Oscillations to hidden photon in reactor and accelerator experiments

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

XXth International Seminar on High Energy Physics QUARKS-2018

Roschino, Valdai, Russia

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:1806.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 ?, ...

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:1806.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 ?, ...

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

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

Widely accepted statements: theory

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

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 ?

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 ?

Disclaimer and the main task

- There are no general theoretical motivation for the New Particles to be of (sub)GeV mass
  but for the feebly coupled light particle best place to show up is the intensity frontier
- Moreover, there are many concrete BSM theories which suggest such theoretical motivations

Disclaimer and the main task

- There are no general theoretical motivation for the New Particles to be of (sub)GeV mass
  but for the feebly coupled light particle best place to show up is the intensity frontier
- Moreover, there are many concrete BSM theories which suggest such theoretical motivations

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 $\tilde{H} = \varepsilon H^*$ 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

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

Massive vectors (paraphotons)

NA64

Vector portal to a secluded sector: e.g. with Dark matter Ψ

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector 0711.4866

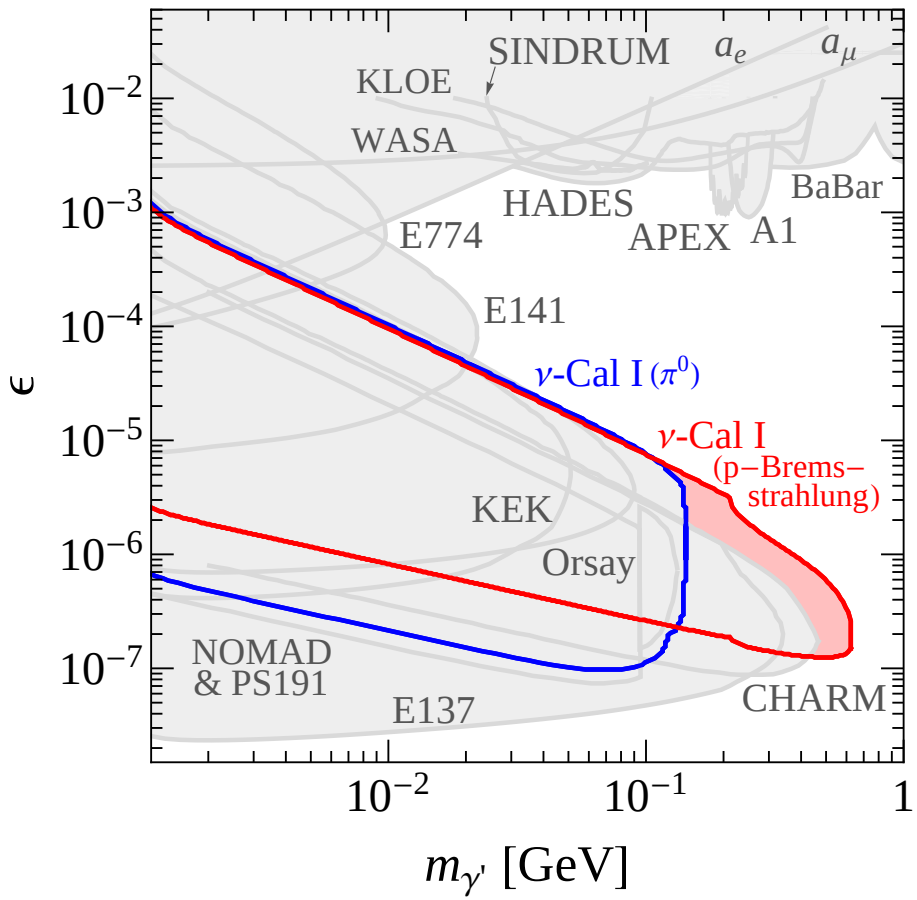
$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu\partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

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

- limit from BBN:

$$\tau_V < 1\,\text{s}, \implies \varepsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-21}$$

