Pulsar Kicks and a possible GW signal

LIGO-G050225-00-R

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[**AK**, Segrè, Fuller, Pascoli, Mocioiu, Semikoz]

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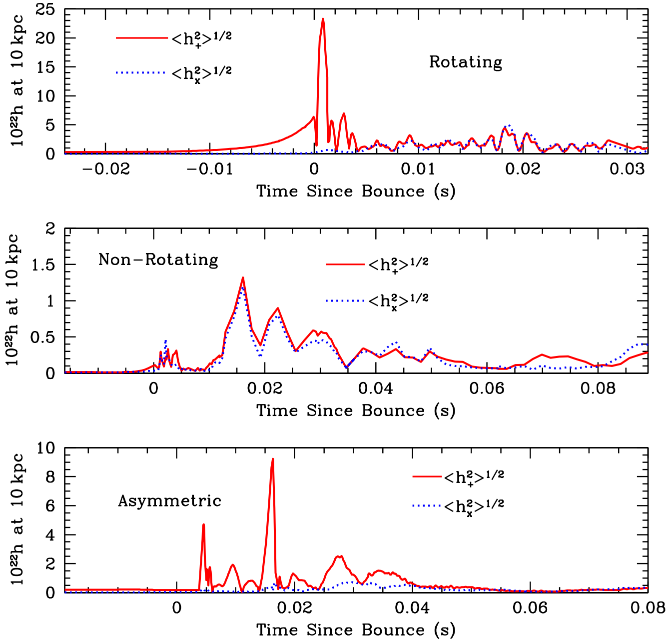
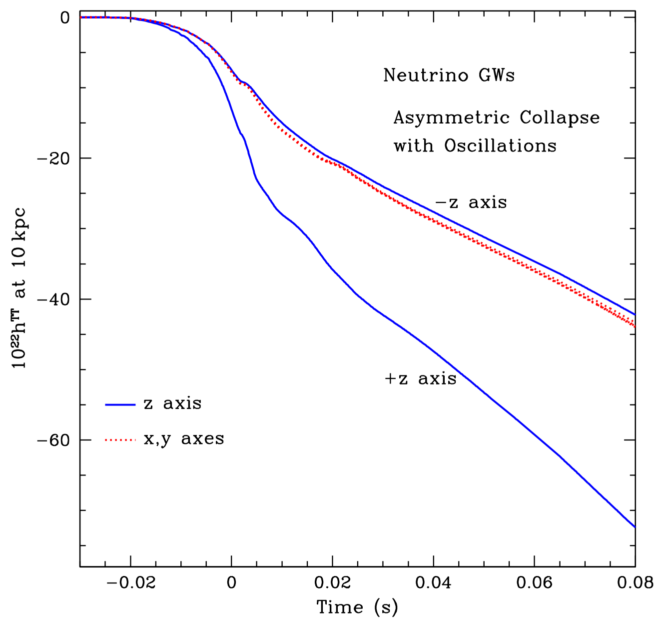
Signal from convection



[Fryer *et al.*]

Signal from neutrinos



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Neutrino signal

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Pulsar velocities

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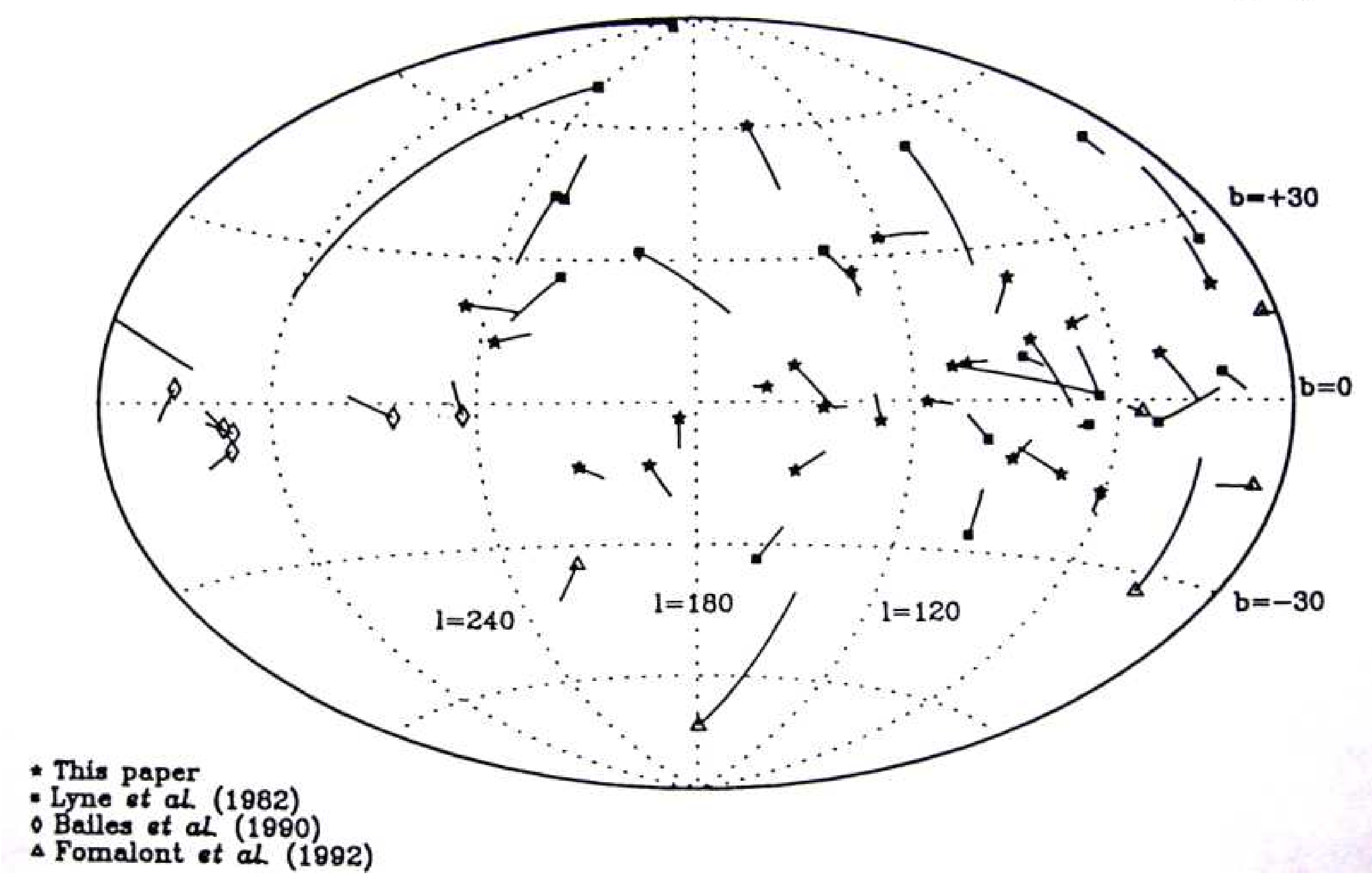
The high-velocity population is so large that some suggested the distribution was two-component [Cordes, Chernoff]


b=+30
b=0
b=-30
l=240
l=180
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★ This paper
▪ Lyne et al. (1982)
◊ Bailes et al. (1990)
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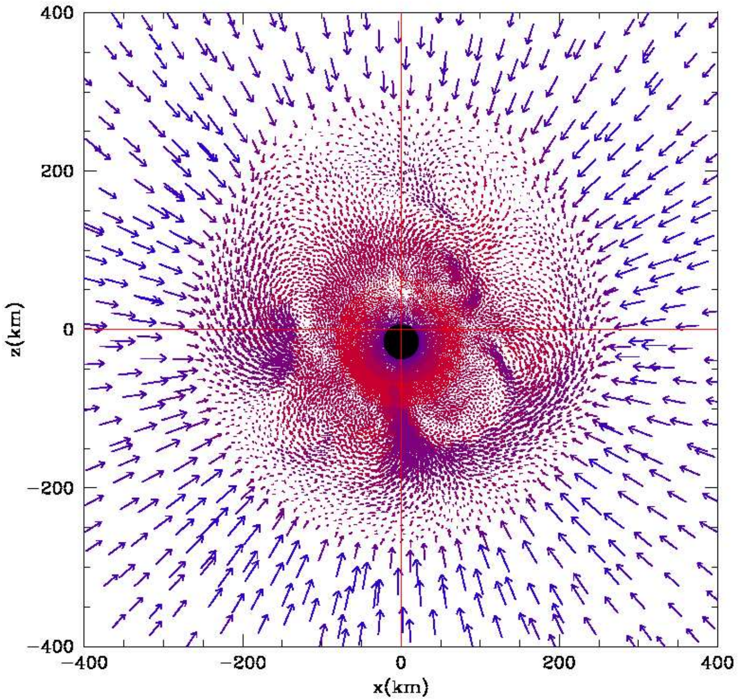
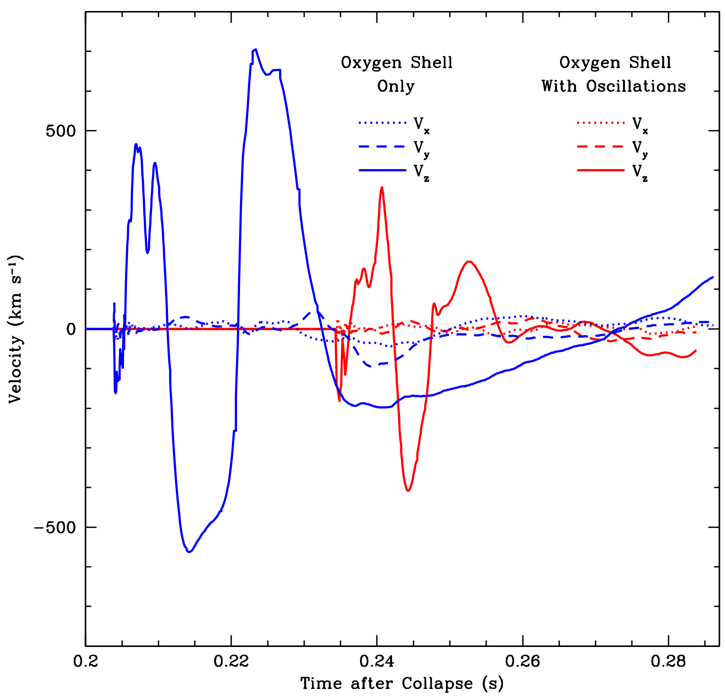
- "cumulative" parity violation [Lai, Qian; Janka] (it's *not* cumulative)

Asymmetric collapse





"...the most extreme asymmetric collapses do not produce final neutron star velocities above 200km/s" [Fryer '03]

Supernova neutrinos

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99% of this energy is emitted in neutrinos

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But what can cause the asymmetry??

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Neutrino magnetic moments are negligible, but the **scattering of neutrinos off polarized electrons and nucleons** is affected by the magnetic field.

