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  - astrophysical hints: pulsar kicks from an anisotropic supernova emission
- Search with X-ray telescopes [Loewenstein]

Бруно Понтекорво

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. $\mu \to e\gamma$)
- 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, and the dark side of the light fermions

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

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

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The number of **dark-side** neutrinos is unknown: **minimum two**

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

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:

$$M = \left(\begin{array}{cc} 0 & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{array}\right)$$

What is the *natural* scale of M?

Seesaw mechanism

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

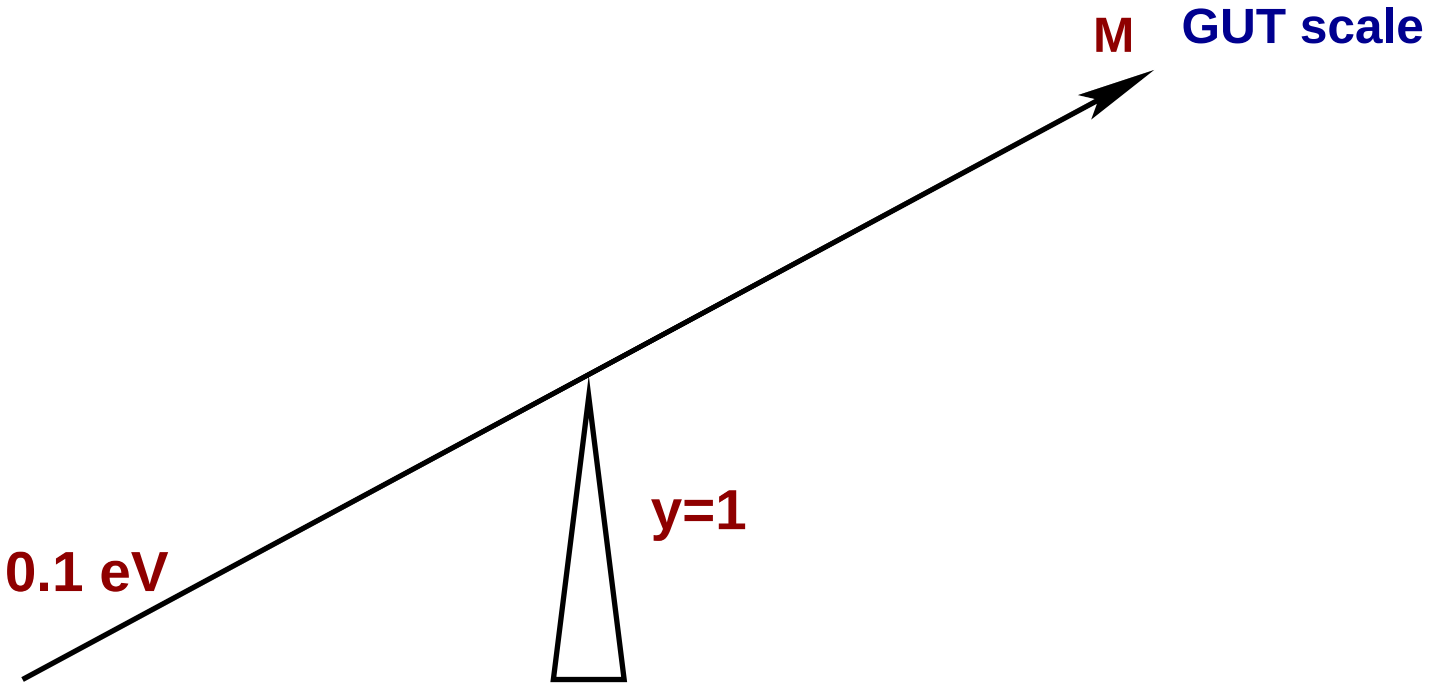
$$D_{ij} = y_{ij} \langle H \rangle$$

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

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

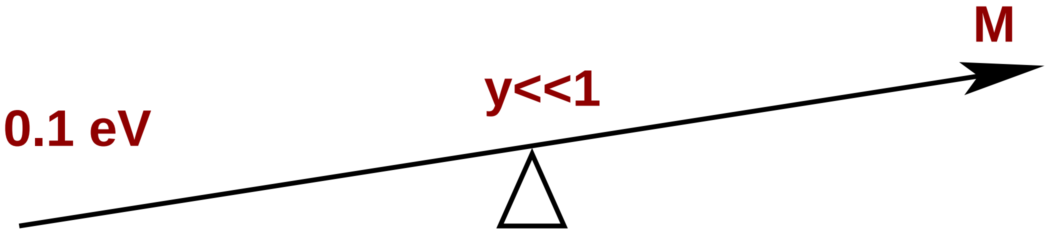
One can understand the smallness of neutrino masses even if the Yukawa couplings are $y \sim 1$ [Gell-Mann, Ramond, Slansky; Yanagida; Glashow; Mohapatra, Senjanović].

Seesaw mechanism



Seesaw mechanism

GUT scale



M

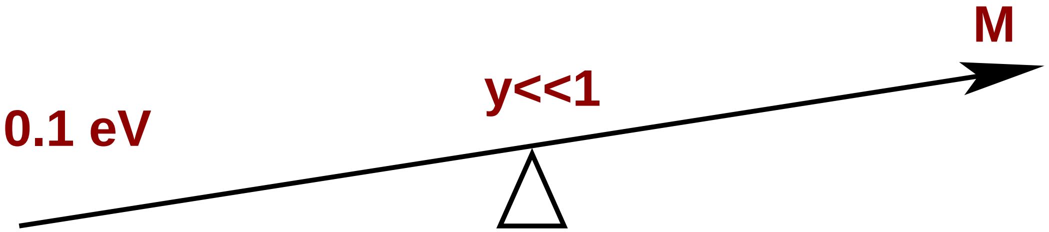
y<<1

0.1 eV

keV scale
(dark matter)
(pulsar kicks)

Seesaw mechanism

GUT scale



keV scale
(dark matter)
(pulsar kicks)

Why keV?

Split seesaw [AK, Takahashi, Yanagida]
Split flavor [Ishida, Jeong, Takahashi]

wrong reasons to dismiss right-handed neutrinos

- LEP measurements of Z width indicate 3 generations of fermions
- Sterile neutrinos are ruled out by CMB measurements of $N_{\rm eff} = \ldots$
- Sterile neutrinos with masses below x keV make dark matter that is too warm
- "XXXX experiment, which claimed evidence of sterile neutrinos, was ruled out by YYYY experiment"
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$N_{\rm eff}$: what it is, and what it is not

$$\rho_{\rm rad} = \left[2 + \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\frac{\pi^2}{30}T^4.$$

The standard model prediction: $N_{\rm eff} = 3.046$.

