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Dynamical origin of neutrino masses and dark matter from a new confining sector

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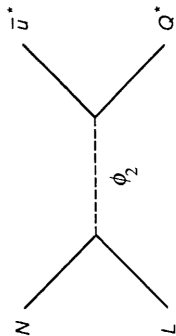


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Neutrino masses from QCD confinement

[Thomas, Xu 1992]



$$\langle \phi_2^0 \rangle \simeq y_u \frac{\Lambda^3}{m_{\phi_2}^2}$$

- QCD chiral condensate $\Lambda^3 \equiv \langle \bar{u}u \rangle \simeq (200 \text{ MeV})^3$
- inert doublet ϕ_2 ($m_{\phi_2}^2 > 0$)
à la **Type II Seesaw**

[Schechter, Valle; Cheng, Li; Wetterich, Lazarides, Shafi 1980]

- Z_2 ($N, \bar{u}, \phi_2$ **odd**)
forbids couplings to ϕ_{SM}

$$m_\nu = y_\nu y_u \frac{\Lambda^3}{m_{\phi_2}^2} \simeq 0.05 \text{ eV} \cdot y_\nu y_u \left(\frac{13 \text{ TeV}}{m_{\phi_2}} \right)^2$$

Neutrino masses from QCD confinement

Problem:

- Massless u -quark due to $\mathbb{Z}_2$ symmetry
- Massless u -quark ruled out by lattice [Funcke, Urbach et al. 2020]
(QCD instantons not enough)
- QCD embedded in larger group: UV instantons
 - e.g. $SU(3)^3$ [Agrawal, Howe 2017]
 - e.g. color-flavor unific. $SU(9)$ [Cordova, Hong, Koren 2024]
- $\bar{u}$ **even** + dim. 5 operator φ **odd** [Davoudiasl et al. 2022]

$$c_5 \frac{\varphi}{\Lambda_{UV}} Q \phi_2^\dagger \bar{u}$$

The basic idea

DM

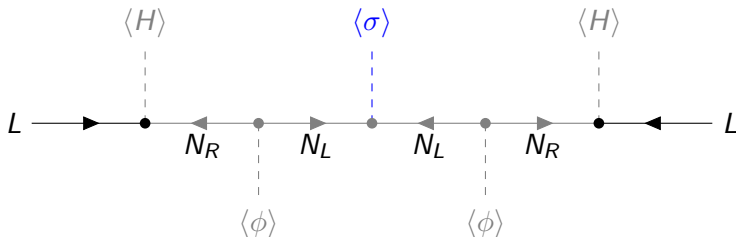
- use BSM group $SU(3)_D$ instead of QCD
- hidden sector (HS) DM with conf. scale Λ_D
- $\Lambda_D \simeq (1 - 100) \text{ TeV}$ **fixed** by $h^2 \Omega_{DM} = 0.12$

Neutrino masses

- easier to couple HS to SM gauge singlets N
- keep **low scale** approach to m_ν

Low scale: Inverse Seesaw (ISS)

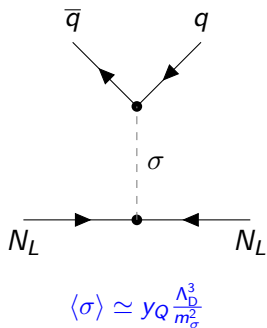
- $(N_L, N_R^\dagger)$ Dirac fermion with mass $M_D = y_D \langle \phi \rangle$ for $\mu = y_{N_L} \langle \sigma \rangle = 0$
- $(N_L, N_R^\dagger)$ **Pseudo**-Dirac fermion for $\mu \neq 0$
- $m_\nu \simeq 0.05 \text{ eV} \cdot y_\nu^2 \left(\frac{\mu}{1 \text{ keV}} \right) \left(\frac{35 \text{ TeV}}{M_D} \right)^2$ **Why is μ so small?**



[Mohapatra, Valle 1986]

Small μ from HS confinement

$$-\mathcal{L}_D = \underbrace{y_Q \sigma \bar{q}_L q_R}_{\langle \bar{q}_L q_R \rangle = \Lambda_D^3} + y_{N_L} \sigma \bar{N}_L^c N_L + y_{N_R} \sigma \bar{N}_R^c N_R + \underbrace{m_\sigma^2 \sigma^2}_{m_\sigma^2 > 0, \sigma \in \mathbb{R}} + \dots$$



