New light on Dark Photons

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arXiv:1302.3884, arXiv:1304.3461 w/ H. An and M.Pospelov

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Outline

- New resonance in the stellar production of "Dark Photons" (Hidden Photons, Paraphotons, Secluded Vectors, Dark Vectors,...) [corrects previous calculation]

  => correction factor can be very large
  => rules out parameter space for existing experimental setups

- Emission of longitudinal states dominates stellar energy loss for ~ sub-eV Dark Photons

  => new detection prospects from Dark Matter searches

- Cosmological aspects

Dark Photons

Model parameters

$\kappa,\ m_V,\ (e',\ m'_h)$

$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times U(1)'$ with Vector V_μ

$$-\frac{\kappa'}{2} F^Y_{\mu\nu} V^{\mu\nu} \xrightarrow[\text{scale}]{\text{below EW}} -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu}$$

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

Stueckelberg case

$$\mathcal{L} \supset -\frac{1}{2} m_V V^2_\mu$$

"hard photon mass"

Higgsed case

$$\mathcal{L} \supset -\frac{1}{2} m_V V^2_\mu + e' m_V h' V^2_\mu + \frac{1}{2} e'^2 h'^2 V^2_\mu$$

+ h' self-interactions

The Dark Photon Landscape*

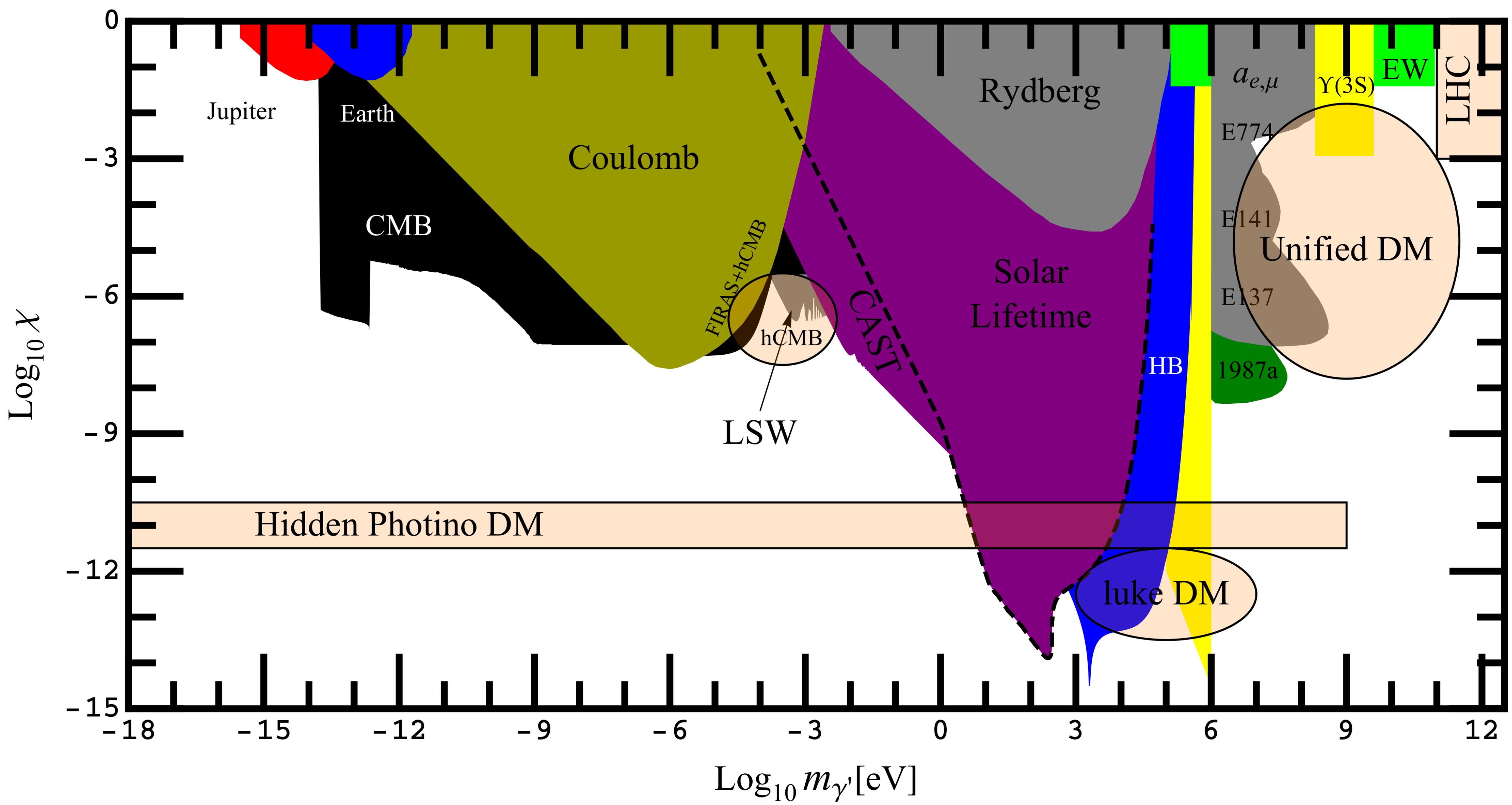
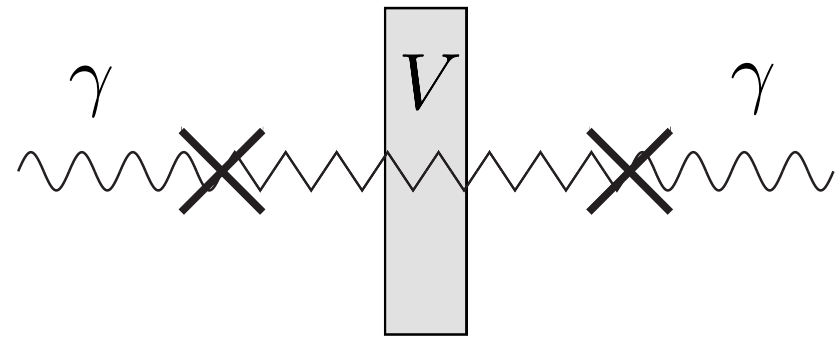


Fig. from Ringwald, Jaeckel, 2010

*before March 2013

LSW region



- light-shining-through-wall experiments

few m

$$P_{\rm LSW} = 16\kappa^4 \sin^2\left(\frac{l_1 m_V^2}{4\omega}\right)\sin^2\left(\frac{l_2 m_V^2}{4\omega}\right)$$

"optical regime"

$$\Rightarrow m_V = \mathcal{O}(\mathrm{meV})$$

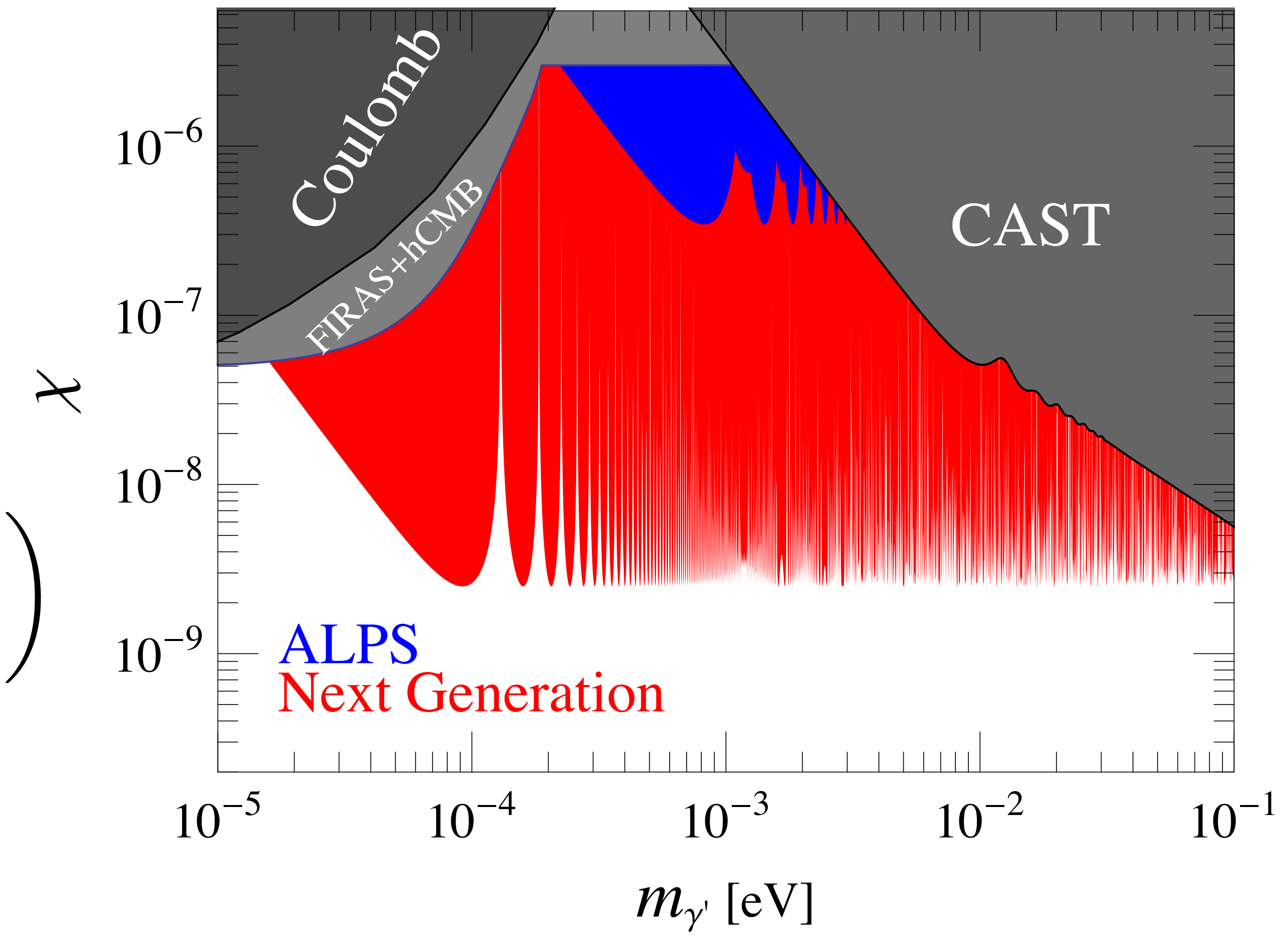
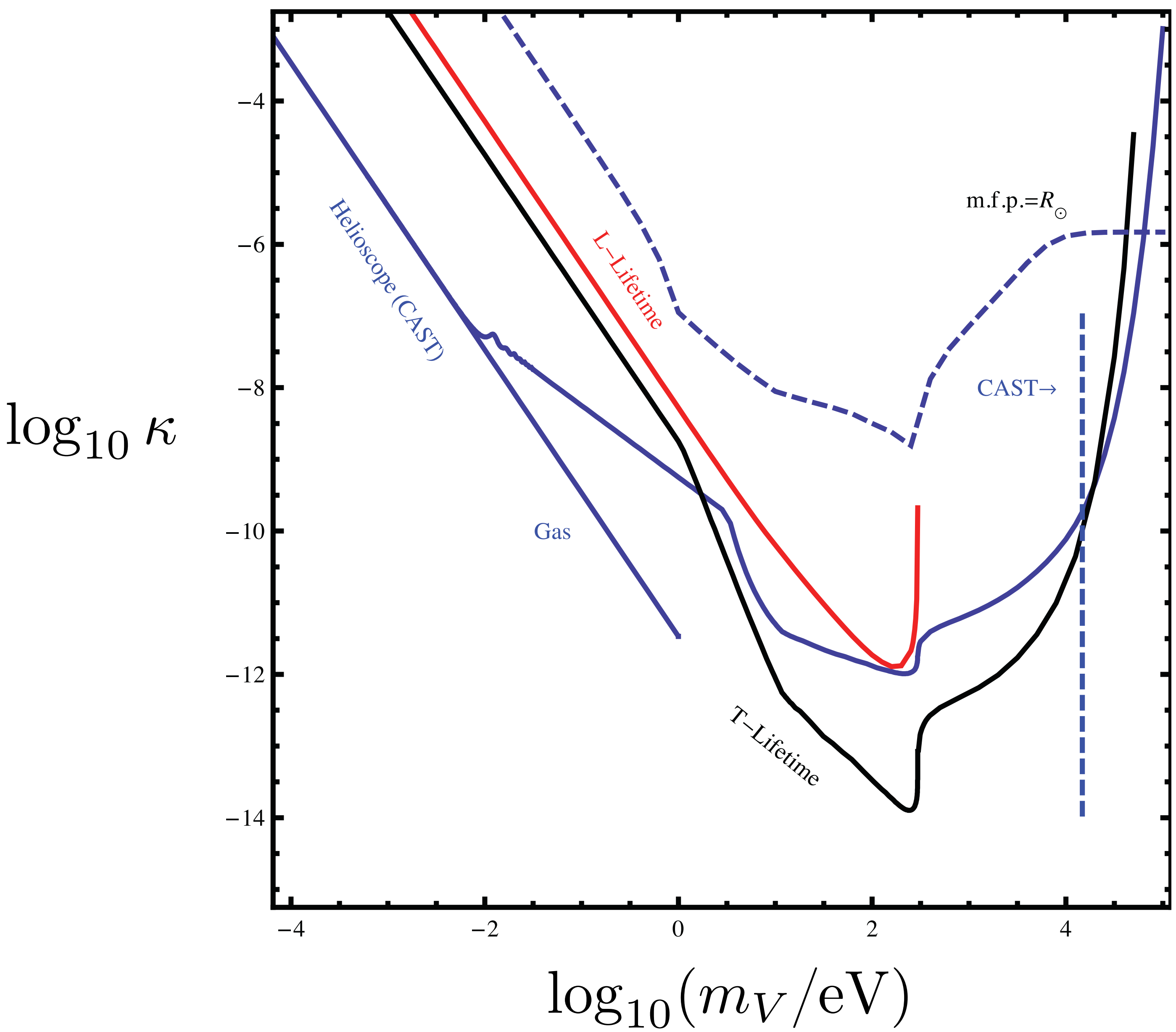
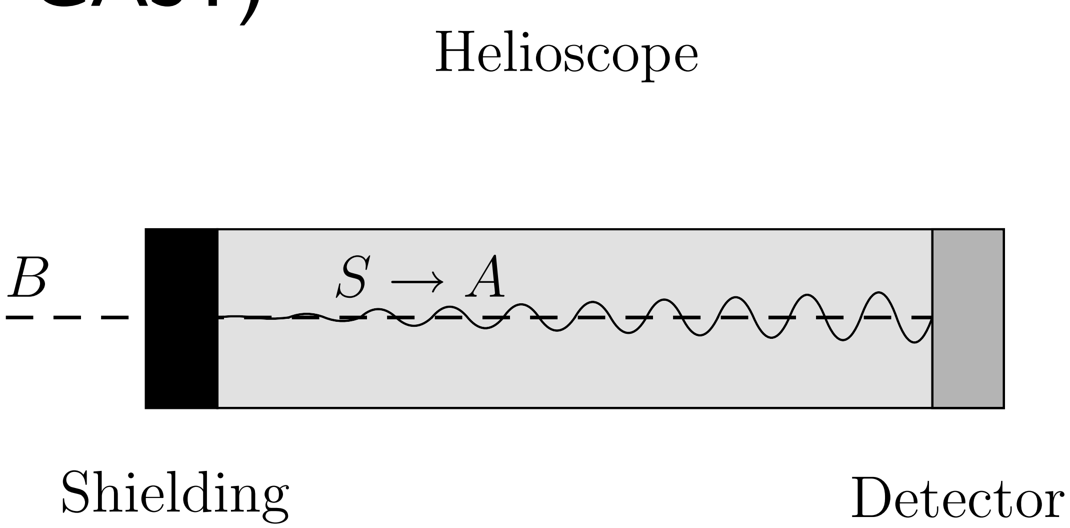


