Light Dark Matter

Martin Bauer
IPPP Durham

Edinburgh, 20. February 2019

What is the DM scale?

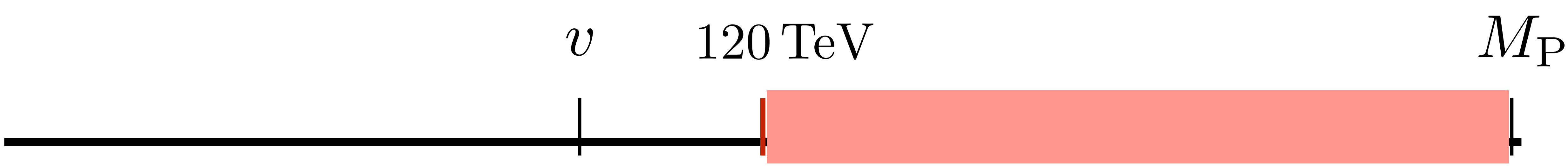
What is the DM scale?

$$\left(\frac{\Omega_X}{0.2}\right) \approx \frac{10^{-8}\,\mathrm{GeV}^{-2}}{\sigma}$$

$$\sigma \sim \frac{g^4}{m_\chi^2}$$

$$g^2 \lesssim 4\,\pi$$

$$\Rightarrow \quad m_\chi \lesssim 120\,\mathrm{TeV}$$



What is the DM scale?

$$\left(\frac{\Omega_X}{0.2}\right) \approx \frac{10^{-8}\,\mathrm{GeV}^{-2}}{\sigma}$$

$$\Gamma = n \cdot \sigma = H$$

$$(m_\chi T)^{\frac{3}{2}} e^{-\frac{m_\chi}{T}} \cdot \sigma = \frac{T^2}{M_{\mathrm{Pl}}}$$

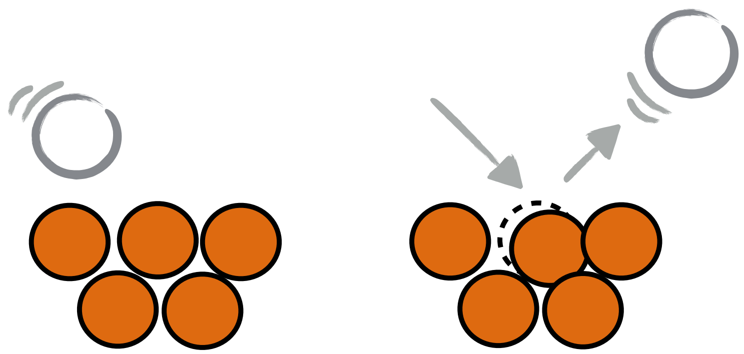
$$m_\chi > \frac{1}{\sigma M_{\mathrm{Pl}}} \qquad \Rightarrow m_\chi > 0.1\,\mathrm{eV}$$

$$\sigma \sim \frac{g^4}{m_\chi^2}$$

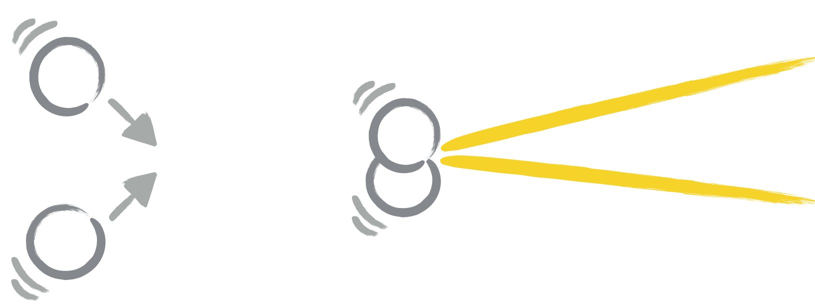
$$g^2 \lesssim 4\,\pi$$

$$\Rightarrow \qquad m_\chi \lesssim 120\,\mathrm{TeV}$$

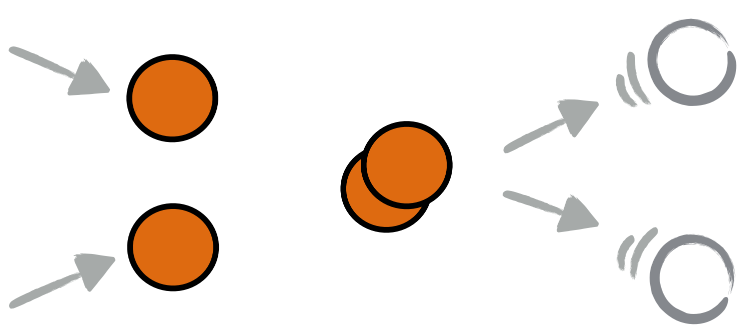
Extensive Programme



Direct detection



Indirect detection



Collider searches

What is the DM scale?

What do we know about the scale of DM?

What is the DM scale?

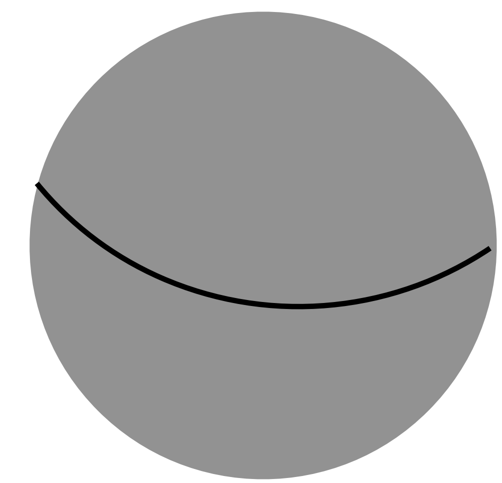
What do we know about the scale of DM?

For Fermions, the Fermi exclusion principle provides a lower limit

$$\left(\frac{9\pi M}{4m_\chi^4 R^3}\right)^{1/3} \leq \sqrt{\frac{2G_N M}{R}}$$

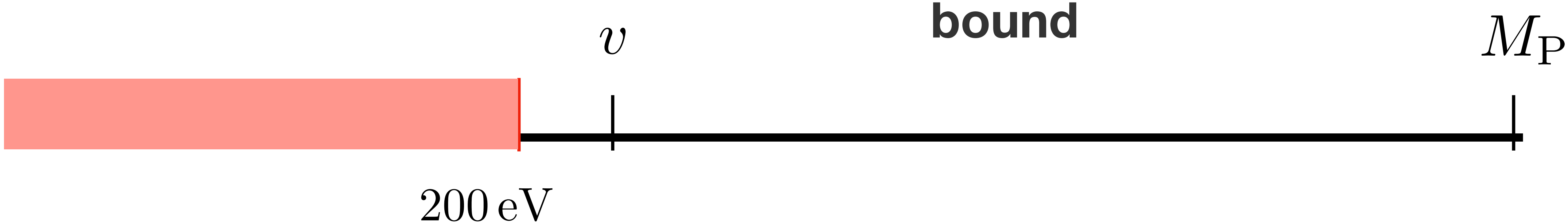
$$\Rightarrow \quad m_\chi \gtrsim 200\,\mathrm{eV}$$

dwarf galaxies



$$M \approx 10^7 M_\odot$$
$$R \approx 500\,\mathrm{pc}$$

Tremaine-Gunn bound



What is the DM scale?

For bosons there is no such lower limit.

There is however a scale that is particularly motivated:

$$m_\phi \approx 10^{-22}\,\mathrm{eV} \qquad \Rightarrow \qquad \lambda_{dB} = \frac{hc}{10^{-3} m_\phi} \approx 1\,\mathrm{kpc}$$

What is the DM scale?

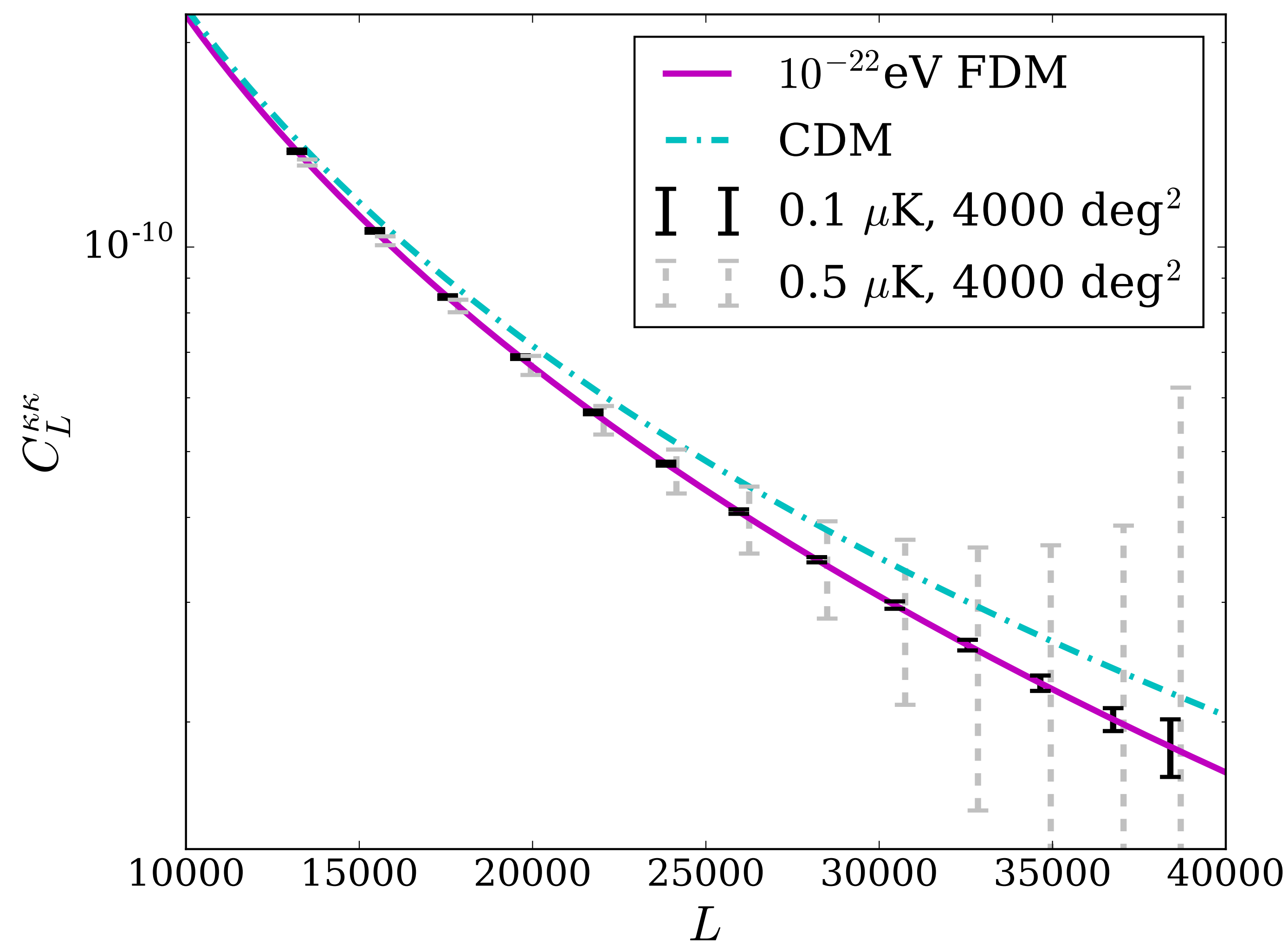
For bosons there is no such lower limit.

There is however a scale that is particularly motivated:

$$m_\phi \approx 10^{-22}\,\mathrm{eV} \qquad \Rightarrow$$

$$\lambda_{dB} = \frac{hc}{10^{-3} m_\phi} \approx 1\,\mathrm{kpc}$$

Suppresses small scale sub-halos, addressing the missing satellites problem and cusp-core.



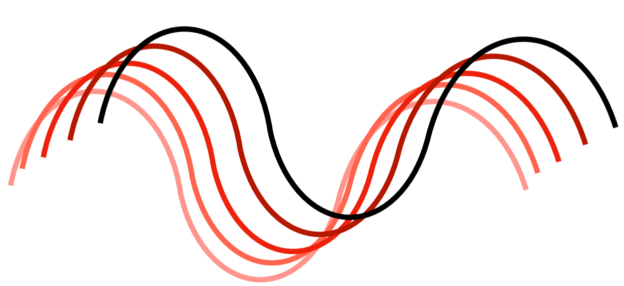
[1710.03747]

What is the DM scale?

