A Light $L_\mu - L_\tau$ Gauge Boson for $g_\mu - 2$, Dark Matter etc

Manuel Drees, Wenbin Zhao

Bonn University & Bethe Center for Theoretical Physics

Contents

arXiv:2107.14528

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(1) The Model

(2) $g_\mu - 2$: Explaining the measurement

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(4)Dark Matter

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(4)Dark Matter

(5)$N_{\rm eff}$ and Hubble tension

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(1)The Model

(2)$g_\mu - 2$: Explaining the measurement

(3)"Neutrino Tridents": upper bound on the coupling

(4)Dark Matter

(5)$N_{\rm eff}$ and Hubble tension

(6)More constraints

(7)511 keV photons from the GC

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$4.2\,\sigma$ deviation in $g_\mu - 2$: evidence for new interaction of muons!

$\Longrightarrow$ consider $L_\mu - L_\tau$!

The Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} - g_X X_\rho \left(\bar\mu \gamma^\rho \mu - \bar\tau \gamma^\rho \tau + \overline{\nu_{\mu,L}} \gamma^\rho \nu_{\mu,L} - \overline{\nu_{\tau,L}} \gamma^\rho \nu_{\tau,L} \right)$$
$$- \frac{1}{4} X_{\rho\sigma} X^{\rho\sigma} + \frac{1}{2} m_X^2 X_\rho X^\rho + \bar\psi \left(i \partial\!\!\!/ - m_\psi - g_X q_\psi X\!\!\!/ \right) \psi$$

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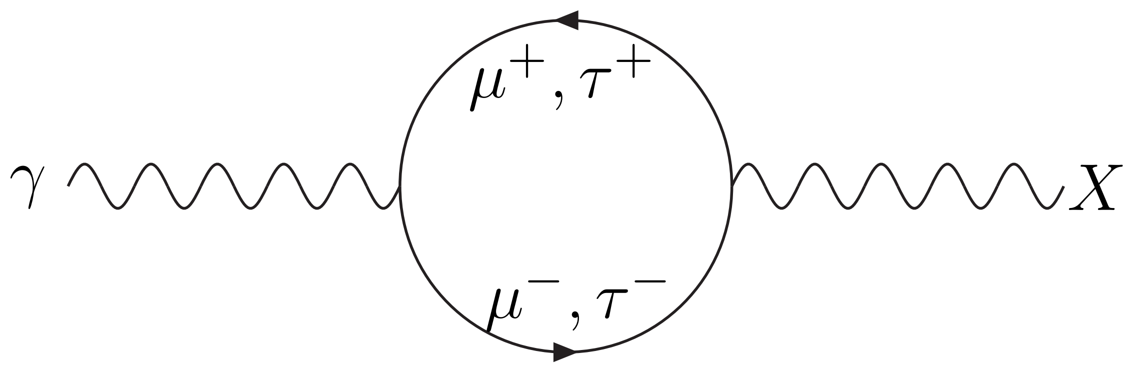
Relevant parameters:

- New gauge coupling g_X
- Mass of new gauge boson m_X
- DM mass m_ψ
- DM charge q_ψ

Kinetic Mixing

Is $1-$loop effect:



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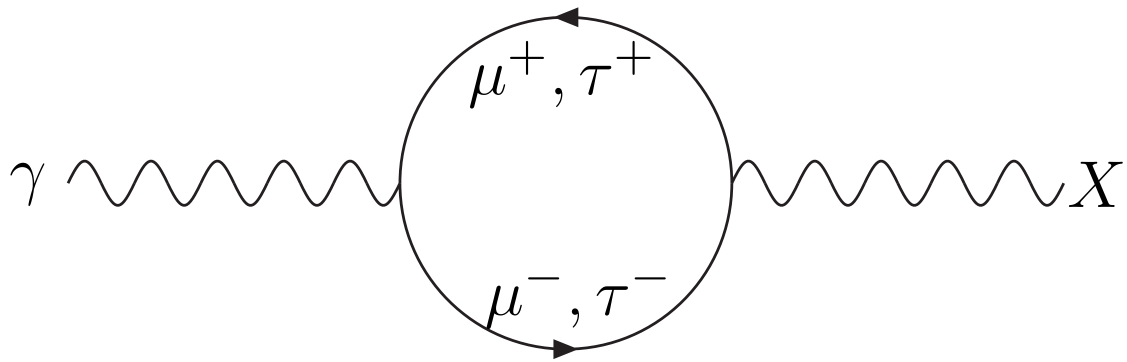

Adds $\delta\mathcal{L} = \epsilon e X_\rho J^\rho_{\rm em}$, with $\epsilon = \frac{e g_X}{6\pi^2} \ln\left(\frac{m_\tau}{m_\mu}\right) \simeq \frac{g_X}{70}$

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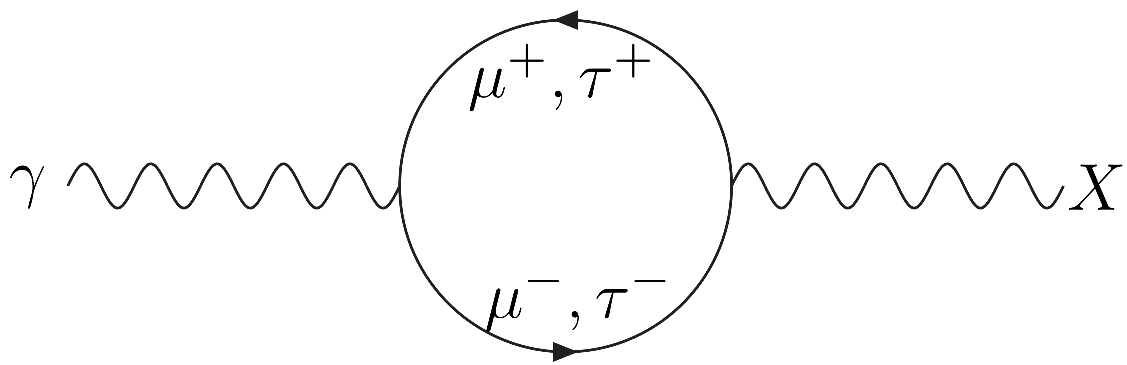

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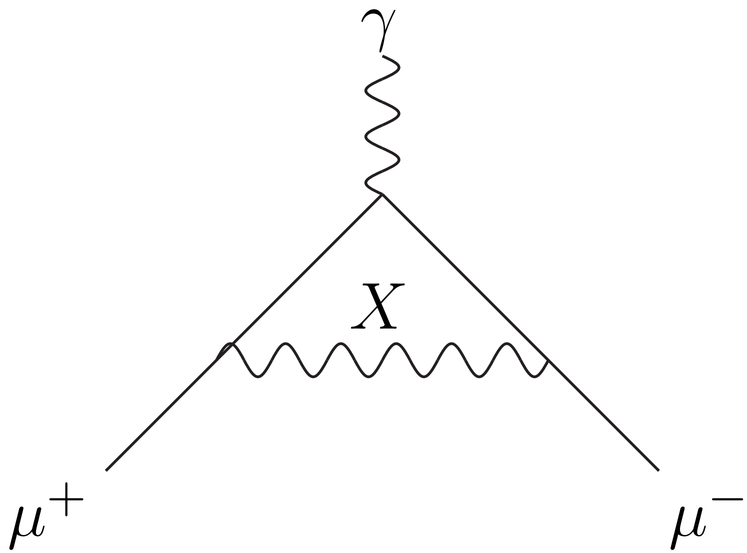
ψ is "millicharged particle", with charge $g_\psi g_X/70$!

