

COSPA 2013

Dark Matter Detectors as Dark
Photon Helioscopes

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In collaboration with Maxim Pospelov and Josef Pradler

[PLB 725 \(2013\) 190, arXiv:1302.3884](#)

[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

- SM as part of the low energy effective theory

$$L_{\text{eff}} = L_{\text{SM}} + L_{\text{dark matter}} + L_{\text{neutrino}} + \dots$$

- Higher dimensional operators: New physics effects are suppressed by large scales.
- Marginal operators:

$\bar{L}HN$ Neutrino mass

$|H|^2 S^2$ Higgs portal

$B^{\mu\nu}V_{\mu\nu}$ Kinetic mixing

→ Dark photon

Motivations

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

$\bar{L}HN$ Neutrino mass

$|H|^2 S^2$ Higgs portal

$B^{\mu\nu} V_{\mu\nu}$ Kinetic mixing


Dark photon

Why dark photon?

- Related to the dark sector
- 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!)

Why dark photon?

- Related to the dark sector
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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.
- We should use dark matter detector to detect sub-keV dark photon instead of previous proposed ones.

The Lagrangian

The Standard Model

Extra vector field

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

$$G^{\alpha\mu\nu} \quad W^{i\mu\nu} \quad B^{\mu\nu} \quad V^{\mu\nu}$$



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



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

Below EW breaking ,

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

Origins of mass

- Massive $U(1)$ gauge theory

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

- 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

- Lagrangian

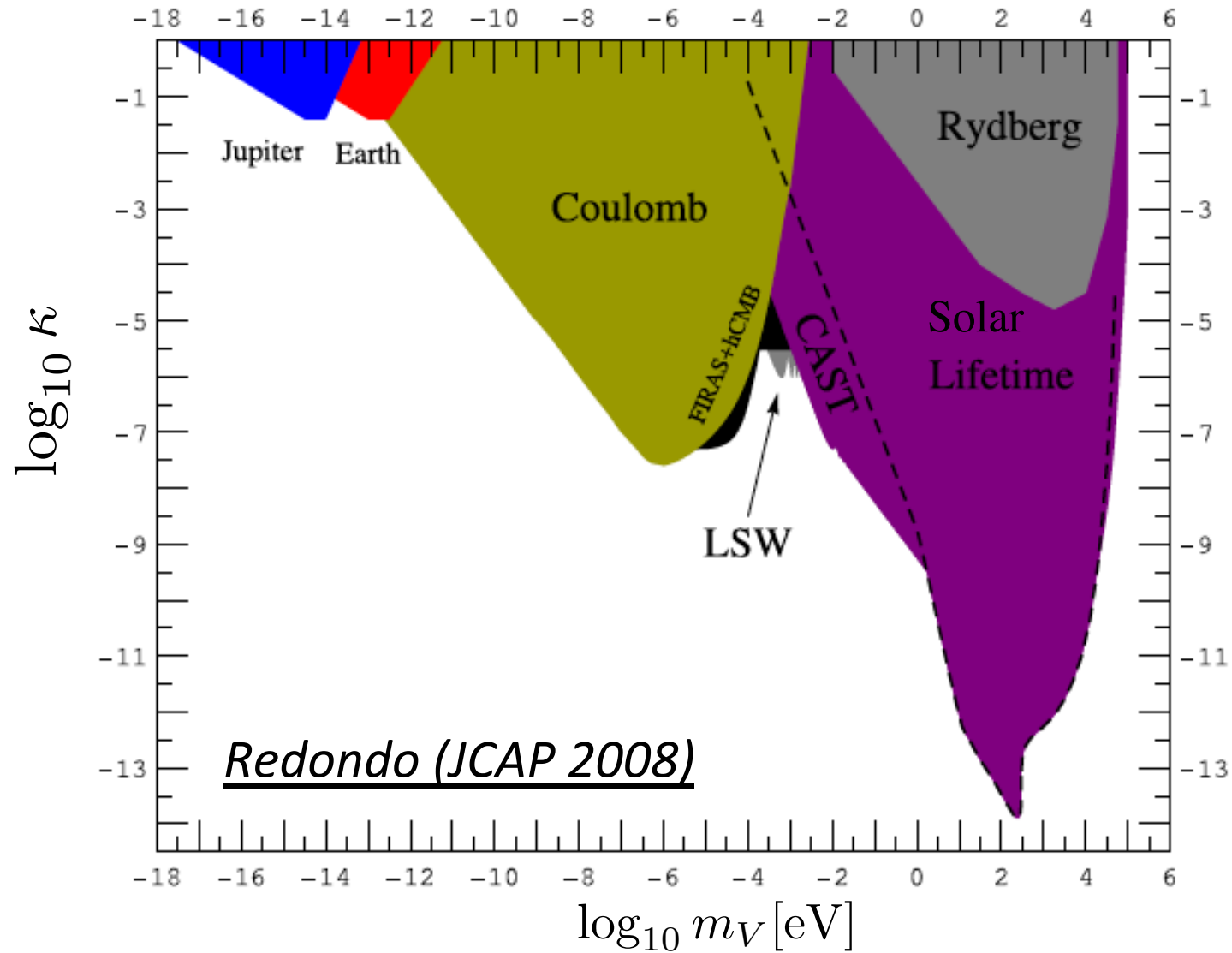
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu^2 + eJ_{\text{em}}^\mu A_\mu$$

- Only two unknown parameters

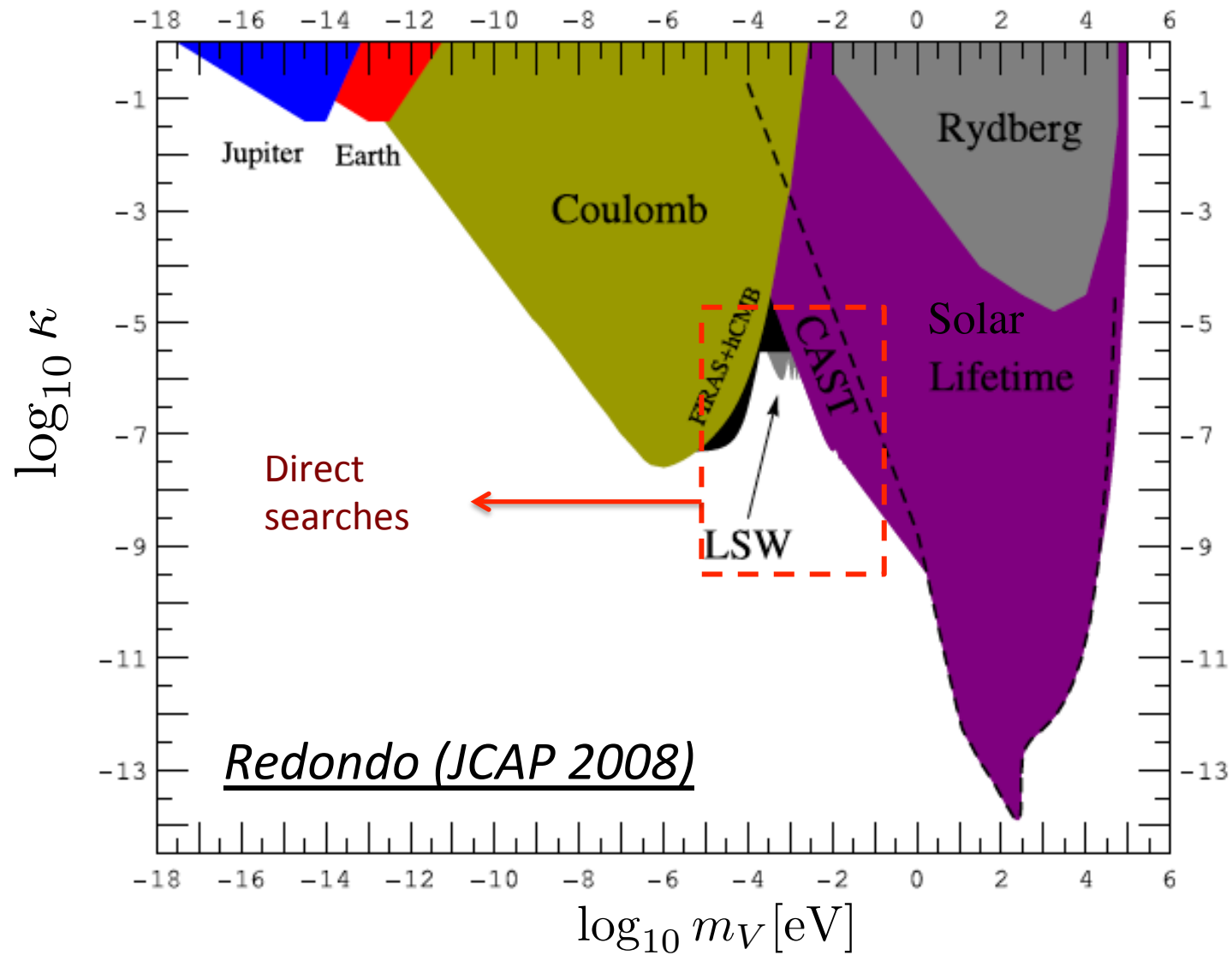
κ and m_V

- A lot of studies have already been done.

