Dark Photon:

Stellar Constraints and Direct Detection

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PRL 111 (2013) 041302, arXiv: 1304.3461

Motivations

- The Standard Model (SM) is very successful.

- However, still something is missing:
  - Baryogenesis
  - Dark matter
  - Neutrino masses
  - ...

- SM must not be the complete theory for particle physics.

Motivations

- How to extend SM?
  - Higher dimensional operators: New physics effects are suppressed by large scales.
  - Marginal operators:

$\bar{L}HN$	Neutrino mass
$\lvert H\rvert^2 S^2$	Higgs portal
$B^{\mu\nu}V_{\mu\nu}$	Kinetic mixing

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Dark photon

Why dark photon?

- 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!)

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- Technically natural (A simple extension of SM, why not!)
- We found the literature was incorrect. The stellar constraints and detecting methods are completely changed.

Outline

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

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The Lagrangian

The Standard Model

Extra vector field

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

$$G^{a\mu\nu} \qquad W^{i\mu\nu} \qquad \underbrace{B^{\mu\nu} \qquad V^{\mu\nu}}_{-\frac{1}{2}\kappa' B_{\mu\nu} V^{\mu\nu}}$$

Below EW breaking ,

$$\downarrow$$

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

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

Origins of mass

- Massive $U(1)$ gauge theory

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

Would-be Goldstone

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

No! (Naturalness)

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

Stueckelberg case

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

Higgsed case

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

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

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Stueckelberg case

- Lagrangian

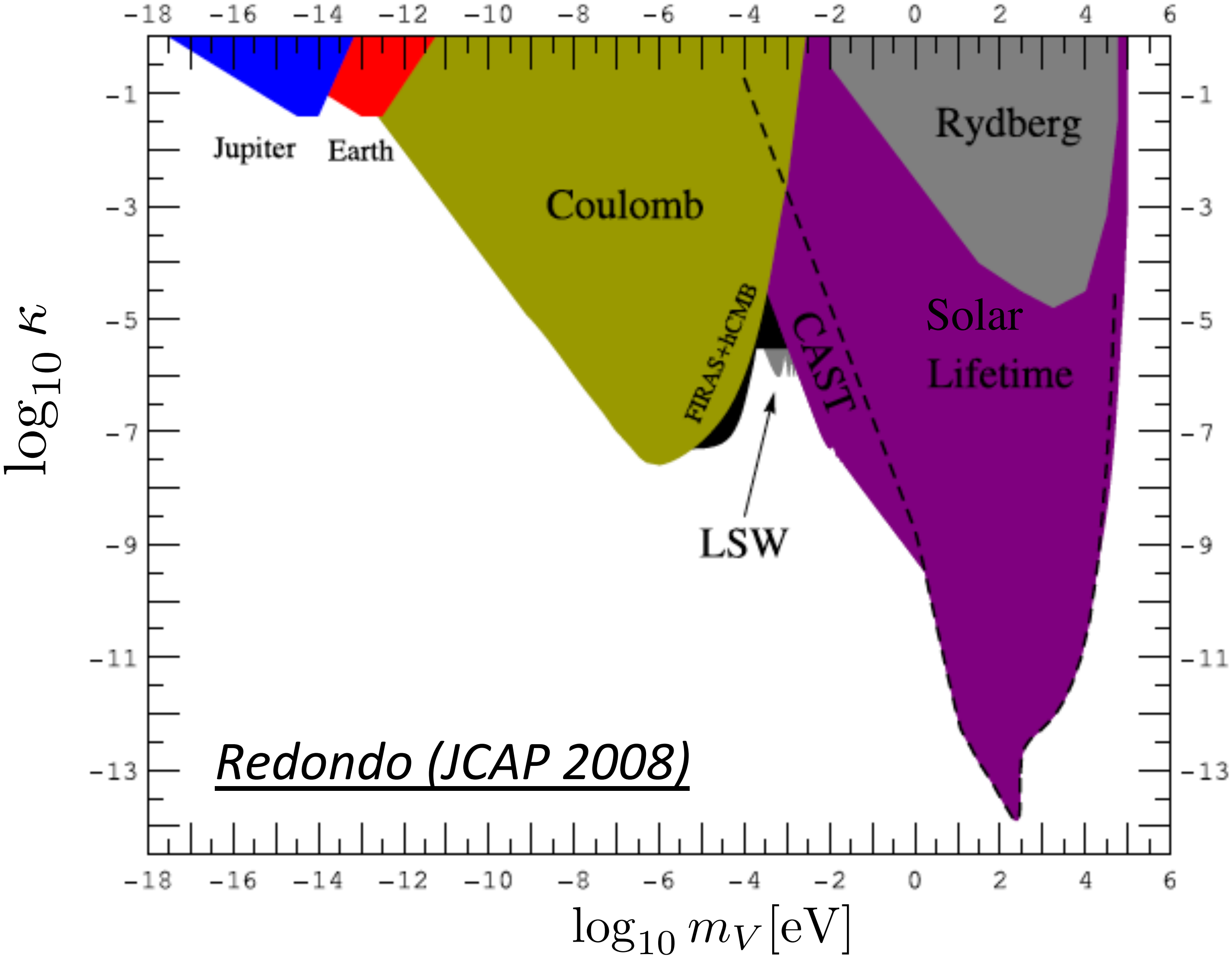
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu^2 + eJ^\mu_{\rm em}A_\mu$$

- Only two unknown parameters

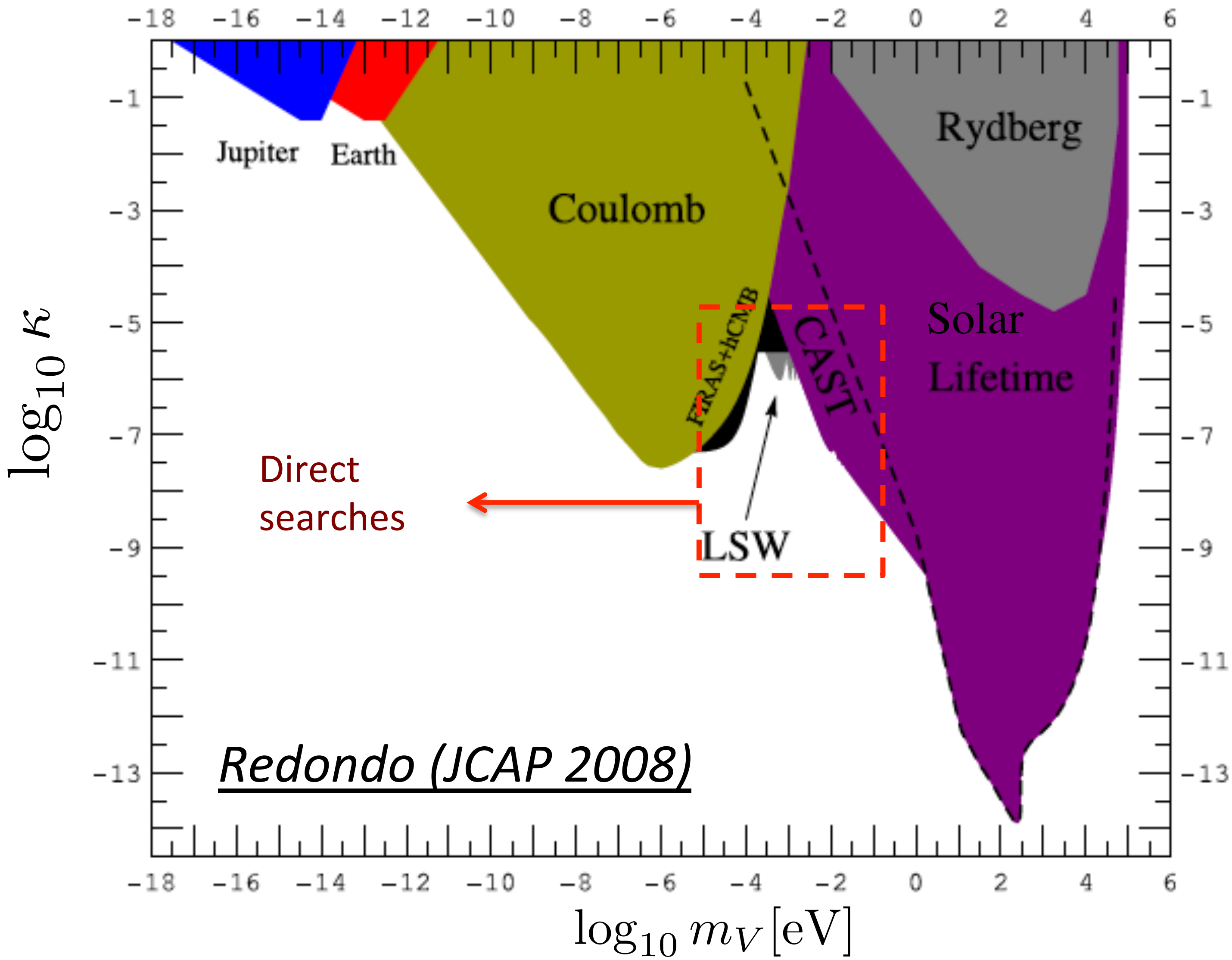
$$\kappa \quad \text{and} \quad m_V$$

- A lot of studies have already been done.

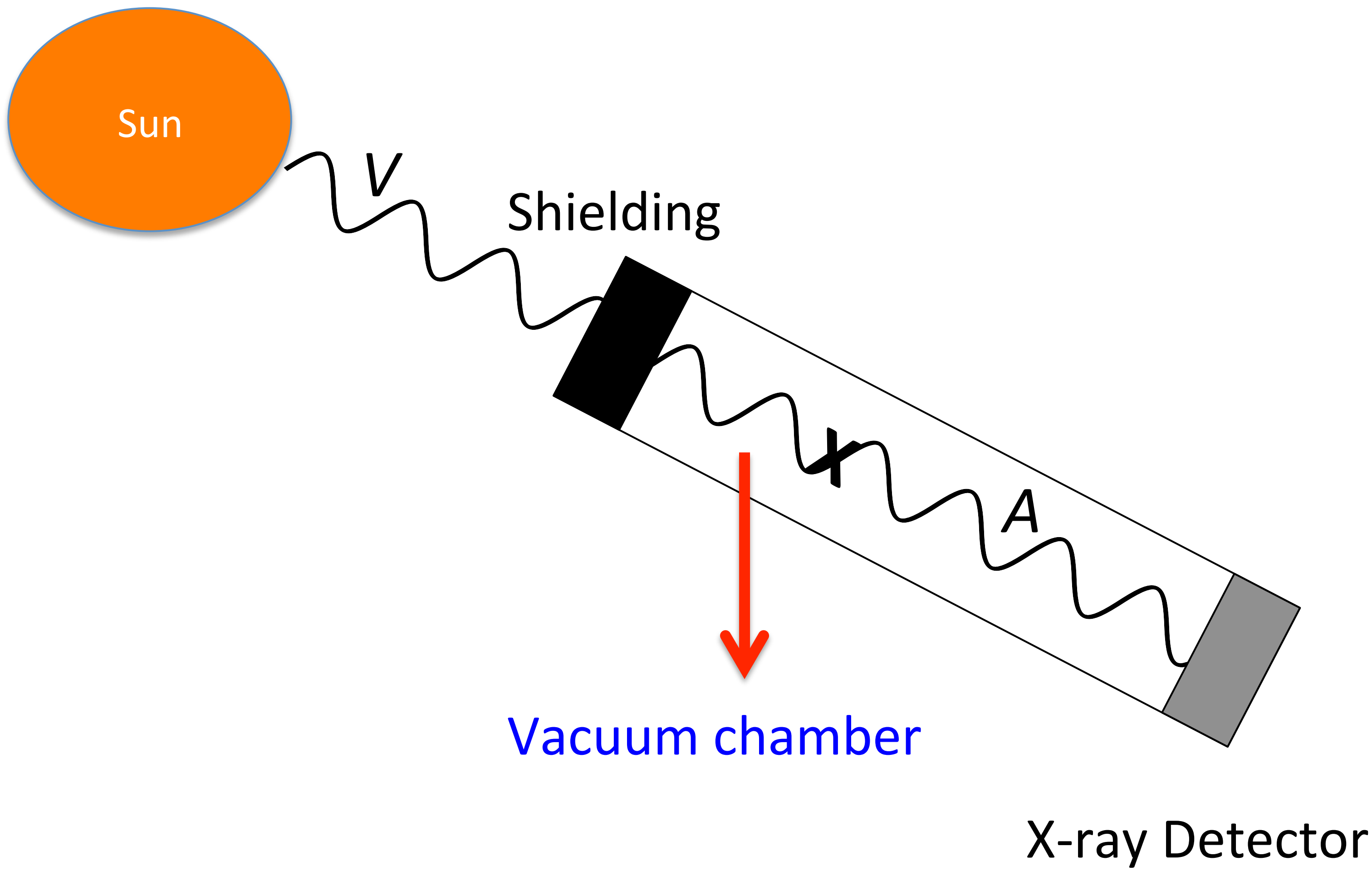
Previous results



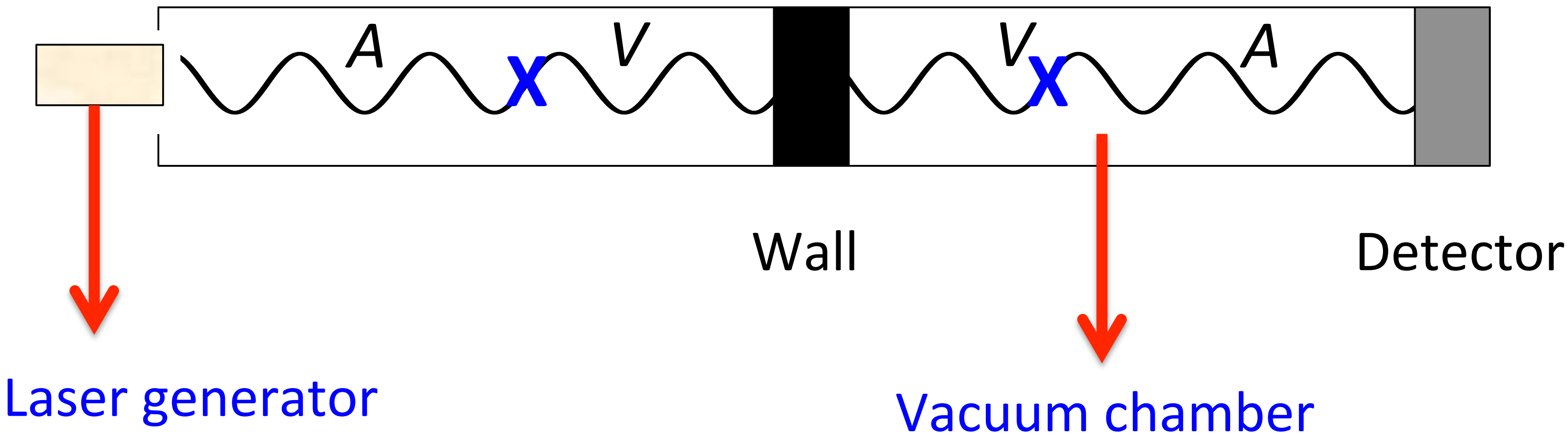
Previous results



CAST experiment



Light shining through the wall (LSW)



