Sterile neutrinos: the dark side of the light fermions

- Sterile neutrino: a well-motivated dark matter candidate
  - observed neutrino masses imply the existence of right-handed singlets, which can naturally be light in *split seesaw*
  - 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
- X-ray line from dark matter decay
- Search with X-ray telescopes
- Enhanced H_2 and the star formation

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 ⇒ axion [Weinberg,Wilczek]
    Supersymmetry ⇒ LSP, gravitino, Q-balls.
  - **Neutrino masses** ⇒ at least two right-handed neutrinos are introduced in seesaw Lagrangian. If one of the Majorana masses is ∼ several keV, the corresponding sterile neutrino is a viable dark matter candidate. [Dodelson, Widrow]

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

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

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:

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

What is the *natural* scale of M?

Seesaw mechanism

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

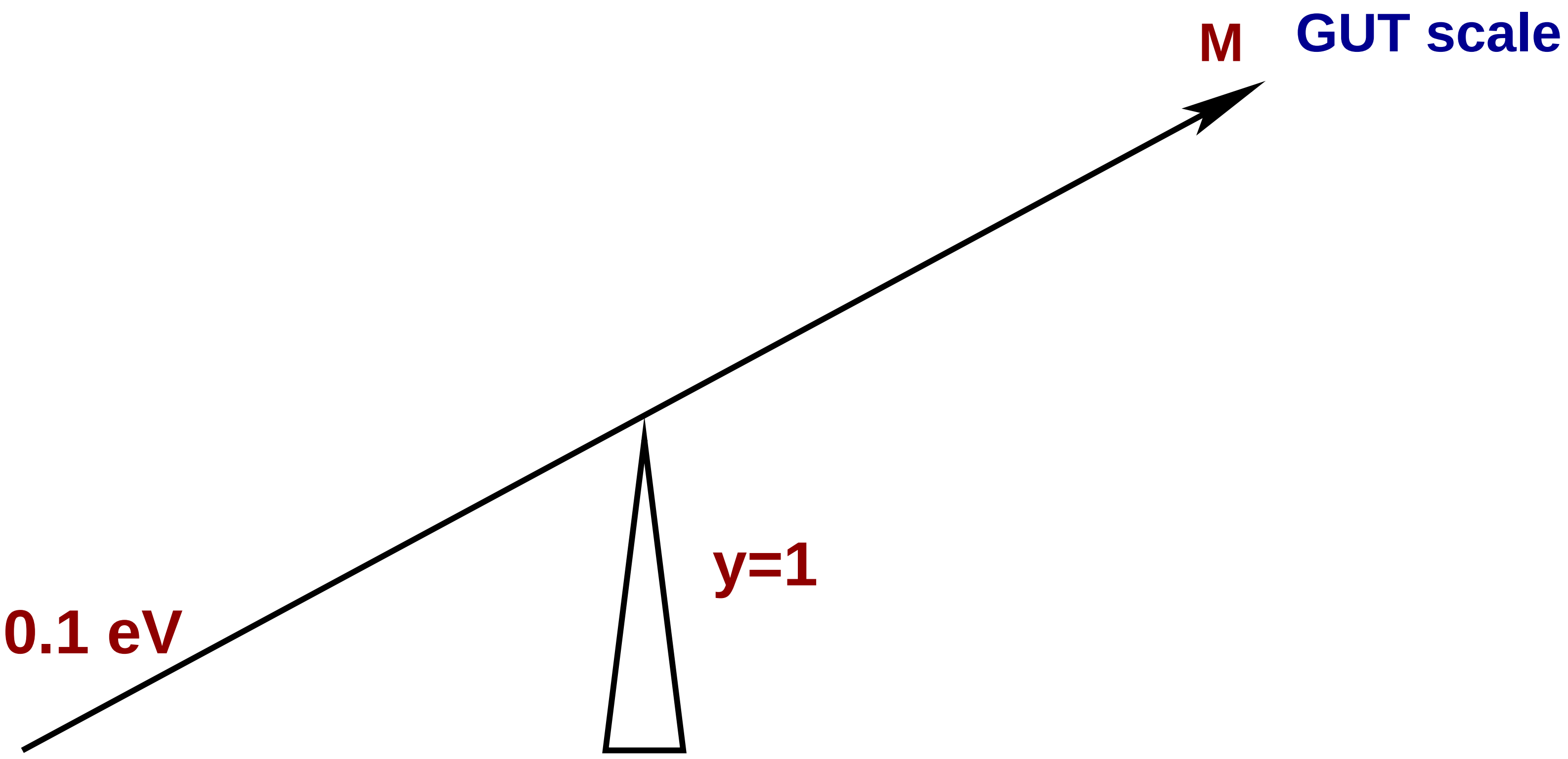
$$D_{ij} = y_{ij} \langle H \rangle$$

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

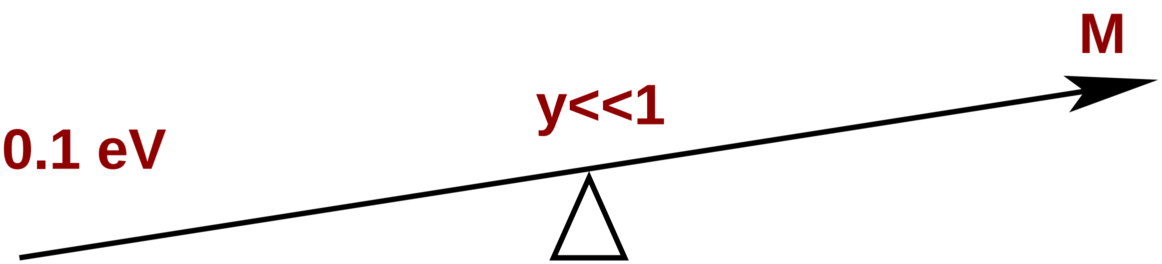
$$m_\nu \sim \frac{y^2 \langle H \rangle^2}{M}$$

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].

