Dark matter interactions with muons in neutron stars

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Dark matter couplings

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

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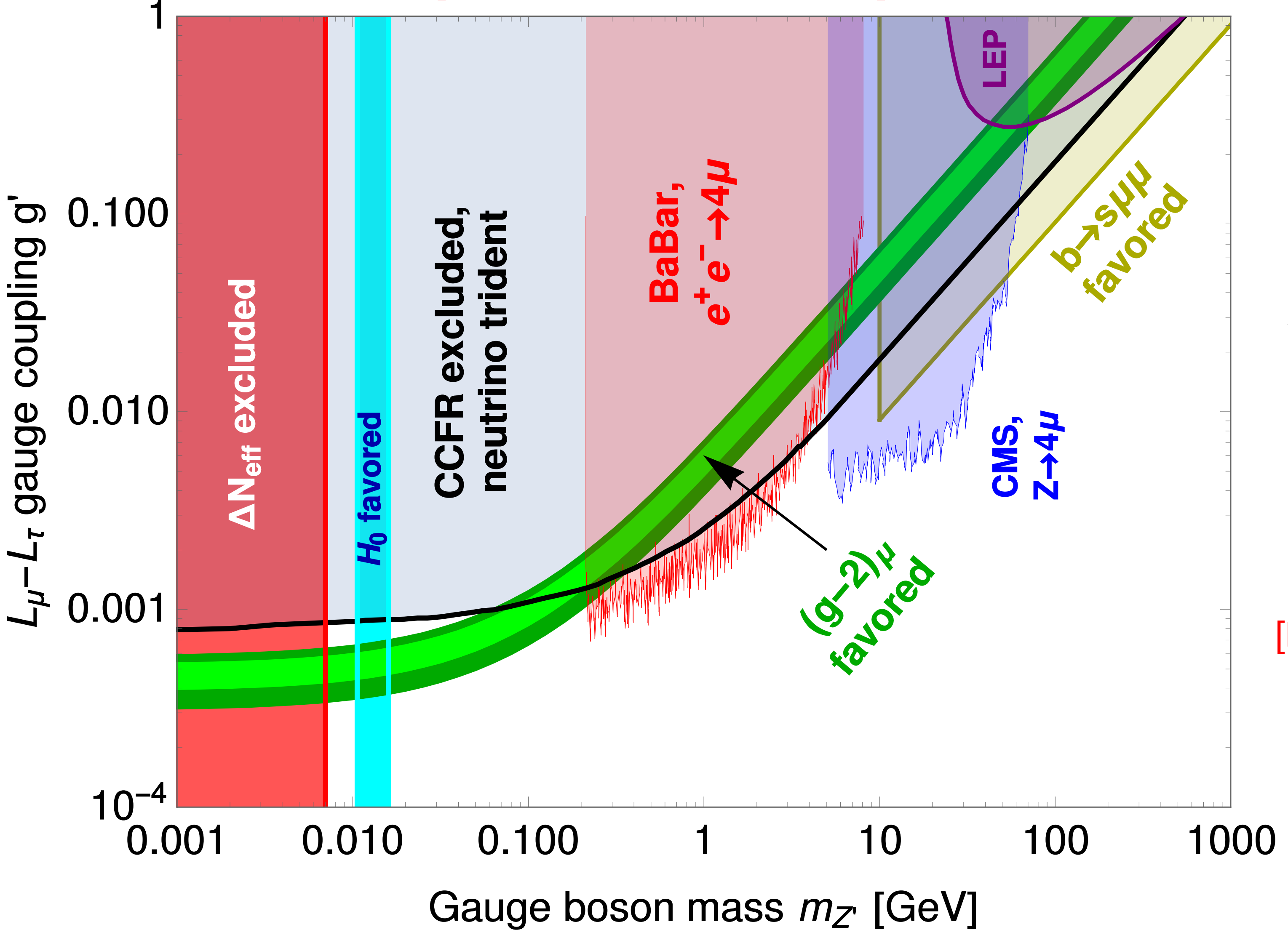
- Typical WIMP model:
  - Thermal production via coupling to *any* SM particle.
  - Strong constraints on couplings to gauge bosons and first-gen fermions from direct detection.
- Easy way out:
  - DM couplings only to higher generations!
  - Simple realization: DM charged under $U(1)_{L_\mu - L_\tau}$.

    [Cirelli, Kadastik, Raidal, Strumia, 0809.2409; Baek, Ko, 0811.1646]

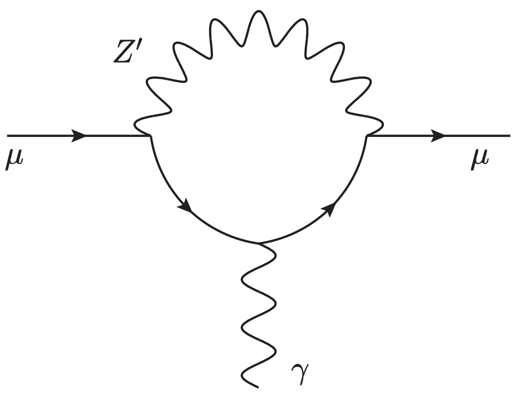
    - Anomaly-free $U(1)_{L_\mu - L_\tau}$ interesting independently!

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

[JH, Garani, 1906.10145]



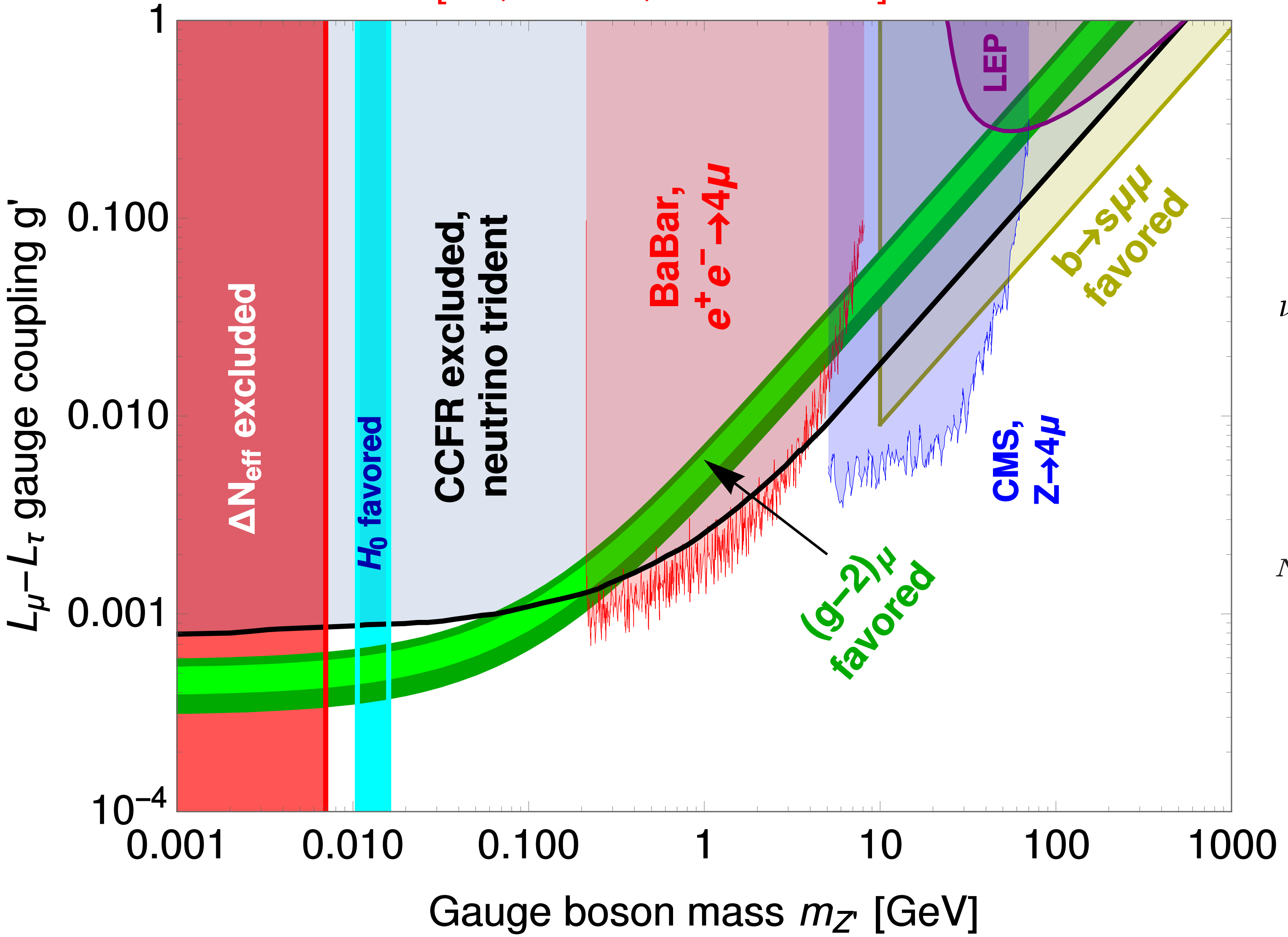
$(g-2)_\mu$:



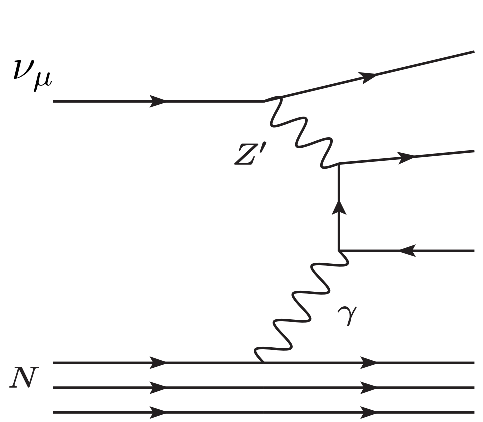
[He, Joshi, Lew, Volkas, '91]

3-4σ deviation!

[JH, Garani, 1906.10145]

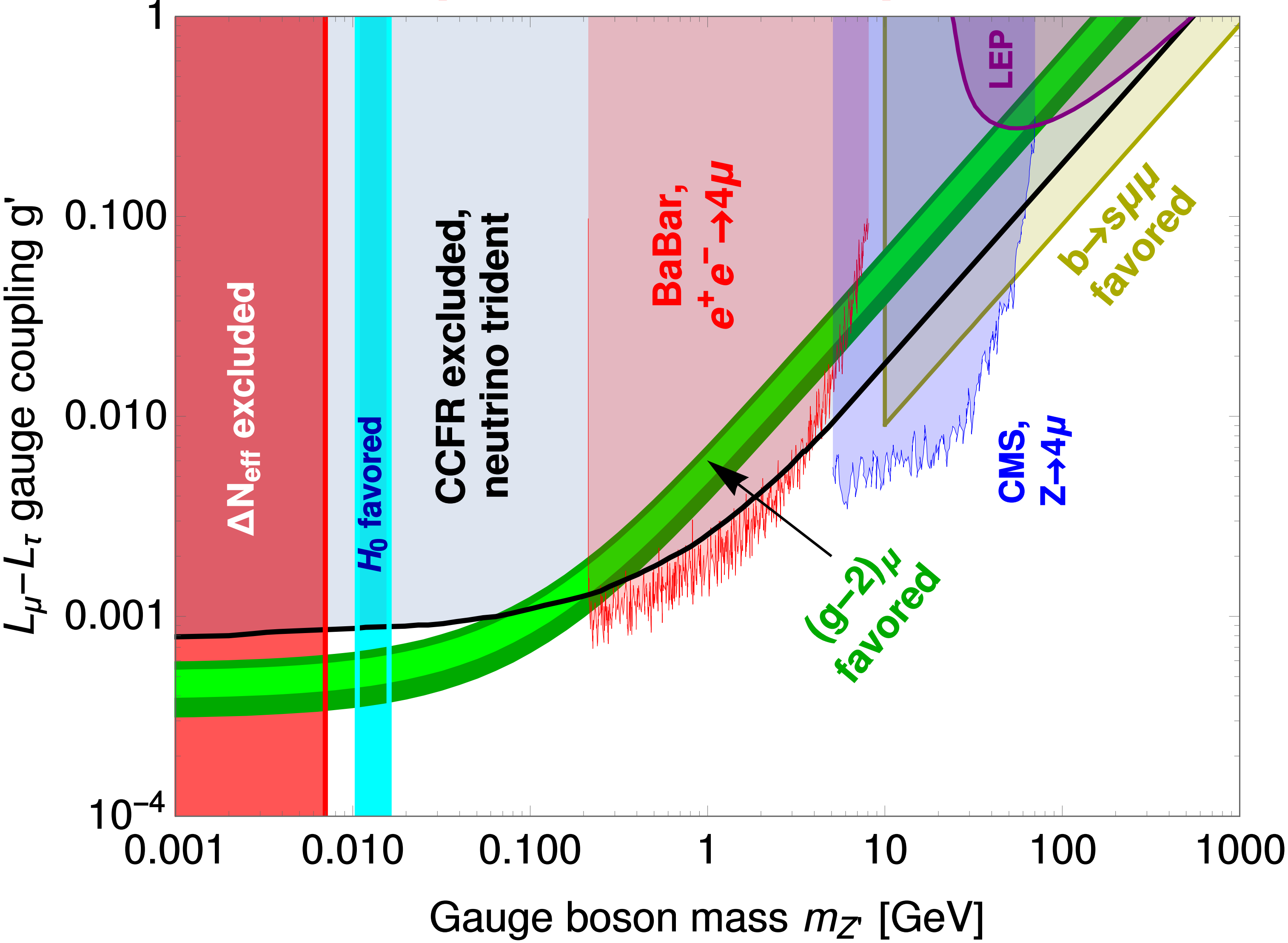


ν trident:

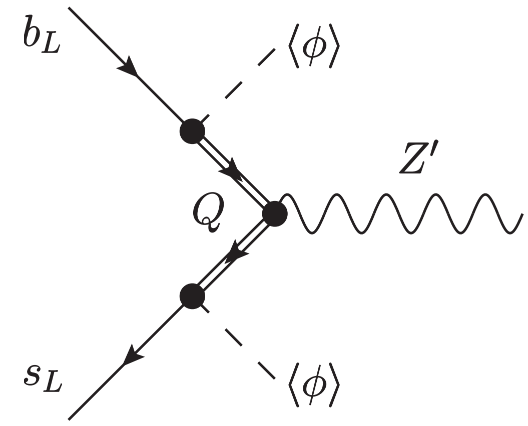


[Altmannshofer, Gori, Pospelov, Yavin, ‘14]

