Oscillations to dark photons in particle physics experiments

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Talk is based on and aimed at stimulating

- D.G., A.Makarov, I.Timiryasov, arXiv:1411.4007
- M.Danilov, S.Demidov, D.G., arXiv:1804.10777
- S.Demidov, S.Gninenko, D.G., arXiv:1810.xxxxx
- …
- TEXONO, DANSS,…
- NA64, invisible and visible modes
- SHiP ν_τ-detector…, when it is fixed
- DUNE Near Detector…, when it is fixed
- exps at Fermilab ?, T2K ?, …

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In short

- A new (massive) vector field X_μ singlet with respect to SM gauge group

$$\varepsilon X_{\mu\nu} F^{\mu\nu}$$

- X_μ can be emitted and absorbed in the Compton process
- For light X_μ, that is $M_X \ll 1$ MeV, only missing/recoil E are signatures
- In a relativistic case, $M_X \ll E_X$, nothing depends on mass M_X

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Accelerator experiments: invisible mode, $\propto \varepsilon^2$

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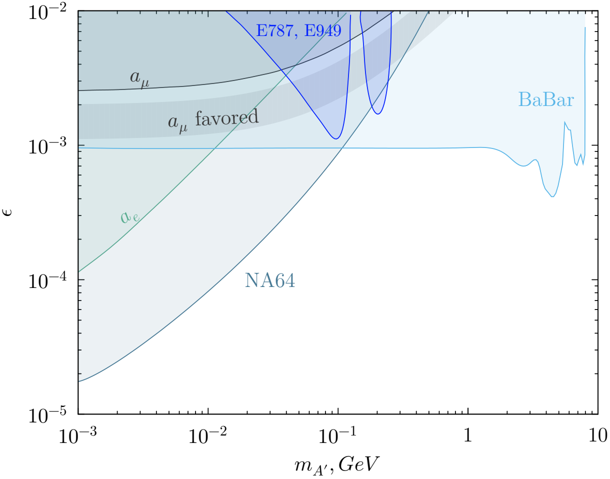

NA64 sensitivity to invisible vectors

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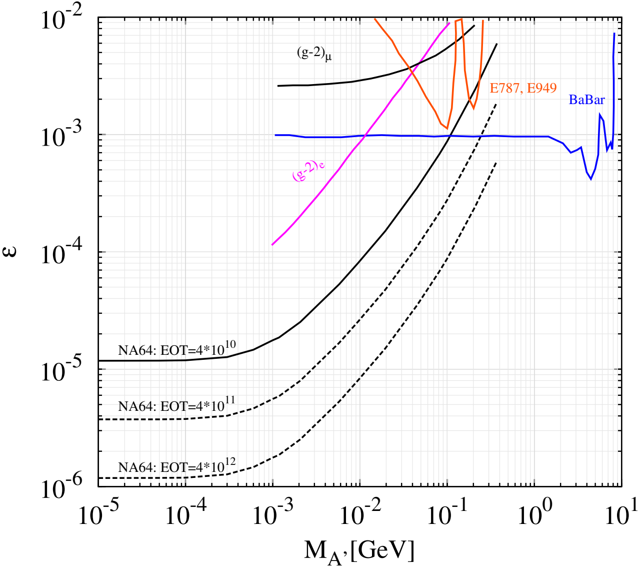
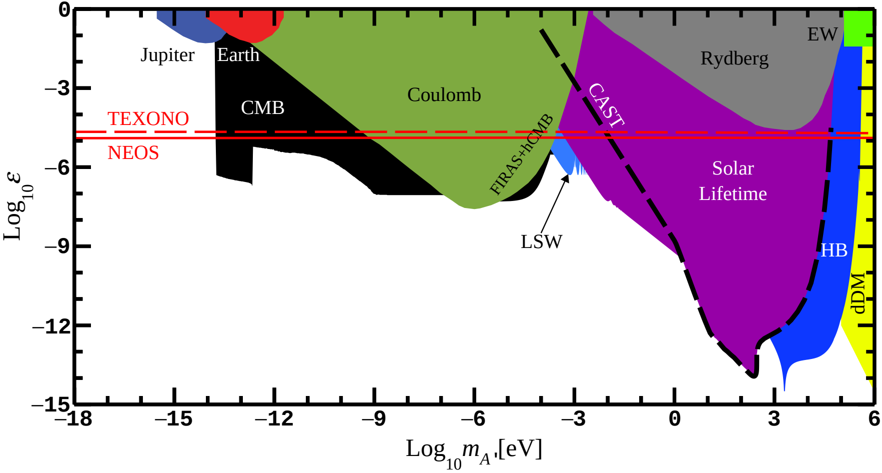