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



1311.5104

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

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

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

Massive vectors: decays are under control

Decay into SM via mixing with photon

into leptons

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

into hadrons

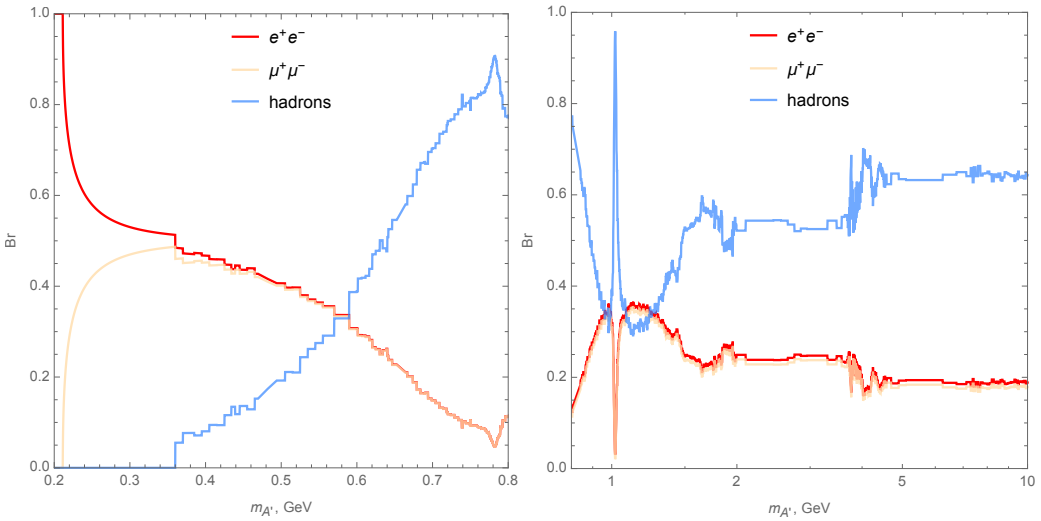
$$\Gamma_{A'}^{\rm hadrons} = \frac{1}{3}\alpha_{\rm QED} m_{A'} \varepsilon^2 \cdot R(m_{A'}),$$