Core collapse supernova

Onset of the collapse: $t = 0$

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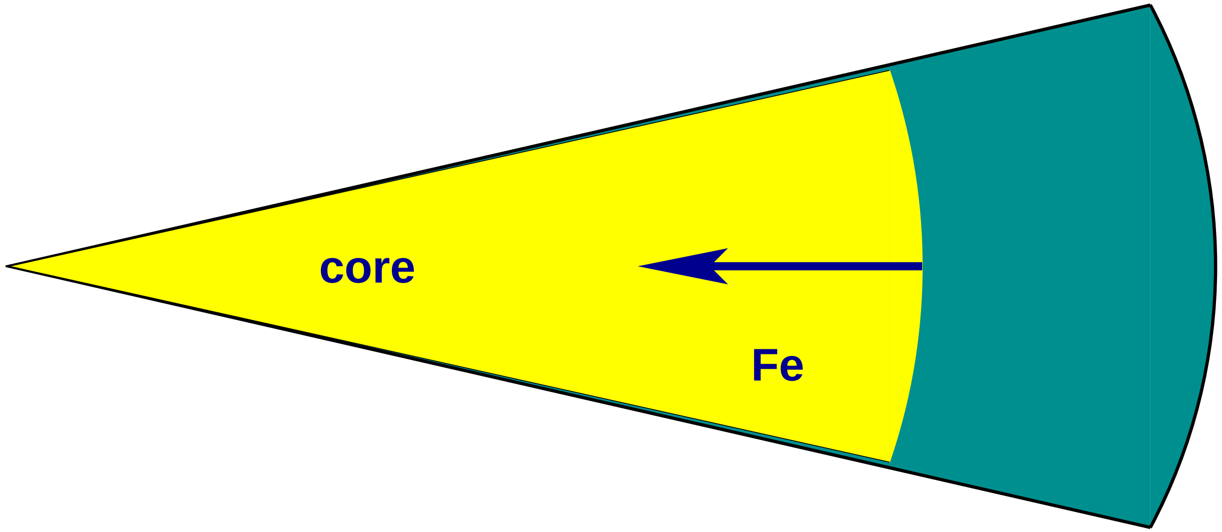
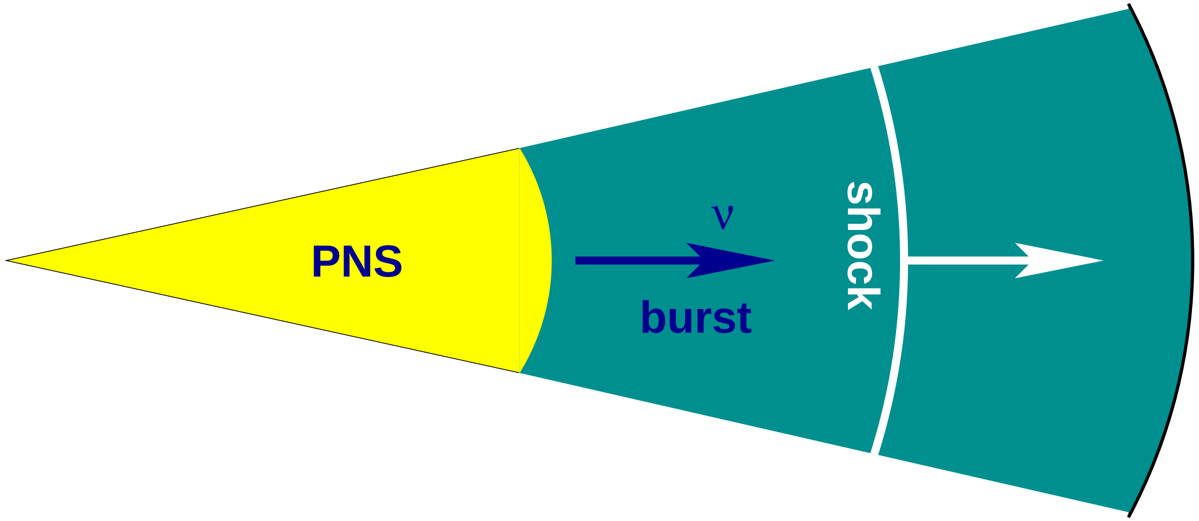


Core collapse supernova

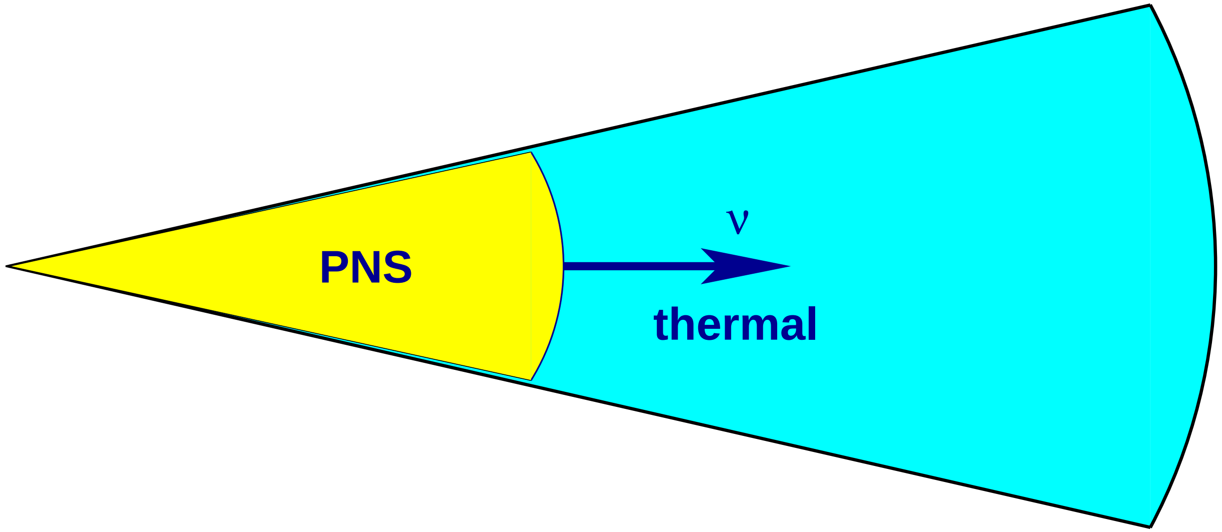
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



Protoneutron star formed. Neutrinos are trapped. The shock wave breaks up nuclei, and the initial neutrino come out (a few %).

Core collapse supernova

Thermal cooling: $t = 10 - 15$ s



Most of the neutrinos emitted during the cooling stage.

Electroweak processes producing neutrinos (urca),

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

have an asymmetry in the production cross section, depending on the spin orientation.

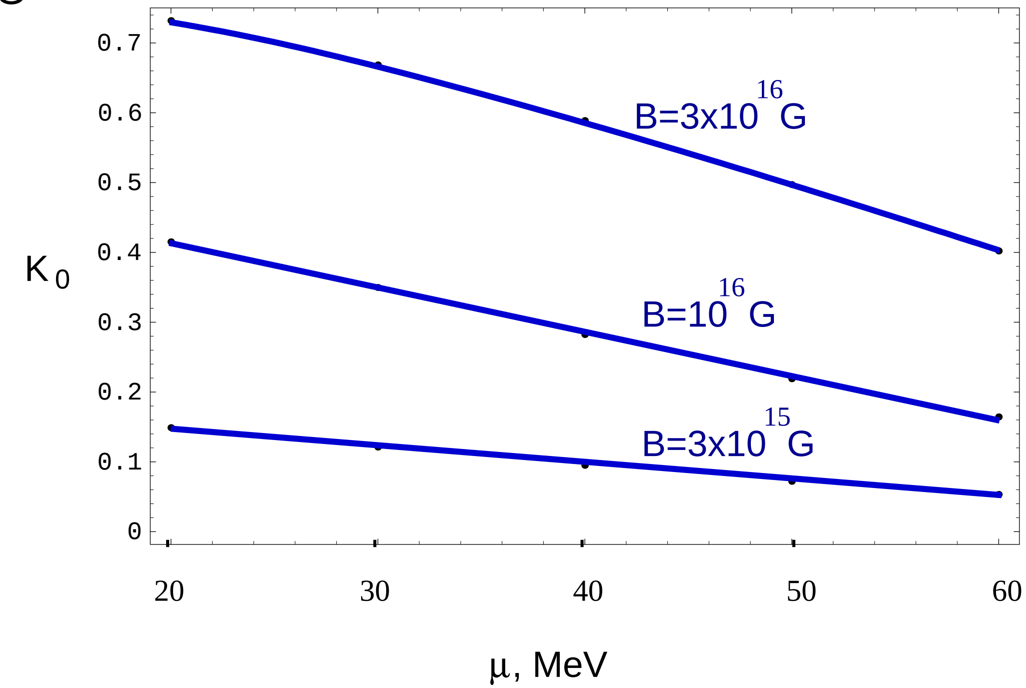
$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

The asymmetry:

$$\tilde{\epsilon} = \frac{g_V^2 - g_A^2}{g_V^2 + 3g_A^2} k_0 \approx 0.4\, k_0,$$

where k_0 is the fraction of electrons in the lowest Landau level.

In a strong magnetic field,



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Pulsar kicks from the asymmetric production of neutrinos?
[Chugai; Dorofeev, Rodionov, Ternov]

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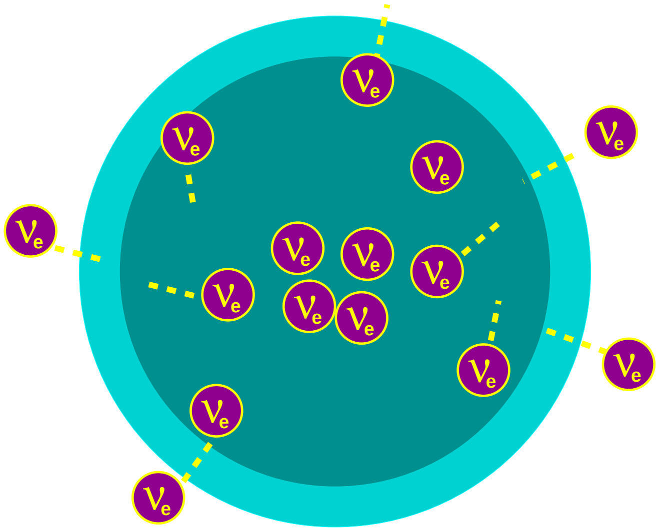

Neutrinos are trapped at high density.

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Rescattering washes out the asymmetry [Vilenkin; AK,Segrè, Vilenkin].

