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Neutrino Oscillations as a Gravitational Wave Detector?

Based on arXiv:2405.05000 [hep-ph]

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Neutrino Frontiers '24

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Outline

Motivation and Main Idea

Motivation

Neutrinos

$\hookrightarrow$ Neutrinos oscillate!

$\hookrightarrow$ Probability depends on propagation length L

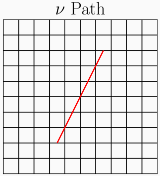
Gravitational Waves (GWs)

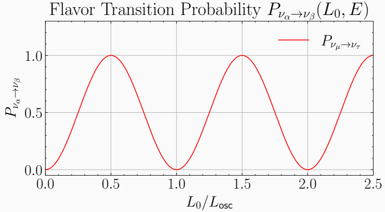
$\hookrightarrow$ Stretch and compress space-time by ΔL

$\tilde{L} = L + \Delta L$

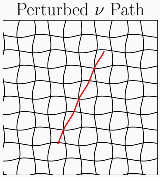
$\boxed{\text{Neutrino oscillations as GW detectors?}}$

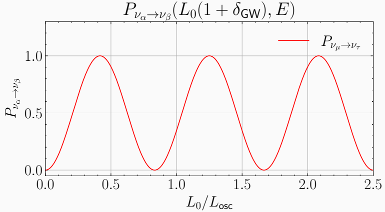
Flat Spacetime $g_{\mu\nu} = \eta_{\mu\nu}$





Gravitational Wave (GW) Spacetime $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$



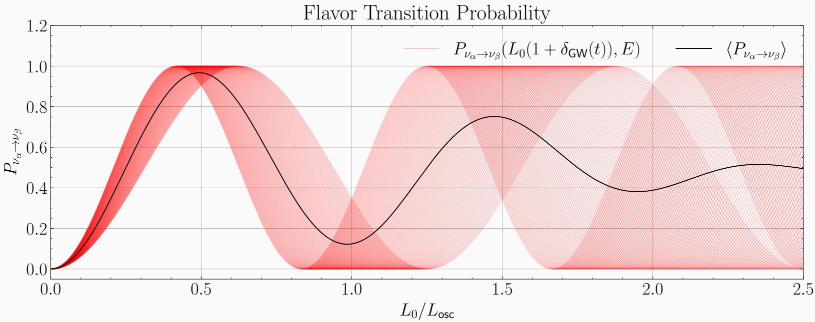


The Main Idea

- Path perturbation $\Delta L = L_0 \delta_{\mathsf{GW}}$ depends on time
- Time (usually) not used in neutrino oscillation analyses

$\Rightarrow$ Average over duration of experiment T_{exp}

$\Rightarrow$ **Decoherence**



Observability Conditions

Observability of the GW Induced Effect

(i) Deviation ΔL is on order of oscilation length L_{osc}

(ii) Wave packet decoherence occurs later than GW induced decoherence

$$\Rightarrow \quad L_{\text{min}}(E) < L_0 < L_{jk}^{\text{coh}}$$

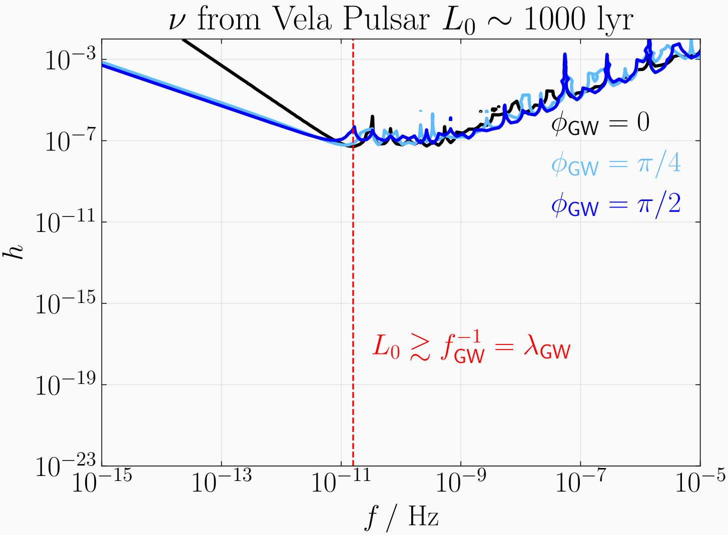
(iii) Neutrino origin must be smaller than L_{osc}

Most Promising Scenario

High energy, galactic neutrinos!

