SHEDDING NEW LIGHT ON STERILE NEUTRINOS

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1401.2549 and 1403.2727

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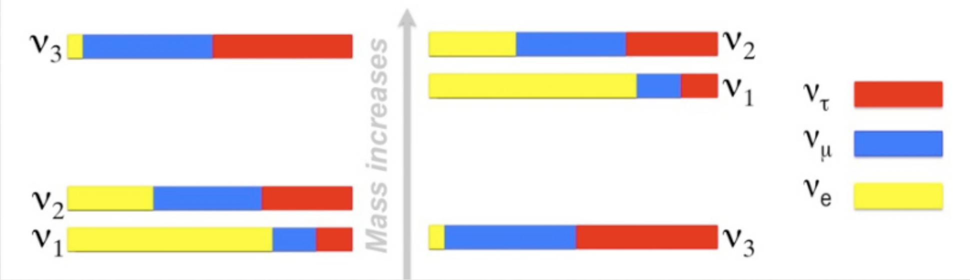
Motivation for sterile neutrinos

- No experimental evidence seen in favour of new physics responsible for:
    - Observed dark matter abundance
    - Origin of the baryon-antibaryon asymmetry
- Would like **well-motivated, testable** models to guide pheno. study
- There is strong evidence for new physics from neutrino oscillations: at least two massive SM neutrinos
    - Simplest explanation: there is a partner gauge-singlet neutrino *N* for each SM neutrino



Taken from **Lujan-Peschard *et al.*, 1301.4577**

$$\mathcal{L}_{\text{see}-\text{saw}} = F\, L\Phi N + \frac{M_N}{2} N^2$$

$$m_{\text{SM}\,\nu} \approx \frac{F^2 \langle\Phi\rangle^2}{M_N}$$

- Standard lore is that $F \sim 1$, $M_N \sim M_{\text{GUT}}$, but the *N* could be much lighter
    - If *N* are at/below weak scale, then they and associated physics are accessible at current experiments

$$F \sim 10^{-7} \left(\frac{m_{\text{SM}\,\nu}}{0.1\ \text{eV}}\right)^{1/2} \left(\frac{M_N}{\text{GeV}}\right)^{1/2} \left(\frac{100\ \text{GeV}}{\langle\Phi\rangle}\right)$$

Motivation for sterile neutrinos

- In the sub-weak-scale mass range, *N* are called sterile neutrinos
- Could these new states resolve the questions of DM & baryogenesis?
  - New singlets: possible dark matter candidate if at least one stable
  - *N* break global *B*-*L* number symmetry -> can lead to baryon-antibaryon asymmetry
  - Unified framework called the neutrino minimal SM (νMSM)

    Asaka, Shaposhnikov hep-ph/0505013; Asaka, Blanchet, Shaposhnikov, hep-ph/0503065
- For *generic* choices of parameters, sterile neutrinos satisfying see-saw and DM stability constraints are actually **too sterile:**
  - Dark matter production is too inefficient to explain observed abundance
  - Yukawa couplings are too feeble to generate observed baryon asymmetry
  - *N* can be hard to produce/observe in experiments

New interactions

- The minimal model is only viable if there is some kind of resonant enhancement of certain rates
  - Typically arise as mass degeneracies and/or relative tuning of the Yukawa matrix entries

- **Our motivation:** Do we need to live in tuned parameter space?
Can moving "beyond minimality" enhance DM/baryon asymmetry prod?
  - We find that each of DM/baryogenesis can be achieved for completely generic parameters with one additional field coupled to the **visible sector**
  - Can look for these new particles/interactions; cosmological implications for particle physics searches

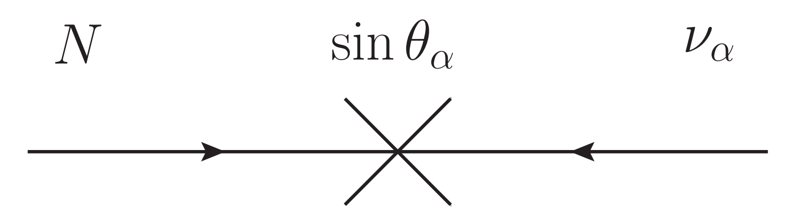
- In the interest of time, I'll focus on the DM question in this talk

Sterile neutrino DM

- Is *N* a viable dark matter candidate?
    - Does it have the correct abundance?
    - Is it sufficiently long-lived?

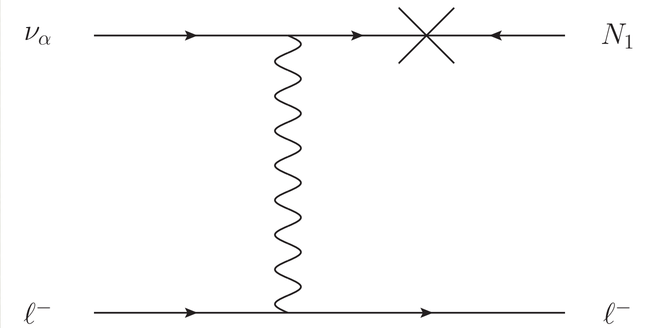
- *N* talk to SM fields through its mixing with the SM neutrino

$$\mathcal{M} = \begin{pmatrix} 0 & F\langle\Phi\rangle \\ F\langle\Phi\rangle & M_N \end{pmatrix}$$



$$\sin\theta_\alpha(T=0) \approx \frac{F_\alpha\langle\Phi\rangle}{m_N}$$

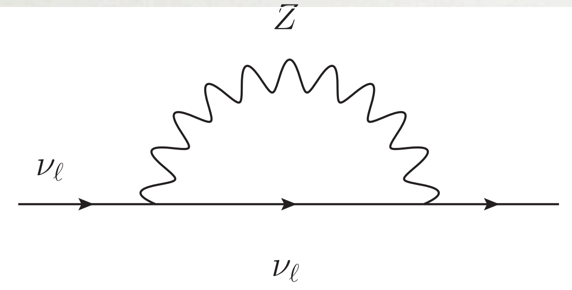
- *N* is slowly created through SM electroweak processes (**Dodelson, Widrow, 1993**)



