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  - star formation

New Scientist (June 17, 2006)

Article about sterile neutrinos

Sterile neutrinos

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. $\mu \rightarrow e\gamma$)
- 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

$$\{\nu_e, \nu_m u, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \dots, \nu_{s,N}\}$$

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:

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

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What is the *natural* scale of M?

Seesaw mechanism (talk by Mohapatra)

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].

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In the absence of theory of Yukawa couplings, one is looking for naturalness arguments, but the notion of naturalness is not model-independent.

't Hooft's naturalness criterion

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

Small breaking of the symmetry $\Rightarrow$ small number

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

Small M is technically **natural**.

Clues from cosmology?

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- 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]

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

consider all allowed values for the sterile neutrino masses

and consider the following lagrangian:

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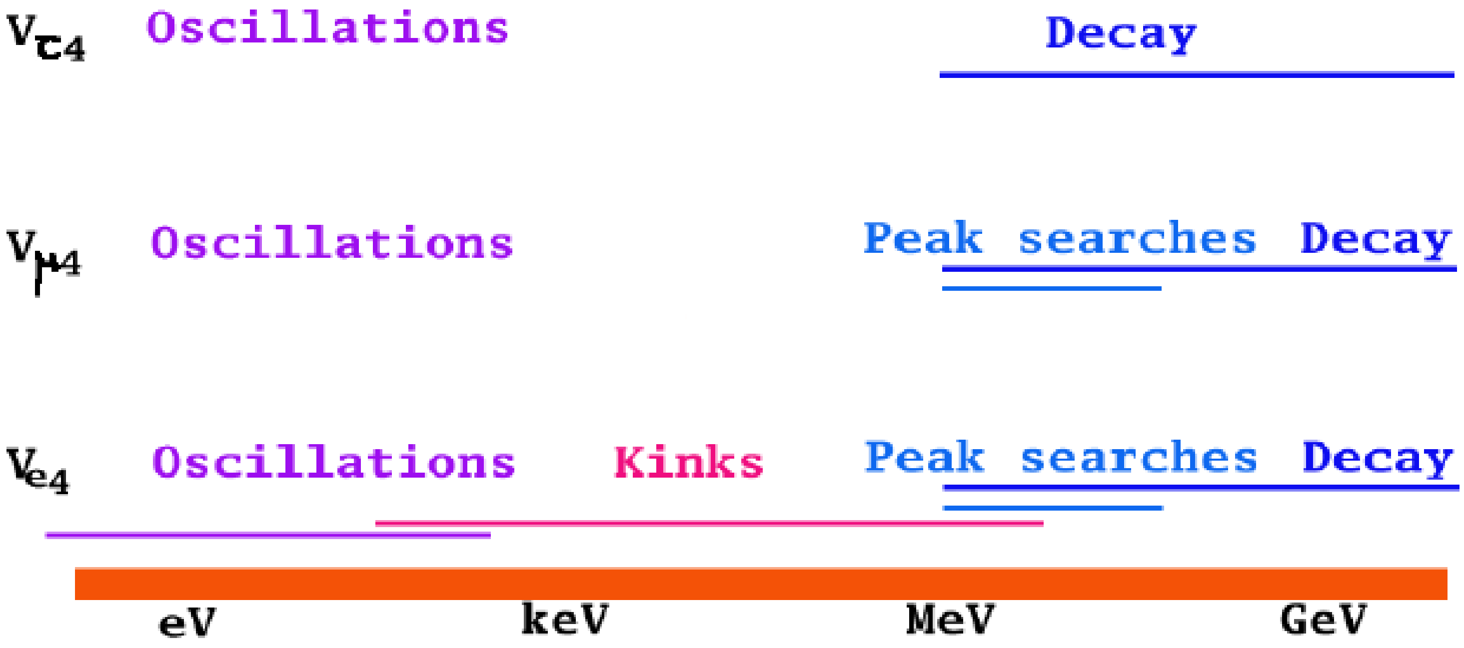
where M is can be small [de Gouvêa; Asaka, Blanchet, Shaposhnikov]

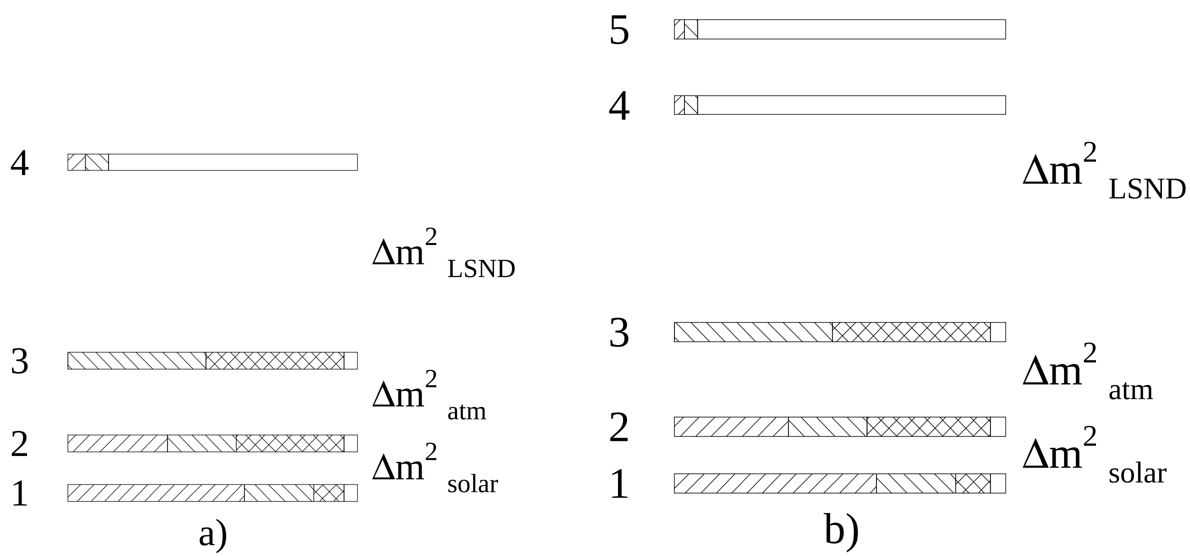
Experimental limits



[Pascoli]

Neutrino oscillations

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



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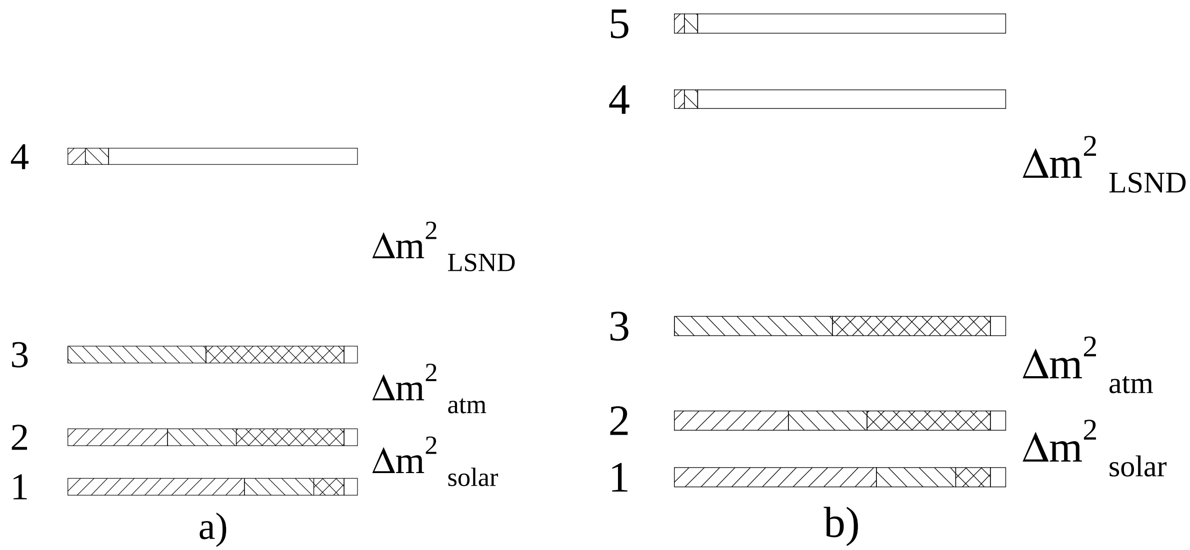

