PLANCK 2025 @ Padova
Dynamical origin of neutrino masses and dark matter from a new confining sector

[2403.17488] Phys.Rev.D 110 (2024) 3

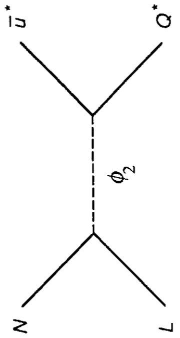
w. Juan Herrero-Garcia & Giacomo Landini
Maximilian Berbig (berbig@ific.uv.es)

Vniversitat de València
IFIC Institut de Física Corpuscular
CSIC Consejo Superior de Investigaciones Científicas

Financiado por la Unión Europea NextGenerationEU
Gobierno de España
Plan de Recuperación, Transformación y Resiliencia

Neutrino masses from QCD confinement

[Thomas, Xu 1992]



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

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

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

- $\mathcal{Z}_2$ (N, $\overline{u}$, ϕ_2 **odd**)
  forbids couplings to ϕ_{SM}

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

Neutrino masses from QCD confinement

Problem:

- Massless u-quark due to $\mathcal{Z}_2$ 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]
- $\overline{u}$ **even** + dim. 5 operator φ **odd** [Davoudiasl et al. 2022]

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

The basic idea

DM

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

Neutrino masses

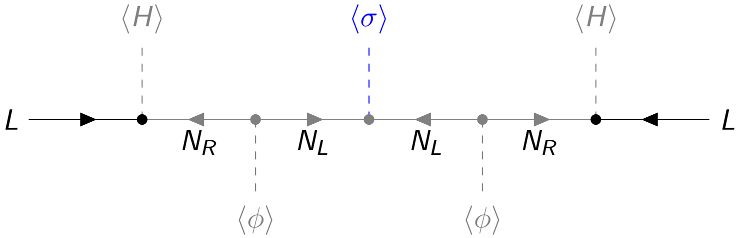
- easier to couple HS to SM gauge singlets N
- keep low scale approach to m_ν

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 $\mu \neq 0$

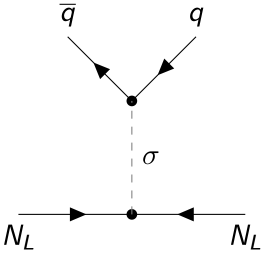
- $m_\nu \simeq 0.05\,\text{eV} \cdot y_\nu^2 \left(\frac{\mu}{1\,\text{keV}}\right)\left(\frac{35\,\text{TeV}}{M_D}\right)^2$ Why is μ so small?



[Mohapatra, Valle 1986]

Small μ from HS confinement

$$-\mathcal{L}_{\rm D} = \underbrace{y_Q \sigma \overline{q_L} q_R}_{\langle \overline{q}_L q_R \rangle = \Lambda_{\rm D}^3} + y_{N_L} \sigma \overline{N_L^c} N_L + y_{N_R} \sigma \overline{N_R^c} N_R + \underbrace{m_\sigma^2 \sigma^2}_{m_\sigma^2 > 0,\ \sigma \in \mathbb{R}} + \dots$$



$$\langle \sigma \rangle \simeq y_Q \frac{\Lambda_{\rm D}^3}{m_\sigma^2}$$

	$SU(3)_{\rm D}$	$\mathcal{Z}_4$	$U(1)_{\rm D}$	#
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

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

Particle Spectrum

accidental (global) symmetries: $\underbrace{\mathrm{U}(1)_\mathrm{D}}_{\text{dark baryon number}} \otimes \underbrace{\mathrm{U}(1)_\mathrm{A}}_{\text{broken by } y_q \text{ \& anomalous}}$

- meson $\mathcal{M} = |\bar{q}q\rangle$
  - single flavor of q $\to$ no pNGB π_D (overclosure, decays during BBN...)
  - $J^p = 0^-$ analogous to η' of QCD
  - $m_\mathcal{M} \simeq \Lambda_\mathrm{D}$
- baryon $\mathcal{B} = |qqq\rangle$
  - spin 3/2 analogous to Δ in QCD
  - stabilized by $\mathrm{U}(1)_\mathrm{D}$ at renormalizable lvl. (expl. $\mathrm{U}(1)_{\not{D}}$ at $d = 8$)
  - mass between $(N_c, 10)\Lambda_\mathrm{D}$, set $m_\mathcal{B} \simeq 5\Lambda_\mathrm{D}$

Cosmology

1. RD with $m_\sigma \gg T_{\rm RH} \gg M_D,\ \Lambda_{\rm D}$, σ only acts as portal

2. N produced from SM via $LH \leftrightarrow N$
   $T_N^{\rm in} \simeq 7 \times 10^7\,{\rm GeV} \cdot \left(\frac{y_\nu}{10^{-4}}\right)^2$

