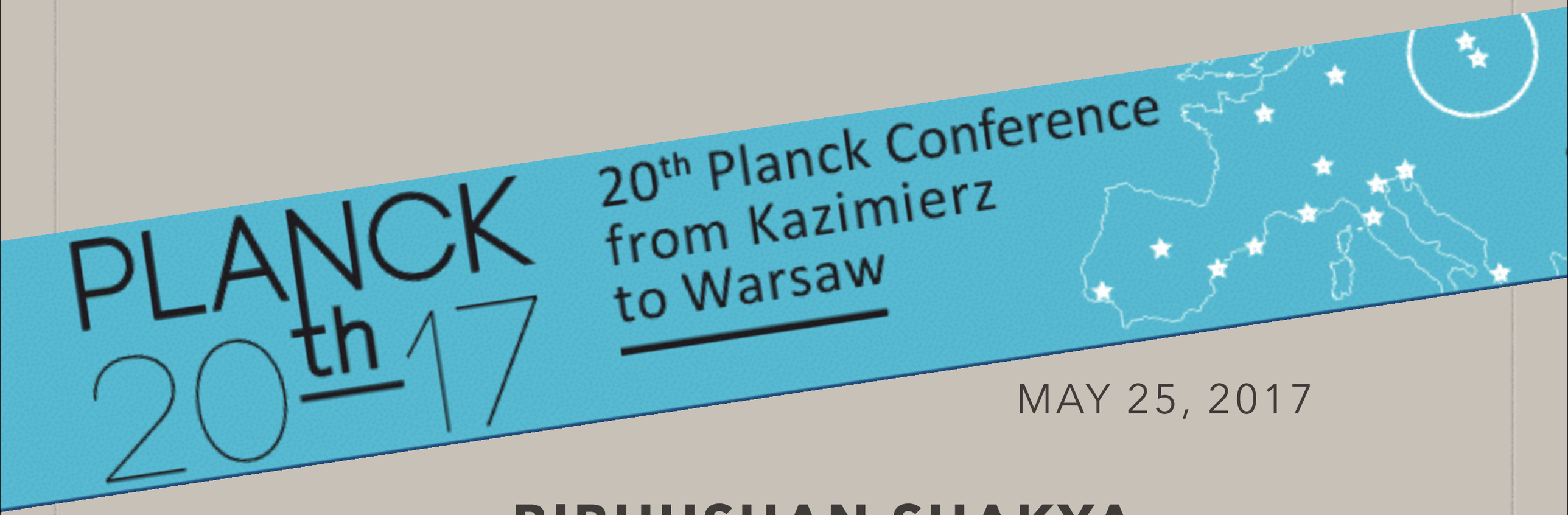
SUPERSYMMETRIC ASPECTS OF STERILE NEUTRINO DARK MATTER



MAY 25, 2017

BIBHUSHAN SHAKYA

UNIVERSITY OF Cincinnati

MICHIGAN CENTER FOR THEORETICAL PHYSICS
UNIVERSITY OF MICHIGAN

BASED ON

Sterile Neutrino Dark Matter with Supersymmetry
B. Shakya, J. D. Wells
arXiv:1611.01517

Cosmological imprints of frozen-in light sterile neutrinos
S. B. Roland, B. Shakya
arXiv:1609.06739

Sterile neutrino dark matter from freeze-in
B. Shakya
Mod.Phys.Lett. A31 (2016) no.06, 1630005, arXiv:1512.02751

PeV neutrinos and a 3.5 keV X-ray line from a PeV scale supersymmetric neutrino sector
S. B. Roland, B. Shakya, J. D. Wells
Phys.Rev. D92 (2015) no.9, 095018, arXiv:1506.08195

Neutrino masses and sterile neutrino dark matter from the PeV scale
S. B. Roland, B. Shakya, J. D. Wells
Phys.Rev. D92 (2015) no.11, 113009, arXiv:1412.4791

MOTIVATION

STERILE NEUTRINO DARK MATTER

- popular alternative to the WIMP paradigm
- right-handed neutrinos necessary for neutrino masses
- recent observational hint (7 keV X-ray line)

