A ν scalar in the early universe and $(g-2)_\mu$

Jia Liu
Peking University

With Navin McGinnis, Carlos E.M. Wagner and Xiao-Ping Wang

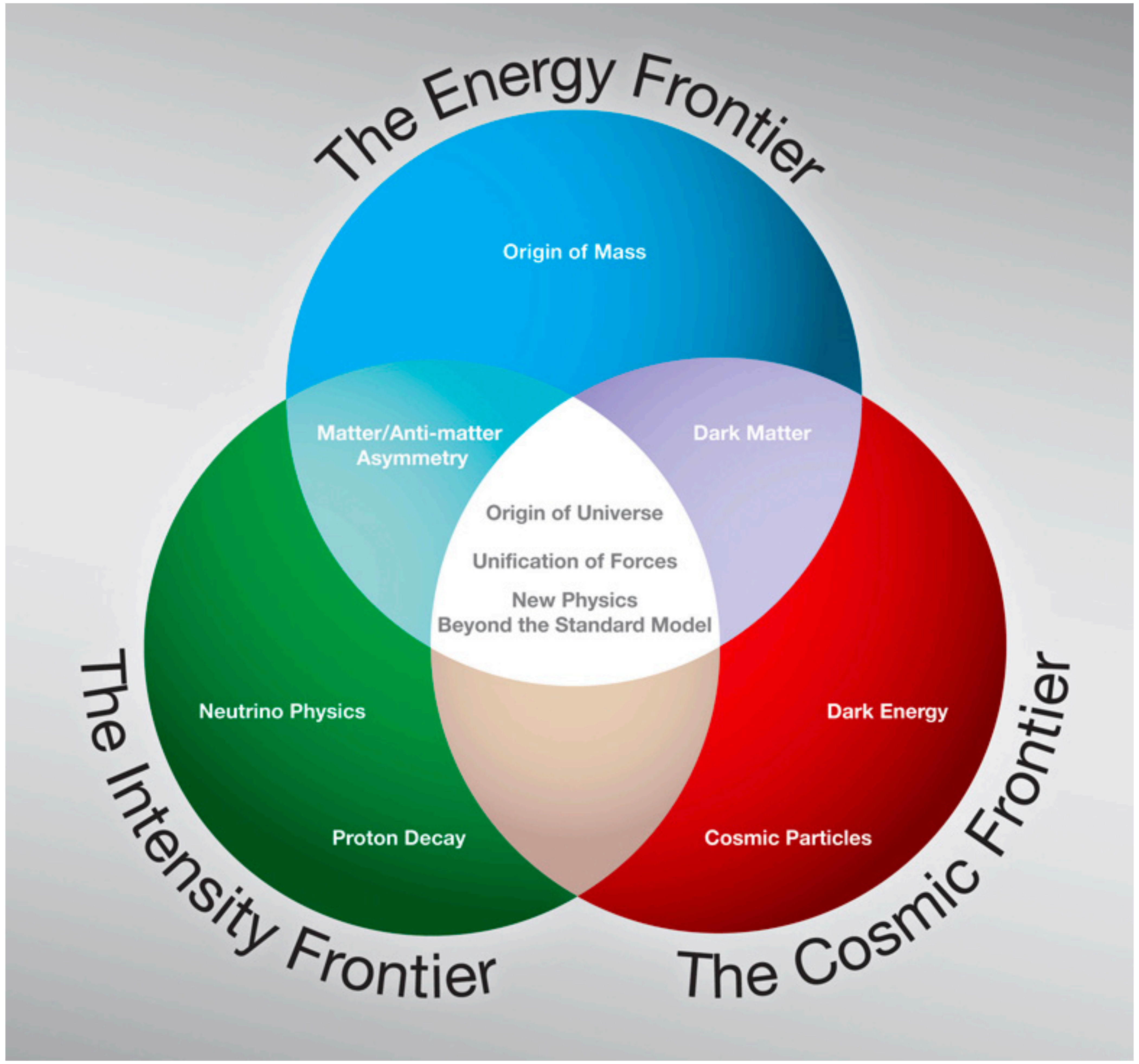
1810.11028 [JHEP 1903 (2019) 008]
2001.06522 [JHEP 2004 (2020) 197]
2110.14665 [PRD 105 (2022) 5, L051702]

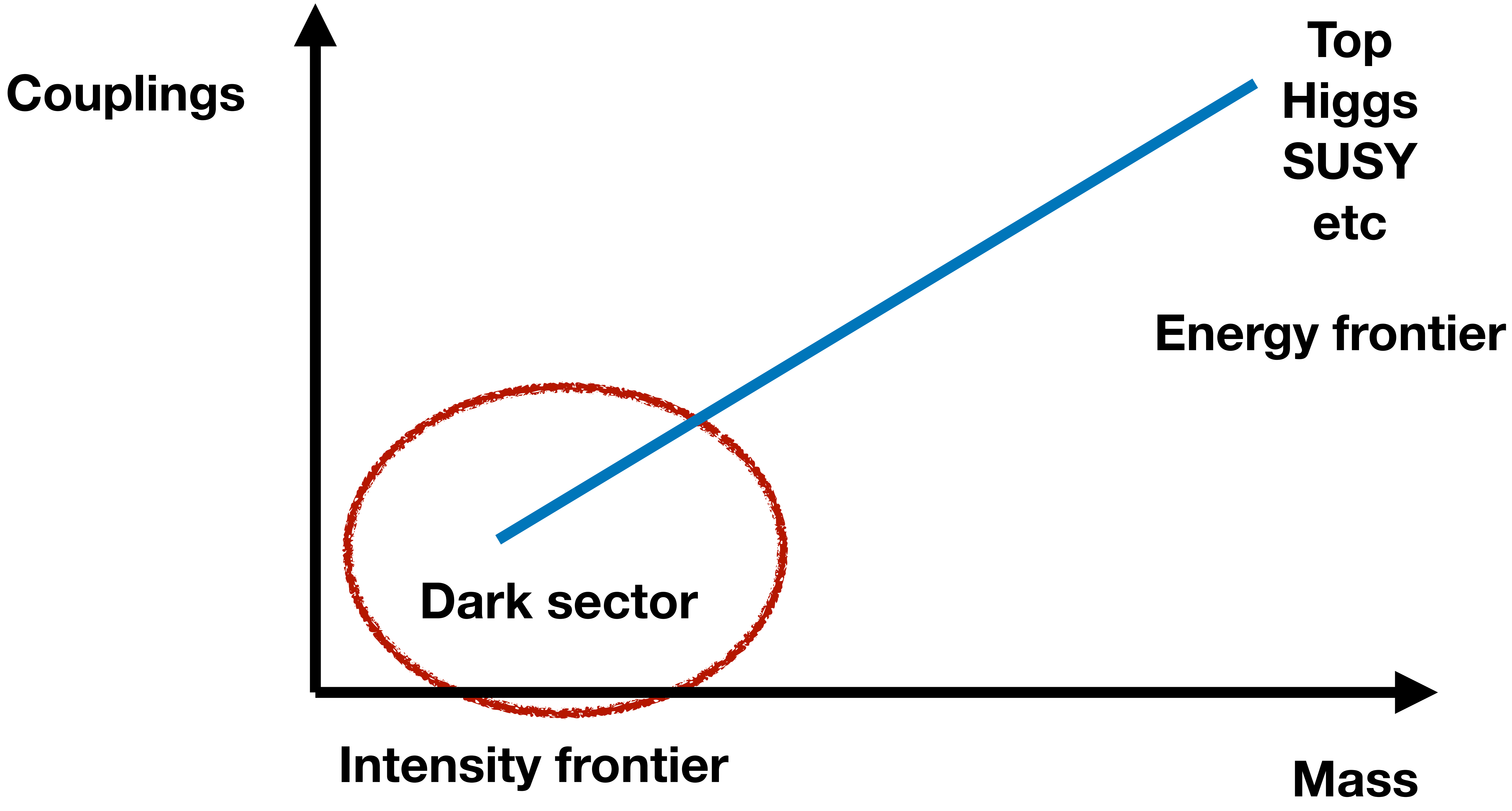
International Conference on Neutrinos and Dark Matter (NuDM-2022)
09/28/2022

Outline

- The light dark sector and $(g-2)_{e/\mu}$
- The cosmological triangle
- The ν scalar in the early universe and $(g-2)_{\mu}$
- Summary

The heavy and the light





- Dark sector particles
  - New light weakly coupled particles
  - Do not interact with the known strong, weak, or electromagnetic forces
- Today we focus on the light dark sector particles

The news from muon g-2

First results from Fermilab's Muon g-2 experiment strengthen evidence of new physics

April 7, 2021

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Media contact

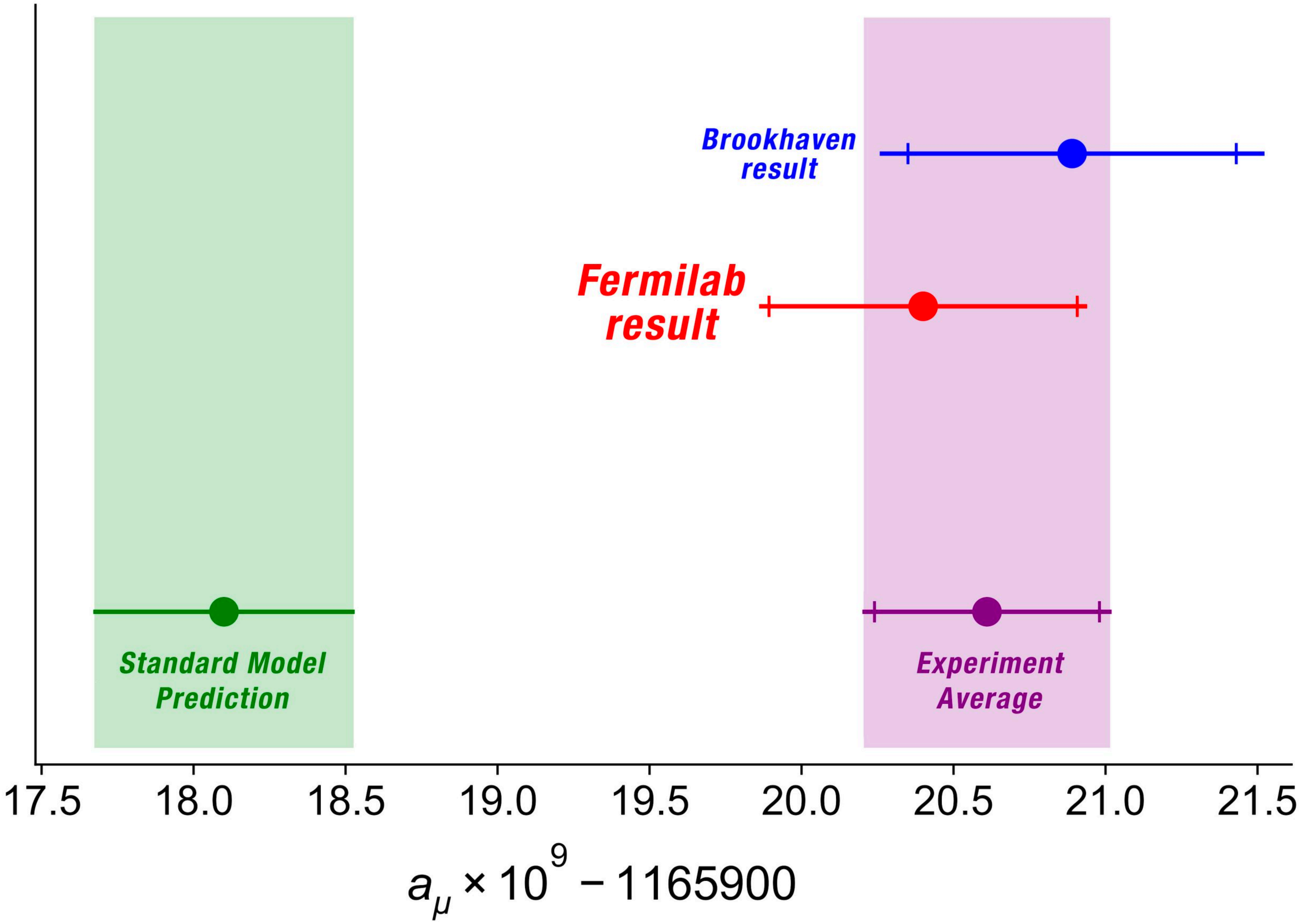
- Tracy Marc, Fermilab, media@fnal.gov, 224-290-7803

The long-awaited first results from the Muon g-2 experiment at the U.S. Department of Energy's Fermi National Accelerator Laboratory show fundamental particles called muons behaving in a way that is not predicted by scientists' best theory, the Standard Model of particle physics. This landmark result, made with unprecedented precision, confirms a discrepancy that has been gnawing at researchers for decades.

