Lepton number violation and dark matter

- Neutrino masses: the seesaw mechanism, *well adjusted*, allows for **dark matter in the form of sterile (right-handed) neutrinos**

- Pulsar velocities explained by the same sterile neutrino with 2-20 keV mass (emission from a supernova is anisotropic!) Other astrophysical hints: reionization, star formation

- A singlet Higgs boson with an L violating coupling to neutrinos facilitates the mass generation and the production of relatively cold sterile neutrinos

- X-ray bounds and the future prospects, including Suzaku observations (together with Loewenstein, Biermann)

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:

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

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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 $y \approx \text{some intersection number}$ 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 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 $\Rightarrow$ small number

What if one apples this criterion to sterile neutrinos? Symmetry increases for $M \to 0$, 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.

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 neutrino 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

"ν**MSM**" of Shaposhnikov et al.: $M_1 \sim \mathrm{keV}$, $M_2 \approx M_3 \sim \mathrm{GeV}$

Astrophysical clues: dark matter

Dark matter – a simple (minimalist) solution: use one of the particles already introduced to give the neutrino masses

$\Rightarrow$ **sterile neutrino**

side benefit: explanation of the pulsar kicks, supernova asymmetries

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.; Boyanovsky]
- 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

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

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

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

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

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

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

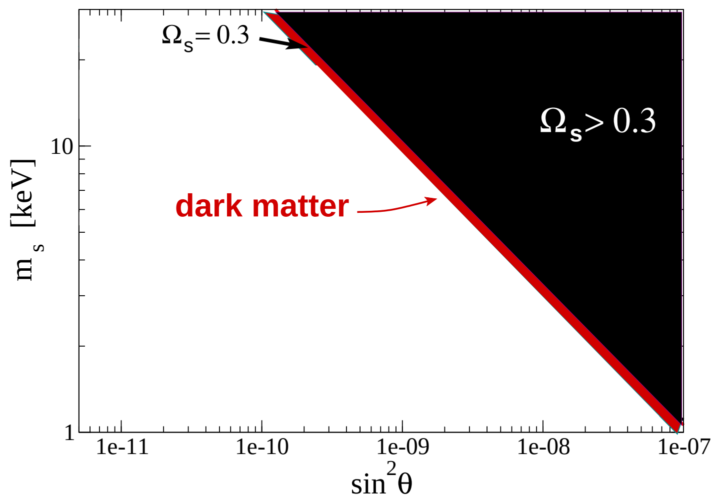
For small angles,

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

Production of sterile neutrinos peaks at temperature

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

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



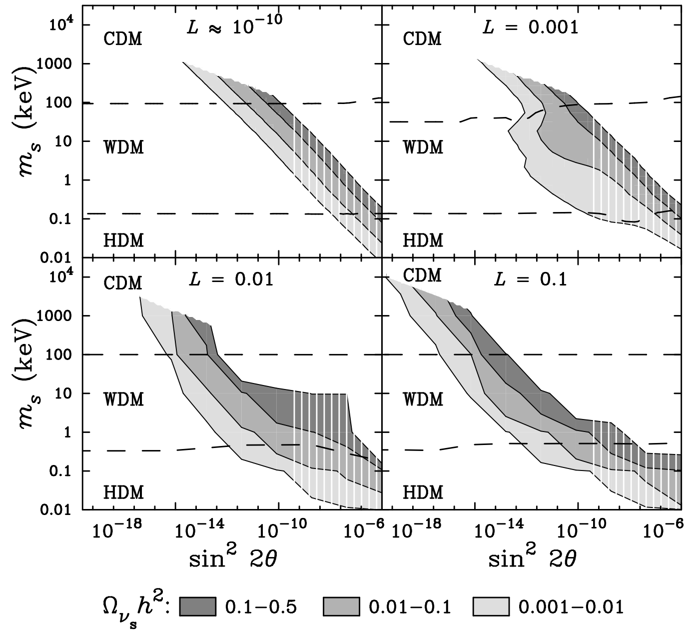
$$\Omega_{\nu_2} \sim 0.3 \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_s}{\mathrm{keV}}\right)^2$$

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

Hadronic uncertainties under control [Asaka, Laine, Shaposhnikov]

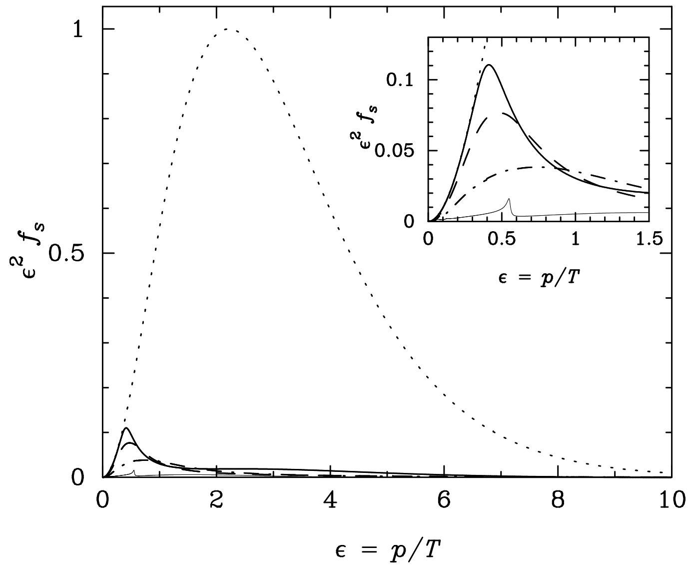
Lepton asymmetry and the MSW resonance

If the lepton asymmetry L is non-zero, sterile neutrinos can be produced on resonance.
[Fuller, Shi; Abazajian, Fuller, Patel]
The amount of dark matter and the momentum distribution depend on L.

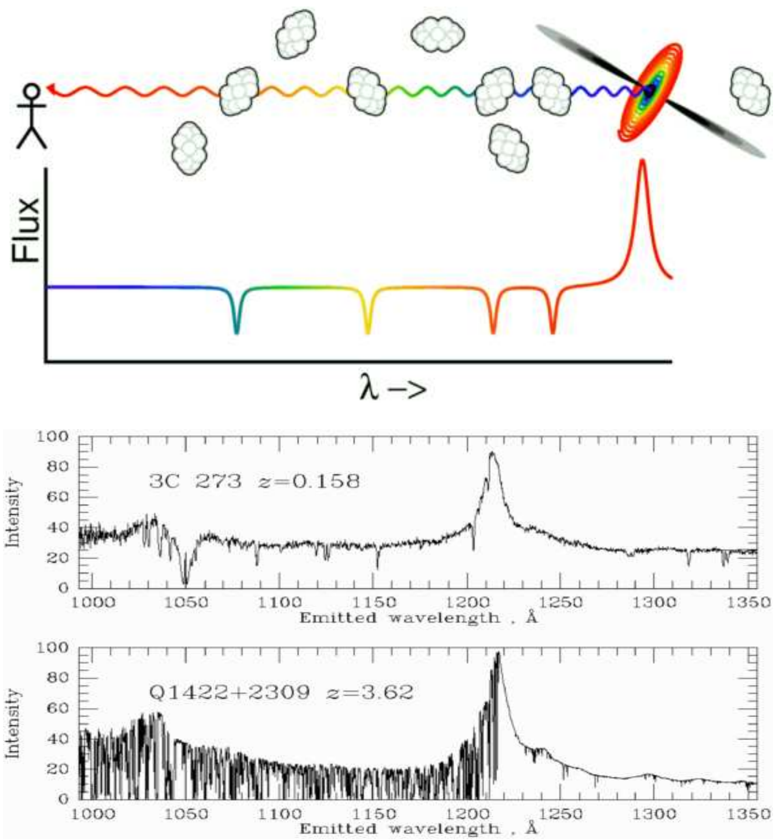


Lepton asymmetry and the MSW resonance

MSW resonance favors the low-momentum neutrinos. The dotted line is the normalized active neutrino spectrum. The thick-solid, dashed, dot-dashed lines correspond to $L = 0.01$, mass around 1 keV, and different mixing angles. [Fuller, Shi; Abazajian, Fuller, Patel]



Dark matter and the Lyman-α forest.



Dark matter and the Lyman-α forest.

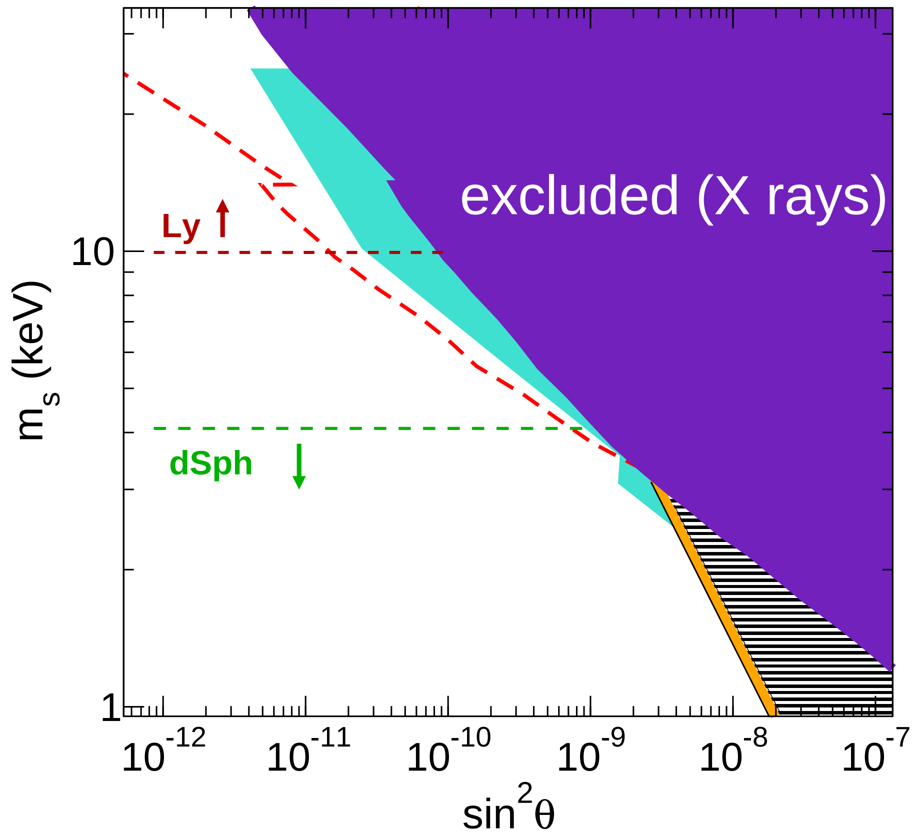
The bounds depend on the production mechanism.

