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*, or thanks to some flavor symmetries **[Lindner]**
  - several production mechanisms can generate the correct abundance of dark matter (warm or cold, depending on the production scenario)
- Astrophysical hints: pulsar kicks from an anisotropic supernova emission
- First dedicated X-ray search for dark matter using *Chandra*, *XMM-Newton*, *Suzaku*.

cf. talks by Lindner and de Gouvêa

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:

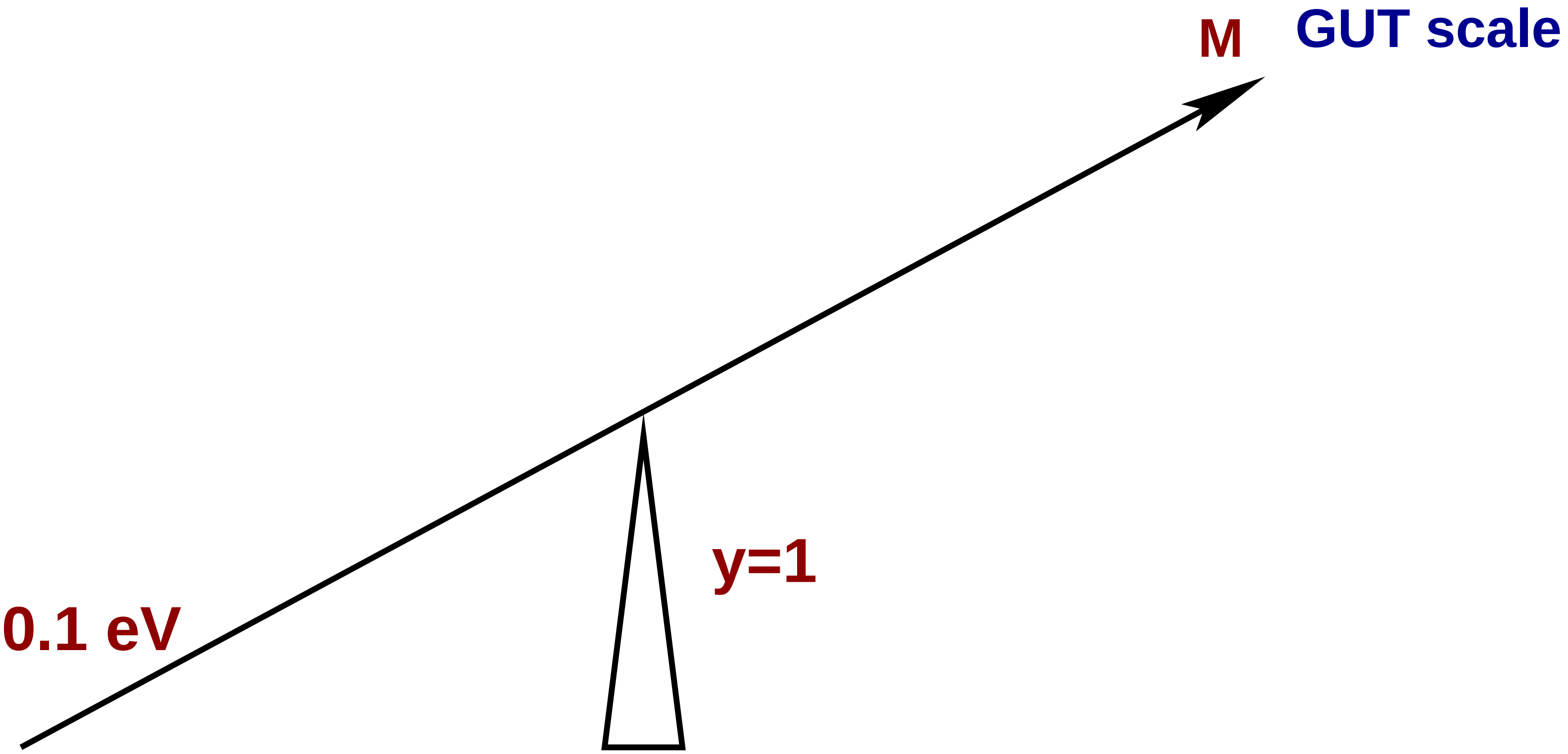
$$D_{ij} = y_{ij} \langle H \rangle$$

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

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

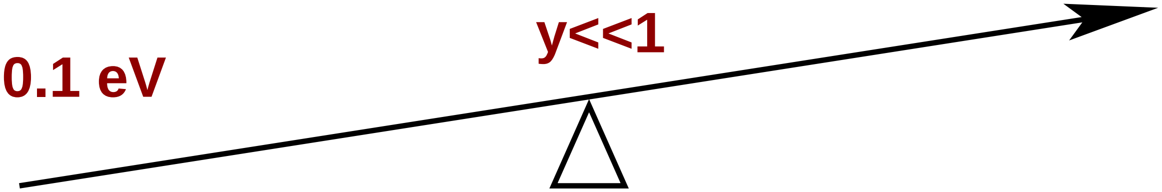
One can understand the smallness of neutrino masses even if
the Yukawa couplings are $y \sim 1$
[Gell-Mann, Glashow, Minkowski, Mohapatra, Ramond, Senjanović, Slansky, Yanagida].

