Dynamical origin of neutrino masses and dark matter from confinement

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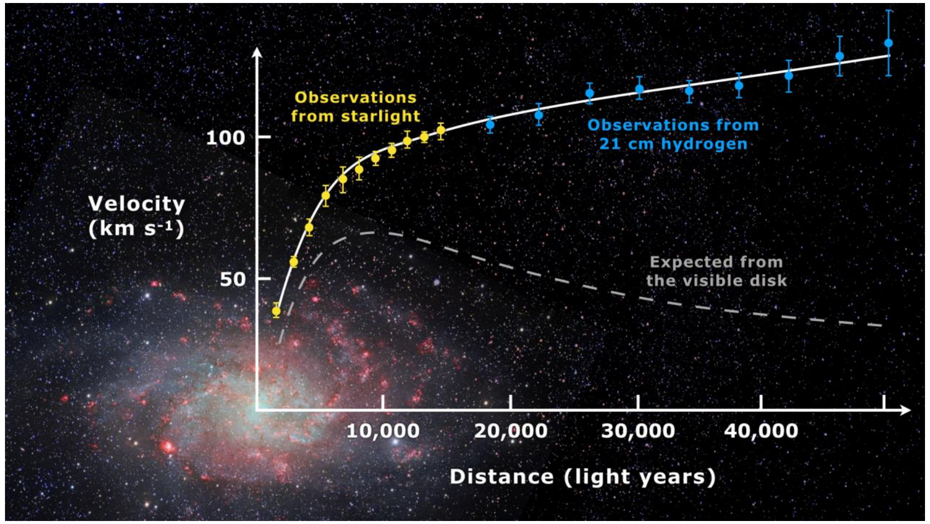
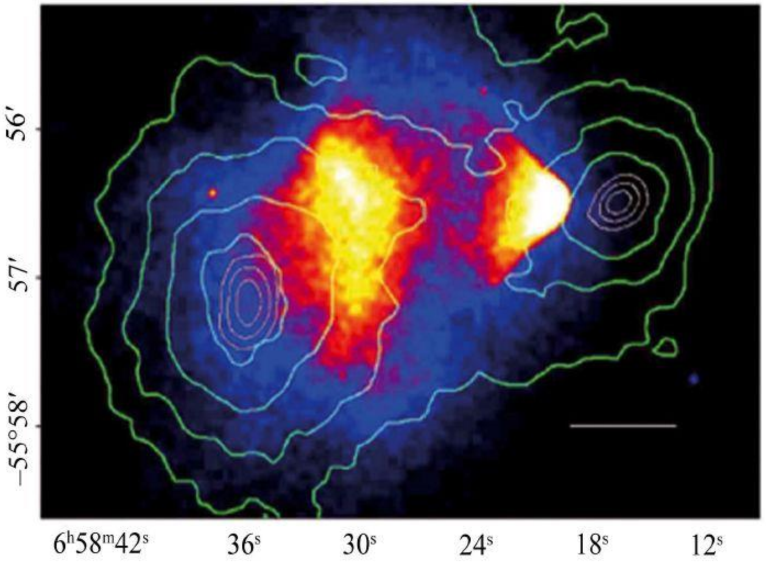
based on **arXiv [2403.17488]** Maximilian Berbig, Juan Herrero-Garcia, GL

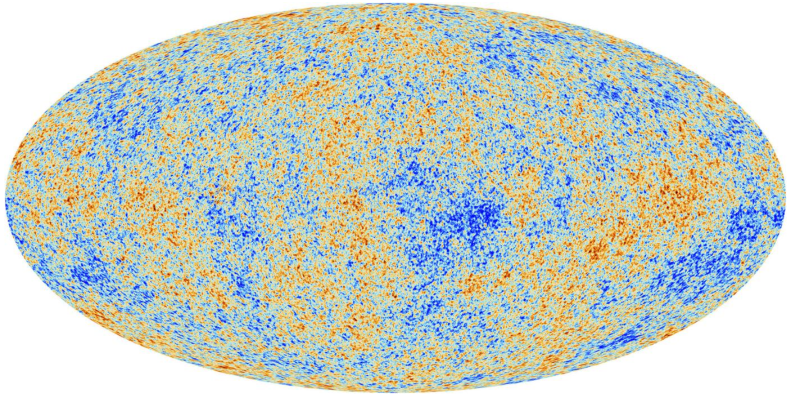
Dark Matter

Dark Matter existence is supported by astrophysical and cosmological evidence





- Neutral and weakly interacting with SM
- Cosmologically stable
- Cold (non-relativistic at structure formation)



Neutrino masses

Neutrinos are massless in the Standard Model

$$L = (\nu_L, e_L) \qquad \text{no} \quad \nu_R$$

Accidental U(1) lepton number conservation

Neutrino oscillations require massive neutrinos

↓

Combining oscillation and cosmological data

$$0.05 \text{ eV} \lesssim \sum m_\nu \lesssim 0.12 \text{ eV}$$

The See-Saw

Introduce RHN $N_R \sim (1,1)_0$

$$\Delta\mathcal{L}_{\text{lepton}} \sim y_\nu \bar{L}\widetilde{H} N_R + \frac{1}{2} M_N \overline{N_R^c} N_R$$

<u>Dirac mass</u> <u>Majorana mass</u>

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$m_D = y_\nu v_H/\sqrt{2}$

$m_D \ll M_N$ →

$$m_\nu = m_D M_N^{-1} m_D^T \sim \frac{v_H^2}{M_N}$$

→ $m_\nu \sim 0.05$ eV if $M_N \sim 10^{14}$ GeV

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Dirac mass   Majorana mass

Many variants have been studied!

(type II-III see-saw, inverse see-saw, linear see-saw, scotogenic,…)

Majorana masses are a **crucial** ingredient

Inverse See-Saw

2 basic ingredients

1) Small breaking of lepton number (μ-term)

→ Explicit or spontaneous breaking

→ Need to be small $m_\nu \propto \mu$

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Inverse See-Saw

2 basic ingredients

1) Small breaking of lepton number $(\mu\text{-term})$

→ Explicit or spontaneous breaking

→ Need to be small $m_\nu \propto \mu$

→ We will propose a **dynamical** generation

2) Extended fermionic sector

→ Need at least 2 new fermionic fields $N_R, N_L \sim (1,1)_0$

Inverse See-Saw

$$\Delta\mathcal{L}_{\text{lepton}} \sim y_\nu \bar{L}\widetilde{H}N_R + M_D\overline{N_L}N_R + \frac{1}{2}\mu\overline{N_R^c}N_R$$

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→ $m_\nu \sim 0.05$ eV if $\mu \sim$ keV

$M_D \sim 10$ TeV

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Potentially testable

Inverse See-Saw

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Dirac mass   Majorana mass

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_D \\ 0 & M_D^T & \mu \end{pmatrix}$$

How to generate such a small lepton number breaking parameter?

$\mu \ll m_D \ll M_D$

$$m_\nu \sim m_D (M_D^T)^{-1} \mu M_D^{-1} m_D^T \sim \mu \frac{v_H^2}{M_D^2}$$

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Gauge confinement

New confining dark sector → we focus (for simplicity) on $SU(3)_D$

1 vector-like dark quark in the fundamental representation (q_L, q_R)

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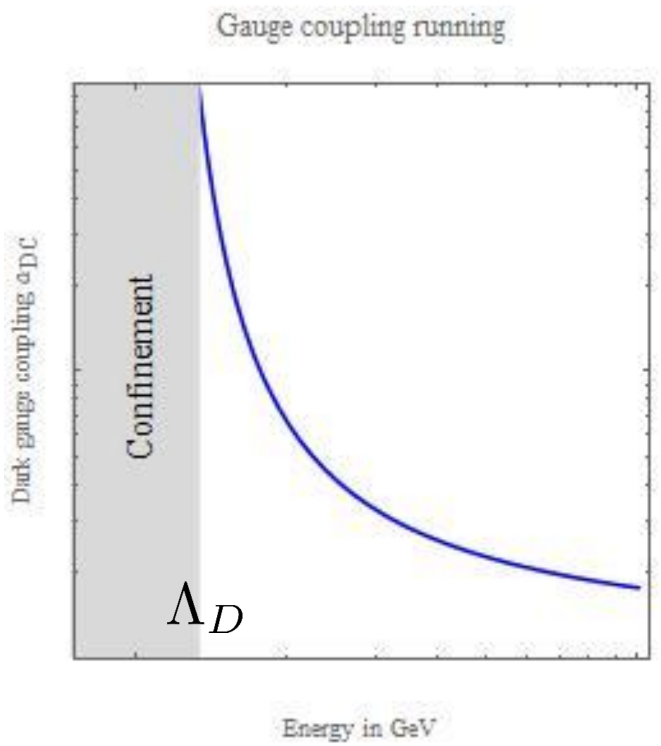

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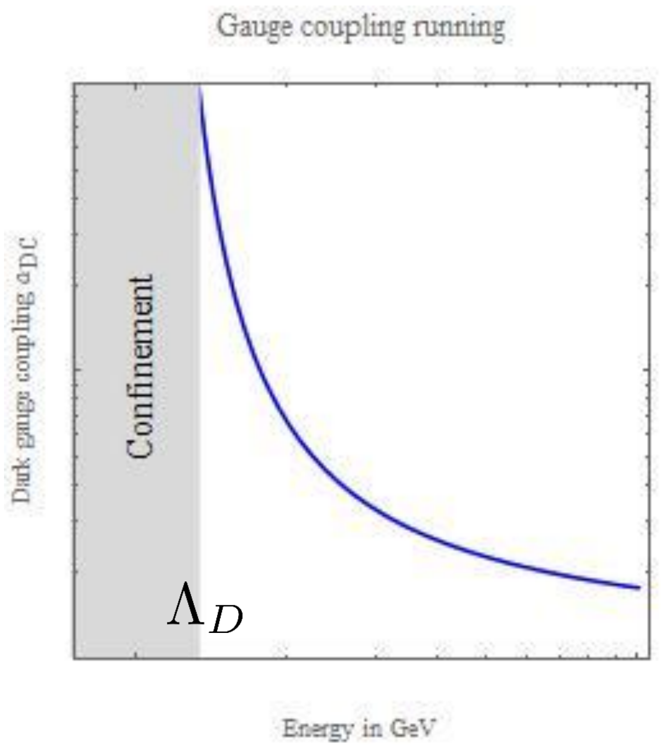
(1) Quark condensate $\langle \overline{q_L} q_R \rangle \simeq \Lambda_D^3$

(similar to QCD)



