SHEDDING NEW LIGHT ON STERILE NEUTRINOS

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Neutrinos, dark matter, and baryogenesis

- Neutrino sector offers some clues for BSM physics and cosmology:
  - Non-zero masses and mixings necessitate extending the SM
  - Baryogenesis:
    - Majorana masses for sterile neutrinos can violate lepton number
    - Yukawa couplings between active & sterile neutrinos give new *CP* phases and possible departures from equilibrium
  - Dark matter:
    - Small Yukawa couplings and lack of SM gauge interactions make sterile neutrinos excellent dark matter candidates
- In fact, a minimal model with SM + three sterile neutrinos (and nothing else) is capable of simultaneously accounting for neutrino masses, DM, baryogenesis!
  - "Neutrino minimal SM" (νMSM)
  - **Asaka, Shaposhnikov 2005; Asaka, Blanchet, Shaposhnikov 2005...**
  - All new physics below weak scale

Neutrinos, dark matter, and baryogenesis

- How does this work for each phenomenon?
  - Neutrino masses: Type-I see-saw mechanism
    - Two LH neutrino masses are generated through see-saw couplings to two sterile neutrinos

$$\mathcal{L}_{\mathrm{Type-I}} = F\, L\Phi N + \frac{M}{2} N^2 \qquad\qquad m_{\mathrm{SM}\,\nu} = \frac{F^2 \langle \Phi \rangle^2}{M}$$

  - Baryogenesis: Lepton asymmetry created through scattering & oscillations of the heaviest 2 sterile neutrinos; transferred to baryons through $B + L$ anomaly
    - Requires at least 2 sterile neutrinos with masses ~ GeV
    - Mass degeneracy + Yukawa tuning ~ 10^5 - 10^6 or more (usually more)
  - Dark matter: Lightest sterile neutrino is dark matter; created through mixing with SM neutrino
    - Requires lightest sterile neutrino ~ keV
    - Nearly decoupled from SM for stability - 1 massless SM neutrino
    - Mass degeneracy of other 2 sterile neutrinos ~ 10^{15} or more

Neutrinos and tuning

- The "minimal model" has much more structure than one might expect in a truly minimal model
- One may explain this structure with new symmetries/ interactions in the sterile sector
    - Challenging to probe
- Our approach: consider how new visible sector states and interactions can enhance the baryon asymmetry, give the correct DM abundance, and alleviate the tuning
    - For baryogenesis, this can be accomplished with an extended Higgs sector (specifically, a "leptophilic" Higgs)
    - For sterile neutrino dark matter, this can be accomplished with a new light (MeV-GeV) gauge interaction
- The physics responsible for DM and baryogenesis are essentially independent from one another, so I consider each separately

Overview

1. **Baryogenesis through neutrino oscillations: tale of N_2 and N_3**
    - Overview of mechanism
    - Asymmetry and parameters for the minimal model
    - Baryogenesis in a Two Higgs Doublet Model

2. **Sterile neutrino dark matter: tale of N_1**
    - Production and decay of sterile neutrino dark matter
    - Sterile neutrinos and new, light gauge interactions
    - Recent 3.6 keV X-ray line anomaly

Baryogenesis overview

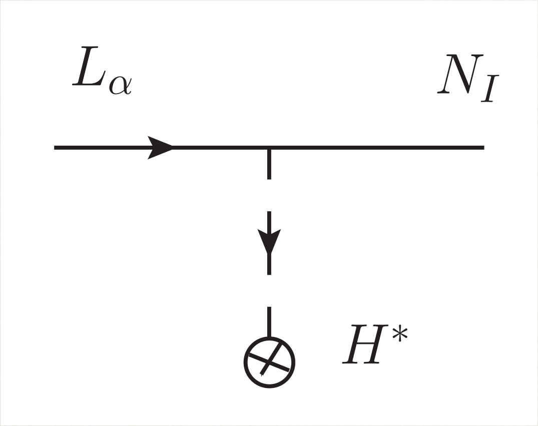
$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

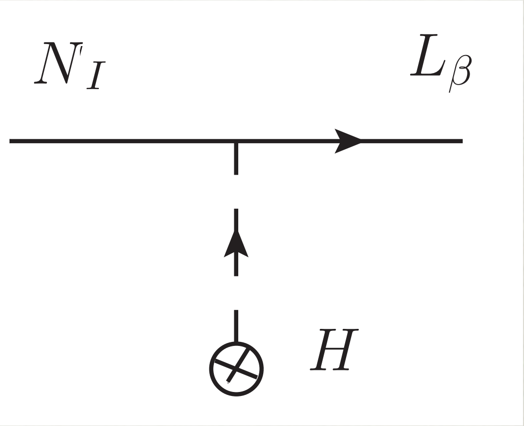
- Baryogenesis occurs through the creation, oscillation, and re-scattering of the heavy sterile neutrino states, N_2 and N_3
  - **Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005**.
- The νMSM satisfies the three Sakharov conditions for baryogenesis:
  1. **Baryon number violation.** Lepton number is broken by N mass and couplings; lepton asymmetry is transferred to a baryons via the $B + L$ anomaly
  2. ***CP* violation.** Three new CP phases in the Yukawa matrix
  3. **Departure from thermal equilibrium.** For small Yukawa couplings, N scattering is equilibrium for all T above the weak scale

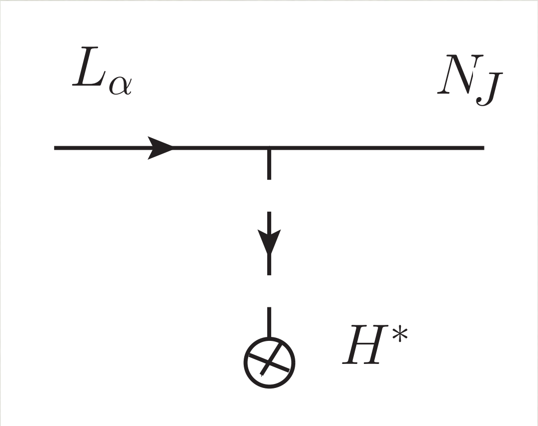
$$F^2 \sim 10^{-14} \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right) \left(\frac{m_N}{\mathrm{GeV}}\right) \left(\frac{100\ \mathrm{GeV}}{\langle\Phi\rangle}\right)^2$$

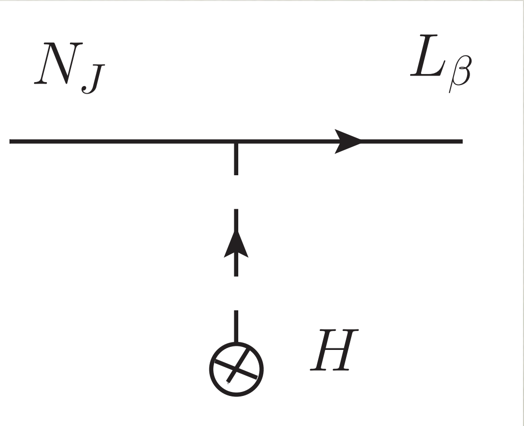
Asymmetry Generation

- The physical mechanism for baryogenesis:
    1. No primordial abundance of N_2, N_3; slowly populated by L_α scattering, and subsequently scatter back into SM leptons (out of equilibrium)



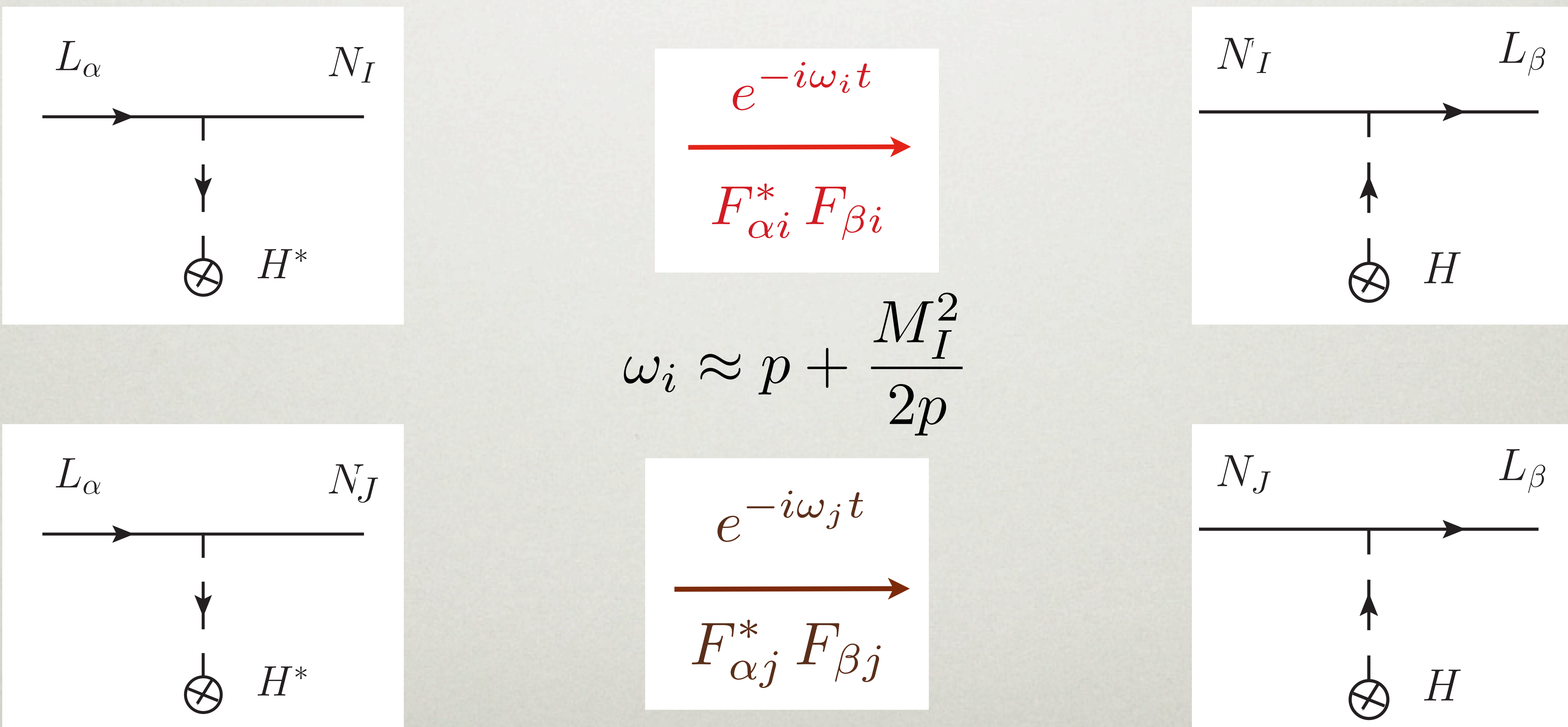






Asymmetry Generation

- The physical mechanism for baryogenesis:
  1. No primordial abundance of N_2, N_3; slowly populated by L_α scattering, and subsequently scatter back into SM leptons (out of equilibrium)
  2. Sterile neutrinos are created in interaction eigenstates (i.e. coherent superpositions of mass states). N scatterings are out of equilibrium and so the neutrinos coherently oscillate
  3. N scatter back into a different flavour L_β.



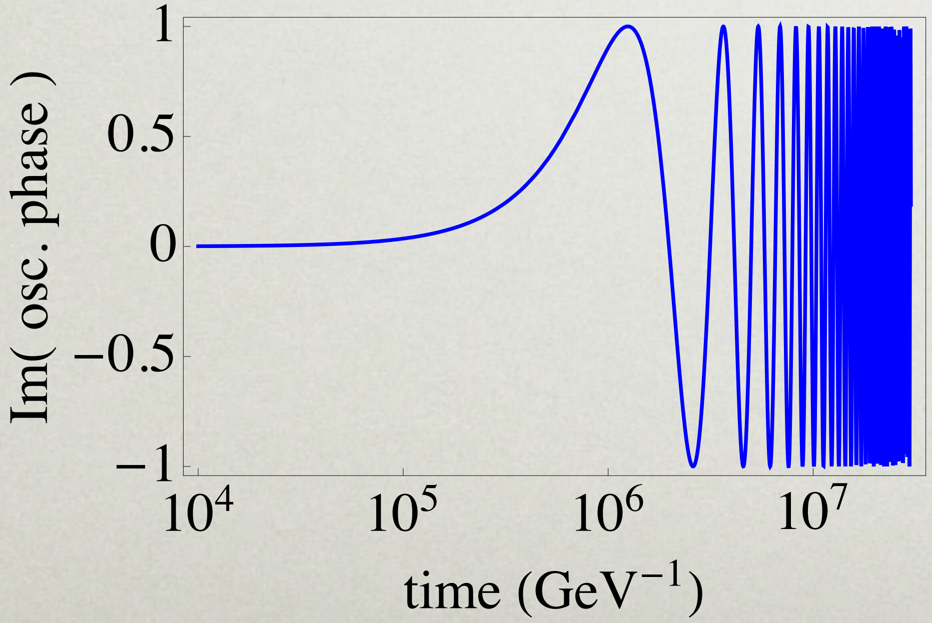
Asymmetry Generation

- The physical mechanism for baryogenesis:
    3. N scatter back into a different flavour L_β. The interference of the different mass eigenstates gives an asymmetry:

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt' \, \frac{M_3^2 - M_2^2}{2T(t')}\right)\right] \mathrm{Im}\left[F_{\alpha 3} F^*_{\beta 3} F^*_{\alpha 2} F_{\beta 2}\right]$$

    4. When oscillation becomes rapid, the asymmetry produced from each scattering averages to 0.

$$(M_3^2 - M_2^2)/T \sim H$$



$$\frac{n_{\Delta L,\alpha}}{s} \sim \frac{M_{\rm Pl}^{4/3}}{(M_3^2 - M_2^2)^{2/3}} \mathrm{Im}\left[(FF^\dagger)^2\right]_{\alpha\alpha}$$

Asymmetry Generation

- The physical mechanism for baryogenesis:

  3. *N* scatter back into a different flavour L_β. The interference of the different mass eigenstates gives an asymmetry:

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt'\,\frac{M_3^2 - M_2^2}{2T(t')}\right)\right]\mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right]$$