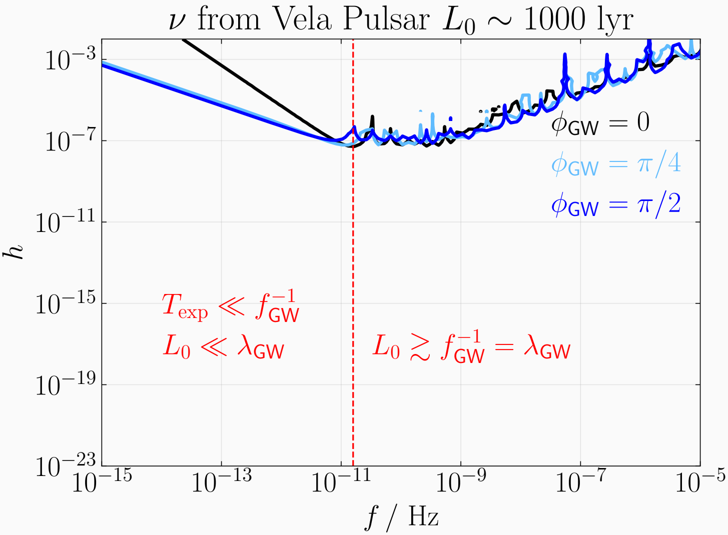
Neutrinos from Galactic Pulsars

Neutrinos from Galactic Pulsars



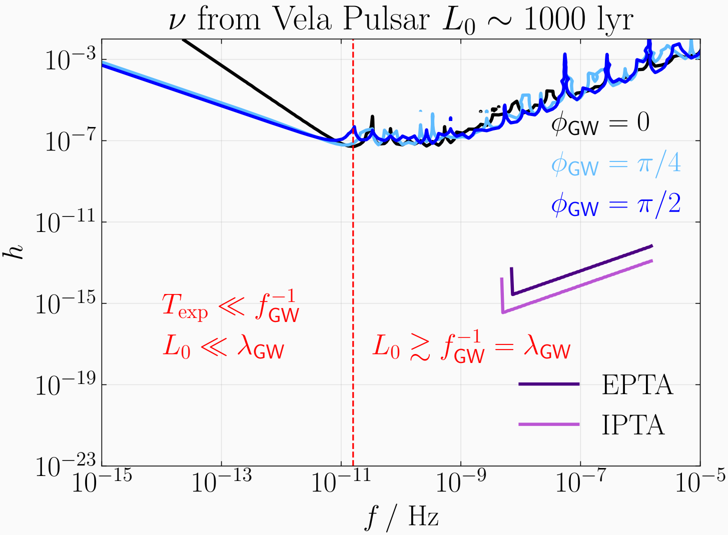
[Hellmann, SK, Päs, Tabet (2024)]

Neutrinos from Galactic Pulsars



[Hellmann, SK, Päs, Tabet (2024)]

Neutrinos from Galactic Pulsars



[Hellmann, SK, Päs, Tabet (2024)]

Drawbacks and How to Avoid Them

Ultra low frequency GWs: $f^{-1} \gg T_{\text{exp}}$

- ΔL barely changes during experiment $\rightarrow$ reduced significance
- Sensitivity becomes strongly phase dependent

Solution

Extend running time to $f^{-1} = \mathcal{O}(1000\text{yr})$!

