Pulsar kicks
and a possible signal from a nearby supernova

- Pulsar kicks and dark matter may have a common explanation
- If so, peculiar signal may be detected LIGO and LISA

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

LIGO-G050029-00-Z

Gravity waves from a supernova

- Supernovae would have made a much better source if the explosions were asymmetric
- Pulsars receive a kick at birth in a supernova. Origin unknown.
- Some explanations of the pulsar kicks predict a strong signal

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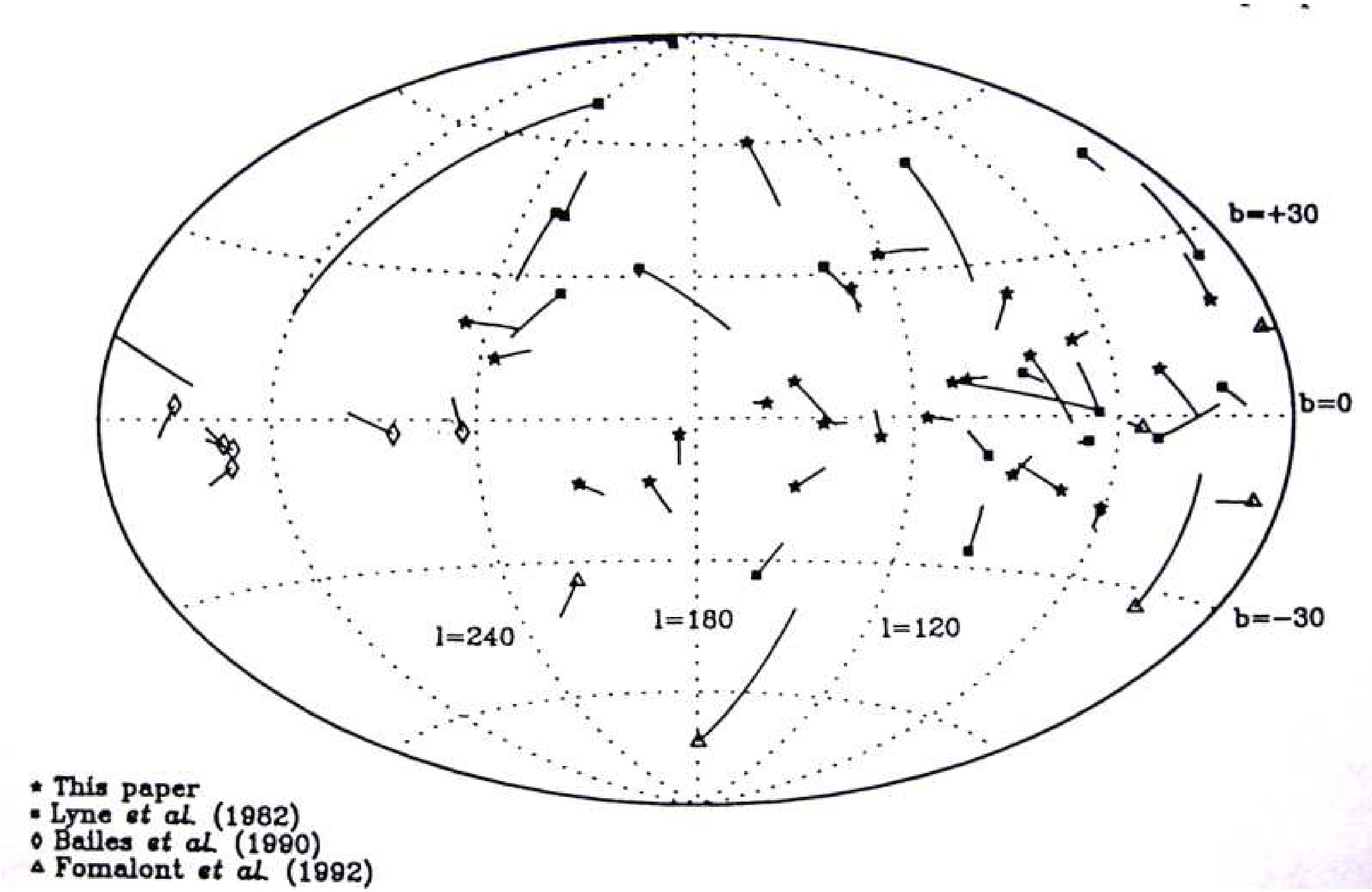
Pulsar velocities

Pulsars have large velocities, $\langle v \rangle \approx \mathbf{250 - 450\ km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

A significant population with $v > \mathbf{700\ km/s}$,
about 15 % have $v > \mathbf{1000\ km/s}$, up to $\mathbf{1600\ km/s}$.
[Arzoumanian *et al.*; Thorsett *et al.*;]

The high-velocity population is so large that some suggested the distribution is two-component, with average velocities $v_1 \approx \mathbf{90 km/s}$ and $v_2 \approx \mathbf{500 km/s}$ [Cordes, Chernoff]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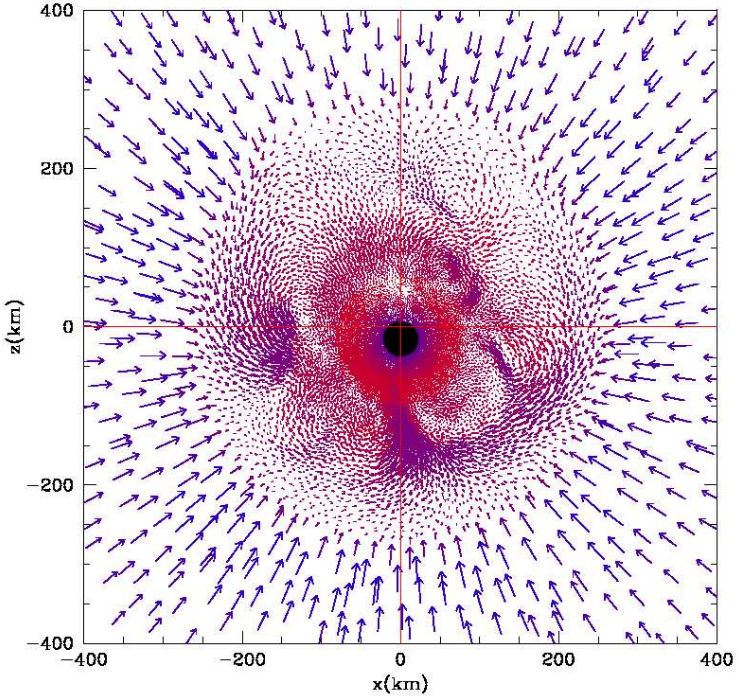
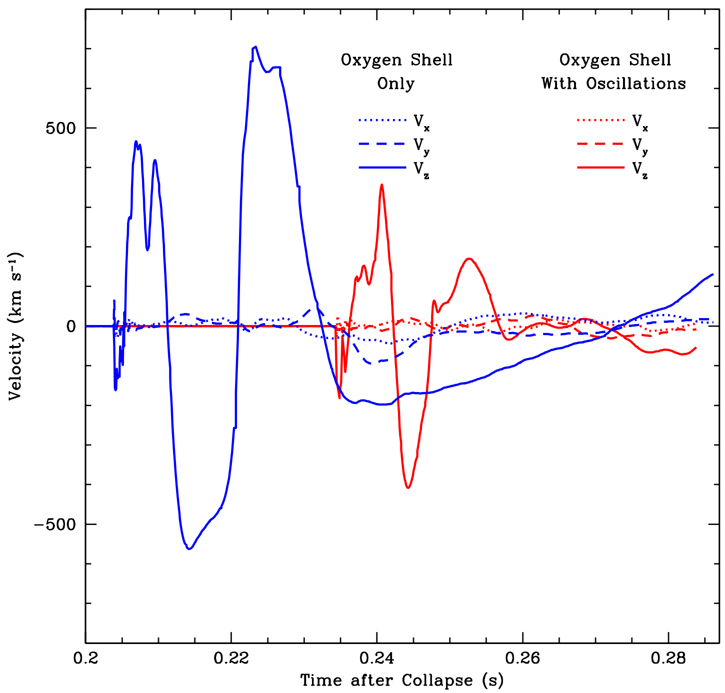
★ This paper
▪ Lyne et al. (1982)
◊ Bailes et al. (1990)
△ Fomalont et al. (1992)

Proposed explanations:

- asymmetric collapse [Shklovskii] (small kick)
- evolution of close binaries [Gutt, Gunn, Ostriker] (not enough)
- acceleration by EM radiation [Harrison, Tademaru] (kick small, predicted polarization not observed)
- asymmetry in EW processes that produce neutrinos [Chugai; Dorofeev, Rodinov, Ternov] (asymmetry washed out)
- "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

Nuclear reactions in stars lead to a formation of a heavy iron core. When it reaches $M \approx 1.4 M_\odot$, the pressure can no longer support gravity. $\Rightarrow$ collapse.

