A little theory of everything

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The Standard Model

- We love it because it works so well
- We hate it because it works so well
- Where is the new physics hiding?
- We know there has to be new physics:
- Inflation
- Baryogenesis
- Dark Matter
- Neutrino mases

Could we address all these things in a minimal, interrelated way?

Affleck-Dine Inflation

Earlier, we took a step in that direction, linking inflation to the baryon asymmetry.

It used the Affleck-Dine mechanism for baryogenesis, but *during* and not after inflation.

Let's review the usual Affleck-Dine mechanism first.

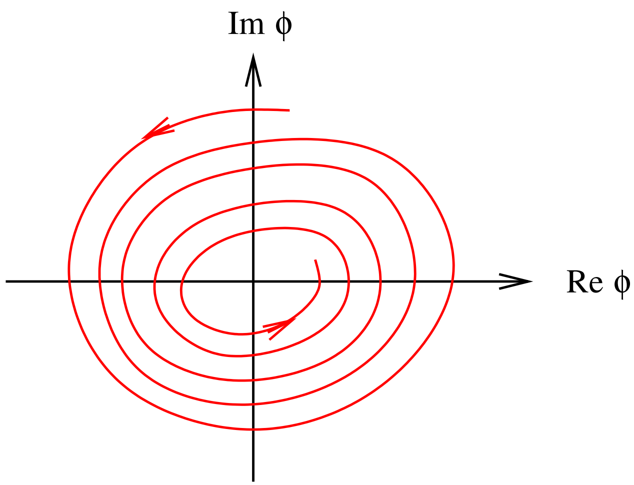
Affleck-Dine baryogenesis

The Affleck-Dine mechanism is one of the oldest and simplest baryogenesis proposals (Nucl.Phys. B249, 1985)

Scalar field ϕ carries baryon number, has potential

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

with B-violating coupling λ'. CP symmetry $\phi \to -\phi^*$ is broken by initial condition $\langle\phi\rangle \neq 0$.



Field spirals around; baryon number evolves as

$$\dot{n}_B = i(\phi^*\ddot{\phi} - \ddot{\phi}^*\phi) = -3Hn_B + 8\lambda'(\phi^4 + \phi^{*4})$$

$|\phi| \sim t^{-3/4}$ is Hubble damped; $m^2\phi^2$ eventually dominates over $\lambda'\phi^4$ and created baryon number is conserved.

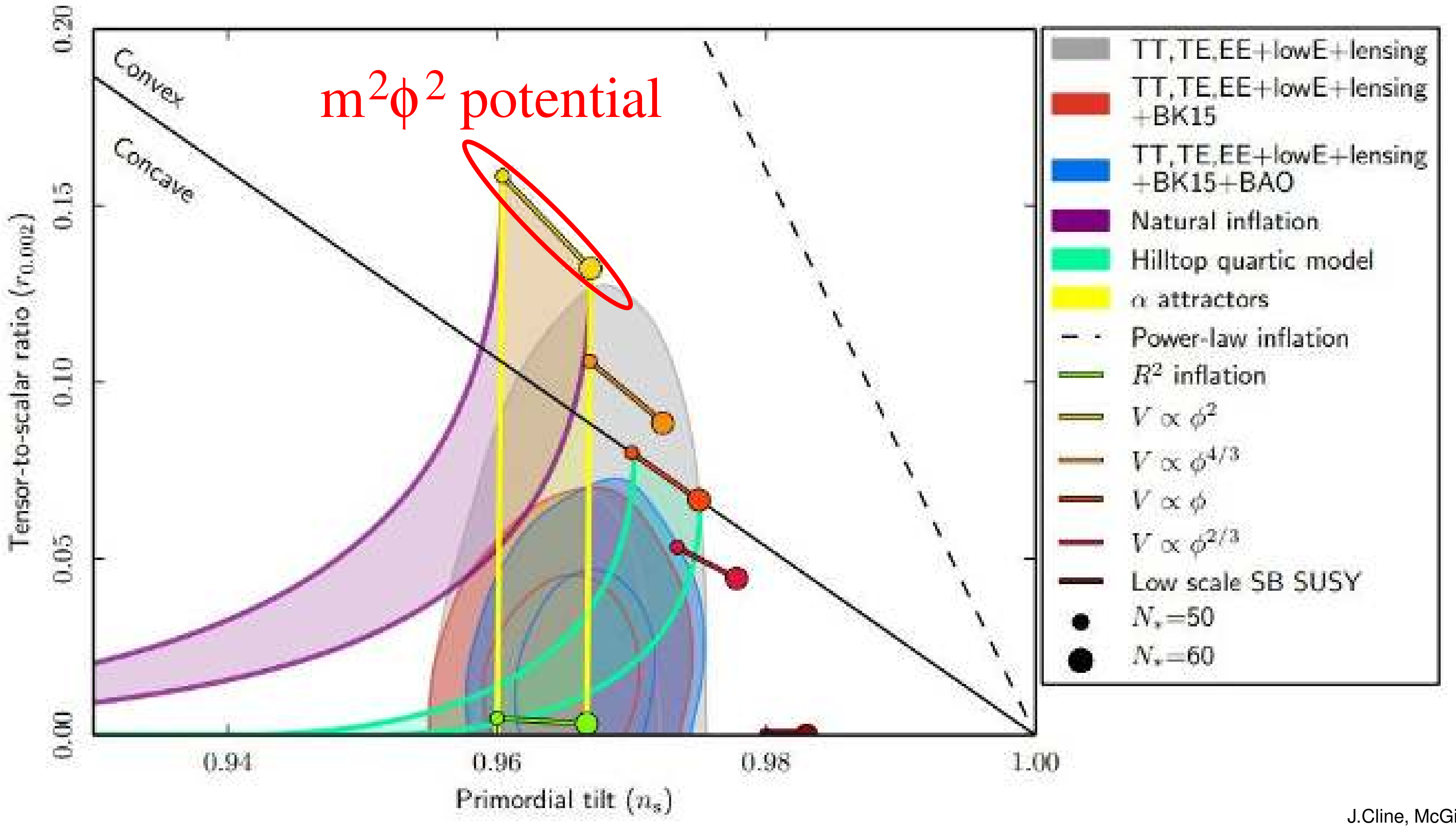
Very efficient mechanism, tends to give a large baryon asymmetry.

Can the same V give inflation?

Usually we assume the AD field is some field different from the inflaton, that gets excited during inflation.

We (and others) asked, could it be the same field?

Yes, but Planck rules out its predicted large tensor perturbations r!



Nonminimal coupling to gravity

There is a simple fix for chaotic inflation (also Higgs inflation):

$$\mathcal{L}_{\rm grav} \to \frac{m_P^2}{2}\sqrt{-g}R\left(1+2\xi|\phi|^2\right)$$

Then Weyl-rescale the metric (go to Einstein frame), $g_{\mu\nu} \to g_{\mu\nu}/(1+2\xi|\phi|^2)$. This rescales the potential,

$$V \to \frac{V}{(1+2\xi|\phi|^2)^2}$$

making it flatter at large $|\phi|$, decreasing r versus n_s.

