

Light Dark World 2022 will bring together global experts from experiment and theory to discuss recent advances and develop new opportunities to study new light particles beyond the Standard Model, including light gauge boson, light scalar, light dark matter, axion, light sterile neutrinos, and dark energy fields.

#### Invited Speakers

Asimina Arvanitaki (Perimeter)  
Michael Baker (Melbourne)  
Amit Bhoonah (Pittsburgh)  
Koun Choi (IBS CUP)  
Christina Gao (Fermilab)  
Rohini Godbole (IIS)  
Sungwoo Hong (KAIST)  
Hyung Do Kim (SNU)  
Yeongduk Kim (IBS CUP)  
Shigeki Matsumoto (Kavli IPMU)  
Kazunori Nakayama (Tohoku)  
Seodong Shin (JBNU)  
Xiaoping Wang (Beihang)  
Neal Weiner (NYU)  
Jonghee Yoo (SNU)

#### Organizing Committee

Brian Batell (Pittsburgh)  
Kazuki Enomoto (KAIST)  
Akshay Ghalsasi (Pittsburgh)  
Samuel Lane (KAIST)  
Hye-Sung Lee (KAIST)

<https://indico.cern.ch/e/LDW2022>

# Time-varying resonant mass @ collider and beam dump experiments



**Xiao-Ping Wang (王小平)**

Dec, 14 @ LDW2022



Base On: arXiv:2206.14221

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



# Dark Matter Evidence

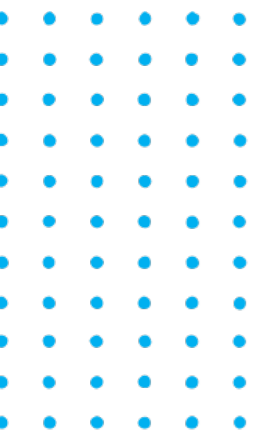
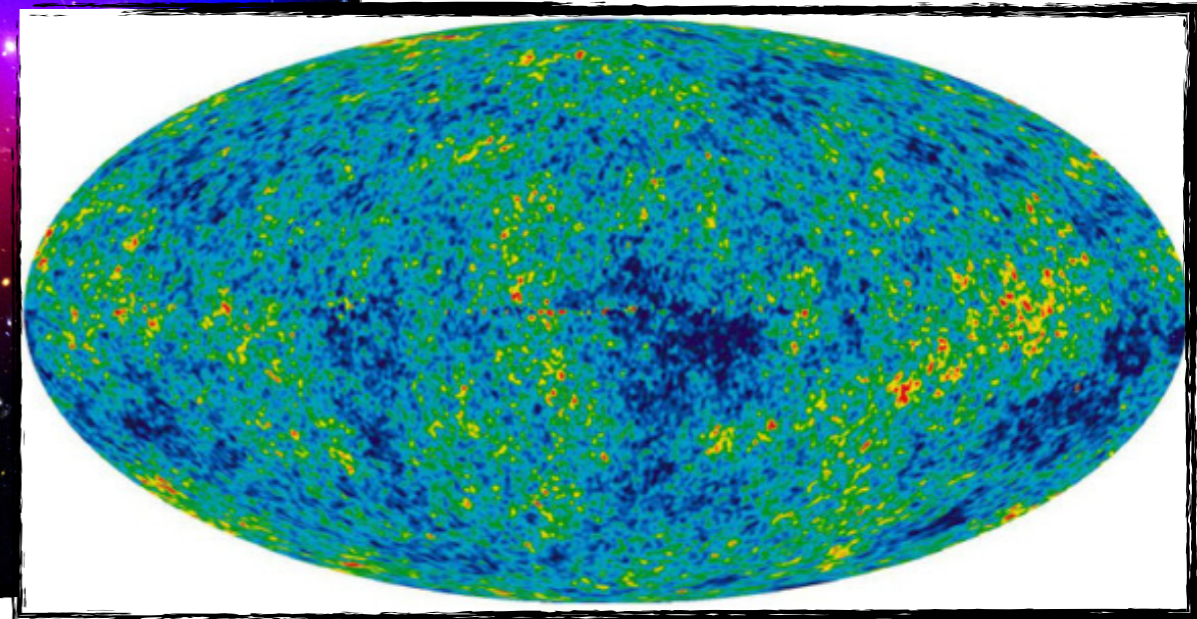
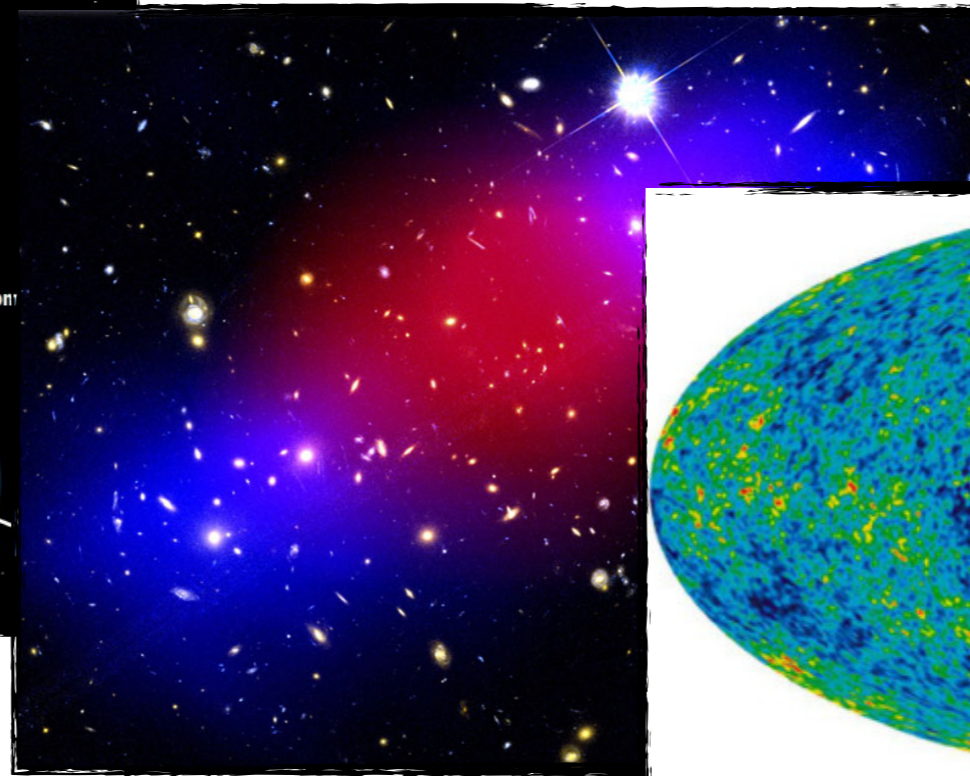
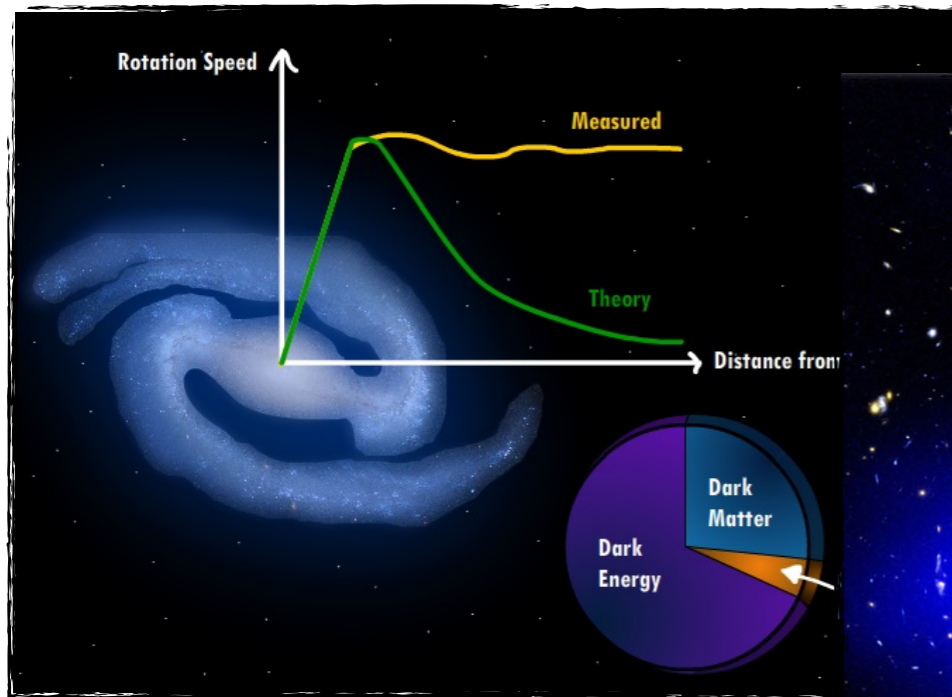