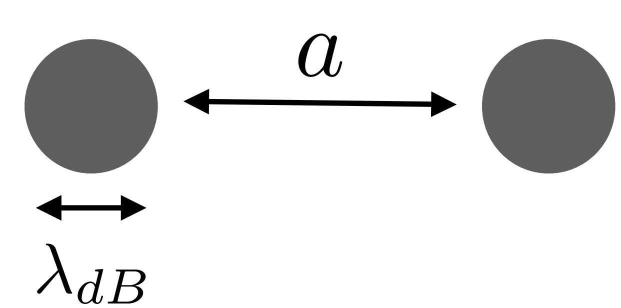
For very light scalar fields, the occupation number is very high and the field can be treated classically.

QFT

Large (continuous) occupation number. Classical field theory



Large spacing. Particle mechanics

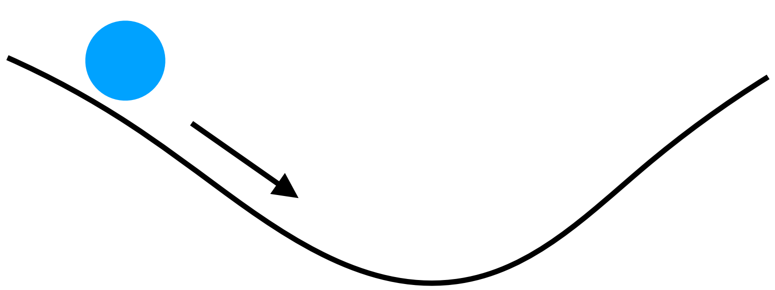


Ultralight Dark Matter

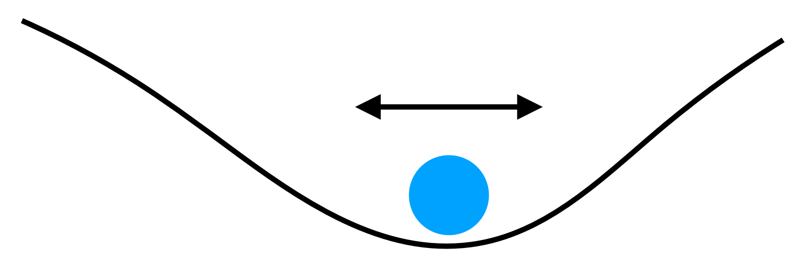
For very light scalar fields, the occupation number is very high and the field can be treated classically.

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \mu^4(1 - \cos a)$$

Relic density from misalignment:

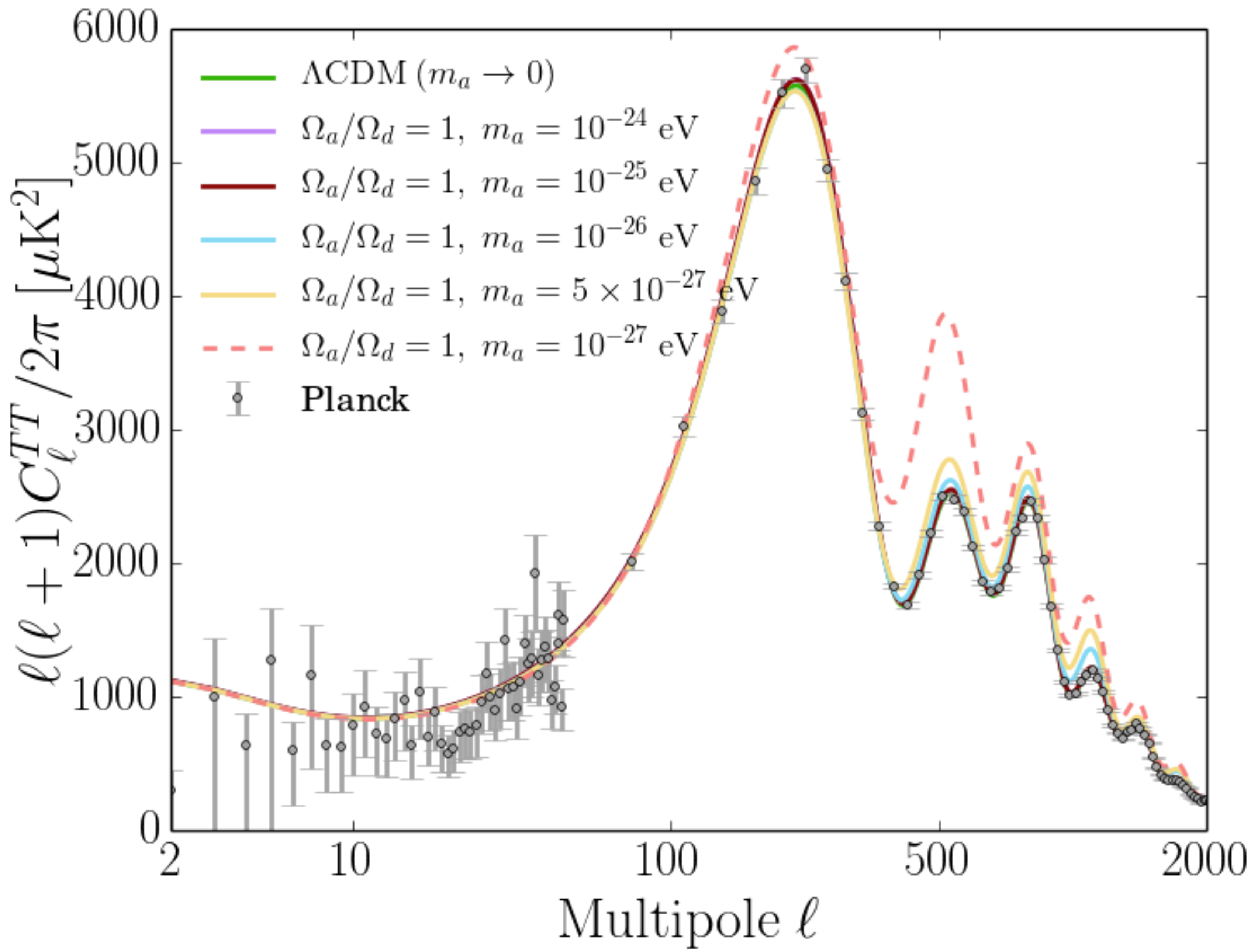


early universe: Hubble friction



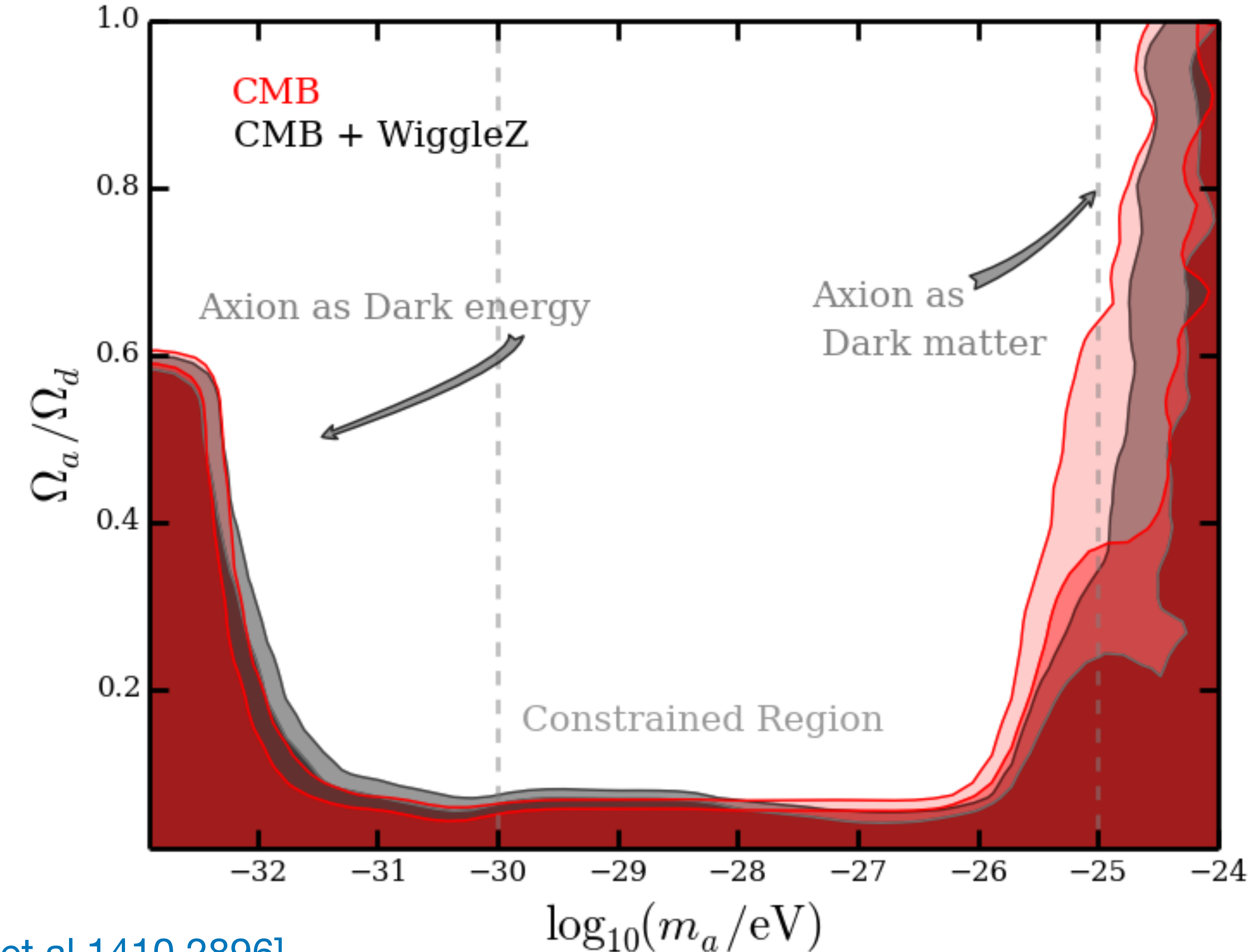
late universe: oscillations

Cosmological constraints



[Marsh et al 1410.2896]

Cosmological constraints



[Marsh et al 1410.2896]

Ultralight Dark Matter

Scalar Dark Matter

$$\mathcal{L} = \frac{\phi}{\Lambda} m_\psi \bar{\psi}\psi - \frac{1}{4g^2}\frac{\phi}{\Lambda} F^{\mu\nu}F_{\mu\nu} + \ldots$$

$$\phi = \phi_0 \cos(m_\phi t)$$

$$m_\psi \to \left(1 + \frac{\phi_0}{\Lambda}\cos(m_\phi t)\right)$$

$$\alpha \to \left(1 - \frac{\phi_0}{\Lambda}\cos(m_\phi t)\right)$$

Pseudoscalar Dark Matter (Axion)

$$\mathcal{L} = \frac{\partial^\mu a}{f}\bar{\psi}\gamma_\mu\gamma_5\psi - \frac{a}{f}F^{\mu\nu}\tilde{F}_{\mu\nu} + \ldots$$

$$a = a_0 \cos(m_a t)$$

Time varying spin-dependent effects

Ultralight Dark Matter

Scalar Dark Matter

Atomic clocks

Optical Cavities

Fifth-force searches

Pseudoscalar Dark Matter (Axion)

Magnetometers

Nuclear magnetic Resonance

Torion Pendula

Ultralight Dark Matter

Pseudoscalar Dark Matter (Axion)