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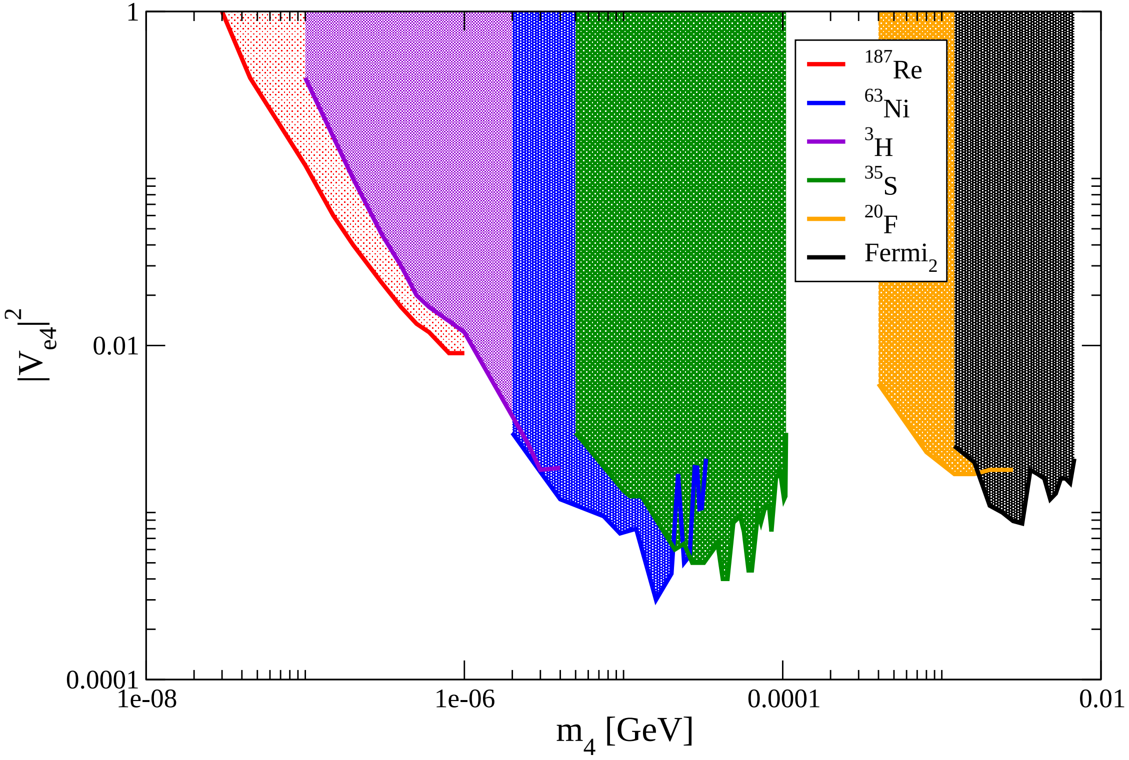
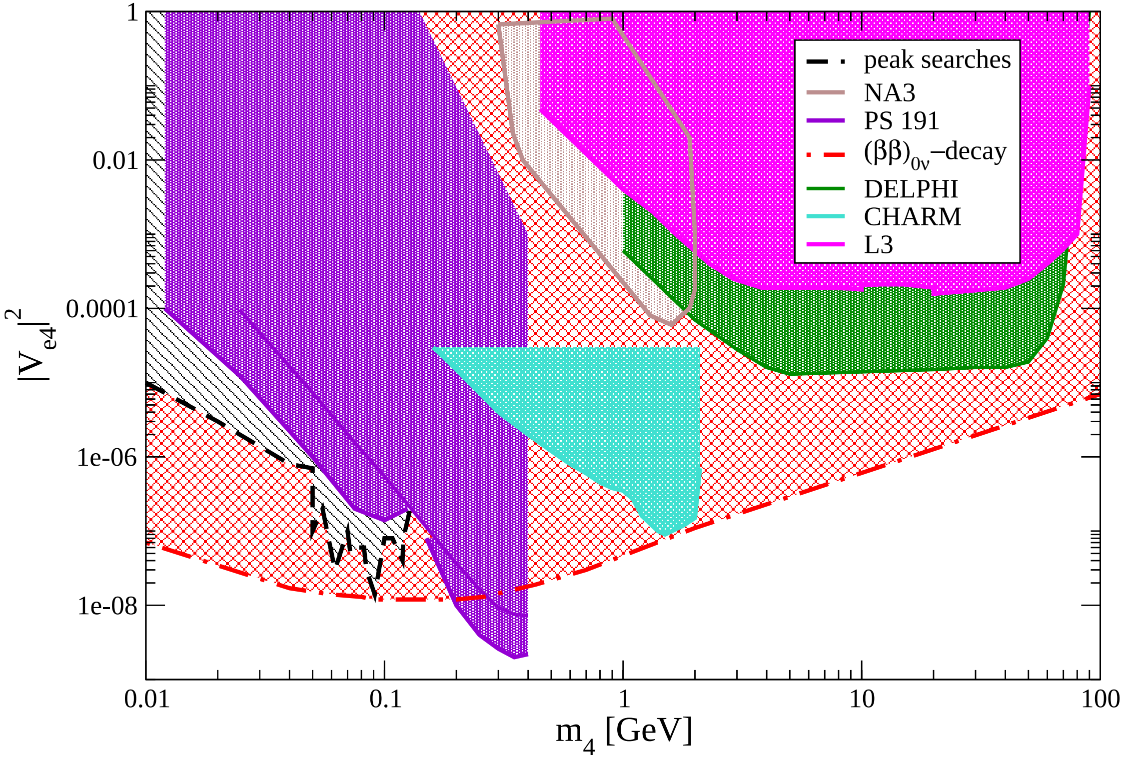
new results from MiniBooNE expected soon!

Experimental limits: kinks



[Atre, Han, Pascoli]

Experimental limits: peak searches and decays



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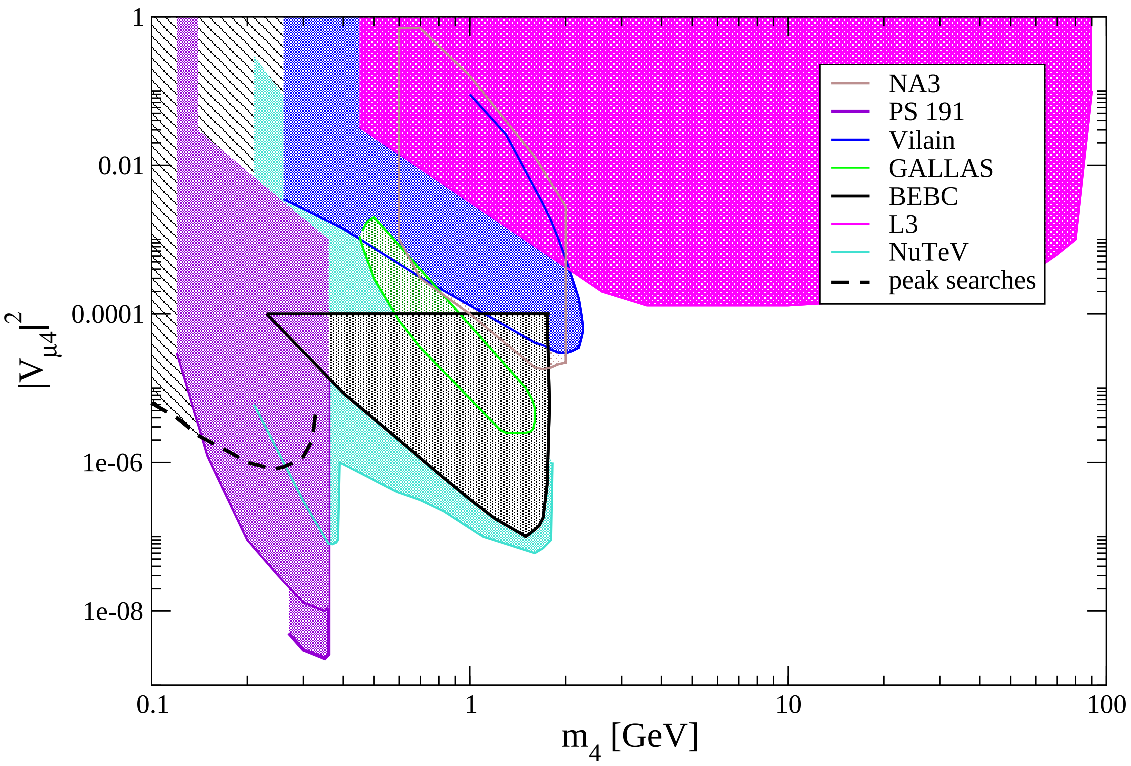
Experimental limits from peak searches and decays



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

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- 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

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Small mass and, therefore, **stability!** No symmetries required.

Sterile neutrinos with a small mixing to active neutrinos

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

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

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

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

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

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

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

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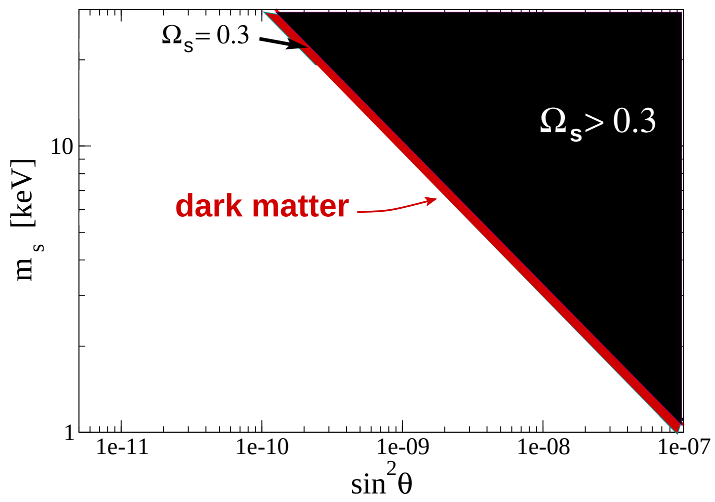
For small angles,

