Dark matter, baryons, and the pulsar kicks

from a keV sterile neutrino

- Dark matter: we have discovered a new particle, we just have to figure out what it is
- Why sterile neutrinos
- Baryogenesis: we observe the asymmtry, we just have to figure out where it comes from
- The role of sterile neutrinos for baryon asymmetry
- Pulsar velocities, and why a keV sterile neutrino can give the pulsar a kick.

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

Dark matter ⇒ new physics

- Very strong evidence for $\boldsymbol{\Omega_m = (0.27 \pm 0.04) > \Omega_b = (0.044 \pm 0.004)}$

- This is *not* ordinary matter:
  - WMAP measures the ratio of matter coupled to photons to that which is not
  - BBN doesn't allow more baryons
  - Gas collapses into a disk; we need a spherical halo

- The Standard Model has no candidate for dark matter: need new physics

Dark matter: what is it?

Can take guesses based on...

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

Dark matter: beautiful theoretical ideas

SUSY is an appealing theoretical idea

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

- **Lightest supersymmetric particle**, stable because of **R-parity**
  - **neutralino**
  - **gravitino**
  - **axino**
- **SUSY Q-balls**, stable for gauge-mediated SUSY breaking, thanks to the **baryon number and energy conservation**.

Theoretically motivated! Mass vs cross section OK.

By no means minimal. No experimental evidence so far.

What if the LHC sees no evidence of supersymmetry?

No compelling reason (like R-parity) to expect a **stable** particle with mass $\sim$100 GeV

A lighter particle can naturally be stable on cosmological time scales

However, one does not want to make it too light: if lighter than **keV**, it will erase structure on small scales

keV is OK

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**

Small mass and, therefore, **stability!**

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

Sterile neutrinos in the early universe

Sterile neutrinos are produced in primordial plasma through

- off-resonance oscillations. [Dodelson, Widrow; Abazajian, Fuller, Dolgov, Hansen...]
- oscillations on resonance, if the lepton asymmetry is non-negligible [Fuller, Shi]

The mixing angle is suppressed at high temperature [Stodolsky]

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

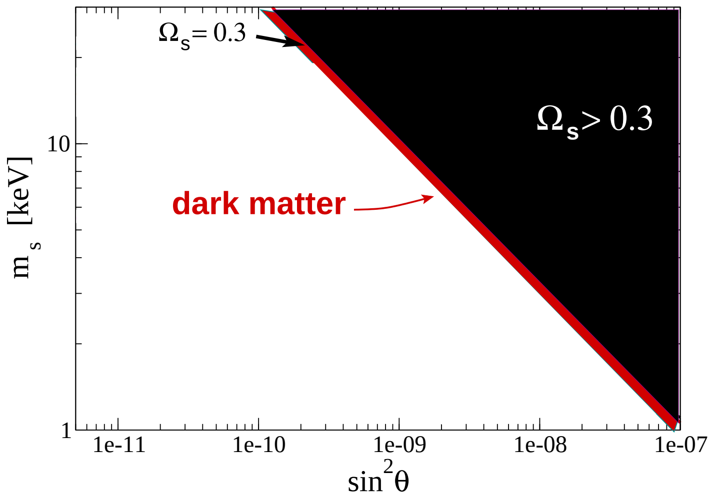
For small angles,

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

Production of sterile neutrinos peaks at temperature

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

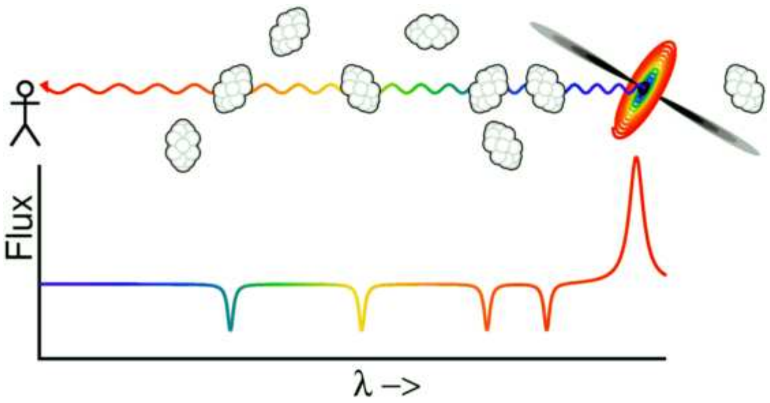
The resulting density of relic sterile neutrinos in conventional cosmology, in the absence of a large lepton asymmetry:

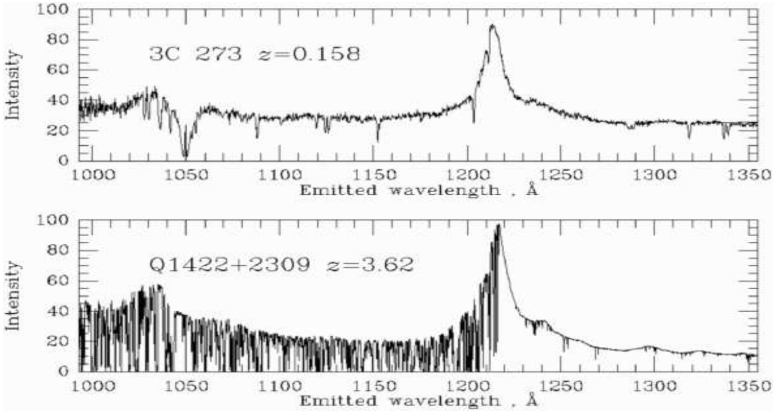


$$\Omega_{\nu_2} \sim 0.3 \left(\frac{\sin^2 2\theta}{10^{-8}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^2$$

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

Lyman-α forest: a look at the small-scale structure





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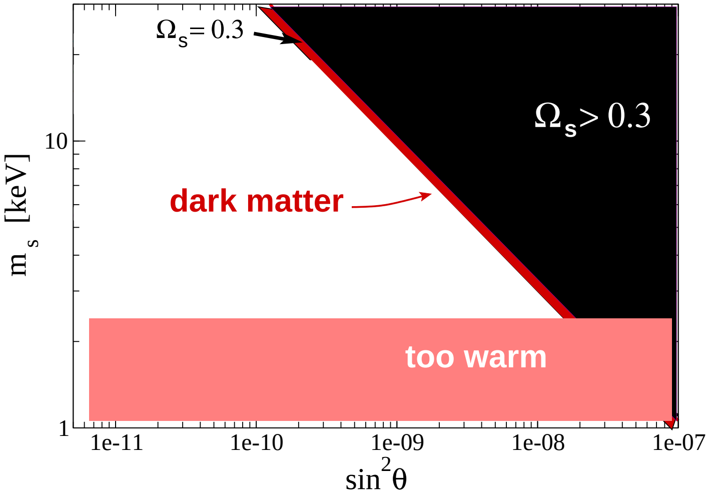
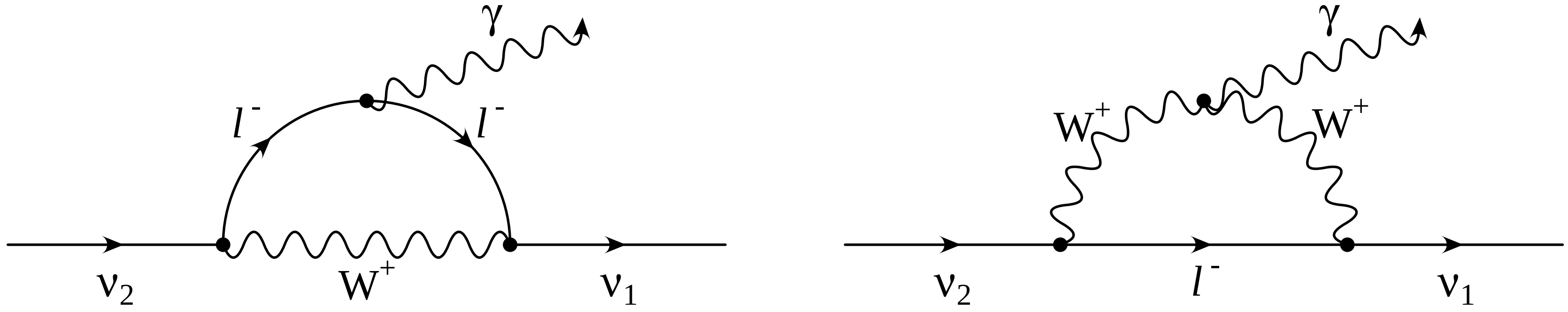


Lyman-α forest clouds show significant structure on small scales. Dark matter must be cold enough to preserve this structure.

