Oscillations into hidden photons and direct searches

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'Windows on the Universe'

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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:1809.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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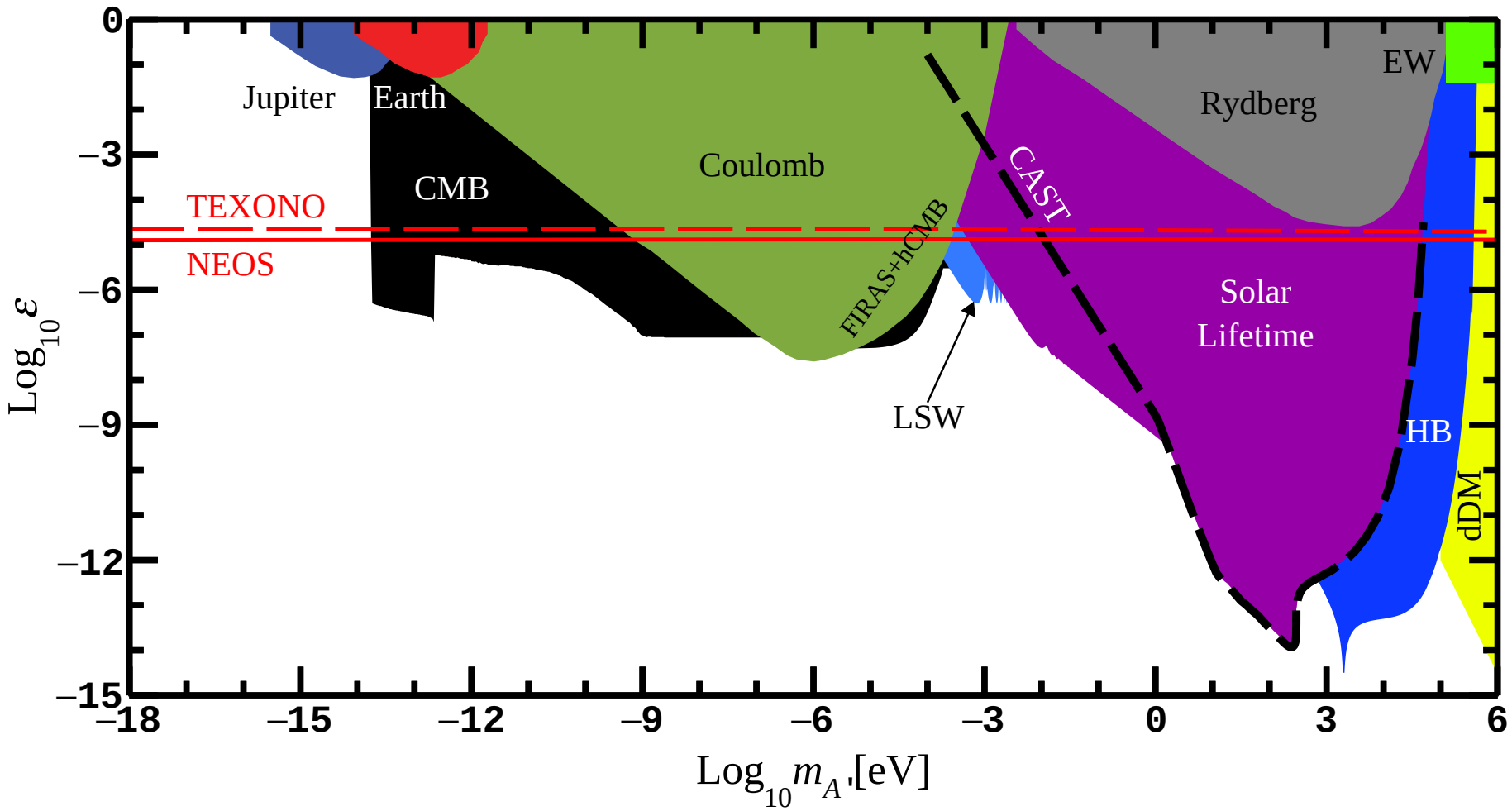
Results based on Compton scattering