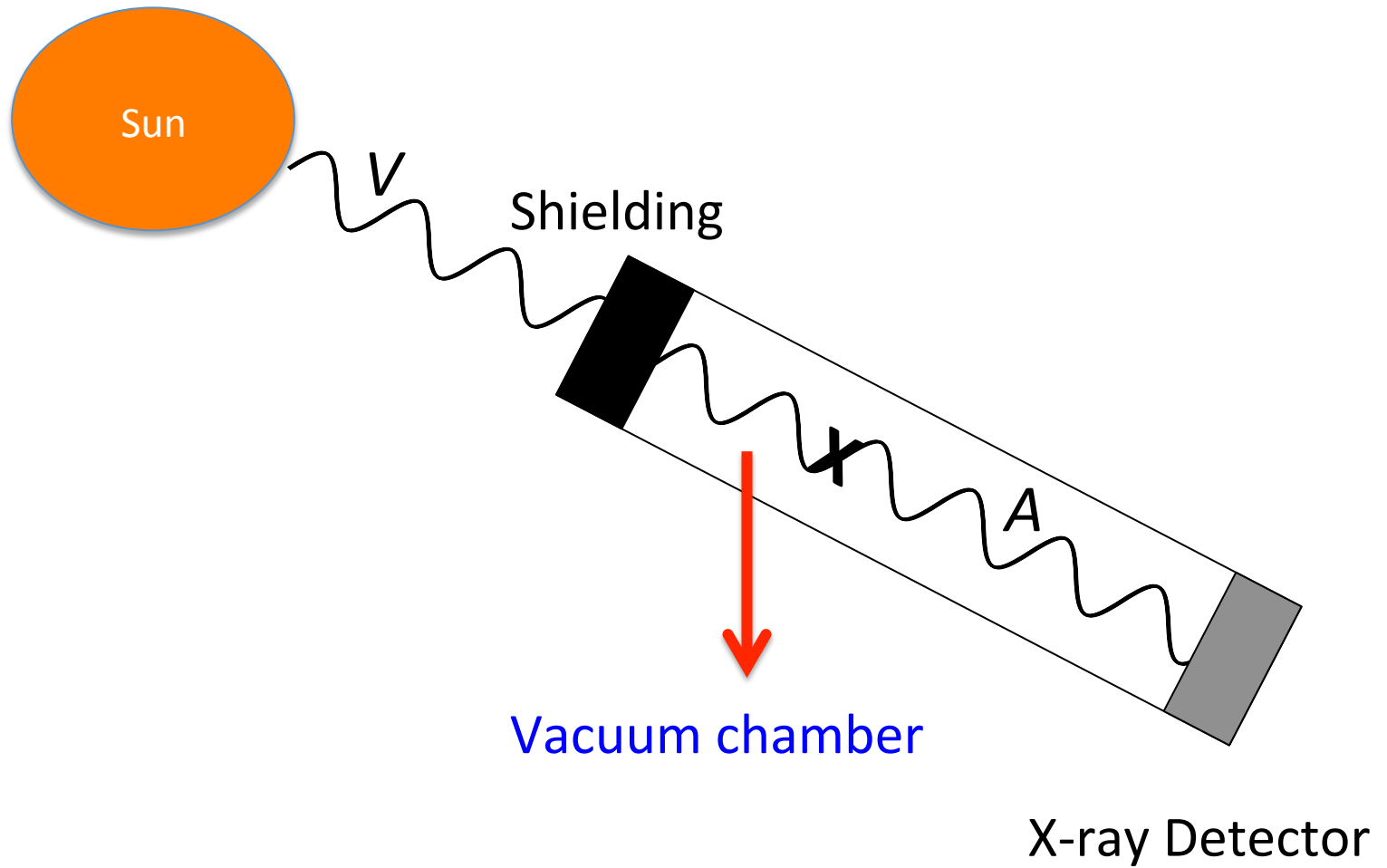
Previous results



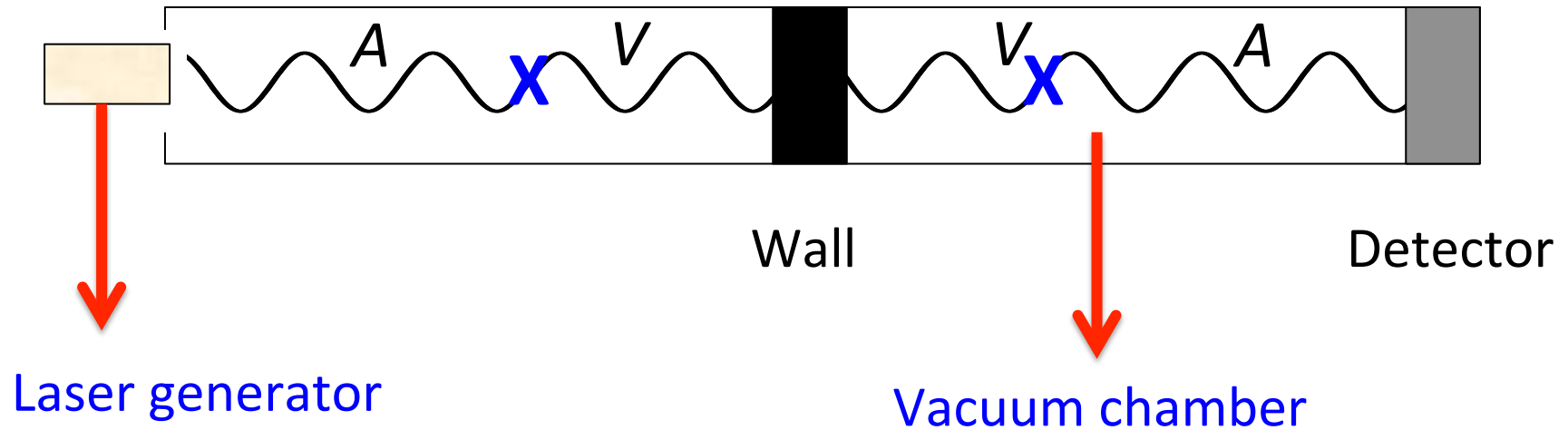
Previous results



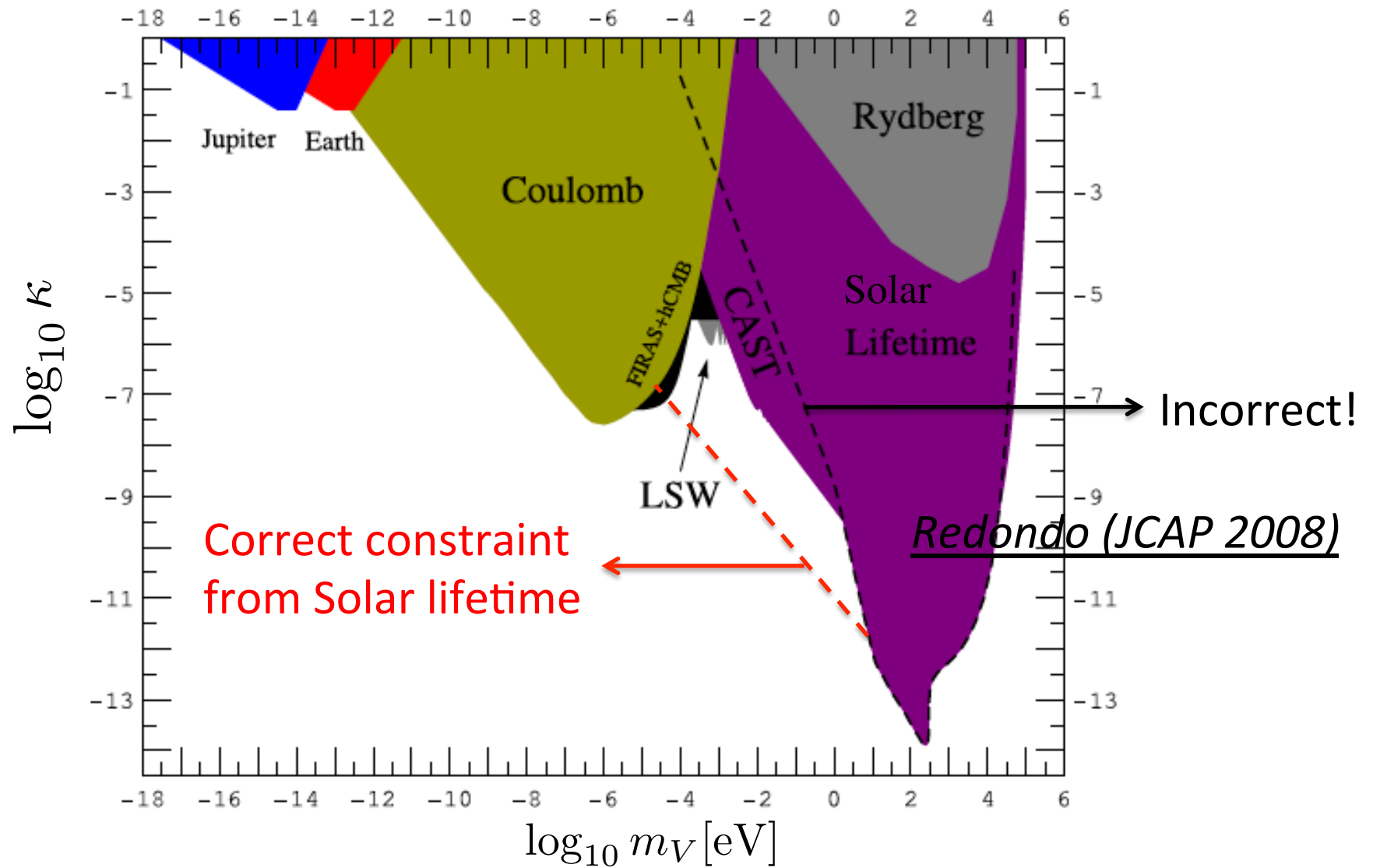
CAST experiment



Light shining through the wall (LSW)