Fig. from Redondo, Ringwald, 2010
see also Bähre et al. 2013

Helioscope DP detection



DP flux can be detected via "X-ray regeneration" (e.g. in CAST)

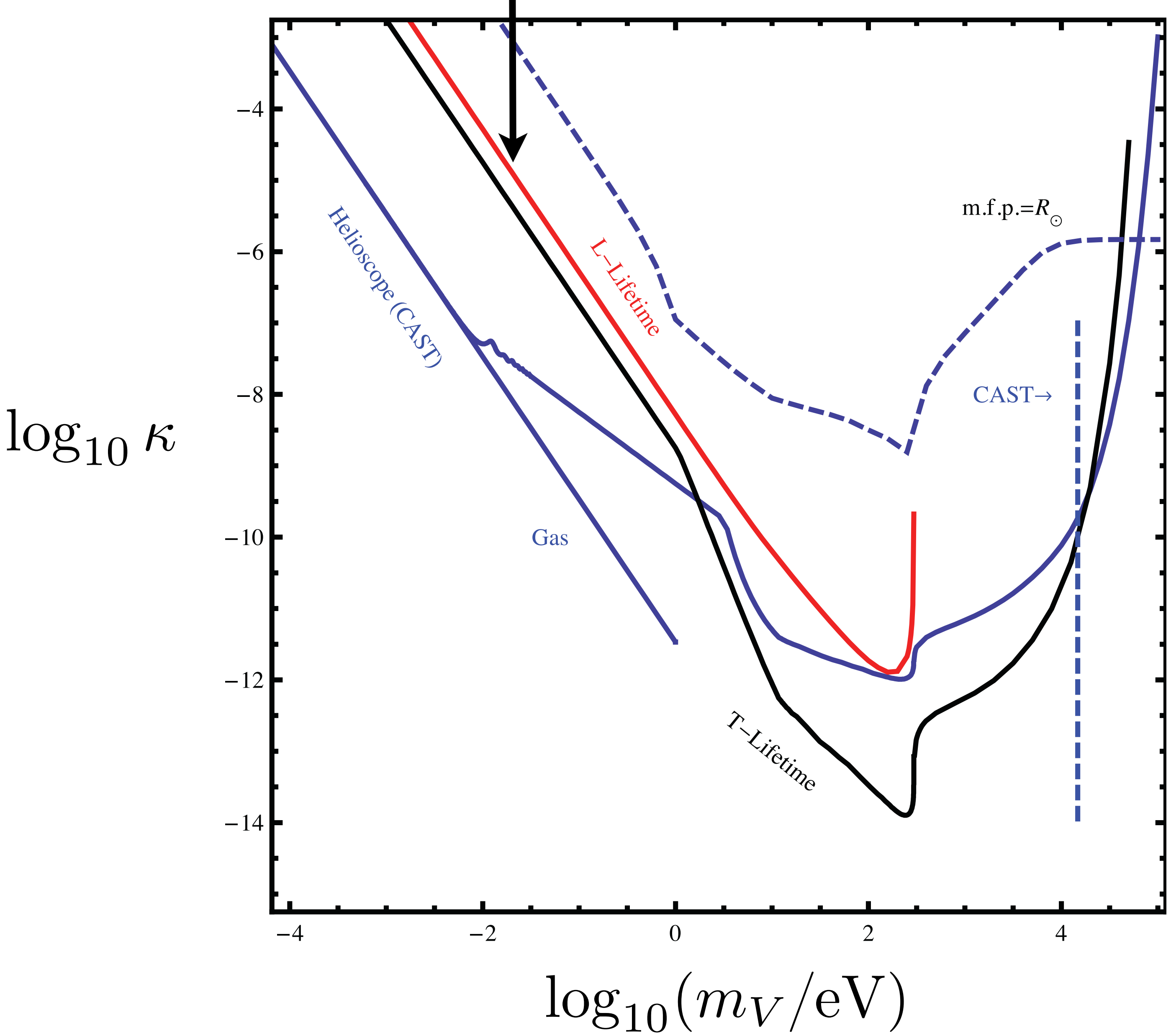


Redondo 2008

Helioscope DP detection

$\mathrm{Rate}_{SM\to V_L} \propto \kappa^2 m_V^4$

=> we argue for a different scaling $\kappa^2 m_V^2$



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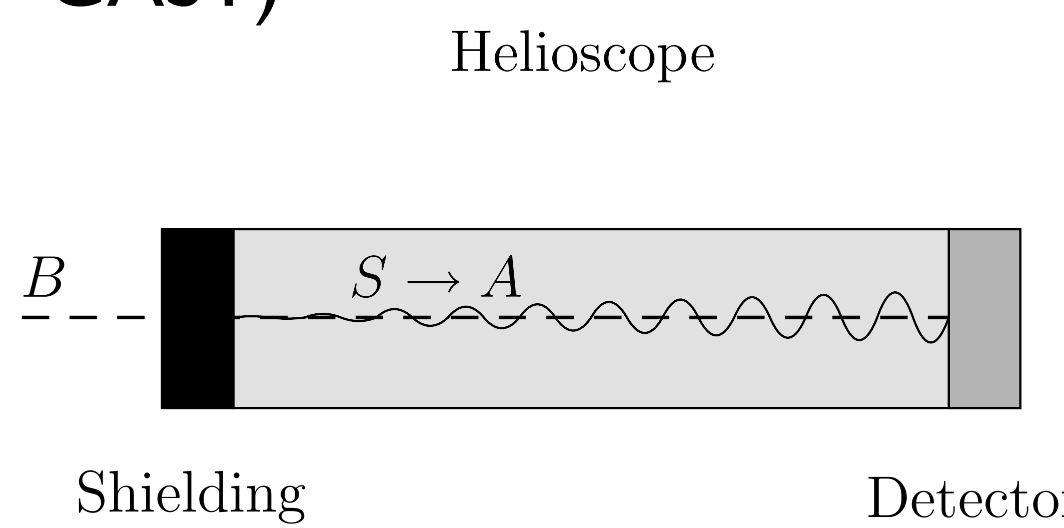
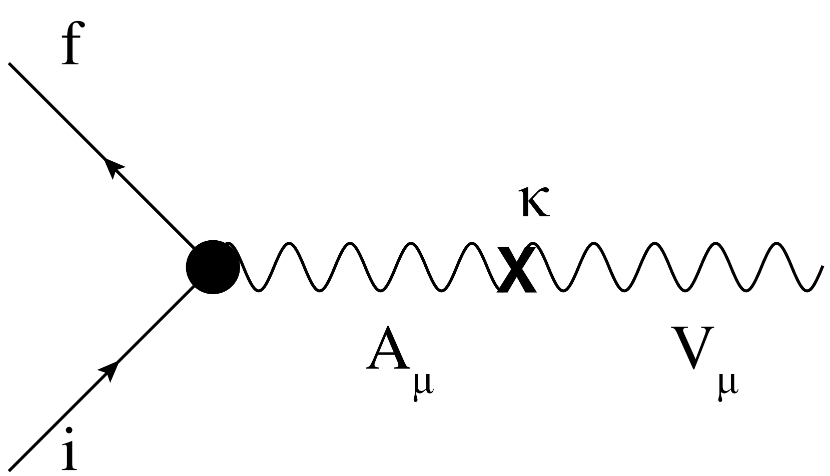


Redondo 2008

Solar production - revisited

- for $m_V \lesssim 1\,\mathrm{keV}$ hidden photons are produced in the solar interior

$$\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} + e J^{\mu}_{\mathrm{em}} A_{\mu} \xrightarrow{\text{on-shell V}} \mathcal{L}_{\mathrm{int}} = -\kappa m_V^2 A_\mu V^\mu + e J^{\mu}_{\mathrm{em}} A_\mu .$$



medium propagator

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

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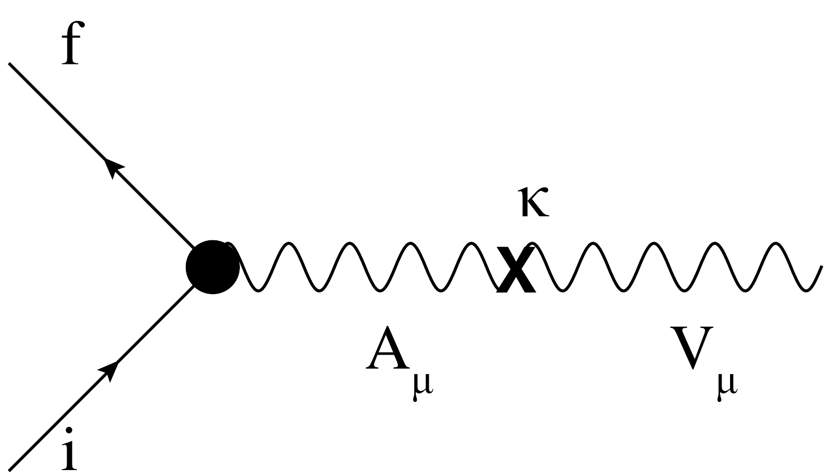

medium propagator

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

$$\epsilon^L = m_V^{-1} (|\vec{k}|, 0, 0, \omega)$$

longitudinal modes: $\langle A_0, A_0 \rangle = \frac{1}{|\vec{k}|^2}$. $\quad (k \simeq \omega \gg \omega_p)$

