Light Dark World 2017

October 19 - 21, 2017

University of Pittsburgh, PA, USA

EXOTIC PHENOMENOLOGY FROM THE STERILE NEUTRINO SECTOR

BIBHUSHAN SHAKYA

University of Cincinnati

Leinweber Center for Theoretical Physics, University of Michigan

Based on arXiv:171x.xxxxx [hep-ph], 1611.01517 [hep-ph] with James D. Wells

NEUTRINOS — BSM PHYSICS!

NEUTRINOS — BSM PHYSICS!

SEESAW MECHANISM

- Add right-handed (sterile) neutrinos N_i

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

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

- **What is the mass scale M?**

NEUTRINOS — BSM PHYSICS!

SEESAW MECHANISM

- Add right-handed (sterile) neutrinos N_i

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

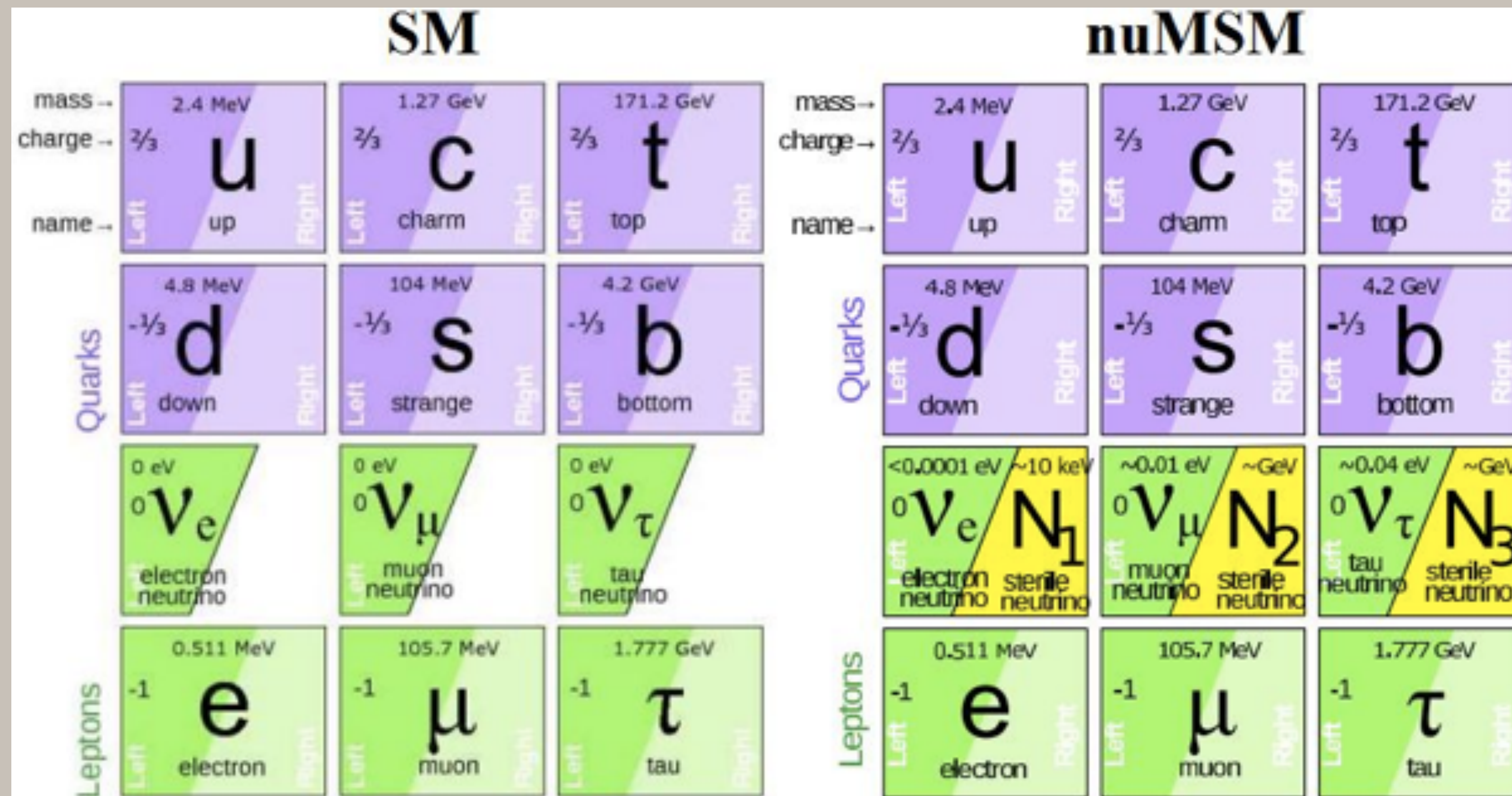
$$M \gg y\langle h \rangle \rightarrow m_a \sim \frac{(y\langle h \rangle)^2}{M}$$

- **What is the mass scale M?**

M ~ 10^{14} GeV, y~O(1)
GUT scale seesaw
natural numbers
hopeless phenomenology

M ~ GeV, y~O(10^{-7})
low scale seesaw
unnatural numbers
rich phenomenology

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.

STERILE NEUTRINO AS DARK MATTER

- traditional approach: Dodelson-Widrow mechanism: produced via active-sterile oscillation due to mixing with active neutrinos
- if at keV scale, can be (warm) dark matter

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

- **recent observational motivation: 3.5 keV X-ray signal!**
- constrained by X-ray line searches (gives upper bound) and Lyman-alpha measurements (gives lower bound) [together, these now rule out the DW mechanism]

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

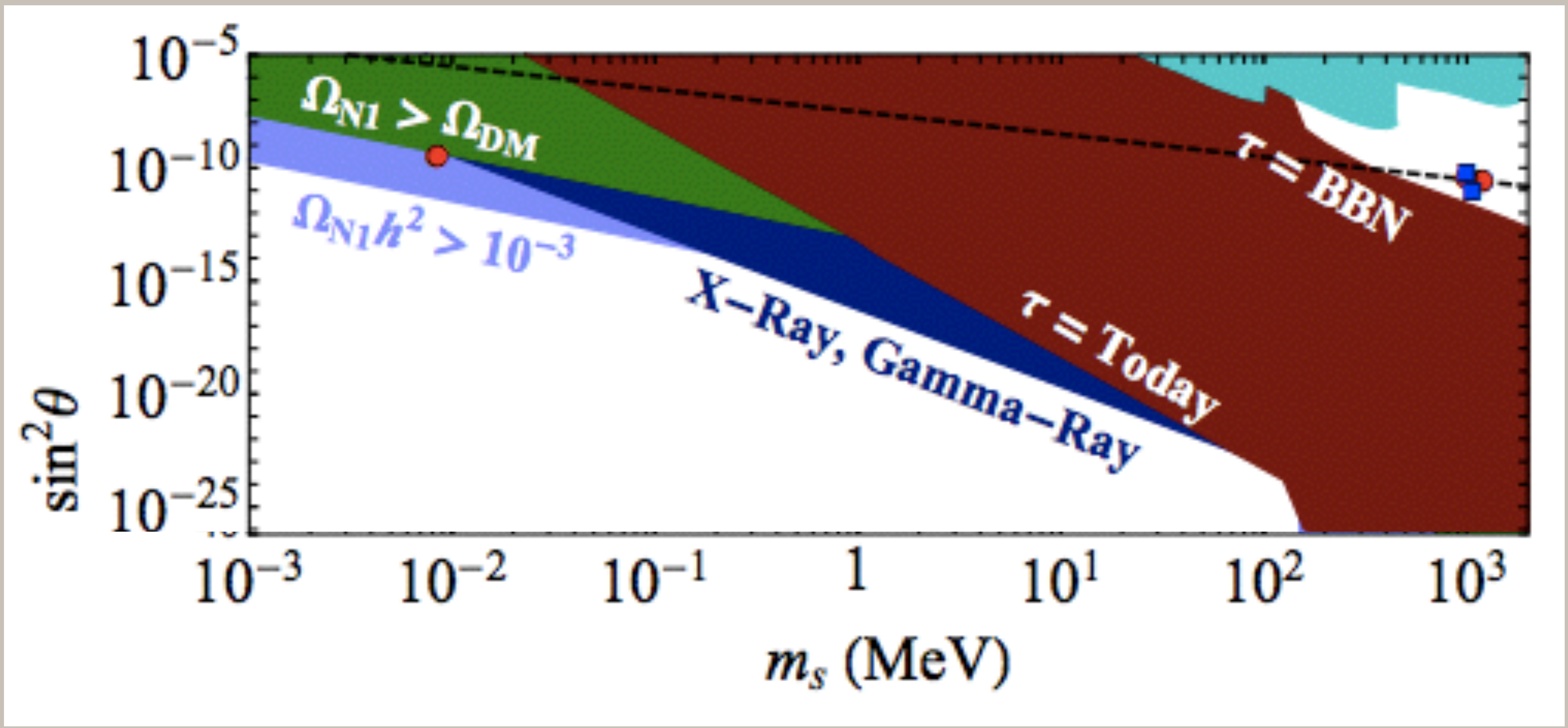
- additional gauge interactions lead to equilibrium and freeze-out, overproduced abundance fixed by entropy dilution
- potential tension from BBN constraints

