Dark matter in the form of sterile neutrinos

- Sterile neutrino: a well-motivated dark matter candidate
- Astrophysical hints: pulsar kicks from an anisotropic supernova emission
- X-ray line from dark matter decay
- Search with X-ray telescopes
- Enhanced formation of H_2 and the star formation

Neutrino masses and dark matter

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:

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

What is the *natural* scale of M?

Seesaw mechanism

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

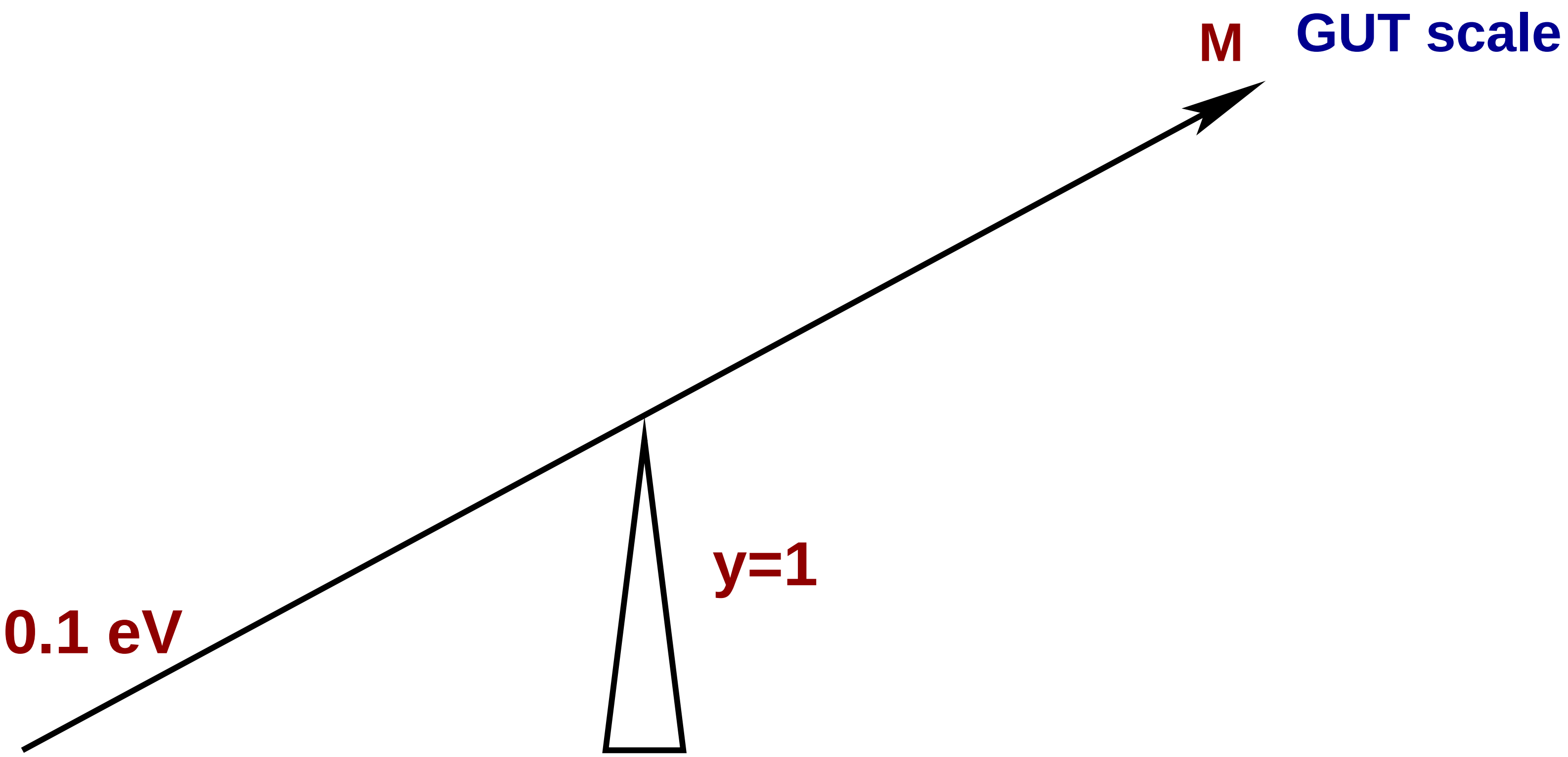
$$D_{ij} = y_{ij} \langle H \rangle$$

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

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

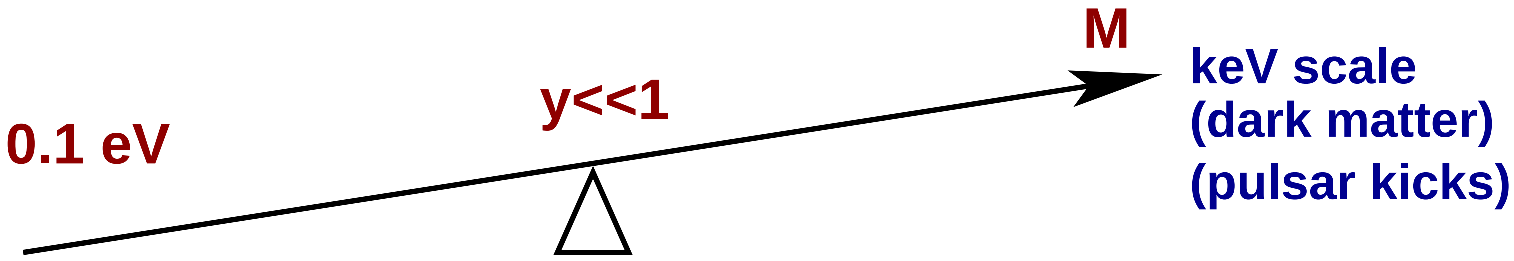
One can understand the smallness of neutrino masses even if the Yukawa couplings are $y \sim 1$ [Gell-Mann, Ramond, Slansky; Yanagida; Glashow; Mohapatra, Senjanović].

Seesaw mechanism



Seesaw mechanism

GUT scale



0.1 eV

y<<1

M

keV scale
(dark matter)
(pulsar kicks)

Pulsar kicks and dark matter?

