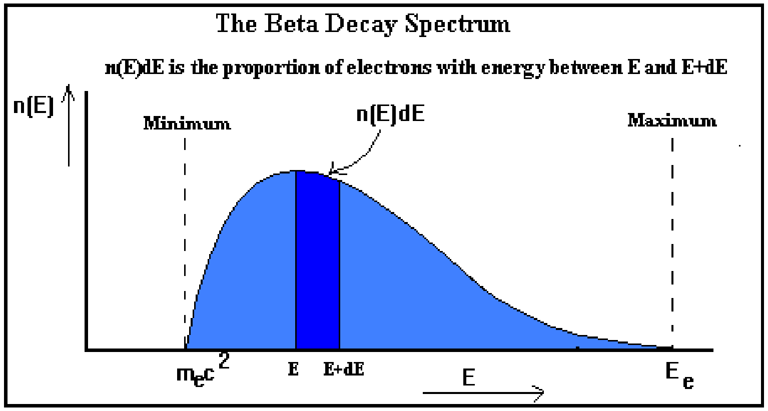
Sterile neutrinos: the dark side of the light fermions

- Neutrino masses and the advent of sterile/right-handed neutrinos
- Sterile neutrinos as dark matter with mass in the keV range.
- Models of keV sterile neutrinos
- Clues from cosmology
- Clues from astrophysics, including supernovae
- Detection in X-rays: strategy and results
- Other dark matter candidates amenable to detection in X-rays
- Future prospects

Before being considered for *missing mass*, neutrinos were discovered as *missing energy* in β-decays



$$A_1 \to A_2 + e^-$$

Why is the electron energy not equal the mass difference between the two nuclei? Is the energy conserved?

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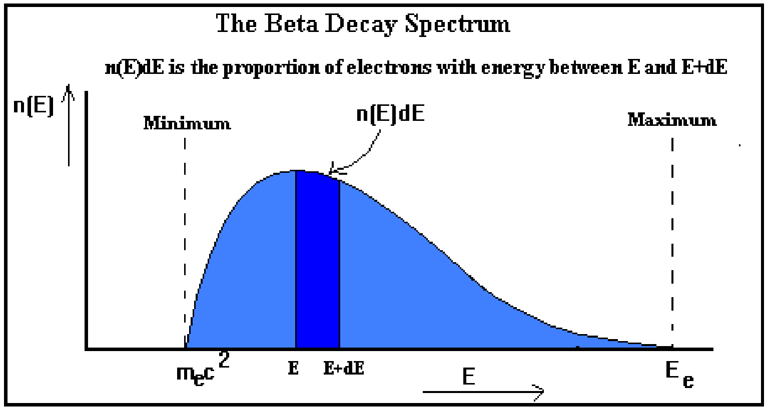

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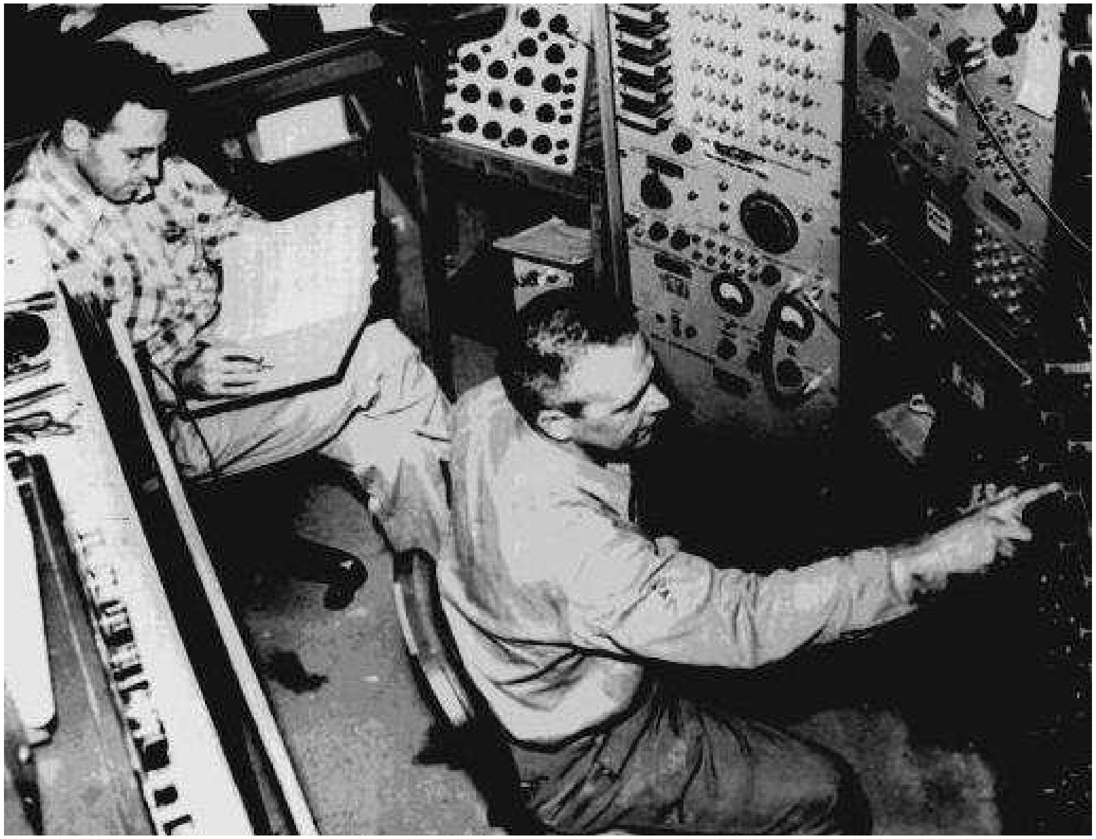
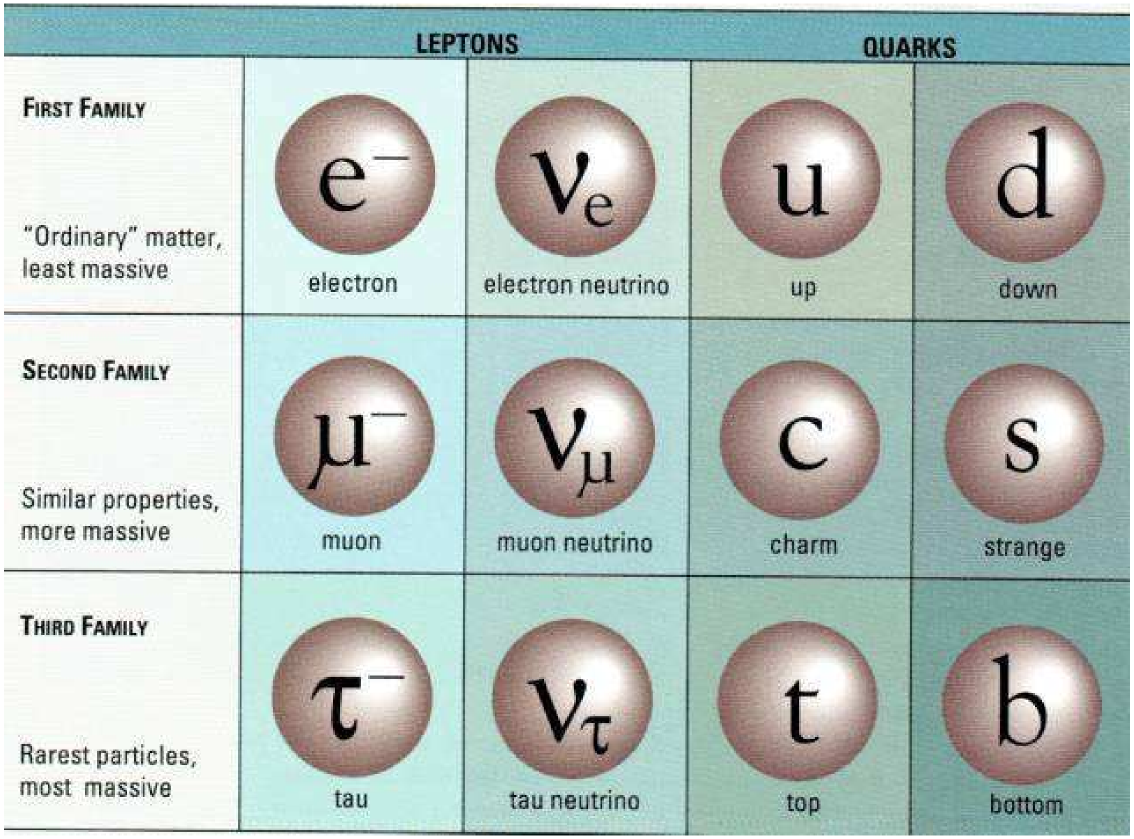
$$A_1 \to A_2 + e^- + \text{new particle}$$

Reines and Cowan detect neutrinos!



Thee families of fermions



Neutrino masses, and the dark side

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

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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)]

New Scientist (June 17, 2006)

Article about sterile neutrinos

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
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$N_{\rm eff}$: what it is, and what it is not

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

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

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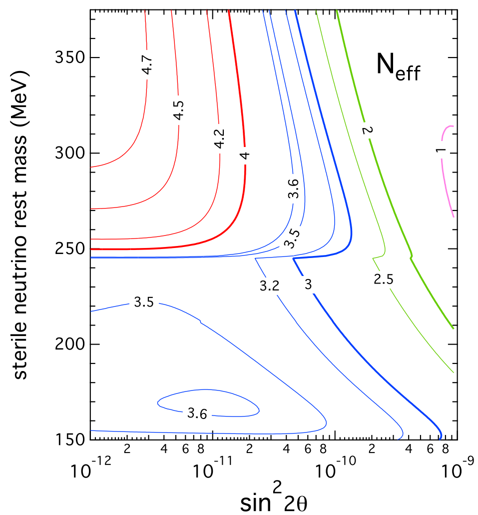

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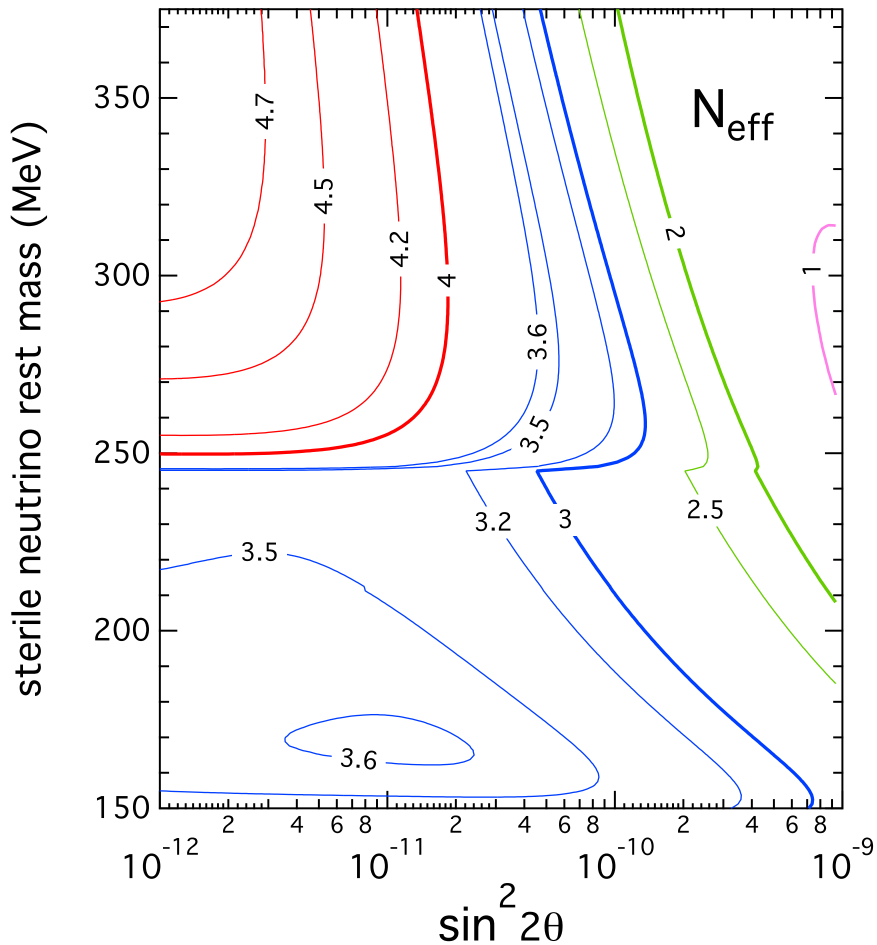

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where H is the Higgs boson and L_α $(\alpha = e, \mu, \tau)$ are the lepton doublets. The mass matrix:

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What is the *natural* scale of M?

Seesaw mechanism

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

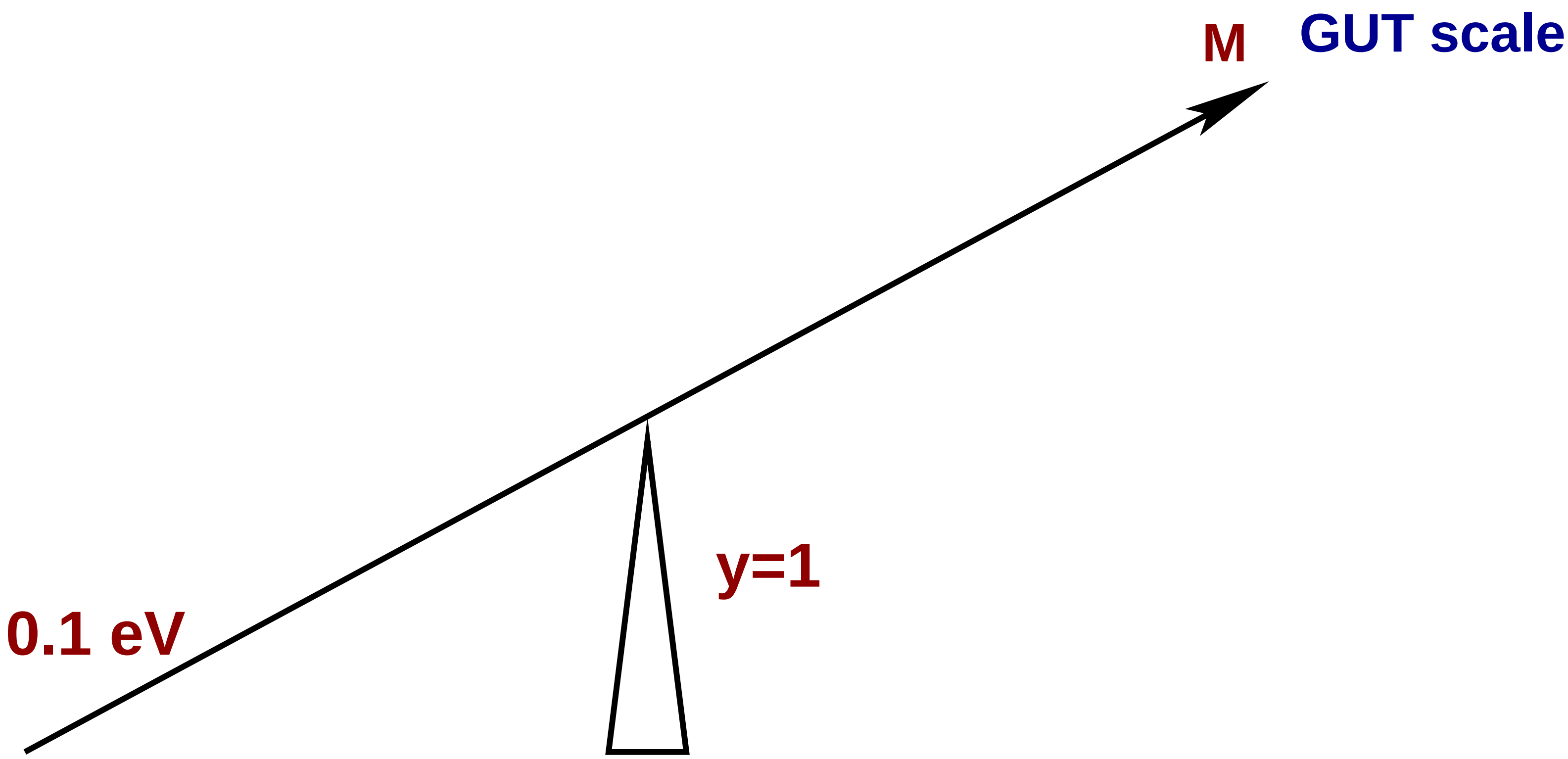
$$D_{ij} = y_{ij} \langle H \rangle$$

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, Minkowski].