- Evidence from different scale

Galaxy

Cluster

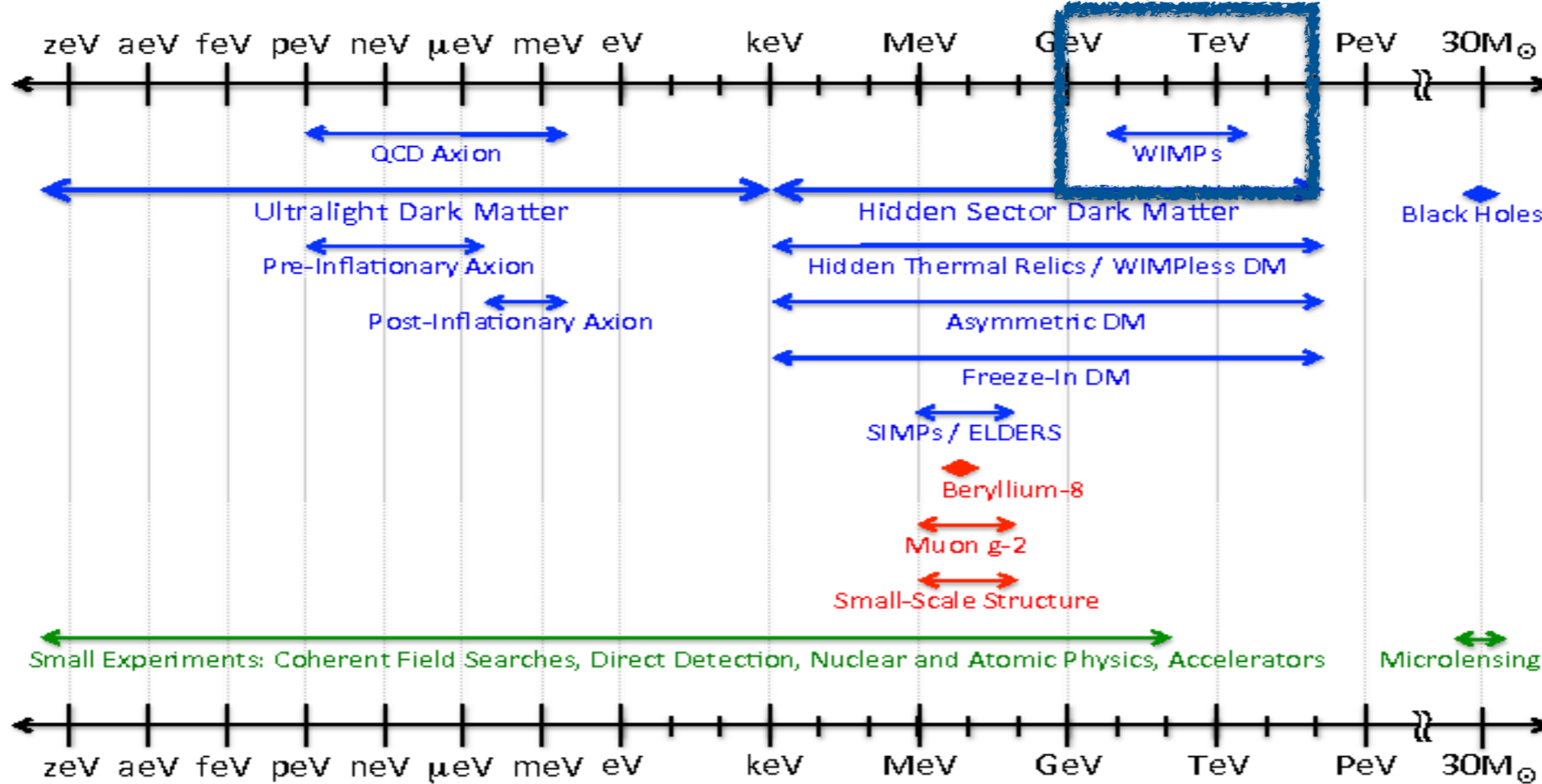
Universe





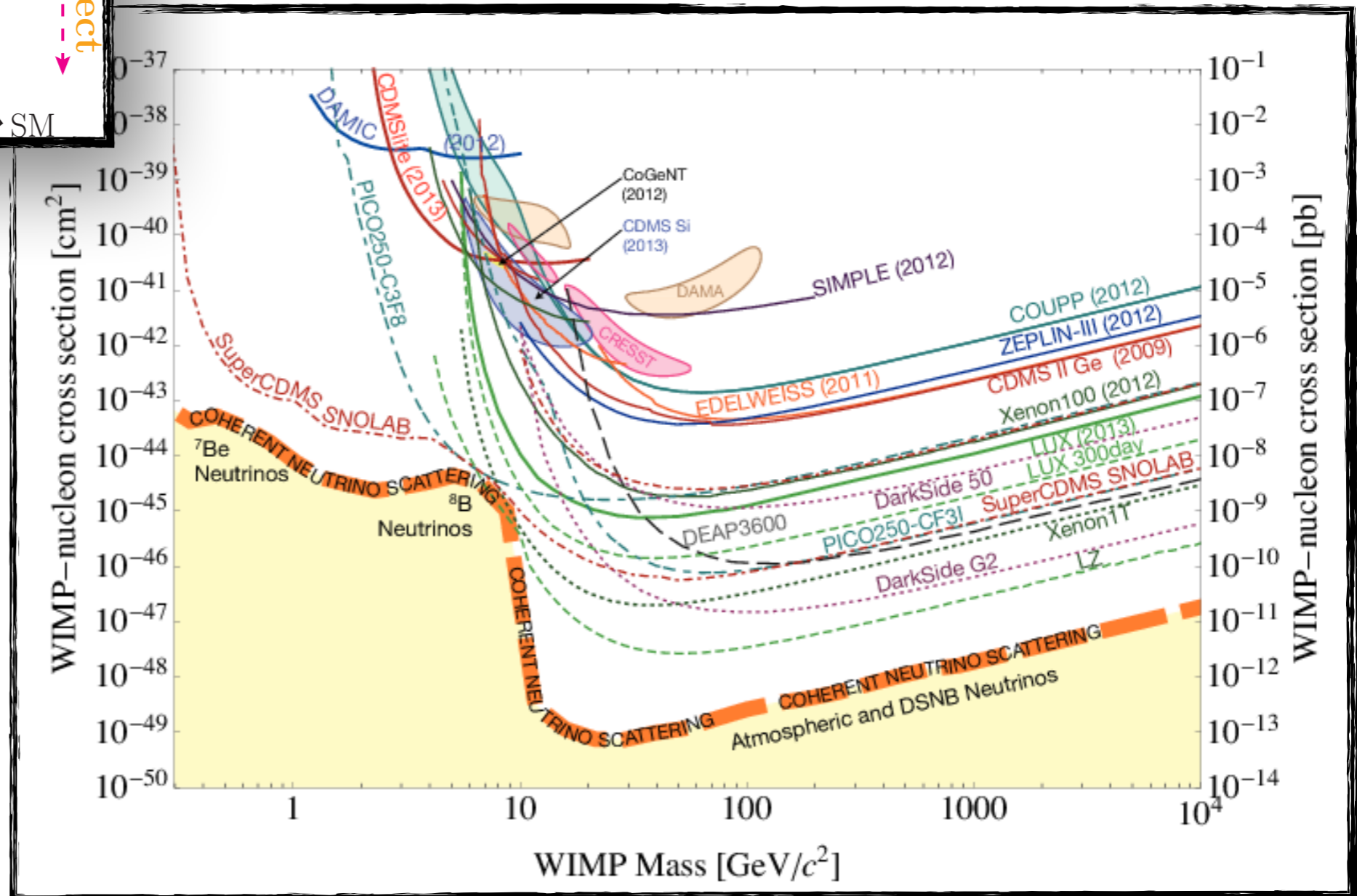
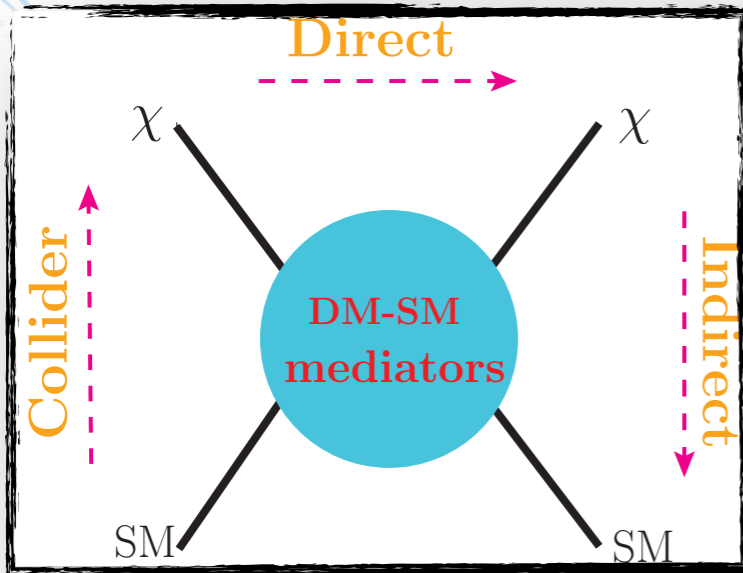
# Dark matter mass range

