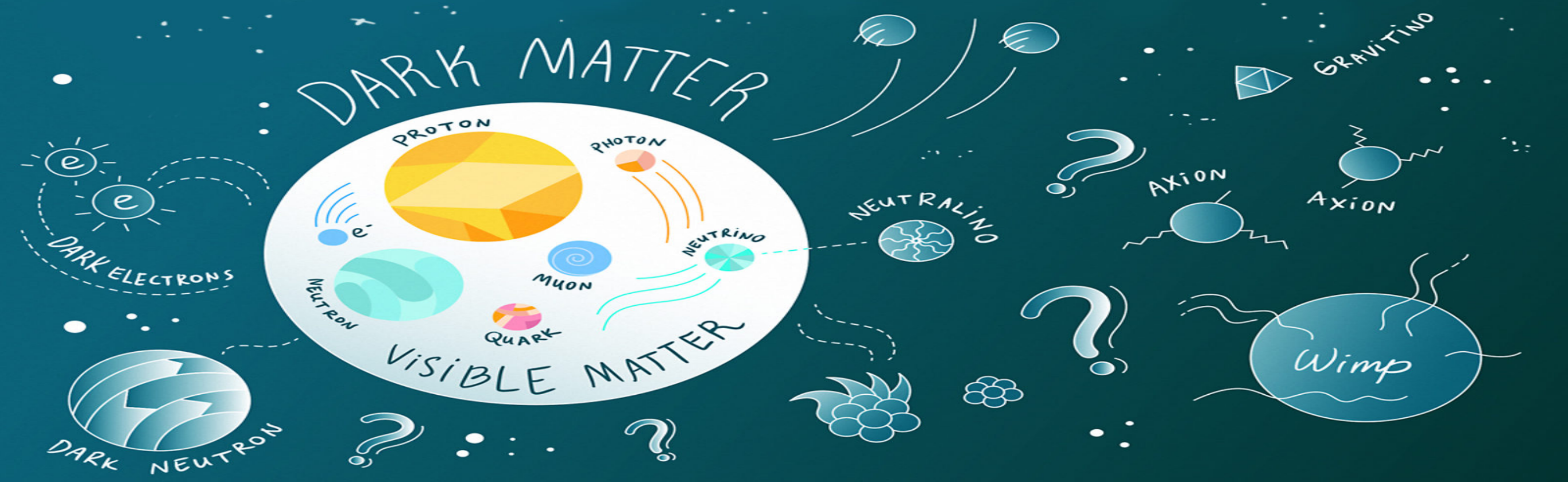




Ultralight dark matter and time-varying signal @ collider and beam dump experiments



Xiao-Ping Wang (王小平)

Apr, 15 @ 深地液氩暗物质、中微子研讨会

Base On: arXiv:2206.14221

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



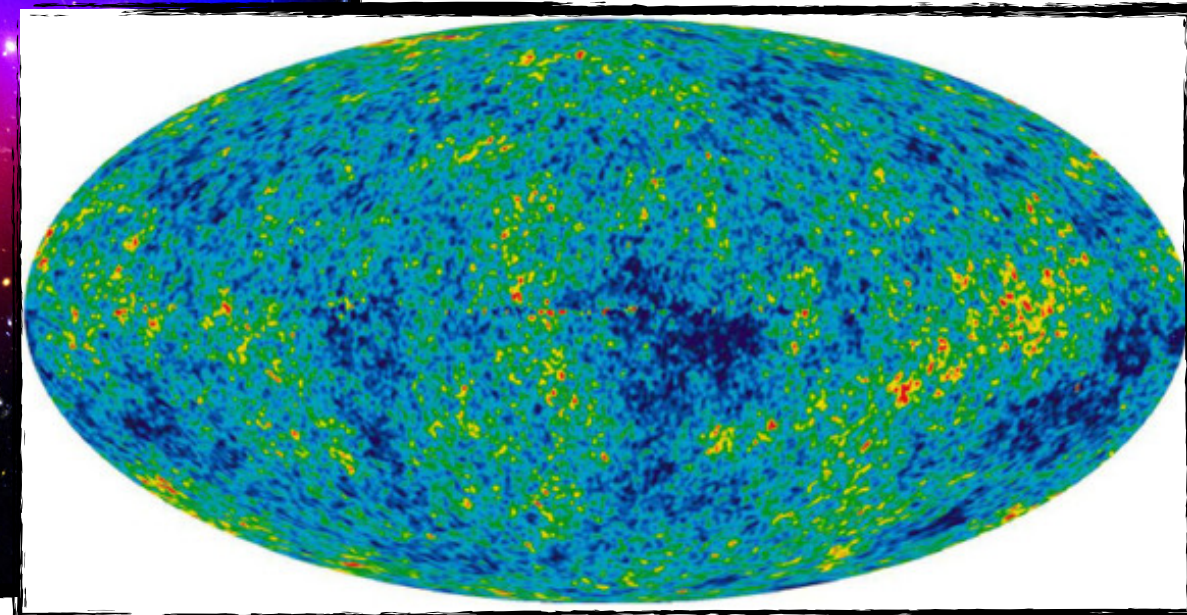
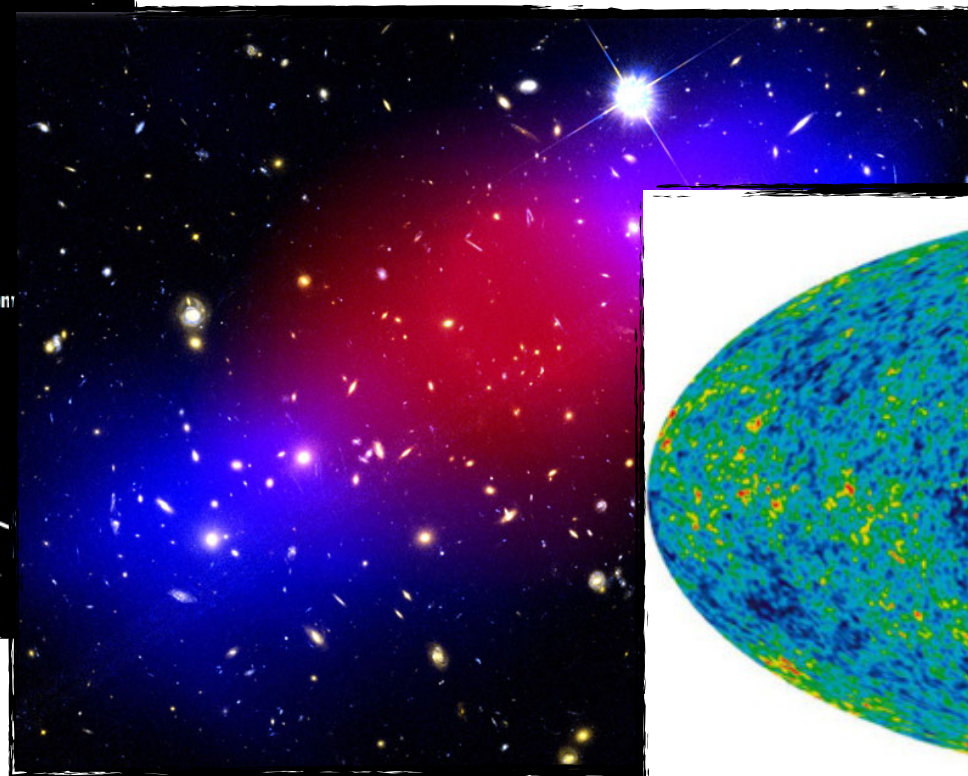
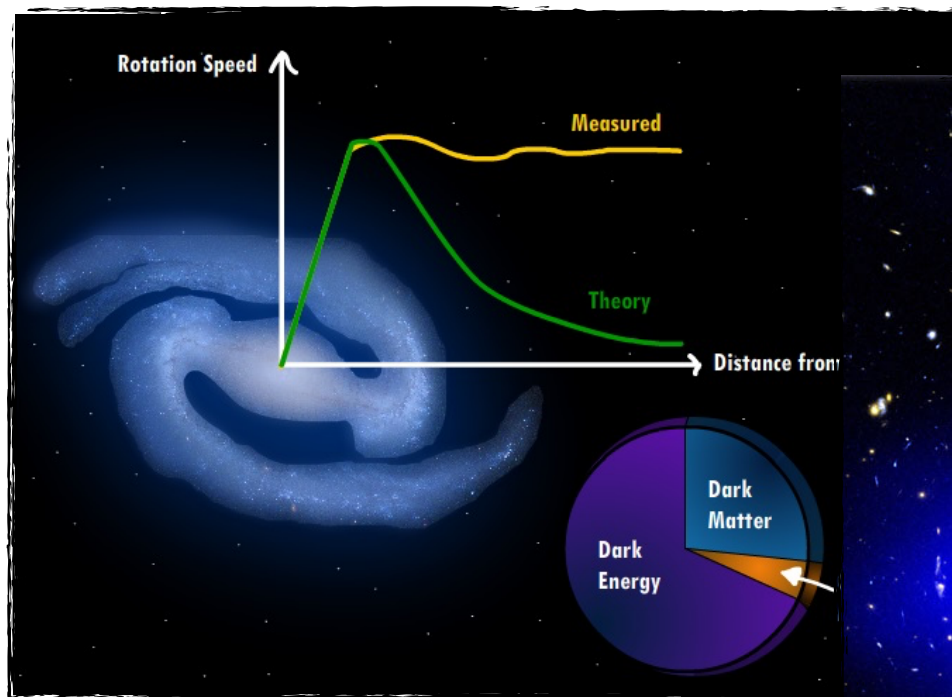
Dark Matter Evidence

