Ultralight dark matter and time-varying signal @ collider and beam dump experiments

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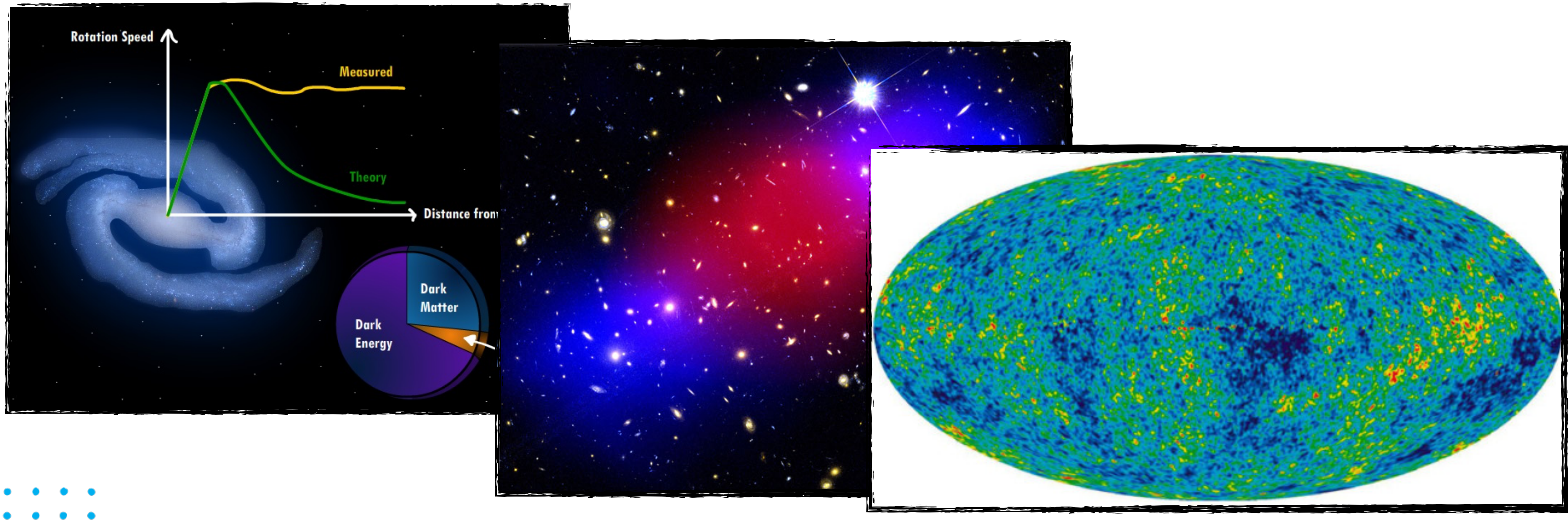
Base On: arXiv:2206.14221

Collaborated with: Jia Liu, Jinhui Guo, Yuxuan He and Kepan Xie

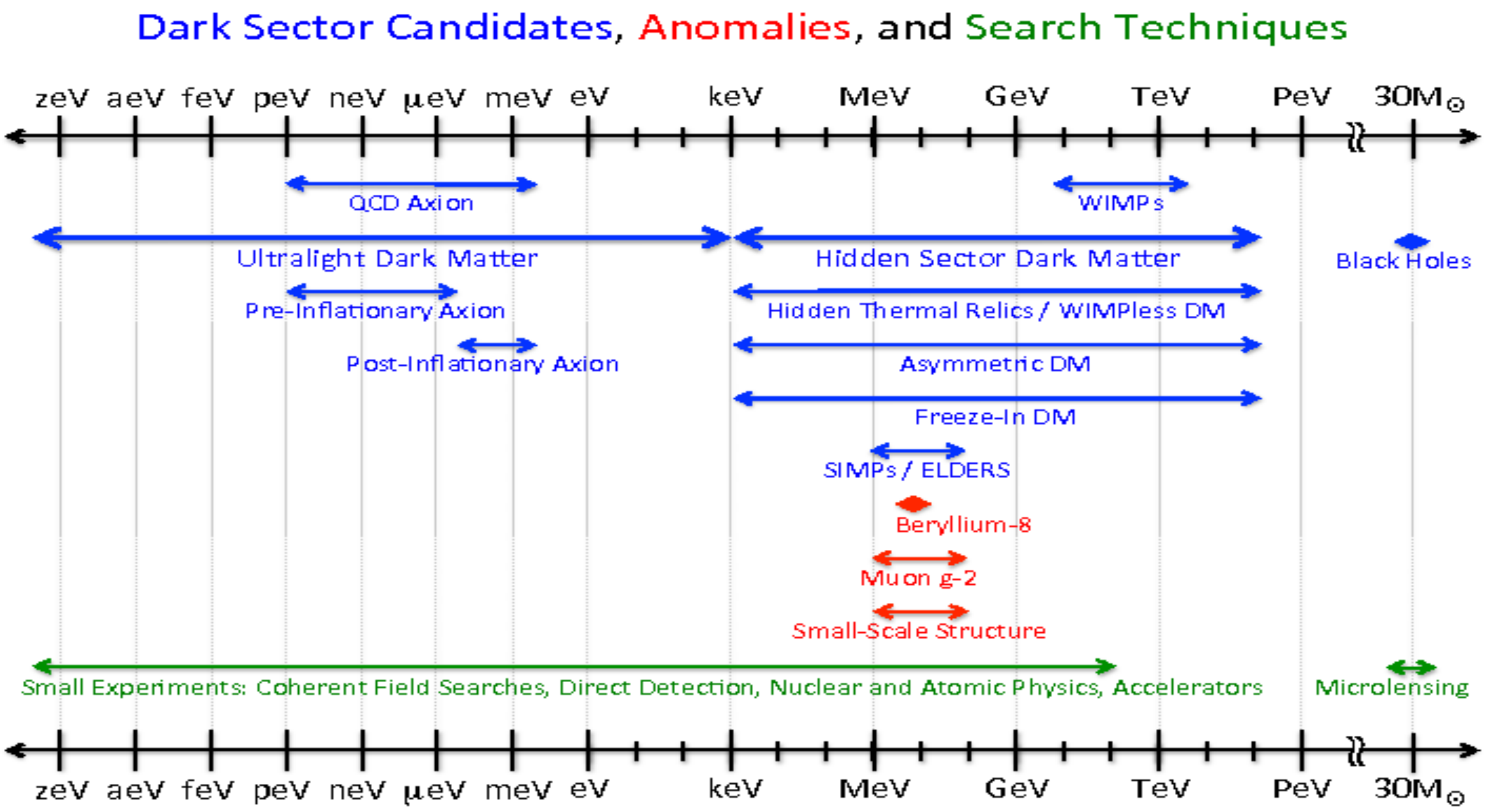
Dark Matter Evidence

- **Evidence from different scale**

Galaxy Cluster Universe



Dark matter mass range



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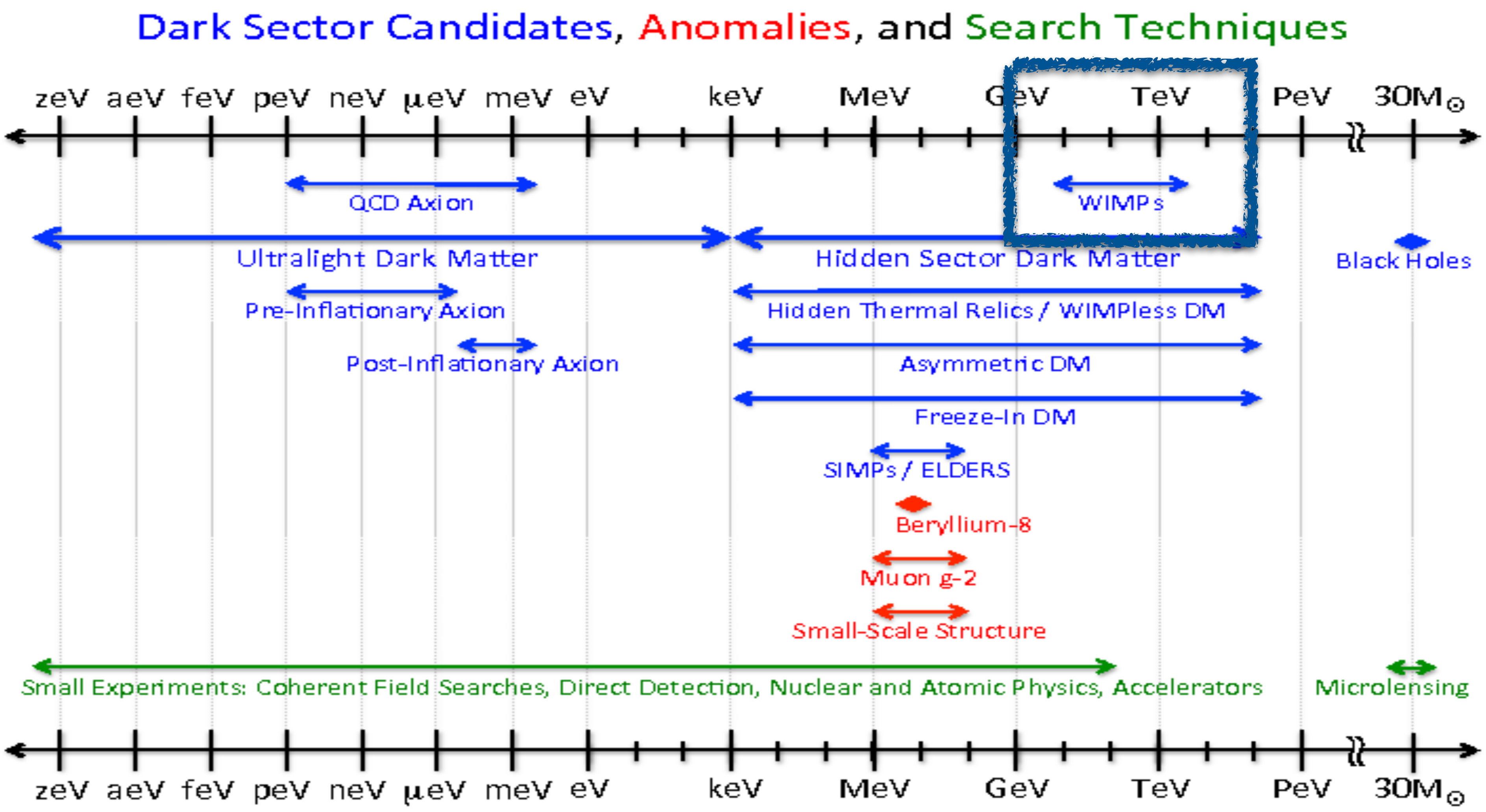
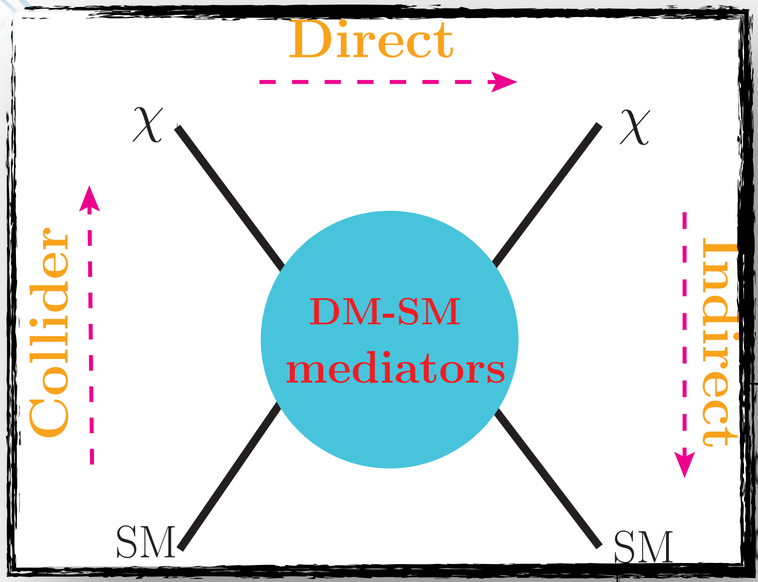
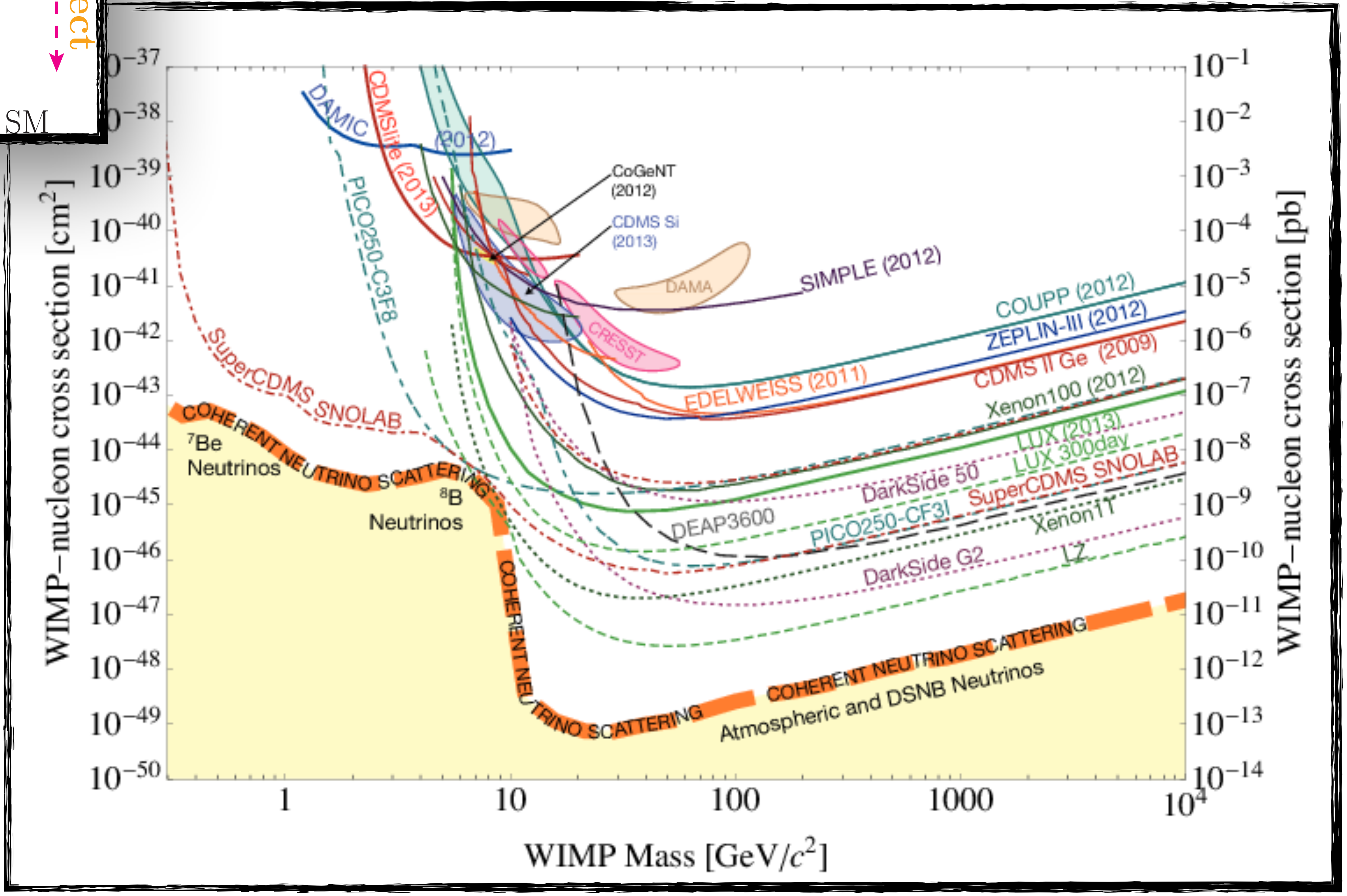