[**JH**, Garani, 1906.10145]

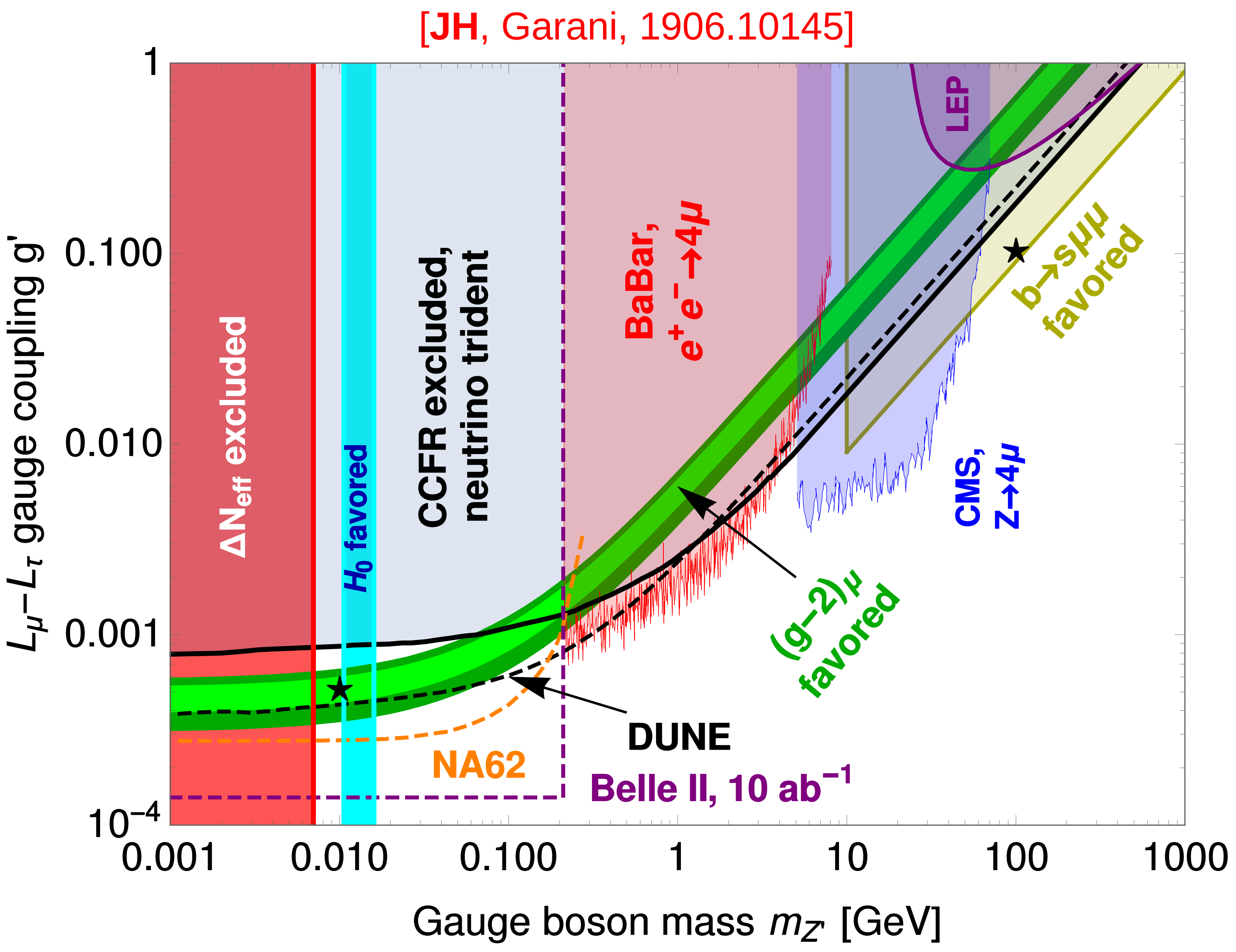


Add bs coupling

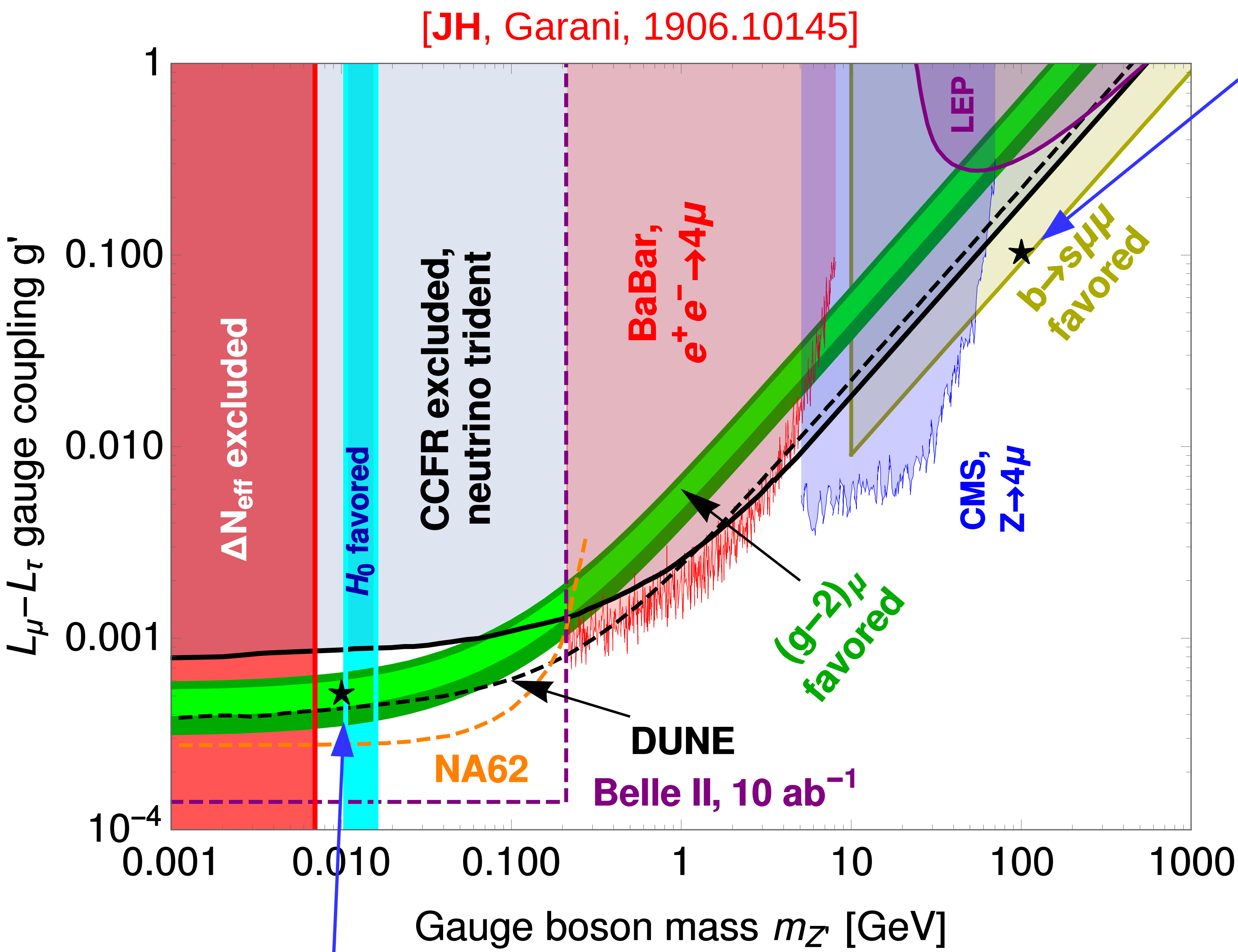


to explain b $\to$ s$\mu\mu$ LHCb anomalies.

