第五届粒子物理前沿研讨会

The Fifth Workshop on Frontiers of Particle Physics

Searching for ultralight Dark Matter

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Commun.Phys. 6 (2023) 225
arXiv:2306.08039, *2309.16600* *(ChangE collaboration)*

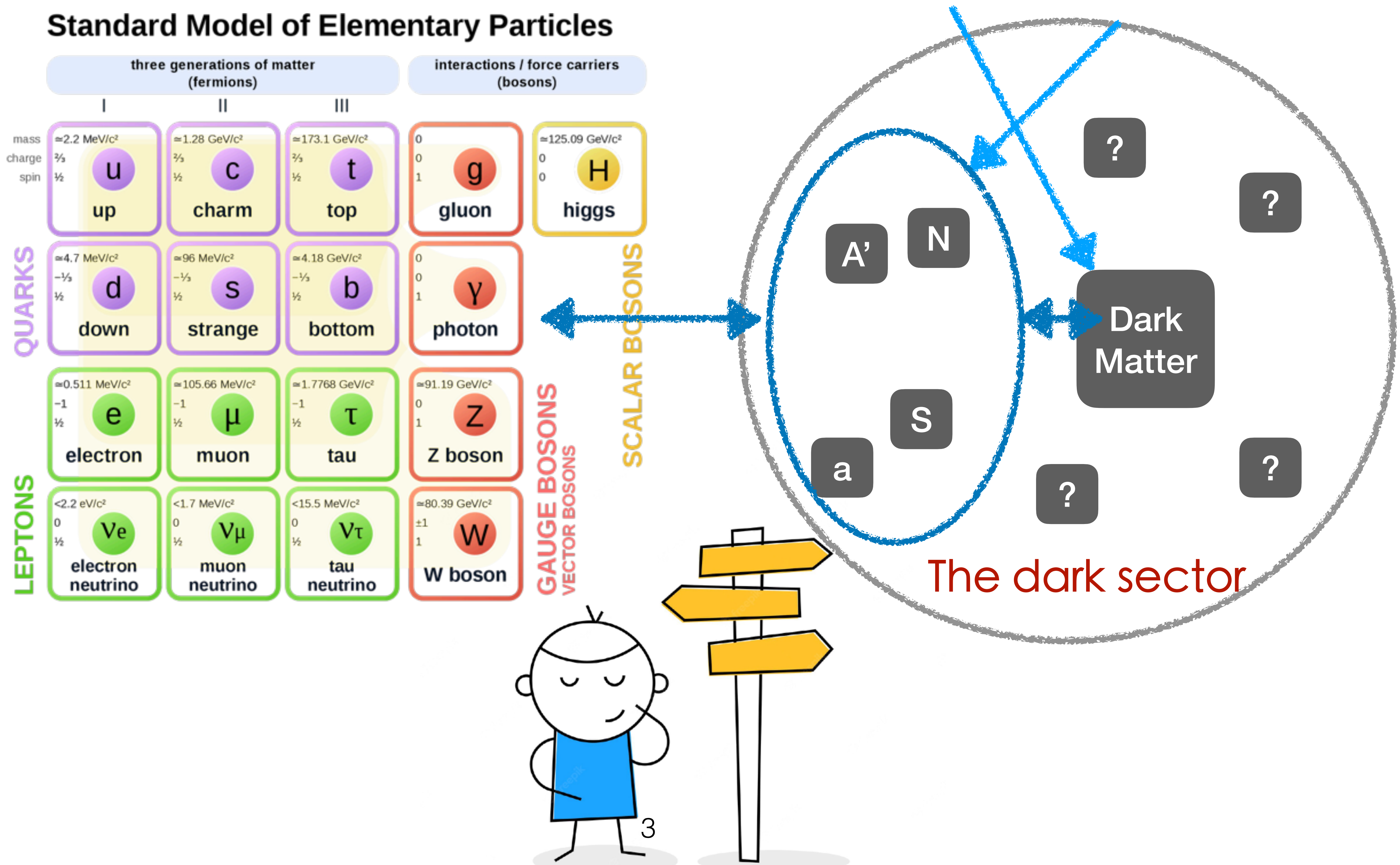
Outiline

- Introduction to ultralight bosonic dark matter
- ALP DM search via Hybrid-Spin Resonance
- Scalar DM search via neutrino oscillation
- Scalar DM search via dark mediator
- Summary

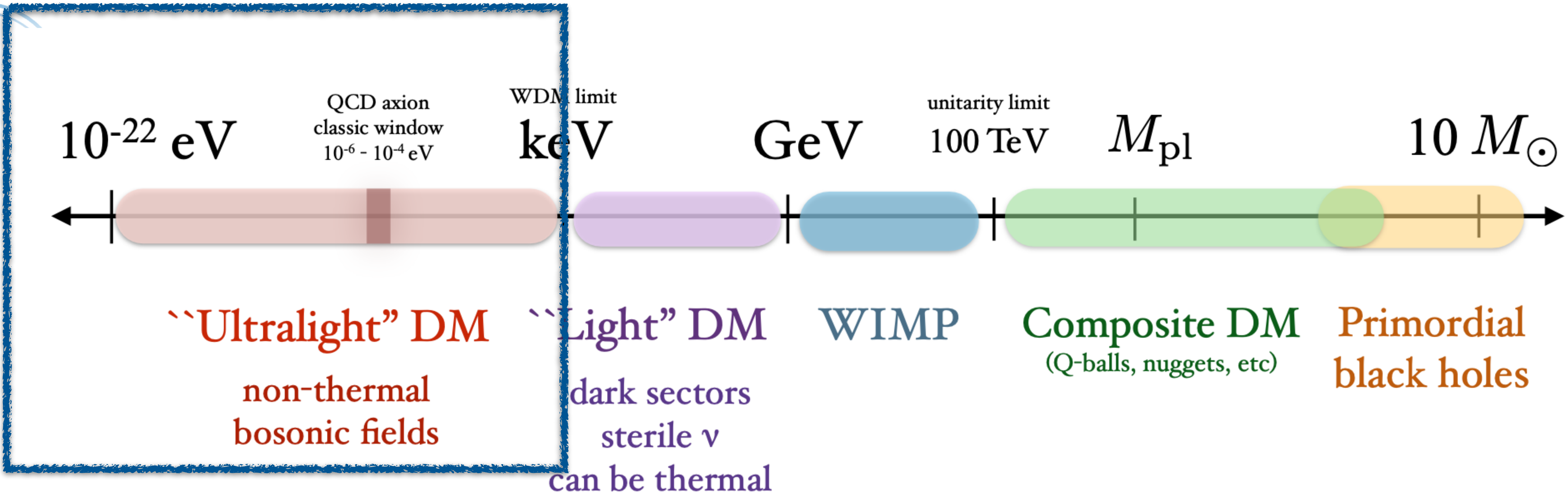
We are at a cross road

- Standard Model
  =fermions+force

- Dark sector
  =DM+dark



Dark matter mass range



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

- Ultralight: $m \lesssim \text{keV}$
- Bosonic: Pauli-exclusion for fermonic DM
- Behave as classical fields ($m \lesssim \mathcal{O}(1)$ eV)
- Typical models:
  - Pseudo-scalar: Axion, Axion-like Particle
  - Dark Scalar: dilaton-like coupling
  - Vector: kinetic mixing dark photon, $U(1)_{B-L}$ dark photon etc

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?

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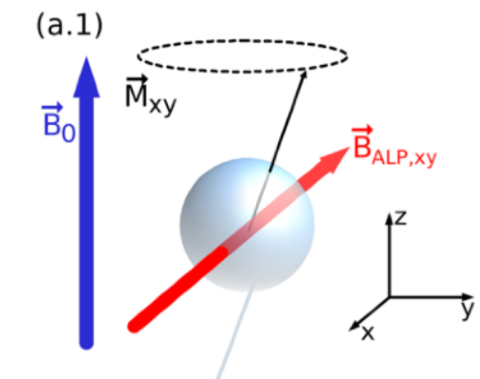
ALP couples to nucleon

- Axion couples to SM particles

$$\mathscr{H}_{\sigma} = g_{\mathrm{aNN}}\sqrt{2\rho_{\mathrm{DM}}}\cos\left(m_{\mathrm{a}}t\right)\vec{v}\cdot\vec{\sigma}_{\mathrm{N}} = \gamma\vec{B}_{\mathrm{ALP}}\cdot\vec{\sigma}$$

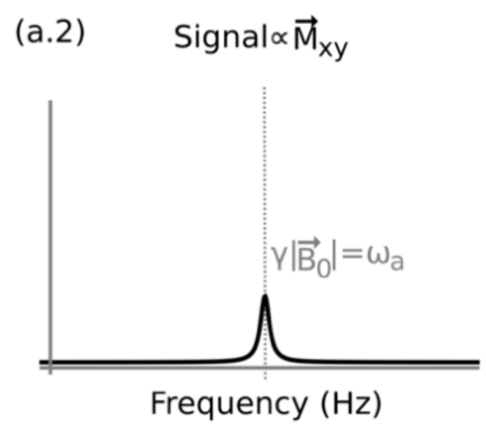


- Oscillate the mass at Larmor frequency

$$\vec{B}_{\mathrm{ALP}} = g_{aNN}\sqrt{2\rho_{\mathrm{DM}}}\cos(m_a t) = g_{aNN}\sqrt{2\rho_{\mathrm{DM}}}\cos(\omega_a t)$$

- Bloch Equations

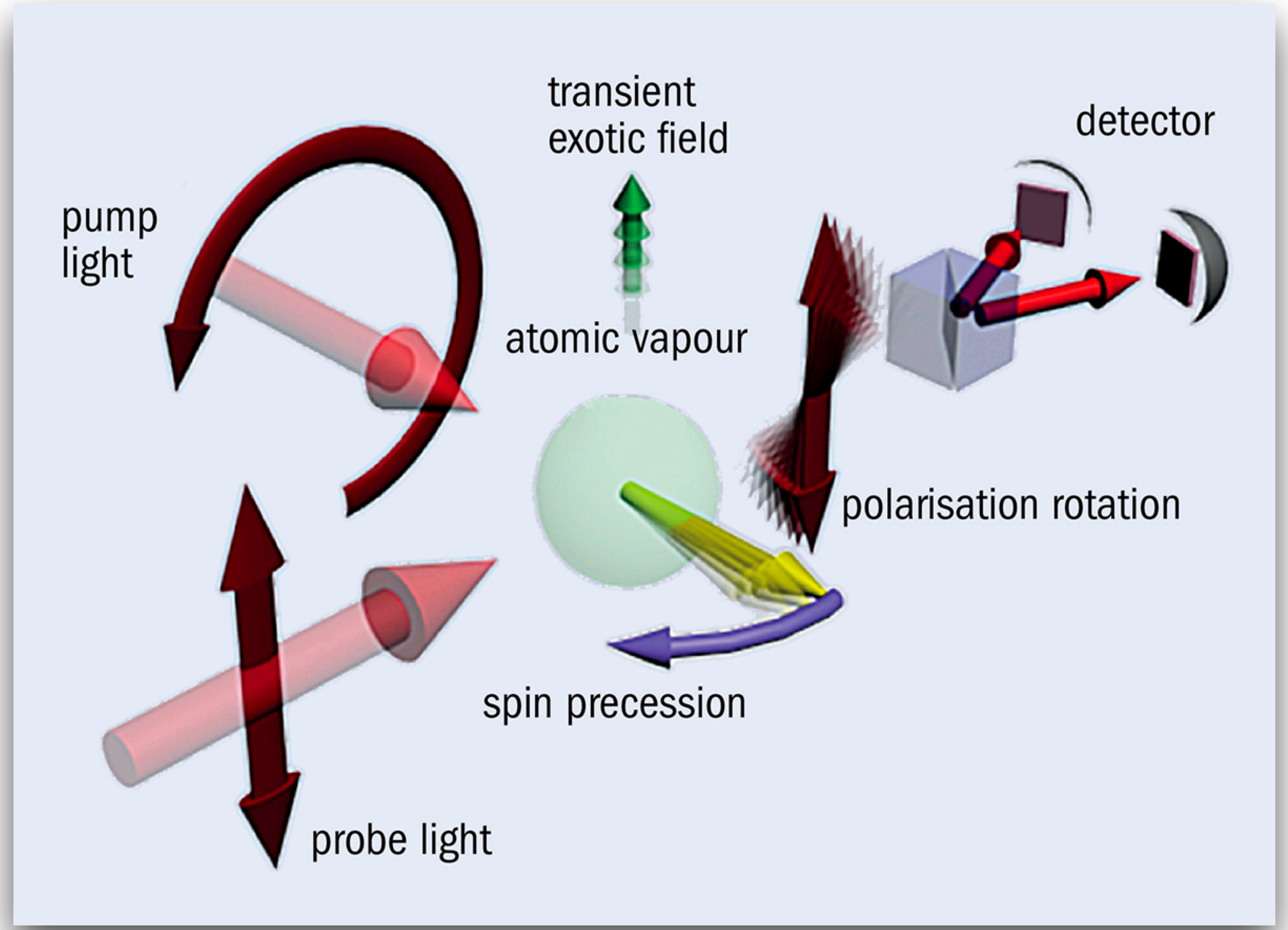
$$\frac{d\vec{M}}{dt} = \gamma\vec{M}\times\vec{B}$$