WIMP search status





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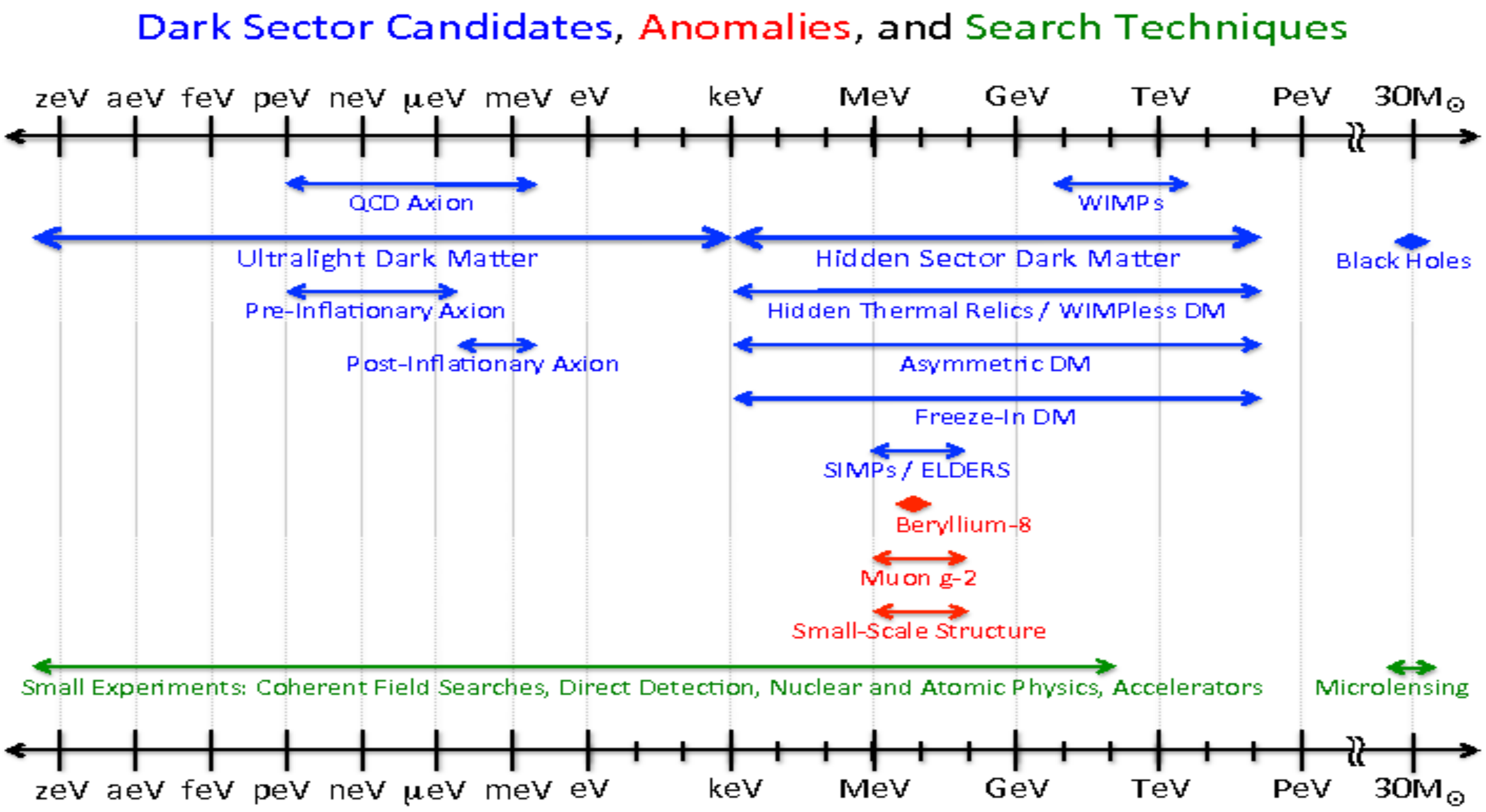
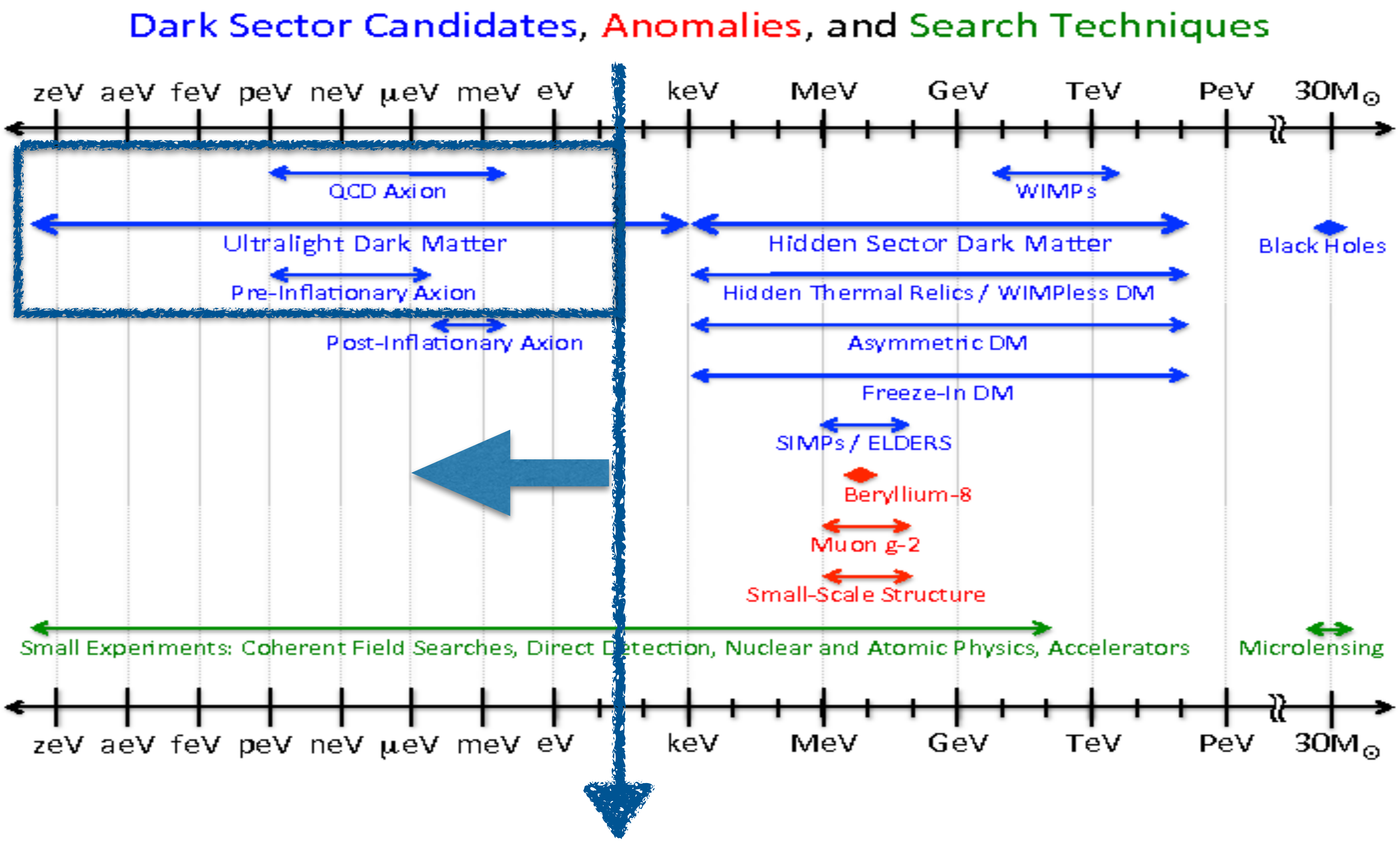


Dark matter mass range



$$m_\phi \lesssim 30\text{eV}\left(\frac{250\ \text{km/s}}{\langle v^2\rangle^{1/2}}\right)^{3/4}\left(\frac{\rho_{\text{DM}}}{0.4\text{GeV/cm}^3}\right)^{1/4}$$

Ultra light dark matter

- Cusp vs Core problem

  ✓Parameterize density profile as $\rho(r) \propto r^{-\alpha}$. Observation shows $\alpha \sim 0$, but simulation predict $1 \leq \alpha \leq 1.5$

- Missing satellites problem

  ✓Milky Way seems to have fewer satellite galaxies (23) than expected in CDM simulations (~100-1000)

- Too big to fail problem

  ✓Predict more subhalos (5-40) with $v_{\max}$> 25 km/s than observed (~0).

