Sterile neutrinos:
the dark side of the light neutrinos

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The actual presentation was delivered using a blackboard, and the slides do not fully correspond to the discussion

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. $\mu\rightarrow e\gamma$)
- vacuum neutrino oscillations
- detection of neutrino oscillations
- astrophysical neutrino oscillations

Sterile neutrinos

The name *sterile* was coined by Bruno Pontecorvo} in a paper [JETP, 53, 1717 (1967)]:

“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”

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 $N_{eff} = \ldots$
- Sterile neutrinos with masses below ~keV make dark matter that is too warm
- XXXX experiment, which claimed evidence of sterile neutrinos, was ruled out by YYYY experiment
- It is unnatural for Majorana mass to be small

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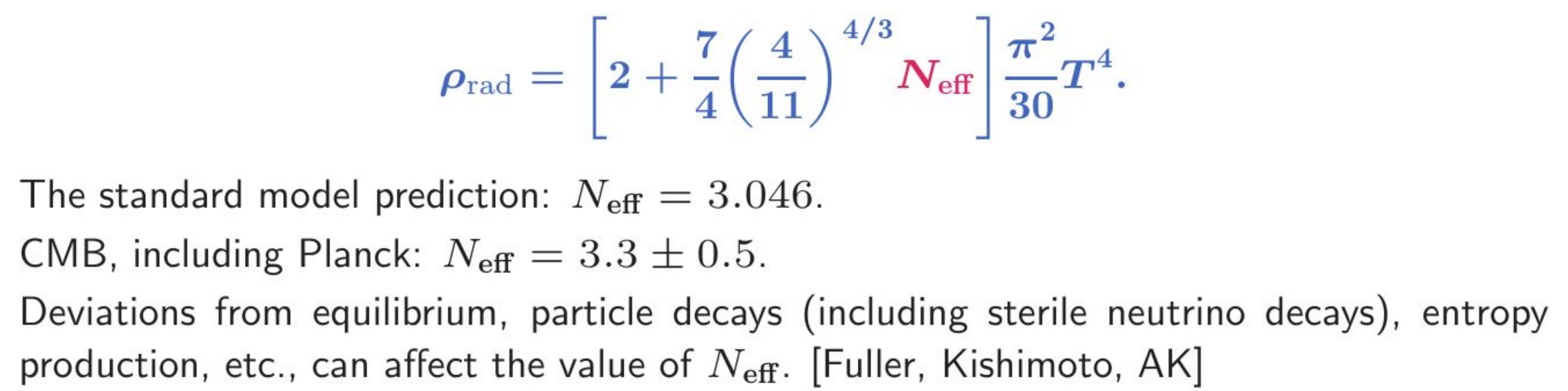
N_{eff}: what it is and what it is not



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

The standard model prediction: $N_{\rm eff} = 3.046$.

CMB, including Planck: $N_{\rm eff} = 3.3 \pm 0.5$.

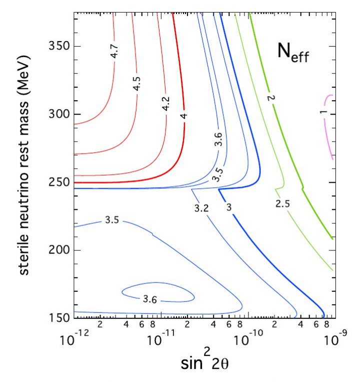
Deviations from equilibrium, particle decays (including sterile neutrino decays), entropy production, etc., can affect the value of $N_{\rm eff}$. [Fuller, Kishimoto, AK]

Add 1 sterile neutrino. What is the new value of N_{eff} =... ?

Depends on the mass and mixing angle...

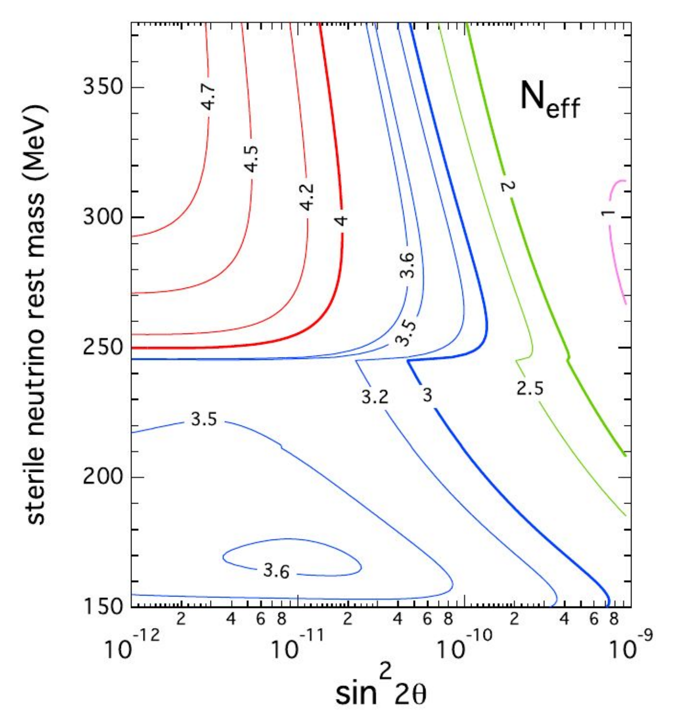
Sterile neutrinos can decay in a variety of modes, depending on the mass. Decays can cause (i) entropy production and dilution of ordinary neutrinos, and (ii) production of non-thermal neutrinos in the final state.

$$\nu_s \rightarrow \underbrace{\text{photons}}_{\text{decrease } N_{\text{eff}}} + \underbrace{\text{decoupled non-thermal } \nu_{e,\mu,\tau}}_{\text{increase } N_{\text{eff}}}$$



[Fuller, Kishimoto, AK]

N_{eff} with 1 additional sterile neutrino



[Fuller, Kishimoto, AK]

N_{eff} can increase or decrease!

Neutrino masses - first BSM physics

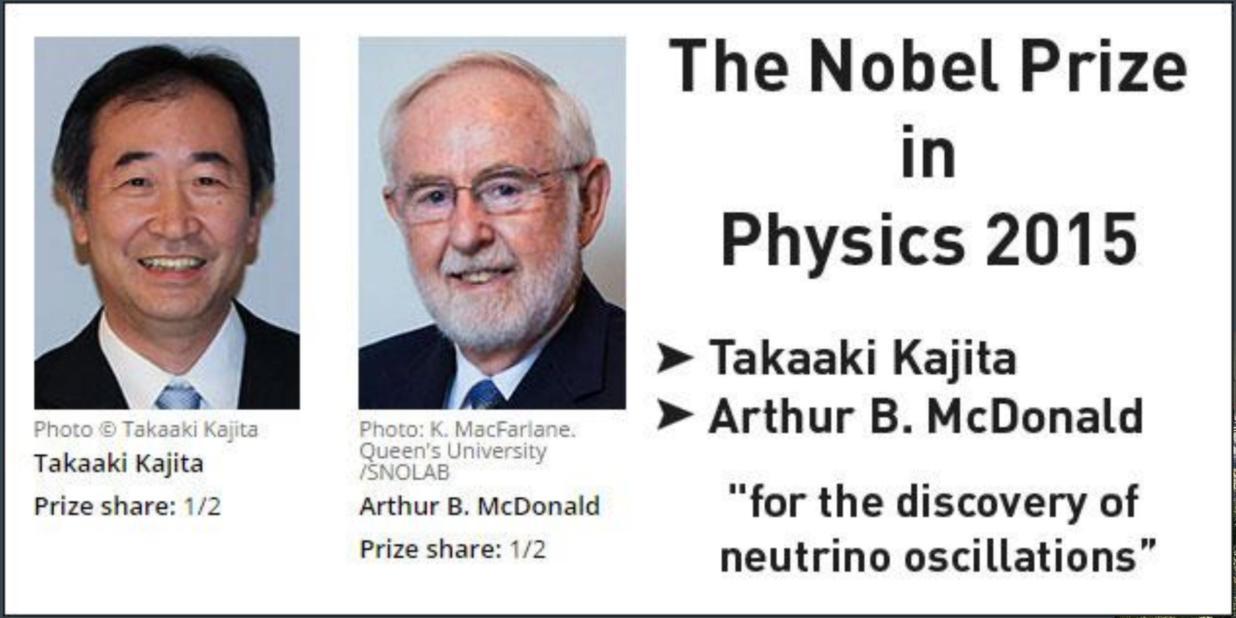


Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

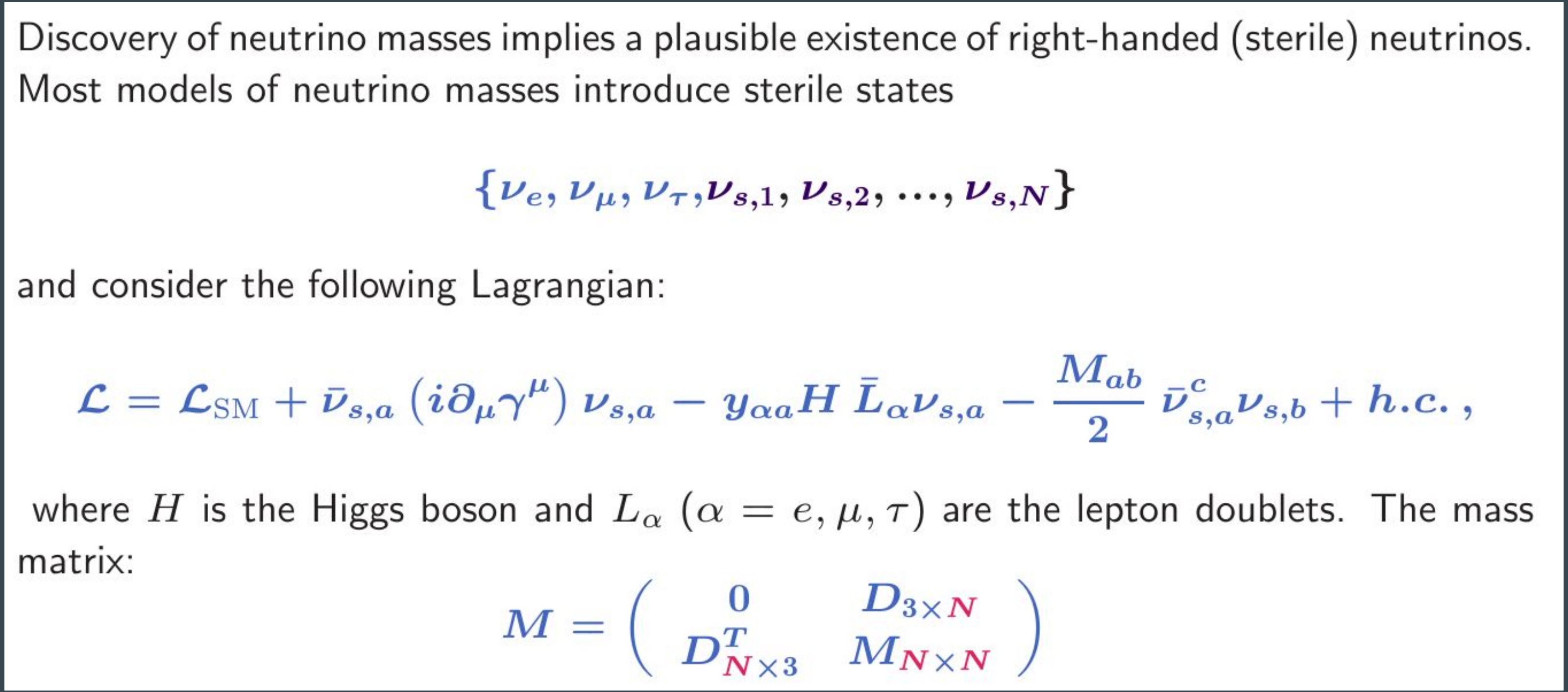
The Nobel Prize in Physics 2015

- **Takaaki Kajita**
- **Arthur B. McDonald**

"for the discovery of neutrino oscillations"

Takaaki Kajita arrives at U. Tokyo
(view from my window at IPMU)

Neutrino masses



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:

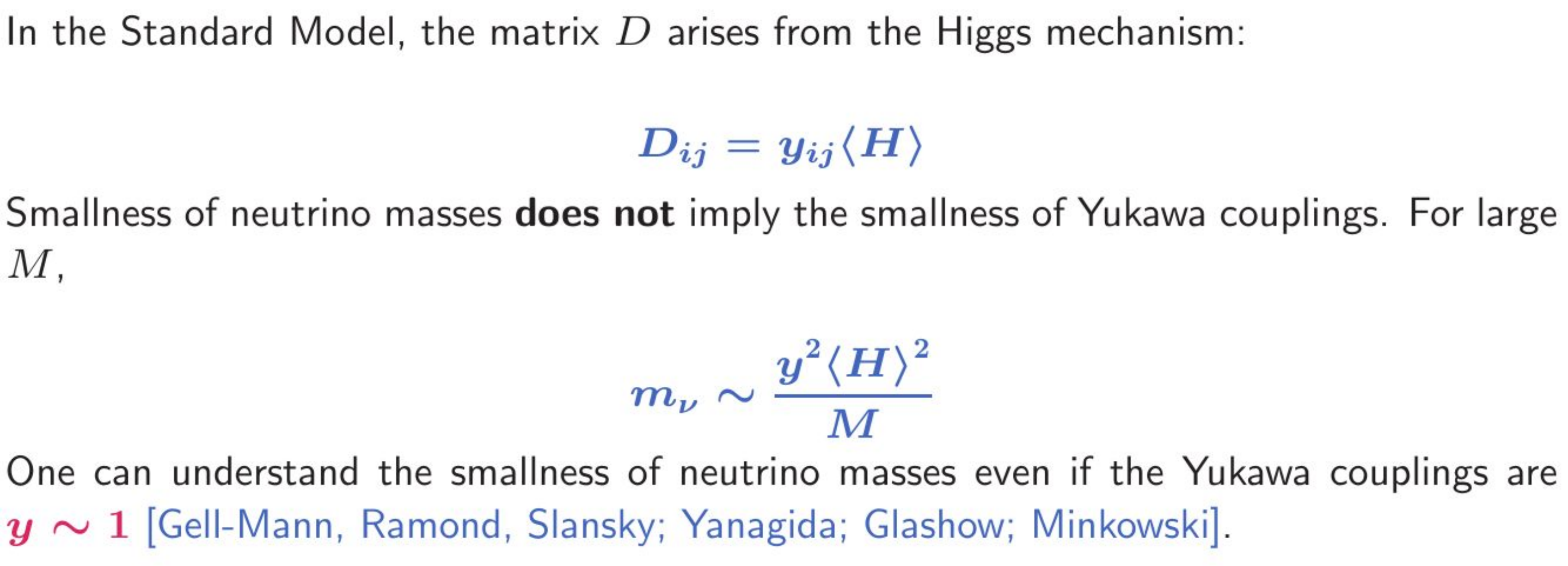
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a}\left(i\partial_\mu\gamma^\mu\right)\nu_{s,a} - y_{\alpha a} H\, \bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2}\, \bar{\nu}^c_{s,a}\nu_{s,b} + h.c.\,,$$

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 M?

