Dark Photon:

Stellar Constraints and Direct Detection

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Motivations

- Related to the dark sector
  - Dark portal
  - Dark matter itself (or part of dark matter)
  - Sommerfeld enhancement

- Solution to muon g-2 problem

- Sub-keV dark photons can be produced inside the Sun and can be detected by detectors at the Earth
- Technically natural (A simple extension of SM, why not!)

Outline

- What is dark photon?
  - Lagrangian
  - Origin of mass
    - Stueckelberg case and Higgsed case
- Stueckelberg case
  - Solar flux and stellar constraints
  - Direct detection
- Higgsed case
  - Solar flux and stellar constraints
  - Direct detection
- Summary

The Lagrangian

The Standard Model

Extra vector field

$$SU(3)_C \times SU(2)_L \times U(1)_Y \qquad U(1)_D$$

$$G^{a\mu\nu} \qquad W^{i\mu\nu} \qquad \underbrace{B^{\mu\nu} \qquad V^{\mu\nu}}$$

$$-\frac{1}{2}\kappa' B_{\mu\nu}V^{\mu\nu}$$

$$\downarrow$$

Below EW breaking ,

$$-\frac{1}{2}\kappa F_{\mu\nu}V^{\mu\nu}$$

$$\mathcal{L} = -\frac{1}{4}F^2_{\mu\nu} - \frac{1}{4}V^2_{\mu\nu} - \frac{1}{2}\kappa F_{\mu\nu}V^{\mu\nu} + eA_\mu J^\mu_{\rm em} \ .$$

Origins of mass

- Massive $U(1)$ gauge theory

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_V^2 \left(V_\mu - \frac{\partial_\mu a}{m_V} \right)^2$$

Would-be Goldstone

- In this talk, $m_V < 1\ \text{keV}$.
- Should there be a dark Higgs?

No! (Naturalness)

Yes! A Higgs at weak scale has just been found.

Stueckelberg case

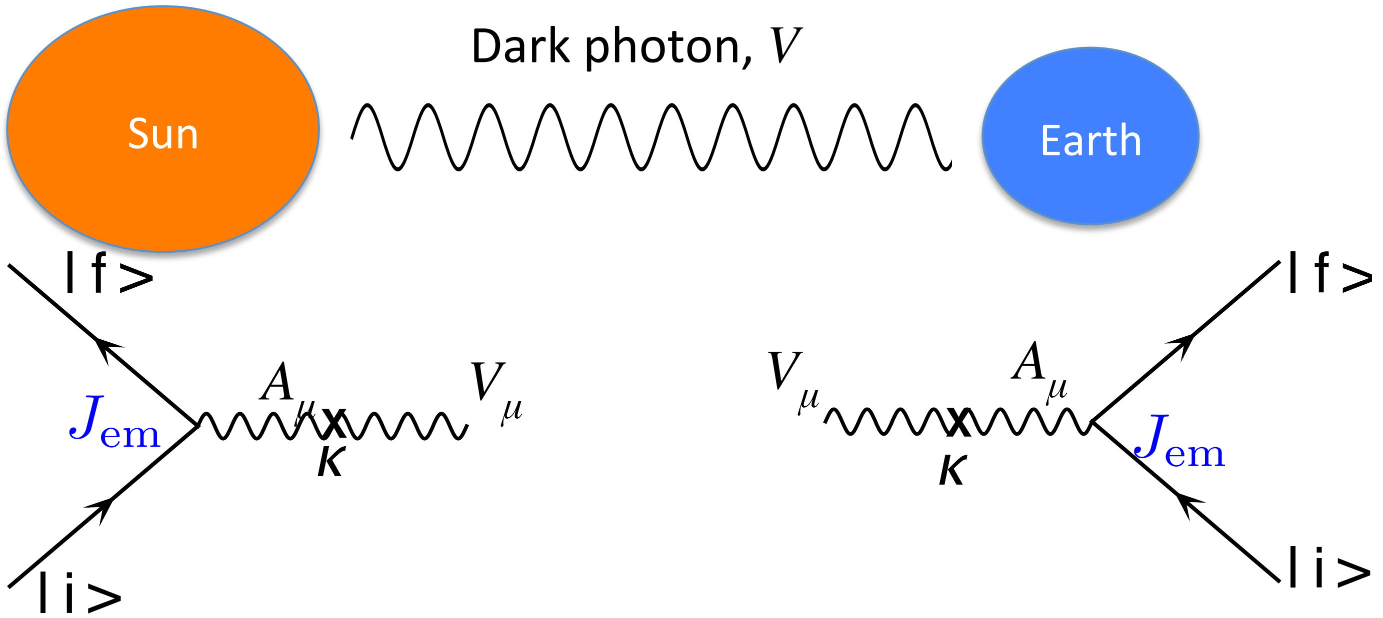
$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_V^2 V_\mu^2$$

Higgsed case

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_V^2 V_\mu^2$$

$$\mathcal{L}_{\text{int}} = e' m_V h' V_\mu^2 + \frac{1}{2} e'^2 h'^2 V_\mu^2$$

Stueckelberg case



– Dark radiation effects the evolution of the stars.

