# Sterile neutrinos as dark matter

- dark matter candidate: sterile neutrino, $m = 2 - 20\,\text{keV}$
- Pulsar kicks can be explained by neutrino oscillations
- Constraints and searches

[**AK**, Segrè, Fuller, Pascoli, Mocioiu, D'Olivo, et al.]

# Dark matter

## The only data at variance with the Standard Model

The evidence for dark matter is very strong:

- 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 signficant dark matter component.
- clusters are filled with hot X-ray emitting intergalactic gas (without dark matter, this gas would dissipate quickly).

# Dark matter: what is it?

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Can make guesses based on...

- ...compelling theoretical ideas
- ...simplicity
- ...observational clues

# Dark matter: beautiful theoretical ideas

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**SUSY** is an appealing theoretical idea

Dark matter comes as part of the package as one of the following:

- **Neutralino**
- **Gravitino** (produced in freeze-out, or non-thermally)
- **Axino**
- **SUSY Q-balls**

Theoretically motivated!! By no means minimal. No experimental evidence so far.

# Dark matter: a simple (minimalist) solution

Need **one** particle ⇒ add just **one** particle
If a fermion, must be gauge singlet (anomalies)
Interactions only through mixing with neutrinos

⇒ **sterile neutrino**

# 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 $\nu_2$ could take place through oscillations.

The coupling of $\nu_2$ 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 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:

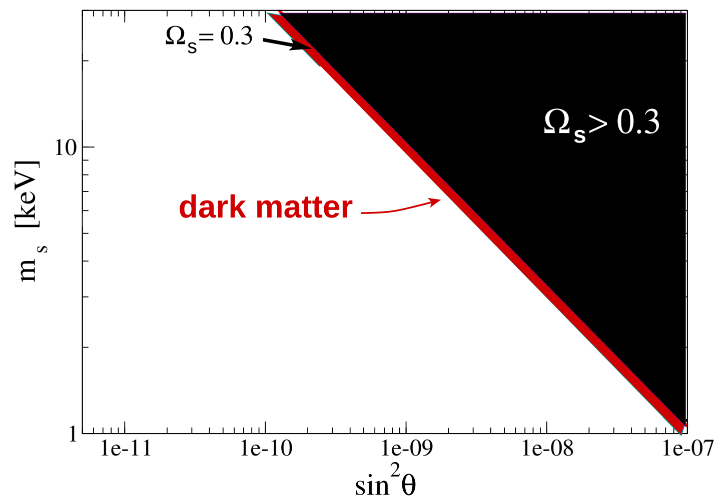
$$\sin^2 2\theta_m = \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V(T))^2}, \quad (3)$$

For small angles,

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

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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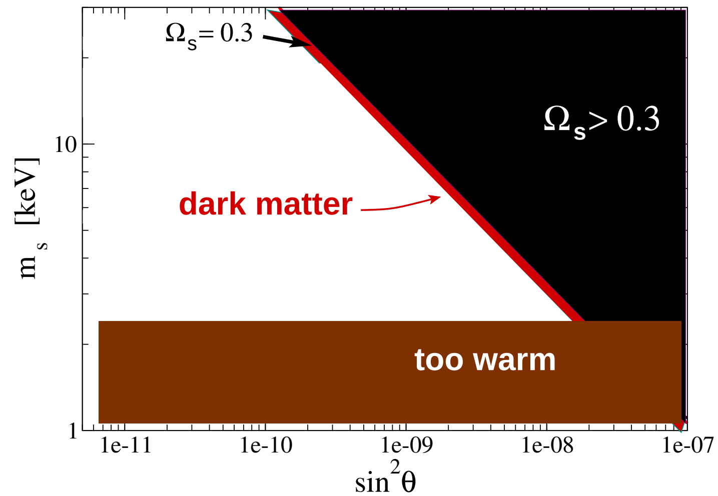
Lyman-$\alpha$ forest clouds show significant structure on small scales. Dark matter must be cold enough to preserve this structure.



# Observational hint: the pulsar velocities

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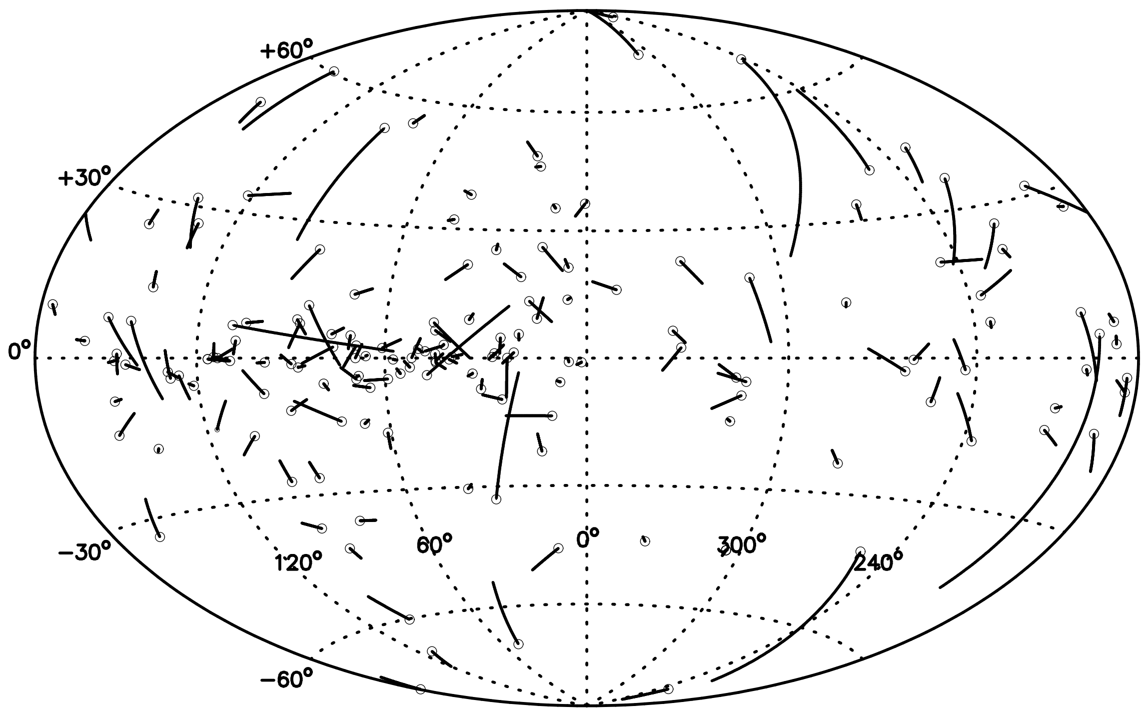
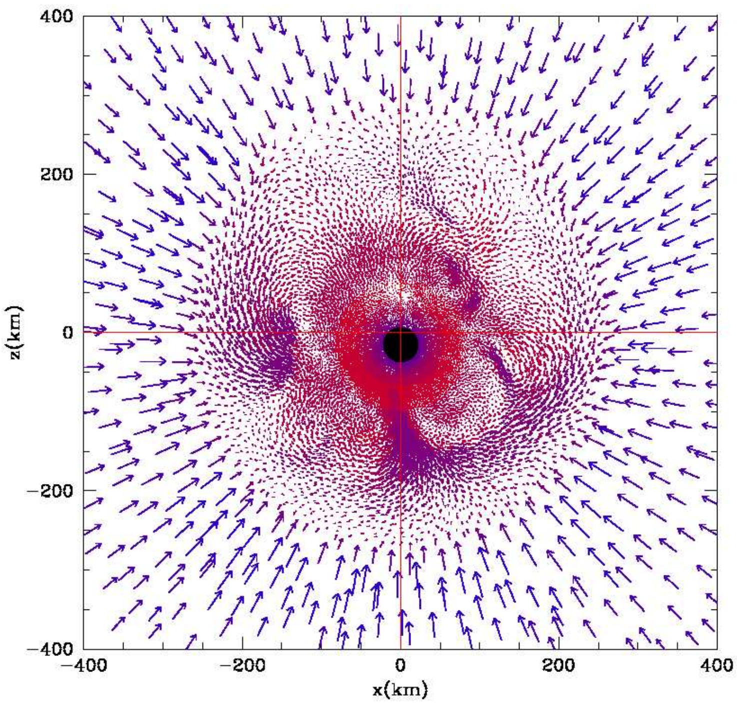
Pulsars have large velocities, $\langle v \rangle \approx \mathbf{250 - 450\ km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.* ]
A significant population with $v > \mathbf{700\ km/s}$,
about **15 %** have $v > \mathbf{1000\ km/s}$, up to $\mathbf{1600\ km/s}$.
[Arzoumanian *et al.*; Thorsett *et al.* ]

