NOT-SO-STERILE NEUTRINOS AND NEW LEPTONIC INTERACTIONS

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Perimeter Institute for Theoretical Physics

BS, Itay Yavin, arXiv:1401.2459, arXiv:1403.2727
and work in progress

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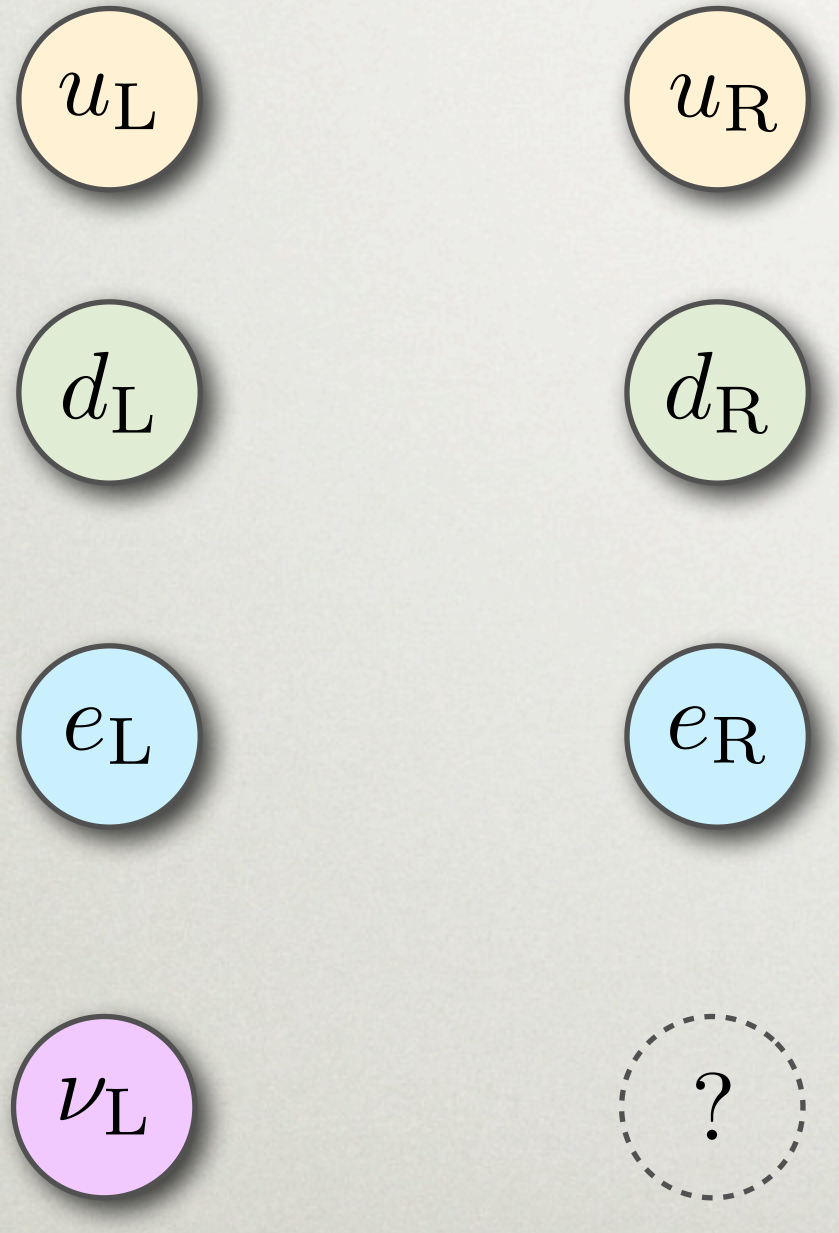
10 November 2014

Why sterile neutrinos?

- The Standard Model has missing pieces:



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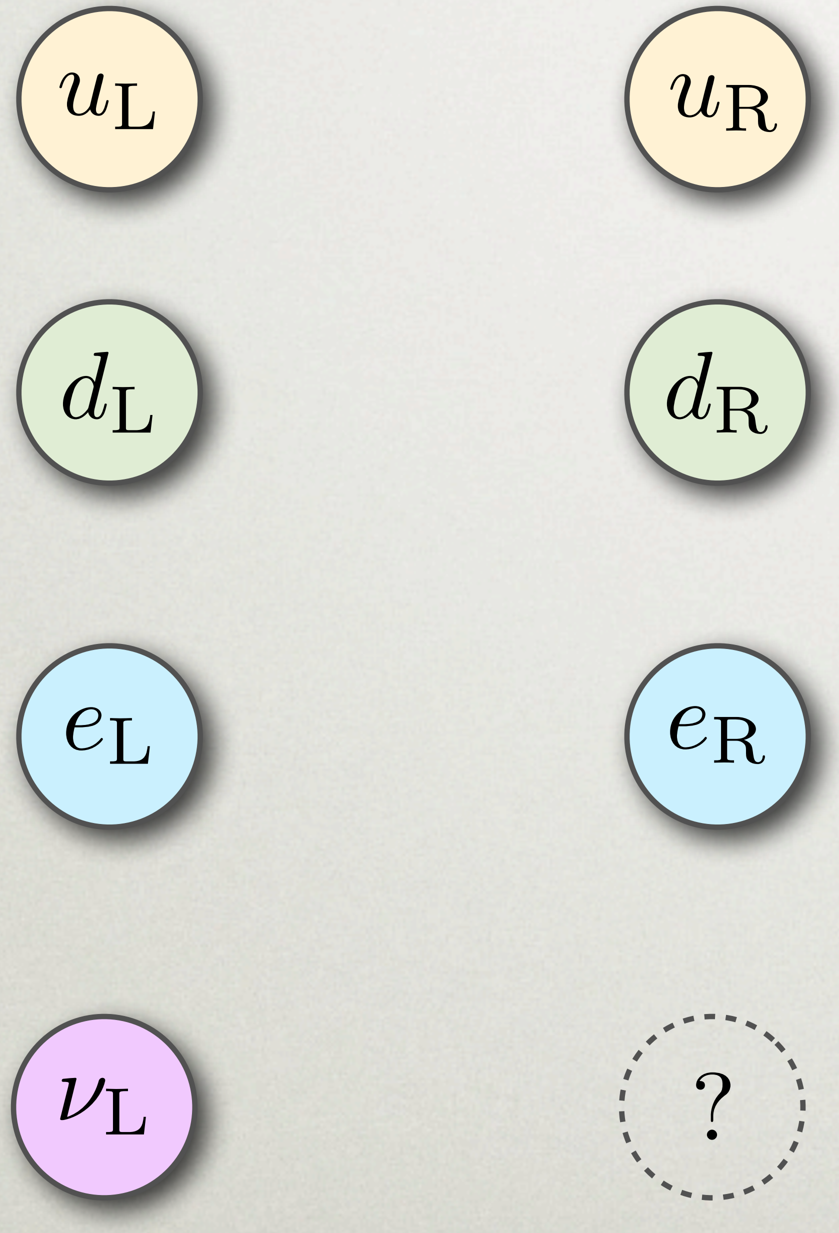
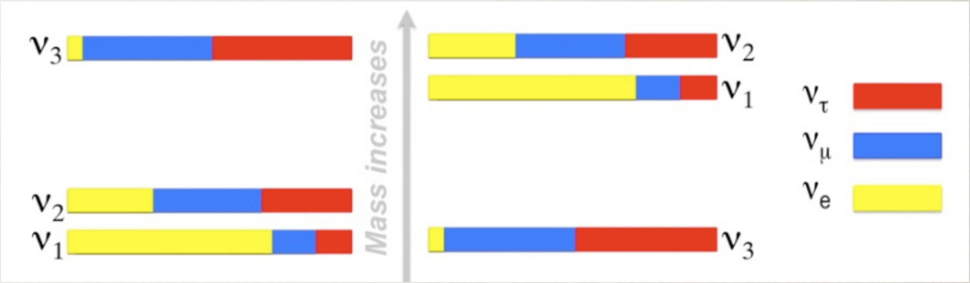


(normal) (inverted)



Lujan-Peschard *et al.*, 2013

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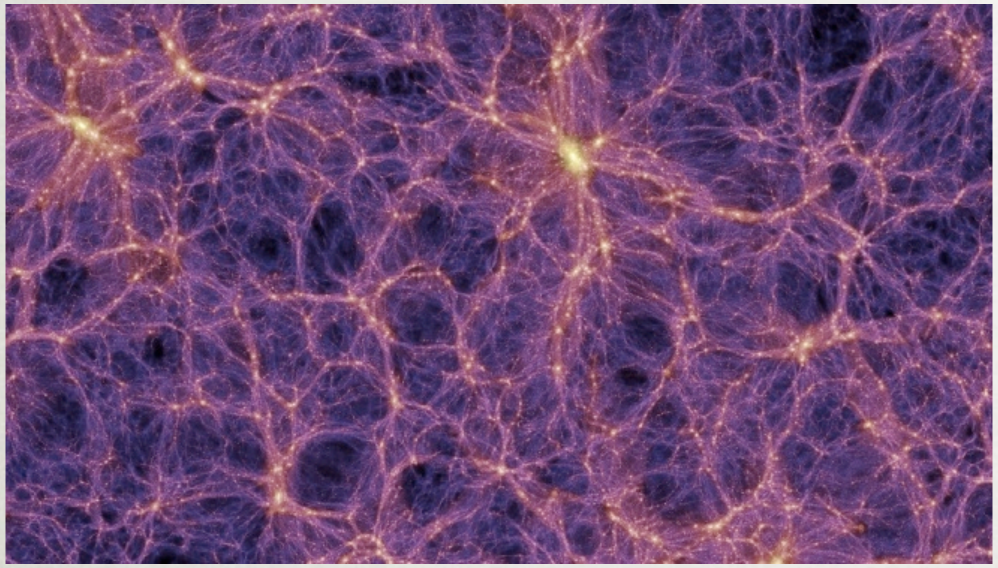
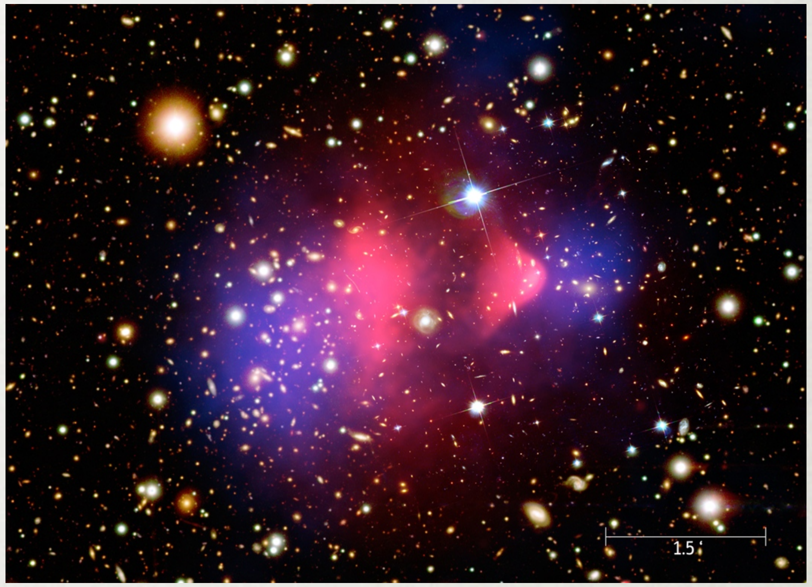
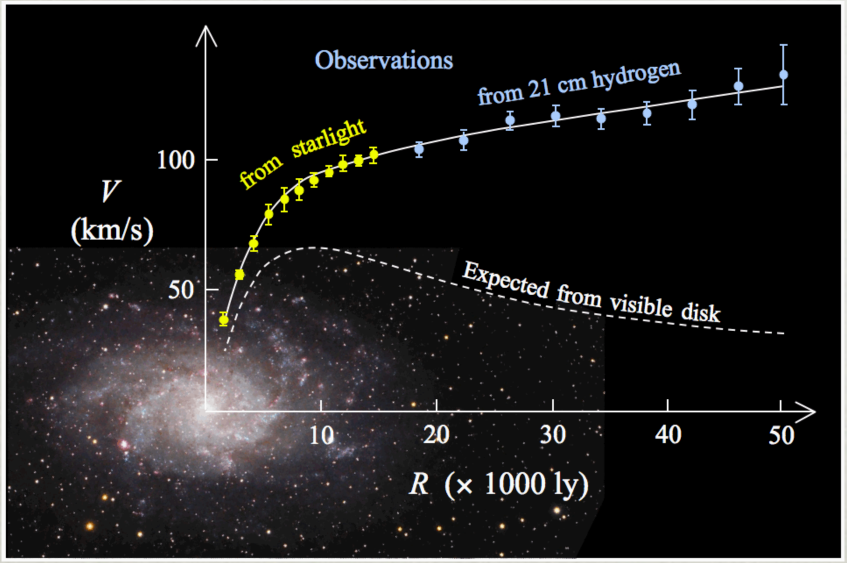


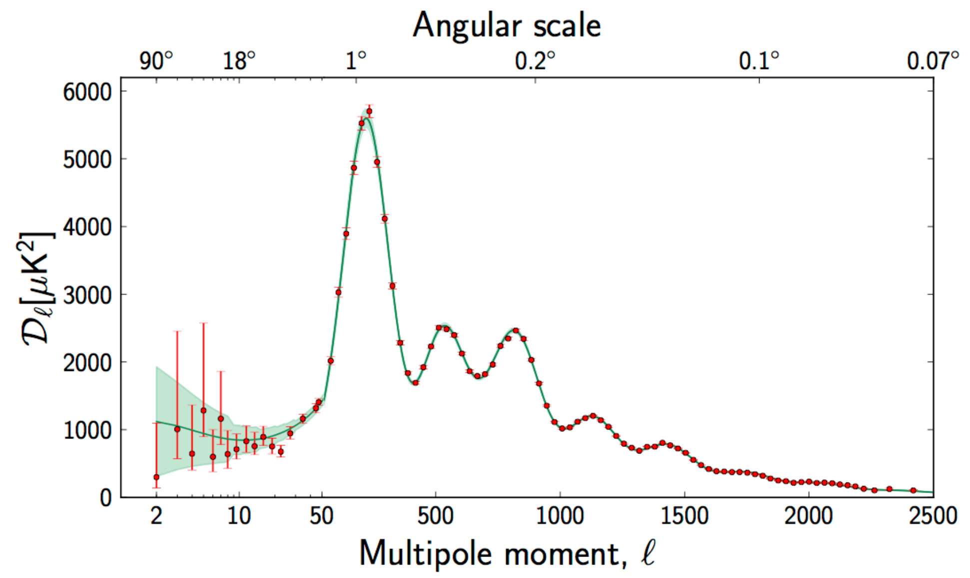
Springel *et al.*, 2005



Clowe *et al.*, 2006; Markevitch *et al.*, 2005



Corbelli, Salucci, 2000



Planck, 2013

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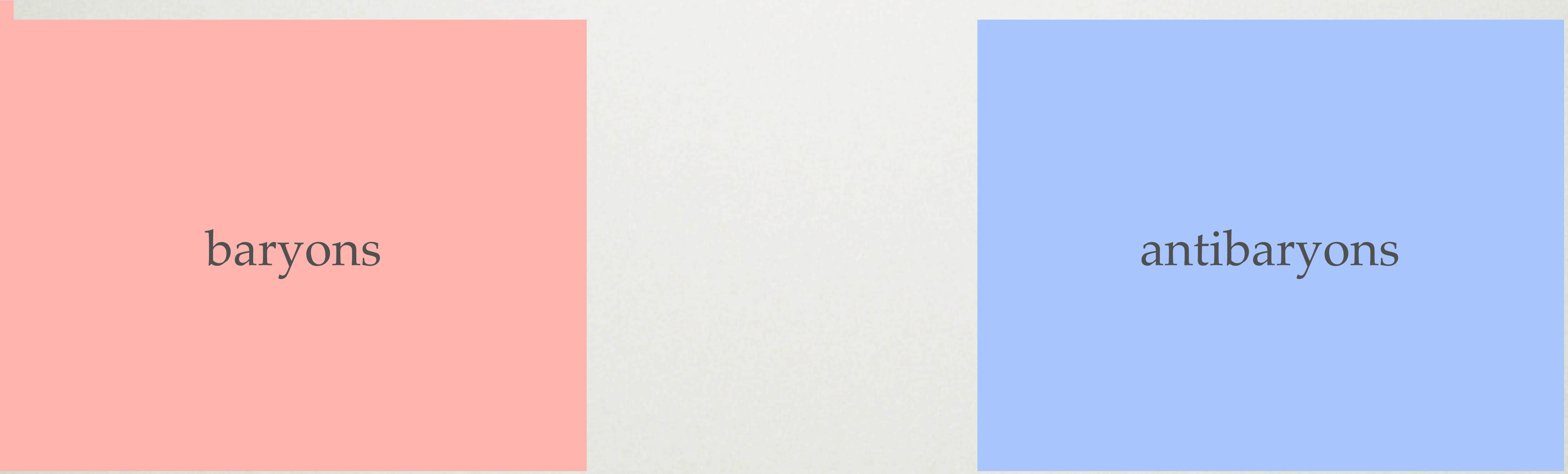

baryons

antibaryons

$$\frac{n_{\Delta B}}{s} \approx 8 \times 10^{-11}$$

Neutrino Minimal SM

- Remarkably, a minimal extension of the SM with only **three sterile neutrinos** (*N*) can fill in all of these missing pieces!
    - The masses of all three sterile neutrinos are **below the weak scale**, and kinematically accessible in current experiments

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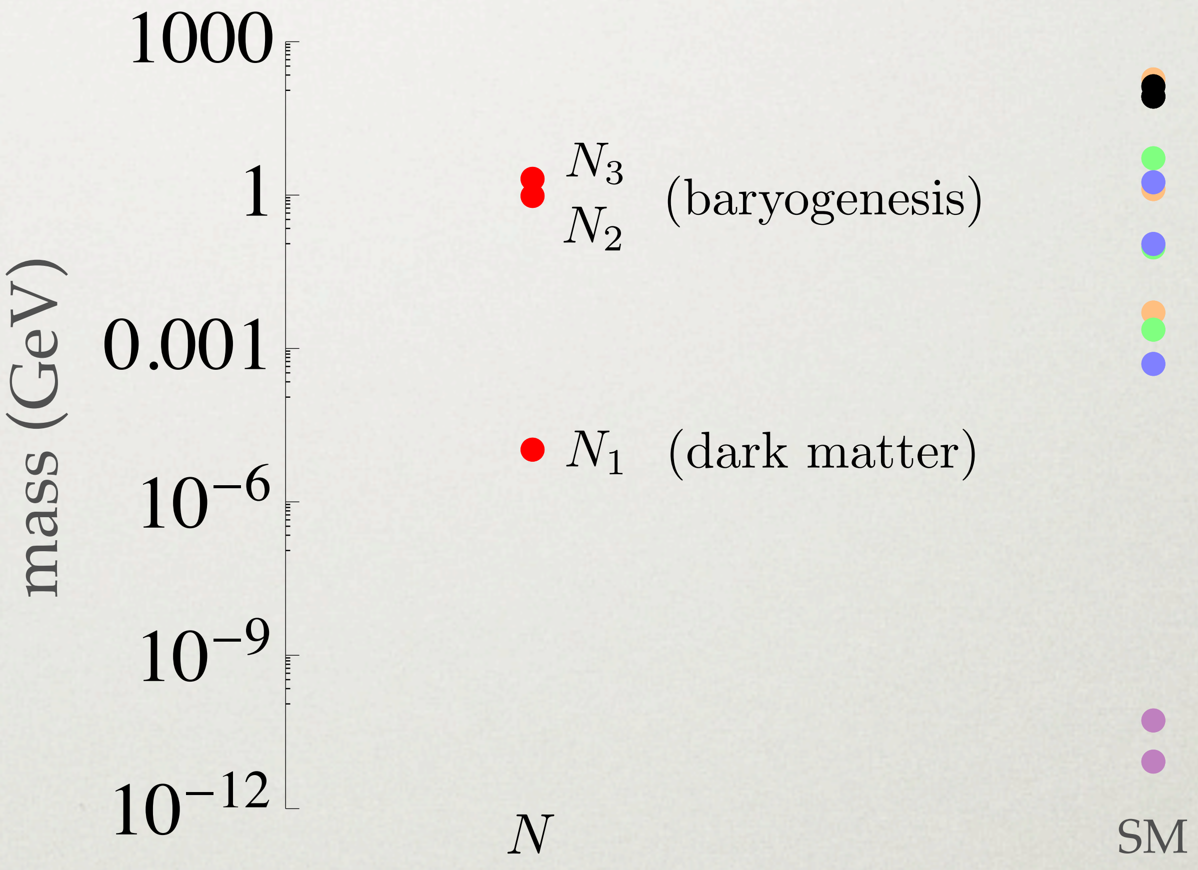

