Explaining self-interacting dark matter and lepton-flavor non-universality with $L_\mu - L_\tau$

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Dark matter couplings

- Typical WIMP model:
  - Thermal production via coupling to *any* SM particle.
  - Strong constraints on DM couplings to gauge bosons and first-gen fermions from direct detection.

Dark matter couplings

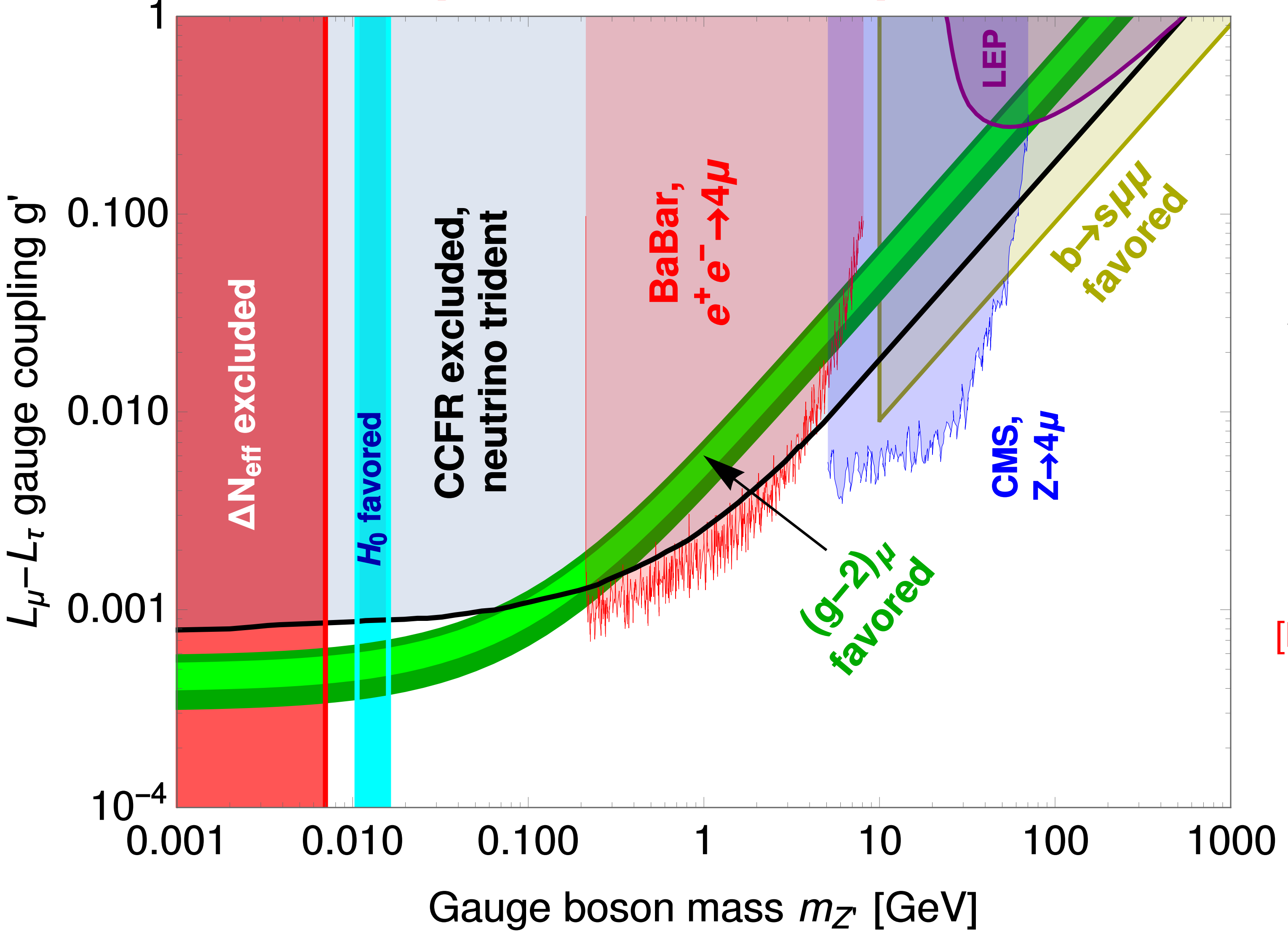
- Typical WIMP model:
  - Thermal production via coupling to *any* SM particle.
  - Strong constraints on DM couplings to gauge bosons and first-gen fermions from direct detection.
- Easy way out:
  - DM couplings only to higher generations!
  - Simple realization: DM charged under $\mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau}$.

    [Cirelli, Kadastik, Raidal, Strumia, 0809.2409; Baek, Ko, 0811.1646; Foldenauer, PRD '19; Hapitas, Tuckler, Zhang, 2108.12440; Holst, Hooper, Krnjaic, PRL '22]

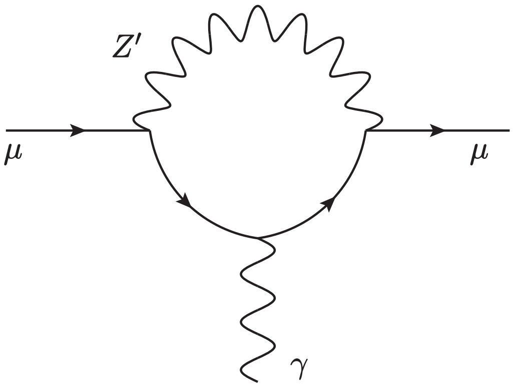
    - Anomaly-free $\mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau}$ interesting independently!

      [He, Joshi, Lew, Volkas, '91; Foot, '91; **JH**, Rodejohann, '11]

[JH, Garani, 1906.10145]