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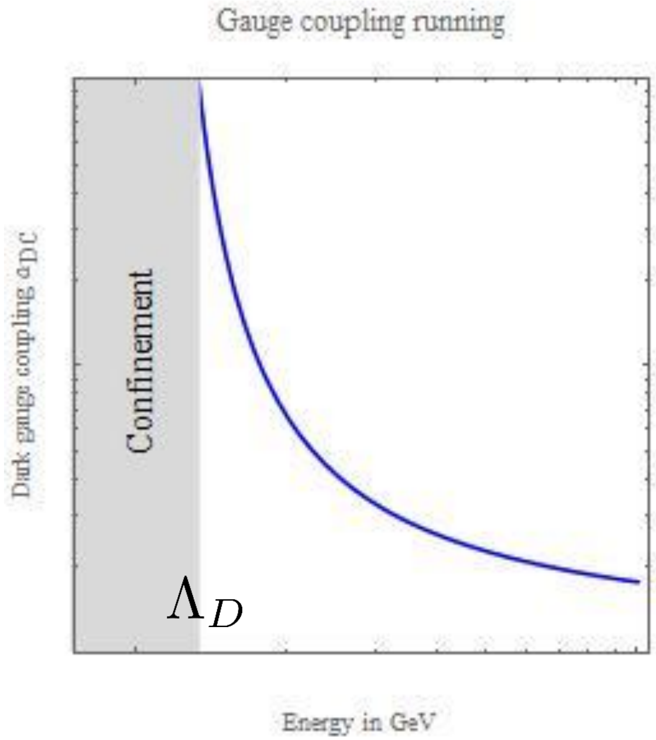

Neutrino mass from confinement

$$\mathcal{L} \sim y_Q \sigma \overline{q_L} q_R + y_{N_R} \sigma \overline{N_R^c} N_R + m_\sigma^2 \sigma^2 \;+ \ldots$$

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Real scalar field

Neutrino mass from confinement

$$\mathcal{L} \sim y_Q \sigma \overline{q_L} q_R + y_{N_R} \sigma \overline{N_R^c} N_R + \underline{m_\sigma^2} \sigma^2 \; + \ldots$$

Hard mass $m_\sigma^2 > 0$

Neutrino mass from confinement

$$\mathcal{L} \sim y_Q \sigma \overline{q_L} q_R + y_{N_R} \sigma \overline{N_R^c} N_R + m_\sigma^2 \sigma^2 + \ldots$$

Example

	$\mathrm{SU}(3)_\mathrm{D}$	$\mathcal{Z}_4$
q_L	$\mathbf{3}$	$-i$
q_R	$\mathbf{3}$	i
N_L	1	i
N_R	1	i
σ	1	-1

No bare masses for the fermions

Scalar couples to quark and RHN sectors

Neutrino mass from confinement

$$\mathcal{L} \sim y_Q \sigma \overline{q_L} q_R + y_{N_R} \sigma \overline{N_R^c} N_R + m_\sigma^2 \sigma^2 \; + ...$$

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Gauge confinement $\langle \overline{q_L} q_R \rangle \simeq \Lambda_D^3$

generate a scalar vev ↓ $V(\sigma) \sim y_Q \langle \bar{q}_L q_R \rangle \sigma + m_\sigma^2 \sigma^2$

$$\langle \sigma \rangle \simeq y_Q \frac{\Lambda_D^3}{m_\sigma^2}$$

Neutrino mass from confinement

$$\mathcal{L} \sim y_Q \sigma \overline{q_L} q_R + y_{N_R} \sigma \overline{N_R^c} N_R + m_\sigma^2 \sigma^2 + \ldots$$

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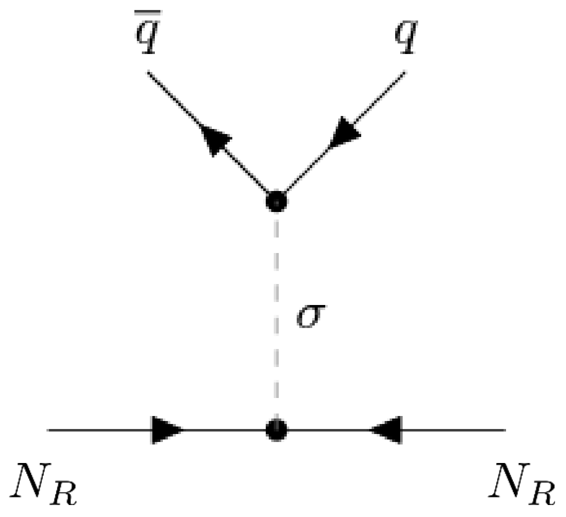
$$\langle \sigma \rangle \simeq y_Q \frac{\Lambda_D^3}{m_\sigma^2}$$

Dynamical generation of Majorana mass $\mu \simeq y_{N_R} y_Q \frac{\Lambda_D^3}{m_\sigma^2}$



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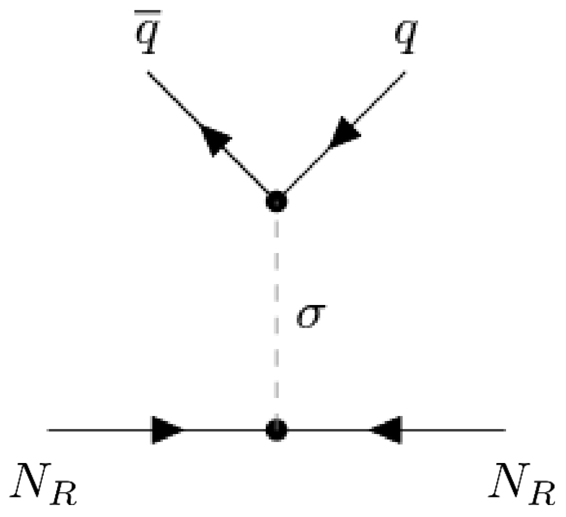

Dynamical generation of Majorana mass $\mu \simeq y_{N_R} y_Q \frac{\Lambda_D^3}{m_\sigma^2}$

Generic mechanism to generate Majorana masses

It can be applied in any neutrino mass model (e.g. Type I see-saw)

Neutrino mass from confinement

$$\mathcal{L} \sim y_Q \sigma \overline{q_L} q_R + y_{N_R} \sigma \overline{N^c_R} N_R + m_\sigma^2 \sigma^2 + \ldots$$

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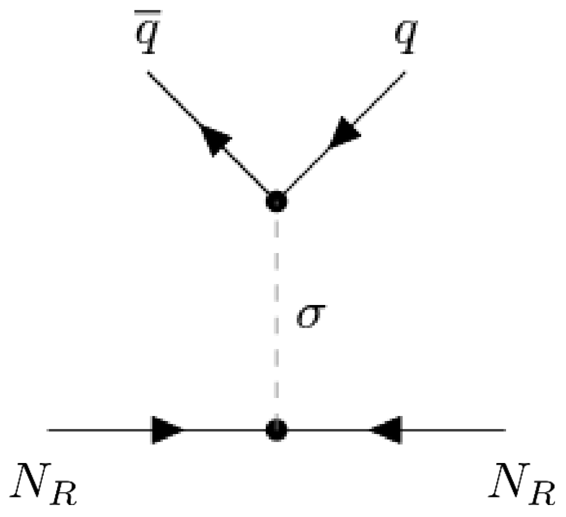


Dynamical generation of Majorana mass $\mu \simeq y_{N_R} y_Q \frac{\Lambda_D^3}{m_\sigma^2}$

If $\Lambda_D \ll m_\sigma$ → dynamical generation of small Majorana mass for inverse see-saw

The Model

	$SU(3)_D$	$\mathcal{Z}_4$	generations
q_L	$\mathbf{3}$	$-i$	1
q_R	$\mathbf{3}$	i	1
N_L	1	i	3
N_R	1	i	3
L	1	i	3
e_R	1	i	3
σ	1	-1	1

Can be generated dynamically by the vev of an additional scalar

$$\mathcal{L}_{LN} = y_e \overline{L} H e_R + y_\nu \overline{L} \tilde{H} N_R + M_D \overline{N_L} N_R + \text{h.c.},$$

$$\mathcal{L}_D = y_Q \sigma \overline{q_L} q_R + y_{N_L} \sigma \overline{N_L^c} N_L + y_{N_R} \sigma \overline{N_R^c} N_R + \text{h.c.},$$

$$V_{\sigma,\varphi} = \left(m_\sigma^2 + \lambda_\sigma \sigma^2 + \lambda_{H\sigma} |H|^2\right) \sigma^2$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & \mu & M_D \\ 0 & M_D^T & \mu' \end{pmatrix}$$

$$m_D = y_\nu \langle H \rangle$$

$$\mu = y_Q y_{N_R} \frac{\Lambda_D^3}{m_\sigma^2} \qquad \mu' = y_Q y_{N_L} \frac{\Lambda_D^3}{m_\sigma^2}$$

The Spectrum

The theory confines at the scale Λ_D

↓

Quarks combine into *baryons* and *mesons*

The Spectrum

The theory confines at the scale Λ_D

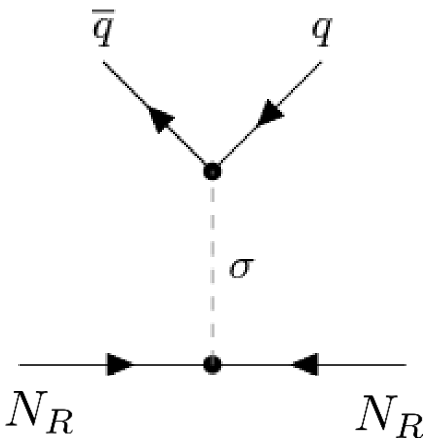
Mesons

The lightest meson is pseudo-scalar

$$m_{\mathcal{M}} \simeq \Lambda_D$$

$$f_{\mathcal{M}} \equiv \langle 0|\overline{q}\gamma_5 q|\mathcal{M}\rangle \sim \Lambda_D^2$$

(with 1 quark flavor there are no light dark pions)



Mesons can decay into neutrinos (both RHNs and active)

The Spectrum

The theory confines at the scale Λ_D

↓

Baryons

$\mathcal{B} \sim qqq$ bound state with spin $3/2$

$$m_{\mathcal{B}} \simeq 5\Lambda_D$$

	$\mathrm{U(1)_D}$
q_L	1
q_R	1
$\mathcal{M}$	0
$\mathcal{B}$	3

Accidental $U(1)_D$ of the renormalizable Lagrangian

Protected up to dimension-8 operators *(spin protection)*

Baryons are stable → **Dark Matter!**

The Cosmology

We assume that $m_\sigma \gg T_{\rm RH} \gg M_D, \Lambda_D$

↓

σ is not in thermal bath

$$\begin{aligned} LL, HH &\leftrightarrow NN \\ LH &\leftrightarrow N \\ NN &\leftrightarrow \overline{q}q \end{aligned}$$