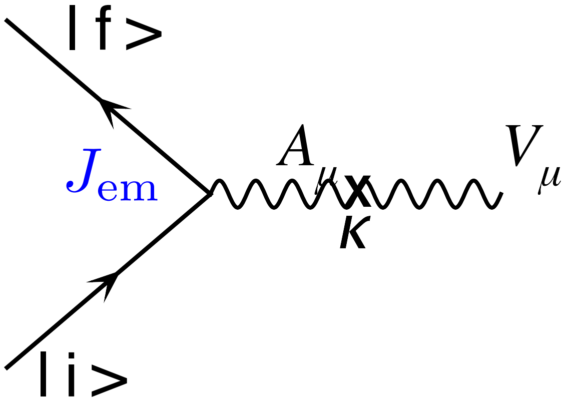
$$P_{\rm dark} \leq 0.1 \times P_{\rm luminous}$$

Gondolo and Raffelt (PRD 2009)

– Can be direct detected on the Earth (CAST, XENON, CoGeNT ...)

Production of dark photon

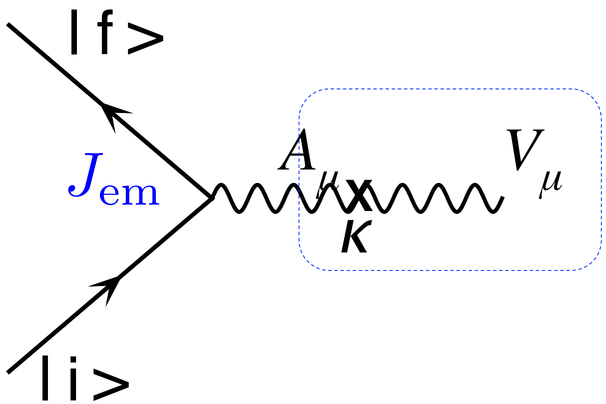
- Matrix element (homework of QFT101)



$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu^2 + eJ^\mu_{\rm em}A_\mu}$$

Production of dark photon

- Matrix element



$$-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} \rightarrow \kappa A_\nu \partial_\mu V^{\mu\nu}$$

E.O.M

$$\kappa m_V^2 A_\nu V^\nu$$

Production of dark photon

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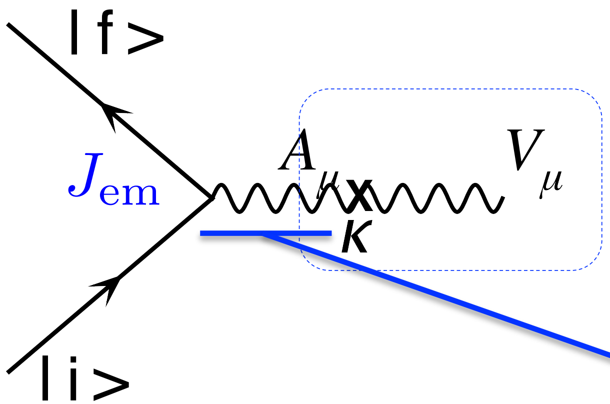

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In the Feynman gauge:

$$\frac{1}{k^2}$$

Production of dark photon

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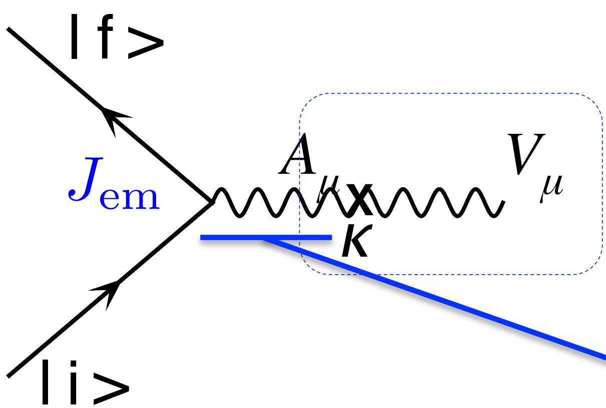
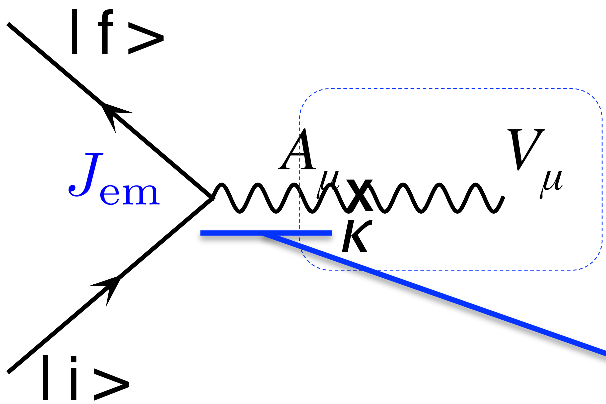