$$\Gamma_N \sim \sum_\alpha \sin^2 2\theta_\alpha(T)\, G_{\mathrm{F}}^2\, T^5$$

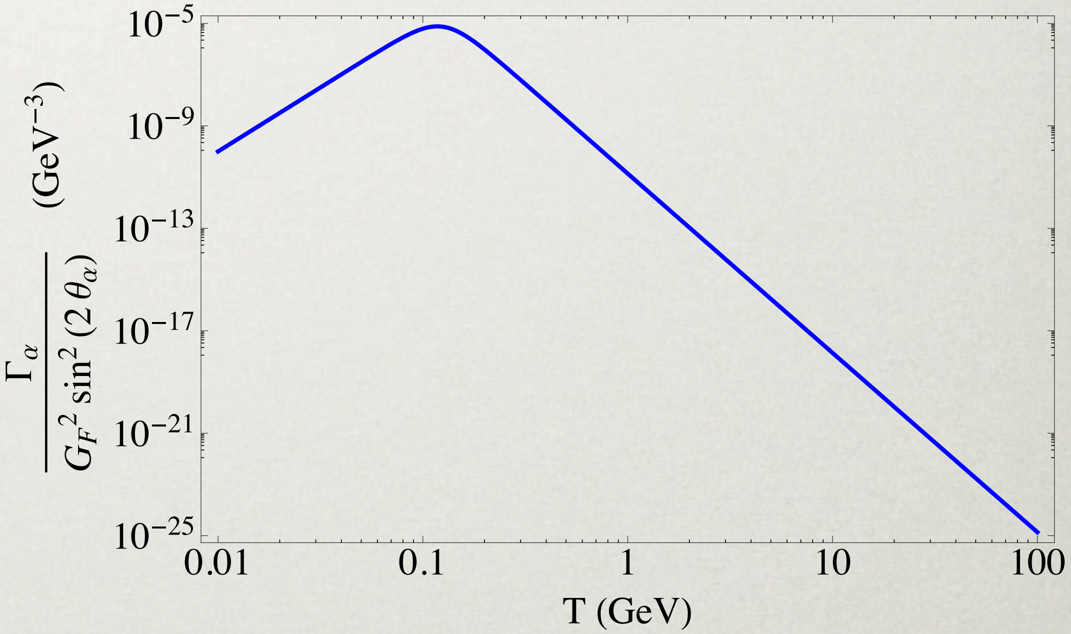
Sterile neutrino DM

- At finite temperature, the thermal mass of the SM neutrinos in the plasma further suppresses the mixing



$$\sin^2 2\theta_\alpha(T) \approx \frac{\sin^2 2\theta_\alpha(T=0)}{\left[1 + 0.27\left(\frac{T}{100\ \mathrm{MeV}}\right)^6\left(\frac{\mathrm{keV}}{M_N}\right)^2\right]^2}$$

$$\Gamma_N \approx \frac{\sin^2 2\theta_\alpha(T=0)\, T^5}{\left[1 + 0.27\left(\frac{T}{100\ \mathrm{MeV}}\right)^6\left(\frac{\mathrm{keV}}{M_N}\right)^2\right]^2}$$



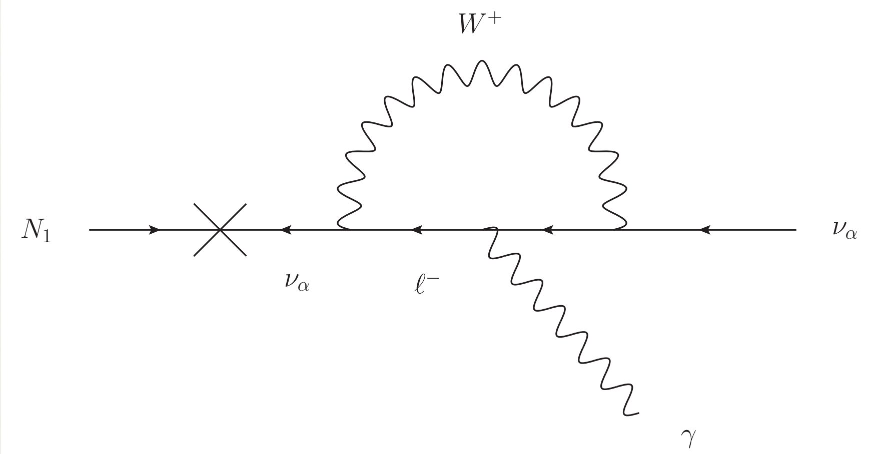
- DM is predominantly created at T ~ few hundred MeV
- Abundance is completely determined by mass and mixing angle

Sterile neutrino DM

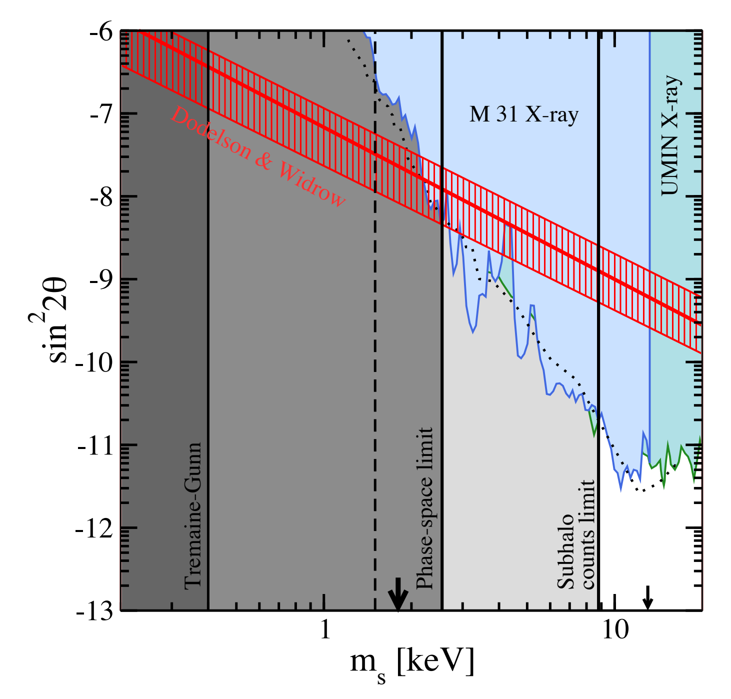
- DM abundance (✓)

$$\Omega_N \approx 0.27 \left(\frac{\sin^2 2\theta}{2 \times 10^{-9}} \right) \left(\frac{M_N}{9 \text{ keV}} \right)^{1.8}$$