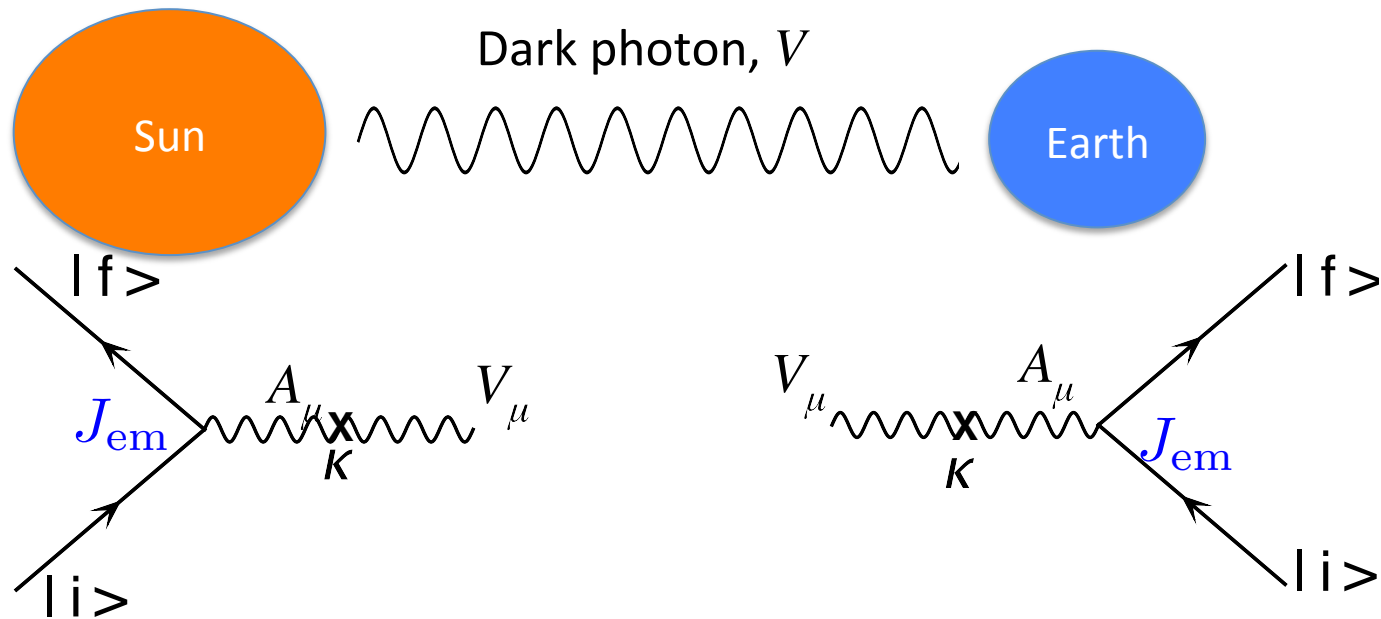
Previous results



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 (Dark matter detector)**
- Higgsed case
- Summary

Stueckelberg case



- Dark radiation effects the evolution of the stars.

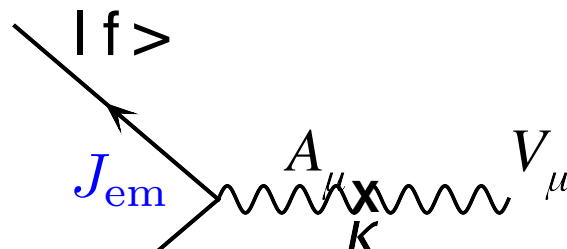
$$P_{\text{dark}} \leq 0.1 \times P_{\text{luminous}}$$

Gondolo and Raffelt (PRD 2009)

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

Production of dark photon

- Matrix element (homework of QFT101)



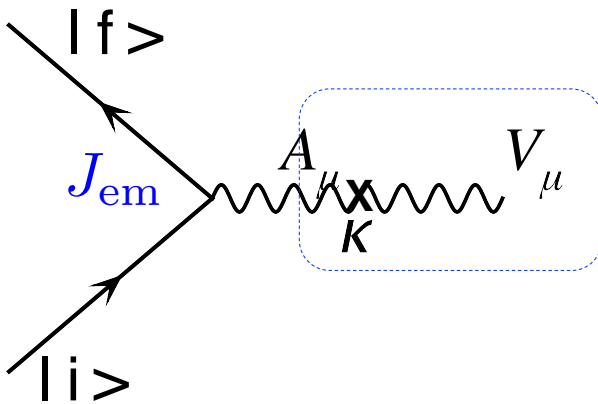
A_μ V_μ
 K

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

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

Production of dark photon

- Matrix element



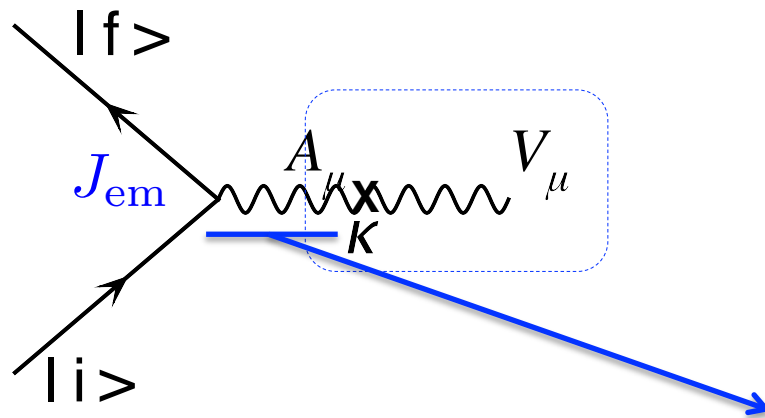
$$-\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} \rightarrow \kappa A_\nu \partial_\mu V^{\mu\nu}$$

E.O.M

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

Production of dark photon

- Matrix element



In the Feynman gauge:

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

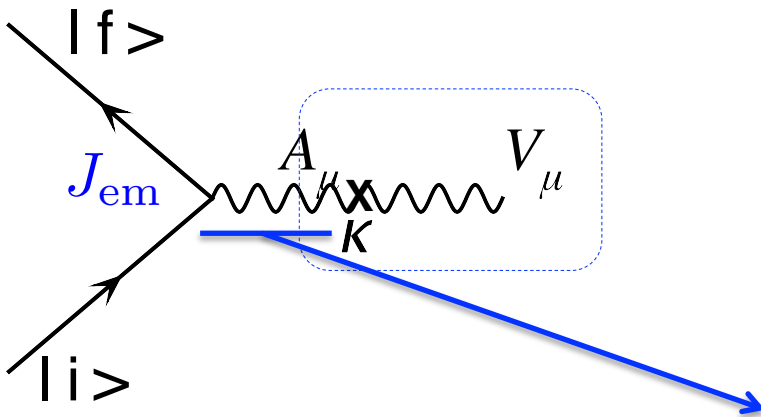
E.O.M

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

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

Production of dark photon

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In the Feynman gauge:

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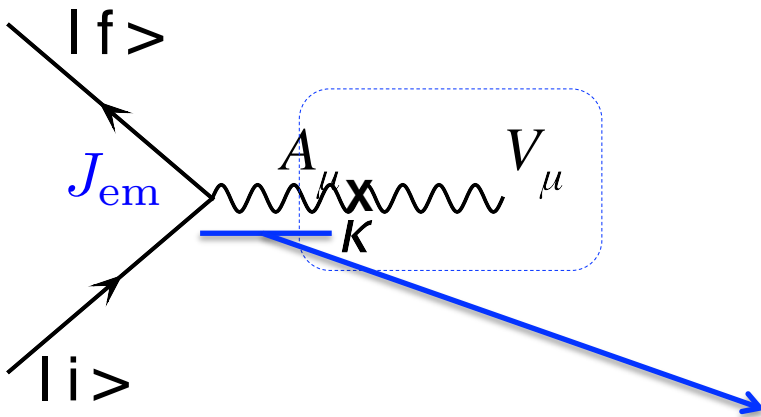


$$\kappa m_V^2 A_\nu V^\nu$$

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

Production of dark photon

- Matrix element



In the Feynman gauge:

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

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

E.O.M

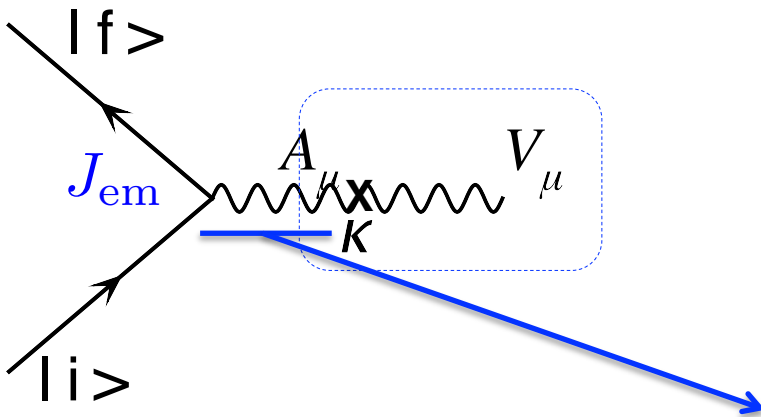
$$\kappa m_V^2 A_\nu V^\nu$$

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

Plasma effect

Production of dark photon

- Matrix element



In the Feynman gauge:

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

E.O.M

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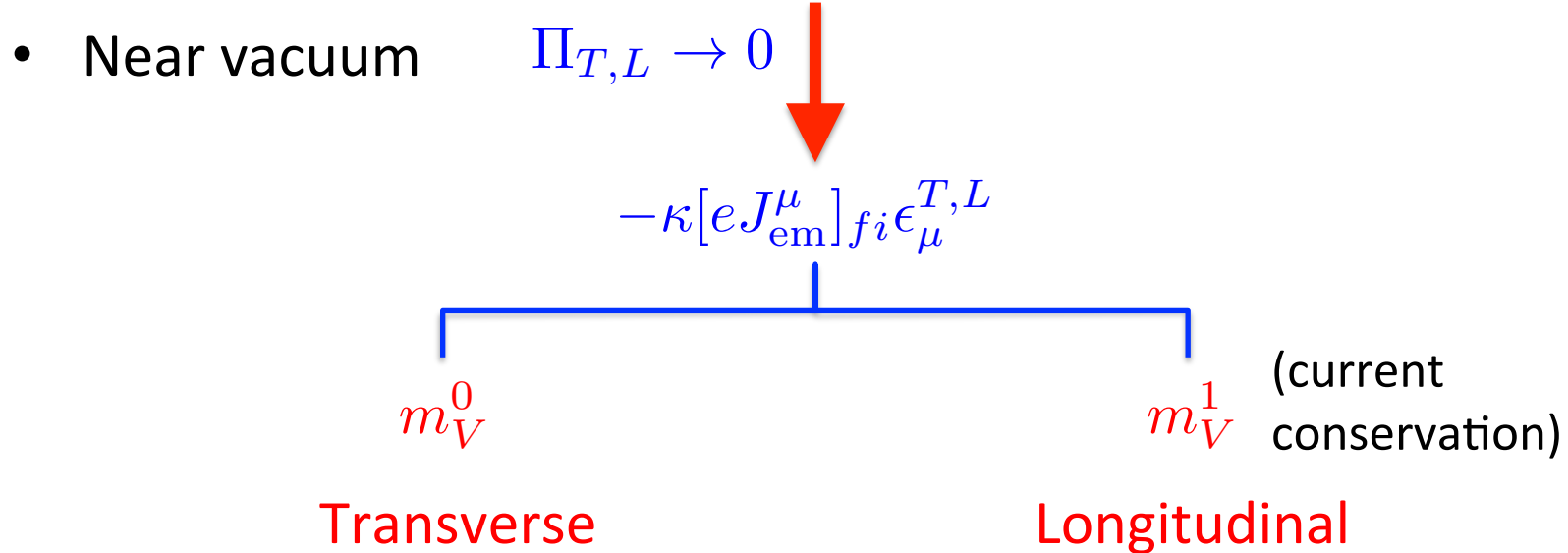
Plasma effect

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

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

Production of dark photon

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



Production of dark photon

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

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

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

- For longitudinal mode

$$J_{\text{em}}^\mu \epsilon_\mu^L \sim m_V \longrightarrow \Pi_L \sim m_V^2 \quad \text{Re}\Pi_L = \omega_p^2 \left(1 - \frac{|\vec{k}|^2}{\omega^2}\right)$$

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

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

Production of dark photon

- Production rate:

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

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

Production of dark photon

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

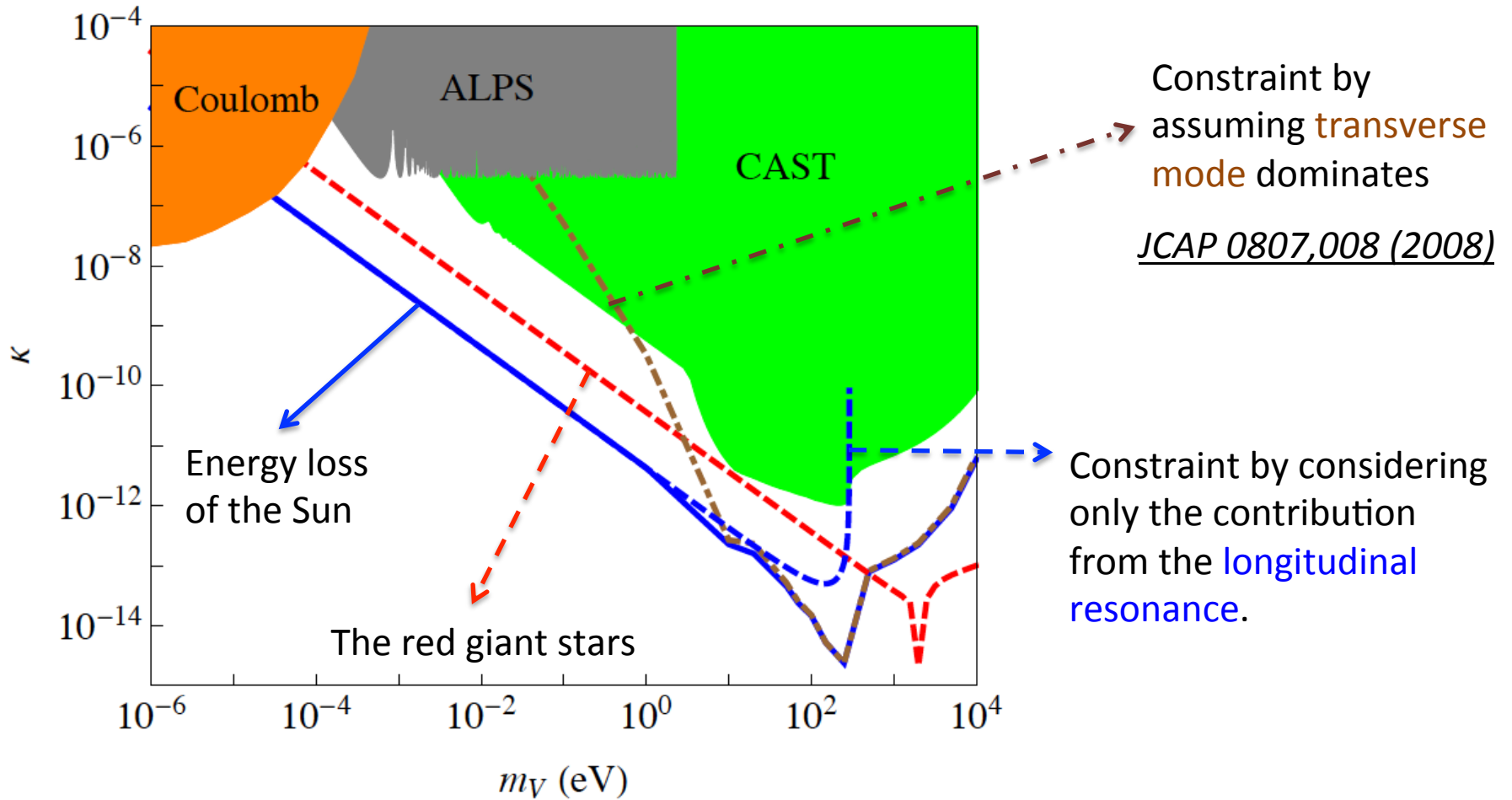
$$\Gamma_L \propto \kappa^2 m_V^2 \omega^{-2}, \text{ both in vacuum and in medium.}$$