CMB, including Planck: $N_{\rm eff} = 3.3 \pm 0.5$.

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Add: 1 sterile neutrino $N_{\rm eff} = ...?$

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Depends on the mass and mixing.

Sterile neutrinos can decay in a variety of modes, depending on the mass. Decays can cause (i) entropy production and dilution of ordinary neutrinos, and (ii) production of non-thermal neutrinos in the final state.

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$$\nu_s \rightarrow \underset{\text{decrease } N_{\rm eff}}{\text{photons}} + \underset{\text{increase } N_{\rm eff}}{\text{decoupled non-thermal } \nu_{e,\mu,\tau}}$$

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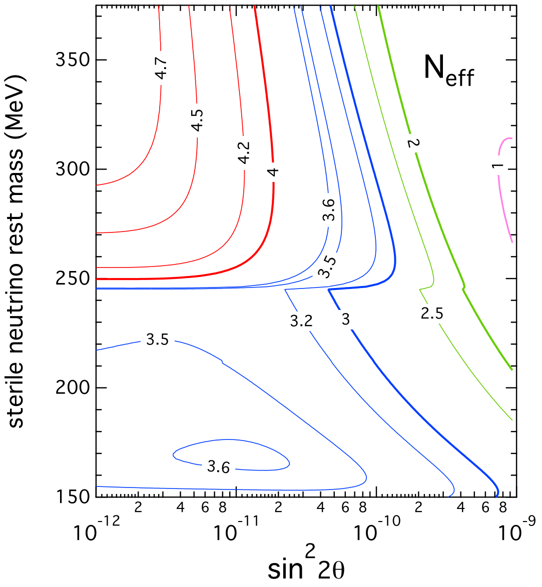
$\nu_s \to$ photons + decoupled non-thermal $\nu_{e,\mu,\tau}$

decrease N_{eff} increase N_{eff}



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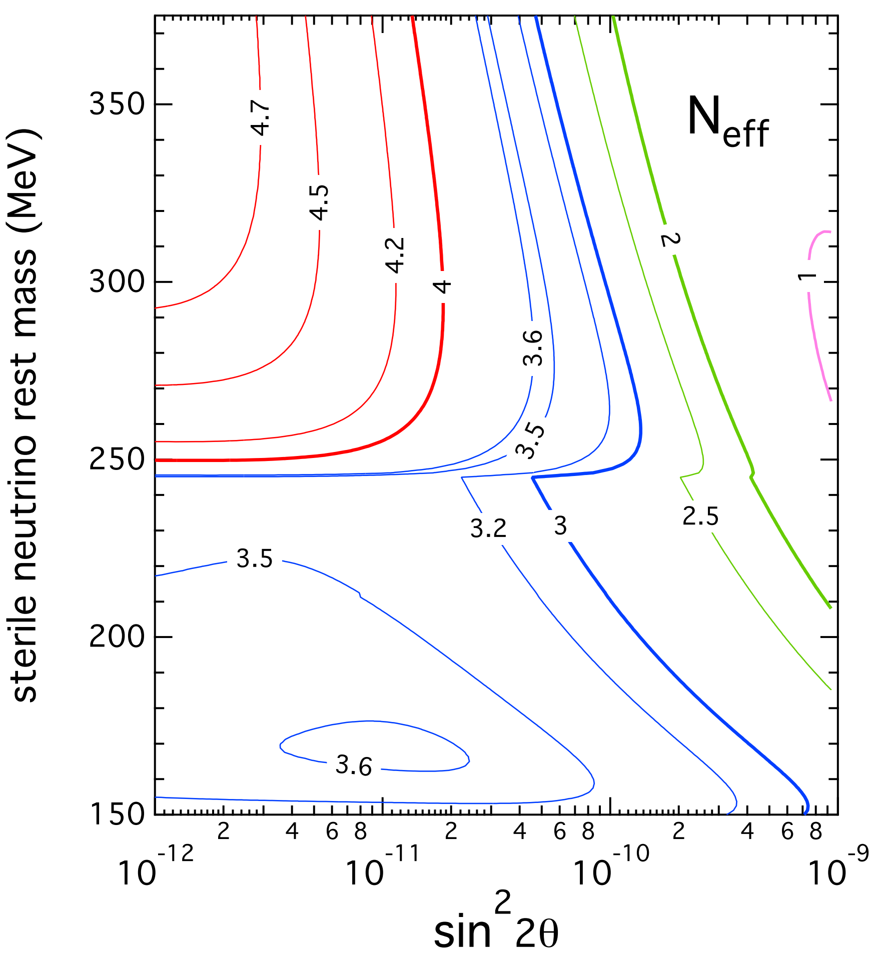


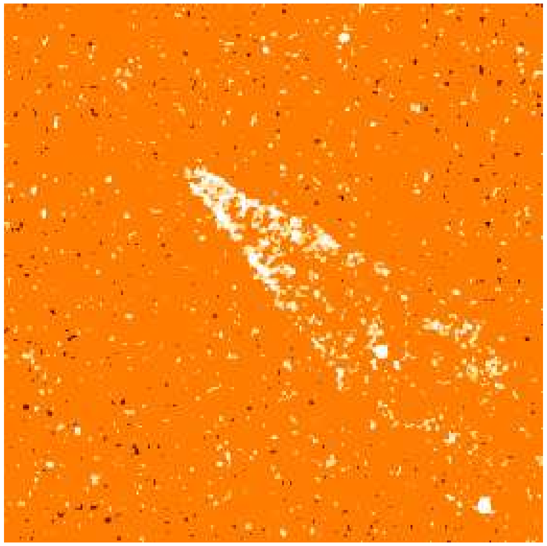
[Fuller, Kishimoto, AK]

The pulsar velocities.