Ultra light dark matter production

- Misalignment mechanism

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$$

- Classical Solution for wave-like dark matter

$$\phi(t) \approx \phi_1 \cos\left(m_\phi t\right) + \phi_2 \sin\left(m_\phi t\right)$$

- Dark matter local density

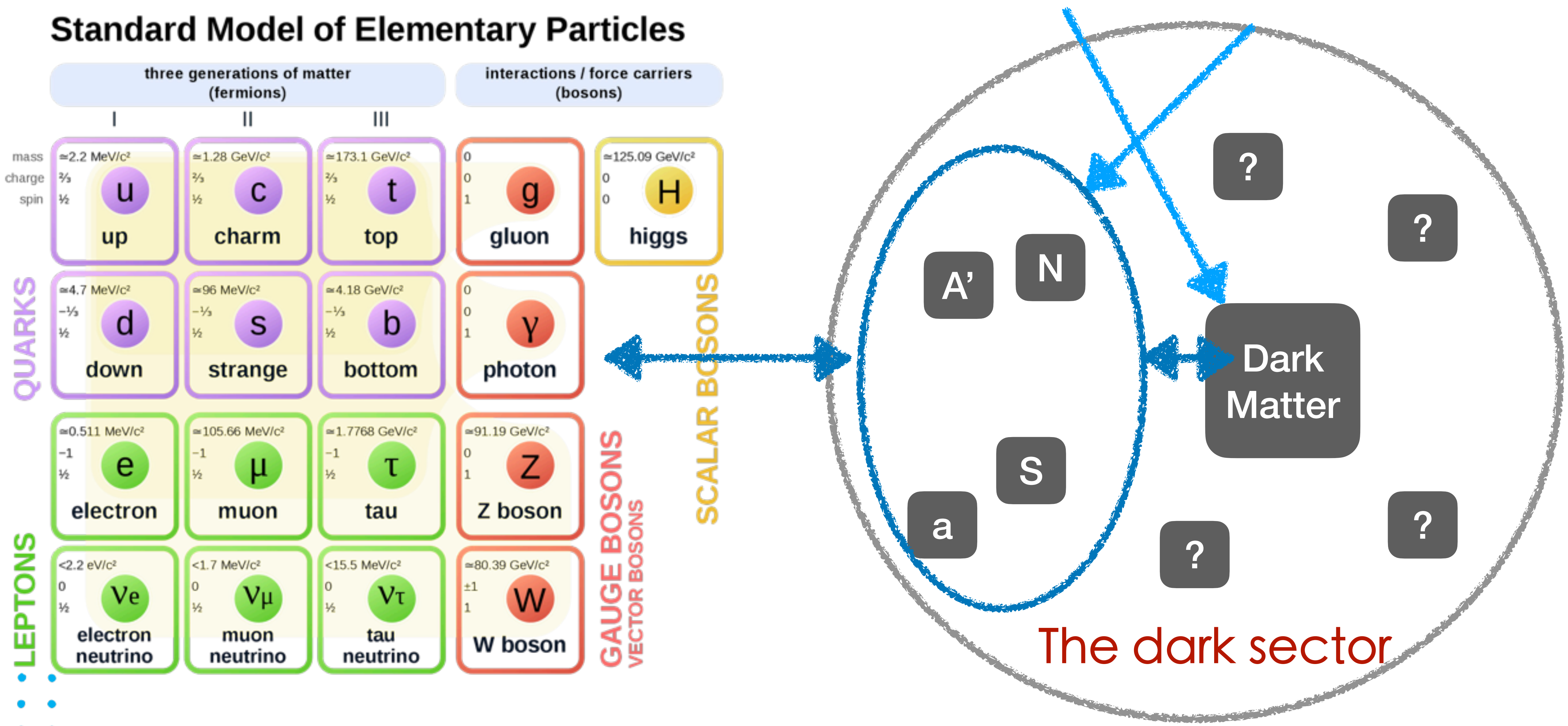
$$\rho_{\rm DM} \approx \left(\left|\phi_1\right|^2 + \left|\phi_2\right|^2\right) m_\phi^2$$

How to search for ultra light DM?

Dark matter-SM mediator

- StandarModel
  =fermions+force

- Dark Sector
  =DM+dark mediator



Dark matter-SM mediator

- StandarModel =fermions+force
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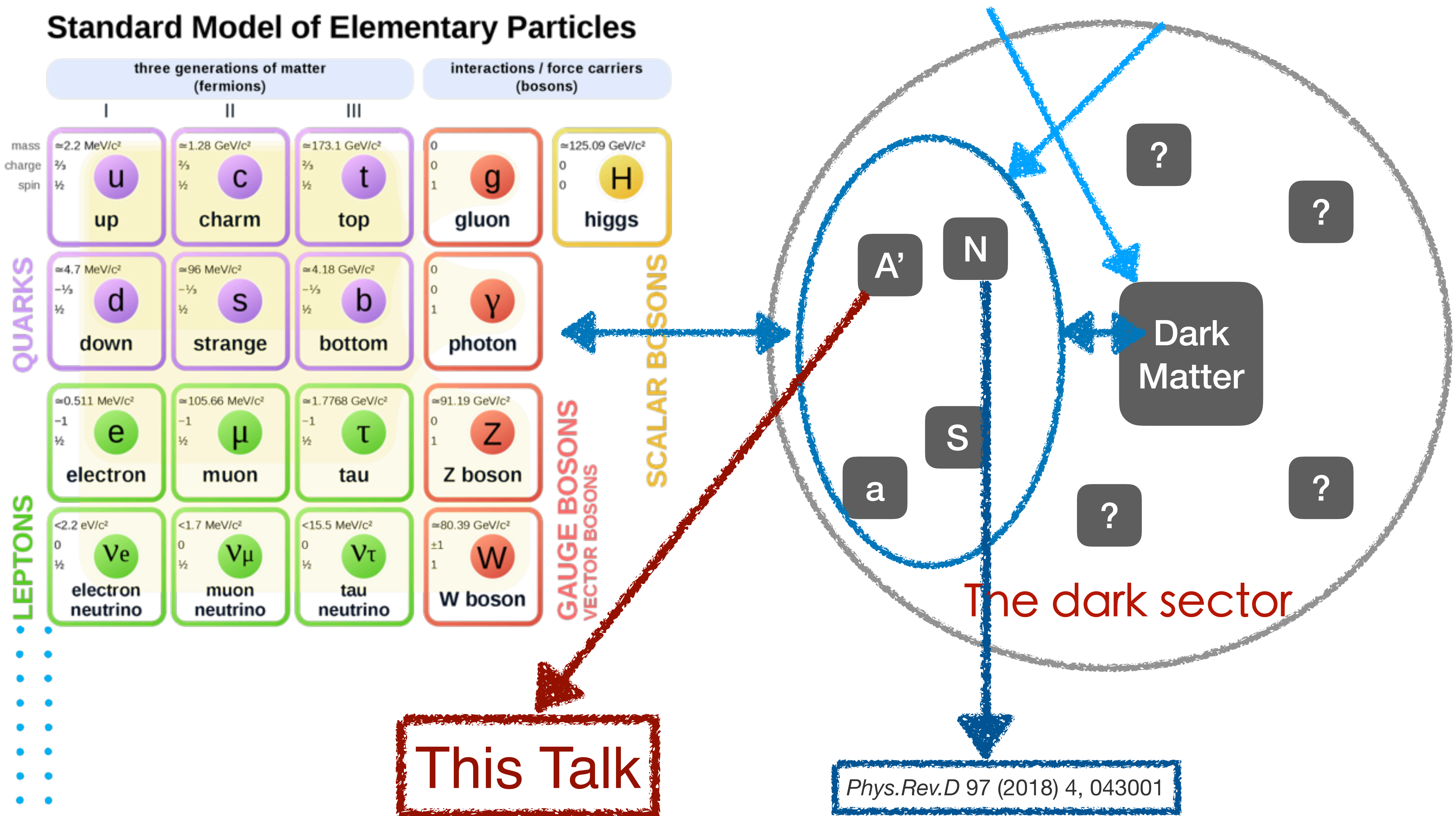


Oscillating A' from wave-like DM

- Wave information to A'

$$\left(D_\mu\phi\right)^* D^\mu\phi \supset \left(g'Q_\phi\right)^2 \phi^*\phi A'_\mu A'^\mu$$

- Oscillating information of A'

$$\tilde{m}_0^2 = m_0^2 + \left(g'Q_\phi\right)^2 \left(\phi_1^*\phi_1 + \phi_2^*\phi_2 - \sqrt{\left(|\phi_1|^2 + |\phi_2|^2\right)^2 + \left(\phi_1\phi_2^* + \phi_1^*\phi_2\right)^2}\right)$$

$$m_{A'}^2(t) = \tilde{m}_0^2 \left[1 + \left(2\left(g'Q_\phi\right)^2 \frac{\sqrt{\left(|\phi_1|^2 + |\phi_2|^2\right)^2 + \left(\phi_1\phi_2^* + \phi_1^*\phi_2\right)^2}}{\tilde{m}_0^2}\right)\cos^2\left(m_\phi t\right)\right]$$

$$\kappa$$

Oscillating A' from wave-like DM

- Wave information to A'

$$\left(D_\mu\phi\right)^* D^\mu\phi \supset \left(g'Q_\phi\right)^2 \phi^*\phi A'_\mu A'^\mu$$

- For simply connect to UV model

$$\arg\left[\phi_1\right] = \arg\left[\phi_2\right] \text{ or } \phi_2 = 0$$

$$\tilde{m}_0 = m_0$$

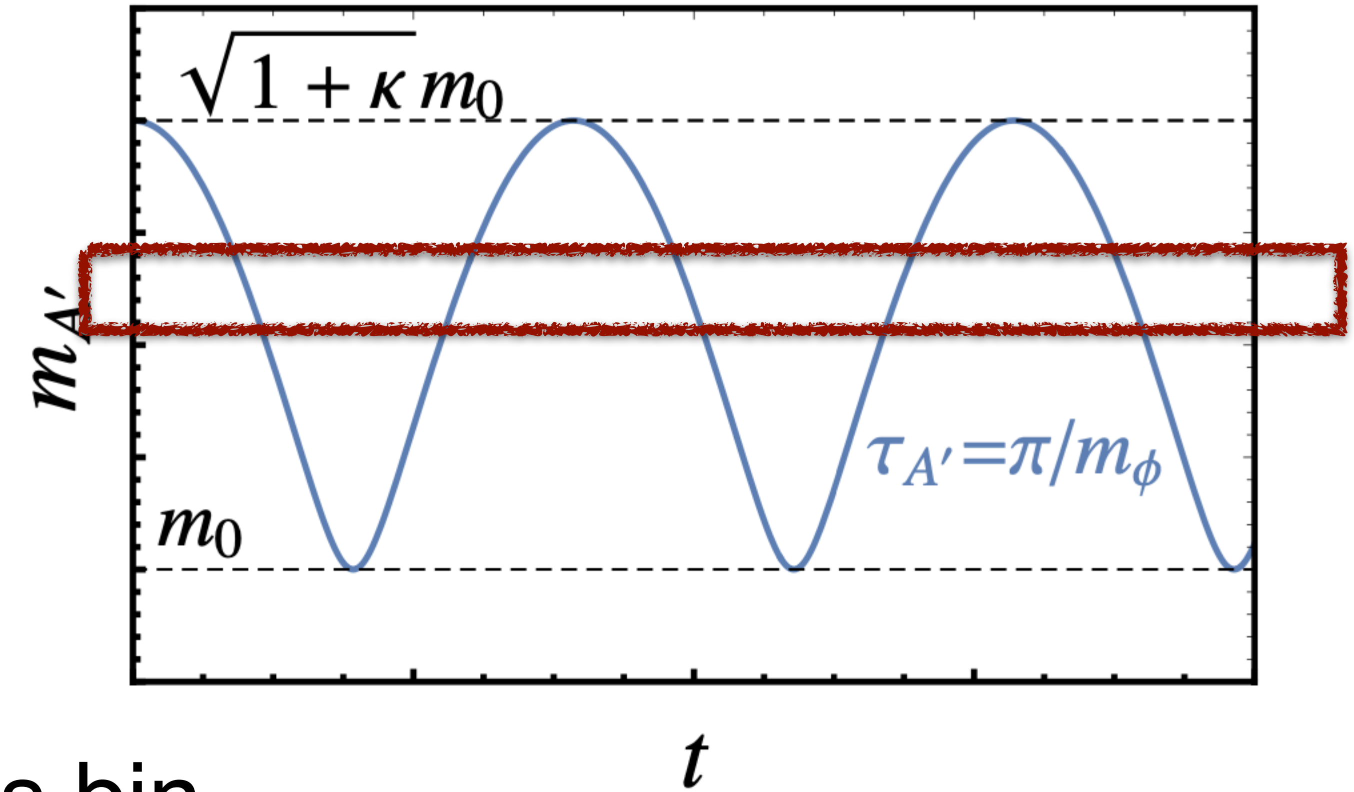
$$\kappa \equiv 10\left(\frac{\rho_{\rm DM}}{0.3{\rm GeV/cm^3}}\right)\left(\frac{g'Q_\phi}{1.5\times10^{-8}}\cdot\frac{10^{-19}{\rm eV}}{m_\phi}\cdot\frac{0.1{\rm GeV}}{m_0}\right)^2$$