- Is it sufficiently long-lived?
  The same mixing for production leads to DM decay:



$$E_\gamma = \frac{M_N}{2}$$

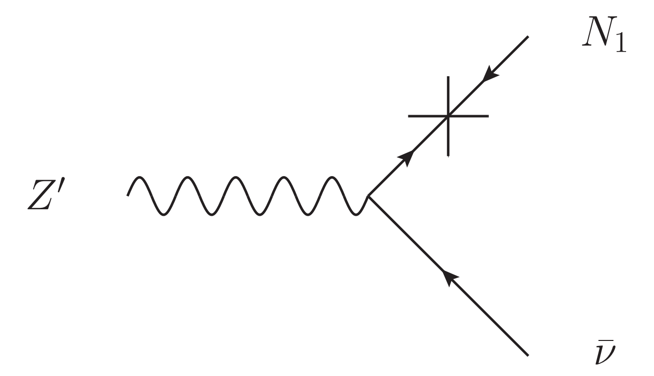


- Together with small-scale structure constraints **completely exclude** the possibility of electroweak *N* production for DM
- Stable DM -> effective *N* interactions **too weak** for Ω_{DM}

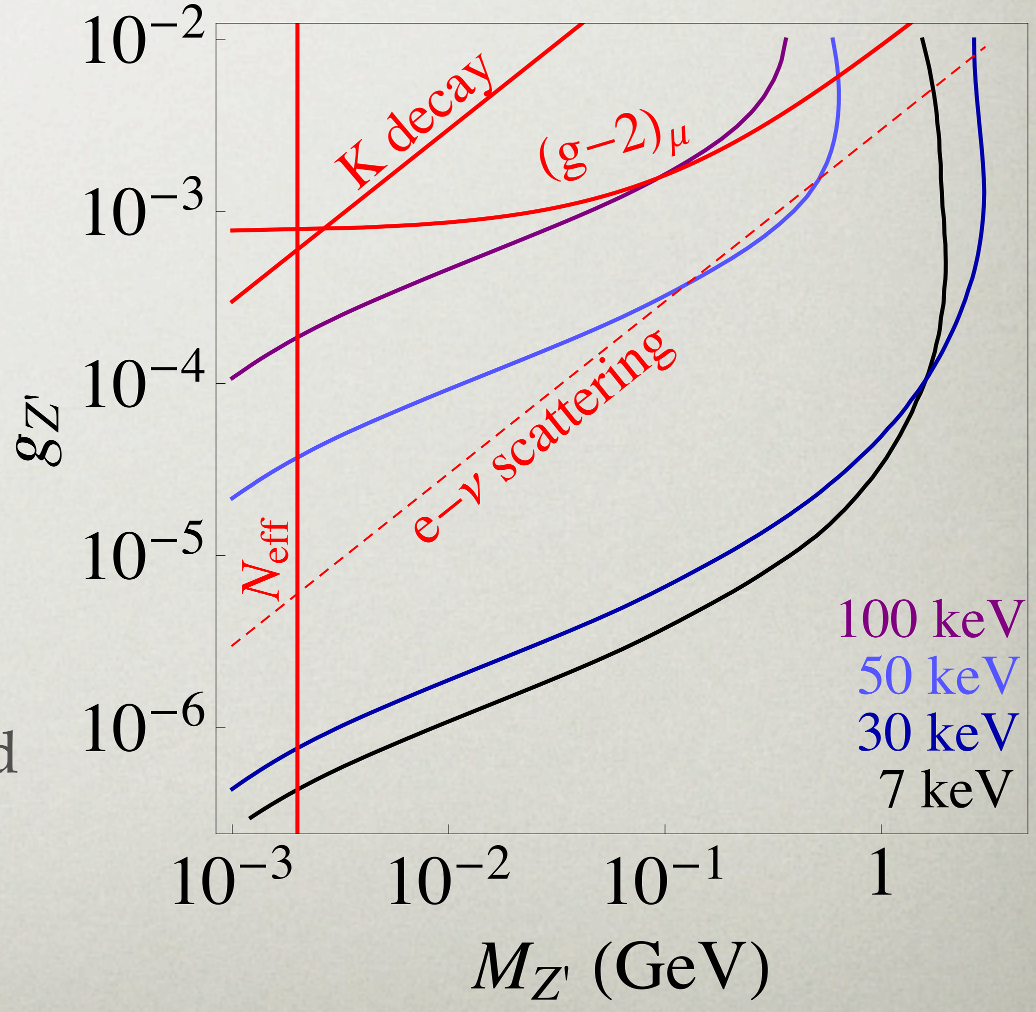
Taken from **Horiuchi *et al.*, 1311.0282**

New lepton forces & *N* DM

- **Our approach:** See that if *any* new interactions couple to SM leptons, they also produce *N* through the same mixing
  - Example: new gauge interaction
  - Anomaly-free choices include: U(1)$_{\mu\text{-}\tau}$, U(1)$_{B\text{-}L}$, …
  - If the new Z′ is in the thermal bath during dominant epoch of *N* prod. (~few hundred MeV), then rapid 1->2 processes give large *N* rate