Seesaw mechanism



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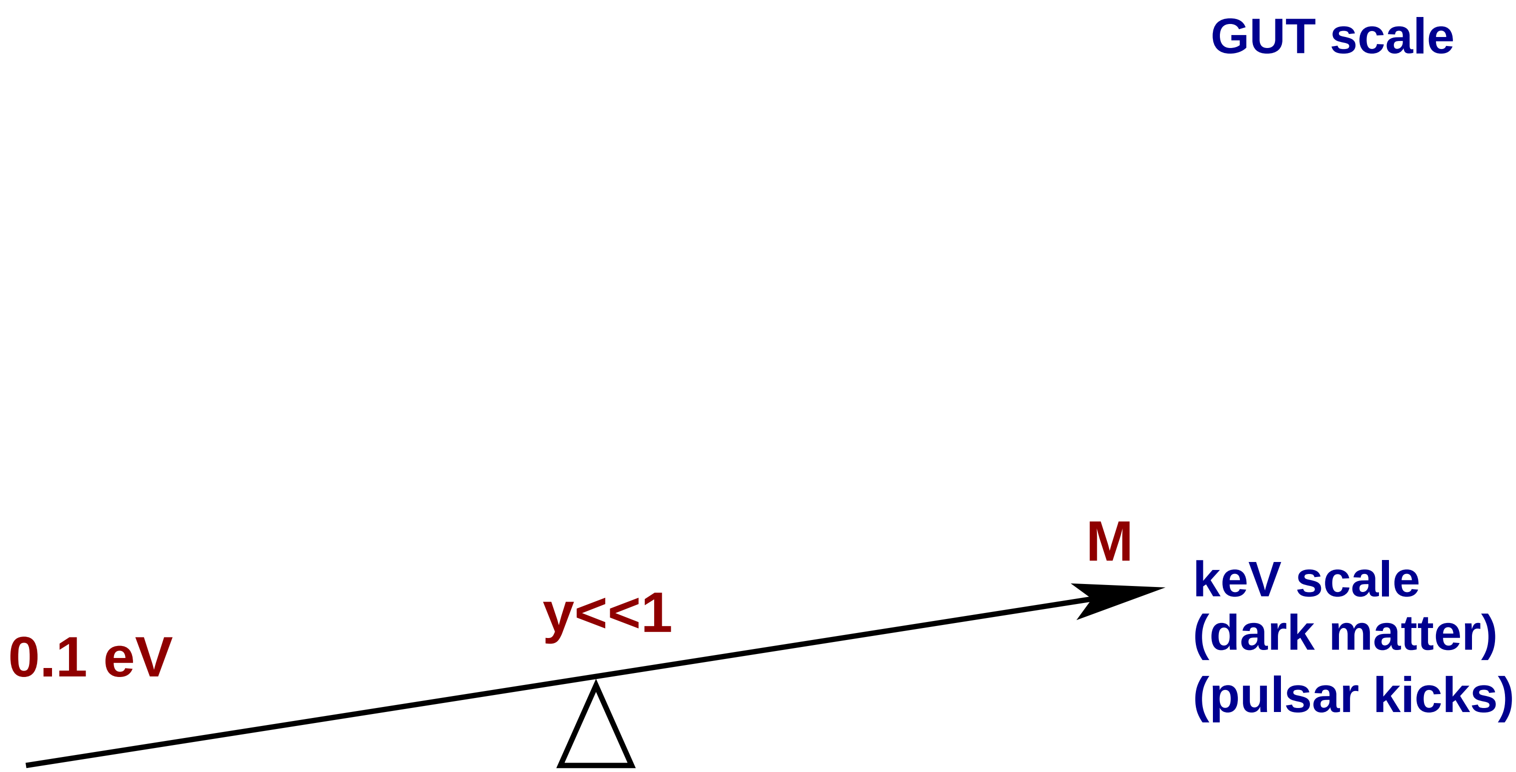

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In the absence of theory of the Yukawa couplings, one is evokes some naturalness arguments.

Naturalness: how natural is a small Majorana mass?

Everyday naturalness is in the eye of the beholder. One needs a definition.

Perturbative naturalness:

$$\textbf{Physical quantity} = \textbf{tree} + (\textbf{1 loop}) + (\textbf{2 loops}) + \ldots$$

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A small Majorana mass implies a small coupling and a small mixing angle
$\Longrightarrow$ **technically natural**.

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Small number is natural if setting it to zero increases the symmetry

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Small M can be considered **natural** (assuming L is a good symmetry).

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- Extra dimensions can make the keV scale natural. [Takahashi, AK, Yanagida]

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Since the fundamental theory of neutrino masses is lacking, one should

consider all allowed values for the singlet/sterile neutrino masses

in the following Lagrangian:

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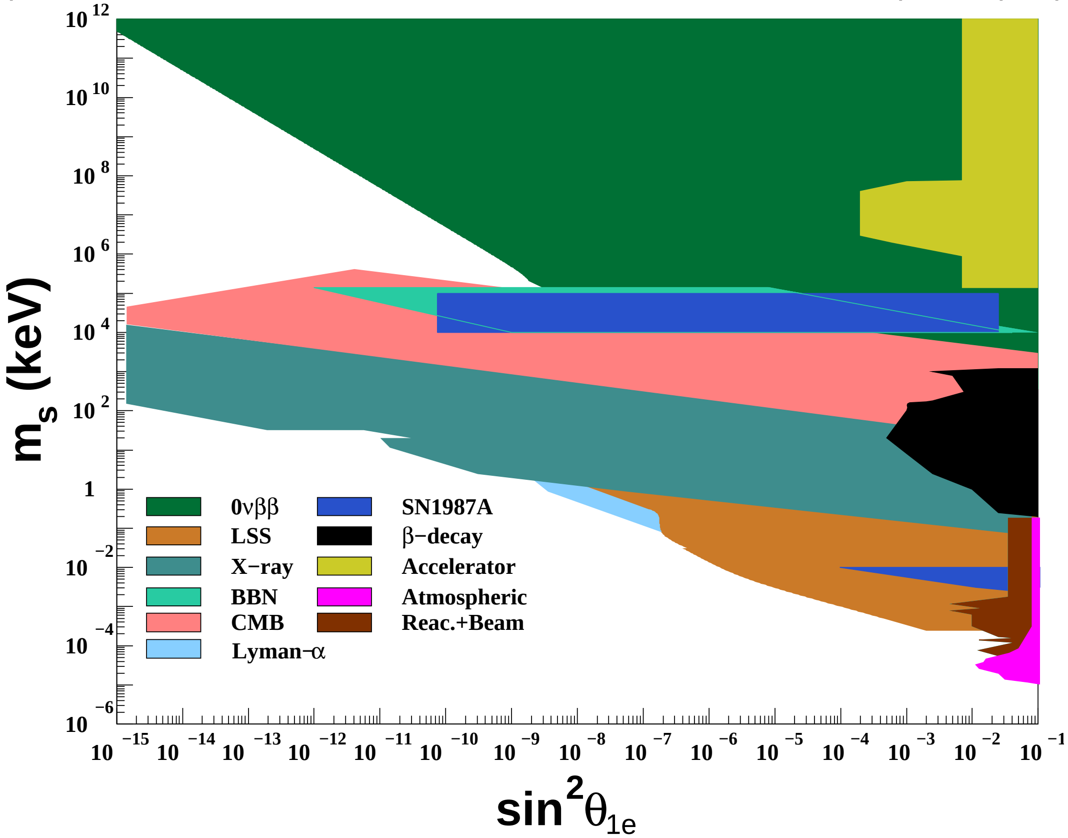
where M is can be small or large

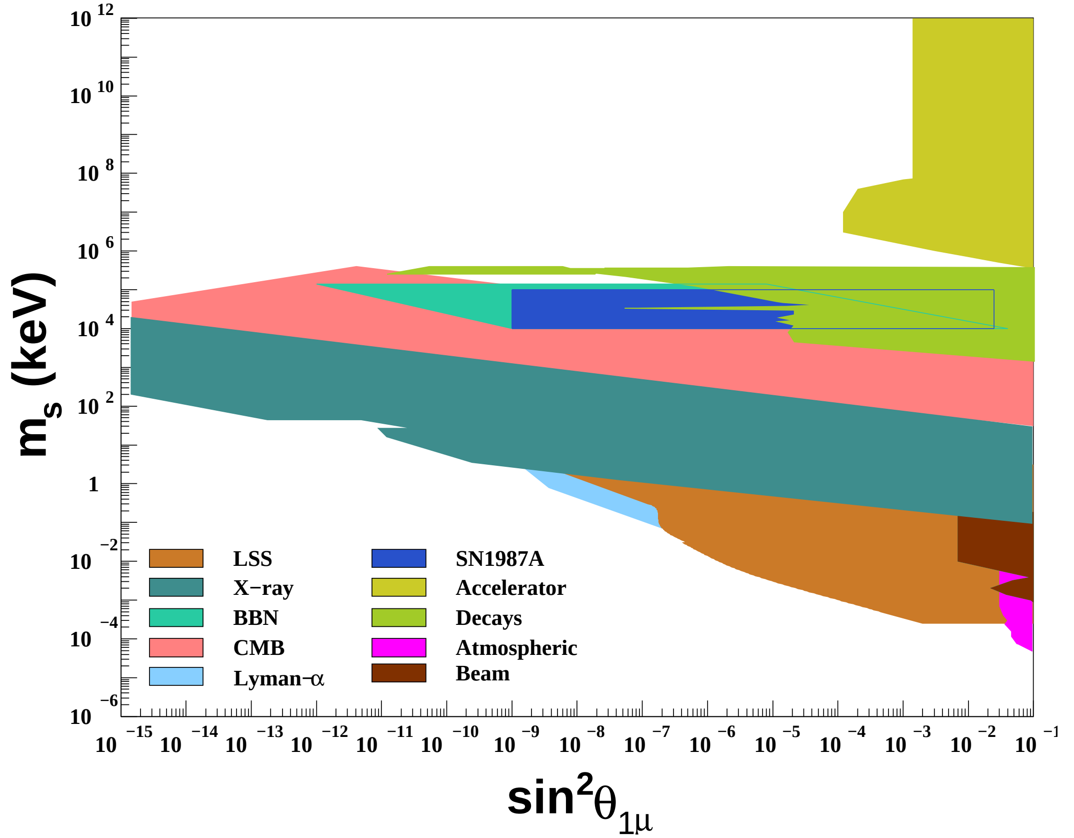
Allowed range of masses and mixing with ν_e

(for a review, see, e.g., A.K. Phys. Rept. 481 (2009) 1)



Allowed range of masses and mixing with ν_μ

(for a review, see, e.g., A.K. Phys. Rept. 481 (2009) 1)



Allowed range of masses and mixing with ν_τ

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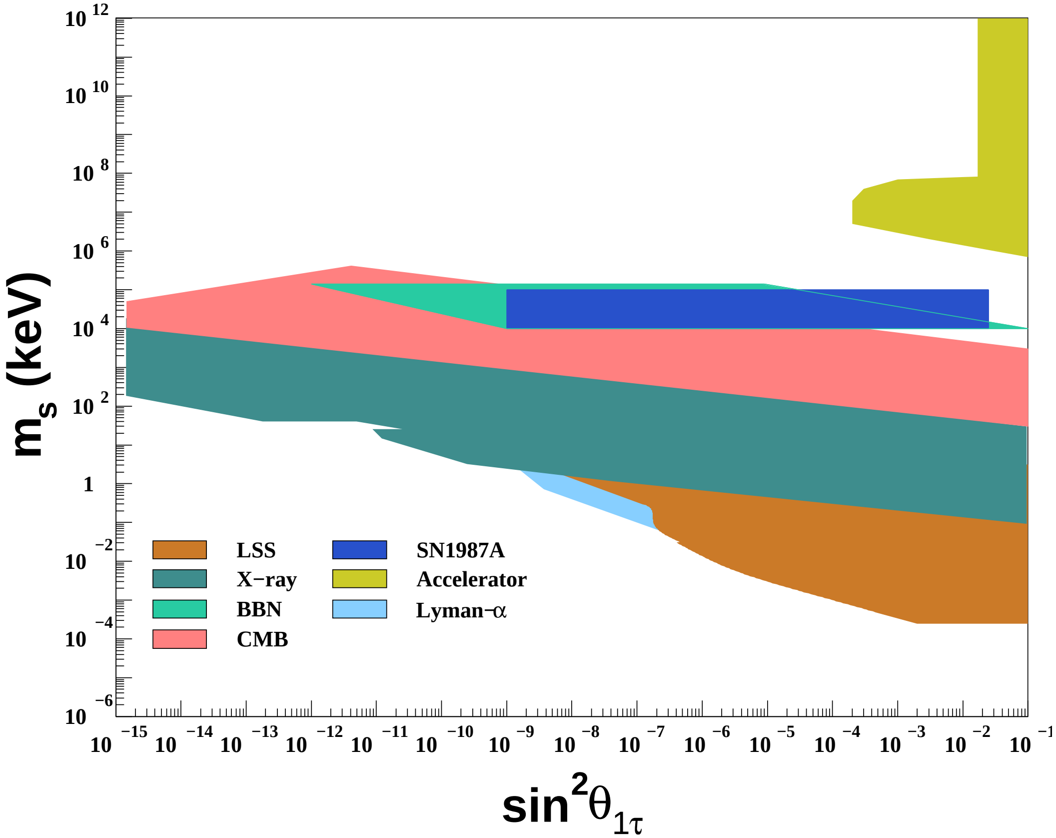


Dark matter: what we know

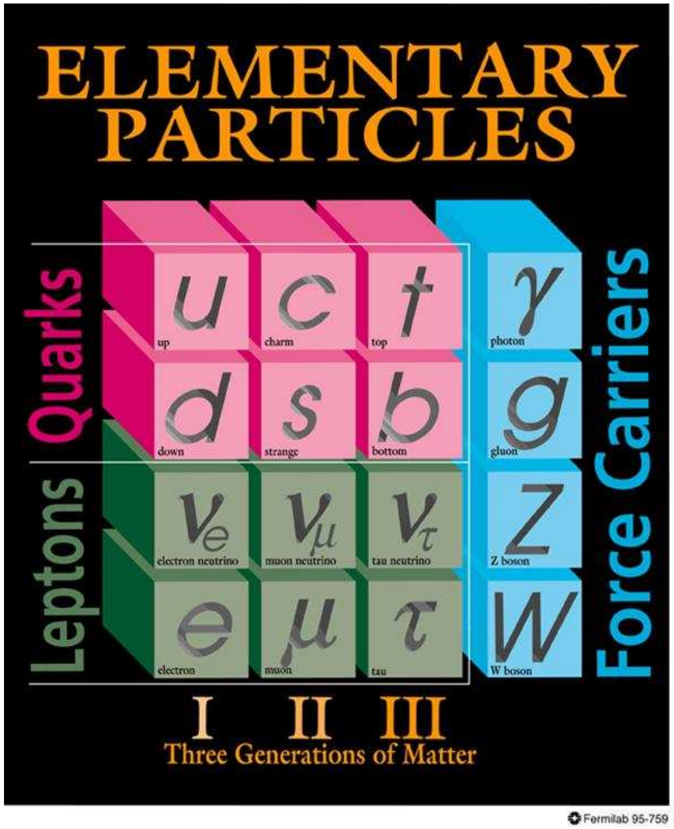
We know:

- dark matter exists
- dark matter is not usual atoms
- cold or warm, not "hot"

We don't know:

- D.M. composition (dark matter experiments)
- D. M. interactions (dark matter experiments)
- cold or warm?