[Altmannshofer, Gori, Pospelov, Yavin, '14; many others...]



[JH, Garani, 1906.10145]
$L_\mu - L_\tau$ gauge coupling g'
Gauge boson mass $m_{Z'}$ [GeV]
1
0.100
0.010
0.001
10^{-4}
0.001
0.010
0.100
1
10
100
1000
ΔN_{eff} excluded
H_0 favored
CCFR excluded, neutrino trident
BaBar, $e^+e^- \to 4\mu$
LEP
CMS, $Z \to 4\mu$
$b \to s\mu\mu$ favored
$(g-2)\mu$ favored
DUNE
NA62
Belle II, 10 ab^{-1}



Benchmark: heavy Z'

$Z' \to \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau, \mu\bar{\mu}, \tau\bar{\tau}$

Benchmark: light Z'. Only $Z' \to \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau$ allowed.

Dark matter from L_μ–L_τ?

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

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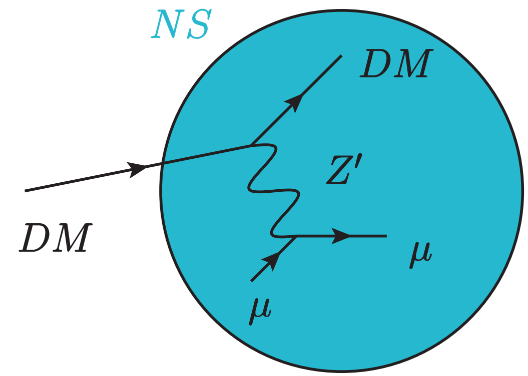
… but could still be captured in neutron stars!

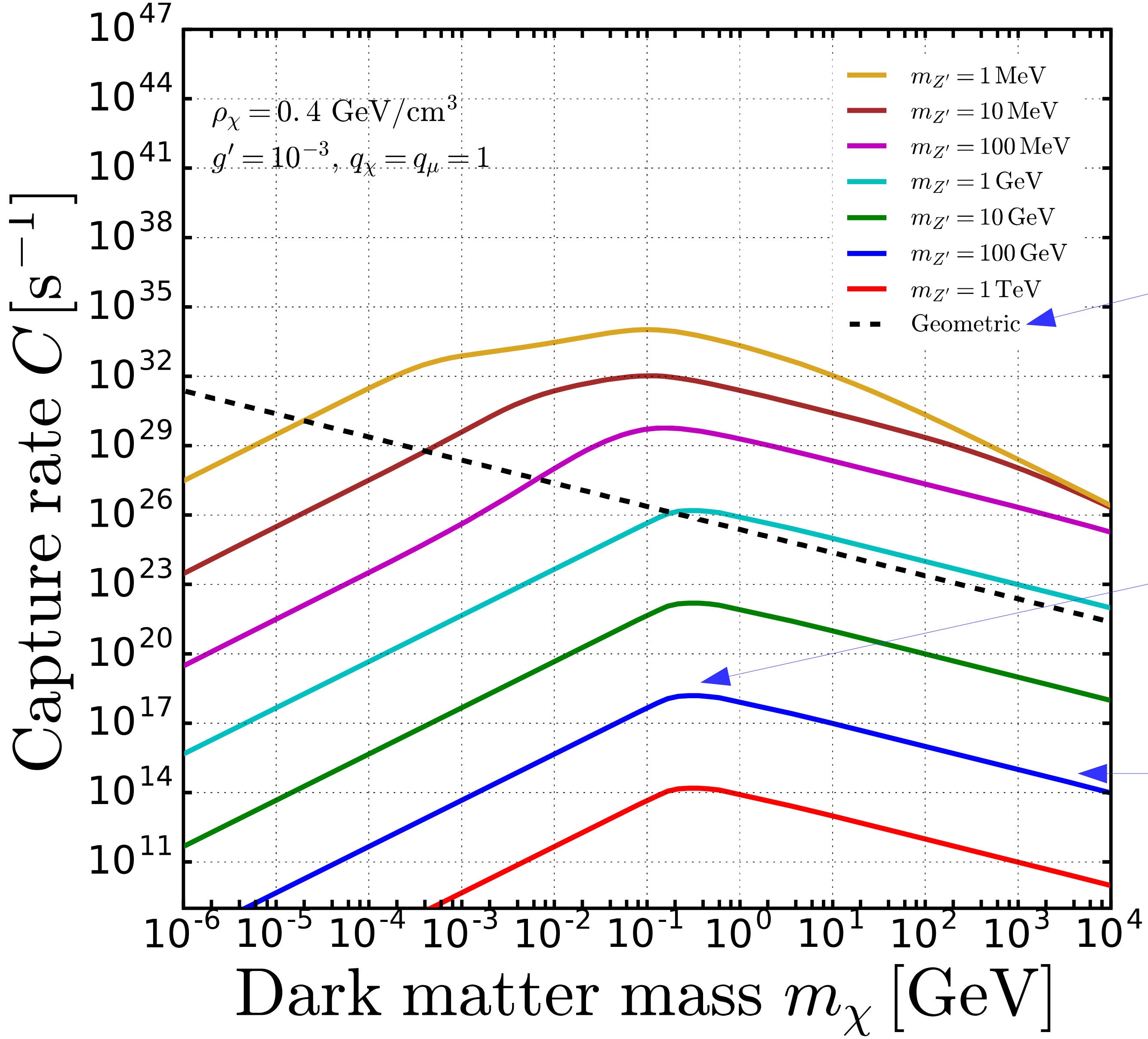
[Garani, Genolini, Hambye, 1812.08773; Bell, Busoni, Robles, 1904.09803]

- 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?





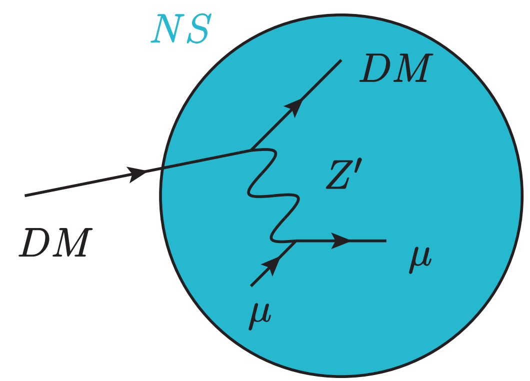
Everything is captured!