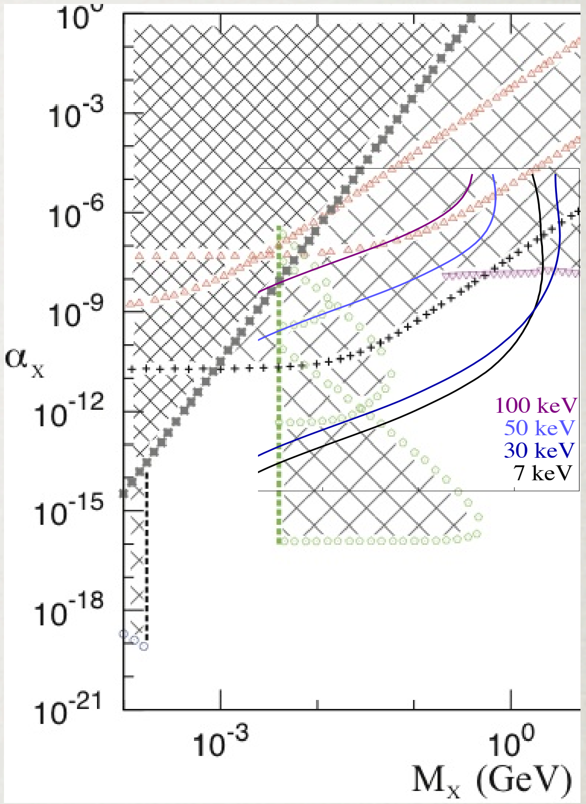
- We focused on currents that only couple to leptons
  - Constraints from muon *g*-2, *N* lifetime, meson/SM gauge boson widths, neutrino-electron scattering constraints (if couples to *e*)
  - Shown: largest mixing angle θ_α allowed by X-ray constraints for given *N* mass



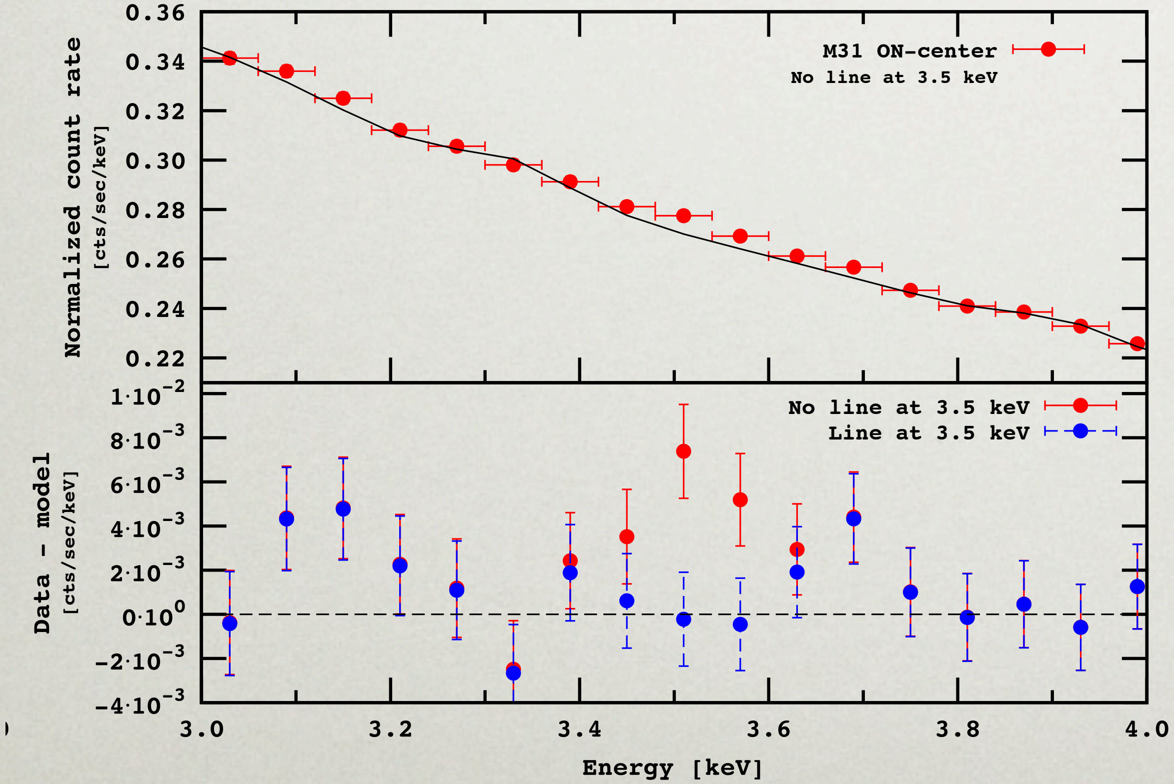
BS, Yavin, 1403.2727
see also Altmannshofer *et al.*, 1406.2332

New lepton forces & *N* DM

- Constraints change depending on U(1) charges
  - Ex: U(1)$_{B\text{-}L}$ (adapted from **Williams et *al.*, 1103.4556)**
  - Much of remaining *B-L* space to be probed by APEX and HPS, improved N_{eff}



- **Possible detection** of 3.57 keV X-ray line in stacked galaxy clusters!



Taken from **Boyarsky *et al.*, 1402.4119**

- 7.15 keV *N* is below small-scale structure bounds for thermal production
- Our mechanism produces somewhat colder *N* than thermal (✓)

Conclusions

- Sterile neutrinos are well-motivated extensions of the SM
    - Can account for neutrino oscillations, dark matter, baryogenesis
    - Related physics kinematically accessible for masses < weak scale

- Minimal models typically produce insufficient DM and baryon asymmetry unless there are severe mass degeneracies, tunings in the Yukawa couplings

- We have shown that models with one new degree of freedom can:
    - Obviate the need for any tuning
    - Give phenomenological probes of physics connected to sterile neutrino cosmology (often complementary to existing strategies)

- Similar story for enhancing baryogenesis through modifications of Yukawa couplings in a 2-Higgs-doublet model (see BS, Yavin, 1401.2459)

- Further development of these ideas, unifying the DM and baryogenesis pictures, are work in progress