flat sensitivity curves ⟶

Results based on Compton scattering

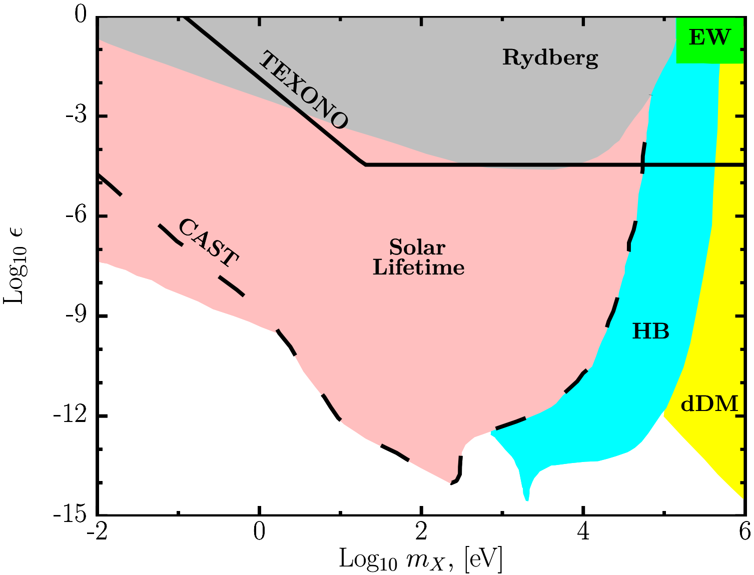
PRL(2017) 1705.02470



$$\frac{\lambda}{10^{14}\,\mathrm{cm}} = 2\pi\,\frac{10^{18}\,\mathrm{eV}}{m_{A'}}$$

10 astronomical units !!

The sensitivity DOES depend on M_X



Widely accepted statements: phenomenology

- Standard Model nicely explains
  almost all results of particle physics experiments
- We definitely need New particle Physics
  - neutrino oscillations (Nobel Prize 2015)
  - baryon asymmetry
  - dark matter
  - inflation-like stage in the early Universe

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- New Heavy particle contribution to the Higgs boson mass lifts it up
  but miraculously $m_h \sim E_{EW}$

Guesswork: a logically possible option

- All the new particles are at (below) E_{EW}
  then quantum contributions to $m_h \sim E_{EW}$ are safe
- Why so far no evidences for such light New Particles ?
- They are only feebly coupled to the Standard Model
  - they are SM gauge singlets (not a GUT)
  - new Yukawa-type couplings ?
  - portal-like couplings ?

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Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

- Scalar portal: SM Higgs doublet H and hidden scalar S

  the simplest dark matter

$$\mathscr{L}_{\text{scalar portal}} = -\beta\, H^\dagger H S^\dagger S$$

- Spinor portal: SM lepton doublet L, Higgs congugate field $\tilde{H} = \epsilon H^*$ and hidden fermion N

  sterile neutrino !!

$$\mathscr{L}_{\text{spinor portal}} = -y \bar{L}\tilde{H}N$$

- Vector portal: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$

  hidden photon

$$\mathscr{L}_{\text{vector portal}} = -\frac{\epsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

Massive vectors (paraphotons)

NA64

Vector portal to a secluded sector:

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector

e.g. with Dark matter Ψ

0711.4866

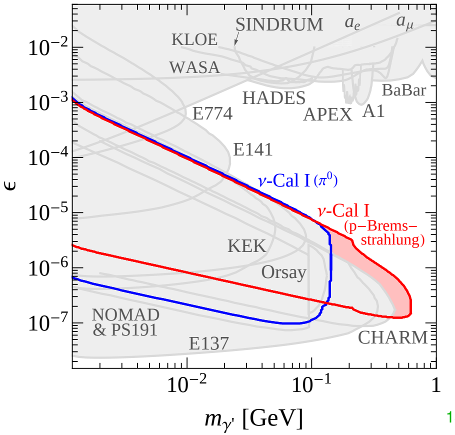
$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu\partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1\,\text{GeV}$

- limit from BBN:

$$\tau_V < 1\,\text{s}\,, \quad \Longrightarrow \varepsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-22}$$

- light for $(g-2)$
- light for Pamela, Fermi, etc



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Production by virtual photon $\quad \sigma \propto \varepsilon^2$

Decay through virtual photon, $\quad \Gamma \propto \varepsilon^2$

$V \to e^+e^-$, $\mu^+\mu^-$, etc

Massive vectors: decays are under control

Decay into SM via mixing with photon

into leptons

$$\Gamma_{A'}^{l^+l^-} = \frac{1}{3}\alpha_{\text{QED}}\, m_{A'}\, \varepsilon^2 \sqrt{1 - \frac{4m_l^2}{m_{A'}^2}} \left(1 + \frac{2m_l^2}{m_{A'}^2}\right),$$

into hadrons

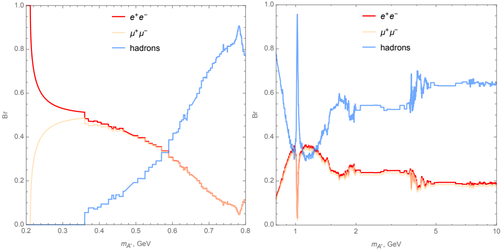
$$\Gamma_{A'}^{\text{hadrons}} = \frac{1}{3}\alpha_{\text{QED}}\, m_{A'}\, \varepsilon^2 \cdot R(m_{A'}),$$

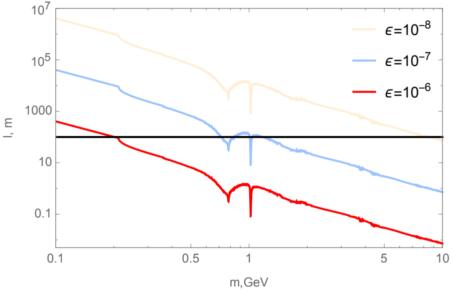
where

$$R(\sqrt{s}) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

and

$$\Gamma_{A'}^{\text{tot}} = \Gamma_{A'}^{e^+e^-} + \Gamma_{A'}^{\mu^+\mu^-} + \Gamma_{A'}^{\text{hadrons}}$$





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Massive vectors: production by protons

- decays of π^0, η^0 and $\rho^{\pm}$, ρ^0, ω

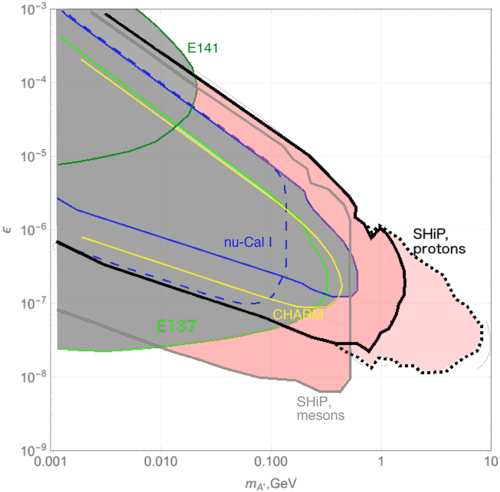
$$\mathrm{Br}_{\pi^0\to A'\gamma} \simeq 2\varepsilon^2 \left(1-\frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathrm{Br}_{\pi^0\to\gamma\gamma}$$