Radiative decay

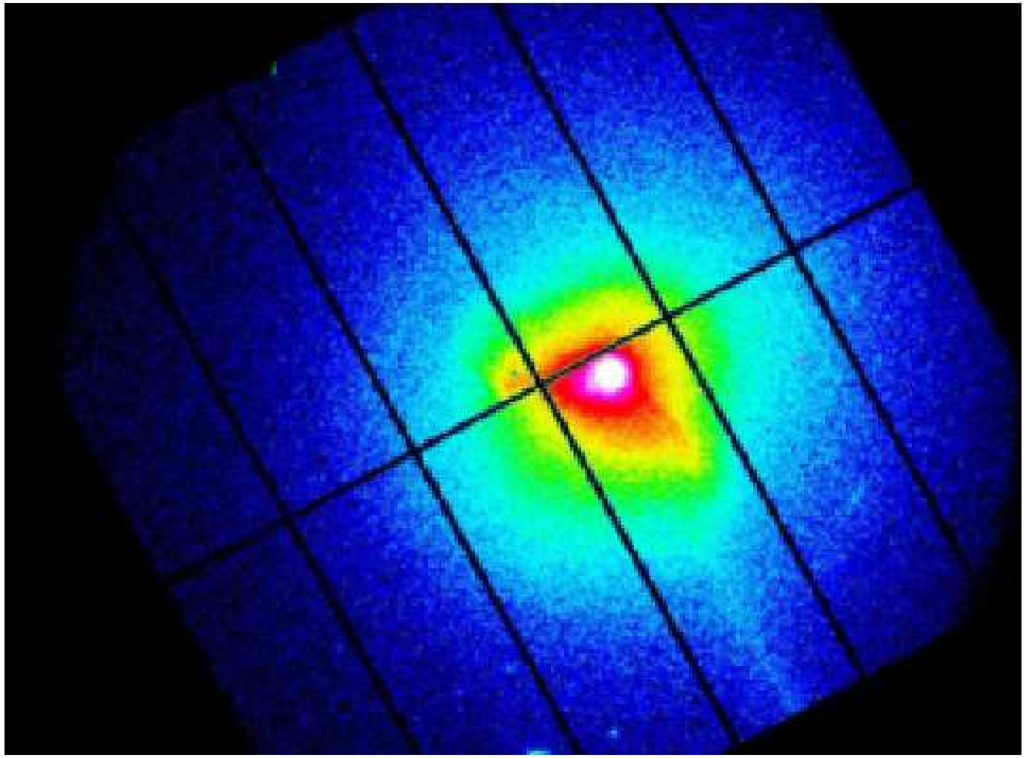
Sterile neutrino in the mass range of interest have lifetimes **longer than the age of the universe**, but they do decay:



Photons have energies $m/2$: X-rays. Large lumps of dark matter emit some X-rays.

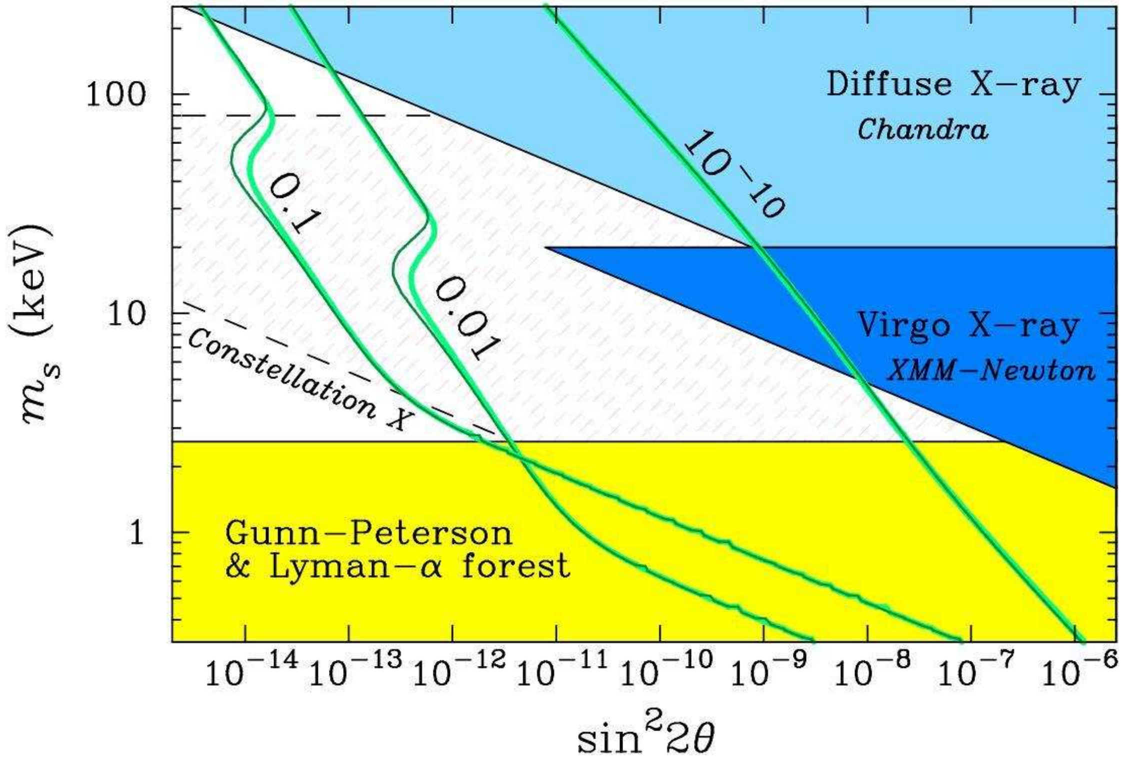
[Abazajian, Fuller, Tucker]

X-ray observations



Virgo cluster image from XMM-Newton

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



Exclusion region depends on the lepton asymmetry of the universe.

Cold or warm dark matter?

CDM works well, but...

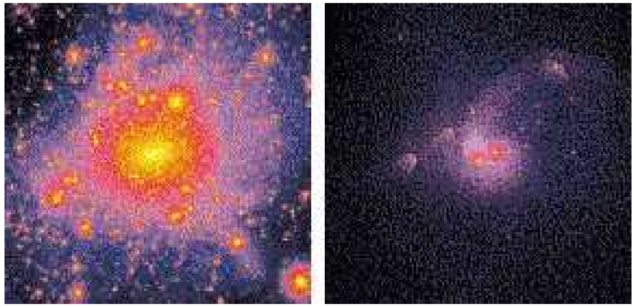
Potential problems with cold dark matter:

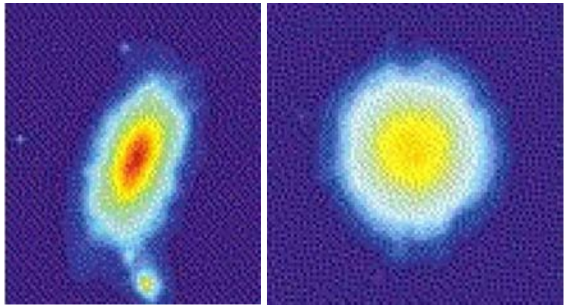
- too much structure on small scales: the self-similar spectrum predicts $\sim \mathbf{10}$ small "satellite galaxies" per galaxy.

- cuspy profile may be in conflict with observations

  [B. Moore, *et al*., Ap. J. **524**, L19 (1999)]

Warm dark matter ($m \approx 1 - 5\ \mathrm{keV}$) can offer a solution

the satellites:  [Moore]

the cusp:  [Moore]

Plotted is the effect of self-interaction. One expects a similar effect from erasing small-scale structure by warm neutrinos. (Needs to be done.)

Baryogenesis

Let us consider the following lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a} \left(i \partial_\mu \gamma^\mu \right) \nu_{s,a} - y_{\alpha a} H \, \bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2} \, \nu_{s,a}^{\bar{c}} \nu_{s,b} + h.c. \, ,$$

where H is the Higgs boson and L_α $(\alpha = e, \mu, \tau)$ are the lepton doublets.
The lightest of sterile neutrinos, $\nu_{s,1}$ is the **keV** dark matter.
The other two sterile neutrinos, $\nu_{s,2}$ and $\nu_{s,3}$ are heavier.
This lagrangian offers a simple scenario for leptogenesis.

A viable scenario for leptogenesis:

- At least one of the $\boldsymbol{\nu_{s,a}}$, for example, $\boldsymbol{\nu_{s,3}}$ has a large enough Yukawa coupling to be in equilibrium at temperatures $T > 100$ GeV. This species is produced with zero asymmetry: $\boldsymbol{L_3 = 0}$.

- CP violation is present in the mixing matrix of the singlets. Neutrino oscillations with CP violation produce a population of $\nu_{s,a}$ with

$$\boldsymbol{L_1 \neq 0,\ L_2 \neq 0,\ L_3 \neq 0,\ \text{but}\ L_{\text{tot}} = L_1 + L_2 + L_3 = 0}$$

- The dark-matter neutrino, $\boldsymbol{\nu_{s,1}}$ is out of equilibrium at all times. Sphalerons convert $\boldsymbol{L_2 + L_3 \neq 0}$ into the baryon asymmetry.

[Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov]

The following Lagrangian describes:

- the Standard Model physics
- dark matter
- baryon asymmetry

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a} \left(i \partial_\mu \gamma^\mu \right) \nu_{s,a} - y_{\alpha a} H \, \bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2} \, \nu^{\bar{c}}_{s,a} \nu_{s,b} + h.c. \, ,$$

where H is the Higgs boson and L_α $(\alpha = e, \mu, \tau)$ are the lepton doublets.
Other tests?

