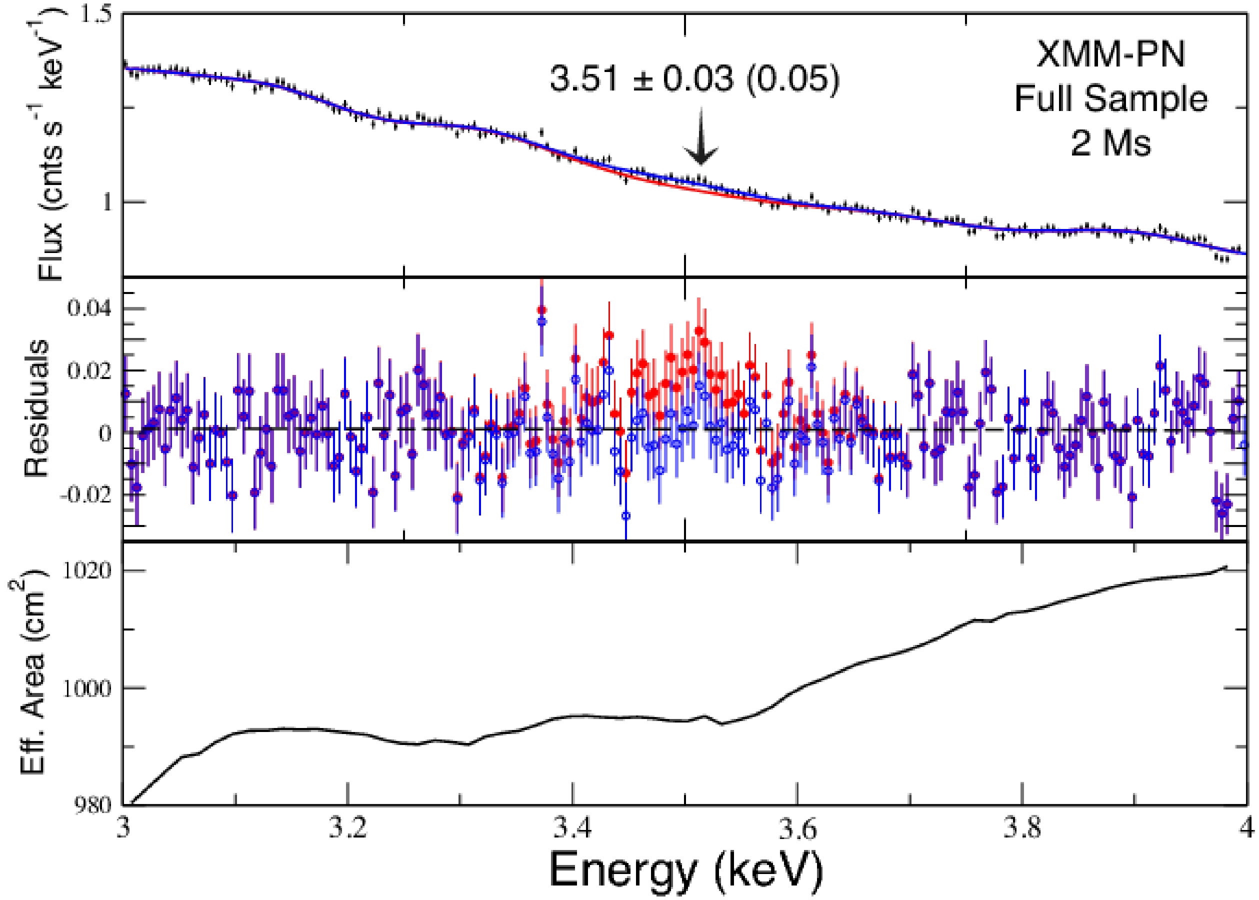
Sterile neutrinos, moduli, and dark matter with a keV mass.