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

Production of sterile neutrinos peaks at temperature

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

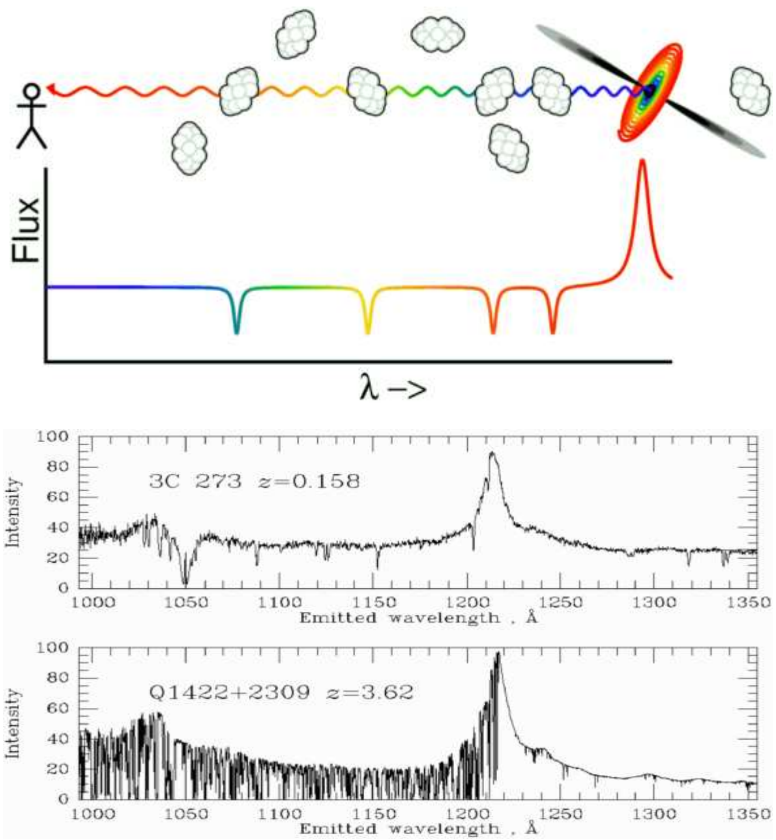


The resulting density of relic sterile neutrinos in conventional cosmology, in the absence of a large lepton asymmetry:

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

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

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



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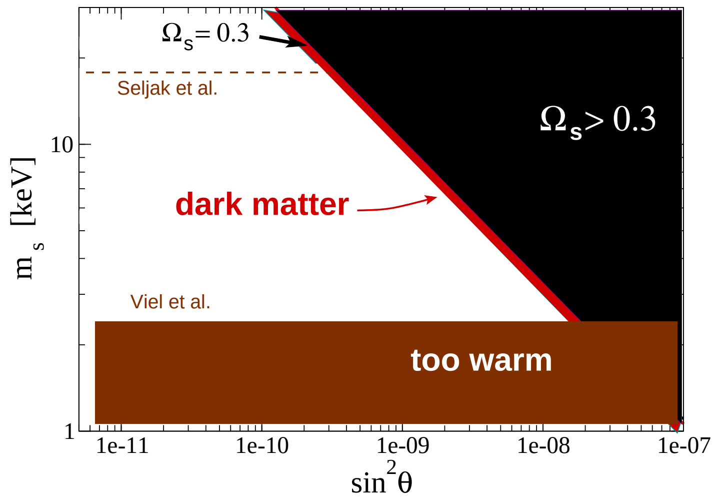

Lyman-α forest clouds show significant structure on small scales. Dark matter must be cold enough to preserve this structure. Lyman-alpha bounds based on high-redshift data are stronger, $m > 10$ keV [Seljak et al.; Viel et al.], but there are unknown systematic errors.

Cold or warm dark matter?

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There are problems with cold dark matter on small scales

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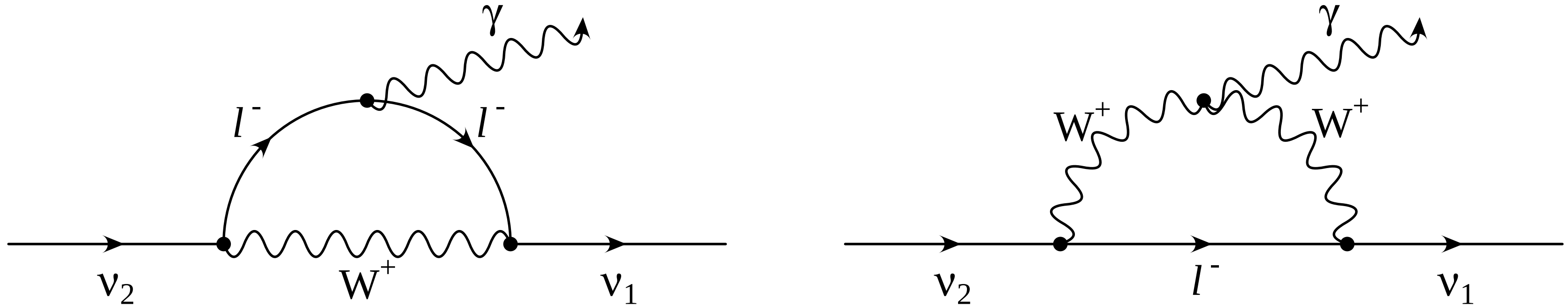
- observations of dwarf spheroidal galaxies $\Rightarrow m \sim$ keV [Gilmore et al.; Strigari et al.]

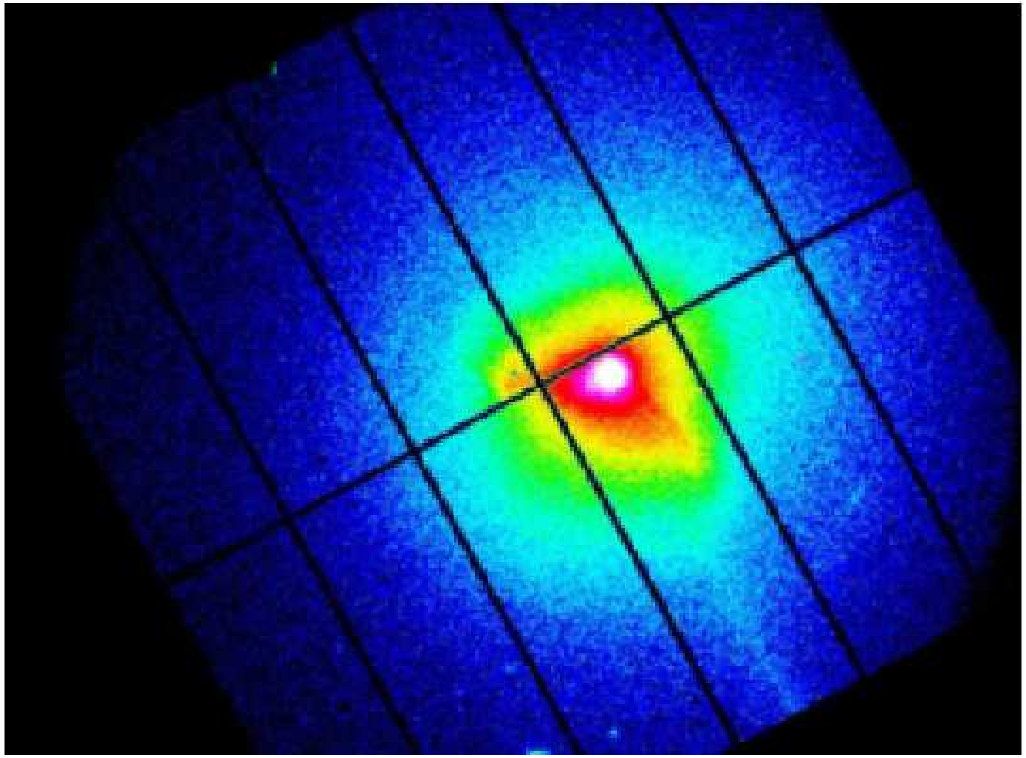
Radiative decay

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



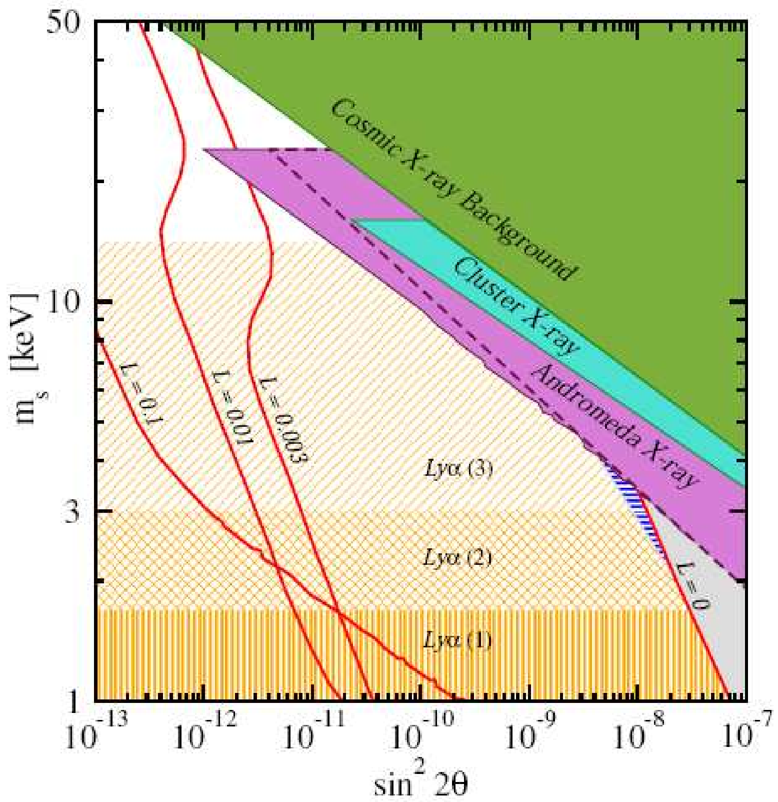
Photons have energies $m/2$: X-rays. Large lumps of dark matter emit some X-rays. [Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]

X-ray observations



Virgo cluster image from XMM-Newton

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



[Abazajian et al; Hansen et al.; Boyarsky et al.; Watson et al.]