- proton bremsstrahlung
  concervatively corrected by the Dirac (electric) form factor of proton

$$F_1 = \frac{1}{\left(1+\frac{q^2}{m_D^2}\right)^2} \to \frac{1}{m_{A'}^4}$$

with Dirac mass squared $m_D^2 = 12/r_D^2$ and the Dirac radius $r_D \approx 0.8\,\mathrm{fm}$

- quark bremsstrahlung



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High Intensity frontier: photon sources

- modern proton beams: JPARC, Fermilab, CERN SPS
  presently operating or under construction
  $10^{20} - 10^{21}$ PoT per year
  T2K, DUNE, SHiP,...
- Nuclear power plants, thermal power $ThP \sim \text{GW}$
  measurements of photon spectrum
  ($E_\gamma > 200\,\text{keV}$) from FRJ-1 reactor core

$$\frac{dN_\gamma}{d\left(E_\gamma/\text{MeV}\right)} \approx 0.6\times 10^{21}\times\frac{ThP}{\text{GW}}\times e^{-\frac{E_\gamma}{0.91\,\text{MeV}}}\times \text{s}^{-1}\,,$$

TEXONO, NEOS, DANSS,... H.Bechteler et al (1984)

Actually all neutrino oscillation experiments

light shining through the wall

reactor: $\gamma \to \gamma'$

detector: $\gamma' + e^- \to e^-$ mimics $\bar{\nu} + e^- \to e^-$

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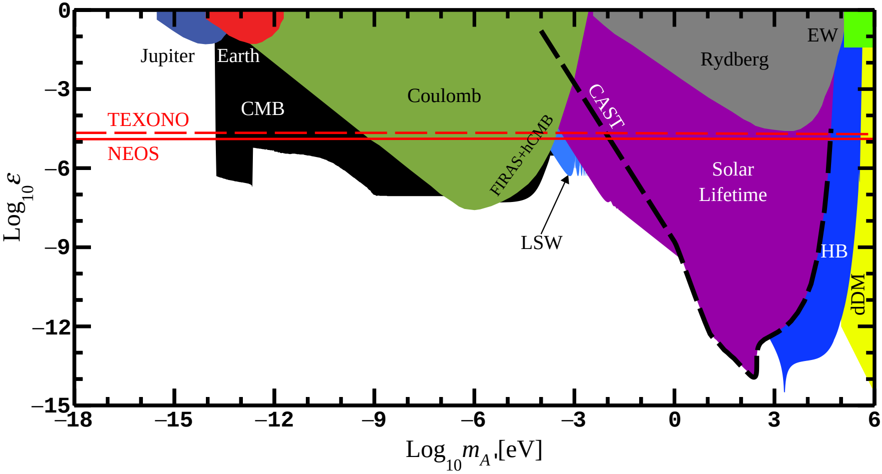

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Something is wrong...

How do we describe very light particles which mix to each other ? ...

say, neutrino... ?

...but oscillations, of course !

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Description

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}X_{\mu\nu}^2 - \frac{\varepsilon}{2}X_{\mu\nu}F^{\mu\nu} + \frac{m_X^2}{2}X_\mu^2 - eA_\mu j_{em}^\mu$$

One can make kinetic term diagonal by $X_\mu \to X_\mu + \varepsilon A_\mu$

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}X_{\mu\nu}^2 + \frac{m_X^2}{2}\left(X_\mu + \varepsilon A_\mu\right)^2 - eA_\mu j_{em}^\mu + \mathscr{O}(\varepsilon^2)$$

