

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

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Muon magnetic moment

- Measured at Brookhaven:

$$a_{\mu}^{\text{exp}} = 116592089(63) \times 10^{-11}.$$

[hep-ex/0602035, ~3k citations]

- Repeated at Fermilab:

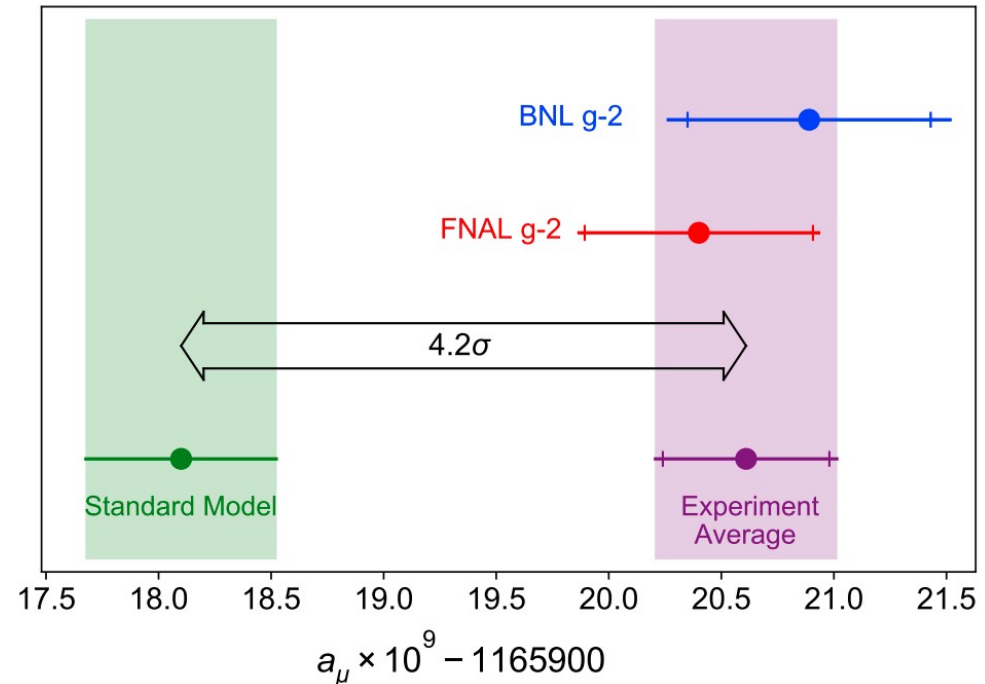
$$a_{\mu}^{\text{exp}} = 116592040(54) \times 10^{-11}.$$

[2104.03281, ~1k citations]

- Difference with SM prediction: [Aoyama+, 2006.04822]

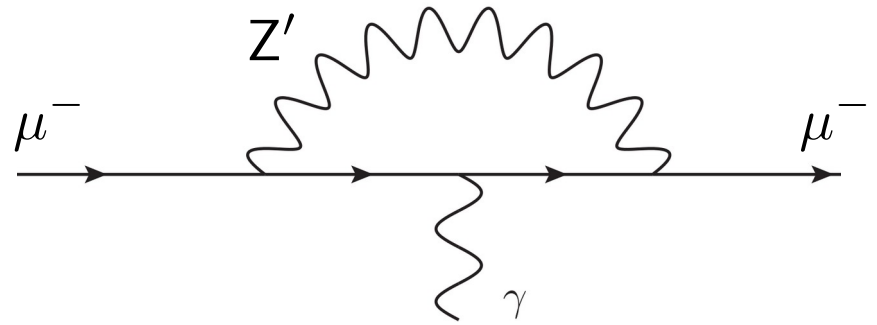
$$a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = (251 \pm 59) \times 10^{-11}. \quad (4\sigma)$$

- Anomalous moment $a = (g-2)/2$ is anomalous!
- More data and more hadronic calculations on the way.
- Reliable anomaly, explain via new particles in loop!



Z' constraints

- For $M_{Z'} < 10 \text{ MeV}$: BBN & CMB constraints on N_{eff} . [Escudero+ '19]
- Couplings of electron « muon.
- Couplings to quarks *suppressed* to satisfy neutrino oscillations in matter.



[JH, Lindner, Rodejohann, Vogl, '19;
Coloma, Gonzalez-Garcia, Maltoni, '21]

- Couple to μ but not e & q .
- Only anomaly-free Z':

$$U(1)_{L_\mu - L_\tau}$$

[tiny loophole: Greljo+ '22]

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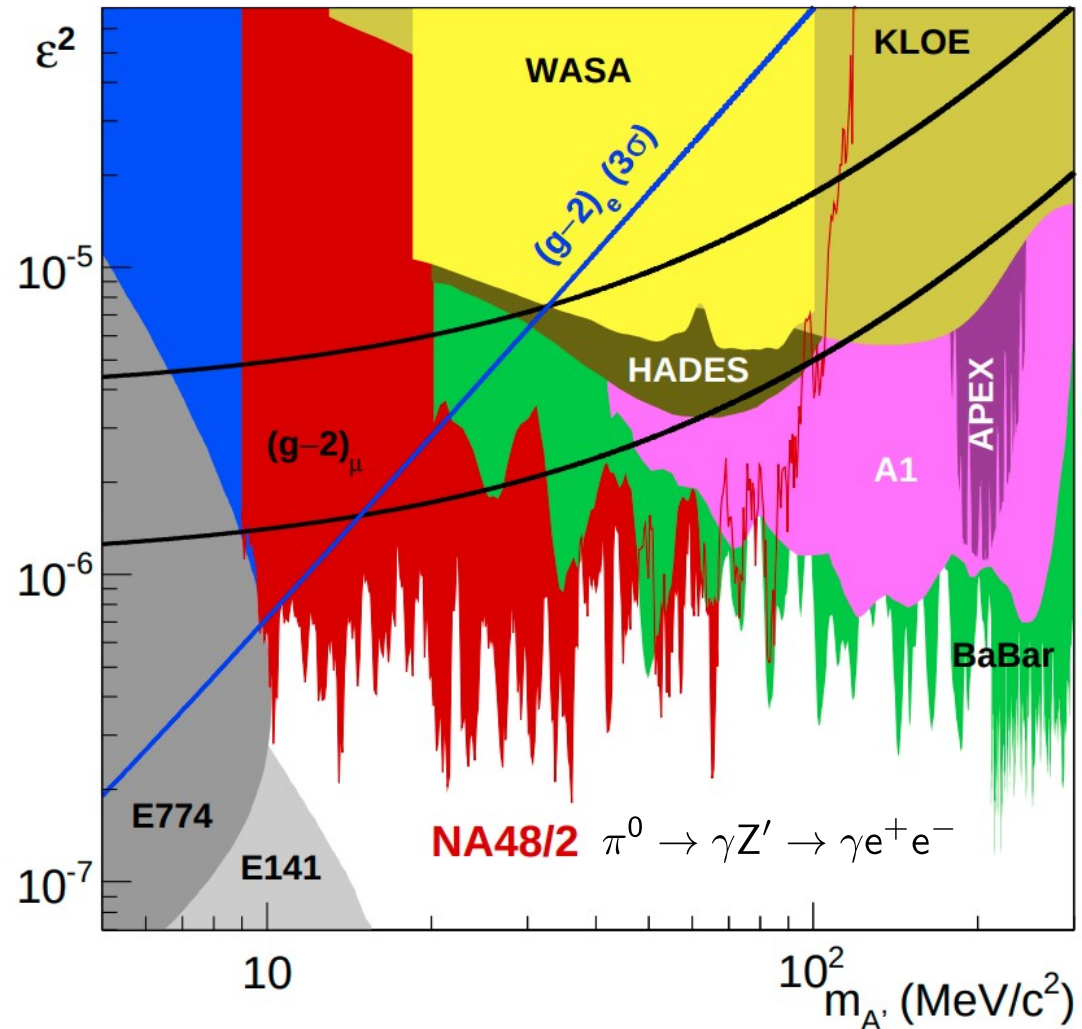
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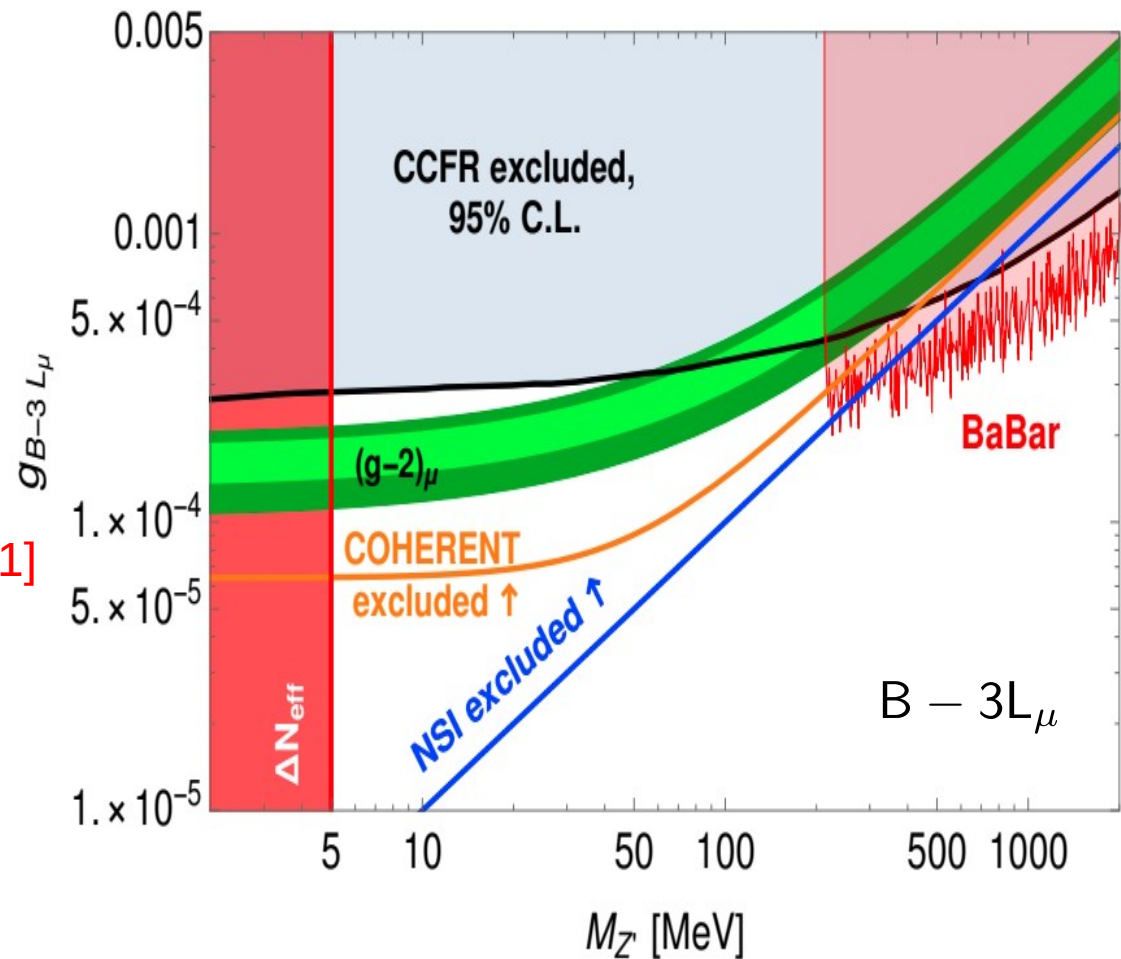
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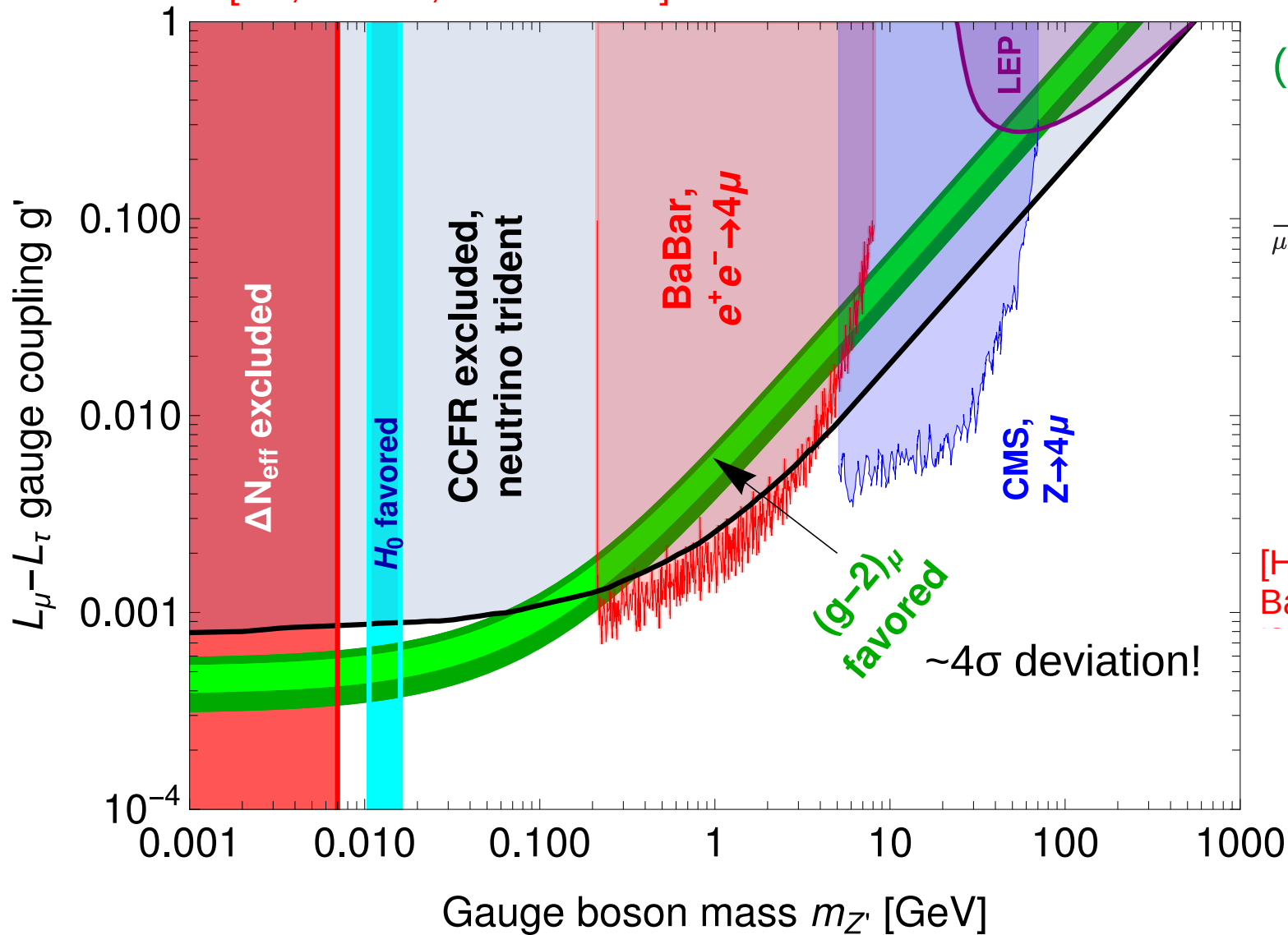
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[tiny loophole: Greljo+ '22]