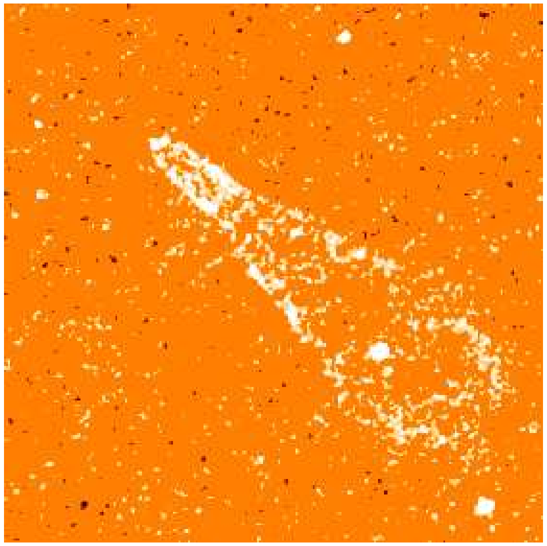
Pulsars have large velocities, $\langle v \rangle \approx 250 - 450$ km/s.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

A significant population with $v > 700$ km/s,
about **15 %** have $v > 1000$ km/s, up to 1600 km/s.
[Arzoumanian *et al.*; Thorsett *et al.*]

A very fast pulsar in Guitar Nebula

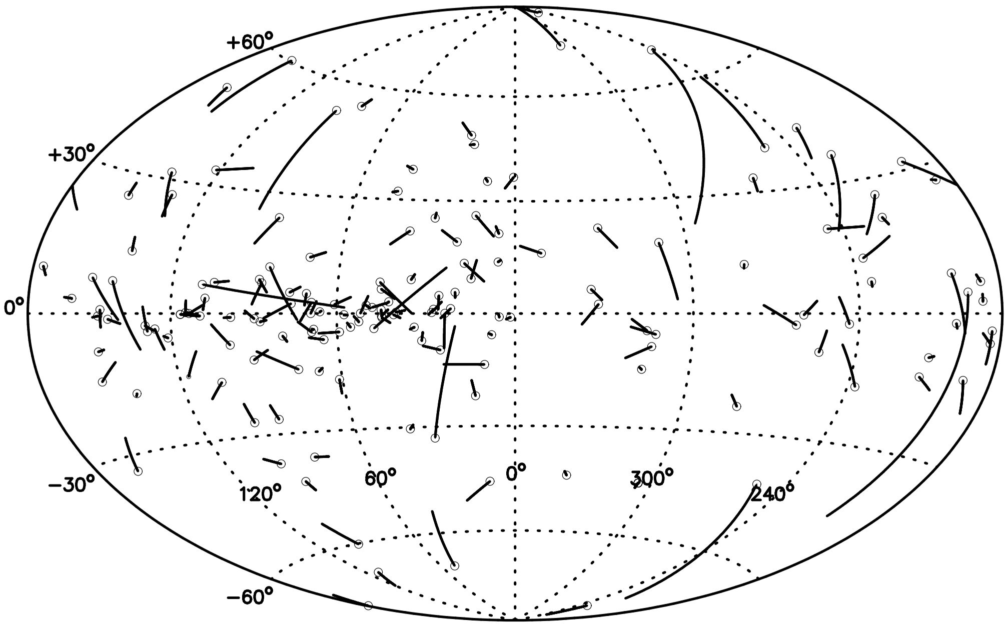


HST, December 1994



HST, December 2001

Map of pulsar velocities



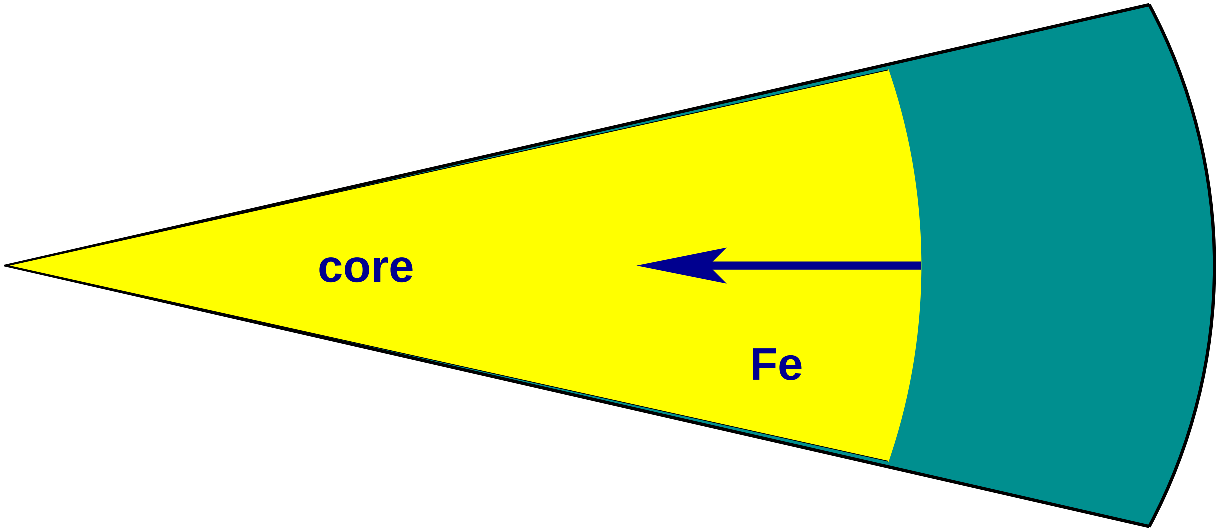
Proposed explanations:

- 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"...

Currently, hopes for SASI. (Can it be consistent with $\vec{\Omega} - \vec{v}$ correlation?)