## Dark Sector Candidates, Anomalies, and Search Techniques





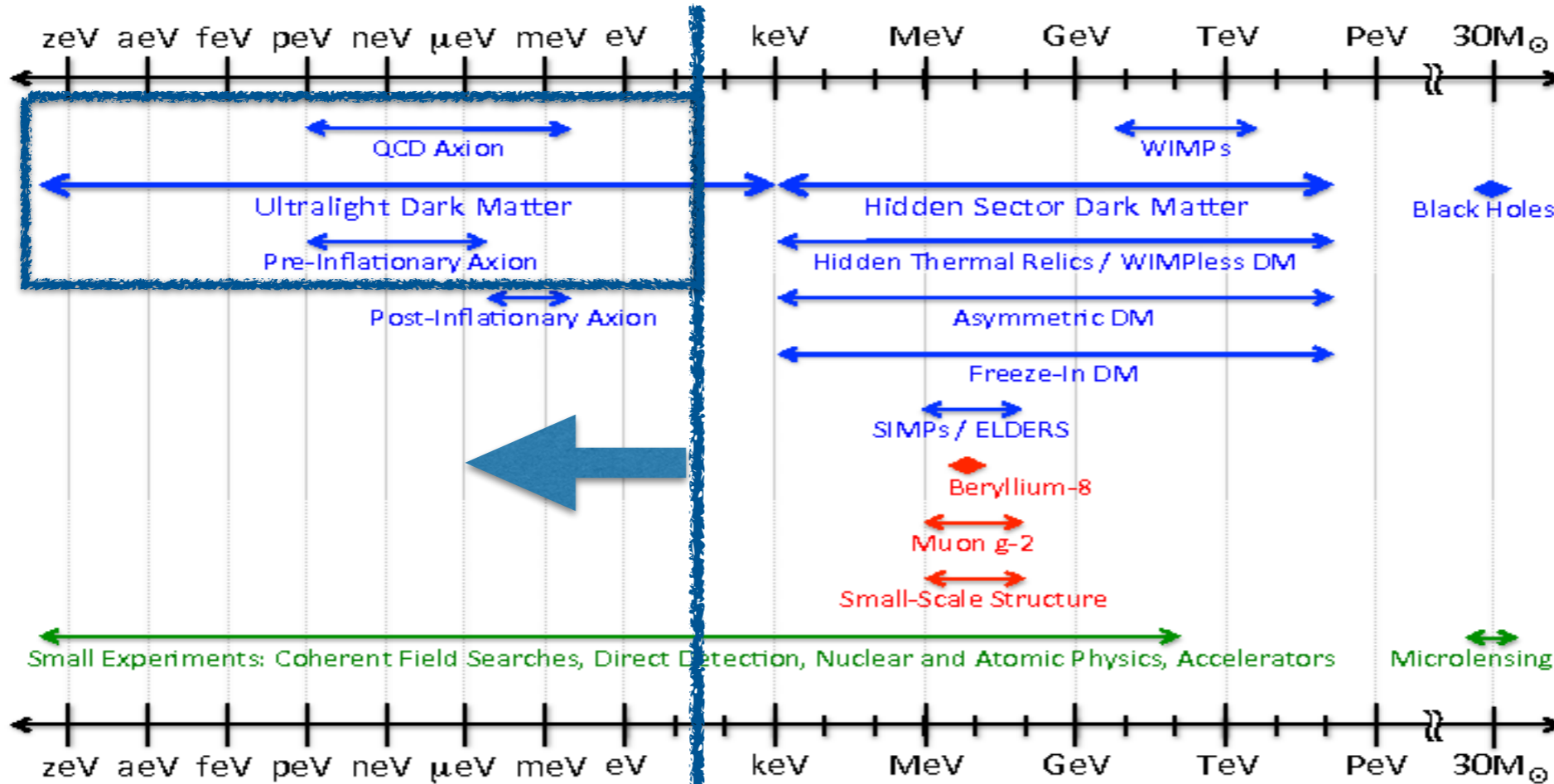
# WIMP search status





# Dark matter mass range

## Dark Sector Candidates, Anomalies, and Search Techniques



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



# 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 ( $\sim 100-1000$ )

- Too big to fail problem

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



# Ultra light dark matter production

- Misalignment mechanism

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

- Classical Solution for wave-like dark matter

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

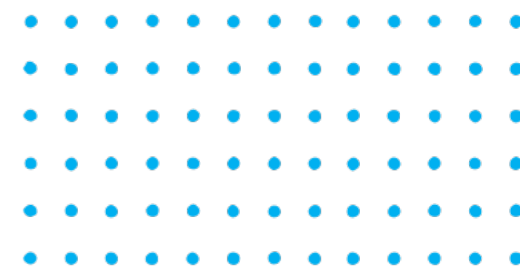
- Dark matter local density

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

**How to search for ultra light DM?**



# Dark matter-SM mediator

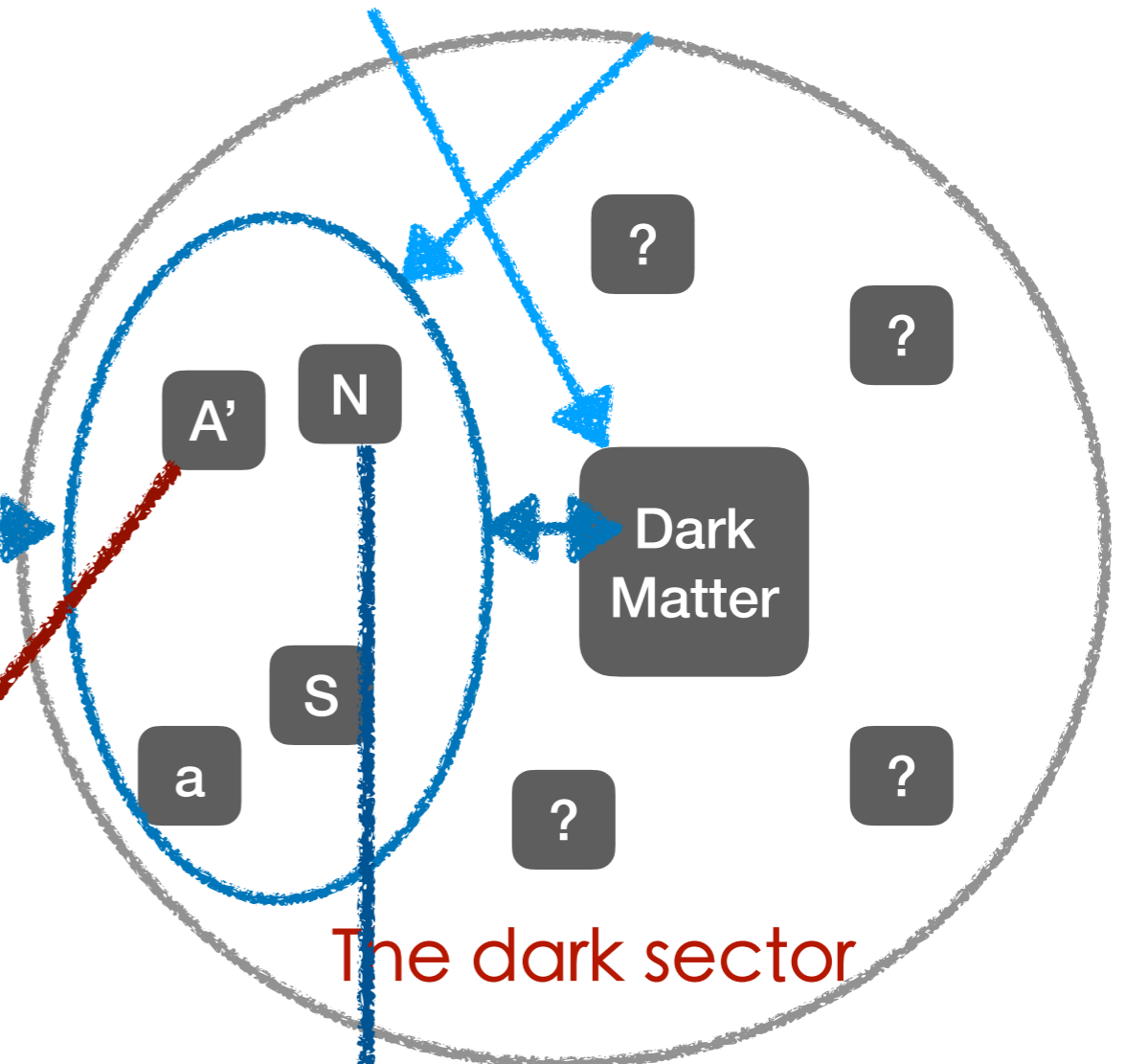


- Standard Model = fermions + force

- Dark Sector = DM + dark mediator

## Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ <b>u</b> up	mass $\approx 1.28 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ <b>c</b> charm	mass $\approx 173.1 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ <b>t</b> top	0 0 1 <b>g</b> gluon	mass $\approx 125.09 \text{ GeV}/c^2$ 0 0 <b>H</b> higgs
<b>QUARKS</b> mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ <b>d</b> down	mass $\approx 96 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ <b>s</b> strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ <b>b</b> bottom	0 0 1 <b><math>\gamma</math></b> photon	<b>SCALAR BOSONS</b>
mass $\approx 0.511 \text{ MeV}/c^2$ charge $-1$ spin $\frac{1}{2}$ <b>e</b> electron	mass $\approx 105.66 \text{ MeV}/c^2$ charge $-1$ spin $\frac{1}{2}$ <b><math>\mu</math></b> muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge $-1$ spin $\frac{1}{2}$ <b><math>\tau</math></b> tau	0 1 <b>Z</b> Z boson	
<b>LEPTONS</b> mass $< 2.2 \text{ eV}/c^2$ charge 0 spin $\frac{1}{2}$ <b><math>\nu_e</math></b> electron neutrino	mass $< 1.7 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ <b><math>\nu_\mu</math></b> muon neutrino	mass $< 15.5 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ <b><math>\nu_\tau</math></b> tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ charge $\pm 1$ spin 1 <b>W</b> W boson	



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  $A'$

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

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



$\mathcal{K}$



# 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

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



$$\tilde{m}_0 = m_0, \quad \kappa \equiv \frac{2 \left(g'Q_\phi\right)^2 \rho_{\text{DM}}}{m_\phi^2 m_0^2}$$

