Sterile neutrinos: the dark side of the light fermions

- Sterile neutrino: a well-motivated dark matter candidate [Dodelson, Widrow; Fuller et al., Shaposhnikov et al.]
  - observed neutrino masses imply the existence of right-handed singlets, which can naturally be light [Lindner et al.; AK, Takahashi, Yanagida]
  - several production mechanisms can generate the correct abundance for dark matter (warm or cold, depending on the production scenario)
- Astrophysical hints: pulsar kicks from an anisotropic supernova emission [AK, Segrè; Fuller et al.]
- X-ray line from dark matter decay
- Search with X-ray telescopes
- Enhanced H_2 and the star formation [Biermann, AK, Stasielak]

Neutrino masses

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

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

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

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)]

Motivation

- **Dark matter:** need (at least) one non-Standard-Model particle. Must guess the answer before a discovery can be made.
  - **Compelling theoretical ideas?**
    Strong CP $\Rightarrow$ axion
    Supersymmetry $\Rightarrow$ LSP, gravitino, Q-balls.
  - **Neutrino masses** $\Rightarrow$ at least two right-handed neutrinos are introduced in seesaw Lagrangian. If one of the Majorana masses is $\sim$ several keV, the corresponding sterile neutrino is a viable dark matter candidate. [Dodelson, Widrow]
- **Pulsar kicks:** if a sterile/right-handed neutrino exists with a mass of $\sim$ several keV, its emission from a cooling neutron star is anisotropic enough to explain the observed velocities of pulsars. [Kusenko, Segrè; Fuller *et al.*]

Is small Majorana mass natural? Is dark matter produced cold enough?

Neutrino masses and light sterile neutrinos

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:

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

What is the *natural* scale of M?

Seesaw mechanism

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

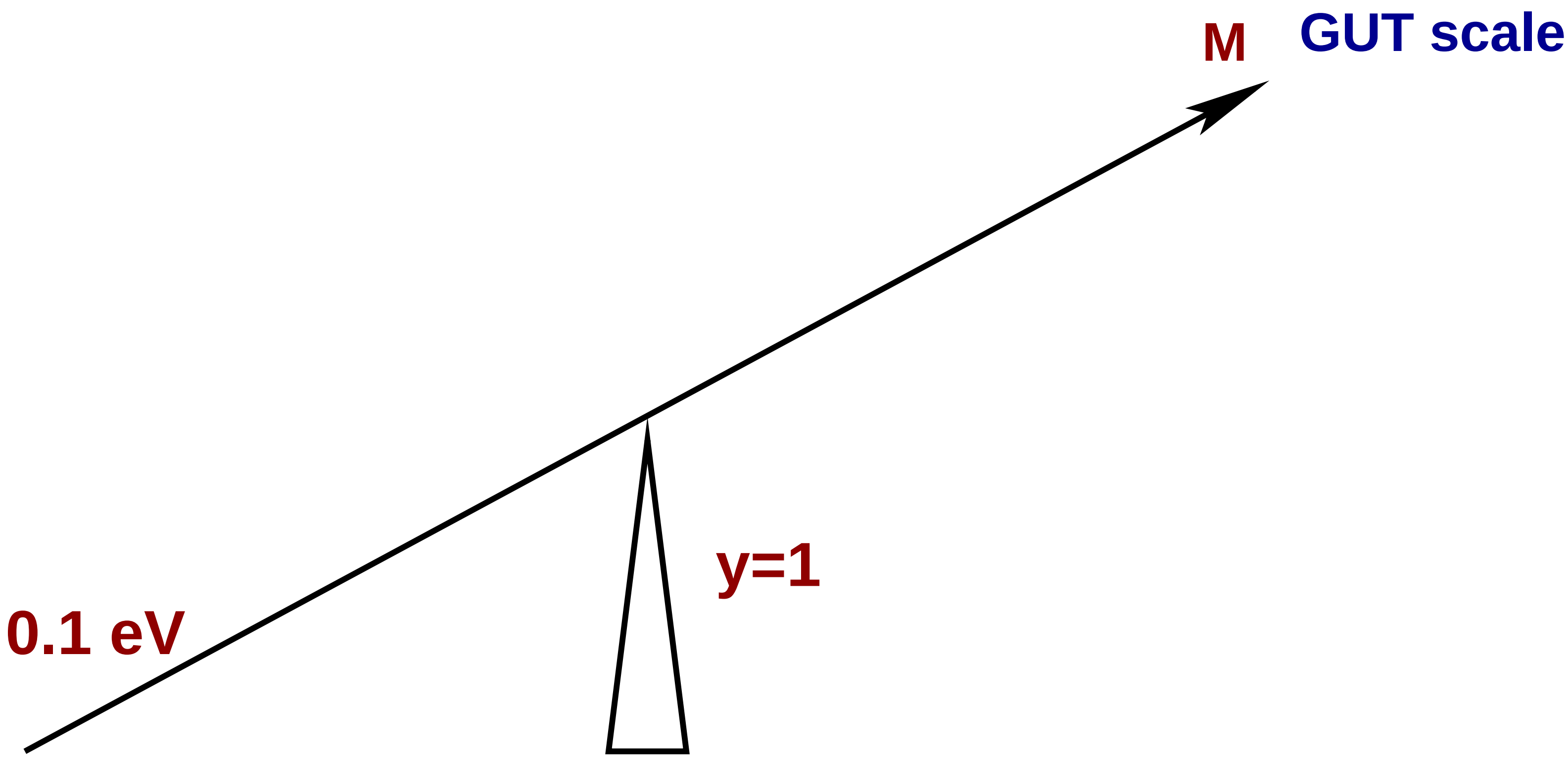
$$D_{ij} = y_{ij} \langle H \rangle$$

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

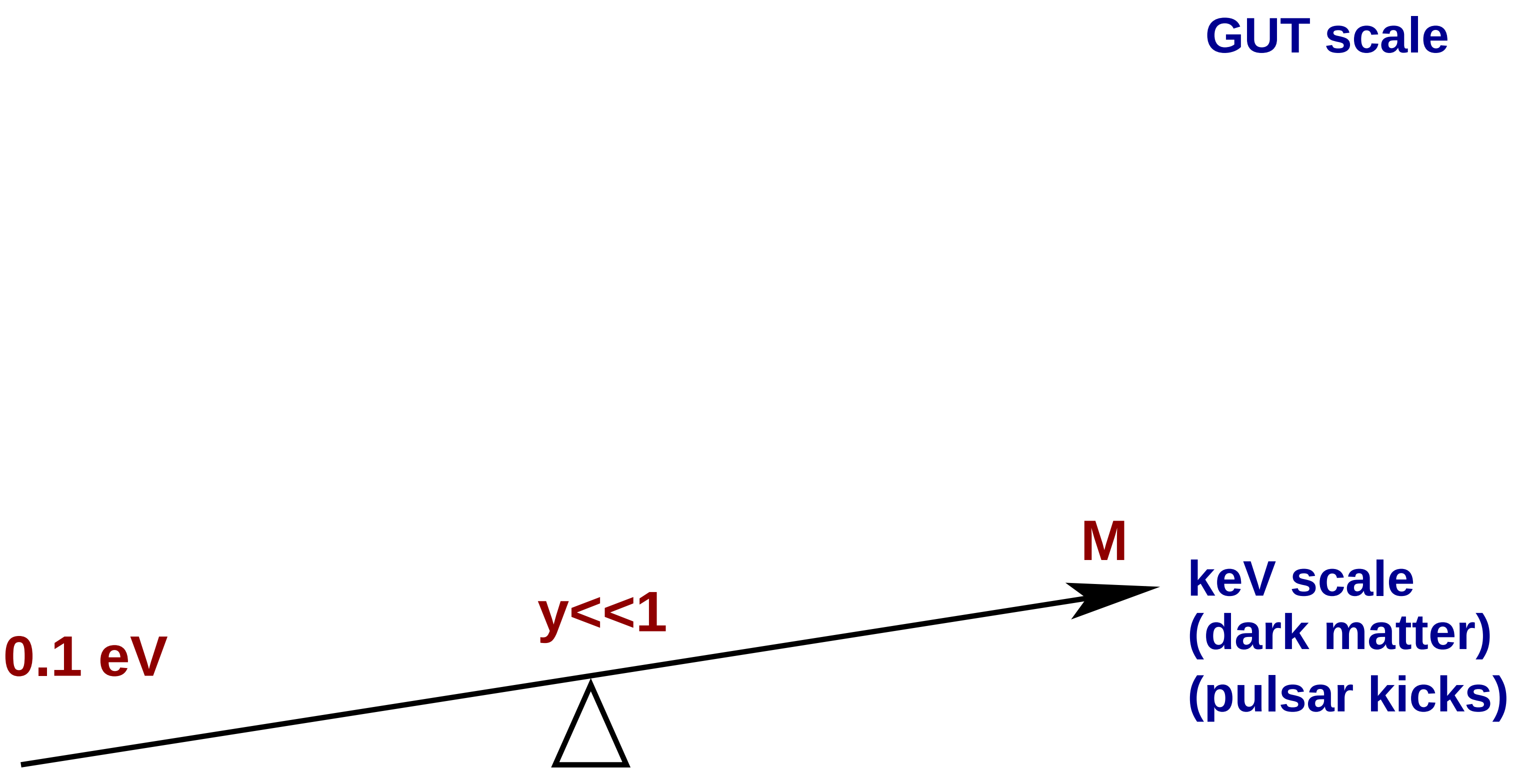
$$m_\nu \sim \frac{y^2 \langle H \rangle^2}{M}$$