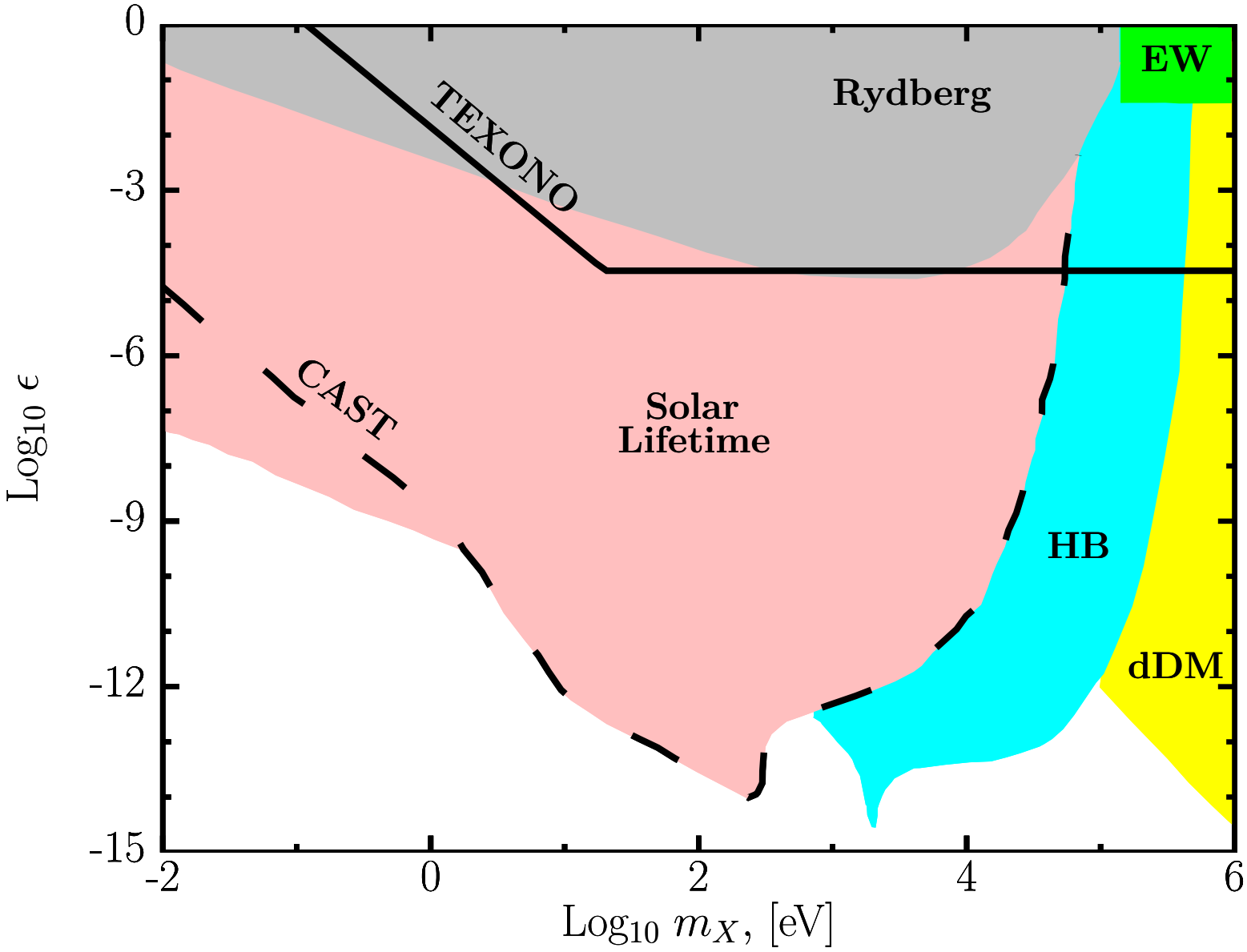
PRL(2017) 1705.02470



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

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

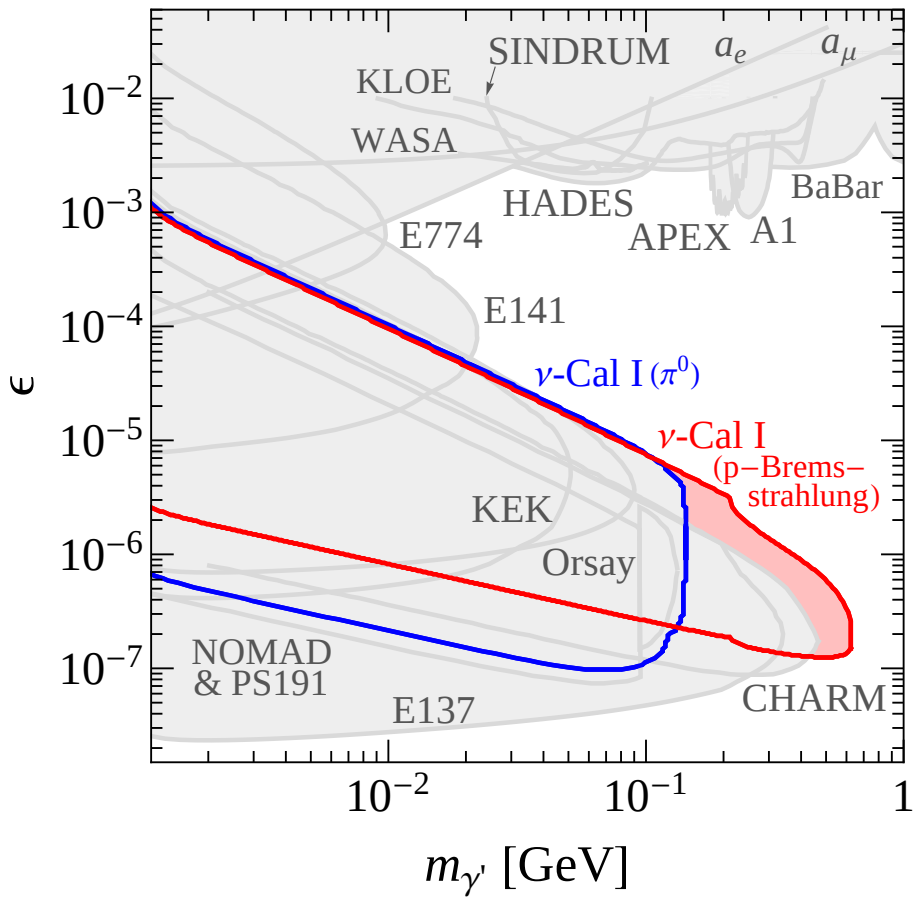
$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu\partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