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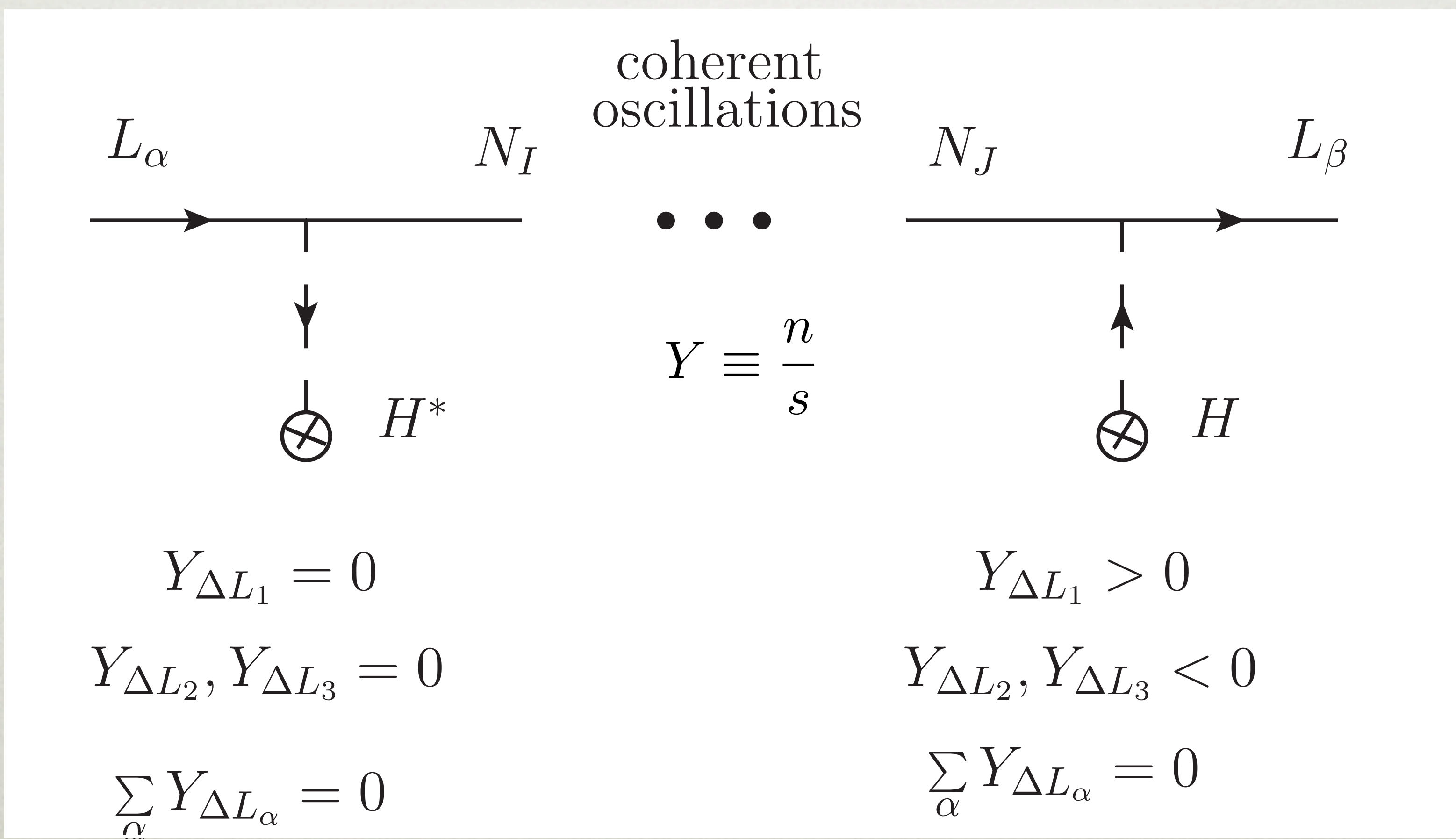
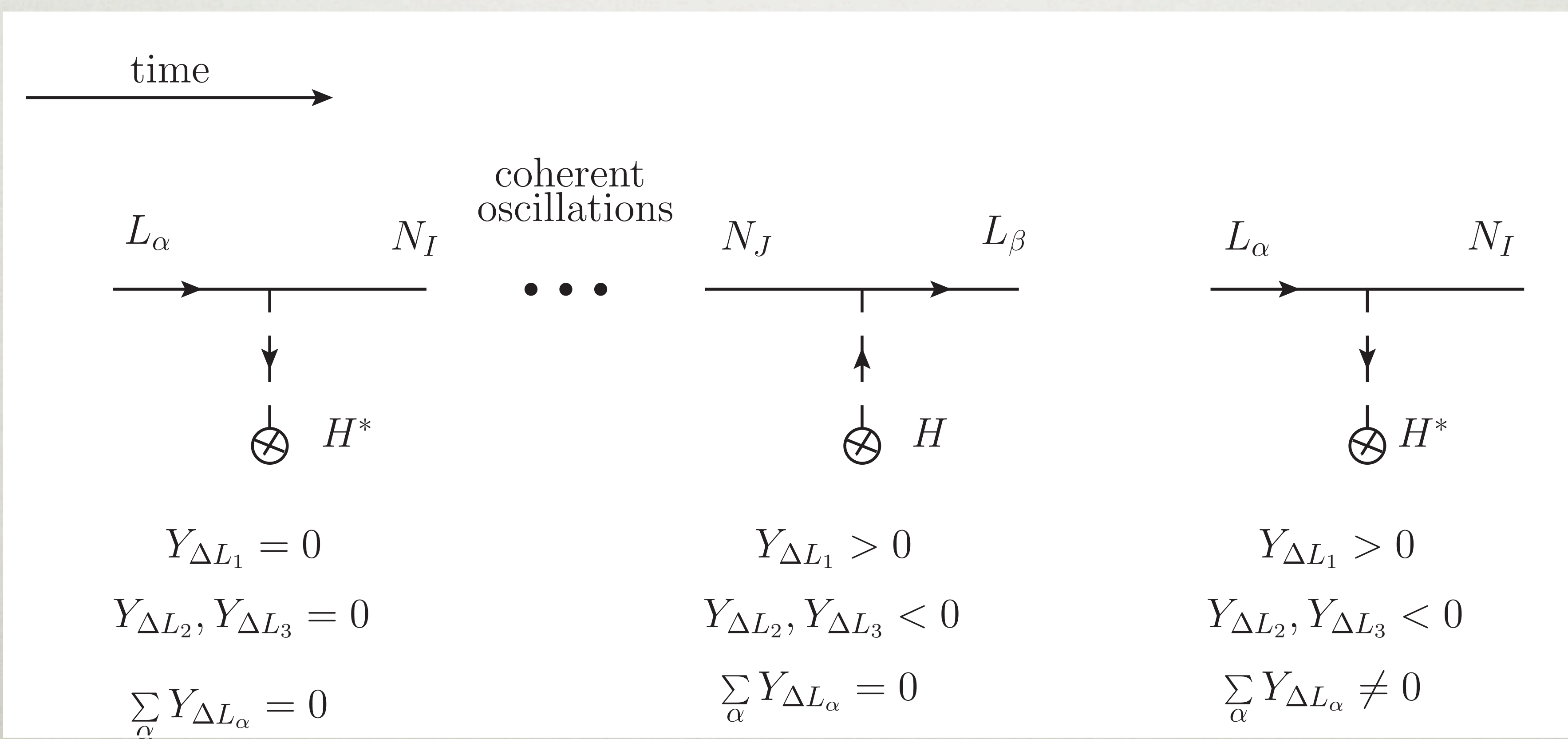


Asymmetry Generation

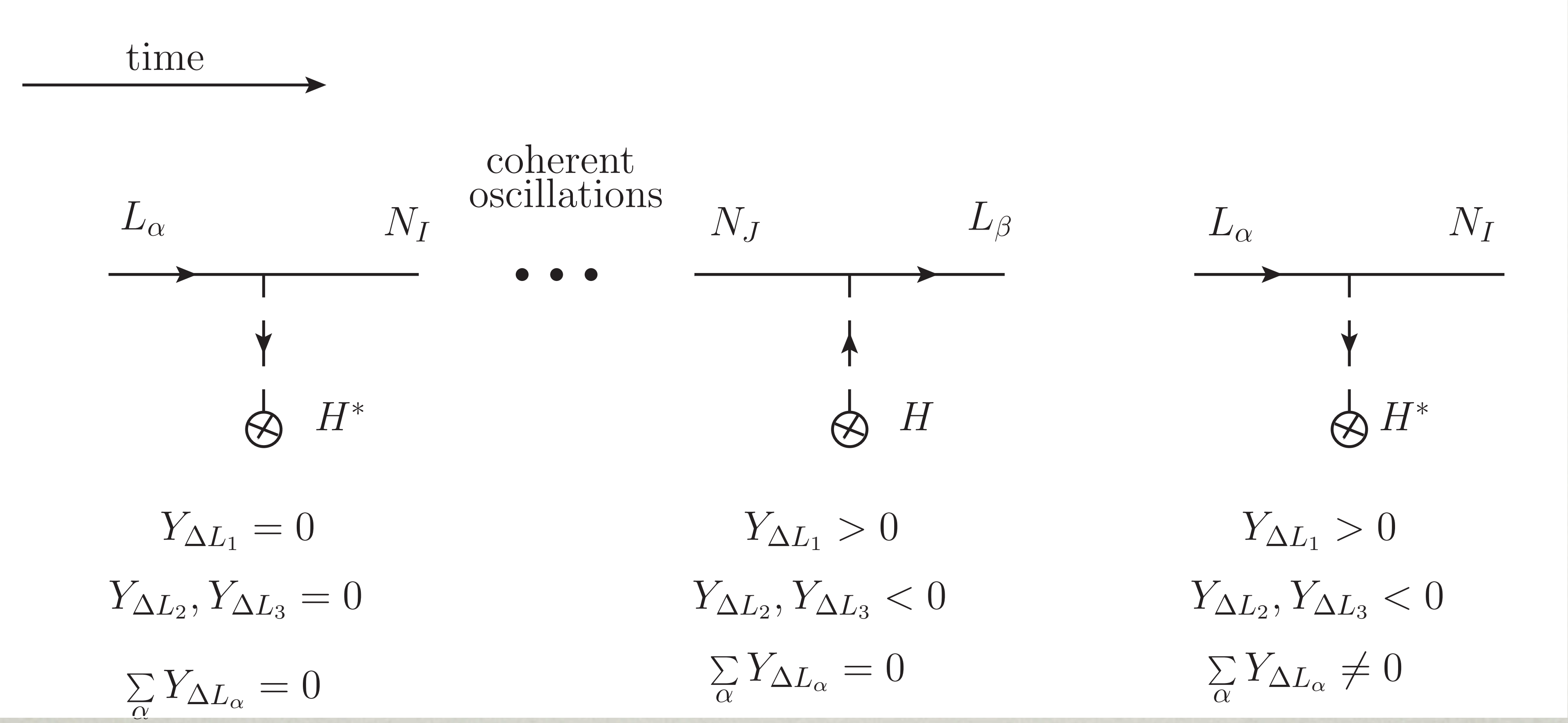
- So far, there is no net lepton asymmetry, and no baryon asymmetry
  5. An asymmetry in L_α automatically implies a faster rate for $L_\alpha \to N$ than $\bar{L}_\alpha \to \bar{N}$
  6. This results in a non-zero SM lepton number asymmetry, which is transferred to baryon number by sphalerons
  7. The electroweak phase transition shuts off sphaleron processes, freezing in the baryon asymmetry

$$\Gamma(L_{\rm tot} \to N) - \Gamma(\bar{L}_{\rm tot} \to \bar{N}) = \sum_\alpha Y_{\Delta L_\alpha} \Gamma(L_\alpha \to N)$$



Symmetry Violation

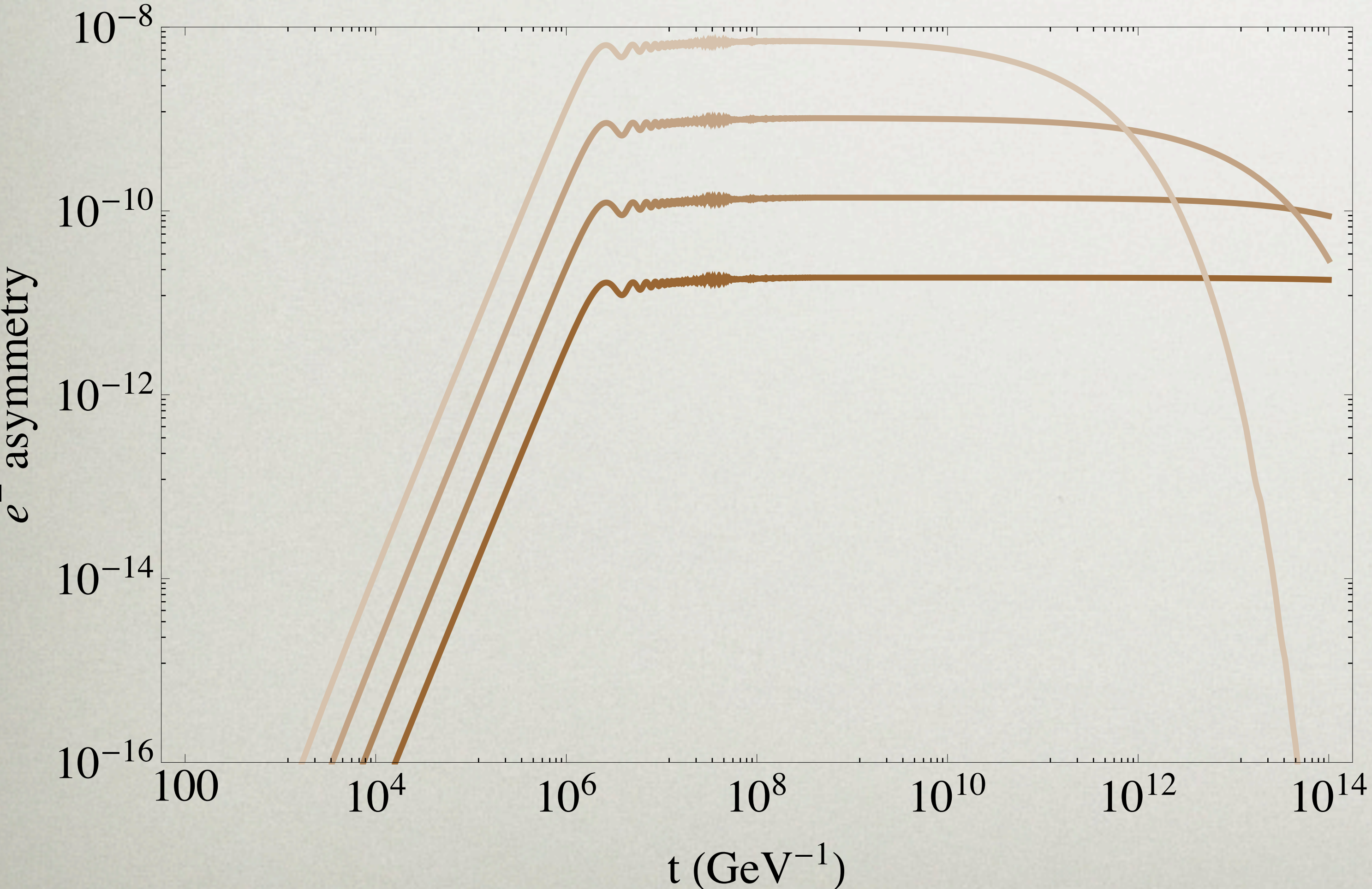
- Through all of these interactions, a global $L + N$ symmetry is preserved
  - Equal and opposite asymmetries in L and N
  - There is also explicit violation of this symmetry through the N Majorana mass, but effects are suppressed by $(M_N / T)^2$
  - When N and L all come into equilibrium, the asymmetry is destroyed



Asymmetry Generation

- What factors control the size of the final baryon asymmetry?
  - **Yukawa couplings.** The larger the Yukawa couplings, the larger the scattering rates
  - Larger F means larger individual lepton flavour asymmetries
  - Rate of individual lepton flavour → total lepton asymmetry also faster

$$\frac{n_{\Delta L,\alpha}}{s} \sim \frac{M_{\rm Pl}^{4/3}}{(M_3^2 - M_2^2)^{2/3}} \mathrm{Im}\left[(FF^\dagger)^2\right]_{\alpha\alpha}$$

