Looking for dark matter in the neutrino sector

- Theory: the seesaw mechanism, *well adjusted*

- Experimental bounds and searches

- Astrophysical hints:
  - dark matter
  - pulsar velocities
  - star formation

Sterile neutrinos

Бруно Понтекорво

The name "sterile" was coined by **Bruno Pontecorvo** in a paper [JETP, **53**, 1717 (1967)], which also discussed

- lepton number violation
- neutrinoless double beta decay
- rare processes (e.g. $\mu \to e\gamma$)
- vacuum neutrino oscillations
- detection of neutrino oscillations
- astrophysical neutrino oscillations

Pontecorvo: neutrino oscillations can *"convert potentially active particles into particles that are, from the point of view of ordinary weak interactions,* **sterile**, *i.e. practically unobservable, since they have the "incorrect" helicity"* [JETP, **53**, 1717 (1967)]

Neutrino masses

Discovery of neutrino masses implies a plausible existence of right-handed (sterile) neutrinos. Most models of neutrino masses introduce sterile states

$$\{\nu_e, \nu_\mu, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \ldots, \nu_{s,N}\}$$

and consider the following lagrangian:

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

where H is the Higgs boson and L_α $(\alpha = e, \mu, \tau)$ are the lepton doublets. The mass matrix:

$$M = \left(\begin{array}{cc} \tilde{m}_{3\times 3} & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{array}\right)$$

Neutrino masses

Discovery of neutrino masses implies a plausible existence of right-handed (sterile) neutrinos. Most models of neutrino masses introduce sterile states

$$\{\nu_e, \nu_\mu, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \ldots, \nu_{s,N}\}$$

and consider the following lagrangian:

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

where H is the Higgs boson and L_α $(\alpha = e, \mu, \tau)$ are the lepton doublets. The mass matrix:

$$M = \begin{pmatrix} 0 & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{pmatrix}$$

What is the *natural* scale of M?

Seesaw mechanism

In the Standard Model, the matrix D arises from the Higgs mechanism:

$$D_{ij} = y_{ij} \langle H \rangle$$

Smallness of neutrino masses **does not** imply the smallness of Yukawa couplings. For large M,

$$m_\nu \sim \frac{y^2 \langle H \rangle^2}{M}$$

One can understand the smallness of neutrino masses even if the Yukawa couplings are $y \sim 1$ [Gell-Mann, Ramond, Slansky; Yanagida; Glashow; Mohapatra, Senjanović].

Is $y \sim 1$ better than $y \ll 1$?

Depends on the model.

- If $y \approx$ some intersection number in string theory, then $y \sim 1$ is natural
- If y comes from wave function overlap of fermions living on different branes in a model with extra-dimensions, then it can be exponentially suppressed, hence, $y \ll 1$ is natural.

In the absence of theory of the Yukawa couplings, one is evokes some naturalness arguments.

’t Hooft’s naturalness criterion

Small number is natural if setting it to zero increases the symmetry

Small breaking of the symmetry ⇒ small number

- Pion masses are small because the massless pions correspond to exact chiral symmetry **natural**

- Gauge hierarchy problem: small $\boldsymbol{M_{\rm Higgs}/m_{\rm Planck}}$ is **not natural in the Standard Model** because setting $\boldsymbol{M_{\rm Higgs}=0}$ does not increase the symmetry. In a supersymmetric extension, $\boldsymbol{M_{\rm Higgs}\approx M_{\rm Higgsino}}$, and setting $\boldsymbol{M_{\rm Higgsino}} = 0$ increases the overall (chiral) symmetry. Hence, a light Higgs is **natural in SUSY models**.

- Cosmological constant problem: $\Lambda \longrightarrow 0$ does not increase the symmetry. Hence, **not natural**.

What if we apply this criterion to sterile neutrinos? Symmetry increases for $M \longrightarrow 0$, namely, the chiral symmetry of right-handed fields.

Small M is technically **natural**.

Clues from cosmology?

Baryon asymmetry of the universe could be generated by **leptogenesis**

However, leptogenesis can work for both $M \gg 100$ GeV and $M < 100$ GeV:

- For $M \gg 100$ GeV, heavy sterile neutrino decays can produce the lepton asymmetry, which is converted to baryon asymmetry by sphalerons [Fukugita,Yanagida]

- For $M < 100$ GeV, neutrino oscillations can produce the lepton asymmetry, which is converted to baryon asymmetry by sphalerons [Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov]

Over the years, neutrino physics has shown many theoretical prejudices to be wrong: neutrinos were expected to be massless, neutrinos were expected to have small mixing angles, etc.

Since the fundamental theory of netrino masses is lacking, one should

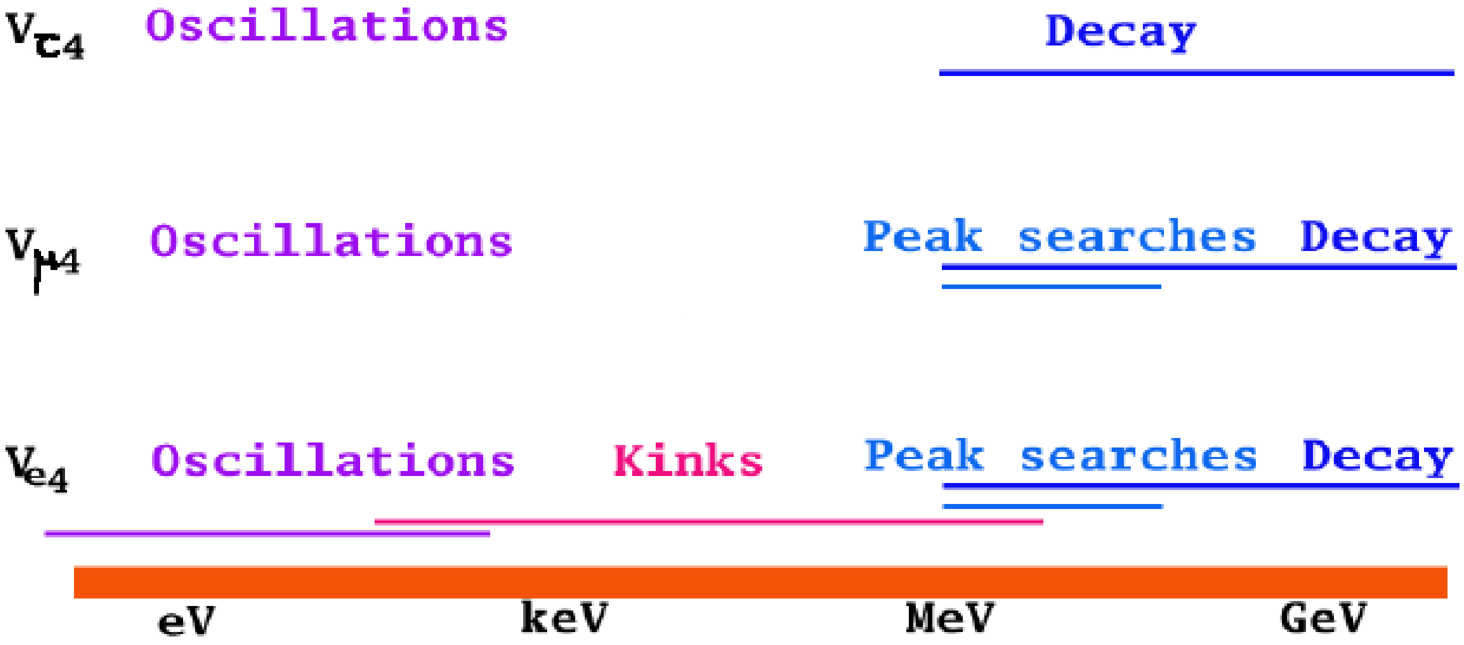
**consider all allowed values
for the sterile neutrino masses**

in the following lagrangian:

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

where M is can be small or large
[de Gouvêa; Asaka, Blanchet, Shaposhnikov]

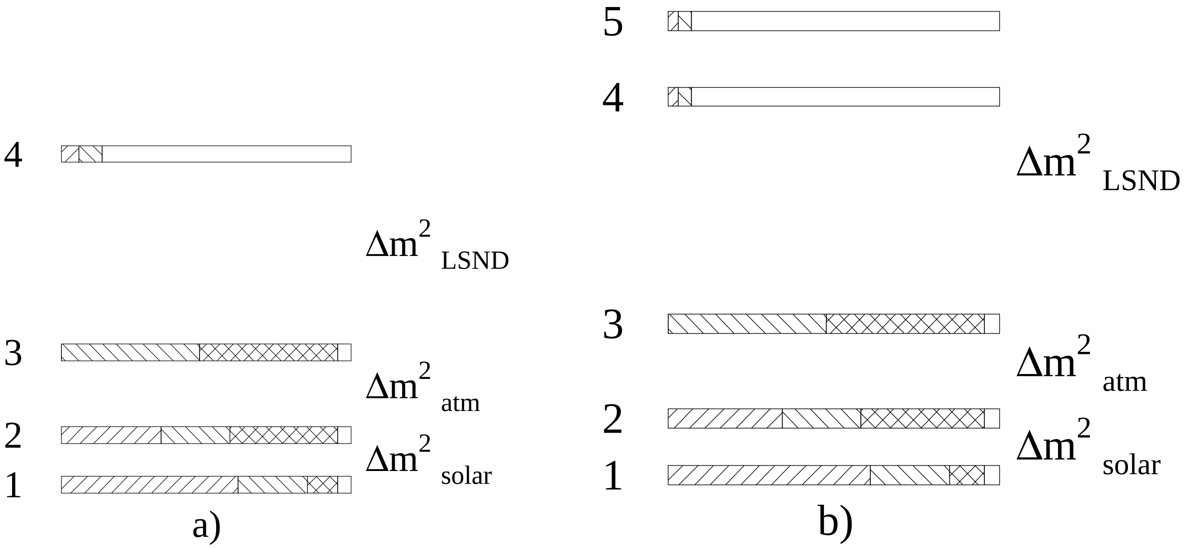
Experimental limits



[Pascoli]

