# Sterile neutrinos, moduli, and dark matter with a keV mass.

- Dark matter candidates at a keV scale: sterile neutrinos, string/supersymmetry moduli
- Warm or cold, depending on the production scenario
- Particle physics models
- – Sterile neutrinos and an SU(2) singlet Higgs boson
  – Sterile neutrinos and the Split Seesaw
  – String/supersymmetry moduli
- Detection strategy: the search for a keV line

Бруно Понтекорво

## 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)]

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If the mass is in the several keV range, sterile neutrinos can

- make up all (or part of) dark matter [Dodelson, Widrow; Abazajian, Fuller et al.]
- explain the observed velocities of pulsars via anisotropic emission from a supernova explosion [AK, Sengrè; Fuller, AK, Mocioiu, Pascoli]

# Neutrino masses and light sterile neutrinos

Discovery of the 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 $L_\alpha$ $(\alpha = e, \mu, \tau)$ 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:

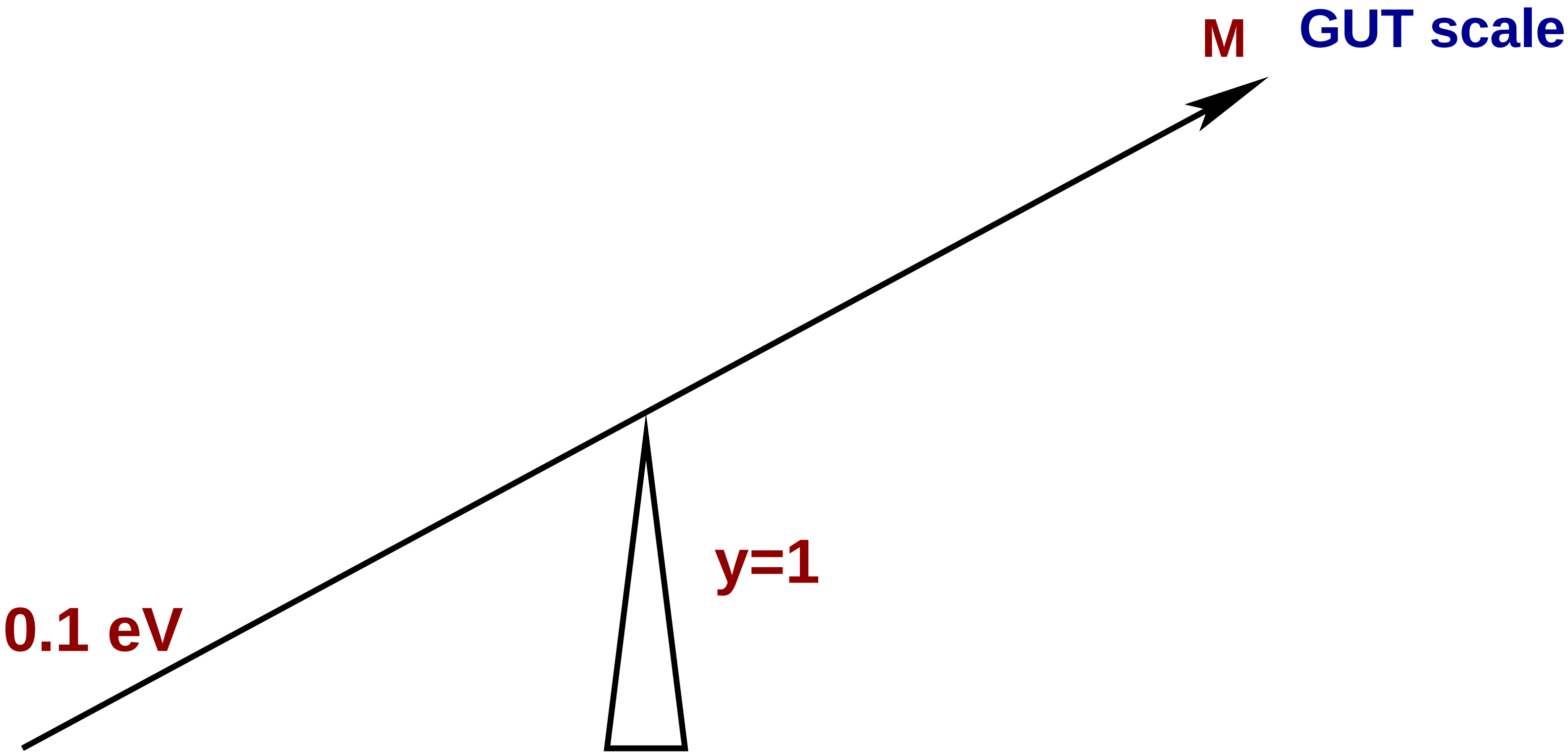
$$D_{ij} = y_{ij}\langle H\rangle$$

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



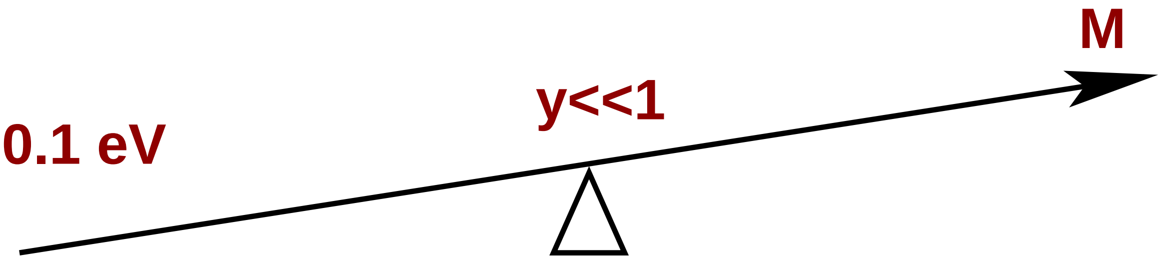
M GUT scale

y=1

0.1 eV

# Seesaw mechanism

**GUT scale**



**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, $\nu$MSM **[Shaposhnikov et al.]**.
- Use **lepton number** conservation as the reason for a small mass **[de Gouvêa]**.
- Use **flavor symmetries**, new gauge symmetries **[Lindner et al.]**
- **Singlet Higgs** (discussed below) at the electroweak scale can generate the Majorana mass. Added bonuses:
  - production from $S \to NN$ at the electroweak scale generates *the right amount* of dark matter.
  - production from $S \to NN$ at the electroweak scale generates *colder* dark matter. A **"miracle"**: EW scale and mass at the keV scale (for stability) $\Rightarrow$ **correct DM abundance**. **[AK; AK, Petraki]**
- **Split seesaw** (discussed below) makes the scale separation natural. Dark matter cooled by various effects. $\Rightarrow$ **democracy of scales**