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

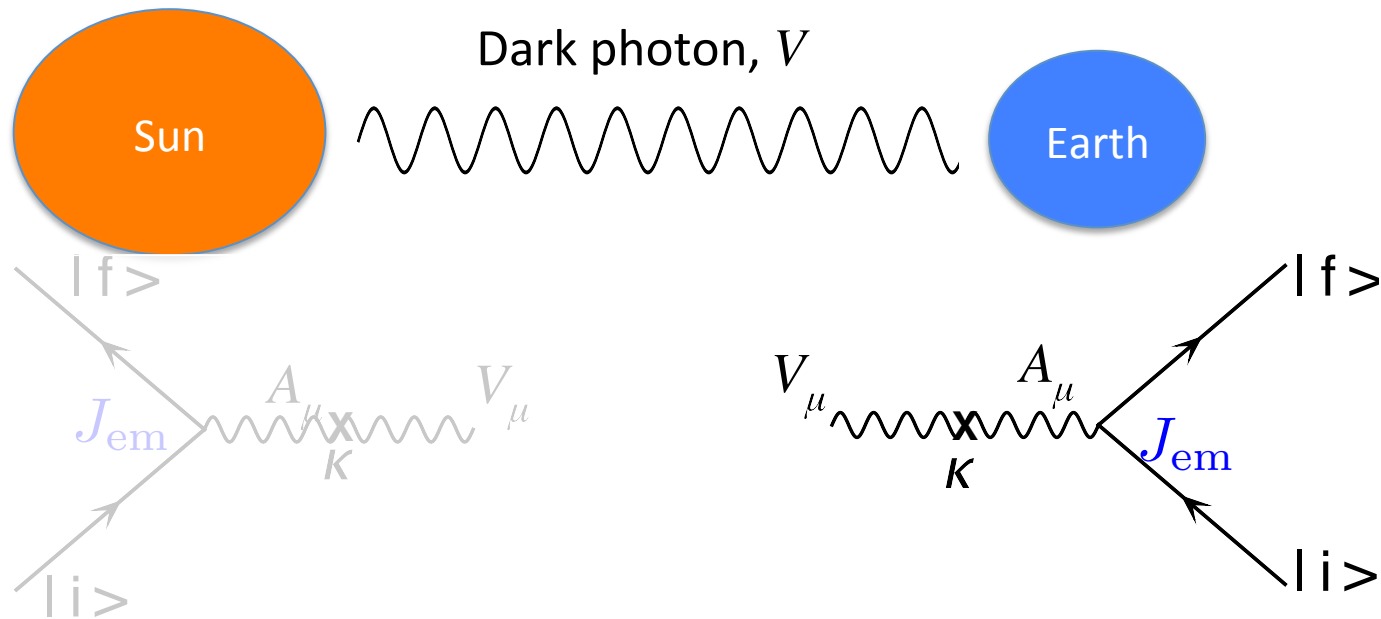
$$\Pi_L = \omega_p^2 - |\vec{k}|^2 \quad \longrightarrow \quad \Gamma_L \propto m_V^4$$

Not correct!

Stellar constraints



Direct detection



- Dark radiation effects the evolution of the stars.

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

Gondolo and Raffelt (PRD 2009)

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

Stueckelberg case

- Signal rate

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

Total absorption rate

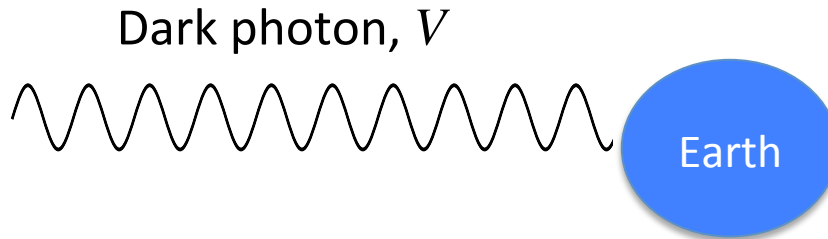
Solar flux

Branching ratio to the desired signal.

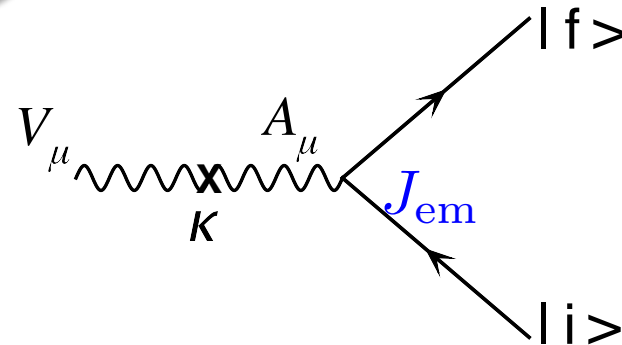
T – mode dominates , $1 \text{ eV} \lesssim m_V \lesssim 300 \text{ eV}$

L – mode dominates , $m_V \ll 1 \text{ eV}$

Total absorption rate



$$\mathcal{M} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}} [e J_{\text{em}}^\mu] f_i \epsilon_\mu^{T,L}$$



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

$$\Delta \epsilon_r = \epsilon_r - 1$$



Relative permittivity

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

Total absorption rate

- Total absorption rate

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

Total absorption rate

- Total absorption rate

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

$$\Gamma_L = \frac{\kappa^2 m_V^2 \text{Im} \epsilon_r}{|\epsilon_r|^2 \omega} \xrightarrow{m_V^2 \gg \omega^2 |\Delta \epsilon_r|} \kappa^2 \omega \text{Im} \epsilon_r$$

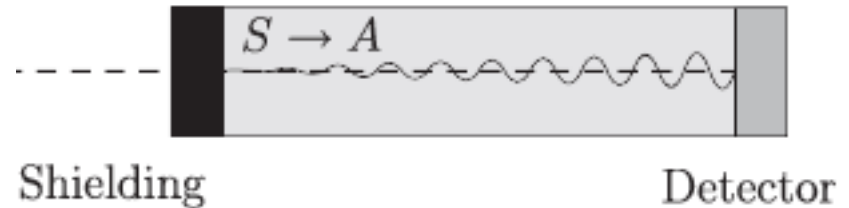
- $\Delta \epsilon_r \propto n_A$, Atom number density

$$- m_V^2 \ll \omega^2 |\Delta \epsilon_r| \quad \Gamma_T \propto n_A^{-1} \quad \Gamma_L \propto n_A$$

$$- m_V^2 \gg \omega^2 |\Delta \epsilon_r| \quad \Gamma_T \propto n_A \quad \Gamma_L \propto n_A$$

Total absorption rate

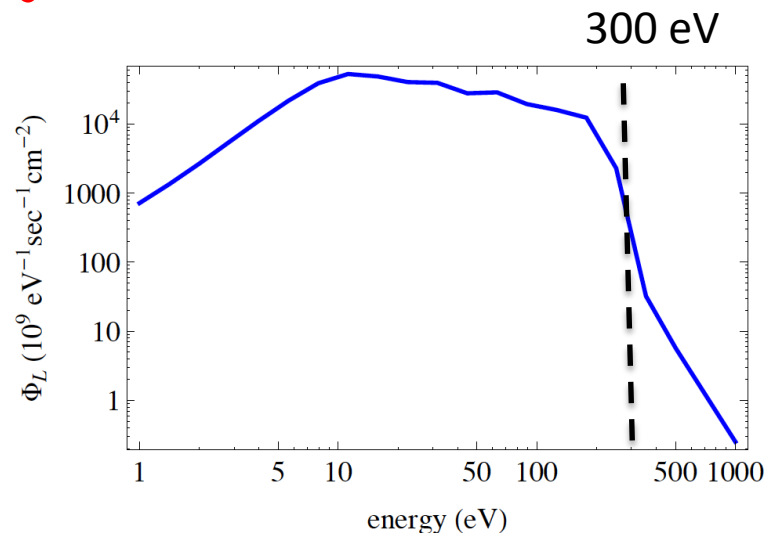
- The old idea based on the **incorrect** result that the **dark flux is dominated by the transverse mode.** *JCAP 0807,008 (2008)*
- $\Gamma_T \propto n_A^{-1}$
- For sub-eV dark photon The effective atom number density should as small as possible.
- CAST experiment
 - Invented to detect axions
 - Shielding + 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, $1 \text{ eV} \lesssim \omega_p \lesssim 300 \text{ eV}$

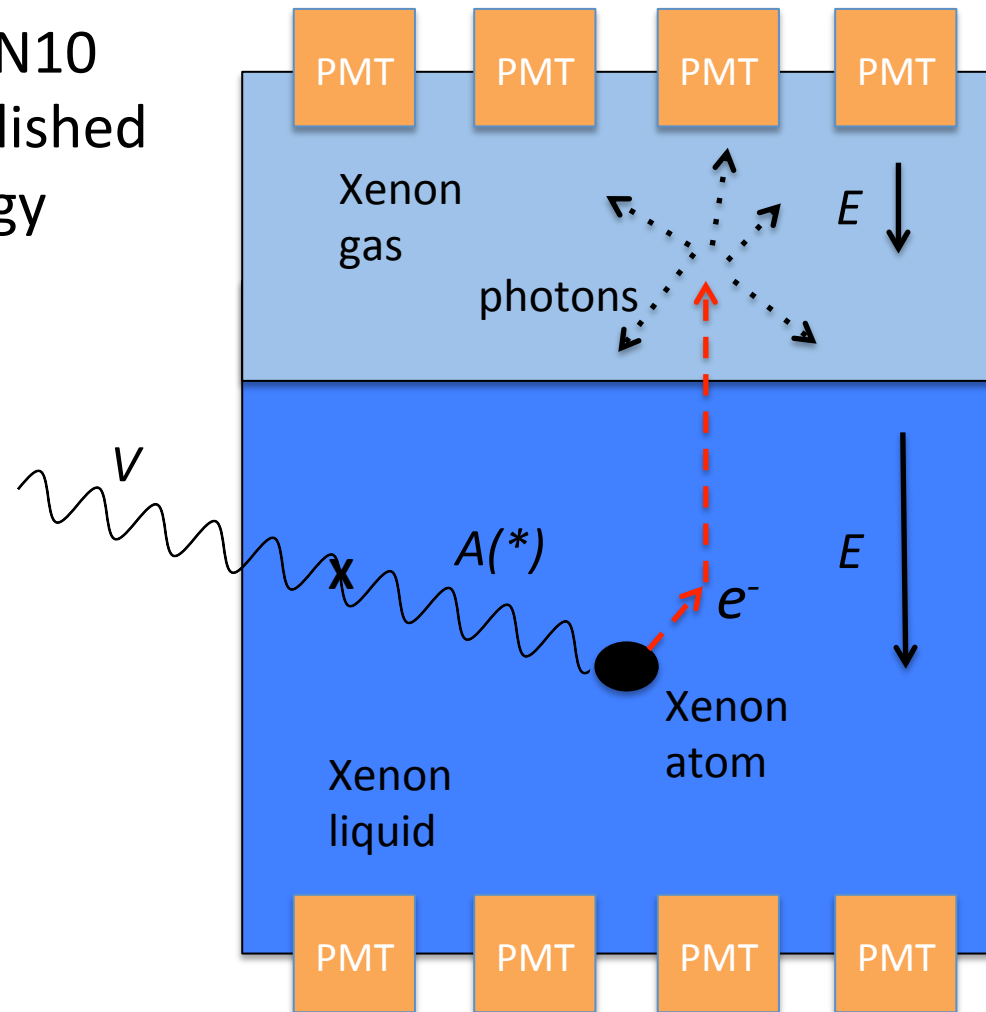
The detector should be able to detect $\sim 100 \text{ eV}$ energy deposition