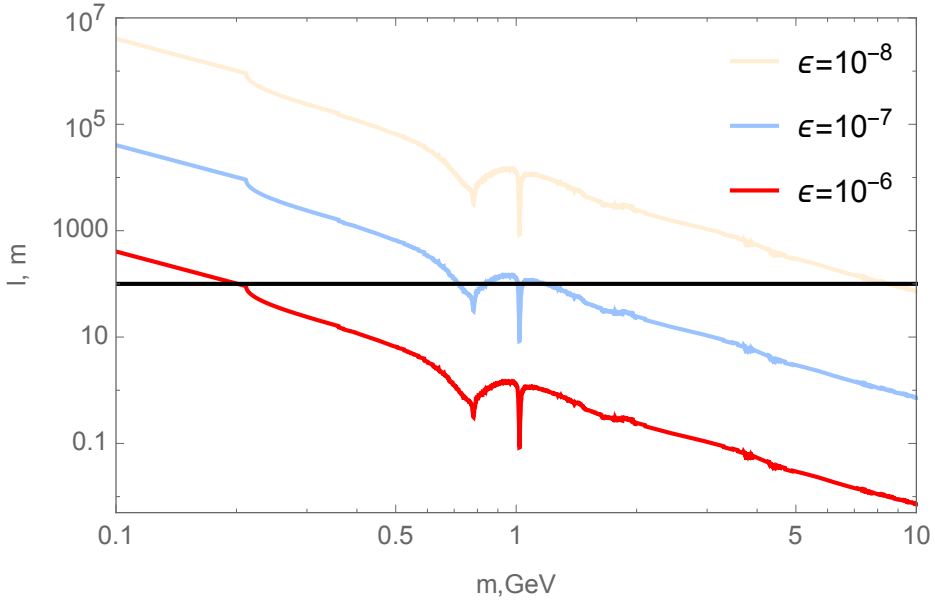
where

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

and

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





1411.4007

Massive vectors: production by protons

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

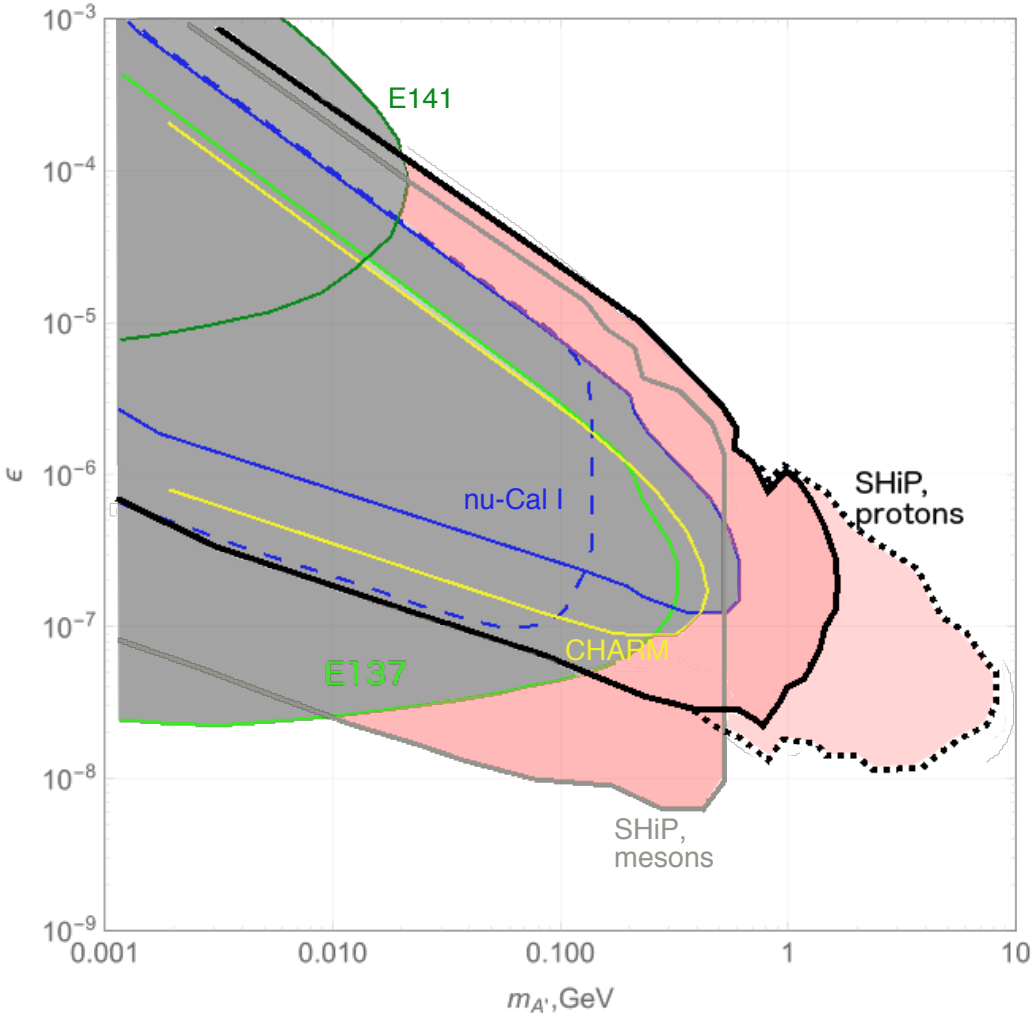
$$\mathrm{Br}_{\pi^0\to A'\gamma} \simeq 2\varepsilon^2 \left(1-\frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathrm{Br}_{\pi^0\to\gamma\gamma}$$

- 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



1411.4007

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 $ThP \sim$ GW
  measurements of photon spectrum
  ($E_\gamma > 200$ keV) from FRJ-1 reactor core

$$\frac{dN_\gamma}{dE_\gamma} \approx 0.6 \times 10^{21} \times \frac{ThP}{\text{GW}} \times e^{-\frac{E_\gamma}{0.91\,\text{MeV}}},$$

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 $\bar{\nu} + e^- \to e^-$

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 $ThP \sim$ GW
  measurements of photon spectrum
  ($E_\gamma > 200$ keV) from FRJ-1 reactor core

$$\frac{dN_\gamma}{dE_\gamma} \approx 0.6 \times 10^{21} \times \frac{ThP}{\text{GW}} \times e^{-\frac{E_\gamma}{0.91\,\text{MeV}}},$$