Sterile neutrino explains: the pulsar kicks [AK, Segré; Fuller et al.], enhanced supernova explosions [Fryer, AK; Hidaka, Fuller]

Dark matter – a simple (minimalist) solution: use one of the particles already introduced to give the neutrino masses [Dodelson, Widrow; Abazajian, Fuller; Dolgov, Hansen; AK; Shaposhnikov et al.; Petraki; Boyanovsky]

$\Rightarrow$ sterile neutrino

need mass in the range of 1-25 keV for both pulsar kicks and dark matter

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

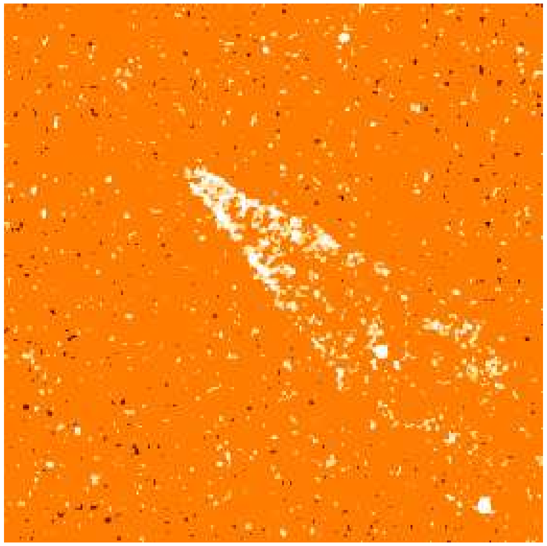
[AK, Segrè; Fuller, AK, Mocioiu, Pascoli; Barkovich, D'Olivo, Montemayor]

The pulsar velocities.

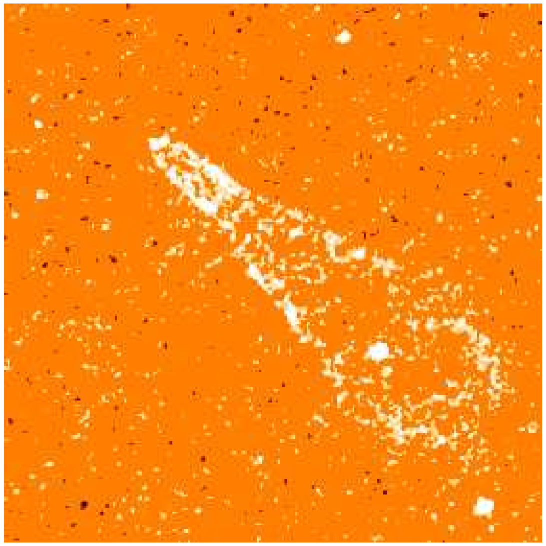
Pulsars have large velocities, $\langle v \rangle \approx 250 - 450\ \mathrm{km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

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

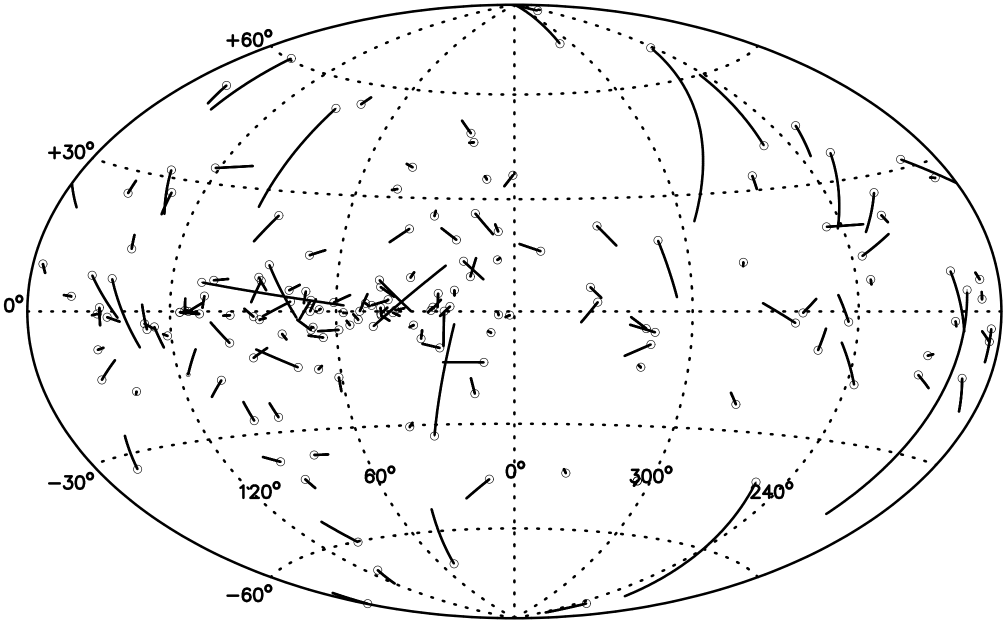


HST, December 1994



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

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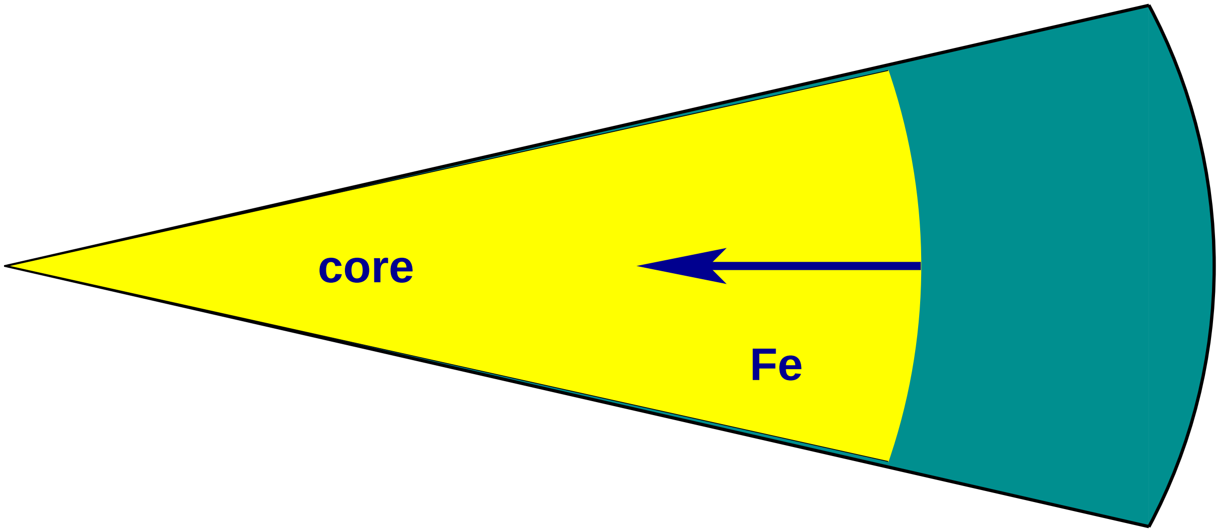
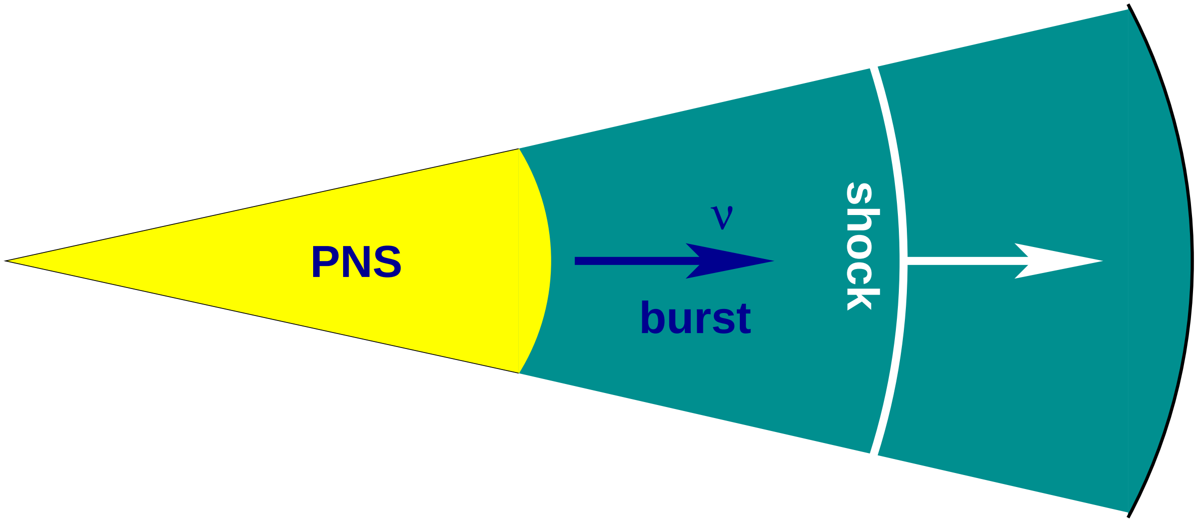