Seesaw mechanism



Seesaw mechanism

GUT scale



M

y<<1

0.1 eV

keV scale
(dark matter)
(pulsar kicks)

Various approaches to small Majorana masses

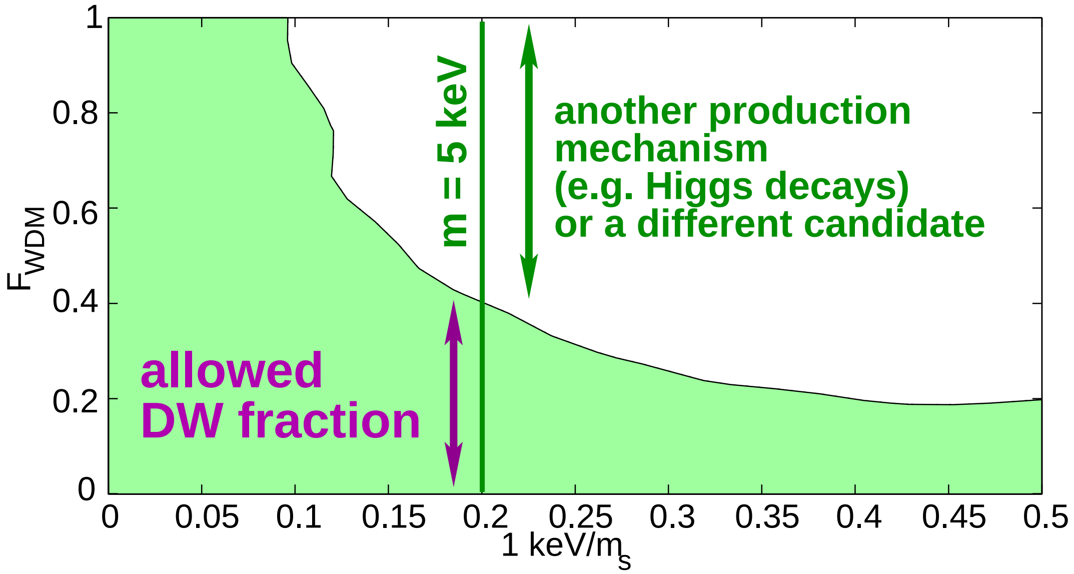
- Just write them down.
  - One sterile keV sterile neutrino, the dark matter candidate [Dodelson, Widrow].
  - Three sterile neutrinos, one with a several keV mass (dark matter) and two degenerate with GeV masses and a keV splitting, νMSM [Shaposhnikov et al.].
- Use lepton number conservation as the reason for a small mass **[de Gouvêa]**.
- Use flavor symmetries, new gauge symmetries **[Lindner]**
- **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 $\nu_a \rightarrow \nu_s$ 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 $S \to NN$ 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 $T \sim m_S$ from decays $S \to NN$:

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

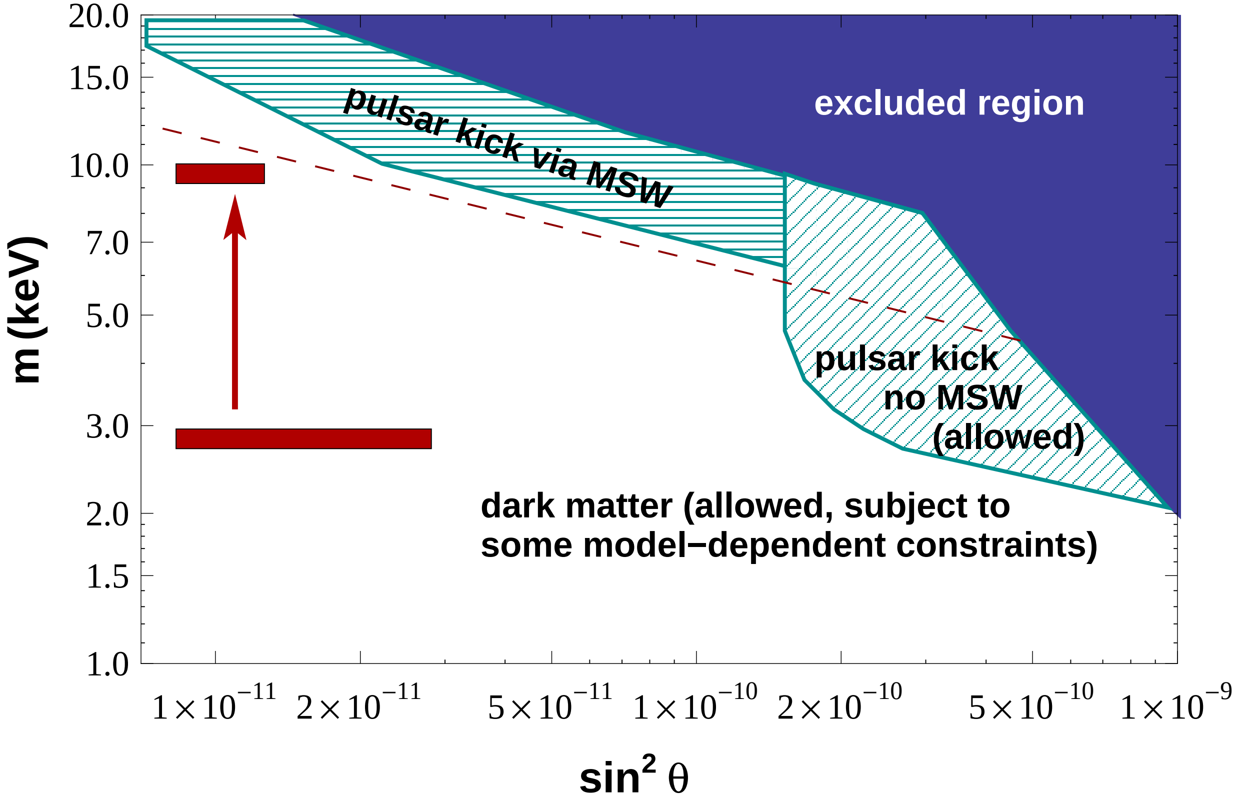
Here ξ is the dilution factor due to the change in effective numbers of degrees of freedom.