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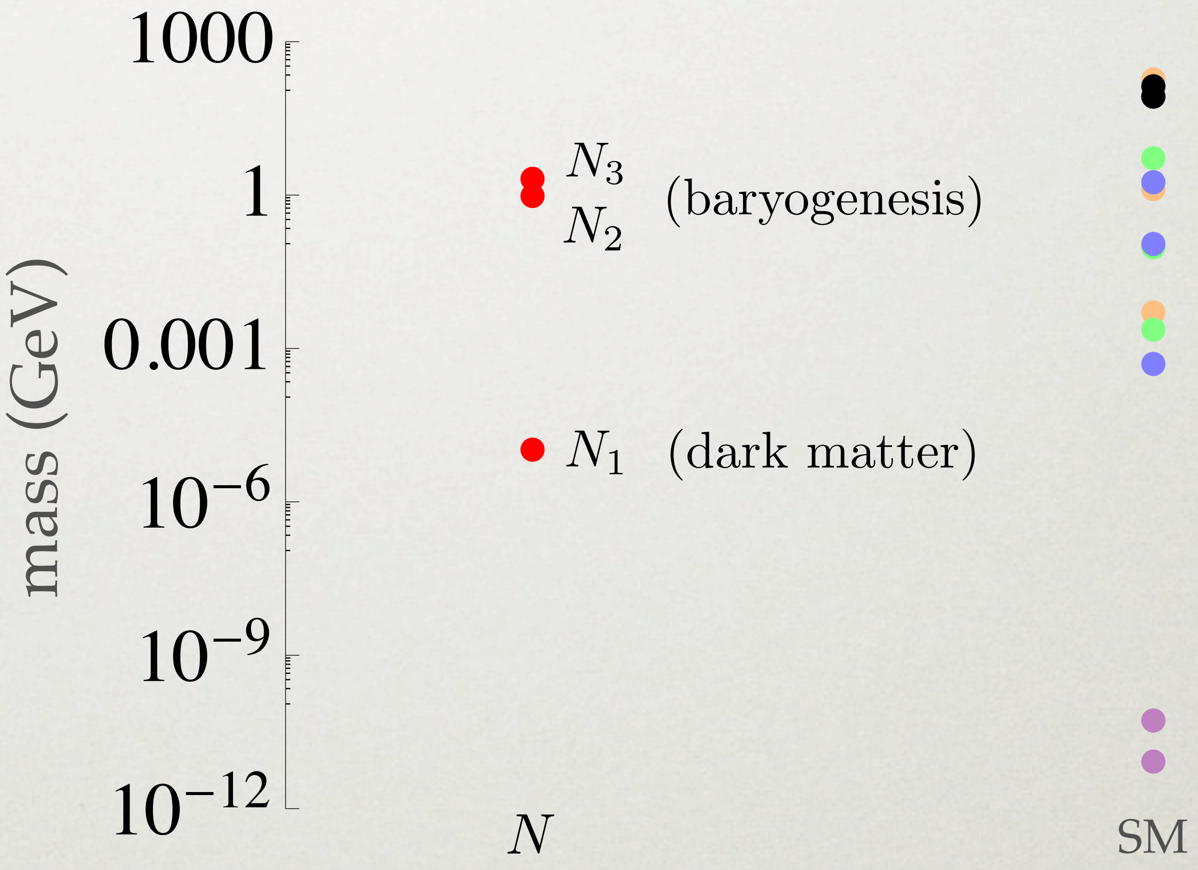

- Called the **neutrino minimal SM** (νMSM)
  - Asaka, Shaposhnikov 2005; Asaka, Blanchet, Shaposhnikov 2005; Canetti, Drewes, Frossard, Shaposhnikov 2012; ...

Too-sterile neutrinos

- The model is highly predictive because sterile neutrinos only interact with the SM through the Yukawa couplings

- However, it turns out that sterile neutrinos are **too sterile** if they interact only through the see-saw coupling
    - With just the νMSM, you generically predict **insufficient abundances of DM and baryons**

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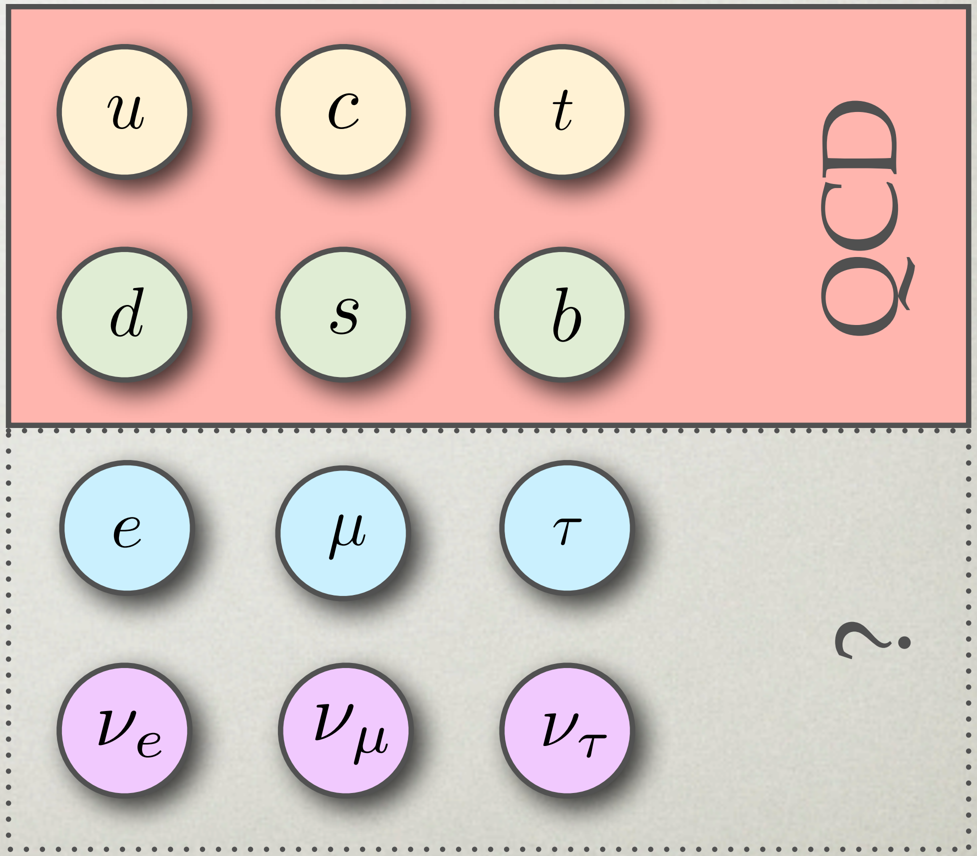
- For sterile neutrinos to be viable, we need them to be **not-so-sterile**

- For both baryogenesis & dark matter, we expect new leptonic interactions at the weak scale (or below)



Outline

- **Baryogenesis through sterile neutrino oscillations**
    - Mechanism of baryogenesis
    - Tuning in the minimal model
    - Baryogenesis with a leptophilic Higgs & phenomenology

- **Sterile neutrino dark matter**
    - Sterile neutrino dark matter in the νMSM
    - Sterile neutrino dark matter with a new leptonic gauge interaction
    - Phenomenological probes of new leptonic interactions

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 production, oscillation, and re-scattering of the heavy sterile neutrino states, N_2 and N_3
  - Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005;... Drewes, Garbrecht 2012

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2. **CP violation:** Three new CP phases in the Yukawa matrix

3. **Departure from thermal equilibrium:** For small Yukawa couplings, N scattering is out of equilibrium for all T above the weak scale

$$\Gamma_N \propto |F|^2 T \lesssim H(T) \qquad |F|^2 \sim 10^{-14} \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right) \left(\frac{m_N}{\mathrm{GeV}}\right) \left(\frac{100\ \mathrm{GeV}}{\langle\Phi\rangle}\right)^2$$

Lightning Review of CPV

$$\mathcal{M}(a \to b) = x\, e^{i\phi} \qquad\qquad |\mathcal{M}(a \to b)|^2 = x^2$$

$$\longrightarrow$$

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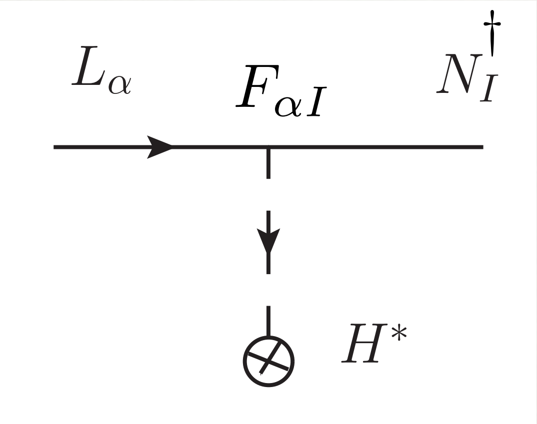
$$\Delta|\mathcal{M}|^2 = -4x_1x_2\sin\phi\sin\theta$$

Asymmetry Generation

- The physical mechanism for baryogenesis:
  - No primordial abundance of N_2, N_3
  - N_2, N_3 slowly populated by L_α scattering (approximately thermal spectrum)



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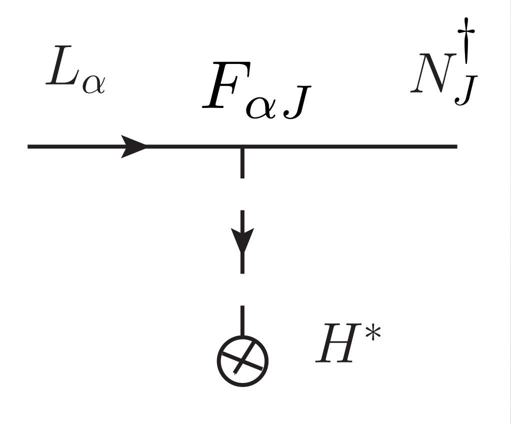

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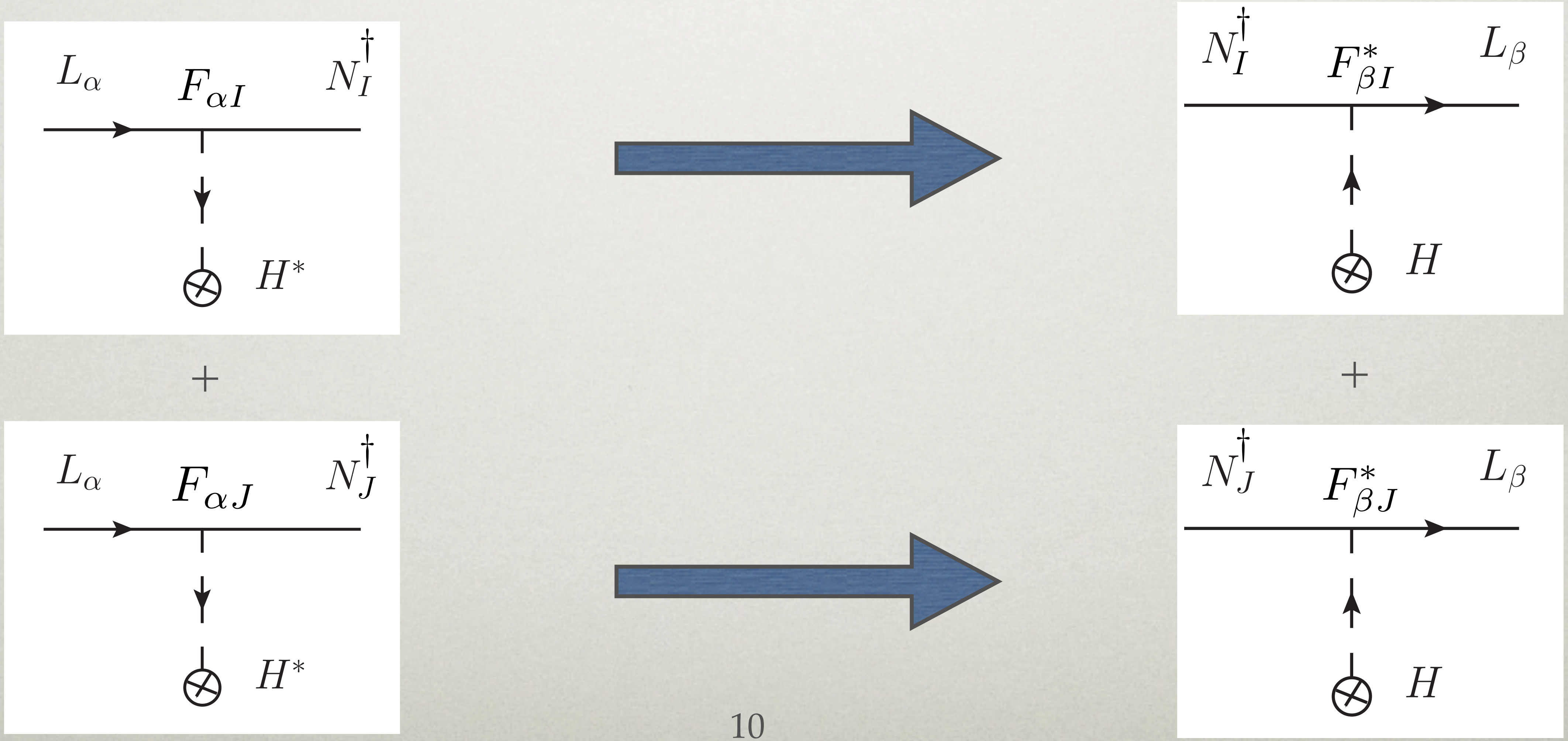

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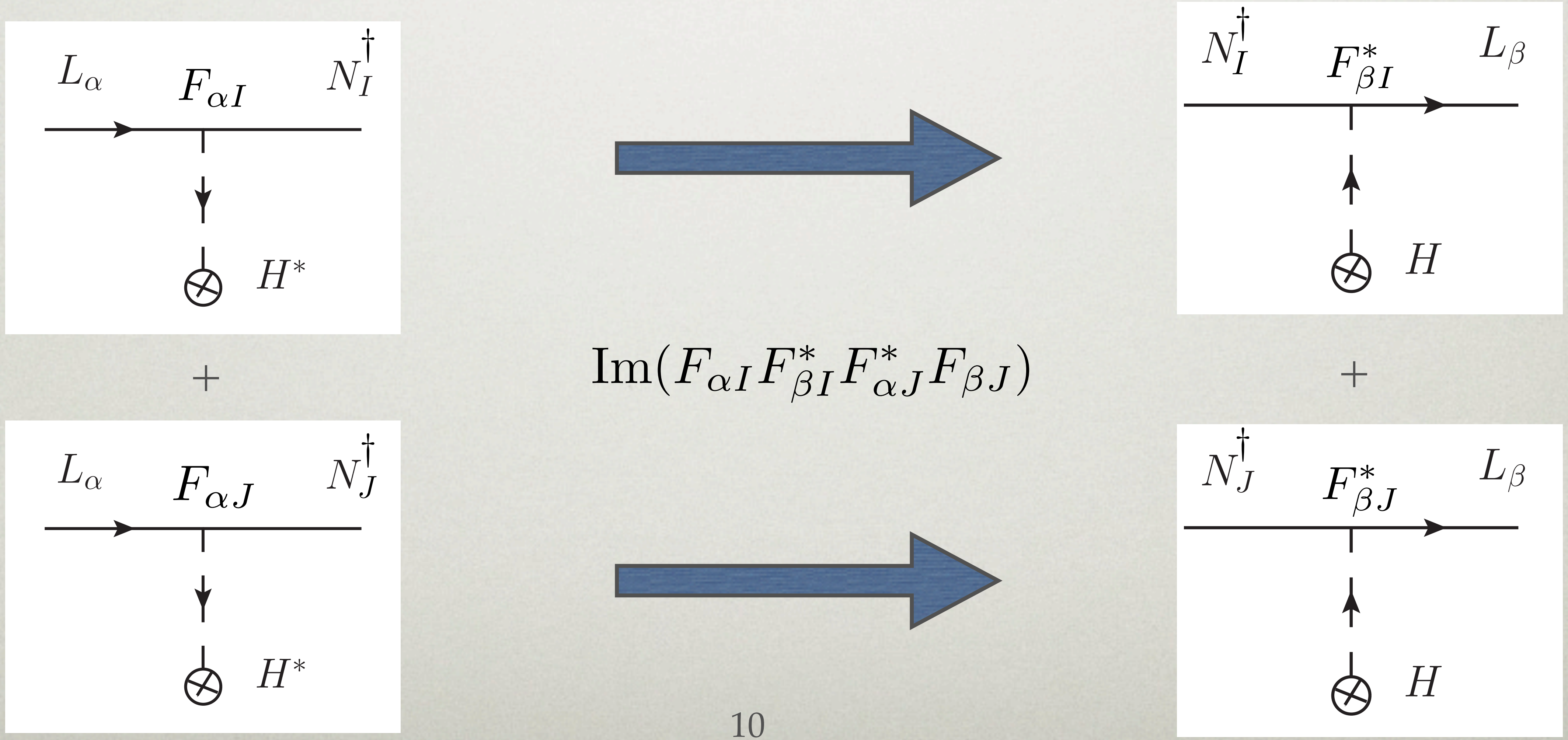
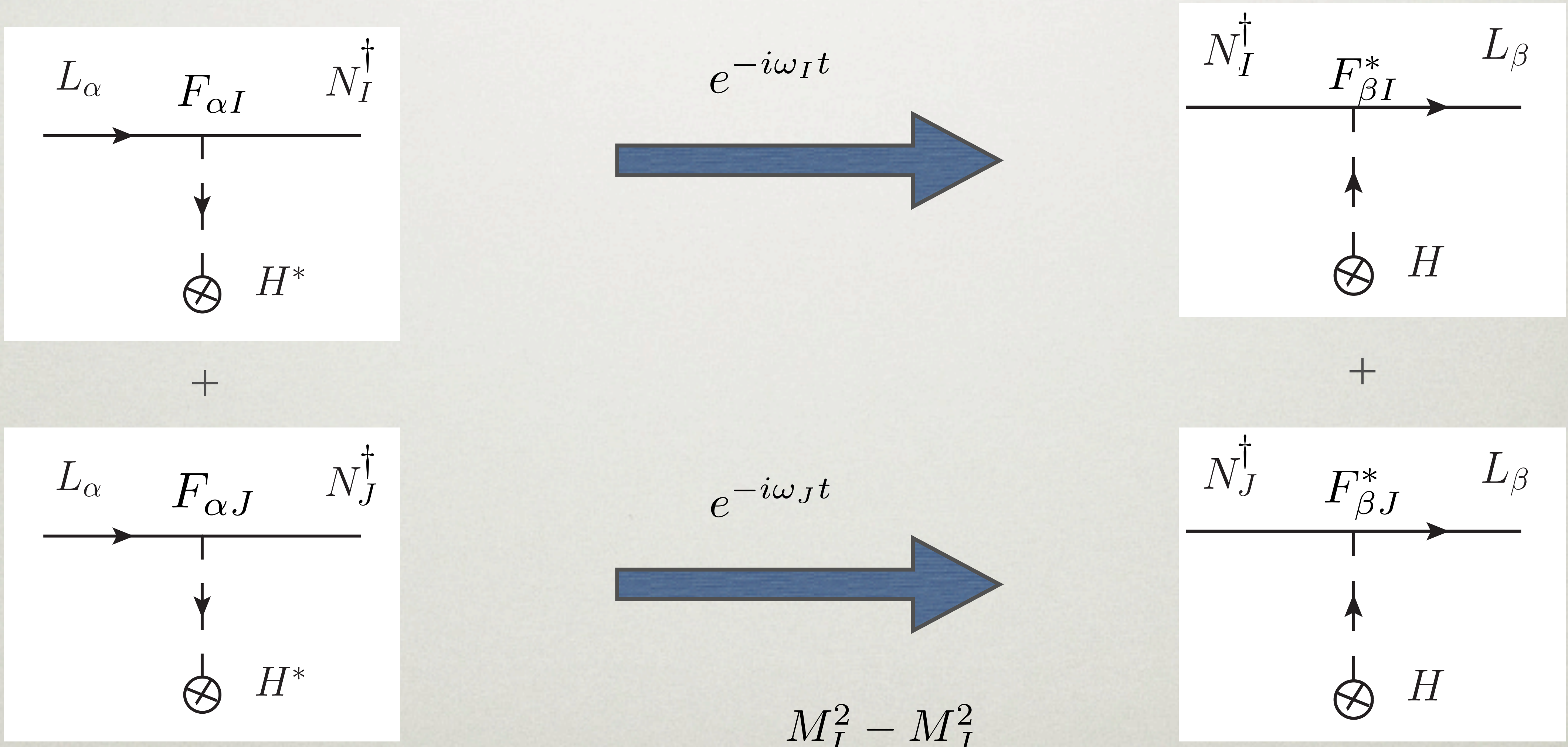
  - We have a CP-odd phase, but **where is the CP-even phase?**



$$\mathrm{Im}(F_{\alpha I} F^*_{\beta I} F^*_{\alpha J} F_{\beta J})$$

Asymmetry Generation

- *N* is produced in a **coherent superposition** of mass eigenstates
- Because *N* scattering is out of equilibrium, **there is no decoherence** between scattering!
- Each diagram acquires a **CP-even propagation phase** (Schrödinger equation)