Neutrino oscillations

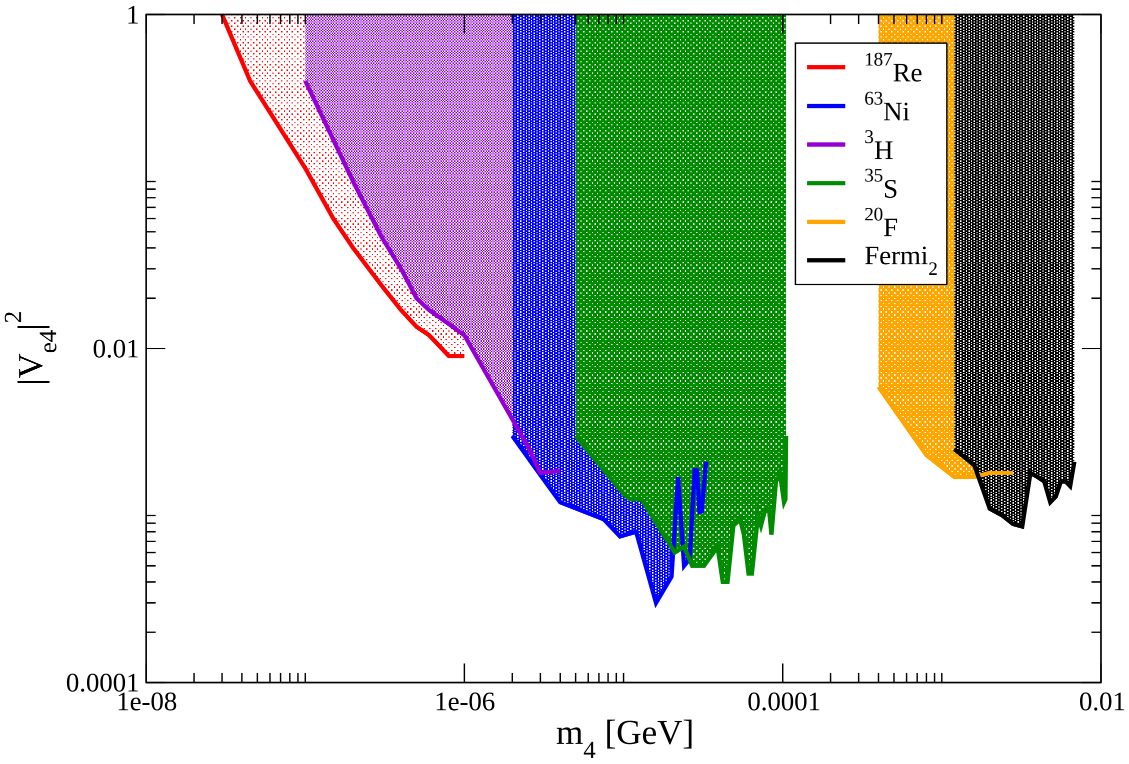
Need more than 3 neutrinos to fit (1) solar, (2) atmospheric, (3) LSND:



The scheme 3+2 (b) fits the data much better than the 3+1 (a) [Sorel, Conrad, Shaevitz].

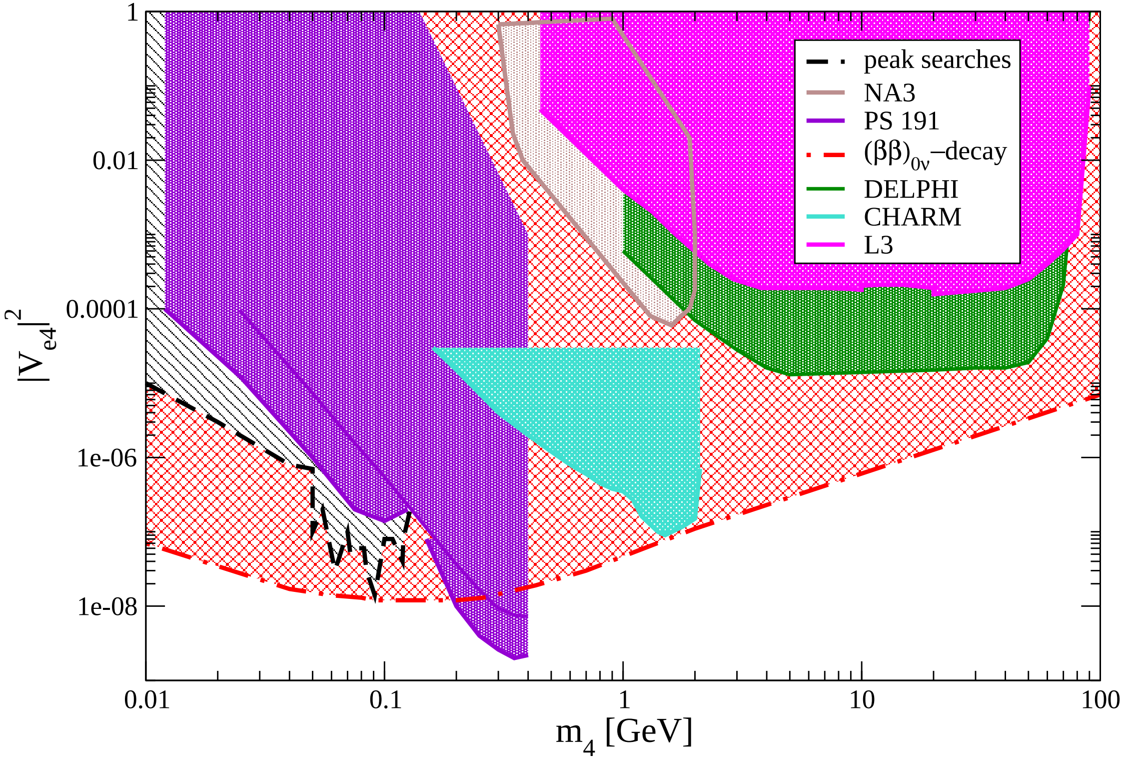
new results from MiniBooNE expected soon!

Experimental limits: kinks



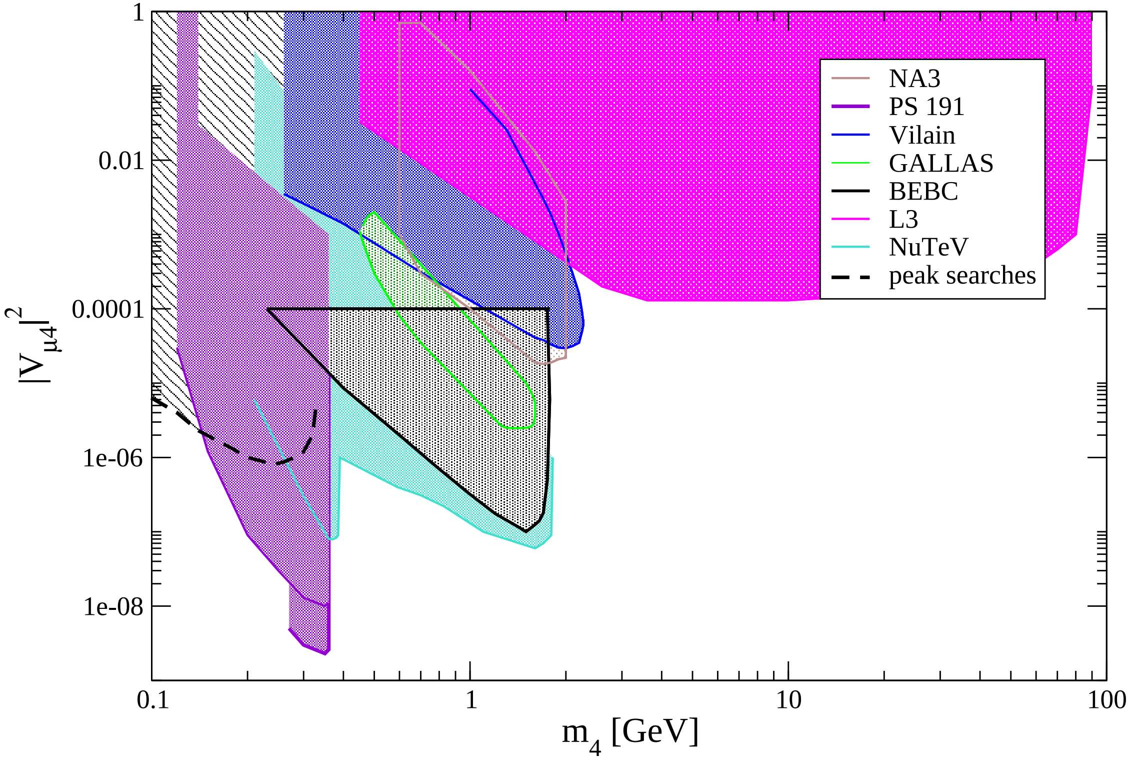
[Atre, Han, Pascoli]

Experimental limits: peak searches and decays



[Atre, Han, Pascoli]

Experimental limits from peak searches and decays



[Atre, Han, Pascoli; AK, Pascoli, Semikoz]

Astrophysical clues: dark matter

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; some (merging) clusters show displacement of dark and baryonic matter

Dark matter: a simple (minimalist) solution

Need **one** particle ⇒ use of of the particles already introduced to give the neutrino masses

⇒ **sterile neutrino**

sub-MeV mass implies **stability!** No symmetries required. (Cf. heavy WIMPs need a symmetry to be stable, e.g., the R-parity.)

Sterile neutrinos in the early universe

Sterile neutrinos are produced in primordial plasma through

- off-resonance oscillations. [Dodelson, Widrow; Abazajian, Fuller; Dolgov, Hansen; Asaka, Laine, Shaposhnikov et al.]
- oscillations on resonance, if the lepton asymmetry is non-negligible [Fuller, Shi]
- **production mechanisms which do not involve oscillations**
  - inflaton decays directly into sterile neutrinos [Shaposhnikov, Tkachev]
  - Higgs physics: both mass and production [AK]

Active–sterile oscillations

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

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 $\nu_e \rightarrow \nu_s$ conversion in presence of matter is

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

where λ_{osc} is the oscillation length, and λ_{s} is the scattering length.