- Evidence from different scale

Galaxy

Cluster

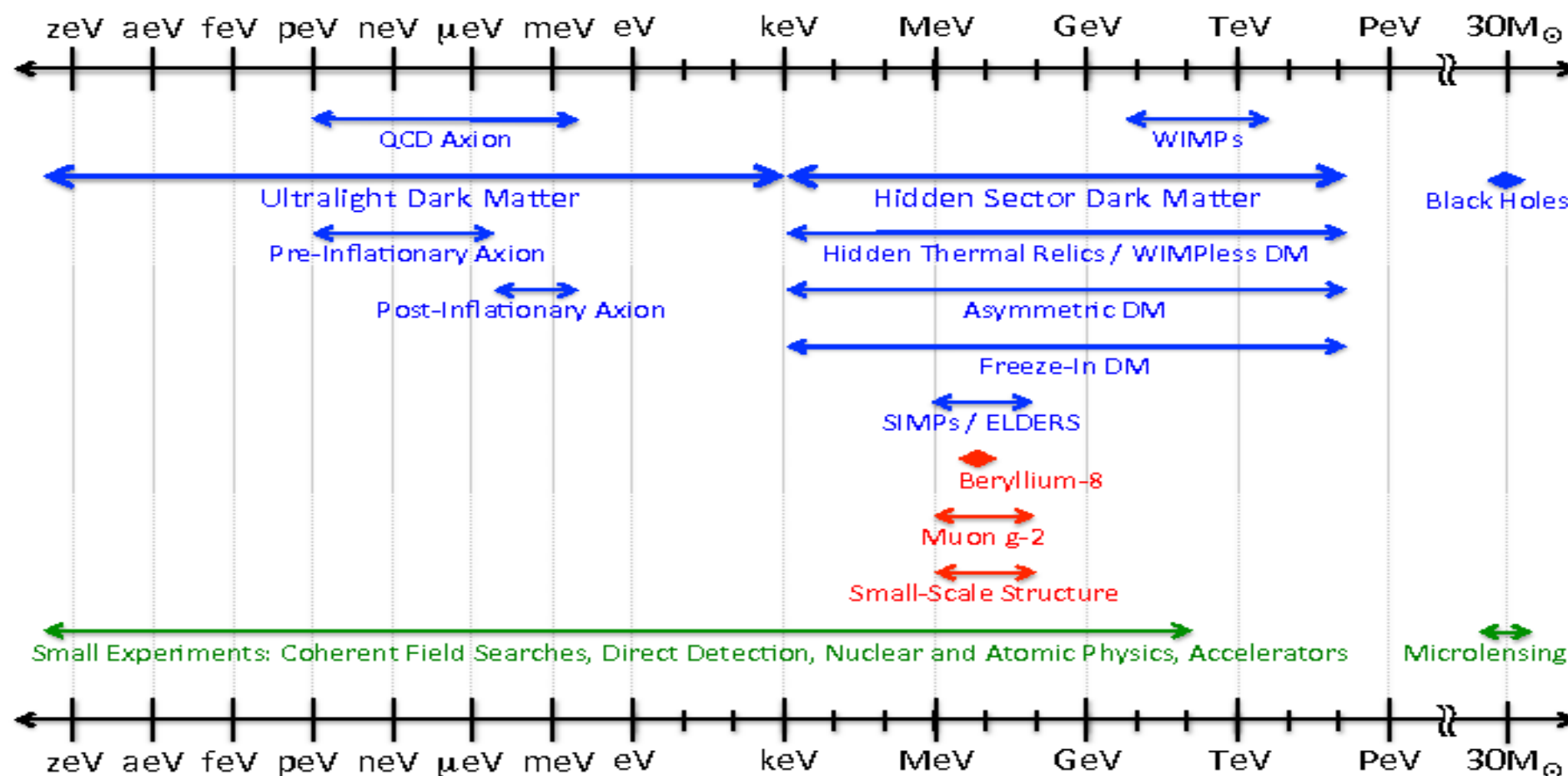
Universe





Dark matter mass range

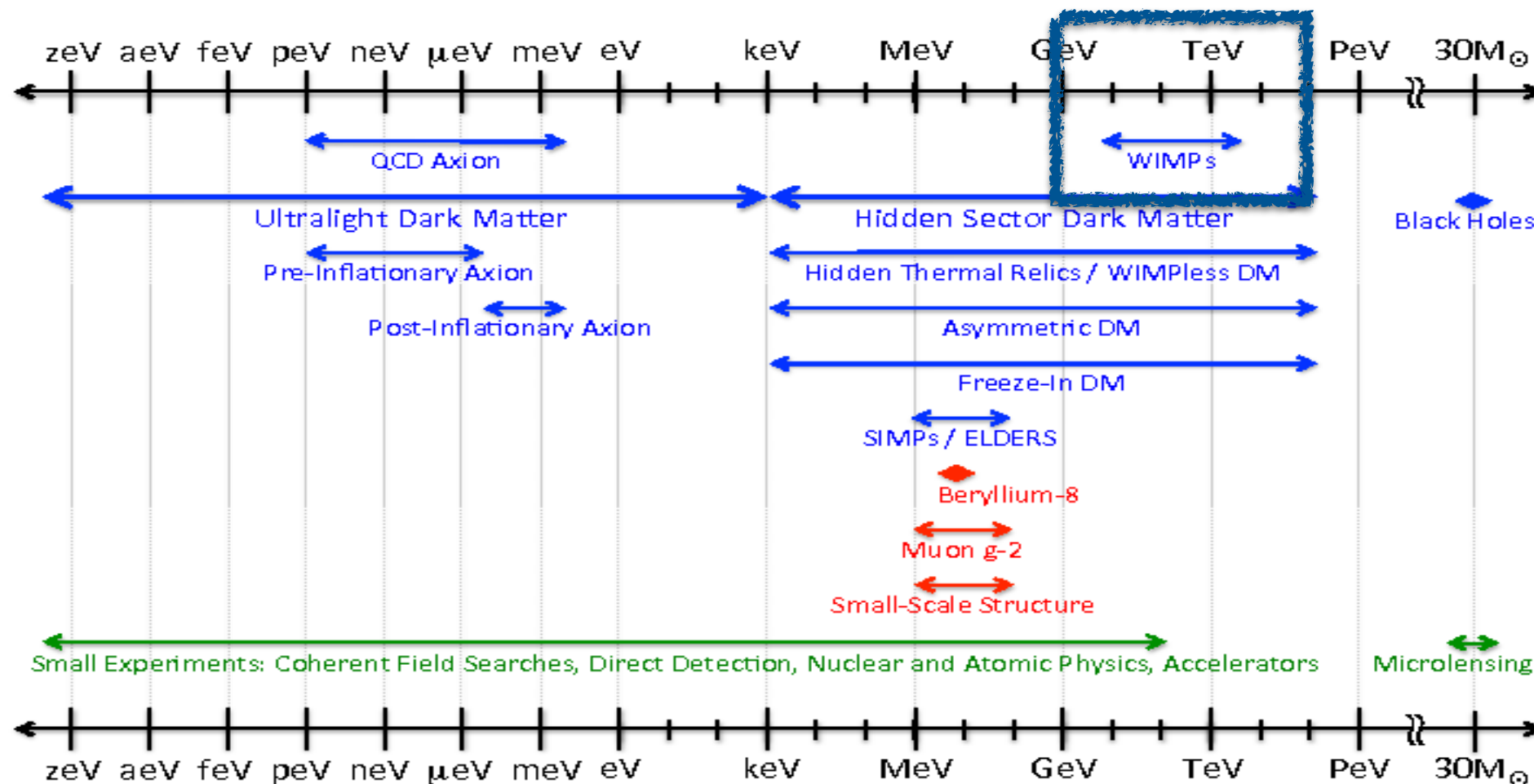
Dark Sector Candidates, Anomalies, and Search Techniques





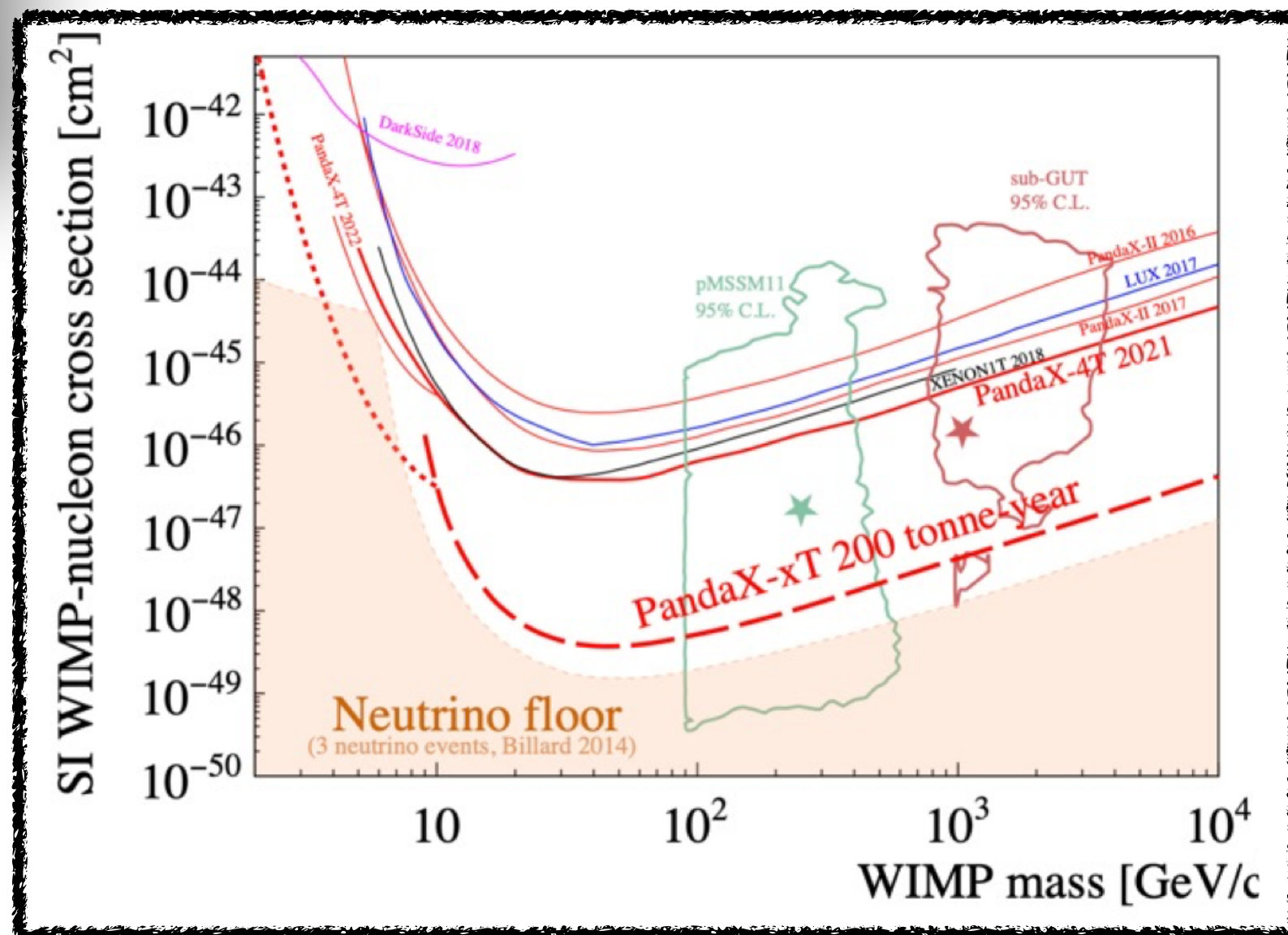
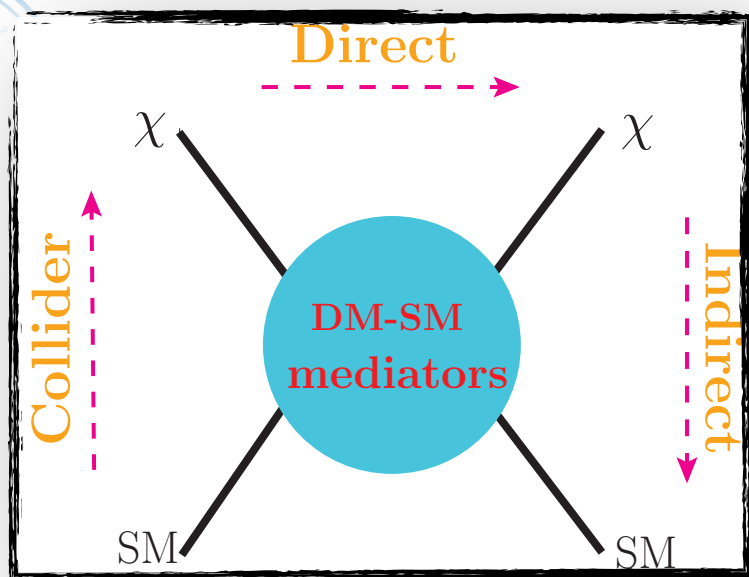
Dark matter mass range