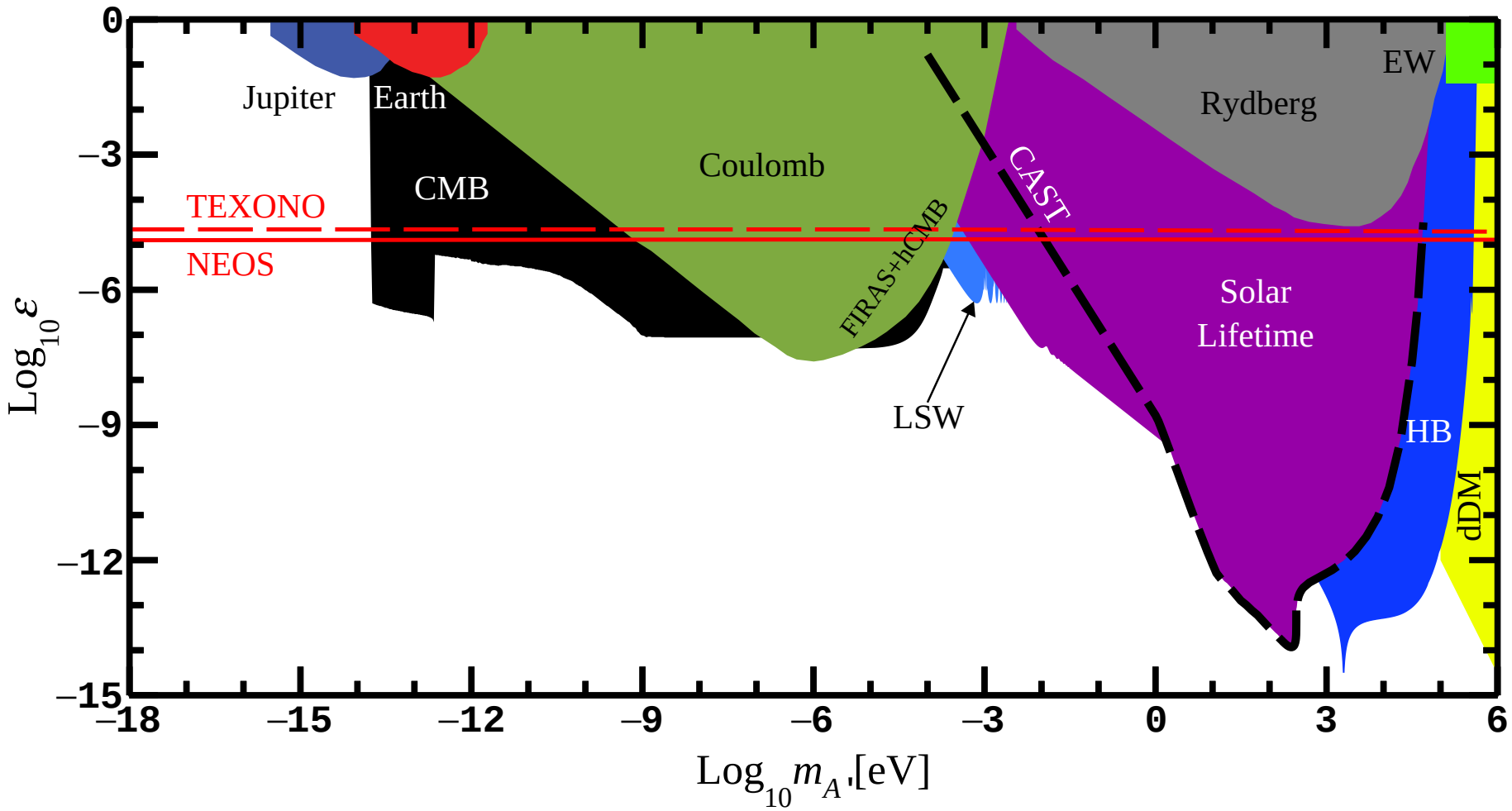
TEXONO, NEOS, DANSS,... H.Bechteler et al (1984)
Actually all neutrino oscillation experiments

light shining through the wall

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

Results based on Compton scattering

1705.02470



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

10 astronomical units !!

Something is wrong...

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

say, neutrino...?

...but oscillations, of course !

Something is wrong...

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

say, neutrino...?

...but oscillations, of course !

Something is wrong...

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

say, neutrino...?

...but oscillations, of course !

Something is wrong...

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

say, neutrino...?

...but oscillations, of course !

Description

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

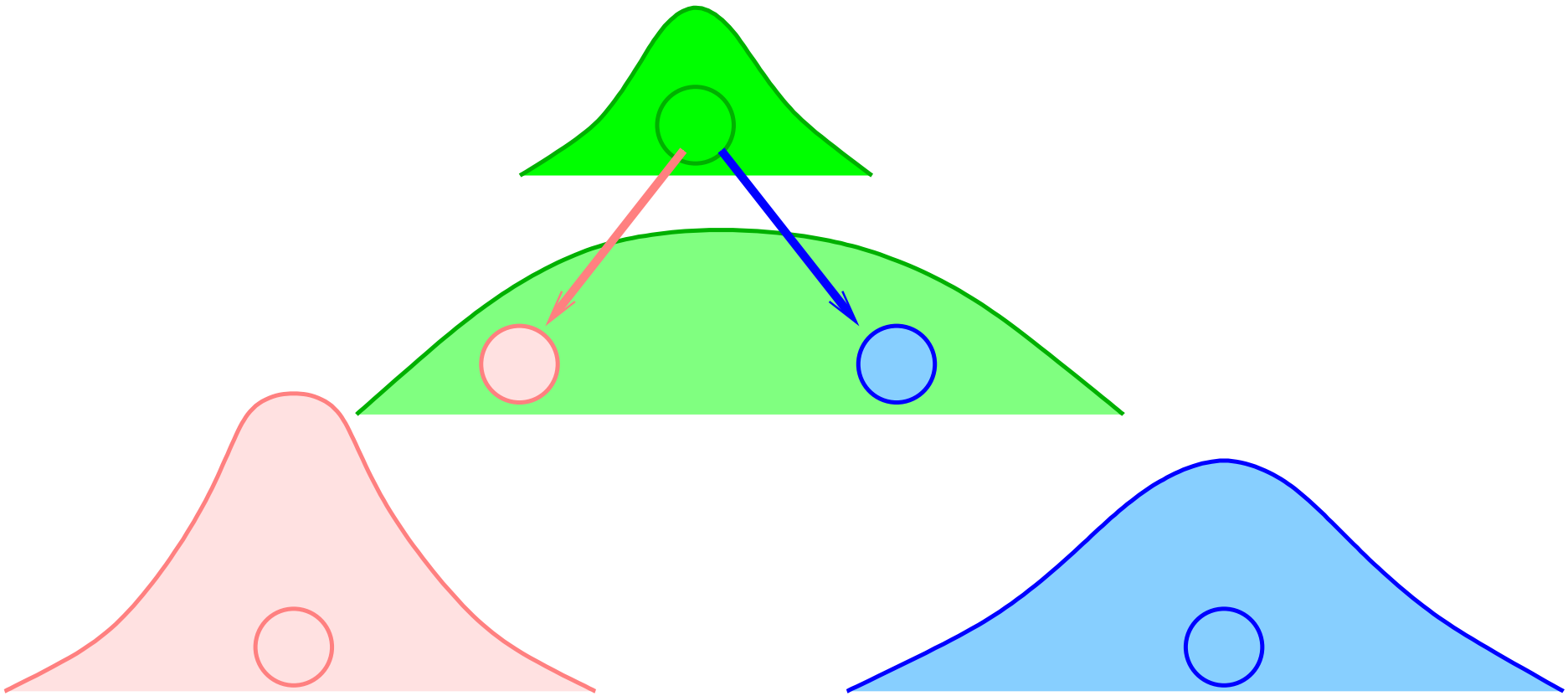
One can make kinetic term diagonal by $X_\mu \to X_\mu + \varepsilon A_\mu$