The dark sector is produced from the SM bath and thermalizes

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We assume that $m_\sigma \gg T_{\rm RH} \gg M_D, \Lambda_D$

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$$LH \leftrightarrow N$$
$$NN \leftrightarrow \overline{q}q$$

The dark sector is produced from the SM bath and thermalizes

<u>Confinement</u> $T \simeq \Lambda_D$

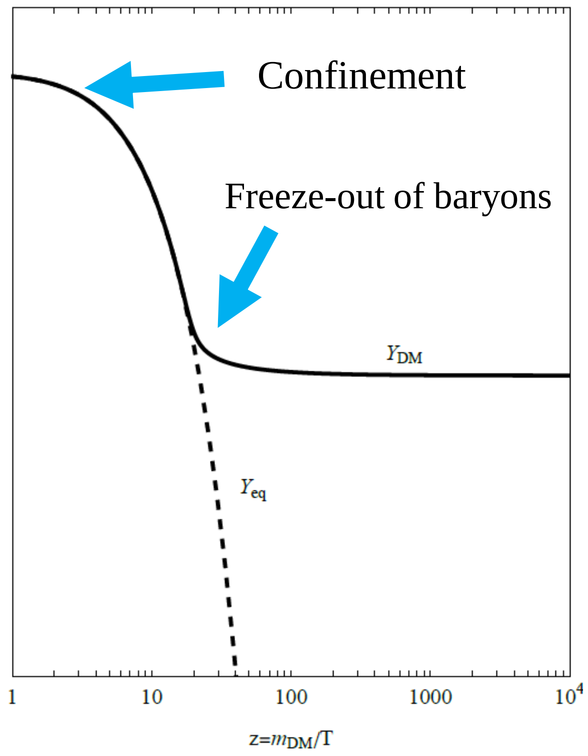
Strong (dark) interactions convert baryons to mesons

$$\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M}$$

Mesons decay to neutrinos keeping equilibrium with the SM

$$\Gamma(\mathcal{M} \to NN) \simeq \frac{y_Q^2 y_N^2}{32\pi} \frac{\Lambda_D^5}{m_\sigma^4} \qquad \Lambda_D > 2M_D$$

The Cosmology



Baryon DM freeze-out

$$\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M}$$

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

The DM relic abundance can be reproduced if $\Lambda_D \sim (1 - 100)$ TeV

Indirect Detection: neutrino lines

Baryons annihilate to mesons

$$\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M}$$

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

Indirect Detection: neutrino lines

Baryons annihilate to mesons decay to heavy neutrinos

$$\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M} \quad \longrightarrow \quad \mathcal{M} \to NN$$

$$E_{\mathcal{M}} \simeq m_{\mathcal{B}} \qquad E_N \simeq m_{\mathcal{B}}/2$$

Indirect Detection: neutrino lines

Baryons annihilate to mesons		decay to heavy neutrinos		decay to active neutrinos
$\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M}$	→	$\mathcal{M} \to NN$	→	$N \to h\nu_L$
$E_{\mathcal{M}} \simeq m_{\mathcal{B}}$		$E_N \simeq m_{\mathcal{B}}/2$		$E_\nu \simeq m_{\mathcal{B}}/4$

Indirect Detection: neutrino lines

Baryons annihilate to mesons → decay to heavy neutrinos → decay to active neutrinos

$$\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M} \qquad \mathcal{M} \to NN \qquad N \to h\nu_L$$

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<u>Monochromatic neutrino lines</u> $E_\nu \simeq m_{\mathcal{B}}/4 \sim (1-100)\ \mathrm{TeV}$

Indirect Detection: neutrino lines

Baryons annihilate to mesons | decay to heavy neutrinos | decay to active neutrinos

$\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M}$ → $\mathcal{M} \to NN$ → $N \to h\nu_L$

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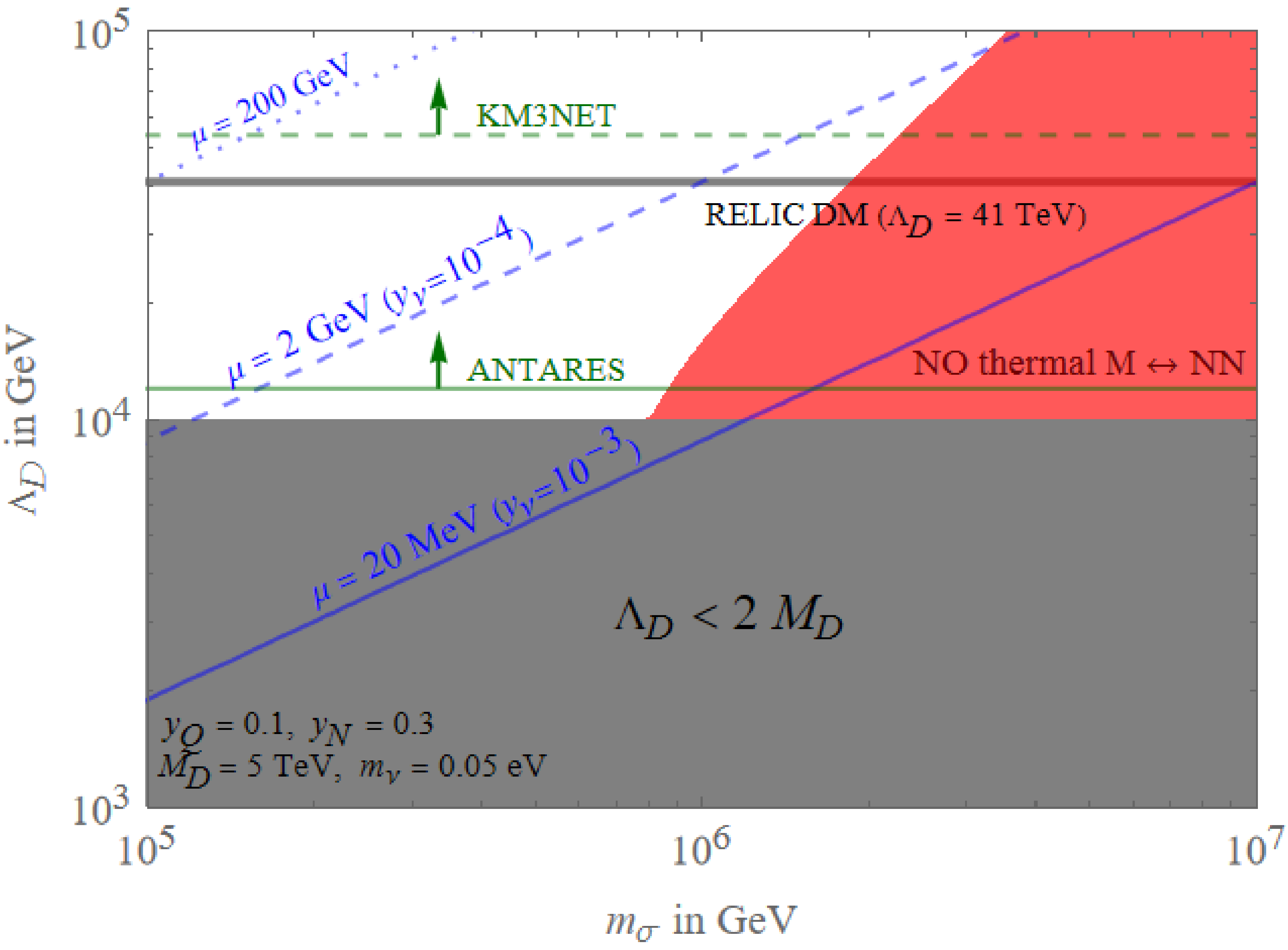
Monochromatic neutrino lines $E_\nu \simeq m_{\mathcal{B}}/4 \sim (1-100)$ TeV

Testable with **neutrino telescopes**!

Current bound from ANTARES collaboration → $\Lambda_D > 12\ \text{TeV}\ \sqrt{\frac{0.25\times10^{-24}\text{cm}^3/\text{s}}{\langle\sigma v\rangle}}$

It will be improved by KM3NeT up to $\Lambda_D \simeq 54$ TeV



μ = 200 GeV
KM3NET
RELIC DM (Λ_D = 41 TeV)
μ = 2 GeV (y_ν=10^{-4})
ANTARES
NO thermal M ↔ NN
μ = 20 MeV (y_ν=10^{-3})
$\Lambda_D < 2\ M_D$
$y_Q = 0.1,\ y_N = 0.3$
M_D = 5 TeV, m_ν = 0.05 eV
Λ_D in GeV
m_σ in GeV
10^5
10^4
10^3
10^6
10^7

Backup slides

Dark baryon number

Higher-dimensional operators breaks dark baryon number

The first baryon number-breaking operators arise at dimension 8 for spin 3/2
(spin protection)

$$\frac{c_8^{(1)}}{\Lambda_{\rm UV}^4}(qqq)_\mu \overline{L}\left(D^\mu \tilde{H}\right) + \text{h.c.},$$
$$\frac{c_8^{(2)}}{\Lambda_{\rm UV}^4}(qqq)_\mu \left[\gamma^\alpha,\gamma^\beta\right]\gamma^\mu N_{L,R} B_{\alpha\beta} + \text{h.c.},$$
$$\frac{c_{10}}{\Lambda_{\rm UV}^6}(qqq)_\mu N_{L,R}\left(\partial^\mu \overline{q} q\right) + \text{h.c.},$$
$$\frac{c_{11}}{\Lambda_{\rm UV}^7}(qqq)_\mu \overline{L}\left(\partial^\mu \overline{q} q\right)\tilde{H} + \text{h.c.},$$

→ $\mathcal{B} \to h\nu, Z\nu, Wl, HZ\nu, \gamma N, \ldots$

$\tau_B \gtrsim 10^{28}$ sec → $\Lambda_{\rm UV} \gtrsim 10^{12}$ GeV $\left(\frac{\Lambda_D}{40 \text{ TeV}}\right)$

(DM indirect detection)

