The dark axion portal at CEvNS experiments

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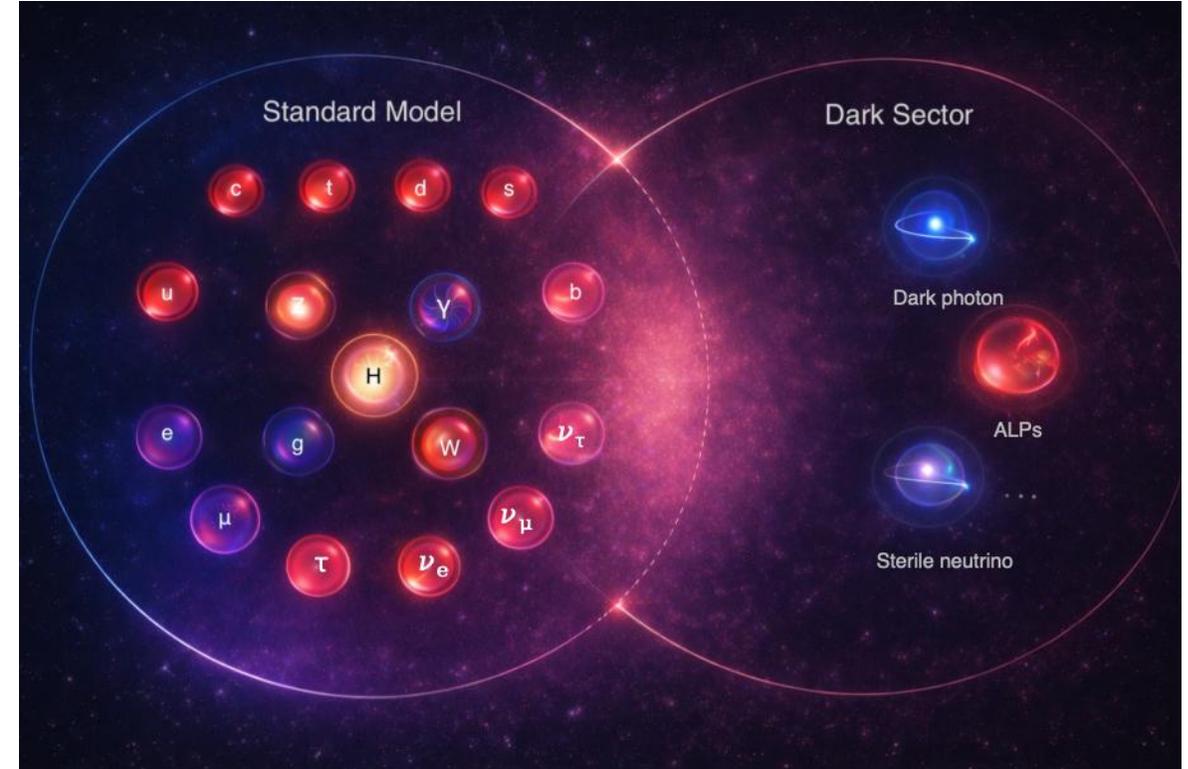
[2]School of Physics, Southeast University