$$\omega_I - \omega_J \approx \frac{M_I^2 - M_J^2}{2T}$$

Asymmetry Generation

- The CP-violating rate comes from the interference of the diagrams

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

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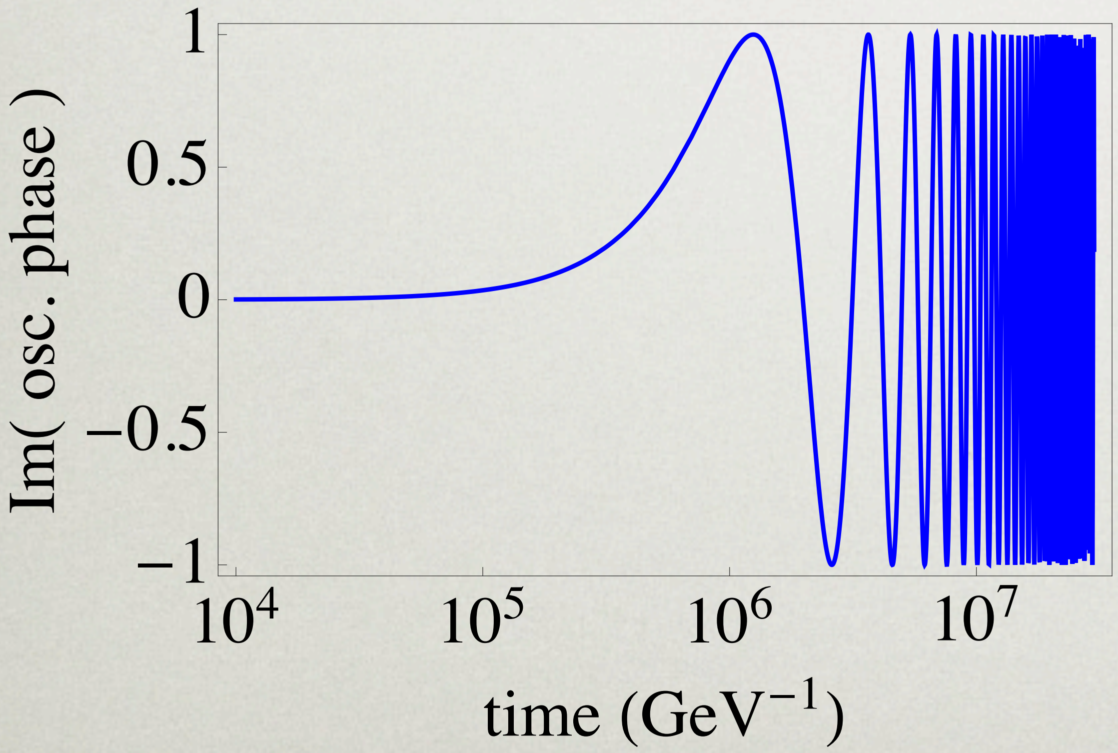
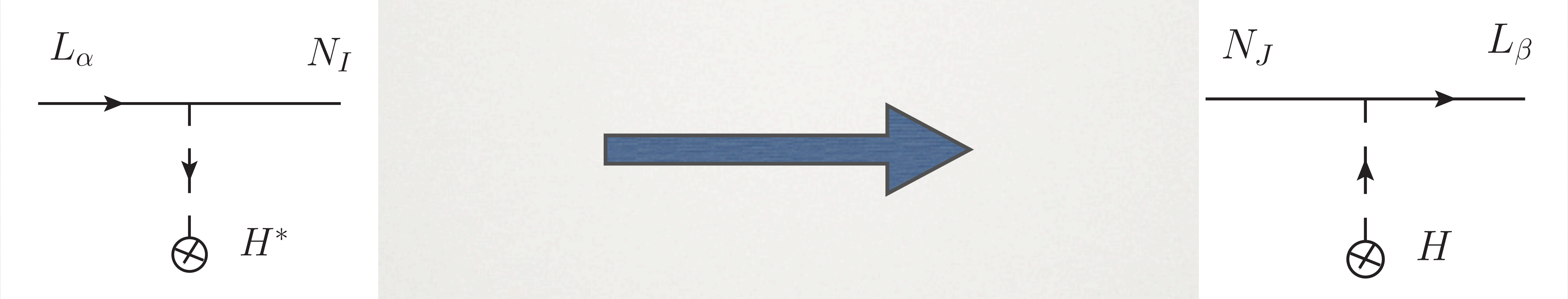


Asymmetry generation effectively **stops** when

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

$$(T \gg M_N)$$

Asymmetry Generation



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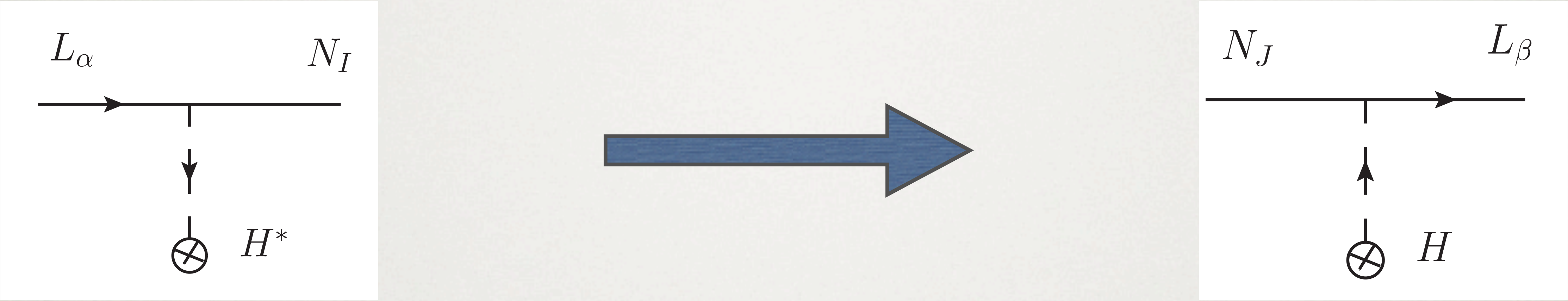

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  - Asymmetries in individual flavours
  - Sphalerons couple to total lepton number

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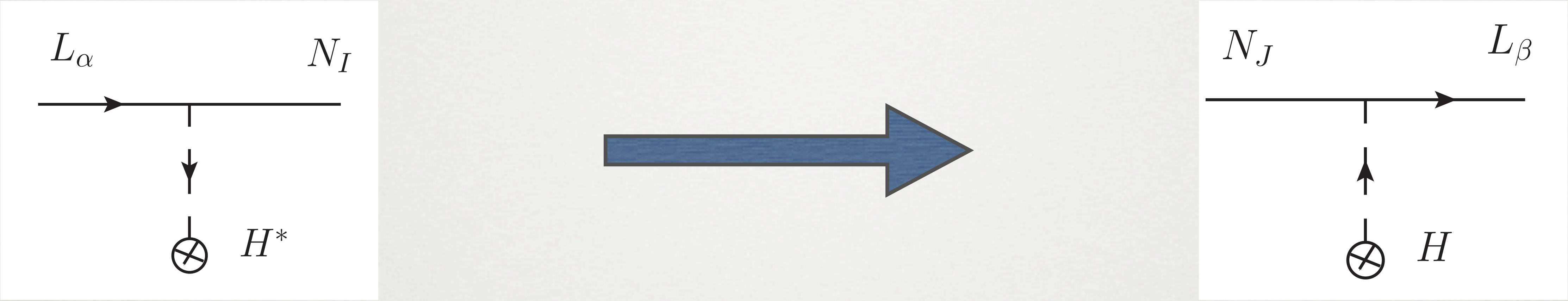

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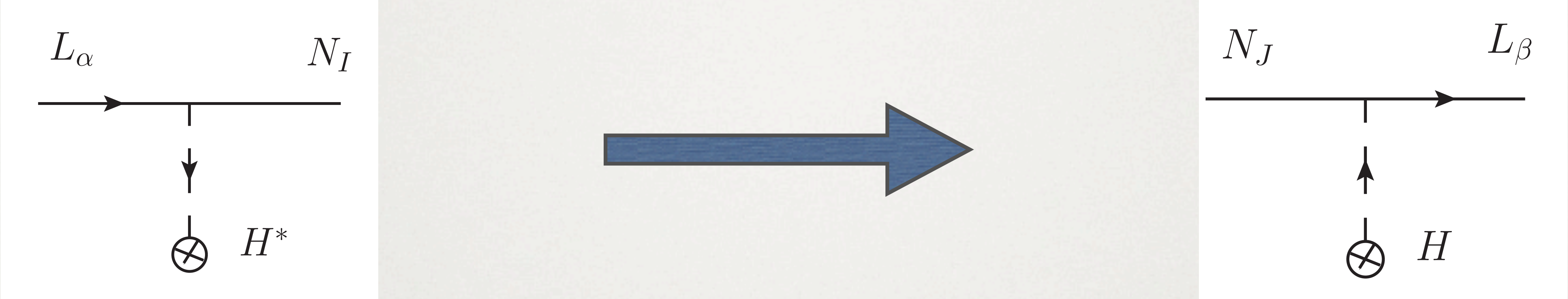

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Asymmetry Generation

- Recap:
  - Out-of-equilibrium *N* production and scattering lead to **lepton flavour** asymmetries at *O*(F^4)
  - Subsequent scatterings convert the flavour asymmetries into a **total lepton** asymmetry at *O*(F^6)

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

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- Comments:
  - No **explicit** violation of total *L*+*N* symmetry (this is suppressed by $(M_N/T)^2$)
  - This means that if *N* equilibrate, the baryon asymmetry is completely destroyed
  - Baryon asymmetry **frozen in** when sphalerons decouple at T_{EW} (must be before equilibration time)

Baryon asymmetry in the minimal model

- What parameters control the size of the baryon asymmetry?

Parametric Dependence

- **Yukawa couplings:**
  - Normalize number densities to entropy density

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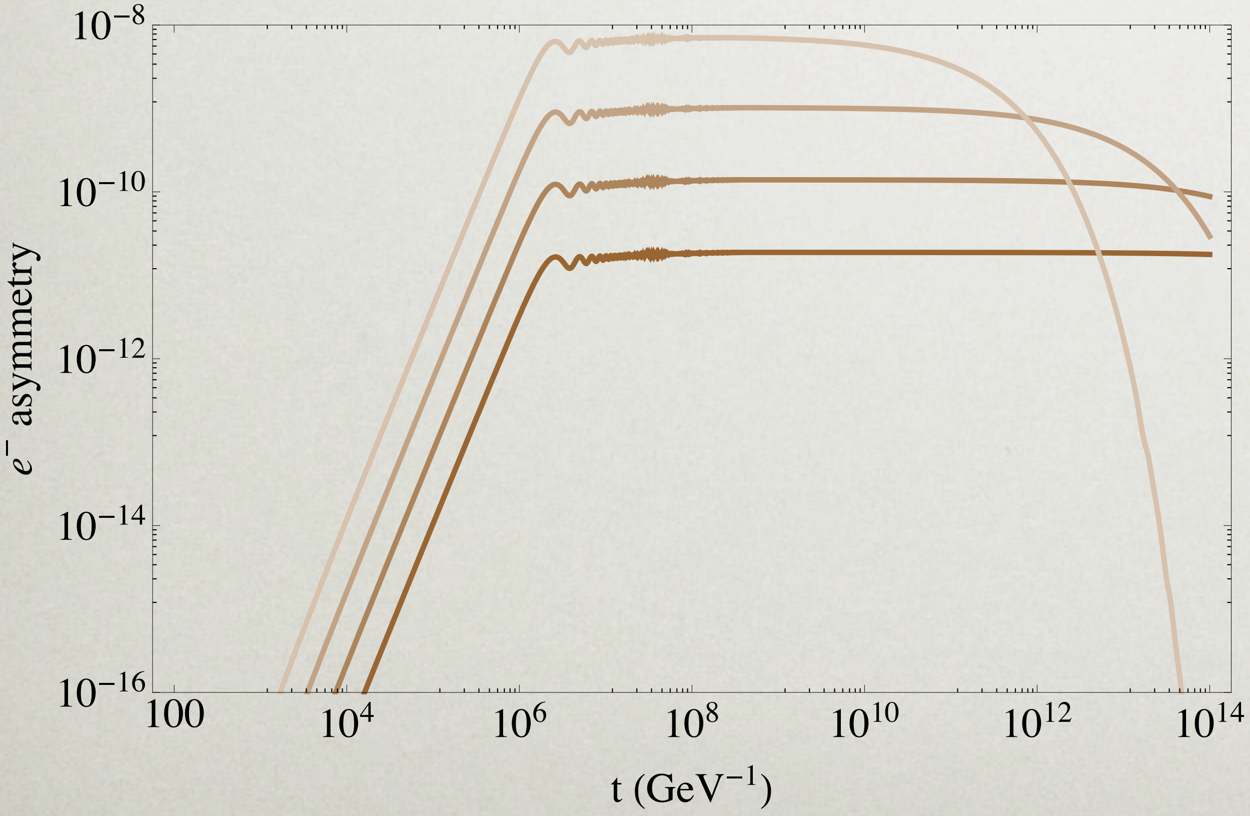

lighter colour =
larger Yukawa coupling

Parametric Dependence

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  - Asymmetry is predominantly generated over the first oscillation
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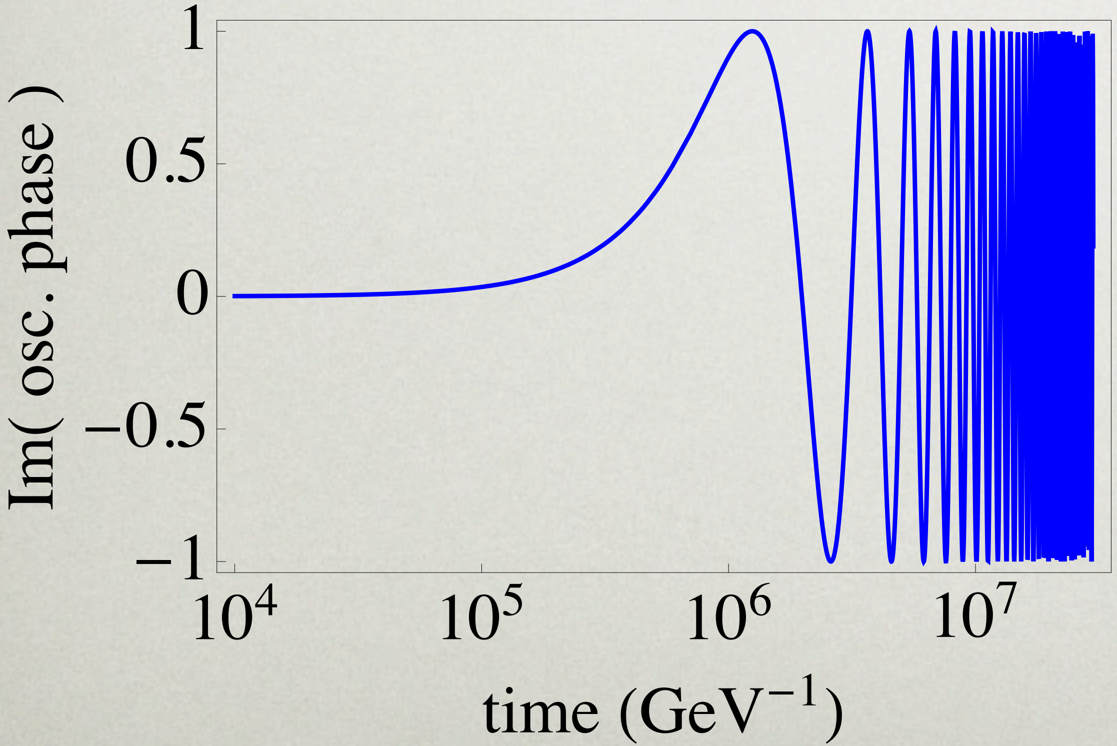
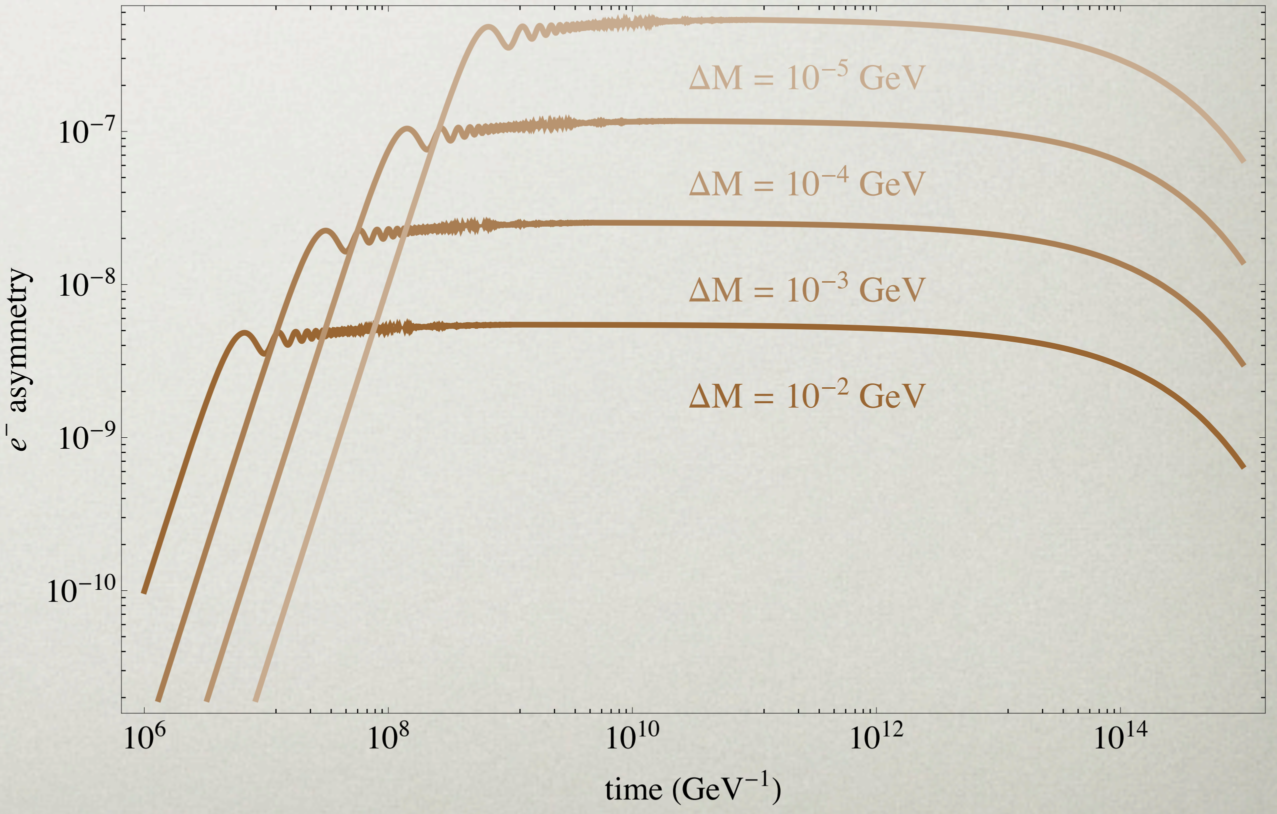
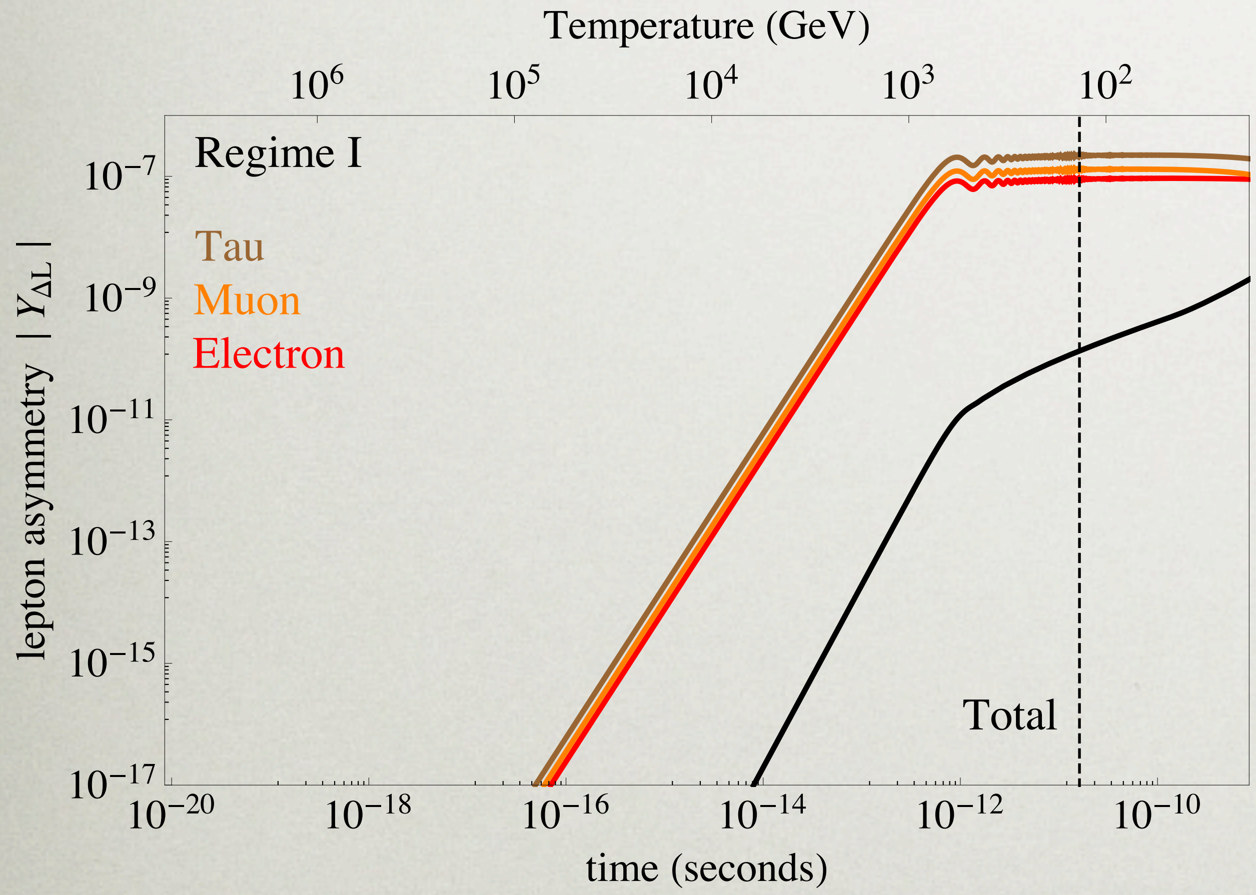