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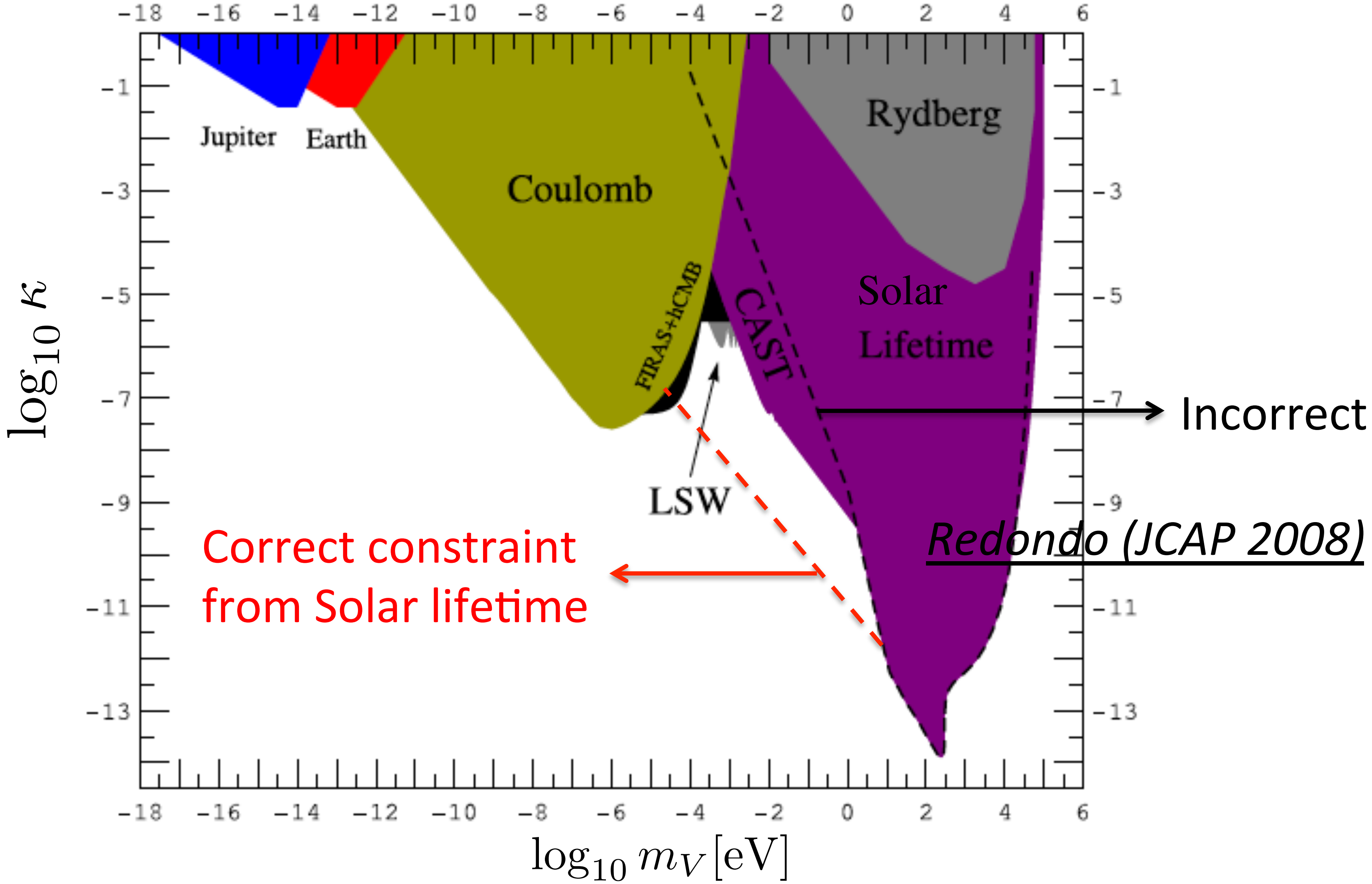

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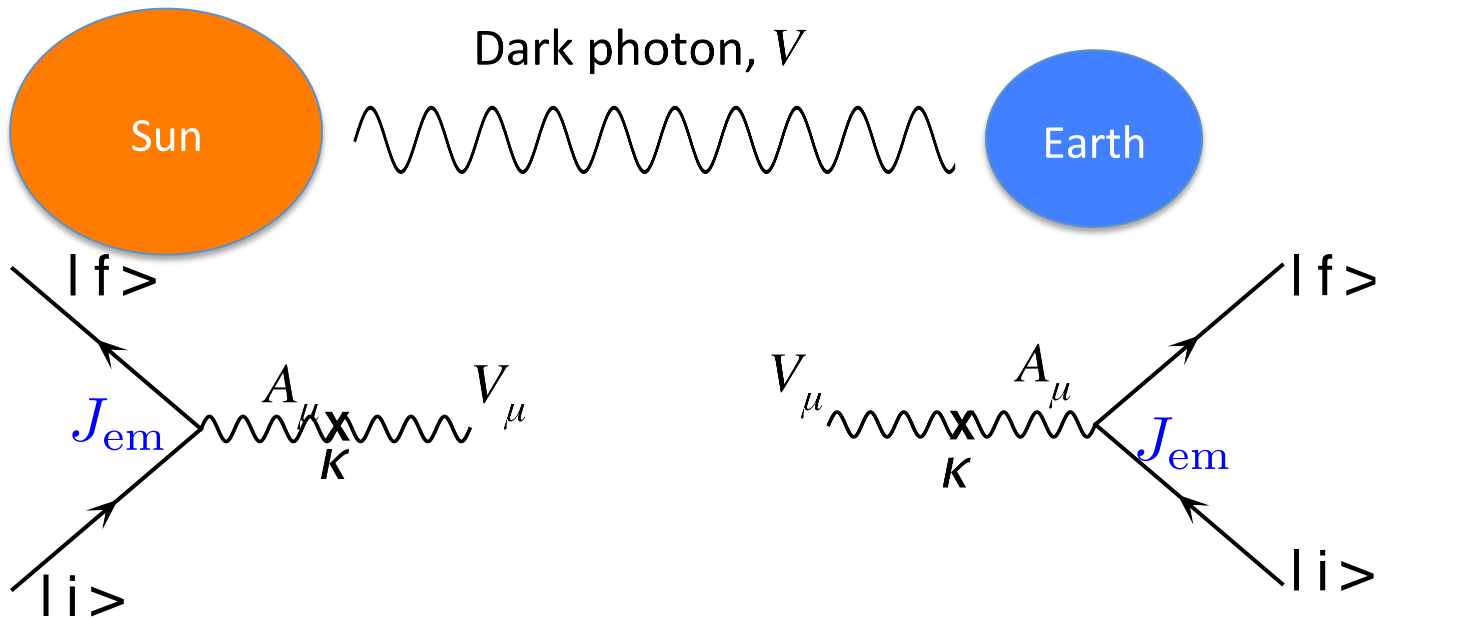
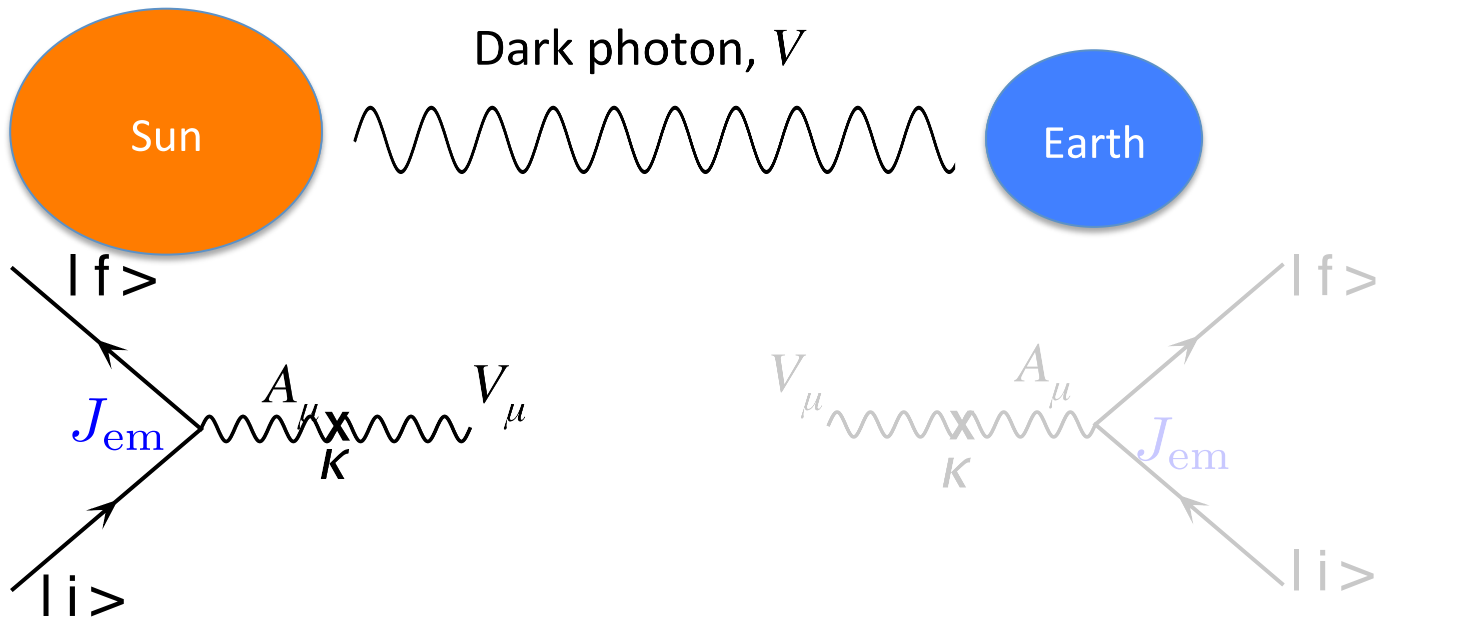
Stueckelberg case



- 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 ...)

Stueckelberg case



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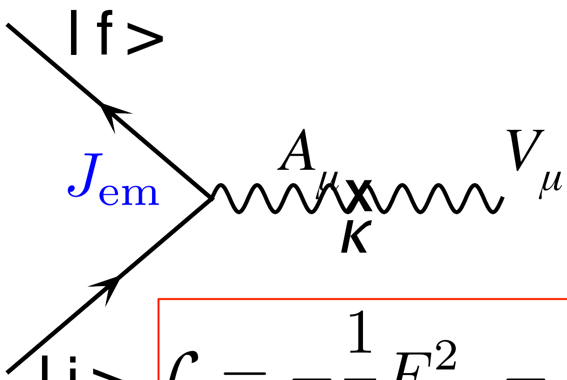
Production of dark photon

- Matrix element (homework of QFT101)

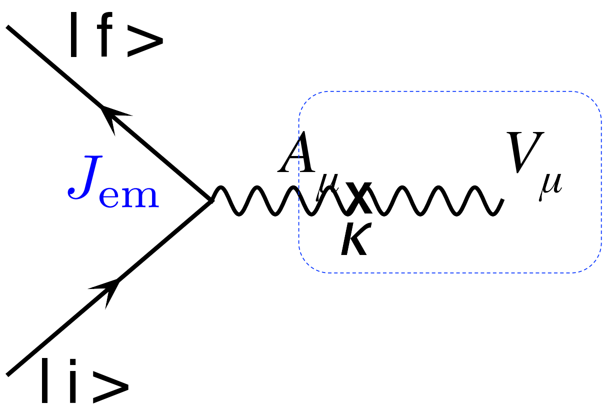


$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu^2 + eJ^\mu_{\rm em}A_\mu}$$

  - Two free parameters m_V and κ, technically natural.
  - Very simple diagram and Lagrangian.
  - Everything is under control.

Production of dark photon

- Matrix element



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

E.O.M

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

Production of dark photon

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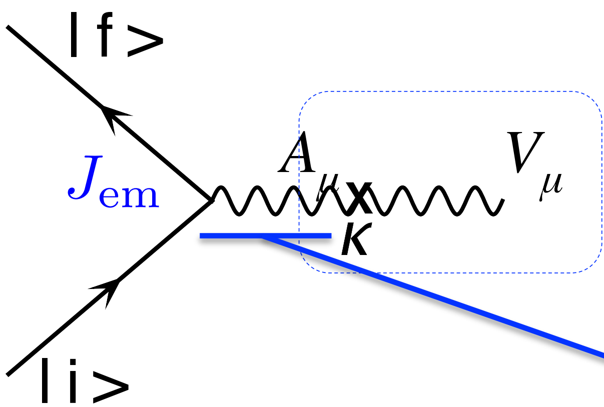
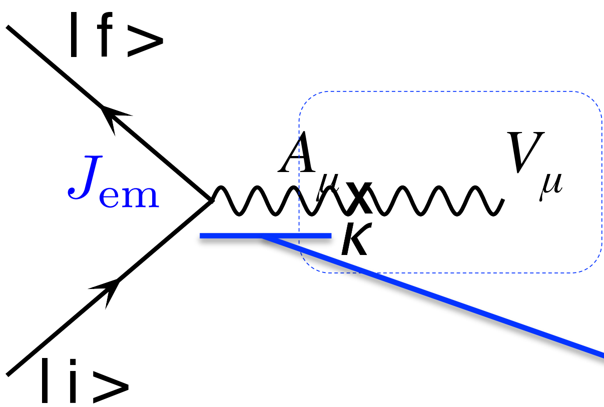


In the Feynman gauge:

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

Production of dark photon

- Matrix element



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E.O.M

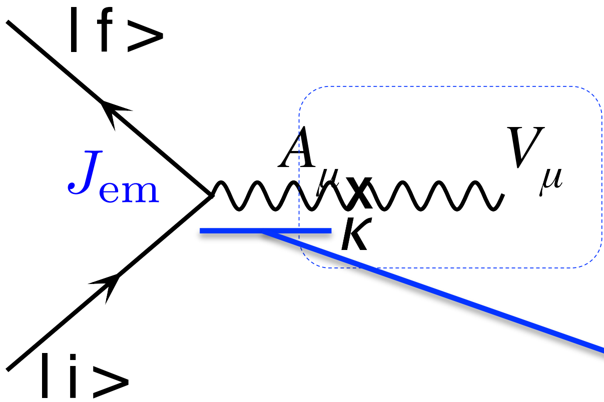
$$\kappa m_V^2 A_\nu V^\nu$$

In the Feynman gauge:

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

Production of dark photon

- Matrix element



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

E.O.M

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

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

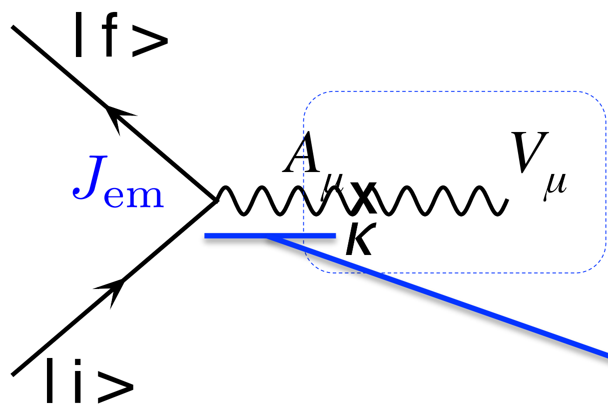
Plasma effect

In the Feynman gauge:

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

Production of dark photon

- Matrix element



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

E.O.M

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Plasma effect

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

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 | m_V^1 (current conservation)

Transverse | Longitudinal

Production of dark photon

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

- Inside a thermal plasma (with 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

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

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

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

Production of dark photon

- Production rate:

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

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

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arXiv:0801.1527 (JCAP 0807,008 (2008))

$$\Pi_L = \omega_p^2 - |\vec{k}|^2 \quad \longrightarrow \quad \Gamma_L \propto m_V^4$$

Not correct!