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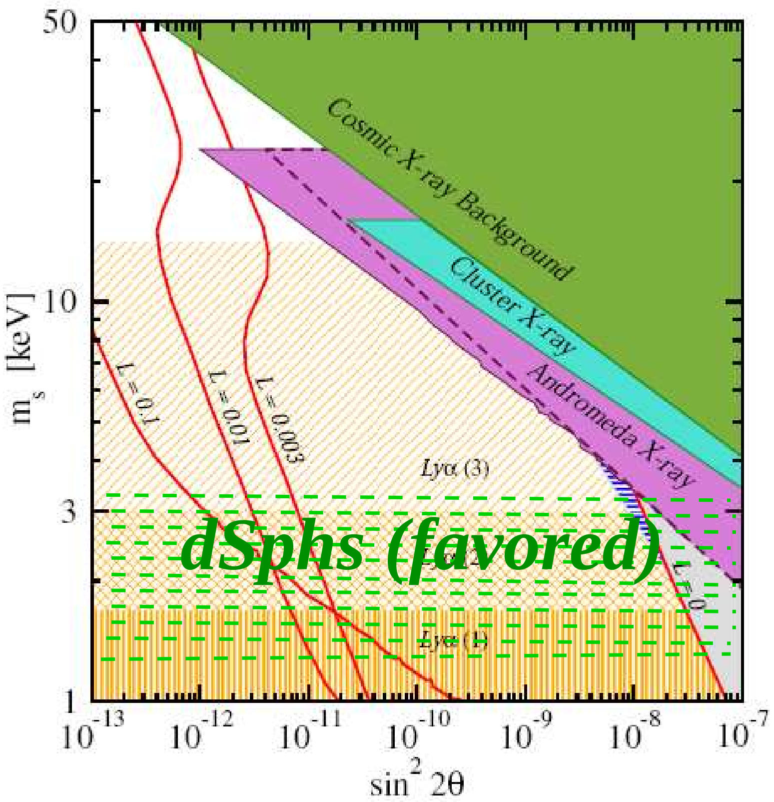

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Astrophysical clues: supernova

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- Sterile neutrino emission from a supernova is anisotropic

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- 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.

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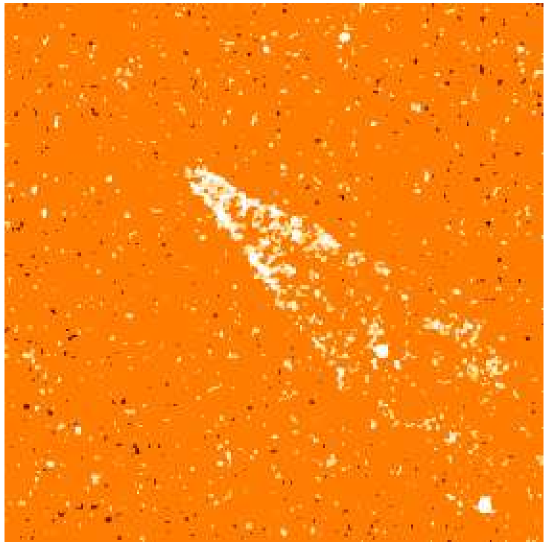
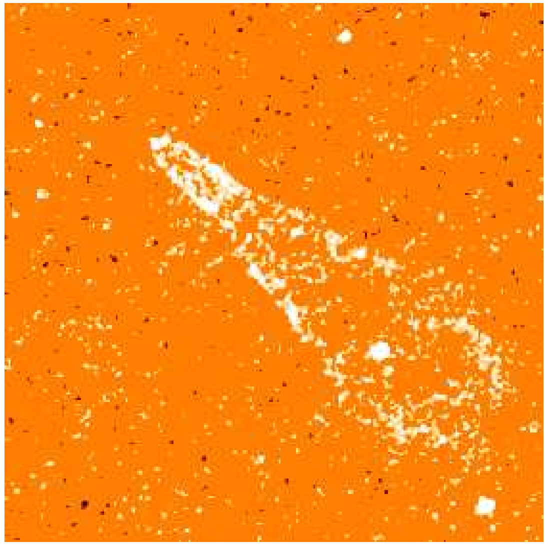
Pulsars have large velocities, $\langle v \rangle \approx \mathbf{250 - 450\ km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

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.*]

A very fast pulsar in Guitar Nebula

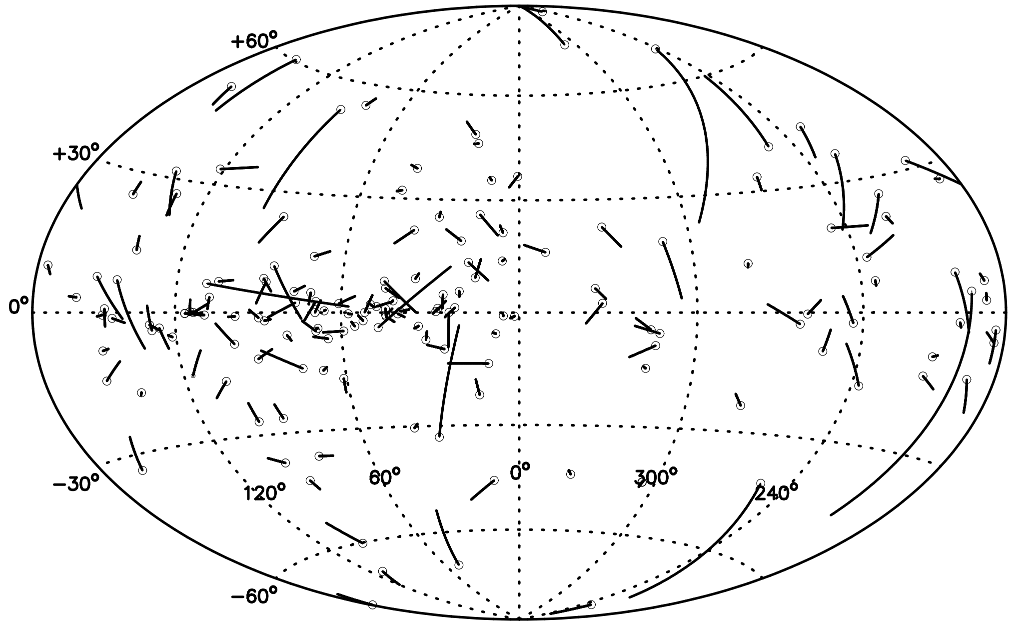


HST, December 1994



HST, December 2001

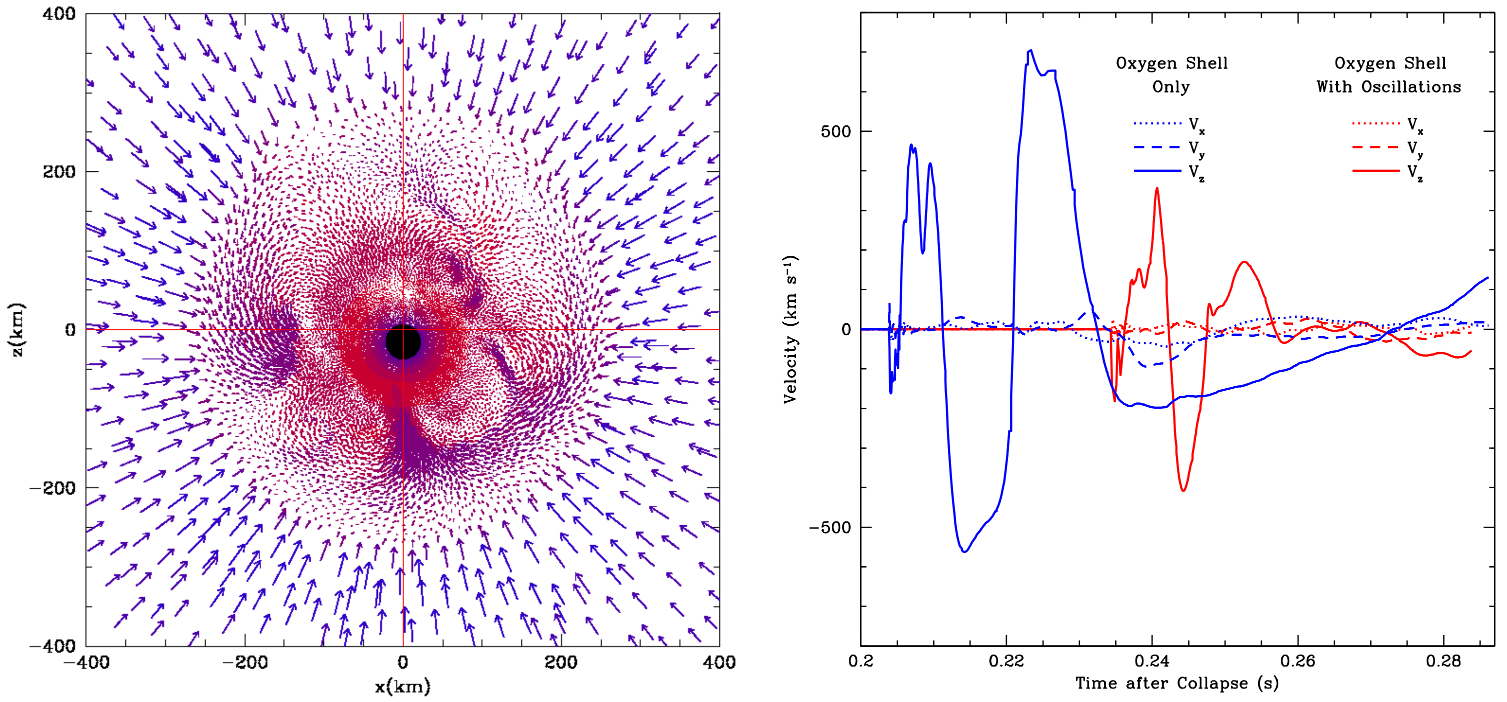
Map of pulsar velocities



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 (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:

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

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99% of this energy is emitted in neutrinos

Pulsar kicks from neutrino emission?