Back-up slides

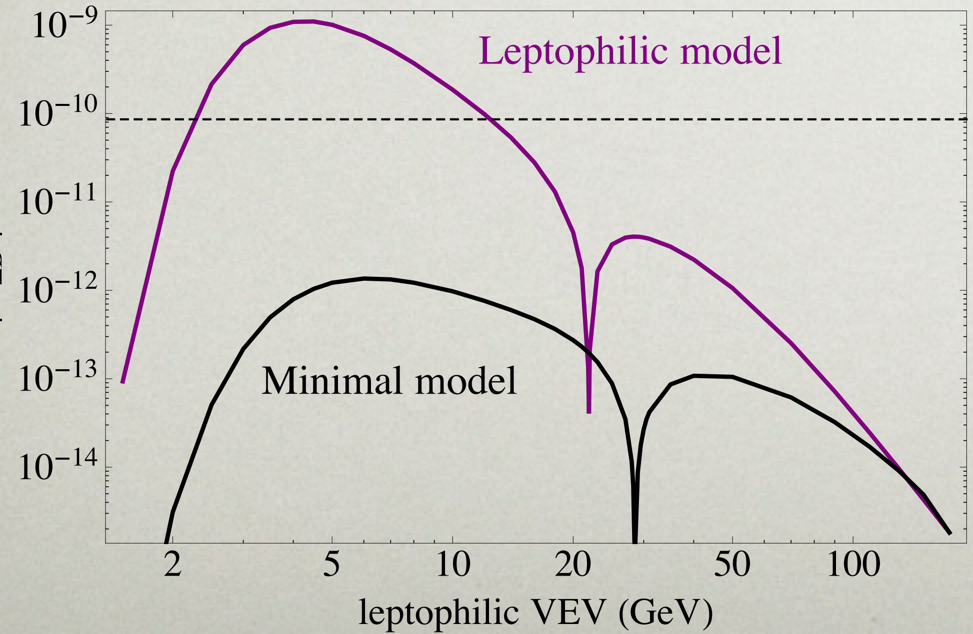
Quick peek: Baryogenesis

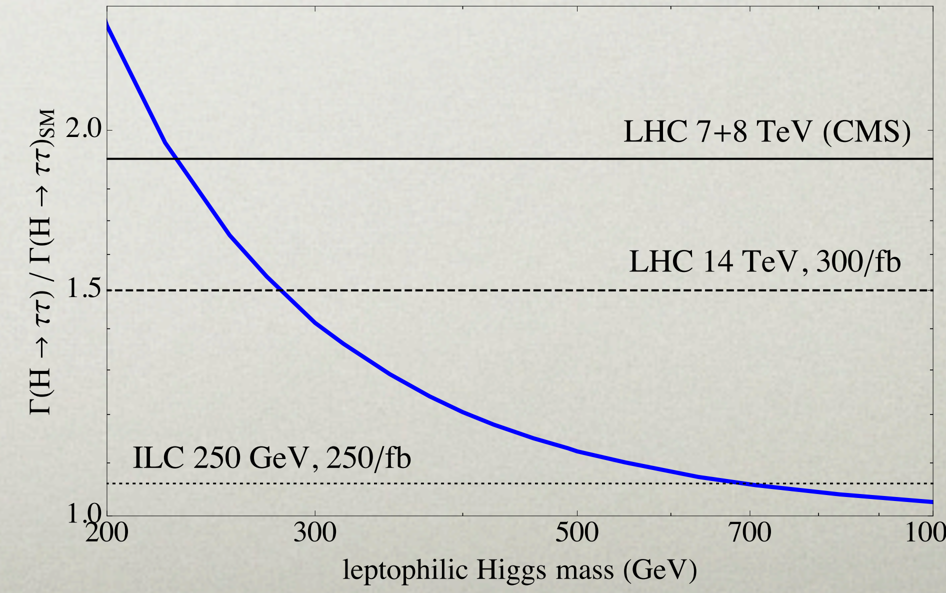
- Baryogenesis proceeds via “leptogenesis through neutrino oscillations”
    - Baryon asymmetry requires small sterile neutrino mass splittings and large scattering rates (Yukawa couplings)
    - Looking at see-saw relation, these conditions are in conflict!

$$M_N \approx \frac{F^2 \langle \Phi \rangle^2}{m_{\mathrm{SM}\,\nu}}$$

- Once again, the Yukawa couplings are **too small** (for fixed *N* mass)
- **Our approach:** With non-standard interactions, the Yukawa couplings can naturally be much larger
    - Example: If Φ is a non-SM Higgs coupling to leptons, its VEV can be *smaller*, giving larger *F*
    - Much larger asymmetries possible than even the tuned minimal model
    - No degeneracy or alignment of parameters needed