Constraints

Small active-sterile neutrino mixings evade current bounds

$$|V_{iN}|^2 \simeq m_\nu/\mu \lesssim 10^{-8} \qquad i = e, \mu, \tau$$

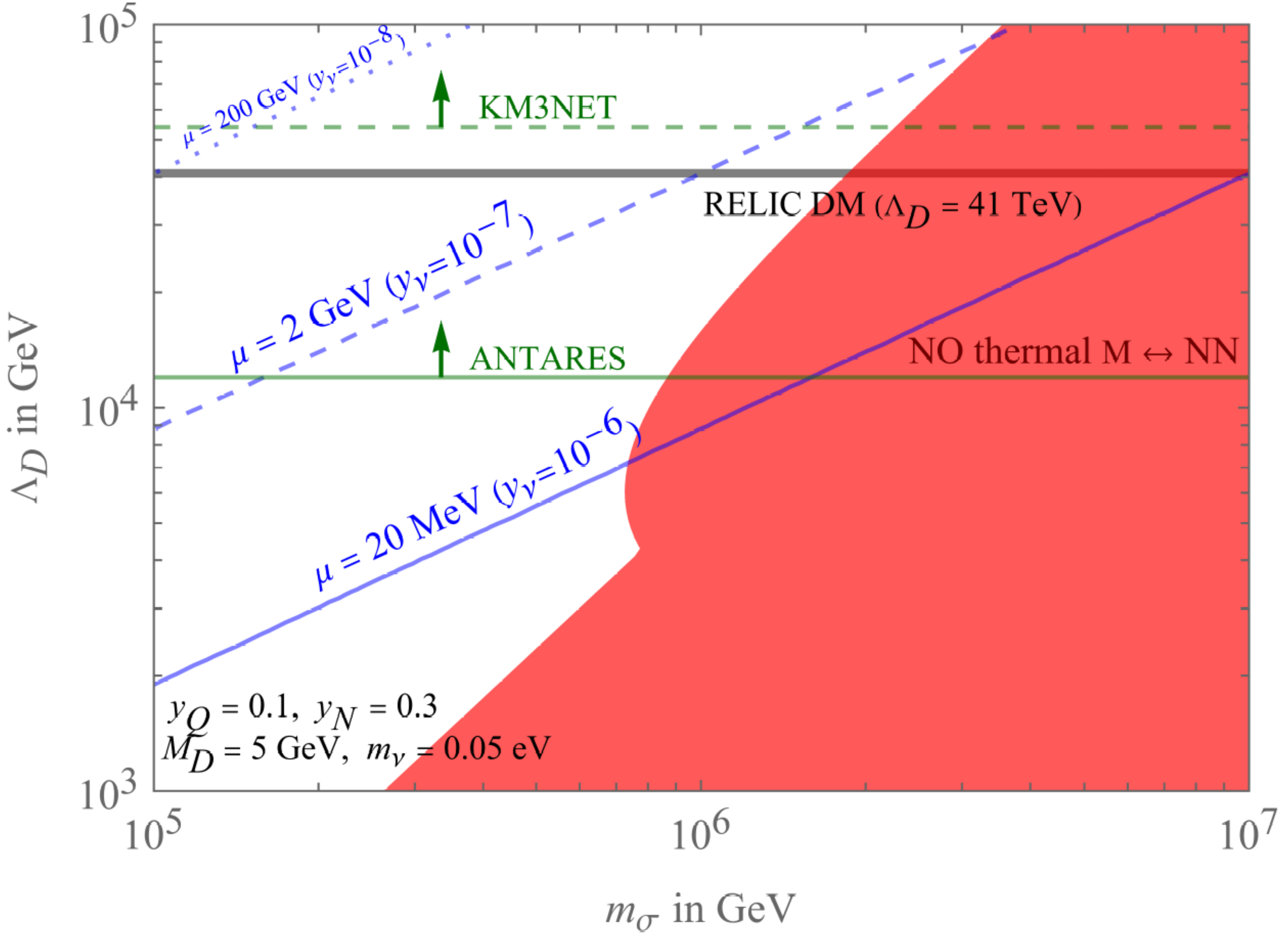
EW precision observables	$|V_{iN}| \lesssim 10^{-3}$	$M_D \sim \text{TeV}$
$\mu \to e\gamma$	$|V_{eN} V_{\mu N}| \lesssim 10^{-5}$	$M_D \sim 100$ GeV-10 TeV
Electron dipole moment	$d_e^{\max} \simeq 10^{-[31,32]} e$ cm	$(d_e^{\exp} < 1.1 \times 10^{-29} e)$ cm

DM Direct detection bounds are evaded

Very small mixing among the SM Higgs and σ

$$\theta_{h\sigma} \propto \frac{v_H \langle \sigma \rangle}{m_\sigma^2} \sim \frac{v_H \Lambda_D^3}{m_\sigma^4} \ll 1$$

Lighter Dirac masses imply smaller Yukawa couplings



$|V_{iN}|^2 \simeq m_\nu/\mu \lesssim 10^{-8}$ Close to experimental sensitivity for GeV-ish RHN