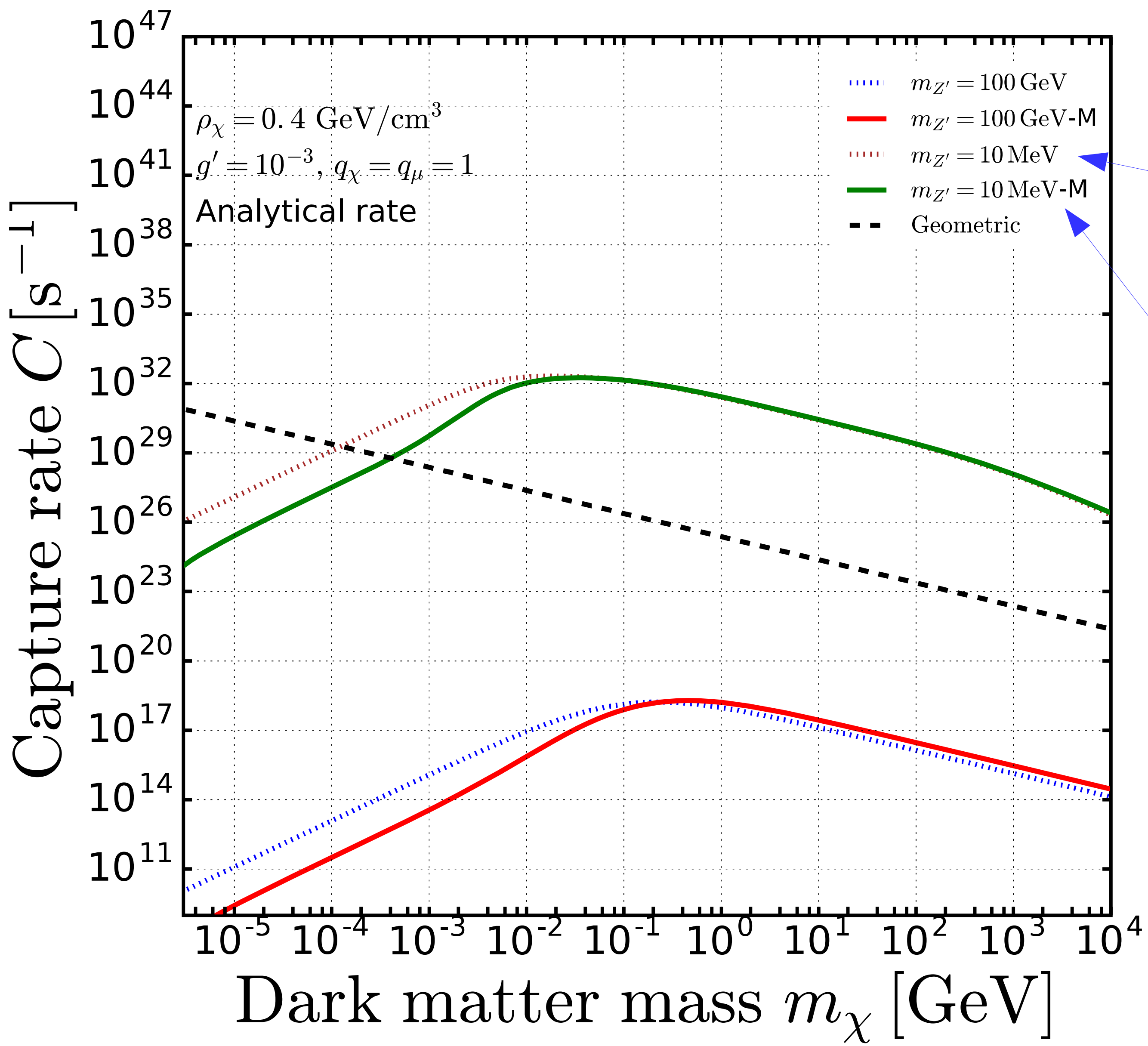
Capture most efficient for $m_{DM} \sim m_\mu$.

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

[**JH**, Garani, 1906.10145]

Scalar~Dirac~Majorana DM





Dirac DM

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

Majorana DM

$$\Downarrow$$

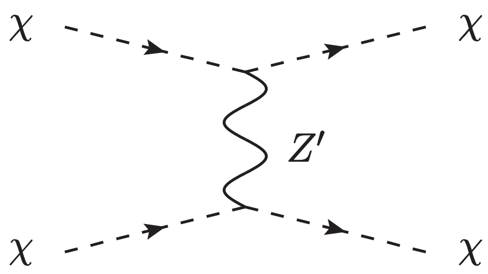
$$\overline{\chi}\gamma_\alpha\gamma_5\chi\,\overline{\mu}\gamma^\alpha\mu$$

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. ↯ [Kouvaris, Tinyakov, '10, '11]
  - Repulsive self-interactions. ↯ [Bell, Melatos, Petraki, '13, Bramante, Fukushima, Kumar, '13]



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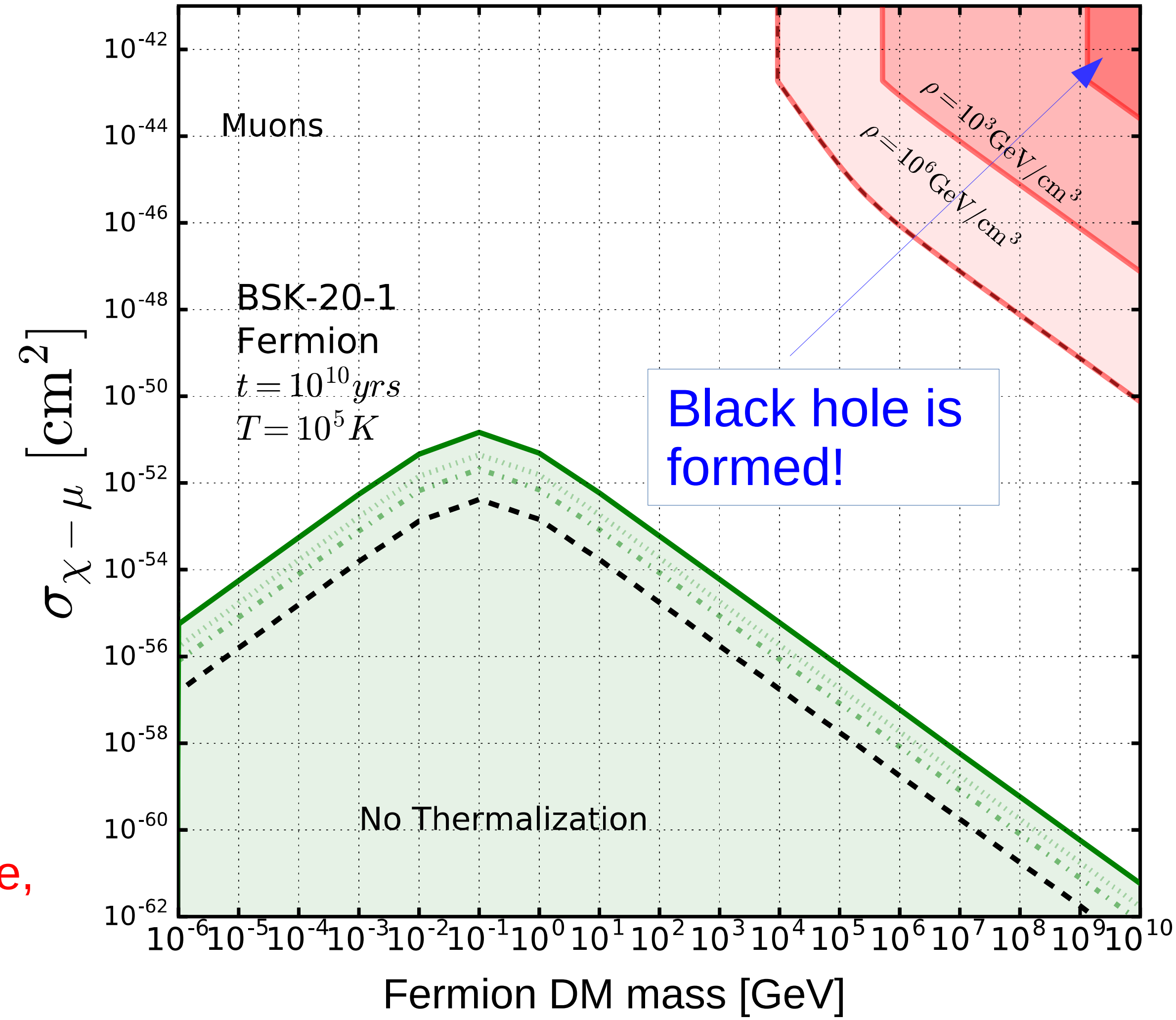