Freeze-in*

*unrelated to active-sterile mixing

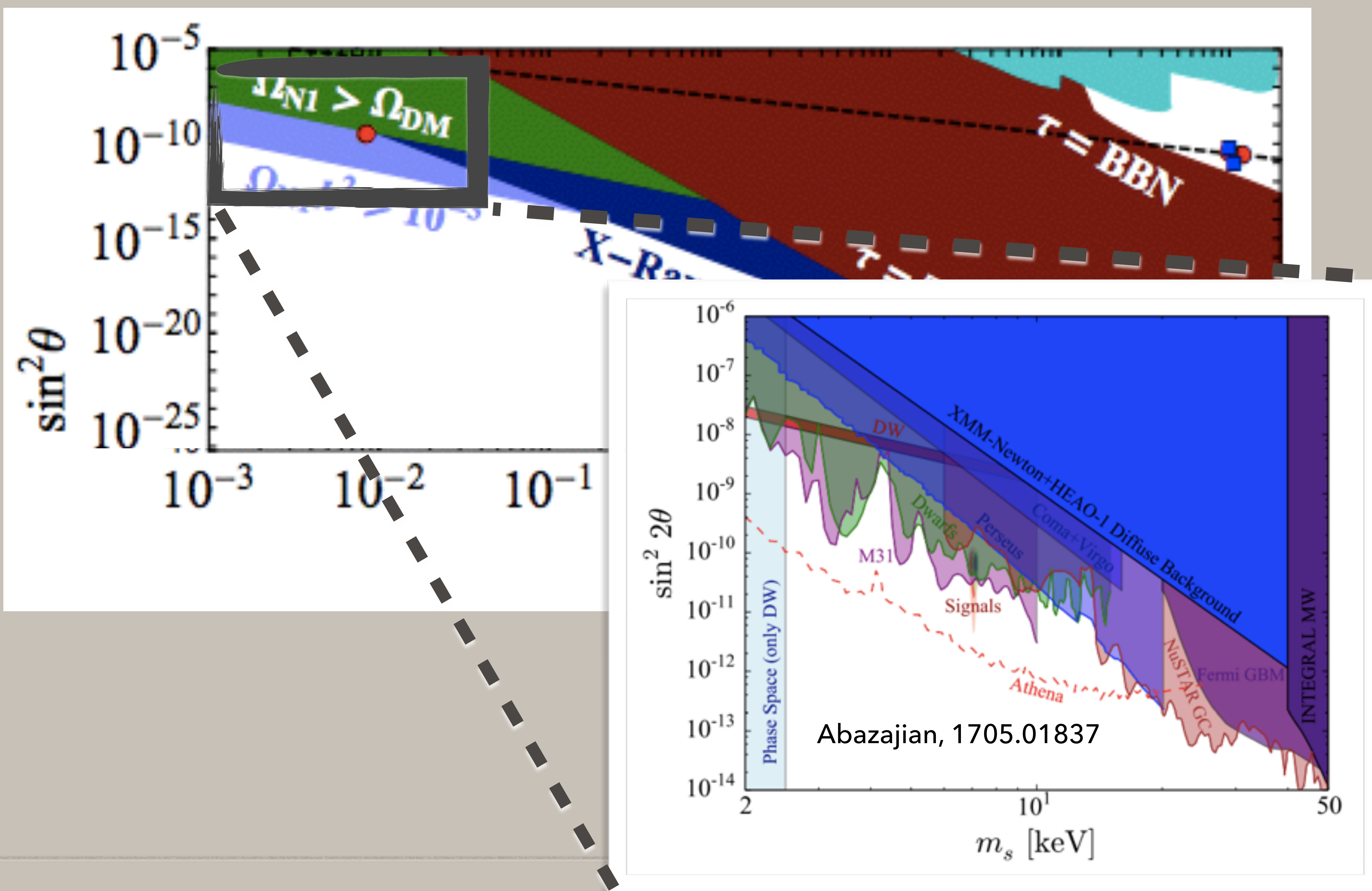
- feeble coupling to some (BSM) particle in the thermal bath leads to gradual production over the history of the Universe. even colder!