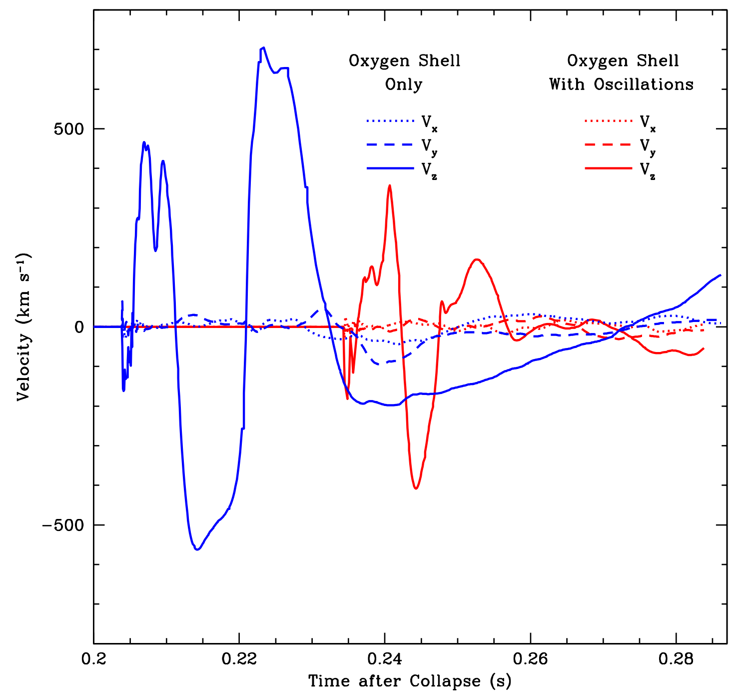

+60°
+30°
0°
−30°
−60°
120°
60°
0°
300°
240°

# Proposed explanations:

- asymmetric collapse [Shklovskii] (small kick)
- evolution of close binaries [Gott, 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:

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

99% of this energy is emitted in neutrinos

# Pulsar kicks from neutrino emission?

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

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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: $t = 0$

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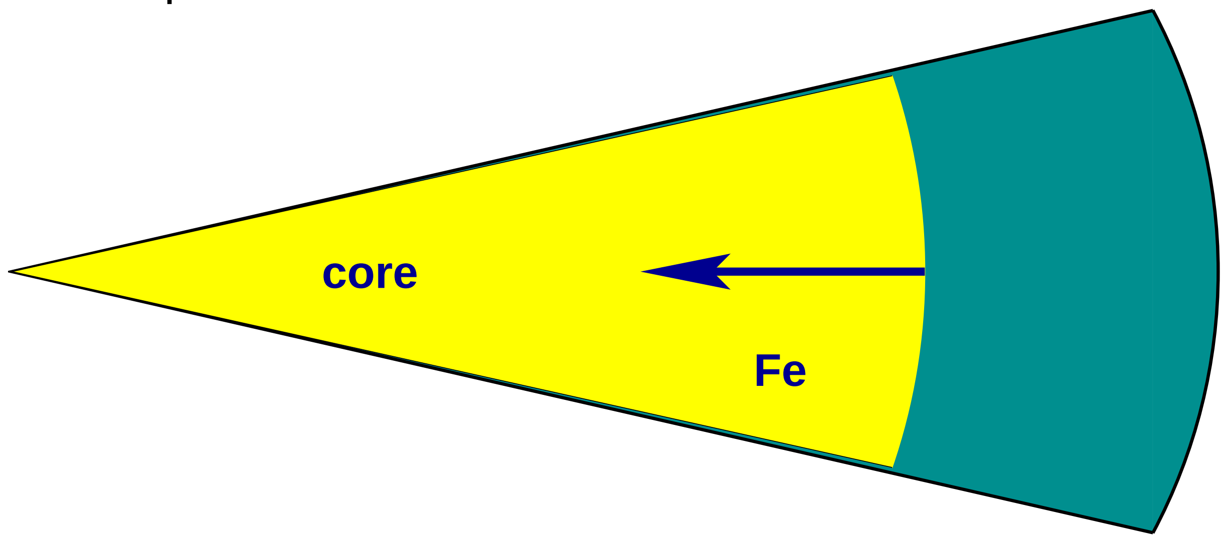
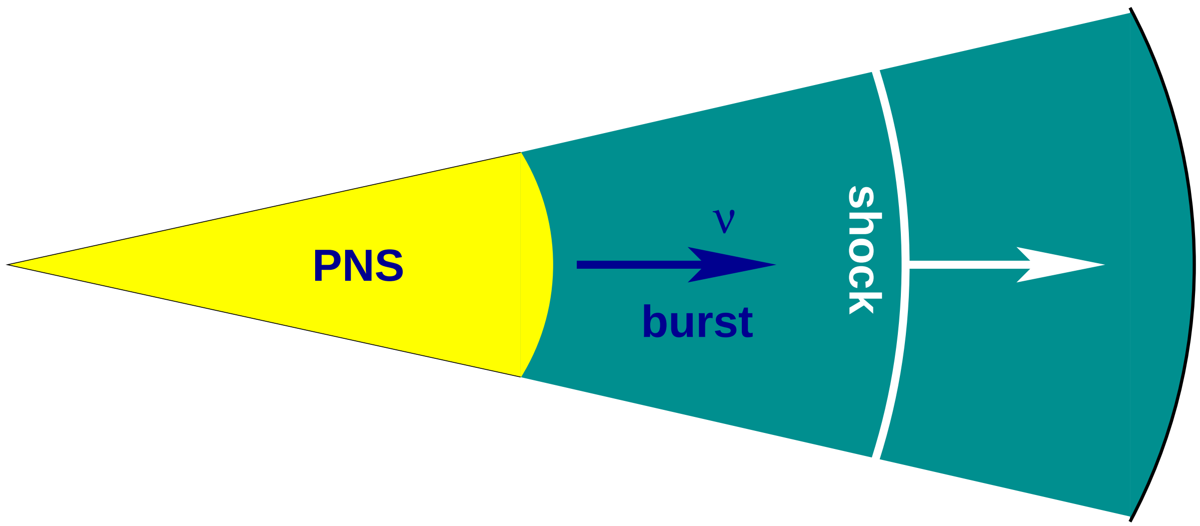