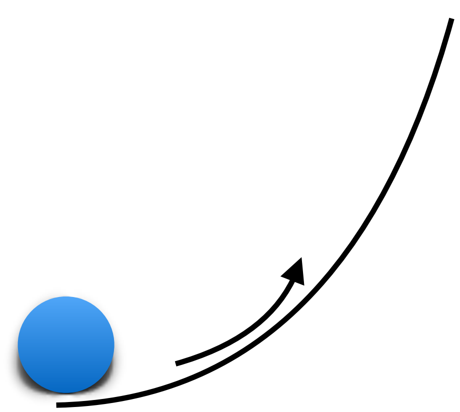
Axions

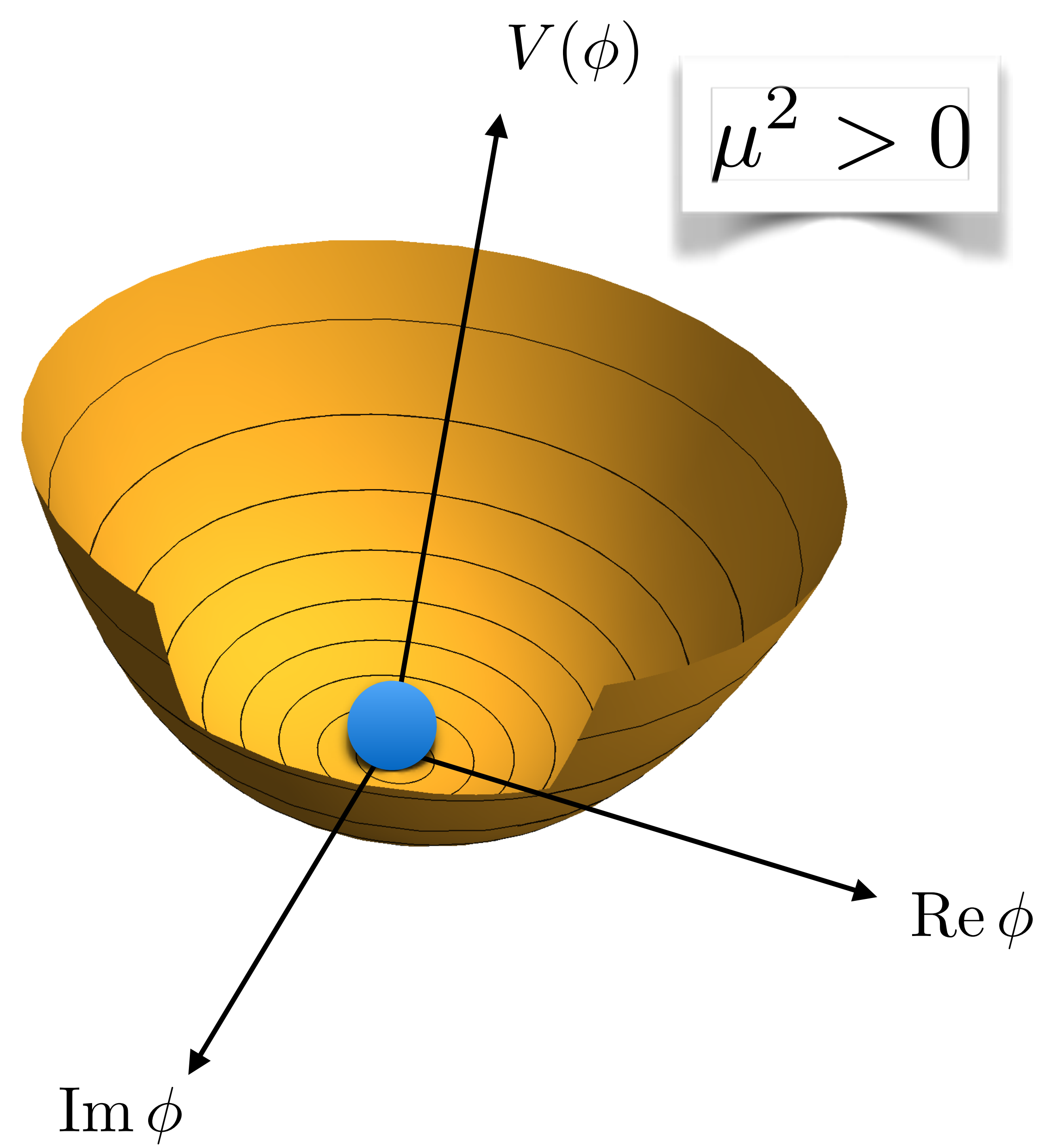
Every spontaneously broken continuous symmetry gives rise to massless spin-0 fields.

$$V(\phi) = \mu^2 \phi\phi^\dagger + \lambda(\phi\phi^\dagger)^2$$

$$\phi = \mathrm{Re}\,\phi + i\,\mathrm{Im}\,\phi$$

$$m_R^2 = m_I^2 = \mu^2$$





Axions

Every spontaneously broken continuous symmetry gives rise to massless spin-0 fields.

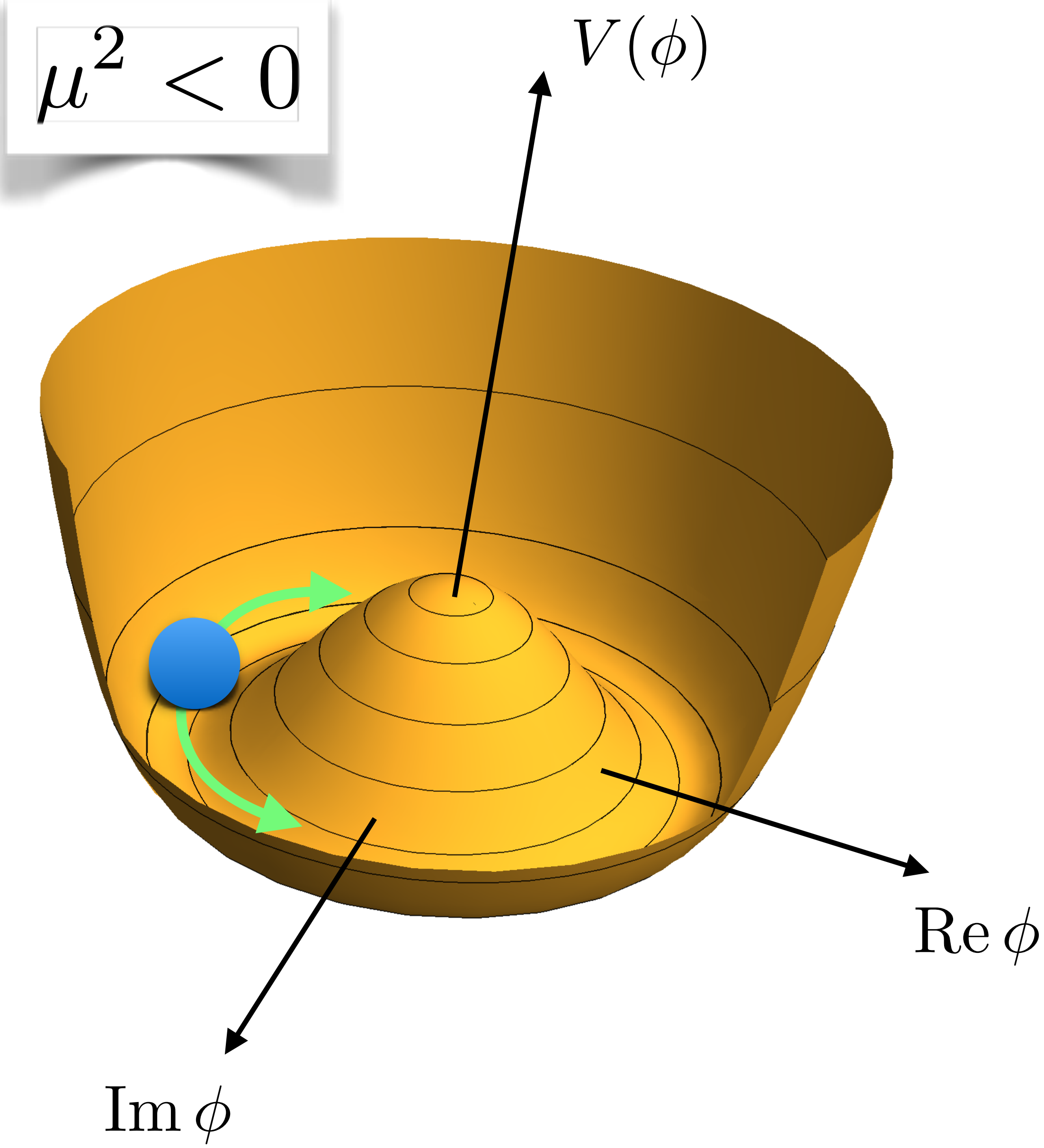
$$V(\phi) = \mu^2 \phi\phi^\dagger + \lambda\,(\phi\phi^\dagger)^2$$

$$\phi = (f+s)e^{ia/f}$$

$$m_s^2 = 4\lambda f^2 = |\mu^2|$$

$$m_a^2 = 0$$

$$\mu^2 < 0$$



Axions

Since the GB corresponds to the phase of a complex field, it is protected by a shift symmetry

$$\phi = (f + s)e^{ia/f}$$

it is protected by a shift symmetry

$$e^{ia(x)/f} \to e^{i(a(x)+c)/f} = e^{ia(x)/f} e^{ic/f}$$

This symmetry forbids a mass term, and all couplings are suppressed by the UV scale

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \, \partial^\mu a + c_\mu \frac{\partial^\nu a}{4\pi f} \, \bar{\mu}\gamma_\nu \mu + \ldots$$

Axions

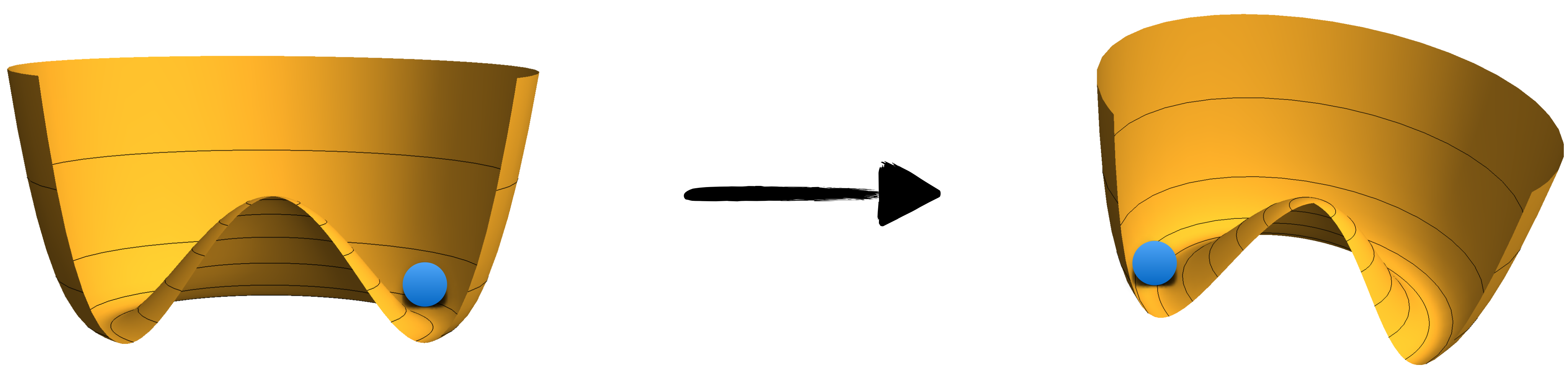
An exactly massless boson is problematic.

- Explicit (external) symmetry breaking

$$\mathcal{L} \ni m^2(\phi\phi + \phi^\dagger\phi^\dagger) \qquad m_a^2 = m^2$$

- Anomalous symmetry breaking

$$\mathcal{L} \ni \Lambda_{\rm QCD}^4 \cos\frac{\varphi}{f} \qquad m_a^2 = \frac{\Lambda_{\rm QCD}^4}{f^2}$$



Axions

The most famous example is the pion

ρ, P, N

$$\mathcal{L}_{\rm QCD} = \bar{q}_L i \not{D}\, q_L + \bar{q}_R i \not{D}\, q_R + m_q \bar{q}_L q_R$$

$$\langle \bar{q}_L q_R \rangle = \Lambda^3_{\rm QCD} \approx {\rm GeV}^3$$

The pion mass is controlled by the explicit breaking through light quark masses

$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda^3_{\rm QCD} \quad \approx (140\,{\rm MeV})^2$$

π

Axions

The most famous example is the pion

other states at f

$$\mathcal{L}_{\rm QCD} = \bar{q}_L i \not{D}\, q_L + \bar{q}_R i \not{D}\, q_R + m_q \bar{q}_L q_R$$

$$\langle \bar{q}_L q_R \rangle = \Lambda^3_{\rm QCD} \approx {\rm GeV}^3$$

The pion mass is controlled by the explicit breaking through light quark masses

$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda^3_{\rm QCD} \quad \approx (140\,{\rm MeV})^2$$

axion

Do we need to be super-sensitive?

