The Photon Self-Energy

and its Implications for Dark Matter Searches

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McGill

Motivation

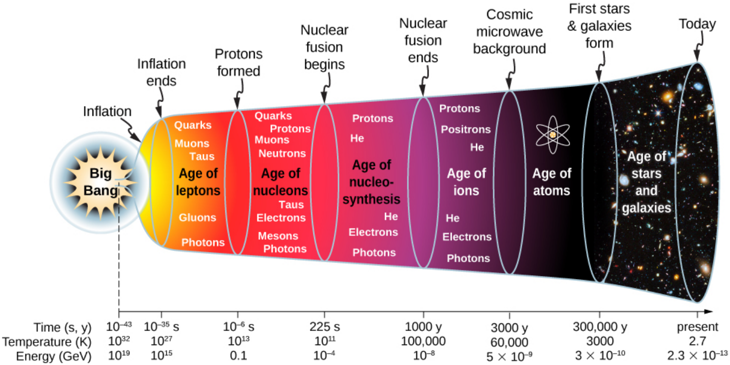
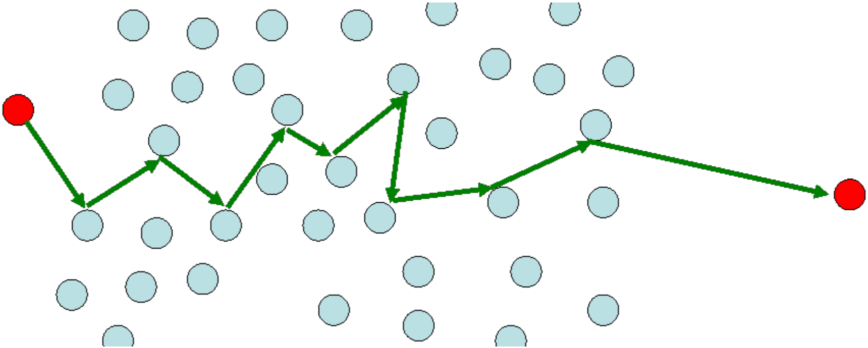


fig.: https://phys.libretexts.org/

In-medium behavior

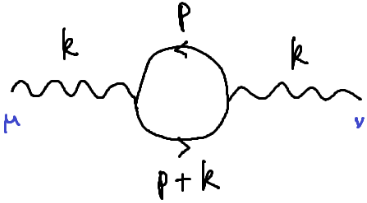


Photon:
- Effective mass
- One new longitudinal (L) mode

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

Photon self-energy

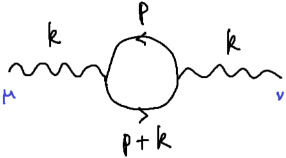
Finite temperature field theory



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

$$\times \frac{(p \cdot k)(k^\mu p^\nu + k^\nu p^\mu) - (k^2) p^\mu p^\nu - (p \cdot k)^2 \eta^{\mu\nu}}{(p \cdot k)^2 - \frac{1}{4}(k^2)^2}$$

Photon self-energy



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

- $\mathrm{Re}\,\Pi$: effective masses
- $\mathrm{Im}\,\Pi$: absorption and dissipation effects

Homogeneous and isotropic

$$\Pi^{\mu\nu} = e_L^\mu e_L^\nu \pi_L + \sum_{i=1,2} e_{T_i}^\mu e_{T_i}^\nu \pi_T$$

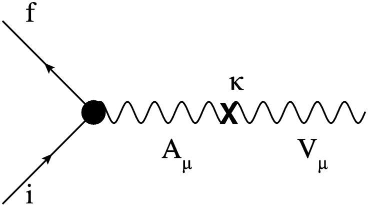
Dispersion relation

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

Propagator

$$D \sim \frac{i}{\omega^2 - k^2 - \pi_{L,T}}$$

$$\mathcal{L} \supset \frac{1}{2}\kappa V_{\mu\nu} F^{\mu\nu}$$

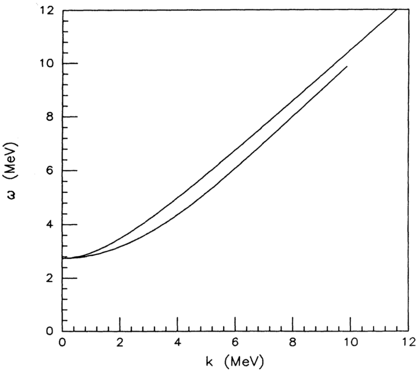


Resonance

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

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

Braaten and Segel prescription



$T = 8.6$ MeV, $\mu = 46.7$ MeV

On-shell

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

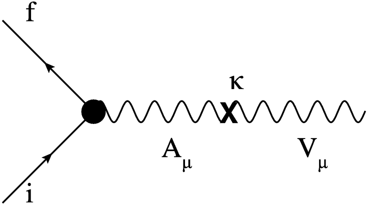
$$\pi_L \sim \omega_P^2 \left[1 - G(v_*^2 k^2/\omega^2)\right]$$
$$\pi_T \sim \omega_P^2 \left[1 + \tfrac{1}{2} G(v_*^2 k^2/\omega^2)\right]$$

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

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

Braaten and Segel prescription

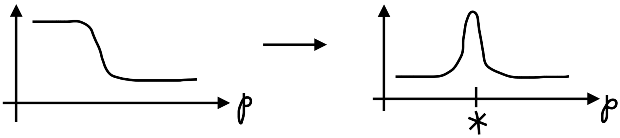
Also valid off-shell? No!



We need off-shell expressions!