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

Cooling changes the clustering properties

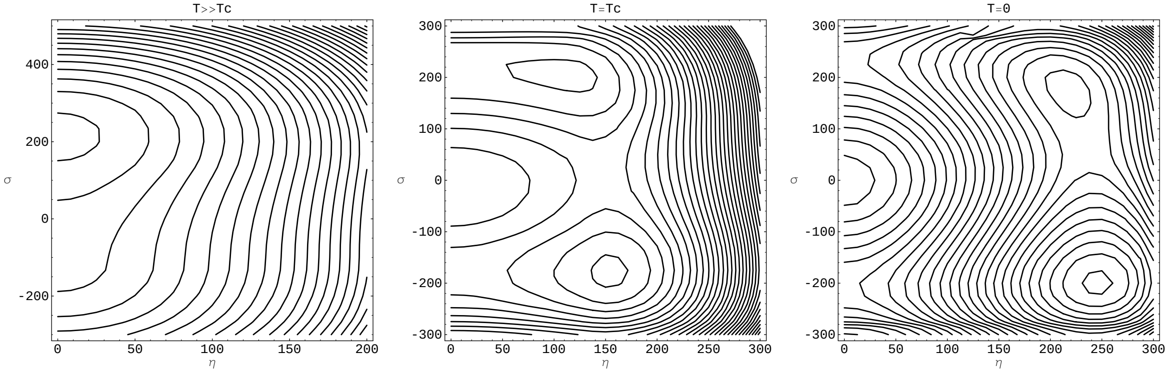


[AK, PRL **97**:241301 (2006); Petraki, AK, PRD 77, 065014 (2008); Petraki, PRD 77, 105004 (2008)]

Implications for the EW phase transition and the LHC

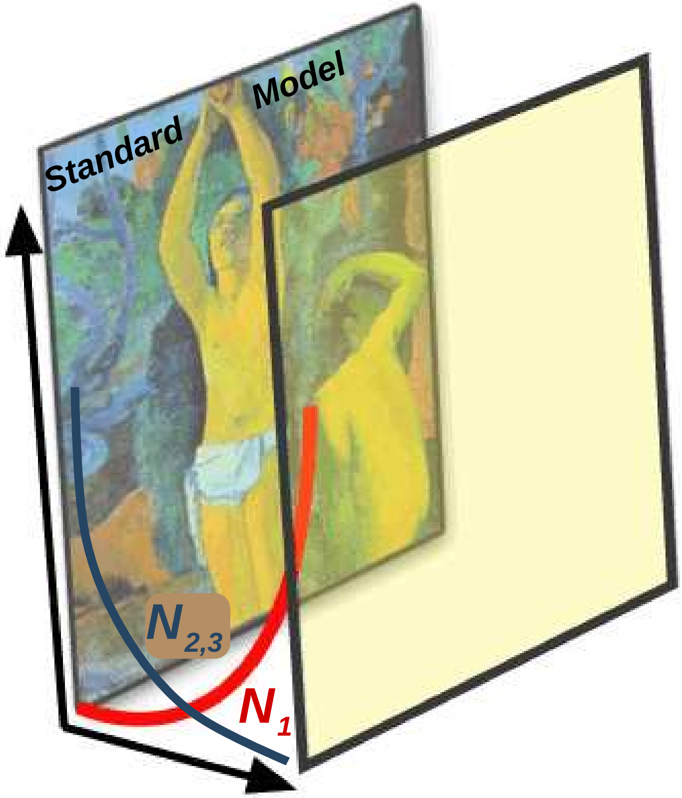
One may be able to discover the *singlet Higgs* at the LHC [Profumo, Ramsey-Musolf, G. Shaughnessy; Davoudiasl et al.; O'Connell et al.; Ramsey-Musolf, Wise]