Emission of sterile neutrinos from a supernova

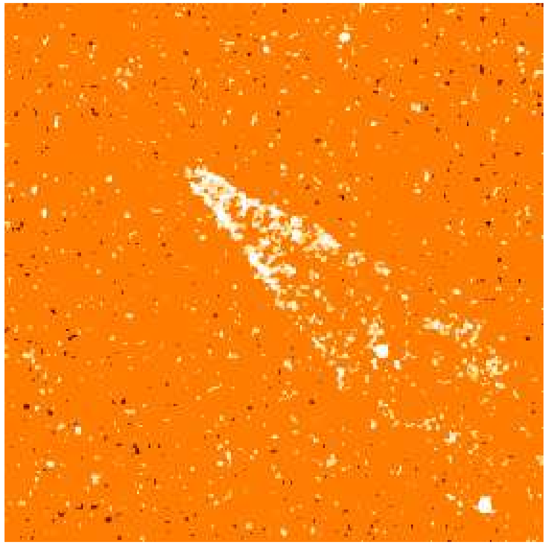
- Sterile neutrino emission from a supernova is anisotropic
- Sterile neutrinos with masses and mixing angles consistent with dark matter can explain the pulsar velocities

[AK, Segrè; Fuller, AK, Mocioiu, Pascoli]

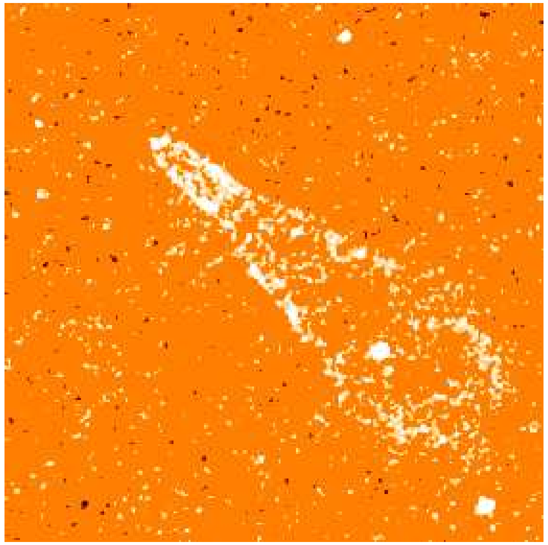
The pulsar velocities.

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.*]

A very fast pulsar in Guitar Nebula

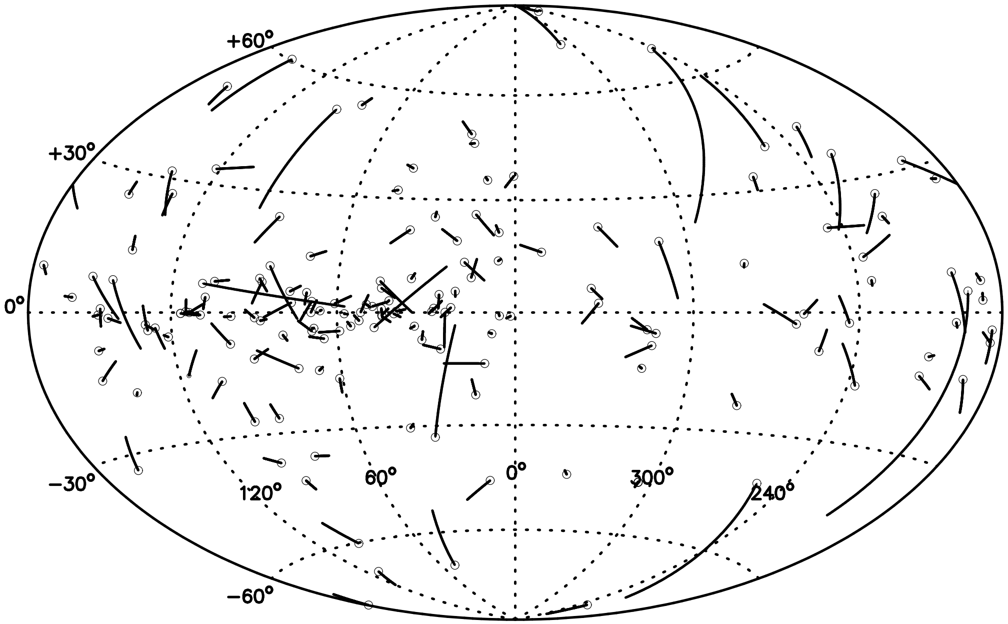


HST, December 1994



HST, December 2001

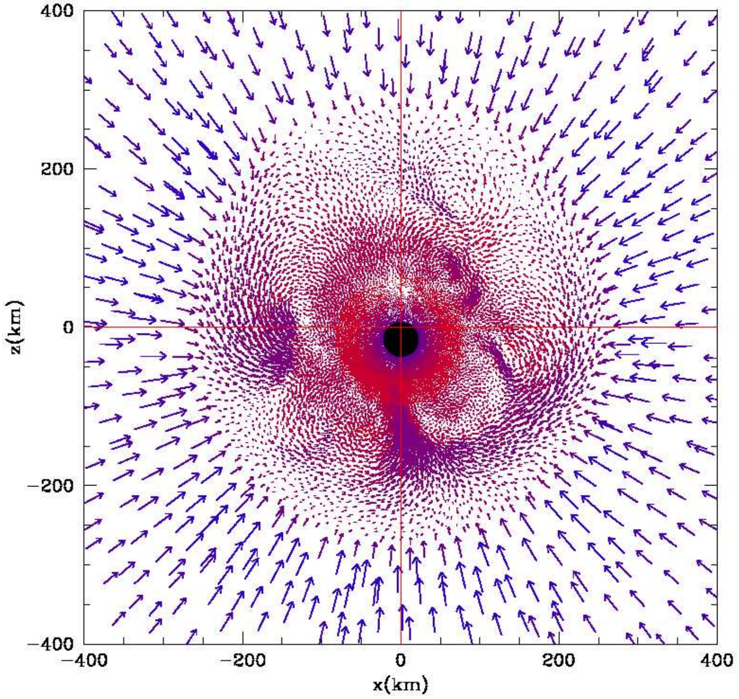
Map of pulsar velocities

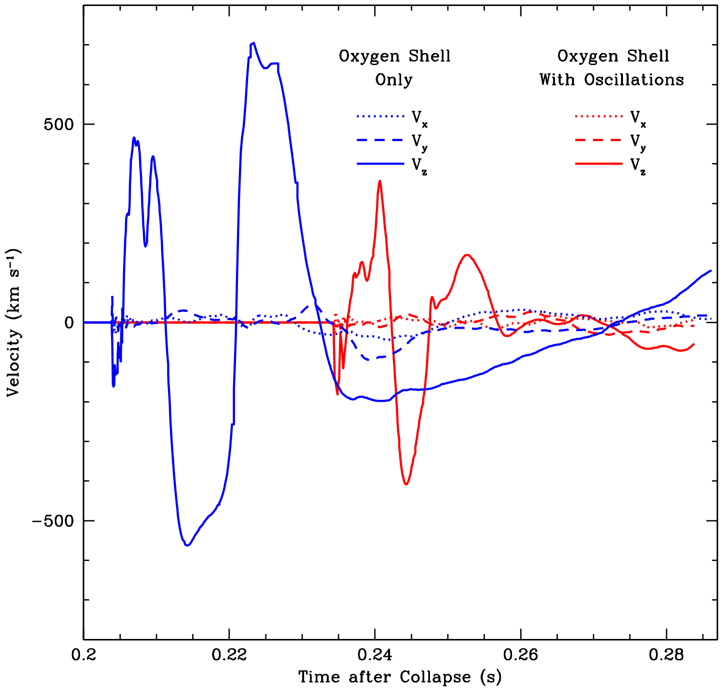


Proposed explanations:

- 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)

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:

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

99% of this energy is emitted in neutrinos

Pulsar kicks from neutrino emission?

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

$$\boldsymbol{M_\odot v \sim 10^{41}}\ \mathrm{g\,cm/s}$$

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

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

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*

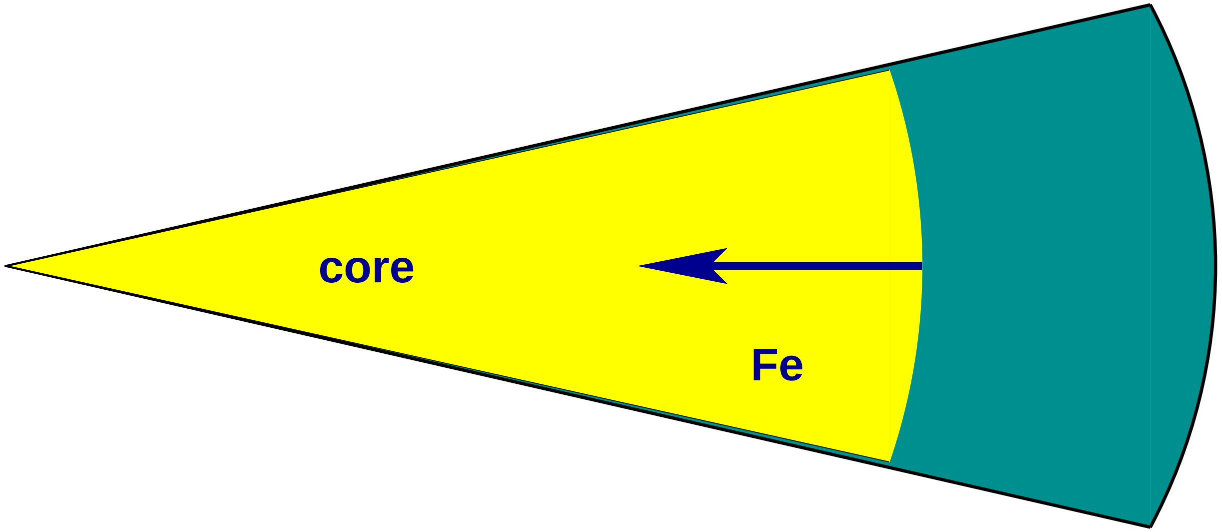
⇒ some neutron stars have surface magnetic fields as high as $10^{15} - 10^{16}$ **G**.