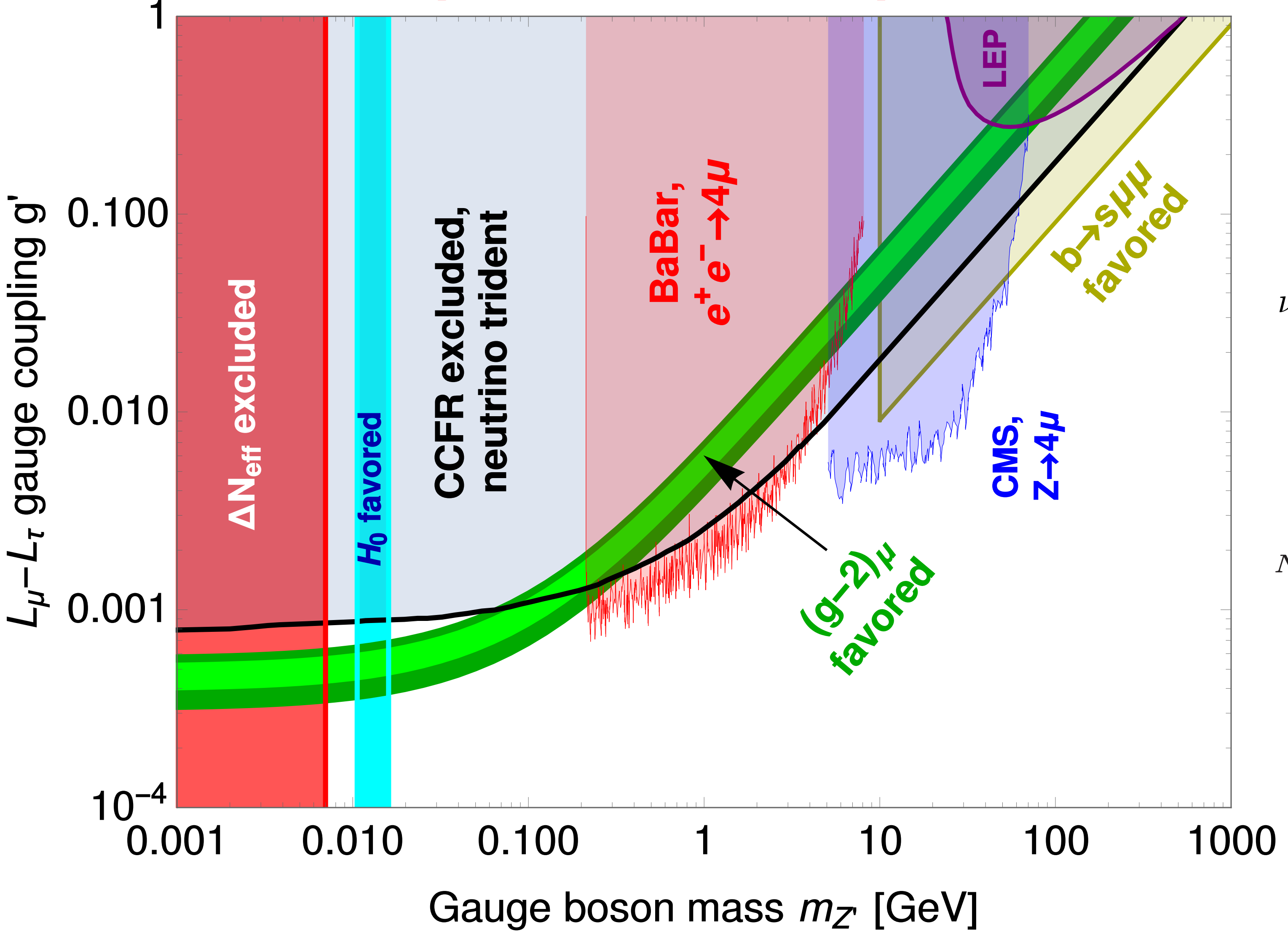
$(g\text{-}2)_\mu$:



[He, Joshi, Lew, Volkas, '91]

4σ deviation!
BNL+Fermilab

[**JH**, Garani, 1906.10145]



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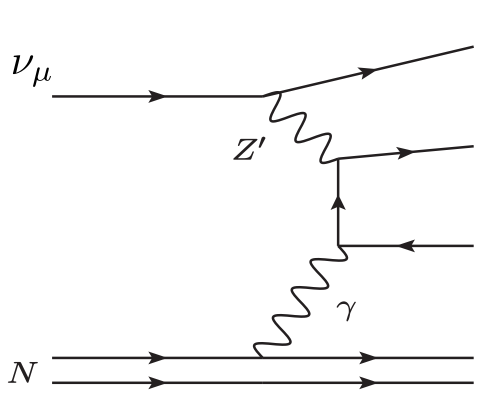
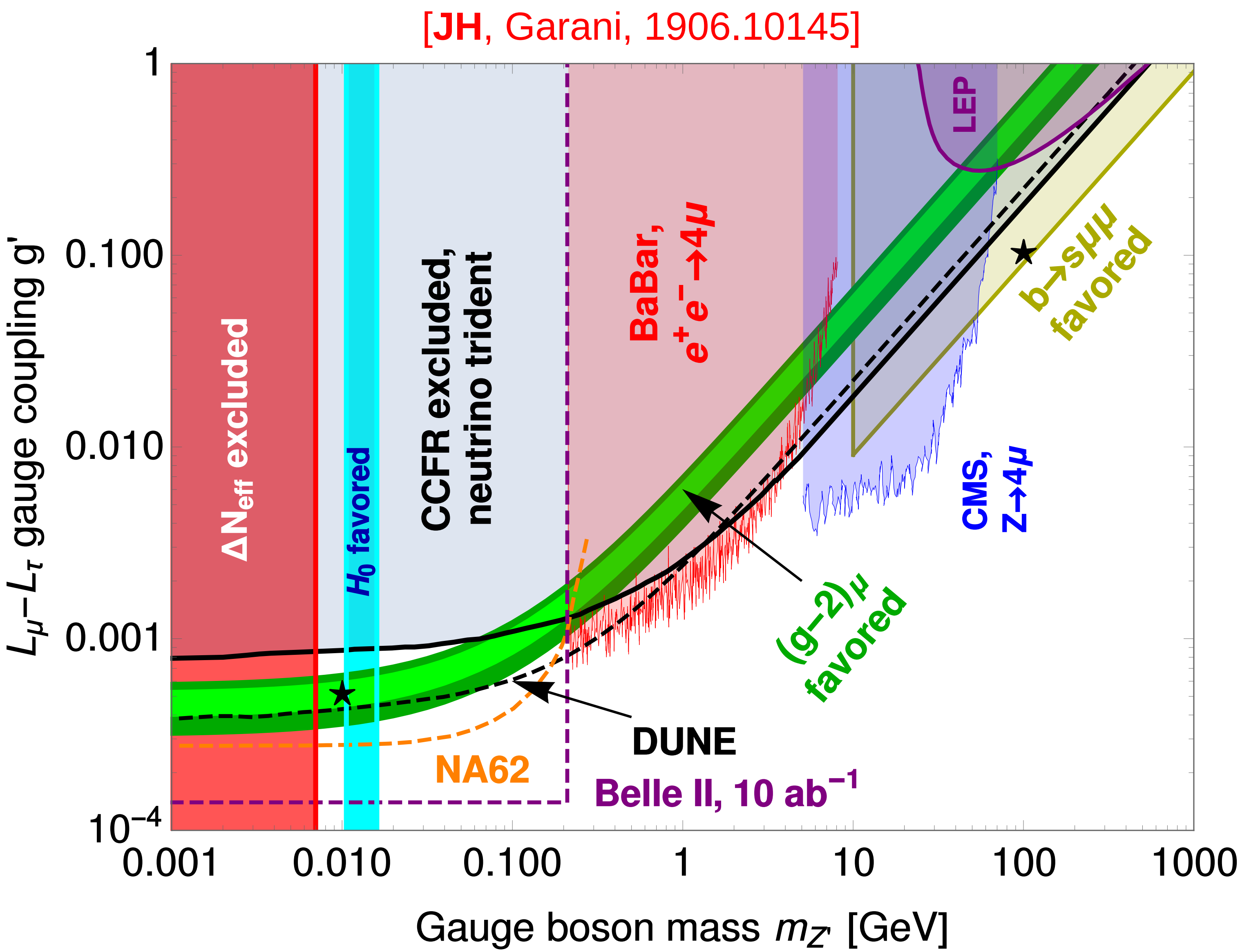


[Altmannshofer, Gori, Pospelov, Yavin, ‘14]



g-2 motivated region entirely testable!

Dark matter from $L_\mu – L_\tau$?

- DM under $\mathrm{U}(1)_{L_\mu - L_\tau}$: stability, Z' mediator, asymmetry(?).
- Z' mediator could be light: DM DM $\rightarrow$ Z' Z'.
  - Large DM self interactions? [Kamada+, 1805.00651]
- **No** constraints from direct detection...