Dark Sector Candidates, Anomalies, and Search Techniques





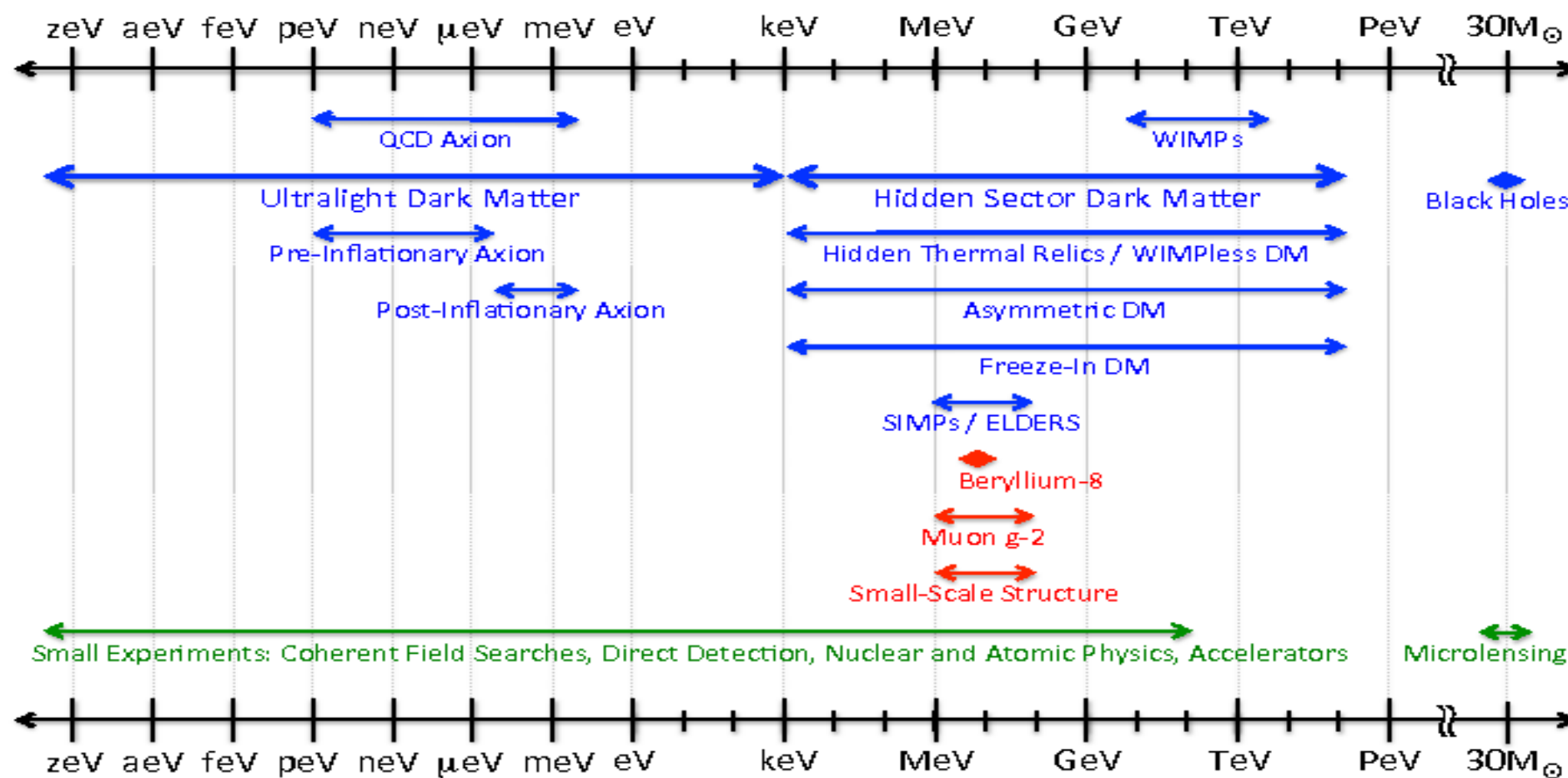
WIMP search status





Dark matter mass range

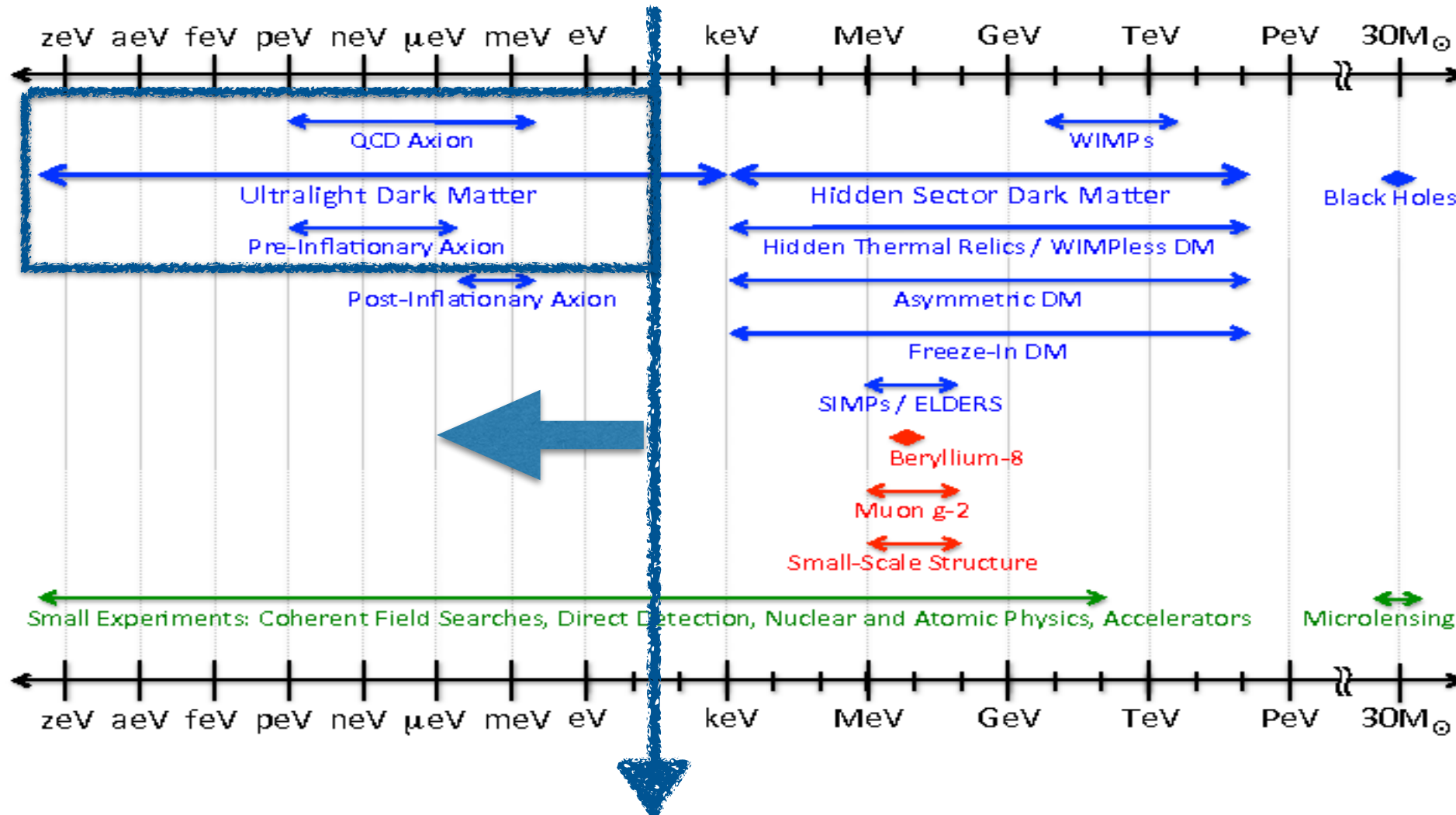
Dark Sector Candidates, Anomalies, and Search Techniques





Dark matter mass range

Dark Sector Candidates, Anomalies, and Search Techniques



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



Ultralight 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 ($\sim 100-1000$)

- 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

$$\phi(t) \approx \phi_1 \cos(m_{\phi}t) + \phi_2 \sin(m_{\phi}t)$$

- Dark matter local density

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

How to search for ultra light DM?



Dark matter-SM mediator



- Standard Model
= fermions + force

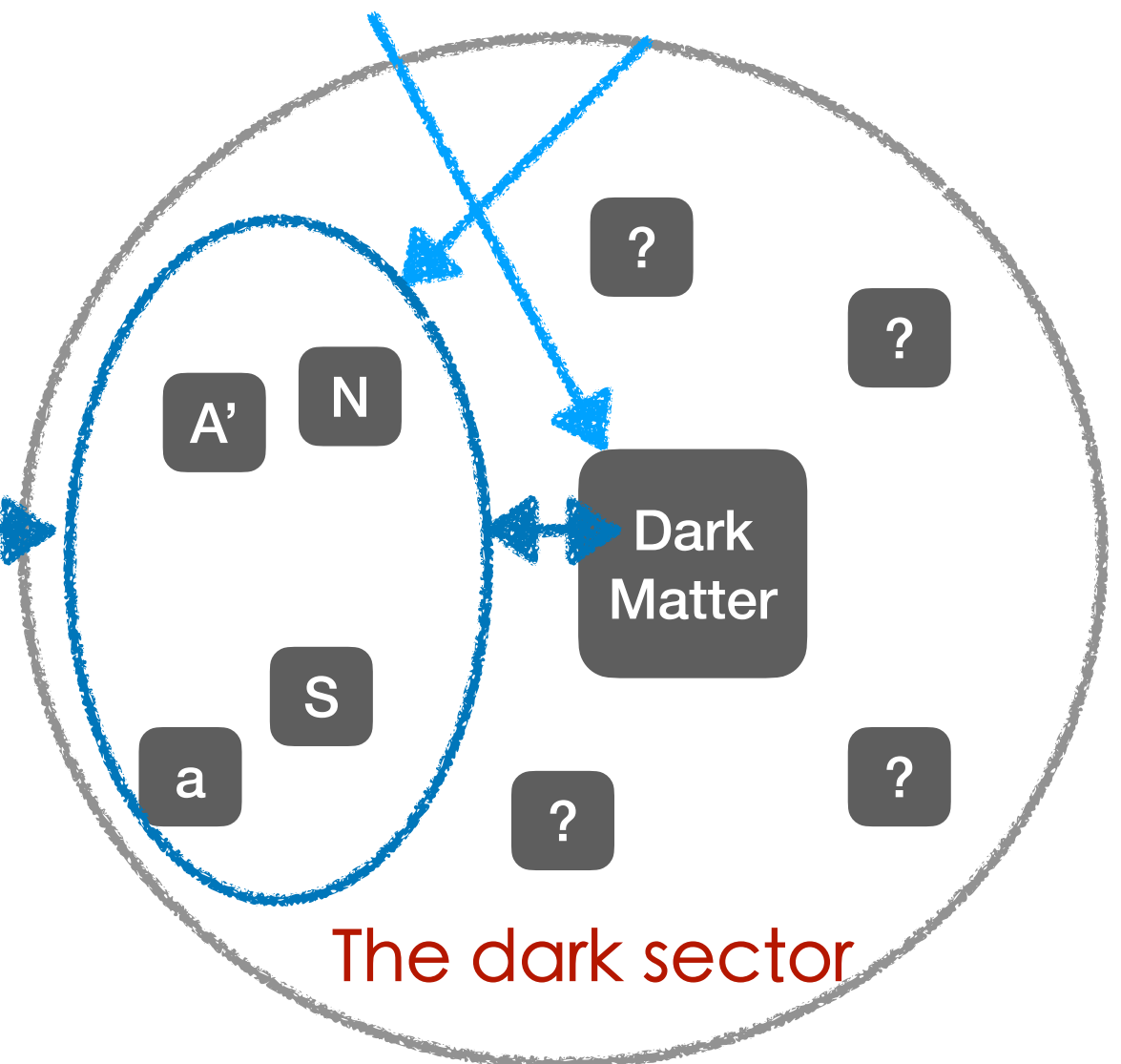
- Dark Sector
= DM + dark mediator

Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
QUARKS	$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 g gluon	$\approx 125.09 \text{ GeV}/c^2$ 0 0 H higgs
	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 γ photon	
	$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau	$\approx 91.19 \text{ GeV}/c^2$ 0 1 Z Z boson	
LEPTONS	$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$< 1.7 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1 W W boson	

SCALAR BOSONS (points to Higgs)

GAUGE BOSONS VECTOR BOSONS (points to photon, Z, W)