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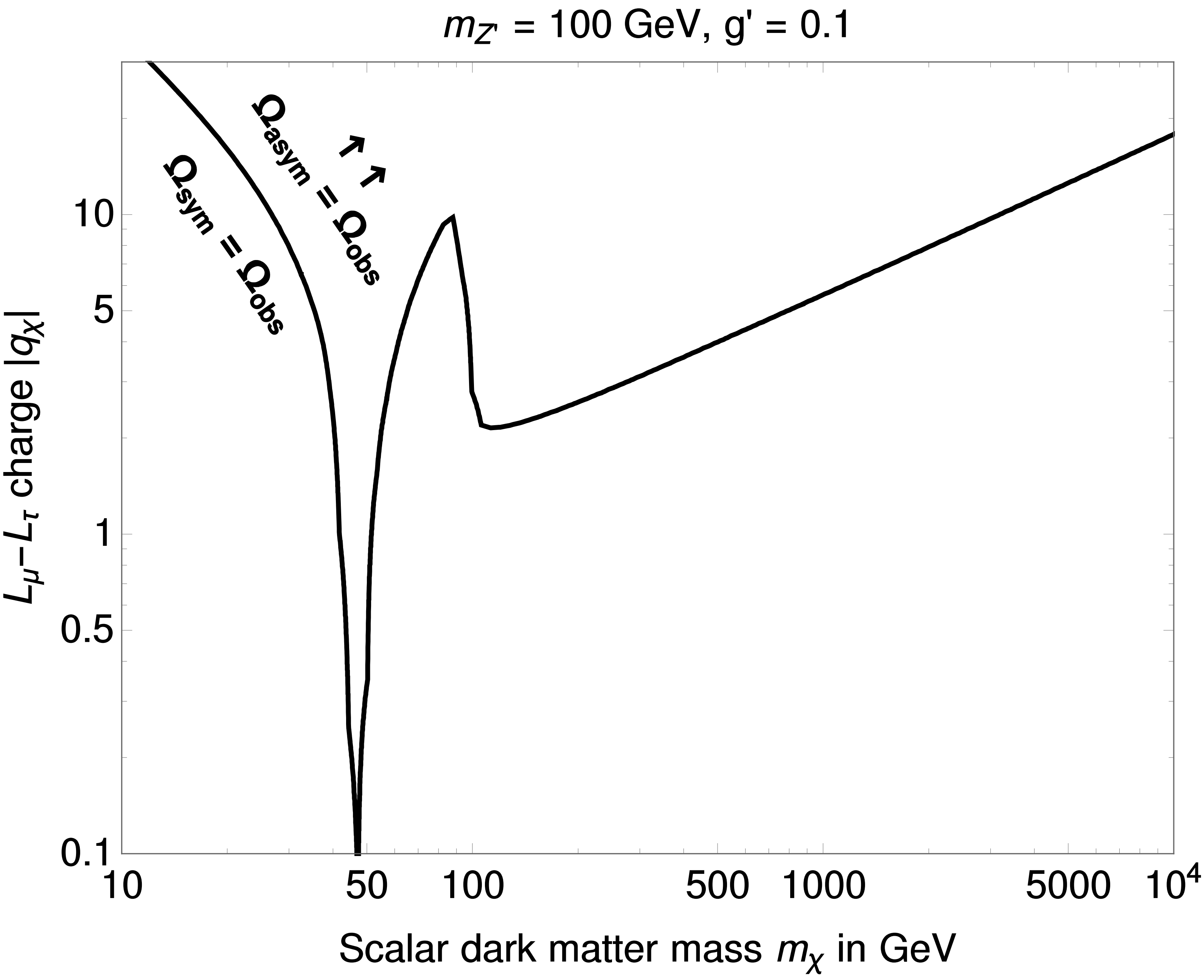
  - Repulsive self-interactions. ⚡ [Bell, Melatos, Petraki, '13, Bramante, Fukushima, Kumar, '13]
- Always: infalling DM heats the NS! (from < 1000K to ~2000K)

[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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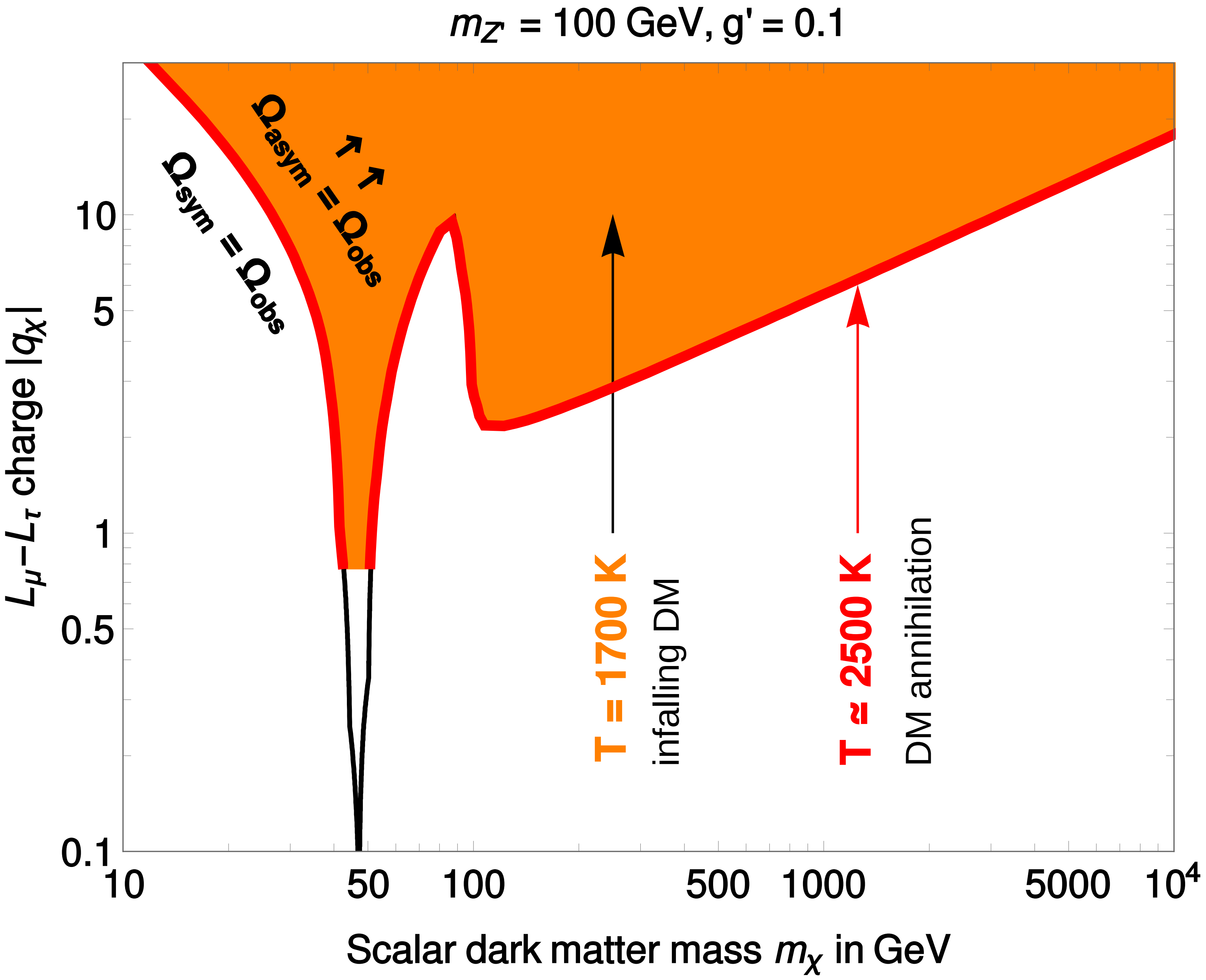