$$m_{A'}^2(t) = m_0^2(1+\kappa\cos^2(m_\phi t))$$

Oscillating A' from wave-like DM

- Oscillating property

$$m_{A'}^2(t) = m_0^2(1 + \kappa\cos^2(m_\phi t))$$
$$= m_{A'}^2(t + \tau)$$



- Event number in the ith mass bin

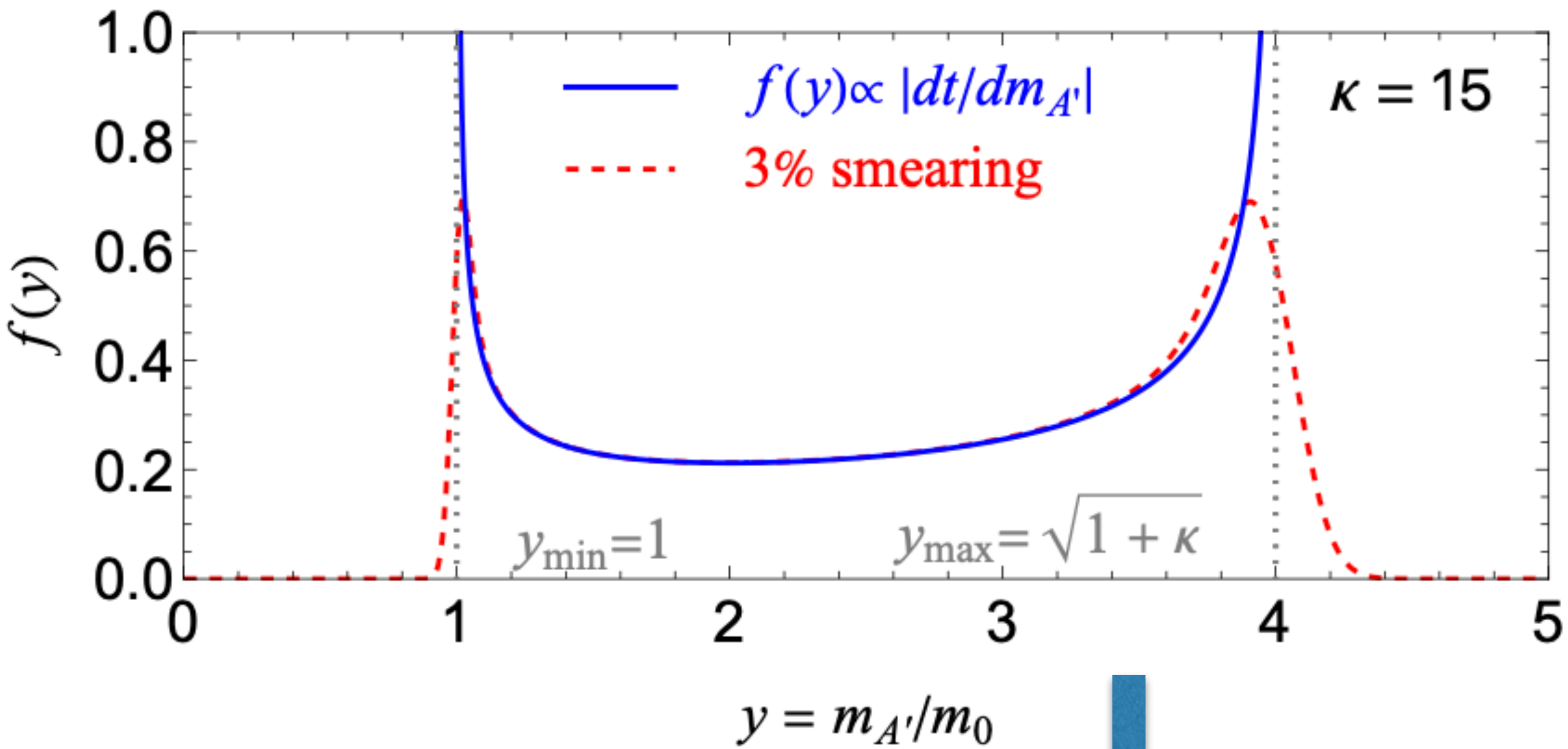
$$N_i = \sigma_{\rm res}^{(i)}\epsilon_i\, \mathrm{L}\frac{\Delta t_i}{t_{\rm exp}} = \frac{\sigma_{\rm res}^{(i)}\epsilon_i\, \mathrm{L}}{\tau}\int_{m_i}^{m_{i+1}}\left|\frac{dt}{dm_{\rm res}}\right| dm_{\rm res}$$

$$\left|\frac{dt}{dm_{\rm res}}\right| \rightarrow \frac{\tau}{m_0} f(y)$$

Oscillating A' from wave-like DM

- Oscillating property

$$f(y) = \frac{2y}{\pi\sqrt{\left(y^2 - y_{\rm min}^2\right)\left(y_{\rm max}^2 - y^2\right)}}$$

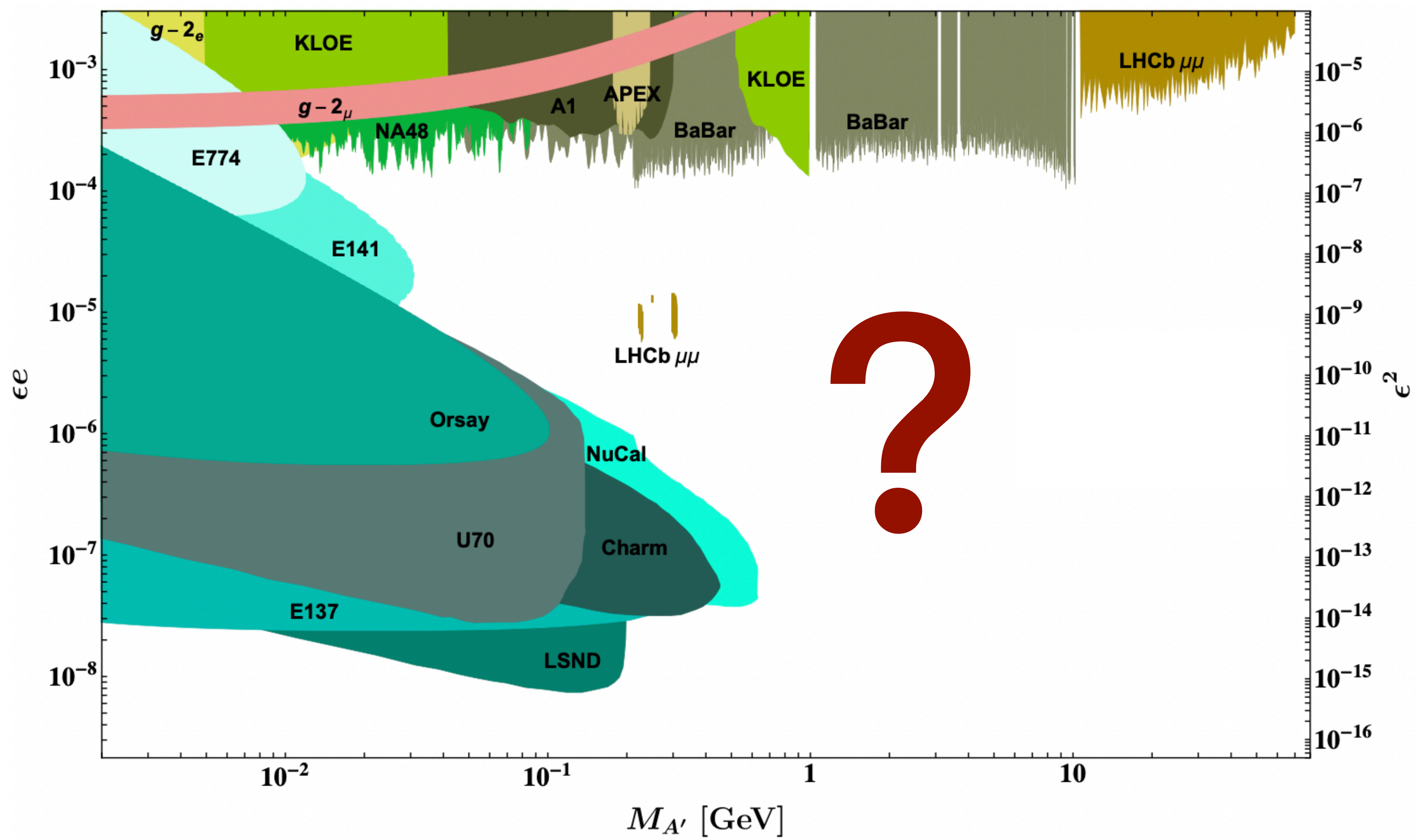


$$\frac{\int_{y_{\rm max}-\Delta}^{y_{\rm max}} f(y)dy}{\int_{y_{\rm min}}^{y_{\rm min}+\Delta} f(y)dy} \to \sqrt{\frac{y_{\rm max}}{y_{\rm min}}}$$

Oscillating A' effect on experiments?