Seesaw mechanism



Seesaw mechanism



GUT scale

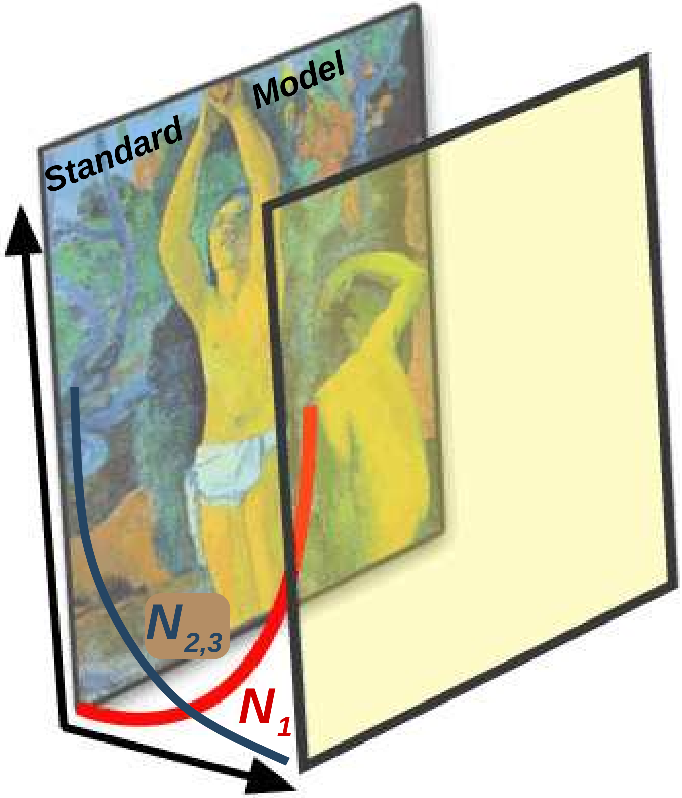
keV scale
(dark matter)
(pulsar kicks)

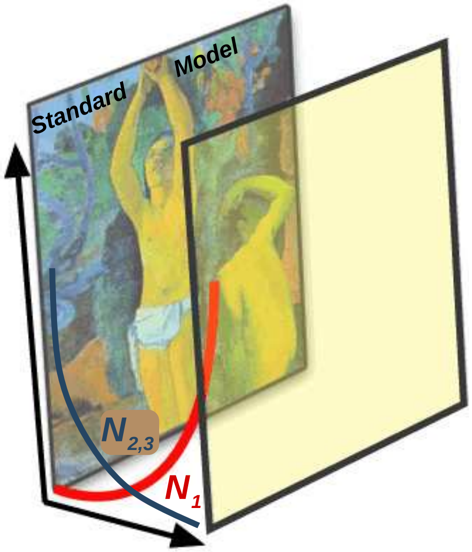
Various approaches to small Majorana masses

- Just write them down. One sterile neutrino with a several keV mass, 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]. According to 't Hooft's criterion, a small number is *natural* if setting it to zero increases the symmetry. Setting $M/M_{\rm Planck}$ to zero increases the lepton number symmetry.
- Use singlet Higgs S at the electroweak scale to 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.

    This prodction is associated with a **"miracle"**: if one requires the singlet at the EW scale (where the doublet is), and mass at the keV scale (for stability), then the caclulated **abundance comes out to be just right**. [AK; AK, Petraki]

Split seesaw





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

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

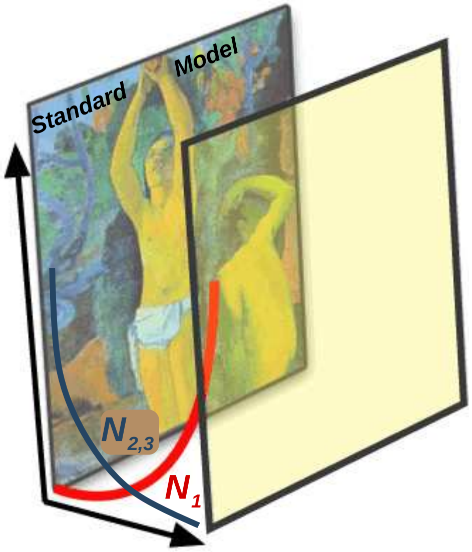
The zero mode: $(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0$. behaves as $\sim \exp(\pm mz)$. The 4D fermion:

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

Also, a 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:

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

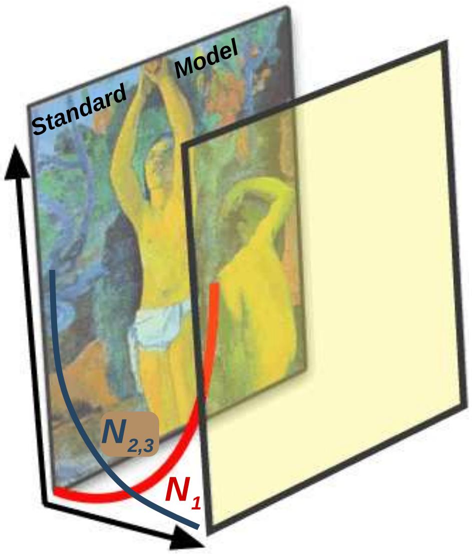
$$y_{d=4} = y_{d=5}\sqrt{\frac{2m_i}{M(e^{2m_i\ell}-1)}}$$

successful seesaw relation unchanged:

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

[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
  $M_{2,3} \sim 10^{15}\mathrm{GeV}$

