

LIGHT EXTENDED NEUTRINO SECTORS: FOUNDATIONS AND PHENOMENOLOGY

SnowMass2021

MINI-WORKSHOP ON NEUTRINO THEORY
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REFERENCES

Neutrino masses and sterile neutrino dark matter from the PeV scale

S. B. Roland, B. Shakya, J. D. Wells, 1412.4791

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, 1506.08195

Sterile neutrino dark matter from freeze-in

B. Shakya, 1512.02751

Cosmological imprints of frozen-in light sterile neutrinos

S. B. Roland, B. Shakya, 1609.06739

Sterile Neutrino Dark Matter with Supersymmetry

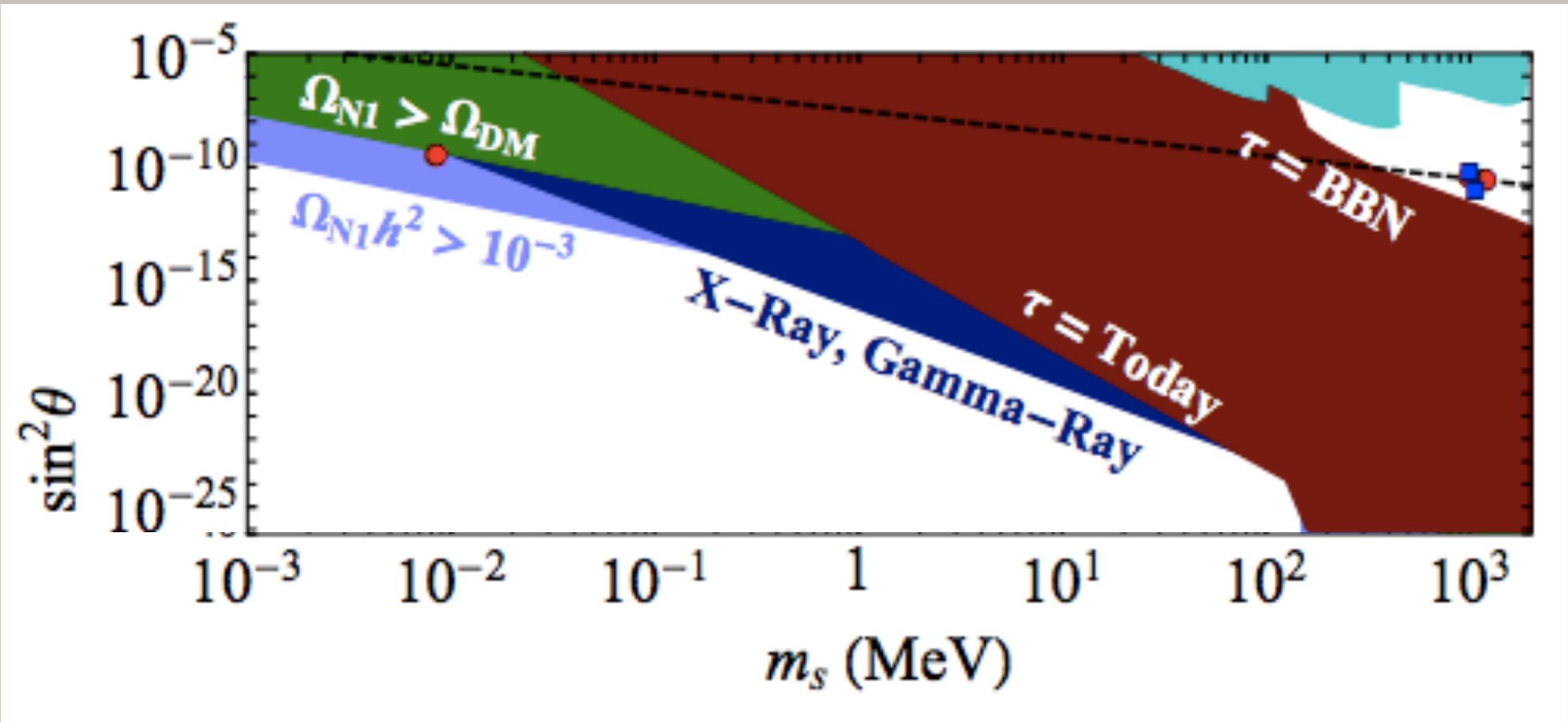
B. Shakya, J. D. Wells, 1611.01517

Exotic Sterile Neutrinos and Pseudo-Goldstone Phenomenology

B. Shakya, J. D. Wells, 1801.02640

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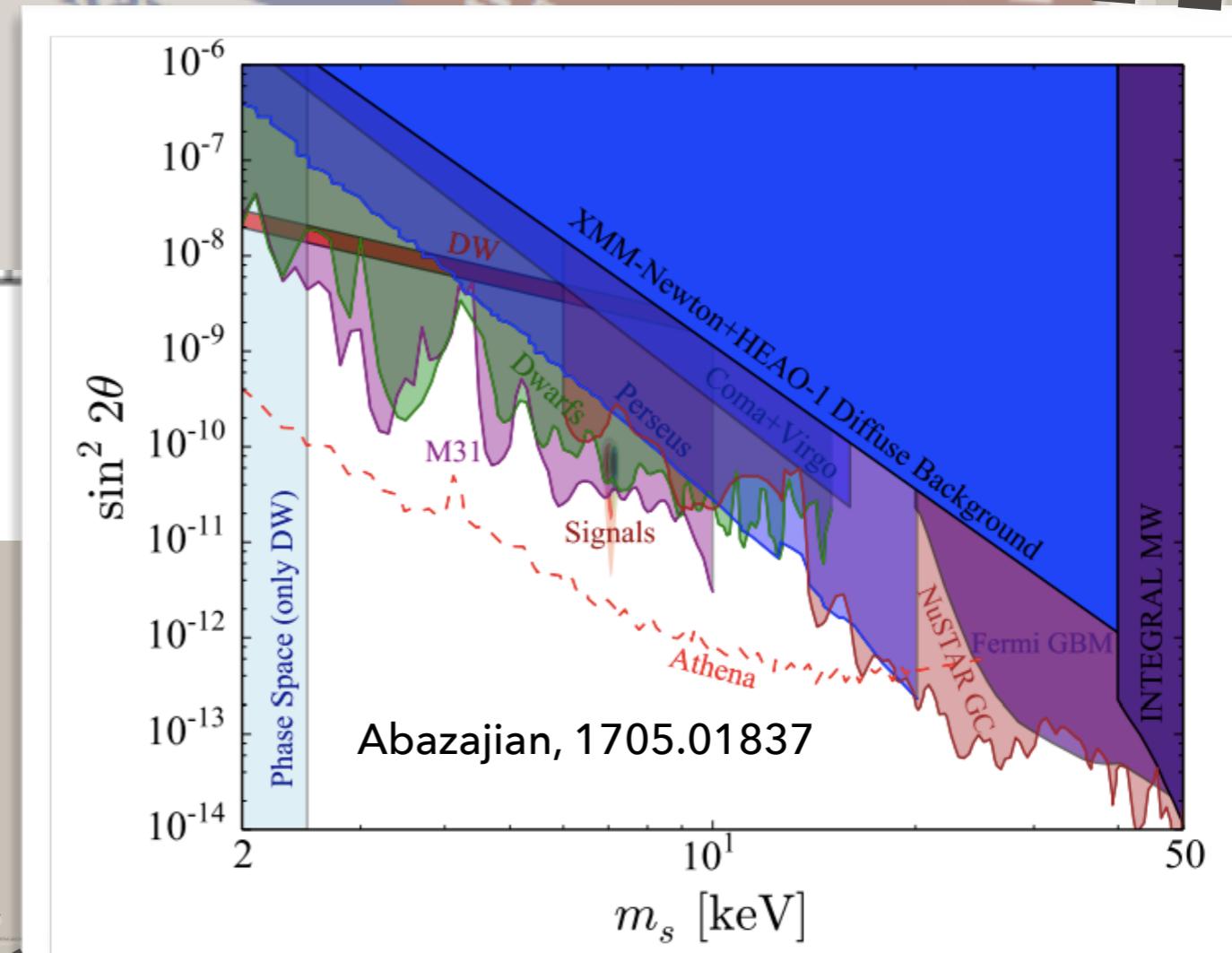
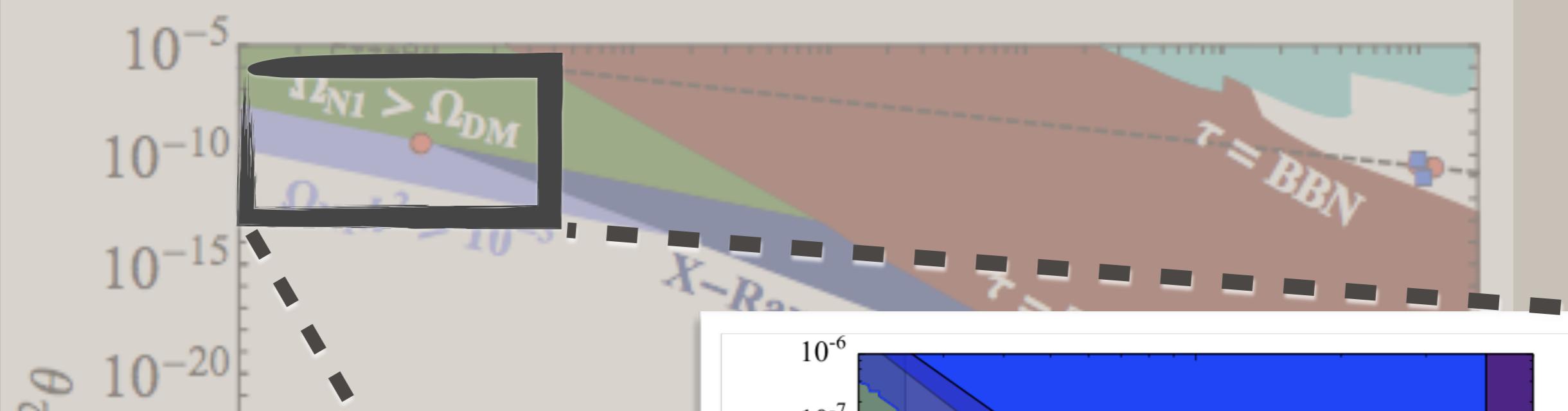
PARAMETER SPACE FOR STERILE NEUTRINOS