# Core collapse supernova

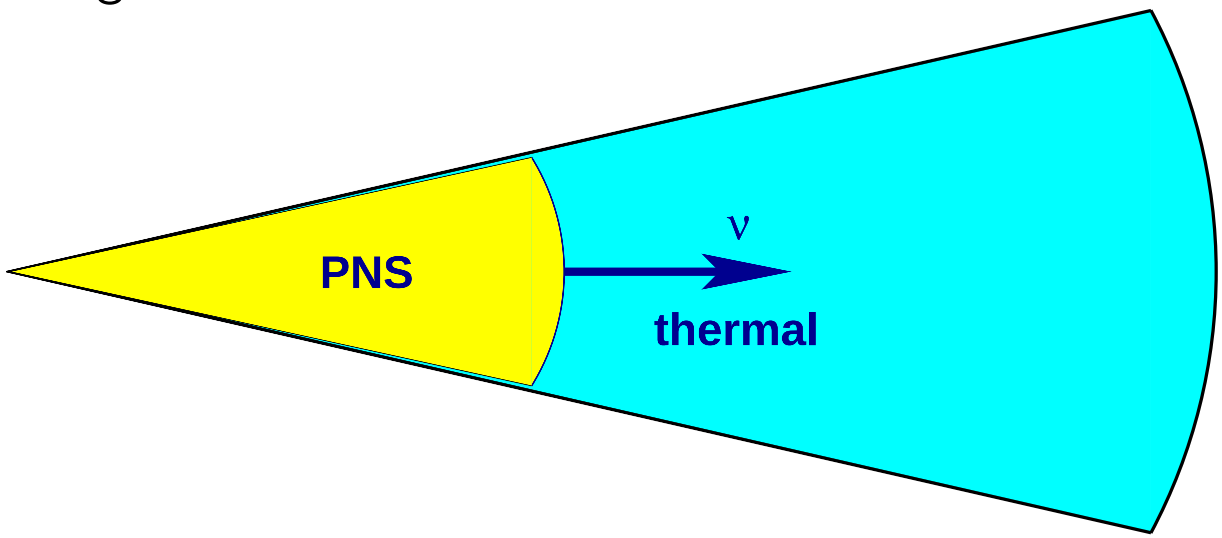
Shock formation and "neutronization burst": $t = 1 - 10$ ms




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.

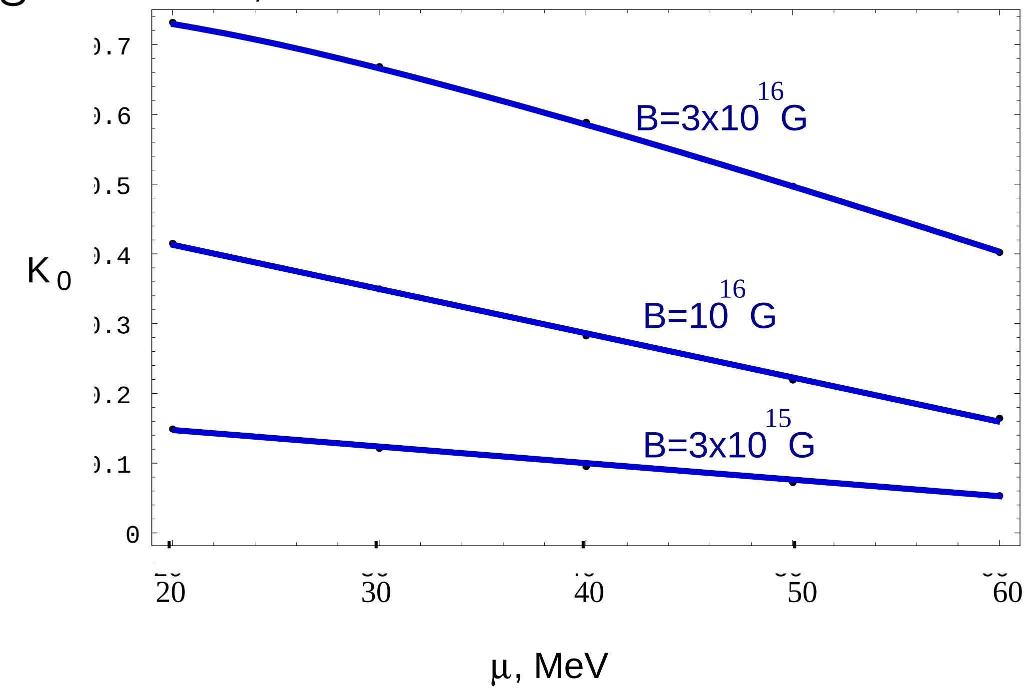
$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

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,

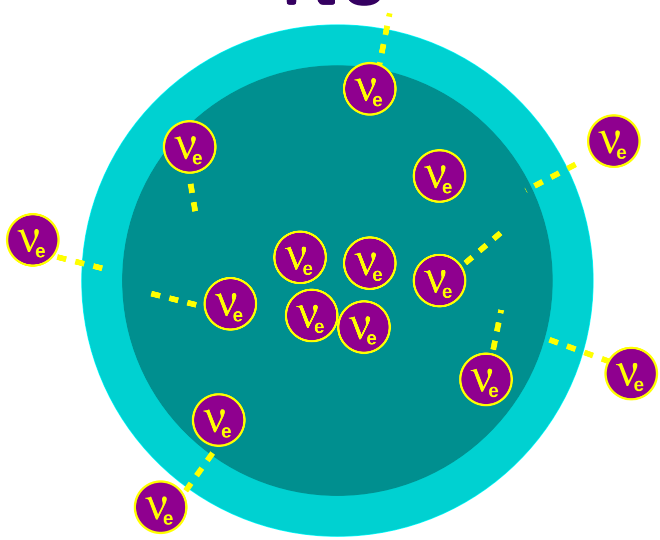



$k_0$ is the fraction of electrons in the lowest Landau level.

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?

## No




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?

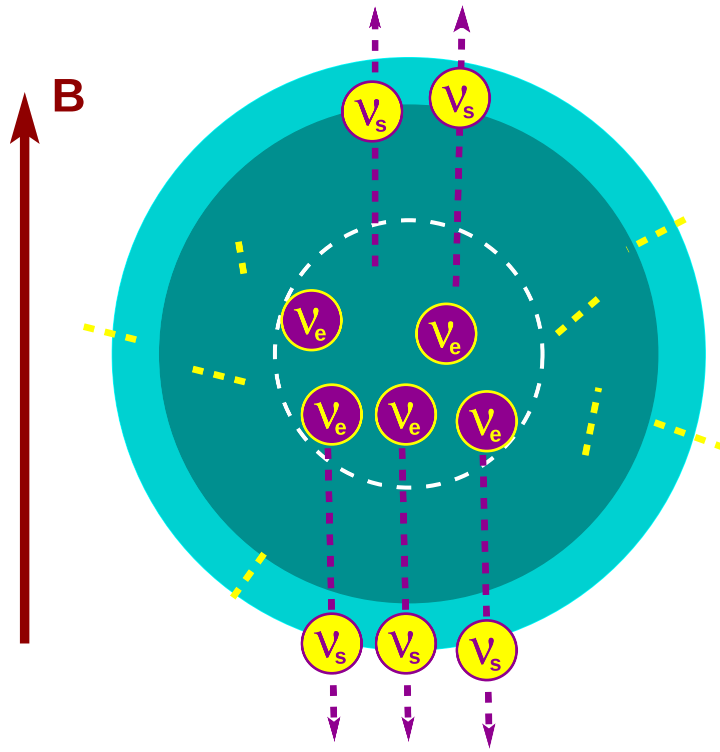
## No

Rescattering washes out the asymmetry [Vilenkin ApJ 451, 700 (1995); AK,Segrè, Vilenkin, PLB 437,359 (1998); Arras,Lai, ApJ 519, 745 (1999)].

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.



# Active-sterile conversions in a neutron star

In matter, there is a potential $V_m$ for $\nu_e$, but not for $\nu_s$:

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

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

Mixing angle in matter is different from vacuum:

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

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

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

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 $V_m \gg (\Delta m^2/2k)$.
The coupling of $\nu_2$ to weak currents is also suppressed, and $\sigma \propto \sin^2 \theta_m$.