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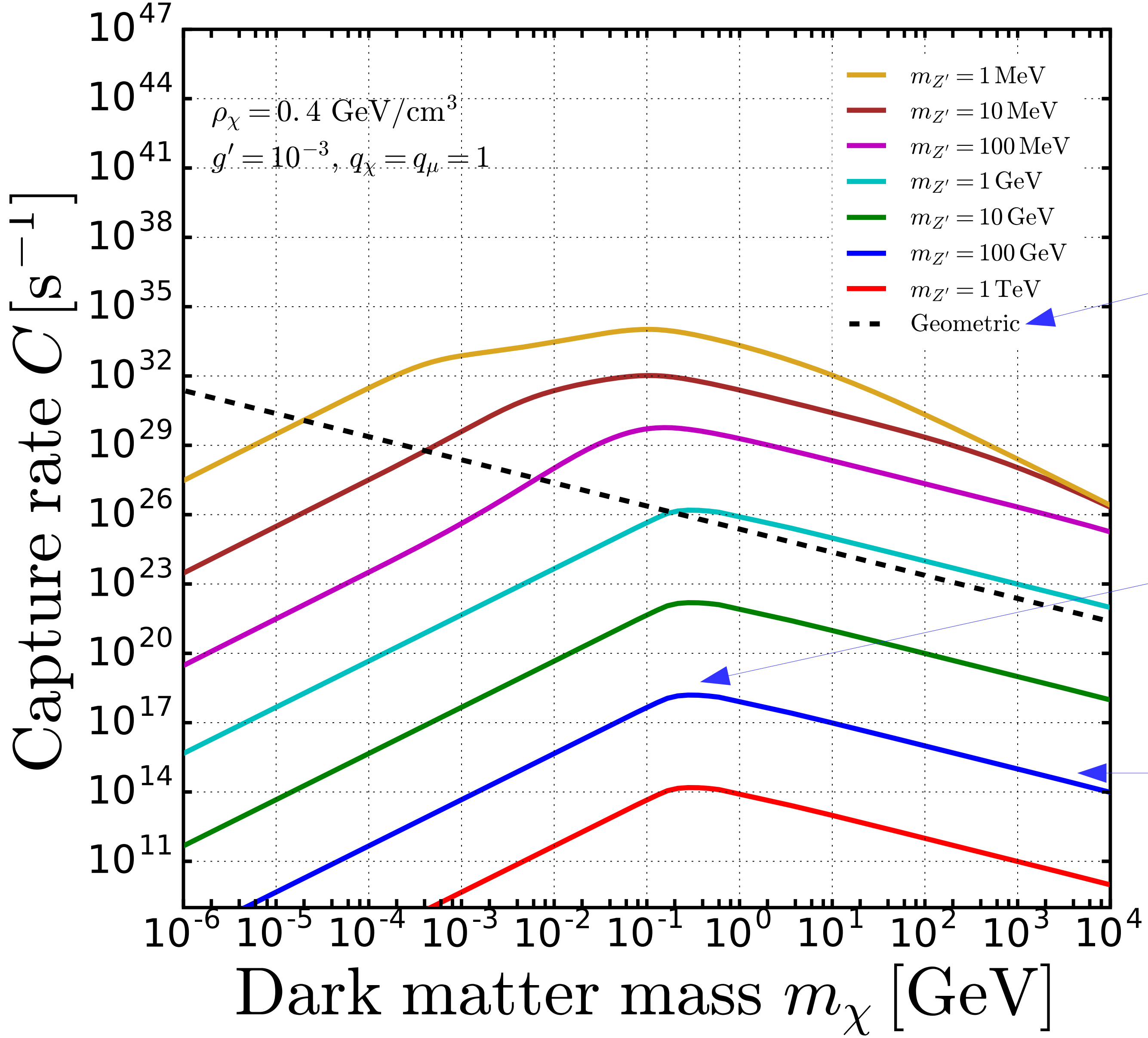
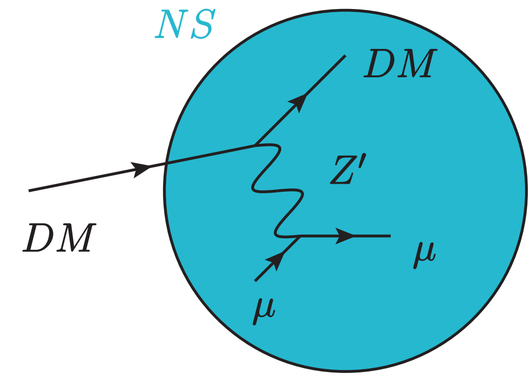
  … but could still be captured in neutron stars!

  [Garani, Genolini, Hambye, 1812.08773; Bell, Busoni, Robles, 1904.09803]
  - NS contain 10^{57} neutrons and 10^{55} muons.
  - Capture for $\sigma_{\mathrm{DM}\mu} > 5 \times 10^{-43}\mathrm{cm}^2$.
  - Also take Pauli blocking and velocities into account.

[**JH**, Garani, 1906.10145]

DM capture in neutron star?





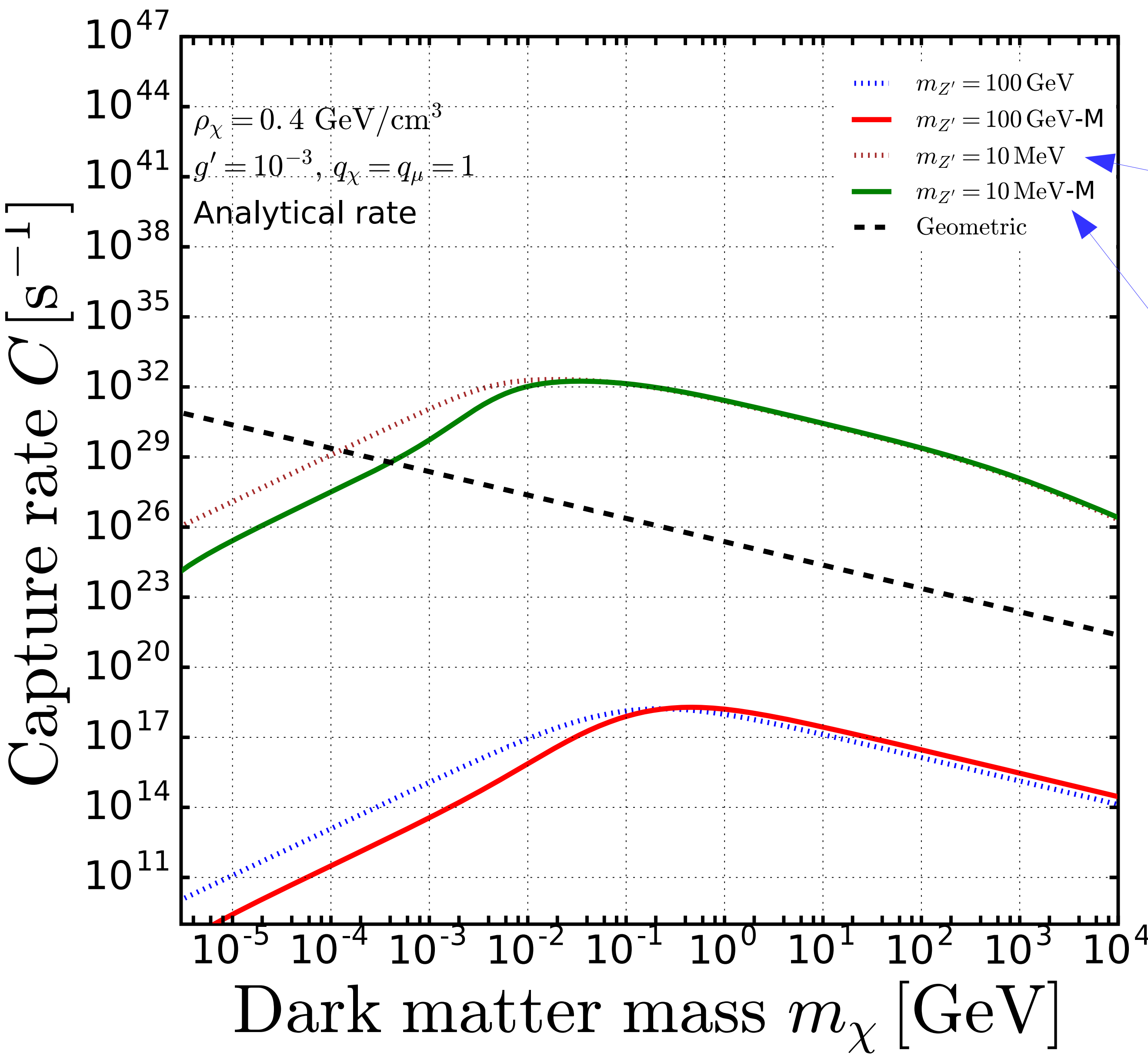
Everything is captured!