3. HS q produced from N bath via $NN \leftrightarrow qq$, $qq \leftrightarrow gg$
   $\Lambda_{\rm D} > T_q^{\rm in} > 100\,{\rm GeV} \cdot (y_q y_N)^{-\frac{1}{3}} \left(\frac{m_\sigma}{10^6\,{\rm GeV}}\right)^{\frac{4}{3}}$

4. $T \simeq \Lambda_{\rm D}$ HS confines $\rightarrow$ bound states $\mathcal{B}$, $\mathcal{M}$ formed

Cosmology

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

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

- Freezes out at

$$T^{\mathrm{out}}_{\mathcal{B}\mathcal{M}} \simeq \frac{m_\mathcal{B}}{25} \simeq \frac{\Lambda_\mathrm{D}}{5}$$

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

- Freezes out later at

$$T^{\mathrm{out}}_{\overline{N}N\mathcal{M}} \simeq \frac{m_\mathcal{M}}{25} \simeq \frac{\Lambda_\mathrm{D}}{25}$$

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

IDD signal: neutrinos

- $\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M}$ produces $\mathcal{M}$ with

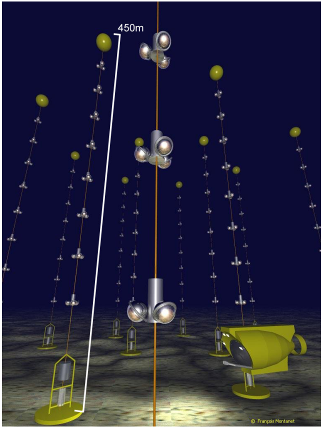
$$E_{\mathcal{M}} \simeq m_{\mathcal{B}}$$

- $\mathcal{M} \to \overline{N}N$ produces N with

$$E_N \simeq \frac{m_{\mathcal{B}}}{2}$$

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

$$E_\nu \simeq \frac{m_{\mathcal{B}}}{4}$$



source: PoS QG-PH (2007) 02

$$\Lambda_{\rm D} > 12\,\text{TeV} \cdot \sqrt{\frac{0.25 \times 10^{-24}\ \text{cm}^3/\text{s}}{\langle \sigma |\vec{v}| \rangle}}$$ [ANTARES, 2015]

IDD signal: neutrinos

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

$$E_\nu \simeq \frac{m_{\mathcal{B}}}{4} \simeq \frac{5}{4}\Lambda_{\mathrm{D}}$$

- projection $\Lambda_{\mathrm{D}} > 54\,\mathrm{TeV}$ [KM3NeT]

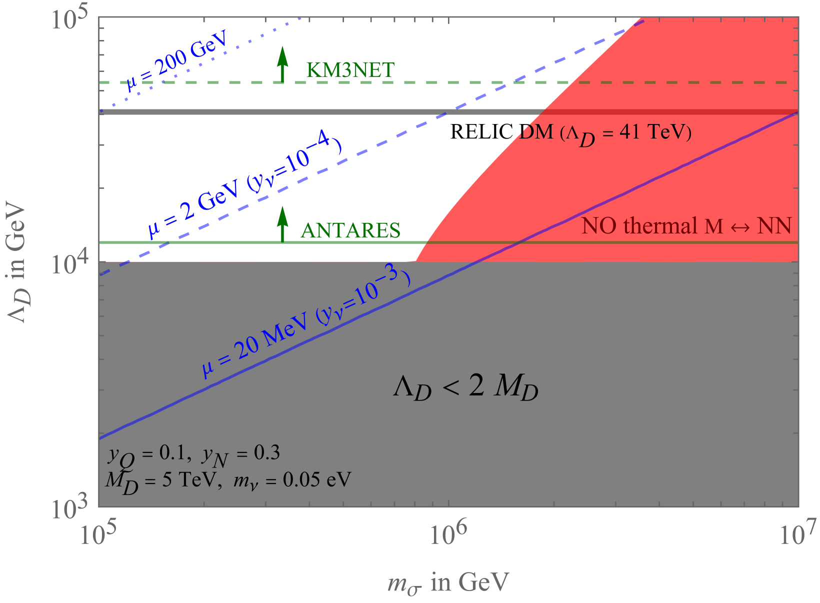
- recently observed 220 PeV event requires too large

$$\Lambda_{\mathrm{D}} = 176\,\mathrm{PeV}$$

- event not be explained in this model $\to$ astrophysics!