⇒ **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.

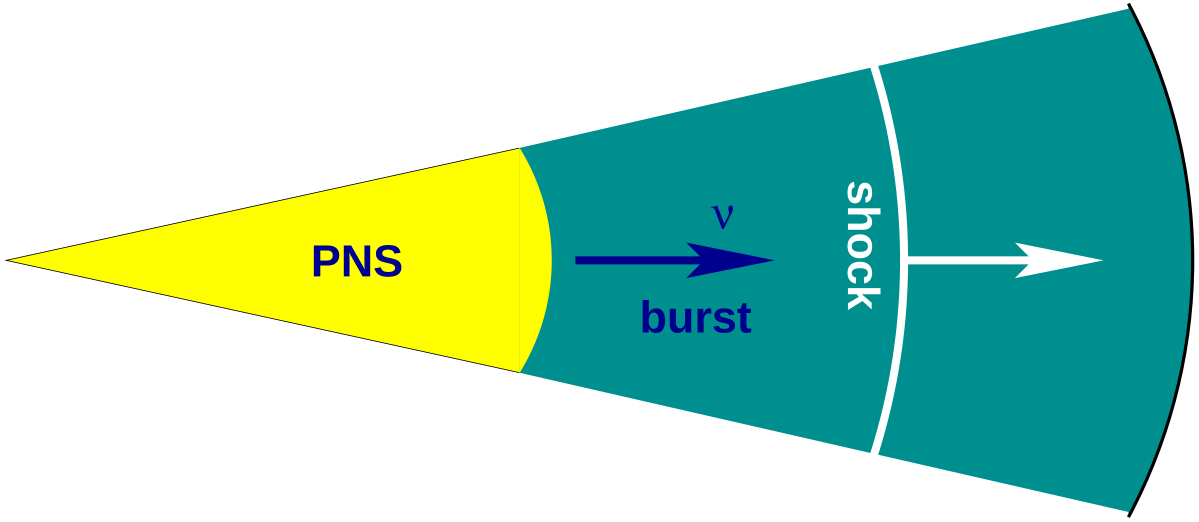
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

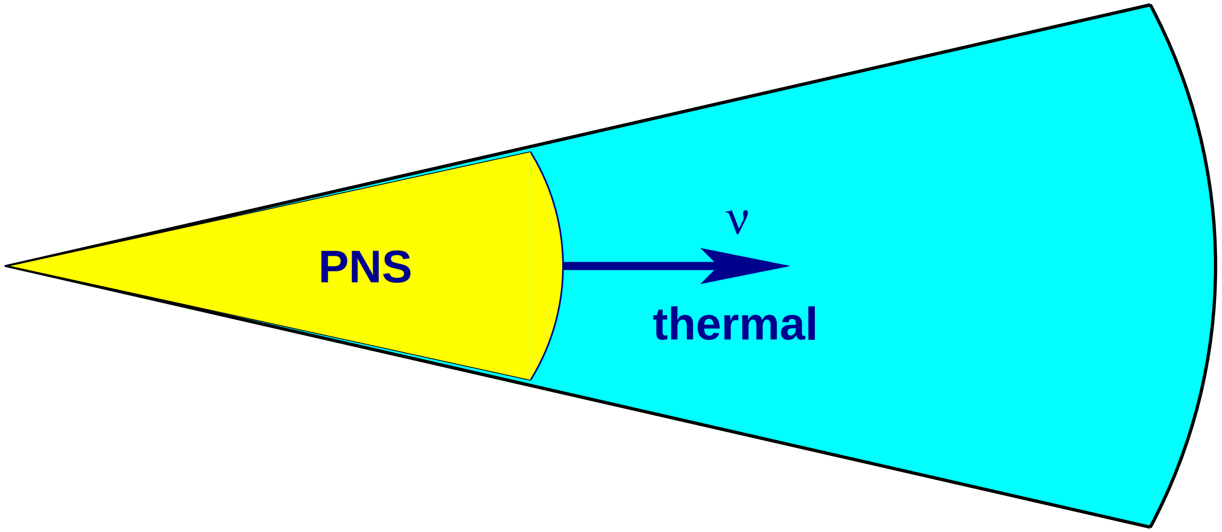
Shock formation and "neutronization burst": $t = 1 - 10$ ms



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.

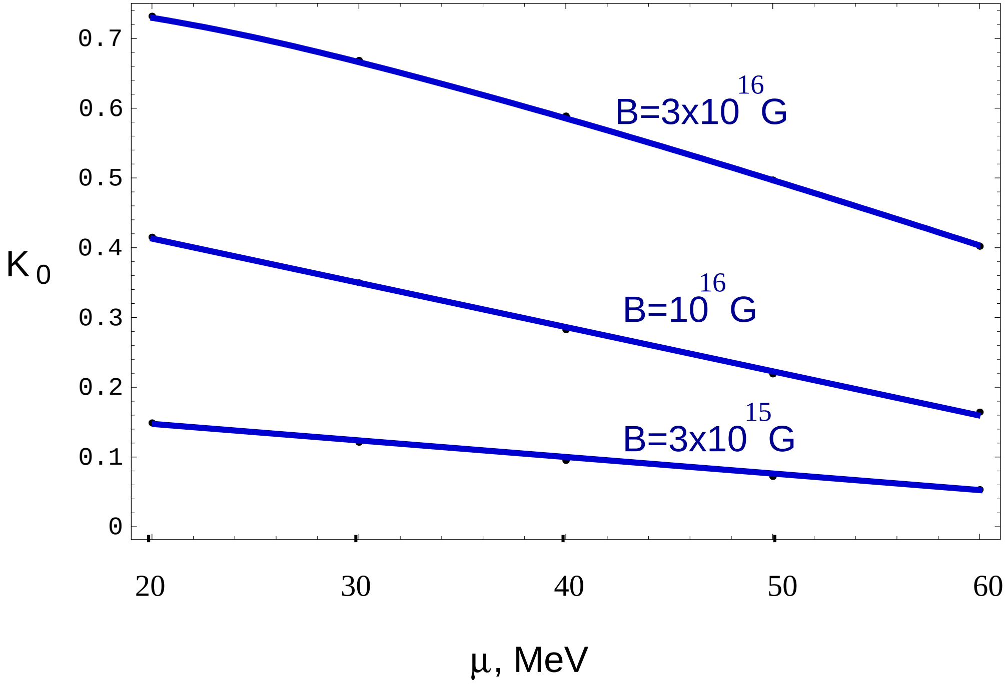
$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

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,

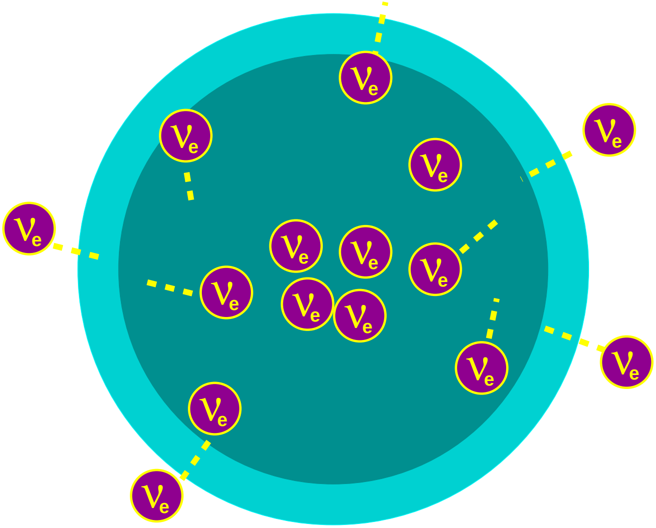


k_0 is the fraction of electrons in the lowest Landau level.

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?

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!

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:

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

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

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

where $V_0 = G_F \rho/\sqrt{2} m_n \simeq 3.8 \mathrm{eV} (\rho/10^{14} \mathrm{g cm}^{-3})$
Mixing is suppressed when $V_m \gg (\Delta m^2/2k)$.
The coupling of ν_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 $\nu_e \rightarrow \nu_s \quad \Rightarrow V_m$ decreases