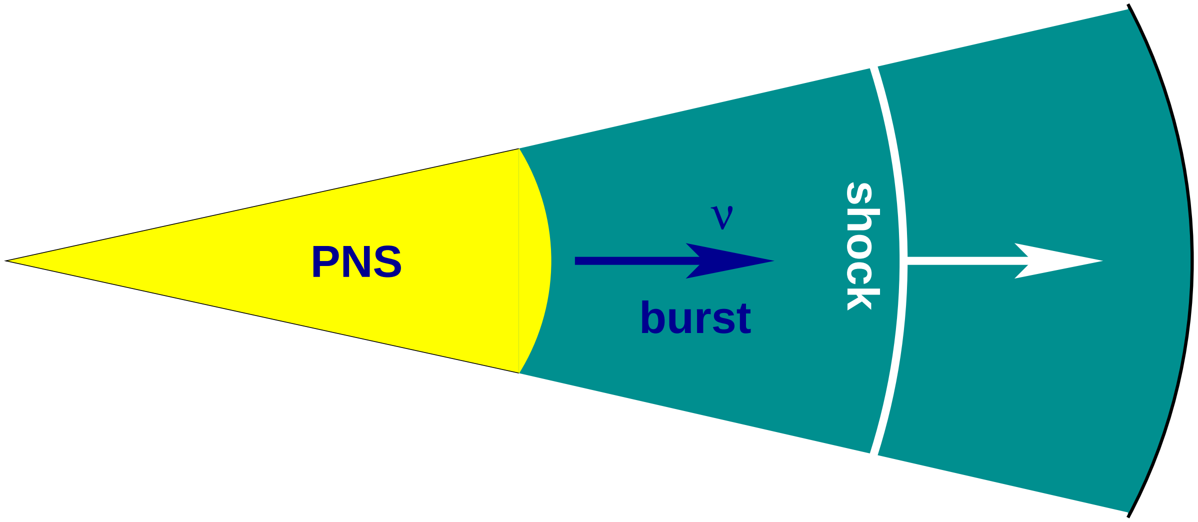
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

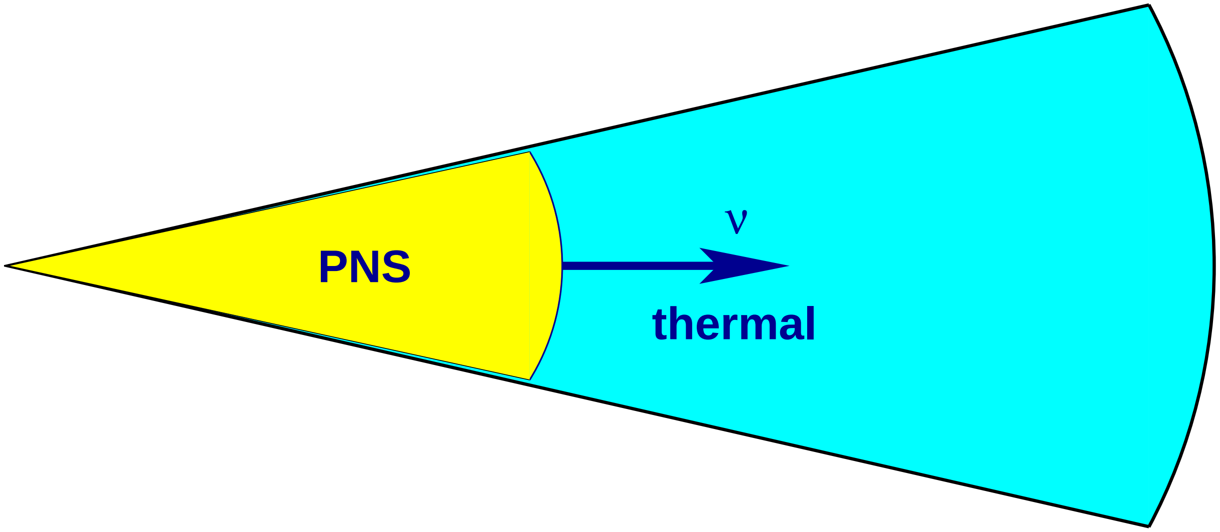
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



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.

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 ⇒ 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 $\mathbf{B \sim 10^{12} - 10^{13}}$ **G**.

Recent discovery of *soft gamma repeaters* and their identification as *magnetars*

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

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

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

Electroweak processes producing neutrinos (urca),

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

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

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

The asymmetry:

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

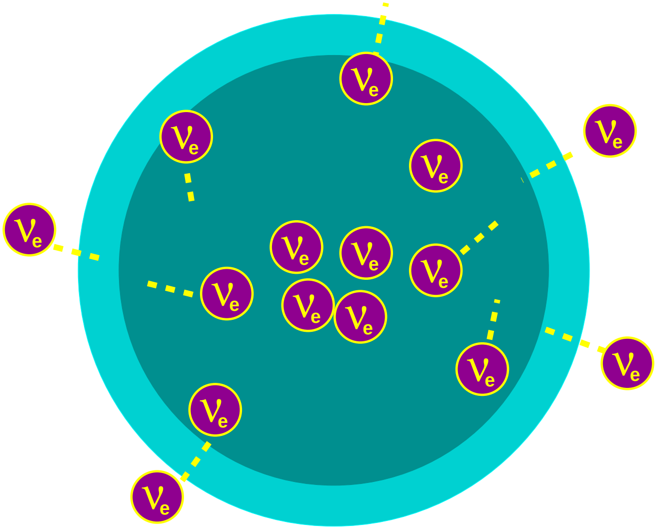
where k_0 is the fraction of electrons in the lowest Landau level.

$k_0 \sim 0.3$ in a strong magnetic field.

$\Rightarrow\sim 10\%$ **anisotropy??**

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?

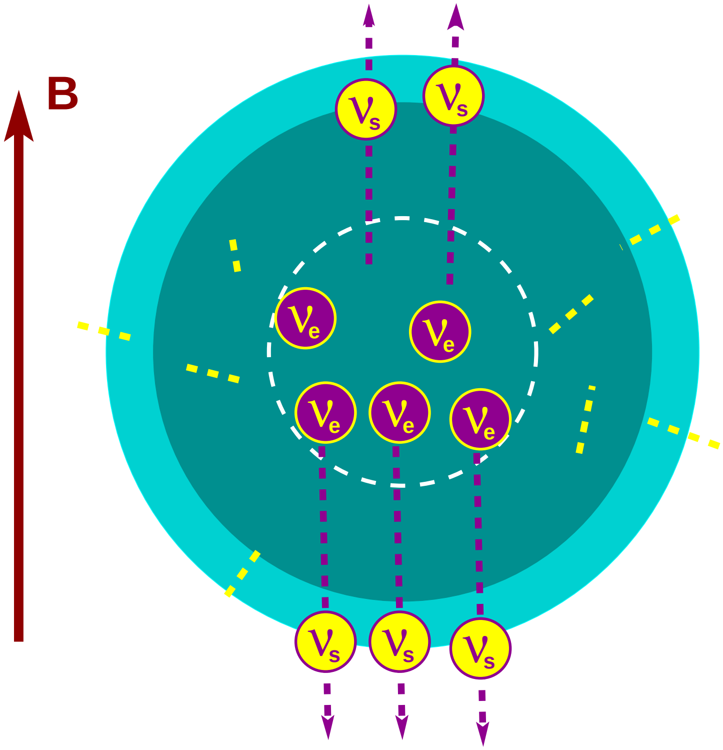
No

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].