PARAMETER SPACE FOR STERILE NEUTRINOS

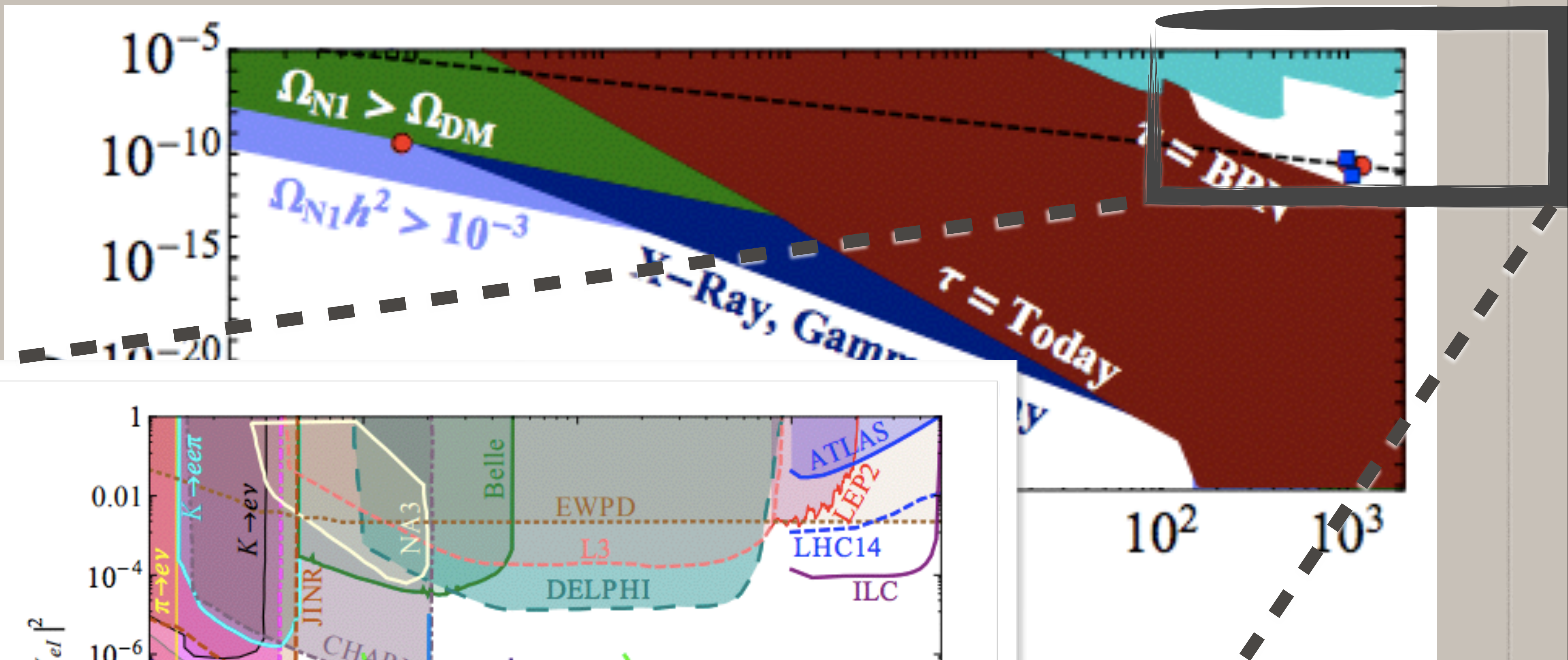


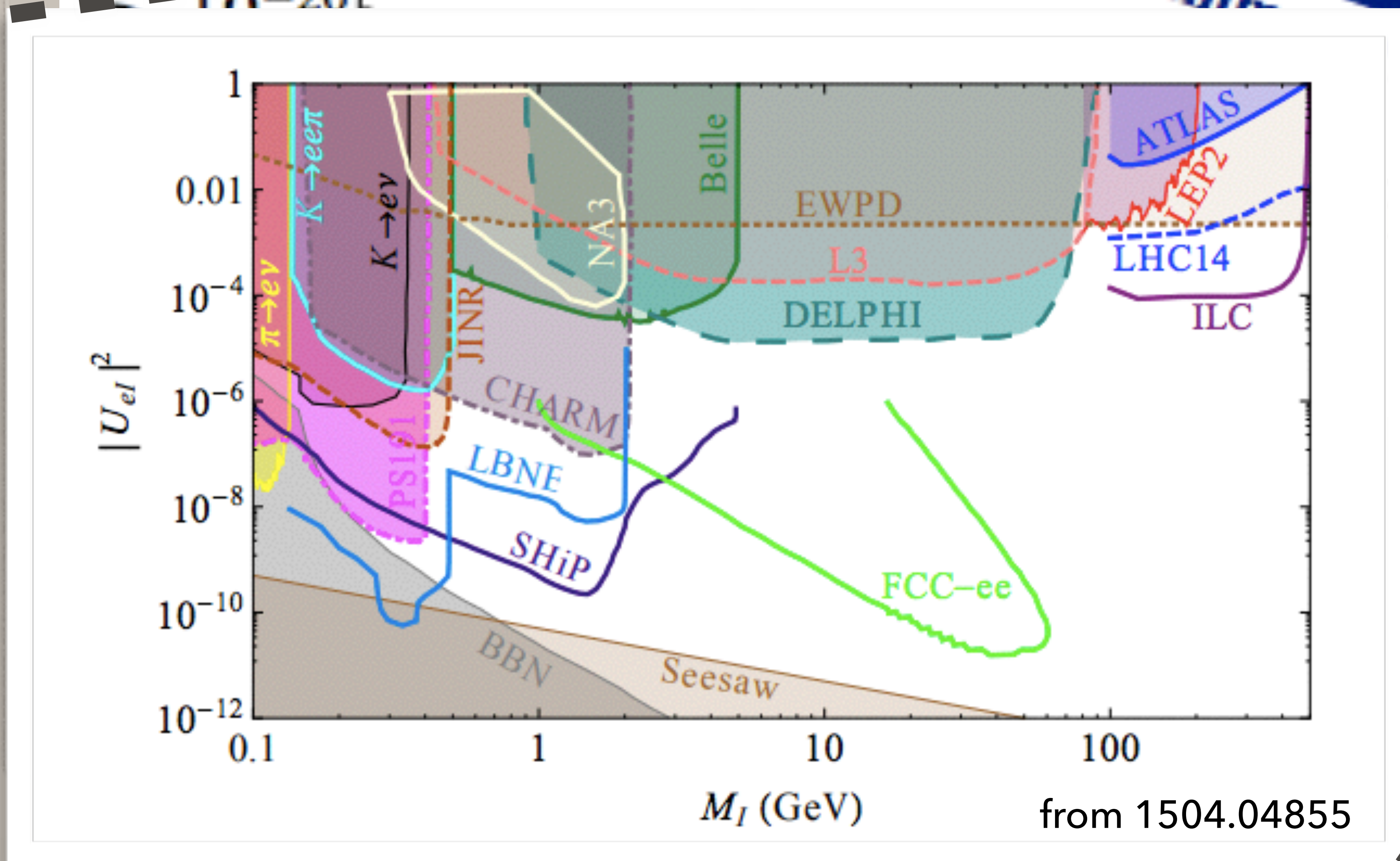
from Roland, Shakya, Wells, 1412.4791 [hep-ph]

PARAMETER SPACE FOR STERILE NEUTRINOS



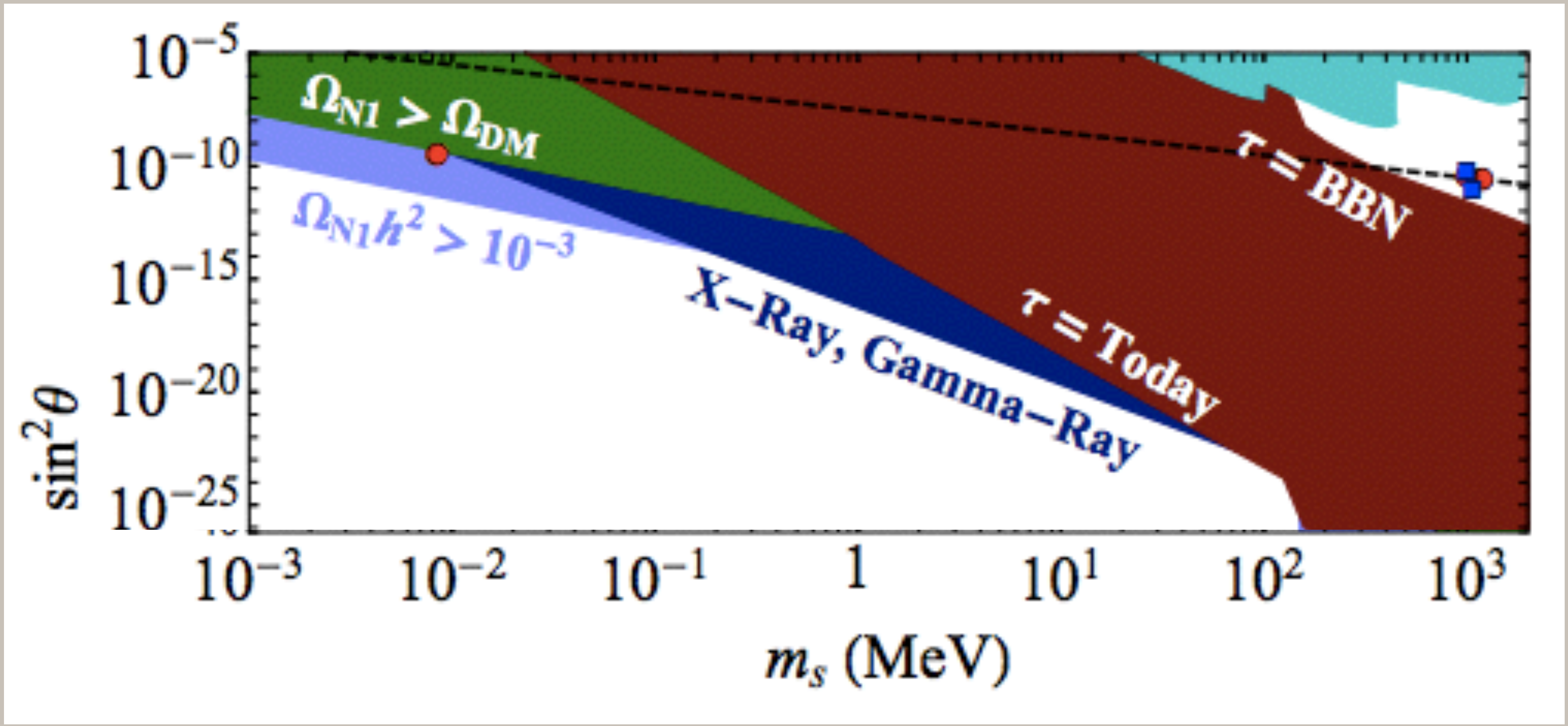
PARAMETER SPACE FOR STERILE NEUTRINOS





from 1504.04855

PARAMETER SPACE FOR STERILE NEUTRINOS



NOTE: All of these properties/constraints/projections assume "traditional" sterile neutrino interactions, ie mixing with active neutrino and subsequent electroweak interactions…

NEED FOR "NEW" PHYSICS IN THE NEUTRINO SECTOR

(WITH LIGHT STERILE NEUTRINOS)

"unnatural" parameters in the (sterile) neutrino sector:

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

Hints of an underlying structure?

additional structure? new particles? new symmetries?