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

Therefore, [Abazajian, Fuller, Patel]

$$V_m \rightarrow 0$$

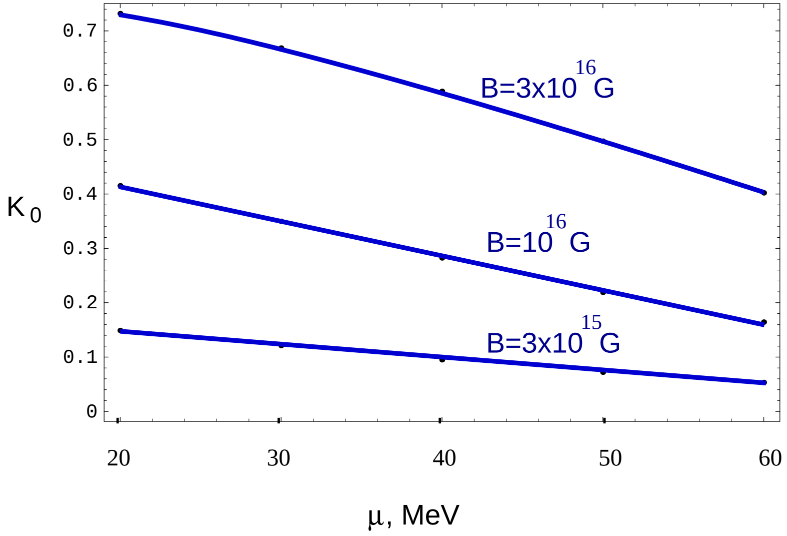
$$\sin \theta_m \rightarrow \sin \theta_0$$

production of ν_s is unsuppressed

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

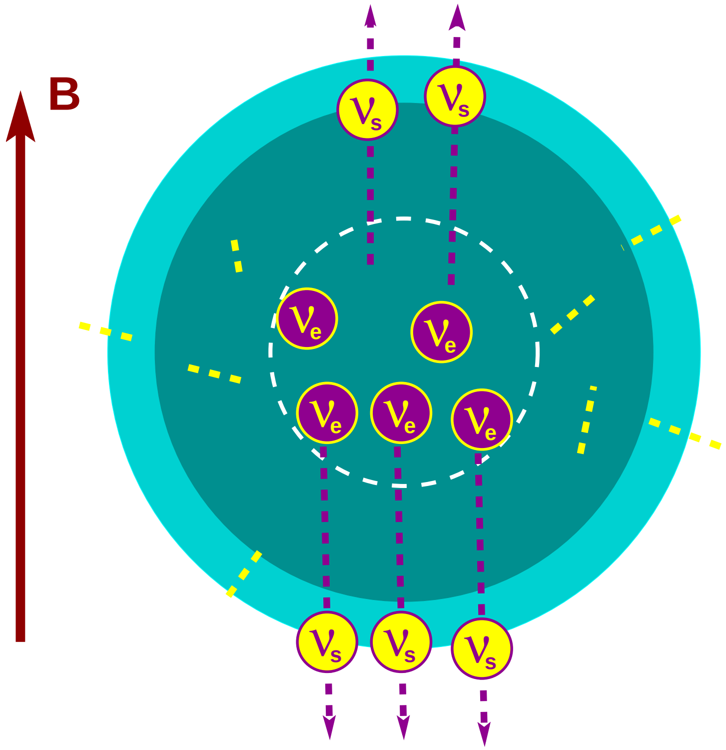
$$p + e^- \rightleftharpoons n + \nu_e \text{ and } n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

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



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 $V_m \rightarrow 0$ to occur faster than ~ 1 s.

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

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.

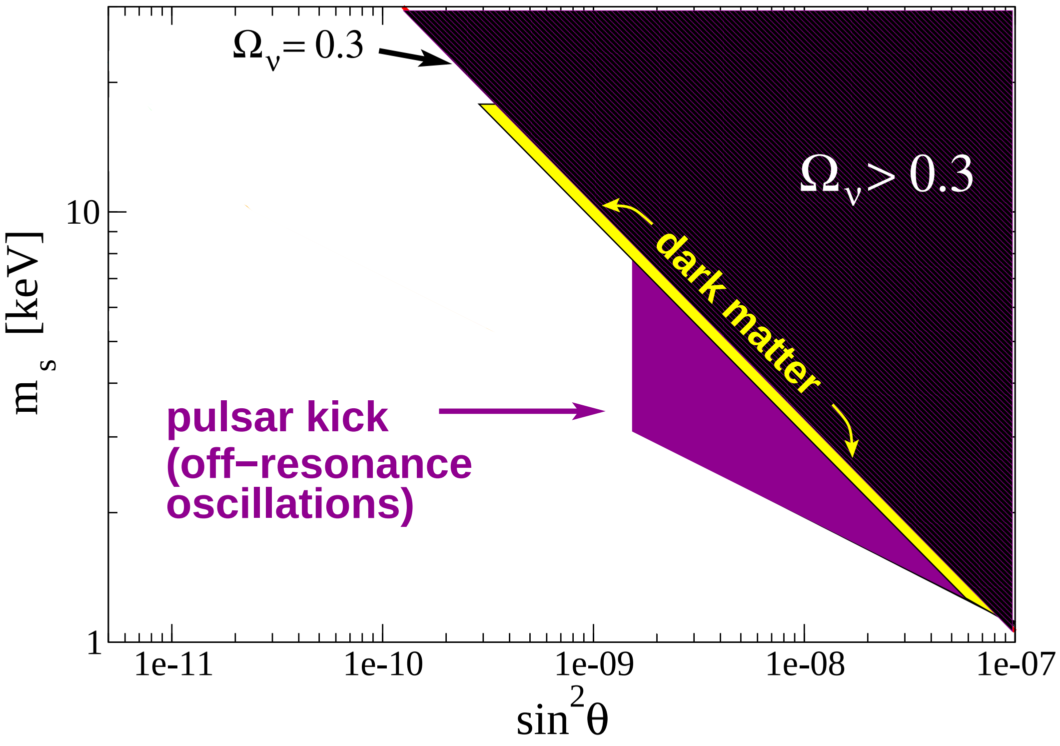
[Abazajian, Fuller, Patel]

$$\begin{aligned}\tau_V^{\mathrm{on-res}} &\simeq \frac{2^5\sqrt{2}\pi^2 m_n}{G_F^3\rho}\frac{(V_m^{(0)})^6}{(\Delta m^2)^5\sin 2\theta}\left(e^{\frac{\Delta m^2/2V_m^{(0)}-\mu}{T}}+1\right)\\ &\sim \left(\frac{2\times 10^{-9}\mathrm{s}}{\sin 2\theta}\right)\left(\frac{10^{14}\frac{g}{cm^3}}{\rho}\right)\left(\frac{20\,\mathrm{MeV}}{T}\right)^6\left(\frac{\Delta m^2}{10\,\mathrm{keV}^2}.\right)\end{aligned}$$

$$\begin{aligned}\tau_V^{\mathrm{off-res}} &\simeq \frac{4\sqrt{2}\pi^2 m_n}{G_F^3\rho}\frac{(V_m^{(0)})^3}{(\Delta m^2)^2\sin^2 2\theta}\frac{1}{\mu^3}\\ &\sim \left(\frac{6\times 10^{-9}\mathrm{s}}{\sin^2 2\theta}\right)\left(\frac{V_m^{(0)}}{0.1\mathrm{eV}}\right)^3\left(\frac{50\mathrm{MeV}}{\mu}\right)^3\left(\frac{10\mathrm{keV}^2}{\Delta m^2}\right)^2 .\end{aligned}$$

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

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



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

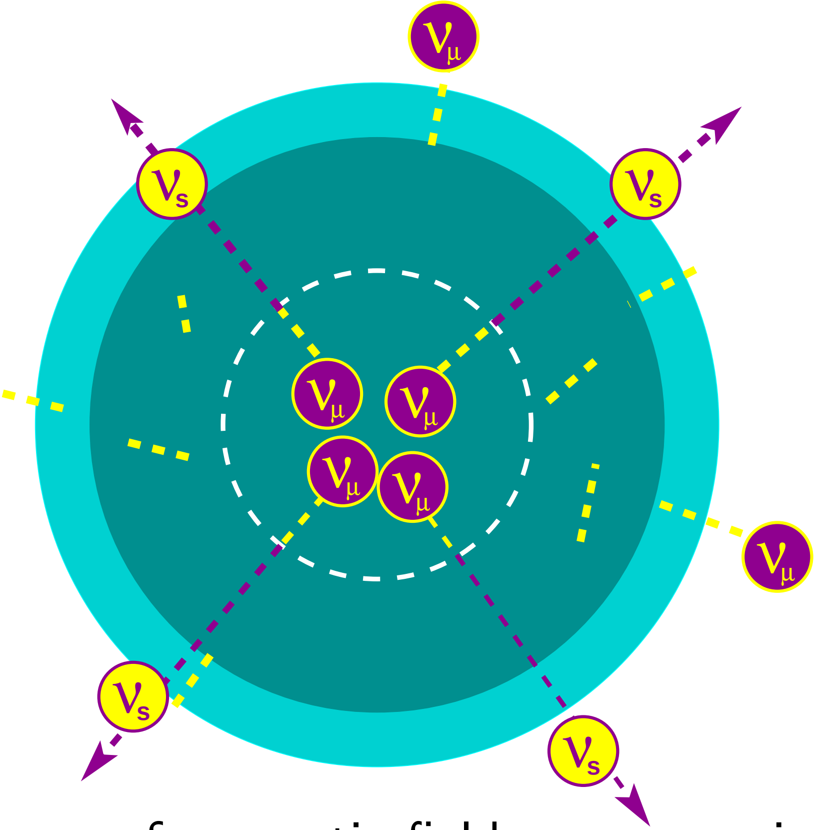
$$\frac{m_i^2}{2k}\cos 2\theta_{ij} + V(\nu_i) = \frac{m_j^2}{2k}\cos 2\theta_{ij} + V(\nu_j) \tag{12}$$

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.