BS, Yavin, 1401.2459





Resonant production

- The minimal model can still work with ***non-thermal production***

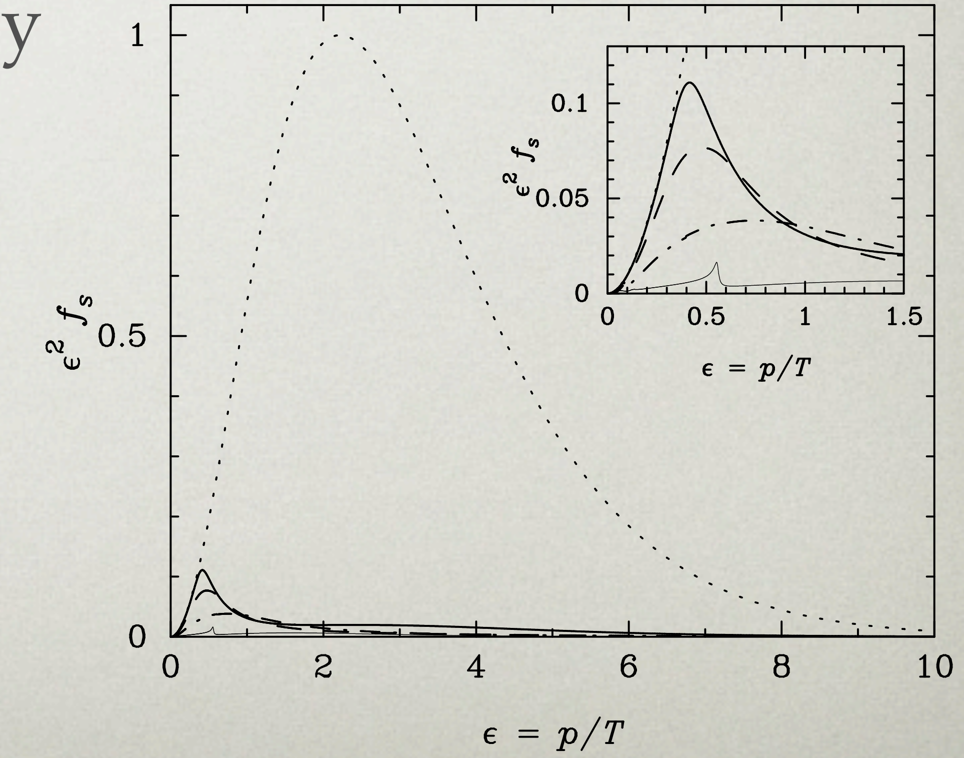
$$V_\nu \approx 2\sqrt{2}G_\mathrm{F}(N_\nu - N_{\bar{\nu}}) - \frac{7\pi}{90\alpha}\sin^2(2\theta_\mathrm{W})G_\mathrm{F}^2 T^4 E_\nu$$

$$\sin^2(2\theta_{\mathrm{m},\alpha 1}) = \frac{\sin^2(2\theta_{\alpha 1})}{\sin^2(2\theta_{\alpha 1}) + \left(\cos 2\theta_{\alpha 1} - \frac{2V_{\nu,\alpha}E}{M_{N_1}^2}\right)^2}$$

  - MSW resonant enhancement of mixing angle when $V_\nu \approx \frac{M_{N_1}^2}{2E}\cos 2\theta$ **(Shi, Fuller 1999)**

- Need a large, late-time lepton asymmetry
- Spectrum is typically colder than thermal

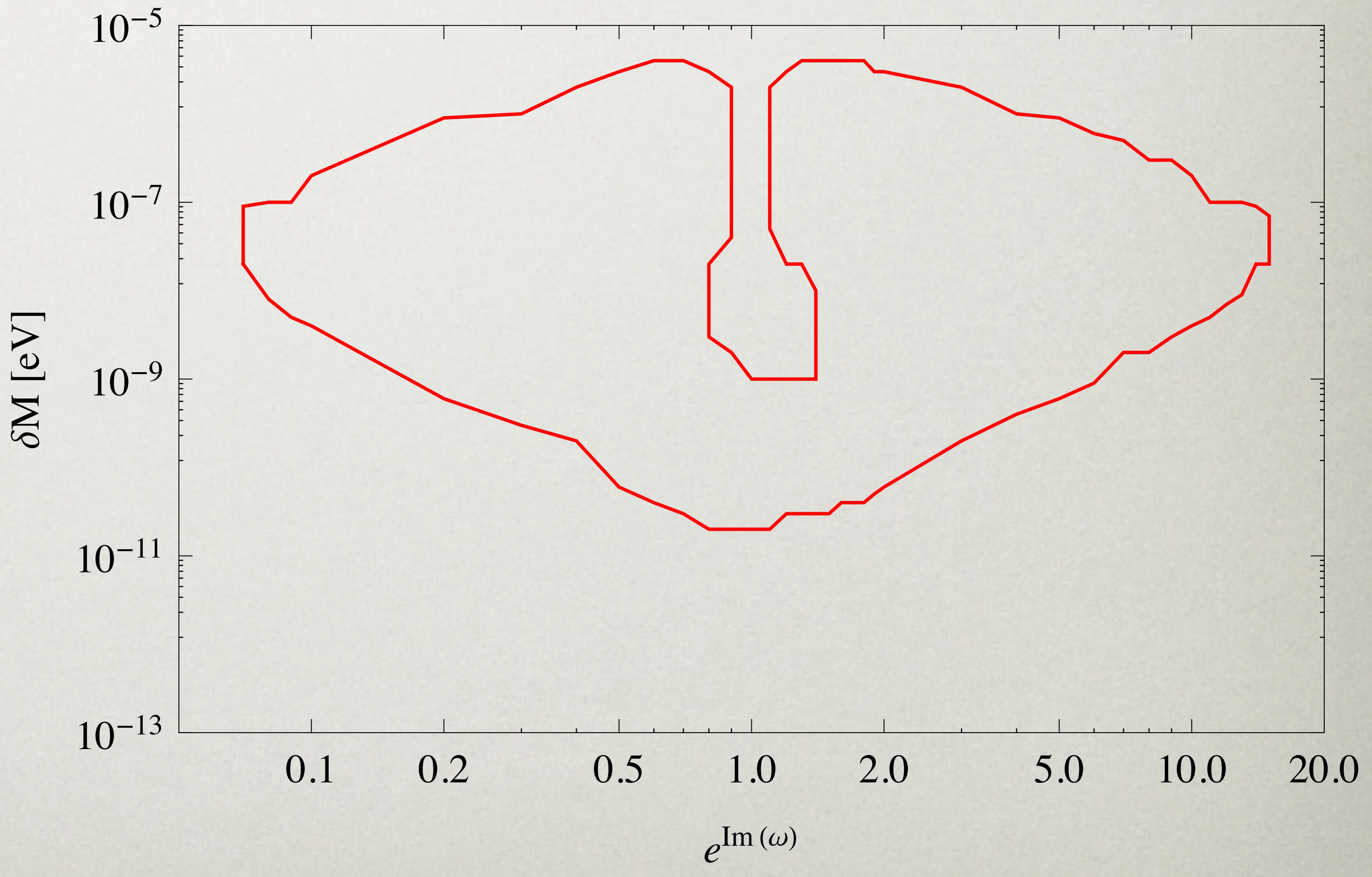
$$\frac{E_{\nu,\mathrm{res}}}{T} \approx 0.1245\left(\frac{M_N^2\cos 2\theta}{\mathrm{keV}^2}\right)\left(\frac{10^{-2}}{\mathcal{L}}\right)\left(\frac{100\ \mathrm{MeV}}{T}\right)^4$$