Braaten, Segel 1993

Scaling with vector mass

- transverse modes:

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

- longitudinal modes, Stueckelberg case:

$$\text{Rate}_{SM\to V_L} \propto \kappa^2 m_V^2 \omega^{-2}, \quad \text{both in vacuum and in medium. } (k \simeq \omega \gg \omega_p)$$

=> enhancement by $\omega_p^2/m_V^2 \sim 10^{10}$ in LSW region

- longitudinal modes, Higgsed case:

$$\text{Rate}_{SM\to V+h'} \propto \alpha' \kappa^2 (m_V)^0$$

Scaling with vector mass

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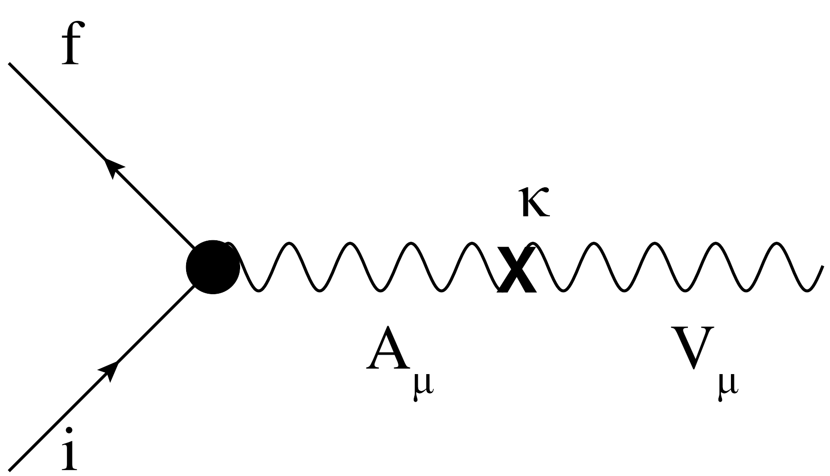
"nature does not like to skip an order"
M. Pospelov

Solar production - revisited

- for $m_V \lesssim 1\,\mathrm{keV}$ hidden photons are produced in the solar interior

$$\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} + e J^\mu_{\rm em} A_\mu \xrightarrow{\text{on}-\text{shell V}} \mathcal{L}_{\rm int} = -\kappa m_V^2 A_\mu V^\mu + e J^\mu_{\rm em} A_\mu .$$



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

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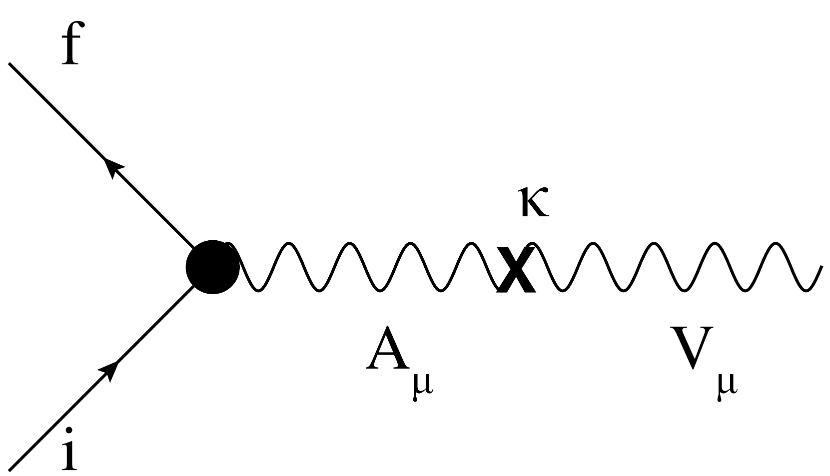

$$\mathcal{M}_{i\to f+V_{T,L}} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}} [e J^{\mu}_{\mathrm{em}}]_{fi} \epsilon_\mu^{T,L}$$

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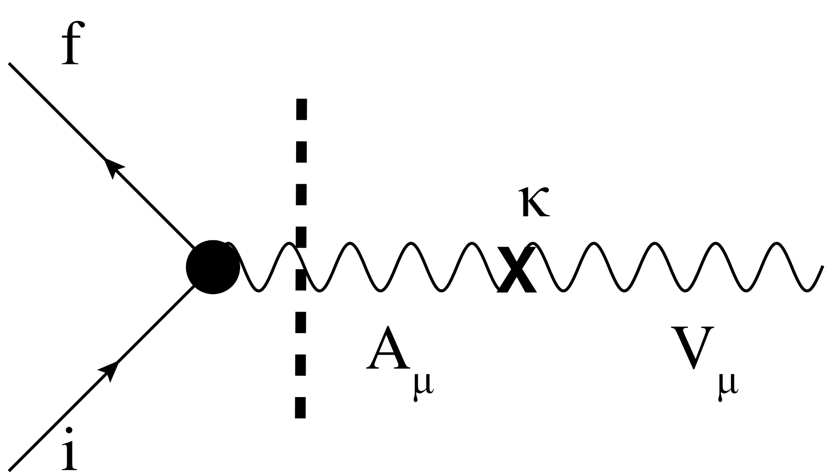

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Transverse Resonance

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

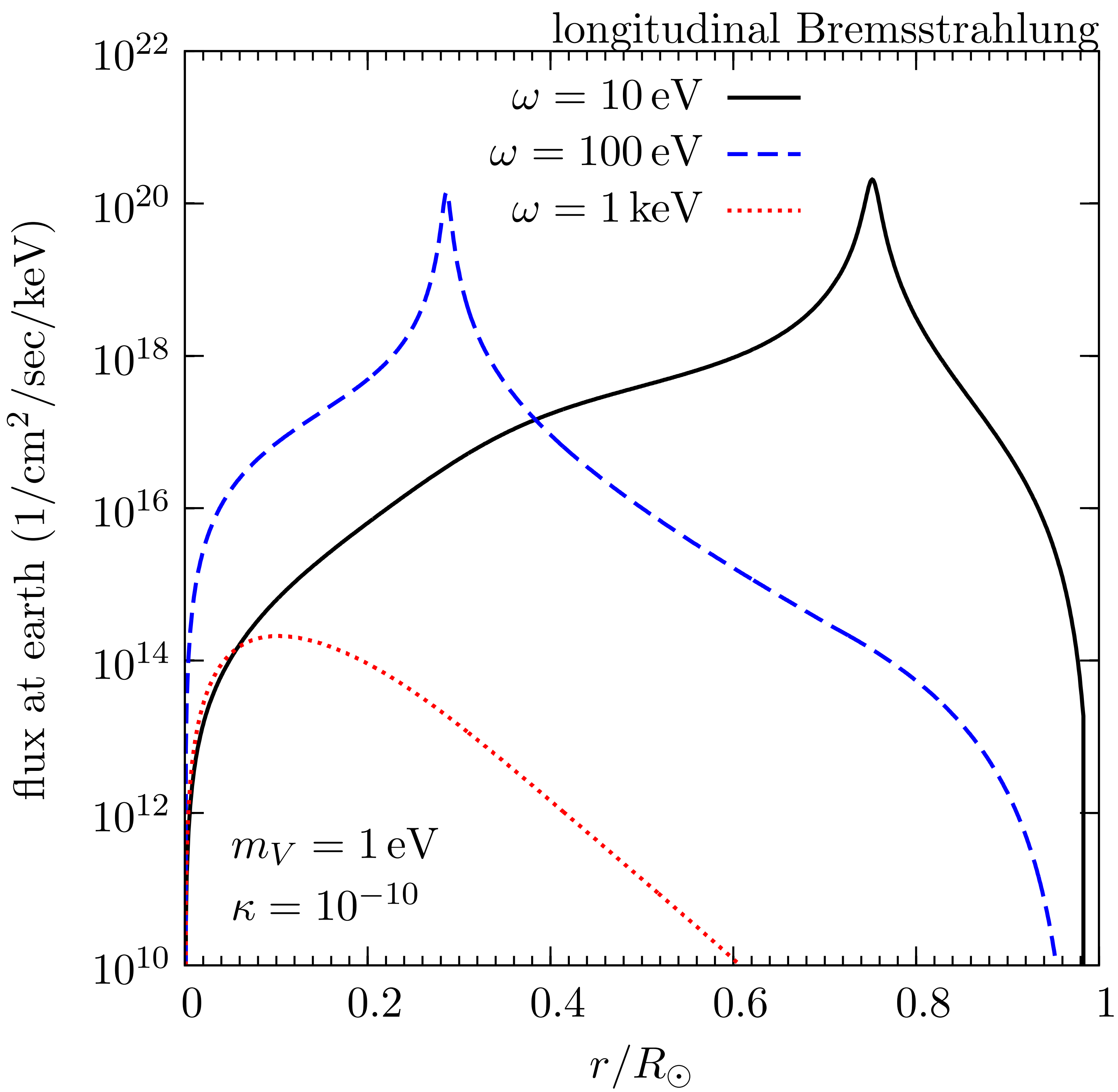
($\omega_p^2 = 4\pi\alpha n_e/m_e$ plasma freq.)

Longitudinal Resonance

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

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

Stellar energy loss



resonant emission in the longitudinal mode

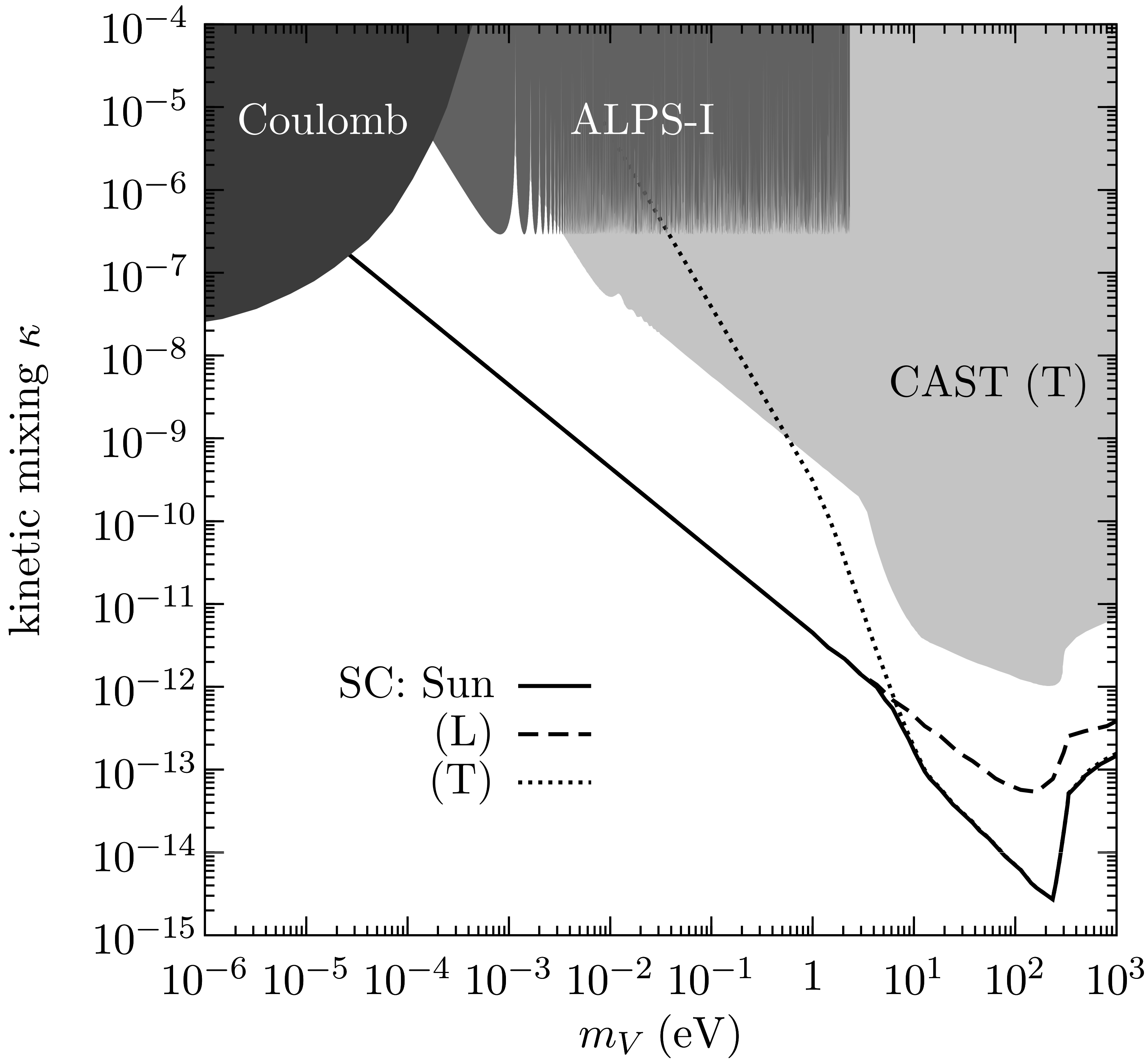
inside the sun:

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

=> resonance can always be met for

$$m_V \lesssim 1\,\mathrm{eV}$$

Stellar energy loss - revised



criterion for sun

$$L_{\rm dark} \leqslant 0.1 L_\odot$$

$$L_\odot = 4 \times 10^{26}\,\text{Watt}$$

SNO, 8B flux
[Gondolo, Raffelt, 2009]

Helioscope
and LSW experiments
find themselves inside
excluded regions

[Higgsed case:
see also Ahlers et al 2008]

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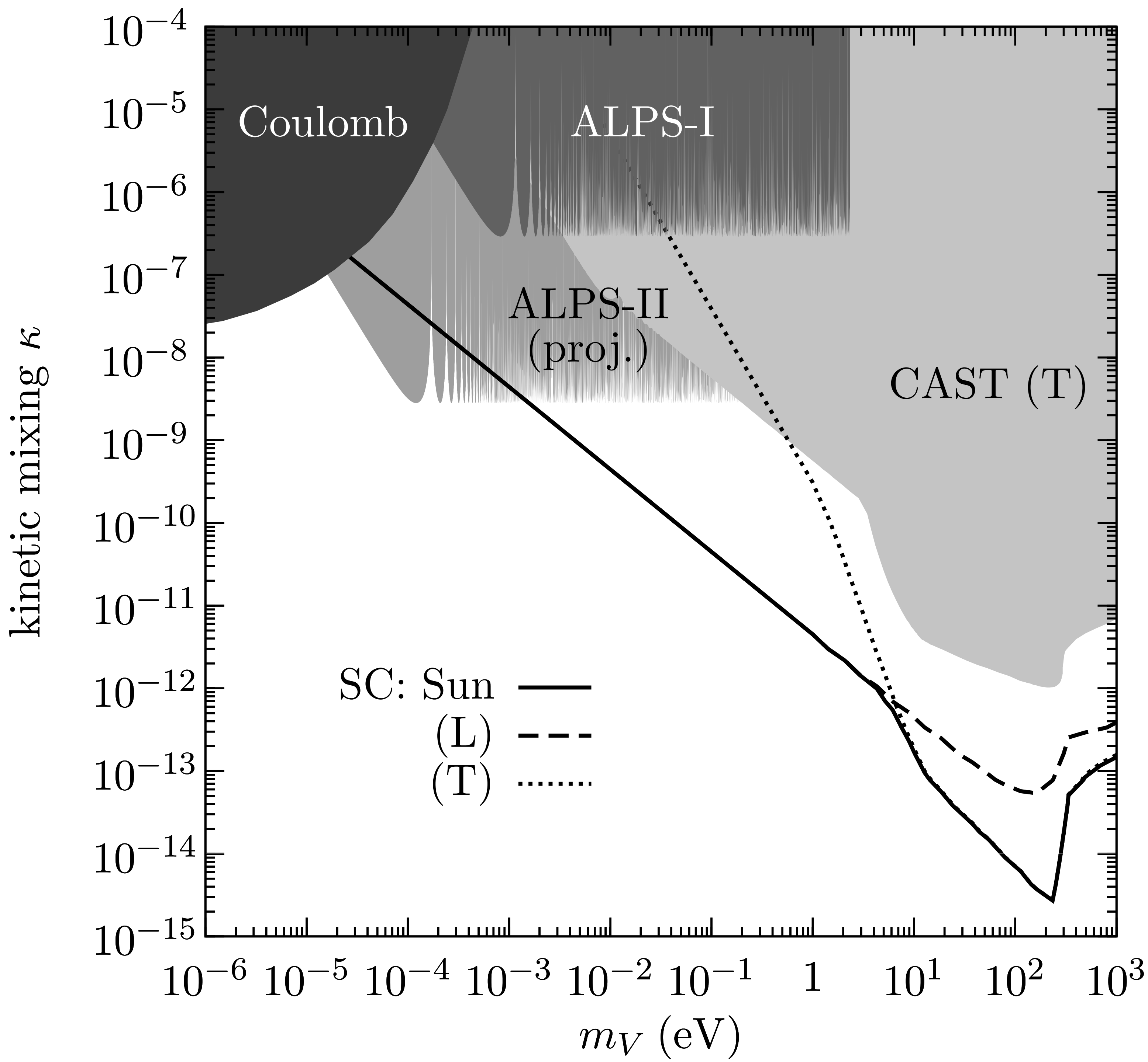

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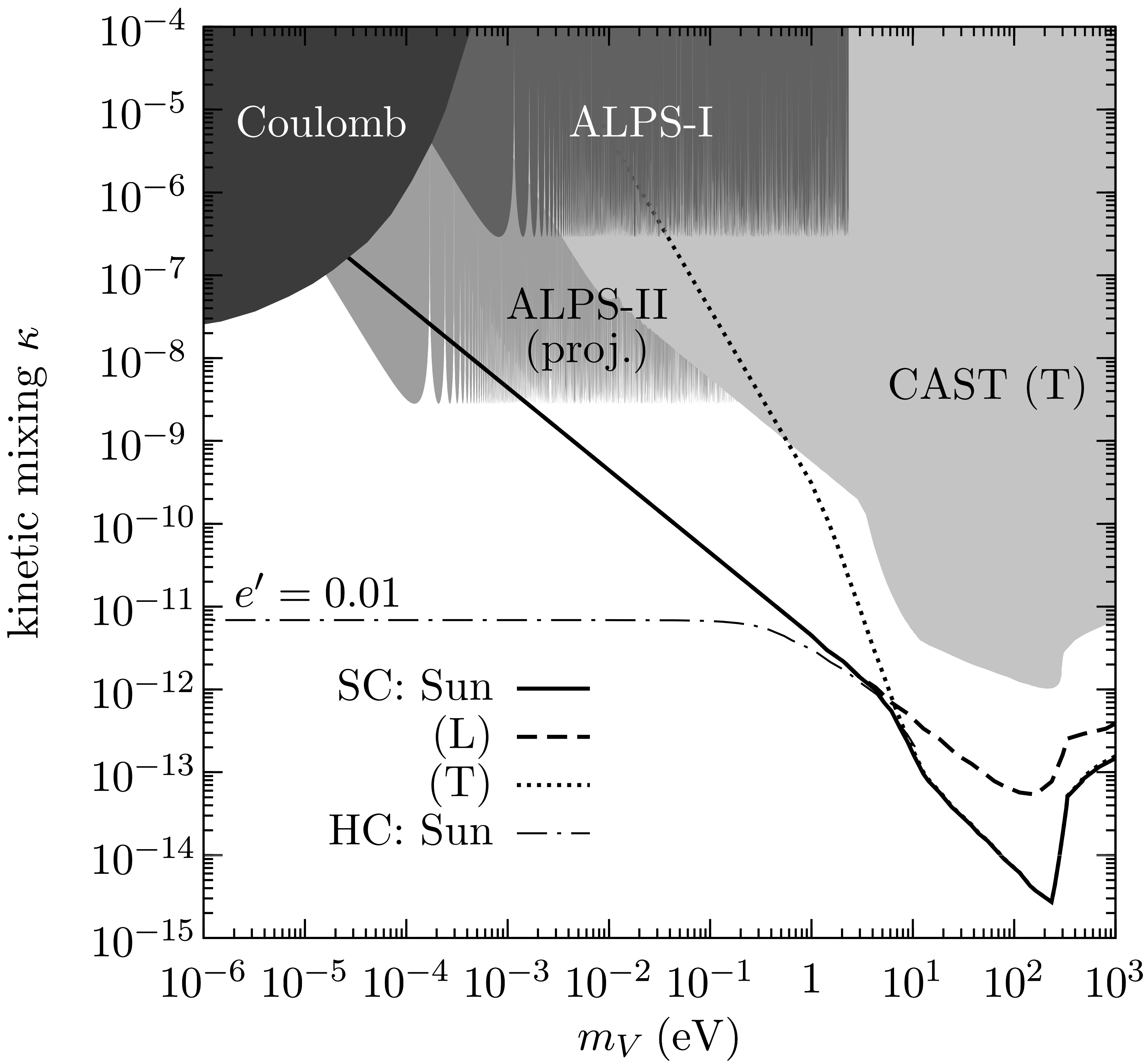

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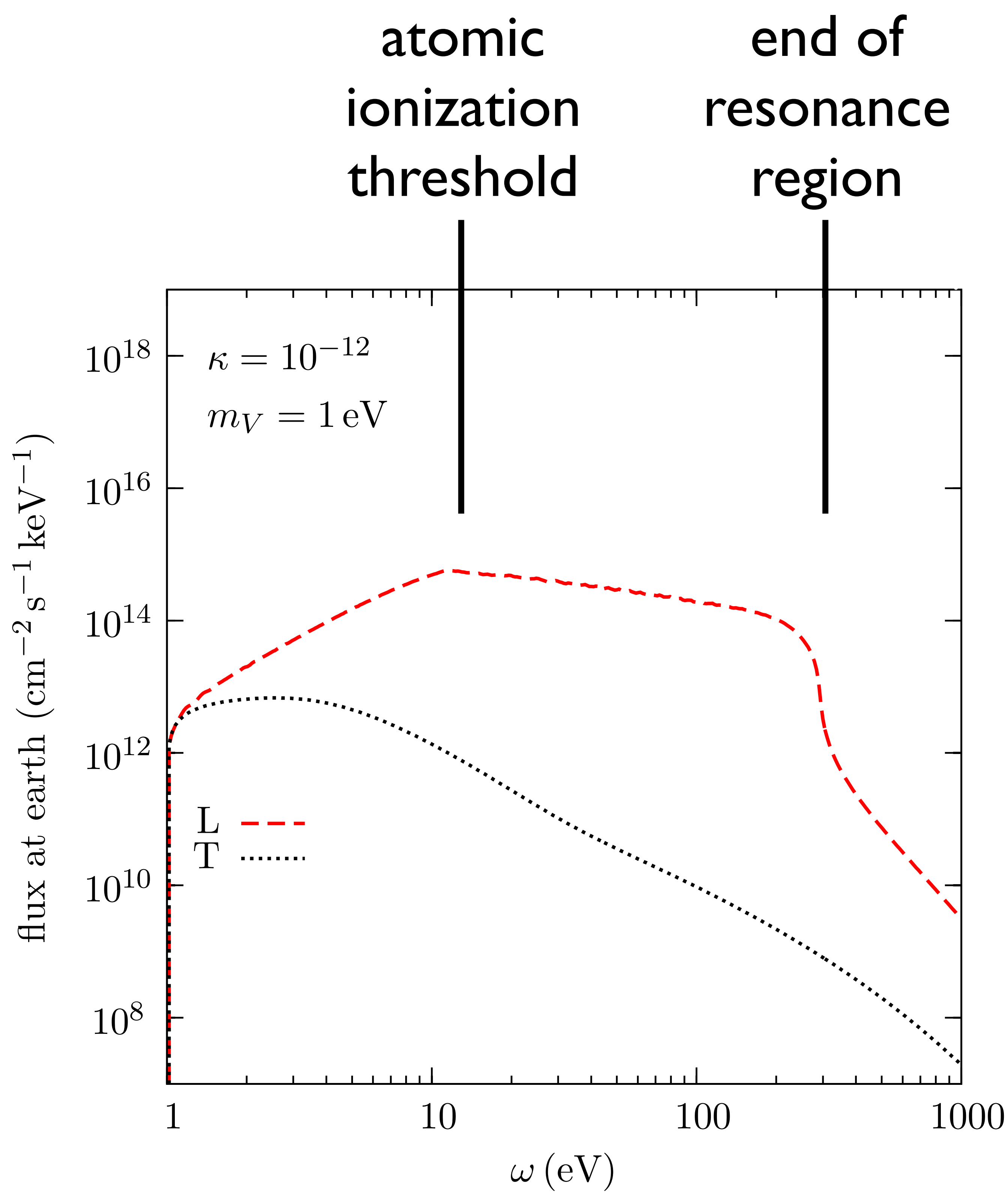
Direct detection of Dark Photons