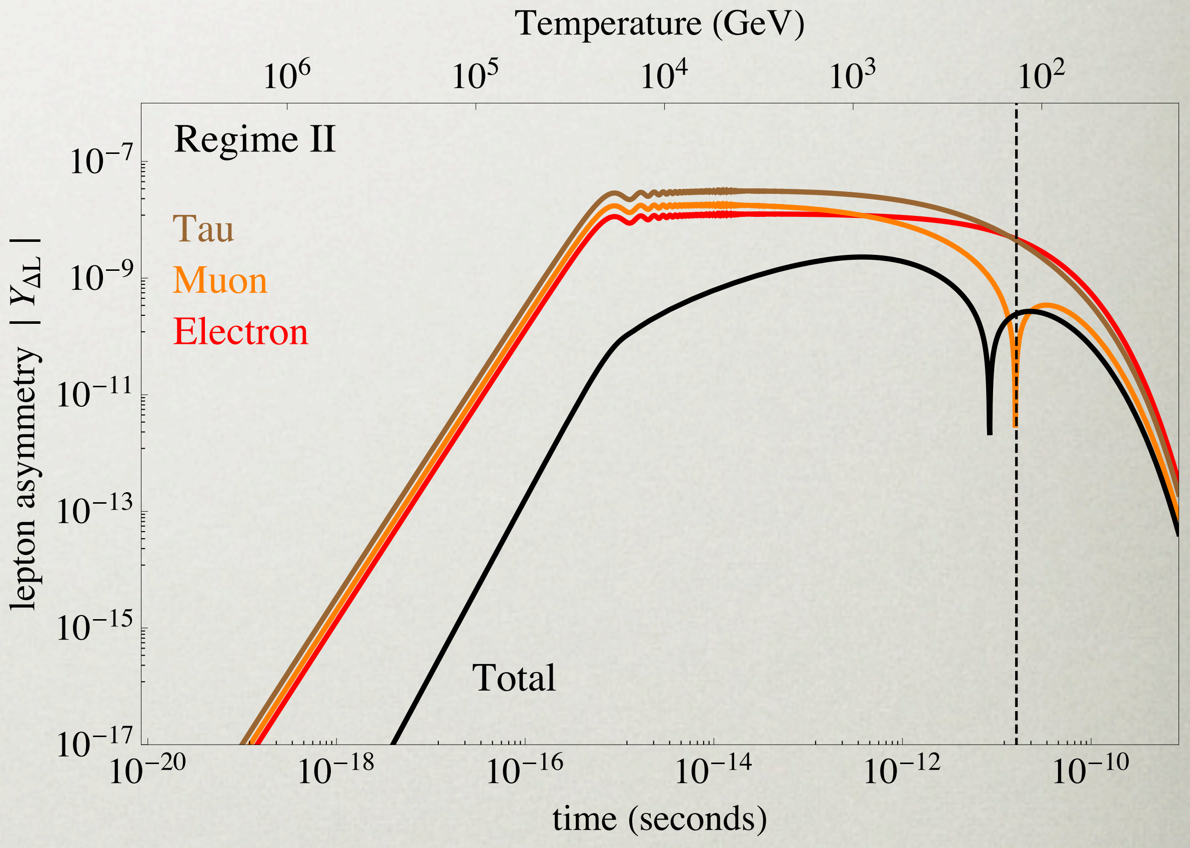
Asymmetry Generation

- Can get correct baryon asymmetry with either mass degeneracy and / or large Yukawa couplings

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



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



Large Yukawas?

- But in the minimal model, can we have arbitrary Yukawa couplings?
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- When you do the decomposition carefully:
  - LH and RH neutrino masses
  - Three LH (real) mixing angles and two LH CP phases (δ, η)
  - One **complex** RH mixing angle, ω, which does not appear in LH neutrino mass formula

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- Yukawa couplings can be arbitrarily large!
  - Cancellation among Yukawa entries gives **same** LH neutrino masses $(F F^{\mathrm{T}} \ll F F^{\dagger})$

Large Yukawas?

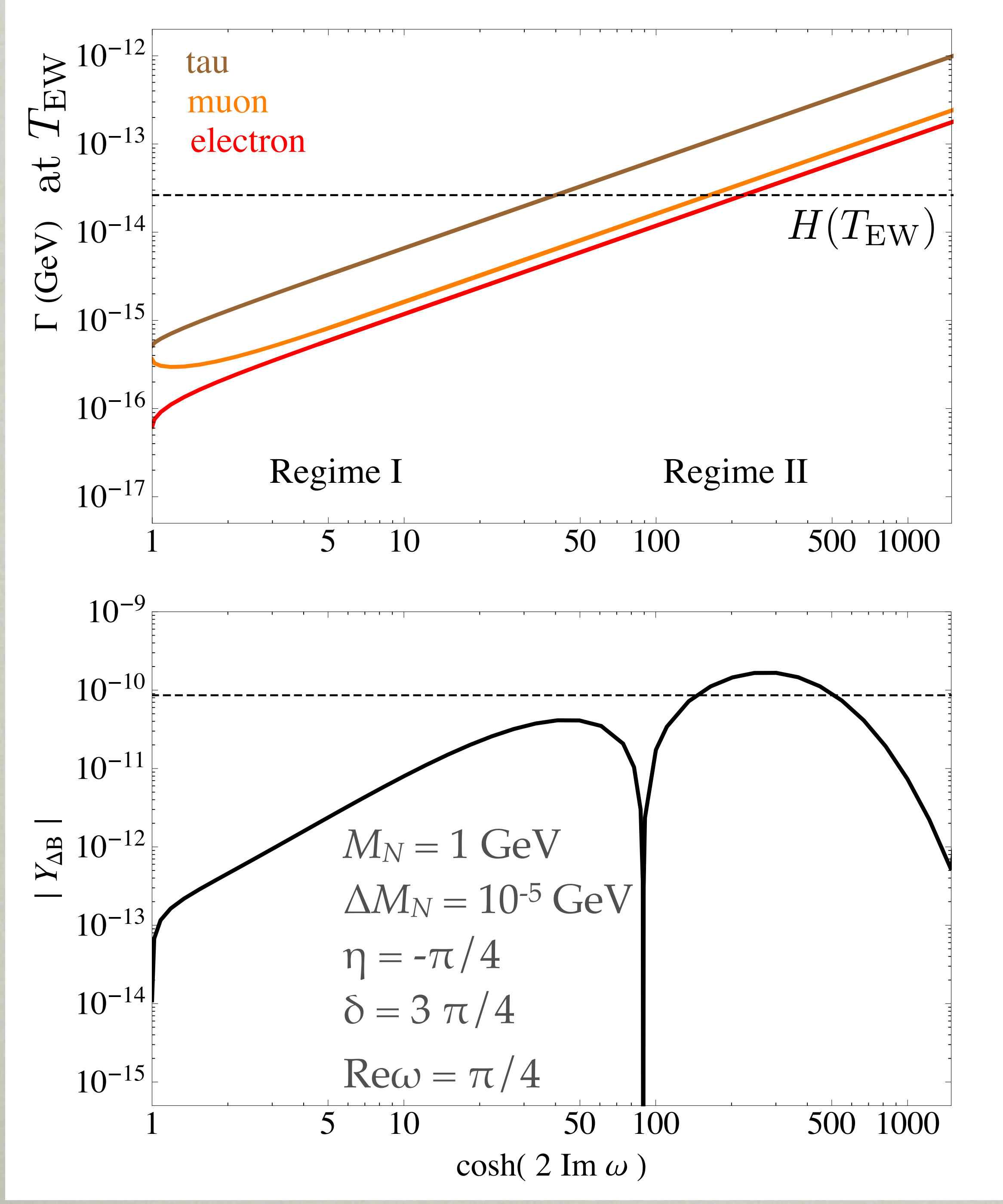
- Yukawa couplings can be arbitrarily large!
    - But at what cost?
    - Look at how physical quantities vary with theory parameters (Giudice, Barbieri, 1988)

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

- Whether the minimal model requires degenerate masses, tuned Yukawas, or both depends on numerology

Numerical results

- Indeed, we do find that the most generic parts of parameter space do not produce a sufficiently large baryon asymmetry



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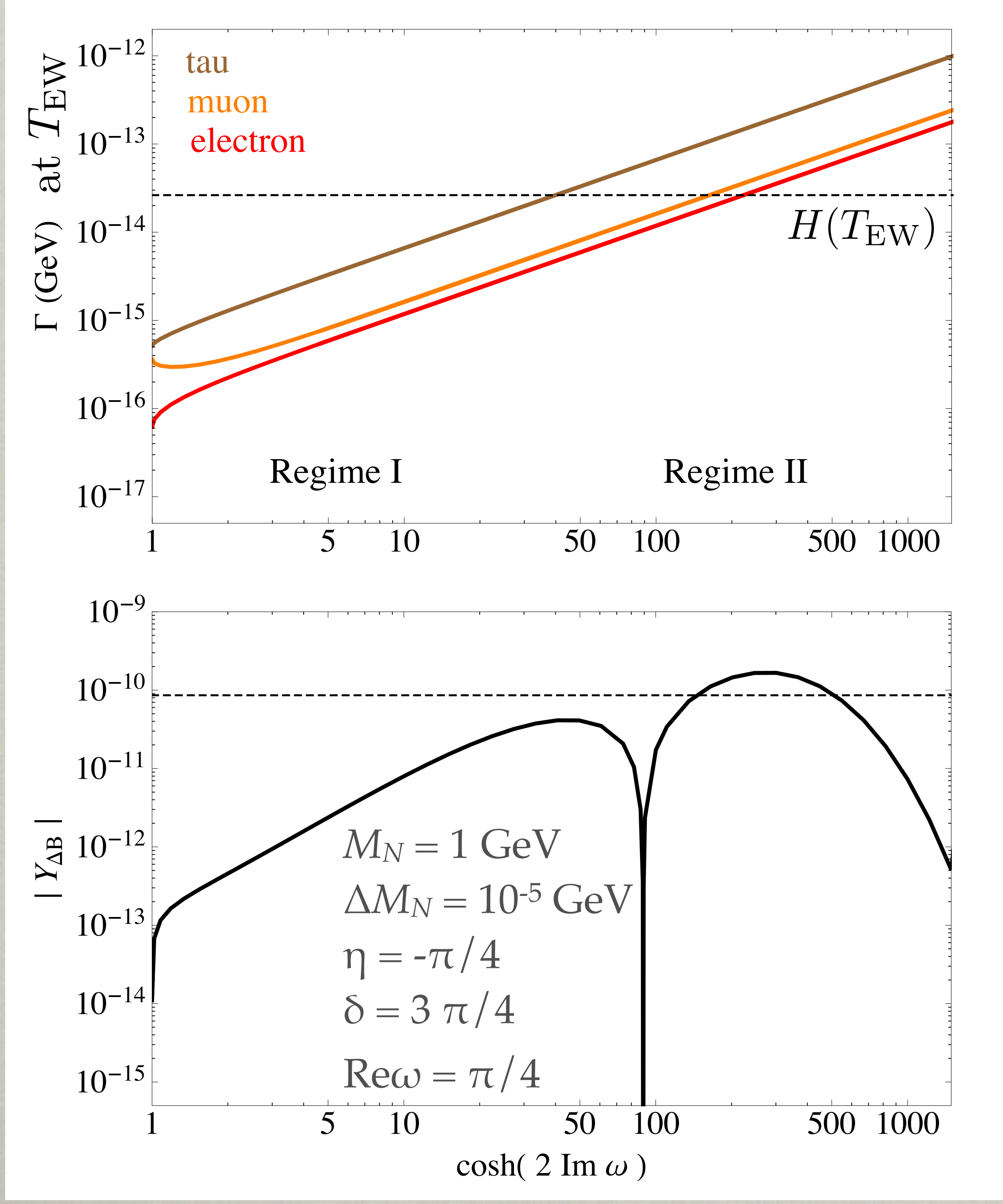
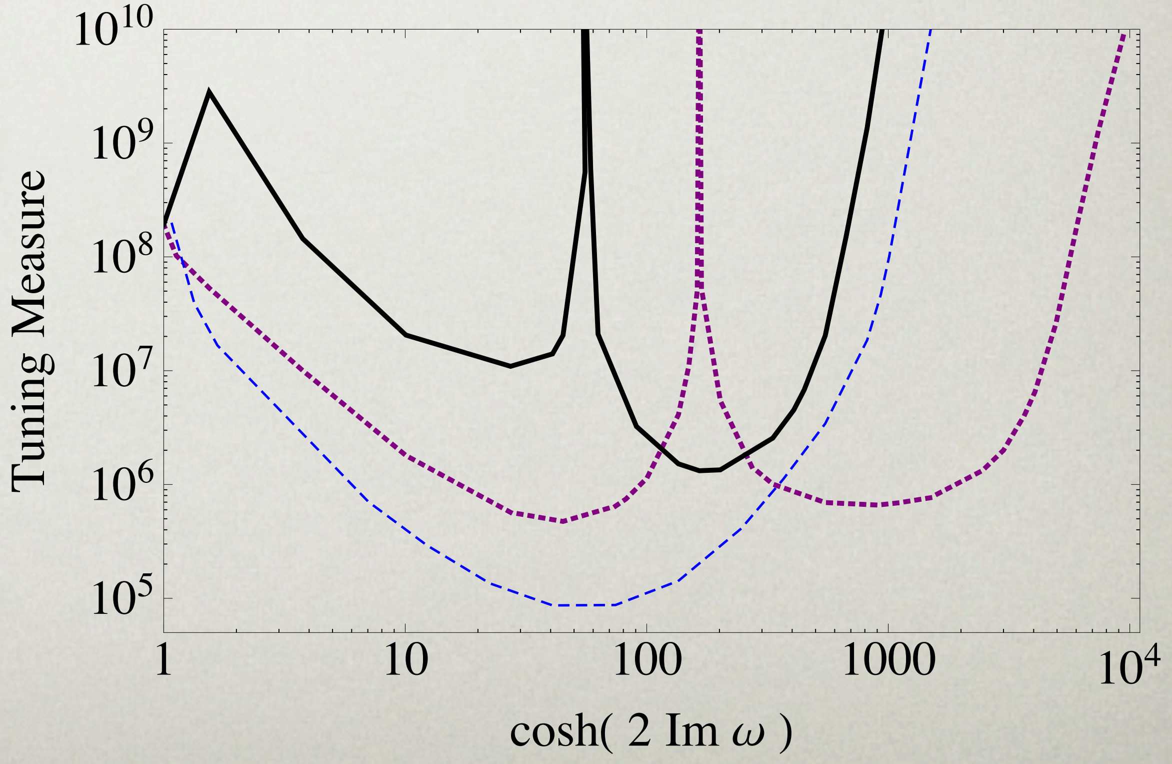


$$\text{tuning/alignment} = \frac{M}{\Delta M}\cosh(2\mathrm{Im}\,\omega)$$



Baryon asymmetry with an extended Higgs sector

Yukawas in a 2HDM

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

- Up until now, we have taken $\Phi = \Phi_{\mathrm{SM}}$
- If $\langle \Phi \rangle < \langle \Phi \rangle_{\mathrm{SM}}$, the Yukawa couplings are naturally larger than in the conventional see-saw

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- **Our proposal:** a leptophilic two Higgs doublet model
  - "Leptophilic": SM-like Higgs doublet couples to quarks, new Higgs doublet couples to leptons (avoids FCNCs)
  - Smallness of charged lepton masses can be a consequence of small VEV for leptophilic Higgs

Possibility of 2HDM in νMSM also mentioned in Drewes, Garbrecht 2012

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Possibility of 2HDM in νMSM also mentioned in Drewes, Garbrecht 2012

- 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...

Yukawas in a 2HDM

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

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

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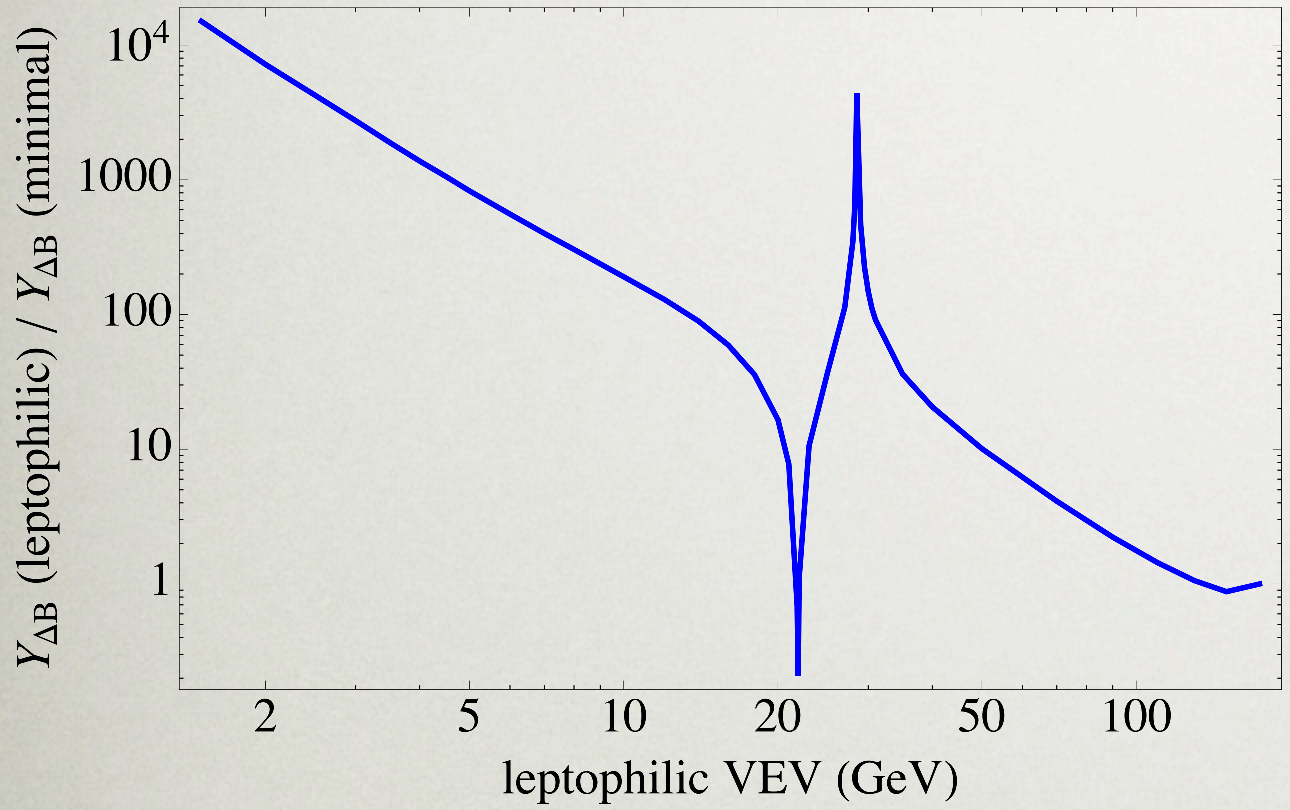
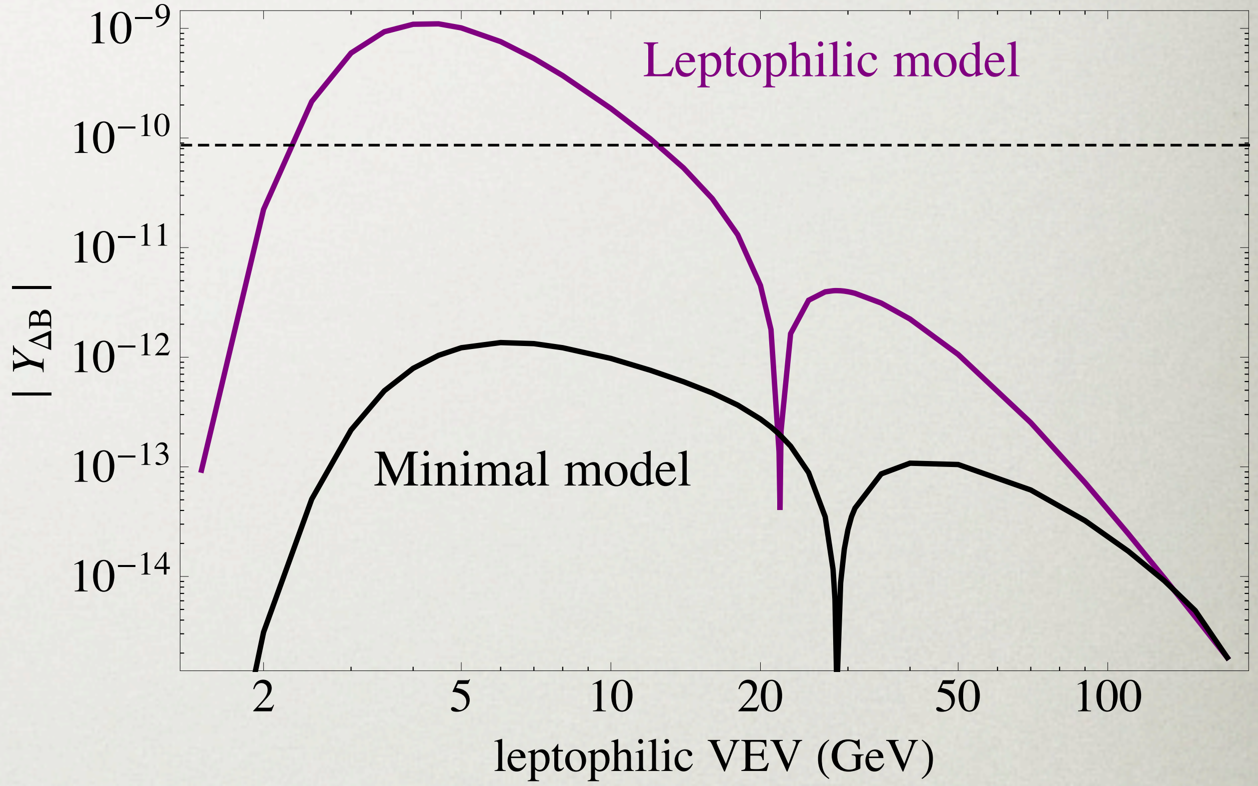
- A smaller Higgs VEV gives a quadratic enhancement of the baryon asymmetry over the tuned model