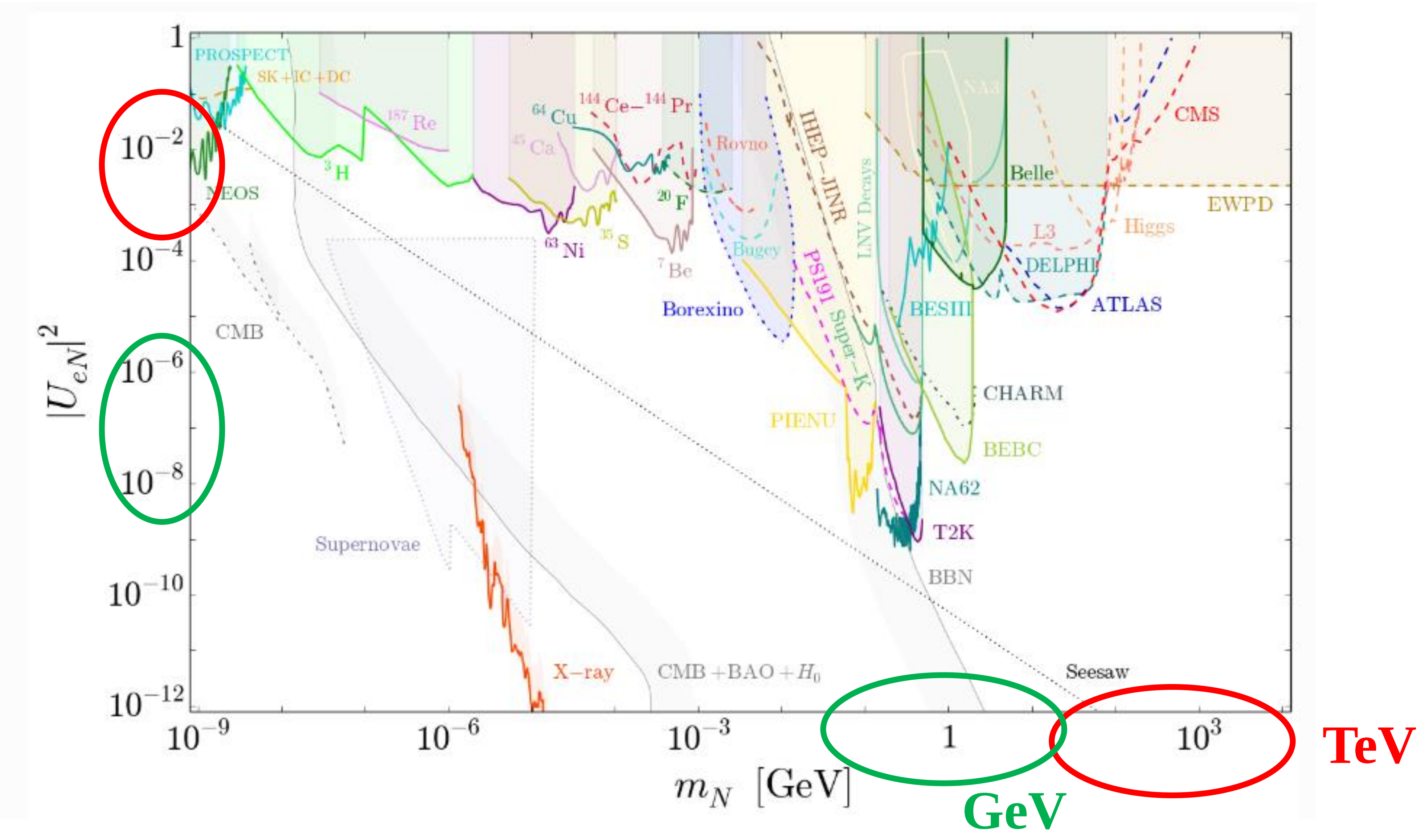


Figure made by Patrick Bolton, *https://www.hep.ucl.ac.uk/~pbolton/index.html*

Indirect Detection: neutrino lines

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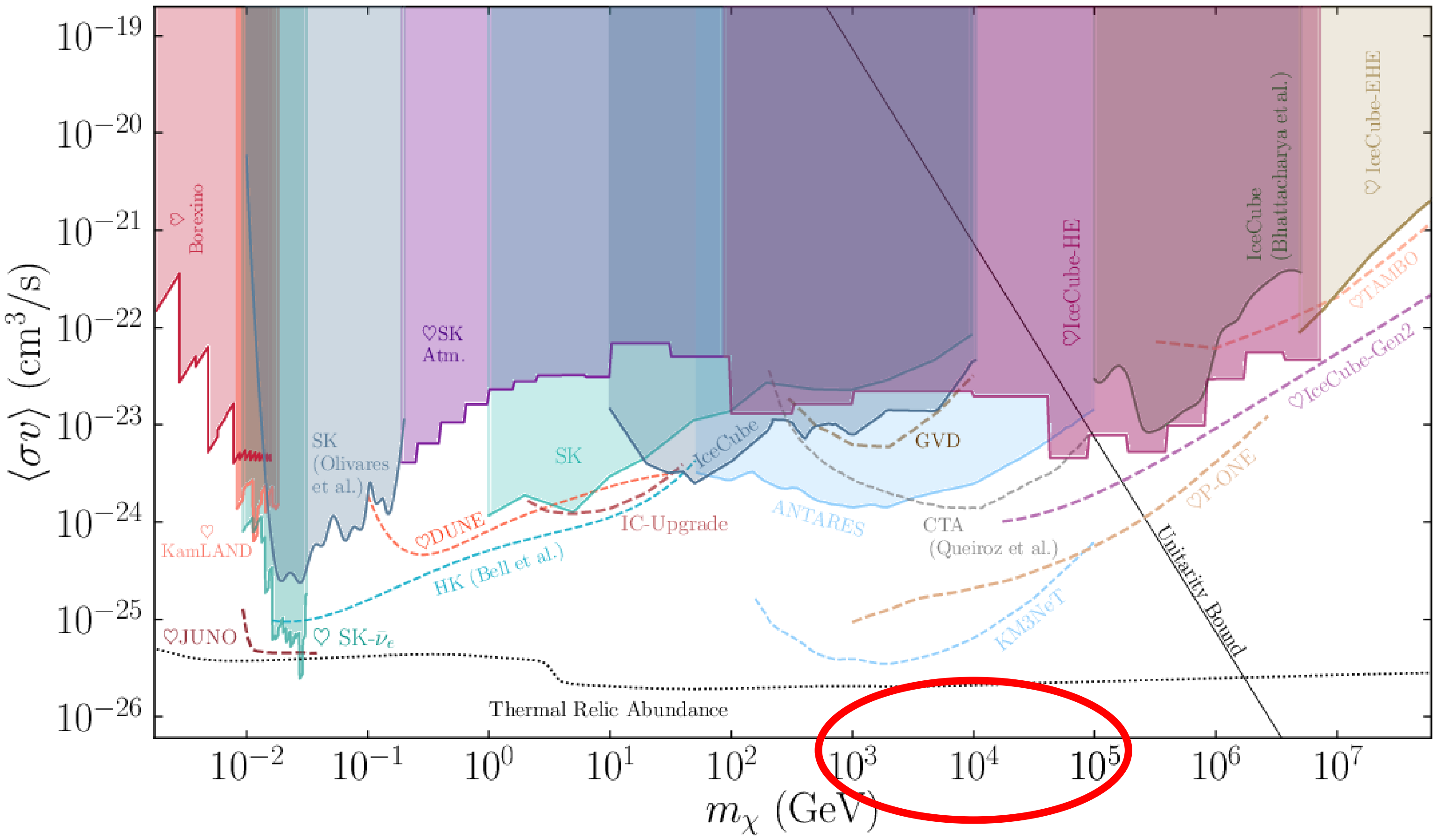

Figure made by *C. Arguelles, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa and A. Vincent [1912.09486]*

Dark sector thermalization

$$LL, HH \leftrightarrow NN$$
$$LH \leftrightarrow N$$

$$\Gamma \sim \frac{y_\nu^2}{32\pi} T \longrightarrow \Gamma \gg H \longrightarrow T < 7 \times 10^7 \text{ GeV} \left(\frac{y_\nu}{10^{-4}}\right)^2 \sqrt{\frac{106.75}{g_*}}$$

$$NN \leftrightarrow \bar{q}q$$

$$\Gamma \sim y_Q y_N \frac{T^5}{m_\sigma^4} \longrightarrow \Gamma \gg H \longrightarrow T > 100 \text{ GeV} \times \frac{1}{(y_Q y_N)^{1/3}} \left(\frac{m_\sigma}{10^6 \text{ GeV}}\right)^{4/3}$$

$$< \Lambda_D \sim 1 - 100 \text{ TeV}$$

The Cosmology

We assume that $m_\sigma \gg T_{\rm RH} \gg M_D, \Lambda_D$

After dark confinement $T < \Lambda_D$

All hadrons are not relativistic

$$m_{\rm hadron} \gtrsim \Lambda_D \gtrsim T$$

However they inherit the initial (relativistic) quark abundance

$$Y_q = \frac{n_q}{s} = \frac{135\zeta(3)}{\pi^4 g_s}$$

Over-abundance of dark hadrons?

The Cosmology

We assume that $m_\sigma \gg T_{\rm RH} \gg M_D, \Lambda_D$

<u>After dark confinement</u> $T < \Lambda_D$

Meson (inverse) decays to neutrinos keep the hadrons in thermal equilibrium with the SM

$$\Gamma(\mathcal{M} \to NN) \simeq \frac{y_Q^2 y_N^2}{32\pi} \frac{\Lambda_D^5}{m_\sigma^4} \qquad \Lambda_D > 2M_D$$

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Hadrons evolves with the same temperature of the SM

$$Y_{\rm hadron} \sim \exp(-m_{\rm hadron}/T)$$

The Cosmology

For a non-relativistic (decoupled) dark sector

$$R \equiv \frac{s_D}{s}$$

$$s_D \approx \frac{\rho_D^{\rm eq}}{T_D} = \frac{M n_D^{\rm eq}}{T_D} \qquad n_D^{\rm eq} = \left(\frac{M T_D}{2\pi}\right)^{3/2} e^{-M/T_D} \qquad T_d \sim 1/\log a$$

$$Y_D^{\rm eq} \equiv \frac{n_D^{\rm eq}}{s} = \frac{n_D^{\rm eq}}{s_D} R = \frac{T_D}{M} R \qquad \frac{T_D^*}{M} \approx \frac{1}{3 \log Q} \qquad \log Q \simeq \mathcal{O}(1-10)$$

$$R \sim \mathcal{O}(0.1) \qquad \frac{\Omega h^2}{0.12} \simeq \left(\frac{M}{0.4\ \text{eV}}\right) \frac{R}{3 \log Q} \simeq \frac{M}{100\ \text{eV}}$$

DM is either over-abundant or excluded (Bullet cluster, Lyman-alpha,...)

Cross section

O(1) factors are unknow because strong dynamics is non-perturbative

$$\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M}$$

Dimensional analysis → geometrical cross-section

$$\sigma v \sim 1/\Lambda_D^2$$

$\mu = m_{\mathcal{B}}/2$ $\quad |\vec{v}| \simeq \sqrt{T/m_{\mathcal{B}}}$

$$l_{\max} \sim \mu v b \sim \sqrt{T m_{\mathcal{B}}}/2\Lambda_D < 1$$

$m_{\mathcal{B}} \simeq 5\Lambda_D$

$b \sim 1/\Lambda_D$

The cross section is dominated by the s-wave contribution

Dark pions

With more than 1 flavor of dark quarks the spectrum contains dark pions

$$m_\pi \simeq \Lambda_D^2 / m_\sigma \qquad\qquad m_\pi < M_D$$

Dark pions decay into active neutrinos

$$\Gamma_\pi \sim m_\nu^2 \Lambda_D^4 / m_\sigma^5$$

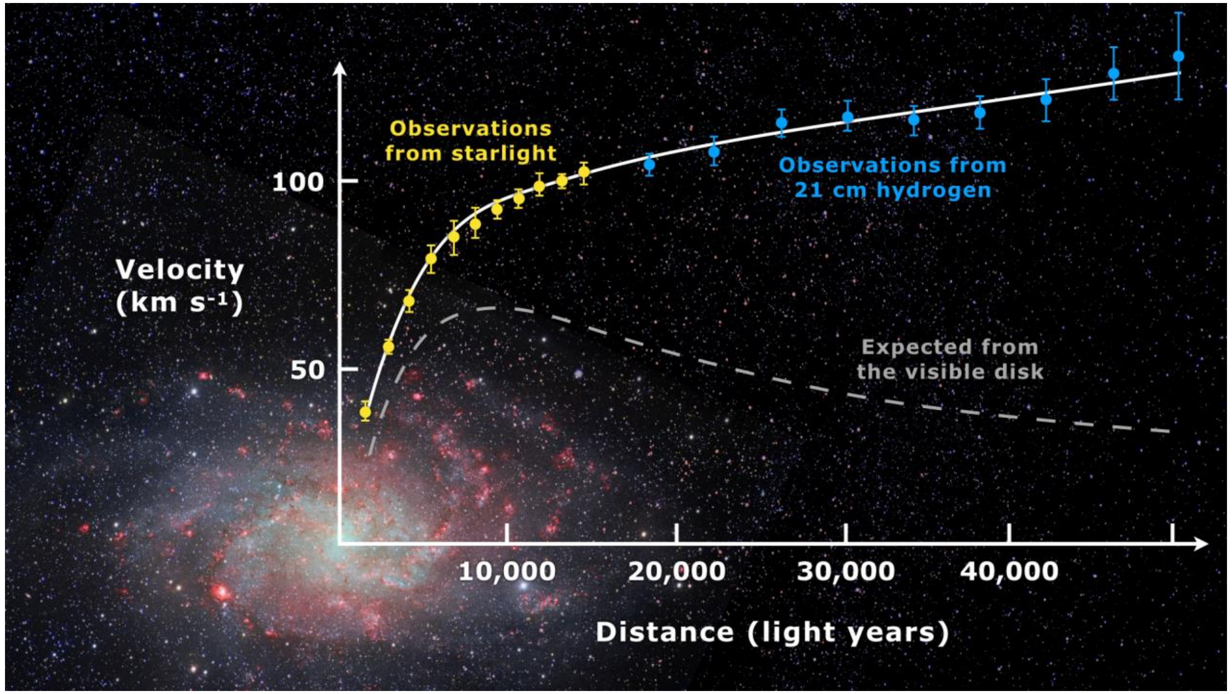
Decay is super-slow → BBN constraints

Overclosure

(pions decouple with relativistic abundance)