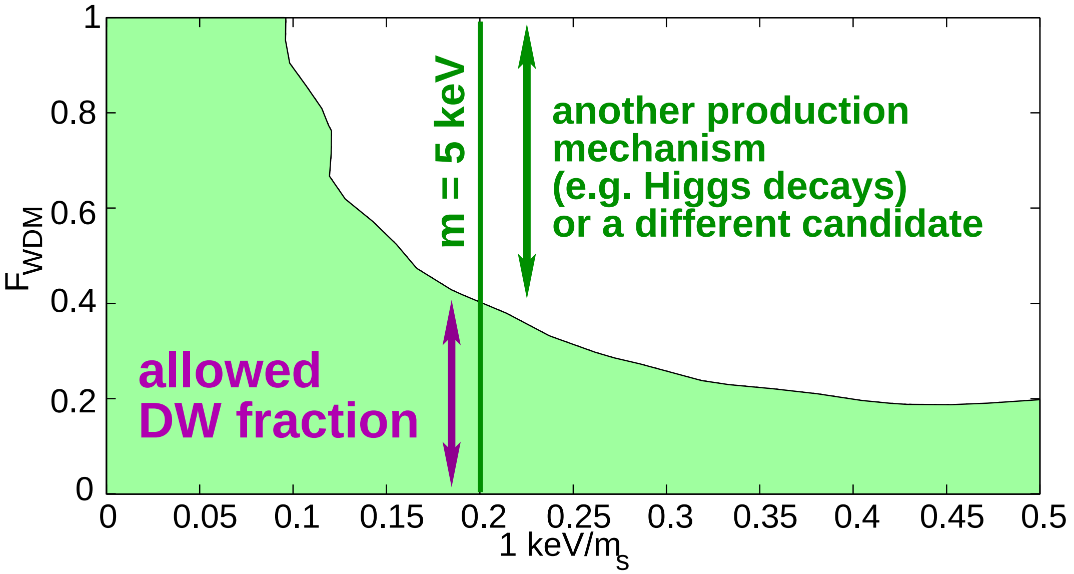
[AK, Takahashi, Yanagida]

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.]
- **Resonant neutrino 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**
- **Split seesaw**: [AK, Takahashi, Yanagida]
  Two production mechanisms, **cold** and **even colder**.

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]

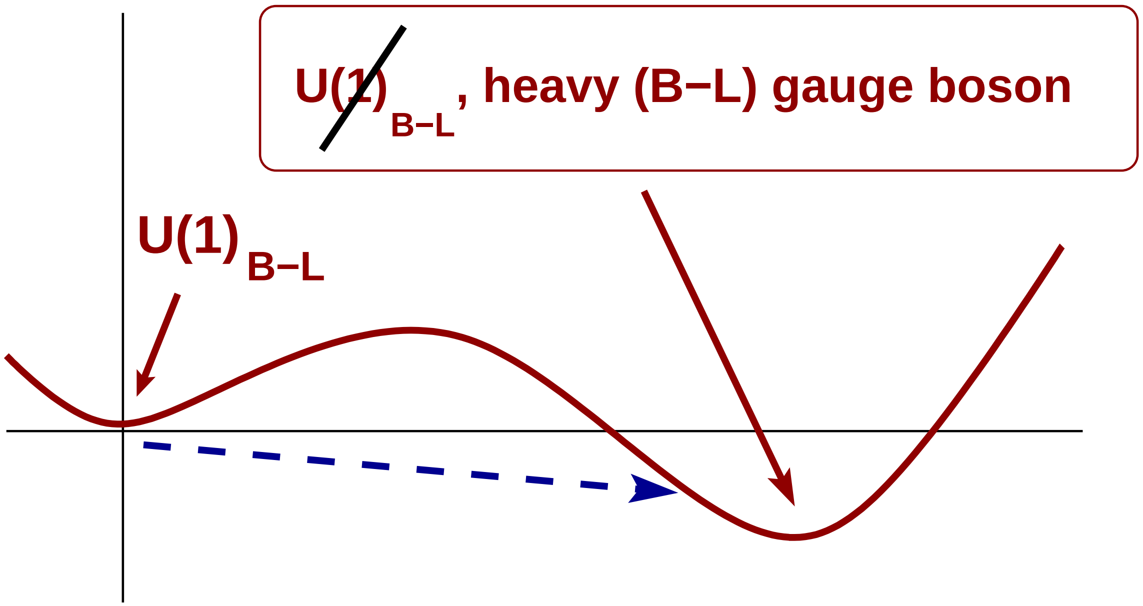
Dark matter production in Split Seesaw: two scenarios

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



$U\cancel{(1)}_{B-L}$, heavy (B−L) gauge boson

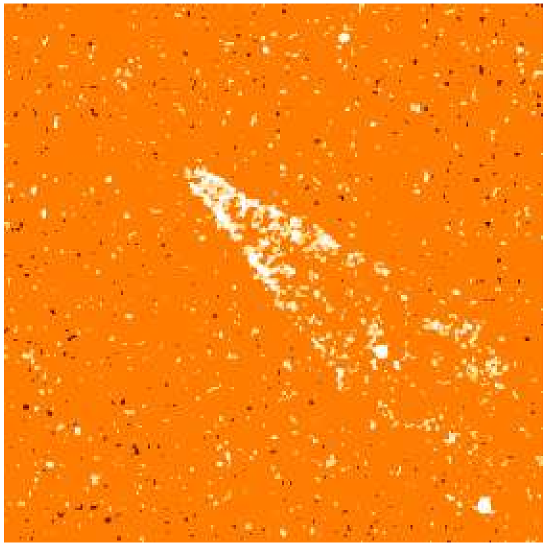
$U(1)_{B-L}$

The pulsar velocities.

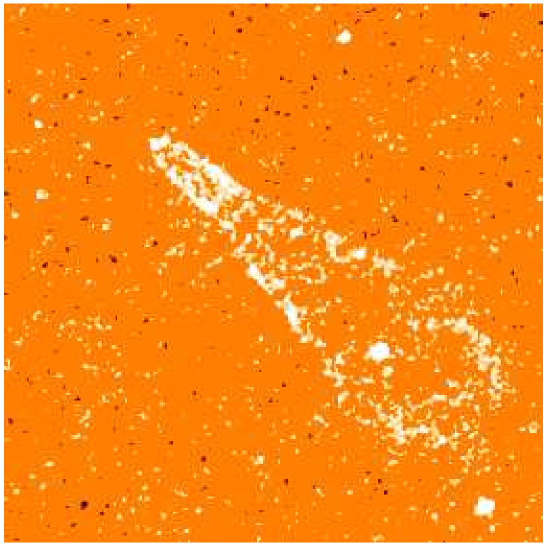
Pulsars have large velocities, $\langle v \rangle \approx 250 - 450$ km/s.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

