NOT-SO-STERILE NEUTRINOS AND NEW LEPTONIC FORCES

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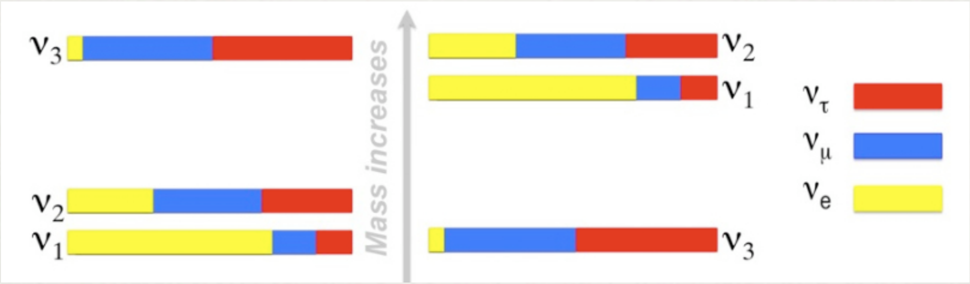
Theoretical Perspectives on New Physics at the Intensity Frontier

University of Victoria

11 September 2014

Why sterile neutrinos?

- Sterile (right-handed) neutrinos are a **well-motivated** extension of the SM
    - All other fermions come in pairs of LH and RH fermions
    - Simplest way of accounting for neutrino masses and mixings
    - Sterile neutrinos are viable dark matter candidates!



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

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

- Sterile neutrinos are singlets which mix with the SM neutrinos
    - Only allowed interactions with the SM are through the mixing
    - Very predictive!

Too-sterile neutrinos

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

- But....sterile neutrinos have a problem
    - No symmetry stabilizes the sterile neutrino: can decay to SM neutrinos
    - If sterile neutrinos are sufficiently stable, then they are **too sterile**
    - The production of *N* through the SM mixing is too slow and there is **insufficient abundance of *N* to account for dark matter!**
- For sterile neutrinos to be viable, we them to be **not-so-sterile**
    - There could be new interactions in the sterile sector, but these are almost impossible to probe (exception: Petraki, Kusenko 2007)
- Our proposal: A new interaction among **SM neutrinos** also increases the sterile neutrino production rate through mixing
    - We find a new **leptonic force** in the MeV-GeV mass range can enhance the *N* production while preserving constraints on the decay
    - Very predictive, different couplings than dark photon searches

Outline

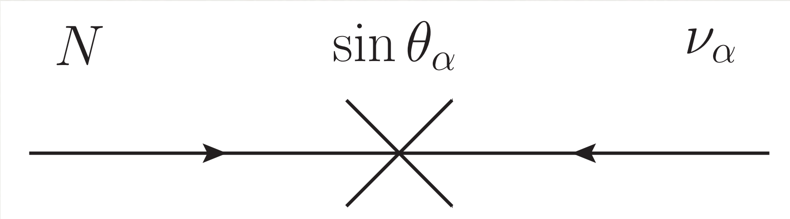
1. Sterile neutrino production & decay in minimal model
2. Not-so-sterile neutrinos and new leptonic forces
3. Intensity frontier as a probe of not-so-sterile neutrinos

Minimal Sterile Neutrinos

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

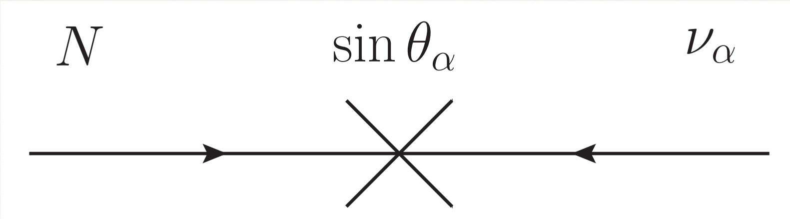
- Consider a simple scenario with one generation of *N* mixing with one generation of L_α
- After electroweak symmetry breaking, the sterile and LH neutrinos mix

$$\mathcal{M} = \begin{pmatrix} 0 & F\langle\Phi\rangle \\ F\langle\Phi\rangle & M_N \end{pmatrix} \qquad \sin\theta_\alpha = \frac{F\langle\Phi\rangle}{M_N}$$

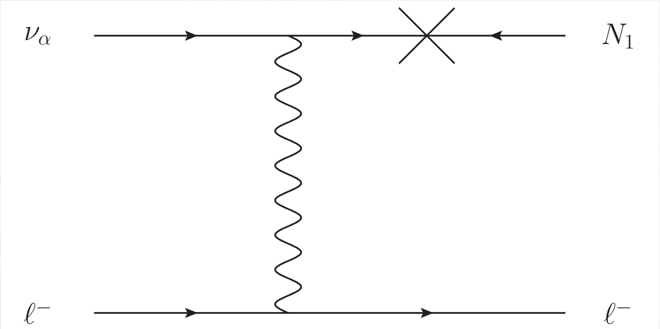


- The **key question**: is *N* a viable dark matter candidate?
  - Does it have the correct abundance?
  - Is it sufficiently long-lived?

Sterile Neutrino Production



- Assume vanishing initial abundance of *N*
- Sterile neutrinos are produced through the **electroweak gauge interactions** in the early universe

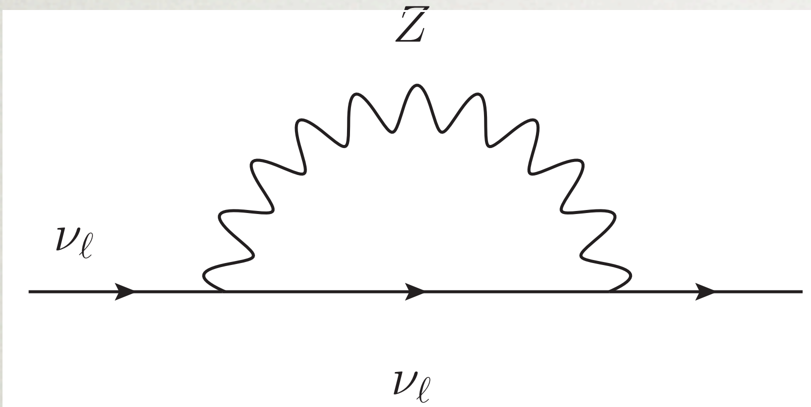


$$\Gamma_N \sim \sum_\alpha \sin^2 2\theta_\alpha(T)\, G_{\mathrm{F}}^2\, T^5$$

- This is called the **Dodelson-Widrow mechanism** (Dodelson, Widrow 1993)
- In order to calculate the rate, we need to know the mixing angle at **finite temperature**

Sterile Neutrino Production

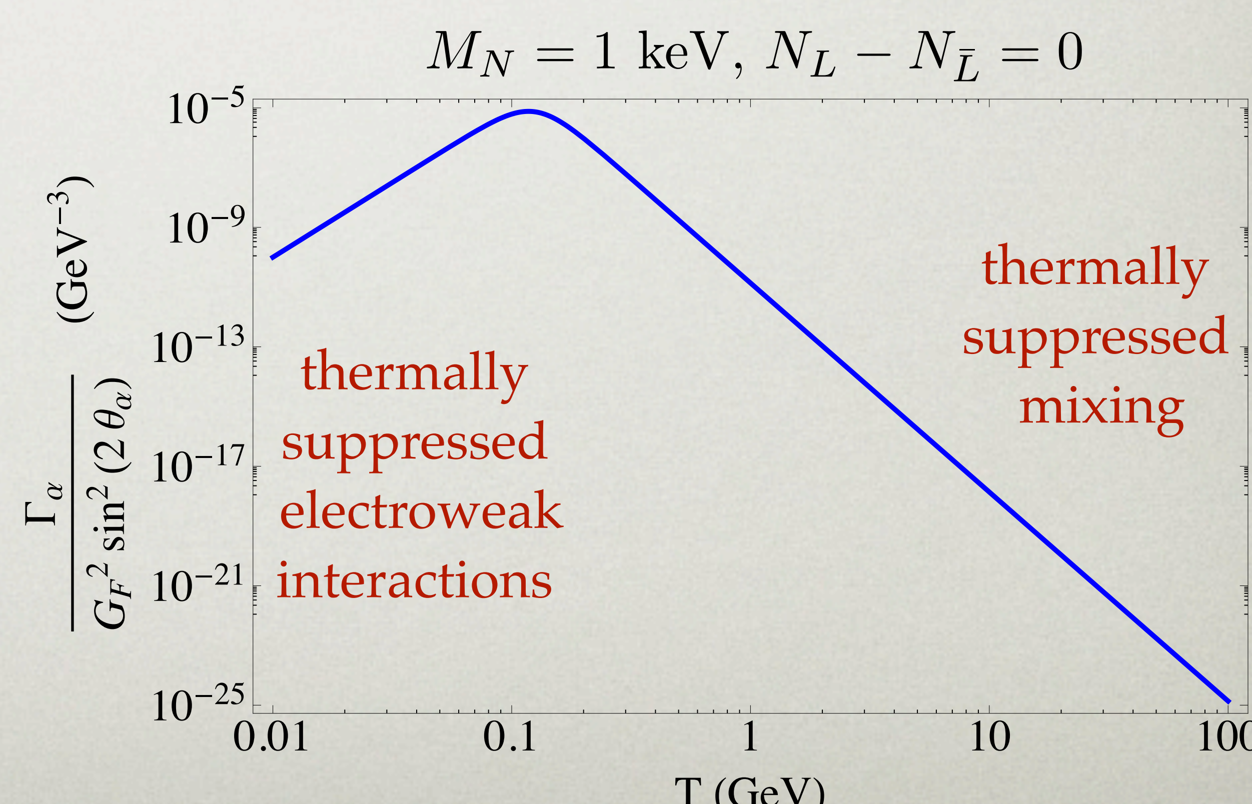
- The propagation of neutrinos is affected by the hot, dense medium of the early universe
    - Interactions with the background plasma give rise to a **thermal mass** to the SM neutrinos
    - This modifies the mass matrix (background potential) and **suppresses the mixing with sterile neutrinos** (Nötzold, Raffelt 1988)