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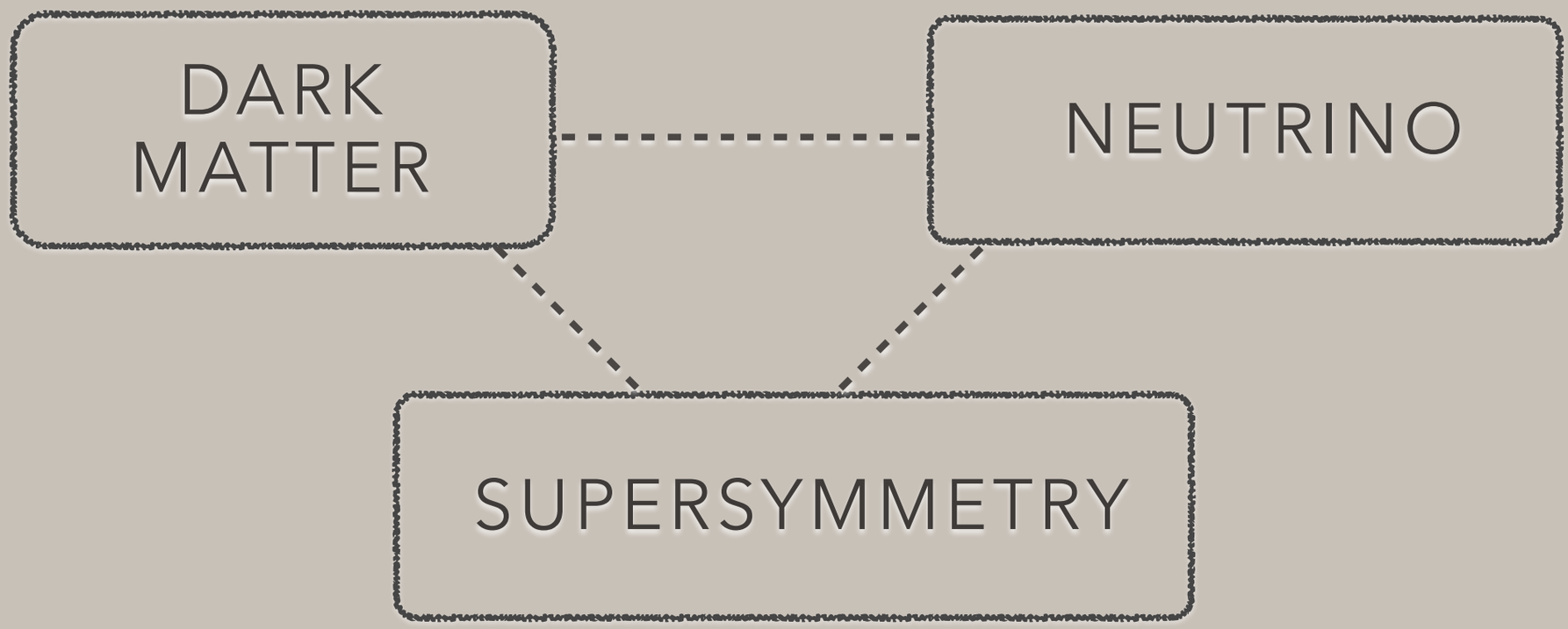
SUPERSYMMETRY

- might not be at the weak scale, solve the hierarchy problem, or provide wimp dark matter...
- appealing for several other reasons (gauge coupling unification, mathematical elegance, stable vacua in string theory...)
- most likely realized in nature at some (heavy?) scale!

THIS TALK



Theory: Can this connection give insight on parameters needed for dark matter?

Phenomenology: Does the underlying (supersymmetric) theory modify observable dark matter properties?

STERILE NEUTRINO DARK MATTER

(A LIGHTNING REVIEW)

traditional approach: Dodelson-Widrow mechanism: production via active-sterile oscillation due to mixing with active neutrinos

constrained by **X-ray line searches** (gives upper bound) and **Lyman-alpha measurements** (gives lower bound); together, these now rule out the DW mechanism

several escape routes:

- resonant production (Shi-Fuller mechanism): lepton chemical potential in plasma
- freeze-out: additional gauge interactions lead to equilibrium and freeze-out
- freeze-in: gradual production through feeble coupling to some BSM particle in the bath

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many realizations:

inflaton (0604236); radion (0711.1570); scalar in extended Higgs sector (0711.4646, 0609081, 0702143,1105.1654,1306.3996, 1409.4330, 1411.2773); scalar breaking a new symmetry in the neutrino sector (1412.4791)

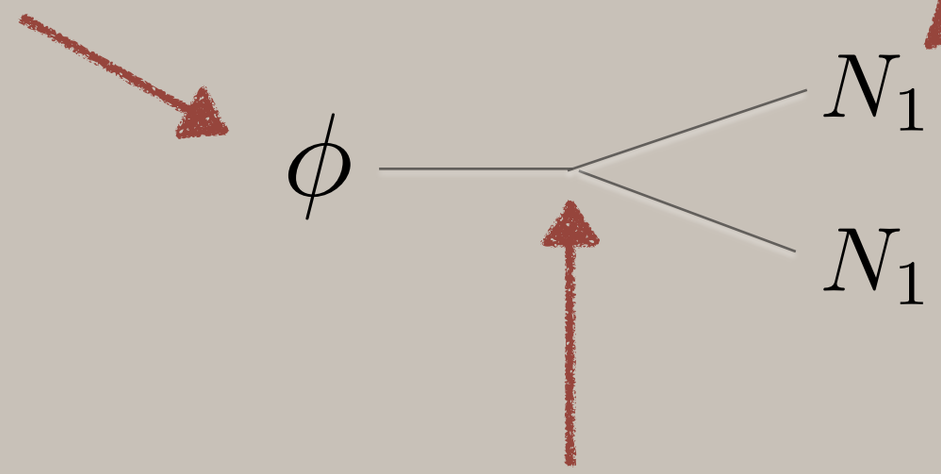
[for a review: Shakya, 1512.02751]

STERILE NEUTRINO DARK MATTER FROM FREEZE-IN

Basic ingredients

1. some BSM particle in the early Universe that decays to DM

3. Sterile neutrino DM candidate, (effectively) stable



(technically natural, corresponds to a Z_2 symmetry for N_1)

[does not need to be at keV scale]

2. some feeble coupling ($x^2 < \frac{m_\phi}{M_{\rm Pl}}$)

$$\mathcal{L} \supset y_{ij} L_i h N_j + x_i \phi \bar{N}_i^c N_i + \lambda (H^\dagger H) \phi^2$$

