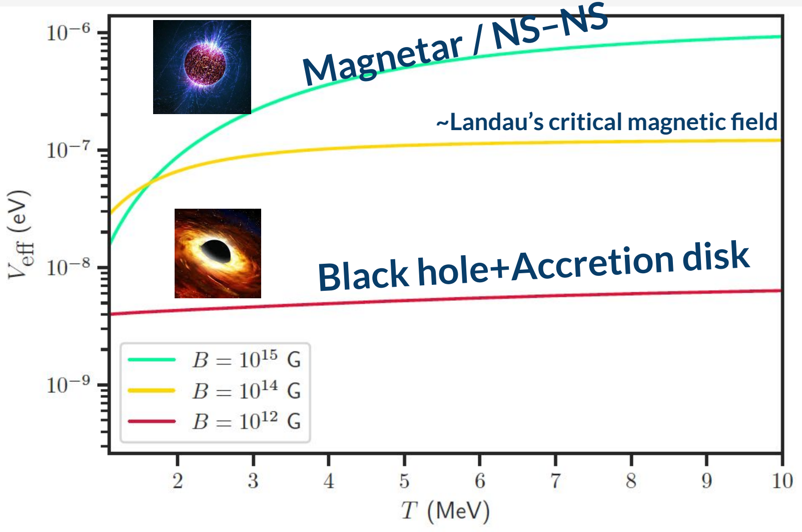
- Prior to the prompt emission
- Dominated by thermal processes
- Extreme conditions are required
- Fireball model

- pairs annihilation ($e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x$),
- plasmon decay ($\gamma \rightarrow \nu_x + \bar{\nu}_x$),
- photo-neutrino emission ($\gamma + e^- \rightarrow e^- + \nu_x + \bar{\nu}_x$),
- positron capture ($n + e^+ \rightarrow p + \bar{\nu}_e$),
- electron capture ($p + e^- \rightarrow n + \nu_e$),

Neutrino potential in a magnetized fireball

$$V_{\text{eff}} \propto (B, T, \mu, \varphi)$$

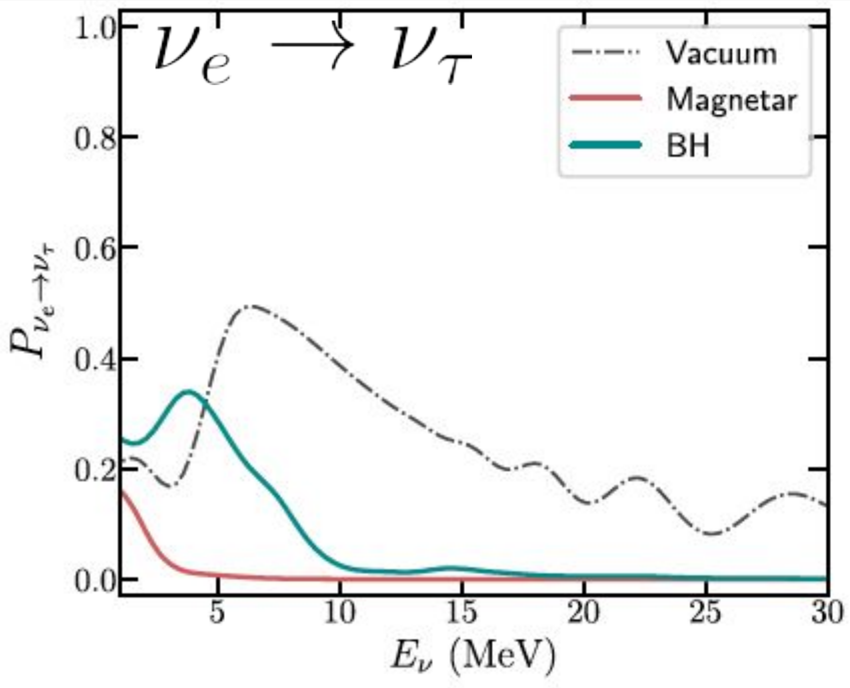
(Fraija, N., 2014)