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

$$\Gamma_N(T) \approx G_{\rm F}^2 \, \sin^2 2\theta_\alpha(T)\, T^5$$

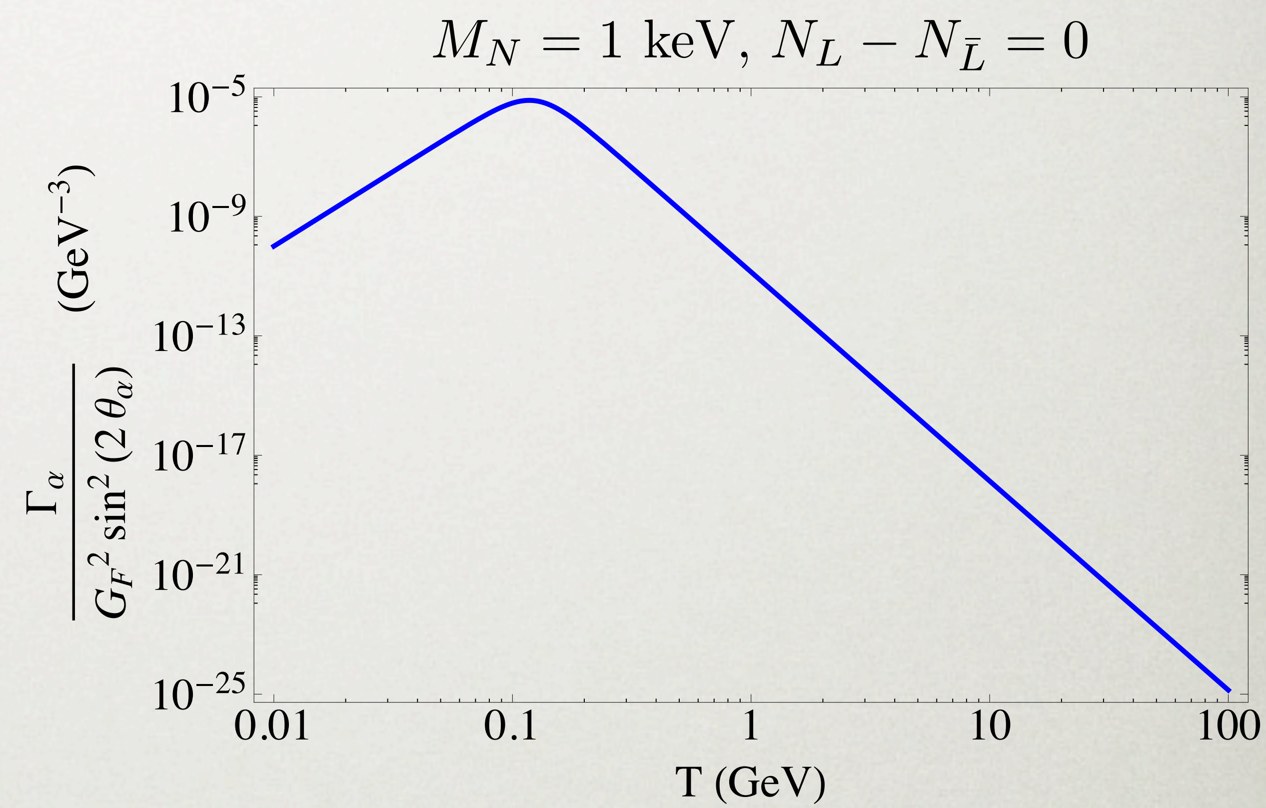
$$\sin^2 2\theta_\alpha(T) \approx \frac{\sin^2 2\theta_\alpha(T=0)}{\left[1 + 0.27\left(\frac{T}{100\ \rm MeV}\right)^6 \left(\frac{\rm keV}{M_N}\right)^2\right]^2}$$



Sterile Neutrino Production

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

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



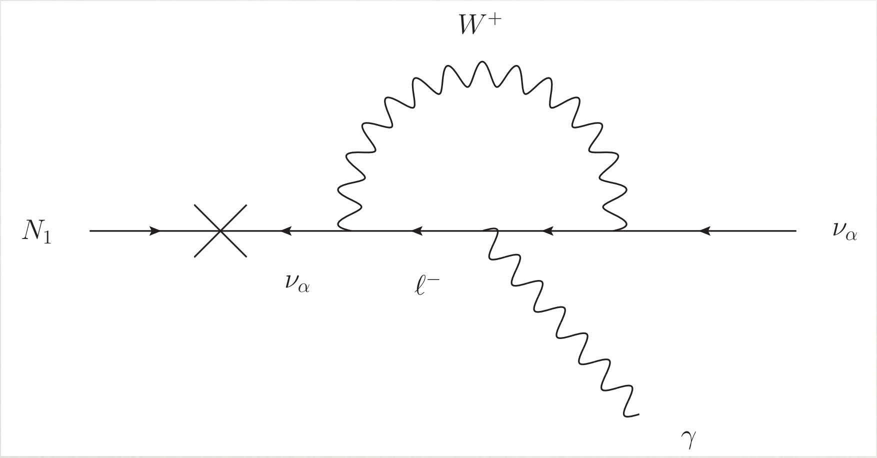
- DM abundance (✓)

Sterile Neutrino Decay

- DM abundance (✓)

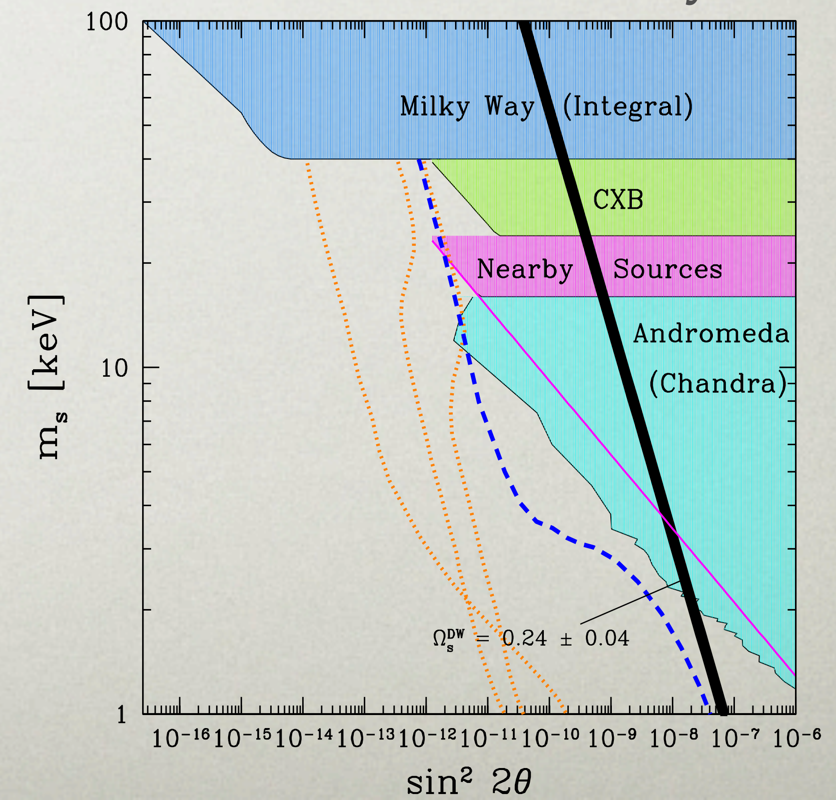
$$\Omega_N \approx 0.27 \left(\frac{\sin^2 2\theta}{2\times 10^{-9}}\right)\left(\frac{M_N}{9\ \mathrm{keV}}\right)^{1.8}$$

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



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

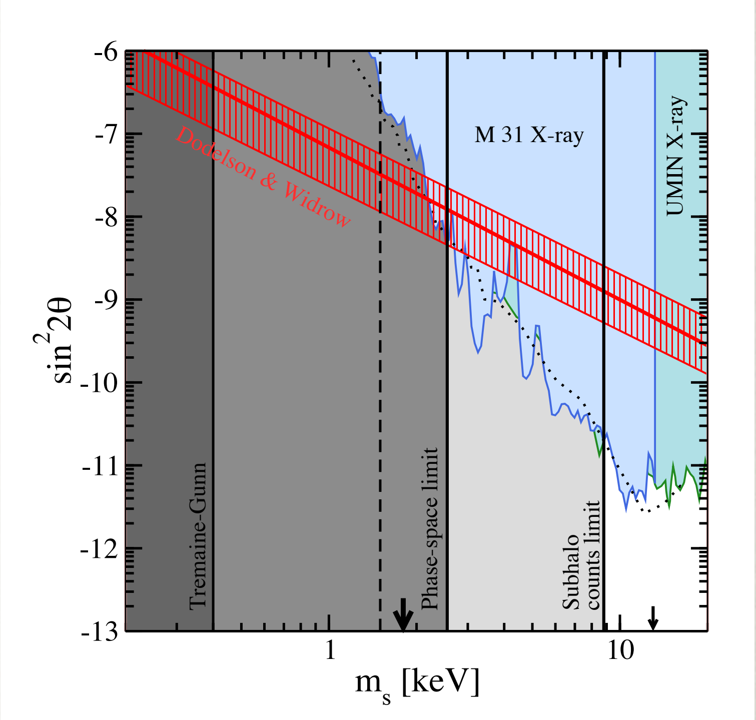
Taken from **Watson, Li, Polley 2012**



- This leads to the strongest constraint: bounds on photon line in stacked galaxy clusters
- Absence of signal → $M_N \lesssim 2$ keV