Baryogenesis and a 2HDM

- Compare leptophilic 2HDM with VEV v to the minimal model where the Yukawa couplings are tuned to be the same magnitude





- 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
  - This is in addition to direct searches for the sterile neutrino states (SHIP experiment,...)
- Can probe through modification to the SM-like Higgs tau Yukawa coupling

$\lambda_\tau \to \lambda_\tau \tan\beta \sin\alpha$ $\tan\beta = \frac{\langle H \rangle}{\langle \Phi_\ell \rangle}$ $\alpha \equiv \text{mixing angle}$

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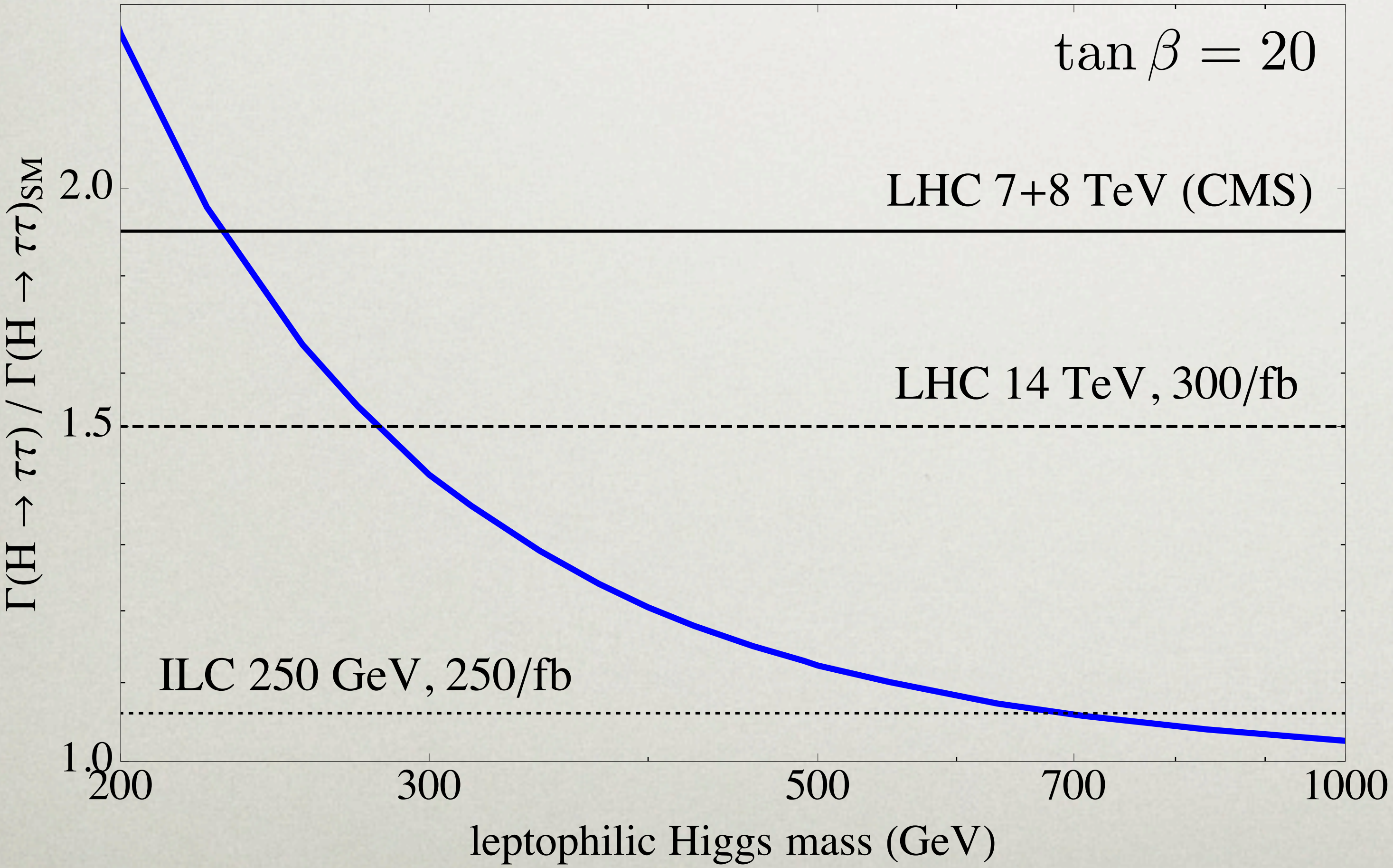


Assume minimal mixing from mu-term

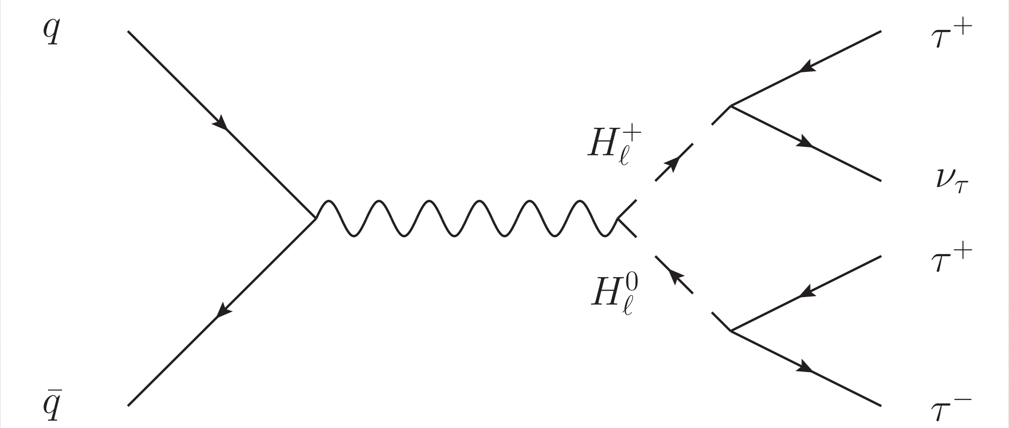
Calculated with 2HDMC

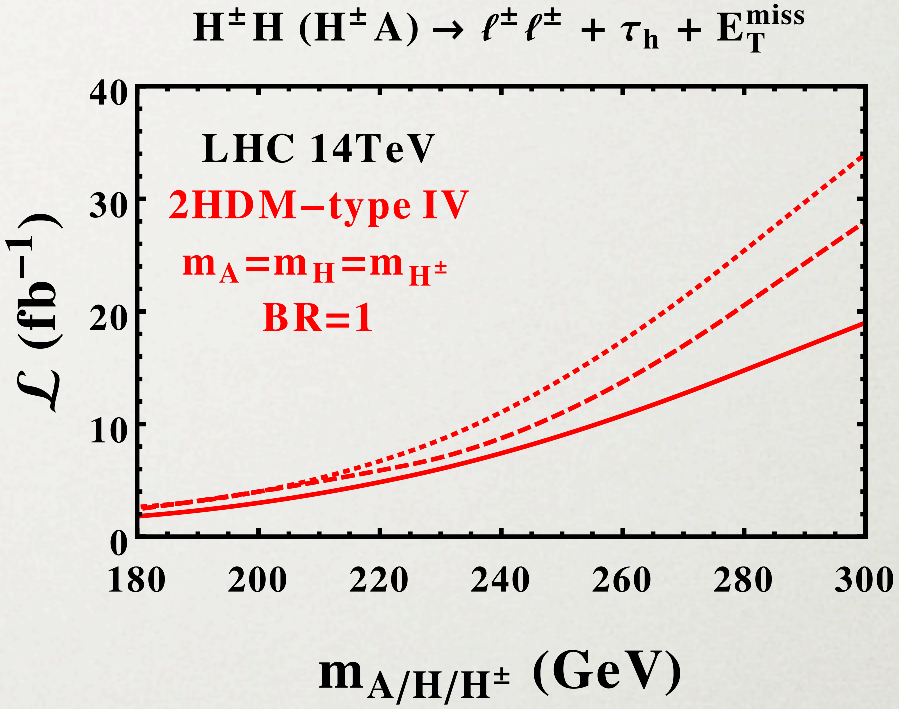
Future projections derived from Peskin, 2012

Recent 8 TeV scan:
ex. Ferreira *et al.*, 2014

2HDM Phenomenology

- Can also search directly for the new Higgs states (model-independent)





  - A promising search channel is same-sign dileptons + hadronic tau (current bound = 150 GeV)
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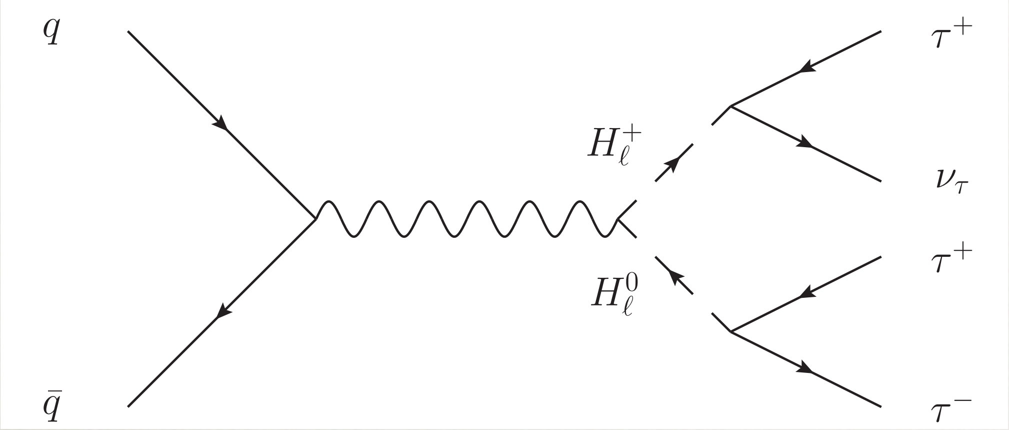

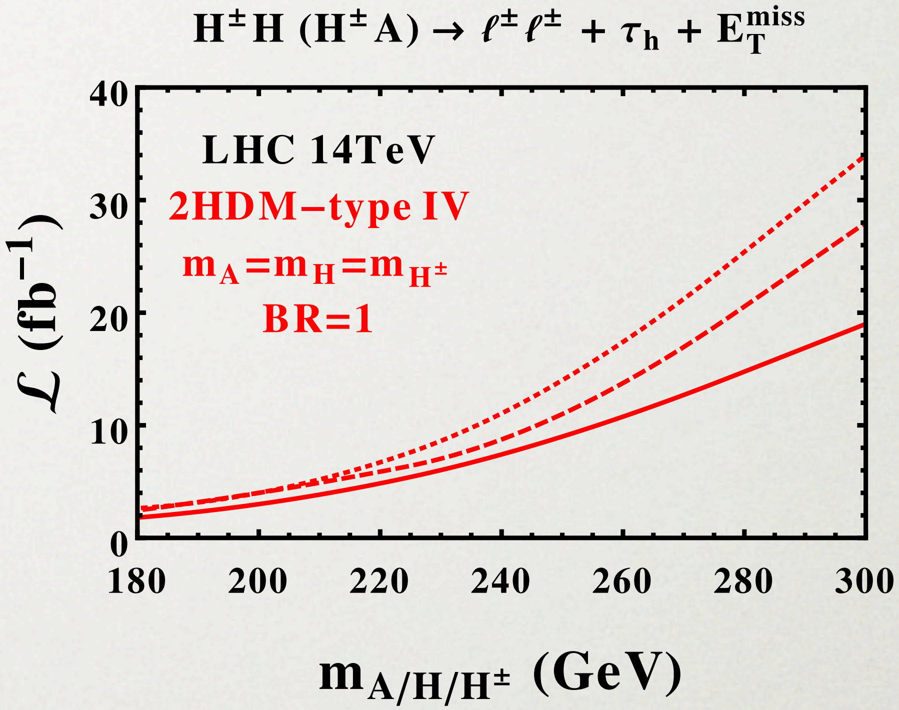

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- There are other, more exotic possibilities
  - New Higgs could **only** give mass to neutral leptons
  - If new H decays to lepton + RH neutrino, there are strong bounds from slepton searches
  - Sensitive to model details: new Higgses could also decay through Higgs mixing

- Low-scale leptogenesis suggests broad searches for leptonic interactions!

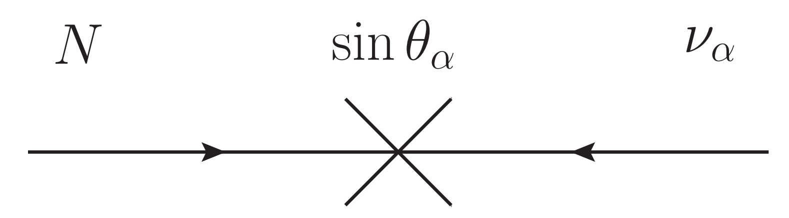
Sterile neutrino dark matter & the νMSM

Minimal Sterile Neutrinos

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

- The **lightest** *N* is the dark matter candidate
  - Assume for simplicity that it mixes with only one generation of L_α
  - We will see that N_1 mixing is too small to contribute to LH neutrino masses

- After electroweak symmetry breaking, the LH and RH neutrinos mix



$$\sin\theta_\alpha = \frac{F\langle\Phi\rangle}{M_N}$$

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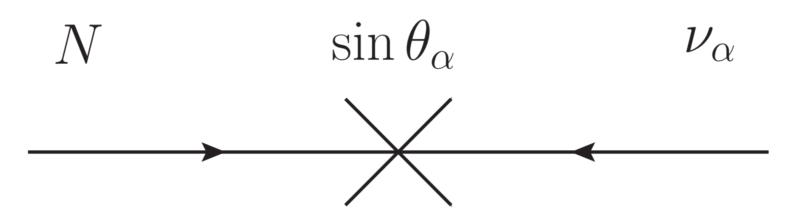

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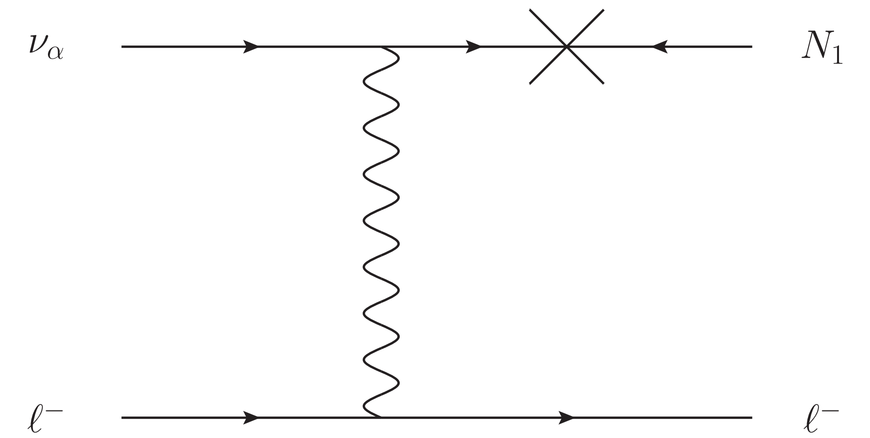
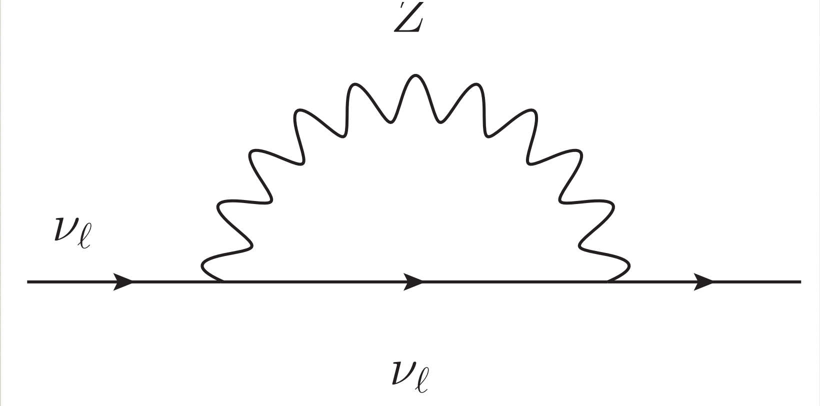


- DM is produced through SM electroweak interactions
- This is the **Dodelson-Widrow mechanism** (1993)

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

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)



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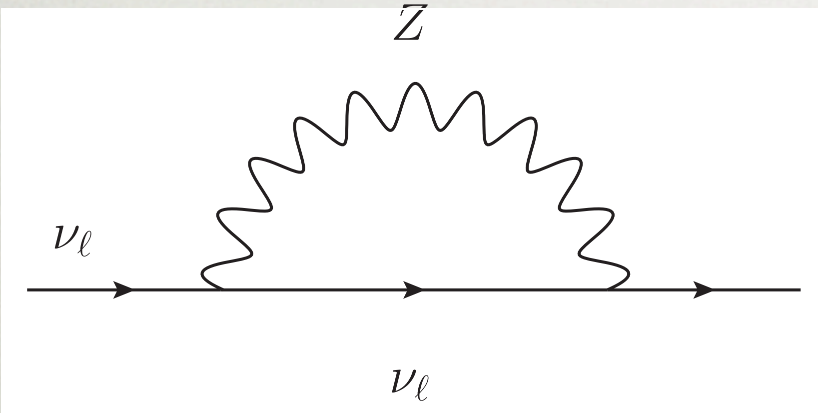

