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
- Mimic the signal of light dark matter

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
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- Summary

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The Lagrangian

The Standard Model

Extra vector field

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

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

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

$$\downarrow$$

Below EW breaking ,

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

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

Origins of mass

- Massive $U(1)$ gauge theory

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

Would-be Goldstone

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

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

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

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Direct Detection

- Signal rate

Total absorption rate

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

Flux from the Sun

Branching ratio to the desired signal.

  - Total absorption rate;
  - Solar flux;
  - Branching ratio to desired signals.

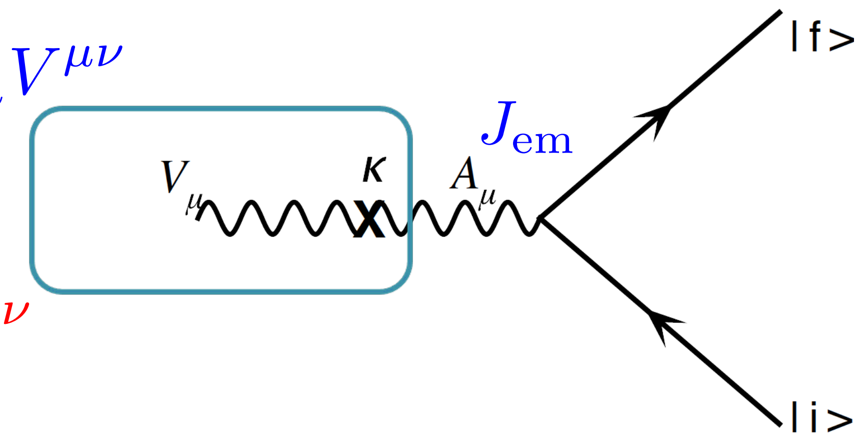
Total absorption rate

- Feynman diagram:

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

E.O.M

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



- Matrix element:

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

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

Correlation function inside the medium

Total absorption rate

- m_V scaling

$$k_\mu J^\mu_{\rm em} = 0 \quad \rightarrow \quad J^\mu_{\rm em}\epsilon^L_\mu \sim m_V \quad \rightarrow \quad \Pi_L \sim m_V^2$$

- Non-magnetic material

$$\Pi_T = -\omega^2 \Delta\varepsilon_r \qquad \Delta\varepsilon_r = \varepsilon_r - 1$$
$$\Pi_L = -(\omega^2 - |\vec{k}|^2)\Delta\varepsilon_r$$

Relative permittivity

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

- In the small m_V limit,

$$\mathcal{M}_T \sim m_V^2 \ , \ \ \mathcal{M}_L \sim m_V \ .$$

Total absorption rate

- Total absorption rate

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

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

Unitarity $\downarrow$

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

$\downarrow$

$$\begin{aligned}\Pi_T &= -\omega^2\Delta\varepsilon_r \\ \Pi_L &= -(\omega^2 - |\vec{k}|^2)\Delta\varepsilon_r\end{aligned} \longrightarrow \mathrm{Im}\Pi_T\ ,\ \ \mathrm{Im}\Pi_L$$

Total absorption rate

- Total absorption rate

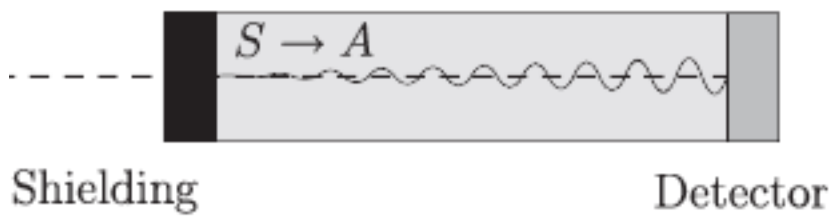
$$\Gamma_T = \frac{\kappa^2\omega\left(\frac{m_V^2}{\omega^2|\Delta\epsilon_r|}\right)^2 \mathrm{Im}\varepsilon_\mathrm{r}}{1+\frac{2m_V^2\omega^2\mathrm{Re}\Delta\varepsilon_r+m_V^4}{\omega^4|\Delta\varepsilon_r|^2}} \xrightarrow{m_V^2 \ll \omega^2|\Delta\varepsilon_r|} \kappa^2\omega\left(\frac{m_V^2}{\omega^2|\Delta\varepsilon_r|}\right)^2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

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

- $$\boxed{\begin{array}{c} \Delta\varepsilon_r \propto n_A, \ \text{Atom number density} \\ \Gamma_T \propto n_A^{-1} \qquad \Gamma_L \propto n_A \end{array}}$$

If transverse modes dominate

- $\Gamma_T \propto n_A^{-1}$
- The effective atom number density should as small as possible.
- CAST experiment



  - Unevenly distributed low density detector
- Dark matter detectors
  - Signal rates depend on the gap between the shielding and the detector
  - Daily modulation and annual modulation

If longitudinal mode dominates

- $\Gamma_L \propto n_A$
- High density, large volume $\longrightarrow$ dark matter detectors
- No significant modulations

Longitudinal or transverse, it's a question!