+ SUPERSYMMETRY

fields → supermultiplets → spin $(0, 1/2)$ components

ϕ	Φ	(ϕ, ψ)
N_1	$\mathcal{N}_i$	$(\tilde{N}_i, N_i)$

right-handed / sterile sneutrino

Lagrangian →

$$\mathcal{L} \supset y_{ij} L_i h N_j + x_i \phi \bar{N}_i^c N_i + \lambda (H^\dagger H) \phi^2$$

Superpotential

$$W \supset y_{ij} \mathcal{L}_i H_u \mathcal{N}_j + x_i \Phi \mathcal{N}_i \mathcal{N}_i + \sqrt{\lambda} \Phi H_u H_d$$

additional terms:

$$x_i \psi N_i \tilde{N}_i + \sqrt{\lambda} \phi \tilde{H}_u \tilde{H}_d + \sqrt{\lambda} \psi h \tilde{H}$$

$$\mathcal{L}_{soft} \supset y_{ij} A_{y_{ij}} \tilde{L}_i h_u \tilde{N}_j + x_i A_{xi} \phi \tilde{N}_1 \tilde{N}_1 + \sqrt{\lambda} A_\lambda \phi h_u h_d$$

many new particles/ interactions/ decay modes !

THE STERILE SNEUTRINO $\tilde{N}_1$

PRODUCTION $\phi \to \tilde{N}_1 \tilde{N}_1$ if allowed, due to the soft term $x_i A_{x\,i} \phi \tilde{N}_1 \tilde{N}_1$

(similarly from psi)

DECAY

charged under the approximate / exact Z_2 symmetry that stabilizes N_1.

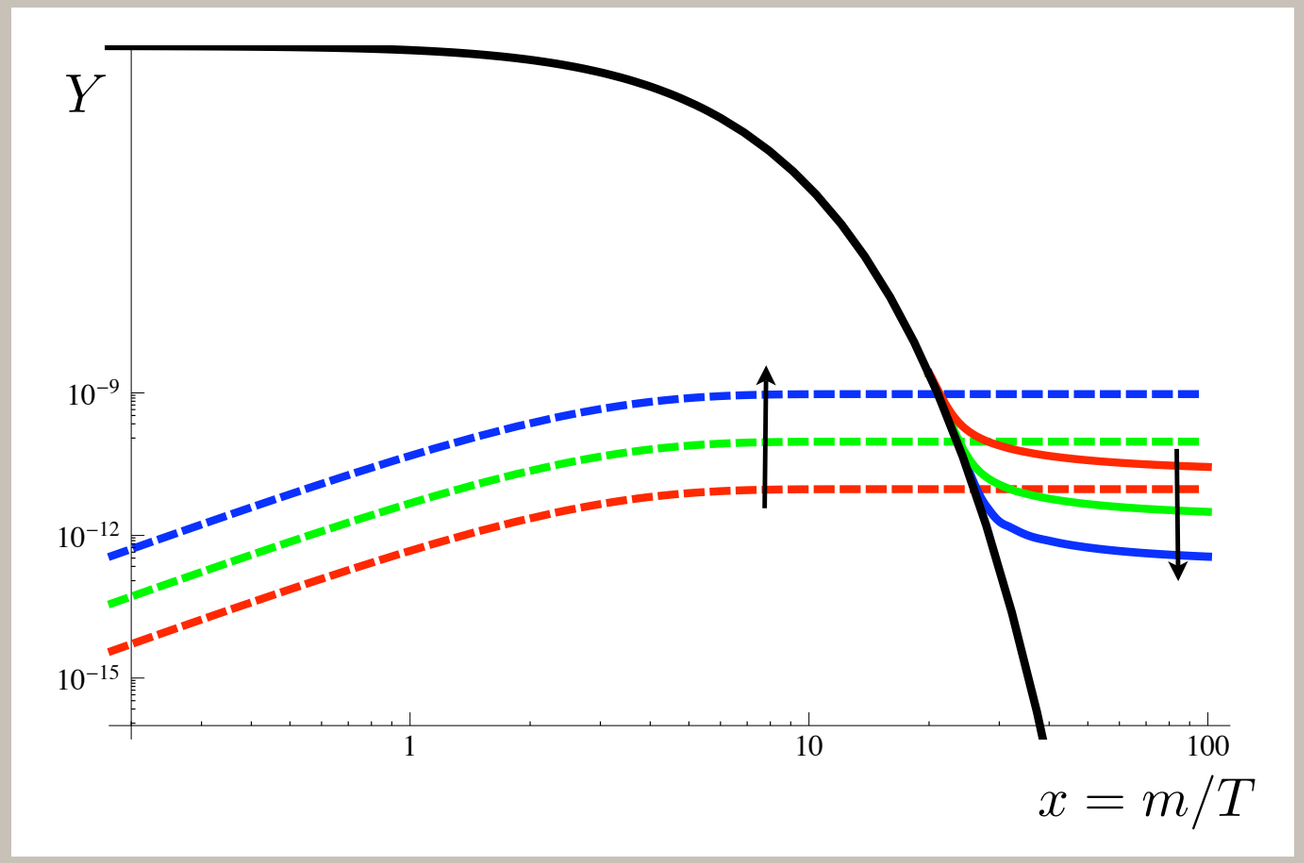
must decay into N_1 ; must go through $x_i \psi N_i \tilde{N}_i$ with the feeble coupling x_1

$$\text{If } m_{\tilde{N}_1} > m_\psi, \quad \tilde{N}_1 \to \psi N_1$$

$$\text{if } m_{\tilde{N}_1} < m_\psi, \quad \tilde{N}_1 \to N_1 \tilde{H} h \quad \text{through an off-shell } \psi$$