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]

$$V_m \to 0$$

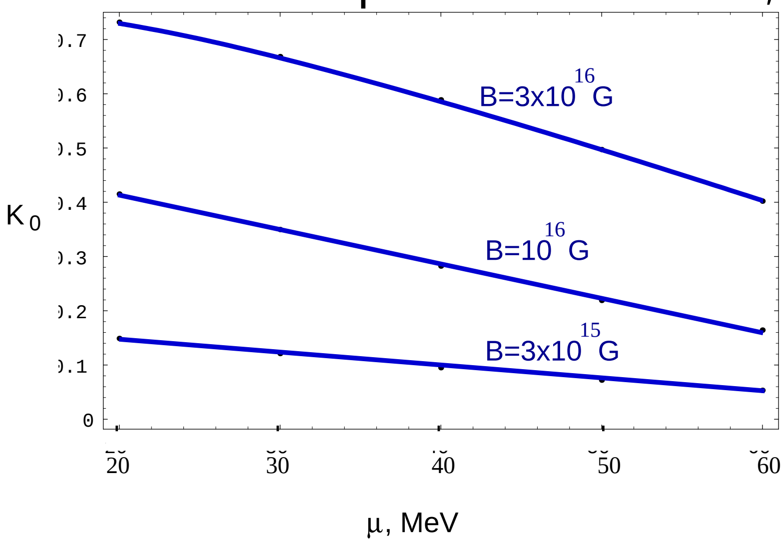
$$\sin\theta_m \to \sin\theta_0$$

production of $\nu_s$ is unsuppressed

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

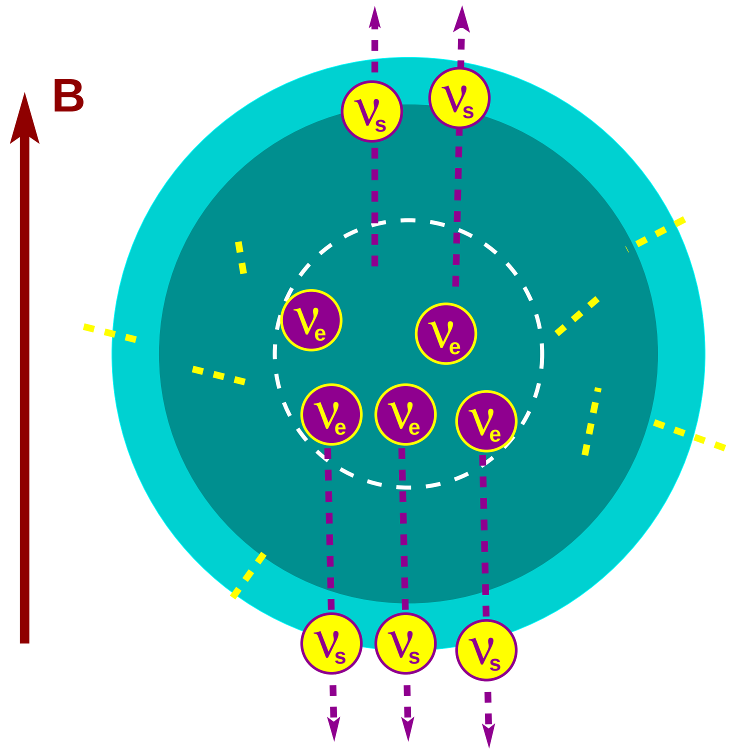
$$p + e^- \rightleftharpoons n + \nu_e \text{ and } n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

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




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 $\sim 1$ s.

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

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]

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

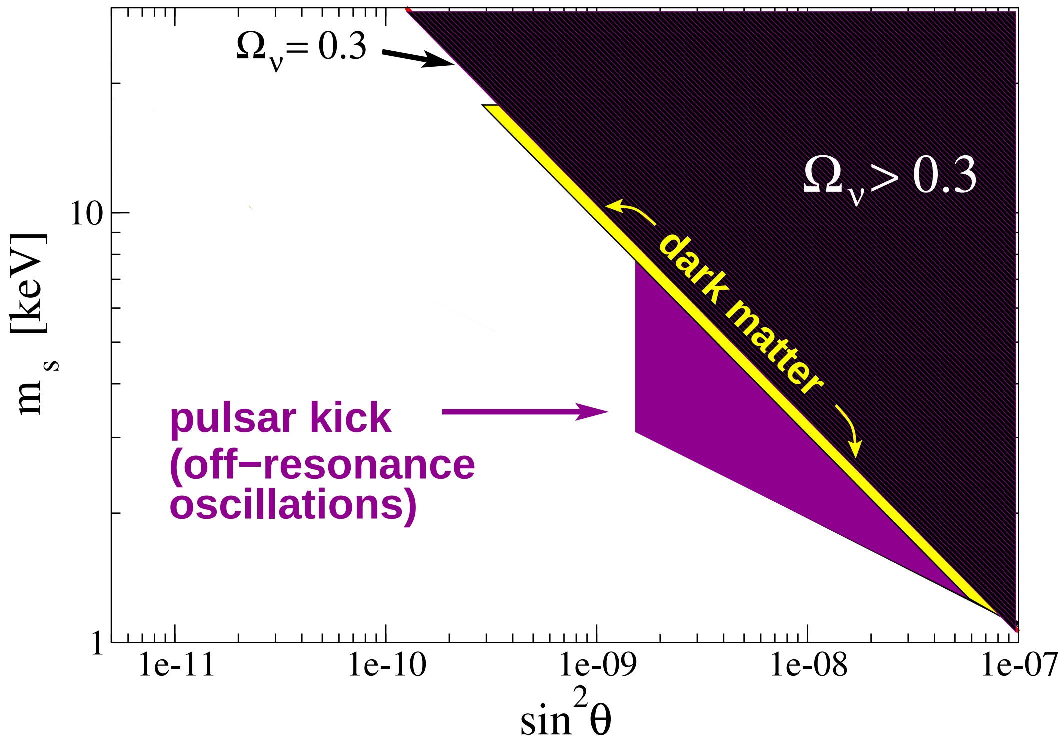
$$\sim \left(\frac{2\times 10^{-9}{\rm s}}{\sin 2\theta}\right)\left(\frac{10^{14}\frac{g}{cm^3}}{\rho}\right)\left(\frac{20\,{\rm MeV}}{T}\right)^6\left(\frac{\Delta m^2}{10\,{\rm keV}^2}.\right)$$

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

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

[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:

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

$$c_L^Z = \frac{eG_F}{\sqrt{2}} \left(\frac{3N_e}{\pi^4}\right)^{1/3}$$

The resonance condition is

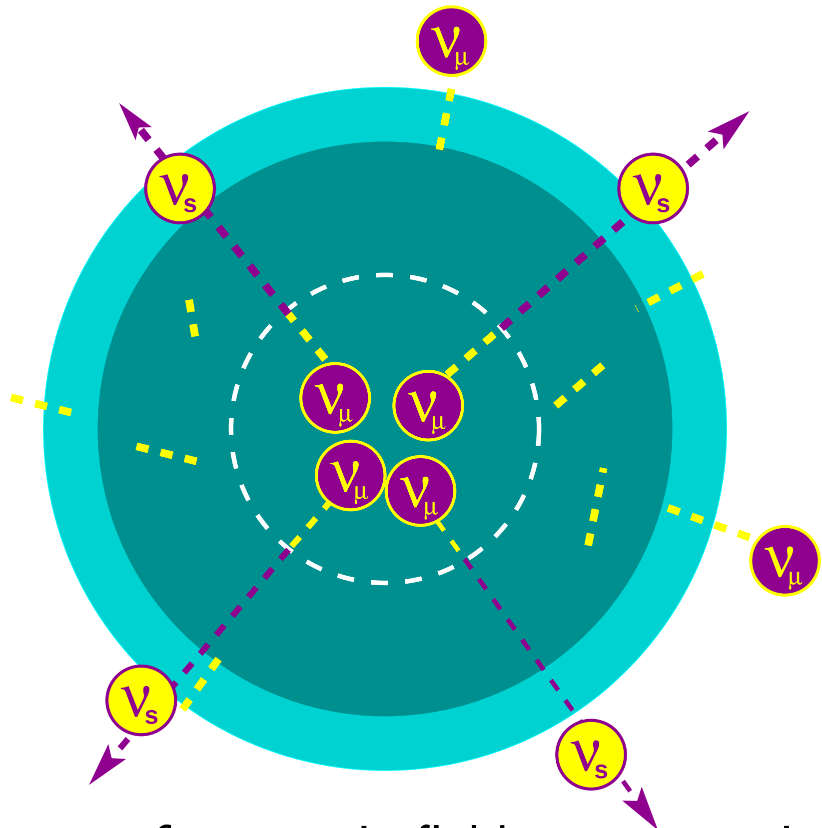
$$\frac{m_i^2}{2k}\cos 2\theta_{ij} + V(\nu_i) = \frac{m_j^2}{2k}\cos 2\theta_{ij} + V(\nu_j) \tag{12}$$

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.