Core collapse supernova

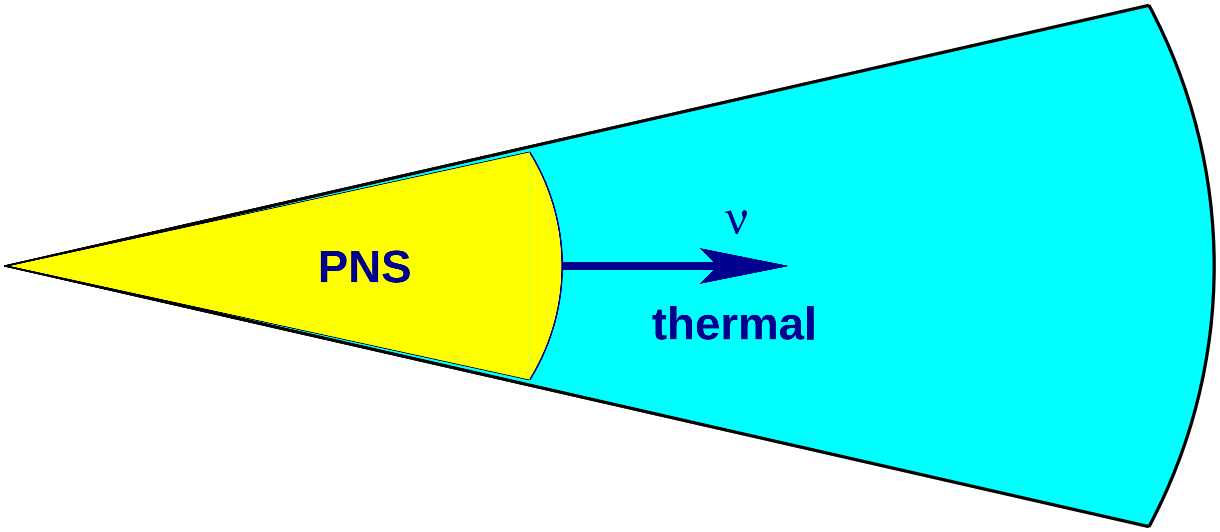
Shock formation and "neutronization burst": $t = 1 - 10$ ms



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

Core collapse supernova

Thermal cooling: $t = 10 - 15$ s



Most of the neutrinos emitted during the cooling stage.

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

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

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:

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

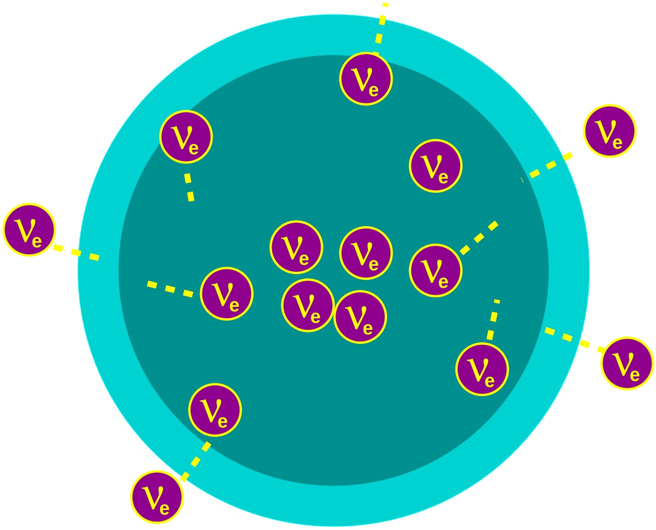
where k_0 is the fraction of electrons in the lowest Landau level.

$k_0 \sim 0.3$ 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?

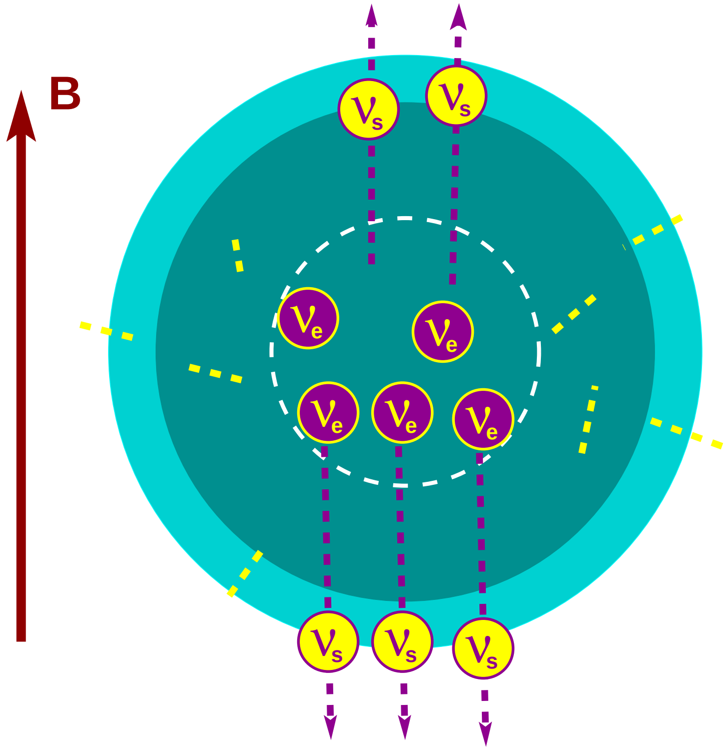
No

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].