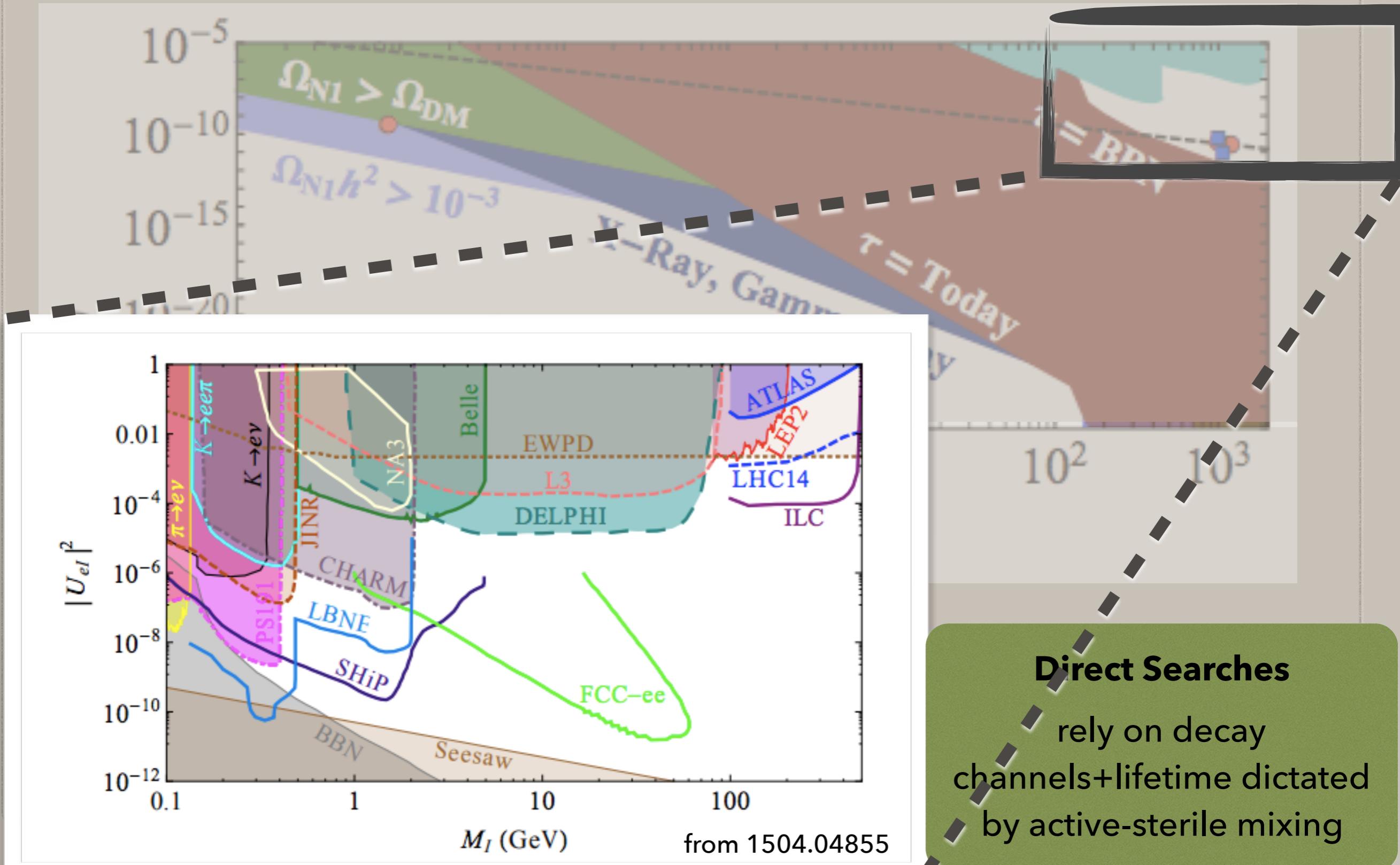
from Roland, Shakya, Wells, 1412.4791 [hep-ph]