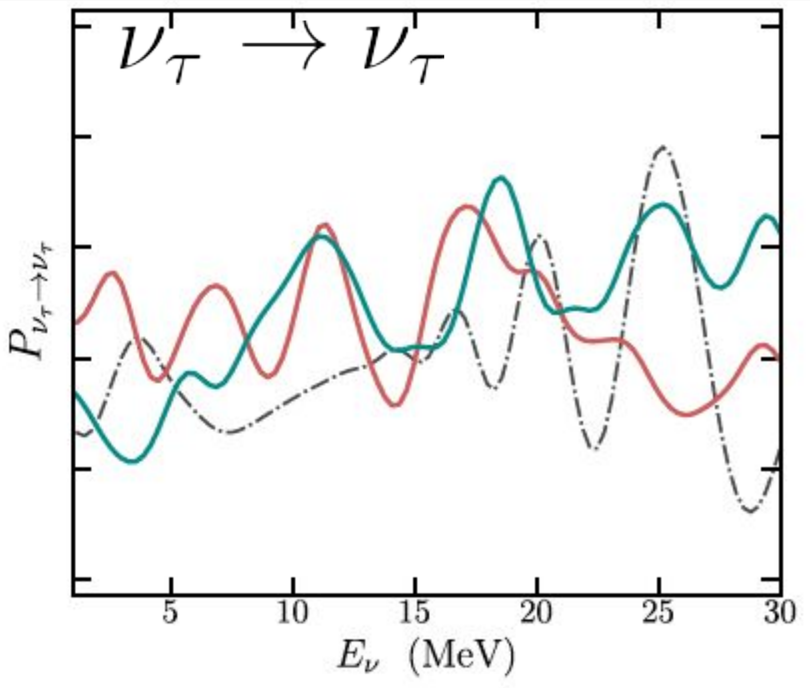
- **Limit cases (B_c~10^{14} G)**
- **Moderate** magnetic field ($B<B_c$)
  - B~10^{12} G
- **Strong** magnetic field ($B>B_c$)
  - B>10^{15} G
  - For $B>B_c$, the quantum effects are important
  - Spin is aligned to the magnetic field lines.
  - It can significantly influence the dynamics, radiation mechanisms, and evolution.