$$\lambda_{FS} \approx 1\,\mathrm{Mpc} \left(\frac{\mathrm{keV}}{m_s}\right) \left(\frac{\langle p_s \rangle}{3.15\,T}\right)_{T \approx 1\,\mathrm{keV}}$$

The ratio

$$\left(\frac{\langle p_s \rangle}{3.15\,T}\right)_{T \approx 1\,\mathrm{keV}} = \begin{cases} 0.9 & \text{for production off} - \text{resonance} \\ 0.6 & \text{for MSW resonance (depends on L)} \\ 0.2 & \text{for production at T} > \text{100 GeV} \end{cases}$$

For DW production, is Ly-α in conflict with dSphs?



[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 $S \to NN$ 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 $\boldsymbol{T \sim m_S}$ from decays $\boldsymbol{S \rightarrow NN}$:

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

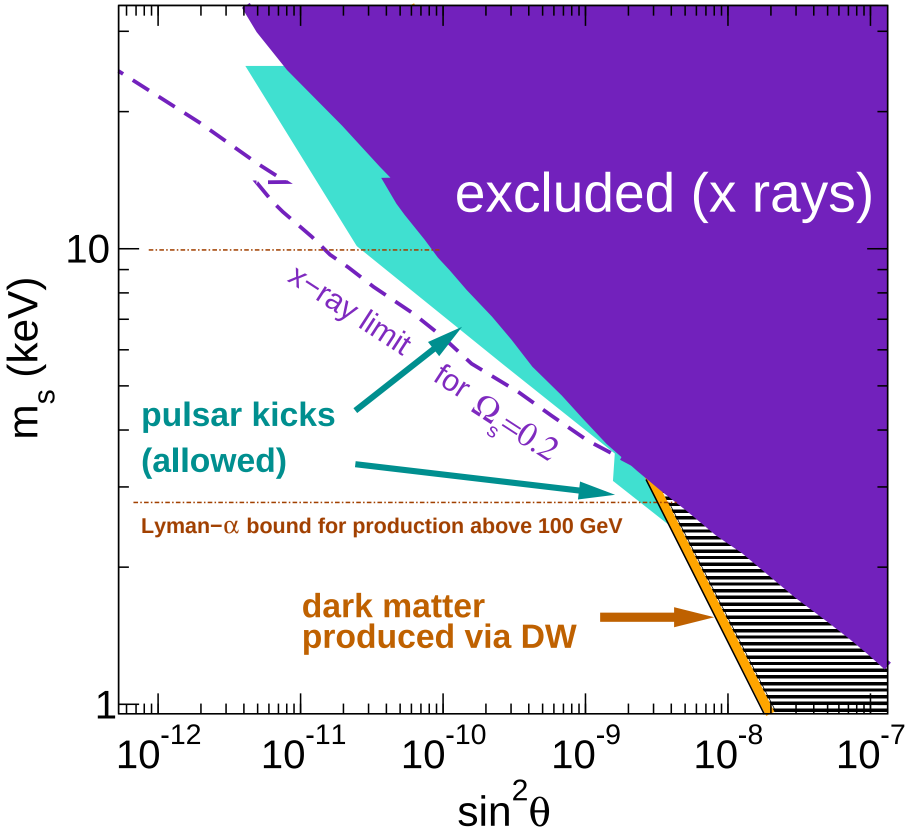
Here ζ is the dilution factor due to the change in effective numbers of degrees of freedom.

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

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

(NB: if $\tilde{m}_S < \mathrm{GeV} \ll \langle S \rangle$, one could make S an inflaton [Shaposhnikov, Tkachev], but then $\zeta \approx 1$, no redshift/cooling: DM probably too warm.)

Cooling changes the bounds



[AK, PRL **97**:241301 (2006)]

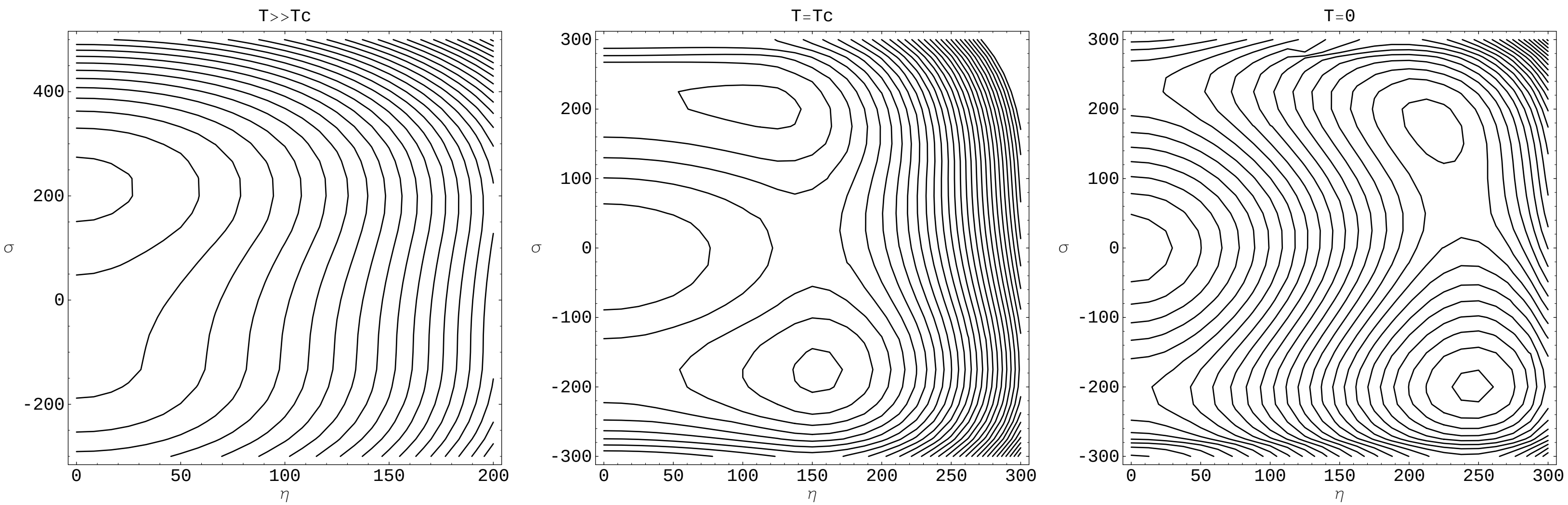
Implications for the EW phase transition and the LHC

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

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

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.]

Electroweak phase transition



First-order transition, CP in the Higgs sector $\Longrightarrow$ **electroweak baryogenesis**

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

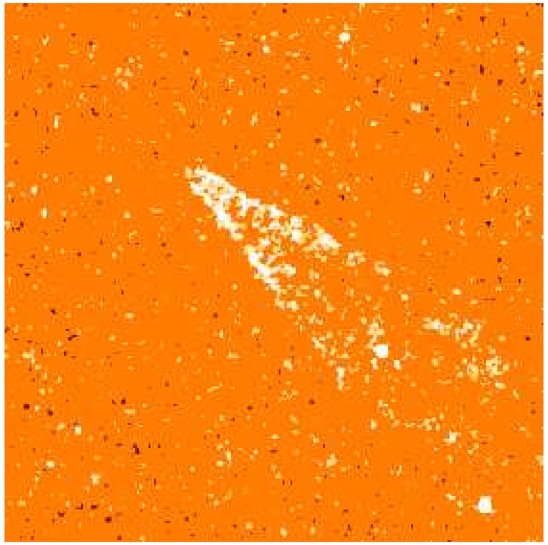
[AK, Segrè; Fuller, AK, Mocioiu, Pascoli; Barkovich, D'Olivo, Montemayor]

The pulsar velocities.

