The Photon self-energy

and its implications on dark photon searches

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CRAQ
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Fonds de recherche – Nature et technologies
Fonds de recherche – Santé
Fonds de recherche – Société et culture

Trottier Space Institute at McGill
Institut spatial Trottier de McGill

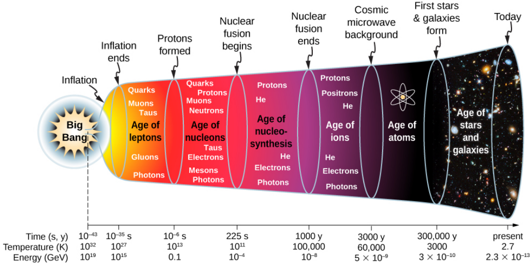
I will talk about

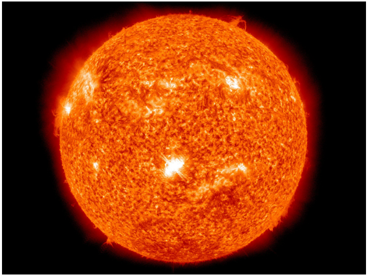
- Astroparticle physics
- Hot and dense medium
- Modified photon behavior
- Real vs **virtual** photons
- Dark photon

Warning!

$$c = \hbar = k_B = 1$$

High-temperature high-density environments

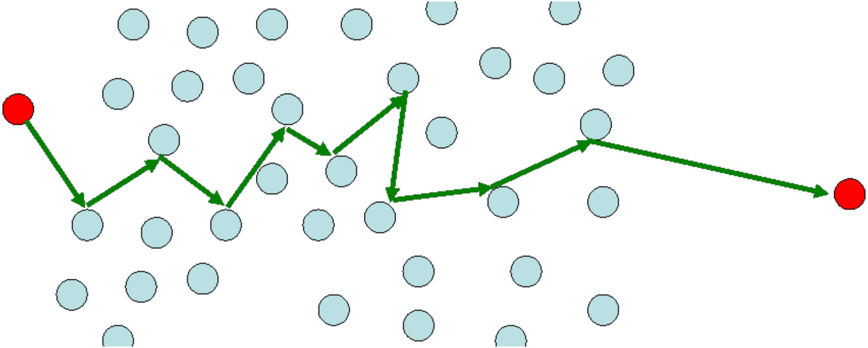




electron-positron plasma

fig.: https://phys.libretexts.org/
https://education.nationalgeographic.org

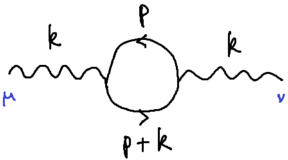
In-medium behavior



Photon:
- Effective mass
- One new longitudinal (L) mode

fig.: https://www.globalsino.com/

Photon self-energy



$$\Pi^{\mu\nu} = 16\pi\alpha \int \frac{d^3p}{(2\pi)^3}\frac{1}{2E_p}\left[f_{FD}(E_p) + \bar{f}_{FD}(E_p)\right] \times \frac{(p\cdot k)(k^\mu p^\nu + k^\nu p^\mu) - (k^2)p^\mu p^\nu - (p\cdot k)^2\eta^{\mu\nu}}{(p\cdot k)^2 - \frac{1}{4}(k^2)^2}$$

Homogeneous and isotropic

$$\Pi^{\mu\nu} = P_L^{\mu\nu}\pi_L + P_T^{\mu\nu}\pi_T$$

Complex-valued self-energy $\Pi^{\mu\nu}$

- $\mathrm{Re}\,\pi_{L,T}$: effective masses squared

$$\omega^2 - k^2 = \mathrm{Re}\{\pi_{L,T}\}$$

- $\mathrm{Im}\,\pi_{L,T}$: absorption and dissipation effects

Braaten and Segel (real photons)