Production of dark photon

- Resonant production

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

Transverse resonance

$$m_V^2 = \mathrm{Re}\Pi_T = \omega_p^2$$

$$\Downarrow$$

$$m_V^2 = \omega_p^2$$

Longitudinal resonance

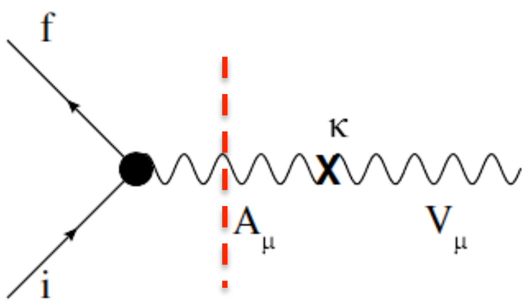
$$m_V^2 = \mathrm{Re}\Pi_L = \omega_p^2 m_V^2/\omega^2$$

$$\Downarrow$$

$$\omega^2 = \omega_p^2$$

Production of dark photon

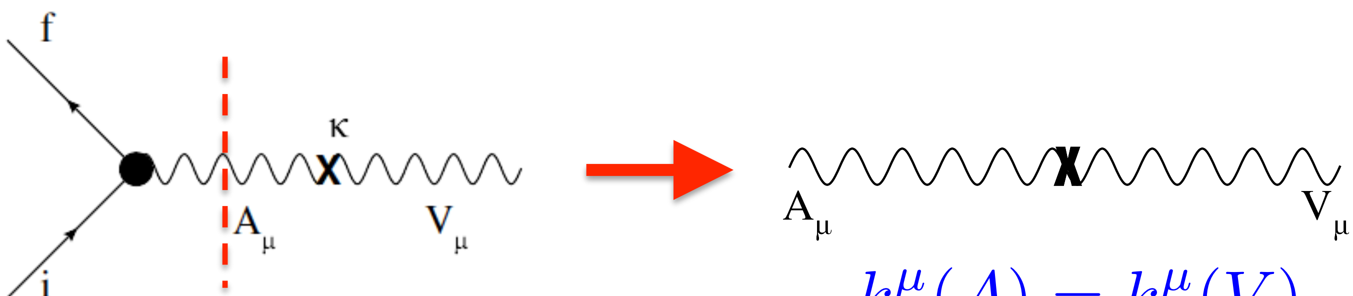
- Resonant production



On shell due to the thermal effect

Production of dark photon

- Resonant production



On shell due to the thermal effect

$$k^\mu(A) = k^\mu(V)$$

- In thermal field theory, this is equivalent to that a thermal bath of photon slowly transits into dark photons.

Production of dark photon

- Matching on shell conditions

  - Transverse photon

Dark photon

$$\omega^2 - |\vec{k}|^2 = \omega_p^2 \qquad\qquad \omega^2 - |\vec{k}|^2 = m_V^2$$

$$m_V^2 = \omega_p^2$$

  - Longitudinal photon (plasmon)

(collective motion of electrons)

$$\omega^2 = \omega_p^2 \qquad\qquad \omega^2 - |\vec{k}|^2 = m_V^2$$

$$\omega^2 = \omega_p^2$$

Production of dark photon

- Bose-Einstein distribution for both T-photon and L-plasmon, the dark radiation powers are

$$\frac{dP_T}{dV\,d\omega} = \frac{\kappa^2 \omega_p^4 \sqrt{\omega^2 - \omega_p^2}}{2\pi(e^{\omega/T} - 1)} \delta(m_V - \omega_p)$$

$$\frac{dP_L}{dV\,d\omega} = \frac{\kappa^2 m_V^2 \omega_p^2 \sqrt{\omega^2 - m_V^2}}{4\pi(e^{\omega/T} - 1)} \delta(\omega - \omega_p)$$

- Inside the Sun, $1 \text{ eV} \lesssim \omega_p \lesssim 300 \text{ eV}$

- $\boxed{\begin{array}{l} \text{T} - \text{mode dominates} \;, \quad 1 \text{ eV} \lesssim m_V \lesssim 300 \text{ eV} \\ \text{L} - \text{mode dominates} \;, \quad m_V \ll 1 \; eV \end{array}}$

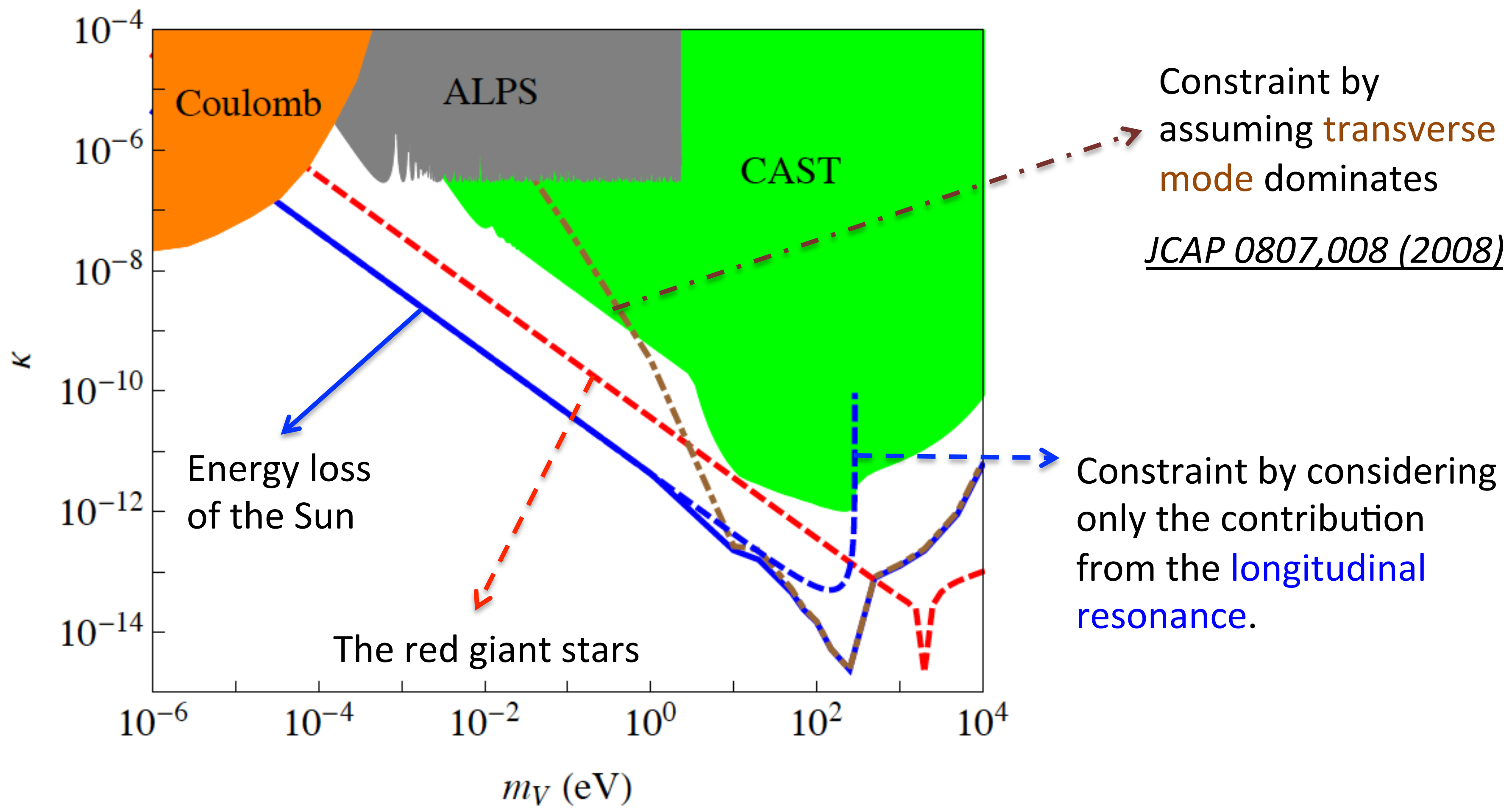
Production of dark photon

- Non-resonant production

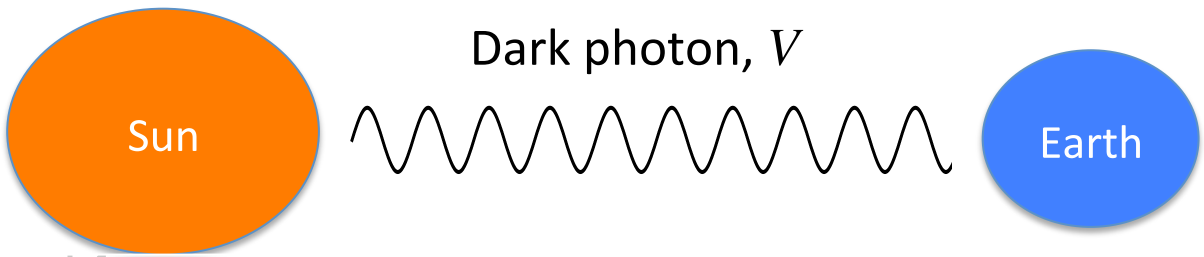
  - Bremsstrahlung
  - Compton scattering

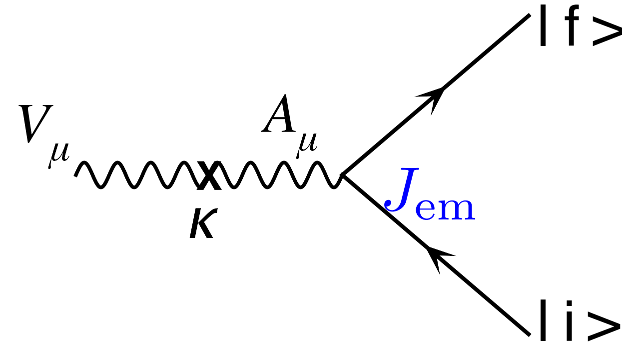
- Inside the Sun Bremsstrahlung dominates

Stellar constraints



Direct detection





– Dark radiation effects the evolution of the stars.

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

Gondolo and Raffelt (PRD 2009)

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

Stueckelberg case

- Signal rate

Total absorption rate

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

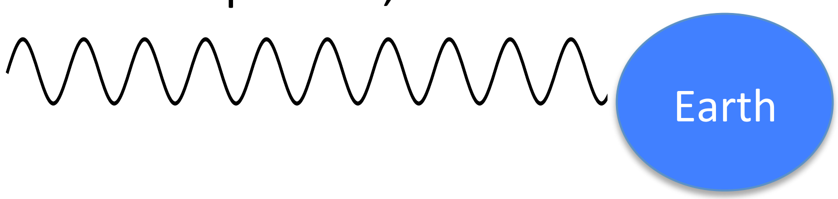
Solar flux

Branching ratio to the desired signal.