Same is true for ν_μ, ν_τ, with charges $\pm g_X/70$.

$g_\mu - 2$



Gives contribution to $a_\mu = (g_\mu - 2)/2$ (Leveille, 1977):

$$\Delta a_\mu = \frac{g_X^2}{8\pi^2} \int_0^1 dx \frac{2m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) m_X^2}$$

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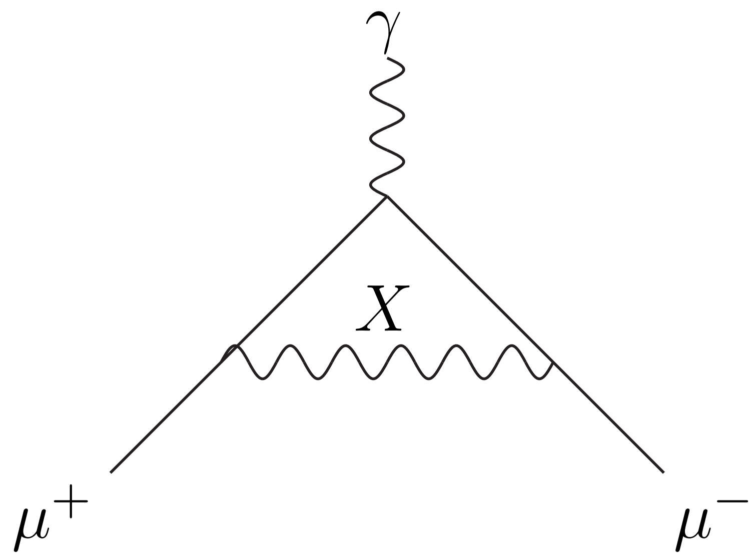

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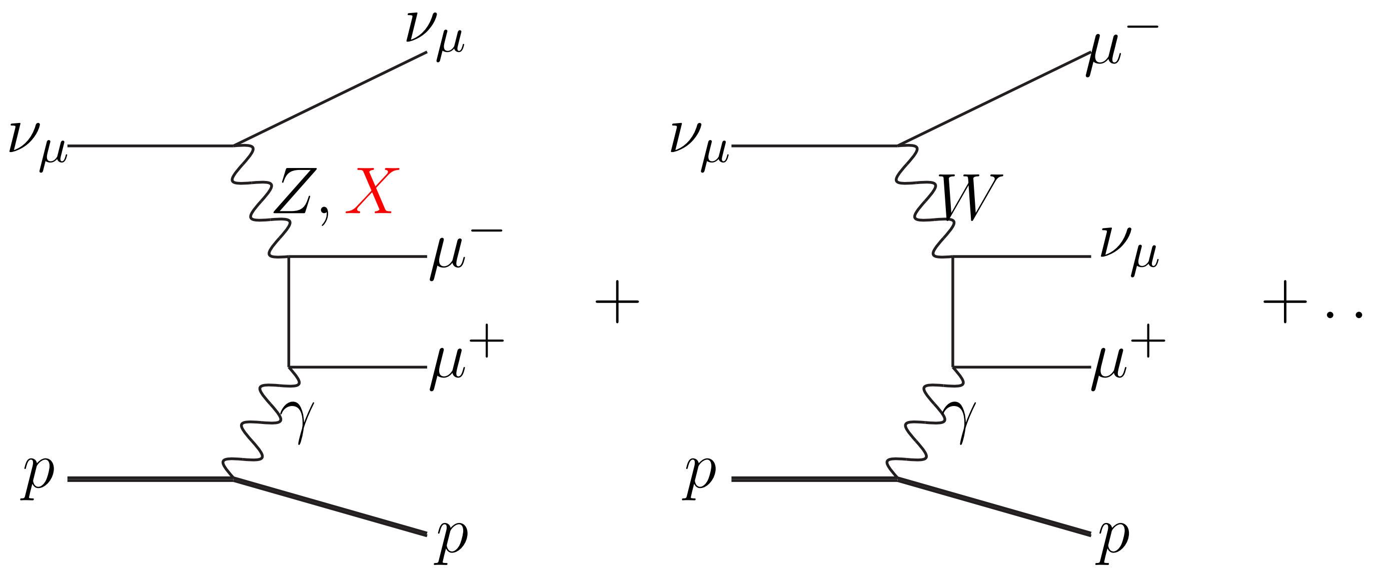
Need:

$$g_X \simeq \begin{cases} 4.4 \cdot 10^{-4} & m_X^2 \ll m_\mu^2 \\ 5.4 \cdot 10^{-4} \frac{m_X}{m_\mu} & m_X^2 \gg m_\mu^2 \end{cases}$$

Neutrino Trident

Refers to $\nu_\mu p \to \nu_\mu \mu^+ \mu^- p$. (3 charged tracks, hence "trident".) Has been observed in 1980's (CHARM, CCFR); rediscovered as BSM test by Pospelov (2006).



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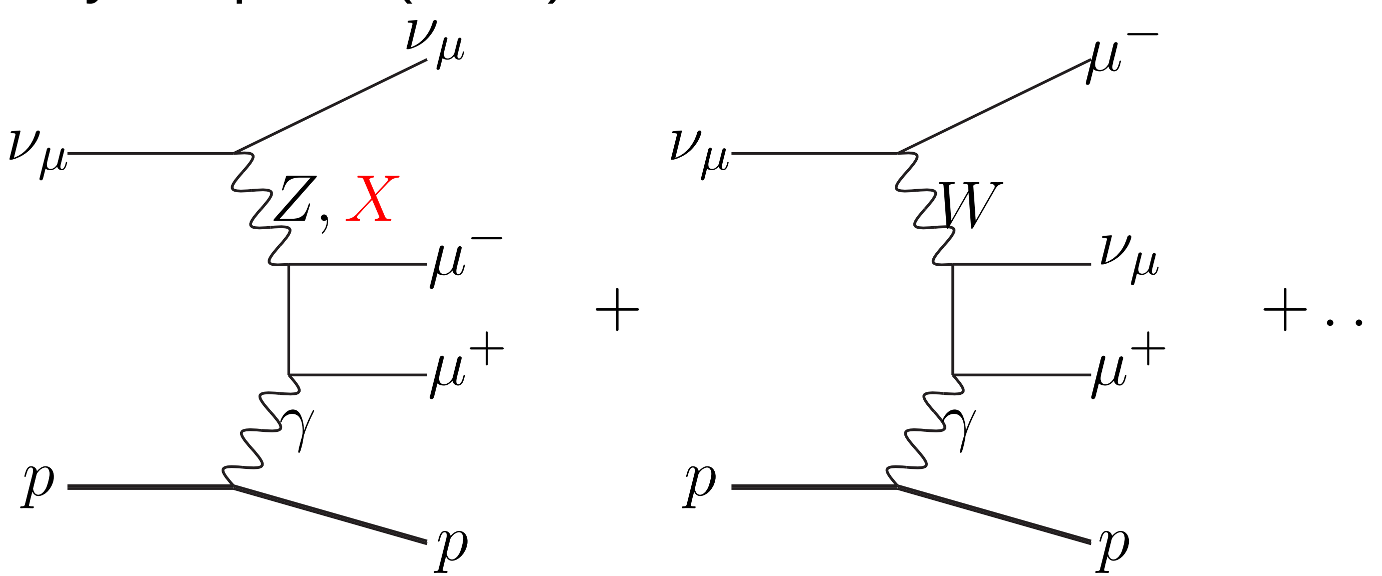