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

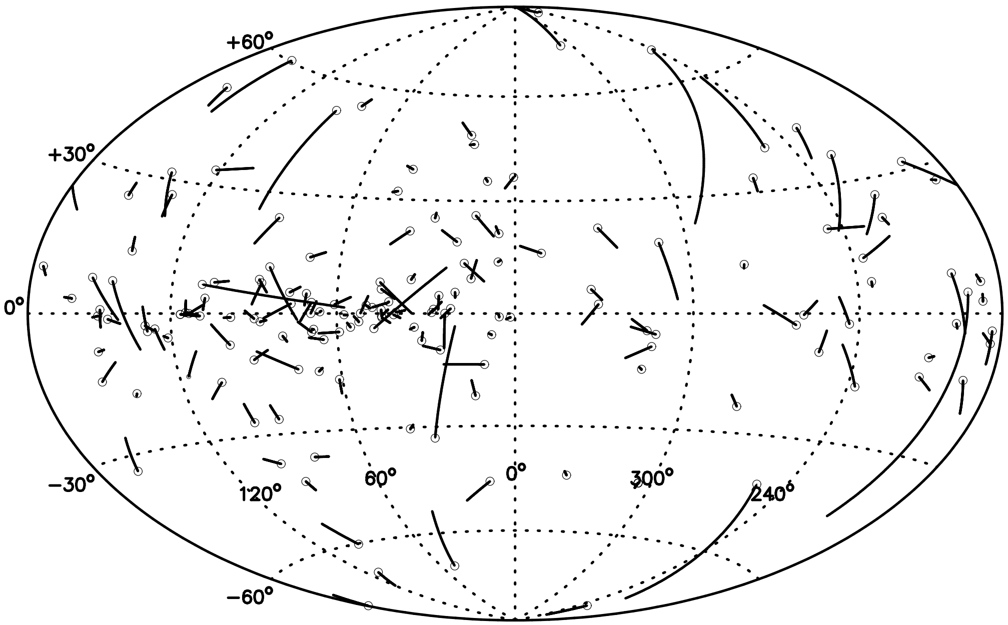


HST, December 1994



HST, December 2001

Map of pulsar velocities



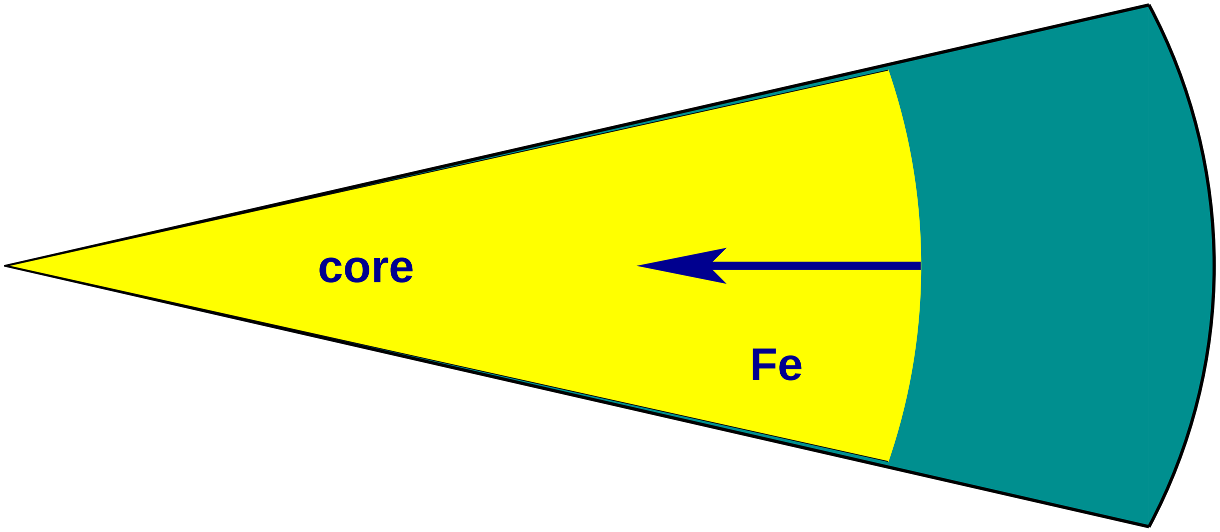
Proposed explanations:

- 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?)

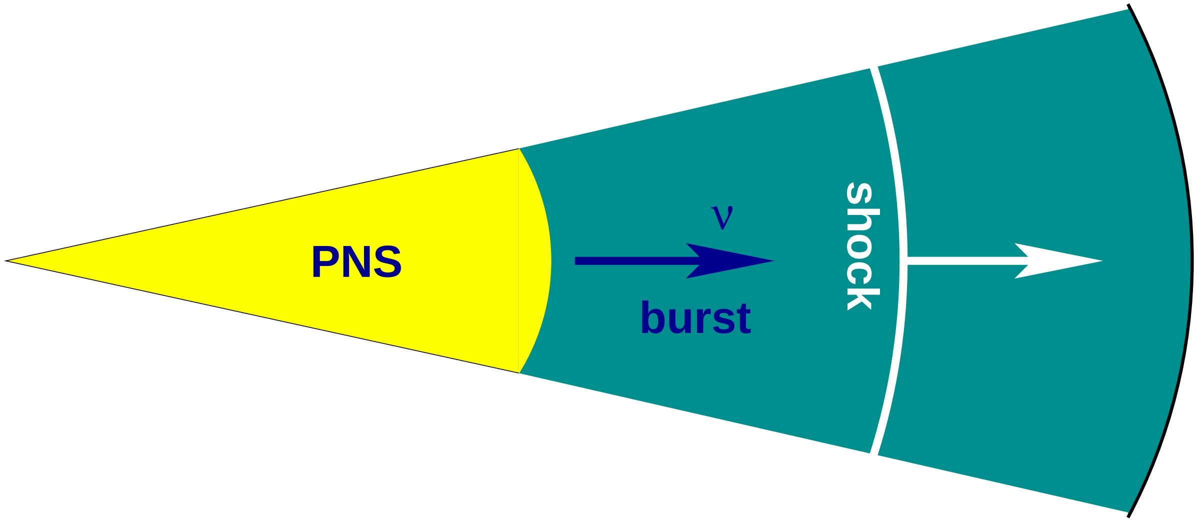
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