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



Various approaches to small Majorana masses

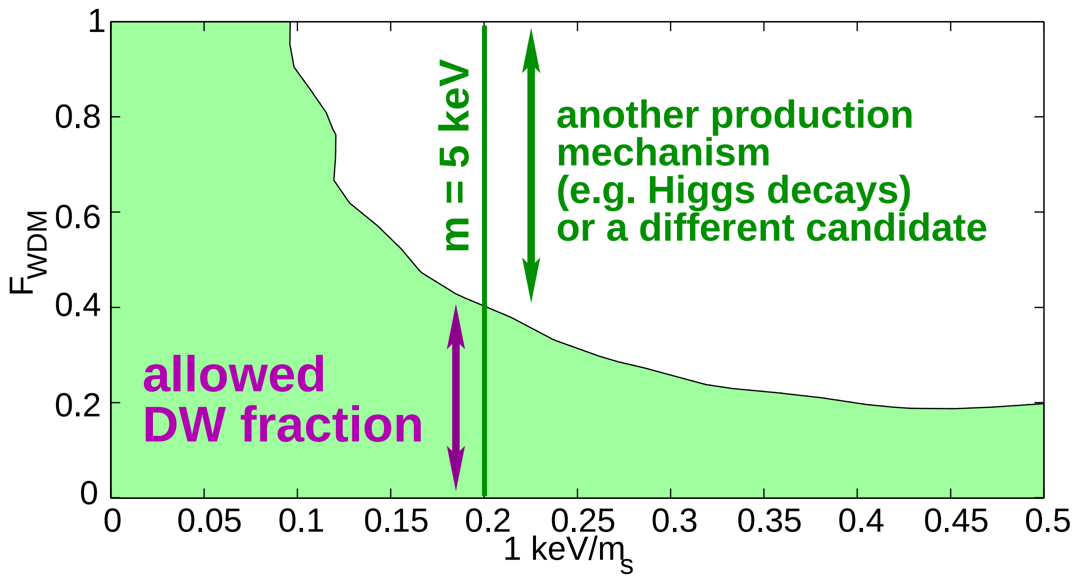
- Just write them down.
  - One sterile keV sterile neutrino, the dark matter candidate **[Dodelson, Widrow]**.
  - Three sterile neutrinos, one with a several keV mass (dark matter) and two degenerate with GeV masses and a keV splitting, νMSM **[Shaposhnikov et al.]**.
- Use **lepton number** conservation as the reason for a small mass **[de Gouvêa]**.
- Use **flavor symmetries**, new gauge symmetries **[Lindner et al.]**
- **Singlet Higgs** (discussed below) at the electroweak scale can generate the Majorana mass. Added bonuses:
  - production from $S \to NN$ at the electroweak scale generates *the right amount* of dark matter.
  - production from $S \to NN$ at the electroweak scale generates *colder* dark matter. A **"miracle"**: EW scale and mass at the keV scale (for stability) $\Rightarrow$ **correct DM abundance**. **[AK; AK, Petraki]**
- **Split seesaw** (discussed below) makes the scale separation natural. Dark matter cooled by various effects. $\Rightarrow$ **democracy of scales**

Sterile neutrinos as dark matter: production scenarios

Production **color coded** by **"warmness"** **vs** **"coldness"**:

- **Neutrino oscillations off resonance** [Dodelson, Widrow] No prerequisites; production determined by the mixing angle alone; no way to turn off this channel, except for low-reheat scenarios [Gelmini et al.]
- **MSW resonance in $\nu_a \to \nu_s$ oscillations** [Shi, Fuller] Pre-requisite: sizable lepton asymmetry of the universe. The latter may be generated by the decay of heavier sterile neutrinos [Laine, Shaposhnikov]
- **Higgs decays** [AK, Petraki] Assumes the Majorana mass is due to Higgs mechanism. **Sterile miracle: abundance a "natural" consequence of singlet at the electroweak scale**. Adantage: "natural" dark matter abundance
- **Split seesaw**: [AK, Takahashi, Yanagida]
  Two production mechanisms, **cold** and **even colder**.
  Adantage: "naturally" low mass scale

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]

Challenges to CDM = hints of WDM

- Cored profiles of dwarf spheroidals [Gilmore, Wyse; Strigari et al.]
- Minimal size of dSphs [Wyse et al.]
- overproduction of the satellite halos for galaxies of the size of Milky Way [Klypin; Moore]
- 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]
- 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.]

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 $T \sim m_S$ from decays $S \rightarrow NN$:

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

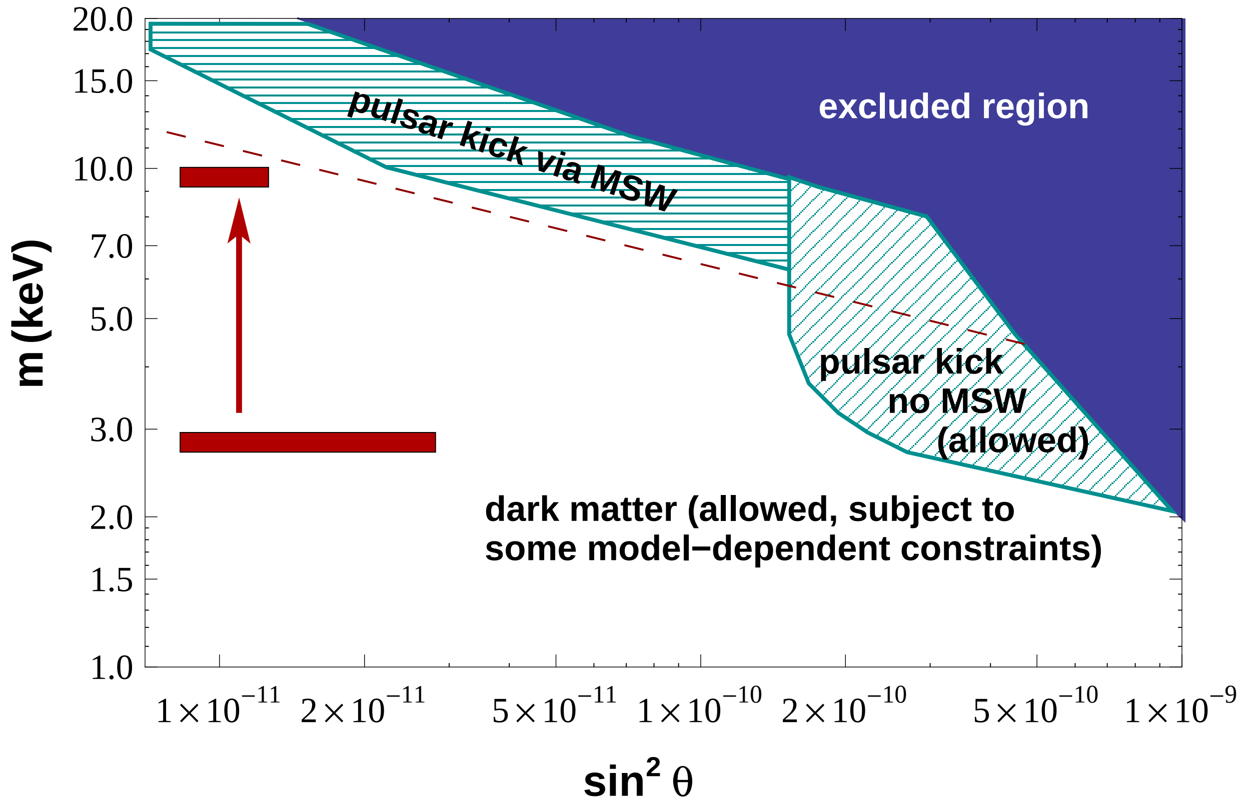
Here ξ is the dilution factor due to the change in effective numbers of degrees of freedom.

$\langle S \rangle \sim 10^2\,\mathrm{GeV}$ (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]

Cooling changes the clustering properties

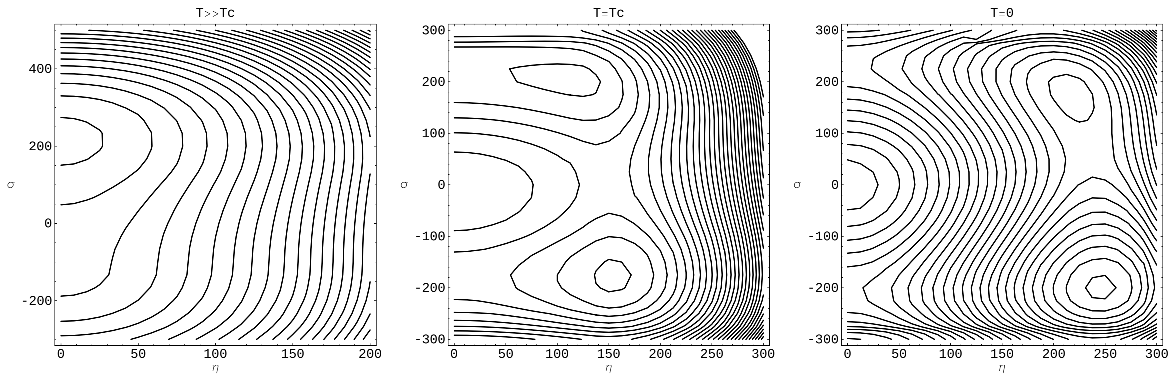


[AK, PRL **97**:241301 (2006); Petraki, AK, PRD 77, 065014 (2008); Petraki, PRD 77, 105004 (2008)]