Solar flux

- Total production rate m_V scaling

$$\Gamma_T^{\rm prod} \propto \kappa^2 m_V^4 \omega_p^{-4}$$
$$\Gamma_L^{\rm prod} \propto \kappa^2 m_V^2 \omega^{-2}$$

- In *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!

Solar flux

- Resonant production

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

Transverse resonance

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

$$\Downarrow$$

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

Longitudinal resonance

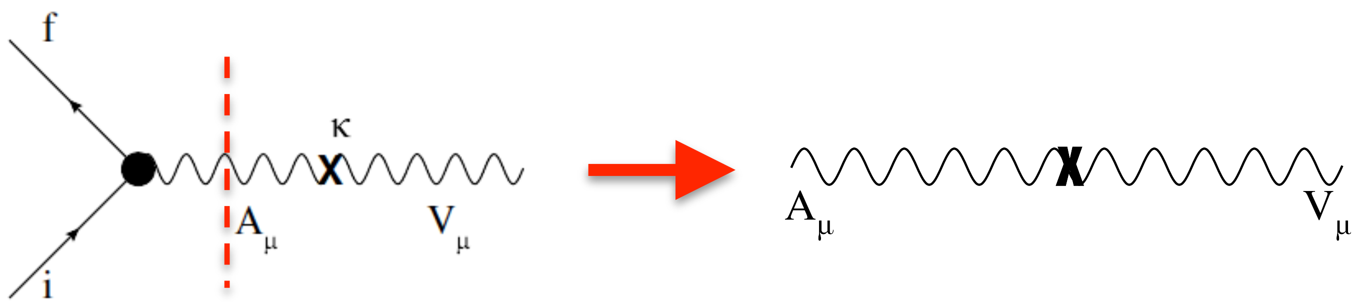
$$m_V^2 = \text{Re}\Pi_L = \omega_p^2 m_V^2/\omega^2$$

$$\Downarrow$$

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

Solar flux

- Resonant production



On shell

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

Solar flux

- Resonant production
  - On shell conditions

Transverse photon

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

Dark photon

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

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

  - Longitudinal plasmon

(collective motion of electrons)

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

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

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

Solar flux

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

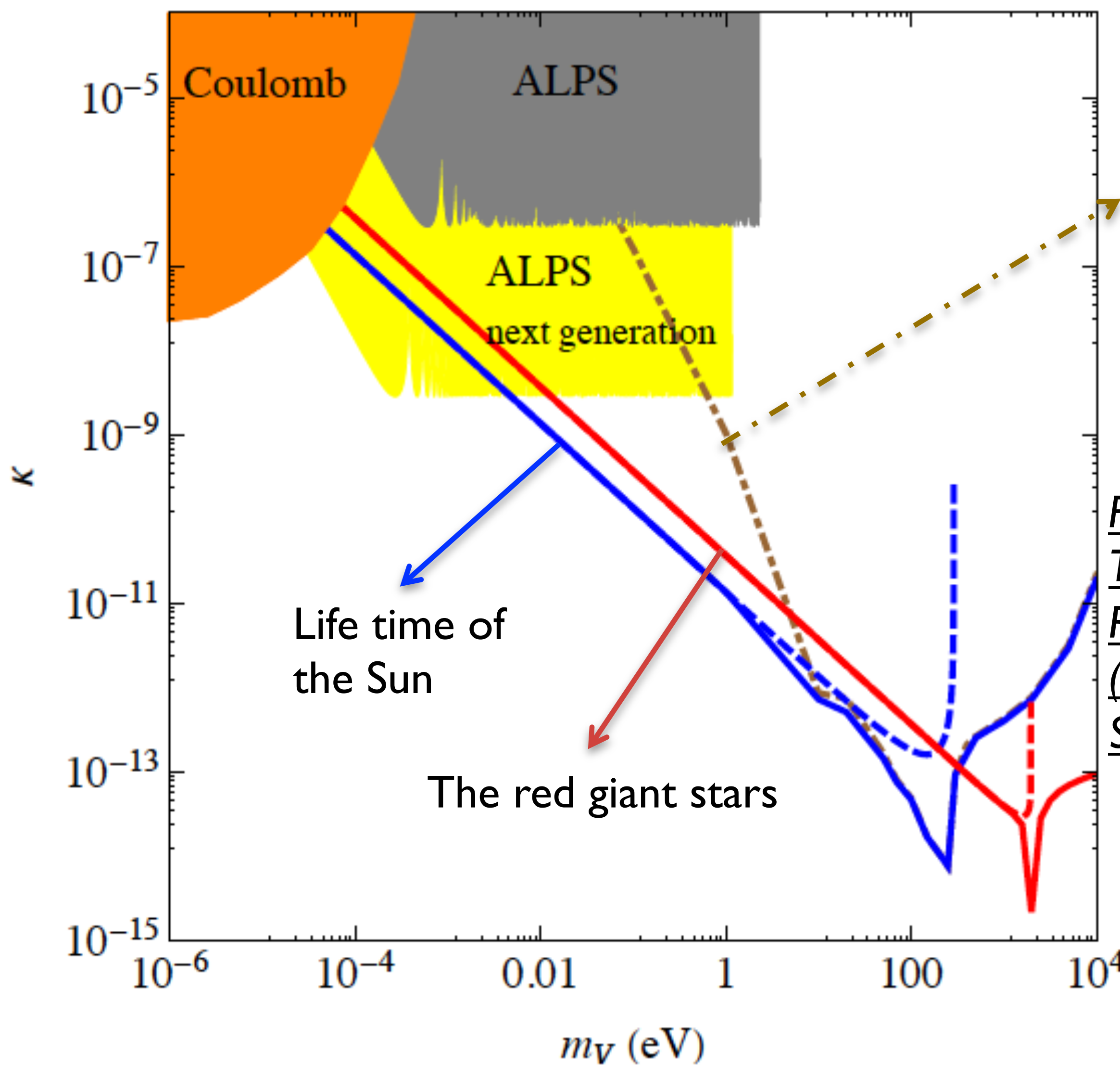
$$\frac{dP_T}{dV\,d\omega} = \frac{\kappa^2 \omega_p^4 \sqrt{\omega^2 - \omega_p^2}}{2\pi (e^{\omega/T} - 1)} \delta(m_V - \omega_p)$$