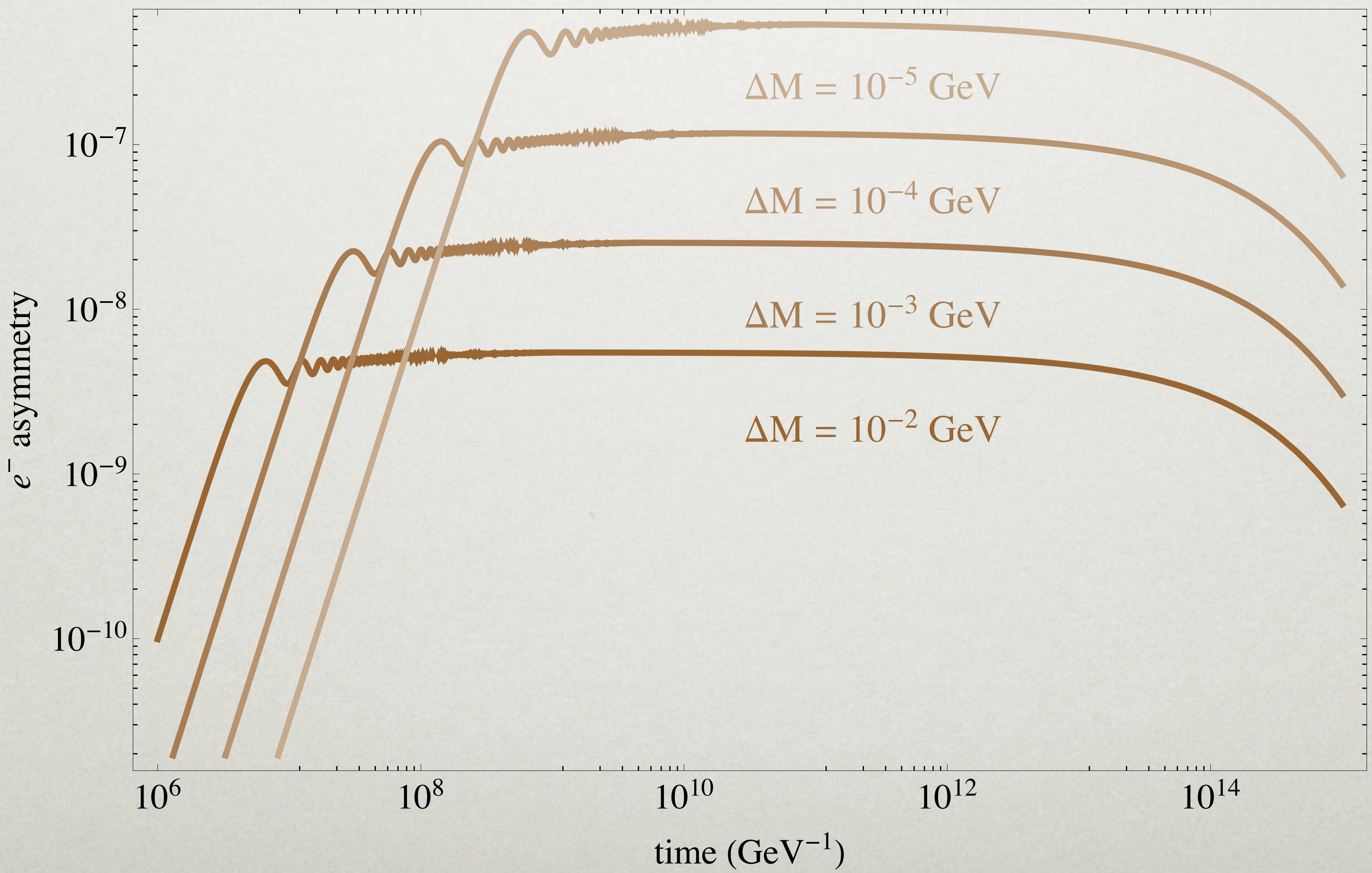


lighter colour =
larger Yukawa coupling

Asymmetry Generation

- What factors control the size of the final baryon asymmetry?
  - **Mass splittings.** The asymmetry is predominantly generated over the first oscillation. At later times, the Hubble expansion is slower, and so there is a longer time for an asymmetry to develop.

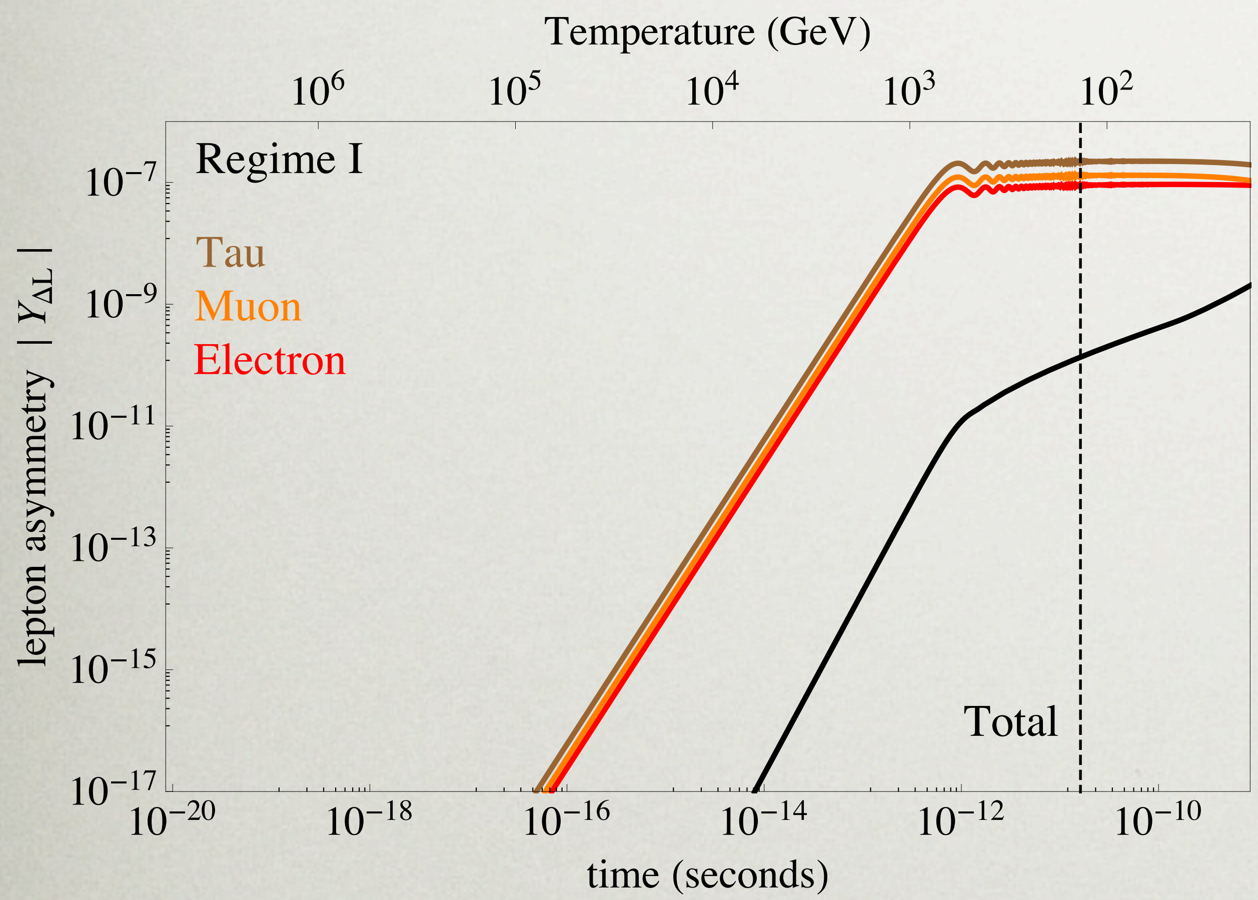
$$\frac{n_{\Delta L,\alpha}}{s} \sim \frac{M_{\rm Pl}^{4/3}}{(M_3^2 - M_2^2)^{2/3}} \mathrm{Im}\left[(FF^\dagger)^2\right]_{\alpha\alpha}$$



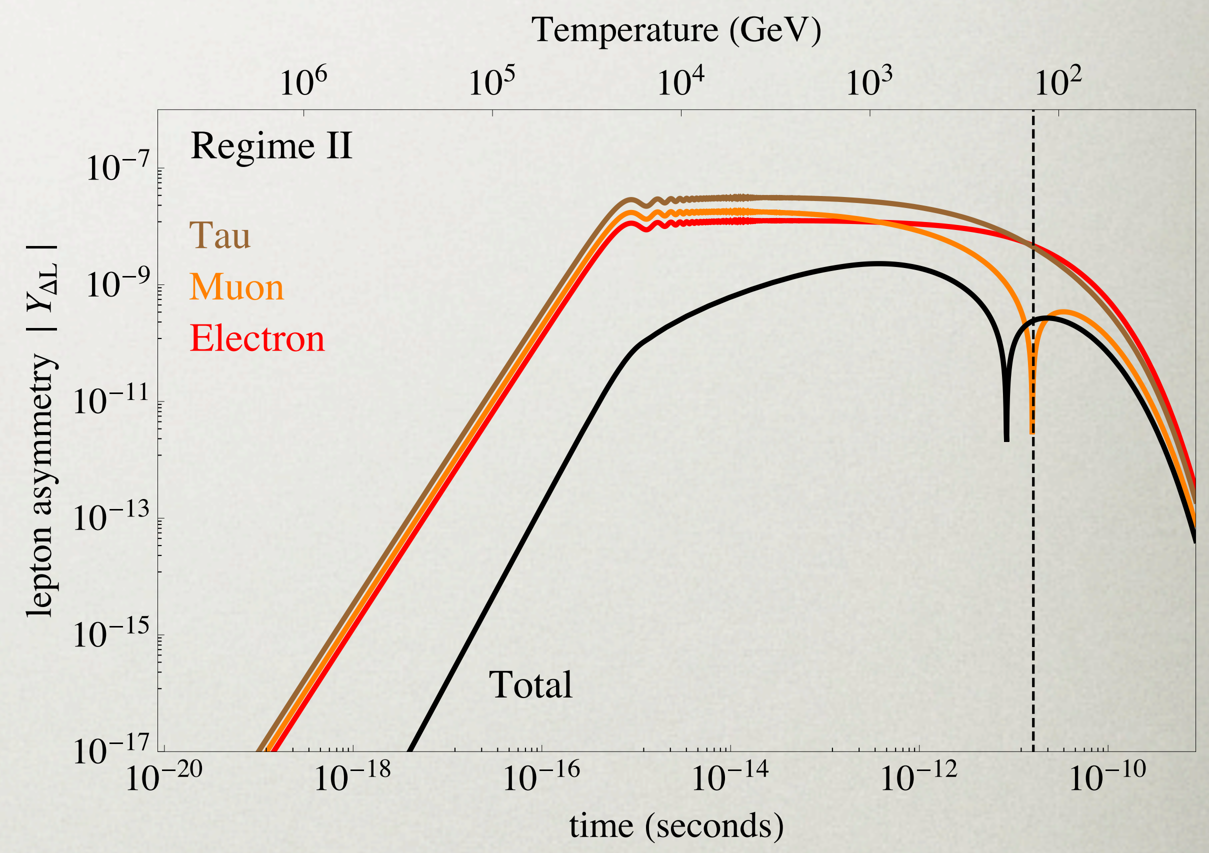
Asymmetry Generation

- Put this all together: three time scales $t_{\rm osc}$, $t_{\rm w}$, $t_{\rm eq}$
- Asymmetry at EW scale fixed to give observed baryon asymmetry

Regime I: $t_{\rm osc} < t_{\rm w} < t_{\rm eq}$



Regime II: $t_{\rm osc} < t_{\rm eq} \sim t_{\rm w}$



$$t_{\rm eq} \sim \frac{1}{|F|^2 T} \qquad t_{\rm osc} \sim \left(\frac{\sqrt{M_{\rm Pl}}}{M_3^2 - M_2^2}\right)^{2/3} \qquad t_{\rm w} \approx (140\ {\rm GeV})^{-1}$$

Model Parameterization

$$(m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- Naïvely, the masses determine the Yukawa coupling magnitudess
- The see-saw fixes FF^{T}, not $FF^\dagger$
    - If there is a large cancellation between real/imaginary terms, then $FF^{\mathrm{T}} \ll FF^\dagger$
    - Yukawa rates can be much larger than naïve see-saw values
  - The Yukawa couplings can be parameterized by:
    1. Two LH neutrino masses and two RH neutrino masses
    2. Three LH real mixing angles and two LH *CP* phases: Majorana (η) and Dirac (δ)
    3. One complex RH mixing angle (ω)

$$FF^\dagger \sim \frac{m_\nu\, M_N}{\langle\Phi\rangle^2} \cosh(2\mathrm{Im}\,\omega)$$

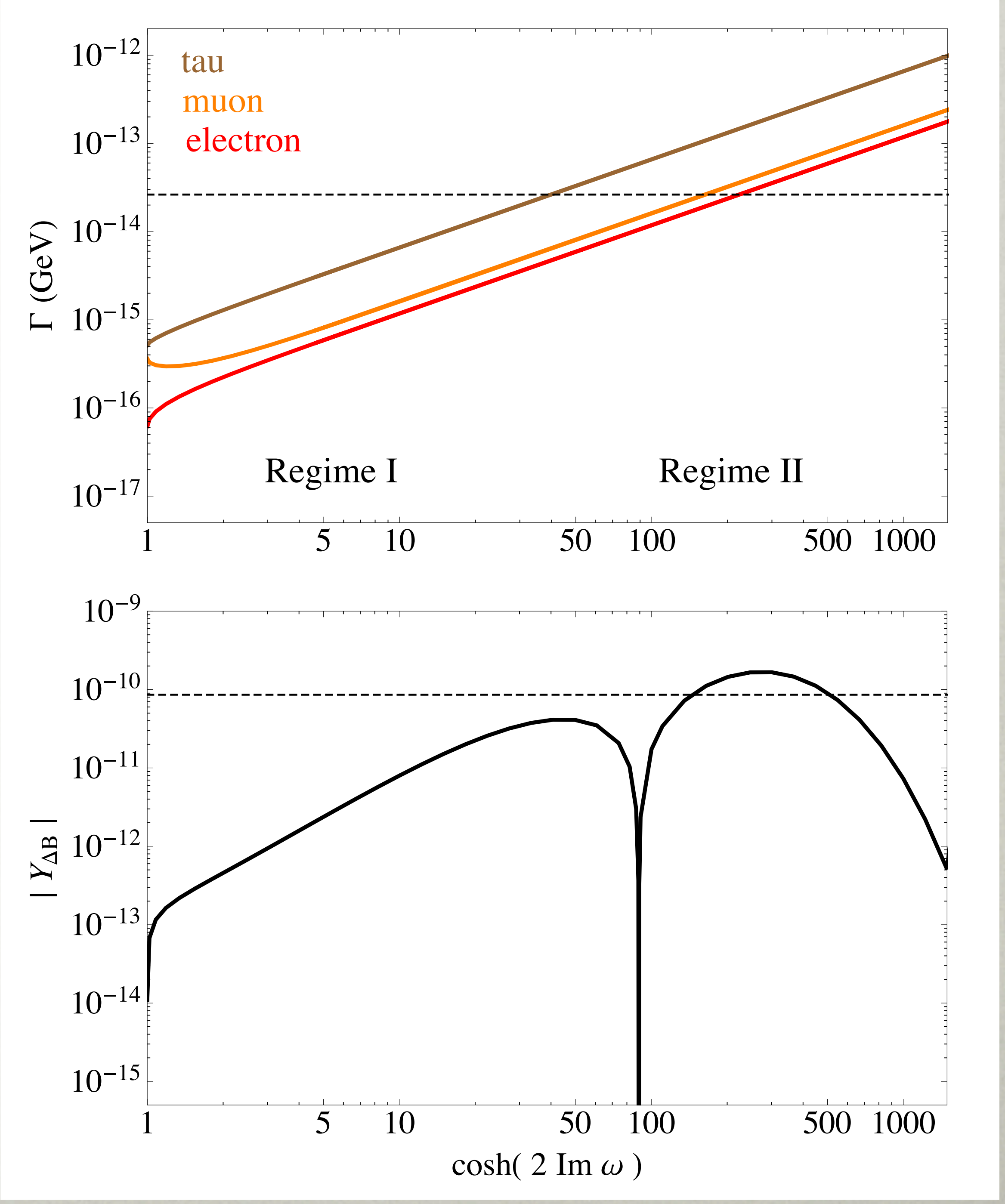
- Large Yukawa rates and small see-saw masses are only consistent due to intricate cancellations between different terms in the Yukawa matrix

$$\frac{d\log m_\nu}{dF} \sim \cosh(2\mathrm{Im}\,\omega)$$

Numerical results

- Indeed, we find that the most generic parts of parameter space ($\Delta M_N \sim M_N$ and $|F|^2 \sim FF^T$) do not produce enough of an asymmetry
  - In fact, both mass degeneracy and tuned Yukawas are generally needed in the minimal model
- Ex: $M_N = 1$ GeV