- each decay produces an N_1 particle
- can be fairly long lived (and dominate energy density)
- must decay before LSP decoupling

FREEZE-OUT VS FREEZE-IN



from hep-ph 0911.1120

*Freeze-out: earlier properties are washed out, decoupling is an **IR dominated** process*

*Freeze-in: DM never "thermalizes", final properties are **sensitive to details from the early Universe***

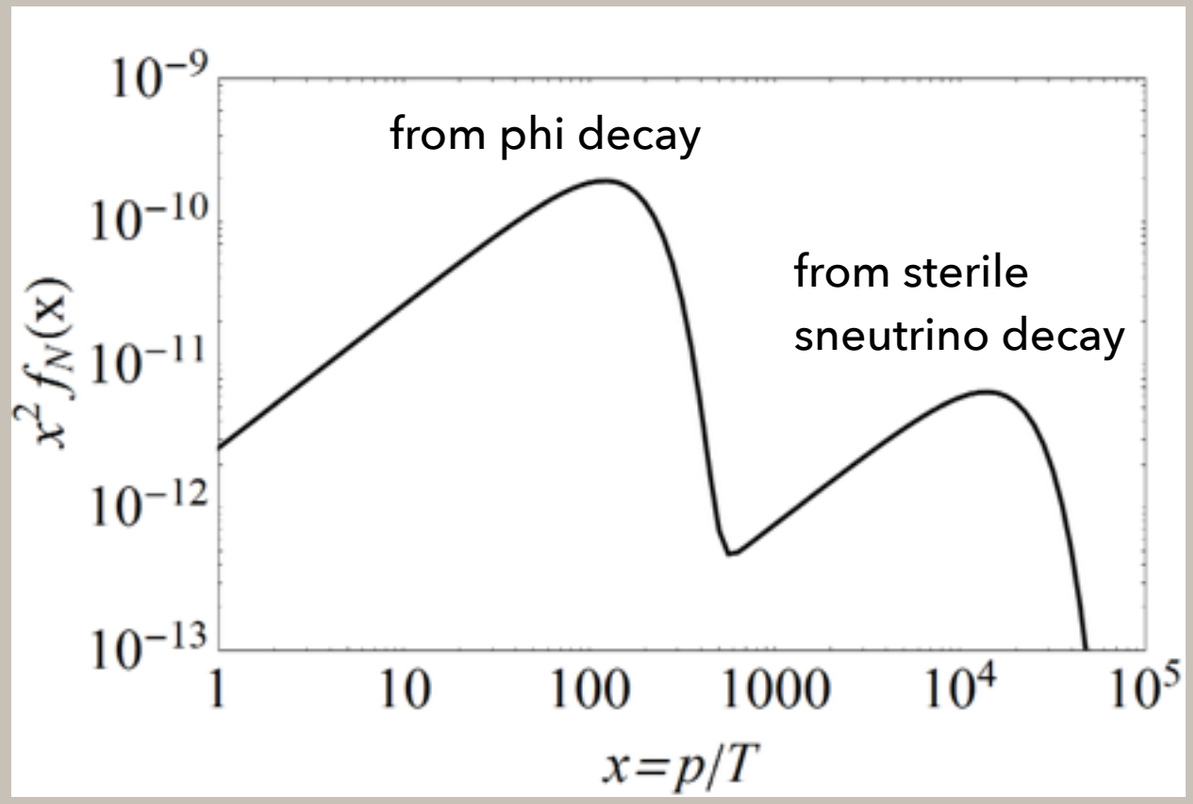
RELIC DENSITY AND COMPOSITION

(at least) two distinct production mechanisms: phi decay, sterile sneutrino decay

the two populations don't talk to each other!

second population is hotter

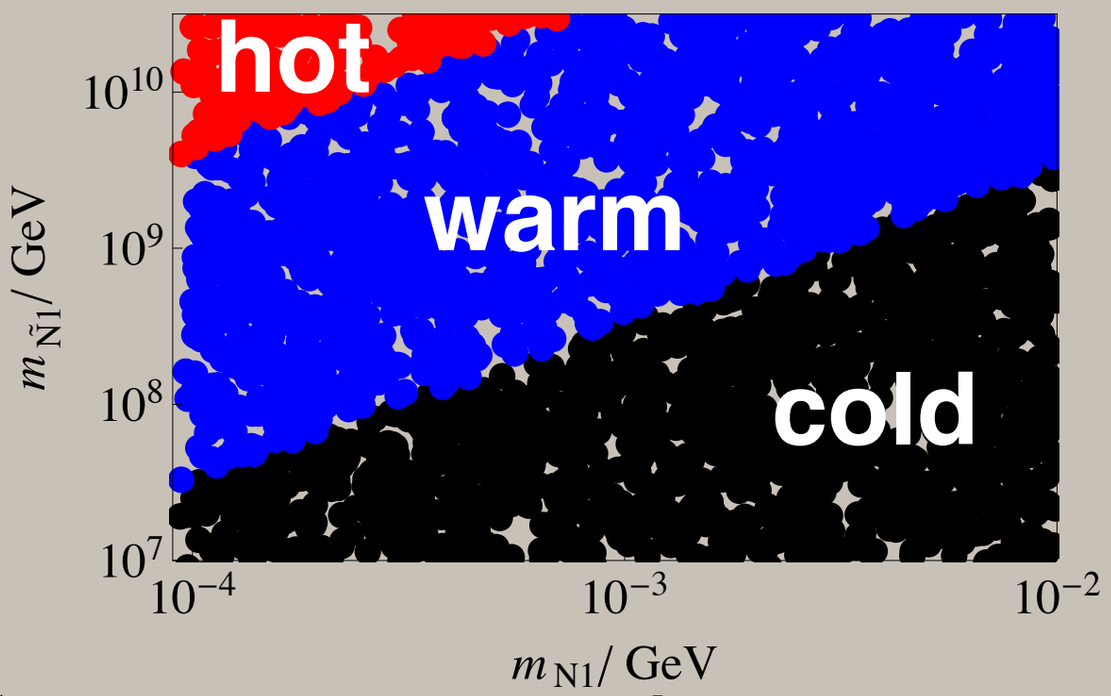
(sterile sneutrino is long-lived and decays out of equilibrium)