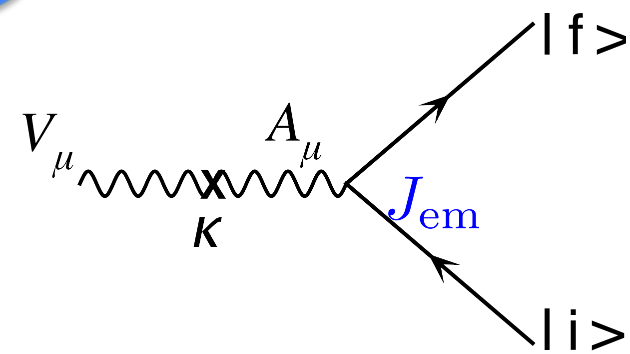
$$\mathrm{T-mode\ dominates}\ , \quad 1\ \mathrm{eV} \lesssim m_V \lesssim 300\ \mathrm{eV}$$
$$\mathrm{L-mode\ dominates}\ , \quad m_V \ll 1\ eV$$

Total absorption rate

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

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

Total absorption rate

- Total absorption rate

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

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

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

Total absorption rate

- Total absorption rate

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

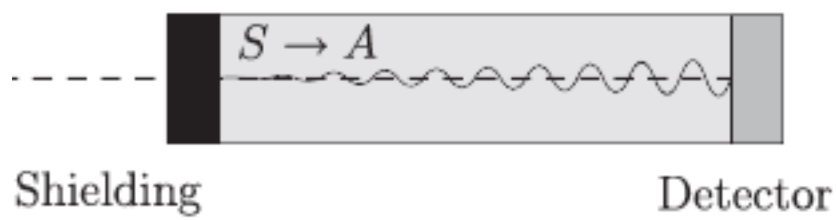
$$\xrightarrow{m_V^2 \gg \omega^2|\Delta\varepsilon_r|} \kappa^2\omega\mathrm{Im}\varepsilon_r$$

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

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

Total absorption rate

- The old idea based on the incorrect result that the dark flux is dominated by the transverse mode. *JCAP 0807,008 (2008)*
- $\Gamma_T \propto n_A^{-1}$
- For sub-eV dark photon The effective atom number density should as small as possible.
- CAST experiment



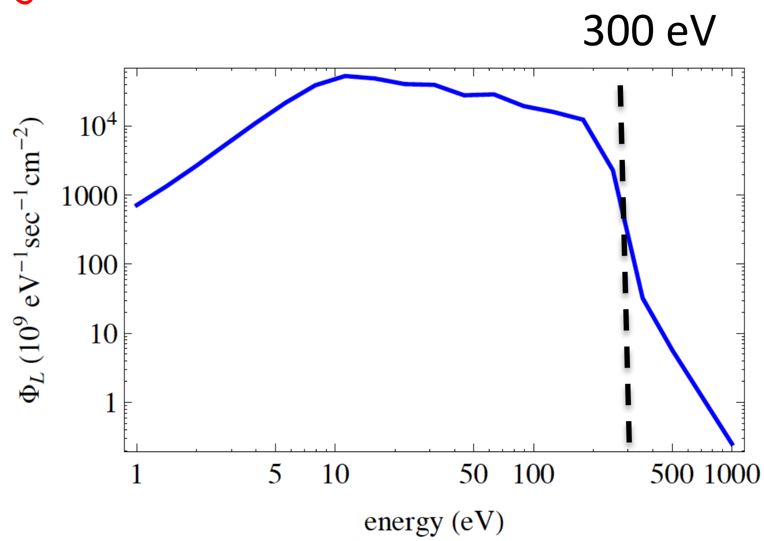
  - Invented to detect axions
  - Shielding + large cavity + Detector
  - Unevenly distributed low density detector

Total absorption rate

- Based on the correct analysis, 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 ➡ dark matter detectors
- Inside the Sun, $1 \text{ eV} \lesssim \omega_p \lesssim 300 \text{ eV}$

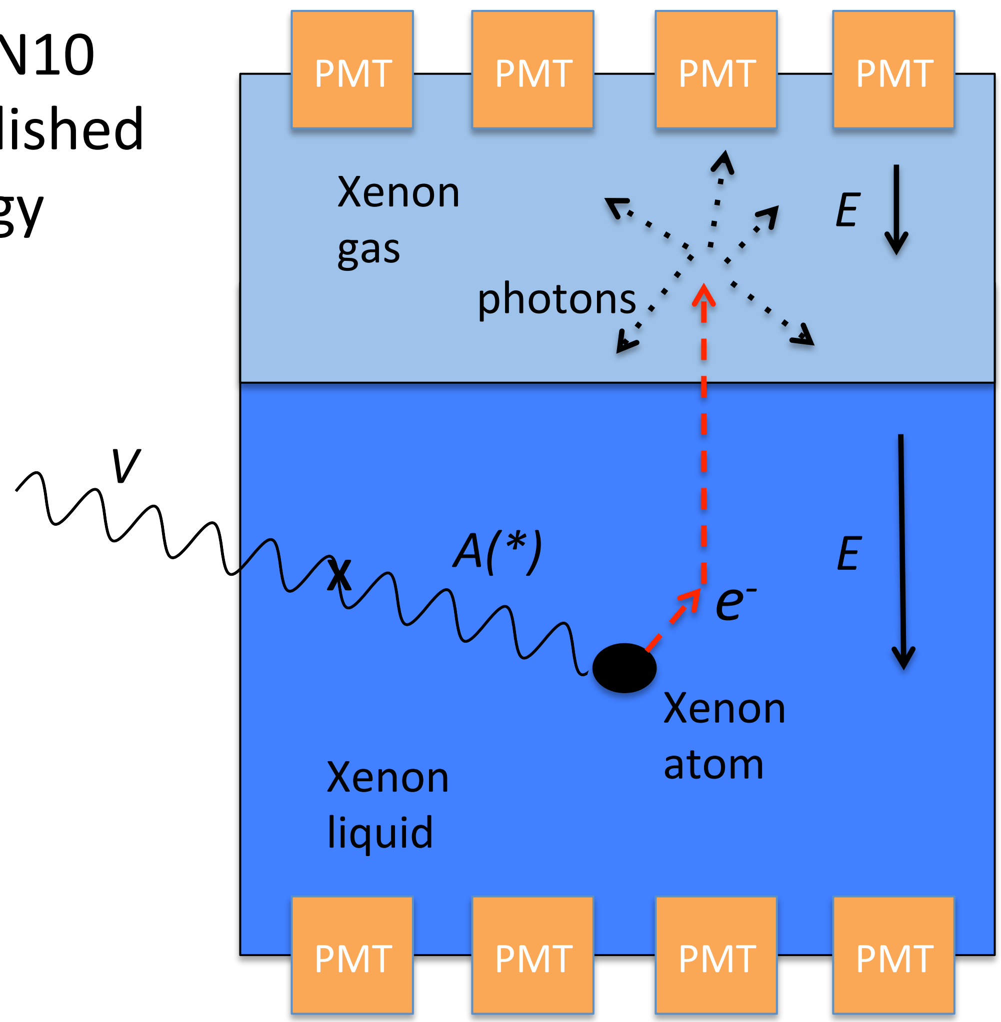
The detector should be able to detect ~ 100 eV energy deposition



XENON10 constraint

- Up to now only XENON10 collaboration has published the result in this energy region.

  $1\ \mathrm{eV} \lesssim \omega_p \lesssim 300\ \mathrm{eV}$



XENON10 constraint

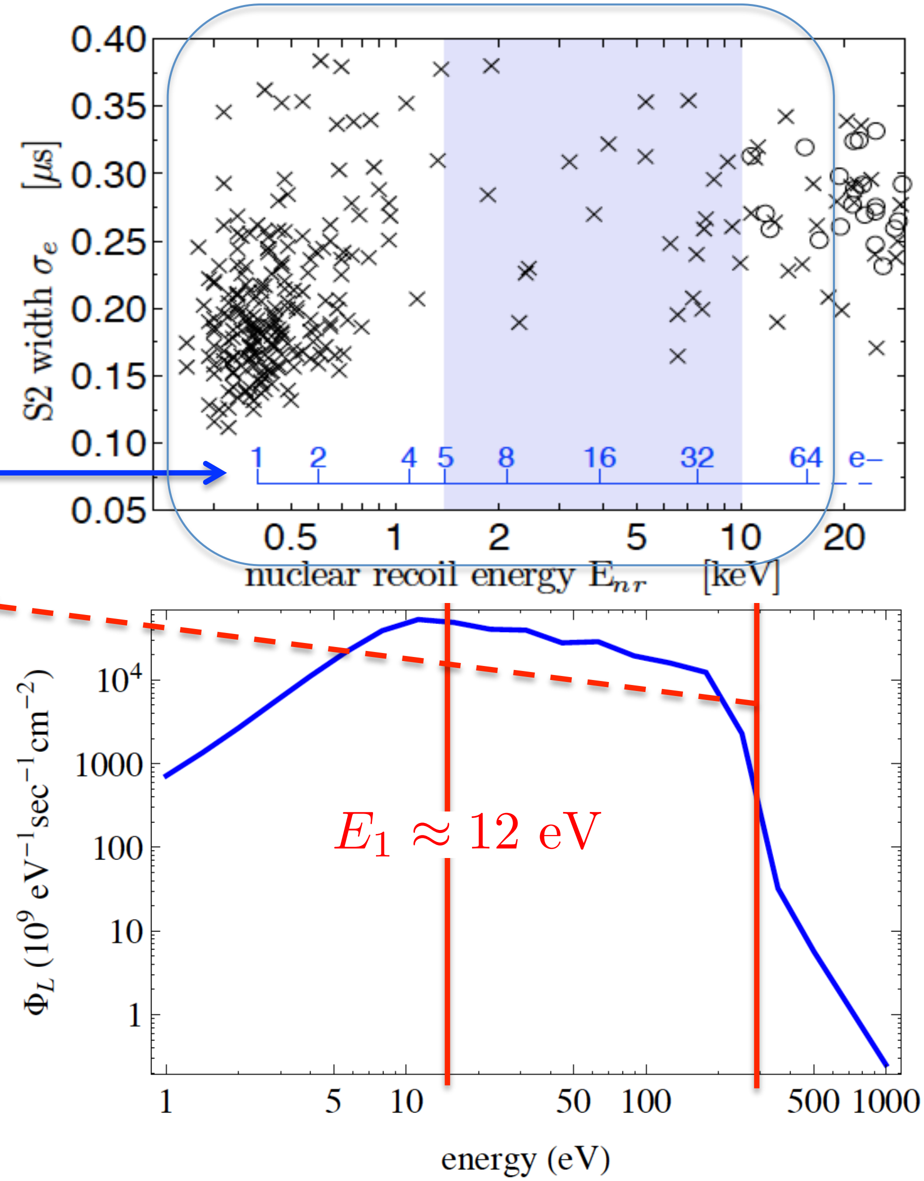
- XENON10

Number of electrons

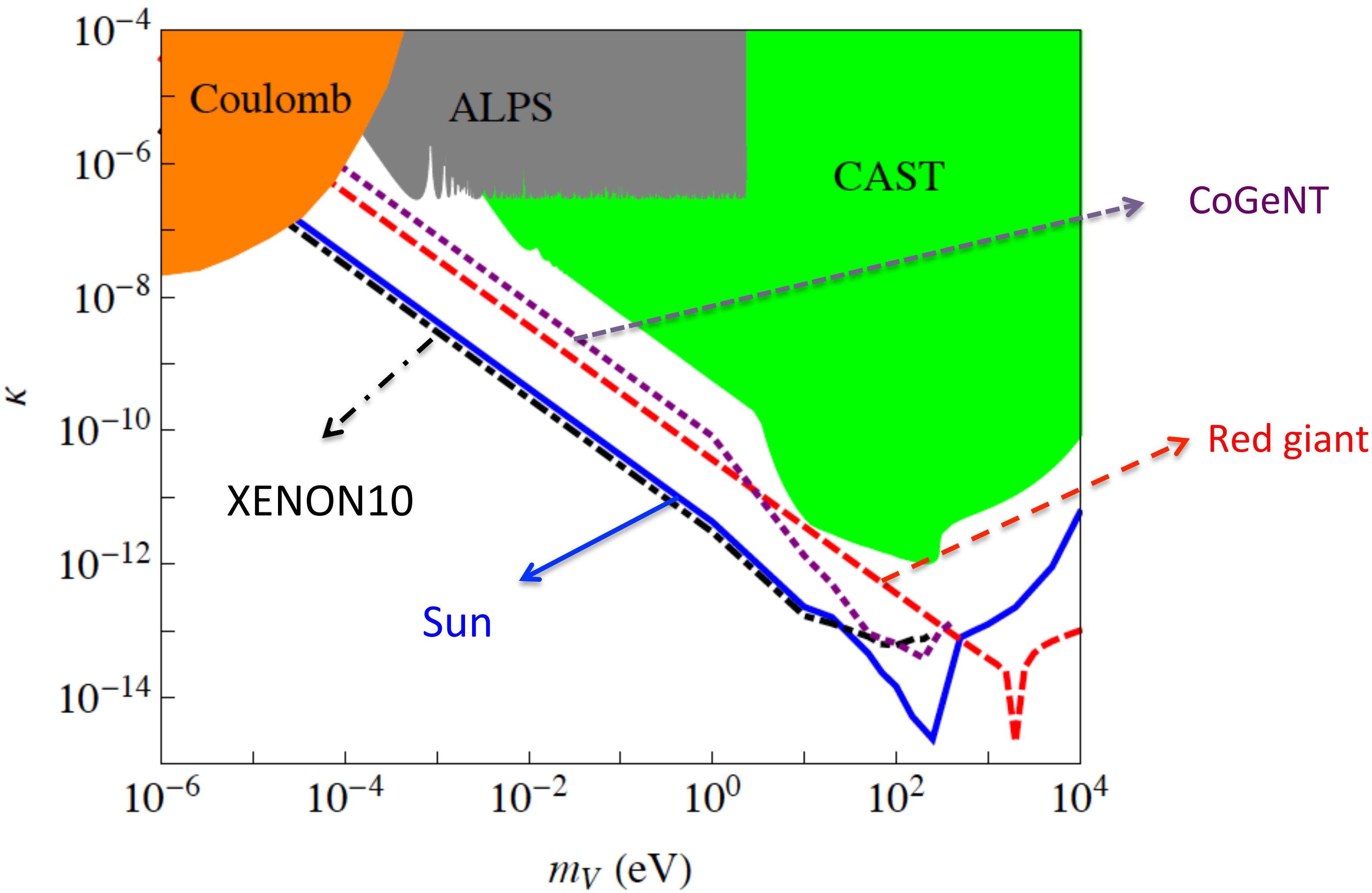
300 eV ~ 25 electrons

- $\mathrm{Br} \approx 1$

  Photo-ionization dominates.