Time varying Axion B_{ALP} drives spin precession

$\rightarrow$ produces transverse magnetization

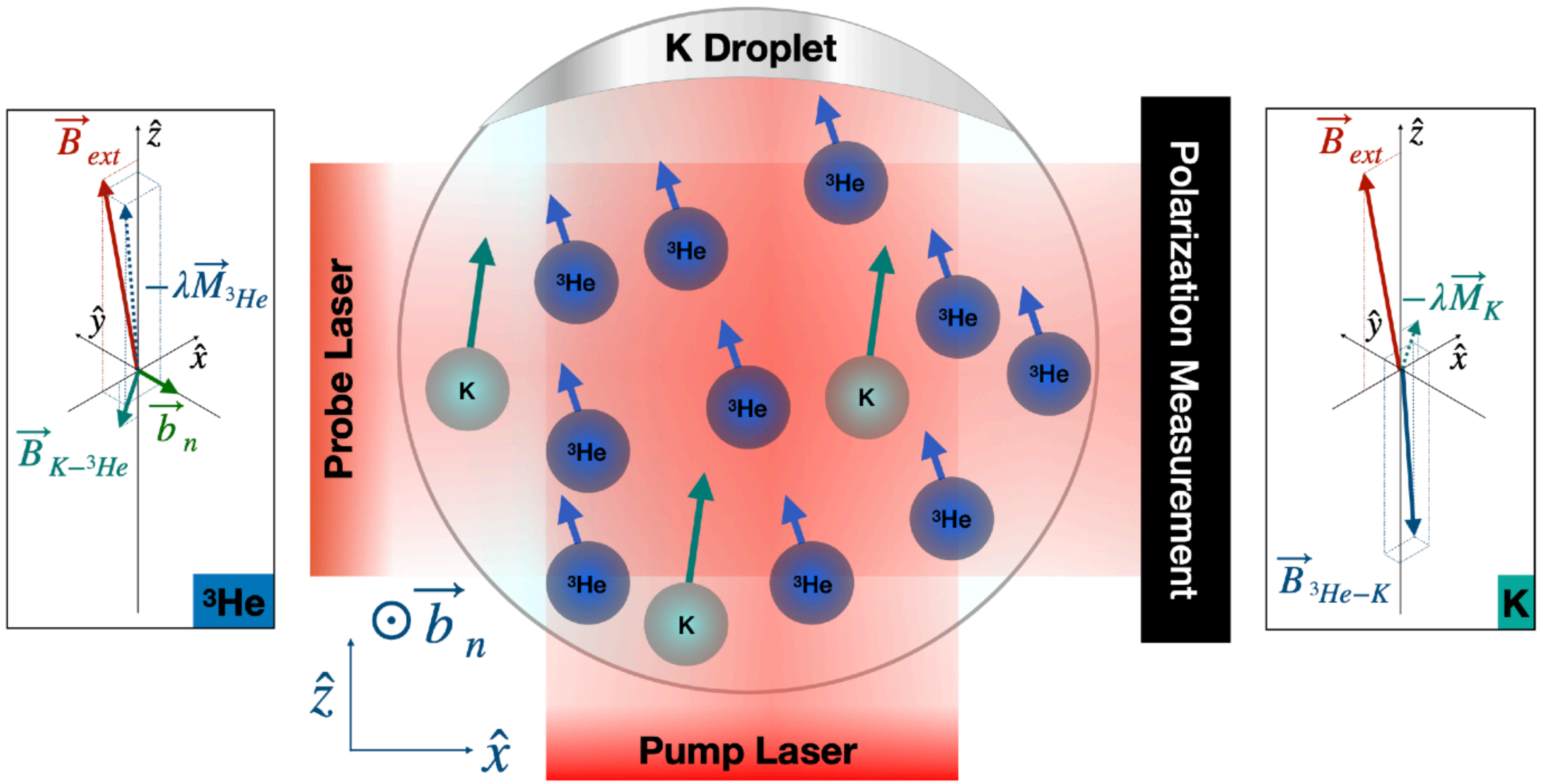
Detection of g_{aNN}



$$S_{\perp}\left(\omega = m_a\right) = \frac{b_{\perp} + \gamma B_{\perp}\left(\omega = m_a\right)}{\left(\gamma B_z - m_a\right) + i\Gamma} S_z$$

Comagnetometer

- Alkali atoms and nobel-gas atom



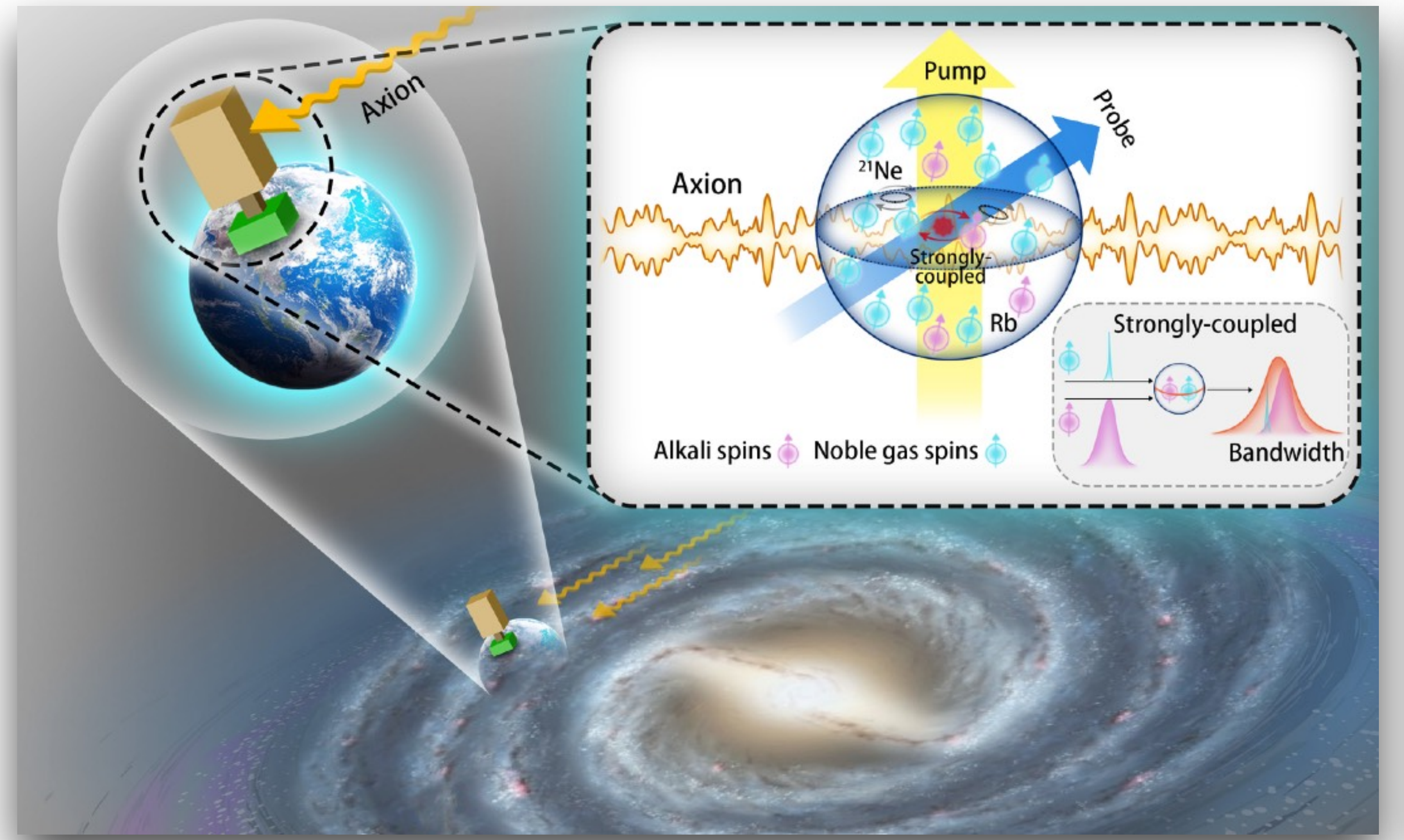
$$\frac{\delta \mathbf{P^e}}{\delta t} = \frac{\gamma_e}{Q}\left[\mathbf{B} + \mathbf{L} + \boxed{\lambda M_0^n \mathbf{P}^{\mathrm{n}}} + \mathbf{b}^{\mathrm{e}}\right] \times \mathbf{P^e} - \mathbf{\Omega} \times \mathbf{P^e} + \frac{R_p \mathbf{S_p} + R_m \mathbf{S_m} \boxed{+ R_{\mathrm{se}}^{\mathrm{ne}} \mathbf{P}^{\mathrm{n}}}}{Q} - \frac{\{R_1^e, R_2^e, R_2^e\}}{Q} \mathbf{P^e}$$

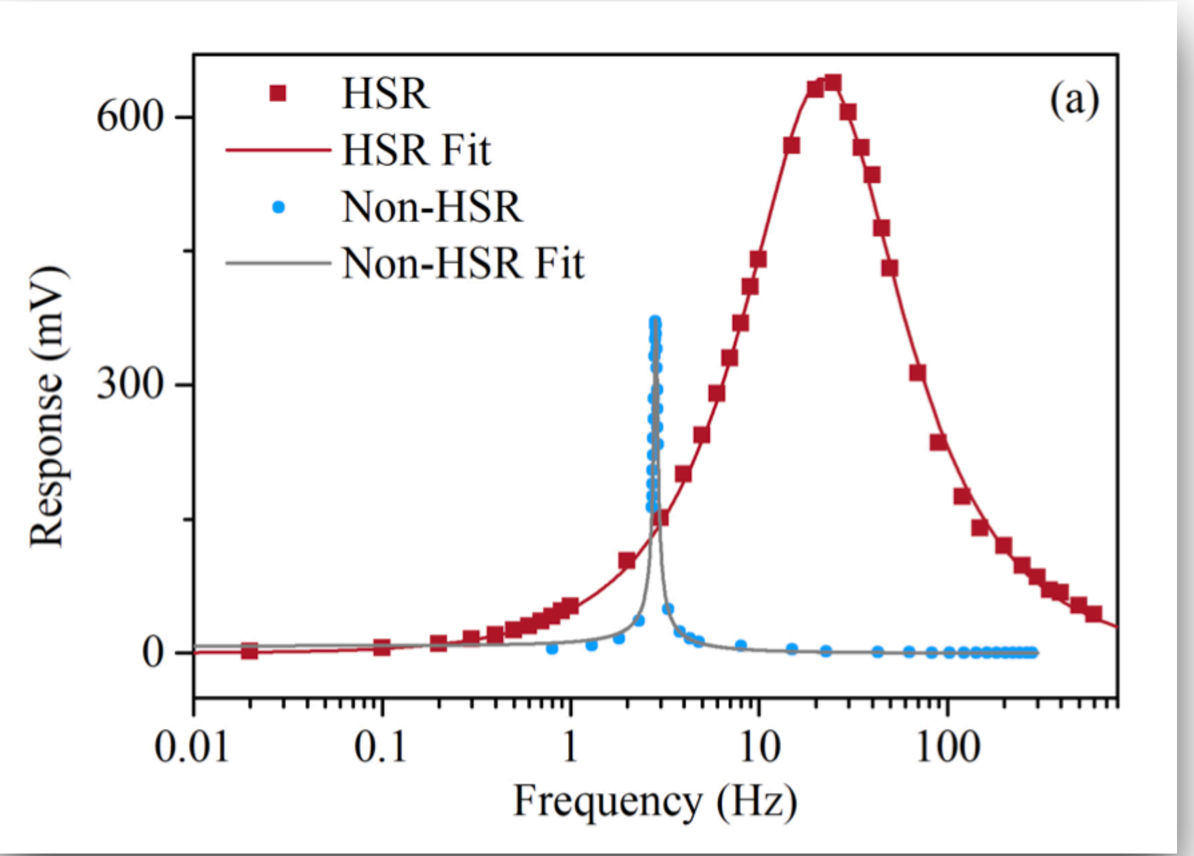
spin interaction spin exchange collision

$$\frac{\delta \mathbf{P^n}}{\delta t} = \gamma_n \left(\mathbf{B} + \boxed{\lambda M_0^e \mathbf{P^e}} + \boxed{\mathbf{b^n}}\right) \times \mathbf{P^n} - \Omega \times \mathbf{P^n} \boxed{+ R_{\mathrm{se}}^{\mathrm{en}} \mathbf{P^e}} - \{R_1^n, R_2^n, R_2^n\}\, \mathbf{P^n}$$