None of the known particles can be dark matter



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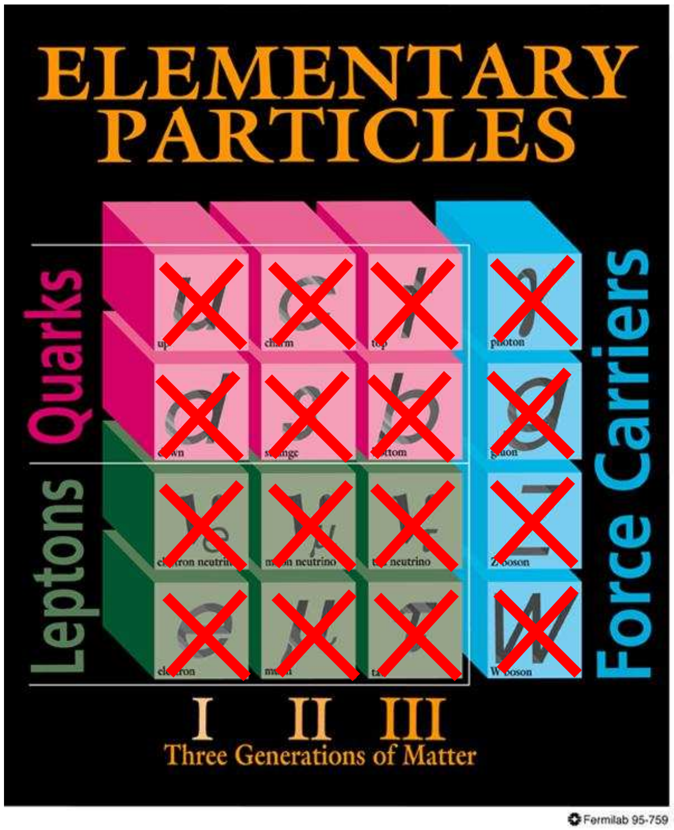
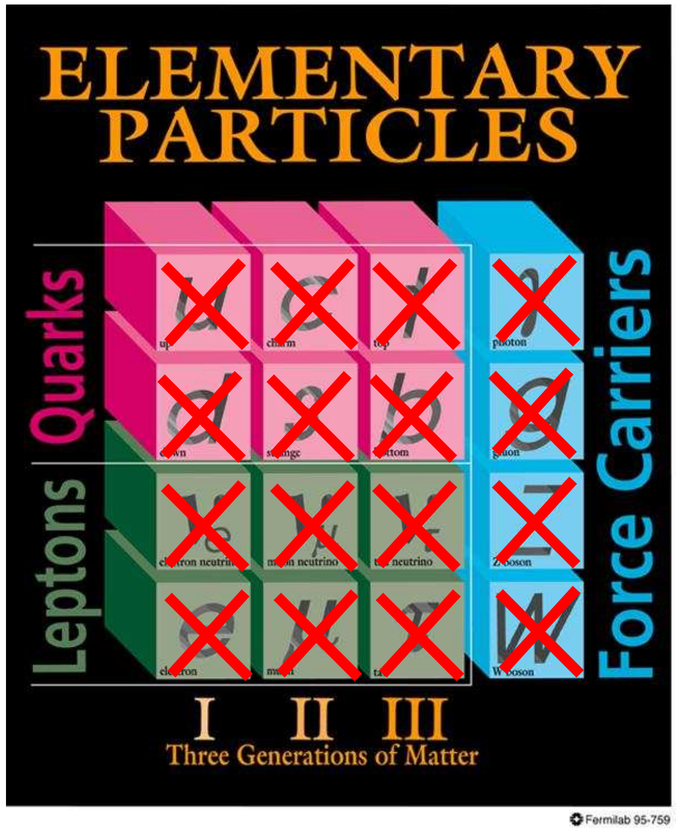


Dark matter ⇒ new physics (at least one new particle)



The early universe: relic neutrinos and dark matter

Ordinary (active) neutrinos contribute a negligible amount to dark matter.

$$\sum_j m(\nu_j) < \Omega_{\nu\bar{\nu}} h^2 (94\,\mathrm{eV}) < \Omega_{\mathrm{matter}} h^2 (94\,\mathrm{eV}) \approx 13\,\mathrm{eV} \quad (1)$$

[Gerstein + Zeldovich]

Experiments suggest much smaller masses.

Also, **hot!**

Neutrinos make a negligible contribution to matter density of the universe.

Sterile neutrinos with small mixing to active neutrinos

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- perhaps, a minimal extension of the Standard Model consistent with dark matter

Sterile neutrinos with small mixing to active neutrinos

$$\begin{cases} |\nu_1\rangle = \cos\theta_m |\nu_e\rangle - \sin\theta_m |\nu_s\rangle \\ |\nu_2\rangle = \sin\theta_m |\nu_e\rangle + \cos\theta_m |\nu_s\rangle \end{cases} \quad (2)$$

The almost-sterile neutrino, $|\nu_2\rangle$ was never in equilibrium.

Dodelson – Widrow. Production of ν_2 is in oscillations.

$|\nu_1\rangle$ (in equilibrium) $\longrightarrow$ $|\nu_2\rangle$ (out of equilibrium)

Abundance

$$n \propto (\sin^2\theta_m(T)) \, (M_{\rm Planck}/T^2)$$

at the highest temperature for which the oscillations are not suppressed.

Production by neutrino oscillations [Dodelson–Widrow]

$$\sin^2 2\theta_m \approx \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V_m - V_T)^2},$$

Here V_m and V_T are the effective matter and temperature potentials. In the limit of small angles and small lepton asymmetry, the mixing angle can be approximated as

$$\sin\theta_m \approx \frac{\sin\theta}{1 + 0.27\zeta \left(\frac{T}{100\,\mathrm{MeV}}\right)^6 \left(\frac{\mathrm{keV}^2}{\Delta m^2}\right)}$$

where $\zeta = 1.0$ for mixing with the electron neutrino, and $\zeta = 0.30$ for ν_μ and ν_τ.

Dodelson–Widrow production

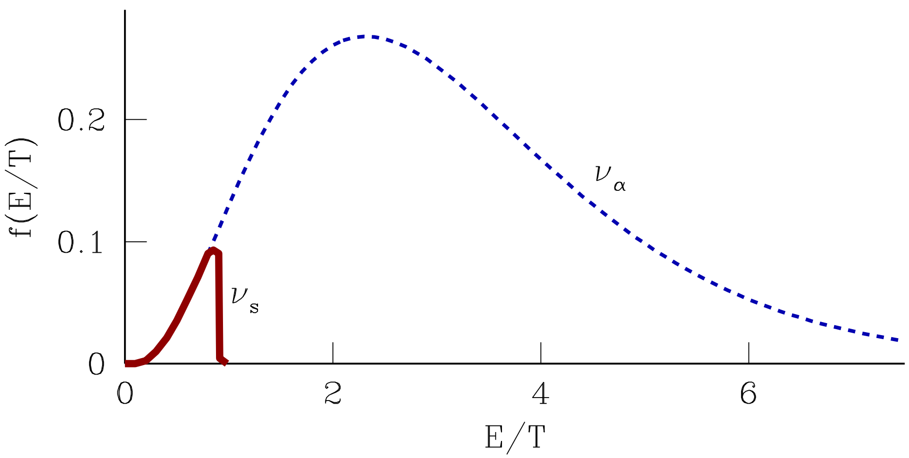
$$\sin\theta_m \approx \frac{\sin\theta}{1+0.27\zeta\left(\frac{T}{100\,\mathrm{MeV}}\right)^6\left(\frac{\mathrm{keV}^2}{\Delta m^2}\right)}$$

The resulting density of relic sterile neutrinos [Dodelson, Widrow]:

$$\boldsymbol{\Omega_{\nu_2} \sim 0.3\left(\frac{\sin^2 2\theta}{10^{-8}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^2}$$

Shi–Fuller production

If a lepton asymmetry $\sim 10^{-2}$ is created at temperature T such that $100\,\mathrm{MeV} < T < 10^2\,\mathrm{GeV}$, then the oscillations are enhanced by the MSW resonance. Furthermore, the resonance picks out the low-momentum part of the distribution. Hence, the population of dark matter particles have less free streaming than the same particles produced via Dodelson–Widrow process.



νMSM and the sterile neutrino masses

νMSM [Shaposhnikov et al.]: The Standard Model is augmented by three right-handed neutrinos with masses

$$M_1 \sim \text{a few keV}, \quad M_{2,3} \sim 0.1 - 10 \text{ GeV}, \quad |M_2 - M_3|/(M_2 + M_3) \ll 10^{-5}$$

- Dark matter is explained by the keV sterile neutrino
- Leptogenesis is realized via neutrino oscillations [Akhmedov,Rubakov,Smirnov]
- The same oscillations can generate the lepton asymmetry large enough to facilitate dark matter production a la Shi–Fuller.

A very economical model that explains both dark matter and ordinary matter abundances in the universe.

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 $S \to NN$:

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

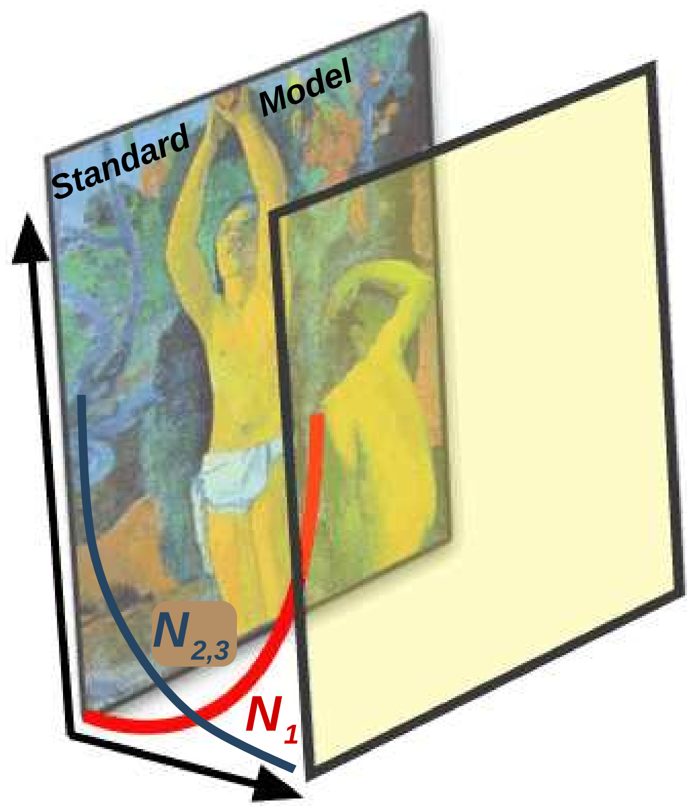
Here ξ is the dilution factor due to the change in effective numbers of degrees of freedom.

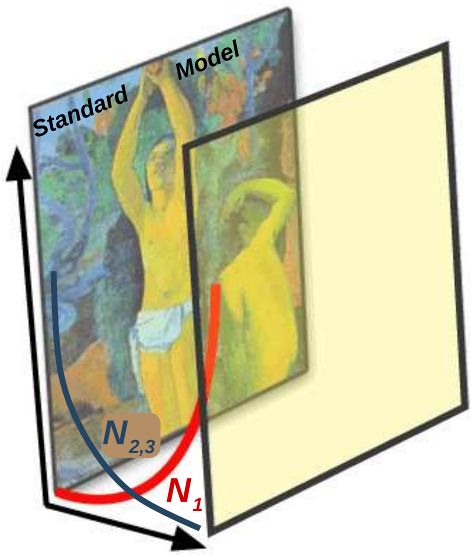
$\langle S \rangle \sim 10^2\,\mathrm{GeV}$ (EW scale)
$M_s \sim \mathrm{keV}$ (for stability) $\Rightarrow h \sim 10^{-8}$

$$\Rightarrow \Omega \approx 0.2$$

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

Split seesaw





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

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

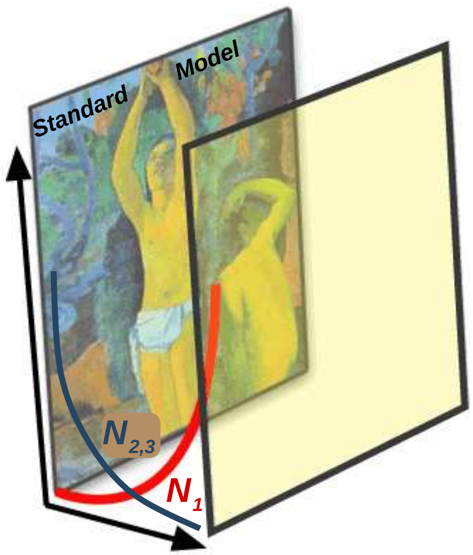
The zero mode: $(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0$. behaves as $\sim \exp(\pm mz)$. The 4D fermion:

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

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:

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

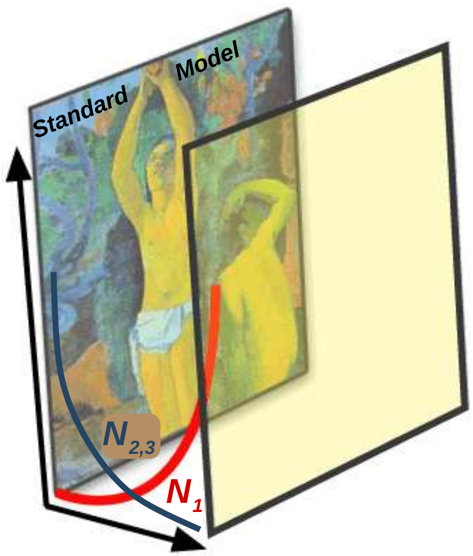
$$y_{d=4} = y_{d=5}\sqrt{\frac{2m_i}{M(e^{2m_i\ell}-1)}}$$

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

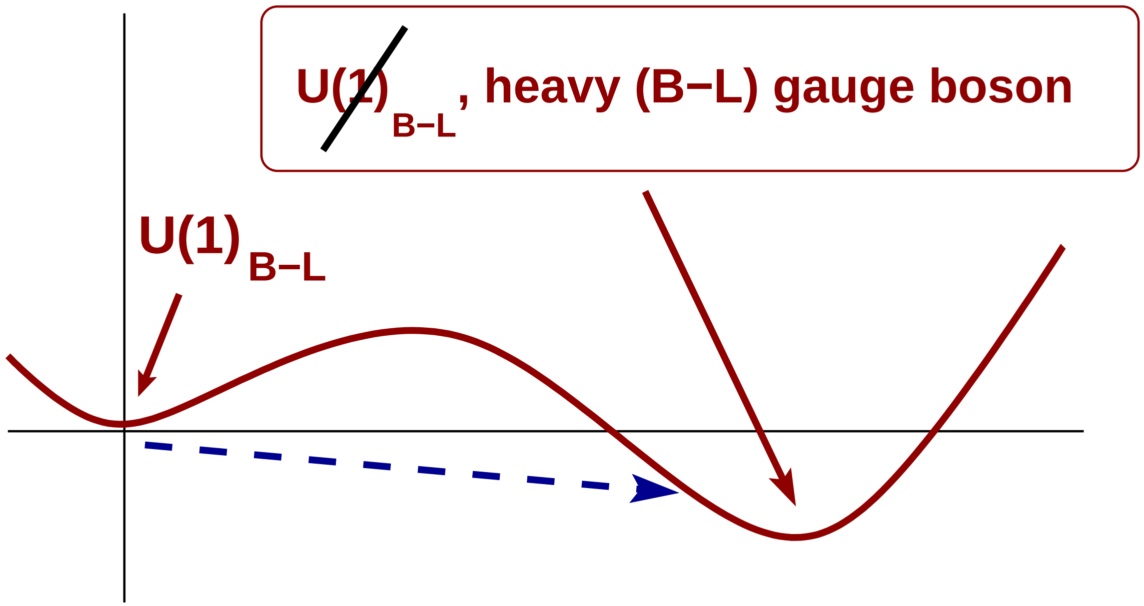
[AK, Takahashi, Yanagida]

Dark matter production in Split Seesaw: two scenarios

The $\mathrm{U}(1)_{(B-L)}$ 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 $T_R \sim 5\times10^{13}\,\mathrm{GeV} \ll \times\langle\phi\rangle$, 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 $\mathrm{U}(1)_{(B-L)}$ 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.