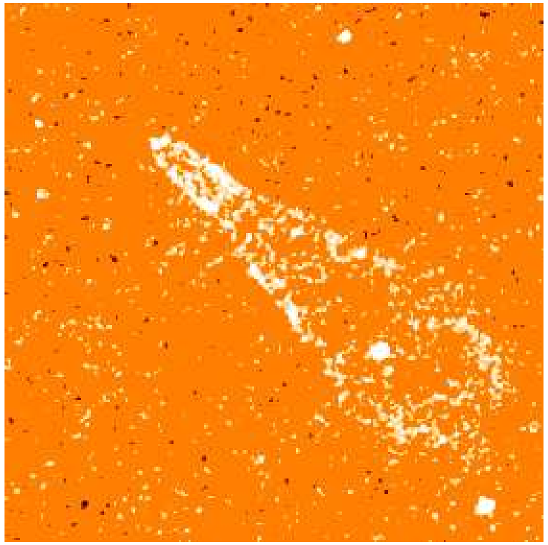
Pulsars have large velocities, $\langle v \rangle \approx \mathbf{250 - 450\ km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

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

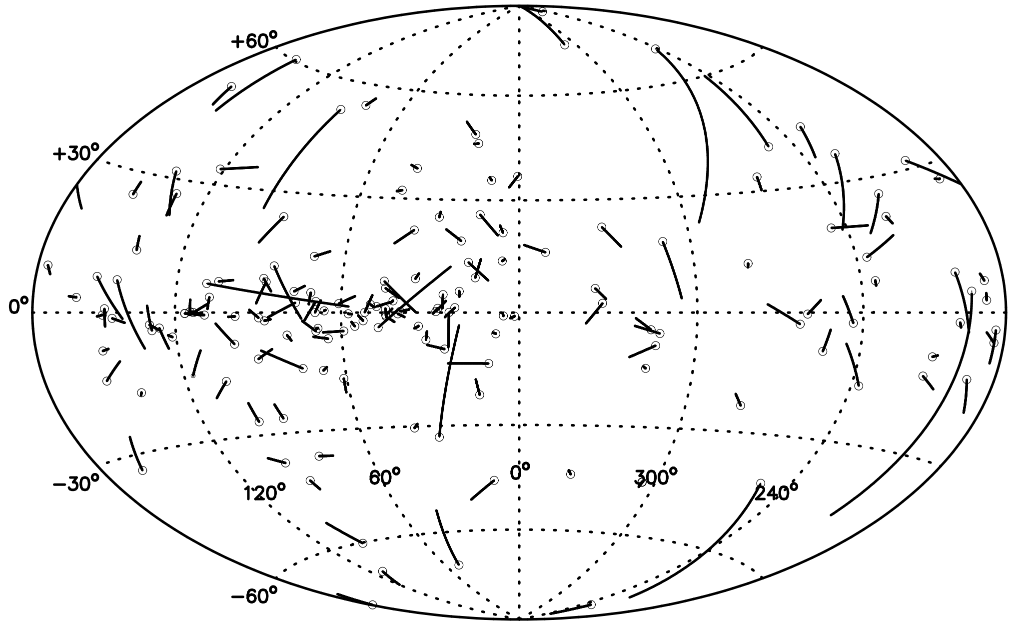


HST, December 1994



HST, December 2001

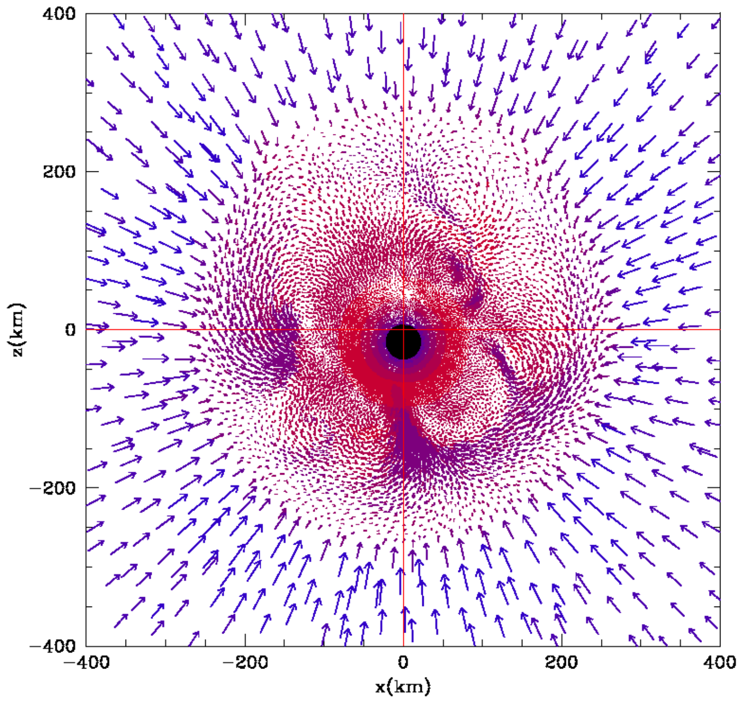
Map of pulsar velocities

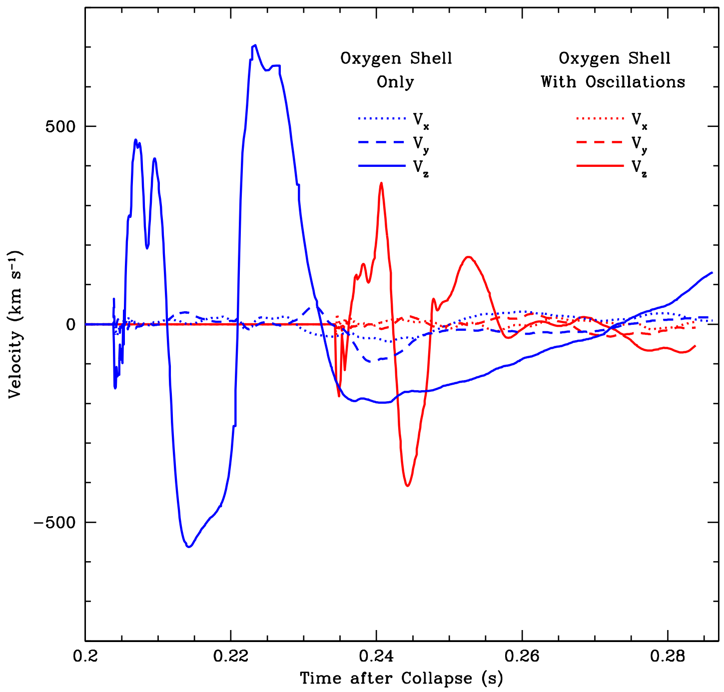


Proposed explanations:

- 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

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

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

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

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*

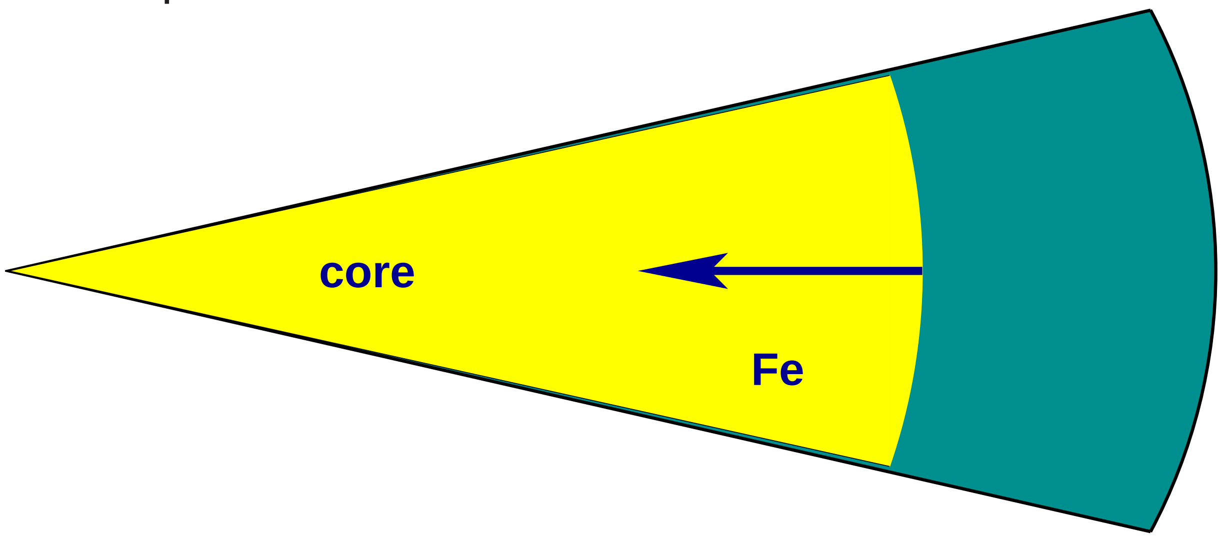
$\Rightarrow$ some neutron stars have surface magnetic fields as high as $10^{15} - 10^{16}$ G.

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

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

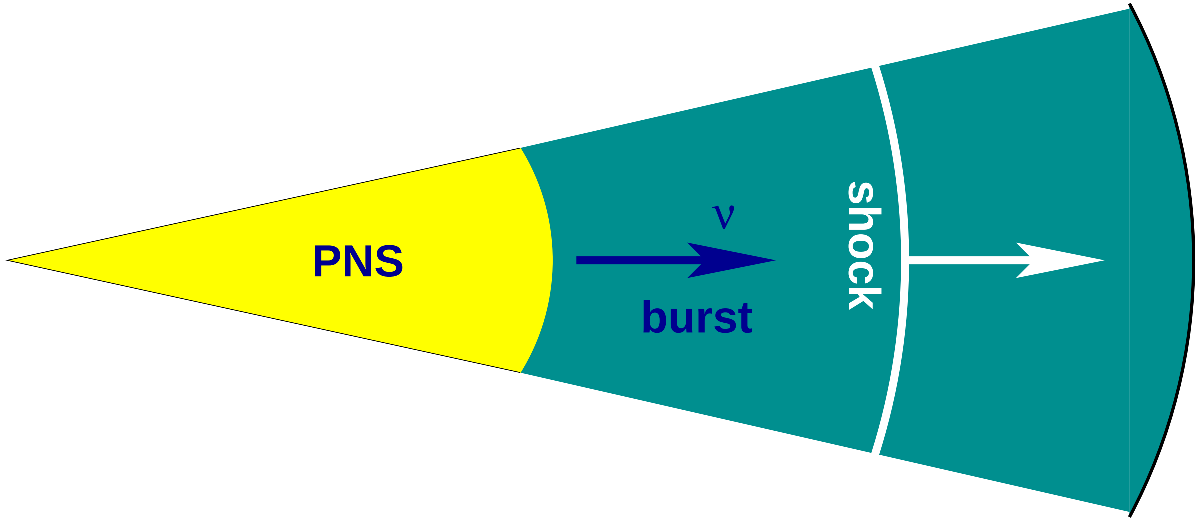
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