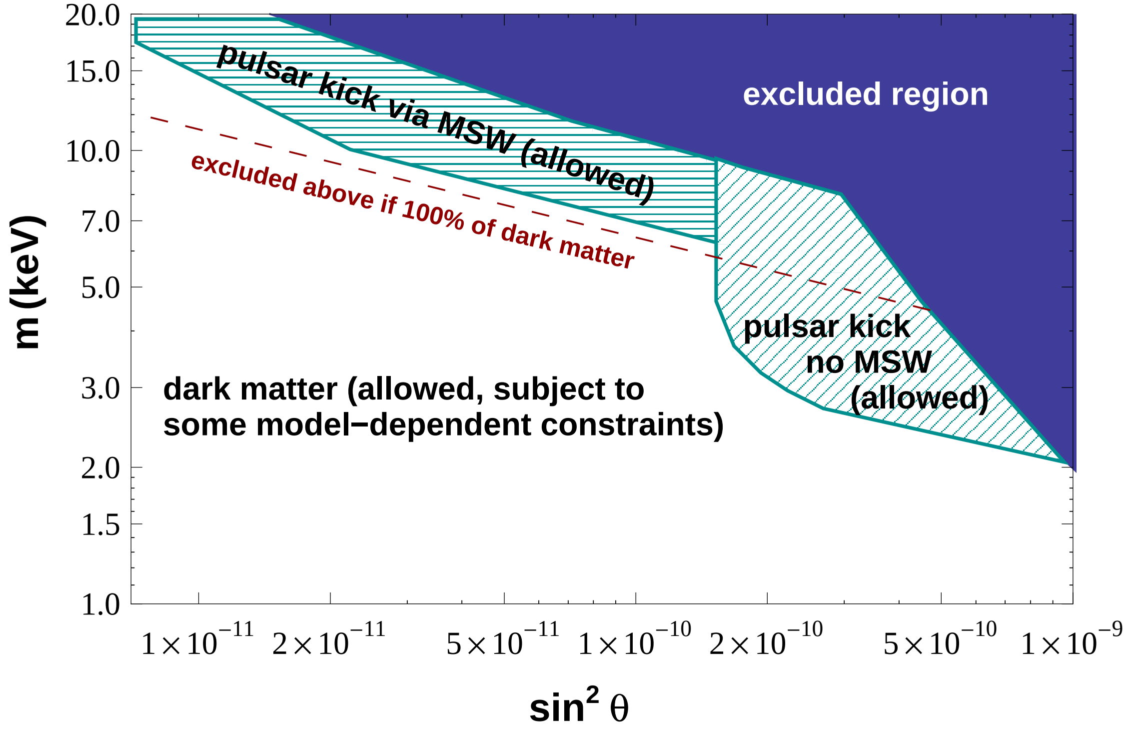
However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

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



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

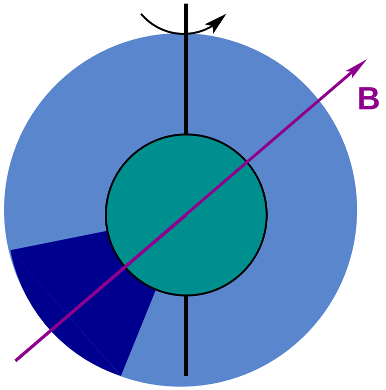
Pulsar kicks



[AK, Segrè; Fuller, AK, et al.]

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]

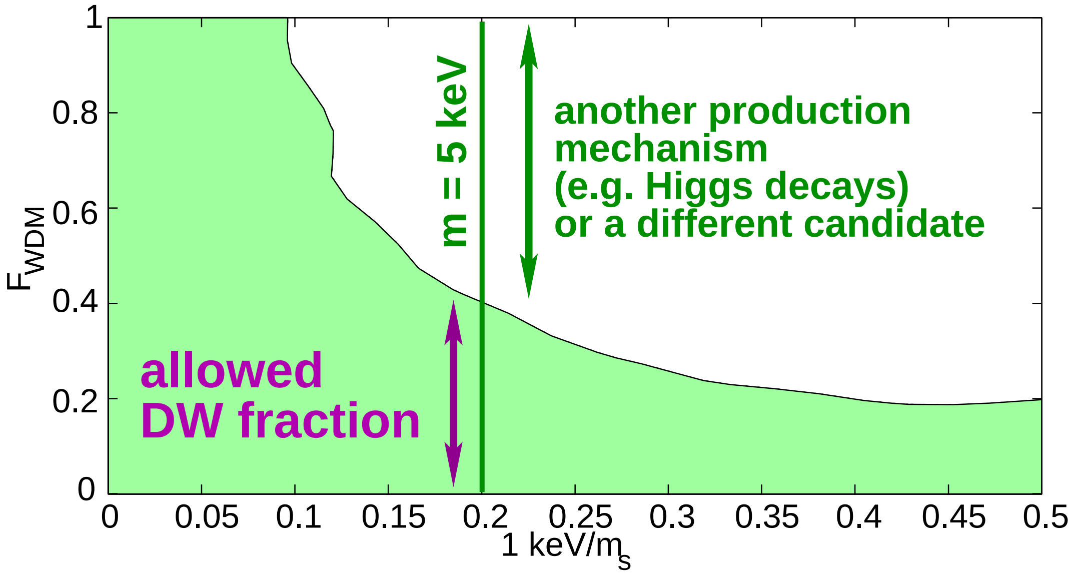


Sterile neutrinos as dark matter

Can be produced by the following mechanisms,
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** (although the existence of singlets may seem unnatural). Also, inflaton decays can also contribute to the population of dark matter [Tkachev,Shaposhnikov]

Free-streaming and Lyman-α bounds



[Boyarsky, Lesgourgues, Ruchayskiy, Viel] **but beware of systematic errors...**

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

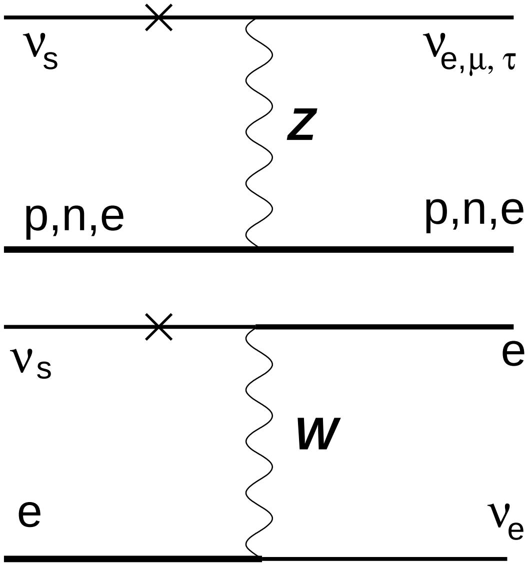
Challenges to CDM = hints of WDM

- Cored profiles of dwarf spheroidals [Gilmore, Wyse; Strigari et al.]
- Minimal size of dSphs [Wyse]
- 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; Abazajian]
- 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.]

