UNIVERSITY OF WISCONSIN
PARTICLE THEORY SEMINAR
FEBRUARY 28, 2017

STERILE NEUTRINO DARK MATTER WITH SUPERSYMMETRY

BIBHUSHAN SHAKYA

UNIVERSITY OF Cincinnati

MICHIGAN CENTER FOR THEORETICAL PHYSICS UNIVERSITY OF MICHIGAN

BASED ON

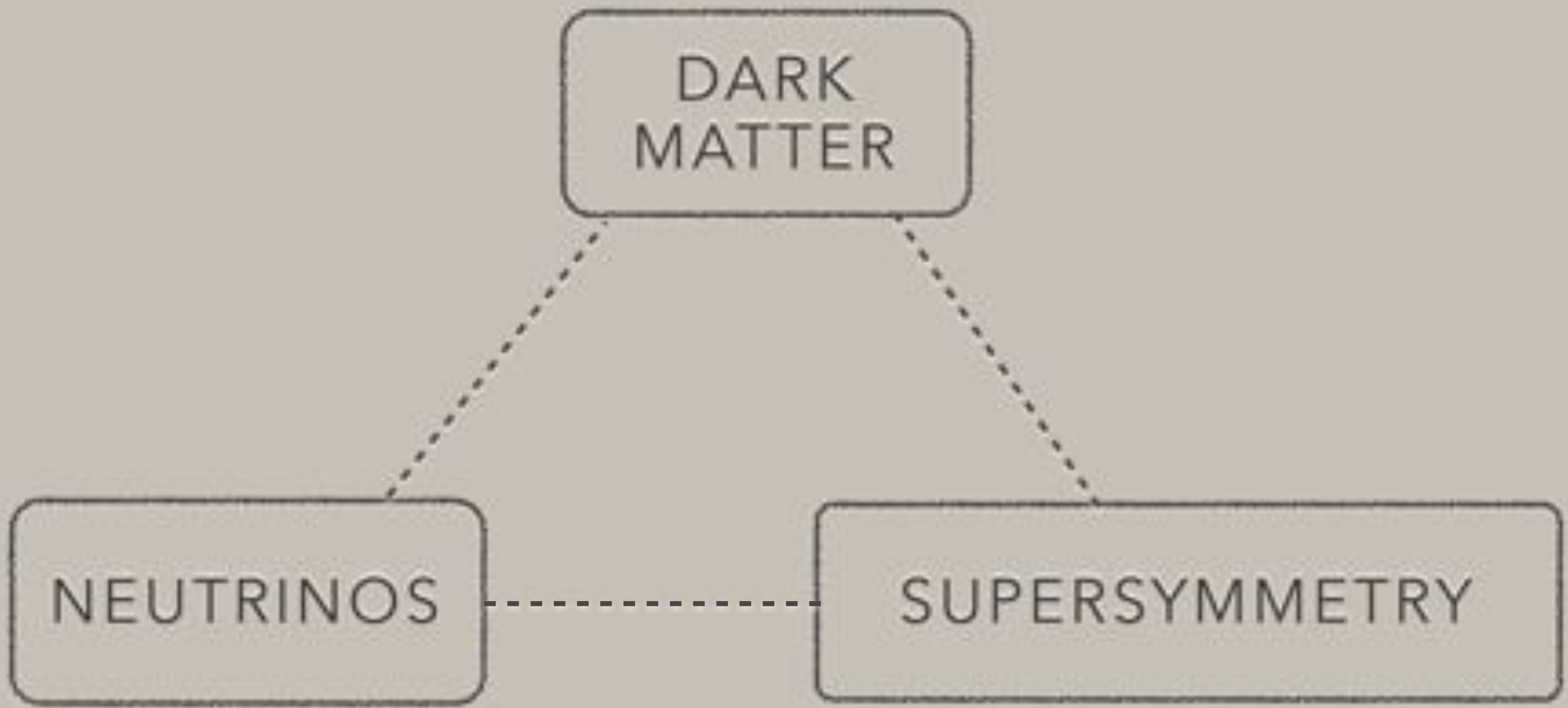
Sterile Neutrino Dark Matter with Supersymmetry
B. Shakya, J. D. Wells
arXiv:1611.01517

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

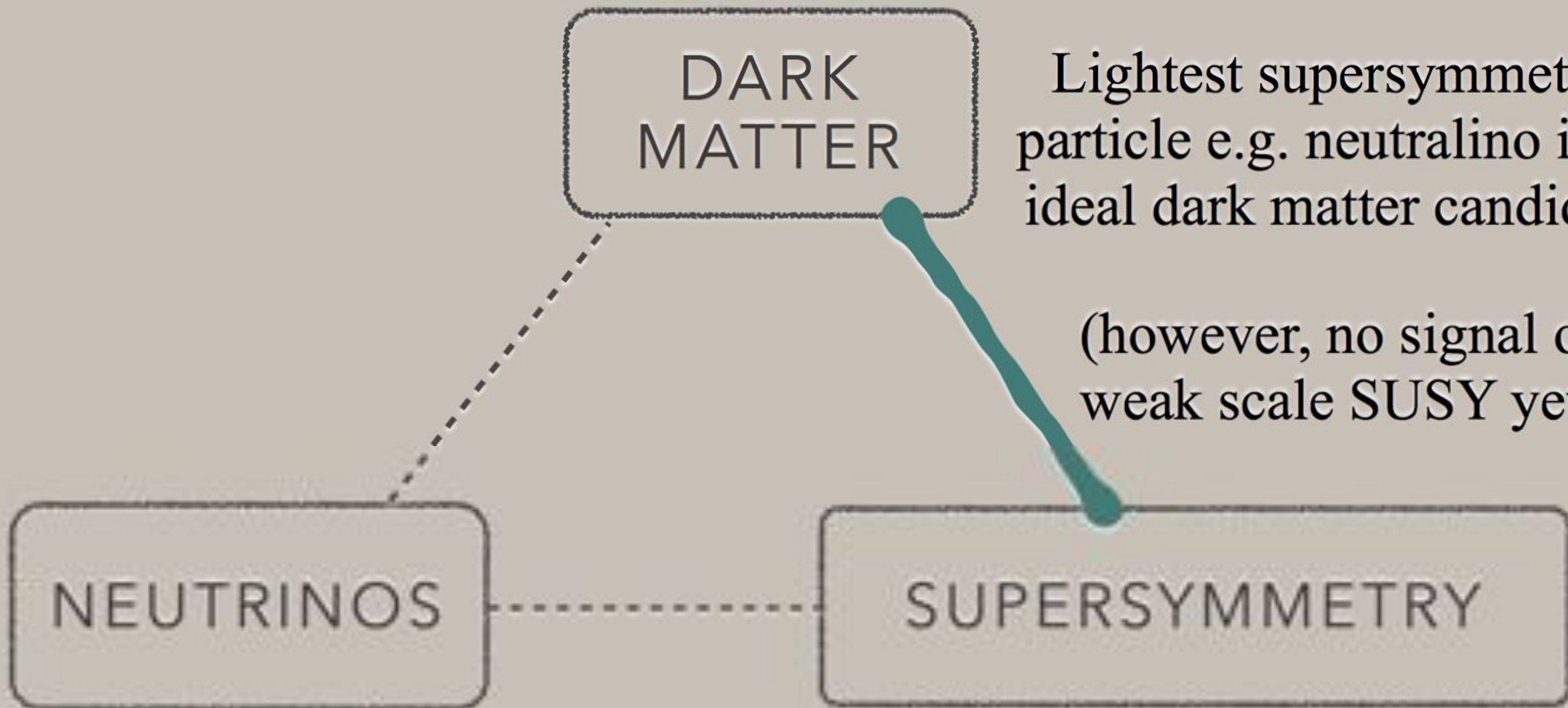
Sterile neutrino dark matter from freeze-in
B. Shakya
Mod.Phys.Lett. A31 (2016) no.06, 1630005, arXiv:1512.02751

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

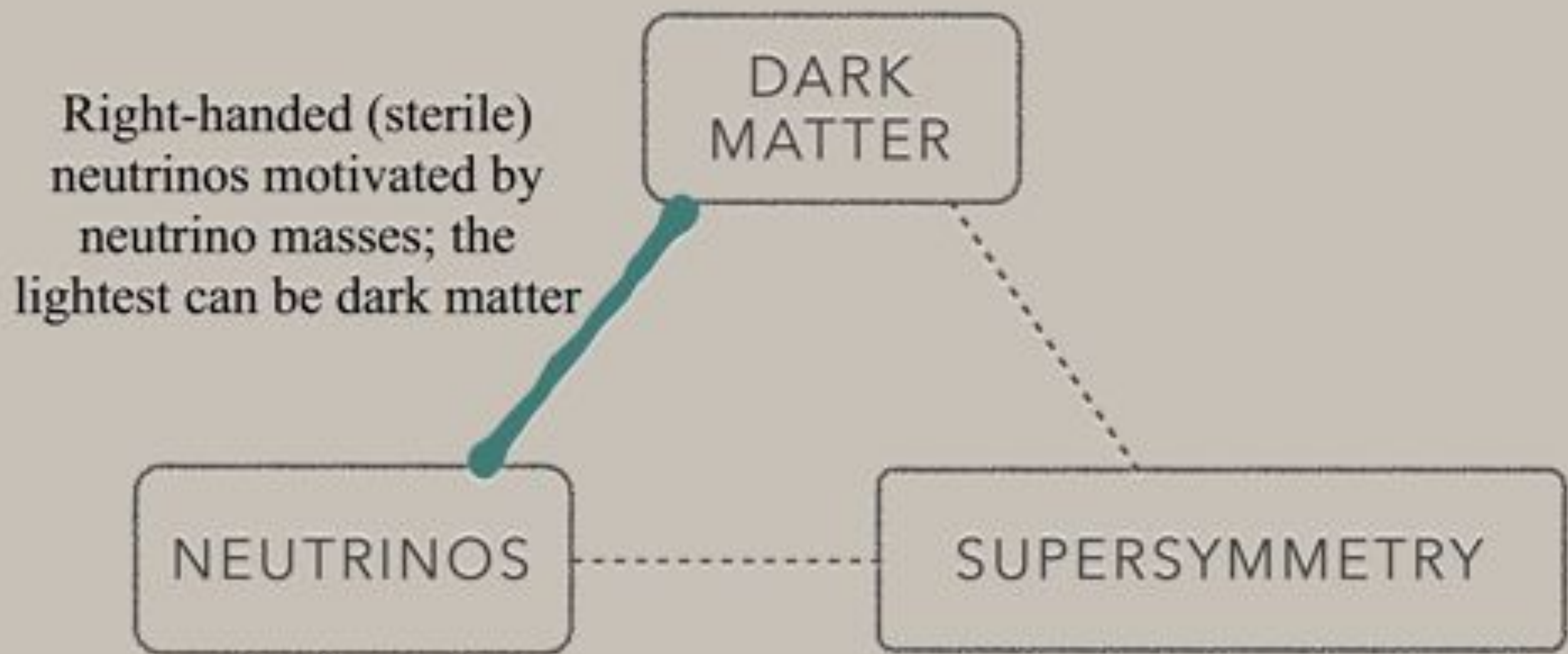

DARK MATTER
NEUTRINOS
SUPERSYMMETRY

WIMP "miracle"



Lightest supersymmetric particle e.g. neutralino is an ideal dark matter candidate

(however, no signal of weak scale SUSY yet)


Right-handed (sterile) neutrinos motivated by neutrino masses; the lightest can be dark matter
DARK MATTER
NEUTRINOS
SUPERSYMMETRY

3.5 KEV X-RAY LINE

recently in:

SEARCHING FOR THE 3.5 KEV LINE IN THE DEEP FIELDS WITH CHANDRA: THE 10 MS OBSERVATIONS

Nico Cappelluti[1,2,3], Esra Bulbul[4], Adam Foster[5], Priyamvada Natarajan[1,2,3], Megan C. Urry[1,2,3], Mark W. Bautz[4], Francesca Civano[5], Eric Miller[4], and Randall K. Smith[5]