Energy released:

$$\Delta E \sim \frac{G_N M^2_{\rm Fe\ core}}{R} \sim 10^{53} {\rm erg}$$

99% of this energy is emitted in neutrinos

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Pulsar kicks from neutrino emission?

Pulsar with $v \sim 500$ km/s has momentum

$$M_{\odot} v \sim 10^{41} \text{ g cm/s}$$

SN energy released: 10^{53} erg $\Rightarrow$ in neutrinos. Thus, the total neutrino momentum is

$$P_{\nu;\,\text{total}} \sim 10^{43} \text{ g cm/s}$$

a **1% asymmetry** in the distribution of **neutrinos**

is sufficient to explain the pulsar kick velocities

But what can cause the asymmetry??

Magnetic field?

Neutron stars have large magnetic fields. A typical pulsar has surface magnetic field $B \sim 10^{12} - 10^{13}$ G.

Recent discovery of *soft gamma repeaters* and their identification as *magnetars*

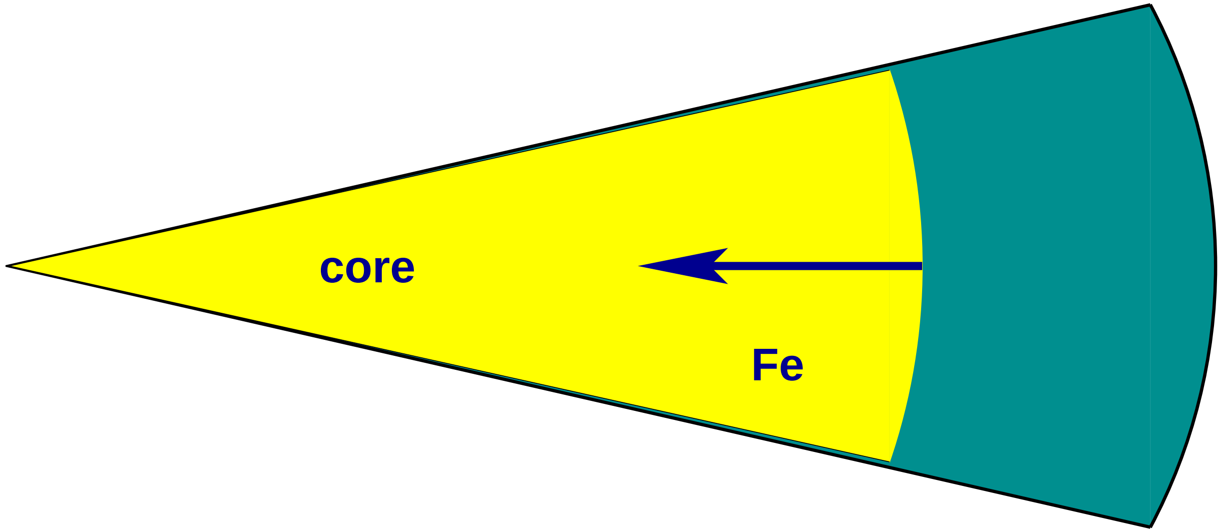
$\Rightarrow$ some neutron stars have surface magnetic fields as high as $10^{15} - 10^{16}$ G.

$\Rightarrow$ **magnetic fields inside can be $10^{15} - 10^{16}$ G.**

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

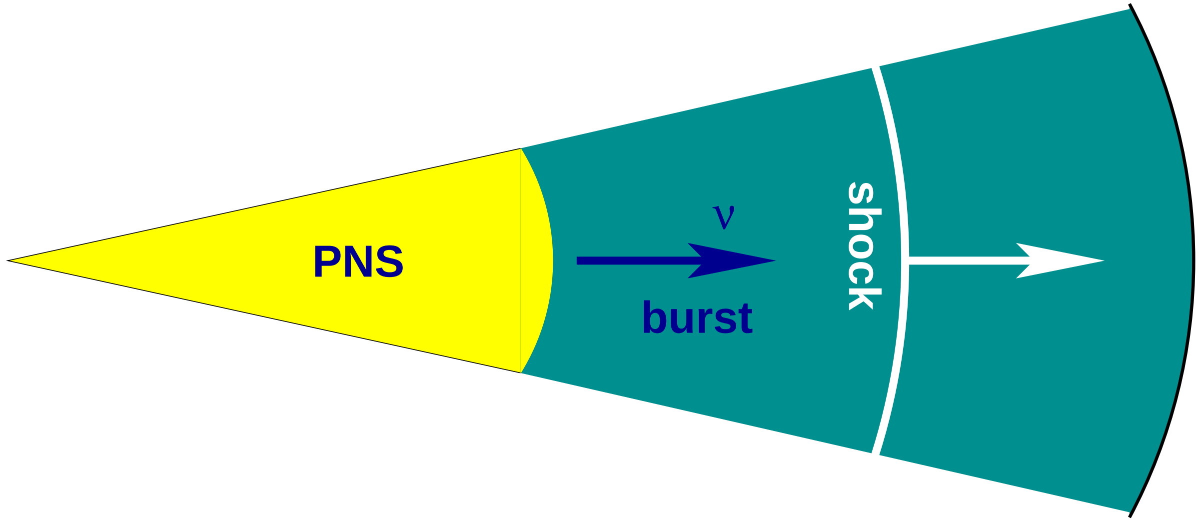
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

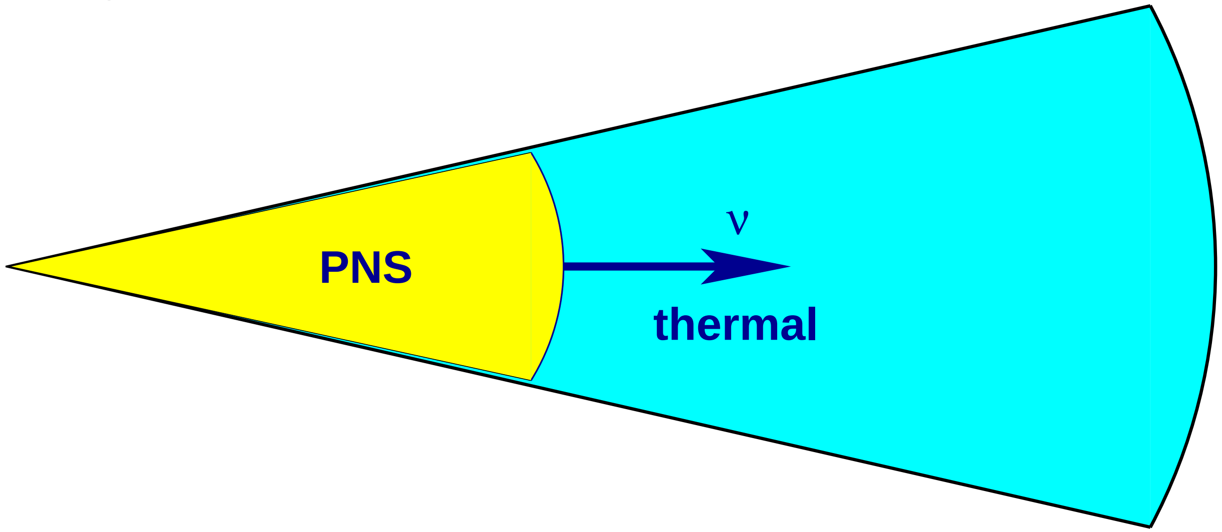
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



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.