Implications for the EW phase transition and the LHC

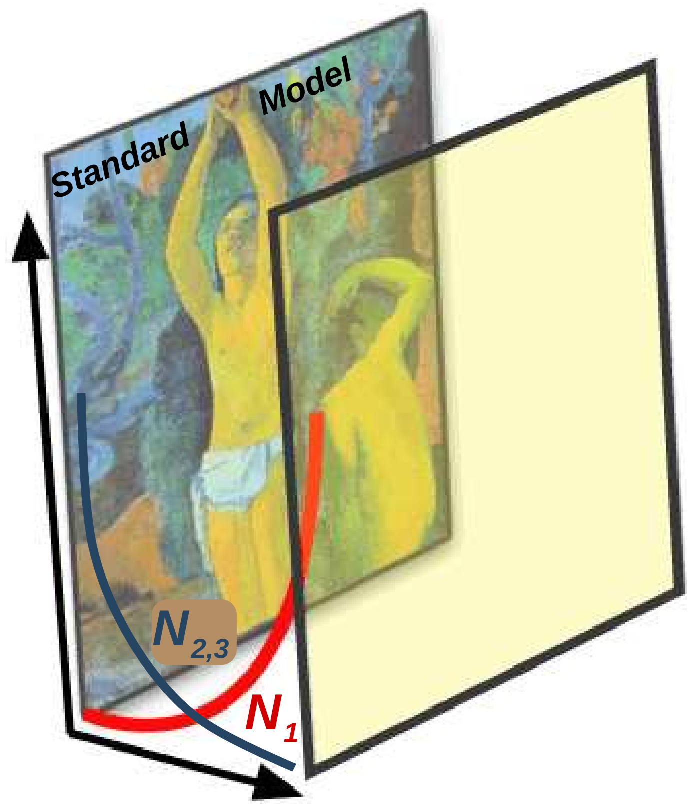
One may be able to discover the *singlet Higgs* at the LHC [Profumo, Ramsey-Musolf, G. Shaughnessy; Davoudiasl et al.; O'Connell et al.; Ramsey-Musolf, Wise]

The presence of S in the Higgs sector changes the nature of the electroweak phase transition [AK, Petraki]

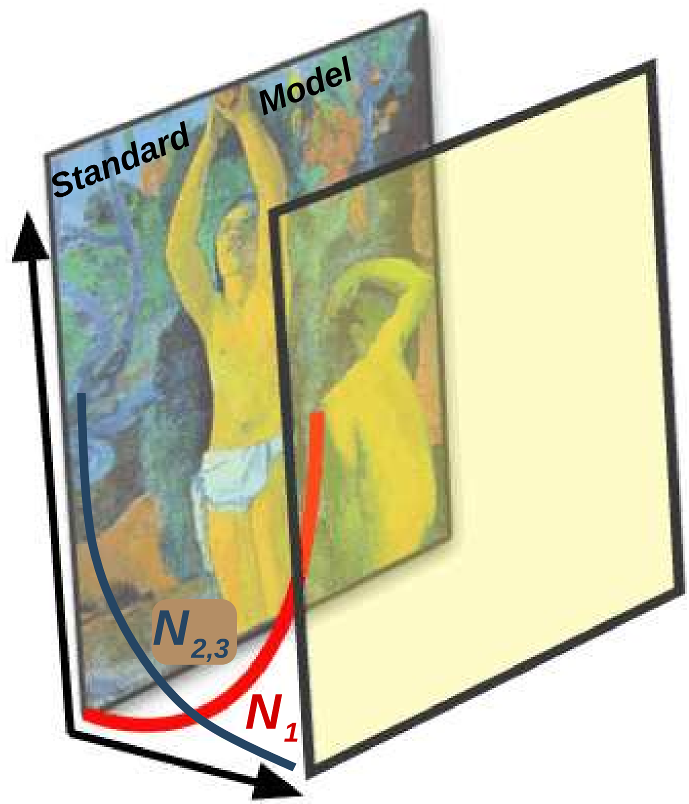


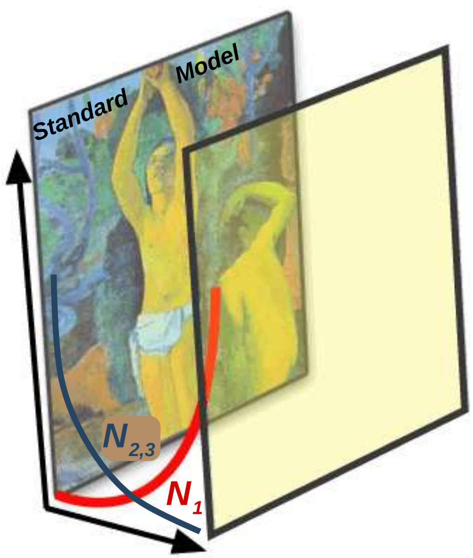
First-order transition, CP in the Higgs sector $\Longrightarrow$ **electroweak baryogenesis**

Split seesaw



Split seesaw





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

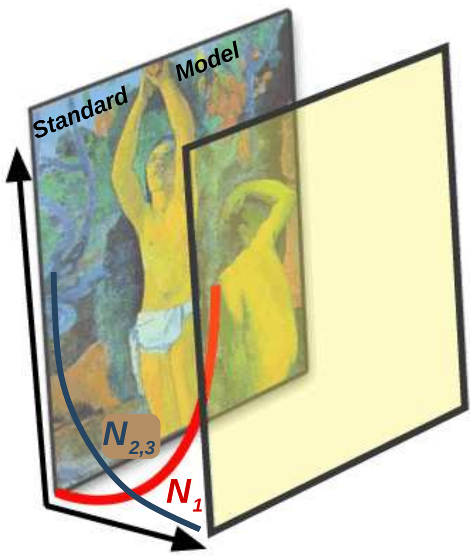
$$S = \int d^4x\, dz\, M \left(i\bar{\Psi}\Gamma^A\partial_A\Psi + m\bar{\Psi}\Psi \right),$$

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 $U(1)_{(B-L)}$ 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:

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

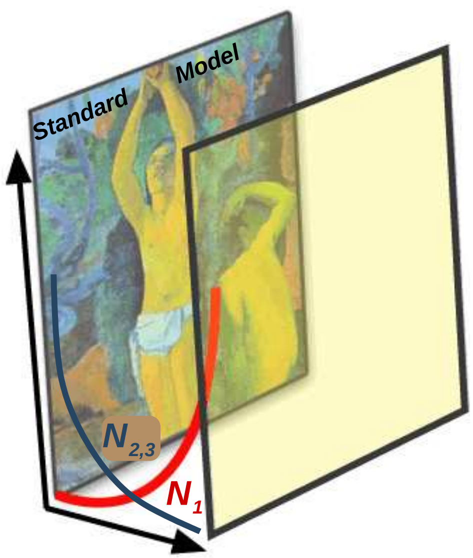
$$y_{d=4} = y_{d=5}\sqrt{\frac{2m_i}{M(e^{2m_i\ell}-1)}}$$

successful seesaw relation unchanged:

$$\boldsymbol{m_\nu \sim \frac{y^2_{d=4}\langle H\rangle^2}{M^{(R)}_{d=4}} = \frac{y^2_{d=5}\langle H\rangle^2}{M^{(R)}_{d=5}}}$$

[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]

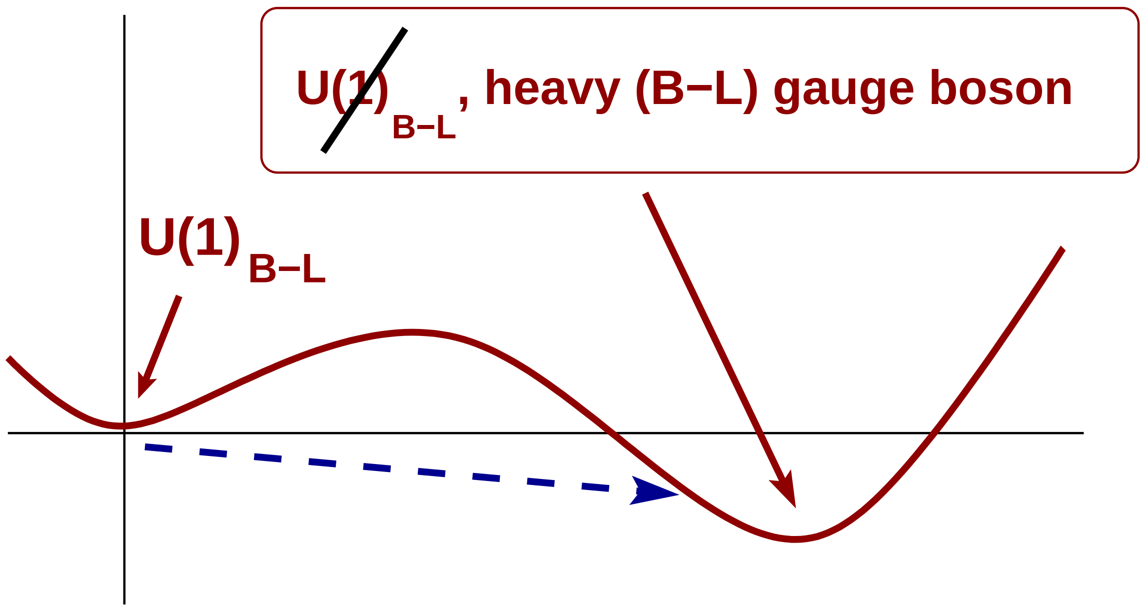
Dark matter production in Split Seesaw: two scenarios

The U$(1)_{(B-L)}$ gauge boson couples to right-handed neutrinos. It becomes massive due to the Higgs VEV $\langle\phi\rangle \sim 10^{15}$GeV.

1. Reheat temperature $T_R \sim 5 \times 10^{13}\,\mathrm{GeV} \ll \times \langle\phi\rangle$, and sterile/righthanded neutrinos are out of equilibrium. Thermal abundance is never reached; correct DM abundance is controlled by T_R.
2. Reheat temperature $T_R > \langle\phi\rangle$, and sterile/right-handed neutrinos are in equilibrium before the first-order U$(1)_{(B-L)}$ phase transition. After the transition, the temperature is below the $(B-L)$ gauge boson mass, and right-handed neutrinos are out of equilibrium. The entropy released in the first-order phase transition dilutes DM density and red-shifts the particle momenta.

The free-streaming length is further reduced by the entropy production from SM degrees of freedom. Both (1) and (2) produce acceptable DM abundace. DM from (2) is colder than from (1) by a factor ≈ 5, and colder than DW dark matter by factor ≈ 15.