Small-Scale Structure

- $M_N \lesssim 2$ keV → warm dark matter
- Suppresses growth of structure on **small scales**
- Most conservative constraints come from counting the # Andromeda subhalos
- Production of *N* through SM gauge interactions + mixing is **completely ruled out!**
- Sterile neutrinos are **too sterile**



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

- The minimal model can only work with a **resonant enhancement** of the mixing between SM and sterile neutrinos (Shi, Fuller 1999)
- Requires very large late-time lepton asymmetry (>10^6 times bigger than baryon asymmetry)

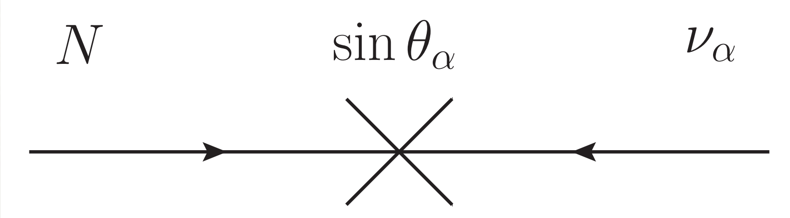
$$V_\nu \approx 2\sqrt{2} G_\mathrm{F}(N_\nu - N_{\bar{\nu}}) - \frac{7\pi}{90\alpha}\sin^2(2\theta_\mathrm{W}) G_\mathrm{F}^2 T^4 E_\nu$$

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

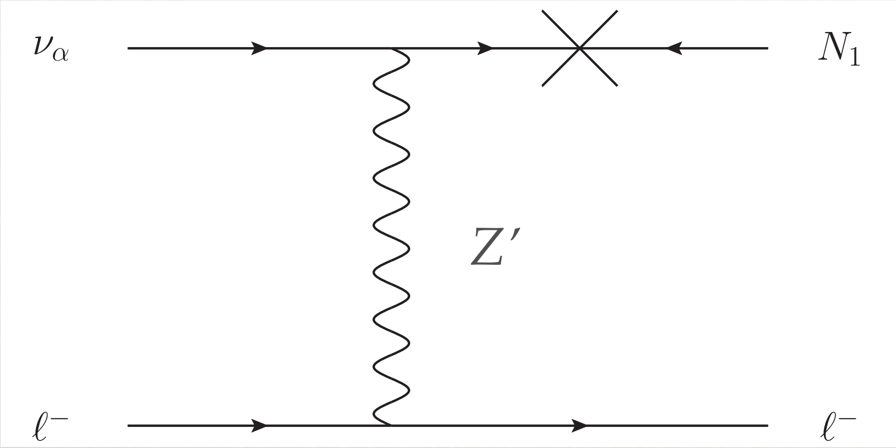
Not-so-sterile neutrinos and new leptonic forces

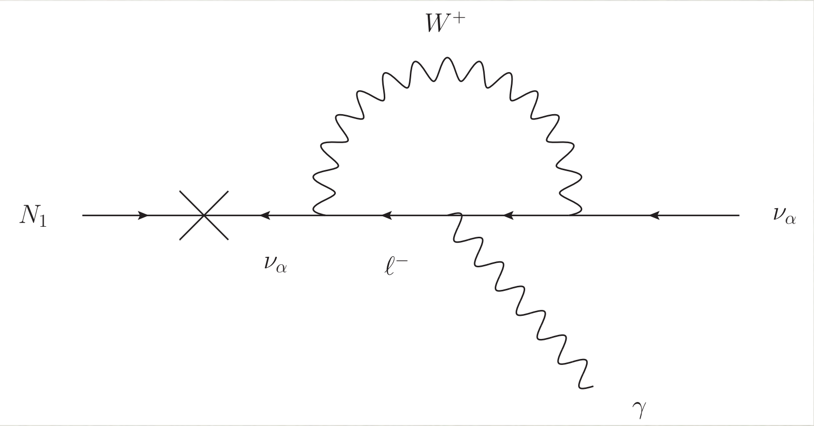
Not-so-sterile neutrinos

- To incorporate a natural model of sterile neutrino dark matter, we need to make them **less sterile**
    - Mixing ensures that any new interaction coupled to SM neutrinos also couples to sterile neutrinos



- But does any new contribution to *N* production also lead to its decay into a photon line?



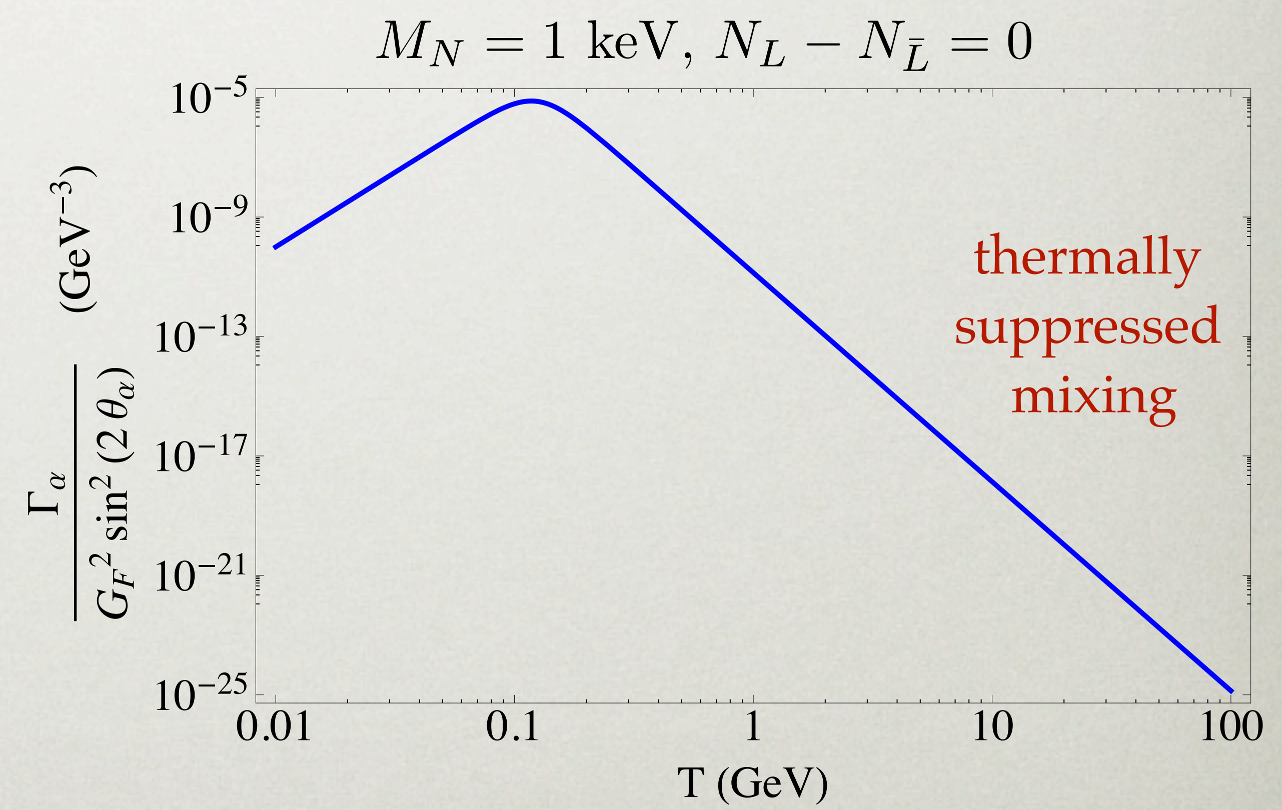


- A **neutral current** interaction contributes to production but **not the decay to photons**
    - Sterile neutrino production is enhanced with new **leptonic interactions**

New Leptonic Interactions

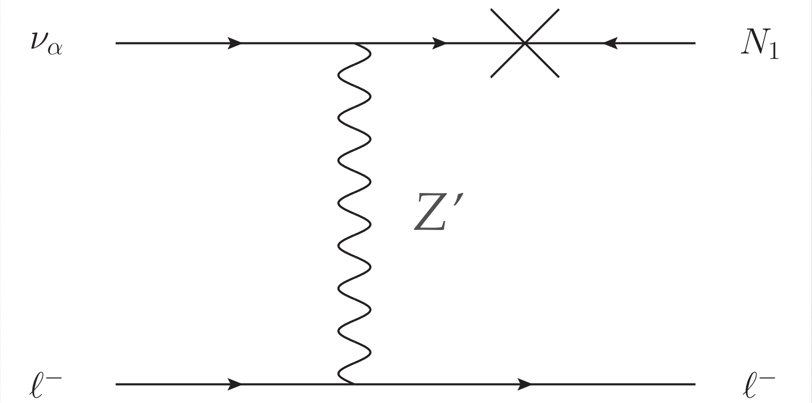
- A **neutral current** interaction contributes to production but **not the decay to photons**
  - Reasonable choice: new U(1)′ gauge interaction, Z′ force mediator
  - Anomaly-free: B - L, L_i - L_j
  - The cosmology only really cares that Z′ couples to leptons (but phenomenology depends on other charged states)
- What is the mass & coupling of this new force?