XENON10 constraint

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

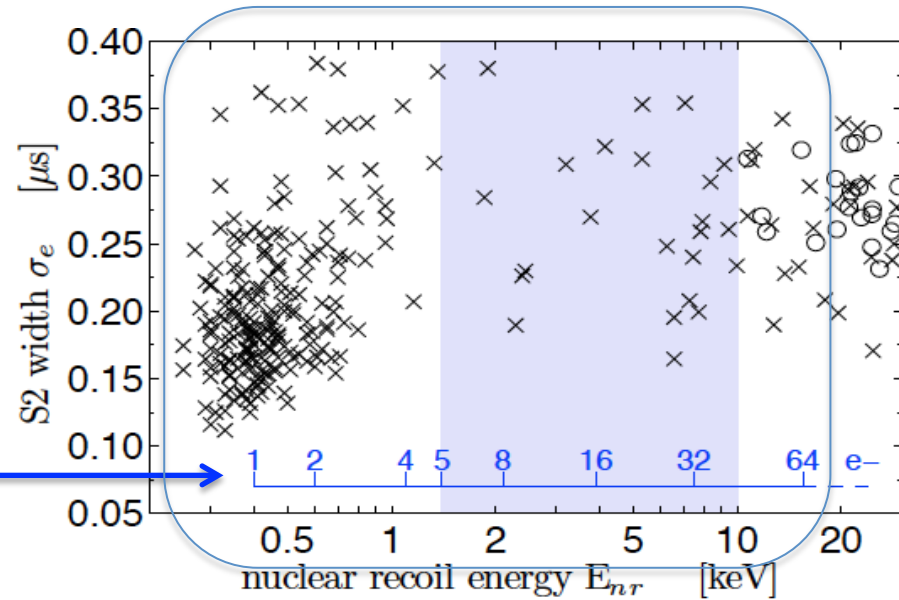
$$1 \text{ eV} \lesssim \omega_p \lesssim 300 \text{ eV}$$