Dark matter production in Split Seesaw: second scenario

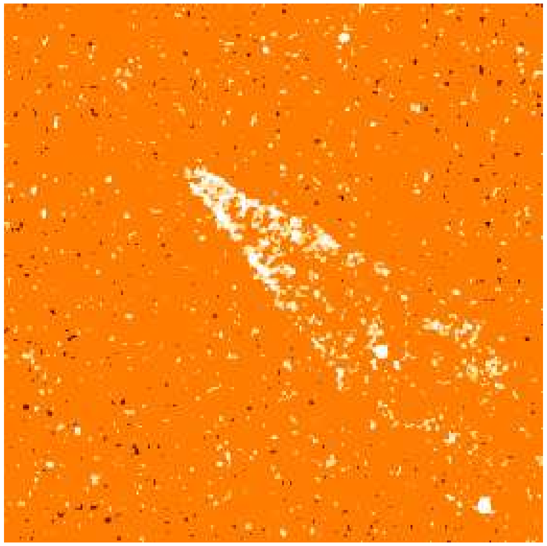


The pulsar velocities.

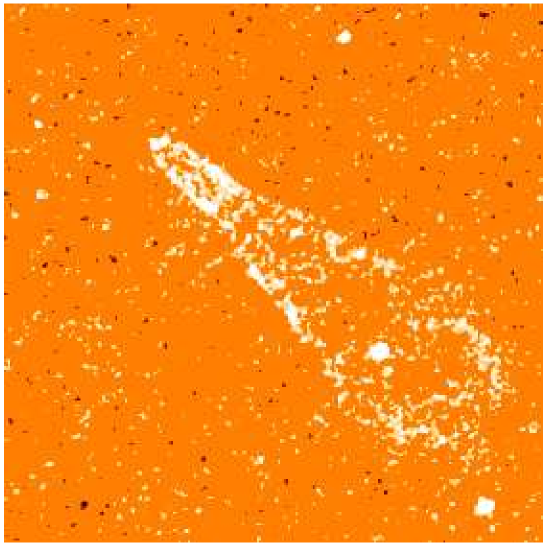
Pulsars have large velocities, $\langle v \rangle \approx 250 - 450\ \mathrm{km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

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

A very fast pulsar in Guitar Nebula

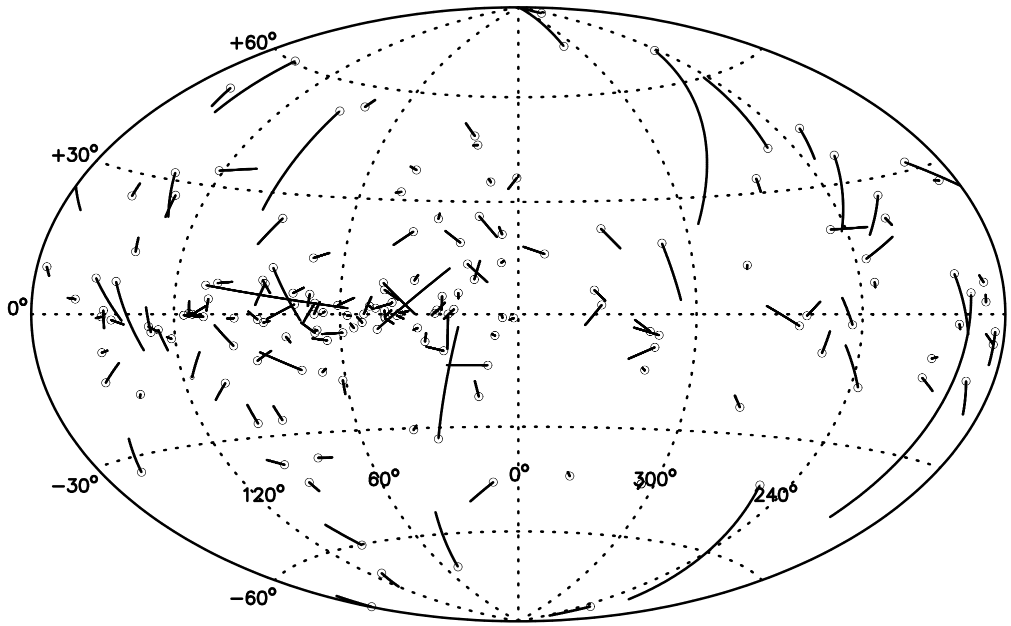


HST, December 1994



HST, December 2001

Map of pulsar velocities



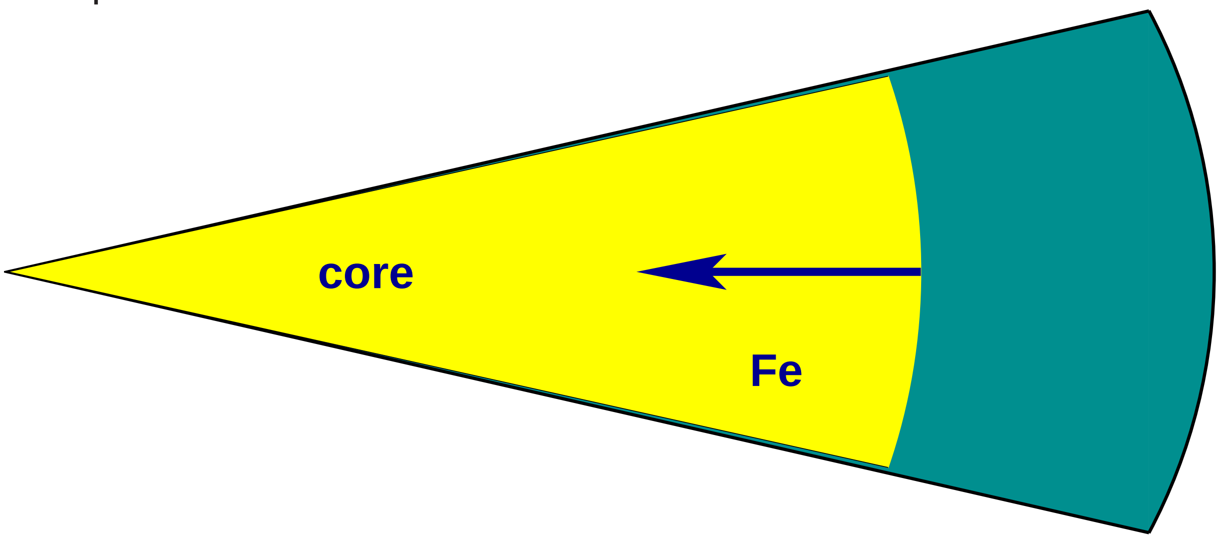
Proposed explanations:

- 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?)

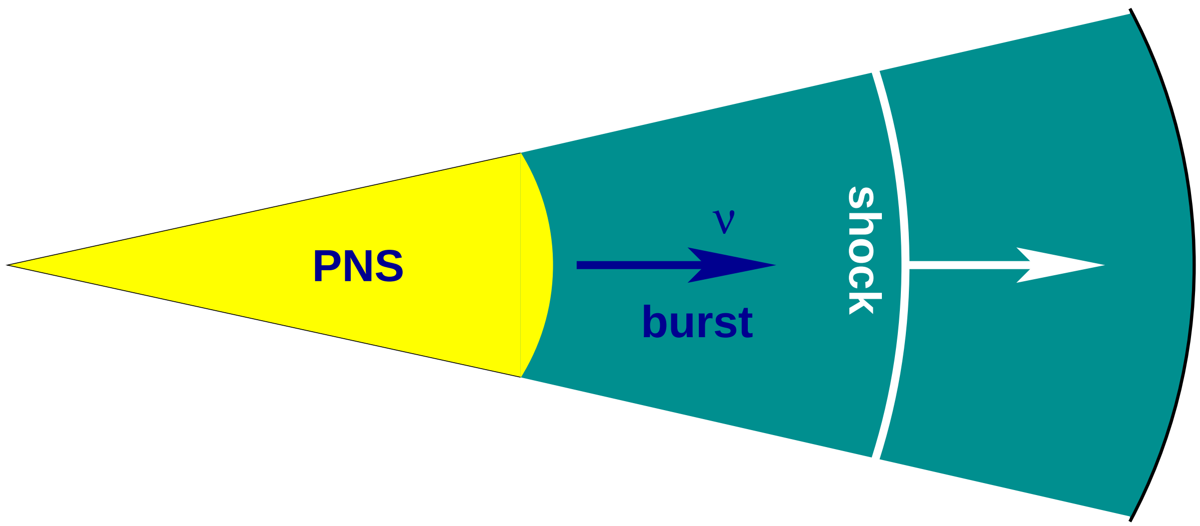
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

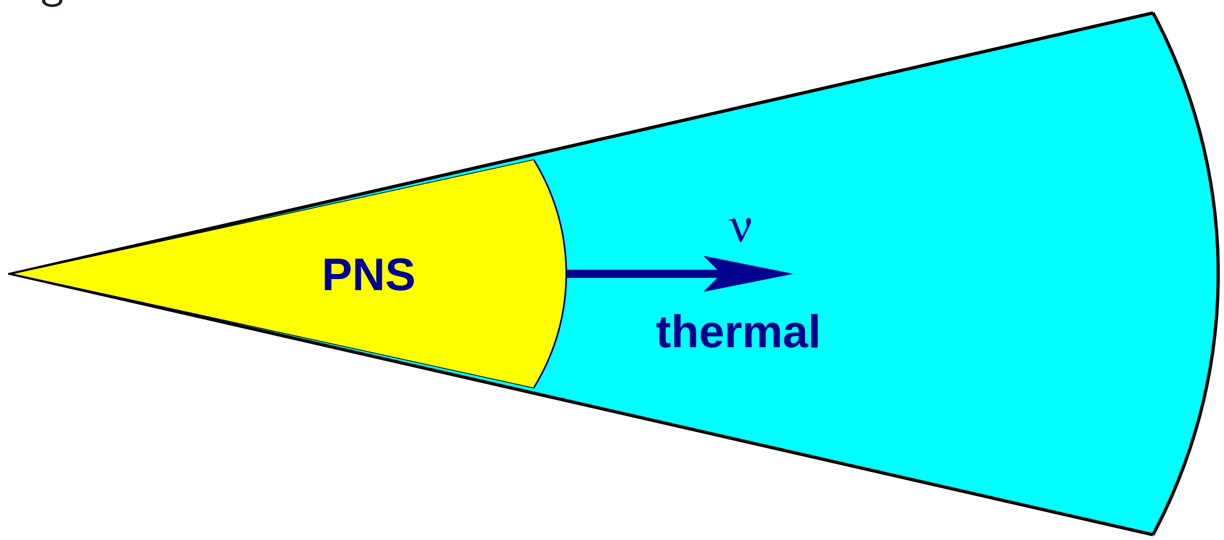
Shock formation and "neutronization burst": $t = 1 - 10$ ms



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

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

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

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

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.