The strong evidence that muons deviate from the Standard Model calculation might hint at exciting new physics. Muons act as a window into the subatomic world and could be interacting with yet undiscovered particles or forces.

"Today is an extraordinary day, long awaited not only by us but by the whole international physics community," said Graziano Venanzoni, co-spokesperson of the Muon g-2 experiment and physicist at the Italian National Institute for Nuclear Physics. "A large amount of credit goes to our young researchers who, with their talent, ideas and enthusiasm, have allowed us to achieve this incredible result."

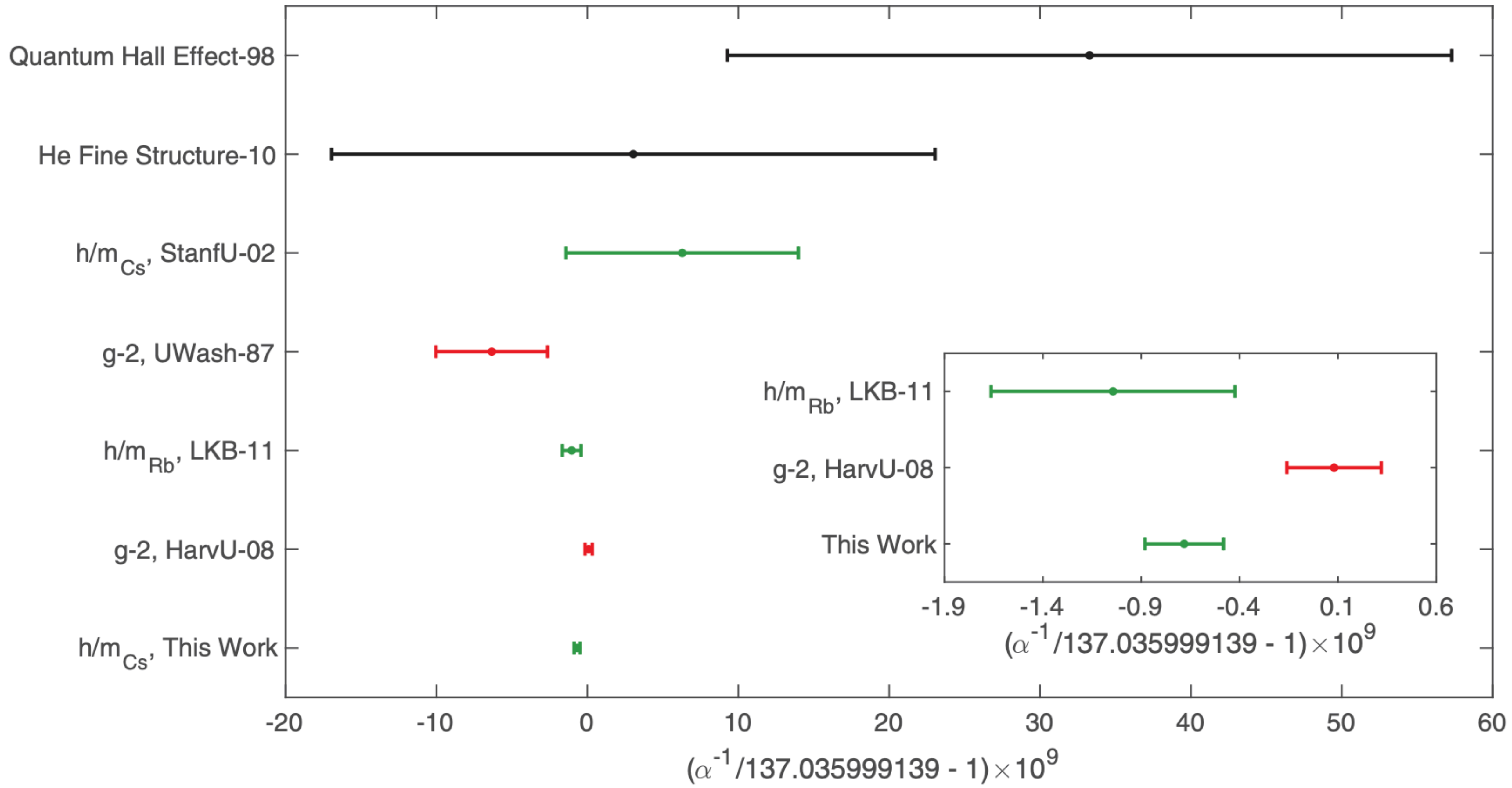
- The big news from the muons
- The muonic window to New Physics



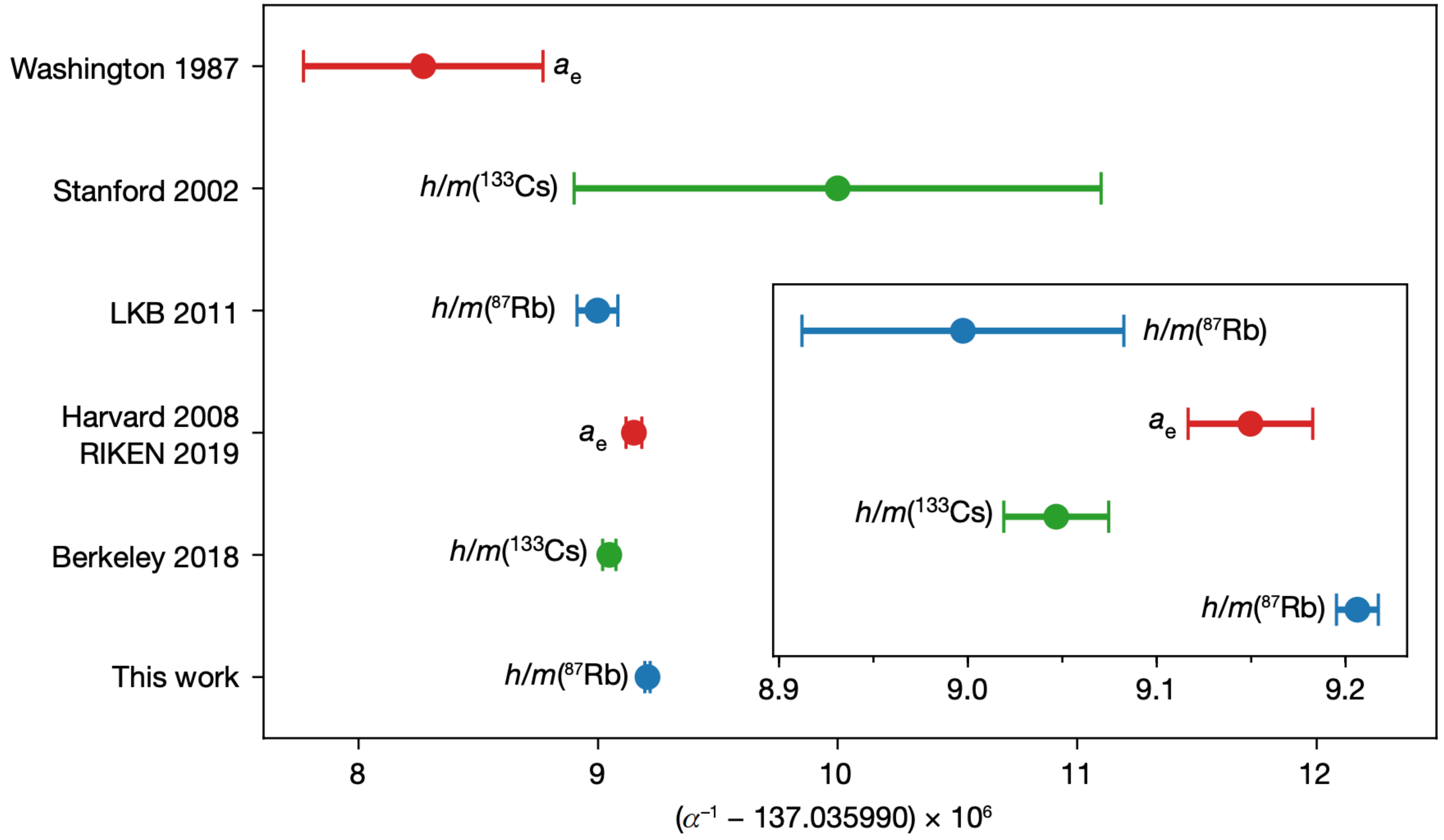
- $\Delta a_\mu = (2.51 \pm 0.59) \times 10^{-9}$
- The Brookhaven + Fermilab results
  - $4.2\ \sigma$ tension to the SM

The status of electron g-2

Parker et al., Science 360, 191–195 (2018)



Morel et al., Nature 588, 61–65 (2020)



2018 Cs : $\Delta a_e = a_e^{\rm exp} - a_e^{\rm th} = (-88 \pm 36) \times 10^{-14}$

- **Negative value and a (- 2.4 σ) discrepancy**

2020 Rb : $\Delta a_e = a_e^{\rm exp} - a_e^{\rm th} = (48 \pm 36) \times 10^{-14}$

- Positive value and a (+ 1.6 σ) discrepancy
- **A 2.4σ discrepancy with its own result in 2011!**

- The two experiments are in tension at $\sim 4\sigma$, waiting for future experiments to see if there is something interesting in electron sector.