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

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

and similar to the neutrino having mixing in the mass matrix

Production of a mixed state



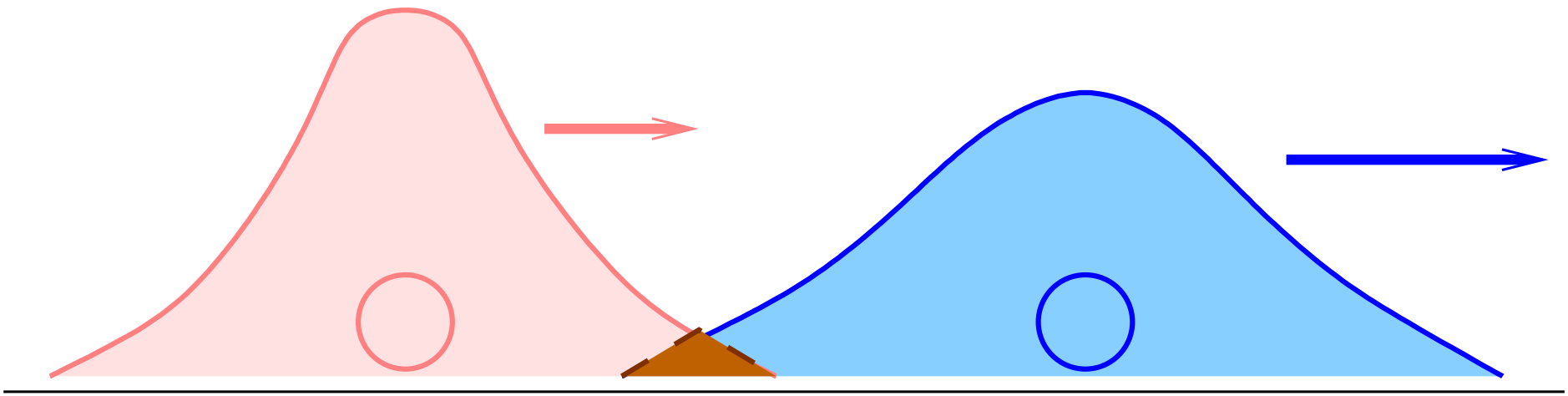
vacuum oscillations: $P(A \to X) = (2\varepsilon)^2 \sin^2\left(\frac{m_X^2 L}{4E}\right)$

Mass-state separation : coherence loss in vacuum

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

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

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



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

Hidden photons from reactor: matter effect

- photons 'get mass' in matter

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

hence $m_X^2 \to \Delta m^2 \equiv \sqrt{(m_X^2 - m_\gamma^2)^2 + 4\varepsilon^2 m_X^4}$