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

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

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

Stellar constraints



Considering only the transverse contribution.

$$P_{\rm dark} \leq P_{\rm luminosity}$$

Frieman, Dimopoulos and Turner (PRD 1987), Raffelt and Dearborn (PRD 1988), Raffelt and Starkman (PRD 1989)

Requirement to detectors

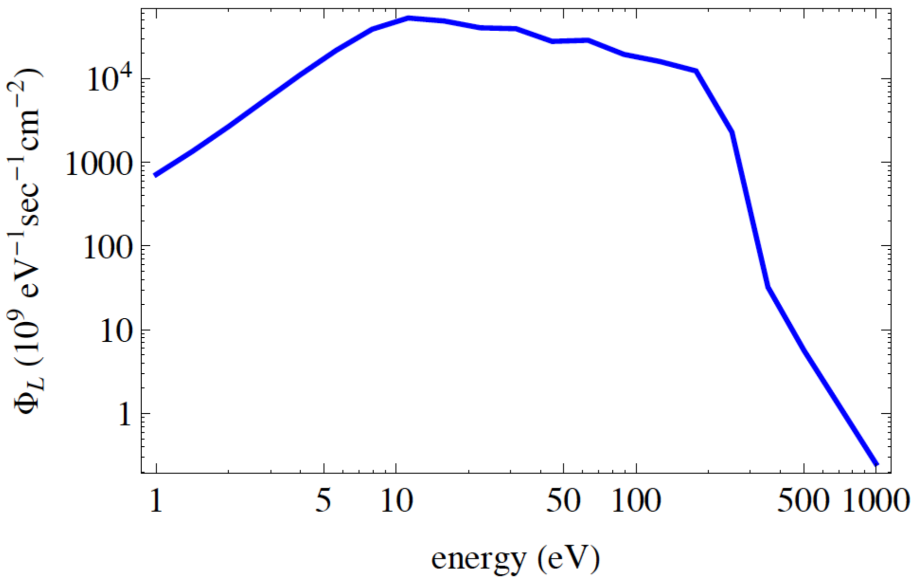
- Based on the correct analysis, the total absorption rate for the solar dark flux

$$\Gamma^{\rm abs} \propto n_A$$

- High density, large volume

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

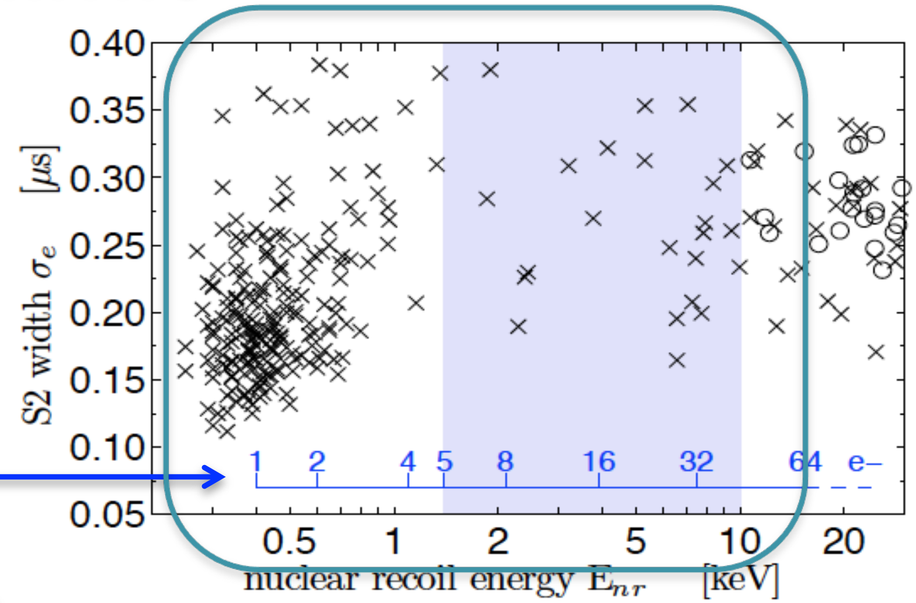
  The detector should be able to detect ~ $100\ {\rm eV}$ energy deposition