Measurement agrees with SM prediction
$\Longrightarrow$ strong upper bound on g_X for given m_X!

Dark Matter

- Want to employ usual "thermal WIMP" mechanism:

$$\Omega_\psi h^2 \sim 0.1 \cdot \frac{1 \text{ pb}}{\langle v\sigma(\psi\bar{\psi} \to \text{anything else})\rangle} \stackrel{!}{=} 0.12$$

Ω: scaled mass density;
h: scaled Hubble parameter;
$\langle \dots \rangle$: thermal average.

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- Here:

$\psi\bar{\psi} \to \nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$;

$\psi\bar{\psi} \to \ell^+\ell^- \; (\ell = \mu, \tau), \text{ if } m_\psi > m_\ell$;

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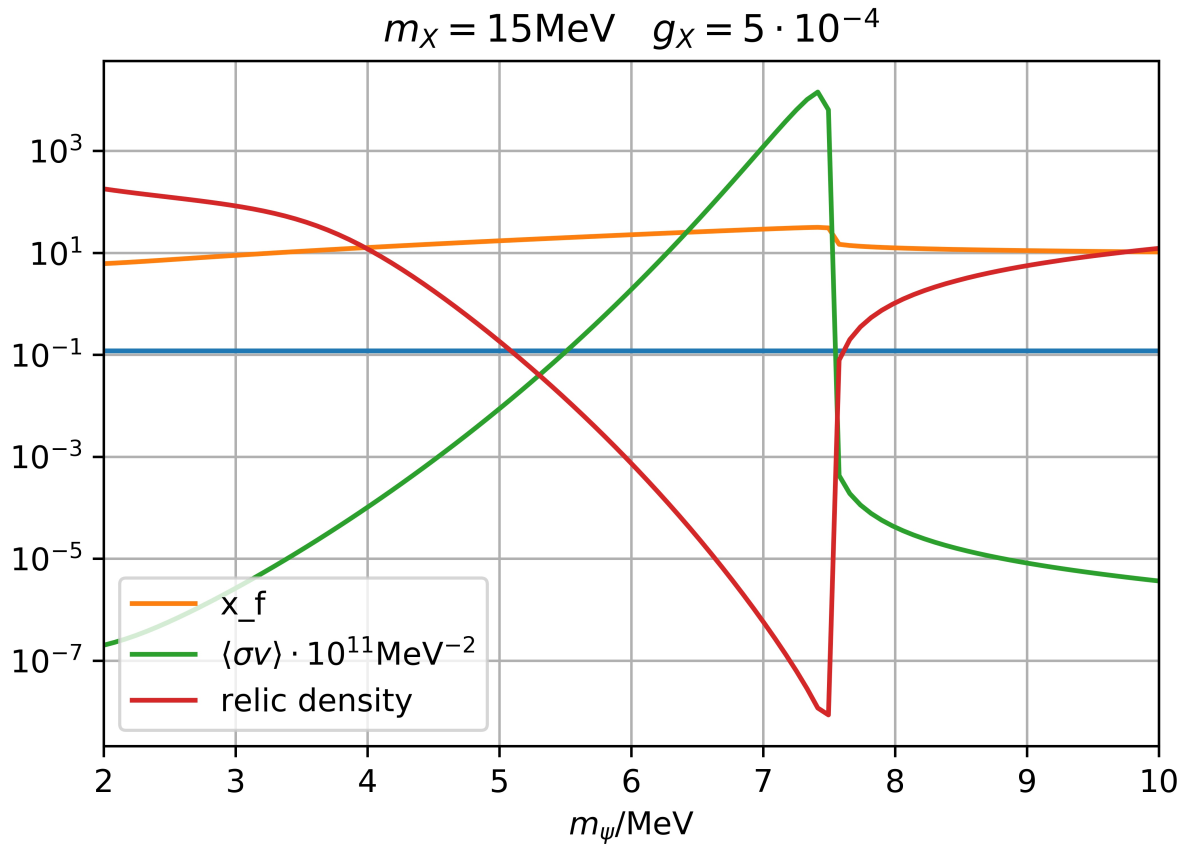
- $g_\mu - 2$ constraint: $\sigma(\psi\bar\psi \to \text{anything})$ is too small unless $m_\psi \simeq m_X/2$! (Resonance enhancement.)