Comagnetometer in Hybrid Spin Resonance

ChangE experiment: Kai Wei, .. **XPW** .. et al, 2306.08039

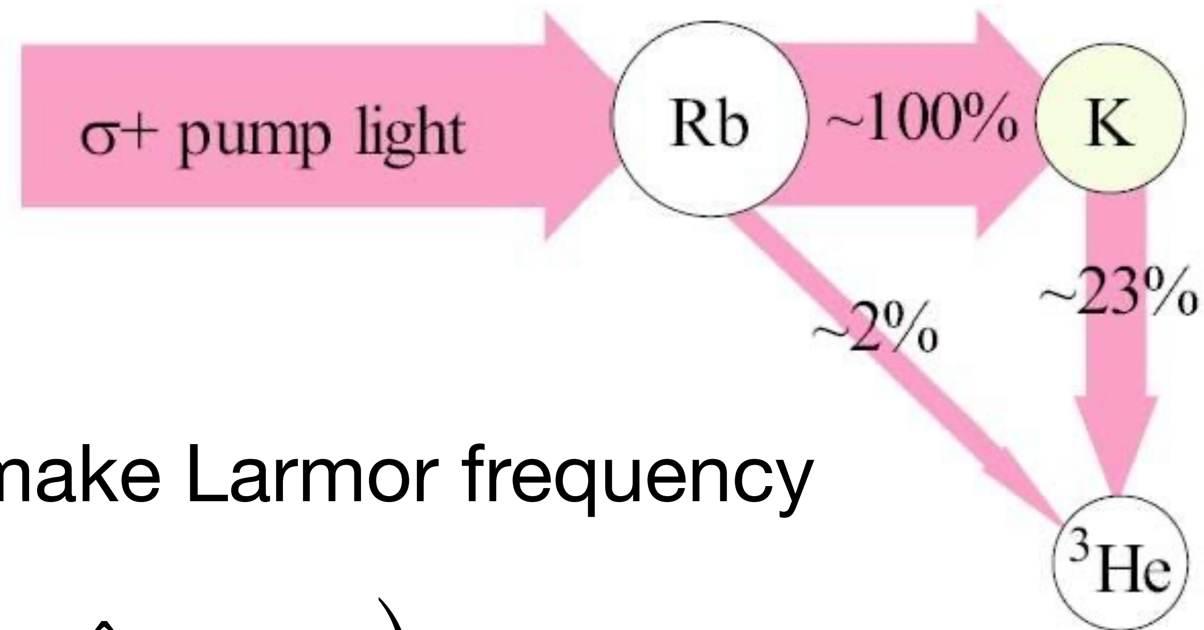




- Smaller amplification but with much wider resonance
  - Do not need to scan (e.g. 35 months)
  - Long-time measurement at single point to compensate amplification lost

Hybrid Spin Resonance

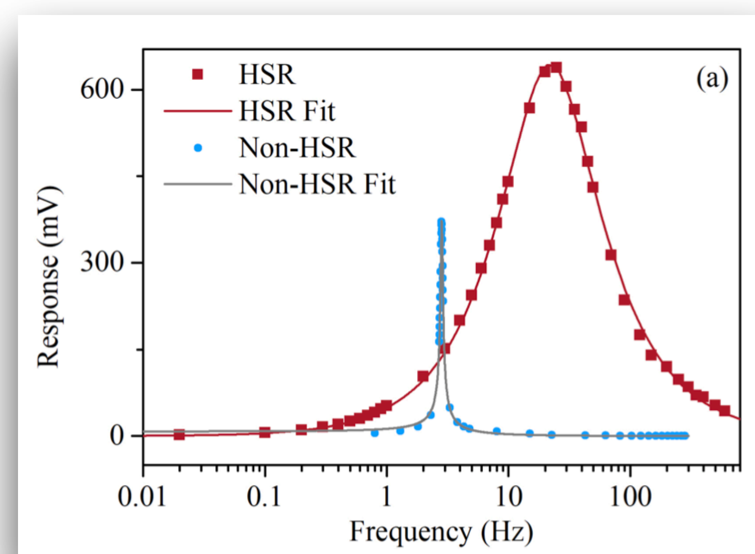
- Spin-exchange Optical Pumping:



- Method: tune external B field to make Larmor frequency equal (HSR region)

$$\omega_{\text{alkali}} = \gamma_{\text{alkali}} \left(\hat{B}_{\text{ext}} + \hat{B}_{\text{noble}} \right)$$

$$\omega_{\text{noble}} = \gamma_{\text{noble}} \left(\hat{B}_{\text{ext}} + \hat{B}_{\text{alkali}} \right)$$



- Require $\omega_{\text{alkali}} = \omega_{\text{noble}}$

$$B_{\text{HSR}} \sim -B_{\text{noble}}$$

Stochastic nature of ULDM

- Random phase in different p mode

$$\nabla a(x) = \sum_{p} \boxed{\sqrt{\frac{2N_p}{V\omega_p}}} \cos(\omega_p t - \boldsymbol{p}\cdot\boldsymbol{x} + \boxed{\phi_p})\,\boldsymbol{p}$$

ϕ_p: is uniform random variable in [0, 2Pi]

- Signal is stochastic instead of deterministic

1905.13650, NC 2021

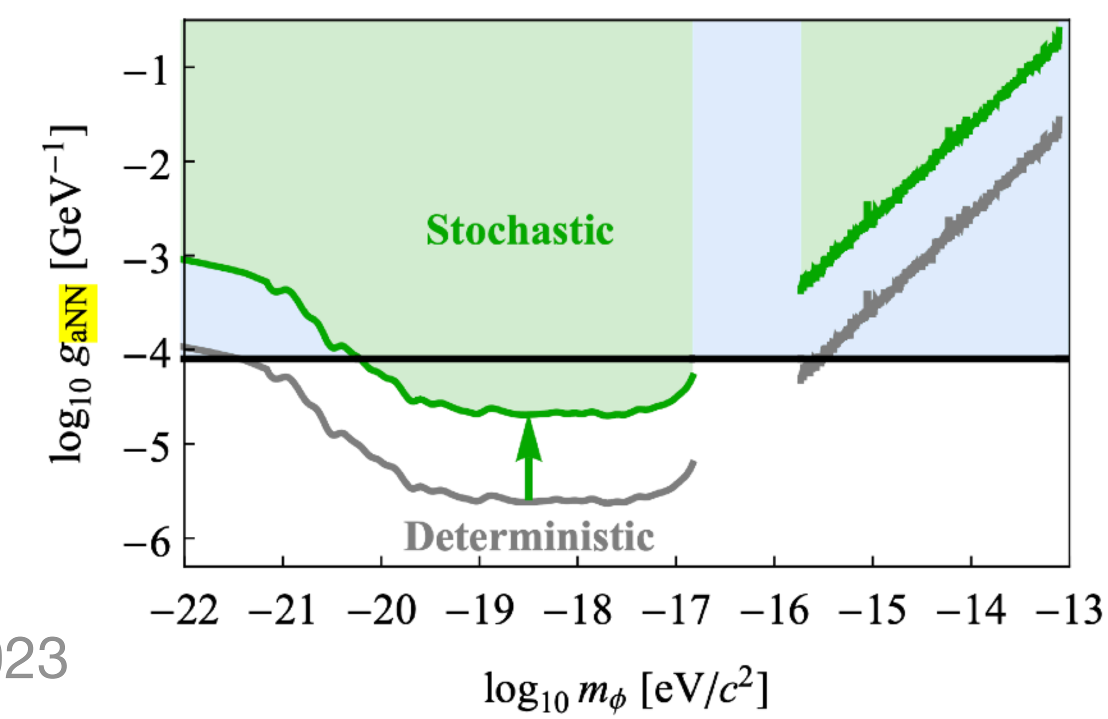
$$\beta_j = \frac{g_{aN}}{\gamma_N} \nabla a(j\Delta t) \cdot \hat{\mathbf{m}}(j\Delta t)$$

$$A_k = \frac{2}{N}\mathrm{Re}[\tilde{\beta}_k], \quad B_k = -\frac{2}{N}\mathrm{Im}[\tilde{\beta}_k].$$

$$L(\mathbf{d}|g_{aNN}, \sigma_b^2) = \frac{1}{\sqrt{(2\pi)^{2N}\det(\Sigma)}} \exp\left(-\frac{1}{2}\mathbf{d}^T\Sigma^{-1}\mathbf{d}\right)$$

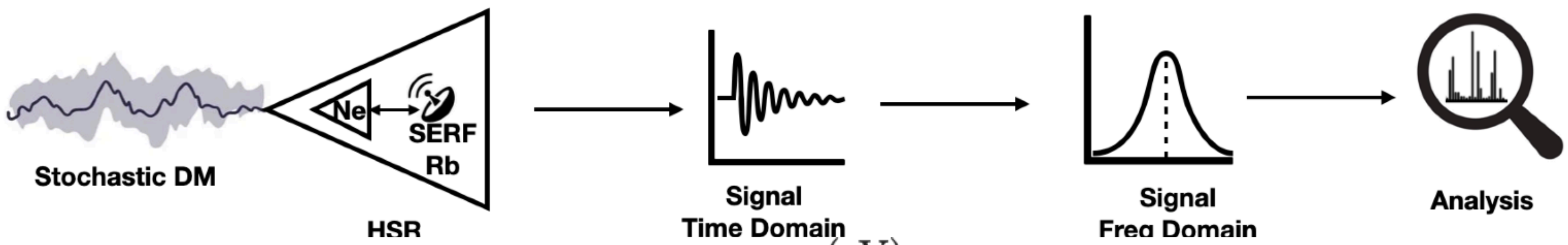
$$\Sigma = \Sigma_a + \sigma_b^2 \cdot \mathbb{1}$$

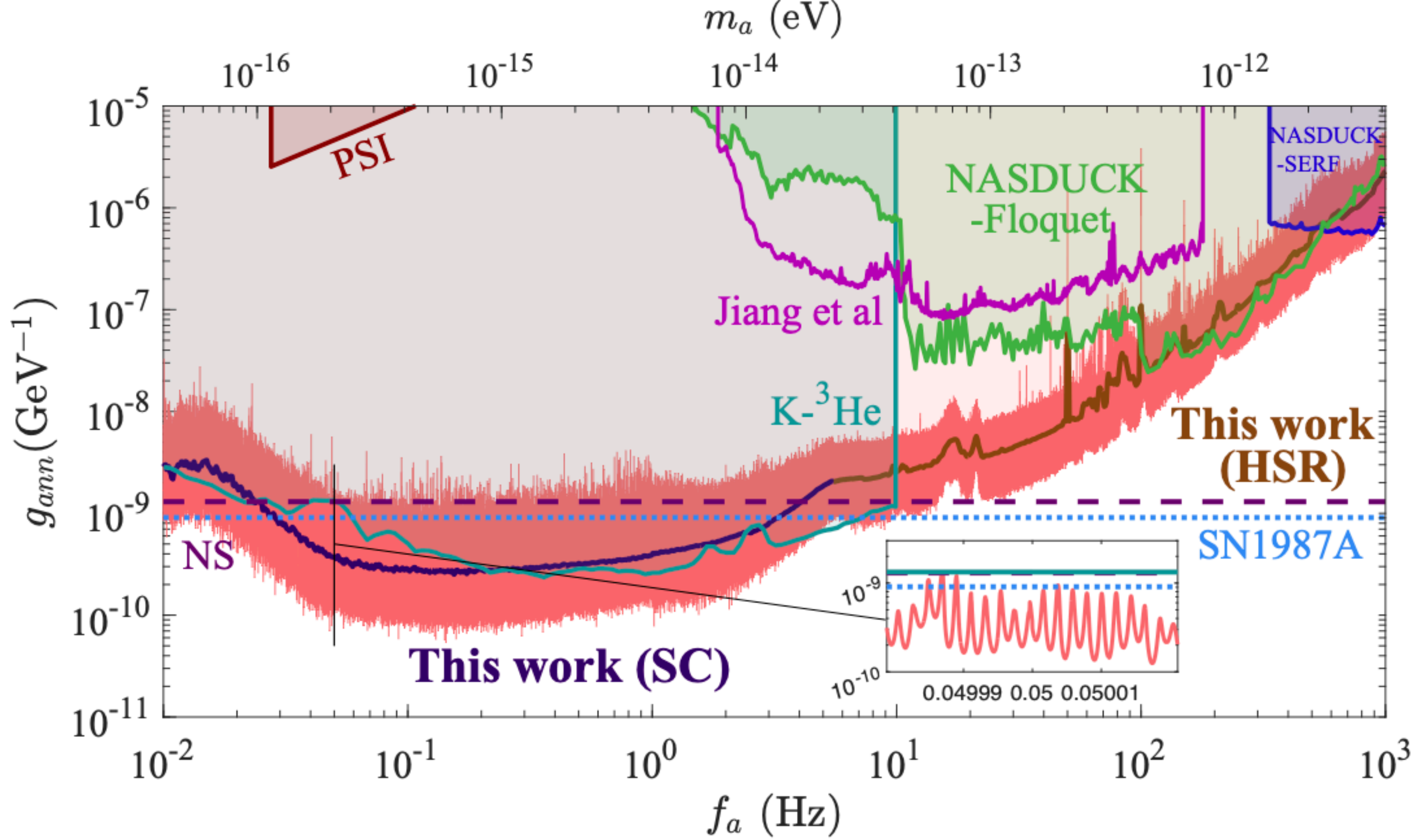
Junyi Lee et al, 2209.03289, PRX 2023



$$\boxed{\gamma^{\text{stoch}}_{95\%} = 8.4\,\gamma^{\text{det}}_{95\%}}$$

Comagnetometer HSR search on ALP DM





- The experiments has long duration at single working point

  Data-1 = 209 hr, Data-2 = 4 hr (underground)

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Ultra light DM couples to Neutrino