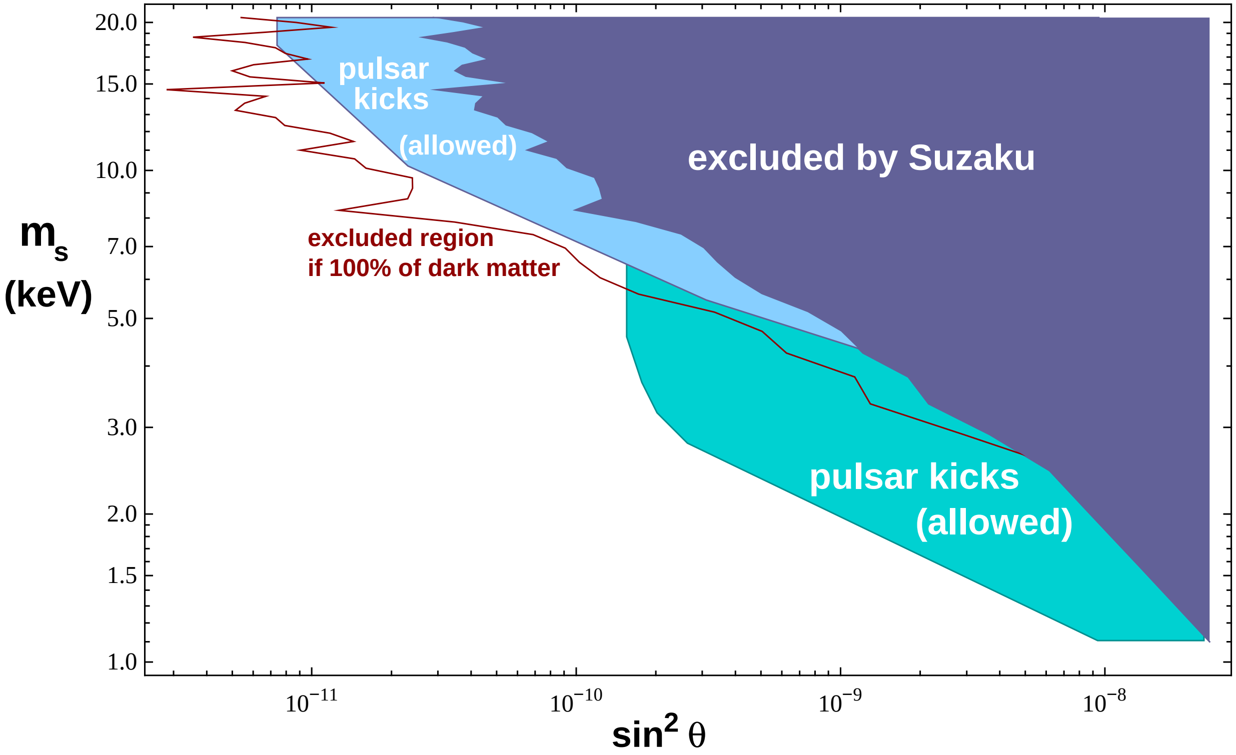
However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

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



The mass and mixing required for the pulsar kick are consistent with dark matter.

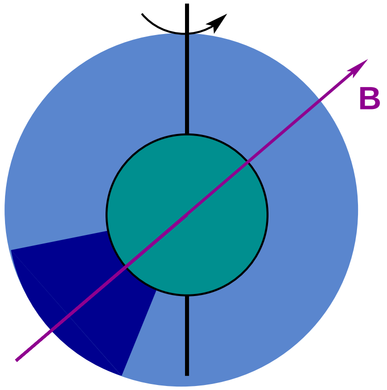
Pulsar kicks



[AK, Segrè; Fuller, AK, Mocioiu, Pascoli; Barkovich et al., Kishimoto]

Other predictions

- 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 (and is observed!), because
  - the direction of rotation remains unchanged
  - only the z-component survives
- **Stronger**, different supernova [Hidaka, Fuller; Fuller, AK, Petraki]
- **Delayed kicks** [AK, Mandal, Mukherjee '08]



Sterile neutrinos as dark matter: production scenarios

Production **color coded** by **“warmness”** **vs** **“coldness”**:

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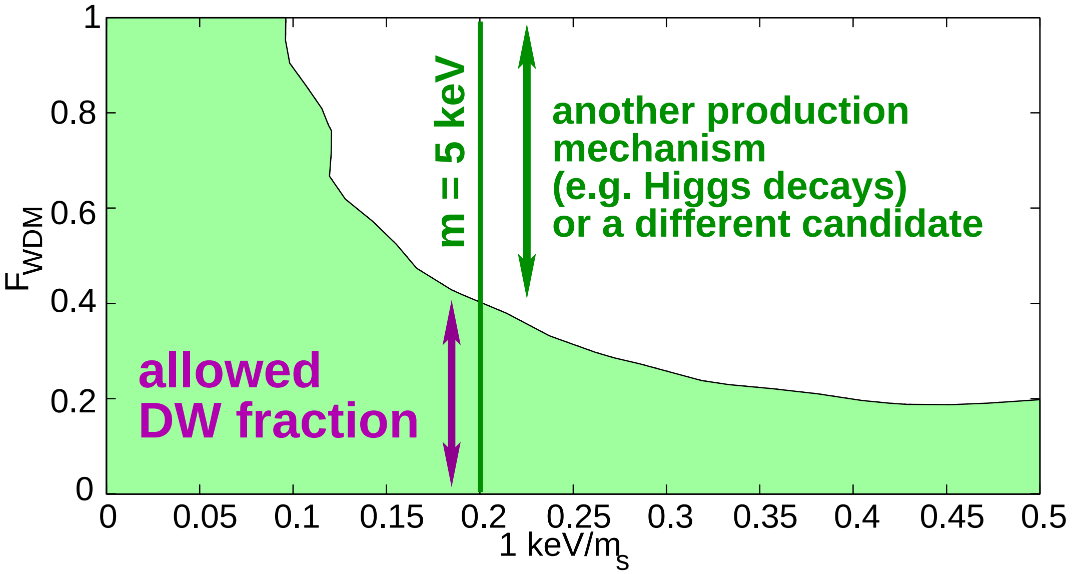
- **Split seesaw**: [AK, Takahashi, Yanagida]. Two production mechanisms, **cold** and **even colder**. Advantage: “naturally” low mass scale

Generically, two components: colder and warmer

Lyman-α bounds on Dodelson-Widrow production



[Boyarsky, Lesgourgues, Ruchayskiy, Viel] (beware of systematic errors...)