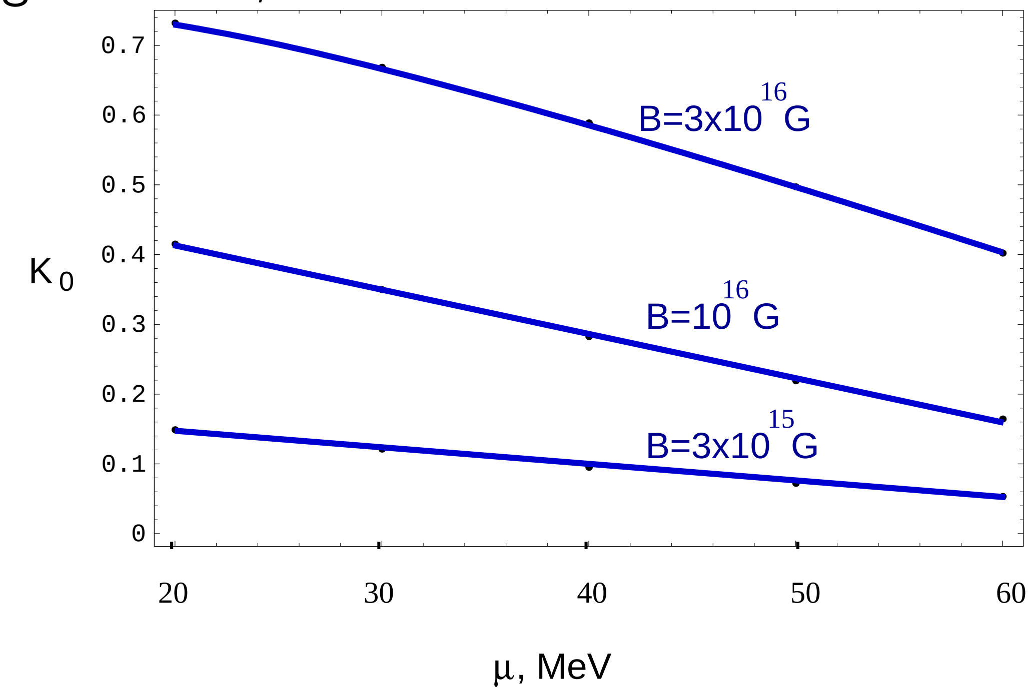
$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

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.

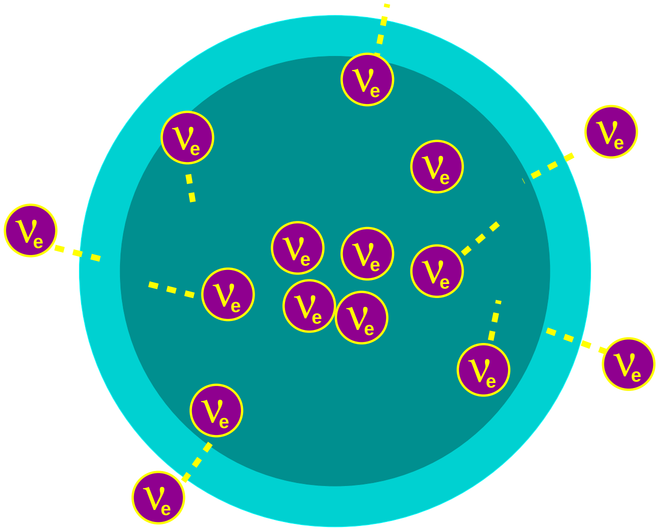
In a strong magnetic field,



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

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

Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?



Neutrinos are trapped at high density.

Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

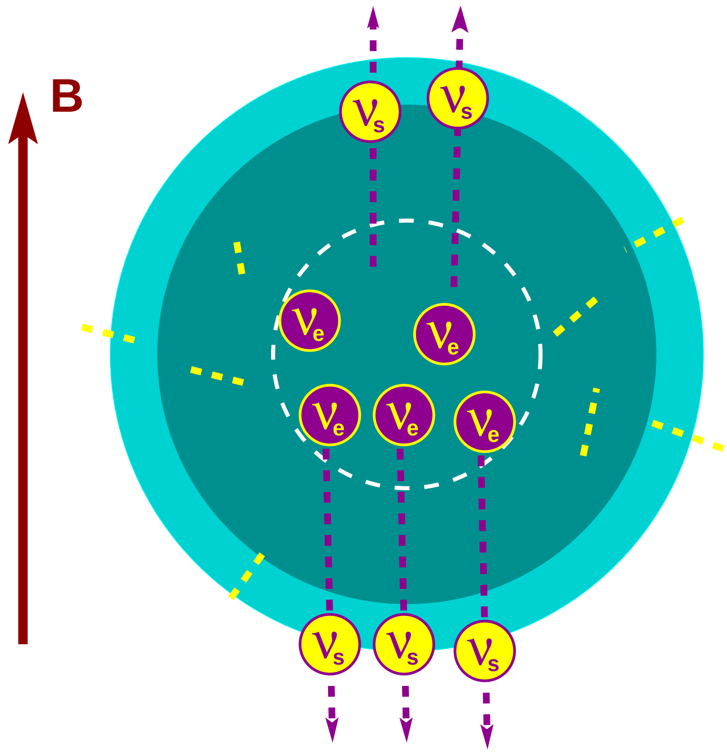
No

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

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

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

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

The coupling of ν_2 to weak currents is also suppressed, and $\sigma \propto \sin^2\theta$.

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 oscillatino length, and $\lambda_{\rm s}$ is the scattering length.

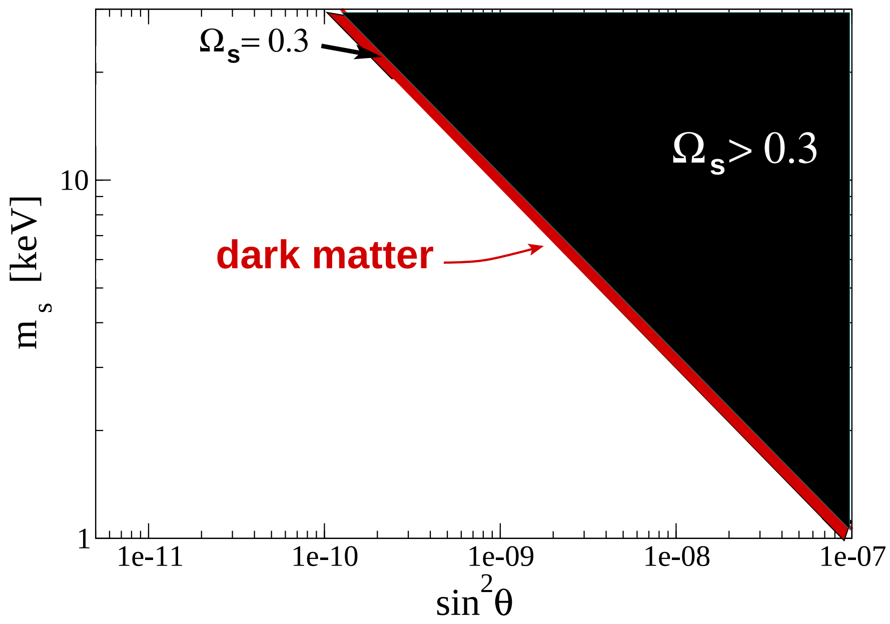
Sterile neutrinos in cosmology: dark matter

Sterile neutrinos are produced in primordial plasma through oscillations.

The resulting density of relic sterile neutrinos:

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

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



A sterile neutrino in this range, consistent with dark matter, can also explain the observed velocities of pulsars though $\nu_e \longrightarrow \nu_s$ oscillations in a supernova.

Active-sterile conversions in a neutron star

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

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

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

Mixing angle in matter is different from vacuum:

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

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

$$\simeq (-0.2 ... + 0.5) V_0, \quad (5)$$

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 $V_m \gg (\Delta m^2 / 2k)$.

$$\begin{cases} |\nu_1\rangle = \cos\theta_m|\nu_e\rangle - \sin\theta_m|\nu_s\rangle \\ |\nu_2\rangle = \sin\theta_m|\nu_e\rangle + \cos\theta_m|\nu_s\rangle \end{cases} \tag{6}$$

The coupling of ν_2 to weak currents is also suppressed, and $\sigma \propto \sin^2\theta$.