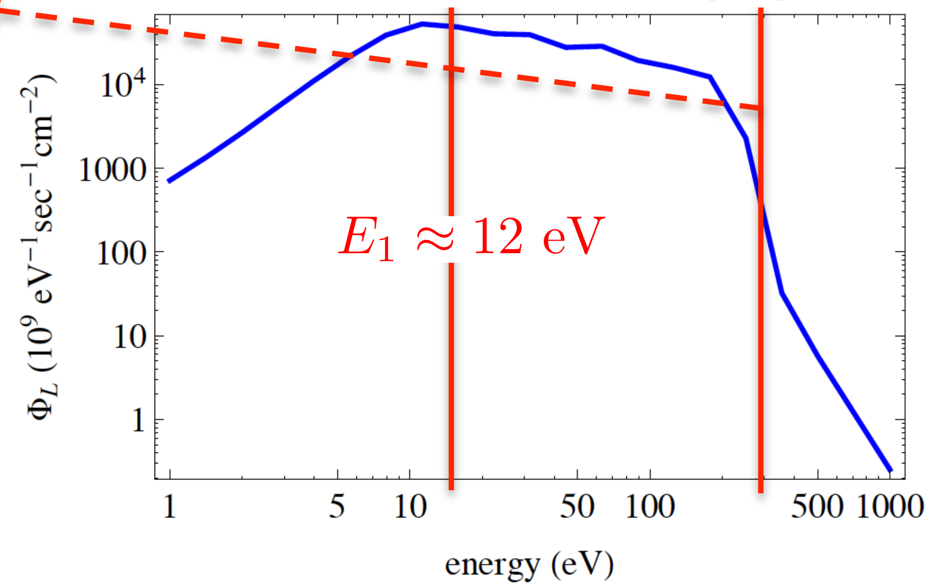
XENON10 limit

- XENON10

Number of electrons



300 eV ~ 25 electrons

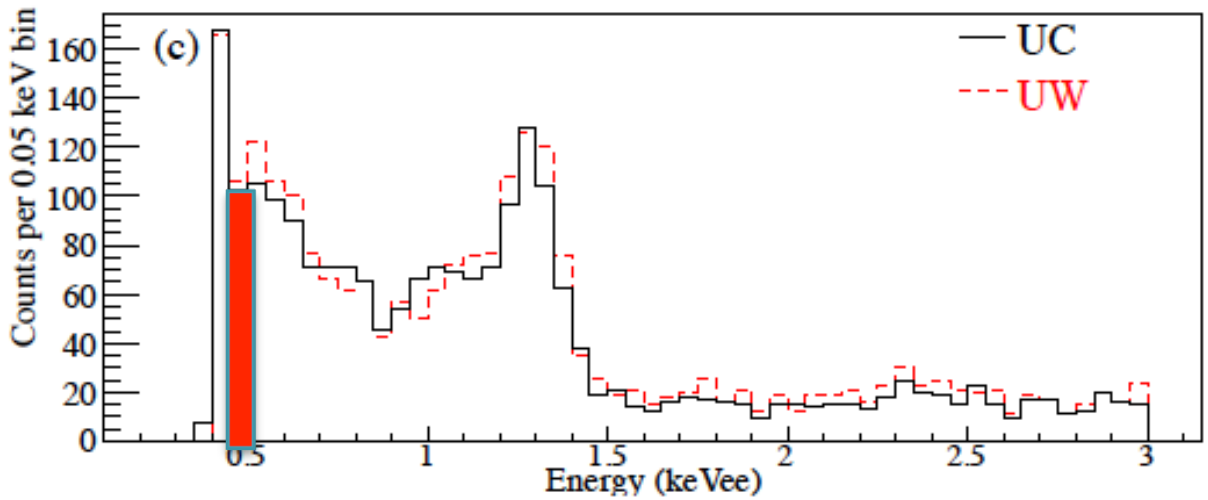


- $\mathrm{Br} \approx 1$

Photo-ionization dominates.

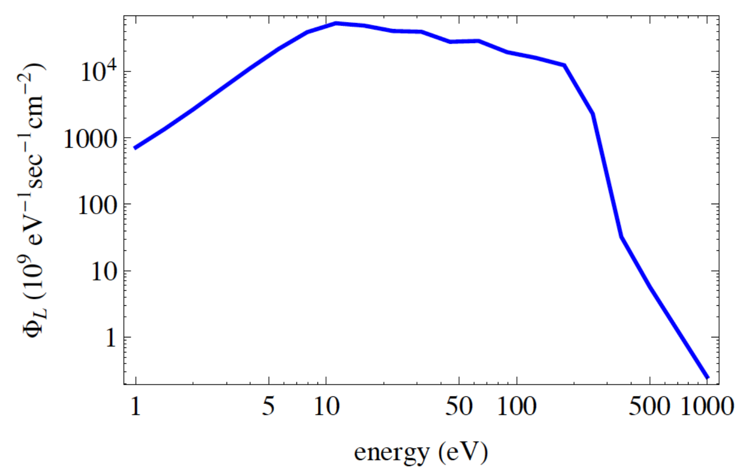
CoGeNT limit

- CoGeNT data available from 400 eV.