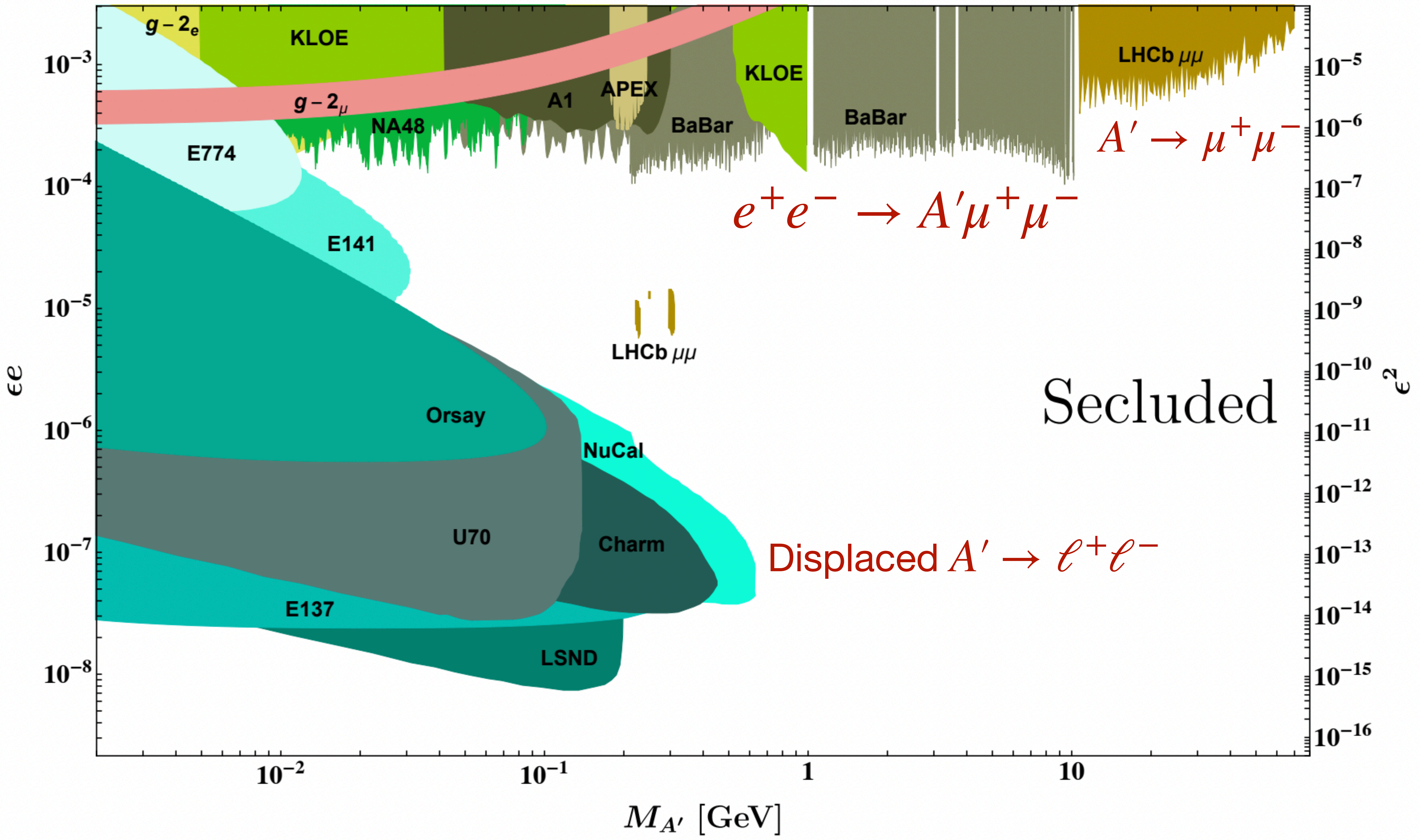
The new physics models for muon g-2

- The heavy solutions: SUSY, leptoquark, vector-like heavy leptons etc…
- The light solutions:
  - Mostly bosonic neutral mediators
  - Charged mediators should be quite heavy due to strong constraints from low energy experiments
  - Vectors: dark photon solution
  - Scalars: dark Higgs, axion-like particles, …

Light dark photon and muon g-2

- Flavor universal : kinetic mixing dark photon

Bauer et al: 1803.05466 (JHEP)



$$\mathcal{L} \supset \epsilon F'_{\mu\nu} B^{\mu\nu}$$

$$\Rightarrow \mathcal{L} \supset \epsilon e A'_\mu J^\mu_{\rm em}$$

$\pi^0 \to \gamma A', A' \to e^+e^-$

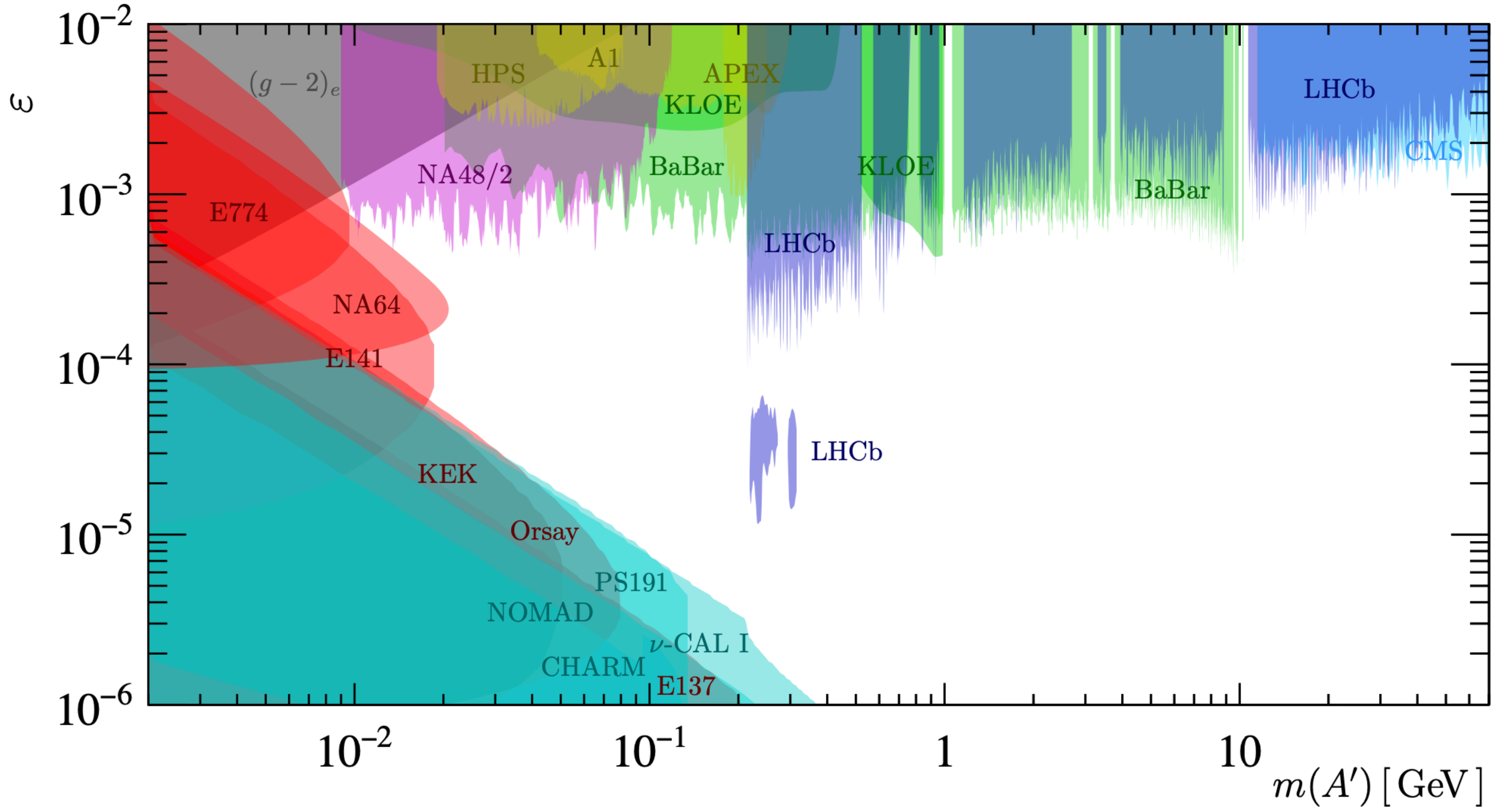
$e^+e^- \to \gamma A'$

Visible dark photon can not explain muon g-2!

Light dark photon and muon g-2

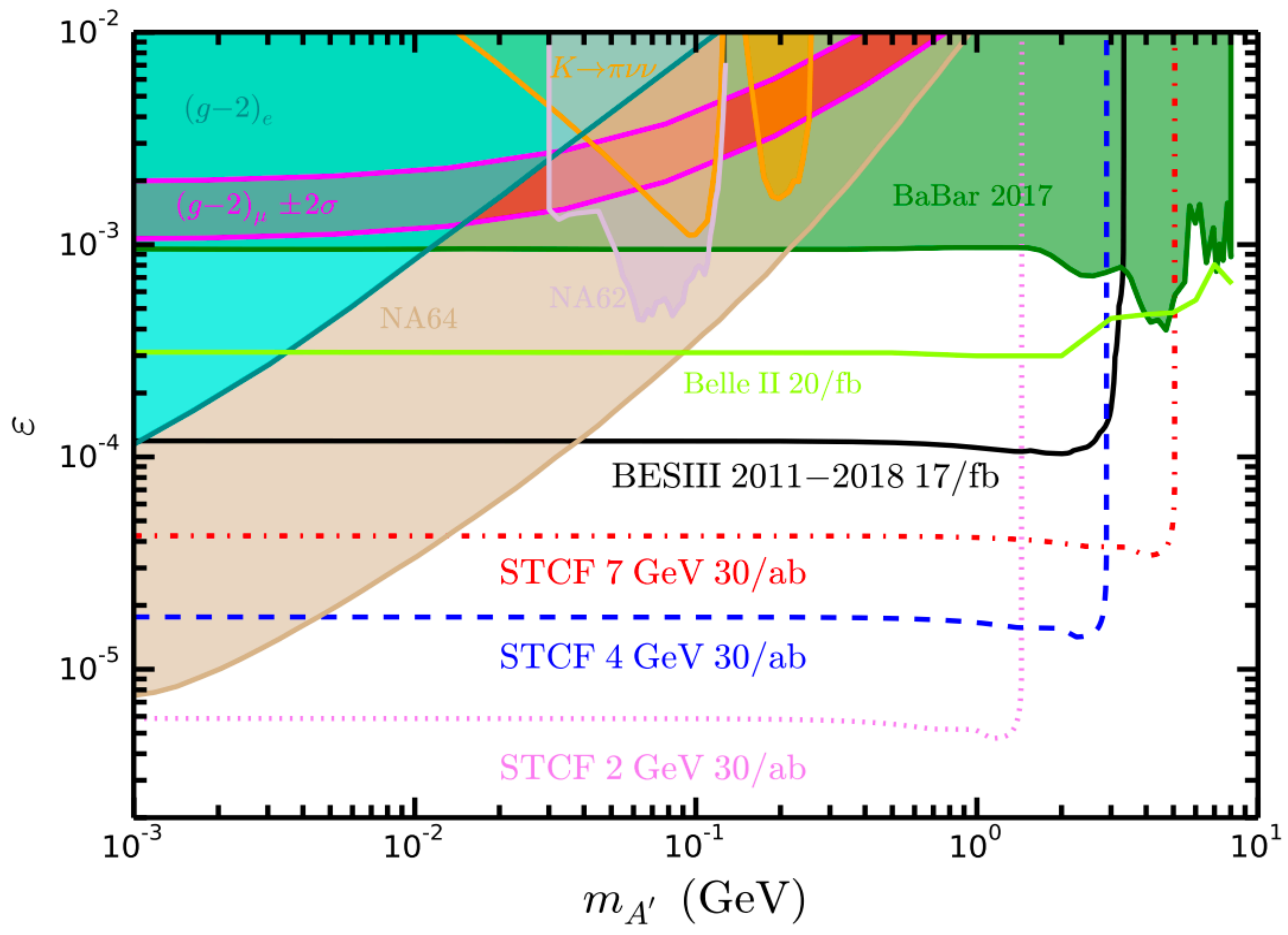
- Flavor universal : kinetic mixing dark photon
- Further experimental updates

Visible A': $A' \to \ell^+\ell^-$



LHCb: 1910.06926 (PRL)

