Dark sectors: a theory introduction

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Workshop on status and perspectives of physics at high intensity
LNF - 11/11/2022

Outline

- What are dark sectors? Why do we need them?

- Dark sector portals

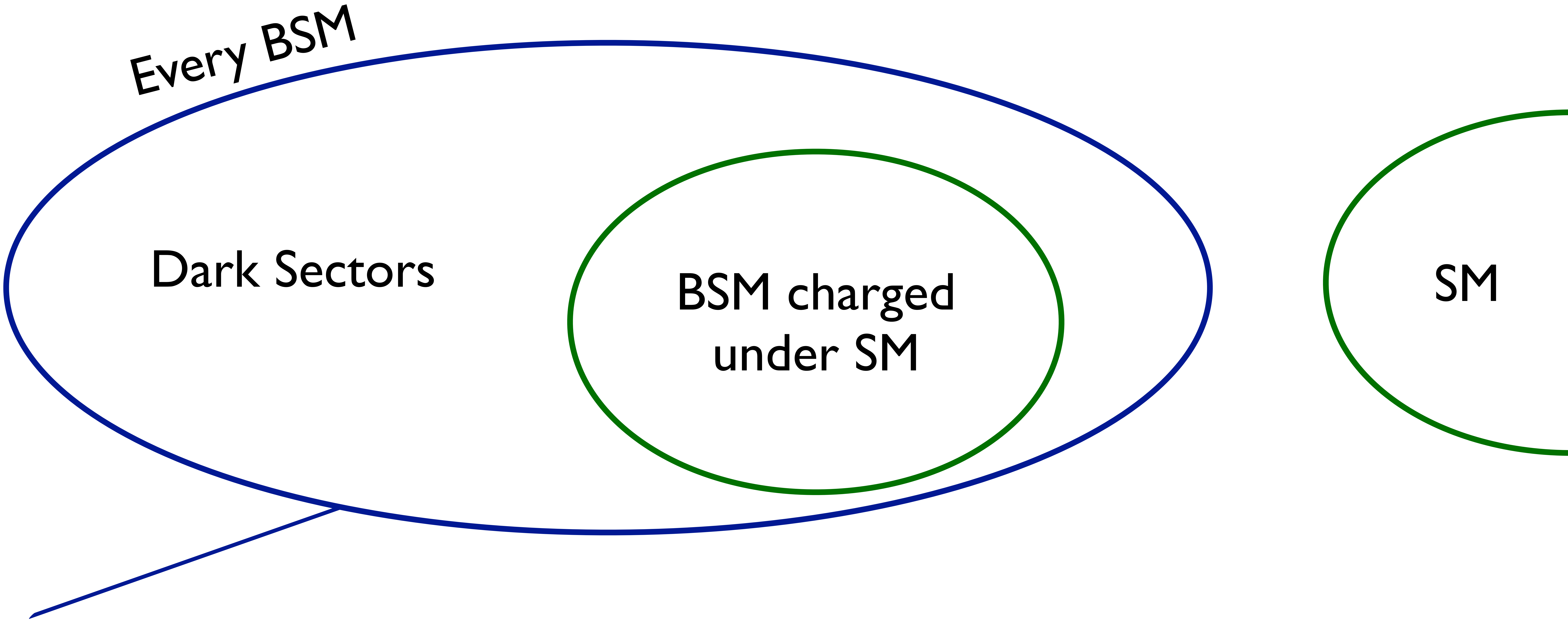
  vector, scalar, fermion, ALPs

- Two examples:

  1. the $(g-2)_\mu$ problem
  2. the X17 anomaly

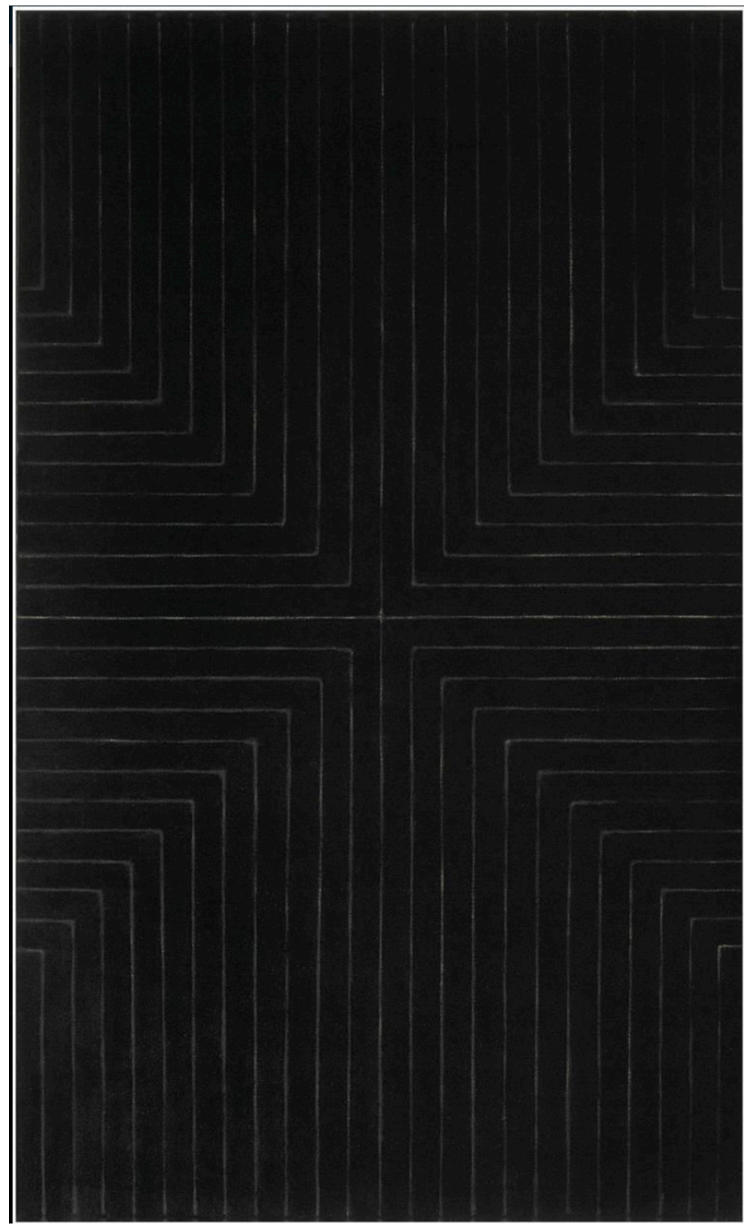
Definition

Dark sector: a collection of particles that is neutral under the SM forces but it is interacting with some (or several) new force(s).



Schools

Minimalism



Die Fahne Hoch! (Frank Stella, 1959)

Extend the SM with a small set of fields

Realism

The Gleaners (Jean-François Millet, 1857)

Address SM problems in detail: hierarchy problem, dark matter, …

Schools

Minimalism

Realism

+ limited number of options

+ simple

+ possibility to use benchmarks

- possibility to use benchmarks

- motivation

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From TATE website on minimalism:
Aesthetically, minimalist art offers a highly purified form of beauty. It can also be seen as representing such qualities as truth (because it does not pretend to be anything other than what it is), order, simplicity and harmony.

Schools

Minimalism

+ limited number of options

+ simple

+ possibility to use benchmarks

- possibility to use benchmarks

- motivation

Realism

+ motivated

+ predictive

- too many models

- too many variables

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Realism

+ motivated

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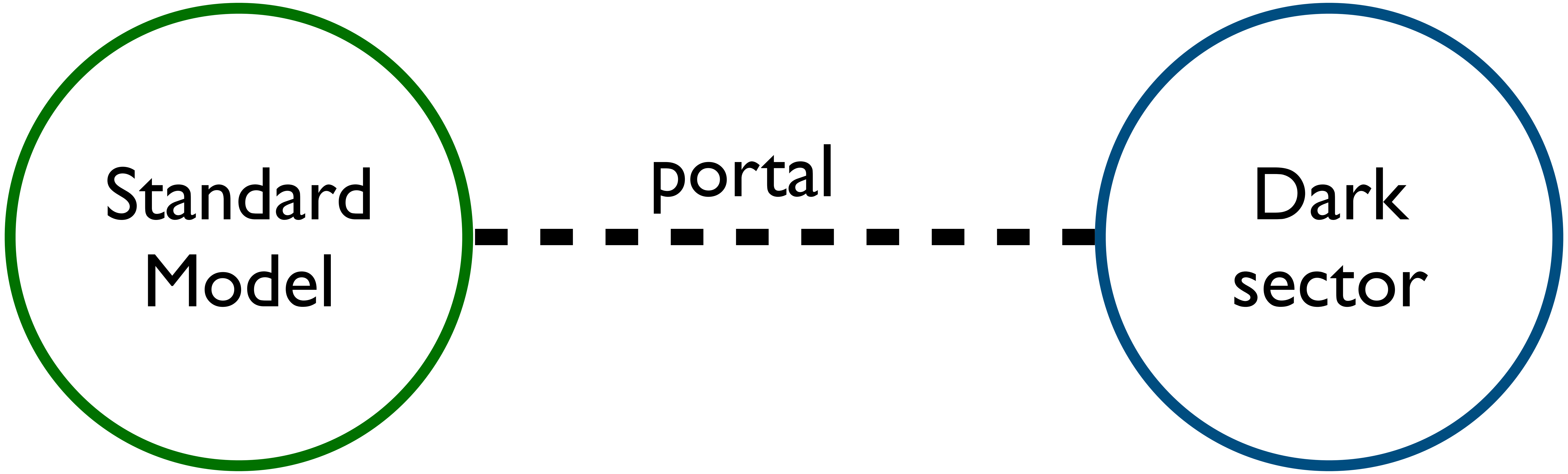
- too many models

- too many variables

1. A model independent approach for dark sectors is impossible.
2. Relying too much on minimal or realistic models may be dangerous.

Portals



Standard Model

portal

Dark sector

Which portals are important?