On the other hand, free-streaming properties [Petraki, Boyanovsky] can explain observations of dwarf spheroidal galaxies [Gilmore, Wyse]

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 $S \rightarrow NN$ 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 $\boldsymbol{S \to NN}$:

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

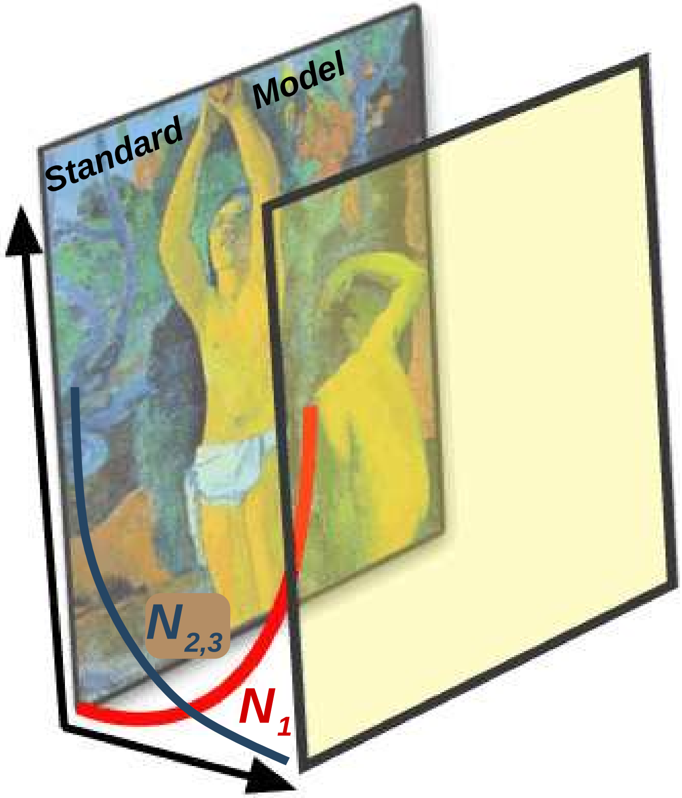
Here ξ is the dilution factor due to the change in effective numbers of degrees of freedom.

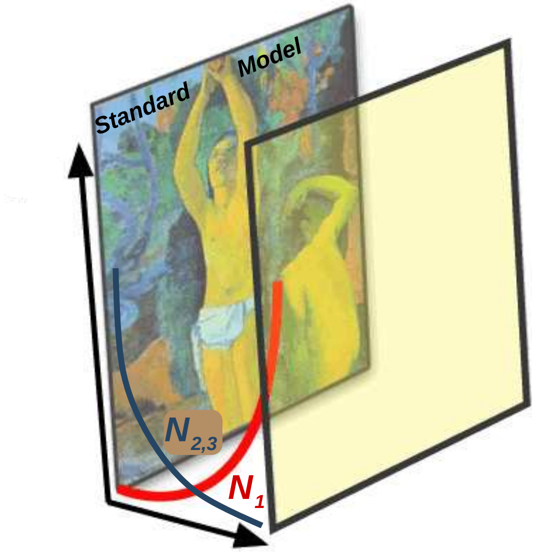
$\langle S\rangle \sim 10^2\ \mathrm{GeV}$ (EW scale)
$M_s \sim \mathrm{keV}$ (for stability) $\Rightarrow h \sim 10^{-8}$

$$\Rightarrow \Omega \approx 0.2$$

The sterile neutrino momenta are red-shifted by factor $\xi^{1/3} > 3.2$. [AK, Petraki]

Split seesaw





Standard Model on $z = 0$ brane. A Dirac fermion with a bulk mass m:

$$S = \int d^4x\, dz\, M \left(i\bar{\Psi}\Gamma^A\partial_A\Psi + m\bar{\Psi}\Psi \right),$$

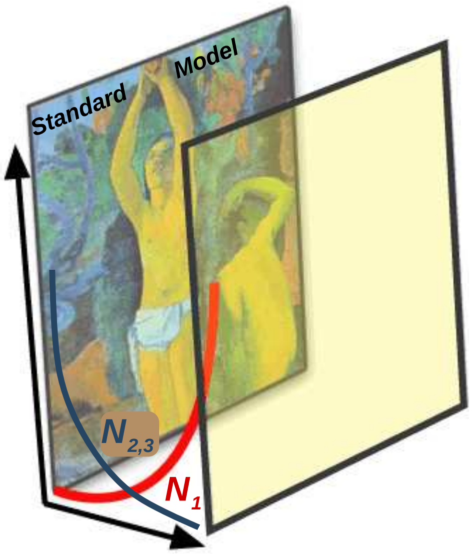
The zero mode: $(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0$. behaves as $\sim \exp(\pm mz)$. The 4D fermion:

$$\Psi_R^{(0)}(z,x) = \sqrt{\frac{2m}{e^{2m\ell}-1}}\frac{1}{\sqrt{M}}e^{mz}\psi_R^{(4D)}(x).$$

Also, a $\mathrm{U}(1)_{(B-L)}$ gauge boson in the bulk, $(B-L) = -2$ Higgs ϕ on the SM brane. The VEV $\langle\phi\rangle \sim 10^{15}$GeV gives right-handed neutrinos heavy Majorana masses.