- Production of N strongly suppressed above ~ few hundred MeV
- Consider separately the limits $M_{Z'} \gg$ GeV, and $M_{Z'} \lesssim$ GeV



New Leptonic Interactions

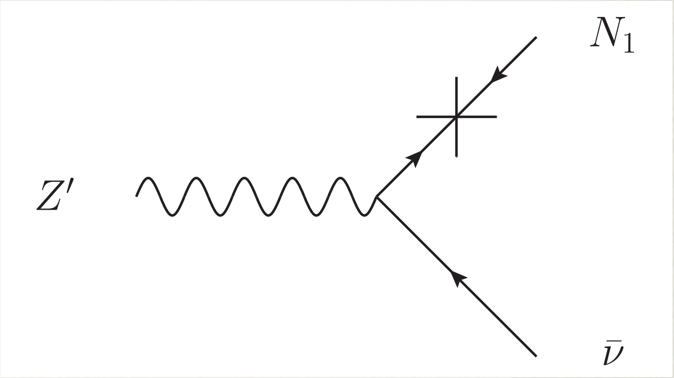
- $M_{Z'} \gg \text{GeV}$
    - Production of N only occurs below a few hundred MeV
    - N production mediated by off-shell Z'

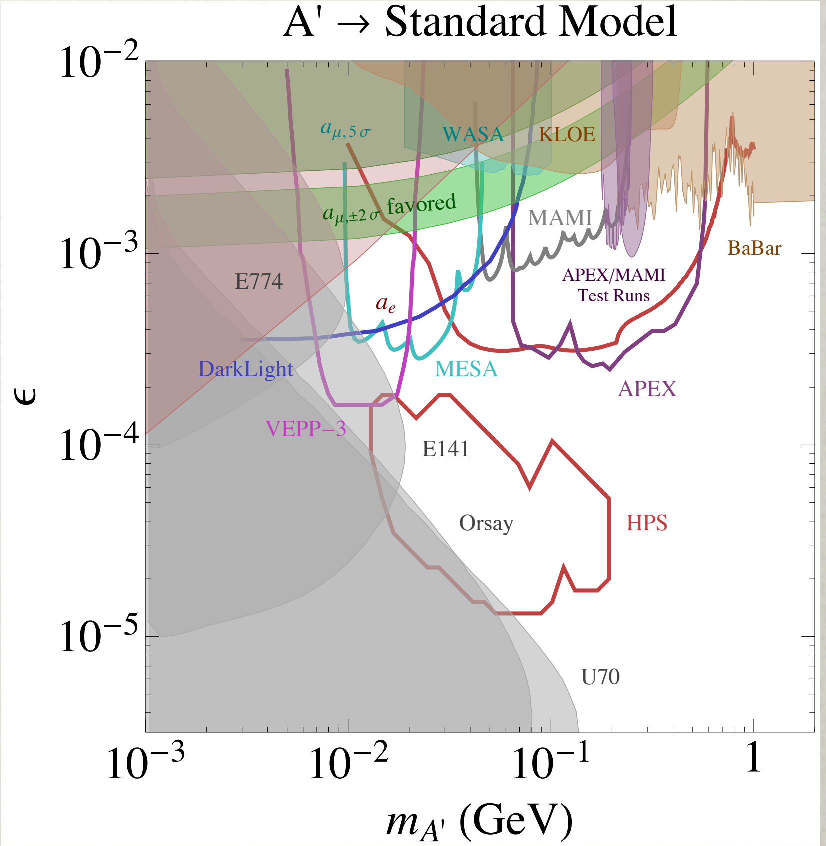


- This is exactly analogous to production of N through electroweak gauge interactions, but with G_F replaced with G'
- Since the electroweak interactions are **too weak** to produce enough N, this means that $G' \gg G_F$
- This is **ruled out** from excessive contributions to the lepton magnetic dipole moments, LEP, etc.

New Leptonic Interactions

- $M_{Z'} \lesssim$ GeV
    - Z' still present in thermal bath at time of largest N mixing
    - $1 \to 2$ processes dominate
    - Similar dynamics to direct N production from singlet decays (Shaposhnikov, Tkachev 2006; Petraki, Kusenko 2007)



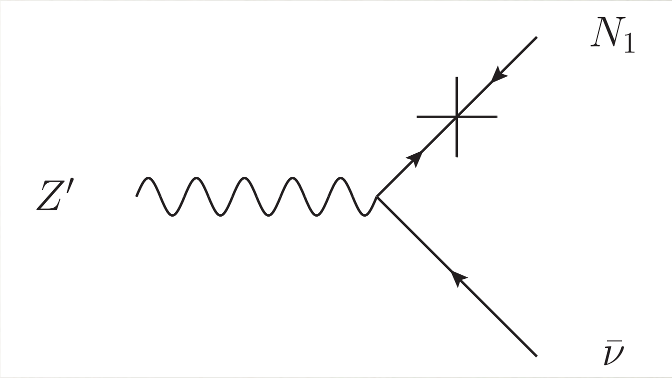


- This new force is precisely in the light force "window" at the intensity frontier

Taken from **Adrian *et al.* 2013**

Not-so-sterile Neutrinos & U(1)'

- When are most N produced?



$$\Gamma_{Z'} \sim g'^2 \sin^2 2\theta M_{Z'} \qquad\qquad H \sim \frac{T^2}{M_{\rm Pl}}$$

$$\frac{\Gamma}{H} \sim \frac{g'^2 \sin^2 2\theta M_{Z'} M_{\rm Pl}}{T^2}$$

- The number of N produced per Hubble time **grows** as the universe **cools**
- Most N are produced at the lowest temperature where Z′ is still in the thermal bath ($T \sim M_{Z'}$)

$$Y_N \equiv \frac{n_N}{s} \sim \frac{g'^2 \sin^2 2\theta M_{\rm Pl}}{M_{Z'}}$$

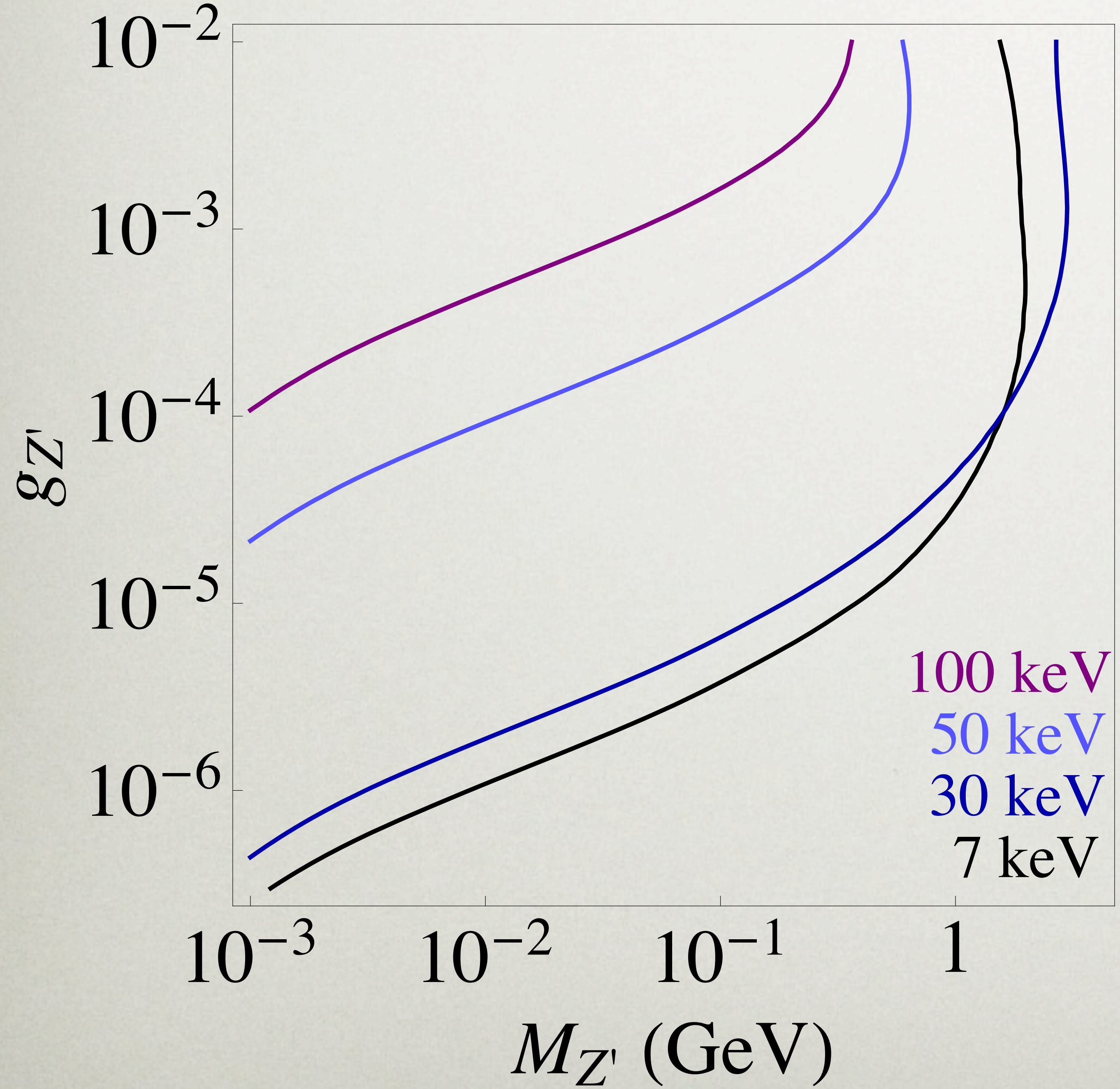
- Our calculations include all finite-T effects from SM gauge and Z′ interactions
- Thermal effects of Z′ computed in non-equilibrium QFT without assumptions on $M_{Z'}$

c.f. Wu, Ho, Boyanovsky 2009

- Include damping of neutrino mixing induced by new force (quantum Zeno effect)