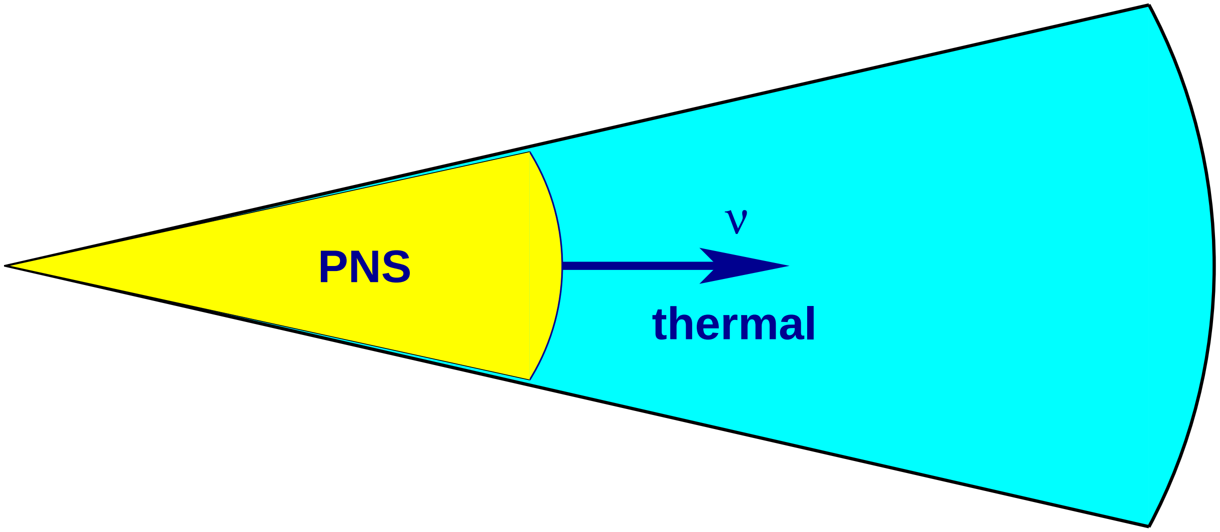
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



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

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

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

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

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:

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

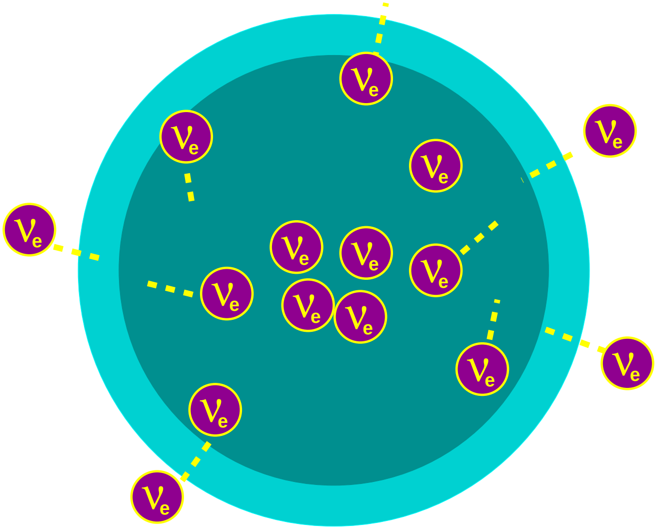
where k_0 is the fraction of electrons in the lowest Landau level.

$k_0 \sim 0.3$ 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?

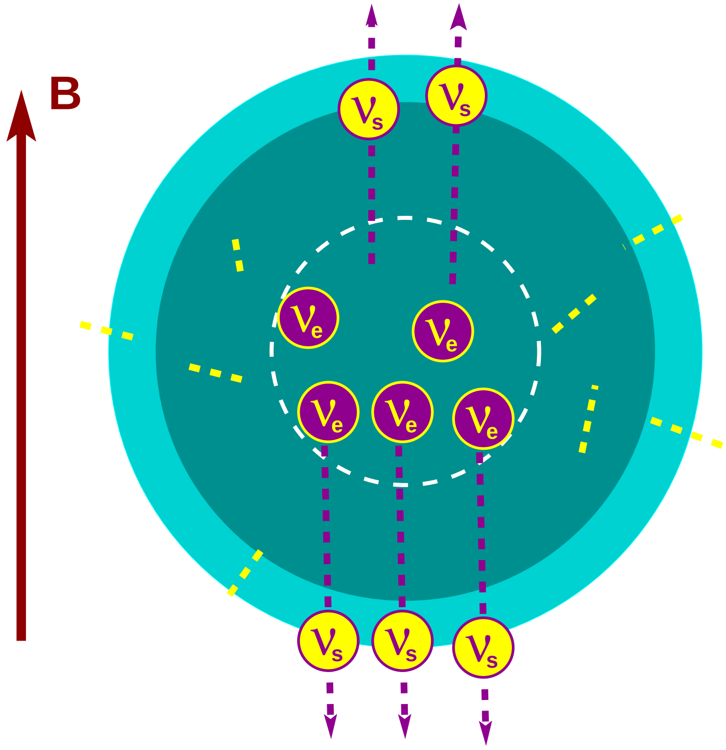
No

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].