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



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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

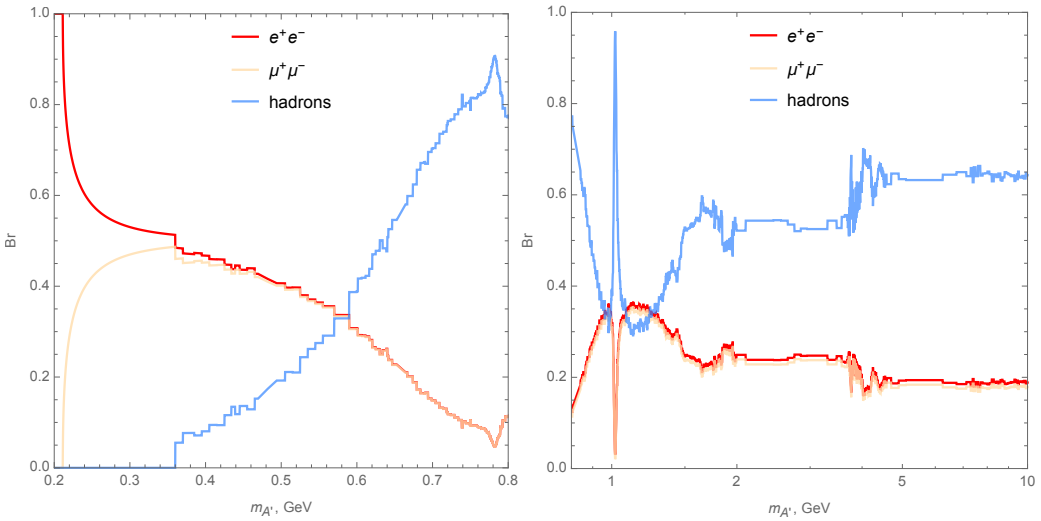
$$\Gamma_{A'}^{\rm hadrons} = \frac{1}{3}\alpha_{\rm QED} m_{A'} \varepsilon^2 \cdot R(m_{A'}),$$

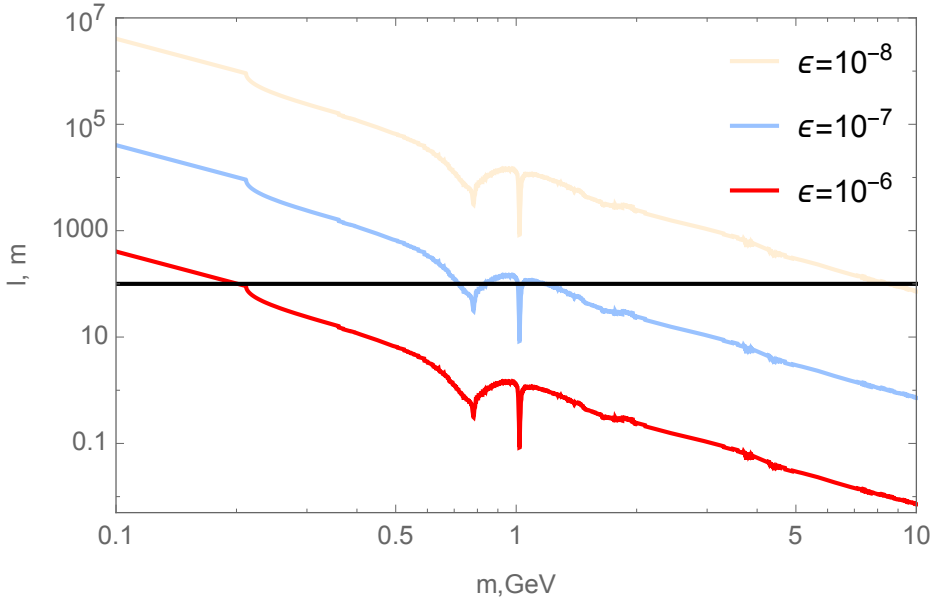
where

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

and

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





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Massive vectors: production by protons