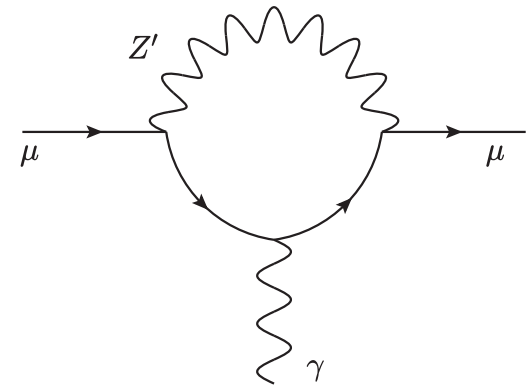


Current $L_\mu - L_\tau$ constraints

[JH, Garani, 1906.10145]



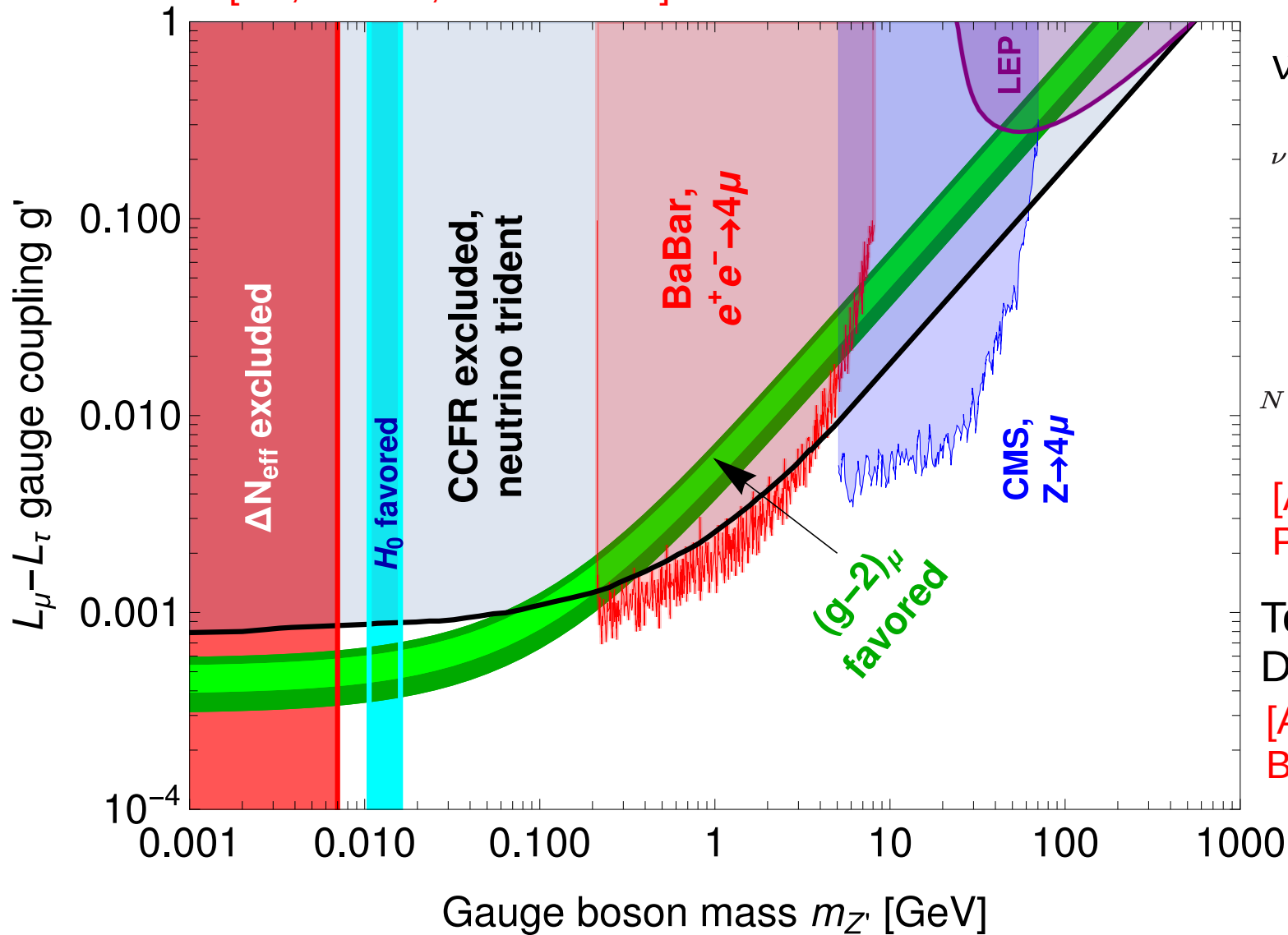
$(g-2)_\mu$:



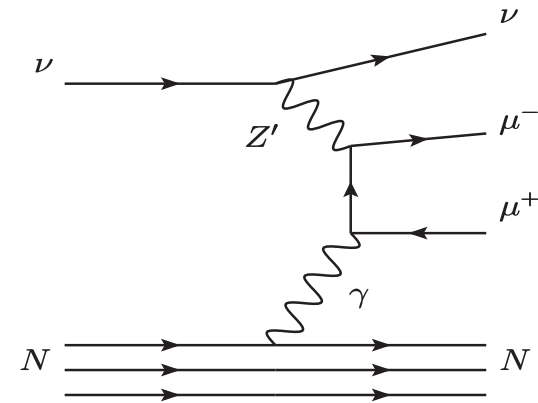
[He, Joshi, Lew, Volkas, '91;
Baek, Deshpande, He, Ko,
Ma, Roy, Roy, '02]

Current $L_\mu - L_\tau$ constraints

[JH, Garani, 1906.10145]



ν trident:



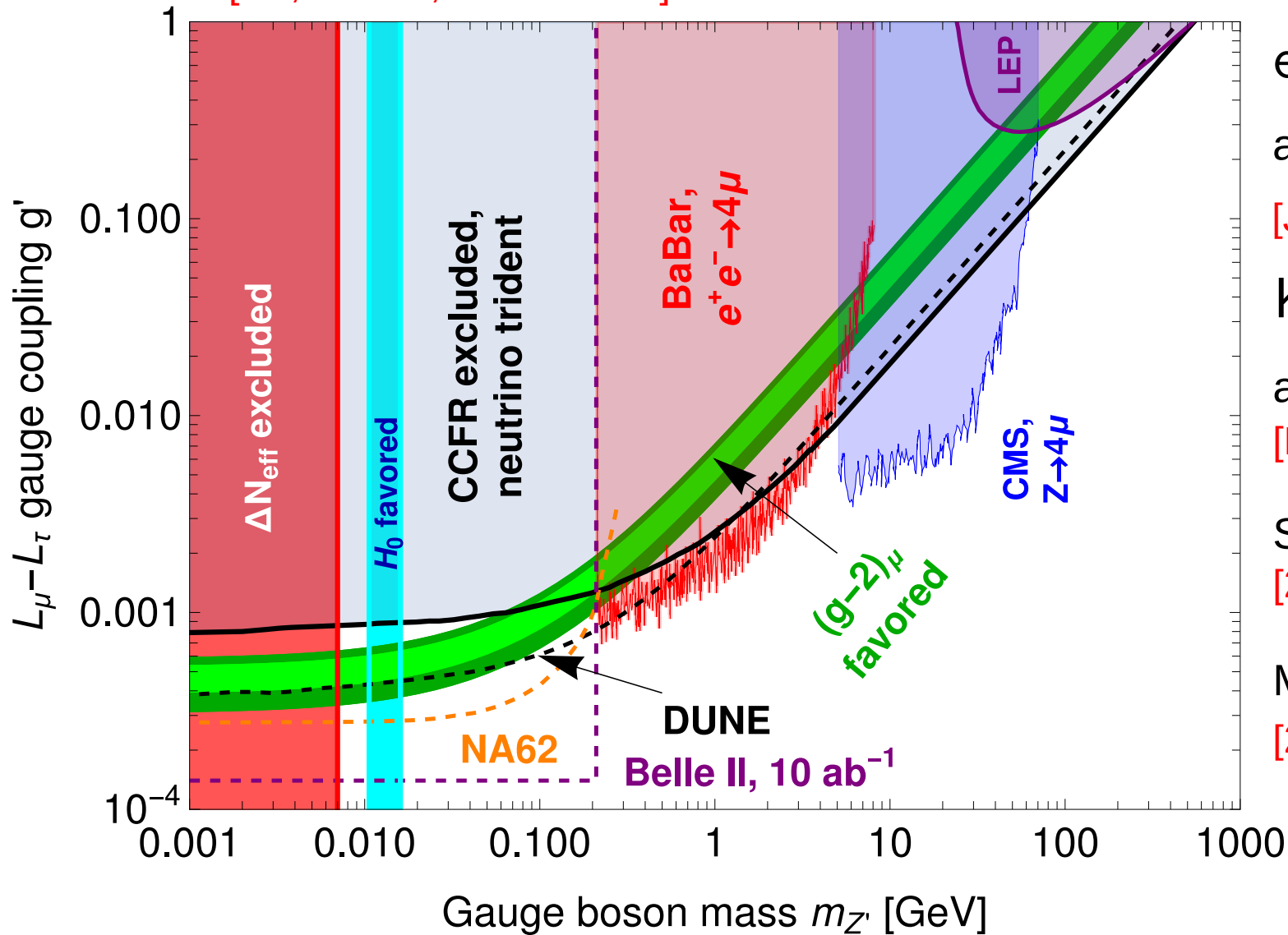
[Altmannshofer, Gori, Pospelov, Yavin, '14]

To be improved by DUNE!

[Altmannshofer+ '19; Ballett+ '19]

Future $L_\mu - L_\tau$ constraints

[JH, Garani, 1906.10145]



Invisible Z' :

$$e^+e^- \rightarrow \mu^+\mu^-Z'$$

at Belle II.

[Jho+, 1904.13053]

$$K \rightarrow \mu\nu Z'$$

at NA62.

[Krnjaic+, 1902.07715]

See also NA64:

[2206.03101]

MUonE:

[2109.10093]

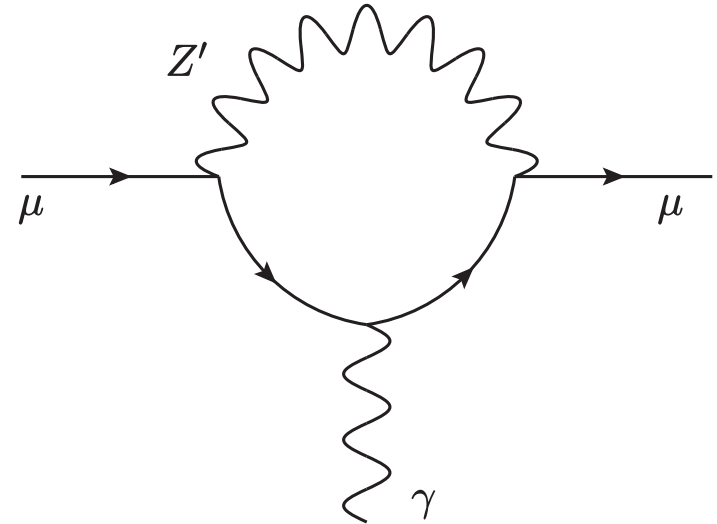
**$g-2$ motivated
region entirely
testable!**

We did it!