Mixing is suppressed at high temperature [Dolgov, Barbiieri; Stodolsky]

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

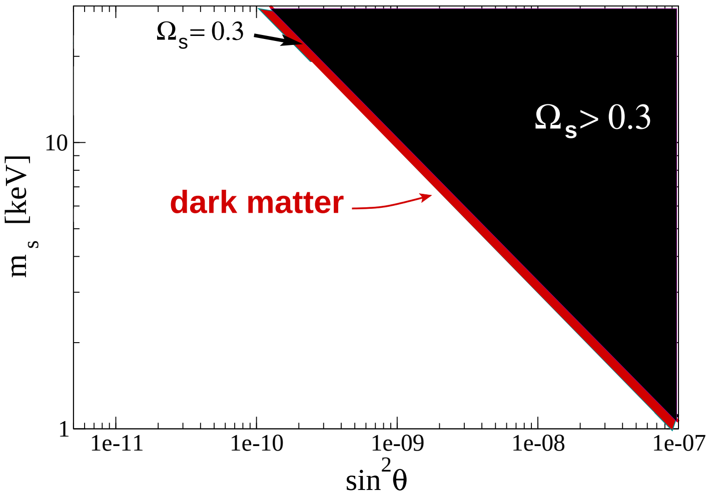
For small angles,

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

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:



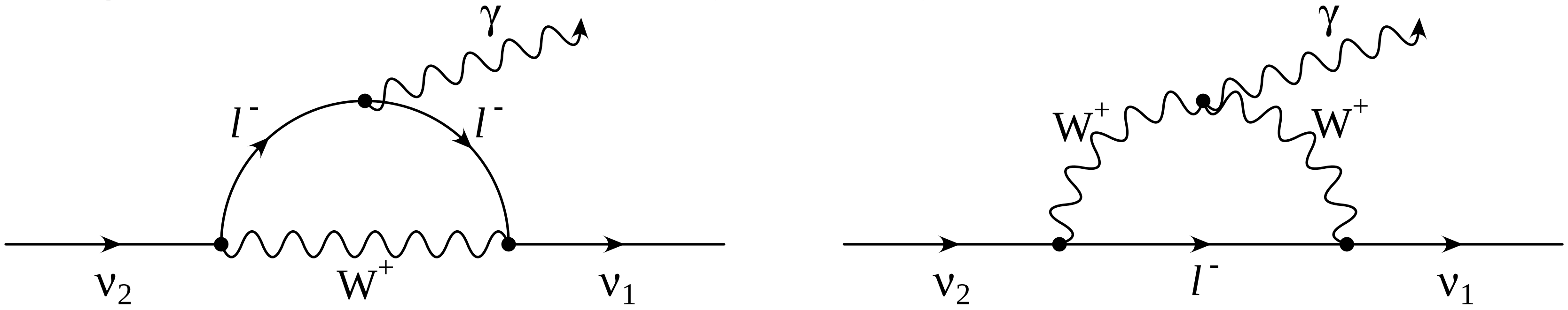
$$\Omega_{\nu_2} \sim 0.3 \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_s}{\mathrm{keV}}\right)^2$$

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

Hadronic uncertainties under control [Asaka, Laine, Shaposhnikov]

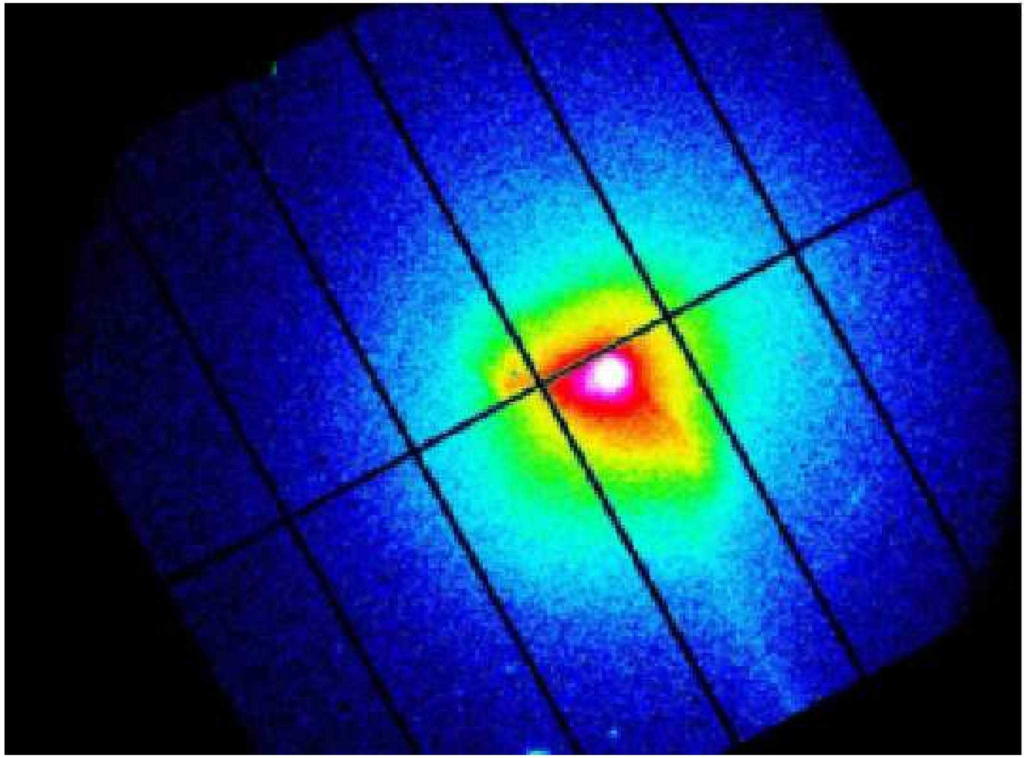
Radiative decay

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



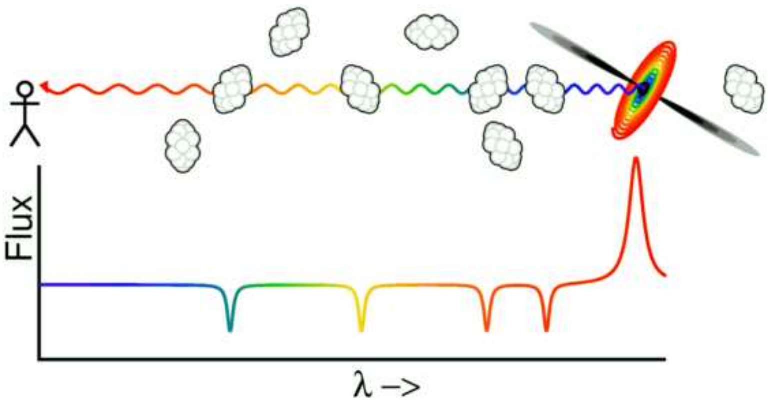
Photons have energies $m/2$: X-rays. Large lumps of dark matter emit some X-rays. [Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]

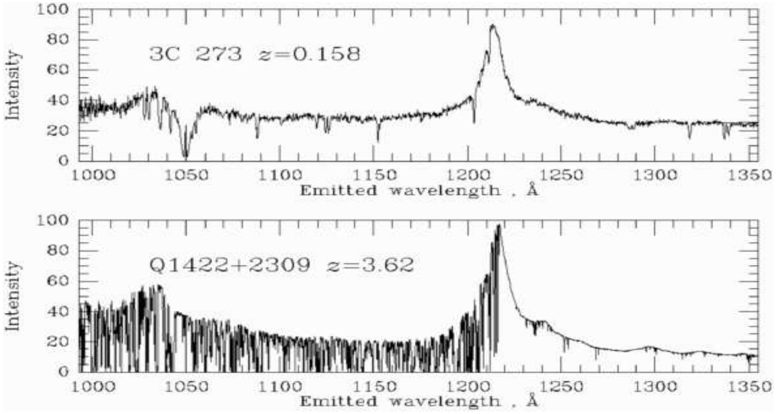
X-ray observations



Virgo cluster image from XMM-Newton

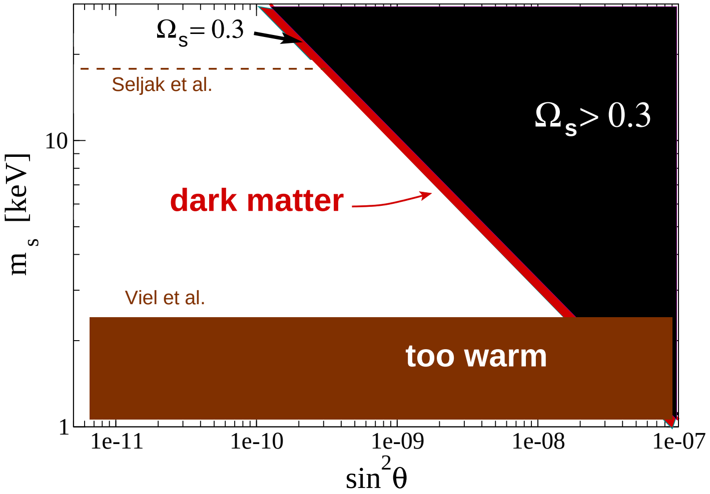
Dark matter and the Lyman-α forest.





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

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



Lyman-α forest clouds show significant structure on small scales. Dark matter must be cold enough to preserve this structure. Lyman-alpha bounds based on high-redshift data are stronger, $m > 10$ keV [Seljak et al.; Viel et al.], but there are unknown systematic errors.

Cold or warm dark matter?

CDM works well, but...

There may be problems with cold dark matter on small scales

WDM works equally well on the large scales.

Some CDM problems eliminated by WDM

- overproduction (by an order of magnitude!) of the satellite halos for galaxies of the size of Milky Way.

- WDM can reduce the number of halos in low-density voids. [Peebles]

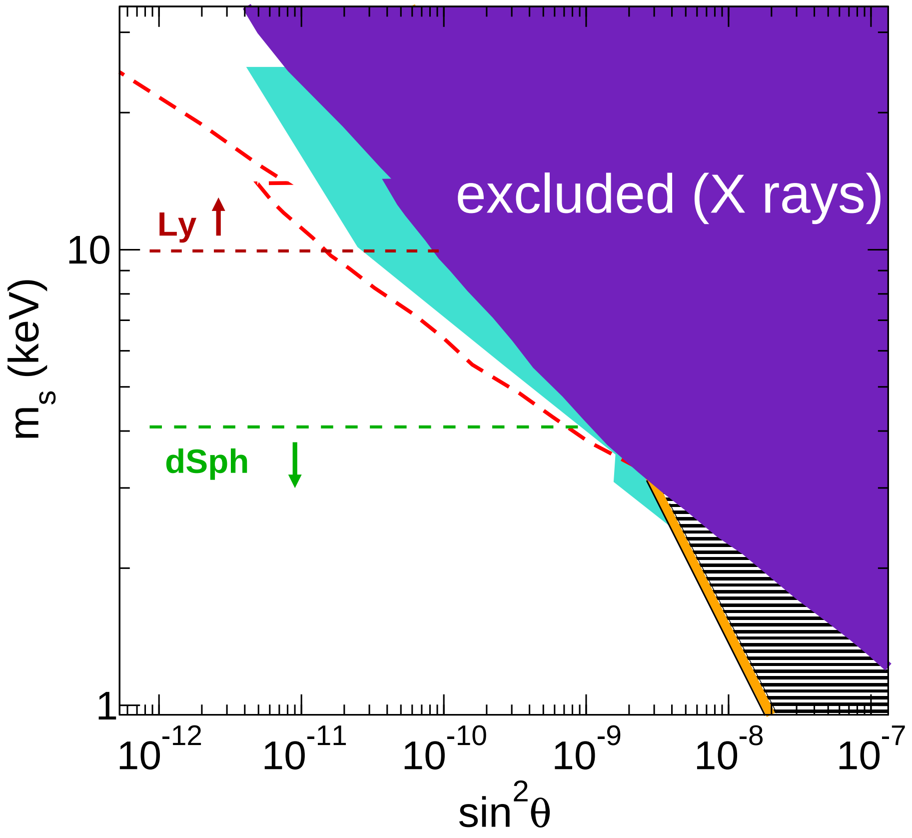
- observed densities of the galactic cores (from the rotation curves) are lower than what is predicted based on the ΛCDM power spectrum. [Dalcanton et al.; van den Bosch et al.; Moore; Abazajian]

- The "angular-momentum problem": in CDM halos, gas should cool at very early times into small halos and lead to massive low-angular-momentum gas cores in galaxies. [Dolgov]

- disk-dominated (pure-disk) galaxies are observed, but not produced in CDM because of high merger rate. [Governato et al.; Kormendy et al.]