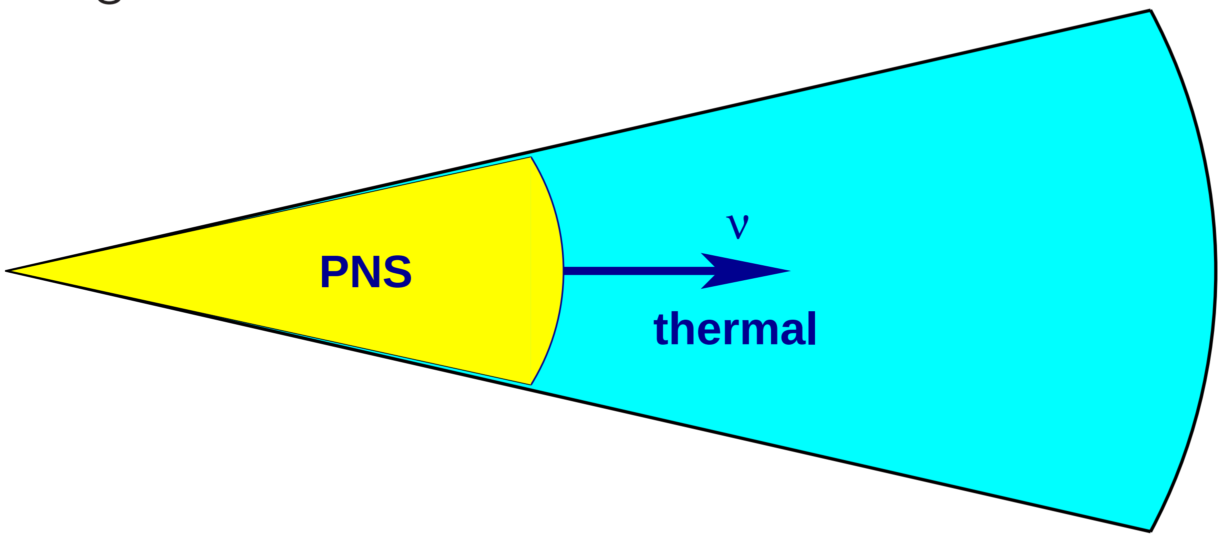
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



Protoneutron star formed. Neutrinos are trapped. The shock wave breaks up nuclei, and the initial neutrino come out (a few %).

Core collapse supernova

Thermal cooling: $t = 10 - 15$ s



Most of the neutrinos emitted during the cooling stage.

Electroweak processes producing neutrinos (urca),

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

have an asymmetry in the production cross section, depending on the spin orientation.

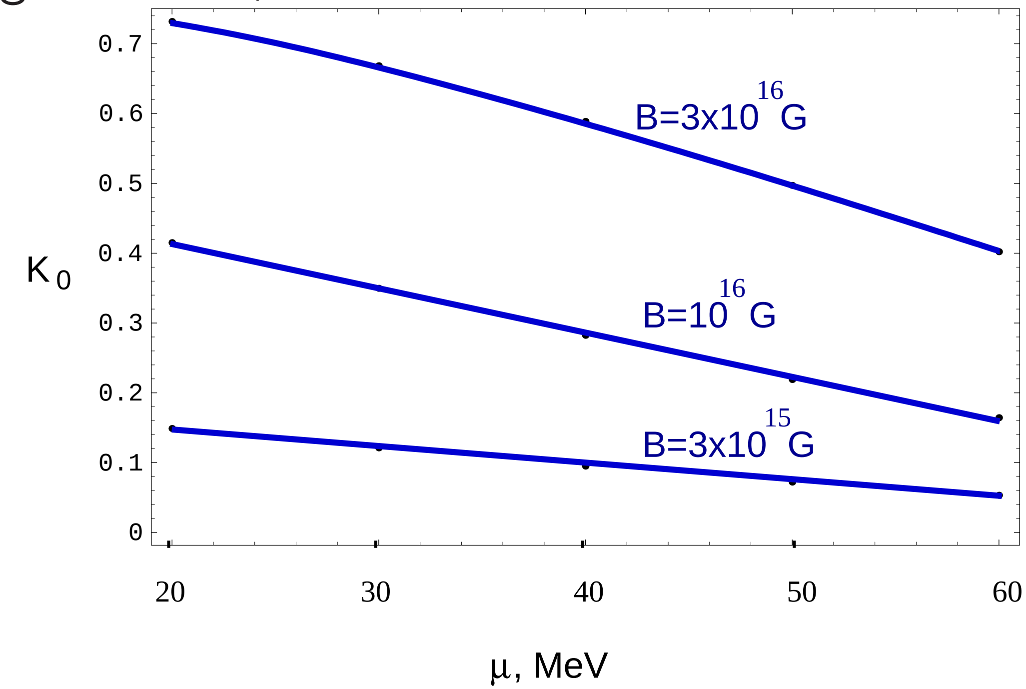
$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

The asymmetry:

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

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

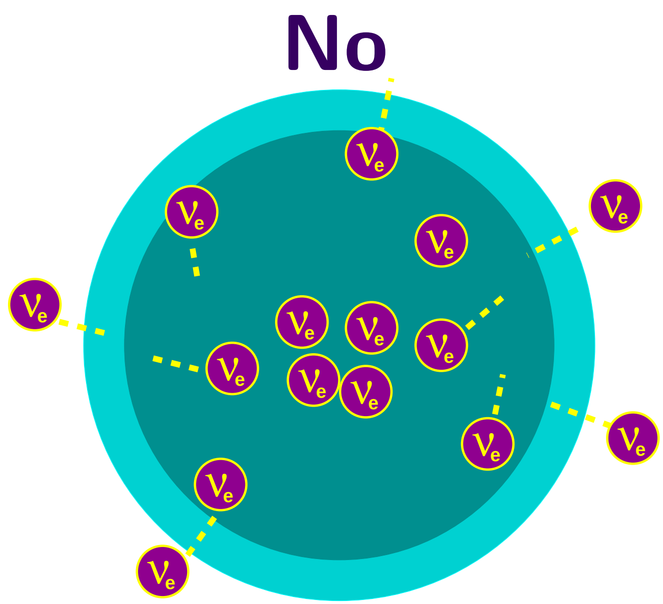
In a strong magnetic field,



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

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

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



Neutrinos are trapped at high density.

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

No

Rescattering washes out the asymmetry

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].

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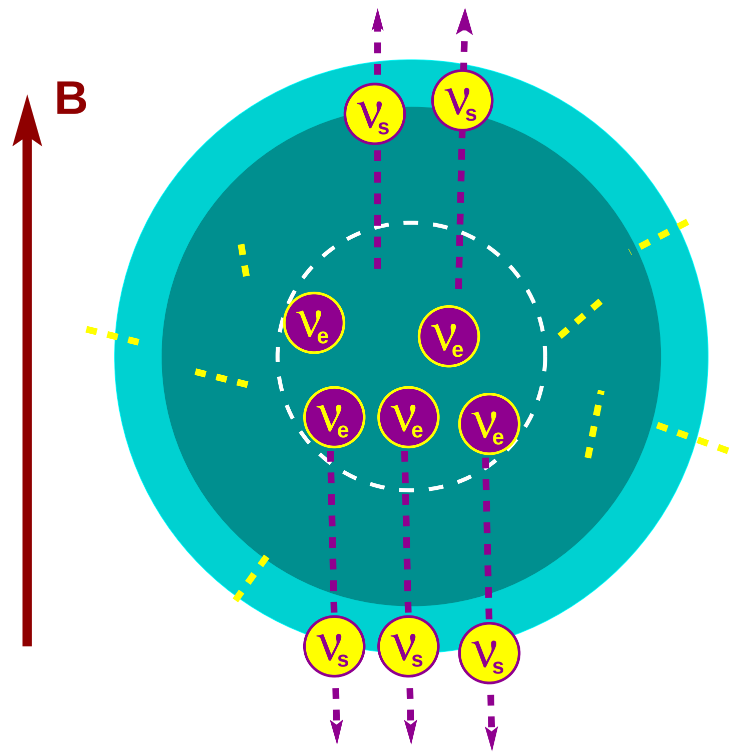
However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

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


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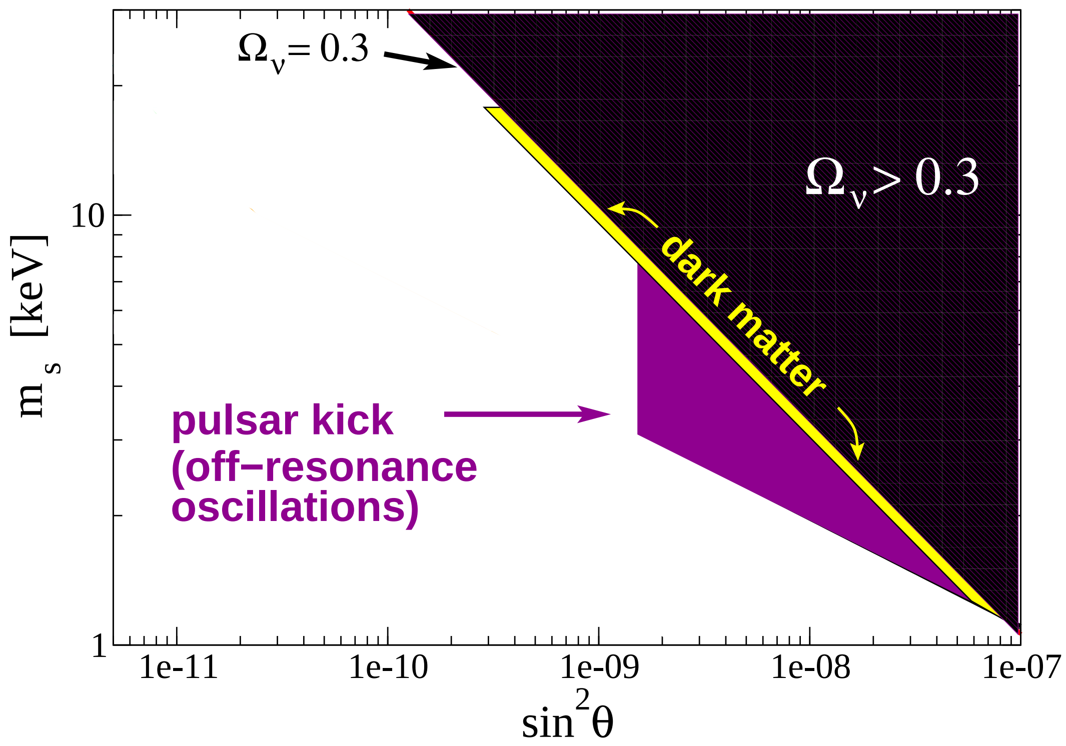
Allowed range of parameters (time scales, fraction of total energy emitted):