"STRUCTURE" IN THE NEUTRINO SECTOR

- Recall: traditional seesaw requires

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

Naively: GUT/Planck scale

“STRUCTURE” IN THE NEUTRINO SECTOR

- Recall: traditional seesaw requires

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

Naively: GUT/Planck scale

- Assume RH neutrinos **charged under some new symmetry: U(1)′: forbids Majorana mass term.**

  - If other SM fields also charged under this (e.g. some variant of lepton number), Dirac mass term still allowed; otherwise, the Dirac mass term is also forbidden.

  - Assume U(1)′ spontaneously broken by the vev of some scalar field.

  - If gauged, gauge boson around the scale of symmetry breaking.
    If global, massless Goldstone boson.

CASE STUDY: MAJORON MODEL

$$\mathcal{L} = -\overline{L} y N_R H - \frac{1}{2}\overline{N}_R^c \lambda N_R \sigma + \text{h.c.},$$

- $U(1)_L$ or $U(1)_{B-L}$, with L(σ)= -2. σ gets a vev f to spontaneously break the symmetry

$$\sigma = (f + \sigma^0 + \mathrm{i}J)/\sqrt{2}$$

Goldstone boson (``Majoron")

- Sterile neutrinos get mass ~λ f
- J can get a small mass from gravitational effects or explicit symmetry breaking terms
- J couples to neutrinos, resulting in "exotic" decays such as N → Jv, J → v v
- J couplings suppressed by m_v/f, can be sufficiently long-lived to be dark matter

A MODIFIED NEUTRINO SECTOR

- Consider the variation where none of the SM fields are charged under the U(1)′. Dirac mass term is also forbidden.
- Introduce an exotic field φ with equal and opposite charge to N. The leading order gauge invariant term is

$$\mathcal{L} \supset \frac{1}{\Lambda} L h N \phi$$

- This generates a Dirac mass once h and φ both get vevs

A MODIFIED NEUTRINO SECTOR

- Consider the variation where none of the SM fields are charged under the U(1)′. Dirac mass term is also forbidden.
- Introduce an exotic field φ with equal and opposite charge to N. The leading order gauge invariant term is

$$\mathcal{L} \supset \frac{1}{\Lambda} L h N \phi$$

- This generates a Dirac mass once h and φ both get vevs
- **Motivation:** Think of (Nφ) as a hidden sector analog of (Lh). ``Real” RHN mass at scale Λ, integrated out. Seesaw is high scale, yet a low energy effective seesaw relation materializes between N and L!
- Lepton number broken at a much higher scale; decouple the scale of lepton number breaking from the scale of Majorana masses for RHNs

A MODIFIED NEUTRINO SECTOR

- Consider the variation where none of the SM fields are charged under the U(1)′. Dirac mass term is also forbidden.
- Introduce an exotic field φ with equal and opposite charge to N. The leading order gauge invariant term is

$$\mathcal{L} \supset \frac{1}{\Lambda} L h N \phi$$

- This generates a Dirac mass once h and φ both get vevs
- **Motivation:** Think of (Nφ) as a hidden sector analog of (Lh). ``Real” RHN mass at scale Λ, integrated out. Seesaw is high scale, yet a low energy effective seesaw relation materializes between N and L!
- Lepton number broken at a much higher scale; decouple the scale of lepton number breaking from the scale of Majorana masses for RHNs
    - **ASIDE/BONUS:** With the right choice of parameters, φ decays can lead to freeze-in production of sterile neutrino dark matter with the correct relic density! (Roland, Shakya, Wells, 1412.4791 [hep-ph])

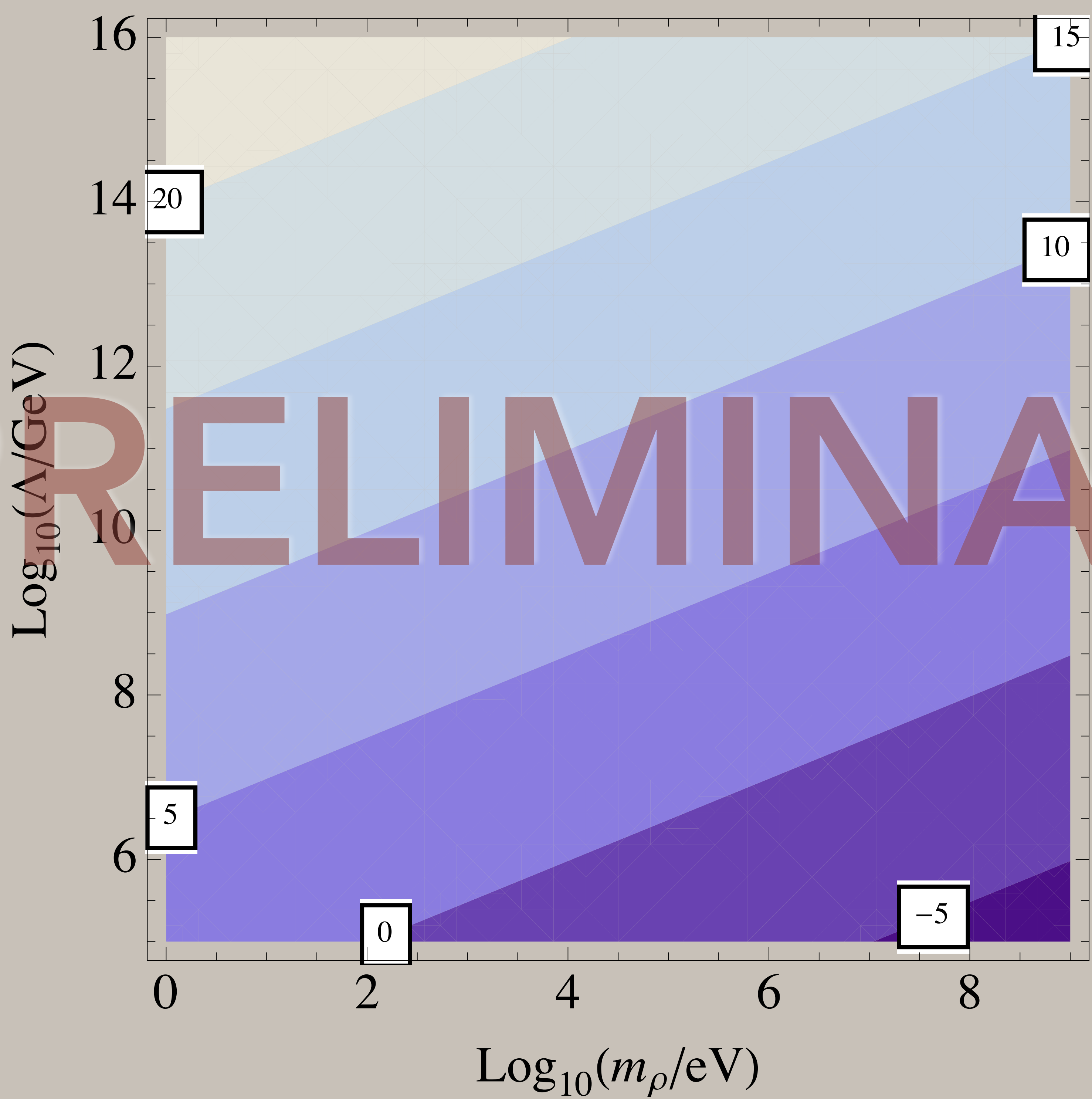
A MODIFIED NEUTRINO SECTOR

- Consider the variation where none of the SM fields are charged under the U(1)′. Dirac mass term is also forbidden.
- Introduce an exotic field φ with equal and opposite charge to N. The leading order gauge invariant term is