Stueckelberg case



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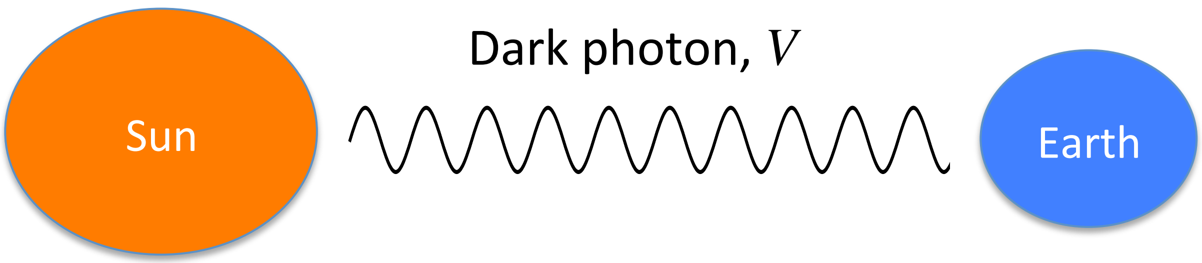
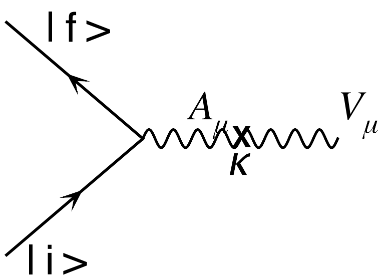
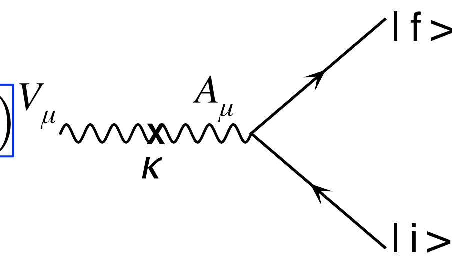
Higgsed case



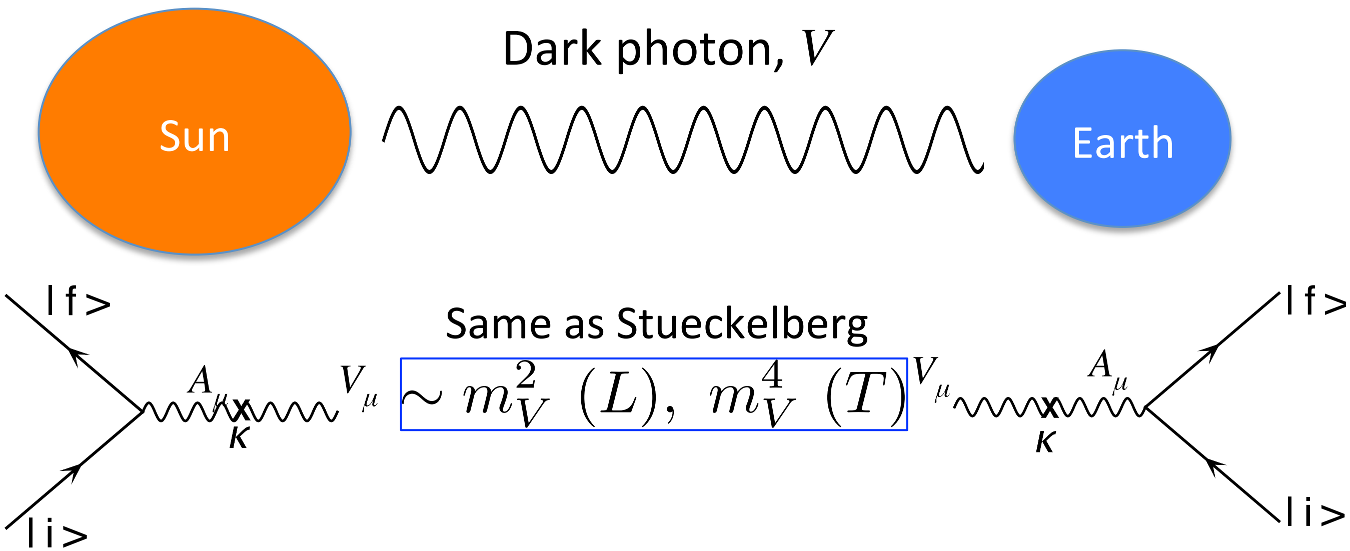
Same as Stueckelberg



$$\boxed{\sim m_V^2 \ (L), \ m_V^4 \ (T)}$$

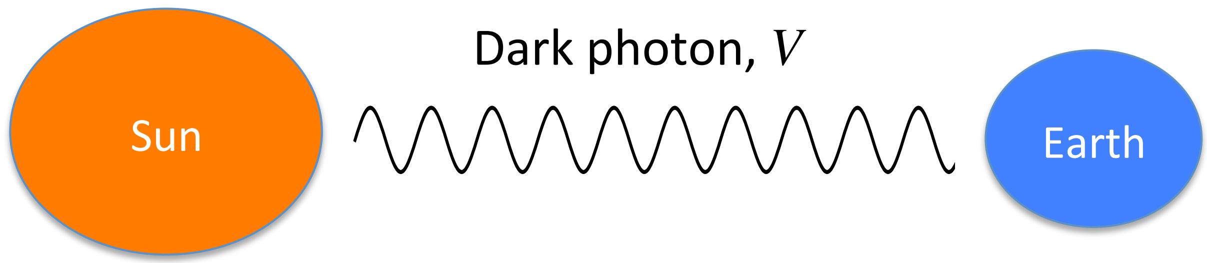


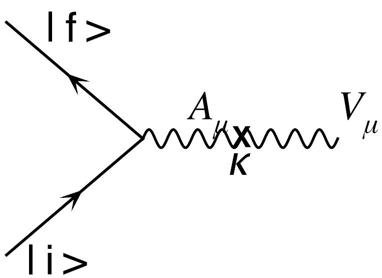
Higgsed case



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

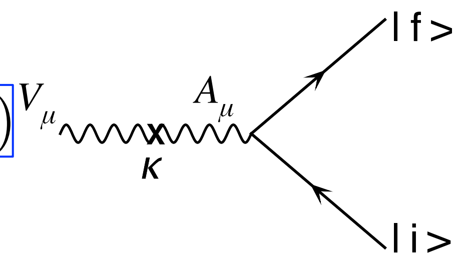
Higgsed case



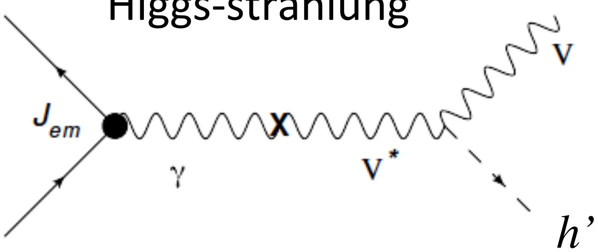


Same as Stueckelberg

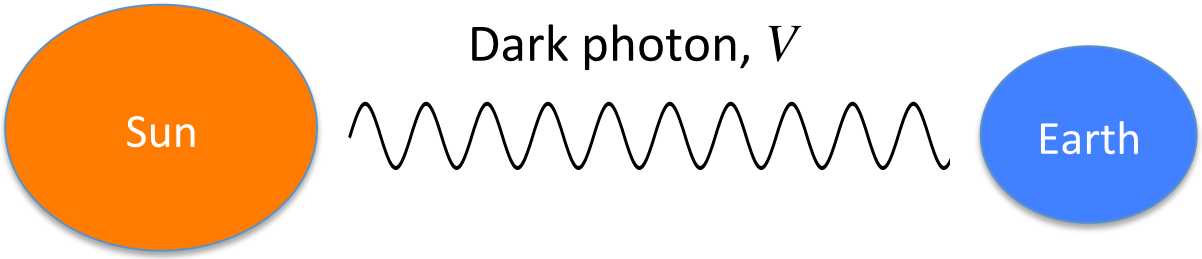
$$\boxed{\sim m_V^2 \ (L), \ m_V^4 \ (T)}$$

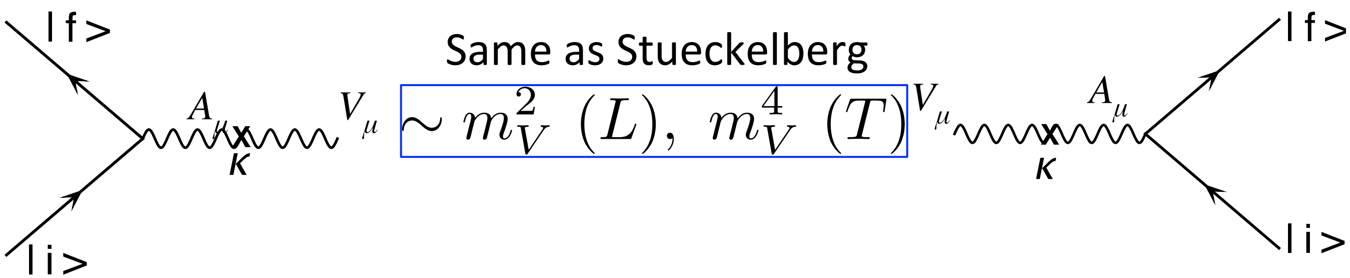


Higgs-strahlung

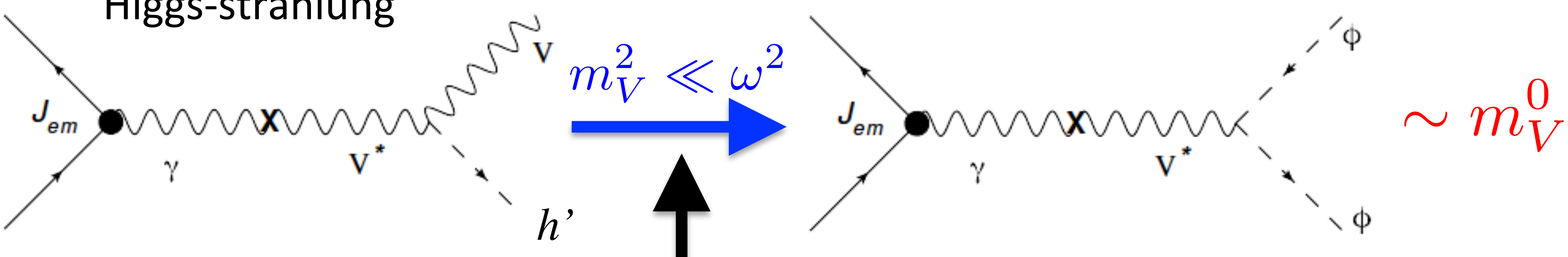


Higgsed case





Higgs-strahlung



Goldstone equivalence theorem

Higgsed case

- Higgs-strahlung

$$\begin{aligned} &\text{Dominant,} && m_V \ll \omega_p, \\ &\text{subdominant,} && m_V \sim \omega_p. \end{aligned}$$

Phase space suppression

Higgsed case

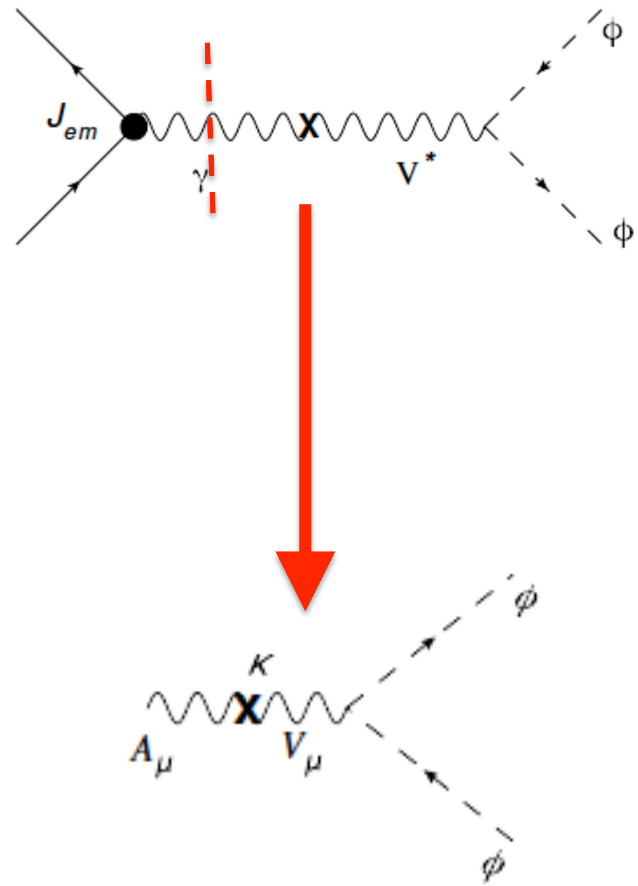
- Higgs-strahlung

Dominant, $\quad m_V \ll \omega_p,$
subdominant, $\quad m_V \sim \omega_p.$

- Resonance decay

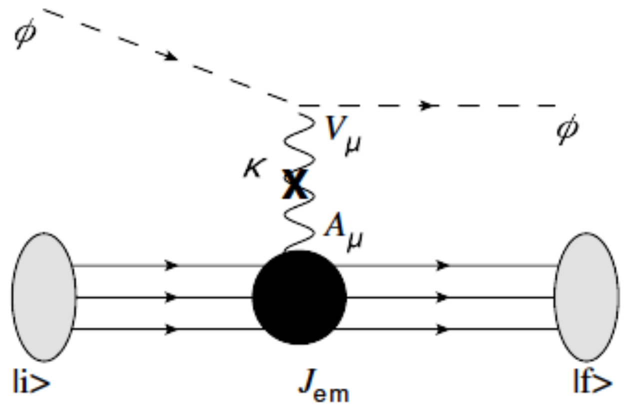
$$N_L \sim \omega_p^3 \ , \quad N_T \sim T^3$$
$$T^3 \gg \omega_p^3, \ \text{in the Sun}$$

Transverse photon decay dominates.



Higgsed case

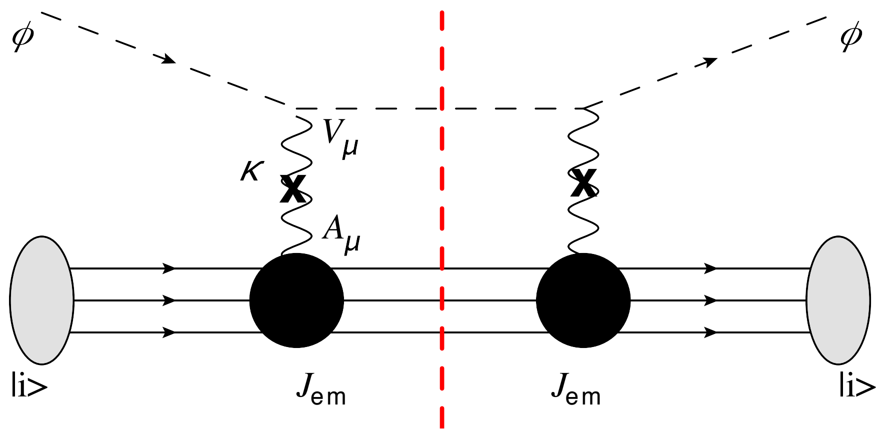
- Dark Higgs inelastic scattering process dominates in small m_V region, using the Goldstone equivalence theorem:



$\sim m_V^0$

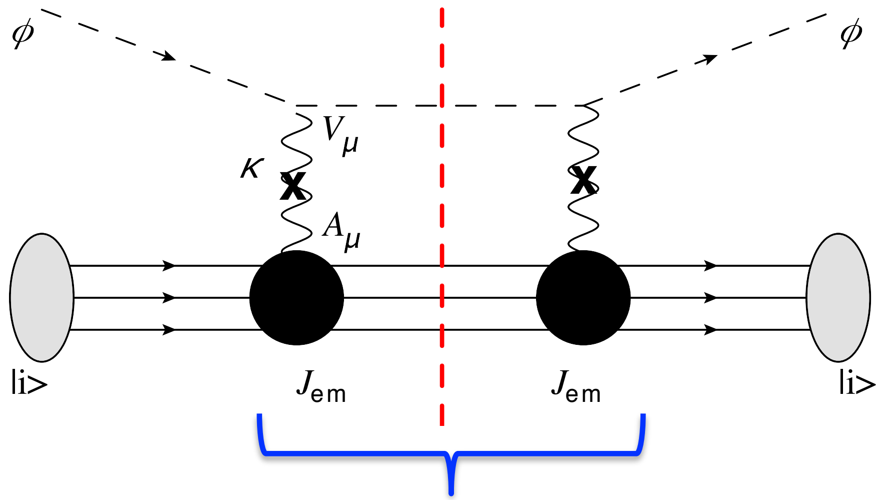
Higgsed case

- Total absorption rate:



Higgsed case

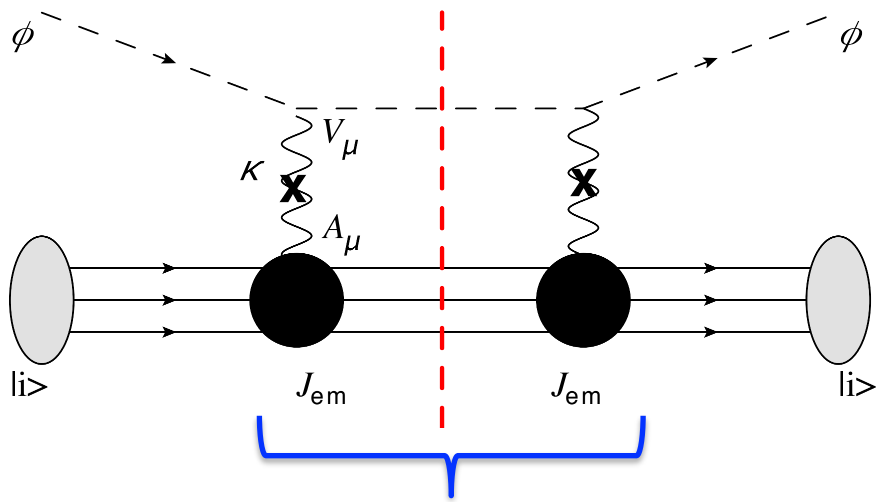
- Total absorption rate:



$$-2\mathrm{Im}\langle J^{\mu\dagger}_{\rm em}, J^{\nu}_{\rm em}\rangle \;\rightarrow\; \mathrm{Im}\Pi_T \ , \ \ \mathrm{Im}\Pi_L$$

Higgsed case

- Total absorption rate:

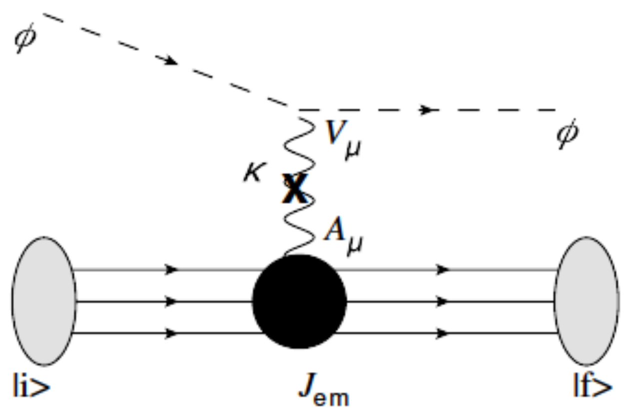


$$-2\mathrm{Im}\langle J^{\mu\dagger}_{\rm em}, J^{\nu}_{\rm em}\rangle \rightarrow \mathrm{Im}\Pi_T \;,\; \mathrm{Im}\Pi_L$$

$$\Pi_T = -\omega^2 \Delta\varepsilon_r$$
$$\Pi_L = -(\omega^2 - |\vec{k}|^2)\Delta\varepsilon_r$$

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.

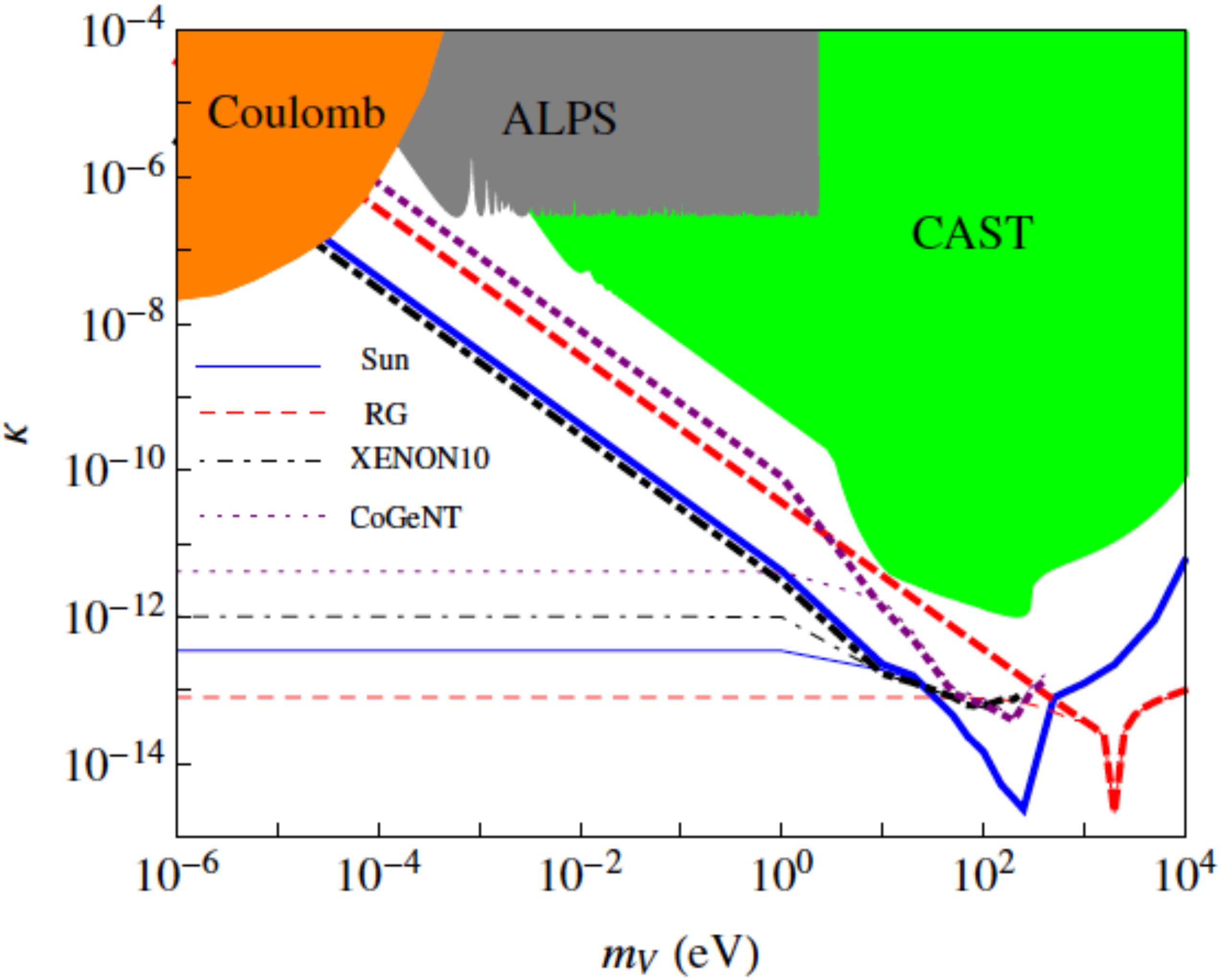
$$\frac{d\Gamma}{d\omega} \approx \frac{\kappa^2 e'^2}{4\pi^2} \frac{E-\omega}{E} \left[\log\left(\frac{4E(E-\omega)}{\omega^2 |\Delta\varepsilon_r|} \right) - 1 \right] \mathrm{Im}\varepsilon_r(\omega)$$

Energy injected into the medium

Energy of incoming Higgs

Permittivity

Higgsed case



$e' = 0.1$

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.
- We hope that XENON collaboration will continue publishing results of S_2 only analysis.
- For the Higgsed case, we expect the next generation of dark matter detector to have more sensitivity.

Backups

Stueckelberg case

- Lagrangian

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

Trivial, isn't it?

- A little bit nontrivial in a thermal bath, the photon propagator is modified. In the Coulomb gauge:

$$\langle A^i, A^j \rangle = \frac{1}{\omega^2 - |\vec{k}|^2 - \Pi_T}\left(\delta^{ij} - \frac{k^i k^j}{\vec{k}^2}\right)$$

$$\langle A^0, A^0 \rangle = \frac{1}{|\vec{k}|^2 - \frac{|\vec{k}|^2}{\omega^2 - |\vec{k}|^2}\Pi_L}, \quad 4 \text{ momentum} \quad q = (\omega, \vec{k})$$

$$\Pi^{\mu\nu} = \Pi_T \sum_{i=1,2} \epsilon_i^{T\mu}\epsilon_i^{T\nu} + \Pi_L \epsilon^{L\mu}\epsilon^{L\nu}$$

Stueckelberg case

- Total absorption rate

$$\Gamma^{\rm abs}_{T,L} = \frac{1}{2\omega}\sum_f |\mathcal{M}_{i\to f+V_{T,L}}|^2$$

$$\sim \sum_f \langle i|J^{\mu\dagger}_{\rm em}|f\rangle\langle f|J^{\nu}_{\rm em}|i\rangle = \langle i|J^{\mu\dagger}_{\rm em}J^{\nu}_{\rm em}|i\rangle$$

Dispersion relation

$$-2{\rm Im}\langle J^{\mu\dagger}_{\rm em}, J^{\nu}_{\rm em}\rangle$$

$$\Pi_T = -\omega^2\Delta\varepsilon_r$$

$$\Pi_L = -(\omega^2 - |\vec{k}|^2)\Delta\varepsilon_r$$

$${\rm Im}\Pi_T \ , \quad {\rm Im}\Pi_L$$

$\Delta\varepsilon_r = \varepsilon_r - 1$ Relative permittivity

Motivations

- Dark matter
  - Dark matter mediator
  - Dark matter itself
  - Sommerfeld enhancement
- Solution to muon g-2 problem
- Why not? Completely natural theory.

Origins of mass

- Massive $U(1)$ gauge theory

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

Would-be Goldstone

- In this talk, $m_V < 1 \ \mathrm{keV}$.

Origins of mass

- Massive $U(1)$ gauge theory

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

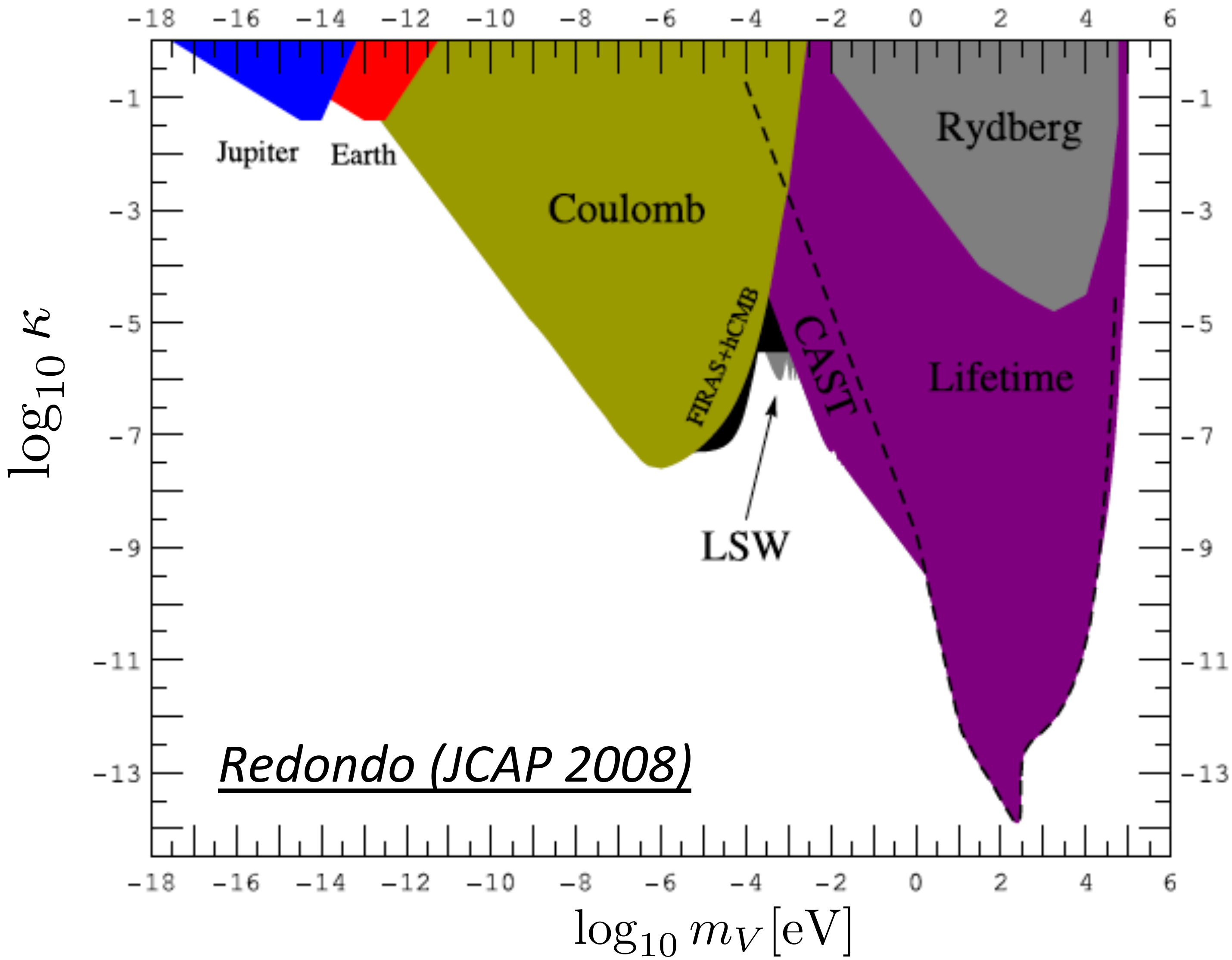
Would-be Goldstone

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

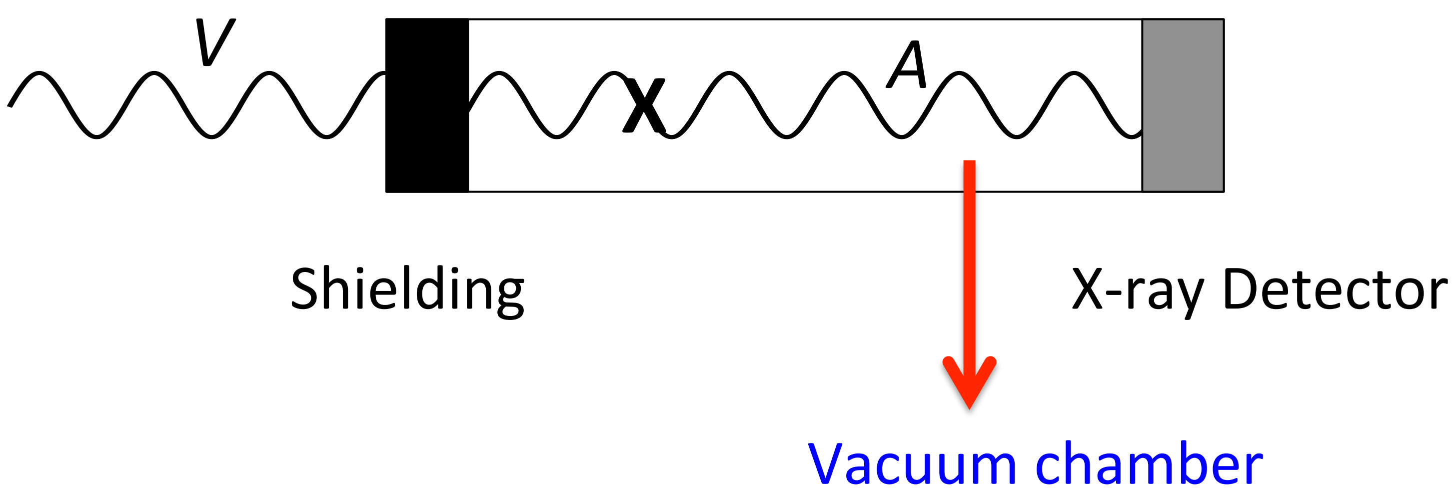
Outline

- What is dark photon?
  - Lagrangian
  - Origin of mass
    - Stueckelberg case and Higgsed case
- Stellar constraints
  - Stuekelberg case and Higgsed case
- Direct detection
  - Stuekelberg case and Higgsed case
- Summary