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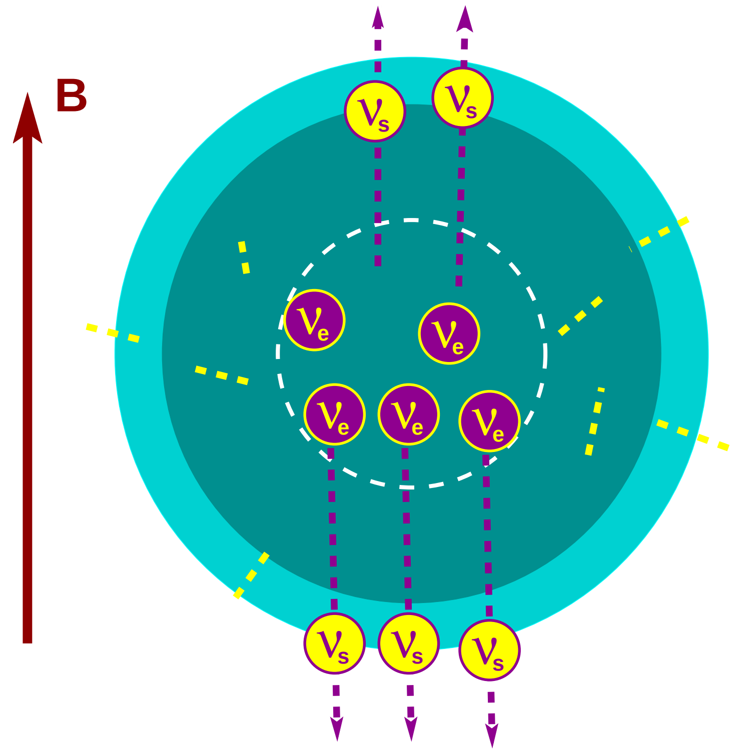
In approximate thermal equilibrium the asymmetries in scattering amplitudes do not lead to an anisotropic emission. Only the outer regions, near neutrinospheres, contribute (a negligible amount).

However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

Sterile neutrinos leave the star without scattering. Hence, they give the pulsar a kick.



Sterile neutrinos with a small mixing to active neutrinos

$$\begin{cases} |\nu_1\rangle = \cos\theta|\nu_e\rangle - \sin\theta|\nu_s\rangle \\ |\nu_2\rangle = \sin\theta|\nu_e\rangle + \cos\theta|\nu_s\rangle \end{cases} \quad (1)$$

The almost-sterile neutrino, $|\nu_2\rangle$ was never in equilibrium. Production of ν_2 could take place through oscillations.

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The probability of $\nu_e \to \nu_s$ conversion in presence of matter is

$$\langle P_{\rm m}\rangle = \frac{1}{2}\left[1+\left(\frac{\lambda_{\rm osc}}{2\lambda_{\rm s}}\right)^2\right]^{-1}\sin^2 2\theta_m, \tag{2}$$

where $\lambda_{\rm osc}$ is the oscillation length, and $\lambda_{\rm s}$ is the scattering length.

Sterile neutrinos in cosmology: dark matter

Sterile neutrinos are produced in primordial plasma through oscillations. The mixing angle is suppressed at high temperature:

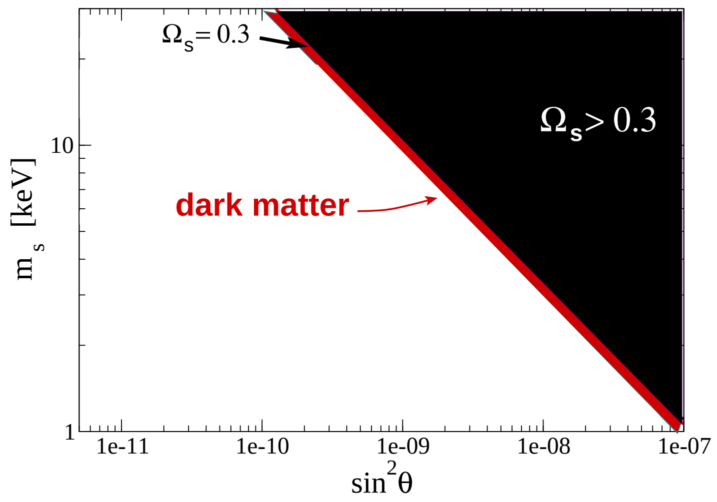
$$\sin^2 2\theta_m = \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V(T))^2}, \quad (3)$$

For small angles,

$$\sin 2\theta_m \approx \frac{\sin 2\theta}{1 + 0.79 \times 10^{-13} (T/MeV)^6 (\mathrm{keV}^2/\Delta m^2)} \quad (4)$$

Production of sterile neutrinos peaks at temperature

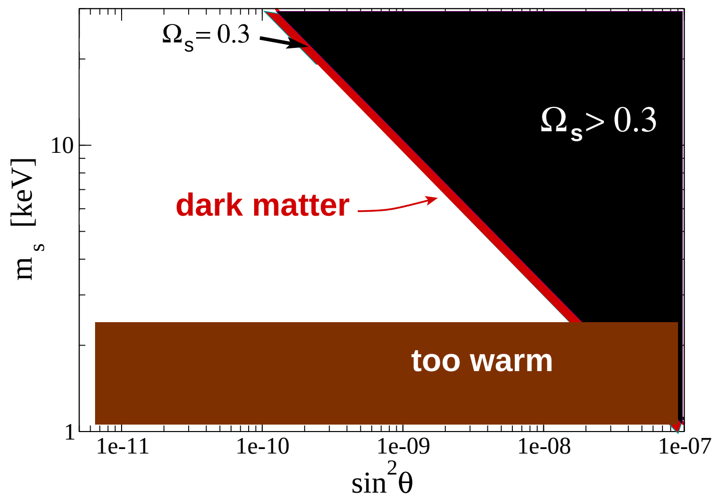
$$T_{\max} = 130\,\mathrm{MeV} \left(\frac{\Delta m^2}{\mathrm{keV}^2} \right)^{1/6}$$



The resulting density of relic sterile neutrinos in conventional cosmology, in the absence of a large lepton asymmetry:

$$\Omega_{\nu_2} \sim 0.3 \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_s}{\text{keV}}\right)^2$$

[Dodelson, Widrow; Dolgov, Hansen; Fuller, Shi; Abazajian, Fuller, Patel]



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- galactic rotation curves cannot be explained by the disk alone
- cosmic microwave background radiation
- gravitational lensing of background galaxies by clusters is so strong that it requires a significant dark matter component.
- clusters are filled with hot X-ray emitting intergalactic gas (without dark matter, this gas would dissipate quickly).

Active-sterile conversions in a neutron star

In matter, there is a potential V_m for ν_e, but not for ν_s:

$$\begin{aligned} V(\nu_s) &= 0 \\ V(\nu_e) &= -V(\bar{\nu}_e) = V_0\,(3\,Y_e - 1 + 4\,Y_{\nu_e}) \\ V(\nu_{\mu,\tau}) &= -V(\bar{\nu}_{\mu,\tau}) = V_0\,(Y_e - 1 + 2\,Y_{\nu_e}) \end{aligned}$$

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The difference $V_m \equiv V(\nu_e) - V(\nu_s)$

Mixing angle in matter is different from vacuum:

$$\sin^2 2\theta_m = \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V_m)^2}, \quad (5)$$

$$V_m = \frac{G_F \rho}{\sqrt{2} m_n}(3Y_e - 1 + 4Y_{\nu_e} + 2Y_{\nu_\mu} + 2Y_{\nu_\tau}) \quad (6)$$

$$\simeq (-0.2 ... + 0.5)V_0, \quad (7)$$

where $V_0 = G_F \rho/\sqrt{2} m_n \simeq 3.8\mathrm{eV}(\rho/10^{14}\mathrm{gcm}^{-3})$

Mixing is suppressed when $V_m \gg (\Delta m^2/2k)$.

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However, the matter potential can evolve on short time scales.

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Therefore,

$$V_m \rightarrow 0$$

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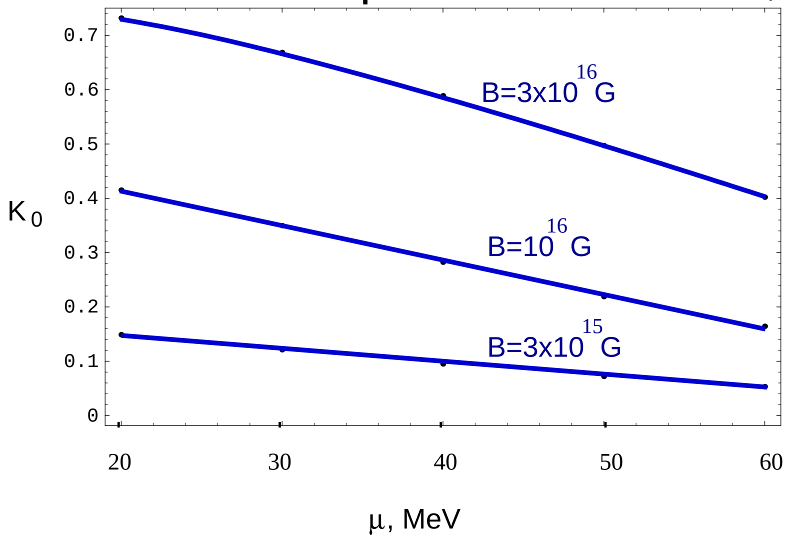
production of ν_s is unsuppressed

Electroweak processes (urca) producing neutrinos, including sterile neutrinos,

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

have asymmetry in the production cross section, depending on the spin orientation. In polarized medium, the asymmetry is of the order $0.4 \times k_0$:



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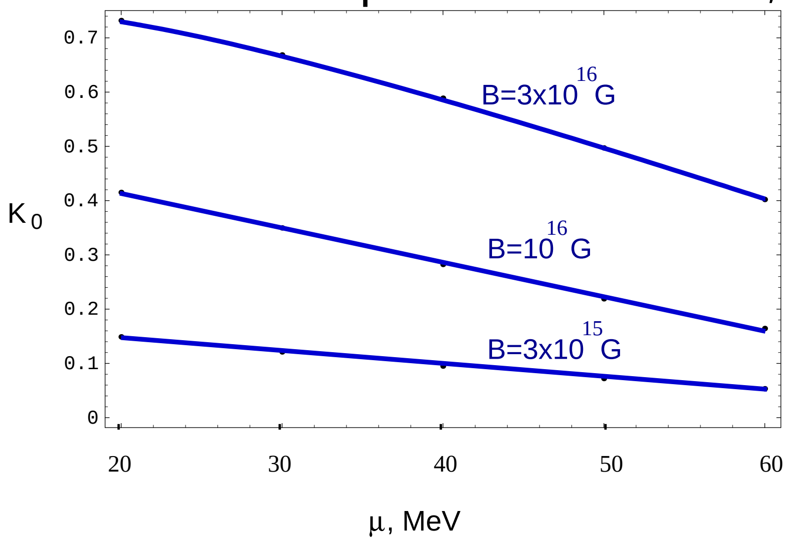
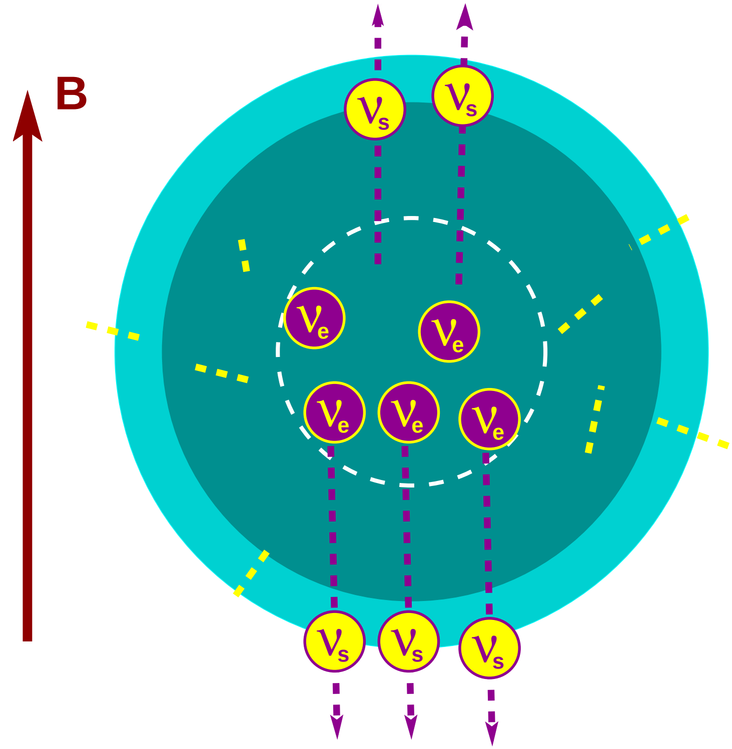