Dark Photon absorption in Atoms

best sensitivity in the sub-keV energy regime

=> Xenon Dark Matter experiments

drift voltage: one electron is ionizes, efficiency almost 100% that it will be detected



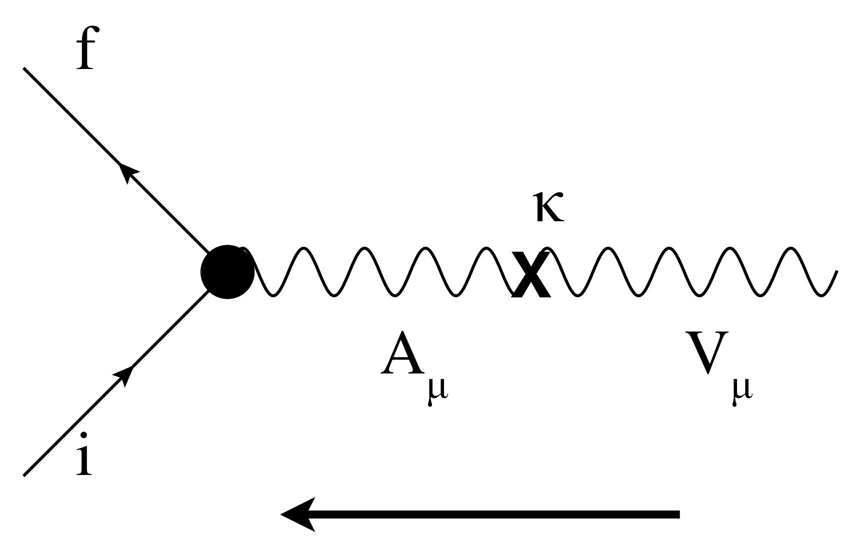
Direct detection of Dark Photons

flux at earth ↓ total absorption rate ↓

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

Analogous to the emission case

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



Direct detection of Dark Photons

Absorption rate

$$\Gamma^{\rm abs}_{T,L} = \frac{\kappa^2_{T,L} e^2 \epsilon_\mu^{T,L*} \epsilon_\nu^{T,L}}{2\omega} \int d^4x e^{iq\cdot x} \langle i | J^{\mu\dagger}_{\rm em}(x) J^\nu_{\rm em}(0) | i \rangle$$

correlation function inside the medium

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

$$\Gamma^{\rm abs}_{T,L} = -\frac{\kappa^2_{T,L}{\rm Im}\Pi_{\rm T,L}}{\omega}$$

optical theorem

$$\kappa^2_{T,L} = \frac{\kappa^2 m_V^4}{(m_V^2 - {\rm Re}\,\Pi_{T,L})^2 + ({\rm Im}\,\Pi_{T,L})^2}$$

Direct detection of Dark Photons

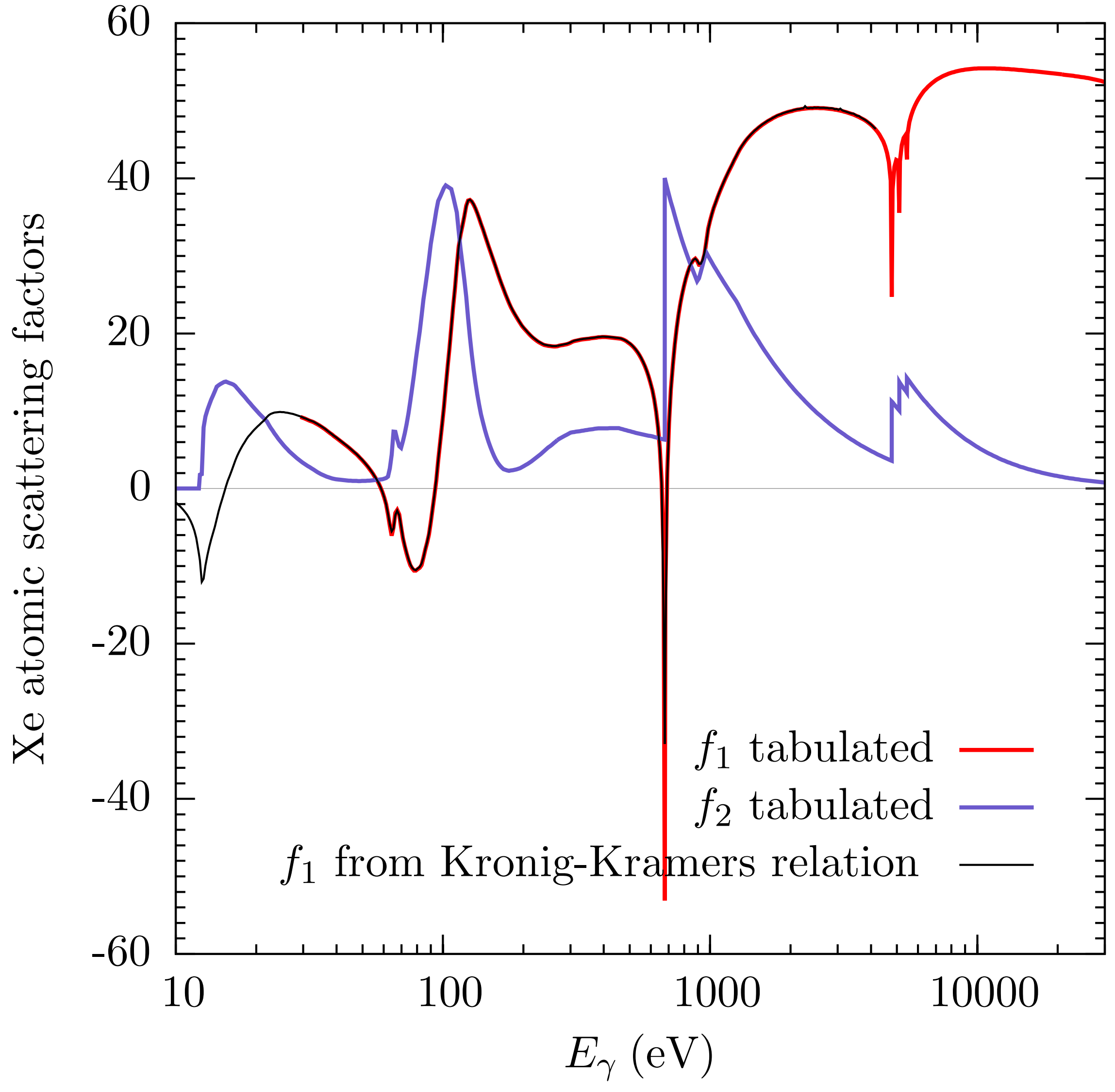
Making contact with "optical", measured quantities

$$n_{\rm ref} = 1 - \frac{r_e \lambda^2 n}{2\pi}(f_1 + i f_2)$$

$$\Pi_L = -m_V^2 \left[n_{\rm refr}^2 - 1 \right]$$

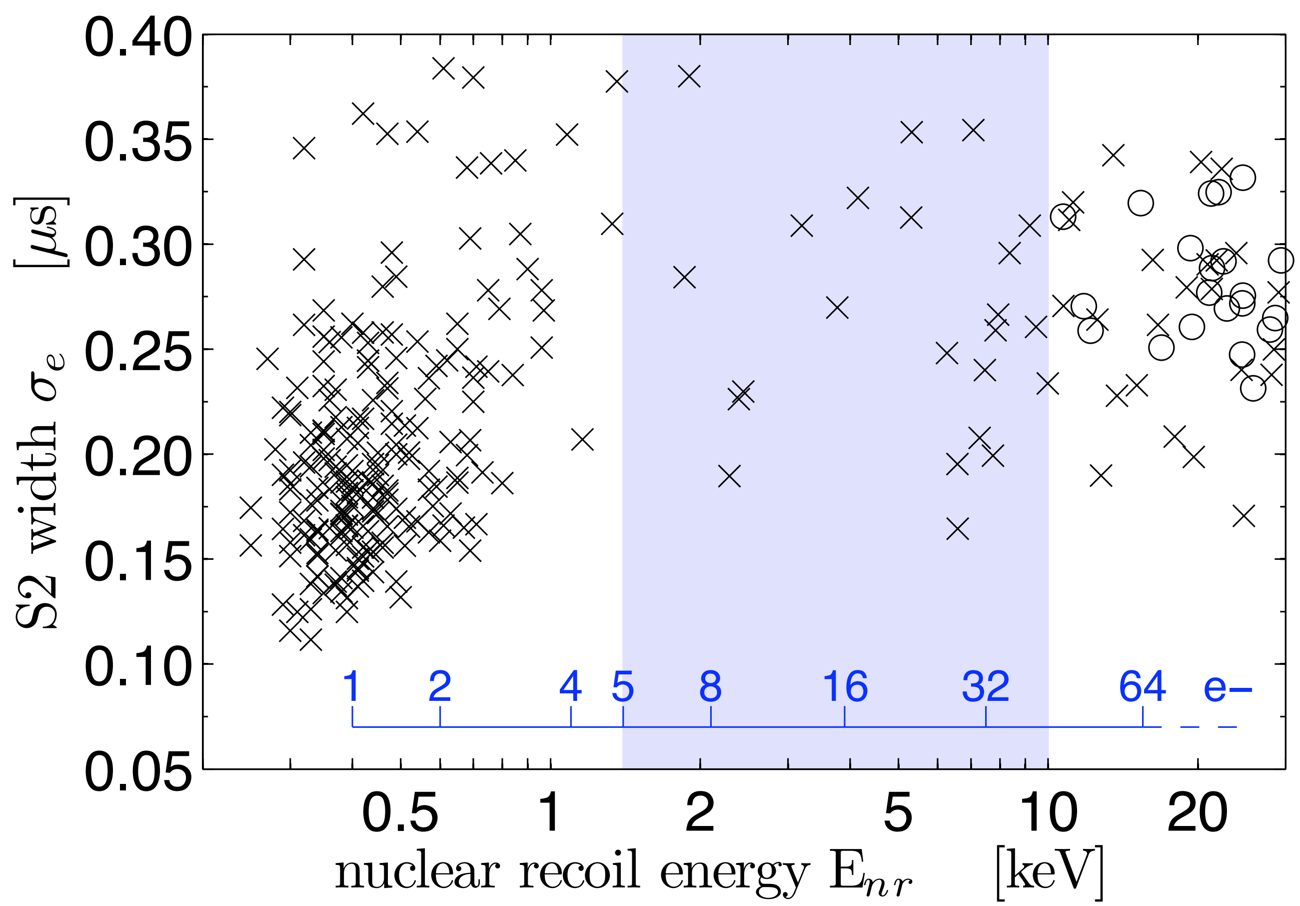
$$\Pi_T = -\omega^2 \left[n_{\rm refr}^2 - 1 \right]$$

$$\Gamma^{\rm abs}_{T,L} = -\frac{\kappa^2_{T,L} {\rm Im}\Pi_{\rm T,L}}{\omega}$$