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

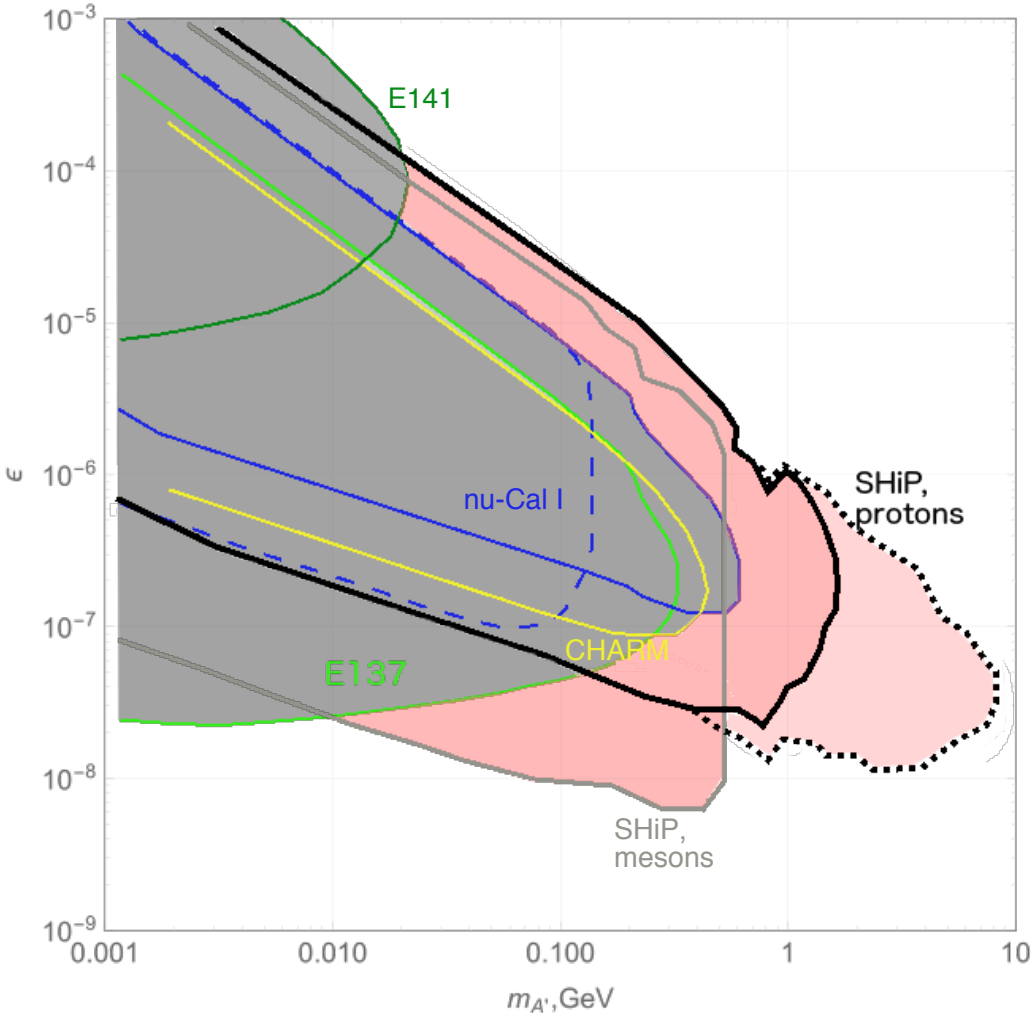
$$\mathrm{Br}_{\pi^0\to A'\gamma} \simeq 2\varepsilon^2 \left(1-\frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathrm{Br}_{\pi^0\to\gamma\gamma}$$

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

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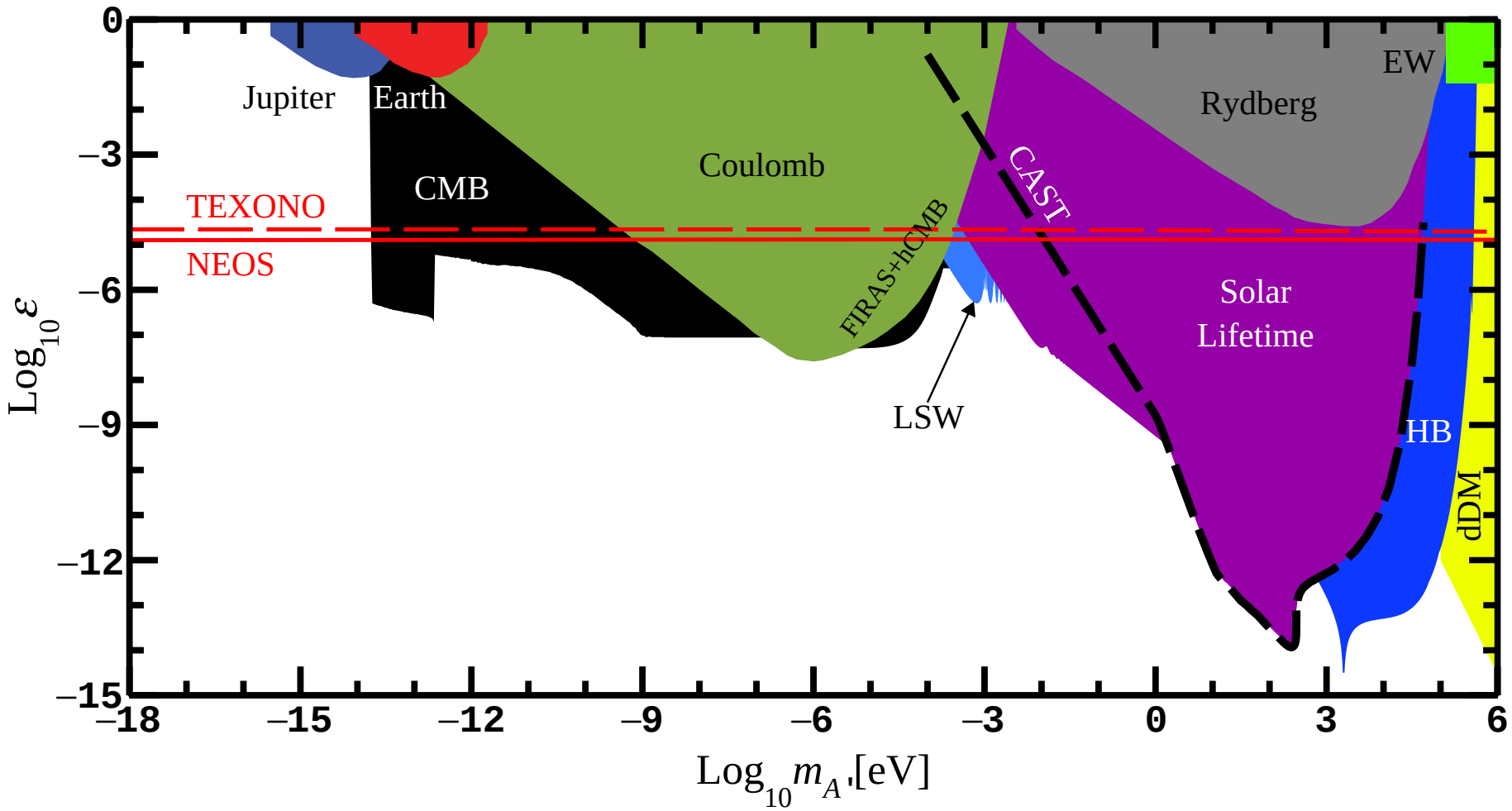