The asymmetry in sterile neutrinos is not affected by rescattering.
Sterile neutrinos escape

Sterile neutrinos leave the star without scattering. Hence, they give the pulsar a kick.



If the fraction of energy emitted in sterile neutrinos is

$$r_{\mathcal{E}} = \left(\frac{\mathcal{E}_{\rm s}}{\mathcal{E}_{\rm tot}} \right) \sim 0.05 - 0.7, \quad (11)$$

(as it can easily be), then the resulting momentum asymmetry is

$$\epsilon \sim 0.02 \left(\frac{k_0}{0.3} \right) \left(\frac{r_{\mathcal{E}}}{0.5} \right), \quad (12)$$

which is sufficient to explain the pulsar kick velocities.

Parameter range: need the equilibration of $V_m \to 0$ to occur faster than ~ 1 s.

$$\tau_V \simeq \frac{V_m^{(0)} m_n}{\sqrt{2} G_F \rho} \Big(\int d\Pi \frac{\sigma_\nu^{\rm urca}}{e^{(\epsilon_\nu - \mu_\nu)/T} + 1} \langle P_m(\nu_e \to \nu_s) \rangle - \int d\Pi \frac{\sigma_{\bar\nu}^{\rm urca}}{e^{(\epsilon_{\bar\nu} - \mu_{\bar\nu})/T} + 1} \langle P_m(\bar\nu_e \to \bar\nu_s) \rangle \Big)^{-1}, \quad (13)$$

where $d\Pi = (2\pi^2)^{-1} \epsilon_\nu^2 \, d\epsilon_\nu$, and $V_m^{(0)}$ is the initial value of the matter potential V_m.

[Abazajian, Fuller, Patel]

$$\tau_V^{\rm on-res} \simeq \frac{2^5\sqrt{2}\pi^2 m_n}{G_F^3\rho}\frac{(V_m^{(0)})^6}{(\Delta m^2)^5\sin 2\theta}\left(e^{\frac{\Delta m^2/2V_m^{(0)}-\mu}{T}}+1\right)$$

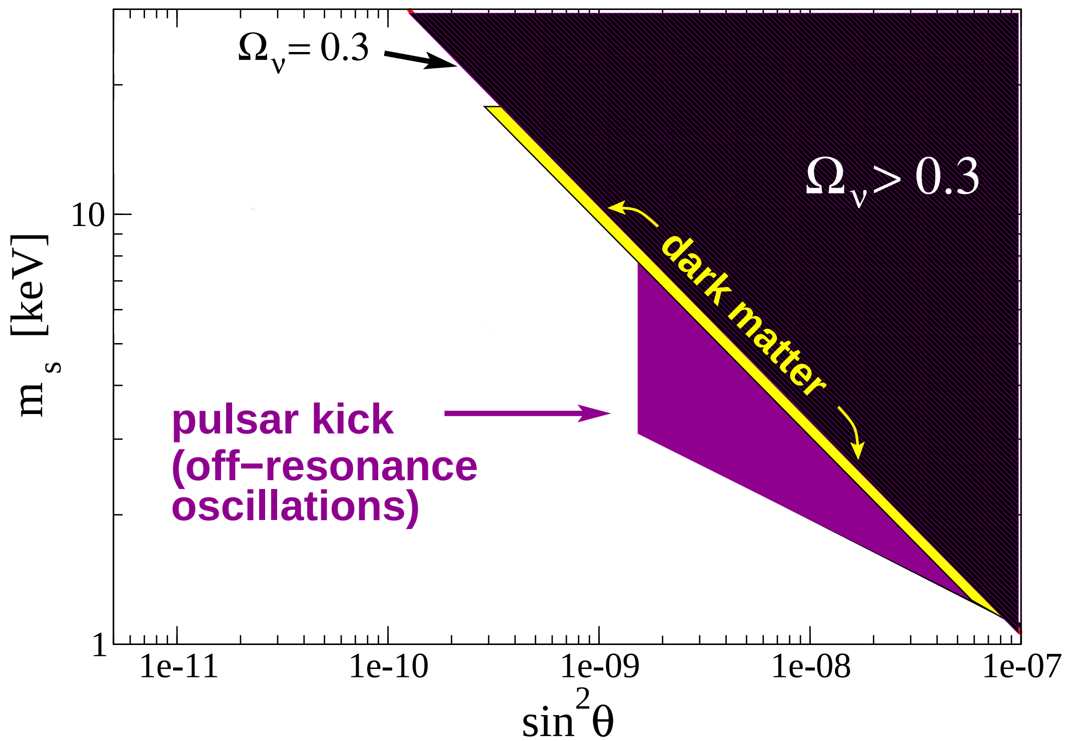
$$\sim \left(\frac{2\times 10^{-9}{\rm s}}{\sin 2\theta}\right)\left(\frac{10^{14}\frac{g}{cm^3}}{\rho}\right)\left(\frac{20\,{\rm MeV}}{T}\right)^6\left(\frac{\Delta m^2}{10\,{\rm keV}^2}.\right)$$

$$\tau_V^{\rm off-res} \simeq \frac{4\sqrt{2}\pi^2 m_n}{G_F^3\rho}\frac{(V_m^{(0)})^3}{(\Delta m^2)^2\sin^2 2\theta}\frac{1}{\mu^3}$$

$$\sim \left(\frac{6\times 10^{-9}{\rm s}}{\sin^2 2\theta}\right)\left(\frac{V_m^{(0)}}{0.1{\rm eV}}\right)^3\left(\frac{50{\rm MeV}}{\mu}\right)^3\left(\frac{10{\rm keV}^2}{\Delta m^2}\right)^2.$$

[Fuller,**AK**,Mocioiu,Pascoli]

Allowed range of parameters (time scales, fraction of total energy emitted):



[Fuller,**AK**,Mocioiu,Pascoli]

Resonant active-sterile neutrino conversions in matter

Matter potential:

$$
\begin{aligned}
V(\nu_s) &= 0 \\
V(\nu_e) &= -V(\bar{\nu}_e) = V_0\,(3\,Y_e - 1 + 4\,Y_{\nu_e}) \\
V(\nu_{\mu,\tau}) &= -V(\bar{\nu}_{\mu,\tau}) = V_0\,(Y_e - 1 + 2\,Y_{\nu_e}) \; + \; c_L^Z \frac{\vec{k}\cdot\vec{B}}{k}
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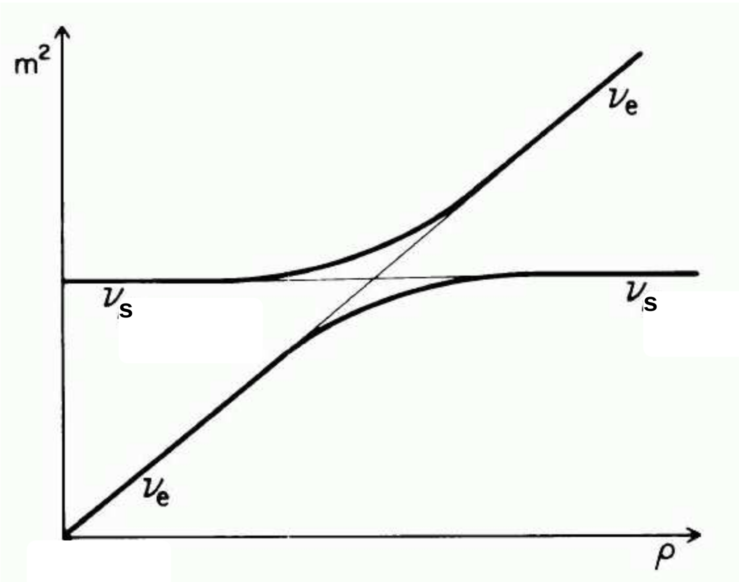
$$
c_L^Z = \frac{eG_F}{\sqrt{2}} \left(\frac{3N_e}{\pi^4}\right)^{1/3}
$$

[D'Olivo *et al.*]

Mikheev–Smirnov–Wolfenstein (MSW) effect

When $m_1^2 - m_2^2 = 2E$,
or $\frac{m_1^2 - m_2^2}{2E} = V$,
$\Rightarrow$ **level crossing**



The resonance condition is

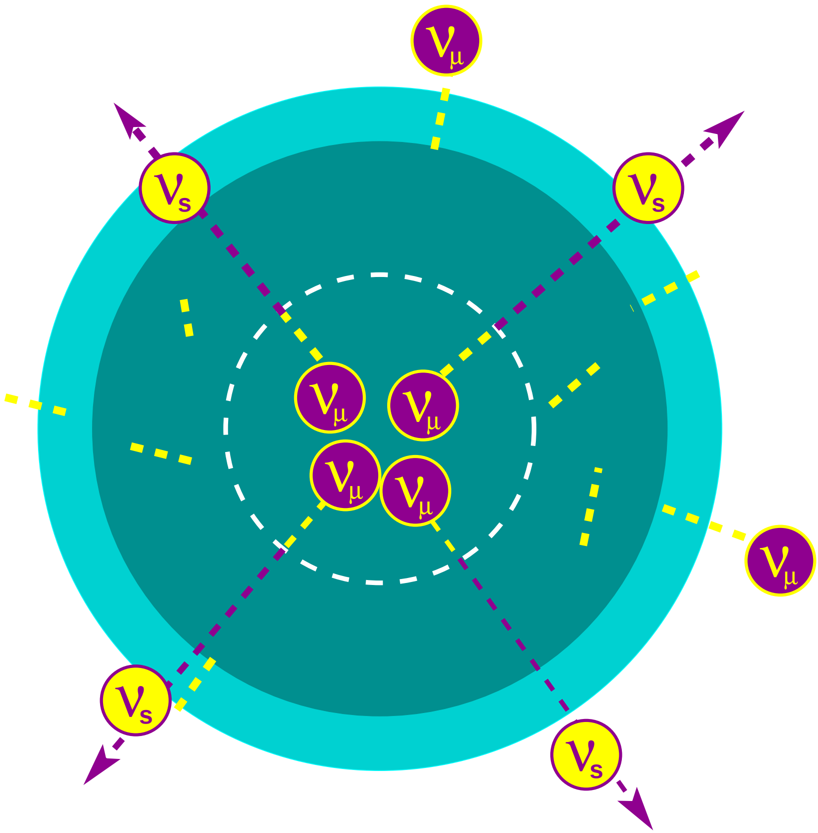
$$\frac{m_i^2}{2k} \cos 2\theta_{ij} + V(\nu_i) = \frac{m_j^2}{2k} \cos 2\theta_{ij} + V(\nu_j) \tag{14}$$

The resonance is affected by the magnetic field and occurs at different density depending on $\vec{k} \cdot \vec{B}$, that is depending on direction.