	$SU(3)_D$	Z_4	$U(1)_D$	#
q_L	3	$-i$	1	1
q_R	3	i	1	1
N_L	1	i	0	3
N_R	1	i	0	3
L	1	i	0	3
e_R	1	i	0	3
σ	1	-1	0	1

$$\mu_{L,R} \simeq 10 \text{ keV} \cdot y_Q y_{N_{L,R}} \left(\frac{\Lambda_D}{10 \text{ TeV}} \right)^3 \left(\frac{3.1 \times 10^8 \text{ GeV}}{m_\sigma} \right)^2$$

Particle Spectrum

accidental (global) symmetries:

$$\underbrace{\mathrm{U}(1)_D}_{\text{dark baryon number}} \otimes \underbrace{\mathrm{U}(1)_A}_{\text{broken by } y_q \text{ \& \; anomalous}}$$

- meson $\mathcal{M} = |\bar{q}q\rangle$
 - **single flavor** of $q \rightarrow$ no pNGB π_D (overclosure, decays during BBN...)
 - $J^P = 0^-$ analogous to η' of QCD
 - $m_{\mathcal{M}} \simeq \Lambda_D$
- baryon $\mathcal{B} = |qqq\rangle$
 - spin 3/2 analogous to Δ in QCD
 - stabilized by $\mathrm{U}(1)_D$ at renormalizable lvl. (expl. $\mathrm{U}(1)_{\emptyset}$ at **$d = 8$**)
 - mass between $(N_c, 10)\Lambda_D$, set $m_{\mathcal{B}} \simeq 5\Lambda_D$

Cosmology

① RD with $m_\sigma \gg T_{\text{RH}} \gg M_D, \Lambda_D$, σ only acts as portal

② N produced from SM via $LH \leftrightarrow N$

$$T_N^{\text{in}} \simeq 7 \times 10^7 \text{ GeV} \cdot \left(\frac{y_\nu}{10^{-4}} \right)^2$$

③ HS q produced from N bath via $NN \leftrightarrow qq, qq \leftrightarrow gg$

$$\Lambda_D > T_q^{\text{in}} > 100 \text{ GeV} \cdot (y_q y_N)^{-\frac{1}{3}} \left(\frac{m_\sigma}{10^6 \text{ GeV}} \right)^{\frac{4}{3}}$$

④ $T \simeq \Lambda_D$ HS confines $\rightarrow$ bound states $\mathcal{B}$, $\mathcal{M}$ formed

Cosmology

- $\bar{\mathcal{B}}\mathcal{B} \leftrightarrow \bar{\mathcal{M}}\mathcal{M}$ via s-wave $\rightarrow$ fixes Λ_D for relic abund.

$$\langle \sigma_D |\vec{v}| \rangle \simeq \frac{\pi}{\Lambda_D^2} \simeq 2.2 \times 10^{-26} \frac{\text{cm}^3}{\text{s}} \cdot \left(\frac{41 \text{ TeV}}{\Lambda_D} \right)^2$$

- Freezes out at

$$T_{\bar{\mathcal{B}}\mathcal{M}}^{\text{out}} \simeq \frac{m_{\mathcal{B}}}{25} \simeq \frac{\Lambda_D}{5}$$

- HS temp. = SM temp. via $\bar{N}N \leftrightarrow \mathcal{M}$

- Freezes out later at

$$T_{\bar{N}N\mathcal{M}}^{\text{out}} \simeq \frac{m_{\mathcal{M}}}{25} \simeq \frac{\Lambda_D}{25}$$