Dark matter production in Split Seesaw: second scenario



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

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**. Advantage: "natural" dark matter abundance
- **Split seesaw**: [AK, Takahashi, Yanagida]. Two production mechanisms, **cold** and **even colder**. Advantage: "naturally" low mass scale

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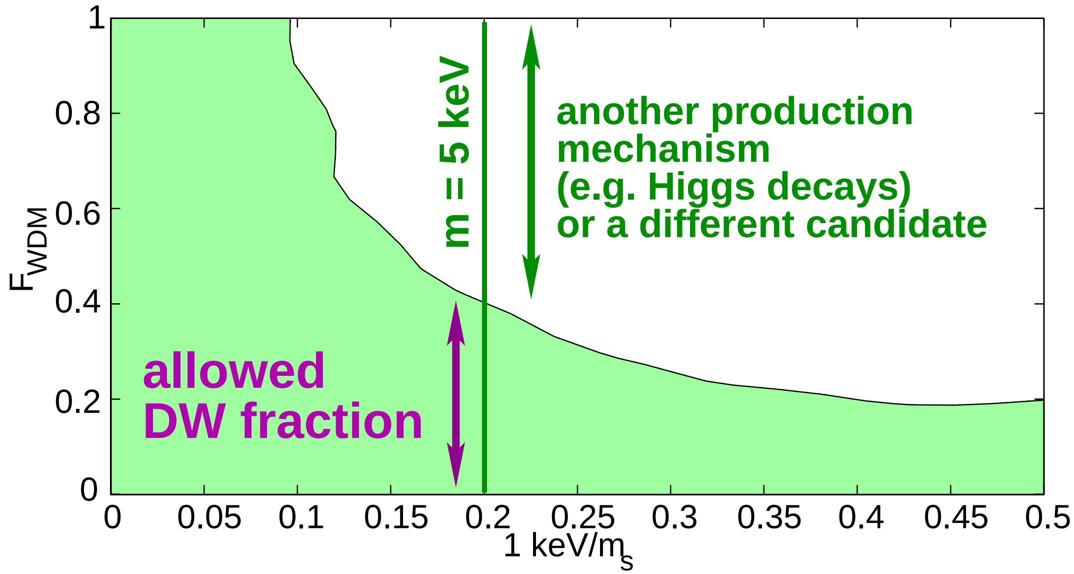
Generically, two components: colder and warmer

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]

Challenges to CDM = hints of (two-component) 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.]

Astrophysical clues: supernova

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- 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]

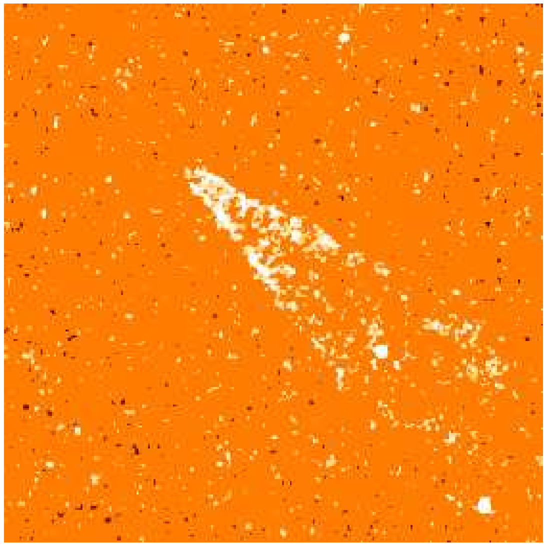
The pulsar velocities.

The pulsar velocities.

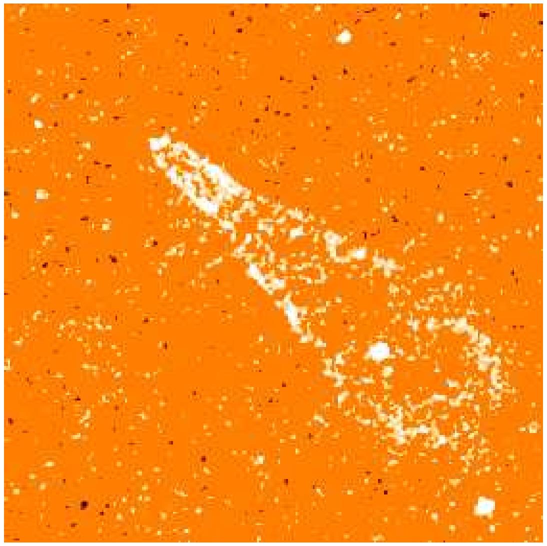
Pulsars have large velocities, $\langle v \rangle \approx 250 - 450$ km/s.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

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

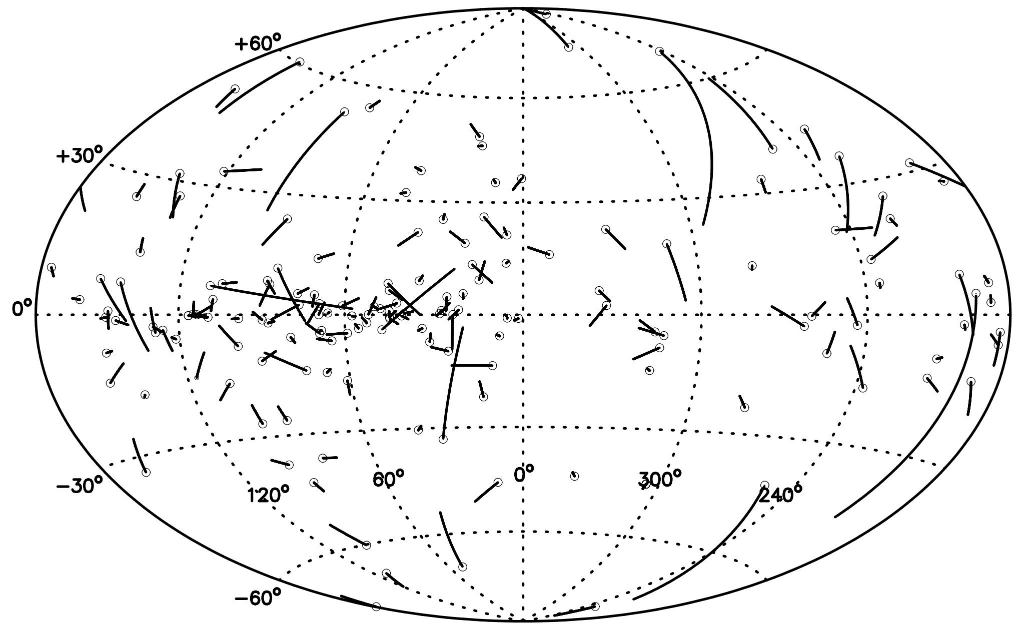


HST, December 1994



HST, December 2001

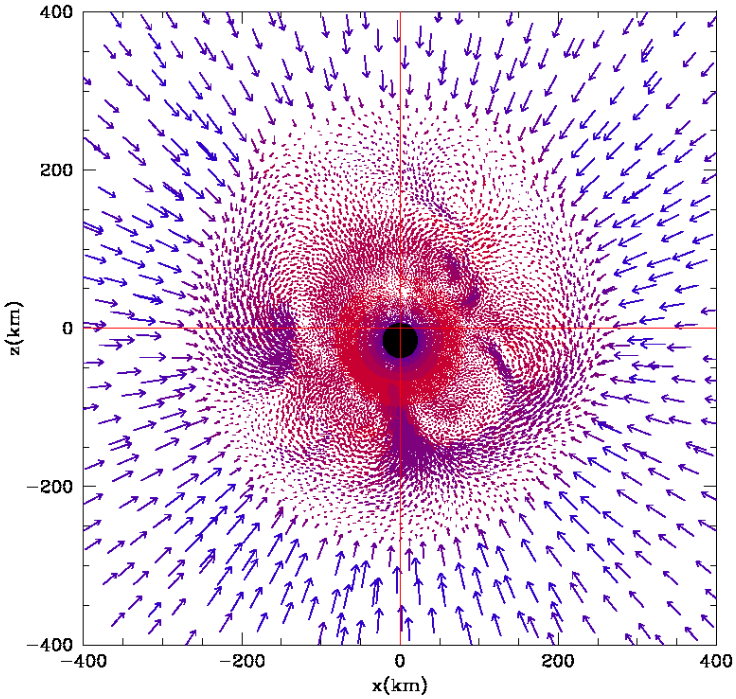
Map of pulsar velocities

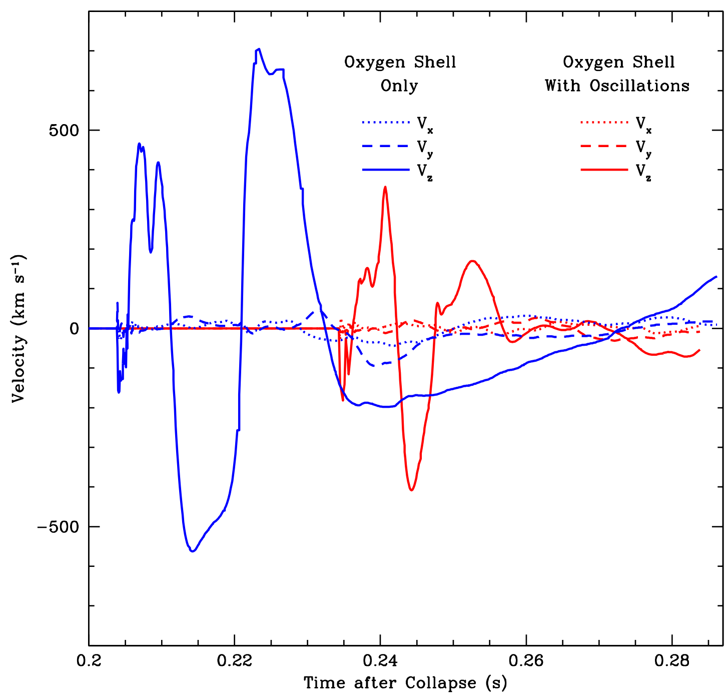


Proposed explanations:

- 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"...

Asymmetric collapse





"...the most extreme asymmetric collapses
do not produce final neutron star velocities above 200km/s" [Fryer '03]

Supernova neutrinos

Nuclear reactions in stars lead to a formation of a heavy iron core. When it reaches $M \approx 1.4 M_{\odot}$, the pressure can no longer support gravity. $\Rightarrow$ collapse.

Energy released:

$$\Delta E \sim \frac{G_N M^2_{\rm Fe\ core}}{R} \sim 10^{53} \rm erg$$

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99% of this energy is emitted in neutrinos

Pulsar kicks from neutrino emission?

Pulsar with $v \sim 500$ km/s has momentum

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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.

Core collapse supernova

Onset of the collapse: $t = 0$

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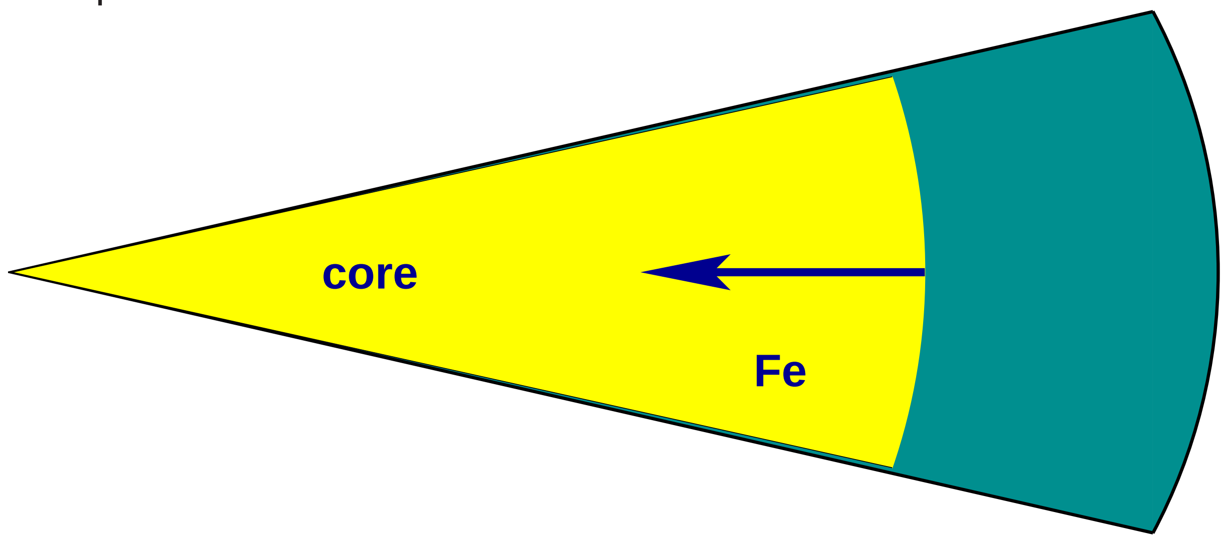
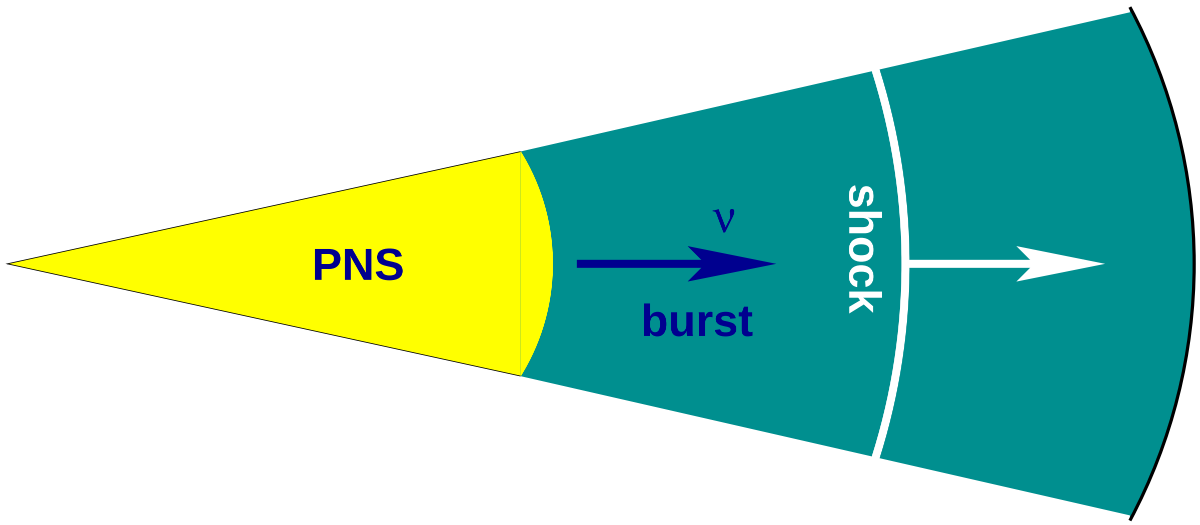


Core collapse supernova

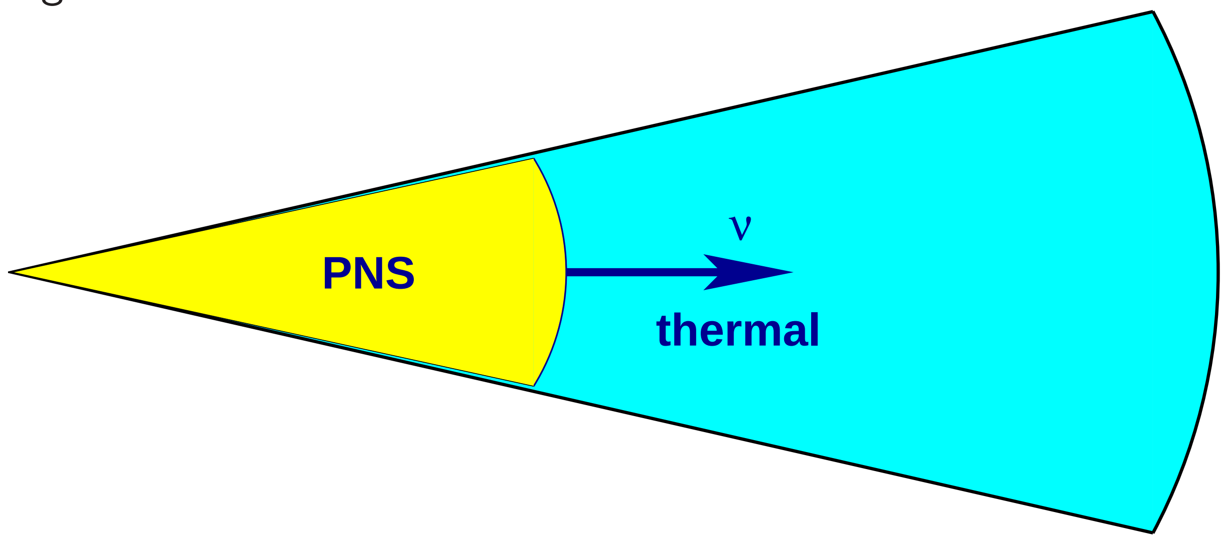
Shock formation and "neutronization burst": $t = 1 - 10$ ms



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.