taken from **Abazajian, Fuller, Patel 2001**

Resonant production

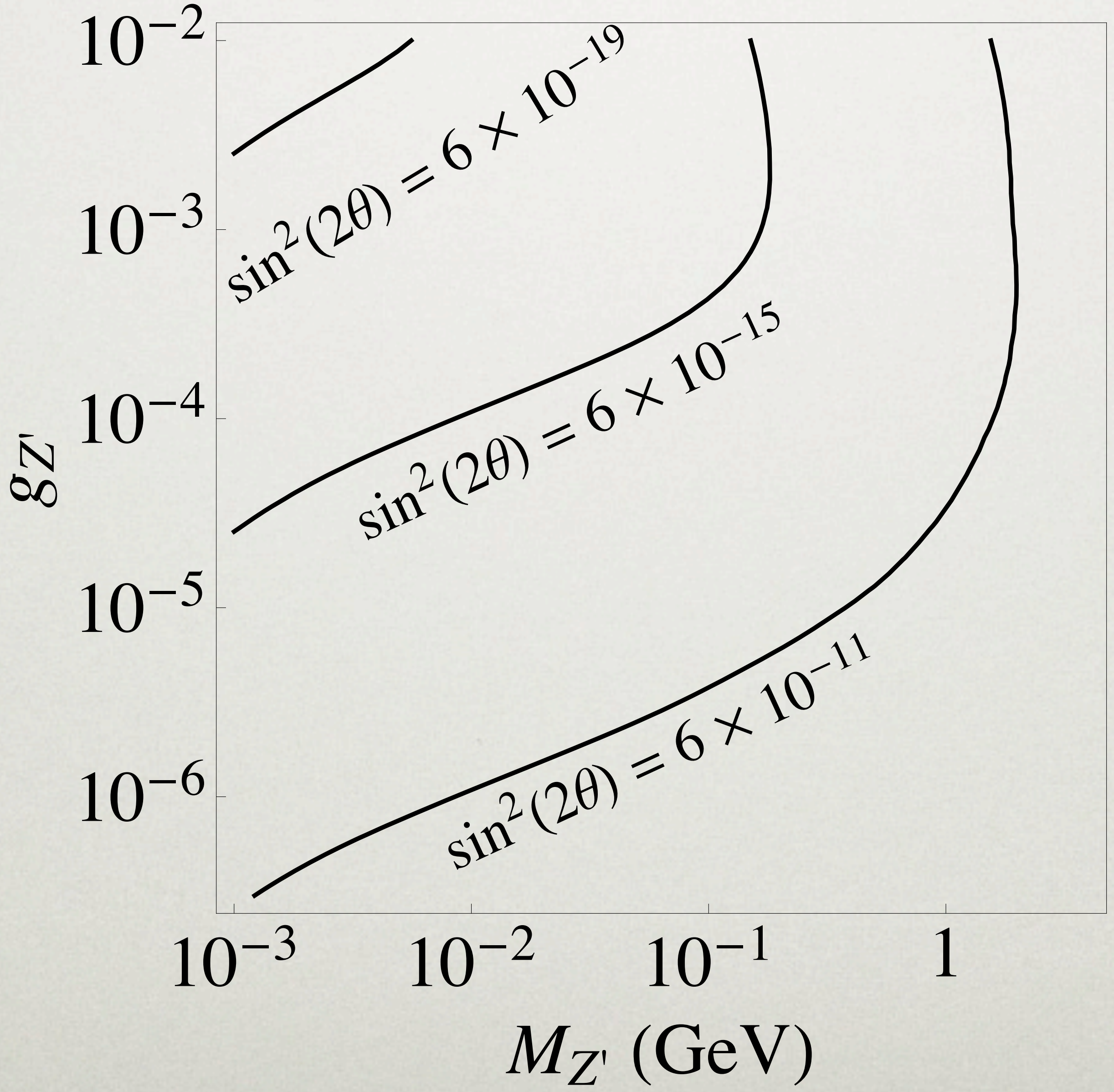
- Can occur for lepton asymmetries ≳ 10^{-5}
  - Need large asymmetry from leptogenesis below weak scale
  - Achieved in the minimal model through resonant leptogenesis from the decay of the heavier sterile neutrinos; highly degenerate spectrum needed
  - Shown at right: N_2 and N_3 are 10 GeV, from **Canetti *et al.* 2012**