- observations of dwarf spheroidal galaxies $\Rightarrow m \sim$ keV [Gilmore et al.; Strigari et al.]

For DW production, Ly-α conflicts with dwarf spheroids.



[Viel et al.; Seljak et al., Gilmore et al.]

Neutrino masses: new scale or new Higgs physics?

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a \left(i \partial_\mu \gamma^\mu \right) N_a - y_{\alpha a} H \, \bar{L}_\alpha N_a - \frac{M_a}{2} \, \bar{N}_a^c N_a + h.c. \, ,$$

To explain the pulsar kicks and dark matter, one needs $M \sim$ **keV**. Is this a new fundamental scale? Perhaps. Alternatively, it could arise from the Higgs mechanism:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a \left(i \partial_\mu \gamma^\mu \right) N_a - y_{\alpha a} H \, \bar{L}_\alpha N_a - h_a \, S \, \bar{N}_a^c N_a + V(H, S)$$

$$M = h \langle S \rangle$$

Now $S \longrightarrow NN$ decays can produce sterile neutrinos

For small h, the sterile neutrinos are out of equilibrium in the early universe, but S is in equilibrium. There is a new mechanism to produce sterile dark matter at $T \sim m_S$ from decays $S \to NN$:

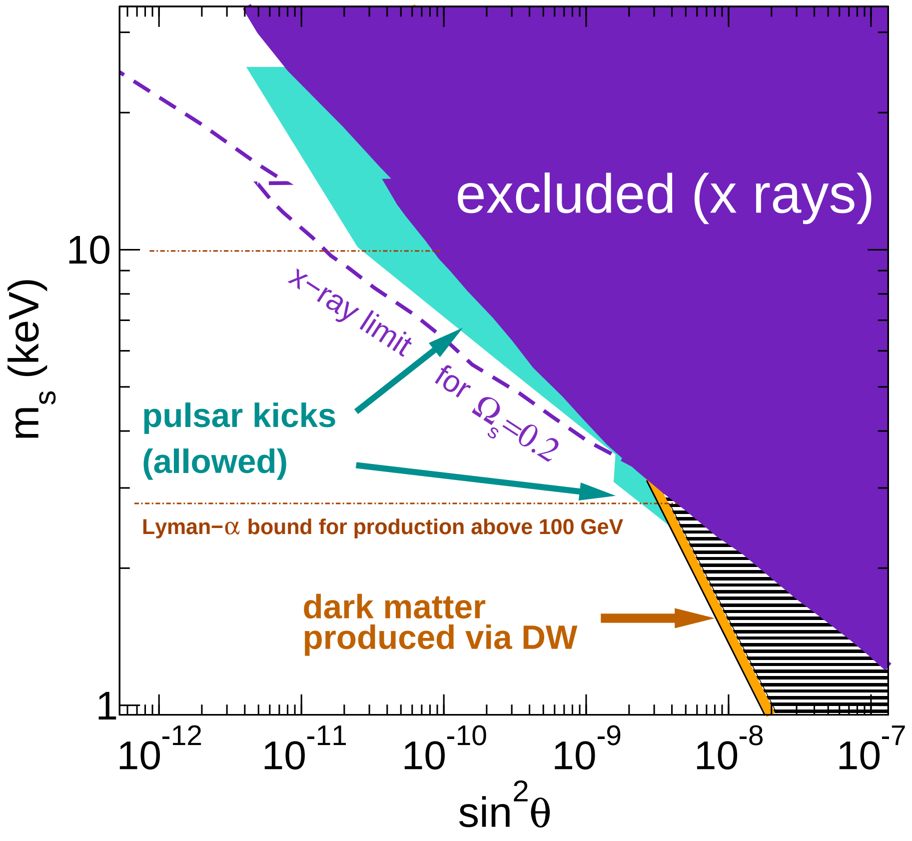
$$\Omega_s = 0.2 \left(\frac{33}{\xi}\right) \left(\frac{h}{1.4 \times 10^{-8}}\right)^3 \left(\frac{\langle S \rangle}{\tilde{m}_S}\right)$$

Here ζ is the dilution factor due to the change in effective numbers of degrees of freedom.

The sterile neutrino momenta are red-shifted by factor $\zeta^{1/3} \approx 3$.

$$\langle S \rangle = \frac{M_s}{h} \sim \frac{\text{few keV}}{1.4 \times 10^{-8}} \sim 10^2\,\text{GeV}$$

Cooling changes the bounds



[AK, PRL **97**:241301, hep-ph/0609081]

Implications for the EW phase transition and the LHC

The presence of S in the Higgs sector changes the nature of the electroweak phase transition, which now proceeds in two stages:

$$\{S=0, H=0\} \longrightarrow \{S\neq 0, H=0\} \longrightarrow \{S\neq 0, H\neq 0\}$$

One may be able to discover the *invisible Higgs* at the LHC in the $Z+H_{\rm inv}$ channel, as well as in the weak boson fusion channel. In some range of masses, the discovery is possible at the LHC with $10\ {\rm fb}^{-1}$ in the $Z+H_{\rm inv}$ channel [Davoudiasl et al.] LHC phenomenology [O'Connell et al.]

Astrophysical clues: supernova

- Sterile neutrino emission from a supernova is anisotropic due to
  1. asymmetries in the urca cross sections
  2. magnetic effects on neutrino oscillations

- Sterile neutrinos with masses and mixing angles consistent with dark matter can explain the pulsar velocities

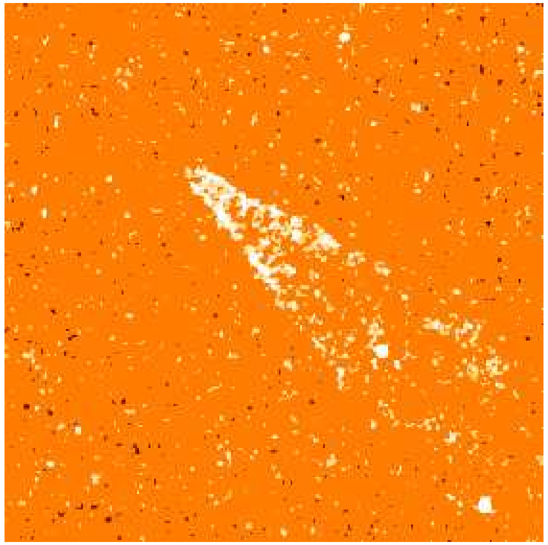
[AK, Segrè; Fuller, AK, Mocioiu, Pascoli; Barkovich, D'Olivo, Montemayor]

The pulsar velocities.

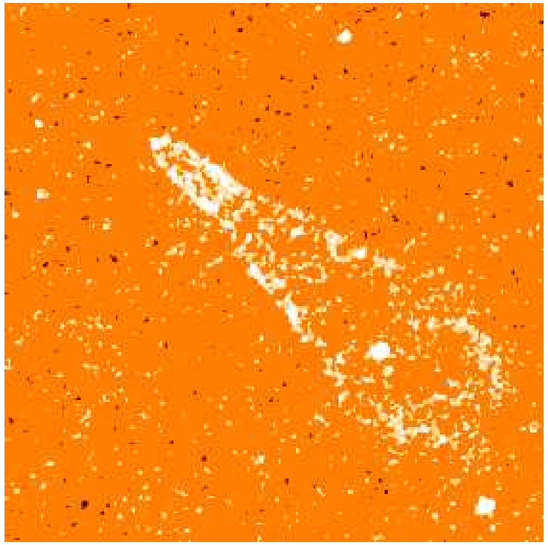
Pulsars have large velocities, $\langle v \rangle \approx \mathbf{250 - 450\ km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