PARAMETER SPACE FOR STERILE NEUTRINOS

Sterile Neutrino Dark Matter:
X-ray + Lyman-alpha rule out DM
from Dodelson-Widrow (DW)
production
need alternate mechanism, e.g.
freeze-in, that does not need active-
sterile mixing



PARAMETER SPACE FOR STERILE NEUTRINOS



NEED FOR “NEW” PHYSICS IN THE NEUTRINO SECTOR

(WITH LIGHT STERILE NEUTRINOS)

“unnatural” parameters in the (sterile) neutrino sector:

- < GeV scale masses for sterile neutrinos
- tiny Yukawa couplings ($y < 10^{-7}$)
- production of sterile neutrino DM beyond DW

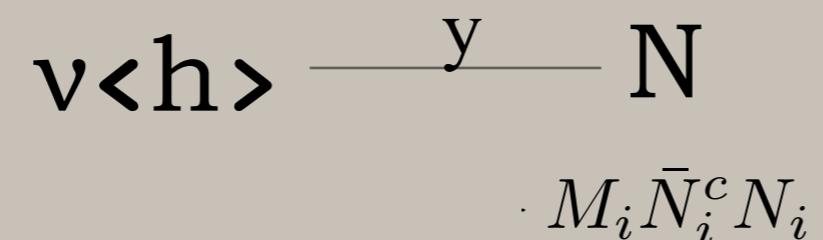
Hints of an underlying structure?

additional structure? new particles? new symmetries?
novel phenomenology?

WHY ARE STERILE NEUTRINOS LIGHT?

Why are the **active (Standard Model) neutrinos** light?

1. symmetry protection
2. mass partner is a singlet



$$M \gg y\langle h \rangle \rightarrow m_a \sim \frac{(y\langle h \rangle)^2}{M}$$

WHY ARE STERILE NEUTRINOS LIGHT?

What if the same thing happens with a “sterile neutrino” ν' ?