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.

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

The asymmetry:

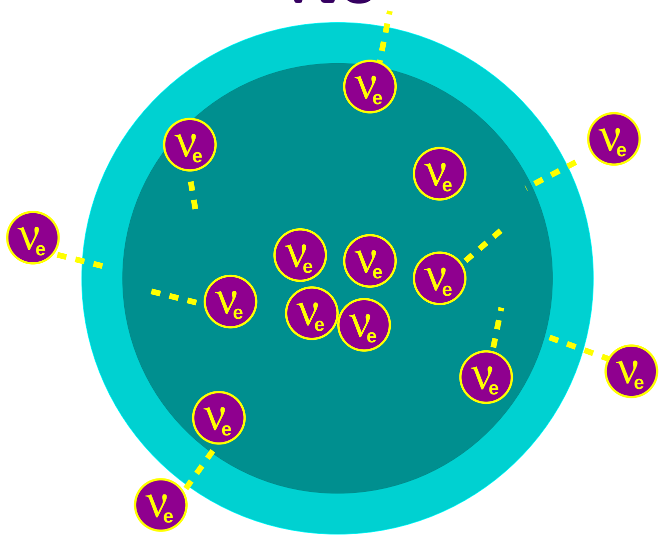
$$\tilde{\epsilon} = \frac{g_V^2 - g_A^2}{g_V^2 + 3g_A^2} k_0 \approx 0.4\, k_0,$$

where k_0 is the fraction of electrons in the lowest Landau level.
$k_0 \sim 0.3$ 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?

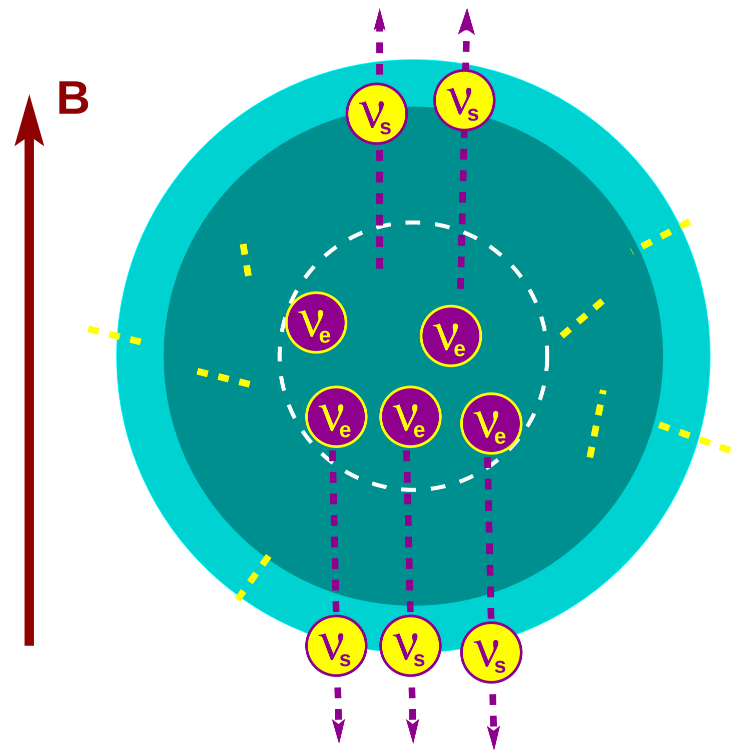
No

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].

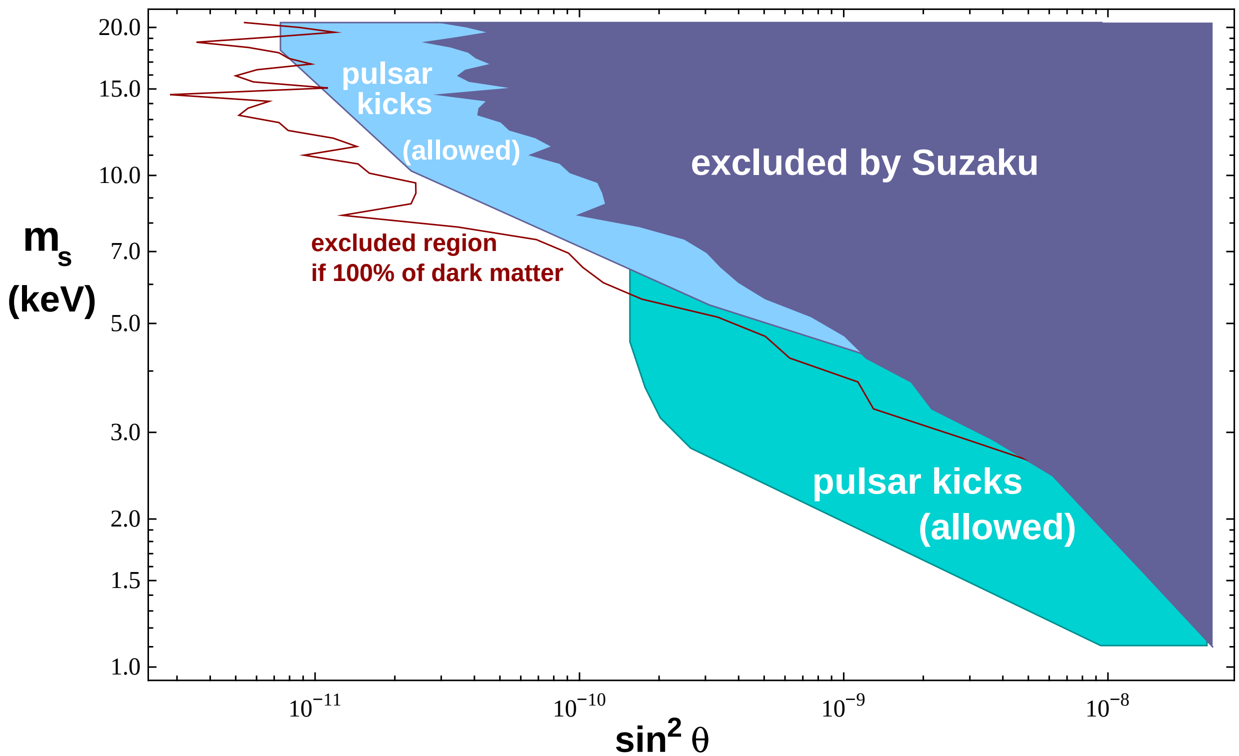
However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

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



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

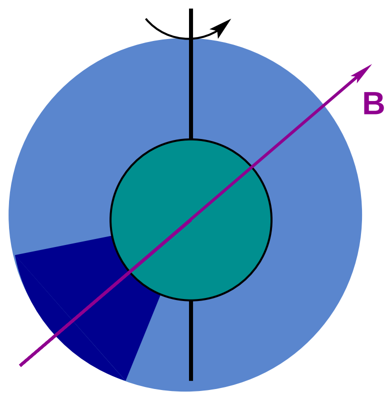
Pulsar kicks



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

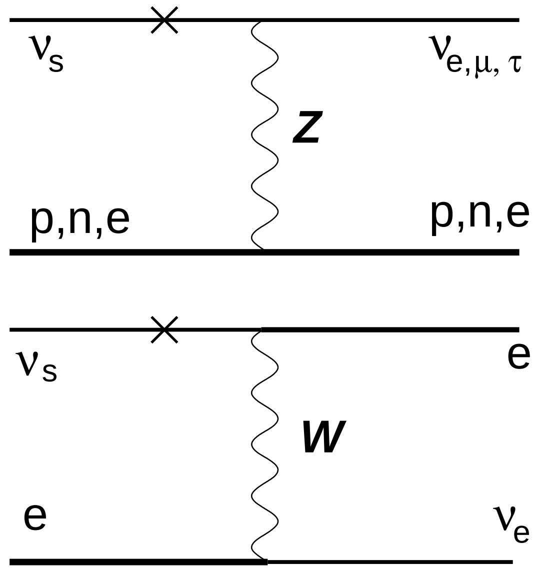
Other predictions

- 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]



What's taking us so long?