At $$\frac{T_0^2}{M_{\rm Pl}} = m = \frac{\mu^2}{f}$$ $$H \sim m$$

the energy densities read $\rho_\phi \sim \mu^4$ $\rho_\gamma \sim T_0^4$

At matter-radiation $T_1 = 1\mathrm{eV}$ equality they should be equal

$$\frac{\mu^4}{T_0^4}\frac{T_0}{T_1} \sim 1$$

Do we need to be super-sensitive?

At $$\frac{T_0^2}{M_{\rm Pl}} = m = \frac{\mu^2}{f} \qquad\qquad H \sim m$$

the energy densities read $\rho_\phi \sim \mu^4 \qquad \rho_\gamma \sim T_0^4$

At matter-radiation $T_1 = 1{\rm eV}$ equality they should be equal

$$\frac{\mu^4}{T_0^4}\frac{T_0}{T_1} \sim 1$$

It follows for axions

$$f \sim \frac{M_{\rm Pl}^{3/4} T_1^{1/2}}{m^{1/4}} \sim 0.5 \times 10^{17}\,{\rm GeV}$$

"almost like a WIMP miracle "

-Witten

[1610.08297]

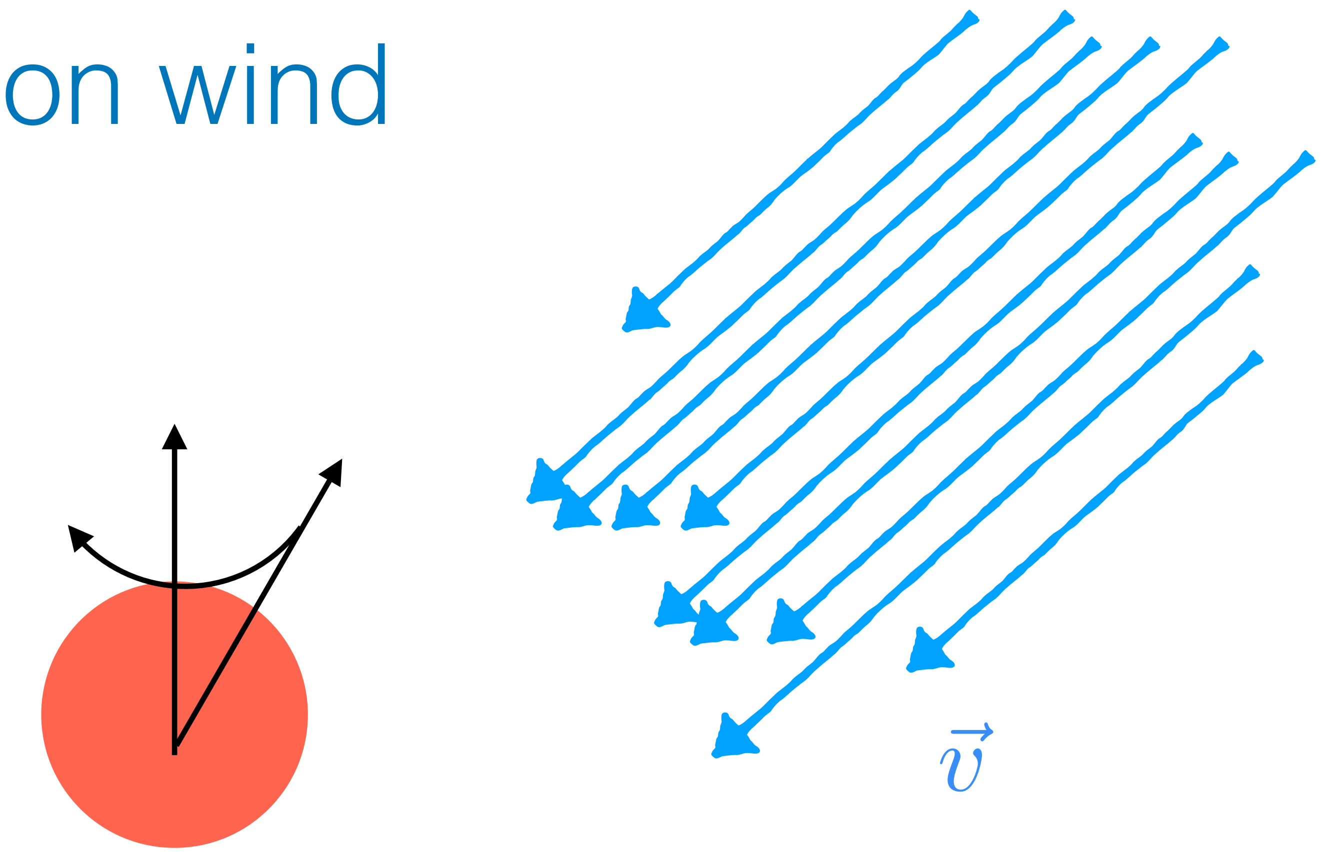
Axions

Spin-dependent effects

$$\mathcal{L} = \frac{\partial^\mu a}{f} \bar{\psi}\gamma_\mu\gamma_5\psi \longrightarrow g_{\mathrm{aNN}} \left(\partial_\mu a\right) \bar{N}\gamma^\mu\gamma_5 N$$

$$H_{\mathrm{wind}} \approx g_{aNN} \nabla a \cdot \boldsymbol{\sigma}_N$$

Axion wind



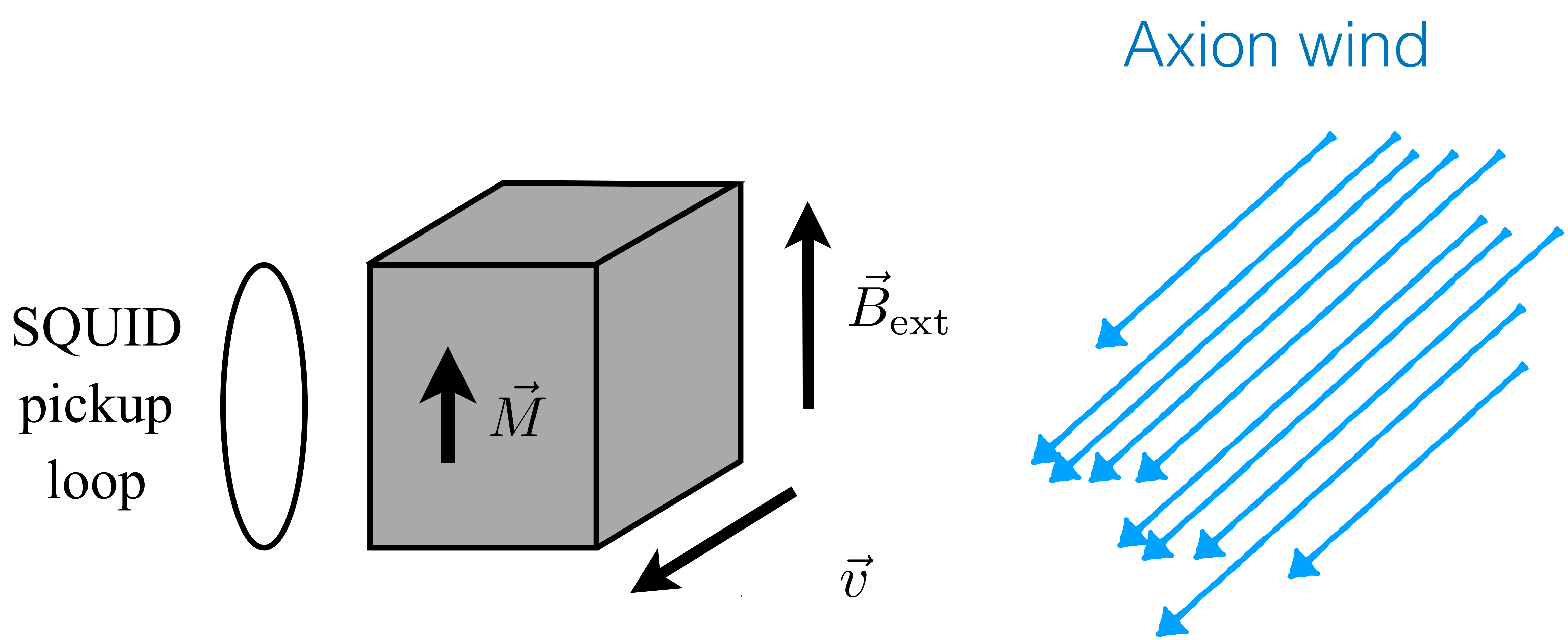
Nucleon Spin
rotates about
Dark Matter
velocity

Axions

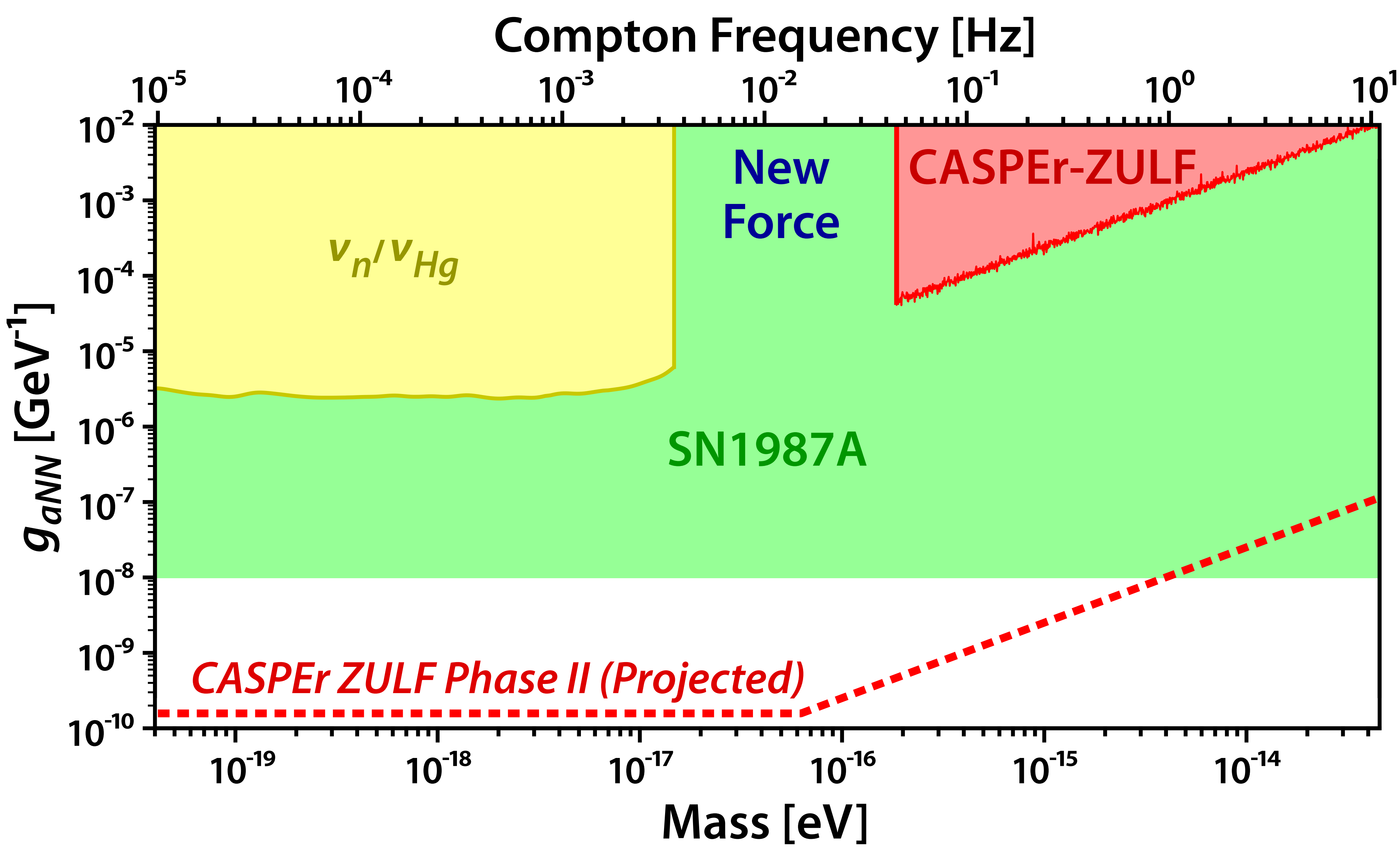
Spin-dependent effects

$$H_{\mathrm{aNN}} = \gamma \vec{B}_{\mathrm{ALP}} . \vec{\sigma}_{\mathrm{N}}$$

$$\vec{B}_{\mathrm{ALP}} = g_{\mathrm{aNN}} \frac{\sqrt{2\rho_{\mathrm{DM}}}}{\gamma} \cos(\omega_{\mathrm{a}} t) \vec{v}.$$