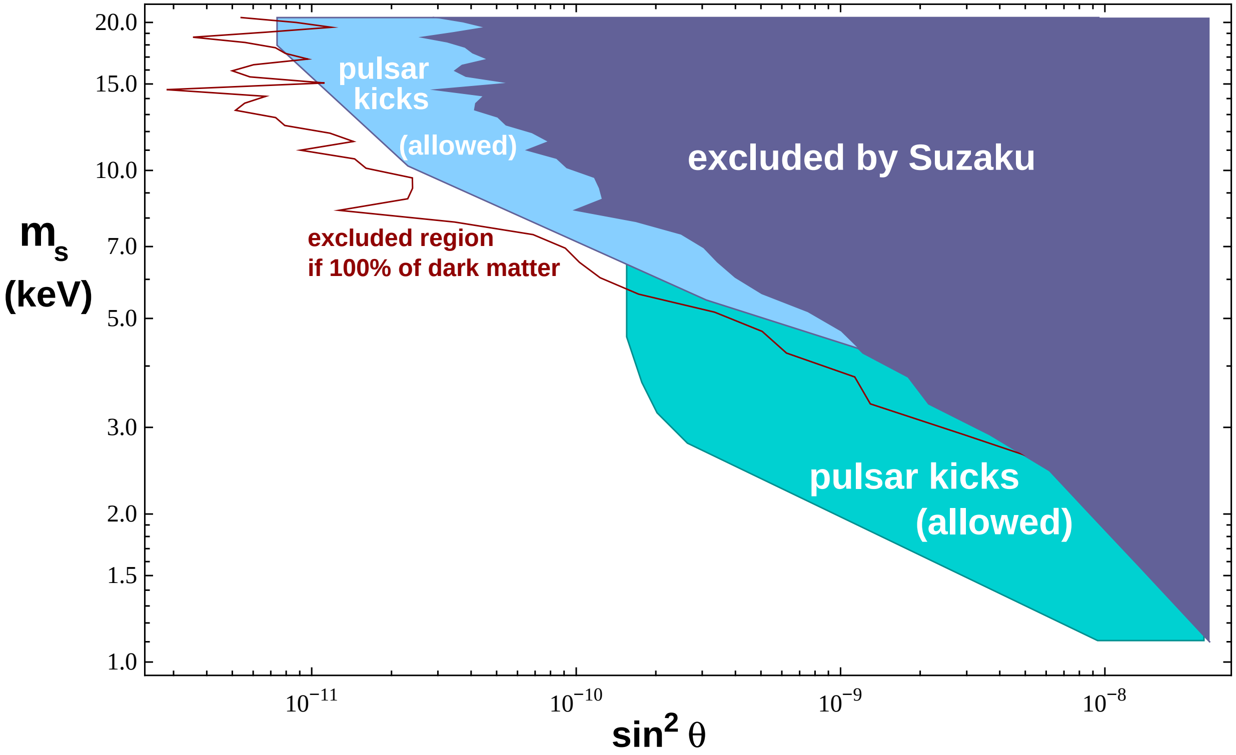
However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

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



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

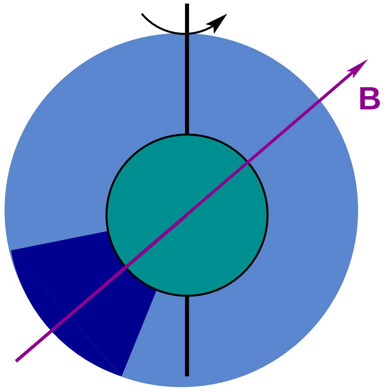
Pulsar kicks



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

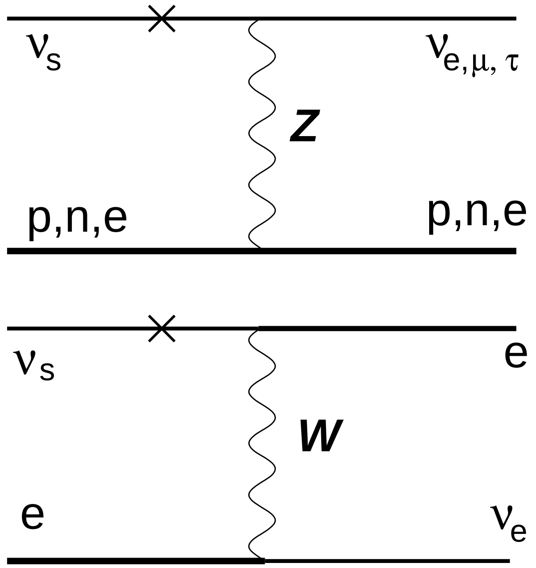
Other predictions

- 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]**

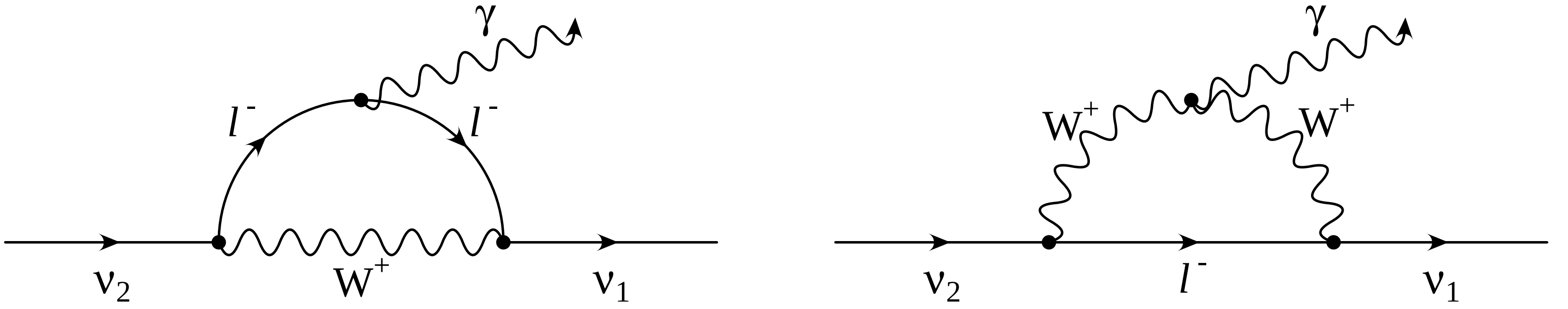


Rates low:

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

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.	$\mathbf{1''}$	$6''$	$90''$
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$\times$3 cm^2
NXB rate	~ 0.01 ct/s/arcmin^2	~ 0.01 ct/s/arcmin^2	$\boldsymbol{\sim 10^{-3}}$ **cts/s/**$\mathbf{arcmin^2}$

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!