$$\mathcal{L} \supset \frac{1}{\Lambda} L h N \phi$$

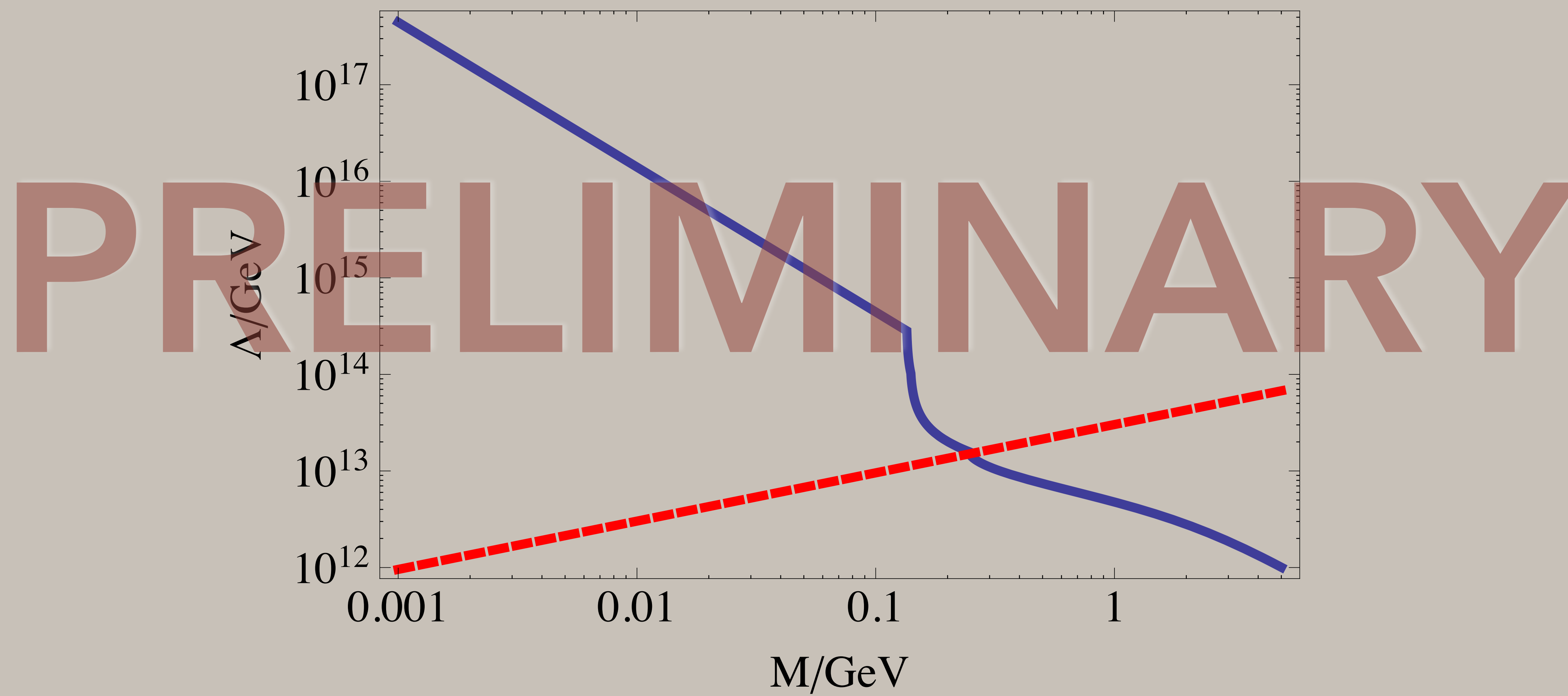
- This generates a Dirac mass once h and φ both get vevs
- Write φ=(<φ>+φ+iρ)/ sqrt(2).
- ρ is the Goldstone. Note: NOT a Majoron (has nothing to do with breaking of lepton number!)
- Different operator/scales from the Marojon setup; can have different decay widths/lifetimes.
- Free parameters: Λ, <φ>, M, m_ρ

GOLDSTONE LIFETIME



Contours in Log10(τ/s)

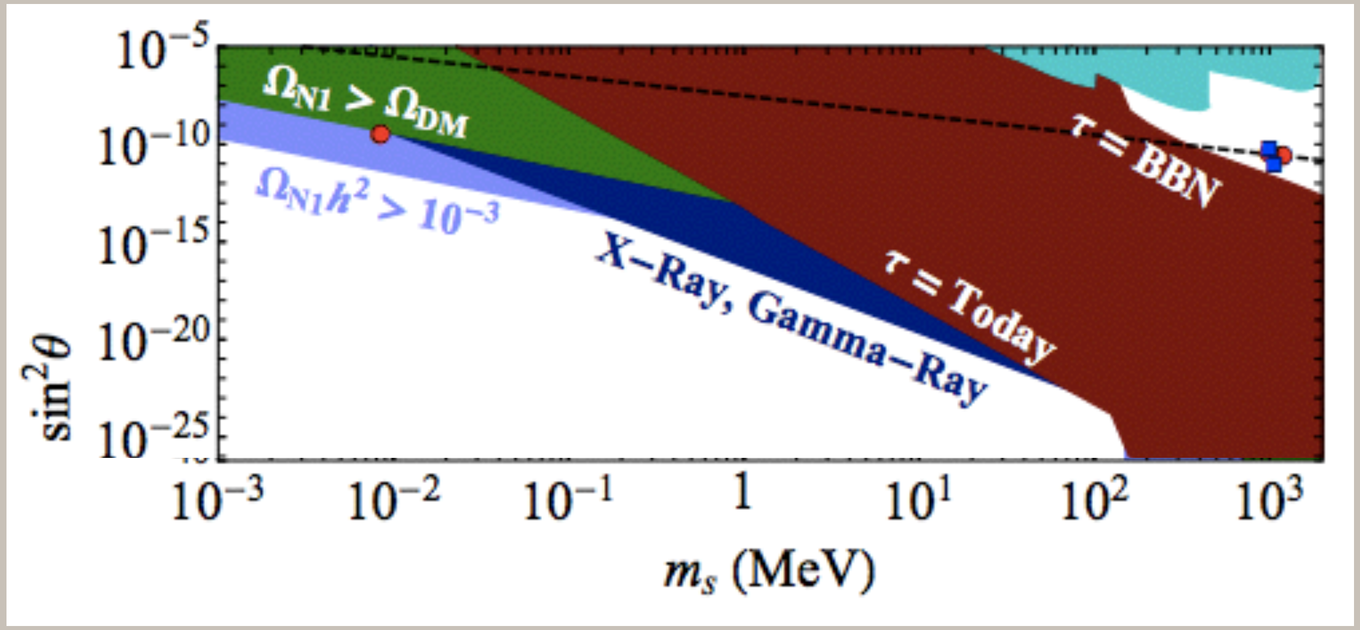
MODIFYING BOUNDS FROM BBN



- Blue: Cutoff scale below which exotic decay channel of sterile neutrino dominates over traditional channels
- Red: Cutoff below which BBN bounds can be evaded