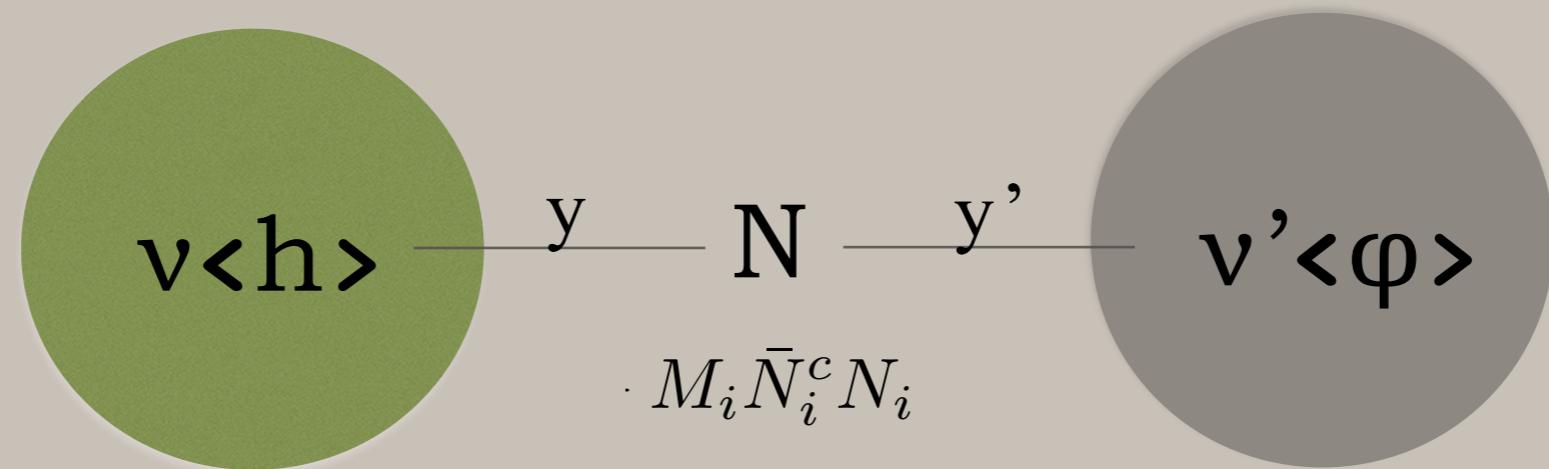
ν' charged under some **additional symmetry ($U(1)'$)**, broken by the **vev of an exotic higgs ϕ**

$$\nu \langle h \rangle \xrightarrow{y} N \xrightarrow{y'} \nu' \langle \phi \rangle$$

$$M_i \bar{N}_i^c N_i$$

$$M \gg y \langle \phi \rangle \rightarrow m_{\nu'} \sim \frac{(y' \langle \phi \rangle)^2}{M}$$

HEAVY NEUTRINO PORTAL TO A HIDDEN SECTOR



Integrate out heavy portal N 's:

low energy effective seesaw between the hidden sector
“sterile neutrinos” v' and SM neutrinos v

IMPLICATIONS

neutrino sector extended with additional symmetries, particles:

refer to these
as N from
hereon

in particular:
 N_1 =dark
matter?

- **sterile neutrinos** (exotic fermions in a hidden sector, light because masses suppressed by the seesaw mechanism)
- **higgs boson** (responsible for breaking the symmetry the sterile neutrinos are charged under)
- **Goldstone boson** (if symmetry is global)
- **gauge boson(s)** (if gauge symmetry)

Do these lead to interesting physics?

WHAT IS THE SCALE OF U(1)' BREAKING?

$m_{\nu'}$	M	$\langle \phi \rangle$	Motivation
keV-GeV	GUT scale	100 TeV- 100 PeV	Split Supersymmetry
eV	GUT scale	few hundred GeV	twin Higgs
keV-GeV	10^{10} GeV	few hundred GeV -TeV	dark matter+collider signatures