Invisible A': $A' \to$ **Missing Energy**

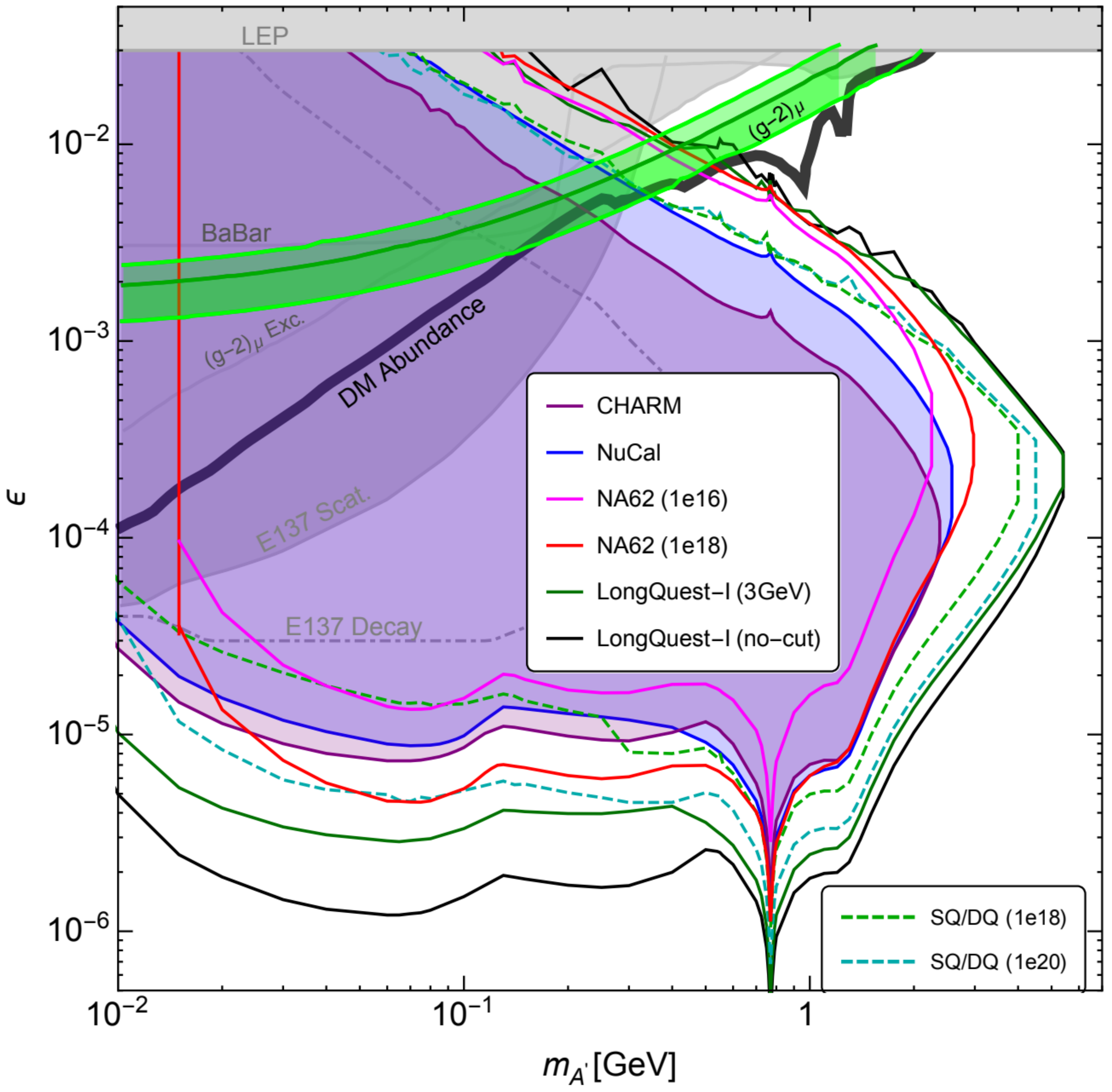


BESIII: 1907.07046 (PRD)

Light dark photon and muon g-2

- Flavor universal : kinetic mixing dark photon
- Recent developments:
  - Incorporating Inelastic Dark Matter
  - $A' \to \chi_1\chi_2,\ \chi_2 \to \chi_1 + f\bar{f}$
  - A' decays to MET + soft objects
  - Muon g-2 and dark matter simultaneously satisfied for large mass splitting

$$\Delta \equiv \frac{m_{\chi_2} - m_{\chi_1}}{m_{\chi_1}} = 0.4$$



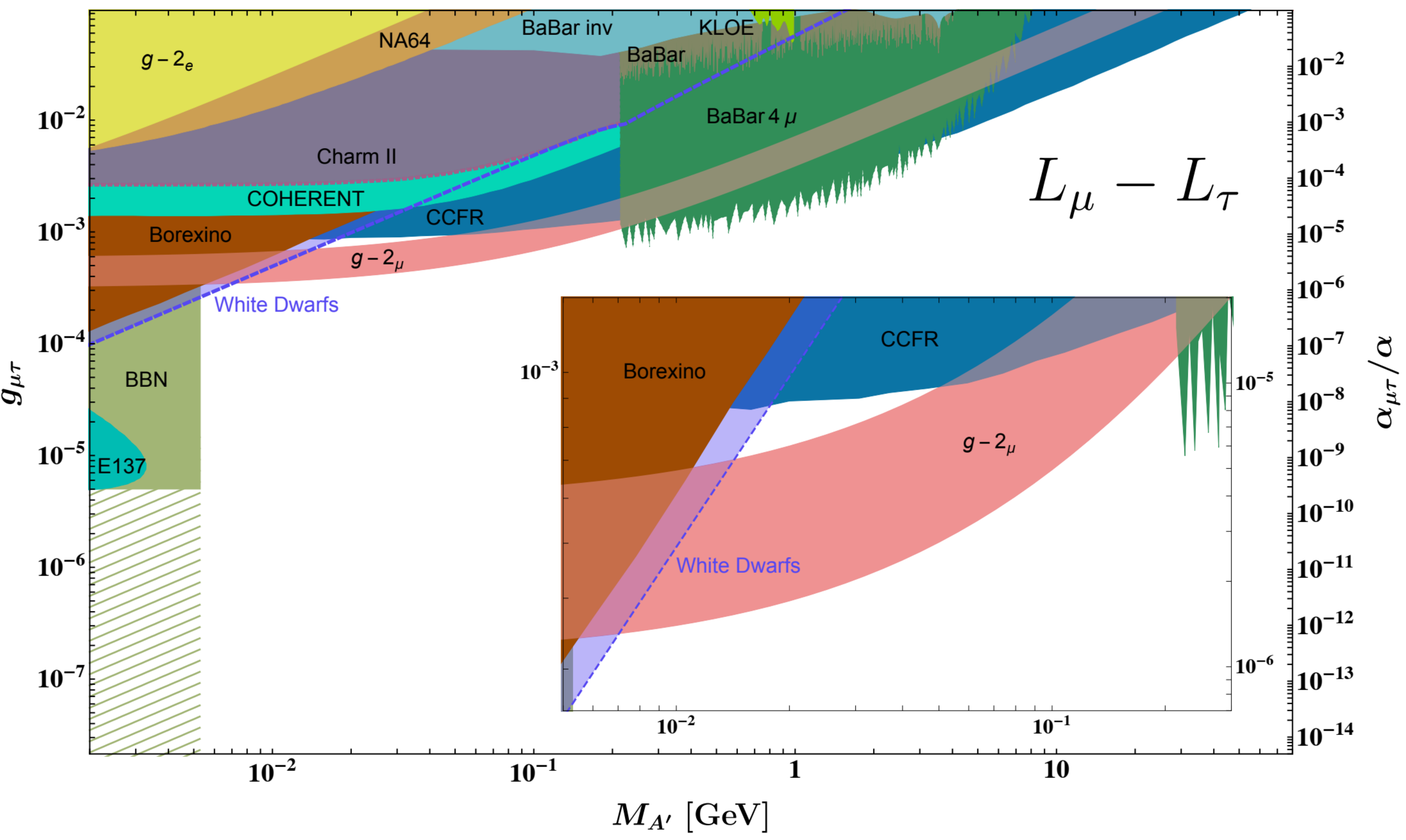
(a) iDM: $\Delta = 0.4$, α_D=0.1. With muon $g-2$ and DM regimes.

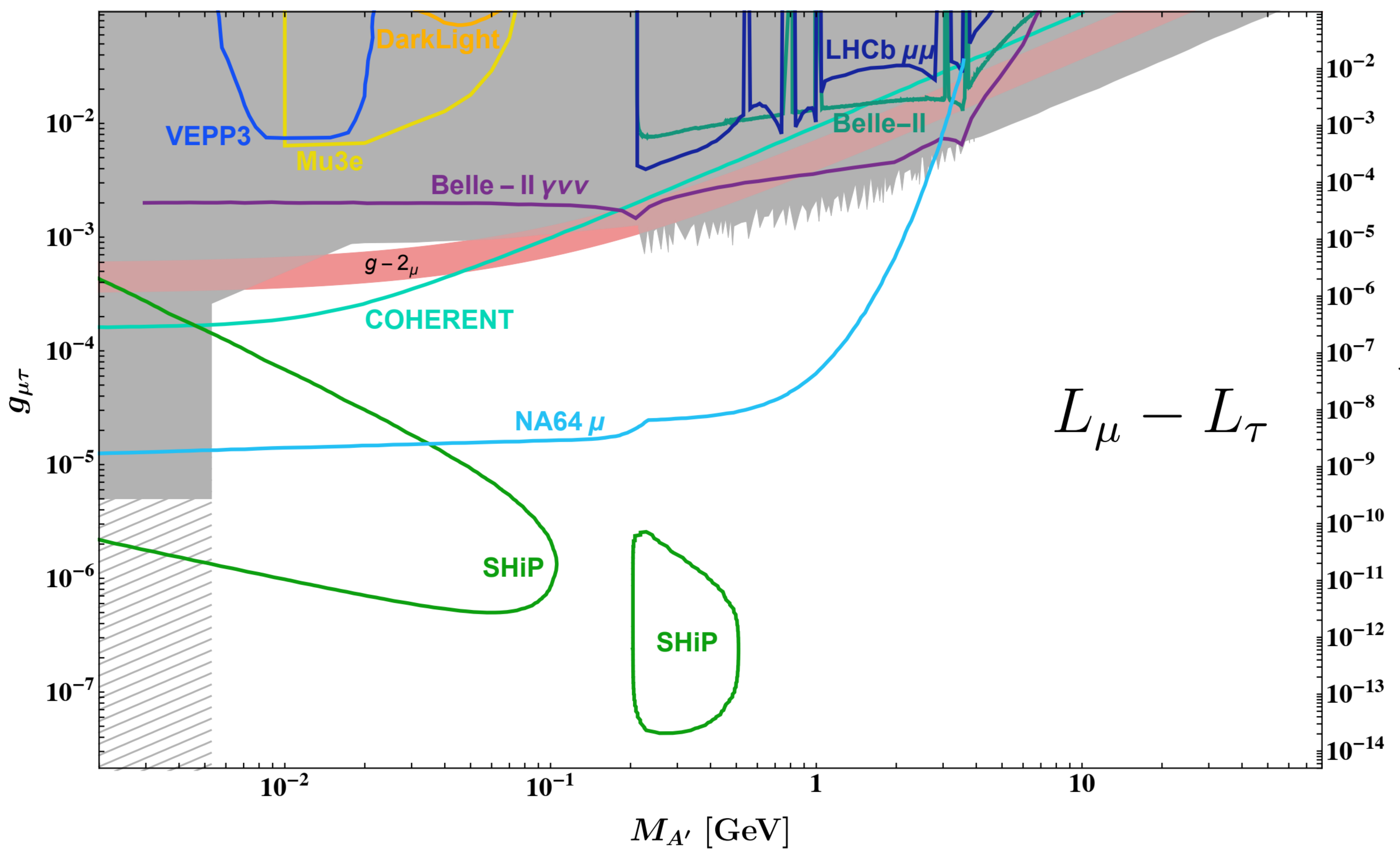
Tsai et al: 1908.07525 (PRL)
See also, Gopolang Mohlabeng 1902.05075 (PRD)

Light dark photon and muon g-2

- Flavor specific : $U(1)_{L_\mu - L_\tau}$ dark photon
- $m_{A'} \in [10,100]$ MeV still viable for muon g-2

$$\mathscr{L} = g' A'_\alpha \times \left(\bar{L}_\mu \gamma^\alpha L_\mu - \bar{L}_\tau \gamma^\alpha L_\tau + \bar{\ell}_\mu \gamma^\alpha \ell_\mu - \bar{\ell}_\tau \gamma^\alpha \ell_\tau \right)$$