- Resolved **muon g-2** via gauge boson à la Schwinger!
- $U(1)_{L_\mu - L_\tau}$ needs

$$g' \simeq 5 \times 10^{-4} - 10^{-3},$$
$$M_{Z'} \simeq 10 - 200 \text{ MeV}.$$

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

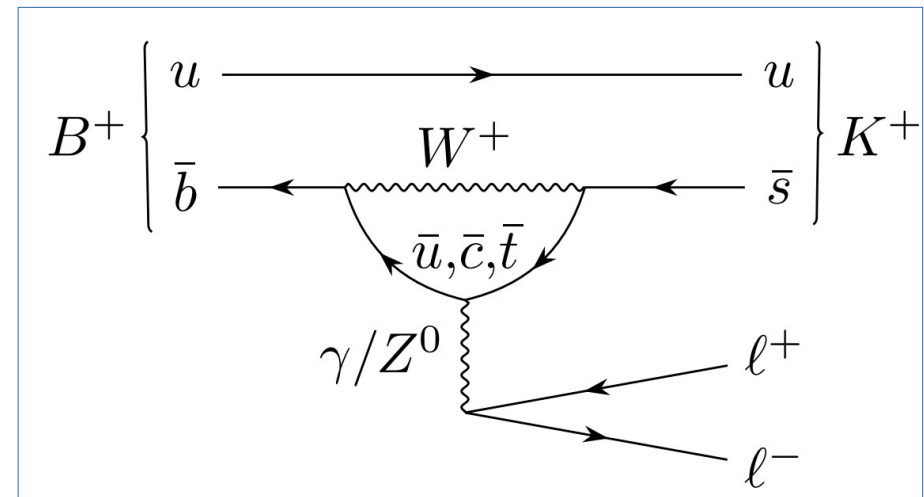


What else can $L_\mu - L_\tau$ do?

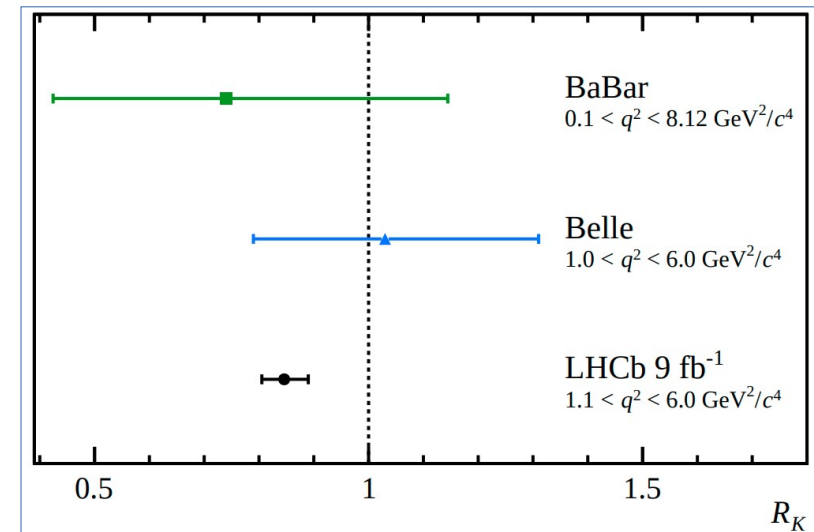
It induces lepton-flavor non-universality: e, μ, τ interact differently!

$$R_{K^{(*)}} \equiv \frac{\Gamma(B \rightarrow K^{(*)} \mu \mu)}{\Gamma(B \rightarrow K^{(*)} e e)}$$

- Neutral current,
loop-level SM: $R_{K^{(*)}} \simeq 1$.
- **LHCb** anomaly:
 - $R(K) = 0.85$, (3σ)
 - $R(K^*) = 0.69$, (2.5σ)



[LHCb, Nature '22]



Belle II will increase significance!

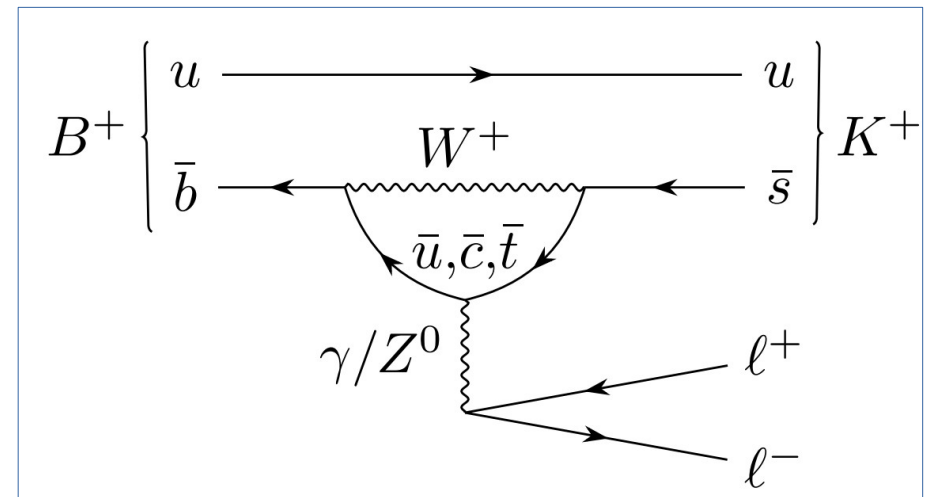
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- Neutral current,
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- **LHCb anomaly**:
 - $R(K) = 0.85$, (3σ)
 - $R(K^*) = 0.69$. (2.5σ)
- Global fit to all $b \rightarrow s \mu \mu$ data:
new operator

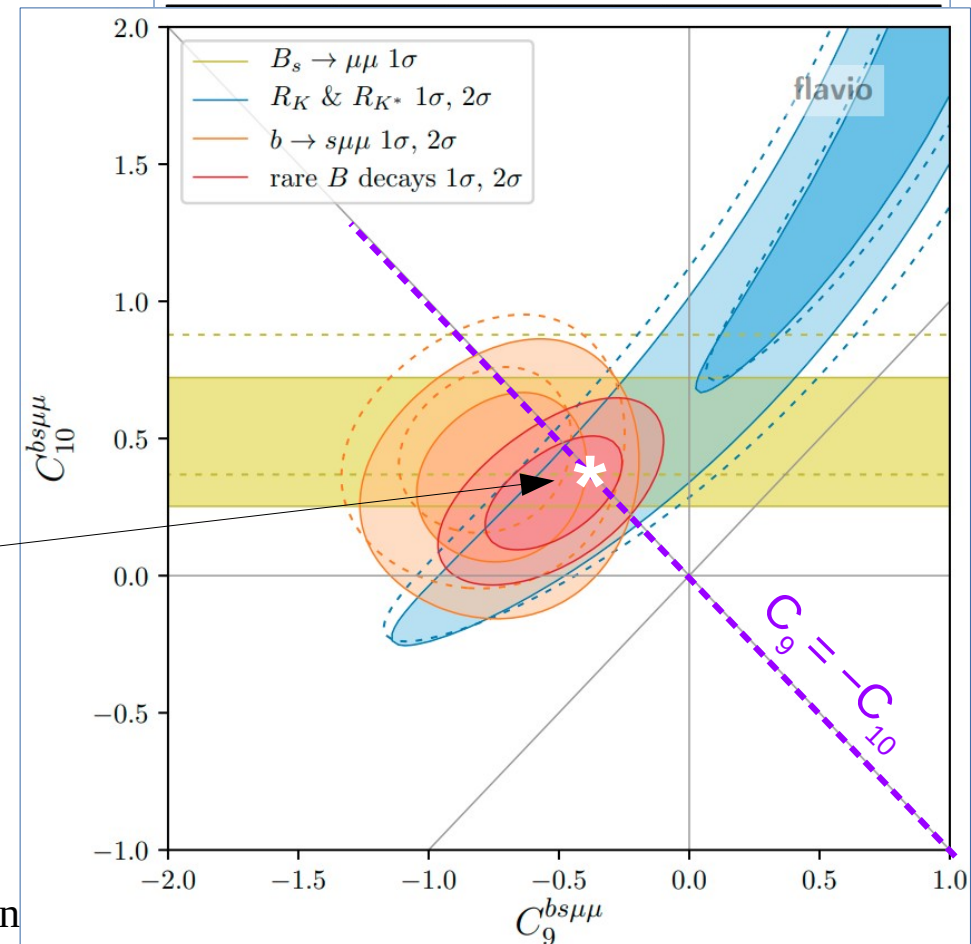
$$\frac{1}{(35 \text{ TeV})^2} \bar{s} \gamma_\alpha P_L b \bar{\mu} \gamma^\alpha P_L \mu.$$

preferred at **5.6σ** !

[other fits agree, e.g. 2104.08921]

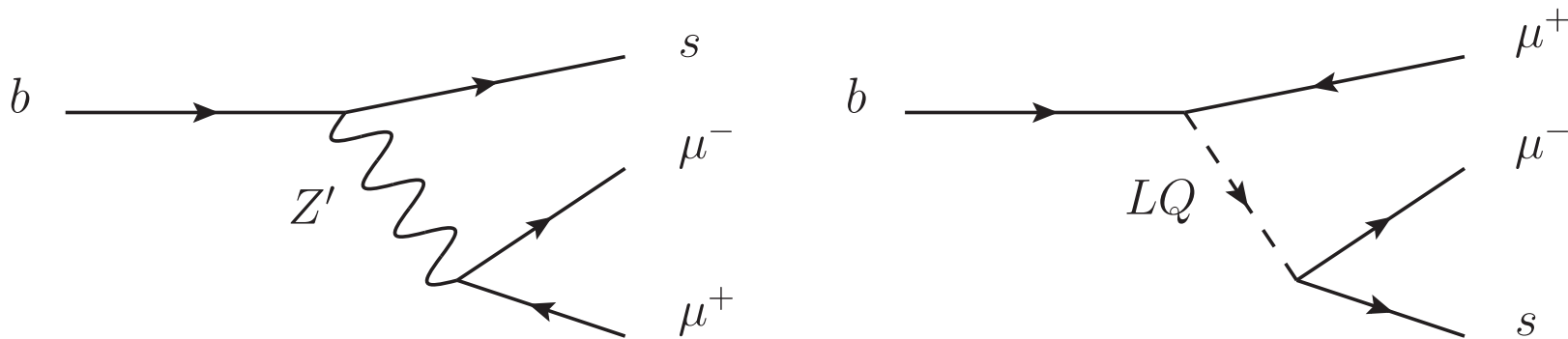


[Altmannshofer, Stangl, 2103.13370]



New-physics implications

- How do you get this operator $\frac{1}{(35 \text{ TeV})^2} \bar{s} \gamma_\alpha P_L b \bar{\mu} \gamma^\alpha P_L \mu$?
- Tree level: **Z'** or **leptoquark**. [see hep-ph]



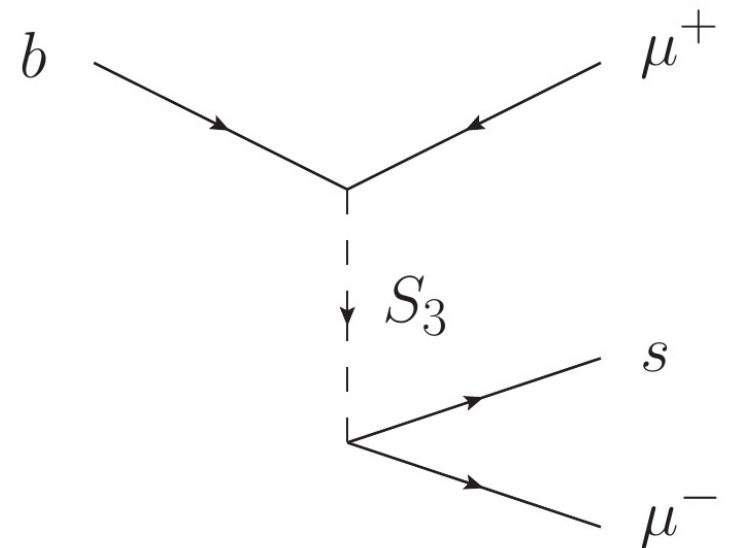
- Heavy Z' could be modification of $L_\mu - L_\tau$, but no Δa_μ .
- Unique scalar leptoquark: $S_3 \sim (\mathbf{3}, \mathbf{3}, -1/3)$. [Angelescu+, '18 & '21]

$$\mathcal{L} = y_{ij} \bar{Q}_i S_3 L_j^c + x_{ij} Q_i Q_j S_3$$

- Leads to **proton decay** and lepton-flavor violation!

