新物理模型

Jia Liu (刘佳)
北京大学物理学院

暗物质与新物理暑期学校2022
07/11/2022

提纲

- 轴子类轴子模型
- 暗光子模型
- 中微子模型

提纲：轴子

- The axion and strong CP problem
- Visible and invisible axion models
- Axion dark matter, ALP and experimental searches
- Summary

The QCD axion and the Strong CP problem

$$\mathscr{L} \supset -\frac{\theta g_s^2}{32\pi^2} G\tilde{G} - \left(\bar{u}_L M_u u_R + \bar{d}_L M_d d_R + \mathrm{h.c.}\right)$$

- The CKM matrix from $M_{u,d}$
  - CP violating phase θ_{CP} ~ 1.2 radian
- QCD induced CP violating phase, $\bar{\theta}$

$$\bar{\theta} = \theta + \arg\left[\det\left[M_u M_d\right]\right]$$

- $\bar{\theta}$ is invariant under quark chiral rotation

$$d^n_{\mathrm{EDM}} \sim \theta \times 10^{-16} \text{ e cm}$$

- According to neutron EDM experiment

$$d^n_{\exp} < 10^{-26} \text{ e cm}$$

$$\bar{\theta} \lesssim 1.3 \times 10^{-10} \text{ radian}$$

The Peccei-Quinn solution to Strong CP problem

- Experiment requires $\bar{\theta} = \theta + \arg\left[\det\left[M_u M_d\right]\right] \lesssim 10^{-1}\mathrm{rad}$
- PQ: promote the constant $\bar{\theta}$ to a dynamical field, a
- Vafa-Witten theorem: vector-like theory (QCD) has ground state $\langle\theta\rangle = 0$
- Introduce a *global* PQ-symmetry $U(1)_{\mathrm{PQ}}$, *anomalous* under the QCD
  - The massless Goldstone boson a is called *axion*
    - $a \to a + \kappa f_a \;\Rightarrow \mathcal{S} \to \mathcal{S} + \frac{\kappa}{32\pi^2}\int d^4x G\tilde{G}$, cancels $\bar{\theta}$
    - Low energy: $\mathscr{L} = \sum_q \bar{q}\left(iD_\mu\gamma^\mu - m_q\right)q - \frac{1}{4}GG + \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G} + \frac{1}{2}\left(\partial_\mu a\right)^2 + \mathscr{L}_{\mathrm{int}}[\partial_\mu a]$

Model independent visible axion properties

- For two flavor QCD, $q = (u, d)^T$
- $\mathscr{L} \supset \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G} + \frac{1}{4}g_{a\gamma}^0 aF\tilde{F} - \bar{q}_L M_q q_R + \frac{\partial_\mu a}{2f_a}\bar{q}c_q^0\gamma^\mu\gamma_5 q + h.c.$
- The three QCD related terms can be eliminated to 2 d.o.f.
- Choose to eliminate $G\tilde{G}$ term by quark field redefinition in a-related chiral rotation
  - A new quark field: $q' = \exp\left(i\frac{a}{2f_a}\gamma_5 Q_a\right)q$
  - $\mathscr{L} \supset \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{1}{4}g_{a\gamma}F\tilde{F} - \bar{q}'_L M_{q'} q'_R + \frac{\partial_\mu a}{2f_a}\bar{q}' c_q \gamma^\mu\gamma_5 q' + h.c.$

Model independent visible axion properties

- In the new basis
- $\mathscr{L} \supset \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{1}{4} g_{a\gamma} a F\tilde{F} - \bar{q}'_L M_a q'_R + \frac{\partial_\mu a}{2f_a} \bar{q}' c_q \gamma^\mu \gamma_5 q' + h.c.$
- $c_q = c_q^0 + Q_q\,,\ g_{a\gamma} = g_{a\gamma}^0 - 2N_c \frac{\alpha_{em}}{2\pi f_a} \mathrm{Tr}[Q_a Q^2]$
- Quark mass is complex: $M_a = \exp\left(i\frac{a}{2f_a}Q_a\right) M_q \exp\left(i\frac{a}{2f_a}Q_a\right)$
- Subtlety: fix the basis (gauge) and follow through the whole calculation
  - E.g. BR$(K^- \to \pi^- a)$ was overestimated by 40 times for ~35 years

Bauer, Neubert et al: 2102.13112 (PRL)

  - The auxiliary chiral rotation should not affect physical observables

The axion and Chiral Lagrangian

- The generic low energy Lagrangian is

$$\mathscr{L} \supset \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{1}{4} g_{a\gamma} F\tilde{F} - \bar{q}_L M_a q_R + \frac{\partial_\mu a}{2f_a}\bar{q} c_q \gamma^\mu \gamma_5 q + h.c.$$

- Two flavor quarks $q = (u, d)$; quark mass term $M_a = e^{i\frac{aQ_a}{2f_a}} M_q e^{i\frac{aQ_a}{2f_a}}$

- Below the QCD scale, one needs the chiral axion Lagrangian

$$\mathscr{L}_a^{\chi PT} = \frac{f_\pi^2}{4}\mathrm{Tr}\left[(D^\mu U)^\dagger D_\mu U + 2B_0(UM_a^\dagger + M_a U^\dagger)\right] + \frac{\partial^\mu a}{4f_a}\mathrm{Tr}[c_q \sigma^a] J_\mu^a$$

$$U \equiv e^{i\pi^a \sigma^a / f_\pi}$$

$$J_\mu^a \equiv e^{i\pi^a \sigma^a / f_\pi}$$

Axion mass and interaction with pions

$$\mathscr{L}_a^{\chi PT} = \frac{f_\pi^2}{4}\mathrm{Tr}\left[(D^\mu U)^\dagger D_\mu U + 2B_0(UM_a^\dagger + M_a U^\dagger)\right] + \frac{\partial^\mu a}{4f_a}\mathrm{Tr}[c_q\sigma^a]J_\mu^a$$

- Axion mass: $m_a^2 \simeq (Q_u + Q_d)^2 \dfrac{m_u m_d}{(m_u + m_d)^2}\dfrac{m_\pi^2 f_\pi^2}{f_a^2}$
- Axion-π^0 mixing: $\theta_{a\pi} \simeq \dfrac{(Q_d m_d - Q_u m_u)}{(m_u + m_d)}\dfrac{f_\pi}{f_a}$
- Axion-pion couplings: $-\dfrac{3}{2}\dfrac{\epsilon}{f_a f_\pi}\partial_\mu a\left(2\partial^\mu\pi^0\pi^+\pi^- - \pi^0\partial^\mu\pi^+\pi^- - \pi^0\pi^+\partial^\mu\pi^-\right)$
- Coefficient: $\epsilon = -\dfrac{1}{2}\left(\dfrac{Q_d m_d - Q_u m_u}{m_u + m_d} + c_d^0 - c_u^0\right)\dfrac{f_\pi}{f_a}$

提纲：轴子

- The axion and strong CP problem
- Visible and invisible axion models
- Axion dark matter, ALP and experimental searches

The invisible axion models

- SM particles does not directly charge under $U(1)_{\rm PQ}$
    - KSVZ model:
        - Heavy vector-like quark: $Q_{L,R}$
        - Q_L and Q_R has different charge under $U(1)_{\rm PQ}$
        - A heavy complex scalar $\Phi = re^{ia}$ charge under $U(1)_{\rm PQ}$
        - Yukawa: $y\Phi\bar{Q}_L Q_R \supset \frac{yf_a}{\sqrt{2}}e^{ia/f_a}\bar{Q}_L Q_R$
        - Low energy: $\mathscr{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G}$

The invisible axion models

- Induce a complex scalar with very large vev

- DFSZ model:
  - Two Higgs doublet $H_{u,d}$ and a complex singlet Φ charged under $U(1)_{\mathrm{PQ}}$, with phase factor $e^{i\phi_{u,d,0}}$
  - Similar to previous UV model, but $\langle\Phi\rangle \gg v_h$
  - Yukawa: $\left(\bar{Q}Y_u H_u u_R + \bar{Q}Y_d H_d d_R + \bar{L}Y_e H_d e_R\right) + h.c.$
  - Potential term: e.g. $H_u H_d \Phi^2$,
  - Axion mode: $a = \frac{1}{f_a}\sum_{i=u,d,0} Q_i v_i \phi_i$
  - Low energy: $\mathscr{L} \supset \frac{\alpha_s}{8\pi^2}\frac{a}{f_a}G\tilde{G} + \frac{\alpha_{em}}{8\pi}\frac{E}{N}\frac{a}{f_a}F\tilde{F} - \bar{f}_L M_f f_R + \frac{\partial_\mu a}{2f_a}\bar{f}c_f\gamma^\mu\gamma_5 f$

The visible QCD axion constraints

- The visible axion is highly constrained by pion measurements

experimental limit on observable	translates into bound on model	expectation for generic MeV axions (LO in χPT)	expectation for MeV axion variant in (3.1) (NLO in χPT)	reason
beam dumps (see Fig.1)	$\tau_a \lesssim 10^{-13}$ s (see Fig.1)	$\tau_a < 10^{-12}$ s if $\lvert Q_e^{\rm PQ}\rvert \sim \mathcal{O}(1)$ $\tau_a \gtrsim 10^{-11}$ s if $Q_e^{\rm PQ} = 0$	$\lvert Q_e^{\rm PQ}\rvert \sim \mathcal{O}(1)$ $\tau_a \lesssim 10^{-13}$ s for $m_a \gtrsim 5 - 10$ MeV	MB
$\text{Br}(\pi^+ \to e^+\nu(a \to e^+e^-)) \lesssim 10^{-10}$	$\lvert\theta_{a\pi}\rvert \lesssim (0.5 - 0.7) \times 10^{-4}$	$\lvert\theta_{a\pi}\rvert \sim \mathcal{O}(0.01 - 0.1)\left(\frac{\text{GeV}}{f_a}\right)$	$\theta_{a\pi} \sim (0.2 \pm 3) \times 10^{-3}\left(\frac{\text{GeV}}{f_a}\right)$	PP, NLO
$\Delta\text{Br}(\pi^0 \to e^+e^-) \lesssim 2 \times 10^{-8}$	$Q_e^{\rm PQ} \times \theta_{a\pi} \lesssim 1.6 \times 10^{-4}\left(\frac{f_a}{\text{GeV}}\right)$			
$\text{Br}(K^+ \to \pi^+(a \to e^+e^-)) \lesssim 10^{-5} - 10^{-6}$	$\lvert\theta_{a\eta_{ud}}\rvert \lesssim 10^{-4}$ if octet enhanced $\lvert\theta_{a\eta_{ud}}\rvert \lesssim 10^{-2}$ if not	$\lvert\theta_{a\eta_{ud}}\rvert \sim \mathcal{O}(10^{-3} - 10^{-2})\left(\frac{\text{GeV}}{f_a}\right)$	$\theta_{a\eta_{ud}} \sim (-2 \pm 8) \times 10^{-3}\left(\frac{\text{GeV}}{f_a}\right)$	NLO
$\text{Br}(K^+ \to \pi^+(a \to \gamma\gamma)) \lesssim 10^{-9}$ $\text{Br}(\Phi \to \gamma(a \to e^+e^-)) \lesssim 5 \times 10^{-5}$	$\lvert\theta_{a\eta_s}\rvert \lesssim \mathcal{O}(10^{-1})$	$\lvert\theta_{a\eta_s}\rvert \sim \mathcal{O}(10^{-2})\left(\frac{\text{GeV}}{f_a}\right)$	$\theta_{a\eta_s} \sim (1 \pm 2) \times 10^{-2}\left(\frac{\text{GeV}}{f_a}\right)$	NLO
$\text{Br}(K^+ \to \pi^+(a \to \text{inv})) \lesssim 0.5 \times 10^{-10}$	$\text{Br}(a \to \text{inv}) \lesssim \mathcal{O}(10^{-4})$ (assuming $\tau_a < 10^{-12}$ s)	$\text{Br}(a \to \nu\bar{\nu}) \sim (Q_\nu^{\rm PQ} m_\nu / Q_e^{\rm PQ} m_e)^2$	$\text{Br}(a \to \chi\bar{\chi}) \sim (Q_\chi^{\rm PQ} m_\chi / Q_e^{\rm PQ} m_e)^2$ $\chi = \nu_{(e,\mu,\tau,s)}$, sub-MeV DM, ...	MB

Alves, Weiner, 1710.03764, JHEP 07(2018)092

The pionphobic axion and Atomki experiment

- Old solution: pion-phobic axion (not elegant but can work)

$$\theta_{a\pi} \simeq \frac{(Q_d m_d - Q_u m_u)}{(m_u + m_d)} \frac{f_\pi}{f_a}$$

$$\Rightarrow \theta_{a\pi} \lesssim 10^{-4}$$

$$m_u/m_d \simeq 0.47 \pm 0.06, \; \& \; Q_u \simeq 2Q_d$$

Can be tested by 3-body decay: $K \to \pi\pi a$
Pospelov et al: 2002.04623

- Atomki anomaly see bumpy feature from $^8\mathrm{Be}*$ and $^4\mathrm{He}*$ decays

$$^8\mathrm{Be}^*(17.64) \;\to\; {}^8\mathrm{Be}(0) + e^+e^- \;,$$
$$\Delta E = 17.64 \text{ MeV}, \quad \Delta I \approx 1\,,$$

$$^8\mathrm{Be}^*(18.15) \;\to\; {}^8\mathrm{Be}(0) + e^+e^- \;,$$
$$\Delta E = 18.15 \text{ MeV}\;, \quad \Delta I \approx 0\,.$$

$$(\mathrm{E0}) \quad {}^4\mathrm{He}^*(20.49) \to {}^4\mathrm{He}(0) + (\gamma^* \to e^+e^-)\,,$$
$$\Delta E = 20.49 \text{ MeV}\,, \quad \Delta I = 0\,,$$

$$(\mathrm{M0}) \quad {}^4\mathrm{He}^*(21.01) \to {}^4\mathrm{He}(0) + (a \to e^+e^-)\,,$$
$$\Delta E = 21.01 \text{ MeV}\,, \quad \Delta I = 0\,,$$

- It might be connect to 17MeV pion-phobic axion which couples to electrons.

Alves, 2009.05578, PRD 103(2021)5, 055018

The UV model building

- The visible axion receives stringent constraint, but pion-phobic axion can be safe
- It has to couple to 1st gen fermions with $Q_u = 2Q_d$
- Atomki experiments and electron g-2 can be explained if axion couples to electron
- The requirements of 1st gen quarks coupling, CKM matrix and quark mass generation are non-trivial: fully determines the UV Yukawa
- SM Higgs can decay to axion pair, resulting lepton-jet features

JL, N. McGinnis, C. E.M. Wagner, X.P. Wang 2102.10118 [JHEP]

The UV model building

- Pion-phobic QCD axion with coupling to electron

$$\mathscr{L}_{int} = \sum_{f=e,u,d,} m_f e^{iQ_f a/f_a} \bar{f}_L f_R + h.c. \approx \sum_f g_a^f ia\bar{f}\gamma_5 f, \quad g_a^f = \frac{Q_f m_f}{f_a}.$$

$$g_a^{\gamma\gamma} = \frac{\alpha}{4\pi f_\pi}\left(\theta_{a\pi} + \frac{5}{3}\theta_{a\eta_{ud}} + \frac{\sqrt{2}}{3}\theta_{a\eta_s}\right),$$

- The goal: couples to 1st gen fermions, CKM matrix and quark mass generation

$$\mathscr{L}_{\rm PQ}^{\rm Yuk} \supset -\sum_{i=1,2,3}\left(\bar{Q}^i Y_u^{i1} H_u u_R^1 + \bar{Q}^i Y_d^{i1} H_d d_R^1 + \bar{L}^i Y_e^{i1} H_e e_R^1\right) + h.c.$$

$$\mathscr{L}_{\rm SM}^{\rm Yuk} \supset -\sum_{i=1,2,3}\sum_{j=2,3}\left(\bar{Q}^i Y_u^{ij}\tilde{H} u_R^j + \bar{Q}^i Y_d^{ij} H d_R^j + \bar{L}^i Y_e^{ij} H e_R^j\right) + h.c.$$

Particles	H	H_u	$H_{d,e}$	u_R	d_R	e_R	ϕ_f
$SU(2)_L$	2	2	2	1	1	1	1
$U(1)_Y$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{2}{3}$	$-\frac{1}{3}$	-1	0
$U(1)_{\rm PQ}$	0	$-Q_u$	$-Q_{d,e}$	Q_u	Q_d	Q_e	$-Q_f$

$Q_u = 2,\ Q_d = 1;\ Q_e = 1/2$ or $1/3$

Quark mass and CKM matrix

- Up and Down quark mass diagonalization ($V_R = 1$)

$$M_u \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} Y_u^{11} v_u & Y_u^{12} v & Y_u^{13} v \\ Y_u^{21} v_u & Y_u^{22} v & Y_u^{23} v \\ Y_u^{31} v_u & Y_u^{32} v & Y_u^{33} v \end{pmatrix} = V_{u_L} \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} V_{u_R}^\dagger \qquad V_{\rm CKM} = V_{u_L}^\dagger V_{d_L} .$$

- The specific Higgs H_u couples to 1st gen up-quark only

$$\bar{Q}^i Y_u^{i1} H_u u_R^1 = \overline{Q^m}^i \left(V_{u_L}^\dagger\right)^{ij} Y_u^{j1} H_u u_R^{1,m} = \sqrt{2}\frac{m_u}{v_u} \overline{Q^m}^1 H_u u_R^{1,m}, \qquad \Rightarrow \left(V_{u_L}^\dagger\right)^{ij} Y_u^{j1} = \sqrt{2}\frac{m_u}{v_u}(1,0,0)^T .$$

- The unitary matrix can be decomposed into

$$V_{u_L}^\dagger = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_x & s_x \\ 0 & -s_x & c_x \end{pmatrix} \begin{pmatrix} (Y_u^{j1})_\parallel^T \\ (Y_u^{j1})_{\perp 1}^T \\ (Y_u^{j1})_{\perp 2}^T \end{pmatrix} \qquad Y_u^{j1} = \sqrt{2}\frac{m_u}{v_u} \begin{pmatrix} c_{13} \\ 0 \\ s_{13} \end{pmatrix} \qquad x = \theta_{23}$$

- The Yukawa coupling is fully fixed by requirements: CKM and 1st gen only coupling

The axion couplings

- The scalar potential

$$V_{\rm PQ} = \left(A_u \phi_u^* H \cdot H_u + A_d \phi_d^* H^\dagger H_d + A_e \phi_e^* H^\dagger H_e + A_\phi \phi_u^* \phi_d^2 + B_\phi \phi_d^* \phi_e^n\right) + h.c.,$$

$$V_{\rm dia} = \sum_\Phi -\mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi \left(\Phi^\dagger \Phi\right)^2,$$