Seesaw mechanism



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

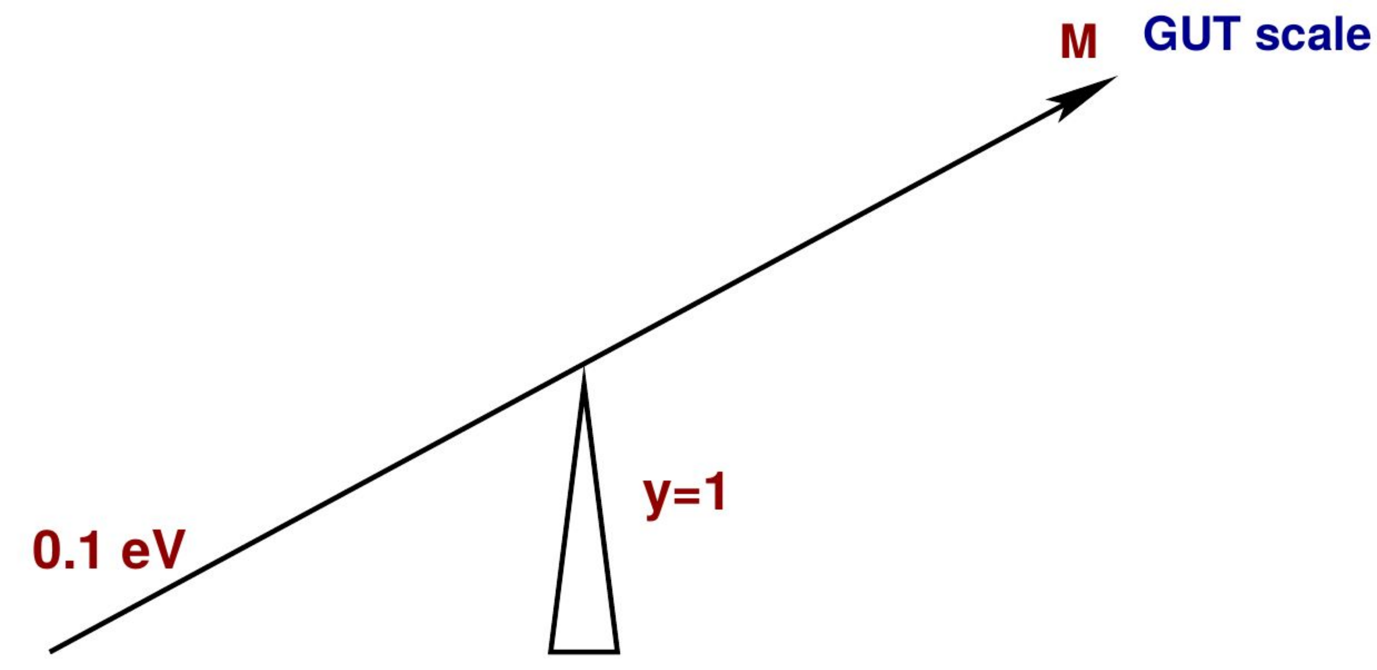
$$D_{ij} = y_{ij} \langle H \rangle$$

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

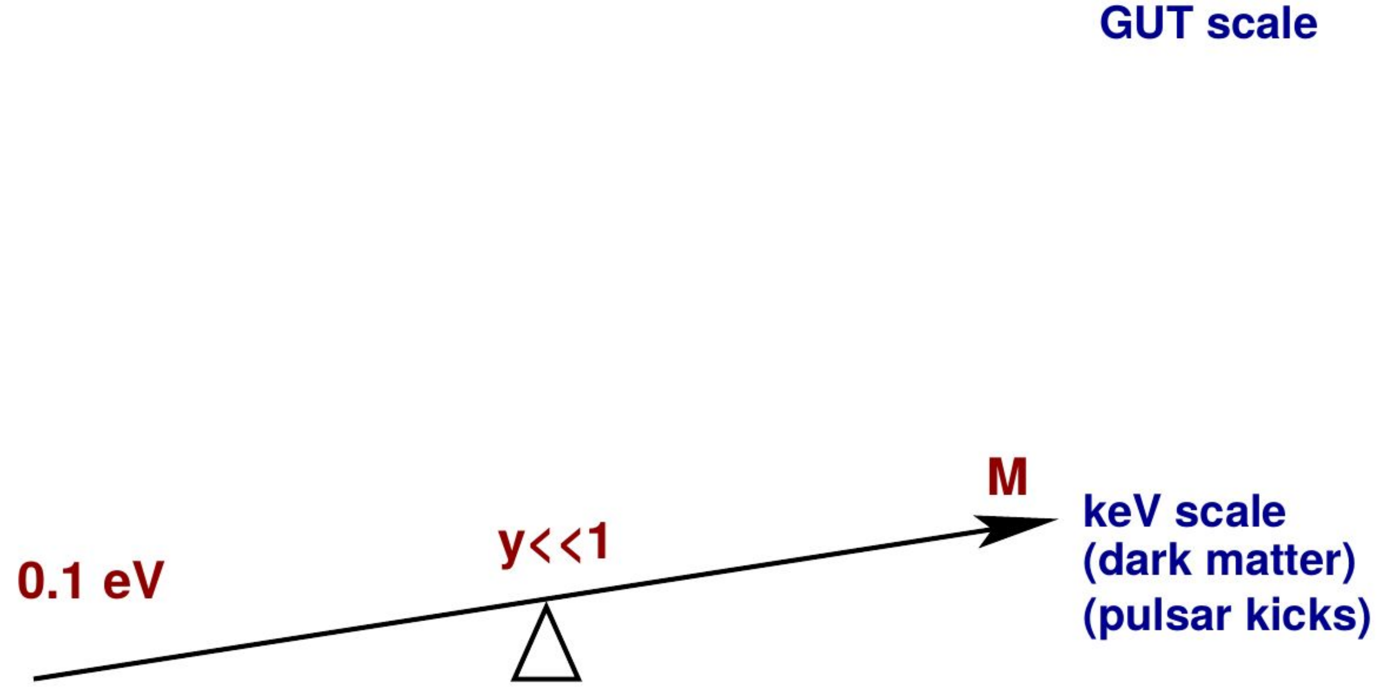
$$m_\nu \sim \frac{y^2 \langle H \rangle^2}{M}$$

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

Seesaw mechanism



Seesaw mechanism



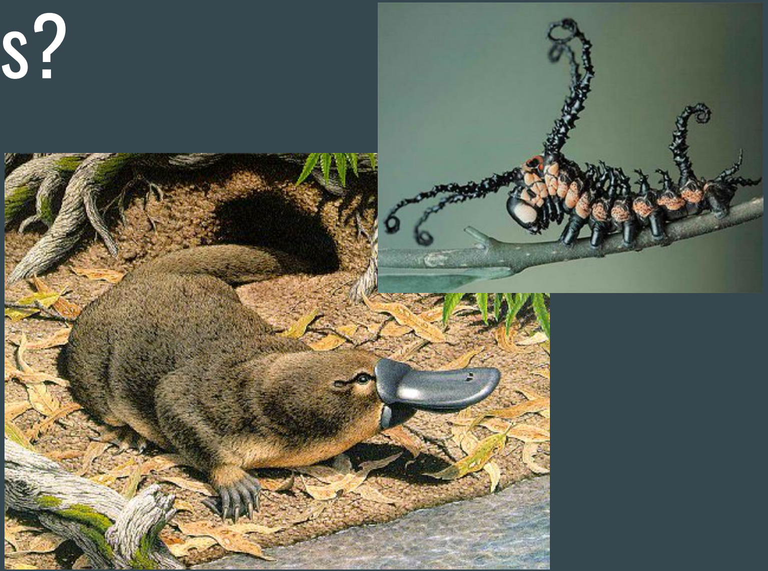
Is $y \sim 1$ better than $y \ll 1$?

Depends on the model.

- If $y \approx \text{some intersection number}$ in string theory, then $y \sim 1$ is natural
- If y comes from wave function overlap of fermions in models with extra-dimensions, then it can be exponentially suppressed, hence, $y \ll 1$ can be natural.

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

How natural is a small Majorana mass?



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

Perturbative naturalness:

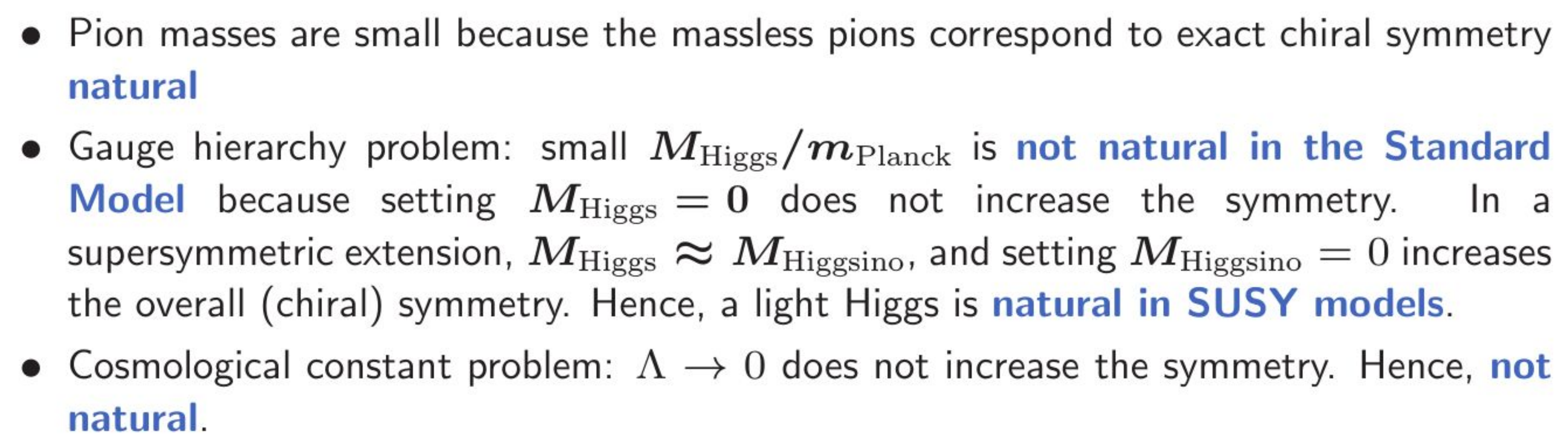
Physical quantity = tree + 1-loop + 2-loop...

Unnatural if large cancellations are required.

A small mixing angle ⇒ small corrections, technically natural

‘t Hooft: criterion for naturalness

Small number is natural if setting it to zero increases symmetry



- Pion masses are small because the massless pions correspond to exact chiral symmetry **natural**
- Gauge hierarchy problem: small $M_{\mathrm{Higgs}}/m_{\mathrm{Planck}}$ is **not natural in the Standard Model** because setting $M_{\mathrm{Higgs}} = 0$ does not increase the symmetry. In a supersymmetric extension, $M_{\mathrm{Higgs}} \approx M_{\mathrm{Higgsino}}$, and setting $M_{\mathrm{Higgsino}} = 0$ increases the overall (chiral) symmetry. Hence, a light Higgs is **natural in SUSY models**.
- Cosmological constant problem: $\Lambda \to 0$ does not increase the symmetry. Hence, **not natural**.

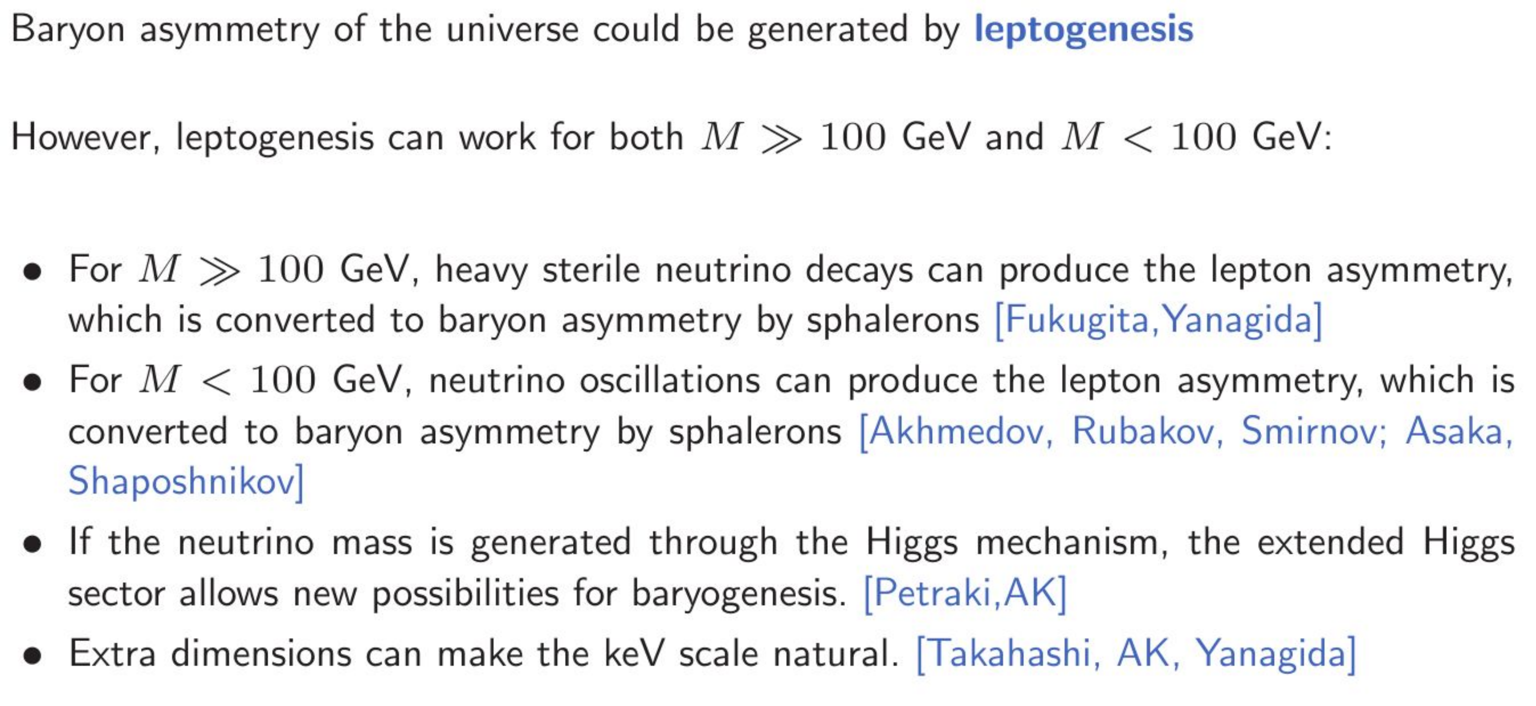
‘t Hooft: criterion for naturalness

Small number is natural if setting it to zero increases symmetry

Apply to sterile neutrinos: M→0 increases the symmetry (lepton number).