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

$$\langle P_{\rm m}\rangle = \frac{1}{2}\left[1 + \left(\frac{\lambda_{\rm osc}}{2\lambda_{\rm s}}\right)^2\right]^{-1} \sin^2 2\theta_m, \tag{7}$$

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

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

$$V_m = \frac{G_F \rho}{\sqrt{2} m_n}(3Y_e - 1 + 4Y_{\nu_e} + 2Y_{\nu_\mu} + 2Y_{\nu_\tau}). \tag{8}$$

$V_m > 0 \quad \Rightarrow$ Transitions $\nu_e \to \nu_s \quad \Rightarrow V_m$ decreases

$V_m < 0 \quad \Rightarrow$ Transitions $\bar{\nu}_e \to \nu_s \quad \Rightarrow V_m$ increases

Therefore, [Abazajian, Fuller, Patel]

$$V_m \to 0$$

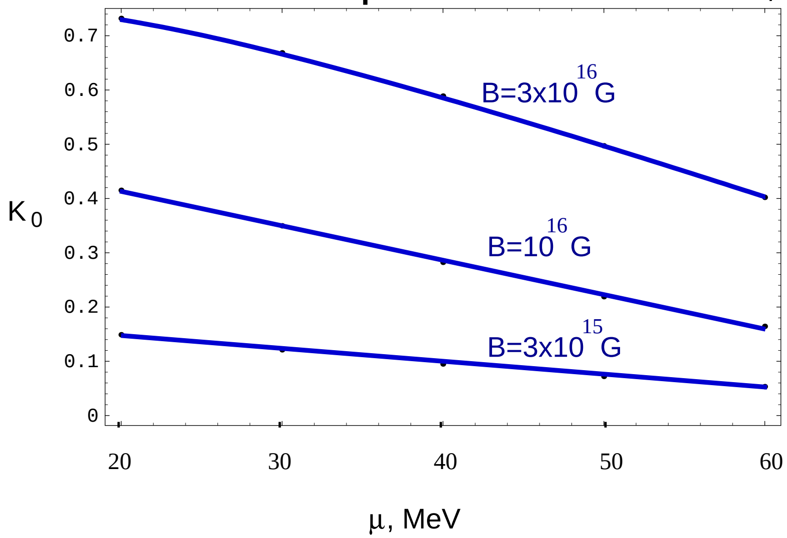
$$\sin\theta_m \to \sin\theta_0$$

production of ν_s is unsuppressed

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

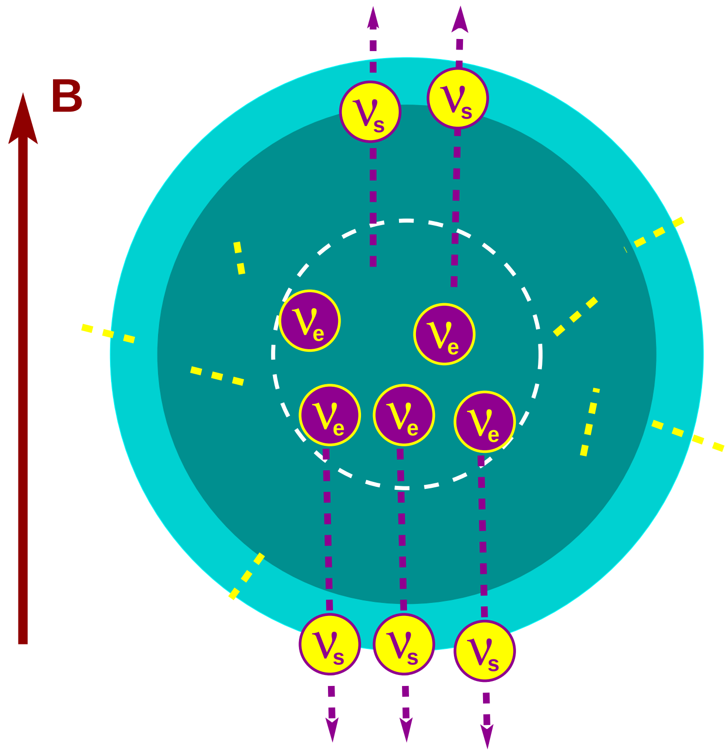
$$p + e^- \rightleftharpoons n + \nu_e \text{ and } n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

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



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

$$r_{\mathcal{E}} = \left(\frac{\mathcal{E}_{\rm s}}{\mathcal{E}_{\rm tot}} \right) \sim 0.05 - 0.7, \tag{9}$$

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

$$\epsilon \sim 0.02 \left(\frac{k_0}{0.3} \right) \left(\frac{r_{\mathcal{E}}}{0.5} \right), \tag{10}$$

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.

$$\tau_V \simeq \frac{V_m^{(0)} m_n}{\sqrt{2} G_F \rho} \Big(\int d\Pi \frac{\sigma_\nu^{\rm urca}}{e^{(\epsilon_\nu - \mu_\nu)/T} + 1} \langle P_m(\nu_e \to \nu_s) \rangle - \int d\Pi \frac{\sigma_{\bar\nu}^{\rm urca}}{e^{(\epsilon_{\bar\nu} - \mu_{\bar\nu})/T} + 1} \langle P_m(\bar\nu_e \to \bar\nu_s) \rangle \Big)^{-1}, \quad (11)$$

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]

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

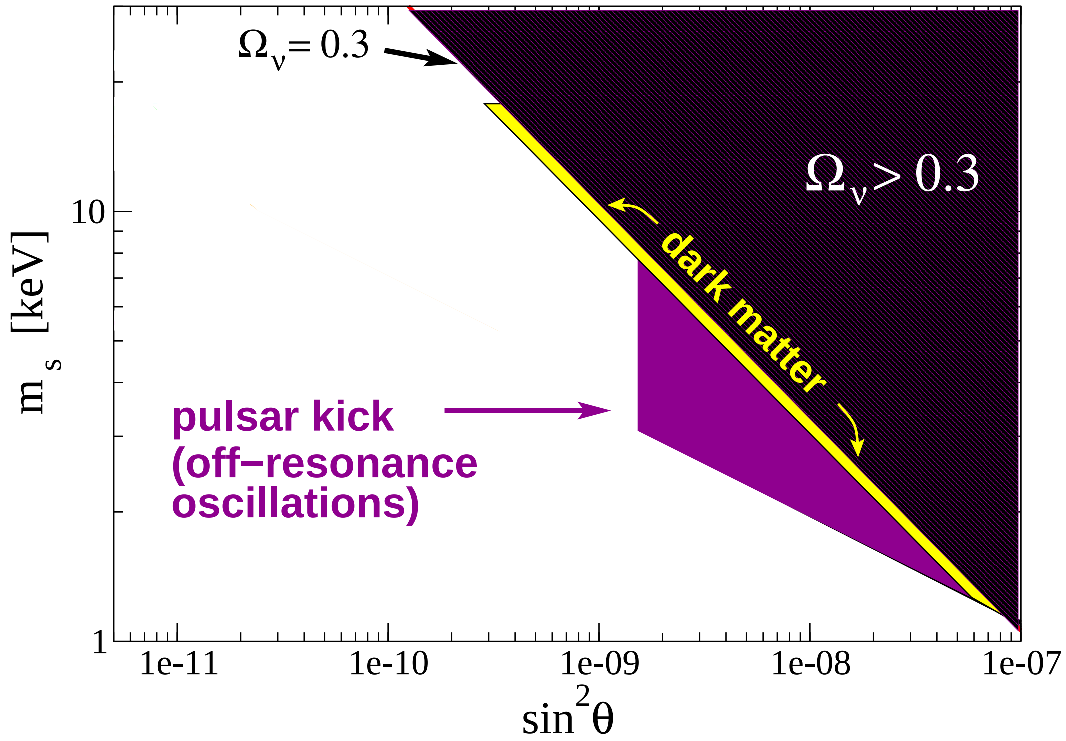
$$\sim \left(\frac{2\times 10^{-9}\text{s}}{\sin 2\theta}\right)\left(\frac{10^{14}\frac{g}{cm^3}}{\rho}\right)\left(\frac{20\,\text{MeV}}{T}\right)^6\left(\frac{\Delta m^2}{10\,\text{keV}^2}.\right)$$