Draft version January 30, 2017

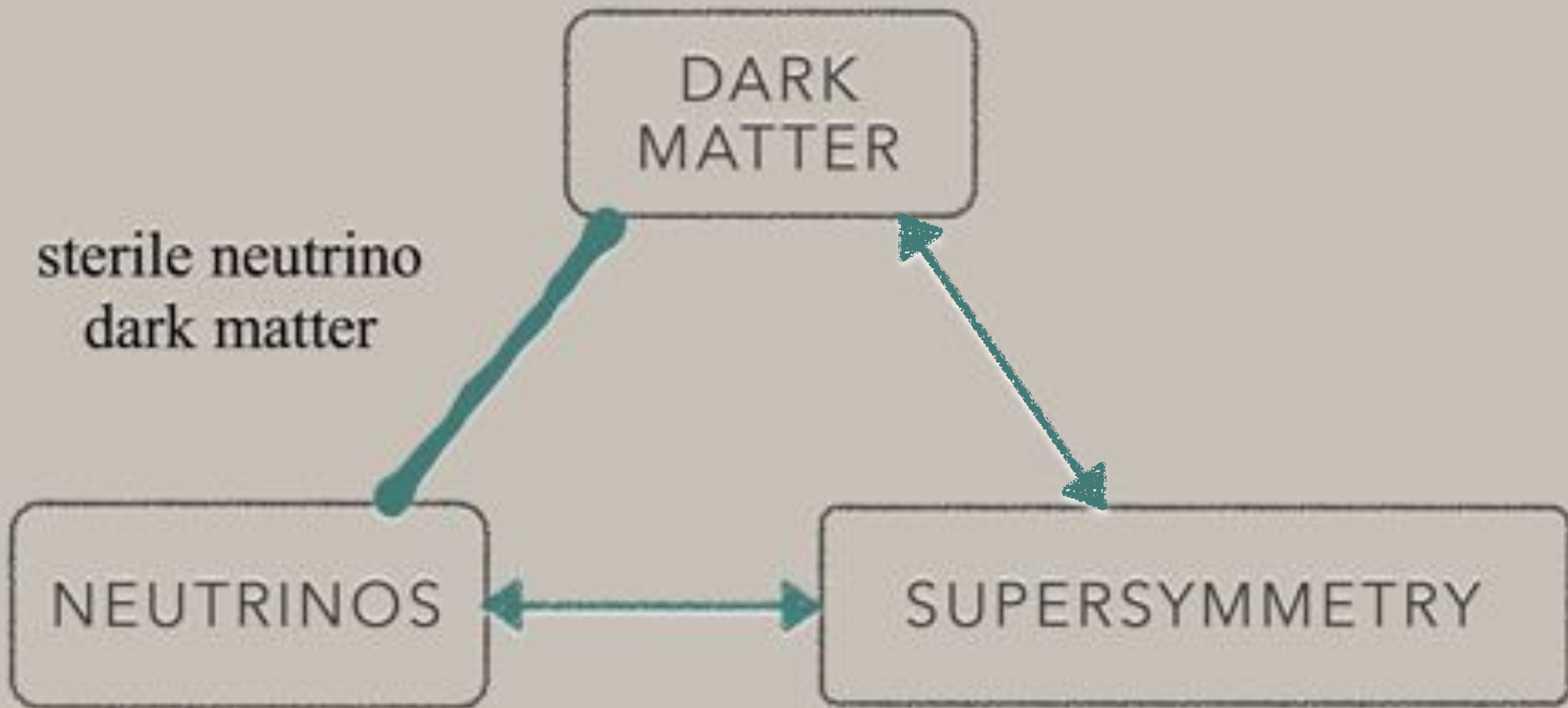
ABSTRACT

In this paper we report a 3σ detection of an emission line at ~3.5 keV in the spectrum of the Cosmic X-ray Background using a total of ~10 Ms Chandra observations towards the COSMOS Legacy and CDFS survey fields. The line is detected with an intensity is $8.8 \pm 2.9 \times 10^{-7}$ ph cm^{-2}s^{-1}. Based on our knowledge of *Chandra*, and the reported detection of the line by other instruments, we can rule out an instrumental origin for the line. We cannot though rule out a background fluctuation, in that case, with the current data, we place a 3σ upper limit at 10^{-6} ph cm^{-2}s^{-1}. We discuss the interpretation of this observed line in terms of the iron line background, S XVI charge exchange, as well as arising from sterile neutrino decay. We note that our detection is consistent with previous measurements of this line toward the Galactic center, and can be modeled as the result of sterile neutrino decay from the Milky Way when the dark matter distribution is modeled with an NFW profile. In this event, we estimate a mass m_s ~7.02 keV and a mixing angle $\sin^2(2\theta)$= 0.69–2.29 $\times 10^{-10}$. These derived values of the neutrino mass are in agreement with independent measurements toward galaxy clusters, the Galactic center, and M31.

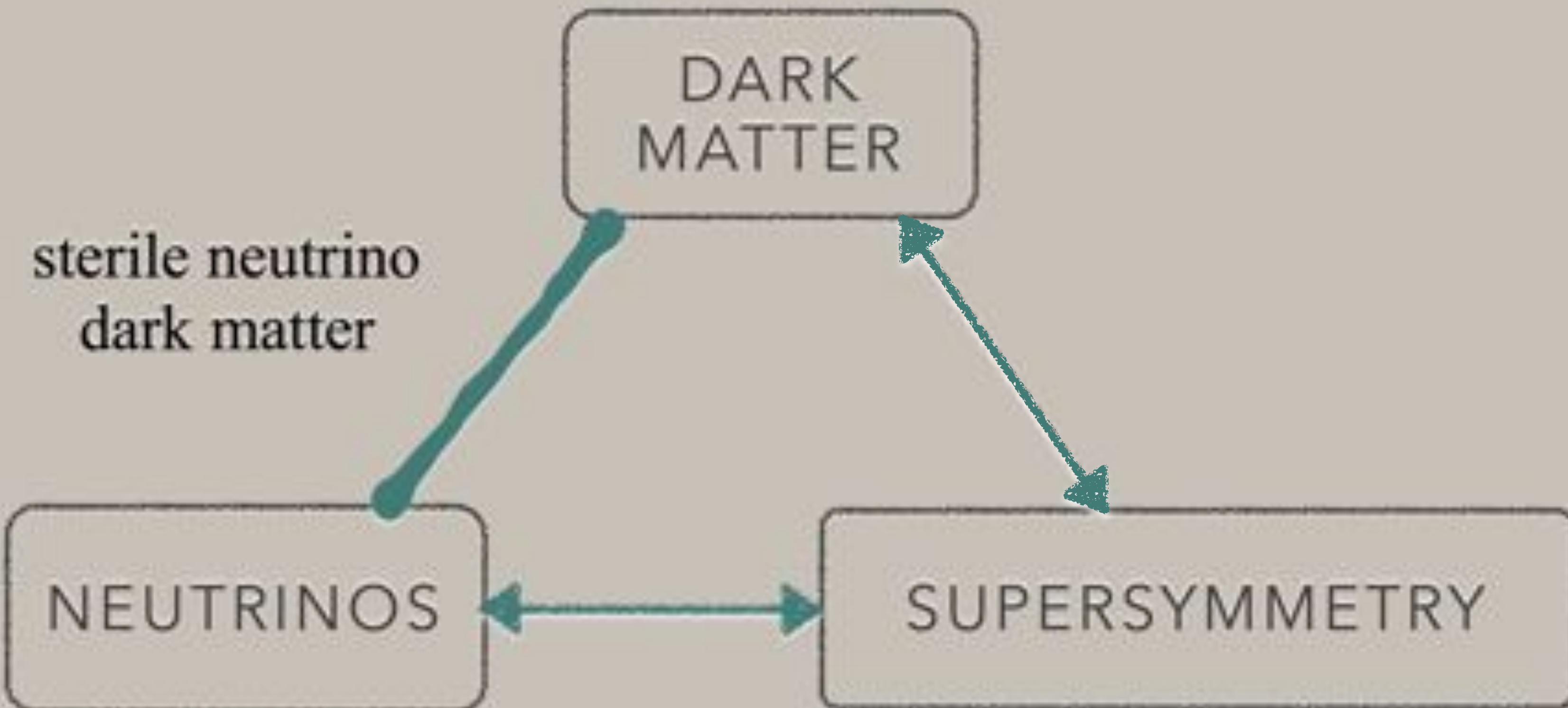
compatible with ~3.5 keV X-ray line from 2014; many papers fitting to ~7 keV sterile neutrino dark matter

potential mismodeling of background (Jeltema and Profumo (2014)), situation unclear; some resolution ~2021?

THIS TALK


DARK MATTER
sterile neutrino dark matter
NEUTRINOS
SUPERSYMMETRY

THIS TALK



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

Theoretical: What can the dark matter properties of the sterile neutrino tell us about the underlying supersymmetric theory?

STERILE NEUTRINO AS DARK MATTER:

A QUICK REVIEW

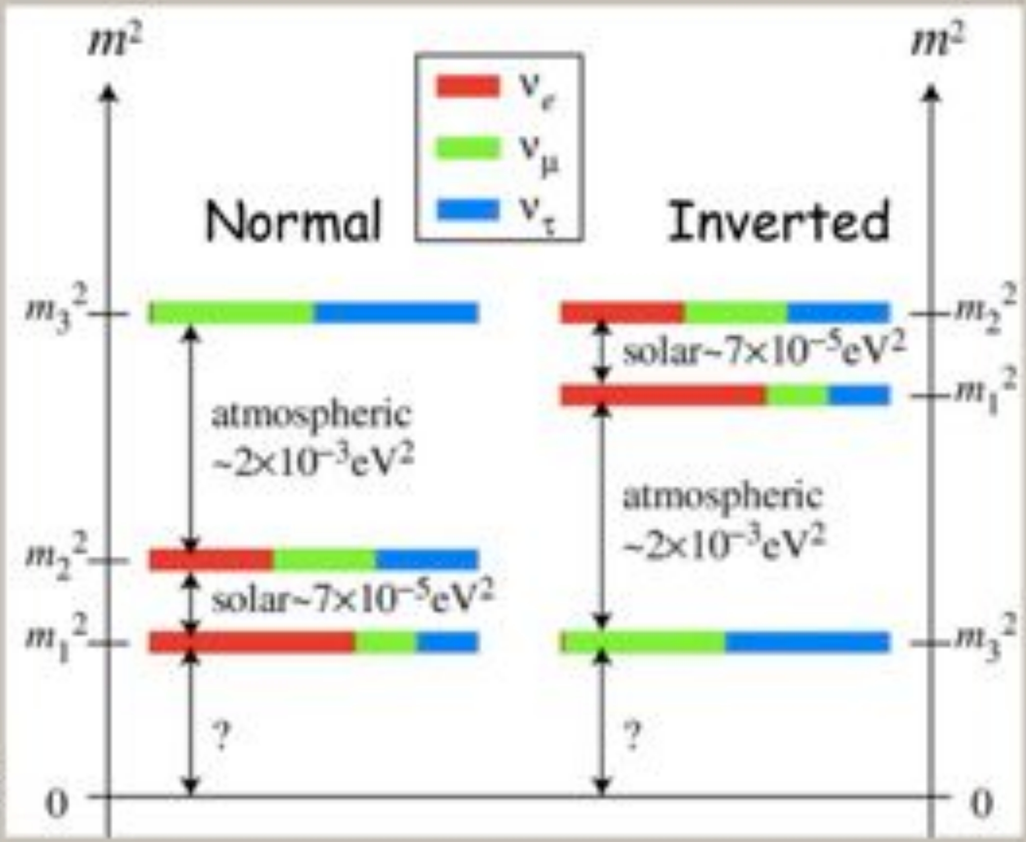
NEUTRINO MASSES

Neutrino sector requires physics beyond the Standard Model!

Neutrinos are massless in the Standard Model

However, solar and atmospheric oscillation data require mass differences.

Absolute mass scale unknown. Measurements constrain the sum to be < 0.23 eV.