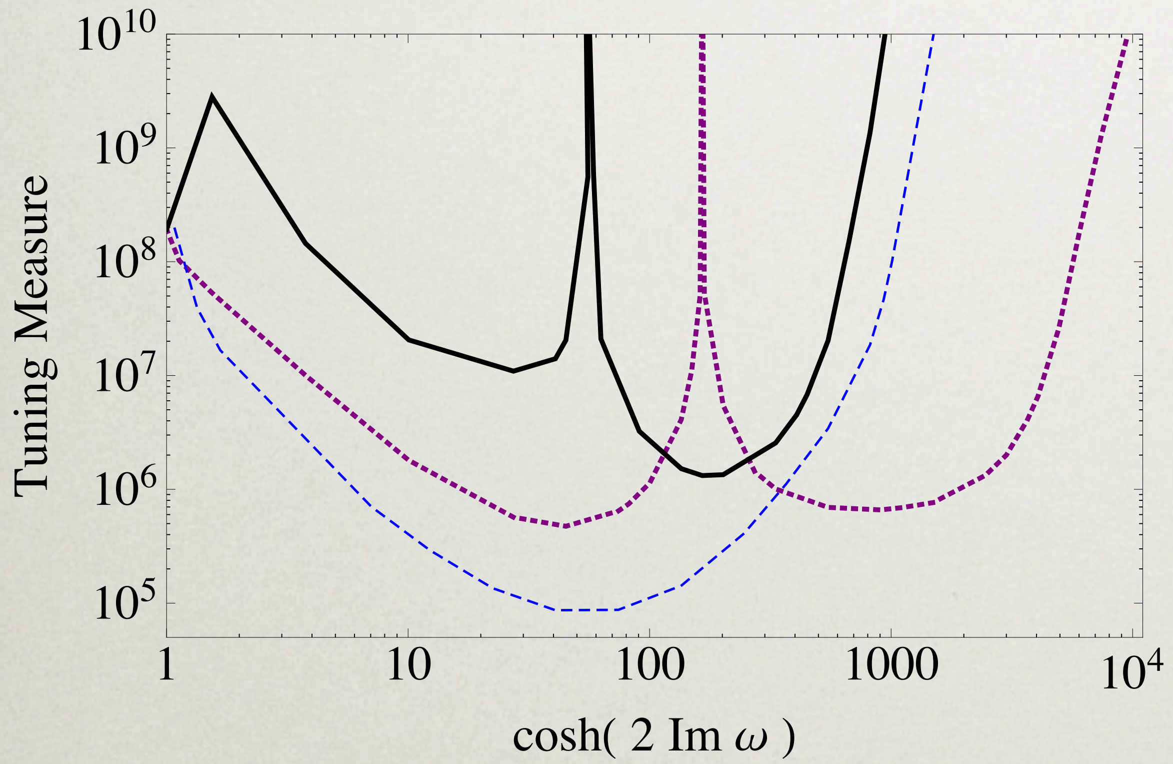
$\Delta M = 10^{-5}$
$\eta = -\pi/4$
$\delta = 3\,\pi/4$
$\mathrm{Re}\,\omega = \pi/4$



Numerical results

$$\text{tuning/alignment} = \frac{M}{\Delta M}\cosh(2\mathrm{Im}\,\omega)$$

- For each point in parameter space, we find ΔM_N and $\mathrm{Im}(\omega)$ needed to get observed baryon asymmetry
- No part of the parameter space is more generic than 1 part in 10^5
    - Most of the parameter space is much more so



Black	**Purple**	**Blue**
$\eta = \pi/4$	$\eta = -\pi/4$	$\eta = 2.42$
$\delta = \pi/4$	$\delta = -\pi/4$	$\delta = 0.5$
$\mathrm{Re}\omega = \pi/4$	$\mathrm{Re}\omega = \pi/4$	$\mathrm{Re}\omega = \pi/2$

- Changing M_N also does not substantially affect the result
    - Larger mass raises Yukawa coupling but requires more mass degeneracy (and vice-versa)

Baryogenesis through neutrino oscillations

Two Higgs doublet model

Yukawas in a 2HDM

$$(m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- Up until now, we have been assuming $\Phi = \Phi_{\mathrm{SM}}$
  - Tuning required to increase Yukawa couplings for fixed masses
- If $\langle\Phi\rangle < \langle\Phi\rangle_{\mathrm{SM}}$, the Yukawas are naturally larger than in the conventional see-saw
- **Our proposal:** a leptophilic two Higgs doublet model
  - "Leptophilic" - SM-like Higgs doublet couples to quarks, new Higgs doublet couples to leptons
  - Smallness of charged lepton masses can be a consequence of small VEV for leptophilic Higgs
- This immediately alleviates some of the needed alignment. But we saw that, even when the Yukawa couplings were optimally tuned, we still needed degenerate sterile neutrinos

Speculation of 2HDM in νMSM also in **Drewes, Garbrecht 2012**

Yukawas in a 2HDM

$$\text{asymmetry creation rate} \sim \mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right] \sim \frac{m_\nu^2 M_N^2}{\langle\Phi\rangle^4}\cosh(2\mathrm{Im}\,\omega)$$

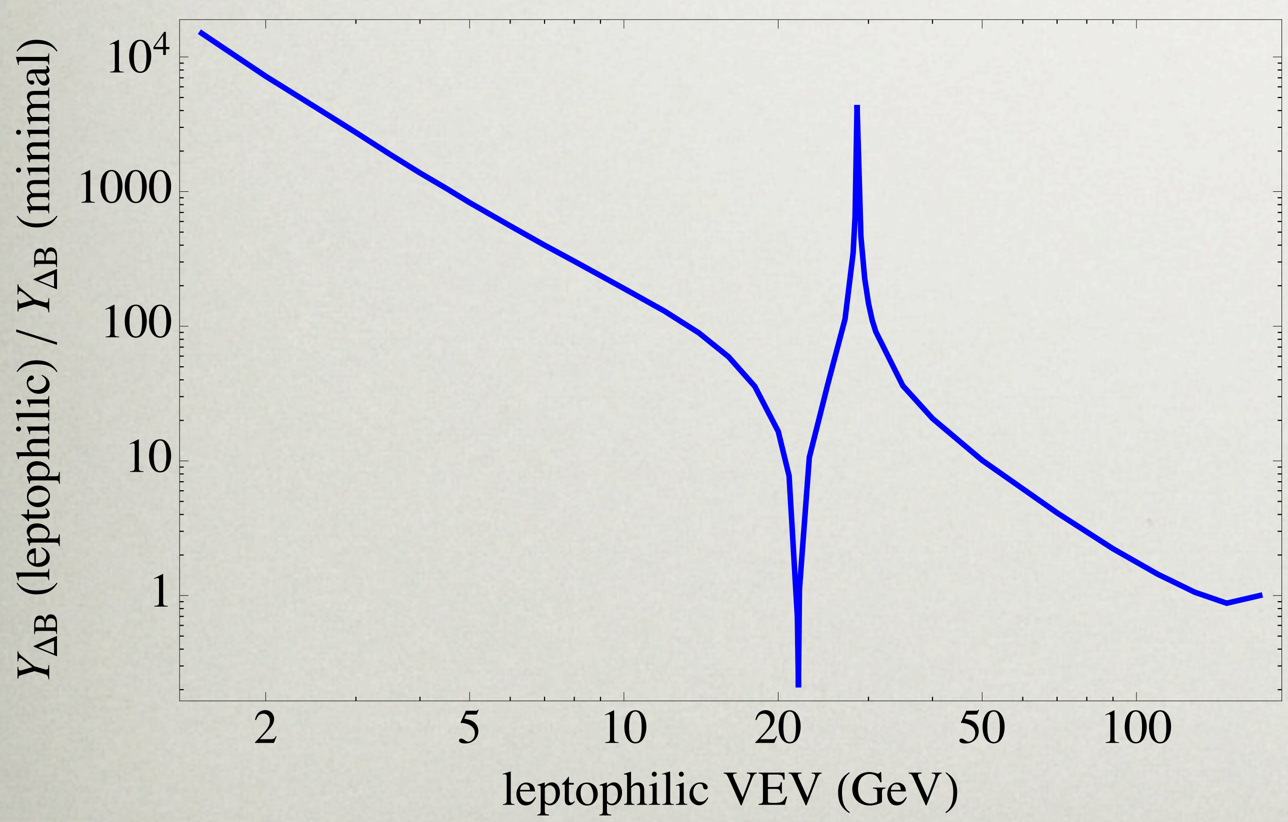
$$\text{asymmetry equilibration rate} \sim FF^\dagger \sim \frac{m_\nu M_N}{\langle\Phi\rangle^2}\cosh(2\mathrm{Im}\,\omega)$$

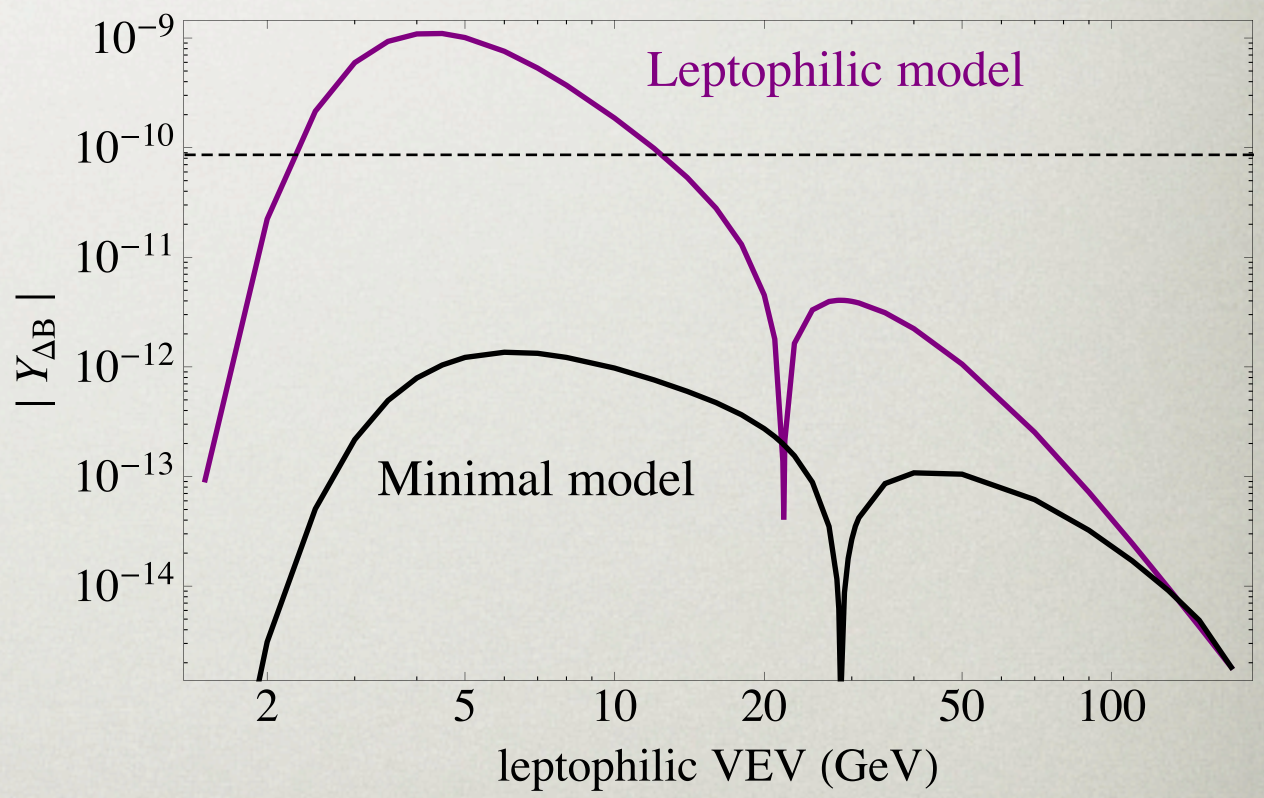
- In the asymmetry creation rate, there is a partial cancellation of the Yukawa couplings when the couplings are tuned to be large
  - Related to the cancellation that ensures validity of the see-saw relation
- The asymmetry from tuned Yukawa couplings is not as large as you would expect
  - Larger Yukawa couplings from a smaller Higgs VEV gives a quadratic enhancement of the baryon asymmetry over the tuned model

Baryogenesis and a 2HDM

- Depending on leptophilic VEV, can get observed baryon asymmetry with:
  - Non-degenerate spectrum
  - No tuning of the Yukawa couplings needed
  - Generic phases OK (1/2 - 1/3 of total parameter space)

$M_2 = 0.5$ GeV
$M_3 = 1.5$ GeV
$\omega = \pi/4 + i$
$\eta = \delta = -\pi/4$





2HDM Phenomenology

- Connection between enhanced baryon asymmetry and extended Higgs sector
- Can probe through modification to the SM-like Higgs tau Yukawa coupling
    - Current bound is 225 GeV; reach of 300 GeV with LHC 300/fb, 700 GeV with ILC
- Can also search directly for the heavy Higgs states
    - A promising channel is same-sign dileptons + hadronic tau(s)
        - Bound is $M_H \gtrsim 150$ GeV (**Liu, Shuve, Weiner, Yavin 2013**)
- There is also the possibility that the leptophilic Higgs only gives mass to the neutrinos
    - Heavy Higgs states decay through the neutrino Yukawa to mu/tau + neutrino
    - Bound of $M_H \gtrsim 300$ GeV from slepton searches

Baryogenesis Summary

- Baryogenesis through neutrino oscillations is an interesting possibility with different parametric dependence than other baryogenesis mechanisms

- Baryogenesis in the minimal νMSM involves alignments and/or tuning of parameters to greater than one part in 10^5 (usually more)
    - However, nothing inherent to the mechanism requires mass degeneracy

- The baryon asymmetry can be greatly enhanced in models with two Higgs doublets if the Higgs coupling to sterile neutrinos has a small VEV

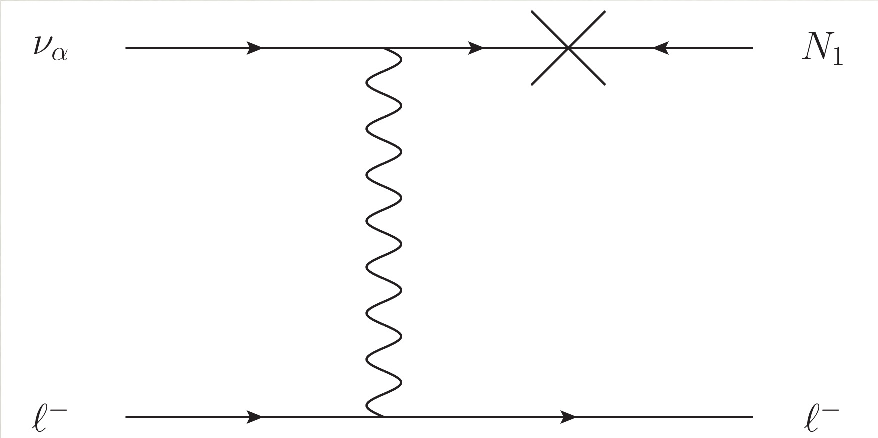
- Generic spectra give the observed baryon asymmetry in a 2HDM, and there are also improved prospects for detection