If L is a “good enough” symmetry, small M is natural

Clues from cosmology?



Baryon asymmetry of the universe could be generated by **leptogenesis**

However, leptogenesis can work for both $M \gg 100$ GeV and $M < 100$ GeV:

- For $M \gg 100$ GeV, heavy sterile neutrino decays can produce the lepton asymmetry, which is converted to baryon asymmetry by sphalerons [Fukugita,Yanagida]
- For $M < 100$ GeV, neutrino oscillations can produce the lepton asymmetry, which is converted to baryon asymmetry by sphalerons [Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov]
- If the neutrino mass is generated through the Higgs mechanism, the extended Higgs sector allows new possibilities for baryogenesis. [Petraki,AK]
- Extra dimensions can make the keV scale natural. [Takahashi, AK, Yanagida]

Over the years, neutrino physics has shown many theoretical prejudices to be wrong: neutrinos were expected to be massless, neutrinos were expected to have small mixing angles, etc.

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

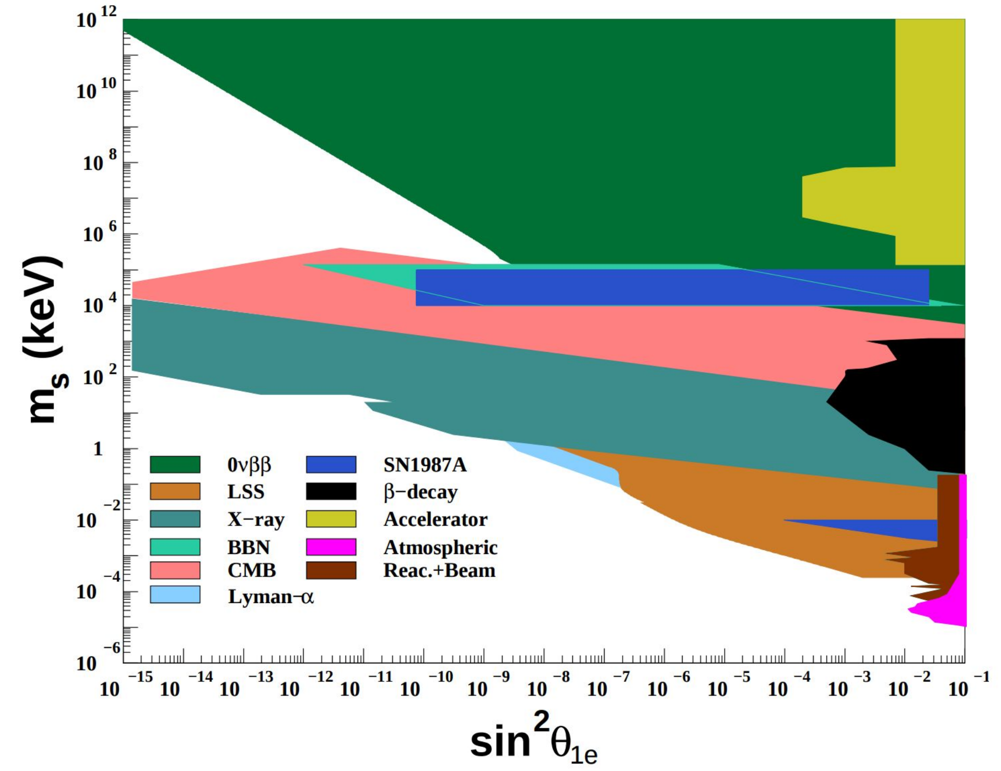
consider all allowed values
for the singlet/sterile neutrino masses

in the following Lagrangian:

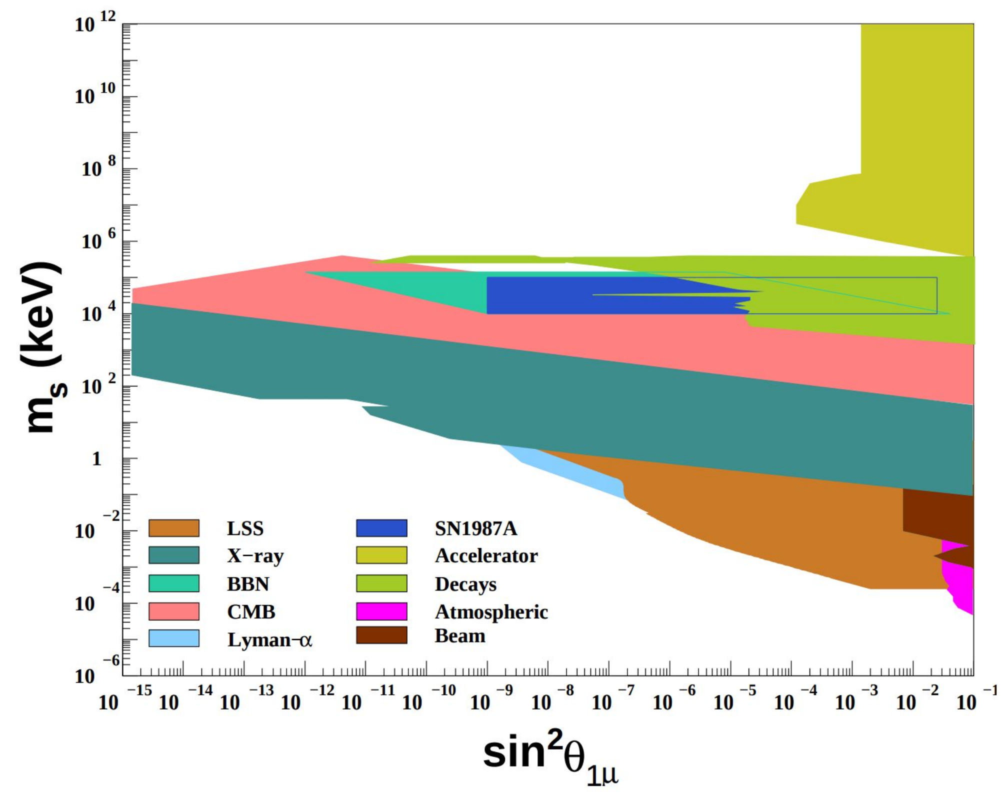
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a}\left(i\partial_\mu\gamma^\mu\right)\nu_{s,a} - y_{\alpha a} H\,\bar{L}_\alpha \nu_{s,a} - \frac{M_{aa}}{2}\,\bar{\nu}^c_{s,a}\nu_{s,a} + h.c.\,,$$

where M is can be small or large

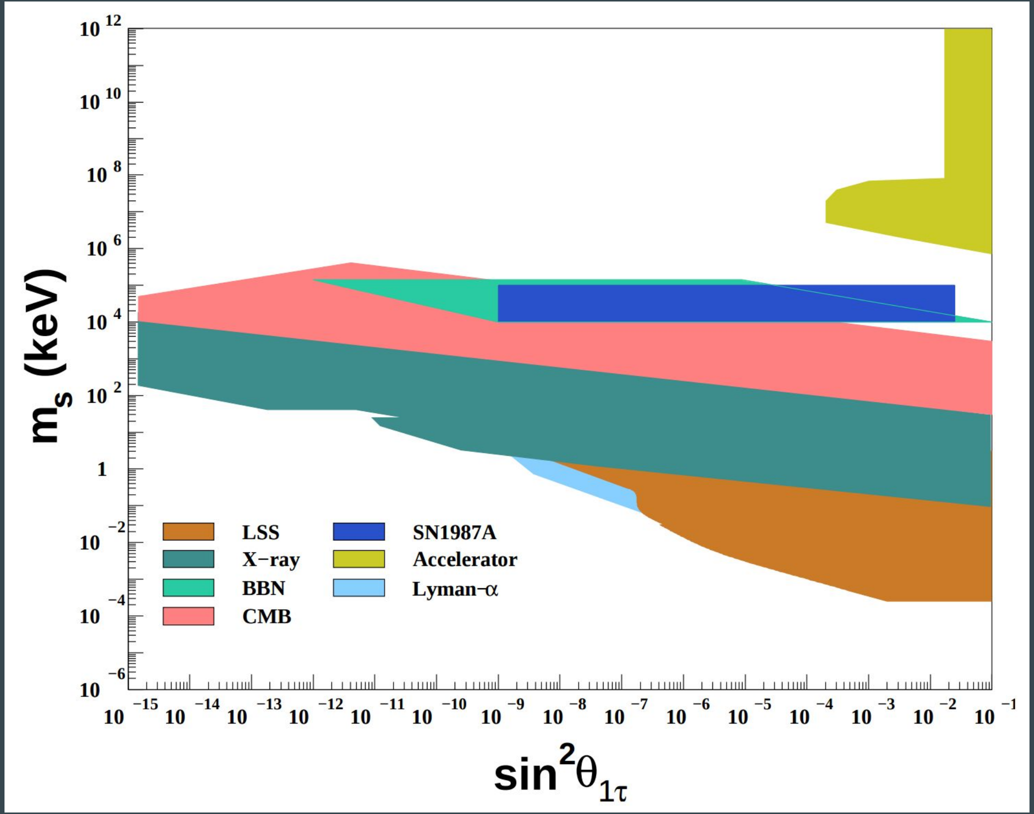
Allowed range of mass and mixing with ν_e



Allowed range of mass and mixing with ν_μ



Allowed range of mass and mixing with ν_τ



Sterile neutrinos as dark matter

A well-motivated dark matter candidate

- neutrino masses are most easily explained if right-handed neutrinos exist. If one of them has mass in the keV mass range, it can be dark matter
- models exist, in which the abundance is “natural” (a non-WIMP miracle)
- depending on the production mechanism, can be warm or (practically) cold dark matter
- can explain the observed pulsar velocities
- can be discovered by a radiative decay line using X-ray telescopes:

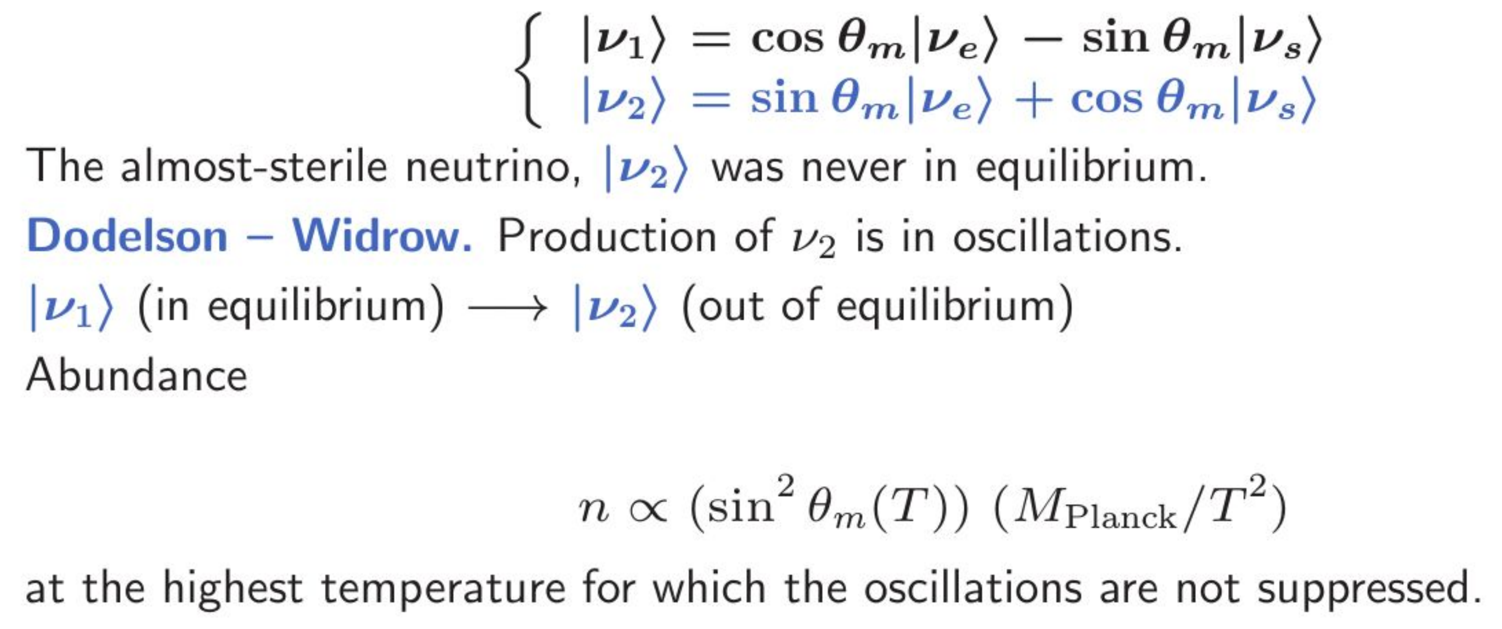
$$\nu_s \to \nu_{e,\mu,\tau}\gamma, \quad E_\gamma = \frac{m_s}{2} \Rightarrow \text{narrow spectral line}$$

For review, see, e.g., *A.K., Sterile neutrinos: the dark side of the light fermions, Phys. Rept. 481 (2009) 1*

Same signature -- from supersymmetry/strings moduli dark matter

[Murayama et al.; Loewenstein, AK, Yanagida]

Sterile neutrinos as dark matter



$$\begin{cases} |\boldsymbol{\nu}_1\rangle = \cos\boldsymbol{\theta}_m|\boldsymbol{\nu}_e\rangle - \sin\boldsymbol{\theta}_m|\boldsymbol{\nu}_s\rangle \\ |\boldsymbol{\nu}_2\rangle = \sin\boldsymbol{\theta}_m|\boldsymbol{\nu}_e\rangle + \cos\boldsymbol{\theta}_m|\boldsymbol{\nu}_s\rangle \end{cases}$$

The almost-sterile neutrino, $|\boldsymbol{\nu}_2\rangle$ was never in equilibrium.