Not-so-sterile Neutrinos & U(1)’

- For each M_N, use mixing angle at limit allowed by X-ray constraints



7 keV, $\sin^2(2\theta) = 6 \times 10^{-11}$

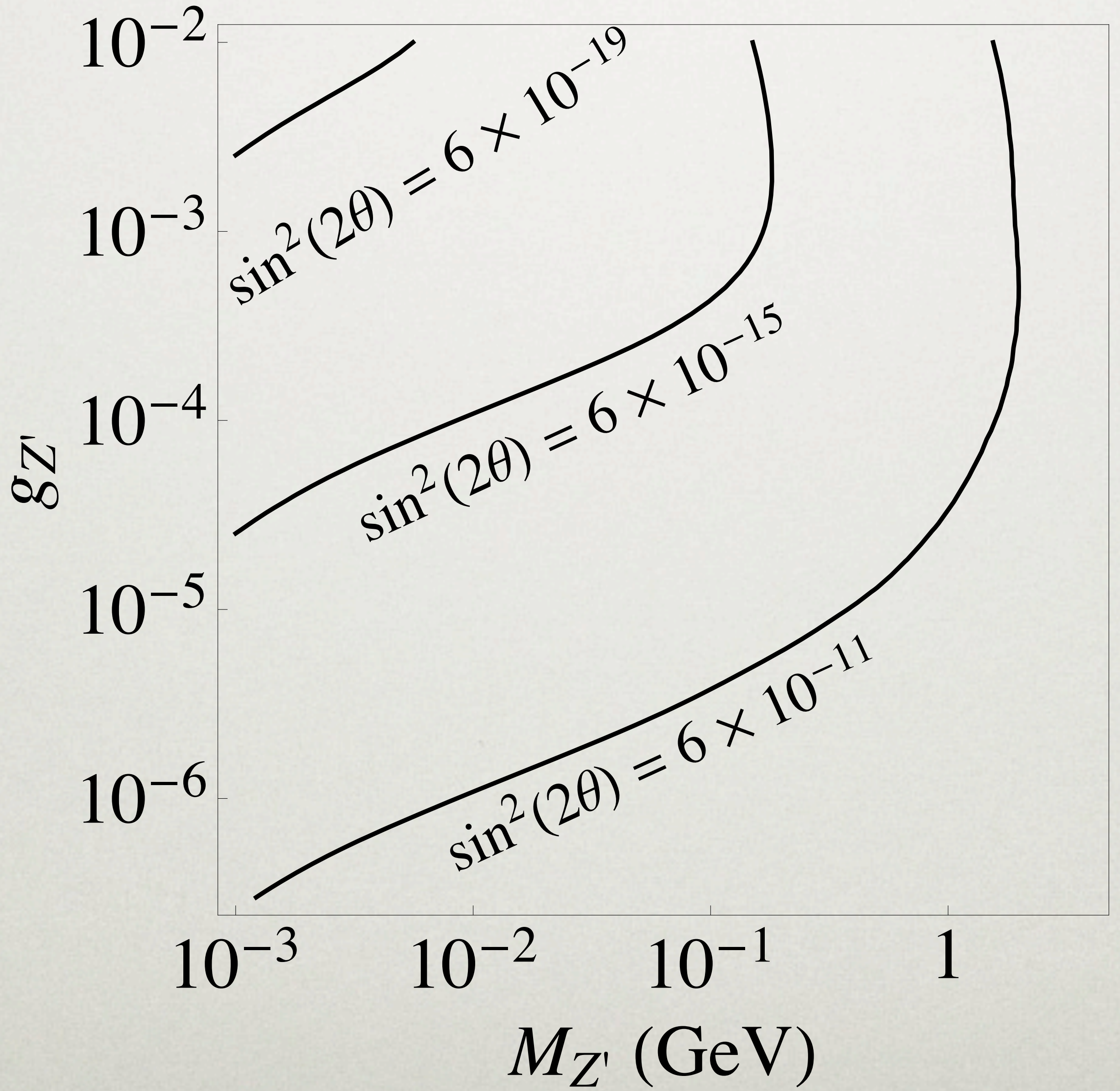
30 keV, $\sin^2(2\theta) = 5 \times 10^{-12}$

50 keV, $\sin^2(2\theta) = 1.25 \times 10^{-15}$

100 keV, $\sin^2(2\theta) = 2.5 \times 10^{-17}$

Not-so-sterile Neutrinos & U(1)’

- Dependence on mixing angle for fixed mass (7 keV sterile neutrino shown)
- Complementarity between direct and astrophysical probes



Not-so-sterile neutrinos and the intensity frontier

Z' constraints

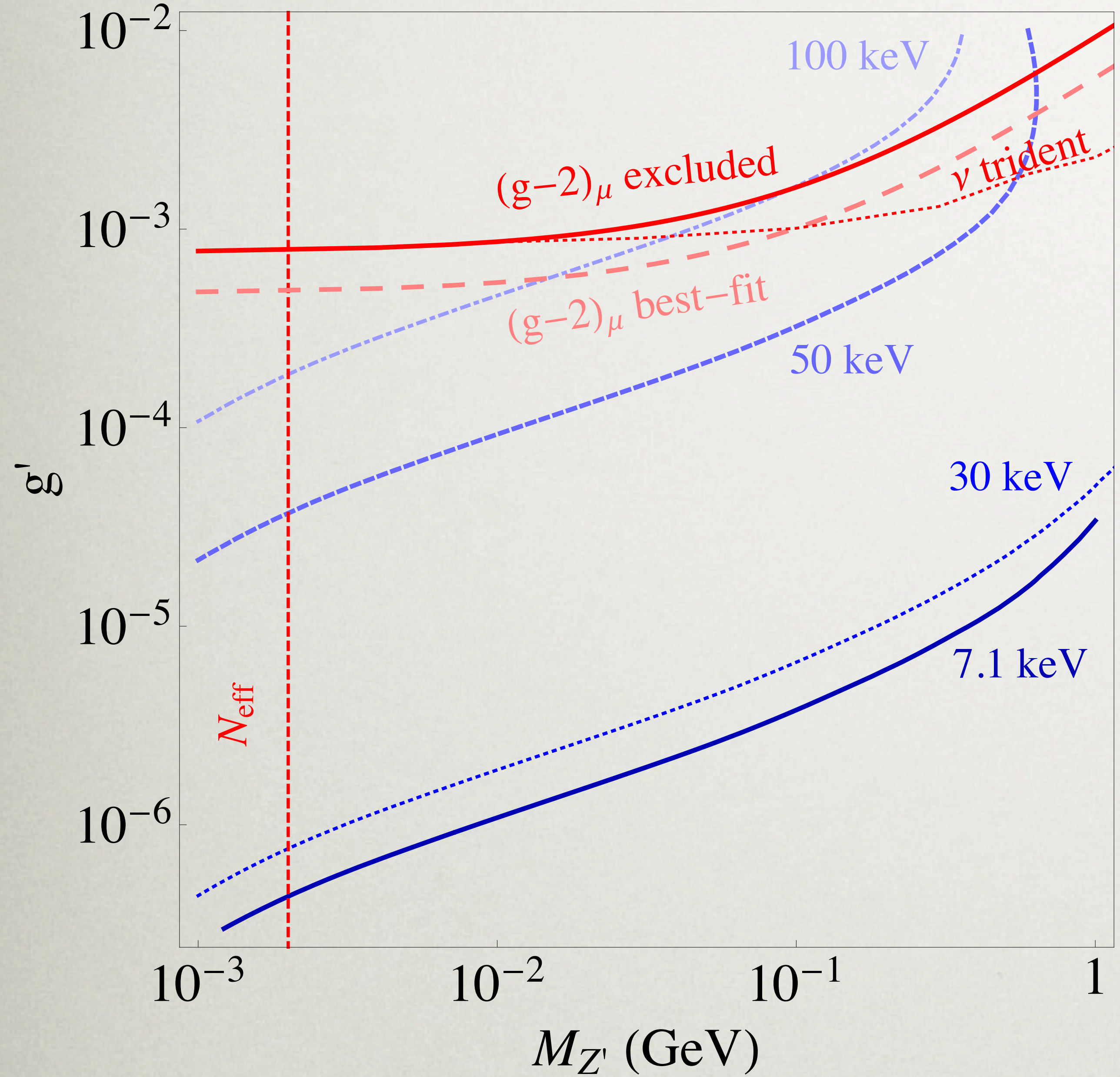
- **Mass:**
  - Since the Z' decays into neutrinos, constraints on the effective number of neutrino species imply $M_{Z'} \gtrsim 2$ MeV

