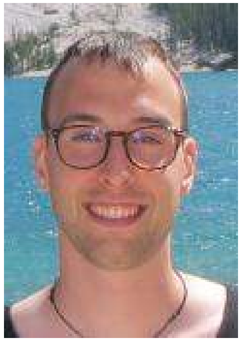
A little theory of everything

Jim Cline, McGill University

JC, M. Puel, T. Toma,
1909.12300,
2001.11505



JC, G. Gambini,
work in progress

King's College London TPPC, 13 Jan. 2021

Shortcomings of the standard model

The standard model is extremely successful, but leaves us wondering about the origin of:

- ν mass
- cosmological inflation
- dark matter
- matter-antimatter asymmetry

Could we economically tie them all together ?

We introduce new ideas for doing so, that transcend the particular model I present here.

“Affleck-Dine” Inflation

Previously we introduced *Affleck-Dine inflation*, where complex inflaton can produce a particle asymmetry during inflation [2]

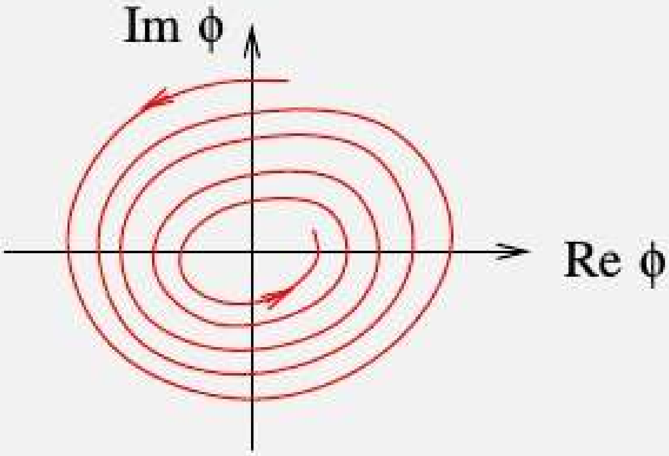
$$V = m_\phi^2|\phi|^2 + \lambda|\phi|^4 + i\lambda'(\phi^4 - \phi^{*4})$$

With nonminimal coupling $\xi|\phi|^2 R$ to gravity, this can satisfy Planck constraints on CMB temperature fluctuations.

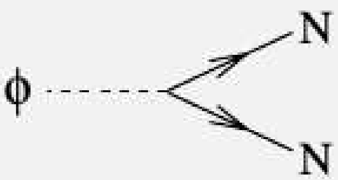
New idea: inflaton generates the asymmetry itself, *during* inflation. But it still needs to get transferred to the SM sector: this is where HNL’s come in.

Nonstandard leptogenesis

Suppose ϕ carries lepton number $L = 2$.



Asymmetry in $\phi - \phi^*$ (lepton number) created *during* inflation, while field bends in complex plane. Transfer it to *heavy neutral leptons* (HNLs)—GeV-scale quasi-Dirac sterile neutrinos, by inflaton decay:



$$\mathscr{L} = g_\phi\, \phi(\bar{N}_R N_R^c + \bar{N}_L N_L^c)$$

Lepton asymmetry is transferred to HNLs. They pass it on to the SM, and the dark matter HNL.

New features: DM abundance is very simply related to the lepton asymmetry since one of the N's is the DM.

HNLs must be (quasi-)Dirac, to avoid washing out the asymmetry.

CP violation is spontaneous — inflationary initial conditions. No new CP violation is needed.

So it is consistent to leave the strong CP problem out of our list.

Novel ideas:

Heavy RH ν_R's are integrated out; they are above the inflation scale.

Yukawas of N's are aligned with those of usual ν_R's.

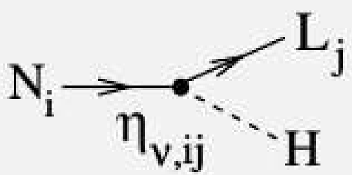
This is radiatively stable: technically natural.

η_ν matrix is rank 2: one N_i is stable DM.

3 HNL's are nearly degenerate, due to approximate dark flavor symmetry

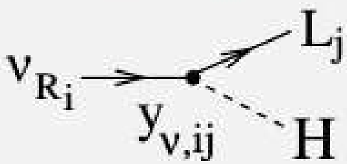
NHLs and neutrinos

HNLs can have mass mixing with νs via Higgs:



$$\Longrightarrow \begin{array}{cc} \begin{pmatrix} m_\nu & \eta_\nu^T v & 0 \\ \eta_\nu v & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix} & \begin{array}{c} \nu_L \\ N_R^c \\ N_L \end{array} \end{array}$$

Minimal flavor violation* ansatz: we assume that η_{ij} aligns with the ν Yukawa couplings:



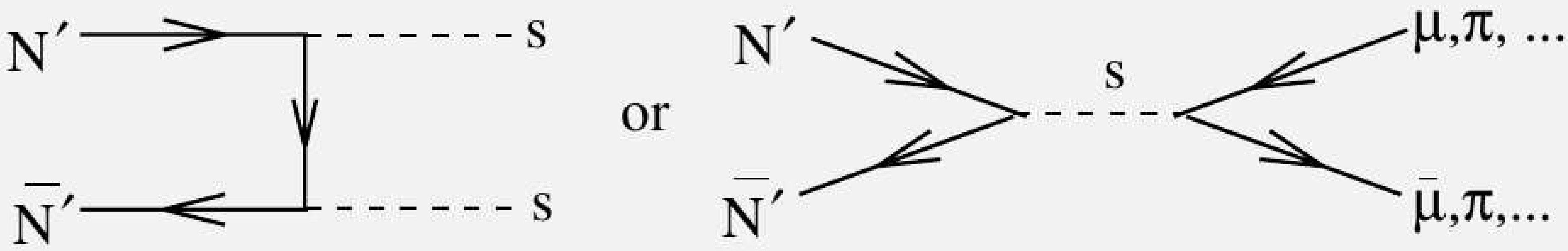
$$= y_{\nu,ij}\bar{\nu}_{R,i} H L_j, \qquad \underline{y_{\nu,ij} = k\,\eta_{\nu,ij}}$$

Assume $\nu_{R,i}$ are superheavy, integrate them out to get m_ν. Take 3 HNLs to be degenerate: approximate flavor symmetry, weakly broken by $\eta_{\nu,ij}$. MFV makes theory highly predictive, allows one HNL to be <u>dark matter</u>.