Electroweak processes producing neutrinos (**urca**),

$$p + e^- \rightleftharpoons n + \nu_e \quad n + e^+ \rightleftharpoons p + \bar{\nu}_e, \ldots$$

George Gamow

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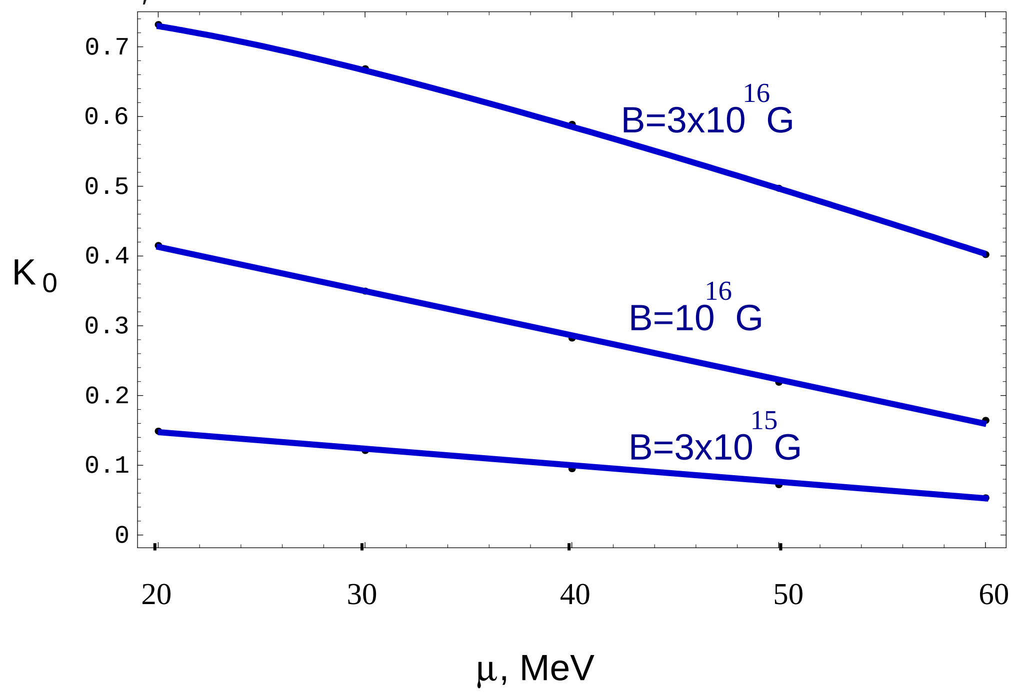
$$\sigma(\uparrow \; e^-, \uparrow \; \nu) \neq \sigma(\uparrow \; e^-, \downarrow \nu)$$

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.

In a strong magnetic field,



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

Pulsar kicks from the asymmetric production of neutrinos?
[Chugai; Dorofeev, Rodionov, Ternov]

Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

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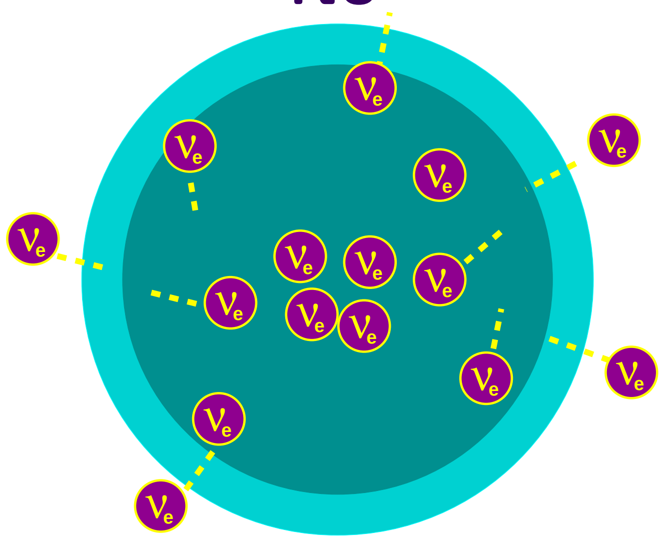

Neutrinos are trapped at high density.

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Rescattering washes out the asymmetry

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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].

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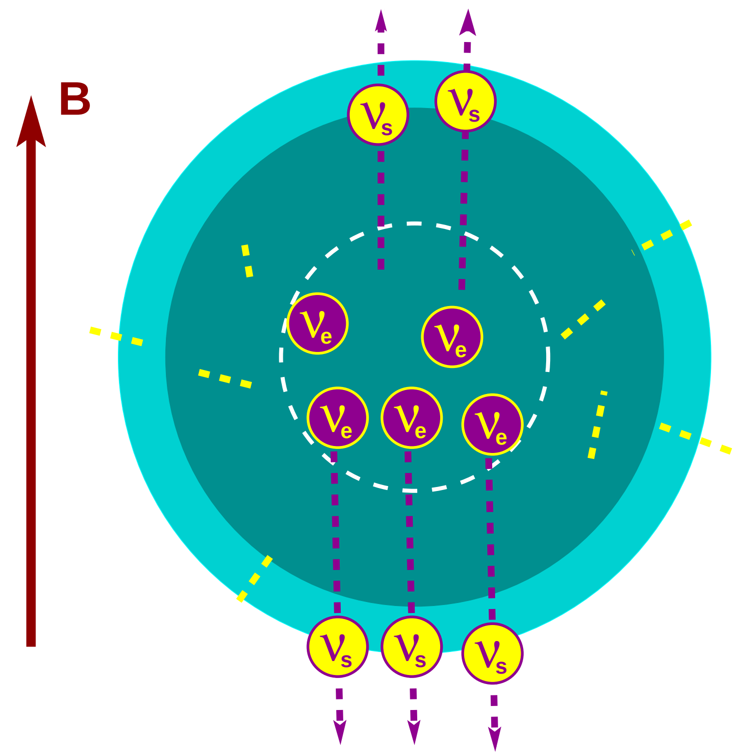
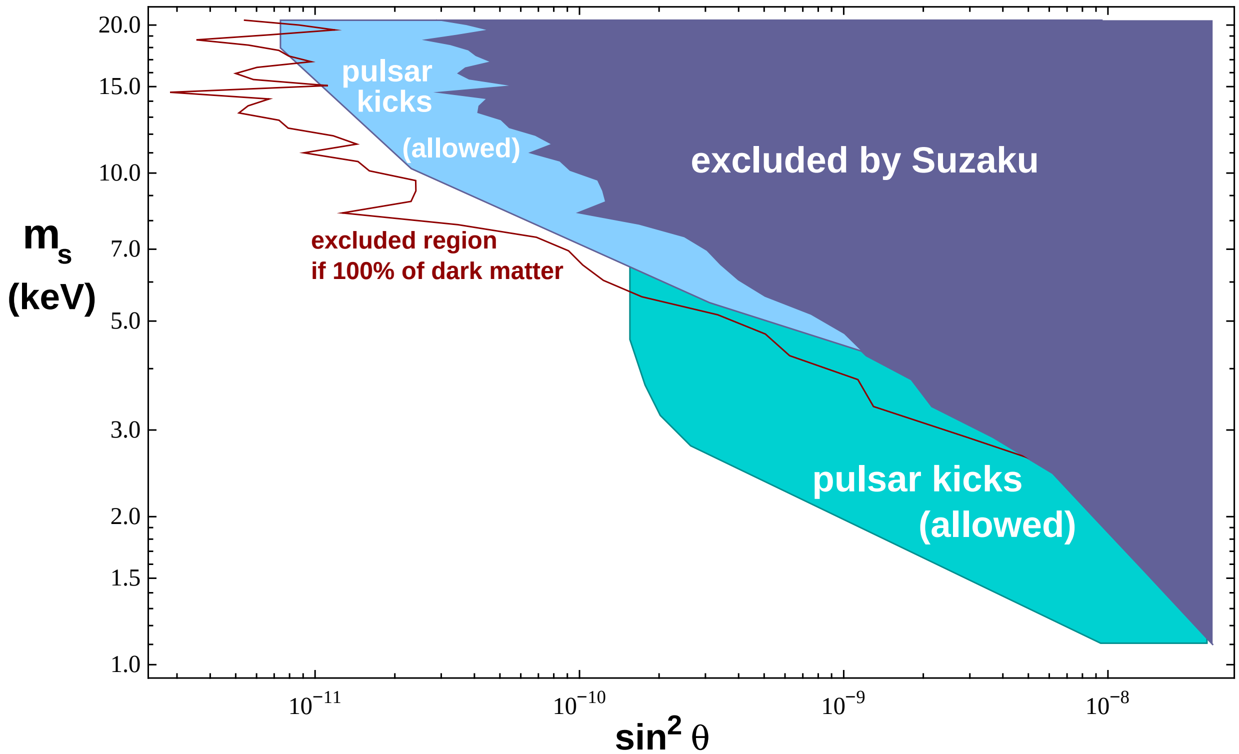
However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

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



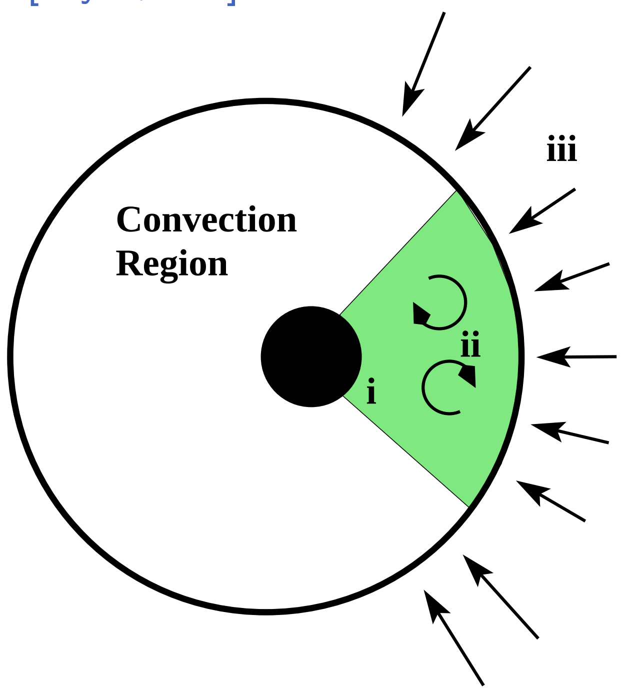
The mass and mixing required for the pulsar kick are consistent with dark matter.

Pulsar kicks focus the search



Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK]



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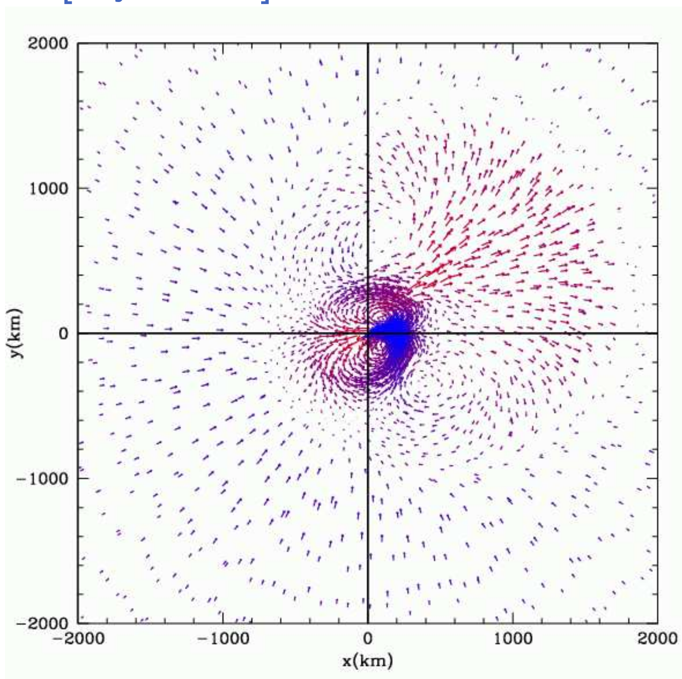
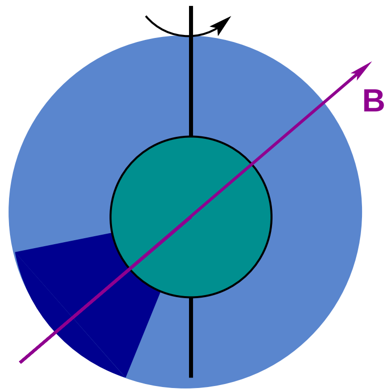


Other predictions of the pulsar kick mechanism

- 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, because
  - the direction of rotation remains unchanged
  - only the z-component survives

  this correlation recently confirmed



Astrophysical clues: star formation and reionization

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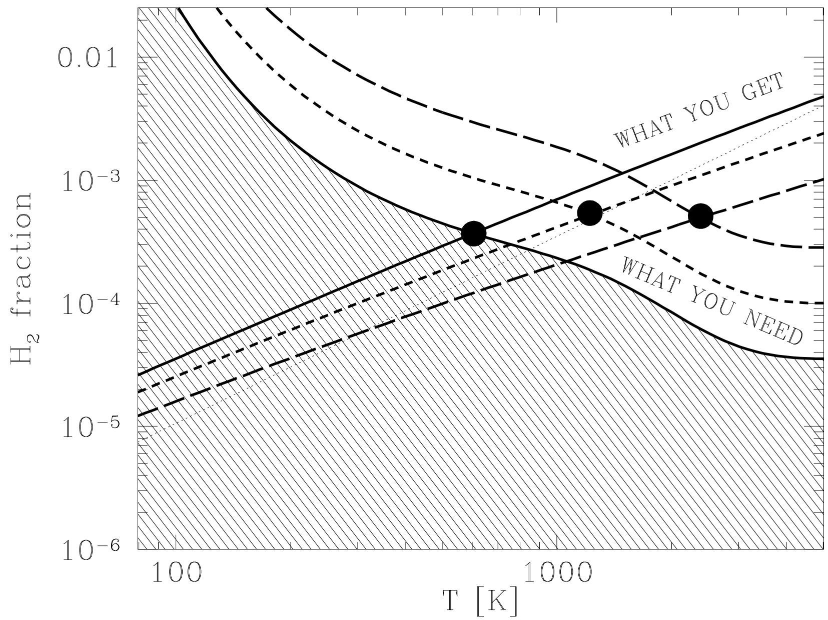
Molecular hydrogen is necessary for star formation



[Tegmark, et al., ApJ **474**, 1 (1997)]

Molecular hydrogen

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

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In the presence of ions the following reactions are faster:

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

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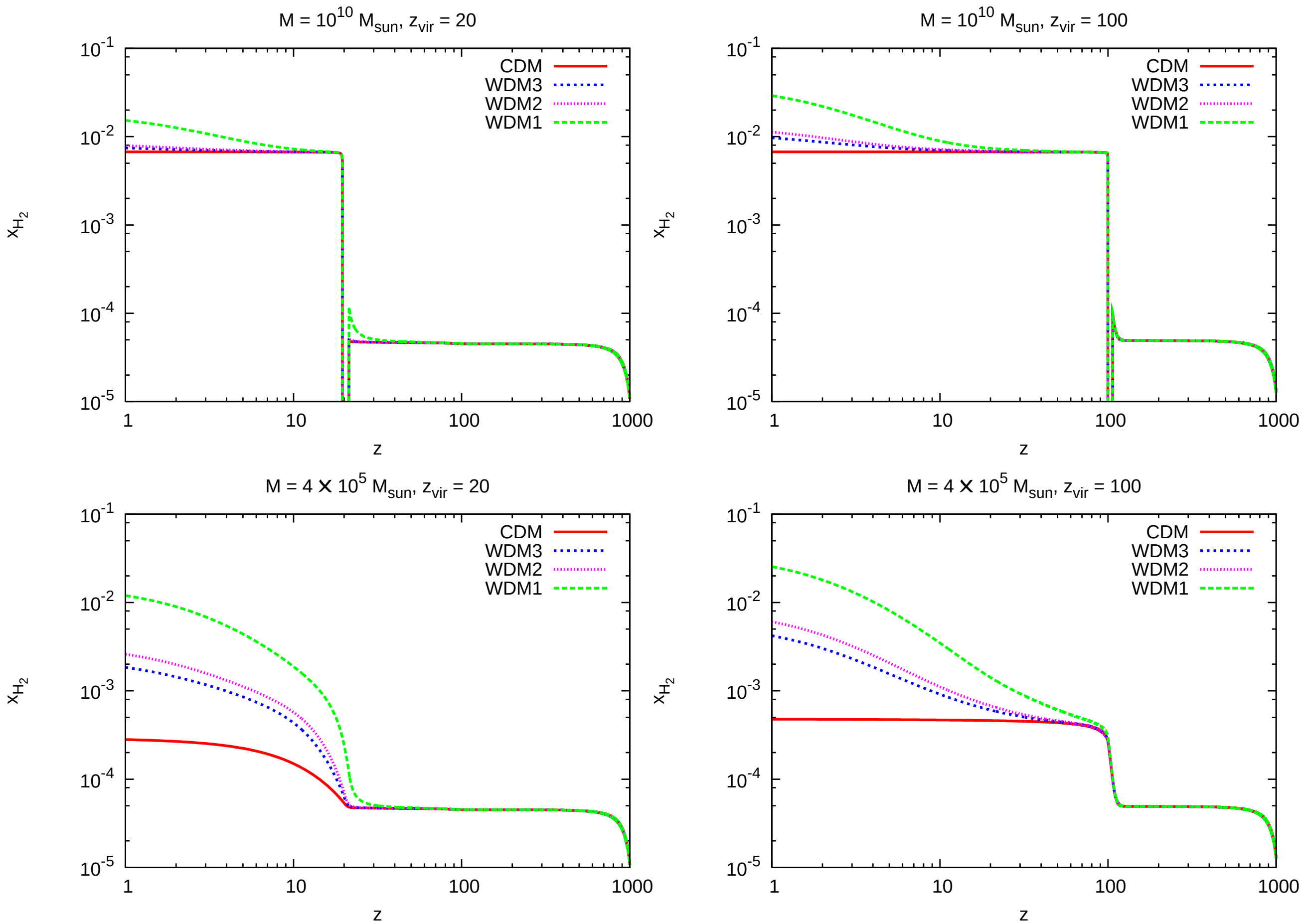
H^+ catalyze the formation of molecular hydrogen