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

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

[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

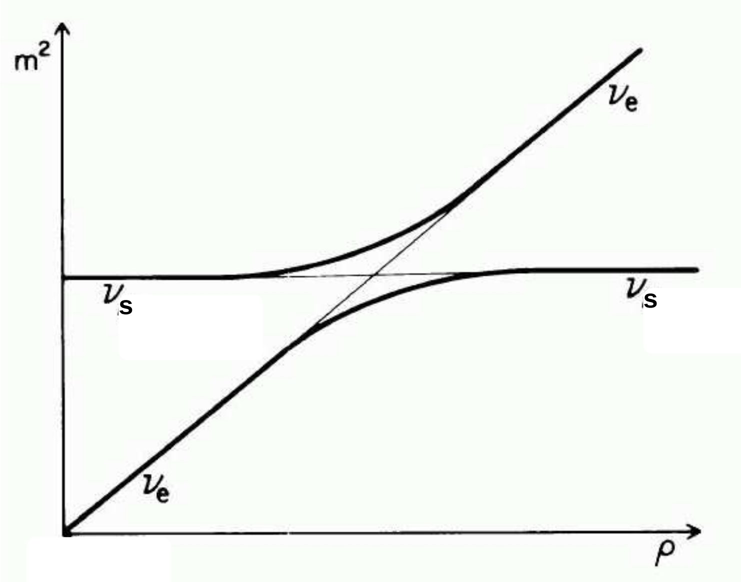
Matter potential:

$$\begin{aligned} V(\nu_s) &= 0 \\ V(\nu_e) &= -V(\bar{\nu}_e) = V_0\,(3\,Y_e - 1 + 4\,Y_{\nu_e}) \\ V(\nu_{\mu,\tau}) &= -V(\bar{\nu}_{\mu,\tau}) = V_0\,(Y_e - 1 + 2\,Y_{\nu_e}) \;+\; c_{_L}^{_Z}\,\frac{\vec{k}\cdot\vec{B}}{k} \end{aligned}$$

$$c_{_L}^{_Z} = \frac{eG_{_F}}{\sqrt{2}}\left(\frac{3N_e}{\pi^4}\right)^{1/3}$$

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

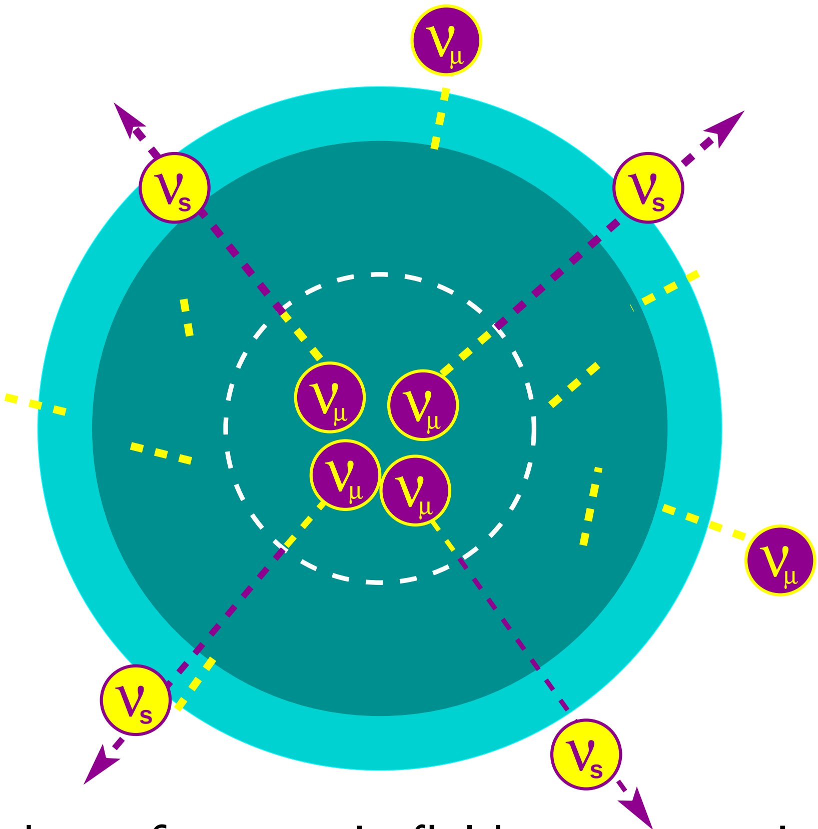
$$\frac{m_i^2}{2k}\cos 2\theta_{ij} + V(\nu_i) = \frac{m_j^2}{2k}\cos 2\theta_{ij} + V(\nu_j) \tag{12}$$

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.

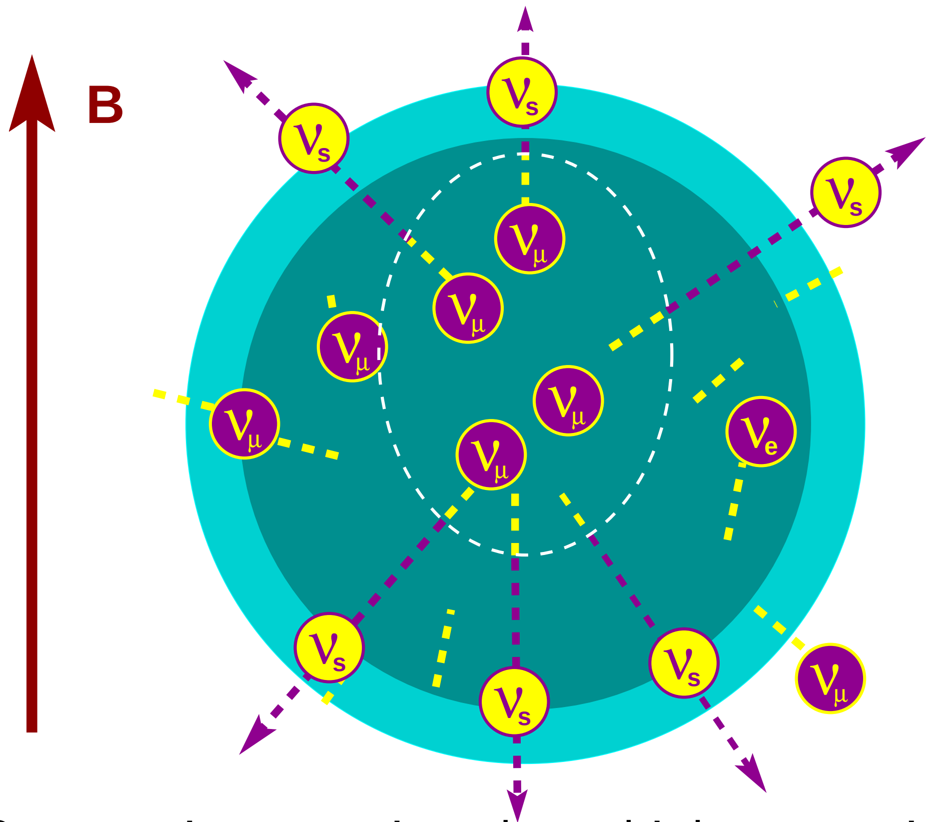
Temperature is a function of r. The energy of an escaping sterile neutrino depends on the temperature of at the point it was produced.

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



In the absebce of magnetic field, ν_s escape isotropically

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



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:

$$r(\phi) = r_0 + \delta \cos \phi, \tag{13}$$

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

$$2 \frac{dN_n(r)}{dr} \delta \approx e \left(\frac{3N_e}{\pi^4} \right)^{1/3} B. \tag{14}$$

This yields

$$\delta = \left(\frac{3N_e}{\pi^4}\right)^{1/3} \frac{e}{2} B \Big/ \frac{dN_n(r)}{dr} = \frac{e\mu_e}{2\pi^2} B \Big/ \frac{dN_n(r)}{dr}, \quad (15)$$

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):

$$\frac{\Delta k}{k} = \frac{1}{3} \frac{T^4(r_0-\delta) - T^4(r_0+\delta)}{T^4(r_0)} \approx \frac{8}{3} \frac{1}{T} \frac{dT}{dr} \delta \quad (16)$$

$$\approx \frac{4e}{3\pi^2} \left(\frac{\mu_e}{T} \frac{dT}{dN_n}\right) B \quad (17)$$

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,

$$\frac{\Delta k}{k} = \frac{4e\sqrt{2}}{\pi^2} \frac{\mu_e \mu_n^{1/2}}{m_n^{3/2} T^2} B. \tag{18}$$

At the core density $\rho \sim 10^{14}$ g/cm^3, one gets the asymmetry

$$\boldsymbol{\frac{\Delta k}{k} = \frac{4e\sqrt{2}}{\pi^2} \frac{\mu_e \mu_n^{1/2}}{m_n^{3/2} T^2} B \sim 0.01 \left(\frac{B}{10^{15}\mathrm{G}} \right)} \tag{19}$$

[AK,Segrè]

A more careful calculation gives the same order of magnitude [Barkovich *et al.*, PR **D66**, 123005 (2002); AK, Segrè, PR **D D59** 061302 (1999)].