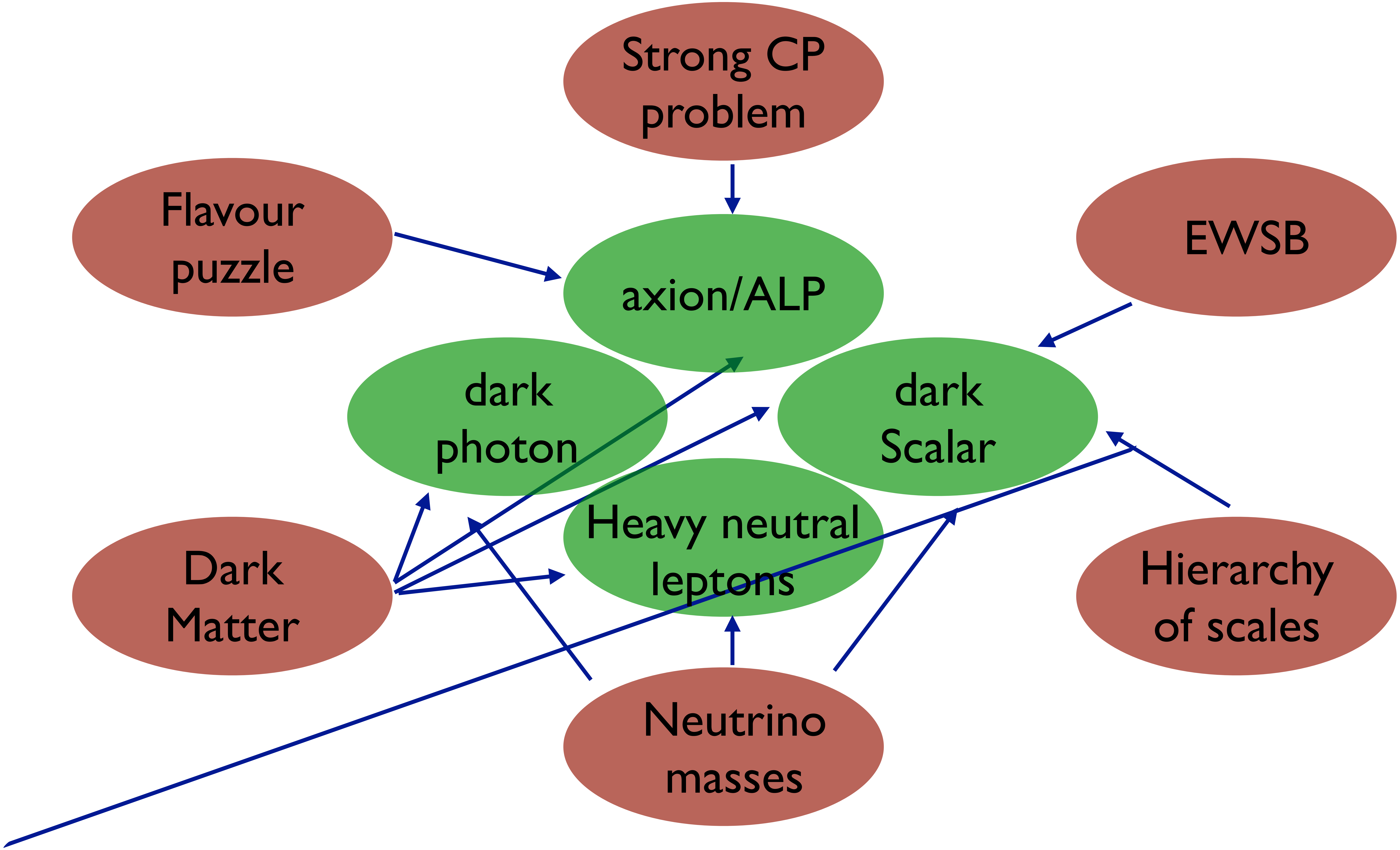
Couplings are constrained by Lorentz invariance and SM symmetries.

Portals

Vector portal	$\frac{1}{2}\frac{\epsilon}{\cos\theta_w}F^Y_{\mu\nu}F'^{\mu\nu}$	Vector couplings scale with electric charge
Scalar portal	$(\mu\phi + \lambda\phi^2)H^\dagger H$	Scalar couplings scale with Yukawas
Neutrino portal	$y_n N(LH)$	Fermion mixing with neutrinos
Axion portal	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$	Where $F_{\mu\nu}$ can be the photon field or the gluon

Others: vectors may couple with any global conserved SM current $(B-L,\ L_\mu - L_\tau, \dots)$

Motivation



Strong CP problem

Flavour puzzle

EWSB

axion/ALP

dark photon

dark Scalar

Heavy neutral leptons

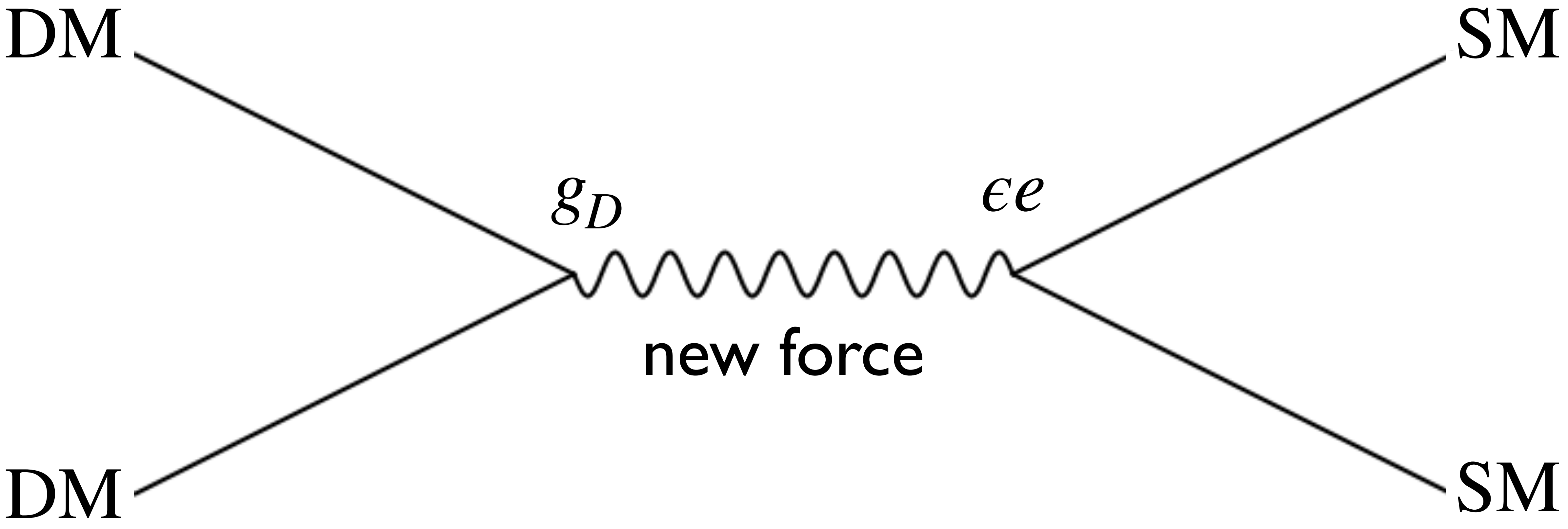
Dark Matter

Hierarchy of scales

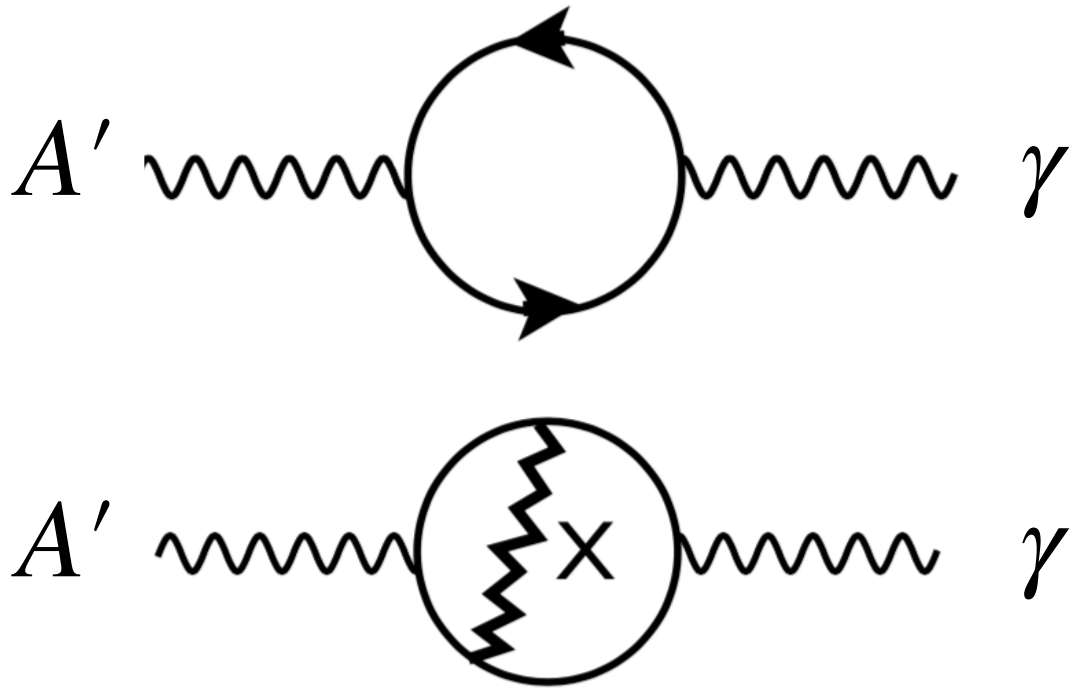
Neutrino masses

Dark sector DM

Assume DM charged under a new force:



Vector portal $$\frac{1}{2}\frac{\epsilon}{\cos\theta_w}F^{Y}_{\mu\nu}F'^{\mu\nu}$$