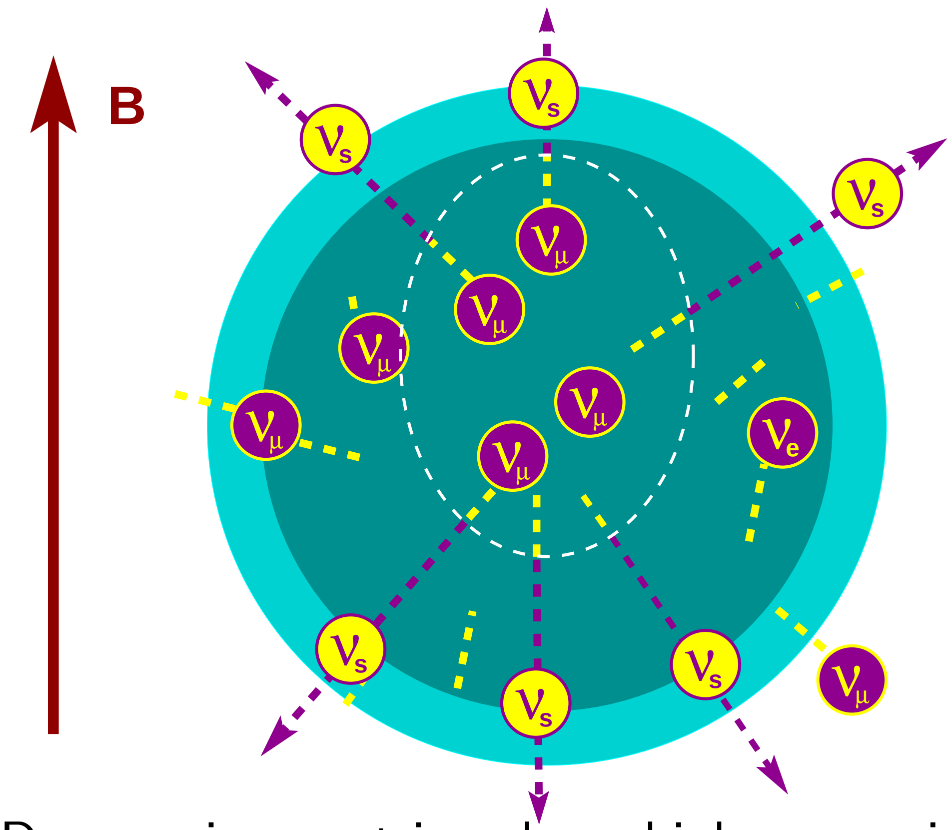
Temperature is a function of r. The energy of an escaping sterile neutrino depends on the temperature of at the point it was produced.

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, 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

The asymmetry in the outgoing momentum

$$\frac{\Delta k}{k} \sim 0.01 \left(\frac{B}{10^{15}\mathrm{G}} \right)$$

[AK, Segrè; Barkovich *et al.*]

The core density $\rho \sim 10^{14}$ g/cm^3 determines the $\mathbf{\Delta m^2 \sim (3\,keV)^2}$

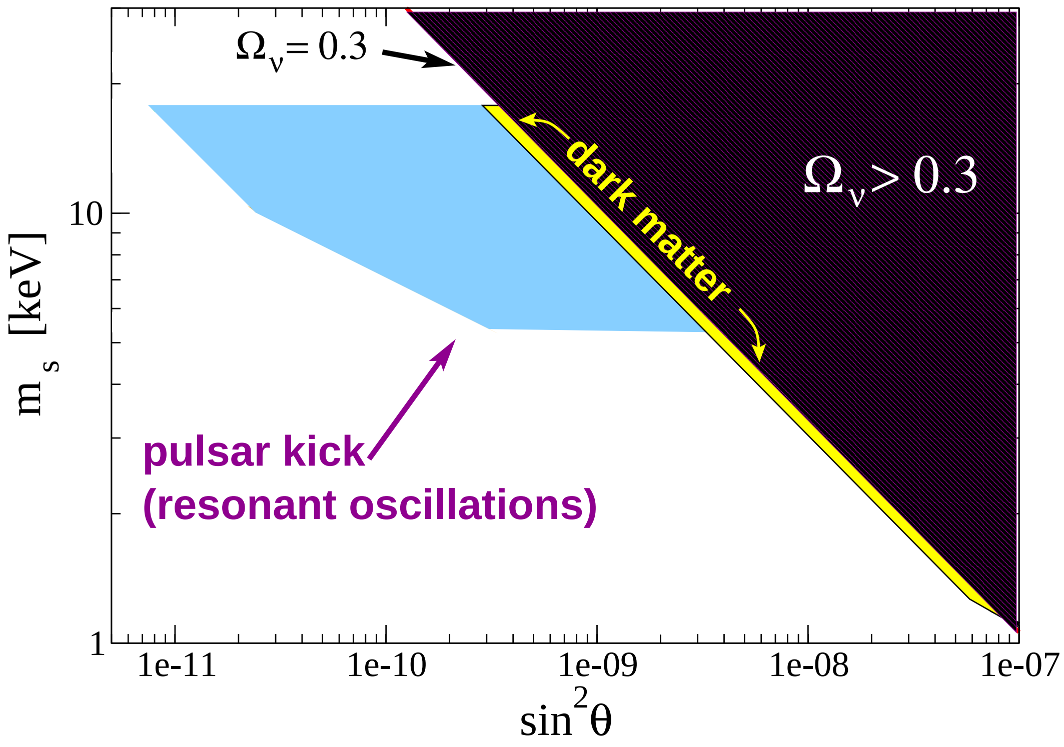
Adiabaticity: the oscillation length

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

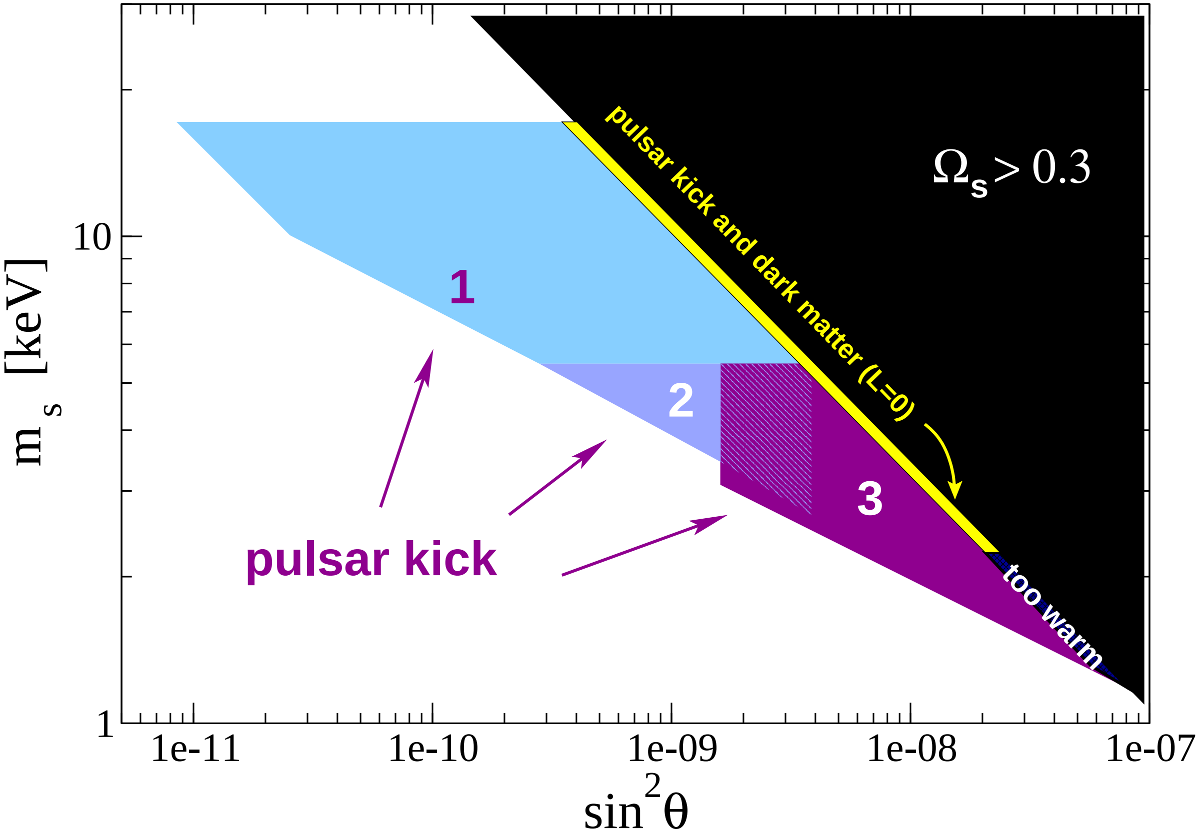
must be smaller than (1) the scale height of density (2) the mean free path of neutrinos. ⇒

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

The range of parameters:

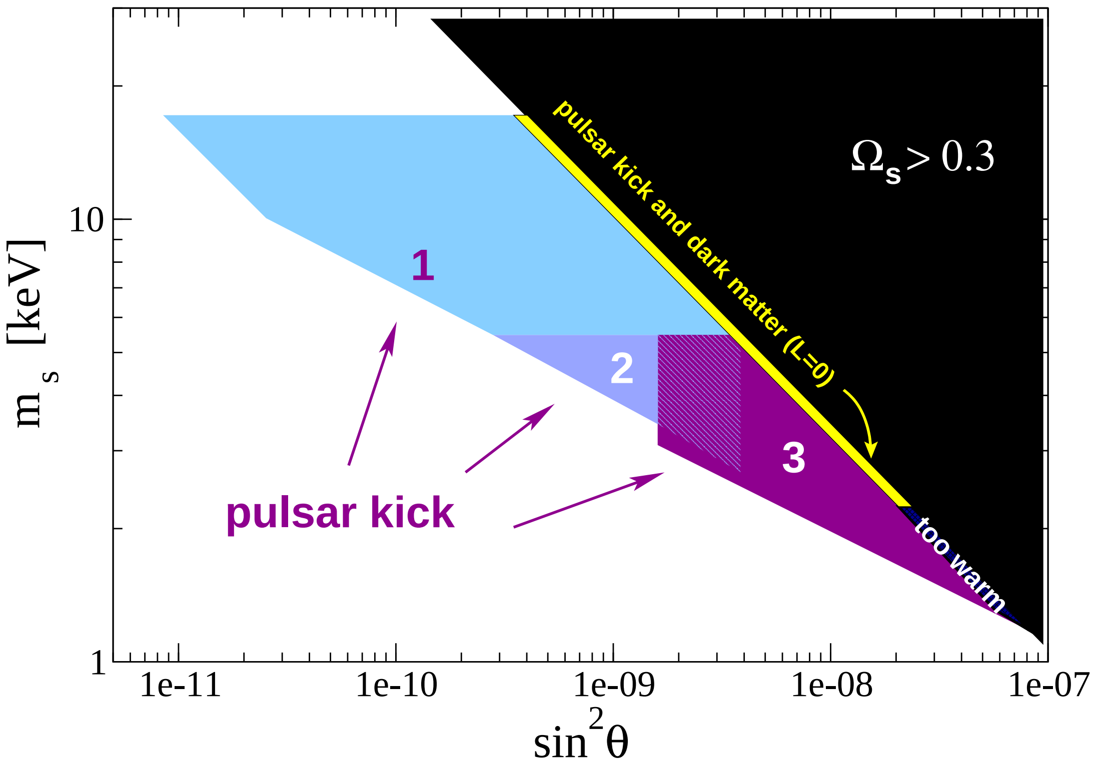


Resonance (Mikheev-Smirnov) & off-resonance oscillations

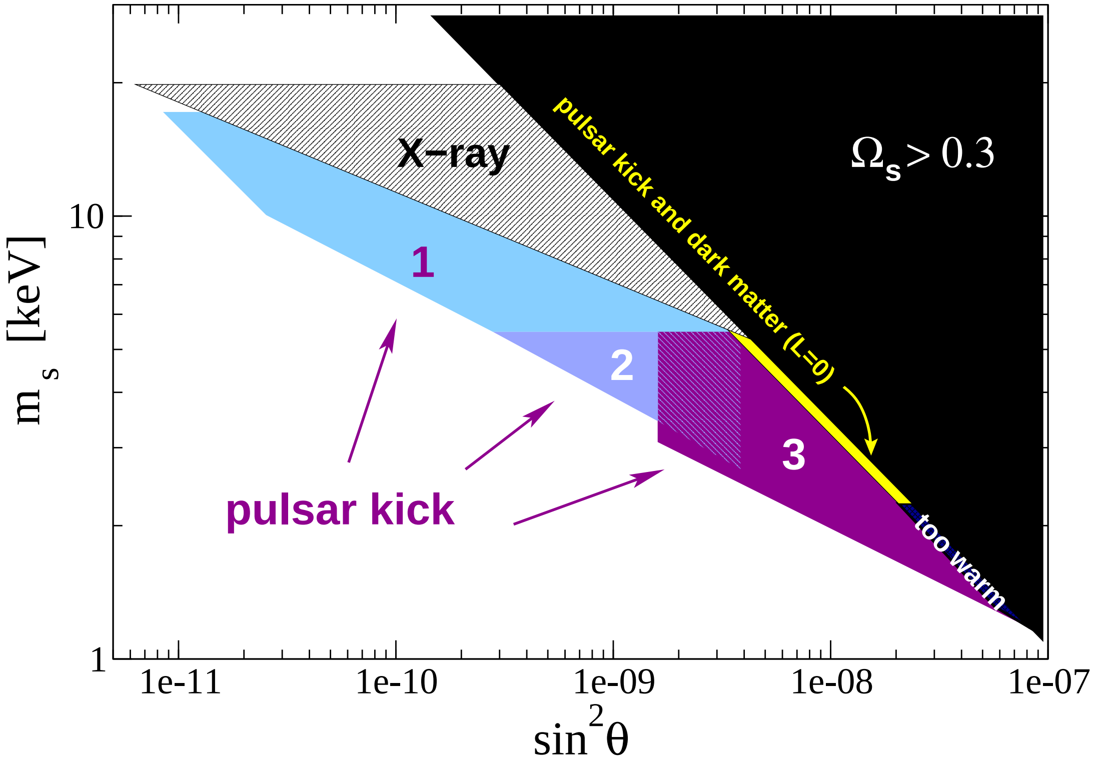


[A.K., Segrè, PL **B396**, 197 (1997); Fuller, A.K.,Mocioiu,Pascoli, PR **D 68**, 103002 (2003)]

Chandra, XMM-Newton limit

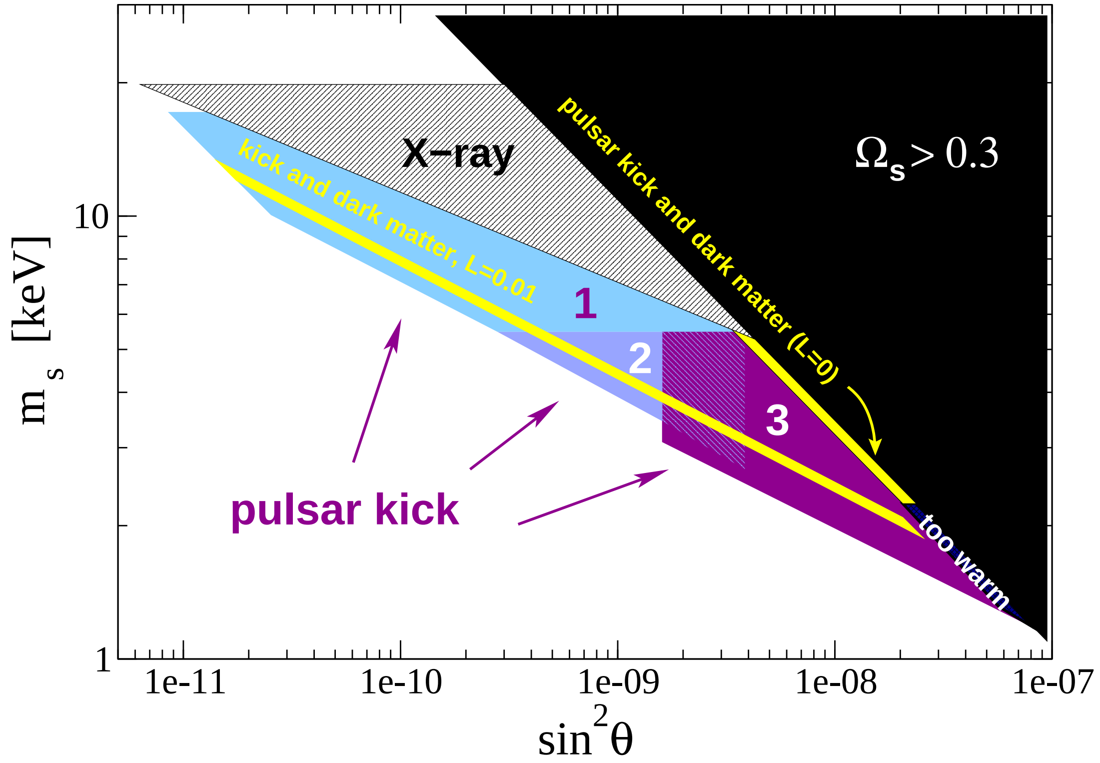


Chandra, XMM-Newton limit



[Abazajian, Fuller, Tucker]

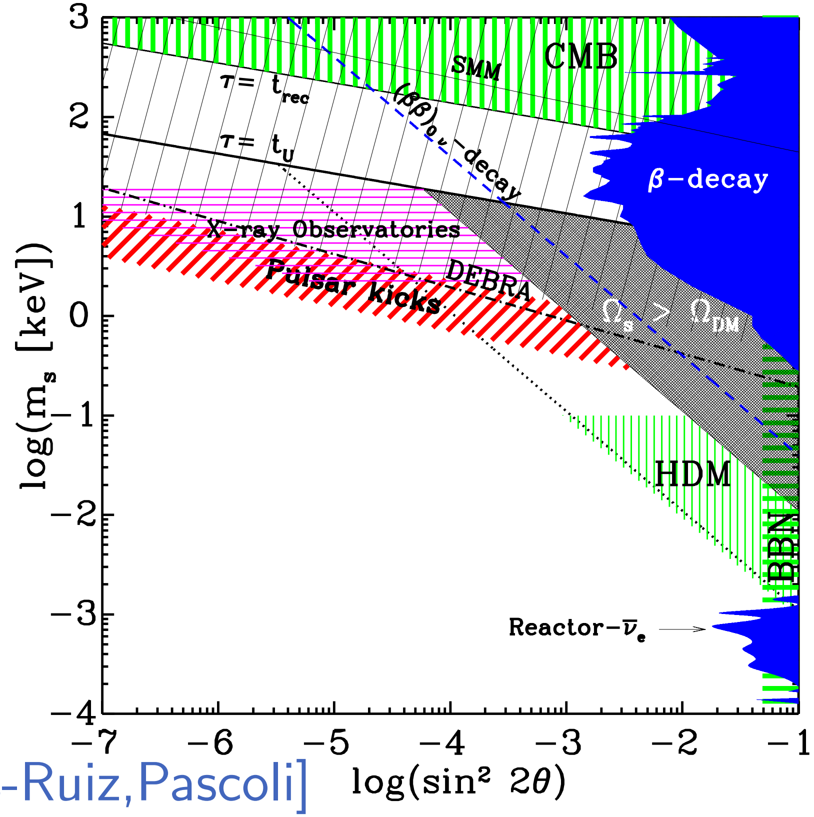
Chandra, XMM-Newton limit



non-zero lepton asymmetry changes the dark matter range

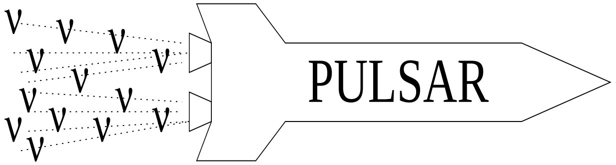
[Abazajian, Fuller, Tucker]