As a result, the active neutrinos convert to sterile neutrinos at different depths on different sides of the start.

Temperature is a function of r. The energy of an escaping sterile neutrino depends on the temperature of at the point it was produced.

The magnetic field shifts the position of the resonance because of the $\frac{\vec{k}\cdot\vec{B}}{k}$ term in the potential:



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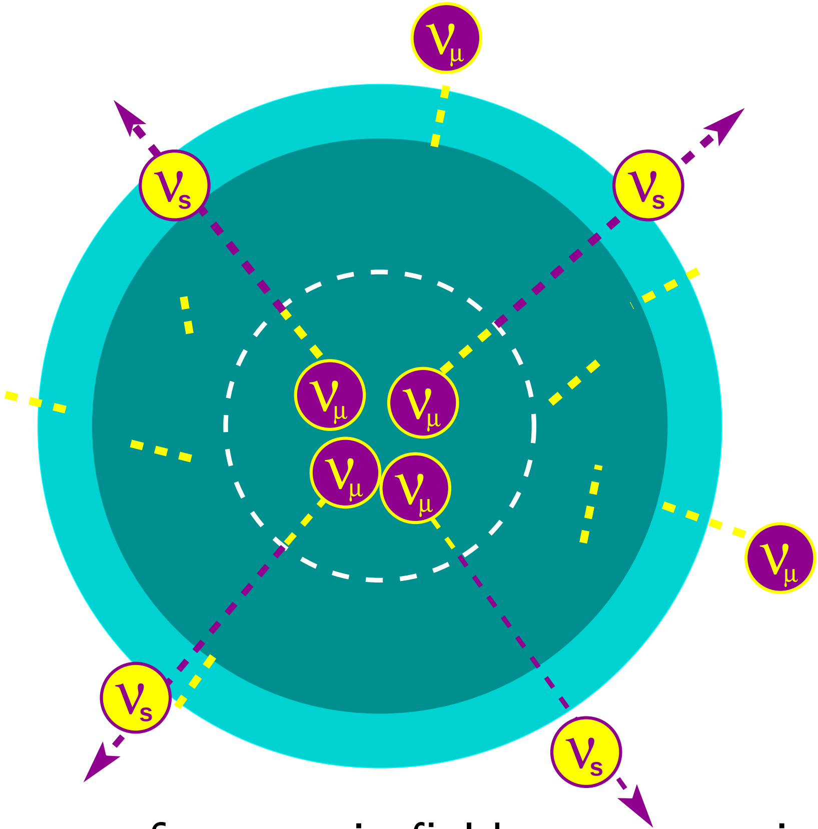

In the absence of magnetic field, ν_s escape isotropically

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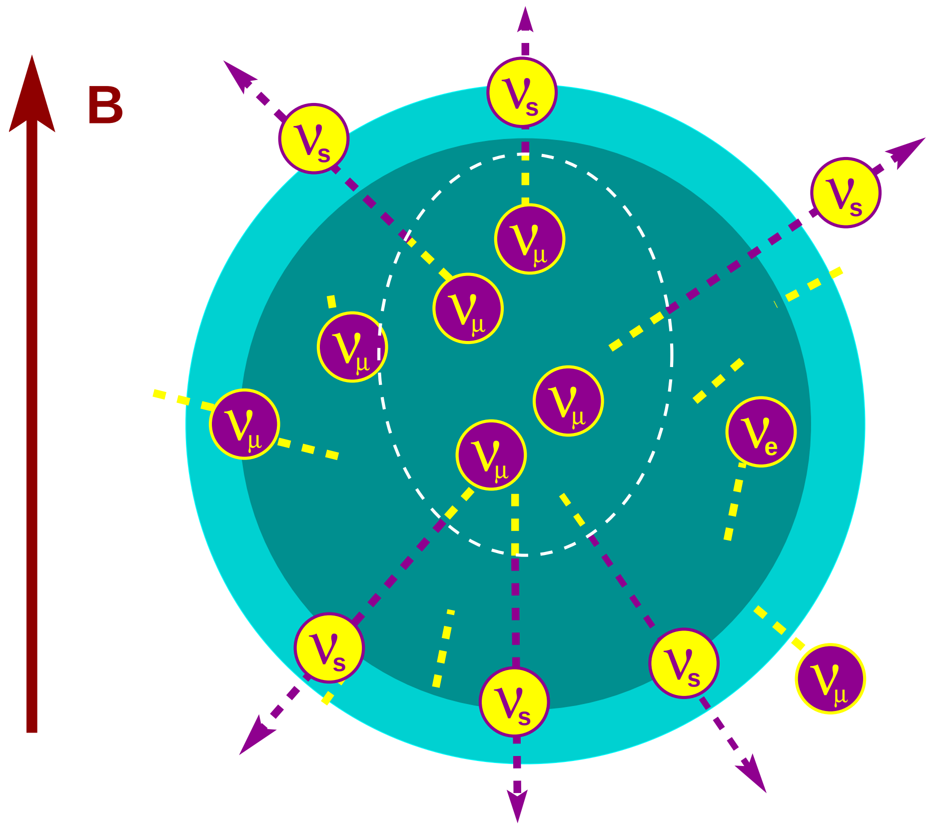

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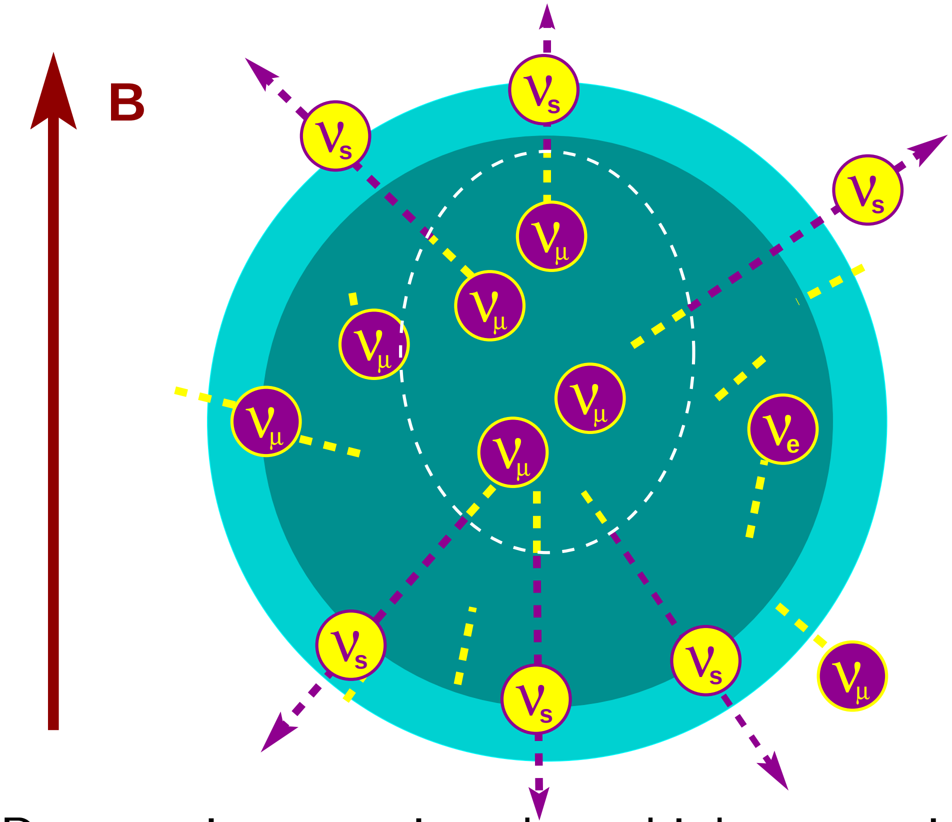

Down going neutrinos have higher energies

A crude estimate of the kick

The mean energy of emitted sterile neutrinos is proportional to the temperature at the point of production. The point of resonant conversion depends on direction:

$$r(\phi) = r_0 + \delta \cos \phi, \quad (15)$$

where $\cos\phi = (\vec{k}\cdot\vec{B})/k$ and δ is determined by the equation:

$$2\frac{dN_n(r)}{dr}\delta \approx e\left(\frac{3N_e}{\pi^4}\right)^{1/3} B. \quad (16)$$

This yields

$$\delta = \left(\frac{3N_e}{\pi^4}\right)^{1/3} \frac{e}{2} B \Big/ \frac{dN_n(r)}{dr} = \frac{e\mu_e}{2\pi^2} B \Big/ \frac{dN_n(r)}{dr}, \tag{17}$$

where $\mu_e \approx (3\pi^2 N_e)^{1/3}$ is the chemical potential of the degenerate (relativistic) electron gas.

Asymmetry in the outgoing momentum (assuming Stefan-Boltzmann):

$$\frac{\Delta k}{k} = \frac{1}{3} \frac{T^4(r_0 - \delta) - T^4(r_0 + \delta)}{T^4(r_0)} \approx \frac{8}{3} \frac{1}{T} \frac{dT}{dr} \delta \tag{18}$$

$$\approx \frac{4e}{3\pi^2} \left(\frac{\mu_e}{T} \frac{dT}{dN_n}\right) B \tag{19}$$

Estimate the derivative $\frac{dT}{dN_n}$ using $\boldsymbol{N_n = \frac{2(m_n T)^{3/2}}{\sqrt{2}\pi^2} \int \frac{\sqrt{z}dz}{e^{(z-\mu_n)/T}+1}}$.