keeping X_μ sterile with respect to $U(1)_{em}$

and similar to the neutrino having mixing in the mass matrix

Hamiltonian

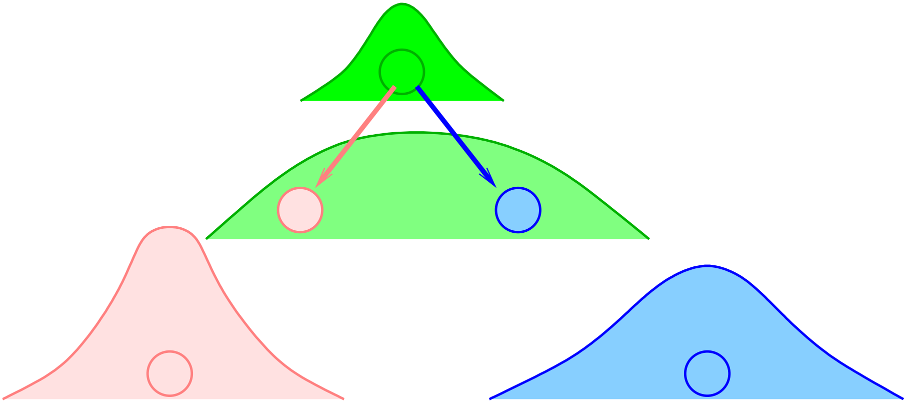
Ultrarelativistic regime

$$p = \sqrt{E^2 - m^2} = E - \frac{m^2}{2E} + \dots$$

the Hamiltonian reads $(A_\mu\,,\,X_\mu)$

$$H = \frac{1}{2E}\begin{pmatrix} \varepsilon^2 m_X^2 & -\varepsilon m_X^2 \\ -\varepsilon m_X^2 & m_X^2 \end{pmatrix}$$

Production of a mixed state



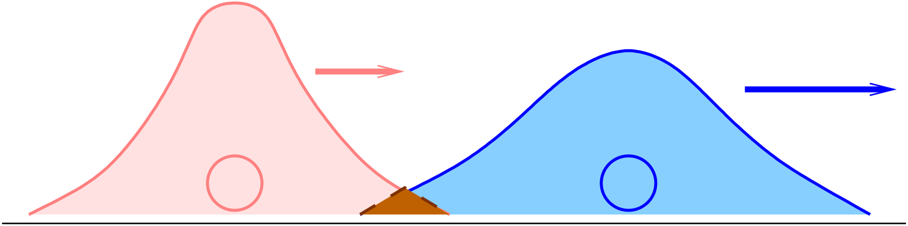
vacuum oscillations: $P(A\to X) = (2\varepsilon)^2 \sin^2\left(\frac{m_X^2 L}{4E}\right)$

Mass-state separation : coherence loss in vacuum

photons come from decaying fission fragments $\tau = 10^{-12} - 10^{-11}\,\mathrm{s}$

initial size: $\sigma \sim 1/\tau \sim 0.03 - 0.3\,\mathrm{cm}$ shorter than oscillation length

$$L_{osc} \approx 2.5\,\mathrm{cm} \times \frac{E_\gamma}{1\,\mathrm{MeV}} \frac{(10\,\mathrm{eV})^2}{m_X^2}$$



$$l_{coh} \sim 6 \times 10^{8-9}\,\mathrm{cm} \times \left(\frac{E_\gamma}{1\,\mathrm{MeV}}\right)^2 \frac{(10\,\mathrm{eV})^2}{m_X^2}$$ always exceeds L_{osc}

Hidden photons from reactor: matter effect

- photons 'get mass' in matter (plasma frequency $m_\gamma^2 = 4\pi\alpha n_e/m_e$)

  in water $m_\gamma \sim 20\,\text{eV}$

  hence $m_X^2 \to \Delta m^2 \equiv \sqrt{(m_X^2 - m_\gamma^2)^2 + 2\varepsilon^2 m_X^2\,(m_X^2 + m_\gamma^2)}$

  always exceed $m_\gamma \sim 20\,\text{eV}$ (except resonance $m_X = m_\gamma$)

- photons rescatter and 'get absorbed' in matter

  in water for $E = 1 - 10\,\text{MeV}$ we have $1/\Gamma \simeq 10\,\text{cm}$

$$H = \frac{1}{2E}\begin{pmatrix} \varepsilon^2 m_X^2 + m_\gamma^2 - i\Gamma E & -\varepsilon m_X^2 \\ -\varepsilon m_X^2 & m_X^2 \end{pmatrix}$$

in the media. . .