LGRB progenitors

CASE 1: Magnetar

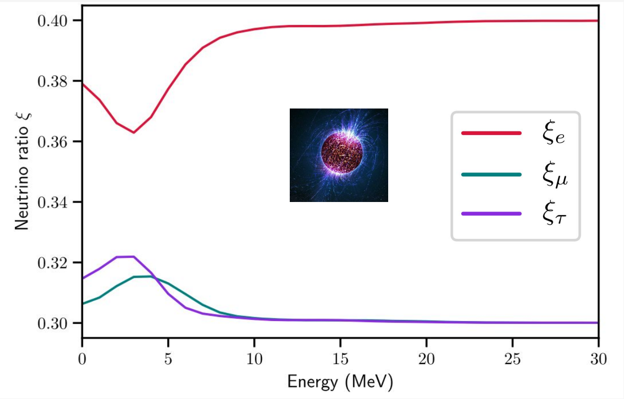


CASE 2: BH+Disk

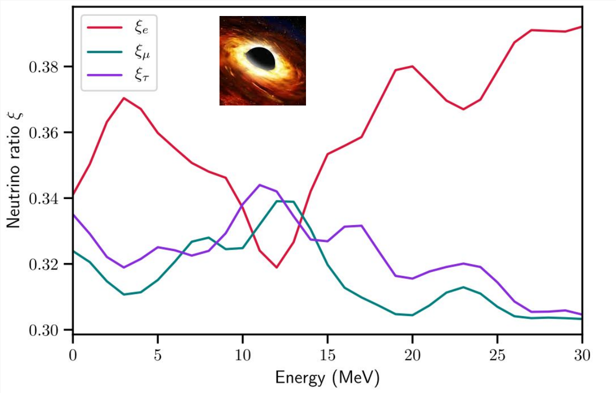


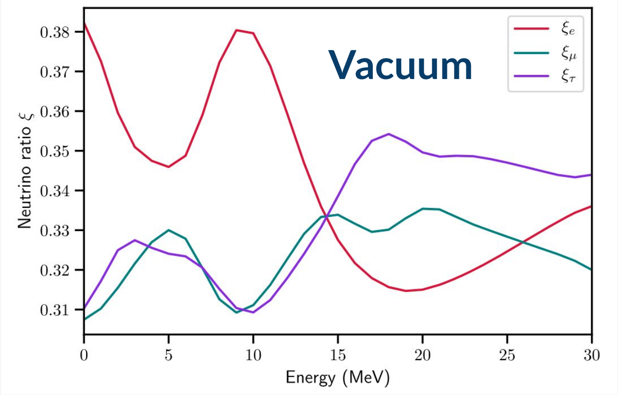
Neutrino ratios

Magnetar



BH+Disk

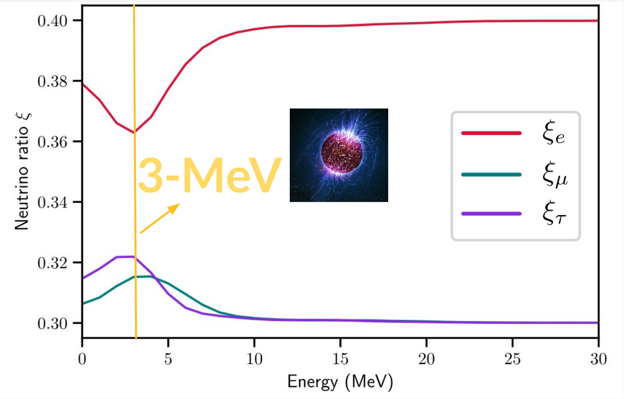




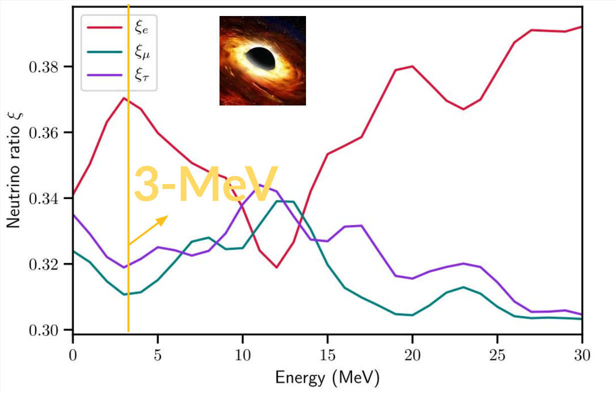
- Neutrino properties are sensitive to magnetic field variations
- It could help to identify the initial magnetic field conditions during the neutrino emission.