Dark matter, **pulsar kicks** from a **several-keV sterile neutrino**: **proposed in 1990s!**
Why have not experiments confirmed or ruled out such particles?
All observable quantities are suppressed by $\sin^2\theta \sim 10^{-9}$.
Direct detection? $\nu_s e \to \nu_e e$. Monochromatic electrons with $E = m_s$. **[Ando, AK]**

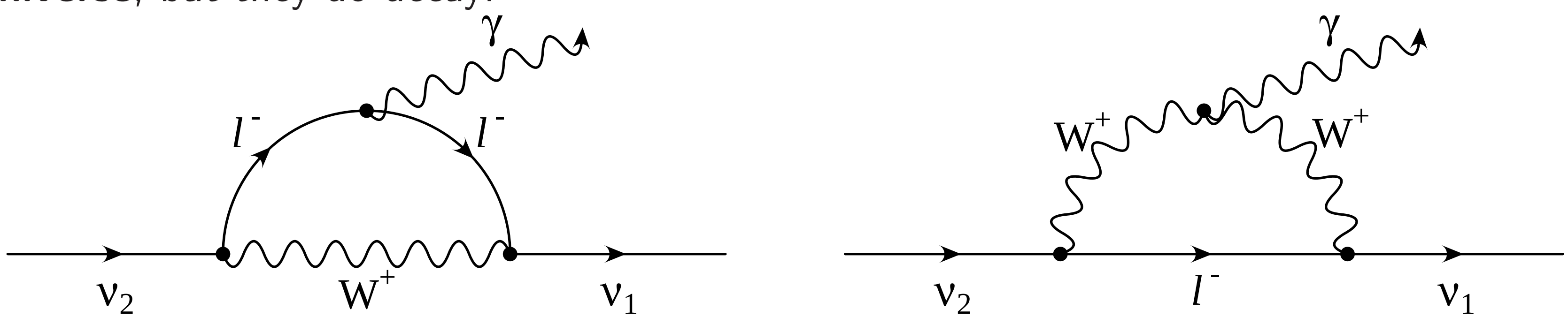


Rates low:

$$R = 4.0 \times 10^{-4}\ \mathrm{yr}^{-1} \left(\frac{m_{\nu_s}}{5\ \mathrm{keV}}\right)\left(\frac{\sin^2\theta}{10^{-9}}\right) \times \left(\frac{M_{\mathrm{det}}}{1\ \mathrm{ton}}\right)\left(\frac{Z}{25}\right)^2\left(\frac{A}{50}\right)^{-1}.$$

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. Concentrations of dark matter emit X-rays. **[Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]**

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.	$1''$	$6''$	$90''$
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	$\sim 10^{-3}$ **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!**

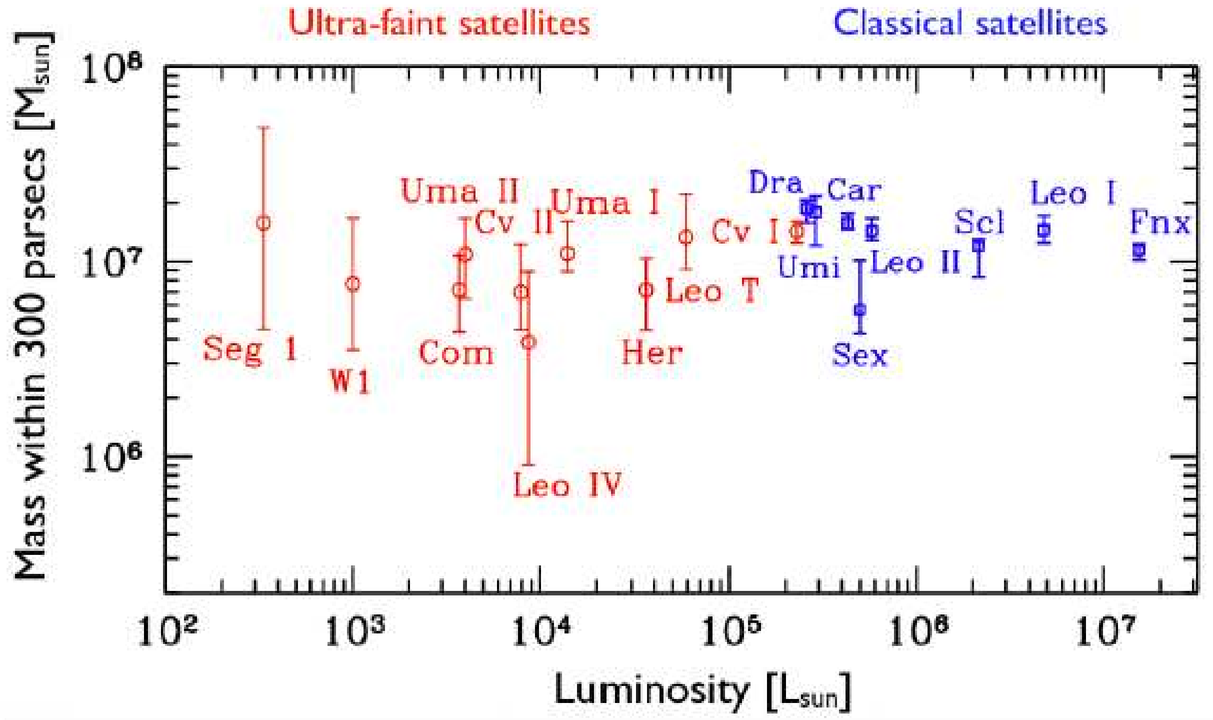
[Loewenstein]

Target selection

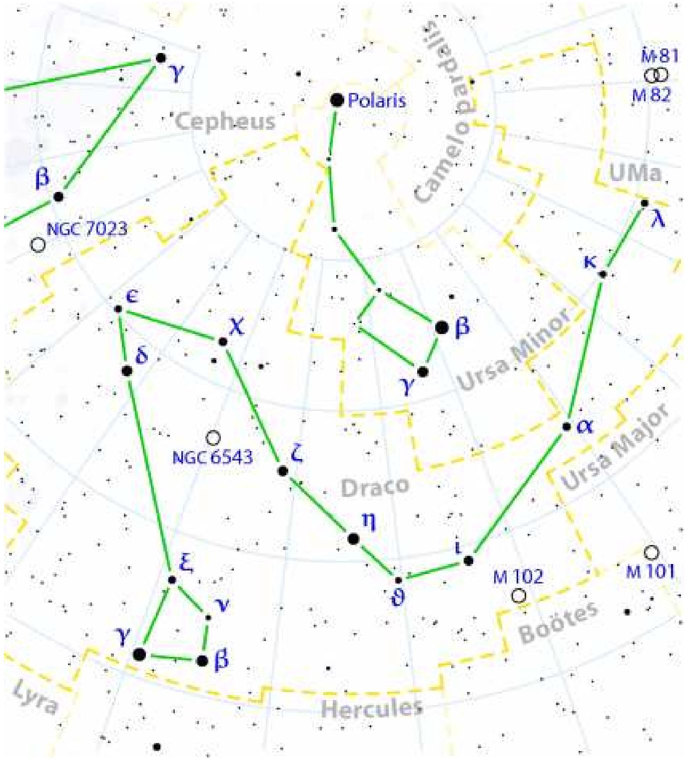
target	dark matter content	background	signal/noise	overall
MW center	high/uncertain	very high	low	far from ideal
MW, "blank sky"	low	low	low	not ideal
nearby galaxy (M31)	high/uncertain	high	low	not ideal
clusters	high	very high	low	not ideal
dSph	high/uncertain	low	high	**best choice**

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

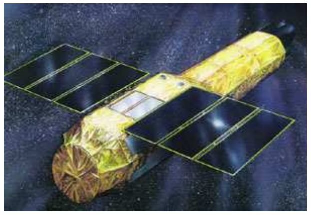


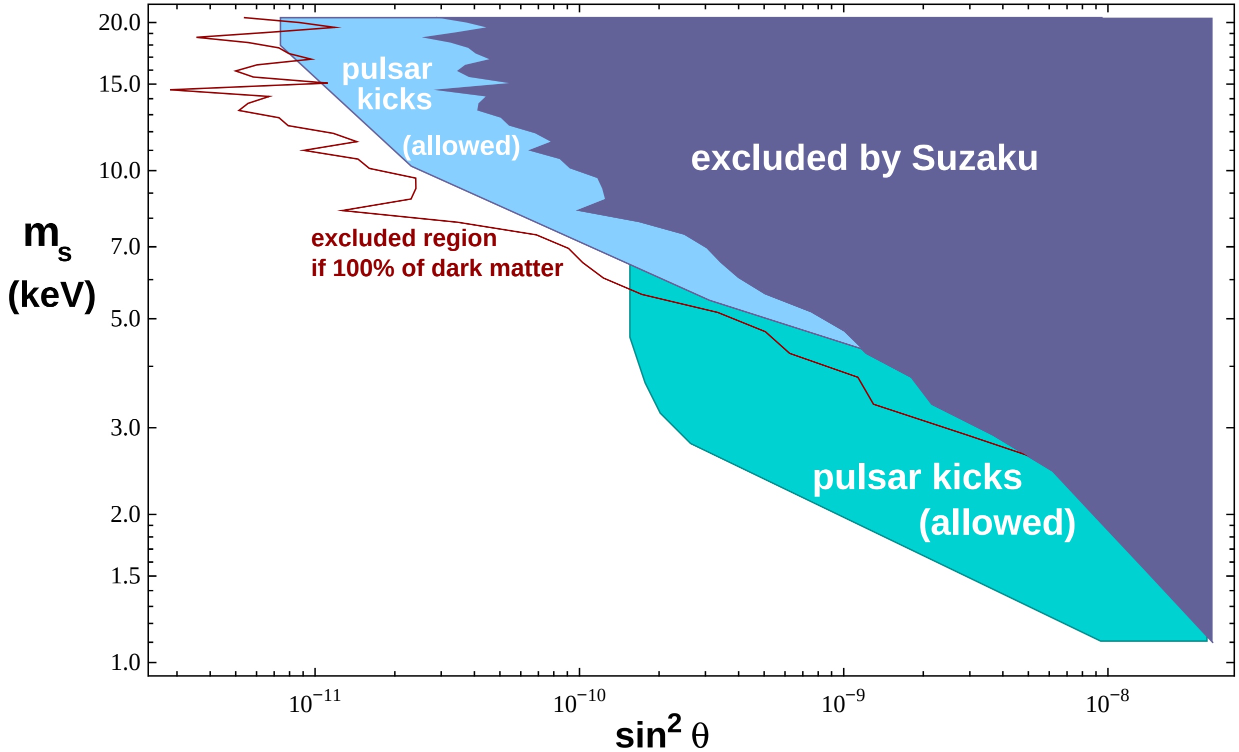
Suzaku observations of dSphs Draco and Ursa Minor