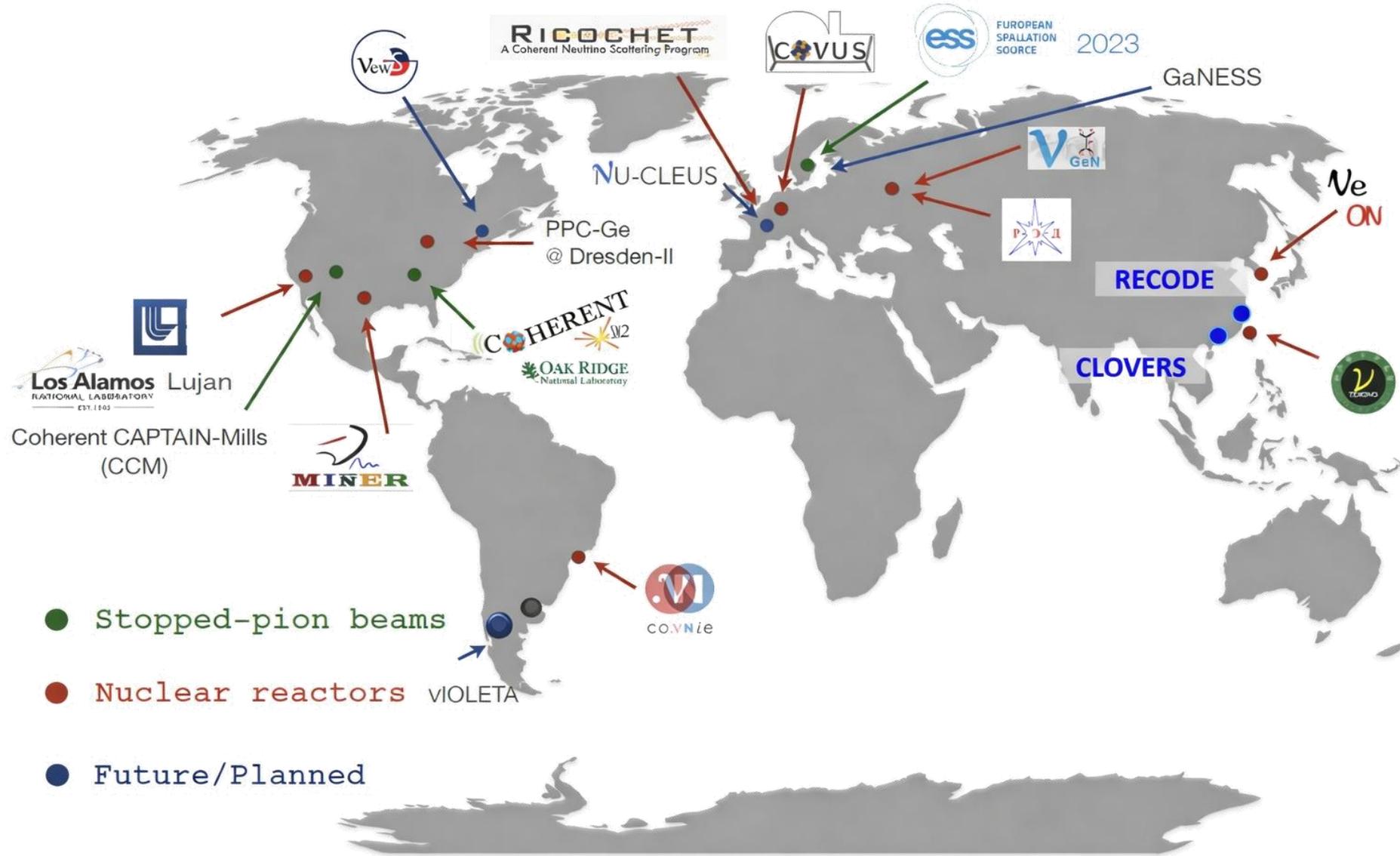**IAS Program on Fundamental Physics** Jan 2026

Dark matter candidates can be connected to the Standard Model sector through portals other than gravitational interactions.

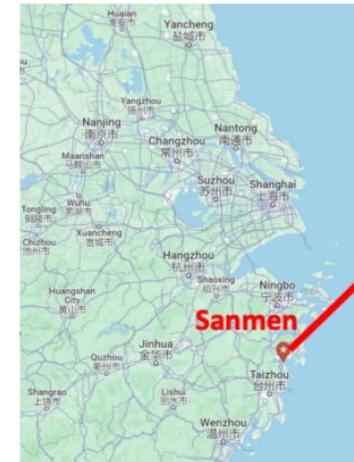Vector portal: $F_{\mu\nu}Z'^{\mu\nu}$

Neutrino portal: LHN

Dark axion portal: $\dfrac{G_{a\gamma'\gamma'}}{4}aZ'_{\mu\nu}\tilde{Z}'^{\mu\nu} + \dfrac{G_{a\gamma\gamma'}}{2}aF_{\mu\nu}\tilde{Z}'^{\mu\nu}$
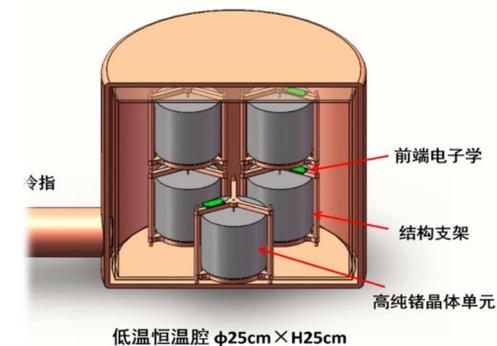
REactor neutrino COherent scattering Detection Experiment

• Sanmen Nuclear Power Plant (AP1000)
- • @Taizhou, Zhejiang
- • Thermal power: 3.4 GW

Project Goals:
• Two Ge arrays (10kg in total)
- • Energy threshold ~ 1 keVnr (~160eVee)
- • ~ 500 CEvNS events/kg/year
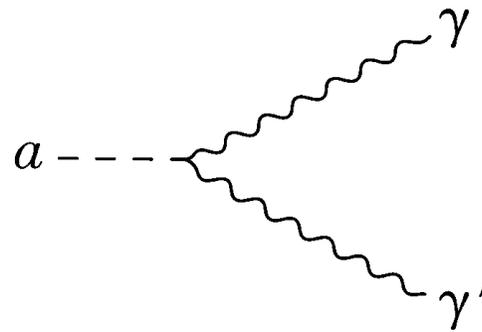- • Background level < 2 counts/kg/keV/day

令指　前端电子学
　　　结构支架
　　　高纯锗晶体单元
低温恒温腔 φ25cm×H25cm

Comparison with other Exps.