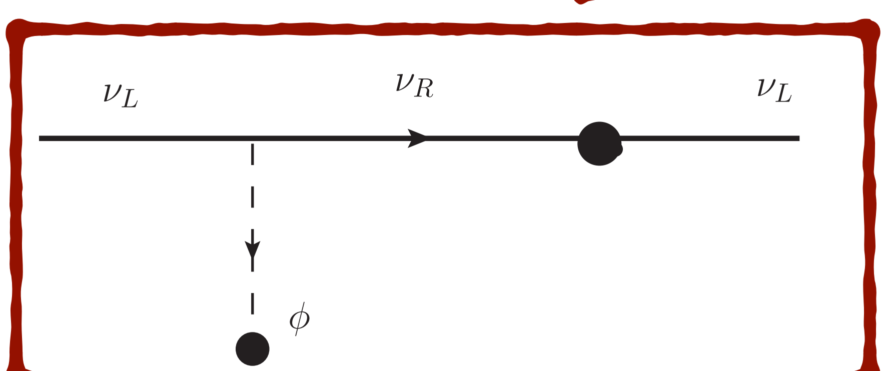
$$\mathcal{L}_{\text{scalar}} = \bar{\nu}_L^{\alpha} i\gamma^{\rho}\partial\nu_L^{\alpha} - \frac{1}{2} m_\nu^{\alpha\beta}\overline{(\nu_L^c)^\alpha}\nu_L^\beta - \frac{1}{2} y^{\alpha\beta}\phi\,\overline{(\nu_L^c)^\alpha}\nu_L^\beta$$

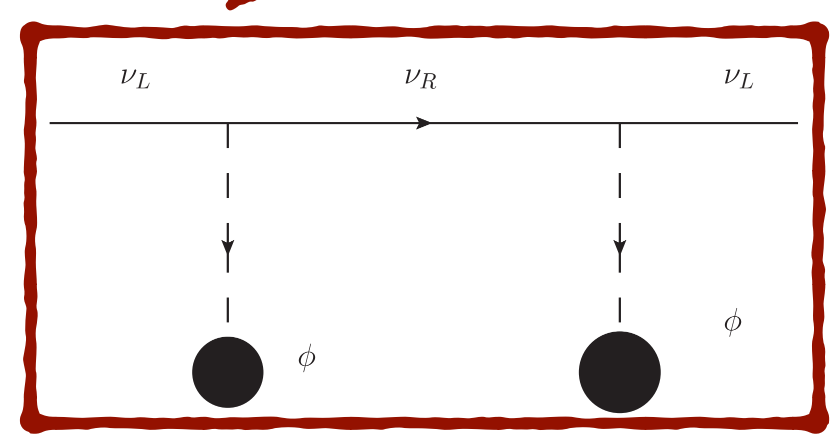
✓ Dispersion relation

$$(E_\nu - V_{\text{eff}})^2 = \vec{p}_\nu^{\,2} + m_\nu^2$$

$$\boxed{m_\nu^2 \sim y\phi m_\nu}$$

$$V_{\text{eff}} = \frac{1}{2E_\nu}\Big(\phi\,(y\,m_\nu + m_\nu\,y) + \phi^2 y^2\Big)$$





Ultra light Scalar Dark matter

$$\boxed{V_{\text{eff}} = \frac{1}{2E_\nu}\left(\phi\left(y\,m_\nu + m_\nu\,y\right) + \phi^2 y^2\right)}$$

✓ Dark Matter Production - misalignment

$$\partial_t\partial_t\phi + 3H\partial_t\phi + m^2\phi^2 = 0$$

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

✓Local density 0.3 GeV/cm^3

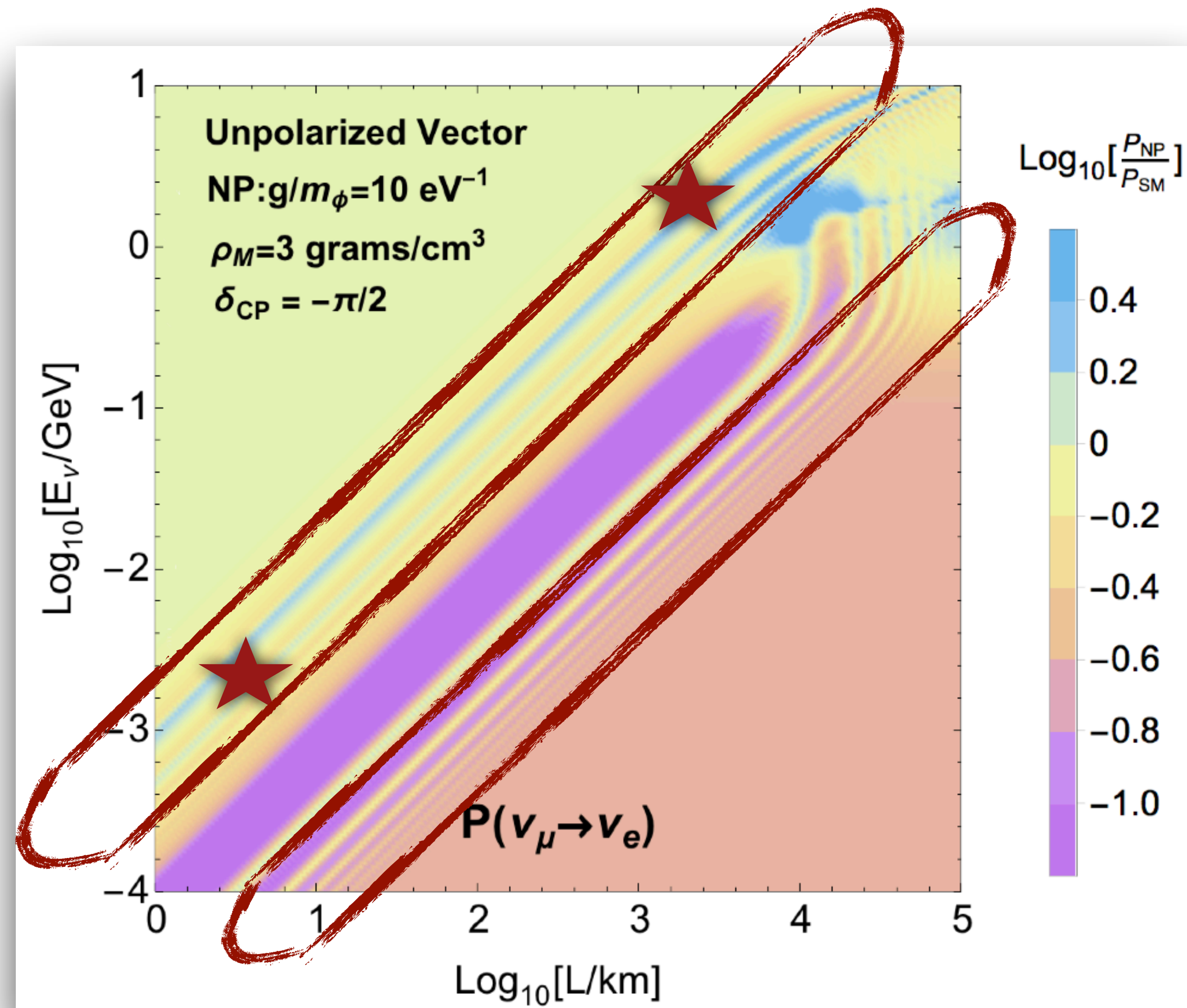
$$\rho_\phi = \frac{1}{2}m_\phi^2\phi_0^2 \xrightarrow{m_\nu^2 \sim y\phi m_\nu} \frac{y}{m_\phi} \sim \frac{m_\nu}{\sqrt{2\rho_\phi}} \sim 10\ \text{eV}^{-1}$$

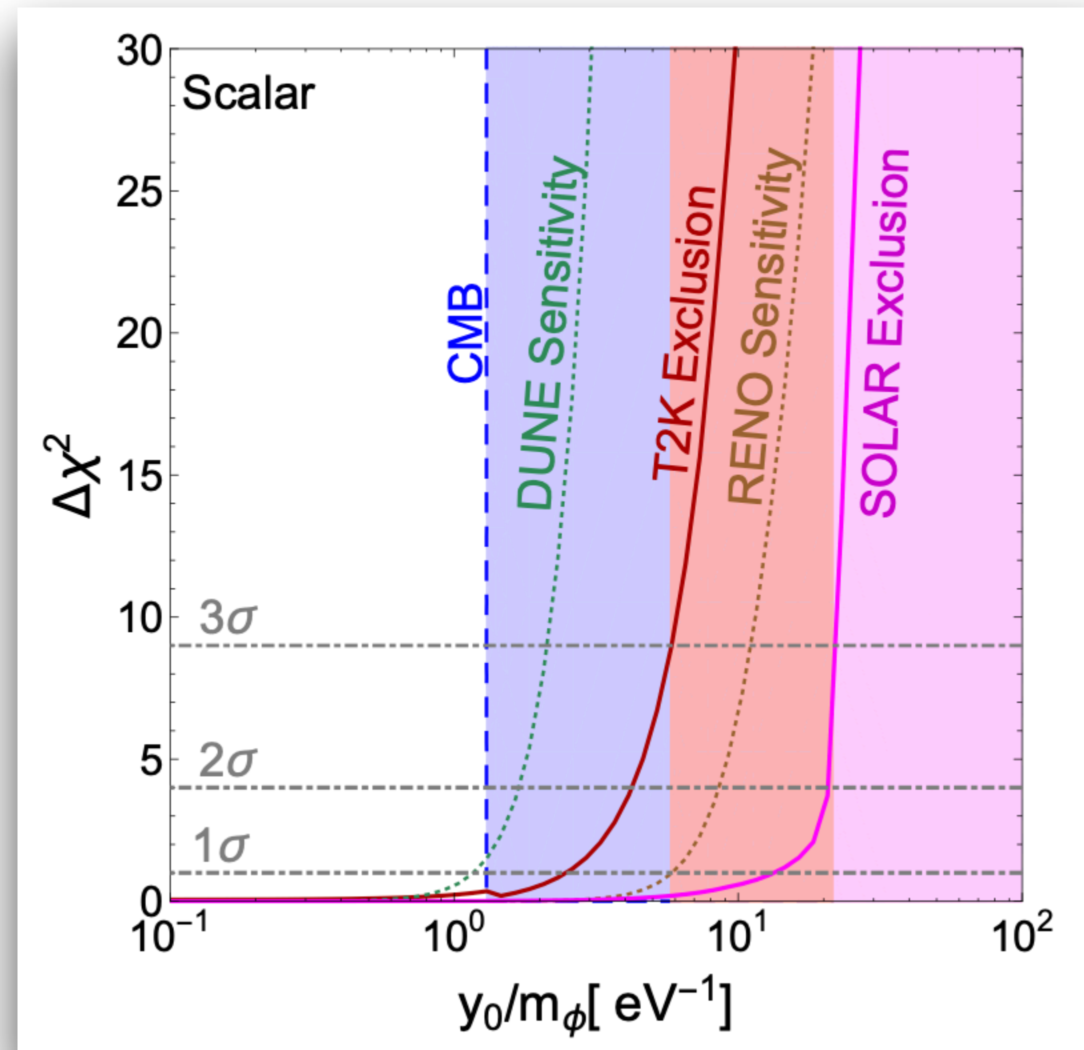
✓ Expansion on probability

$$P_{\alpha\beta} = P_0 + P_1\cos(m_\phi t) + P_2\cos^2(m_\phi t)$$

Neutrino Oscillation from Dark Matter

VB, JK, JL, PP, XPW, *JHEP* 07 (2019) 159





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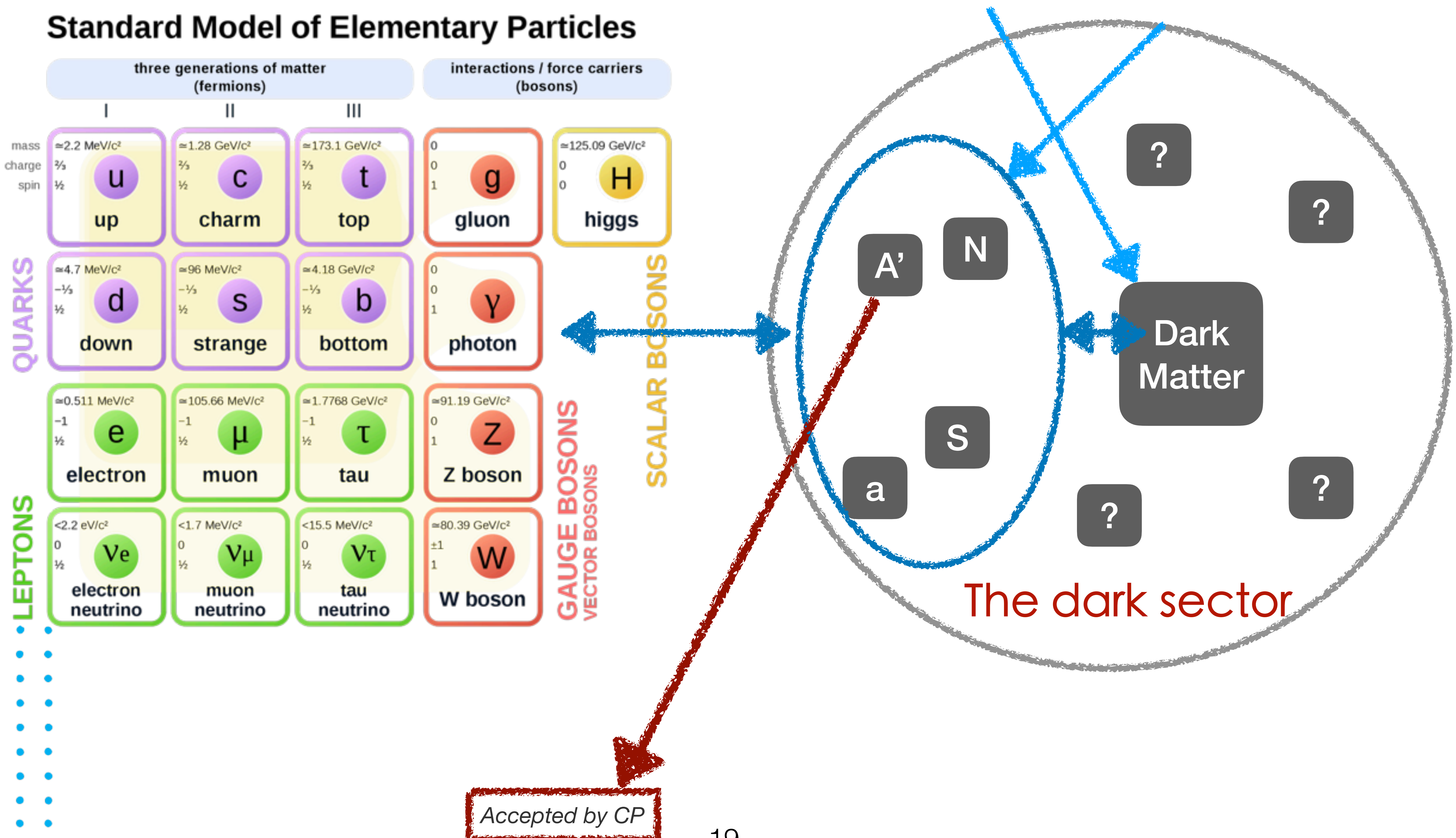
Dark matter-SM mediator