[Fuller, AK, Mocioiu, Pascoli]

Resonance in the magnetic field

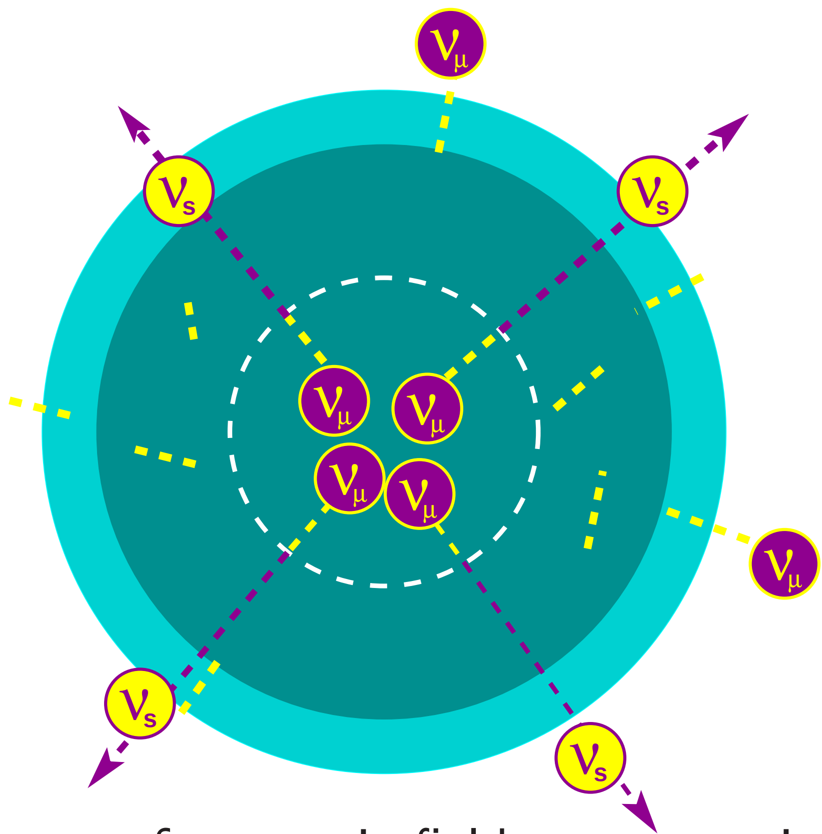
Matter potential:

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

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

[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

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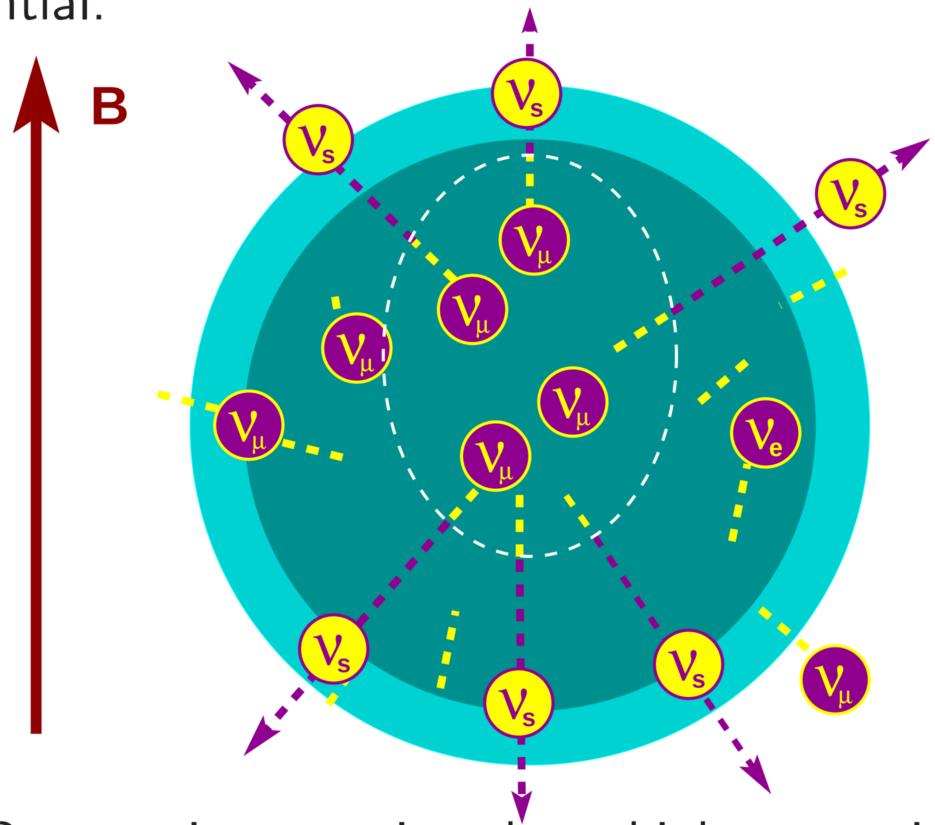
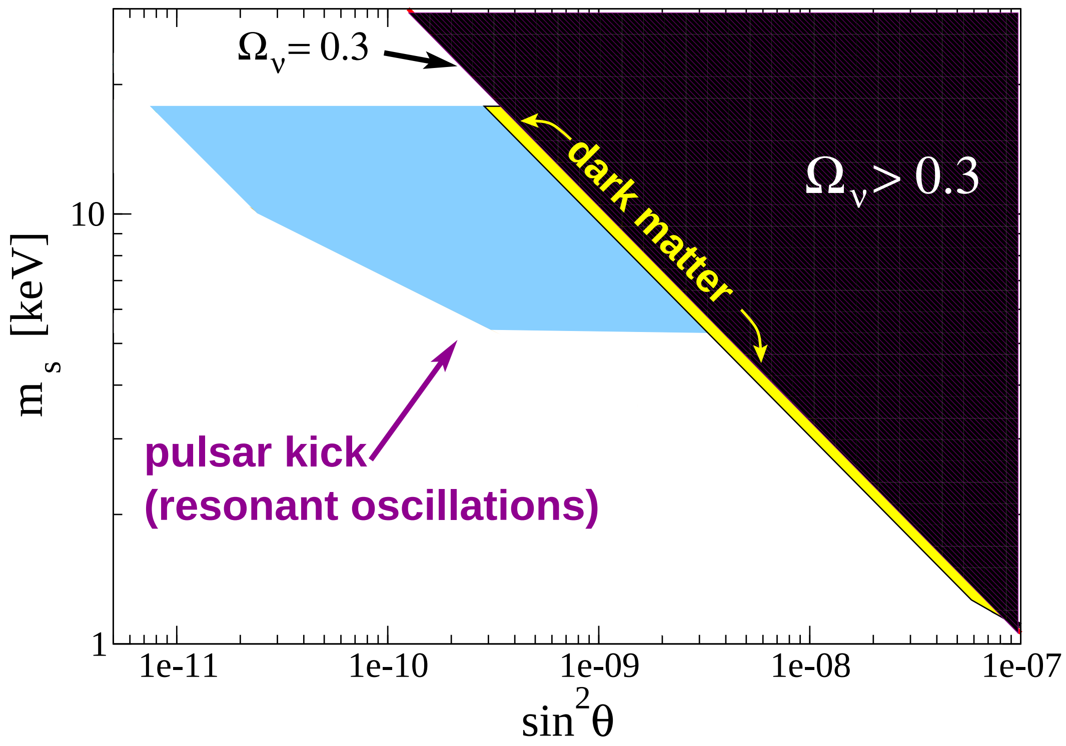