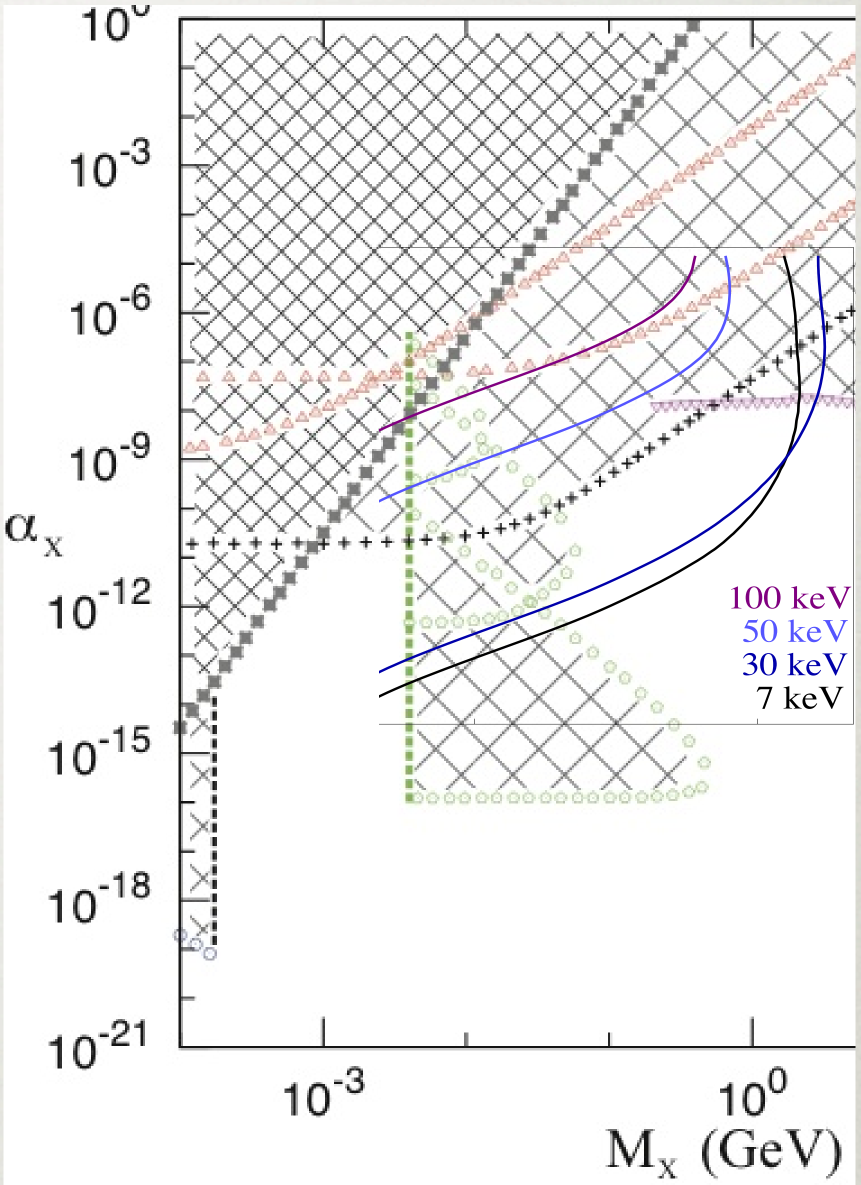
- **Mass + Coupling:**
  - Muon g - 2
  - N lifetime (by mediating N to 3 neutrino decay)
  - Neutrino-electron scattering
  - Neutrino-nucleon interactions (beam dumps)
  - Meson/onium decays
  - Neutrino trident (new since our paper) **Altmannshofer *et al.*, 1406.2332**

- Final constraints depend strongly on fields coupled to Z'