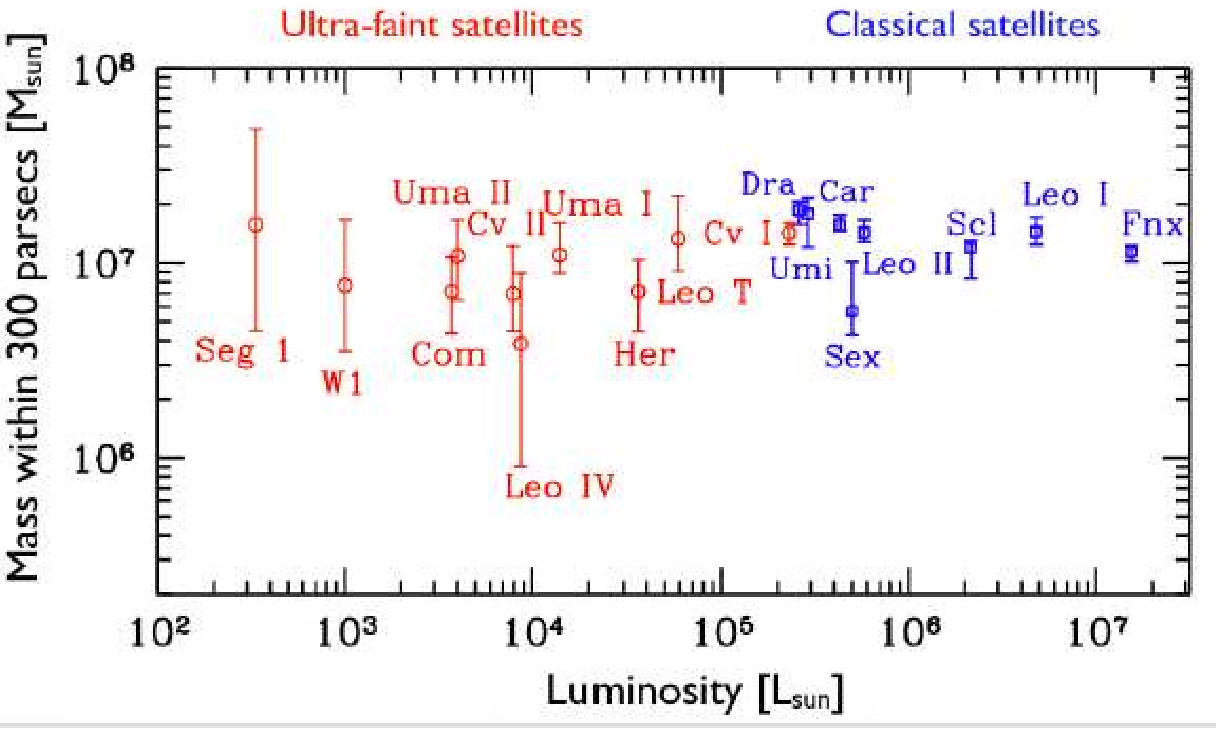
[Loewenstein]

Target selection

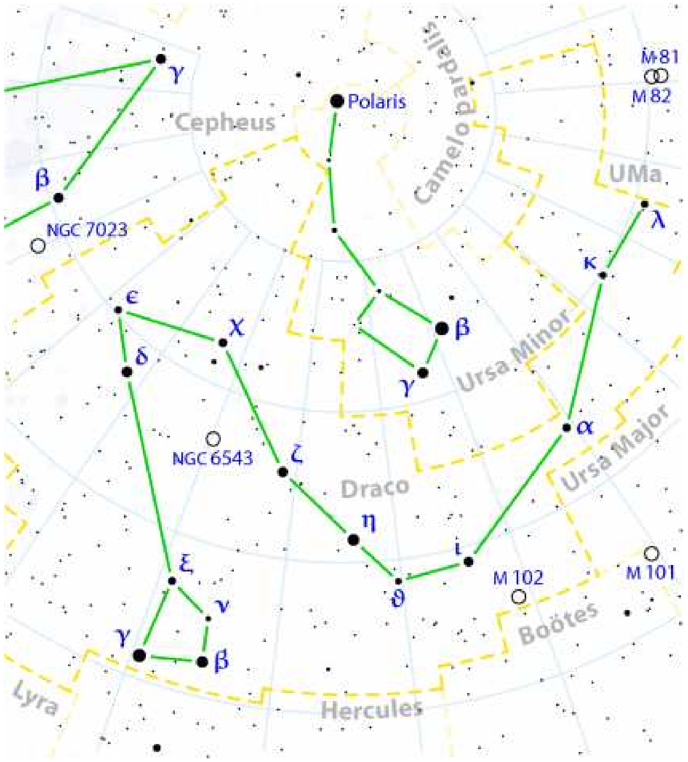
target	dark matter content	background	signal/noise	overall
MW center	high/uncertain	very high	low	far from ideal
MW, “blank sky”	low	low	low	not ideal
nearby galaxy (M31)	high/uncertain	high	low	not ideal
clusters	high	very high	low	not ideal
dSph	high/uncertain	low	high	**best choice**