- The axion as the Goldstone mode

$$\vec{G}_{\rm SM} = \frac{1}{\sqrt{v^2 + v_u^2 + v_d^2 + v_e^2}} \left(v,\ v_u,\ v_d,\ v_e\ 0,\ 0,\ 0 \right),$$

$$\vec{G}_{\rm PQ} \approx \frac{1}{\sqrt{\sum_f Q_f^2 (v_f^2 + v_{\phi f}^2)}} \times \left(-\frac{\sum_f (-1)^f Q_f v_f^2}{v},\ -Q_u v_u,\ Q_d v_d,\ Q_e v_e,\ Q_u v_{\phi_u},\ Q_d v_{\phi_d},\ Q_e v_{\phi_e} \right)$$

- The axion coupling to SM

$$\sum_{f=u,d,e} \frac{m_f}{f_a} Q_f i a \bar{f} \gamma_5 f + Q_{F,\,\rm eff}^{\rm PQ} \sum_{F=\rm 2nd,3rd} \frac{m_F}{f_a} i a \bar{F} \gamma_5 F,$$

$$Q_{F,\,\rm eff}^{\rm PQ} \equiv -\frac{\sum_f (-1)^f Q_f v_f^2}{v^2}.$$

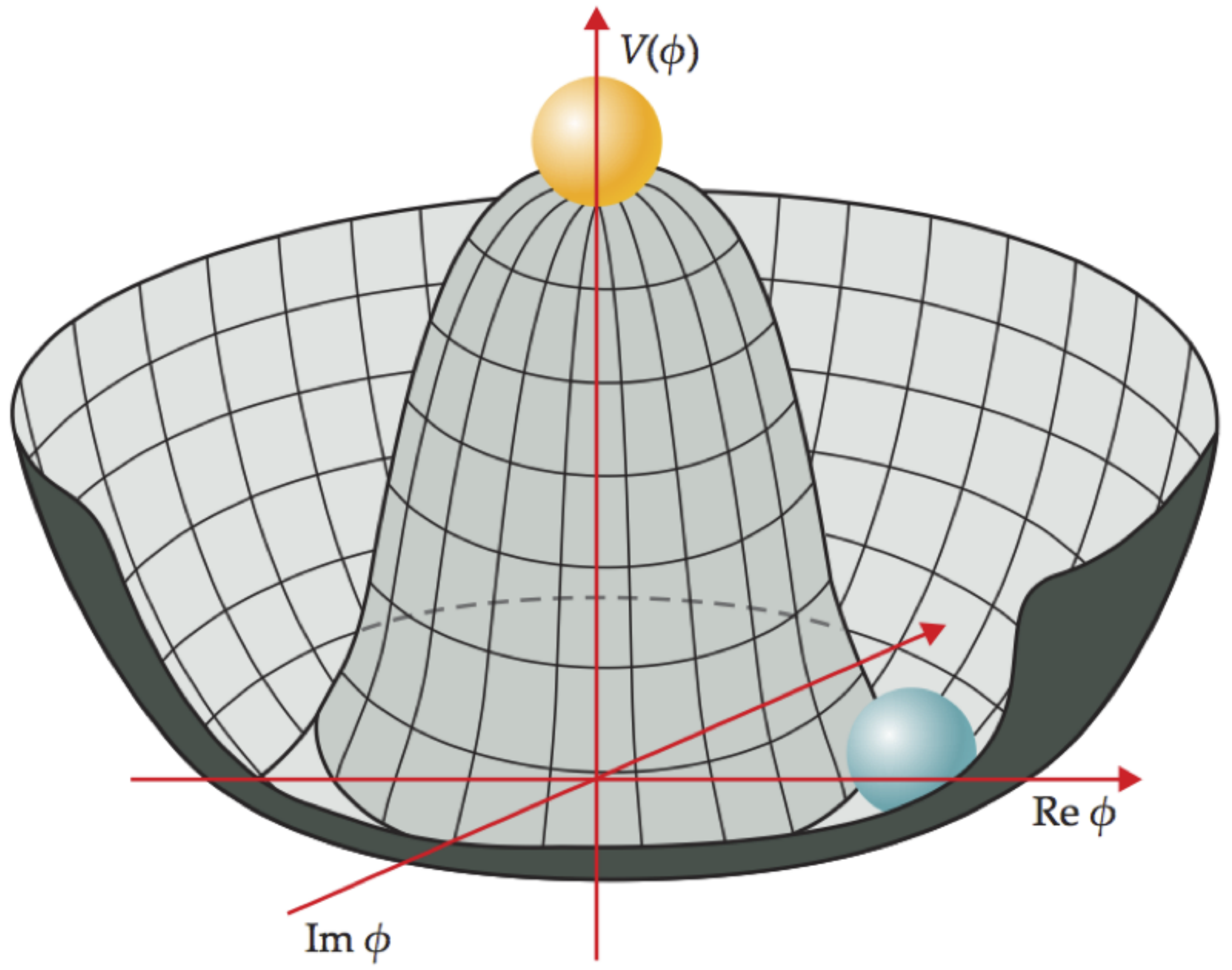
Outline

- The axion and strong CP problem
- Visible and invisible axion models
- Axion dark matter, ALP and experimental searches

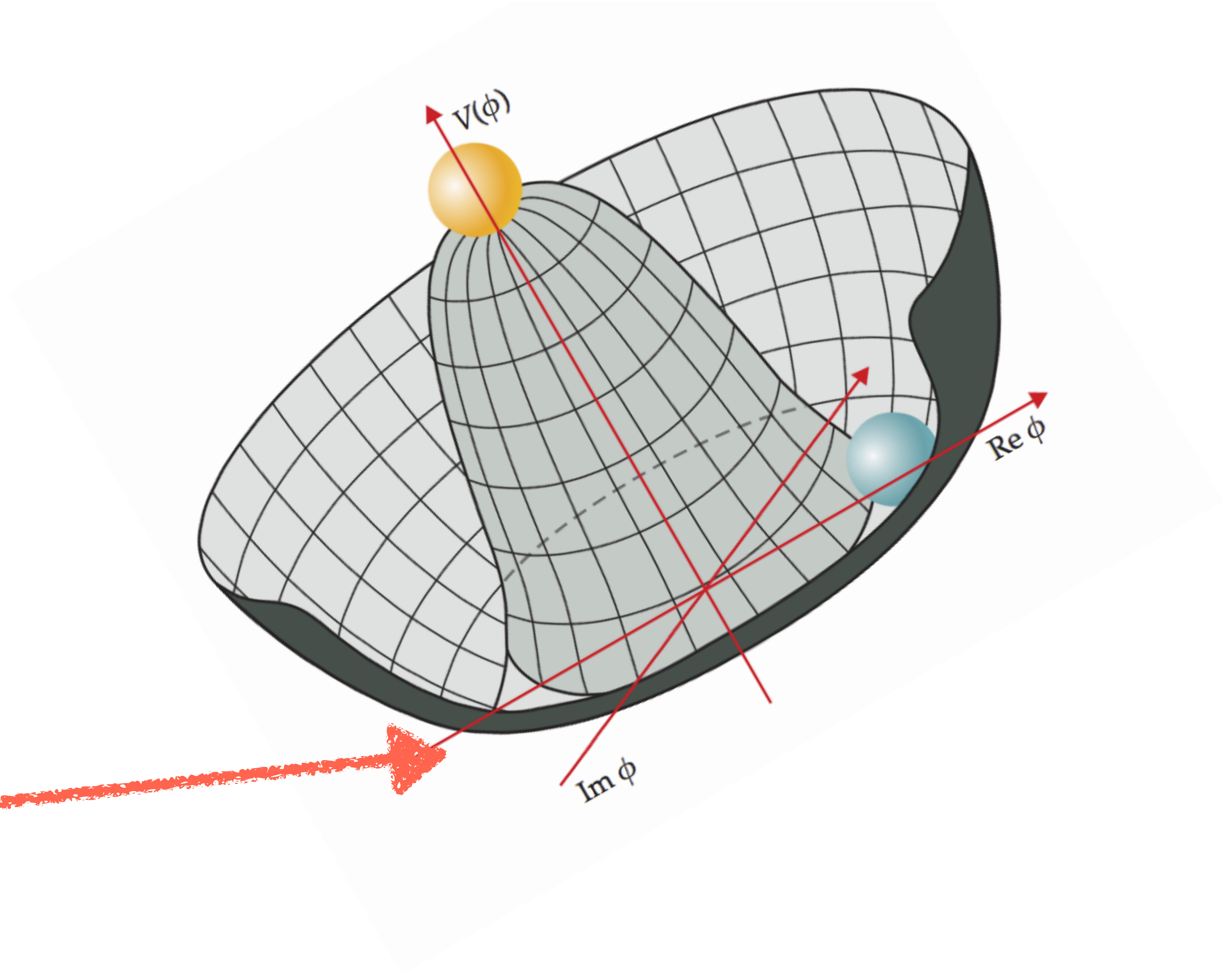
Misalignment and Axion Dark Matter

- Global $U(1)_{PQ}$ symmetry
  - Spontaneous broken leads to massless goldstone (Axion)

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$



- At QCD scale ~ O(1) GeV,
  - Potential from Chiral Lagrangian explicitly breaks the symmetry leads to massive axion
  - Energy stored in coherent oscillation of axion field
  - When $m_\phi \sim \frac{\Lambda^2}{f_\phi} \sim H$, misalignment happens and the fields turns into particles: cold dark matter
  - QCD vacuum picks $\Theta = \theta_{\rm QCD} + \xi\langle a\rangle/f_a = 0$



Experimental searches for Axion-Like Particles axion

$$\mathscr{L}_{\mathrm{ALP}} = g_{ag}\frac{a}{f_a}G\tilde{G} + g_{a\gamma}\frac{a}{f_a}F\tilde{F} + g_{af}\frac{\partial_\mu a}{2f_a}\bar{f}\gamma^\mu\gamma_5 f$$

- Sources of ALP:

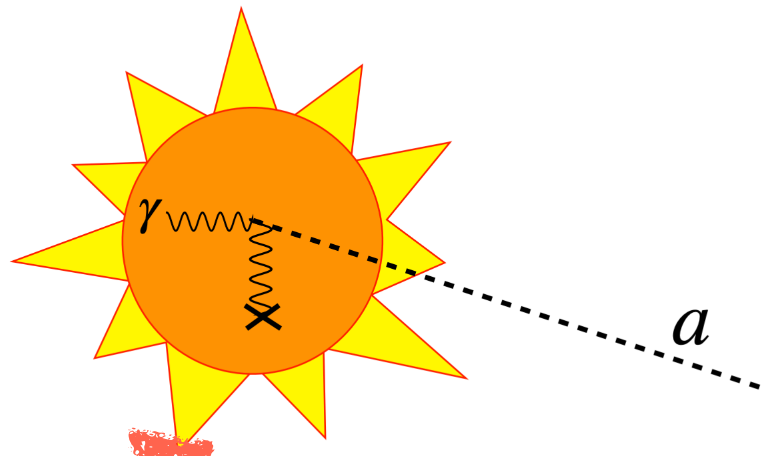
m_a and f_a are not fixed by QCD scale

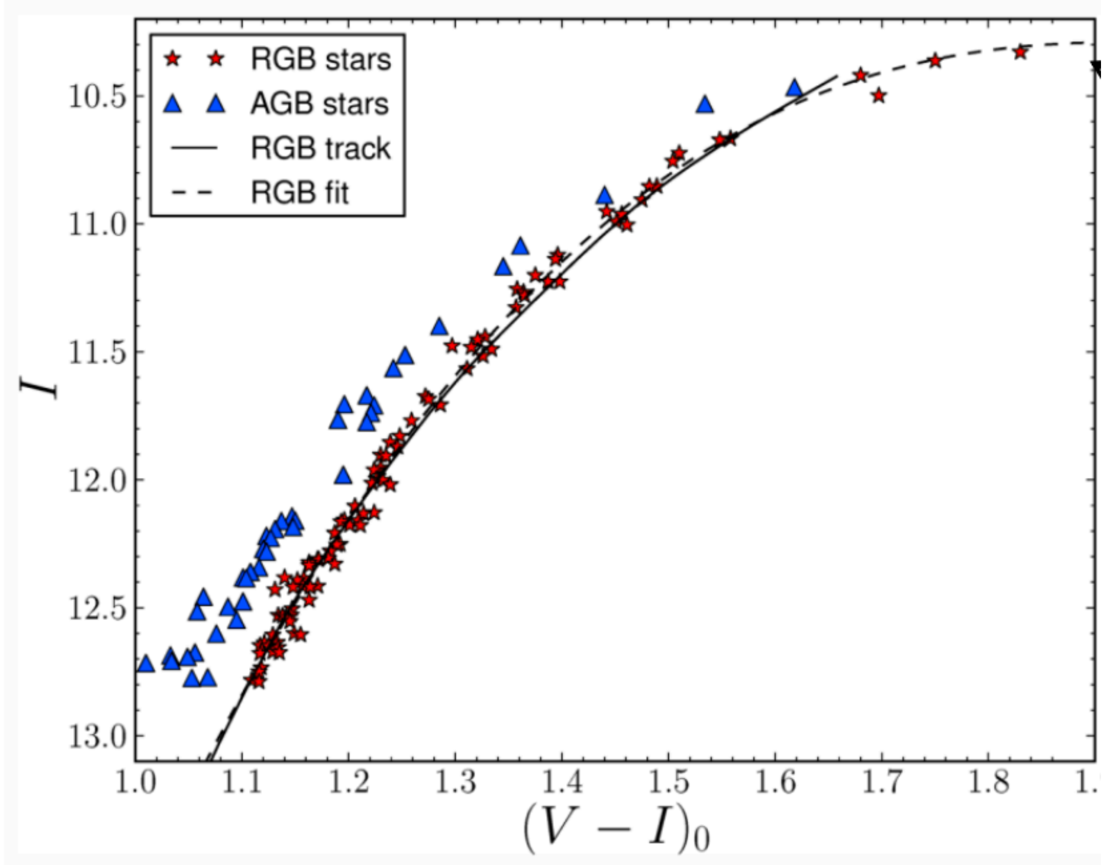
  - Astrophysical objects: Sun, Horizontal Branch, Neutron Star, SuperNova etc…
  - ALP dark matter from misalignment
  - ALP produced inside laboratory: laser conversion, beam dump, ee collider, pp collider
  - ALP as force mediator

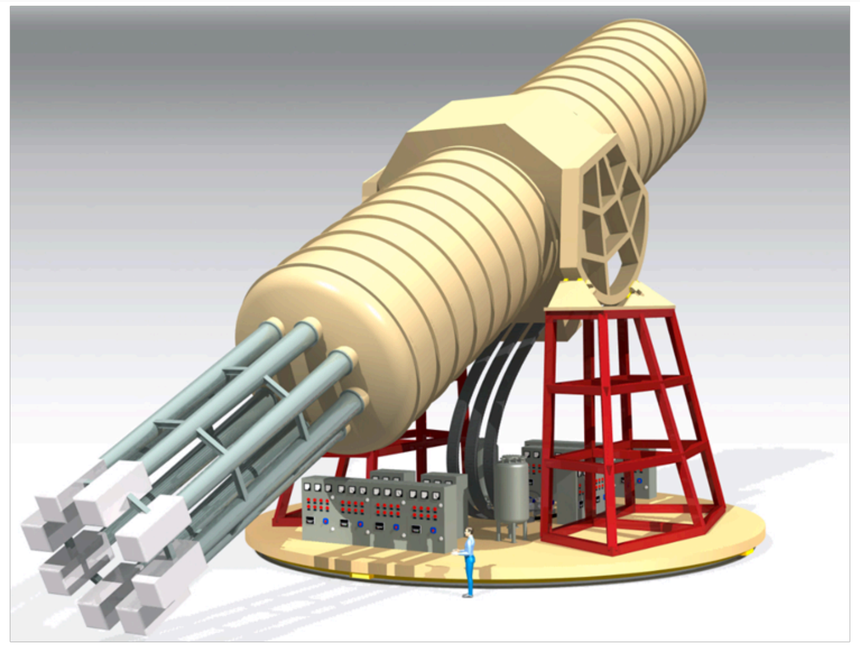
Experimental searches for Axion-Like Particles axion

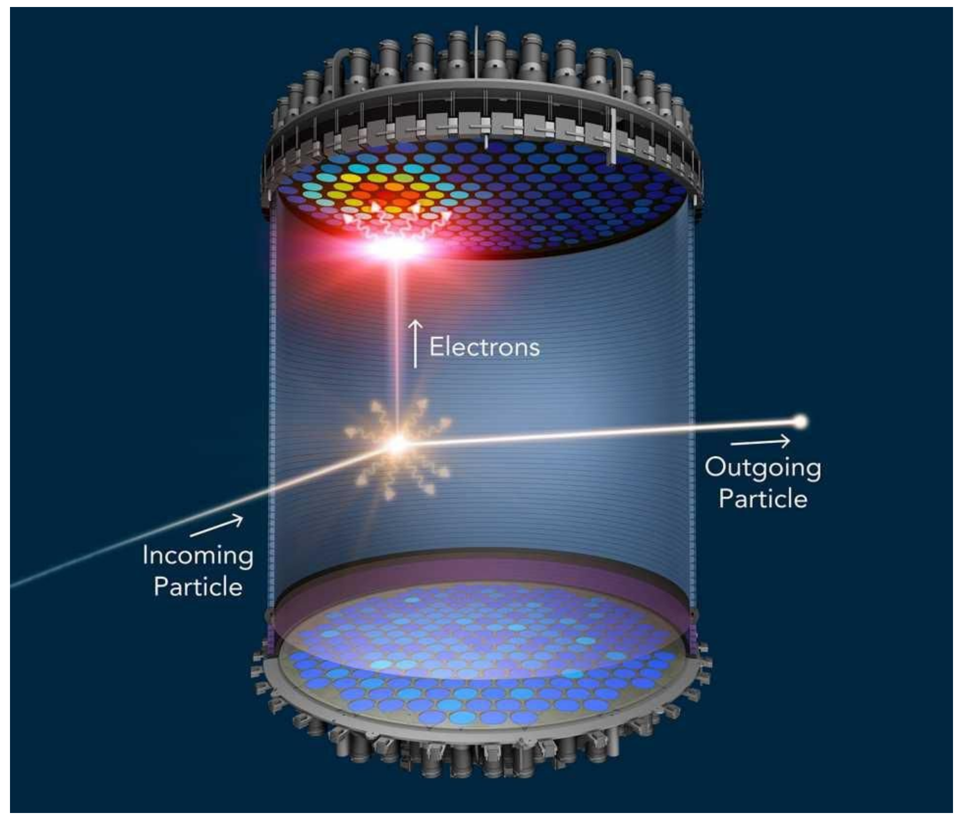
Methodology:

- Dark Matter Axion: haloscopes ..
- Axion independent searches:
  - Rare meson decays
  - Stellar cooling
  - Supernova
  - Helioscopes: solar axion (CAST, IAXO, or DM direct detection searches)
  - Light shining through walls
  - Polarization
  - Fifth force
  - Radio wave detection







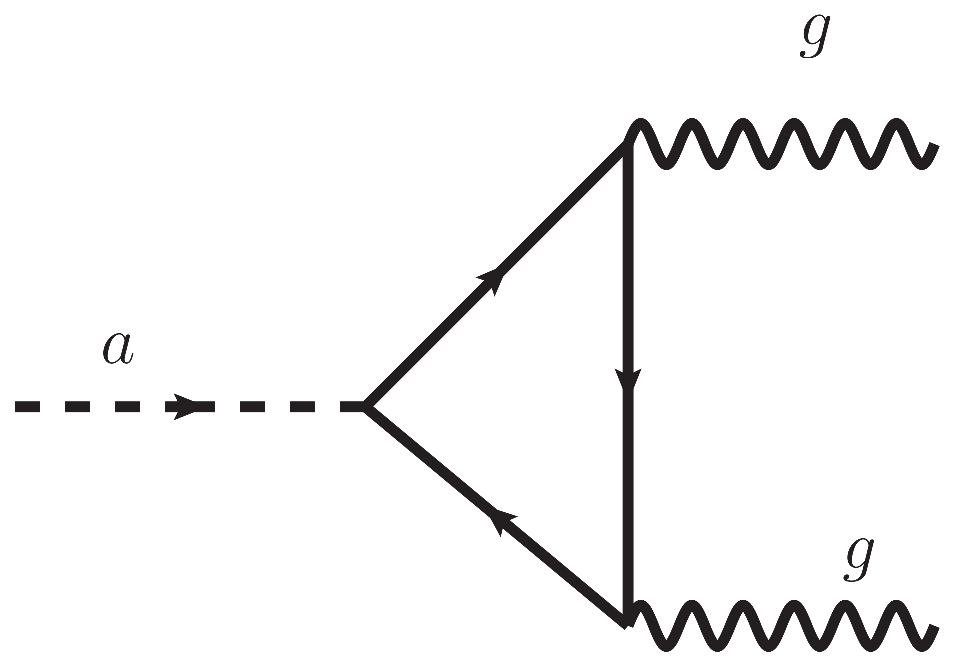


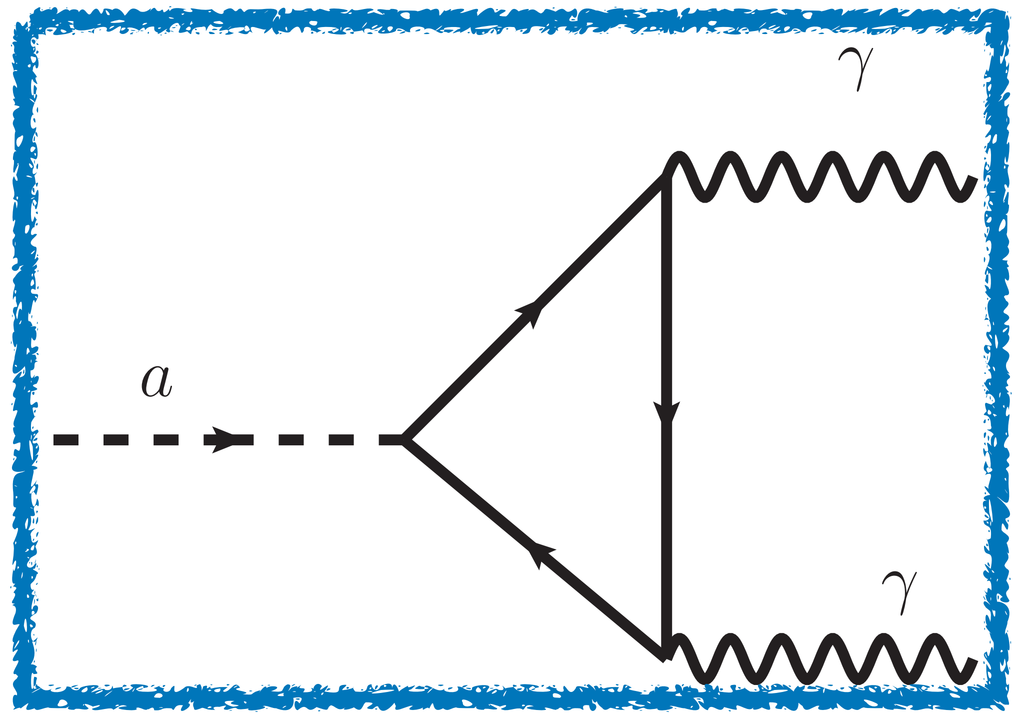
Experimental searches for Axion-Like Particles axion

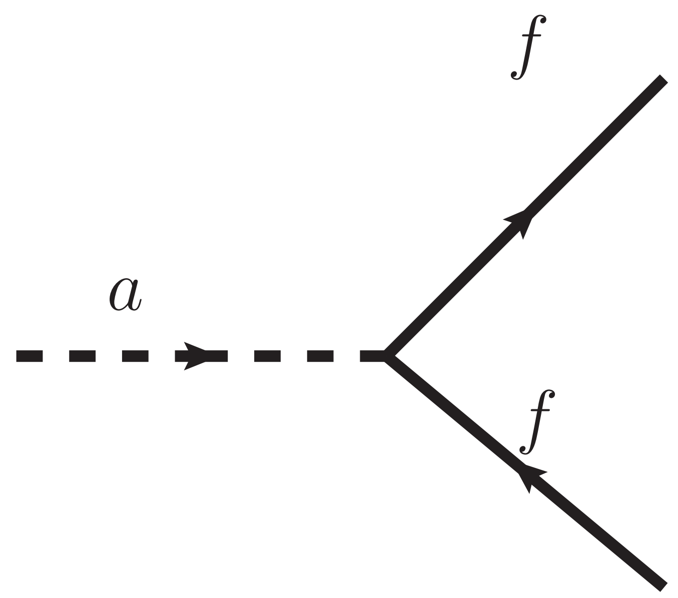
$$\mathcal{L}_{\mathrm{ALP}} = g_{ag}\frac{a}{f_a}G\tilde{G} + g_{a\gamma}\frac{a}{f_a}F\tilde{F} + g_{af}\frac{\partial_\mu a}{2f_a}\bar{f}\gamma^\mu\gamma_5 f$$

- ALP couplings:

$$g_{a\gamma\gamma}aF_{\mu\nu}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta} \sim g_{a\gamma\gamma}a\vec{E}\cdot\vec{B}$$

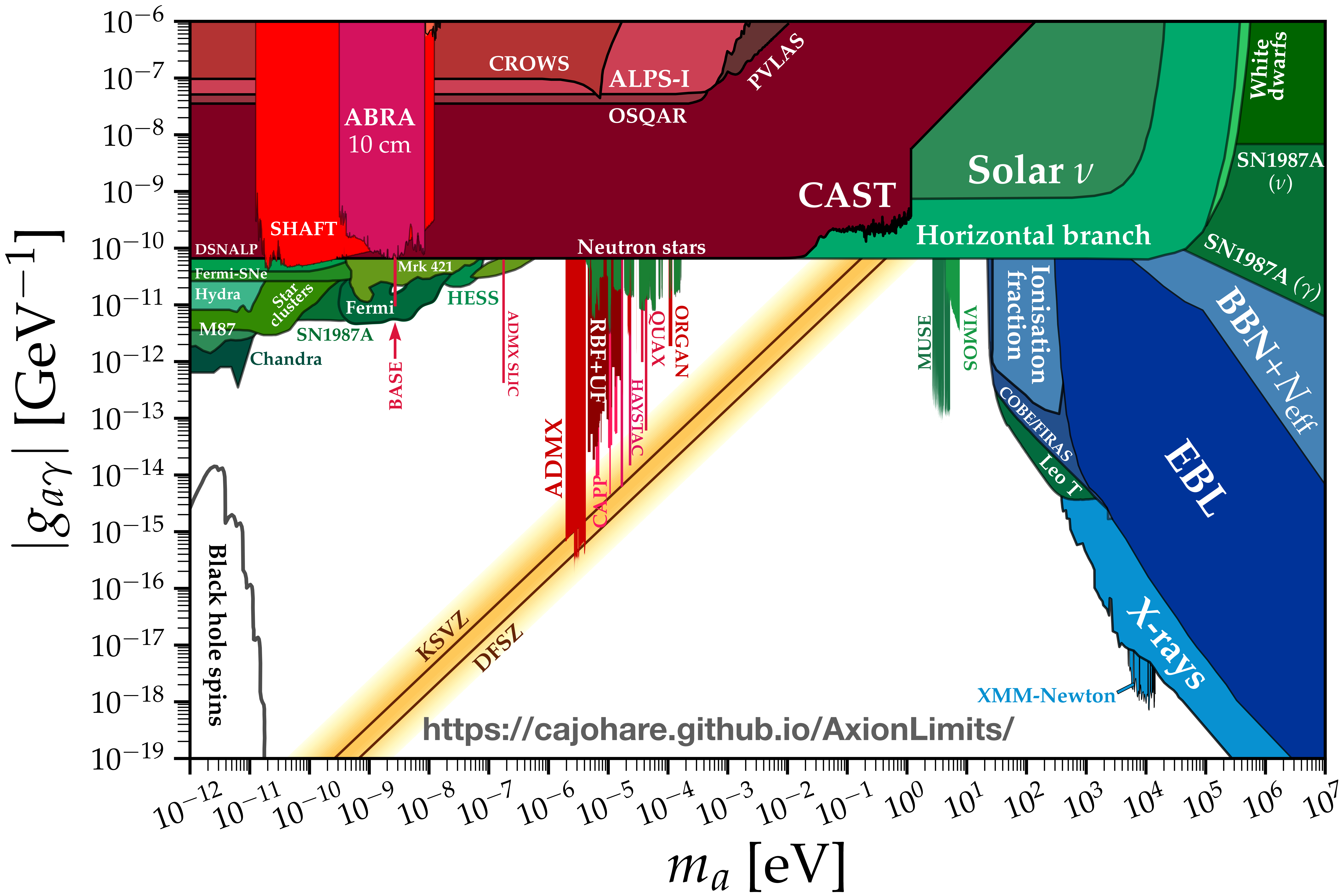




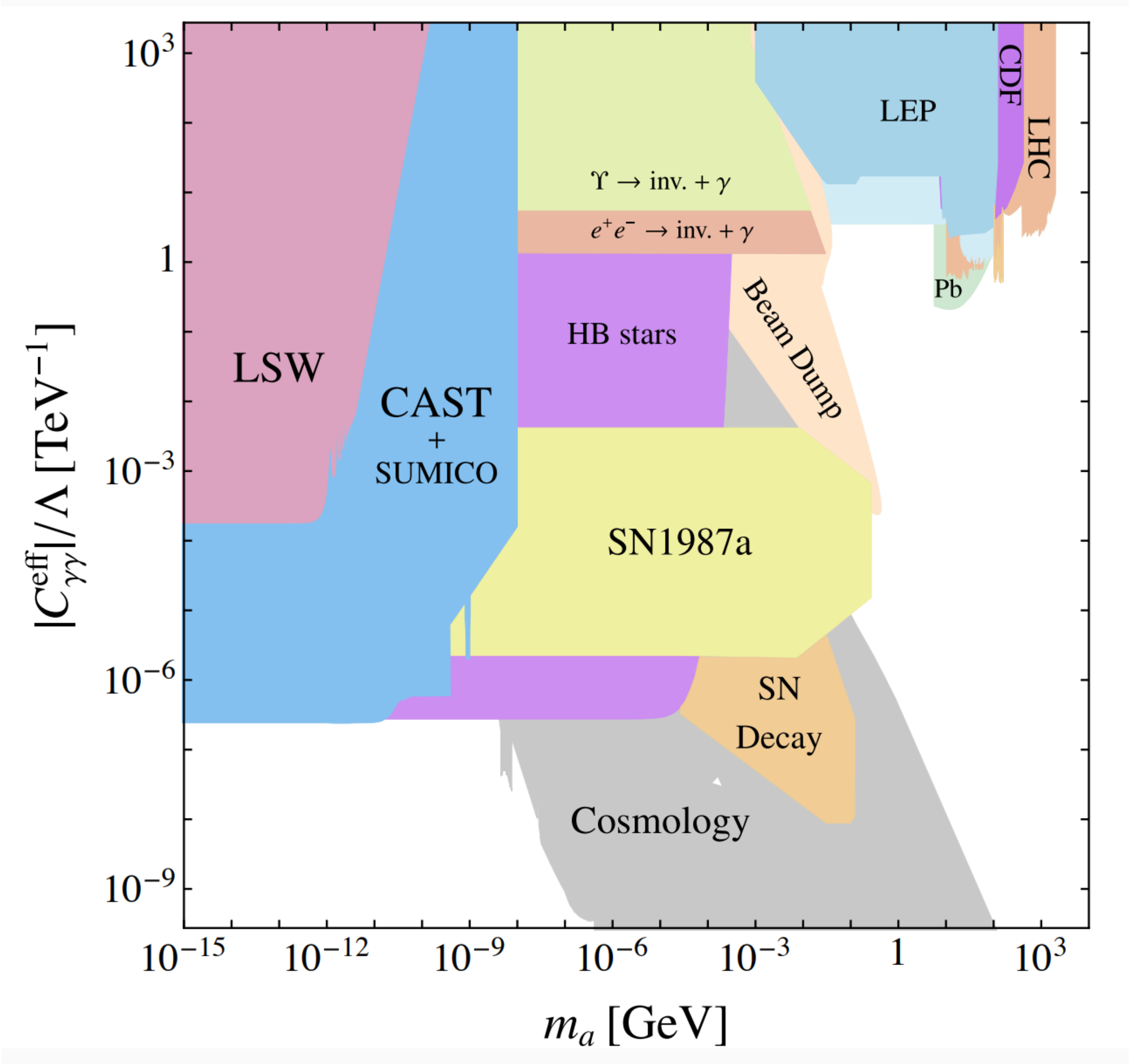


$f = q, \ell, N$

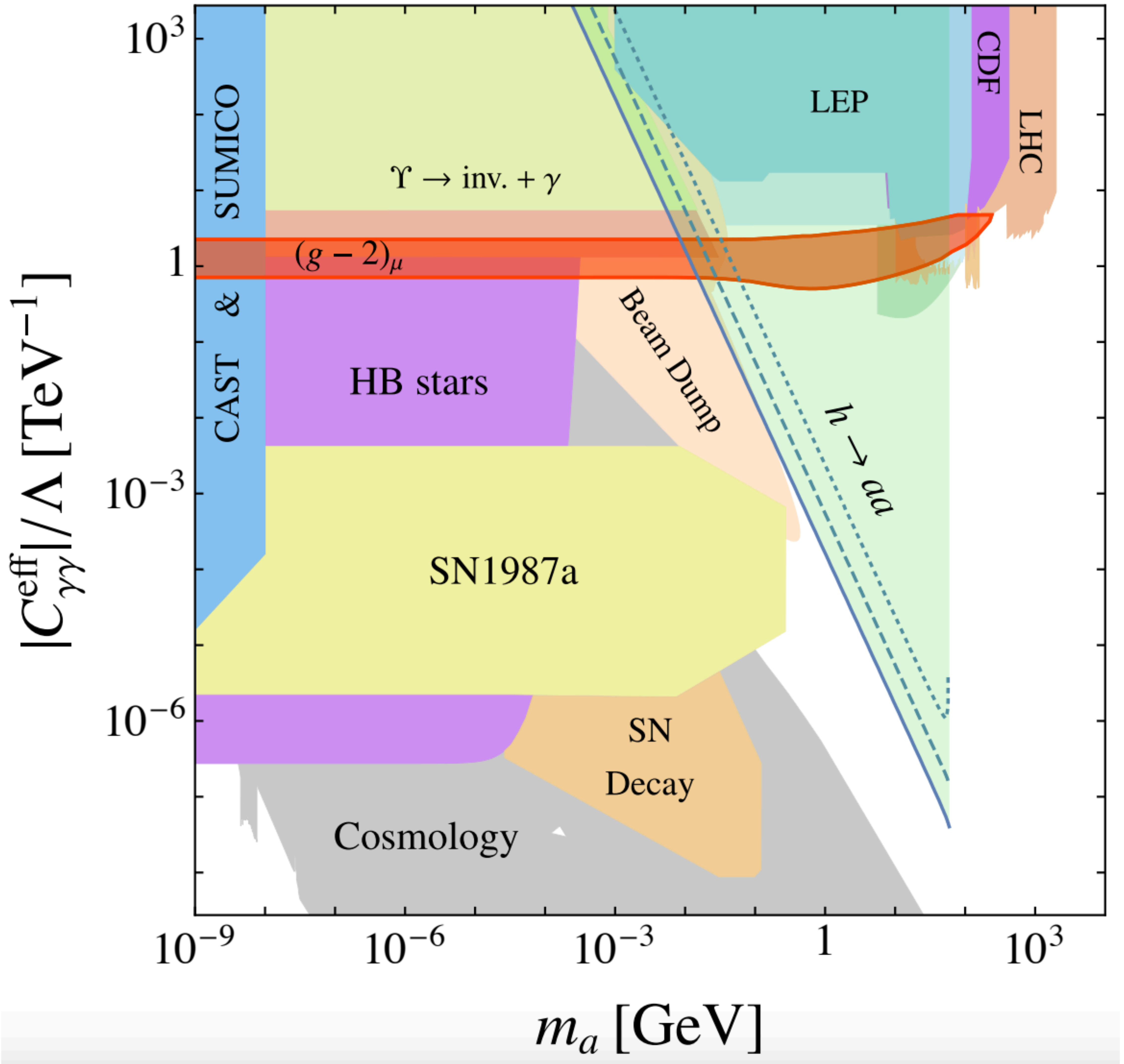
The current status for light/ultralight ALP photon couplings