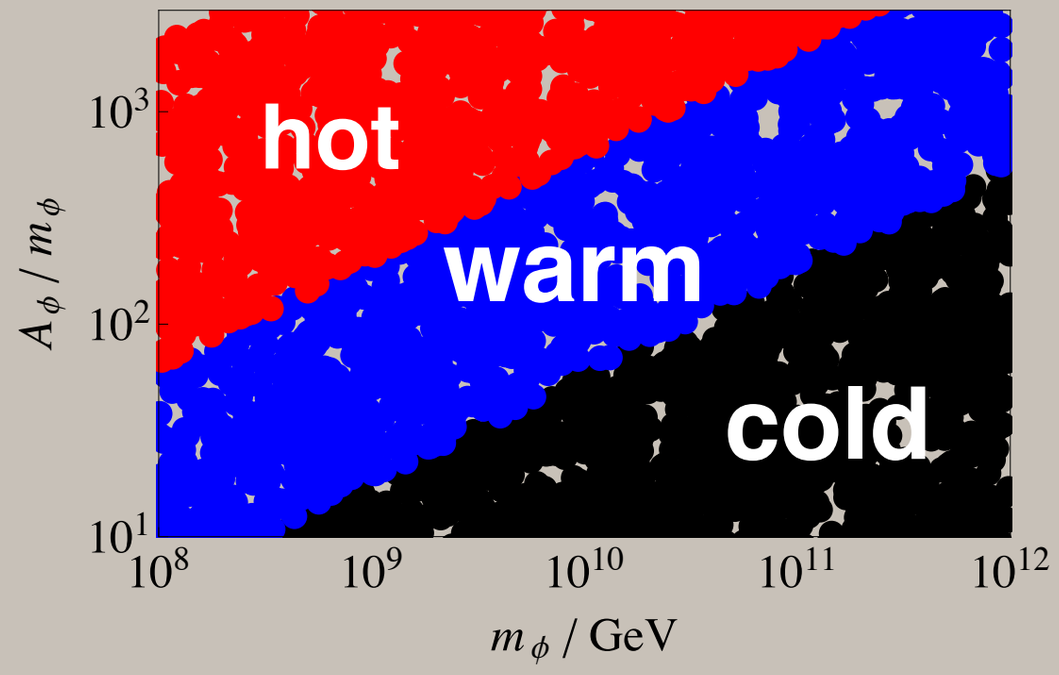


from hep-ph 1609.06739

extremely nontrivial momentum distribution possible!