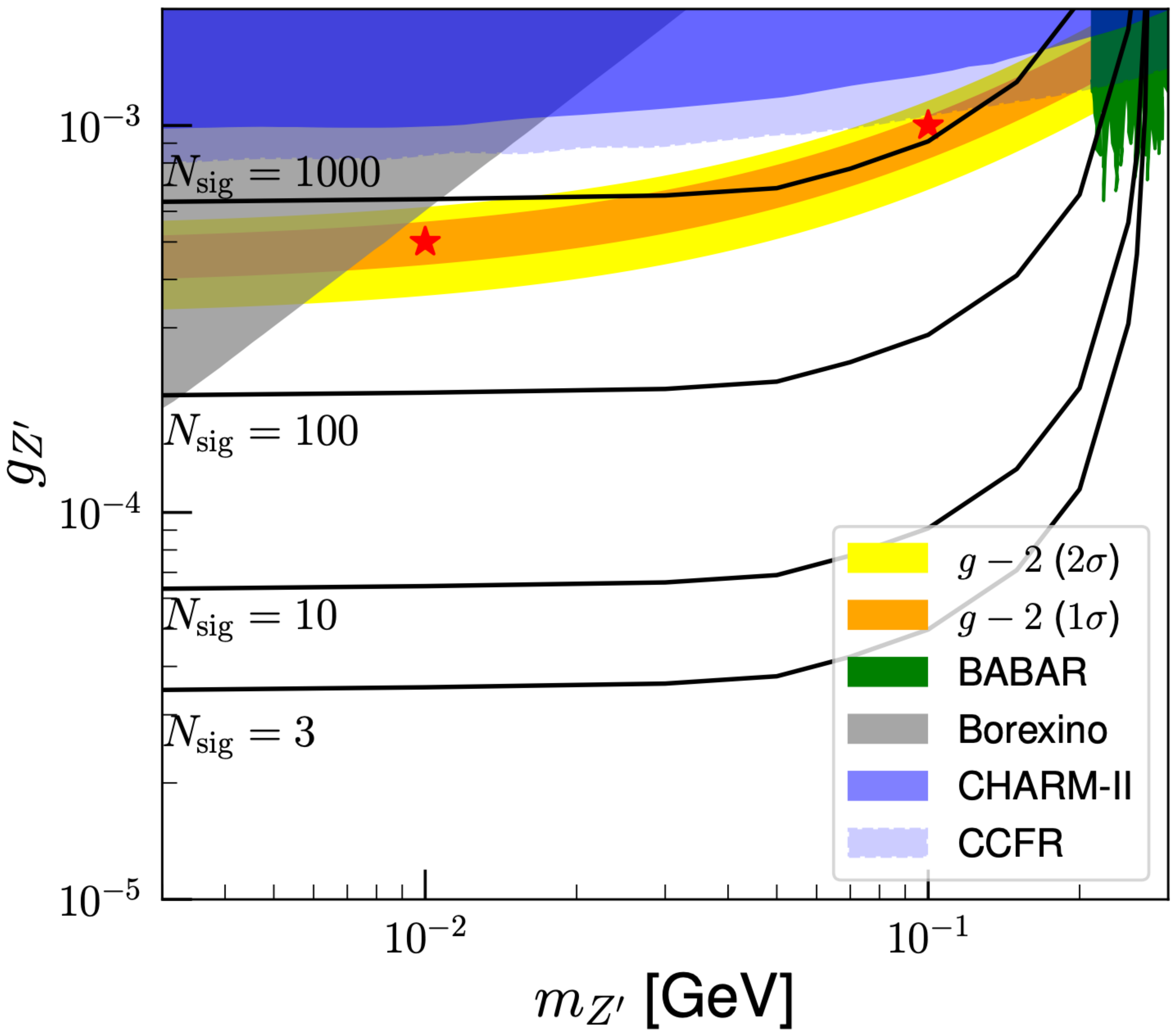




Light dark photon and muon g-2

- Flavor specific : $U(1)_{L_\mu - L_\tau}$ dark photon
- People are still proposing new proposals: e.g. MUonE

$$\mathscr{L} = g' A'_\alpha \times \left(\bar{L}_\mu \gamma^\alpha L_\mu - \bar{L}_\tau \gamma^\alpha L_\tau + \bar{\ell}_\mu \gamma^\alpha \ell_\mu - \bar{\ell}_\tau \gamma^\alpha \ell_\tau \right)$$



- Similar to NA64μ: 10^{12} muons on target from CERN SPS upgraded muon beam
- MUonE: 150 GeV muon + e at rest
  - $\mu e \to \mu e$ measuring hadronic vacuum polarization (HVP) contribution for g-2
  - $\mu e \to \mu e Z' \to \mu e + \mathrm{MET}$

Asai et al: 2109.10093

The new physics models for muon g-2

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  - Charged mediators should be quite heavy due to strong constraints from low energy experiments
  - Vectors: dark photon solution
  - Scalars: dark Higgs, axion-like particles, …

Light dark scalar and muon g-2

- Effective Lagrangian:

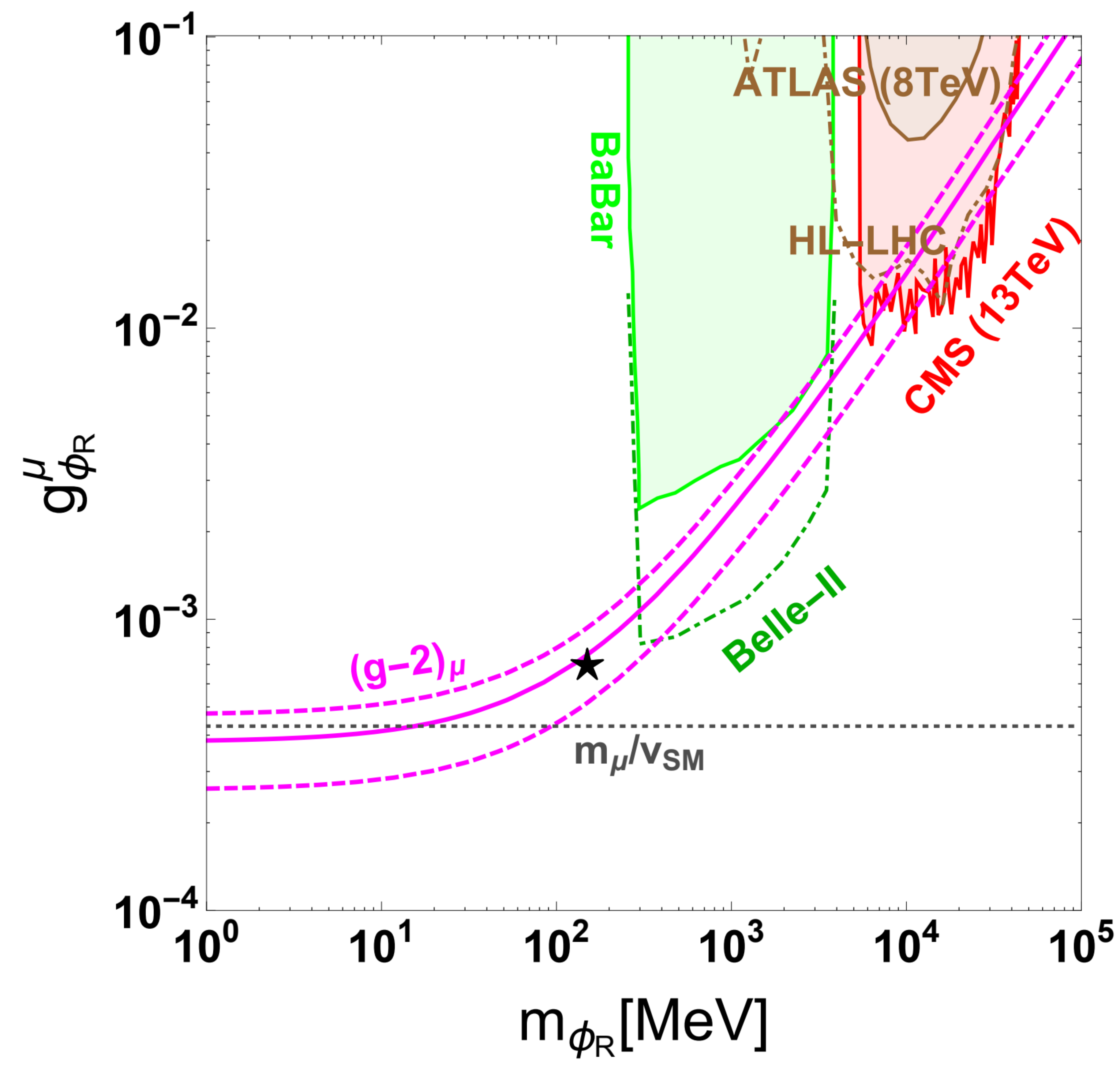
$$\mathscr{L}_{\rm eff} \supset \sum_q \epsilon_q \frac{m_q}{v}\phi \bar{q} q + \sum_\ell \epsilon_\ell \frac{m_\ell}{v}\phi \bar{\ell}\ell + \epsilon_W \frac{2m_W^2}{v}\phi W_\mu^+ W^{\mu -}$$

  - Universal: $\epsilon \equiv \epsilon_q = \epsilon_W = \epsilon_\ell$ (Higgs portal + singlet)
  - Lepton specific: $\epsilon_q \approx \epsilon_W \neq \epsilon_\ell$ (from type-X 2HDM + singlet)
  - Muonic specific: $\epsilon_\mu \neq 0$, others = 0

See Batell et al, 1712.10022

  - Muon g-2:

$$\Delta a_\mu = \frac{m_\mu^2}{8\pi^2 v^2}\epsilon_\ell^2 \int_0^1 dx \frac{(1-x)^2(1+x)}{(1-x)^2 + x(m_\phi/m_\mu)^2}$$



JL, Carlos E.M. Wagner, Xiao-ping Wang: 1810.11028 [JHEP]

Scalars are less constrained comparing with A', due to smaller coupling to e

Light dark scalar and muon g-2

- Effective Lagrangian:

$$\mathcal{L}_{\text{eff}} \supset \sum_q \epsilon_q \frac{m_q}{v} \phi \bar{q} q + \sum_\ell \epsilon_\ell \frac{m_\ell}{v} \phi \bar{\ell} \ell + \epsilon_W \frac{2m_W^2}{v} \phi W_\mu^+ W^{\mu -}$$

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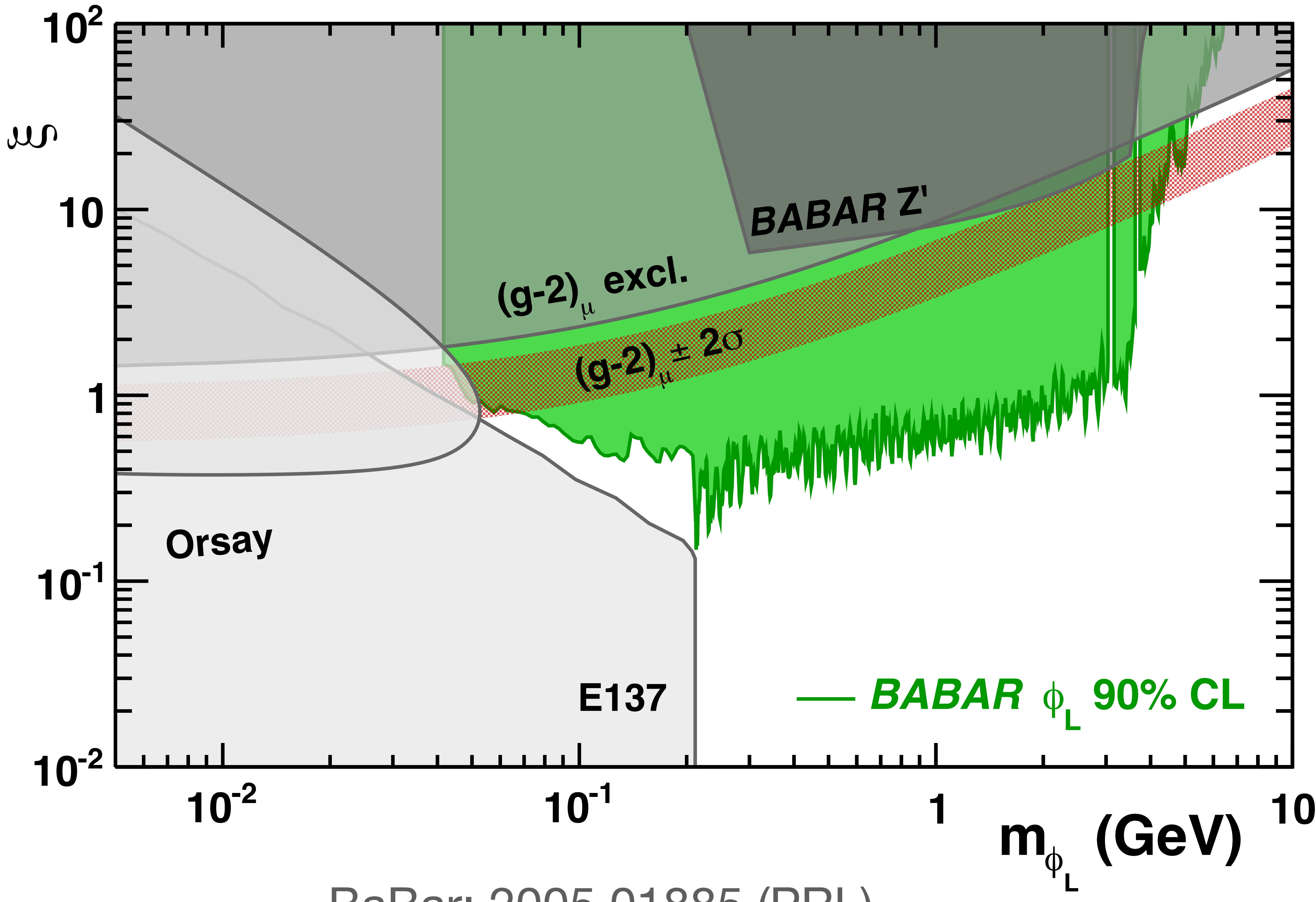
  - Muonic specific: $\epsilon_\mu \neq 0$, others = 0
  - New experiment updates for leptonphilic/universal dark scalar