More anomalies with $L_\mu - L_\tau$

- Can use $L_\mu - L_\tau$ to forbid couplings.
- Take leptoquark $S_3 \sim (\mathbf{3}, \mathbf{3}, -1/3)$: $\mathcal{L} = y_{ij} \bar{Q}_i S_3 L_j^c + x_{ij} Q_i Q_j S_3$
- 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]
- $L_\mu - L_\tau$ ideal symmetry for LFUV in **$b \rightarrow s \mu \mu$** decays.



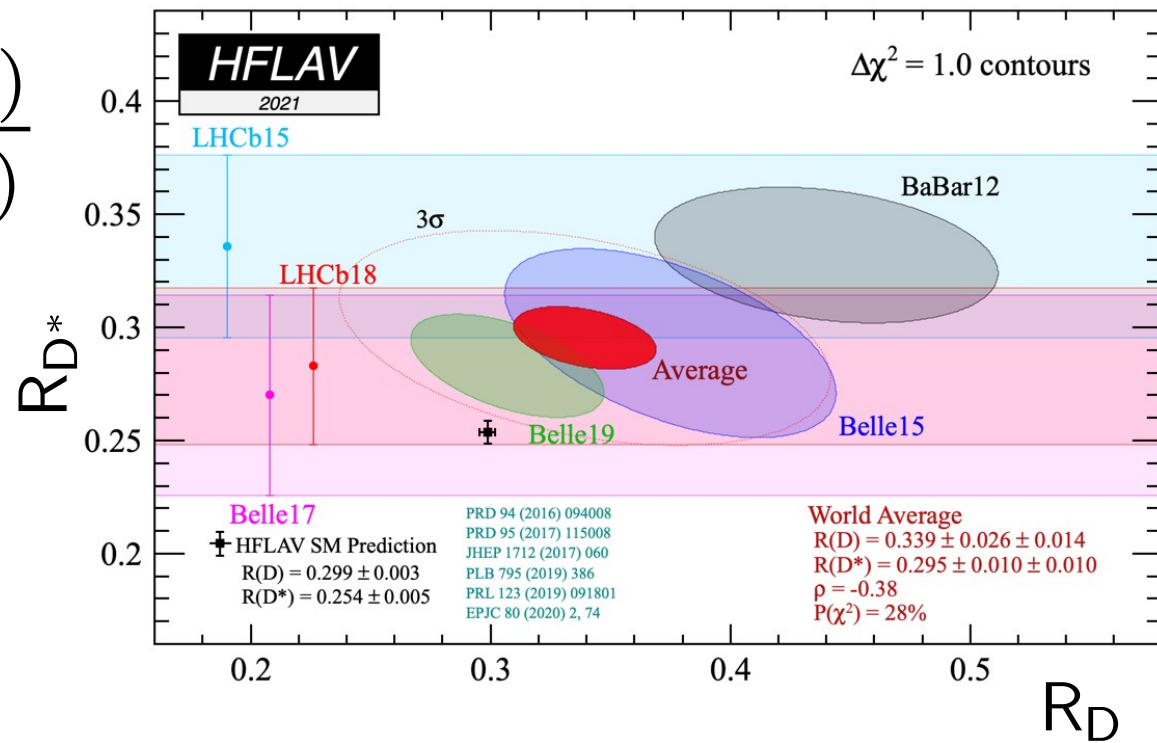
$$R_{D^{(*)}} \equiv \frac{\Gamma(\bar{B} \rightarrow D^{(*)} \tau \nu)}{\Gamma(\bar{B} \rightarrow D^{(*)} \ell \nu)}$$

- Charged current, *tree-level* SM.
- LHCb, BaBar, Belle.
- Good operator

$$\frac{1}{(3 \text{ TeV})^2} \bar{c} \gamma_\alpha P_L b \bar{\tau} \gamma^\alpha P_L \nu.$$

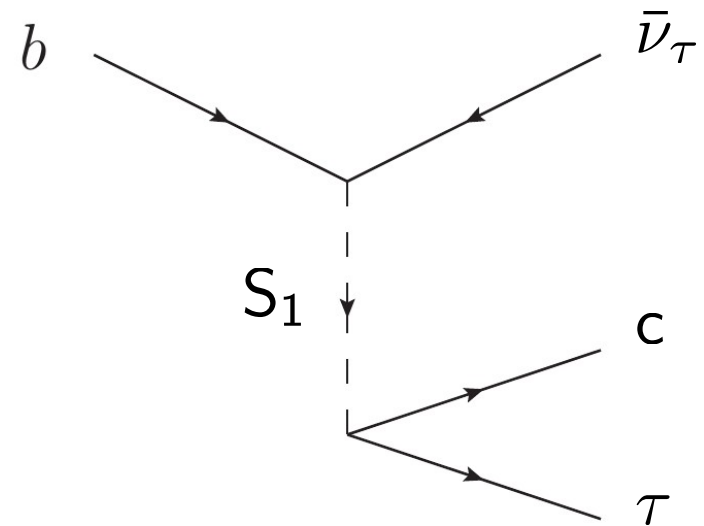
[HFLAV; Bernlochner+, '17; Di Luzio+, '17;...]

- Low scale, many constraints: $B \rightarrow K \nu \nu$, $B_c \rightarrow \tau \nu$. [Li+, 1605.09308; Alonso+, 1611.06676]
- ~~H^\pm~~ or **leptoquark** (S_1 or R_2). [Angelescu+, '18 & '21]
 - Same problem: proton decay and lepton flavor violation!



Even more anomalies with $L_\mu - L_\tau$

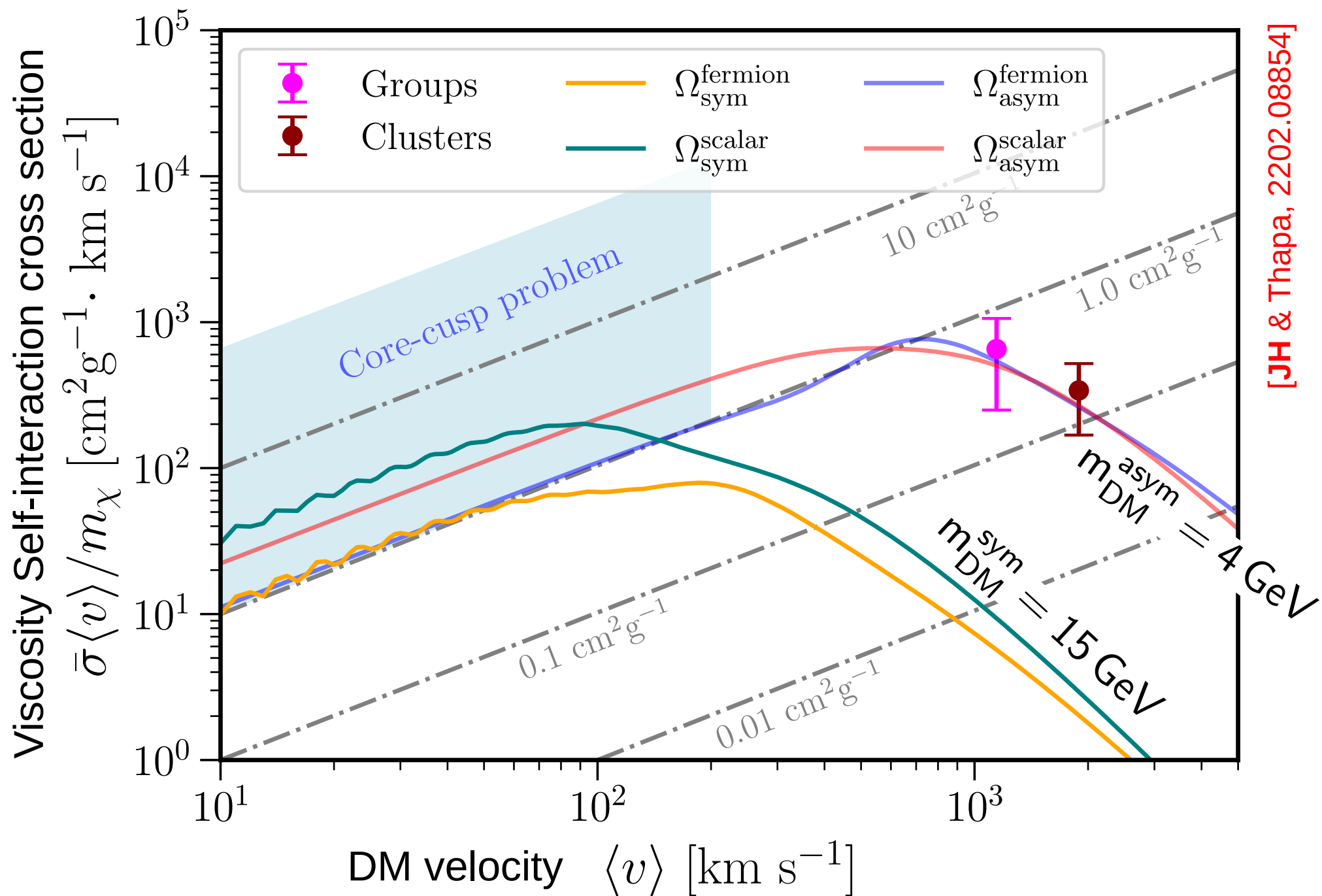
- Can use $L_\mu - L_\tau$ to forbid couplings.
- Take LQ $S_1 \sim (\mathbf{3}, \mathbf{1}, -1/3)$: $\mathcal{L} = y_{ij} \bar{Q}_i S_1 L_j^c + x_{ij} Q_i Q_j S_1 + \dots$
- Charge $S_1 \sim -1$ under $L_\mu - L_\tau$ to get $x_{ij} = 0$, $y_{ij} = y_{i\tau}$.
→ no more **proton decay**, no **lepton flavor violation**,
only coupling to **tauons**!
- Perfect for **$R(D)$ & $R(D^*)$** !
[Angelescu+, 2103.12504, Greljo+, 2103.13991; **JH** & Thapa, 2202.08854]
- $L_\mu - L_\tau$ ideal symmetry for LFUV in **$b \rightarrow c \tau \nu$** decays.



Dark matter from $L_\mu - L_\tau$?

- DM under $U(1)_{L_\mu - L_\tau}$: stability, Z' mediator, asymmetry (?).
[Cirelli, Kadastik, Raidal, Strumia, 0809.2409; Baek, Ko, 0811.1646; Foldenauer, PRD '19; Hapitas, Tuckler, Zhang, 2108.12440; Holst, Hooper, Krnjaic, PRL '22]
- **No** constraints from **direct detection**.
 - (Although DM heats up **neutron stars**!) [JH, Garani, 1906.10145]
- Z' mediator light: $DM\ DM \rightarrow Z' Z'$.
 - Indirect detection ($DM\ DM \rightarrow$ neutrinos) suppressed.
 - Large **DM self interactions**? [Kamada+, '18]
 - Velocity-dependent σ for light Z' ! [JH & Thapa, 2202.08854]
 - Can resolve small-scale structure problems!
[Kaplinghat, Tulin, Yu, 1508.03339]

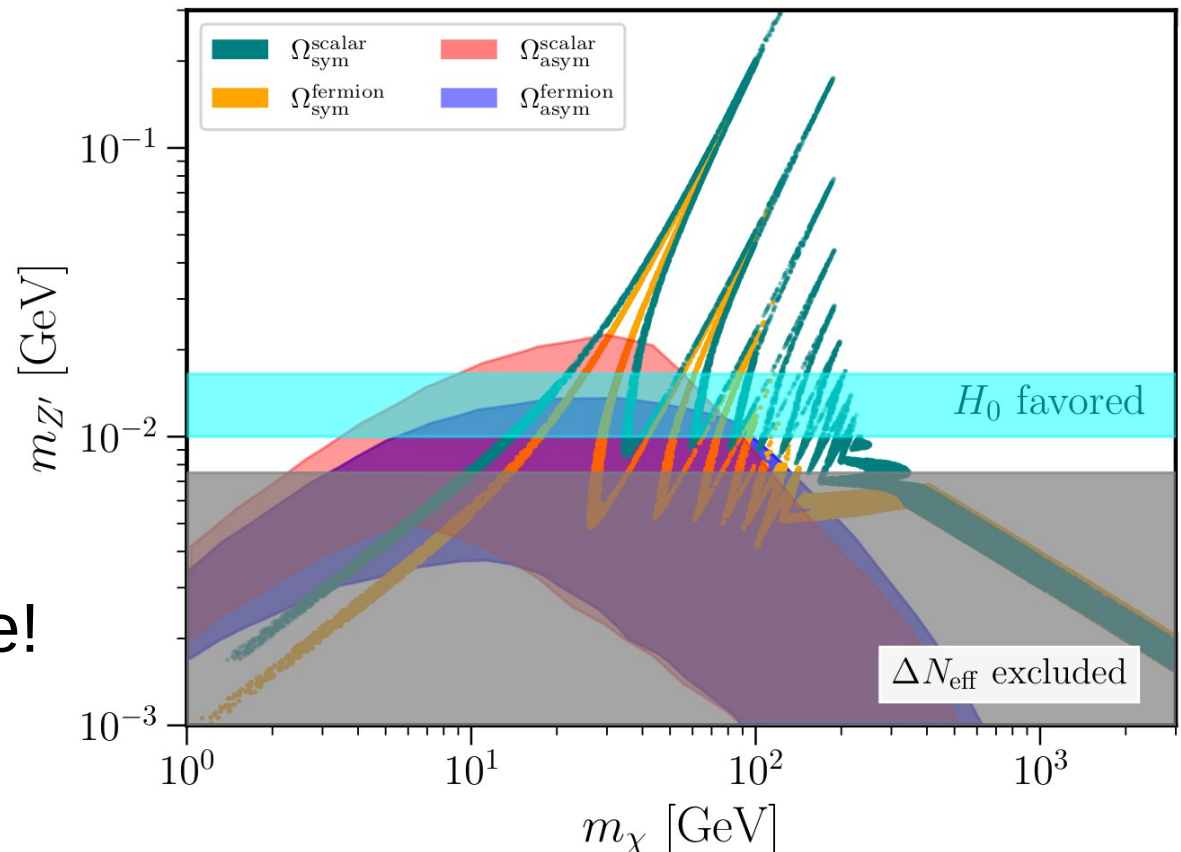
$m_{Z'} = 10 \text{ MeV}$



Small scale structure

- Self-interacting DM cross sections $\sigma/m \sim 1 \text{ cm}^2/\text{g}$ preferred at **small scales** but disfavored in **clusters**.
- Z' Yukawa potential gives good velocity dependence for light Z' ! [Kaplinghat, Tulin, Yu, 1508.03339, PRL '16]
- $L_\mu - L_\tau$ 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]