FREE STREAMING LENGTH





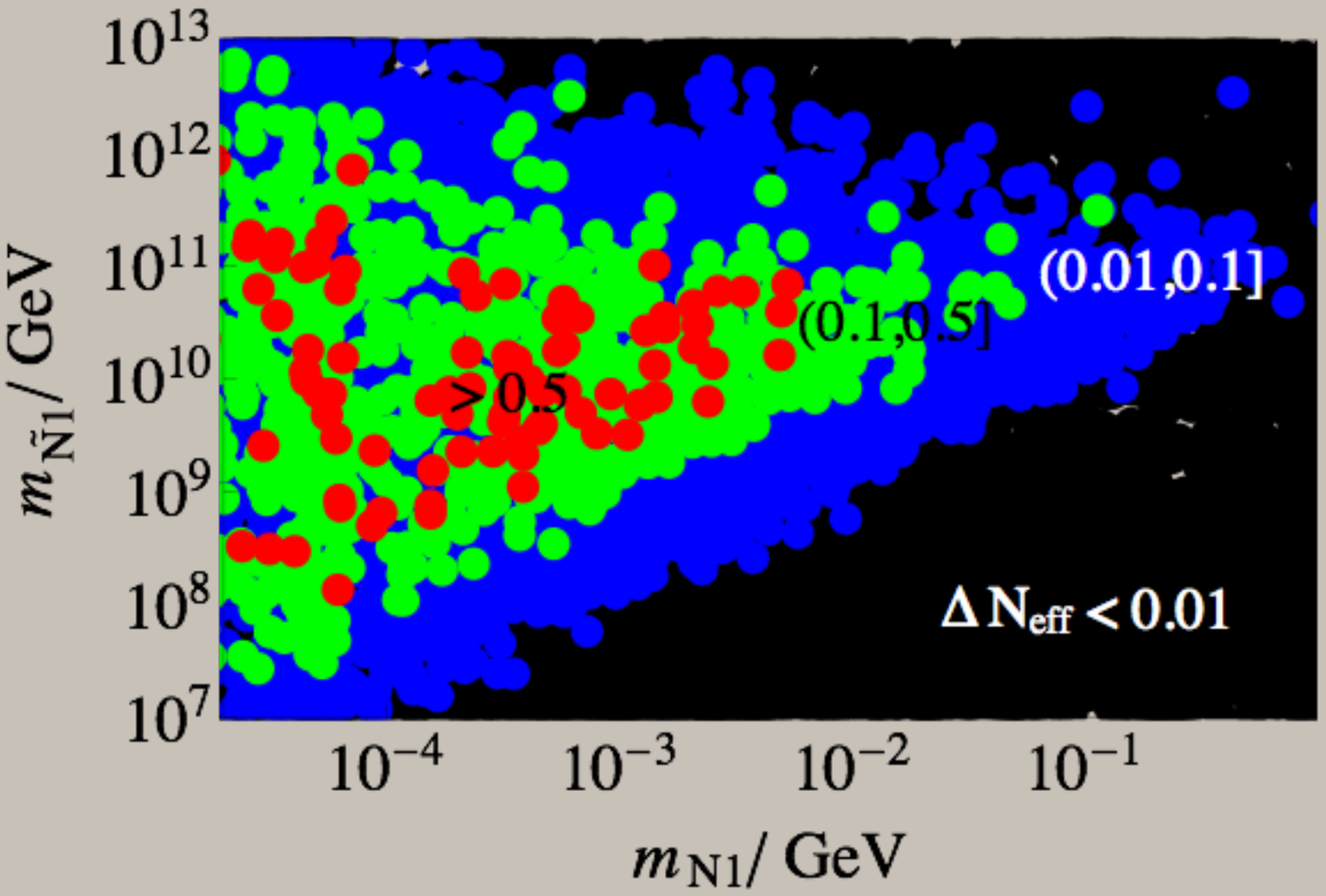
$\tilde{N}_1 \to \psi N_1$ $m_\phi = 10^{11}$ GeV $A_\phi = 10\, m_\phi$ m_{N_1} 1 MeV $m_{\tilde{N}_1}$ 10^6 GeV

coupling x chosen to produce correct relic density

cold/warm/hot dark matter, or some combination, are all possible in this setup

$\Delta N_{\rm eff}$

- cannot be all of DM, else DM today is too hot, inconsistent with structure formation
- can be a subdominant (e.g. <1%) fraction of dark matter (from sterile sneutrino decay), if the rest of dark matter is cold (from phi decay)



$$\Delta N_{\rm eff} = \left. \frac{\rho_{N_1}}{\rho_\nu} \right|_{T=T_{BBN}}$$

- generally needs a multi-component dark matter setup; in our framework, N_1 can be both! cold component from phi decay, hot component from sterile sneutrino decay!

NEED FOR "NEW" PHYSICS IN THE NEUTRINO SECTOR

(WITH LIGHT STERILE NEUTRINO DARK MATTER FROM FREEZE-IN)

"mysteries" in the neutrino sector:

- keV/GeV scale masses for sterile neutrinos
- tiny Yukawa couplings ($y \sim 10^{-7}$)
- BSM particle sourcing DM production
- feeble ($< 10^{-8}$) coupling for DM production

Hints of an underlying structure?

A MODIFIED NEUTRINO SECTOR

- Recall: traditional seesaw requires

$$\mathcal{L} \supset y_{\alpha i} \bar{L}_\alpha H_u^\dagger N_i + M_i \bar{N}_i^c N_i$$

Naively: GUT/Planck scale

- Assume RH neutrinos charged under a new symmetry: U(1)'

- Prohibits the above terms; traditional seesaw not allowed!

A MODIFIED NEUTRINO SECTOR

- Introduce an exotic field φ, equal and opposite U(1)′ charge to N
- This allows the following terms

$$\frac{y}{M_*} L H_u \mathcal{N} \Phi + \frac{x}{M_*} \mathcal{N} \mathcal{N} \Phi \Phi$$