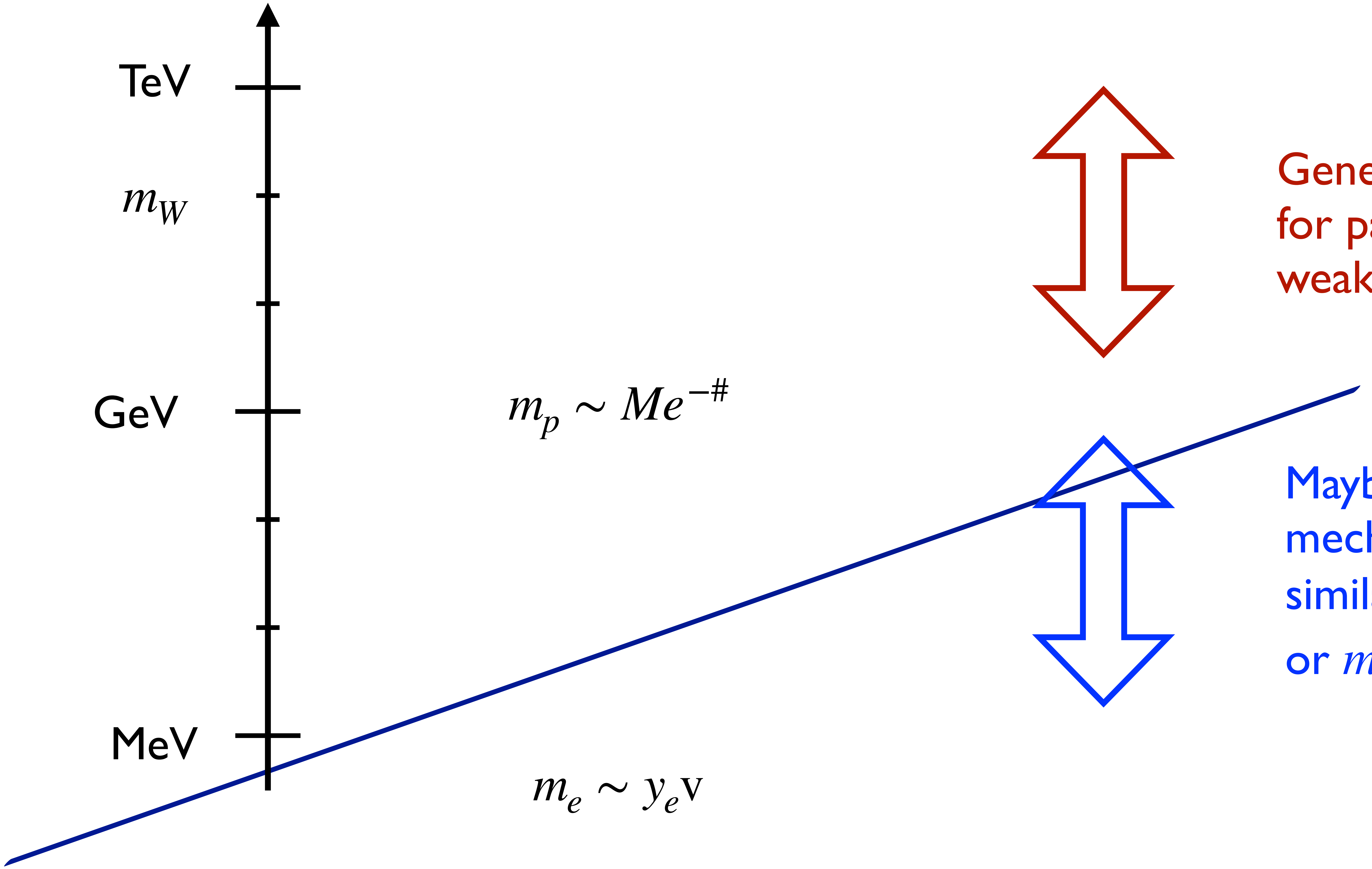


$$\epsilon \sim 10^{-6} - 10^{-2}$$

Dark sector DM

Standard Model

Dark Matter



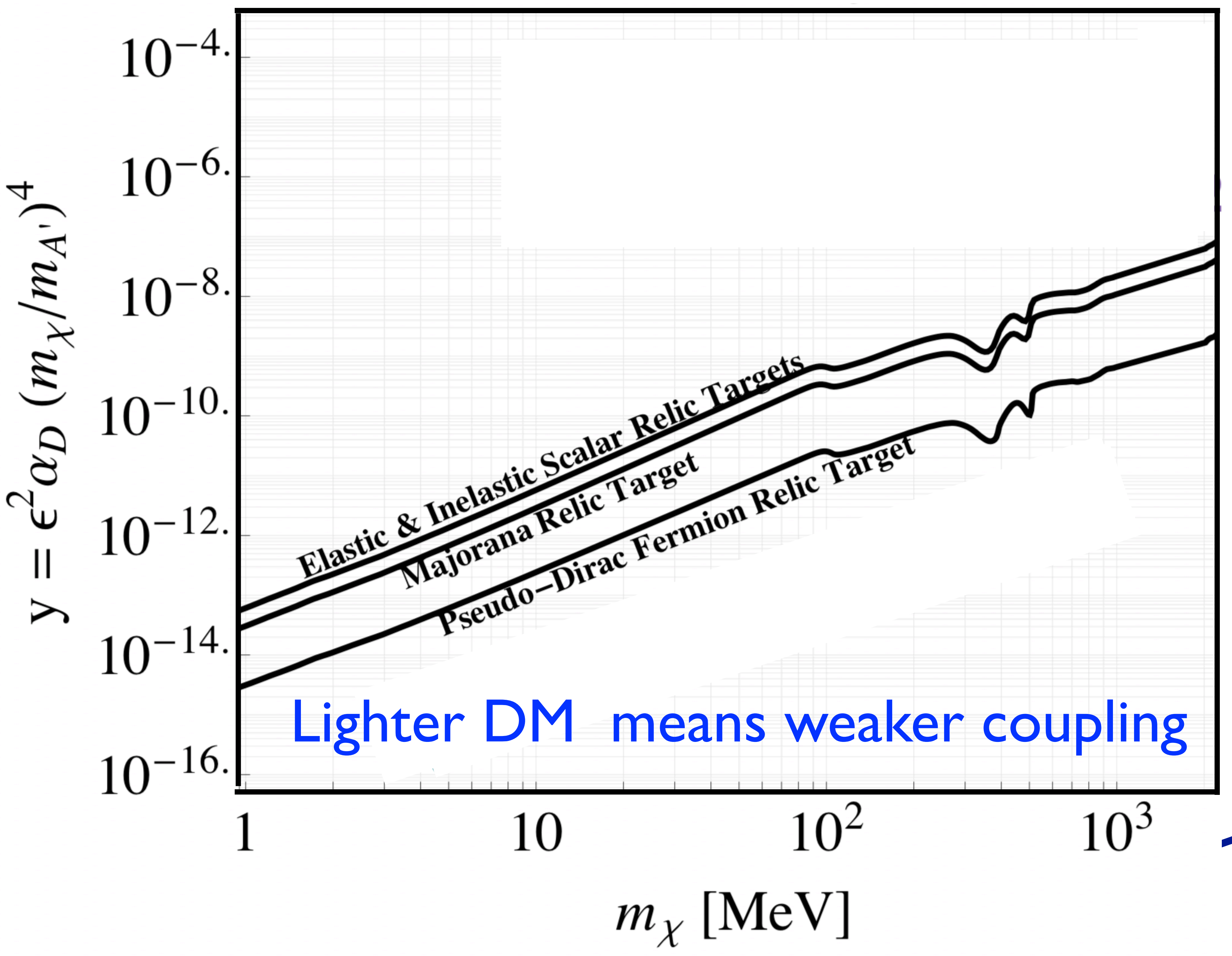
$m_p \sim M e^{-\#}$

$m_e \sim y_e v$

Generic mass scale for particles with weak couplings

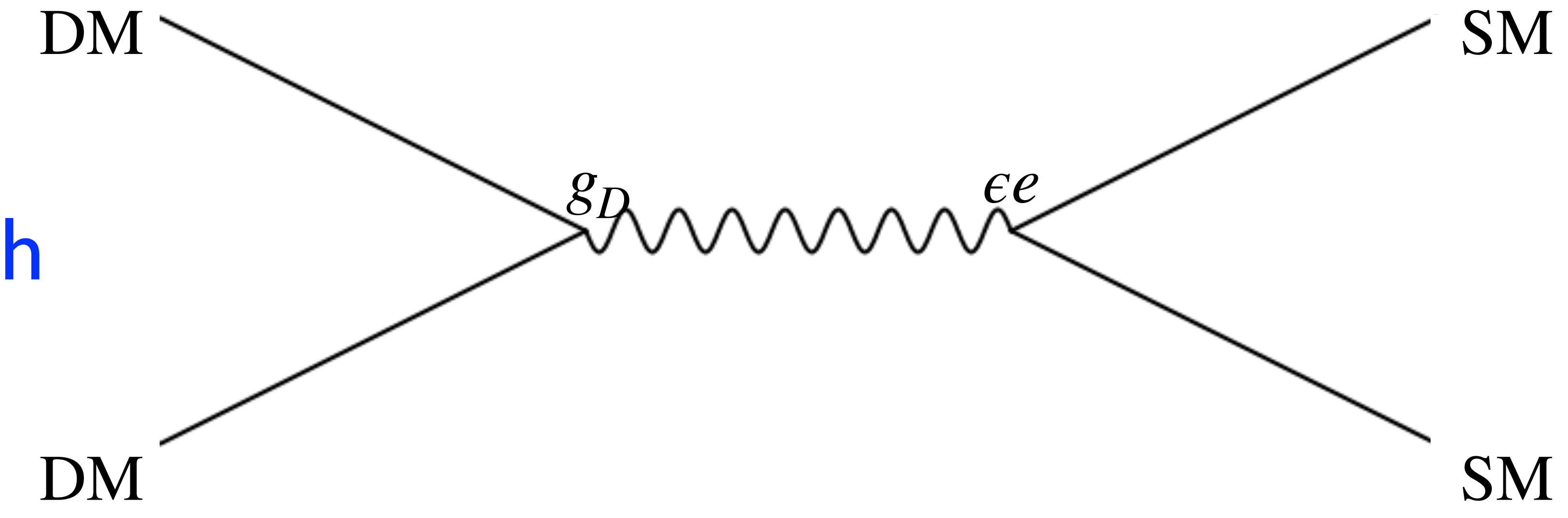
Maybe the DM mass mechanism has similar origins of m_p or m_e

Thermal relic targets



Lighter DM means weaker coupling

Range consistent with expectation for perturbative kinetic mixing



$$\sigma v \sim \frac{\epsilon^2 \alpha\, \alpha_D\, m_{DM}^2}{m_{A'}^4} = \frac{y}{m_{DM}^2}$$

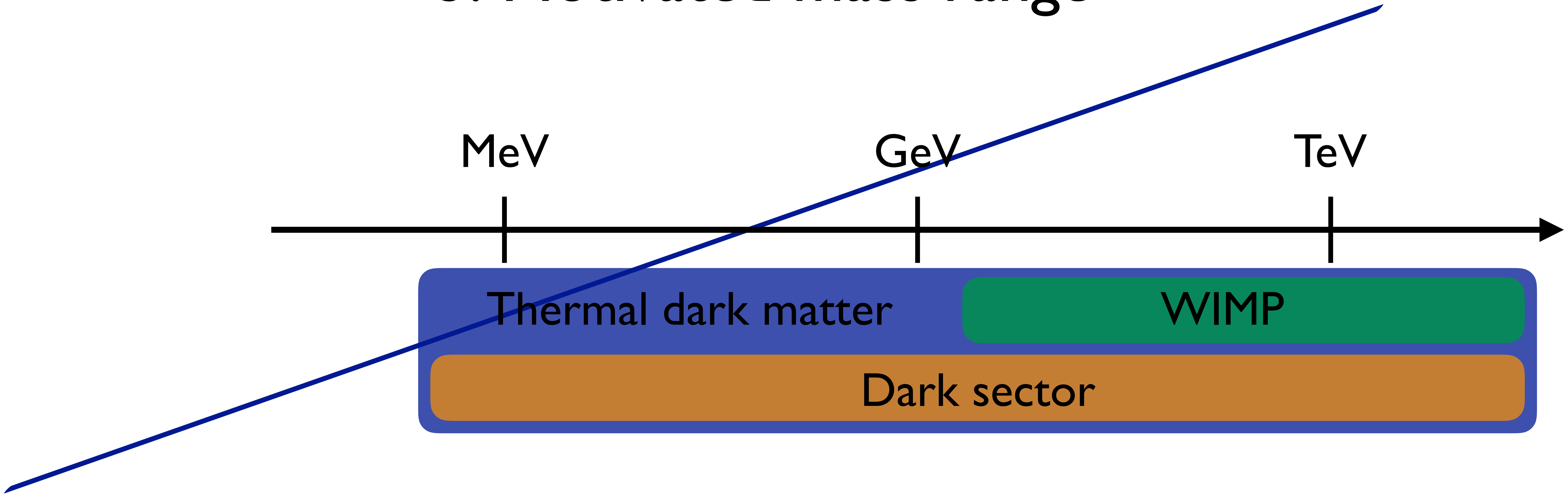
$$\sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