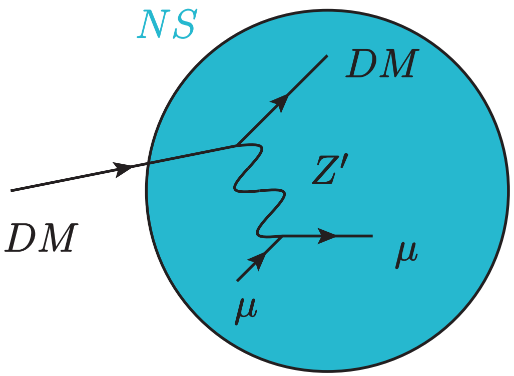
Capture most efficient for $m_{DM} \sim m_\mu$.

$C \propto q_\chi^2 g'^4 / m_{Z'}^4$

[**JH**, Garani, 1906.10145]

Scalar~Dirac~Majorana DM





Dirac DM

$$\overline{\chi}\gamma_\alpha\chi\,\overline{\mu}\gamma^\alpha\mu$$

Majorana DM

$$\Downarrow$$

$$\overline{\chi}\gamma_\alpha\gamma_5\chi\,\overline{\mu}\gamma^\alpha\mu$$

Velocity suppressed σ, but still easily captured!

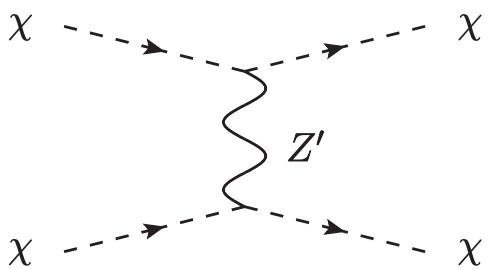
[**JH**, Garani, 1906.10145]

(Muonic) DM in neutron stars

- Easily saturate the capture rate for WIMPs. Then what?
- Asymmetric DM: collect enough to form black hole?
  - Fermi pressure.
  - Repulsive self-interactions.

[Kouvaris, Tinyakov, ’10, ‘11]

[Bell, Melatos, Petraki, ’13,
Bramante, Fukushima, Kumar, ‘13]



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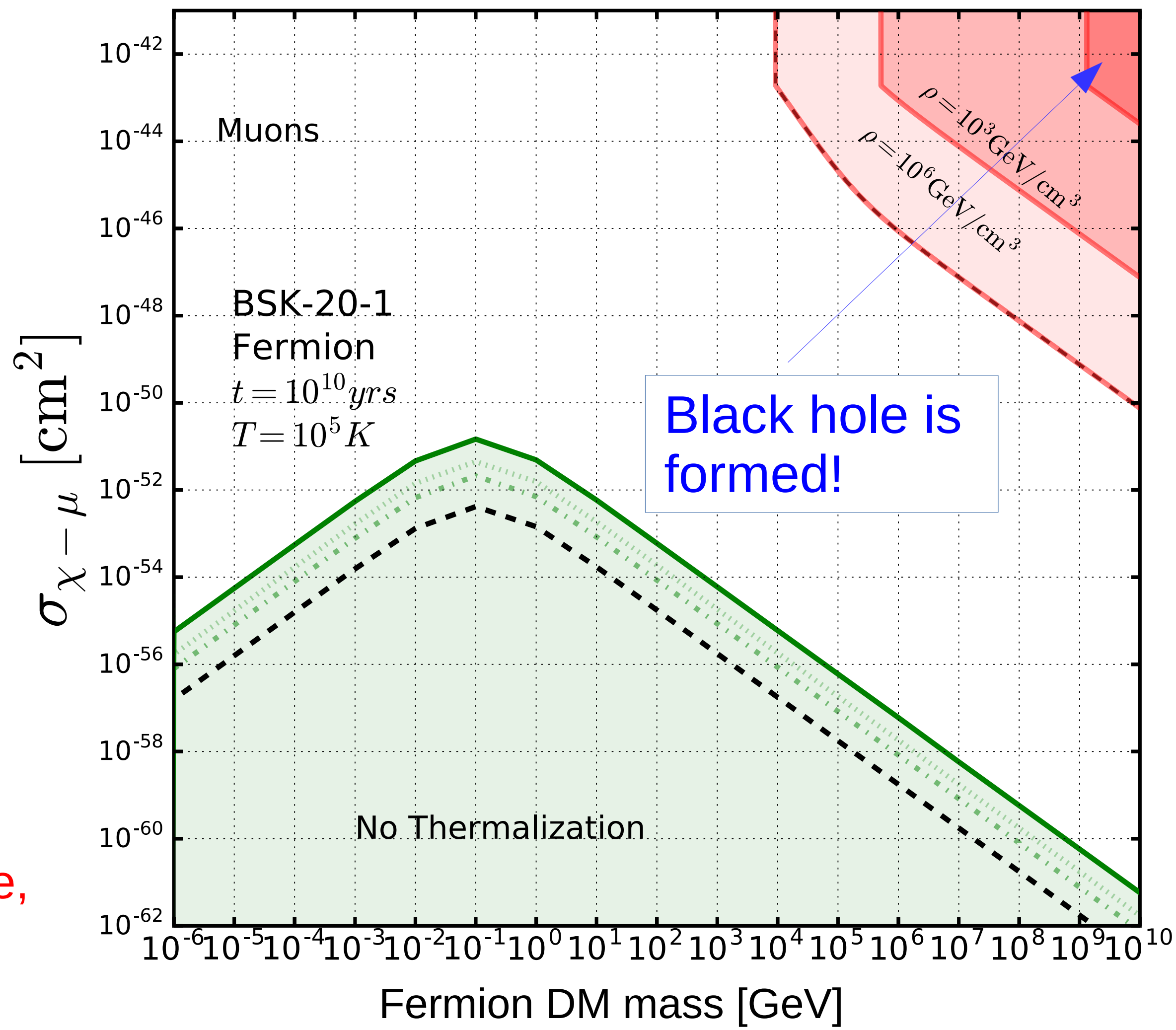

[Garani, Genolini, Hambye, 1812.08773]