Dark Matter experiments as Dark Photon helioscopes

- Xenon10 low threshold study: ionization only



Angle et al. 2011

Dark Matter experiments as Dark Photon helioscopes

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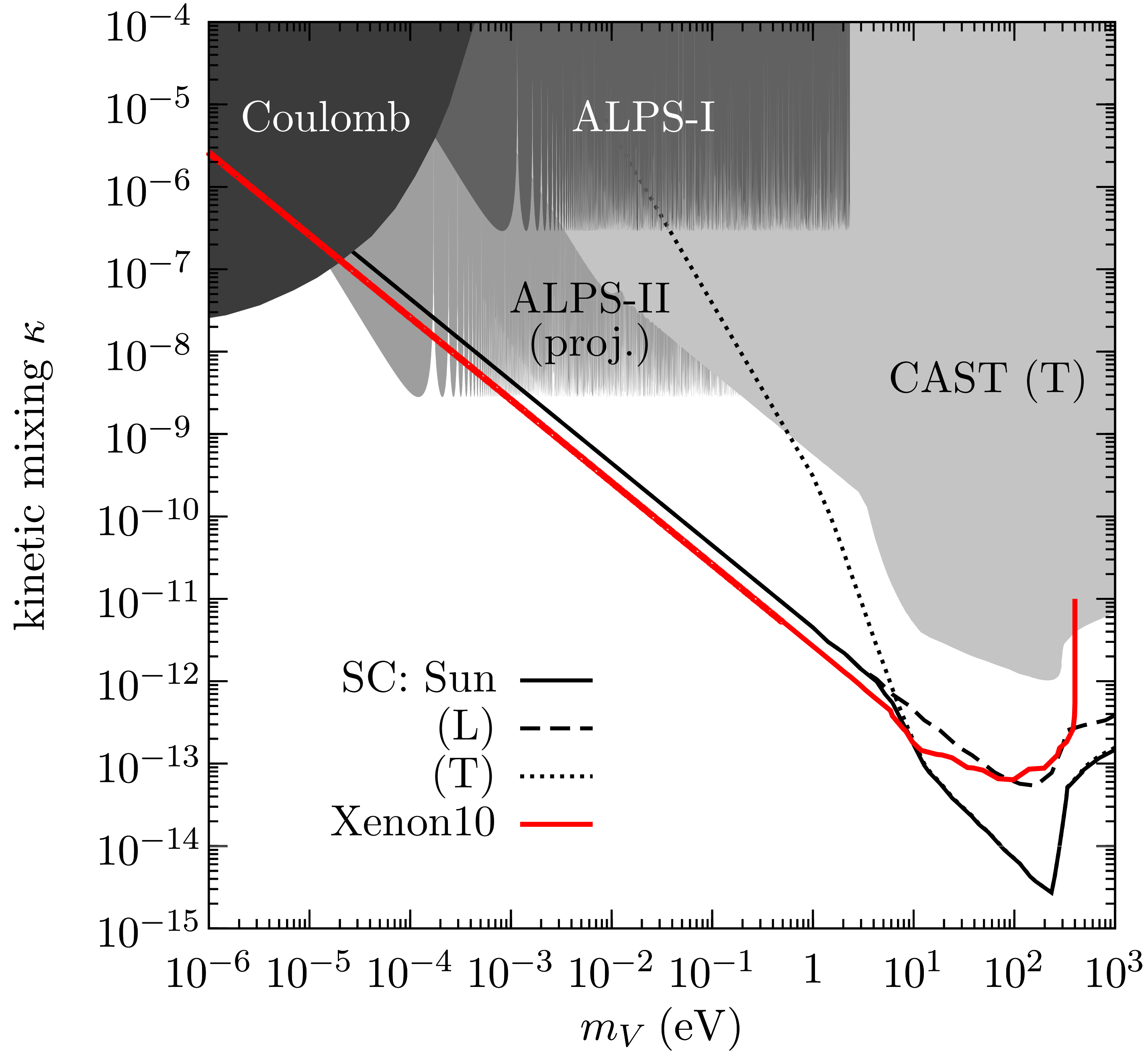
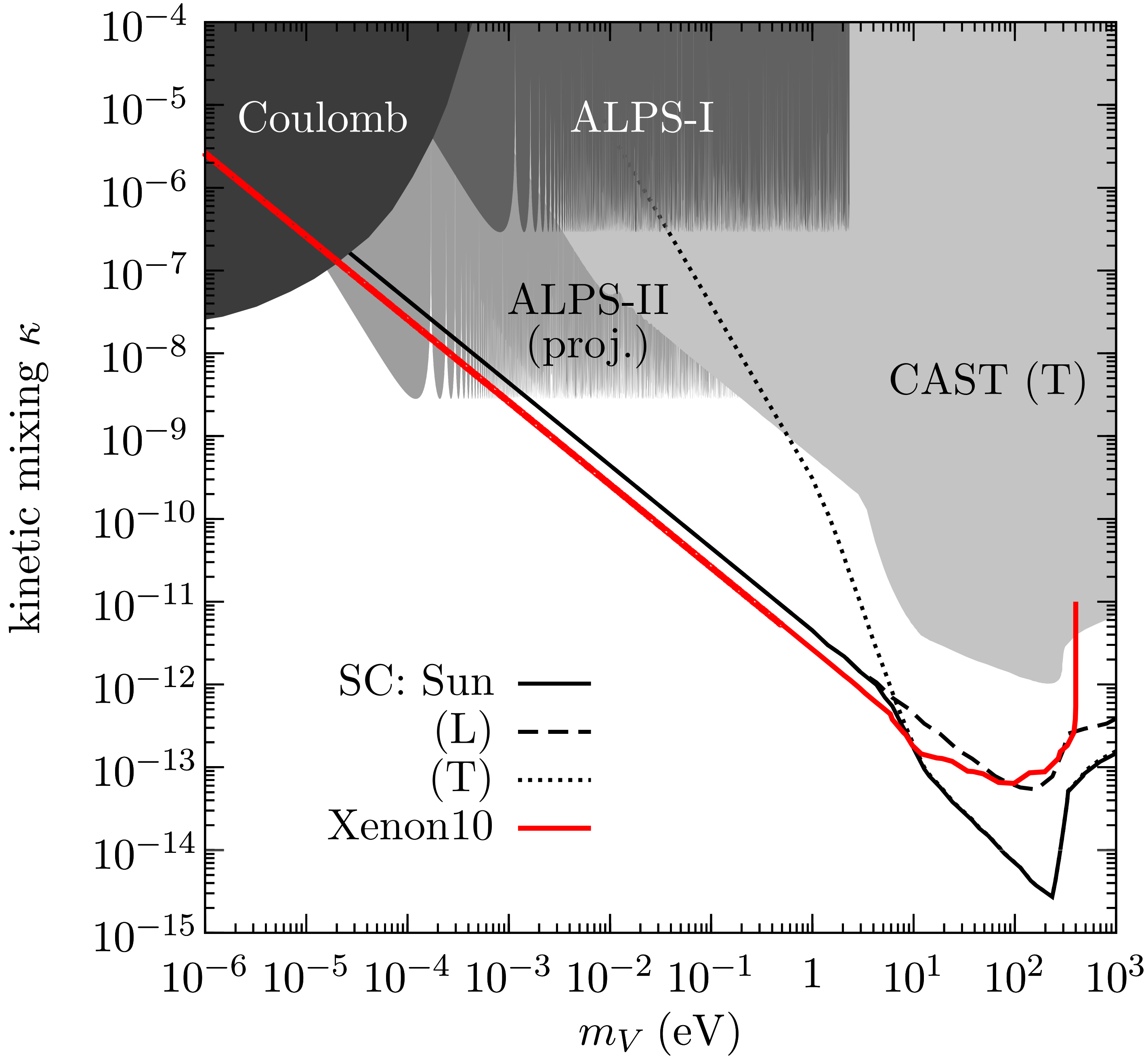
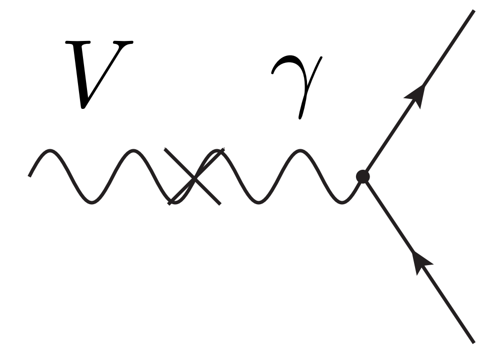


Dark Matter experiments as Dark Photon helioscopes

- Xenon10 low threshold study: ionization only
- CoGeNT does not yield a limit: required flux is not sustained by the sun
- Higgsed case: not yet sensitive to direct detection



Cosmological aspects: Long-lived vectors



$$\tau_V \leqslant 0.05\,\mathrm{s} \times \left(\frac{10^{-10}}{\kappa}\right)^2 \left(\frac{500\,\mathrm{MeV}}{m_V}\right)$$

$m_V > 2m_e$

↓

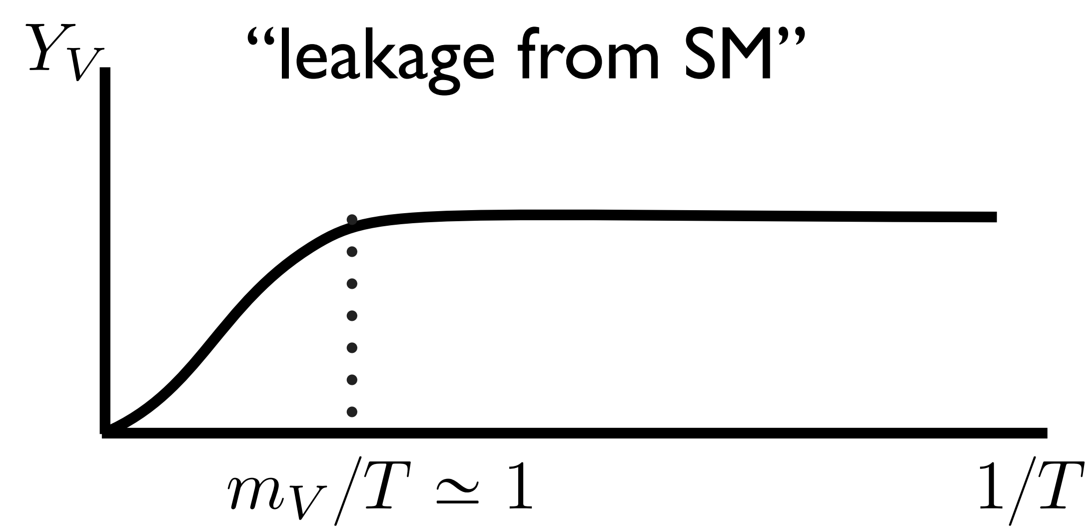
"super-Wimp"