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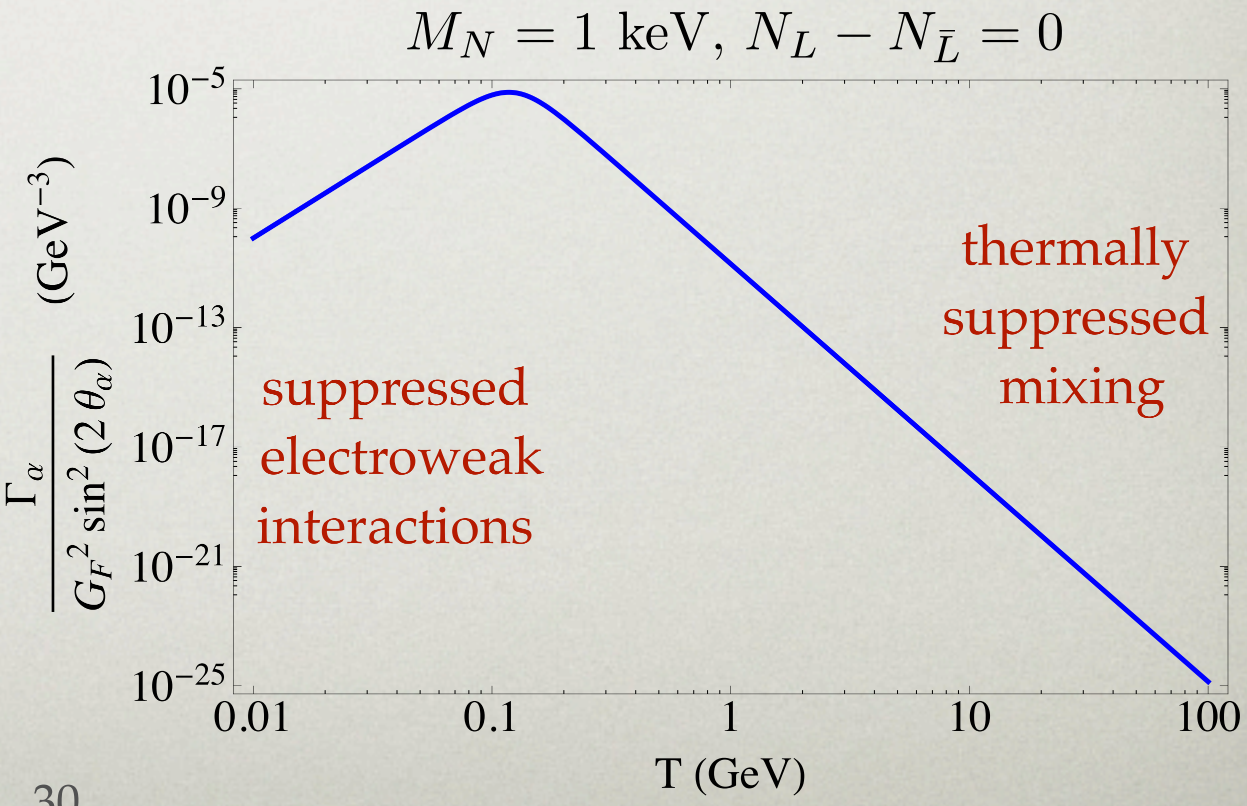
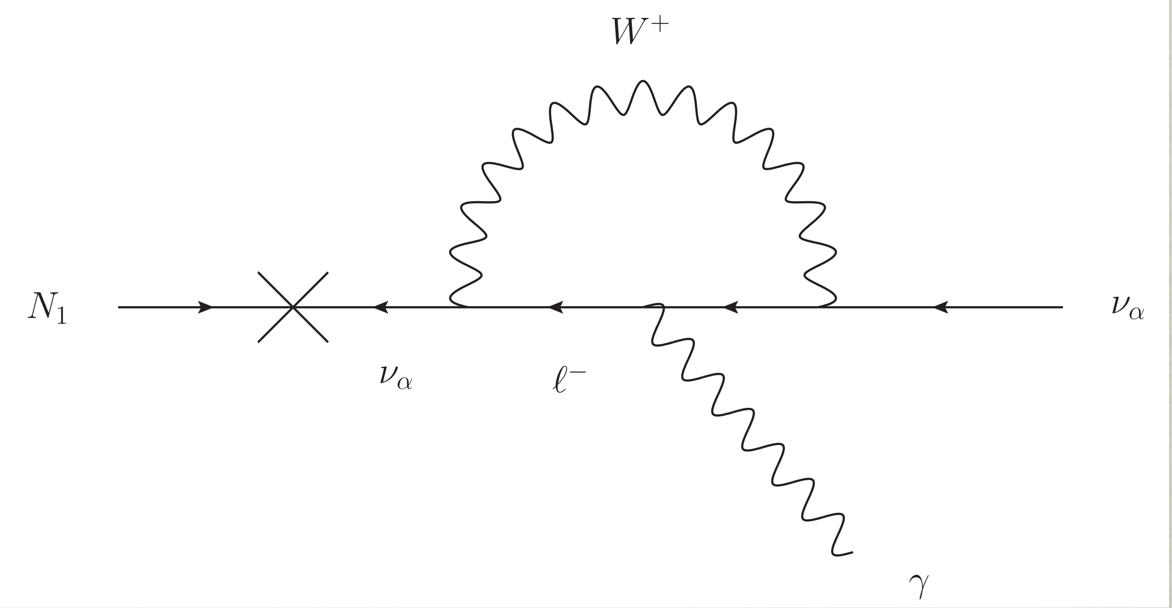


Sterile Neutrino Decay

- 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 to a **photon line**:

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



Taken from Watson, Li, Polley 2012

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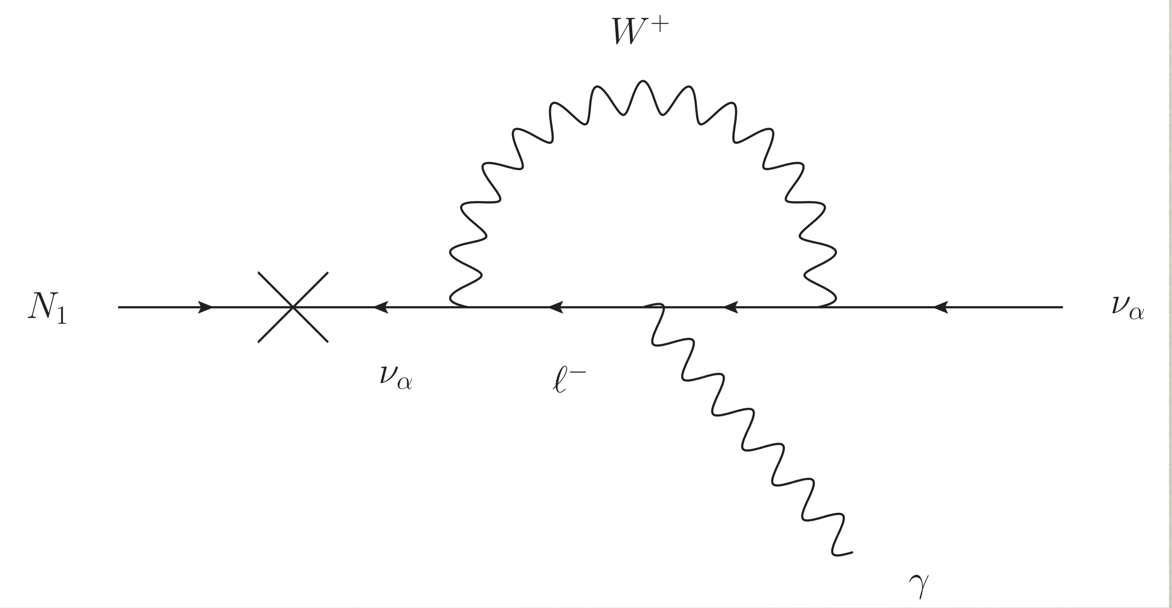

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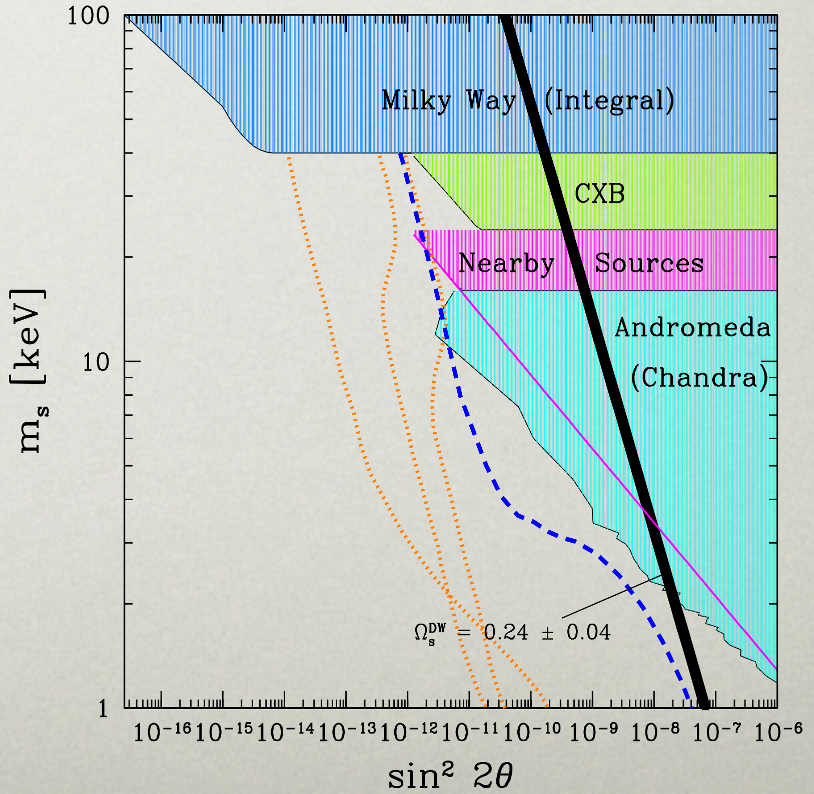
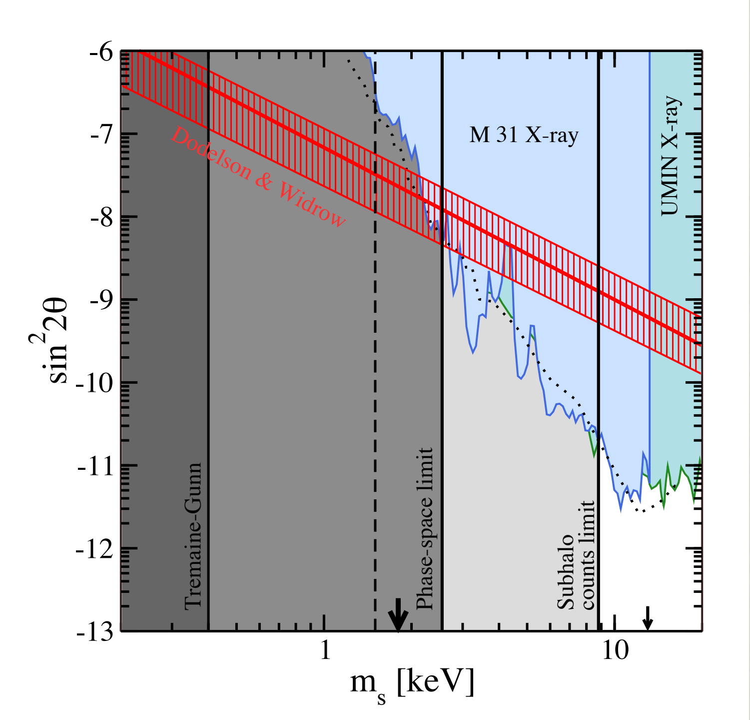


- This leads to bounds on X-ray lines from various sources
- Absence of signal → $M_N \lesssim 2$ keV

Small-Scale Structure

- $M_N \lesssim 2$ keV → warm dark matter
- Suppresses growth of structure on **small scales**
- Production of N through SM gauge interactions + mixing is **completely ruled out!**
- Sterile neutrinos are **too sterile**



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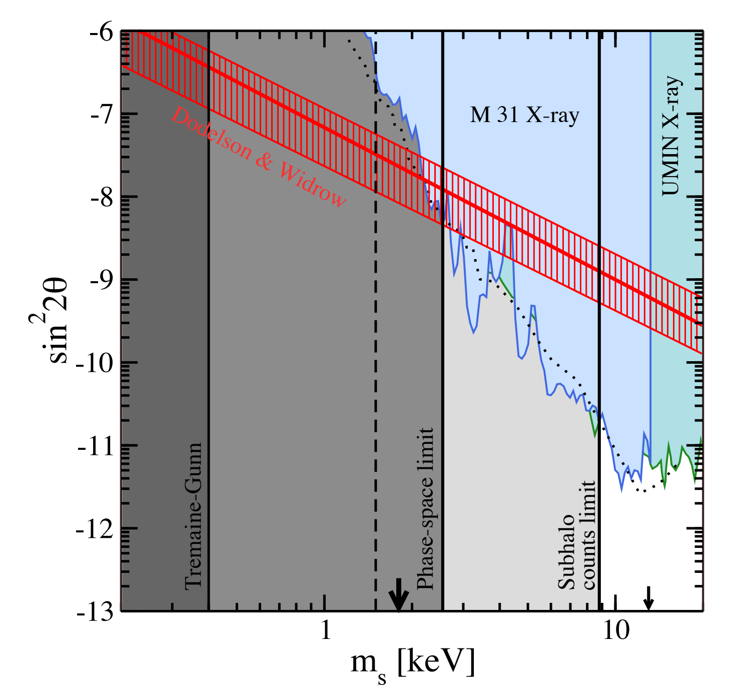

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- The minimal model can only work with a **resonant enhancement** of the mixing between SM and sterile neutrinos (Shi, Fuller 1999)
- Requires very large late-time lepton asymmetry ($>10^6$ times bigger than baryon asymmetry)

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

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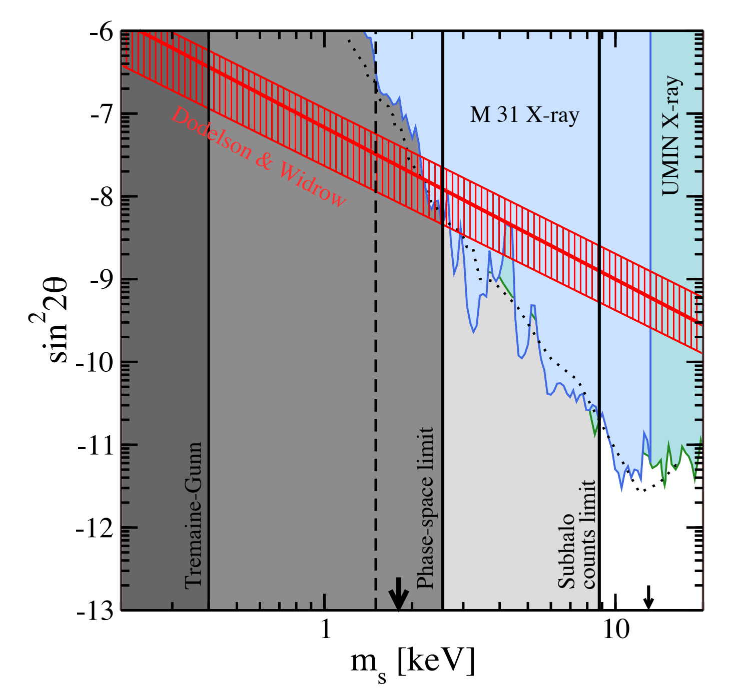

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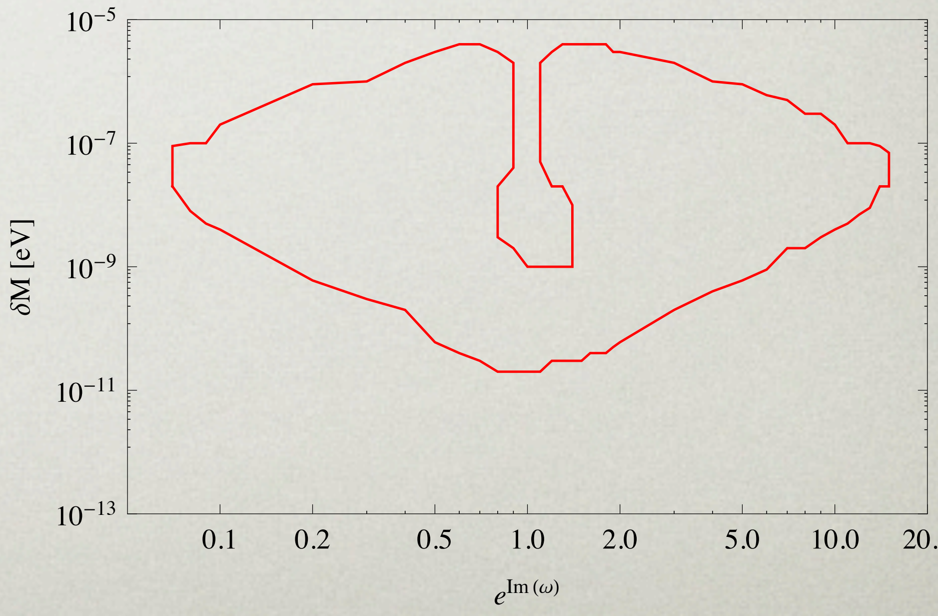
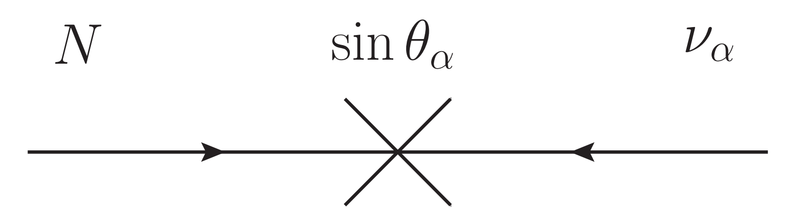


from Canetti *et al.* 2012

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 even without a direct coupling to *N*



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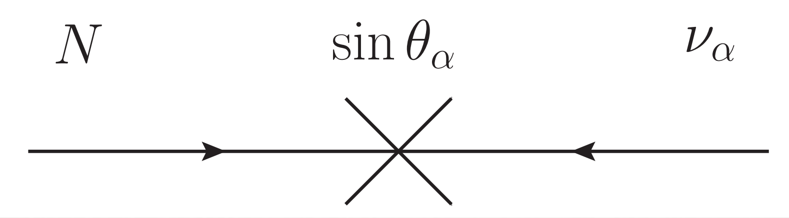
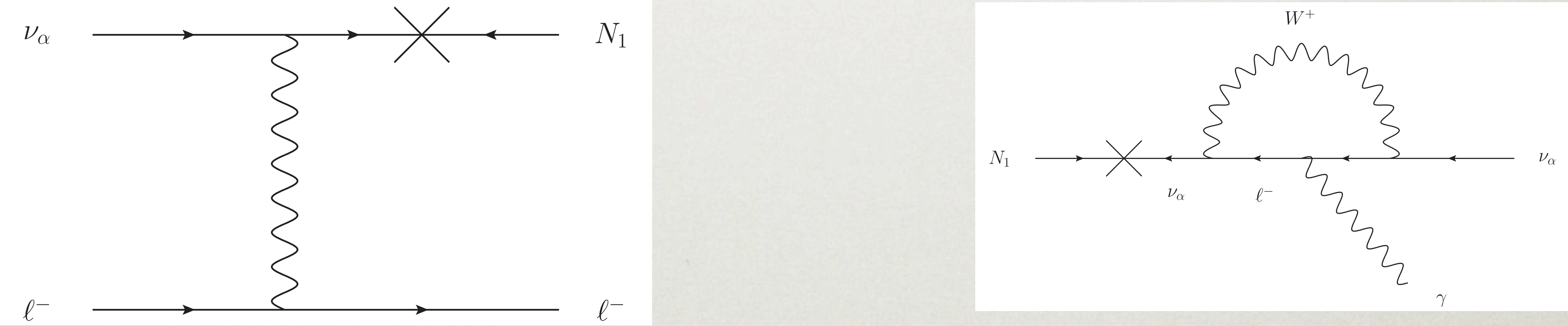


- But does any new contribution to *N* production also lead to its decay into a photon line?



- 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

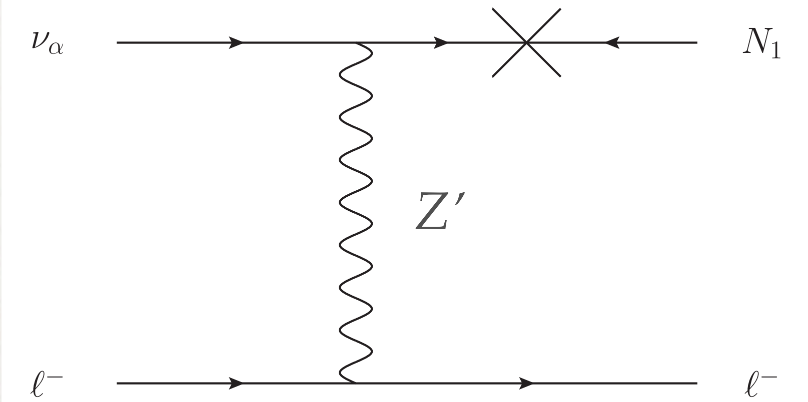
- A **neutral current** interaction contributes to production but **not the decay to photons**
    - Reasonable choice: new U(1)′ gauge interaction, Z′ force mediator
    - Anomaly-free: $B - L$, $L_i - L_j$
    - The cosmology only requires that Z′ couples to SM neutrinos (but phenomenology depends on other charged states)

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

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

New Leptonic Interactions

- $M_{Z'} \gg$ **GeV:**
  - Production of *N* only occurs below a few hundred MeV
  - *N* production mediated by off-shell Z′
  - Since the electroweak interactions are **too weak** to produce enough *N*: $G' \gg G_F$
  - This is **ruled out** from excessive contributions to the lepton magnetic dipole moments, LEP, etc.