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

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

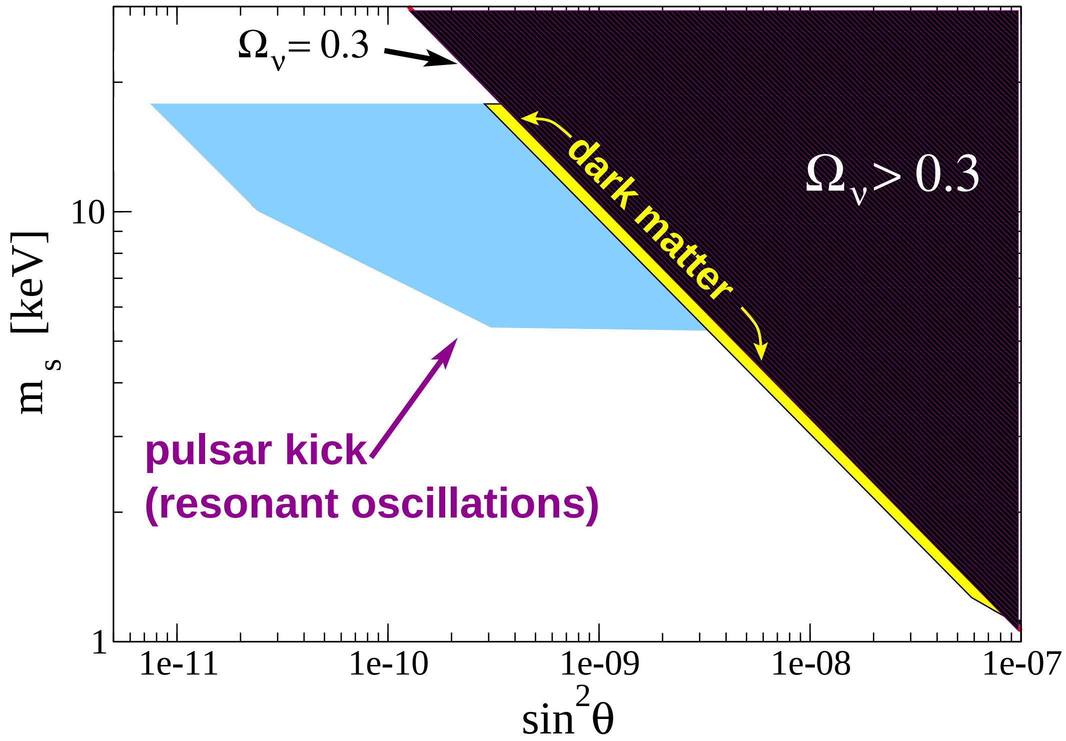
Adiabaticity: the oscillation length

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

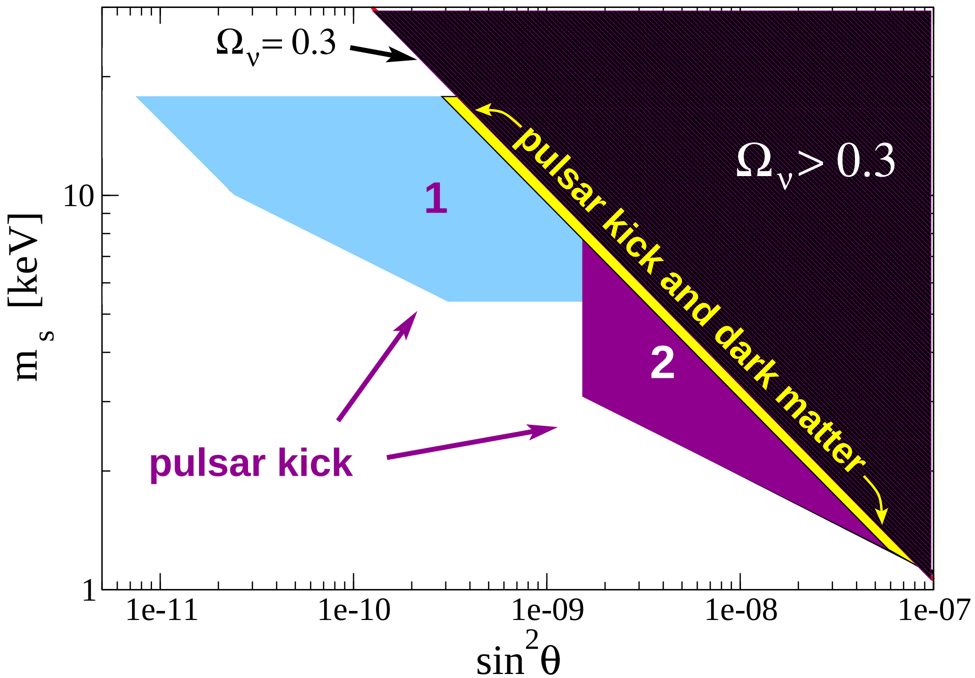
must be smaller than (1) the scale height of density (2) the mean free path of neutrinos. $\Rightarrow$

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

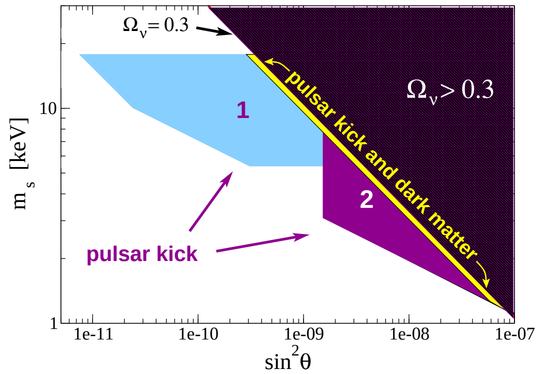
The range of parameters [AK, Segrè; Fuller,**AK**,Mocioiu,Pascoli]:



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



the pulsar kick regions overlap with the dark matter region



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

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?

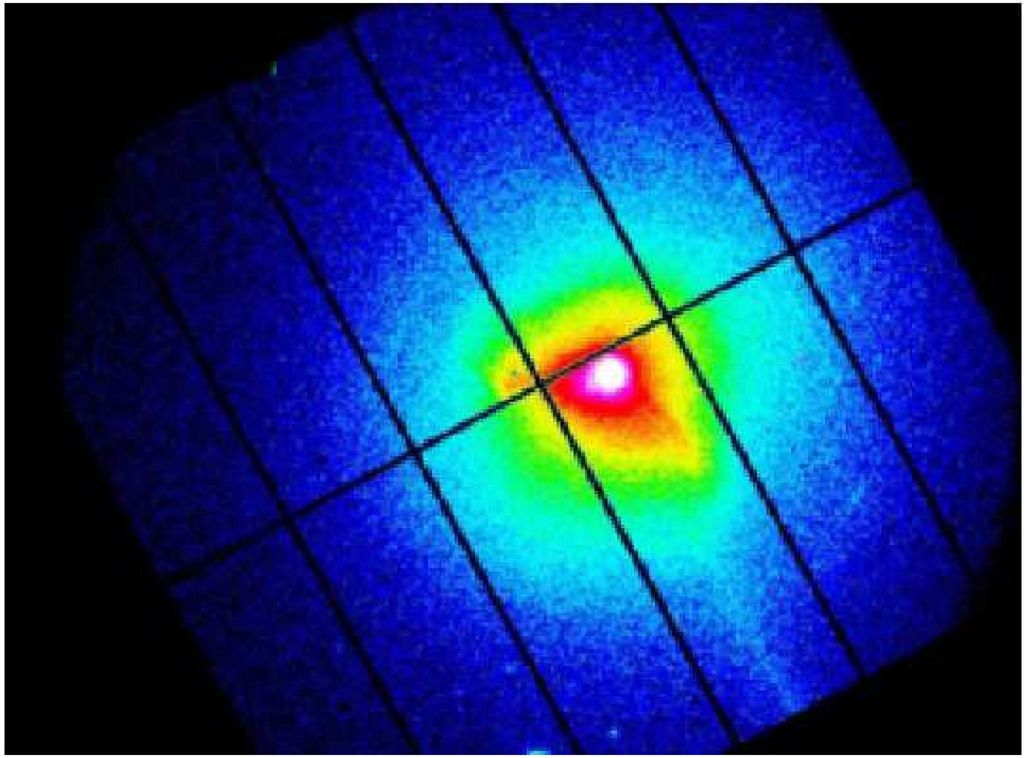
Why not ordinary active neutrinos?