Drawbacks and How to Avoid Them

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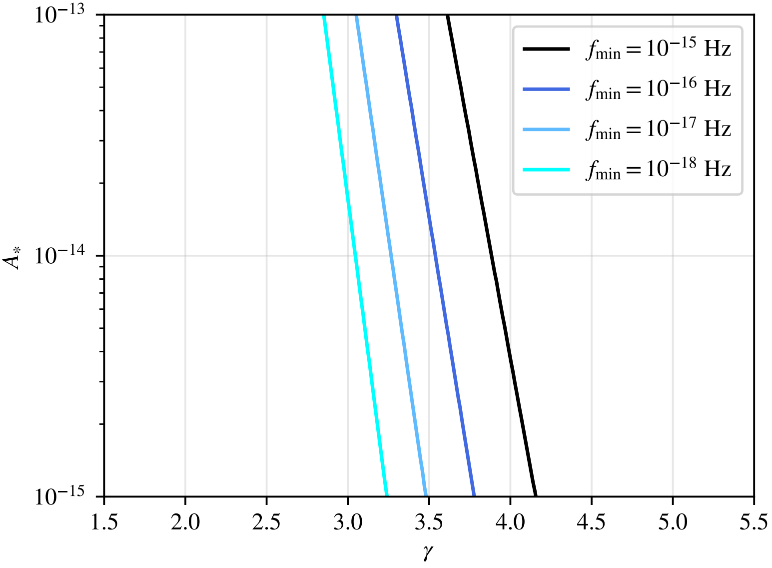
Solution

~~Extend running time to $f^{-1} = \mathcal{O}(1000\text{yr})$!~~

Consider stochastic GW background!

[Dvornikov (2019); Koutsoumbas, Metaxas (2019); Lambiase, Mastrototaro, Visinelli (2022); Hellmann, SK, Päs, Tabet (2024)]

Stochastic GW Background



Summary

Summary

- Neutrino oscillations can probe
  - Exotic, very low frequency, high strain GW signals
  - Stochastic GW background
- Promising candidate sources of neutrinos
  - Galactic Pulsars

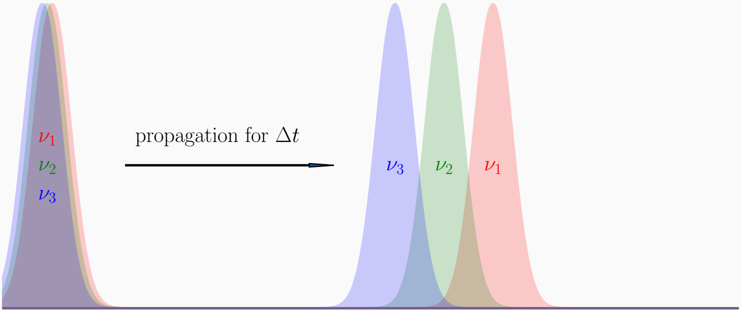
Read more: Hellmann, SK, Päs, Tabet (2024), arXiv:2405.05000

Appendix

WP Decoherence

Mass eigenstates propagate with different group velocities:

$$v_k^g = \frac{\mathrm{d}E_k}{\mathrm{d}p} \approx 1 - \frac{m_k^2}{2p^2}$$



Modified Oscillation Probability

Full unaveraged oscillation probability

$$\hat{P}_{ab}(E,L) = \sum_j |U_{aj}|^2 |U_{bj}|^2 + 2\sum_{j<k} \mathrm{Re}\left(U_{aj}^* U_{bj} U_{ak} U_{bk}^* \exp\left[-2\pi i \frac{L}{L_{jk}^{\mathrm{osc}}} - \mathcal{D}_{jk}(E,L) \right] \right)$$