NEUTRINO MASSES FROM THE SEESAW

- Add SM-singlet (sterile) right-handed neutrinos N_i

$$y_{ij} L_i h N_j + M_i \bar{N}_i^c N_i$$

$$M \gg y\langle H \rangle \rightarrow m_a \sim (y\langle H \rangle)^2/M$$

- small mixing between active and sterile states

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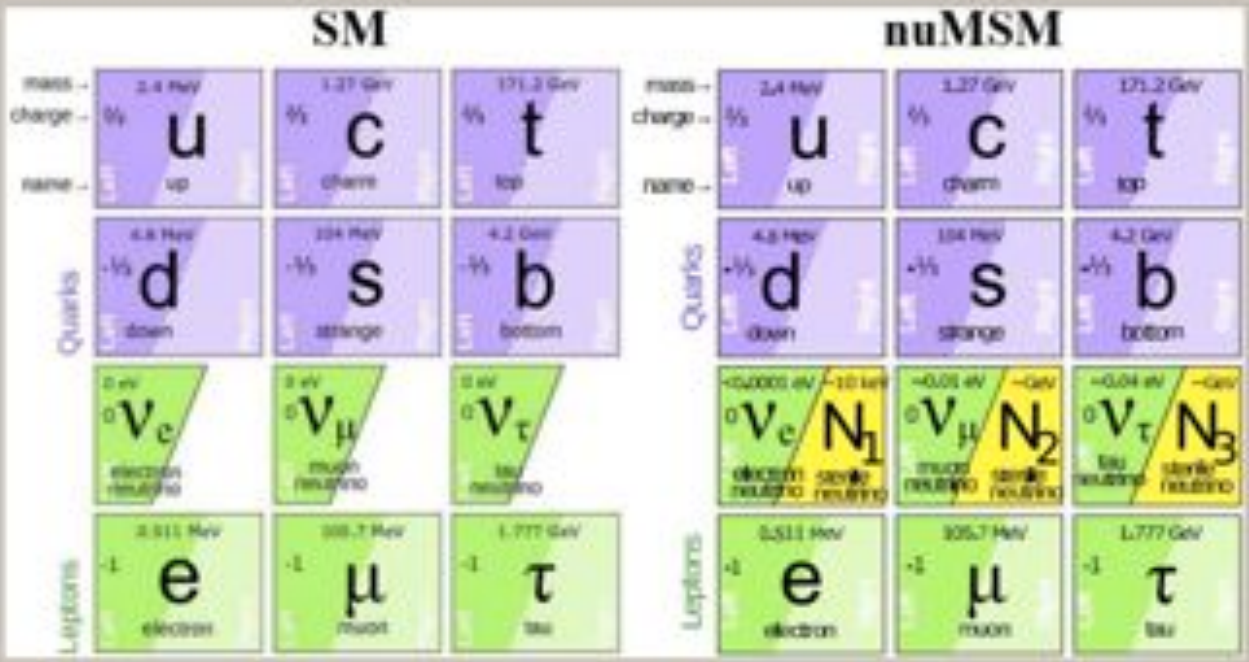
What is the mass scale M?

- y~O(1), M~10^{14} GeV (GUT scale seesaw)
- **N_1 ~ keV can be dark matter**

Neutrino Minimal Standard Model (νMSM)



extensively studied, explains neutrino masses, baryon asymmetry, and dark matter.

T. Asaka, S. Blanchet, and M. Shaposhnikov, Phys.Lett. **B631**, 151 (2005), hep-ph/0503065.
T. Asaka and M. Shaposhnikov, Phys.Lett. **B620**, 17 (2005), hep-ph/0505013.
T. Asaka, M. Shaposhnikov, and A. Kusenko, Phys.Lett. **B638**, 401 (2006), hep-ph/0602150.

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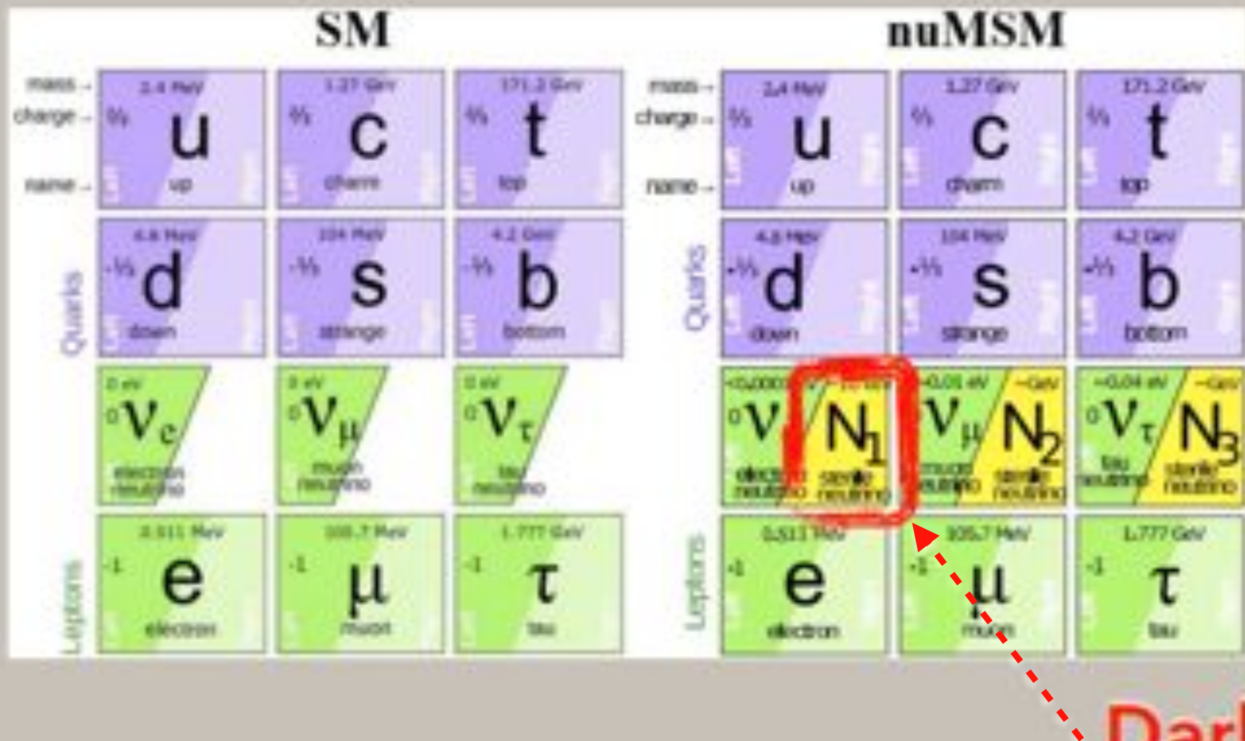

Dark matter!

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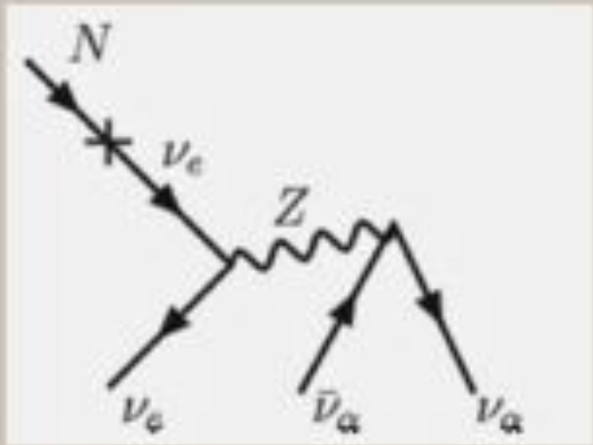
STERILE NEUTRINO AS DARK MATTER

- produced through active-sterile oscillation due to mixing between the two (Dodelson-Widrow mechanism).
- coupling too weak for thermal freeze-out
- if at keV scale, can be dark matter

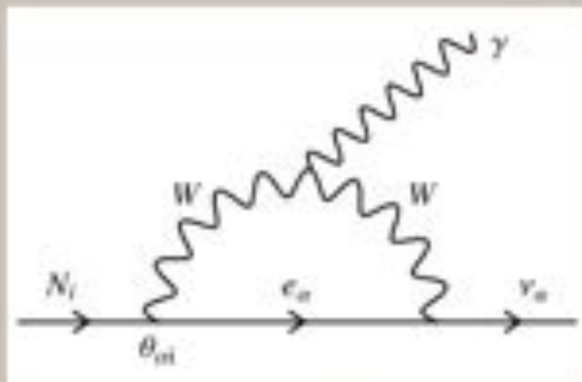
$$\Omega_{N_i} \sim 0.2 \left(\frac{\sin^2\theta}{3 \times 10^{-9}}\right) \left(\frac{m_s}{3\ \mathrm{keV}}\right)^{1.8}$$

- lifetime set by 3 body decays



STERILE NEUTRINO AS DARK MATTER

Main constraint from X-ray line searches



$$\Gamma_{\nu_s \to \gamma \nu_a} = \frac{9\,\alpha_{\rm EM}\,G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta) m_s^5$$

STERILE NEUTRINO AS DARK MATTER

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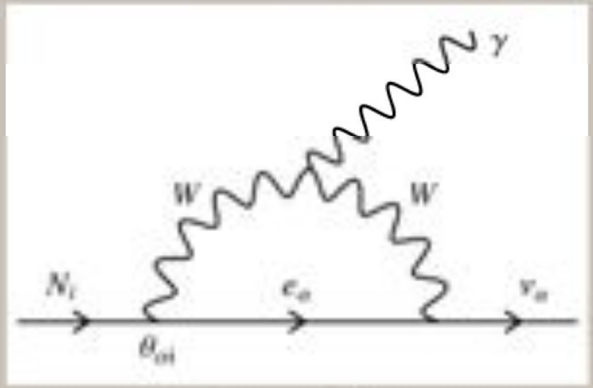
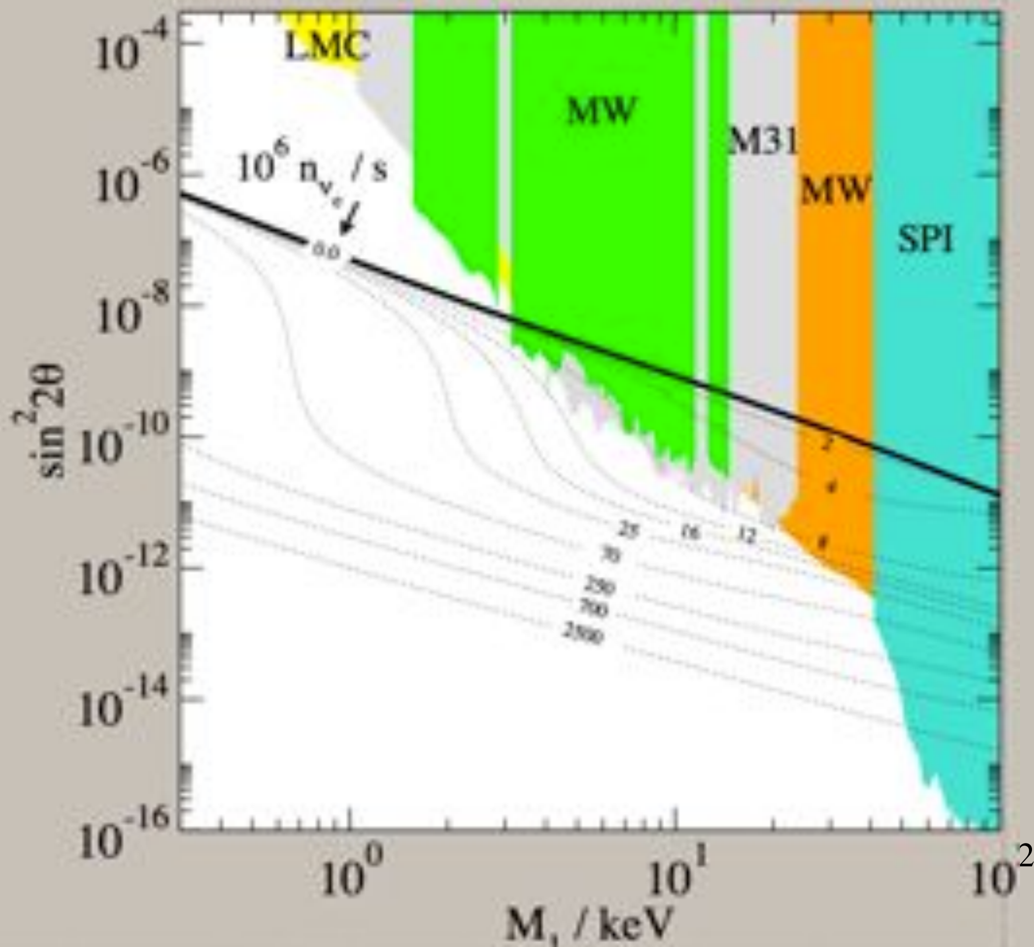


$$\Gamma_{\nu_s \to \gamma \nu_a} = \frac{9\,\alpha_{\rm EM}\,G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta) m_s^5$$

observations constrain m_ν < O (keV) for sterile neutrino that is all of dark matter

Laine, Shaposhnikov, 0804.4543



STERILE NEUTRINO AS DARK MATTER

- Lyman-alpha measurements constrain free streaming lengths of warm dark matter candidates (from structure formation)

$$\Lambda_{FS} \approx 1.2\,\mathrm{Mpc}\left(\frac{\mathrm{keV}}{m_s}\right)\left(\frac{\langle p_s\rangle}{3.15\,T}\right)_{T\approx 1\mathrm{keV}}$$

- required to be less than 0.11 Mpc from Lyman-alpha
- SDSS analysis gives $m_\nu > O(10)$ keV for production through DW mechanism (eg Viel et al, 0709.0131).