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

- photons rescatter and 'get absorbed' in matter

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

- the net result at distances $\gg 1/\Gamma$

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

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

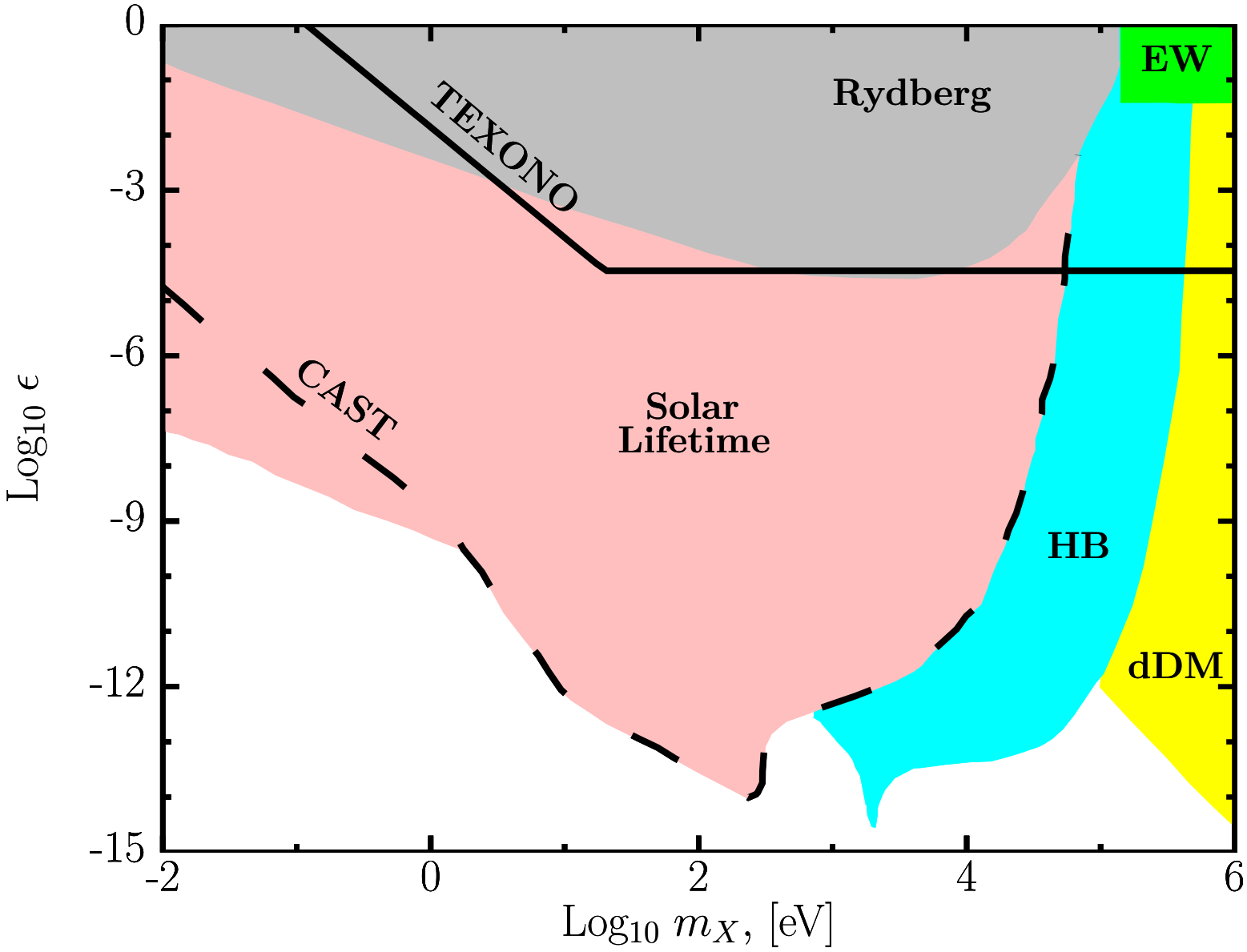
- $m_X \gg m_\gamma \Longrightarrow P = \varepsilon^2$
- $m_X \ll m_\gamma \Longrightarrow P = \varepsilon^2 \times (m_X/m_\gamma)^4$
- resonance $m_X \approx 10\,\mathrm{eV} \Longrightarrow P = 10^5 \varepsilon^2$

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

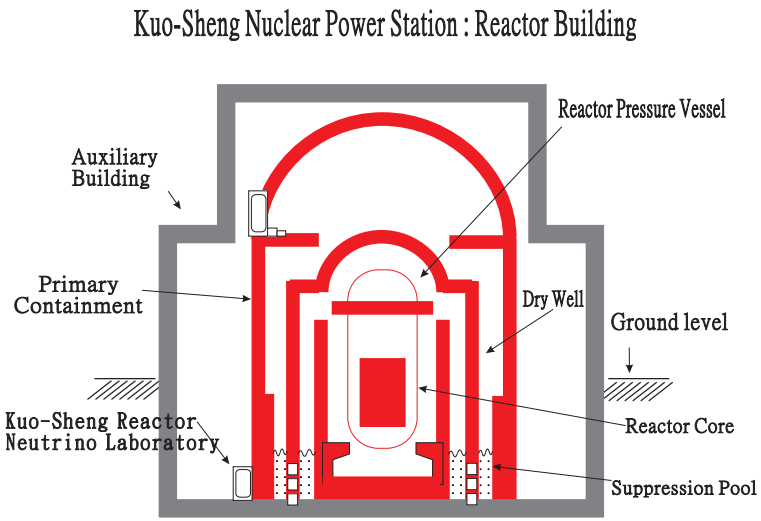
$$P = \varepsilon^2 \times \frac{m_X^4}{\left(\Delta m^2\right)^2} = \frac{\left(\varepsilon m_X^2\right)^2}{\left(m_X^2 - m_\gamma^2\right)^2}$$