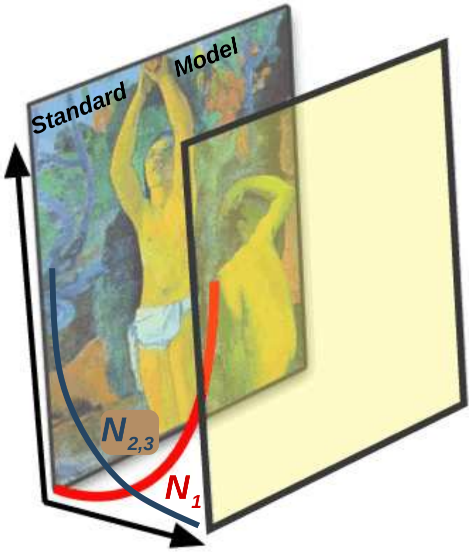
The presence of S in the Higgs sector changes the nature of the electroweak phase transition [AK, Petraki]



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

Split seesaw





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

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

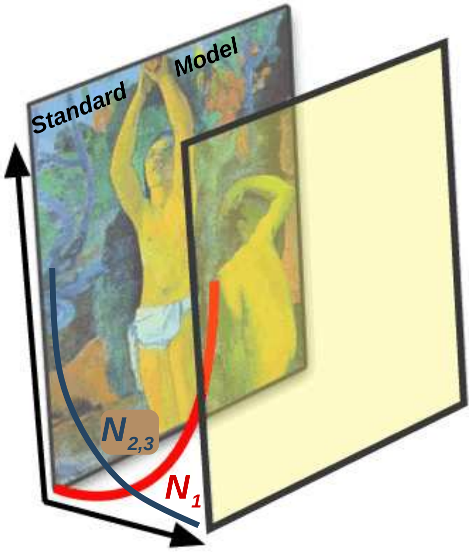
The zero mode: $(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0$. behaves as $\sim \exp(\pm mz)$. The 4D fermion:

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

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:

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

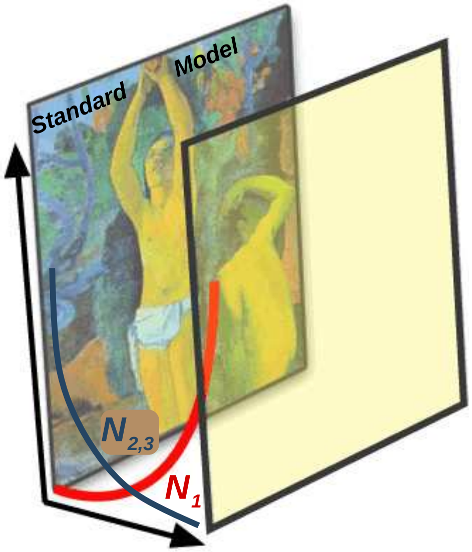
$$y_{d=4} = y_{d=5}\sqrt{\frac{2m_i}{M(e^{2m_i\ell}-1)}}$$

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

[AK, Takahashi, Yanagida]

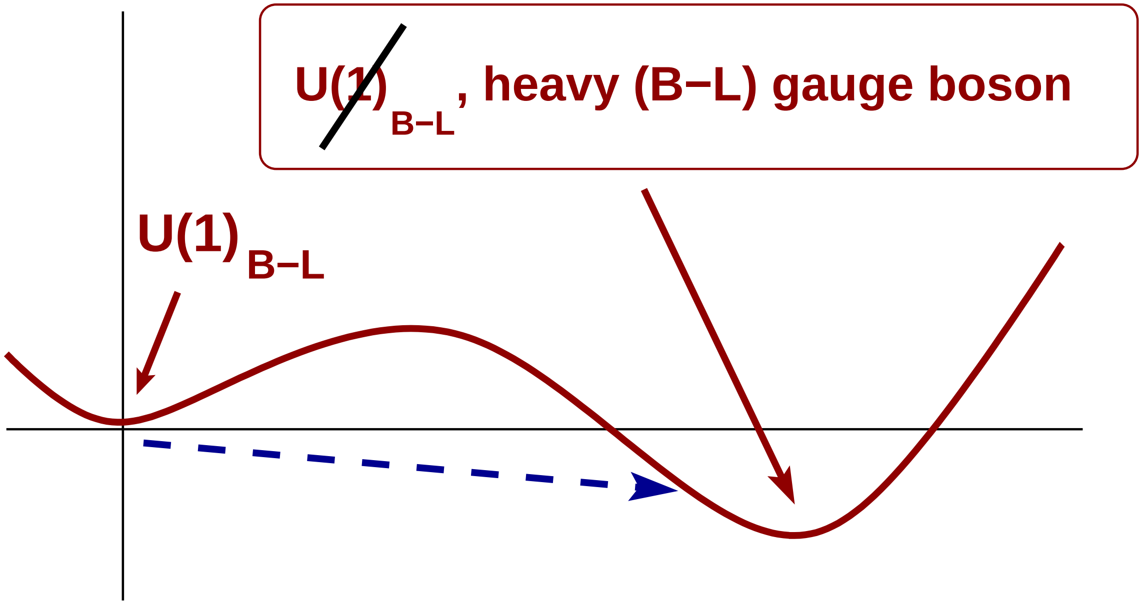
Dark matter production in Split Seesaw: two scenarios