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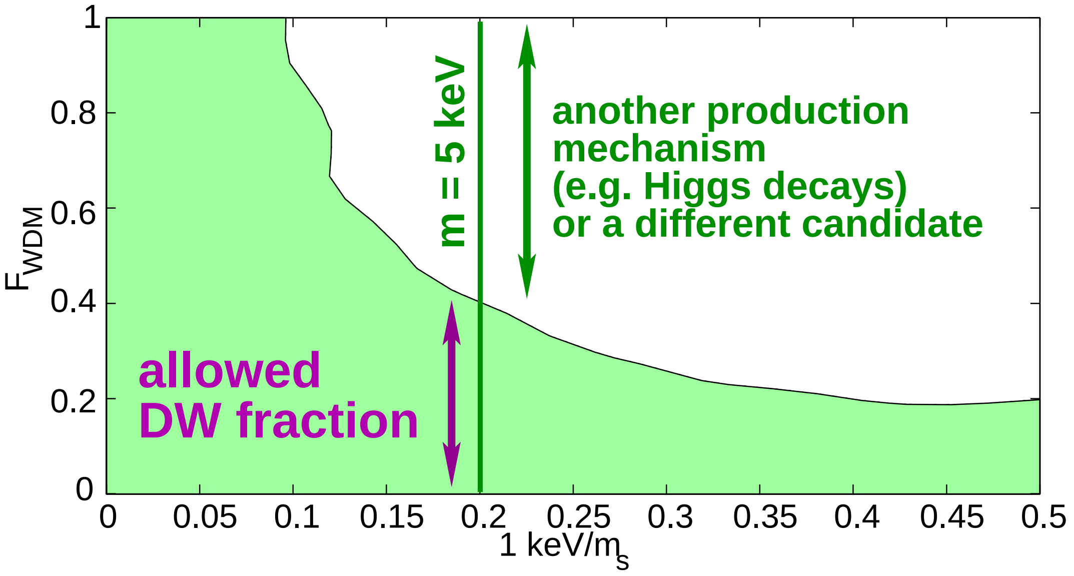
- **Split seesaw**: [AK, Takahashi, Yanagida]
  Two production mechanisms, **cold** and **even colder**.
  Advantage: “naturally” low mass scale

# Lyman-$\alpha$ bounds on Dodelson-Widrow production



[Boyarsky, Lesgourgues, Ruchayskiy, Viel]

Free-streaming properties: [Petraki, Boyanovsky]

# New scale or new Higgs physics?

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a \left(i\partial_\mu \gamma^\mu\right) N_a - y_{\alpha a} H \, \bar{L}_\alpha N_a - \frac{M_a}{2} \, \bar{N}_a^c N_a + h.c.\,,$$

To explain the pulsar kicks and dark matter, one needs $M \sim$ **keV**. Is this a new fundamental scale? Perhaps. Alternatively, it could arise from the Higgs mechanism:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a \left(i\partial_\mu \gamma^\mu\right) N_a - y_{\alpha a} H \, \bar{L}_\alpha N_a - h_a \, S \, \bar{N}_a^c N_a + V(H, S)$$

$$M = h \langle S \rangle$$

Now $S \rightarrow NN$ decays can produce sterile neutrinos.

For small $h$, the sterile neutrinos are out of equilibrium in the early universe, but $S$ is in equilibrium. There is a new mechanism to produce sterile dark matter at $T \sim m_S$ from decays $S \to NN$:

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

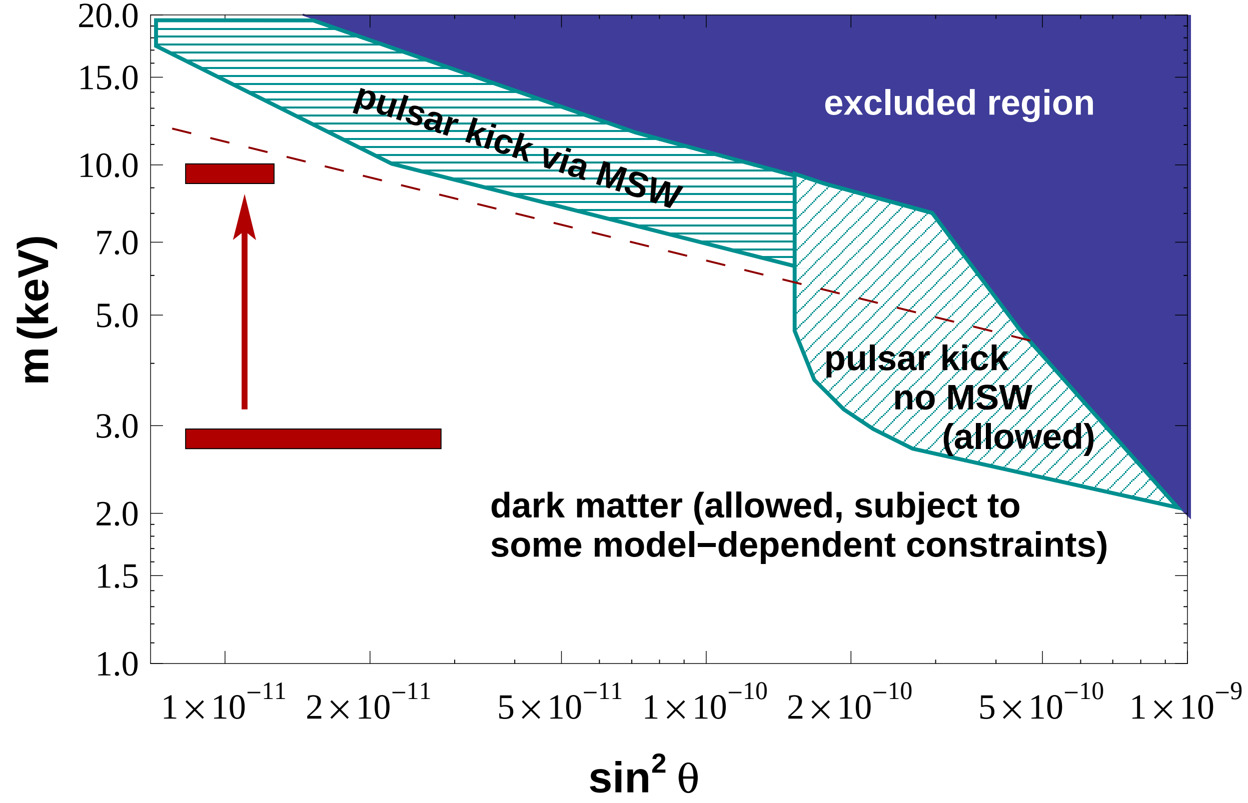
Here $\xi$ is the dilution factor due to the change in effective numbers of degrees of freedom.