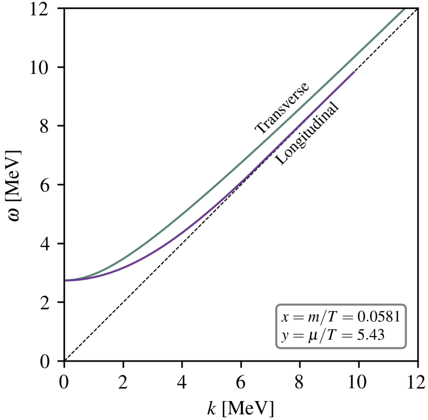
Real photons follow

$$\omega^2 - k^2 = \pi_{L,T}(\omega, k)$$

Approximations

$$\pi_L \sim \omega_P^2 \left[1 - G(v_*^2 k^2/\omega^2)\right]$$
$$\pi_T \sim \omega_P^2 \left[1 + \tfrac{1}{2} G(v_*^2 k^2/\omega^2)\right]$$

$$G(x) = \frac{3}{x}\left[1 - \frac{2x}{3} - \frac{1-x}{2\sqrt{x}} \log\left(\frac{1+\sqrt{x}}{1-\sqrt{x}}\right)\right]$$

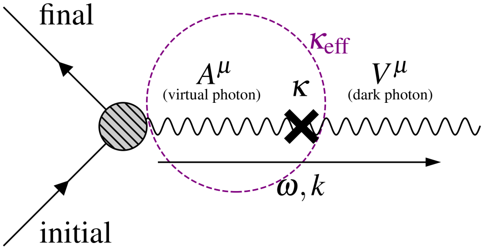


$$T = 8.6 \text{ MeV} \simeq 10^{11} \text{ K}$$
$$\mu = 46.7 \text{ MeV}$$

Braaten, Segel. Phys. Rev. D 48 (1993) 1478–1491
Raffelt. Stars as laboratories for fundamental physics

Dark photon

Spin-1 boson; mass m_V; coupling strength to photon κ.
Production



Resonance

$$\kappa^2_{eff;L,T} = \frac{\kappa^2 m_V^4}{(m_V^2 - \mathrm{Re}\,\pi_{L,T})^2 + (\mathrm{Im}\,\pi_{L,T})^2}$$

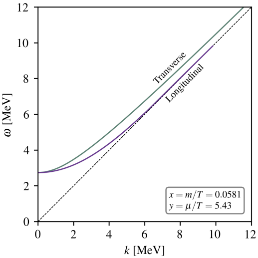
An, Pospelov, Pradler. Phys. Lett. B 725 (2013) 190–195

Virtual photons

Do not follow the dispersion relations

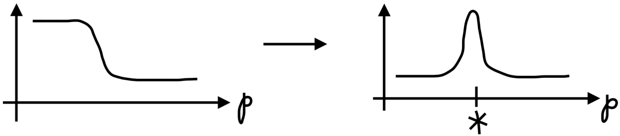
$$\omega^2 - k^2 = \pi_{L,T}(\omega, k)$$

- All values of ω and k
- Not Braaten and Segel



New general analytic approximation

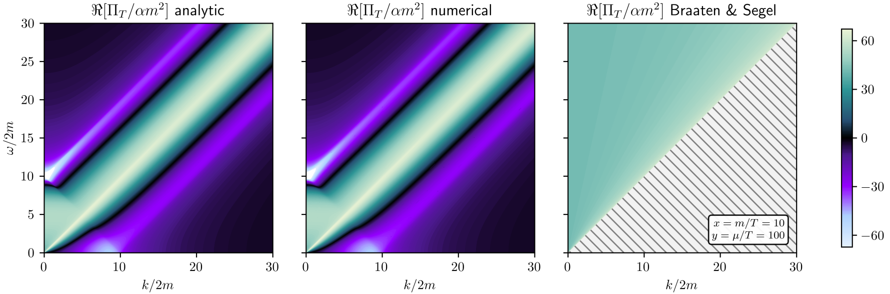
$$\pi_{L,T} \propto \int_0^\infty \mathrm{d}p\,[\ldots](f+\bar{f}) = -\int_0^\infty \mathrm{d}p\,[\ldots]\frac{\mathrm{d}}{\mathrm{d}p}\left(f+\bar{f}\right)$$



$$\mathrm{Re}\left\{\pi_T\right\} \simeq \omega_P^2\left[\frac{2\omega^2+k^2}{2k^2v_*^2}+\frac{(1-v_*^2)(\omega^2-k^2)^2}{4m^2v_*^3}\log\left(\frac{1+v_*}{1-v_*}\right)+\ldots\right]$$