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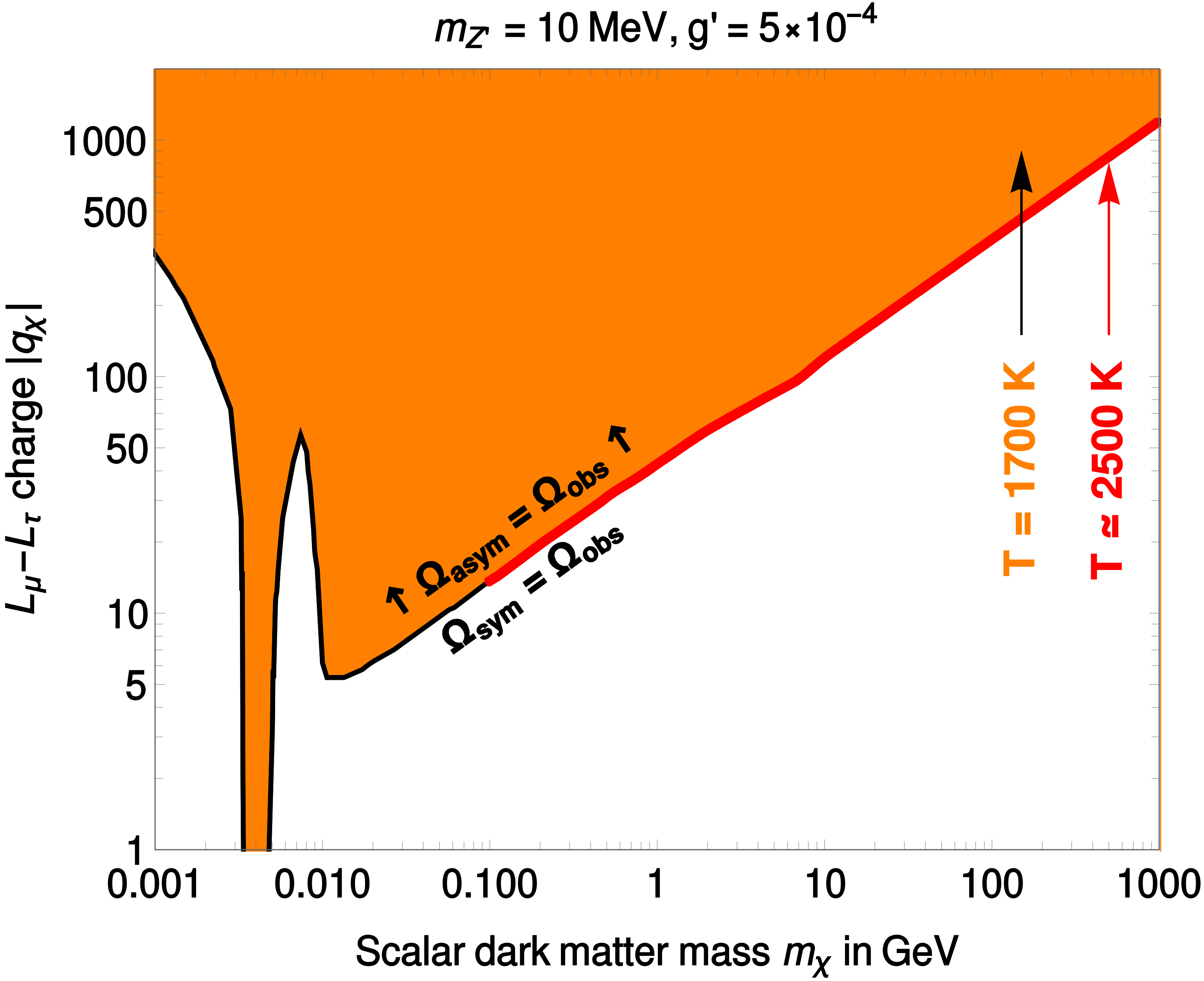