* η_ν breaks dark SU(3) lepton flavor symmetry

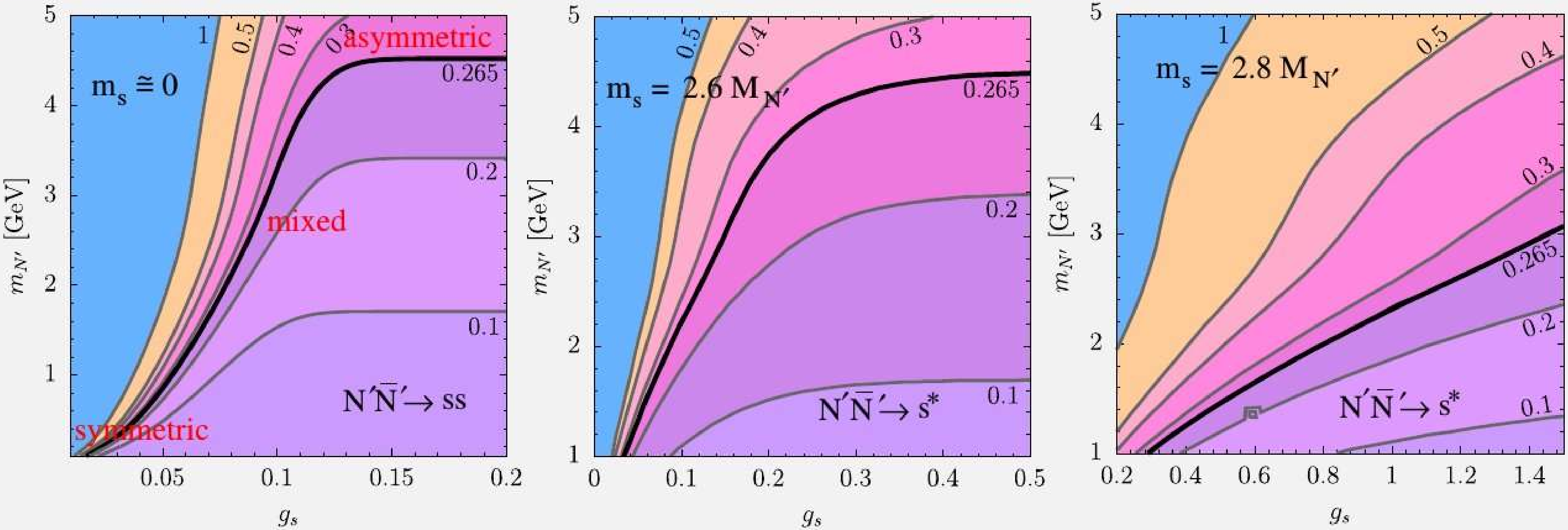
HNL as dark matter

If lightest ν is massless, then $\eta_{\nu,ij}$ has vanishing eigenvalue: gives one HNL (N') that is absolutely stable—DM candidate! But we need new annihilation channel. Add a light singlet scalar s with $g_s\, s\bar{N}_i N_i + \lambda_{hs} s^2 h^2 + \lambda_s (s^2 - v_s^2)^2$,



Novel: stability of DM is tied to masslessness of lightest ν.
Light singlet is mandatory, otherwise DM is too abundant.

DM Relic Density: asymmetric, symmetric or mixed DM



Contours of Ω_{CDM}. DM can be asymmetric, symmetric or in between. Can be heavier (center, right) or lighter (left) than singlet. **If asymmetric, $m_{DM} \sim 4.5$ GeV, and DM density $\sim$ cosmic ν asymmetry.**

Novel: DM can be hybrid of symmetric + asymmetric without significant fine tuning.

N-ν interaction parameters

We can solve for η_ν coupling matrix, given ν mass spectrum m_{ν_i},

$$\eta_{\nu,ij} = \left(\frac{m_{\nu_i}}{\bar\mu_\nu}\right)^{1/2} U^{-1}_{\mathrm{PMNS},ij}$$

up to the unknown $\bar\mu_\nu$ factor. They are bounded by EWPD constraints:

$$\bar\mu_\nu \quad > \quad 0.6\,\mathrm{MeV} \times \left(\frac{4.5\,\mathrm{GeV}}{M_N}\right)^2, \quad \text{normal hierarchy}$$

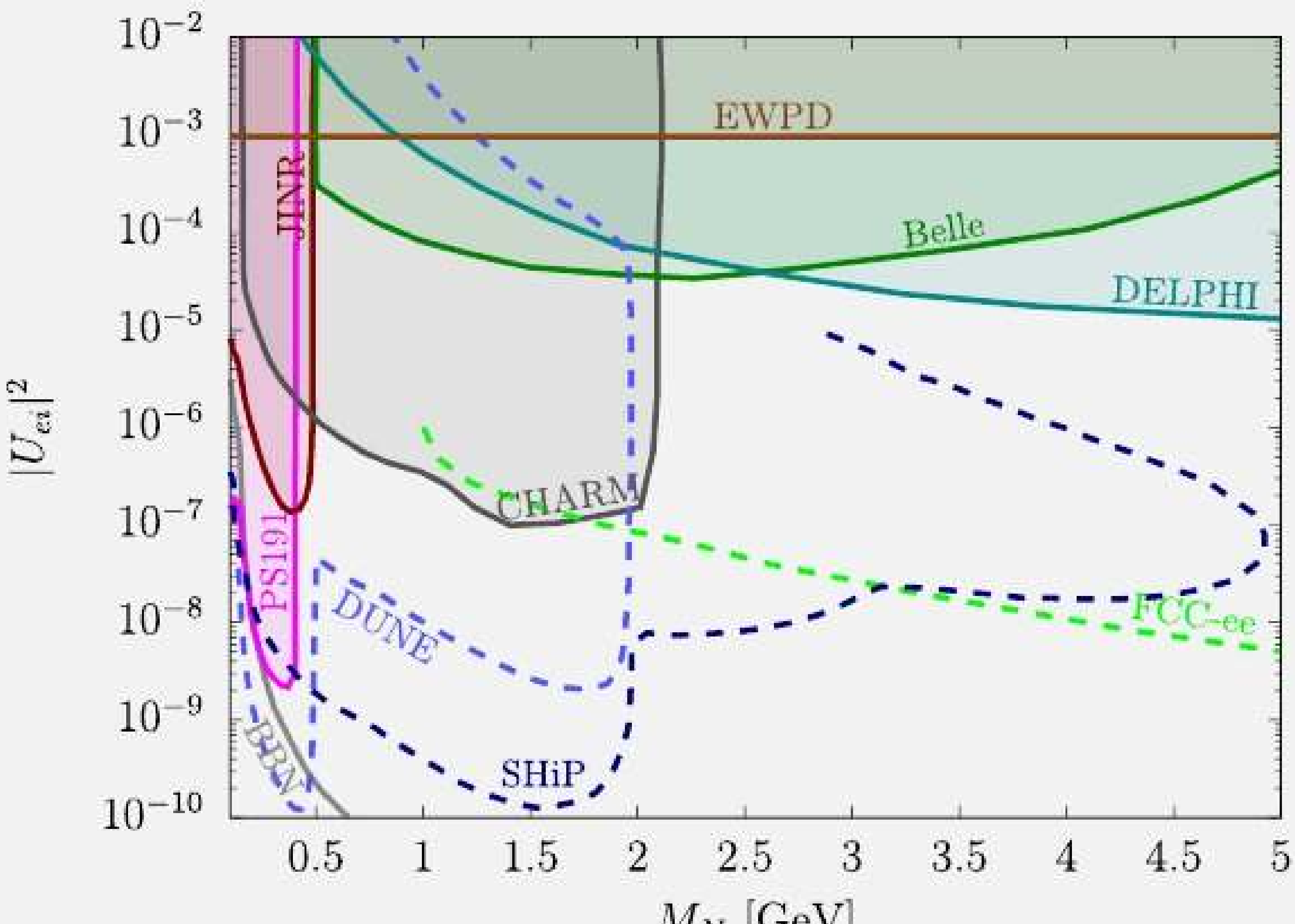
$$|\eta_{\nu,\ell i}| \quad \lesssim \quad 10^{-4} \left|\begin{array}{ccc} 0 & 0.66 & -0.32-0.29\,i \\ 0 & 0.72-0.05\,i & 2.1 \\ 0 & -0.79-0.04\,i & 1.9 \end{array}\right| \times \left(\frac{M_N}{4.5\,\mathrm{GeV}}\right)$$