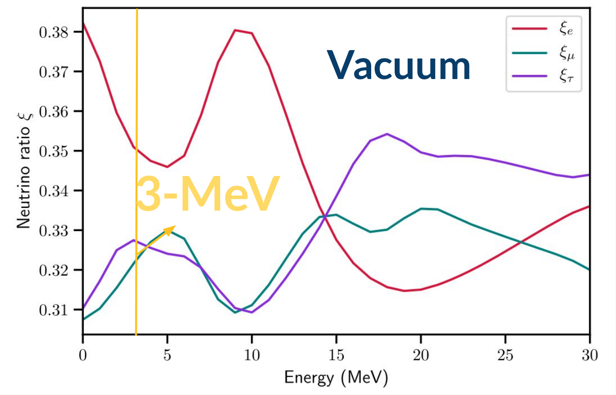
Neutrino ratios

Magnetar



BH+Disk





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For a 3-MeV neutrino

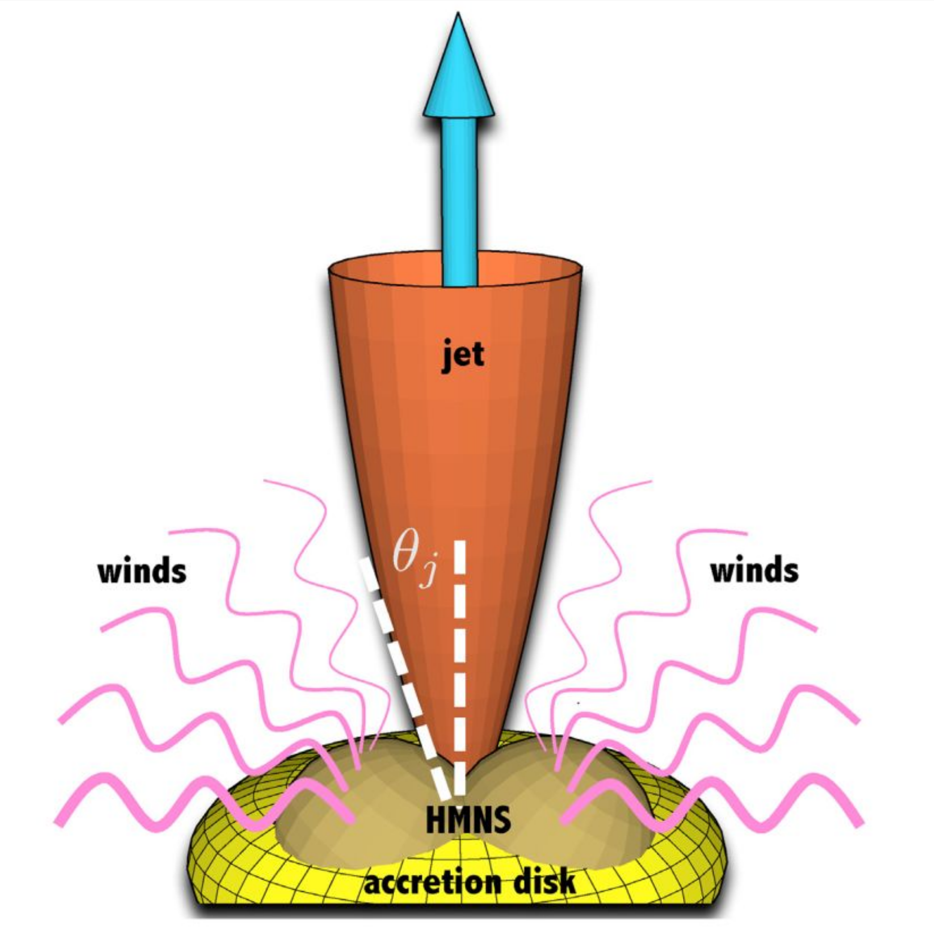
$$\xi_{\text{Magnetar}} = (36.28\%\ \nu_e, 31.53\%\ \nu_\mu, 32.19\%\ \nu_\tau)$$
$$\xi_{\text{BH}} = (37.04\%\ \nu_e, 31.06\%\ \nu_\mu, 31.90\%\ \nu_\tau)$$
$$\xi_{\text{Vacuum}} = (35.12\%\ \nu_e, 32.17\%\ \nu_\mu, 32.75\%\ \nu_\tau)$$

Neutrino propagation in the baryonic winds of the sGRBs.

Two proposed mechanisms:

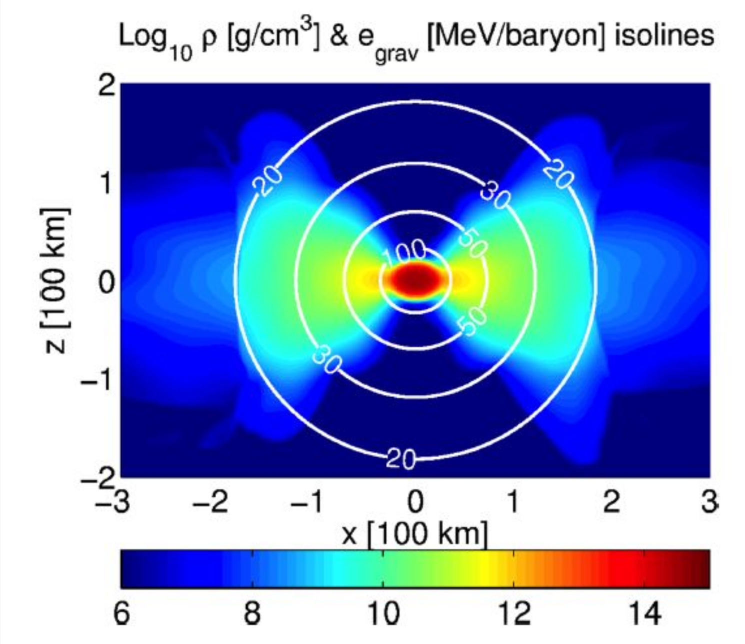
- NDAF: $\nu\bar{\nu}-$annihilation
- MHD processes

¿Do the winds affect the neutrino propagation?