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

$$\Rightarrow \Omega \approx 0.2$$

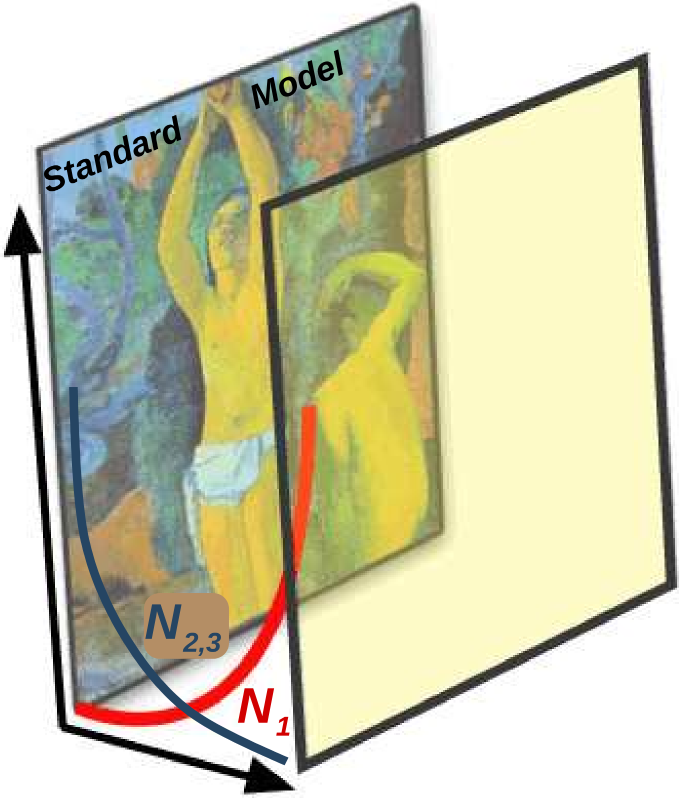
The sterile neutrino momenta are red-shifted by factor $\xi^{1/3} > 3.2$. [AK, Petraki]

# Cooling changes the clustering properties



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

# Split seesaw



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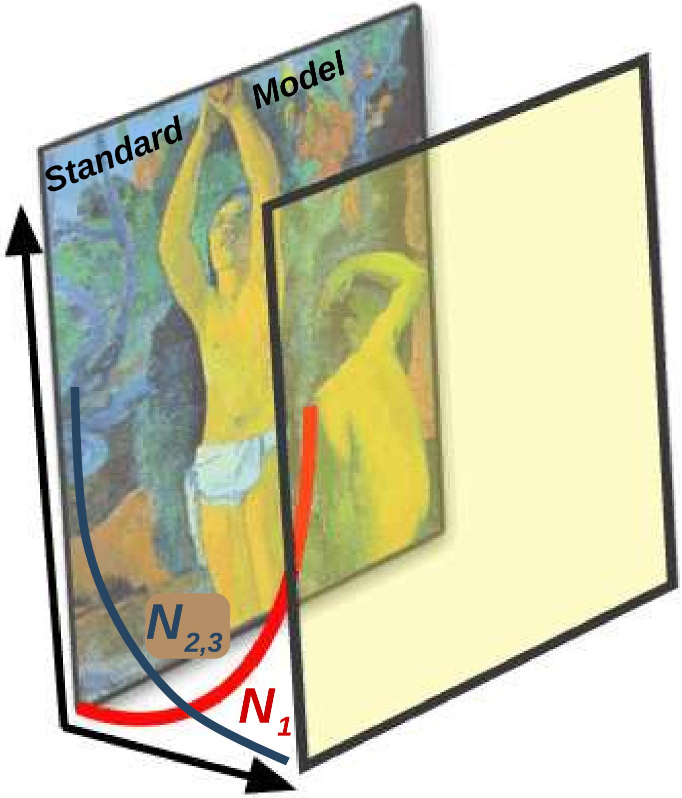
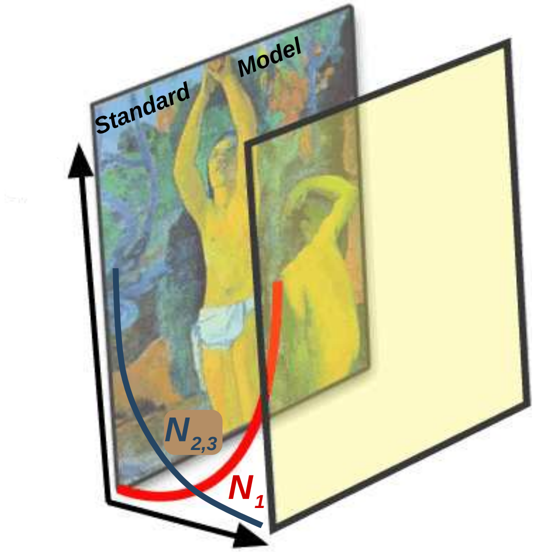