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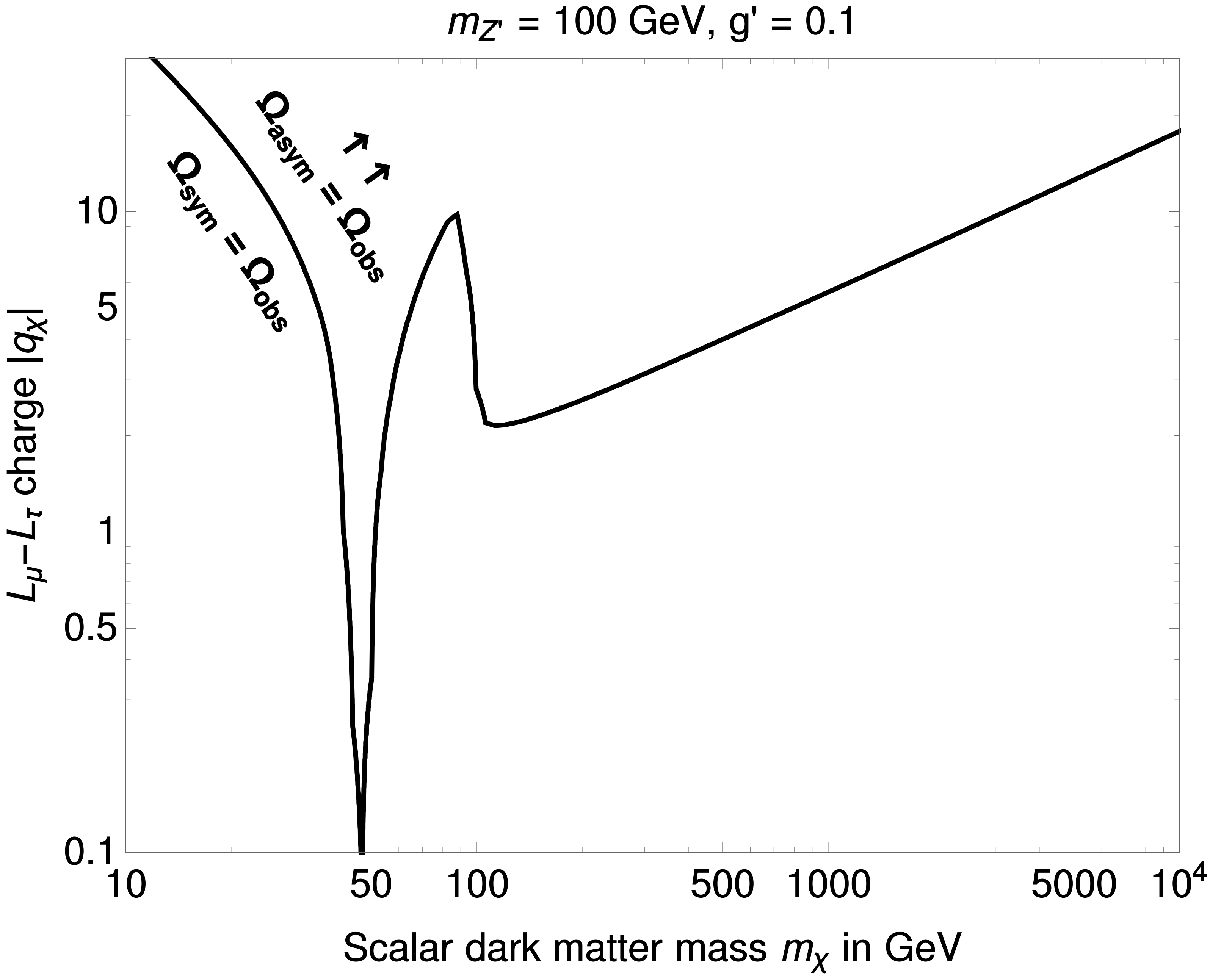
(Muonic) DM in neutron stars

- Easily saturate the capture rate for WIMPs. Then what?
- Asymmetric DM: collect enough to form black hole?
  - Fermi pressure. ⚡ [Kouvaris, Tinyakov, '10, '11]
  - Repulsive self-interactions. ⚡ [Bell, Melatos, Petraki, '13, Bramante, Fukushima, Kumar, '13]
- Always: infalling DM heats the NS! (from < 1000K to ~2000K)

[Baryakhtar, Bramante, Li, Linden, Raj, '17; Raj, Tanedo, Yu, '17; Bell, Busoni, Robles, '18/'19]

- Symmetric DM: more heating from DM annihilations.
- Measure IR spectrum of nearby old NS with JWST?