Axions

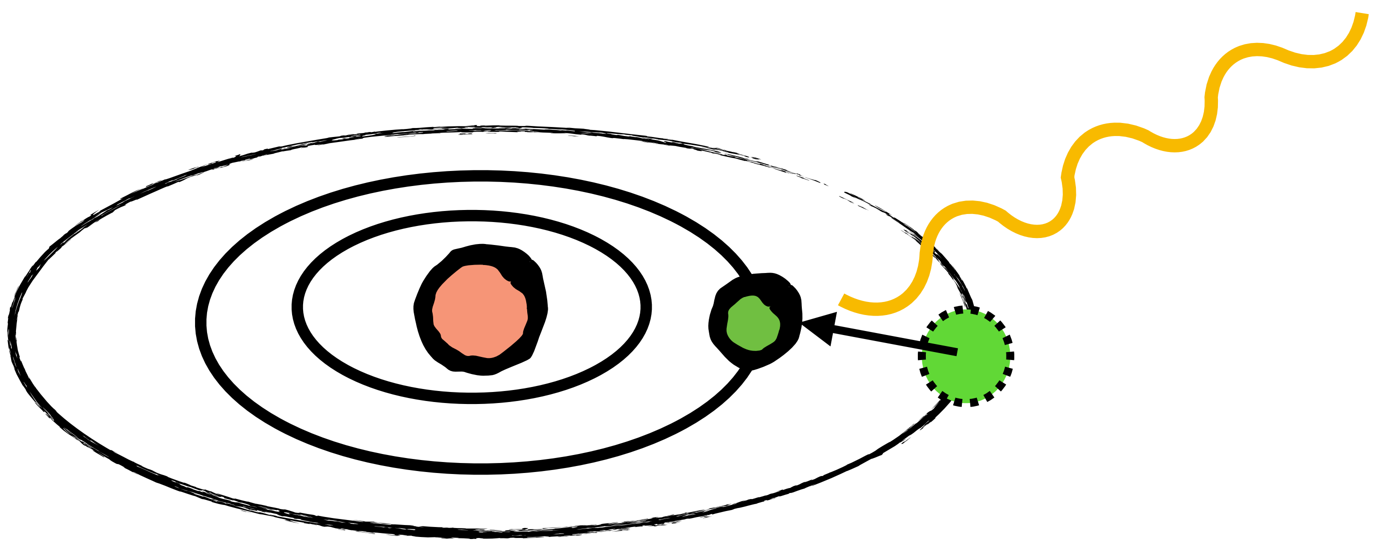


Scan mass by varying ext. magnetic field [1902.04644]

Ultralight Dark Matter

Scalar Dark Matter

Scalar Dark Matter



$$\alpha \to \left(1 - \frac{\phi_0}{\Lambda}\cos(m_\phi t)\right)$$

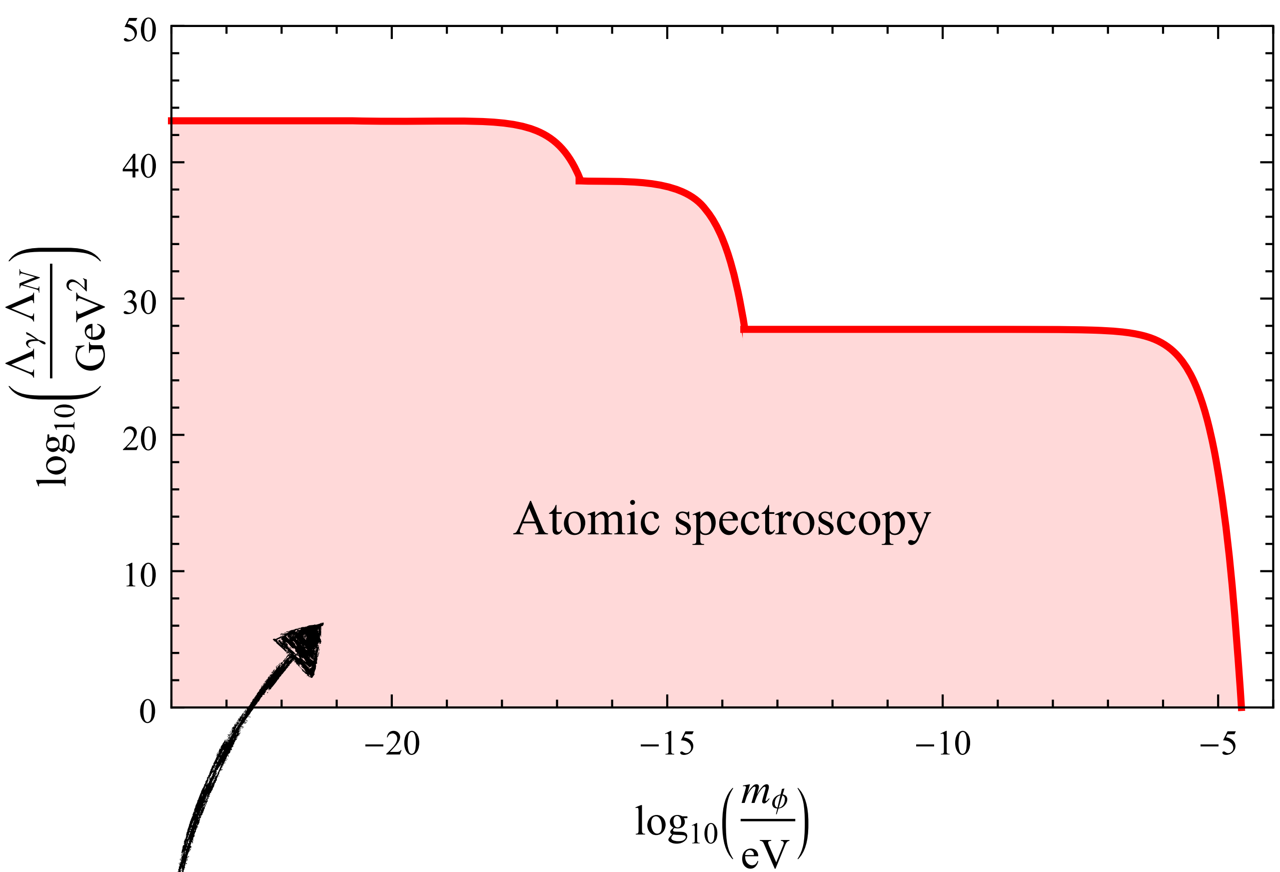
Measure ratios of transition frequencies for different distances

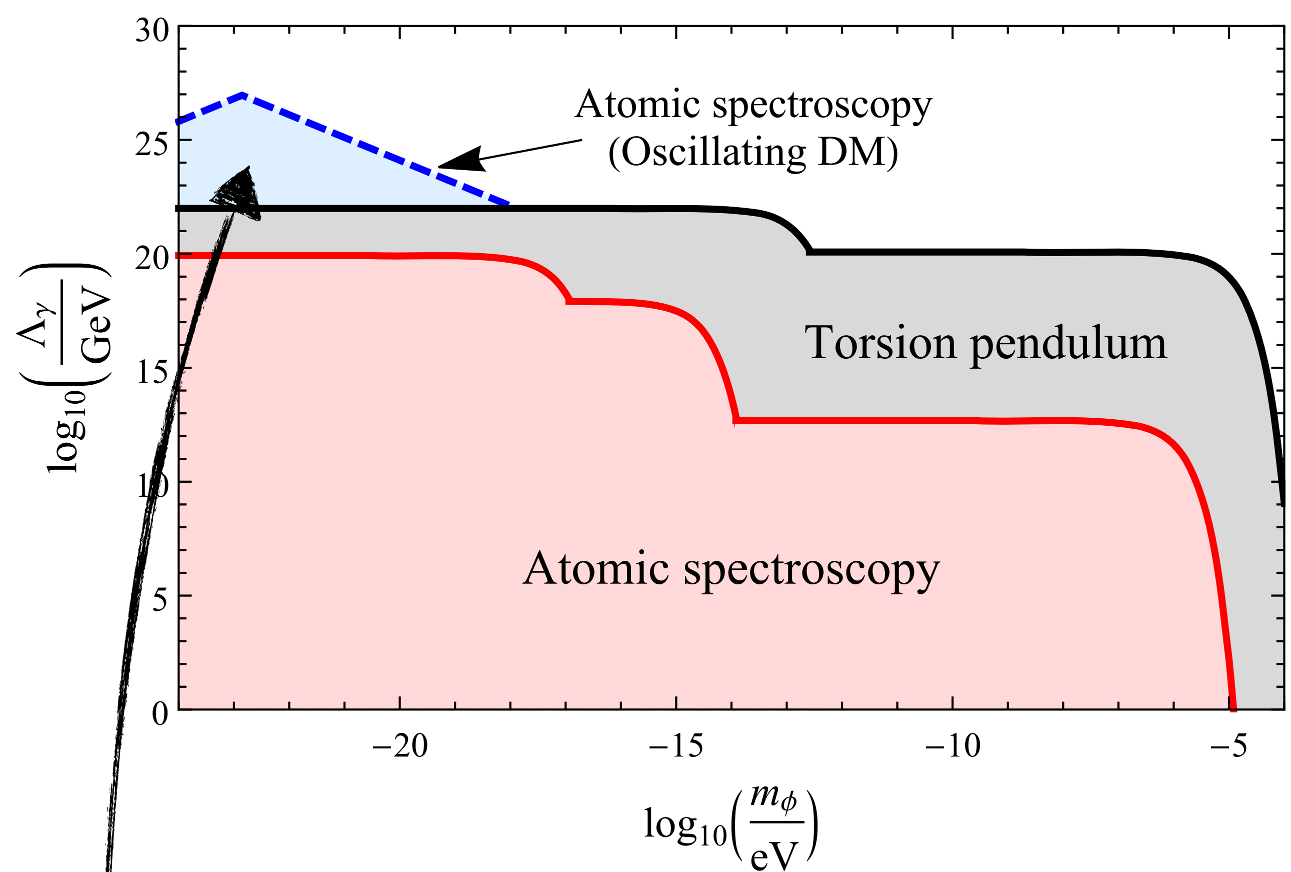
Also sensitive to fifth forces

$$Z\frac{\alpha}{r} \longrightarrow Z\frac{\alpha}{r} + \frac{y_i y_j}{4\pi}\frac{e^{-m_\phi r}}{r}$$

Scalar Dark Matter

Atom spectroscopy in Dysprosium





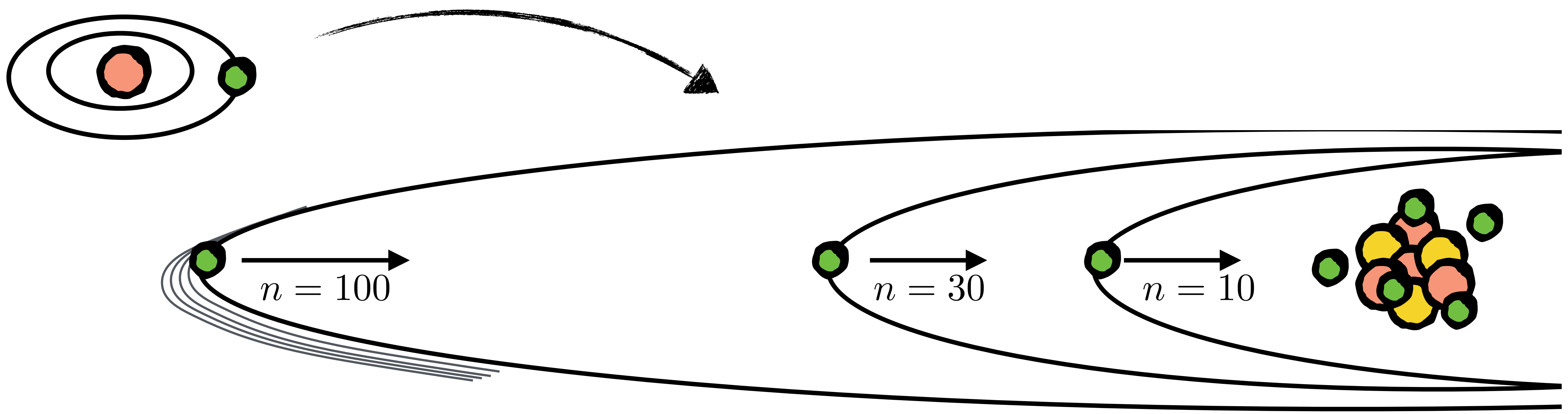
Fifth force

Oscillating signal

PRL **117,** 271601 (2016)

Scalar Dark Matter

Durham Rydberg Spectroscopy experiment



Many more transitions at continuous splitting, estimated 3-6 orders of magnitude improvement.