BaBar: 2005.01885 (PRL)

Utilizes the large tau coupling: $e^+e^- \to \tau^+\tau^-\phi$

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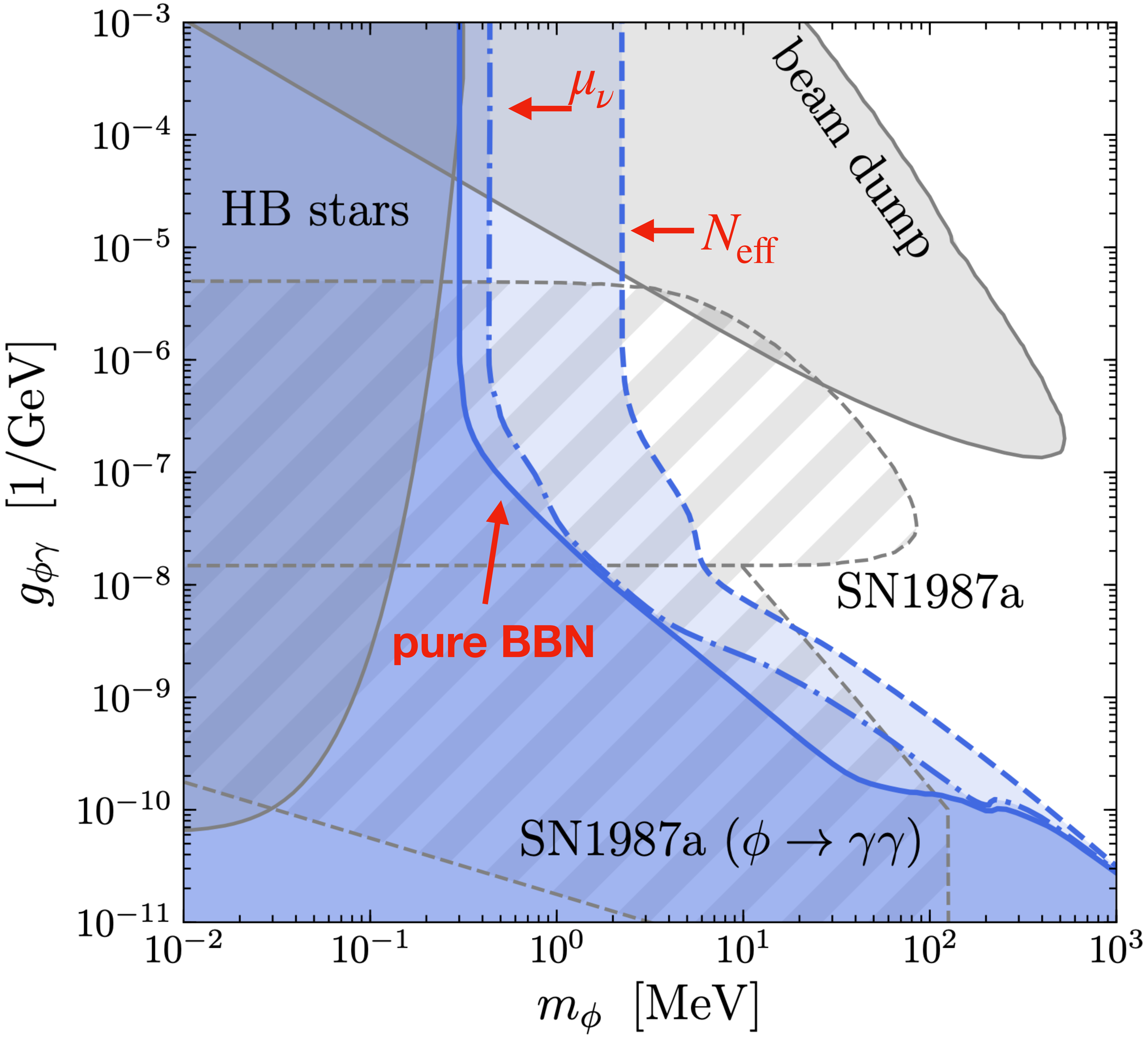
The cosmological triangle

- Referring to Axion-Like Particle searches with photon couplings, works for scalar as well

$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\tau_{\phi\gamma} = \Gamma_{\phi\gamma}^{-1} = \frac{64\pi}{m_\phi^3 g_{\phi\gamma}^2}$$

- Blue solid line from BBN constraints: Y_p, D/H
- Blue dot dashed line: allow varying neutrino chemical potential and $\Delta N_{\rm eff}$
- Blue dashed line: $N_{\rm eff}$ constraints from CMB measurements



Depta et al: 2002.08370 (JCAP)

The cosmological triangle

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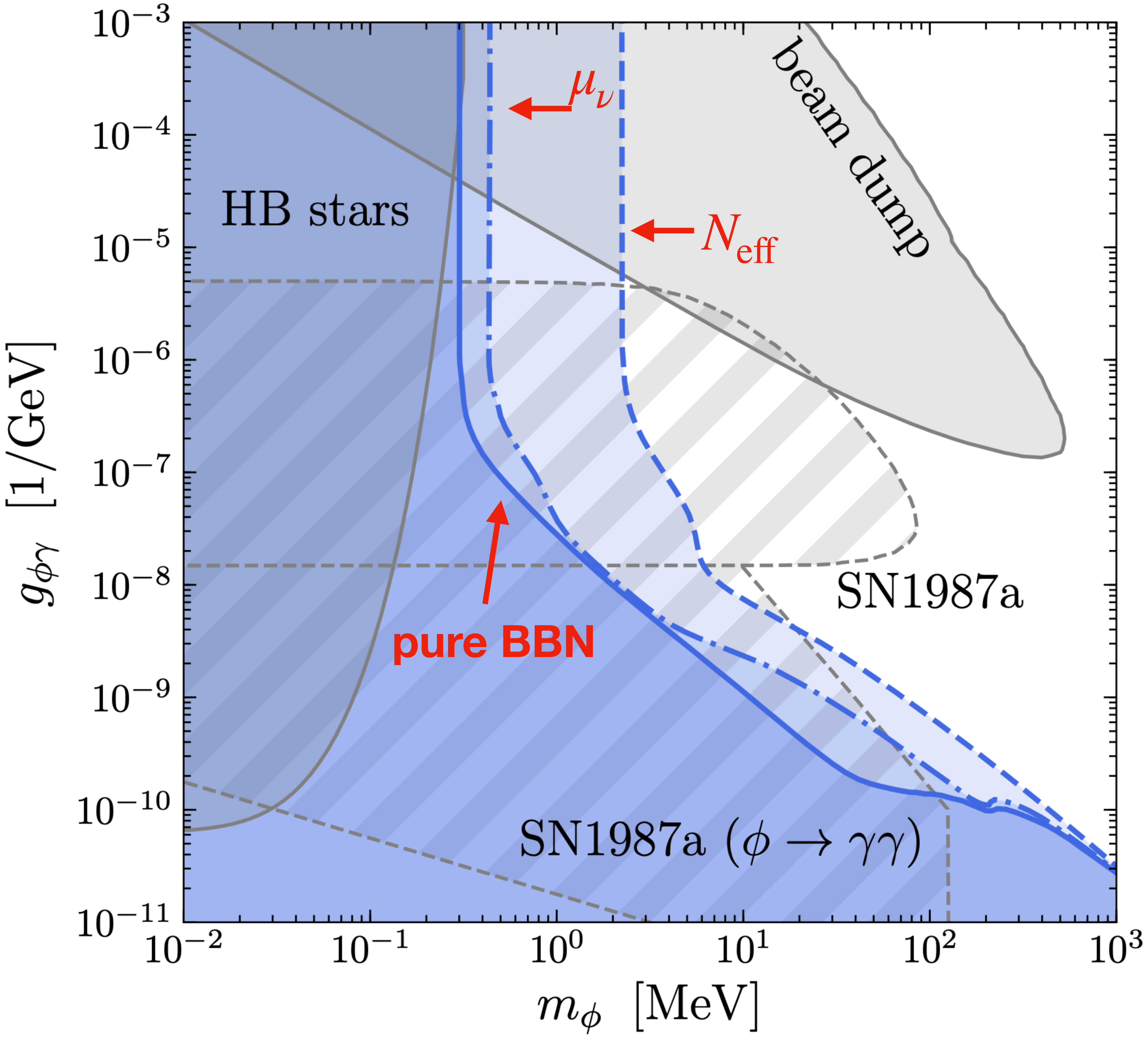
$$\tau_{\phi\gamma} = \Gamma_{\phi\gamma}^{-1} = \frac{64\pi}{m_\phi^3 g_{\phi\gamma}^2}$$

- $N_{\rm eff}$ from CMB constraints constraints:
  - SM value: $\left(T_\nu^0/T_\gamma^0\right) = \left(\frac{4}{11}\right)^{1/3}$ due to e^+e^- annihilation
  - $\phi \to \gamma\gamma$ injects entropy to photons after neutrino decoupling ($T_D^0 \sim 2.3\ \mathrm{MeV}$)
  - Further lowering the ratio T_ν/T_γ