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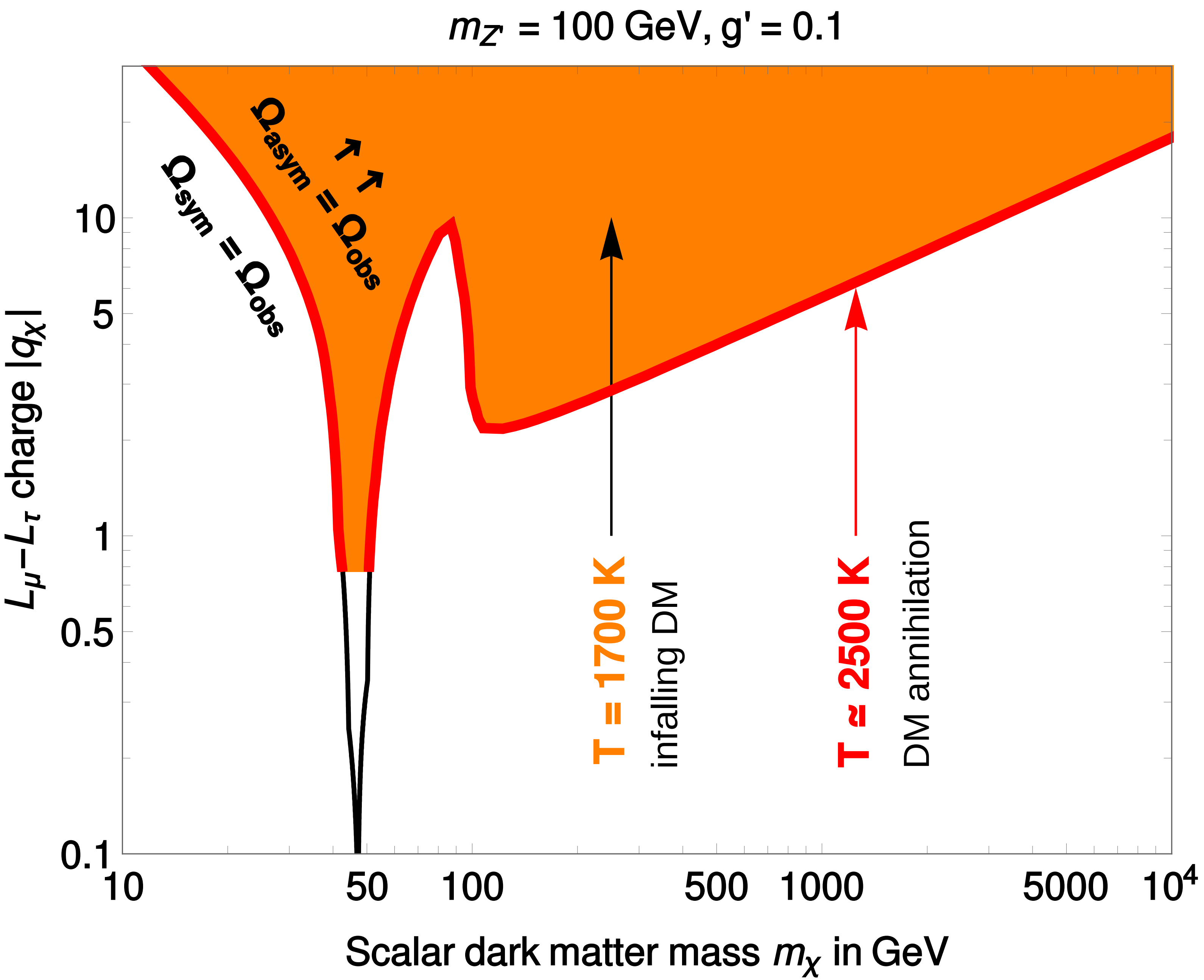
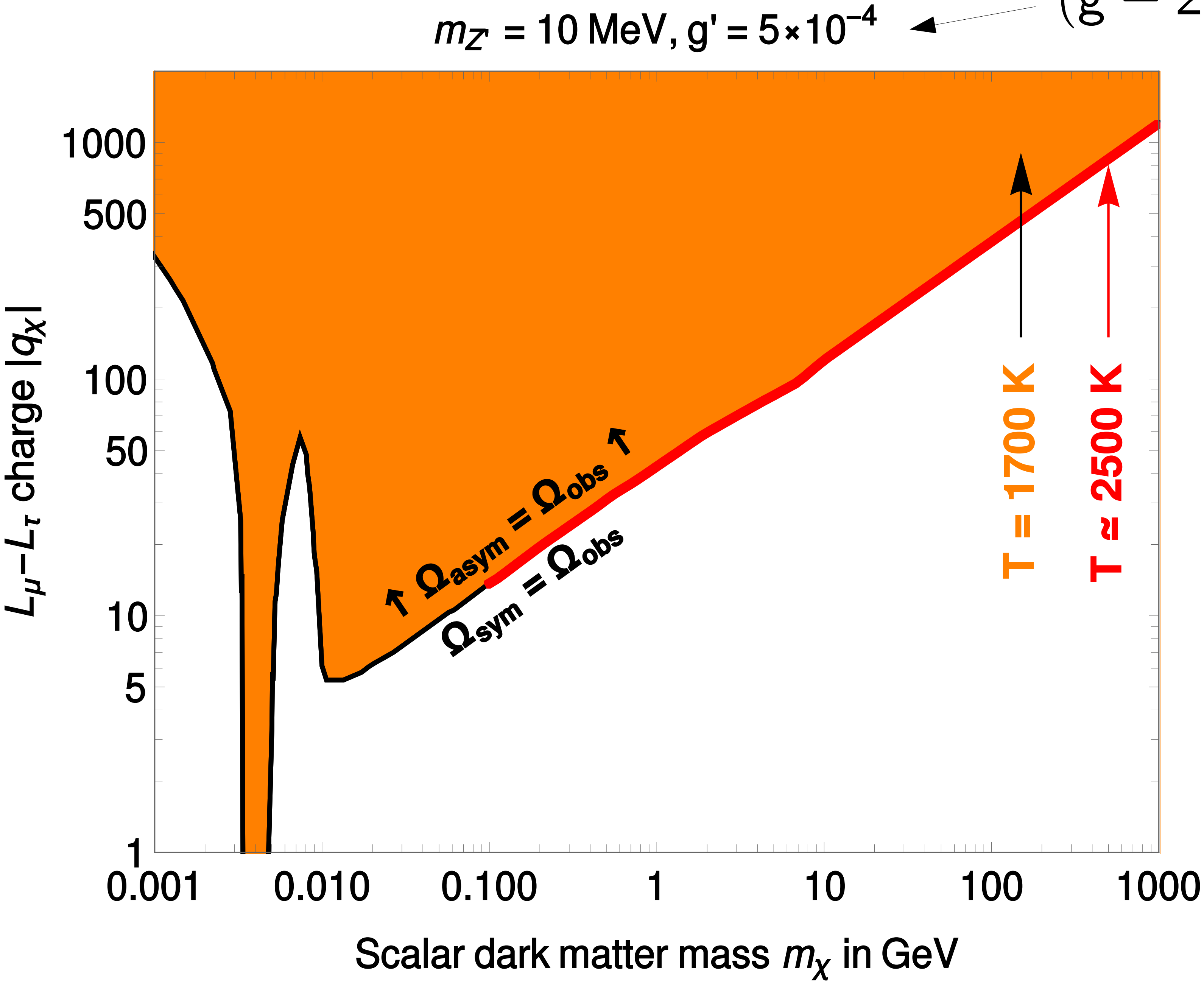


[**JH**, Garani, 1906.10145]

$(g-2)_\mu!$



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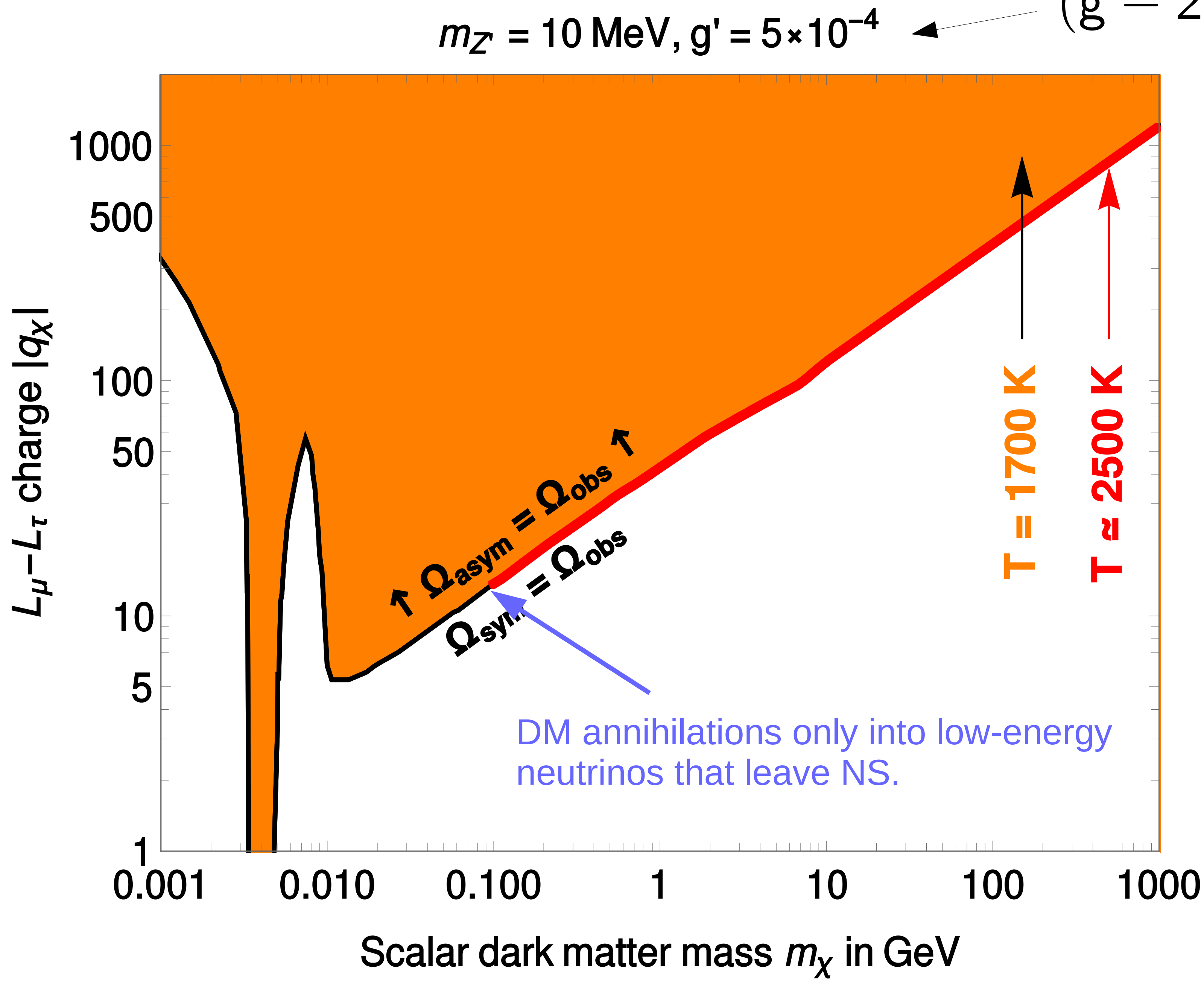