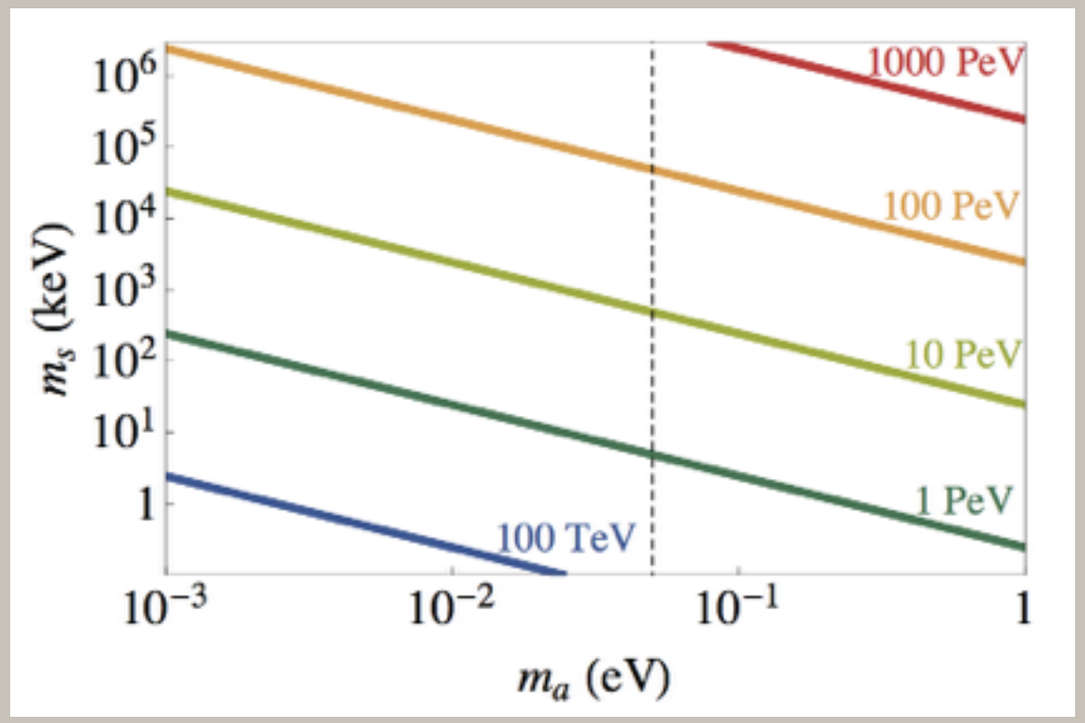
- If the scalar φ gets a vev, U(1)′ broken, effective neutrino mass matrix:

$$M_\nu = \begin{pmatrix} 0 & \frac{\langle\phi\rangle\langle H_u^0\rangle}{M_*}\mathbf{Y} \\ \frac{\langle\phi\rangle\langle H_u^0\rangle}{M_*}\mathbf{Y}^\dagger & \frac{\langle\phi\rangle^2}{M_*}\mathbf{X} \end{pmatrix}$$

$$m_s = m_M = \frac{x\langle\phi\rangle^2}{M_*} \qquad m_a = \frac{m_D^2}{m_M} = \frac{y^2\langle H_u^0\rangle^2}{xM_*}$$

$$\theta \approx \sqrt{\frac{m_a}{m_s}} = \frac{y\langle H_u^0\rangle}{x\langle\phi\rangle} \qquad m_s = \frac{1}{m_a}\left(\frac{y\langle\phi\rangle\langle H_u^0\rangle}{M_*}\right)^2$$

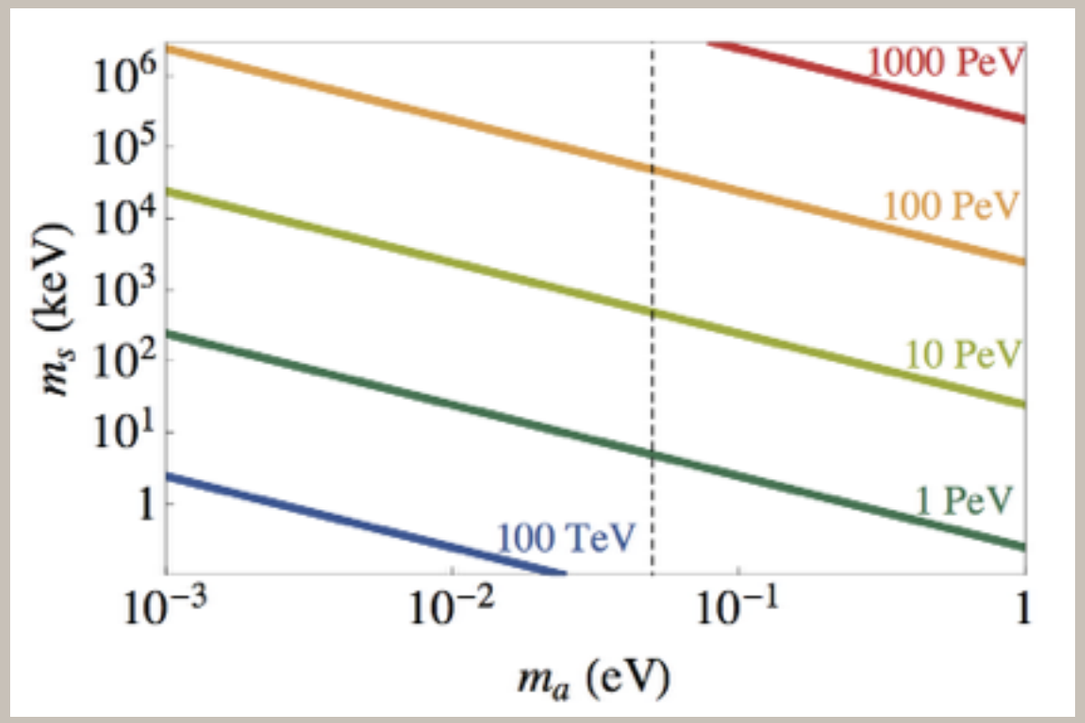
see also hep-ph 9805281, 0006312, 0007001



Contours of y<φ>.

$M_* = M_{GUT} (= 10^{16}\,\mathrm{GeV})$

Can get desired active and sterile masses with O(1) couplings and <φ>~O(1)-O(100) PeV
Maps onto νMSM



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Can get desired active and sterile masses with O(1) couplings and <φ>~O(1)-O(100) PeV Maps onto νMSM

<φ>~O(1)-O(100) PeV~ SUSY breaking scale?