We can get inflation and baryogenesis simultaneously
(if the field twists around during inflation!)
Baryon density is given by

$$n_B = j_B^0 = 2i(\phi^*\dot\phi - \phi\dot\phi^*)$$

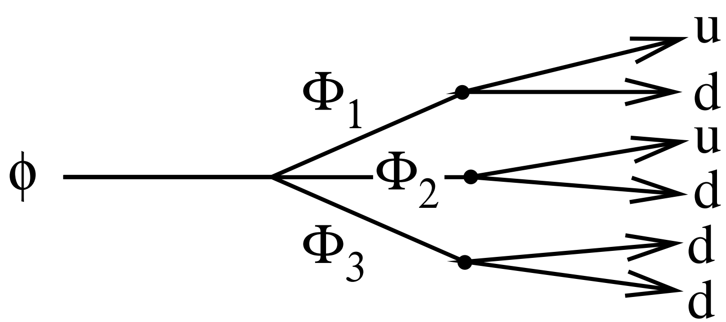
Converting ϕ to SM baryons

But we must turn the ϕ asymmetry into an asymmetry of quarks.

Three color triplet scalars Φ_i to the rescue:

$$V_\Phi = \epsilon_{abd}\left(\lambda''\,\phi^*\,\Phi_1^a\Phi_2^b\Phi_3^d + y_1\Phi_1^a\,\bar{u}^b d^{c,d} + y_2\Phi_2^a\,\bar{u}^b d^{c,d} + y_3\Phi_3^a\,\bar{d}^b d^{c,d}\right) + \text{H.c.}$$

(d^c denotes conjugate field) Then $\phi \to \Phi_1\Phi_2\Phi_3 \to 6q$; the inflaton carries $B = 2$.



Inflaton decay rate is

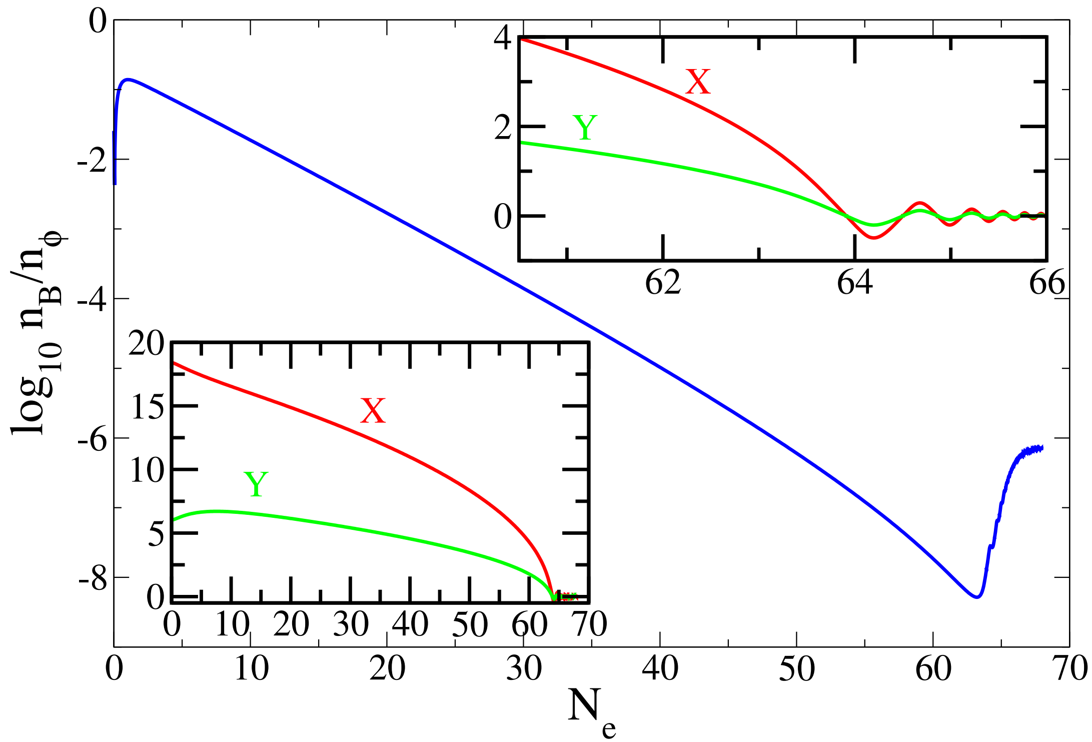
$$\Gamma_\phi \cong \frac{3\,\lambda''^2}{256\pi^3}\,m_\phi \qquad \text{(if } m_\phi \gg m_{\Phi_i}\text{)}$$

This also gives reheating at the same time!

An example

For
$$m_\phi = 5\times 10^{-7}\, m_P, \qquad \lambda = 9\times 10^{-12},$$
$$\lambda' = 7\times 10^{-13}, \qquad \xi = 0.06, \qquad \lambda'' = 8\times 10^{-5},$$

n_B/n_ϕ evolves with number of e-foldings as



Here $\phi = \frac{X+iY}{\sqrt{2}}$

If reheating is perturbative, baryon-to-entropy ratio is

$$\eta_B = \frac{n_B}{s} \cong 0.6\left(\frac{n_B}{n_\phi}\right)\frac{(\Gamma_\phi m_P)^{1/2}}{g_*^{1/4} m_\phi} = 8.6\times 10^{-11} \text{ (Planck)}$$

Could we use leptons instead?

thanks to Joachim Kopp!

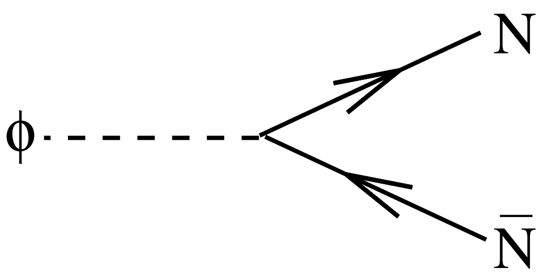
This could allow us to connect with neutrinos.

And maybe a sterile neutrino could be the dark matter.

It’s a kind of leptogenesis, but not the kind you’re familiar with.

Same setup, but now inflaton carries lepton number 2.