The current status for heavy ALP photon couplings

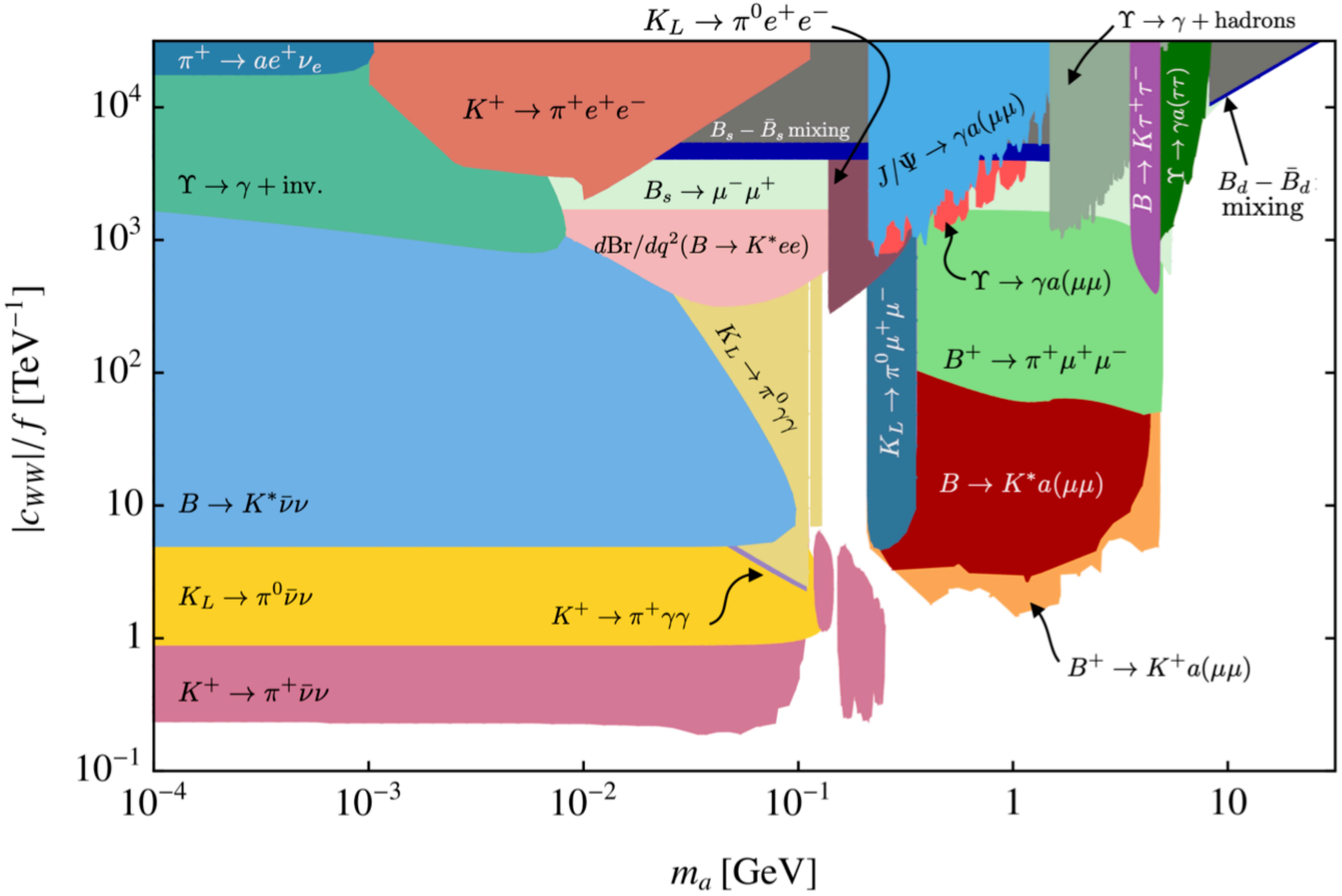


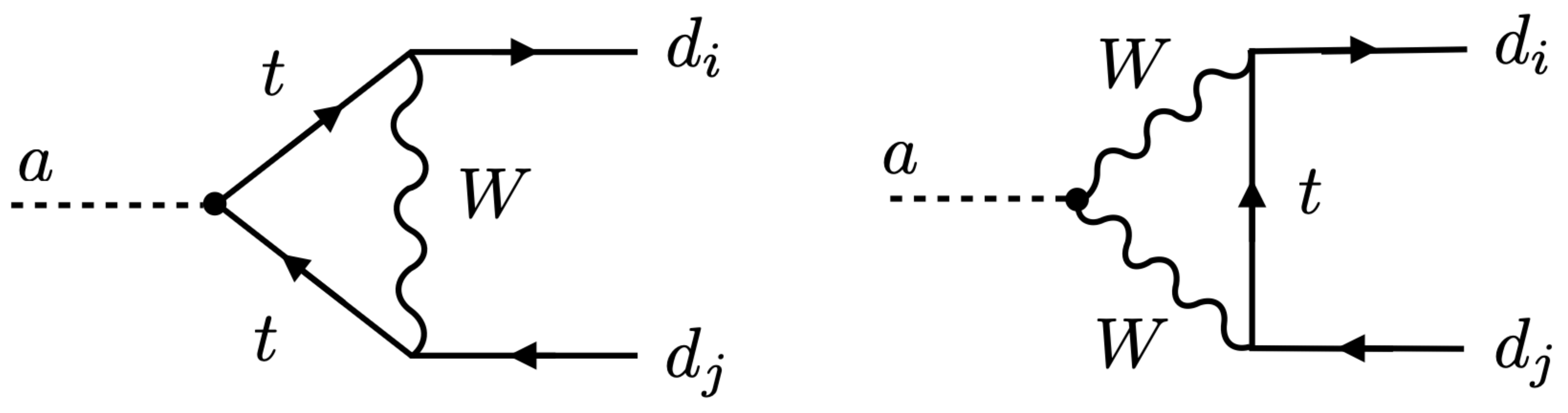
Bauer, Neubert, Thamm 1708.00443 [JHEP]



Similar for $h \to Za$

The RG evolution and flavor probe

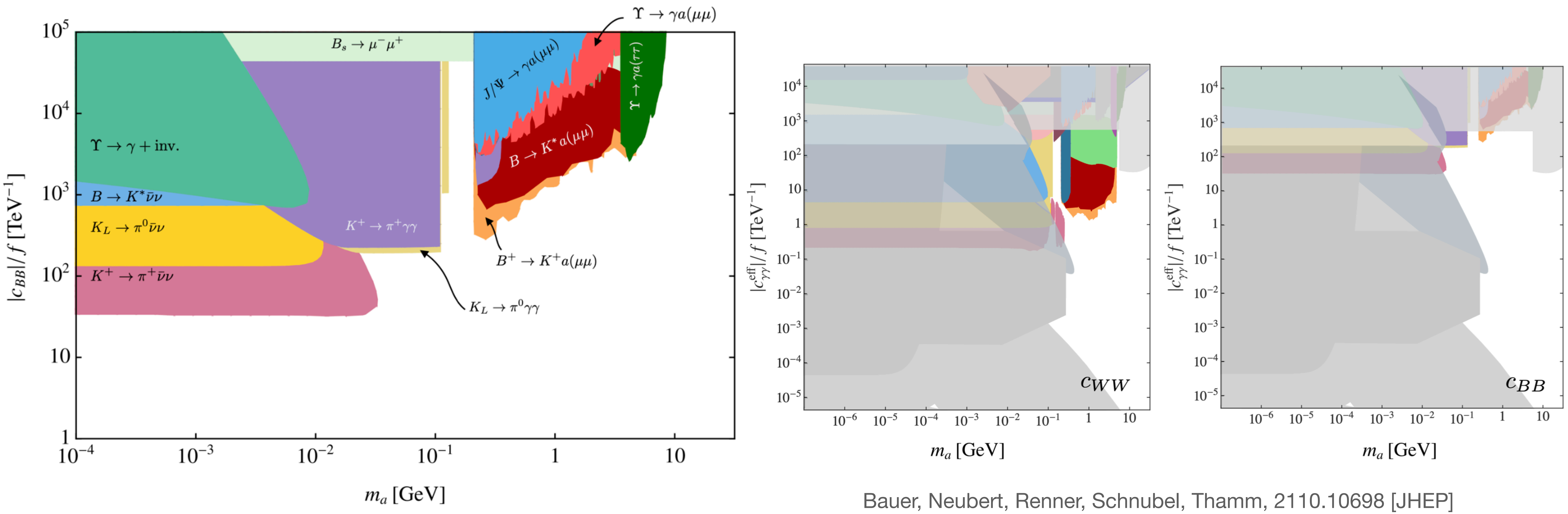




Bauer, Neubert, Renner, Schnubel, Thamm, 2110.10698 [JHEP]

- ALP couplings to all other Wilson coefficients set to zero at $\Lambda = 4\pi f$, $f = 1$ TeV
- RG running will generate flavor violating Wilson coefficients

The RG evolution and flavor probe



Bauer, Neubert, Renner, Schnubel, Thamm, 2110.10698 [JHEP]

- ALP couplings to all other Wilson coefficients set to zero at $\Lambda = 4\pi f$, $f = 1$ TeV
- RG running will generate flavor violating Wilson coefficients

提纲

- 轴子类轴子模型
- 暗光子模型
- 中微子模型

暗光子模型

- SM direct-charged U(1), e.g. B-L

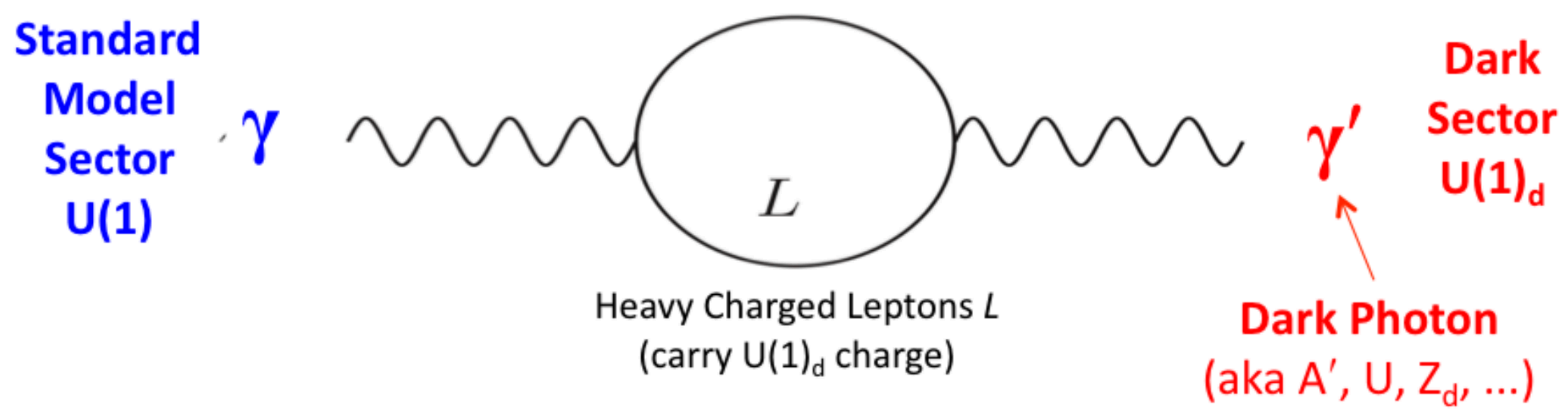
$$\mathscr{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - g' A'_\mu j^\mu_{\mathrm{B-L}}$$

- 特点：
  - 具有质量，直接与SM 费米子有相互作用
  - p +1; e -1; n +1
  - 电中性的原子核：带电数正比于中子数
  - 可以通过fifth force 来探测

暗光子模型

- Kinetic mixing dark photon

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu - \frac{1}{2}\epsilon F_{\mu\nu}F'^{\mu\nu}$$



- 重新定义并正则化动量项

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

- 特点：
  - 具有质量，与光子类似的微弱相互作用
  - 电中性的原子核：不带电

动量混合的暗光子

- 在电弱破缺以前，与Hypercharge场混合

JL, Wang, Yu, 1704.00730 [JHEP]

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i\,\mu\nu} - \frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}K^{\mu\nu}$$

$$+ \ |D_\mu H|^2 + |D_\mu \Phi|^2 + \mu_H^2|H|^2 - \lambda_H|H|^4 + \mu_D^2|\Phi|^2 - \lambda_D|\Phi|^4 - \lambda_{HP}|H|^2|\Phi|^2$$

- 在电弱破缺以后，质量项

$$\Phi = \frac{1}{\sqrt{2}}(v_D + \phi) \ , \qquad H = \frac{1}{\sqrt{2}}(v_H + h) \ ,$$

$$\mathcal{L} \supset \frac{1}{2}\begin{pmatrix} W^{\mu 3} & B^\mu & K^\mu \end{pmatrix}\begin{pmatrix} g^2\frac{v_H^2}{4} & -g'g\frac{v_H^2}{4} & 0 \\ -g'g\frac{v_H^2}{4} & g'^2\frac{v_H^2}{4} & 0 \\ 0 & 0 & g_D^2 v_D^2 \end{pmatrix}\begin{pmatrix} W^3_\mu \\ B_\mu \\ K_\mu \end{pmatrix}$$

- 先进入标准模型的基

$$R_{\theta W} = \begin{pmatrix} c_W & s_W & 0 \\ -s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\mathcal{L} \supset \frac{-1}{4}\begin{pmatrix} Z^{\mu\nu}_{\rm SM} & A^{\mu\nu}_{\rm SM} & K^{\mu\nu} \end{pmatrix}\begin{pmatrix} 1 & 0 & \epsilon t_W \\ 0 & 1 & -\epsilon \\ \epsilon t_W & -\epsilon & 1 \end{pmatrix}\begin{pmatrix} Z_{\mu\nu,\,\rm SM} \\ A_{\mu\nu,\,\rm SM} \\ K_{\mu\nu} \end{pmatrix}$$

$$+\frac{1}{2}\begin{pmatrix} Z^{\mu}_{\rm SM} & A^{\mu}_{\rm SM} & K^{\mu} \end{pmatrix}\begin{pmatrix} m^2_{Z,\,\rm SM} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_K^2 \end{pmatrix}\begin{pmatrix} Z_{\mu,\,\rm SM} \\ A_{\mu,\,\rm SM} \\ K_{\mu} \end{pmatrix},$$

动量混合的暗光子

- 动量项正则化

$$U_1 = \begin{pmatrix} 1 & 0 & 0 \\ -\epsilon^2 t_W & 1 & \epsilon \\ -\epsilon t_W & 0 & 1 \end{pmatrix}, \quad U_2 = \begin{pmatrix} \sqrt{\frac{1-\epsilon^2}{1-\epsilon^2 c_W^{-2}}} & 0 & 0 \\ 0 & 1 & 0 \\ \frac{-\epsilon^3 t_W}{\sqrt{(1-\epsilon^2)(1-\epsilon^2 c_W^{-2})}} & 0 & \frac{1}{\sqrt{1-\epsilon^2}} \end{pmatrix}$$

$$\begin{aligned}\mathcal{L} \supset & \frac{-1}{4}\begin{pmatrix} Z_{\rm SM}^{\mu\nu} & A_{\rm SM}^{\mu\nu} & K^{\mu\nu}\end{pmatrix}(U_1^T)^{-1}(U_2^T)^{-1}\mathbb{I}_3 U_2^{-1}U_1^{-1}\begin{pmatrix} Z_{\mu\nu,\,\rm SM} \\ A_{\mu\nu,\,\rm SM} \\ K_{\mu\nu}\end{pmatrix} \\ & + \frac{1}{2}\begin{pmatrix} Z_{\rm SM}^{\mu} & A_{\rm SM}^{\mu} & K^{\mu}\end{pmatrix}(U_1^T)^{-1}(U_2^T)^{-1}\begin{pmatrix} \frac{m_{Z,\,\rm SM}^2(1-\epsilon^2)^2 + m_K^2\epsilon^2 t_W^2}{(1-\epsilon^2)(1-\epsilon^2 c_W^{-2})} & 0 & \frac{-m_K^2\epsilon t_W}{(1-\epsilon^2)\sqrt{1-\epsilon^2 c_W^{-2}}} \\ 0 & 0 & 0 \\ \frac{-m_K^2\epsilon t_W}{(1-\epsilon^2)\sqrt{1-\epsilon^2 c_W^{-2}}} & 0 & \frac{m_K^2}{1-\epsilon^2}\end{pmatrix} \\ & \times U_2^{-1}U_1^{-1}\begin{pmatrix} Z_{\mu,\,\rm SM} \\ A_{\mu,\,\rm SM} \\ K_{\mu}\end{pmatrix}, \end{aligned} \tag{8}$$

- 质量项对角化

$$R_M = \begin{pmatrix} c_M & 0 & s_M \\ 0 & 1 & 0 \\ -s_M & 0 & c_M \end{pmatrix} \qquad \tan\theta_M = \frac{1}{\beta \pm \sqrt{\beta^2+1}}$$

$$\beta \equiv \frac{m_{Z,\,\rm SM}^2(1-\epsilon^2)^2 - m_K^2(1-\epsilon^2 c_W^{-2}(1+s_W^2))}{2m_K^2\epsilon t_W\sqrt{1-\epsilon^2 c_W^{-2}}}$$

→

$$\begin{pmatrix} \tilde{Z}_\mu \\ \tilde{A}_\mu \\ \tilde{K}_\mu \end{pmatrix} = R_M^T U_2^{-1} U_1^{-1}\begin{pmatrix} Z_{\mu,\,\rm SM} \\ A_{\mu,\,\rm SM} \\ K_\mu \end{pmatrix} = \begin{pmatrix} Z_{\mu,\,\rm SM} - \frac{t_W m_K^2}{m_{Z,\,\rm SM}^2 - m_K^2}\epsilon K_\mu - \frac{m_{Z,\,\rm SM}^4 t_W^2}{2(m_{Z,\,\rm SM}^2 - m_K^2)^2}\epsilon^2 Z_{\mu,\,\rm SM} \\ A_{\mu,\,\rm SM} - \epsilon K_\mu \\ K_\mu + \frac{t_W m_{Z,\,\rm SM}^2}{m_{Z,\,\rm SM}^2 - m_K^2}\epsilon Z_{\mu,\,\rm SM} - \left(\frac{1}{2} + \frac{m_K^4 t_W^2}{2(m_{Z,\,\rm SM}^2 - m_K^2)^2}\right)\epsilon^2 K_\mu \end{pmatrix}$$

动量混合的暗光子

- 最终结果 $\epsilon \ll 1$
  - 质量修正 $\mathcal{O}(\epsilon^2)$

$$m_{\tilde{K}}^2 = m_K^2 + \frac{m_K^2 c_W^{-2} \epsilon^2 (m_{Z,\,\mathrm{SM}}^2 c_W^2 - m_K^2)}{m_{Z,\,\mathrm{SM}}^2 - m_K^2}\,, \quad m_{\tilde{Z}}^2 = m_{Z,\,\mathrm{SM}}^2 + \frac{m_{Z,\,\mathrm{SM}}^4 t_W^2 \epsilon^2}{m_{Z,\,\mathrm{SM}}^2 - m_K^2}$$