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



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

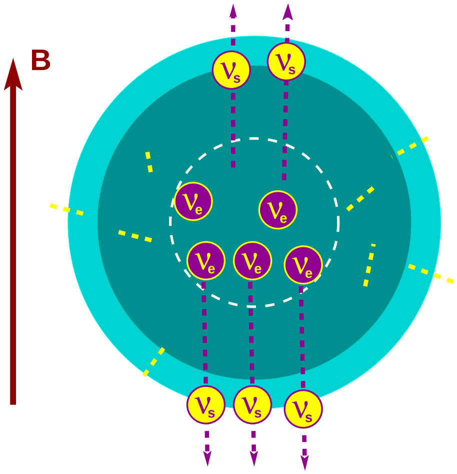
$U(1)_{B-L}$

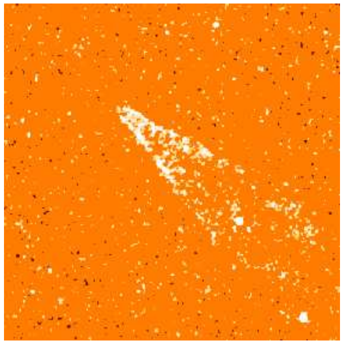
]

Pulsar kicks from asymmetric emission of sterile neutrinos

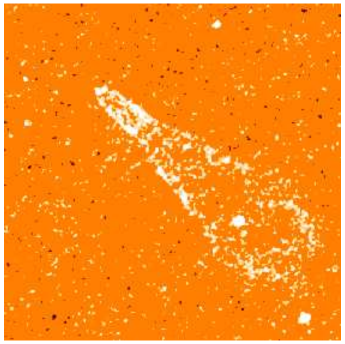
Pulsars have large velocities, $\langle v \rangle \approx \mathbf{250 - 450\ km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

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.*]