It decays to some kind of sterile neutrinos,

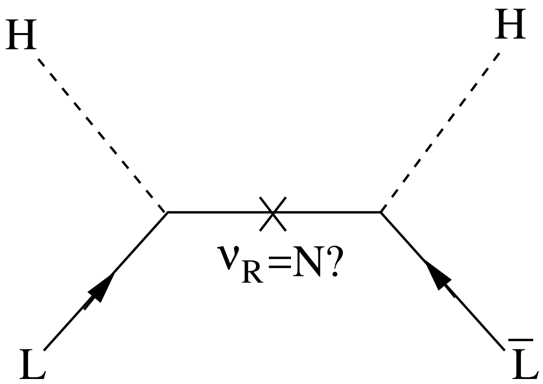


$$\mathcal{L} = g_\phi\, \phi(\bar{N}_R N_R^c + \bar{N}_L N_L^c)$$

that we need to be Dirac, to a good approximation

Heavy neutral leptons (HNL's)

Why couldn't N be the heavy Majorana neutrinos ν_R that give light neutrinos their mass via seesaw mechanism?



$$\to \frac{y_\nu^2}{M_{\nu_R}}(HL)^2 \to \frac{y_\nu^2\, v^2}{M_{\nu_R}}\bar{\nu}\nu^c$$

In that case, any initial lepton asymmetry in N would get washed out right away by mass effects,

e.g., exactly the same diagram, that violates L by $\Delta L = 2$

We need N to be quasi-Dirac to avoid this. HNL's!

Assume the heavy Majorana ν_R's are above the inflation scale to avoid washout.

HNL as dark matter

We could have 3 generations of (degenerate) HNL’s, say.

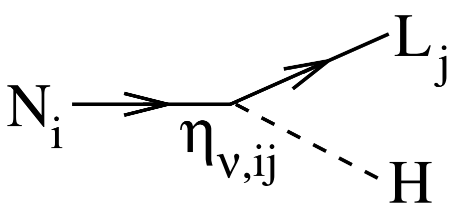
One of them could be the dark matter.

Why would one HNL be stable, and the other two unstable?

We need a symmetry reason—something like MFV, minimal flavor violation.

This idea works, and it links DM stability to a massless neutrino.

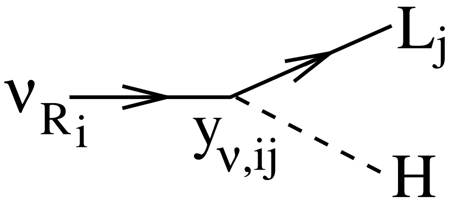
Suppose N_i couples to SM via



$$= \eta_{\nu,ij}\bar{N}_{R,i} H L_j$$

MFV-like coupling

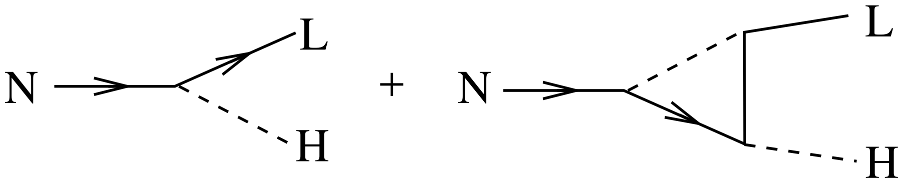
Further, suppose the seesaw coupling $y_{\nu,ij}$ is proportional to $\eta_{\nu,ij}$,



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

There is just one source of lepton flavor violation in the theory, not two.

The setup is radiatively stable,



$$= \eta_{\nu,ij} + \frac{c}{16\pi^2}\,(\eta_\nu \eta_\nu^\dagger \eta_\nu)_{ij}$$

Corrections to flavor-breaking have a constrained form

Dark matter candidate

Suppose η_ν has a vanishing eigenvalue and N_i are all degenerate.

Then in eigenbasis of η_ν, one state N' is noninteracting—it is a stable DM candidate.

It is *asymmetric dark matter*—its asymmetry is determined by lepton asymmetry from inflaton decay.

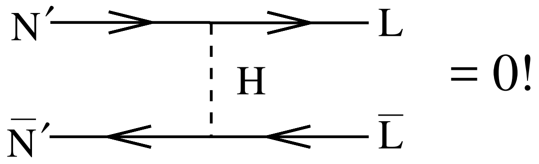
We can relate the DM mass to its abundance and the baryon asymmetry, (μ_B & $\mu_{N'}$ are chemical potentials)

$$m_{N'} \leq \left| \frac{\mu_B}{\mu_{N'}} \right| \frac{\Omega_c}{\Omega_b} m_n = 4.5\,\mathrm{GeV}$$

Inequality is saturated if the symmetric component is absent, must annihilate it away.

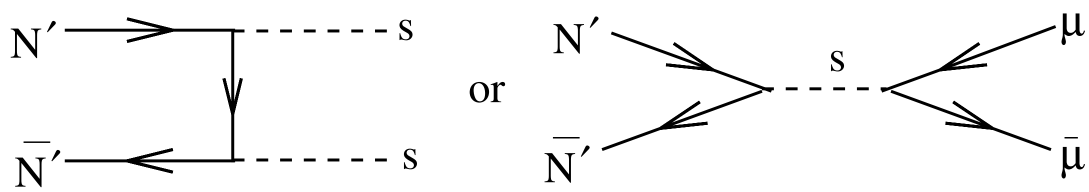
Dark matter annihilation

But symmetric DM component can't annihilate away unless we add something extra.