In the Feynman gauge:

$$\frac{1}{k^2} \rightarrow \frac{1}{k^2 - \Pi_{T,L}}$$

Production of dark photon

- Matrix element



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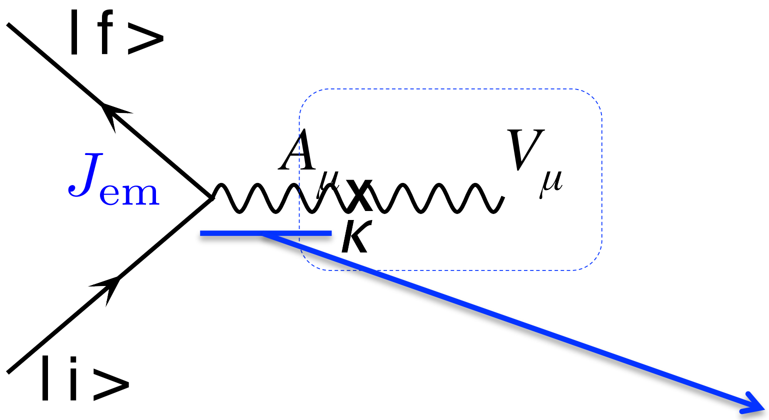
Plasma effect

$$\Pi^{\mu\nu} = e^2 \langle J^\mu_{\rm em}, J^\nu_{\rm em} \rangle = \Pi_T \epsilon_i^{T\mu} \epsilon_i^{T\nu} + \Pi_L \epsilon^{L\mu}\epsilon^{L\nu}$$

Production of dark photon

- Matrix element



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$$\boxed{\mathcal{M} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}}[eJ^\mu_{\rm em}]_{fi}\epsilon_\mu^{T,L}}$$

Production of dark photon

$$\boxed{\mathcal{M} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}}[eJ^\mu_{\rm em}]_{fi}\epsilon_\mu^{T,L}}$$

- Near vacuum $\Pi_{T,L} \to 0$

$$-\kappa[eJ^\mu_{\rm em}]_{fi}\epsilon_\mu^{T,L}$$

m_V^0

Transverse

m_V^1 (current conservation)

Longitudinal

Production of dark photon

$$\boxed{\mathcal{M} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}}[eJ^\mu_{\rm em}]_{fi}\epsilon^{T,L}_\mu}$$

- Inside a thermal plasma (assuming NR electrons)
  - For transverse modes

$$\mathrm{Re}\Pi_T = \omega_p^2 = \frac{4\pi\alpha_{\rm em}n_e}{m_e} \rightarrow \mathcal{M}_{i\to f+V_T} \sim \frac{m_V^2}{\omega_p^2}$$

  - For longitudinal mode

$$J^\mu_{\rm em}\epsilon^L_\mu \sim m_V \rightarrow \Pi_L \sim m_V^2 \qquad \mathrm{Re}\,\Pi_L = \omega_p^2\left(1 - \frac{|\vec{k}|^2}{\omega^2}\right)$$

$$\rightarrow \mathcal{M}_{i\to f+V_L} \sim m_V$$

$$\Pi^{\mu\nu} = e^2\langle J^\mu_{\rm em}, J^\nu_{\rm em}\rangle = \Pi_T\epsilon_i^{T\mu}\epsilon_i^{T\nu} + \Pi_L\epsilon^{L\mu}\epsilon^{L\nu}$$

Production of dark photon

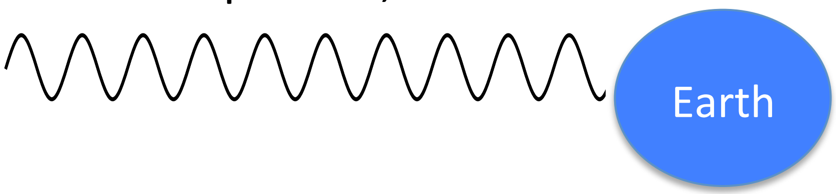
- Production rate:

$$\Gamma_T \propto \begin{cases} \kappa^2 & \text{in vacuum,} \quad m_V \gg \omega_p, \\ \kappa^2 m_V^4 \omega_p^{-4} & \text{in medium,} \quad m_V \ll \omega_p. \end{cases}$$