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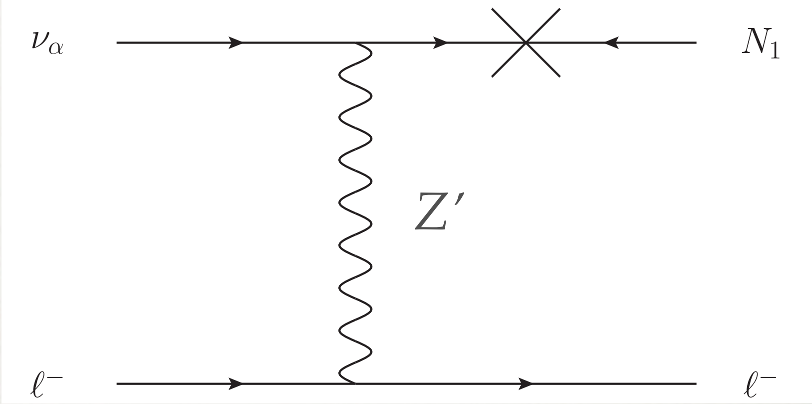
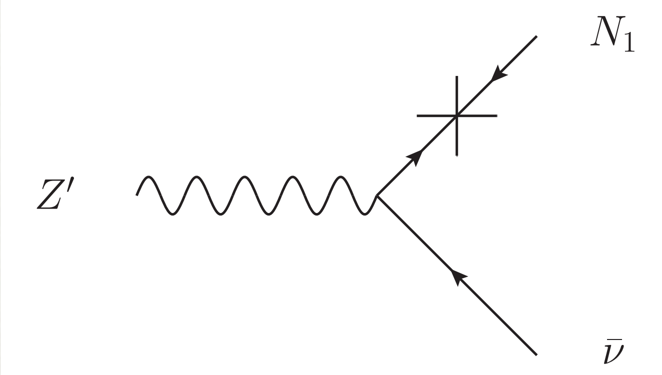
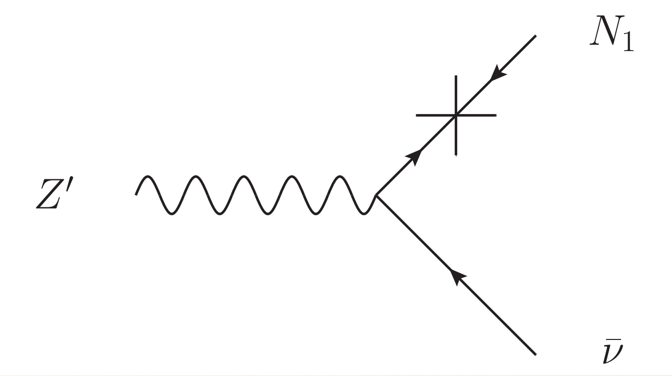


- **$M_{Z'} \lesssim$ GeV:**
  - Z' still present in thermal bath at time of largest *N* mixing
  - 1 → 2 processes dominate
  - Similar dynamics to direct *N* production from singlet decays (Shaposhnikov, Tkachev 2006; Petraki, Kusenko 2007)
  - This new force is precisely in the window probed at the intensity frontier



Not-so-sterile Neutrinos & U(1)’

- Estimate of *N* abundance:



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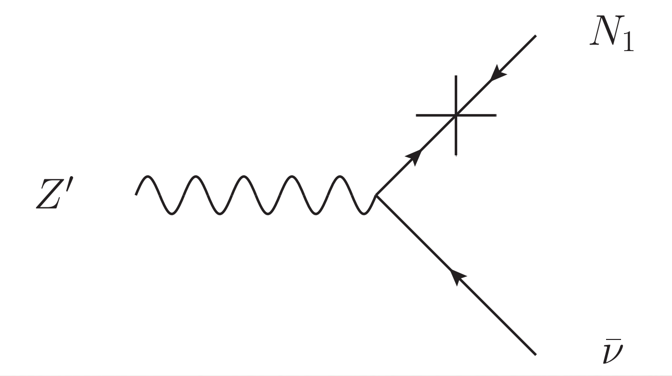

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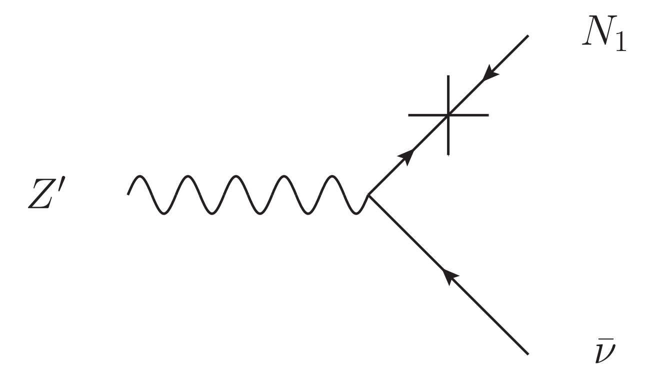
- The number of *N* produced per Hubble time **grows** as the universe cools
- Most *N* are produced at the lowest temperature where Z′ is still in the thermal bath ($T \sim M_{Z'}$)

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

Not-so-sterile Neutrinos & U(1)’

- Estimate of *N* abundance:



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

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

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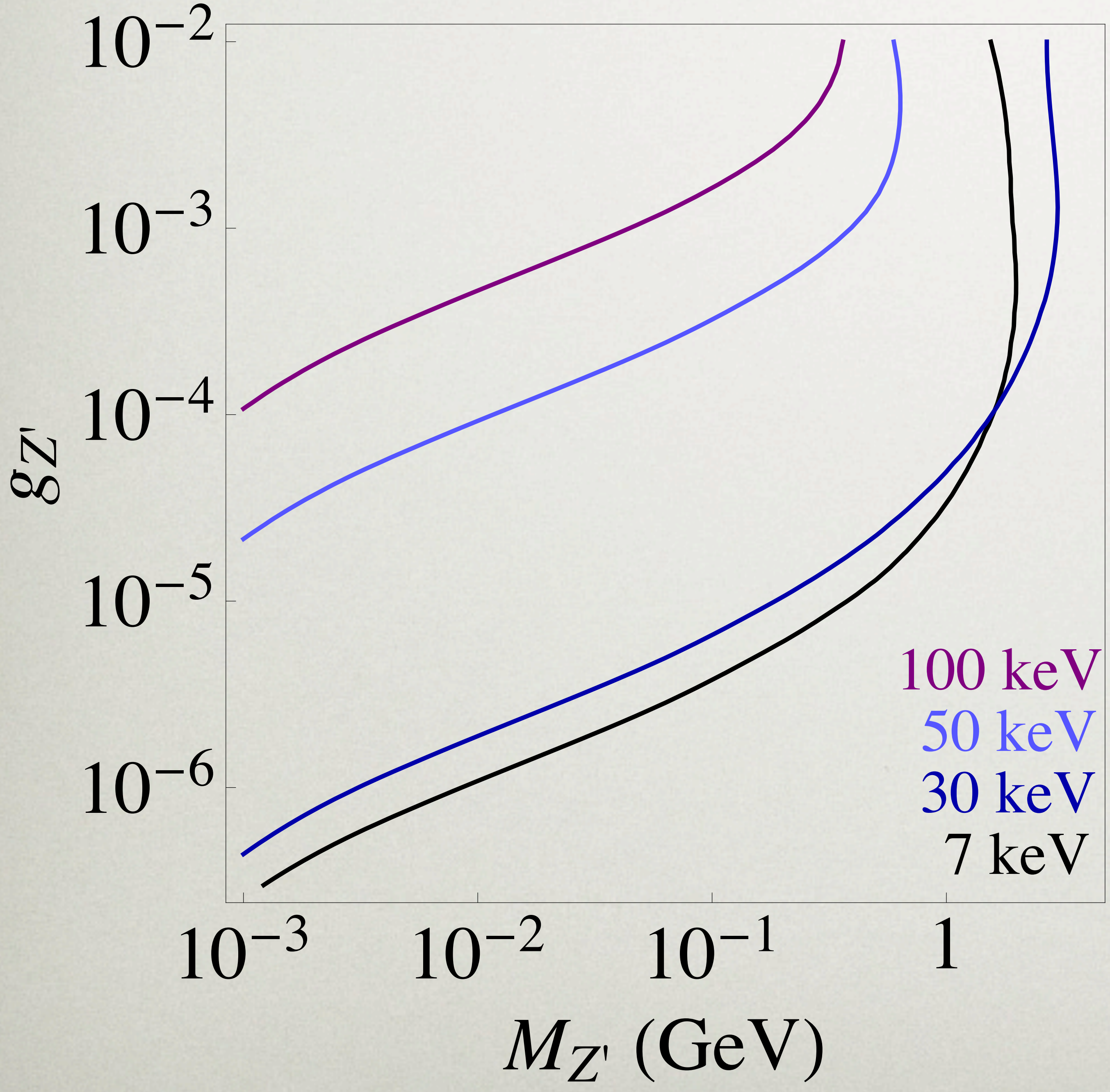
- Our calculations include all 1-loop finite-*T* effects from SM gauge and Z′ interactions
- Thermal effects of Z′ computed in non-equilibrium QFT without assumptions on $M_{Z'}$

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



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

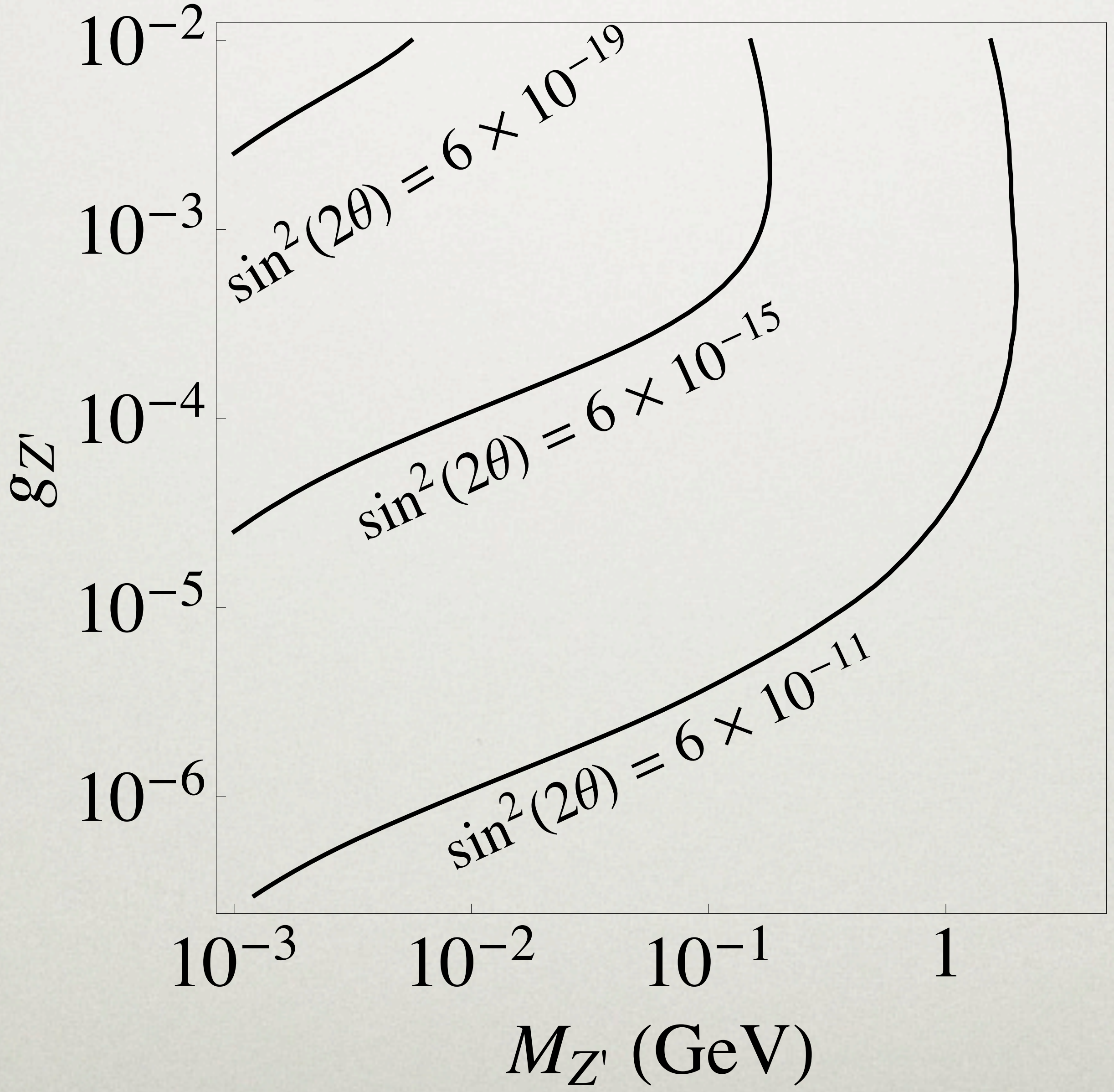
$M_N = 30$ keV, $\sin^2(2\theta) = 5 \times 10^{-12}$

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

$M_N = 100$ 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



Phenomenological probes of new leptonic interactions

Z’ constraints

- **Mass:**
  - Since the Z' decays into neutrinos, constraints on the effective number of neutrino species imply $M_{Z'} \gtrsim 2$ MeV (Planck, 2013)

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- **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)

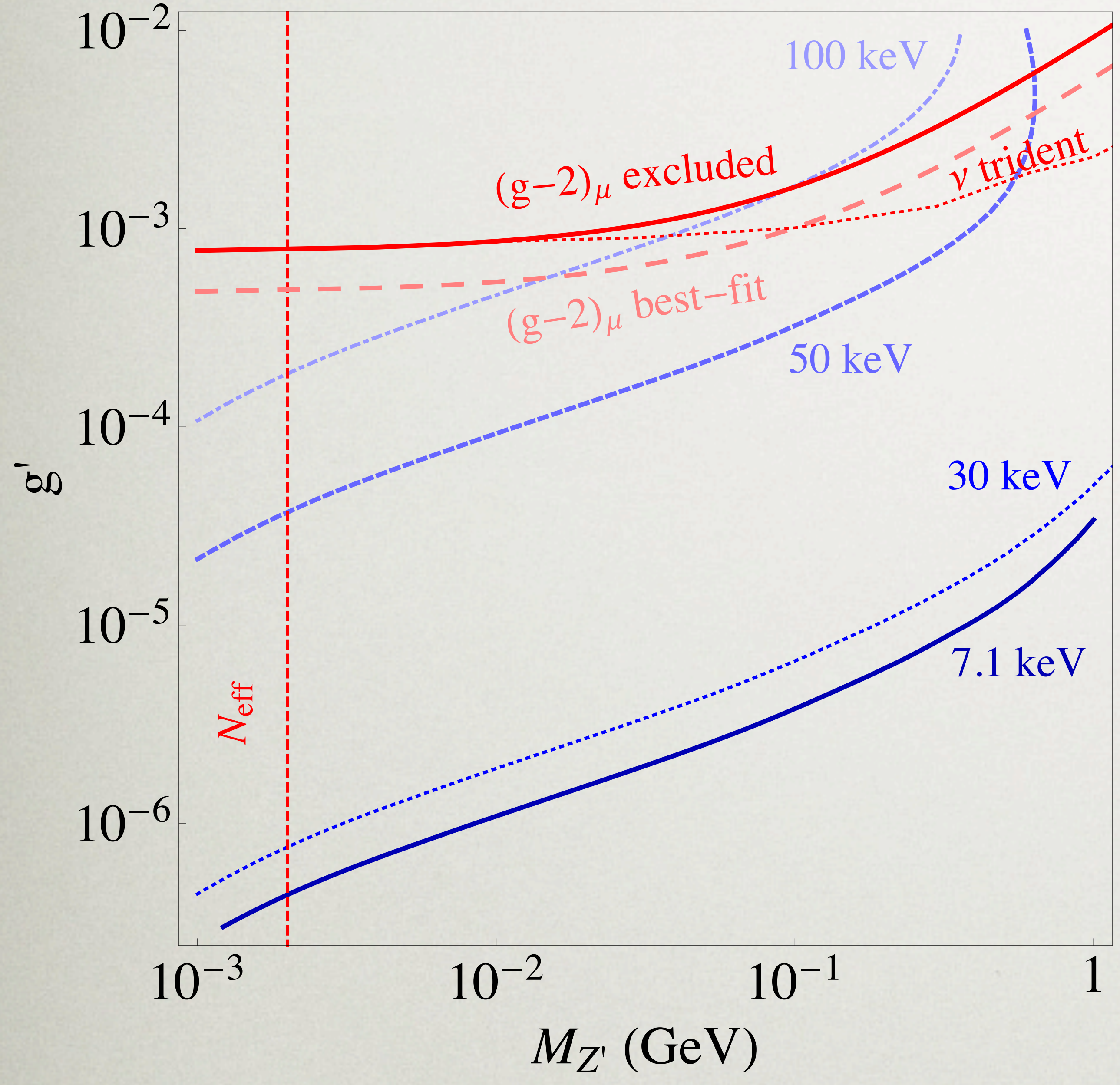
Pospelov, 2008

adapted from Williams et *al.*, 2011

Altmannshofer *et al.*, 2014

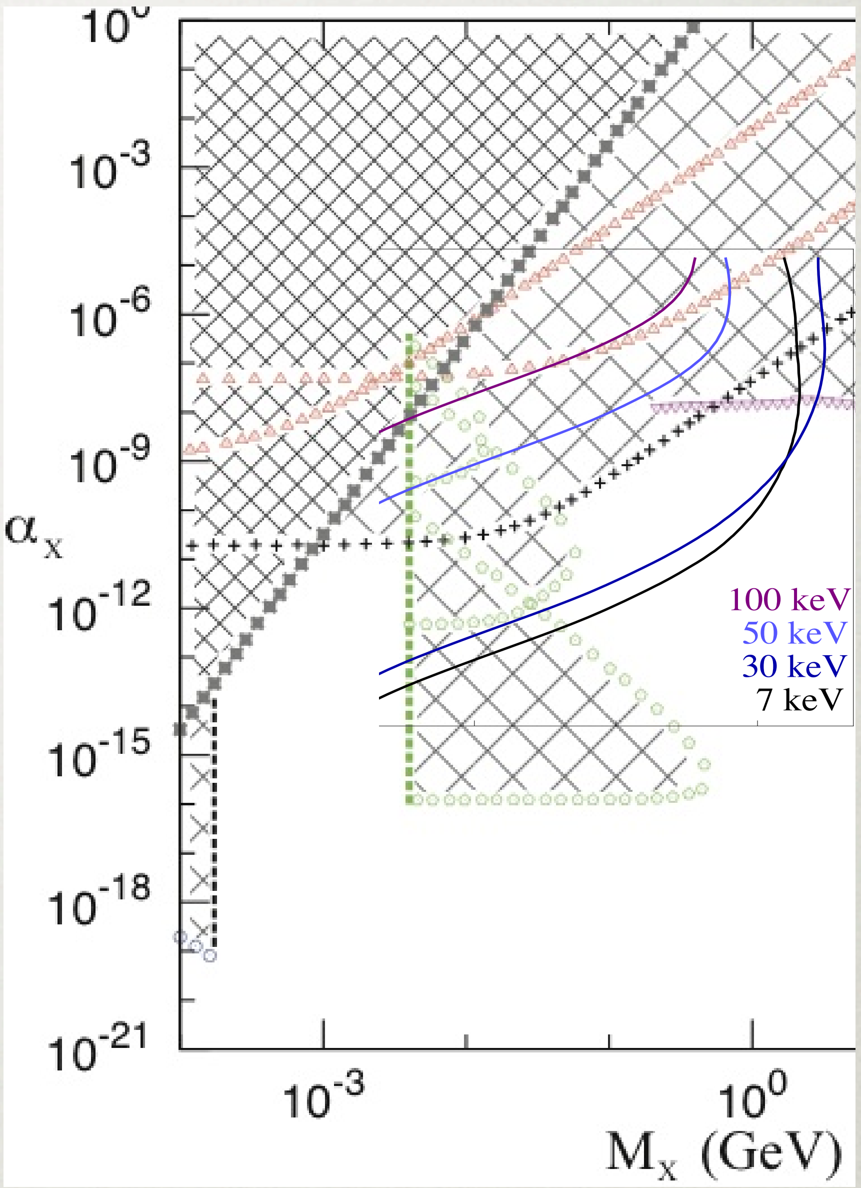
- Final constraints depend strongly on fields coupled to Z'

Z’ constraints



***L_μ - L_τ* current**

adapted from Williams et *al.*, 1103.4556

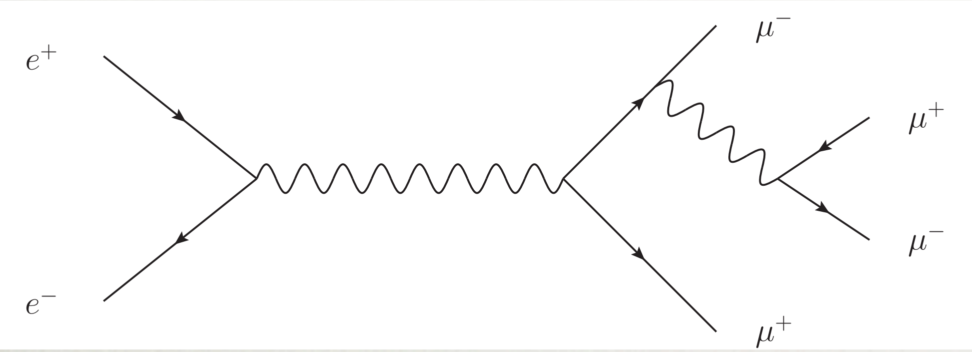


***B* - *L* current**

(Near) Future prospects

Work in progress with B. Échenard, S. Gori

- Constraints are weakest in models with suppressed coupling to e/baryons
  - Lots of heavy flavour leptons at B factories like BaBar!