The dark sector



Dark matter-SM mediator



- Standard Model
= fermions + force

- Dark Sector
= DM + dark mediator

Standard Model of Elementary Particles

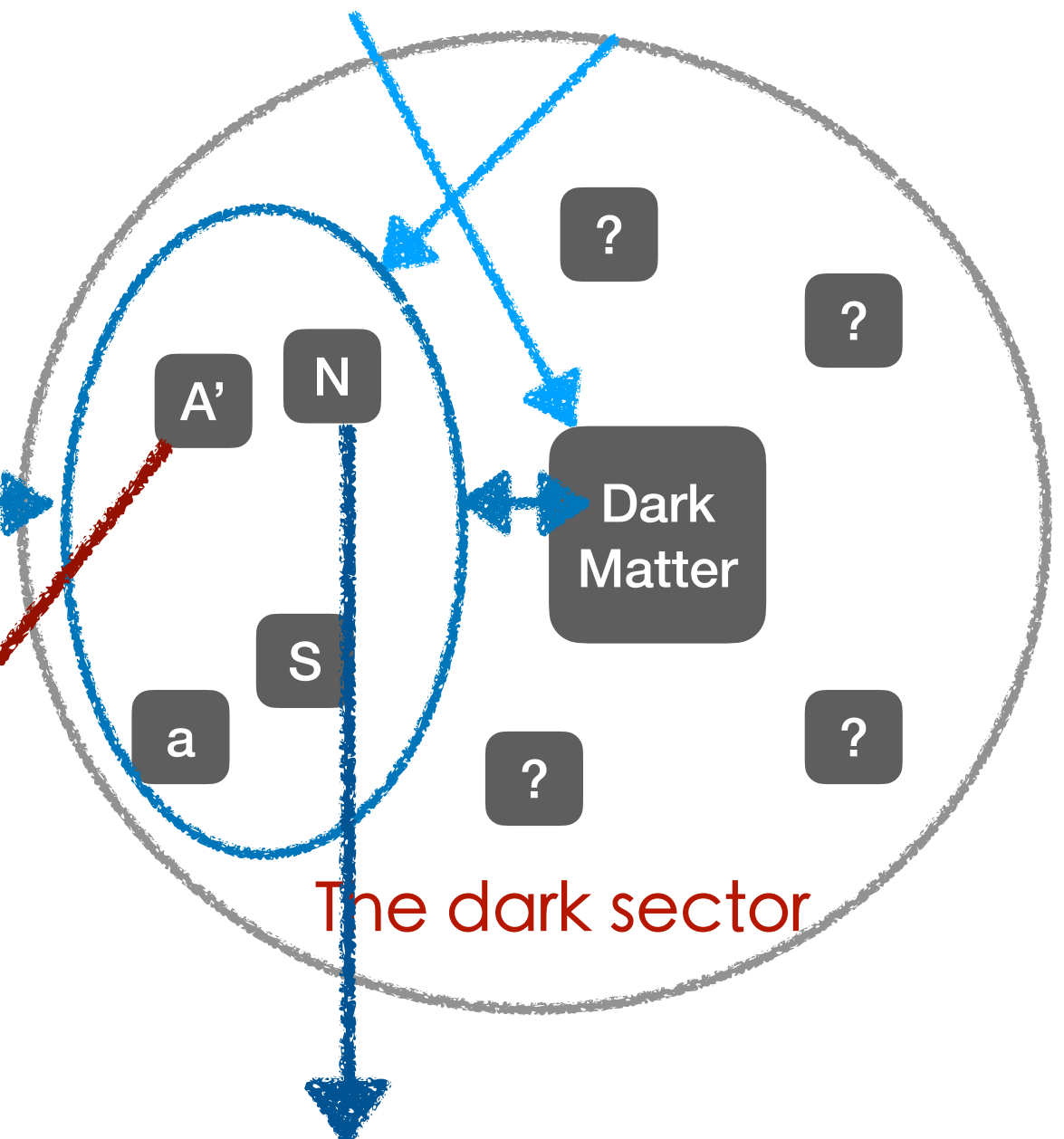
three generations of matter (fermions)			interactions / force carriers (bosons)	
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mass charge spin				
$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	0 0 1	$\approx 125.09 \text{ GeV}/c^2$ 0 0
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e electron	μ muon	τ tau	Z Z boson	
$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$	$< 1.7 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$< 15.5 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1	
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS

LEPTONS

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS



The dark sector

This Talk

Phys.Rev.D 97 (2018) 4, 043001



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'

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

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

$\mathcal{K}$



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

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



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

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

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

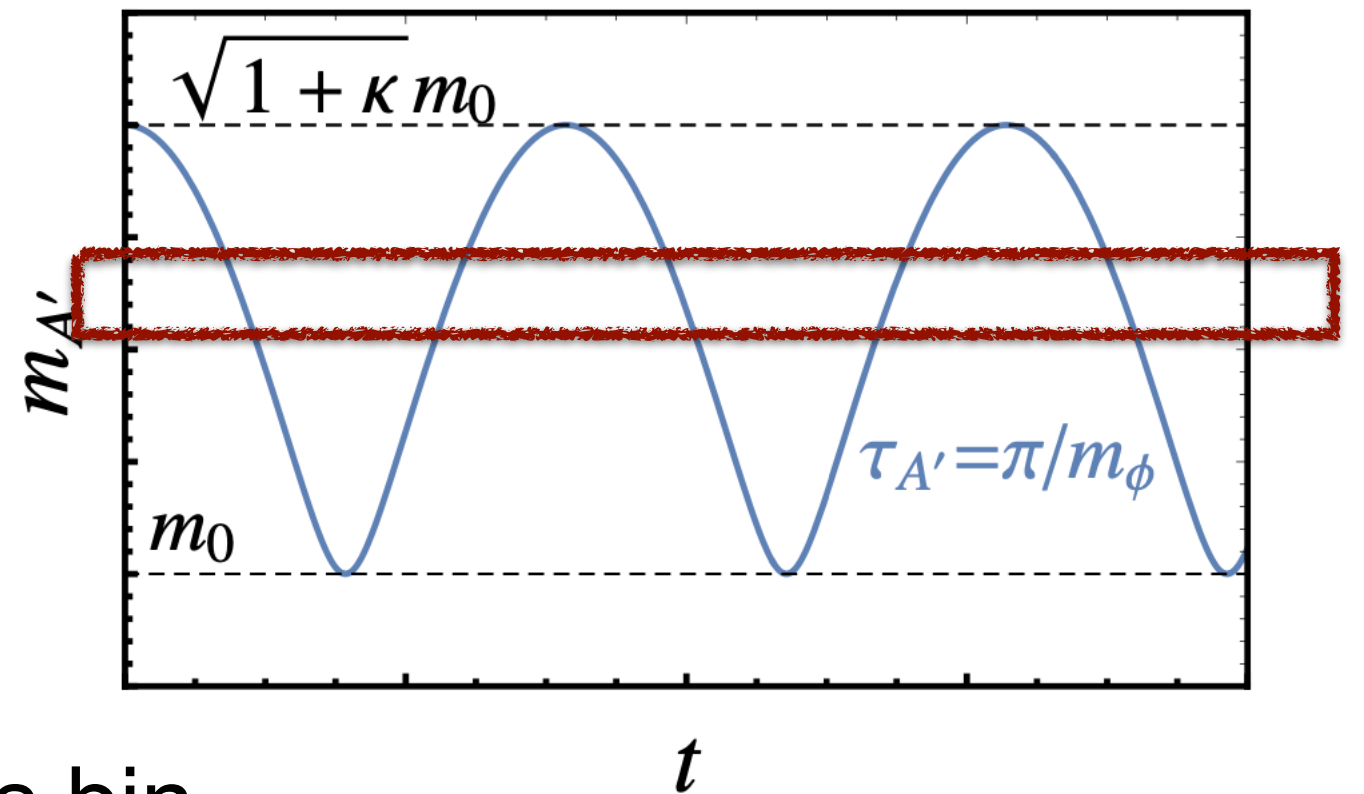


Oscillating A' from wave-like DM

- 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 i th mass bin

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

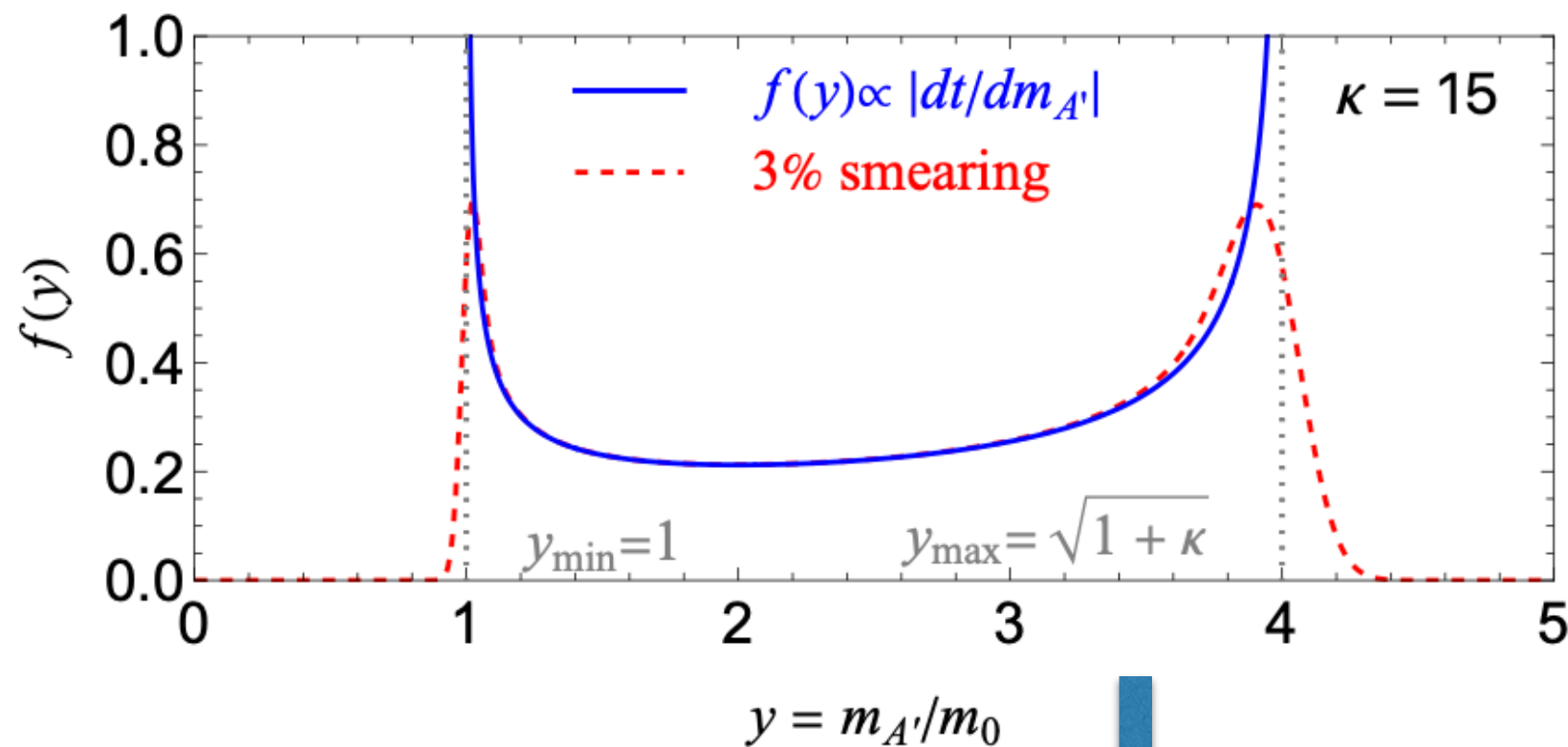
$$\frac{\tau}{m_0} f(y)$$



Oscillating A' from wave-like DM

- Oscillating property

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



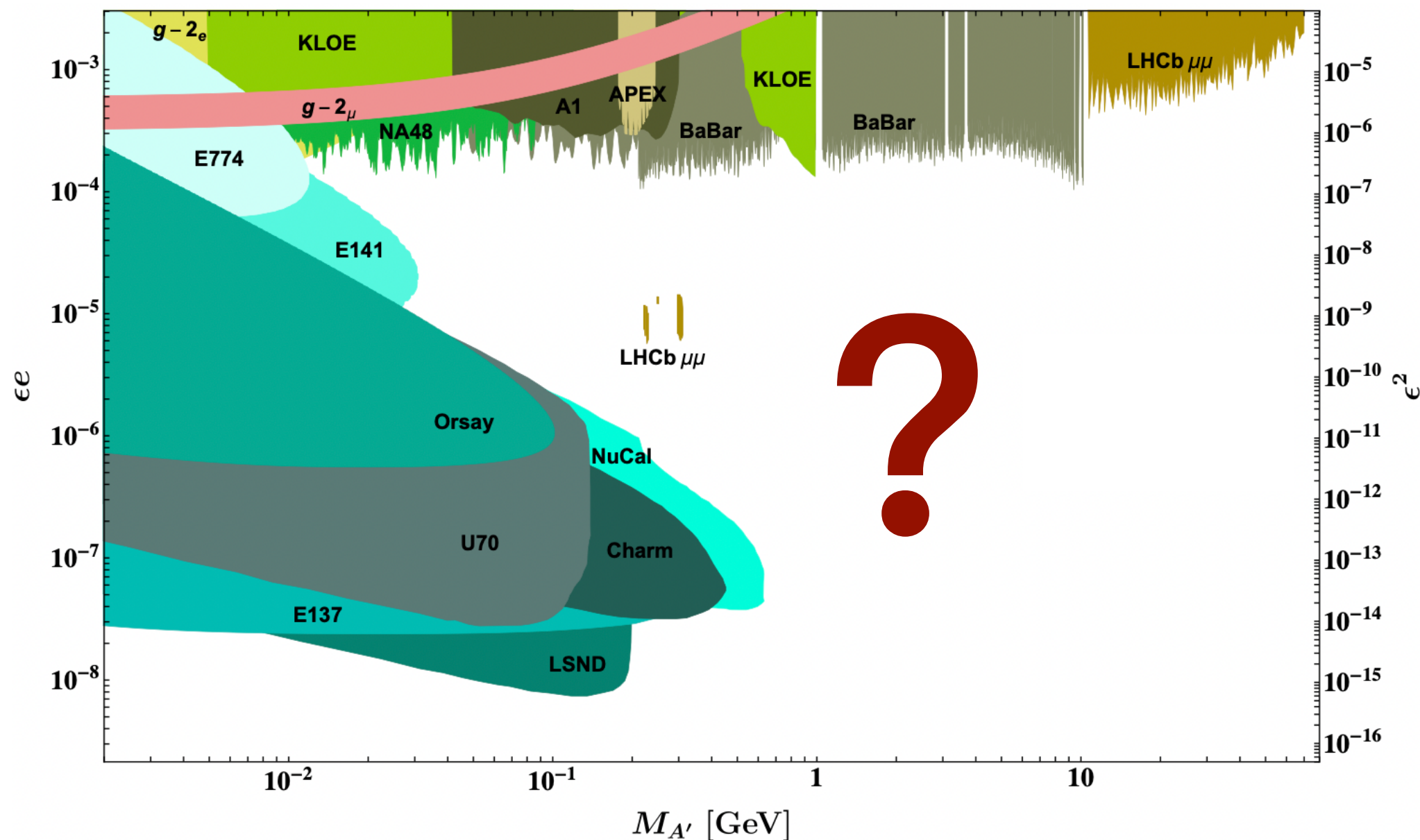
$$\frac{\int_{y_{\max}-\Delta}^{y_{\max}} f(y) dy}{\int_{y_{\min}}^{y_{\min}+\Delta} f(y) dy} \rightarrow \sqrt{\frac{y_{\max}}{y_{\min}}}$$



Oscillating A' effect on experiments?