- A kinetic mixing dark photon A′ with U(1)′ interaction

$$\mathscr{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_0^2 A'_\mu A'^\mu + \epsilon e A'_\mu J^\mu_{\rm em}$$



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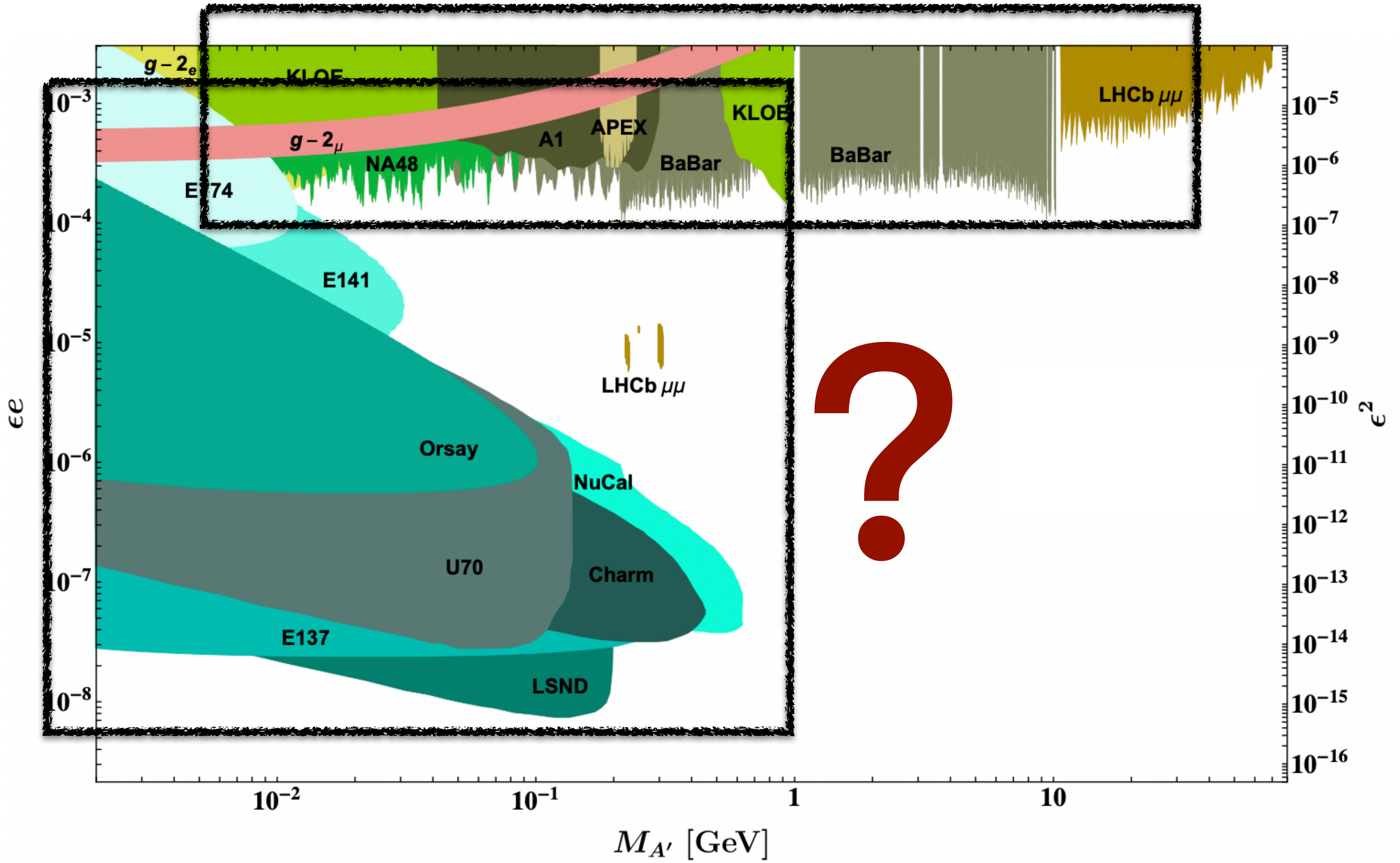
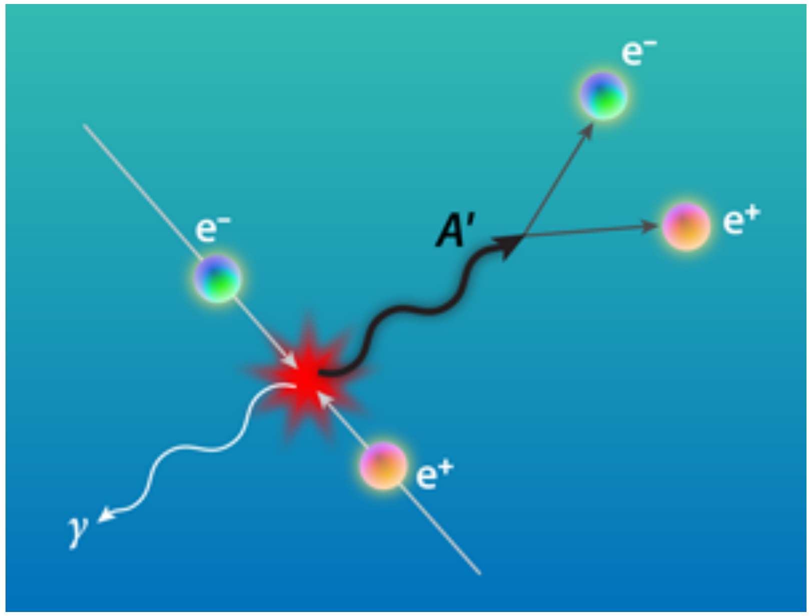


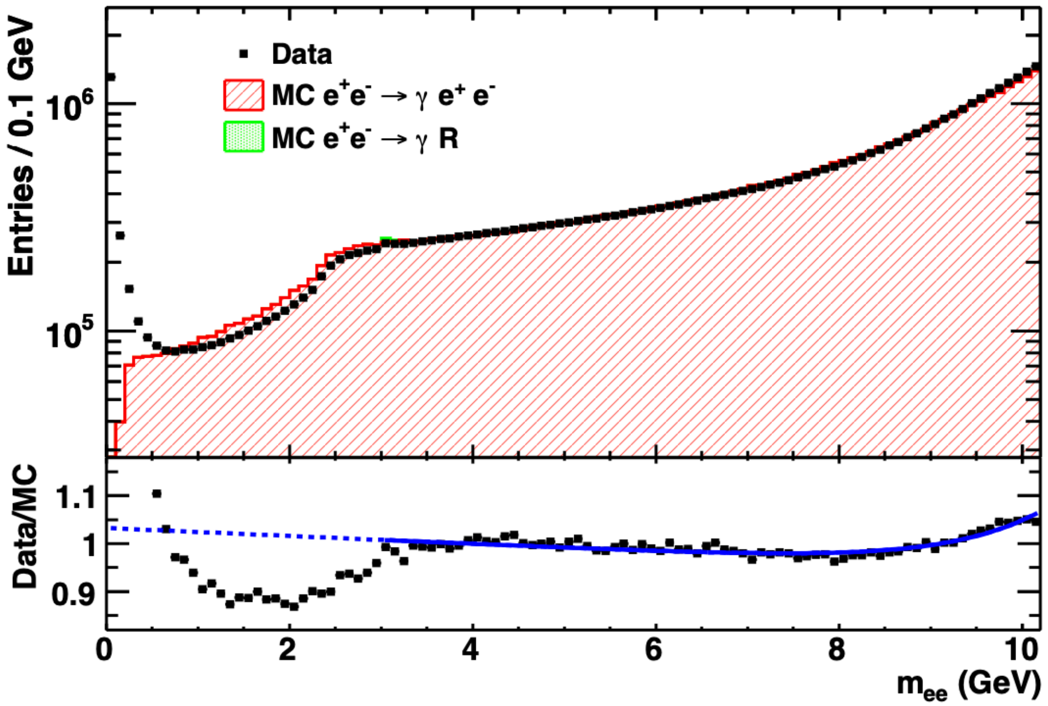
Prompt dilepton final states

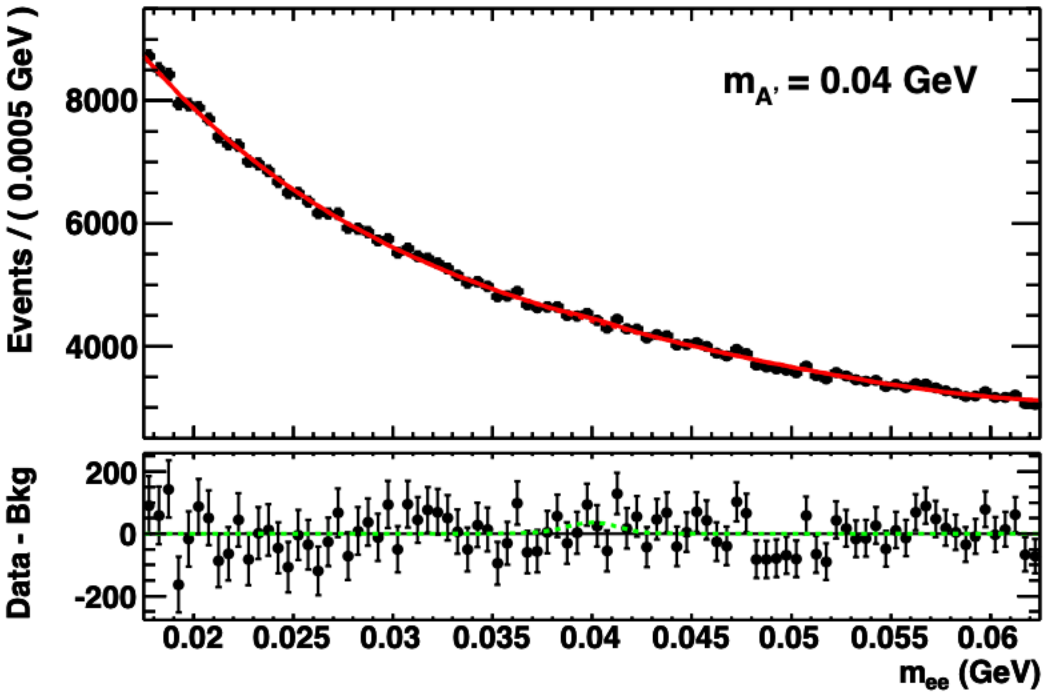
- General dilepton process

$$e^+e^- \to \gamma A', A' \to e^+e^-/\mu^+\mu^-$$



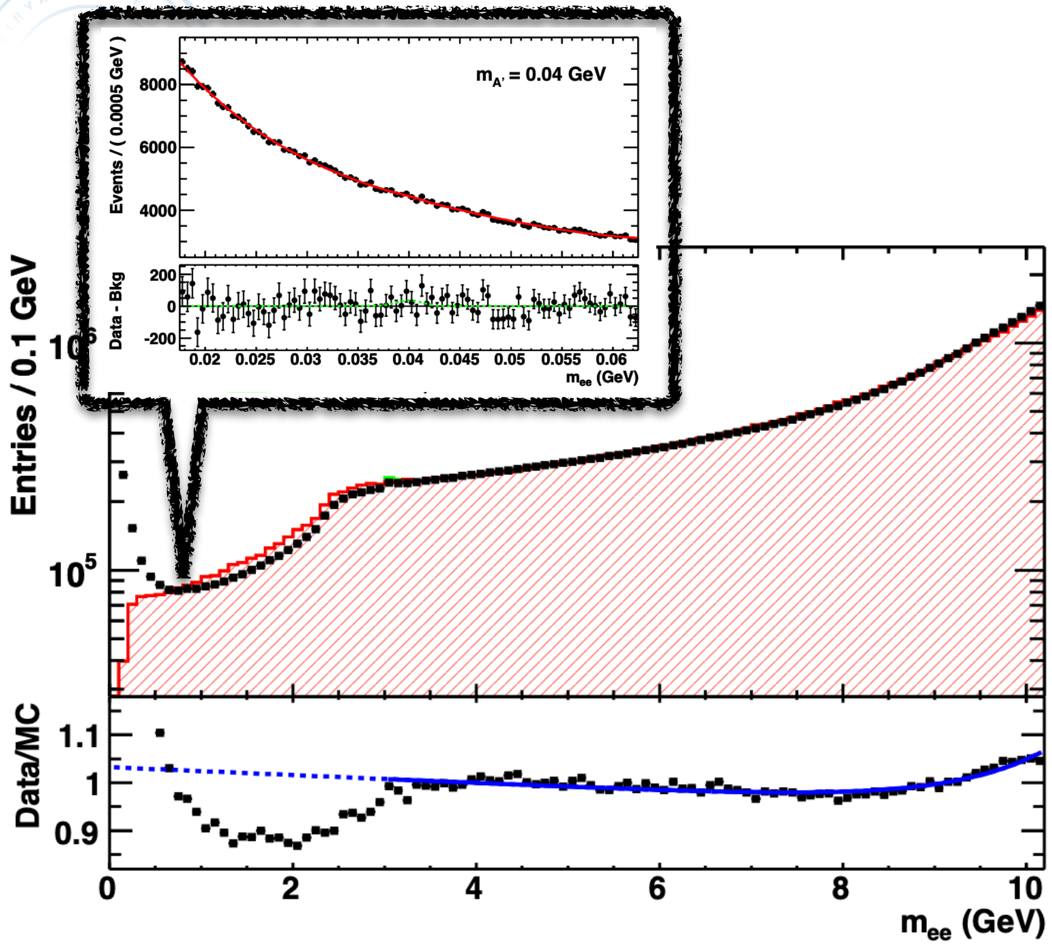
- BaBar data PRL 113, 201801 (2014)