Finally,

$$\frac{\Delta k}{k} = \frac{4e\sqrt{2}}{\pi^2} \frac{\mu_e \mu_n^{1/2}}{m_n^{3/2} T^2} B. \tag{20}$$

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$$\frac{\Delta k}{k} = \frac{4e\sqrt{2}}{\pi^2} \frac{\mu_e \mu_n^{1/2}}{m_n^{3/2} T^2} B \sim 0.01 \left(\frac{B}{10^{15}\mathrm{G}} \right) \tag{21}$$

[AK,Segrè]

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[AK,Segrè]

A more careful calculation gives a similar order of magnitude [Barkovich *et al.*, PR **D66**, 123005 (2002); AK, Segrè, PR **D D59** 061302 (1999); Barkovich *et al.*, hep-ph/0503113].

The core density $\rho \sim 10^{14}$ g/cm^3 determines the

$$\boldsymbol{\Delta m^2 \sim (10\,\mathrm{keV})^2}$$

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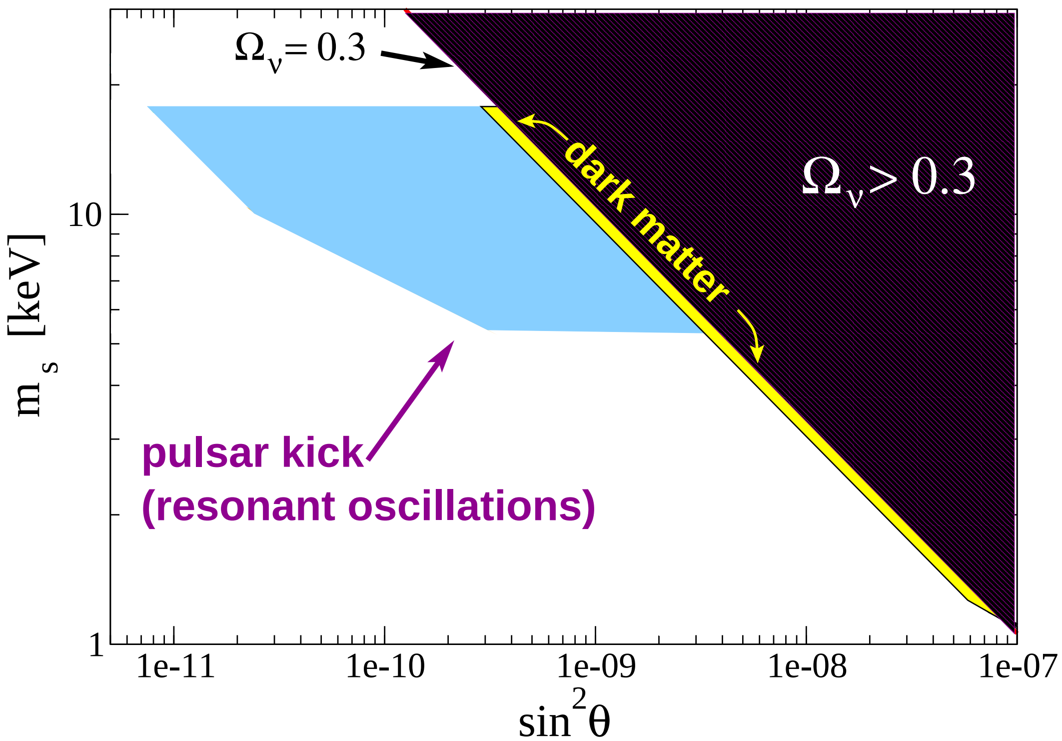
Adiabaticity: the oscillation length

$$\lambda_{\rm osc} \approx \left(\frac{1}{2\pi} \, \frac{\Delta m^2}{2k} \, \sin 2\theta \right)^{-1} \sim \frac{1\,{\rm mm}}{\sin 2\theta}.$$

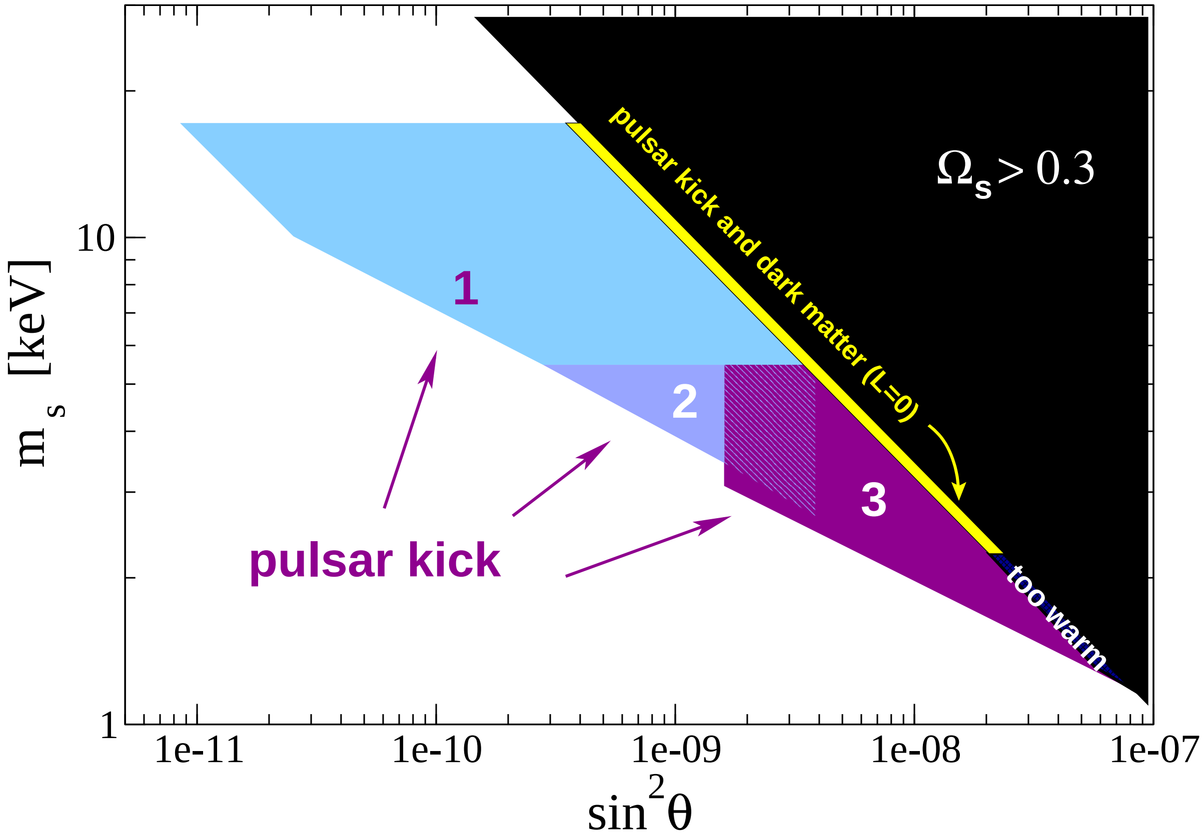
must be smaller than (1) the scale height of density (2) the mean free path of neutrinos. $\Rightarrow$

$$\mathbf{\sin^2\theta \gtrsim 10^{-10}}$$

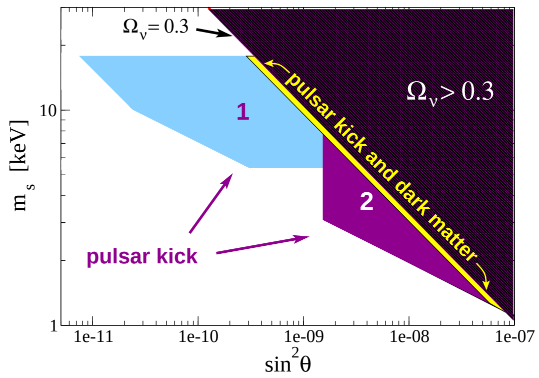
The range of parameters [AK, Segrè; Fuller,**AK**,Mocioiu,Pascoli]:



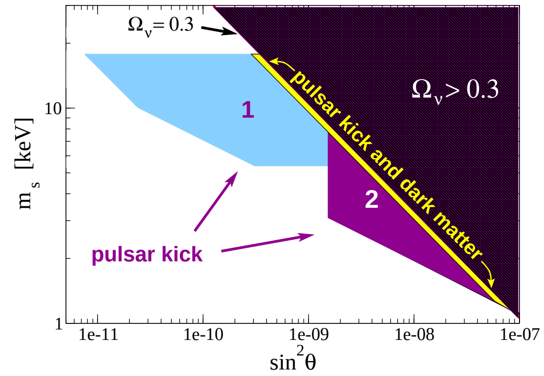
Resonant (1,2) & off-resonant (3) emissions combined:



the pulsar kick regions overlap with the dark matter region



How "natural" is the mixing $\sin^2\theta \sim 10^{-8}$?



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Models of neutrino masses commonly predict:

$$\sin^2\theta \sim \frac{m_1}{m_2} \quad \text{[e.g, Kaus and Meshkov]}$$

for a heavy neutrnio with a **10 keV$= 10^5$eV** mass and a light one with a **10^{-3}eV** mass, this ratio is about right.

Pulsar kicks: why sterile neutrinos?

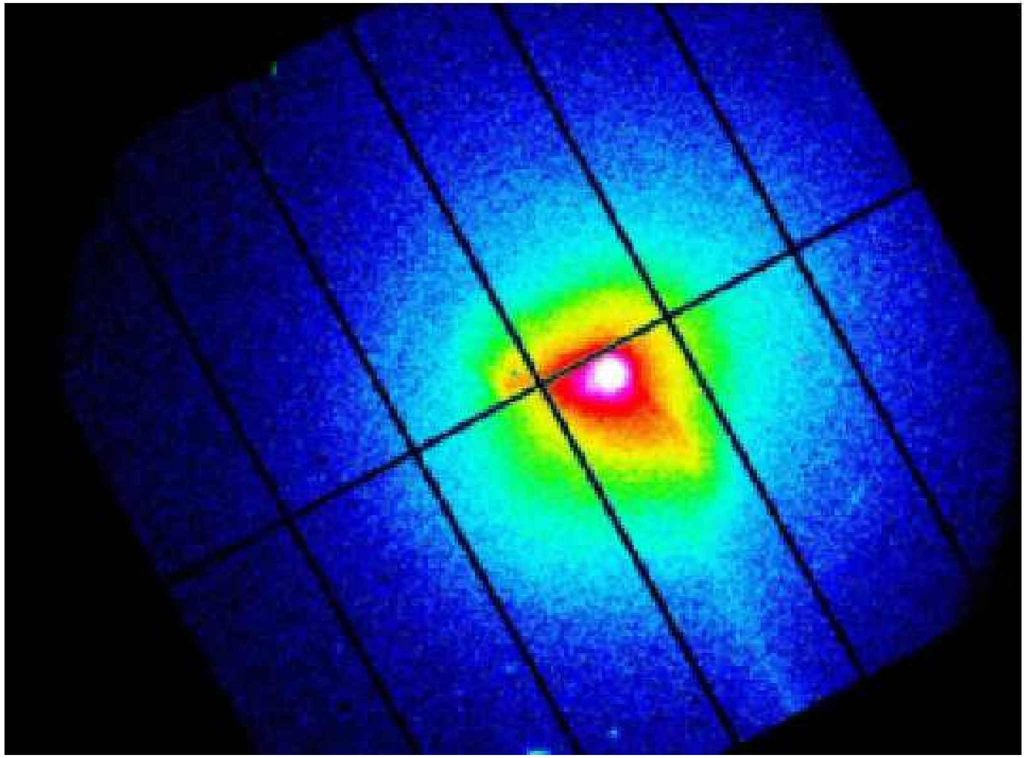
Why not ordinary active neutrinos?