- StandarModel =fermions+force
- Dark Sector =DM+dark mediator



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'

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

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

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

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

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

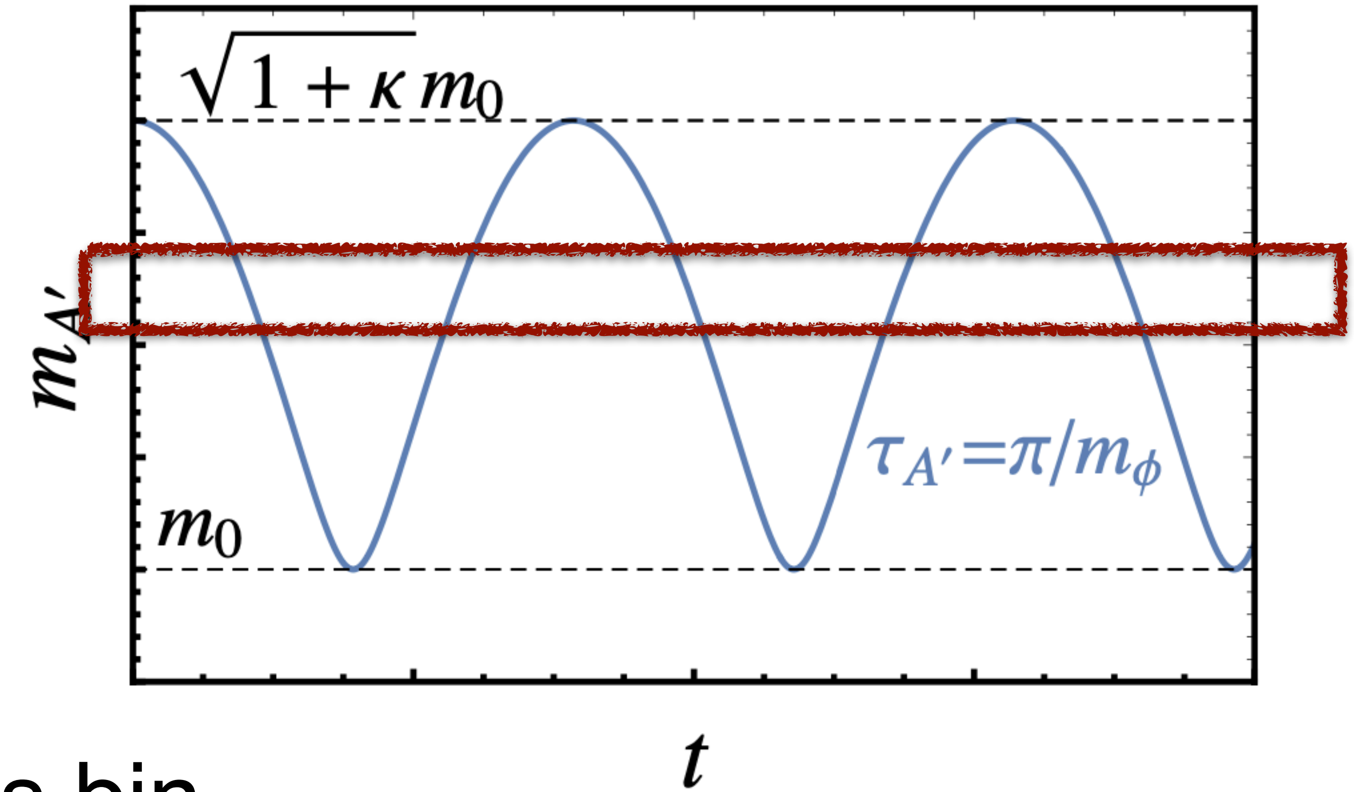
$$\kappa \equiv 10\left(\frac{\rho_{\rm DM}}{0.3{\rm GeV/cm^3}}\right)\left(\frac{g'Q_\phi}{1.5\times10^{-8}}\cdot\frac{10^{-19}{\rm eV}}{m_\phi}\cdot\frac{0.1{\rm GeV}}{m_0}\right)^2$$

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

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

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

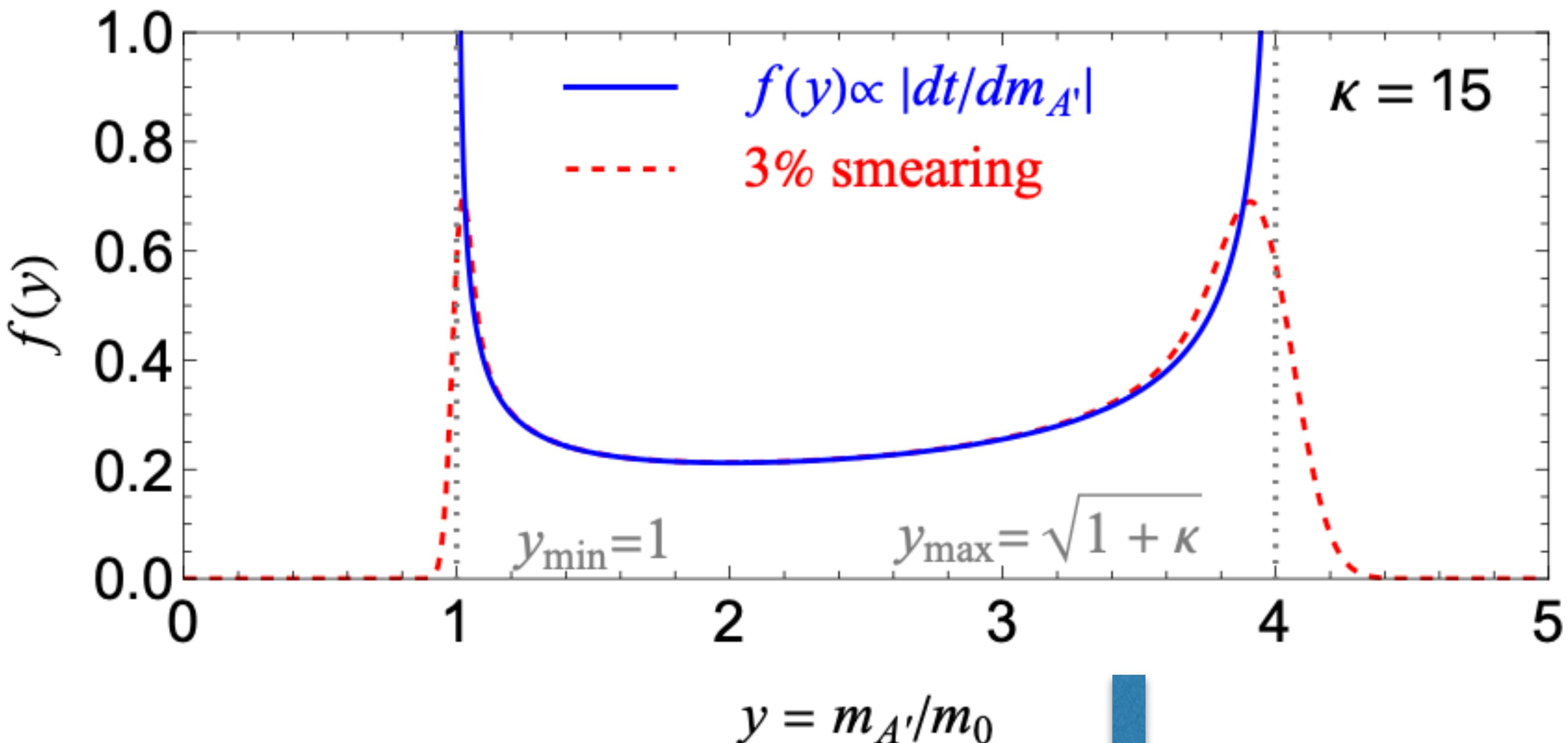
$$\downarrow$$

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

Oscillating A' from wave-like DM

- Oscillating property

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

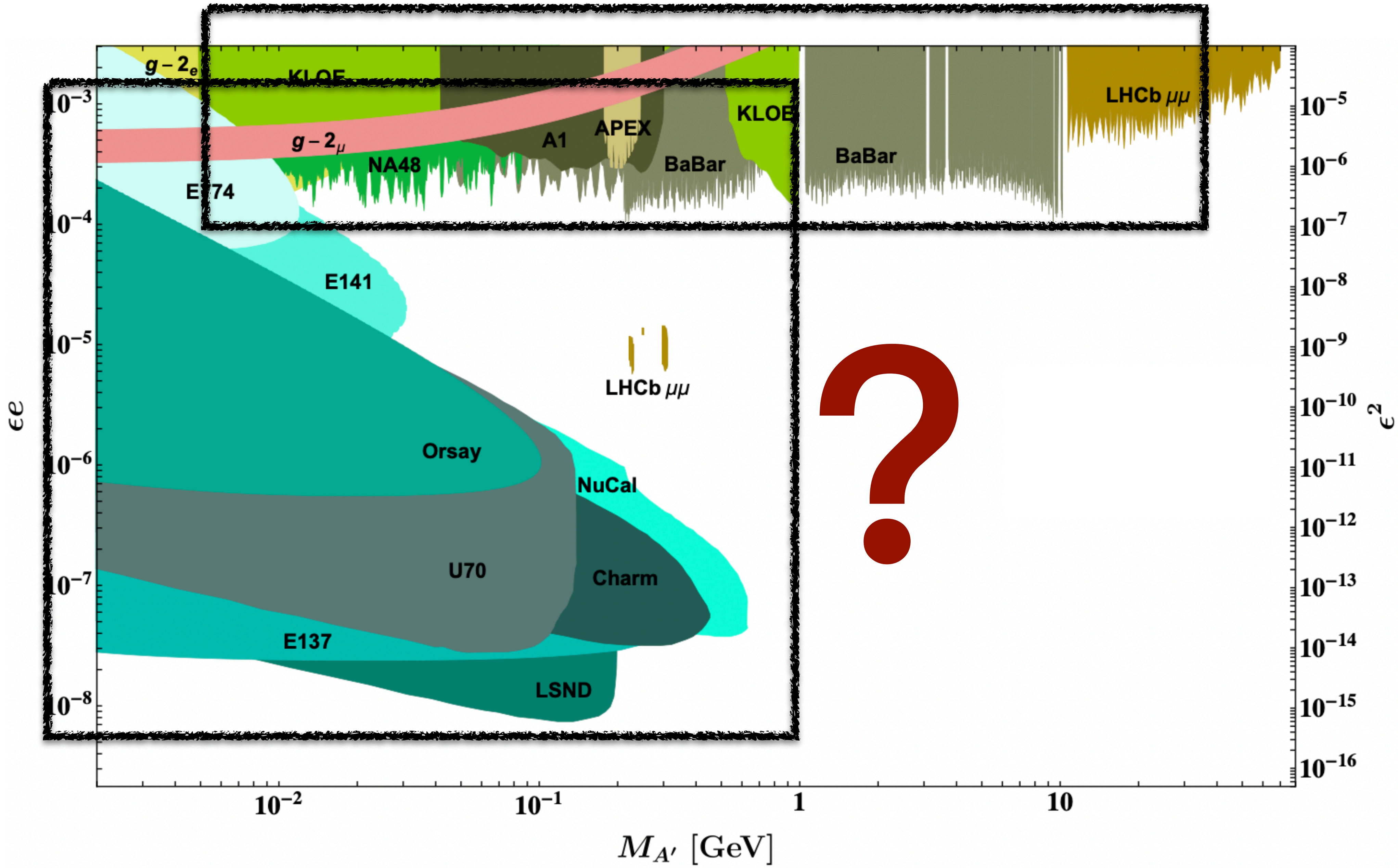


$$\boxed{\frac{\int_{y_{\max}-\Delta}^{y_{\max}} f(y)dy}{\int_{y_{\min}}^{y_{\min}+\Delta} f(y)dy} \to \sqrt{\frac{y_{\max}}{y_{\min}}}}$$

Oscillating A' effect on experiments?