Mixing of N_2 + N_3 with ν_ℓ, $\bar U_\ell = (\sum_i |U_{\ell i}|^2)^{1/2}$, is bounded by

$$\bar U_e < 0.003, \quad \bar U_\mu < 0.009, \quad \bar U_\tau < 0.008$$

HNL constraints and discovery

If $m_{N_i} < m_s$, beam dump constraints bound HNL mixing $U_{\nu,i}$ with ν's, from $N \to \nu f \bar{f}$. Otherwise $N \to \nu s$; precision electroweak bounds from PMNS unitarity still give constraint (EWPD).



Novel: Can relax to EWPD if $N \to s\nu$ is dominant decay channel and s escapes detector.

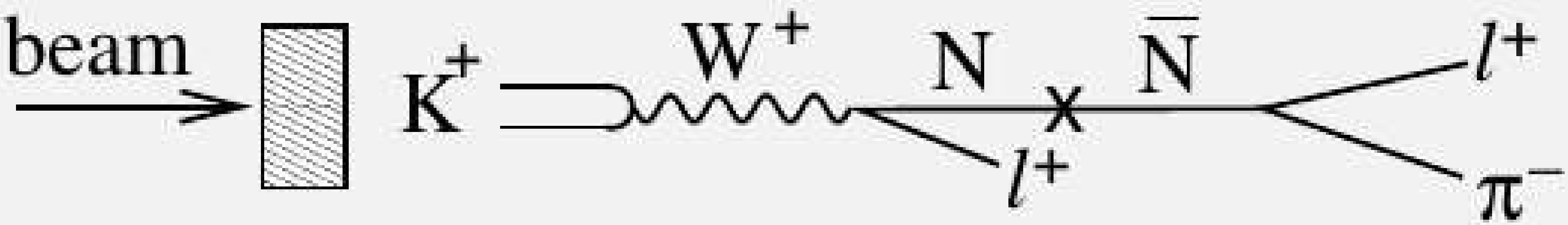
And HNL's must couple simultaneously to all three SM flavors.

N-$\bar{N}$ oscillations

EWPD

Limits $|\eta_\nu| \lesssim 10^{-3}$. HNLs get small Majorana mass $\delta M \sim \eta_\nu^2 m_\nu \sim 10^{-5}$ eV from light νs

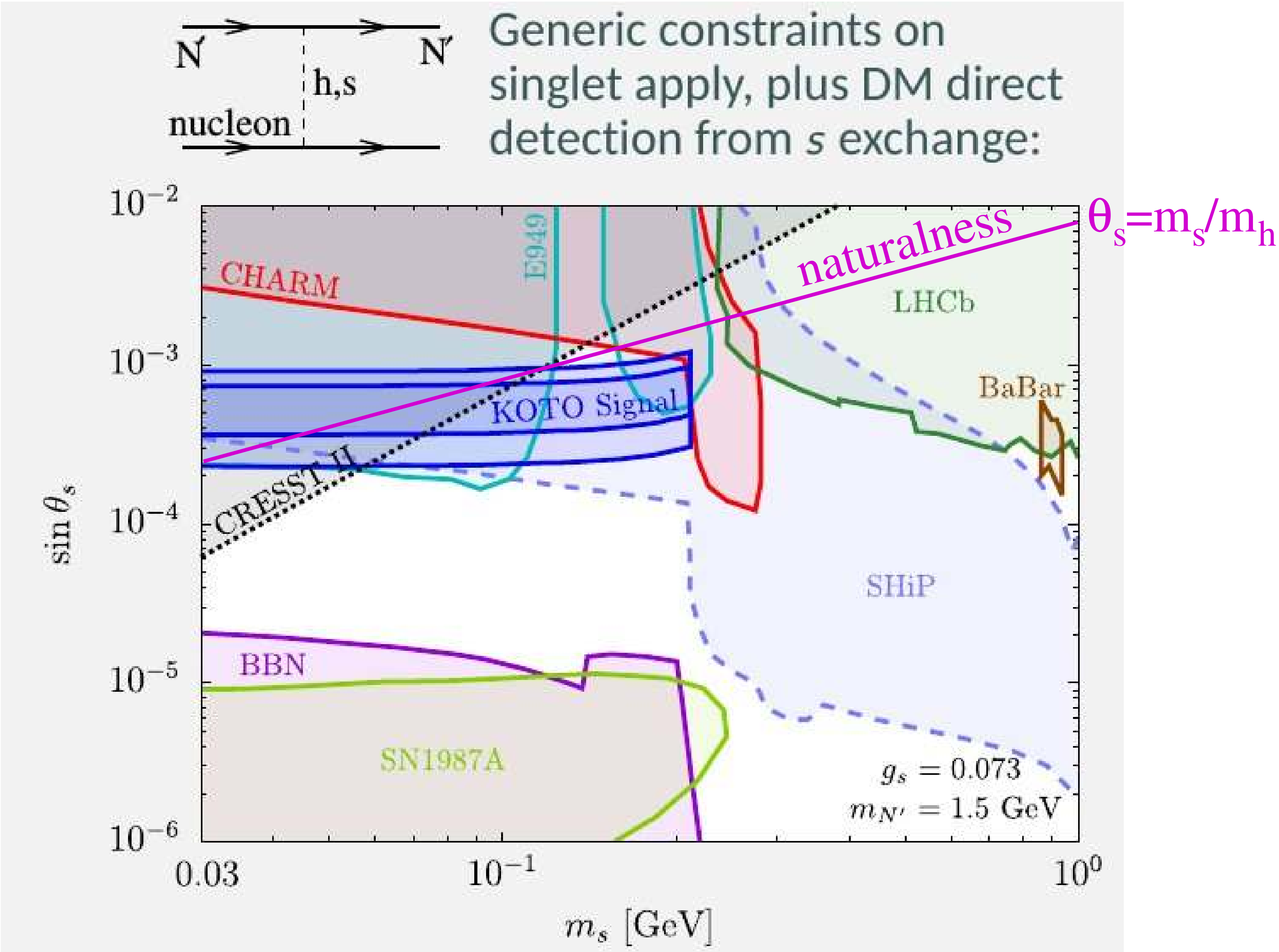
$\implies$ N-$\bar{N}$ oscillations observable at SHiP,[3]