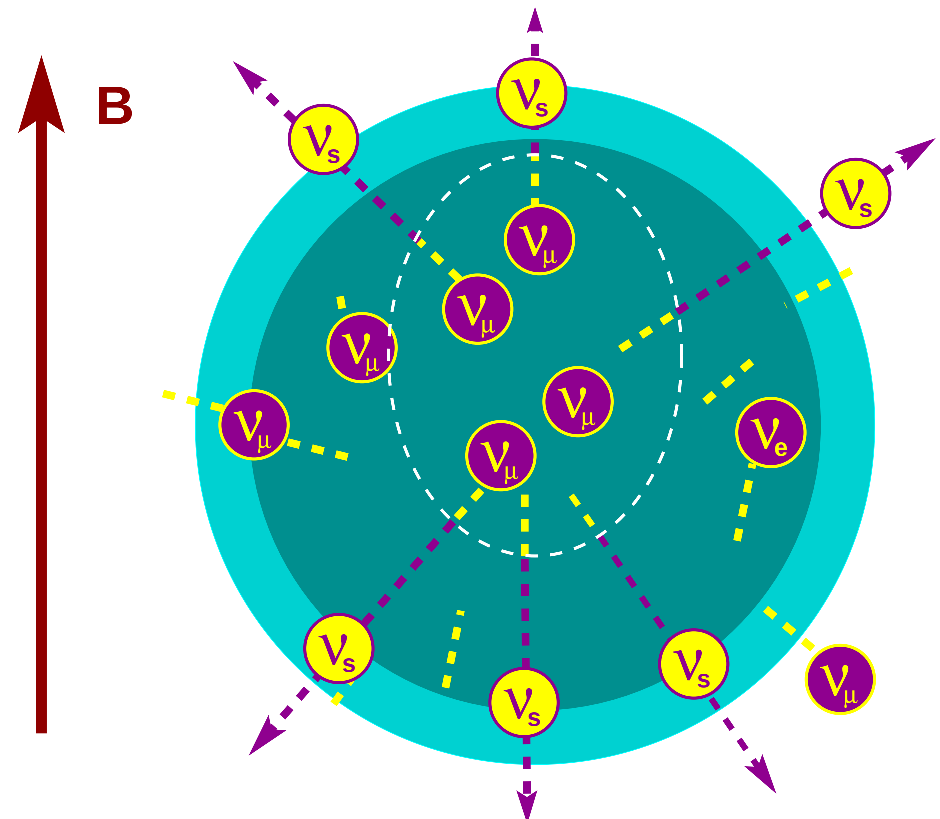
Temperature is a function of $r$. The energy of an escaping sterile neutrino depends on the temperature of at the point it was produced.