New general analytic approximation

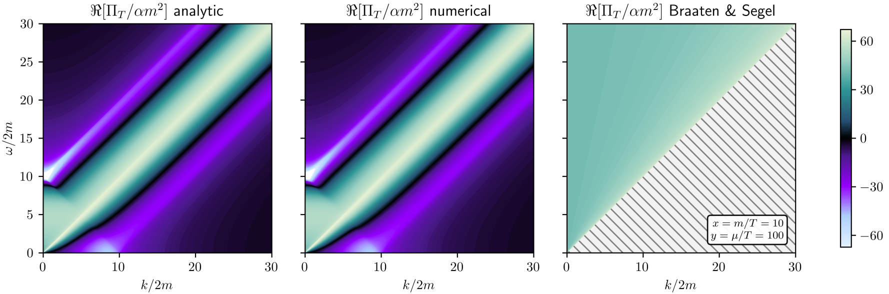
$$\pi_{L,T} \propto \int_0^\infty \mathrm{d}p \, [\dots](f + \bar{f}) = -\int_0^\infty \mathrm{d}p \, [\dots] \frac{\mathrm{d}}{\mathrm{d}p}\left(f + \bar{f}\right)$$



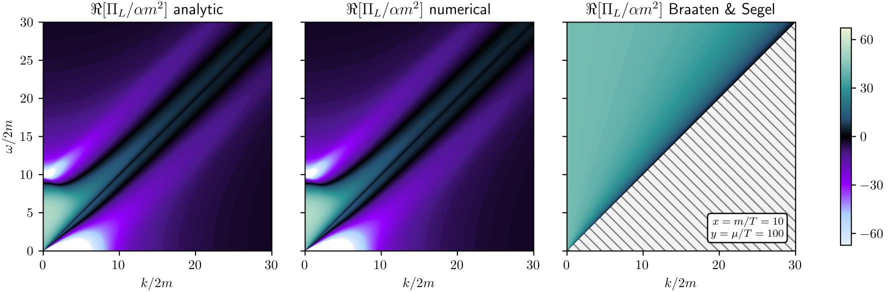
$$\mathrm{Re}\{\pi_T\} \simeq \omega_P^2 \left[\frac{2\omega^2 + k^2}{2k^2 v_*^2} + \frac{(1 - v_*^2)(\omega^2 - k^2)^2}{4m^2 v_*^3} \log\left(\frac{1 + v_*}{1 - v_*}\right) + \dots \right]$$

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

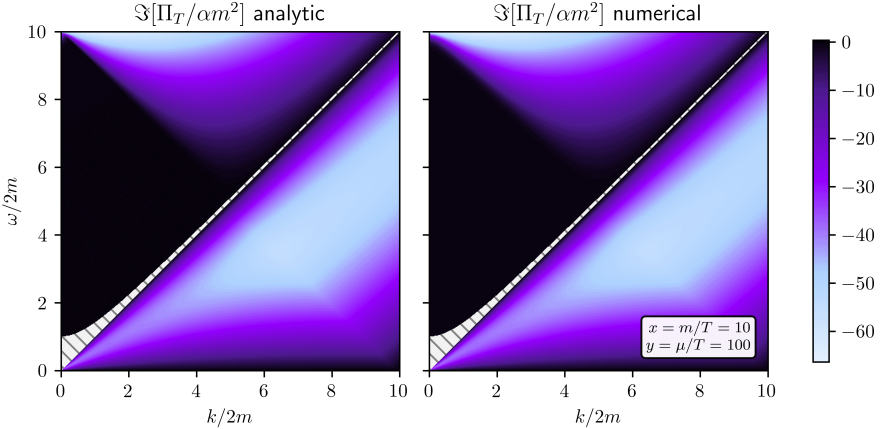
Self-energy: real part (T)



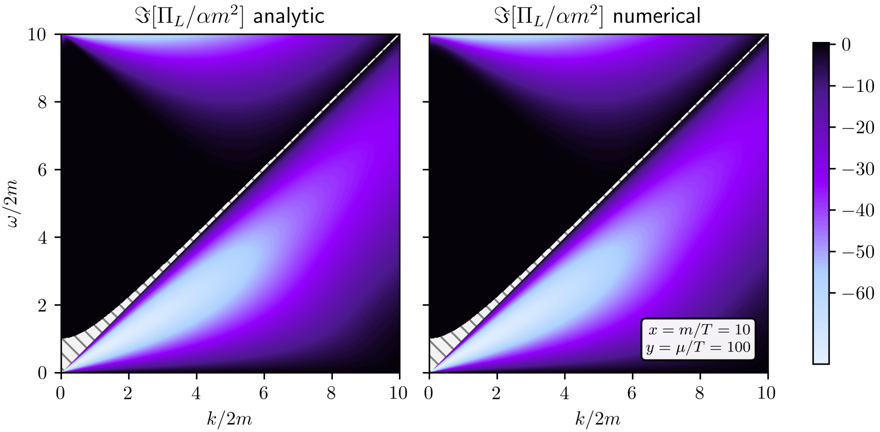
Self-energy: real part (L)



Self-energy: imaginary part (T)

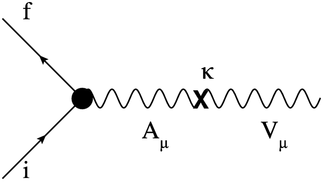


Self-energy: imaginary part (L)



Summary and outlook

- In-medium effects are important!
- New analytical approximation for photon self-energy
- Next steps: dark matter production in early universe



Thank you!

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