Experiment	Detector volume	Threshold	Distance to reactor core	Reactor	Thermal power	Location
RECODE	847.8 cm^3	160 eV	11 m(nearest) 22 m(farthest)	Sanmen NPP	3.4 GWth	China
CONUS	751.46 cm^3	300 eV	17 m	Brokdorf (KBR)	3.9 GWth	Germany
MINER	3085.2 cm^3	100 eV	2.835 m	TRIGA reactor	1 MWth	USA
NEOS	1.008 m^3	3.5 MeV	23.7 m	Hanbit NPP	2.73 GW	Korea

The Lagrangian of dark axion portal can be describe by the following terms[1]:

$$L_{dark\ axion\ portal} = \frac{G_{a\gamma'\gamma'}}{4} a Z'_{\mu\nu} \tilde{Z}'^{\mu\nu} + \frac{G_{a\gamma\gamma'}}{2} a F_{\mu\nu} \tilde{Z}'^{\mu\nu}$$

which provides an opportunity for connections between Standard Model particles when axions and dark photons coexist via vertex：
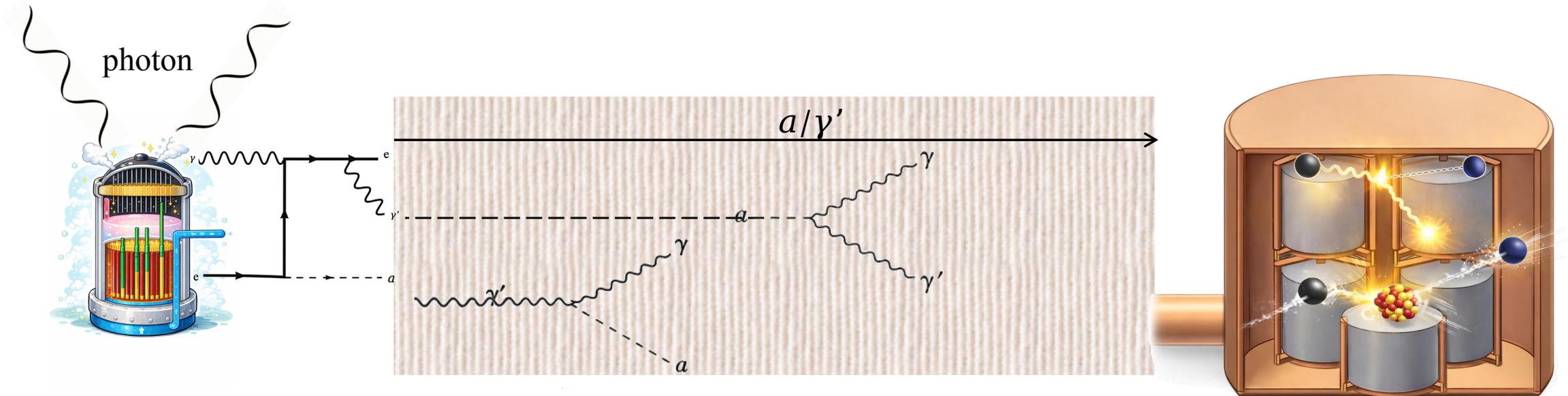

[1] Patrick deNiverville, Hye-Sung Lee, and Young-Min Lee. New searches at reactor experiments based on the dark axion portal. Physical Review D, 103(7), April 2021.
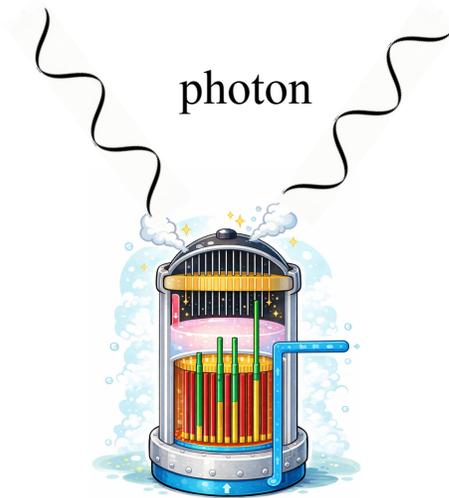
The calculation can be divided into three parts：
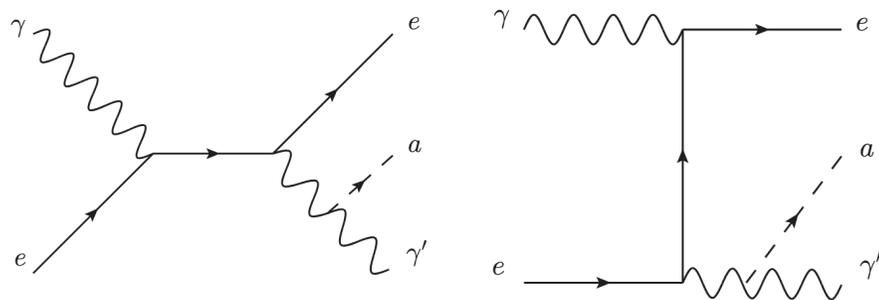
Production   **Flight**   **Detection**