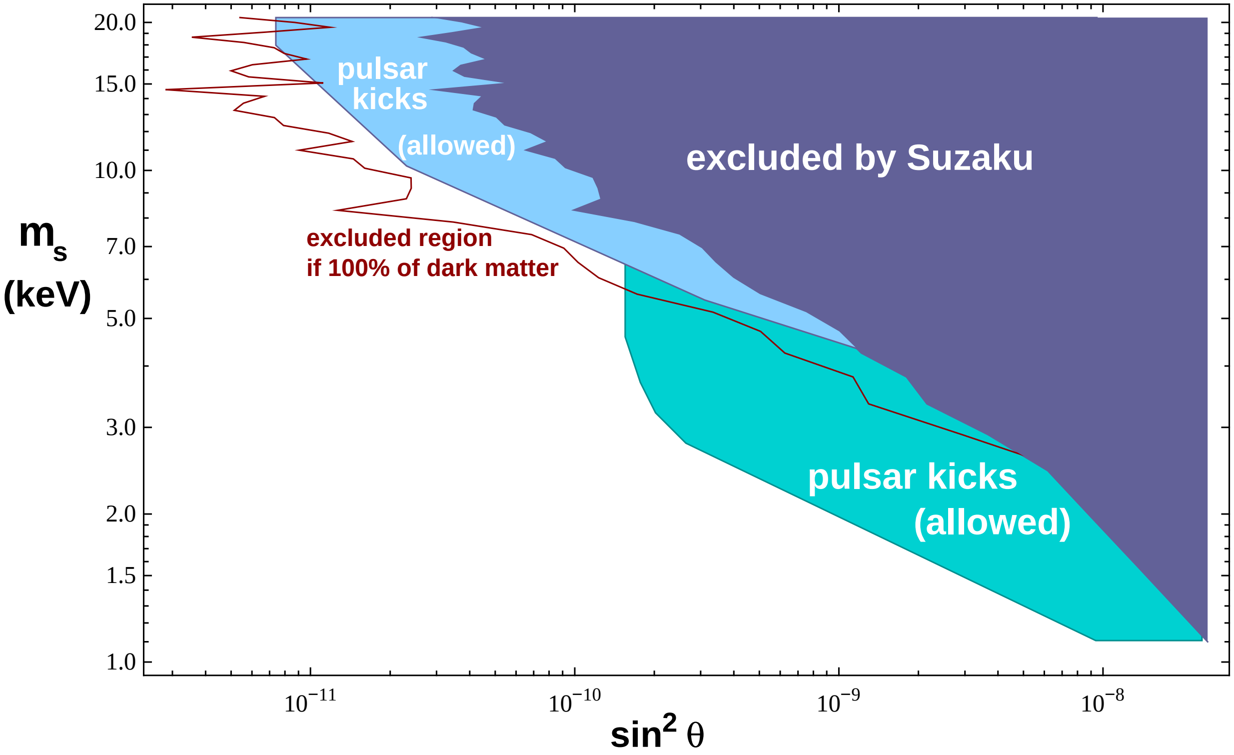


HST, December 1994



HST, December 2001

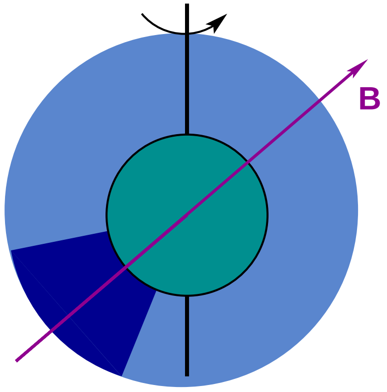
Pulsar kicks



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

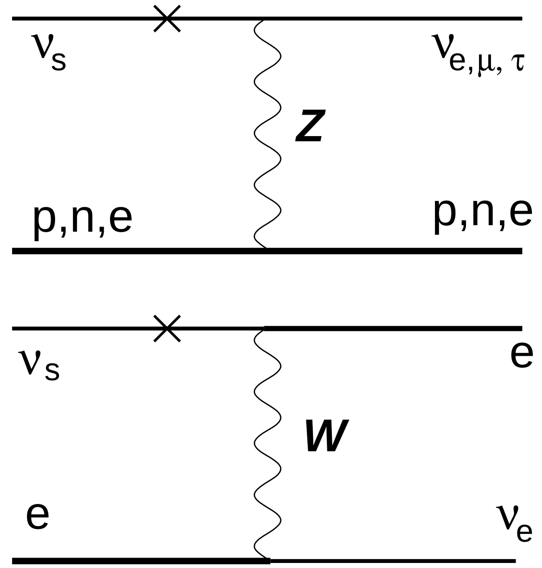
Other predictions

- 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]**

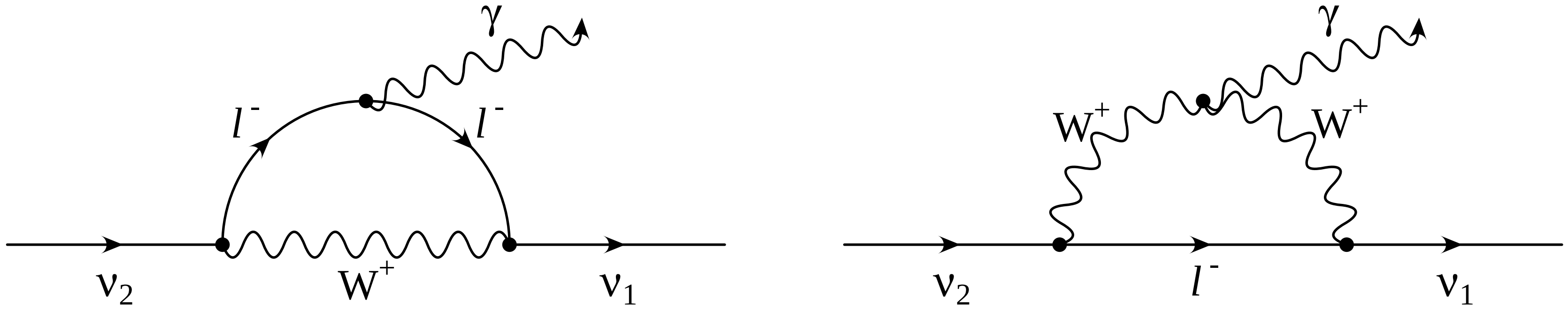


Rates low:

$$R = 4.0\times10^{-4}\ \mathrm{yr}^{-1}\left(\frac{m_{\nu_s}}{5\ \mathrm{keV}}\right)\left(\frac{\sin^2\theta}{10^{-9}}\right)$$
$$\times\left(\frac{M_{\mathrm{det}}}{1\ \mathrm{ton}}\right)\left(\frac{Z}{25}\right)^2\left(\frac{A}{50}\right)^{-1}.$$

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**	400×3 cm^2
NXB rate	~ 0.01 ct/s/arcmin^2	~ 0.01 ct/s/arcmin^2	$\mathbf{\sim 10^{-3}}$ **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!**

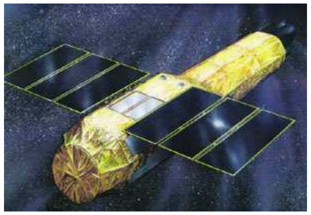
[Loewenstein]