[talk by R. Wyse]

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? $\nu_s e \longrightarrow \nu_e e$. Monochromatic electrons with $E = m_s$. **[Ando, AK]**

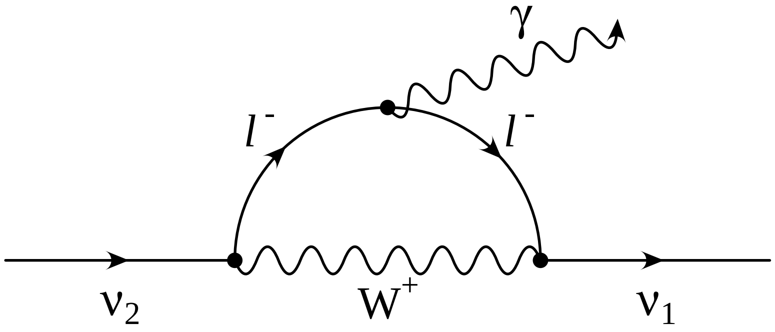


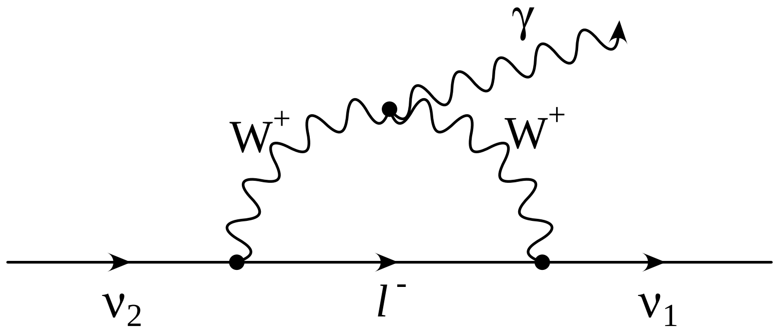
Rates low:

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

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$3 cm^2
NXB rate	~ 0.01 ct/s/arcmin^2	~ 0.01 ct/s/arcmin^2	**$\sim 10^{-3}$ cts/s/arcmin^2**

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

[Loewenstein, talk at Dark Matter 2010]

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, talk at Dark Matter 2010]

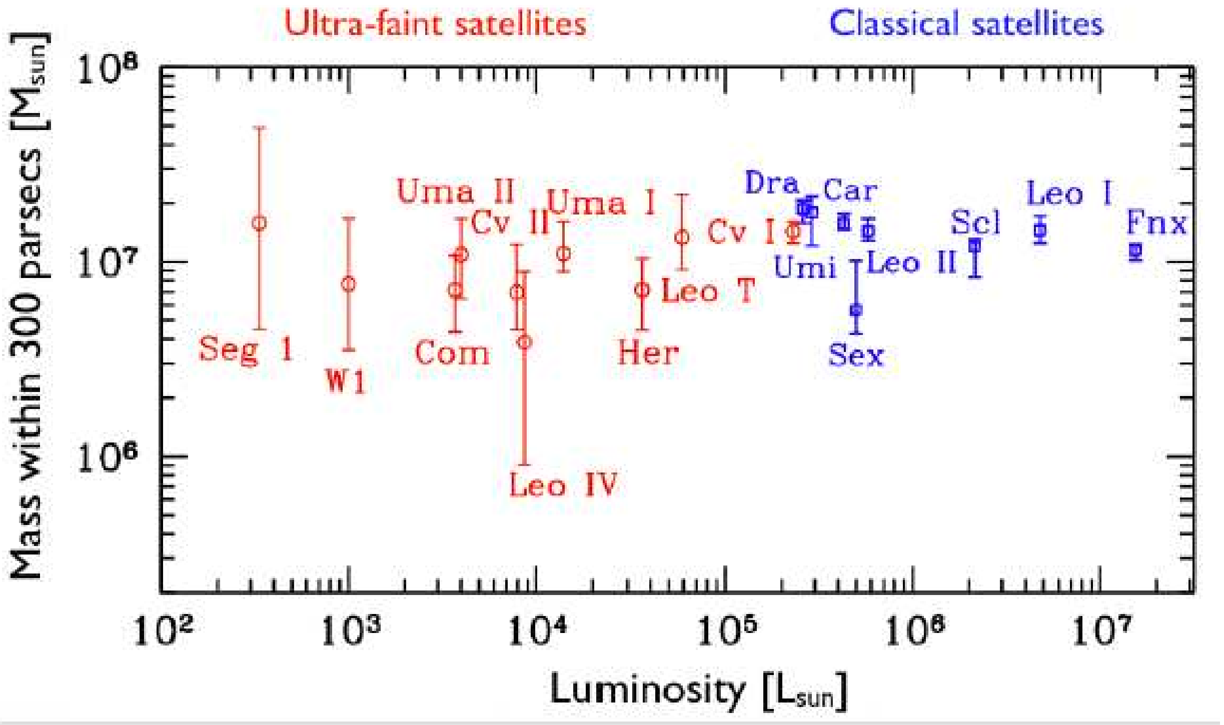
Target selection

[Thanks to Bullock, Kaplinghat, Wyse]

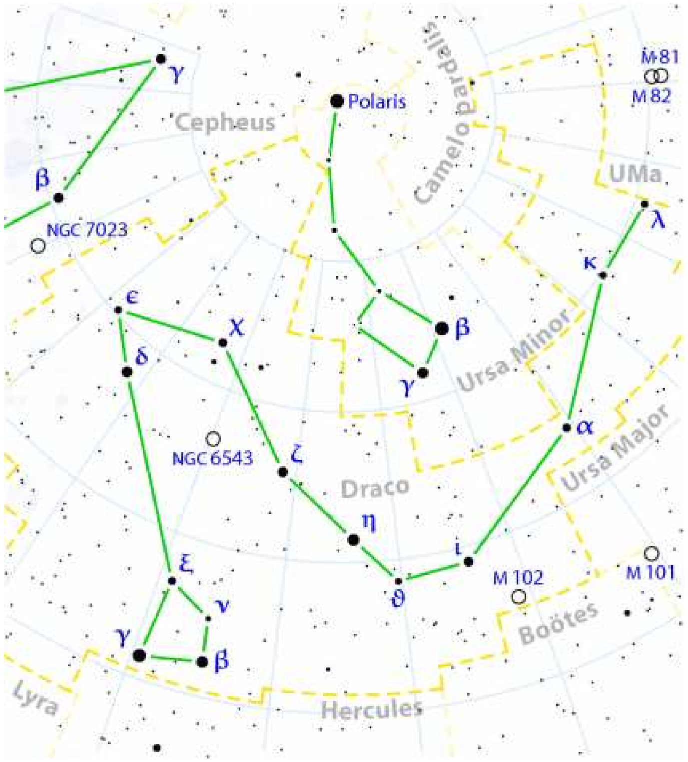
target	dark matter content	background	signal/noise	overall
MW center	high/uncertain	very high	low	far from ideal
MW, "blank sky"	low	low	low	not ideal
nearby galaxy (M31)	high/uncertain	high	low	not ideal
clusters	high	very high	low	not ideal
dSph	high/uncertain	low	high	**best choice**