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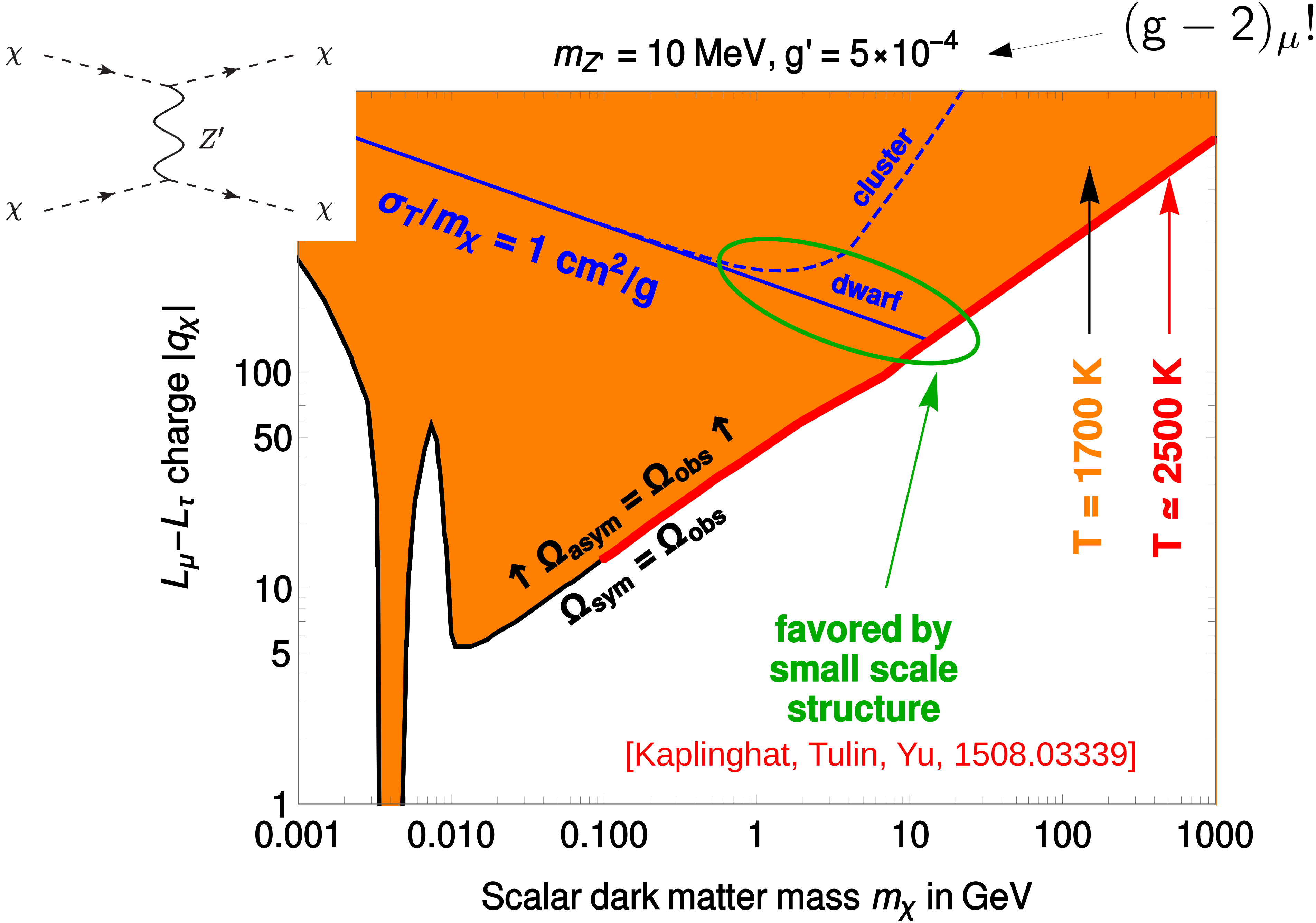


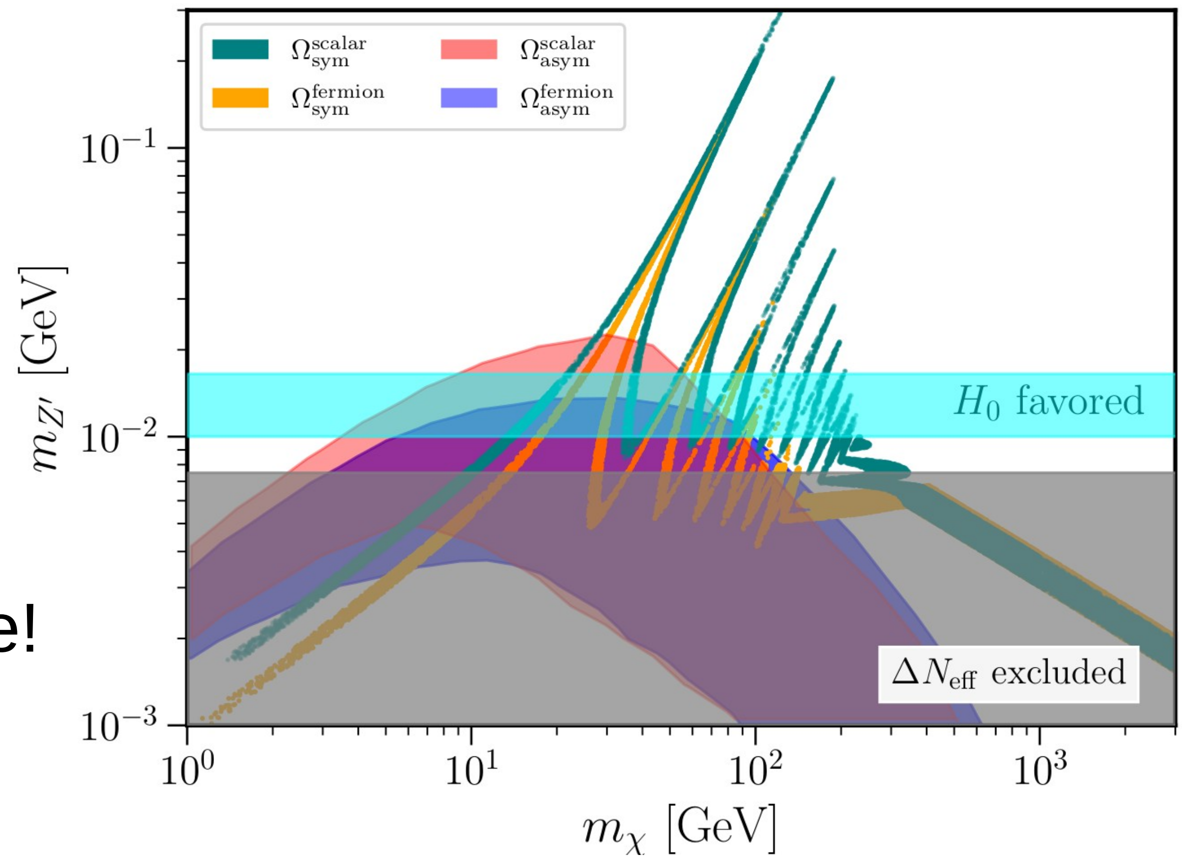
[**JH**, Garani, 1906.10145]

Small scale structure

- Self-interacting DM cross sections $\sigma/\text{m} \sim 1\,\text{cm}^2/\text{g}$ preferred at small scales but disfavored in clusters.
- Z' Yukawa potential gives good velocity dependence for light Z'! [Kaplinghat, Tulin, Yu, 1508.03339]
- L_μ–L_τ avoids CMB constraints. [Bringmann+, PRL '17; Hambye+, '20]

- Small scale structure can be improved in the g-2 region!