Joint Atmol&IPPP QSFP proposal, MB Jones, Carty

Quantum Sensors for Fundamental Physics

first QSFP workshop, Oxford, Oct 2018

New collaborations between atomic physicists and particle physicists.

STFC initiative   40M £

Gauge Mediators

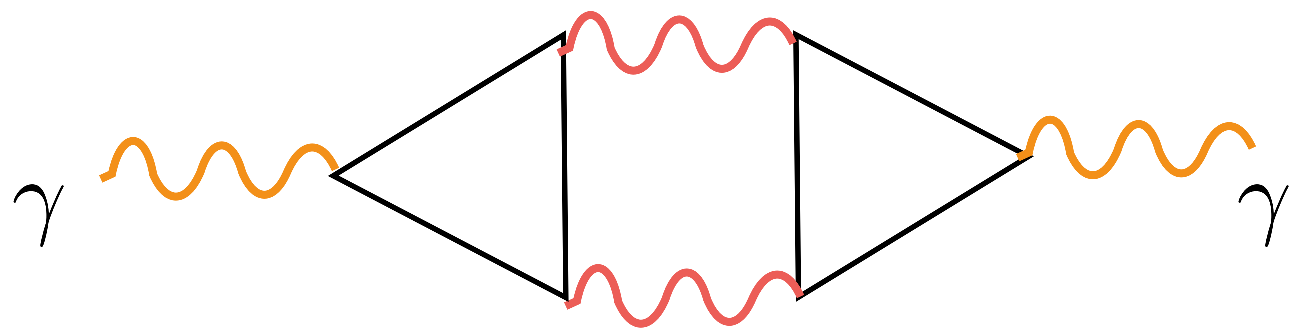
What if the mediator to the Dark Sector is light?

A new gauge boson?

Possible new gauge groups are strongly constrained.

Gauge Mediators

Anomaly cancellation is necessary for gauge invariance.

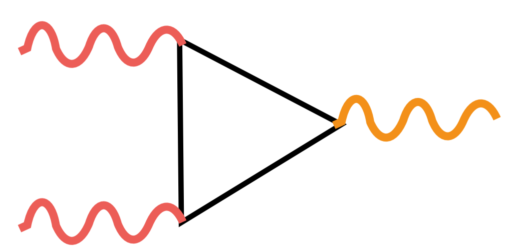


$$\Rightarrow m_\gamma \neq 0$$

[Gross, Jackiw, Phys. Rev. D6, 477 (1972).

All triangle diagrams have to vanish

$$\sum_{\text{Fermions}}$$



$$= 0$$

This fixes the Standard Model hypercharges.

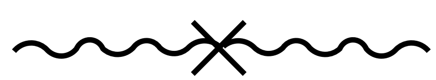
[S. Adler (1969). Physical Review. 177 (5): 2426]   [Bell, Jackiw (1969) Il Nuovo Cimento A. 60:47]

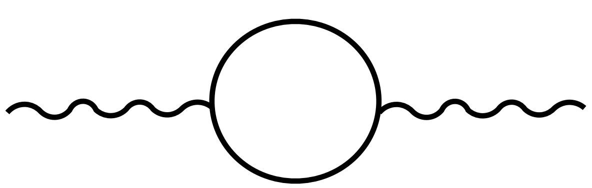
Gauge Mediators

How to couple to the Standard Model?

Even if all SM particles are uncharged, coupling through mixing

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}$$

B_μ  A'_μ ϵ is a free parameter

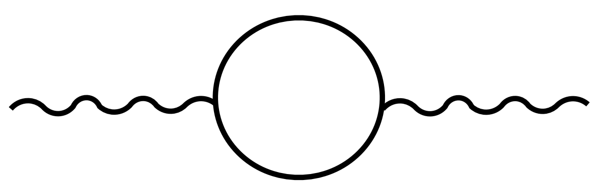
B_μ  A'_μ $\epsilon \propto \frac{g_X e}{8\pi^2} \log \frac{\Lambda^2}{m^2}$

Gauge Mediators

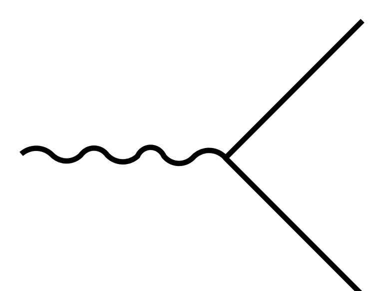
How to couple to the Standard Model?

Even if all SM particles are uncharged, coupling through mixing

B_μ  A'_μ $\quad$ ϵ is a free parameter

B_μ  A'_μ $\quad$ $\epsilon \propto \frac{g_X e}{8\pi^2} \log \frac{\Lambda^2}{m^2}$

Charged SM matter is milli-charged under $U(1)_X$



$$eA_\mu J^\mu_{\mathrm{EM}} - \epsilon e A'_\mu J^\mu_{\mathrm{EM}}$$

Leads to “universal” couplings.

Gauge Mediators

There is a limited number of possible new light gauge bosons consistent with the SM (= anomaly free).

Universal B - L $L_\mu - L_e$ $L_e - L_\tau$ $L_\mu - L_\tau$

[MB, Foldenauer, Jaeckel, 1803.05466]

{Theory detour

These gauge groups are special

Universal

B - L

$L_\mu - L_e$

$L_e - L_\tau$

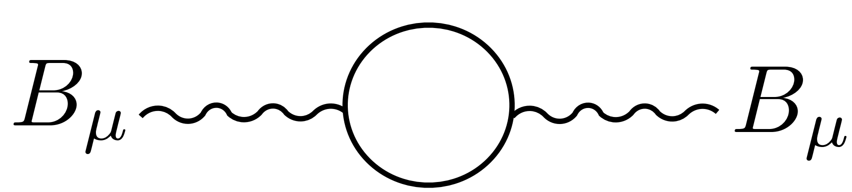
$L_\mu - L_\tau$

Theory detour

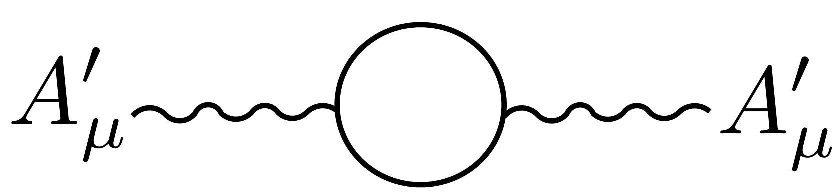
B - L

Even though anomaly free, B-L gauge bosons have divergent one-loop mixing

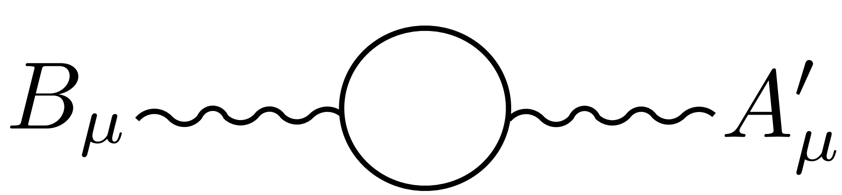
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}$$



divergent $\dfrac{e^2}{\epsilon}$



divergent $\dfrac{g_{B-L}^2}{\epsilon}$



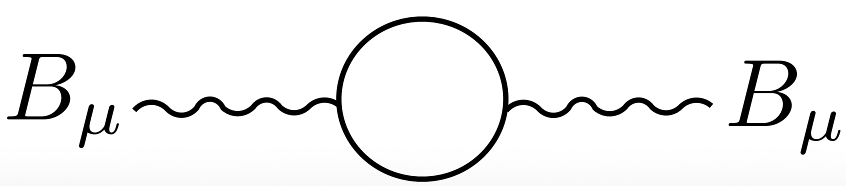
divergent $\dfrac{e\, g_{B-L}}{\epsilon}$

Theory detour

B - L

Even though anomaly free, B-L gauge bosons have divergent one-loop mixing

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}$$



divergent $\frac{e^2}{\epsilon}$

gent $\frac{g_{B-L}^2}{\epsilon}$

gent $\frac{e\, g_{B-L}}{\epsilon}$

Only two field strength tensors.

How to absorb 3 divergencies?

Theory detour

B - L

Even though anomaly free, B-L gauge bosons have divergent one-loop mixing

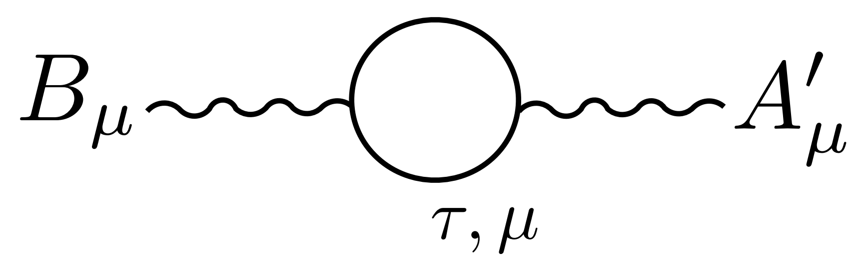
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}$$

The theory tells us that the couplings at the high scale must be related.

$$SU(2)_L \times SU(2_R) \times U(1)_X \rightarrow U(1)_{B-L} \times U(1)_Y$$

Theory detour}

$L_\mu - L_\tau$ For leptonic gauge groups, the mixing is finite!



$$\epsilon_{\mu\tau}(q^2) = -\frac{e g_x}{4\pi^2}\int_0^1 dx\, x(x-1)\;\; 3\log\left(\frac{m_\mu^2 + q^2 x(x-1)}{m_\tau^2 + q^2 x(x-1)}\right)$$

$$\begin{array}{ccc} G_{\text{SM}} & \times & G_{L_\mu - L_\tau} \\ \downarrow & & \downarrow \\ SU(3)_C \times SU(2)_L \times U_Y(1) & \times & U(1)_{L_\mu - L_\tau} \end{array}$$

very predictive model

Gauge Mediators

There is a limited number of possible new light gauge bosons consistent with the SM (= anomaly free, and able to reproduce mixing structures).