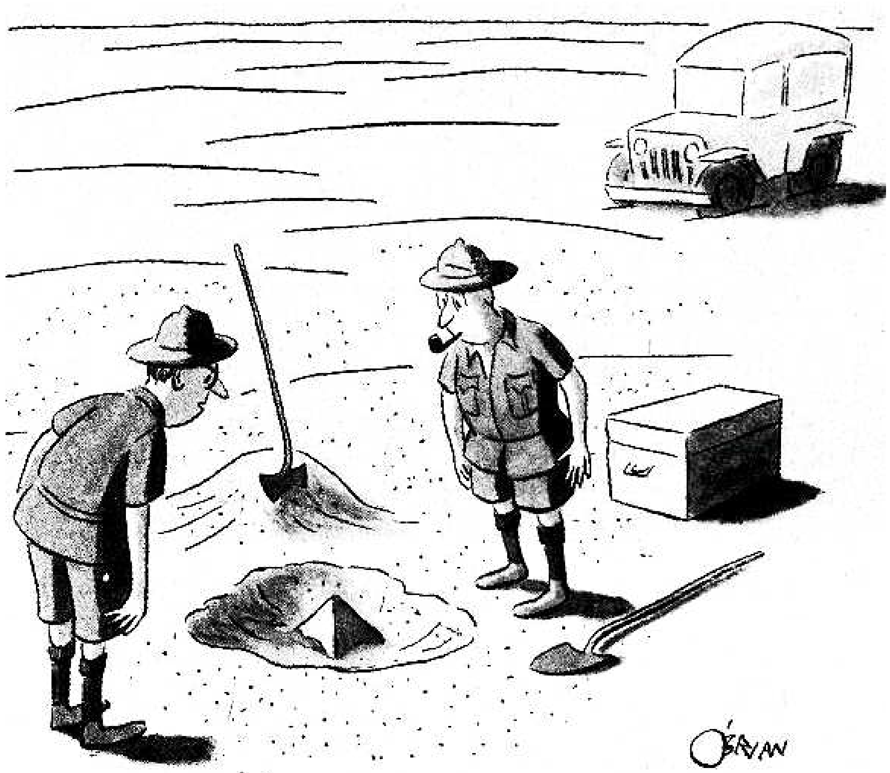
[Biermann, AK, PRL **96**, 091301 (2006)]

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



[Biermann, AK; Stasielak, Biermann, AK]

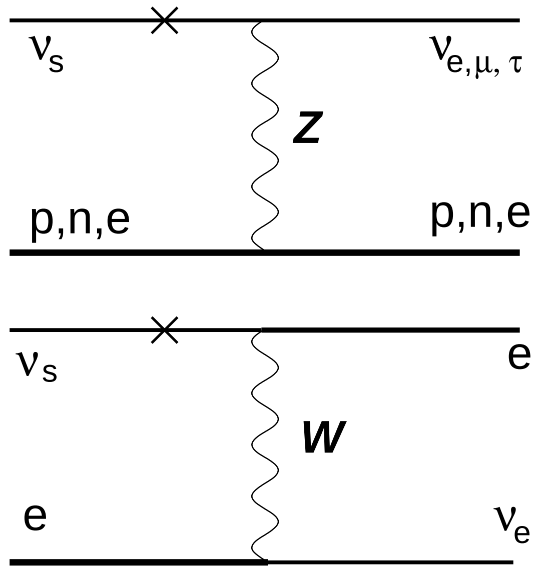
Clues of the possible dark sterile neutrinos



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

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]**

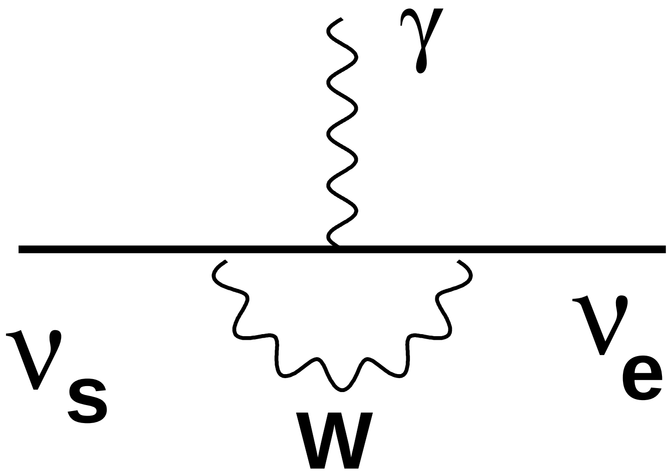


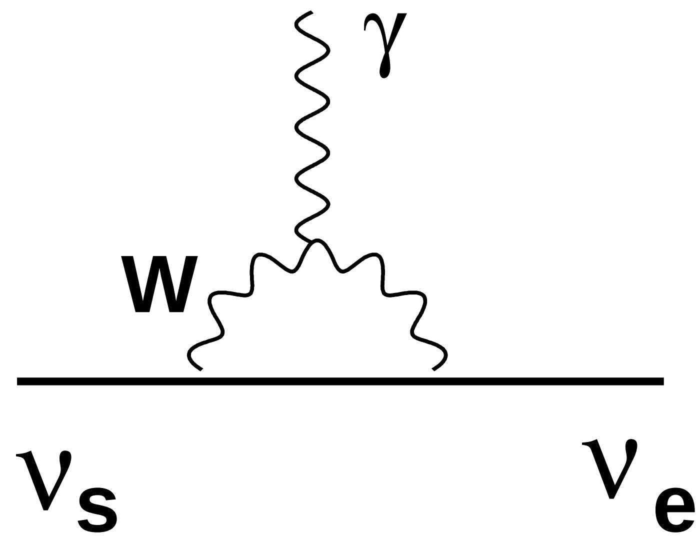
Rates low:

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

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	$\mathbf{\sim 10^{-3}}$ **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!**

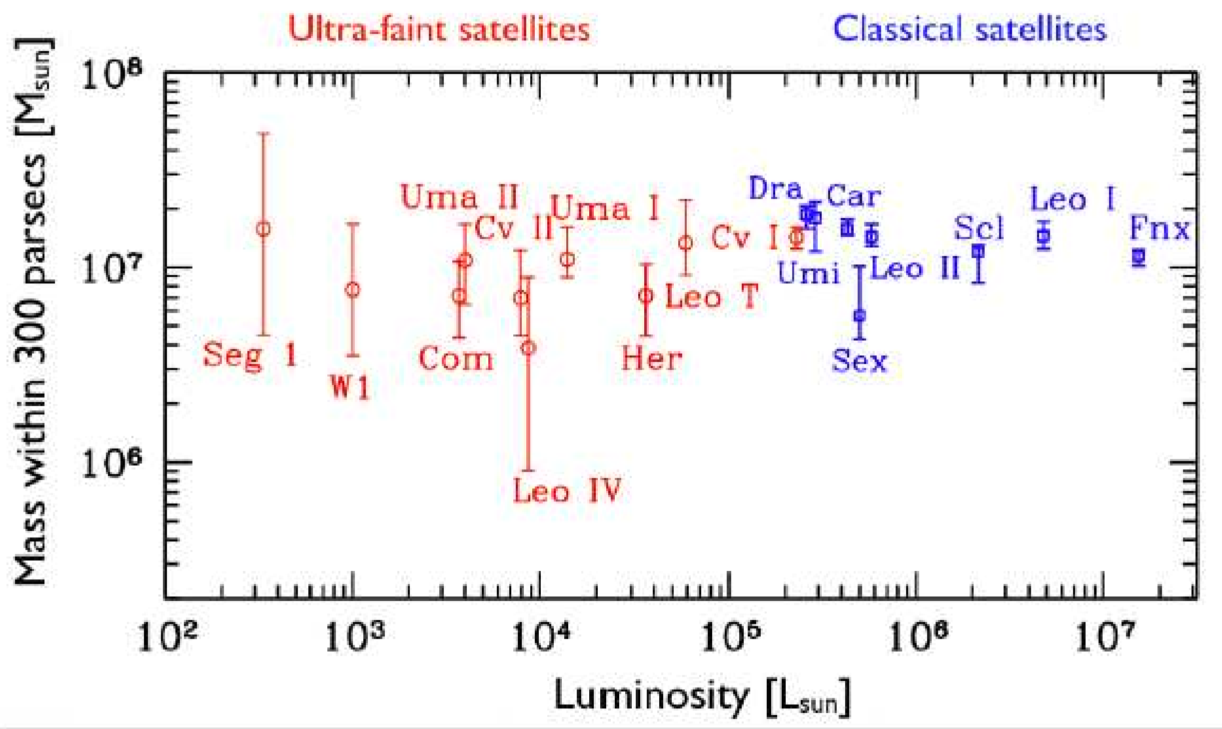
[Loewenstein]

Target selection

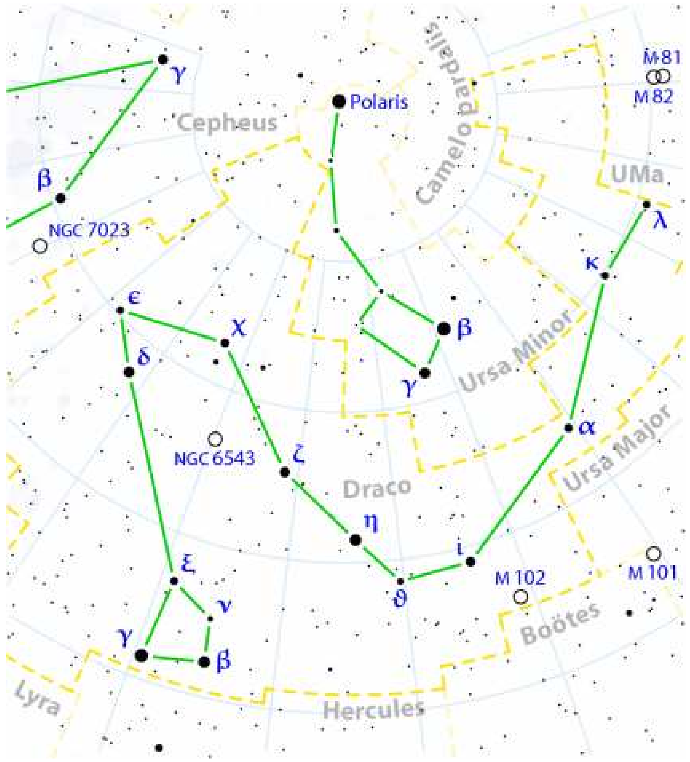
target	dark matter content	background	signal/noise	overall
MW center	high/uncertain	very high	low	far from ideal
MW, "blank sky"	low	low	low	not ideal
nearby galaxy (M31)	high/uncertain	high	low	not ideal
clusters	high	very high	low	not ideal
dSph	high/uncertain	low	high	**best choice**

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

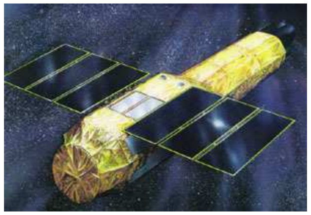


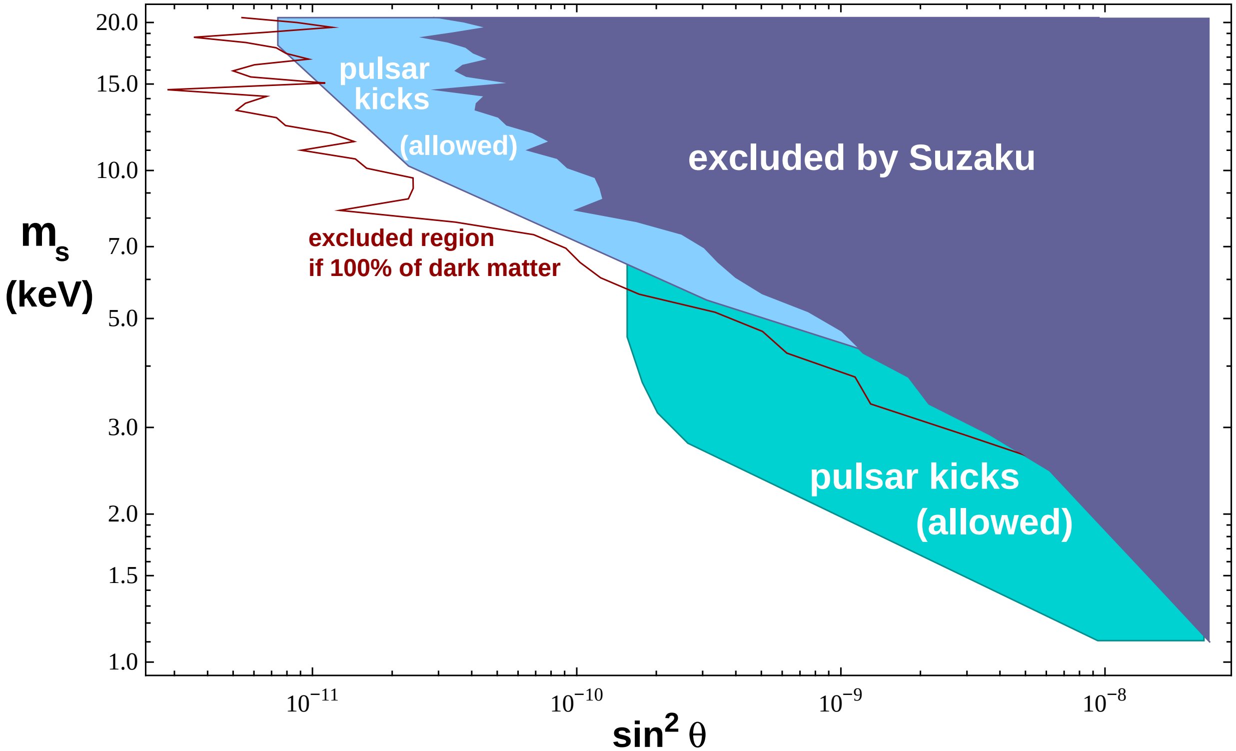
Suzaku observations of dSphs Draco and Ursa Minor