source: IFIC website

Parameter Space (1): $M_D = 5$ TeV



Summary

- $\mu > \mathcal{O}(10\,\text{MeV})$ for ISS from confining HS
- $|V_{iN}|^2 \simeq m_\nu/\mu \lesssim \mathcal{O}\left(10^{-9}\right)$
- DM: spin 3/2 dark baryon $\mathcal{B} \leftrightarrow$ lowest $\text{U}(1)_{\not{D}}$ operator at $d = 8$
- $\Lambda_\text{D} \simeq (1 - 100)$ TeV fixed by $h^2\Omega_\text{DM} = 0.12$
- N portal thermalizing HS and SM
- signals at neutrino telescopes [KM3NeT]

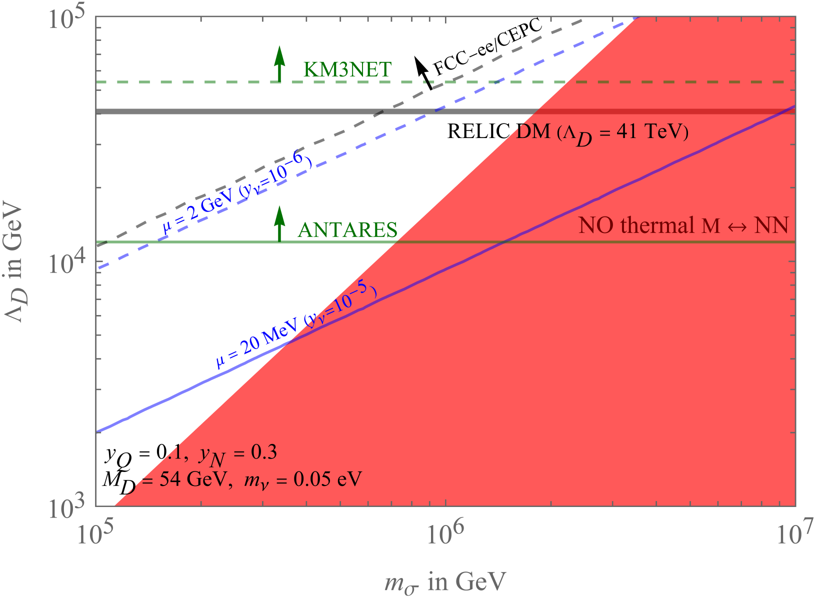
Outro

Thank you for your time and attention!

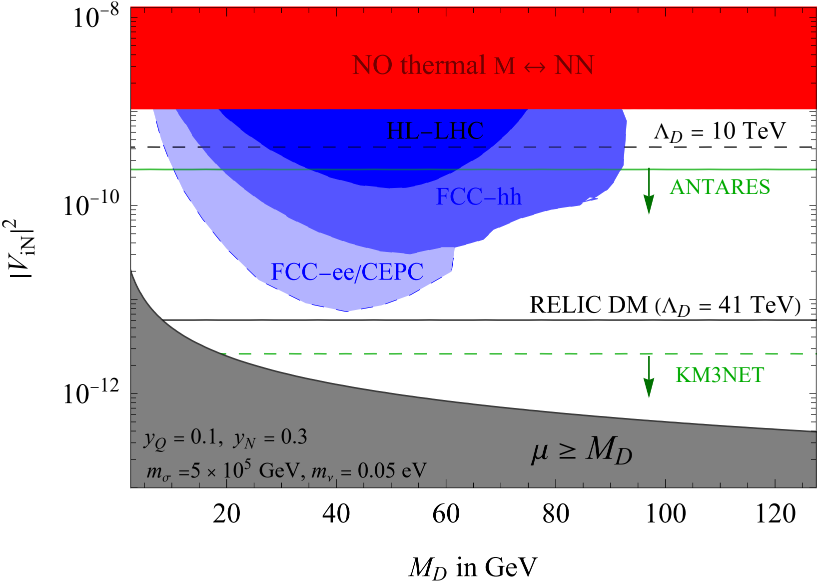
Appendix

Here be dragons

Parameter Space (2) : $M_D = 54\,\text{GeV}$



Displaced Vertex Searches for N



DM decay via higher dimensional operators

- global $\mathrm{U}(1)_\mathrm{D}$ not expected to be exact (quantum gravity)

- spin $3/2 \leftrightarrow$ lowest $\mathrm{U}(1)_{\not{D}}$ operator at $d = 8$

- 3-body decays $\mathcal{B}_\mu \to \sum_i H_0 Z_\mu \nu_i$ and $\mathcal{B}_\mu \to \sum_i H_0 W_\mu l_i$

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

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

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