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

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

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

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

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

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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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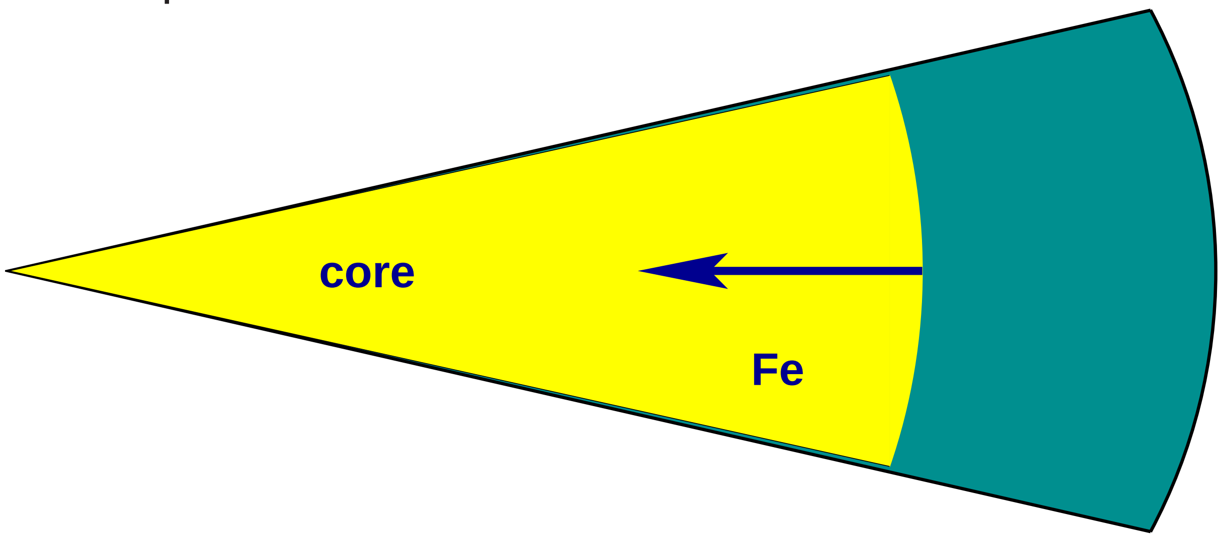
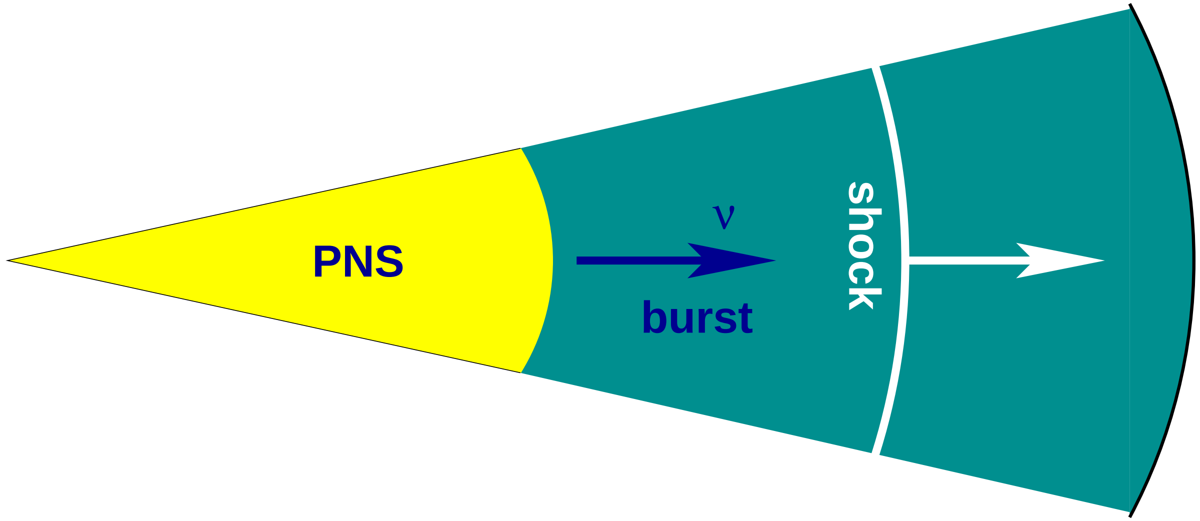


Core collapse supernova

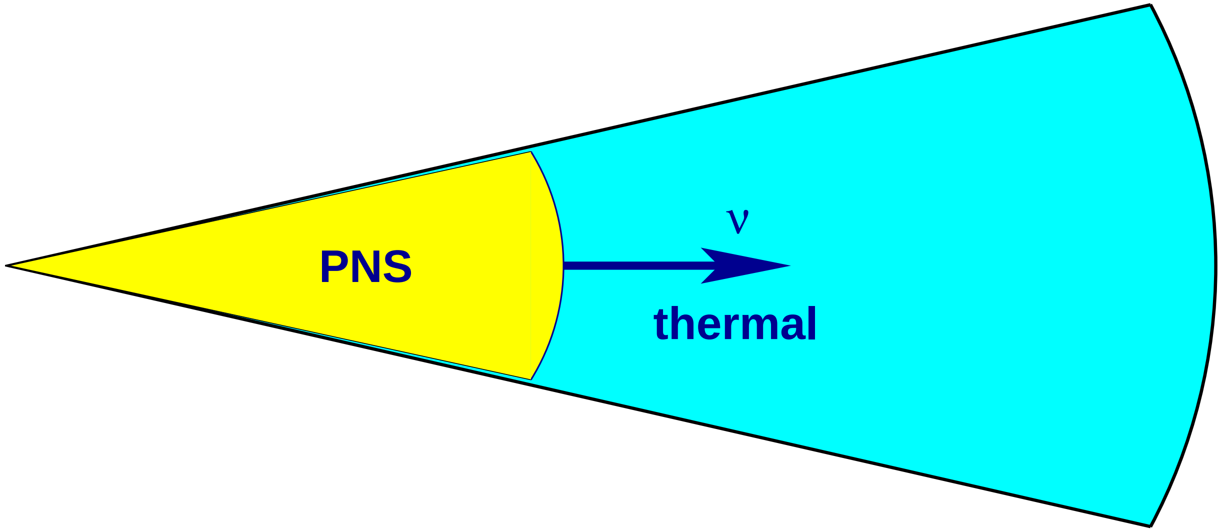
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



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.

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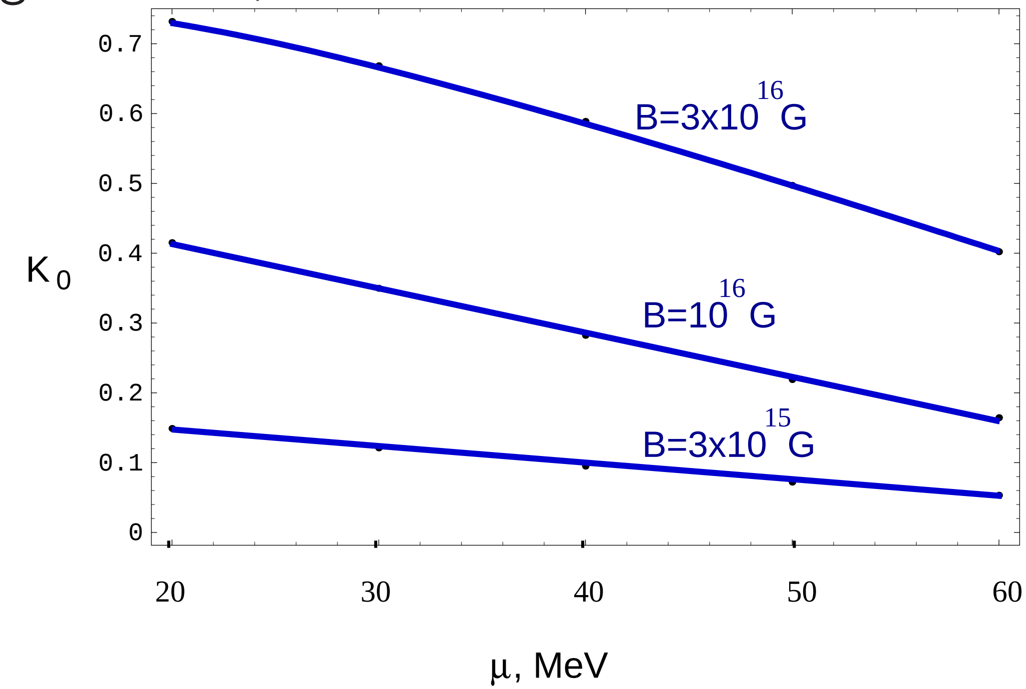
$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

The asymmetry:

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

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

In a strong magnetic field,



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

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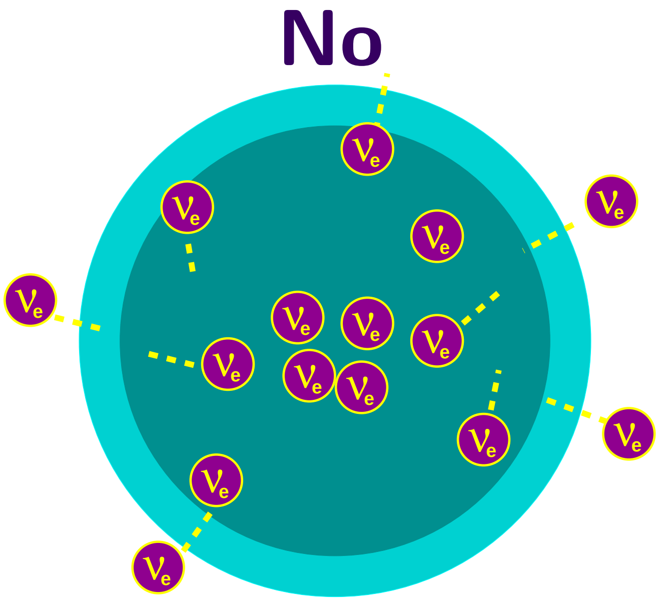

Neutrinos are trapped at high density.

