MPA SUMMER SCHOOL 2023

Thermal Corrections to Freeze-In Dark Matter

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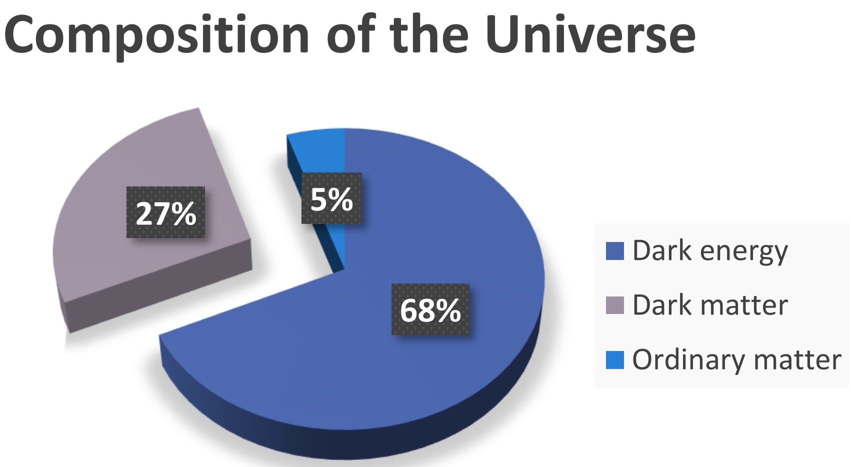
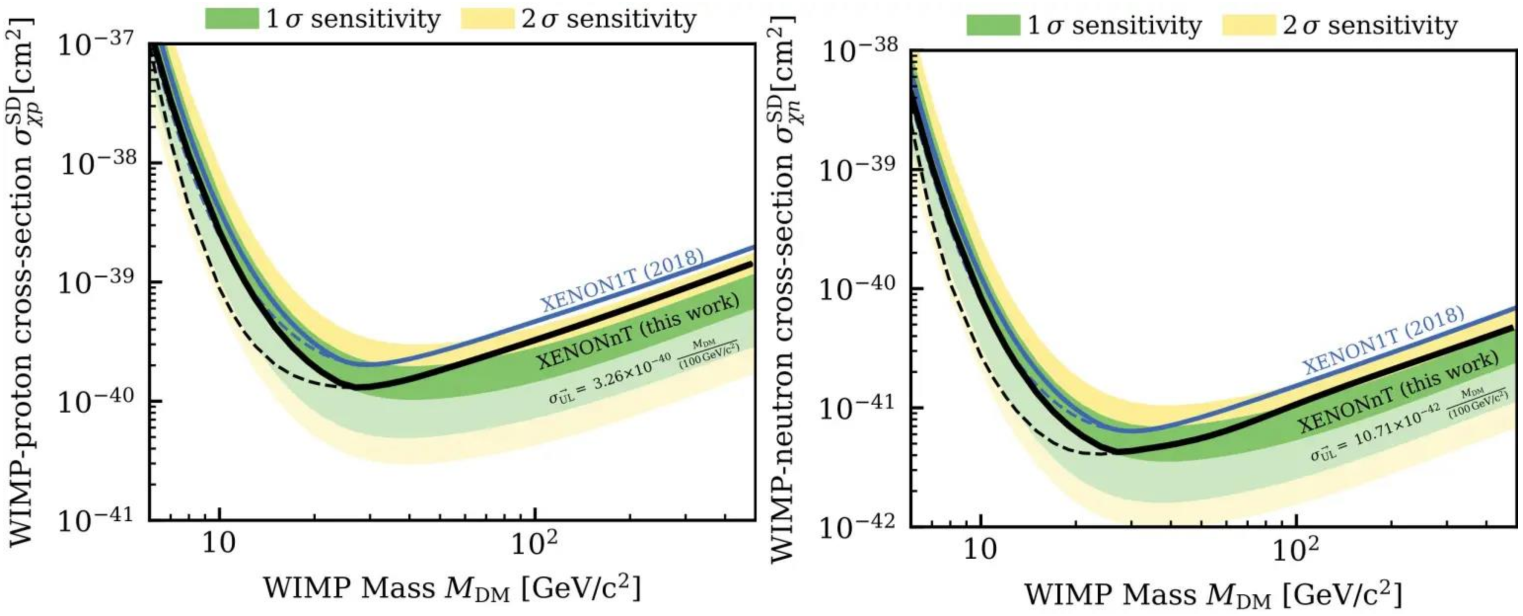
Motivation

- Stringent experimental constraints on DM; FIMPs
- Necessary framework to describe the thermal bath; Thermal Field Theory