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

X-ray limits from *Suzaku*





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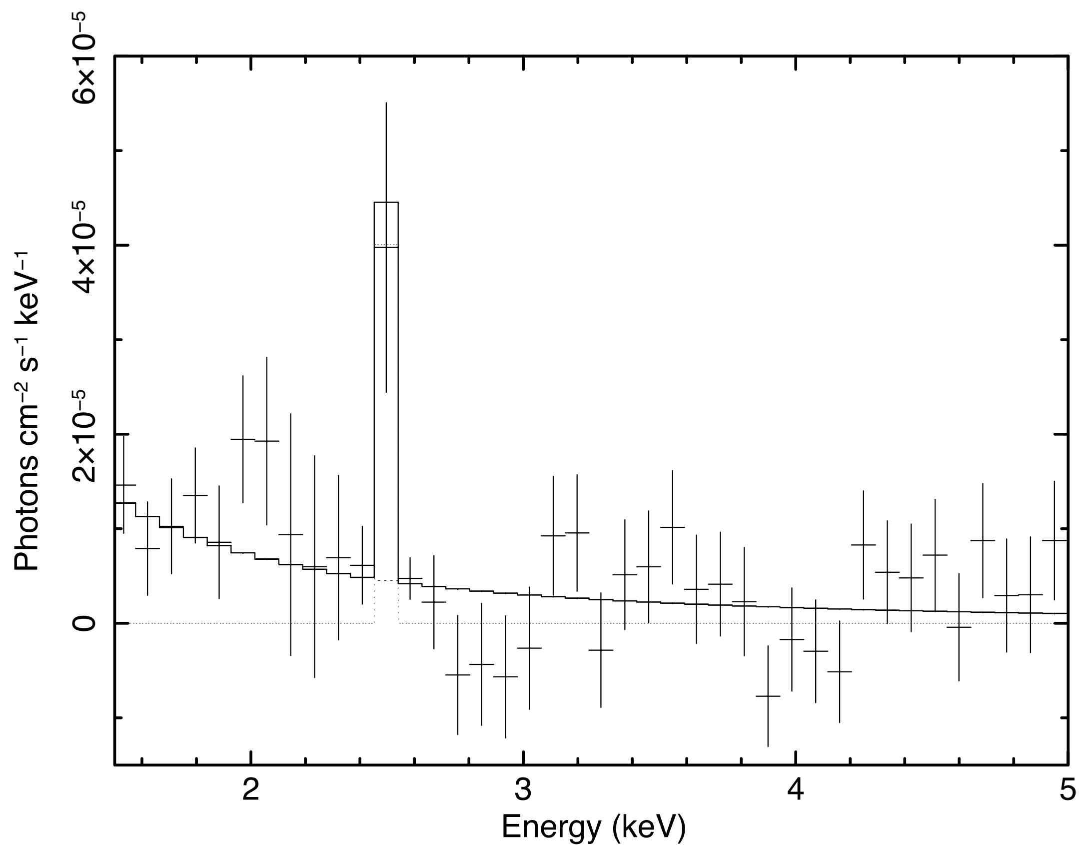
Possible first evidence from *Chandra* observations of Willman-1



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

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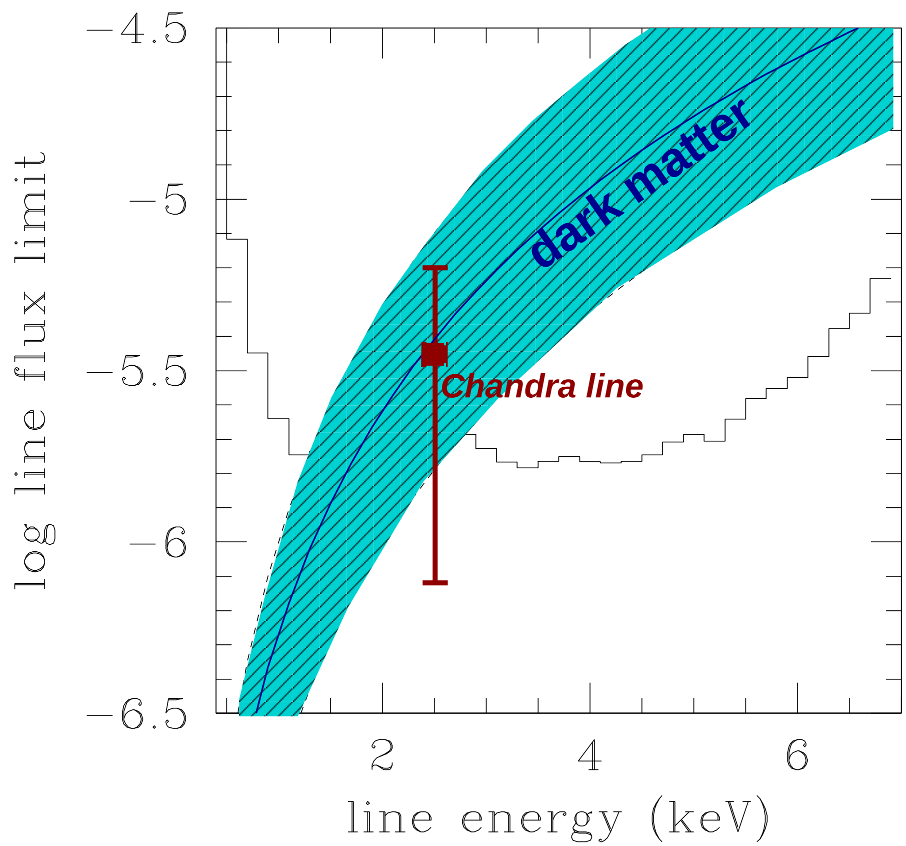


[Loewenstein and A.K., ApJ 714, 652 (2010)]

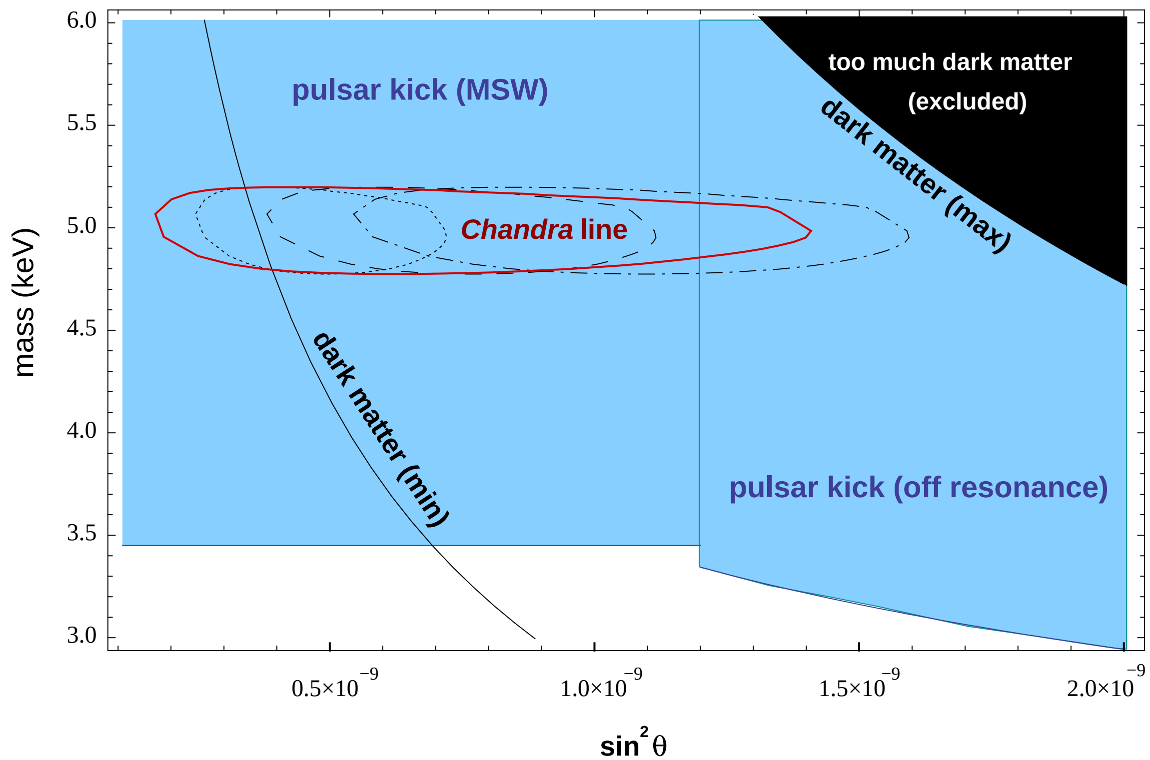
Consistency, not corroboration

- 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



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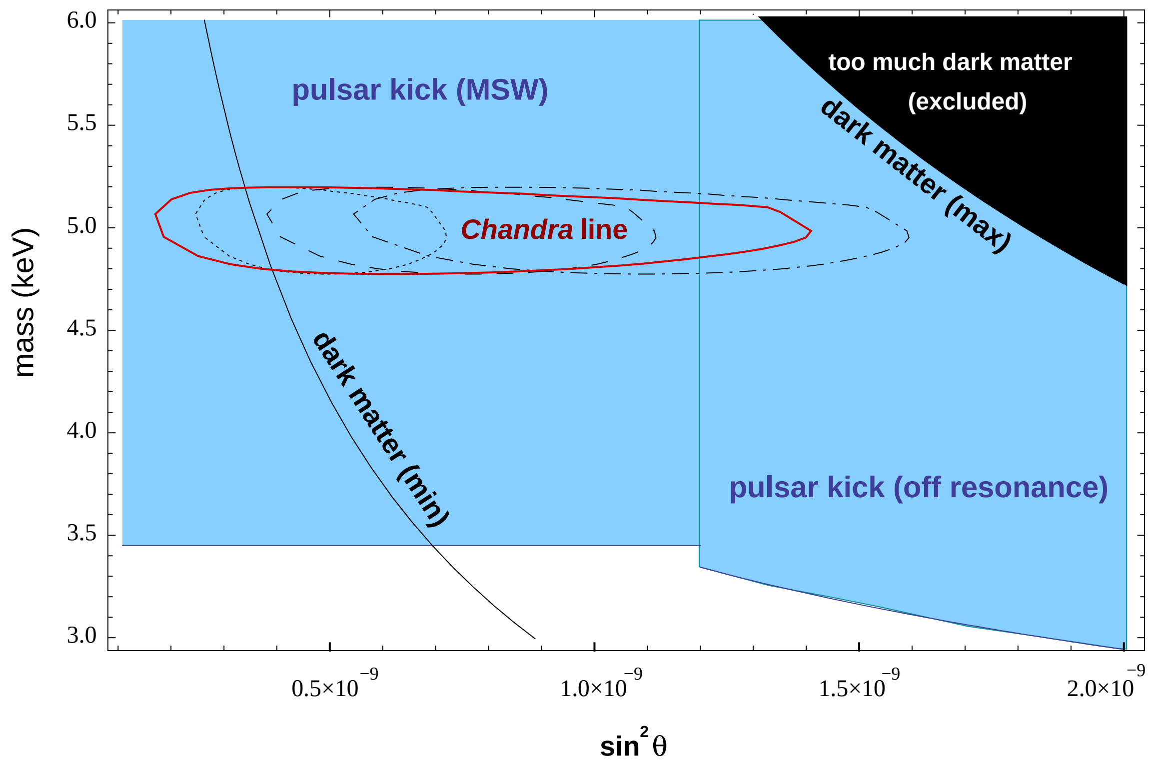

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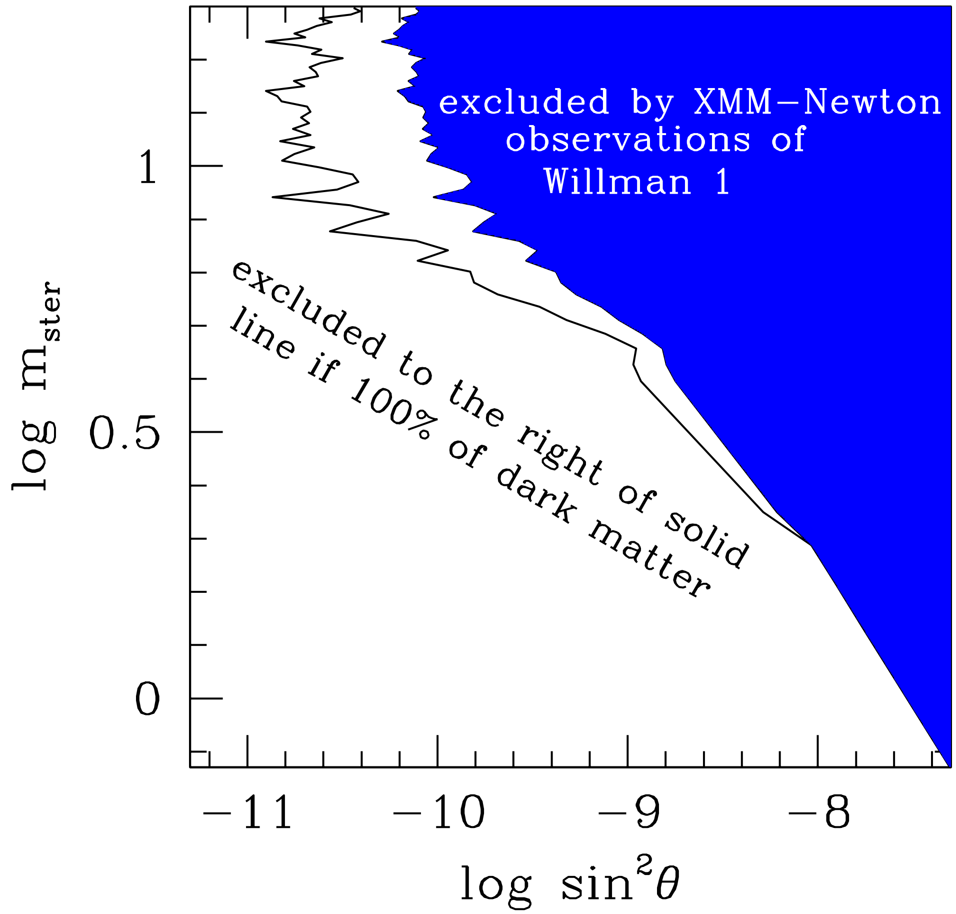
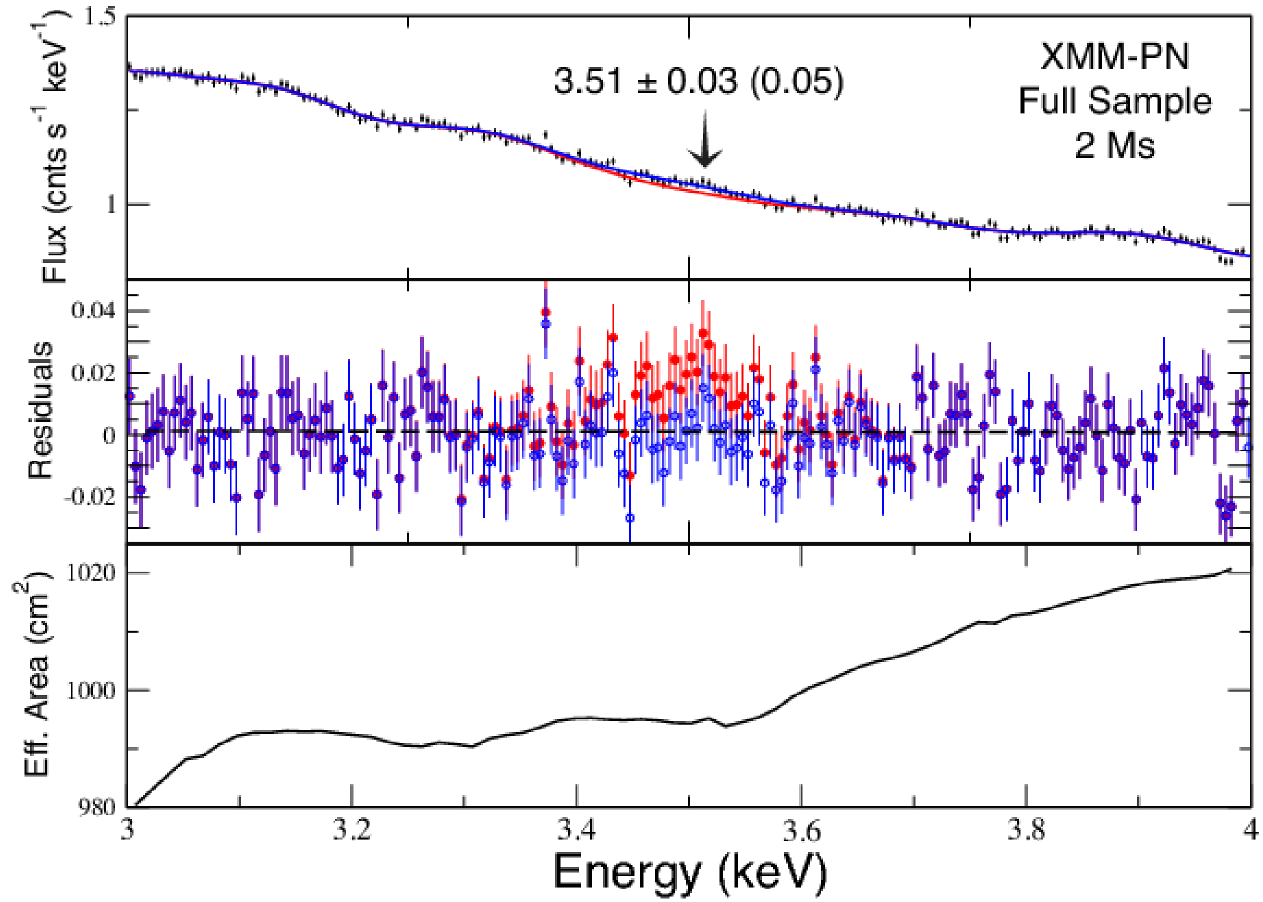
Unfortunately, not confirmed by XMM.