Dark photon: a strong candidate

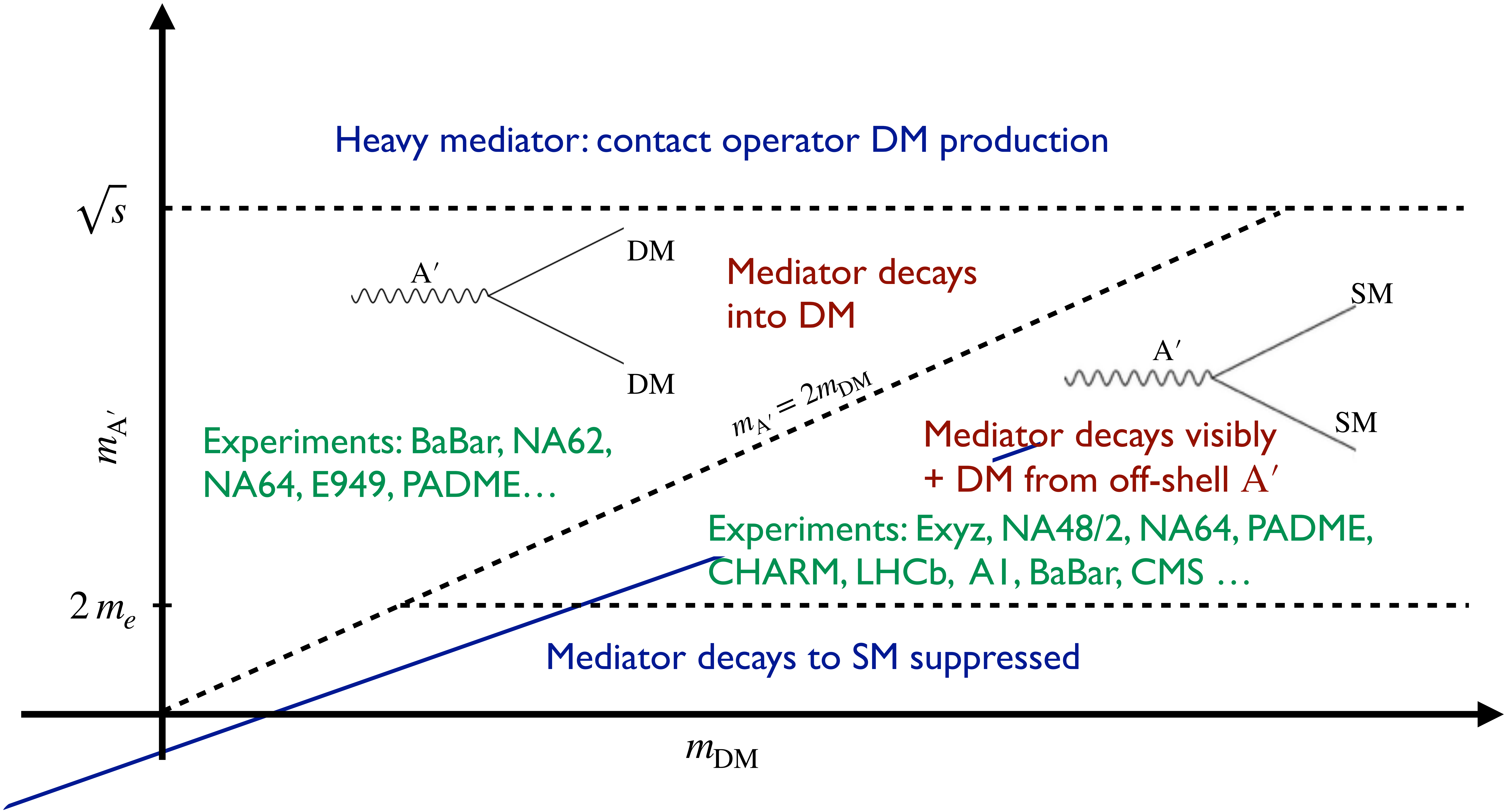
1. Simple and familiar particle content

2. Simple and predictive cosmology (there are other possibilities as well)

3. Motivated mass range



Phenomenology



Heavy mediator: contact operator DM production

Mediator decays into DM

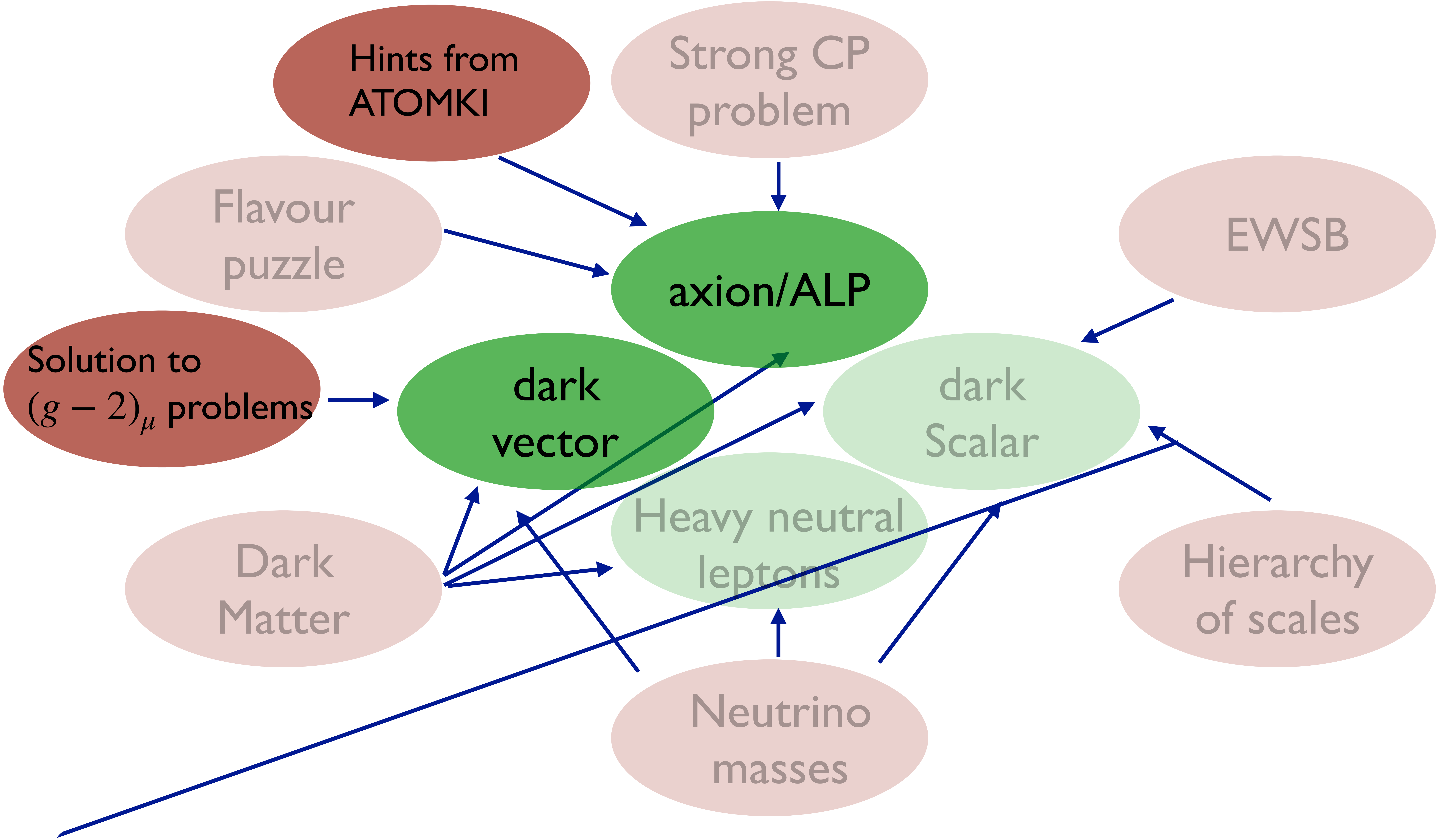
Experiments: BaBar, NA62, NA64, E949, PADME…

Mediator decays visibly + DM from off-shell A'