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The cosmological triangle

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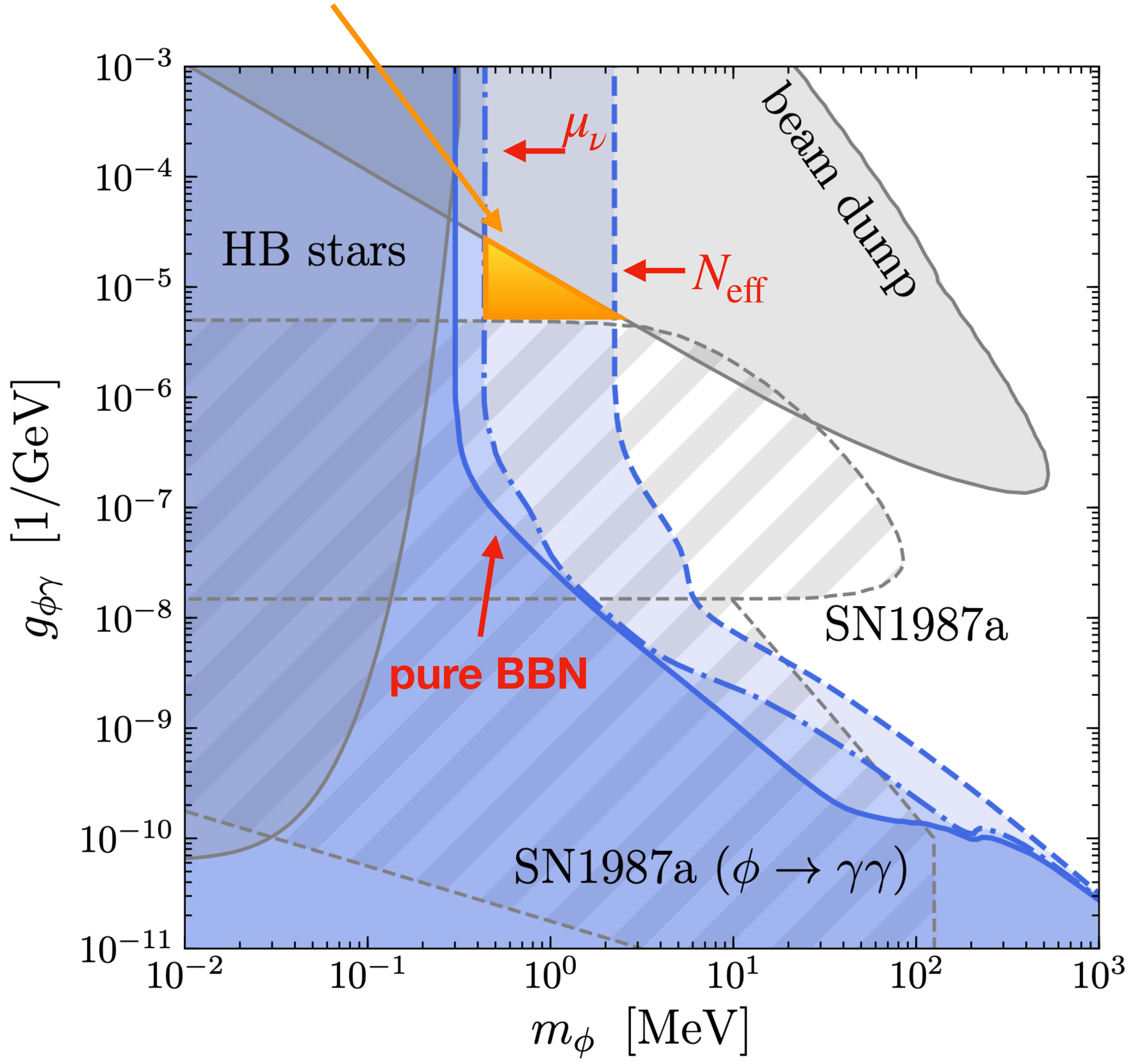
$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\tau_{\phi\gamma} = \Gamma_{\phi\gamma}^{-1} = \frac{64\pi}{m_\phi^3 g_{\phi\gamma}^2}$$

- If one allows extra cosmological setup: $\Delta N_{\rm eff}$ (e.g. dark radiation), to compensate the low T_ν
  - A triangle area is still allowed for MeV ALP, similar for dark scalar



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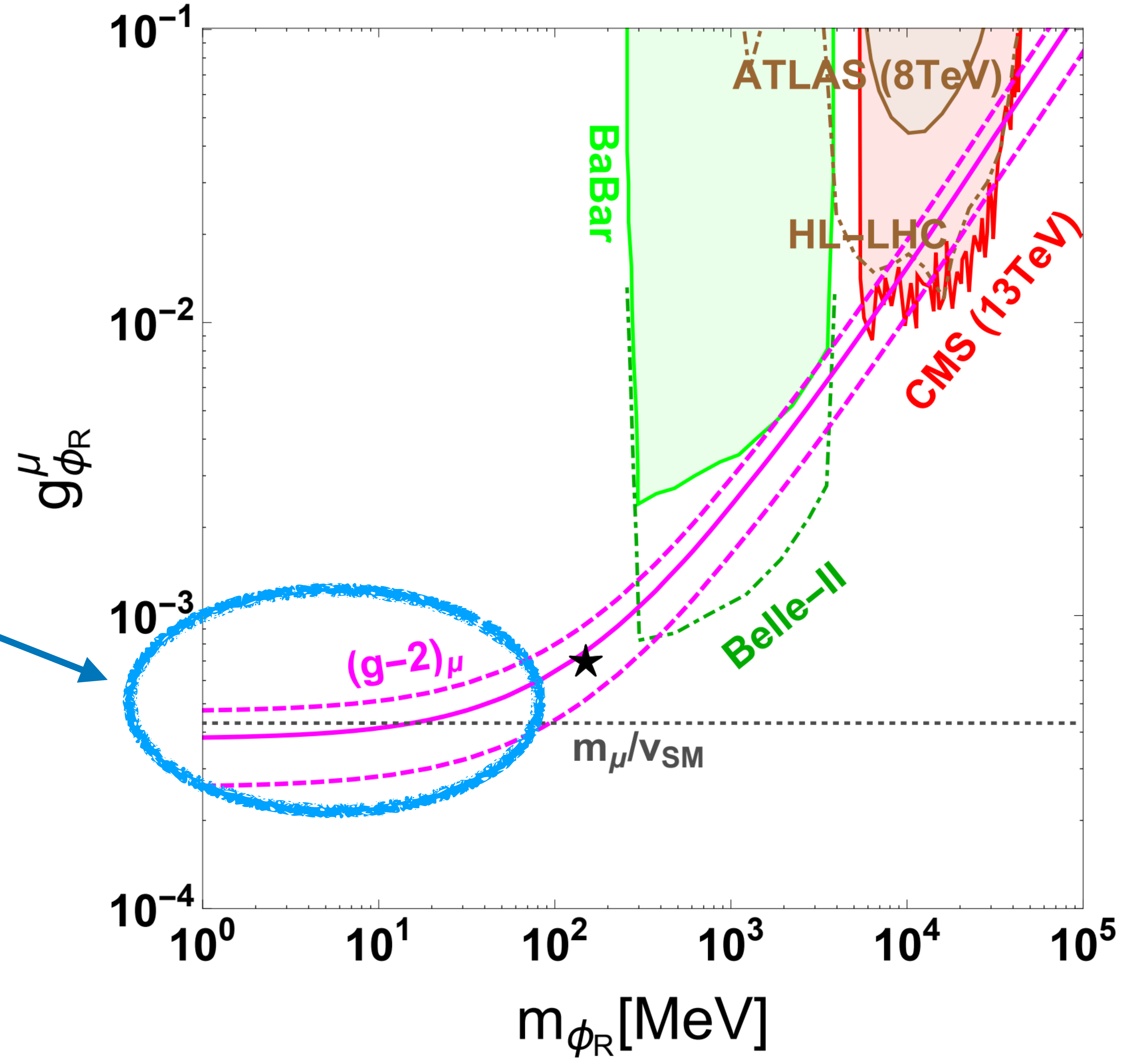
The ν scalar in the early universe and $(g-2)_\mu$

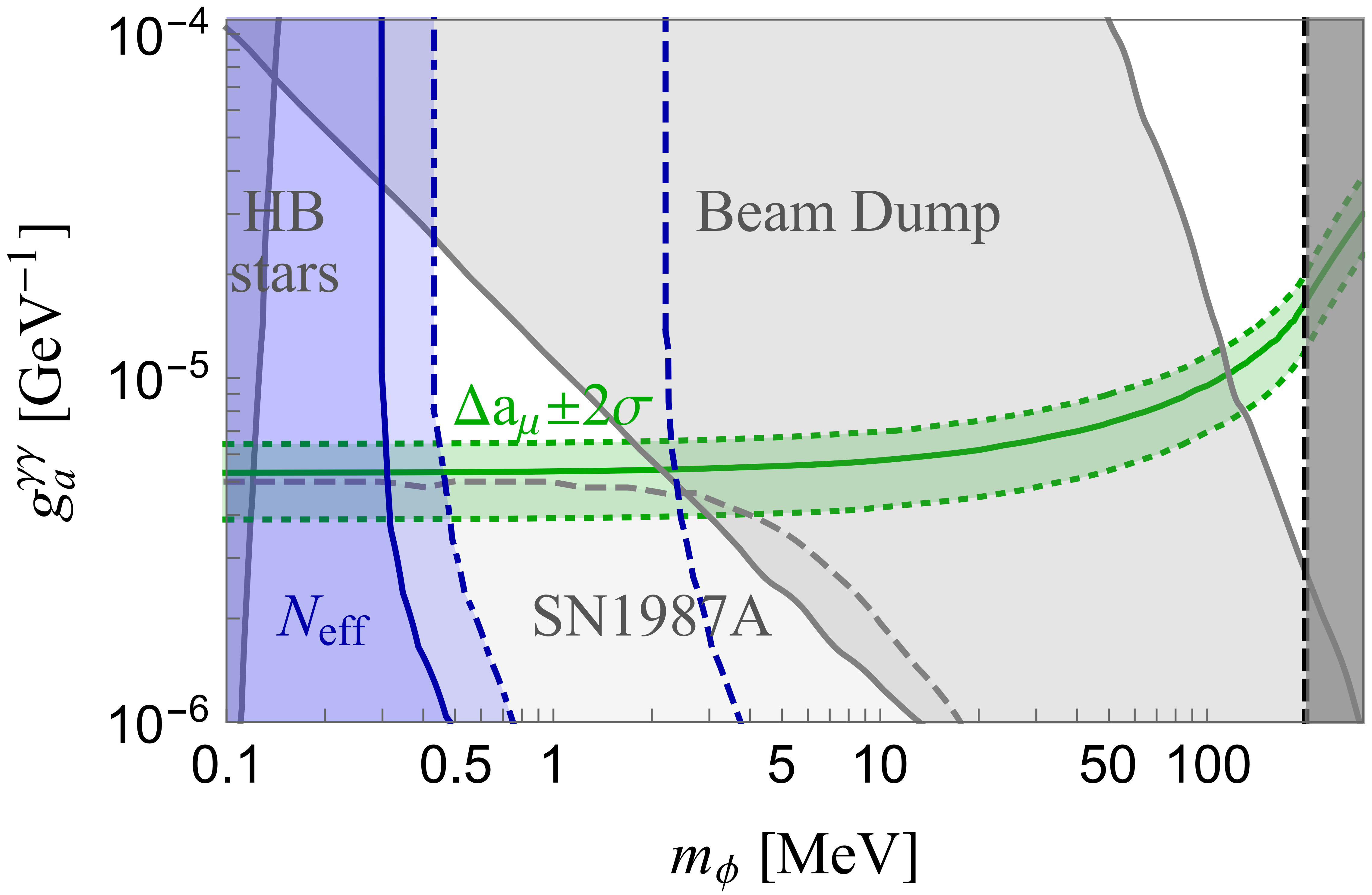
- Our motivation:
  - Light dark scalar ($\lesssim 30$ MeV) with muon coupling same as SM Higgs ($\sim m_\mu/v_h$) can solve $(g-2)_\mu$



JL, Carlos E.M. Wagner, Xiao-ping Wang: 1810.11028 [JHEP]

The ν scalar in the early universe and $(g-2)_\mu$

- Our motivation:
  - Light dark scalar ($\lesssim 30$ MeV) with muon coupling same as SM Higgs ($\sim m_\mu/v_h$) can solve $(g-2)_\mu$
  - Such coupling naturally induce photon couplings at 1-loop
    - $\mathscr{L}_{\text{eff}} \supset -\frac{g_{\gamma\gamma}}{4}\phi F_{\mu\nu}F^{\mu\nu}$
    - Right in the cosmological triangle
    - We are not satisfactory with adding hand-waiving ΔN_{eff}
    - We do it dynamically by coupling scalar to ν (neutrinos) and solve the ν mass problem at the same time



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The model setup

- Low energy model: $\mathscr{L}_{\text{eff}} \supset -g_\mu \phi \bar{\mu}\mu - \left(\frac{g_{\nu_a}}{2}\phi \nu_a \cdot \nu_a + h.c.\right)$
- 1-loop induced photon coupling: $\mathscr{L}_{\text{eff}}^{1-\text{loop}} \supset -\frac{g_{\gamma\gamma}}{4}\phi F_{\mu\nu}F^{\mu\nu}$
- $(g-2)_\mu$ and cosmological triangle fixes:
  - $m_\phi \sim 1 \text{ MeV}, g_\mu \sim m_\mu / v_h$ and $g_\gamma \sim -\frac{2\alpha g_\mu}{3\pi m_\mu}$
  - Only neutrino coupling g_ν is free parameter
  - Problem: $\phi \to \gamma\gamma$ injects entropy to photon plasma, leads to lower T_ν