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

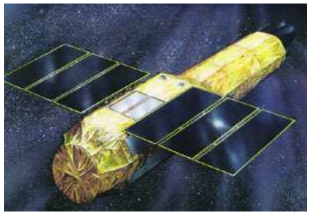


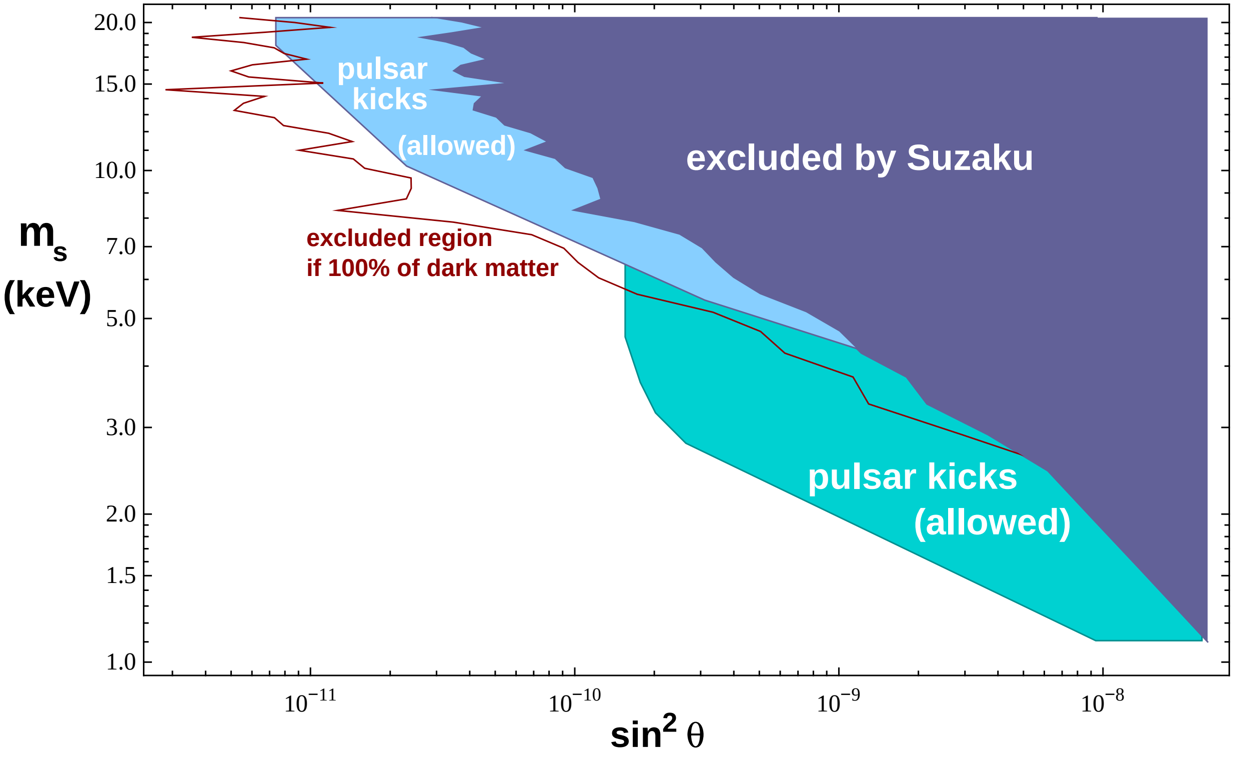
Suzaku observations of dSphs Draco and Ursa Minor



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

X-ray limits from *Suzaku*





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

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

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

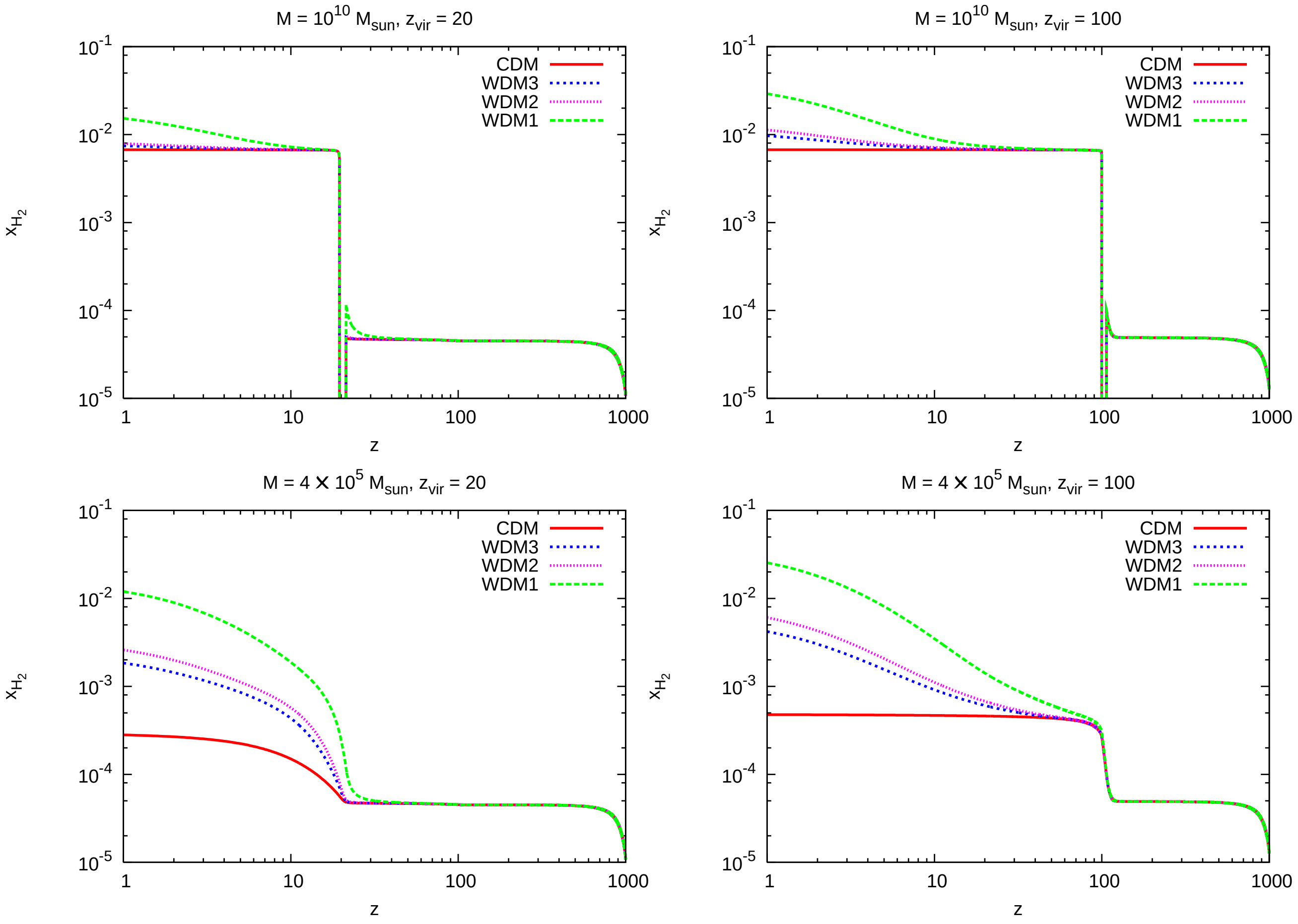
In the presence of ions the following reactions are faster:

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

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
- 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