Dark Matter evidence

Dark Matter existence is supported by astrophysics and cosmology

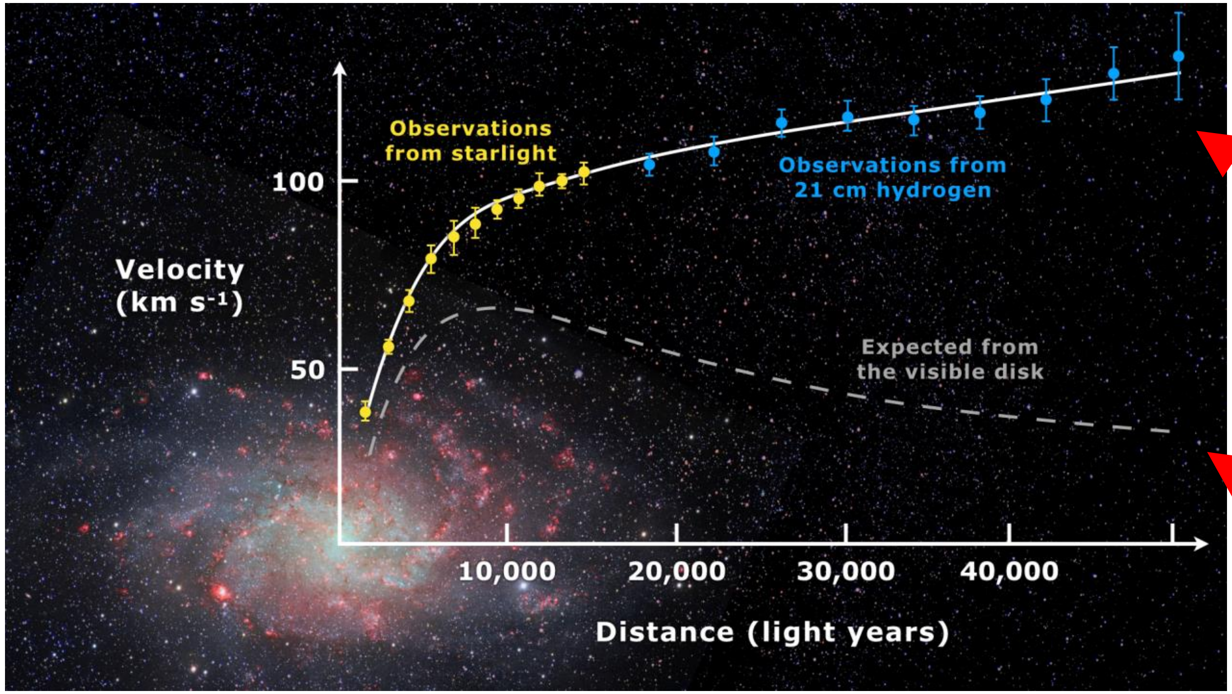


Rotation curves of spiral galaxies flatten at large distances

Dark Matter evidence

Dark Matter existence is supported by astrophysics and cosmology

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$



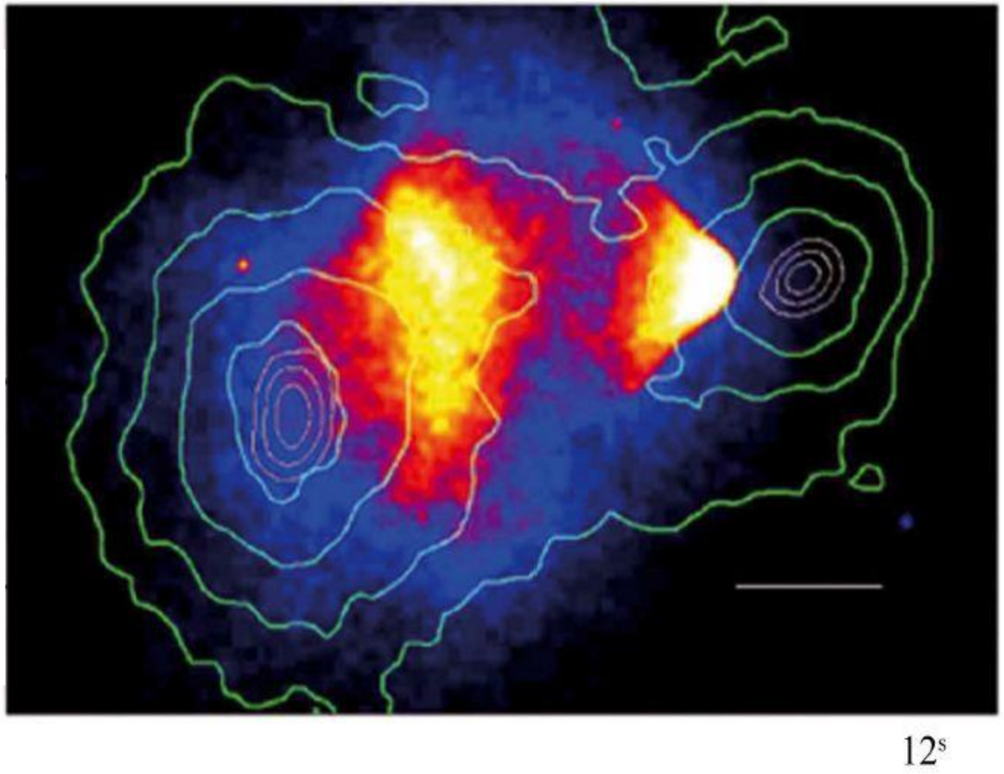
$$M_{\text{dark}}(r) = 4\pi r$$

$$M_{\text{vis}}(r) = M_{\text{vis}}$$

This implies the existence of a *dark* matter halo at large radius

Dark Matter evidence

Dark Matter existence is supported by astrophysics and cosmology

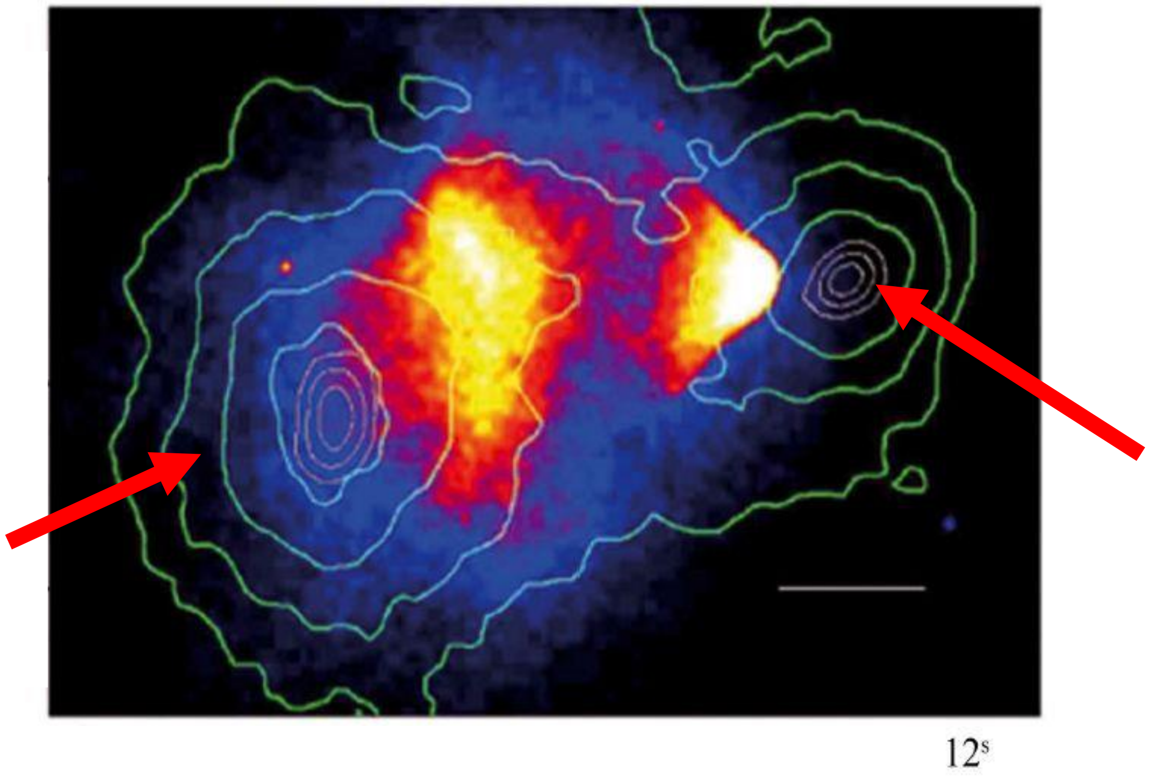


Visible and total matter have different distributions in galaxy clusters

Dark Matter evidence

Dark Matter existence is supported by astrophysics and cosmology

Dark Matter is collison-less:
the 2 DM clouds pass through
each other



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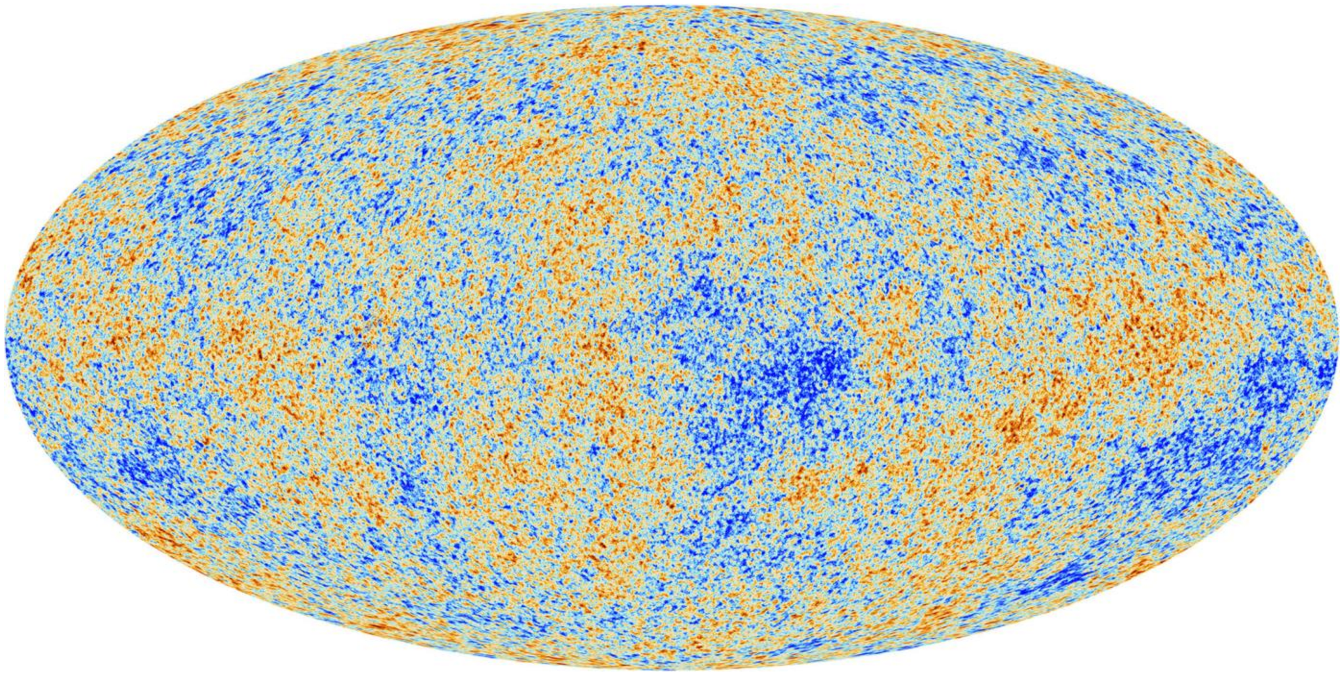
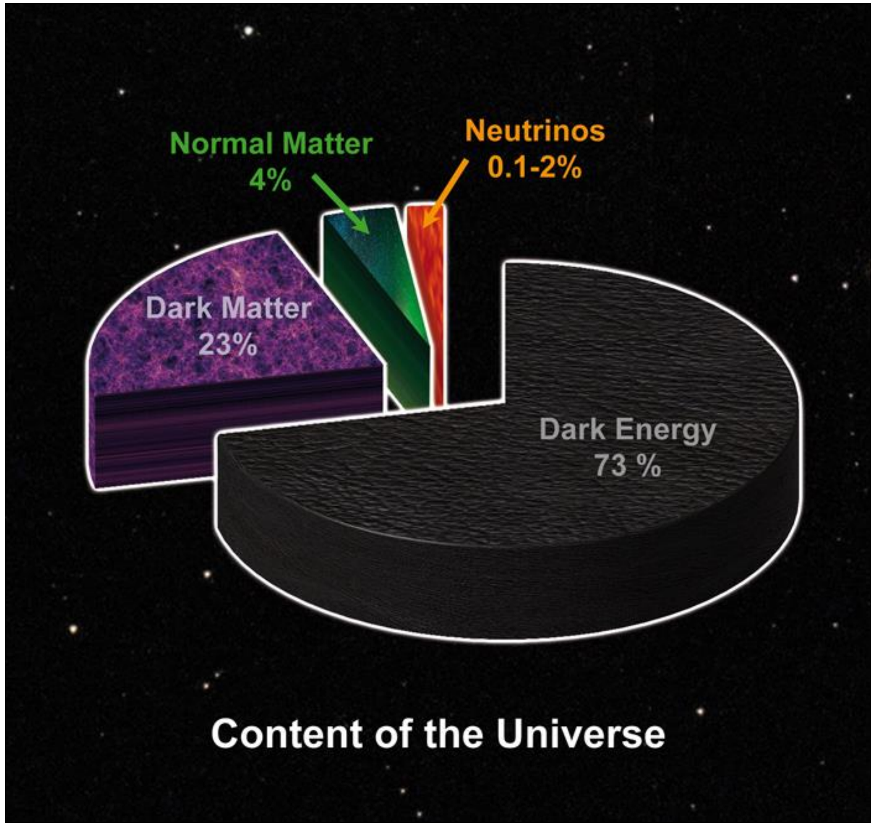