XENON10 constraint

- XENON10

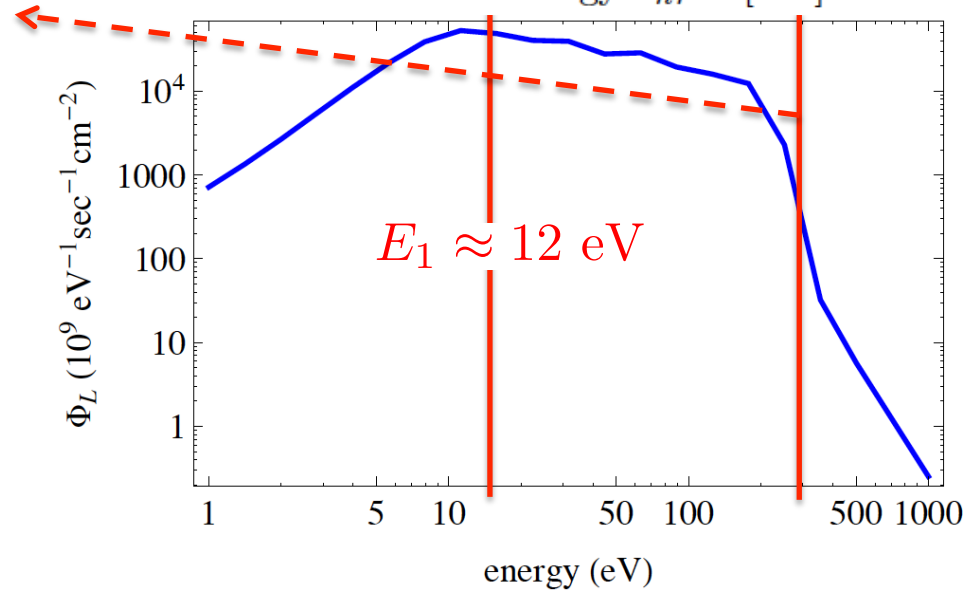
Number of electrons



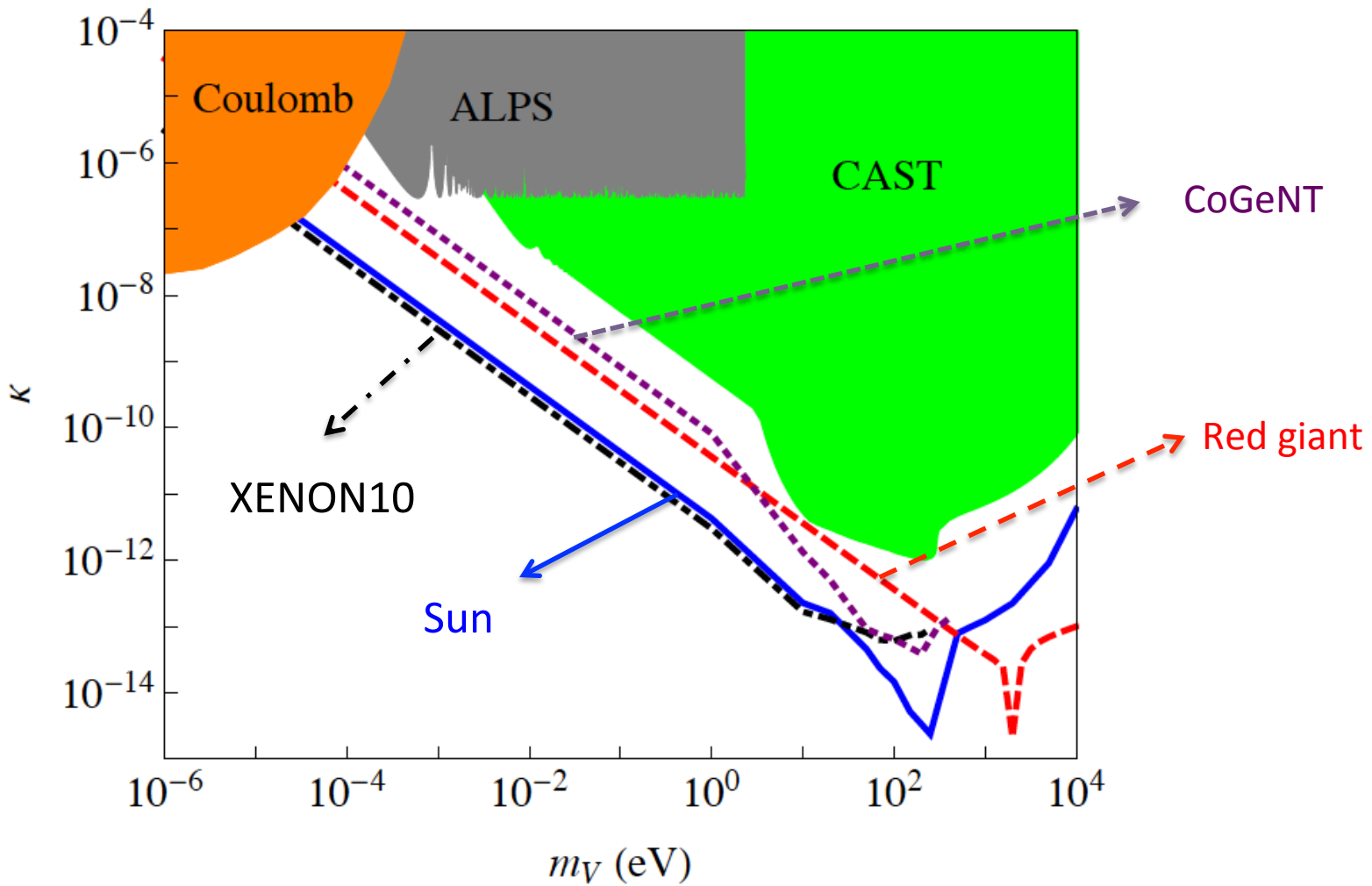
300 eV \sim 25 electrons

- $Br \approx 1$

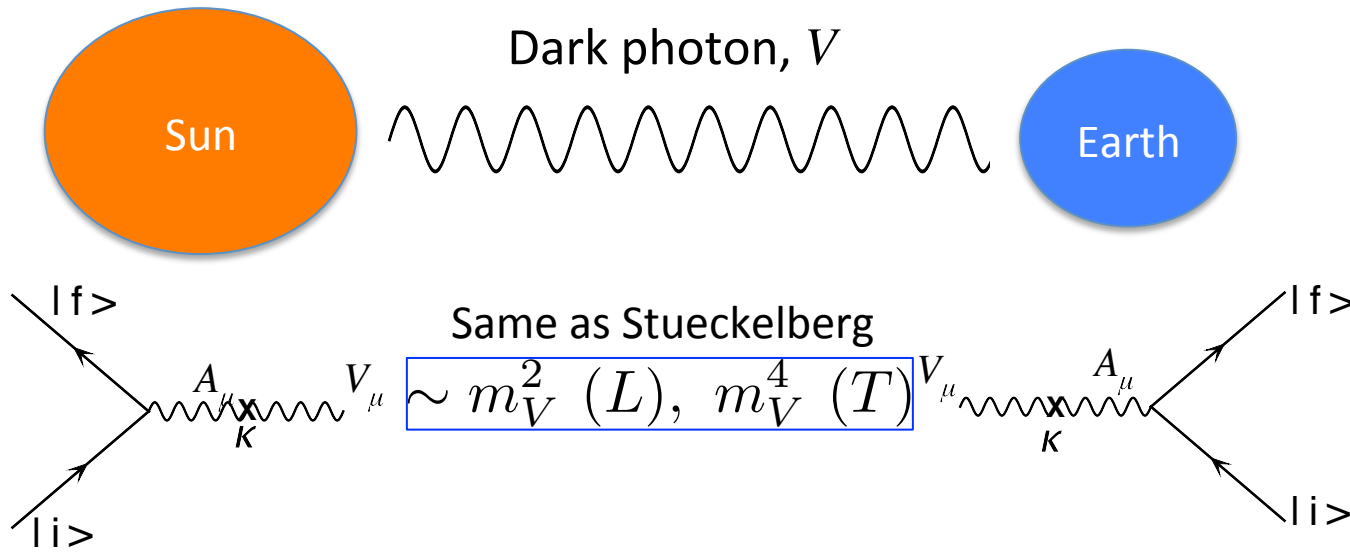
Photo-ionization dominates.