Sterile neutrino dark matter

Minimal model

Sterile neutrino DM

- The lightest sterile neutrino (N_1) is the dark matter
- The production and decay in the minimal model is completely determined by its mass and mixing with LH neutrinos
- **Production:**
  - N_1 is produced through mixing whenever SM leptons undergo weak interactions (**Dodelson, Widrow 1992**)



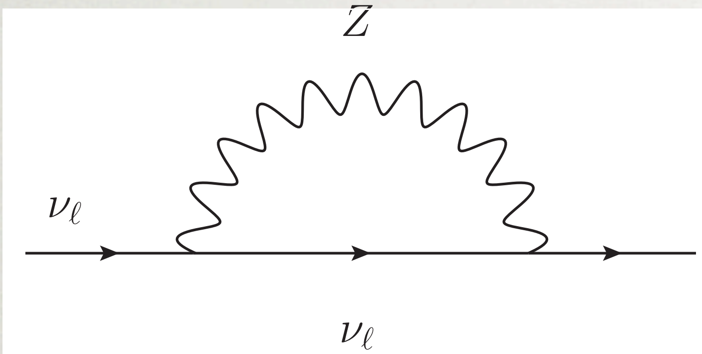
$$\theta_{\alpha 1} = \frac{F_{\alpha 1}\langle\Phi\rangle}{M_1}$$

$$\Gamma_N \sim \sum_\alpha \sin^2\theta_{\alpha 1}\cos^2\theta_{\alpha 1}\, G_{\mathrm{F}}^2 T^5$$

  - At the time of N_1 production, the mixing angle is modified by MSW medium effects due to SM neutrino propagation through the thermal bath (**Wolfenstein 1978; Mikheyev, Smirnov 1985**)

Sterile neutrino production

- The SM neutrino propagating modes have contributions to the finite-T potential from weak interactions (**Nötzold, Raffelt 1988**)

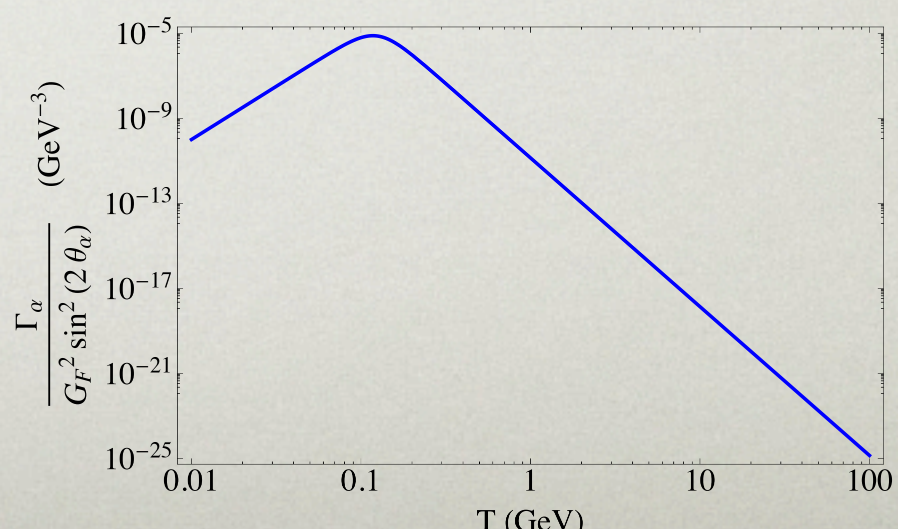


$$V_\nu \approx 2\sqrt{2}G_{\mathrm{F}}(N_\nu - N_{\bar{\nu}}) - \frac{7\pi}{90\alpha}\sin^2(2\theta_{\mathrm{W}})G_{\mathrm{F}}^2 T^4 E_\nu$$

$$\sin^2(2\theta_{\mathrm{m},\alpha 1}) = \frac{\sin^2(2\theta_{\alpha 1})}{\sin^2(2\theta_{\alpha 1}) + \left(\cos 2\theta_{\alpha 1} - \frac{2V_{\nu,\alpha}E}{M_{N_1}^2}\right)^2} \approx \frac{\sin^2(2\theta_{\alpha 1})}{\left[1 + 0.27c_\alpha(\frac{T}{100\ \mathrm{MeV}})^6\left(\frac{\mathrm{keV}}{M_{N_1}}\right)^2\right]}$$

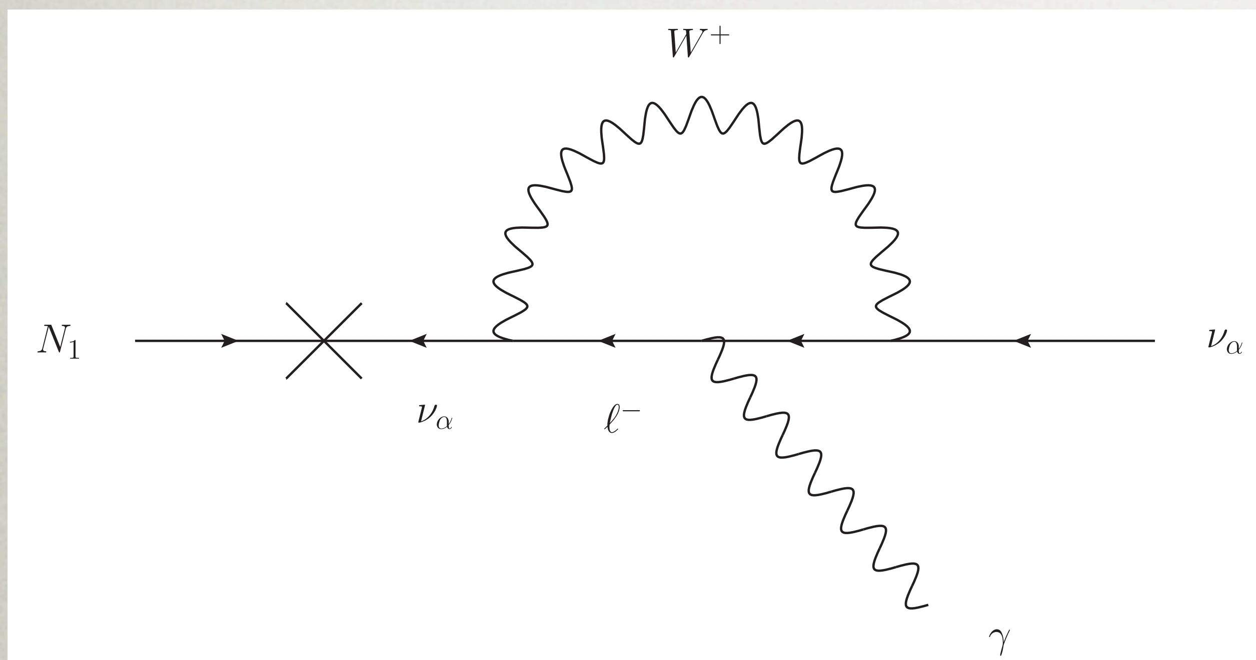
- Competing temperature effects from scattering rate & mixing (no asym.)
  - Ex: 1 keV sterile neutrino, no lepton asymmetry

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



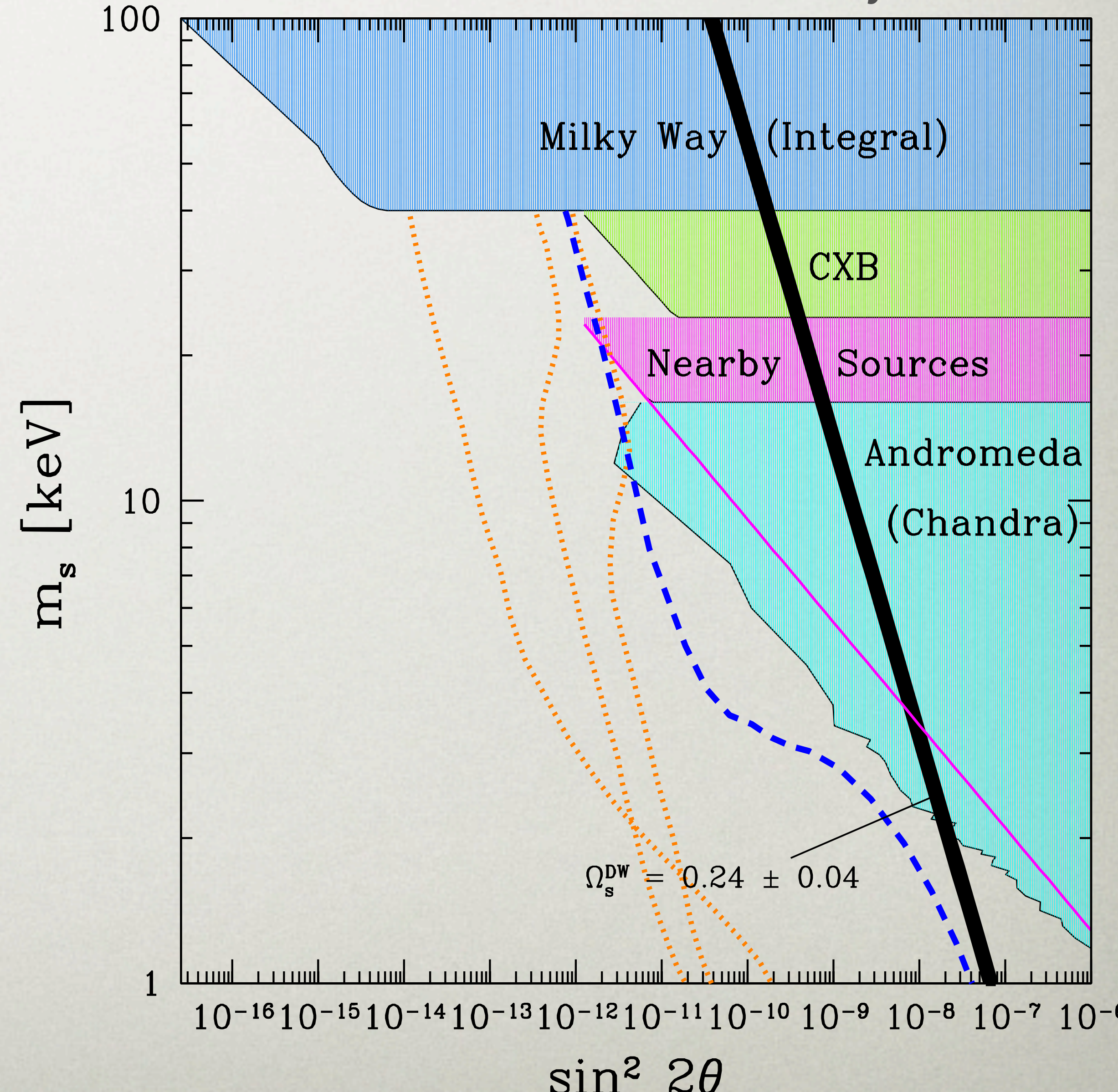
Sterile neutrino DM

- **Decay**: Sterile neutrino also decays through the same (vacuum) mixing
- If N_1 makes up all DM, most constrained decay is to neutrino + photon (ex. **Abazajian, Fuller, Tucker 2001**)
    - Monochromatic X-ray line at $M_{N1}/2$



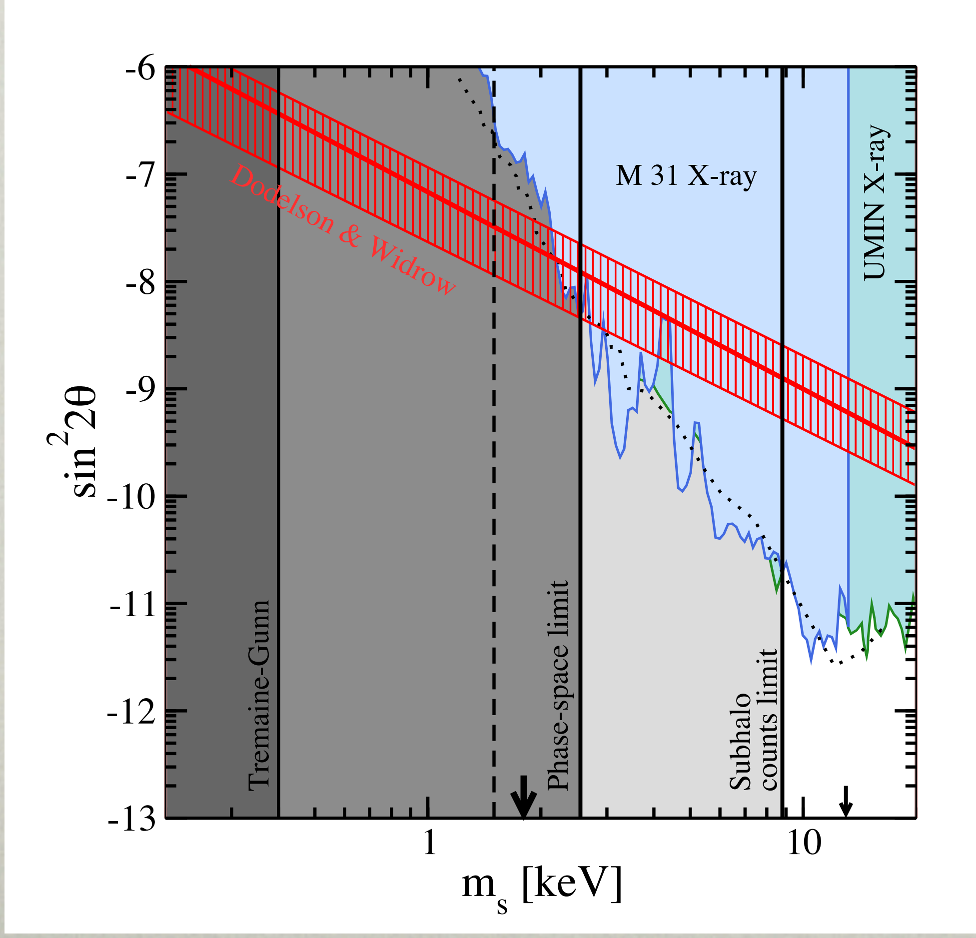
$$\tau_{N_1\to\gamma\nu} \sim 5\times 10^{22}\ \mathrm{s}\left(\frac{1}{\sum_\alpha \sin^2 2\theta_{\alpha 1}}\right)\left(\frac{0.5\ \mathrm{keV}}{M_{N_1}}\right)^5$$

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



Sterile neutrino production

- The mixing angles giving the observed DM abundance are ruled out by X-ray constraints for $M_N \gg$ keV
- For mass ~ keV, sterile neutrinos are warm DM
  - Small-scale structure constraints: Lyman-α, sub-halo counting, etc.
  - Thermally produced sterile neutrinos conservatively ruled out below ~8.8 keV (**Horiuchi *et al.* 2013**) for Dodelson-Widrow production
  - Dodelson-Widrow mechanism is completely excluded!