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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). [Vilenkin,AK, Segrè]

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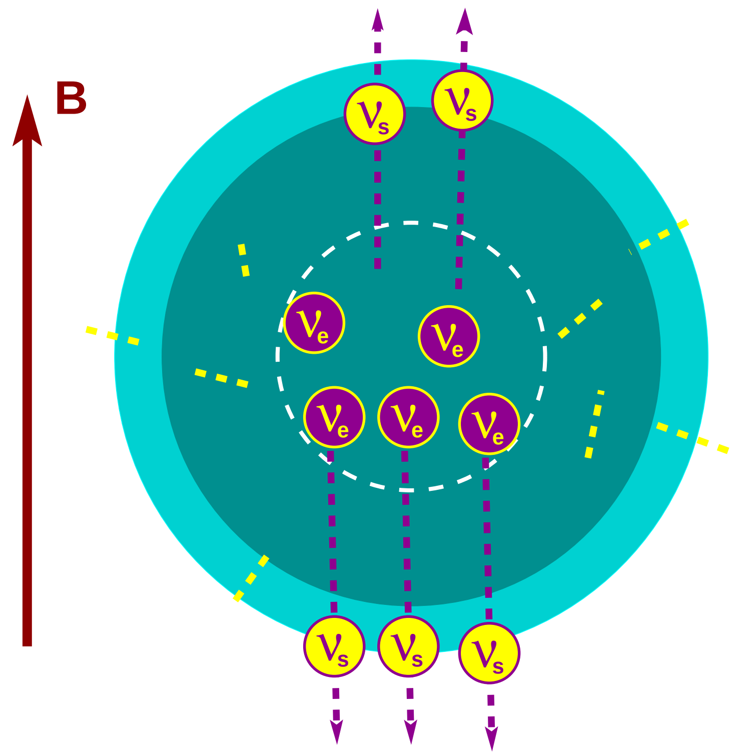
However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

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



B
ν_s
ν_s
ν_e
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ν_e
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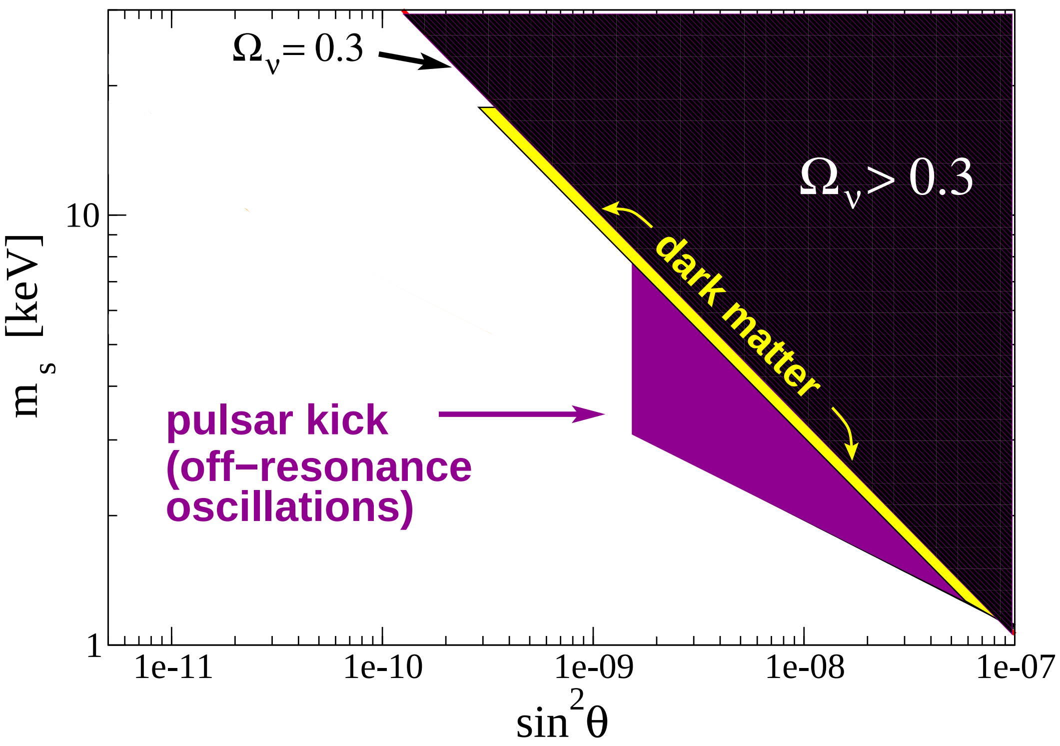
ν_s

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



[Fuller, AK, Mocioiu, Pascoli]

Resonant active-sterile neutrino conversions in matter

Matter potential:

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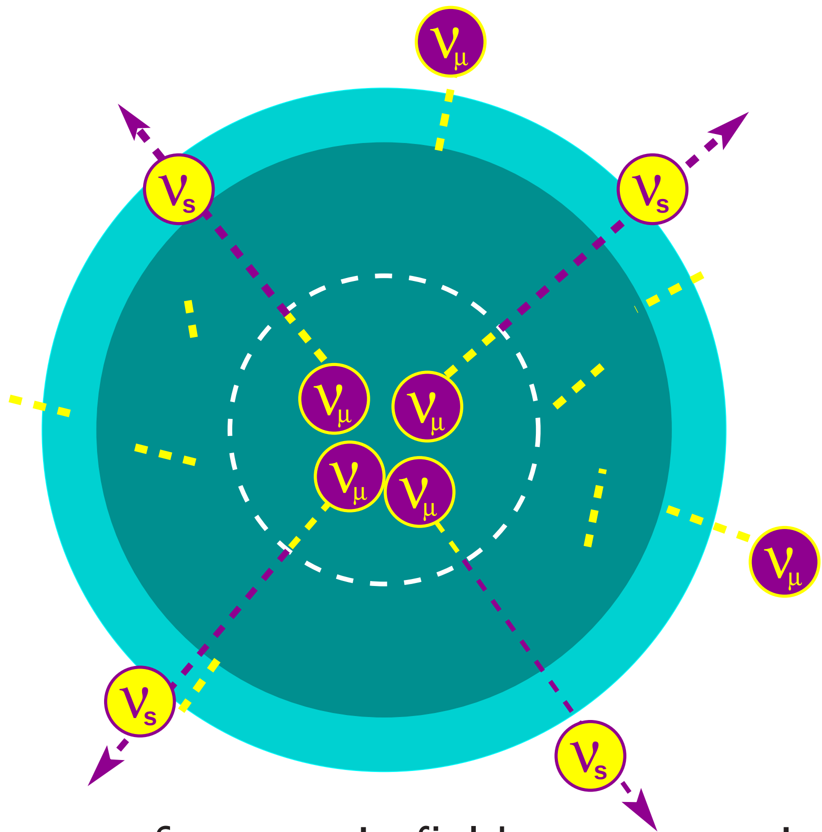
$$
c_L^Z = \frac{eG_F}{\sqrt{2}}\left(\frac{3N_e}{\pi^4}\right)^{1/3}
$$

[D'Olivo, Nieves, Pal]