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

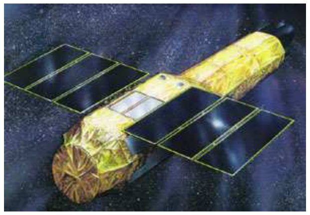


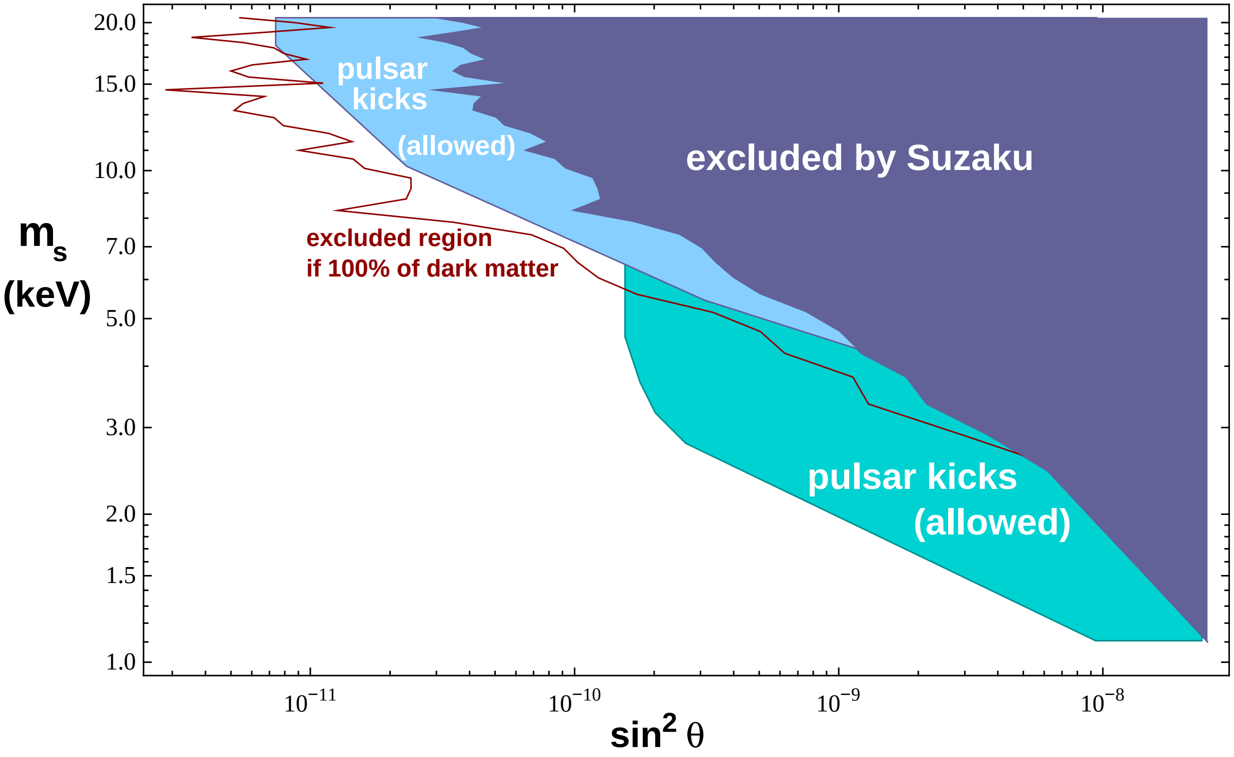
Suzaku observations of dSphs Draco and Ursa Minor