Universal

- couples to all charged matter

B - L

- couples to quarks and leptons

$L_\mu - L_e$

- couples to muons and electrons

$L_e - L_\tau$

- couples to taus and electrons

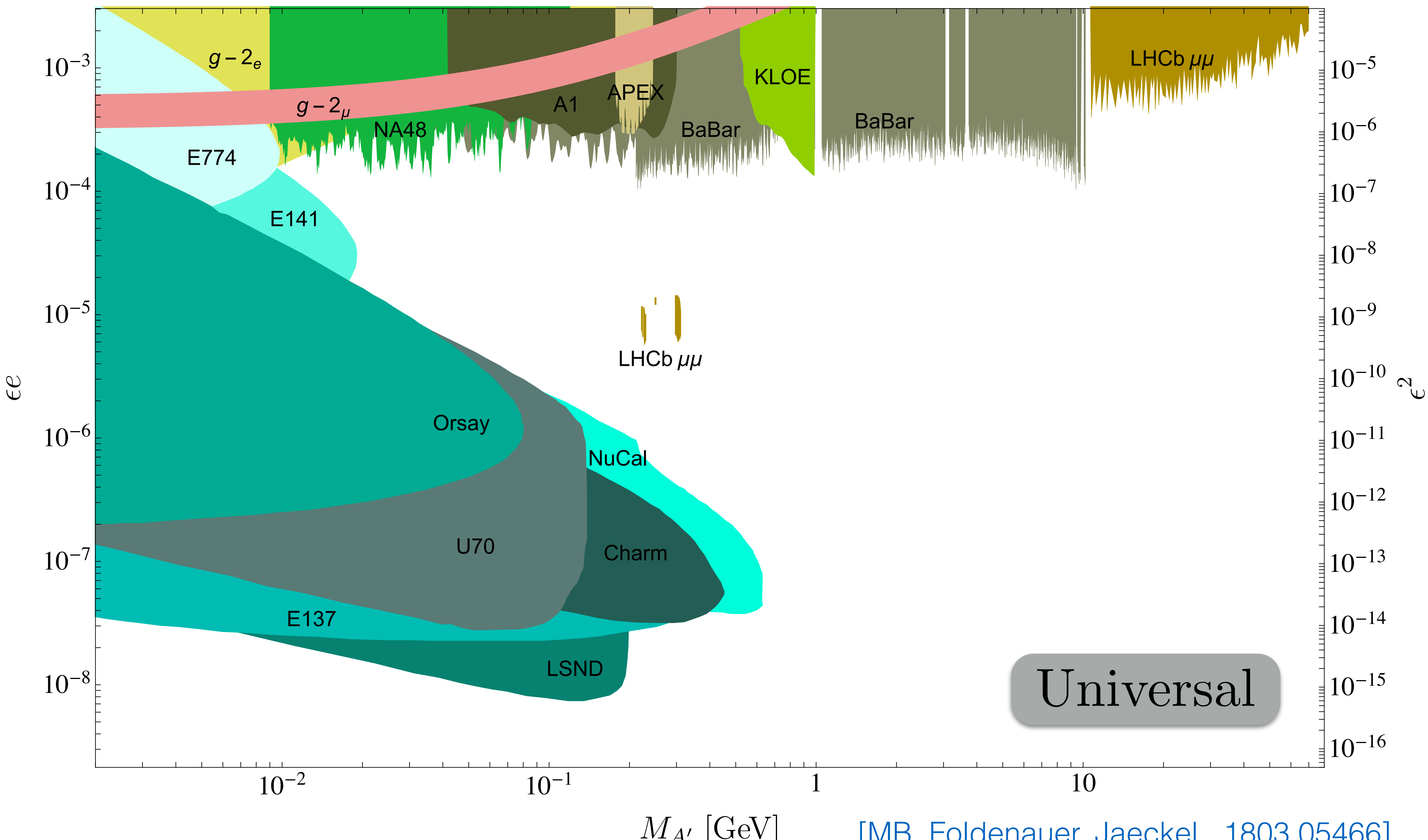
$L_\mu - L_\tau$

- couples to taus and muons

usually constraints are put on the most general case.

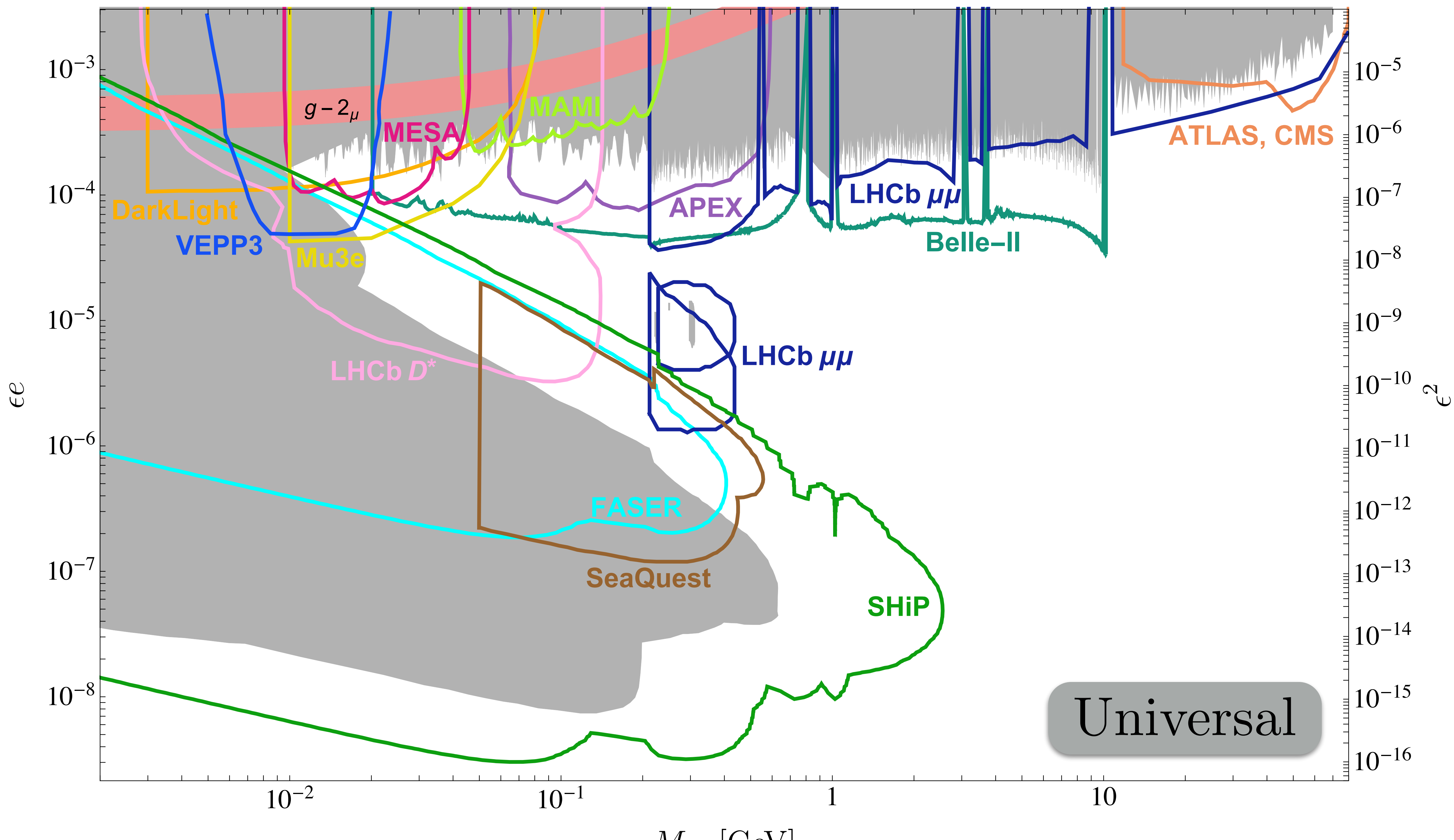
[MB, Foldenauer, Jaeckel, 1803.05466]

Gauge Mediators



[MB, Foldenauer, Jaeckel, 1803.05466]

Gauge Mediators

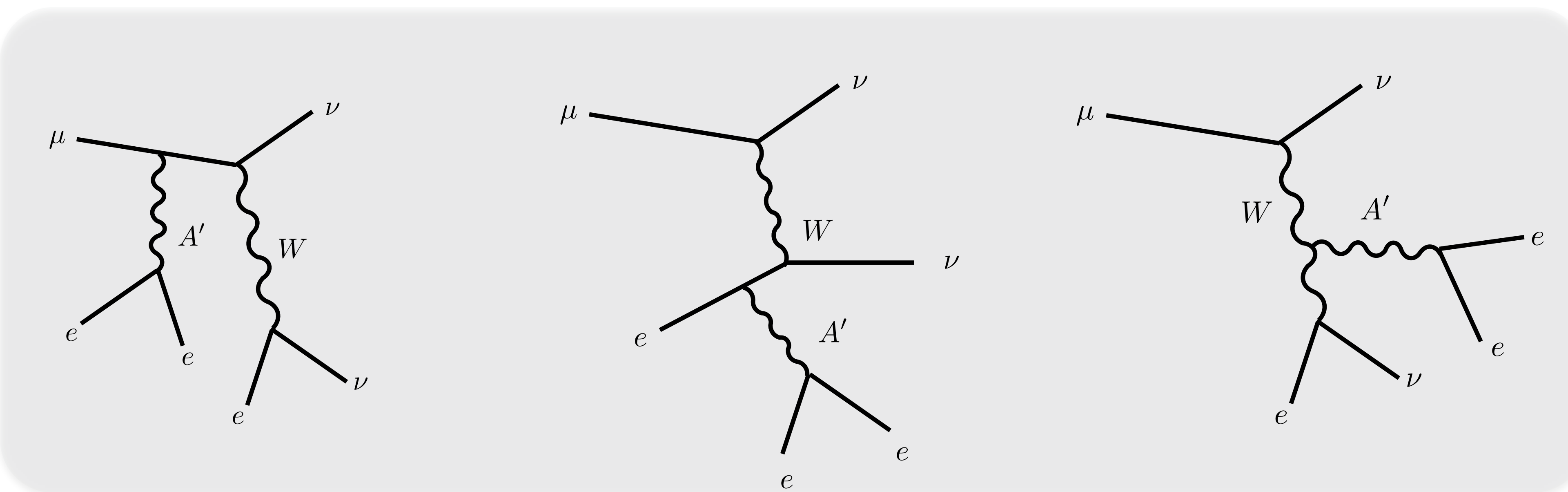


[MB, Foldenauer, Jaeckel, 1803.05466]

Gauge Mediators

The Mu3e experiment can search for light hidden photons

$$\mu^+ \to \gamma' e^+ \nu_e \bar{\nu}_\mu \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$$