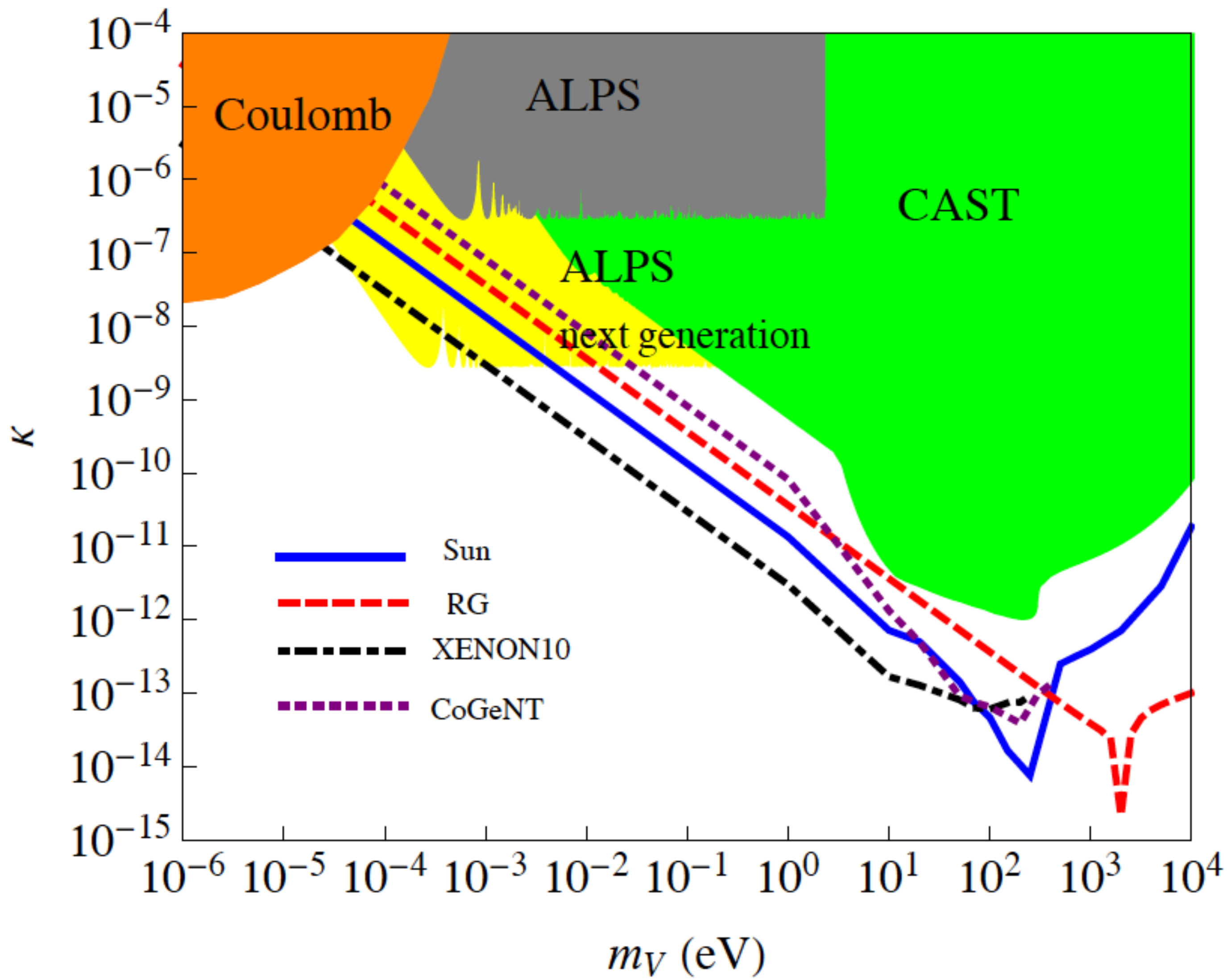


- $\mathrm{Br} \approx 1$

Photo-ionization dominates.