Taken from **Horiuchi *et al.* 2013**

Resonant production

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

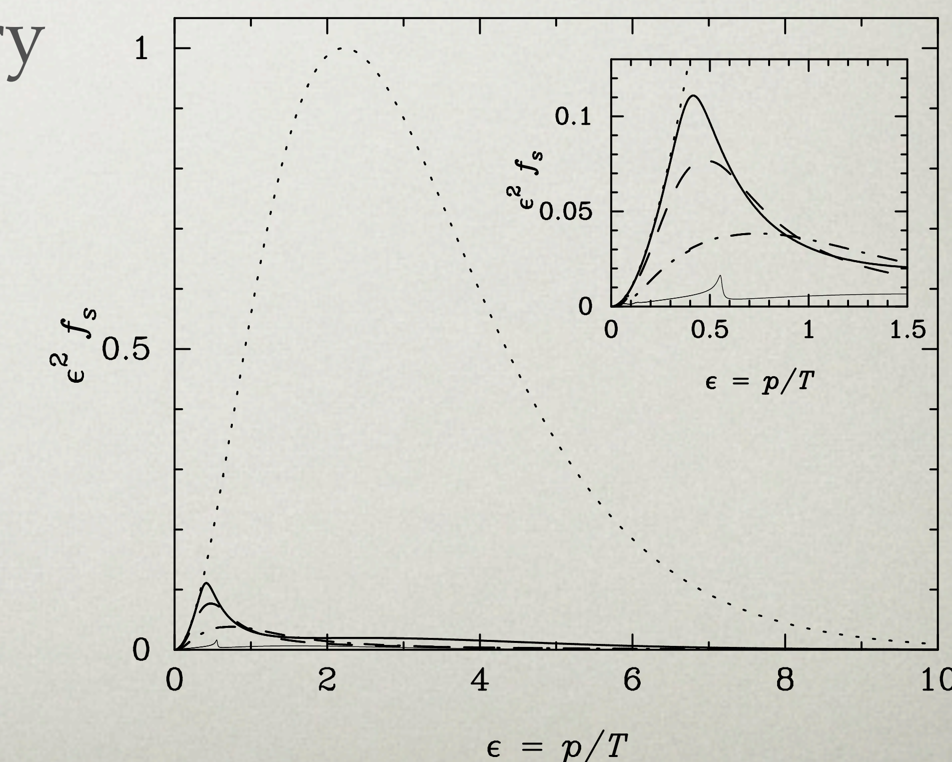
$$V_\nu \approx 2\sqrt{2}G_\mathrm{F}(N_\nu - N_{\bar{\nu}}) - \frac{7\pi}{90\alpha}\sin^2(2\theta_\mathrm{W})G_\mathrm{F}^2T^4E_\nu$$

$$\sin^2(2\theta_{\mathrm{m},\alpha1}) = \frac{\sin^2(2\theta_{\alpha1})}{\sin^2(2\theta_{\alpha1}) + \left(\cos 2\theta_{\alpha1} - \frac{2V_{\nu,\alpha}E}{M_{N_1}^2}\right)^2}$$

  - 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

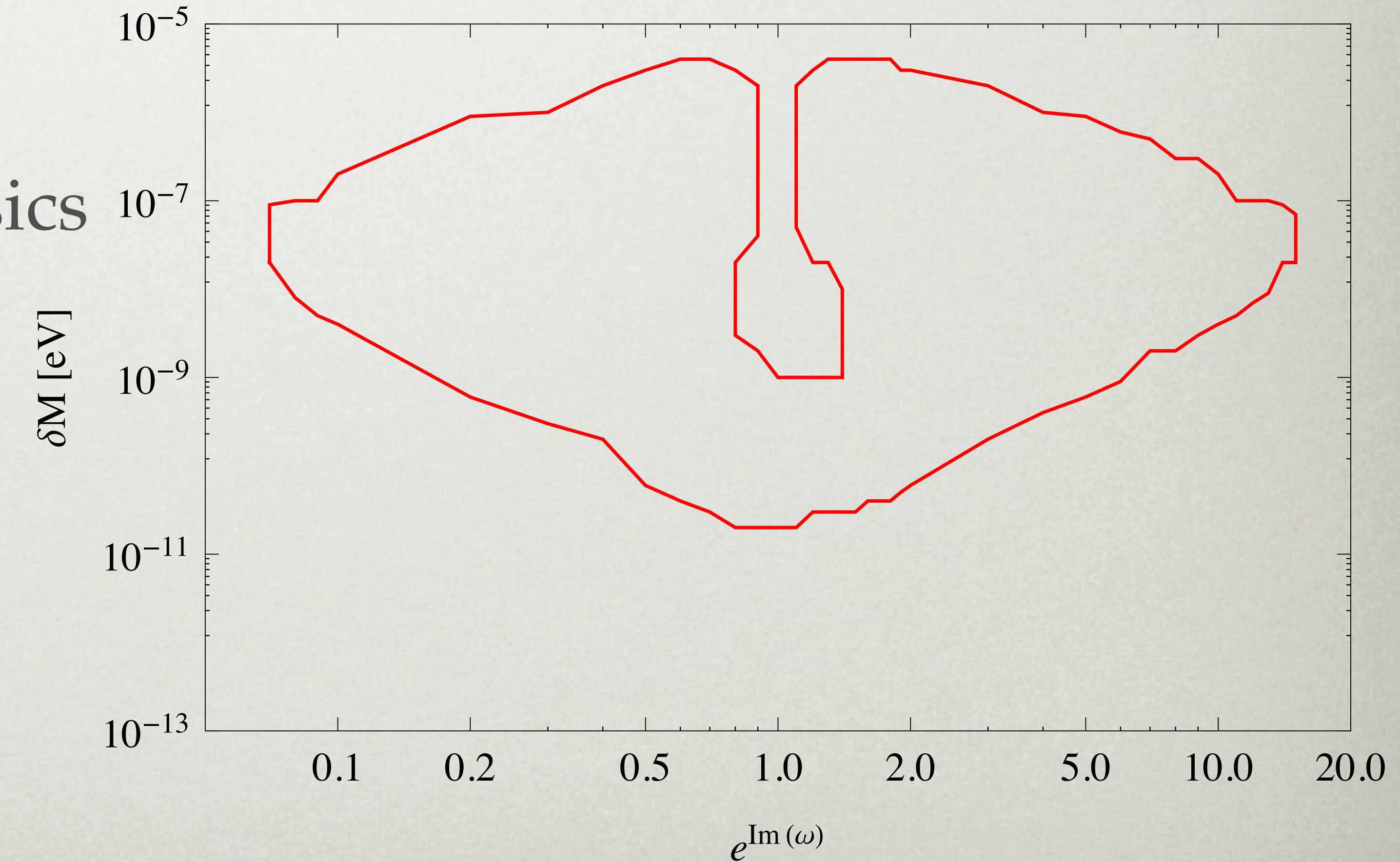
$$\frac{E_{\nu,\mathrm{res}}}{T} \approx 0.1245\left(\frac{M_N^2\cos 2\theta}{\mathrm{keV}^2}\right)\left(\frac{10^{-2}}{\mathcal{L}}\right)\left(\frac{100\ \mathrm{MeV}}{T}\right)^4$$



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

Resonant production

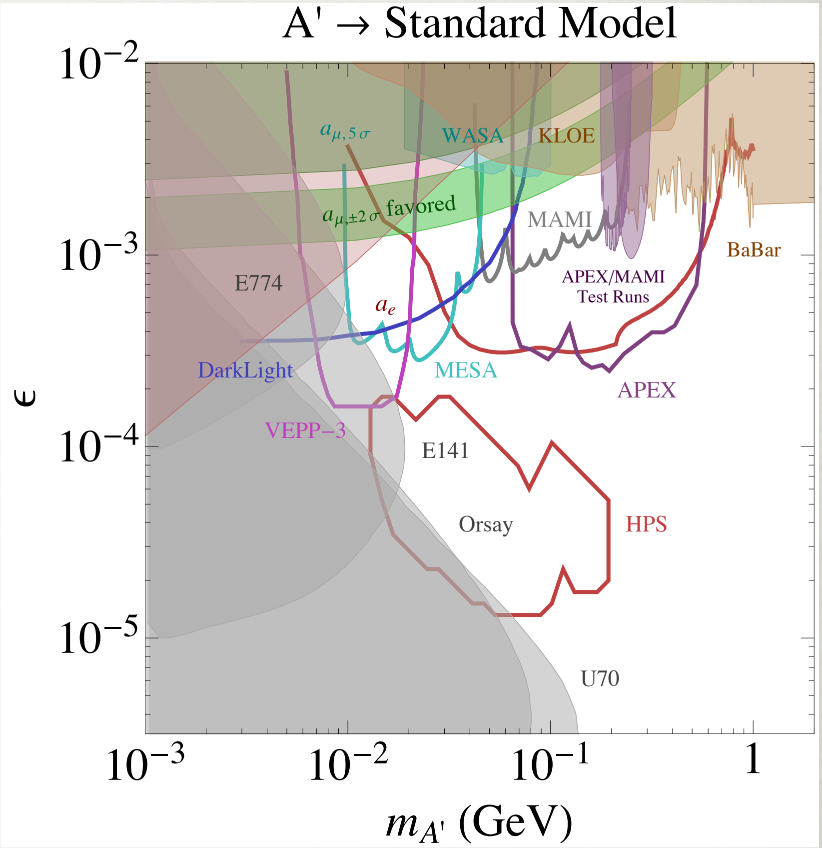
- Can occur for lepton asymmetries ≳ 10^{-5}
  - Need large asymmetry from leptogenesis below weak scale
  - Achieved in the minimal model through resonant leptogenesis from the heavier sterile neutrinos; highly degenerate spectrum needed
  - Shown at right: N_2 and N_3 are 10 GeV, from **Canetti *et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



Sterile neutrino dark matter

New SM neutrino interactions

New interactions



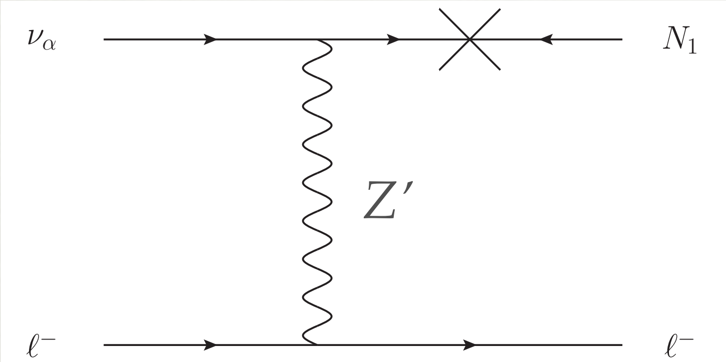
Taken from **Adrian *et al.* 2013**

- Much recent attention on the possibility of new, light forces
- If the new forces couple to LH leptons, we automatically get *N* production as well (à la Dodelson-Widrow)
- **Our proposal:** Consider a new force coupled to the SM-like neutrinos that is stronger than the weak interactions
  - Can produce more sterile neutrinos while satisfying mixing angle bounds
- For concreteness, we consider a new anomaly-free U(1)′ gauge interaction
  - We use $U(1)_{\mu\text{-}\tau}$; different currents simply change constraints on gauge boson
  - For concreteness, we assume mixing is predominantly between *N* and ν_τ

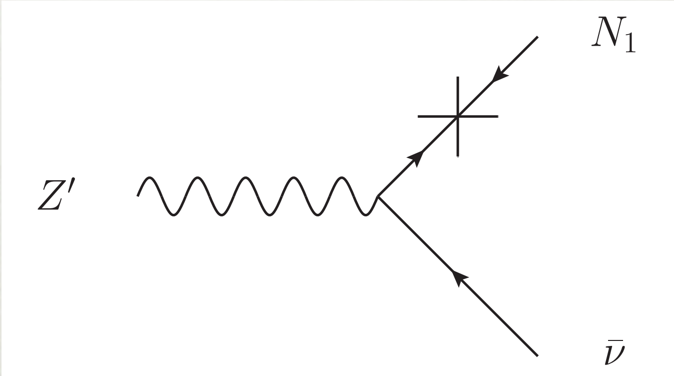
Sterile neutrinos from Z'

- There are two limits to consider:
  - Heavy Z' (> few GeV): contact interaction
    - Need $G' \gg G_F$, ruled out by muon g - 2
  - Lighter Z' (< few GeV): on-shell degrees of freedom present when LH-sterile neutrino mixing becomes large for $T \lesssim$ few hundred MeV

- **On-shell limit:**
  - Sterile neutrino abundance dominated by interactions that are 1 ↔ 2



$$\frac{\Gamma_{1\leftrightarrow 2}}{\Gamma_{2\leftrightarrow 2}} \sim \frac{M_{Z'}}{g_{Z'}^2 T} \gg 1$$



- Similarity to models with production mechanisms in the sterile sector
  - **Shaposhnikov, Tkachev 2006; Petraki, Kusenko 2008; ...**
  - Our model: force couples directly to SM fields and proceeds through mixing (larger coupling/better detection prospects)

Sterile neutrinos from Z'

- As before, we have to consider the thermally corrected mixing angle
    - Can have resonance without lepton asymmetry
    - Resonance develops if: $V^{Z'} = \frac{M_N^2}{2E}\cos 2\theta - V^{\rm SM}$

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

- However, oscillations of active → sterile neutrinos on-resonance are suppressed by the Quantum Zeno effect
    - Rapid interactions mediated by Z' suppress wavefunction overlap that gives oscillation between SM and sterile neutrinos

$$\Gamma_{\nu\to N} \approx \frac{1}{4}\Gamma_\nu \sin^2(2\theta_{\rm m})\,\frac{1}{1+\gamma^2} \qquad \gamma = \frac{\Gamma_\nu}{\Delta E_{\rm osc}} \gg 1$$

- Resonance does not substantially contribute to final N abundance

Sterile neutrinos from Z'

- Dominant contribution to N abundance from non-resonant Z' decays
  - Simplified version of Boltzmann equation (used full BE for numerical analysis)

$$\frac{dY_N}{dx} = \frac{x\langle\Gamma_{Z'\to N}\rangle}{H(M_{Z'})} Y_{Z'} \qquad Y \equiv \frac{n}{s} \qquad x \equiv \frac{M_{Z'}}{T}$$