STERILE NEUTRINO AS DARK MATTER

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- required to be less than 0.11 Mpc from Lyman-alpha
- SDSS analysis gives $m_\nu > O(10)$ keV for production through DW mechanism (eg Viel et al, 0709.0131).

Taken together with the X-ray constraint, rules out sterile neutrino as a dark matter candidate!

STERILE NEUTRINO AS DARK MATTER

Alternatives:

Shi-Fuller mechanism

- Presence of lepton chemical potential in plasma can lead to resonantly amplified production of N_1. Colder non thermal distribution, evades Lyman-alpha bounds
- extremely fine-tuned

Freeze-out

- additional gauge interactions lead to equilibrium and freeze-out, overproduced abundance fixed by entropy dilution
- potential tension from BBN constraints

Freeze-in*

*unrelated to active-sterile mixing

- feeble coupling to some (BSM) particle in the thermal bath leads to gradual production over the history of the Universe

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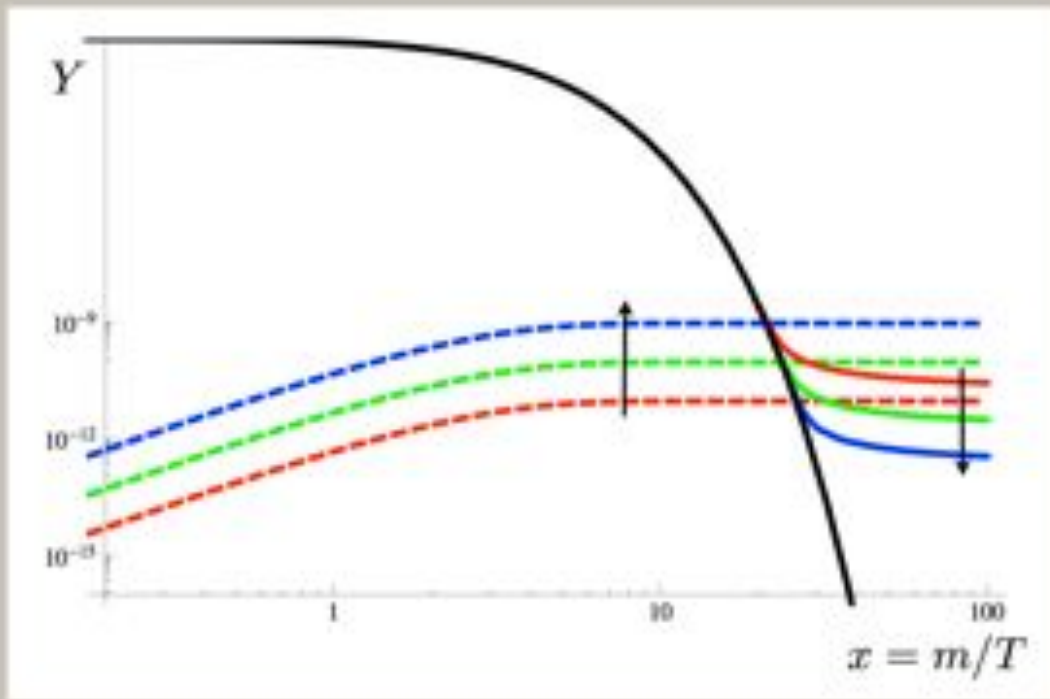
FREEZE-IN VS FREEZE-OUT



from hep-ph 0911.1120

Freeze-out: DM has significant interaction strength with SM, is in equilibrium, decouples

Freeze-in: DM has feeble interaction strength with SM, is never in equilibrium, abundance builds up (freezes in) gradually

STERILE NEUTRINO DARK MATTER FROM FREEZE-IN

many papers; the BSM particle can be [not an exhaustive list]

- inflaton (Shaposhnikov, Tkachev, 0604236)
- radion (Kadota, 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 (Roland, Shakya, Wells, 1412.4791)
- ....

for a review: Shakya, 1512.02751

STERILE NEUTRINO DARK MATTER FROM FREEZE-IN

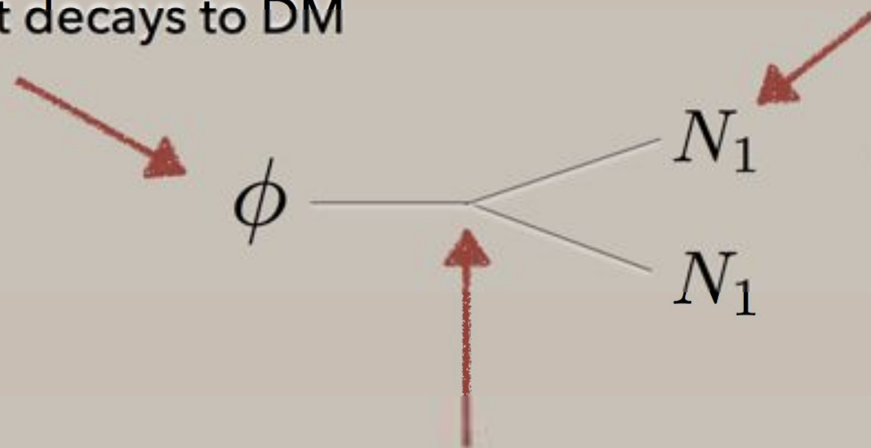
Basic ingredients

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

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

STERILE NEUTRINO DARK MATTER FROM FREEZE-IN

Basic picture

N_1 abundance gradually builds up from phi decays while phi is present in the bath

No dependence on active-sterile mixing: can be arbitrarily small, eliminate constraint from X-rays

N_1 produced earlier in the Universe, redshifts and is cooler, more compatible with Lyman alpha

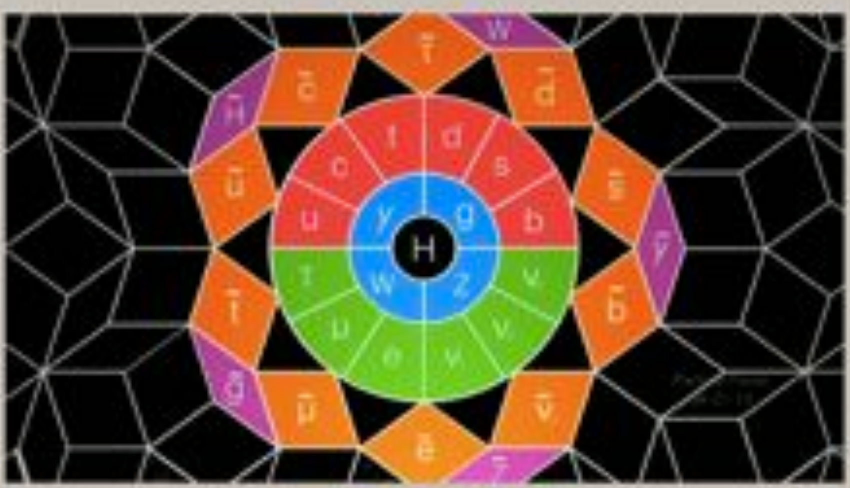
STERILE NEUTRINO

DARK MATTER

+ SUPERSYMMETRY

NO HINT OF WEAK SCALE SUPERSYMMETRY....

BUT SURELY IT EXISTS AT SOME SCALE?



HIERARCHY PROBLEM ✗

DARK MATTER ✗

GAUGE COUPLING UNIFICATION ✓

MATHEMATICAL ELEGANCE ✓

+ 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

* assume R-parity, take stable LSP to be a Higgsino, take to be sub-TeV, forms a small fraction of DM

+ SUPERSYMMETRY

fields	supermultiplets	spin $(0,1/2)$ components
ϕ	Φ	(ϕ, ψ)
N_1	$\mathcal{N}_i$	$(\tilde{N}_i, N_i)$

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

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

in addition to the above Lagrangian (only listing those relevant to this talk):

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

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

+ SUPERSYMMETRY

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possible decay modes for phi

+ SUPERSYMMETRY

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possible decay modes for psi

+ SUPERSYMMETRY

fields	supermultiplets	spin $(0,1/2)$ components
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possible decay modes for sterile sneutrinos (also mixing)

THE STERILE SNEUTRINO $\tilde{N}_1$

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

(similarly from psi)

STERILE NEUTRINO DARK MATTER FROM FREEZE-IN

Basic ingredients

3. Sterile neutrino DM candidate, (effectively) stable

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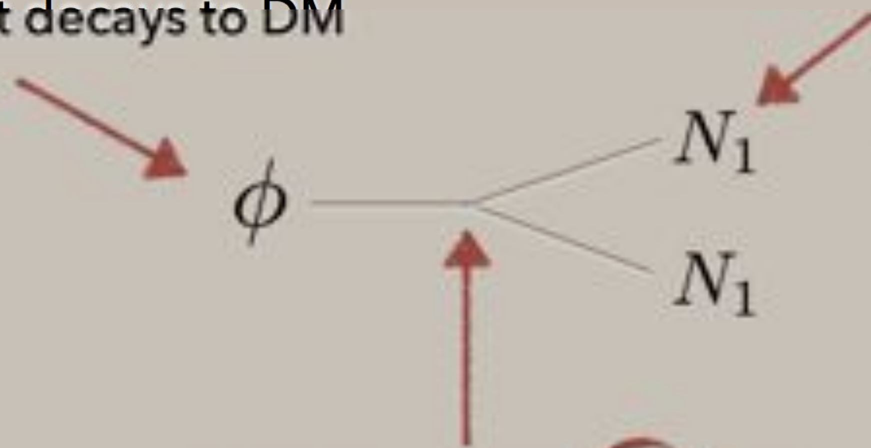

(technically natural, corresponds to a Z_2 symmetry for N_1)

2. feeble coupling ($x < 10^{-7}$)

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

THE STERILE SNEUTRINO $\tilde{N}_1$

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(similarly from psi)

- DECAY

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

- Must decay into N_1; must go through the term $x_i \psi N_i \tilde{N}_i$, characterized by the same feeble coupling x_1. that leads to N_1 freeze-in!

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

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

[note: both must occur before Higgsino decoupling]

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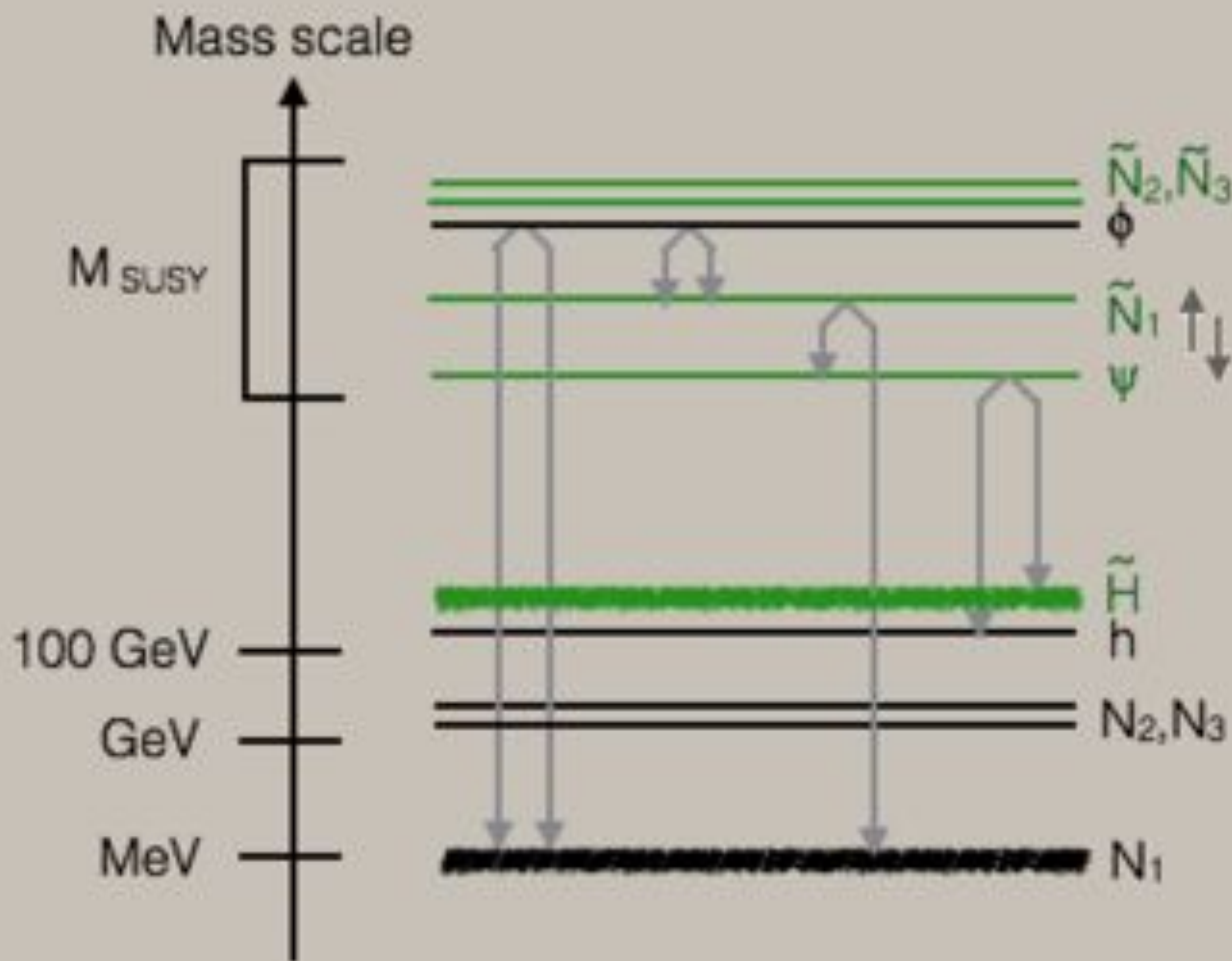
- each decay produces an N_1 particle
- **can be fairly long lived (can even dominate the energy density of the Universe, leading to an early period of matted domination)**