XENON collaboration, D. Wenz talk, 2023

Dark Matter Production

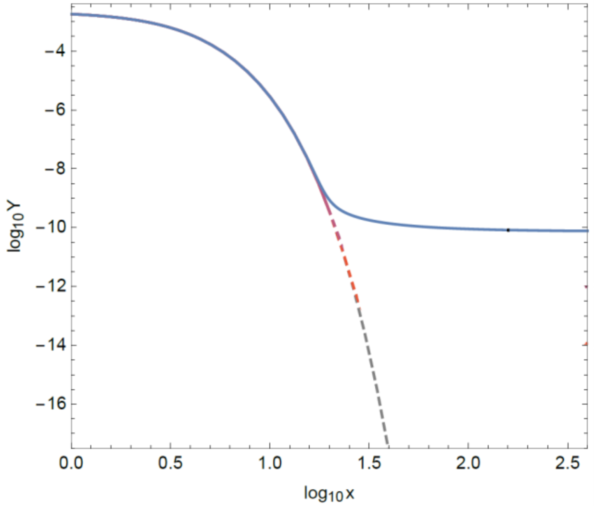
Weakly-Interacting Massive Particle (WIMP)

Weak scale coupling, $y \simeq \mathcal{O}(0.1)$

$Y = n/s$
$x = m/T$

Freeze-out mechanism

$T_{\mathrm{dec}} \sim M/30$



DM depleted by pair annihilations

Adapted from Bernal et al., 2017

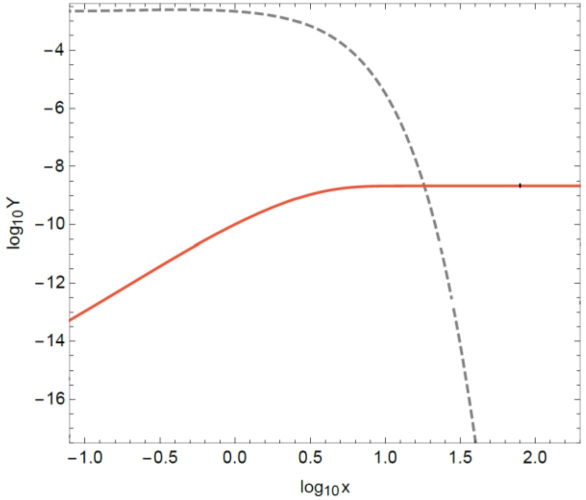
Feebly-Interacting Massive Particle (FIMP)

Very small coupling, $y \simeq \mathcal{O}(10^{-7})$

DM was never in equilibrium with the visible sector

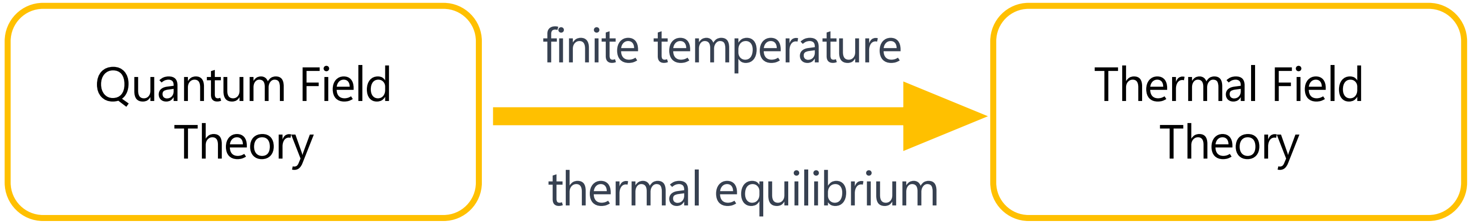
Freeze-in mechanism

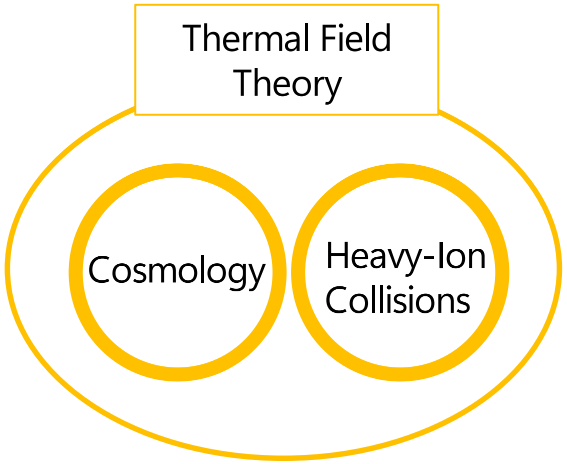
$T_{\mathrm{dec}} \sim M/5$



DM generated through decays, annihilations and $2 \leftrightarrow 2$ scatterings

Thermal Field Theory I





Statistical distributions and thermal excitations lead to e.g. different expectation values

$$\langle A \rangle_0 = \sum_n \langle n|A|n \rangle$$

$$\langle A \rangle_\beta = \frac{1}{Z} \sum_n \langle n|A|n \rangle e^{-\beta H} = \frac{1}{Z} \mathrm{Tr}(e^{-\beta H} A)$$