- 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

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



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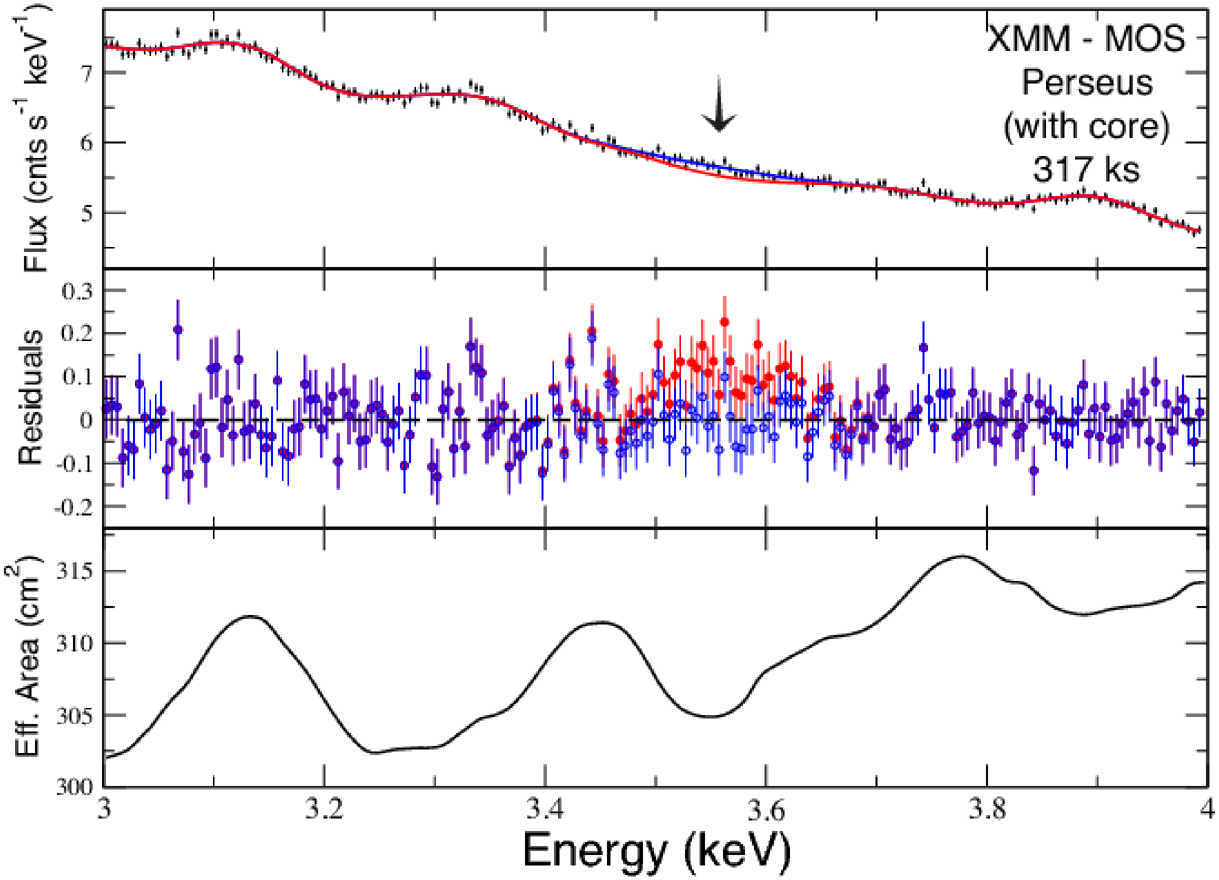

Dark matter, and the origin of a keV scale

Kev Abazajian's talk:
tantalizing hints of 7 keV dark-mater particle [Bulbul et al.; Boyarsky et al.]

Assume known: two body decay $X \rightarrow \gamma Y$.
Unknown:

1. Is $Y \equiv \nu$?
2. Is X a fermion or a boson?

If the dark-matter particle is a fermion and $X \equiv \nu_s \rightarrow \gamma\nu$, this is probably a 7-keV sterile neutrino!
Other possibilities exist, for example, $\phi \rightarrow \gamma\gamma$, where ϕ is one of the supersymmetry/string moduli.
I will explore the possible underlying fundamental physics.

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_α $(\alpha = e, \mu, \tau)$ are the lepton doublets. The mass matrix:

$$M = \left(\begin{array}{cc} 0 & D_{3 \times N} \\ D^T_{N \times 3} & M_{N \times N} \end{array} \right)$$

What is the *natural* scale of M?