Z' constraints

adapted from **Williams et al., 1103.4556**



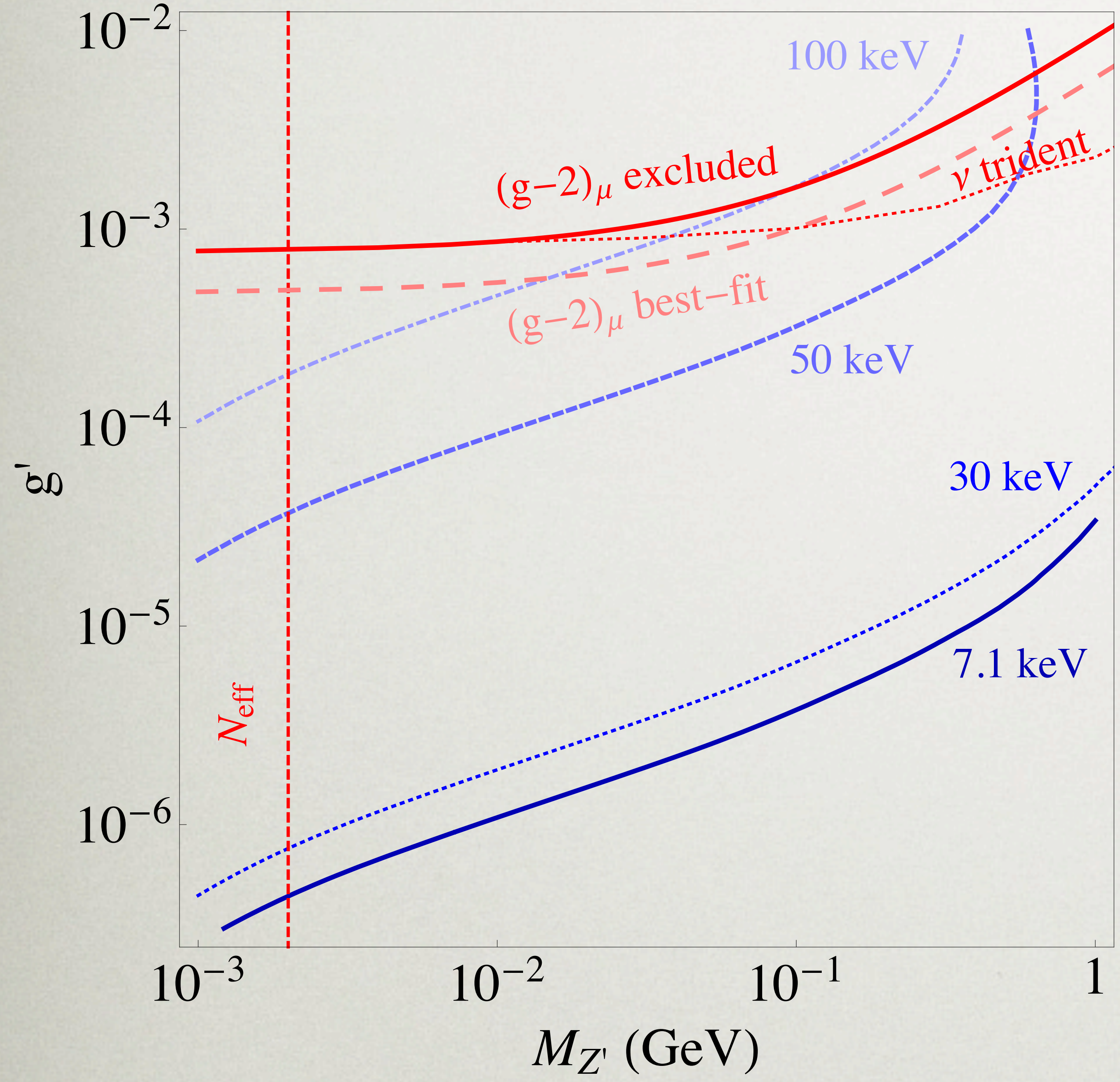


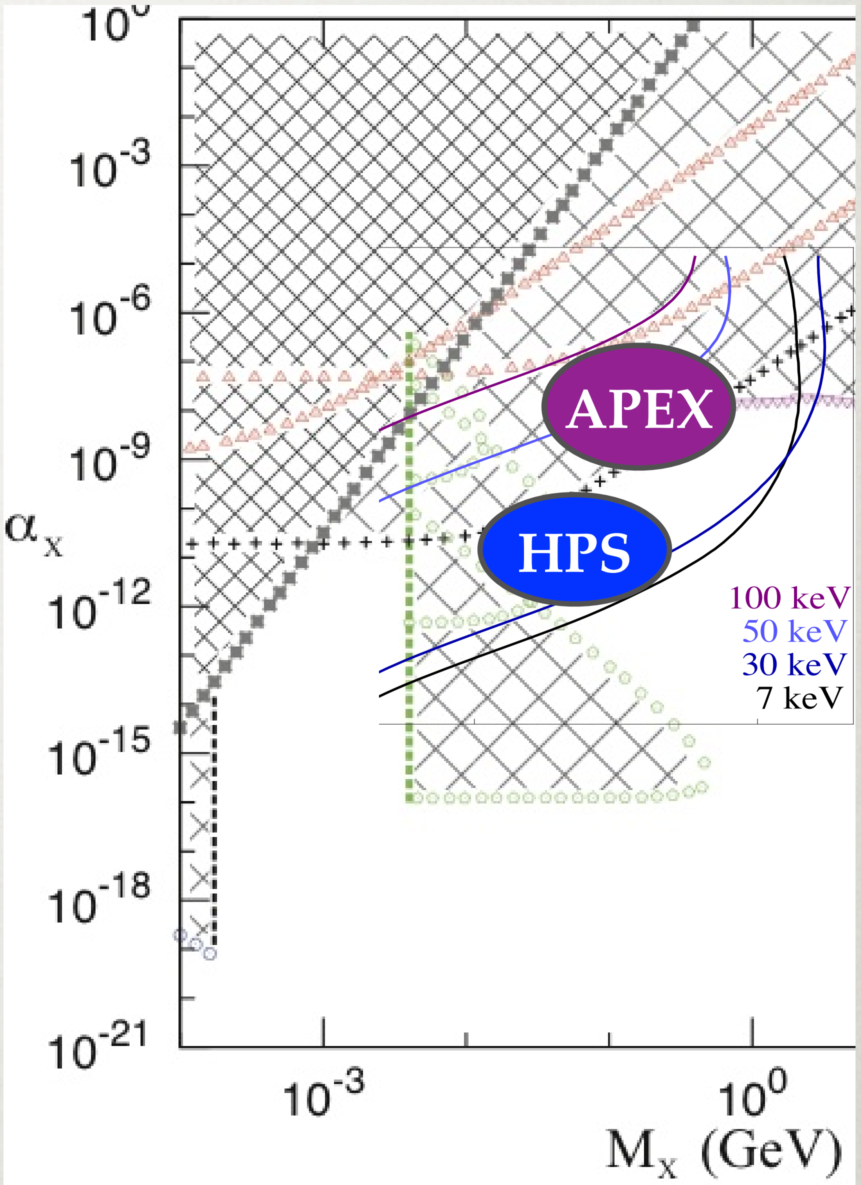
L_μ - L_τ **current**

B - *L* **current**

Z' constraints

adapted from **Williams et *al.*, 1103.4556**



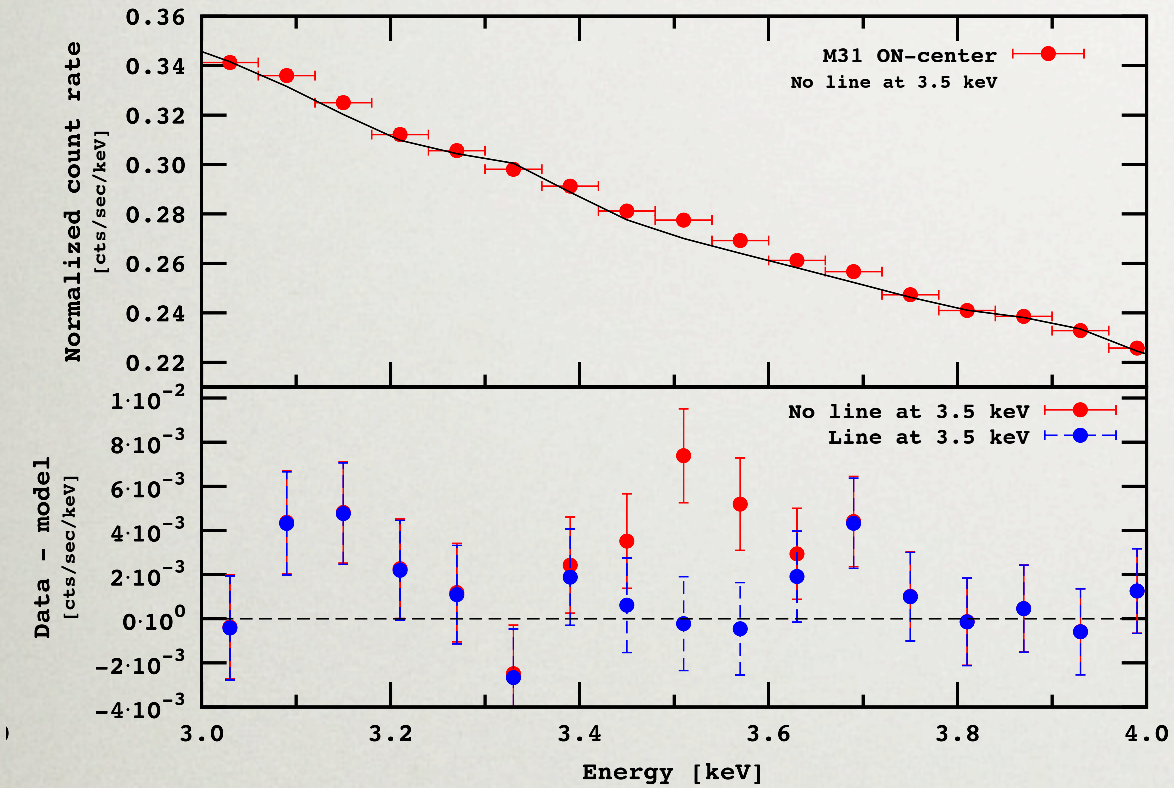


***L*$_\mu$ - *L*$_\tau$ current**

***B* - *L* current**

A possible hint of *N*?

- **Possible detection** of 3.57 keV X-ray line in stacked galaxy clusters! (4σ stat.)



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 (✓)
- If true, very challenging to probe additional Z′

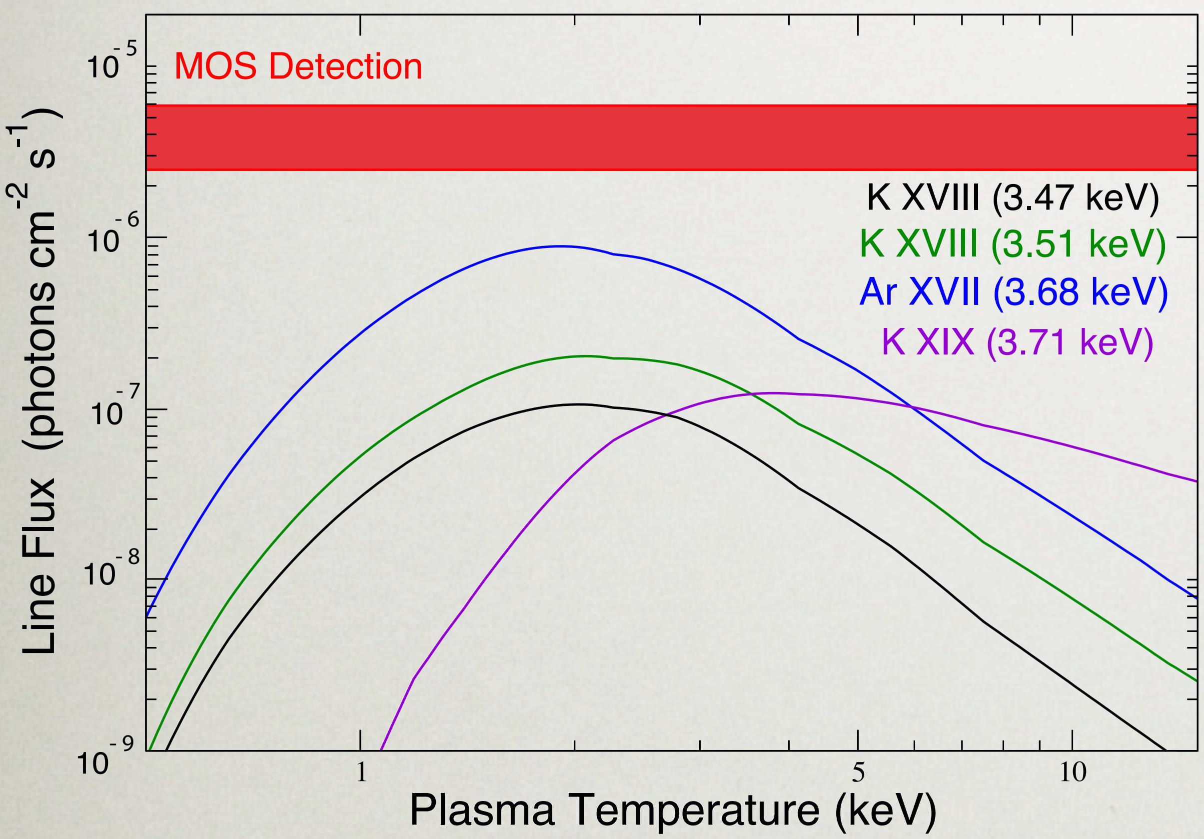
Conclusions

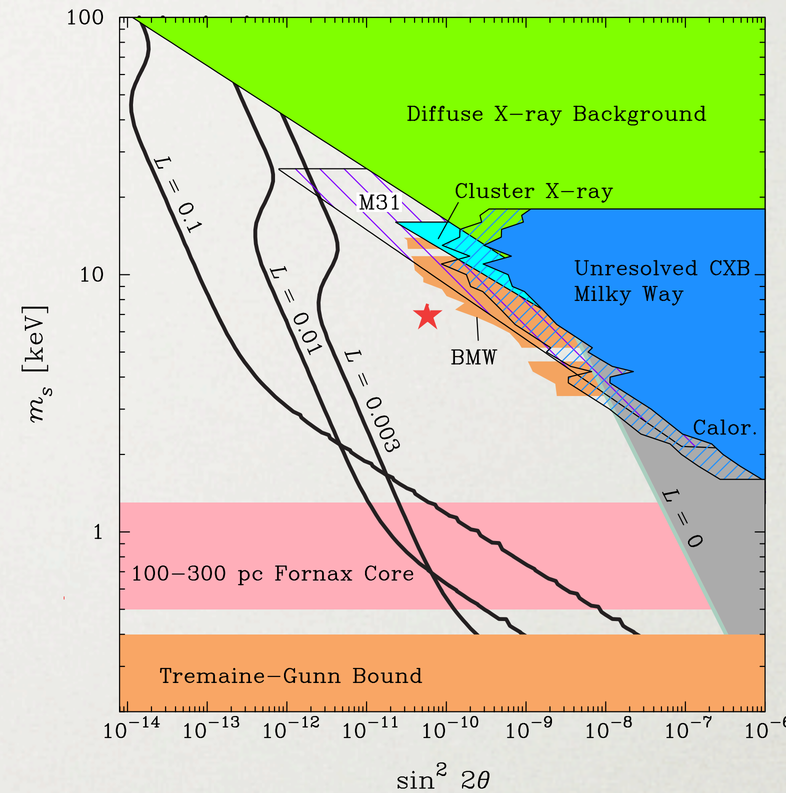
- Sterile neutrinos are well-motivated dark matter candidates, but new interactions are needed to account for the observed abundance
- Our models make a robust prediction for new **leptonic forces** in the MeV-GeV mass range, couplings 10^{-6} - 10^{-3}
- Intensity frontier can serve as a complementary window into physics related to cosmology - very clear target parameter space
- New search strategies needed to close remaining gaps, particularly when the new force does not interact with baryons or first-generation leptons