Relic Density



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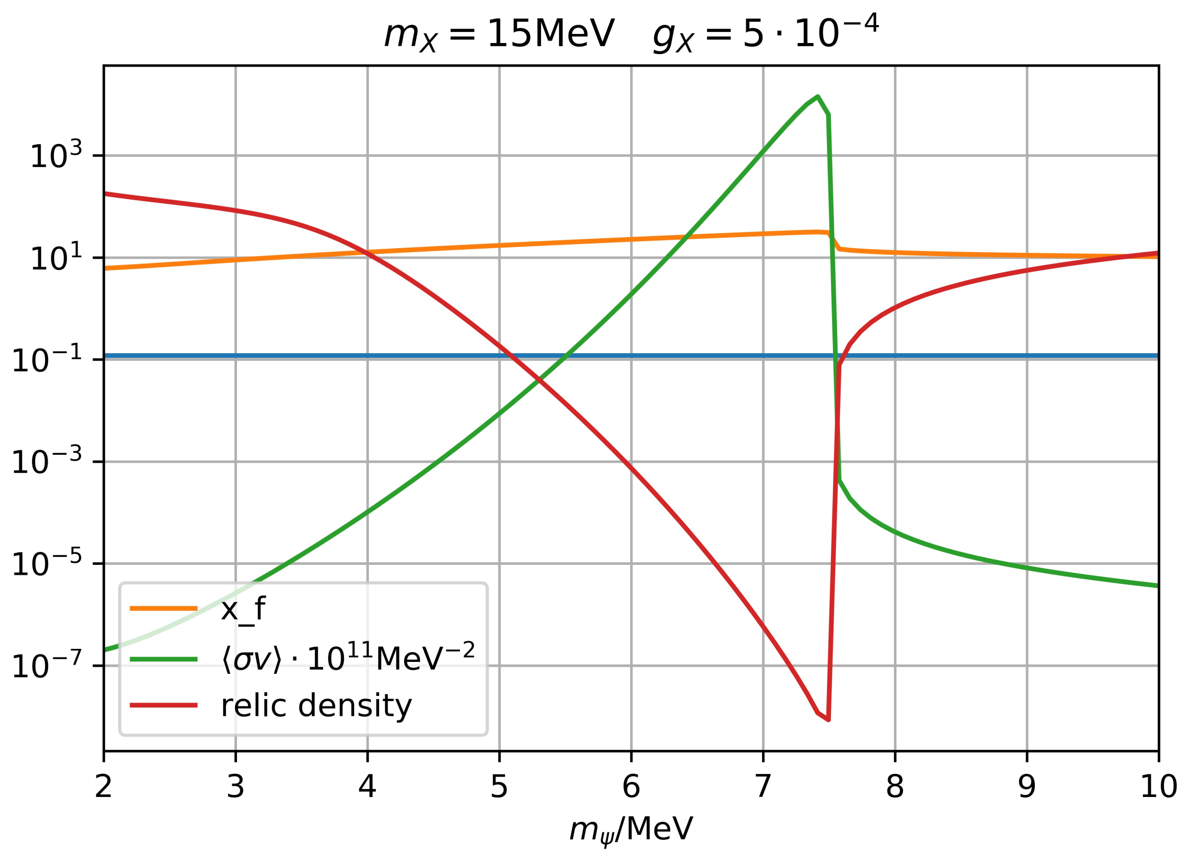

Warning: `MadDM` did not work! Used method of Griest and Seckel (1991)

Direct DM Detection

Will need $m_\psi < m_\mu \implies$ scattering on nuclei is not sensitive!

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Scattering on electrons:

$$\begin{aligned}\sigma(\psi e \to \psi e) &= \frac{\mu_e^2}{\pi} \frac{\epsilon^2 e^2 q_\psi^2 g_X^2}{(m_X^2 + \alpha^2 m_e^2)^2}\,, \\ &\simeq 6 \cdot 10^{-44}\ \mathrm{cm}^2 \left(\frac{g_X}{10^{-3}}\right)^4 \left(\frac{10\ \mathrm{MeV}}{m_X}\right)^4 q_\psi^2\,.\end{aligned}$$

$\mu_e = \frac{m_\psi m_e}{m_\psi + m_e}$

Exptl bound (SENSEI): $\sigma < 5 \cdot 10^{-37}$ cm^2: No problem!

$N_{\rm eff}$ and Hubble Tension

- BBN (in particular, ^{4}He fraction) depends on radiation density, which can be affected by additional "light" degrees of freedom: $\rho_{\rm rad} = \left[1 + N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}\right]\rho_\gamma$.

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- Light ψ annihilate into $\nu_{\mu,\tau}$: decouple from electrons at $T_{\rm d} \simeq 2.3$ MeV
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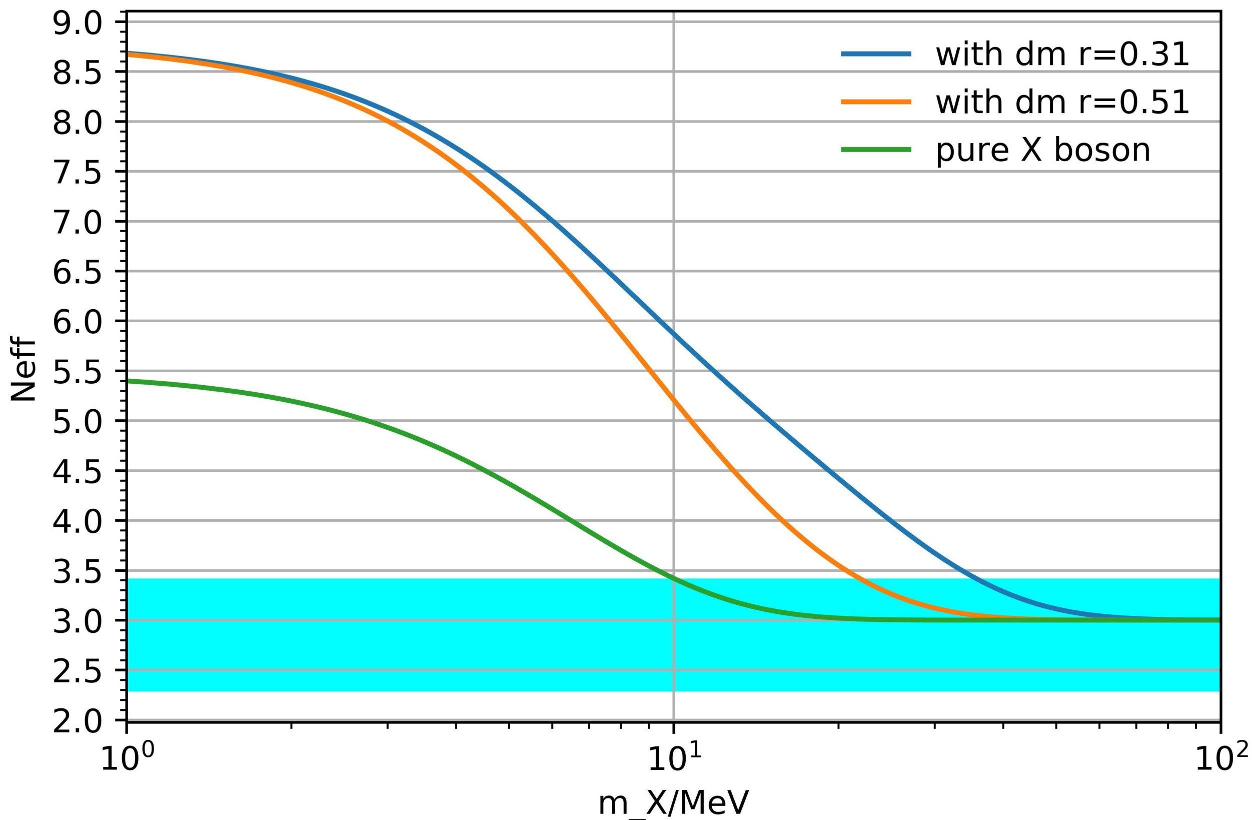
$$N_{\rm eff} = N_\nu \left[1 + \frac{1}{N_\nu} \sum_{i=\psi,X} \frac{g_i}{2} F\left(\frac{m_i}{T_{\nu,D}}\right)\right]^{4/3},$$

$$F(x) = \frac{30}{7\pi^4} \int_x^\infty dy \frac{(4y^2 - x^2)\sqrt{y^2 - x^2}}{e^y \pm 1}.$$