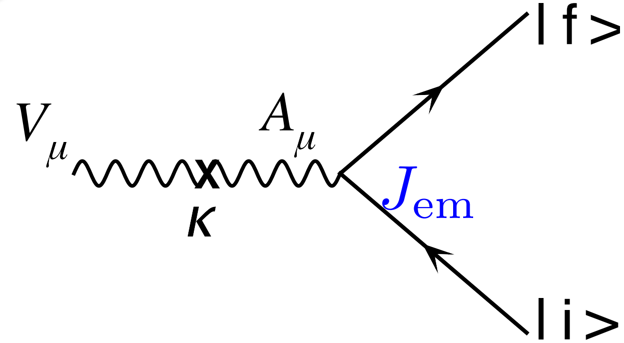
$$\Gamma_L \propto \kappa^2 m_V^2 \omega^{-2}, \quad \text{both in vacuum and in medium.}$$

Direct Detection

Dark photon, V



$$\mathcal{M} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}}[eJ^{\mu}_{\rm em}]_{fi}\epsilon_{\mu}^{T,L}$$



$$\omega_p^2 \longrightarrow \omega^2 \Delta\varepsilon_r$$

$$\Delta\varepsilon_r = \varepsilon_r - 1$$

Relative permittivity

Total absorption rate

- Total absorption rate

$$\Gamma_T = \frac{\kappa^2\omega\left(\frac{m_V^2}{\omega^2|\Delta\epsilon_r|}\right)^2 \mathrm{Im}\varepsilon_r}{1+\frac{2m_V^2\omega^2\mathrm{Re}\Delta\varepsilon_r + m_V^4}{\omega^4|\Delta\varepsilon_r|^2}} \xrightarrow{m_V^2 \ll \omega^2|\Delta\varepsilon_r|} \kappa^2\omega\left(\frac{m_V^2}{\omega^2|\Delta\varepsilon_r|}\right)^2 \mathrm{Im}\varepsilon_r$$

$$\xrightarrow{m_V^2 \gg \omega^2|\Delta\varepsilon_r|} \kappa^2\omega\mathrm{Im}\varepsilon_r$$

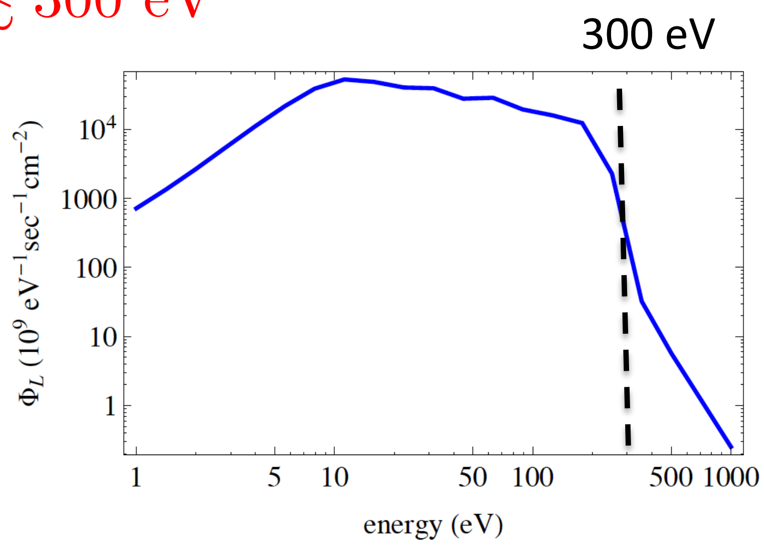
$$\Gamma_L = \frac{\kappa^2 m_V^2 \mathrm{Im}\varepsilon_r}{|\varepsilon_r|^2\omega}$$

- $\Delta\varepsilon_r \propto n_A, \ \text{Atom number density}$
  - $m_V^2 \ll \omega^2|\Delta\varepsilon_r|$ $\quad \Gamma_T \propto n_A^{-1}$ $\quad \Gamma_L \propto n_A$
  - $m_V^2 \gg \omega^2|\Delta\varepsilon_r|$ $\quad \Gamma_T \propto n_A$ $\quad \Gamma_L \propto n_A$