Standard Model on $z = 0$ brane. A Dirac fermion with a bulk mass $m$:

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

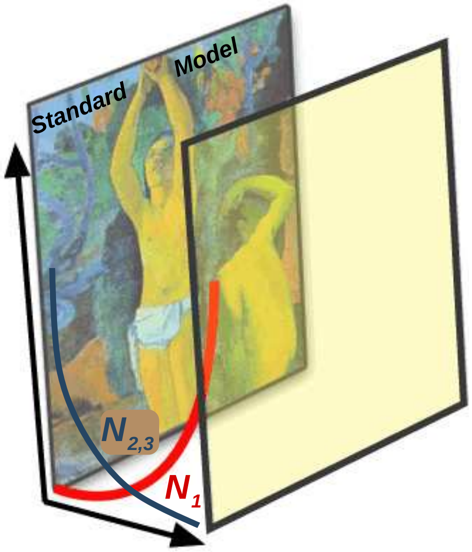
The zero mode: $(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0$. behaves as $\sim \exp(\pm mz)$. The 4D fermion:

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

Also, a U(1)$_{(B-L)}$ gauge boson in the bulk, $(B-L) = -2$ Higgs $\phi$ 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:

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

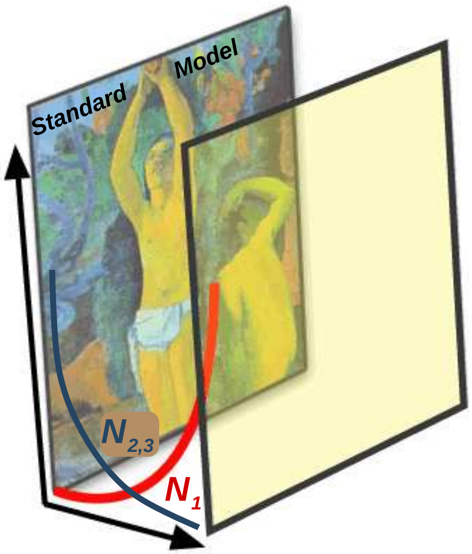
$$y_{d=4} = y_{d=5}\sqrt{\frac{2m_i}{M(e^{2m_i\ell}-1)}}$$

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

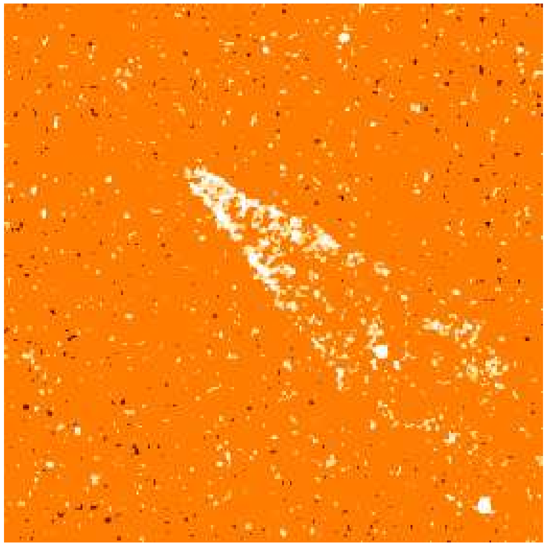
[AK, Takahashi, Yanagida]

# The pulsar velocities.

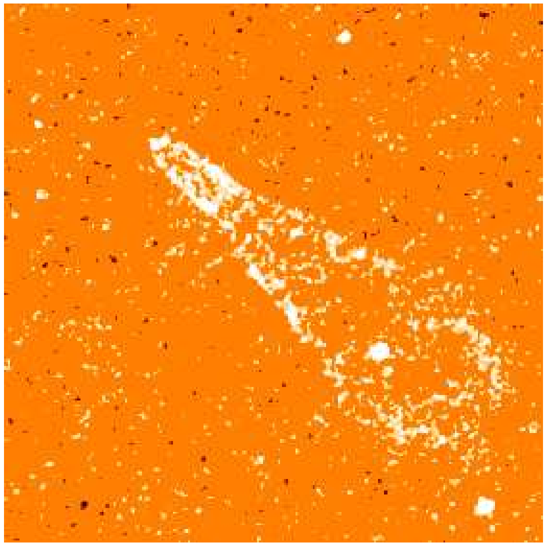
Pulsars have large velocities, $\langle v \rangle \approx 250 - 450\ \mathrm{km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.* ]