via like-sign leptons.

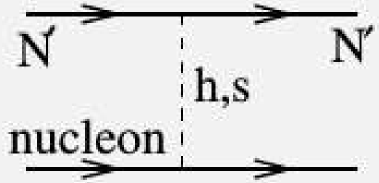
[3] J.-L. Tastet and I. Timiryasov, "Dirac vs. Majorana HNLs (and their oscillations) at SHiP," *JHEP* **04** (2020) 005, arXiv:1912.05520 [hep-ph].

Light scalar constraints

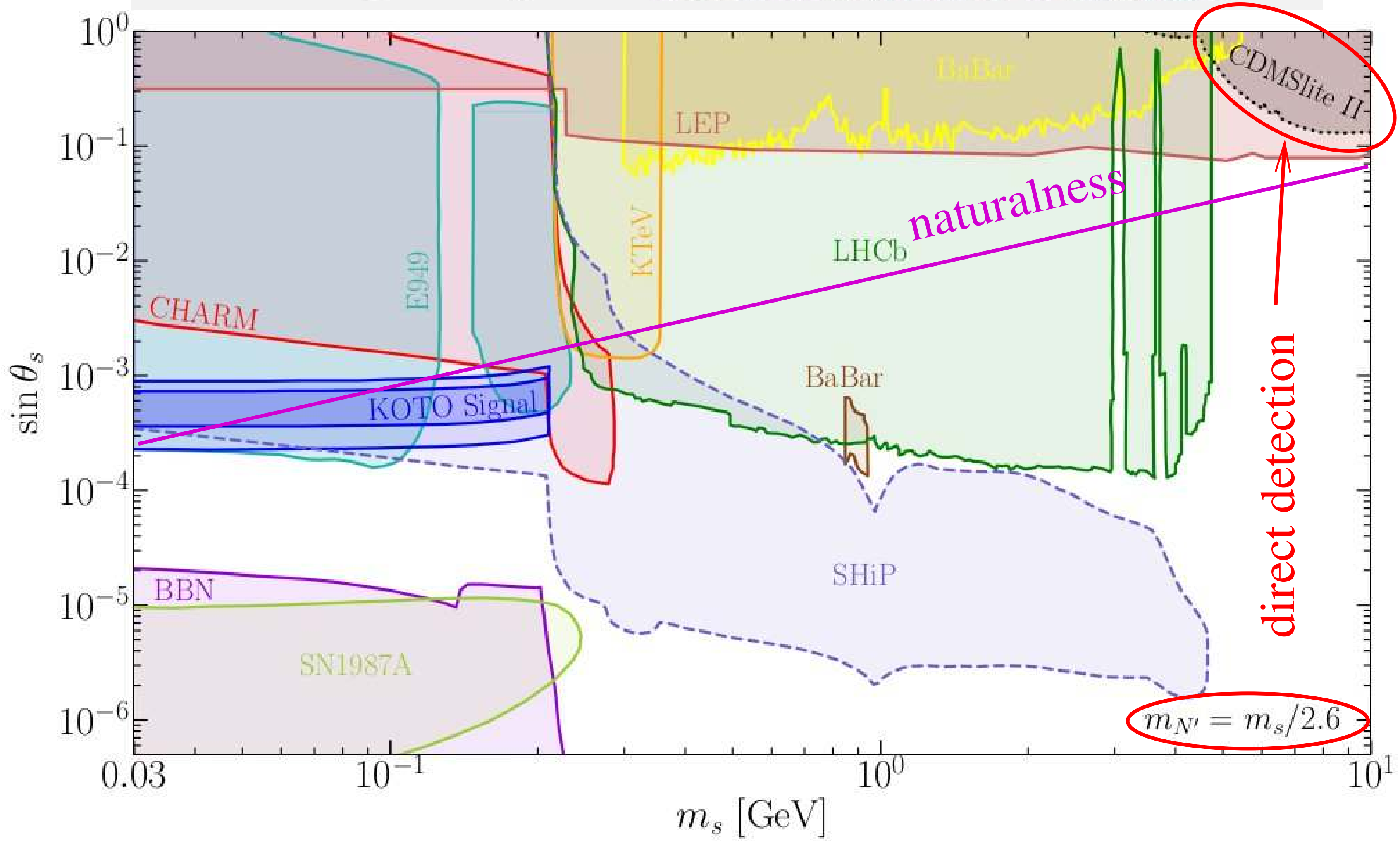


$m_s^2 \cong 2\lambda_s v_s^2 - \frac{1}{2}\theta_s^2 m_h^2$; need $\theta_s \lesssim m_s/m_h$ to avoid fine tuning.