  - 相互作用修正 $\mathcal{O}(\epsilon^1)$

$$\begin{aligned}
\mathcal{L} \supset\ & g Z_{\mu,\,\mathrm{SM}} J_Z^\mu + e A_{\mu,\,\mathrm{SM}} J_{\mathrm{em}}^\mu + g_D K_\mu J_D^\mu \\
=\ & \tilde{Z}_\mu \left(g J_Z^\mu - g_D \frac{m_{Z,\,\mathrm{SM}}^2 t_W}{m_{Z,\,\mathrm{SM}}^2 - m_K^2} \epsilon J_D^\mu + g \frac{m_{Z,\,\mathrm{SM}}^2 (m_{Z,\,\mathrm{SM}}^2 - 2m_K^2) t_W^2}{2(m_K^2 - m_{Z,\,\mathrm{SM}}^2)^2} \epsilon^2 J_Z^\mu - e \frac{m_{Z,\,\mathrm{SM}}^2 t_W}{m_{Z,\,\mathrm{SM}}^2 - m_K^2} \epsilon^2 J_{\mathrm{em}}^\mu \right) \\
& + \tilde{K}_\mu \left(g_D J_D^\mu + g \frac{m_K^2 t_W}{m_{Z,\,\mathrm{SM}}^2 - m_K^2} \epsilon J_Z^\mu + e \epsilon J_{\mathrm{em}}^\mu + g_D \frac{(m_{Z,\,\mathrm{SM}}^4 c_W^2 - 2m_K^2 m_{Z,\,\mathrm{SM}}^2 + m_K^4) c_W^{-2}}{2(m_{Z,\,\mathrm{SM}}^2 - m_K^2)^2} \epsilon^2 J_D^\mu \right) \\
& + \tilde{A}_\mu e J_{\mathrm{em}}^\mu\,. \qquad (15)
\end{aligned}$$

质量混合的暗光子

- 在电弱破缺以前，与Hypercharge场混合

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i\,\mu\nu} - \frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}K^{\mu\nu}$$

$$+\ |D_\mu H|^2 + |D_\mu \Phi|^2 + \mu_H^2|H|^2 - \lambda_H|H|^4 + \mu_D^2|\Phi|^2 - \lambda_D|\Phi|^4 - \lambda_{HP}|H|^2|\Phi|^2$$

- 在电弱破缺以后，质量项

$$\Phi = \frac{1}{\sqrt{2}}(v_D + \phi)\ ,$$

$$H = \frac{1}{\sqrt{2}}(v_H + h)\ ,$$

$$\mathcal{L} \supset \frac{1}{2}\begin{pmatrix} W^{\mu 3} & B^\mu & K^\mu \end{pmatrix}\begin{pmatrix} g^2\frac{v_H^2}{4} & -g'g\frac{v_H^2}{4} & 0 \\ -g'g\frac{v_H^2}{4} & g'^2\frac{v_H^2}{4} & 0 \\ 0 & 0 & g_D^2 v_D^2 \end{pmatrix}\begin{pmatrix} W^3_\mu \\ B_\mu \\ K_\mu \end{pmatrix}$$

通过非阿贝尔项混合的暗光子模型

- Non-abelian 暗光子模型

$$\mathcal{L} = -\frac{1}{4} K^a_{\mu\nu} K^a_{\mu\nu} + (D_\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi)$$

$$\mathcal{L}_{\text{mix}} = \frac{1}{\Lambda^2} (\Phi^\dagger T^a \Phi) K^a_{\mu\nu} B_{\mu\nu}$$

- 自发破缺之后

$$\mathcal{L}_{\text{mix}} \supset \frac{\varepsilon}{2} \left(1 + \frac{\phi}{v_d}\right)^2 \left[\partial_\mu K^3_\nu - \partial_\nu K^3_\mu + g_d (K^1_\mu K^2_\nu - K^2_\mu K^1_\nu)\right] \frac{1}{\cos\theta_w} B_{\mu\nu}$$

- 所需要转动

$$K^3_\mu \to \frac{1}{\sqrt{1 - \frac{1}{4} \frac{\varepsilon^2}{\cos^2\theta_w}}} K^3_\mu$$

$$B_\mu \to B_\mu - \frac{\varepsilon}{\cos\theta_w} \frac{1}{2\sqrt{1 - \frac{1}{4} \frac{\varepsilon^2}{\cos^2\theta_w}}} K^3_\mu ,$$

通过非阿贝尔项混合的暗光子模型

- 最终结果 $\epsilon \ll 1$
  - 质量修正 $\mathcal{O}(\epsilon^2)$

$$m_{K_3}^2 = (m_k - \Delta)^2 = m_k^2 \left(1 + \frac{\varepsilon^2}{\cos^2\theta_w} \frac{(m_k^2 - \cos^2\theta_w m_{Z,\mathrm{SM}}^2)}{m_k^2 - m_{Z,\mathrm{SM}}^2}\right)$$

  - 相互作用修正 $\mathcal{O}(\epsilon^1)$

$$\mathcal{L} \supset K_3^\mu \left(\varepsilon\, e J_{\mathrm{em}}^\mu - \varepsilon g \tan\theta_w \frac{m_k^2}{m_k^2 - m_Z^2} J_Z^\mu\right)$$

  - 更多的 $\mathcal{O}(\epsilon^1)$相互作用

$$\mathcal{L}_{\mathrm{mix}} \supset \frac{\varepsilon}{2}\left(1 + \frac{\phi}{v_d}\right)^2 \left[\partial_\mu K_\nu^3 - \partial_\nu K_\mu^3 + g_d(K_\mu^1 K_\nu^2 - K_\mu^2 K_\nu^1)\right] \frac{1}{\cos\theta_w} B_{\mu\nu}$$

通过非阿贝尔项混合的暗光子模型

- 质量混合的模型

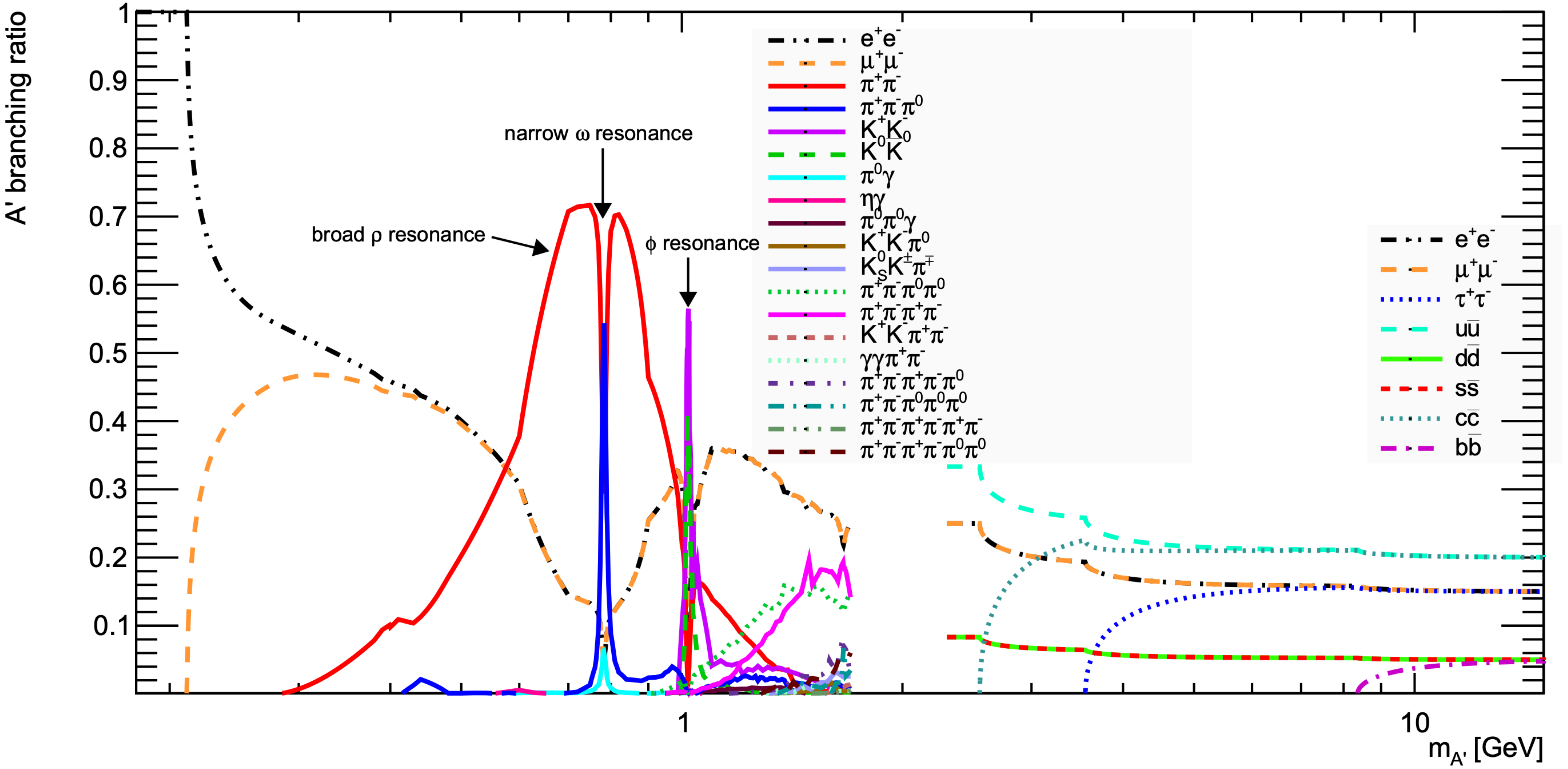
$$\mathcal{L} = -\frac{1}{4} K^a_{\mu\nu} K^a_{\mu\nu} + (D_\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi)$$

$$\mathcal{L} \supset \frac{(\Phi_D^\dagger D^\mu \Phi_D)(\Phi^\dagger D_\mu \Phi)}{\Lambda^2}$$

动量混合暗光子模型的实验限制

- 含有2个自由参数 $\mathscr{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - e\epsilon A'_\mu j^\mu_{\mathrm{em}}$
- 可见衰变分支比

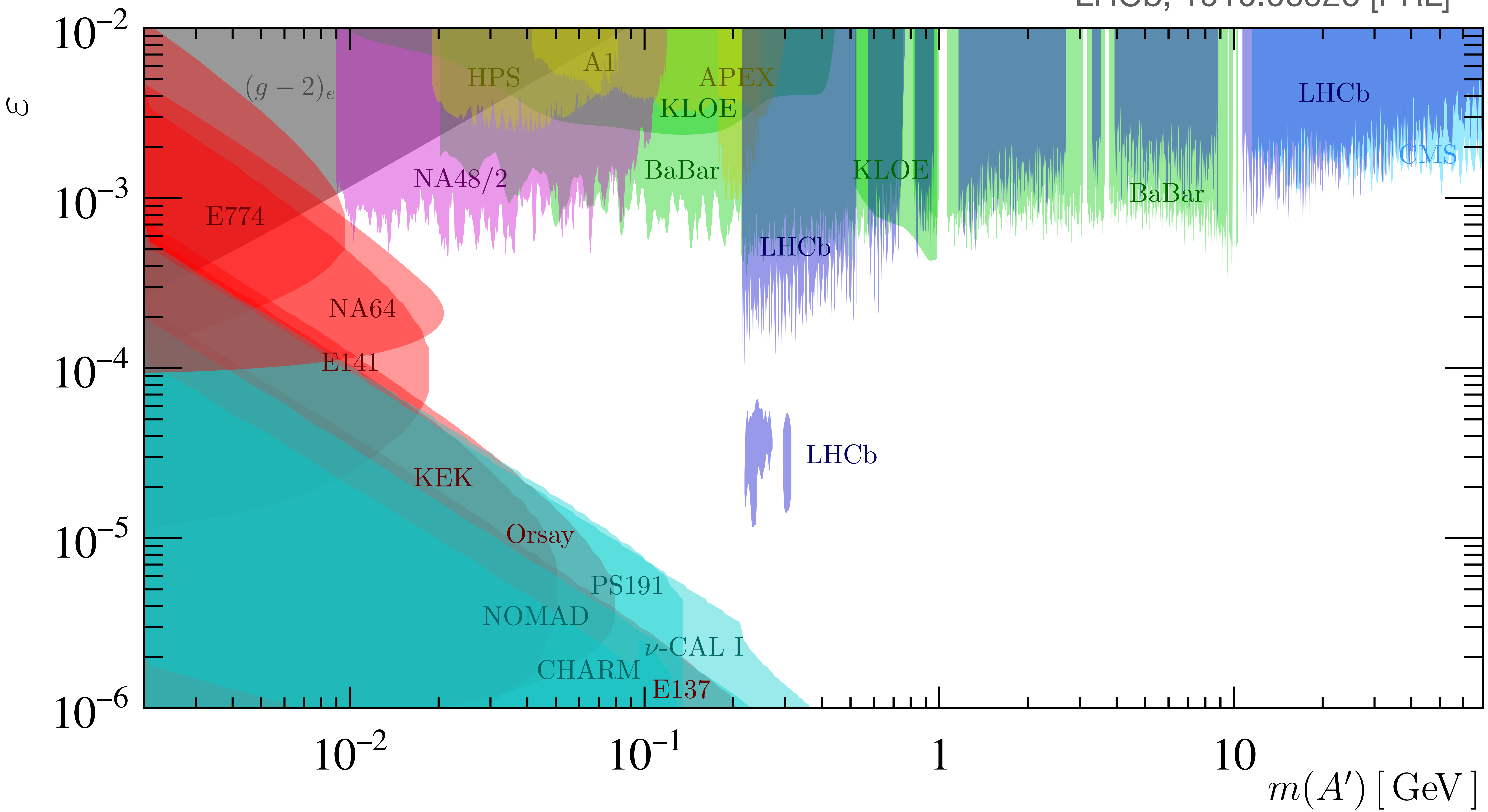
Buschmann, Kopp, JL, Machado, 1505.07459 [JHEP]



动量混合暗光子模型的实验限制

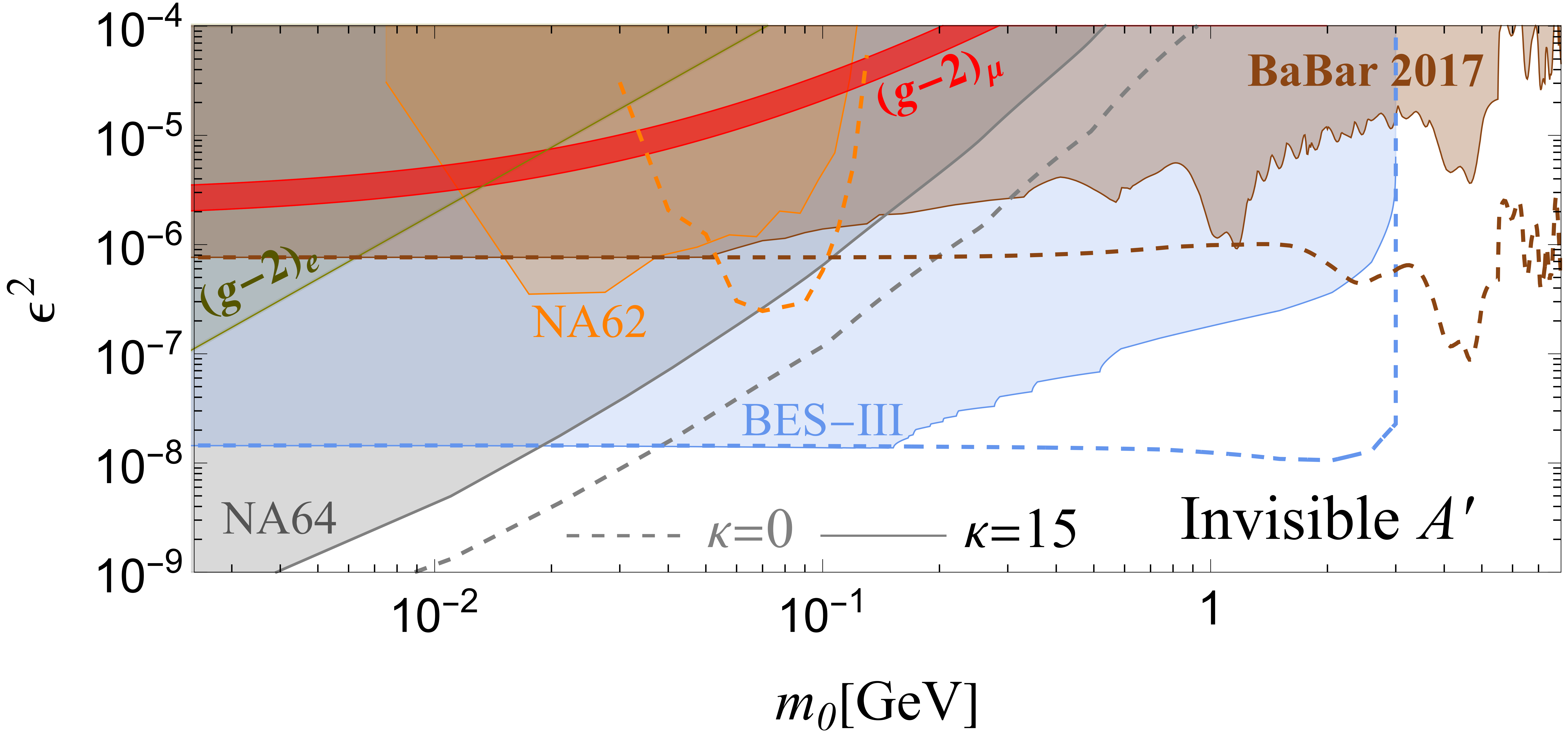
- 可见A’的限制

LHCb, 1910.06926 [PRL]