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

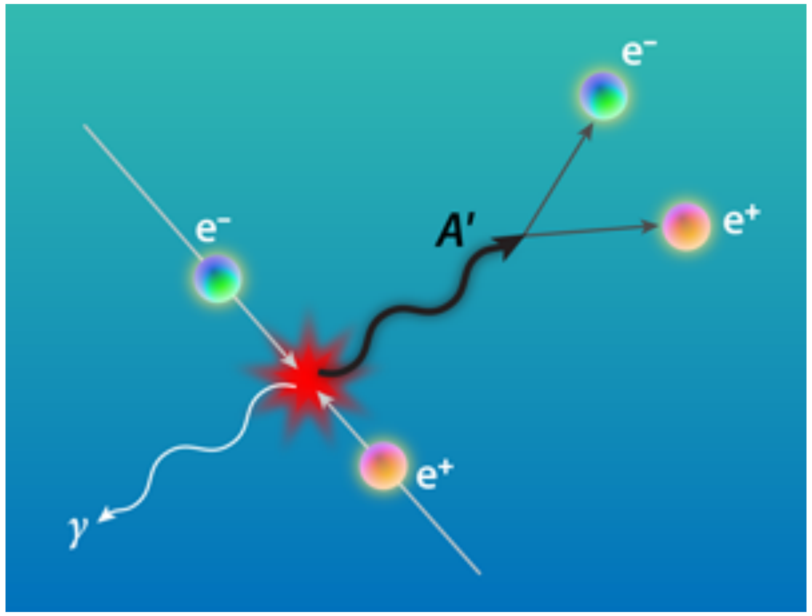
$$\mathscr{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_0^2 A'_\mu A'^\mu + \epsilon e A'_\mu J^\mu_{\rm em}$$



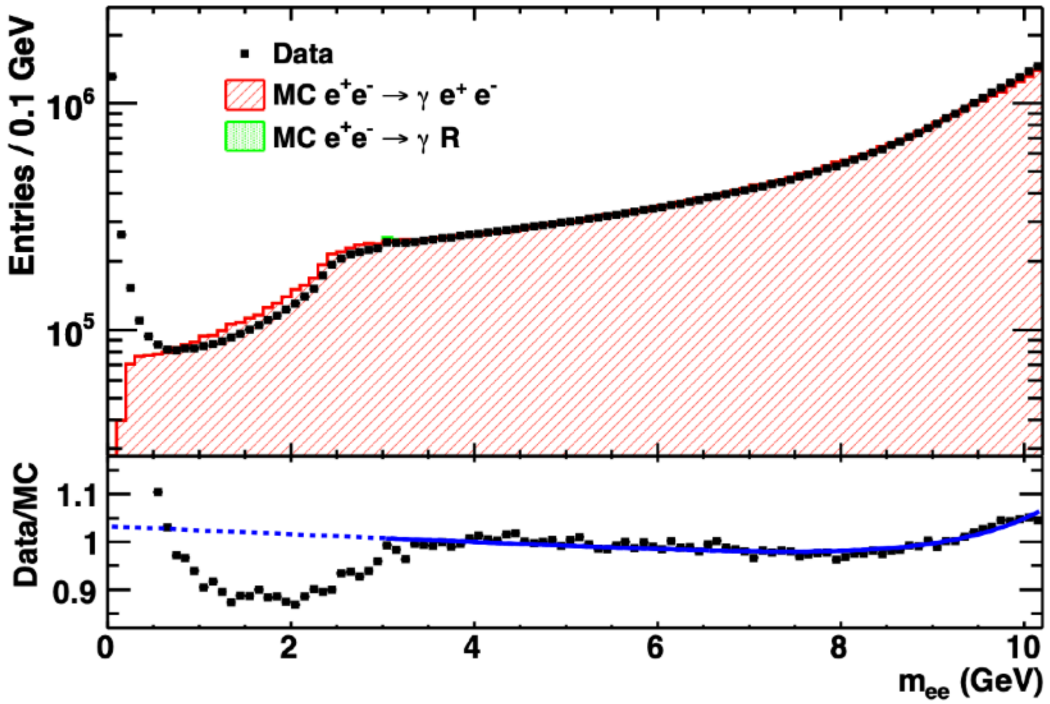
Prompt dilepton final states

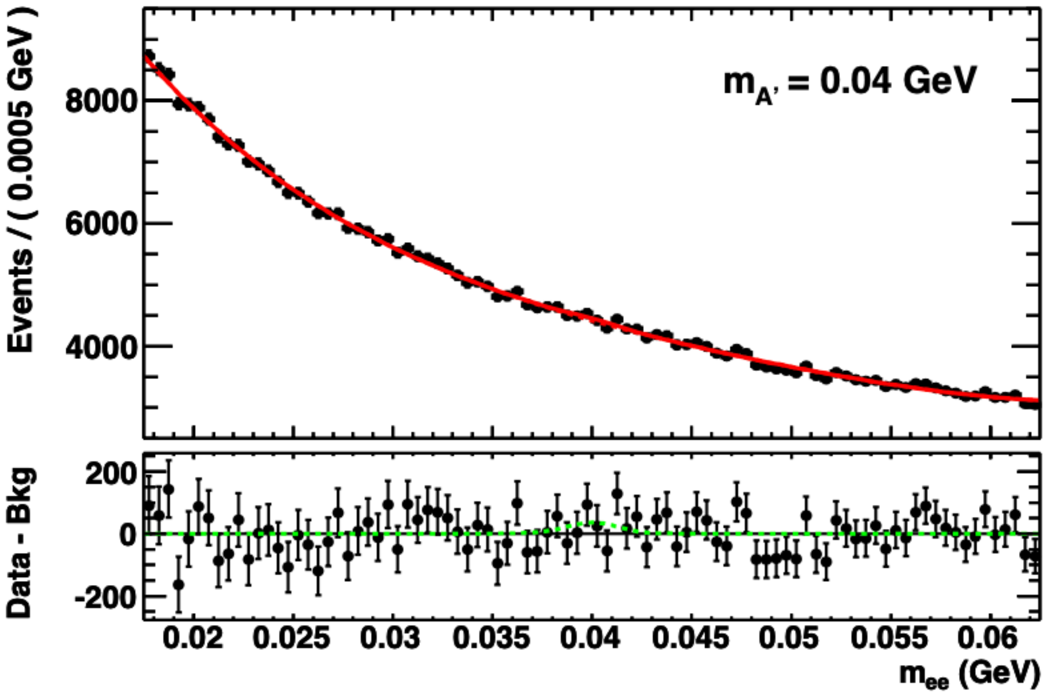
- General dilepton process

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



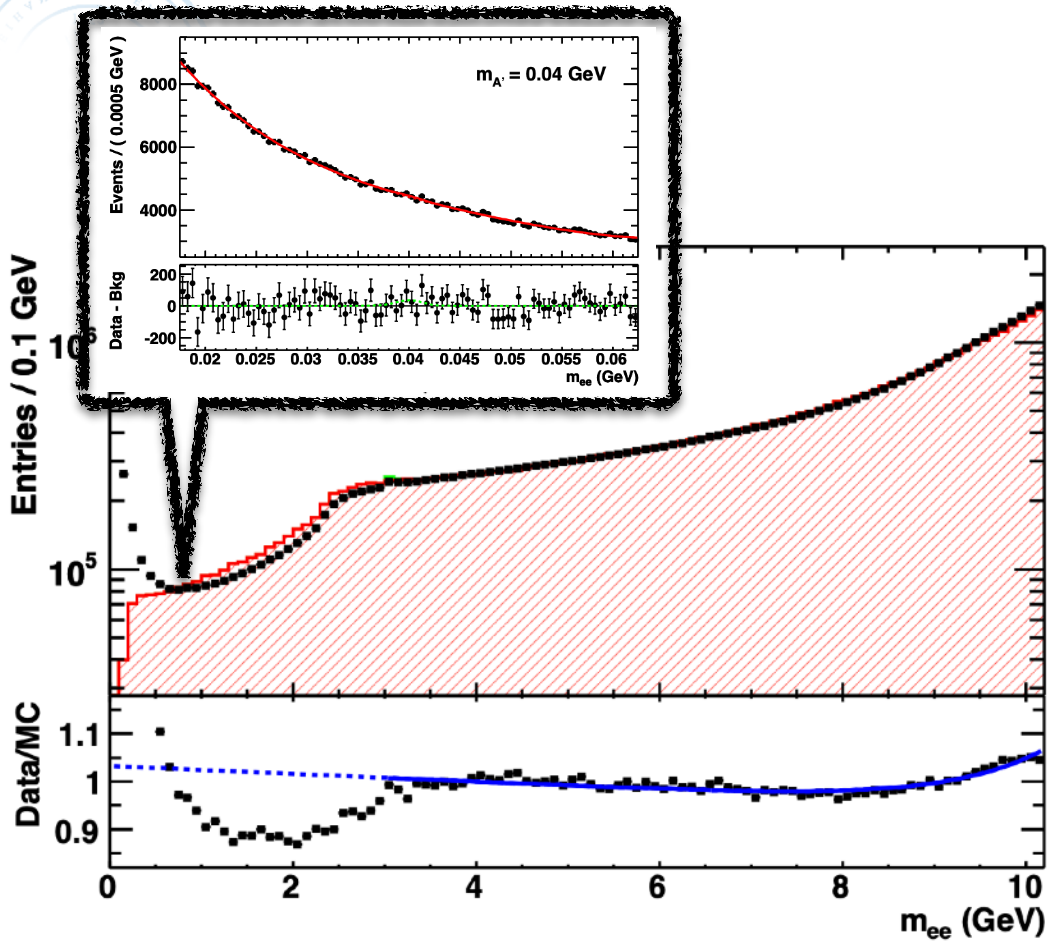
- BaBar data PRL 113, 201801 (2014)

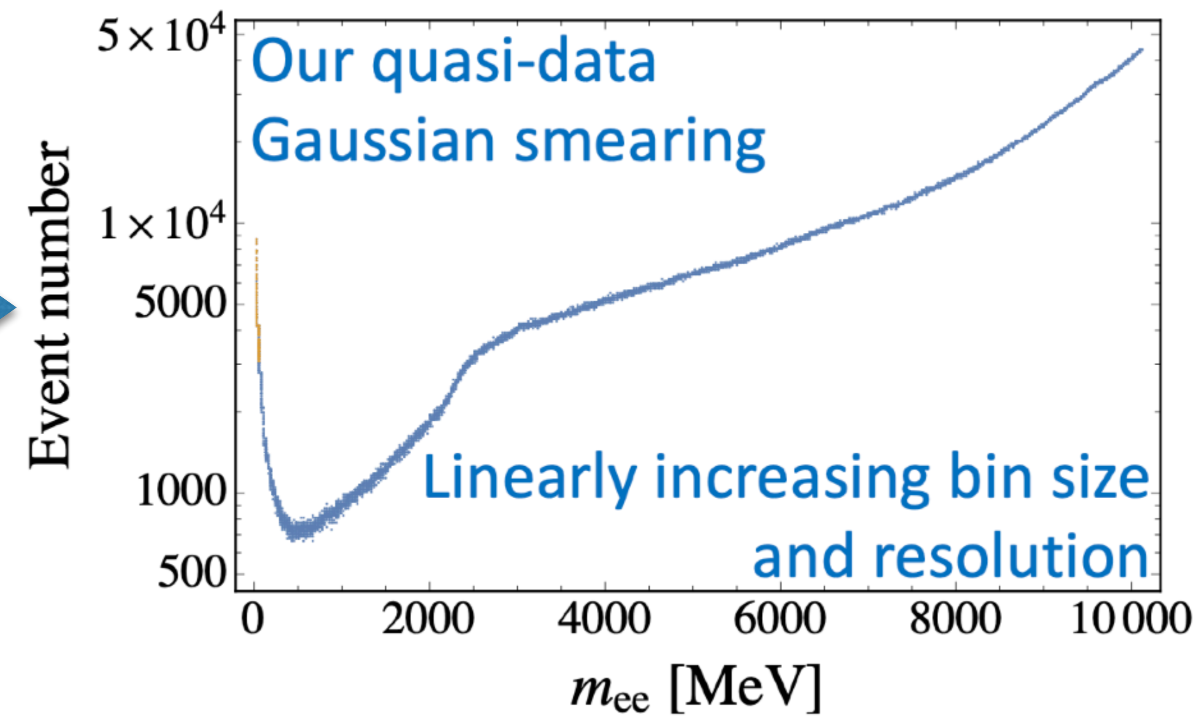




Recast BaBar experiment result

PRL 113, 201801 (2014)





- Log likelihood ratio (LLR)