Seesaw mechanism

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

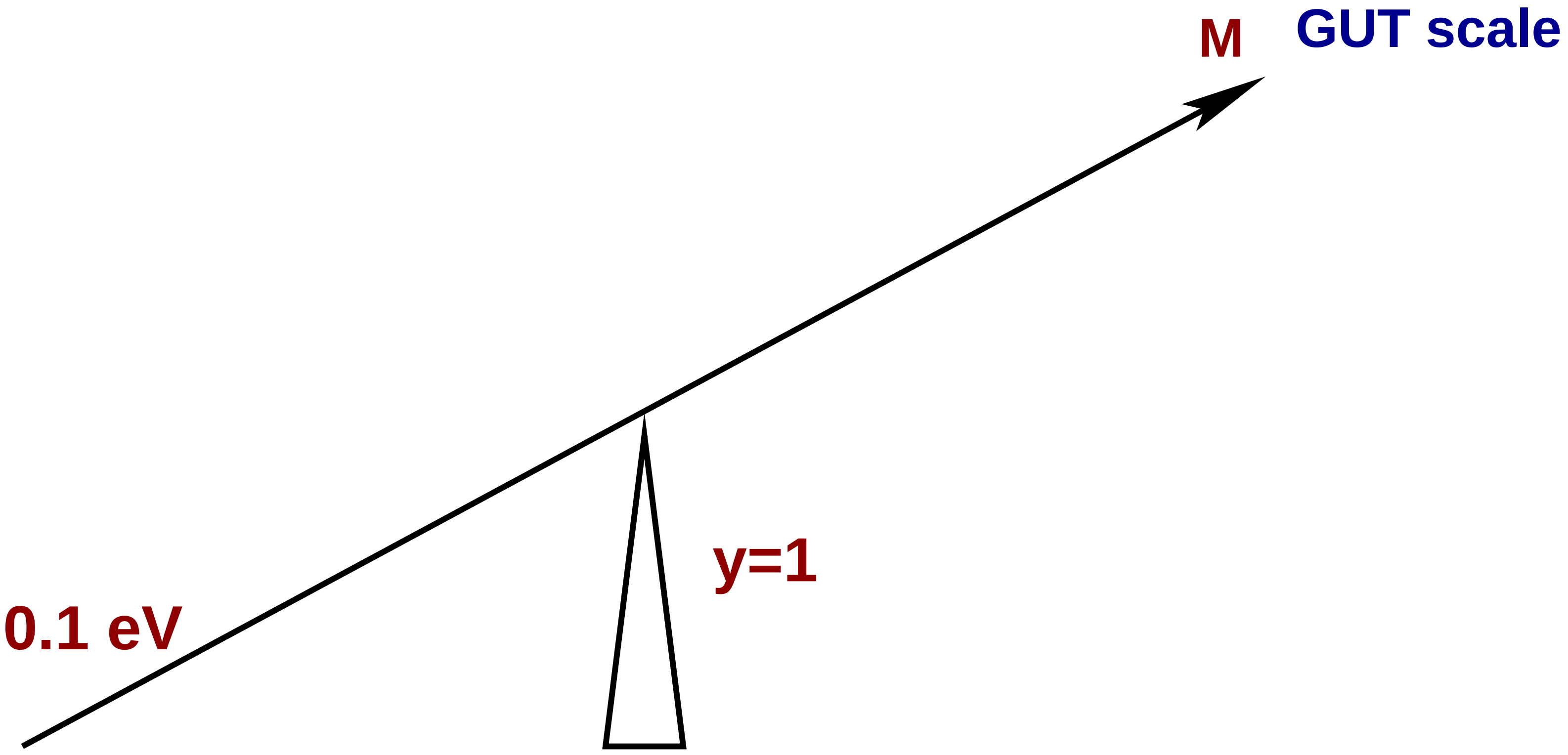
$$D_{ij} = y_{ij} \langle H \rangle$$

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

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

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

Seesaw mechanism



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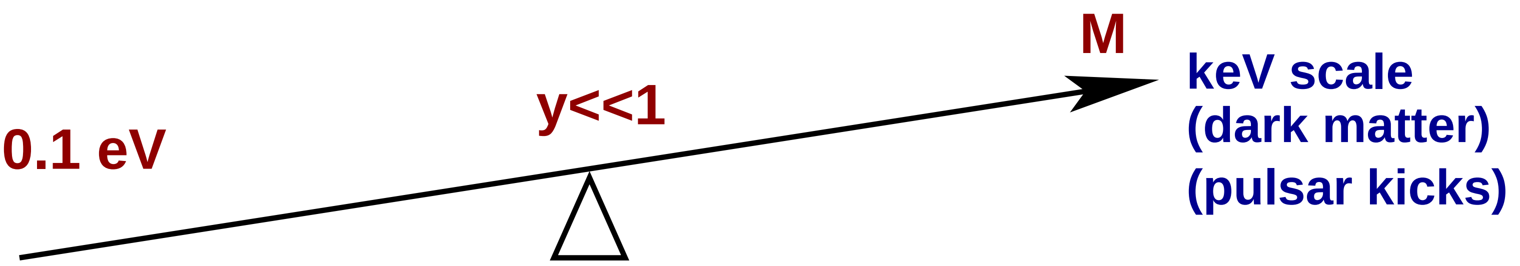

GUT scale

Various approaches to small Majorana masses

- Just write them down.
  - One sterile keV sterile neutrino, the dark matter candidate **[Dodelson, Widrow]**.
  - Three sterile neutrinos, one with a several keV mass (dark matter) and two degenerate with GeV masses and a keV splitting, νMSM **[Shaposhnikov et al.]**.
- Use **lepton number** conservation as the reason for a small mass **[de Gouvêa]**.
- Use **flavor symmetries**, new gauge symmetries **[Lindner 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**

Sterile neutrinos as dark matter: production scenarios

Production **color coded** by **“warmness”** **vs** **“coldness”**:

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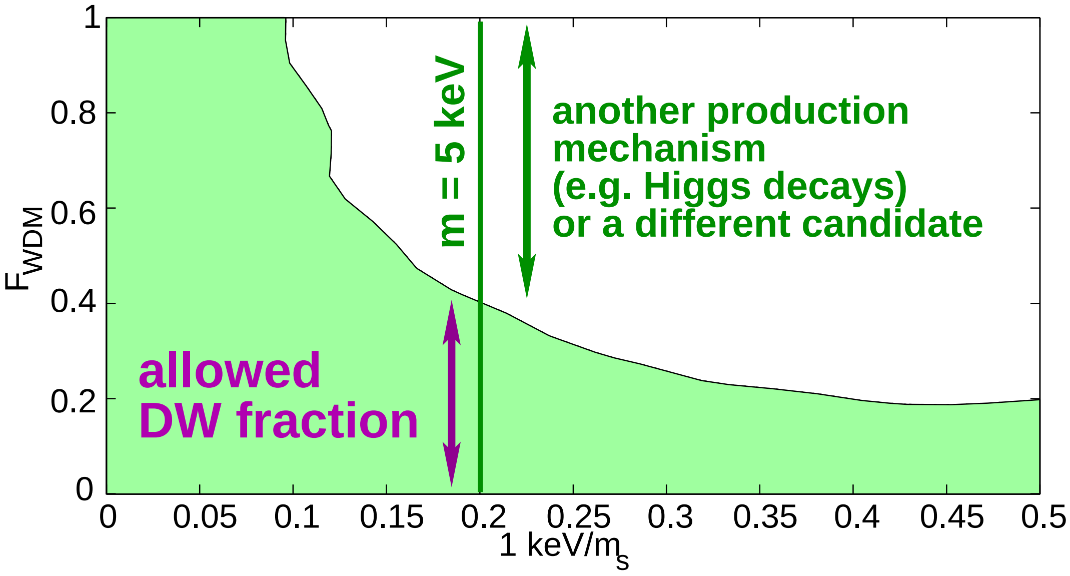
- **Split seesaw**: [AK, Takahashi, Yanagida]
  Two production mechanisms, **cold** and **even colder**.
  Advantage: “naturally” low mass scale

Lyman-α 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 $S \to NN$:

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

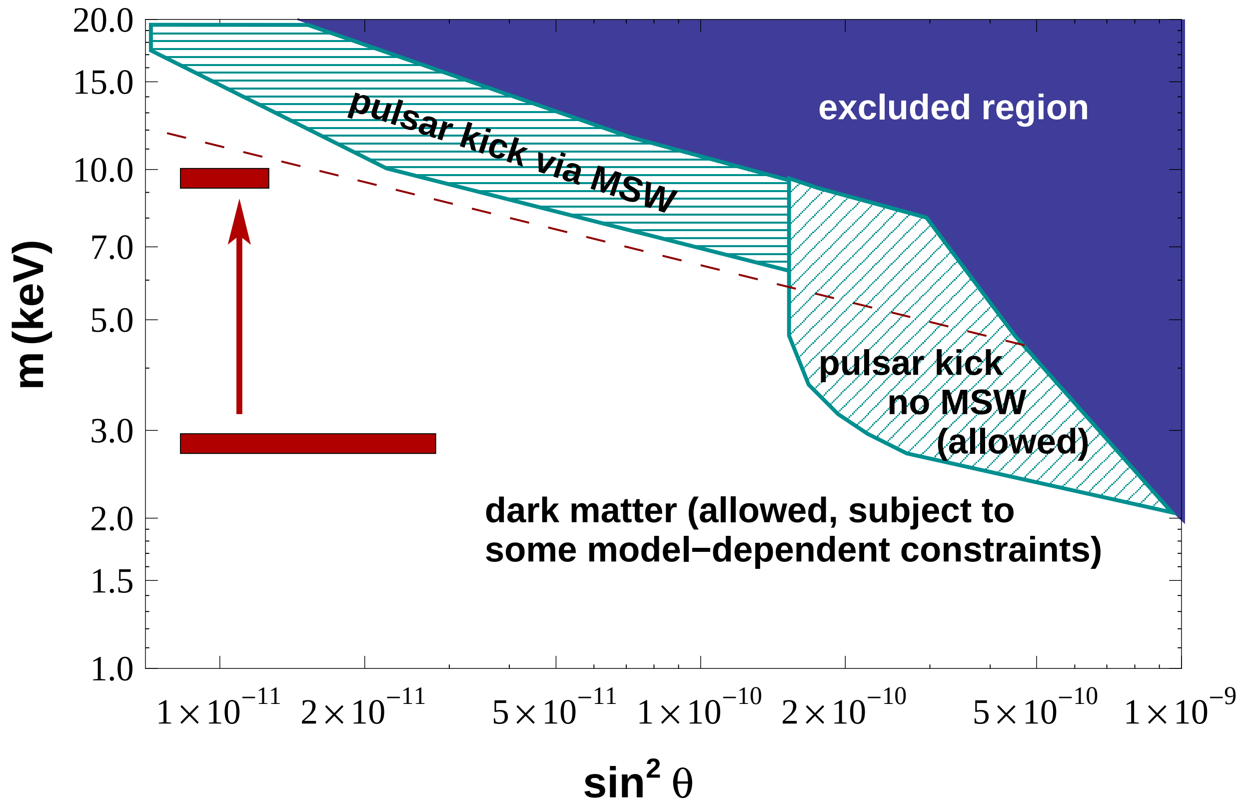
Here ξ is the dilution factor due to the change in effective numbers of degrees of freedom.

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

$$\Rightarrow \Omega \approx 0.2$$

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

Cooling changes the clustering properties

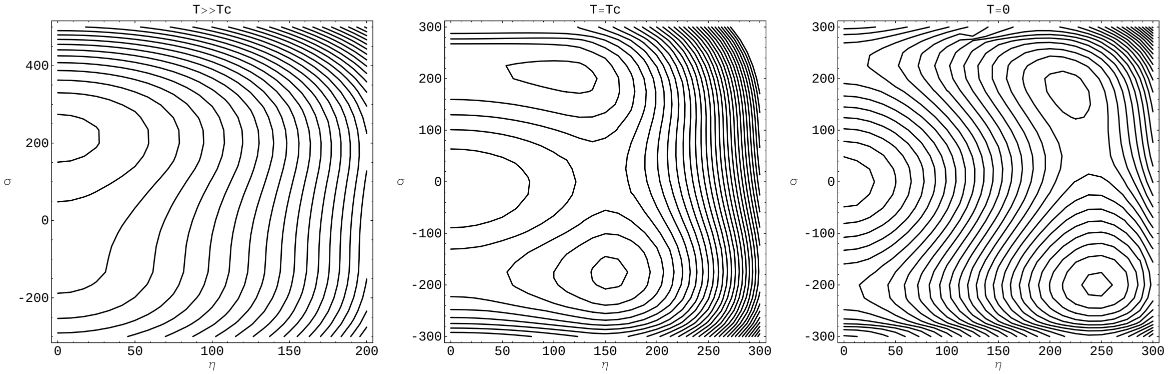


[AK, PRL **97**:241301 (2006); Petraki, AK, PRD 77, 065014 (2008); Petraki, PRD 77, 105004 (2008)]