Experiments: Exyz, NA48/2, NA64, PADME, CHARM, LHCb, A1, BaBar, CMS …

Mediator decays to SM suppressed

Other problems



Hints from ATOMKI

Strong CP problem

Flavour puzzle

axion/ALP

EWSB

Solution to $(g-2)_\mu$ problems

dark vector

dark Scalar

Heavy neutral leptons

Dark Matter

Hierarchy of scales

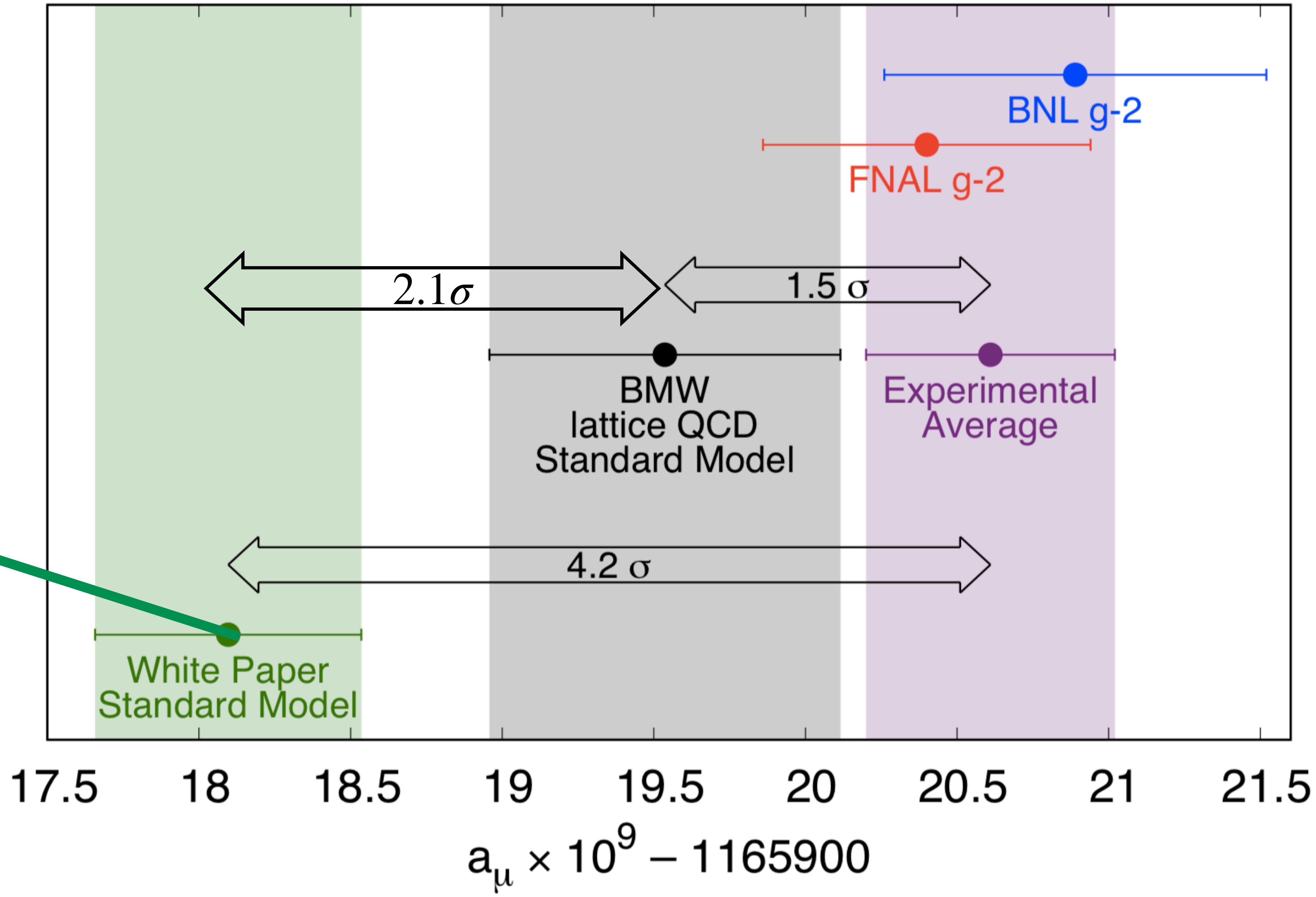
Neutrino masses

Solution to $(g-2)_\mu$ problems

Kernel function ∝ s^{-1}:
lower energies more
important

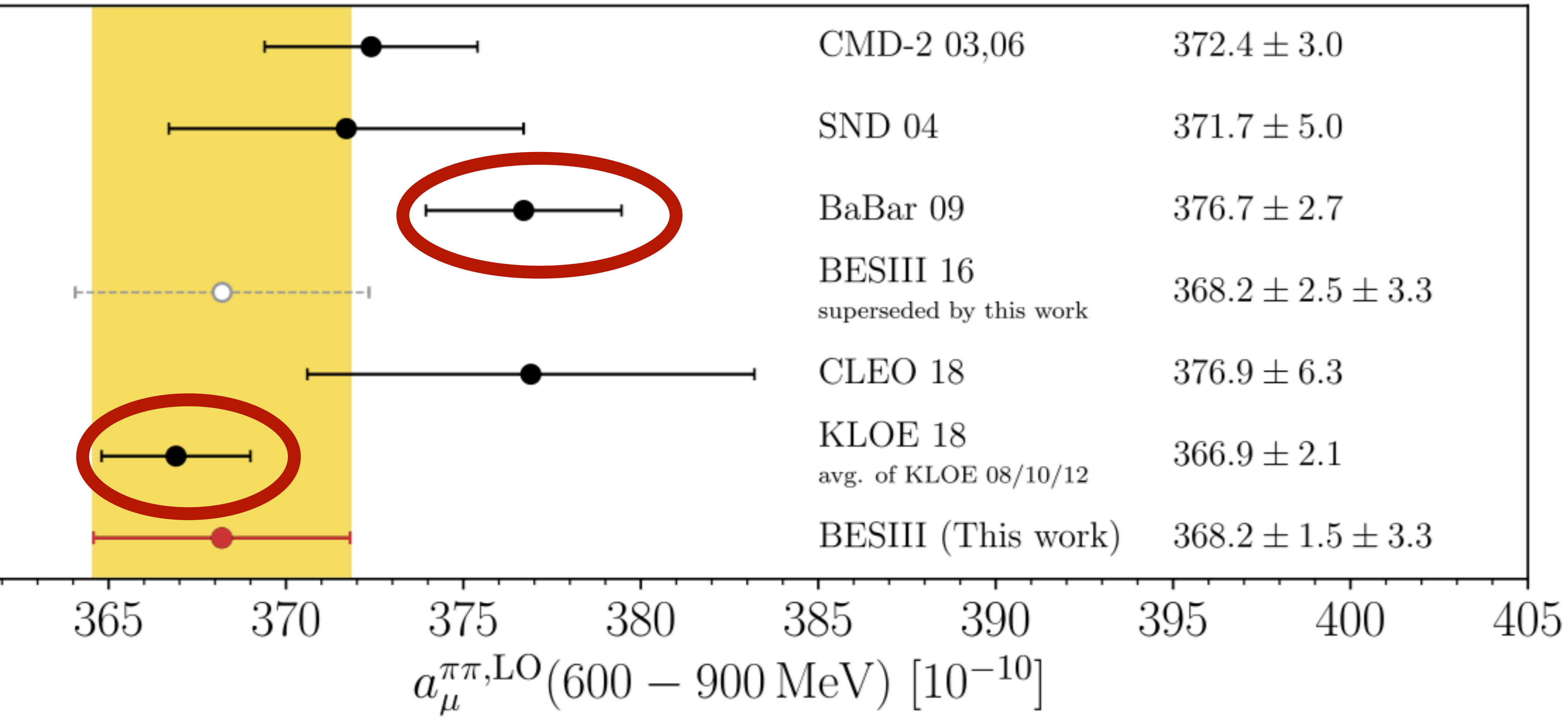
$$a_\mu^{LO,HVP} = \frac{1}{4\pi^3}\int_{s_{th}}^{\infty} ds\,\boxed{K(s)}\,\boxed{\sigma_{\text{had}}(s)}$$

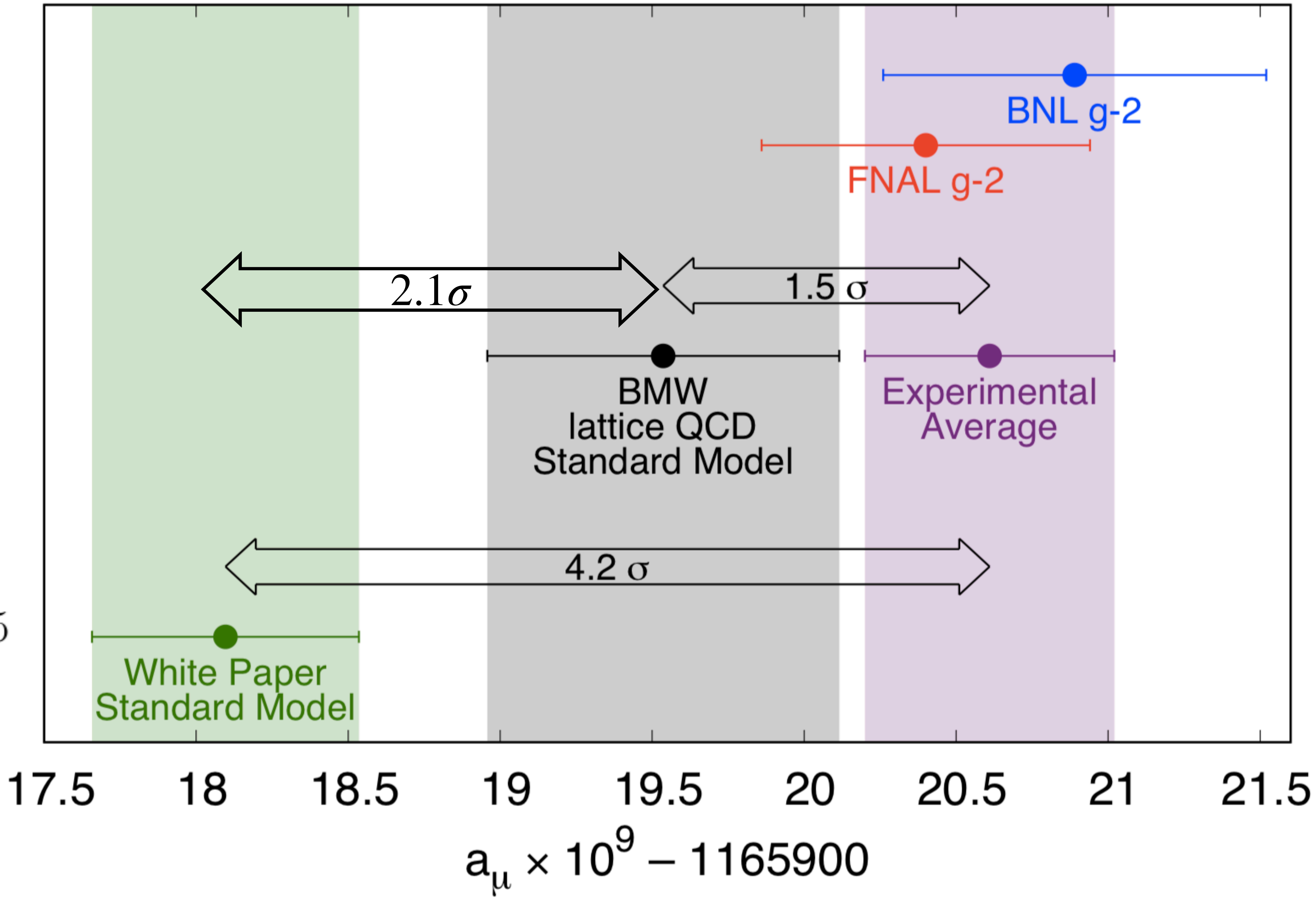
$e^+e^- \to$ hadrons
bare cross section:
experimental input



- Experiment vs SM estimate $\Delta a_\mu = 251(59)\cdot 10^{-11}$
- SM vs lattice estimate
- KLOE vs BaBar (3σ tension)

Solution to $(g-2)_\mu$ problems





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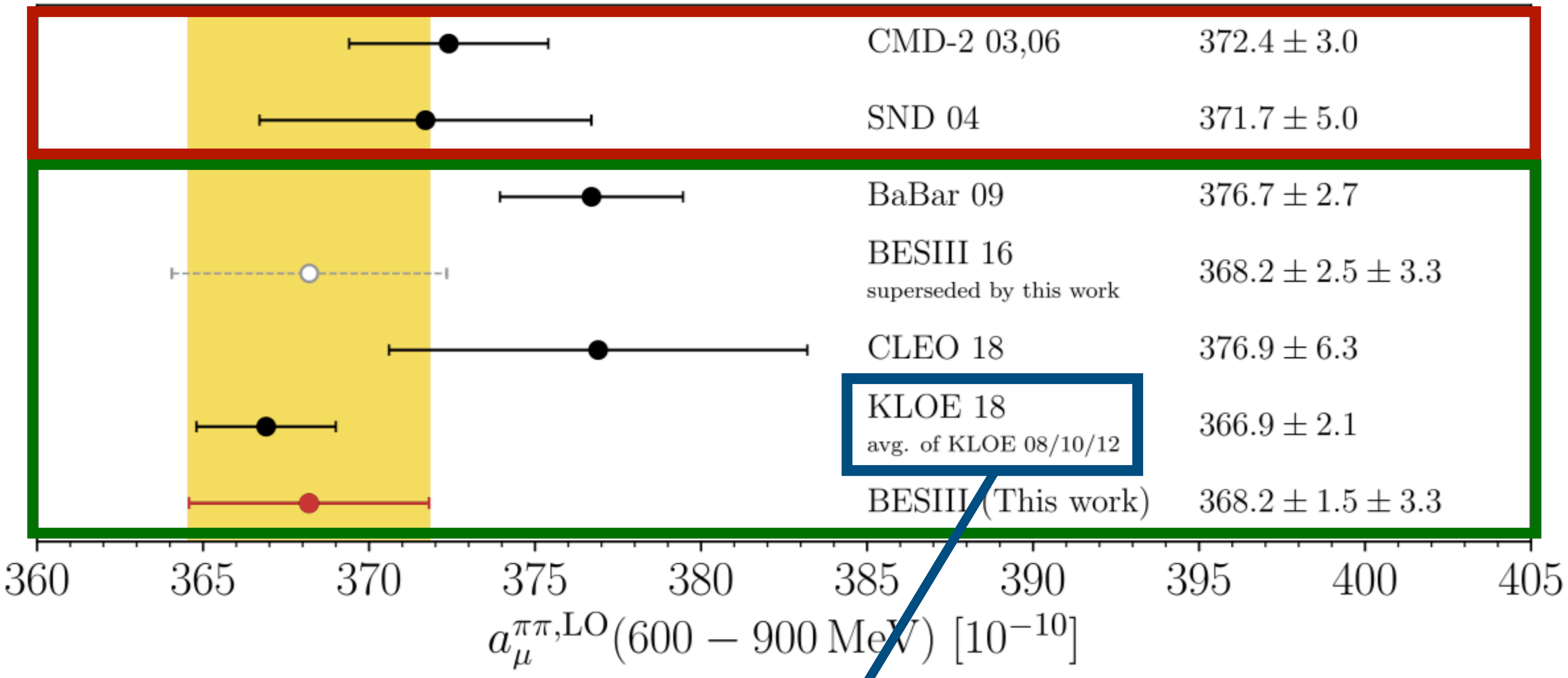

Three different analysis: KLOE08, KLOE10, KLOE12.

Radiative cross section including ISR photon

Radiator function accounting for ISR

$$s\,\frac{d\sigma(\pi^+\pi^-\gamma)}{ds'} = \sigma^0_{\pi\pi}(s')\; H(s',s)$$

$s' = M^2_{\pi\pi}$ → di-pion invariant mass

Solution to $(g-2)_\mu$ problems

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1. **KLOE08**: measurements in the range $0.35 < s'/\mathrm{GeV}^2 < 0.85$ at $\sqrt{s} = 1.0194\ \mathrm{GeV}$ (ϕ meson pole). It requires the knowledge of the luminosity.