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

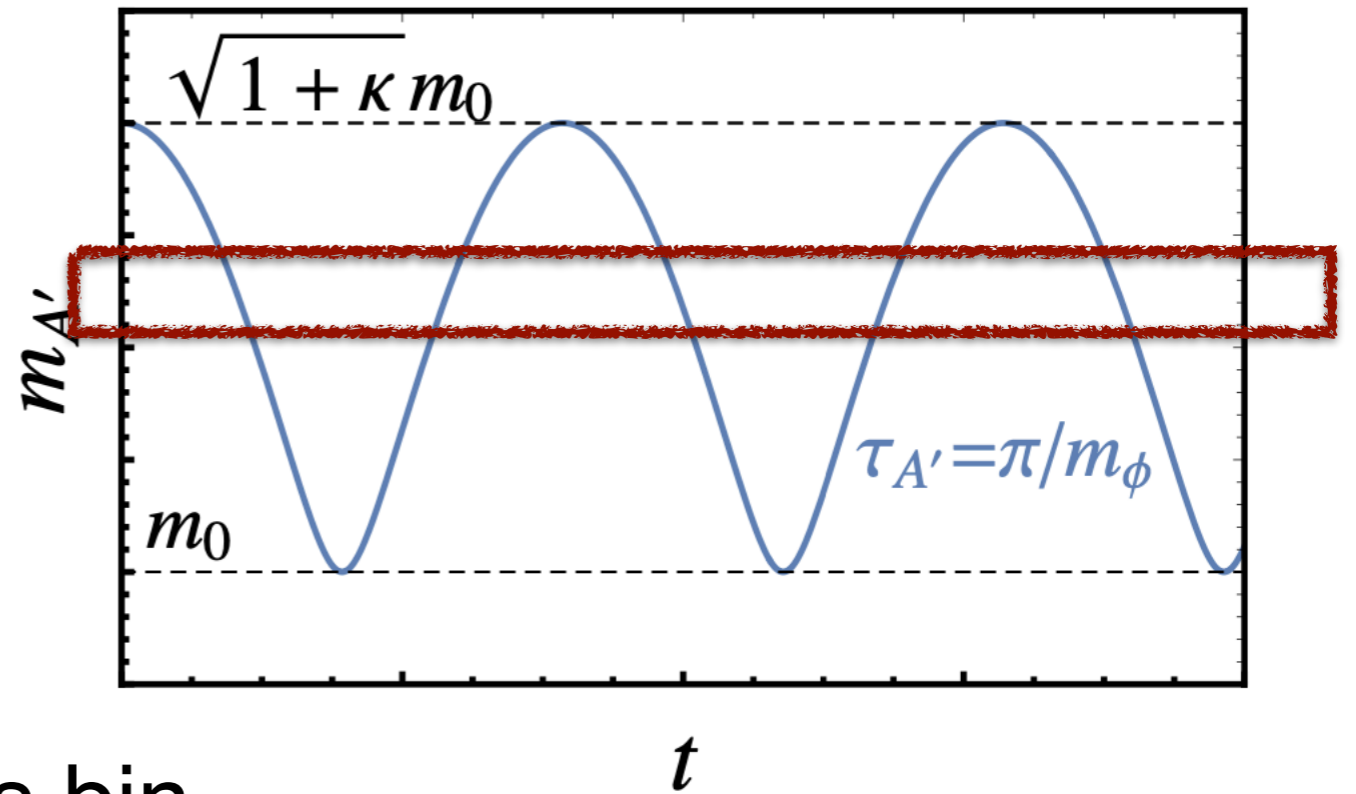


# Oscillating $A'$ from wave-like DM

- Oscillating property

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

$$= m_{A'}^2(t + \tau)$$



- Event number in the  $i$ th mass bin

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

↓

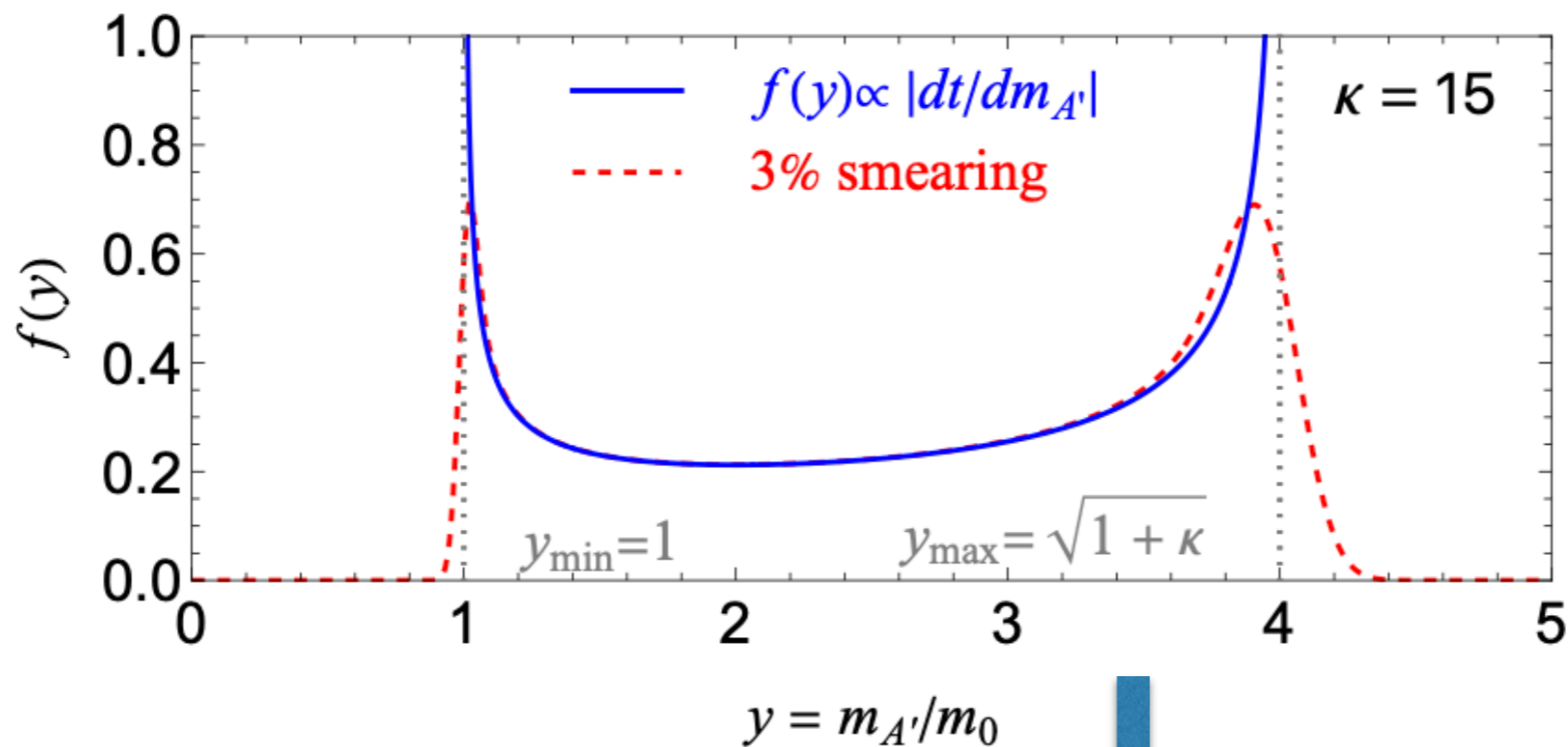
$$\frac{\tau}{m_0} f(y)$$



# Oscillating $A'$ from wave-like DM

- Oscillating property

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



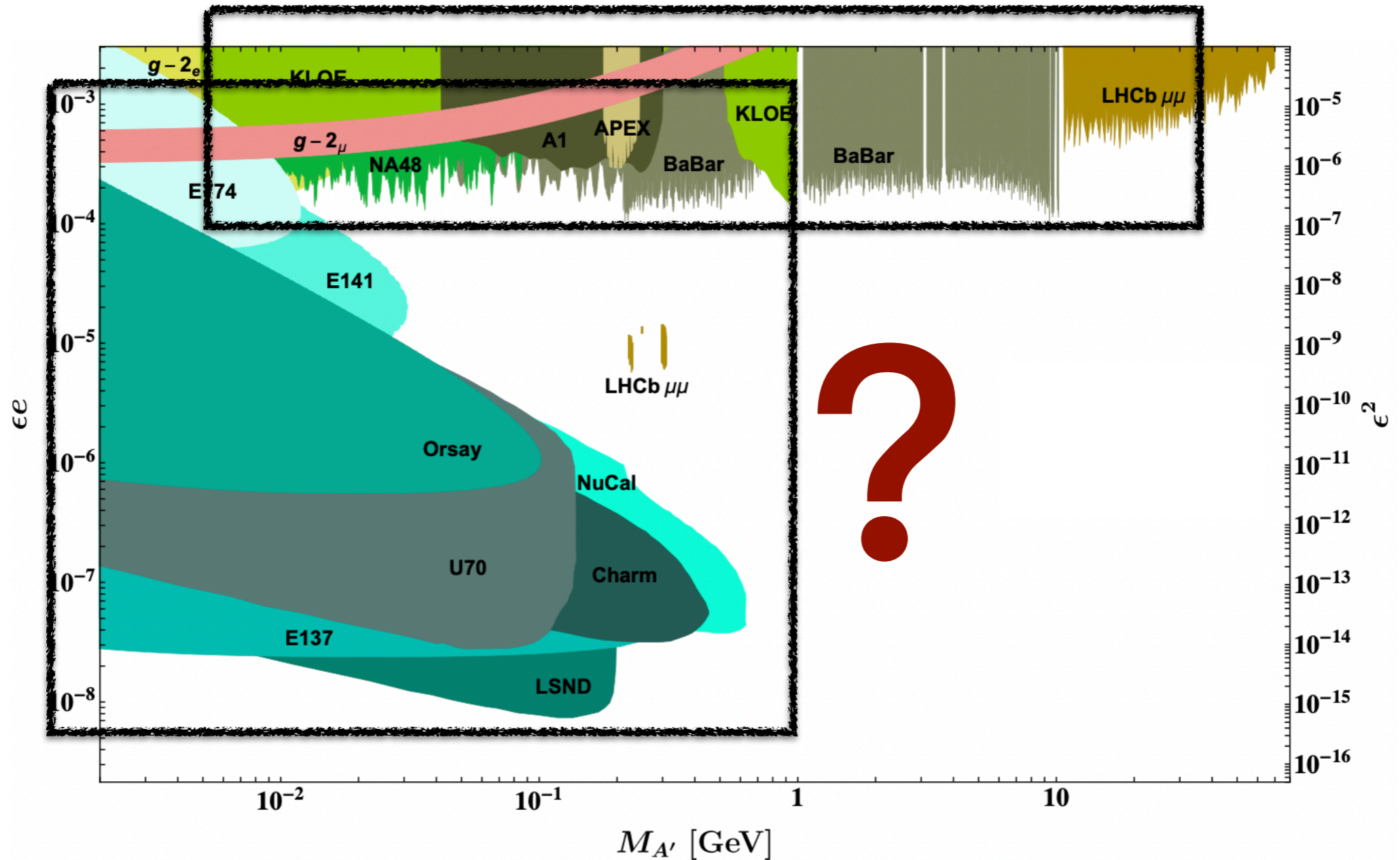
$$\frac{\int_{y_{\max} - \Delta}^{y_{\max}} f(y) dy}{\int_{y_{\min}}^{y_{\min} + \Delta} f(y) dy} \rightarrow \sqrt{\frac{y_{\max}}{y_{\min}}}$$