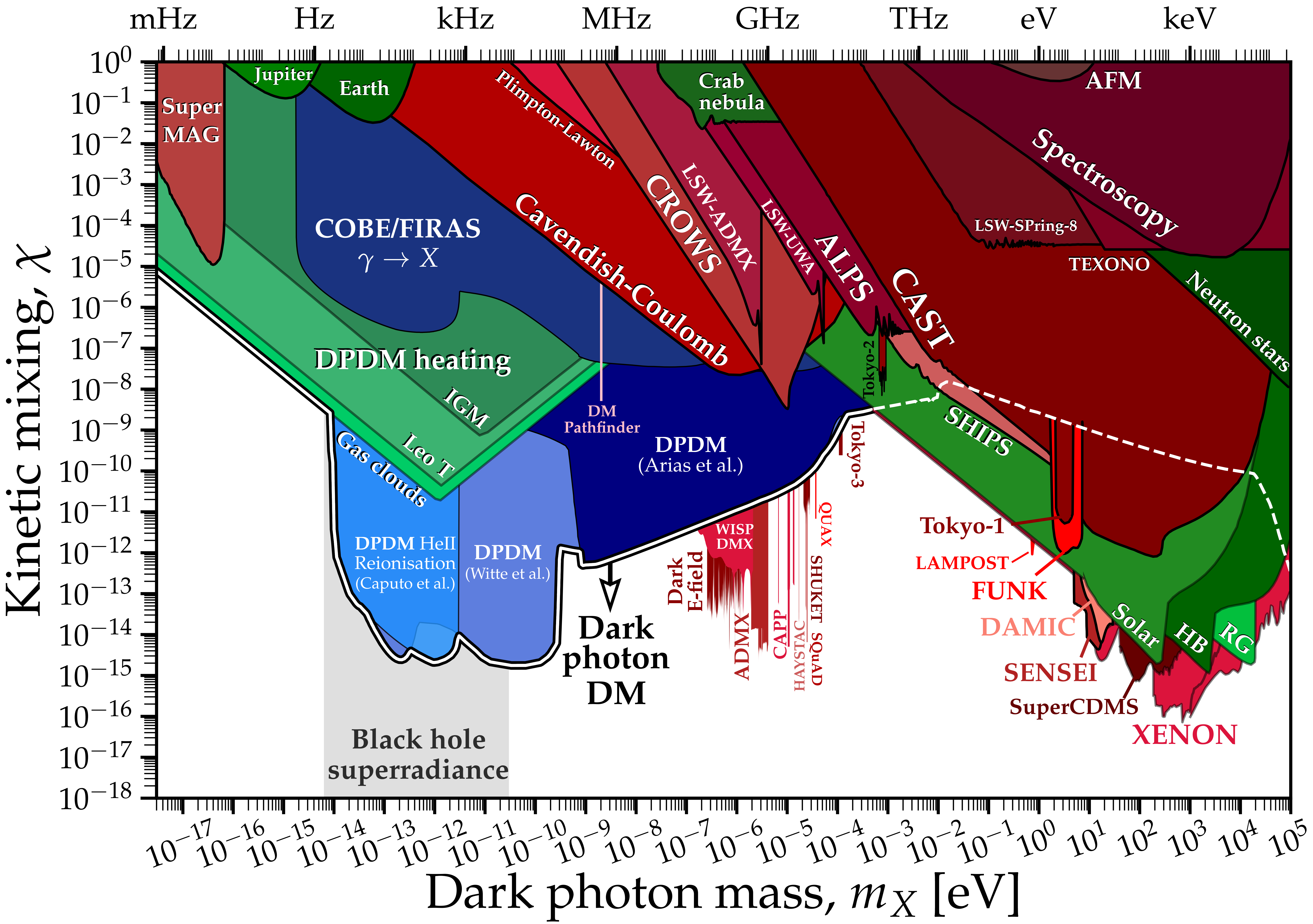
动量混合暗光子模型的实验限制

- 不可见A’的限制



低质量动量混合暗光子模型的实验限制

- A’ mediator
- A’ DM



超轻矢量玻色暗物质的残余丰度

- 超轻质量：Stuckelberg mechanism

$$\mathcal{L}_{\text{Stueck}} = -\frac{1}{2}\partial^\mu A^\nu\ \partial_\mu A_\nu + \frac{1}{2}m^2 A^\mu A_\mu + \frac{1}{2}\partial^\mu B\ \partial_\mu B - \frac{1}{2}m^2\ B^2$$

$$\mathcal{L}_{\text{Stueck}} = -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{2}m^2\left(A^\mu - \frac{1}{m}\partial^\mu B\right)^2 - \frac{1}{2}\left(\partial_\mu A^\mu + m\,B\right)^2$$

- 规范变换

$$\delta A_\mu(x) = \partial_\mu \Lambda(x)$$
$$\delta B(x) = m\ \Lambda(x)$$

- 等效于decoupled Higgs and large λ
- Stuckelberg case occurs naturally in large volume string compactifications

- 残余丰度：
  - Non-minimal enhanced modified Misalignment
    - Homogeneous solution $\partial_i X^\mu = 0\ \rightarrow X_0 = 0$
  - Invariant term $X^\mu X_\mu = -a^{-2}(t)X_iX_i \equiv -\bar{X}_i\bar{X}_i$
  - Vector field cosmological evolution

$$\ddot{\bar{X}}_i + 3H\dot{\bar{X}}_i + \left(m_{\gamma'}^2 + (1-\kappa)(\dot{H} + 2H^2)\right)\bar{X}_i = 0$$

  - The energy density

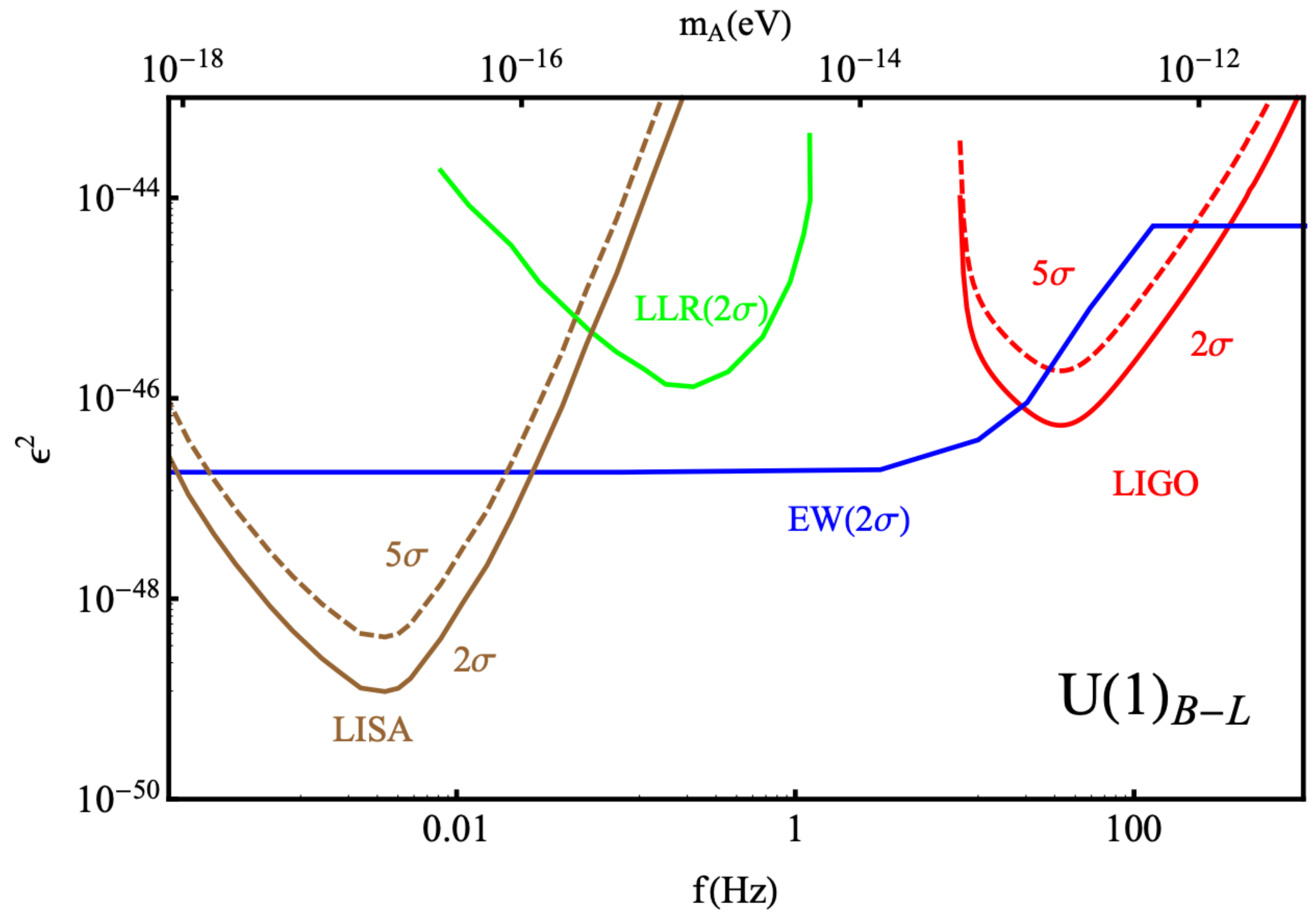
$$\rho(t) = T_0^0 = \frac{1}{2}\left(\dot{\bar{X}}_i\dot{\bar{X}}_i + m_{\gamma'}^2\bar{X}_i\bar{X}_i + (1-\kappa)H^2\bar{X}_i\bar{X}_i + 2(1-\kappa)H\dot{\bar{X}}_i\bar{X}_i\right)$$

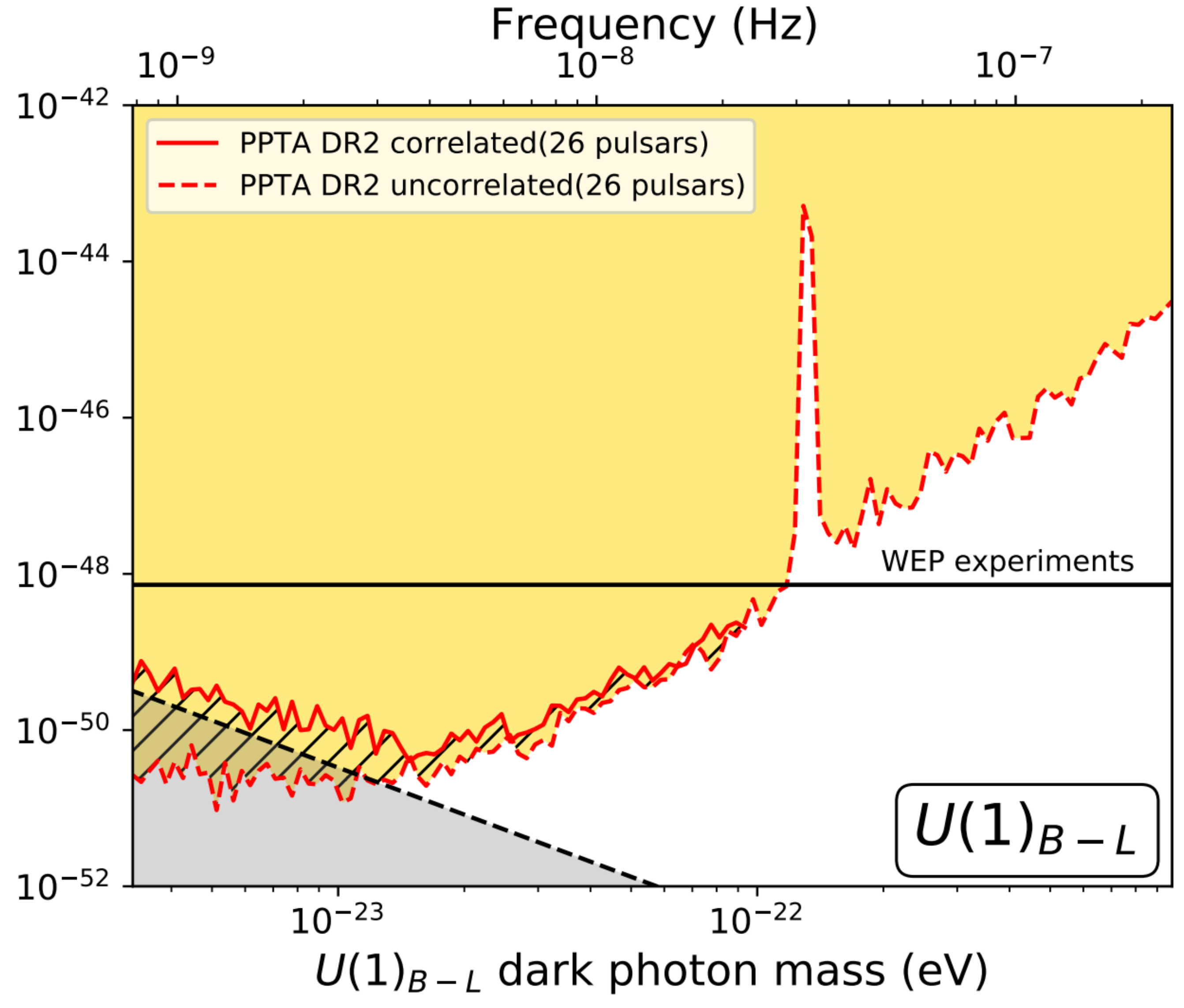
  - non-minimal coupling to gravity
    - $\frac{\kappa}{12}RX_\mu X^\mu$, with $\kappa = 1$ back to scalar case
    - 其它机制：inflationary fluctuations, parametric resonances, cosmic strings

$U(1)_{B-L}$暗光子暗物质

Yue Zhao etc, 1801.10161 (PRL)

- 极小质量：长程相互作用
- 宏观物体：具有极大电荷
- 观测宏观物体的反常位移
  - 第5种力
  - LIGO 引力波探测器的镜子
  - 行星之间的位移
    - Pulsar Timing
    - Gaia …
  - 超轻暗标量粒子暗物质也部分适用





Jing Shu, Yuan Qiang, Yue Zhao etc, 2112.07687 (PRR)

提纲

- 轴子类轴子模型
- 暗光子模型
- 中微子模型

翘翘板模型 Type-I

- 增加Sterile Neutrino

[Minkowski, 1977]

$$\Delta\mathcal{L}_\nu = -\lambda_\nu \bar{L}\tilde{H}N - \frac{m_N}{2}\bar{N}^c N + h.c.$$

- 质量矩阵

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix} \qquad \sin\theta = m_D/m_N$$

- 质量本征值

$$m_\nu \equiv m_1 \simeq \frac{m_D^2}{m_N}, \quad m_2 \simeq m_N + \frac{m_D^2}{m_N} \simeq m_N$$

- 限制条件

$$\sin^2\theta \simeq \frac{m_\nu}{m_N}$$

- 规范相互作用

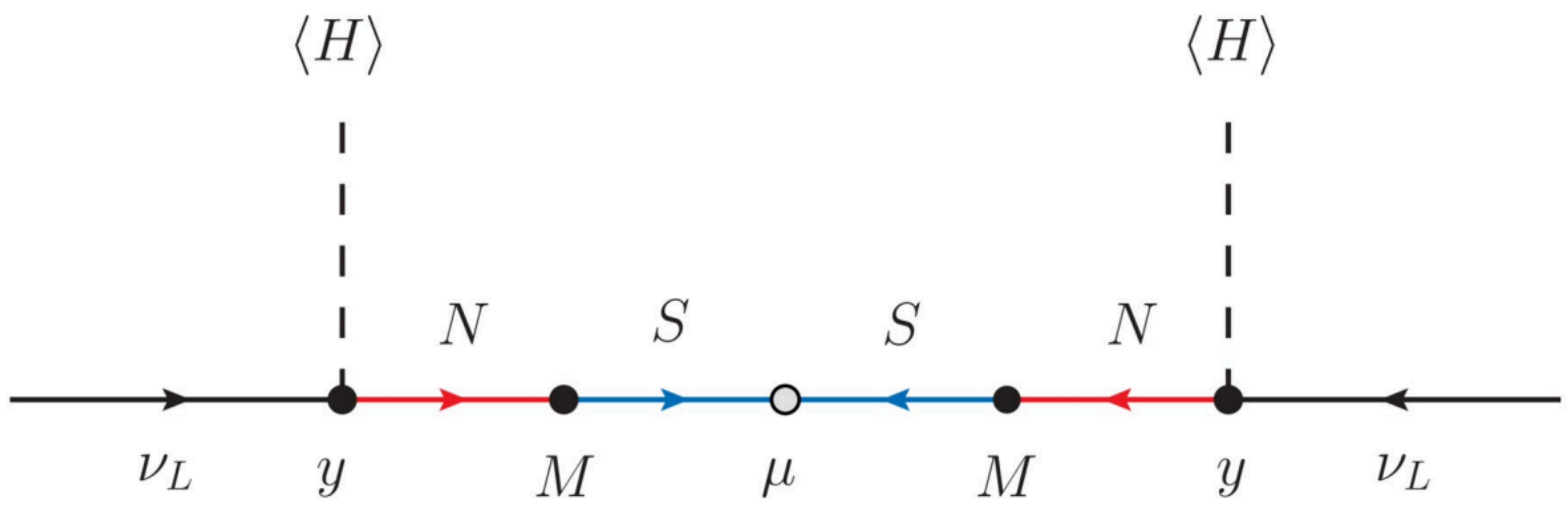
$$\mathcal{L} = \frac{g\sin\theta}{\sqrt{2}}\left(W_\mu \bar{\ell}_L \gamma^\mu N + h.c.\right) - \frac{g\cos\theta\sin\theta}{2\cos\theta_w} Z_\mu \left(\bar{\nu}_L\gamma^\mu N + \bar{N}\gamma^\mu \nu_L\right) + \frac{g\sin^2\theta}{2\cos\theta_w} Z_\mu \bar{N}\gamma^\mu P_L N$$

翘翘板模型 Type-I: inverse seesaw

- 额外增加Sterile Neutrino

$$\mathscr{L} = y\bar{L}NH + M\bar{N}S + \frac{1}{2}\mu\bar{S}^cS + h.c.$$

[Mohapatra, Valle, 1986]



$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

- 混合角 ($\mu \ll m_D \ll M$)

$$\sin^2\theta = \frac{m_\nu}{\mu} \quad \text{(inverse seesaw)}$$

- 质量

$$m_\nu = \mu \left(\frac{m_D}{m_N}\right)^2$$

翘翘板模型 Type-I: linear seesaw

- 额外增加Sterile Neutrino (lepton number?)

$$\mathcal{L}_Y = Y_D \overline{L} H^c N + Y_\epsilon \overline{L} H^c S + M_R \overline{N^c} S + \text{h.c.}$$

$$M_\nu = \begin{pmatrix} 0 & m_D & M_\epsilon \\ m_D^T & 0 & M_R \\ M_\epsilon^T & M_R^T & 0 \end{pmatrix}$$