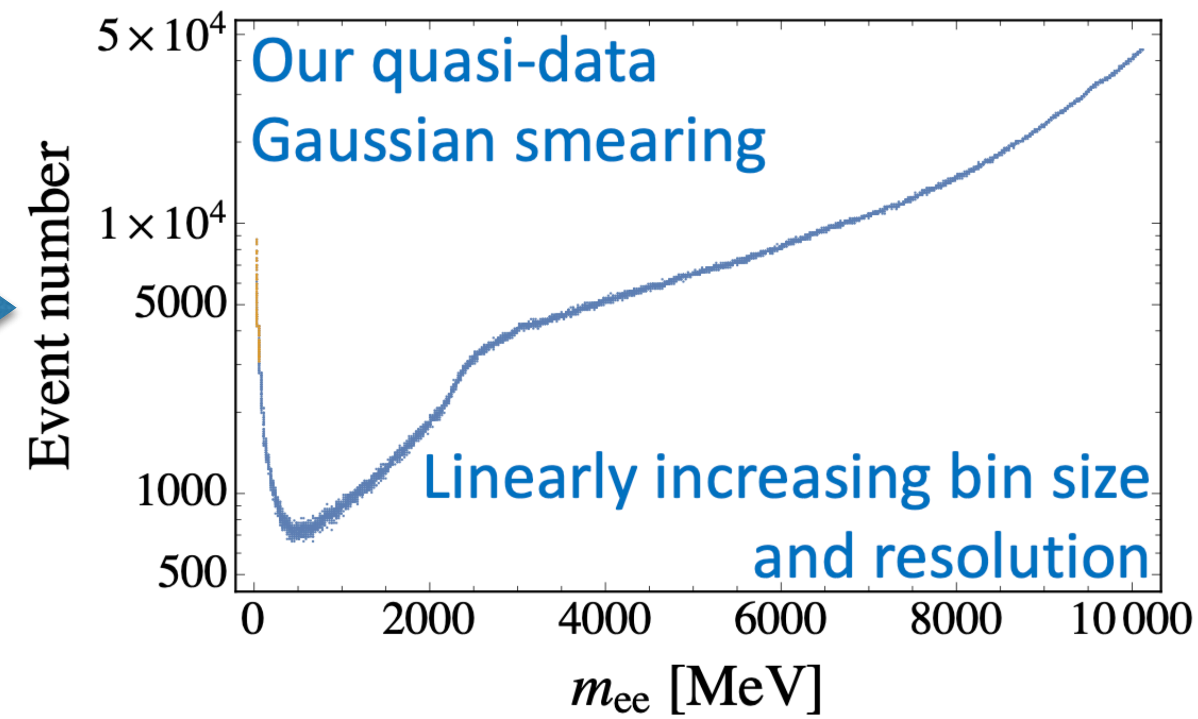




Recast BaBar experiment result

PRL 113, 201801 (2014)





- Log likelihood ratio (LLR)

$$\mathrm{LLR} = -2\log\left[\frac{\mathrm{Max}_{\vec{a}'}\prod_i \mathcal{N}\left(B_i - B\left(m_i, \vec{a}'\right) - Sf_G\left(m_i\right) \mid B_i\right)}{\mathrm{Max}_{\vec{a}}\prod_i \mathcal{N}\left(B_i - B\left(m_i, \vec{a}\right) \mid B_i\right)}\right]$$

Recast BaBar experiment result

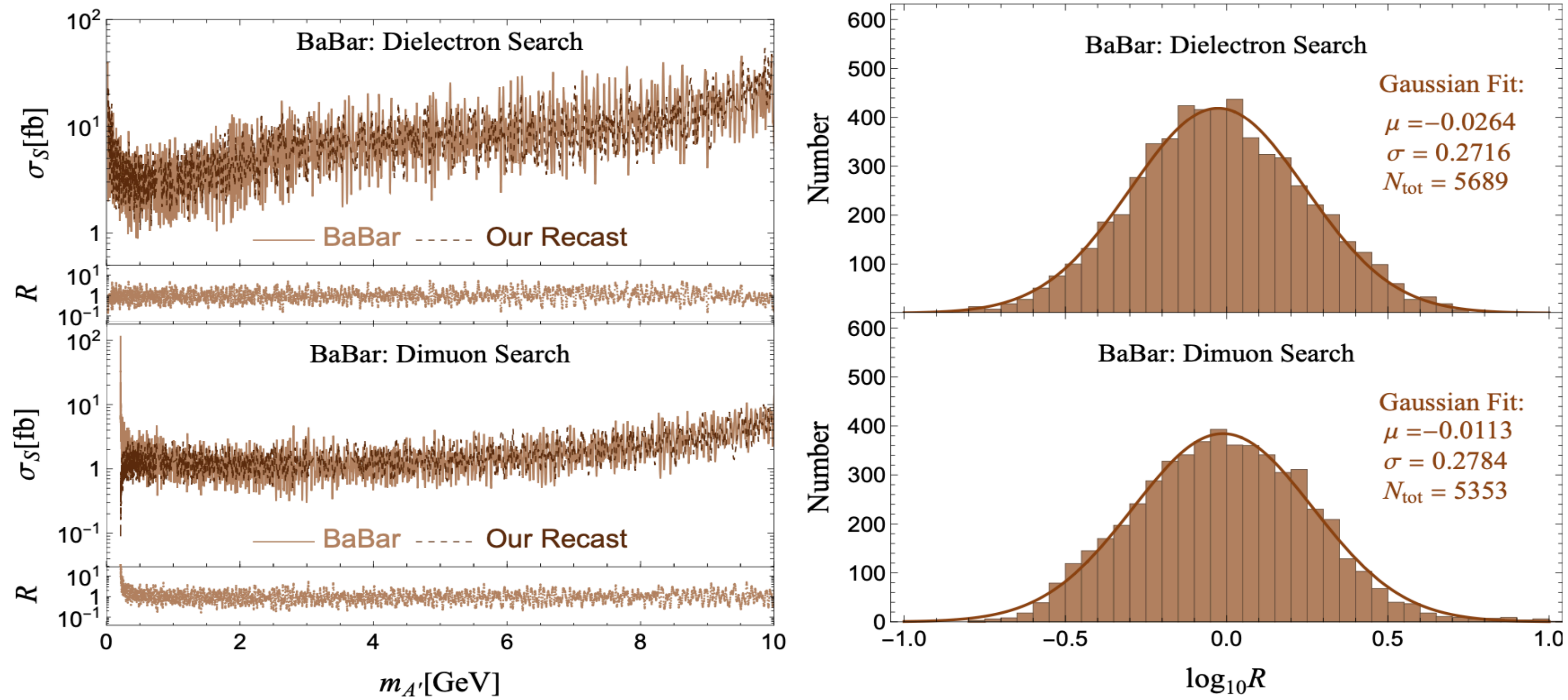
- Traditional single-peak analysis

$$f_G(m_i) = \mathcal{N}\left(m_{A'} - m_i \mid \sigma_{\rm re}^2\right)$$

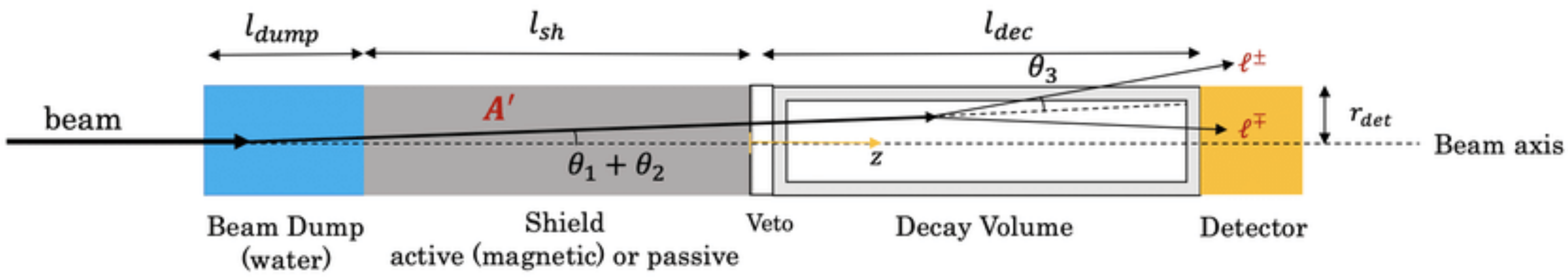
- Double-peak analysis

$$f_S(m_i) = \int_{m_{\rm min}}^{m_{\rm max}} f\left(\frac{m'}{m_0}\right) \mathcal{N}\left(m_i - m' \mid \sigma_{\rm re}^2\right) dm'$$

- Recast result:



Beam Dump Experiments



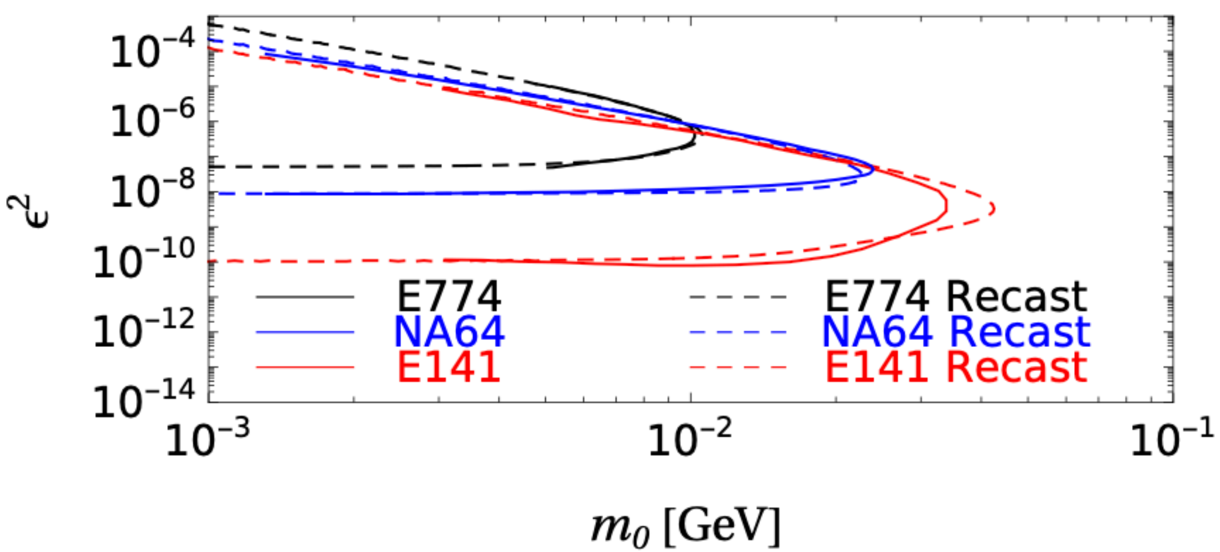
- General event number:

$$N\left(\epsilon, m_{A'}\right)=N_e \mathscr{C}' \epsilon^2 \frac{m_e^2}{m_{A'}^2} e^{-a_1 L_{\text{sh}} \Gamma_{A'}}\left(1-e^{-a_2 L_{\text{dec}} \Gamma_{A'}}\right)$$