Result

$$r = m_\psi / m_X$$



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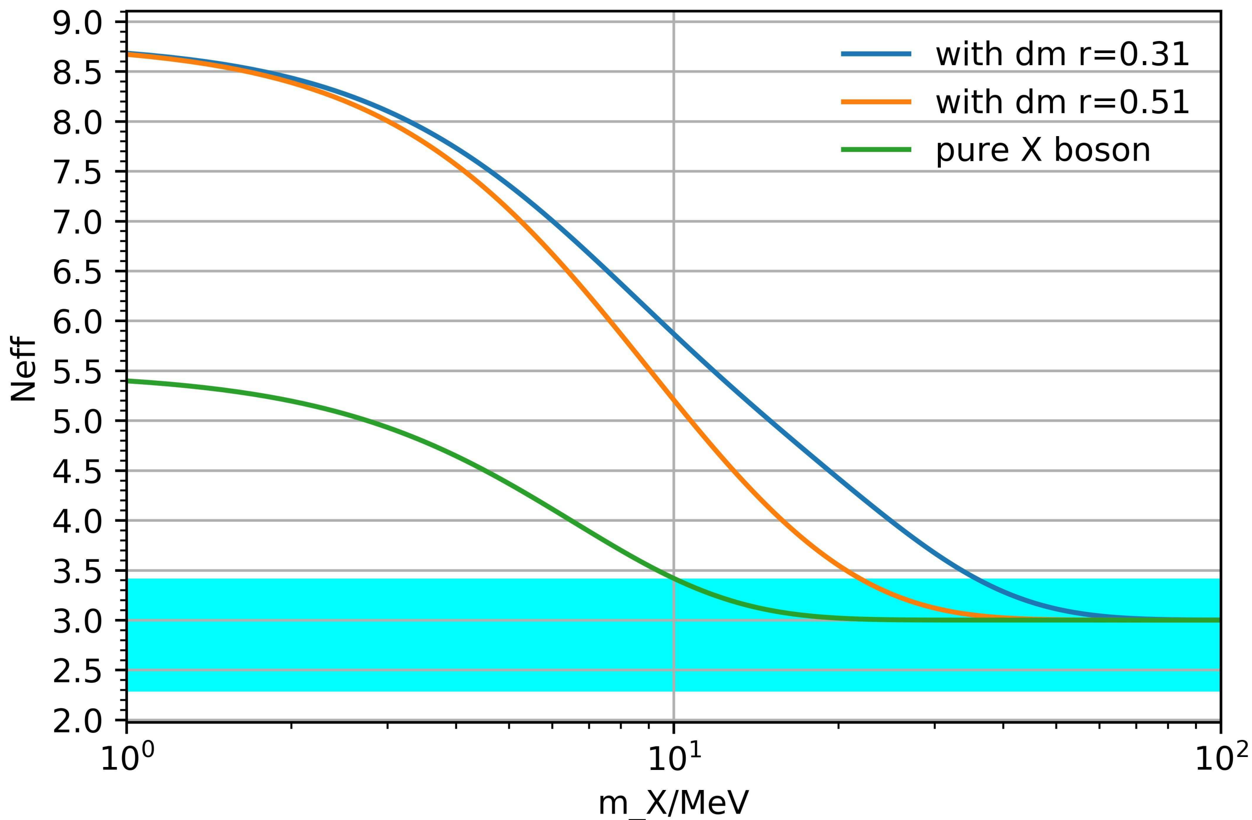
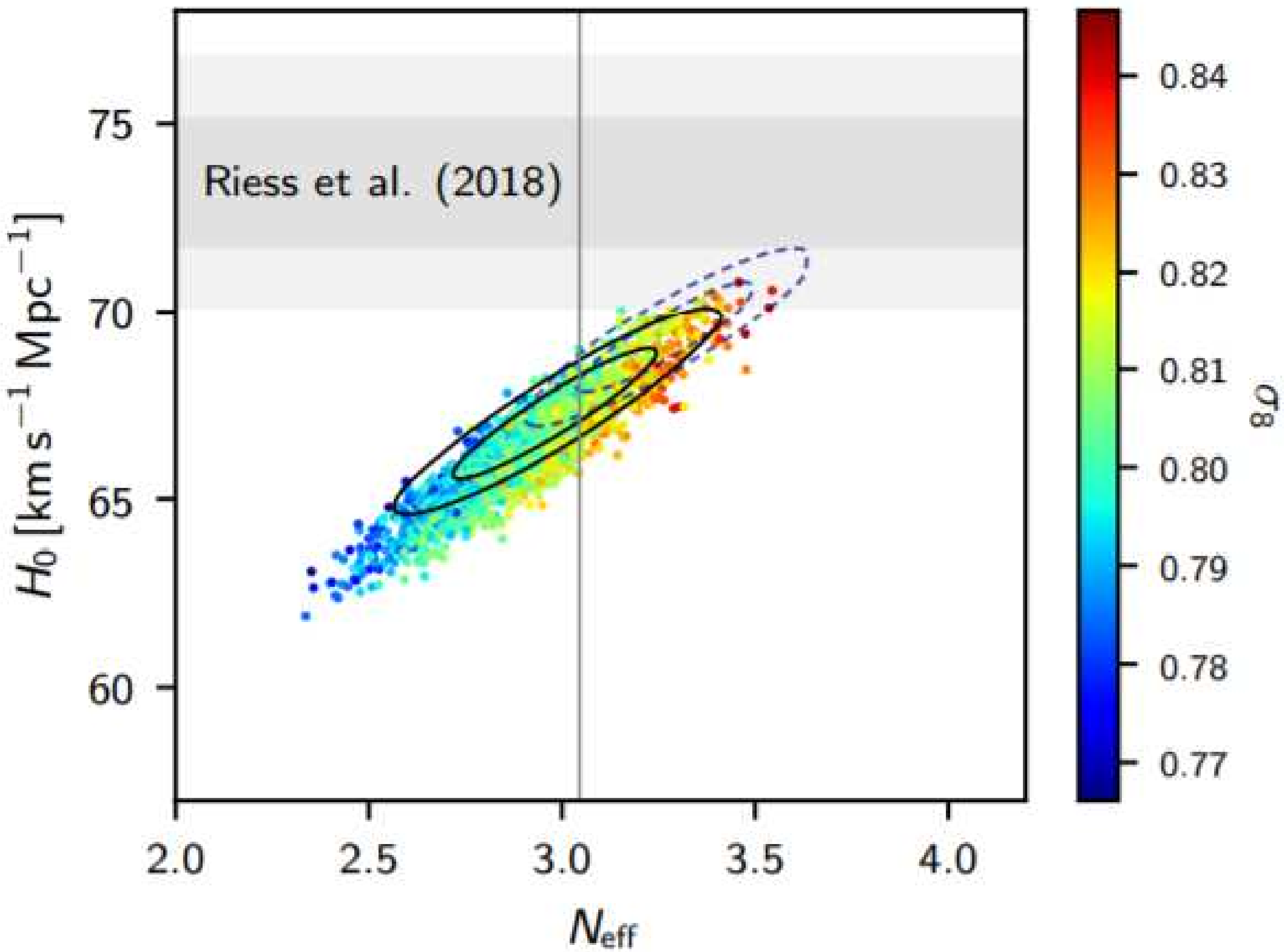