- Other sources of asymmetry possible with new beyond-SM physics

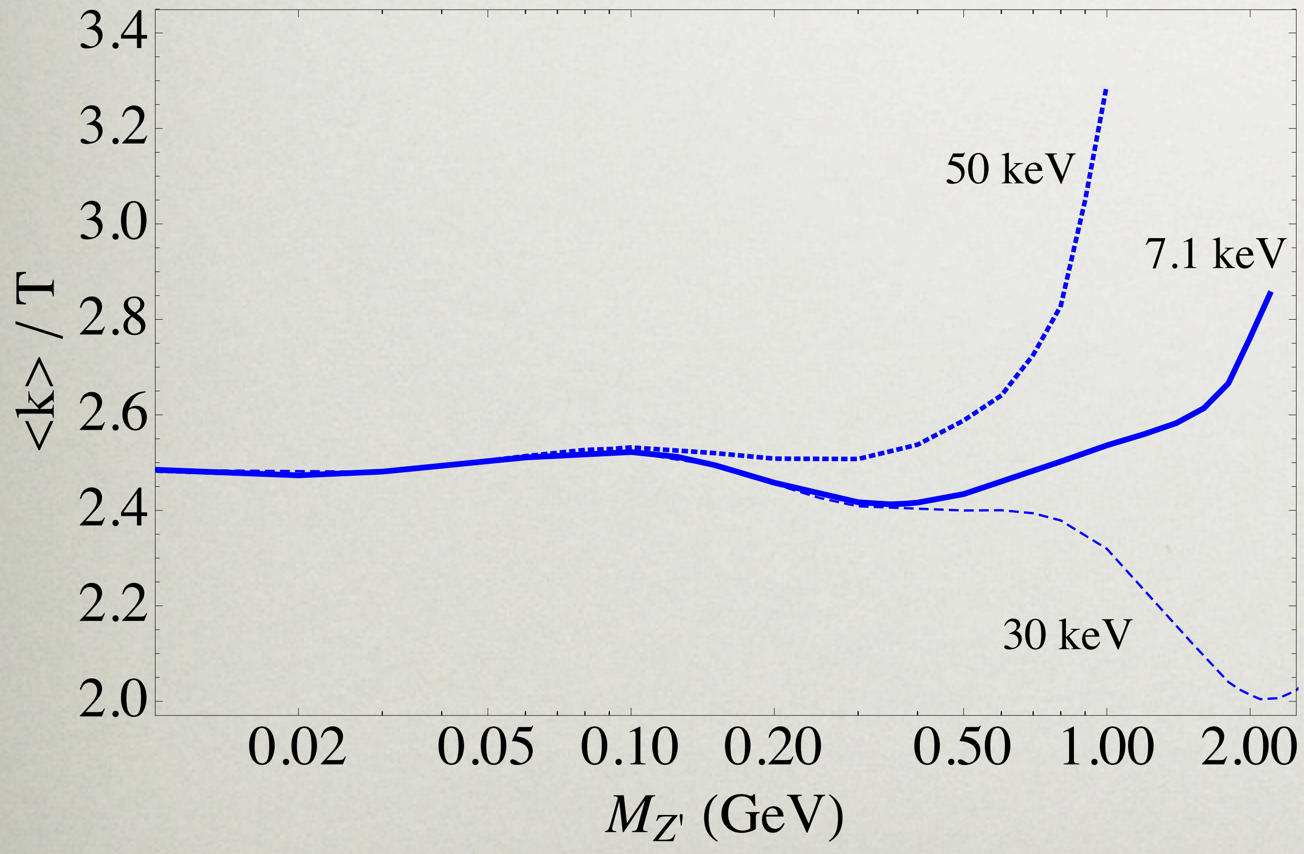
Results

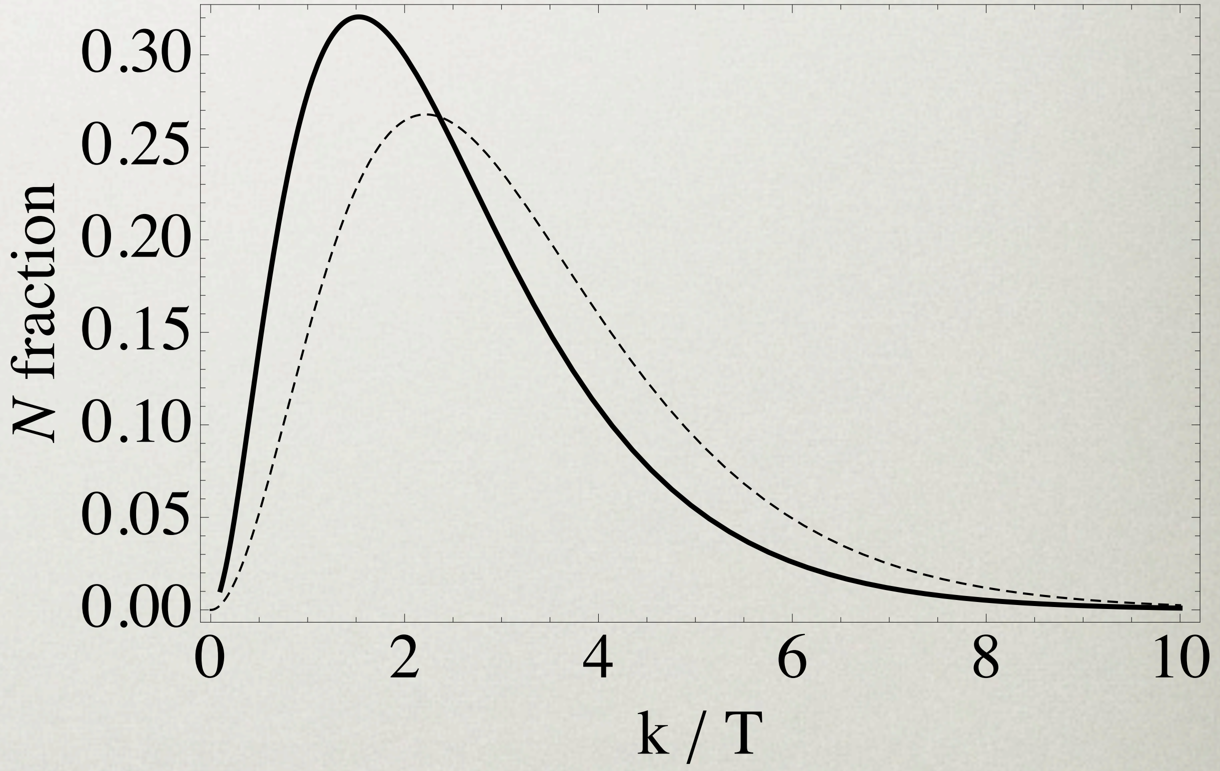
- Show dependence on mixing angle (7 keV sterile neutrino shown here)
- Complementarity between direct and astrophysical probes



Results

- Sterile neutrinos can be hot, warm, or cold **(Abazajian, Fuller, Patel 2001)**
- Sterile neutrino spectrum from Z' is often colder than thermal
- Sensitivity to QCD phase transition and thermal effects
    - We show spectrum relative to photon bath at $T = 1$ MeV





(solid) $M_N = 7.1$ keV, $M_{Z'} = 300$ MeV
(dashed) thermal distribution