Transition amplitude

$$A\left(\gamma\to\gamma'\right)=\varepsilon\,\frac{m_X^2}{2\,E}\int_0^L dl\,\mathrm{e}^{-i\int_0^l dl'\,\frac{m_X^2-m_\gamma^2(l')}{2\,E}-\int_0^l dl'\,\Gamma(l')/2}\,,$$

and for the transfer probability

$$P(\gamma\to\gamma')=\left|A\left(\gamma\to\gamma'\right)\right|^2$$

which in homogeneous matter simplifies to

$$P\left(\gamma\to\gamma'\right)=\frac{\varepsilon^2\,m^4}{\left(\Delta m^2\right)^2+E^2\Gamma^2}\left(1+\mathrm{e}^{-\Gamma L}-2\,\mathrm{e}^{-\frac{\Gamma L}{2}}\cos\left(\frac{\Delta m^2 L}{2\,E}\right)\right)$$

Oscillations at various situations

In the source (reactor core) of size $\gg 1/\Gamma$

$$P = \varepsilon^2 \times \frac{m_X^4}{\left(\Delta m^2\right)^2 + E_\gamma^2 \Gamma^2} = \frac{\left(\varepsilon m_X^2\right)^2}{\left(m_X^2 - m_\gamma^2\right)^2 + E_\gamma^2 \Gamma^2}$$

low absorption $E_\gamma \Gamma \approx 2 \times \left(\frac{E_\gamma}{1\ \mathrm{MeV}}\right)\left(\frac{10\,\mathrm{cm}}{1/\Gamma}\right)\ \mathrm{eV}^2 \ll m_\gamma^2 \sim (20\,\mathrm{eV})^2$

- $m_X \gg m_\gamma \Longrightarrow P = \varepsilon^2$
- $m_X \ll m_\gamma \Longrightarrow P = \varepsilon^2 \times (m_X/m_\gamma)^4$
- resonance (maximum mixing) $m_X \approx 10\,\mathrm{eV} \Longrightarrow P = \mathrm{e}^{-\Gamma L/2} \sin^2\left(\varepsilon \frac{m_X^2 L}{2E}\right)$

  price: very long distance

Similar in the detector (e.g. prompt e^-) of size $\gg 1/\Gamma$

$$P \propto \varepsilon^2$$

Limits from TEXONO: $N_s \propto \varepsilon^2 \times \varepsilon^2$

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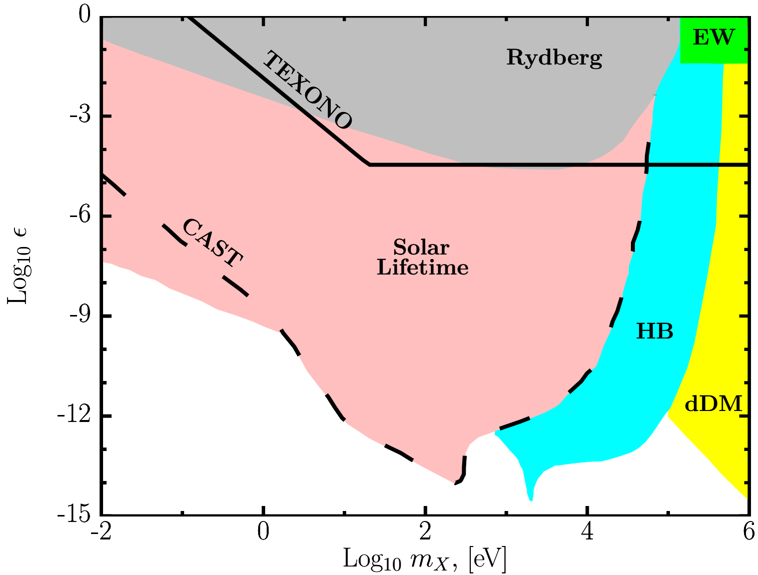
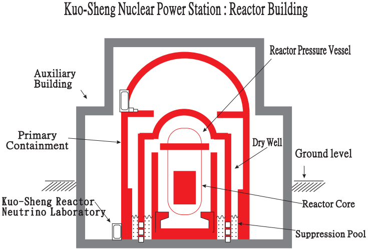