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

# A very fast pulsar in Guitar Nebula

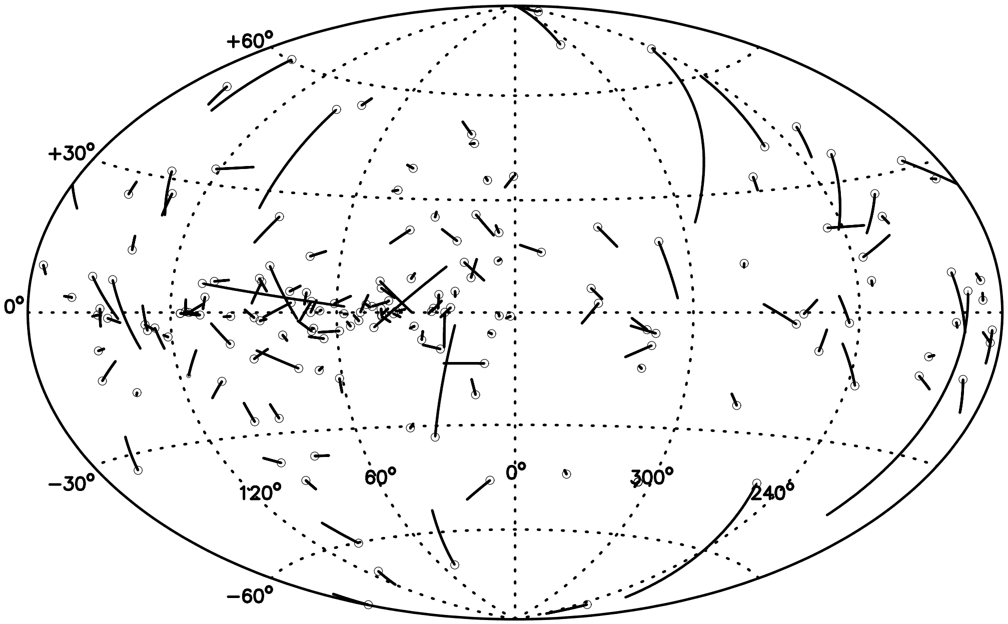


**HST, December 1994**



**HST, December 2001**

# Map of pulsar velocities



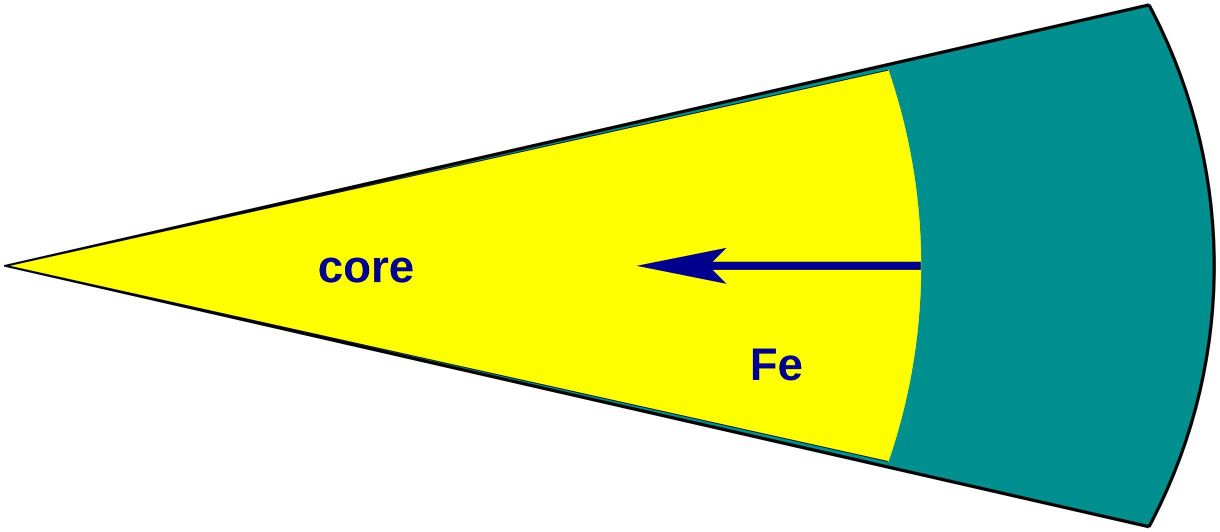
# Proposed explanations:

- asymmetric collapse [Shklovskii] (small kick)
- evolution of close binaries [Gott, Gunn, Ostriker] (not enough)
- acceleration by EM radiation [Harrison, Tademaru] (kick small, predicted polarization not observed)
- asymmetry in EW processes that produce neutrinos [Chugai; Dorofeev, Rodinov, Ternov] (asymmetry washed out)
- "cumulative" parity violation [Lai, Qian; Janka] (it's *not* cumulative )
- various exotic explanations
- explanations that were "not even wrong"...

Currently, hopes for SASI. (Can it be consistent with $\vec{\Omega} - \vec{v}$ correlation?)