Light scalar constraints

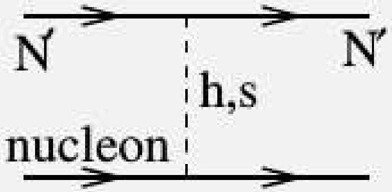


Generic constraints on singlet apply, plus DM direct detection from *s* exchange:



If $m_s > 2m_N$, the direct detection constraints are greatly relaxed

Light scalar constraints



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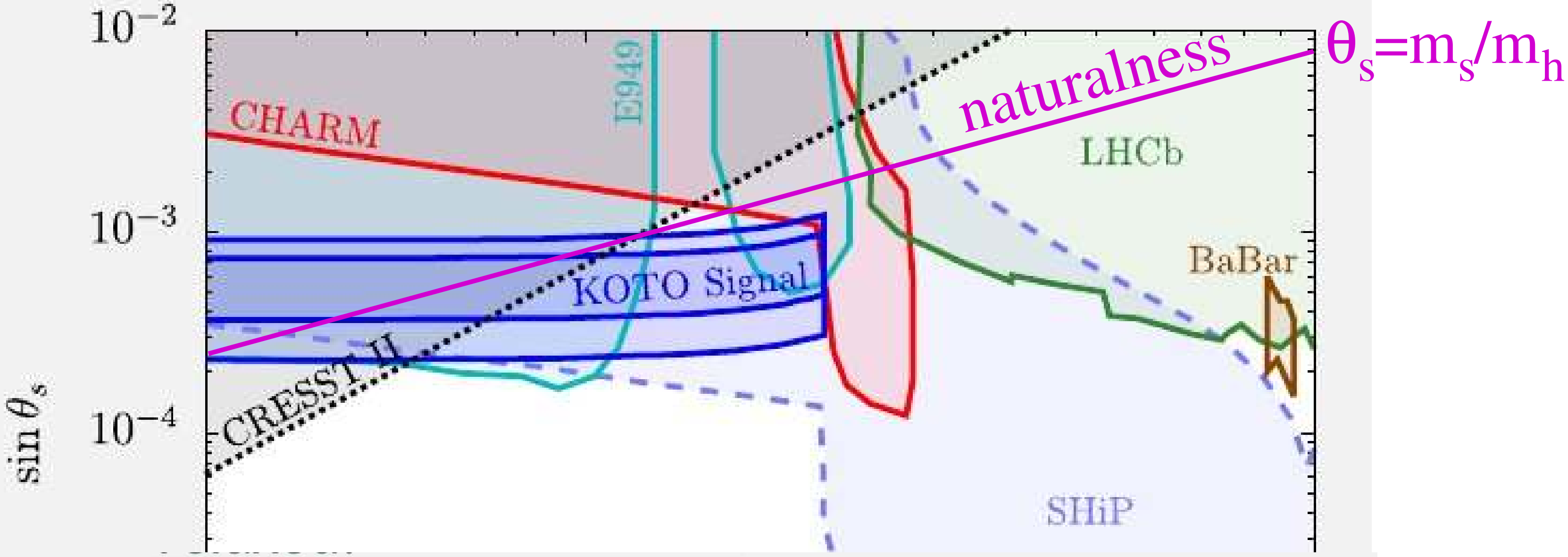
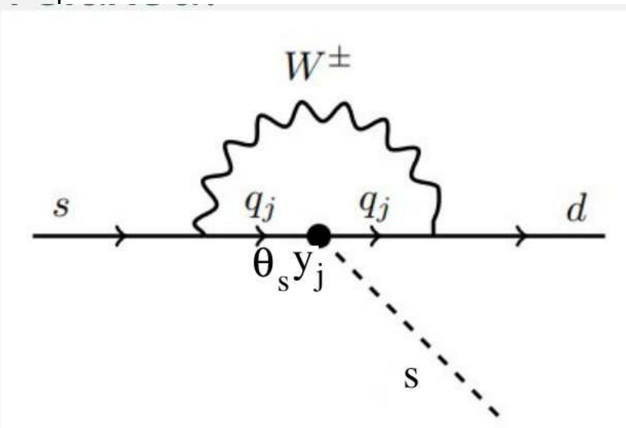




Light singlet can explain KOTO anomalous $K_L \to \pi^0 \nu\nu$ signal in blue region above

Higgs invisible width

We must also be sure that BR$(h \to ss) \lesssim 20\%$. Scalar potential:

$$V(h,s) = \frac{\lambda_h}{4}(h^2 - v^2)^2 + \frac{\lambda_{hs}}{4}(h^2 - v^2)(s^2 - v_s^2) + \frac{\lambda_s}{4}(s^2 - v_s^2)^2$$

which gives

$$m_s^2 \cong 2\lambda_s v_s^2 - \tfrac{1}{2}\theta_s^2 m_h^2, \qquad \theta_s \cong \lambda_{hs}\frac{v v_s}{m_h^2}$$

The invisible width is $\Gamma_{\rm inv} \cong \frac{\theta_s^2 m_h^3}{32\pi}\left(4\frac{\theta_s}{v} + \frac{1}{v_s}\right)^2$ leading to mild constraint

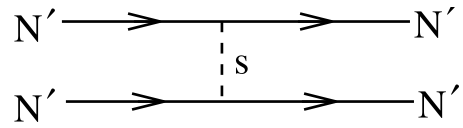
$$\theta_s\left(4\theta_s + \frac{v}{v_s}\right) \lesssim 0.05$$