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

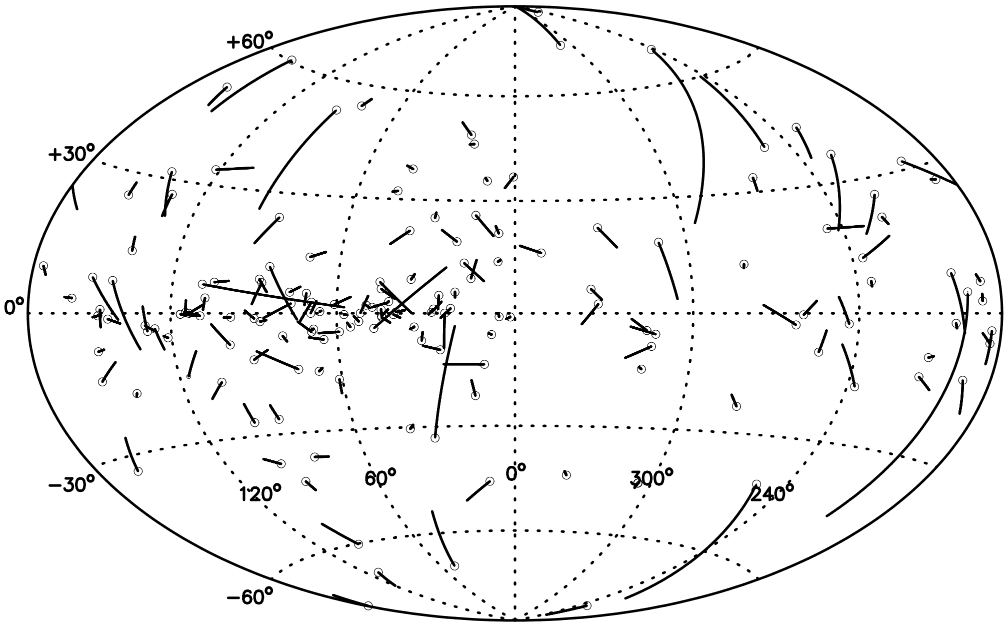


HST, December 1994



HST, December 2001

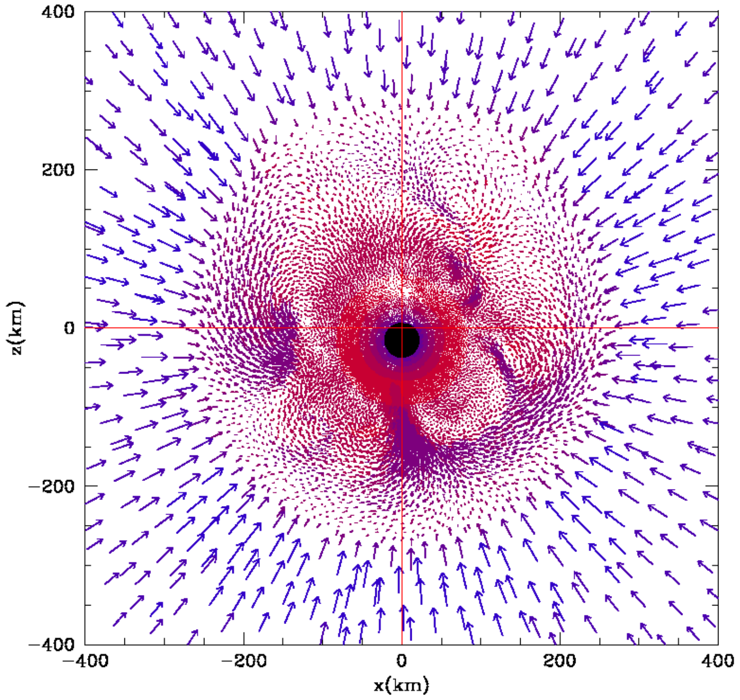
Map of pulsar velocities

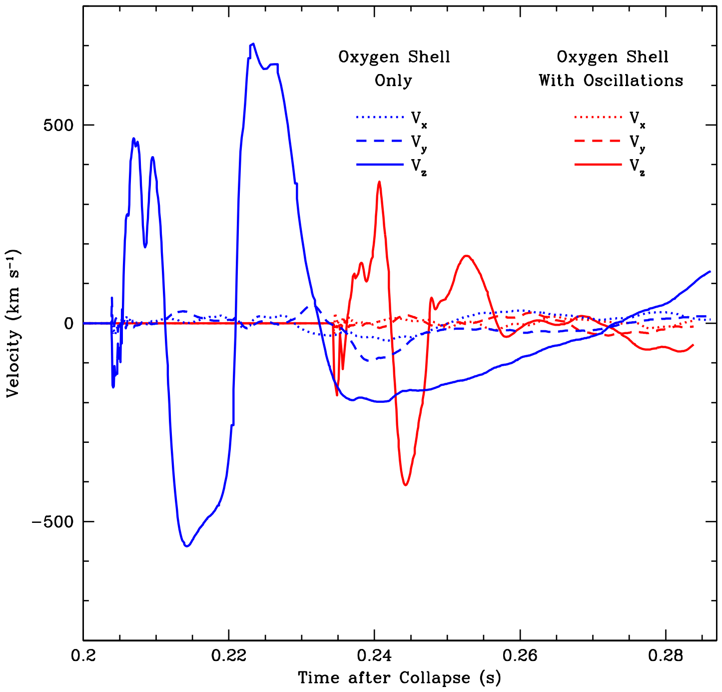


Proposed explanations:

- 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)
- "cumulative" parity violation [Lai, Qian; Janka] (it's *not* cumulative)
- various exotic explanations
- explanations that were "not even wrong"...

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

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 ⇒ 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*

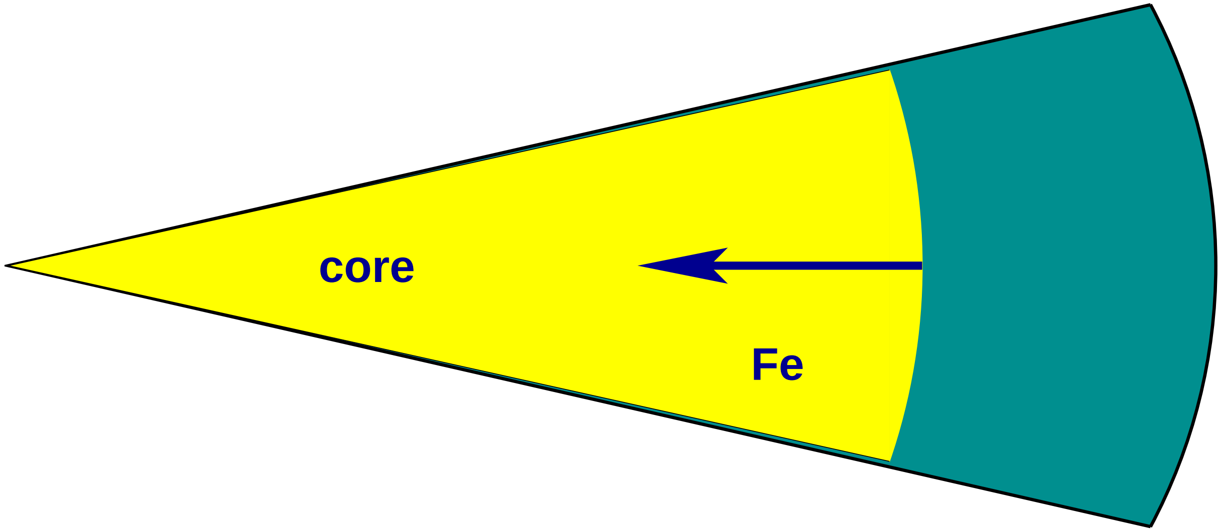
$\Rightarrow$ some neutron stars have surface magnetic fields as high as $10^{15} - 10^{16}$ G.

$\Rightarrow$ **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.

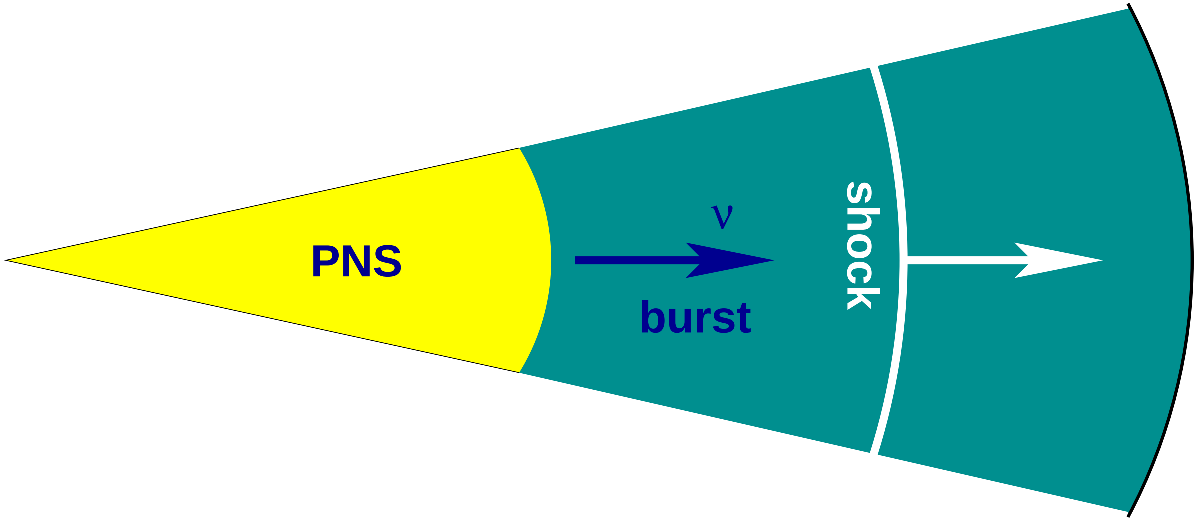
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

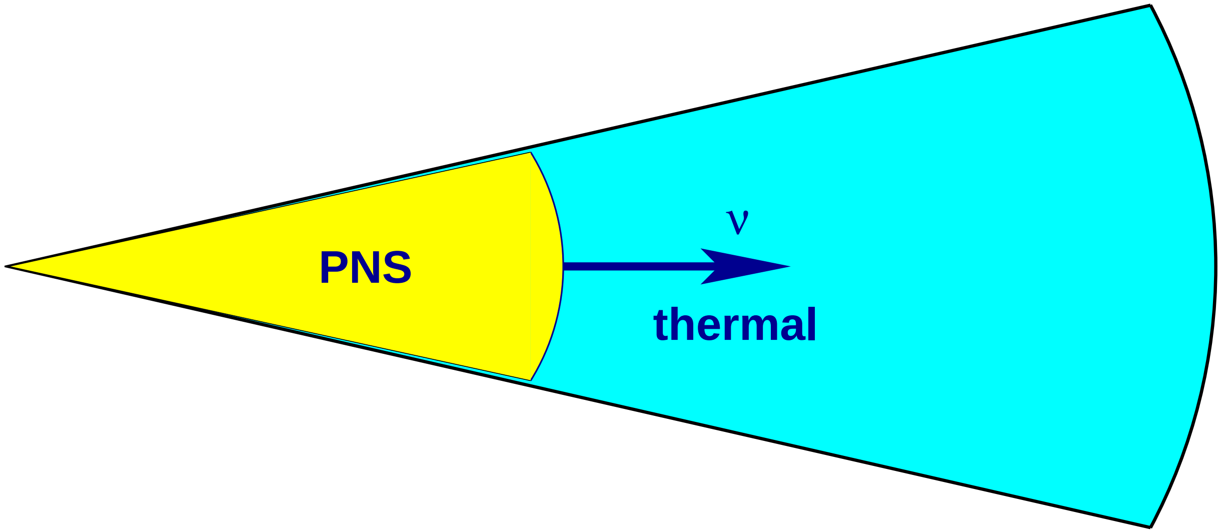
Shock formation and "neutronization burst": $t = 1 - 10$ ms



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.

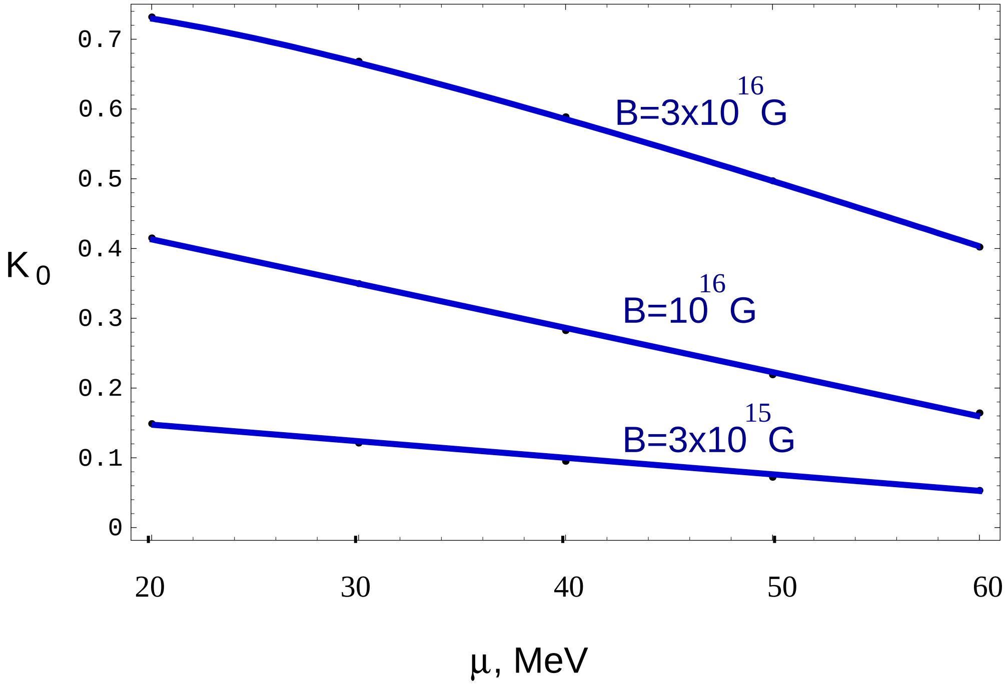
$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

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,

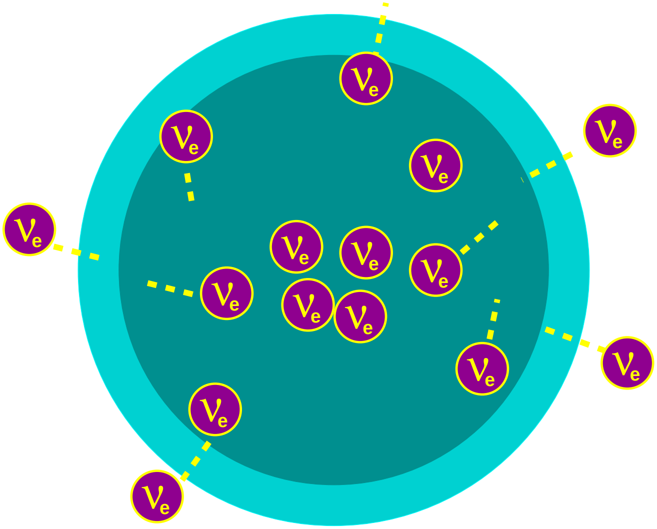


k_0 is the fraction of electrons in the lowest Landau level.