WORKING SPECTRUM



RELIC DENSITY AND COMPOSITION

(at least) two distinct production mechanisms

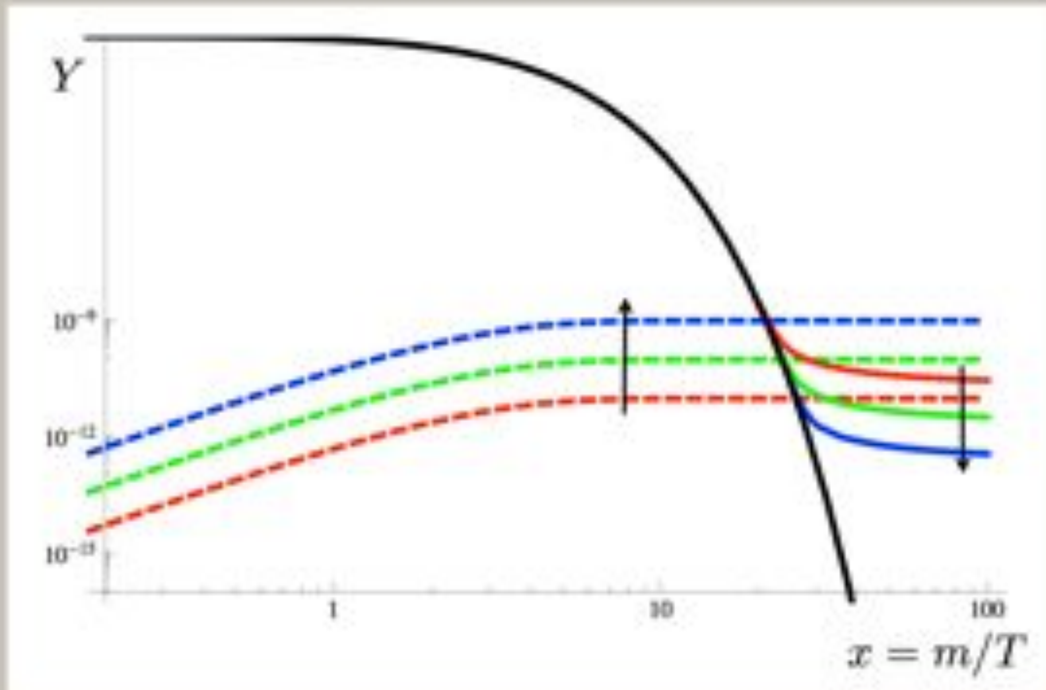
$$\Omega_{N_1} h^2(\phi) \sim \frac{10^{24}\, x^2}{2\pi\, S_{N_{2,3}}} \frac{m_{N_1}}{m_\phi}$$

$$\Omega_{N_1} h^2(\tilde{N}_1) \sim \frac{10^{24}\, x^2}{2\pi\, S_{N_{2,3}}} \frac{m_{N_1}}{m_\phi} \left(\frac{A_\phi}{m_\phi}\right)^2$$

entropy dilution from heavier sterile neutrino decays

sterile sneutrino decay could provide comparable/ dominant abundance

FREEZE-OUT VS FREEZE-IN



from hep-ph 0911.1120

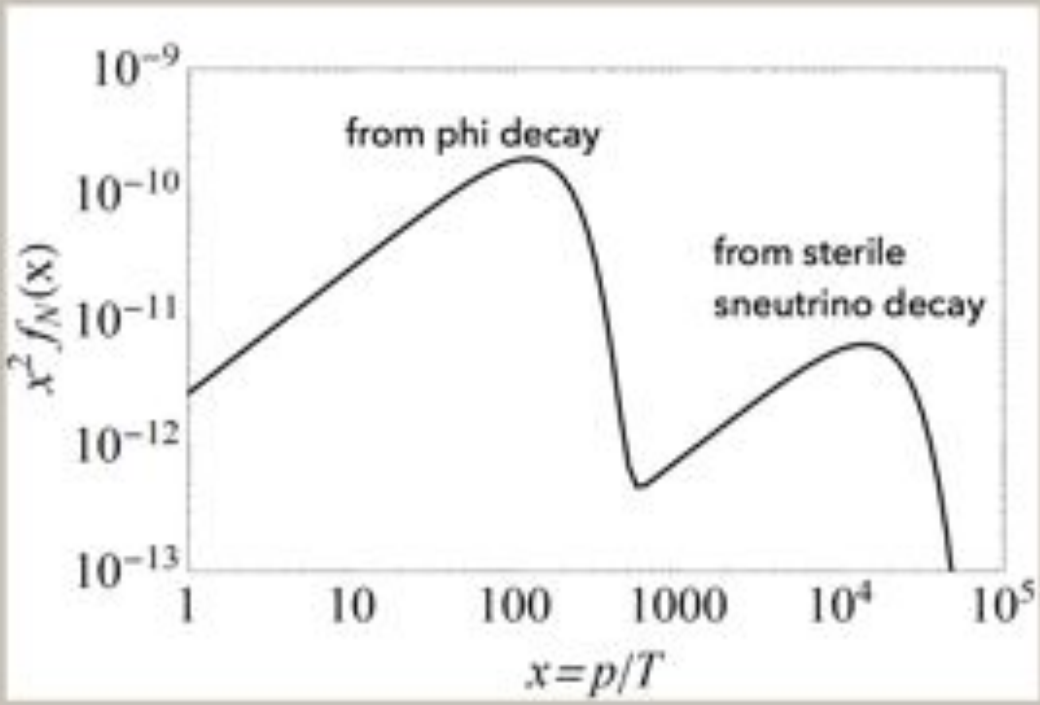
Freeze-out: earlier properties are washed out, decoupling is an IR dominated process

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

RELIC DENSITY AND COMPOSITION

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!

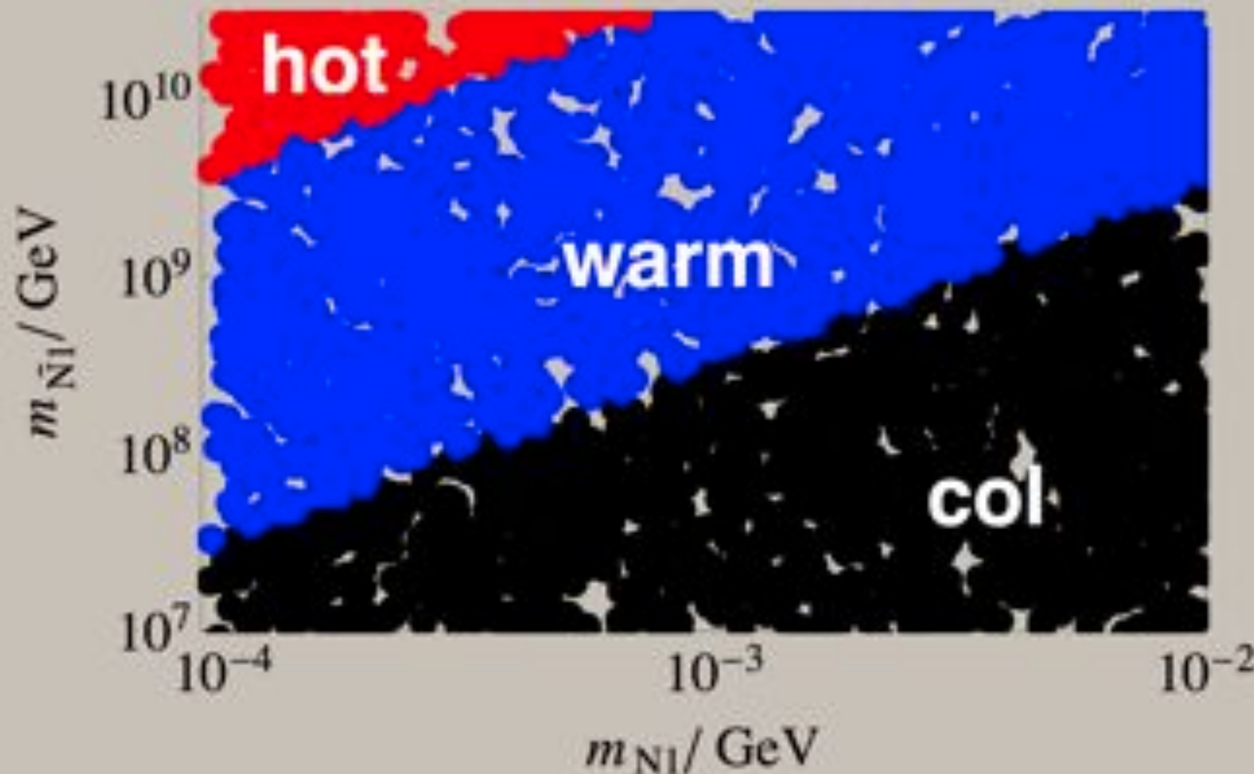
FREE STREAMING LENGTH

$$\Lambda_{FS} = \int_{t_p}^{t_0} \frac{\langle v(t) \rangle}{a(t)} \, \mathrm{d}t$$

Rough categorization

$\Lambda_{FS} \lesssim 0.01 \text{ Mpc}$	cold (most DM models)
$0.01 \lesssim \Lambda_{FS} \lesssim 0.1 \text{ Mpc}$	warm
$0.1 \text{ Mpc} \lesssim \Lambda_{FS}$	hot (ruled out by structure formation)

FREE STREAMING LENGTH

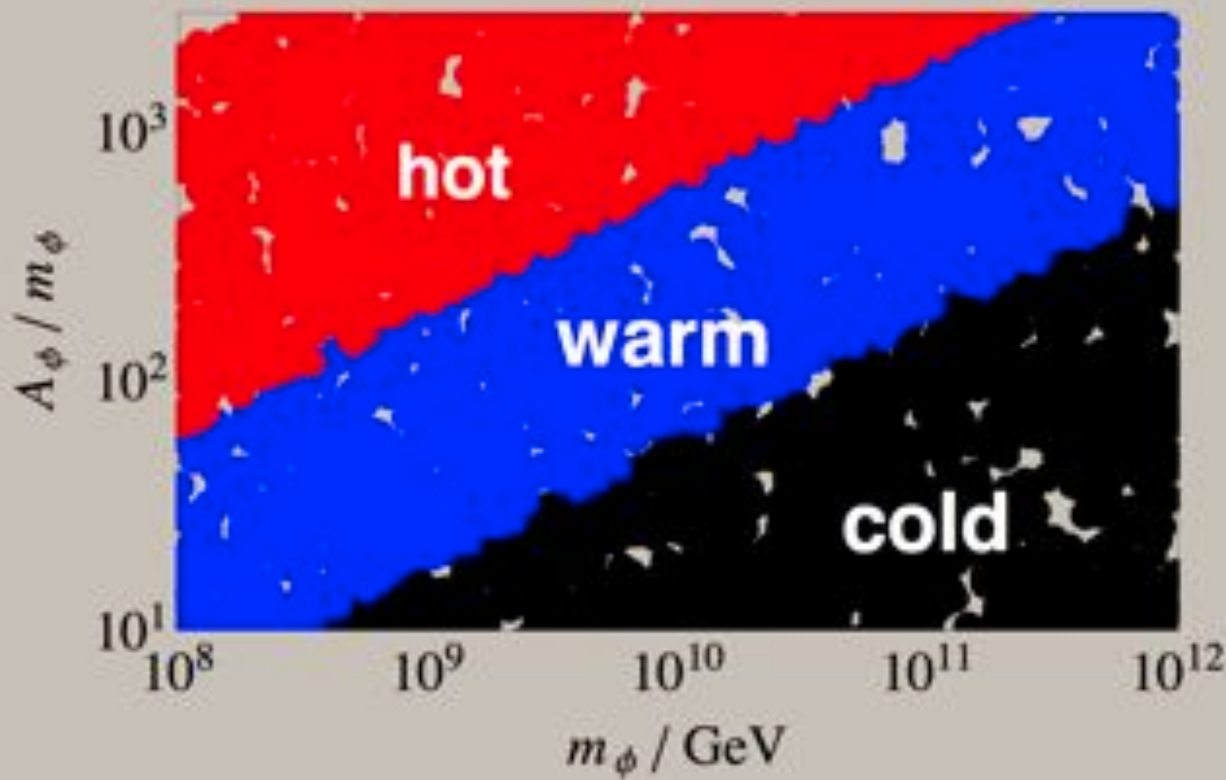


$\tilde{N}_1 \to \psi N_1 \qquad m_\phi = 10^{11}\ \mathrm{GeV} \qquad A_\phi = 10\, m_\phi$