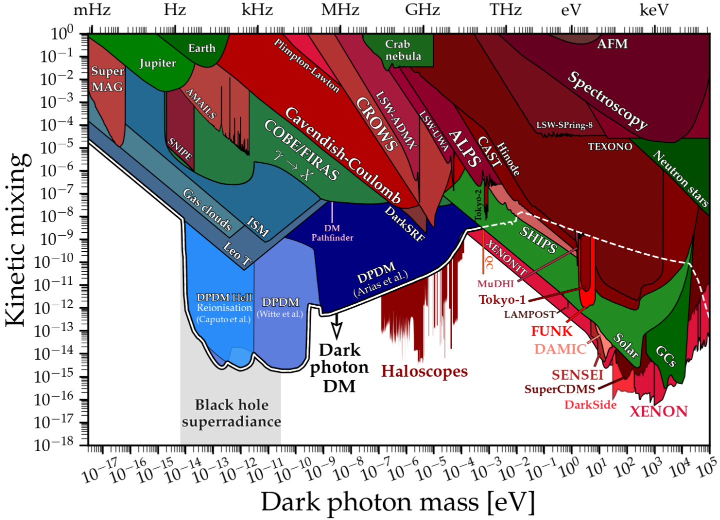
$$\mathrm{Im}\left\{\pi_T\right\} \simeq -\omega_p^2\left[\frac{3\pi\omega(\omega^2-k^2v_*^2)}{8k^3v_*^3}+\ldots\right]$$

Self-energy: real part (T)



arXiv:24XX.XXXXX

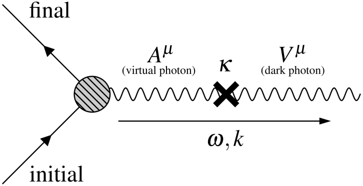
Outlook



Caputo et al. Phys. Rev. D 104 (2021) 095029; https://cajohare.github.io/AxionLimits/docs/dp.html

Summary

- In-medium effects are important!
- Virtual photons are different from real ones
- New analytical approximation for real and virtual photon self-energy
- Next step: update dark photon bounds



Thank you!

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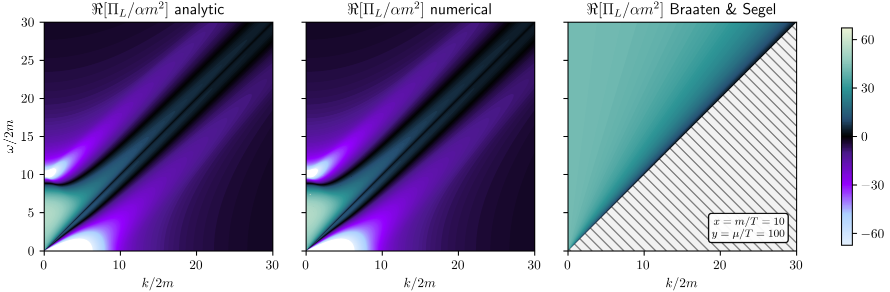
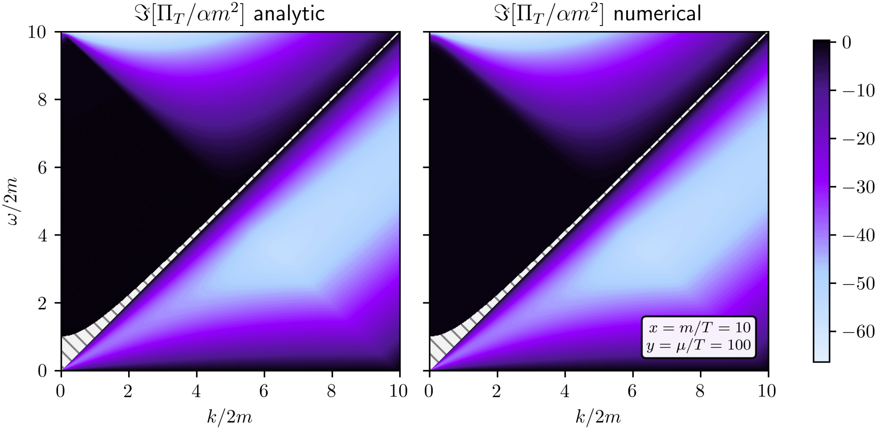
Additional slides

Self-energy: real part (L)



Self-energy: imaginary part (T)



Self-energy: imaginary part (L)