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?

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?

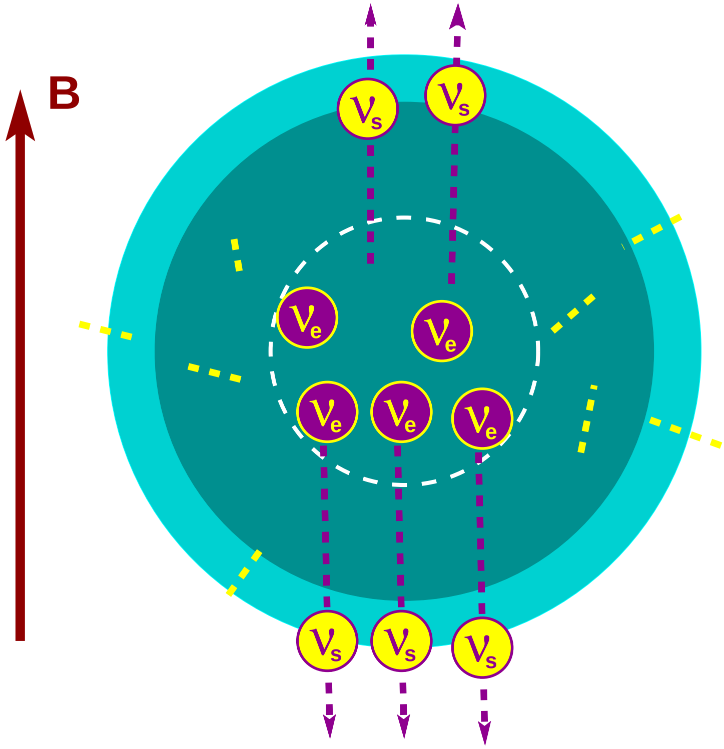
No

Rescattering washes out the asymmetry

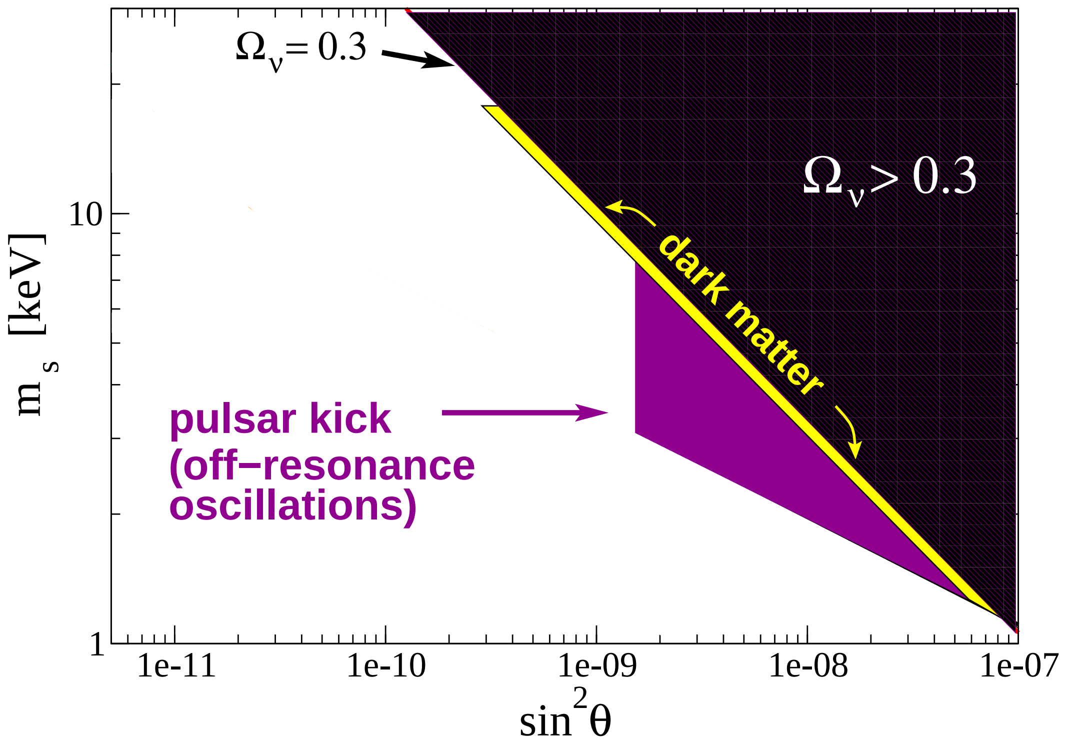
In approximate thermal equilibrium the asymmetries in scattering amplitudes do not lead to an anisotropic emission [Vilenkin,AK, Segrè]. Only the outer regions, near neutrinospheres, contribute, but the kick would require a mass difference of $\sim 10^2$ eV [AK,Segrè].

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

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


B
ν_s
ν_s
ν_e
ν_e
ν_e
ν_e
ν_e
ν_s
ν_s
ν_s

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



[Fuller, AK, Mocioiu, Pascoli]

Resonance and the D'Olivo-Nieves-Pal-Semikoz effect

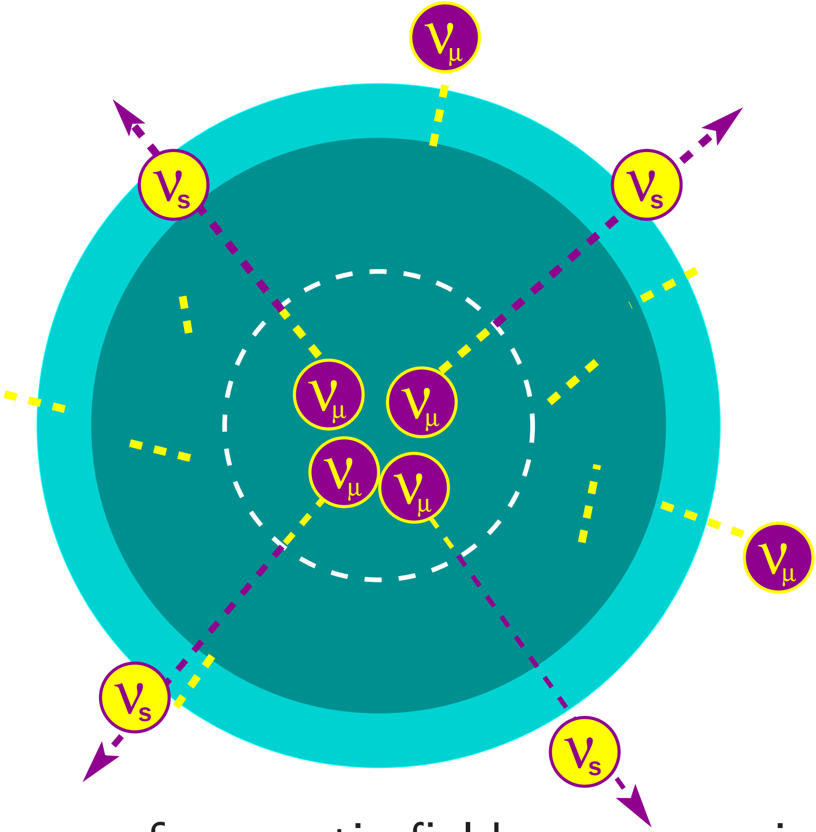
Matter potential:

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

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

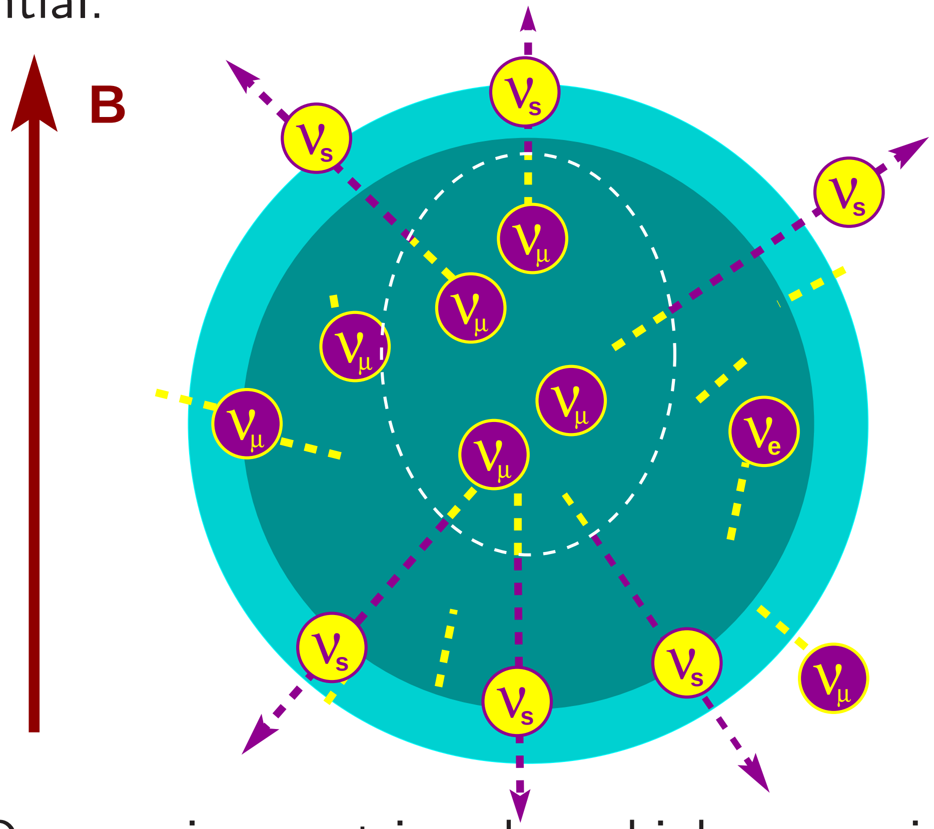
[D'Olivo, Nieves, Pal; Semikoz]