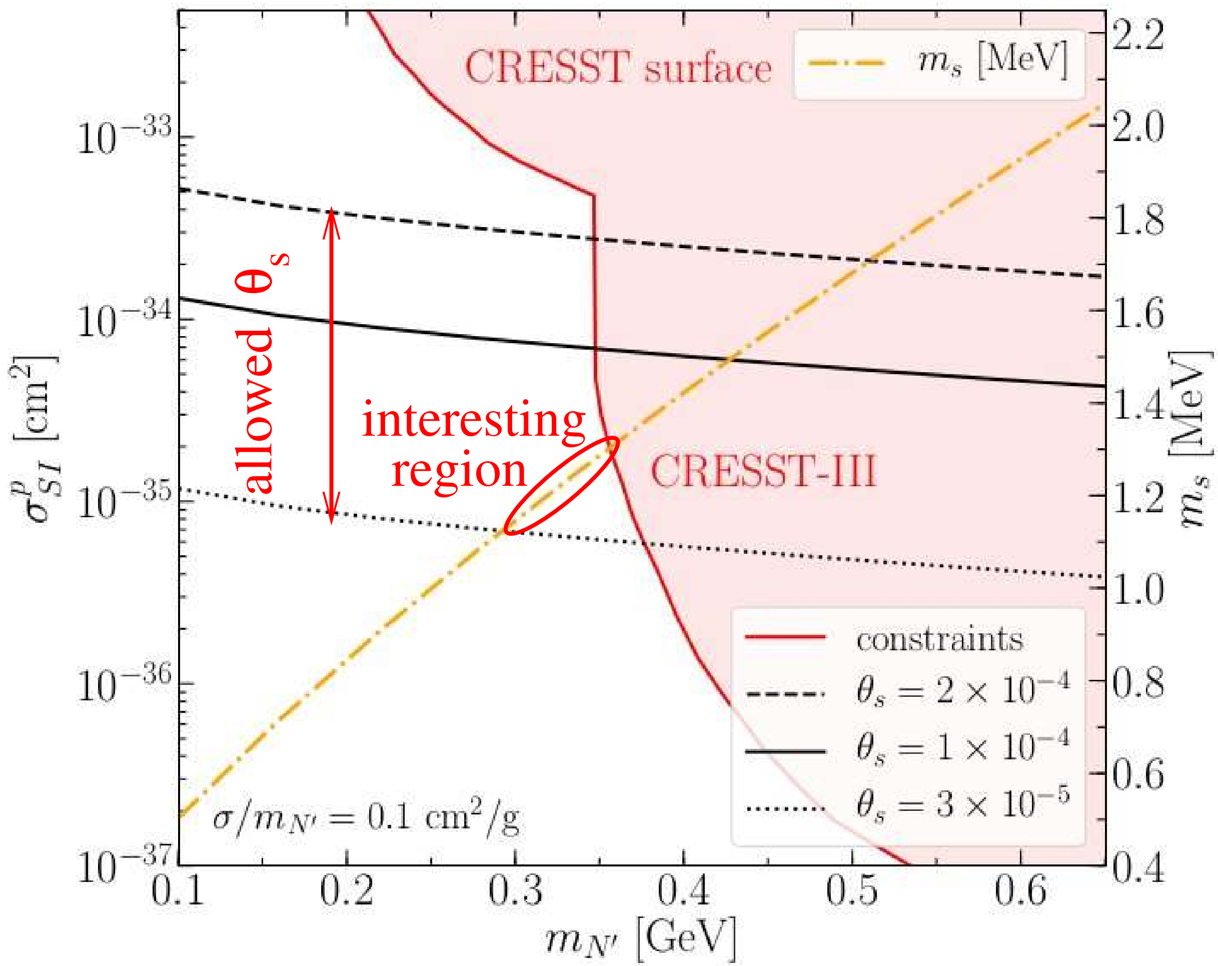
Just need that v_s is not too small.

Astrophysical implications

Indirect detection constraints are weak because $N'\bar{N}' \to ss$ and $N'\bar{N}' \to f\bar{f}$ are velocity-suppressed.

Dark matter self-interactions can be cosmologically important (structure formation)



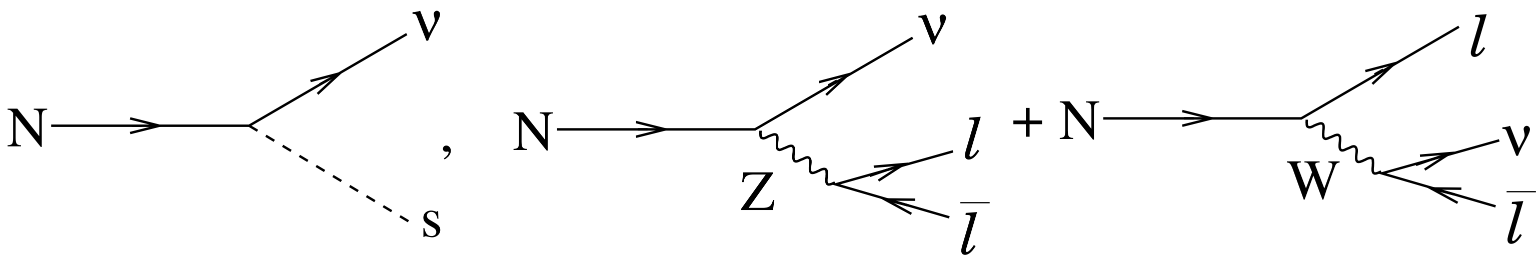


this assumes $\sim$ symmetric DM with light HNL

Another region with large $\sigma/m_{N'}$ is asymmetric DM with $m_{N'} \sim 4.5\,\mathrm{GeV}$, $\theta_s \lesssim 6\times10^{-6}$, $m_s \sim 200-300\,\mathrm{MeV}$.