2. **KLOE10**: measurements in the range $0.1 < s'/\mathrm{GeV}^2 < 0.85$ at $\sqrt{s} = 1\ \mathrm{GeV}$ ($4.5 \cdot \Gamma_\phi$ below the ϕ meson pole). It requires the knowledge of the luminosity.

3. **KLOE12**: relies on the ratio of the number of $\pi^+\pi^-\gamma$ and $\mu^+\mu^-\gamma$ events in the range $0.35 < s'/\mathrm{GeV}^2 < 0.95$. The dependence of the luminosity cancels in the ratio.

Solution to $(g-2)_\mu$ problems

The Luminosity determination

[Darmé, G^{2}dC, Nardi '21]

$$\sigma_{\rm had} \propto \frac{N_{\rm had}}{\boxed{\mathcal{L}_{e^+e^-}}}$$

A smaller luminosity implies a larger hadronic cross section

Total number of $e^+e^- \to e^+e^-$ events

$$\mathcal{L}^{\rm SM}_{e^+e^-} = \frac{\boxed{N_{\rm Bhabha}}}{\boxed{\sigma^{\rm SM}_{\rm eff}}}$$

SM prediction

$$\mathcal{L}_{e^+e^-} = \mathcal{L}^{\rm SM}_{e^+e^-} \frac{\sigma^{\rm SM}_{\rm eff}}{\boxed{\sigma_{\rm eff}}}$$

Full Bhabha cross section including NP

$$\sigma_{\rm eff} = \sigma^{\rm SM}_{\rm eff}(1 + \delta_R)$$

$$a_\mu^{HVP,LO} \to a_\mu^{HVP,LO}(1 + \delta_R)$$

Solution to $(g-2)_\mu$ problems

The $\sigma(\mu\mu\gamma)$ method [Darmé, G^{2}dC, Nardi '21]

Measured value

QED $e^+e^- \to \mu^+\mu^-$ cross section

$$\sigma^0_{\pi^+\pi^-} = \frac{\boxed{N_{\pi^+\pi^-\gamma_{ISR}}}}{\boxed{N_{\mu^+\mu^-\gamma_{ISR}}}}\boxed{\sigma^0_{\mu^+\mu^-}}$$

Measured value

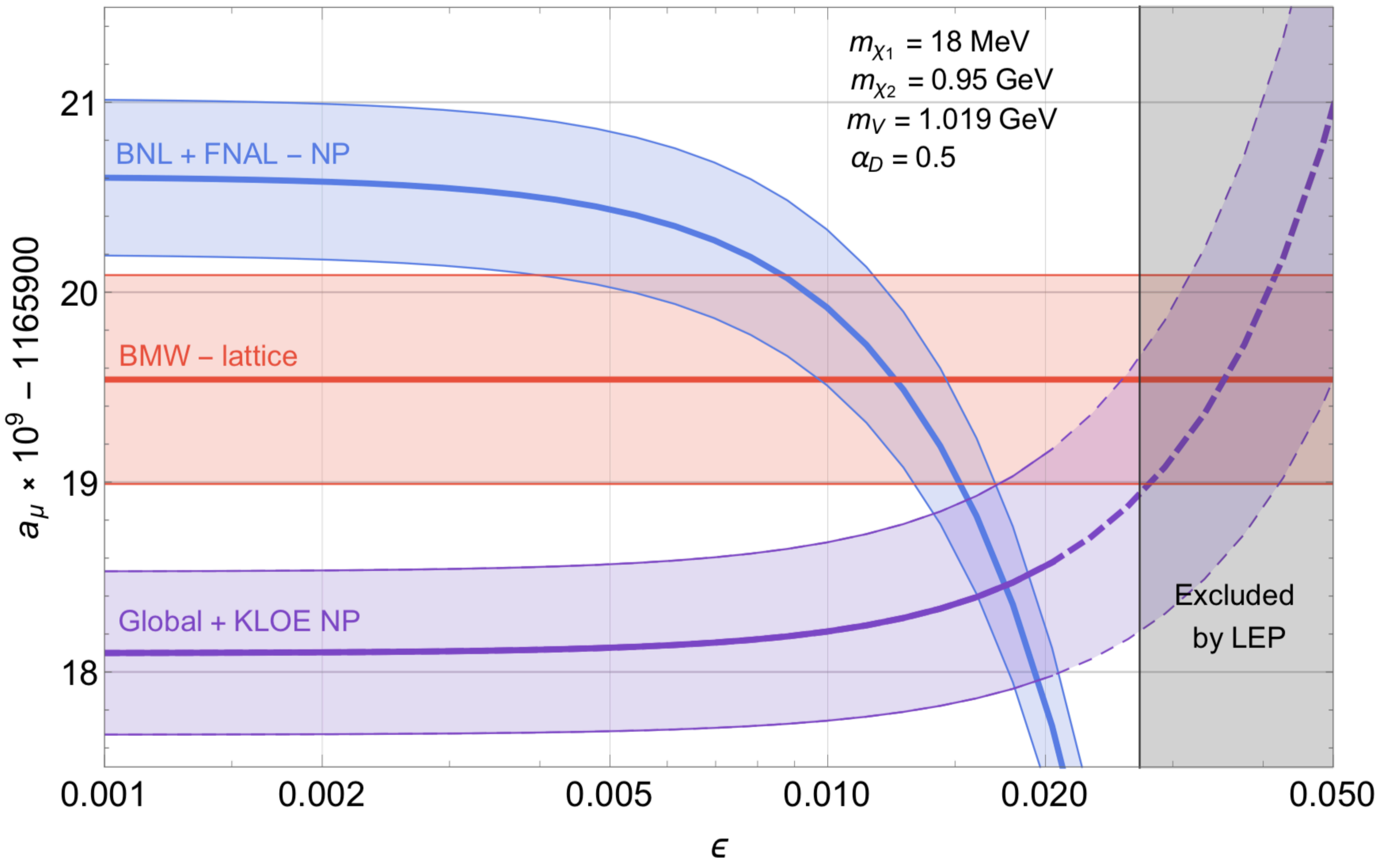
What if we have $\mu^+\mu^-X$ **new physics** events mimicking the $\mu^+\mu^-\gamma$?

$$\sigma^{0\gamma*}_{\pi^+\pi^-} = \frac{N_{\pi^+\pi^-\gamma_{ISR}}}{\boxed{N_{\mu^+\mu^-\gamma_{ISR}} - N^{NP}_{\mu^+\mu^-\gamma_{ISR}}}}\sigma^0_{\mu^+\mu^-} \sim \sigma^0_{\pi^+\pi^-}(1+\delta_\mu(s'))$$