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 $S_1 \sim (\mathbf{3}, \mathbf{1}, -1/3)$ with $L_\mu - L_\tau \sim -1$ to explain $R(D)$ and LQ $S_3 \sim (\mathbf{3}, \mathbf{3}, -1/3)$ with $L_\mu - L_\tau \sim +1$ 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 particles under $L_\mu - L_\tau$.
 - Stability through $U(1)' \rightarrow$ dark matter!
 - Relic abundance through Z' .
 - Self-interactions via light Z' explain **small-scale structure**!

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

Backup

How to get Z'?

- Simplest: promote **global symmetries** of SM:

$$\underbrace{U(\cancel{1})_{B+L}}_{\text{Anomalous. [t Hooft, '76]}} \times \underbrace{U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}}_{\text{Gauge by adding 3 right-handed neutrinos. [Araki, JH, Kubo, '12; He+ '91]}} \times \underbrace{U(1)'}_{\text{Coupling via kinetic mixing. [Galison, Manohar, '84]}}.$$

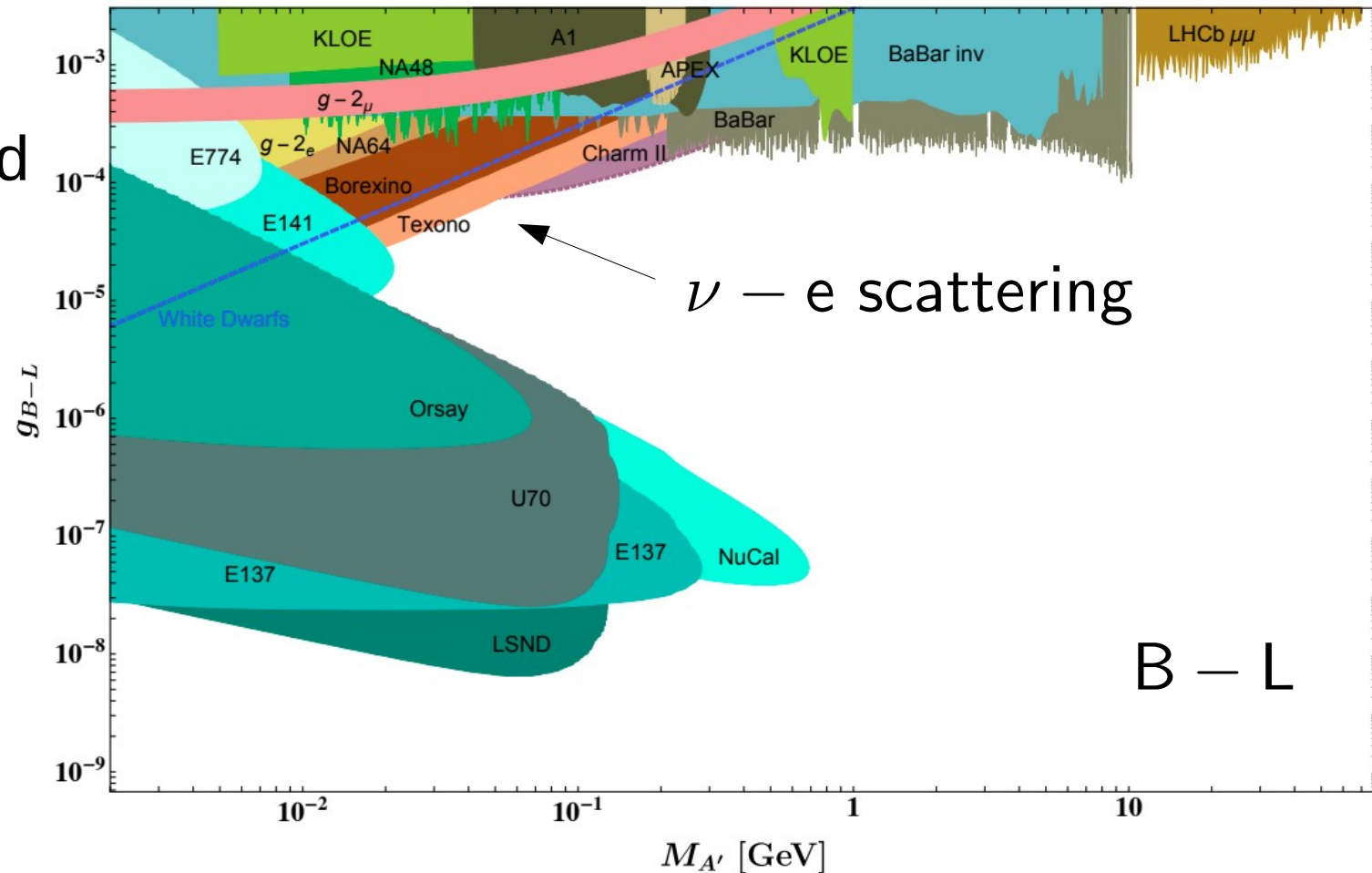
- All give desired Z' **vector coupling** to muons, could mix.
- (More general: charge vector-like fermions under U(1) and mix them with SM fermions. → Arbitrary Z' couplings.) [Fox+ '11]

Baryon minus lepton number

- Z' couplings to **all** SM fermions.
- Δa_μ long excluded by neutrino scattering.

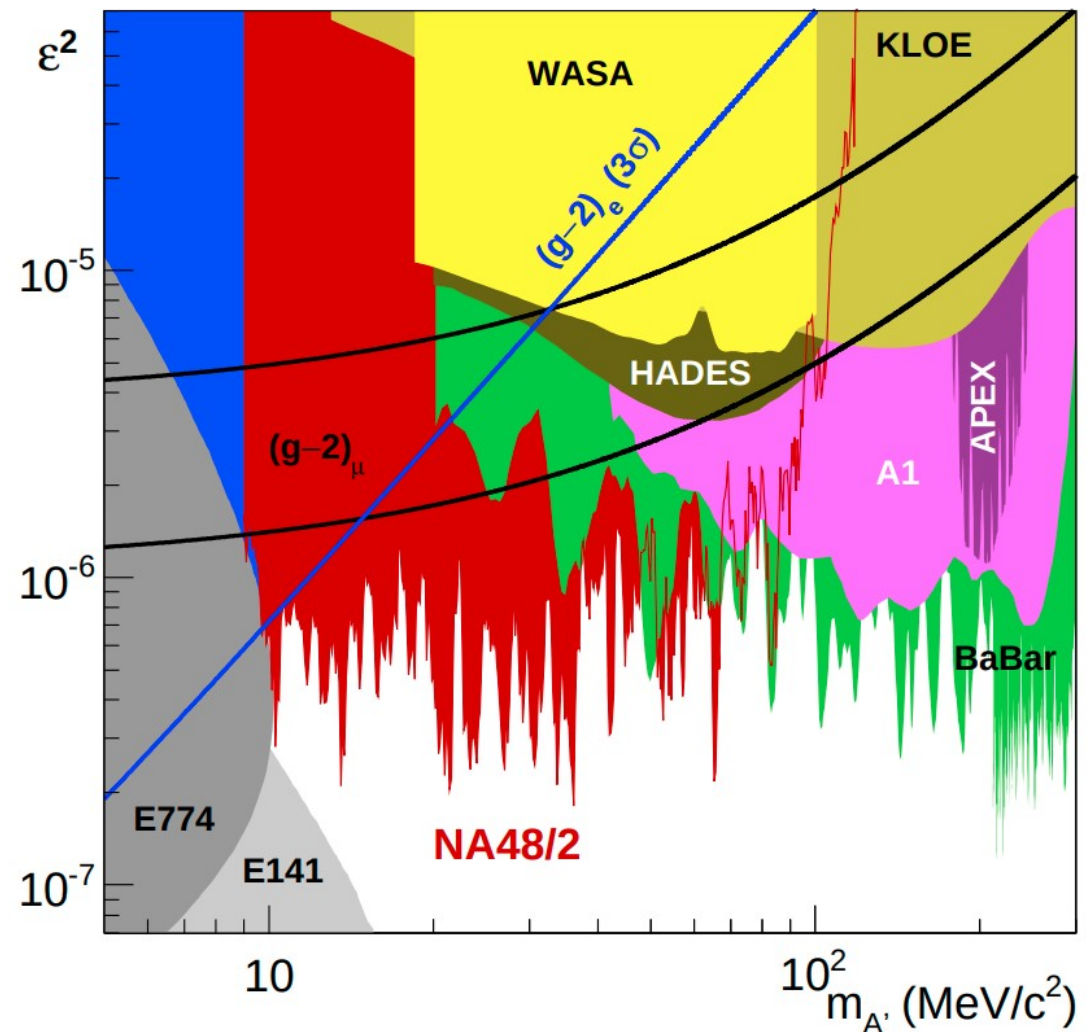
[JH '14; Bauer, Foldenauer, Jaeckel, '18; Ilten, Soreq, Williams, Xue, '18]

- Couplings to electrons and neutrinos exclude $g-2$ region.
- Turn off neutrino couplings?



U(1)': Dark photon

- Massive Z' couples to SM via kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$
- Z' couplings proportional to **electric charge**.
- Constraints from e.g.
 $\pi^0 \rightarrow \gamma Z' \rightarrow \gamma e^+ e^-$
 at NA48/2 [PLB '15]
 and many other
 electron observables.
- Cannot explain Δa_μ .
- Suppress $Z' \rightarrow e^+ e^-$?
 [Mohlabeng, '19]