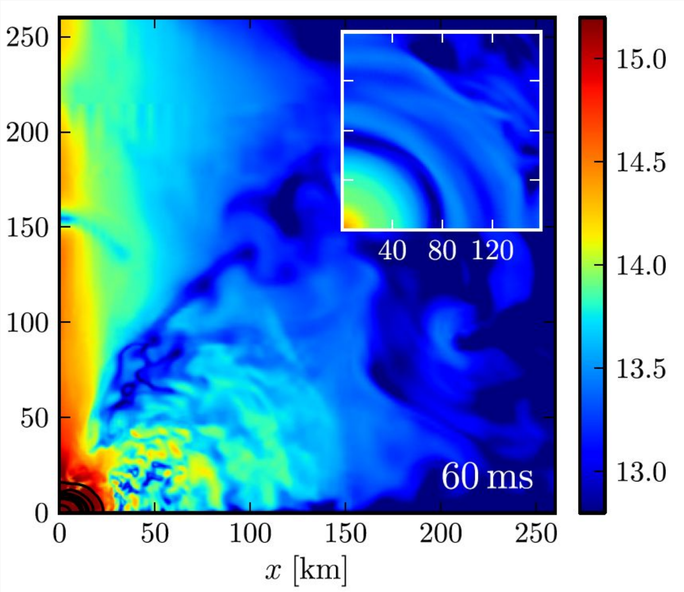
Simulations of the postmerger remnant

CASE 1: HD
Neutrino-driven winds



(Perego, et al.,2014)

CASE 2: MHD
Magnetically-driven winds

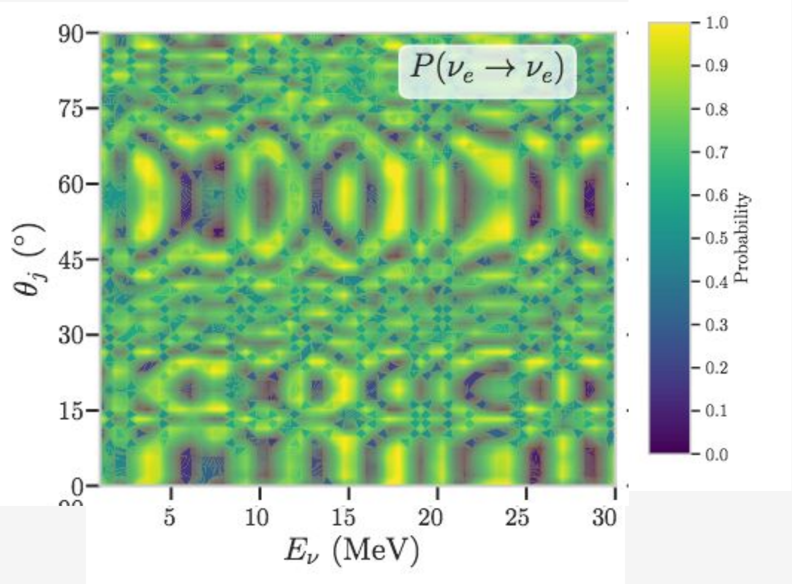


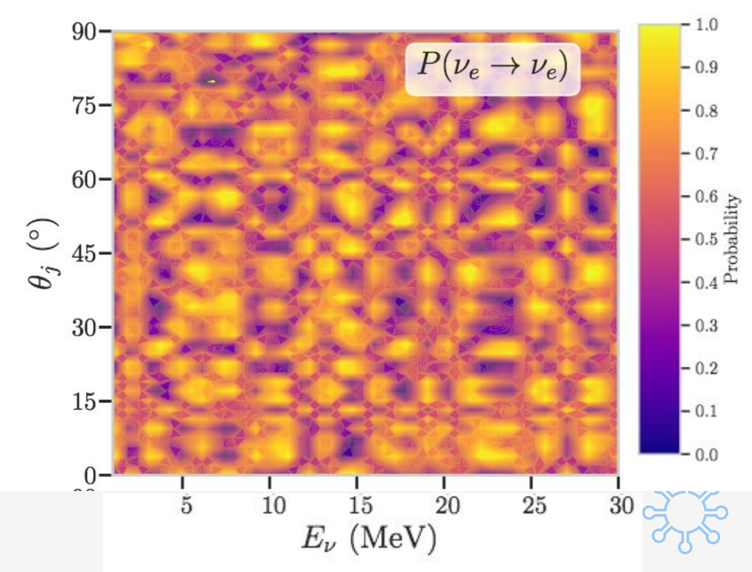
(Siegel, et al.,2014)