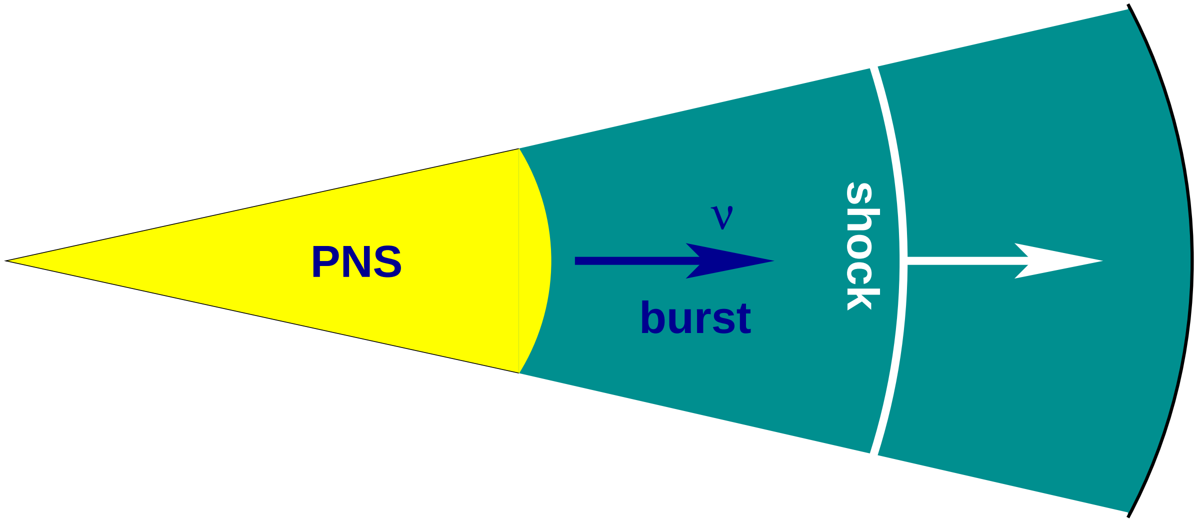
# Core collapse supernova

Onset of the collapse: $t = 0$



# Core collapse supernova

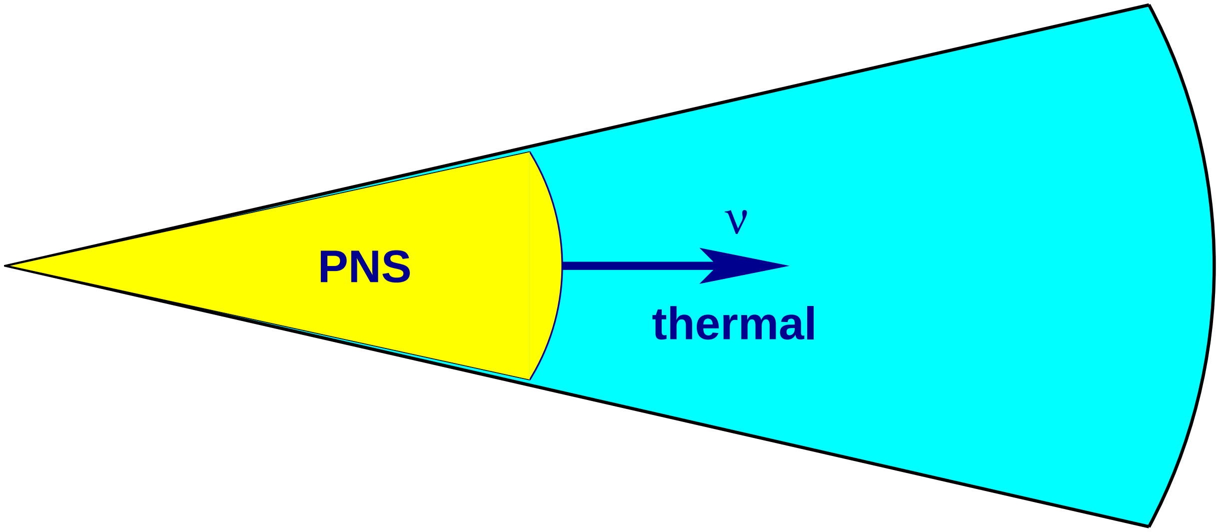
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



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

# Core collapse supernova

Thermal cooling: $\boldsymbol{t = 10 - 15}$ **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 ⇒ 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:

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

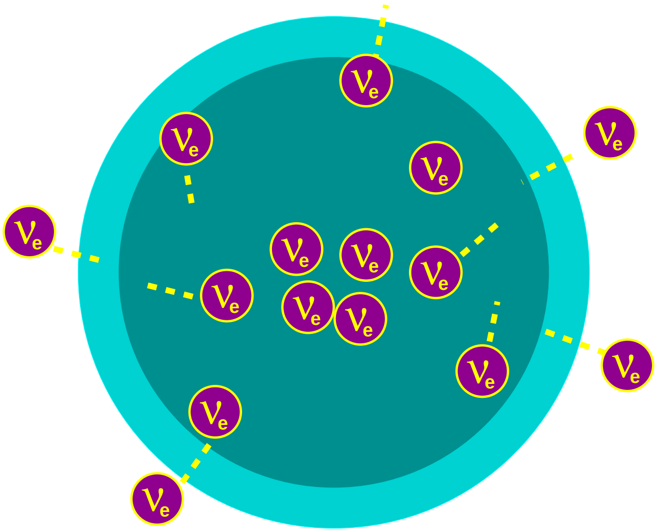
where $k_0$ is the fraction of electrons in the lowest Landau level.

$k_0 \sim 0.3$ in a strong magnetic field.

$$\Rightarrow \sim 10\% \text{ anisotropy??}$$

# 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?

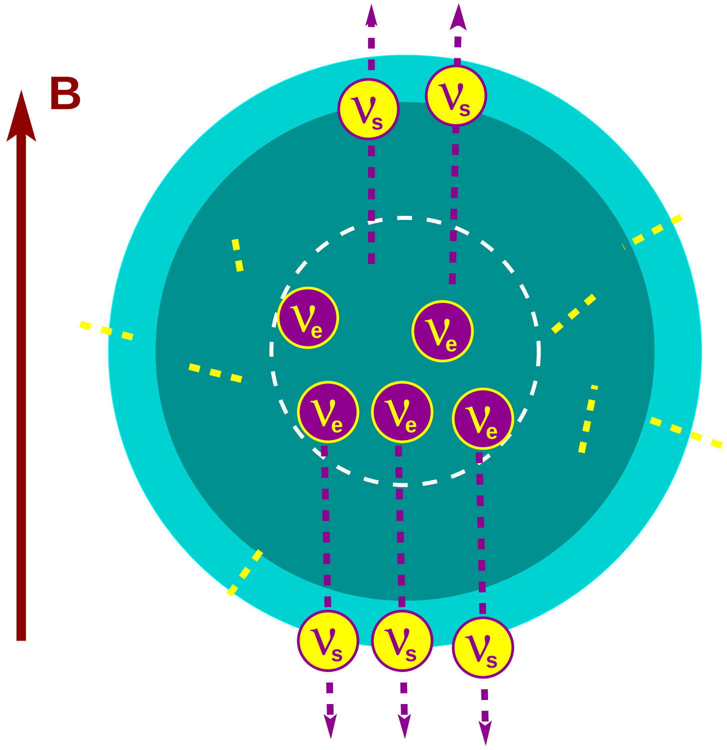
## No

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].