Implications for the EW phase transition and the LHC

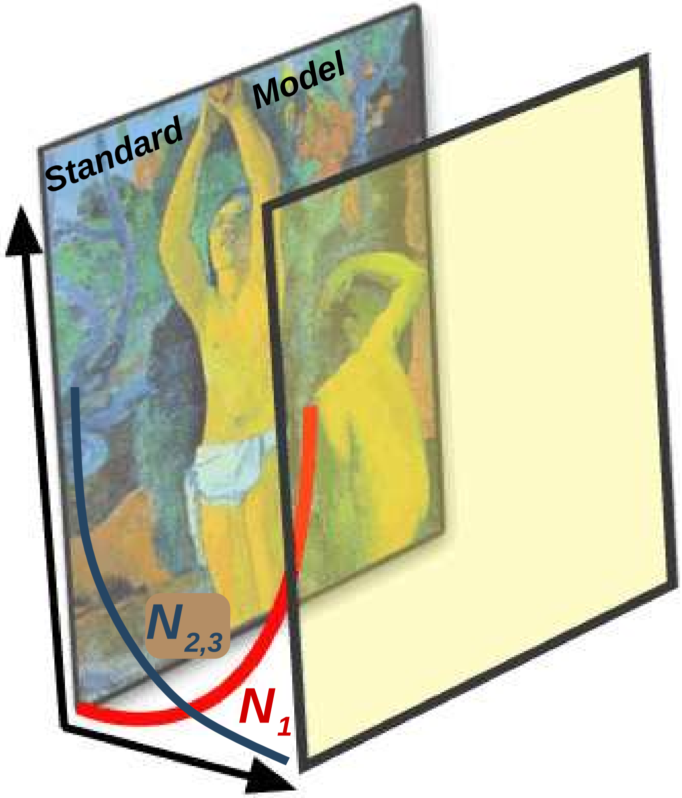
One may be able to discover the *singlet Higgs* at the LHC [Profumo, Ramsey-Musolf, G. Shaughnessy; Davoudiasl et al.; O'Connell et al.; Ramsey-Musolf, Wise]

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



First-order transition, CP in the Higgs sector ⟹ **electroweak baryogenesis**

Split seesaw



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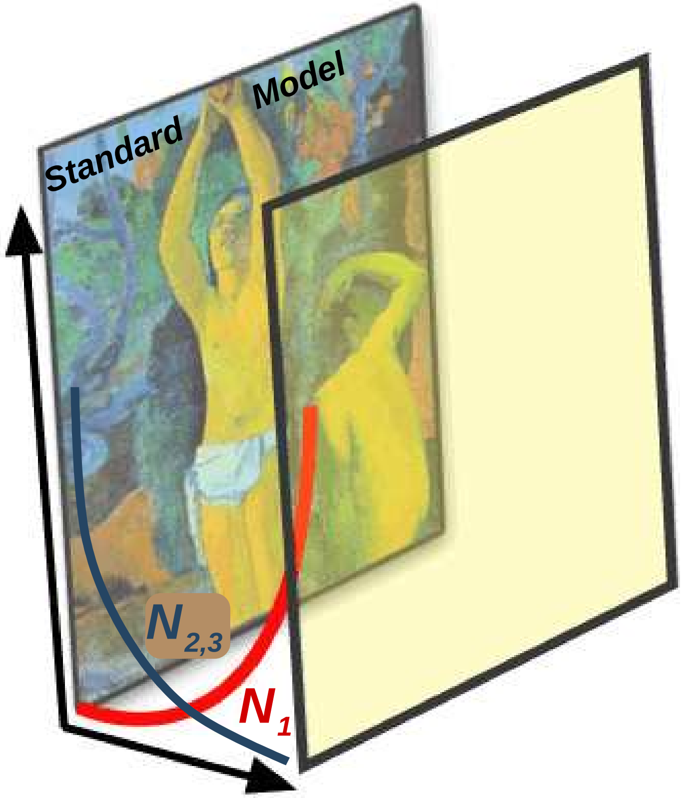
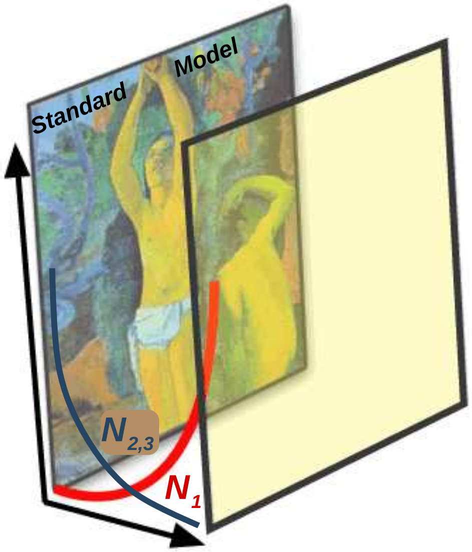




Standard Model on $z = 0$ brane. A Dirac fermion with a bulk mass m:

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

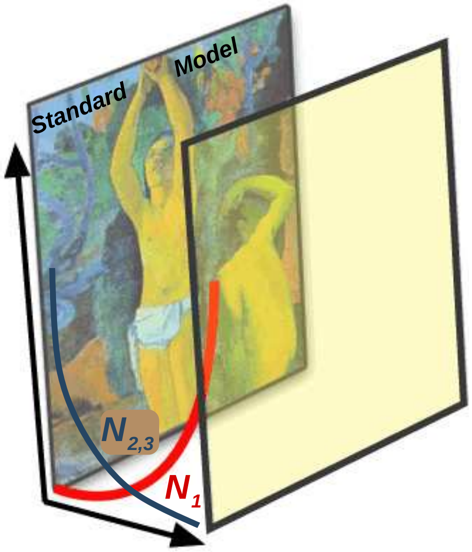
The zero mode: $(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0.$ behaves as $\sim \exp(\pm mz)$. The 4D fermion:

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

Also, a $\mathrm{U}(1)_{(B-L)}$ 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:

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

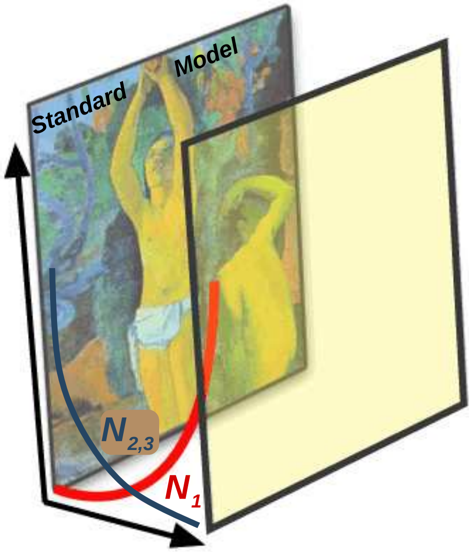
$$y_{d=4} = y_{d=5} \sqrt{\frac{2m_i}{M(e^{2m_i \ell} - 1)}}$$

successful seesaw relation unchanged:

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

[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]

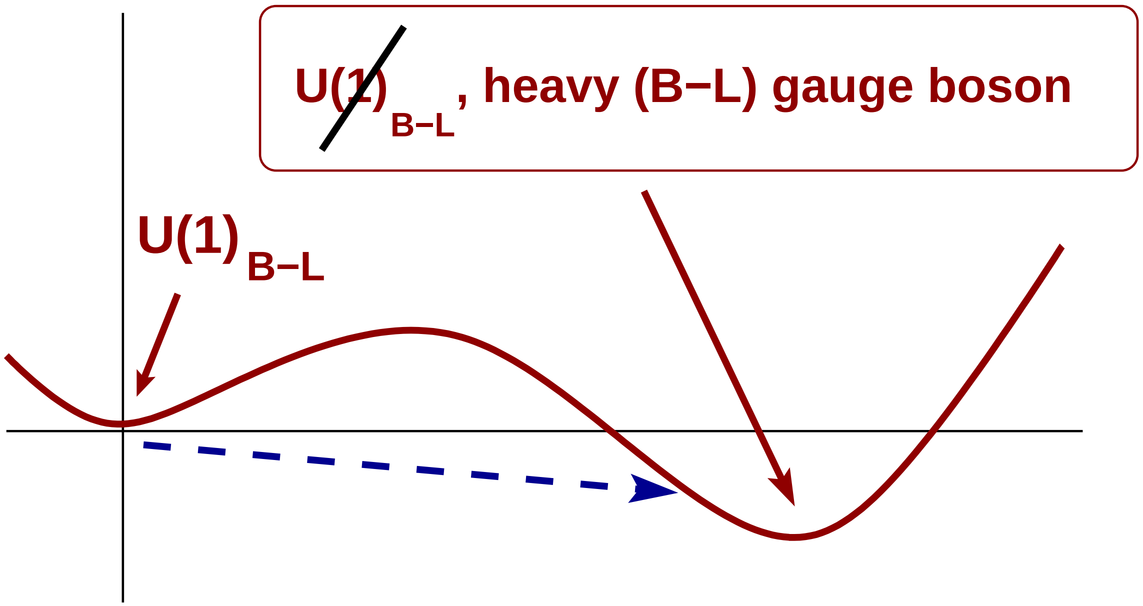
Dark matter production in Split Seesaw: two scenarios

The U$(1)_{(B-L)}$ gauge boson couples to right-handed neutrinos. It becomes massive due to the Higgs VEV $\langle\phi\rangle \sim 10^{15}$GeV.

1. Reheat temperature $T_R \sim 5\times 10^{13}\,\mathrm{GeV} \ll \times\langle\phi\rangle$, and sterile/righthanded neutrinos are out of equilibrium. Thermal abundance is never reached; correct DM abundance is controlled by T_R.
2. Reheat temperature $T_R > \langle\phi\rangle$, and sterile/right-handed neutrinos are in equilibrium before the first-order U$(1)_{(B-L)}$ phase transition. After the transition, the temperature is below the $(B-L)$ gauge boson mass, and right-handed neutrinos are out of equilibrium. The entropy released in the first-order phase transition dilutes DM density and red-shifts the particle momenta.

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

Dark matter production in Split Seesaw: second scenario



Moduli

- Generic prediction of string theory
- SUSY flat directions ⇒ scalars that are massless in the limit of exact SUSY, but acquire a mass from SUSY breaking.

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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:

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

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]:

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

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:

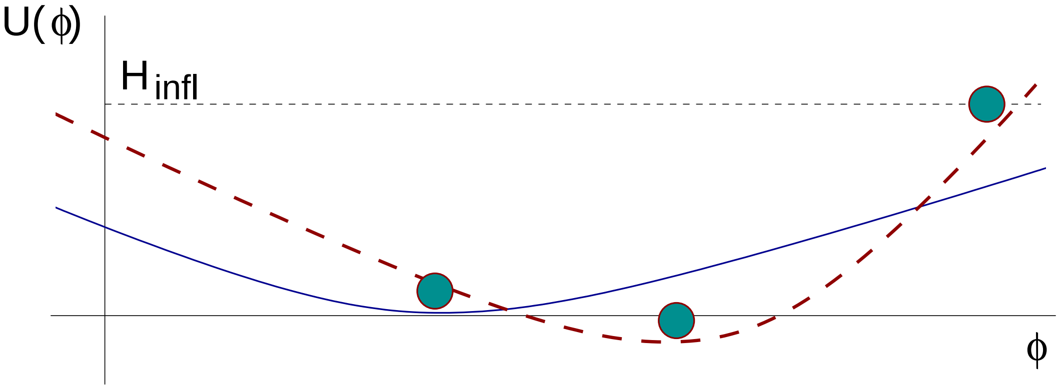
$$\phi \to \gamma\gamma \ \ \text{(a narrow X-ray line)}$$