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



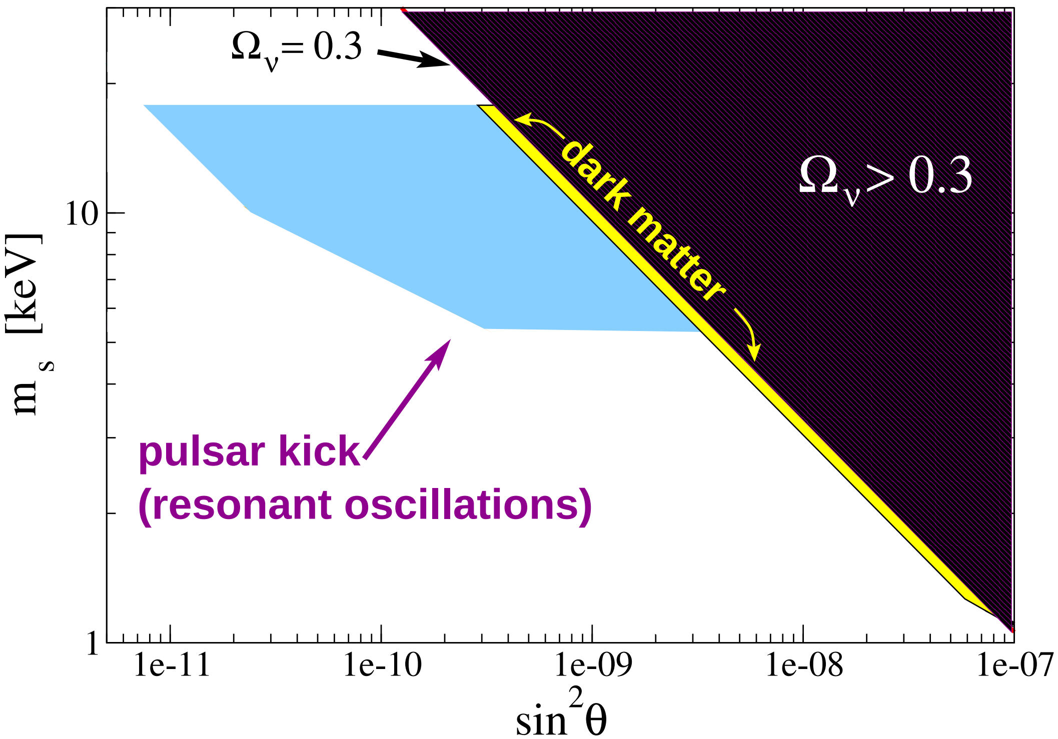

In the absence of magnetic field, $\nu_s$ escape isotropically

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

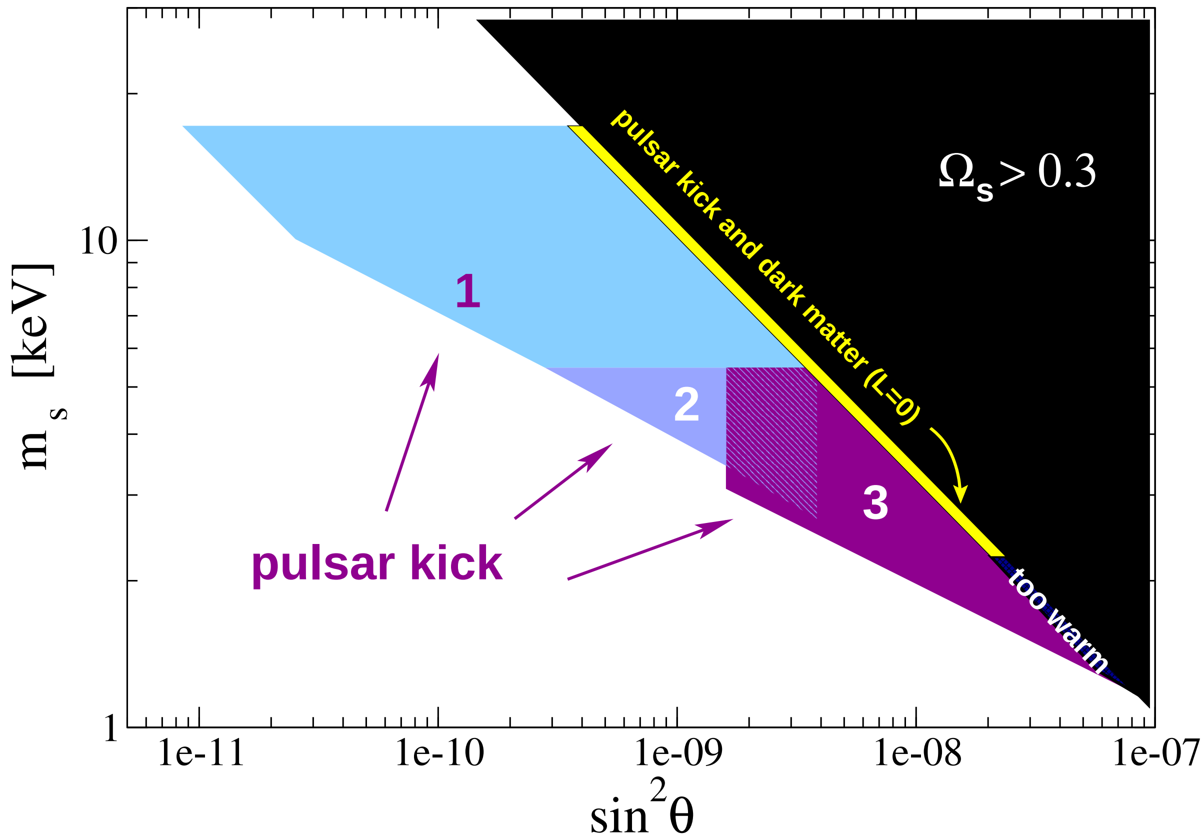



Down going neutrinos have higher energies

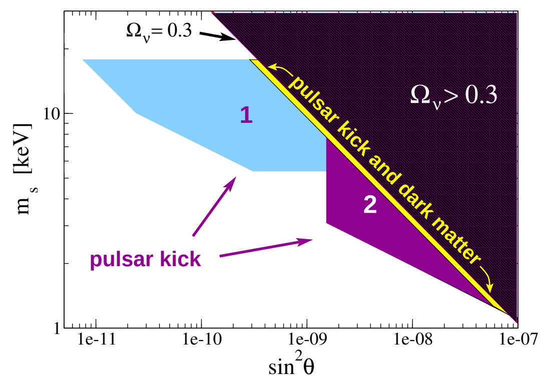
The range of parameters [AK, Segrè; Fuller,**AK**,Mocioiu,Pascoli]:



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




the pulsar kick regions overlap with the dark matter region




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

Models of neutrino masses commonly predict:

$$\sin^2\theta \sim \frac{m_1}{m_2}$$

for a heavy neutrnio with a **10 keV$= 10^4$eV** mass and a light one with a **$10^{-3}$eV** mass, this ratio is about right.

# Pulsar kicks: why sterile neutrinos?

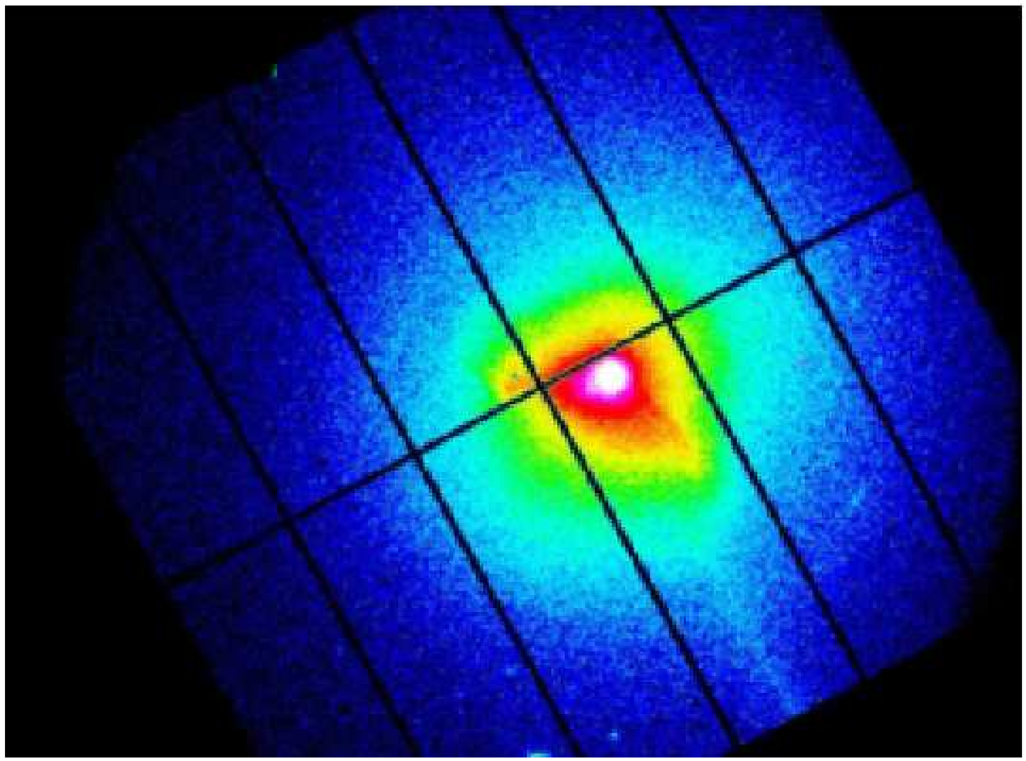
Why not ordinary active neutrinos?

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 $\tau$ neutrinospheres, at density $\rho \sim 10^{11} - 10^{12}$ g/cm$^3$. This density corresponds to

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

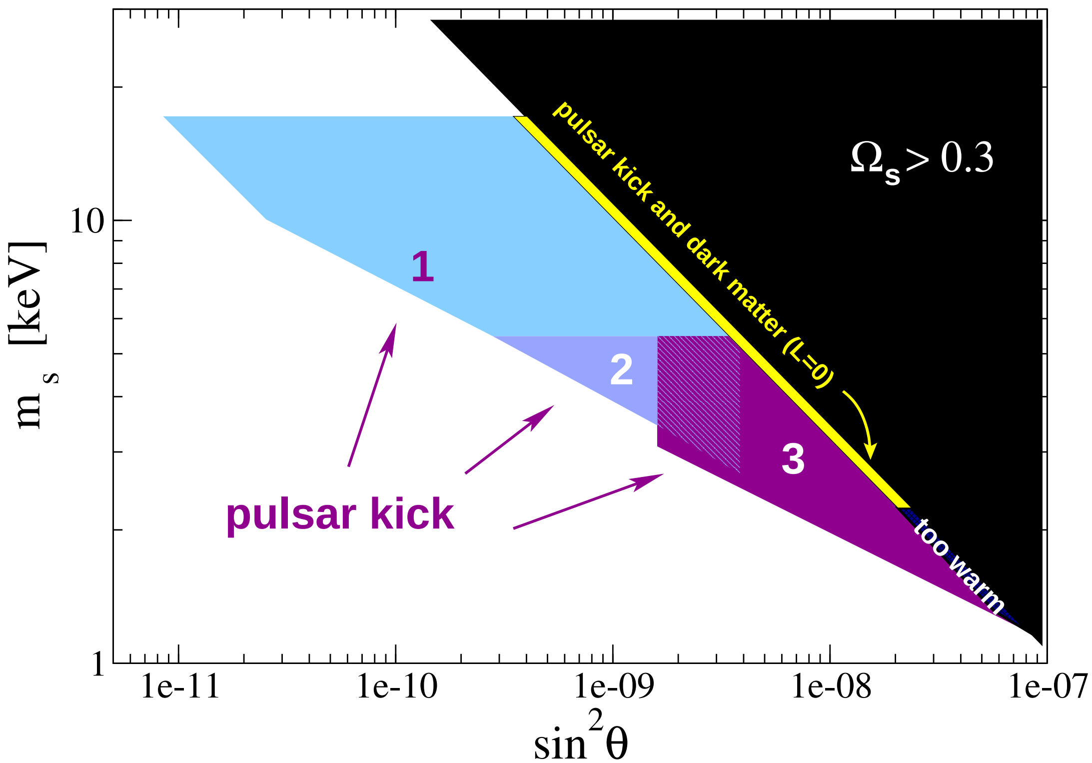
This is inconsistent with experimental/cosmological limits.