BBN: $N_{\mathrm{eff}} < 3.4$

$N_{\rm eff} > 0$ can relax Hubble Tension



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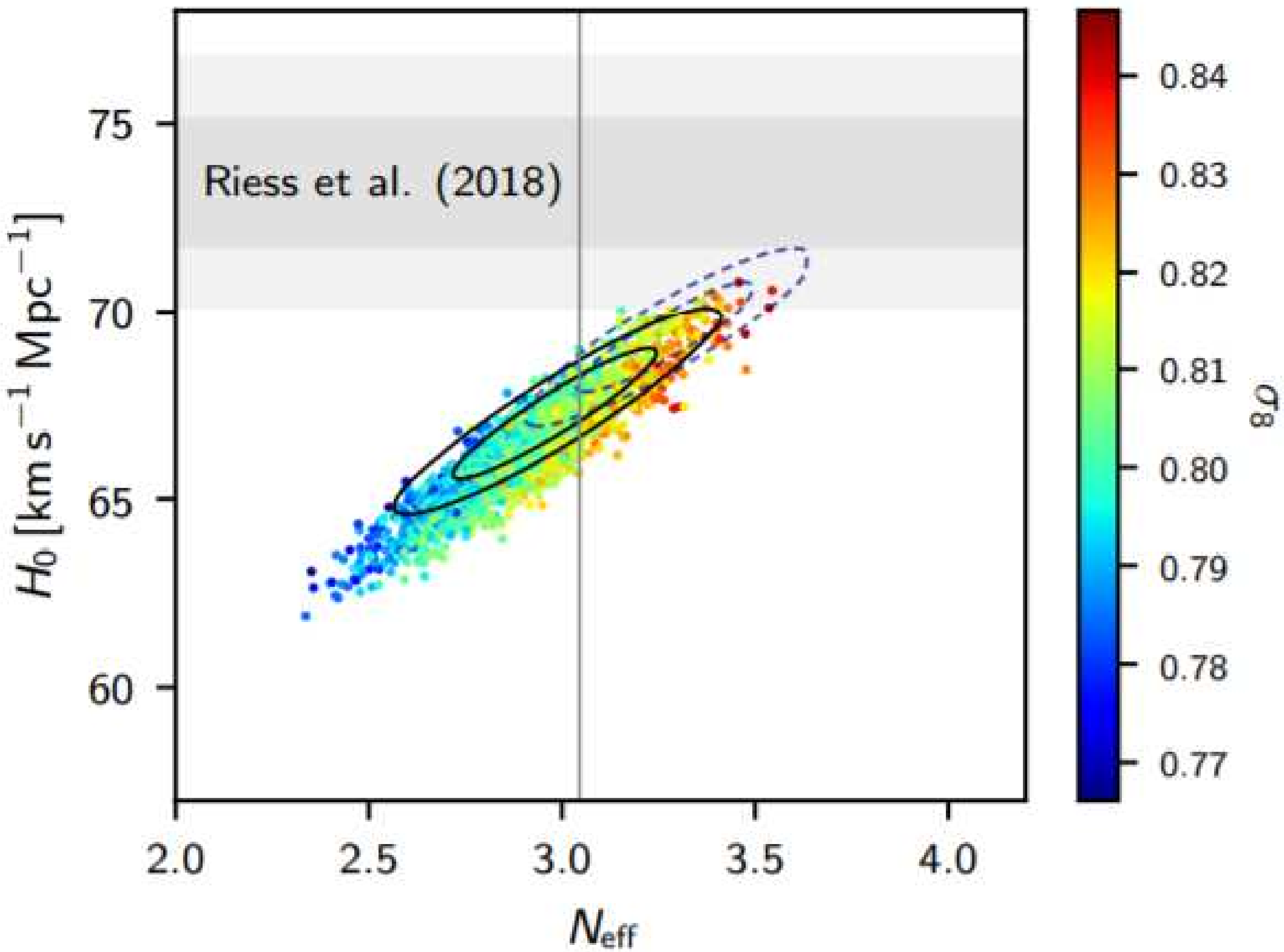

Interpret $3.2 \leq N_{\rm eff} \leq 3.4$ as relaxing Hubble tension.

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- COHERENT: X exchange contributes to ν_μ scattering on nuclei via kinetic mixing with photon. Bound slightly weaker than that from Tridents.

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  - $pp \to 3\mu + \text{missing } E_T$: published LHC limits weaker than Trident bound. MD, M. Shi, Z. Zhang, 1811.12446

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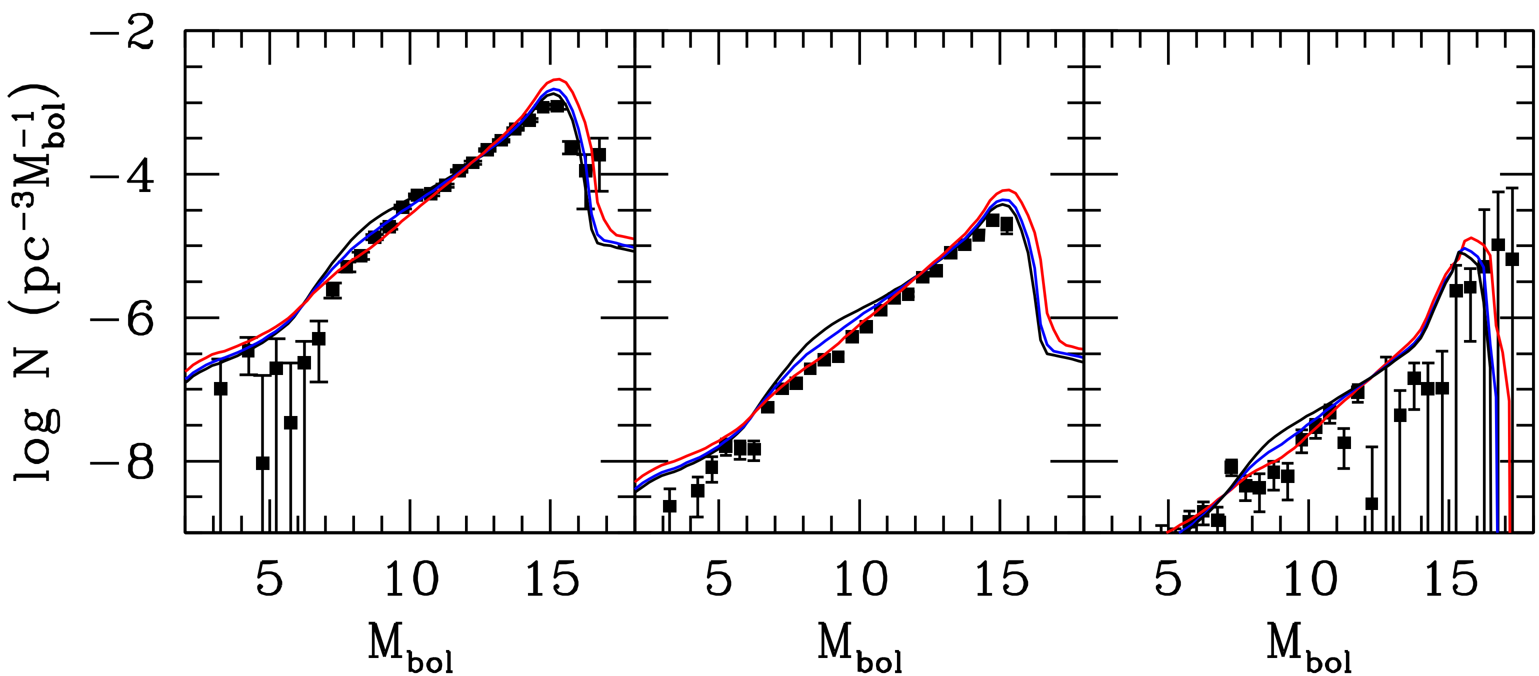
- Evidence for BSM contribution for WD cooling! Isern et al., 1805.00135