Production：

photon

photon flux : $\frac{dN_\gamma}{dE_\gamma} = \frac{0.58 \times 10^{18}}{\sec \cdot \mathrm{MeV}} \frac{P}{\mathrm{MW}} e^{-E_\gamma/(0.91\mathrm{MeV})}$

The energy spectrum of axions or dark photons generated near the reactor core via the process $\gamma + \mathrm{e} \to \mathrm{e} + \mathrm{a} + \gamma'$ is given by:

$$\frac{\mathrm{dN_{a/\gamma'}}}{\mathrm{dE_{a/\gamma'}}} = \int \mathrm{dE_\gamma} \frac{1}{\sigma_{\mathrm{tot}}} \frac{\mathrm{dN_\gamma}}{\mathrm{dE_\gamma}} \frac{\mathrm{d}\sigma_{\gamma\mathrm{e}\to\mathrm{ea}\gamma'}}{\mathrm{dE_{a/\gamma'}}}$$
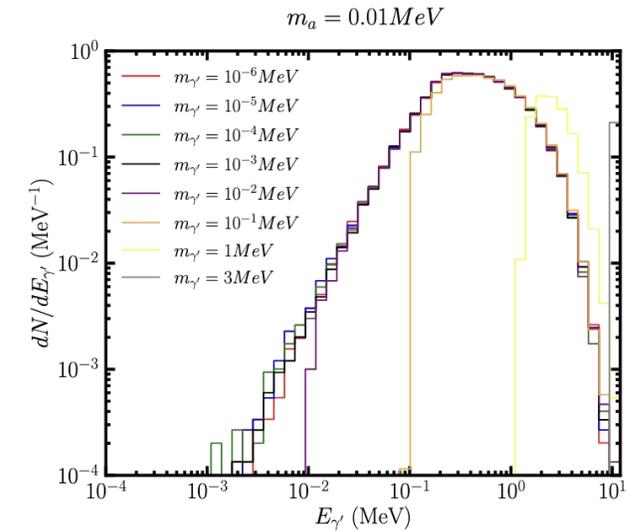
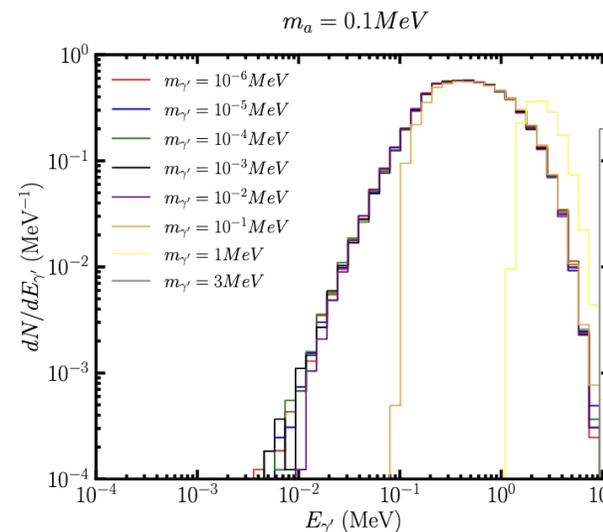The Compton scattering cross section is a sufficiently good approximation.

The normalized dark photon energy spectra corresponding to different dark photon masses when the axion mass is fixed at $10^{-3}, 10^{-2}, 10^{-1}$ and 1 MeV.
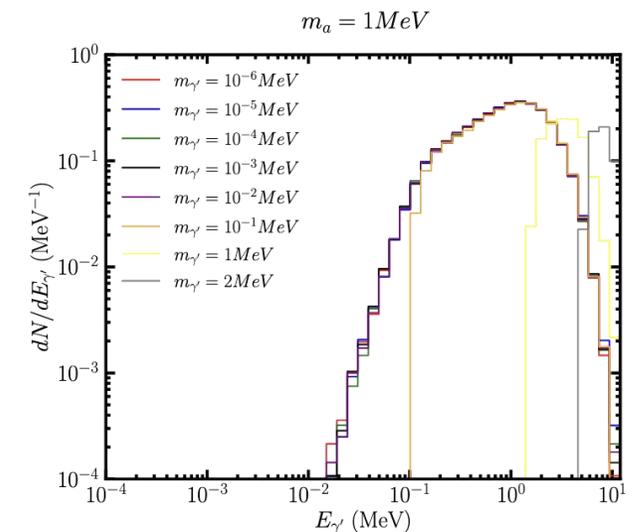