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

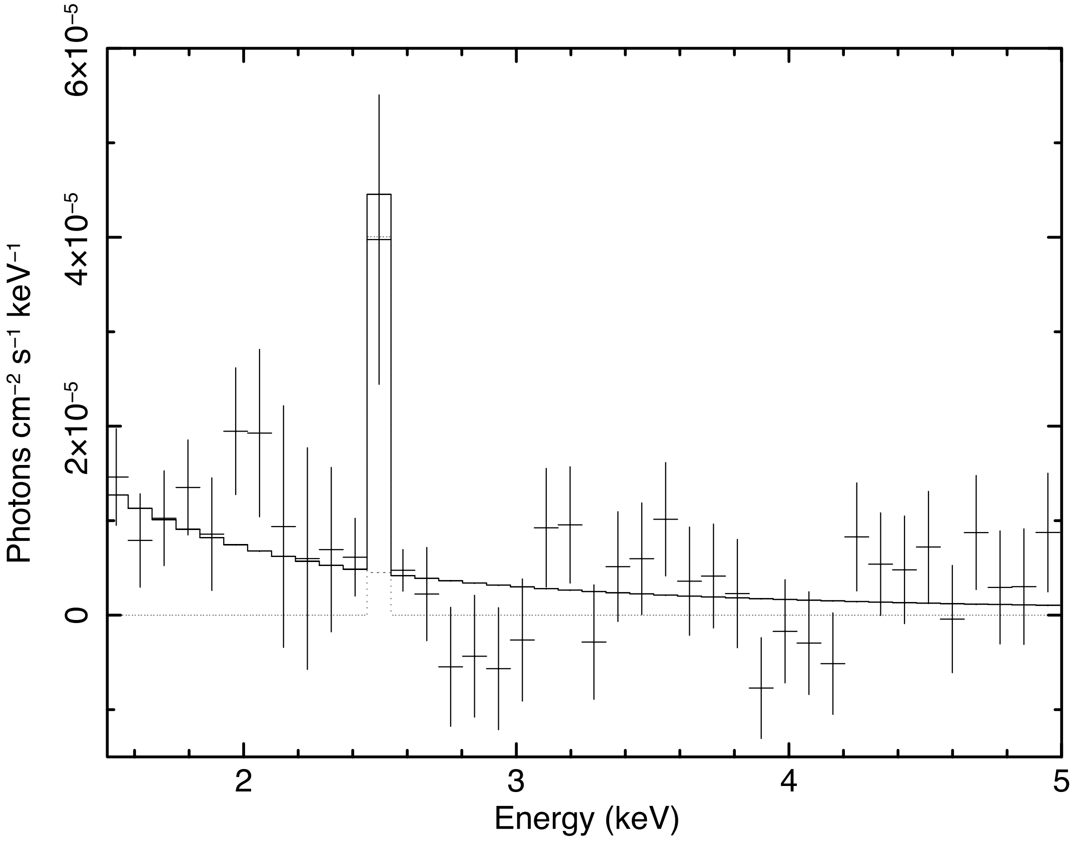
X-ray limits from *Suzaku*





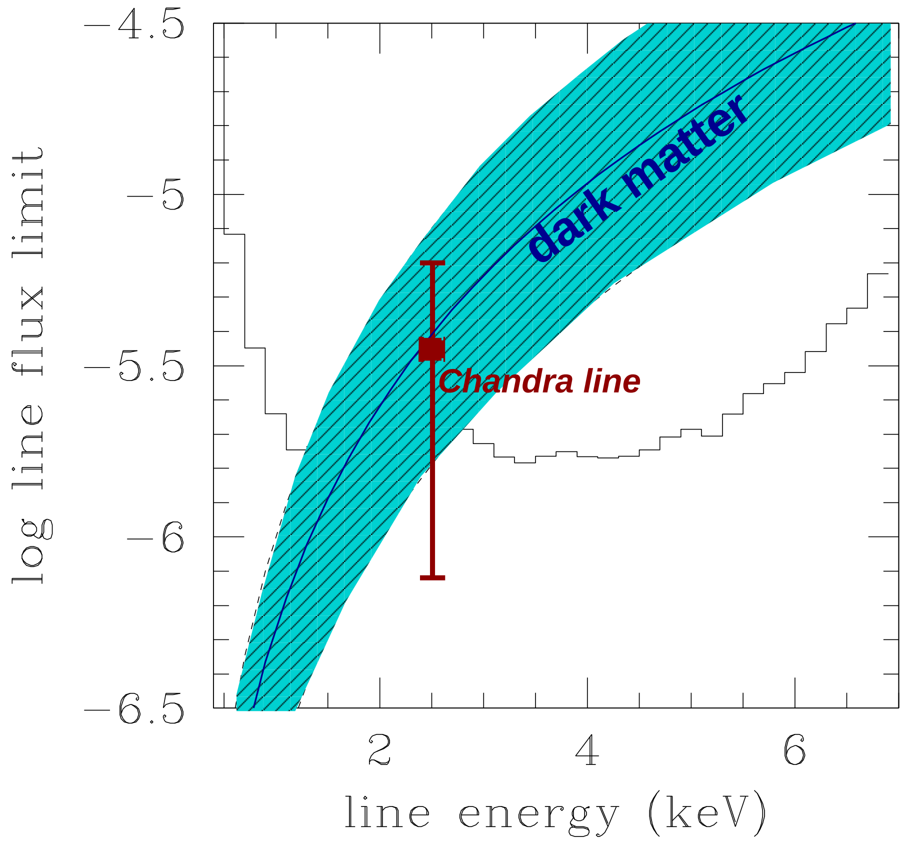
[Loewenstein, A.K., Biermann, ApJ 700, 426 (2009)]

Possible first evidence from *Chandra* observations of Willman-1



[Loewenstein and A.K., ApJ, in press (arXiv:0912.0552)]

Possible first evidence from *Chandra*



[Loewenstein and A.K., ApJ, in press (arXiv:0912.0552)]

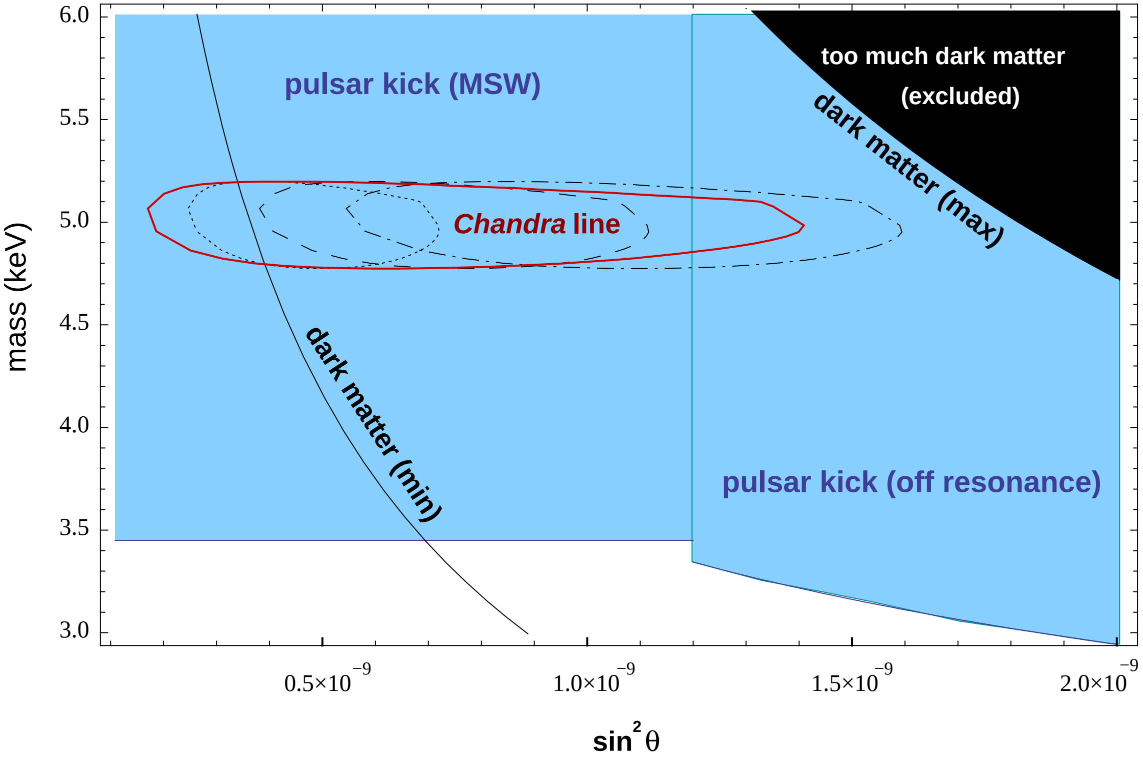
Consistency, not corroboration

- Marginal detection in Chandra data on Willman 1
- Small excess at 2.5 keV in the Suzaku XIS1 Ursa Minor spectrum ($< 2\sigma$). Simulations based on Chandra signal do not predict a statistically significant detection.
- No evidence of a line at 2.5 keV in the Chandra blank sky spectra (with or without the particle background removed).