Down going neutrinos have higher energies

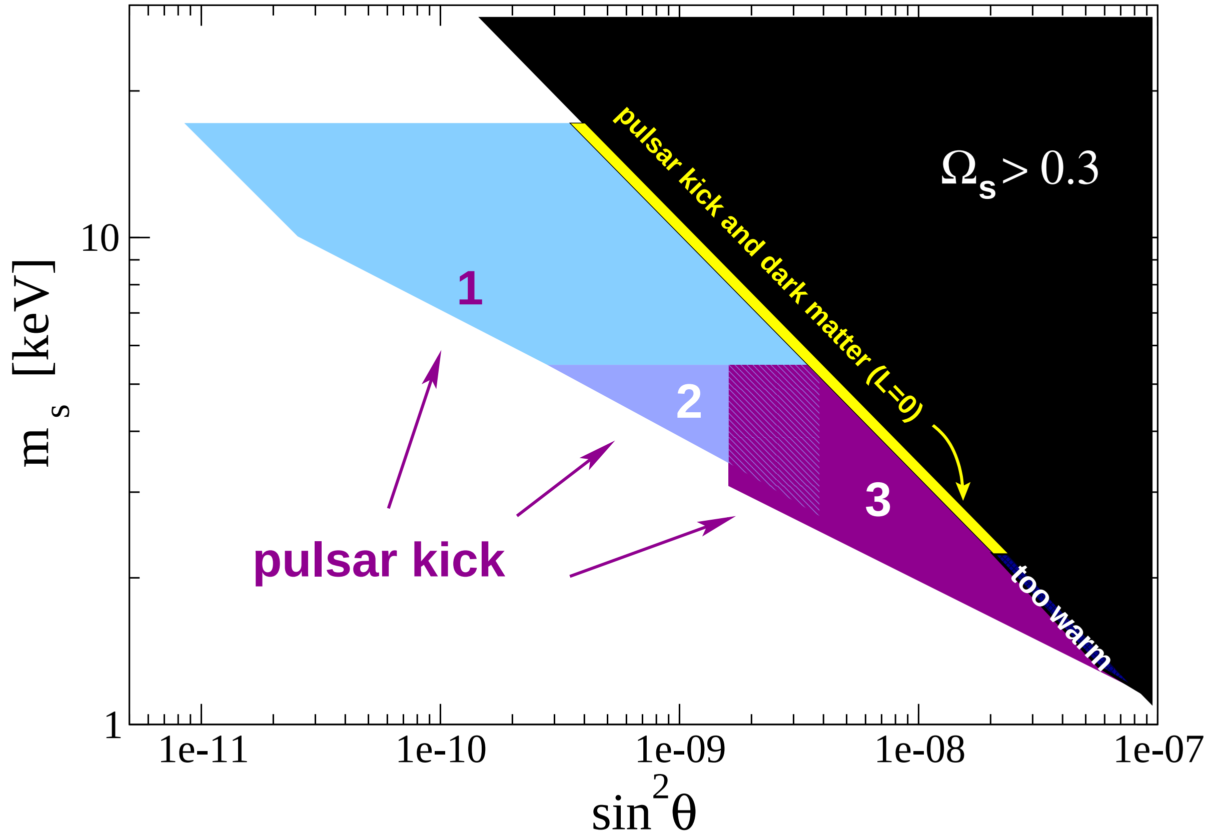
of the

The range of parameters for off-resonance transitions:



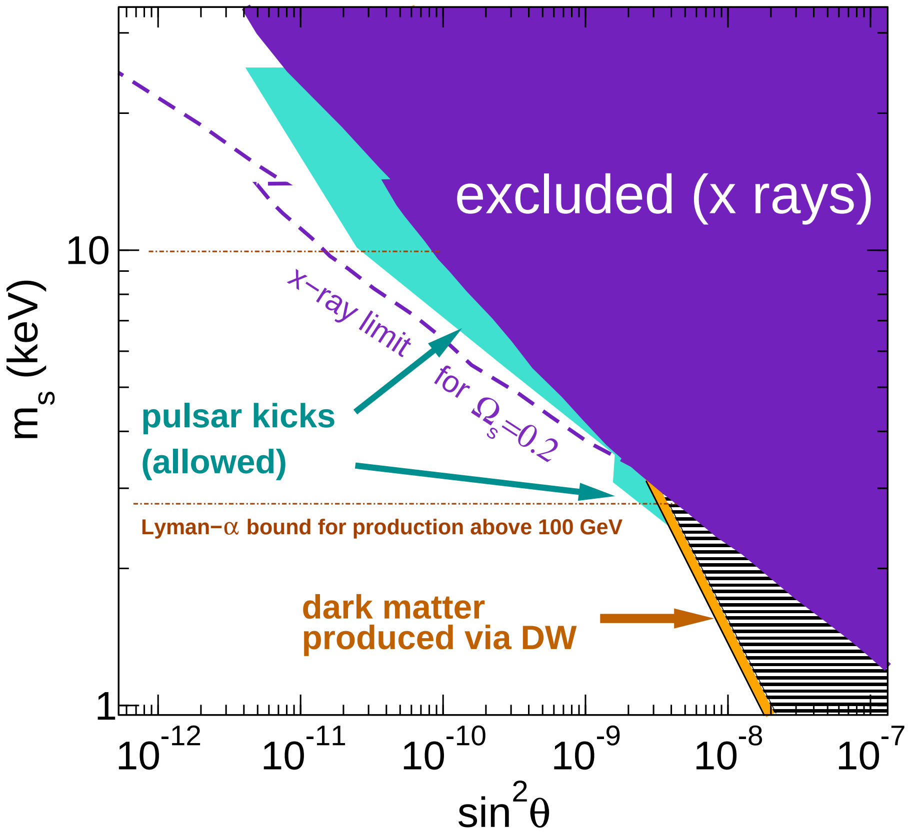
[AK, Segrè]

Resonance & off-resonance oscillations



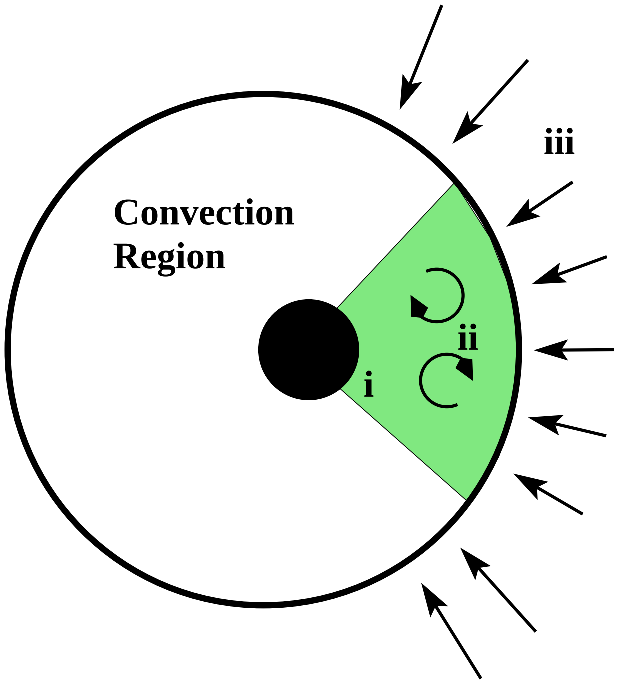
[A.K., Segrè; Fuller, A.K.,Mocioiu,Pascoli; Barkovich, D'Ollivo, Montemayor]

Allowed range of masses and mixing angles



Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK]



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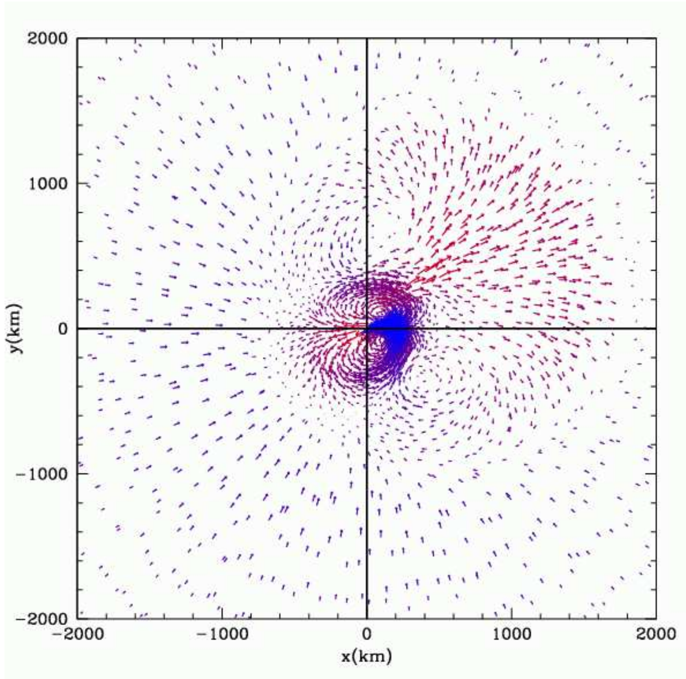
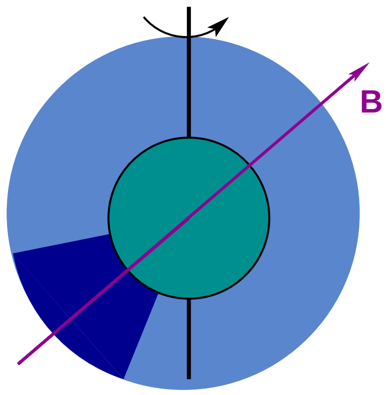


Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK]

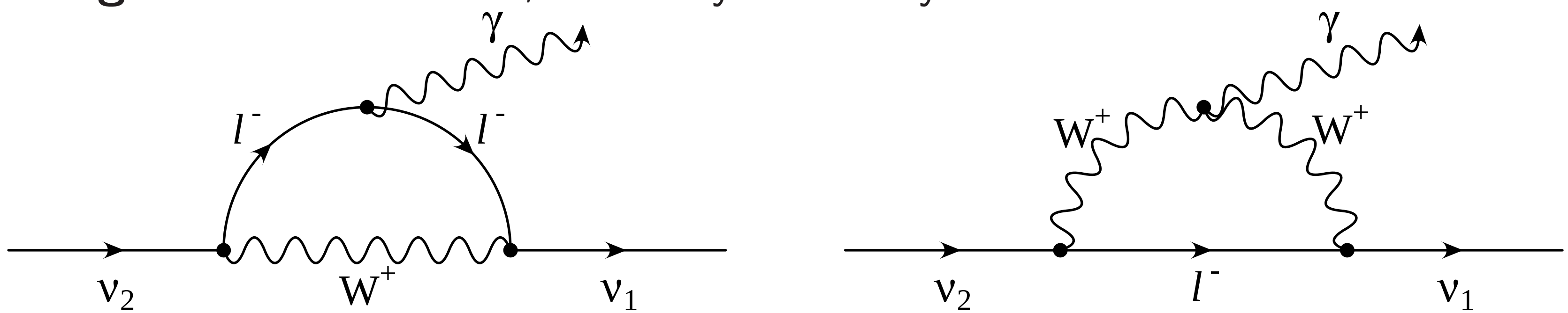
- **No $B - v$ correlation** expected because
  - the magnetic field *inside* a hot neutron star during the *first ten seconds* is very different from the surface magnetic field of a cold pulsar
  - rotation washes out the x, y components