(a)

(b)

(c)

(d)

Attenuation during the flight

When $m_a > m_{\gamma'}$, the decay channel $a \to \gamma + \gamma'$ is allowed, leading to:

$$\Gamma_{a \to \gamma\gamma'} = \frac{G^2_{a\gamma\gamma'}}{32\pi} m_a^3 \left(1 - \frac{m^2_{\gamma'}}{m^2_a} \right)^3, \qquad \Gamma_{\gamma' \to a\gamma} = 0$$
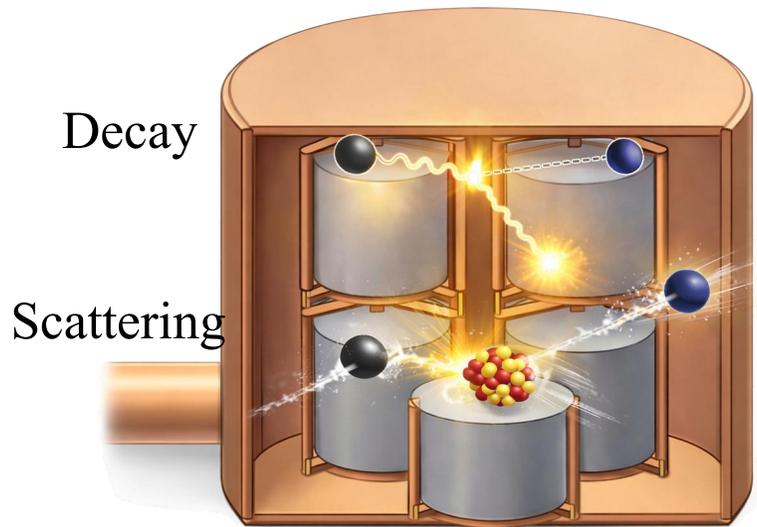
Axions can decay, leading to an attenuation of the flux.

When $m_{\gamma'} > m_a$, the decay channel $\gamma' \to \gamma + a$ is allowed, leading to:

$$\Gamma_{\gamma' \to a\gamma} = \frac{G^2_{a\gamma\gamma'}}{96\pi} m_{\gamma'}^3 \left(1 - \frac{m^2_a}{m^2_{\gamma'}} \right)^3, \qquad \Gamma_{a \to \gamma\gamma'} = 0$$

Dark photons can decay, leading to an attenuation of the flux.

Detection

Decay signal spectrum：

The fraction decaying inside the detector

$$P_{decay} = \exp\left(-\frac{L}{c\beta\gamma\tau}\right) - \exp\left(-\frac{L + \sqrt[3]{V}}{c\beta\gamma\tau}\right)$$

$$\frac{dS_\gamma^{Decay}}{dE_\gamma} = \frac{A\Delta t}{4\pi L^2} \int dE \frac{dN_{a/\gamma'}^{core}}{dE} P_{decay} P_{E\rightarrow E_\gamma}$$
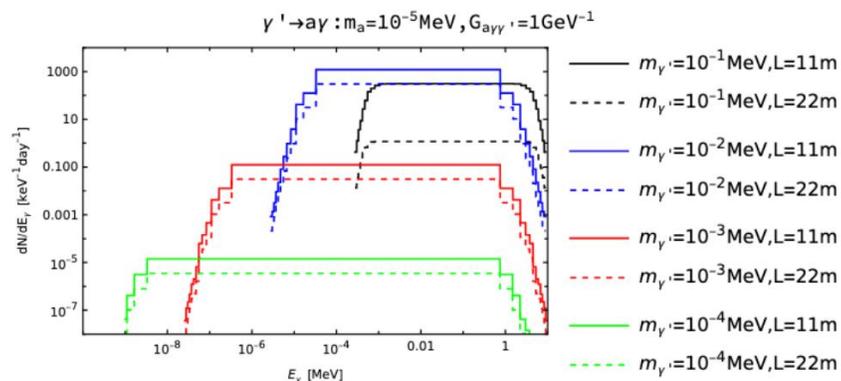
The probability for a parent particle with energy E to produce a photon with energy E_γ .

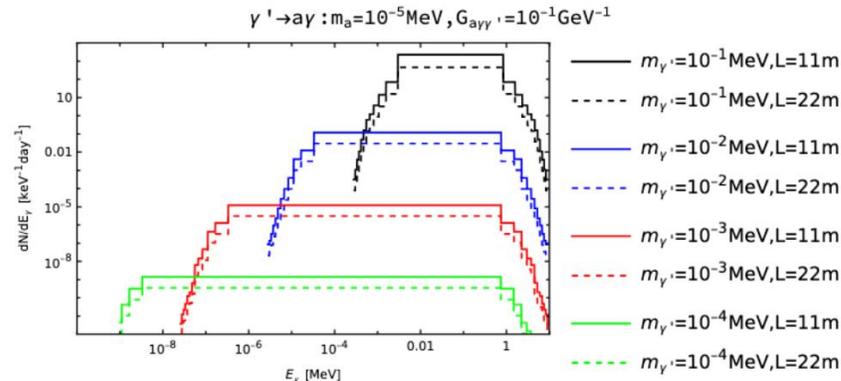$$P_{E\rightarrow E_\gamma} = \frac{1}{2\beta\gamma E_{CM}}$$

$\beta\gamma = \frac{P}{m}$, E_{CM} is the energy of the photon in the center-of-mass frame of the parent particle.