EXOTIC STERILE NEUTRINO PHENOMENOLOGY

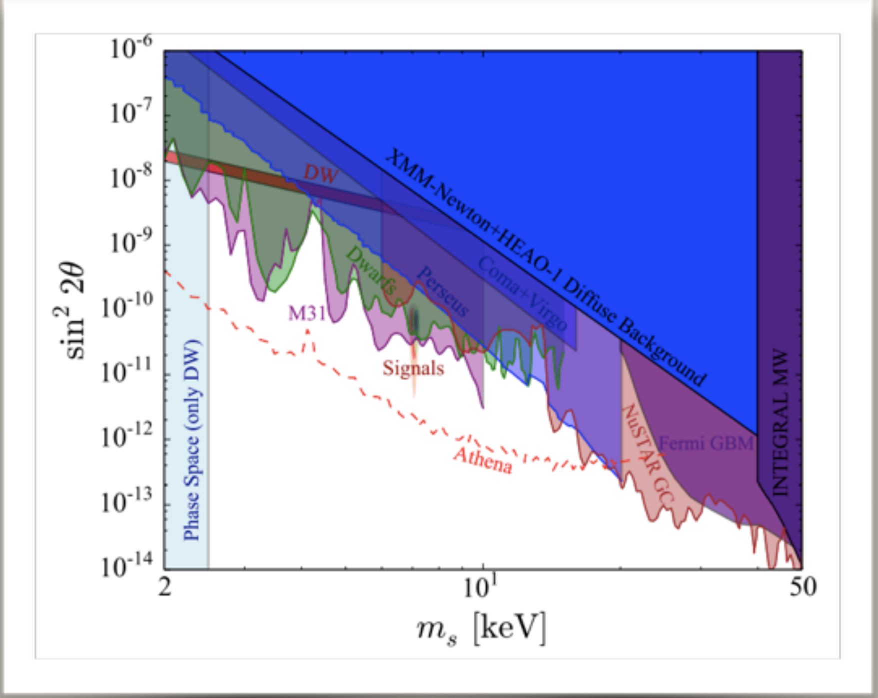
COSMOLOGY



- Modify BBN bounds on sterile neutrinos: seesaw neutrinos can be lighter!
- Late injection of active neutrinos into the Universe from Goldstone decays
- Contributions to N_{eff}, at both BBN and CMB
- CMB imprints: Goldstone bosons recouple to cosmic neutrinos after nucleosynthesis, affect the acoustic oscillations of the electron-photon fluid during the eV era. Deviations in N_{eff} and for the multipole of the n'th CMB peak at large n.

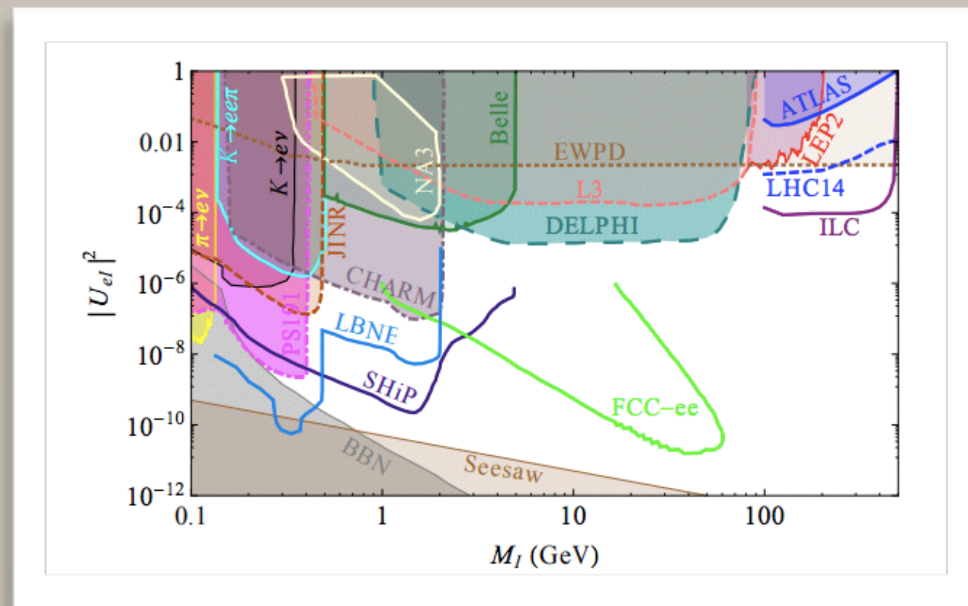
Chacko, Hall, Okui, Oliver PRD 70 (2004) 085008

EXOTIC STERILE NEUTRINO PHENOMENOLOGY
DARK MATTER

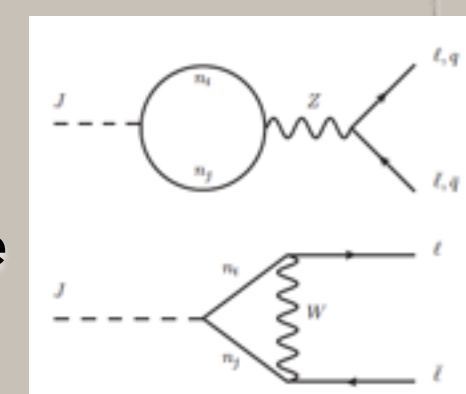


- Traditional decay rates not affected (above X-ray bounds do not change).
- New production mechanism for sterile neutrino dark matter production: Goldstone decay!
- If dark matter is some other species that couples only to sterile neutrinos: possibly dominant neutrino-rich final state signals (e.g. at IceCube)

EXOTIC STERILE NEUTRINO PHENOMENOLOGY
DIRECT SEARCHES



- Traditional decay modes suppressed if decay mode into Goldstone dominant: above ``reaches" disappear!



- Tree level decays into neutrinos invisible, but loop level decays might give signals (e.g. into e+e-) that can be searched for.

- If Goldstone lighter than the heaviest active neutrino, exotic decay modes for known neutrinos!

STERILE NEUTRINO

DARK MATTER
+
(HIGH SCALE)
SUPERSYMMETRY

B. Shakya, J. D. Wells
Phys.Rev. D96 (2017) no.3, 031702

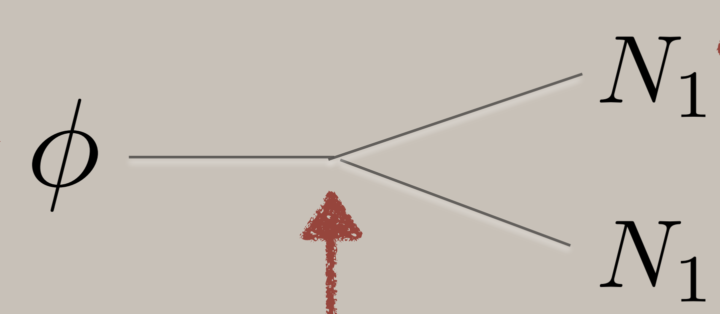
STERILE NEUTRINO DARK MATTER FROM FREEZE-IN

Recall that DW production of sterile neutrino dark matter is now ruled out; need to suppress sterile-active mixing below DW + new production mechanism

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 → Superpotential

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

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

additional terms:

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

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

many new particles/ interactions/ decay modes !

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

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)