Resonance region... $m_X = m_\gamma$



both reactor core and detector are highly inhomogeneous

Requires a good knowledge of the source internal structure

Can be done by the Neutrino Collaborations

Oscillations in inhomogeneous case

$$A\left(\gamma\to\gamma'\right) = \varepsilon\,\frac{m^2}{2\,E}\int_0^L dl\,\mathrm{e}^{-i\int_0^l dl'\,\frac{\Delta m^2(l')}{2\,E} - \int_0^l dl'\,\Gamma(l')/2}\,,$$

which in homogeneous matter simplifies and gives

$$P\left(\gamma\to\gamma'\right) = \frac{\varepsilon^2 m^4}{\left(\Delta m^2\right)^2 + E^2\Gamma^2}\left(1 + \mathrm{e}^{-\Gamma L} - 2\,\mathrm{e}^{-\frac{\Gamma L}{2}}\cos\left(\frac{\Delta m^2 L}{2\,E}\right)\right)$$

Oscillations in a set of layers

introducing for each layer $\mathscr{E}_k = \Delta m_k^2/(2E_k)$ and $\delta = \varepsilon M_X^2/(2E)$

$$\psi(0) \equiv \begin{pmatrix} 1 \\ 0 \end{pmatrix} \to \psi(d) \equiv \begin{pmatrix} e^{-\gamma d} \\ -\frac{\delta}{\mathscr{E}+i\gamma}\left(e^{-\gamma d} - e^{-i\mathscr{E}d}\right) \end{pmatrix} \equiv U(d)\psi(0)\,,$$

where the propagation matrix reads

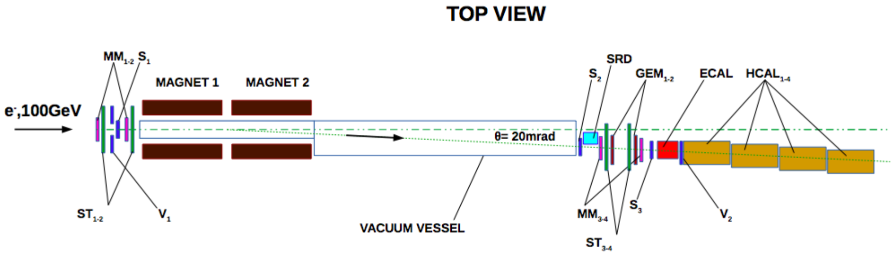
$$U_1(l) = \begin{pmatrix} e^{-\gamma_1 l} & 0 \\ -\frac{\delta}{\mathscr{E}_1+i\gamma_1}\left(e^{-\gamma_1 l} - e^{-i\mathscr{E}_1 l}\right) & e^{-i\mathscr{E}_1 l} \end{pmatrix}$$

then one obtains, $d = \sum_k d_k$

$$P(d) = |\psi_2(d)|^2 = \left|\left(\Pi_{k=n}^{1} U_k(d_k)\right)_{12}\right|^2$$

and sum up over all photons…

Accelerator experiments: NA64, invisible mode, $\propto \varepsilon^2$



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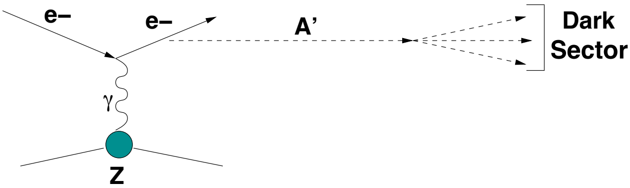

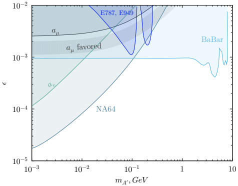

Accelerator experiments: NA64, invisible mode, $\propto \varepsilon^2$

- 'missed' secondary photons of $E_\gamma \sim 50 - 100\,\mathrm{GeV}$

$$L_{osc} \approx 25\,\mathrm{cm} \times \frac{E_\gamma}{100\,\mathrm{GeV}} \frac{(1\,\mathrm{keV})^2}{m_X^2}$$