Canonical ensemble

$$\mathrm{Z} = \mathrm{Tr}(e^{-\beta H})$$

Path integral representation

$$Z = \int D\phi \exp\left(i \int d^4x \, \mathcal{L}\right)$$

The thermal Green functions encode information about the fields in a thermal ensemble

$$G_\beta(x_1, x_2) = \frac{1}{Z} \mathrm{Tr}\left(e^{-\beta H} T_c \phi(x_1) \phi(x_2)\right)$$

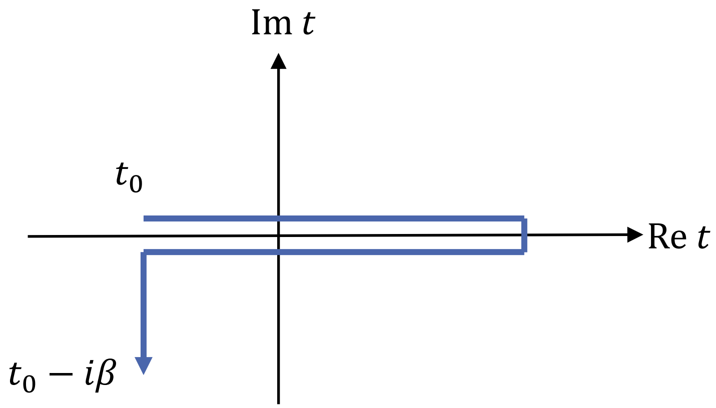
Thermal Field Theory II

Real time formalism (Schwinger-Keldysh)

- Path-ordered approach
- Doubling of degrees of freedom

Free propagator

$$D_F(k_0) = \underbrace{\frac{1}{k_0^2 - \omega^2 + i\eta}}_{\text{zero temperature}} + \underbrace{2\pi n(k_0)\delta\left(k_0^2 - \omega^2\right)}_{\text{finite temperature}}$$



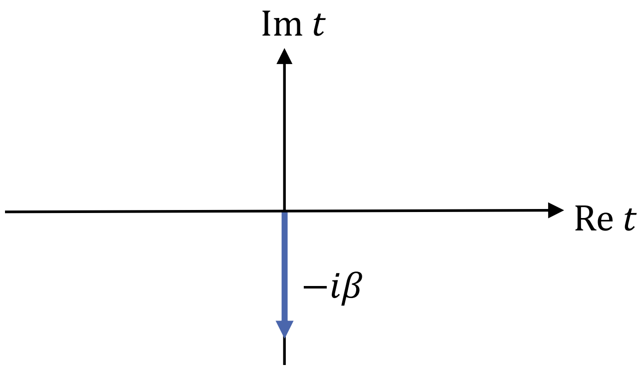
Imaginary time formalism (Matsubara)

- Euclidean signature
- Analytic continuation

$$\int \frac{d^4P}{(2\pi)^4} \rightarrow T \sum_{p_0 = i\omega_n} \int \frac{d^3p}{(2\pi)^3}$$