coupling x chosen to produce correct relic density

heavier sneutrino / lighter neutrino results in more boosted dark matter

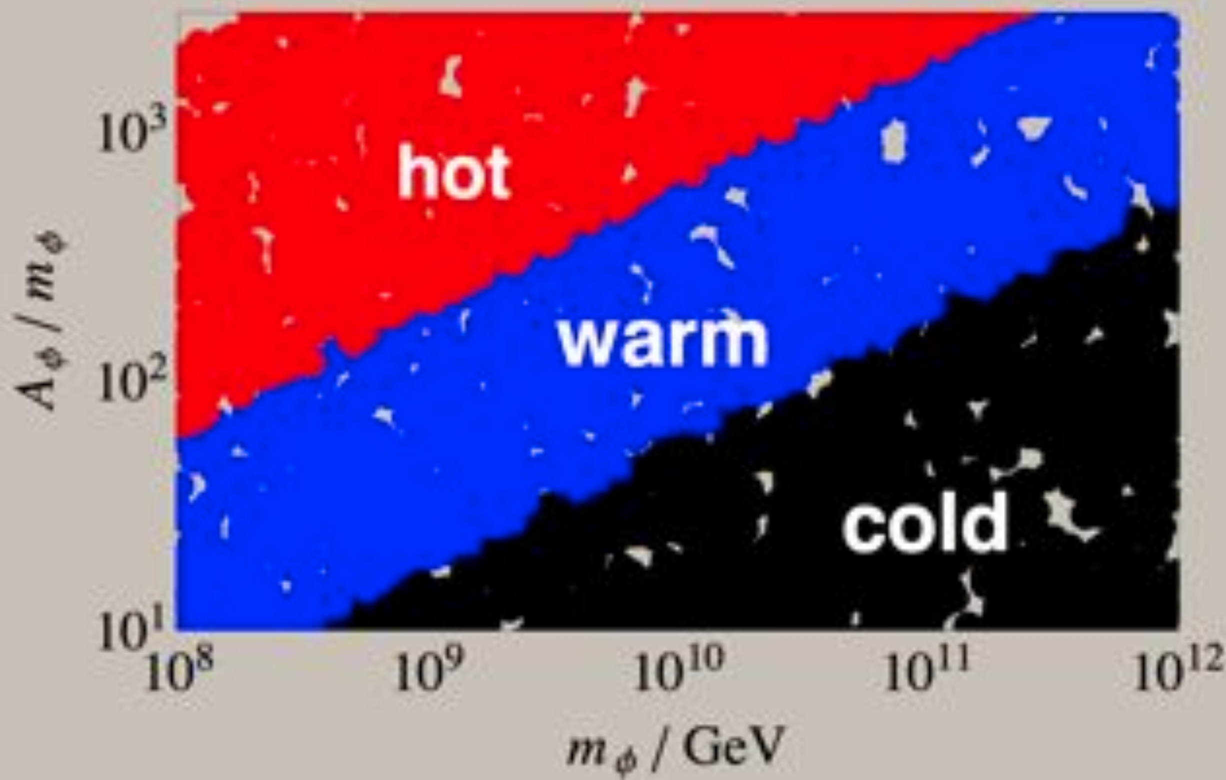
FREE STREAMING LENGTH



m_{N_1} 1 MeV $\quad$ $m_{\tilde{N}_1}$ 10^6 GeV

determined not just by masses, but also by parameters that control lifetime!

FREE STREAMING LENGTH



cold/warm/hot dark matter are all possible in this setup

ΔN_{eff}

if the injected population is sufficiently relativistic, can get contributions to the effective number of relativistic degrees of freedom in the early Universe

(at CMB or BBN. in our setup, only BBN)

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

ΔN_{eff}

- cannot be all of dark matter, else DM today is too hot and inconsistent with structure formation
- can be a subdominant (<1%) fraction of dark matter, if the rest of dark matter is cold
- 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!

ΔN_{eff}

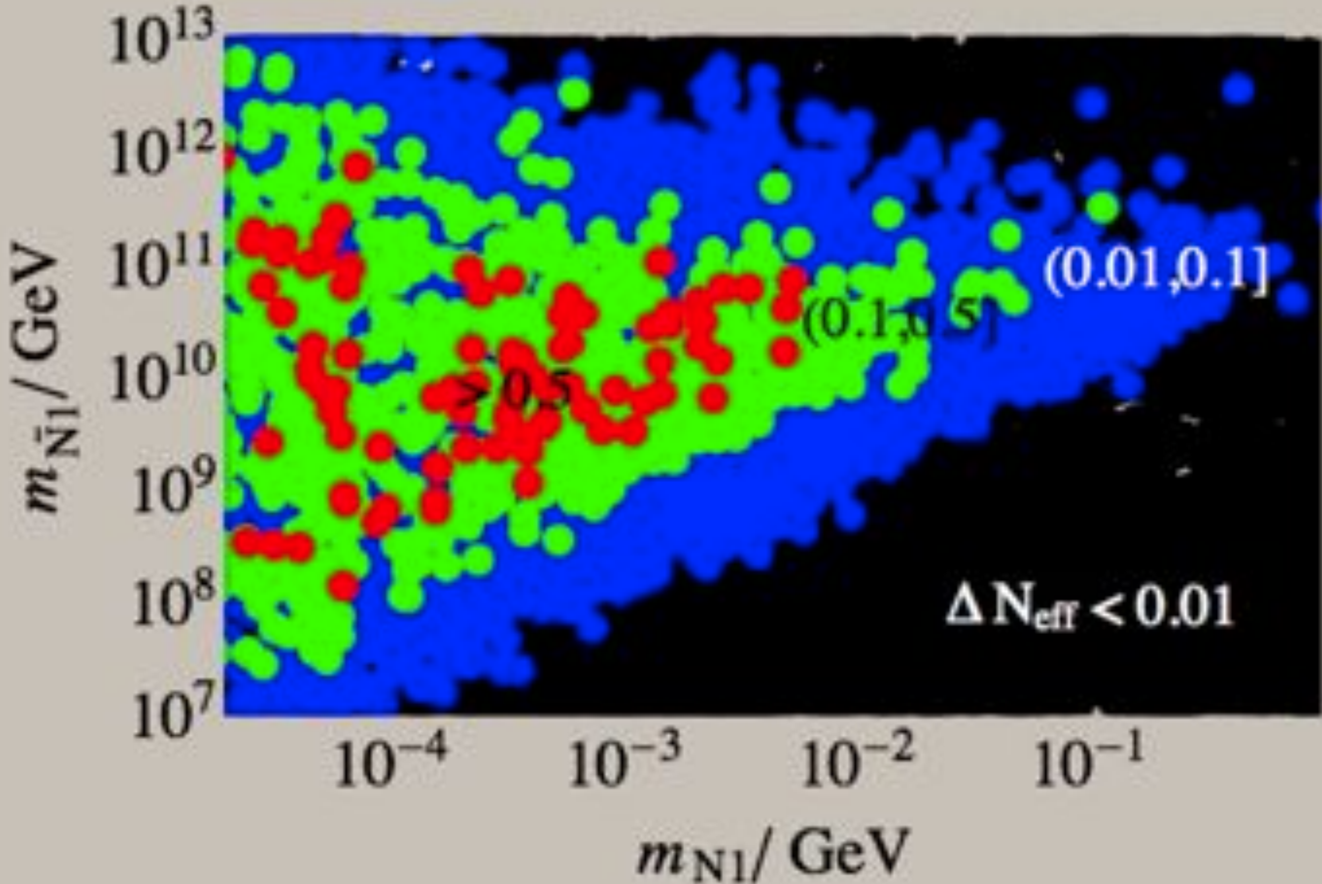
if the injected population is sufficiently relativistic, can get contributions to the effective number of relativistic degrees of freedom in the early Universe

(at CMB or BBN. in our setup, only BBN)

$$\Delta N_{\text{eff}} \approx \frac{10^{-8}}{S_{N_{2,3}}^{1/3}(g_{*SM}/g_{*BBN})^{1/3}}\,\Omega h^2 \frac{m_{\tilde{N}_1}}{T_{decay}} \frac{\text{GeV}}{m_{N_1}}$$

$$\approx 0.2\left(\frac{\Omega h^2}{0.0012}\right)\left(10^{-8}\frac{m_{\tilde{N}_1}}{T_{decay}}\right)\left(\frac{\text{MeV}}{m_{N_1}}\right)\left(\frac{10}{S_{N_{2,3}}}\right)^{1/3}$$

$\Delta N_{\rm eff}$



$A_\phi = 0.1 m_\phi$

$\tilde{N}_1 \rightarrow N_1 \tilde{H} h$ gives 1% DM. cold population from phi decay makes up the rest

STERILE NEUTRINO DM	WITH SUPERSYMMETRY
	• the sterile sneutrino is an important player in the early Universe; long lived and decays to sterile neutrino DM due to structure of the theory
• single production mechanism	• multiple production mechanisms, extends viable parameter space
• single component	• multiple component dark matter with a single constituent
• can be cold/warm/hot	• can be cold/warm/hot, or some combination of all
• cannot be both all of DM and contribute to Neff	• a subdominant component can give N_{eff} contributions, sterile neutrino can still be all of DM

INVERTING THE QUESTION

SO FAR...

WHAT CAN

SUPERSYMMETRY

TELL US ABOUT

STERILE NEUTRINO DARK MATTER?

INVERTING THE QUESTION

NEXT

WHAT CAN

STERILE NEUTRINO DARK MATTER

TELL US ABOUT

THE UNDERLYING (SUPERSYMMETRIC) THEORY ?