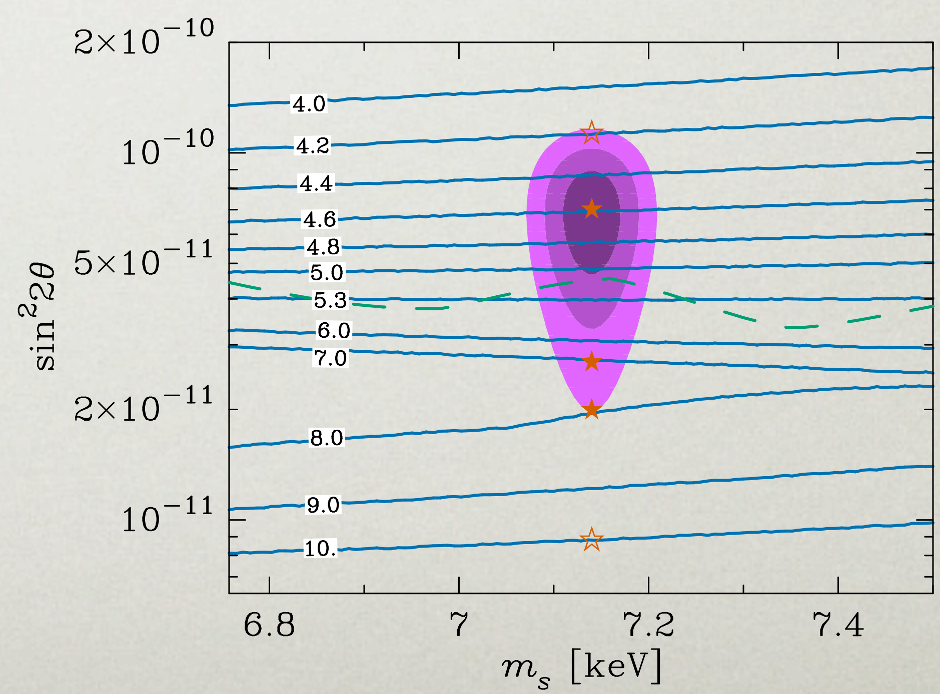
Back-up slides

3.6 keV X-ray line

- Some more plots:



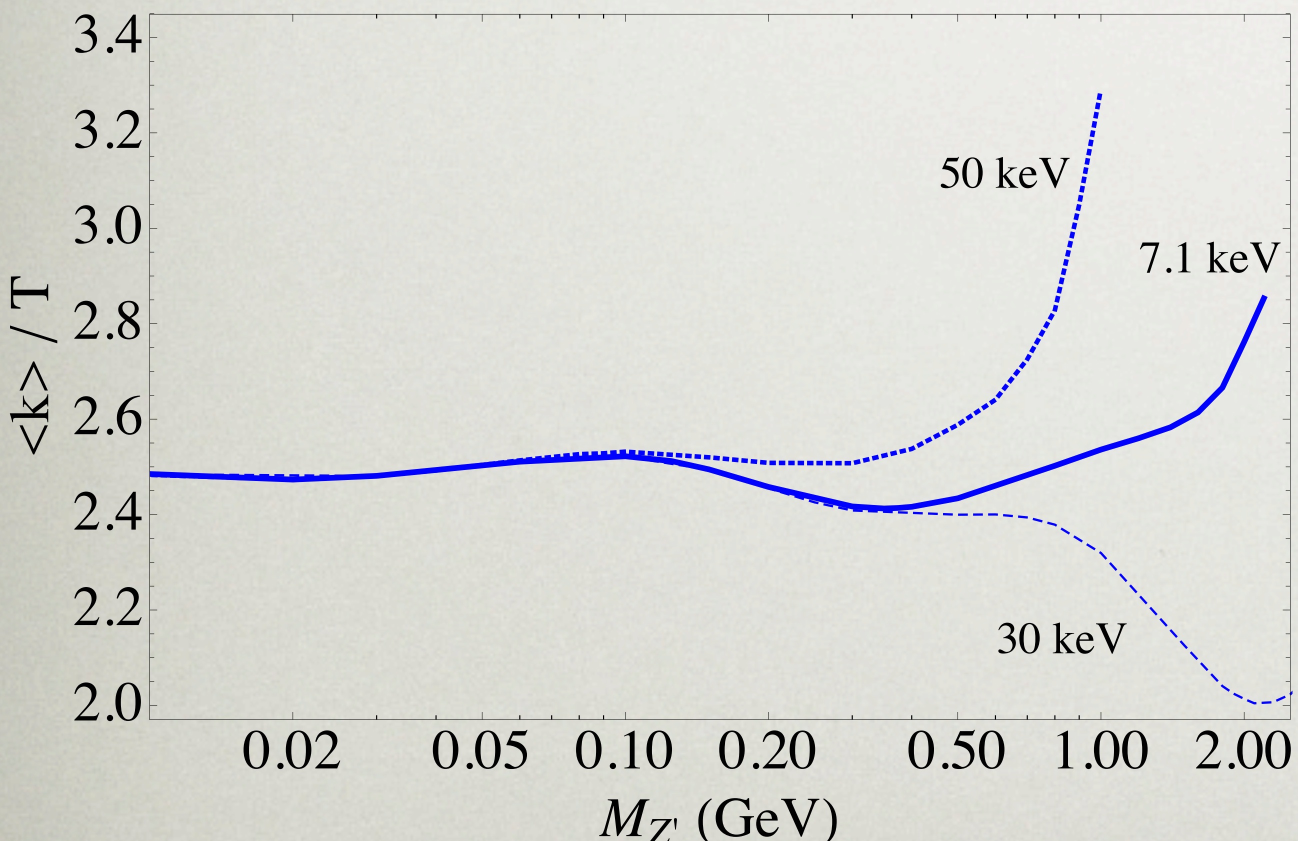


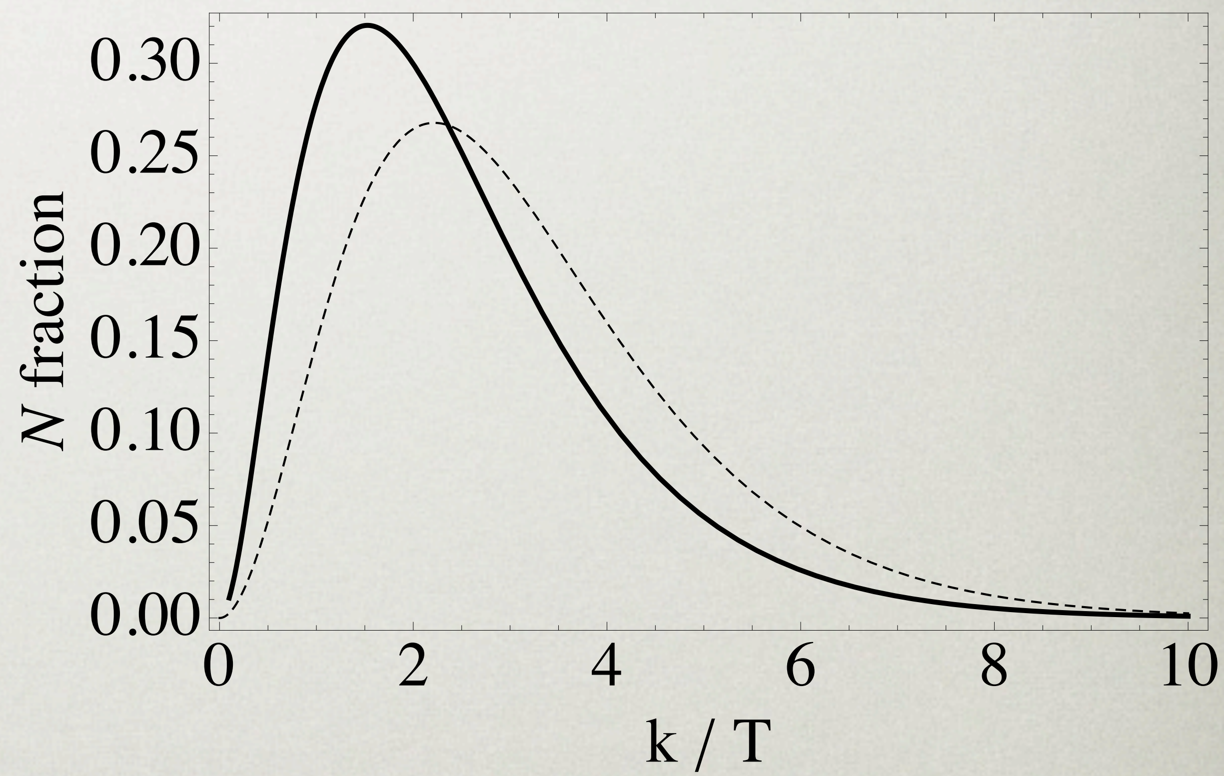


Taken from **Abazajian 2014**

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





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

Model building

- New gauge interaction must be consistent with see-saw Yukawa couplings
  - Depending on charges of Higgs, sterile neutrinos, not all entries of $L\Phi N$ are allowed
  - Constrain model-building possibilities: baryogenesis, neutrino mixings should still be OK
- One possible example for $U(1)_{\mu-\tau}$:
  - Introduce new scalar Σ carrying $U(1)_{\mu-\tau}$; new doublet Dirac fermions X_2, X_3

$$\mathcal{L} = \lambda_2 L_2 \Sigma X_2 + \lambda_3 L_3 \Sigma^* X_3 + f_1 L_1 H N_I + f_2 \bar{X}_2 H N_I + f_3 \bar{X}_3 H N_I \qquad f \ll \lambda$$

  - Low-energy effective theory can give same neutrino Yukawa couplings after Σ breaks $U(1)_{\mu-\tau}$
  - New fields can be at/above weak scale