[Loewenstein, A.K., Biermann, ApJ 700, 426 (2009)]

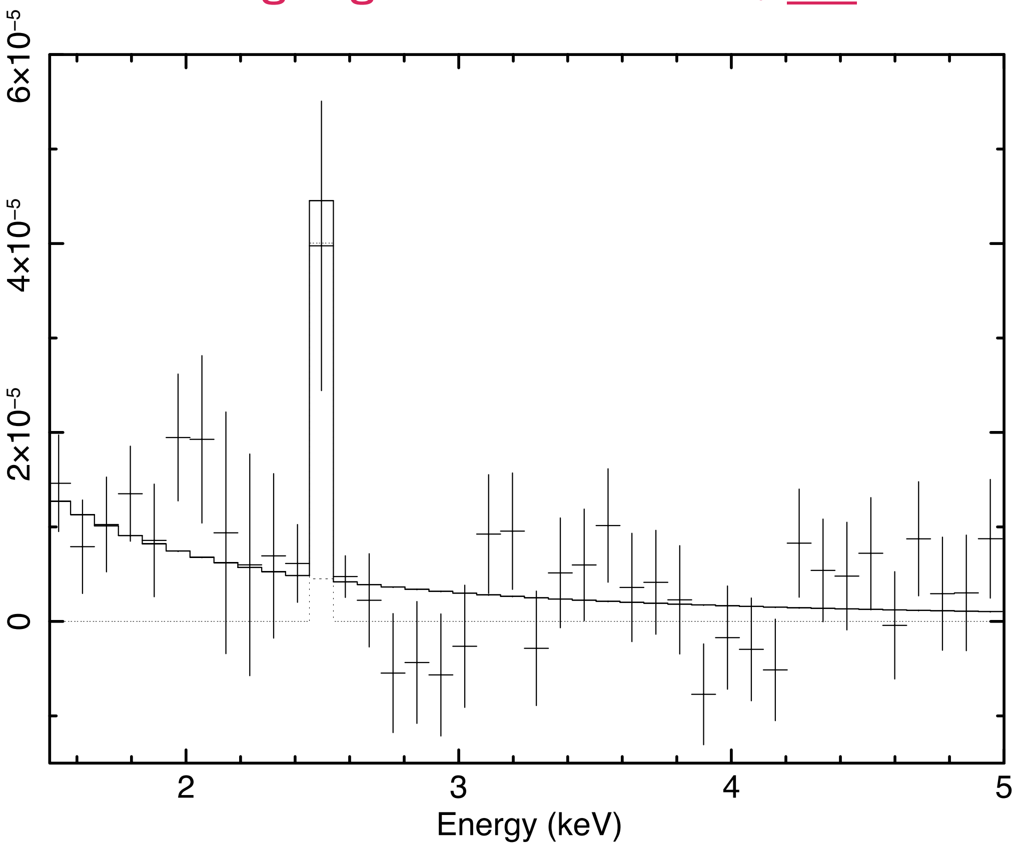
X-ray limits from *Suzaku*

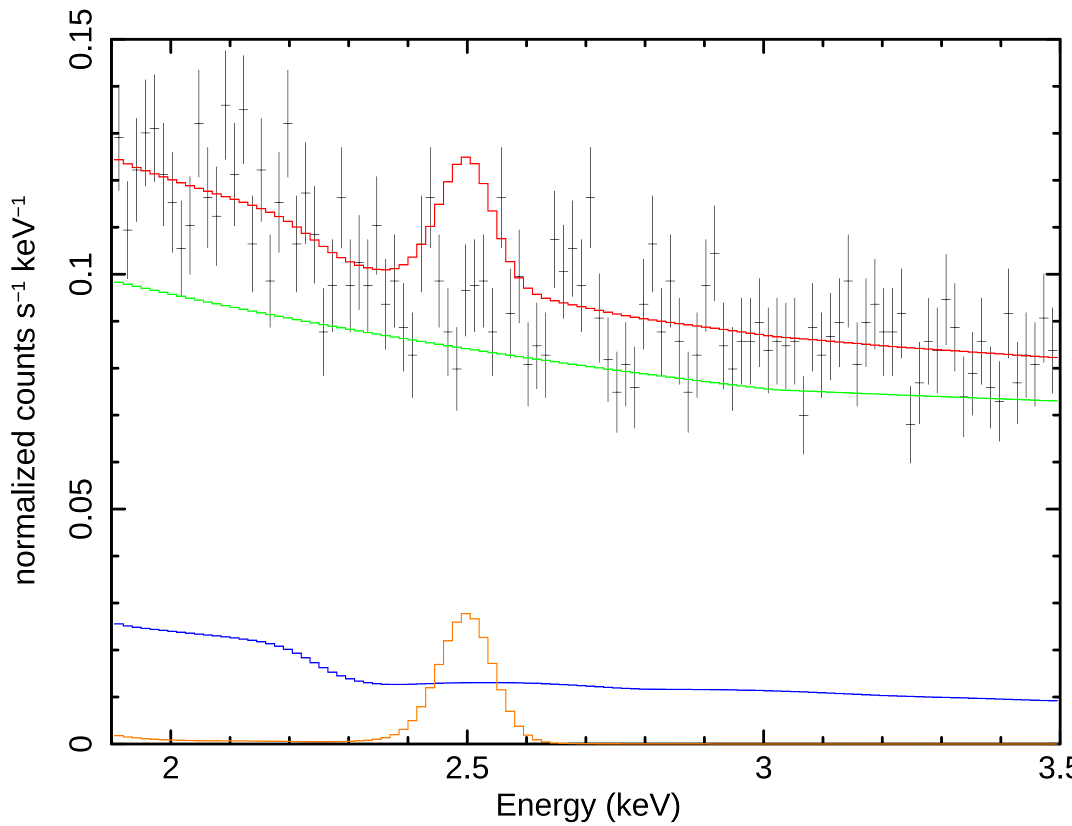




[Loewenstein, A.K., Biermann, ApJ 700, 426 (2009)]

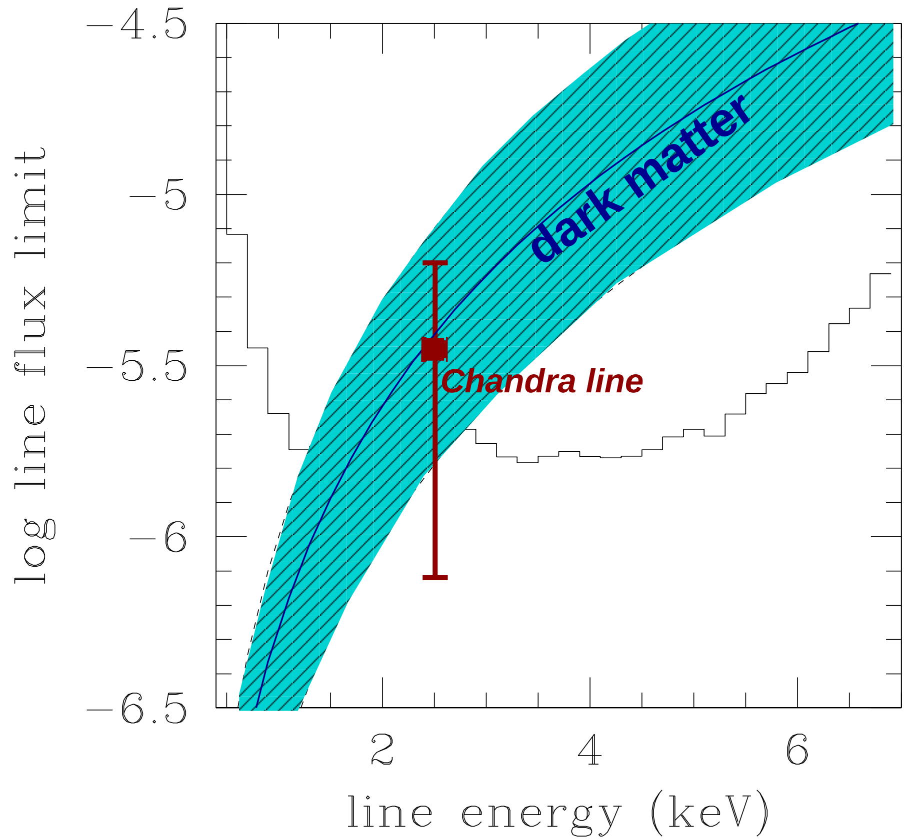
Intriguing *Chandra* feature, not confirmed by *XMM-Newton* (Willman-1)