- 混合角

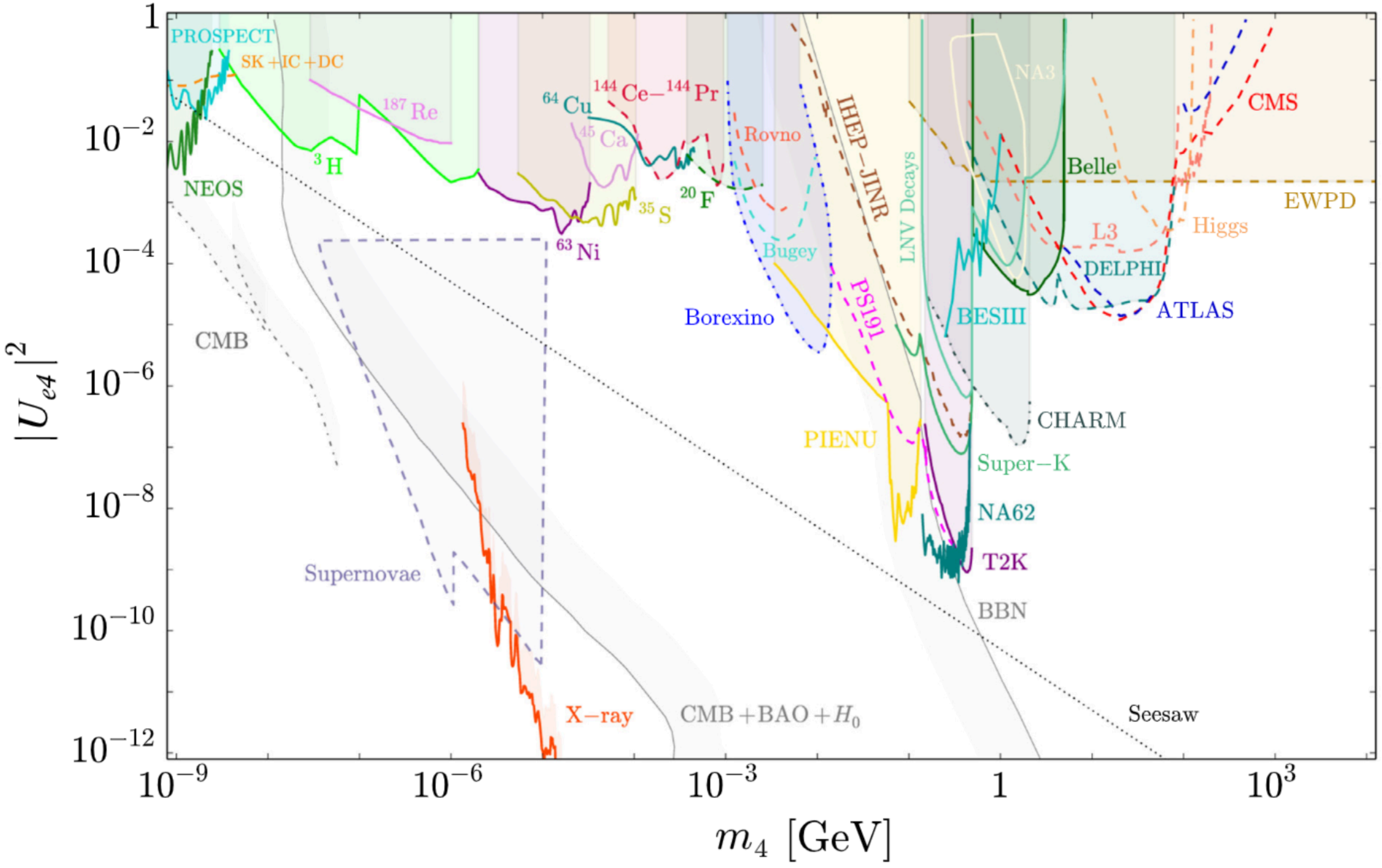
$$\sin\theta = \frac{m_\nu}{m_\psi} \quad \text{(linear seesaw)}$$

- 质量

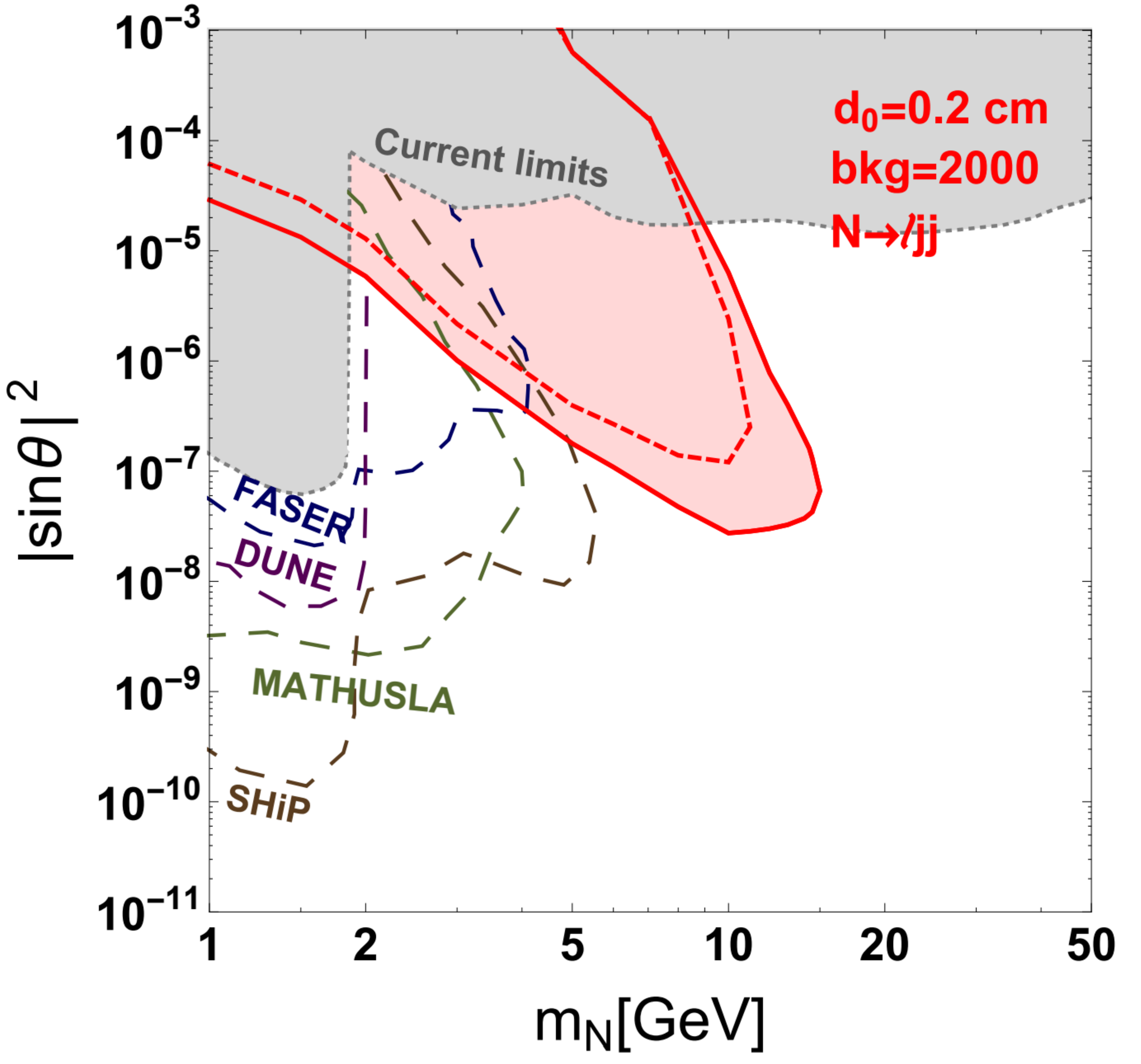
$$m_\nu = m_D M_R^{-1} M_\epsilon^T + M_\epsilon M_R^{T^{-1}} m_D^T$$

翘翘板模型 Type-I

- 两个自由参数模式 $\{m_N, \sin\theta\}$



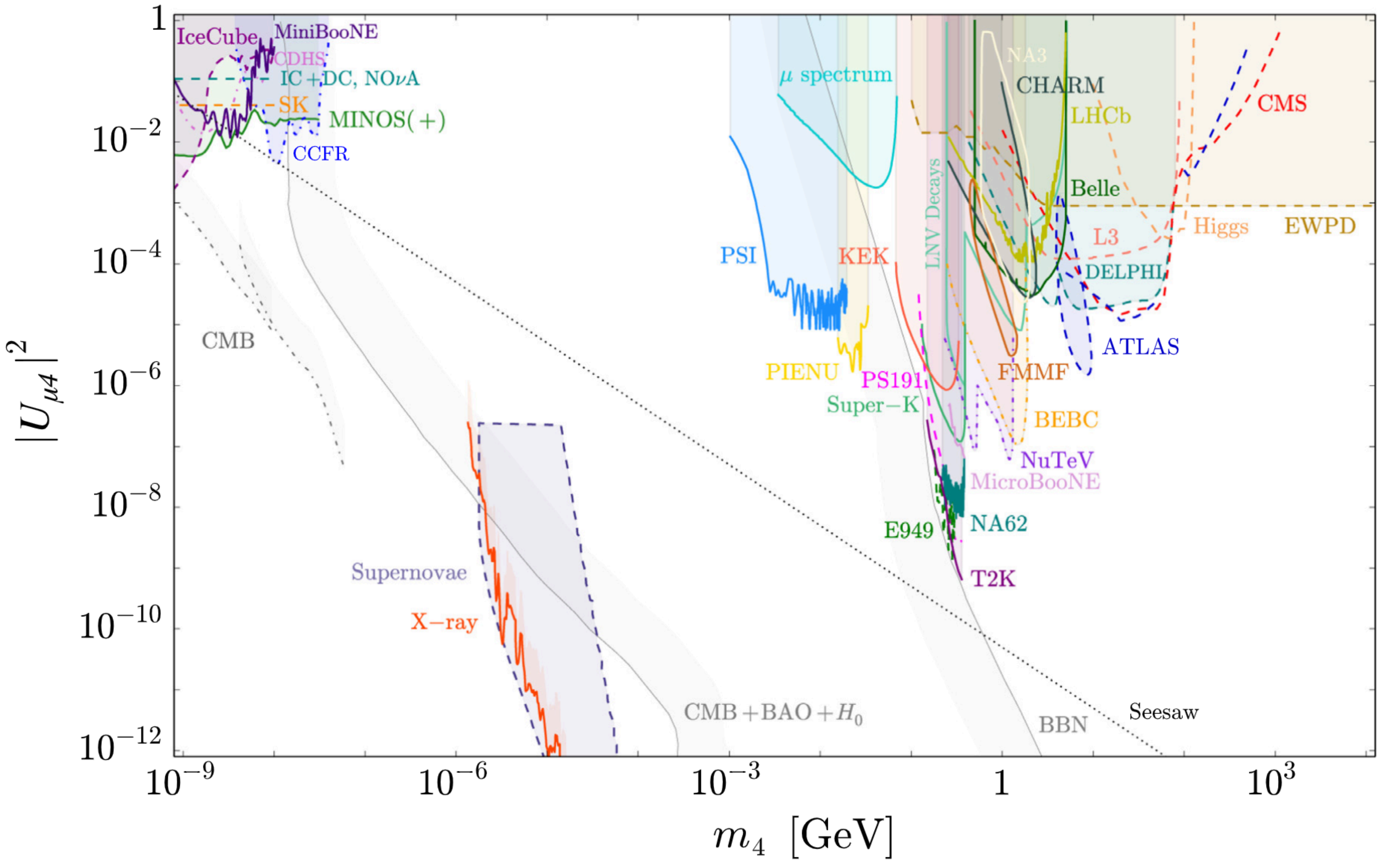
JL, Liu, Wang, Wang, 1904.01020 [JHEP]