The solution: delayed neutrino decoupling

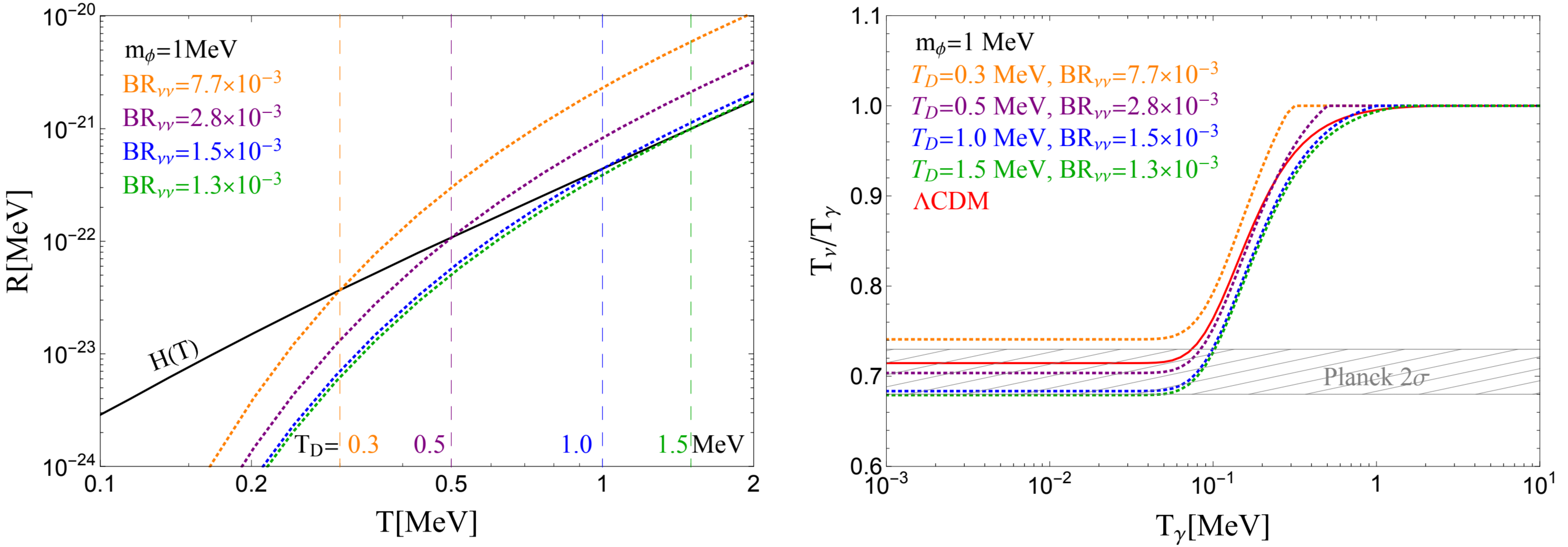
- Solution: ϕ coupling to ν, delayed neutrino decoupling T_D
  - It forces $T_\nu = T_\gamma$ ($T_\gamma < T_D$), therefore entropy injection from e^+e^- shares in ν/γ sectors
  - Therefore, it effectively raises T_ν and compensate the $\phi \to \gamma\gamma$ entropy injection
  - The new decoupling T_D is determined by s-channel resonant interaction $\nu\nu \leftrightarrow \phi^* \leftrightarrow \gamma\gamma$

$$\frac{dn_\nu}{dt} + 3Hn_\nu = \langle \sigma v \rangle_{\rm res} \left(n_{\nu,{\rm eq}}^2 - n_\nu^2 \right)$$

$$R \equiv n_\nu^{\rm eq} \langle \sigma v \rangle \approx \frac{8\sqrt{2\pi}}{3\xi(3)} \Gamma_\phi {\rm BR}_{\gamma\gamma} {\rm BR}_{\nu\nu} x^{-3/2} e^{-x}$$ V.S. Hubble rate

- The new decoupling $x_D = m_\phi / T_D$: $x_D \approx \log\left(\frac{1.67 m_{\rm PL} \Gamma_\phi}{g_*^{1/2} m_\phi^2} {\rm BR}_{\gamma\gamma} {\rm BR}_{\nu\nu} \right) + \frac{7}{2} \log(x_D).$

The delayed neutrino decoupling



- Solution: ϕ coupling to ν, delayed neutrino decoupling T_D
  - A small BR($\phi \to \nu\nu$) solve the cosmological triangle problem
  - We check if it also solves the neutrino mass problem

$$\frac{T_\nu}{T_\gamma} \approx \left(\frac{2 + \frac{7}{2}F(\frac{m_e}{T_\gamma}) + \frac{7}{8}\mathrm{BR}_{\gamma\gamma}F(\frac{m_\phi}{T_\gamma})}{2 + \frac{7}{2}F(\frac{m_e}{T_D}) + \frac{7}{8}\mathrm{BR}_{\gamma\gamma}F(\frac{m_\phi}{T_D})} \cdot \frac{N_\nu + \frac{1}{2}\mathrm{BR}_{\nu\nu}F(\frac{m_\phi}{T_D})}{N_\nu + \frac{1}{2}\mathrm{BR}_{\nu\nu}F(\frac{m_\phi}{T_\gamma})} \right)^{\frac{1}{3}}$$

$$F(y) = \frac{30}{7\pi^4}\int_y^\infty dx \frac{(4x^2 - y^2)\sqrt{x^2 - y^2}}{e^x \pm 1}, \qquad (12)$$

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UV model

Field	$SU(2)_L$	$U(1)_Y$	Z_2
μ_R	1	-1	-1
ϕ	1	0	-1
H	2	$\frac{1}{2}$	$+1$
H'	2	$\frac{1}{2}$	-1
N	1	0	$+1$
N'	1	0	-1

$$\begin{aligned}\mathcal{L}_{UV} &= y_\mu \bar{L}_\mu H' \mu_R + y_{N,i} \left(L_i \cdot H\right) N + y'_{N,j} \left(L_j \cdot H'\right) N' \\ &+ \lambda_N N \cdot N' \phi + \mu_\phi H'^\dagger H \phi \\ &+ \frac{1}{2} m_N N \cdot N + \frac{1}{2} m_{N'} N' \cdot N' + h.c. \qquad (25)\end{aligned}$$

UV model

$$\mathcal{L}_{UV} = y_\mu \bar{L}_\mu H' \mu_R + y_{N,i}\left(L_i \cdot H\right) N + y'_{N,j}\left(L_j \cdot H'\right) N' + \lambda_N N \cdot N' \phi + \mu_\phi H'^\dagger H \phi + \frac{1}{2} m_N N \cdot N + \frac{1}{2} m_{N'} N' \cdot N' + h.c. \quad (25)$$

- Muon specific coupling $g_\mu = y_\mu \frac{v \mu_\phi}{\sqrt{2} m_{H'}^2}$
- Two sterile neutrino setup:
  - One active neutrino is massless
  - Two massive active neutrino can be obtained
  - ϕ couples to heaviest active neutrino dominantly
  - Fits to BR$(\phi \to \nu\nu) \sim \mathcal{O}(0.1\%)$

$$\tilde{m}_{\nu_1} = 0,$$

$$\tilde{m}_{\nu_{2,3}} = \frac{v v'}{\sqrt{2} \lambda_N v_\phi} \left(|\overrightarrow{y_N}||\overrightarrow{y_{N'}}| \mp \overrightarrow{y_N} \cdot \overrightarrow{y_{N'}} \right) \sim 0.1 \mathrm{eV},$$

$$\tilde{m}_{N,N'} \approx \frac{\lambda_N v_\phi}{\sqrt{2}} \pm \frac{m_N + m_{N'}}{2} + \mathcal{O}\left(\frac{1}{\lambda_N v_\phi}\right),$$

$$m_1 = 0, \quad m_2 \simeq 8.7 \times 10^{-3} \mathrm{eV}, \quad m_3 \simeq 0.059 \mathrm{eV}$$

$$g_{\nu_3} \approx 2.5 \times 10^{-10}$$

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Summary

- Light dark sector can solve $(g-2)_\mu$ problem, but is under severe constraints
  - Dark scalar solution is less constrained than dark photon
  - However, needs extra $\Delta N_{\rm eff}$ to save the cosmological triangle
- We build a dynamic model to save the cosmological triangle
  - Solve $(g-2)_\mu$ and neutrino mass simultaneously

Backup slides

UV model details

Field	$SU(2)_L$	$U(1)_Y$	Z_2
μ_R	1	-1	-1
ϕ	1	0	-1
H	2	$\frac{1}{2}$	$+1$
H'	2	$\frac{1}{2}$	-1
N	1	0	$+1$
N'	1	0	-1

$$\begin{aligned}\mathcal{L}_{UV} = &\, y_\mu \bar{L}_\mu H' \mu_R + y_{N,i} \left(L_i \cdot H\right) N + y'_{N,j} \left(L_j \cdot H'\right) N' \\ &+ \lambda_N N \cdot N' \phi + \mu_\phi H'^\dagger H \phi \\ &+ \frac{1}{2} m_N N \cdot N + \frac{1}{2} m_{N'} N' \cdot N' + h.c. \end{aligned} \tag{25}$$

$$g_\mu = y_\mu \frac{v \mu_\phi}{\sqrt{2} m_{H'}^2}$$

$$\begin{pmatrix} \vec{\nu} \\ N \\ N' \end{pmatrix} \approx \begin{pmatrix} \mathbb{I}_{3\times 3} & \frac{\vec{y_N} v + \vec{y_{N'}} v'}{\sqrt{2}\lambda_N v_\phi} & \frac{\vec{y_N} v - \vec{y_{N'}} v'}{\sqrt{2}\lambda_N v_\phi} \\ -\frac{\vec{y_{N'}}^{\mathrm{T}} v'}{\lambda_N v_\phi} & \frac{1}{\sqrt{2}} + z & -\frac{1}{\sqrt{2}} + z \\ -\frac{\vec{y_N}^{\mathrm{T}} v}{\lambda_N v_\phi} & \frac{1}{\sqrt{2}} + z & \frac{1}{\sqrt{2}} + z \end{pmatrix} \begin{pmatrix} \vec{\nu}' \\ \tilde{N} \\ \tilde{N}' \end{pmatrix}$$

$$\mathcal{M}_{ij} = \left(y_{N,i} y_{N',j} + y_{N,j} y_{N',i}\right) \frac{\sqrt{2} v v'}{2 \lambda_N v_\phi},$$

$$\begin{aligned} \tilde{m}_{\nu_1} &= 0, \\ \tilde{m}_{\nu_2} &= \frac{v v'}{\sqrt{2} \lambda_N v_\phi} \left(|\vec{y_N}||\vec{y_{N'}}| - \vec{y_N} \cdot \vec{y_{N'}}\right) \sim 0.1\mathrm{eV}, \\ \tilde{m}_{\nu_3} &= \frac{v v'}{\sqrt{2} \lambda_N v_\phi} \left(|\vec{y_N}||\vec{y_{N'}}| + \vec{y_N} \cdot \vec{y_{N'}}\right) \sim 0.1\mathrm{eV}, \\ \tilde{m}_N &\approx \frac{\lambda_N v_\phi}{\sqrt{2}} + \frac{m_N + m_{N'}}{2} + \mathcal{O}\left(\frac{1}{\lambda_N v_\phi}\right), \\ \tilde{m}_{N'} &\approx \frac{\lambda_N v_\phi}{\sqrt{2}} - \frac{m_N + m_{N'}}{2} \mathcal{O}\left(\frac{1}{\lambda_N v_\phi}\right), \end{aligned}$$

$$g_{\nu_a} = \frac{\tilde{m}_{\nu_a}}{v_\phi}.$$

$$m_1 = 0, \quad m_2 \simeq 8.7 \times 10^{-3}\mathrm{eV}, \quad m_3 \simeq 0.059\mathrm{eV}$$

$$g_{\nu_3} \approx 2.5 \times 10^{-10}$$