All of the above is consistent with a 2.5 keV line from dark matter

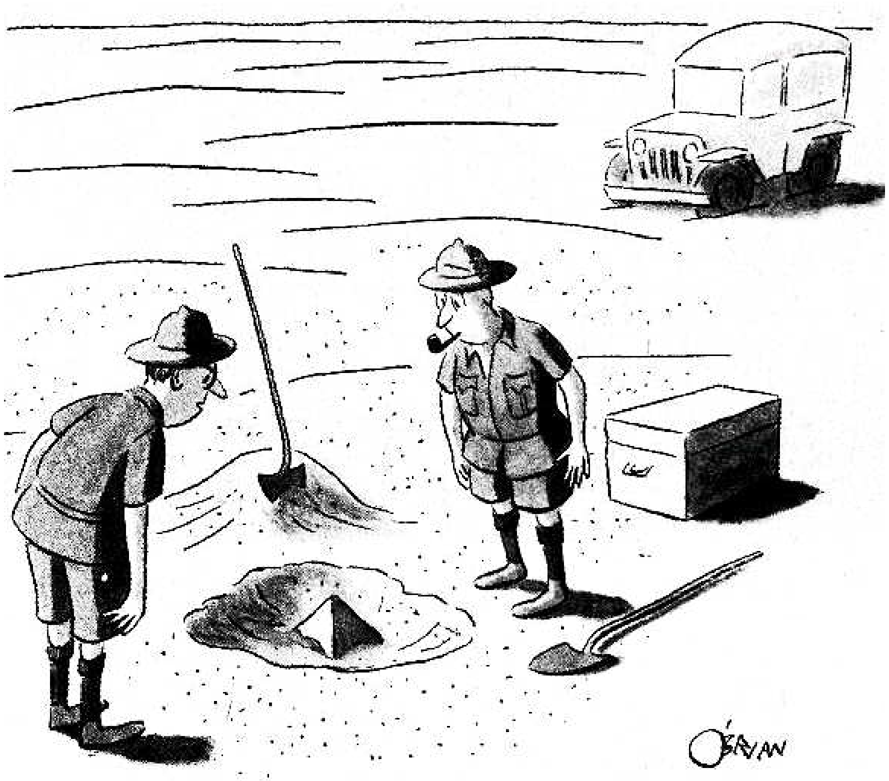
Furthermore, the position of the line, at 2.5 keV, combined with its intensity is consistent with sterile neutrinos comprising 100% of dark matter, based on the mass model of dSph.

Parameters inferred from *Chandra* data



[Loewenstein and A.K., ApJ, in press (arXiv:0912.0552)]

Clues of the sterile neutrinos



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

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

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

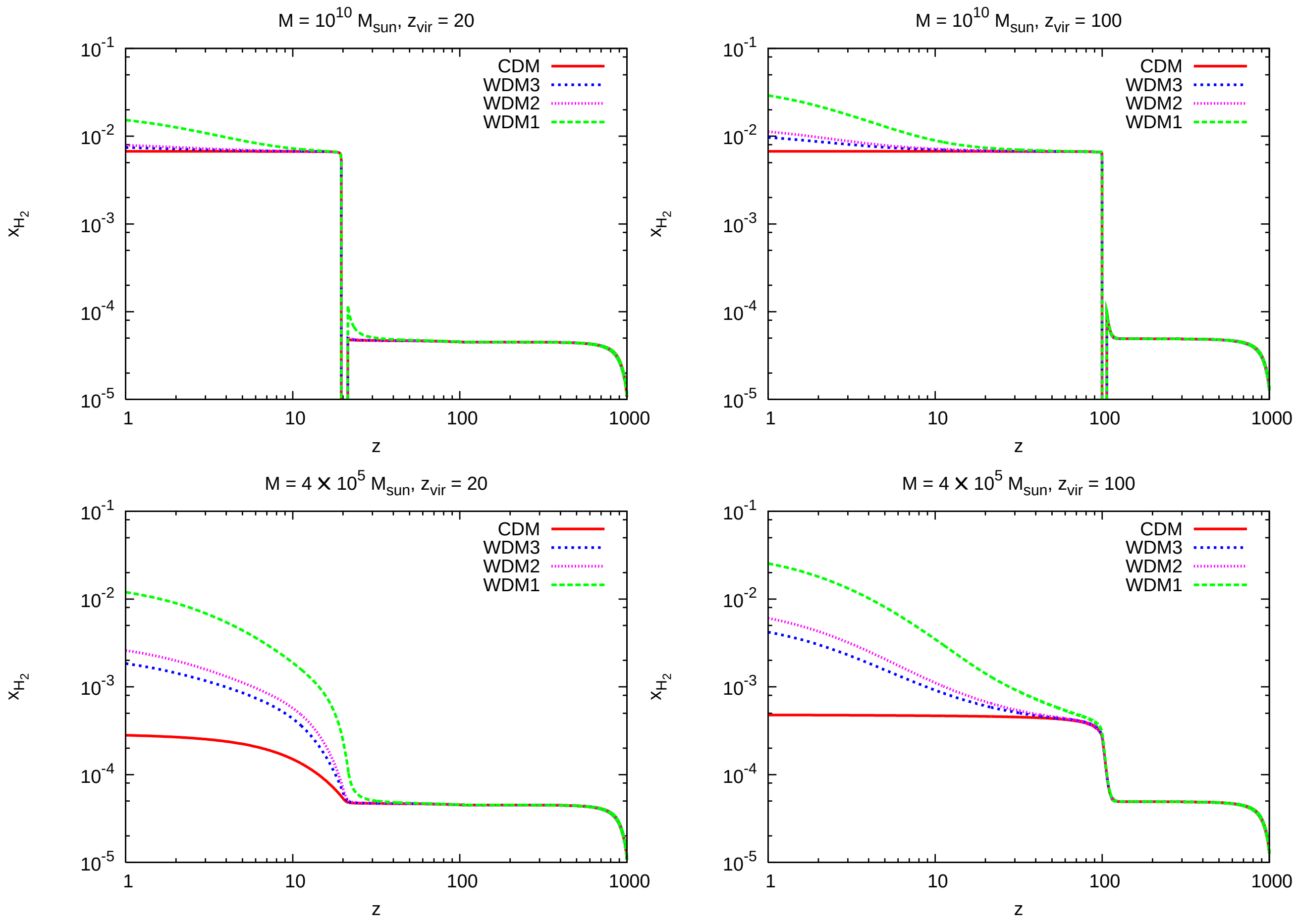
In the presence of ions the following reactions are faster:

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

H^+ produced by X-rays from $\nu_2 \longrightarrow \nu_1\gamma$ 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**
- *Chandra* has an intriguing spectral feature consistent with **5 keV sterile neutrino**; more observations are needed (upcoming observations with XMM-Newton, 2010-2011).
- 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 confirmed, dark matter X-ray line can help map out dark halos
- If confirmed, redshift-distance information inferred from the X-ray line can be used for observational cosmology, including dark energy research