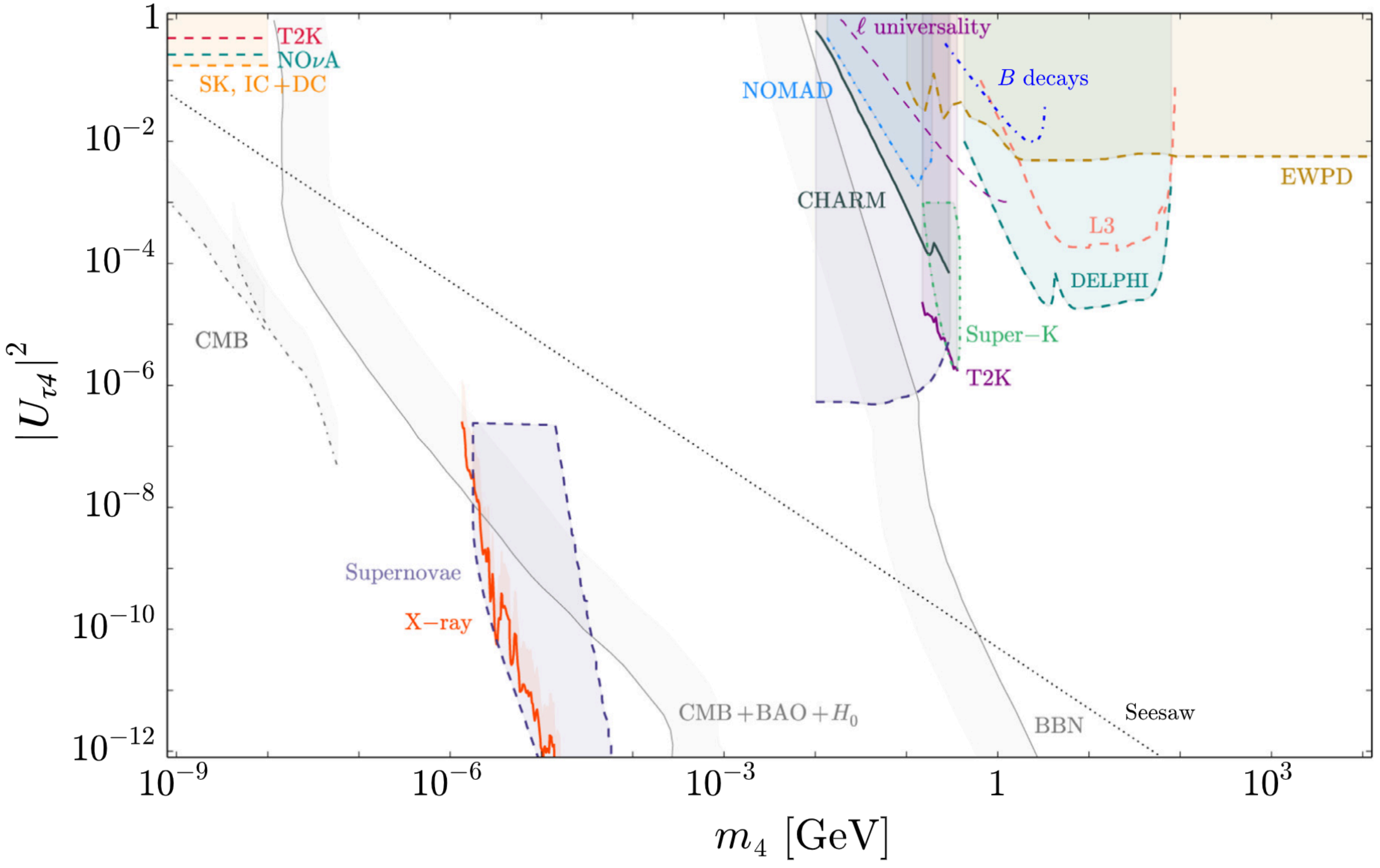


翘翘板模型 Type-I

- 两个自由参数模式 $\{m_N, \sin\theta\}$

Dasgupta, Kopp, Physics Report 2021



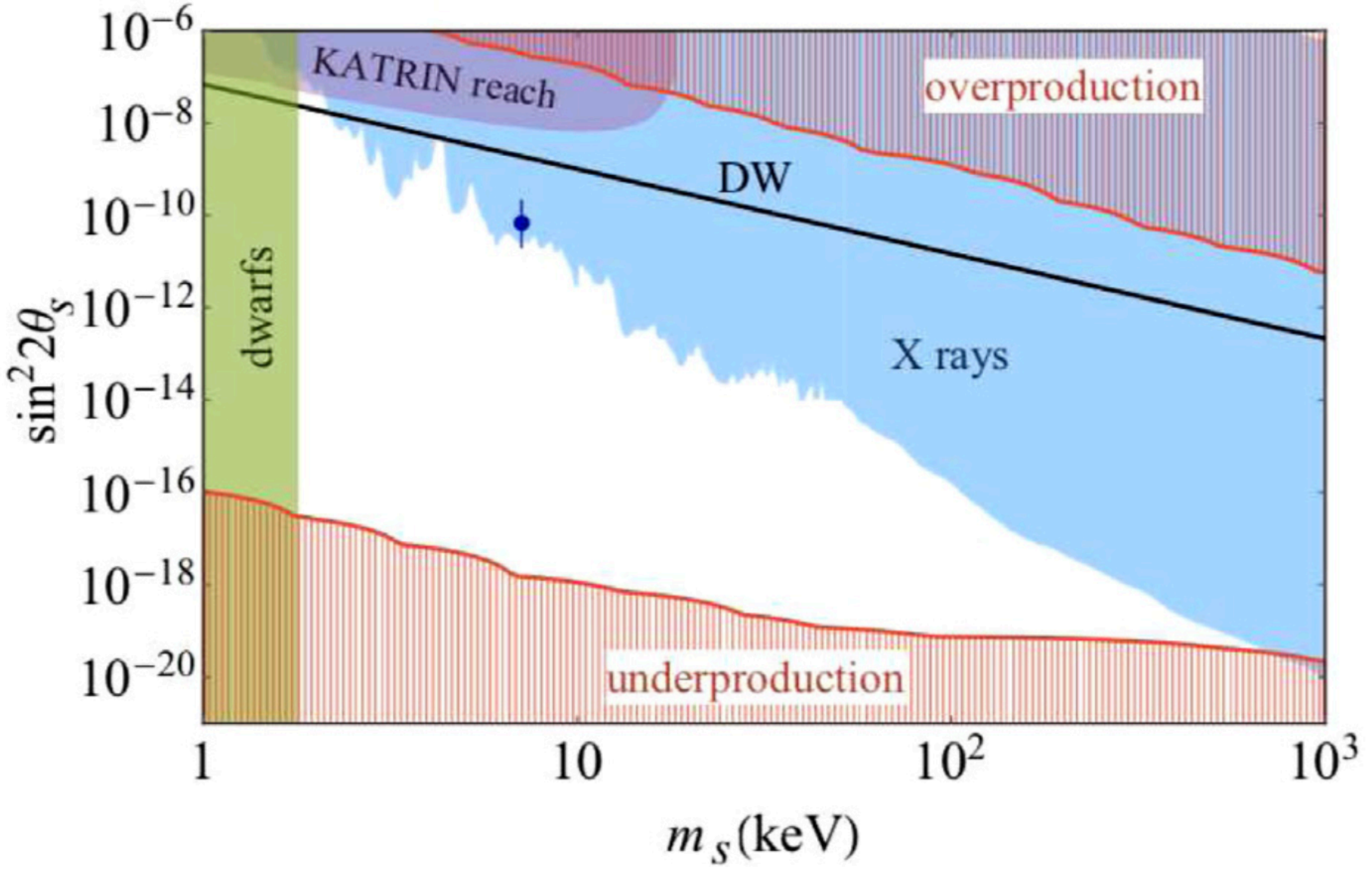


翘翘板模型 Type-I

- Sterile neutrino DM

- Shi-Fuller mechanism

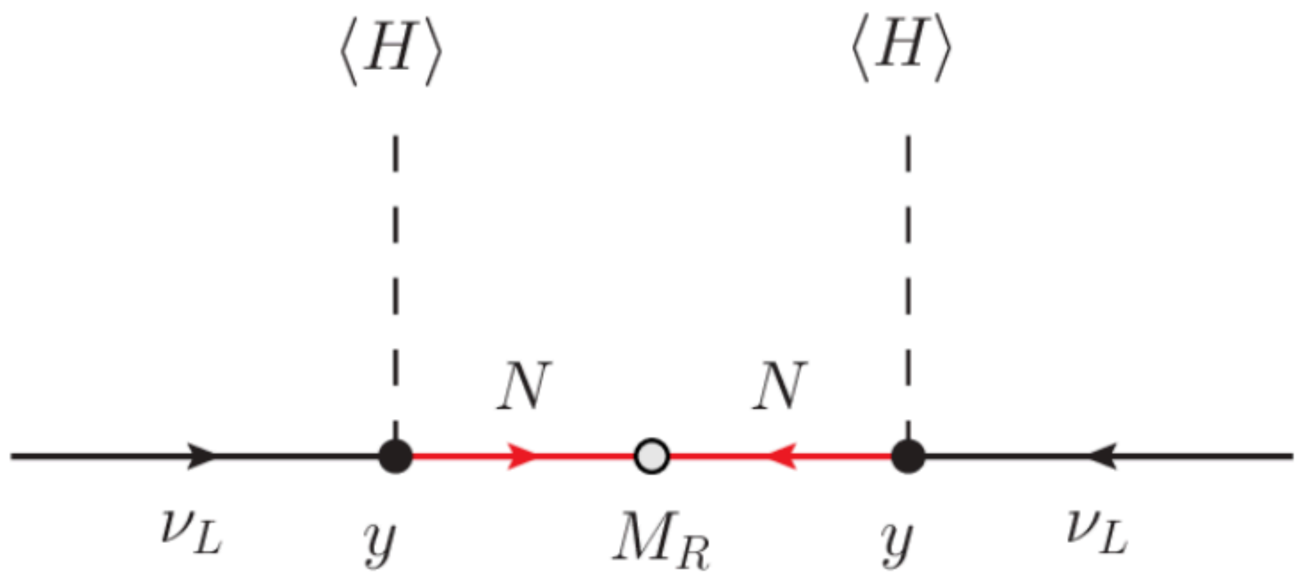
$$\sin^2 2\theta_\mathrm{m} = \frac{\sin^2 2\theta}{\left(\cos 2\theta + \frac{2E_\nu}{\Delta m^2} V_\mathrm{eff}\right)^2 + \sin^2 2\theta}$$

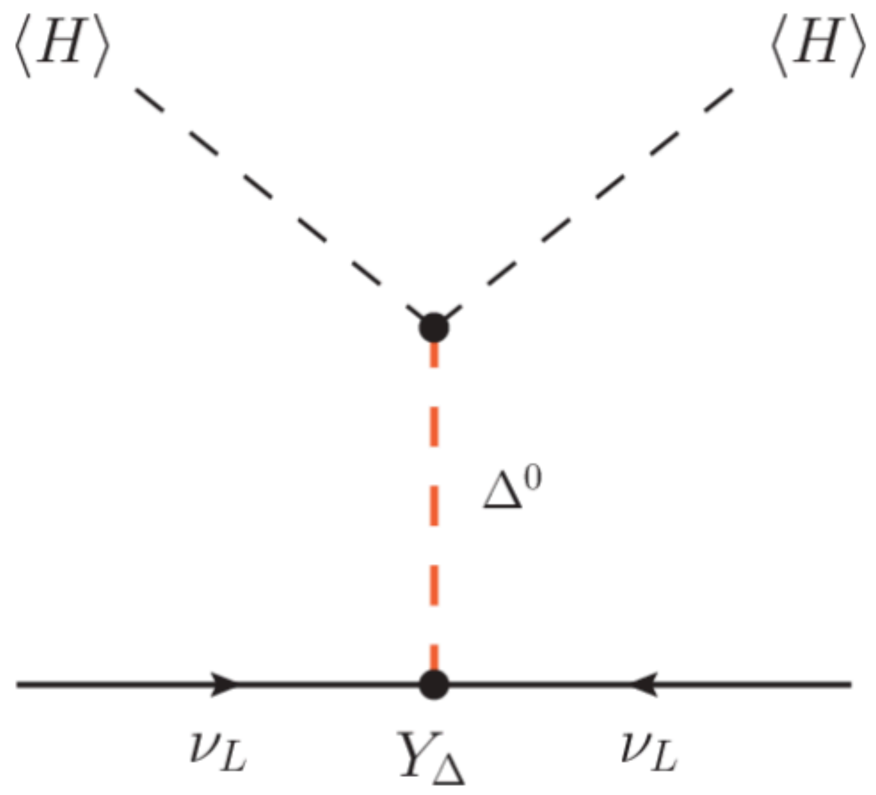


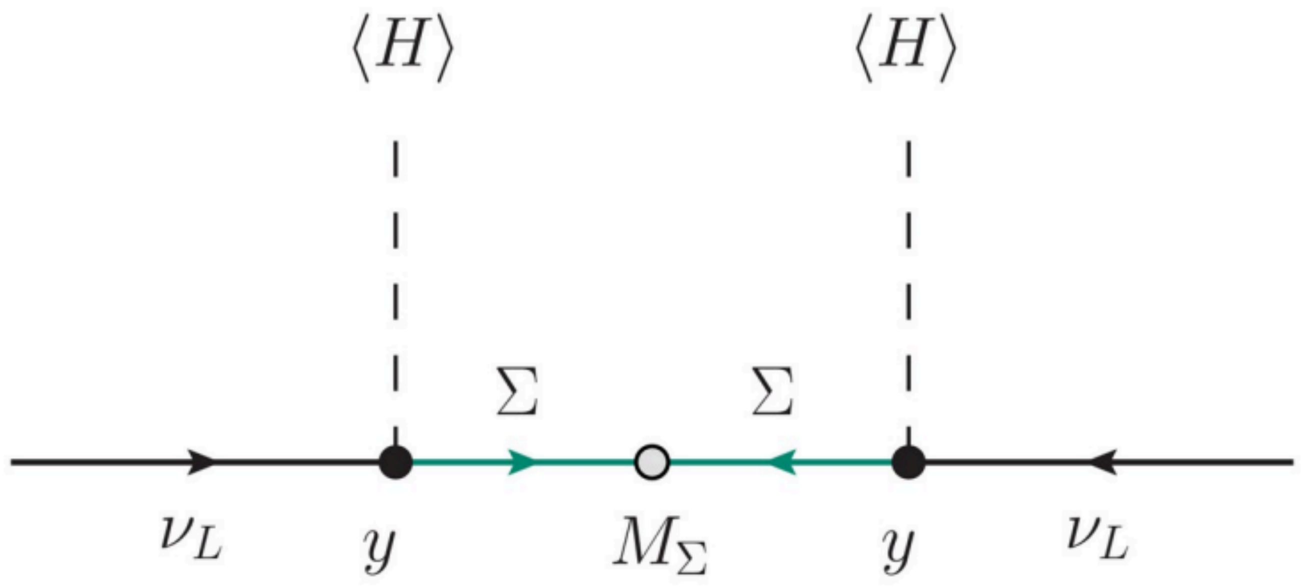
翘翘板模型 其它

- Type-I, II, III

Type-I	Type-II	Type-III







[Minkowski, Yanagida, Mohapatra, Senjanovic, Gell-Mann, Ramond, Slansky, Schechter, Valle]

[Schechter, Valle, Mohapatra, Senjanovic]

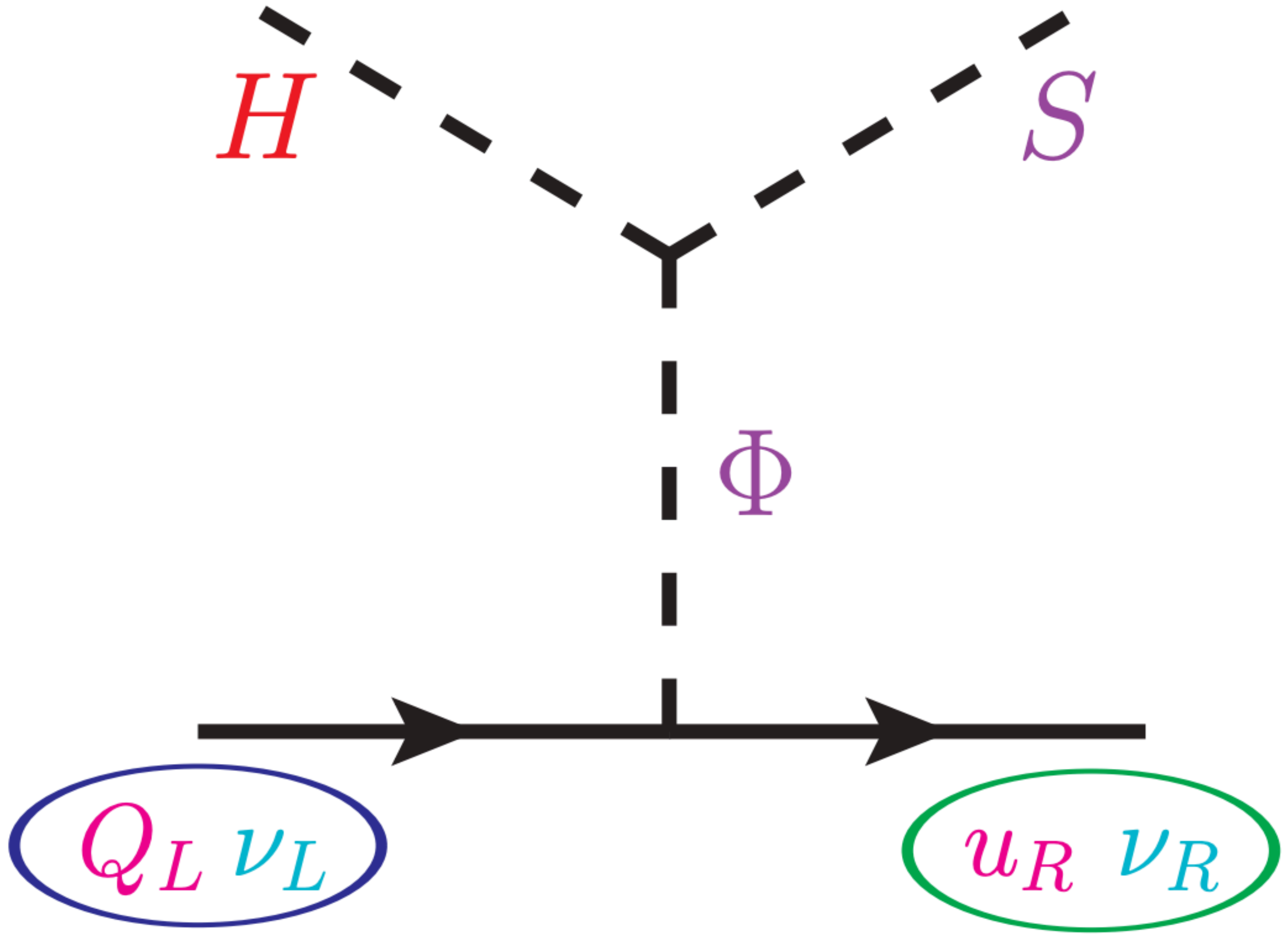
[Foot, Lew, He, Joshi]

Courtesy of Avelino Vicente

Dirac翘翘板模型与强CP问题

P.H. Gu, H.J. He JCAP 2006

- Dirac Seesaw



- Strong CP solution with small up mass

$$\mathrm{Im}[m_u m_d m_s \exp(i\theta)] = |m_u m_d m_s| \exp(i\theta_{\mathrm{QCD}})$$

$$\theta_{\mathrm{QCD}} = \arg[m_u]$$

$$\mathrm{Im}[m_u(1\mathrm{GeV})] < 10^{-3}\mathrm{eV}$$

- 具体参数

$$m_u = m_u^H + m_u^{\mathrm{inst}}$$

$$|m_u^H| \ll |m_u| \simeq |m_u^{\mathrm{inst}}|$$

$$\theta_{\mathrm{QCD}} \simeq \sin\theta^H \frac{|m_u^H|}{|m_u|}(1\mathrm{GeV})$$

$$|m_u^H|(1\ \mathrm{GeV})\ \ \sin\theta^H < 6.5\times 10^{-4}\mathrm{eV}$$

Dirac翘翘板模型与强CP问题

- UV 模型构造

$$\mathcal{L} = Y_\nu \bar{L}_L \bar{\Phi} \nu_R + Y_u \bar{Q}_L \bar{\Phi} u_R + h.c., \qquad \bar{\Phi} = i\sigma_2 \phi^*$$

$$V = m_\Phi^2 \Phi^\dagger \Phi + (\rho S H^\dagger \Phi + h.c.) + \ldots$$

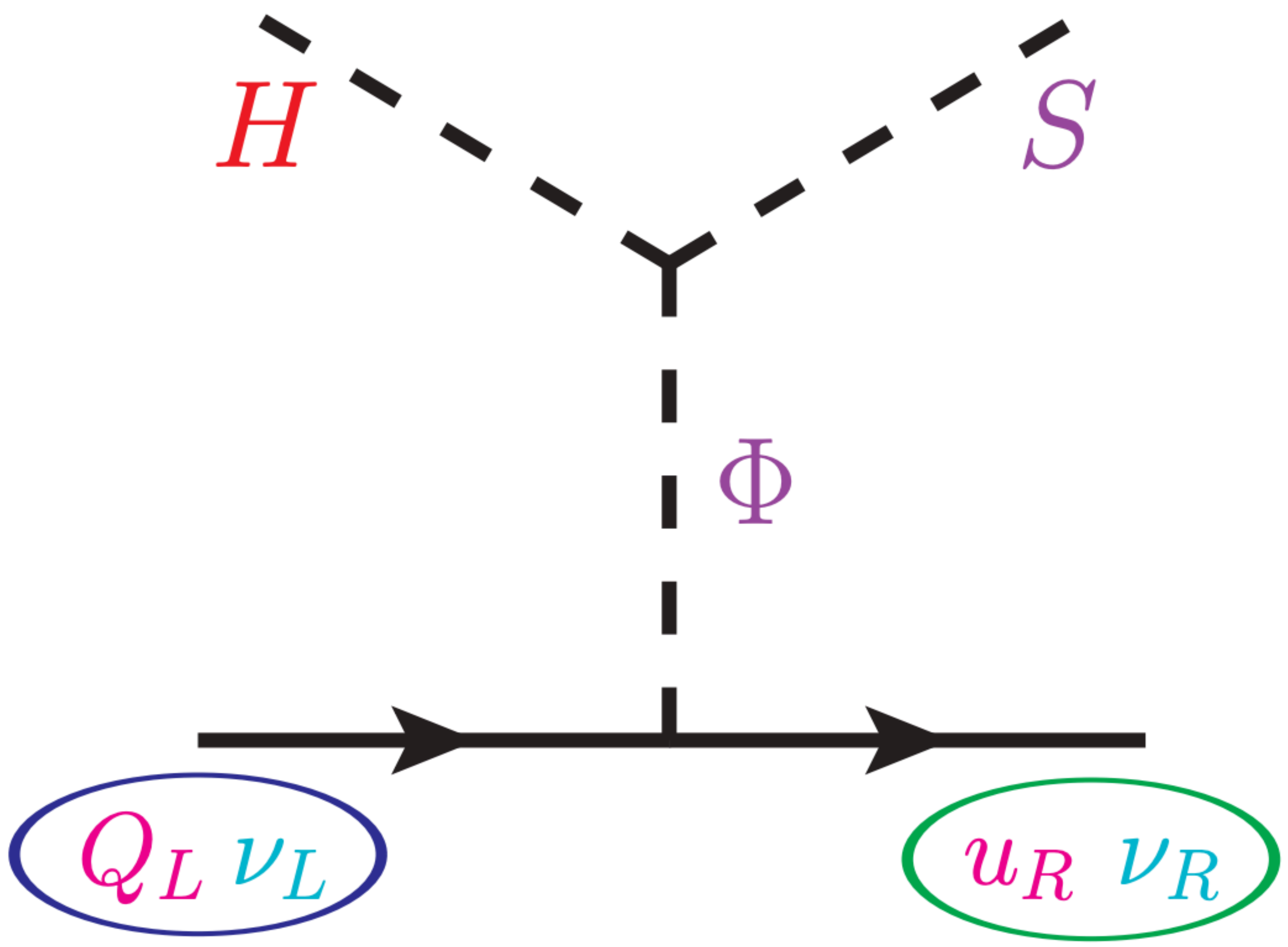
- 质量项

$$m_\nu \simeq Y_\nu \frac{\rho v_s v}{2\, m_\Phi^2}, \qquad m_u^H \simeq Y_u \frac{\rho v_s v}{2 m_\Phi^2}$$

- 超重的希格斯粒子

$$m_\Phi \simeq 6 \times 10^{12}\text{GeV} \left(\frac{Y_\nu}{0.1}\right) \left(\frac{\rho}{0.1 m_\Phi}\right) \left(\frac{v_s}{v}\right) \left(\frac{0.05\text{eV}}{m_\nu}\right)$$

- Yukawa关系 $Y_u(M_Z) < 0.1\ Y_\nu \left(\frac{0.1}{\sin\theta_H}\right), \quad \text{with} \ \ \text{Im}[m_u^H] = |m_u^H| \sin\theta_H$



总结

- 新物理模型多种多样, 只需要满足量子场论要求
    - 轴子类轴子模型
    - 暗光子模型
    - 中微子模型
    - Vector-like fermion, lepto-quark etc…

谢谢观看！

Backup slides