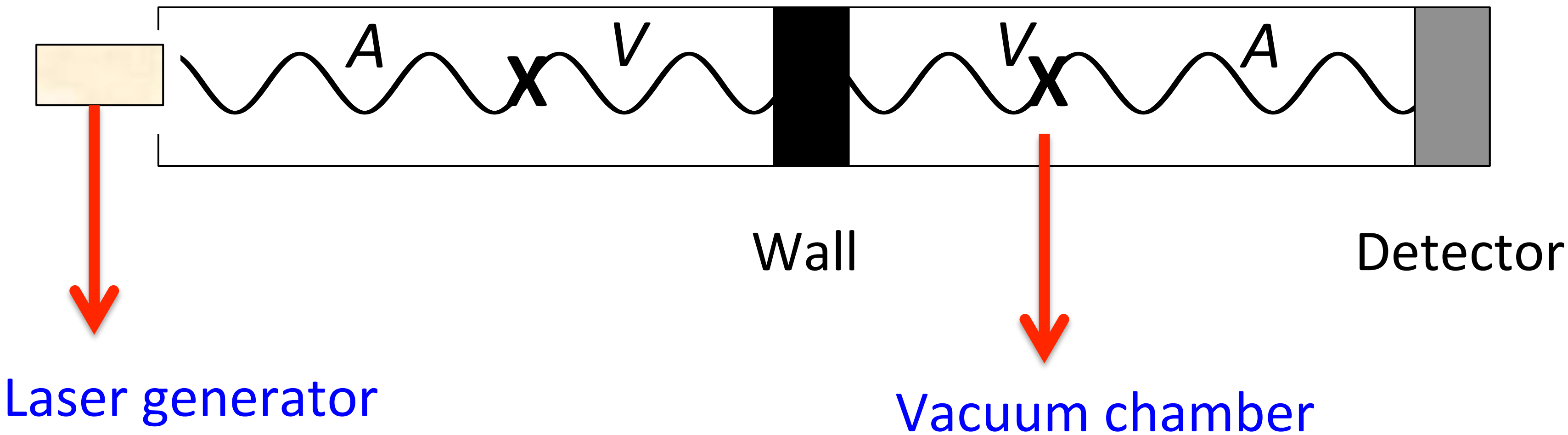
Previous results



CAST experiment



Light shining through the wall (LSW)



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Motivations

- Dark matter
  - Dark matter mediator
  - Dark matter itself
  - Sommerfeld enhancement
- Solution to muon g-2 problem
- Why not? Completely natural theory.
- We found the literature was incorrect. The stellar constraints and detecting methods are completely changed.

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 the EW breaking ,

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

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^2 - \frac{1}{4} V_{\mu\nu}^2 - \frac{1}{2}\kappa F_{\mu\nu} V^{\mu\nu} + e A_\mu J^\mu_{\text{em}} \ .$$

Origins of mass

- Massive $U(1)$ gauge theory

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

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

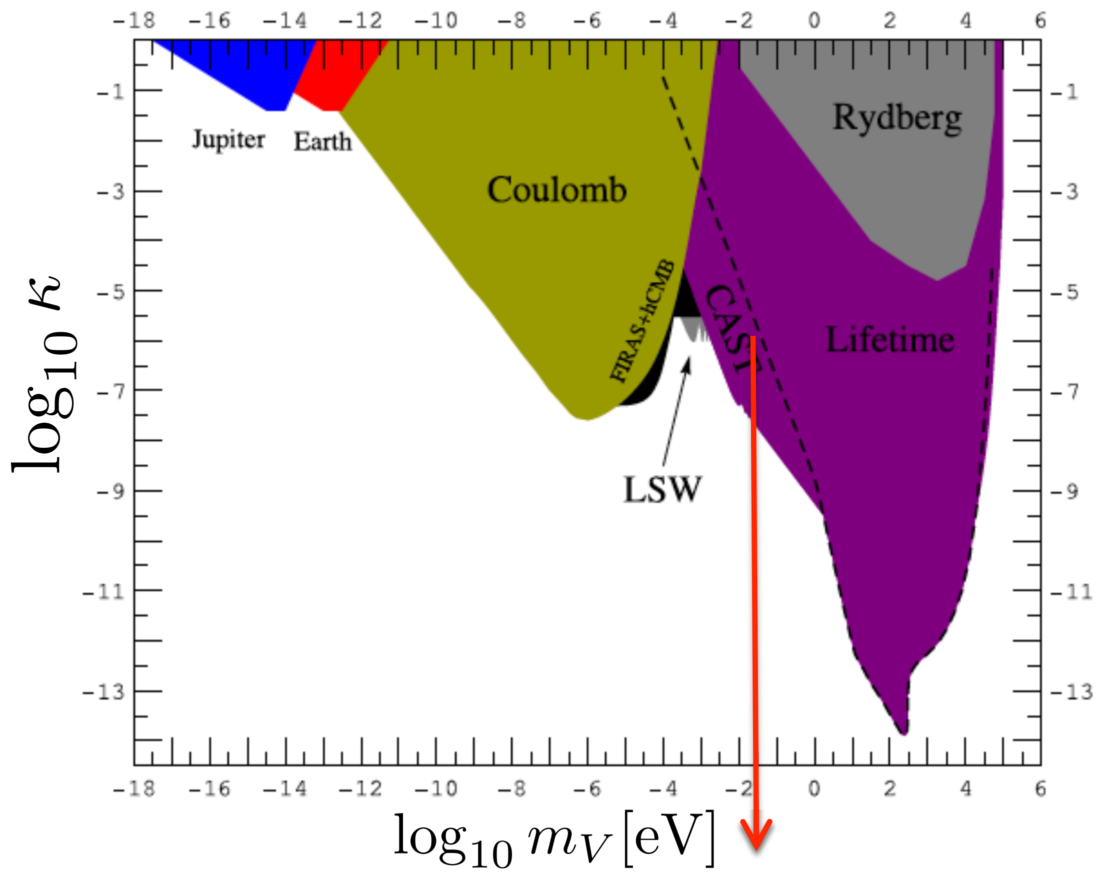
$$\mathcal{L}_{\rm mass} = \frac{1}{2} m_V^2 V_\mu^2$$

Higgsed case

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

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

Previous results



Is this right?

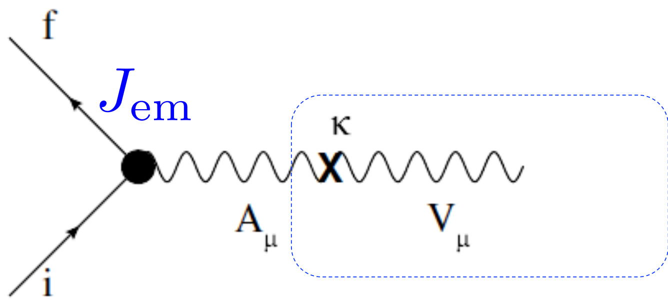
NO!

Redondo (JCAP 2008)

$$\kappa \sim m_V^{-2} \longrightarrow \Gamma \sim m_V^4$$

Production of dark photon

- Matrix element:



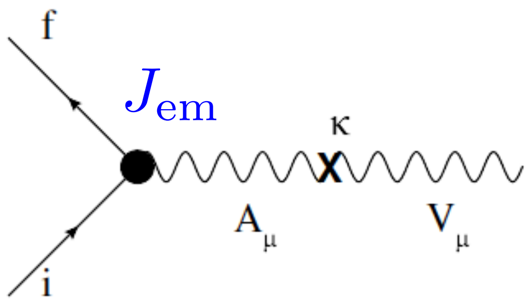
$$-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} \to \kappa A_\nu \partial_\mu V^{\mu\nu} \xrightarrow{\text{E.O.M}} \kappa m_V^2 A_\nu V^\nu$$

- Production rate: $\Gamma \sim \kappa^2 m_V^4 \quad ?$

In the case m_V << the typical energy scale of the process the production rate is suppressed by $m_V{}^4$.

Production of dark photon

- Matrix element:



$$\mathcal{M}_{i\to f+V_{T(L)}} = \kappa m_V^2 \left[eJ_{\mathrm{em}\mu}\right]_{fi} \langle A^\mu, A^\nu\rangle\, \epsilon_\nu^{T(L)}$$

- Coulomb gauge:

$$\vec{k}\cdot\vec{A} = 0$$

$$\langle A^i, A^j\rangle = \frac{1}{\omega^2 - |\vec{k}|^2 - \Pi_T}\left(\delta^{ij} - \frac{k^i k^j}{\vec{k}^2}\right)$$

$$\langle A^0, A^0\rangle = \frac{1}{|\vec{k}|^2 - \frac{|\vec{k}|^2}{\omega^2 - |\vec{k}|^2}\Pi_L},$$

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

Production of dark photon

- Matrix ele

$$
\begin{aligned}
\mathcal{M}_{i\to f+V_T} &= -\frac{\kappa m_V^2}{m_V^2-\Pi_T}[eJ^\mu_{\rm em}]_{fi}\epsilon^T_\mu \ , \\
\mathcal{M}_{i\to f+V_L} &= \frac{\kappa m_V^2}{m_V^2-\Pi_L}\frac{m_V^2}{|\vec{k}|^2}[eJ^0_{\rm em}]_{fi}\epsilon^L_0 \ .
\end{aligned}
$$

Production of dark photon

- Matrix elements:

$$\mathcal{M}_{i\to f+V_T} = -\frac{\kappa m_V^2}{m_V^2-\Pi_T}[eJ^\mu_{\rm em}]_{fi}\epsilon^T_\mu \ ,$$

$$\mathcal{M}_{i\to f+V_L} = \frac{\kappa m_V^2}{m_V^2-\Pi_L}\frac{m_V^2}{|\vec{k}|^2}\boxed{[eJ^0_{\rm em}]_{fi}\epsilon^L_0 \ . \longrightarrow -\frac{|\vec{k}|^2}{m_V^2}J^\mu_{\rm em}\epsilon^L_\mu}$$

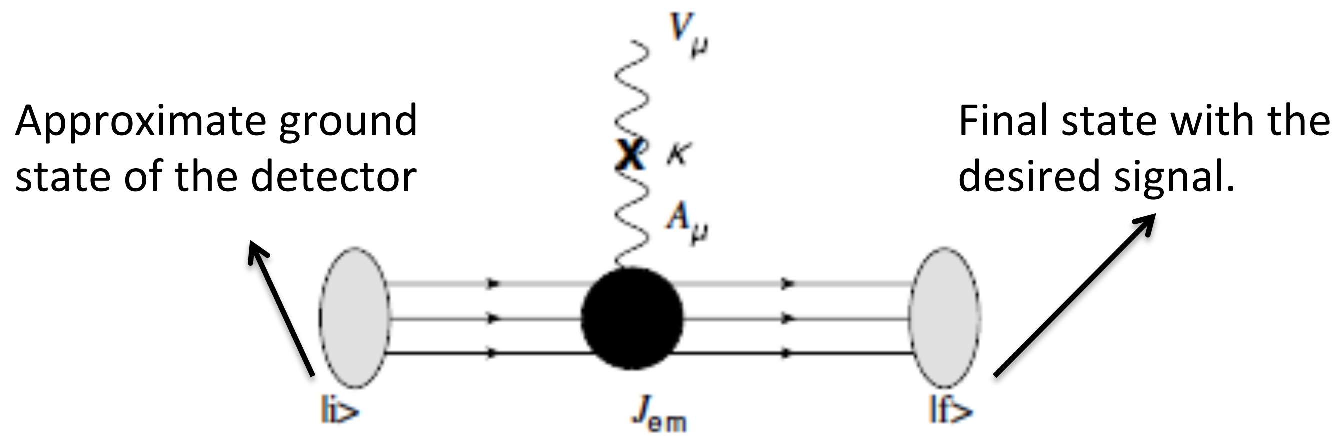
C.C. and E.O.M

$k_\mu J^\mu = 0 \ , k_\mu \epsilon^\mu = 0$

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

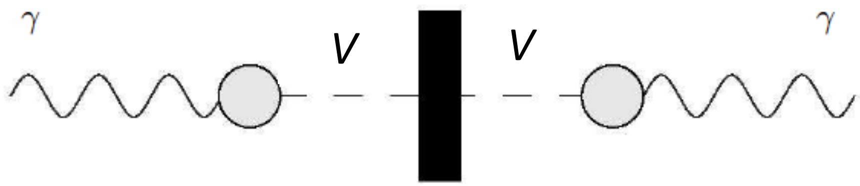
Total absorption rate

- Dark photon interacts with the material through the mixing with photon



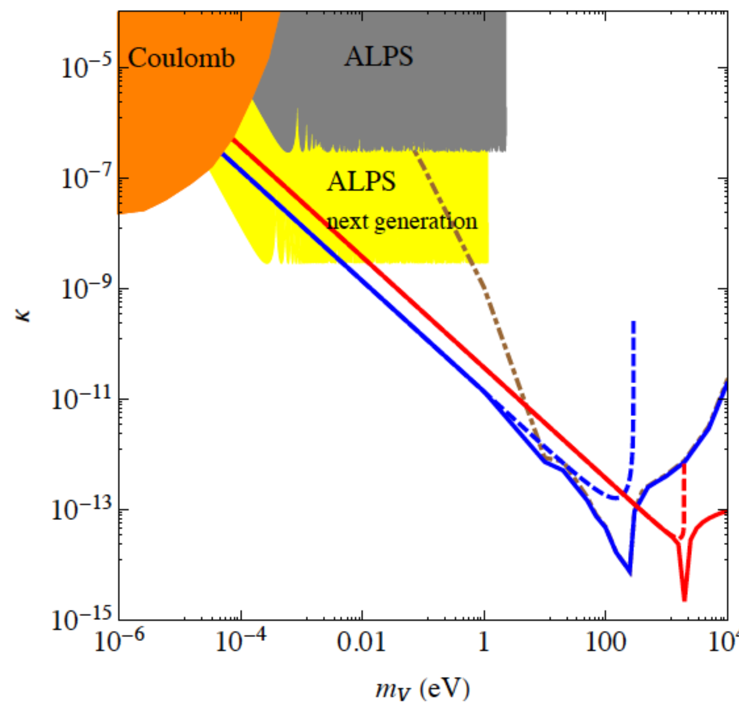
$$\mathcal{M}_{i\to f+V_{T,L}} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}} \langle f|[eJ^\mu_{\rm em}]|i\rangle \epsilon_\mu^{T,L}$$