Dodelson – Widrow. Production of ν_2 is in oscillations.

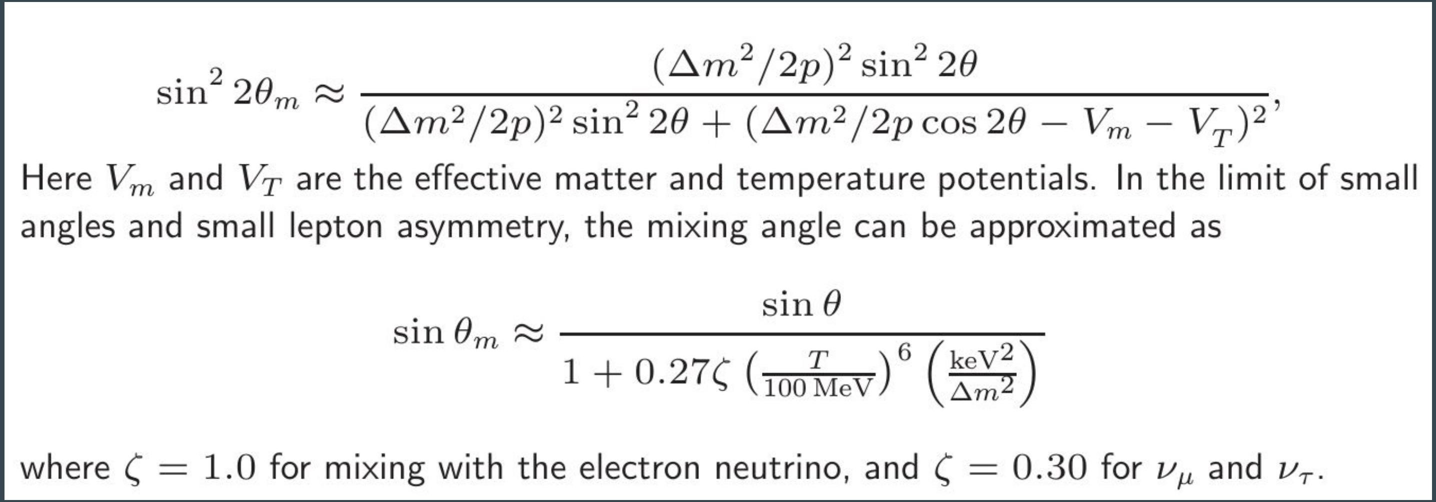
$|\boldsymbol{\nu}_1\rangle$ (in equilibrium) $\longrightarrow$ $|\boldsymbol{\nu}_2\rangle$ (out of equilibrium)

Abundance

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

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

Dodelson-Widrow production

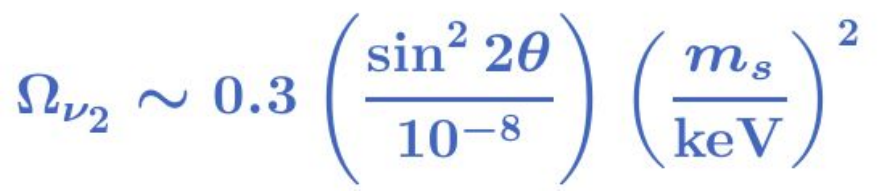


$$\sin^2 2\theta_m \approx \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V_m - V_T)^2},$$

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

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

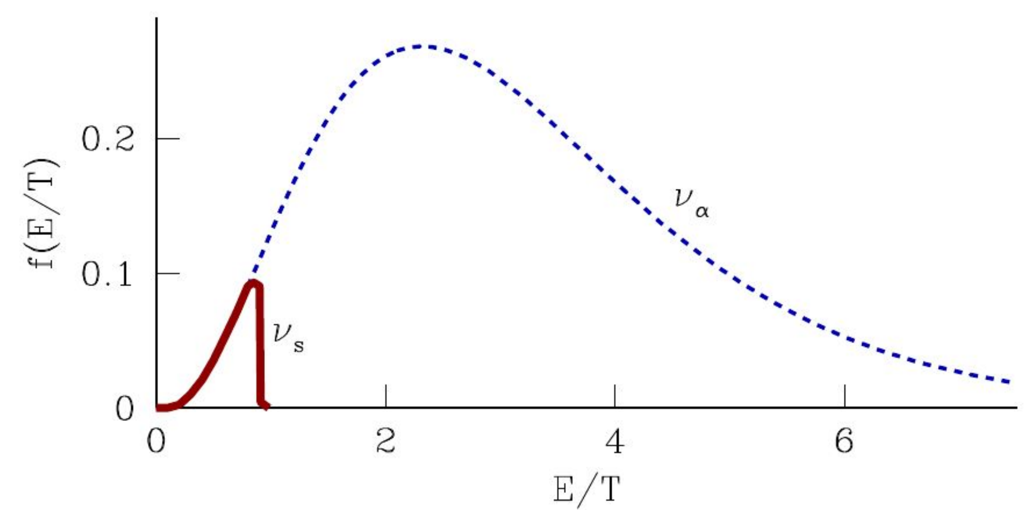
where $\zeta = 1.0$ for mixing with the electron neutrino, and $\zeta = 0.30$ for ν_μ and ν_τ.



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

Shi-Fuller production

In the presence of a lepton asymmetry, MSW resonance enhances production and selects lower-momentum part of the distribution.



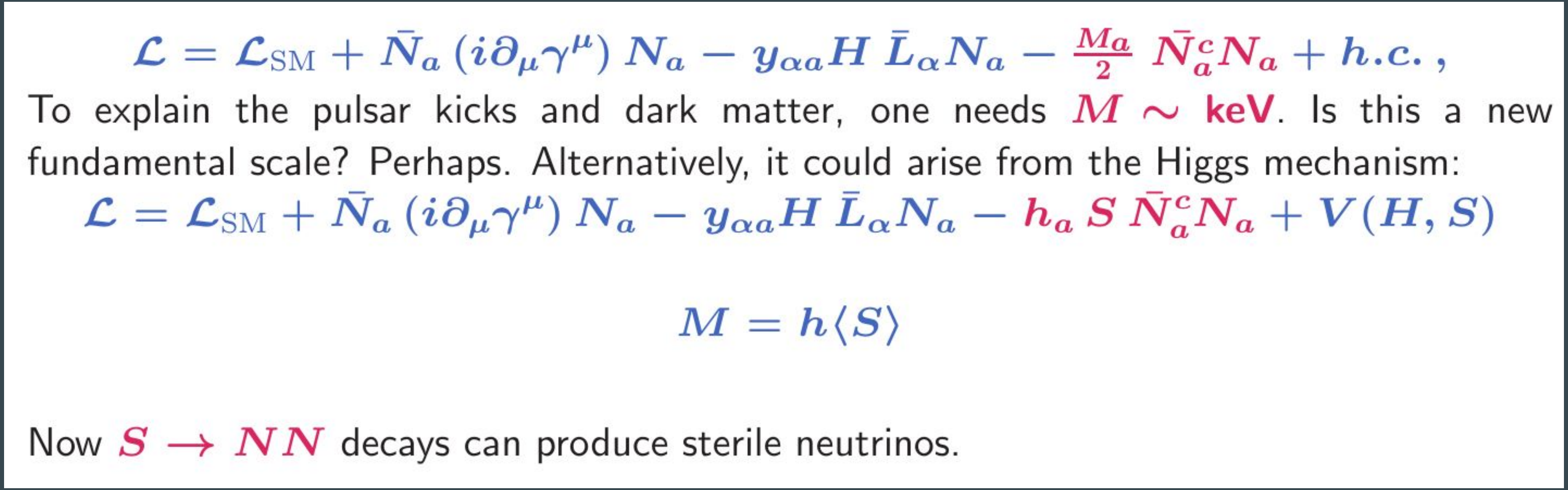
νMSM [Asaka, Blanchet, Shaposhnikov]

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

- Dark matter
- Leptogenesis via neutrino oscillations [Akhmedov, Rubakov, Smirnov]
- For some masses, the same oscillations can generate the lepton asymmetry to allow for Shi-Fuller production mechanism

A very economical model: Standard Model plus three right-handed neutrinos

New scale or new physics (and a non-WIMP miracle)



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

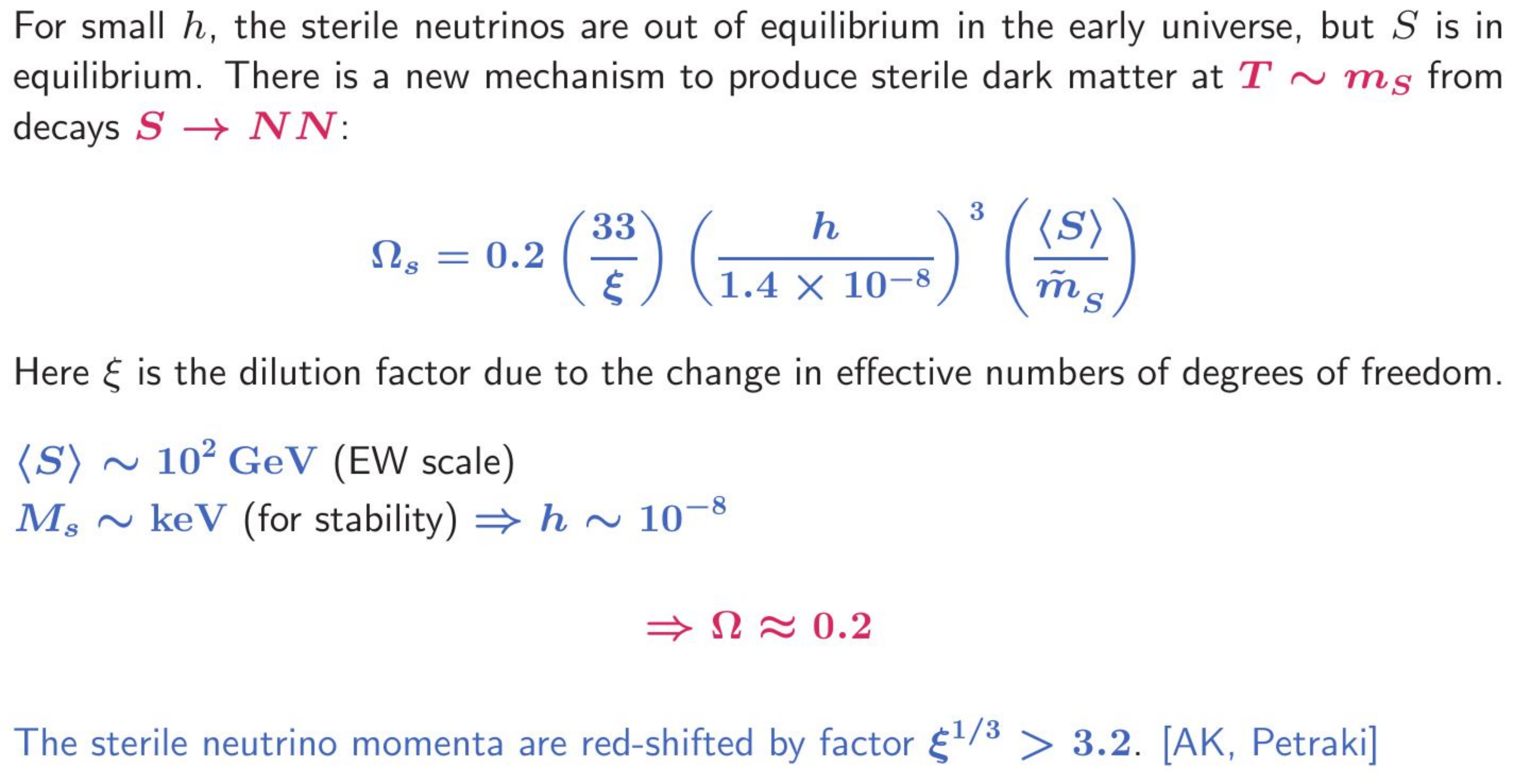
To explain the pulsar kicks and dark matter, one needs $M \sim$ **keV**. Is this a new fundamental scale? Perhaps. Alternatively, it could arise from the Higgs mechanism:

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

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

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

New scale or new physics (and a non-WIMP miracle)



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 $\boldsymbol{T \sim m_S}$ from decays $\boldsymbol{S \to NN}$:

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

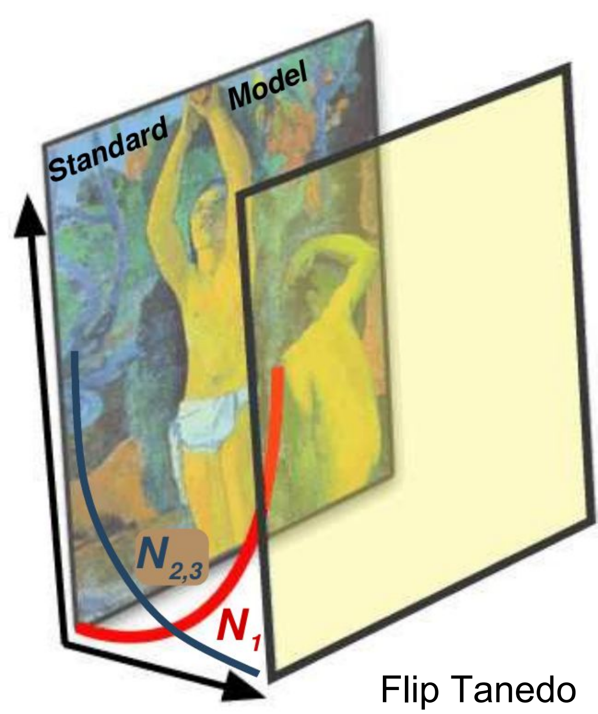
Here ξ is the dilution factor due to the change in effective numbers of degrees of freedom.