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

1804.10777



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

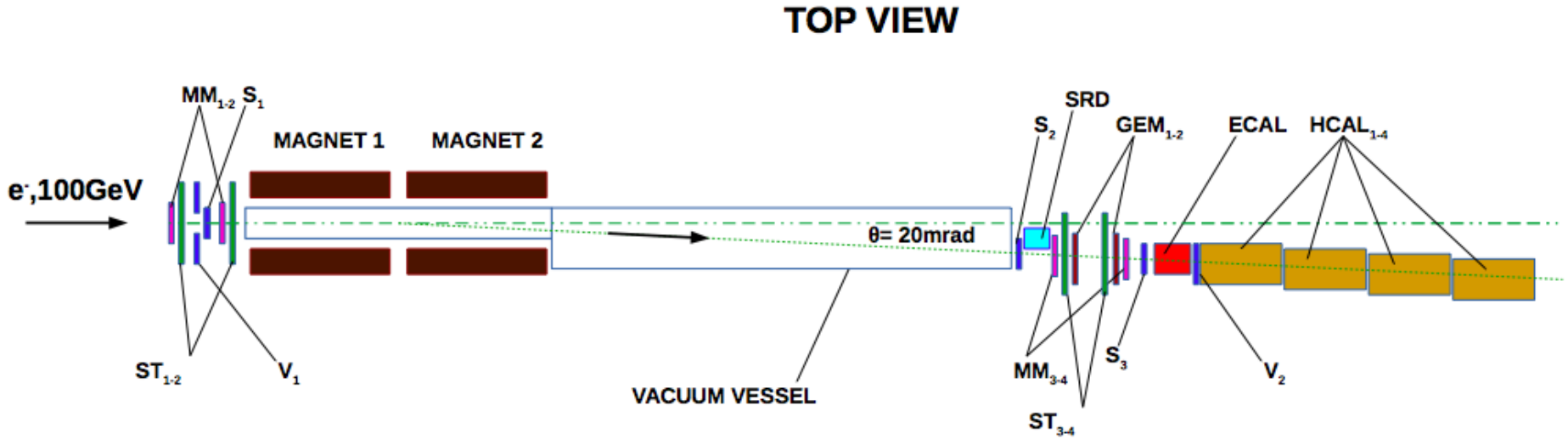


both reactor core and detector are highly inhomogeneous

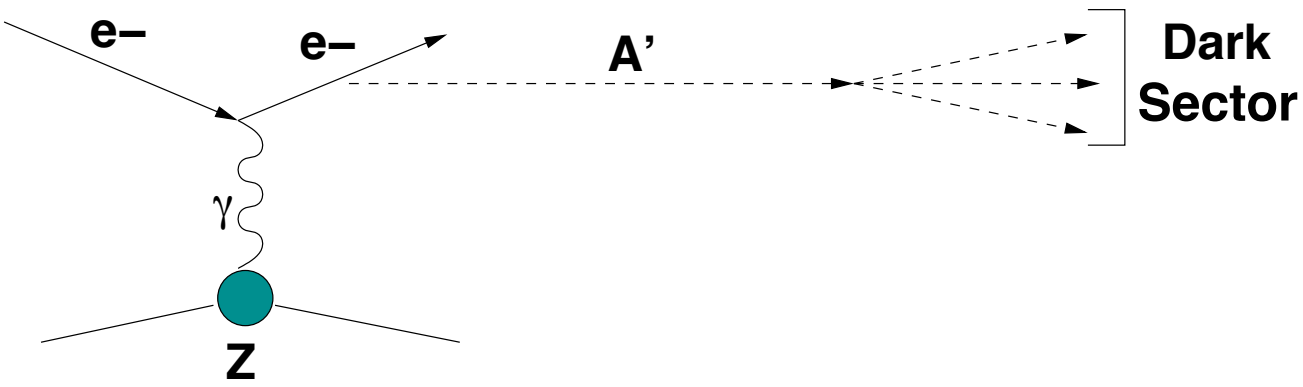
Requires a good knowledge of the source internal structure

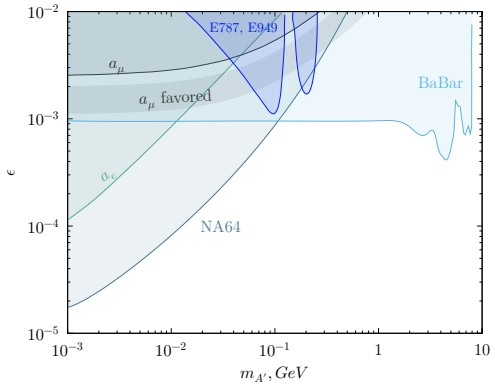
Can be done by the Neutrino Collaborations