The right detector

- The dark flux is dominated by the longitudinal mode.
- $\Gamma_L \propto n_A$ (small m_V) $\Gamma_T \propto n_A$ (large m_V)
- High density, large volume $\rightarrow$ dark matter detectors
- Inside the Sun, $1\ \mathrm{eV} \lesssim \omega_p \lesssim 300\ \mathrm{eV}$

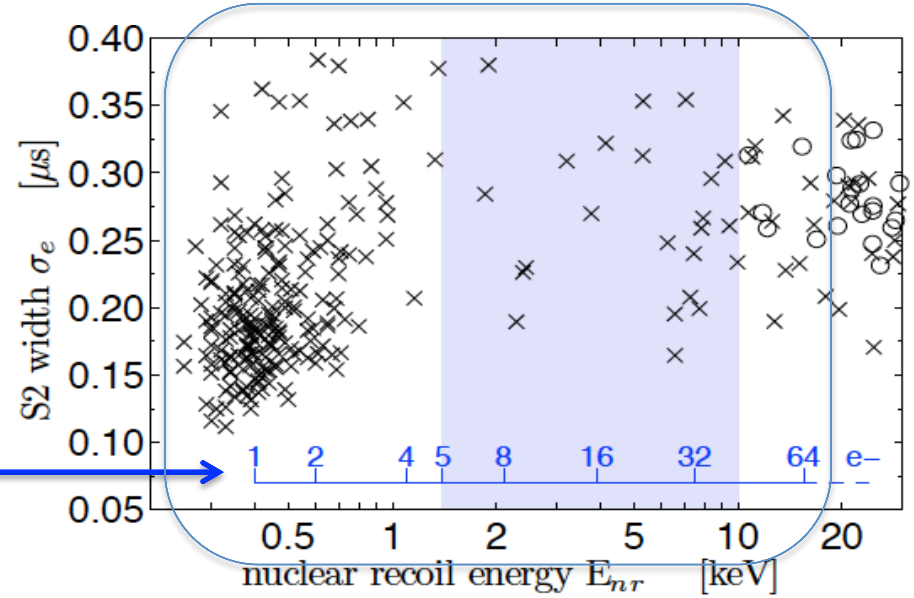
  The detector should be able to detect ~ $100\ \mathrm{eV}$ energy deposition