- DM between GeV and 400 GeV.
- CMB-S4 probes more!



[JH & Thapa, 2202.08854]

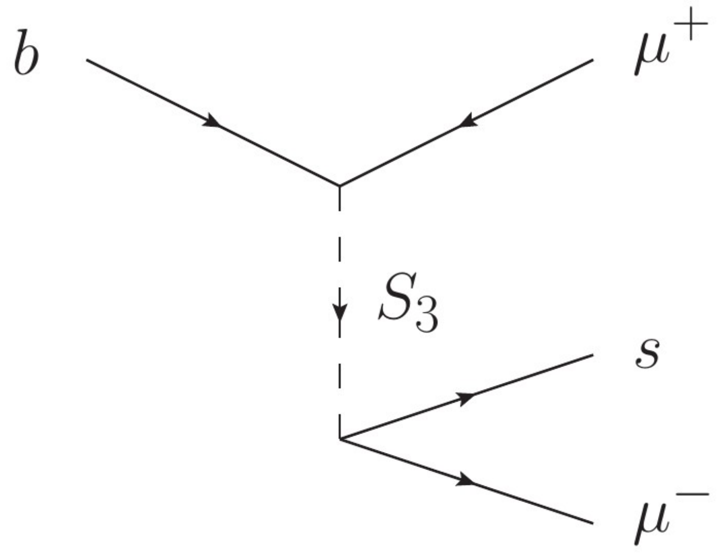
- Muon g-2 ✓
- Stable self-interacting dark matter ✓

What else can $L_\mu – L_\tau$ do for you?

- Would be nice to explain B-meson anomalies…

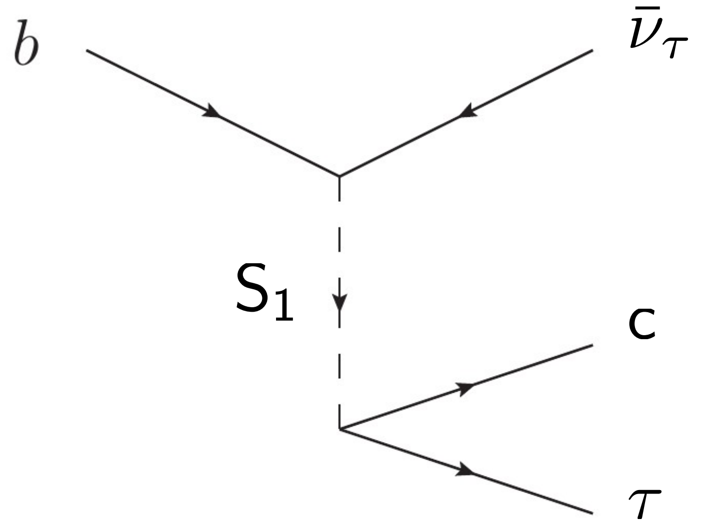
$L_\mu - L_\tau$ beyond the Z'

- Can use $L_\mu - L_\tau$ (or other flavor U(1)') to forbid or enforce couplings.
- Take leptoquark $S_3 \sim$ (**3**,**3**,-1/3): $\mathcal{L} = y_{ij} \bar{Q}_i S_3 L_j^c + x_{ij} Q_i Q_j S_3$
- Charge $S_3 \sim +1$ under $L_\mu - L_\tau$ to get $x_{ij} = 0$, $y_{ij} = y_{i\mu}$.
  → no more proton decay, no lepton flavor violation, only coupling to muons!
- Perfect for R(K) & R(K*)!
  [Hambye, **JH**, PRL '18; Davighi, Kirk, Nardecchia, '20; Greljo, Stangl, Thomsen, '21]
- $L_\mu - L_\tau$ global or gauged, just need to break it in neutrino sector.



$L_\mu - L_\tau$ beyond the Z'

- Can use $L_\mu - L_\tau$ (or other flavor U(1)') to forbid or enforce couplings.
- Take LQ $S_1 \sim$ (**3**,**1**,-1/3): $\mathcal{L} = y_{ij}\bar{Q}_i S_1 L_j^c + x_{ij} Q_i Q_j S_1 + \ldots$
- Charge $S_1 \sim -1$ under $L_\mu - L_\tau$ to get $x_{ij} = 0$, $y_{ij} = y_{i\tau}$.
  → no more proton decay, no lepton flavor violation, only coupling to tauons!
- Perfect for R(D) & R(D*)!
  [Angelescu++, 2103.12504, Greljo++, 2103.13991; **JH** & Thapa, 2202.08854]
- $L_\mu - L_\tau$ global or gauged, just need to break it in neutrino sector.



Summary: a full $L_\mu - L_\tau$ model

- Gauge $L_\mu - L_\tau$ and break it in neutrino sector to get M_ν.
- Add LQ S_1 ~ (**3**,**1**,-1/3) with $L_\mu - L_\tau$ ~ -1 to explain R(D) and LQ S_3 ~ (**3**,**3**,-1/3) with $L_\mu - L_\tau$ ~ +1 to explain R(K).
  - U(1) eliminates proton decay and lepton flavor violation.
- Z' in mass range 10-100 MeV explains $(g-2)_\mu$.
- Charge new singlet fermions/scalars under $L_\mu - L_\tau$.
  - Stability through U(1)' → dark matter!
  - Relic abundance through Z'.
  - Self-interactions via light Z' explain small-scale structure!
  - Heats up neutron stars!

Only $L_\mu - L_\tau$ can do all this!

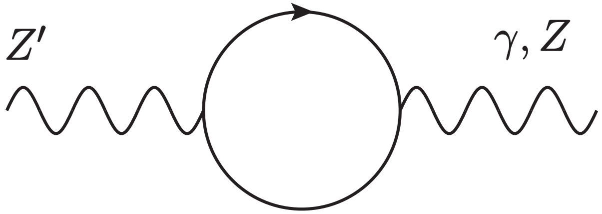
Backup

Kinetic mixing

- Every U(1)' has kinetic mixing with hypercharge,

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\,\epsilon\,F'_{\mu\nu}F^{\mu\nu},$$

plus loop-level mixing. [Galison, Manohar, '84; Holdom, '86]



- Couples light Z' to electric current; important for $L_\mu - L_\tau$, e.g. in direct detection:

$$\sigma_{\chi N} = \frac{Z^2}{A^2}\frac{m^2_{\mathrm{red},\chi N}}{\pi m^4_{Z'}}\left(g' q_\chi\right)^2\left[e\epsilon + \frac{\alpha g'}{3\pi}\log\left(\frac{m_\tau^2}{m_\mu^2}\right)\right]^2$$

[Kopp, Niro, Schwetz, Zupan, '09; Altmannshofer, Gori, Profumo, Queiroz, '09]

- Can suppress direct detection. [Hapitas, Tuckler, Zhang, 2108.12440]