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



1710.00971





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

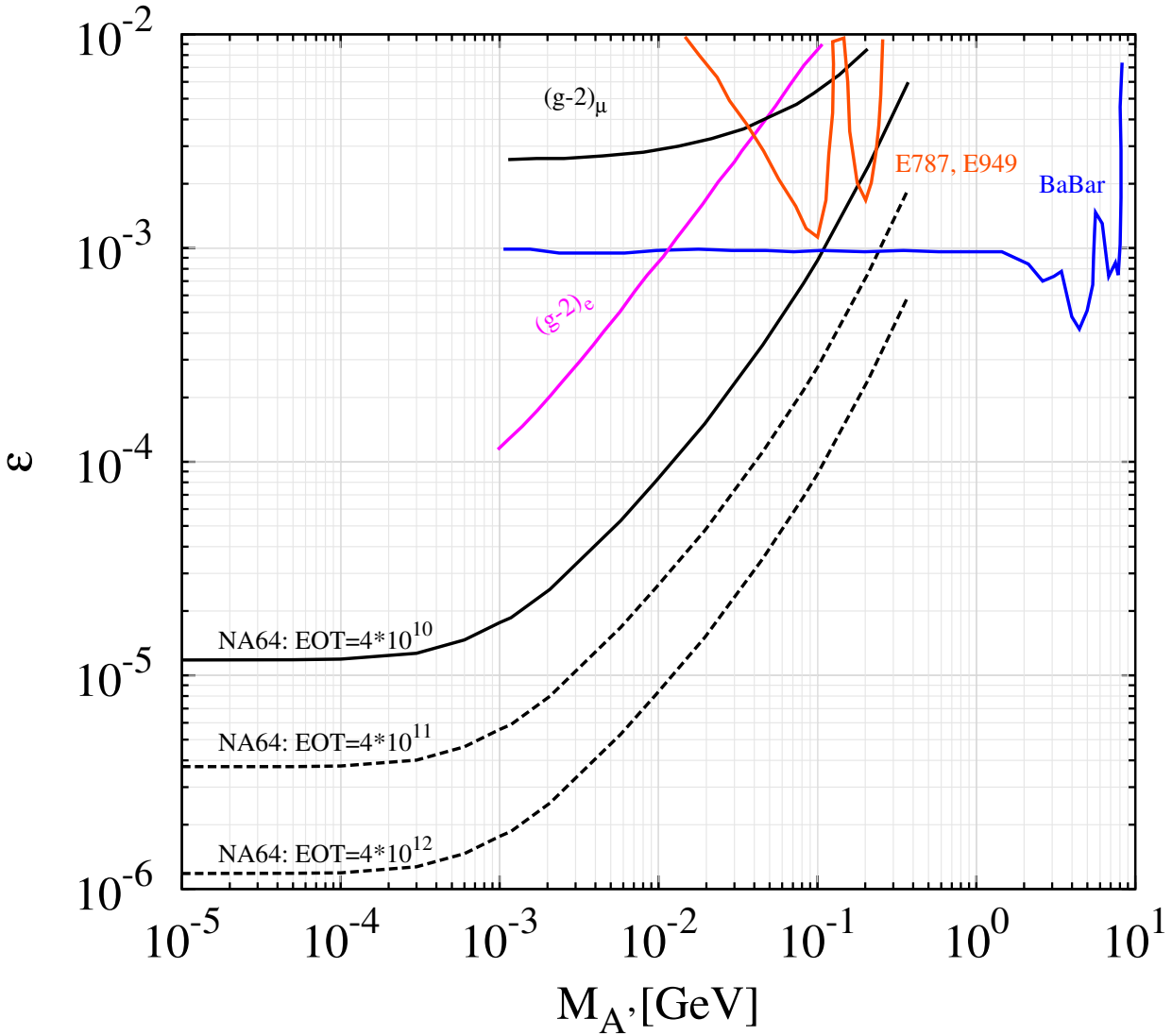
$$E_\gamma \Gamma \simeq \left(\frac{E_\gamma}{100\ \mathrm{GeV}}\right)\left(\frac{1\,\mathrm{cm}}{1/\Gamma}\right)\ (1\,\mathrm{keV})^2 \gg m_\gamma^2 \sim (60\,\mathrm{eV})^2$$

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

1712.05706



Exploiting resonance region with NA64

Other material? No way...

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

need lower energies $E \sim 1\,\mathrm{GeV}$

Developing projects: SHiP, ... DUNE ?

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

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

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

- 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

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

so the sensitivity to light vectors is lost

- One can check for resonance amplification, when ...

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

- Extra bonus: secondary photons...

Backup slides