E_γ is uniformly distributed within the interval $[\gamma(E_{CM} - \beta P_{CM}), \gamma(E_{CM} + \beta P_{CM})]$
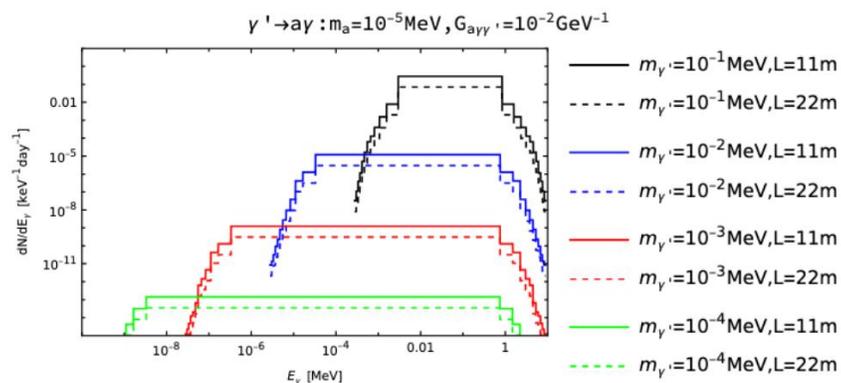
Decay

Scattering

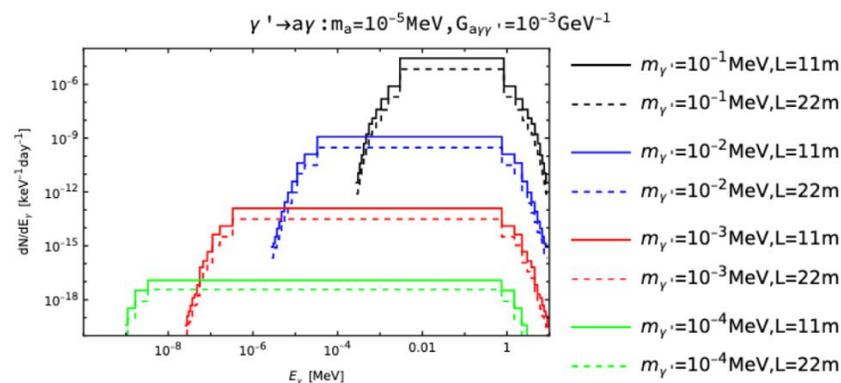Dark photon decay signal spectrum at detctor

(a)

(b)

(c)
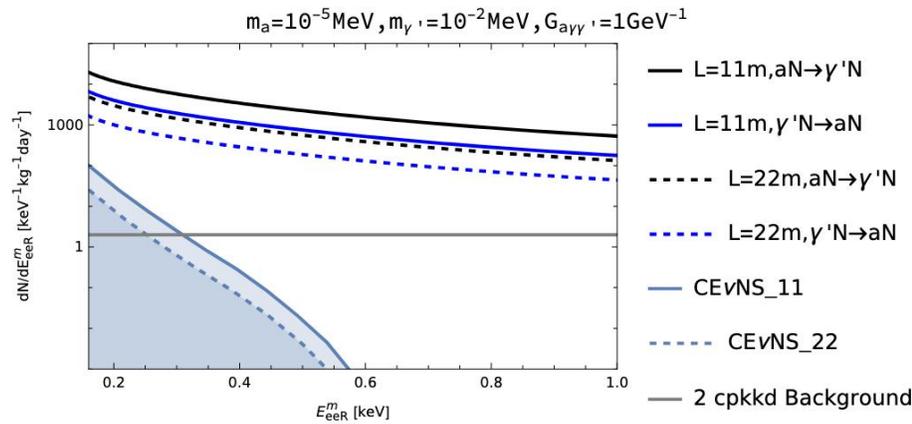
(d)

$m_{\gamma'} > m_a,$
$\gamma' \rightarrow \gamma + a$
is opened

Nuclear recoil spectrum at detctor

(a)

(b)

(c)

(d)

Considering only the decay signal, the expected sensitivities of the RECODE program and other experiments.

Deriving exclusion limits by requiring the statistical significance:

$$\frac{N_s}{\sqrt{N_s + N_b}}$$

to reach 2σ, corresponding to 95% C.L.