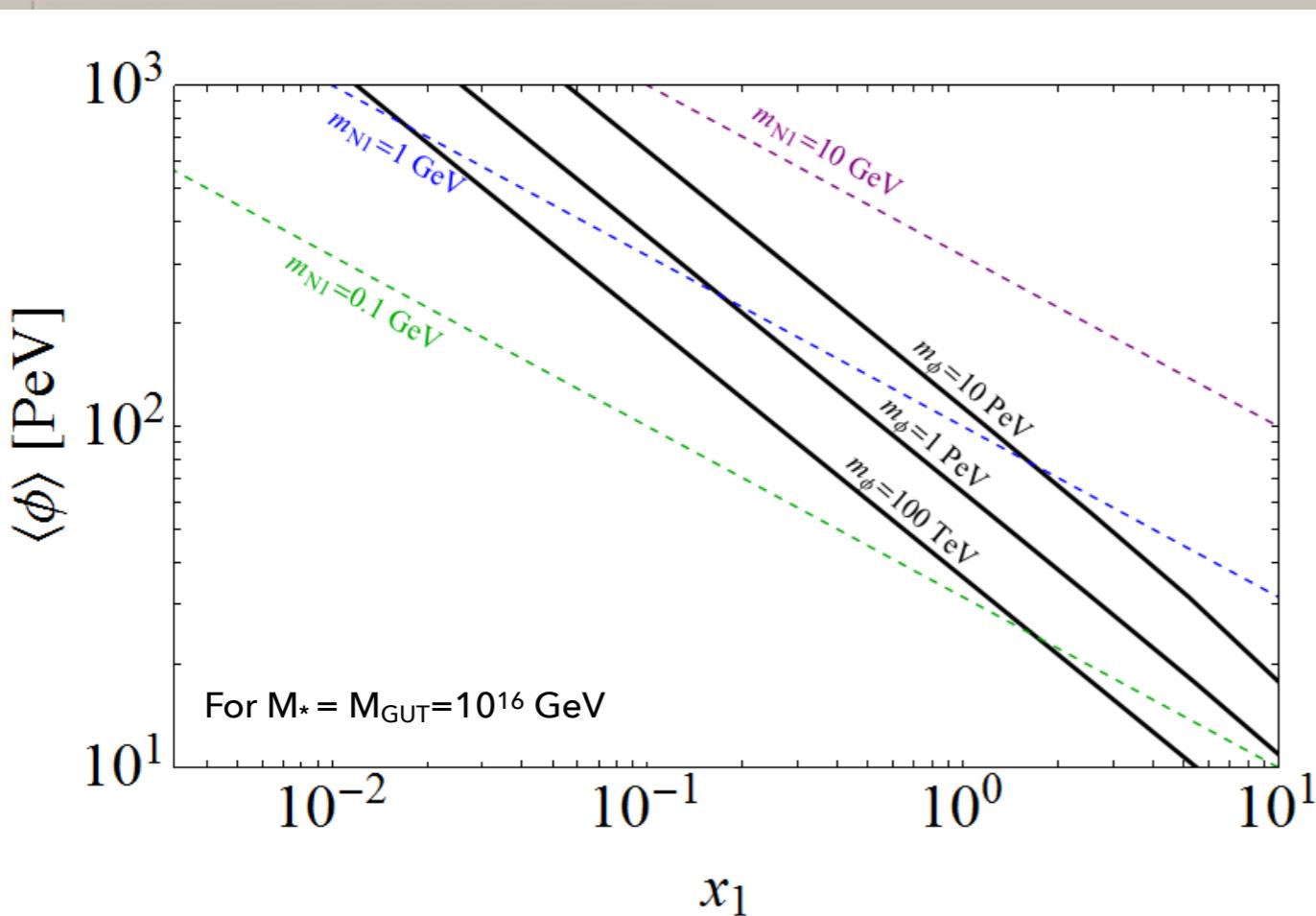
+ more...

DARK MATTER FREEZE-IN FROM HEAVY SCALAR DECAYS

Above U(1)' breaking scale, integrating out the GUT scale seesaw neutrinos (M_*) gives

UV freeze-in from suppressed interaction $LH \rightarrow N\phi$

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



from S. Roland, B. Shakya, 1609.06739

$$\phi \rightarrow N_1 N_1$$

$$x_1 = \frac{2x \langle \phi \rangle}{M_*}$$

“feeble” coupling: (IR) freeze in of FIMP DM

suppression of an intermediate (symmetry breaking) scale by a large (cutoff, e.g. GUT) scale

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

S. Roland, B. Shakya, J. Wells, 1412.4791 [hep-ph]

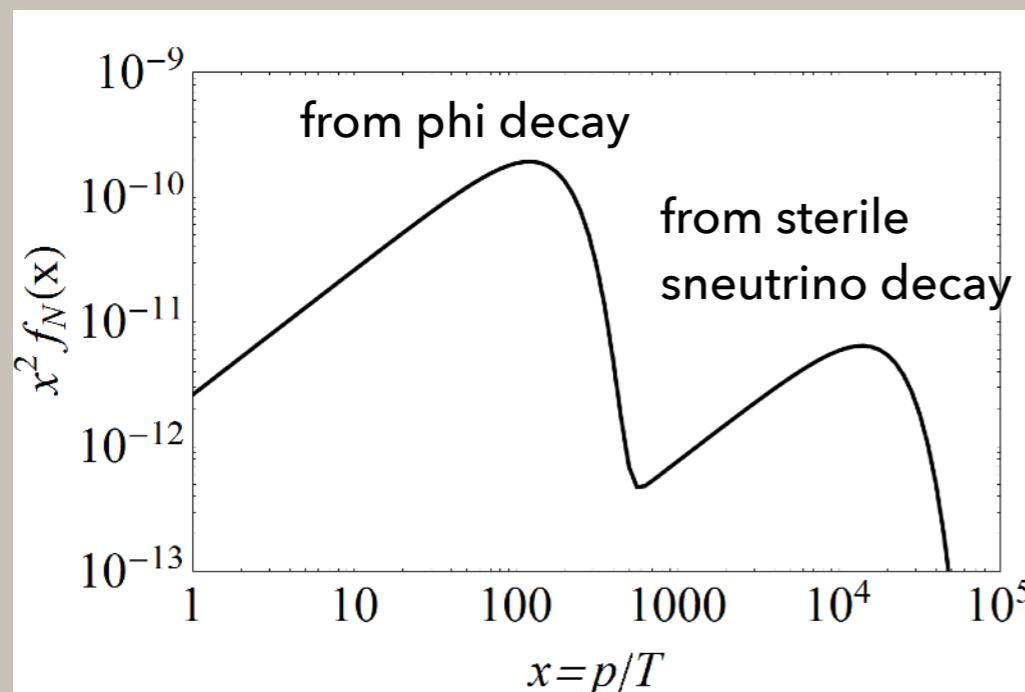
S. Roland, B. Shakya, J. Wells, 1506.08195 [hep-ph]