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

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_0^2 A'_\mu A'^\mu + \epsilon e A'_\mu J_{\text{em}}^\mu$$

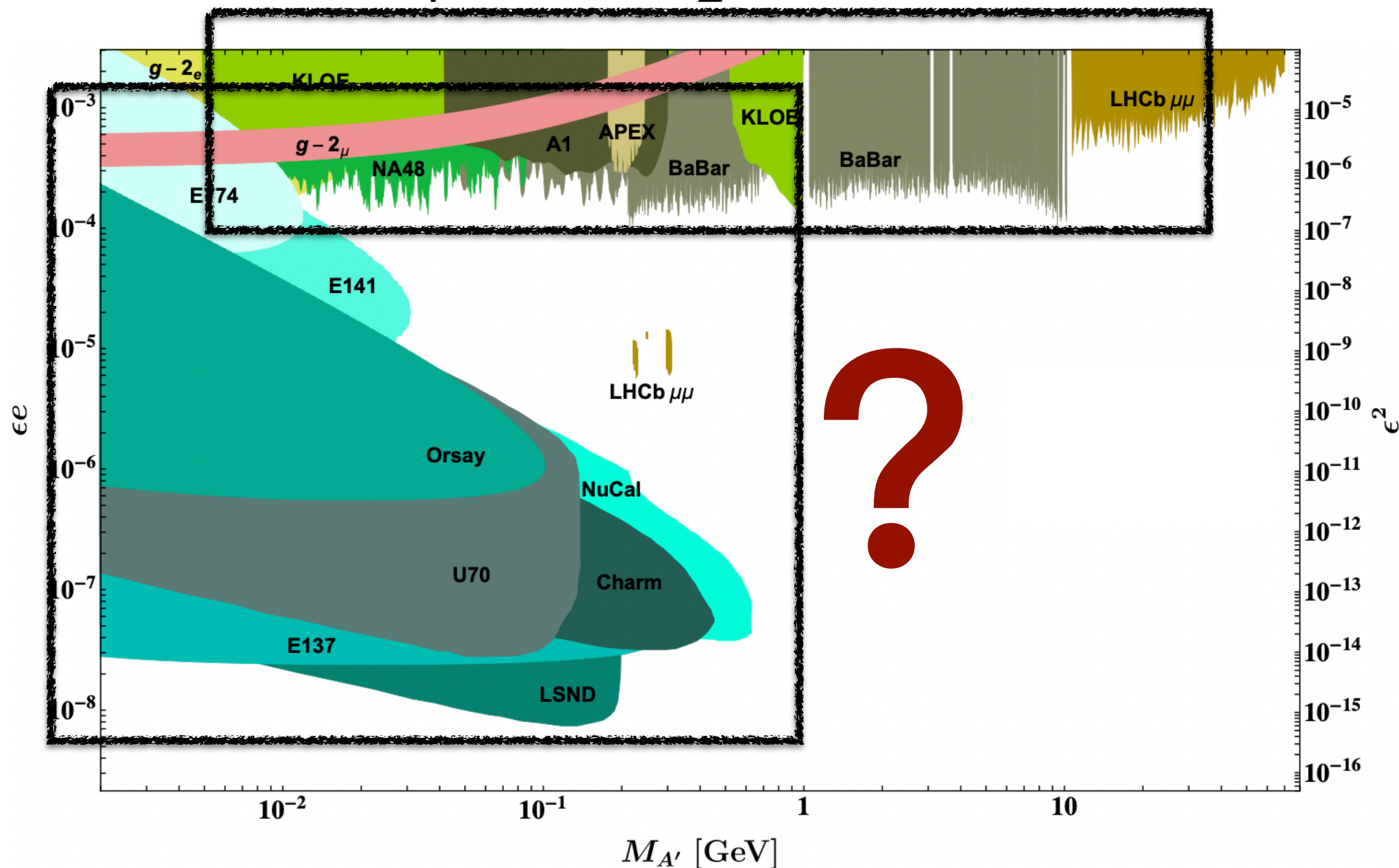




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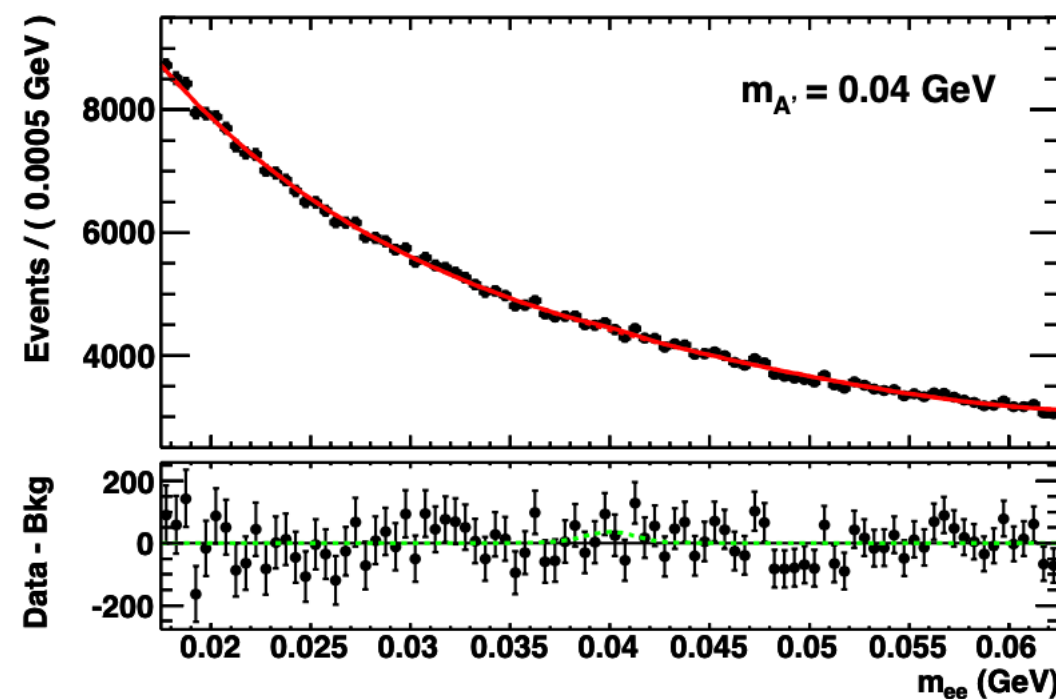
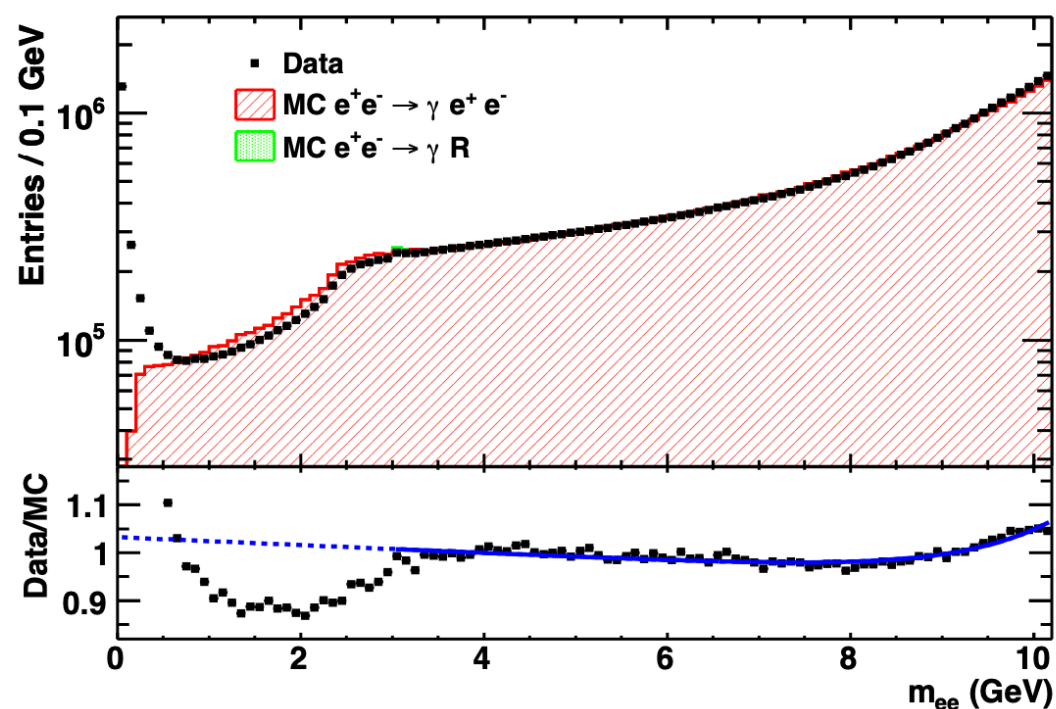
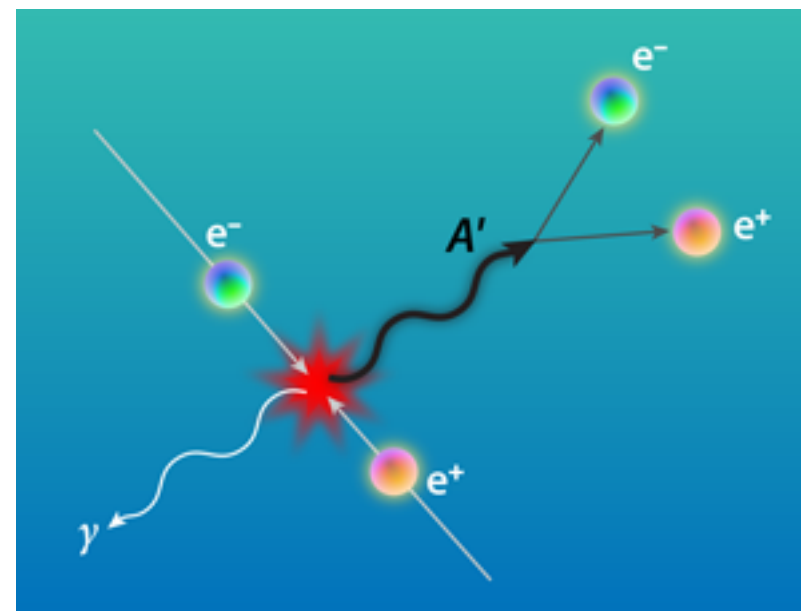