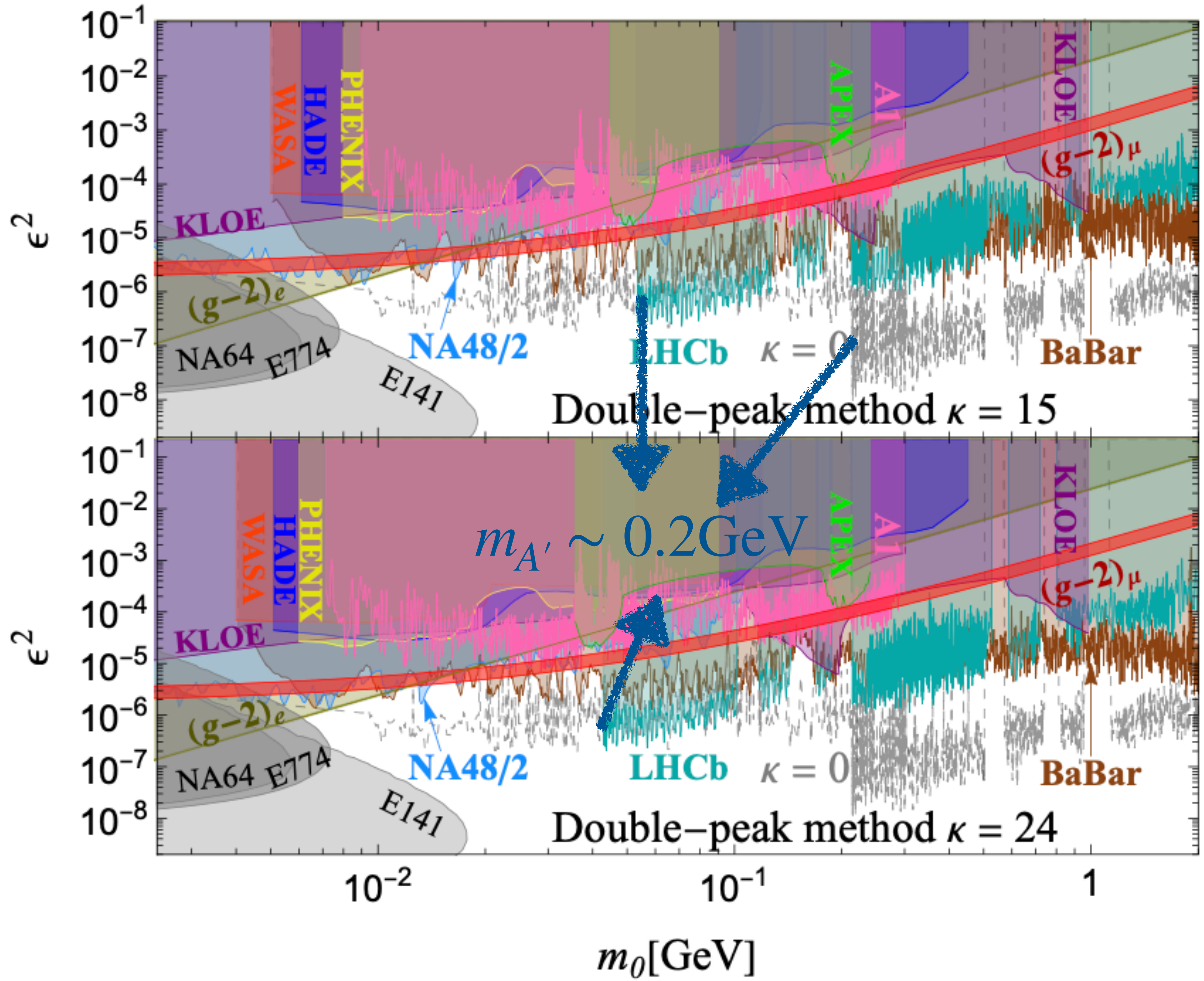
- Including oscillation effect

$$N\left(\epsilon, m_0, \kappa\right)=\frac{1}{\tau} \int_{m_0}^{\sqrt{1+\kappa m_0}} N\left(\epsilon, m_{A'}\right)\left|\frac{dt}{dm_{A'}}\right| dm_{A'}$$

- Our recast result with $\kappa=0$



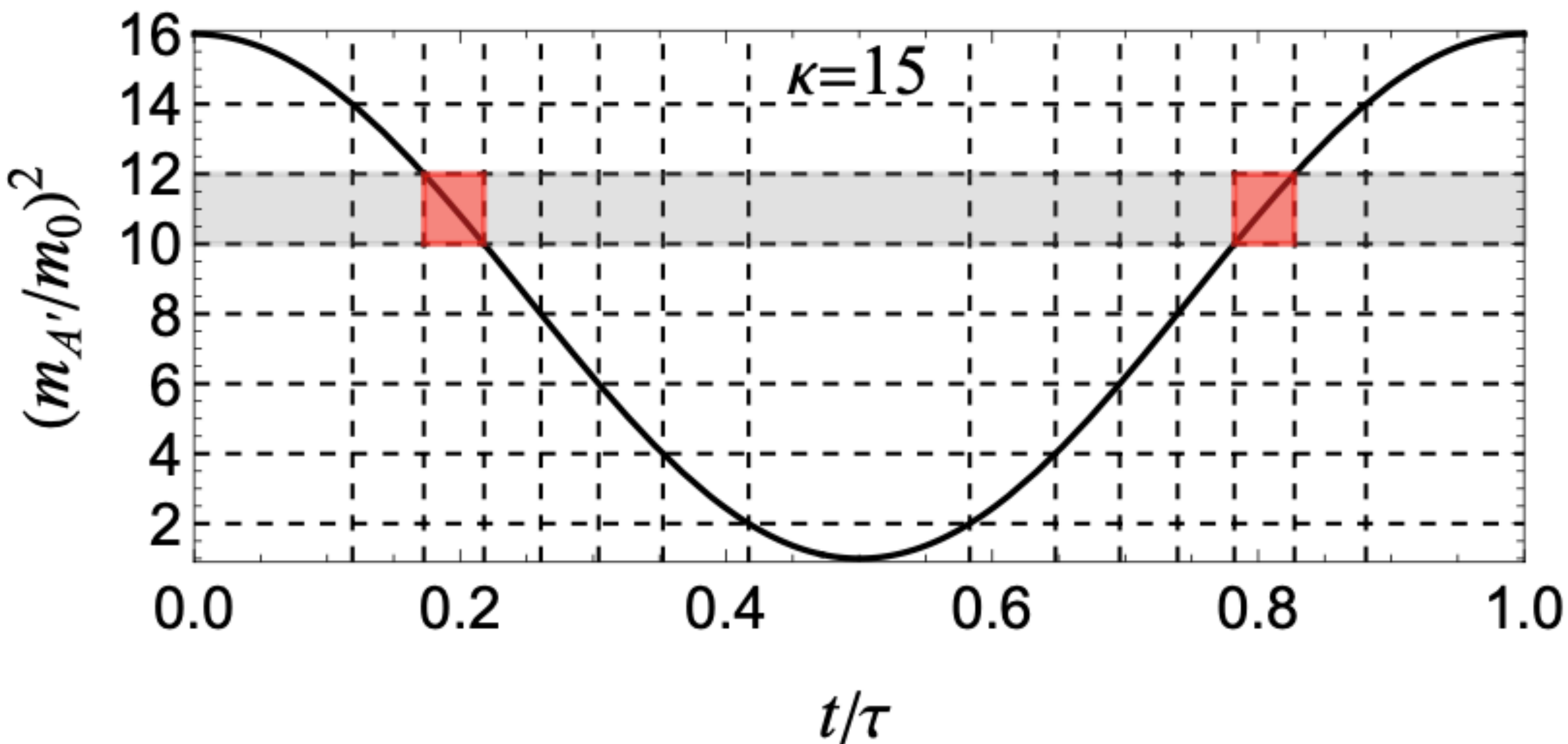
Double-peak analysis result



Improvement with time-varying

- Oscillating property

$$m_{A'}^2(t) = \tilde{m}_0^2(1 + \kappa \cos^2(m_\phi t))$$

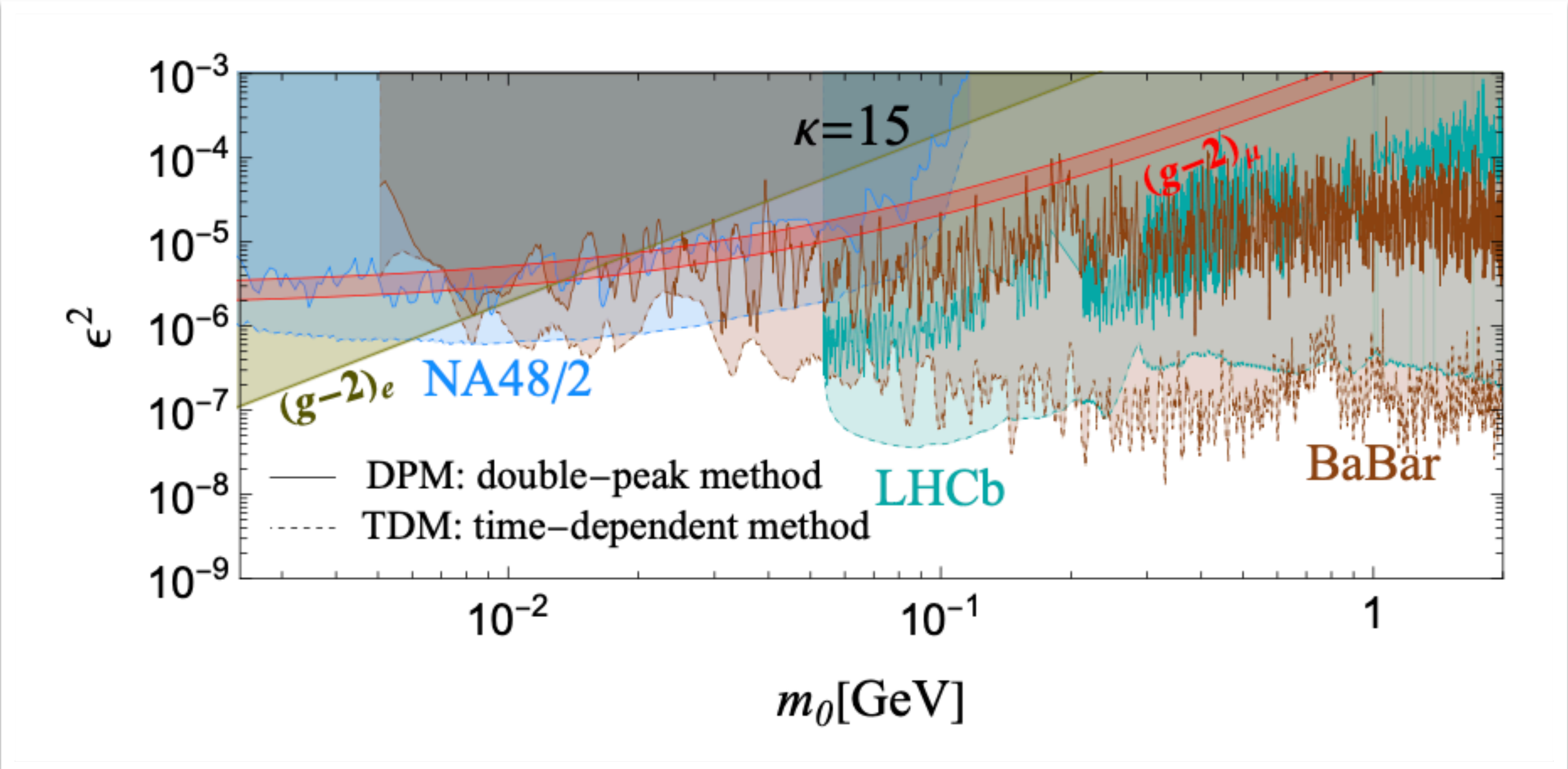


- Background event number

$$N_i^{\rm red} = N_i \frac{1}{\tau} \int_{m_i}^{m_{i+1}} \left| \frac{dt}{dm_{A'}} \right| dm_{A'}$$