- Search for **single** muon resonance in 4-muon final state
- Sensitive to muon *g*-2 region; competitive with trident search!

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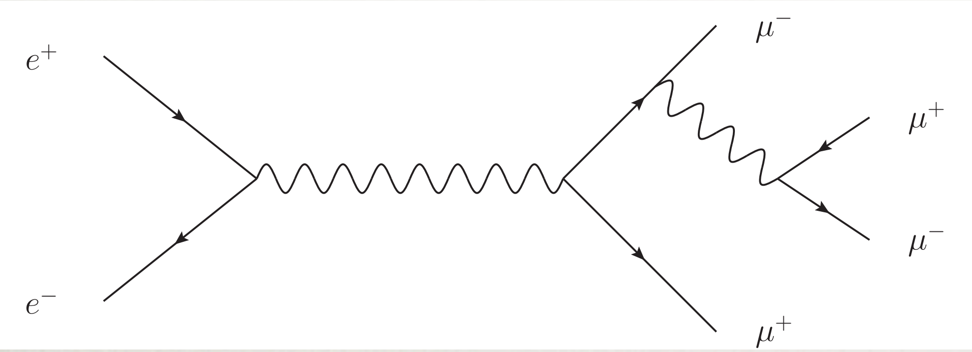
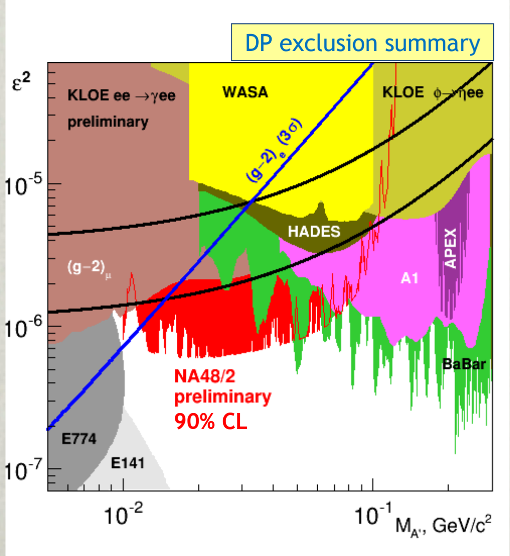


- Search for **single** muon resonance in 4-muon final state
- Sensitive to muon *g*-2 region; competitive with trident search!

- In addition to DM motivation, we are **directly probing** muon *g*-2 coupling



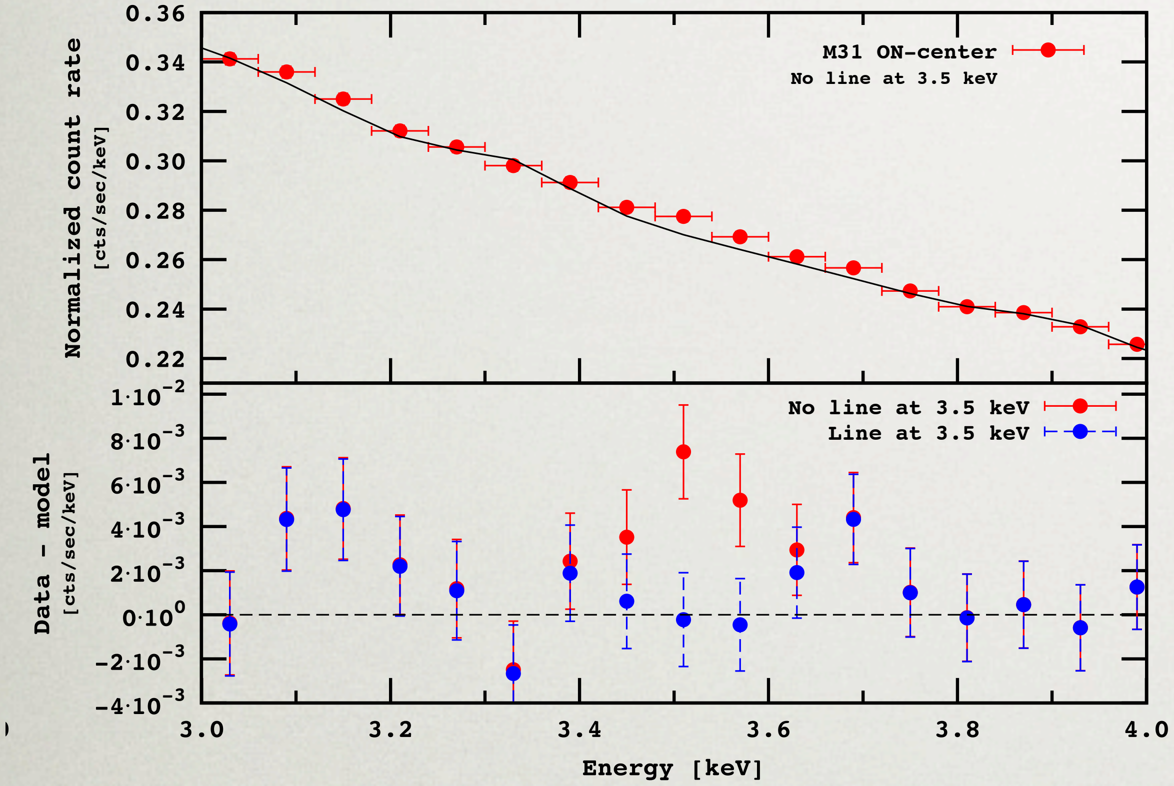
NA48/2 Talk, 2014

- Important in light of recent **full exclusion** of muon g-2 if equal coupling to e/mu (with visible decays)!
- Also looking at **invisible decays**

A possible hint of *N*?

- **Possible detection** of 3.57 keV X-ray line in stacked galaxy clusters, Perseus, M31

Bulbul *et al.*, 2014; Boyarsky *et al.*, 2014



- 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′*

- But there are the usual caveats of potential mis-modelling of background (Jeltema and Profumo, 2014), conflicting measurements, ...

- Let’s see where the dust settles!

Conclusions

- The missing pieces of the SM can be filled in with new sterile neutrino states at **phenomenologically accessible scales**

- The simplest model can explain all of dark matter, baryogenesis, neutrino masses, but with a high degree of parameter alignment/tuning

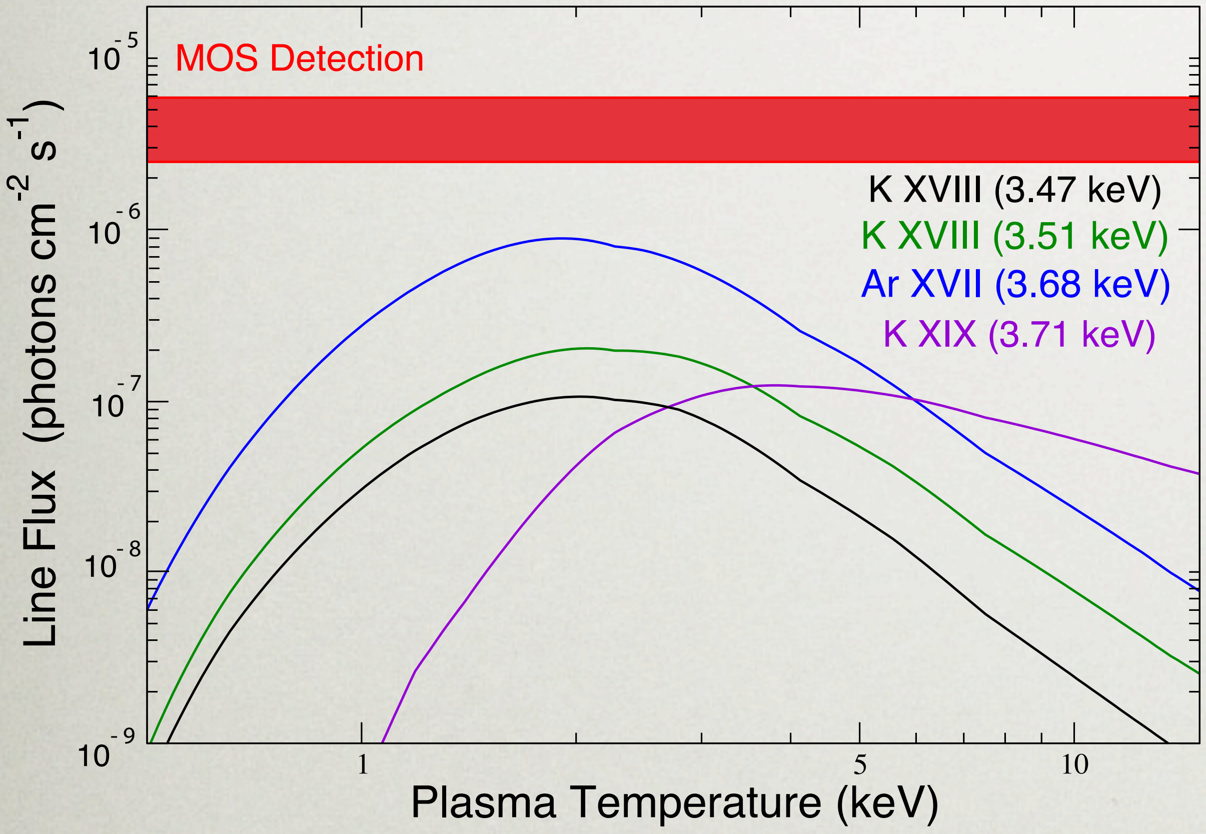
- Models with **new leptonic interactions** at and below the weak scale can substantially enhance the dark matter abundance and baryon asymmetry
  - Robust prediction for interesting new physics with leptons at energy and intensity frontiers
  - Act as independent probes of sterile neutrino cosmology

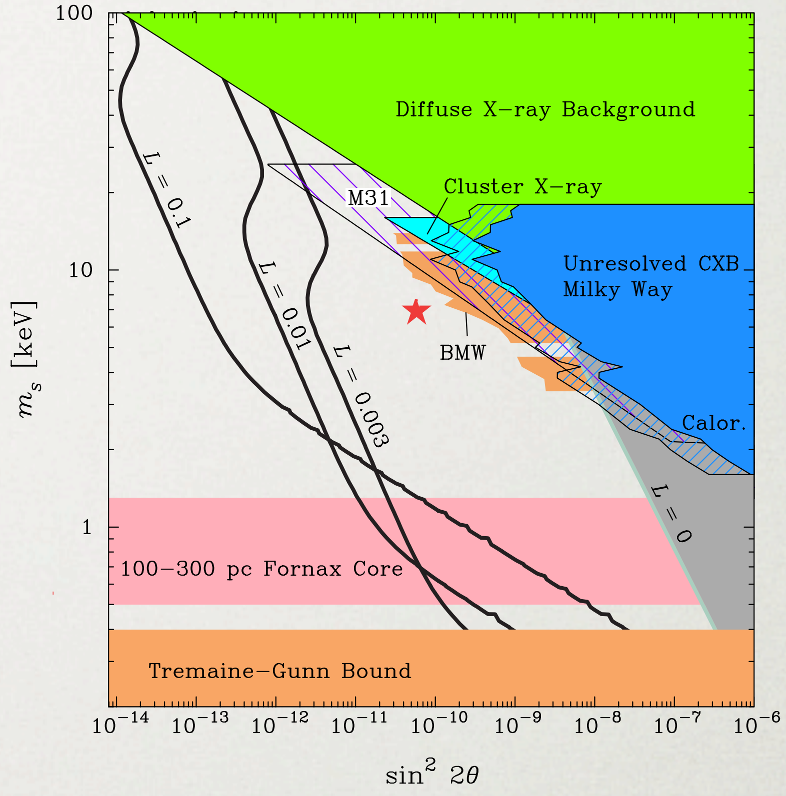
- More work needed to determine the best way to identify most reasonable models, constrain new forces and fields over the allowed range

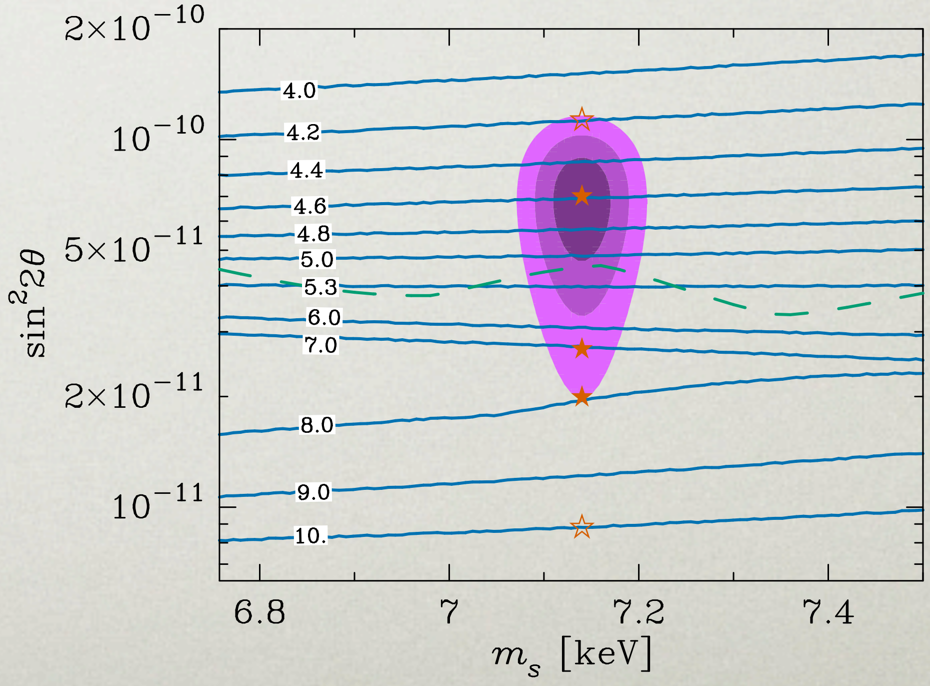
Back-up slides

3.6 keV X-ray line

- Some more plots:



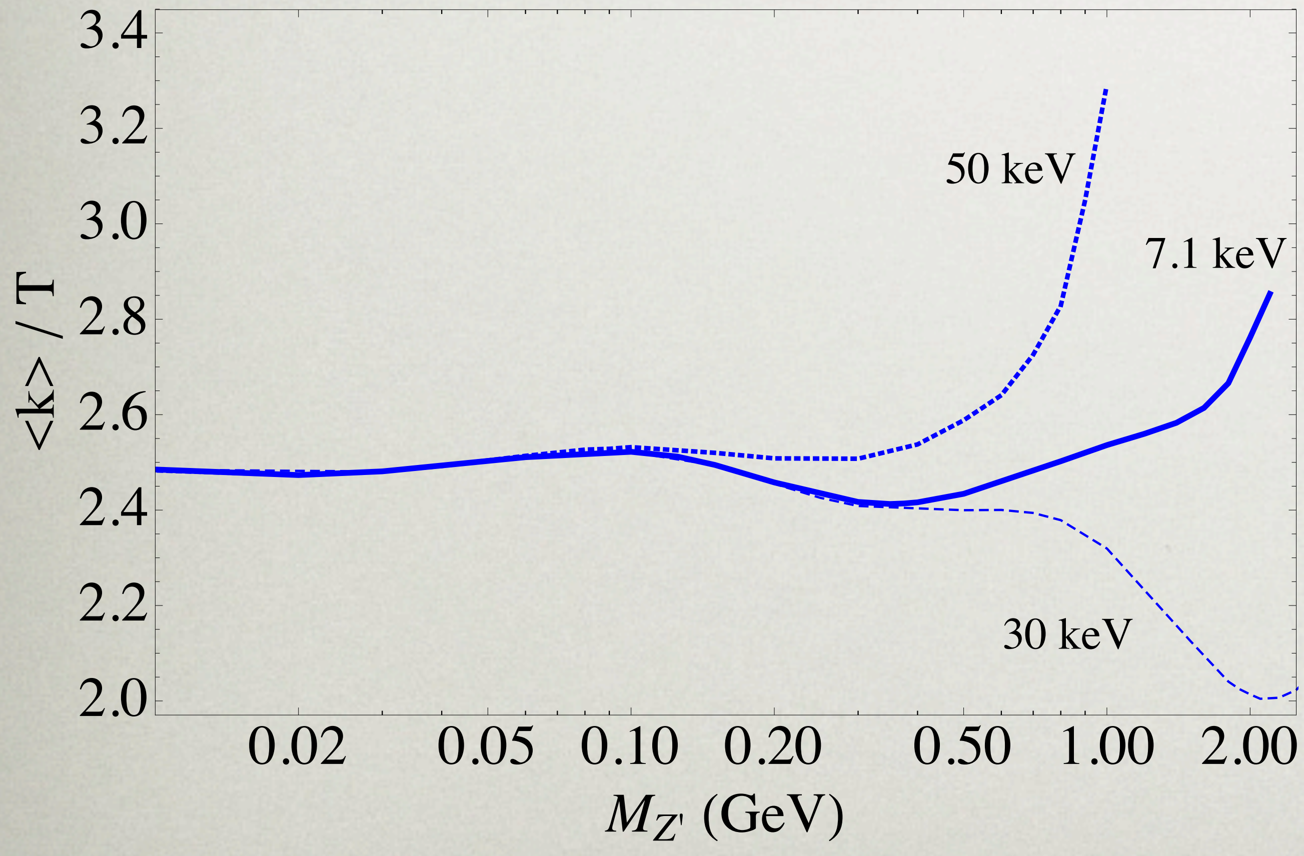


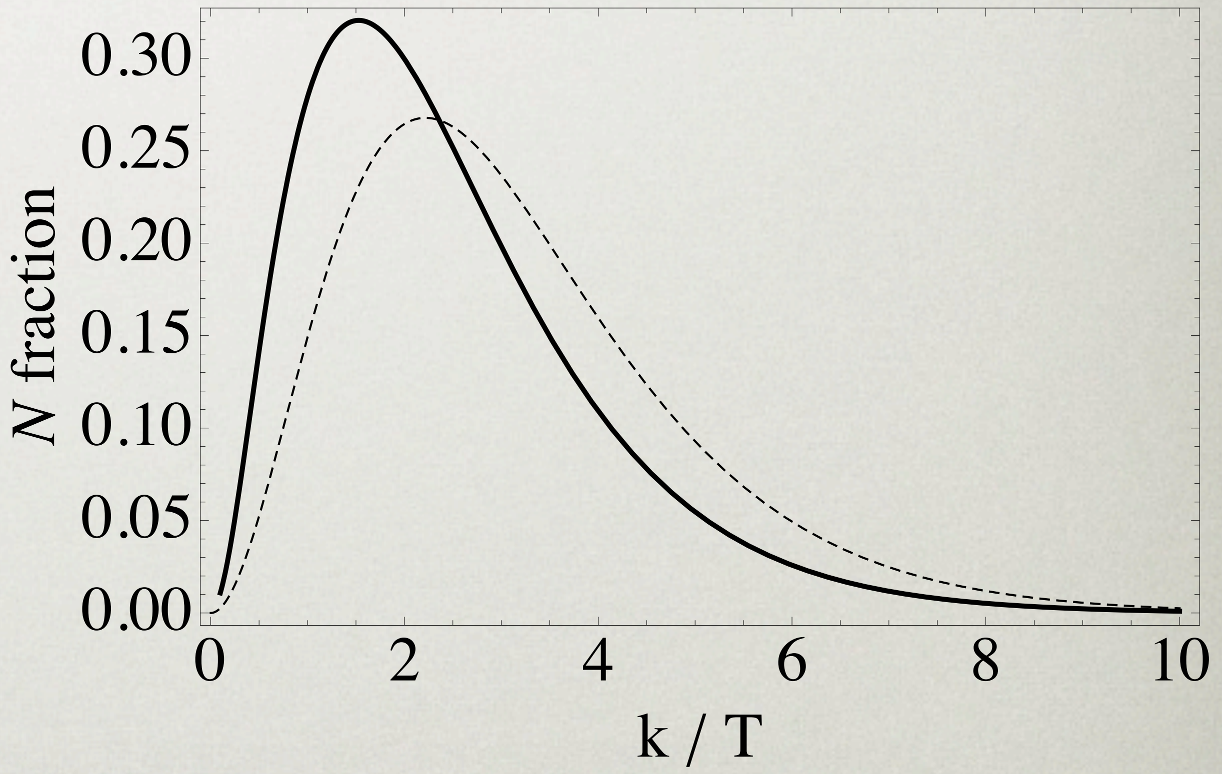


Taken from **Abazajian 2014**

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 $\mathrm{U}(1)_{\mu\text{-}\tau}$:
  - Introduce new scalar Σ carrying $\mathrm{U}(1)_{\mu\text{-}\tau}$; new doublet Dirac fermions X_2, X_3

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

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