is absent because N' does not couple to SM

We add a light singlet scalar s coupling as $g_s s \bar{N}_i N_i$,



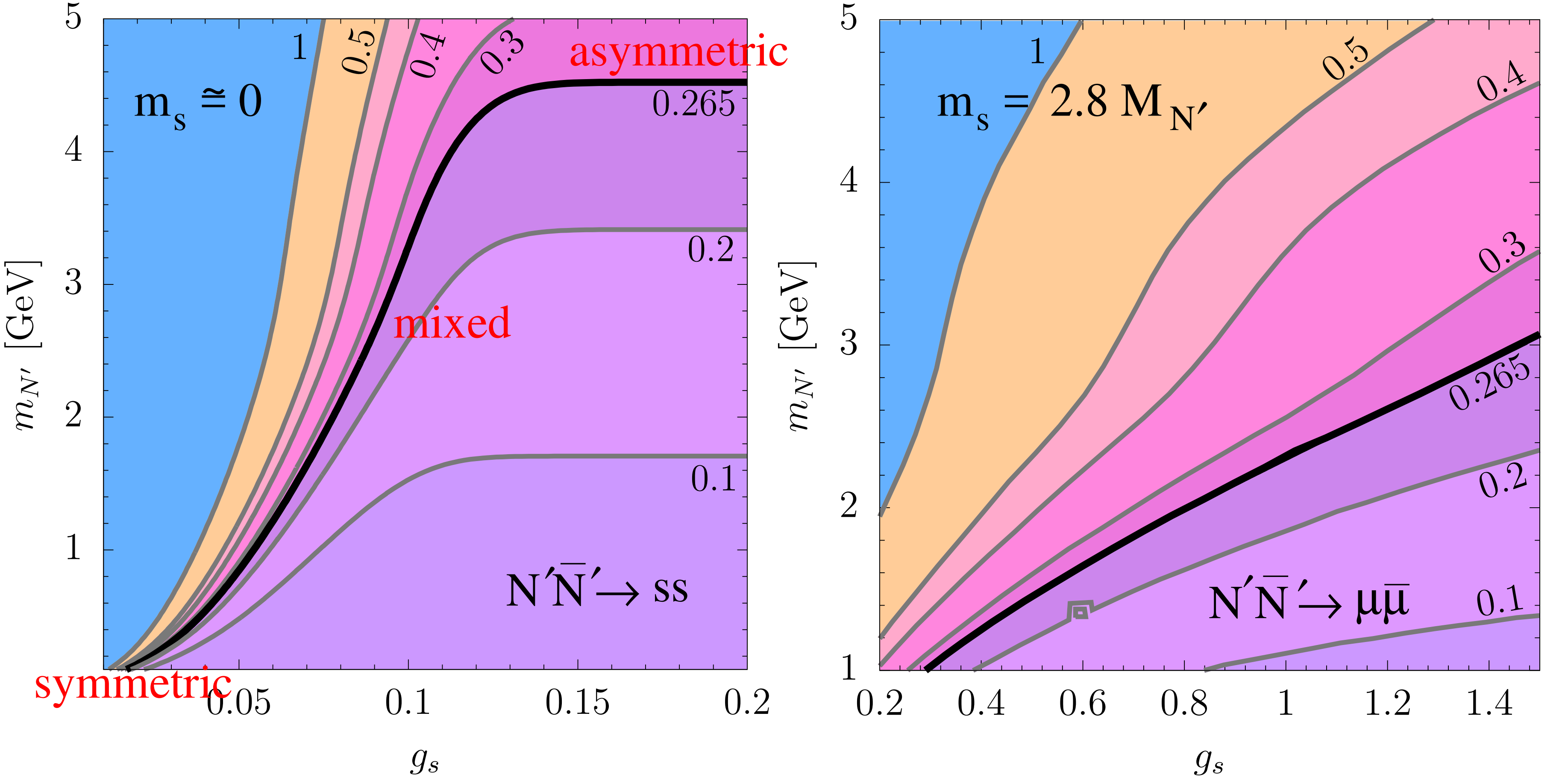
s mixes with Higgs, mixing angle θ_s.

Depending on strength of g_s, the DM can be almost fully asymmetric, fully symmetric, or some admixture.

DM mass $m_{N'}$ is correlated with g_s (and possibly m_s).

Dark matter relic density

By solving Boltzmann equation, including DM asymmetry, we get contours of the relic abundance $\Omega_{\rm cdm}$ in g_s-$m_{N'}$ plane.



For $N'\bar{N}' \to \mu^+\mu^-$ we need only be mildly close to $m_s \sim 2M_{N'}$ resonance.

Neutrino masses / mixings

Below scale of superheavy ν_R, the $(\nu_L,\ N_R^c,\ N_L)$ mass matrix looks like

$$M_\nu = \begin{pmatrix} \epsilon_\nu & \eta_\nu^T\,\bar{v} & 0 \\ \eta_\nu\,\bar{v} & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix}$$

with $\bar{v} = \langle H \rangle = 174\,\mathrm{GeV}$ and

$$\epsilon_\nu = \bar{\mu}_\nu\,\eta_\nu^T\eta_\nu$$

($\bar{\mu}_\nu =$ some mass scale).

Light ν's mix with the HNL's; mixing angles are

$$U_{\ell i} \cong \frac{\eta^T_{\nu,\ell i}\bar{v}}{M_N}$$

N-$\bar{N}$ oscillations

Diagonalizing M_ν gives small Majorana mass to the HNL's,

$$\delta M = \frac{\bar{v}^2}{M_N^2}\,\eta_\nu\,\epsilon_\nu\,\eta_\nu^T = U_{i,\ell}^T\,m_{\nu,\ell\ell'}\,U_{\ell' j}$$

This causes N-$\bar{N}$ oscillations in early universe that could wipe out the lepton/baryon asymmetry if in equilibrium before the electroweak phase transition. Rate is

$$\Gamma_{\Delta L} \sim \frac{M_N^2\,\delta M^2}{M_N^2 \delta M^2 + T^2 \Gamma_{el}^2}\,\Gamma_{el}$$

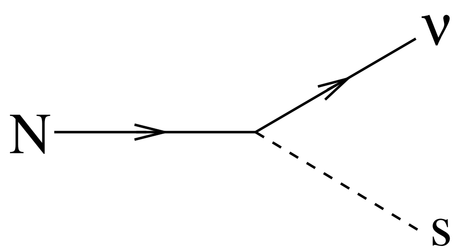
with $\Gamma_{el} \sim \eta_\nu^4 T^5/m_h^4 =$ rate of $NL \to NL$ scattering. Avoiding $\Gamma_{\Delta L} > H$ gives a lower limit on HNL mass,

$$M_N \gtrsim 4\,\mathrm{MeV}$$

We are interested in $M_N \sim \mathrm{GeV}$.