CMB properties and structure formation require DM

Dark Matter evidence

Today most of the Universe is dark!



$$\Omega_{\rm DM} h^2 \simeq 0.12$$

$$\Omega_{\rm DM} \simeq 5\Omega_b$$

Dark Matter fills the 84% of the matter content of the Universe

Dark Matter properties

- Neutral and weakly interacting with the Standard Model sector

- Stable on cosmological scales

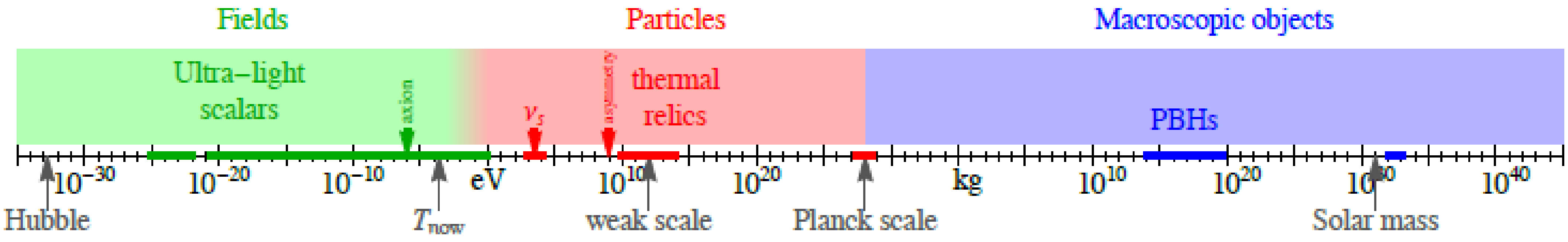
- Cold = non-relativistic at the time of structure formation

Dark Matter is an evidence of physics beyond the Standard Model

Dark Matter candidates

The mass range of DM candidates spans over 80 order of magnitudes

Figure made by *M. Cirelli, A. Strumia, J. Zupan*



Axions/ALPs
Fuzzy DM

WIMPs (TeV)
Sterile neutrinos (keV)

PBHs
Boson stars

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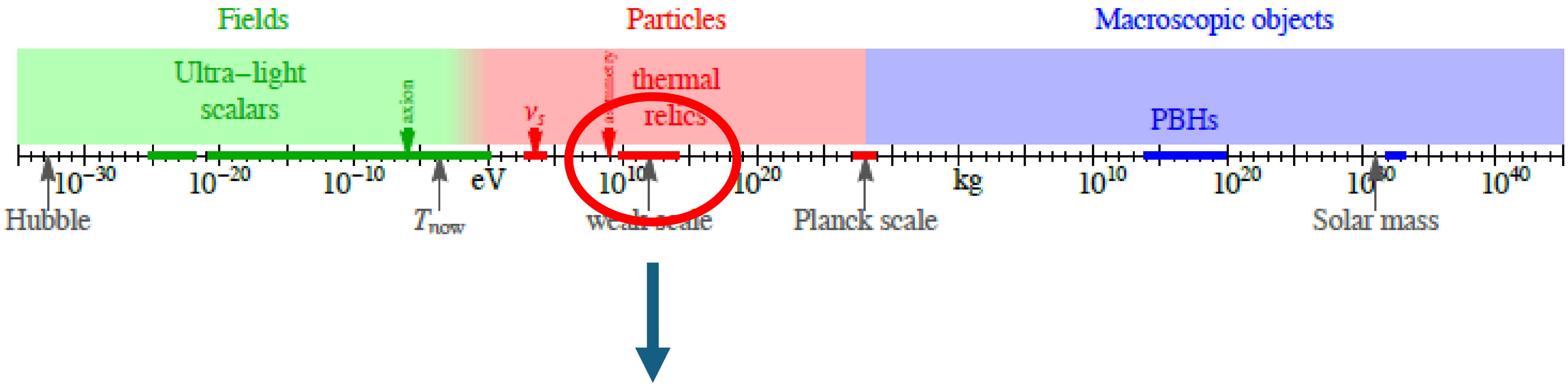
The mass range of DM candidates spans over 80 order of magnitudes

Figure made by *M. Cirelli, A. Strumia, J. Zupan*



New confining sector

Neutrino masses

Neutrinos are massless in the Standard Model

$L = (\nu_L, e_L)$ No ν_R

$$\mathcal{L}_{\text{lepton}} = y_e \bar{L} H e_R + h.c.$$

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No ν_R

$$\mathcal{L}_{\text{lepton}} = y_e \bar{L} H e_R + h.c.$$

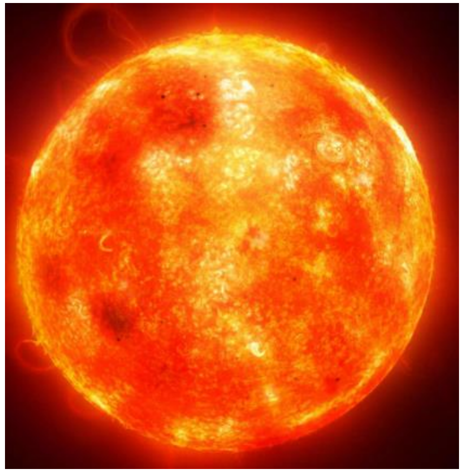
<u>EWSB</u>

$$\langle H \rangle = (0, \frac{v_H}{\sqrt{2}})$$ → $$\mathcal{L}_{\text{lepton}} = m_e(\bar{e}_L e_R + \bar{e}_R e_L)$$ → $$m_e = y_e v_H/\sqrt{2}$$ $$m_\nu = 0$$

Accidental U(1) lepton number conservation

Neutrino masses

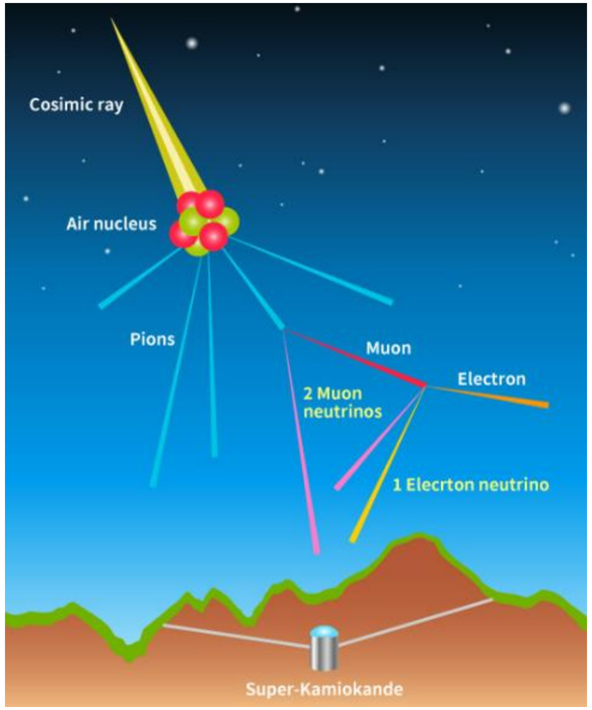
Solar neutrino problem



ν_e

$$N_{\text{observed}} \simeq \frac{1}{3} N_{\text{expected}}$$

Atmospheric neutrino problem



$$\frac{N_{\nu_\mu}}{N_{\nu_e}} < 2$$

Neutrino masses

Neutrino oscillations among different flavors solve the problems

Only possible if flavor basis $\neq$ mass basis

↓

Neutrinos must be massive!

Neutrino masses

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Only possible if flavor basis $\neq$ mass basis

↓

Neutrinos must be massive!

Combining oscillation and cosmological data

$$0.05 \text{ eV} \lesssim \sum m_\nu \lesssim 0.12 \text{ eV}$$

Dirac neutrinos?

Introduce RHN $N_R \sim (1,1)_0$

Assuming lepton number conservation

$$\Delta\mathcal{L}_{\rm lepton} \sim y_\nu \bar{L}\widetilde{H} N_R$$

$$\langle H \rangle = (0, \tfrac{v_H}{\sqrt{2}}) \rightarrow \mathcal{L}_\nu = m_\nu(\bar{\nu}_L N_R + \bar{N}_R \nu_L) \rightarrow m_\nu = y_\nu v_H/\sqrt{2}$$

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$m_\nu \sim 0.05$ eV → $y_\nu \sim 10^{-13}$ → un-observable!

Why lepton number should be a good symmetry?