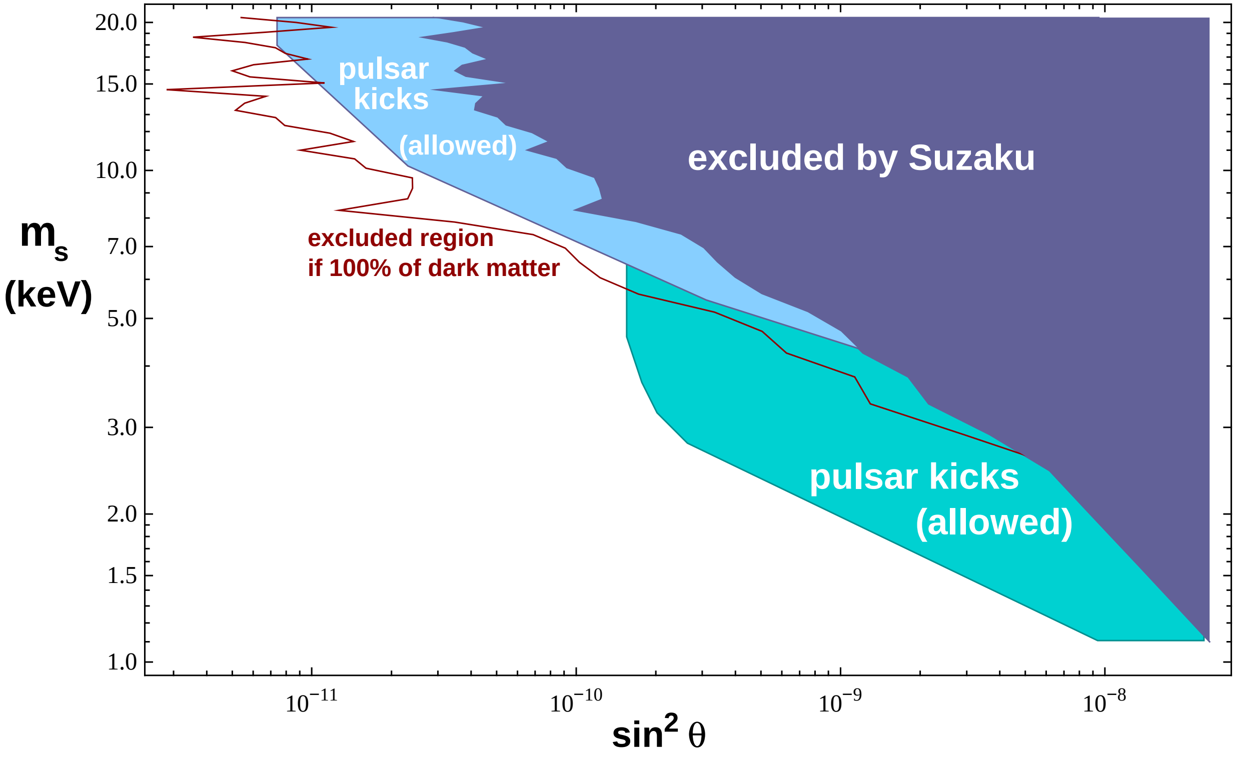
**However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!**

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



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

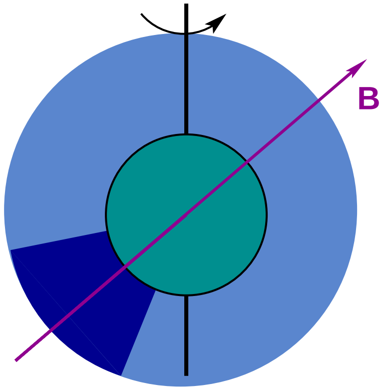
# Pulsar kicks



**[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]



# Moduli

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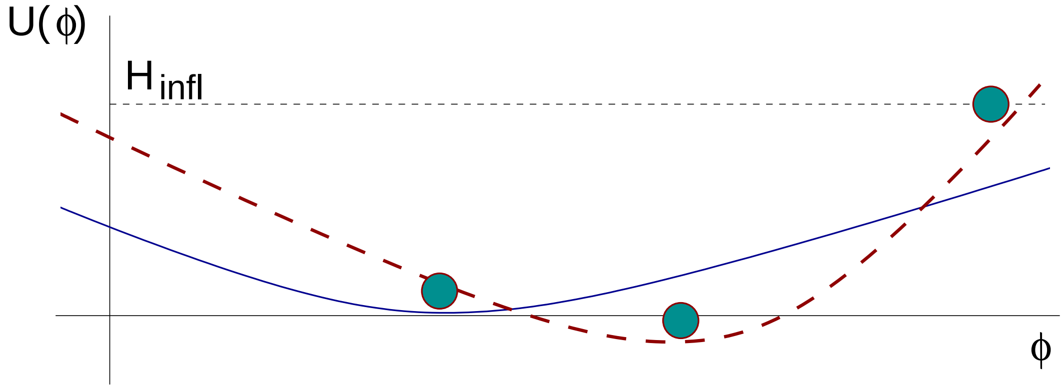
**A viable dark matter candidate [Loewenstein, AK, Yanagida]**

# Scalars during inflation

- Expansion of the universe breaks supersymmetry: the effective potential acquires terms of the form $-cH^2\phi^2$, where $c$ is of order one
- on average, each degree of freedom carries a non-zero energy in the de Sitter universe.



1. the minimum of the effective potential during inflation is displaced, for a light field, by a large amount ($\sim M_{\rm Pl}$)
2. at the end of inflation, the field is not necessarily in the minimum of either de Sitter or flat effective potential

# 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 (superhorion-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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Anthropic selection favors the maximal allowed value $\phi_0$, which corresponds to dark matter density close to the observed $\mathbf{\Omega}_{\rm DM}/\mathbf{\Omega}_{\rm baryon}$.

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

**Can life exist in those parts of the universe where $\Omega_{DM}/\Omega_{baryon} \gg 1$?**

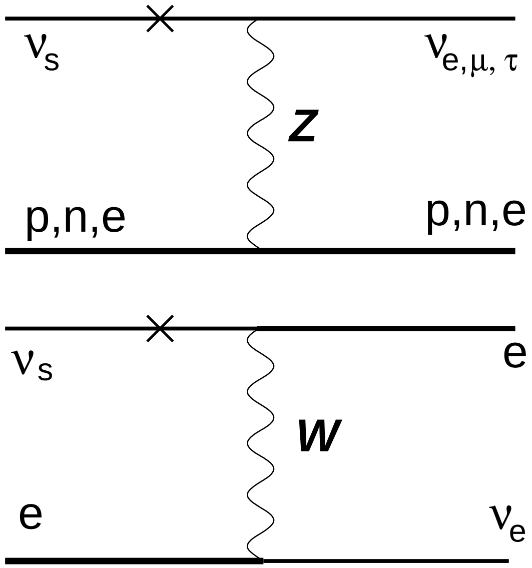
Structures start forming at $T_{\rm eq} \sim 10^5\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{M_{\rm G}}\right)^2$. and only black holes emerge, unless $\mathbf{\Omega}_{\rm DM}/\mathbf{\Omega}_{\rm baryon} < \mathbf{10}$. **[Tegmark, Aguirre, Rees, Wilczek]**

Anthropic selection favors the maximal allowed value $\phi_0$, which corresponds to dark matter density close to the observed $\mathbf{\Omega}_{\rm DM}/\mathbf{\Omega}_{\rm baryon}$.