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

Recast BaBar experiment result

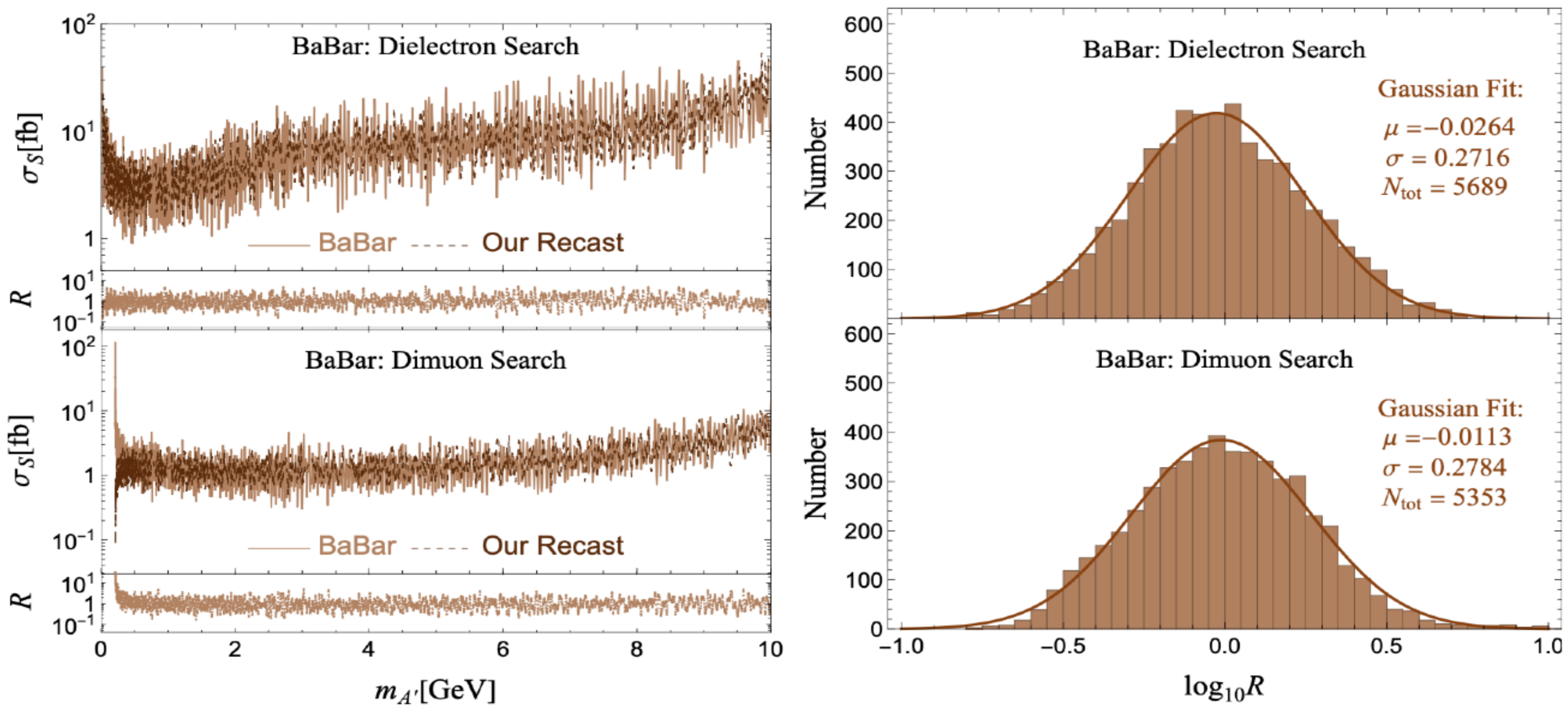
- Traditional single-peak analysis

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

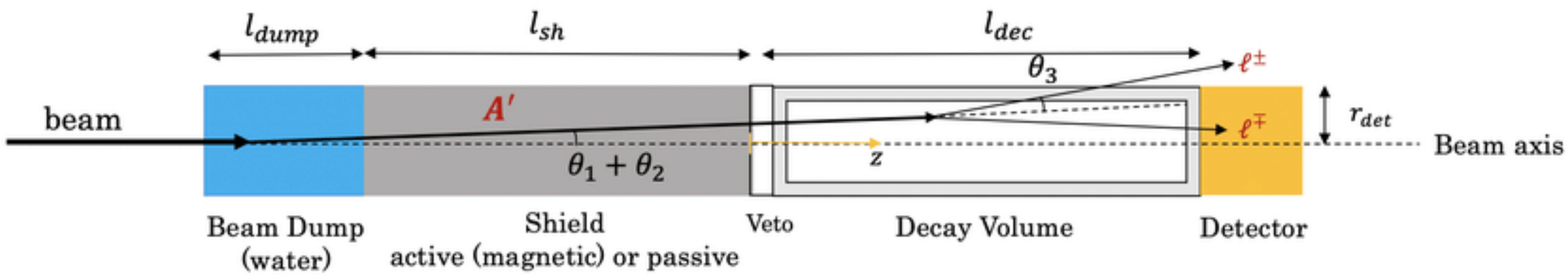
- Double-peak analysis

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

- Recast result:



Beam Dump Experiments



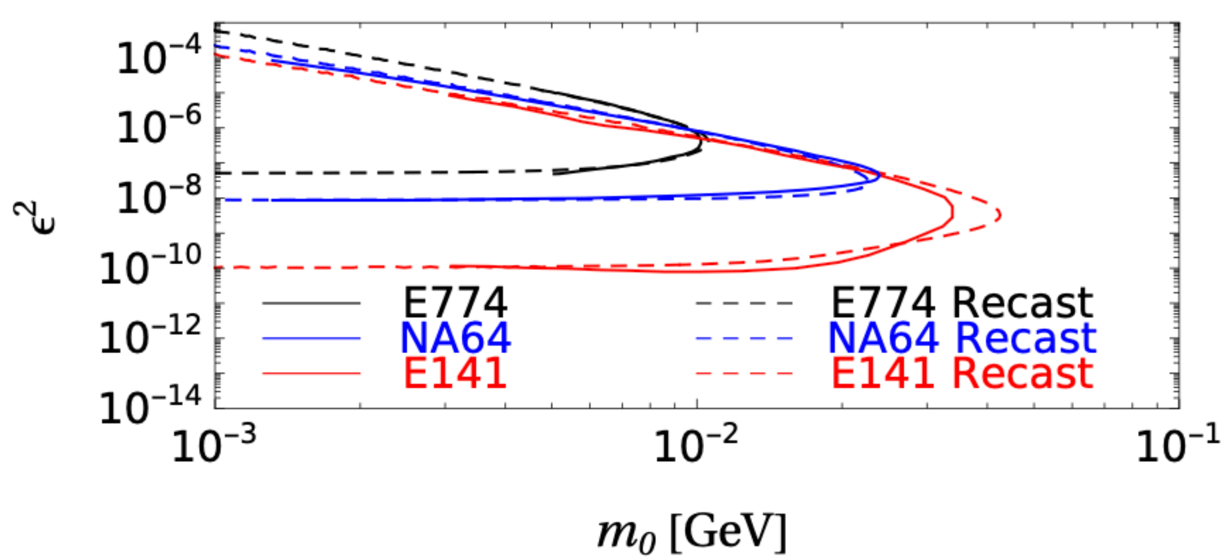
- General event number:

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

- Including oscillation effect

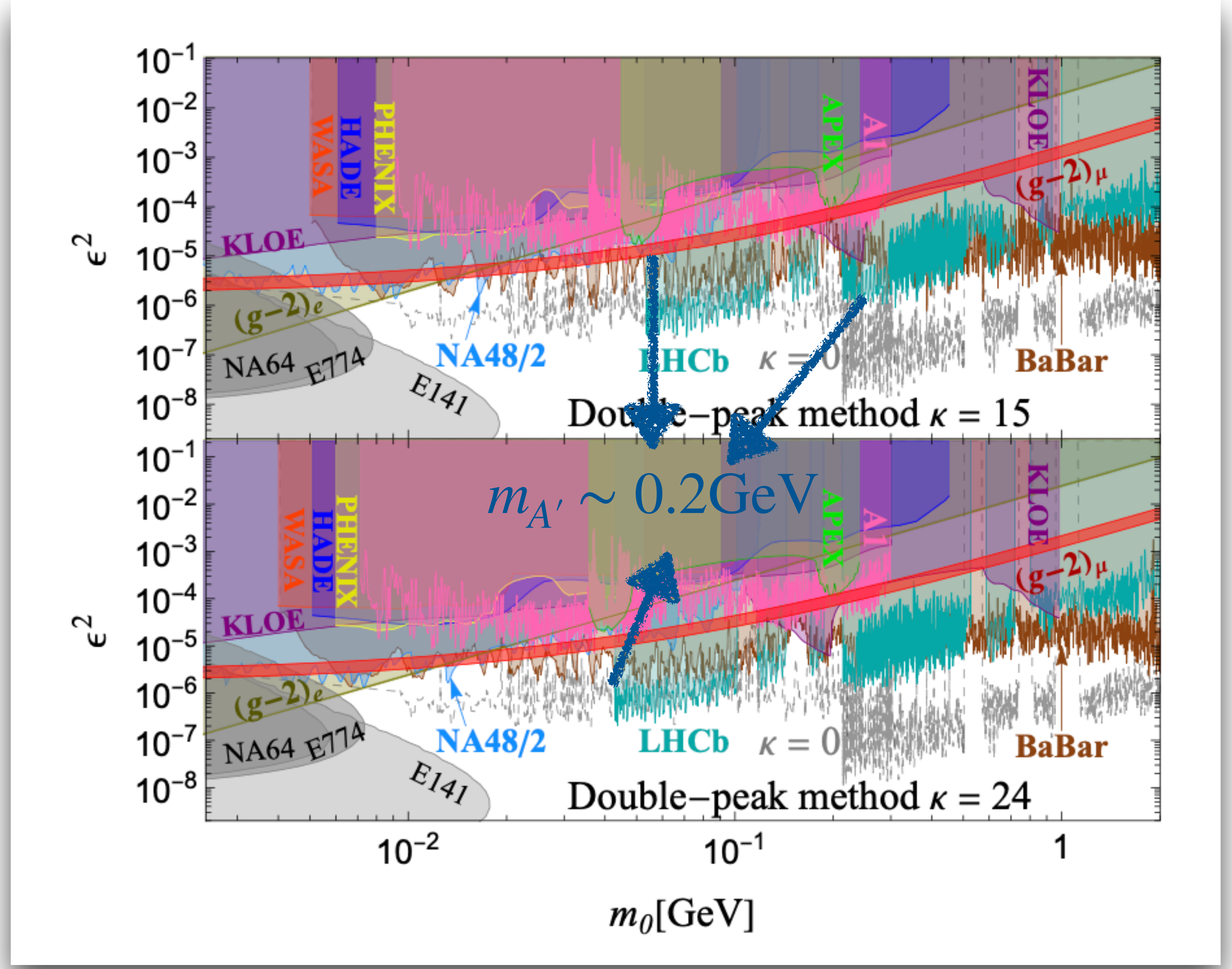
$$N\left(\epsilon, m_0, \kappa\right) = \frac{1}{\tau} \int_{m_0}^{\sqrt{1+\kappa m_0}} N\left(\epsilon, m_{A'}\right) \left| \frac{dt}{dm_{A'}} \right| dm_{A'}$$