(a)

(b)

Projected constraints on the dark axion portal, combining both decay and scattering signals.

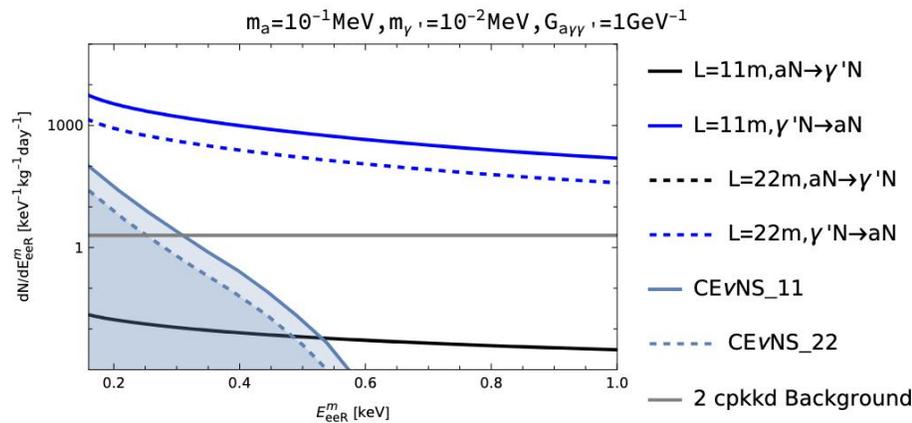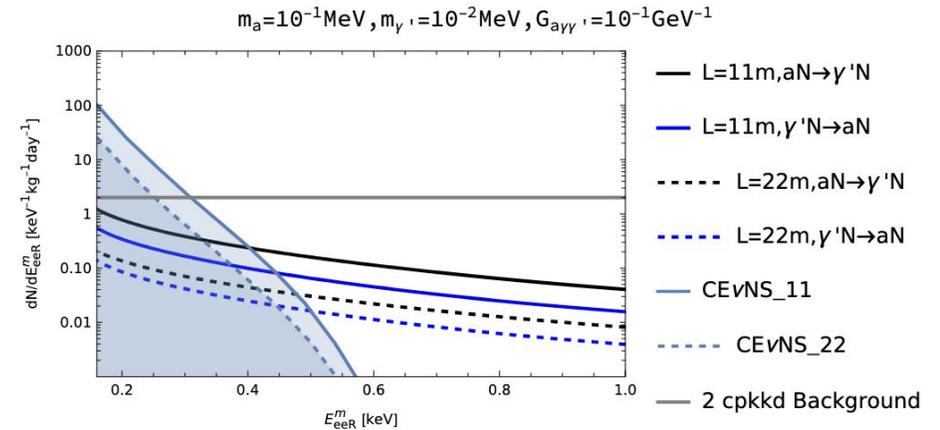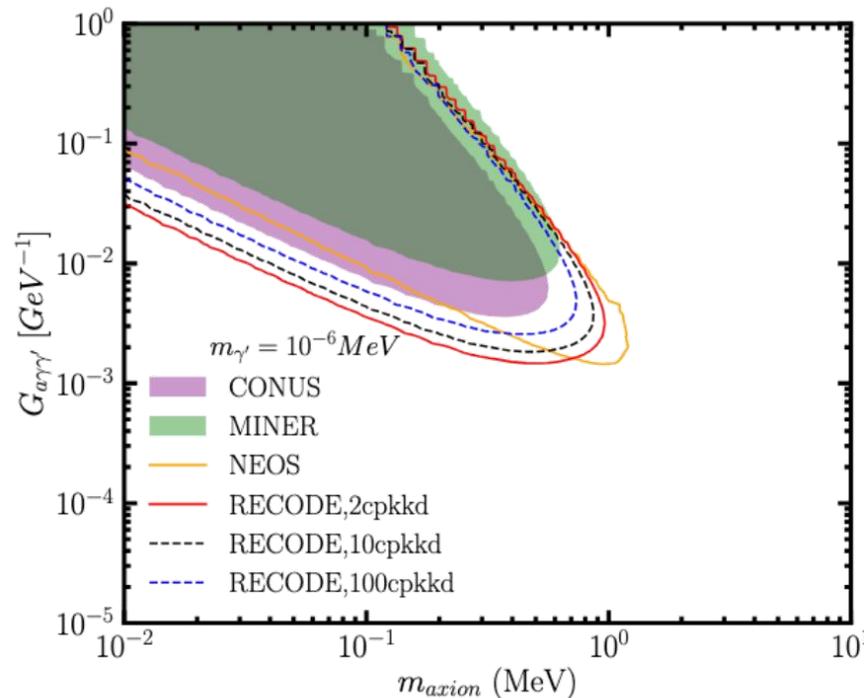We performed a detailed study of the dark axion portal and made the complex calculations feasible by using MadGraph.