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

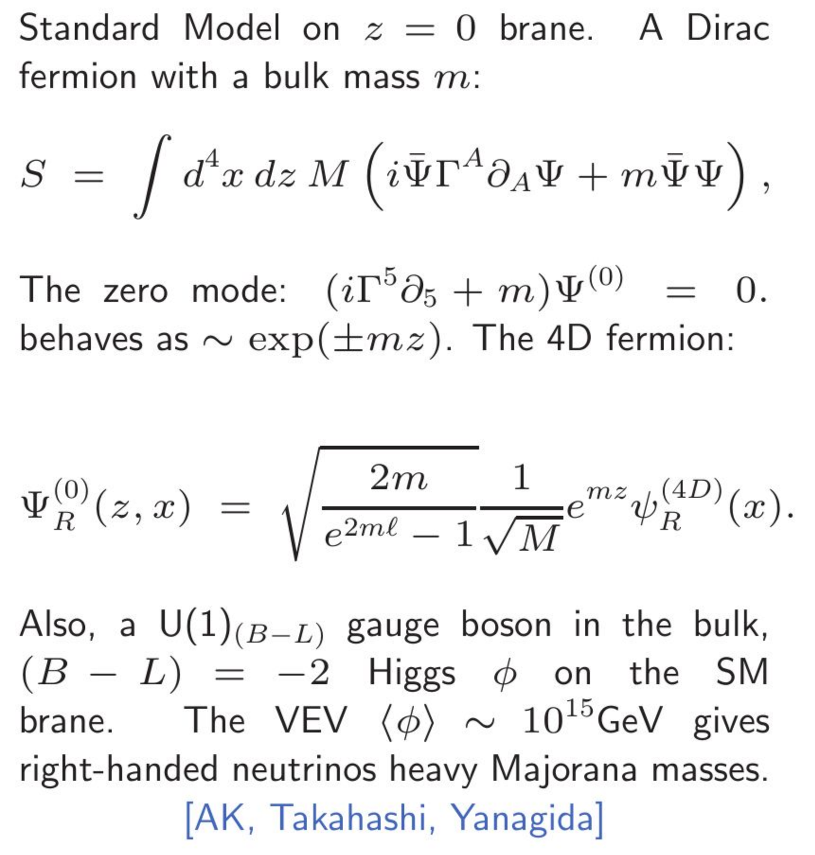
$$\boldsymbol{\Rightarrow \Omega \approx 0.2}$$

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

Split seesaw



Flip Tanedo



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

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

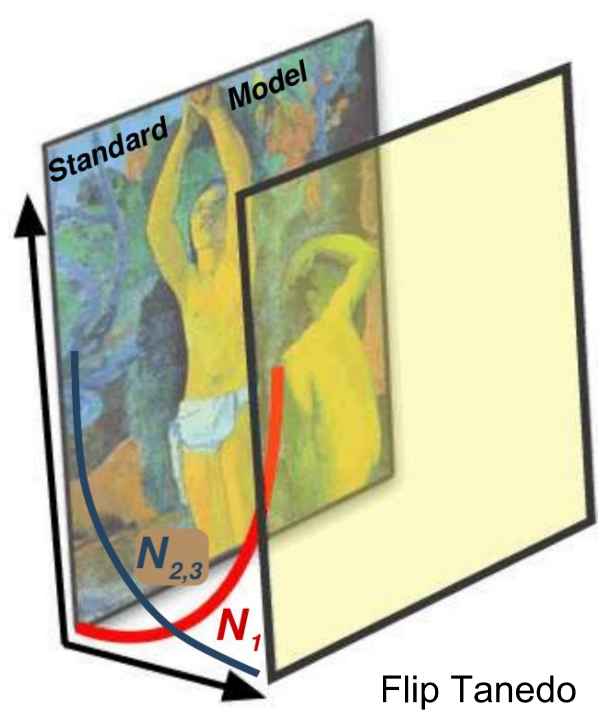
The zero mode: $(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0.$ behaves as $\sim \exp(\pm mz)$. The 4D fermion:

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

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



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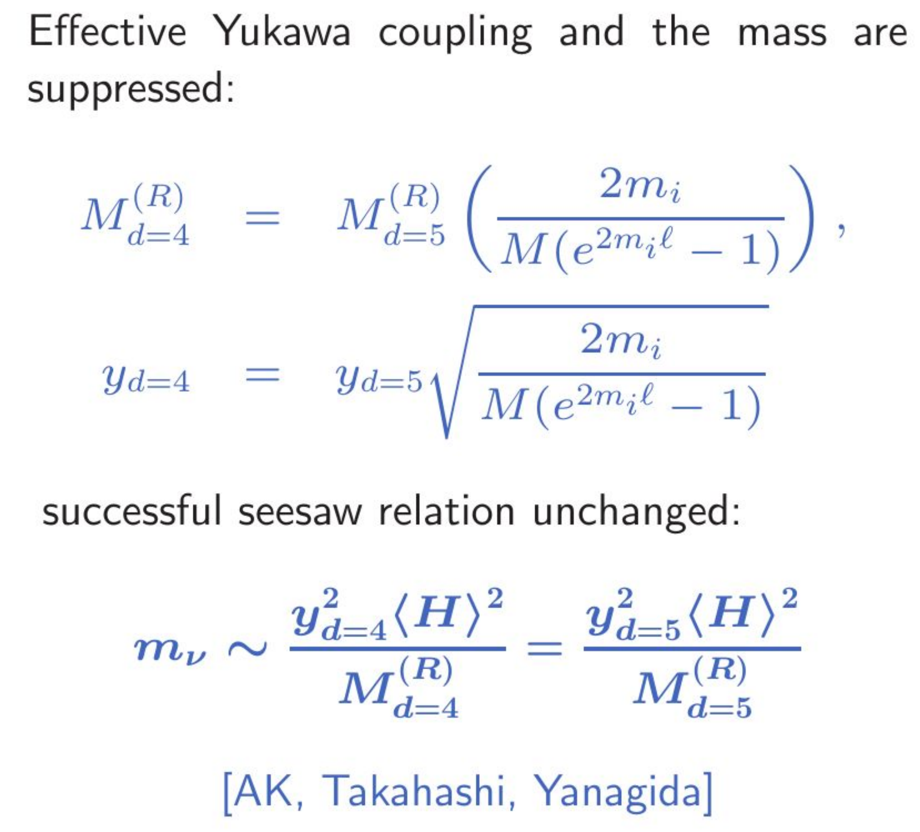


Effective Yukawa coupling and the mass are suppressed:

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

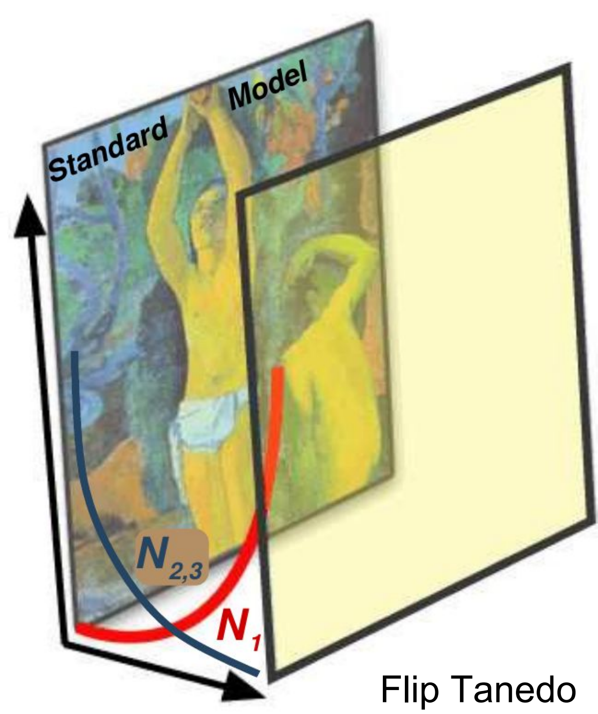
$$y_{d=4} = y_{d=5}\sqrt{\frac{2m_i}{M(e^{2m_i\ell}-1)}}$$

successful seesaw relation unchanged:

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

[AK, Takahashi, Yanagida]

Split seesaw



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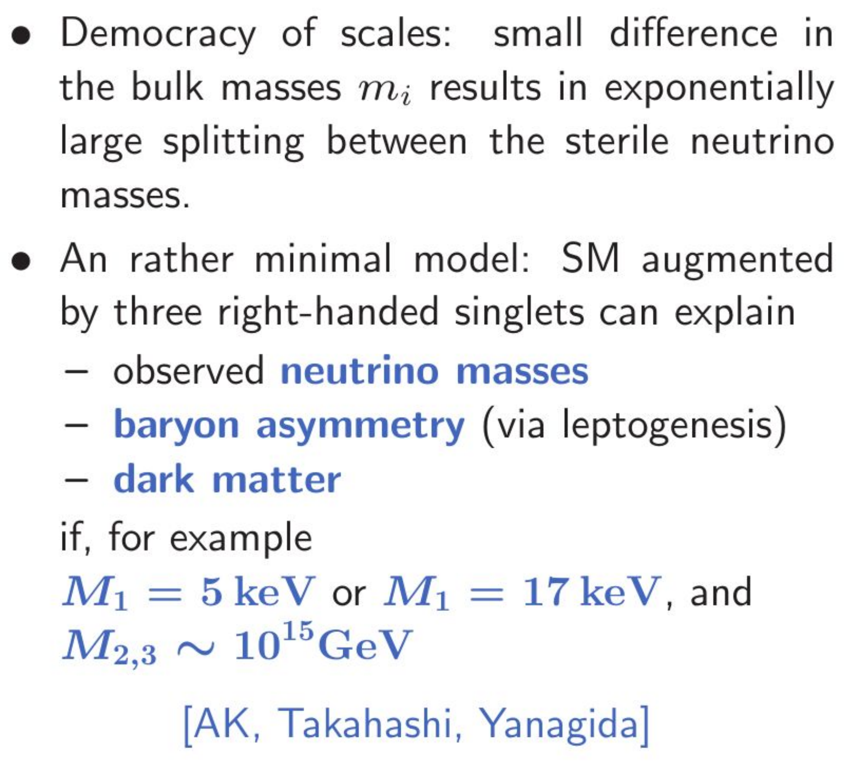
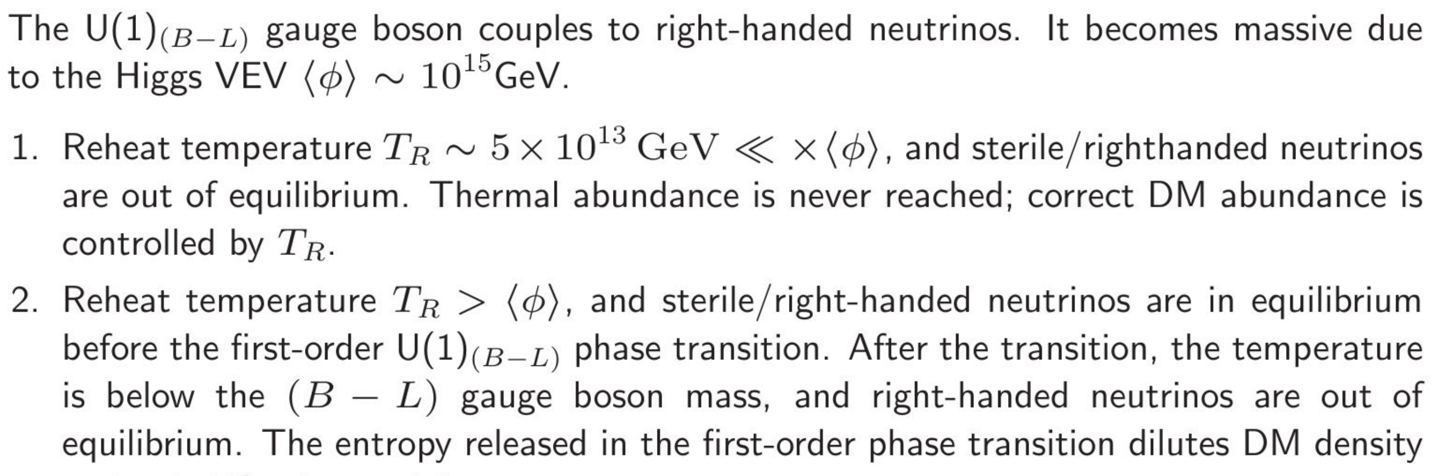


- Democracy of scales: small difference in the bulk masses m_i results in exponentially large splitting between the sterile neutrino masses.
- An rather minimal model: SM augmented by three right-handed singlets can explain
  - observed **neutrino masses**
  - **baryon asymmetry** (via leptogenesis)
  - **dark matter**

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

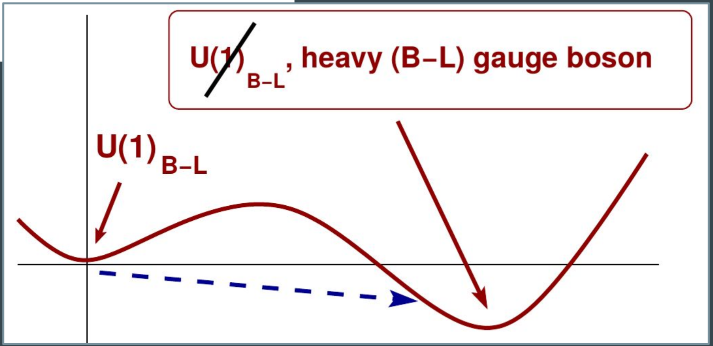
[AK, Takahashi, Yanagida]

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 $T_R \sim 5 \times 10^{13}\,\mathrm{GeV} \ll \times\langle\phi\rangle$, 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 $\mathrm{U}(1)_{(B-L)}$ 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.



Low-reheat universe

What if the universe never reached a (reheat) temperature above what is necessary for BBN (~4 MeV)?