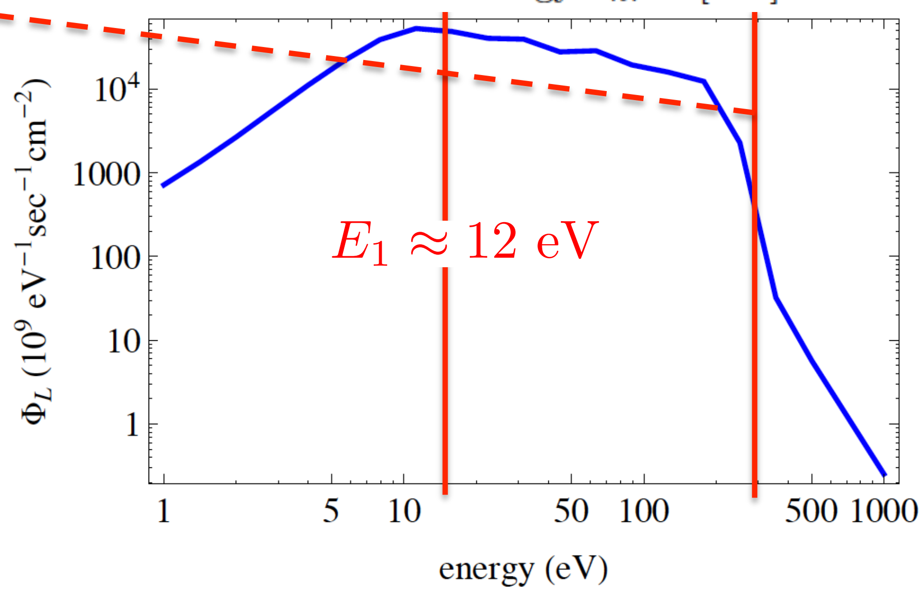
XENON10 constraint

- XENON10

Number of electrons



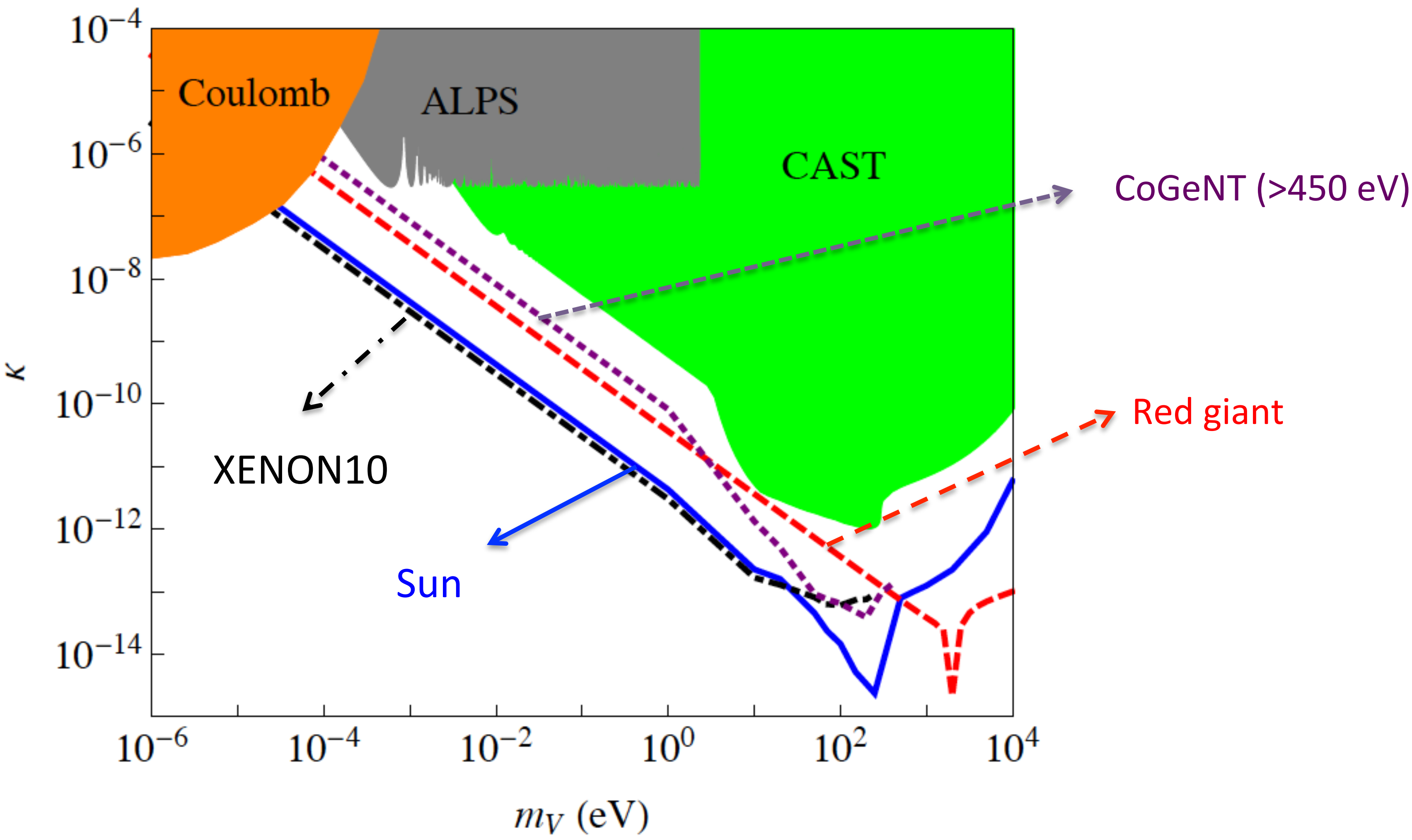
300 eV ~ 25 electrons



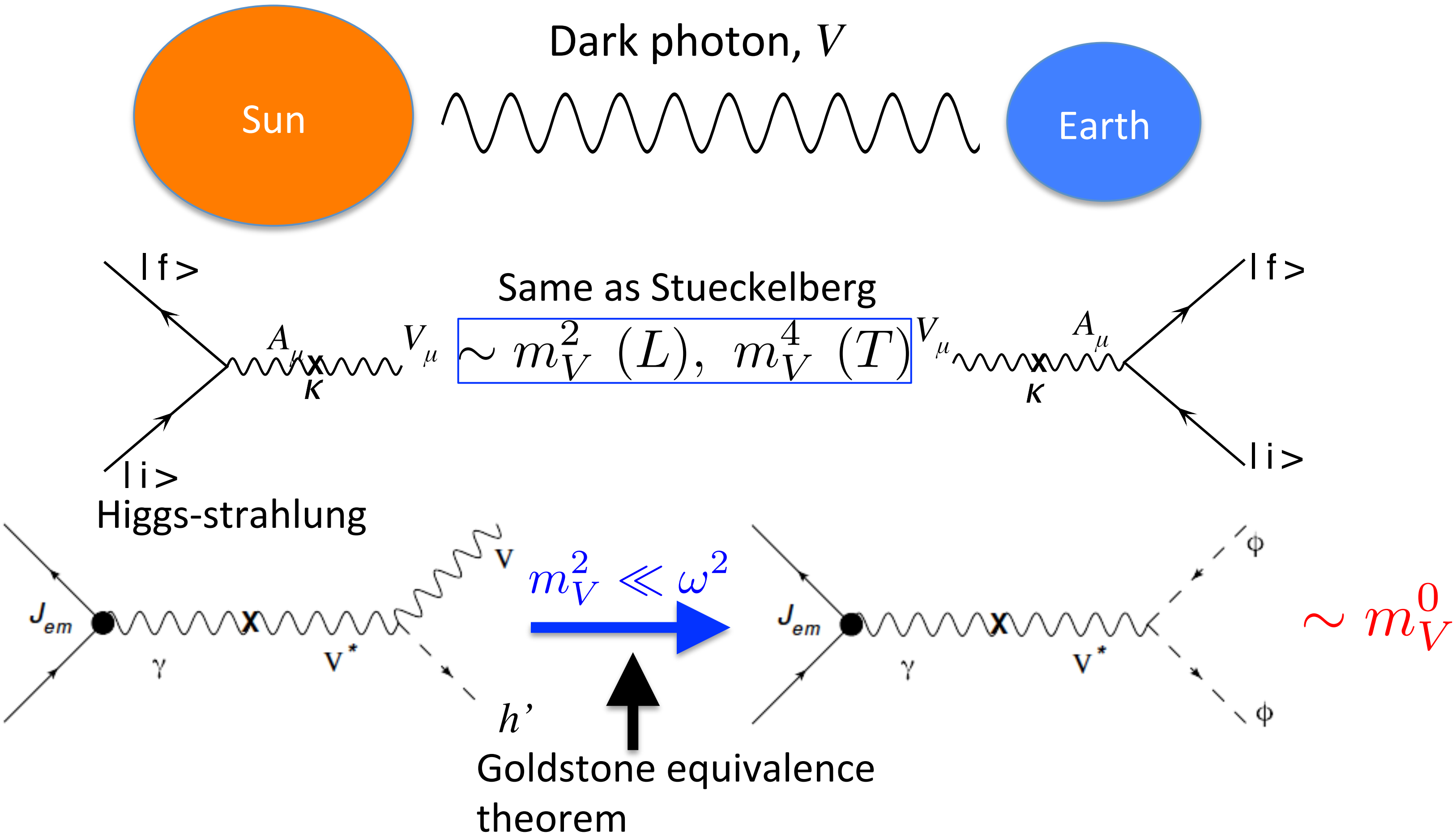
- $\mathrm{Br} \approx 1$

  Photo-ionization dominates.

Stueckelberg case

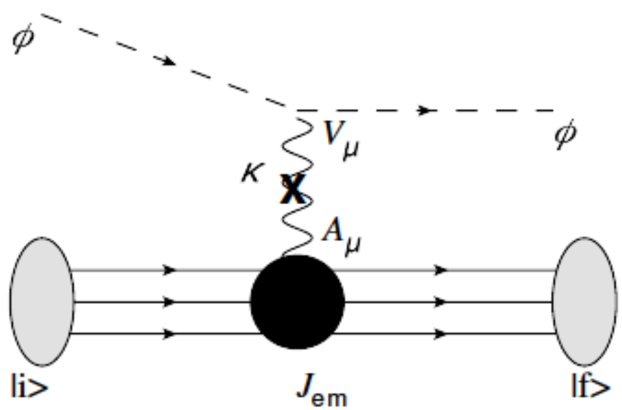


Higgsed case



Higgsed case

- Dark Higgs inelastic scattering process dominates in small m_V region, using the Goldstone equivalence theorem:



$\sim m_V^0$ Dominates in the sub-eV region

Collinear divergence regularized by the medium effect.