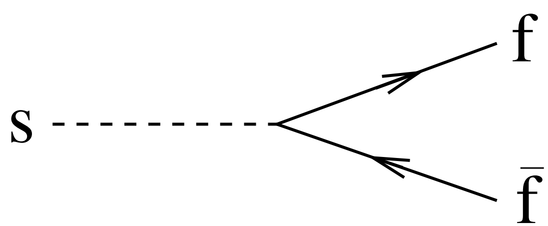
Consequences of HNL mixing

Because of mixing, HNL's decay via $N \to \nu s$, if $M_N > m_s$,



$$\Gamma \sim \frac{g_s^2 |U_{\ell,i}|^2}{16\pi} M_N$$

Our singlet should mix with Higgs and decay to light SM fermions,

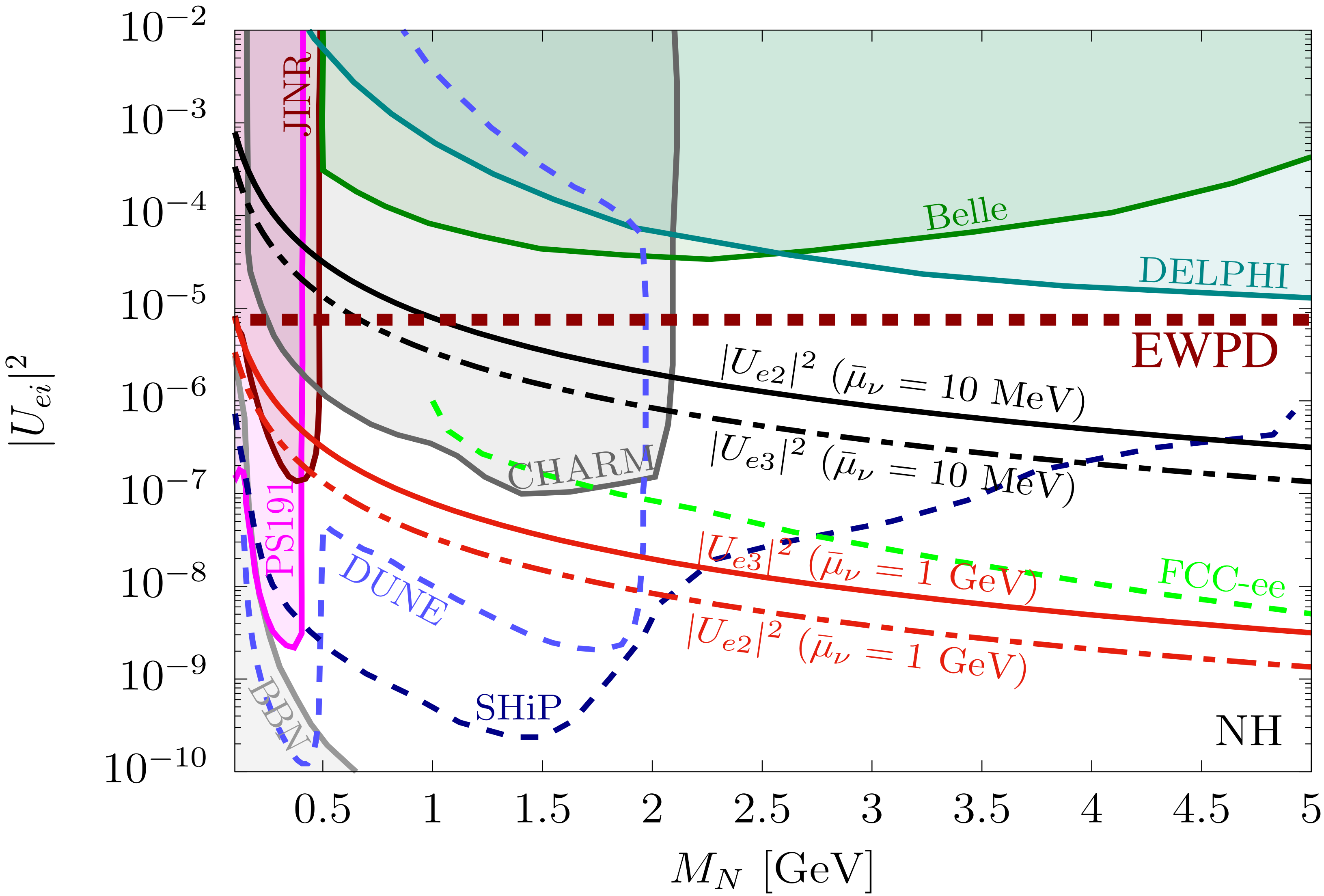


$$\Gamma \sim \frac{m_f^2 \theta_{hs}^2}{16\pi\, v^2} m_s$$

Most studies of HNL's assume weak decays dominate, $N \to \nu \ell \bar{\ell}$, $N \to \ell u \bar{d}$, *etc.* Usual beam dump limits might not apply (s might have very long decay length)

If $m_s > m_N$, usual limits apply.

Bounds on HNL mixing



Even if beam-dump limits are evaded, we get a bound (EWPD) from effect of mixing on SM processes (nonunitarity of PMNS matrix).

N-ν interaction parameters

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

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

up to the unknown $\bar{\mu}_\nu$ factor. They are bounded by EWPD constraints:

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

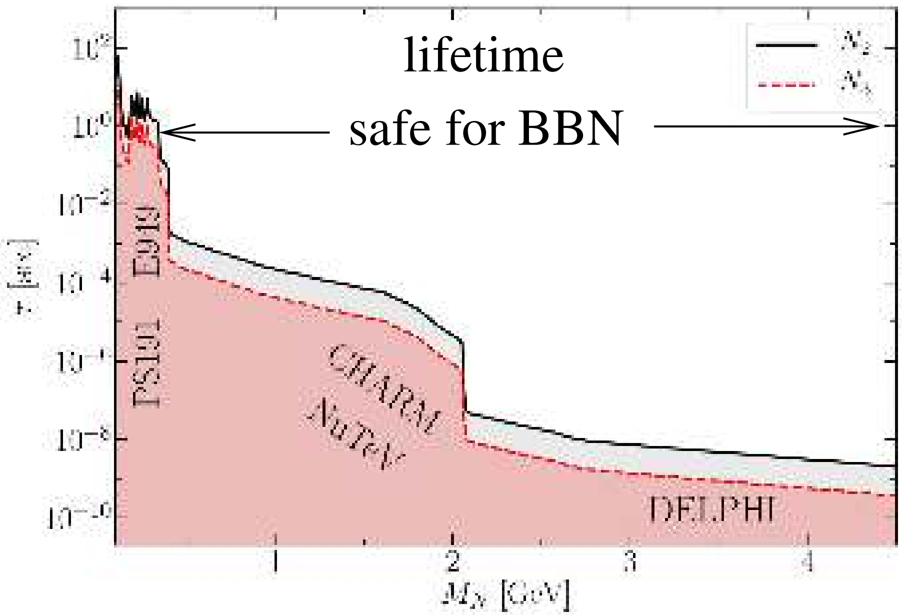
$$|\eta_{\nu,\ell i}| \quad \lesssim \quad 10^{-4} \left| \begin{matrix} 0 & 0.66 & -0.32 - 0.29\,i \\ 0 & 0.72 - 0.05\,i & 2.1 \\ 0 & -0.79 - 0.04\,i & 1.9 \end{matrix} \right| \times \left(\frac{M_N}{4.5\,\text{GeV}}\right)$$

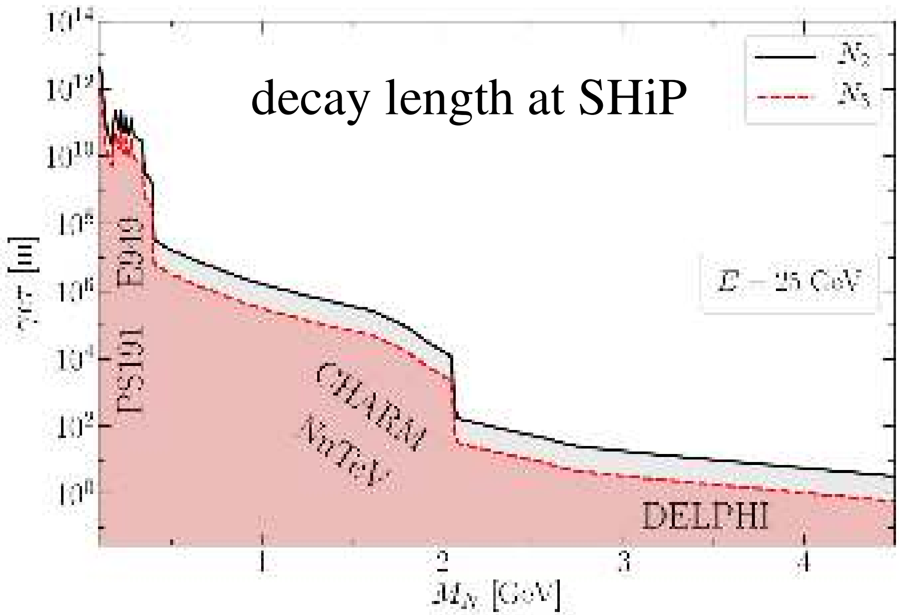
Mixing of $N_2 + N_3$ with ν_ℓ, $\bar{U}_\ell = (\sum_i |U_{\ell i}|^2)^{1/2}$, is bounded by