$$\kappa \lesssim 10^{-12}$$

$$\Gamma_{\mathrm{prod}}(V) \ll H$$

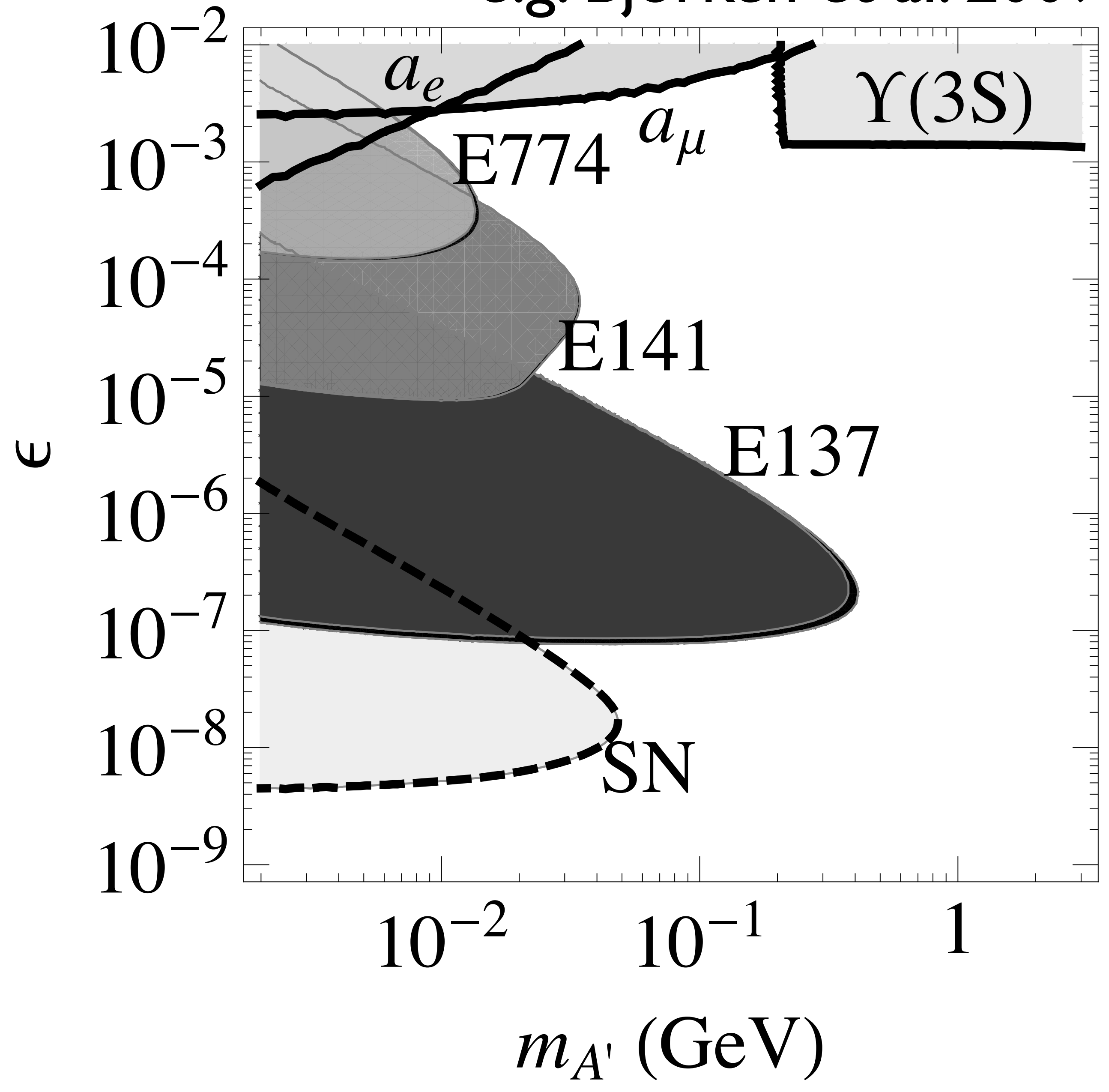
$$\Rightarrow \tau_V > 100\,\mathrm{s}$$

"leakage from SM"