# 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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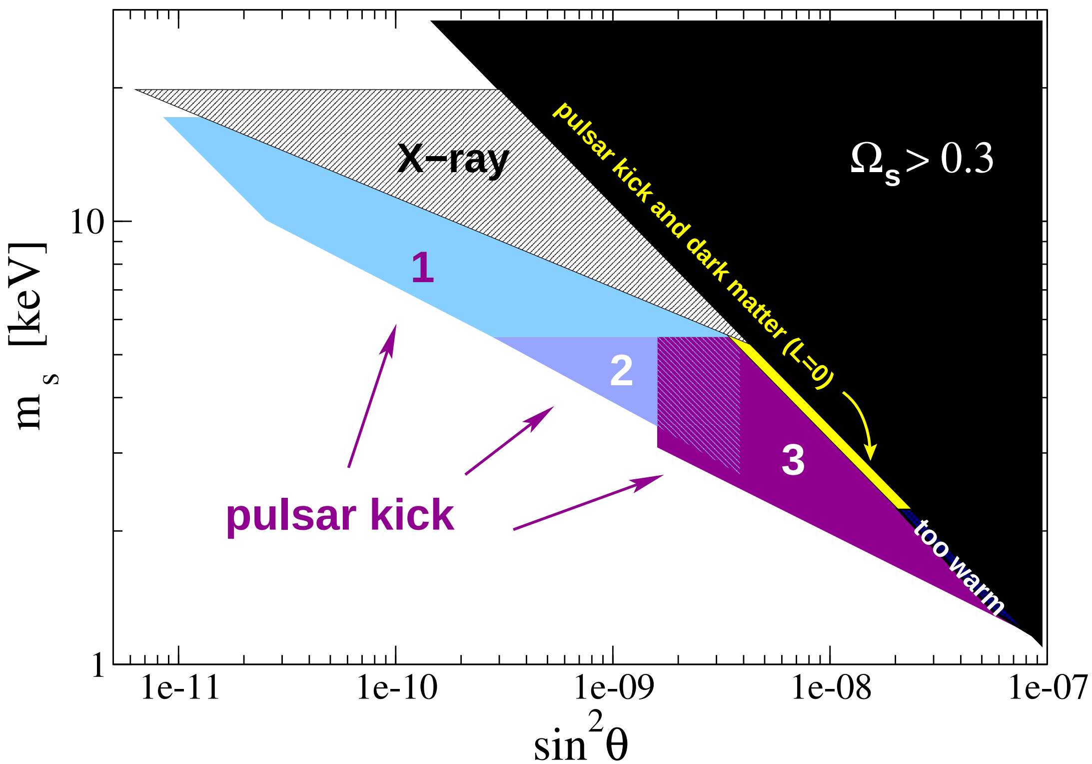


[Abazajian, Fuller, Tucker]

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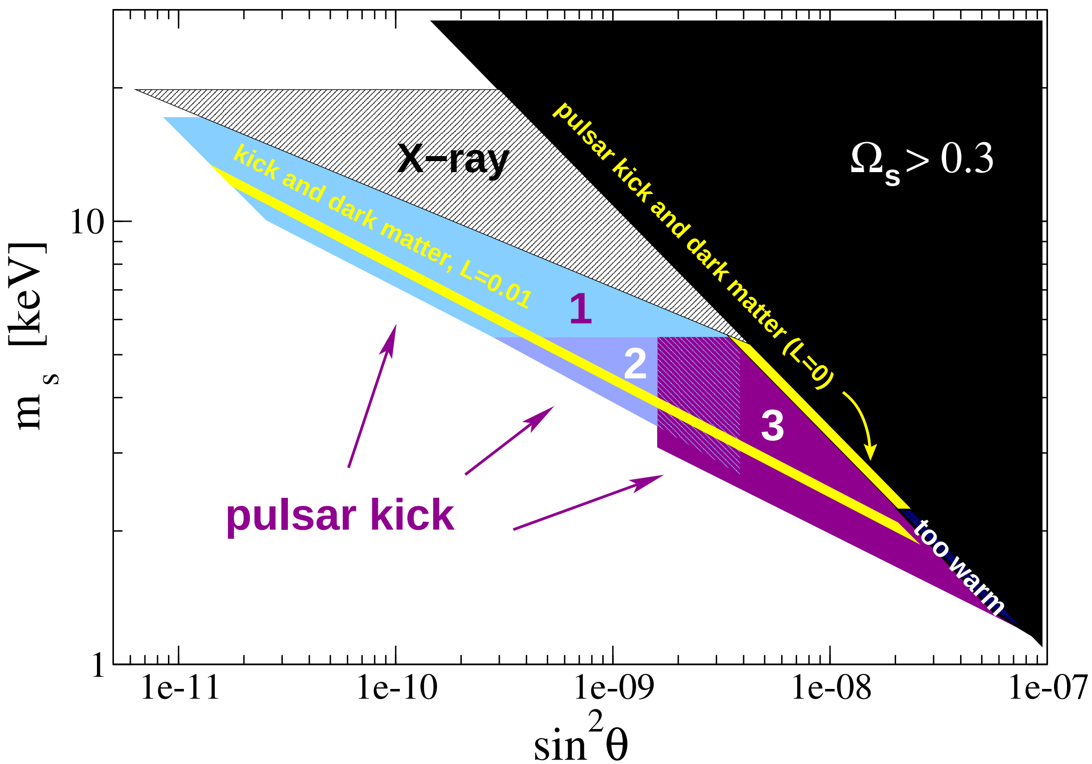
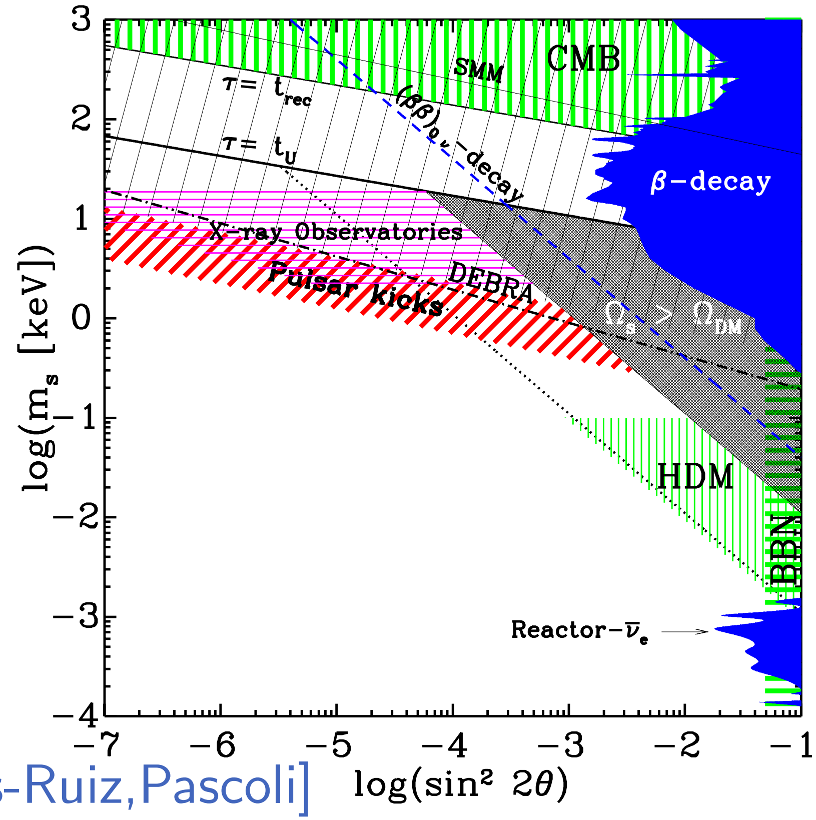



non-zero lepton asymmetry changes the dark matter range

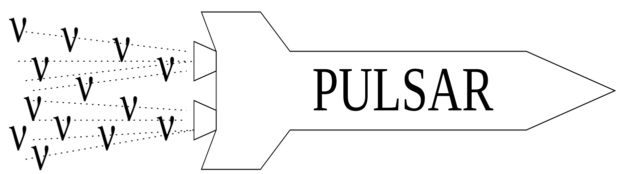
[Abazajian, Fuller, Tucker]