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



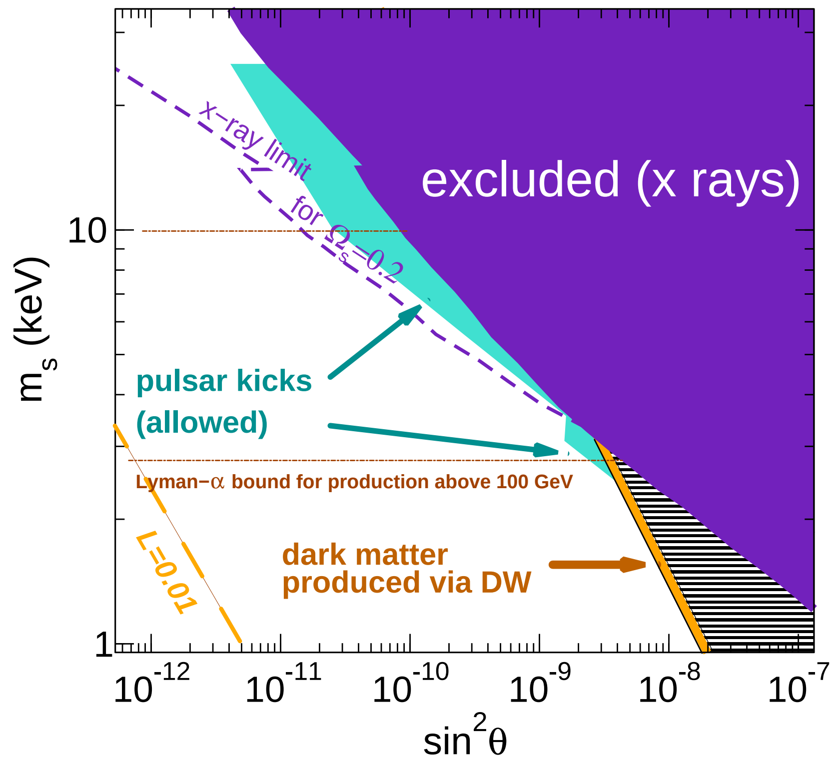
Radiative decay

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

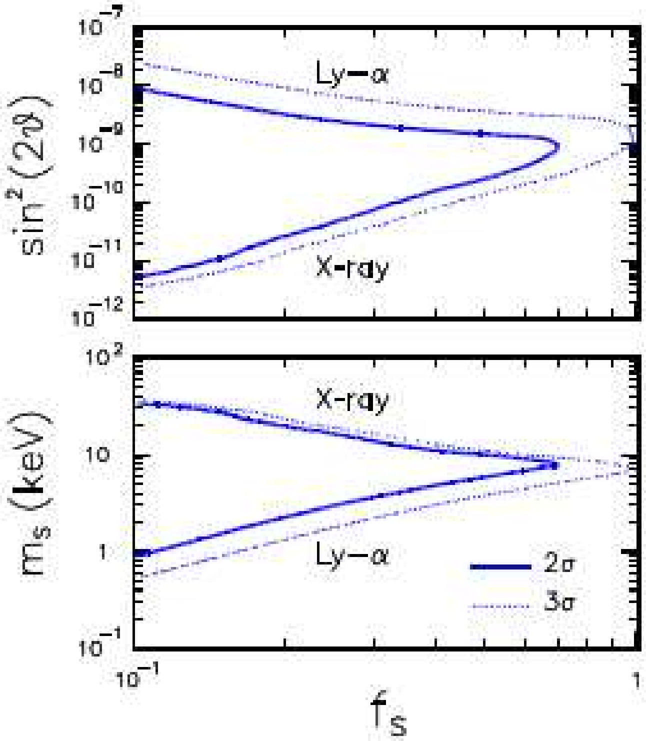


Photons have energies $m/2$: X-rays. Large lumps of dark matter emit some X-rays. [Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]

X-ray observations: the current limits

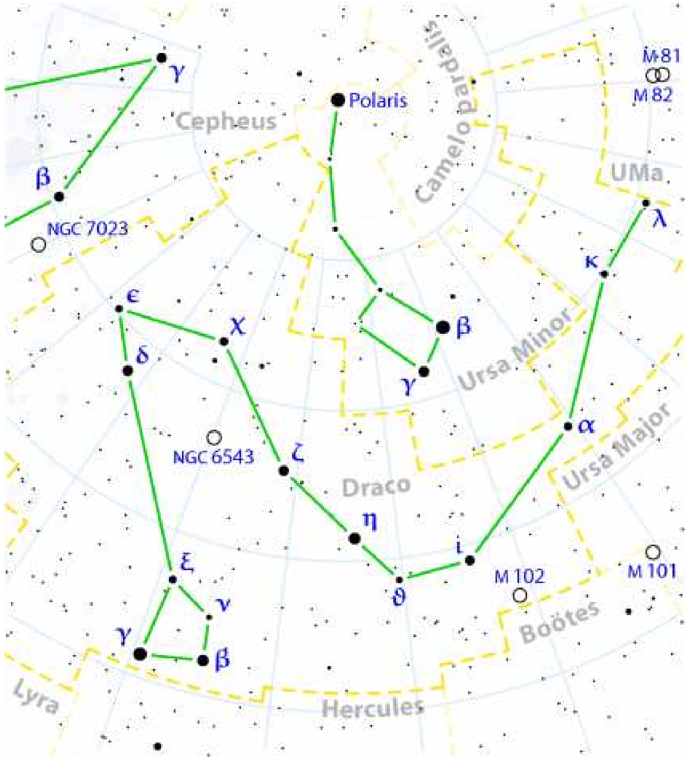


Current limits on subdominant DW dark matter

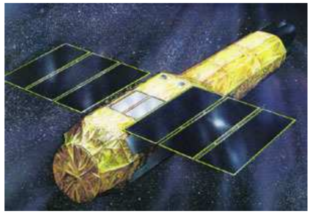


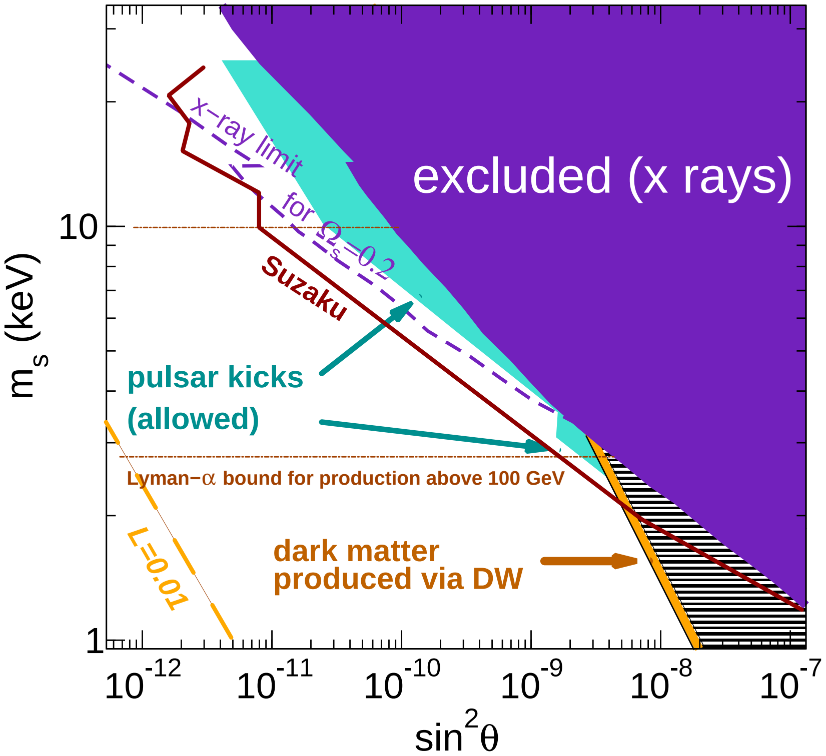
$f_s = \Omega_s/0.2$ [Palazzo, Cumberbatch, Slosar, and Silk]

X-ray observations: Draco and Ursa Minor



X-ray observations: Suzaku reach

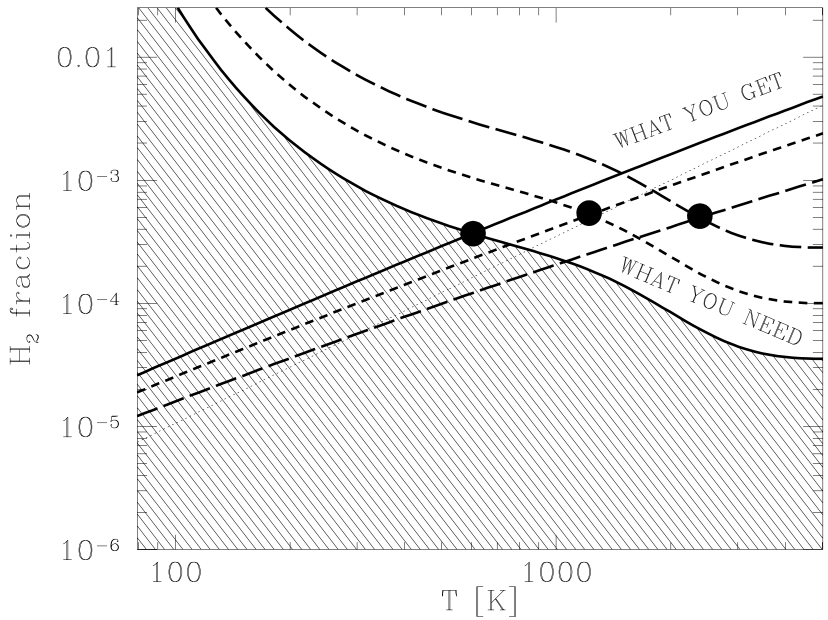




[Loewenstein, Biermann, AK]