Prompt dilepton final states

- General dilepton process

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

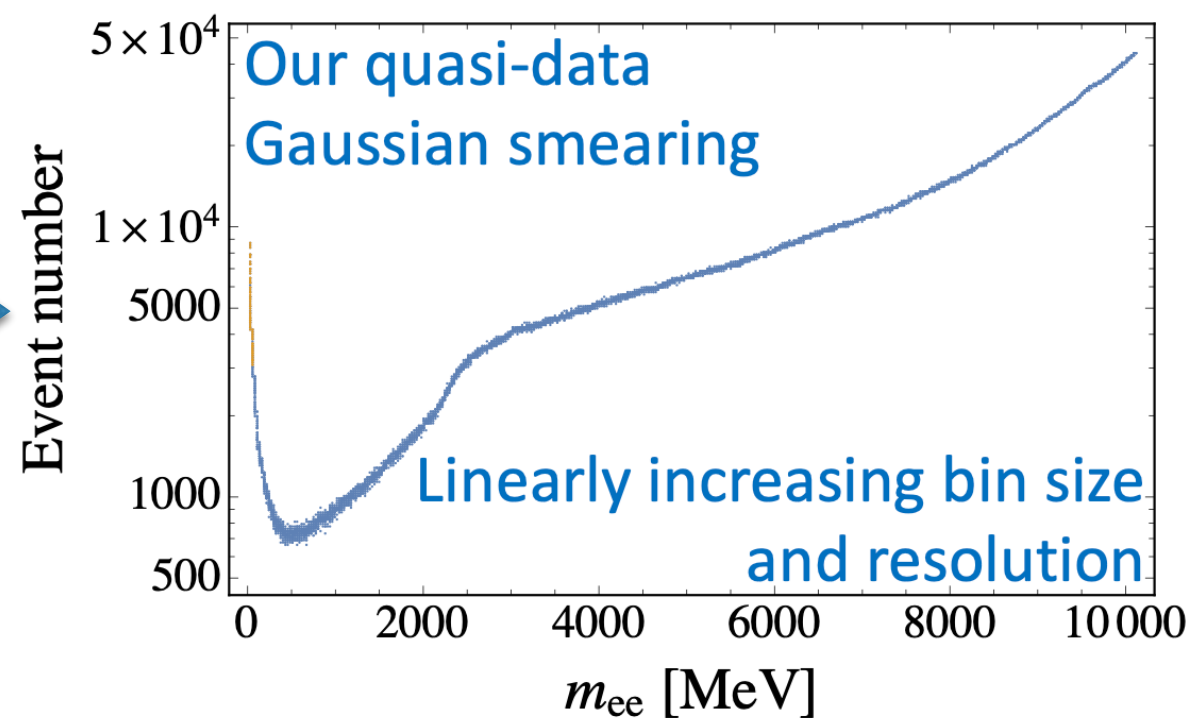
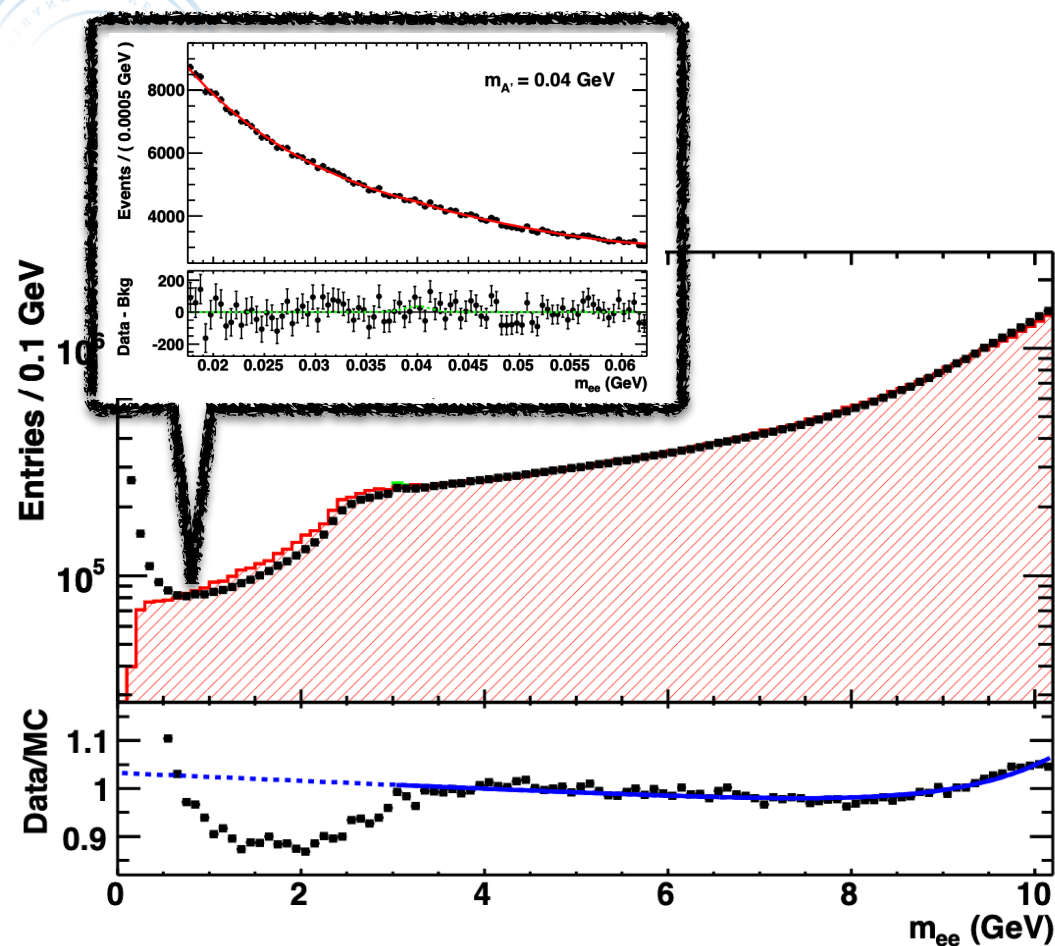
- BaBar data PRL 113, 201801 (2014)





Recast BaBar experiment result

PRL 113, 201801 (2014)



- Log likelihood ratio (LLR)

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



Recast BaBar experiment result

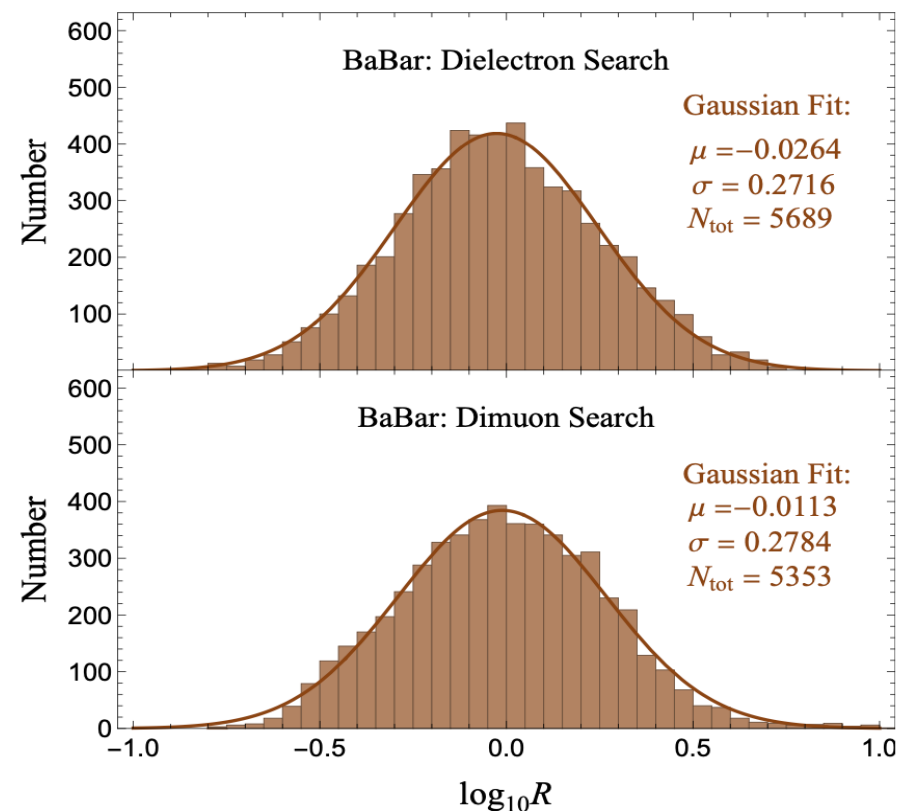
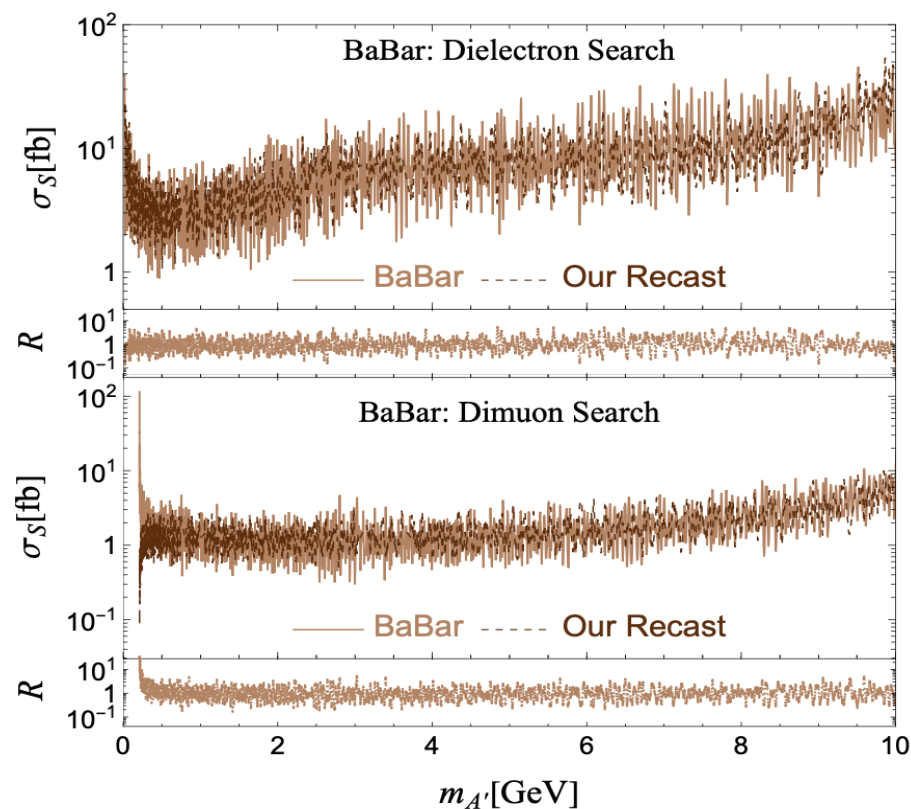
- Traditional single-peak analysis

$$f_G(m_i) = \mathcal{N}(m_{A'} - m_i | \sigma_{\text{re}}^2)$$

- Double-peak analysis

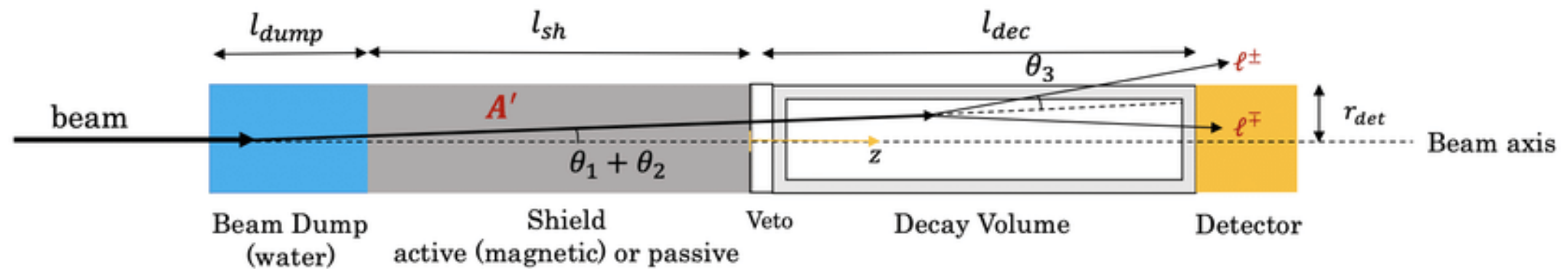
$$f_S(m_i) = \int_{m_{\min}}^{m_{\max}} f\left(\frac{m'}{m_0}\right) \mathcal{N}(m_i - m' | \sigma_{\text{re}}^2) dm'$$

- Recast result:





Beam Dump Experiments



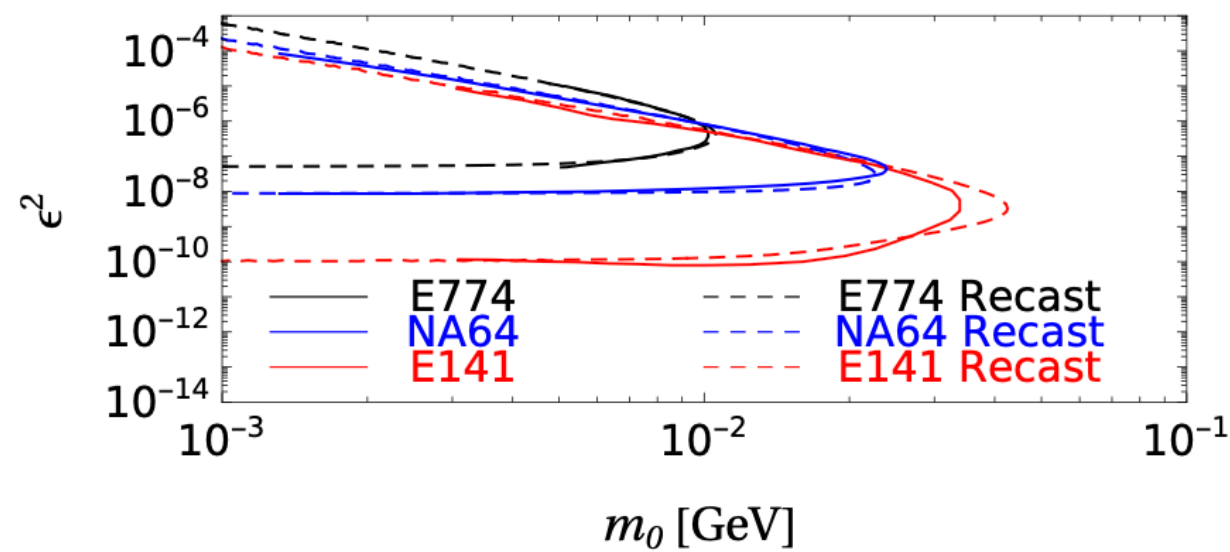
- General event number:

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

- Including oscillation effect

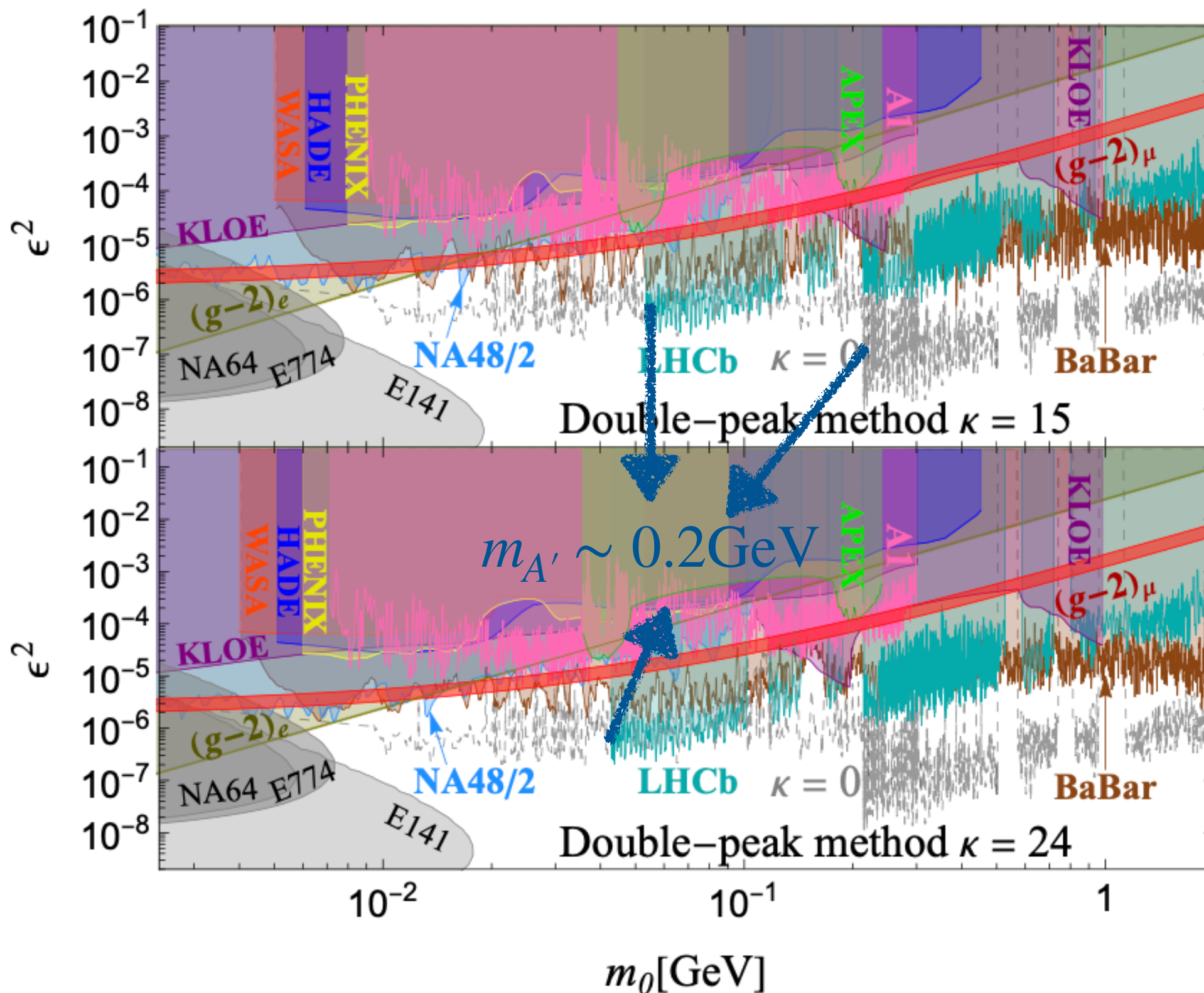
$$N(\epsilon, m_0, \kappa) = \frac{1}{\tau} \int_{m_0}^{\sqrt{1+\kappa} m_0} N(\epsilon, m_{A'}) \left| \frac{dt}{dm_{A'}} \right| dm_{A'}$$