[AK, Takahashi, Yanagida]

Split seesaw



Effective Yukawa coupling and the mass are suppressed:

$$M_{d=4}^{(R)} = M_{d=5}^{(R)} \left(\frac{2m_i}{M(e^{2m_i\ell}-1)} \right),$$

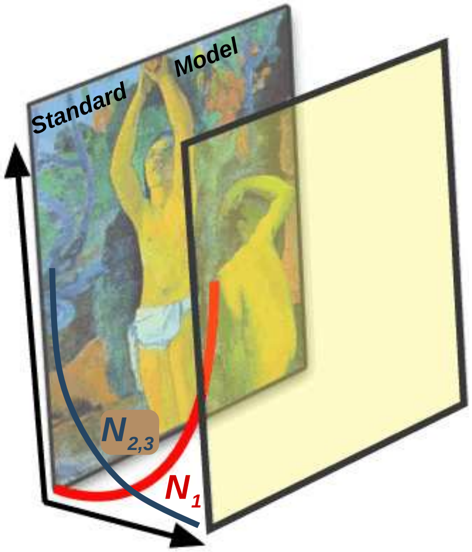
$$y_{d=4} = y_{d=5} \sqrt{\frac{2m_i}{M(e^{2m_i\ell}-1)}}$$

successful seesaw relation unchanged:

$$m_\nu \sim \frac{y_{d=4}^2 \langle H \rangle^2}{M_{d=4}^{(R)}} = \frac{y_{d=5}^2 \langle H \rangle^2}{M_{d=5}^{(R)}}$$

[AK, Takahashi, Yanagida]

Split seesaw: economical, natural extension of SM



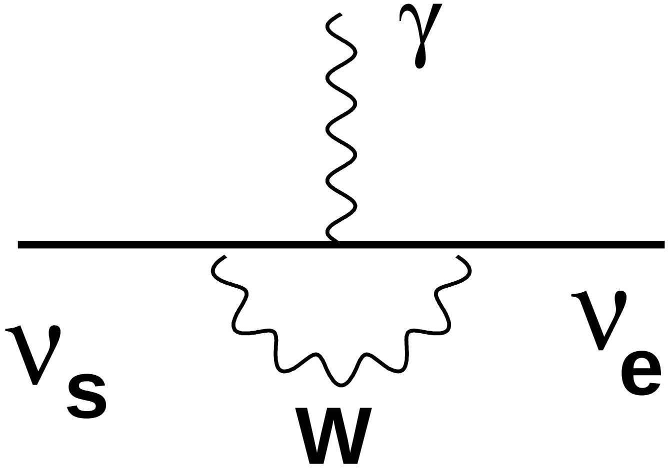
- Democracy of scales: small difference in the bulk masses m_i results in exponentially large splitting between the sterile neutrino masses.
- An rather minimal model: SM augmented by three right-handed singlets can explain
  - observed **neutrino masses**
  - **baryon asymmetry** (via leptogenesis)
  - **dark matter**

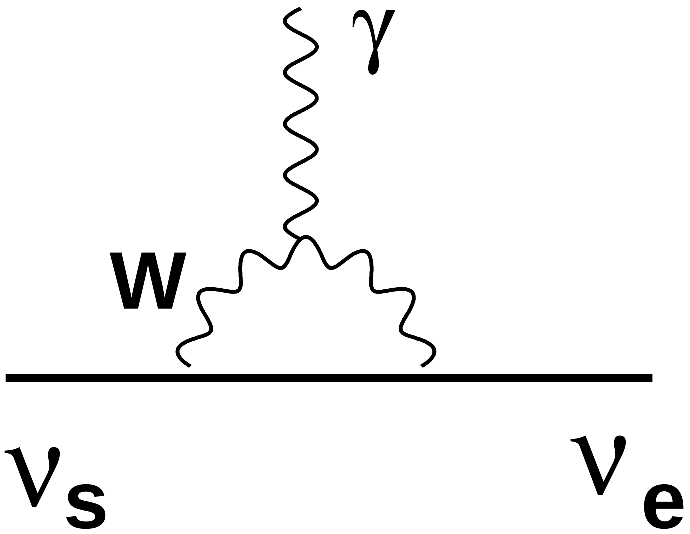
  if, for example
  $M_1 = 5\,\mathrm{keV}$ or $M_1 = 17\,\mathrm{keV}$, and
  $M_{2,3} \sim 10^{15}\mathrm{GeV}$

[AK, Takahashi, Yanagida]

Radiative decays of sterile neutrinos

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. Concentrations of dark matter emit X-rays [Abazajian, Fuller, Tucker].

X-ray telescopes: meet the fleet

	Chandra (I-array)	**XMM-Newton**	**Suzaku**
field of view	$17' \times 17'$	$30' \times 30'$	$19' \times 19'$
angular res.	$\mathbf{1''}$	$6''$	$90''$
energy res.	20 - 50	20 - 50	20 - 50
bandpass	0.4 8 keV	0.2 12 keV	0.3 12 keV
effective area	400 cm^2	$\mathbf{1200 + 2 \times 900\ cm^2}$	400×3 cm^2
NXB rate	~ 0.01 ct/s/arcmin^2	~ 0.01 ct/s/arcmin^2	$\boldsymbol{\sim 10^{-3}}$ **cts/s/arcmin**^{2}

All three telescopes are used in the first dedicated dark matter search

[Loewenstein]

Background

	Non-X-ray (NXB)	Galactic (GXB)	Cosmic (CXB)
origin	particles	halo and LHB	AGN
determining factors	orbit, design	direction	angular resolution
measurement	look at nothing	look at blank sky*	look at blank sky*
correction	subtract (or fit)	subtract* or fit	resolve/subtract* or fit