Evidence for additional WD cooling



Black: SM; red, blue: extra cooling (axions)

$\psi\bar{\psi} \to e^+e^-$ **in the late Universe**

- Requires kinetic $X - \gamma$ mixing
  $\implies \sigma(\psi\bar{\psi} \to e^+e^-) \simeq 2 \cdot 10^{-5} \sigma(\psi\bar{\psi} \to \nu\bar{\nu})$

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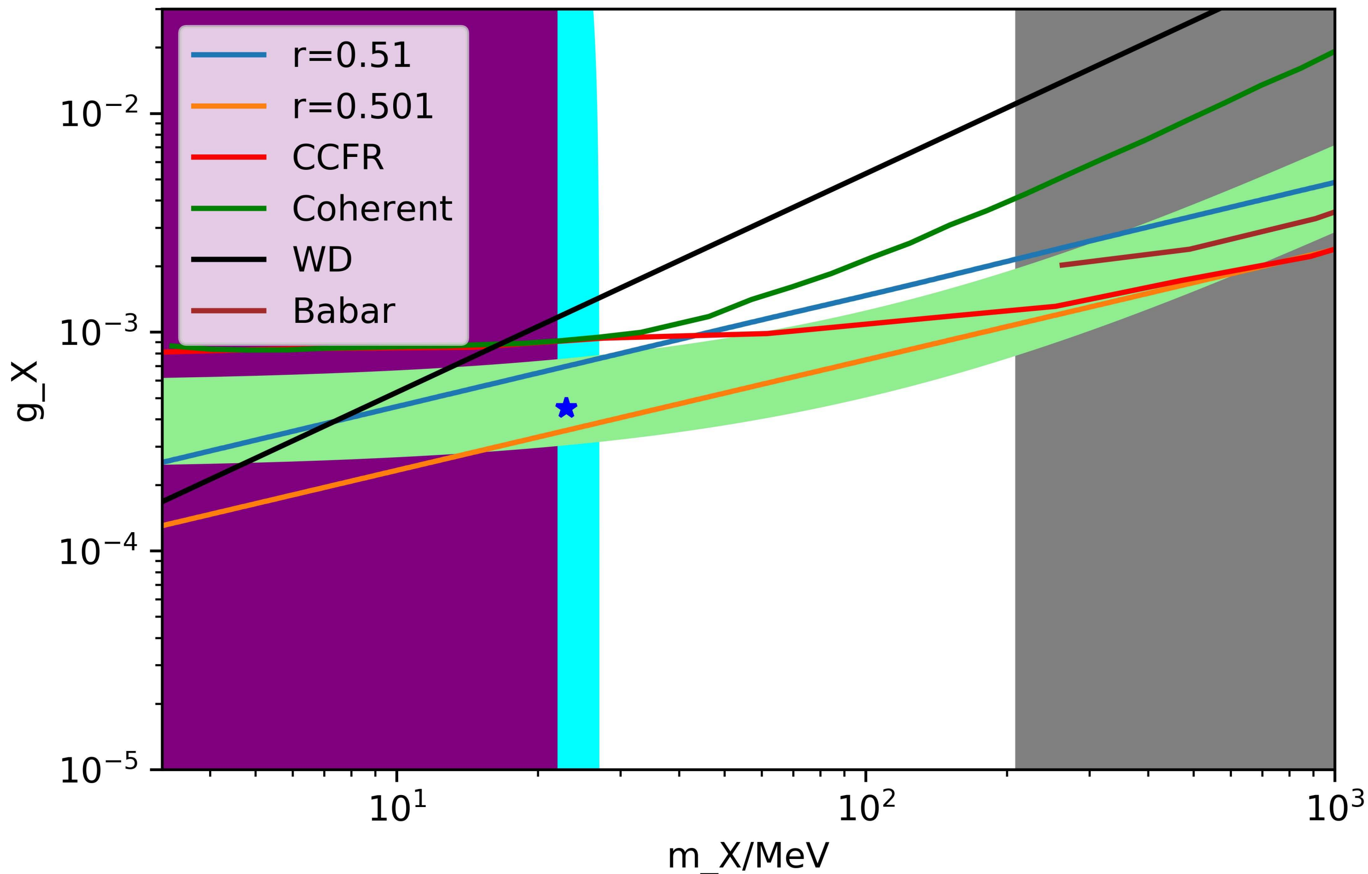
- For $m_\psi \simeq 10$ MeV: Only $\sim 50\%$ of required e^+ can come from DM annihilation; otherwise too many MeV photons. (Beacom and Yuksel, astro–ph/0512411)