- meson $\mathcal{M}$ later decays via $\mathcal{M} \rightarrow \bar{N}N$

IDD signal: neutrinos

- $\bar{B}B \rightarrow \bar{M}M$ produces M with

$$E_M \simeq m_B$$

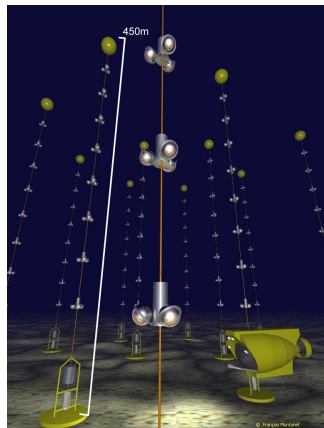
- $M \rightarrow \bar{N}N$ produces N with

$$E_N \simeq \frac{m_B}{2}$$

- $N \rightarrow \nu_L h_{SM}$ produces ν_L with

$$E_\nu \simeq \frac{m_B}{4}$$

$$\Lambda_D > 12 \text{ TeV} \cdot \sqrt{\frac{0.25 \times 10^{-24} \text{ cm}^3/\text{s}}{\langle \sigma |\vec{v}| \rangle}}$$



source: PoS QG-PH (2007) 02

[ANTARES, 2015]

IDD signal: neutrinos

- $N \rightarrow \nu_L h_{\text{SM}}$ produces ν_L with

$$E_\nu \simeq \frac{m_B}{4} \simeq \frac{5}{4} \Lambda_D$$

- projection $\Lambda_D > 54 \text{ TeV}$ [KM3NeT]
- recently observed 220 PeV event requires
too large

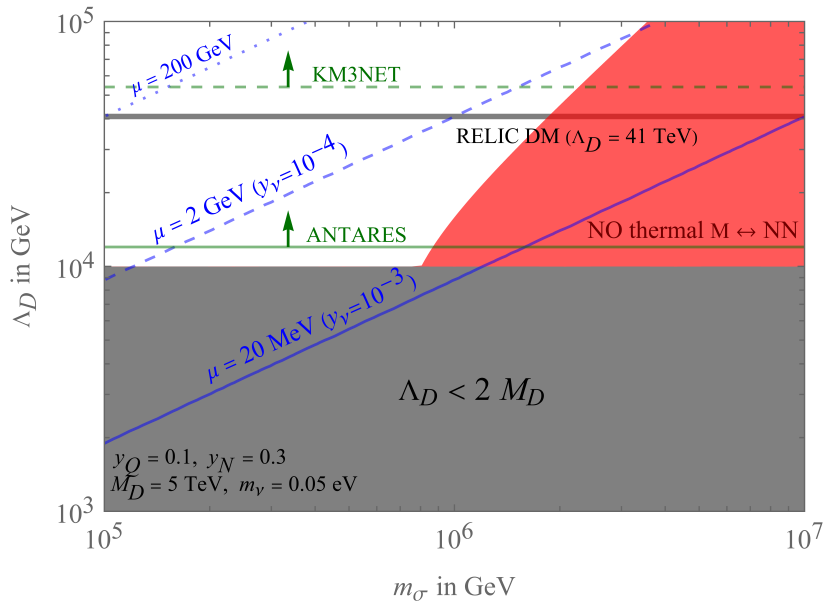
$$\Lambda_D = 176 \text{ PeV}$$

- event not be explained in this model
→ astrophysics!



source: IFIC website

Parameter Space (1): $M_D = 5 \text{ TeV}$



Summary

- $\mu > \mathcal{O}(10 \text{ MeV})$ for ISS from confining HS
- $|V_{iN}|^2 \simeq m_\nu/\mu \lesssim \mathcal{O}(10^{-9})$
- DM: spin 3/2 dark baryon $\mathcal{B} \leftrightarrow$ lowest $U(1)_\mathcal{D}$ operator at $d = 8$
- $\Lambda_D \simeq (1 - 100) \text{ TeV}$ fixed by $h^2\Omega_{\text{DM}} = 0.12$
- N portal thermalizing HS and SM
- signals at neutrino telescopes [KM3NeT]