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

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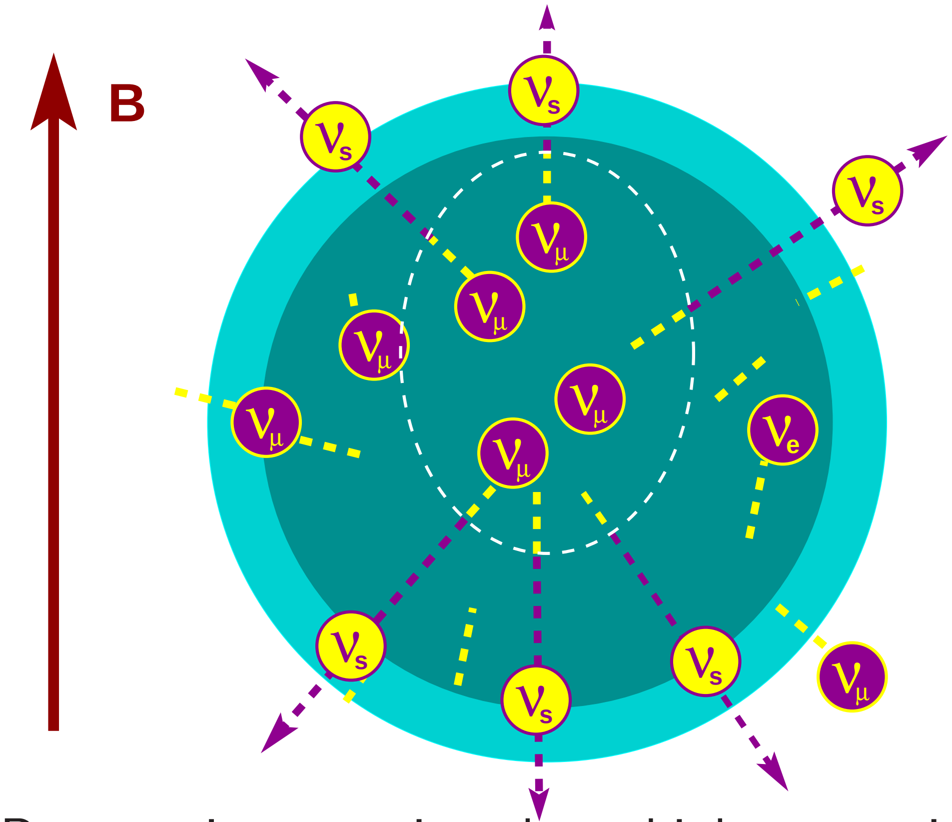
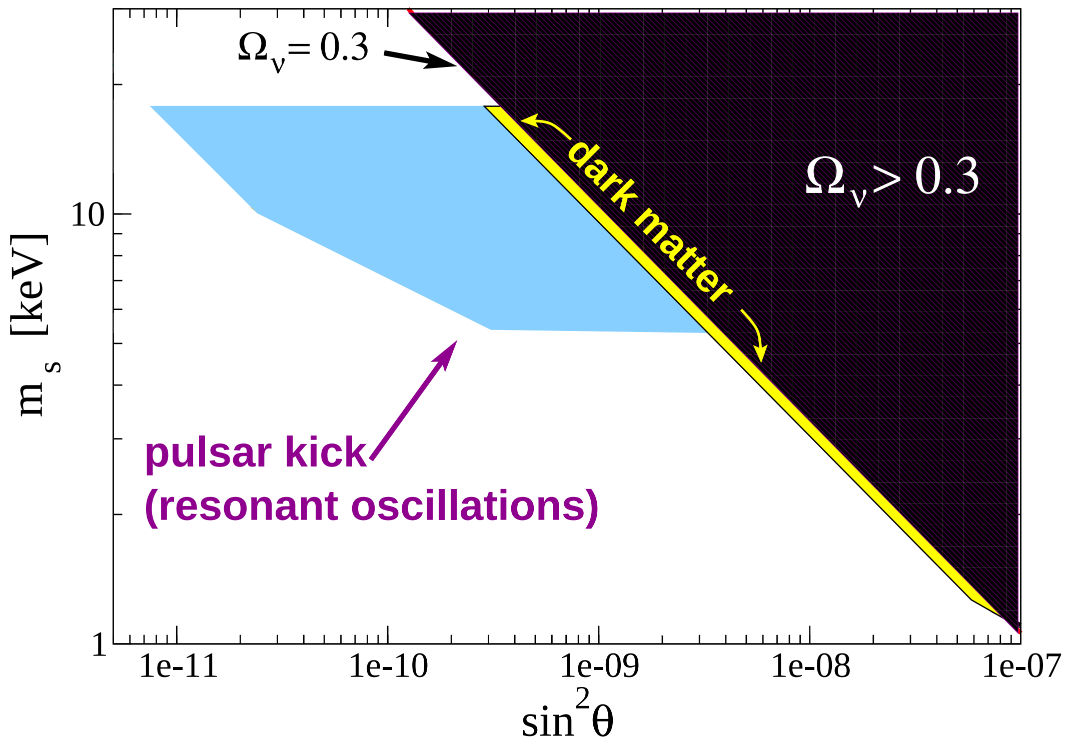


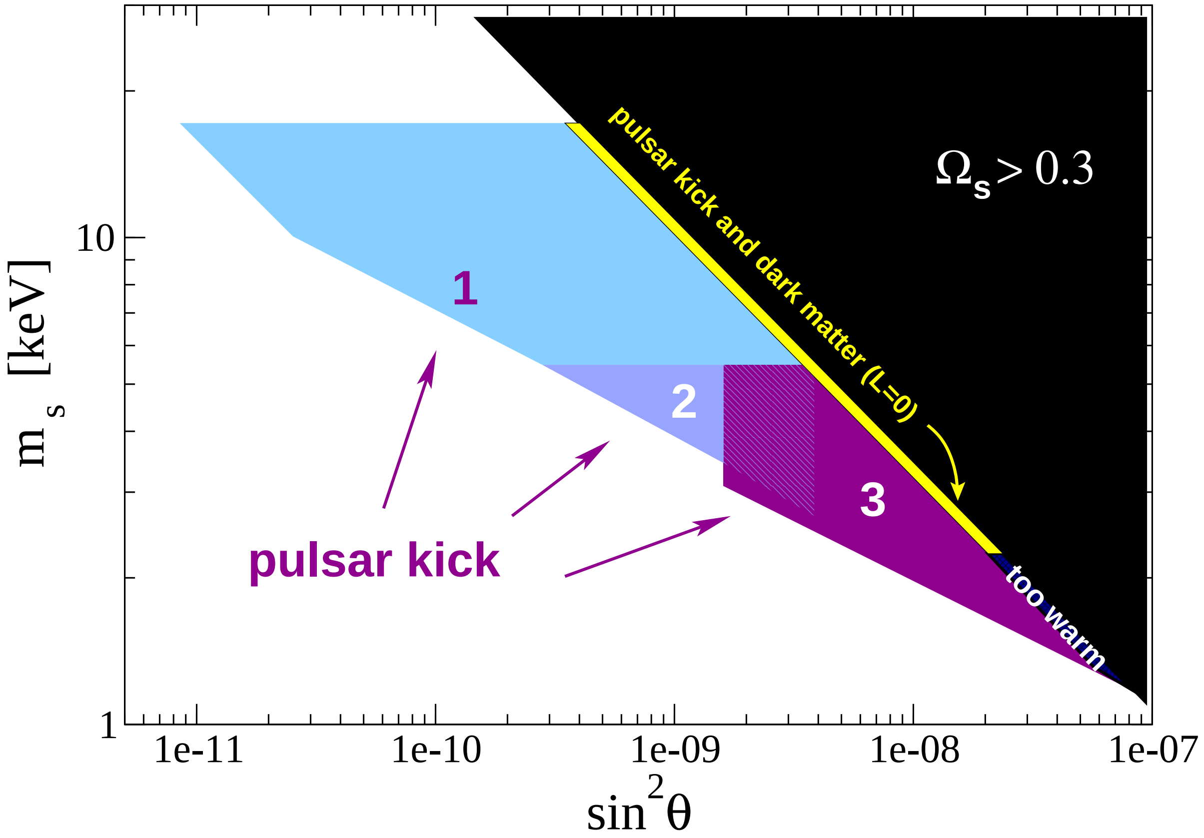
Down going neutrinos have higher energies

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]

Other predictions of the pulsar kick mechanism

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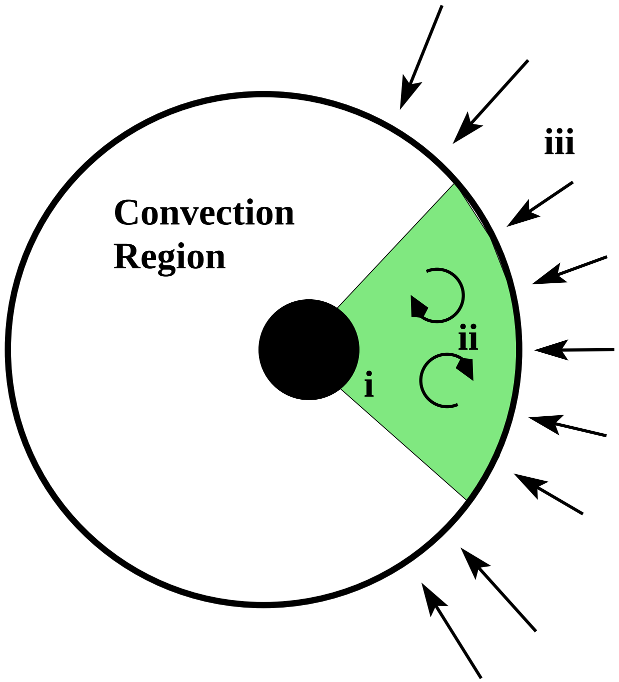
- Stronger supernova shock [Fryer, AK]



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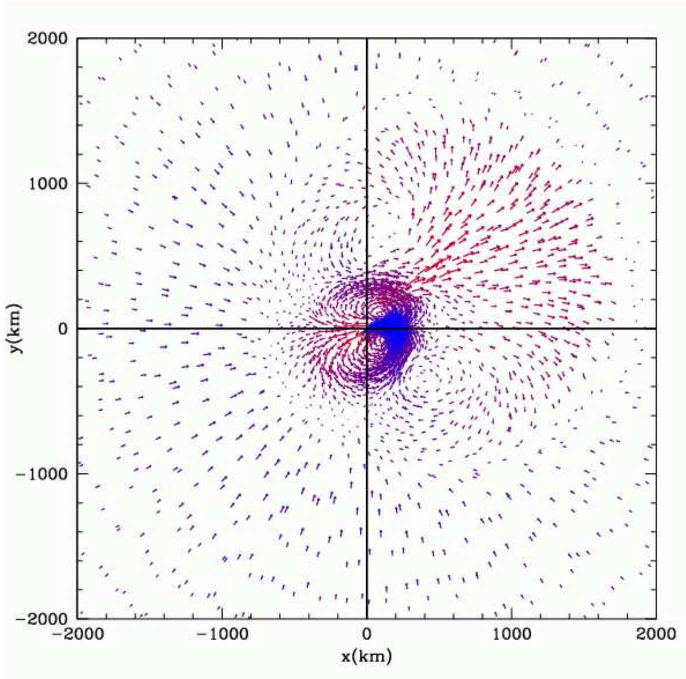

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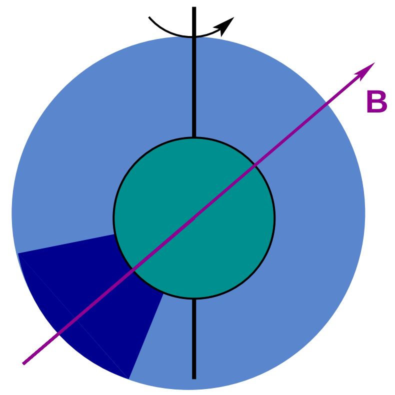
- **Directional $\vec{\Omega} - \vec{v}$ correlation** is expected, because
  - the direction of rotation remains unchanged
  - only the z-component survives



Astrophysical clues: star formation and reionization

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WMAP, three years of data, reionization redshift: $\boldsymbol{z_{\rm r} = 10.9^{+2.7}_{-2.3}}$.
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First stars can ionize gas, but can they form so early?