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

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

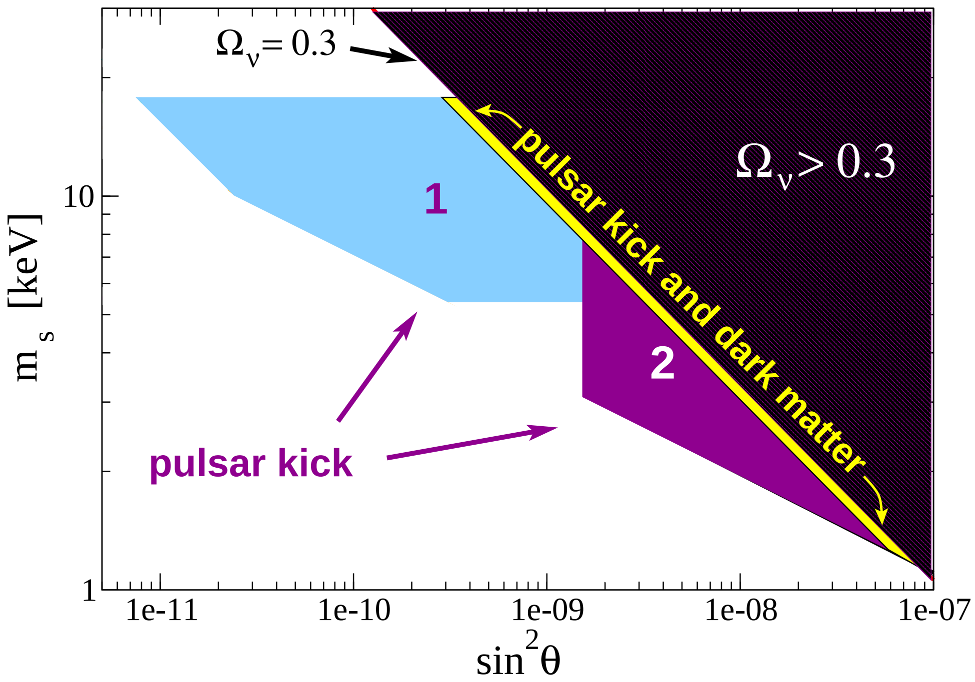
This is inconsistent with experimental/cosmological limits.

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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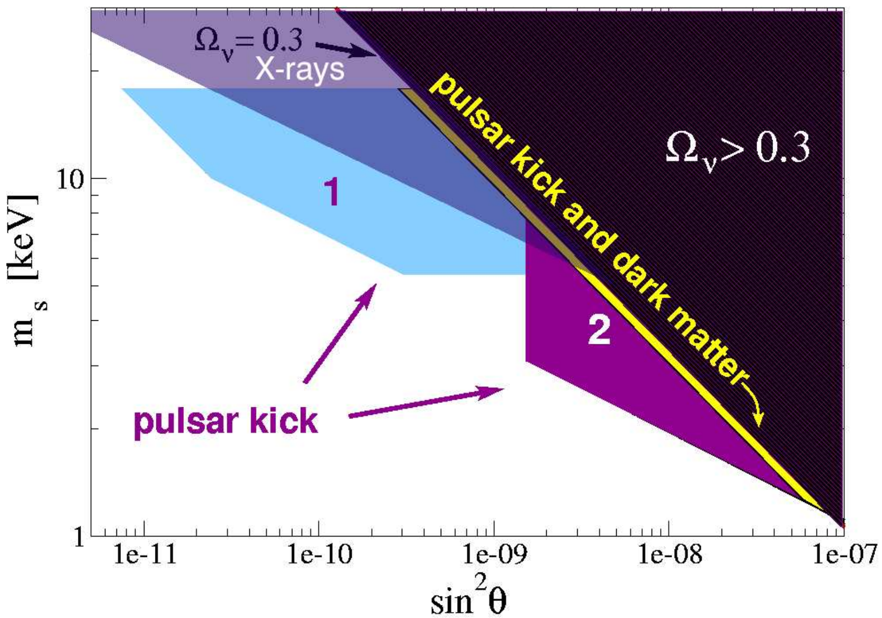
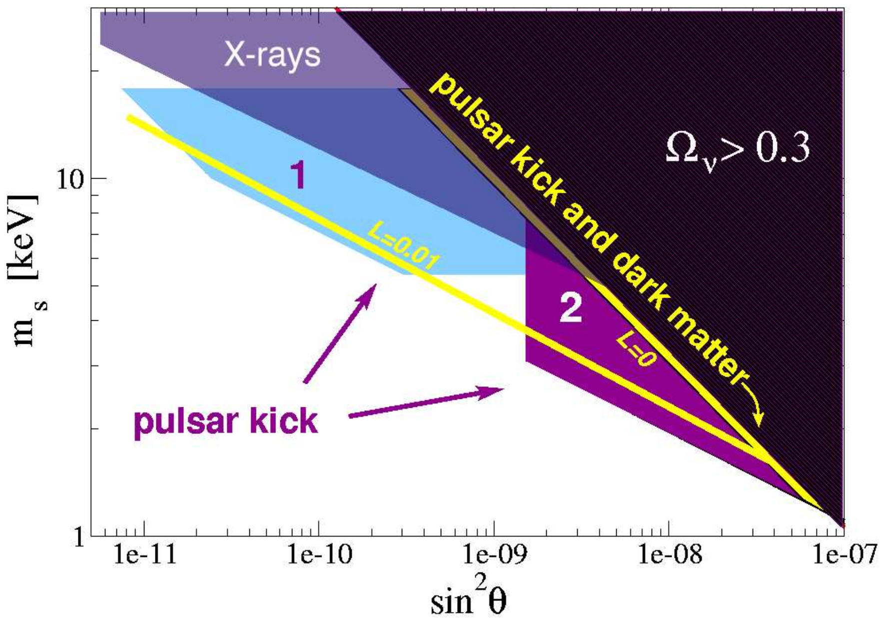


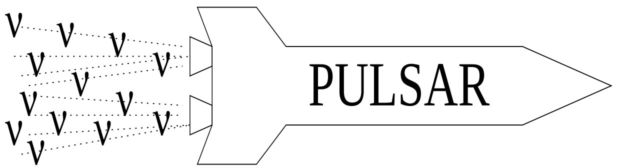
[Abazajian, Fuller, Tucker]

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



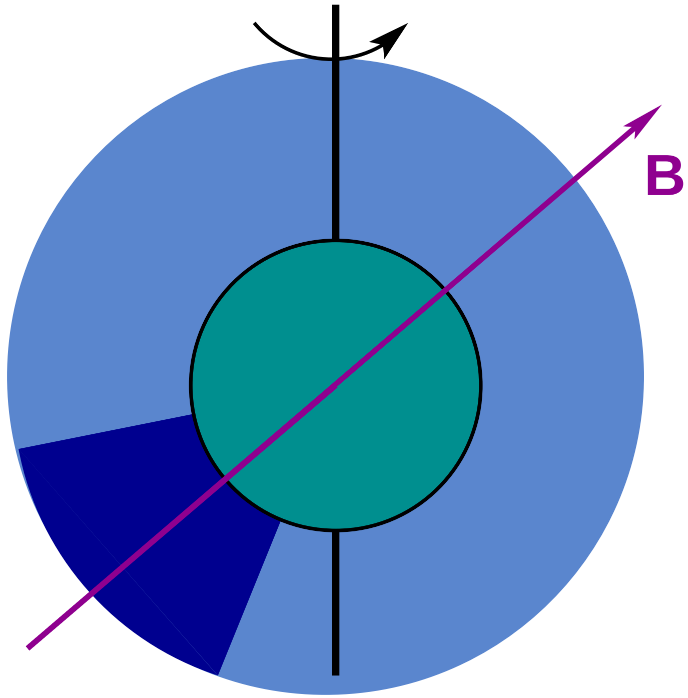
non-zero lepton asymmetry changes the dark matter range
[Abazajian, Fuller, Tucker]