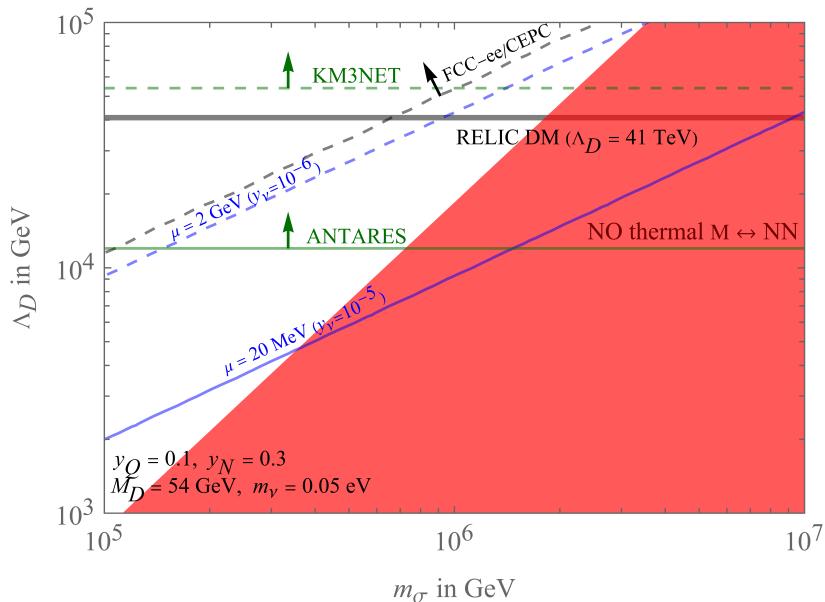
Outro

Thank you for your time and attention!

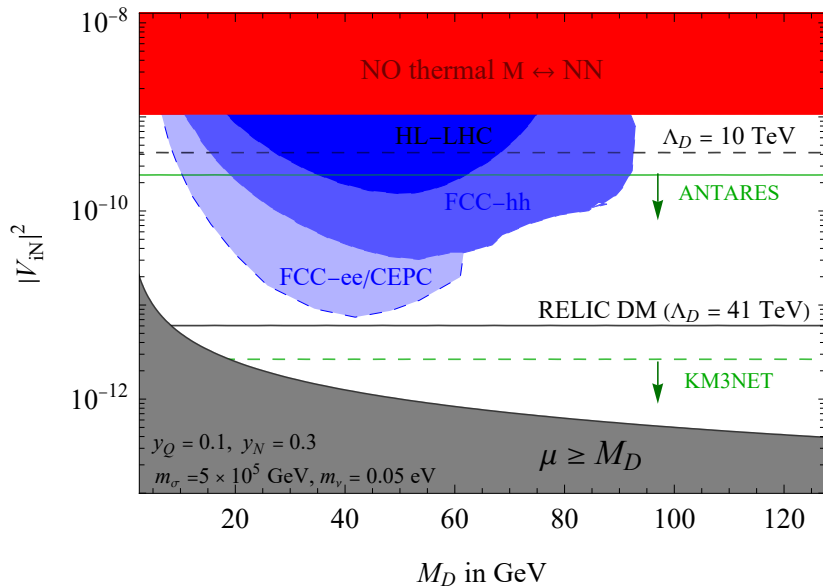
Appendix

Here be dragons

Parameter Space (2) : $M_D = 54$ GeV



Displaced Vertex Searches for N



DM decay via higher dimensional operators

- global $U(1)_D$ not expected to be exact (quantum gravity)
- spin $3/2 \leftrightarrow$ lowest $U(1)_D$ operator at $d = 8$
- 3-body decays $\mathcal{B}_\mu \rightarrow \sum_i H_0 Z_\mu \nu_i$ and $\mathcal{B}_\mu \rightarrow \sum_i H_0 W_\mu l_i$

$$\frac{\Lambda_{UV}}{10^{12} \text{ GeV}} \gtrsim \left| c_8^{(1)} \right|^{\frac{1}{4}} \left(\frac{m_{\mathcal{B}}}{5\Lambda_D} \right)^{\frac{5}{8}} \left(\frac{\Lambda_D}{40 \text{ TeV}} \right)^{\frac{11}{8}} \left(\frac{10^{28} \text{ s}}{\tau_{\mathcal{B}}} \right)^{\frac{1}{8}}$$

- 2-body decays $\mathcal{B}_\mu \rightarrow A_\mu N$ and $\mathcal{B}_\mu \rightarrow Z_\mu N$

$$\frac{\Lambda_{UV}}{6 \times 10^{11} \text{ GeV}} > \left| c_8^{(2)} \right|^{\frac{1}{4}} \left(\frac{m_{\mathcal{B}}}{5\Lambda_D} \right)^{\frac{3}{8}} \left(\frac{\Lambda_D}{40 \text{ TeV}} \right)^{\frac{9}{8}} \left(\frac{10^{28} \text{ s}}{\tau_{\mathcal{B}}} \right)^{\frac{1}{8}}$$