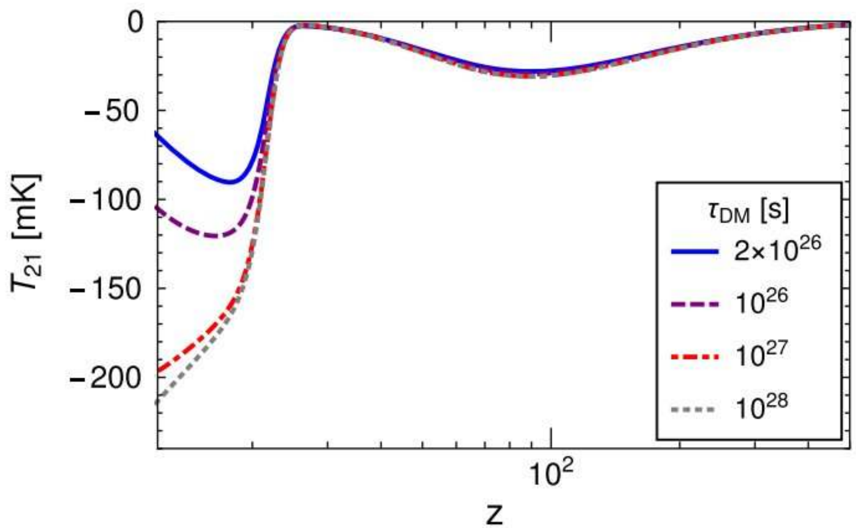
Dark matter decay

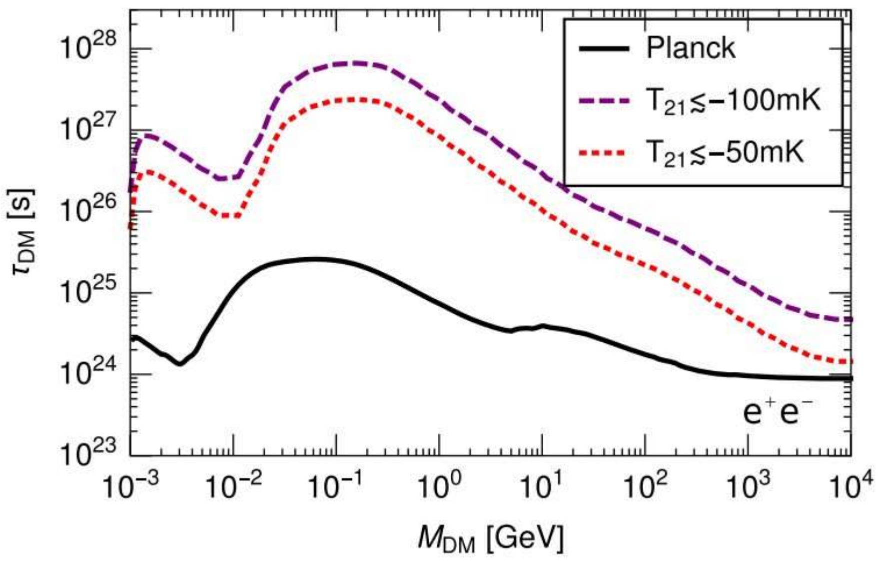
If N' has tiny mixing θ_ν to ν, it can decay, $N' \to \nu s$ if $m_s < m_{N'}$, or $N' \to \nu \ell^+ \ell^-$ if $m_s > m_{N'}$:



CMB constrains the lifetime $\tau \gtrsim 10^{24}\,\mathrm{s}$ (Slatyer & Wu, 1610.06933)

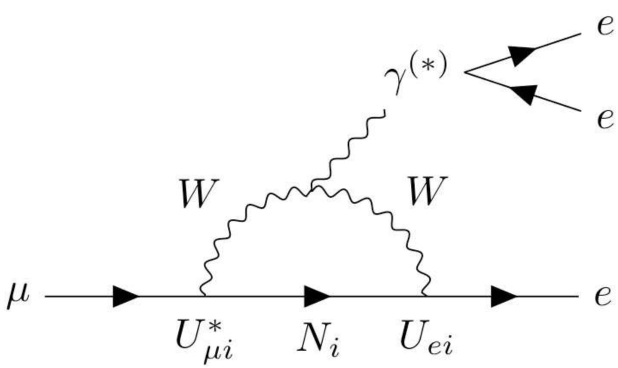
21cm signal is even more sensitive: EDGES constrains $\tau \gtrsim 10^{27}\,\mathrm{s}$ (Clark *et al.*. 1803.09390)

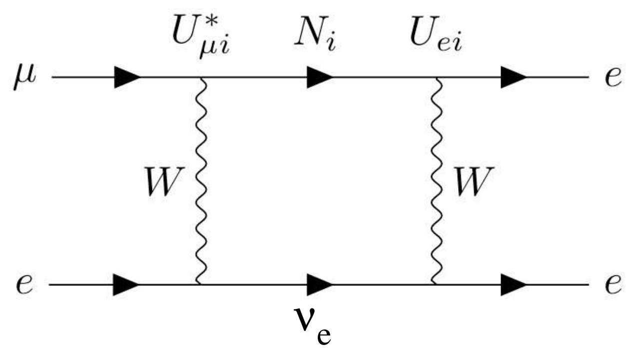




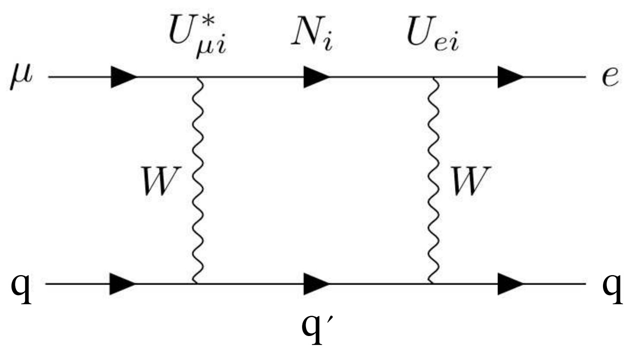
Lepton flavor violation

Typical studies assume HNL couplings to only one flavor at a time. We suggest η_ν has large off-diagonal entries, leading to $\mu \to e\gamma$, $\mu \to 3e$,