The Model

	$\mathrm{SU}(3)_{\mathrm{D}}$	$\mathcal{Z}_4$	generations
q_L	$\mathbf{3}$	$-i$	1
q_R	$\mathbf{3}$	i	1
N_L	1	i	3
N_R	1	i	3
L	1	i	3
e_R	1	i	3
σ	1	-1	1
φ	1	1	1

$$\mathcal{L}_{LN} = y_e \overline{L} H e_R + y_\nu \overline{L} \tilde{H} N_R + y_\varphi \varphi \overline{N_L} N_R + \text{h.c.},$$

$$\mathcal{L}_{\mathrm{D}} = y_Q \sigma \overline{q_L} q_R + y_{N_L} \sigma \overline{N_L^c} N_L + y_{N_R} \sigma \overline{N_R^c} N_R + \text{h.c.},$$

$$V_{\sigma,\varphi} = \left(m_\sigma^2 + \lambda_\sigma \sigma^2 + \lambda_{\varphi\sigma} \varphi^2 + \lambda_{H\sigma} |H|^2\right) \sigma^2 + \left(\mu_\varphi^2 + \lambda_\varphi \varphi^2 + \lambda_{H\varphi} |H|^2\right) \varphi^2,$$

$$V_{\text{soft}} = \left(\kappa_\varphi \varphi^2 + \kappa_\sigma \sigma^2 + \kappa_H |H|^2\right) \varphi,$$

The Model

	$\mathrm{SU}(3)_\mathrm{D}$	$\mathcal{Z}_4$	$\mathcal{Z}_2$	$\mathrm{U}(1)_\mathrm{D}$	generations
q_L	$\mathbf{3}$	$-i$	$+$	1	1
q_R	$\mathbf{3}$	i	$+$	1	1
N_L	1	i	$+$	0	3
N_R	1	i	$-$	0	3
L	1	i	$-$	0	3
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φ	1	1	$-$	0	1

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$\mathcal{Z}_2$ →

- No $\bar{L}HN_L$ coupling (otherwise linear see-saw with different pheno)
- Generate dynamically Dirac mass $M_D \propto \langle\varphi\rangle$

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$\mathcal{Z}_2$ →
- No $\bar{L} H N_L$ coupling (otherwise linear see-saw with different pheno)
- Generate dynamically Dirac mass $M_D \propto \langle \varphi \rangle$

No Domain Walls →
- $\mathcal{Z}_2$ explicitly broken by V_{soft}
- $\mathcal{Z}_4$ explicitly broken by $\langle \overline{q_L} q_R \rangle$

The Model

	$SU(3)_D$	$\mathcal{Z}_4$	$\mathcal{Z}_2$	$U(1)_D$	generations
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$$V_{\text{soft}} = \left(\kappa_\varphi \varphi^2 + \kappa_\sigma \sigma^2 + \kappa_H |H|^2\right)\varphi,$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & \mu & M_D \\ 0 & M_D^T & \mu' \end{pmatrix}$$

$$m_D = y_\nu \langle H \rangle$$
$$M_D = y_\varphi \langle \varphi \rangle$$

$$\mu = y_Q y_{N_R} \frac{\Lambda_D^3}{m_\sigma^2} \qquad \mu' = y_Q y_{N_L} \frac{\Lambda_D^3}{m_\sigma^2}$$

The Spectrum

The theory confines at the scale Λ_D

↓

Mesons

The lightest meson is pseudo-scalar

$$m_{\mathcal{M}} \simeq \Lambda_D$$

$$f_{\mathcal{M}} \equiv \langle 0|\overline{q}\gamma_5 q|\mathcal{M}\rangle \sim \Lambda_D^2$$

With 1 quark flavor there are <u>no</u> light dark pions!

The Spectrum

The theory confines at the scale Λ_D

↓

Baryons

$\mathcal{B} \sim qqq$ bound state with spin $3/2$

$$m_{\mathcal{B}} \simeq 5\Lambda_D$$

	$\mathrm{U(1)_D}$
q_L	1
q_R	1
$\mathcal{M}$	0
$\mathcal{B}$	3

Higher-dimensional operators break dark baryon number

Are baryons decays compatible with bounds on DM?

Indirect Detection: neutrino lines

Baryons annihilate to mesons — decay to heavy neutrinos — decay to active neutrinos

$$\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M} \quad \longrightarrow \quad \mathcal{M} \to NN \quad \longrightarrow \quad N \to h\nu_L$$

$$E_{\mathcal{M}} \simeq m_{\mathcal{B}} \qquad E_N \simeq m_{\mathcal{B}}/2 \qquad E_\nu \simeq m_{\mathcal{B}}/4$$

Monochromatic neutrino lines $E_\nu \simeq m_{\mathcal{B}}/4 \sim (1 - 100)\ \text{TeV}$

Testable with **neutrino telescopes**!

Indirect Detection: neutrino lines

<u>Testable with **neutrino telescopes**!</u>

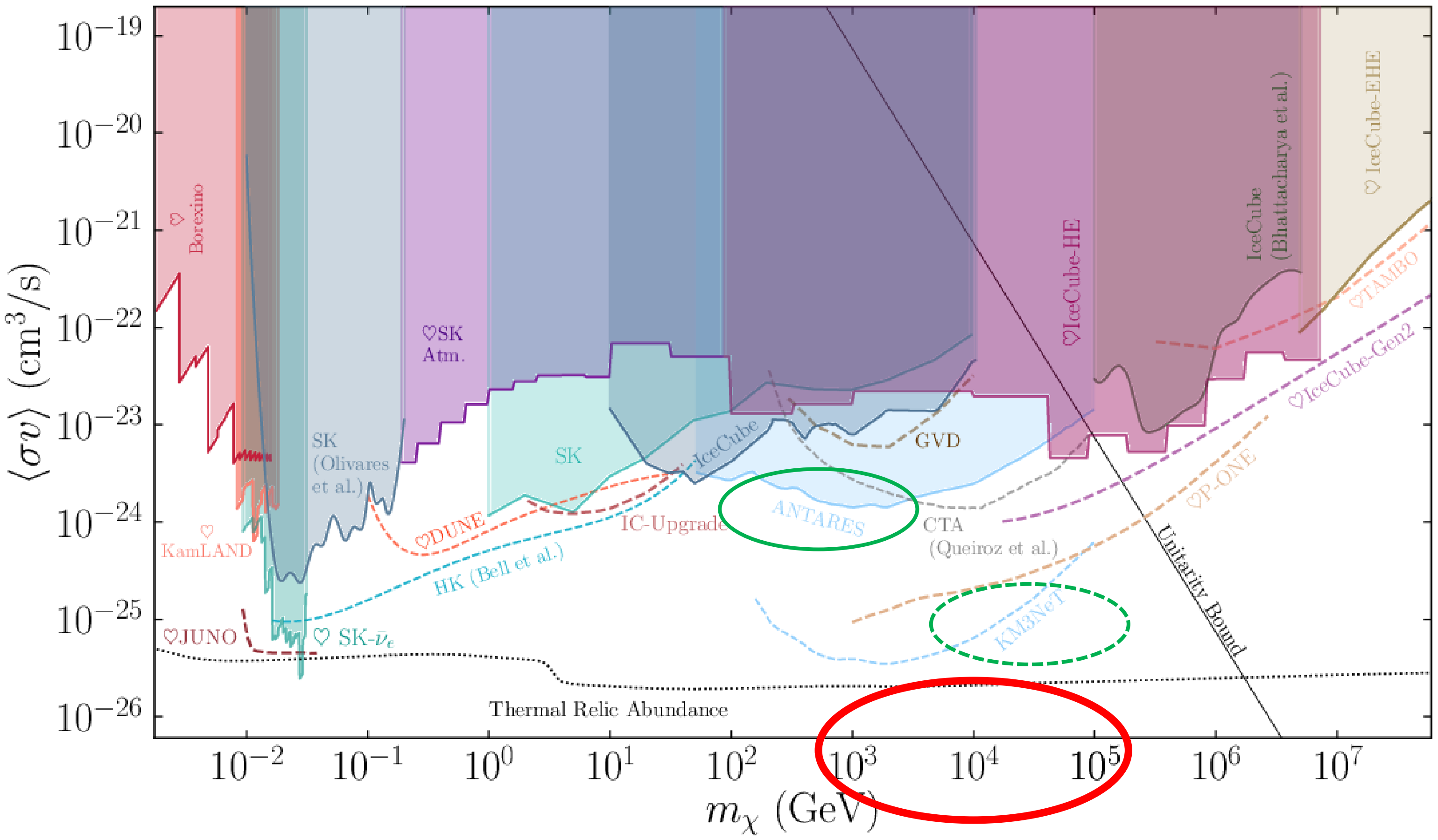

Figure made by *C. Arguelles, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa and A. Vincent [1912.09486]*

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Monochromatic neutrino lines $E_\nu \simeq m_{\mathcal{B}}/4 \sim (1-100)\ \text{TeV}$

Testable with **neutrino telescopes**!

Current bound from ANTARES collaboration → $\Lambda_D > 12\ \text{TeV}\sqrt{\frac{0.25\times 10^{-24}\text{cm}^3/\text{s}}{\langle \sigma v \rangle}}$

The Cosmology

We assume that $m_\sigma \gg T_{\mathrm{RH}} \gg M_D, \Lambda_D$

↓

σ is not in thermal bath

The Cosmology

We assume that $m_\sigma \gg T_{\rm RH} \gg M_D, \Lambda_D$

Before dark confinement $T > \Lambda_D$

The dark sector is produced by steps and thermalize with the SM before confining

$$LL, HH \leftrightarrow NN$$
$$LH \leftrightarrow N$$

→

The Cosmology

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$$LL, HH \leftrightarrow NN$$
$$LH \leftrightarrow N$$

→

$$NN \leftrightarrow \overline{q}q$$

↓

keep thermal equilibrium

$$Y_q = \frac{n_q}{s} = \frac{135\zeta(3)}{\pi^4 g_s}$$

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$$\begin{array}{c} LL, HH \leftrightarrow NN \\ LH \leftrightarrow N \end{array} \quad \rightarrow \quad NN \leftrightarrow \bar{q}q \quad \xrightarrow{\Lambda_D \lesssim 10^{10}\ \text{GeV}} \quad \text{dark confinement}$$

↓

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Quarks combine into hadrons: *baryons* and *mesons*

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Strong (dark) interactions convert baryons to mesons

$$\overline{\mathcal{B}}\mathcal{B} \to \overline{\mathcal{M}}\mathcal{M}$$

Baryons and mesons are kept in thermal equilibrium among them...

The Cosmology

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After dark confinement $T < \Lambda_D$

All hadrons are not relativistic

$$m_{\rm hadron} \gtrsim \Lambda_D \gtrsim T$$

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