# Oscillating $A'$ effect on experiments?

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

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



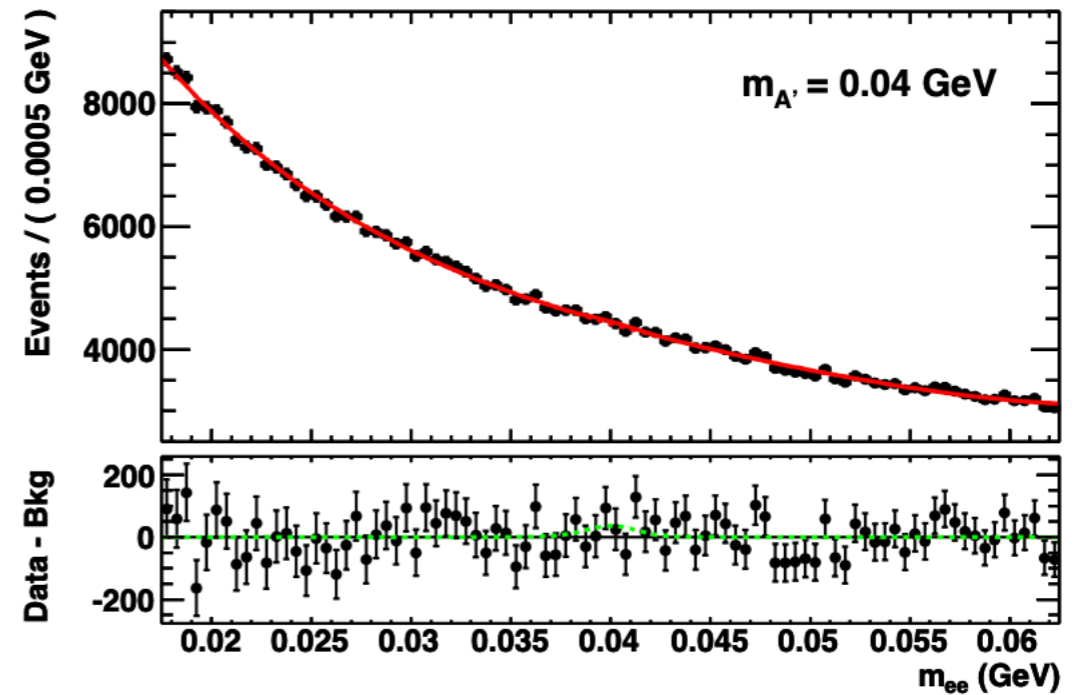
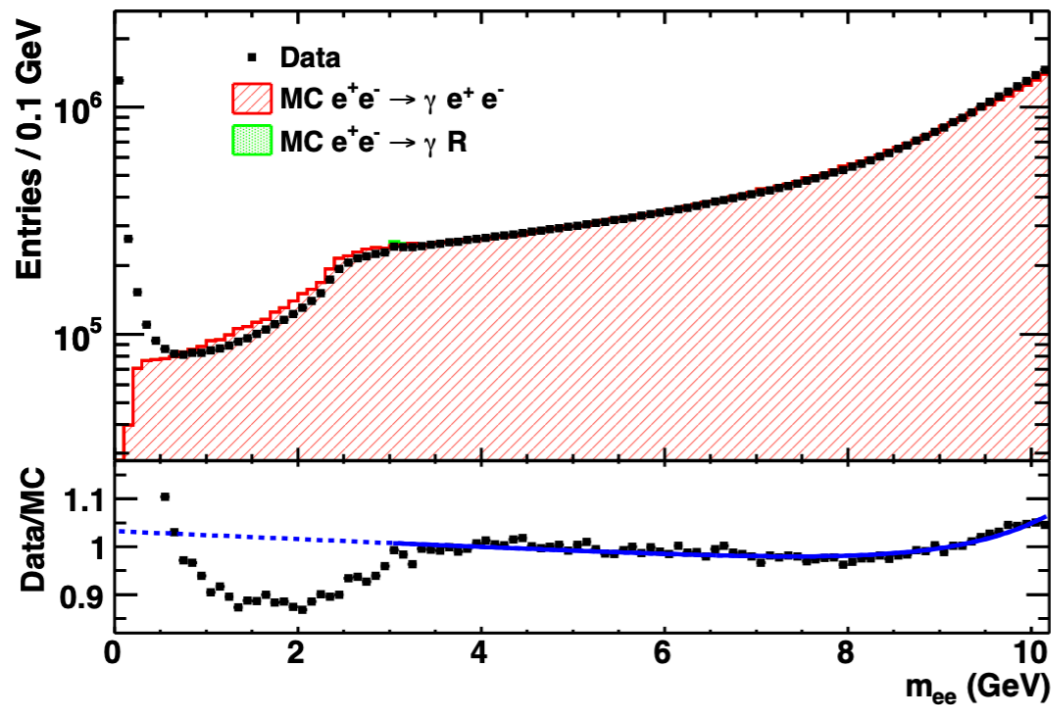
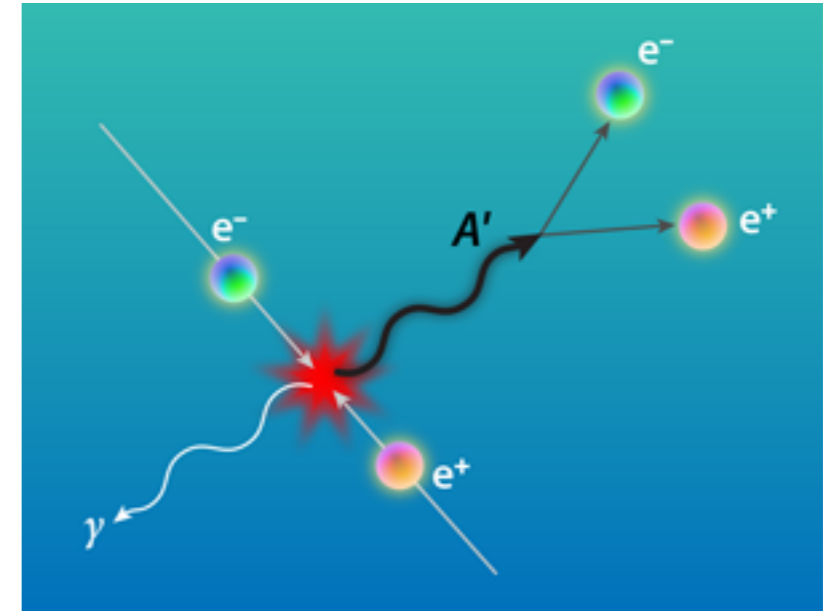


# Prompt dilepton final states

- General dilepton process

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

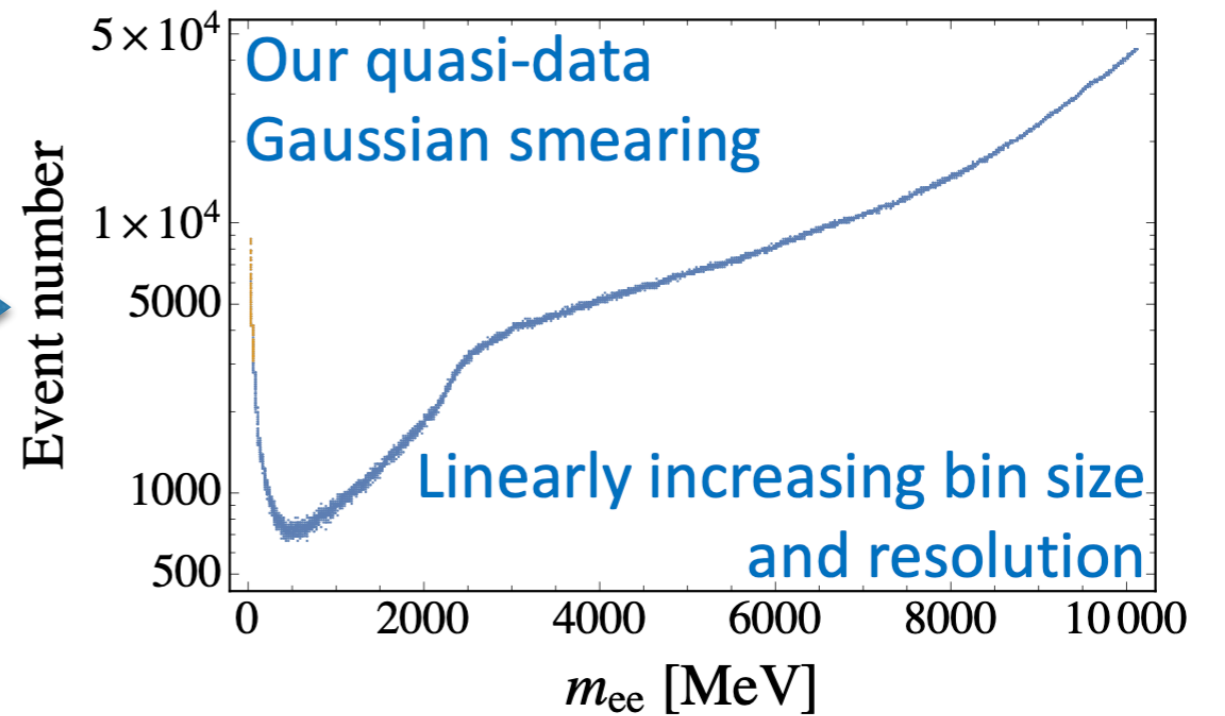
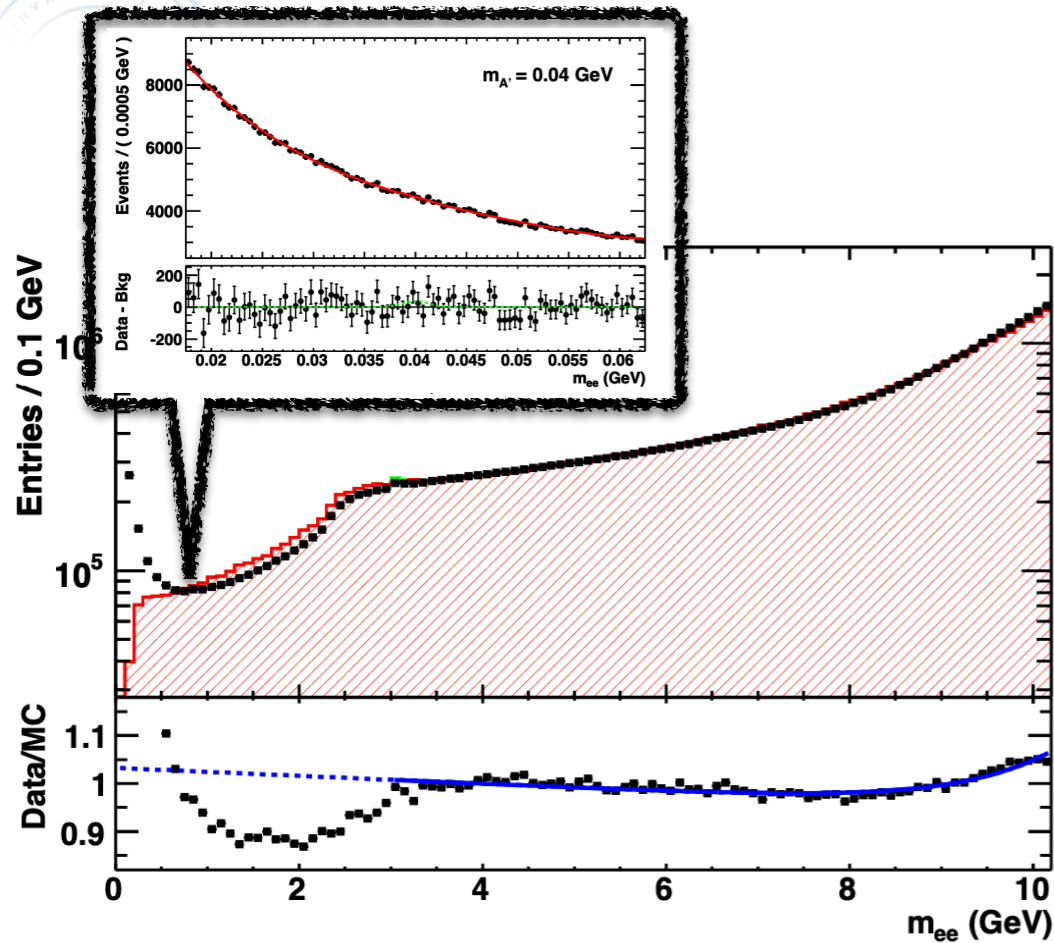
- BaBar data PRL 113, 201801 (2014)