# Different cosmology, different limits



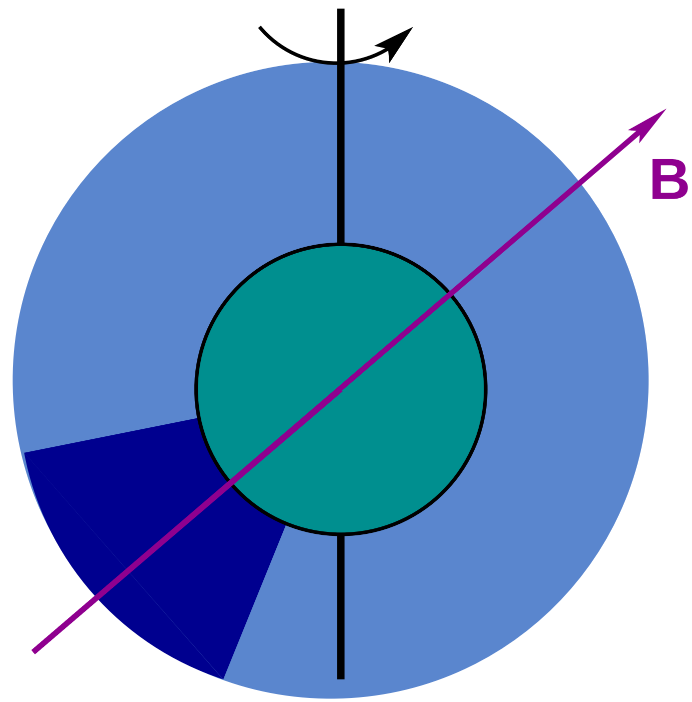

[Gelmini,Palomares-Ruiz,Pascoli]

# 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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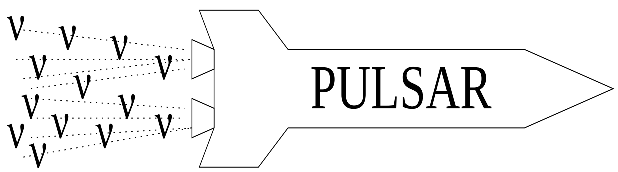


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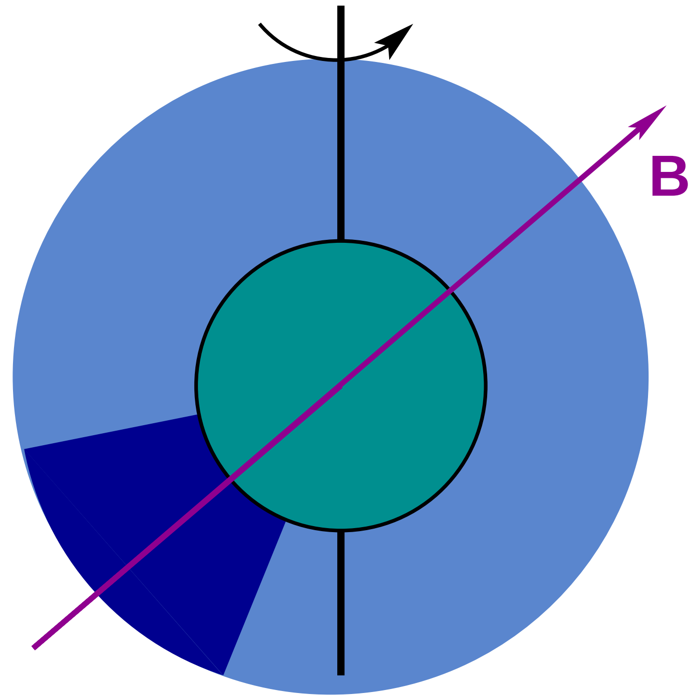
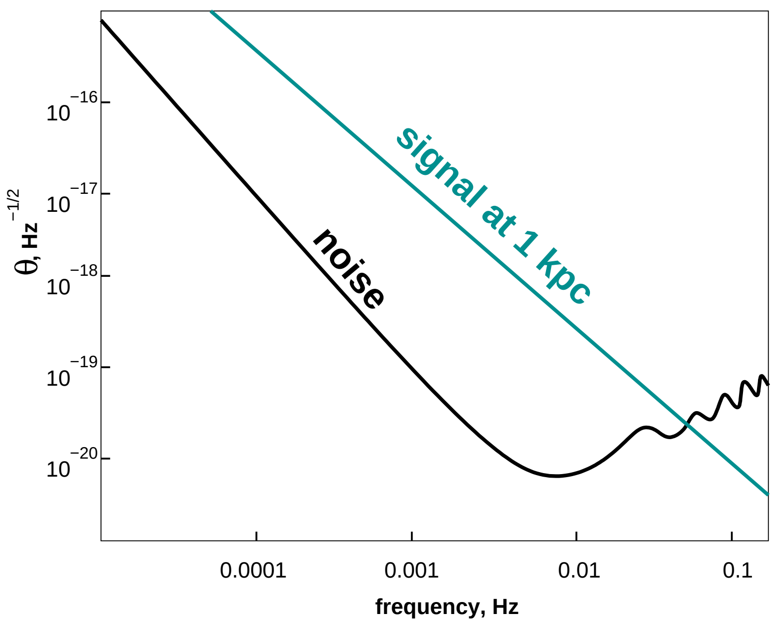
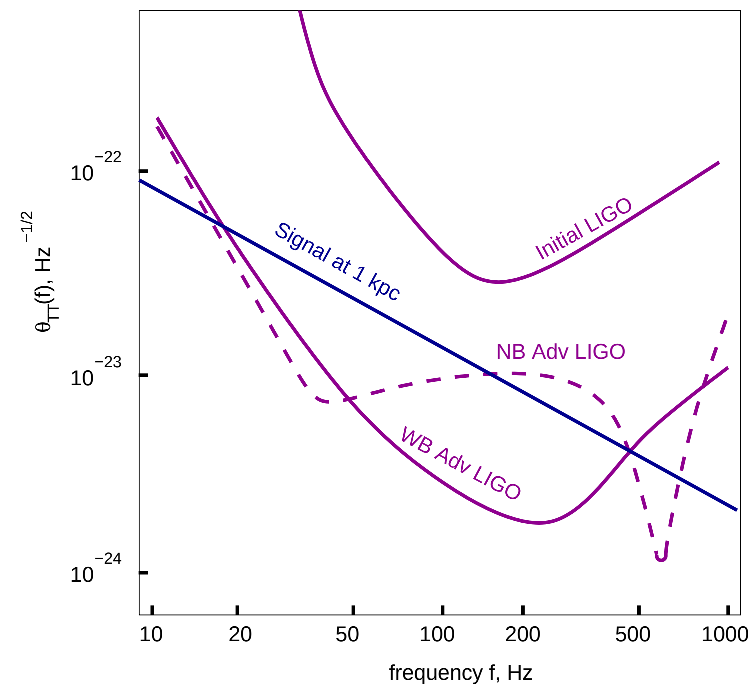


# Gravity waves at LIGO and LISA




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

# 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.

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