Stueckelberg case



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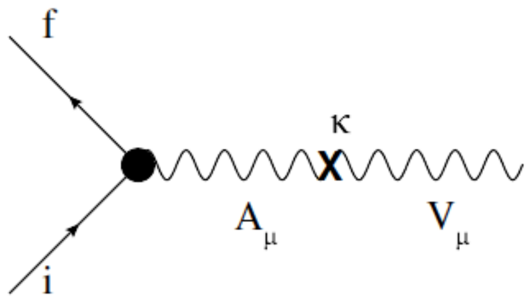
Higgsed case

- Direct detection
  - Solar flux
  - Total absorption rate
  - Branching ratio to desired signal

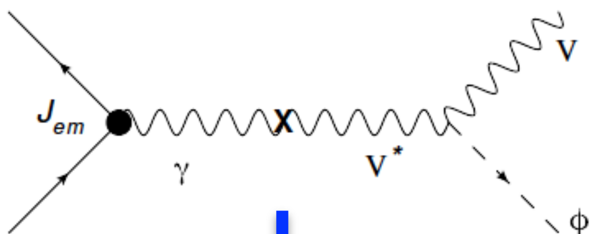
Solar flux

- Processes in the Stueckelberg case are still there:



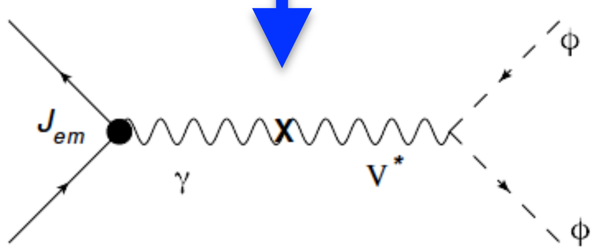
$$\sim m_V^2\ (L),\ m_V^4\ (T)$$

- Higgs-strahlung



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

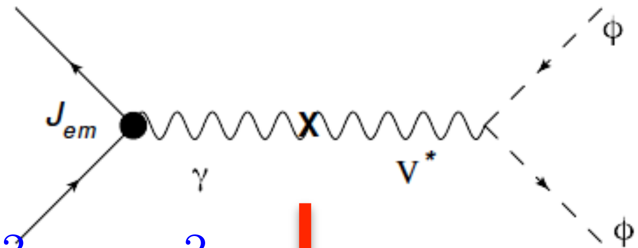
Goldstone equivalence theorem



$$\sim m_V^0$$

Solar flux

- Higgs-strahlung

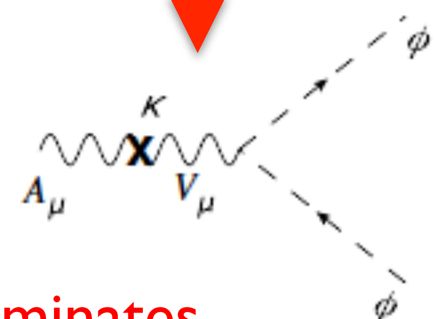


$$\begin{array}{ll} \text{Dominant,} & m_V^2 \ll \omega_p^2 \\ \text{sub}-\text{dominant,} & m_V \sim \omega_p \end{array}$$

- Resonance decay

$$N_L \sim \omega_p^3 \ , \ \ N_T \sim T^3$$

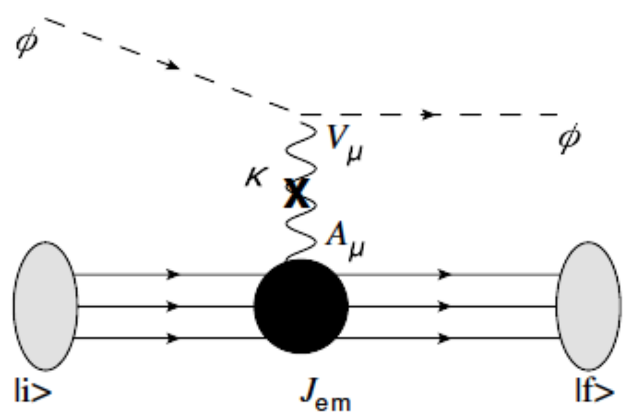
$$T^3 \gg \omega_p^3, \ \text{in the Sun}$$



Transverse photon decay dominates.