Sterile Neutrino Dark Matter from Freeze-In

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

ISSUES:

- $y \sim 10^{-7}$ to explain neutrino masses
- keV - GeV masses for sterile neutrinos put in by hand
- feeble coupling ($x < 10^{-7}$) 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

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

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

A MODIFIED NEUTRINO SECTOR

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

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

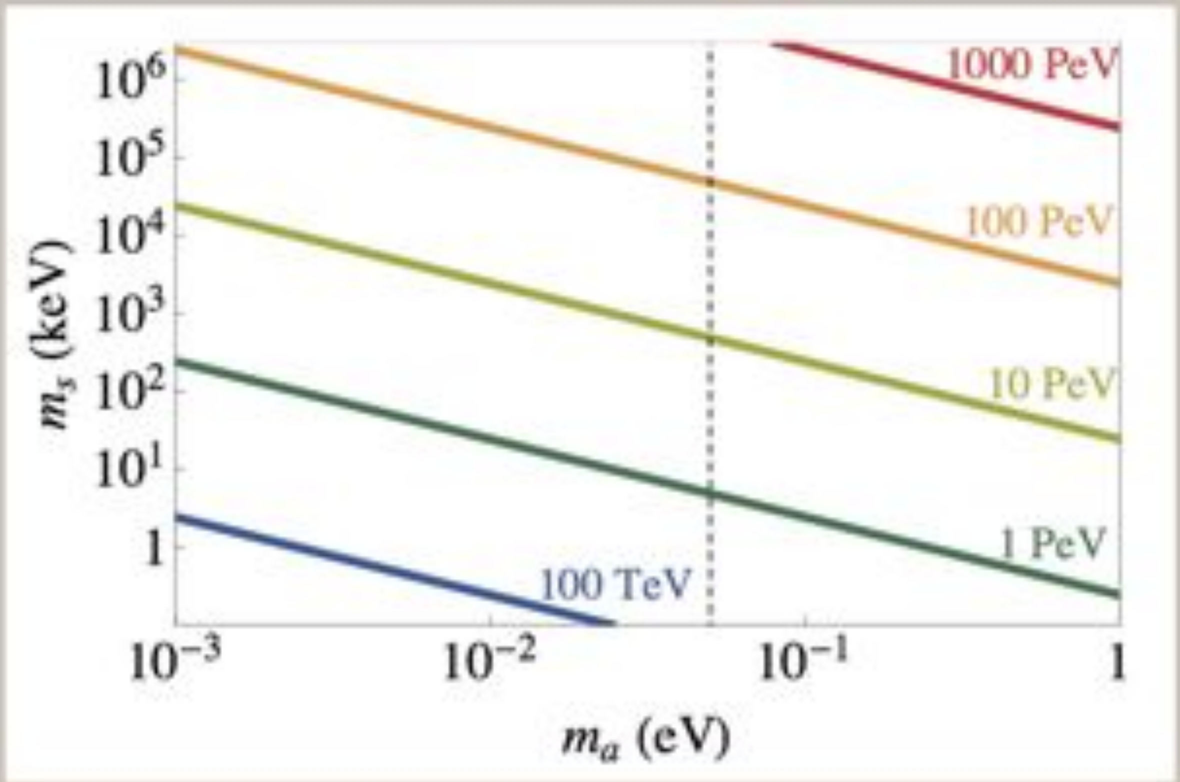
- If the scalar φ gets a vev, U(1)′ broken, effective neutrino mass matrix:

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

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

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

A MODIFIED NEUTRINO SECTOR



Contours of y<φ>. $M_* = M_{GUT} (=10^{16}\,\text{GeV}),\ \tan\beta = 2 \quad 0.001 < x < 2$

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

Maps onto νMSM

PEV SCALE...SUPERSYMMETRY?

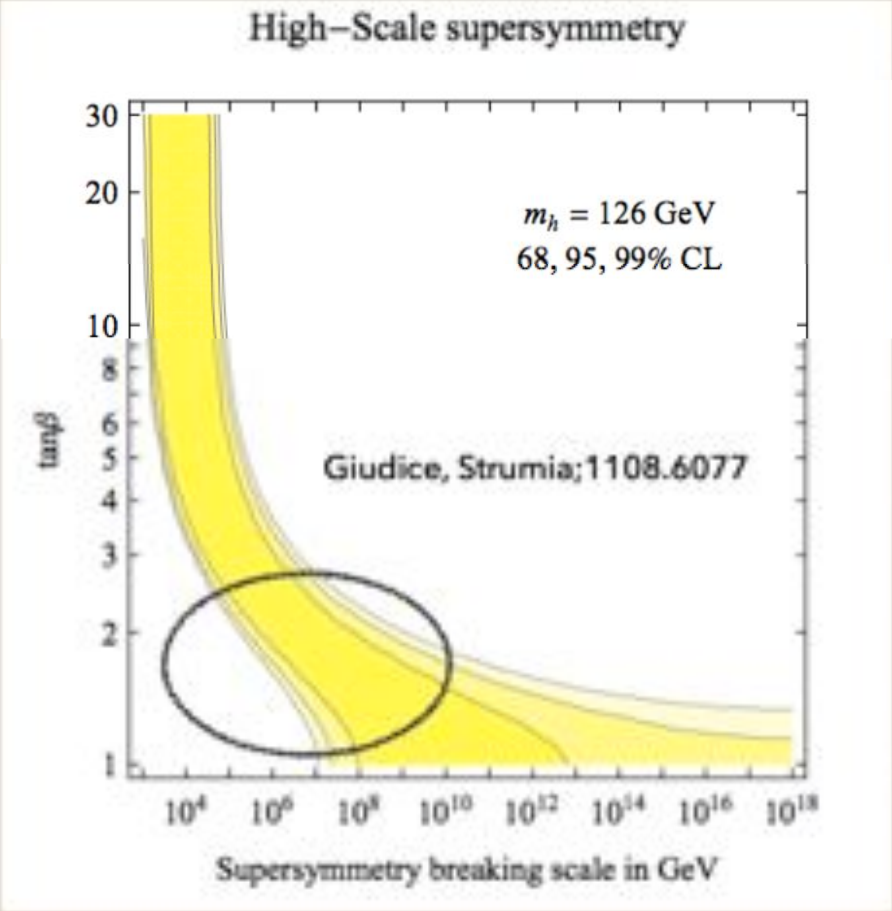
Compatible with m_h=126 GeV

For tanβ ≈ O(1), m_h=126 GeV implies the **scale for supersymmetry (superpartners) is 1-100 PeV**

Suggests the vev of φ and the breaking of U(1)' might be related to SUSY breaking.

PeV Scale SUSY

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.



STERILE NEUTRINO AS DARK MATTER

- (Infrared) Freeze-in

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

Once φ obtains a vev,

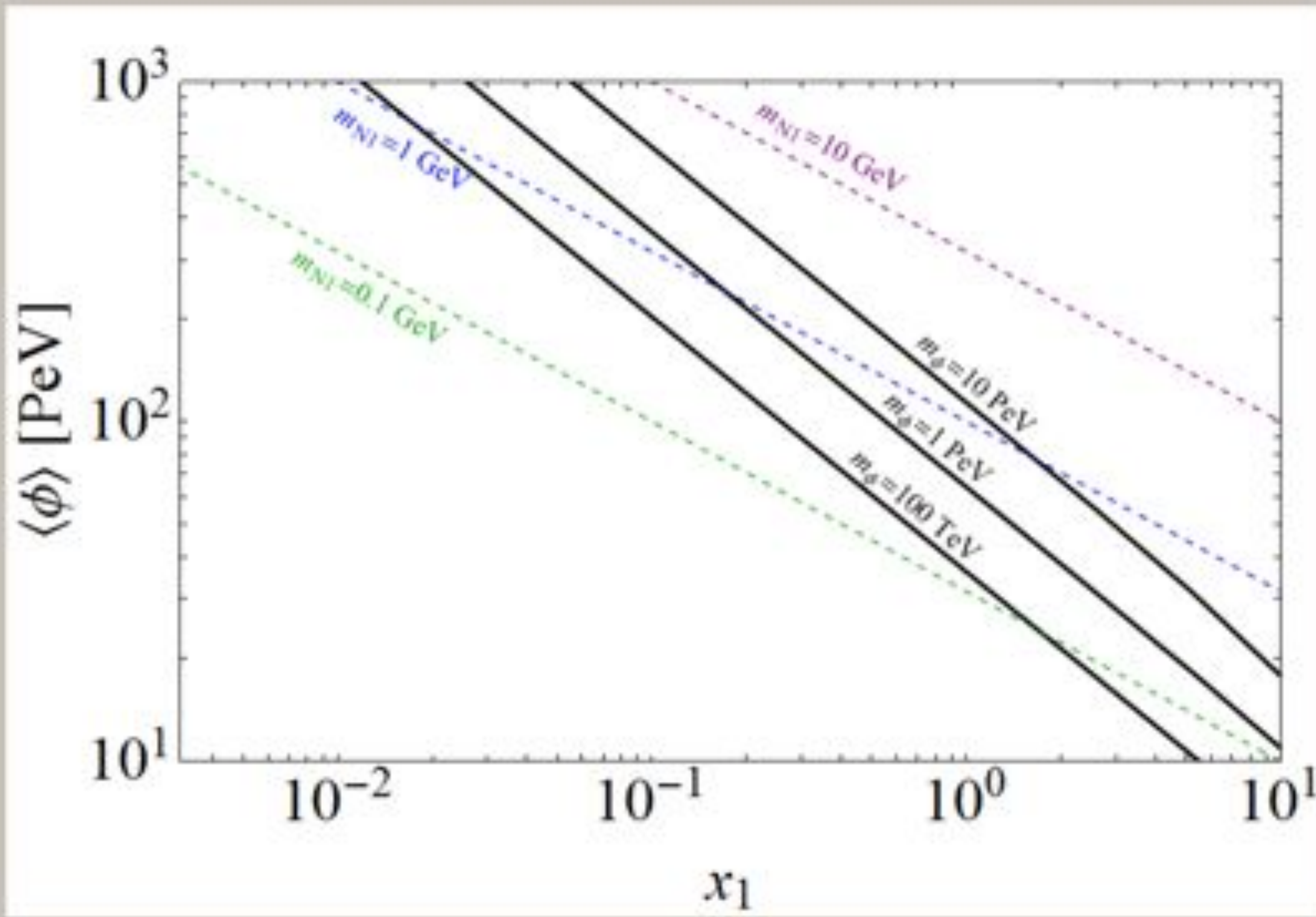
$$\phi \to N_1 N_1 \qquad H_u \to N_1 \nu_a$$

$$x_1 = \frac{2\,x\,\langle\phi\rangle}{M_*} \qquad y_1 = \frac{y\,\langle\phi\rangle}{M_*}$$

↓

$$\Omega_{N_1} h^2 \sim 0.1 \left(\frac{x_1}{1.4 \times 10^{-8}}\right)^3 \left(\frac{\langle\phi\rangle}{m_\phi}\right)$$

PARAMETERS FOR CORRECT ABUNDANCE



Sterile Neutrino Dark Matter from Freeze-In

ISSUES:	RESOLUTION: $\langle\phi\rangle \sim \mathrm{PeV}$
y~10^{-7} for neutrino masses?	$\sim \frac{\langle\phi\rangle}{M_{GUT}}$
keV - GeV mass scales?	$\sim \frac{\langle\phi\rangle^2}{M_{GUT}}$
feeble coupling?	freeze-in, small coupling $\sim \frac{\langle\phi\rangle}{M_{GUT}}$

STERILE NEUTRINO AS DARK MATTER

- (Ultraviolet) Freeze-in

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

(If additional interactions keep φ in equilibrium with thermal bath)

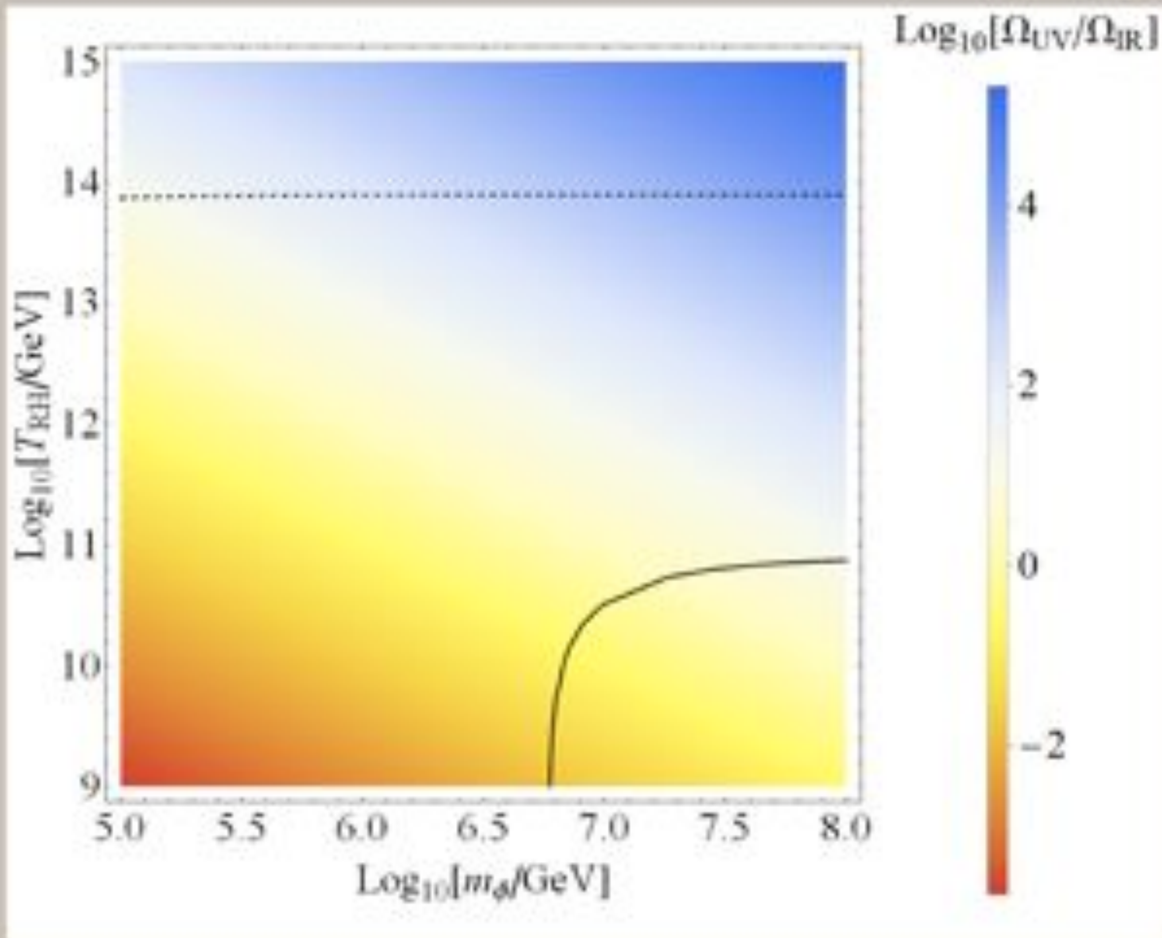
(Doesn't need φ to be in equilibrium)

$$\phi\,\phi \rightarrow N_1\,N_1,\ \phi\,H_u \rightarrow \nu_a\,N_1,\ \phi\,\nu_a \rightarrow H_u\,N_1,\ \text{and}\ H_u, \nu_a \rightarrow \phi\,N_1$$

$$\Omega_{N_1} h^2 \simeq 0.1\, x^2 \left(\frac{m_s}{10\,\mathrm{GeV}}\right)\left(\frac{T_{RH}\, M_P}{M_*^2}\right)$$