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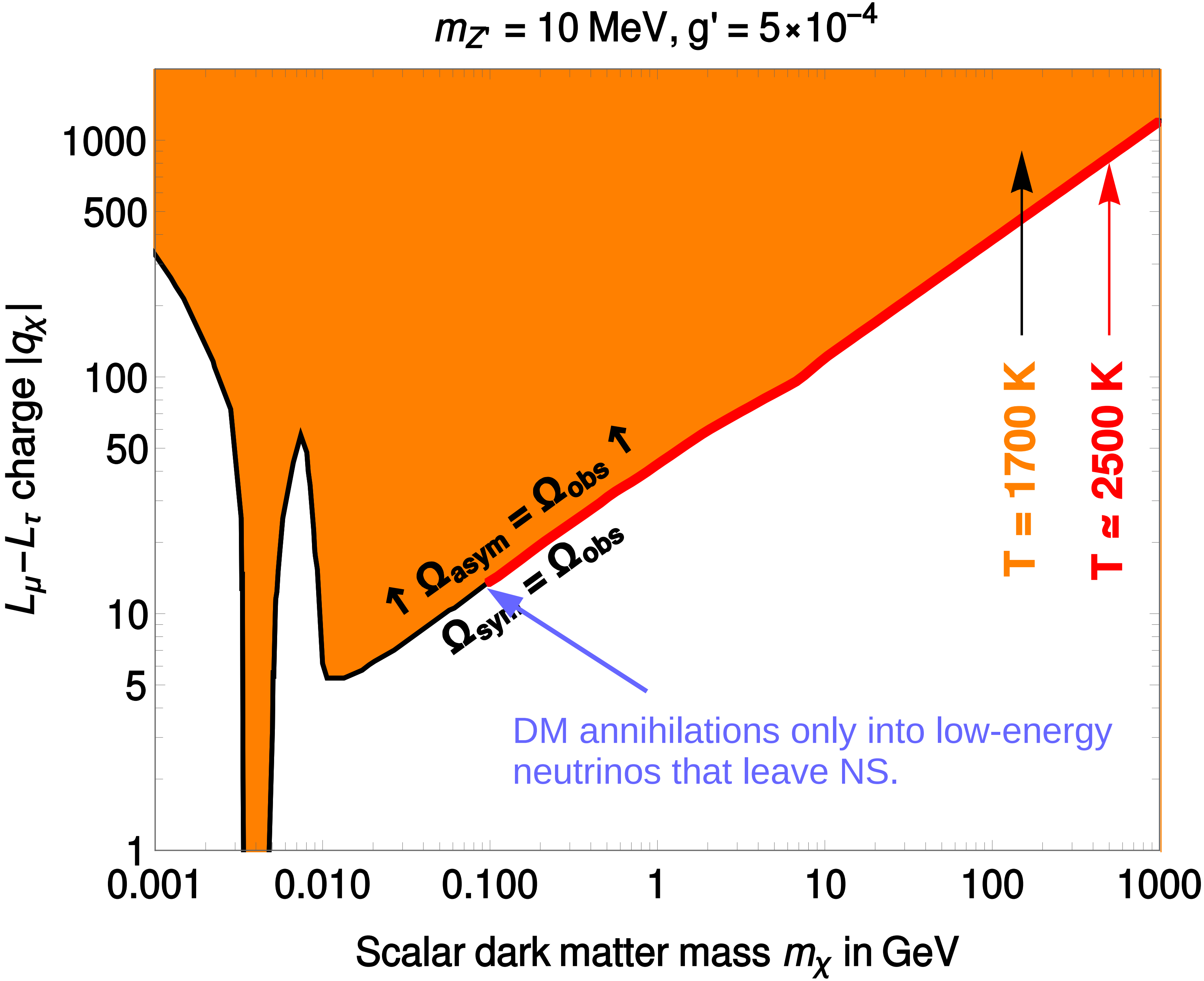

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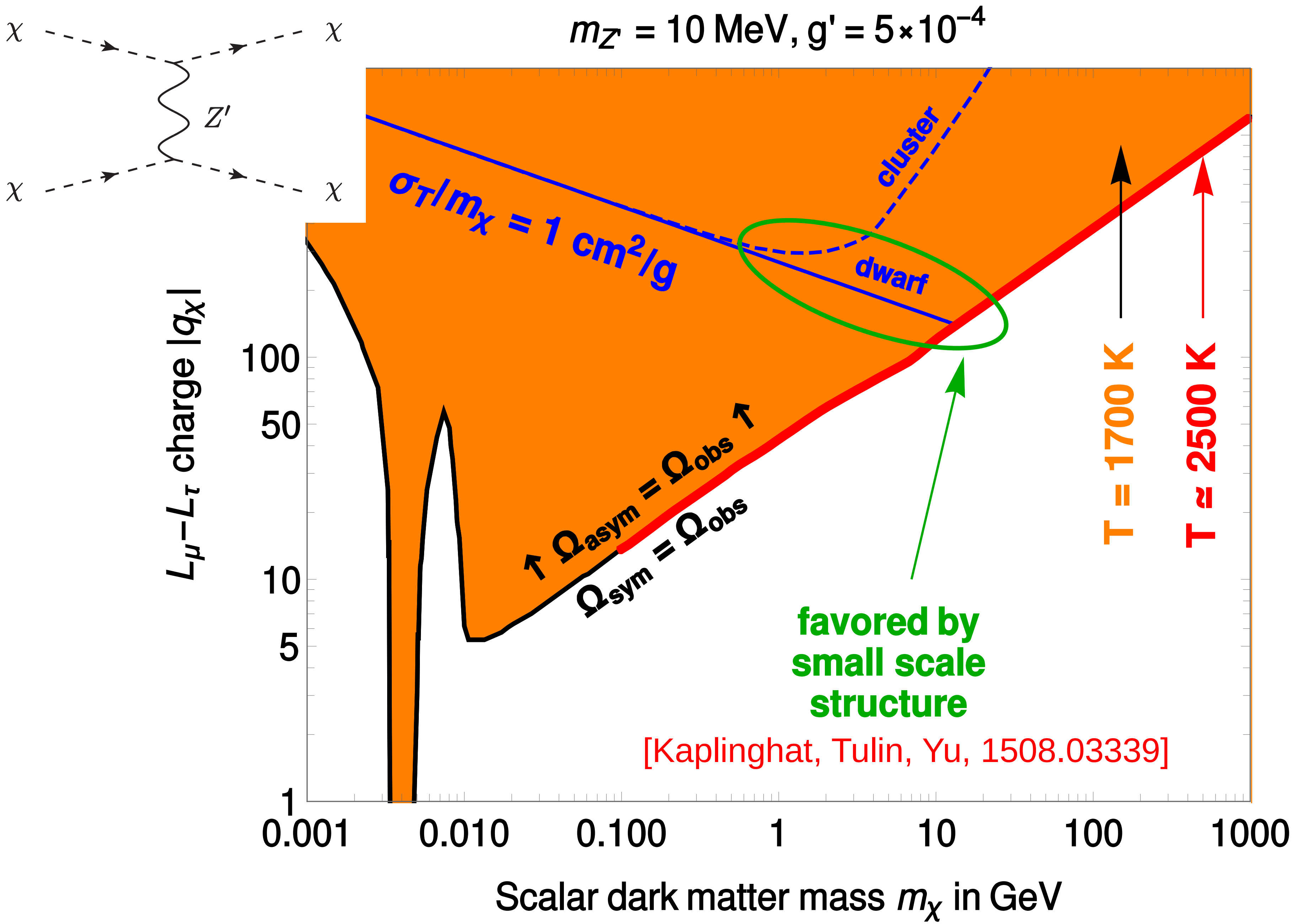

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Summary

- $L_\mu - L_\tau$ interesting U(1) gauge group:
  - Anomaly free & weakly constrained.
  - Could explain $(g\text{-}2)_\mu$ or $\mathrm{b} \to \mathrm{s}\mu\mu$ anomalies.
- $L_\mu - L_\tau$ DM even better:
  - (Light) Z' mediator, stability, asymmetry (?).
  - (In)direct detection suppressed.
  - DM still captured in neutron stars → heating!
  - Light Z' allows for self-interactions $\sigma/\mathrm{m} \sim 1\,\mathrm{cm}^2/\mathrm{g}$.
    → Resolves small-scale structure anomalies!

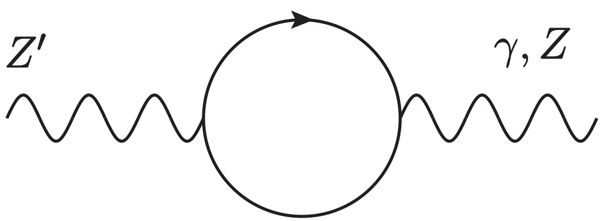
Backup

Kinetic mixing

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

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

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:

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

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