To get a pulsar kick out of $\nu_{\mu,\tau} \leftrightarrow \nu_e$ oscillations, one would require the resonant neutrino conversion to take place between the electron and τ neutrinospheres, at density $\rho \sim 10^{11} - 10^{12}$ g/cm^3. This density corresponds to

$$\left(\Delta m^2\right)^{1/2} \sim 10^2\,\mathrm{eV}$$

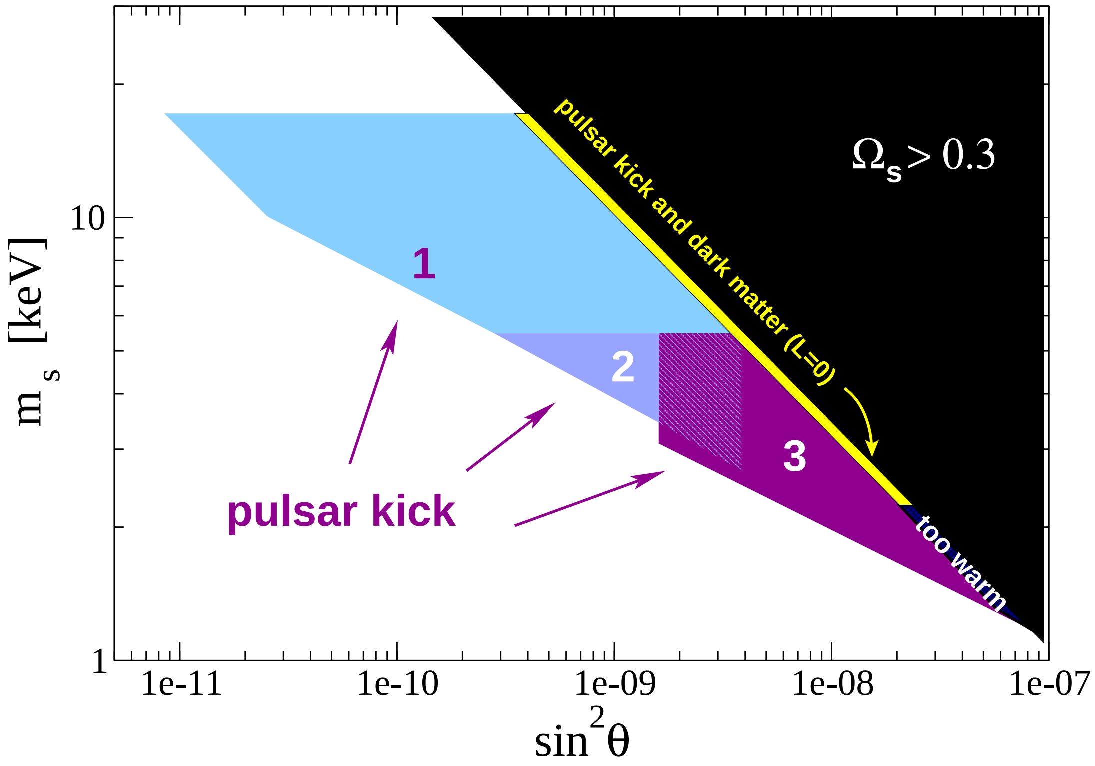
This is inconsistent with experimental/cosmological limits.

Chandra, XMM-Newton can see keV photons.



Virgo cluster image from XMM-Newton

Chandra, XMM-Newton can see photons: $\nu_s \longrightarrow \nu_e \gamma$



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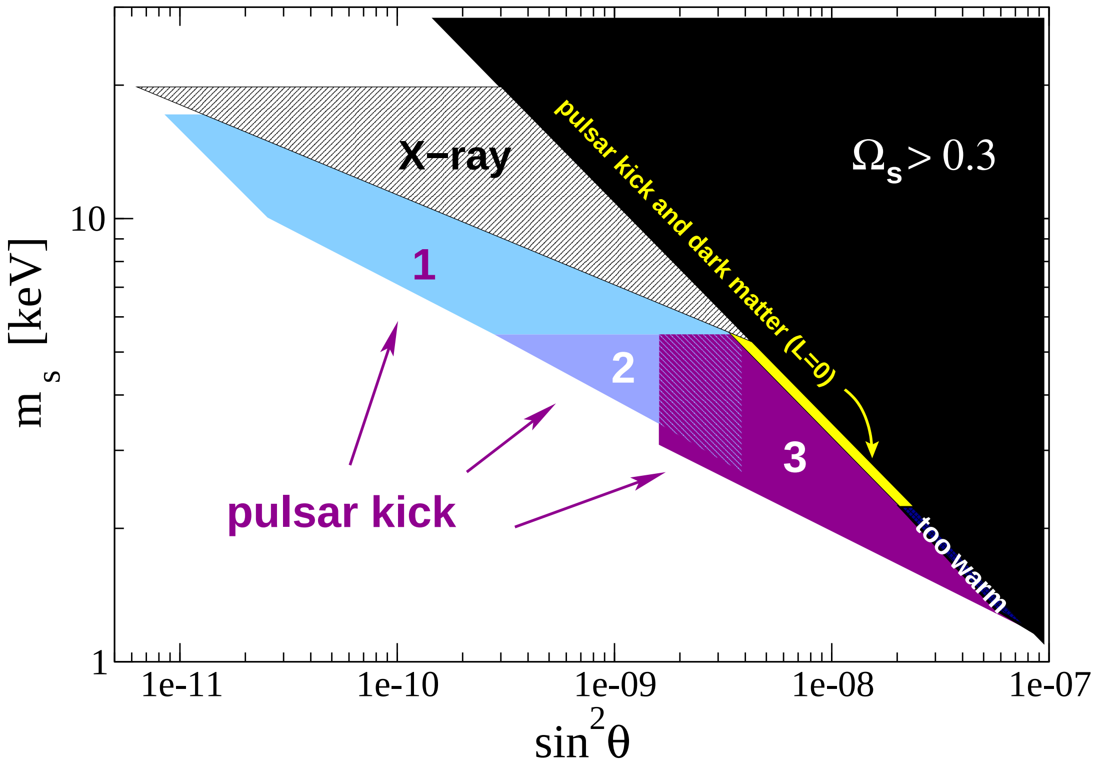

[Abazajian, Fuller, Tucker]

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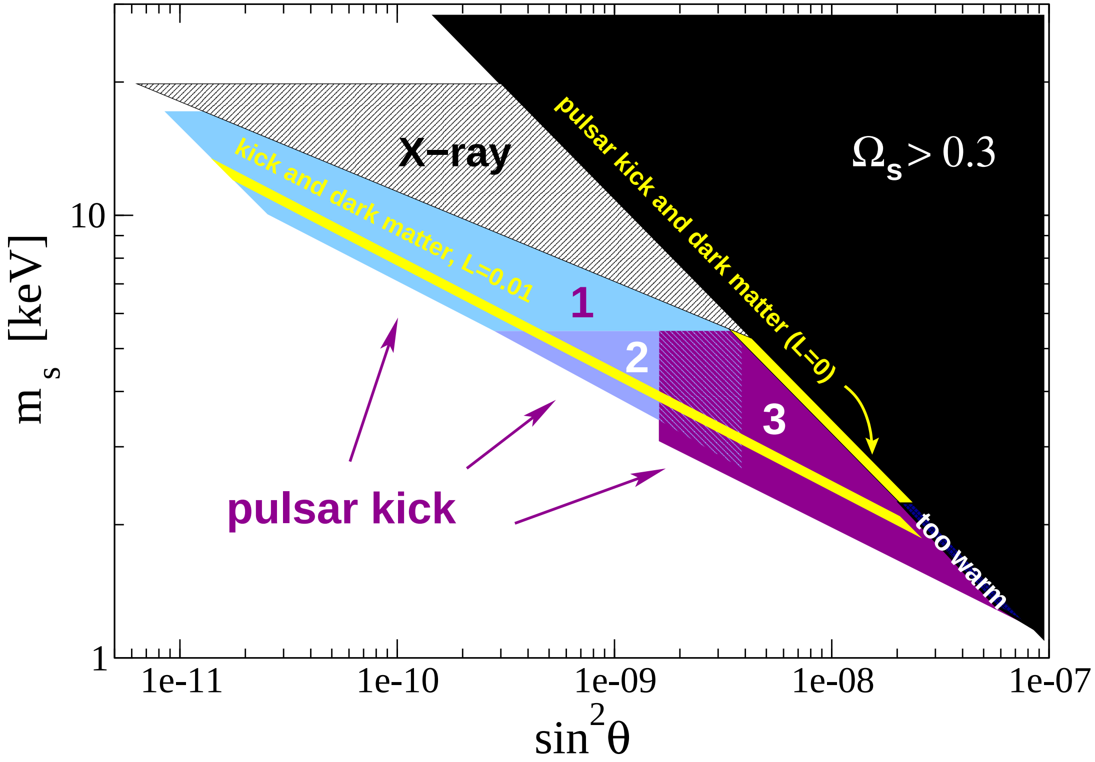
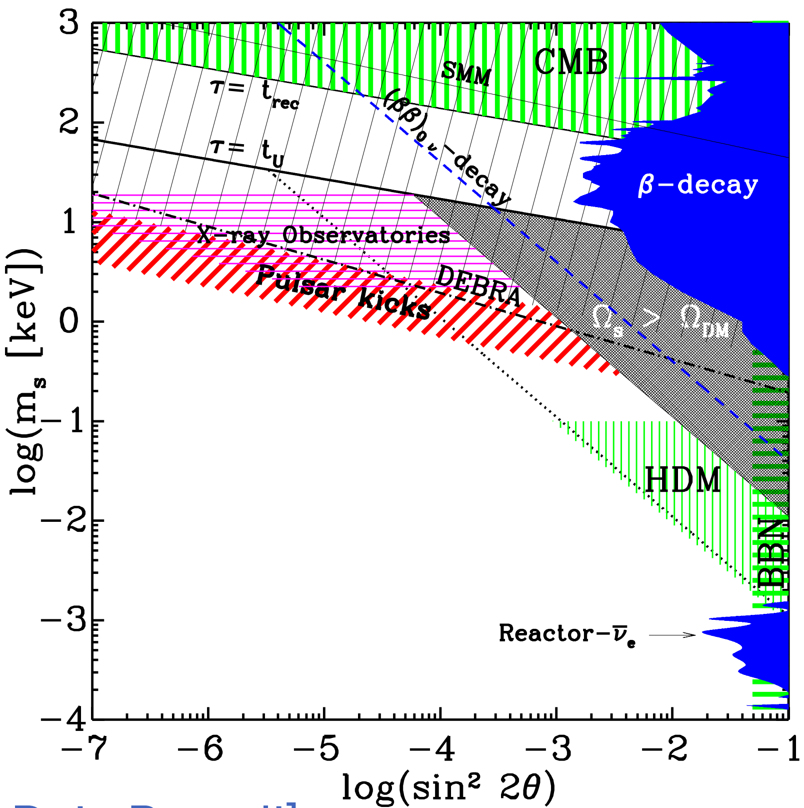


non-zero lepton asymmetry changes the dark matter range

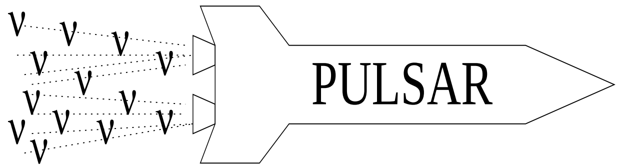
[Abazajian, Fuller, Tucker]