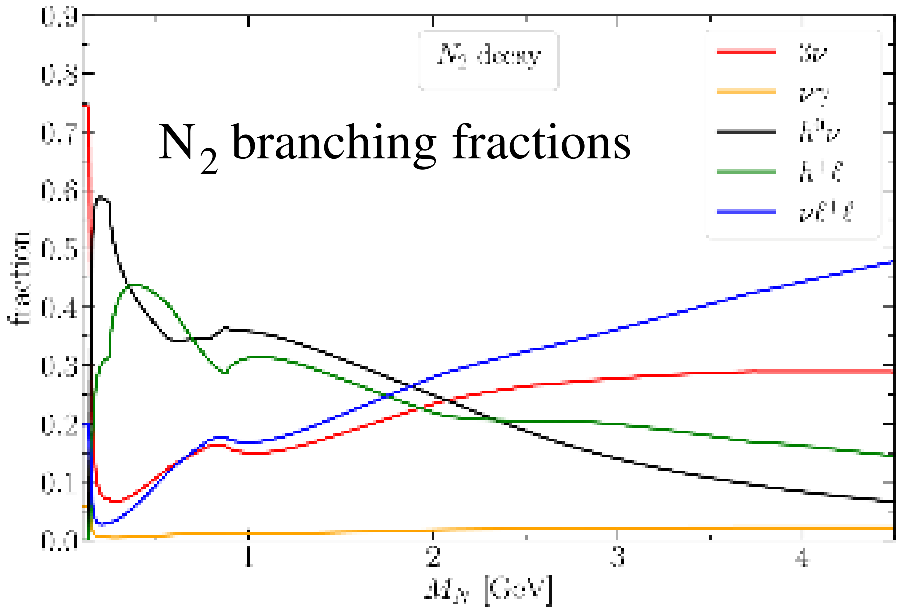
$$\bar{U}_e < 0.003, \quad \bar{U}_\mu < 0.009, \quad \bar{U}_\tau < 0.008$$

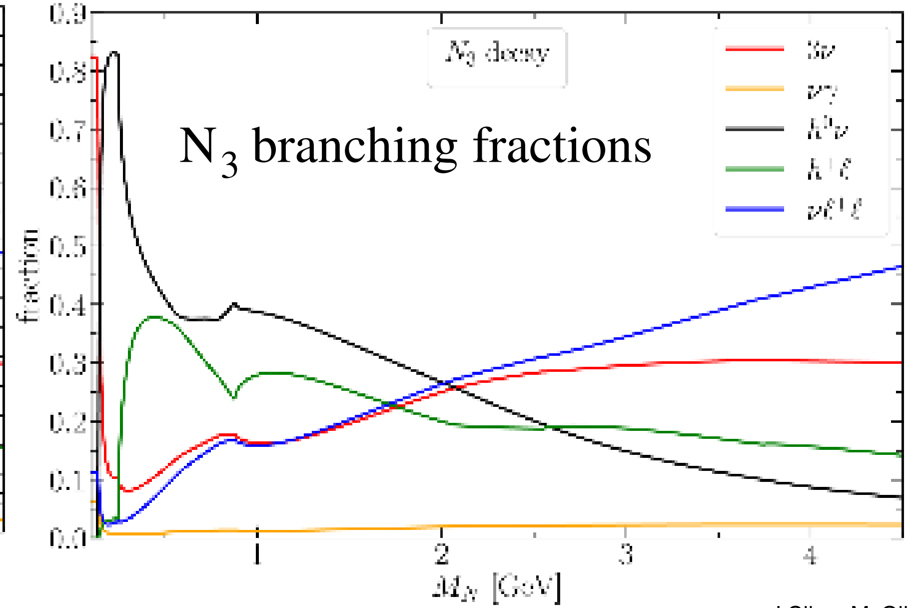
HNL weak decays

If $m_s > m_{N'}$, weak decays of N_i dominate.



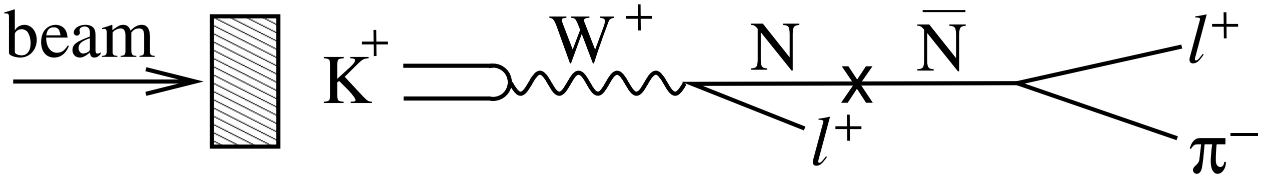






N-$\bar{N}$ oscillations at SHiP

If $m_s > m_{N'}$ then $N \to \ell^- \pi^+$ decays can distinguish N from $\bar{N} \to \ell^+ \pi^-$. Like-sign leptons signify N-$\bar{N}$ oscillations:



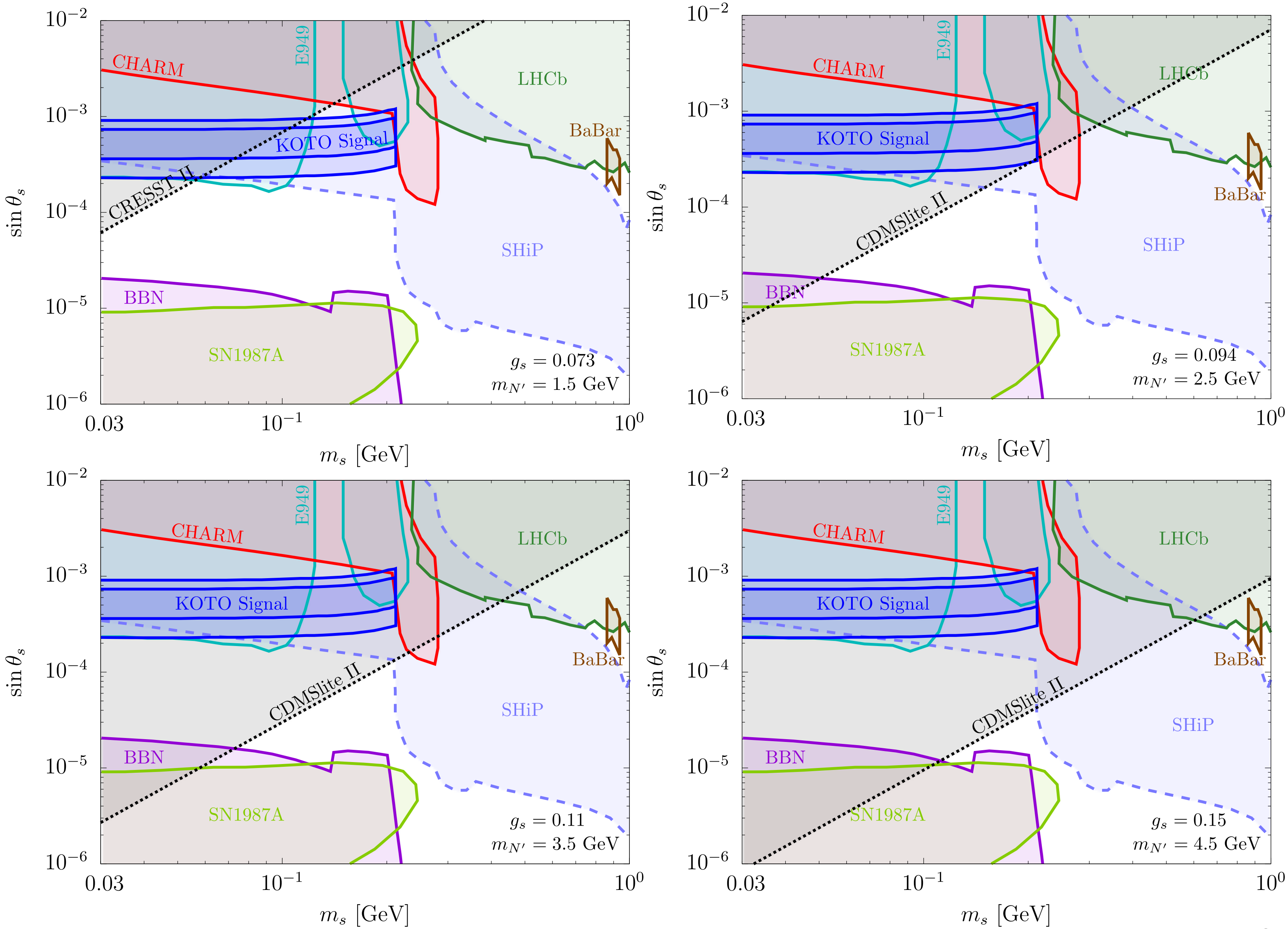
Oscillation length $\sim 1/\delta M$ (recall $\delta M \bar{N} N^c$ Majorana mass term),

$$\delta M \sim \bar{U}_\ell^2 \, m_\nu \sim 10^{-5} \left(\frac{\text{GeV}}{m_N}\right)^2$$

Tastet & Timiryasov, arXiv:1912.05520 show this could be observable at SHiP.

Constraints on singlet

Allowed θ_s versus m_s depends on DM mass via direct detection constraint:

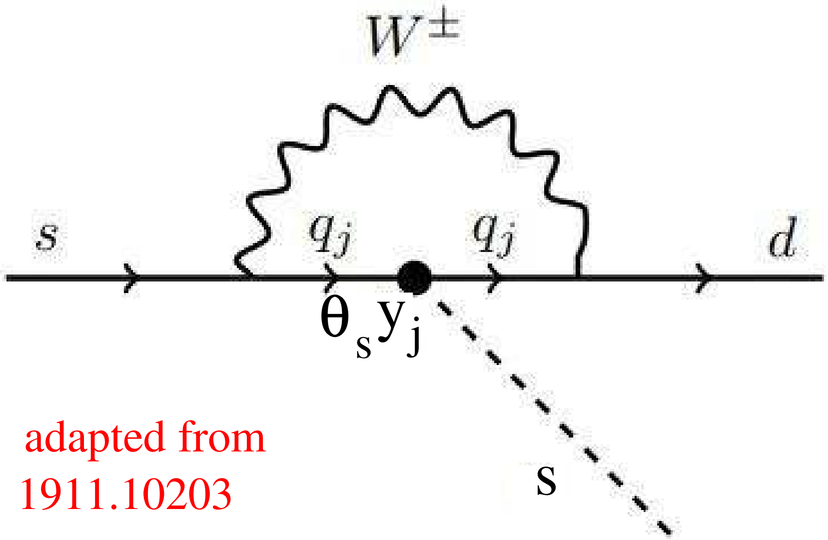


KOTO anomaly

The KOTO experiment searches for $K_L \to \pi^0 \nu\bar{\nu}$.

Excess of 4 events (~ 0.01 expected in SM) was reported in 2019.

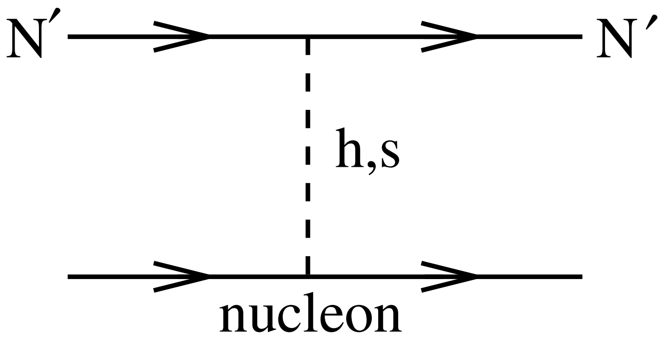
Can be explained by $K_L \to \pi^0 s$ (*e.g.*, Egana-Ugrinovic, Homiller, Meade)