DECAY

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

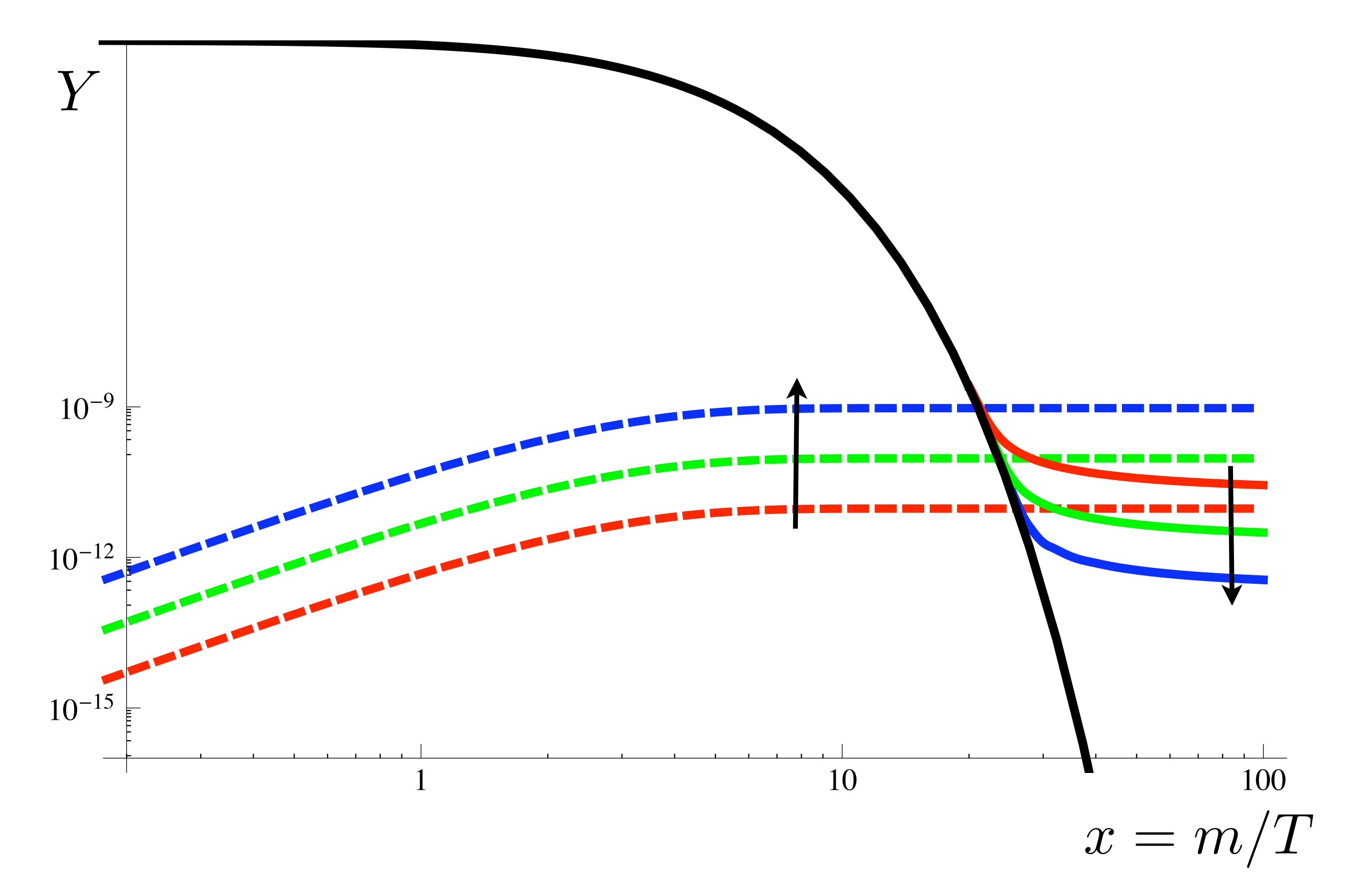
must decay into N_1 ; must go through $x_i \psi N_i \tilde{N}_i$ with the feeble coupling x_1

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

- **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***

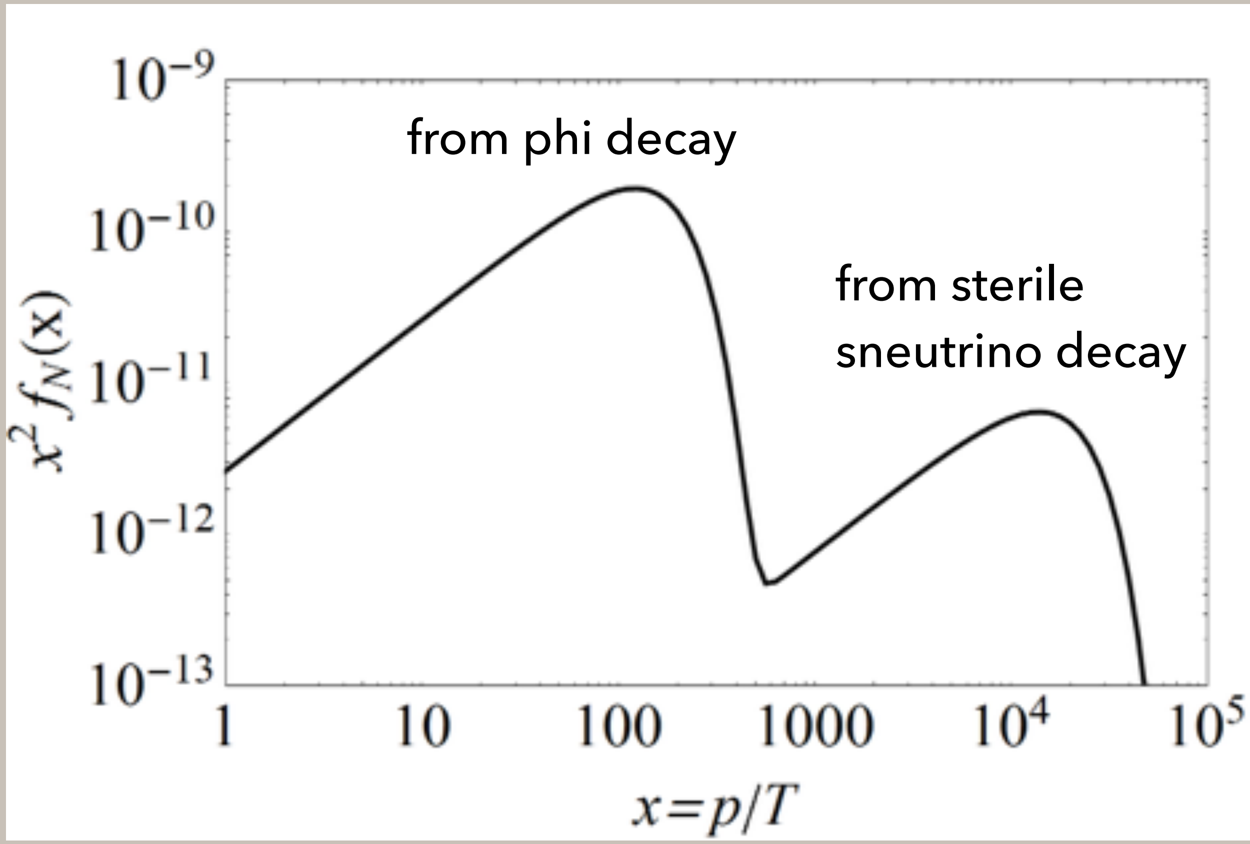
RELIC DENSITY AND COMPOSITION

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

the two populations don't talk to each other!

second population is hotter

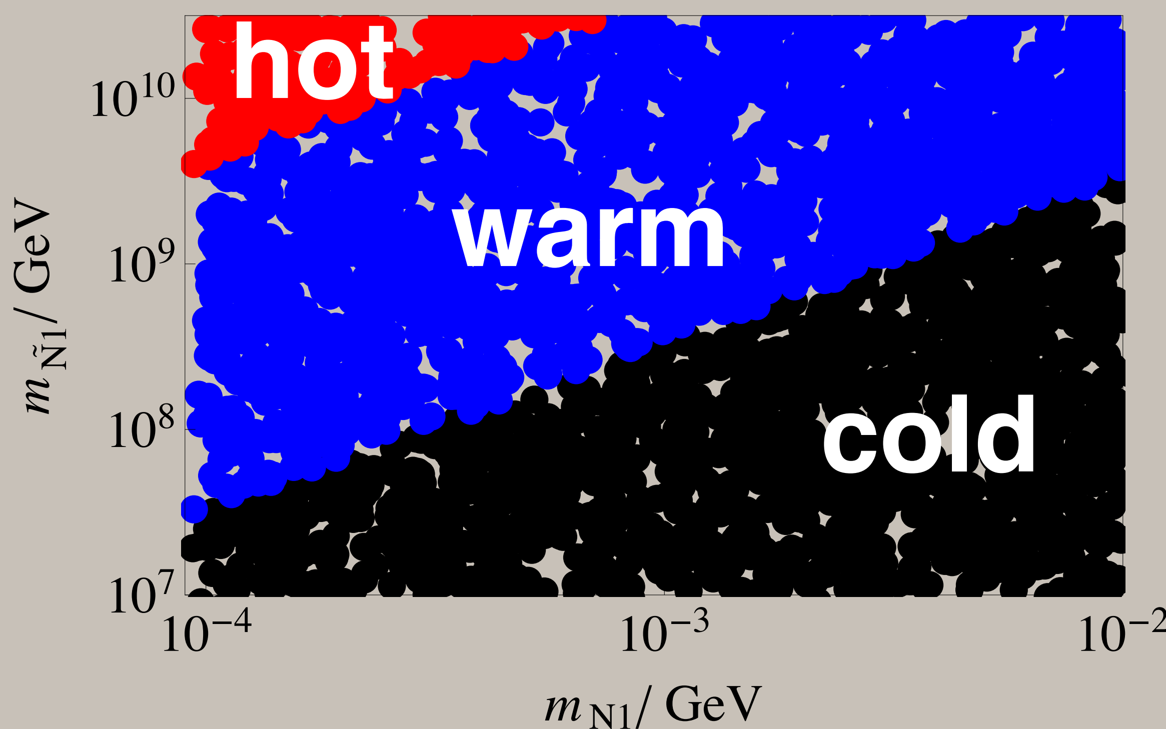
(sterile sneutrino is long-lived and decays out of equilibrium)