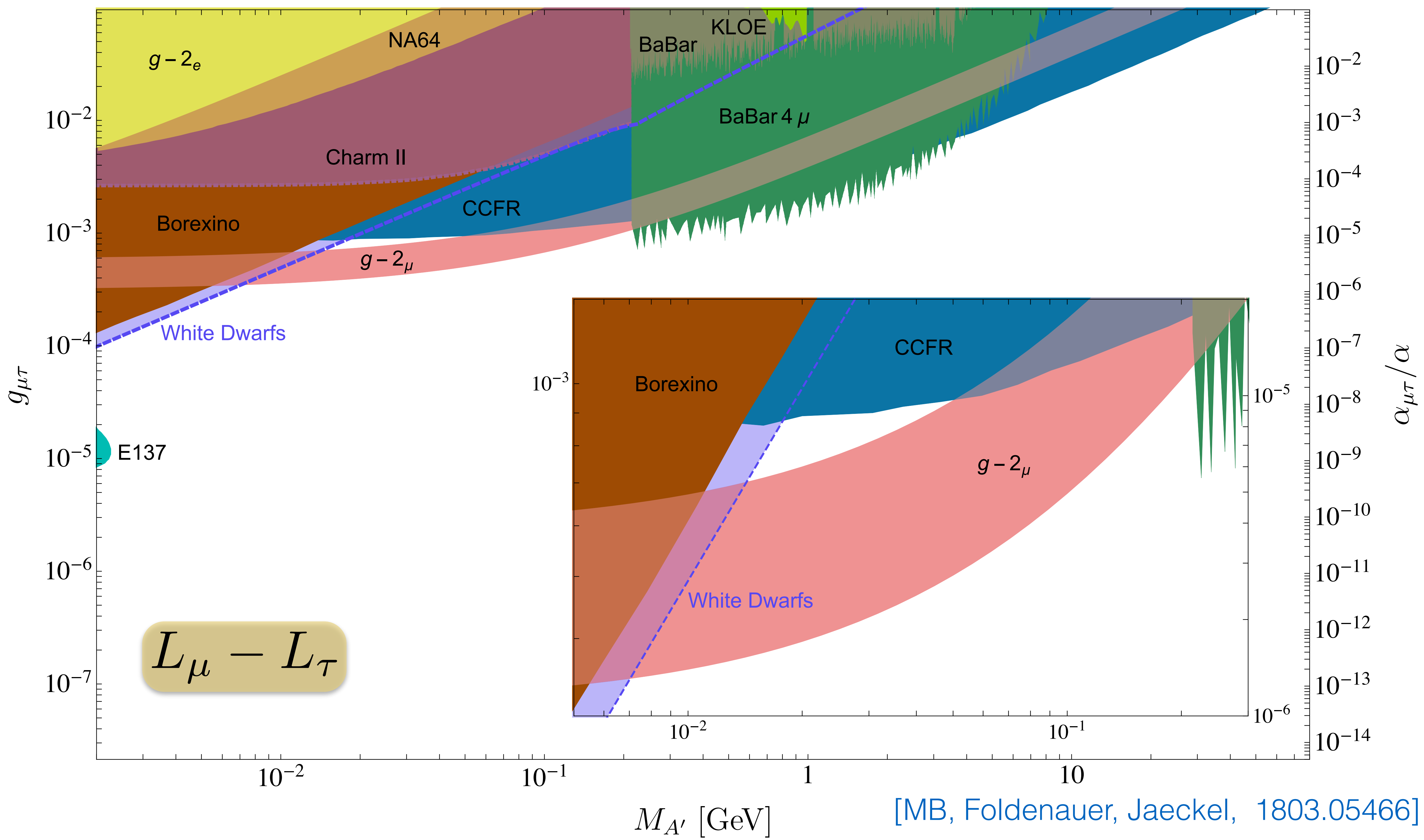
Universal

Prompt decays [Echenard, Essig, Zhong, *1411.1770]*

Displaced vertices [Mu3E collaboration, *in prep.]*

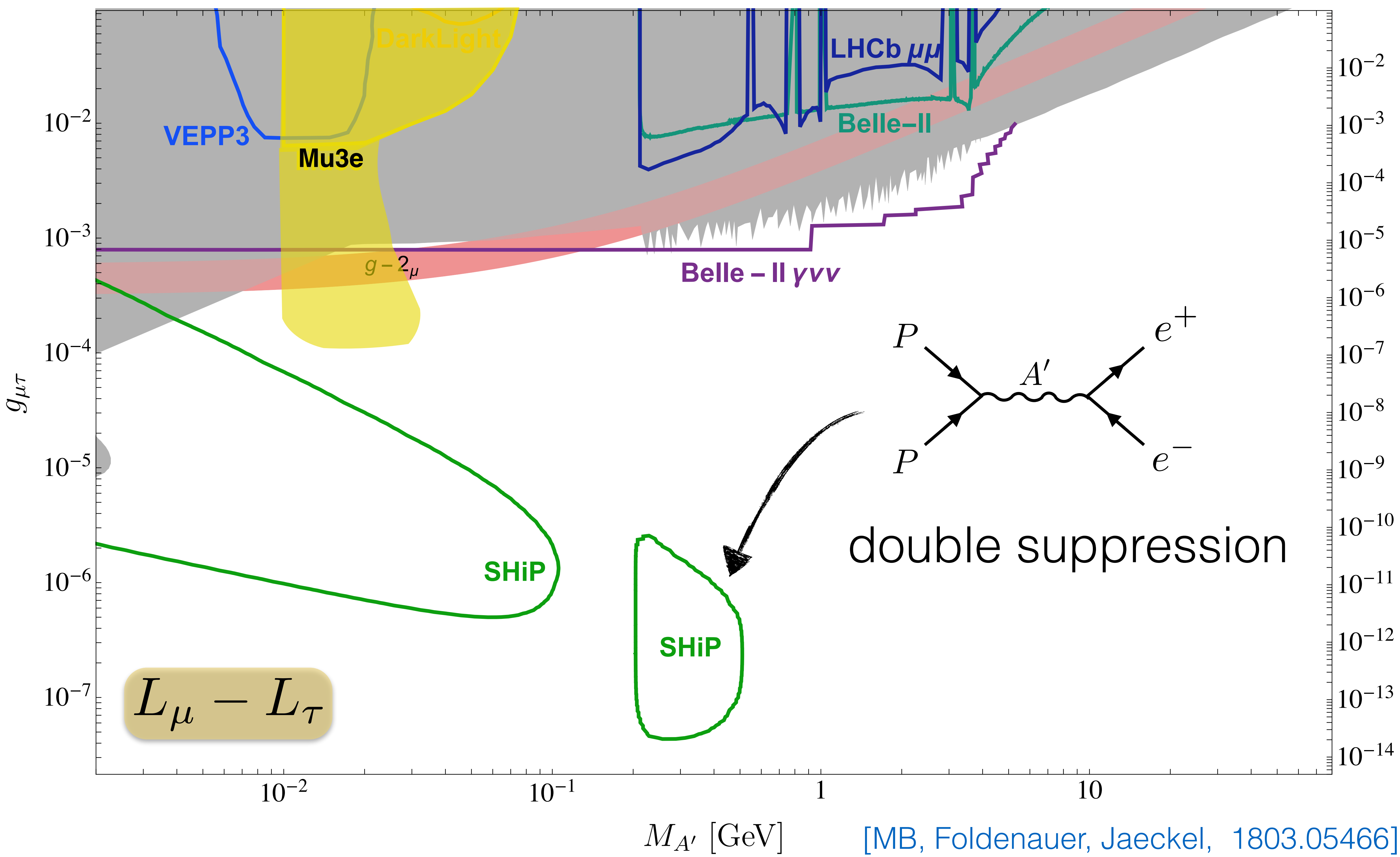
Gauge Mediators

allow for irreducible mixing



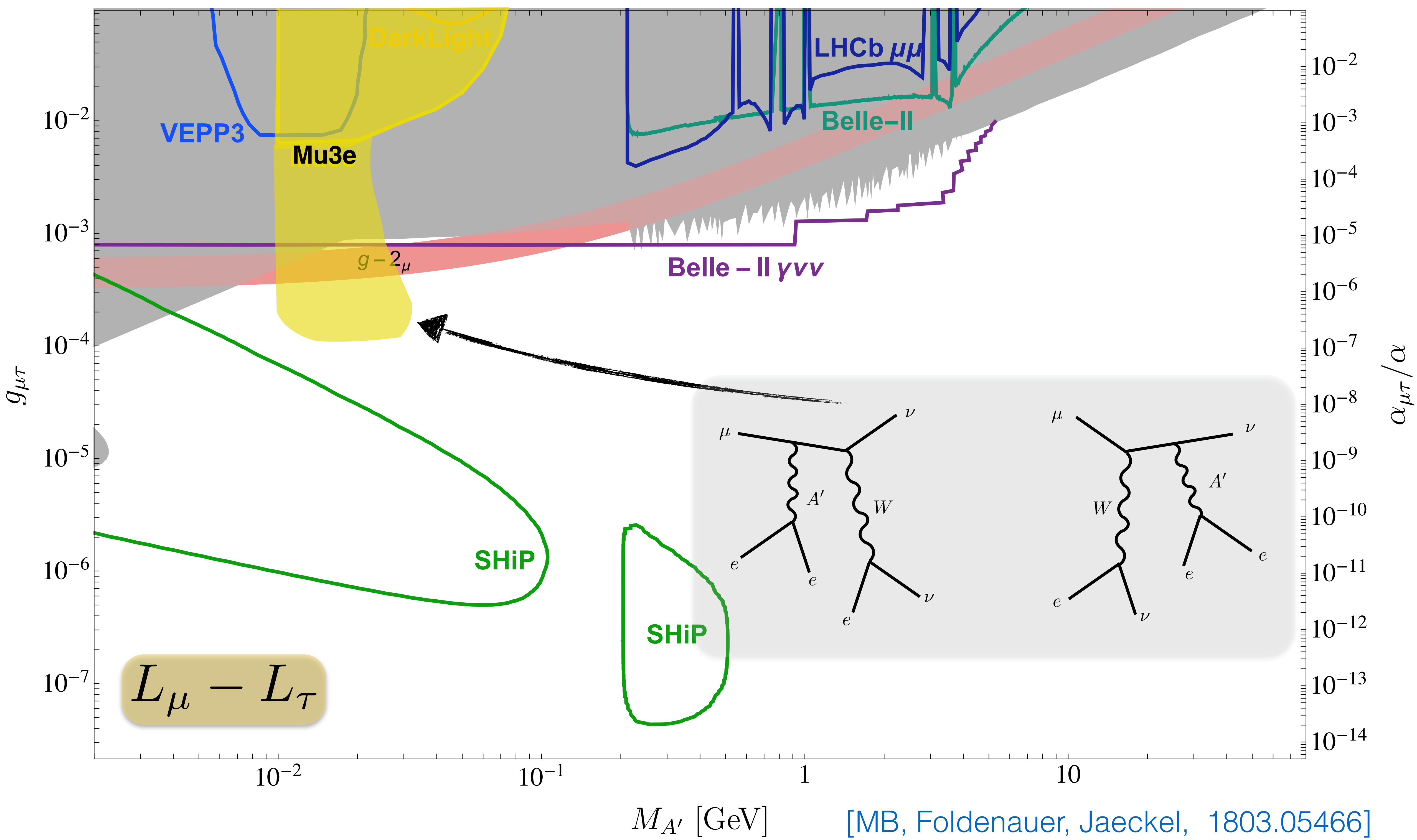
[MB, Foldenauer, Jaeckel, 1803.05466]

Gauge Mediators



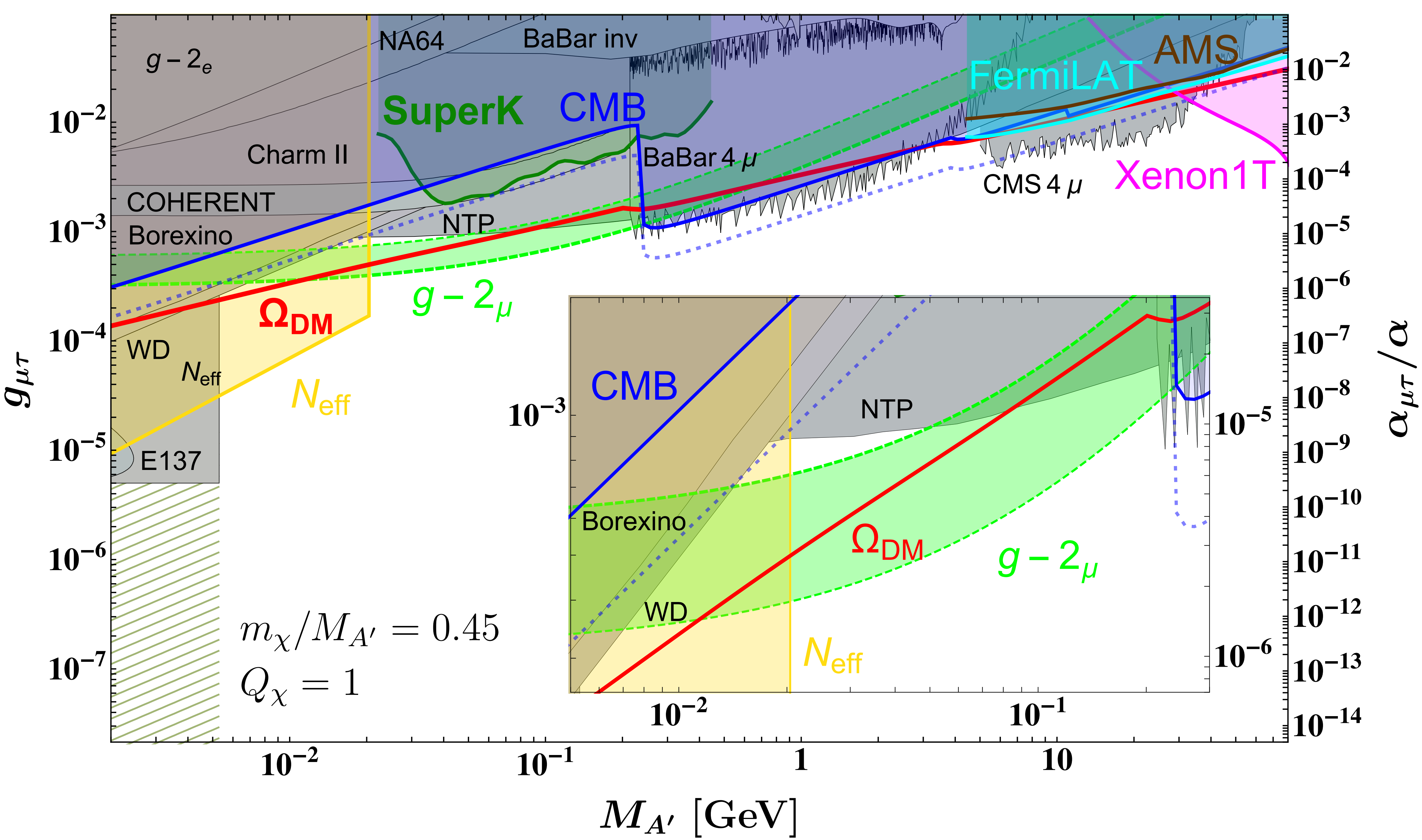
[MB, Foldenauer, Jaeckel, 1803.05466]

Gauge Mediators



[MB, Foldenauer, Jaeckel, 1803.05466]

Gauge Mediators



$Q_\chi = 1 \qquad m_\chi/M_{A'} = 0.45$

[Foldenauer, 1808.03647]

Conclusions

Ultra-light dark matter can be searched for with table-top experiments.

STFC funds this programme with a special initiative (QSFP).

We propose an optical Rydberg spectroscopy experiment in Durham to search for fifth forces and Dark Matter.

Muon experiments can test a special, well-motivated class of mediators to the dark sector.