Gravity waves

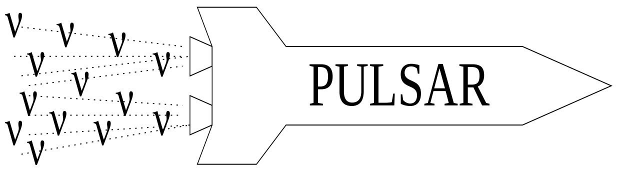


Artist's conception by Roulet [Summer School lectures in Trieste]

Rotating "beam" of neutrinos
is the source of GW

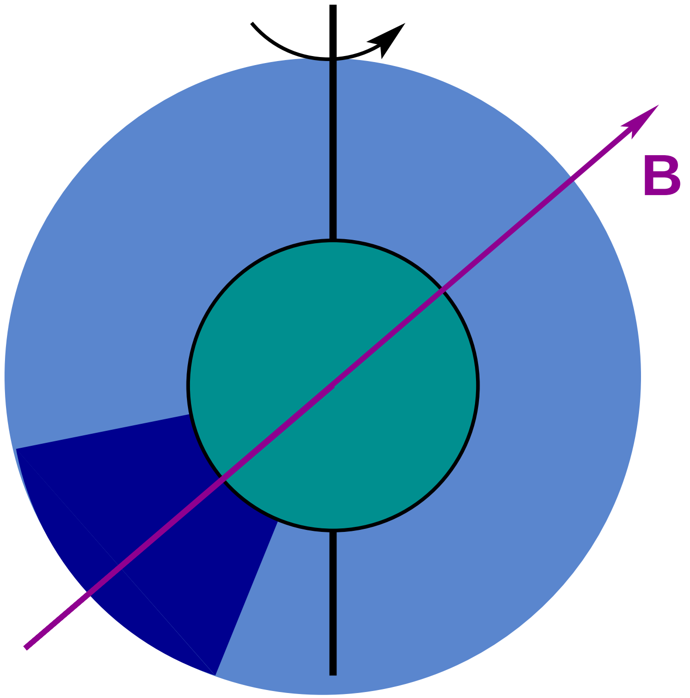


Gravity waves

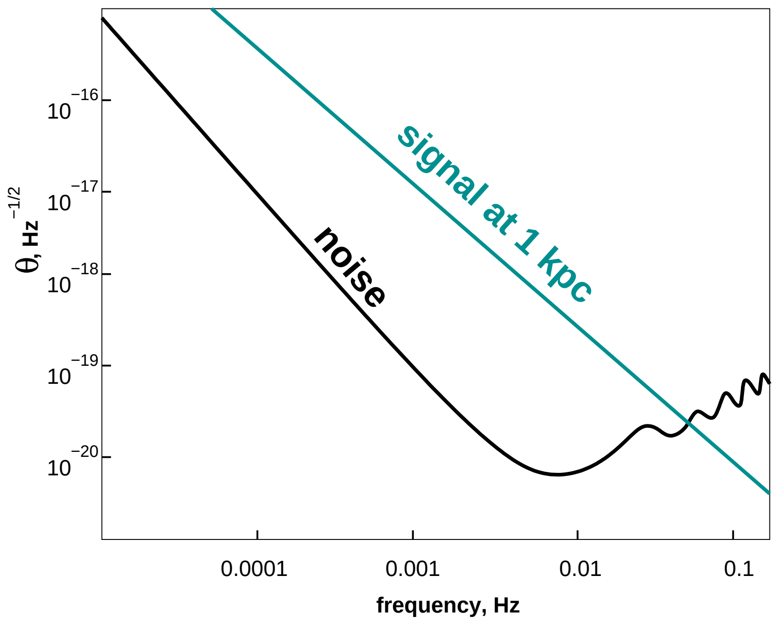


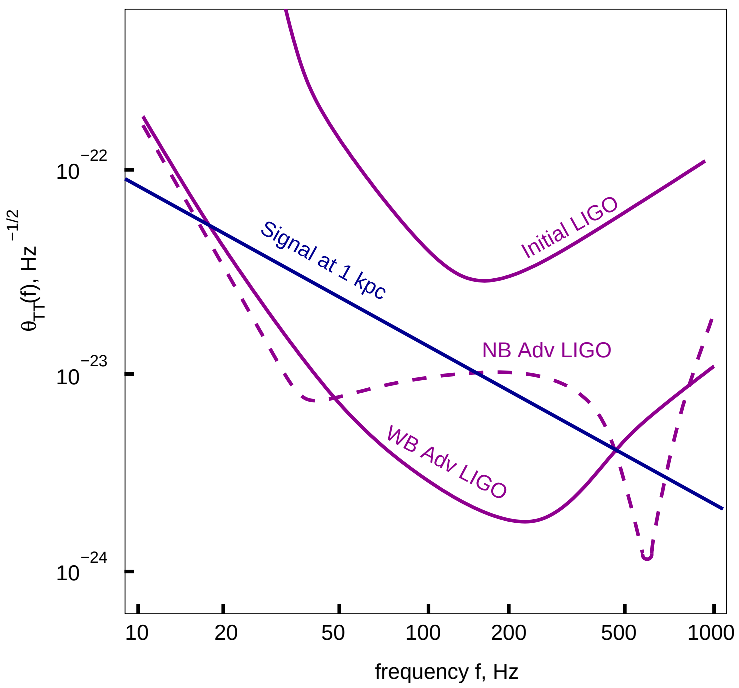
Artist's conception by Roulet [Summer School lectures in Trieste]

Rotating "beam" of neutrinos
is the source of GW



Gravity waves at LIGO and LISA





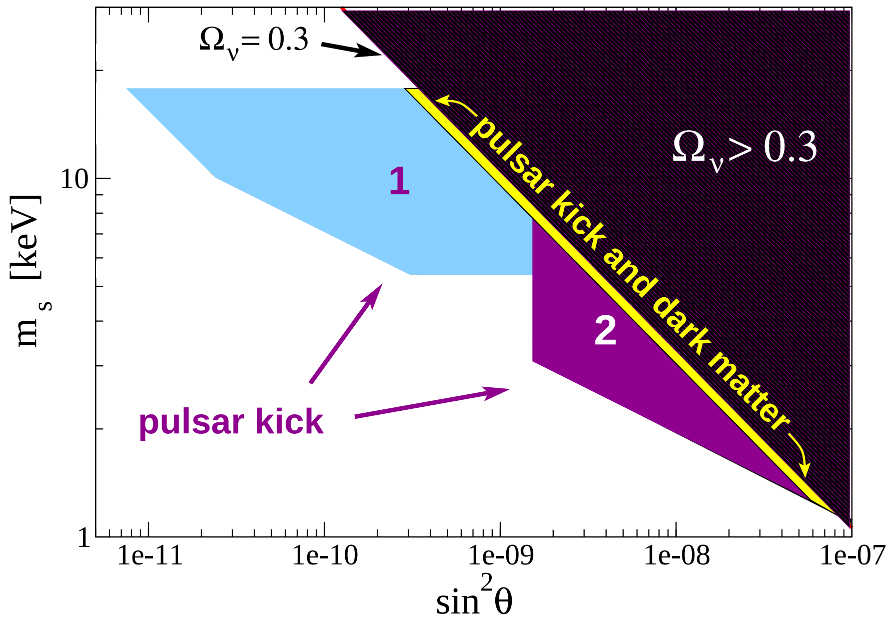
[Loveridge, Phys. Rev. D69 024008 (2004)]

LIGO- G050029- 00- Z

Conclusions

- Sterile neutrinos in the 1-20 keV range can explain the observed pulsar kicks
- The same neutrino could be the dark matter
- **Two puzzles from a single new particle**
- **Minimal extension of the Standard Model that is consistent with cosmology**
- Can verify this mechanism through observations of X-rays from nearby clusters, or from gravity waves in the event of a nearby supernova
- A gravity wave signature not expected form a supernova

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



[**AK**, Segrè, PL B396, 197 (1997)]
[Fuller,**AK**,Mocioiu,Pascoli, Phys. Rev. **D 68**, 103002 (2003)]