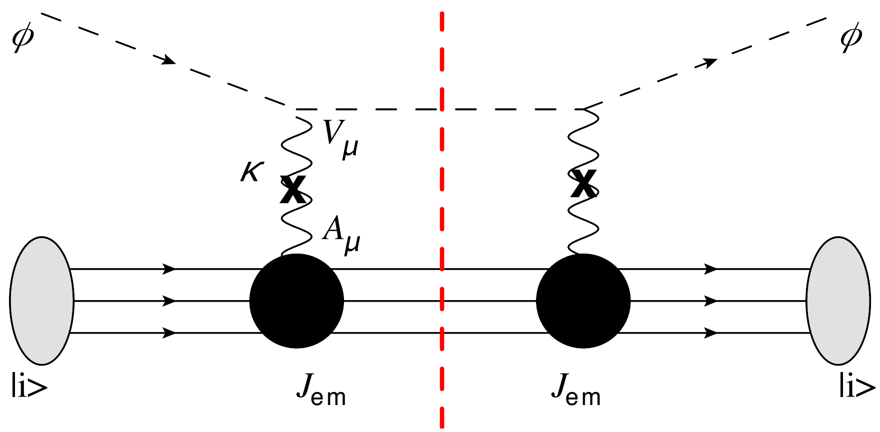
Total absorption rate

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



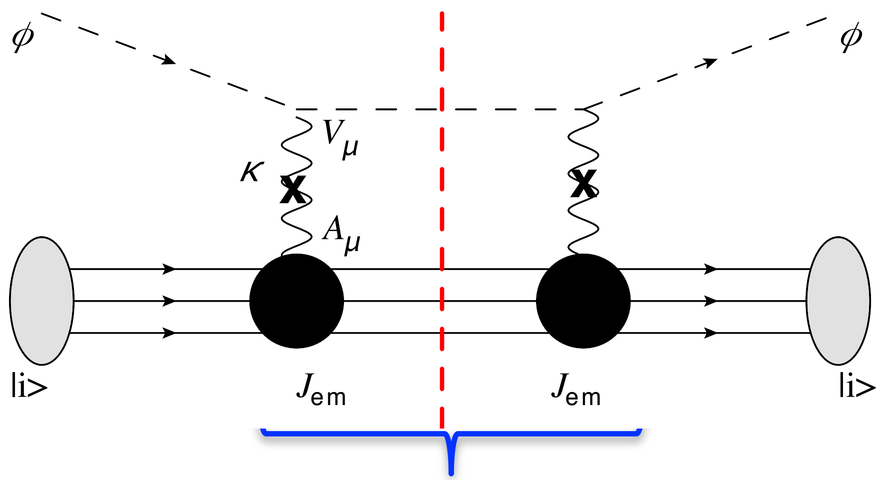
Total absorption rate

- Total absorption rate, summing over all possible final state



Total absorption rate

- Total absorption rate:



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

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

Absorption rate

- 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

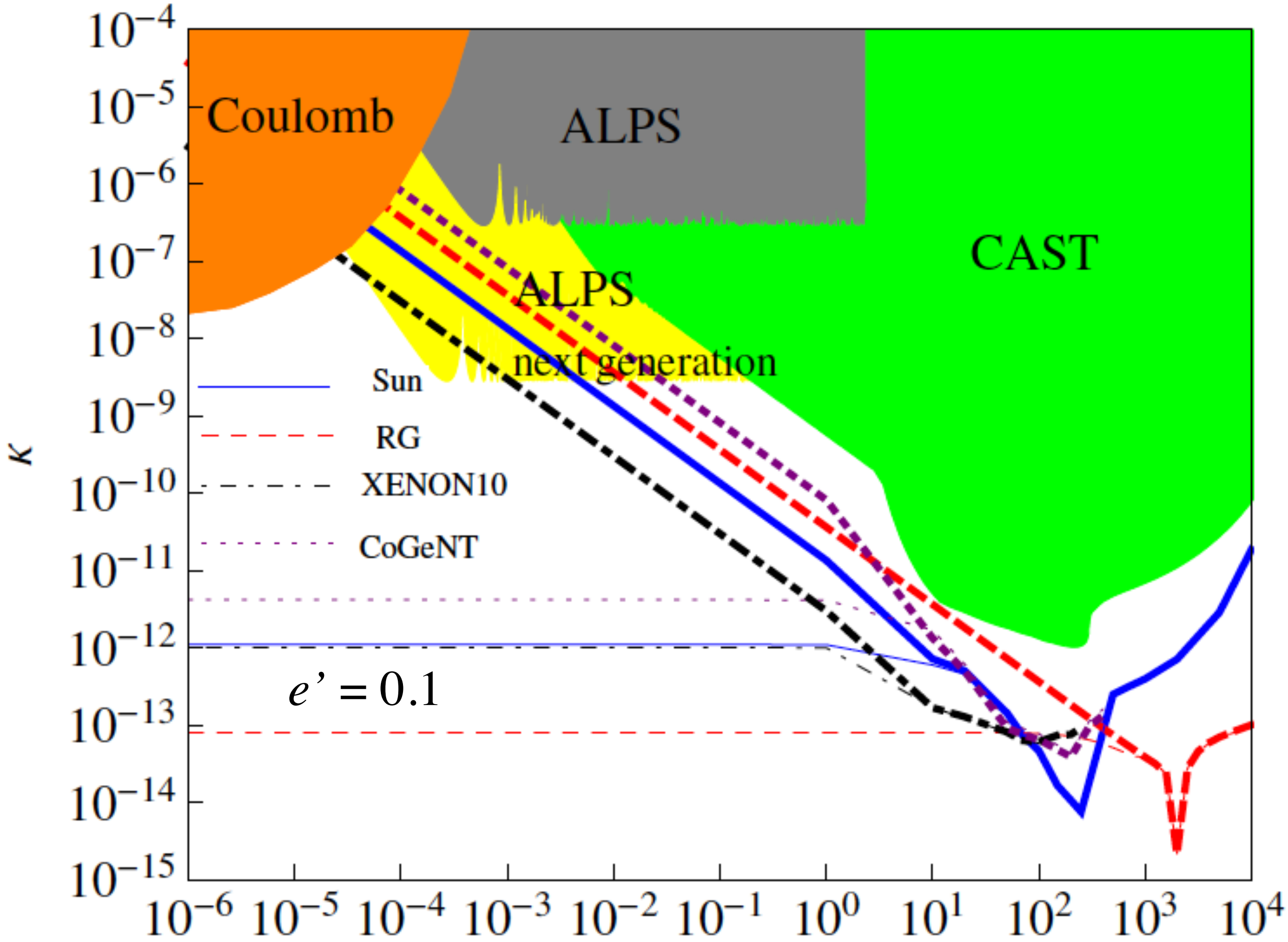
Energy of incoming
Higgs

- $\mathrm{Br} \approx 1$ for both XENON10 and CoGeNT

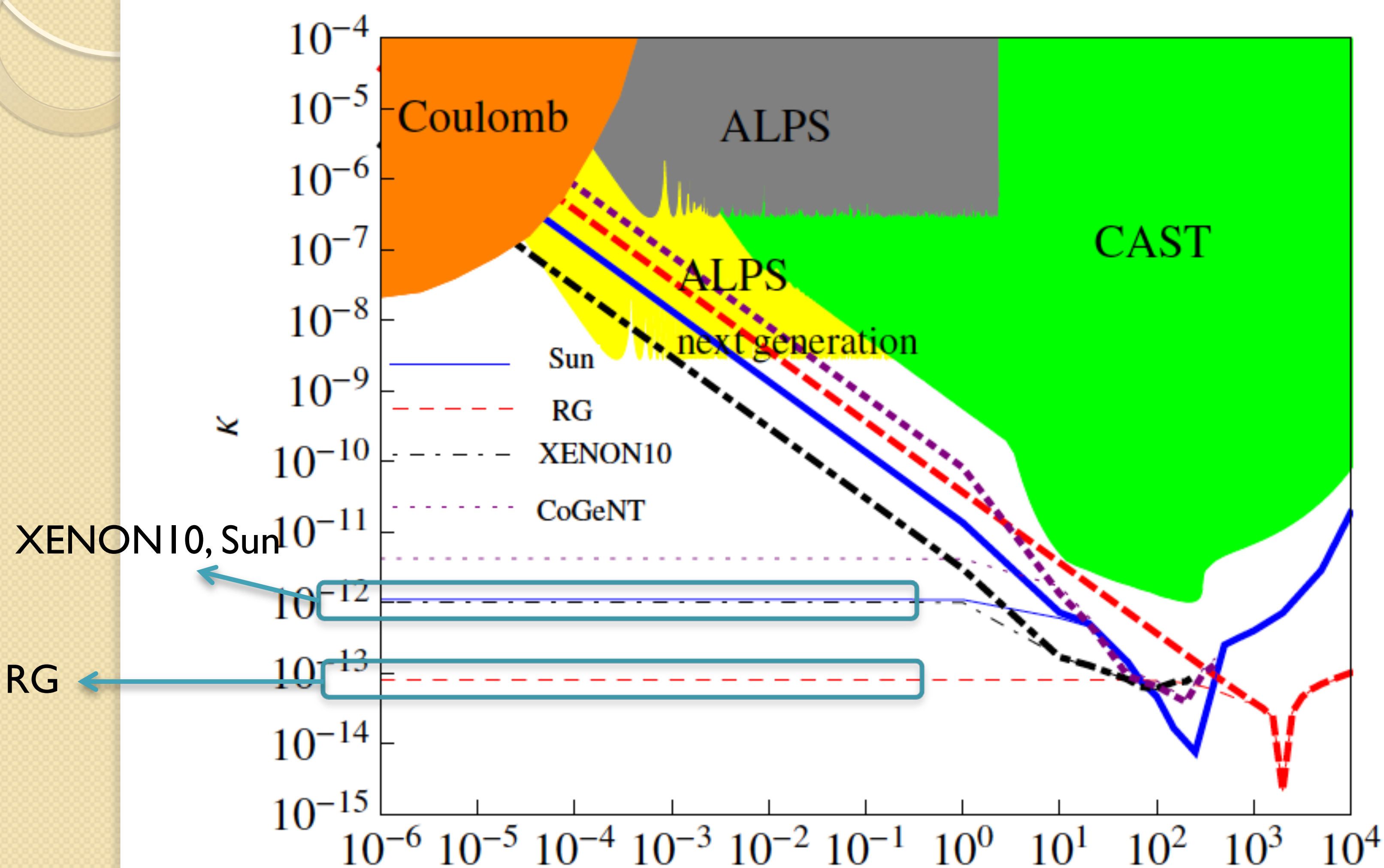
Total absorption rate

- 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.

Higgsed case



Higgsed case



Summary and outlook

- The stellar bounds are significantly strengthened in the small m_V region.
- Large volume, high density materials should be used to build solar dark photon 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 dark matter detector can be more sensitive to the current stellar constraint.
- Future detectors with low electron recoil threshold DAMIC (Alvaro's talk), Sub-MeV detectors (Essig et al), Semiconductor detectors (Graham et al).