# Recast BaBar experiment result

PRL 113, 201801 (2014)



- Log likelihood ratio (LLR)

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



# Recast BaBar experiment result

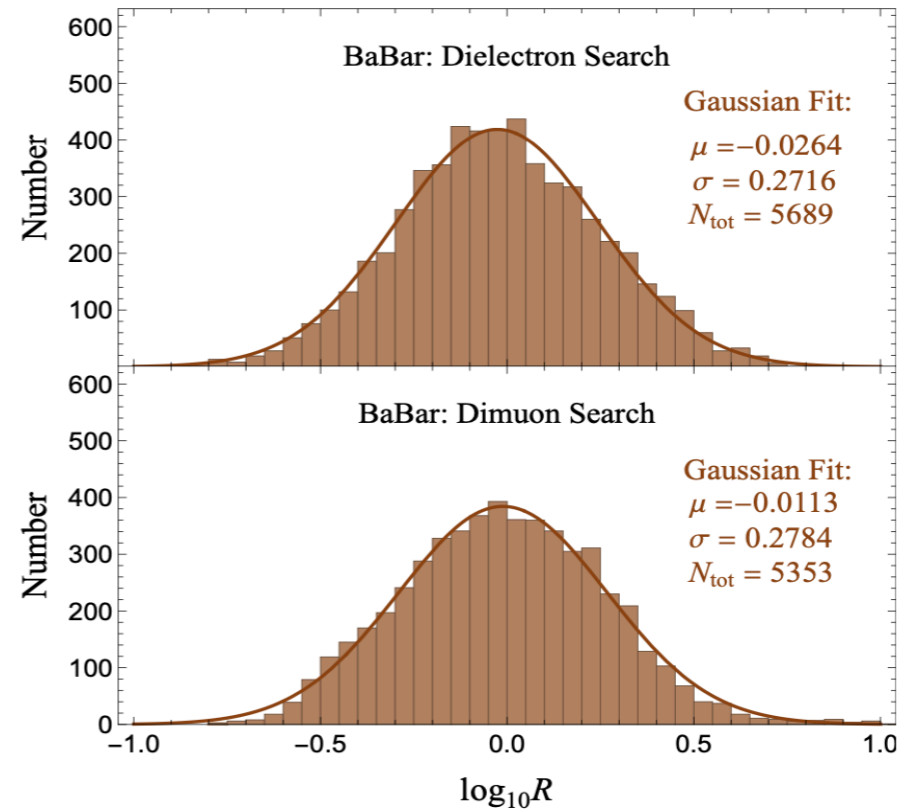
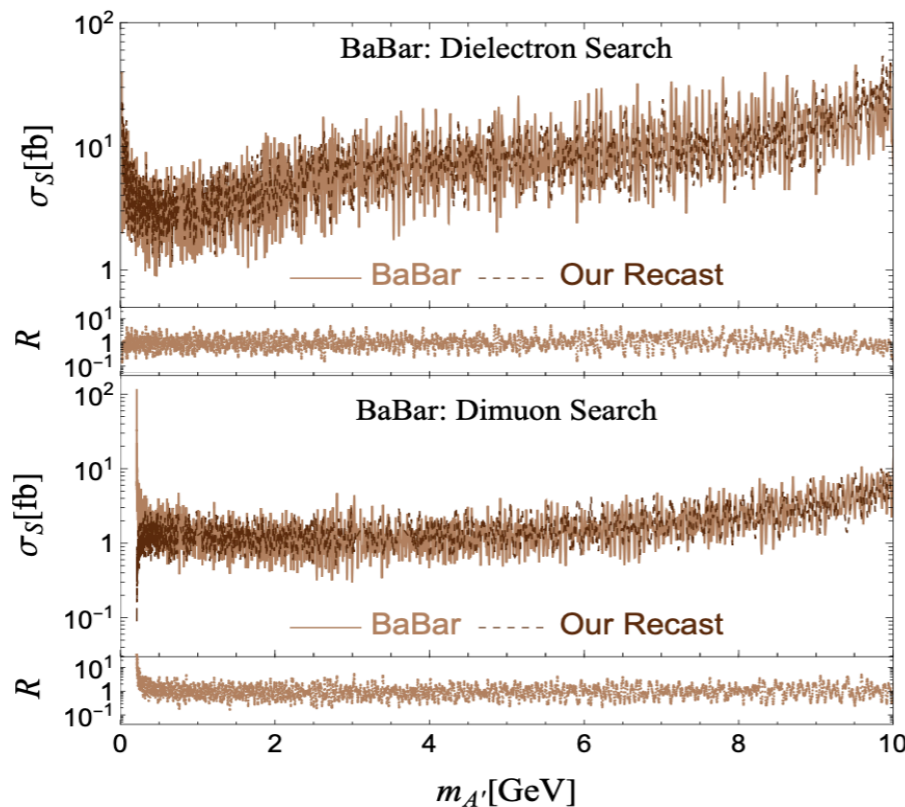
- Traditional single-peak analysis

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

- Double-peak analysis

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

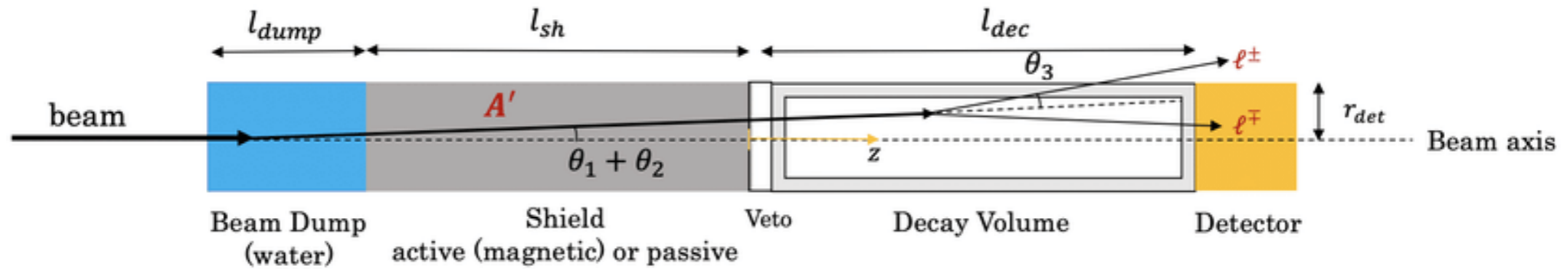
- Recast result:







# Beam Dump Experiments



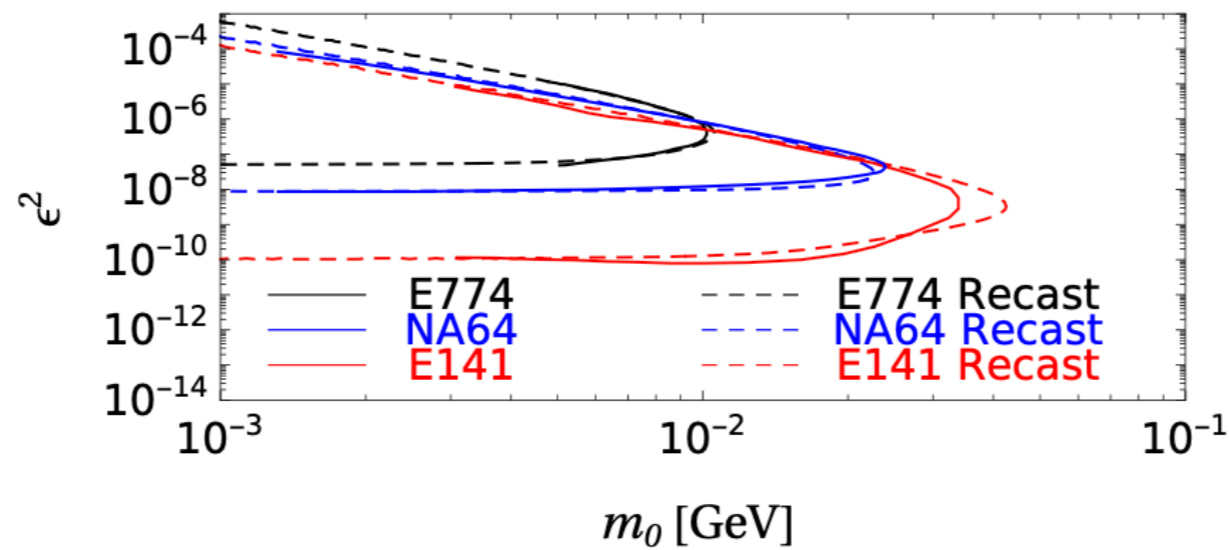
- General event number:

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

- Including oscillation effect

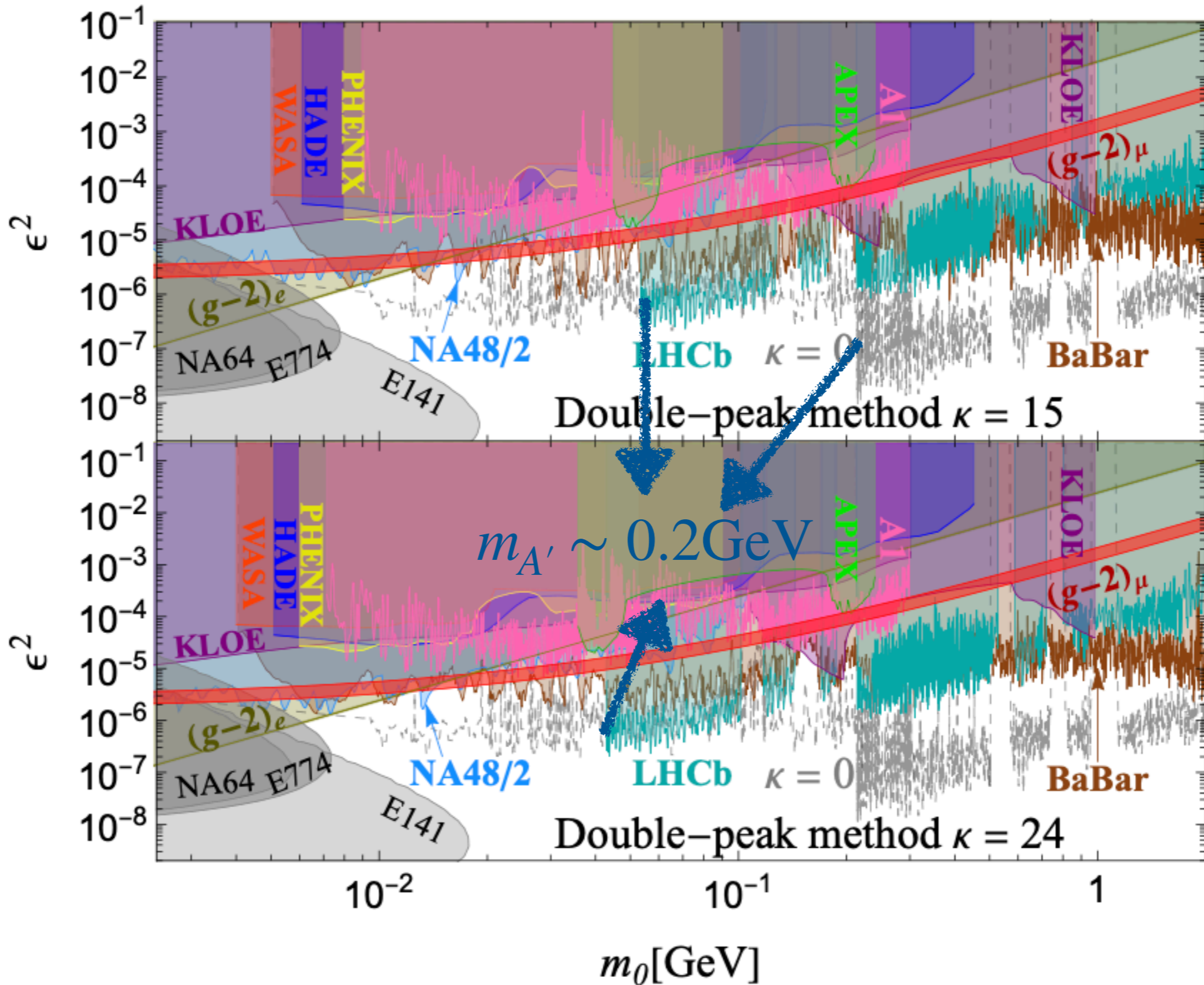
$$N(\epsilon, m_0, \kappa) = \frac{1}{\tau} \int_{m_0}^{\sqrt{1 + \kappa m_0}} N(\epsilon, m_{A'}) \left| \frac{dt}{dm_{A'}} \right| dm_{A'}$$