Different cosmology, different limits



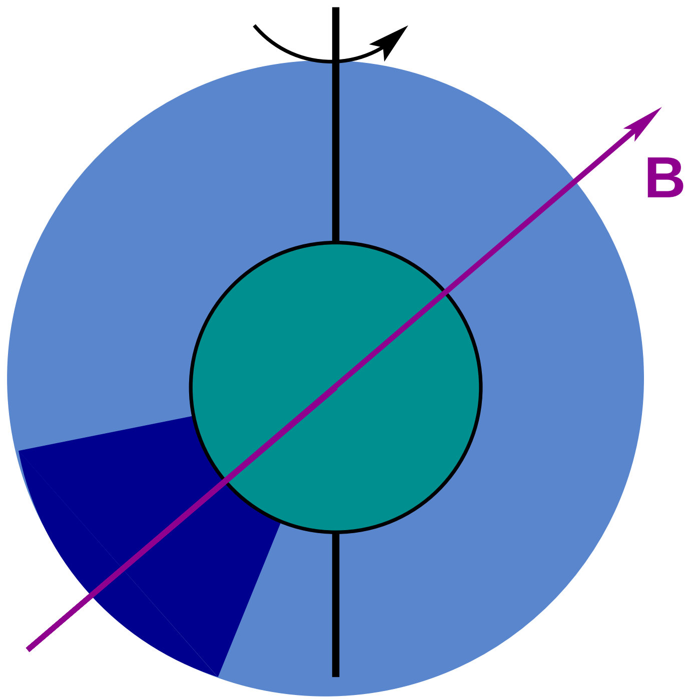
[Gelmini,Palomares-Ruiz,Pascoli]

Gravity waves



Artist's conception by Roulet [Summer School lectures in Trieste]

Rotating "beam" of neutrinos
is the source of GW



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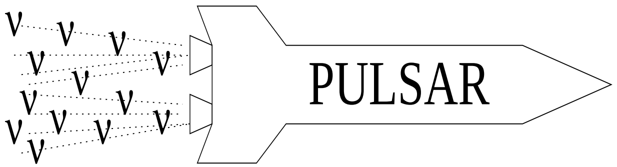

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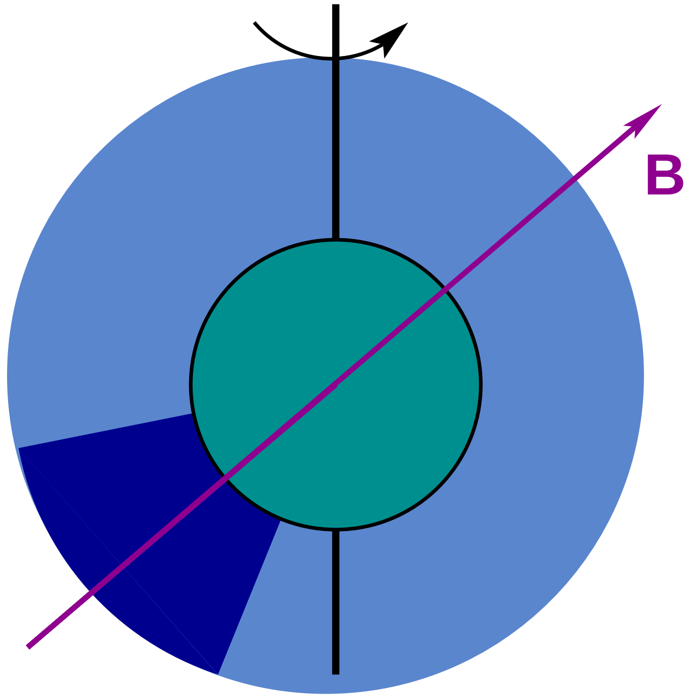

Gravity waves

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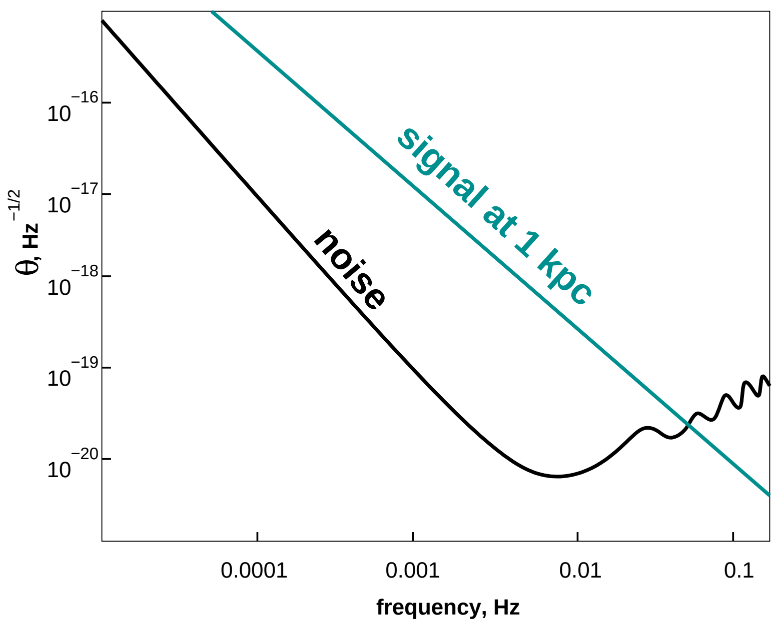
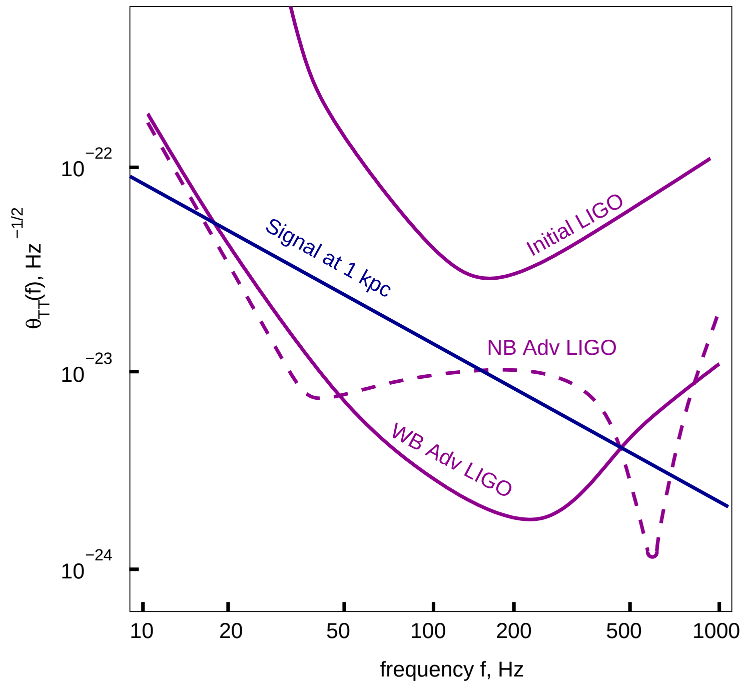
Gravity waves at LIGO and LISA





[Loveridge, PR D **69**, 024008 (2004)]

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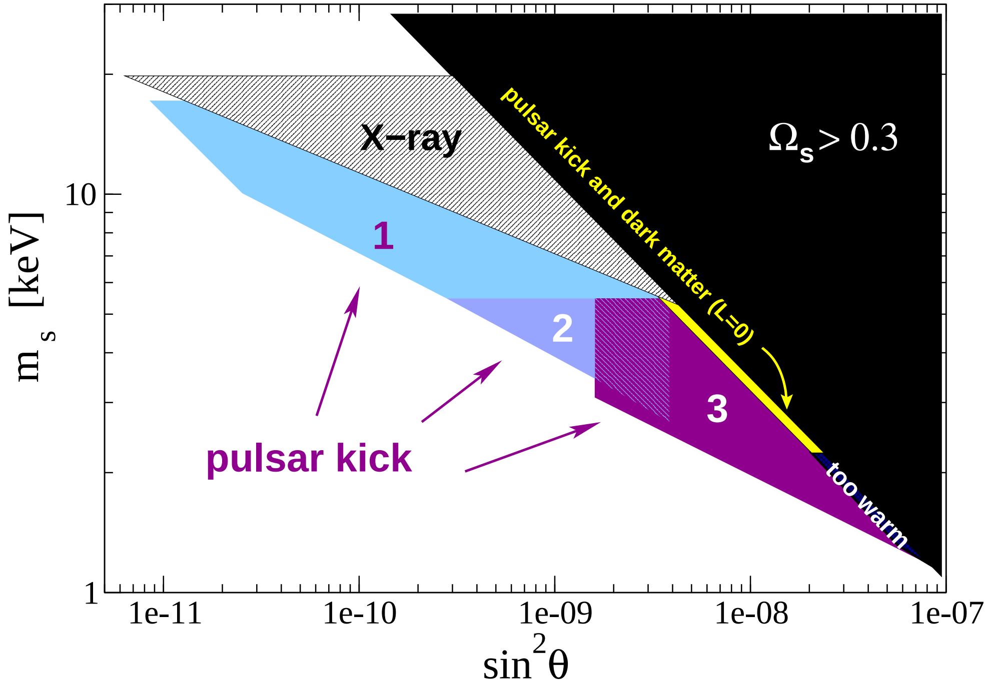

[**AK**, Segrè, PL B396, 197 (1997)]
[Fuller,**AK**,Mocioiu,Pascoli, Phys. Rev. **D 68**, 103002 (2003)]
[**AK**, IJMPD 13, 2065 (2004); astro-ph/0409521]