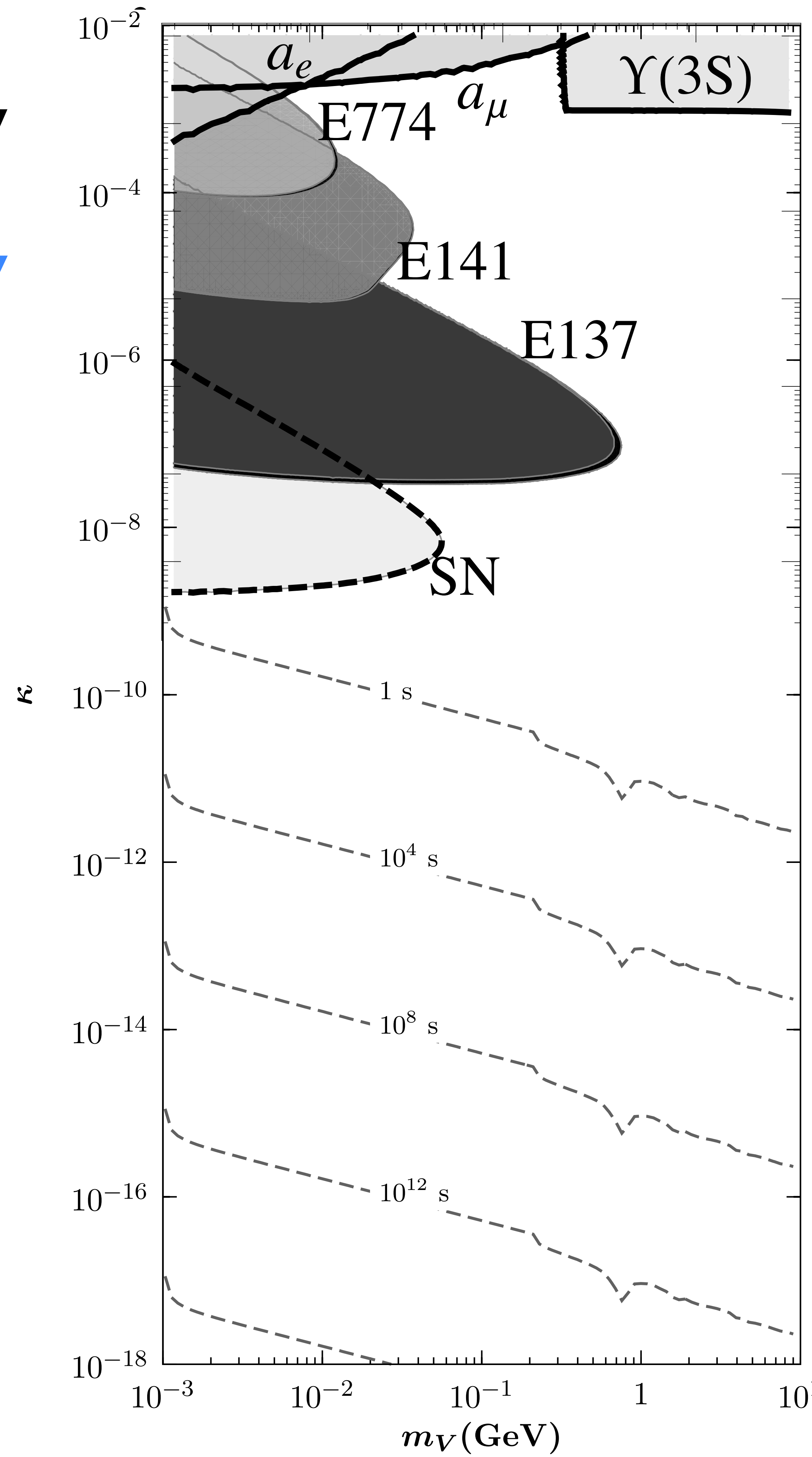
Extending our view
through cosmology

e.g. Bjorken et al. 2009

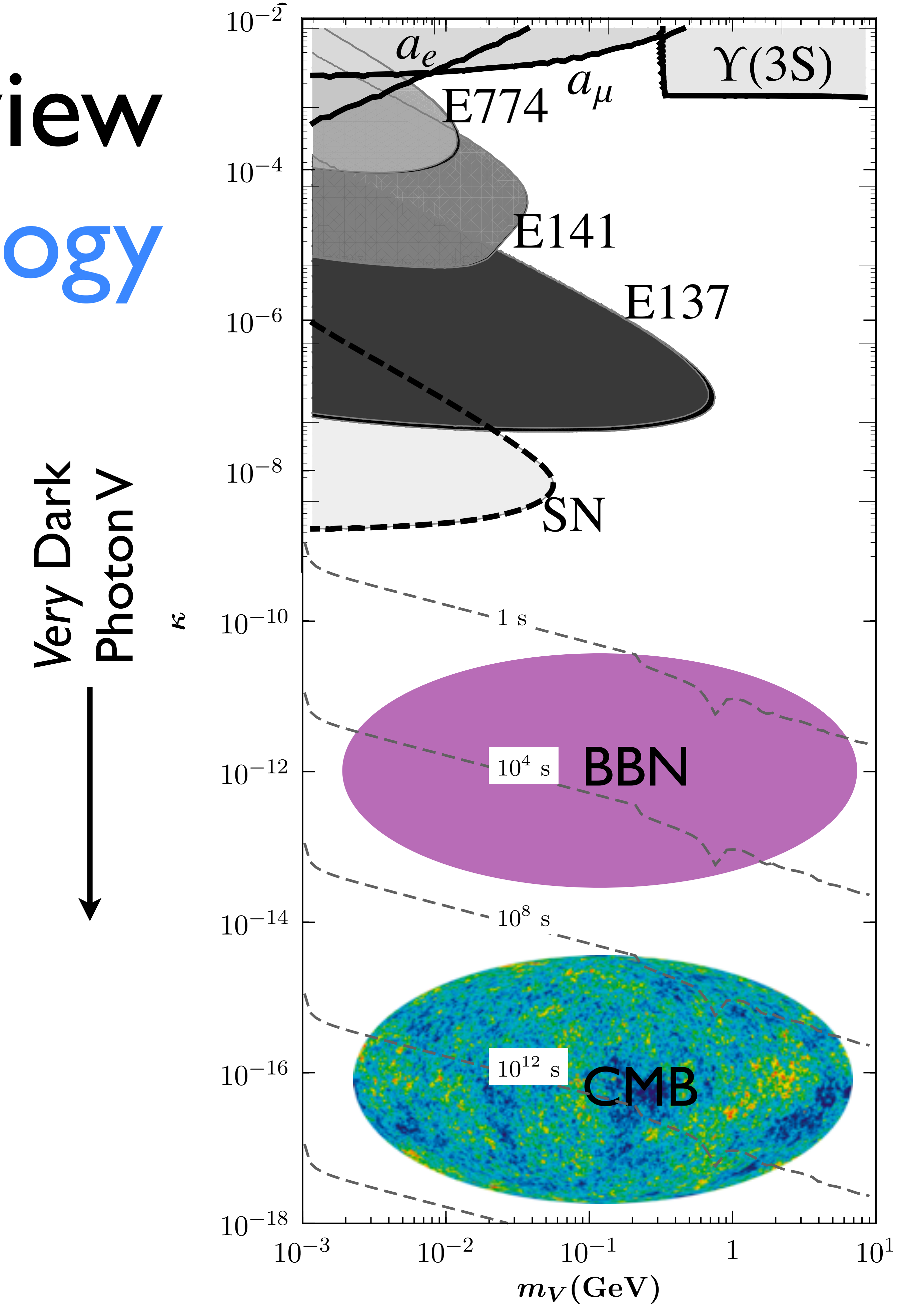


Extending our view through cosmology

Very Dark Photon V



Extending our view through cosmology



Extending our view through cosmology

$$E_{p.b.} = \frac{m_V n_V}{n_b}$$

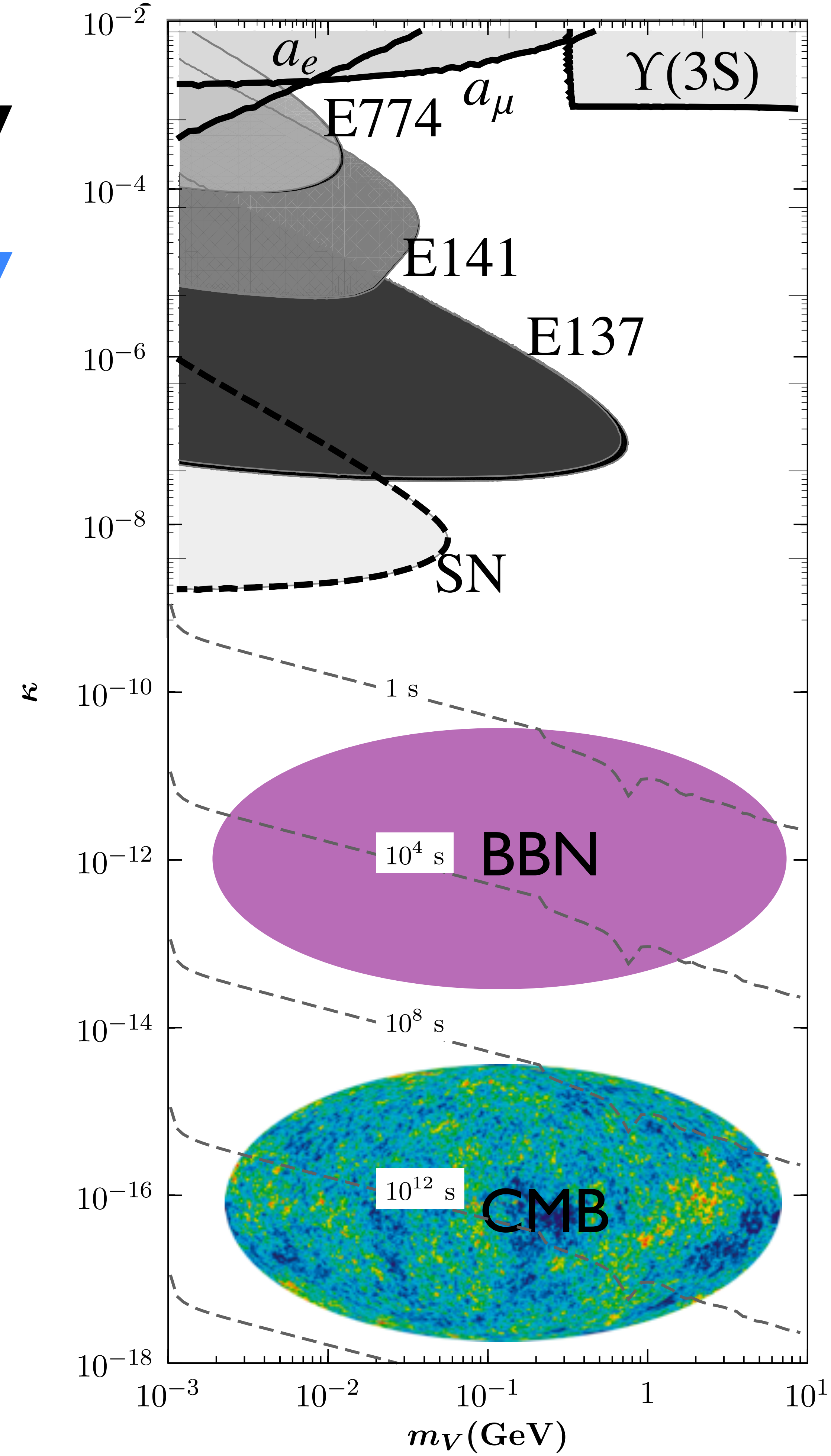
$$\sim \frac{m_V \Gamma_{\rm prod} H^{-1}_{T=m_V}}{n_{b,T=m_V}}$$

$$\sim \alpha_{\rm eff} \times 10^{36}\,{\rm eV}$$

$$\alpha_{\rm eff} = \kappa^2 \alpha$$

$$\Gamma_{\rm prod} \sim \tau_V^{-1} n_\gamma|_{T=m_V}$$

Very Dark Photon V



BBN sensitivity: MeV/baryon

CMB sensitivity: eV/baryon

in preparation with
A. Fradette, M. Pospelov, A. Ritz

Very Dark Photons
Lithium solution

"Soft" hadronic energy injection (t > 100 sec)

- for V above di-pion threshold

$$\pi^- + p \to \pi^0 + n$$

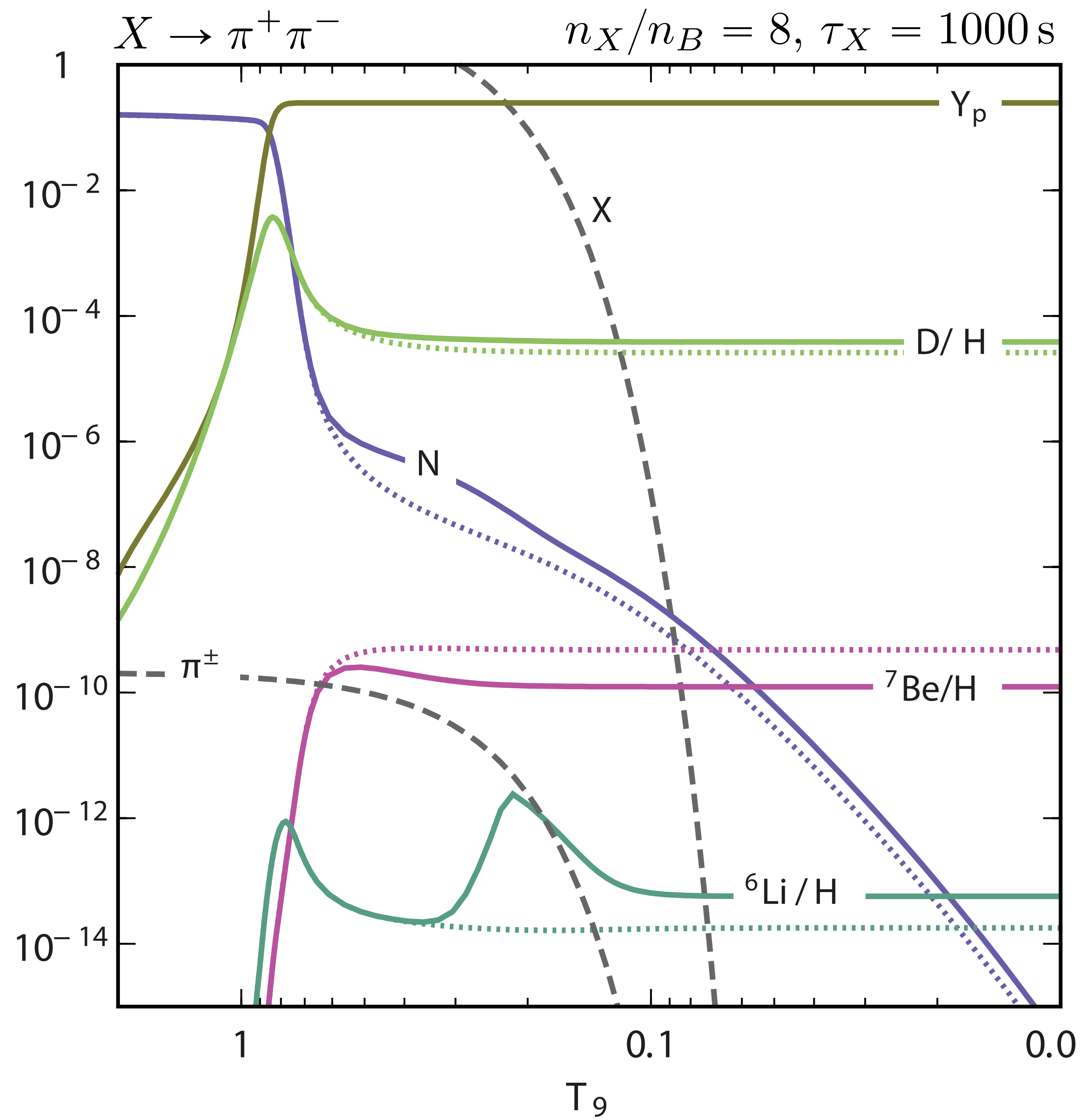
"extra neutrons"

- a generic solution to the lithium problem

$$^7\mathrm{Be} + n \to {}^7\mathrm{Li} + p$$

$$^7\mathrm{Li} + p \to {}^4\mathrm{He} + {}^4\mathrm{He}$$

[see also M. Pospelov, JP 2010]



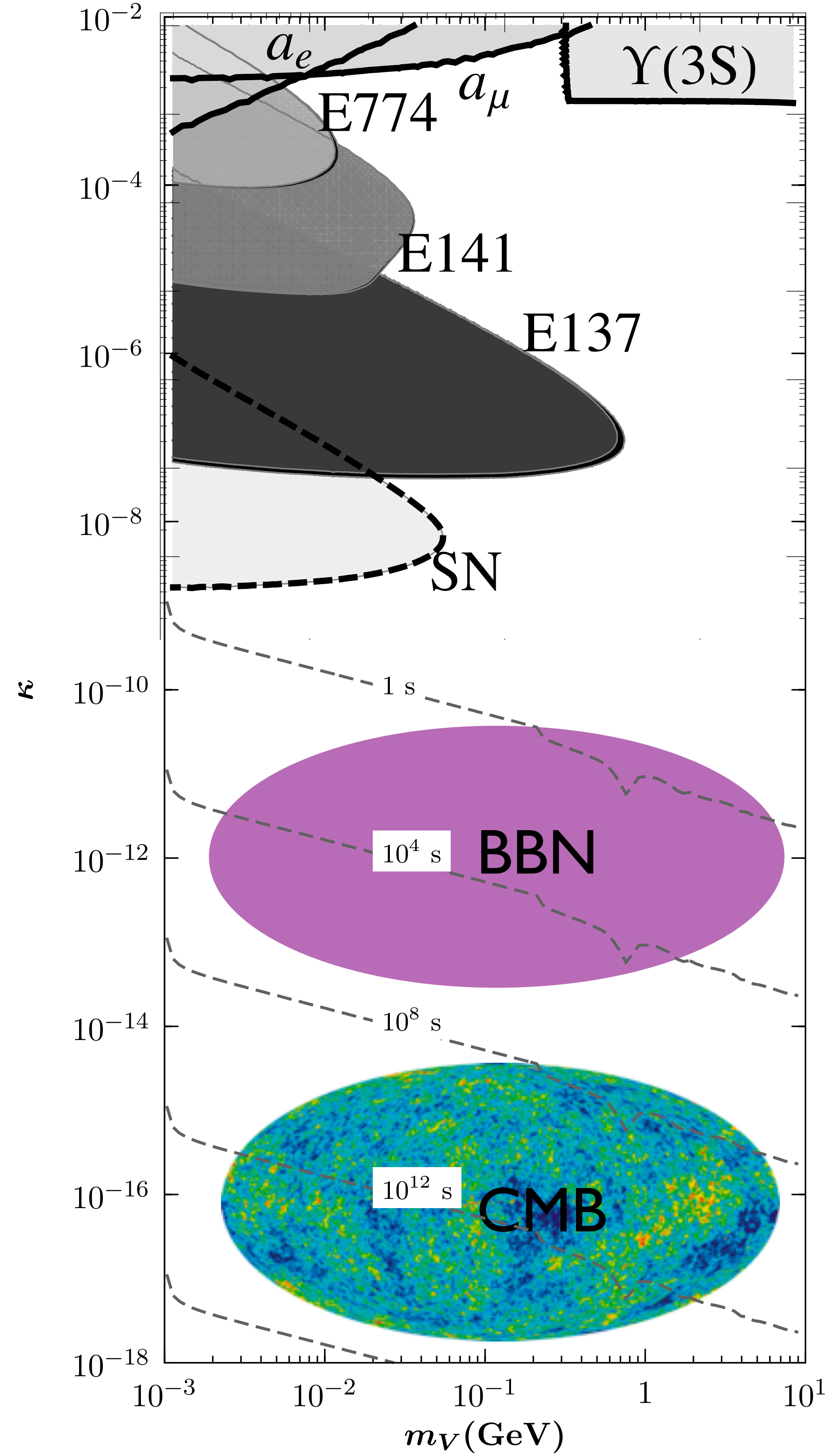
Dark Photons in Cosmology

- long-lived vectors inject energy into the primordial plasma
- Early Universe has unprecedented sensitivity

$$\alpha' = \frac{(\kappa e)^2}{4\pi} > 10^{-38}$$

- BBN/CMB constraints are guaranteed, Li-sweet spots will exist

in preparation with
A. Fradette, M. Pospelov, A. Ritz



Conclusions

Origin of Dark Photon mass plays an important role in the phenomenology of light vectors (Stueckelberg vs. Higgsed case)

Stellar energy loss bounds are strengthened by several orders of magnitude, with important implications for LSW and Helioscope searches (see now also Raffelt and Redondo 2013)

Detection prospects best when using sub-keV low threshold detectors with sensitivity in the electron recoil band

Early Universe constraints on electromagnetic and hadronic energy injection constrain mixing $\kappa \lesssim 10^{-12}$ and $m_V > 1\,\mathrm{MeV}$