[Gelmini et al. PRL 93 (2004) 081302]

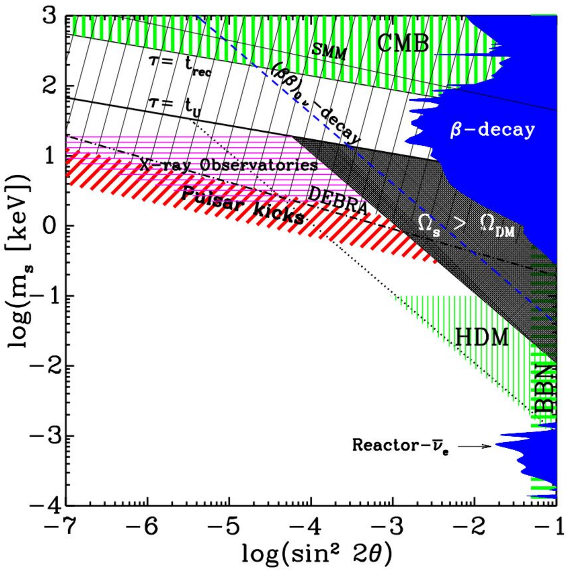


FIG. 1: Bounds and sensitivity regions for $\nu_e \leftrightarrow \nu_s$ oscillations. See text.

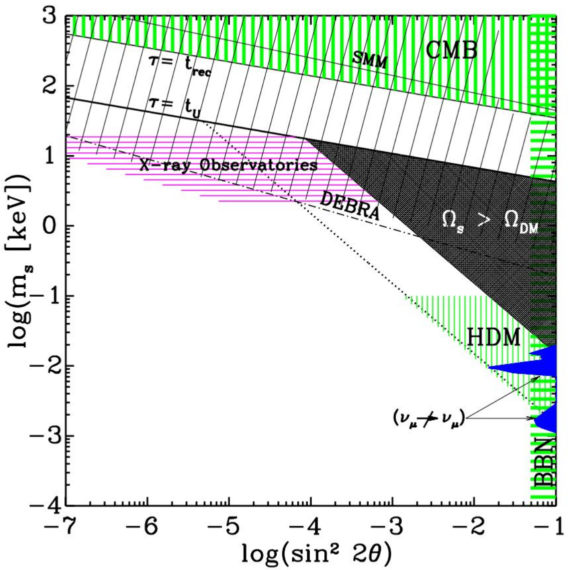
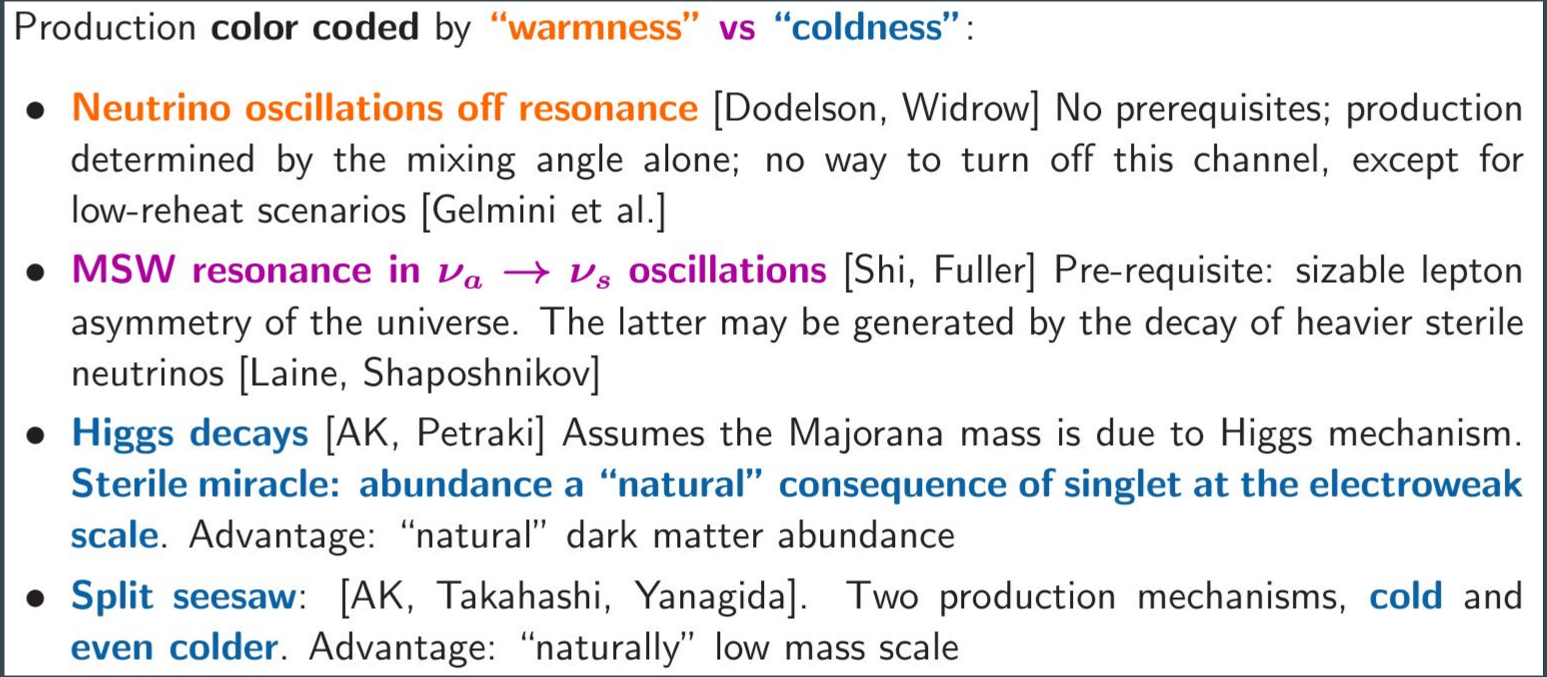


FIG. 2: Same as Fig. 1 for $\nu_{\mu,\tau} \leftrightarrow \nu_s$. For $\nu_\tau \leftrightarrow \nu_s$ the darkest gray-blue excluded region does not apply. See text.

Sterile dark matter: warm vs cold



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

Generically, two components: colder and warmer

Free-streaming depends on the production mechanism

$$\lambda_{FS} \approx 1\,\mathrm{Mpc}\left(\frac{\mathrm{keV}}{m_s}\right)\left(\frac{\langle p_s\rangle}{3.15\,T}\right)_{T\approx 1\,\mathrm{keV}}$$

$$\left(\frac{\langle p_s\rangle}{3.15\,T}\right)_{T\approx 1\,\mathrm{keV}} = \begin{cases} 0.9 \text{ for production off} - \text{resonance} \\ 0.6 \text{ for MSW resonance (depending on } L) \\ 0.2 \text{ for production at T} \gtrsim 100 \text{ GeV} \end{cases}$$

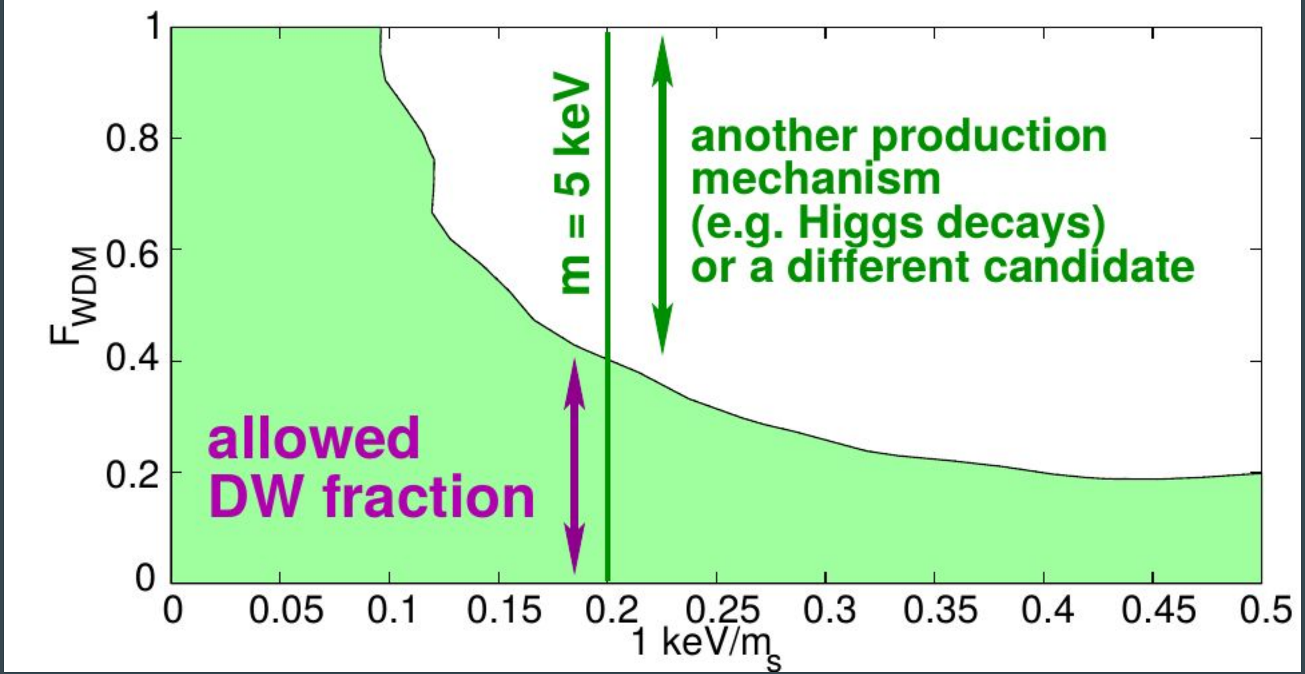
Dodelson-Widrow

Shi-Fuller

Decays, T > GeV

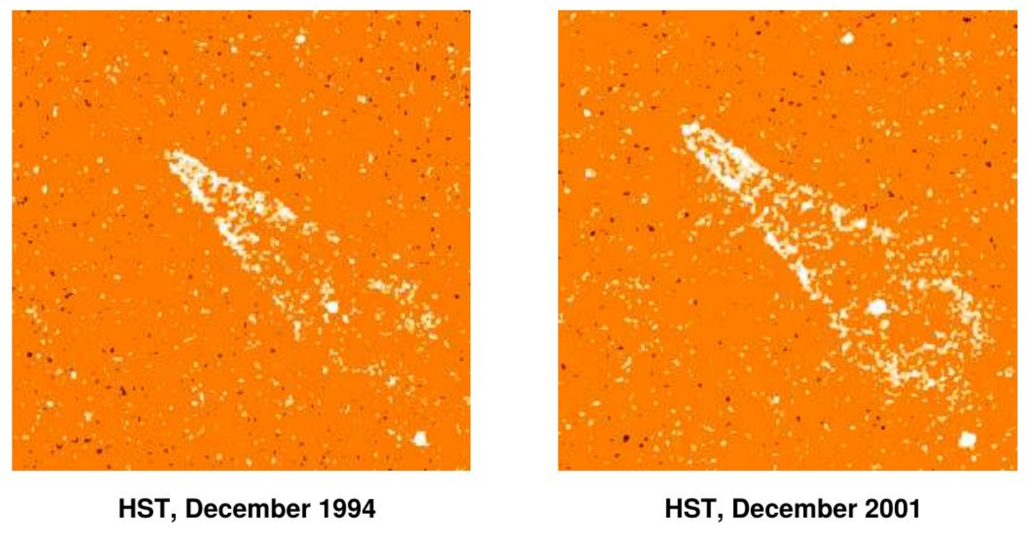
For review, see AK, arXiv:0906.2968

Lyman-α bounds for Dodelson-Widrow production



[Boyarsky et al.]

Astrophysical hints: supernovae and pulsar kicks



Pulsars have velocities ~500 km/s

15% have v>1000 km/s

Explanation is lacking.

Supernova asymmetries may or may not be enough...

Pulsar kicks

A neutron star with v~500 km/s has momentum $Mv \sim 10^{41}$ g cm/s

SN neutrinos have energy 10^{53}erg and carry momentum $P_\nu \sim 10^{43}$ g cm/s

The rest of SN gets only 1% of the energy...

Need a sizable asymmetry in SN, or

a **1% asymmetry** in the distribution of **neutrinos**

SN neutrinos are produced in urca processes

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

In the strong magnetic field of a neutron star, the electrons are polarized:

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

The asymmetry:

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

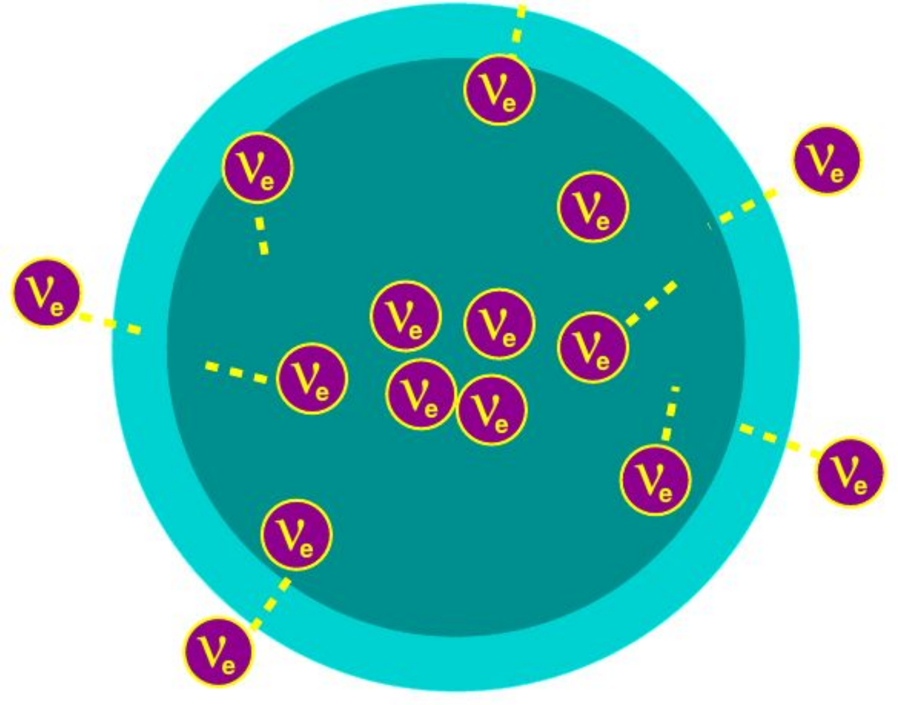
where k_0~0.3,the fraction in the lowest Landau level

Easily ~ 10% asymmetry! (need 1%)

Can ordinary neutrinos explain the pulsar kicks?