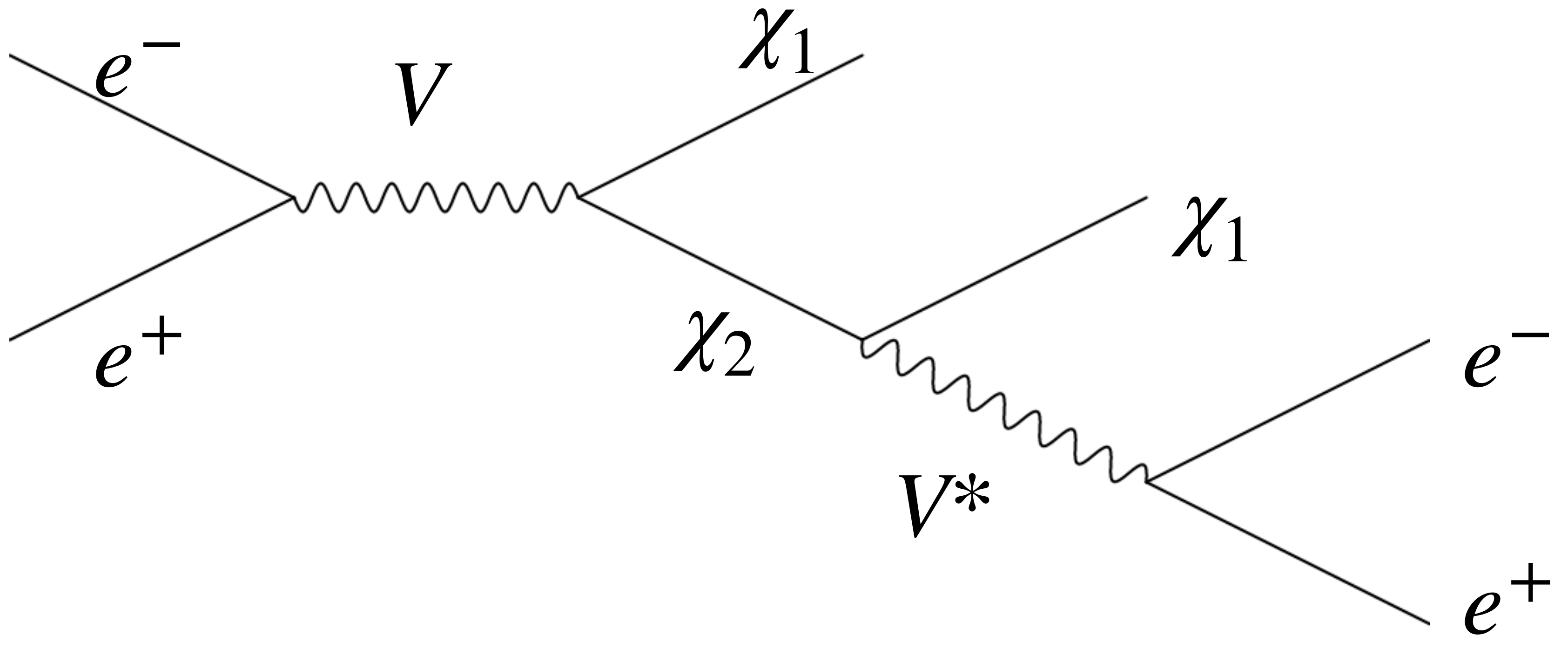
SM inferred value

Solution to $(g-2)_\mu$ problems

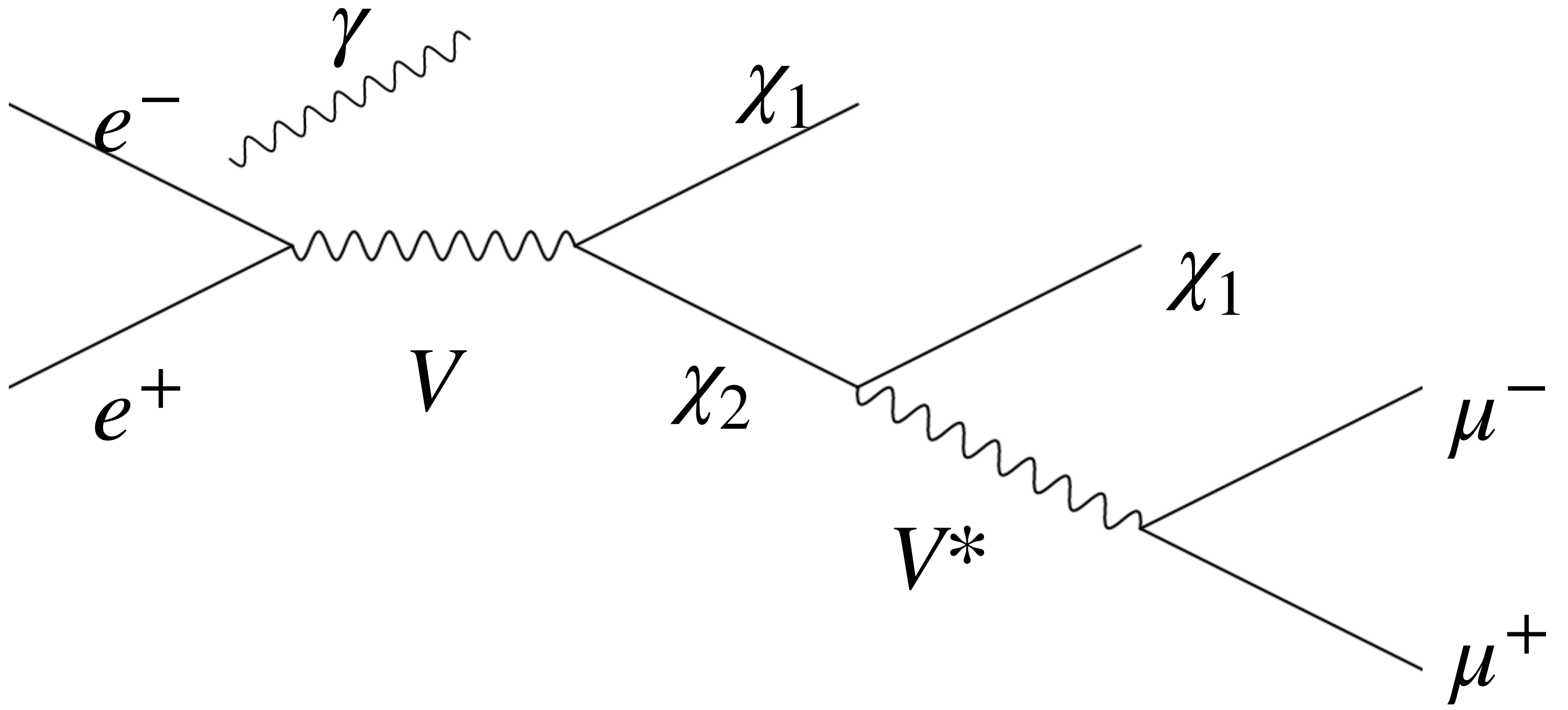
[Darmé, G^{2}dC, Nardi '21]



Shifting KLOE08



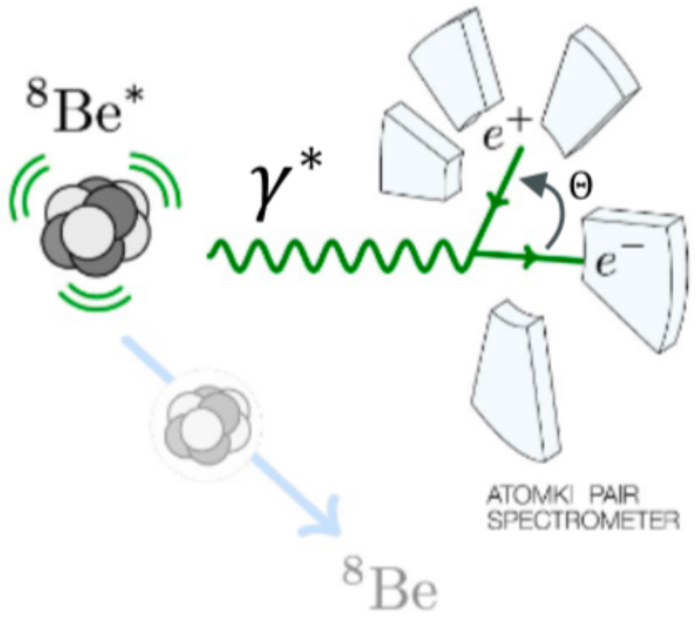
Shifting KLOE12, BESIII and BaBar



The Atomki anomaly

We expect

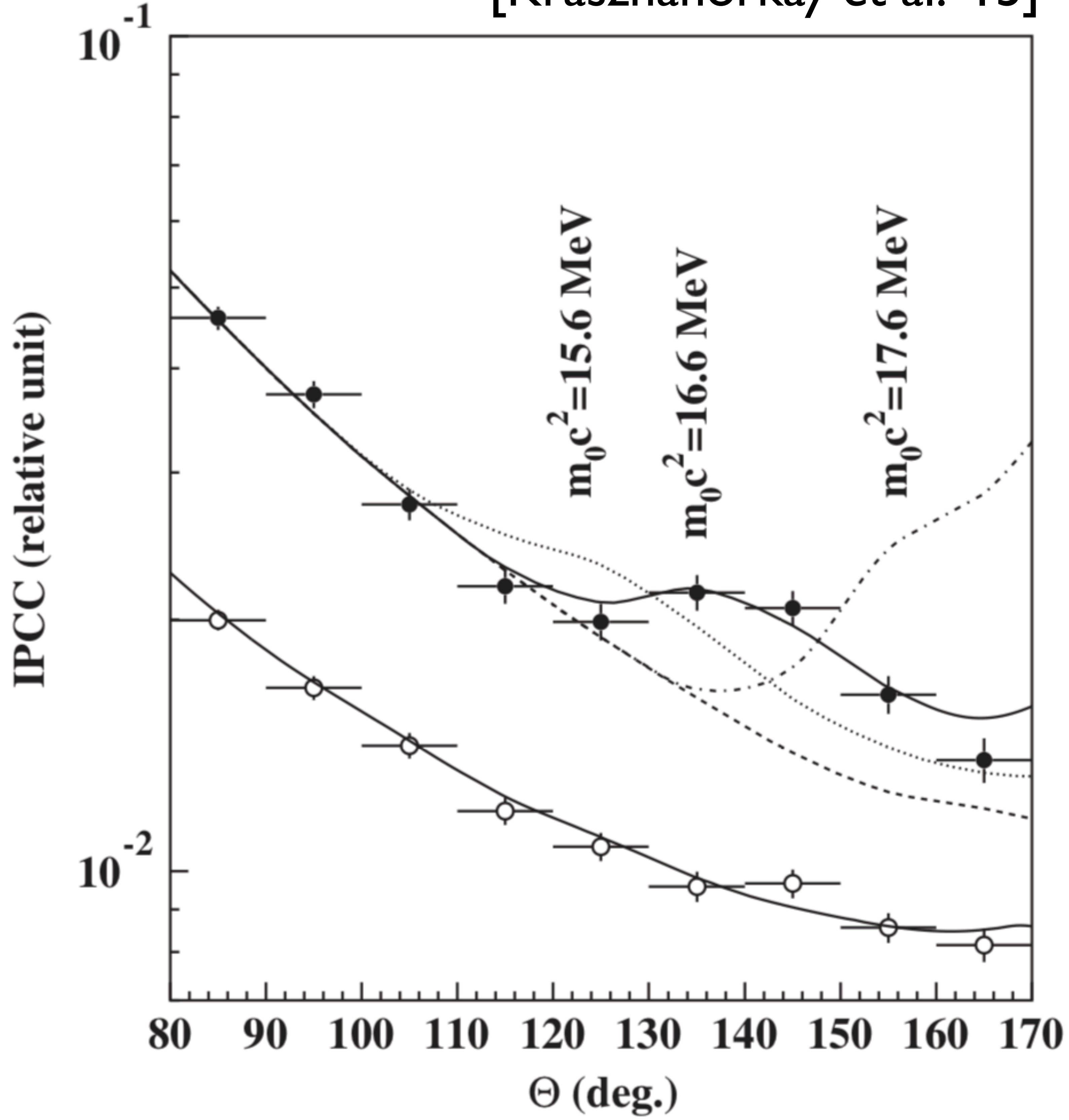
$^8\mathrm{Be}* \to ^8\mathrm{Be}\,\gamma* \to ^8\mathrm{Be}\,e^+\,e^-$



[Feng et al, 1608.03591]

Atomki observes

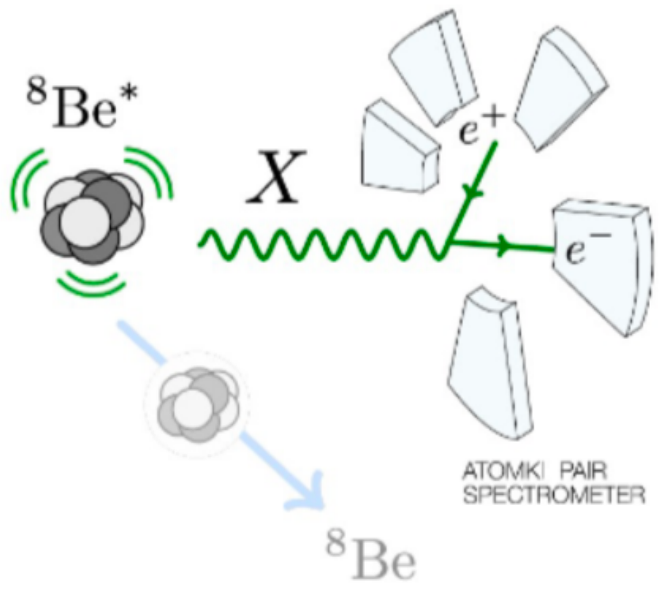
[Krasznahorkay et al. '15]



The Atomki anomaly

Consistent with

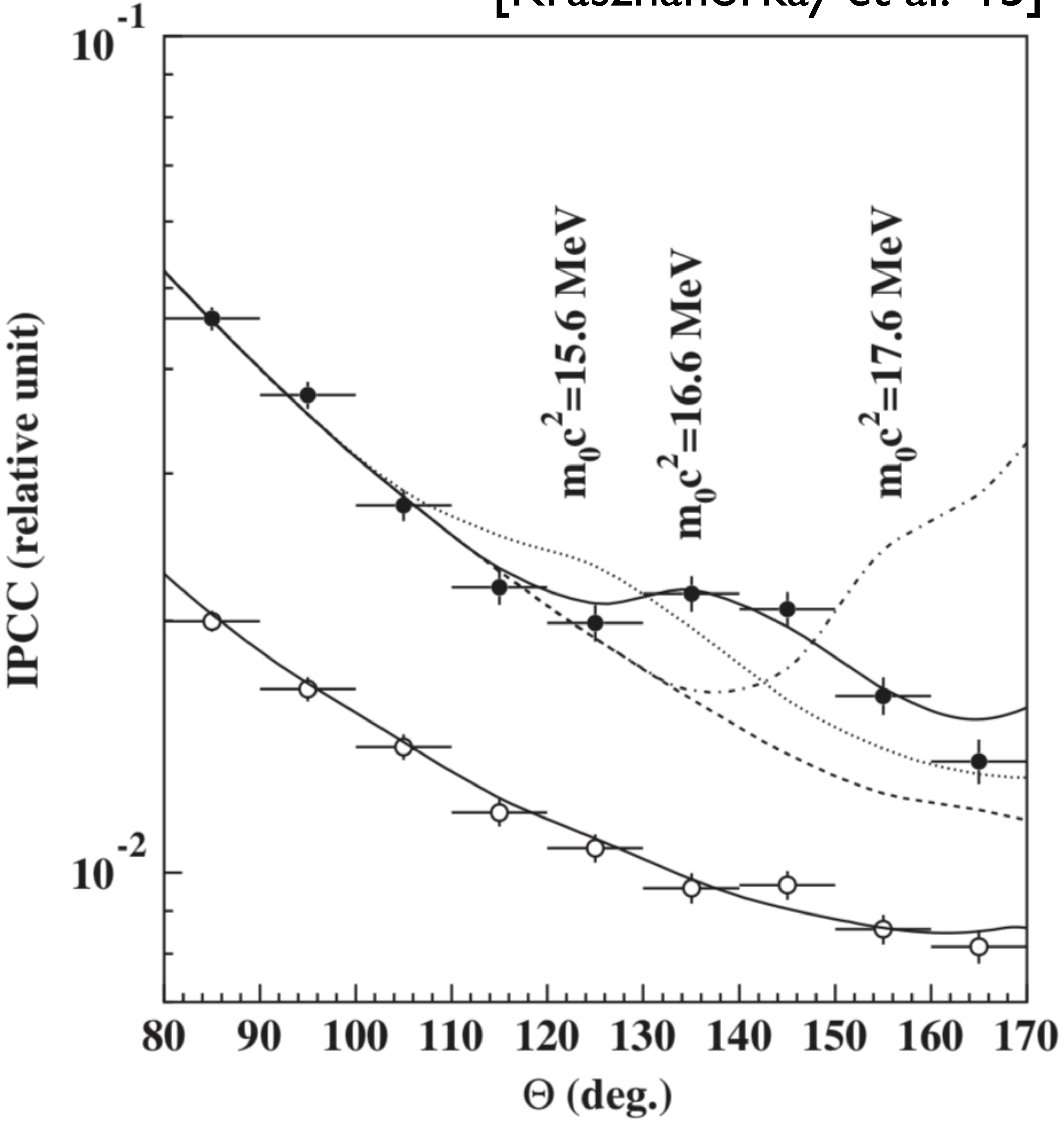
$$^8\text{Be}^* \to {}^8\text{Be}\,X \to {}^8\text{Be}\,e^+e^-$$