Compatible with m_h=126 GeV with heavy superpartners

Split Supersymmetry

J. D. Wells (2003), hep-ph/0306127.
N. Arkani-Hamed and S. Dimopoulos, JHEP **0506**, 073 (2005), hep-th/0405159.
G. Giudice and A. Romanino, Nucl.Phys. **B699**, 65 (2004), hep-ph/0406088.
J. D. Wells, Phys.Rev. **D71**, 015013 (2005), hep-ph/0411041.

NEED FOR "NEW" PHYSICS IN THE NEUTRINO SECTOR

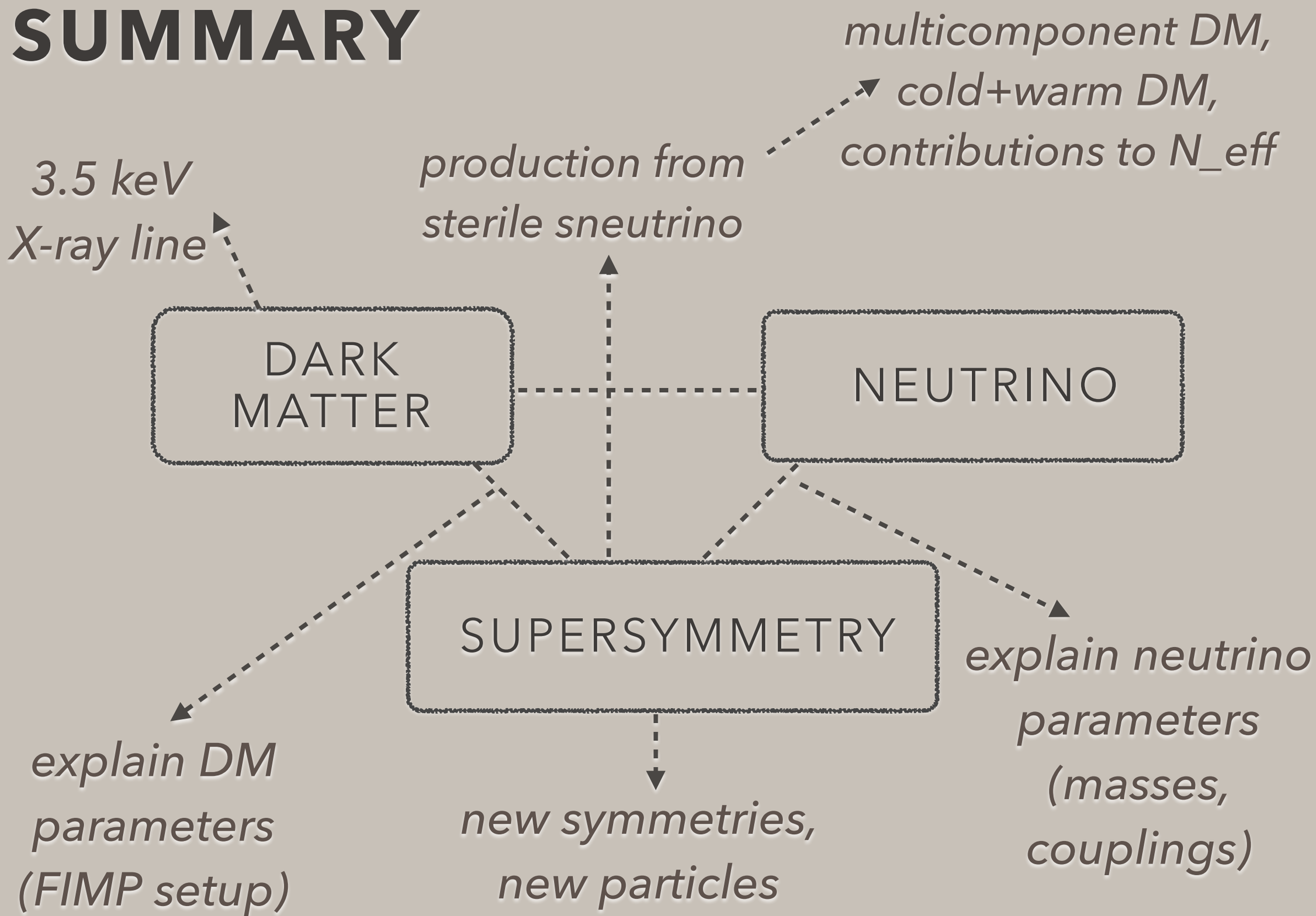
(WITH LIGHT STERILE NEUTRINO DARK MATTER FROM FREEZE-IN)

"mysteries" in the neutrino sector:

- keV/GeV scale masses for sterile neutrinos $\sim \frac{\langle\phi\rangle^2}{M_{GUT}}$
- tiny Yukawa couplings (y~10^{-7}) $\sim \frac{\langle\phi\rangle}{M_{GUT}}$
- feeble coupling for DM from freeze-in $\sim \frac{\langle\phi\rangle}{M_{GUT}}$
- BSM particle sourcing DM production

$\langle\phi\rangle \sim \mathrm{PeV}$ from supersymmetry breaking!

SUMMARY


3.5 keV
X-ray line
production from
sterile sneutrino
multicomponent DM,
cold+warm DM,
contributions to N_eff
DARK
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parameters
(masses,
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