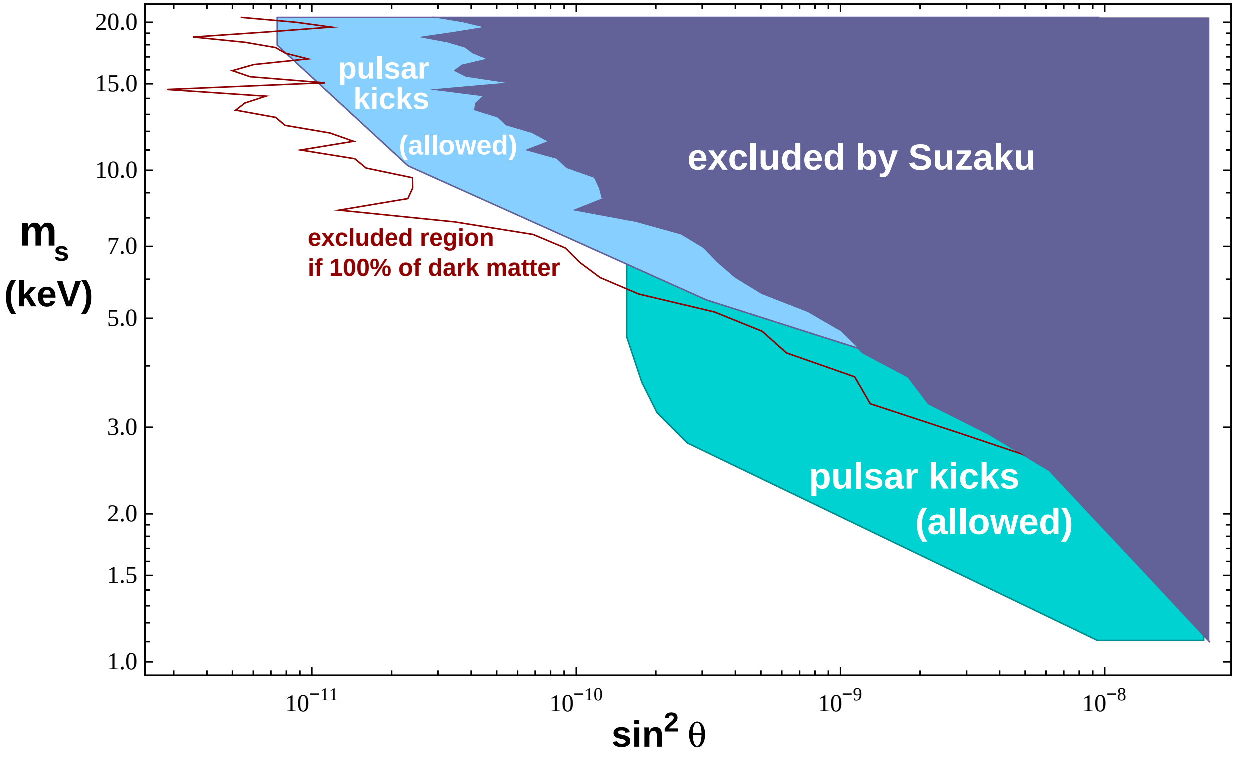
Target selection

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**

[Loewenstein]