The projected sensitivities of the RECODE program and other reactor experiments for probing the dark axion portal presented in this work provide results complementary to other experiments.

The RECODE program will improve the precision of SM studies and enhance sensitivity to other new physics portals.

Thanks!

Using MadGraph with the effective photon approximation method, for
$e^- a \rightarrow e^- X$[1]:

$$\sigma(e^- a \rightarrow e^- X) \approx \int dx \, \boxed{P_{\gamma/e}(x)} \boxed{\sigma(\gamma a \rightarrow X)}$$

Matching the differential spectrum to the effective photon approximation:

Modify the photon PDF file located at .../project/Source/PDF/PhotonFlux.f.

$$\frac{dN_{a/\gamma'}}{dE_{a/\gamma'}} = \int dE_\gamma \, \boxed{\frac{1}{\sigma_{tot}} \frac{dN_\gamma}{dE_\gamma}} \boxed{\frac{d\sigma_{\gamma e \rightarrow ea\gamma'}}{dE_{a/\gamma'}}}$$

Treat the electron as the a particle!

```fortran
real*8 function epa_lepton(x,q2max, mode)
implicit none
double precision sigma_interpolation
integer i, mode, imode
c    mode is +3/-3  for electron and +4/-4 for muon
real*8 x,phi_f
real*8 xin(3:4)
real*8 alpha
real*8 f, q2min,q2max, Ein
real*8 PI, MeVTopb
data PI/3.14159265358979323846/

data xin/0.511d-3, 0.105658d0/ !electron mass in GeV

alpha = .0072992701
imode = abs(mode)
Ein = 0.02

MeVTopb = (0.511*3.86d-11)*(0.511*3.86d-11)*1.0d36
c    MeVTopb是把截面从MeV^-2转换到pb,MadGraph的截面单位是pb,插值的截面是MeV^-2!
// x = omega/E = (E-E')/E
if (x.lt.1) then
    q2min= xin(imode)*xin(imode)*x*x/(1-x)
    if(q2min.lt.q2max) then
        f = 0.58d24*exp(-Ein*x/0.91*1000)*Ein/(sigma_interpolation(Ein*x*1000)*MeVTopb)
c    上边的插值微分截面中要乘以1000,把GeV转换成MeV
    else
        f = 0.
    endif
else
    f= 0.
endif
c    write (*,*) x,dsqrt(q2min),dsqrt(q2max),f
if (f .lt. 0) f = 0
epa_lepton = f

end
```
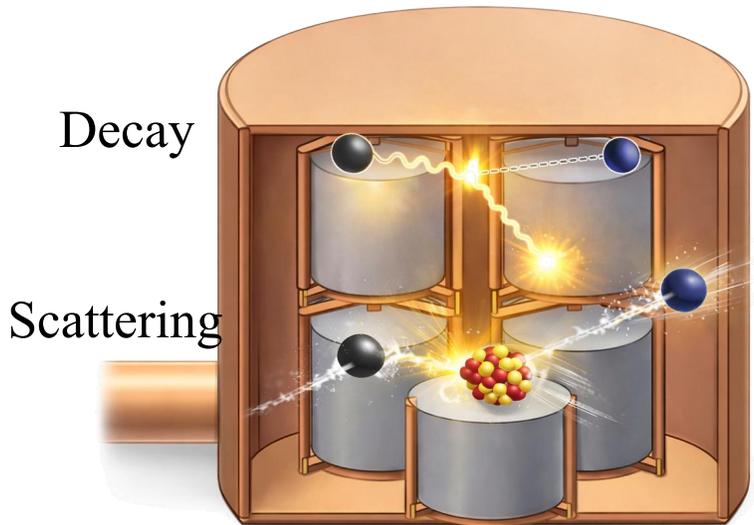
[1] Tao Han. Collider phenomenology: Basic knowledge and techniques. In Theoretical Advanced Study Institute in Elementary Particle Physics: Physics in D 4, pages 407–454, 8 2005.

Detection

Scattering signal spectrum：

$$\frac{dS}{dE_{nR}} = m_{det} \frac{N_T T}{4\pi L^2} \int dE \frac{d\sigma}{dE_{nR}} \frac{dN_{a/\gamma'}^{core}}{dE} \exp\left(-\frac{L}{c\beta\gamma\tau}\right)$$

The observed scattering signal spectrum after accounting for the quenching effect and the detector resolution is:

$$\frac{dS}{dE_{eeR}^m} = \int \frac{dS}{dE_{eeR}} \boxed{\frac{e^{-\frac{(E_{eeR}^m - E_{eeR})^2}{2\delta_E^2}}}{\sqrt{2\pi}\delta_E}} dE_{eeR} \Bigg|_{E_{eeR}=Q(E_{nR})}$$

quenching factor under the Lindhard theory

Decay

Scattering