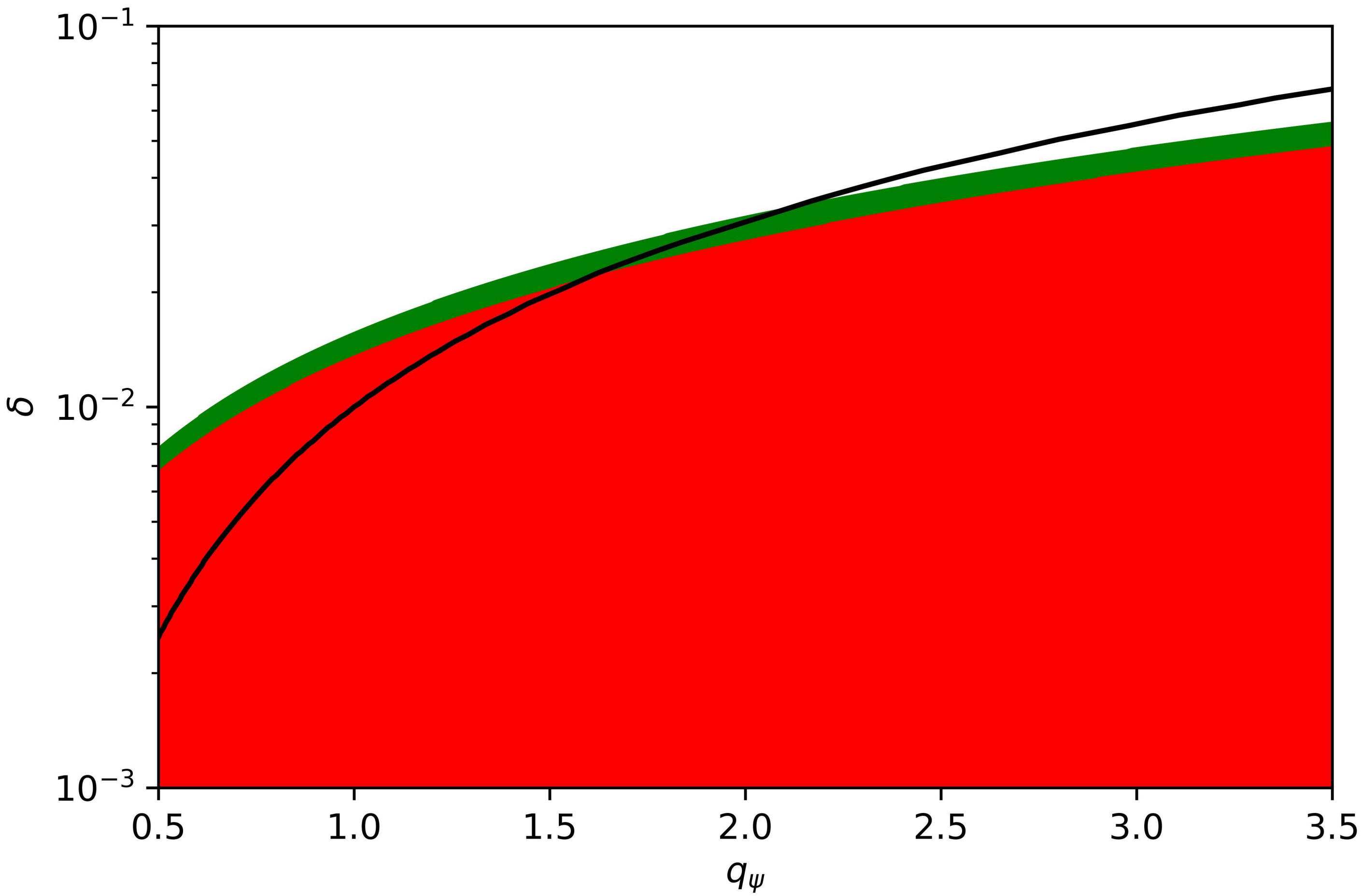
Final Results



Grey: excluded by CMB; purple: excluded by BBN ($N_{\rm eff}$)
green: preferred by $g_\mu - 2$; blue: relaxes Hubble tension

Dependence on DM charge q_ψ

$$\delta = 4m_\psi^2/m_X^2 - 1$$



Black: correct relic density; red: excluded by CMB; green: favored by 511 keV excess

Predictions

- $\langle\sigma(\bar{\psi}\psi \to \nu\bar{\nu})\rangle_{\text{now}} \geq 10^{-25}\text{cm}^3/\text{s}$: easily testable at JUNO via $\nu e \to \nu e$!

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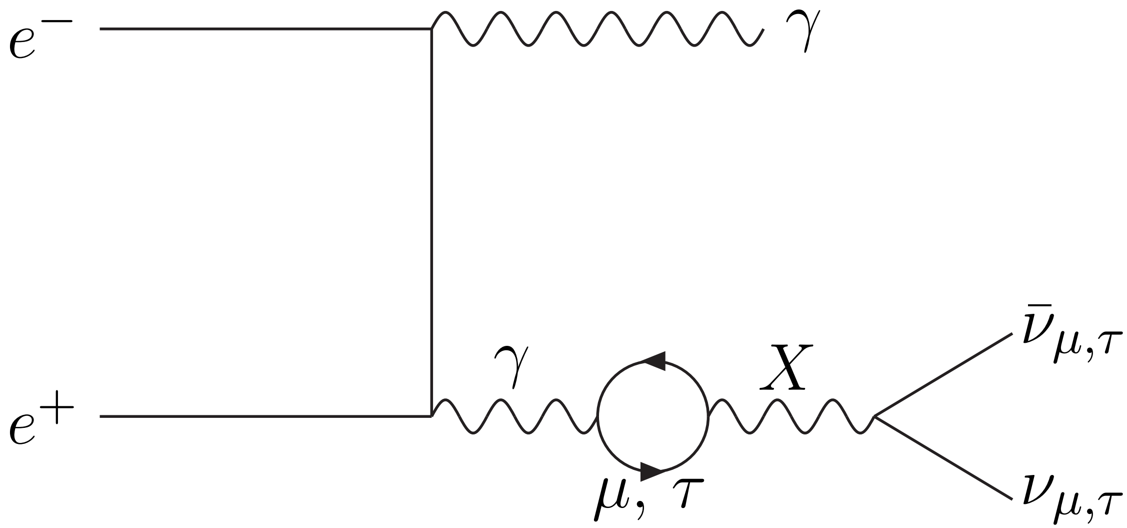
- Slightly improved description of IceCube data: resonant $\nu_{\mu,\tau}$ scattering on relic neutrinos changes flavor ratios. J. Alonso Carpio et al., 2104.15136
- $\sim 250\ \gamma + {\rm nothing}$ events at BELLE-2, with $E_\gamma \simeq \sqrt{s}/2$ in cms system;
  comparable no. of events at super $\tau/$charm factory, if $\mathcal{L} = 2\ {\rm ab}^{-1}/{\rm year}$ N. Borodatchenkova et al., hep–ph/0510147
  Needs single photon trigger!

Contributing Diagram



Effective $g_{eeM} \simeq -e g_{\mu\mu M}/70$.

Summary

- $L_\mu - L_\tau$ model with $m_\psi \sim m_X/2 \simeq 10$ MeV, $g_X \cdot 4.5 \cdot 10^{-4},\ q_\psi \simeq 1$ explains lots of things: Dark Matter; $g_\mu - 2$; easing of Hubble tension; contribution to 511 keV photon flux.

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- Can be tested by future neutrino experiments (JUNO, COHERENT-II), possible high–luminosity low–energy e^+e^- colliders