[Feng et al, 1608.03591]

Atomki observes

[Krasznahorkay et al. '15]



The results of the fit (together with the results from ^{4}He and ^{12}C) implies

$$M_X = \begin{cases} 16.70 \pm 0.35 \pm 0.50 \ \text{MeV} \\ 17.01 \pm 0.16 \ \text{MeV} \\ 16.94 \pm 0.12 \pm 0.21 \ \text{MeV} \end{cases}$$

[Krasznahorkay et al. '15, '18, '21]

The Atomki anomaly

Possible solutions:

1. a light vector X^μ with both vector and axial couplings

$$\mathscr{L} \supset -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X^\mu X_\mu + \sum_{f=\ell,q} X_\mu \bar{f}(g_{Xf} + \gamma^5 g_{Af})f$$

[Feng et al., Kahn et al, Kozaczuk et al, Gu et al , Jia et al, Chen et al , Kitahara et al '16, Delle Rose et al '17, …]

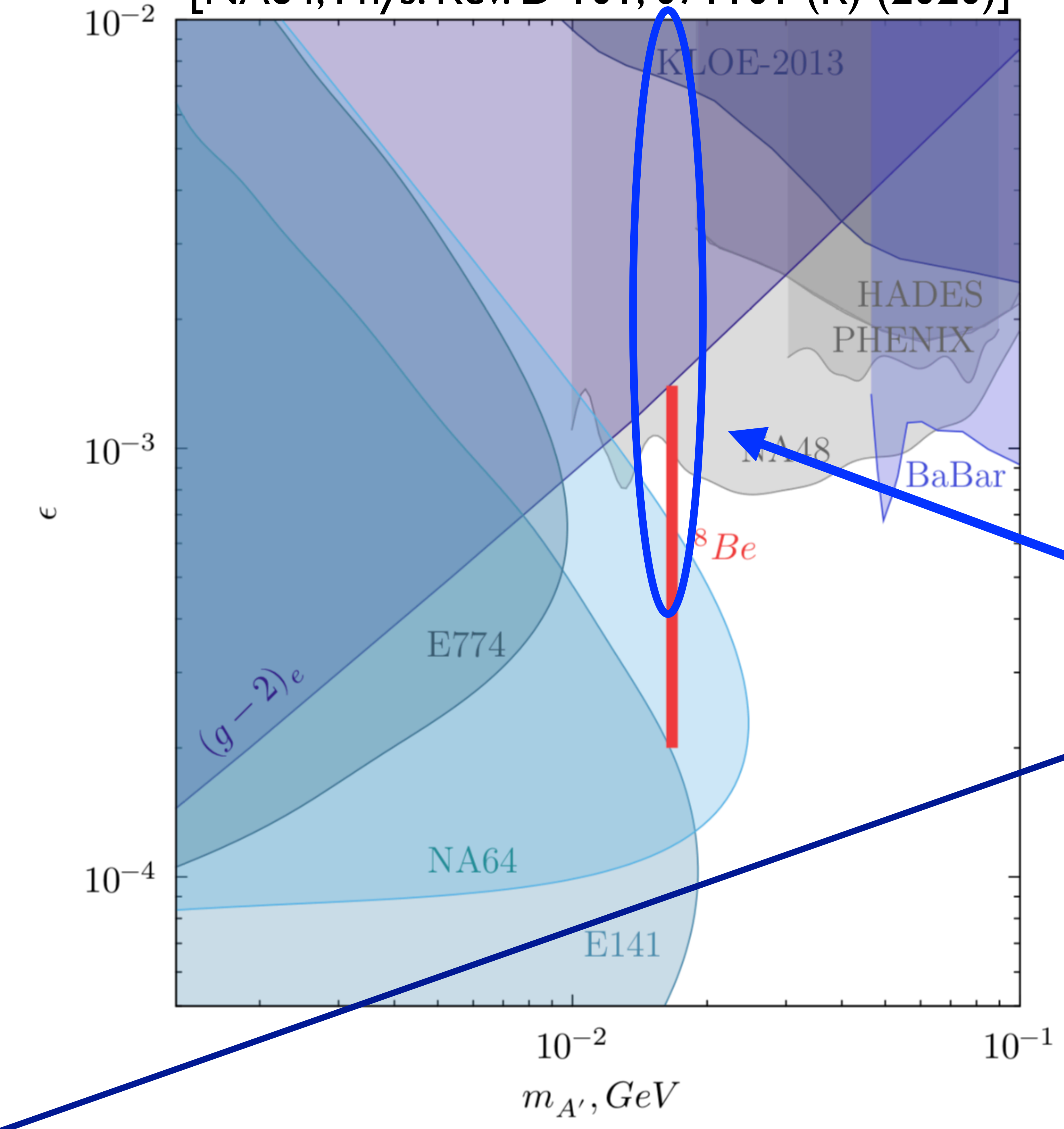
2. an axion-like particle X interacting via

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu X)(\partial^\mu X) - \frac{1}{2}m_X^2 X^2 + \sum_{f=\ell,q} \frac{g_{Xf}}{2}(\partial_\mu X)\bar{f}\gamma^\mu\gamma^5 f$$

[Ellwanger et al, Alves et al, …]

The Atomki anomaly

Vector



[NA64, Phys. Rev. D 101, 071101 (R) (2020)]

$(g-2)_e$ bound is model dependent

NA48/2 bound is not valid if the X17 is protophobic

PADME is targeting the remaining free parameter space, see Mauro's talk [Darmé et al. 2209.09261]

The Atomki anomaly

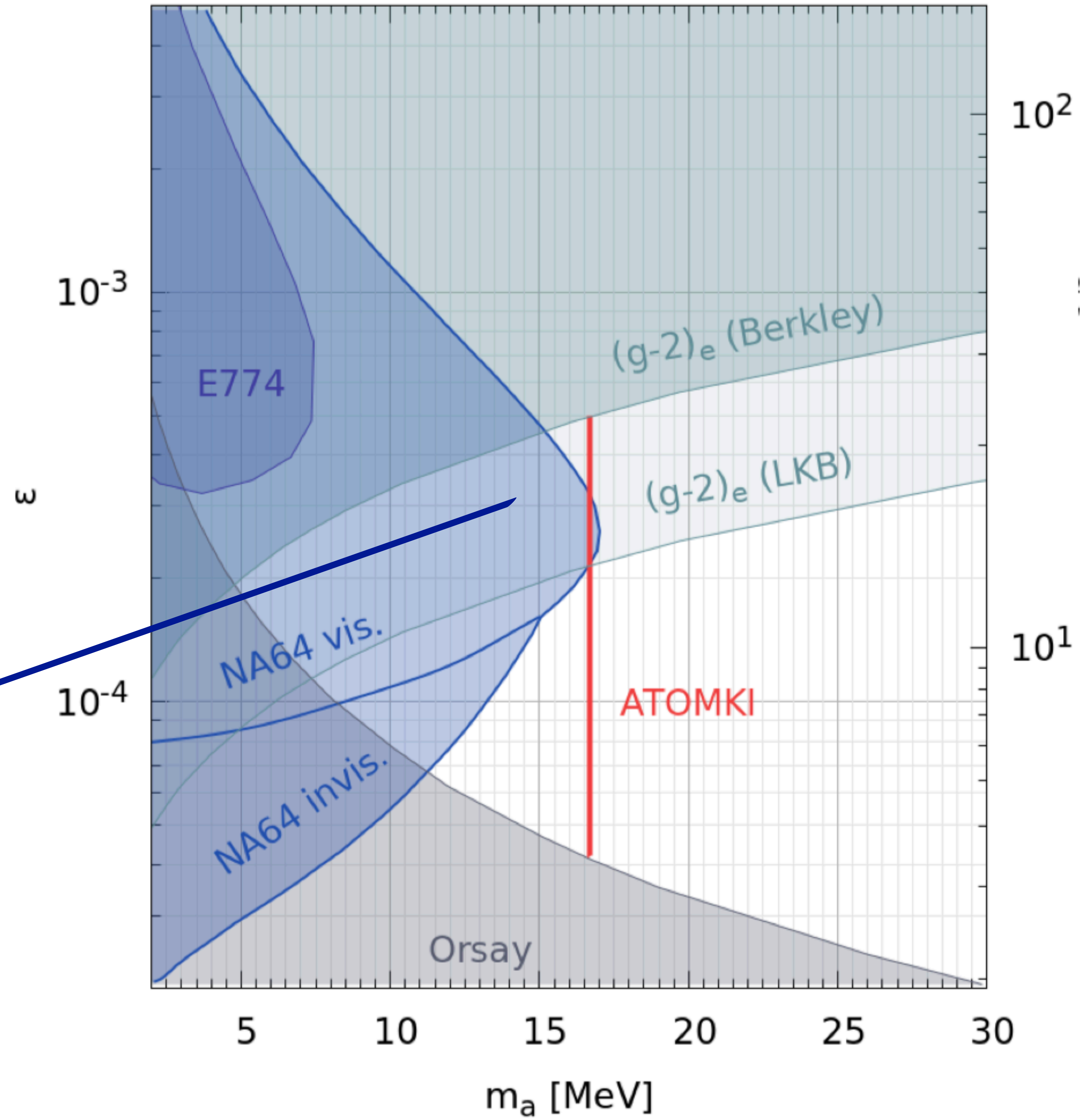
$(g-2)_e$ bound is model dependent

PADME is targeting the remaining free parameter space, see Mauro's talk

[Darmé et al. 2209.09261]

pseudo-scalar

[NA64, Phys. Rev. D 104, L111102 (2021)]



Conclusions

* but keep in mind the assumptions made

Dark sector particles are well motivated*:

1. they can explain the DM abundance
2. they may explain the $(g-2)_\mu$ anomaly
3. they are motivated by experimental hints (X17 at the ATOMKI spectrometer)

High intensity experiments have a unique role to probe this models.