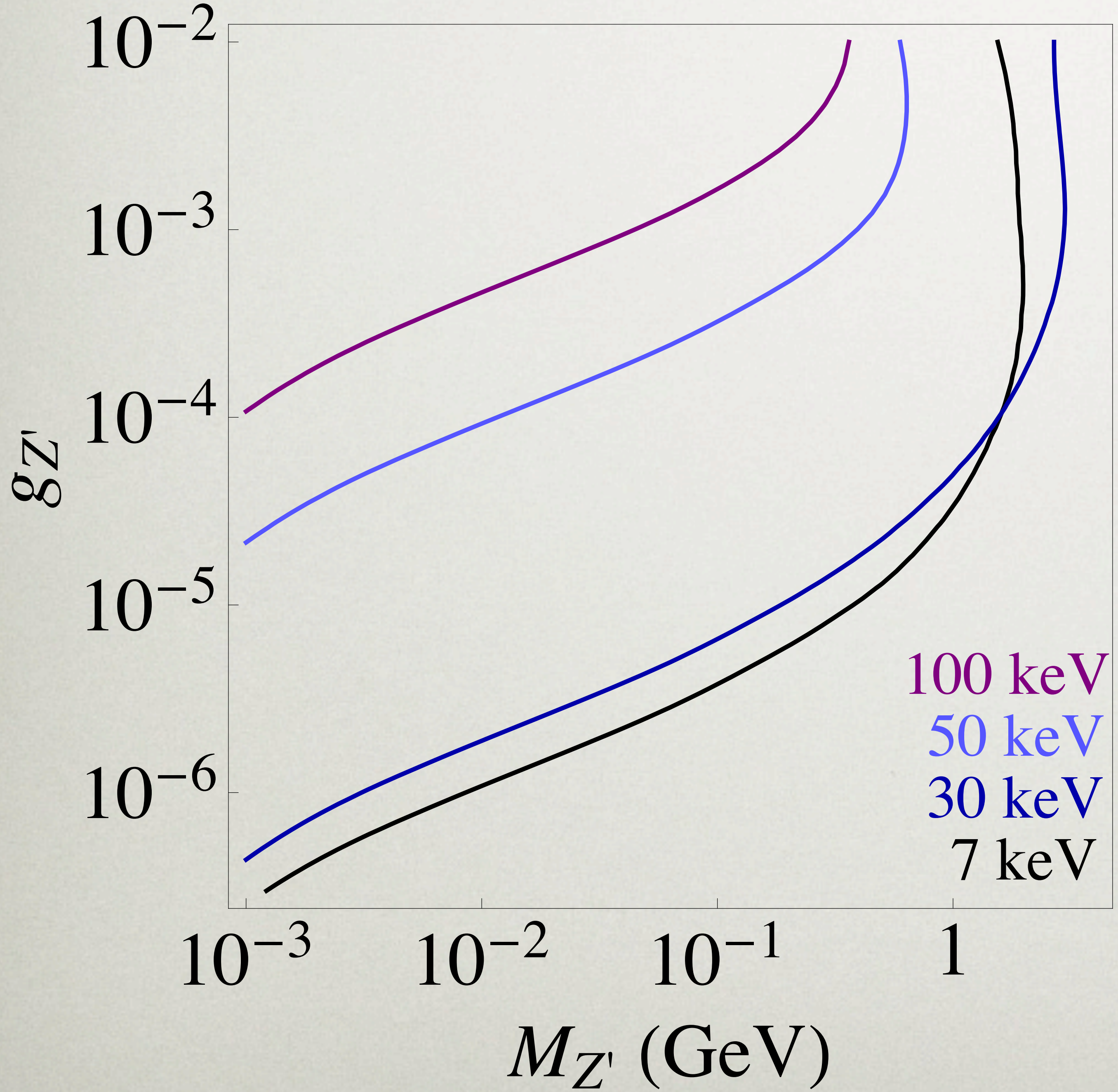
  - Largest production time at x ~ 1-3
  - From dimensional analysis and coupling power counting,

$$Y_N \sim \frac{g_{Z'}^2 \sin^2(2\theta_{\rm m}) M_{\rm Pl}}{M_{Z'}}$$

- This is approx. scaling unless the SM thermal corrections suppress the mixing angle (large Z' mass), or Z' thermal corrections suppress the mixing angle (large coupling)

Results

- Select mixing angles near X-ray bounds for a variety of N masses



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

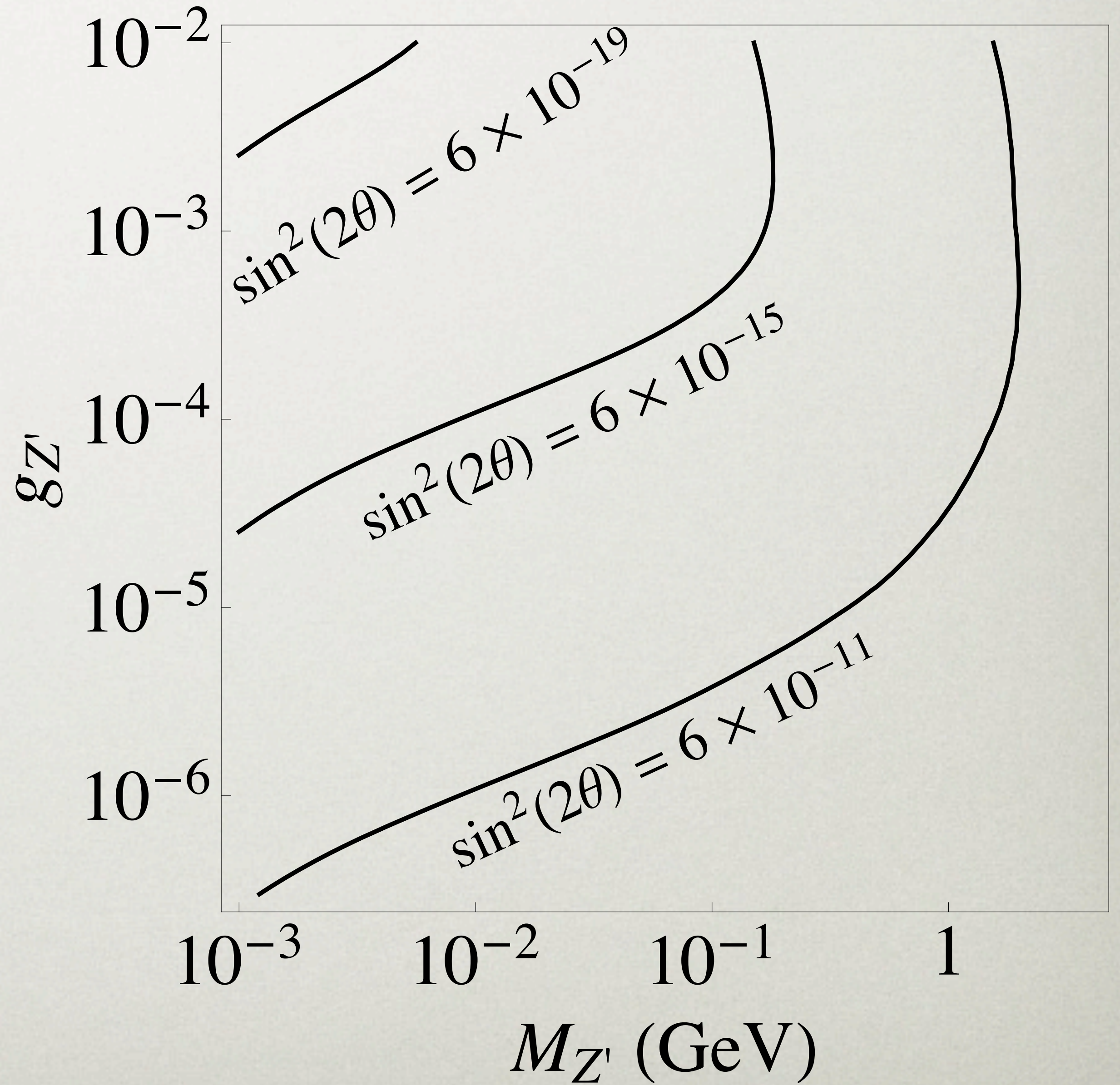
30 keV, $\sin^2(2\theta) = 5 \times 10^{-12}$

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

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

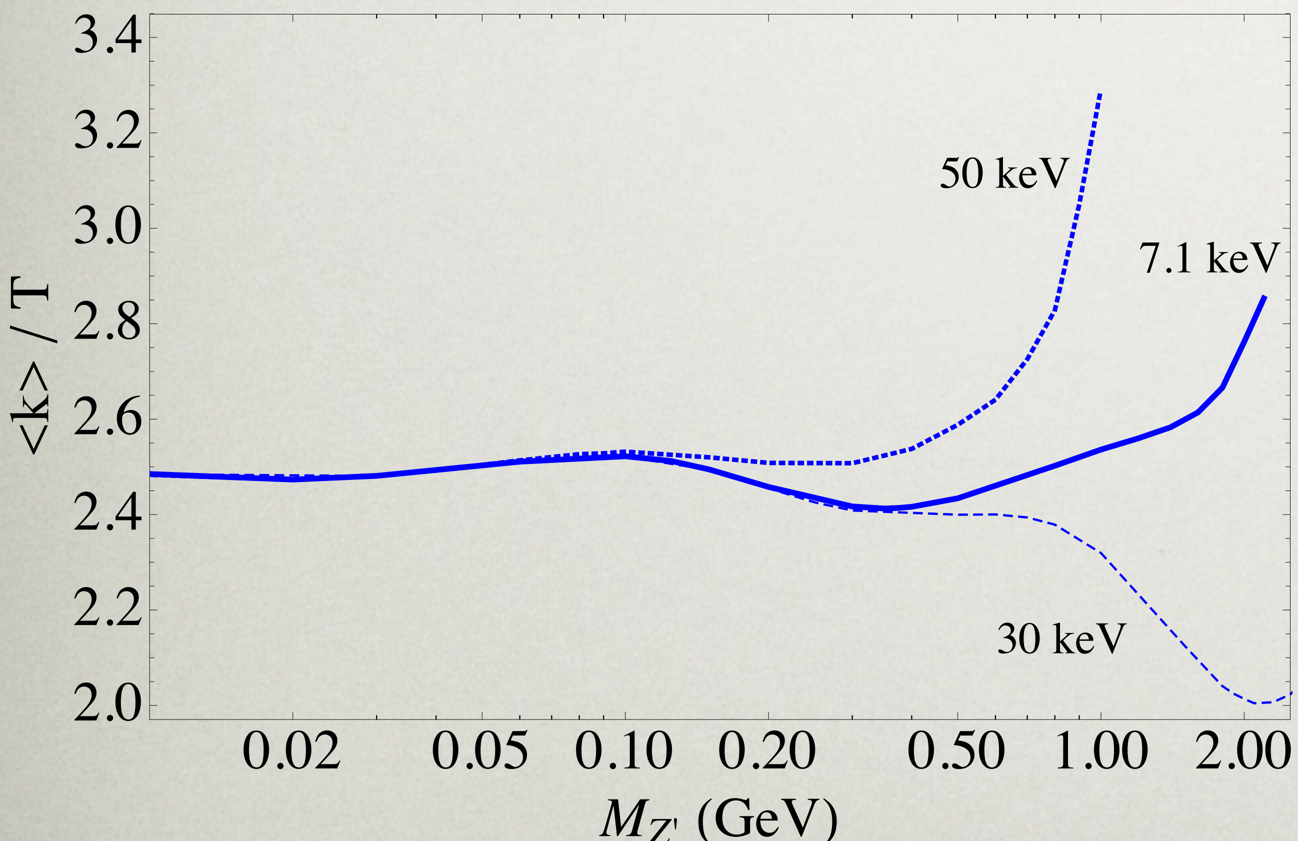
Results

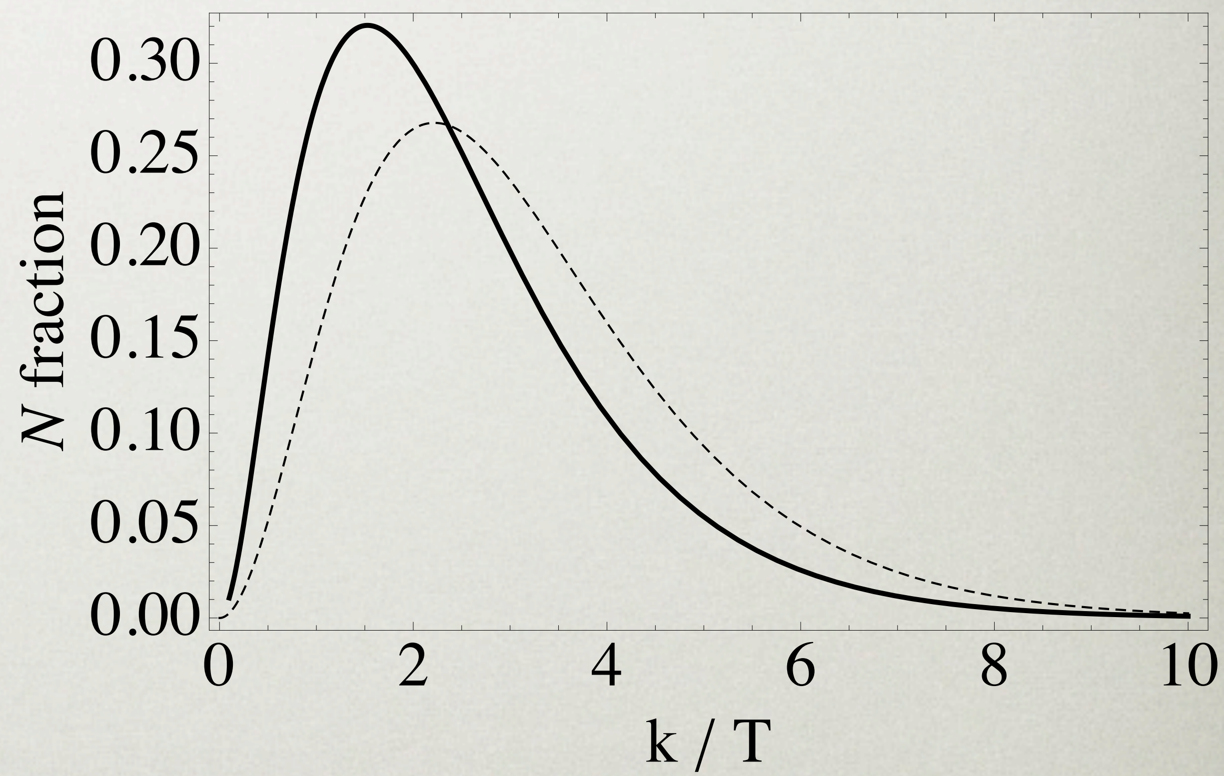
- **Non-resonant production:**
    - Show dependence on mixing angle (7 keV sterile neutrino shown here)
    - Complementarity between direct and astrophysical probes



Results

- Sterile neutrinos can be hot, warm, or cold (**Abazajian, Fuller, Patel 2001**)
- Sterile neutrino spectrum from Z' is often colder than thermal
- I used same mixing angles as before
- Sensitivity to QCD phase transition and thermal effects





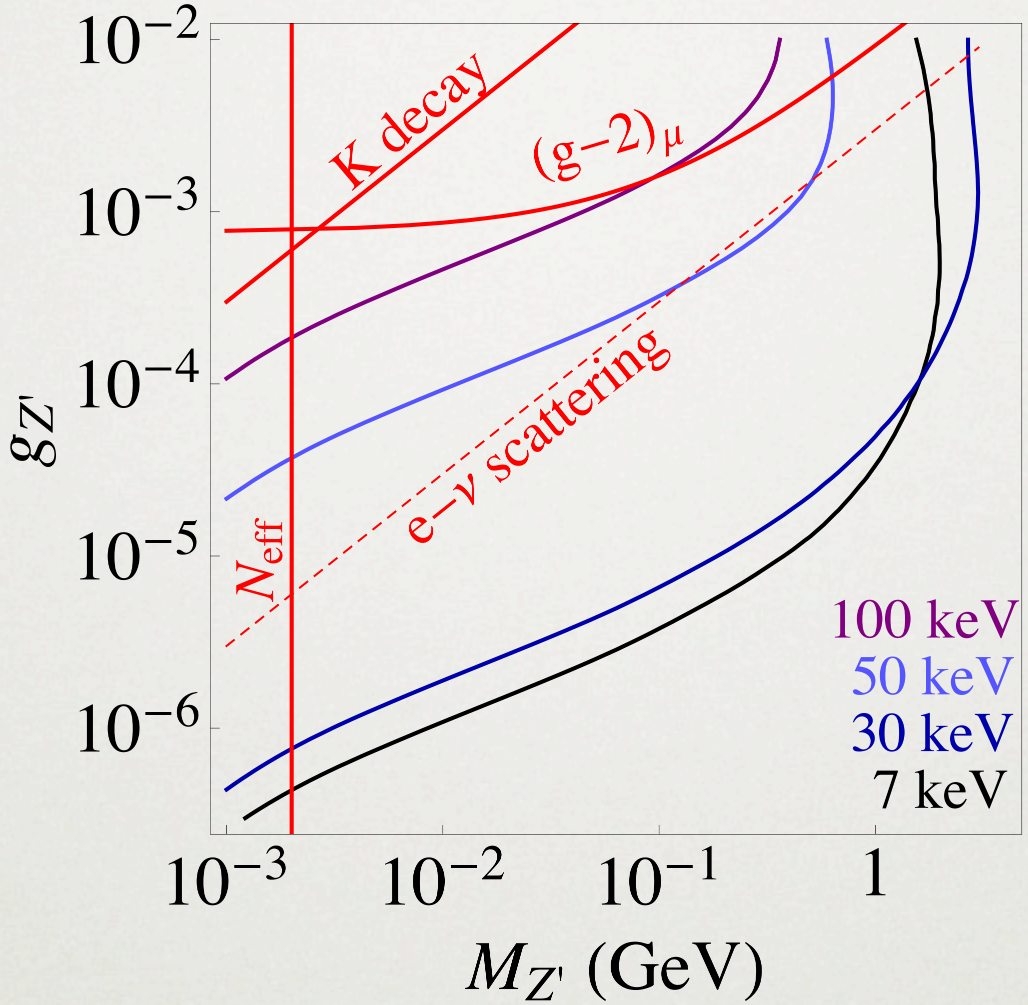
(solid) $M_N = 7.1$ keV, $M_{Z'} = 300$ MeV
(dashed) thermal distribution