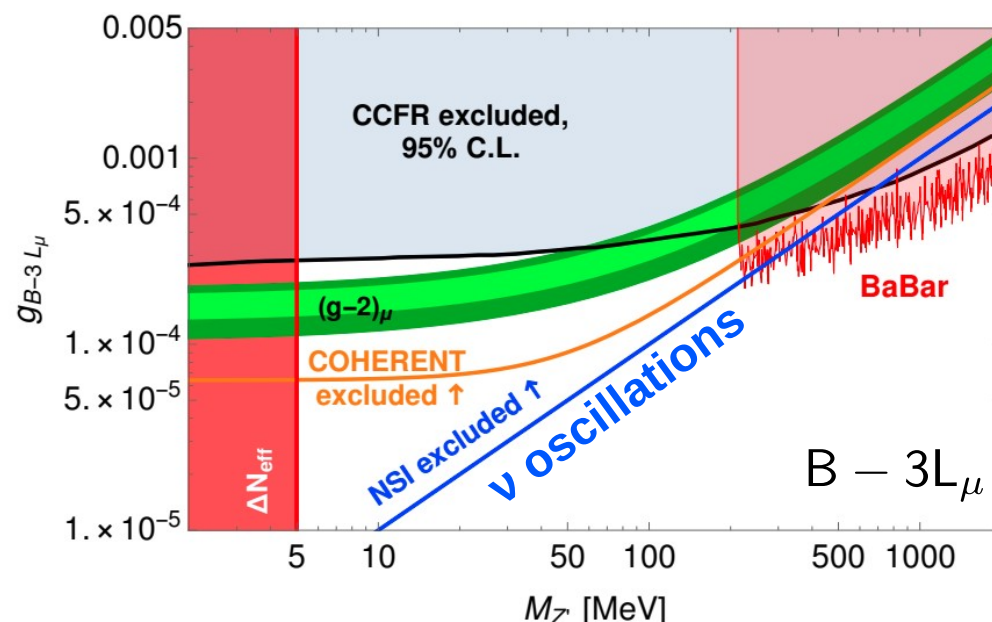
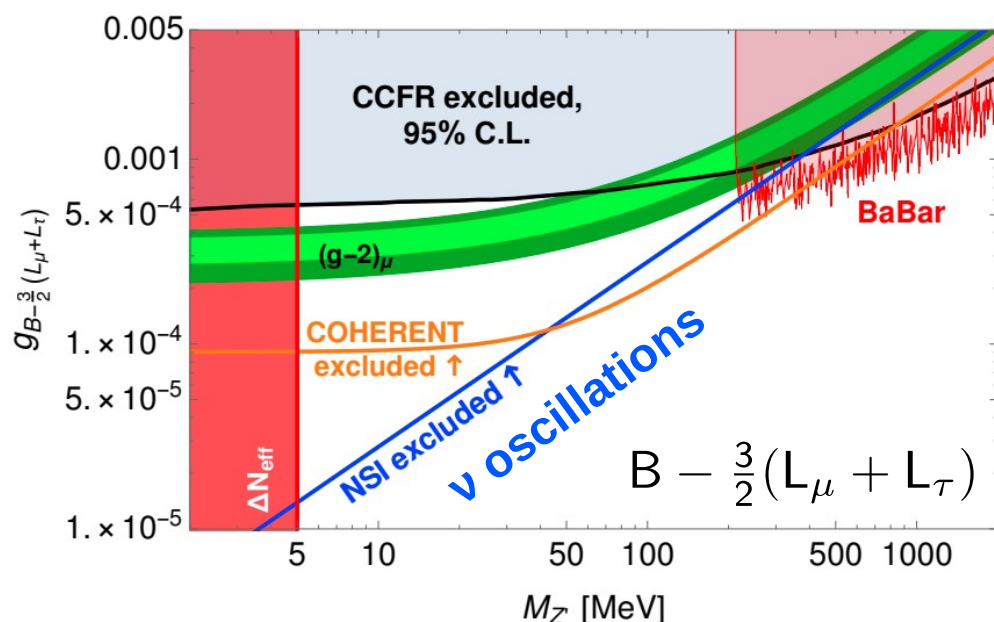


Electronphobic Z'

- Pick electronphobic linear combination of generators

$$U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$$

- Flavor-dependent **neutrino scattering** on quarks/matter!



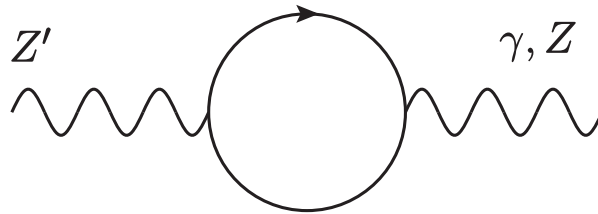
- Neutrino oscillation data excludes Δa_μ region!
[JH, Lindner, Rodejohann, Vogl, '19; Coloma, Gonzalez-Garcia, Maltoni, '21]
- Can't couple to electrons or quarks!

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:

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

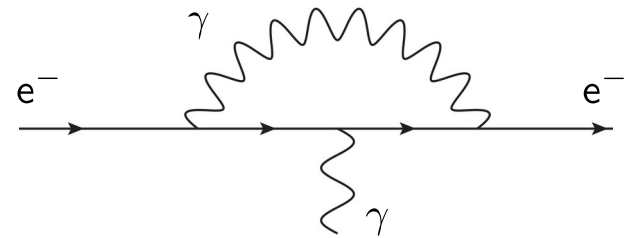
[Kopp, Niro, Schwetz, Zupan, '09; Altmannshofer, Gori, Profumo, Queiroz, '09]

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

Muon magnetic moment (theory)

- Dirac: magnetic moment due to spin is $\mathbf{m} = -g\mu_B\mathbf{S} = -2\mu_B\mathbf{S}$.
- Schwinger '48:

$$g = 2 + \alpha/\pi + \dots$$

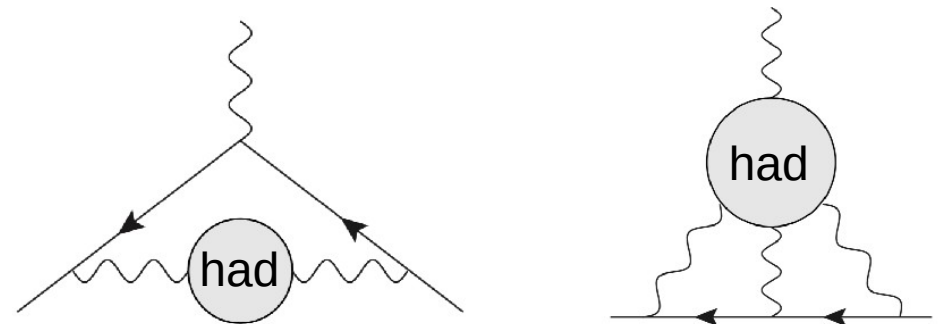


- Today: *anomalous* magnetic moment $a = (g-2)/2$ known to α^5 , plus two-loop order electroweak and hadronic corrections:

$$a_{\mu}^{\text{SM}} = 116591810(43) \times 10^{-11}. \quad [\text{Aoyama+}, 2006.04822]$$

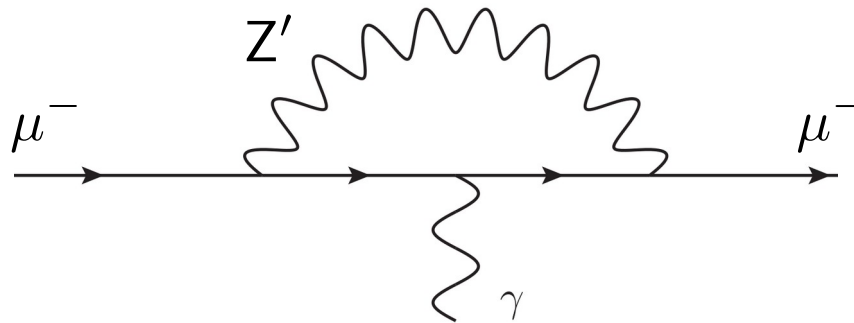
- Main uncertainty: **hadronic!**
Lattice QCD groups *disagree*.

[Borsanyi+, 2002.12347]



New physics

- Simplest resolution of Δa_μ : copy Schwinger.



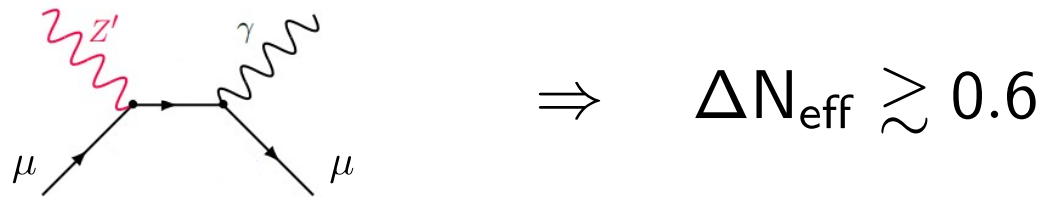
- New gauge boson Z' .

$$\Delta a_\mu \simeq \frac{\alpha'}{2\pi} \quad \Rightarrow \quad \boxed{\alpha' \simeq 1.6 \times 10^{-8}}.$$

Is this allowed?

Too much radiation

- A gauge boson Z' coupled to muons with $\alpha' \simeq 1.6 \times 10^{-8}$ would be **thermalized** with SM in early Universe. [Dolgov '99]



- Contributes too much radiation density at BBN & CMB.
[Planck '18: $\Delta N_{\text{eff}} < 0.3$ @ CMB; Fields+ '20: $\Delta N_{\text{eff}} < 0.4$ @ BBN]

- Save it by making **Z' massive!**

$M_{Z'} \gtrsim 10 \text{ MeV}$ sufficient to suppress N_{eff} . [Escudero+ '19]

(Can even ameliorate Hubble tension around lower bound.)

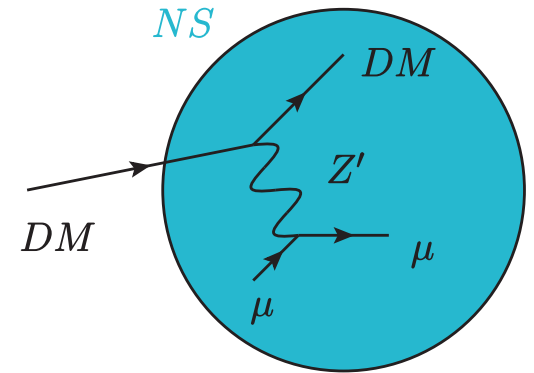
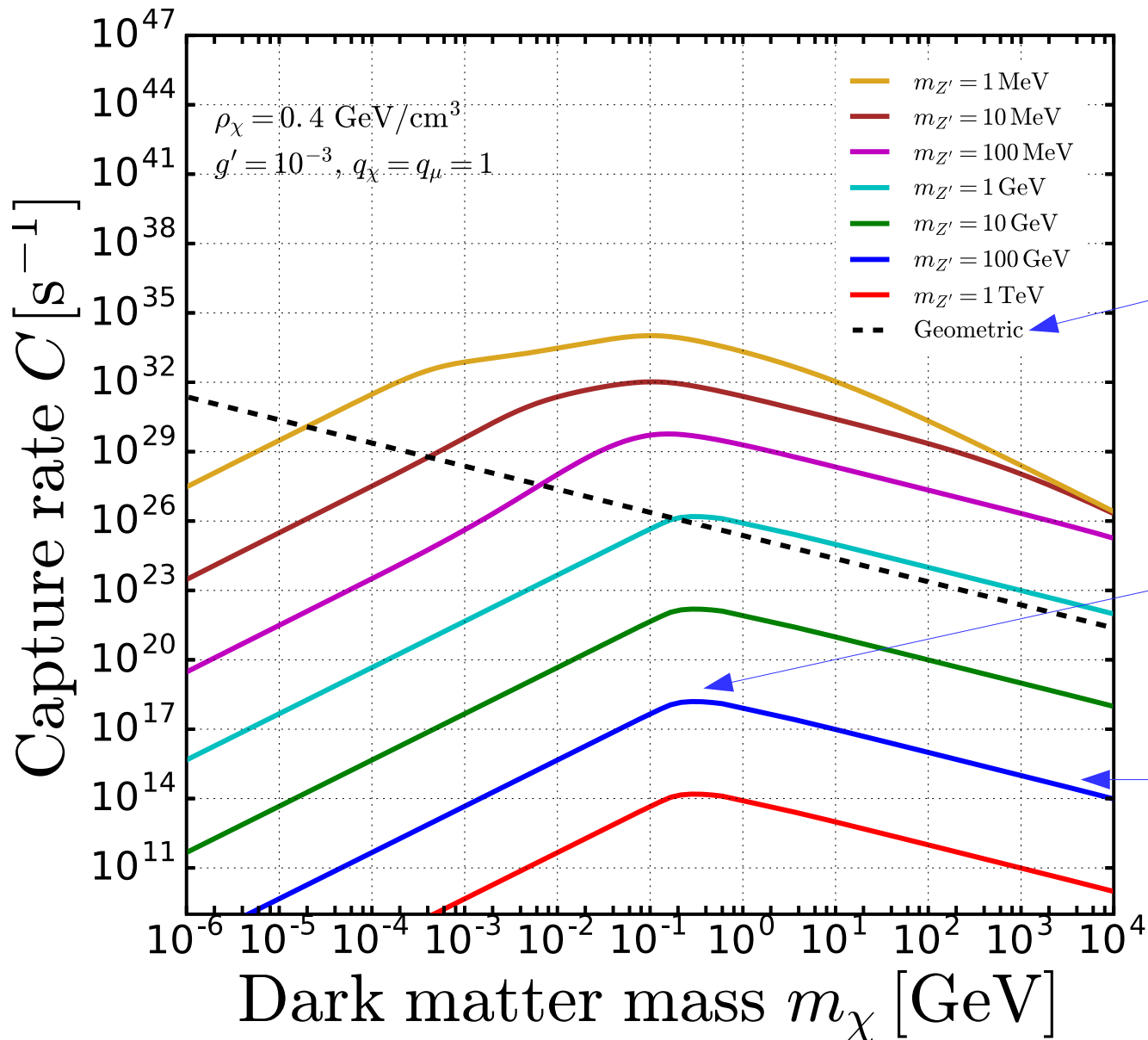
- Heavy Z' : $\Delta a_\mu \simeq \frac{\alpha'}{3\pi} \frac{m_\mu^2}{M_{Z'}^2} \Rightarrow \boxed{M_{Z'}/g' \simeq 190 \text{ GeV} .}$

At electroweak scale, is this allowed?

Dark matter from $L_\mu - L_\tau$?