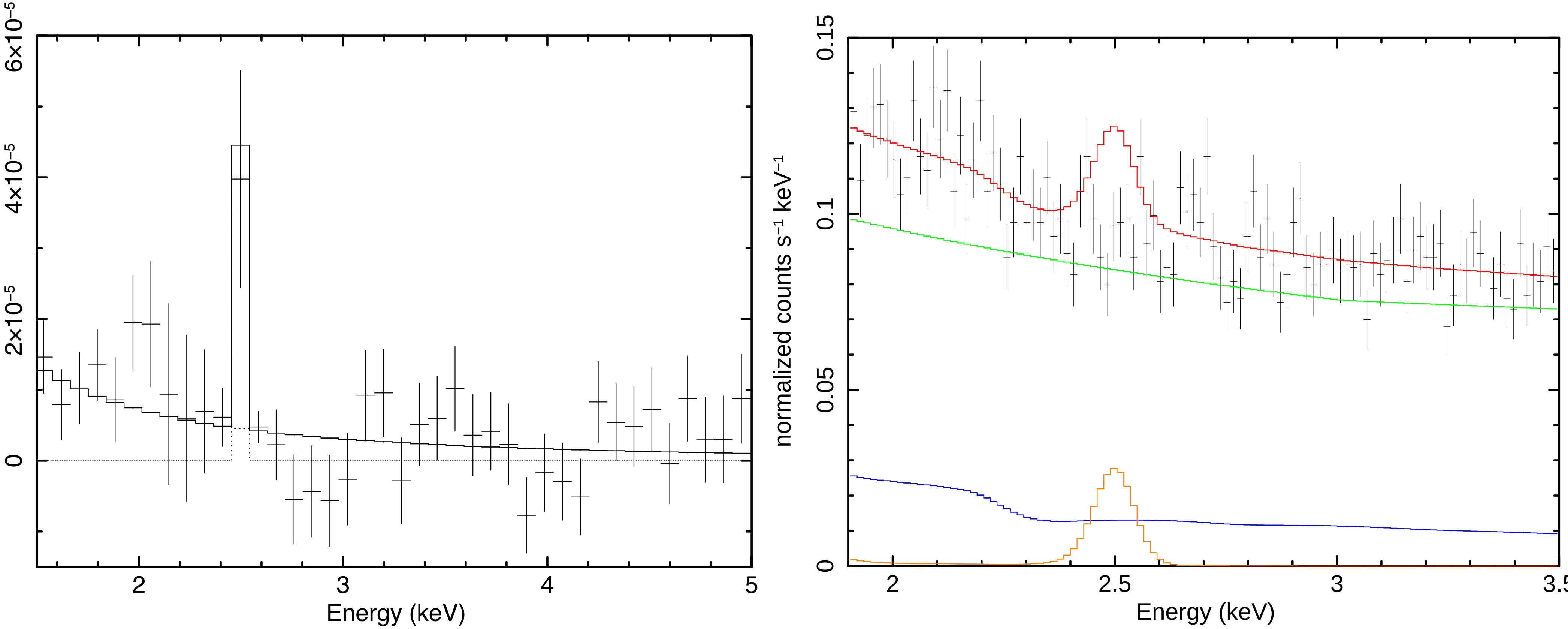
X-ray limits from *Suzaku*





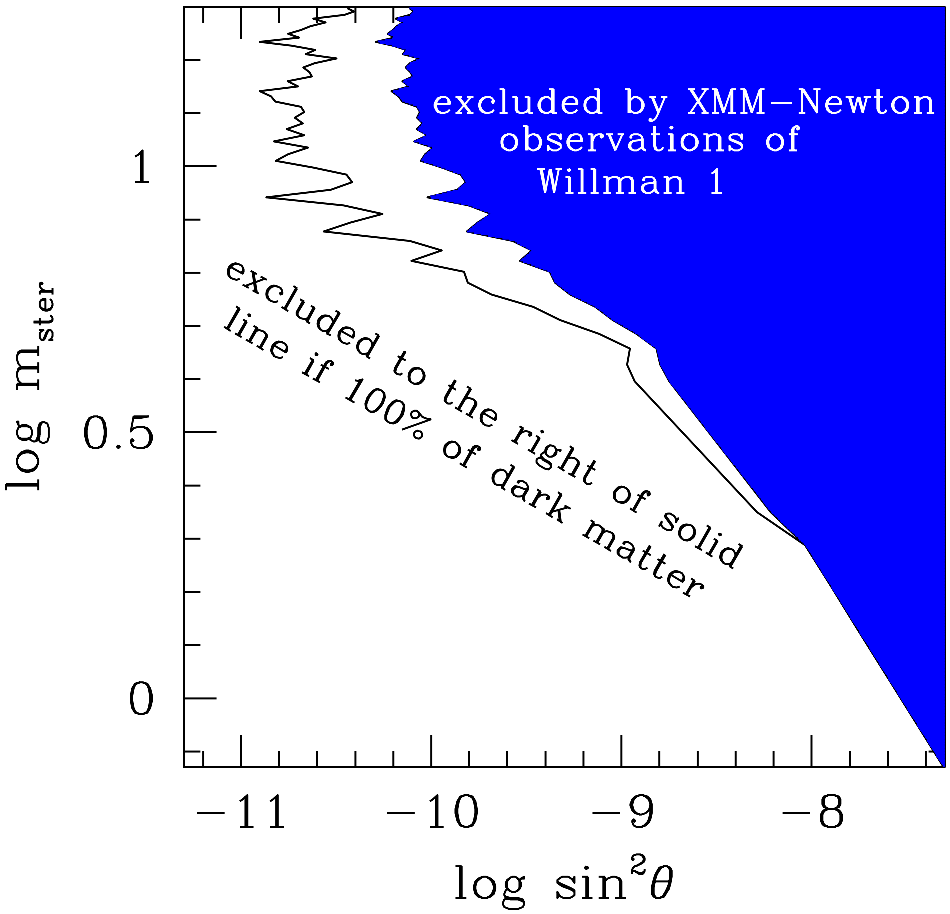
[Loewenstein, A.K., Biermann, ApJ 700, 426 (2009)]

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



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

Latest limits from XMM-Newton (Willman - 1)



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

Summary

- **Sterile neutrino** is a viable **dark matter** candidate
- Corroborating evidence from supernova physics: pulsar kicks
- Models exist for the small Majorana mass
  (e.g., split seesaw, singlet Higgs, flavor symmetries, compositeness, etc.).
- Ongoing search using X-ray telescopes: Chandra, Suzaku, XMM-Newton
- No detection so far, but the search is ongoing