Improvement with time-varying

- Result with time-varying

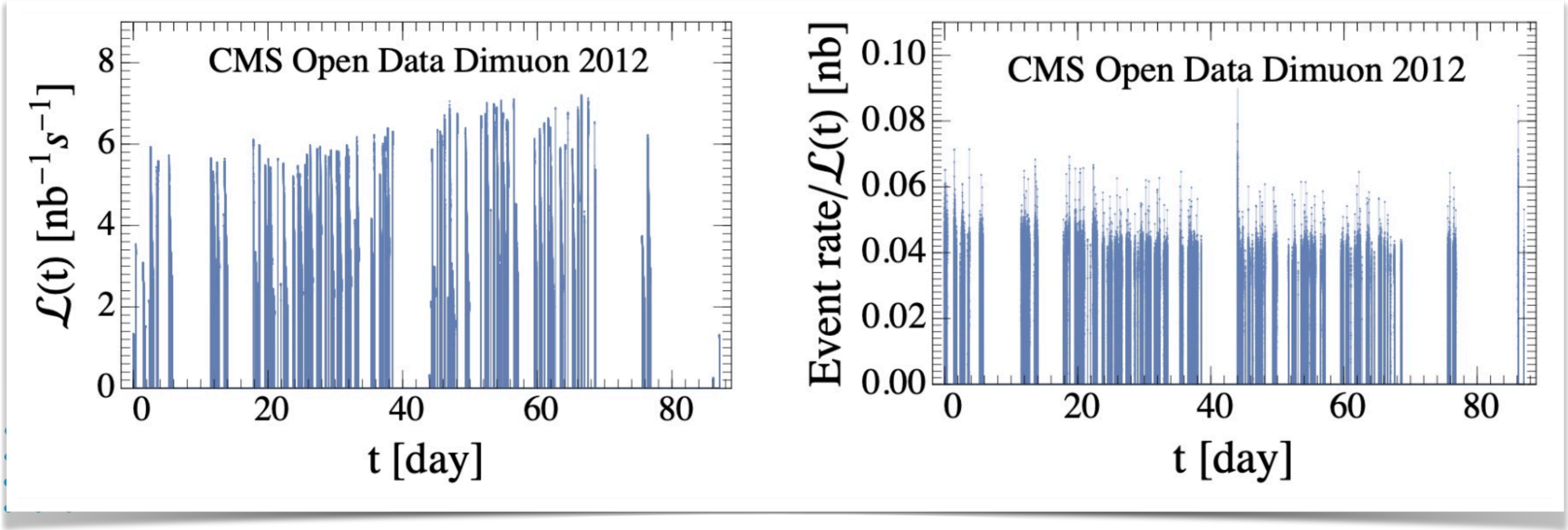


Justify TDM with CMS open data

- CMS open data 2012

$$pp \to \ell^+\ell^-\text{, 8TeV, } \sim 10\, fb^{-1}$$

- Luminosity is not constant



CMS open data

- Oscillating A' property

$$N_i = \frac{\sigma_{\text{res}}^{(i)} \epsilon_i \, \text{L}}{\tau} \int_{m_i}^{m_{i+1}} \left| \frac{dt}{dm_{\text{res}}} \right| dm_{\text{res}} \qquad \frac{\tau}{\tilde{m}_0} f(y)$$

- CMS differential event number

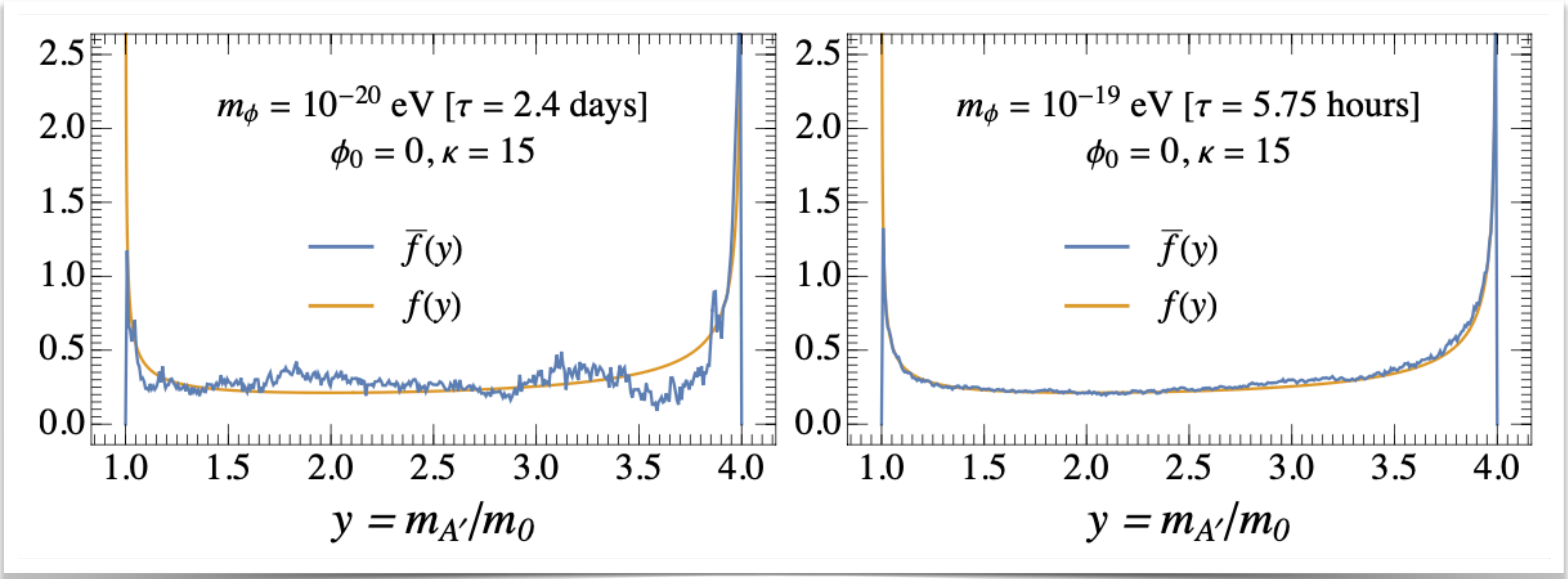
$$\frac{d\sigma_S}{dm_{\ell\ell}} = \epsilon_S \sigma_0 \times \delta\left(m_{\ell\ell} - m_{A'}(t)\right)$$

$$\frac{dN_S}{dm_{\ell\ell}} = \int_{t_1}^{t_2} dt \mathscr{L}(t) \frac{d\sigma_S}{dm_{\ell\ell}} = \epsilon_S \sigma_0 \times \frac{2m_{\ell\ell}}{\pi\sqrt{m_{\ell\ell}^2 - m_0^2}\sqrt{(1+\kappa)m_0^2 - m_{\ell\ell}^2}} \frac{\tau_{A'}}{2} \left[\sum_{i^+} \mathscr{L}\left(t_i^+\right) + \sum_{i^-} \mathscr{L}\left(t_i^-\right)\right]$$

$$L \times \bar{f}\left(m_{\ell\ell}/m_0\right)$$

CMS open data

- Double-peak property

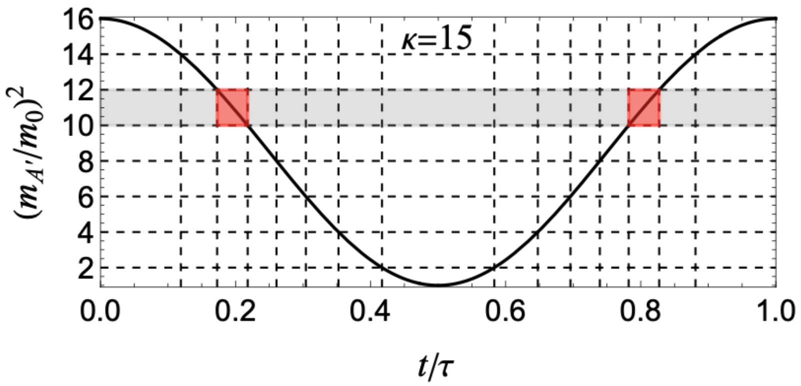


We can use DPM for CMS open data!

CMS result with time information

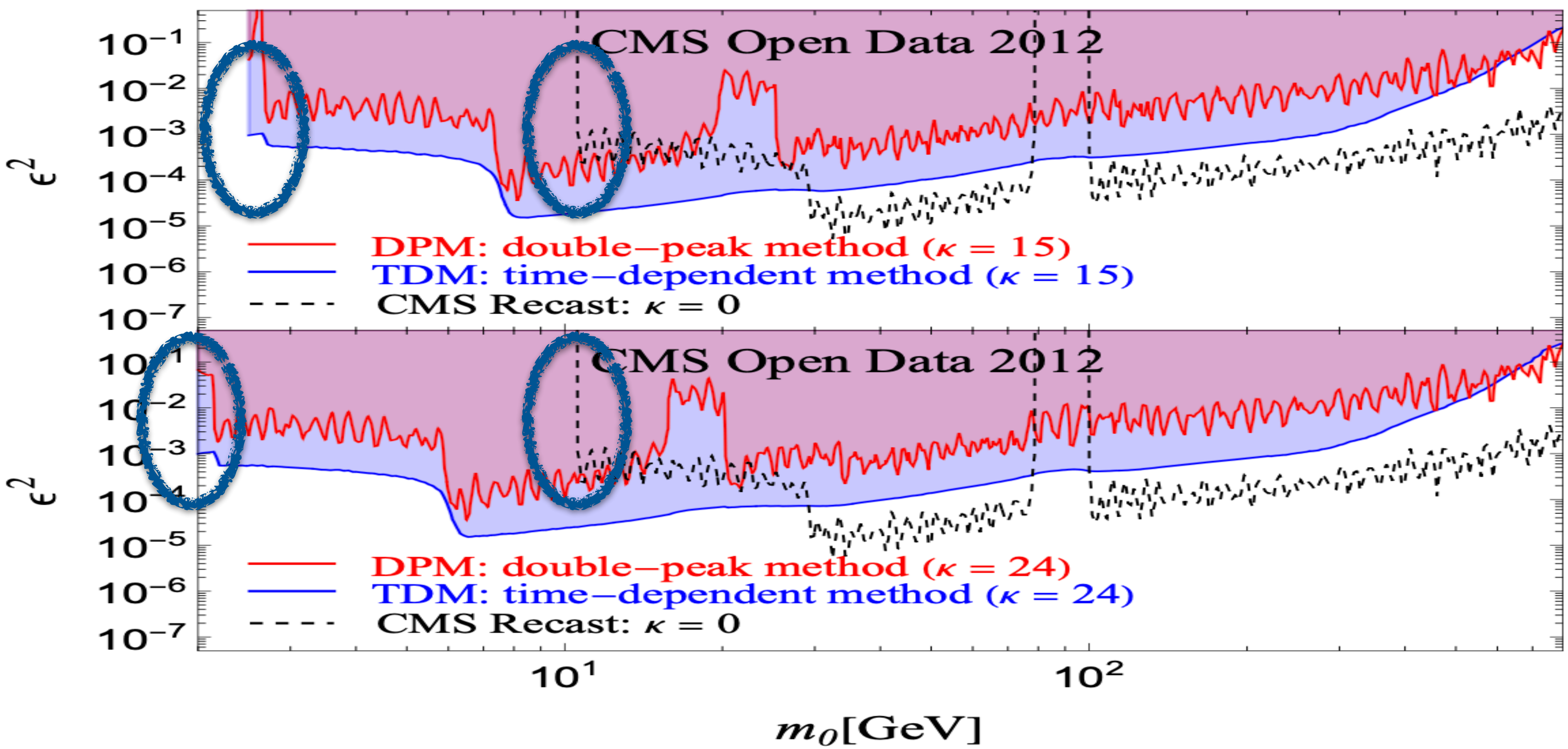
- Double-peak Method

$$\frac{dN_S}{dm_{\ell\ell}} = \sigma\left(m_{\ell\ell}\right)\epsilon_S \frac{f\left(m_{\ell\ell}/m_0\right)}{m_0} \times \frac{\tau_{A'}}{2}\sum_{i^\pm}\mathscr{L}\left(t_{i^\pm}\right)$$



- Time-dependent Method

$$S_{ij} = \int_{t_i}^{t_i+\Delta t} dt \int_{m_j}^{m_j+\Delta m_{\ell\ell}} dm_{\ell\ell} \frac{1}{\sqrt{2\pi}\sigma_m} e^{-\frac{\left(m_{\ell\ell}-m_{A'}(t)\right)^2}{2\sigma_m^2}} \times \mathscr{L}(t) \times \epsilon_S\left(m_{\ell\ell}\right)\sigma_0\left(m_{\ell\ell}\right)$$



Summary

- **Time-varying resonant mass lead to double-peak feature in the invariant mass spectrum**
- **For mass around tens of MeV, the already excluded muon $(g-2)_\mu$ solution from A' becomes viable**
- **Time dependent method can improve the experiment sensitivity by a few orders**
- **We use the real collider data for a time-dependent resonance search and justify that our method works as expected**

Thank you!