- DM under $U(1)_{L_\mu - L_\tau}$: stability, Z' mediator, asymmetry(?).
[Cirelli, Kadastik, Raidal, Strumia, 0809.2409; Baek, Ko, 0811.1646; Foldenauer, PRD '19; Hapitas, Tuckler, Zhang, 2108.12440; Holst, Hooper, Krnjaic, PRL '22]
- Z' mediator could be light: $DM\ DM \rightarrow Z' Z'$.
 - Large DM self interactions? [Kamada+, '18; JH & Thapa, 2202.08854]
- **No** constraints from direct detection...
... but could still be captured in neutron stars!
 - NS contain 10^{57} neutrons and 10^{55} muons.
[Garani, Genolini, Hambye, 1812.08773; Bell, Busoni, Robles, 1904.09803]
 - Capture for $\sigma_{DM\mu} > 5 \times 10^{-43} \text{cm}^2$.
 - Also take Pauli blocking and velocities into account.
[JH, Garani, 1906.10145]

DM capture in neutron star?



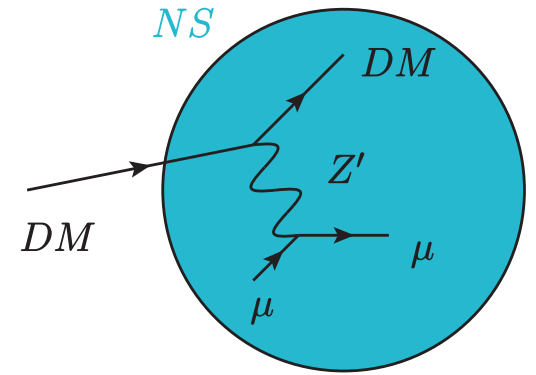
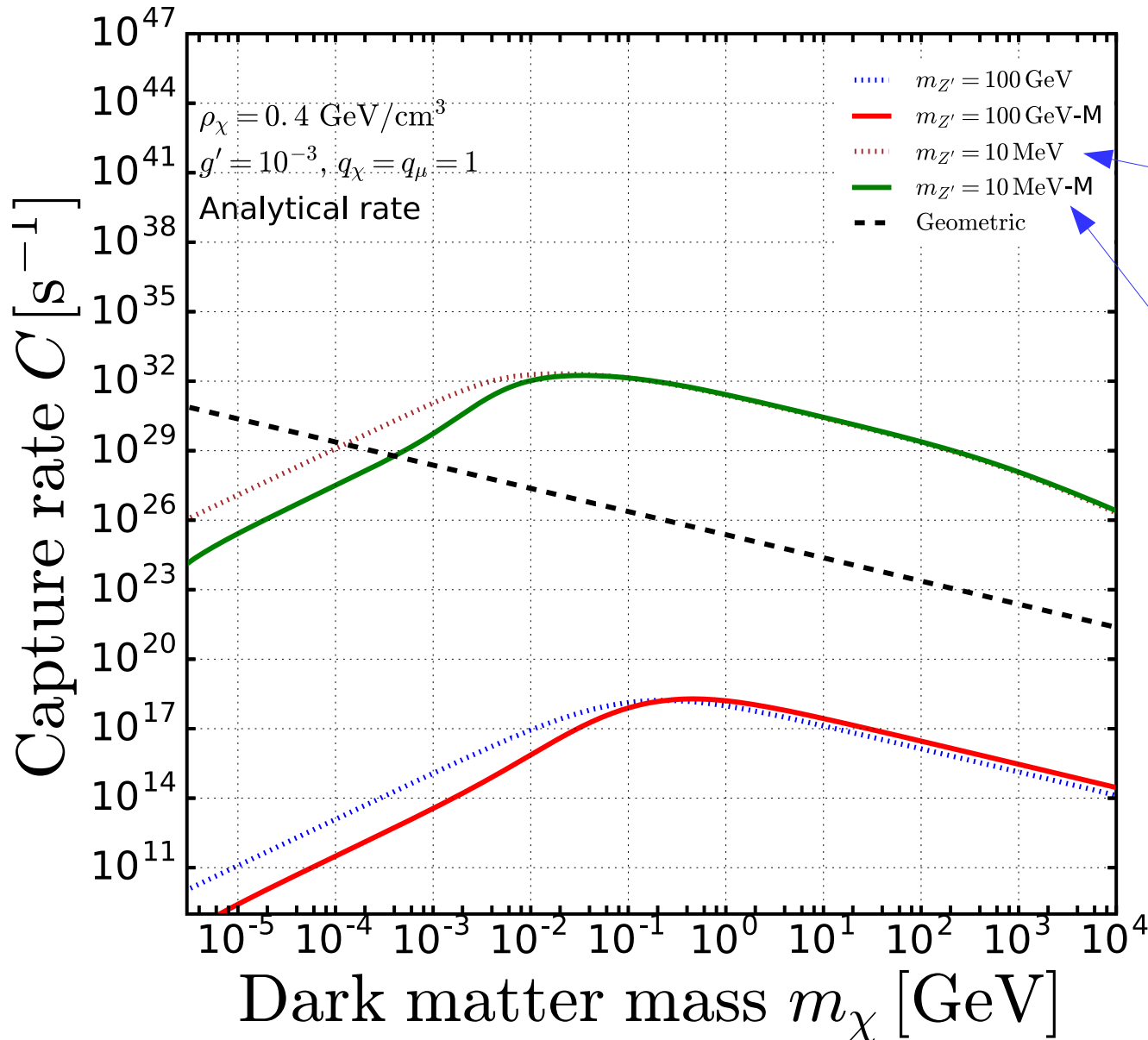
Everything is captured!

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

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

[JH, Garani, 1906.10145]

Scalar~Dirac~Majorana DM



Dirac DM

$$\bar{\chi} \gamma_\alpha \chi \bar{\mu} \gamma^\alpha \mu$$

Majorana DM

$$\bar{\chi} \gamma_\alpha \gamma_5 \chi \bar{\mu} \gamma^\alpha \mu$$

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?

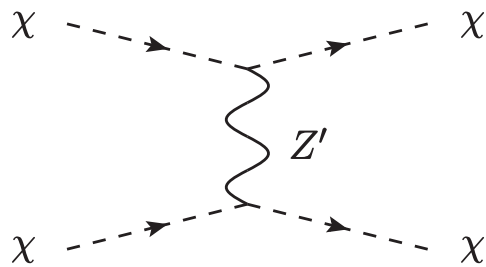
- **Asymmetric DM**: collect enough to form black hole?

- Fermi pressure. ⚡

[Kouvaris, Tinyakov, '10, '11]

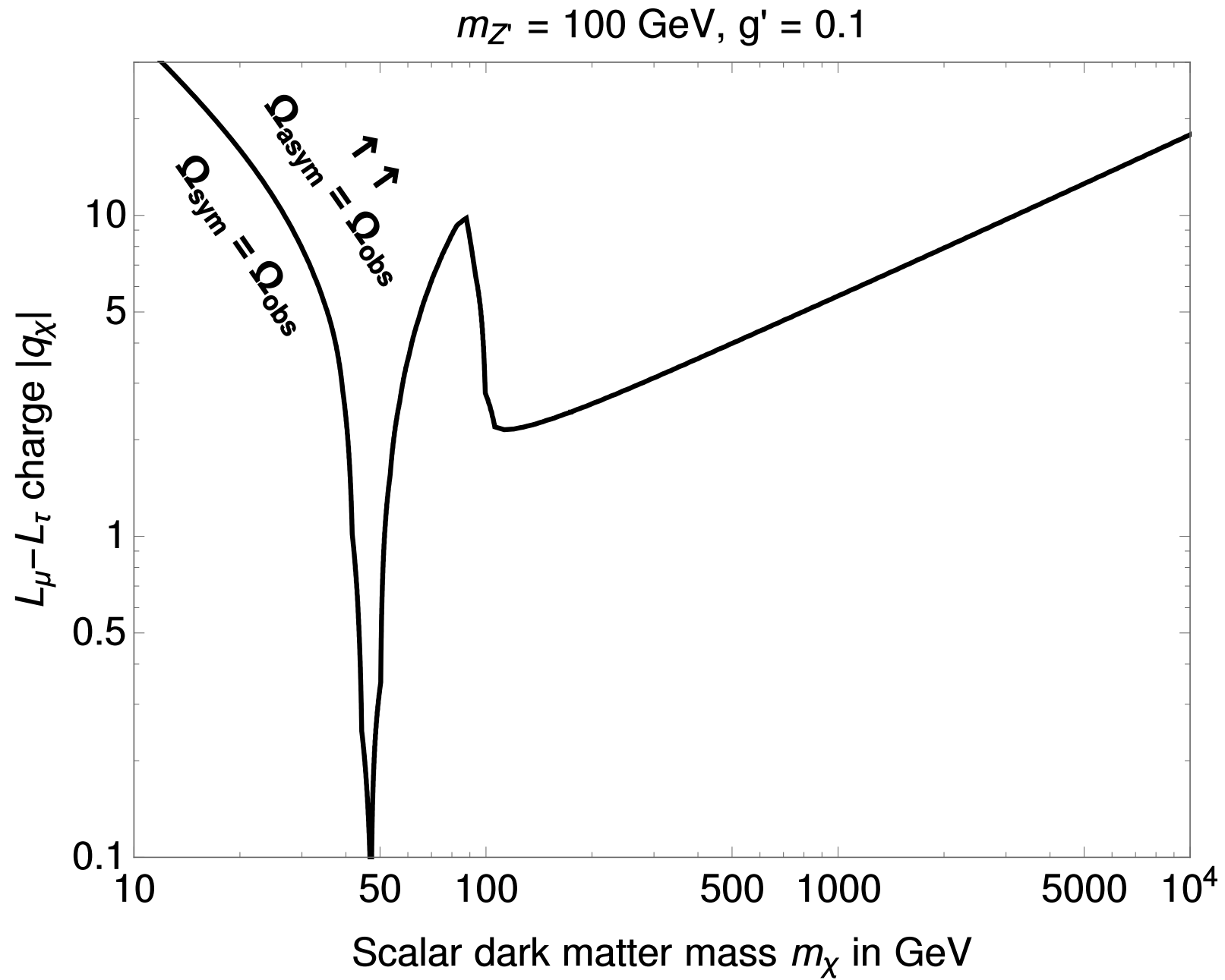
- Repulsive self-interactions. ⚡

[Bell, Melatos, Petraki, '13,
Bramante, Fukushima, Kumar, '13]