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Something is wrong...

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

say, neutrino...?

...but oscillations, of course !

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...but oscillations, of course !

Description

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

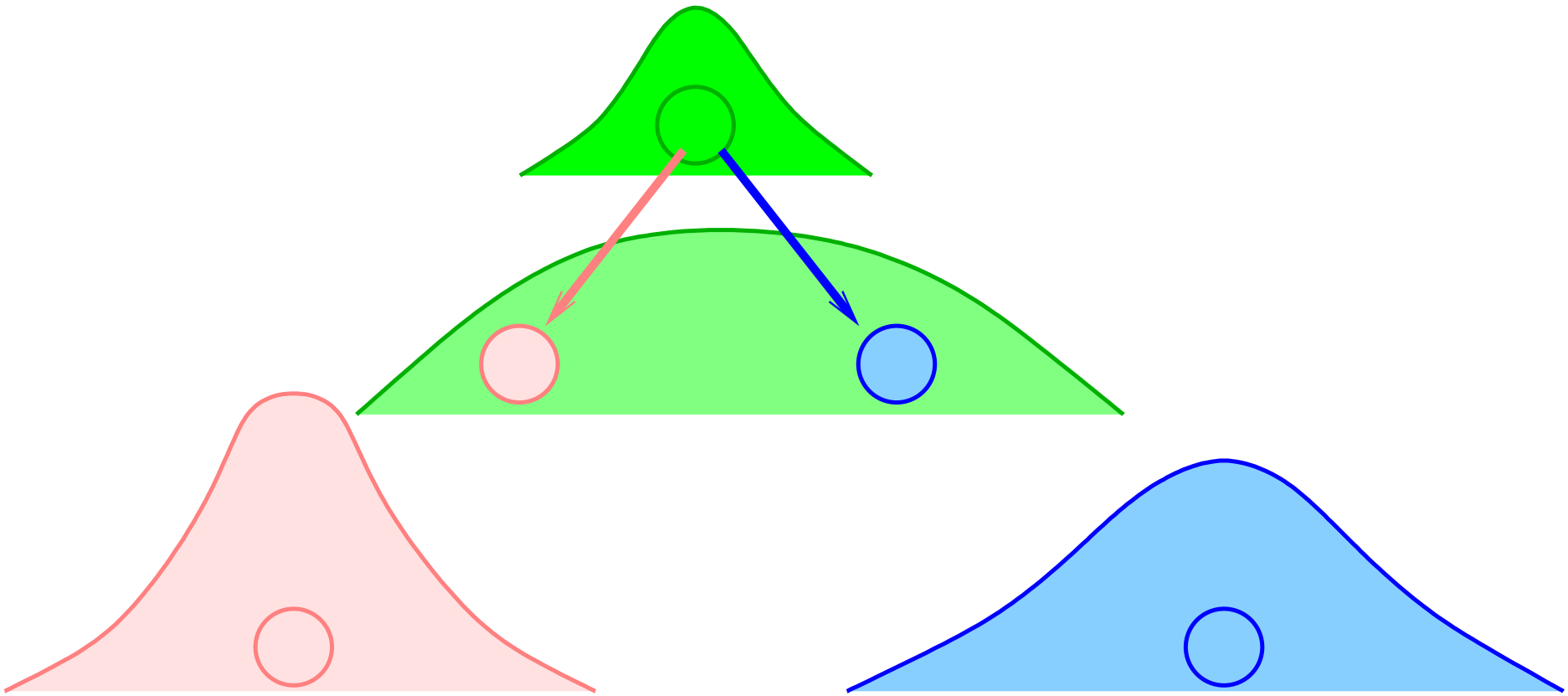
One can make kinetic term diagonal by $X_\mu \to X_\mu + \varepsilon A_\mu$