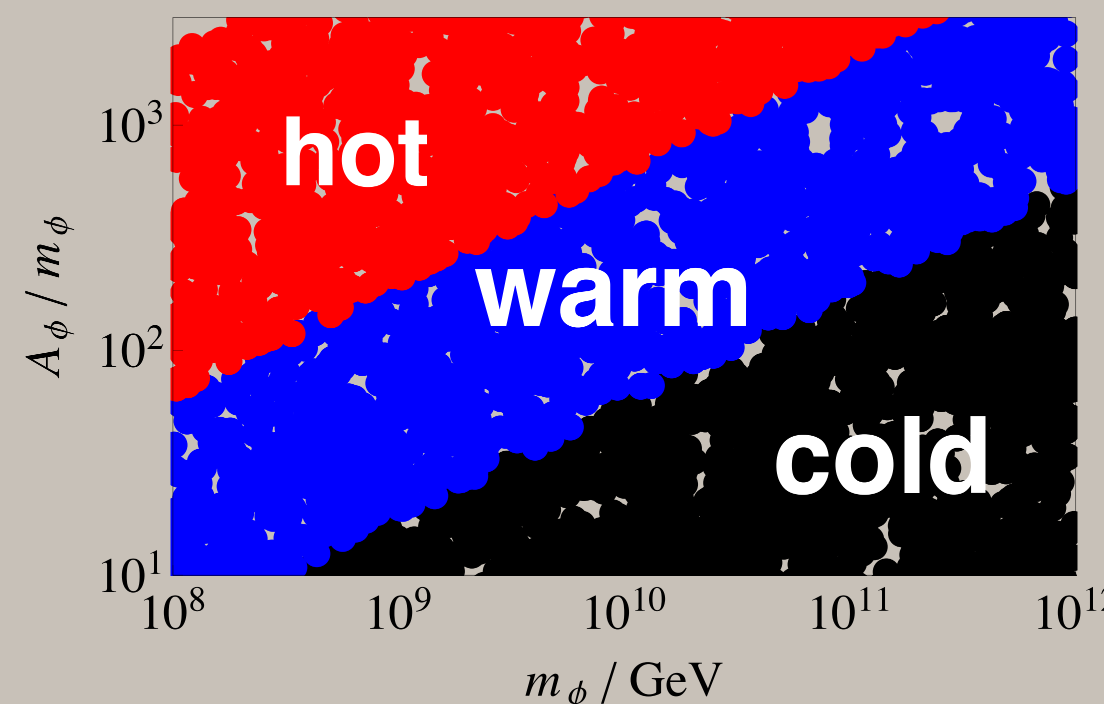


S. Roland, B. Shakya
JCAP 1705 (2017) no.05, 027

extremely nontrivial momentum distribution possible!

FREE STREAMING LENGTH





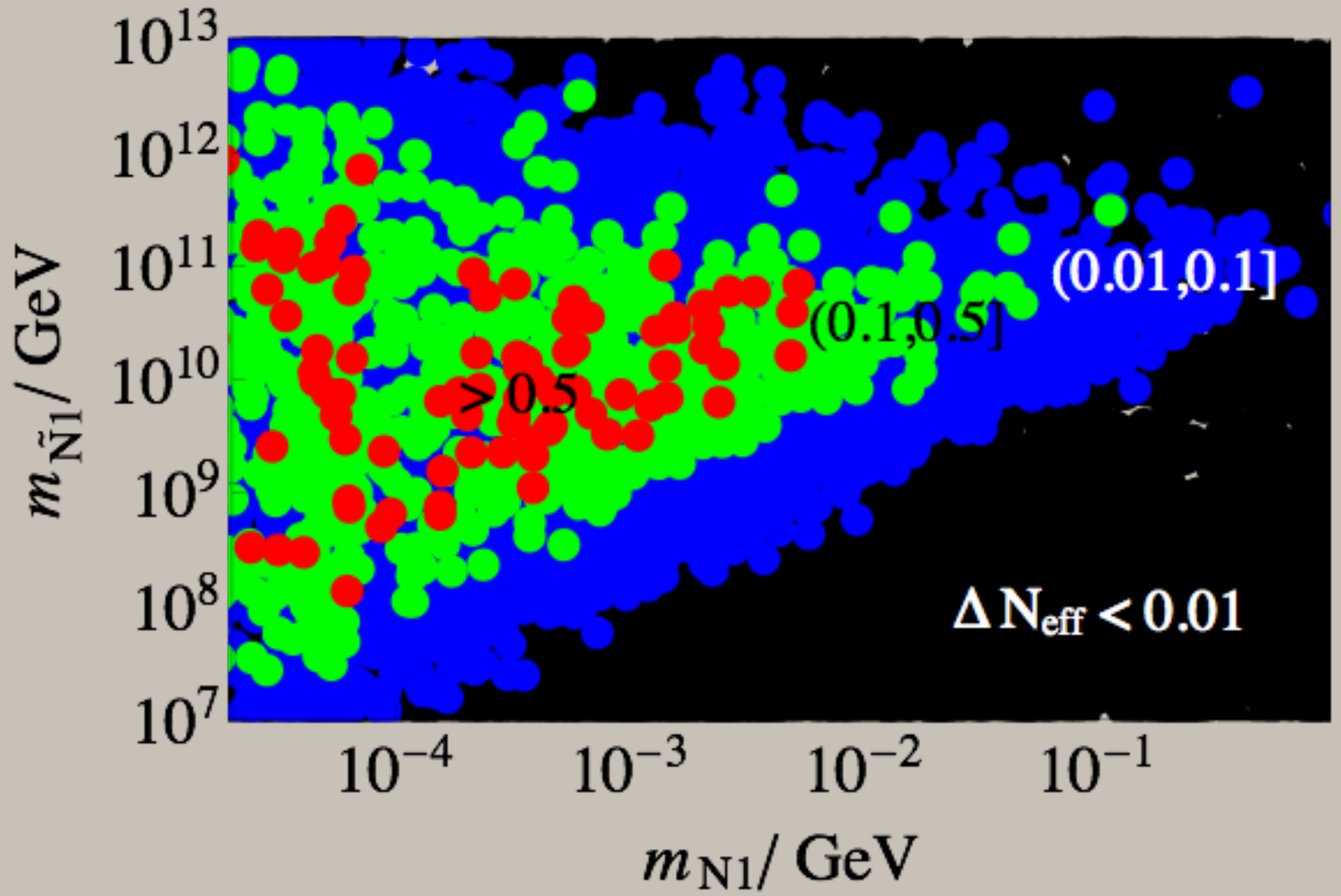
$\tilde{N}_1 \to \psi N_1$ $m_\phi = 10^{11}$ GeV $A_\phi = 10\, m_\phi$ m_{N_1} 1 MeV $m_{\tilde{N}_1}$ 10^6 GeV

coupling x chosen to produce correct relic density

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

ΔN_{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)



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

- 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!

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

SUMMARY

EXOTIC PHENOMENOLOGY IN THE STERILE NEUTRINO SECTOR

COSMOLOGY: *relax BBN bounds, CMB imprints, late injection of neutrinos, contributions to N_{eff}*

GOLDSTONE ⟷ STERILE NEUTRINOS ⟷ SUPERSYMMETRY

DARK MATTER

new production mode from Goldstone decay
neutrino rich final states for DM decay/annihilation

DIRECT SEARCHES

traditional decay modes suppressed;
charged particles from Goldstone decay visible?
new decay modes of active neutrinos

production from sterile sneutrino
multicomponent DM,
warm DM,
contributions to N_{eff}