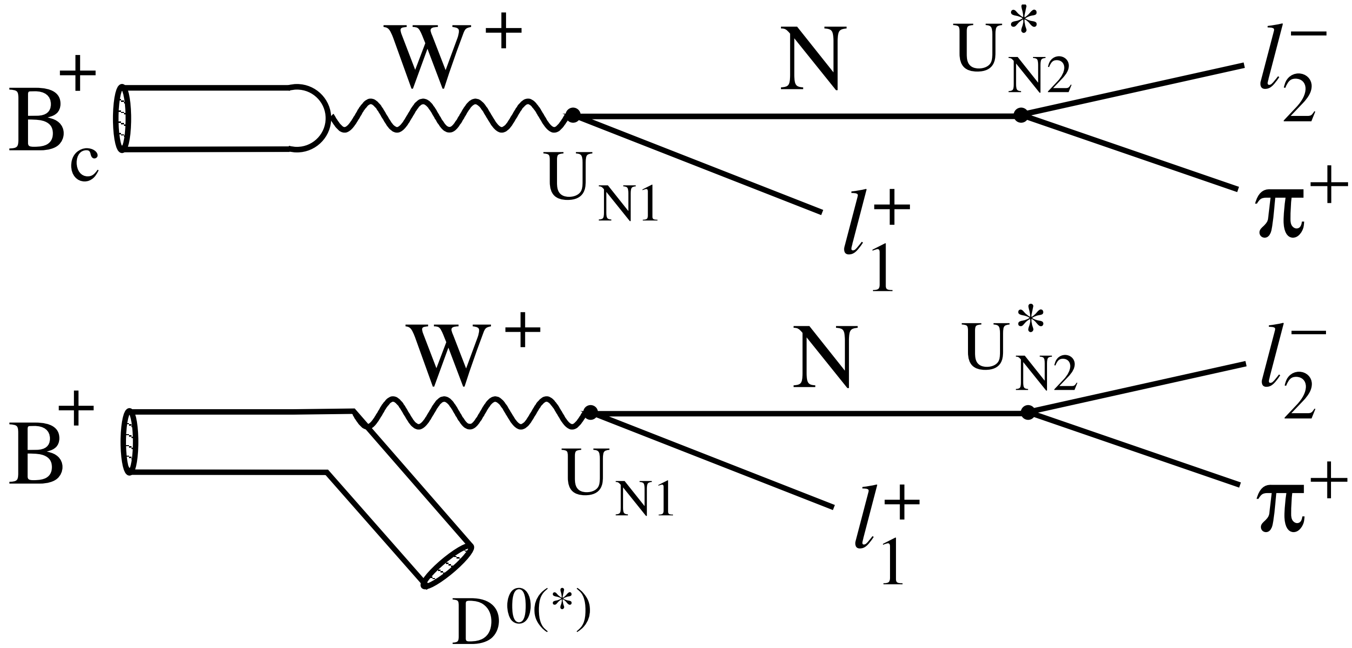
and $\mu \to e$ conversion in nuclei,



Could be probed in future experiments Mu2e (Fermilab) and COMET (KEK).

LFV @ colliders

Large off-diagonal η_ν couplings also lead to LFV B_c and B decays,



Cvetic & Kim, 1606.04140:
LHCb produces many B_c's, with potential to observe first process, and Belle II may probe the second.

Not novel in itself, but our framework motivates $U_{N\mu} \sim U_{N\tau}$.

Naturalness I

Our model is technically natural. Flavor symmetries are weakly broken via MFV principle:

$$N_i \text{ masses:} \quad M_N \delta_{ij} \to M_N \delta_{ij} + \mathcal{O}\left(\frac{\eta_\nu\, m_\ell\, \eta_\nu^\dagger}{16\pi^2}\right)$$

HNL masses remain nearly degenerate under loop corrections.

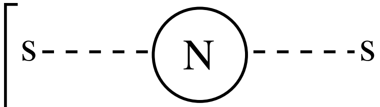
$$\text{DM stability:} \quad \eta_\nu \to \eta_\nu + \mathcal{O}\left(\frac{\eta_\nu\, \eta_\nu^\dagger\, \eta_\nu}{16\pi^2}\right)$$

Vanishing eigenvalue of η_ν is preserved under renormalization

Naturalness II

But isn’t the light singlet fine-tuned? Not necessarily!

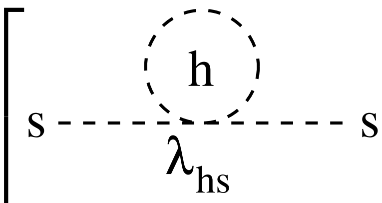
$$\delta m_s = \Big[$$



$$\Big]^{1/2} \sim \frac{g_s}{4\pi} m_N \sim 30\,\mathrm{MeV}$$

along “mixed” branch of DM relic density;

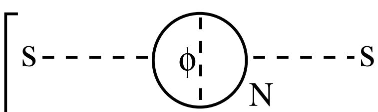
$$\delta m_s = \Bigg[$$



$$\Bigg]^{1/2} \sim \frac{\sqrt{\lambda_{hs}}}{4\pi} m_h = \frac{\sqrt{\theta_s}}{4\pi} \frac{m_h^2}{\sqrt{v v_s}} \sim 100\,\mathrm{MeV}$$

for θ_s in KOTO region and $v_s \sim v$. Light singlet is natural. Even at inflaton threshold, $m_\phi \sim 10^{12}\,\mathrm{GeV}$,

$$\delta m_s = \Big[$$

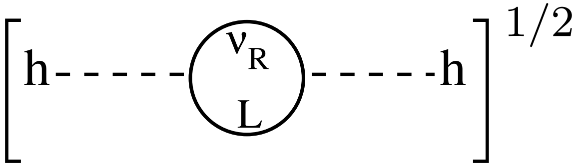


$$\Big]^{1/2} \sim \frac{g_s g_\phi}{16\pi^2} m_\phi \sim 10^{-6}\, T_R$$

where $T_R \sim 10^{-4} g_\phi M_p$ is the reheating temperature after inflation. We just need $T_R < 100\,\mathrm{TeV}$.

Naturalness III

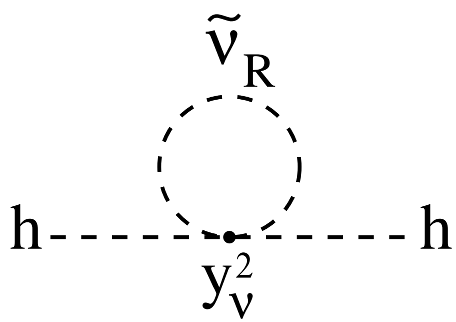
The only real naturalness problem is the usual one with the SM Higgs. There is only one relevant threshold, m_{ν_R},

$\delta m_h =$ 

$\sim \frac{y_\nu}{4\pi} m_{\nu_R} \sim \frac{m_\nu^{1/2} m_{\nu_R}^{3/2}}{4\pi v}$

using seesaw formula $m_\nu = y_\nu^2 v^2 / m_{\nu_R}$. It was suggested (Brivio, Trott 1703.10924) this could explain the weak scale, by choosing $m_{\nu_R} \sim 10^7\,\mathrm{GeV}$.

Alternatively, suppose $m_{\nu_R} \sim v^2/m_\nu \sim 10^{15}\,\mathrm{GeV}$; could some symmetry above this scale can protect m_h?



Summary

We presented a new inflation $+$ leptogenesis mechanism

Two HNL's invoked to transfer lepton asymmetry to the SM.

Their couplings to light ν's are determined by the light neutrino masses/mixings up to one free parameter

HNL's discoverable at SHiP, *etc.*; N-$\bar{N}$ oscillations

Dark matter is third $\sim \mathrm{GeV}$ HNL; can be asymmetric, symmetric or mixture; discoverable by direct detection

DM stability is linked to vanishing m_{ν_1}

A light scalar with Higgs portal is needed to get correct DM abundance (more economical than light vector); KOTO anomaly

Strong DM self-interactions are marginally allowed

No new fine-tuning problems are introduced