- LSW experiments (ALPS collaboration)
  - Invented to search both axions and dark photons



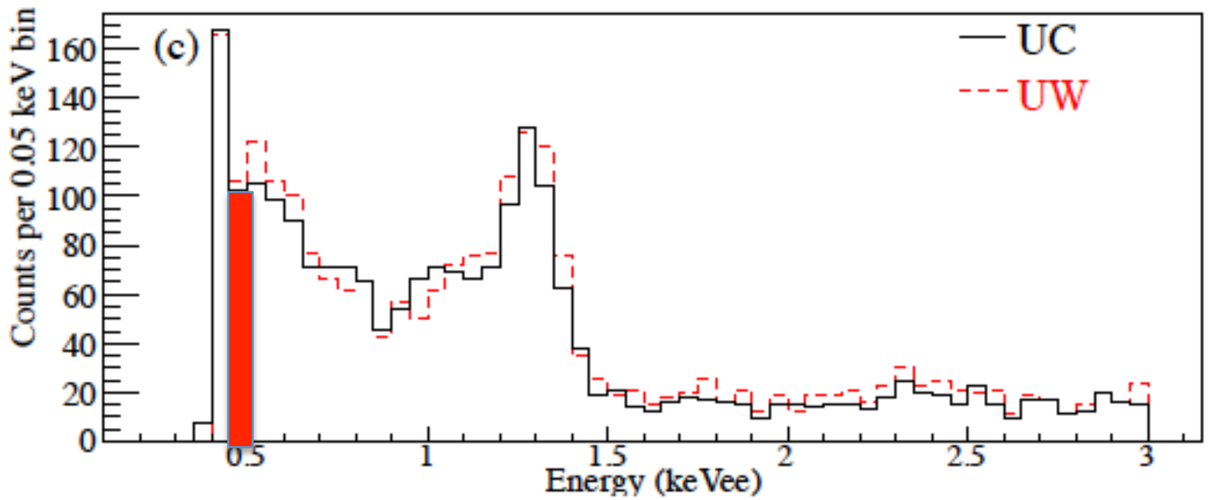
  - The current best ALPS constraints deeply inside the exclusion region of new stellar constraints.

  - A large part of the sensitivity region of the next generation is also excluded.



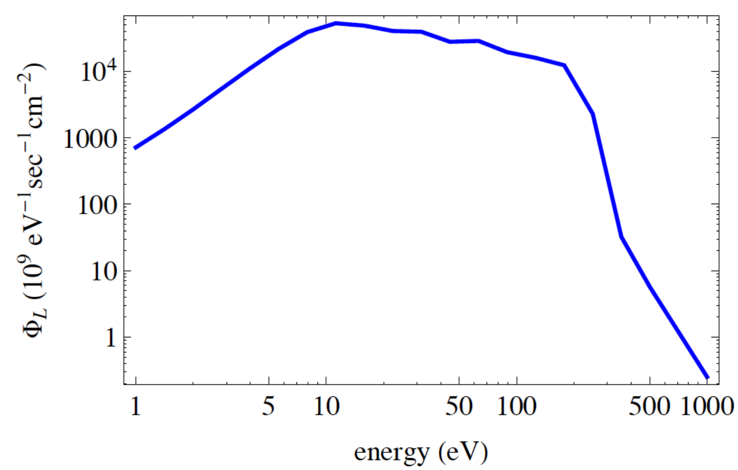
Stueckelberg case

- CoGeNT data available from 400 eV.



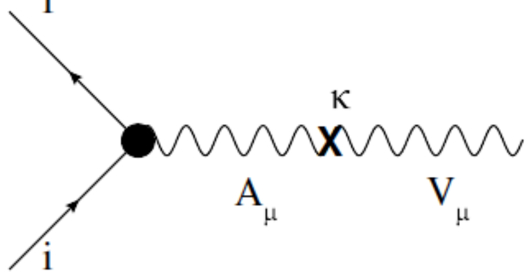
- $\mathrm{Br} \approx 1$

  Photo-ionization dominates.



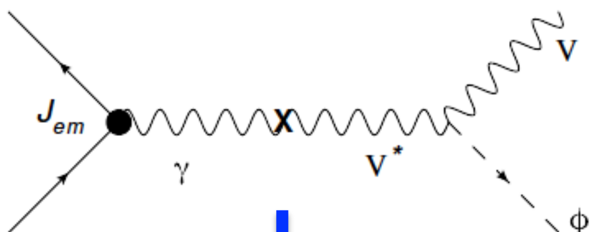
Higgsed case

- Processes in the Stueckelberg case are still there:



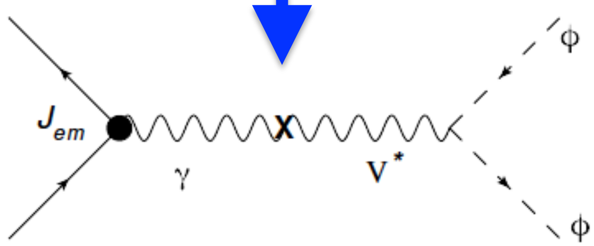
$$\sim m_V^2 \ (L), \ m_V^4 \ (T)$$

- Higgs-strahlung



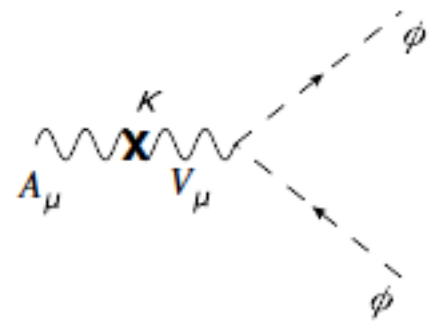
$$m_V^2 \ll \omega^2$$

Goldstone equivalence theorem

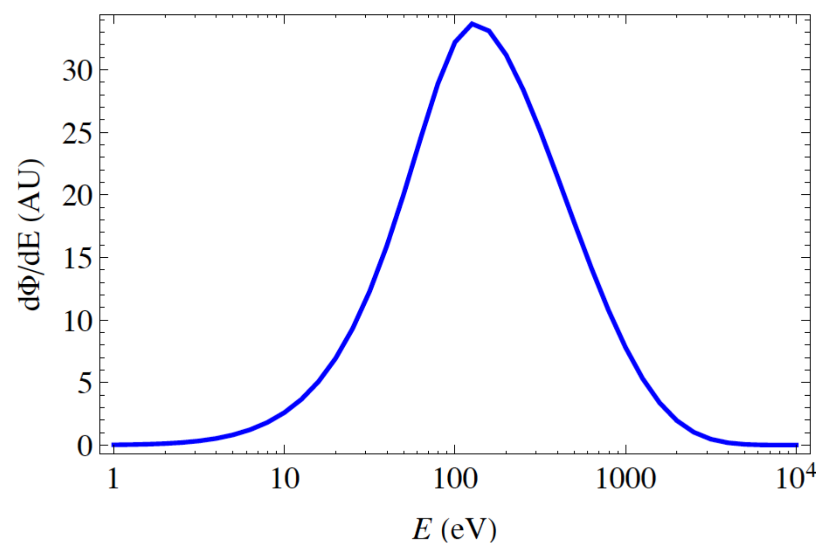


$$\sim m_V^0$$

Higgsed case

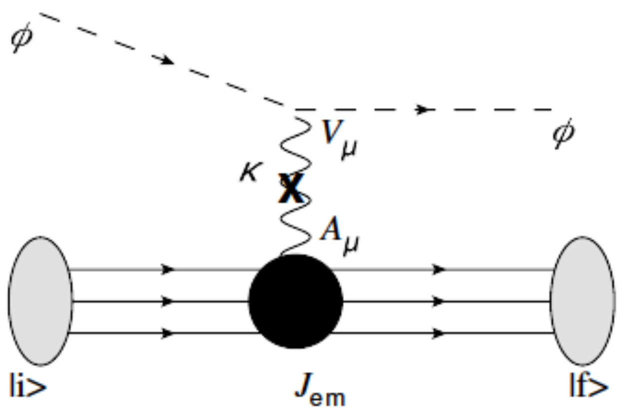


- The solar flux
  - The dominant contribution is from the decay of transverse photon into dark Higgs.
  - Temperature of the Sun can be as high as 1 keV.
  - Include the XENON10 data and CoGeNT data to keV scale.



Higgsed case

- Dark Higgs-strahlung process dominates in small m_V region, using Goldstone equivalence theorem:



- Wave functions of different orbits, effective charges ...

- The diagram is exactly the same as in deep inelastic scattering. Why not using the same trick to calculate the total absorption rate first.

Higgsed case

- Inelastic scattering of dark Higgs

Collinear divergence regularized by the medium effect.

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

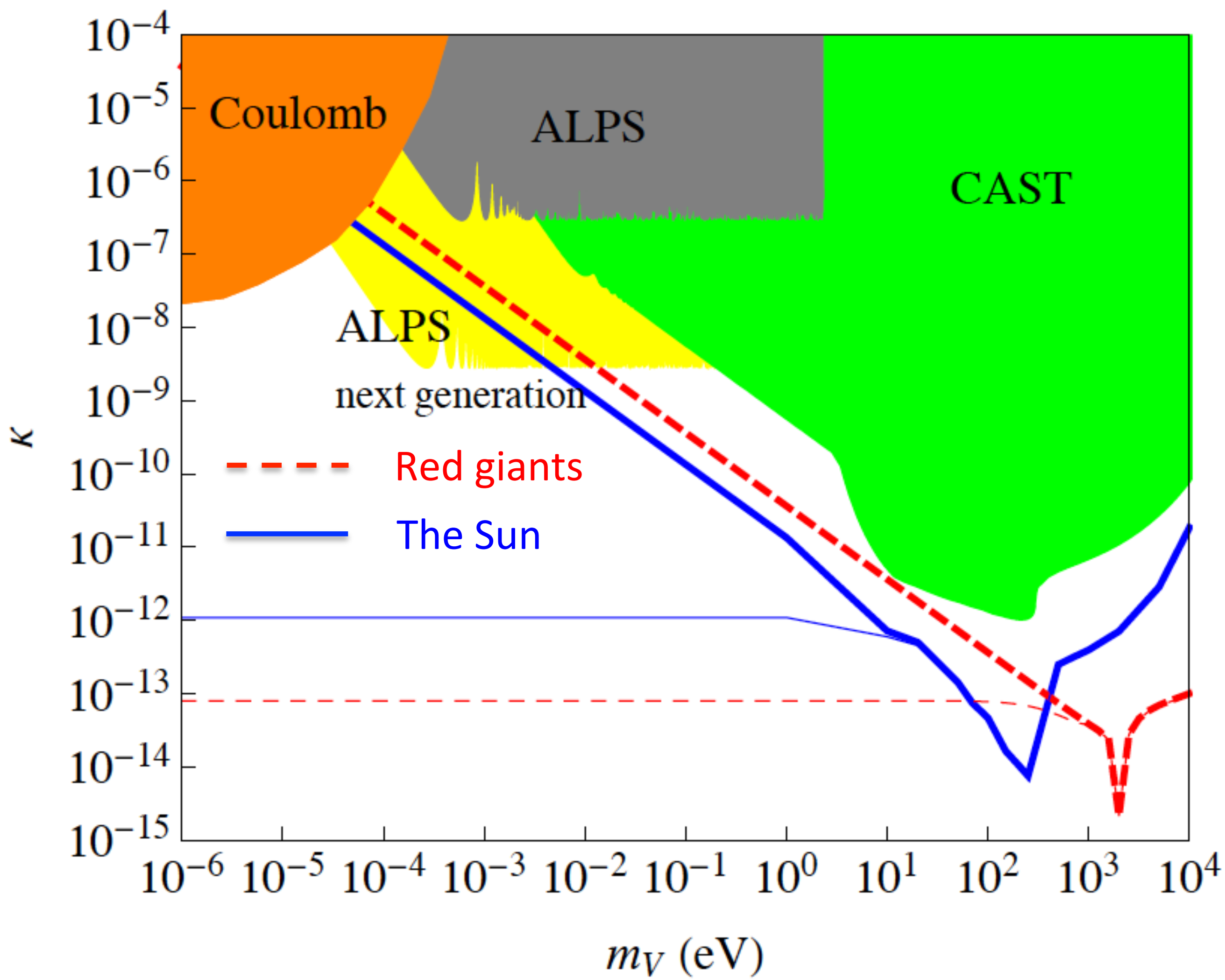
Energy injected into the medium

Energy of incoming Higgs

Higgsed case

- Issue with ε_r
  - Lorentz symmetry is broken by the medium to the SO(3) rotation symmetry.
  - In general, $\varepsilon_r = \varepsilon_r(\omega, |\vec{k}|^2)$.
  - However, the dependence on k^2 is suppressed if $\dfrac{|\vec{k}|^2}{\omega m_e} \ll 1$.
  - This is always true in our situation.

Stellar constraints



$e' = 0.1$