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

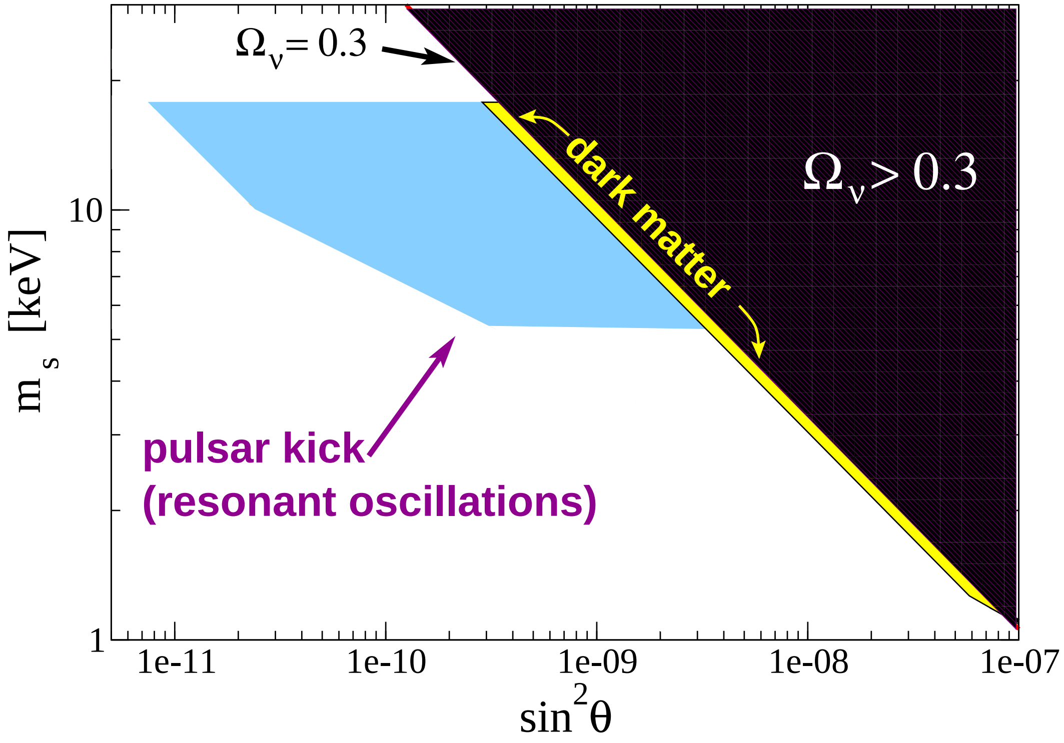
The magnetic field shifts the position of the resonance because of the $\frac{\vec{k}\cdot\vec{B}}{k}$ term in the potential:



Down going neutrinos have higher energies

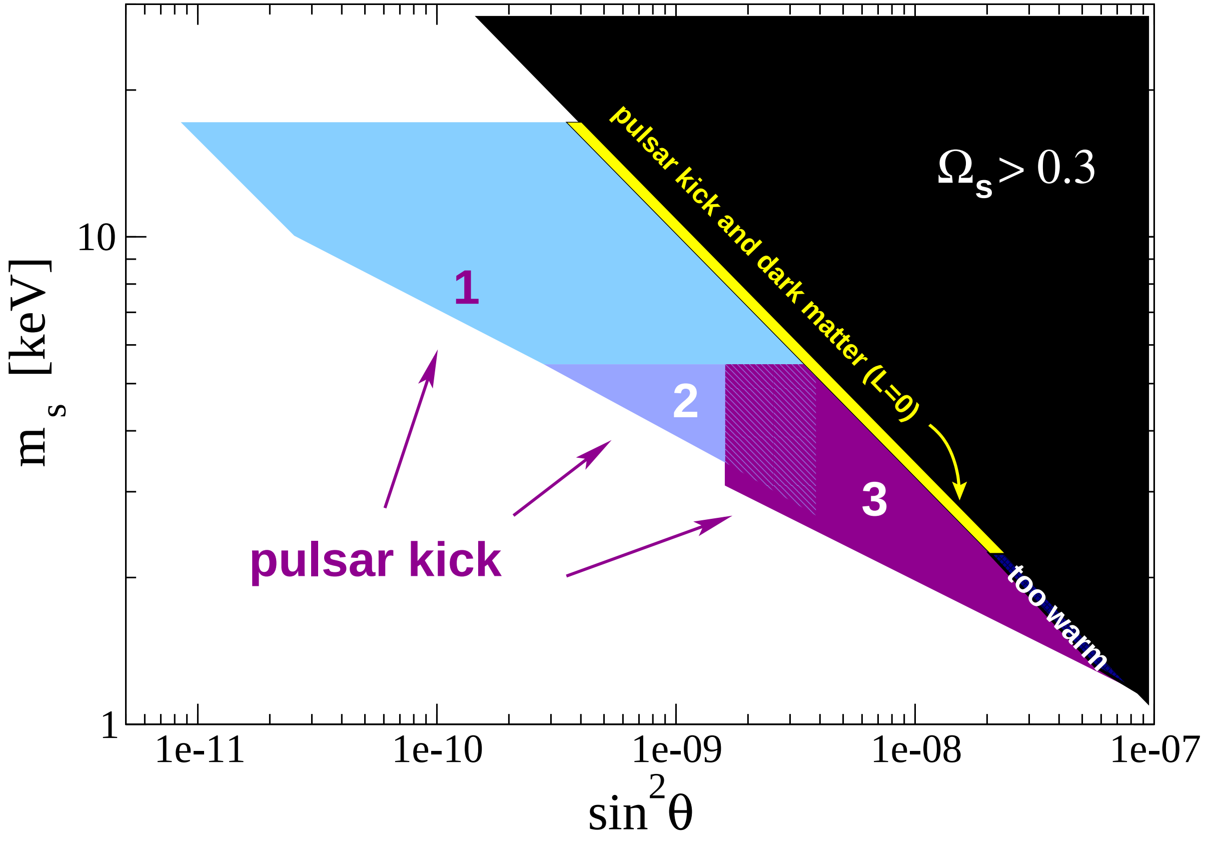
of the

The range of parameters for off-resonance transitions:



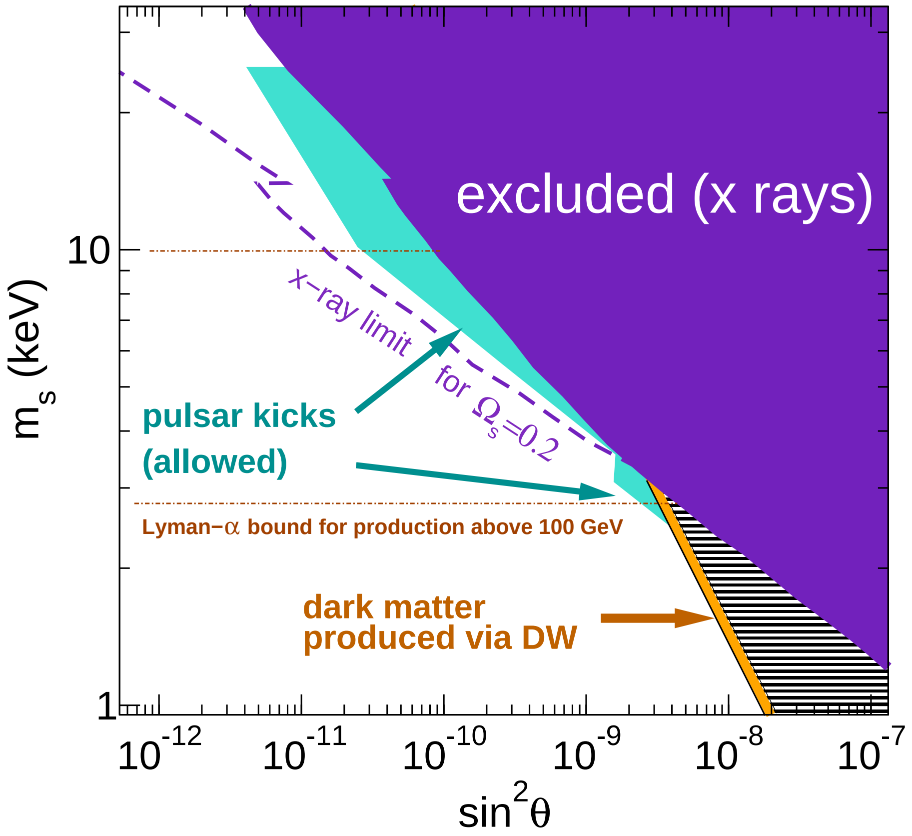
[AK, Segrè]

Resonance & off-resonance oscillations



[A.K., Segrè; Fuller, A.K.,Mocioiu,Pascoli; Barkovich, D’Ollivo, Montemayor]

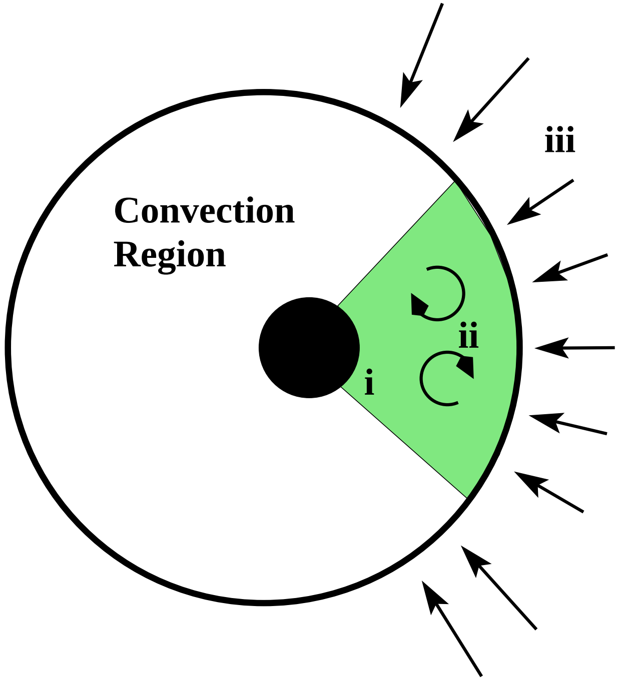
Allowed range of masses and mixnig angles



[AK, PRL 97, 241301, hep-ph/0609081]