Different cosmology, different limits



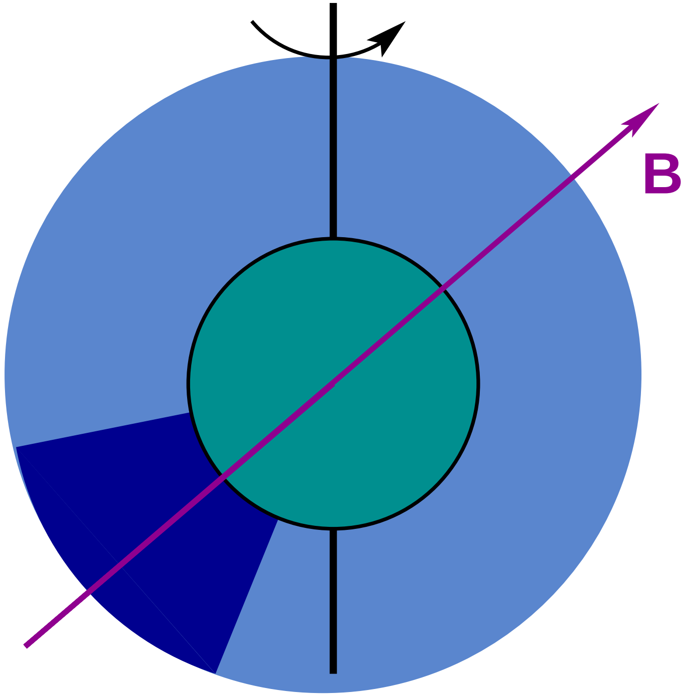
[Gelmini,Palomares-Ruiz,Pascoli]

Gravity waves

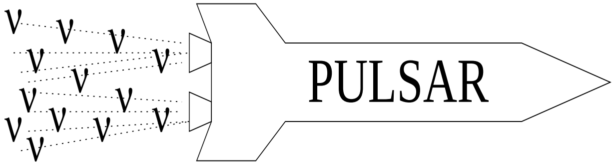


Artist's conception by Roulet [Summer School lectures in Trieste]

Rotating "beam" of neutrinos
is the source of GW



Gravity waves



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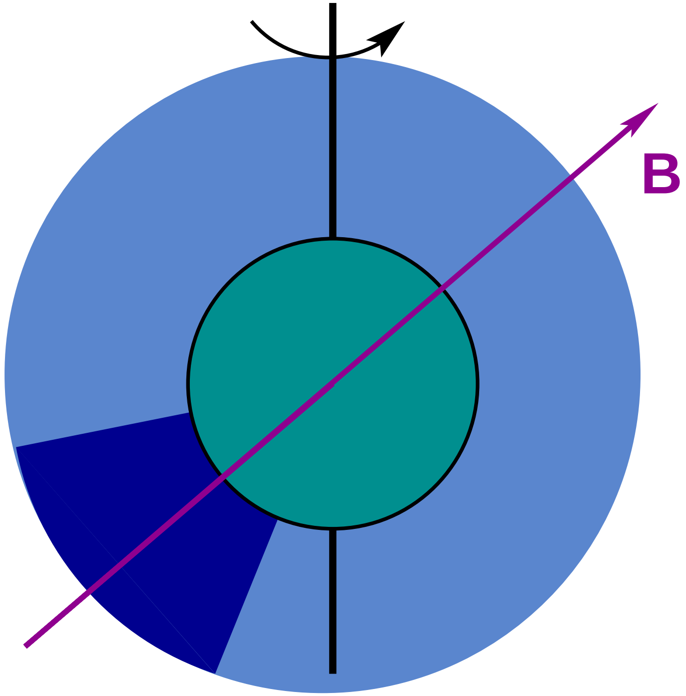
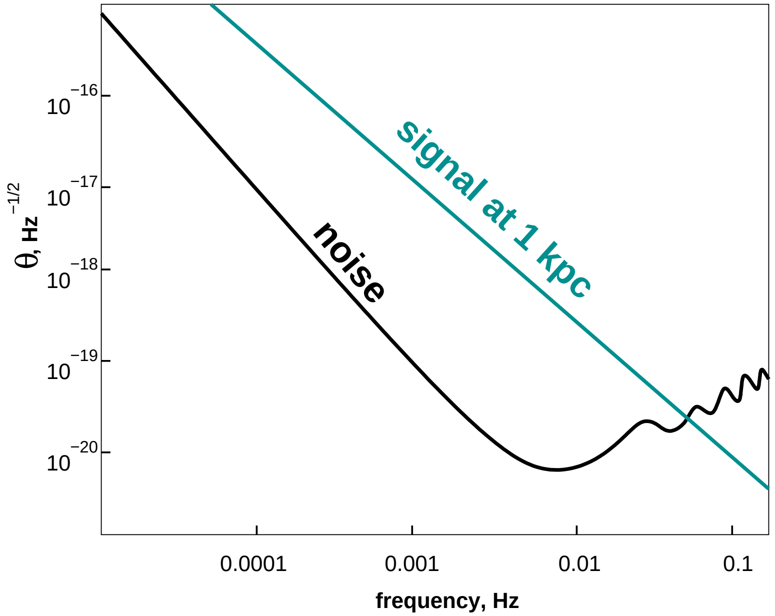
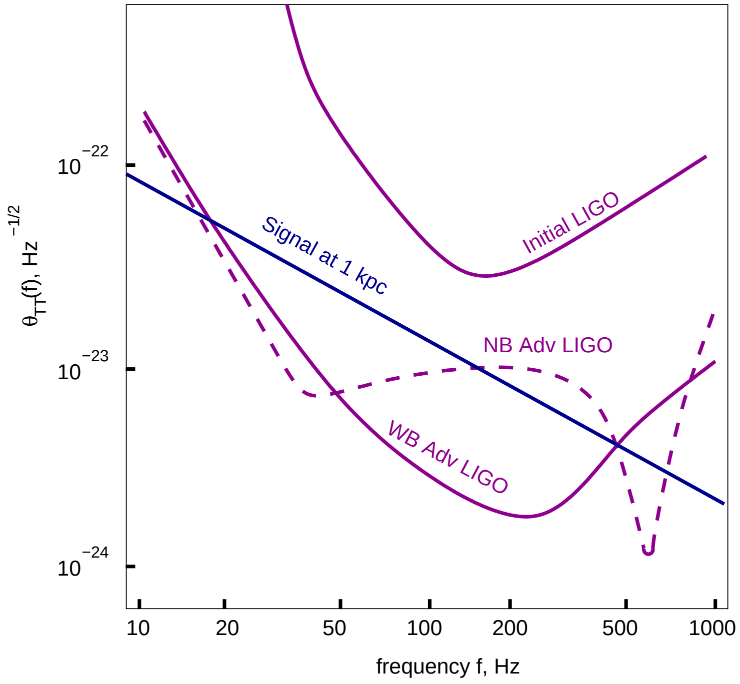


Predicted correlation: direction of $\vec{v}$ and $\vec{\Omega}$.

Gravity waves at LIGO and LISA

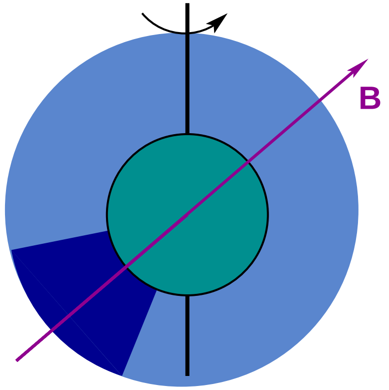




[Loveridge, PR D **69**, 024008 (2004)]

Other predictions of the pulsar kick mechanism

- **No $B - v$ correlation** is expected because
  - the magnetic field *inside* a hot neutron star during the *first ten seconds* is very different from the surface magnetic field of a cold pulsar
  - rotation washes out the x, y components
- **Directional $\vec{\Omega} - \vec{v}$ correlation** is expected, because
  - the direction of rotation remains unchanged
  - only the z-component survives



Conclusion

- A sterile neutrino with keV mass and a small mixing is a viable dark matter candidate
- The same neutrino is emitted from a supernova with a sufficient anisotropy to explain the pulsar velocities
- A rather minimal extension of the Standard Model, the addition of three **sterile neutrinos** explains all the present data, including **dark matter**, the **baryon asymmetry** of the universe, and the **pulsar velocities**
- Observatiobal predictions are within reach; stay tuned.