- Our recast result with $\kappa = 0$





Double-peak analysis result

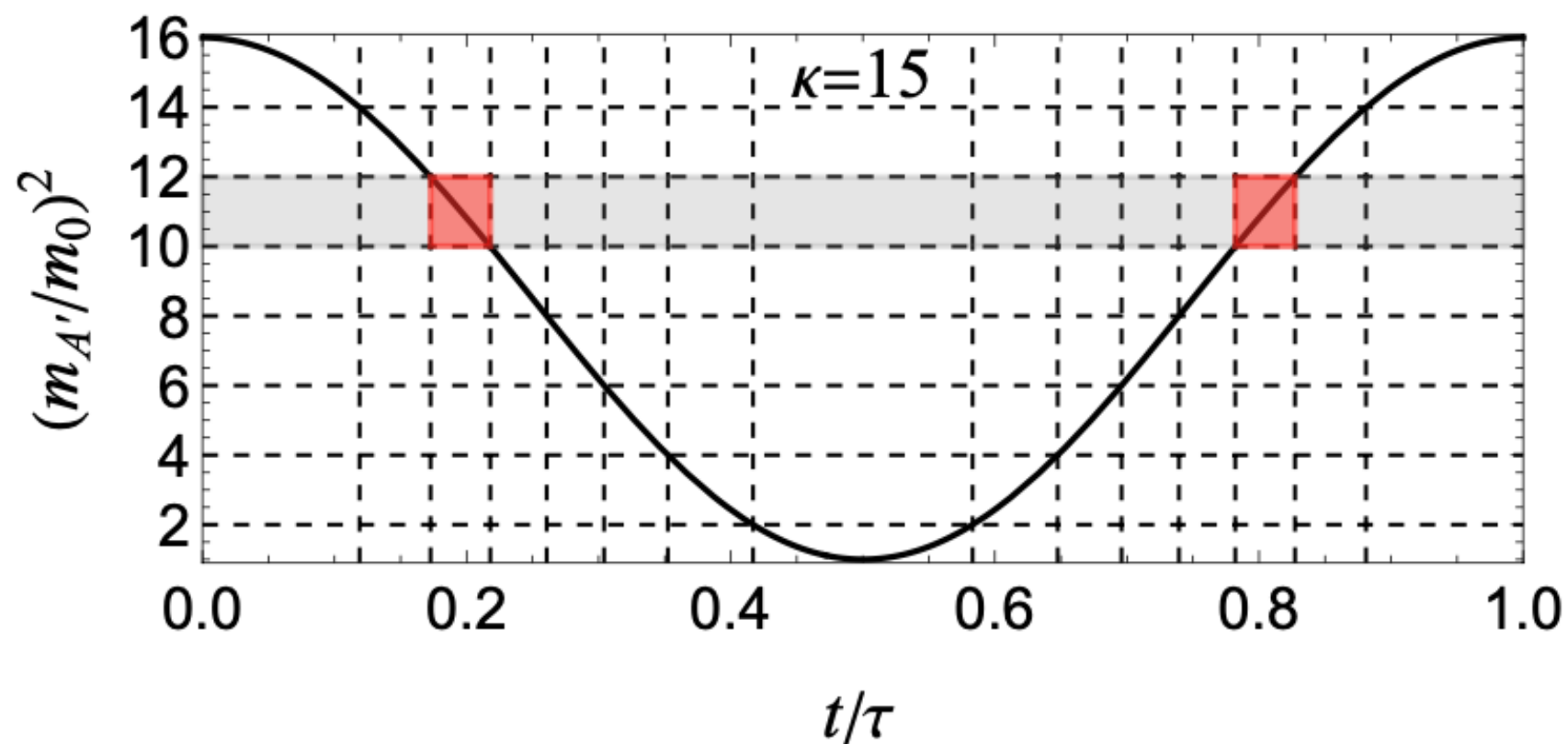




Improvement with time-varying

- Oscillating property

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



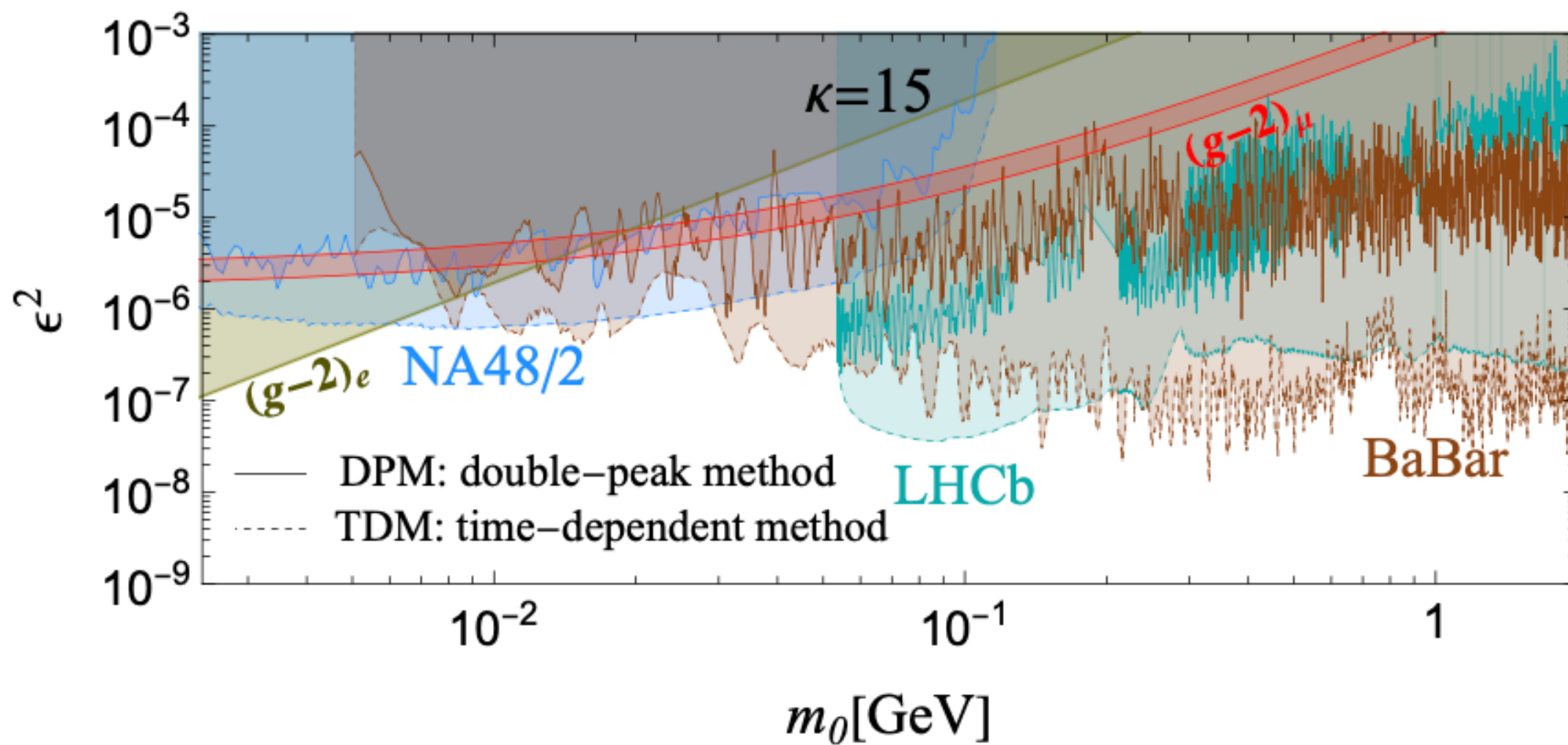
- Background event number

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



Improvement with time-varying

- Result with time-varying



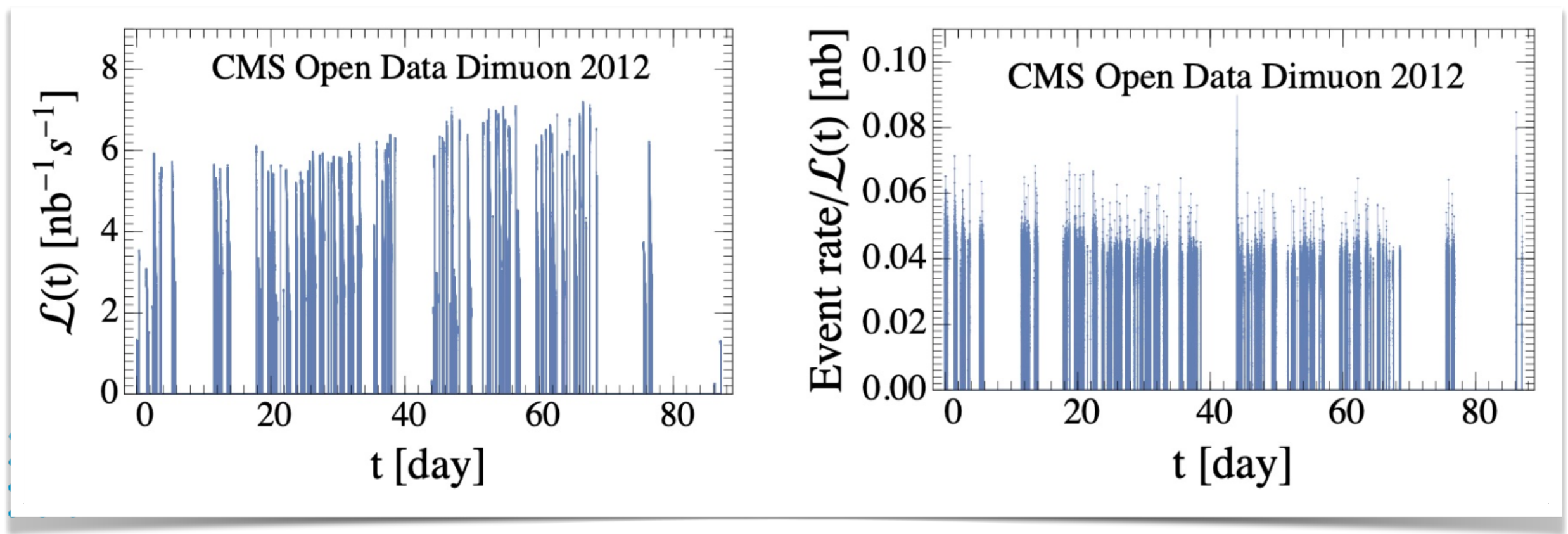


Justify TDM with CMS open data

- CMS open data 2012

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

- Luminosity is not constant





CMS open data

- Oscillating A' property

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

- CMS differential event number

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

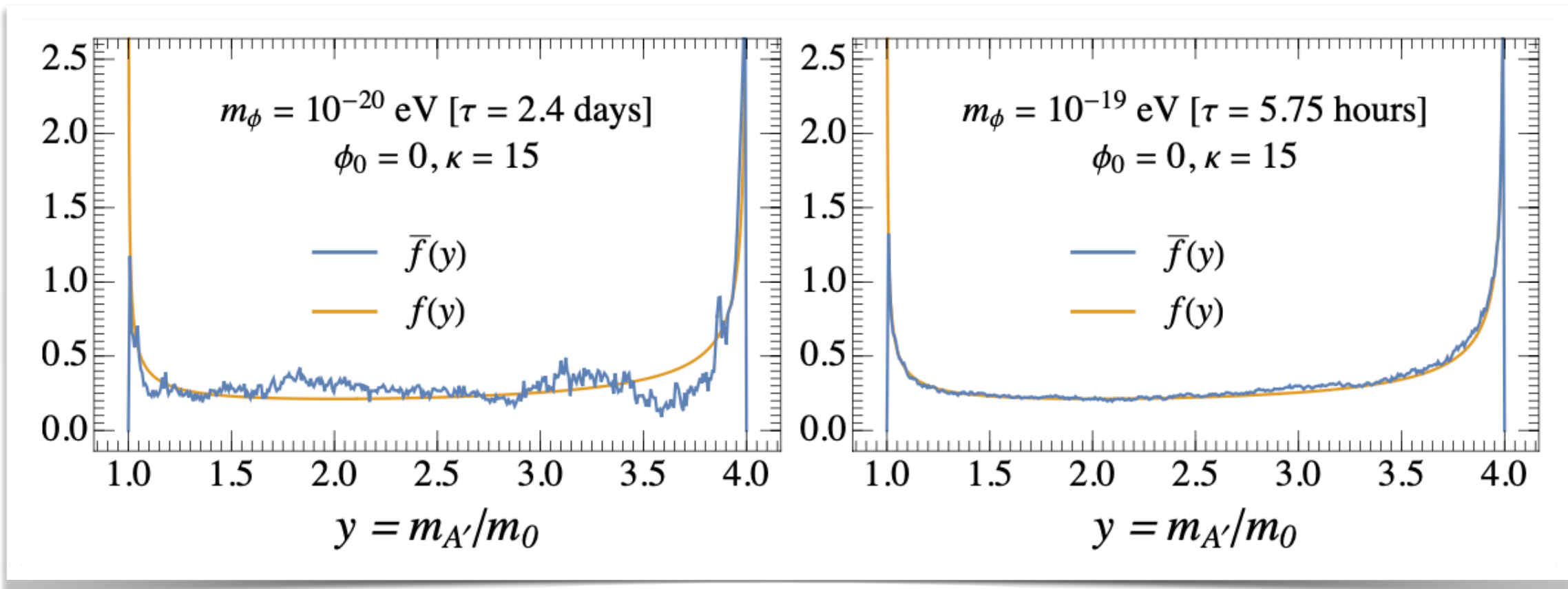
$$\frac{dN_S}{dm_{\ell\ell}} = \int_{t_1}^{t_2} dt \mathcal{L}(t) \frac{d\sigma_S}{dm_{\ell\ell}} = \epsilon_S \sigma_0 \times \frac{2m_{\ell\ell}}{\pi \sqrt{m_{\ell\ell}^2 - m_0^2} \sqrt{(1+\kappa)m_0^2 - m_{\ell\ell}^2}} \frac{\tau_{A'}}{2} \left[\sum_{i^+} \mathcal{L}(t_i^+) + \sum_{i^-} \mathcal{L}(t_i^-)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

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



CMS open data

- Double-peak property



We can use DPM for CMS open data!



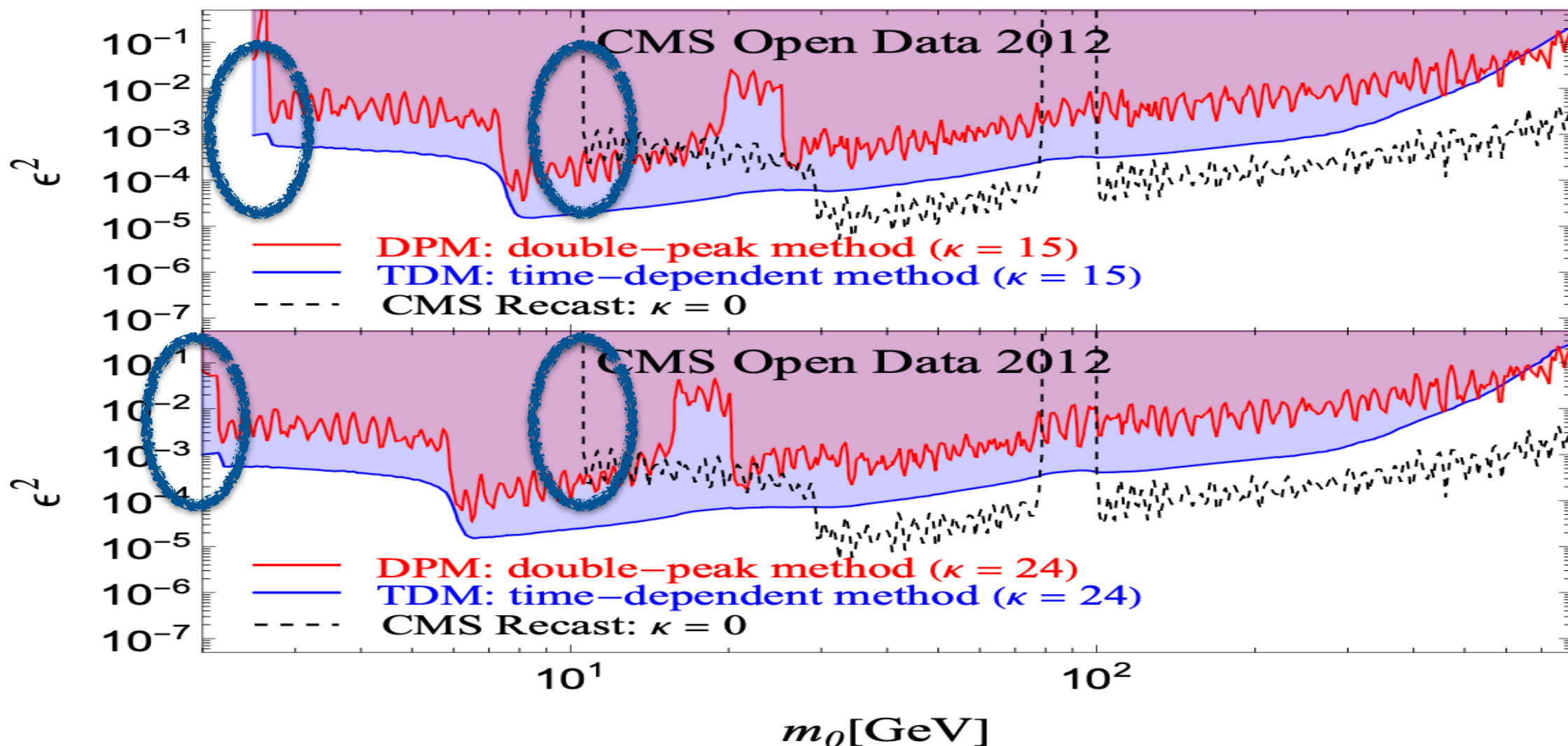
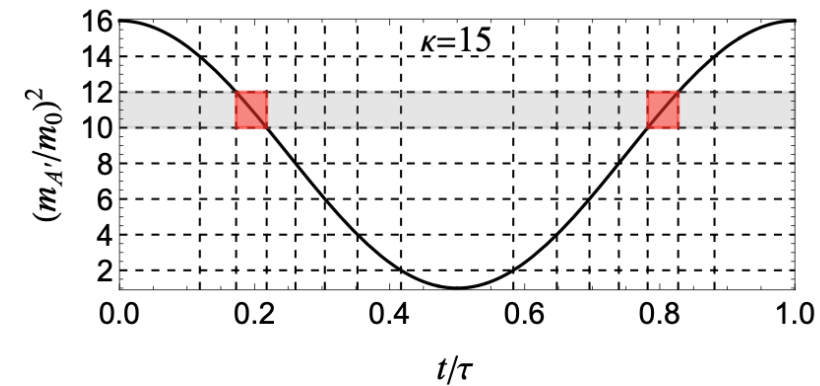
CMS result with time information

- Double-peak Method

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

- Time-dependent Method

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





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!