***don't subtract your signal!**

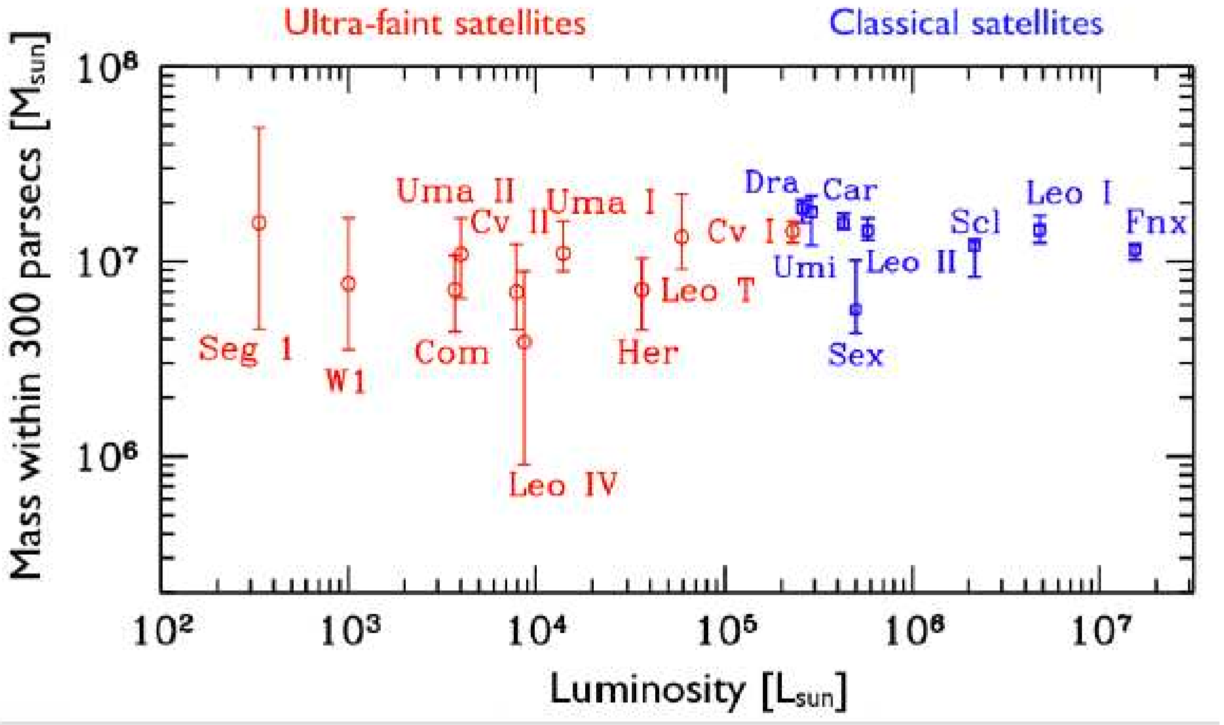
[Loewenstein]

Target selection

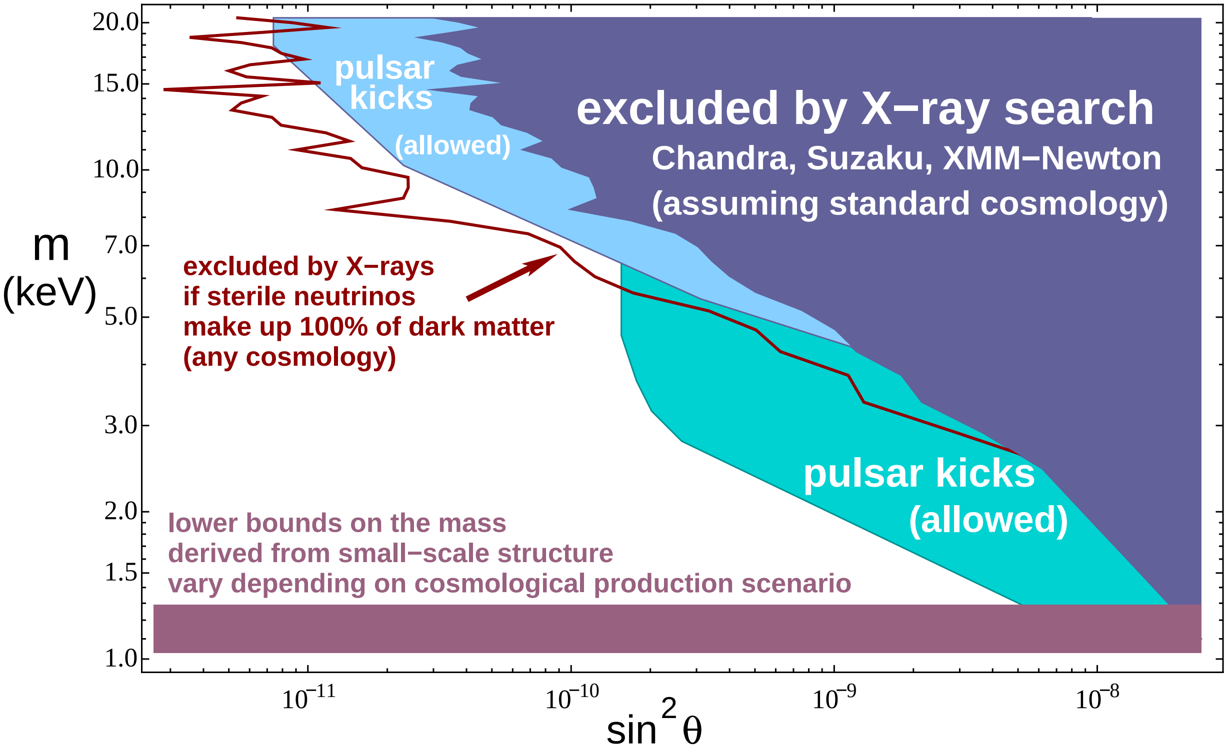
target	dark matter content	background	signal/noise	overall
MW center	high/uncertain	very high	low	far from ideal
MW, “blank sky”	low	low	low	not ideal
nearby galaxy (M31)	high/uncertain	high	low	not ideal
clusters	high	very high	low	not ideal
dSph	high/uncertain	low	high	**best choice**

Example of M31 central region: Central region dominated by baryons, and the dark matter content is uncertain. The most recent measurements of rotation curves rule out high dark matter density in the center (as naive interpretation of N-body simulations would suggest) [Corbelli et al. (2009); Chemin et al. (2009); Saglia et al. (2010)]. The presence of rotating bar is another evidence of low dark matter content in central region. Unresolved stellar emission problematic. Not competitive with dSphs.

Dwarf spheroidal galaxies: dark matter dominated systems



Limits from X-ray searches



[Loewenstein, A.K., Biermann, ApJ 700, 426 (2009); Loewenstein, A.K., ApJ 714 (2010) 652; ApJ. 751 (2012) 82]

Summary

- cosmology (and everything else) allows sterile neutrinos in a broad range of masses.
- $N_{\rm eff}$ is not a direct measure of the number of sterile neutrinos
- a heavy sterile neutrino is an efficient *diluton*: decays, produces entropy
- non-thermal neutrinos from a heavy sterile neutrino decay can affect $N_{\rm eff}$.
- sterile neutrino is a viable **dark matter** candidate
- they can be discovered using X-ray observations; the search is ongoing
- corroborating evidence from supernova physics: pulsar kicks
- X-ray photons produced in the early universe can catalyze formation of $\rm H_2$ and affect the formation of the first stars
- Effects may show up in 21-cm data
- If discovered, dark matter X-ray line can help map out dark halos
- If discovered, redshift-distance information inferred from the X-ray line can be used for observational cosmology, including dark energy research