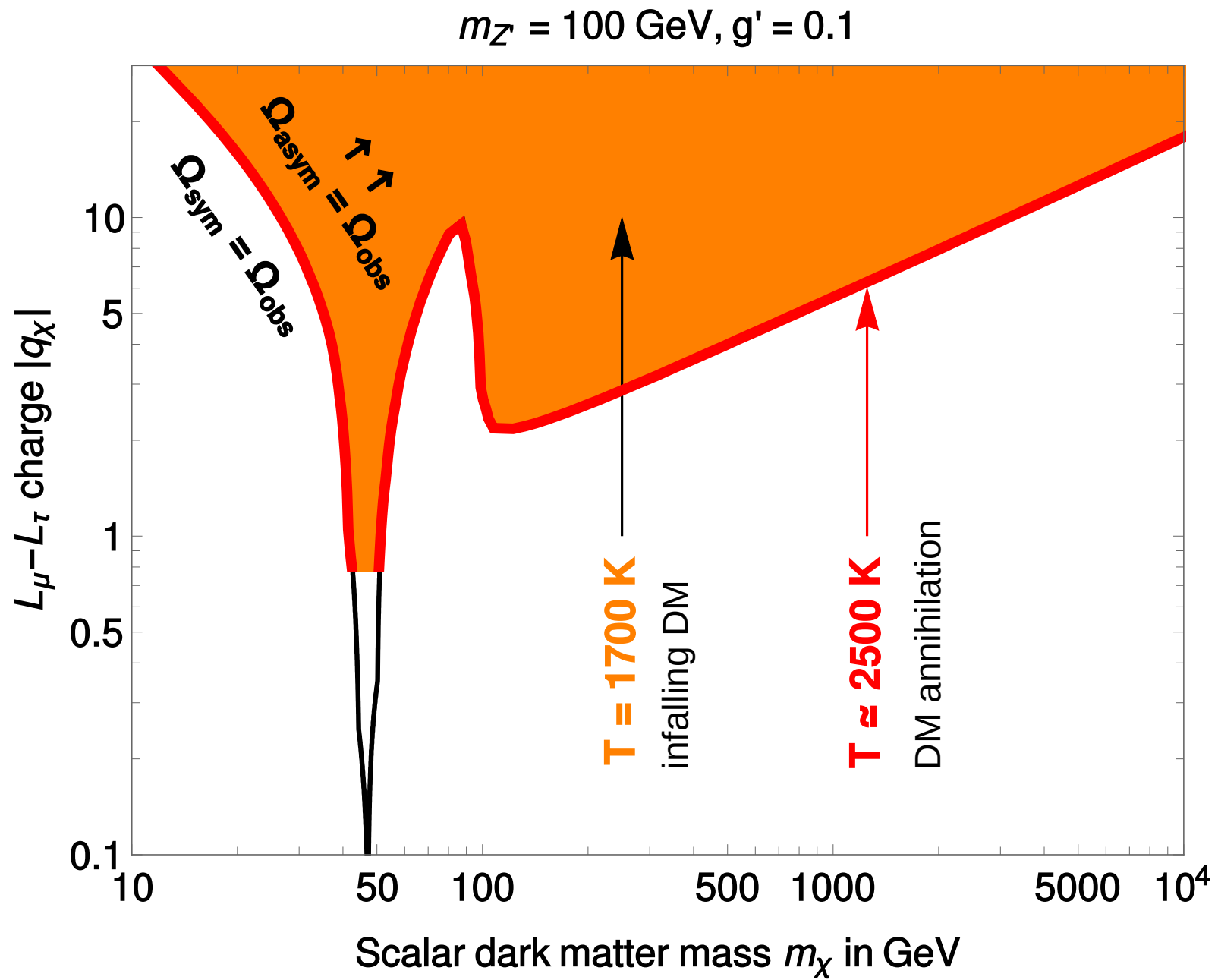


(Muonic) DM in neutron stars

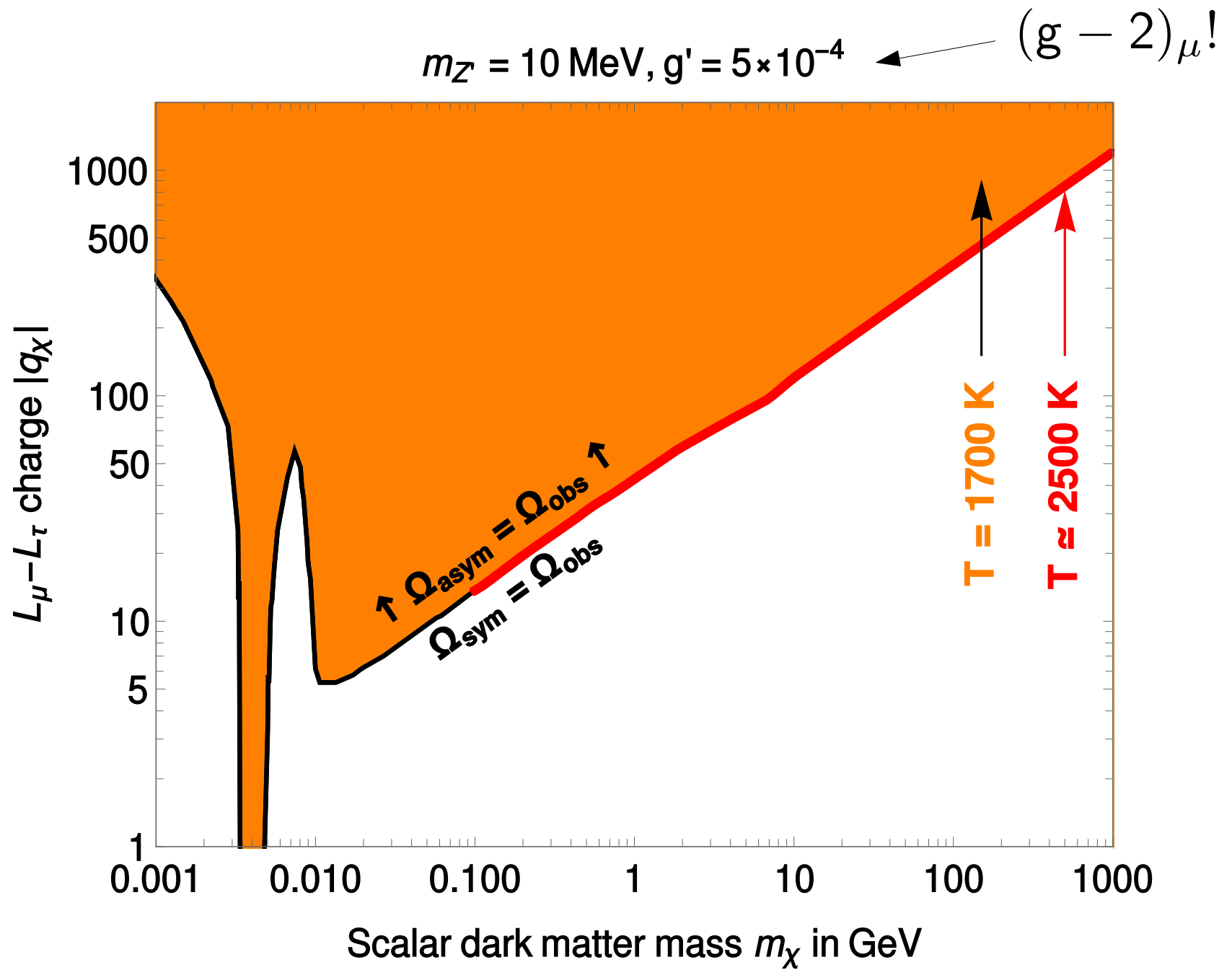
- Easily saturate the capture rate for WIMPs. Then what?
- **Asymmetric DM**: collect enough to form black hole?
 - Fermi pressure. ⚡ [Kouvaris, Tinyakov, '10, '11]
 - Repulsive self-interactions. ⚡ [Bell, Melatos, Petraki, '13, Bramante, Fukushima, Kumar, '13]
- **Always**: infalling DM heats the NS!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



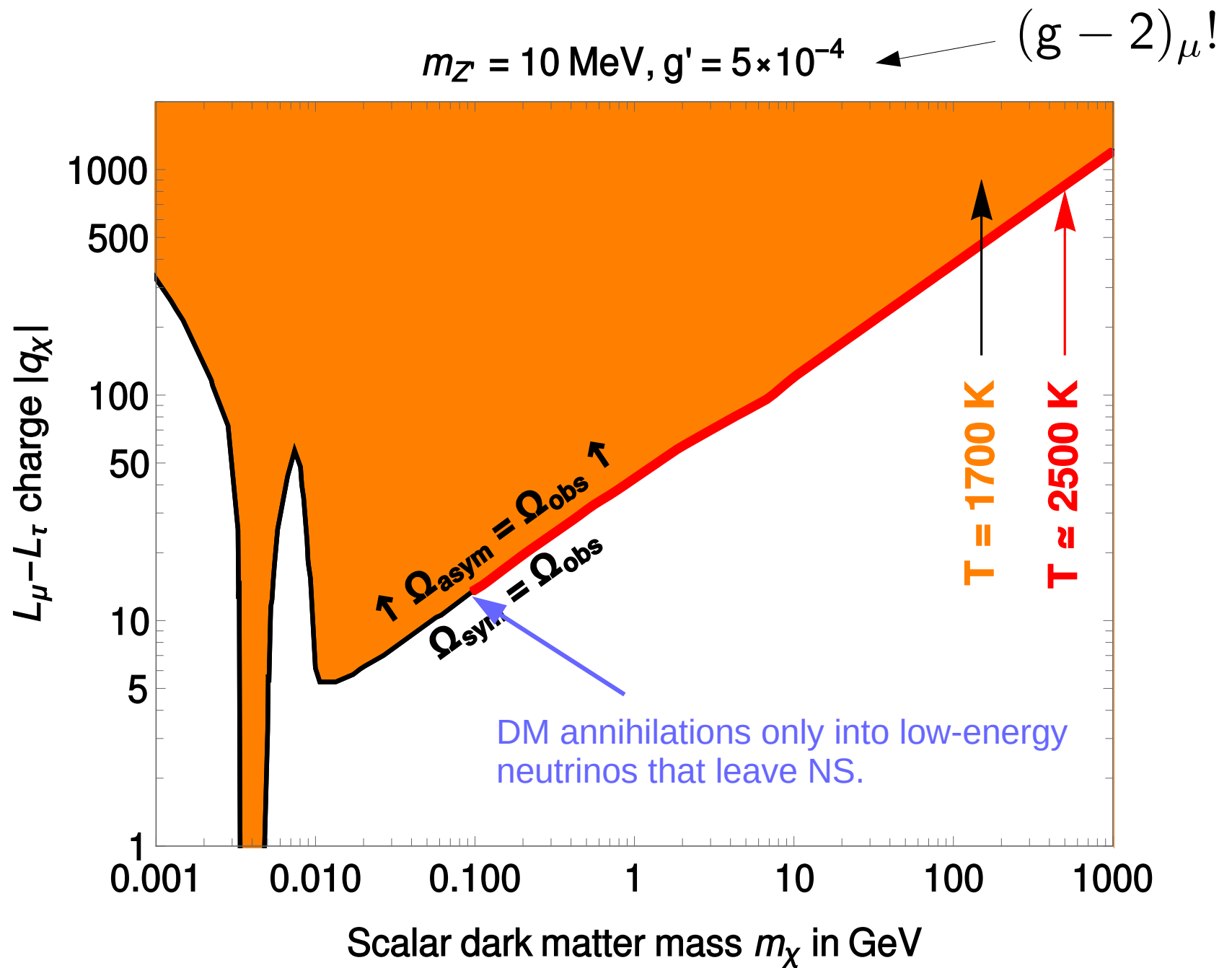
[JH, Garani, 1906.10145]



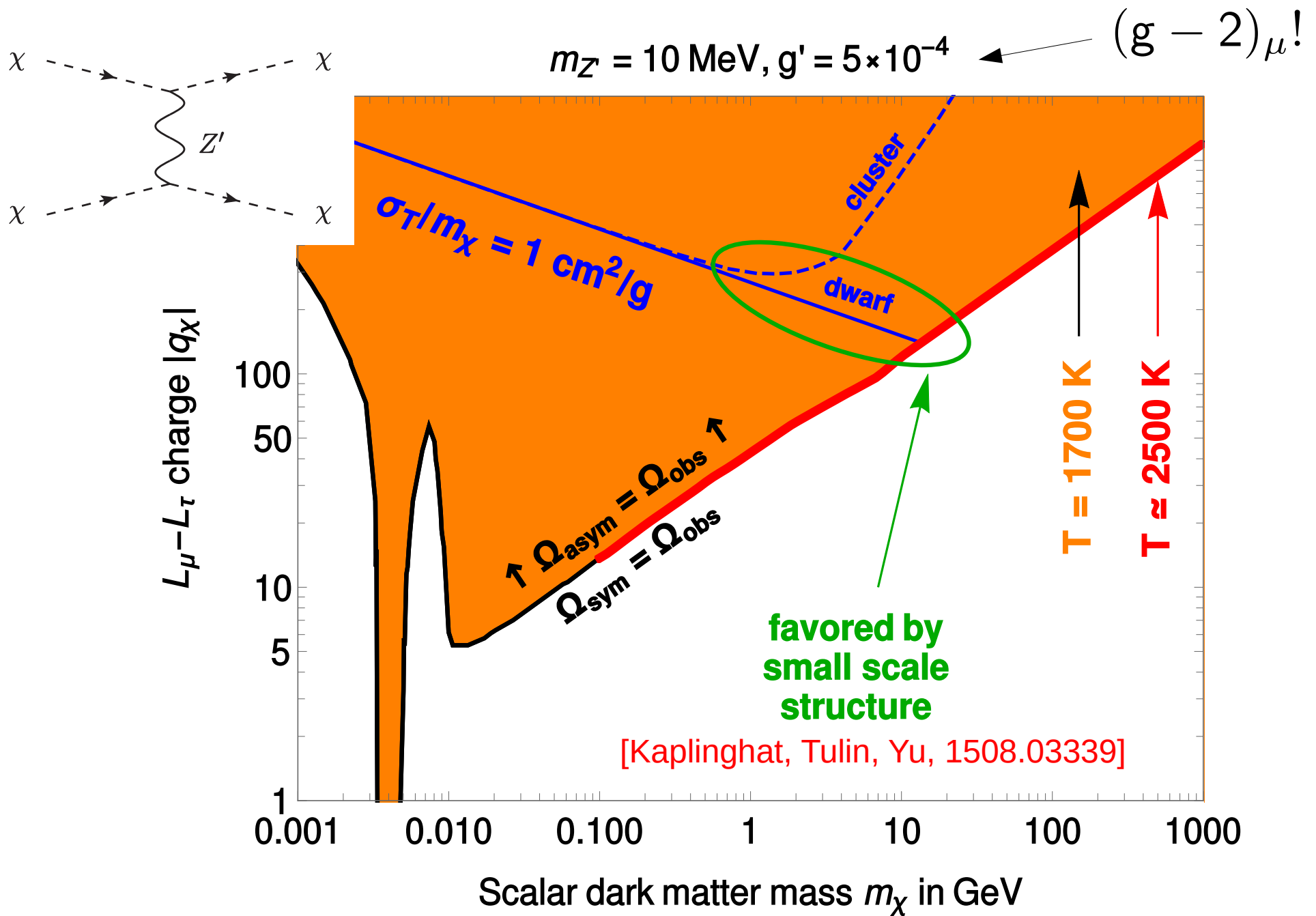
[JH, Garani, 1906.10145]



[JH, Garani, 1906.10145]



[JH, Garani, 1906.10145]



[JH, Garani, 1906.10145]