- Our recast result with  $\kappa = 0$





# Double-peak analysis result

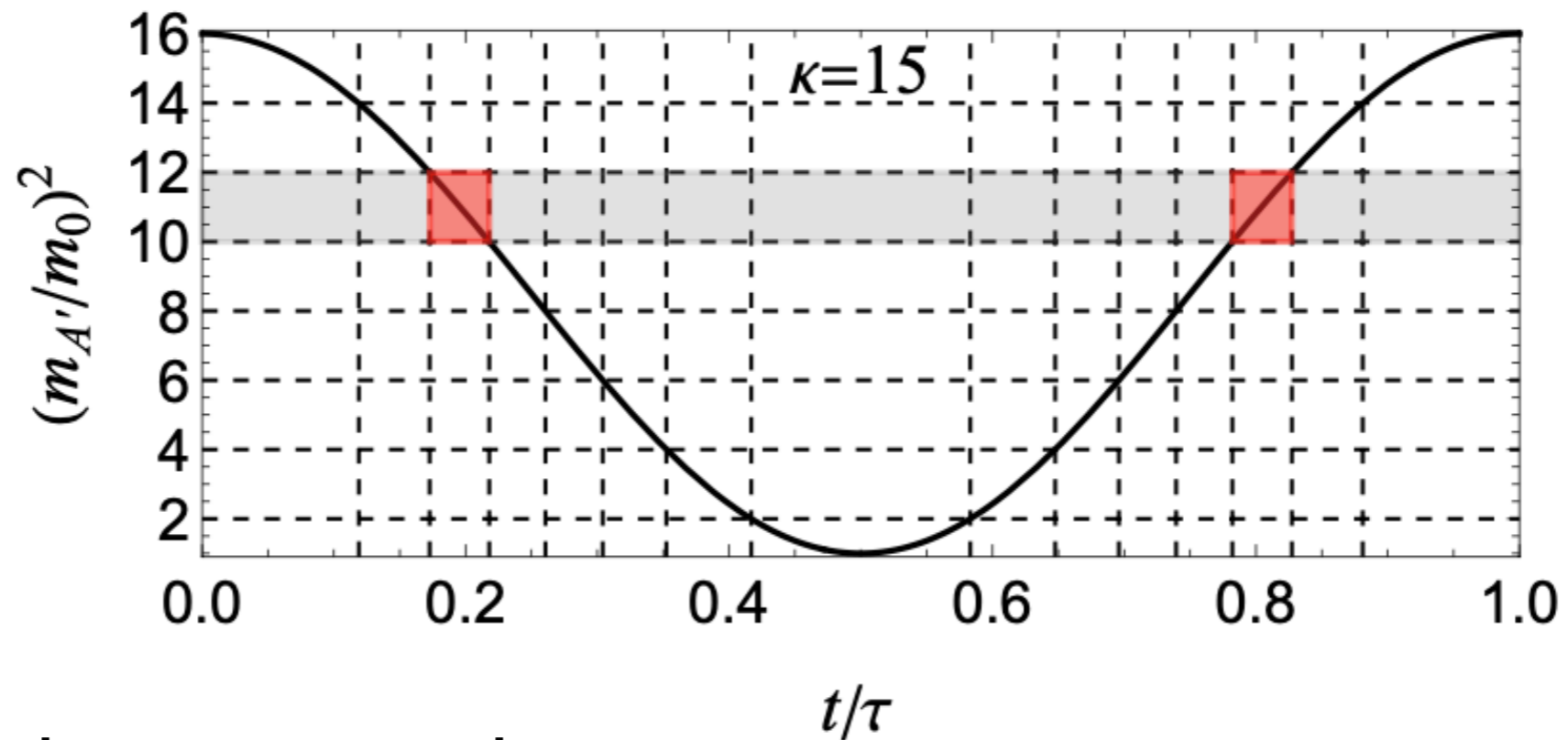




# Improvement with time-varying

- Oscillating property

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



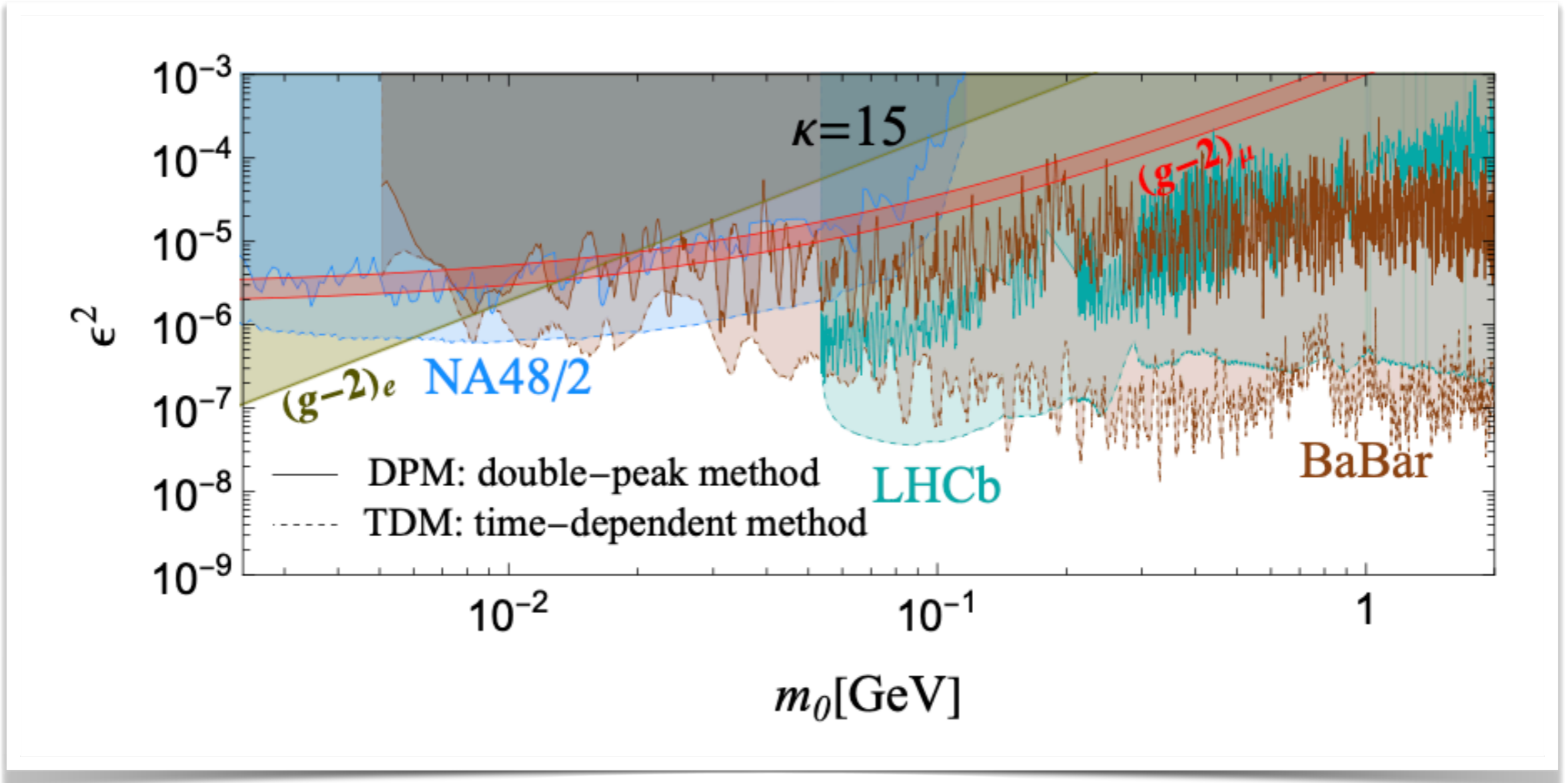
- Background event number

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



# Improvement with time-varying

- Result with time-varying



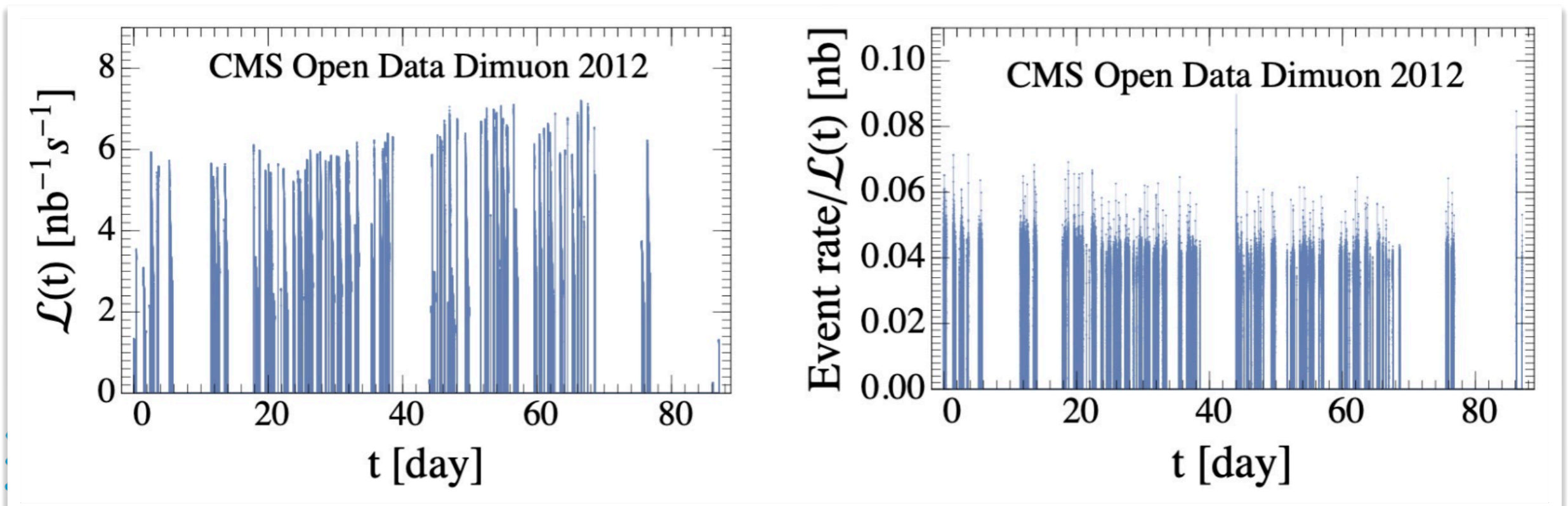


# Justify TDM with CMS open data

- 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

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

- CMS differential event number

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

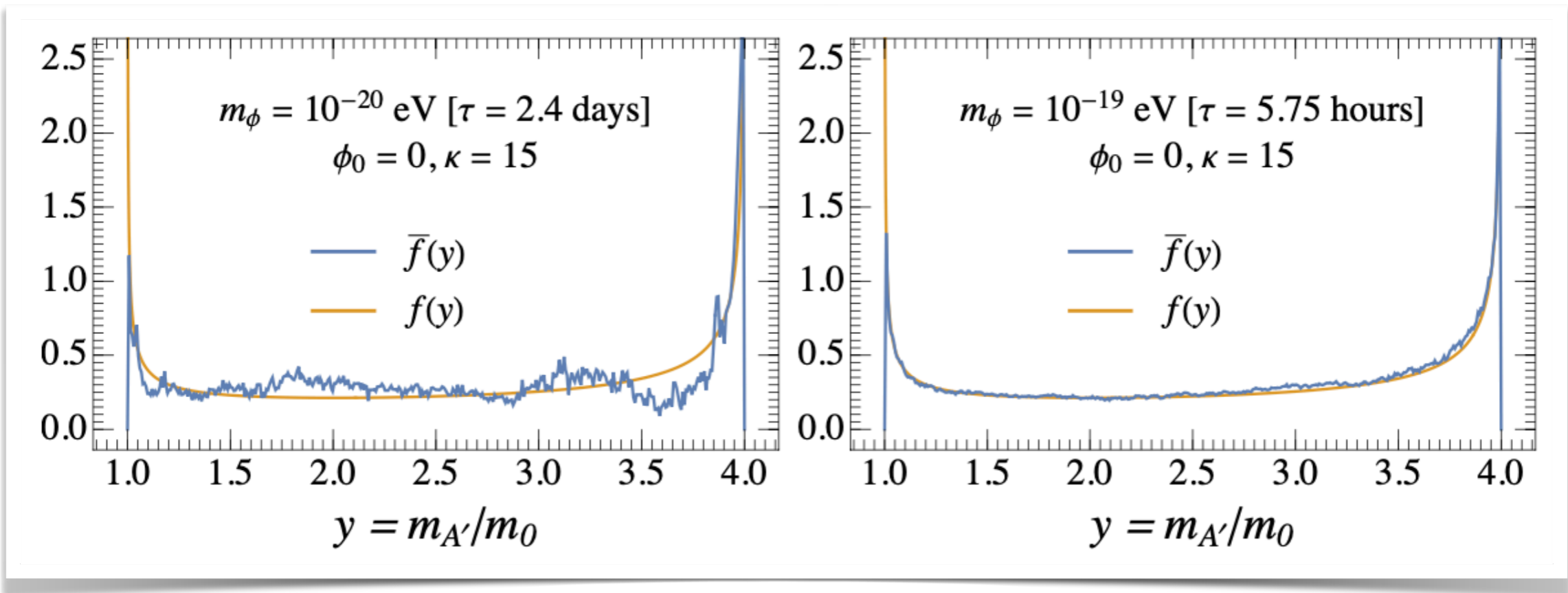
$$\frac{dN_S}{dm_{\ell\ell}} = \int_{t_1}^{t_2} dt \mathcal{L}(t) \frac{d\sigma_S}{dm_{\ell\ell}} = \epsilon_S \sigma_0 \times \frac{2m_{\ell\ell}}{\pi \sqrt{m_{\ell\ell}^2 - m_0^2} \sqrt{(1+\kappa)m_0^2 - m_{\ell\ell}^2}} \frac{\tau_{A'}}{2} \left[ \sum_{i^+} \mathcal{L}(t_i^+) + \sum_{i^-} \mathcal{L}(t_i^-)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

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



# CMS open data

- Double-peak property



**We can use DPM for CMS open data!**



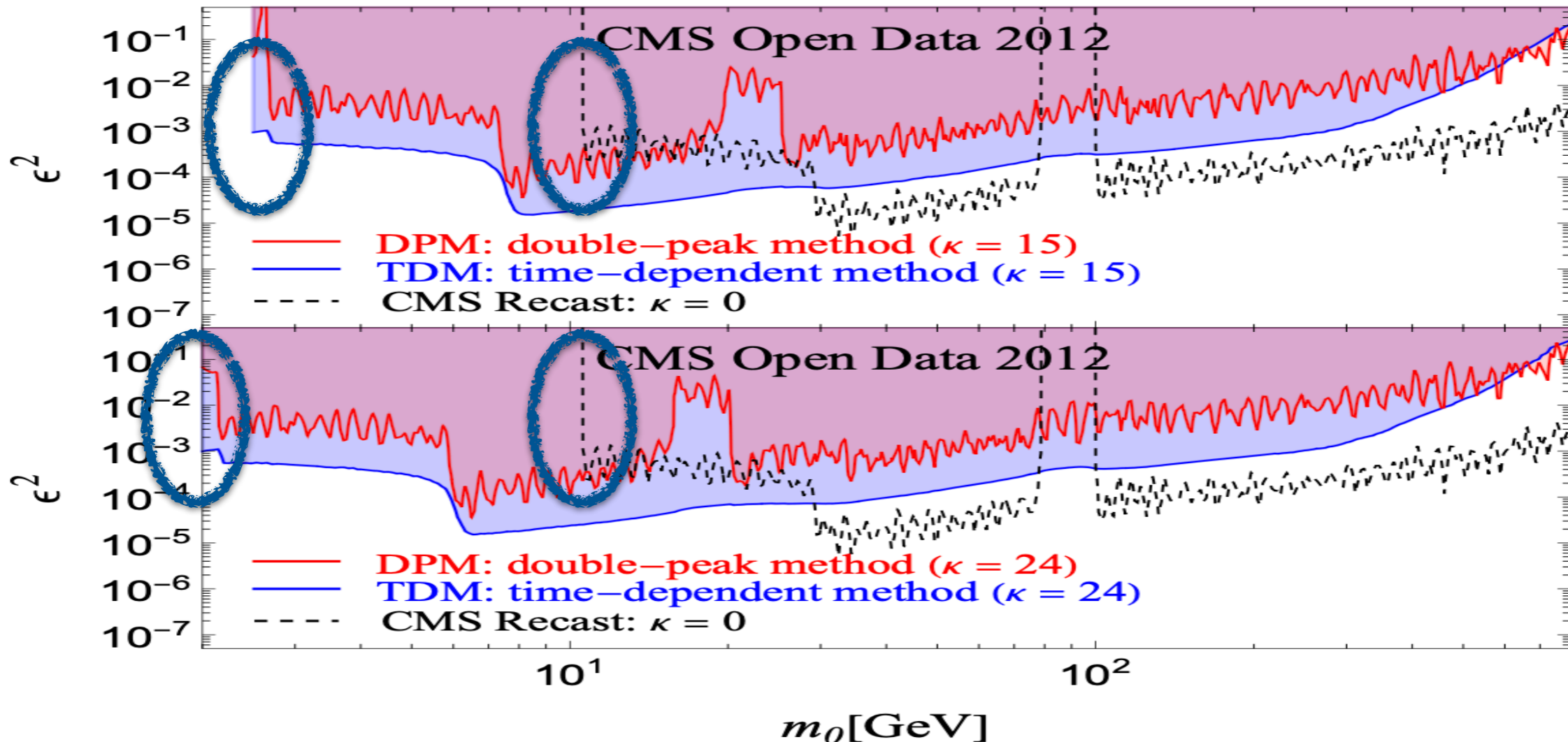
# CMS result with time information

- 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 and found it can lead to double-peak feature in the invariant mass spectrum**
- **The mass spectrum is independent of time as long as the oscillation period is short compared with the variation time scale of instant luminosity**
- **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 order**
- **We use the real collider data for a time-dependent resonance search and justify that our method works as expected**

**Thank you!**