CASE 1:
Neutrino-driven winds

CASE 2:
Magnetically-driven winds

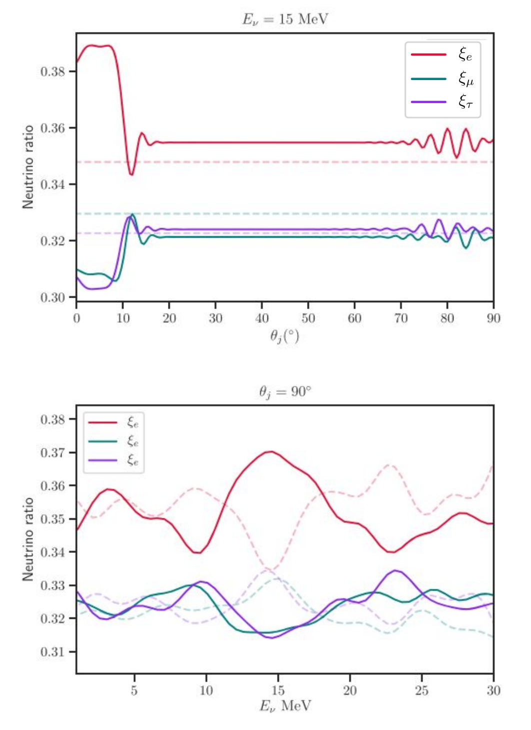
$$\nu_e \to \nu_e$$



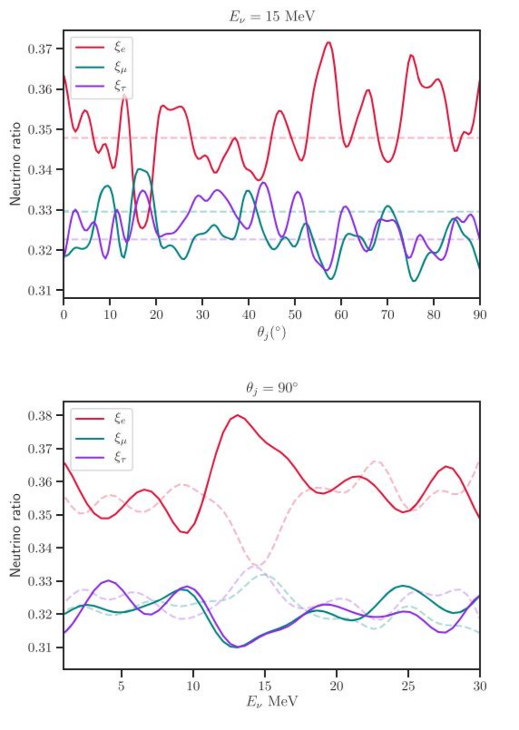


Neutrino ratios (ξ)

Neutrino-driven winds



Magnetically-driven winds



Summary

- Provide valuable information of the innermost regions of GRBs and since neutrinos can leave the source before photons, they can act as precursors to EM emissions.
- The effect of B is a major contributor to the variation of the oscillation probabilities. Then we can study the topology of the initial magnetic field.

Summary

- Provide valuable information of the innermost regions of GRBs and since neutrinos can leave the source before photons, they can act as precursors to EM emissions.
- The effect of B is a major contributor to the variation of the oscillation probabilities. Then we can study the topology of the initial magnetic field.
- By studying neutrino rates in terrestrial detectors, we could characterize the type of progenitor left behind (sGRB and LGRB)
- Combining neutrino observations with EM observations and even gravitational waves can provide a more complete picture of the astrophysical source.

iThank you!

GRB+CE2024

RATIONALE PROGRAM LOCATION REGISTRATION ORGANIZERS PARTICIPANTS CONTACT

A WORKSHOP ON GRBS AND CENTRAL ENGINE POWERED TRANSIENTS

PLAYA DEL CARMEN (MEXICO) | 2 - 6 | DECEMBER 2024

https://bigbang.nucleares.unam.mx/grb2024/