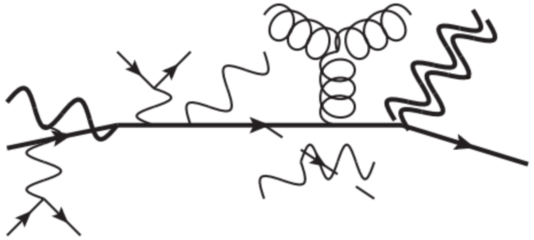
Free propagator

$$\Delta_F(i\omega_n) = \frac{1}{\omega_n^2 + \omega^2}$$



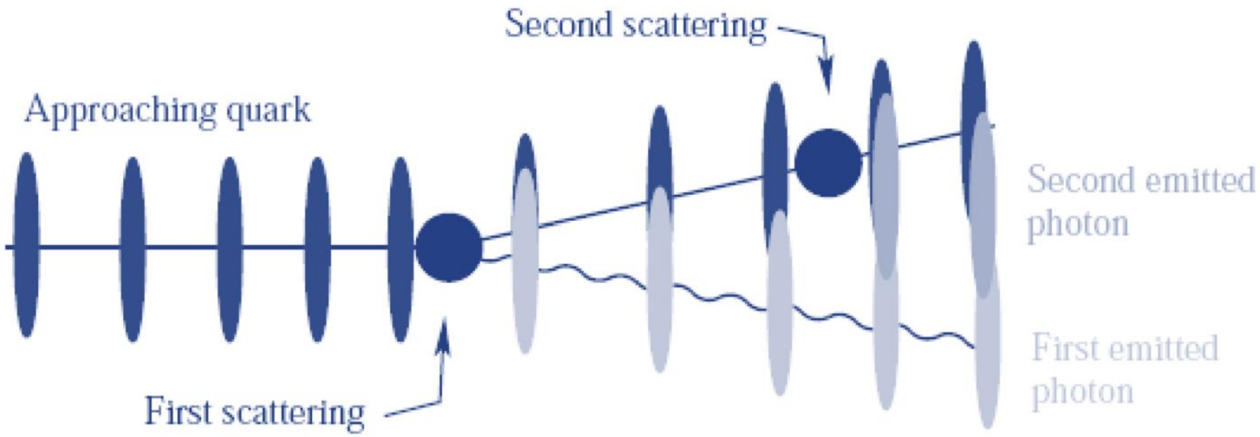
Soft Scattering of FIMPs

Multiple soft scatterings of FIMPs with the thermal bath give relevant contribution to decays and scattering



In a hot plasma with soft gauge interactions,

scattering duration ≫ mean free time between collisions



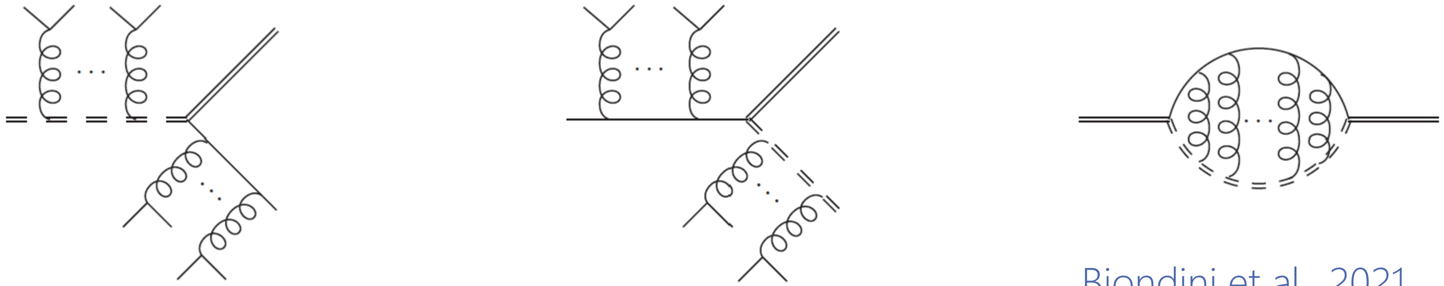
LPM effect: Outgoing gauge bosons interfere with each other, modifying the emission rate

Moore G., 2004

Landau-Pomeranchuk-Migdal (LPM)

Known for suppression of bremsstrahlung in energetic particles transversing dense media

Arbitrary number of soft gauge boson scatterings



Biondini et al., 2021

Optical theorem

→ Take the imaginary part of the self-energy

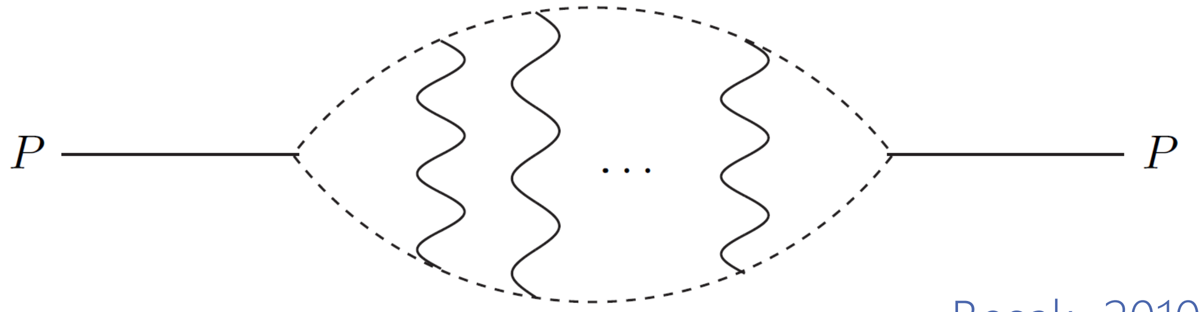
Scales and Effective Theories

IR and collinear divergences breakdown perturbation theory

Move to effective field theories

Different momentums scales:

- Hard scale $P \sim T, P^2 \sim T^2$
- Soft scale $P \sim gT$
- Ultrasoft scale $P \sim g^2T$
- Lightcone scale $P \sim T, P^2 \sim g^2T^2$



Besak, 2010

→ Certain diagrams of higher order in the *loop expansion* are of the same order in the *coupling constant*.

Final Words

Work in progress ☺

- Thermal corrections are specially relevant for FIMPs
- LPM contribution expected to be of order $O(1)$
- Advance in state-of-the-art methods

Questions

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