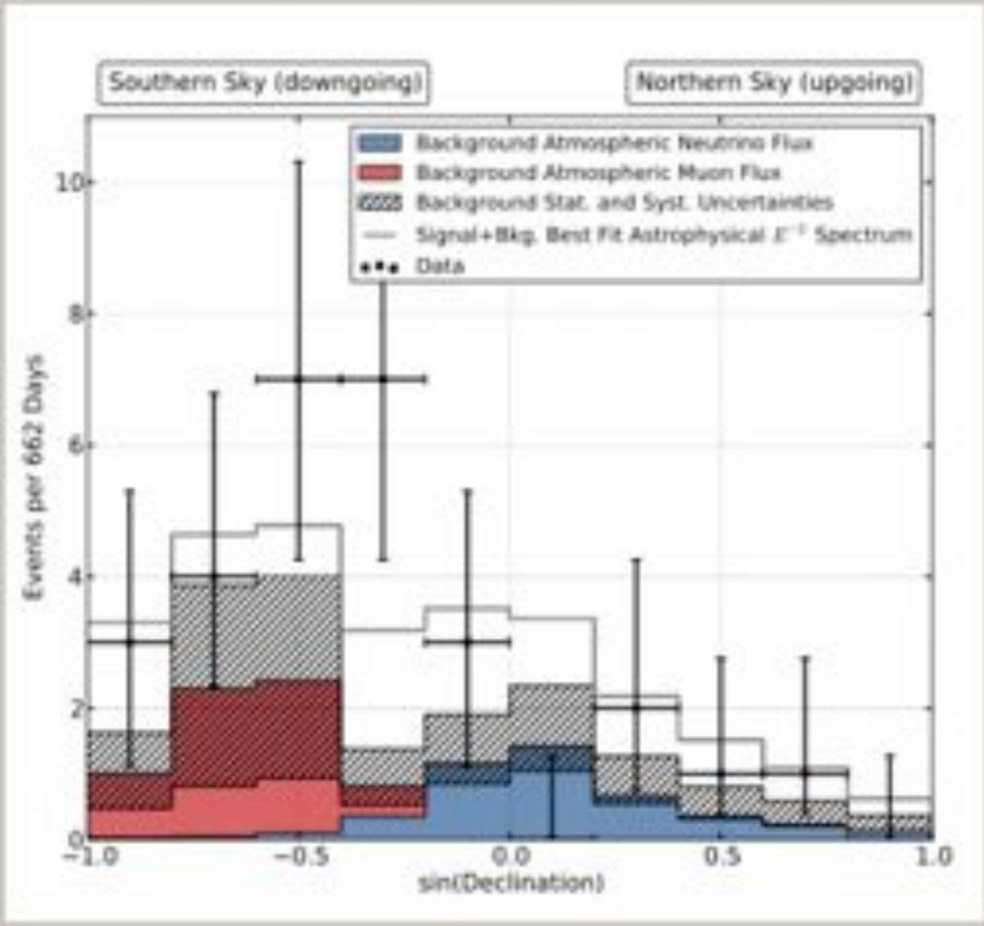
F. Elahi, C. Kolda, and J. Unwin (2014), 1410.6157.
A. Kusenko, F. Takahashi, and T. T. Yanagida, Phys.Lett. **B693**, 144 (2010), 1006.1731.
M. Blennow, E. Fernandez-Martinez, and B. Zaldivar, JCAP **1401**, 003 (2014), 1309.7348.

UV VS IR CONTRIBUTIONS



dotted/dashed curves : contours of correct relic density

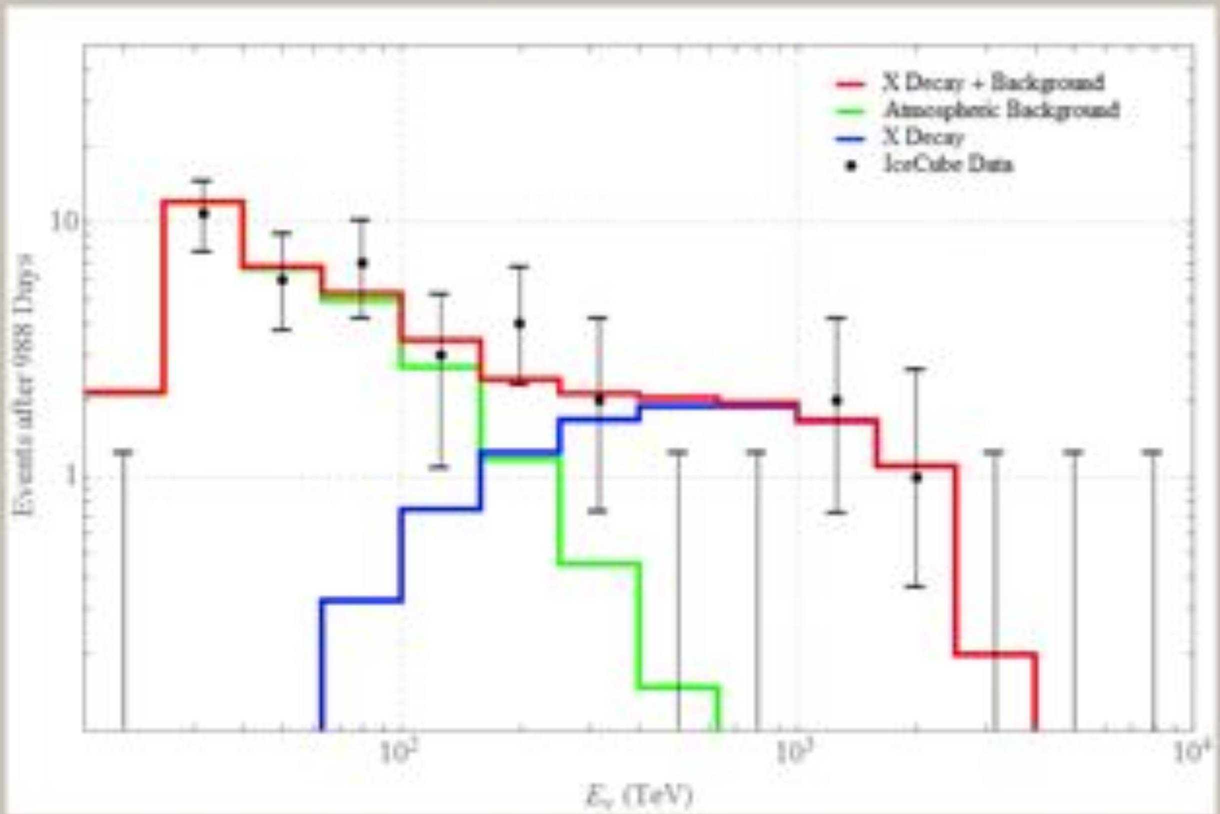
PEV...NEUTRINOS AT ICECUBE!



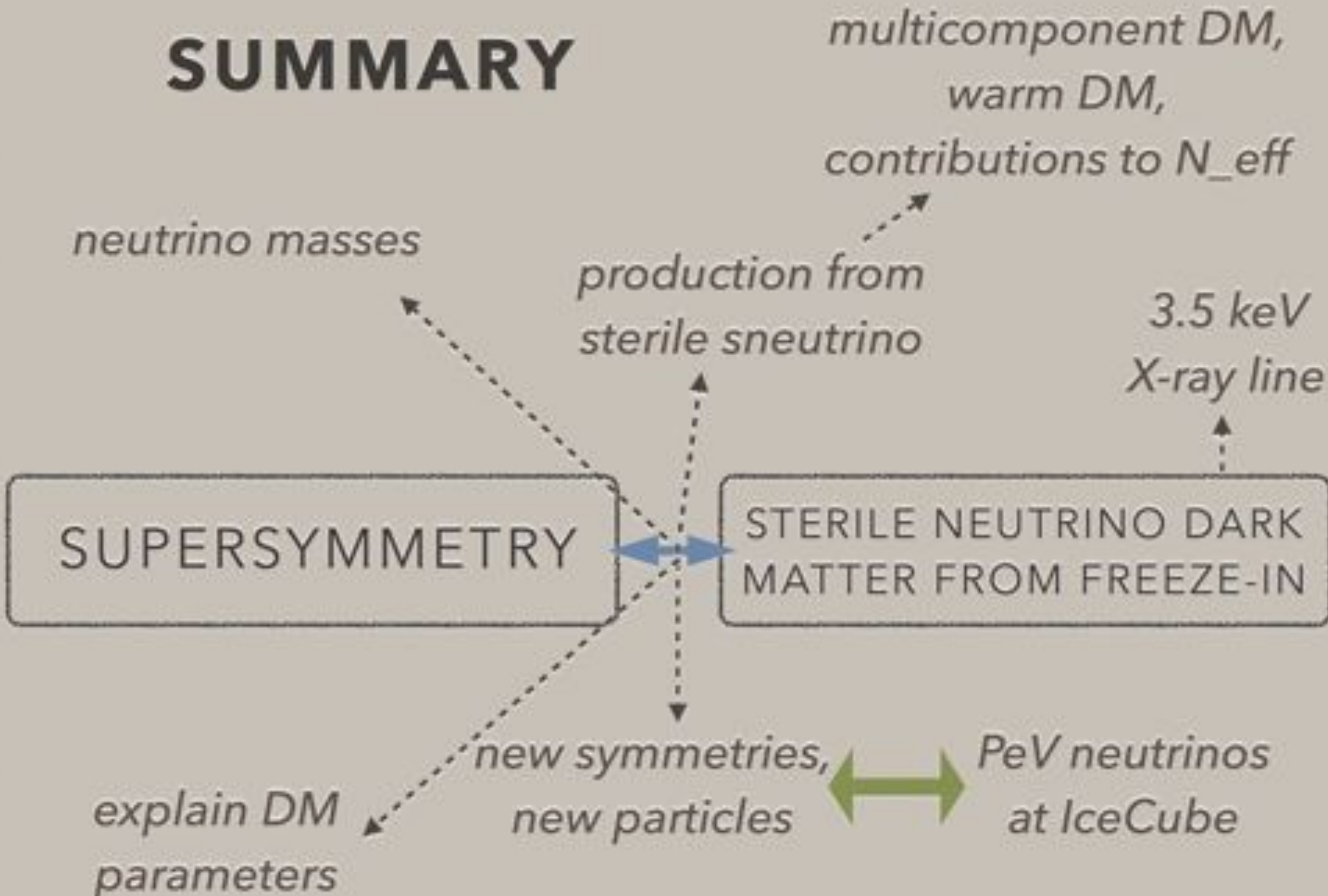
- 37 high energy neutrinos between 30 TeV and 2 PeV; hint of PeV scale dark matter?

PEV...NEUTRINOS AT ICECUBE!

- Can extend the formalism with the same structure, use the U(1)′ symmetry to stabilize another dark matter component X with a PeV scale mass that decays to neutrinos [arXiv:1506.08195]



SUMMARY


multicomponent DM,
warm DM,
contributions to N_eff
neutrino masses
production from
sterile sneutrino
3.5 keV
X-ray line
SUPERSYMMETRY
STERILE NEUTRINO DARK
MATTER FROM FREEZE-IN
explain DM
parameters
new symmetries,
new particles
PeV neutrinos
at IceCube