Astrophysical clues: star formation and reionization

Molecular hydrogen is necessary for star formation



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

Molecular hydrogen

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

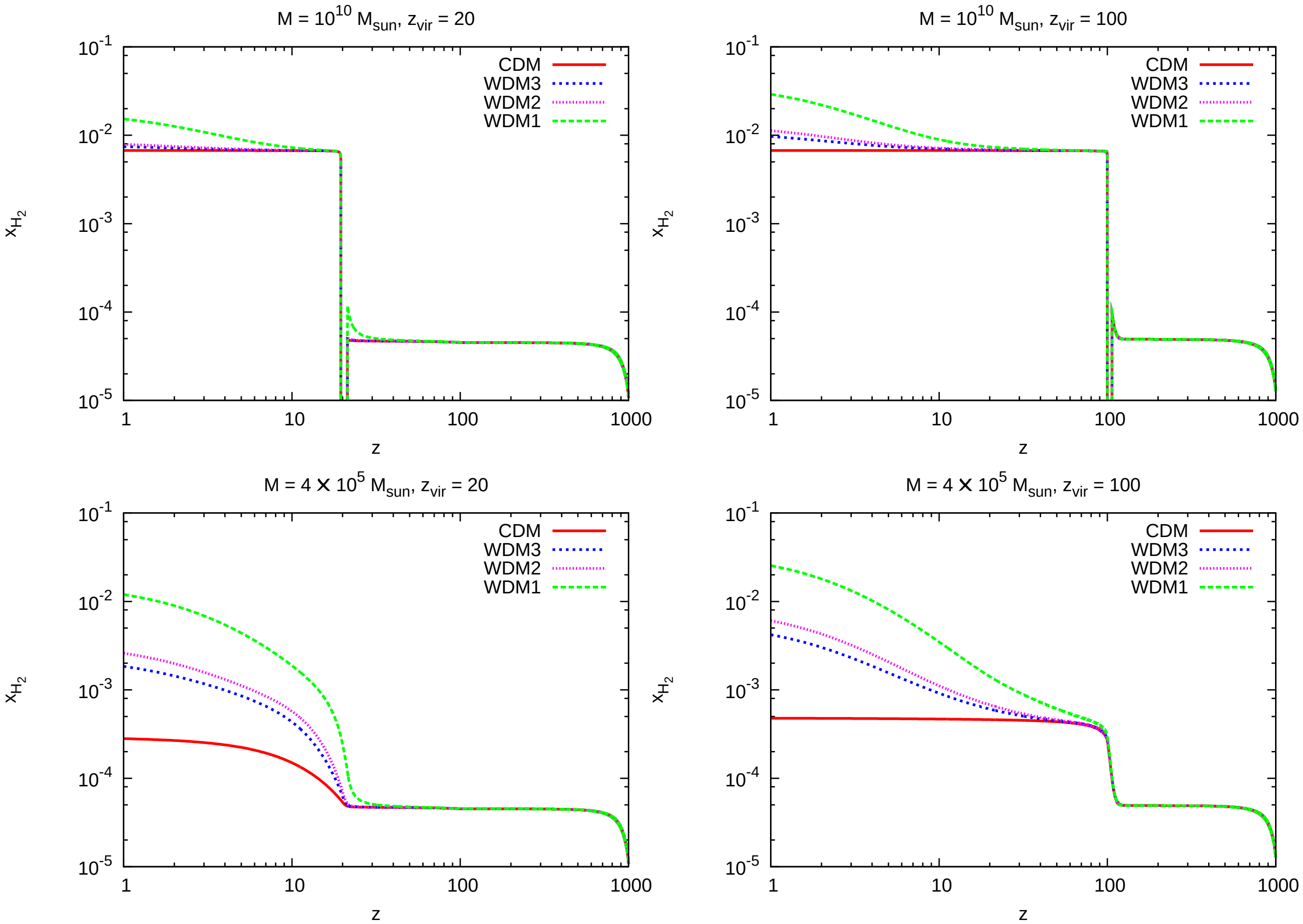
Molecular hydrogen

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

In the presence of ions the following reactions are faster:

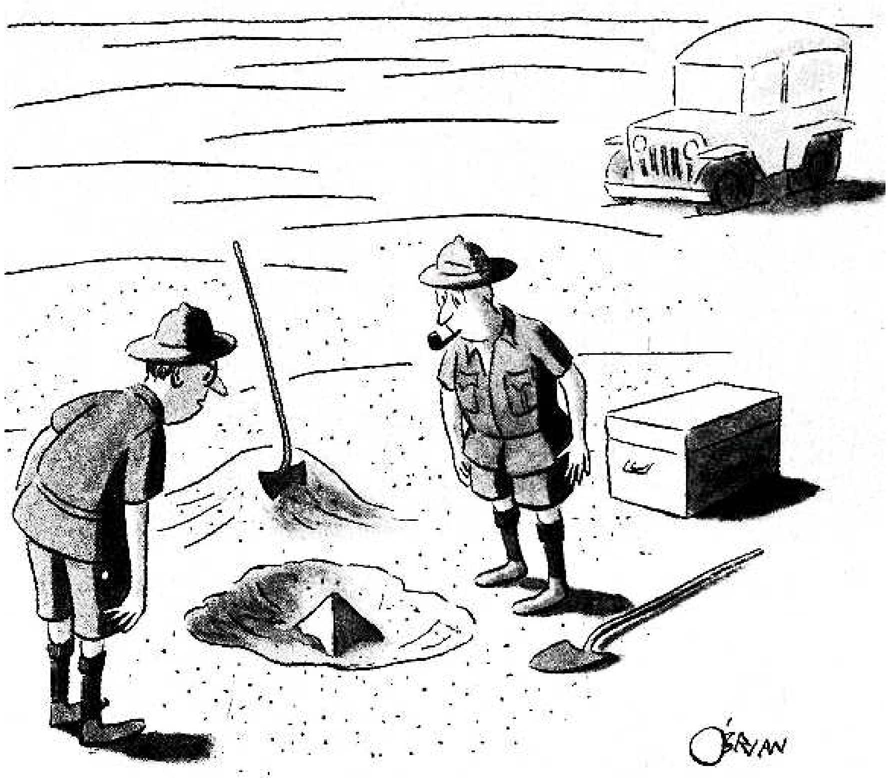
$$\begin{aligned} H^+ + H &\longrightarrow H_2^+ + \gamma, \\ H_2^+ + H &\longrightarrow H_2 + H^+. \end{aligned}$$

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]

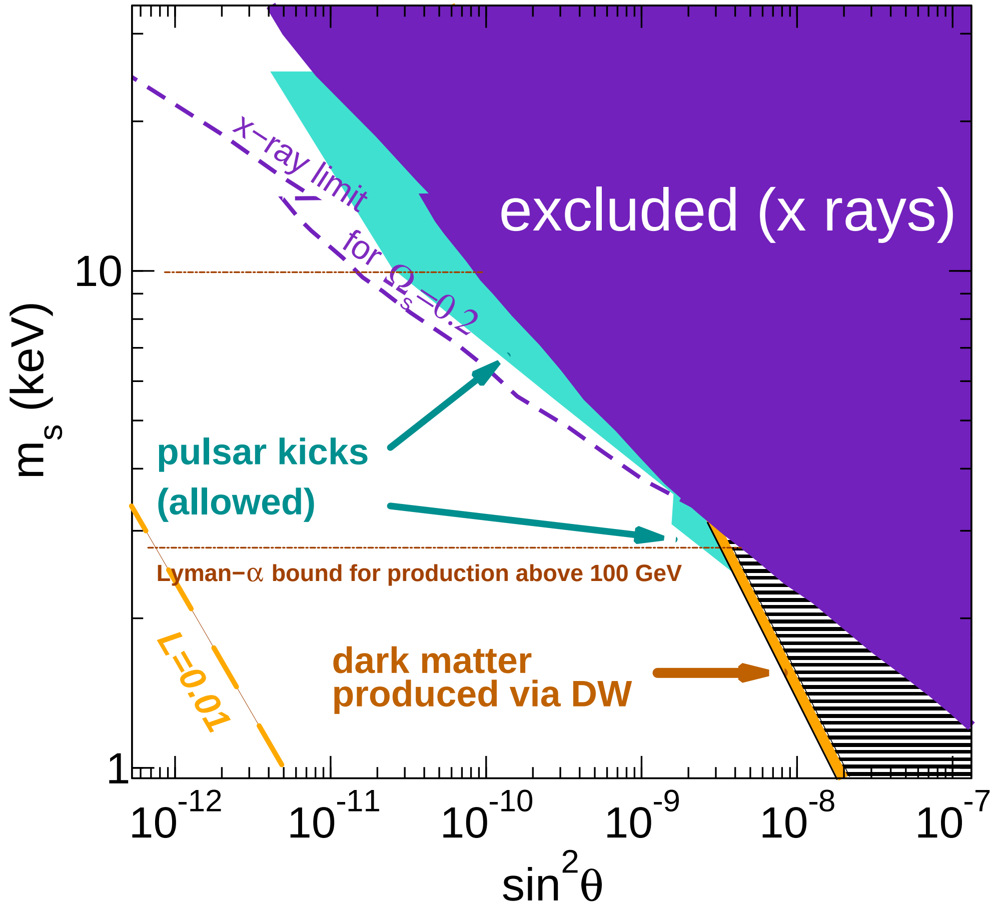
Clues of sterile neutrinos



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)
  - baryon asymmetry of the universe
  - pulsar velocities
- Coldest sterile neutrinos call for a Higgs singlet
- X-ray telescopes (perhaps, Suzaku) can explore the entire region of concordance in the parameter space



excluded (x rays)
x-ray limit
for Ω_s=0.2
pulsar kicks
(allowed)
Lyman-α bound for production above 100 GeV
dark matter
produced via DW
L=0.01
m_s (keV)
sin²θ
10
1
10^-12
10^-11
10^-10
10^-9
10^-8
10^-7