- lead dump: $m_\gamma \simeq 60\,\mathrm{eV} \qquad 1/\Gamma = 1\,\mathrm{cm}$
- high absorption

$$E_\gamma \Gamma \simeq \left(\frac{E_\gamma}{100\ \mathrm{GeV}}\right)\left(\frac{1\,\mathrm{cm}}{1/\Gamma}\right)\ (1\,\mathrm{keV})^2 \gg m_\gamma^2 \sim (60\,\mathrm{eV})^2$$

Consequently

- $m_X \gg 1\,\mathrm{keV} \Longrightarrow P = \varepsilon^2$
- $m_X \ll 1\,\mathrm{keV} \Longrightarrow P = \varepsilon^2 \times (m_X/1\,\mathrm{keV})^4$
- no resonance at $m_X = m_\gamma$

NA64 sensitivity to invisible vectors

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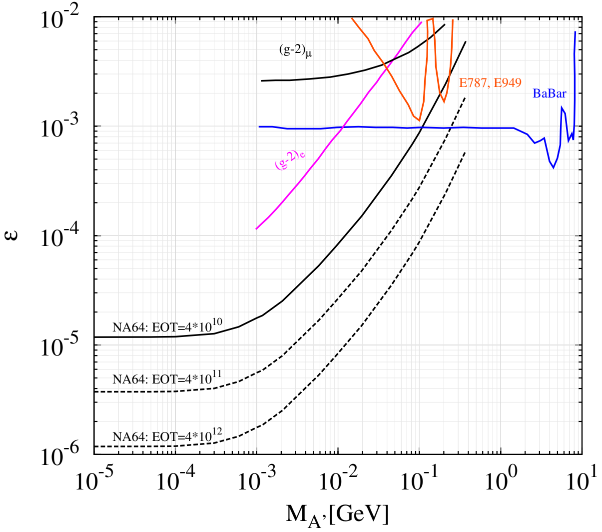

Exploiting resonance region with NA64

$$m_\gamma^2 \quad > \quad \Gamma E_\gamma$$

Other material? No way…

$$m_\gamma^2 \propto n \,, \quad \Gamma \propto n$$

need lower energies $E_\gamma \sim 1\,\text{GeV}$

Developing projects: SHiP, . . . DUNE ?

SHiP: protons of $E = 400\,\text{GeV}$ on target (W-Mo) produce pions:

$E_\gamma \lesssim 10\,\text{GeV}$ $\quad m_\gamma \simeq 100\,\text{eV}\,, \quad 1/\Gamma \simeq 0.5\,\text{cm}$

look for a hit in the ν_τ-detector, $\quad N_s \propto \epsilon^2 \times \epsilon^2$

- non-resonance case: high absoption

$$L_{osc} \approx 5\,\text{cm} \times \frac{E_\gamma}{10\,\text{GeV}} \frac{(700\,\text{eV})^2}{m_X^2}$$

$$E_\gamma \Gamma \approx \left(\frac{E_\gamma}{10\text{ GeV}}\right)\left(\frac{0.5\,\text{cm}}{1/\Gamma}\right)\,(700\,\text{eV})^2 \gg m_\gamma^2 \sim (100\,\text{eV})^2$$

critical mass is $m_X = 700\,\text{eV}$

- resonance case: take soft neutral pions, $E_\pi \sim 0.5\,\text{GeV}$

$$E_\gamma \Gamma \approx \left(\frac{E_\gamma}{250\text{ MeV}}\right)\left(\frac{0.5\,\text{cm}}{1/\Gamma}\right)\,(100\,\text{eV})^2 \simeq m_\gamma^2 \sim (100\,\text{eV})^2$$

Summary

- Oscillations generically suppress production of light hidden photons

$$P = \varepsilon^2 \longrightarrow P = \varepsilon^2 \times \left(\frac{m_X}{m_{crit}} \right)^4$$

where

$$m_{crit}^2 = MAX \left[m_\gamma^2 ,\ E_\gamma \Gamma \right]$$

so the sensitivity to light vectors is lost

- One can check for resonance amplification, when …

$$m_X^2 = m_\gamma^2 \gtrsim E_\gamma \Gamma$$

the signal can be found in 'an excluded region'

- Extra bonus: secondary photons…

Backup slides