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

# Detection: 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 $\boldsymbol{\sin^2\theta \sim 10^{-9}}$.
Direct detection? $\nu_s e \to \nu_e e$. Monochromatic electrons with $E = m_s$. **[Ando, AK]**

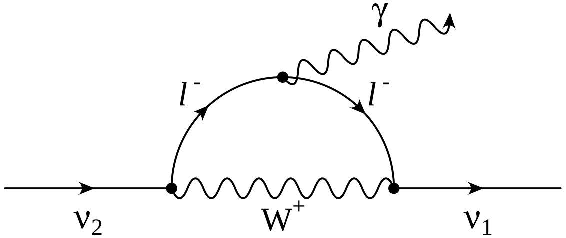


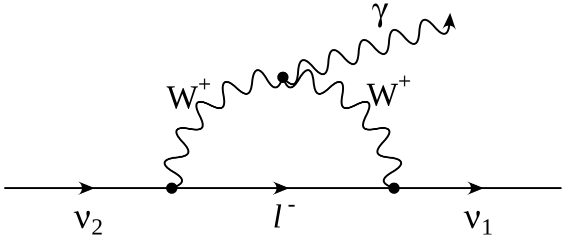
Rates low:

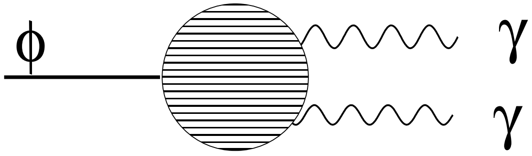
$$R = 4.0 \times 10^{-4}\ \mathrm{yr}^{-1} \left(\frac{m_{\nu_s}}{5\ \mathrm{keV}}\right) \left(\frac{\sin^2\theta}{10^{-9}}\right) \times \left(\frac{M_{\mathrm{det}}}{1\ \mathrm{ton}}\right) \left(\frac{Z}{25}\right)^2 \left(\frac{A}{50}\right)^{-1}.$$

# Radiative decays of sterile neutrinos and moduli

Sterile neutrino in the mass range of interest have lifetimes **longer than the age of the universe**, but they do decay:



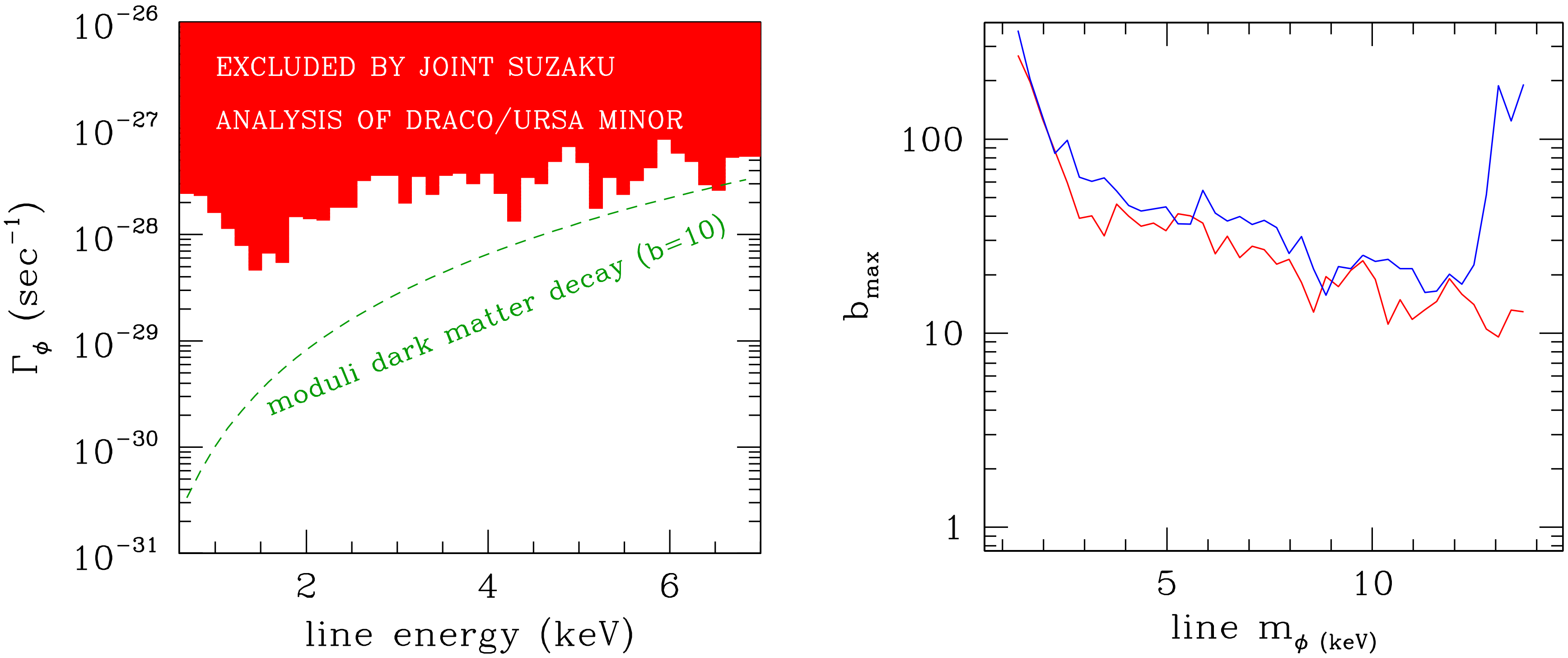




Photons have energies $m/2$: X-rays. Concentrations of dark matter emit X-rays. [Abazajian, Fuller, Tucker; Loewenstein et al., others]

Can one distiguish 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



[Loewenstein, AK, Yanagida]

# Summary

- **sterile neutrinos** and **moduli** are viable **dark matter** candidates
- Small-scale structure can help distiguish between these possibilities
- both can be discovered using X-ray observations; the search is ongoing
- **tantalizing hints of a discovery (Bulbul talk)!**
- 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