with

$$\mathcal{D}_{jk}(E,L) = \left(\frac{L}{L_{jk}^{\mathrm{coh}}} \right)^2$$

$$L_{jk}^{\mathrm{coh}} = 2\sqrt{2} \frac{\sigma_x}{|\Delta v_{jk}|}$$

$$L_{jk}^{\mathrm{osc}} = 4\pi \frac{E}{\Delta m_{jk}^2}$$

Stochastic GW Background - Theory

$$\mathcal{D}_{jk}(E,L) = \left(\frac{L}{L_{jk}^{\mathrm{coh}}}\right)^2 + \Gamma_{jk}(E)L$$

$$\Gamma_{jk}(E) = \frac{3}{64(\gamma-1)}\left(\frac{|A_*|}{f_{\mathrm{yr}}L_{jk}^{\mathrm{coh}}}\right)^2\left(\frac{f_{\mathrm{min}}}{f_{\mathrm{yr}}}\right)$$

with GW frequency distribution

$$h_c(f) = A_*\left(\frac{f}{f_{\mathrm{yr}}}\right)^{\frac{3-\gamma}{2}} \tag{1}$$

The Full Path Deviation to $\mathcal{O}(h)$

For a general GW:

$$\Delta L(t) = -\frac{1}{2} \sum_{r=+,\times} \int \mathrm{d}^3\vec{k}\; h_r(\vec{k}) \frac{A_{\parallel}^{r}(\theta,\varphi)}{\tilde{\omega}} \times \left[\sin(\tilde{\omega} L_0)\cos(\omega t + \phi^r) + \{\cos(\tilde{\omega} L_0) - 1\}\sin(\omega t + \phi^r)\right]$$

with

- $\tilde{\omega} = \omega(1 - \cos(\theta))$
- $A_{\parallel}^{+}(\theta,\varphi) = \sin^2(\theta)\cos(2\varphi)$
- $A_{\parallel}^{+}(\theta,\varphi) = \sin^2(\theta)\sin(2\varphi)$

The Full Path Deviation to $\mathcal{O}(h)$

For an approx. plane GW:

$$\Delta L(t) = -\frac{1}{2} \sum_{r=+,\times} h_r \frac{A_{\|}^{r}(\theta,\varphi)}{\tilde{\omega}} \times \left[\sin(\tilde{\omega} L_0)\cos(\omega t + \phi^r) + \{\cos(\tilde{\omega} L_0) - 1\}\sin(\omega t + \phi^r)\right]$$

with

- $\tilde{\omega} = \omega(1 - \cos(\theta))$
- $A_{\|}^{+}(\theta,\varphi) = \sin^2(\theta)\cos(2\varphi)$
- $A_{\|}^{+}(\theta,\varphi) = \sin^2(\theta)\sin(2\varphi)$

Toy Experiment Set Up

- Neutrino energy range: $E_\nu \in [100\,\mathrm{TeV}, 1\,\mathrm{PeV}]$, 20 bins, linear spacing
- Neutrino flux: $\vec{\phi}(E) = \vec{\phi}_0 E^{-2}$, $\vec{\phi}_0 \propto (1, 2, 0)$
- Number of neutrino events: $N_{\mathrm{tot}} = 6 \times 10^4$
- Assumption: All flavors are detected
- Plus polarized approx. plane GW

Toy Experiment Set Up

Log likelihood ratio test:

- Toy data set (j energy bin index, a flavor index):

$$n_{ja} = \left\lfloor N_{\text{tot}} \int_{E_j}^{E_{j+1}} \rho_a^{\text{std}}(E, L)\, \mathrm{d}E \right\rfloor \tag{2}$$

- Likelihood:

$$\mathcal{L}(h, f) = \prod_{j=1}^{n_E} \prod_{a=1}^{n_{\text{flavors}}} \text{Pois}(n_{ja}, \eta_{ja}(h, f))\,, \tag{3}$$

$$\eta_{ja}(h, f) = N_{\text{tot}} \int_{E_j}^{E_{j+1}} \rho_a(E, L; h, f)\, \mathrm{d}E\,. \tag{4}$$

- Log Likelihood Ratio is approx. χ^2 distributed with 2 d.o.f.