No.

Neutrinos are trapped at high density. Asymmetry is washed out as they diffuse out of the neutron star.



Sterile neutrinos

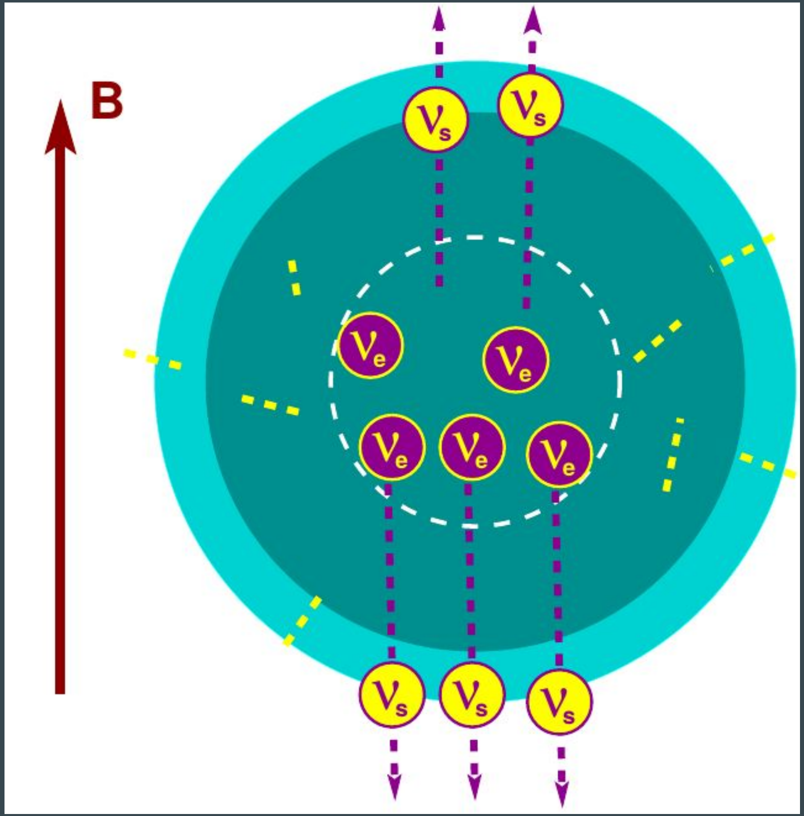
produced in the same processes, with the rates suppressed by $\sin^2\theta$

Scattering cross sections are also suppressed. Therefore,

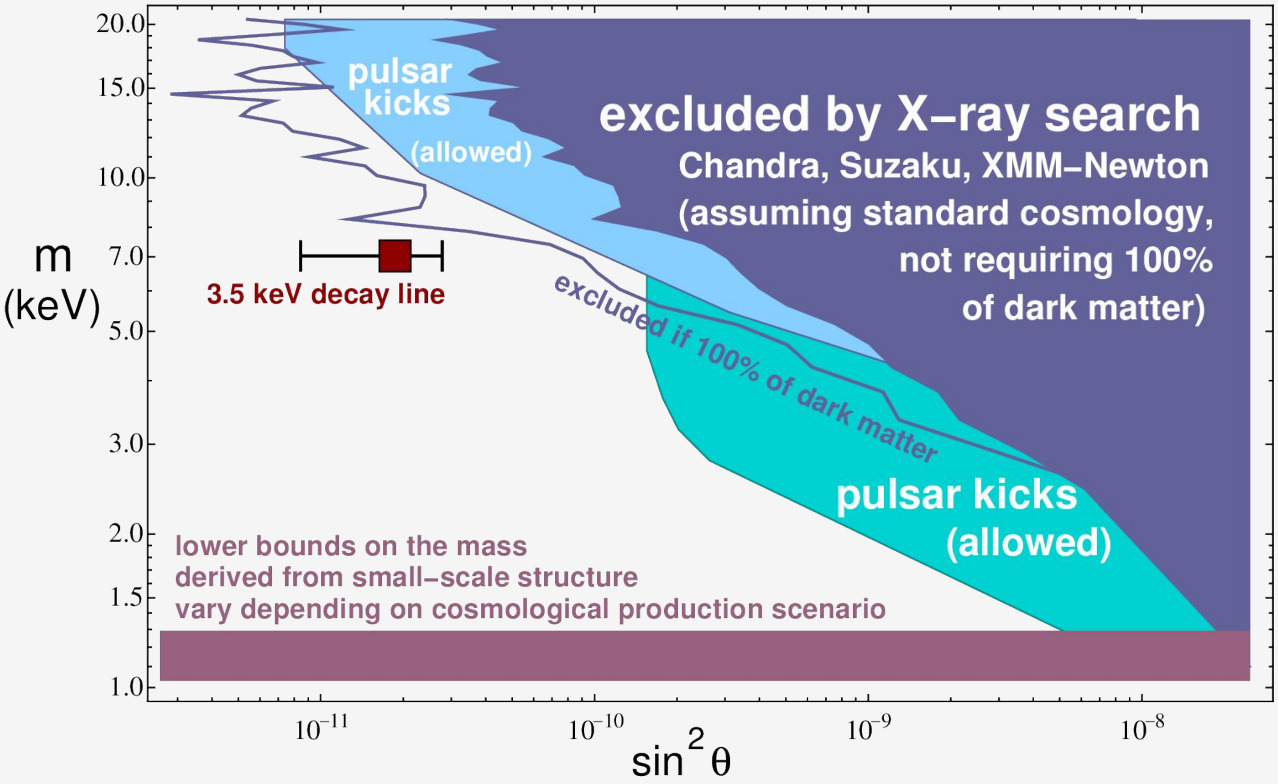
production anisotropy= emission anisotropy

10% energy escaping with 10% asymmetry

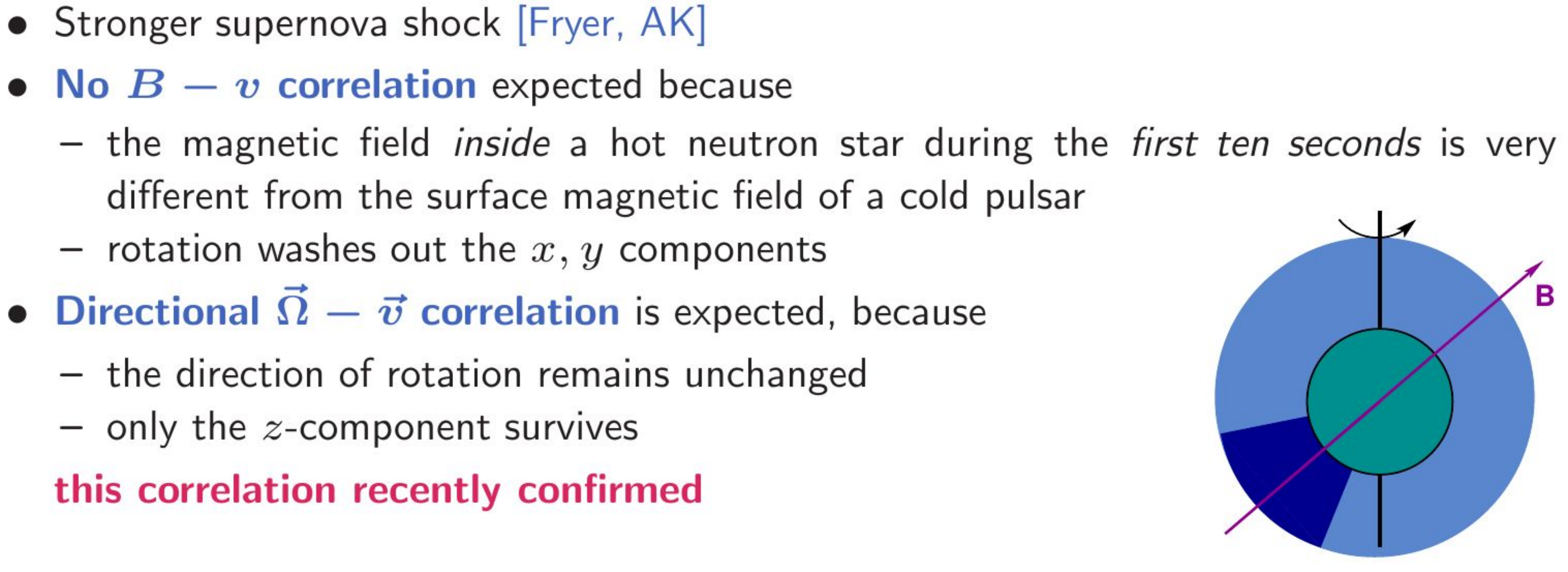
can explain the pulsar kicks



Sterile neutrino mass and mixing



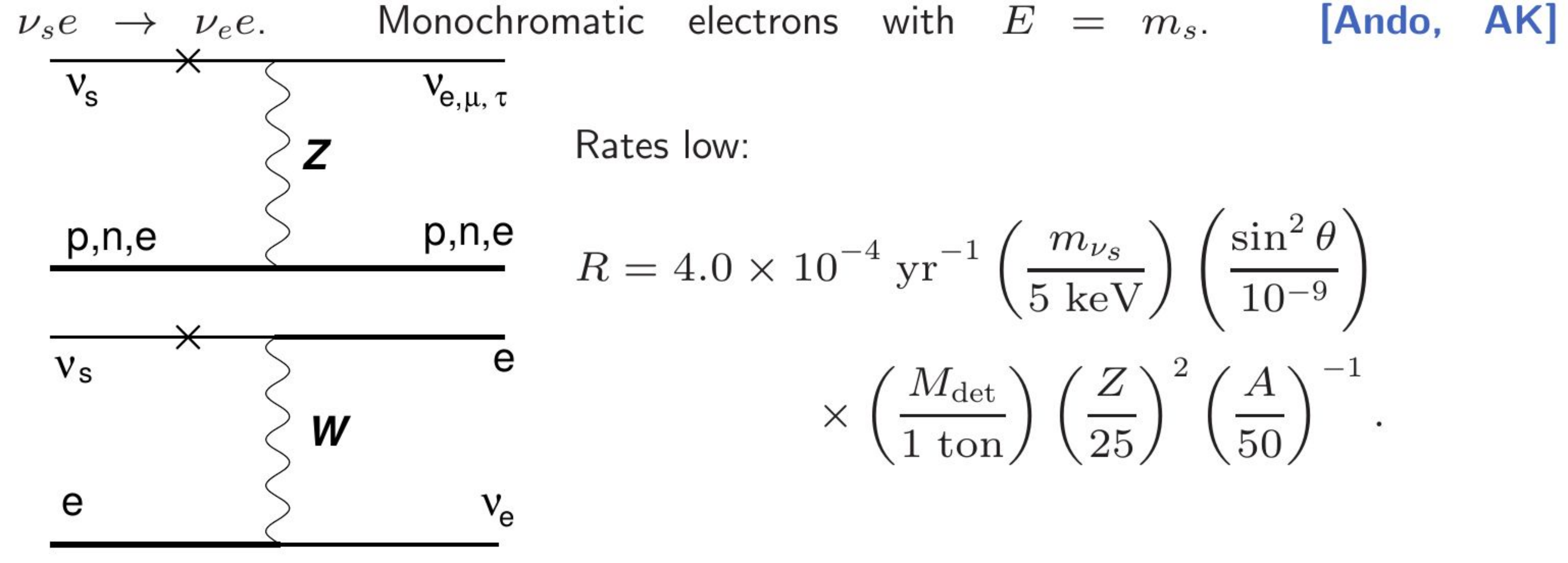
Other predictions of the sterile neutrino kick



- 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

Direct detection?



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

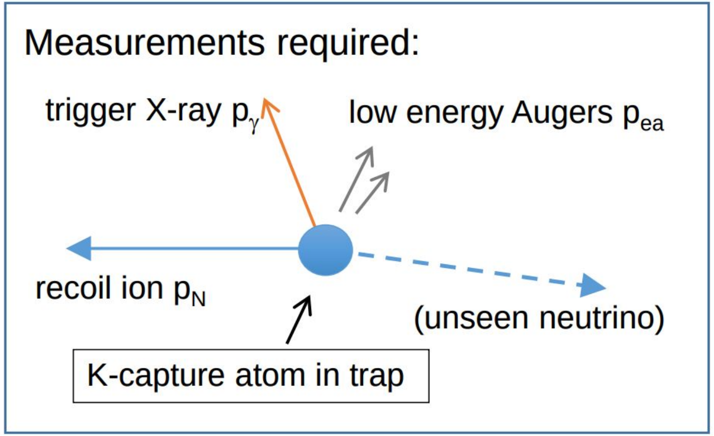
Rates low:

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

HUNTER experiment at UCLA: Cs-131 in an optical trap

(**H**eavy **U**nseen **N**eutrinos by **T**otal **E**nergy-momentum **R**econstruction)

Measurements required:

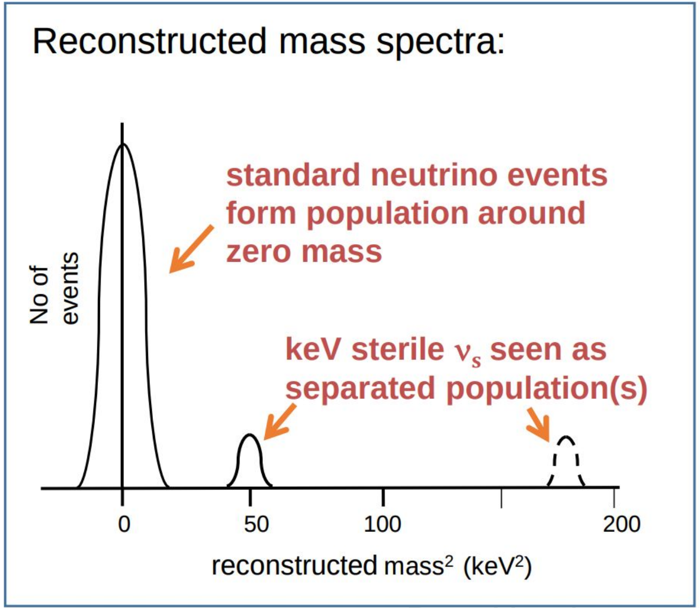


Mass reconstruction formula:

$$m_\nu^2 = [Q - E_a - E_\gamma - E_N]^2 \quad - \quad [\mathbf{p}_\gamma + \mathbf{p}_{ea} + \mathbf{p}_N]^2$$

missing energy missing momentum

Reconstructed mass spectra:



standard neutrino events form population around zero mass

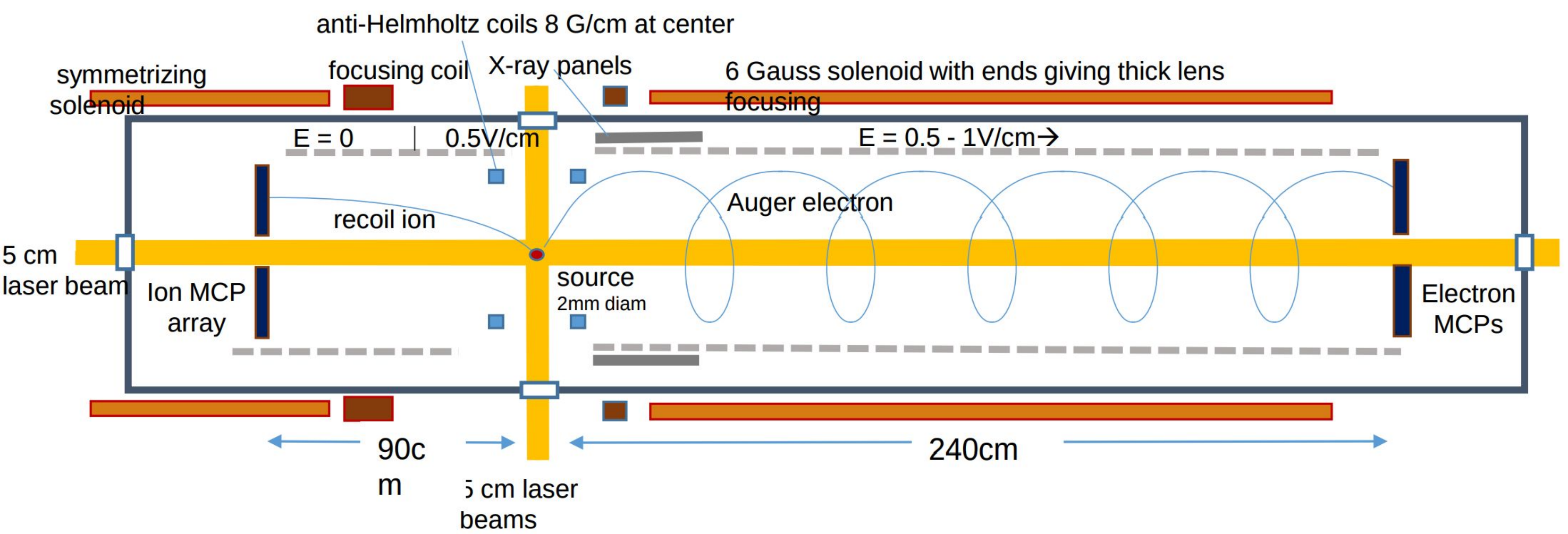
keV sterile ν_s seen as separated population(s)

Paul Hamilton

G. Finocchiaro,
R. Shrock,
Phys.Rev. D46
(1992) R888

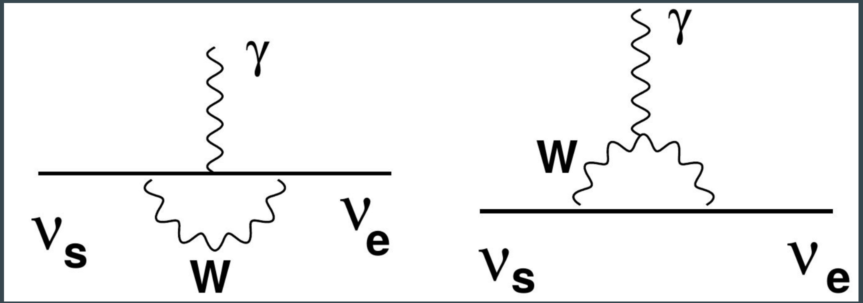
P. Smith,
arxiv:1607.06876

HUNTER experiment at UCLA: Cs-131 in an optical trap



Radiative decay (time scales >> age of universe)

Two-body decay into a photon and an active neutrino.

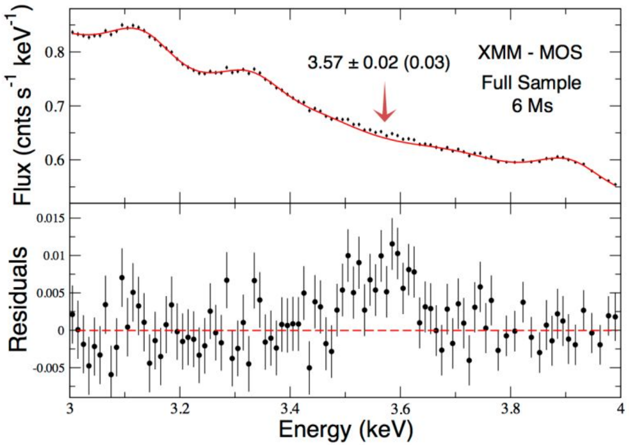


$$\nu_s \to \nu_{e,\mu,\tau}\gamma, \quad E_\gamma = \frac{m_s}{2} \Rightarrow \text{narrow spectral line}$$

Mass ~keV,

an X-ray telescope pointing at a large collection of dark-matter particles can detect a line from dark matter decay.

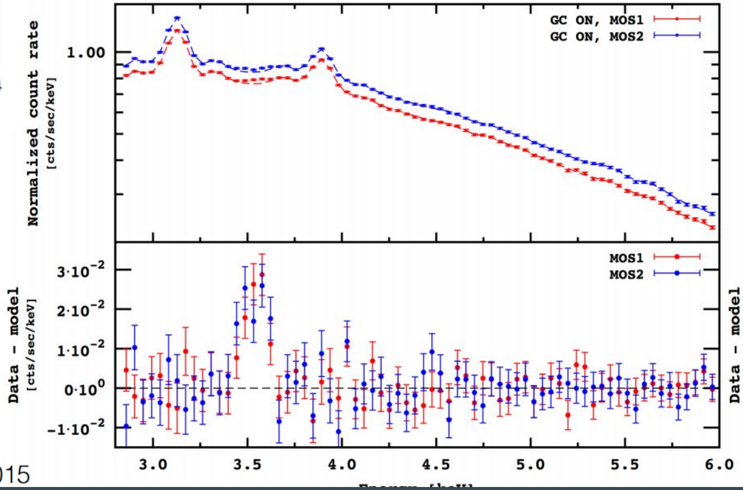
Unidentified 3.5 keV line: is it dark matter?



73 stacked galaxy clusters

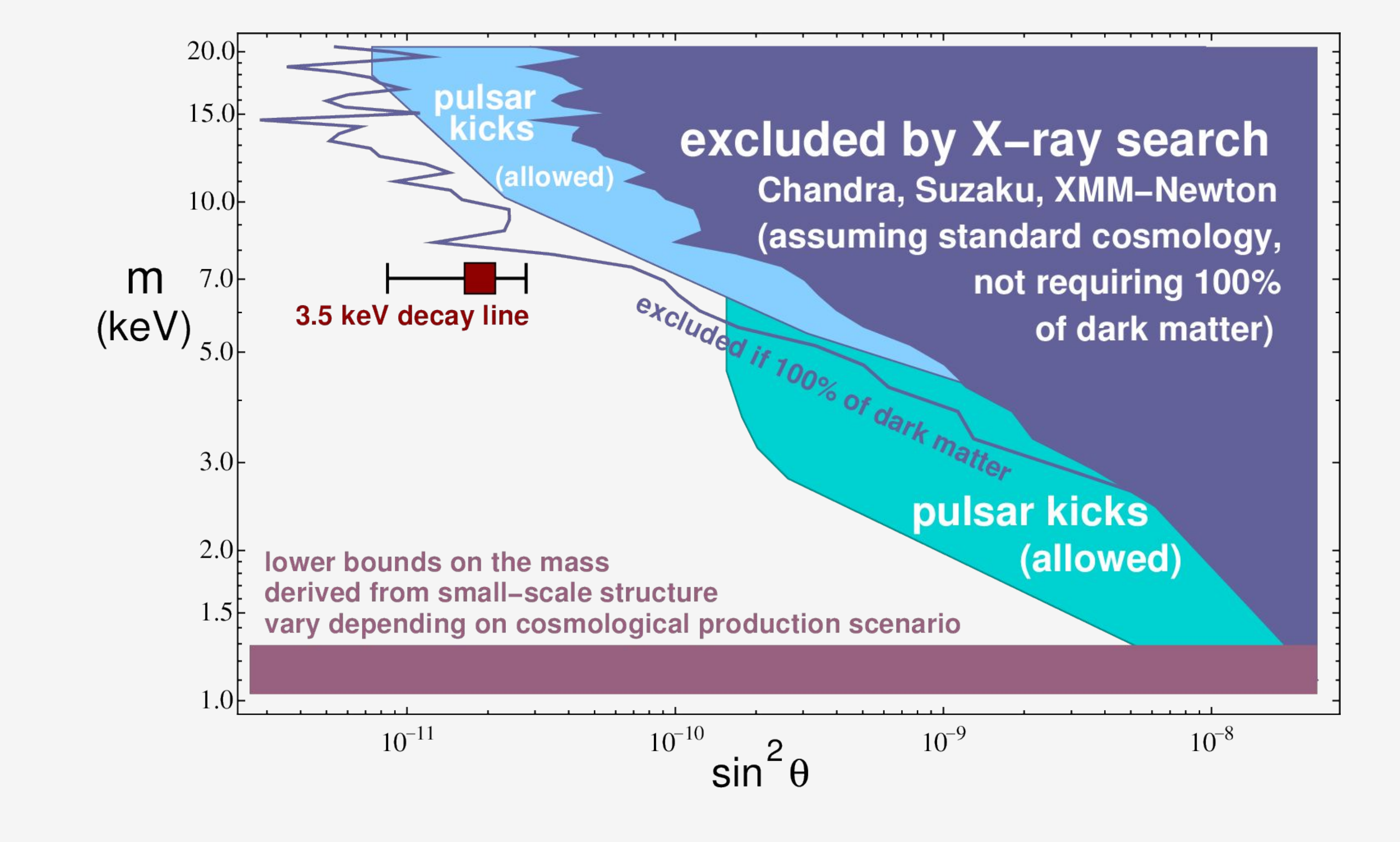
Bulbul et al. 2014
1402.2301

Galactic Center

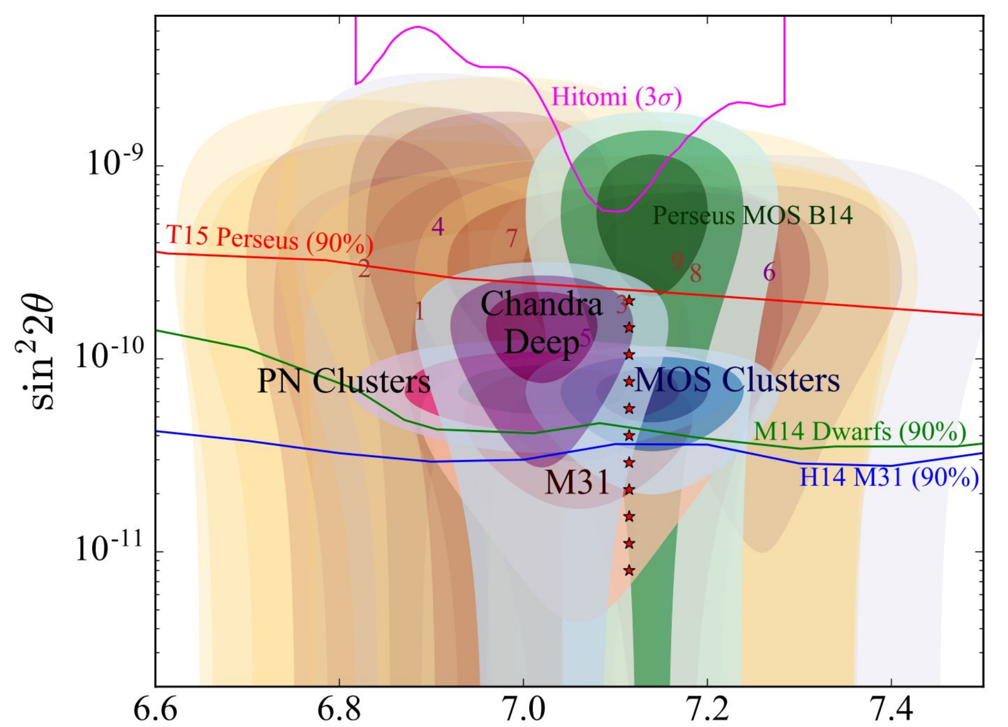


Boyarksy et al. 2015

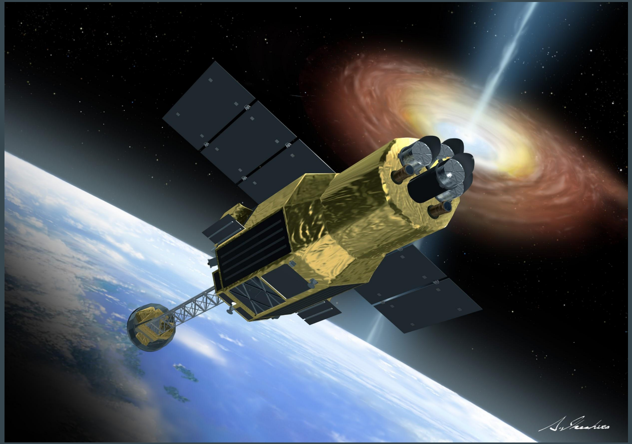
Interpretation as a dark-matter sterile neutrino



3.5 keV line: detected or not?



Abazajian



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

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
- 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