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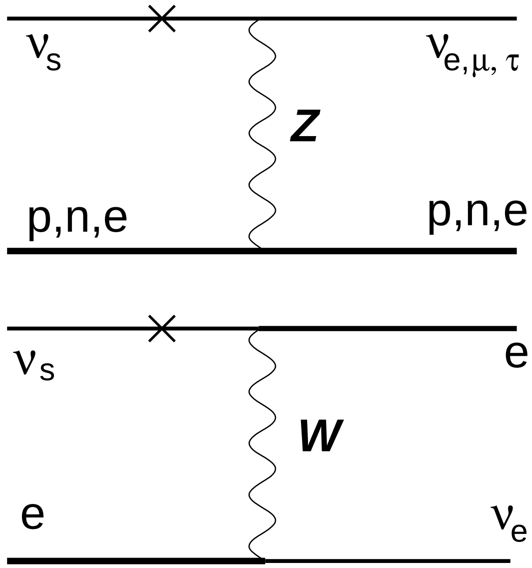
Anthropic solution to moduli problem $\Rightarrow$ correct amount of dark matter.
[AK, Loewenstein, Yanagida]

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

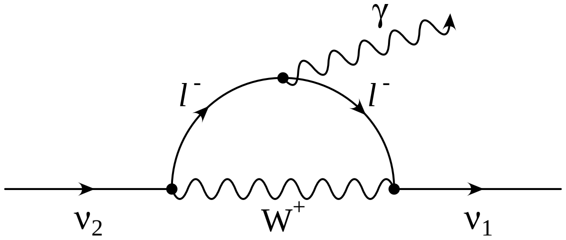


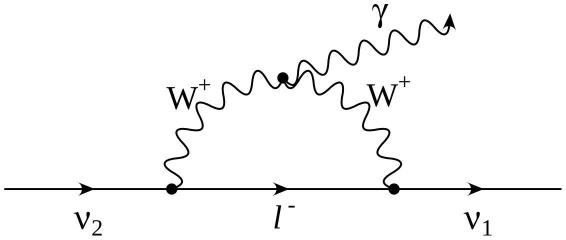
Rates low:

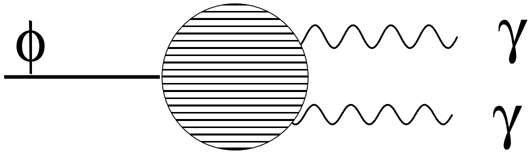
$$R = 4.0 \times 10^{-4}\ \mathrm{yr}^{-1} \left(\frac{m_{\nu_s}}{5\ \mathrm{keV}}\right)\left(\frac{\sin^2\theta}{10^{-9}}\right) \times \left(\frac{M_{\rm det}}{1\ \mathrm{ton}}\right)\left(\frac{Z}{25}\right)^2\left(\frac{A}{50}\right)^{-1}.$$

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:



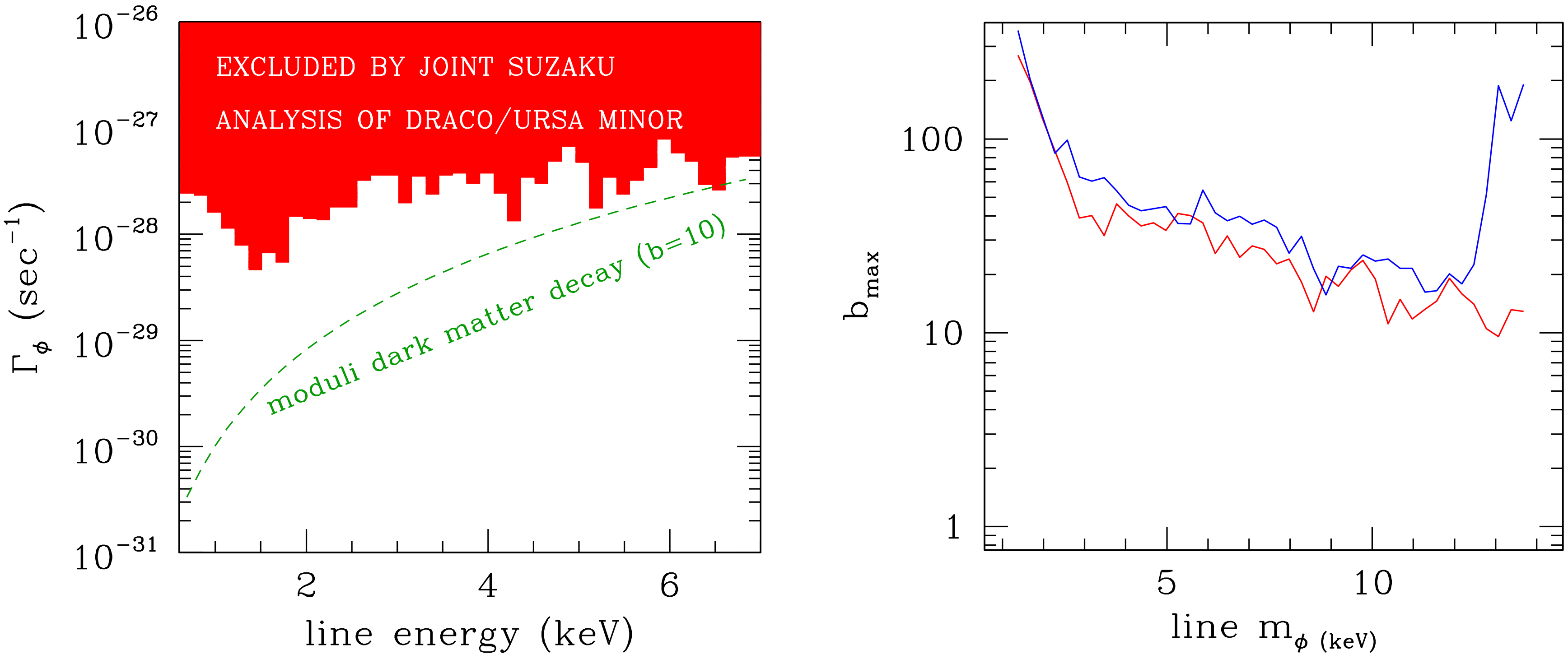




Photons have energies $m/2$: X-rays. Concentrations of dark matter emit X-rays. [Abazajian, Fuller, Tucker; Loewenstein et al., others]

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]

Dark matter decays during the dark ages

- X-rays can contribute to reionization directly [Ferrara, Mapelli, Pierpaoli]
- X-rays can speed up H_2 formation by ionizing gas. [Biermann, AK; Stasielak, Biermann, AK; Ferrara, Mapelli]
- 21-cm observations may detect it [Furlanetto, Oh, Pierpaoli]
- work in progress [Yoshida, Valdes]

Molecular hydrogen

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

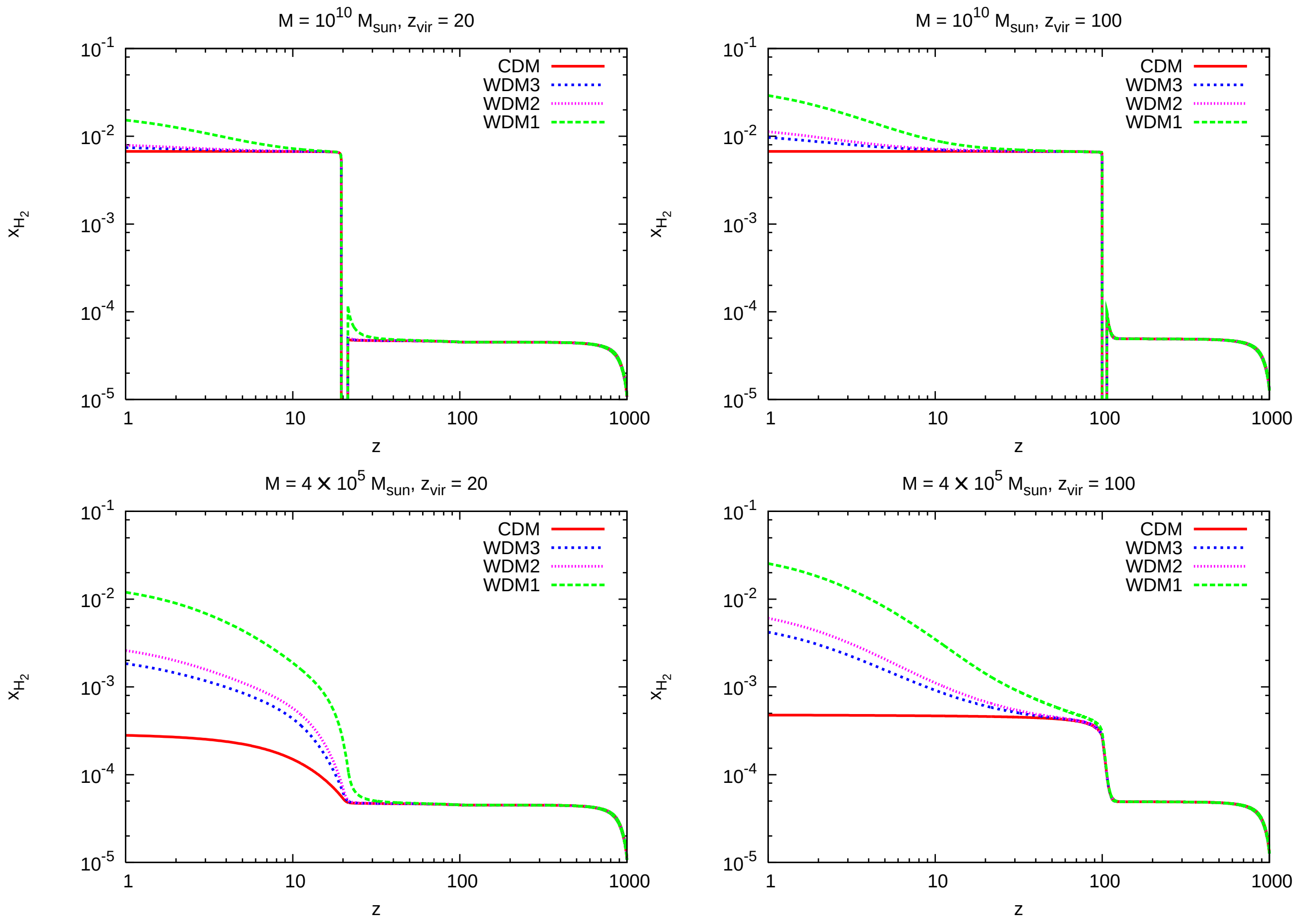
In the presence of ions the following reactions are faster:

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

H^+ produced by X-rays from $\nu_2 \rightarrow \nu_1\gamma$ catalyze the formation of molecular hydrogen

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

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



[Biermann, AK; Stasielak, Biermann, AK]

Summary

- **sterile 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!**
- 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