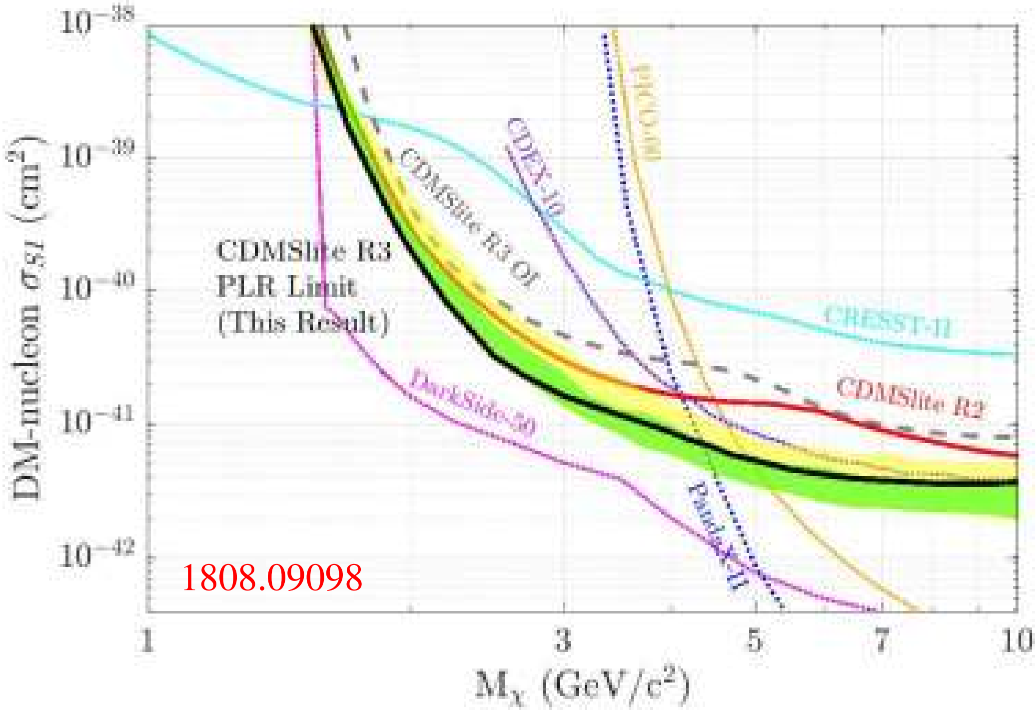


Region near $\theta_s \sim (2-9)\times 10^{-3}$ and $m_s \sim (120-160)\,\mathrm{MeV}$ is viable.

Direct detection

Light singlet mixing angle is constrained by direct DM searches





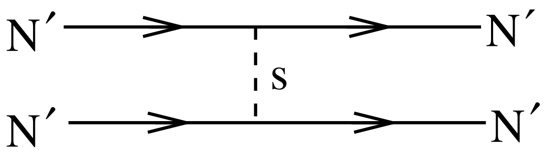
Cross section is

$$\sigma_{\rm SI} = \frac{g_s^2 m_{N'}^2 m_n^4 \, \sin^2 2\theta_s \, f_n^2}{4\pi \left(m_{N'} + m_n\right)^2 \bar{v}^2} \left(\frac{1}{m_h^2} - \frac{1}{m_s^2}\right)^2$$

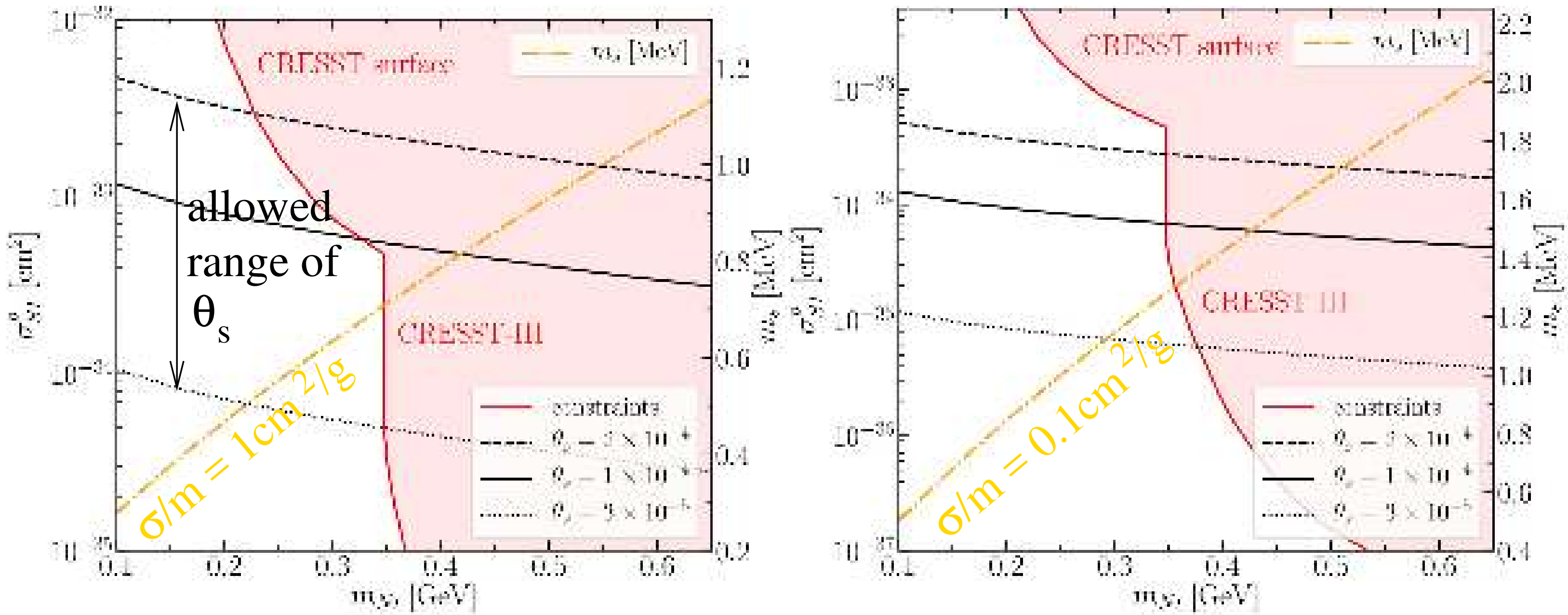
Need $m_{N'} \lesssim 1.5\,{\rm GeV}$ to accommodate KOTO events, if desired.

DM self-interactions?

Small scale structure problems of ΛCDM suggest strong DM self-interactions, $\sigma/m \sim 0.1 - 1\,\mathrm{cm}^2/\mathrm{g}$.



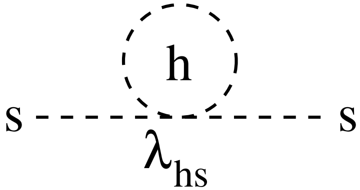
It is challenging but possible to reconcile large σ/m with direct detection



Needs light $m_{N'} \lesssim (0.35 - 0.4)\,\mathrm{GeV}$ and light $m_s \lesssim (0.7 - 1.3)\,\mathrm{MeV}$. Problem for BBN—if $m_s < 2m_e$, the singlet is too long-lived; it persists during BBN and contributes too much to the Hubble expansion.

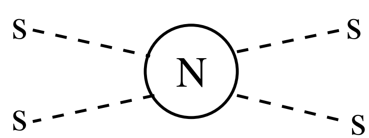
Naturalness

Our theory is technically natural. *E.g.,* light scalar mass gets threshold correction

$\delta m_s^2 =$ 

$\sim \frac{\lambda_{hs}}{16\pi^2} m_h^2 < m_s^2 \sim \lambda_s v_s^2$

while quartic coupling correction is

$\delta\lambda_s =$ 

$\sim \frac{g_s^4}{16\pi^2} < \lambda_s$

Mixing angle is $\theta_s \sim \lambda_{hs} v v_s / m_h^2$. The naturalness constraints above imply

$$\theta_s \lesssim \left(\frac{4\pi\, m_s}{m_h}\right)^3 \left(\frac{1}{\sqrt{\lambda_h}\, g_s^2}\right) \sim 0.008 \quad (\text{for } m_s \sim 0.3, \text{GeV},\ \ g_s \sim 0.1)$$

This is satisfied for phenomenologically interesting parameter region.

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 only marginally allowed