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IMPRINTS OF HEAVY STATES

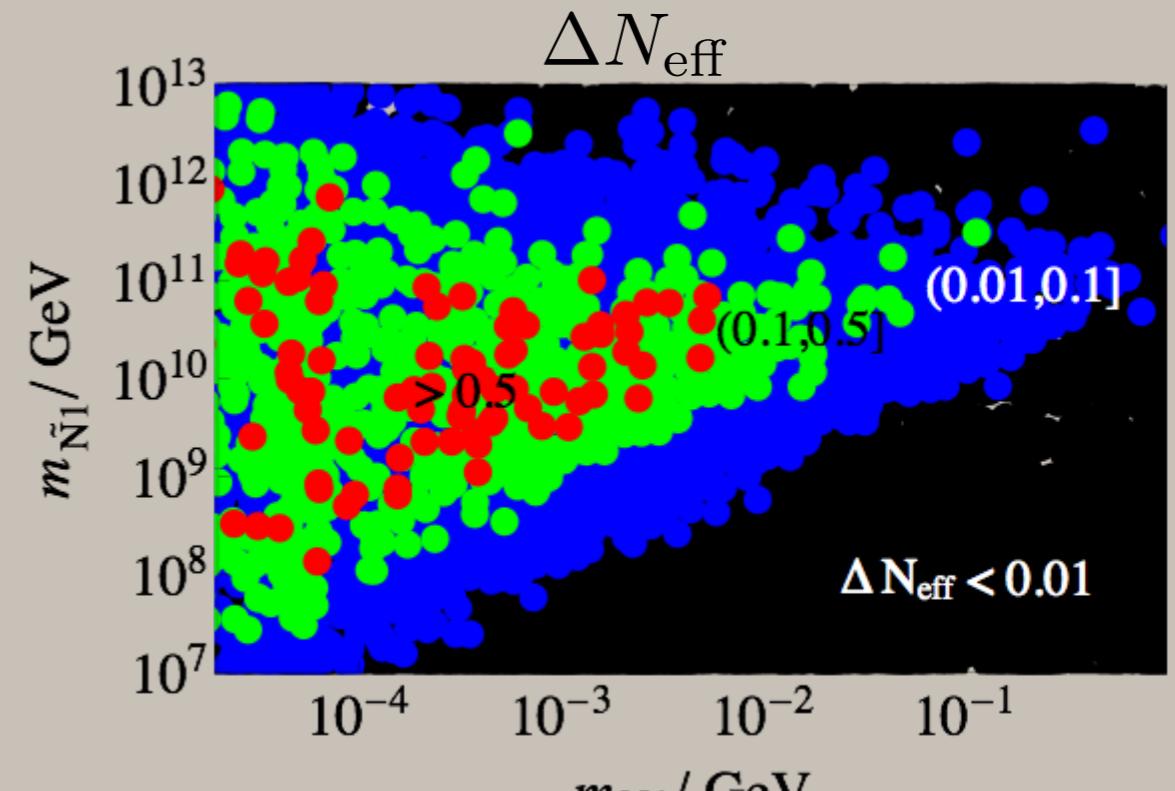
B. Shakya, J. Wells, 1611.01517 [hep-ph]

- e.g. in SUSY, sterile neutrino DM has a heavy superpartner: sterile sneutrino
- sterile sneutrino decays must produce DM (effective Z_2 stabilizing DM): secondary DM production mechanism
- **the two populations don't talk to each other! [Freeze-in: DM never “thermalizes”]**
- second population is hotter (sterile sneutrino is long-lived and decays out of equilibrium)
single species mimics cold+hot DM setup



extremely nontrivial momentum distribution possible!