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

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



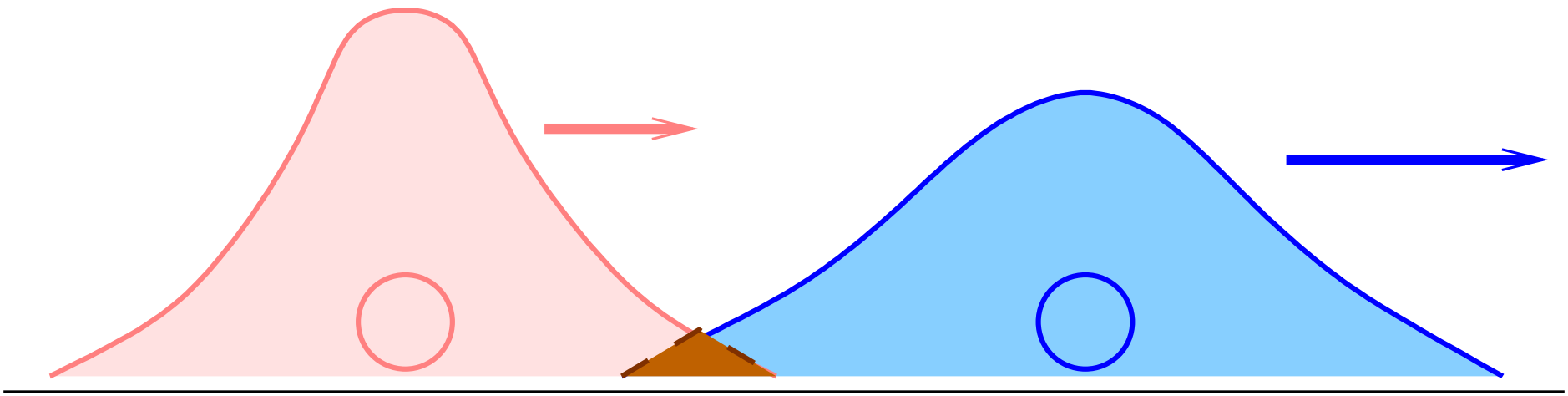
vacuum oscillations: $P(A \to X) = (2\varepsilon)^2 \sin^2\left(\frac{m_X^2 L}{4E}\right)$

Mass-state separation : coherence loss in vacuum

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

initial size: $\sigma \sim 1/\tau \sim 0.03 - 0.3\,\text{cm}$ 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 $\gg 1/\Gamma$

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

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

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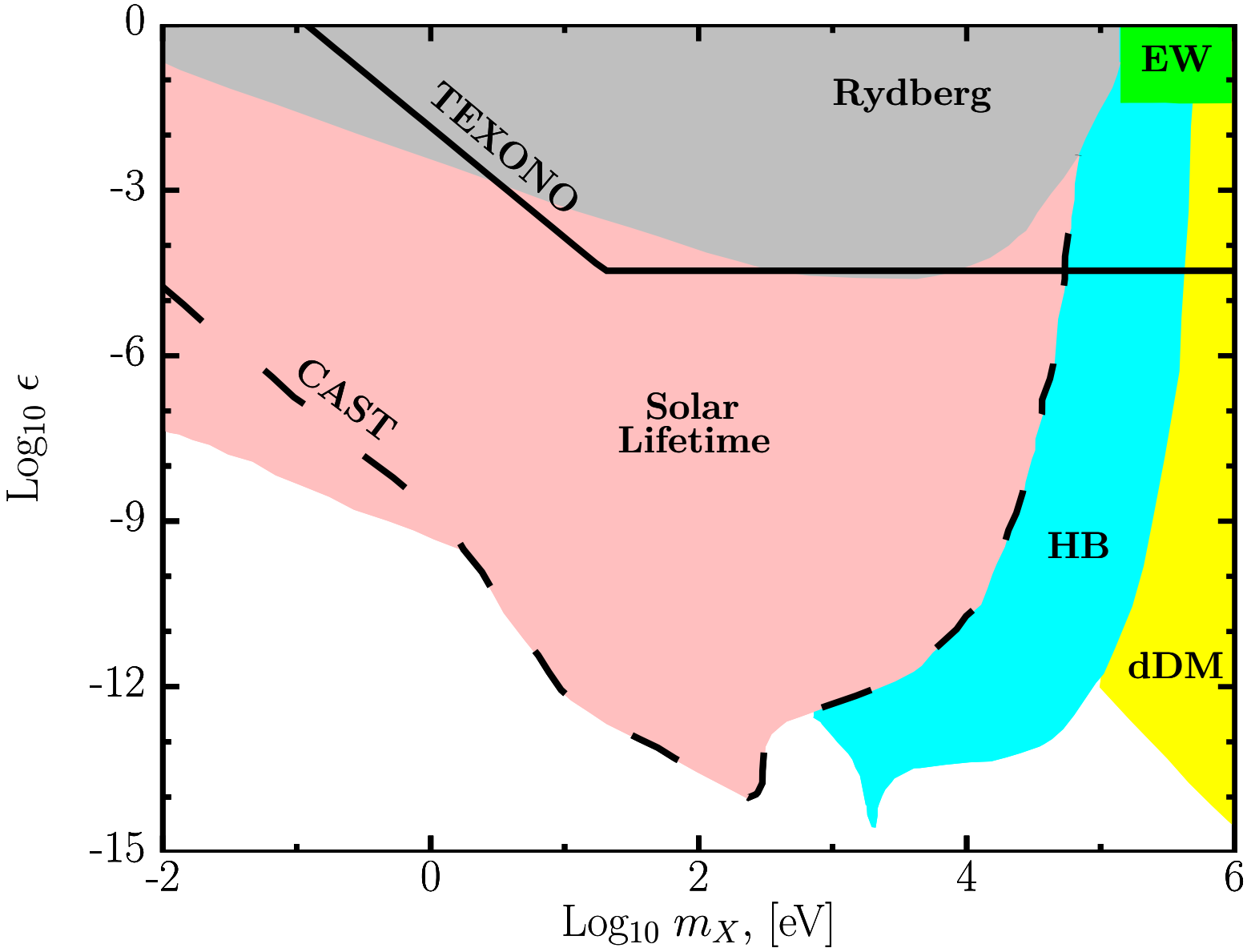
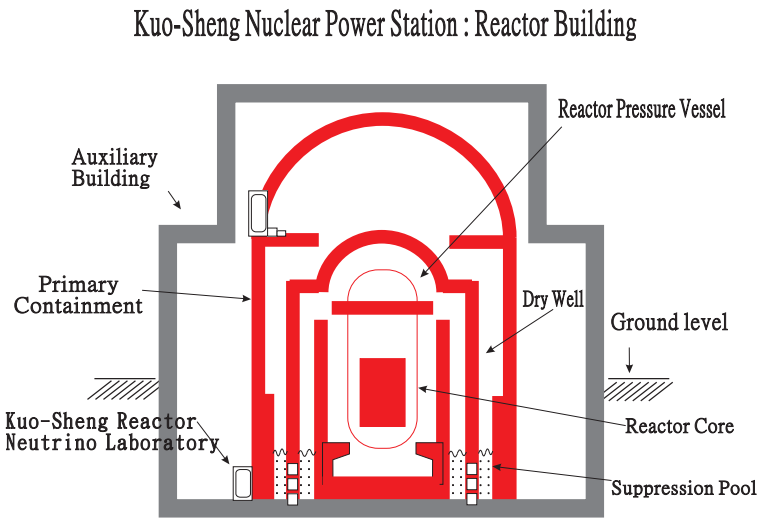