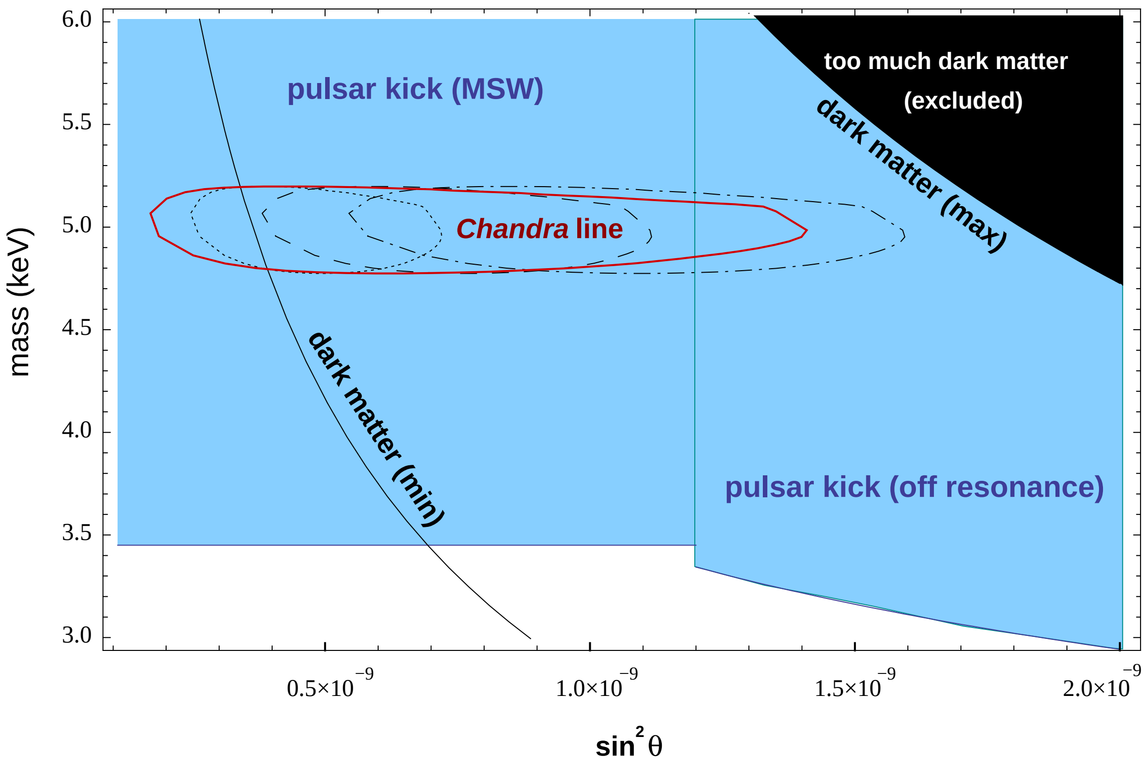
[Loewenstein and A.K., ApJ 714, 652 (2010)]

Spectral feature from *Chandra*



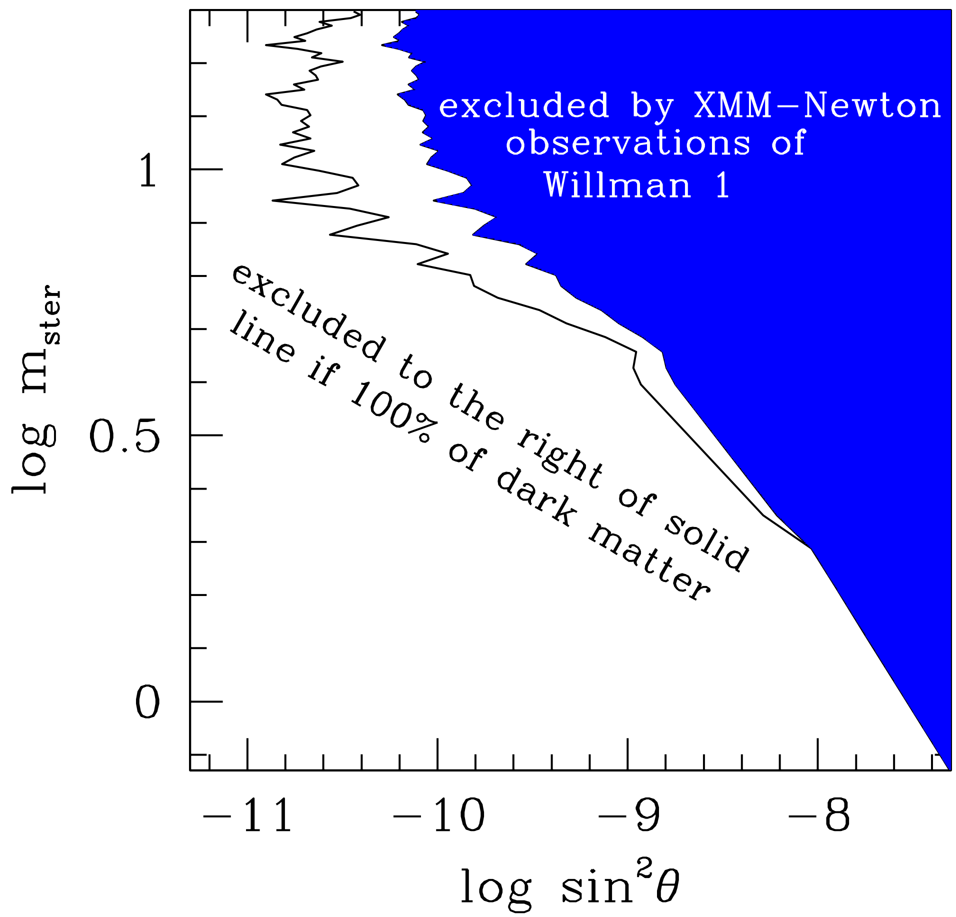
[Loewenstein and A.K., ApJ 714, 652 (2010)]

Parameters inferred from *Chandra* data



Unfortunately, not confirmed by XMM!

Latest limits from XMM-Newton (Willman - 1)



[Loewenstein and A.K., ApJ. 751 (2012) 82]

Dark matter decays during the dark ages

- X-rays can contribute to reionization directly [Ferrara, Mapelli, Pierpaoli]
- X-rays can speed up H_2 formation by ionizing gas.
  [Biermann, AK; Stasielak, Biermann, AK; Ferrara, Mapelli]
- 21-cm observations may detect it [Furlanetto, Oh, Pierpaoli]
- exciting work in progress [Yoshida, Valdes]

Molecular hydrogen

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

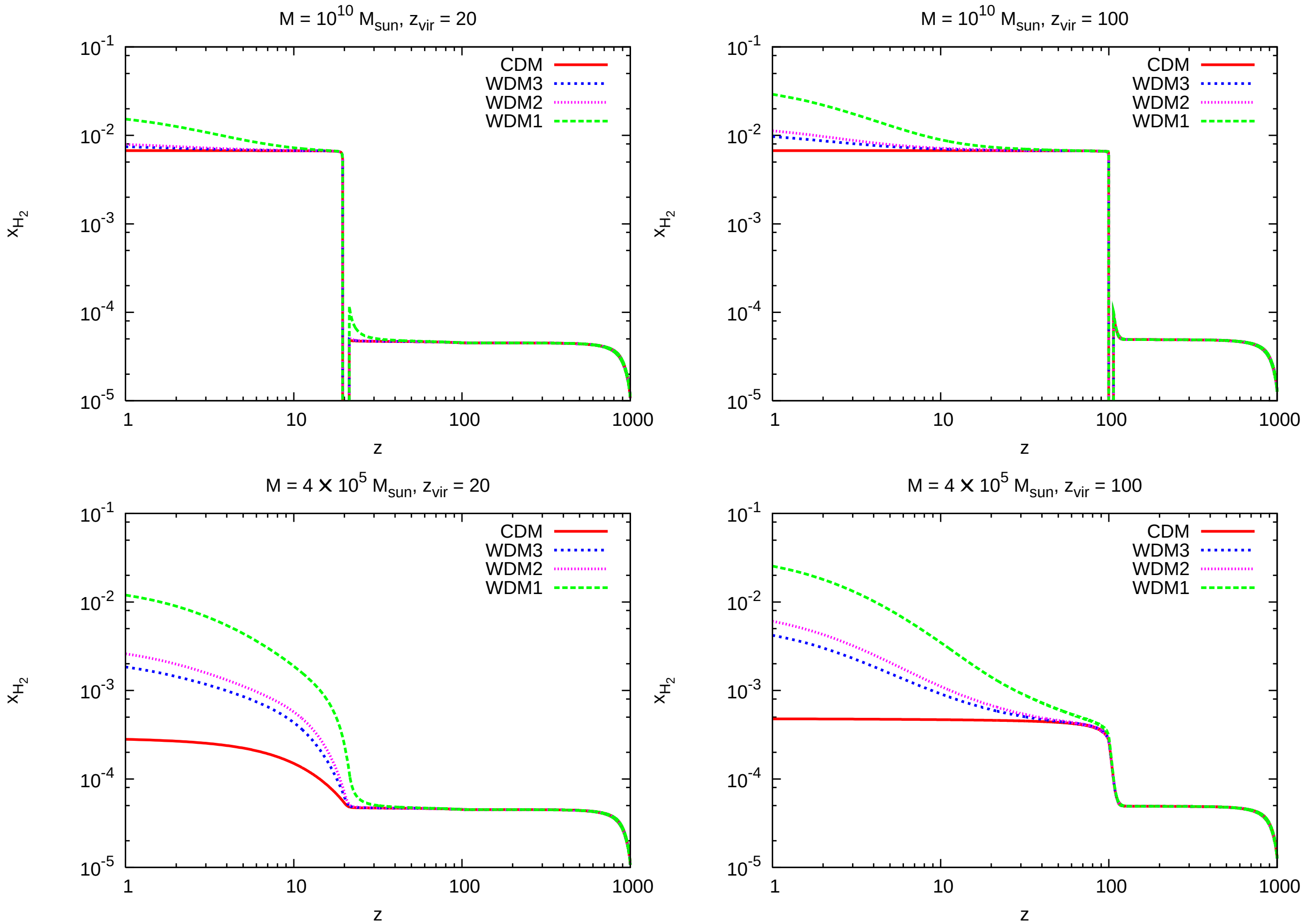
In the presence of ions the following reactions are faster:

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

H^+ produced by X-rays from $\nu_2 \to \nu_1\gamma$ catalyze the formation of molecular hydrogen

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

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



[Biermann, AK; Stasielak, Biermann, AK]

Summary

- **sterile neutrino** is a viable **dark matter** candidate
- Models, theoretical progress: thanks to **Lindner, Shaposhnikov, Yanagida,** etc.
- corroborating evidence from supernova physics: **pulsar kicks**
- X-ray photons produced in the early universe can catalyze formation of 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