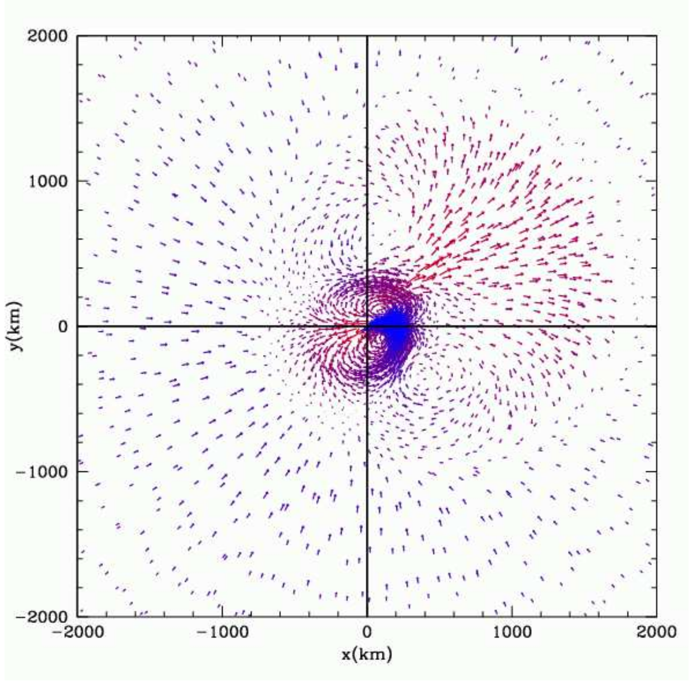
Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK]



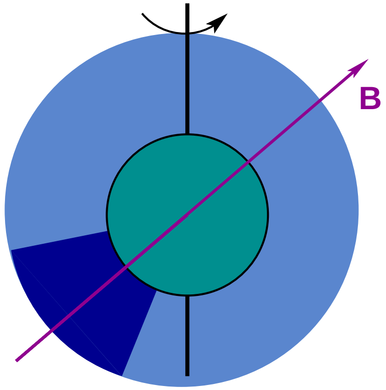
Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK]



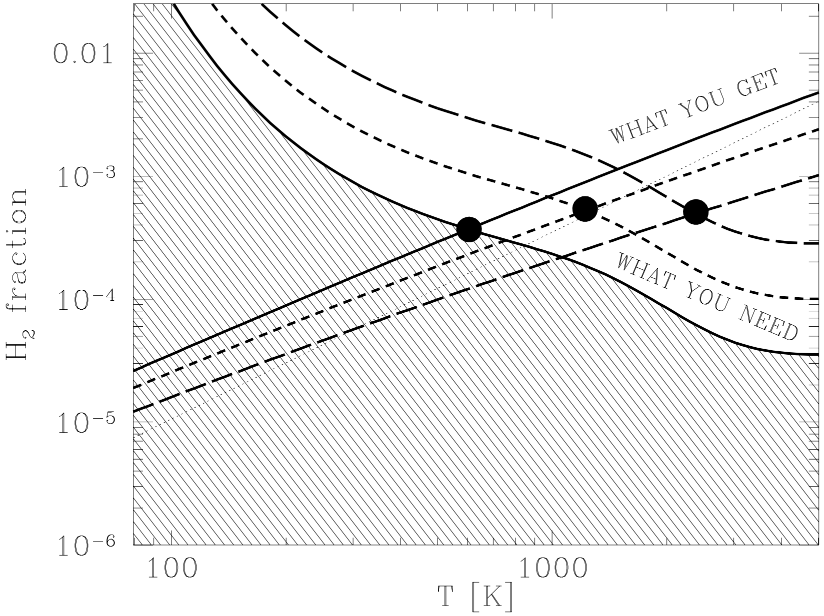
Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK]
- **No $B - v$ correlation** 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



Astrophysical clues: star formation and reionization

Molecular hydrogen is necessary for star formation



[Tegmark, et al., ApJ **474**, 1 (1997)]

Molecular hydrogen

$$H + H \longrightarrow H_2 + \gamma \quad - \quad \text{very slow!}$$

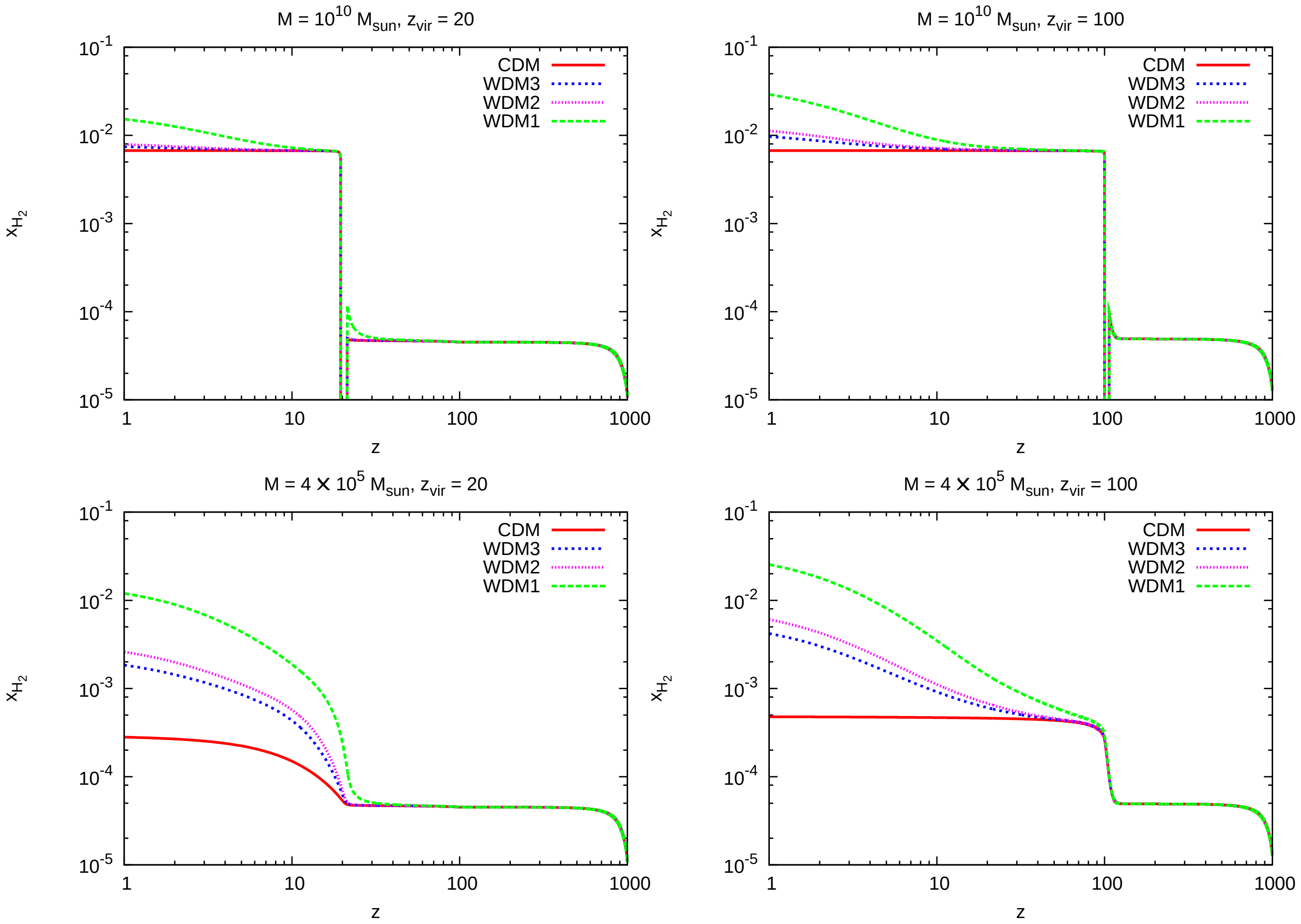
In the presence of ions the following reactions are faster:

$$\begin{array}{rcl} H^+ + H & \longrightarrow & H_2^+ + \gamma, \\ H_2^+ + H & \longrightarrow & H_2 + H^+. \end{array}$$

H^+ catalyze the formation of molecular hydrogen

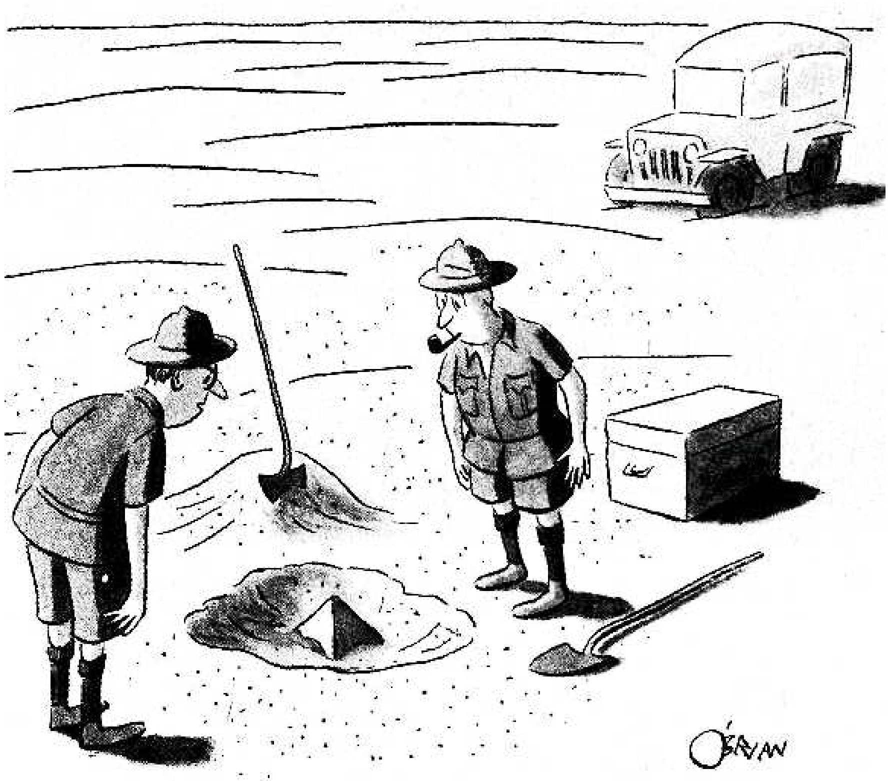
[Biermann, AK, PRL **96**, 091301 (2006)]

[Stasielak, Biermann, AK, ApJ.654:290 (2007)]



[Biermann, AK; Stasielak, Biermann, AK]

Clues of sterile neutrinos



This could be the greatest discovery of the century. Depending, of course, on how far down it goes.

Summary

- Sterile neutrinos almost certainly exists and have masses between eV and the Planck scale.

- A rather minimal extension of the Standard Model, the addition of **sterile neutrinos**, explains all the present data, including
  - dark matter (warm or cold, depending on the mass)
  - baryon asymmetry of the universe
  - pulsar velocities
  - promptness of star formation and reionization

- need MiniBooNE for large mixing angles, X-ray telescopes for small mixing angles, new experiments and new ideas