Resonance region... $m_X = m_\gamma$

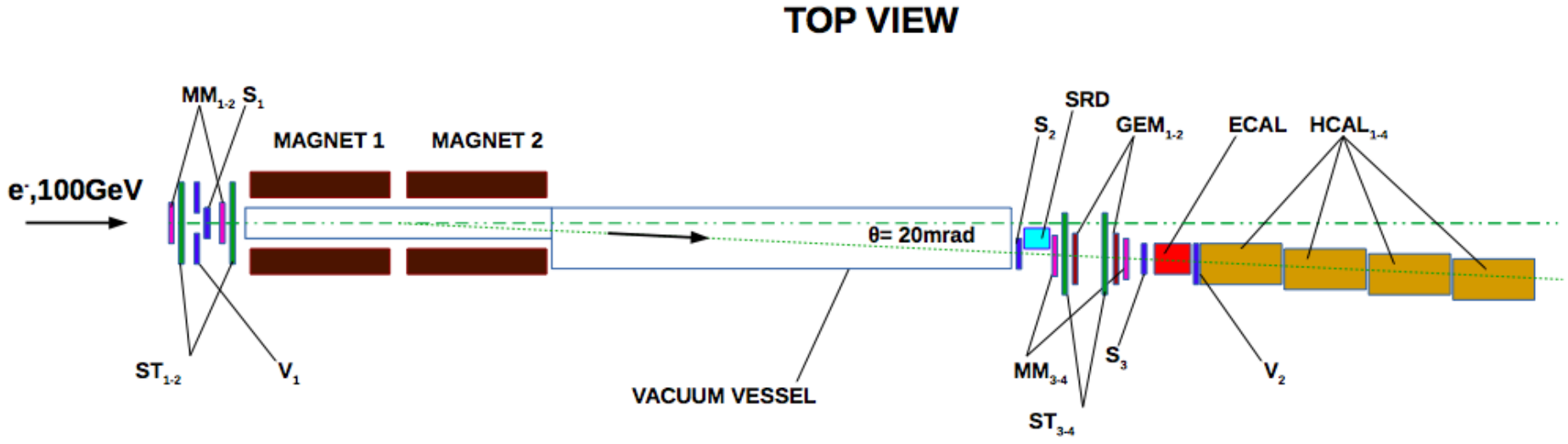


both reactor core and detector are highly inhomogeneous

Requires a good knowledge of the source internal structure

Can be done by the Neutrino Collaborations

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



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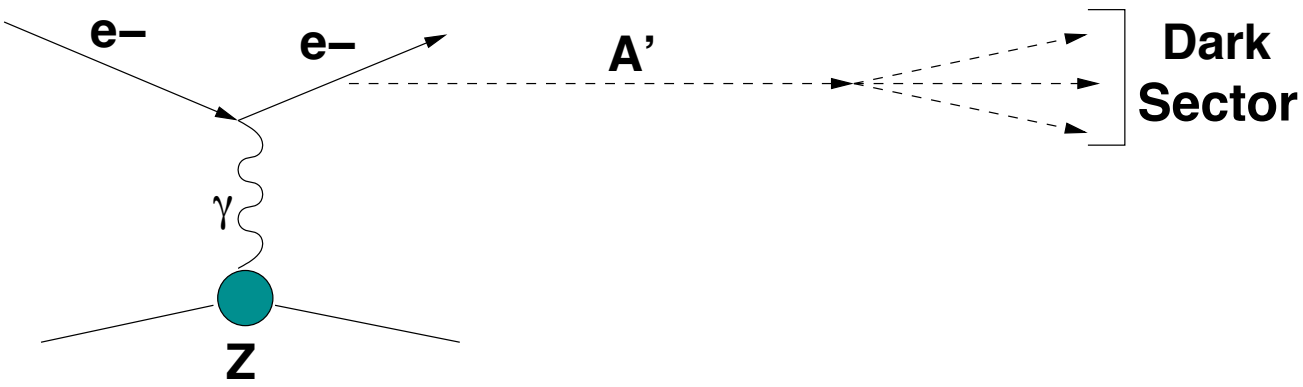