Z' constraints

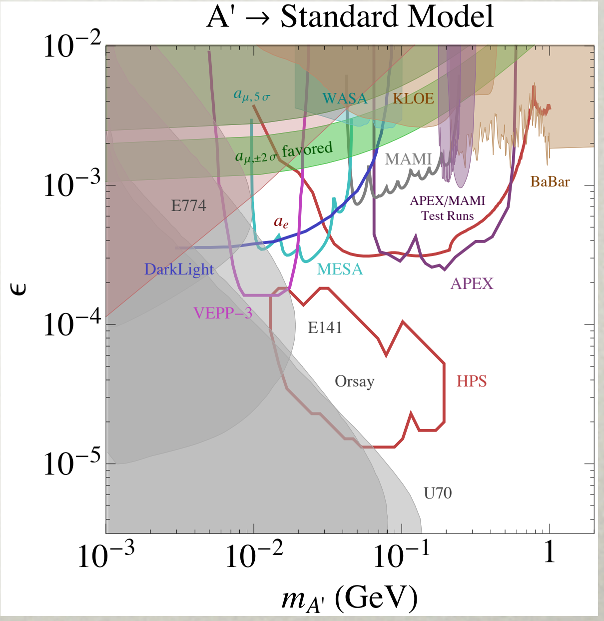
- **Mass:**
  - Since the Z' decays into neutrinos, constraints on the effective number of neutrino species imply $M_{Z'} \gtrsim 2$ MeV
  - The mixing angle is suppressed for $T \gtrsim$ GeV, so for sufficient decays of Z' into sterile neutrinos, $M_{Z'} \lesssim$ few GeV

- **Coupling:**
  - Muon g - 2
  - Contributions to gauge and meson decay widths
  - N lifetime (by mediating N to 3 neutrino decay)
  - *If Z′ also couples to electrons*: neutrino-electron scattering constraints, dark photon searches

Z' constraints



- **Future probes:**
  - For models with coupling to electrons and baryons, future experiments (APEX, HPS) will probe interesting parameter space
  - Muon trident production (neutrino beams)
  - Rare decays (mesons, taus)



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

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

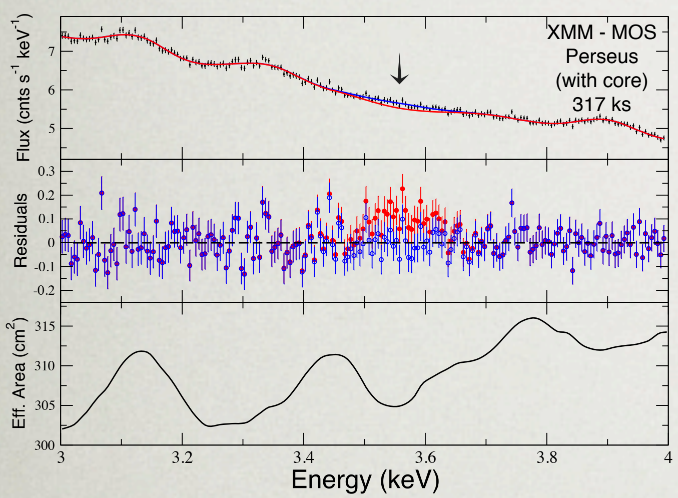
  - Low-energy effective theory can give same neutrino Yukawa couplings after Σ breaks $U(1)_{\mu-\tau}$
  - New fields can be at/above weak scale
  - Baryogenesis can proceed as before, except with scattering through X states

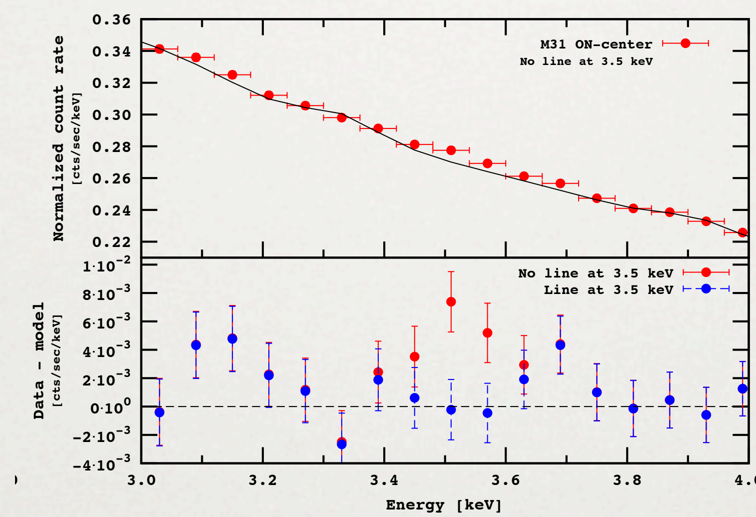
Sterile neutrino dark matter

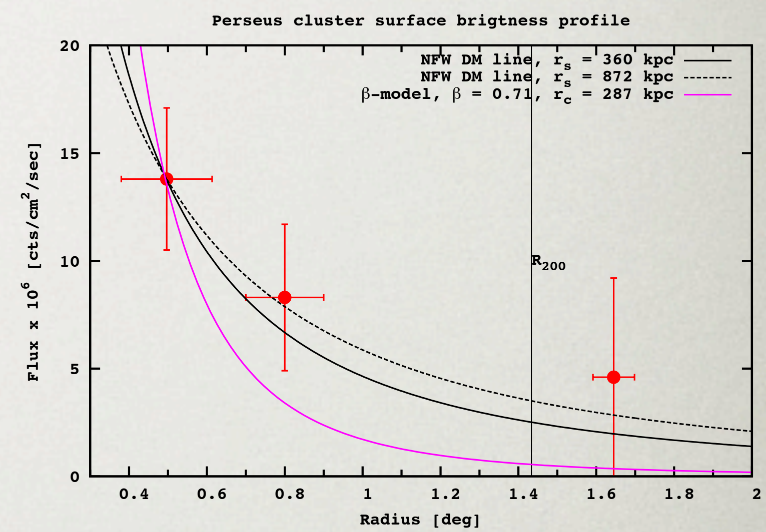
Recent anomaly

3.6 keV X-ray line

- Two groups have recently announced evidence for an X-ray line in observations of Andromeda and various galaxy clusters (Chandra & XMM)







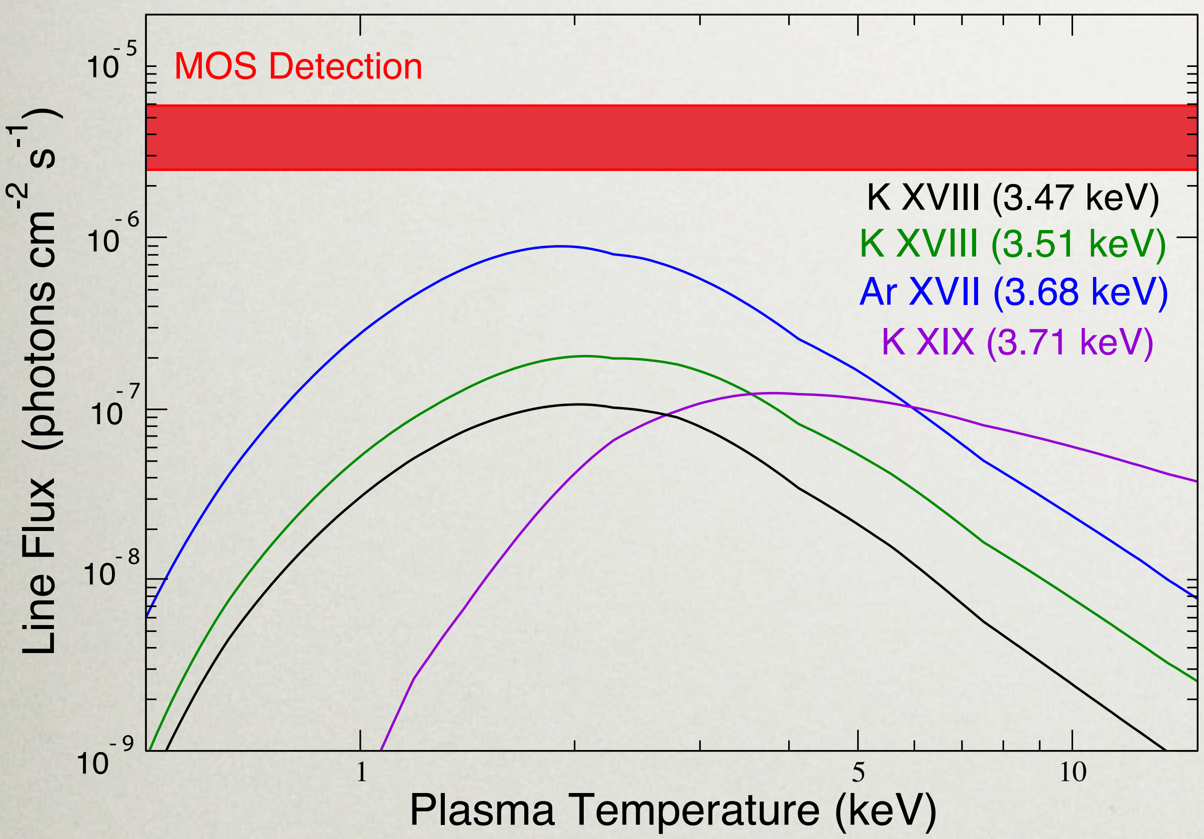
Taken from **Bulbul *et al.* 2014**

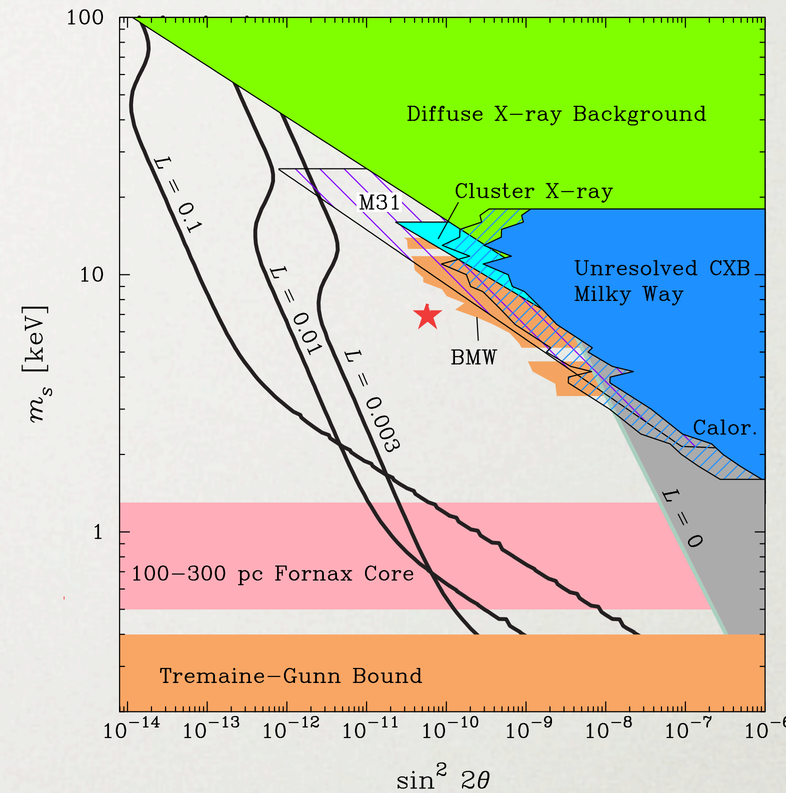
Taken from **Boyarsky *et al.* 2014**

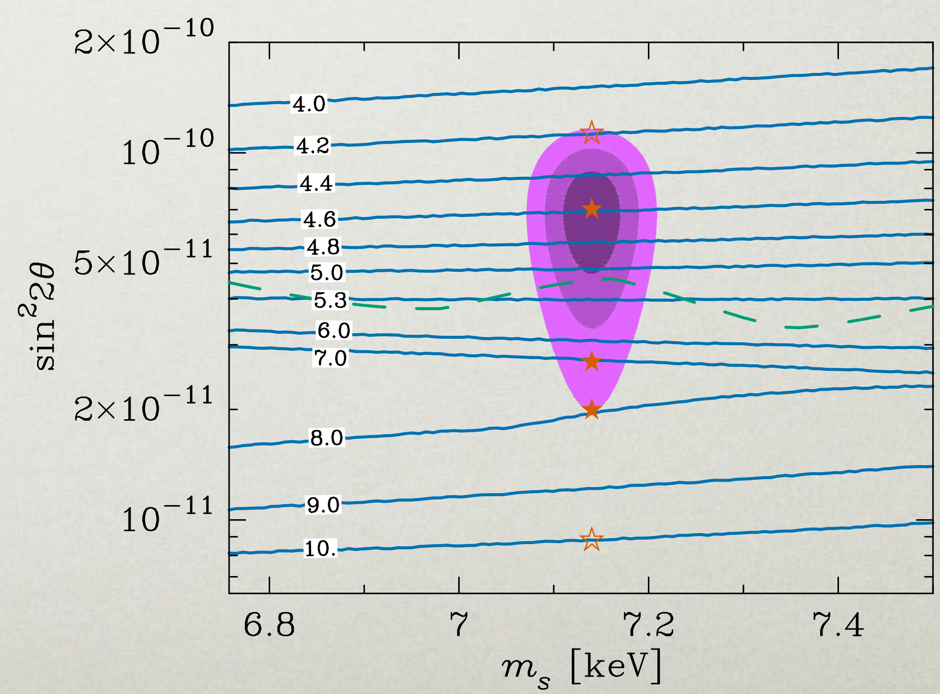
- Seen in several different data sets, but line detection is close to experimental sensitivity and several other nearby faint background lines
- 3.57 keV X-ray line = 7.15 keV sterile neutrino
  - Below small-scale structure constraints! ($M_N > 8.8$ keV)
  - Consistent with resonant production in the presence of a large lepton asymmetry, which generally produces colder neutrinos (Shi-Fuller scenario)
  - Best-fit: $\sin^2(2\theta) \sim 7 \times 10^{-11}$

3.6 keV X-ray line

- Some more plots:







Taken from **Abazajian 2014**

Conclusions

- Models with sterile neutrinos can account for neutrino masses, dark matter, baryogenesis

- Minimal model (SM + 3 sterile neutrinos) can explain all three, but with a high degree of parameter alignment

- Models with new fields (Higgs, gauge interaction) below the weak scale can substantially enhance the dark matter abundance and baryon asymmetry, alleviating the above tuning
    - Also can provide direct experimental probes!

- More work needed to determine the best way to constrain new forces and fields over the allowed range