S. Roland, B. Shakya, 1609.06739 [hep-ph]



subdominant hot component can mimic dark radiation at BBN!

+ GOLDSTONE

B. Shakya, J. Wells, 1801.02640 [hep-ph]

Broken global symmetry -> massless Goldstone η .

Not the Majoron! The symmetry broken is not lepton number...

coupled to neutrinos (both active and sterile) with strength proportional to the neutrino masses (similar to the Majoron)

explicit breaking of global symmetry from nonperturbative gravitational effects:

$$m_\eta^2 \sim f^3/M_{Pl}$$

a pseudo-Goldstone boson

Recall that “sterile neutrinos” themselves are light ($m \sim f^2/M$) because of a seesaw mechanism

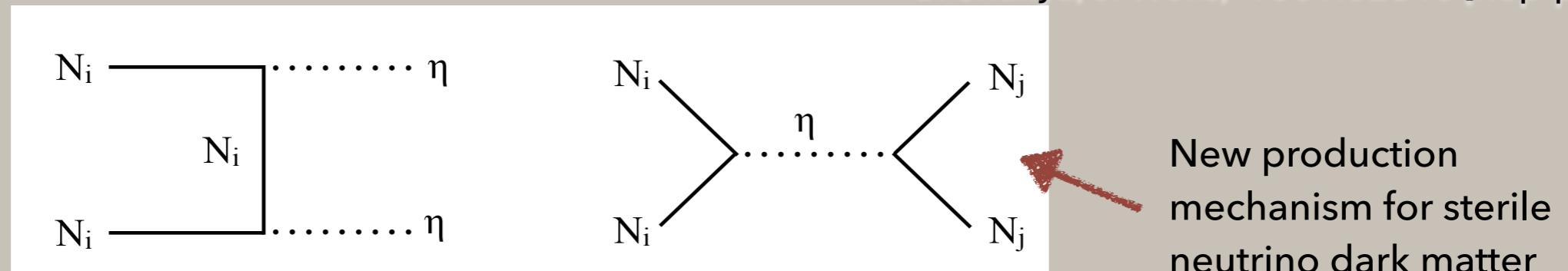
Pseudo-Golstone and sterile neutrinos at the same mass scale if

$$f \sim M^2/M_{Pl}$$

interesting for cosmology?

+ GOLDSTONE COSMOLOGY/DARK MATTER/ DIRECT SEARCH ASPECTS

B. Shakya, J. Wells, 1801.02640 [hep-ph]



- Presence of Goldstone introduces new interactions.

Heavy regime: $m_\eta > m_{N_i}$

Goldstone decay can be a viable source of sterile neutrino dark matter

Light regime: $m_{N_i} > m_\eta > m_\nu$

New sterile neutrino decay channel $N \rightarrow \eta\nu$, giving a 3ν state with no gamma ray counterpart; interesting for neutrino telescopes?

Will also **affect heavy sterile neutrino lifetime and decay channel**: affects bounds/prospects from past (BBN) and present (direct) searches for HNLs

SUMMARY

LIGHT EXTENDED NEUTRINO SECTORS: FOUNDATIONS AND PHENOMENOLOGY

- **light sterile neutrinos likely part of extended sectors** with additional symmetries, particles (higgs, Goldstone/gauge bosons)
- additional structure can be much heavier; sterile neutrinos can be the lightest in the new sector (seesaw mechanism in the hidden sector)

DARK MATTER/COSMOLOGY

- freeze-in production of sterile neutrino dark matter
- nonthermal population can have **nontrivial momentum distributions** carrying imprints of heavy states, **contribute to N_{eff}**

DIRECT SEARCHES

- **new decay modes of light sterile neutrinos**, signatures different from expectations from active-sterile mixing
- modifies constraints on light sterile neutrinos from BBN/cosmology

COLLIDER

- **heavier states (Higgs, gauge bosons) can be within reach of higher energy experiments (LHC)**
- colliders can probe sterile neutrino final states for both SM and exotic Higgs decays