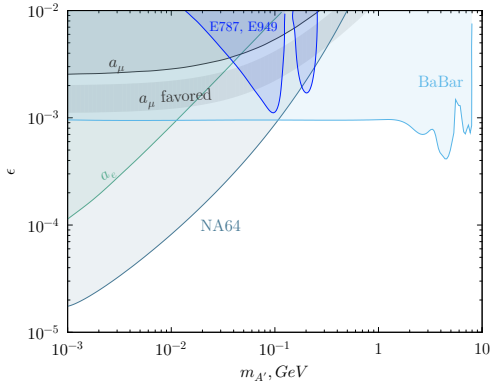

Accelerator experiments: NA64, invisible mode, $\propto \varepsilon^2$

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

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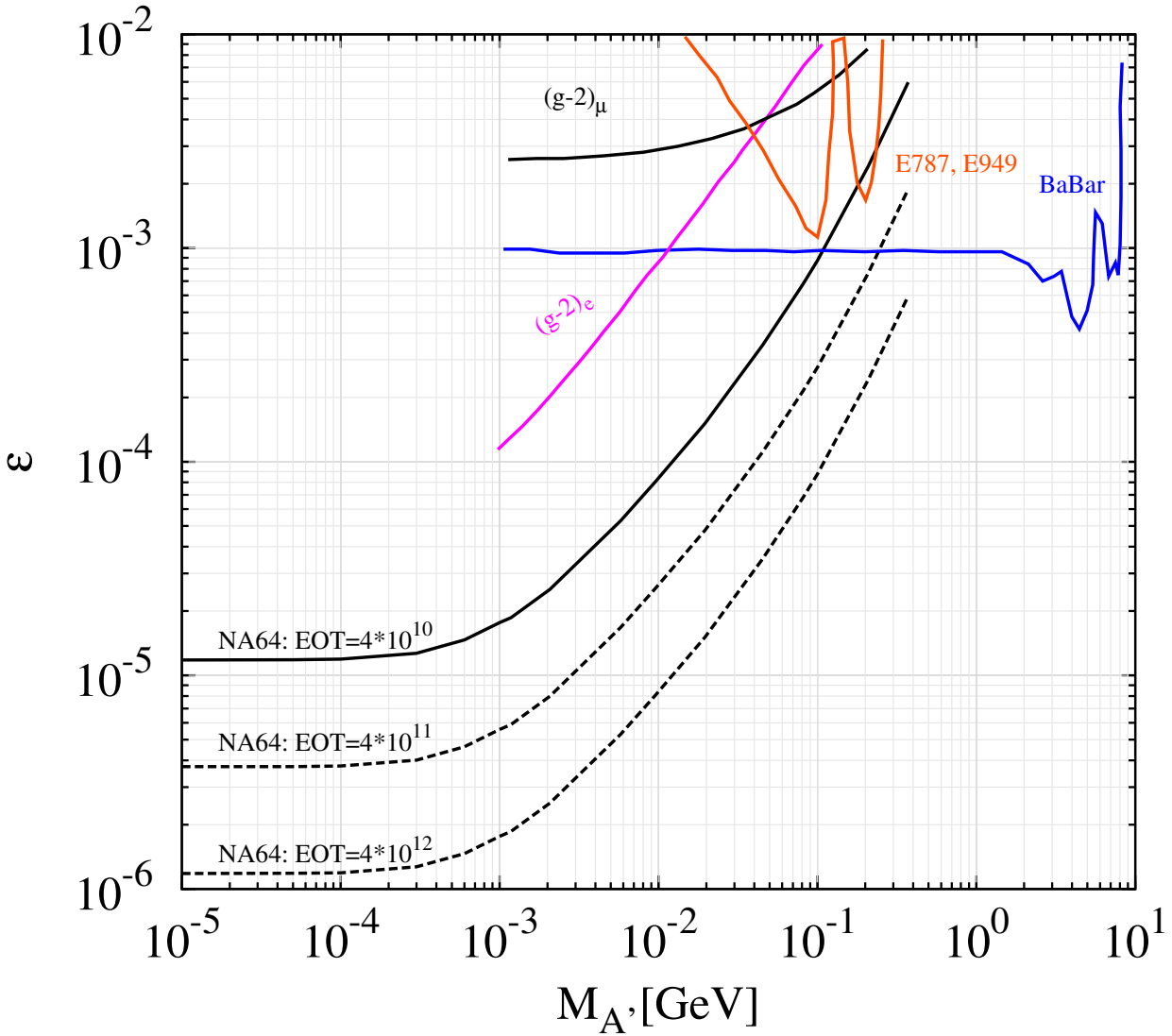

Exploiting resonance region with NA64

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

Other material? No way...

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

need lower energies $E_\gamma \sim 1$ 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