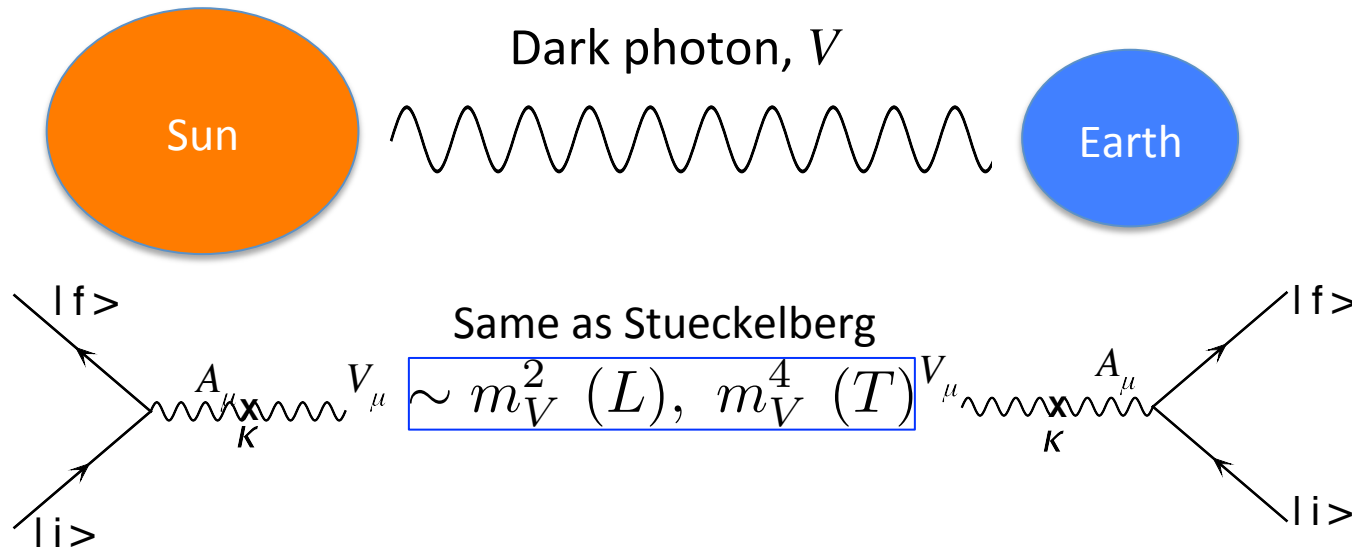
Stueckelberg case



Higgsed case

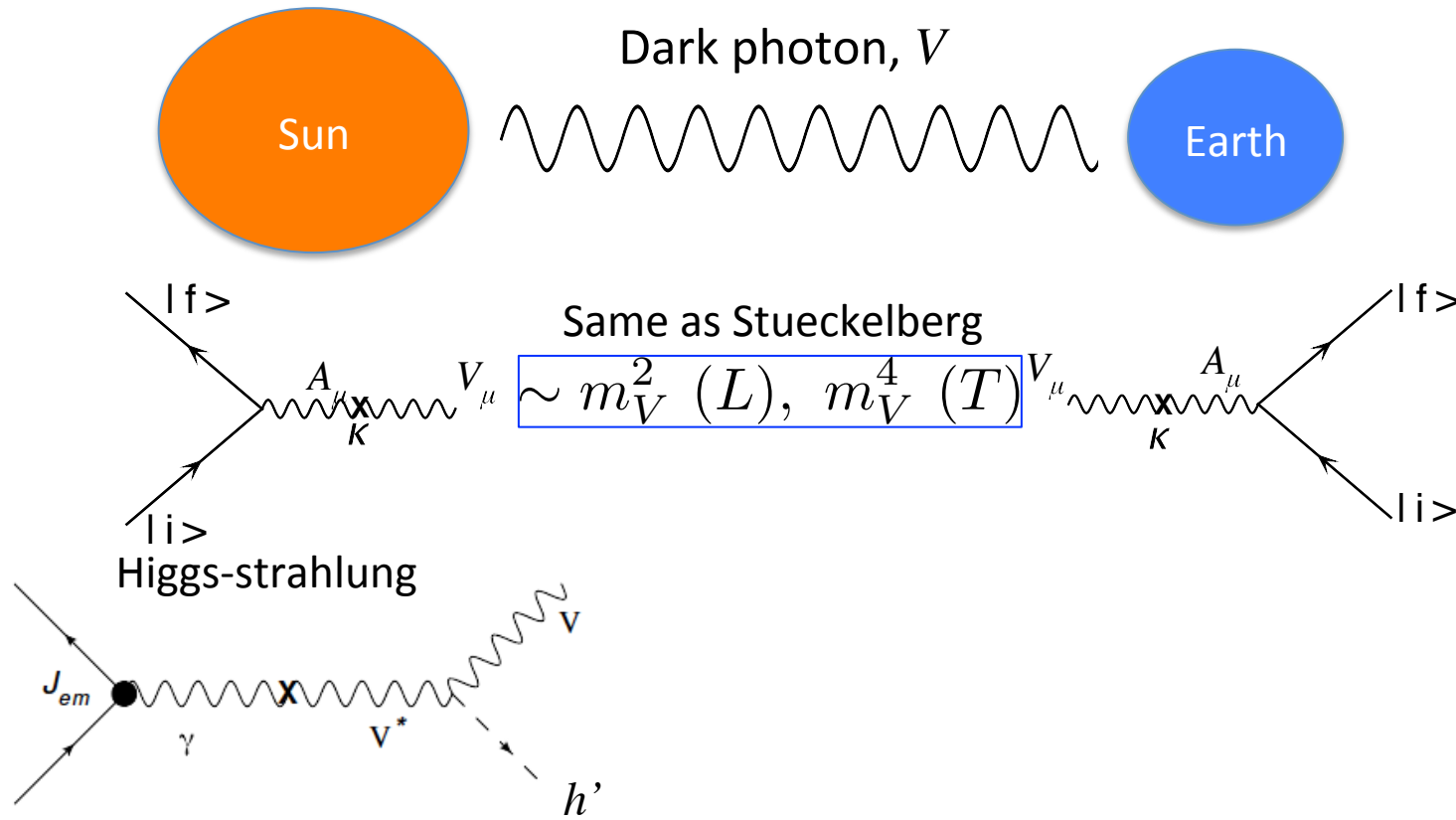


Higgsed case

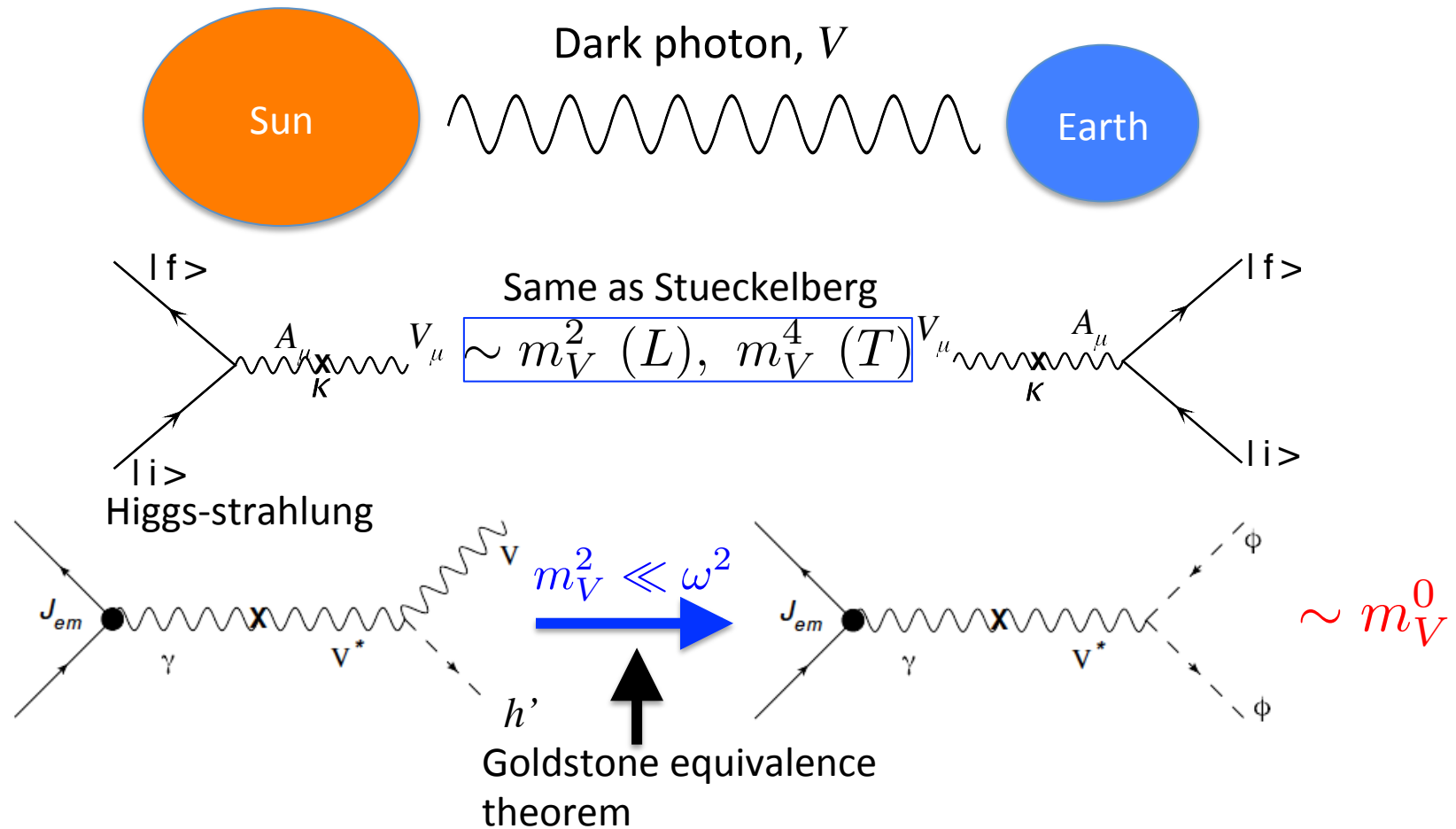


$$\mathcal{L}_{\text{int}} = e' m_V h' V_\mu^2 + \frac{1}{2} e'^2 h'^2 V_\mu^2$$

Higgsed case



Higgsed case



Higgsed case

- Higgs-strahlung

Dominant,
subdominant,

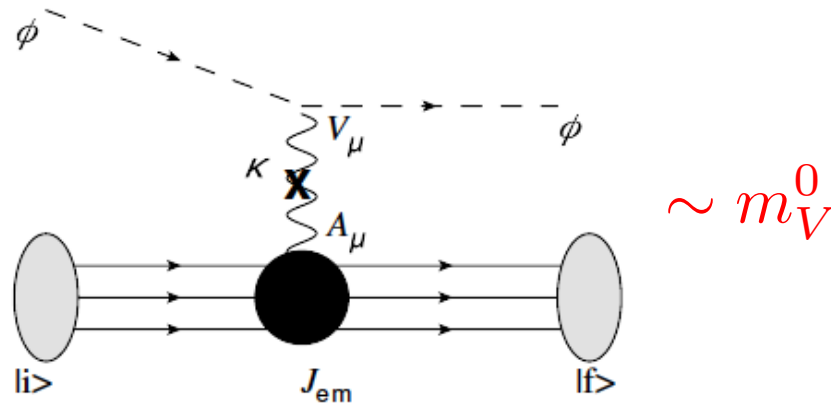
$$m_V \ll \omega_p,$$

$$m_V \sim \omega_p.$$

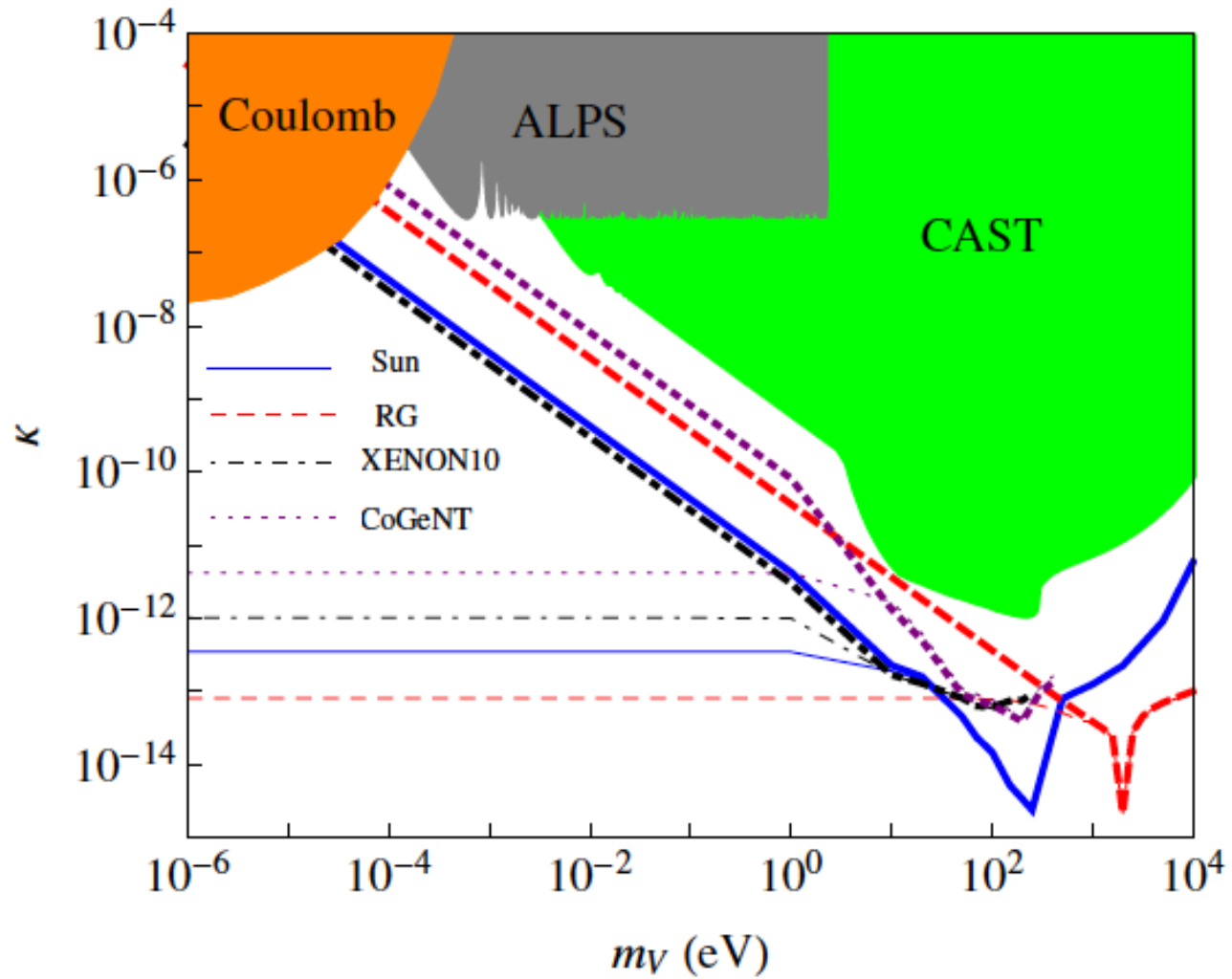
Phase space suppression

Higgsed case

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



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.