- Our recast result with $\kappa = 0$



Double-peak analysis result

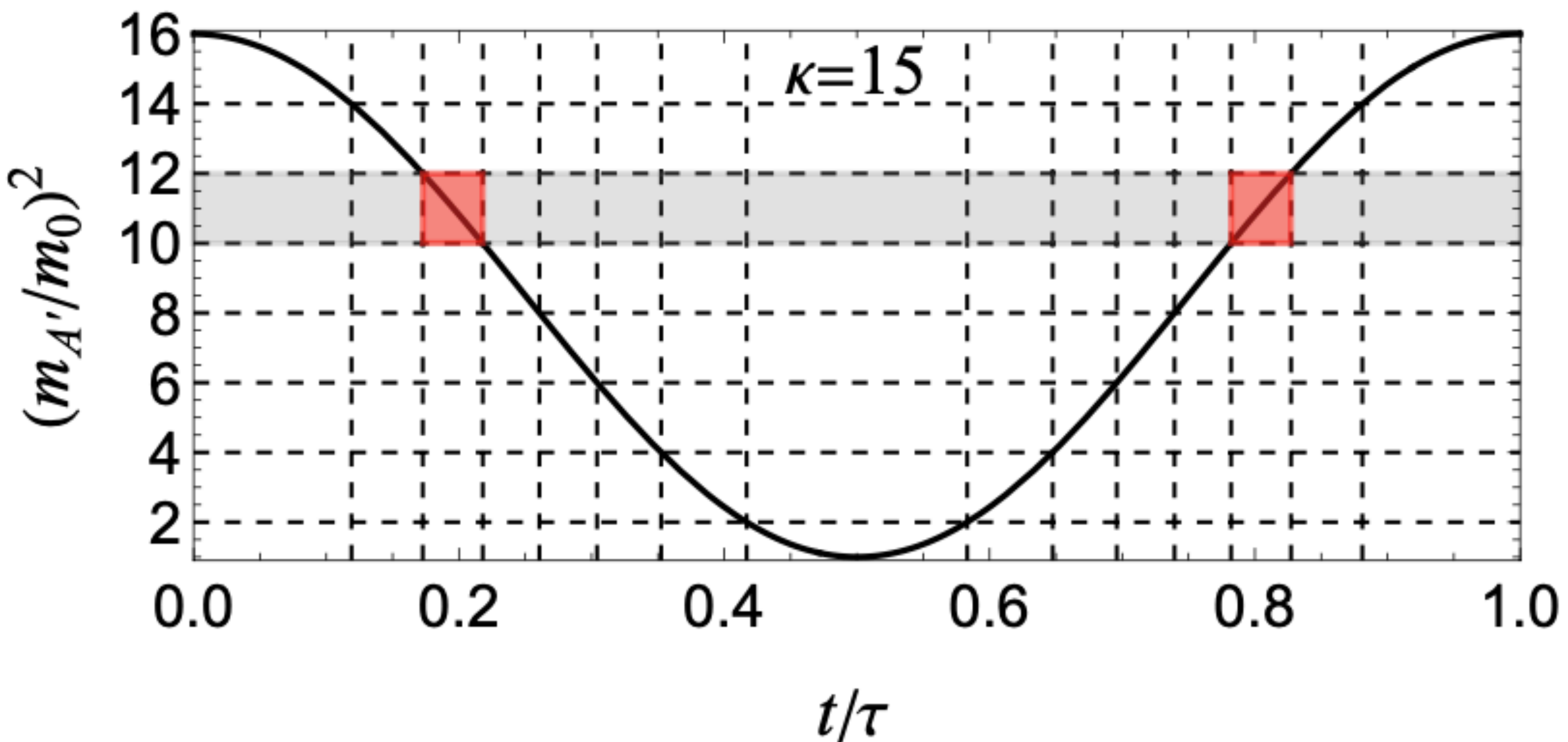
JG, YH, JL, XPW, KPX, arXiv:2206.14221



Improvement with time-varying

- Oscillating property

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

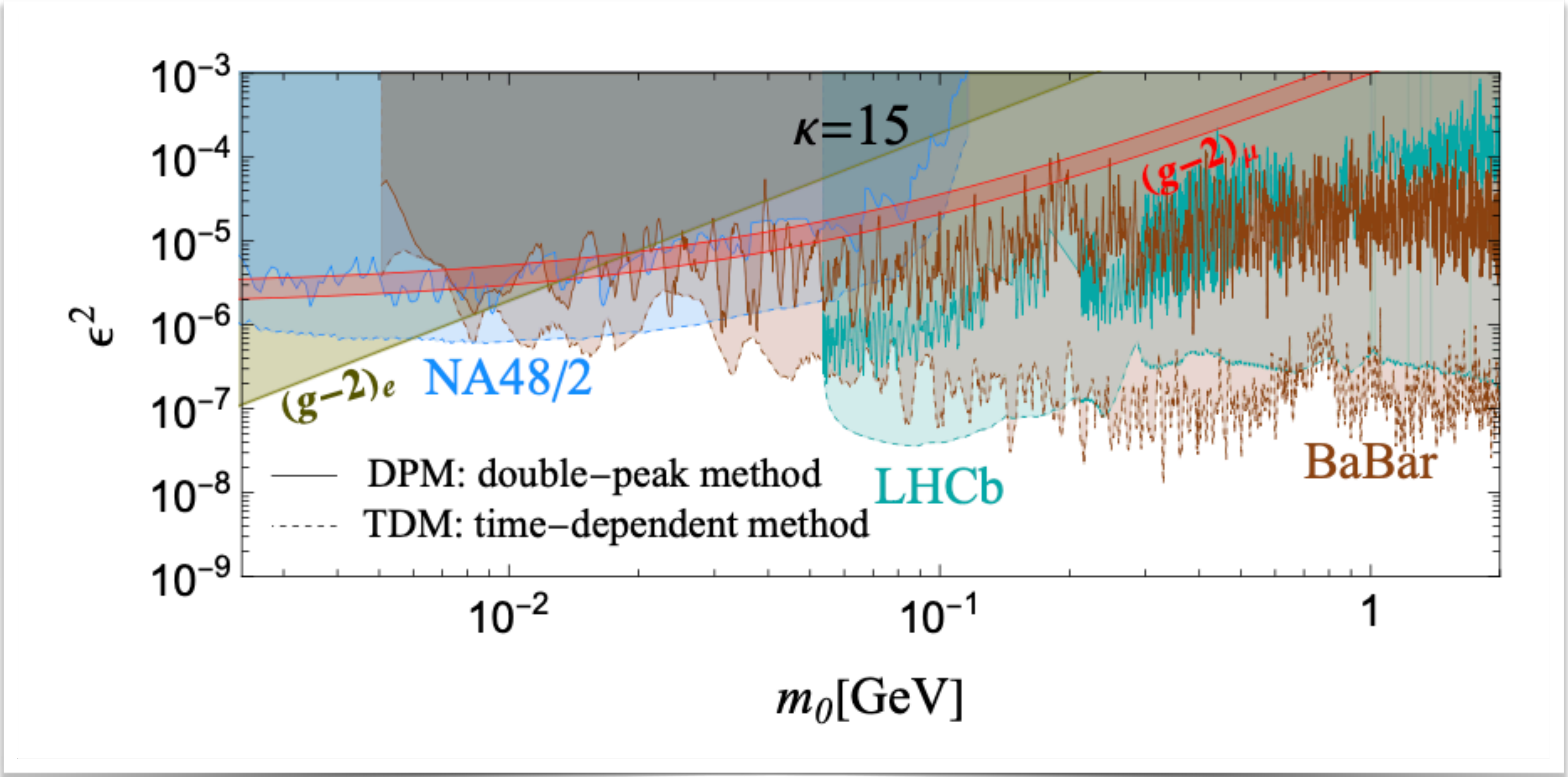


- Background event number

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

Improvement with time-varying

- Result with time-varying

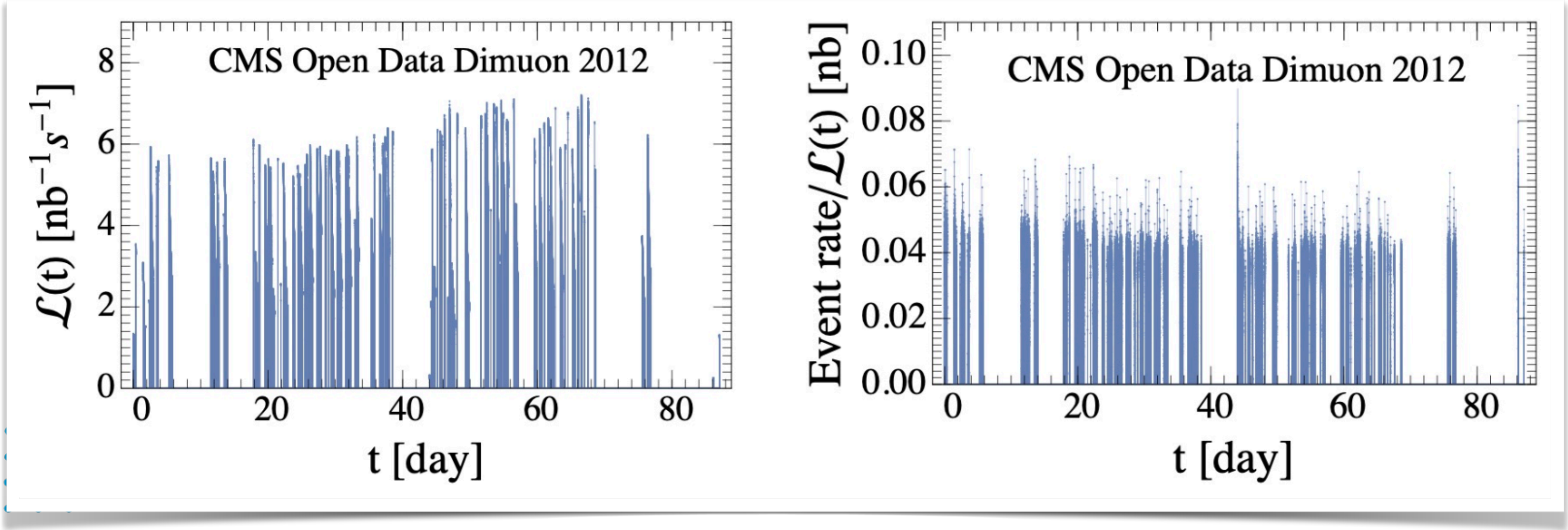


Justify TDM with CMS open data

- CMS open data 2012

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

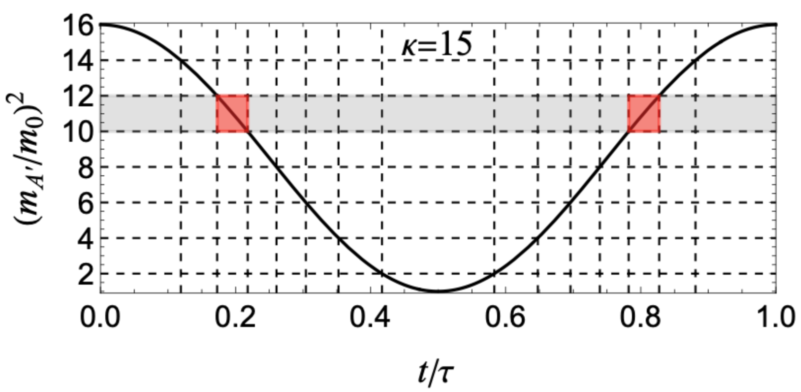
- Luminosity is not constant



CMS result with time information

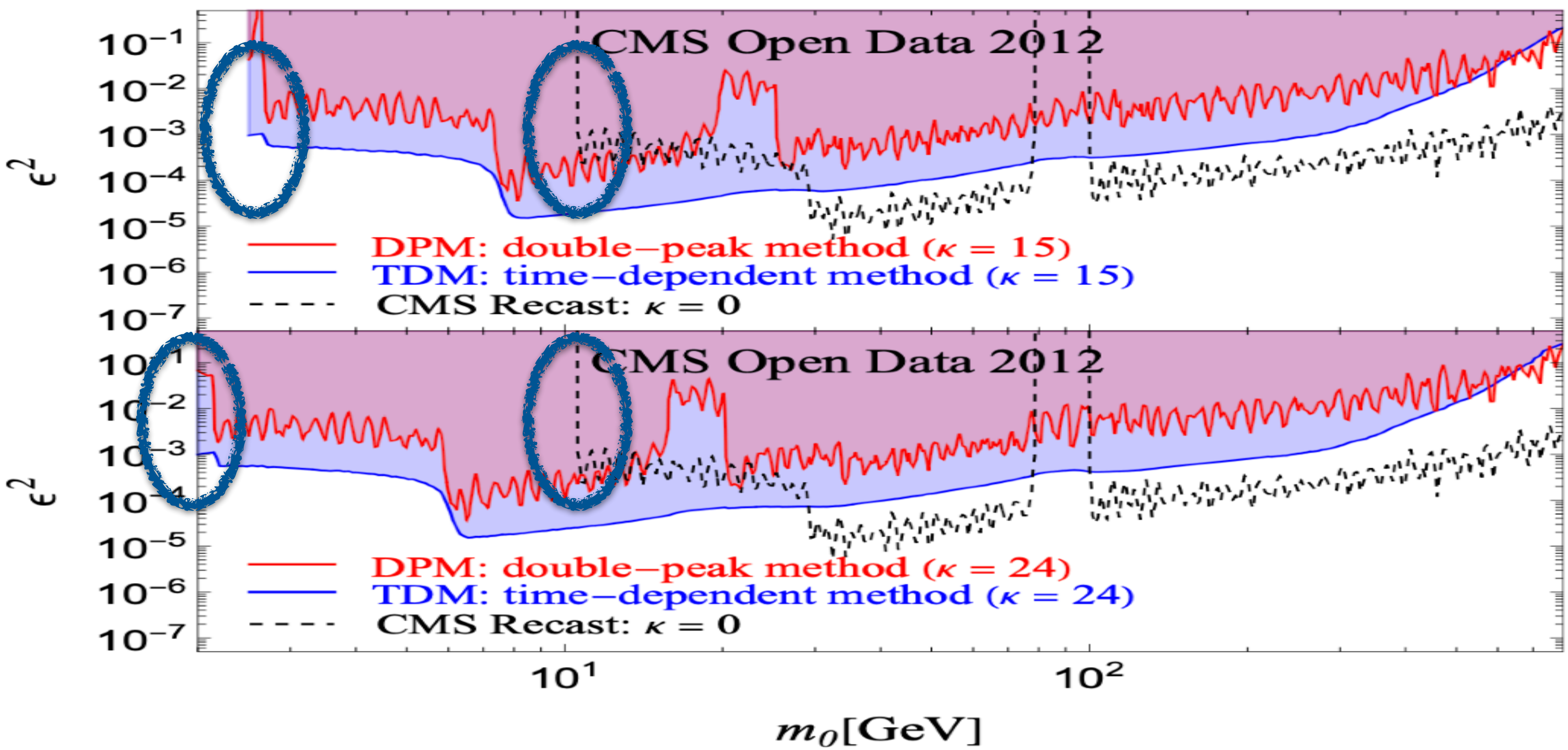
- Double-peak Method

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



- 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

- **The particle property of dark matter is important issue.**
- **Ultra light dark matter has important motivation.**
- **ChangE experiments set competitive limits on ALP-nucleon couplings**
- **Neutrino experiments can be used to detect ultra light DM**
- **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!