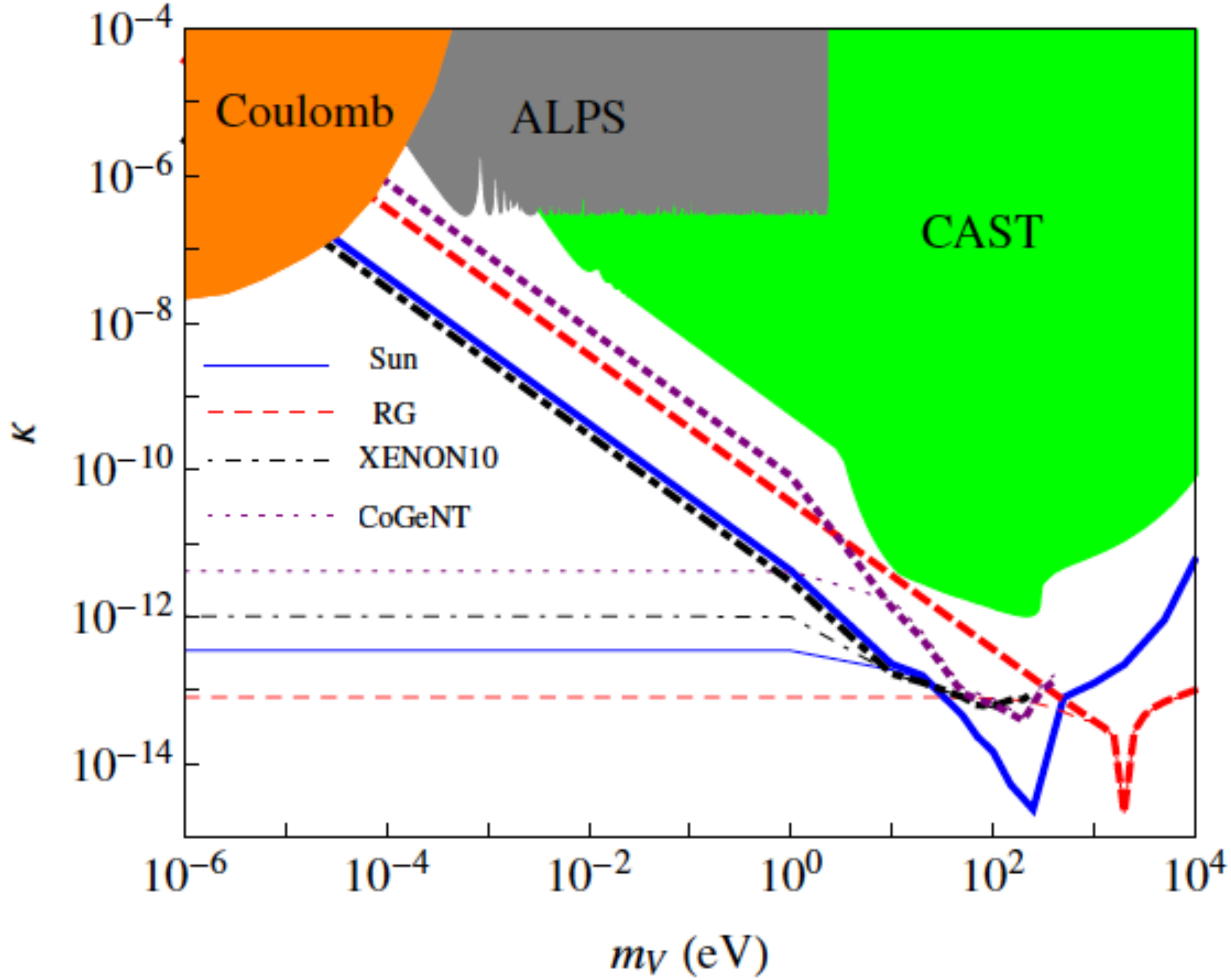
$$\frac{d\Gamma}{d\omega} \approx \frac{\kappa^2 e'^2}{4\pi^2} \frac{E-\omega}{E} \left[\log\left(\frac{4E(E-\omega)}{\omega^2|\Delta\varepsilon_r|}\right) - 1\right] \mathrm{Im}\varepsilon_r(\omega)$$

Energy injected into the medium

Energy of incoming Higgs

Permittivity

Higgsed case



Summary

- The stellar bounds are significantly strengthened in the sub-eV region.
- The apparatus to detect solar dark photon should be changed fundamentally. (dark matter detectors)
- For the Stueckelberg case, the XENON10 result gives the most stringent constraint on the parameter space.
- For the Higgsed case, we expect the next generation of dark matter detector to have more sensitivity.

Detection of dark photon

- Signal rate

Total absorption rate

$$N_{\rm exp} = VT \int_{\omega_{\rm min}}^{\omega_{\rm max}} d\omega \left(\frac{d\Phi_T}{d\omega} \frac{\Gamma_T}{v} + \frac{d\Phi_L}{d\omega} \frac{\Gamma_L}{v} \right) {\rm Br}$$

Solar flux

Branching ratio to the desired signal.

Flux: $\mathrm{T-mode\ dominates}\ , \quad 1\ \mathrm{eV} \lesssim m_V \lesssim 300\ \mathrm{eV}$
$\mathrm{L-mode\ dominates}\ , \quad m_V \ll 1\ eV$