WMAP 3 yrs $\Rightarrow$ new challenge: can one end reionization by $z = 6$ without exceeding the optical depth $\tau_{\mathrm{WMAP}} = 0.10 \pm 0.03$?

Small halos collapse first and start ionizing gas. If reionization is to be completed by $z = 6$, small halos shine to early, too bright, and exceed τ_{WMAP}.

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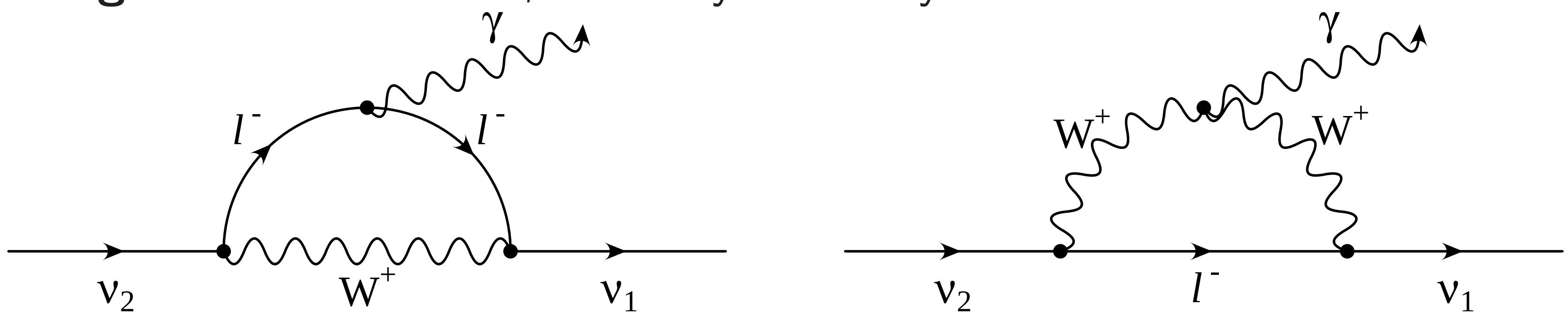
What about sterile neutrinos?

- they are warm $\Rightarrow$ small halos suppressed
- they decay and produce x-rays, and x-rays can ionize gas!

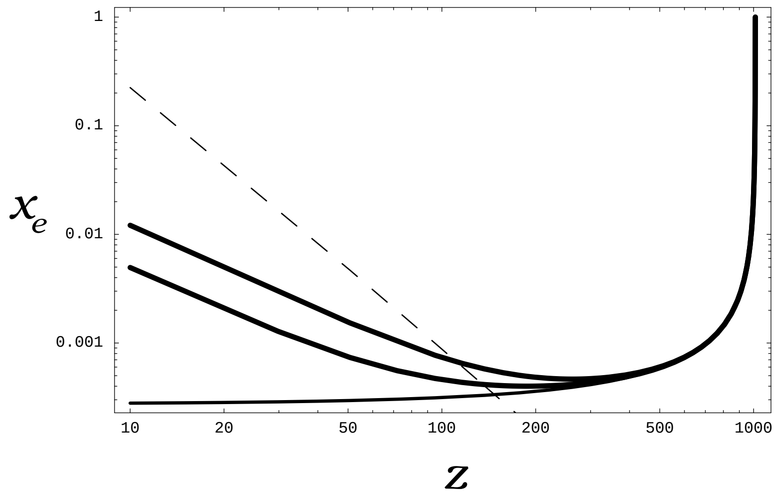
Photons from radiative decays

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. X-rays can ionize gas.

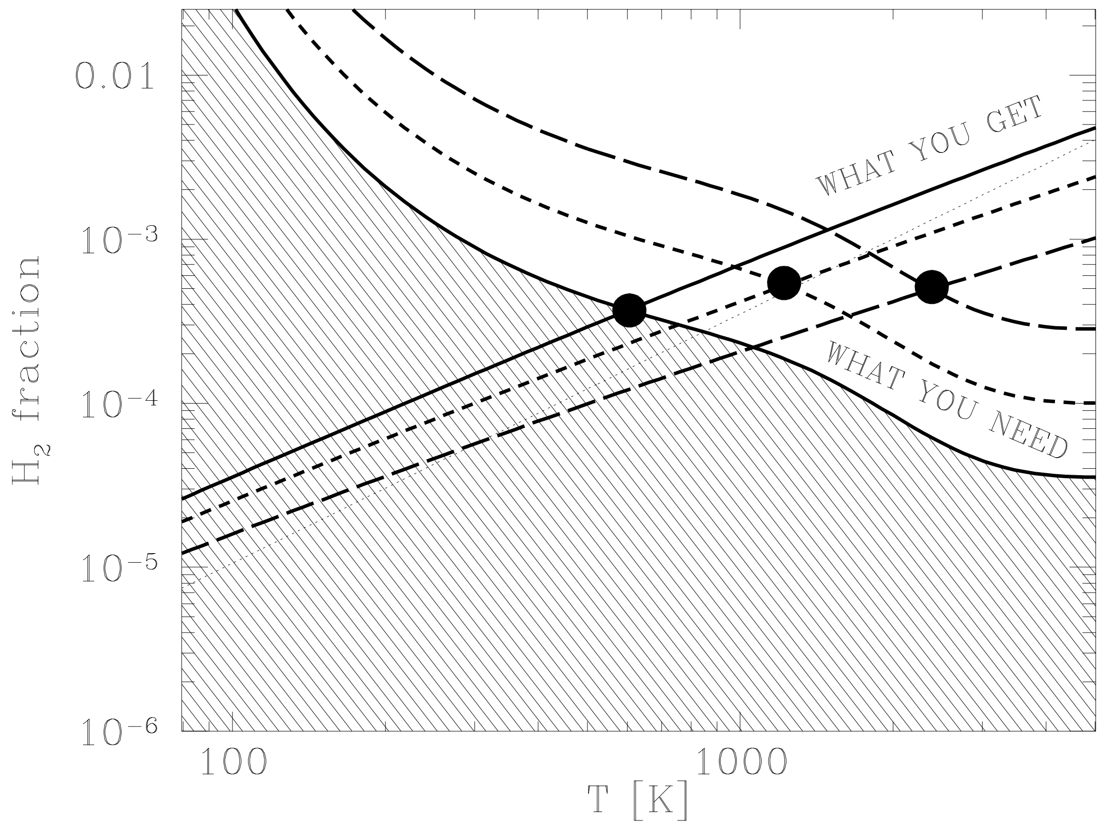
Sterile neutrino decays: an increase in ionization fraction



The ions too few to explain the WMAP results [Ferrara, Mapelli; AK, Biermann]...

...but it's a much higher fraction than in the absence of sterile neutrinos. Ionization catalyzes formation of molecular hydrogen [AK; P.L. Biermann]...

production of molecular hydrogen speeds up gas cooling, halo collapse and star formation



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

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

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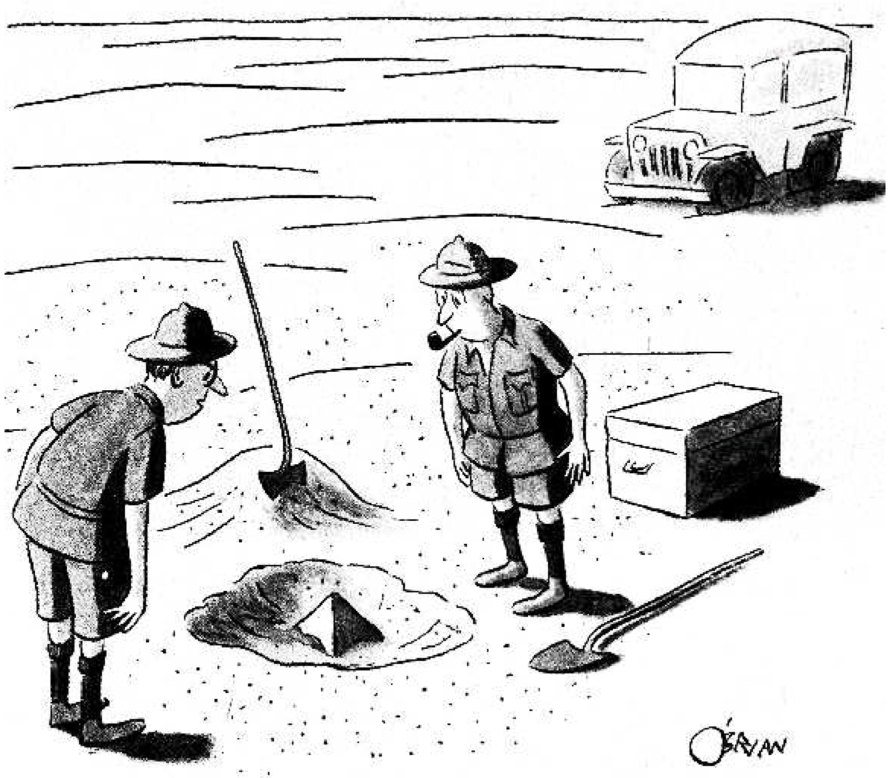
H^+ catalyze the formation of molecular hydrogen!
[Biermann, AK, PRL **96**, 091301 (2006)]
[Stasielak, Biermann, AK, to appear]

Astrophysical clues of sterile neutrinos

The **light** sterile neutrinos can explain:

- existing data on neutrino masses
- dark matter
- baryon asymmetry of the universe (via leptogenesis)
- pulsar kicks
- prompt star formation and reionization

Clues of sterile neutrinos



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

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