Limits from XMM-Newton (Willman - 1)



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

Unidentified line from Bulbul et al.; Boyarsky et al.



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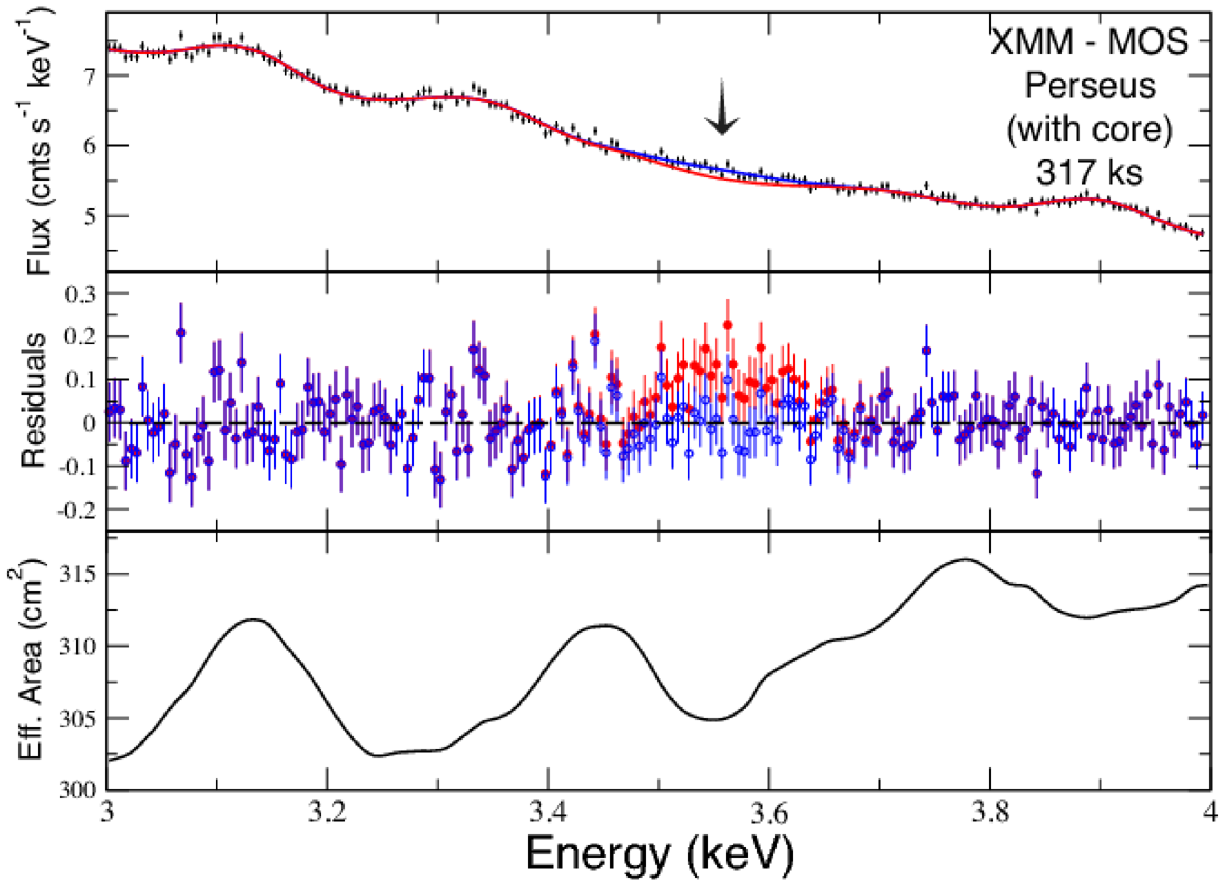

Nothing wrong with the lamp post approach if one doesn't know where one lost one's keys.

Since we have the ability to search for keV mass particles decaying into photons, let's consider other dark matter candidates in this mass range.

Moduli

- Generic prediction of string theory
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A viable dark matter candidate [Loewenstein, AK, Yanagida]

Example: GMSB [Loewenstein, AK, Yanagida]

Break supersymmetry using scalar superfield S with $\langle F_S \rangle \neq 0$ and $\langle S \rangle \neq 0$. Messengers Ψ_i coupled to S via superpotential

$$W = \lambda_{ij} S \Psi_i \bar{\Psi}_j.$$

Mass-squared matrix must be positive definite for stability:

$$\begin{pmatrix} |\lambda\langle S\rangle|^2 & \lambda\langle F_S\rangle^\dagger \\ \lambda\langle F_S\rangle & |\lambda\langle S\rangle|^2 \end{pmatrix} \;\Rightarrow\; M_{\rm mess}^2 \equiv |\lambda\langle S\rangle|^2 \;\geq\; |\lambda\langle F_S\rangle|.$$

In the visible sector, squarks get masses from messengers in loops, and must be heavier than ~ 10 TeV to account for a 125-GeV Higgs [Ibe,Matsumoto,Yanagida]:

$$m_{\rm sq} \simeq \frac{\alpha_3}{4\pi}\frac{\lambda\langle F_S\rangle}{M_{\rm mess}} > 10\ {\rm TeV} \Rightarrow |F| \geq |F_S| > \left(\frac{m_{\rm sq}}{10\ {\rm TeV}}\right)^2 \left(10^6\,{\rm GeV}\right)^2.$$

Therefore,

$$\boldsymbol{m_\phi = \frac{|F|}{M_{\rm Pl}} > 1\ \mathrm{keV}}$$

Couping to photons suppressed by reduced Planck mass:

$$\mathcal{L}_{\rm int} = \frac{1}{4\Lambda_{\rm eff}}\,\phi\, F_{\mu\nu}F^{\mu\nu} = \frac{b}{4M_{\rm Pl}}\,\phi\, F_{\mu\nu}F^{\mu\nu}$$

Hence decay into two X-ray photons is possible:

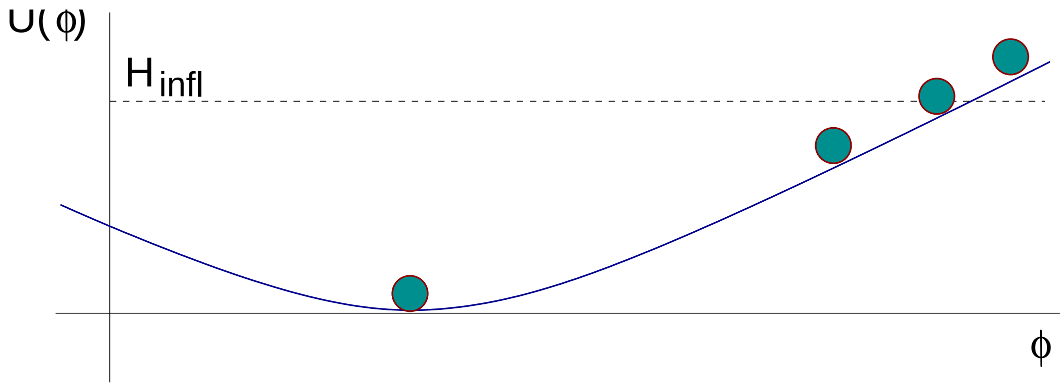
$$\phi \to \gamma\gamma \;\; \text{(a narrow X-ray line)}$$

with a very small decay width:

$$\tau_{\phi\to\gamma\gamma} = \Gamma^{-1}_{\phi\to\gamma\gamma} = 7.6\times 10^{32}\left(\frac{1}{b}\right)^2\left(\frac{1\,\mathrm{keV}}{m_\phi}\right)^3 \mathrm{s.}$$

Scalars in de Sitter space during inflation

- Scalars with $m \ll H$ develop VEVs $\langle\phi\rangle \sim H^2/m$.
  [Bunch, Davies; Starobinsky,Yokoyama, astro-ph/9407016]
- on average, each degree of freedom carries a non-zero energy in the de Sitter universe.



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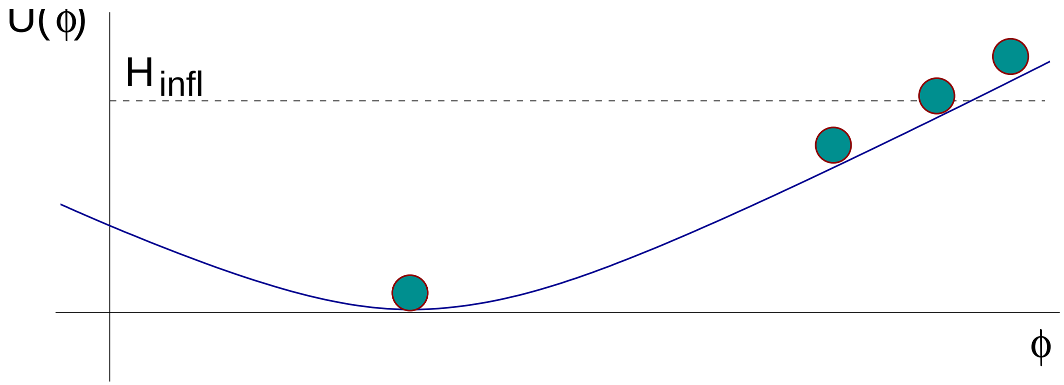

1. Any light field is displaced by a large amount VEV
2. At the end of inflation, the field is not at the minimum of the effective potential. (Another way to think about this is to introduce a correction to the effective potential $-cH^2\phi^2$ due to SUSY breaking in de Sitter space.)

Moduli problem

Oscillating scalar field is a cosmological equivalent of matter. The field starts oscillating when $H \sim m_\phi$, and the temperature is

$$T_\phi \sim (90/\pi^2 g_*)^{1/4} \sqrt{M_{\rm Pl} m_\phi}.$$

The density to entropy ratio is

$$\frac{\rho_\phi}{s} \sim \frac{m_\phi^2 \phi_0^2/2}{(2\pi^2/45) g_* T_\phi^3} \sim \mathbf{10^5\, GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{M_{\rm Pl}}\right)^2.$$

...to be compared with dark matter:

$$\frac{\rho_{\rm DM}}{s} = 0.2\, \frac{\rho_{\rm c}}{s} = \mathbf{3 \times 10^{-10}\, GeV},$$

bad discrepancy. Moreover, the universe with so much dark matter forms only one form of structures: black holes.

The density to entropy ratio is can be small enough in those (superhorizon-size) patches that have $\phi_0 \ll M_{\rm Pl}$:

$$\frac{\rho_\phi}{s} \sim \frac{m_\phi^2 \phi_0^2/2}{(2\pi^2/45) g_* T_\phi^3} \sim 10^{-9}\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{10^{-7} M_{\rm Pl}}\right)^2 .$$

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Structures start forming at $T_{\rm eq} \sim 10^5\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{M_{\rm G}}\right)^2$. and only black holes emerge, unless $\mathbf{\Omega_{\rm DM}/\Omega_{\rm baryon} < 10}$. **[Tegmark, Aguirre, Rees, Wilczek]**

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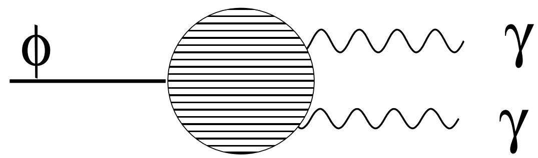
Anthropic solution to moduli problem $\Rightarrow$ correct amount of dark matter.
[AK, Loewenstein, Yanagida]

Radiative decays of moduli

Moduli decay into two photons:



Photons have energies $m/2$: X-rays. Concentrations of dark matter emit X-rays.
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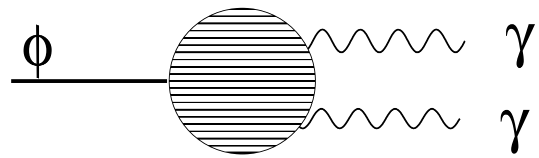

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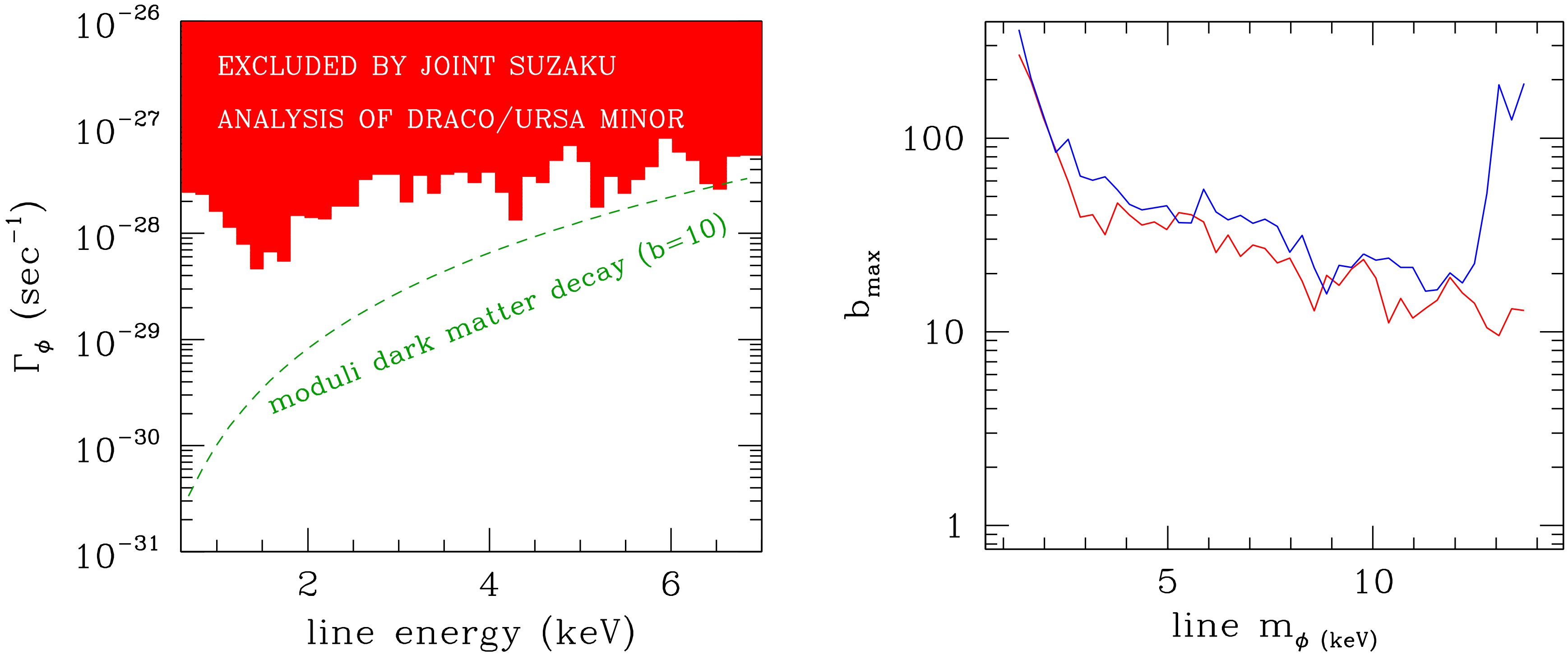
Can one distinguish between sterile neutrinos and moduli? Not from the spectrum. However, **moduli make a very cold dark matter**, while **sterile neutrios can have a measurable free-streaming length**.

Limits on moduli from Suzaku



Summary

- Neutrino masses point to the likely existence of sterile/right-handed neutrinos at some mass scale
- If one of the gauge singlets has mass in the keV range, it can be dark matter
- There are corroborating hints from supernovae and the pulsar kicks
- X-ray observations offer the best chance to discover this dark matter candidate; Astro-H will offer an excellent opportunity
- Other dark matter candidates can produce an X-ray line
- 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