DESY 2025

Thermal Effects in Particle Production

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JGU Mainz

arXiv:2506.11185

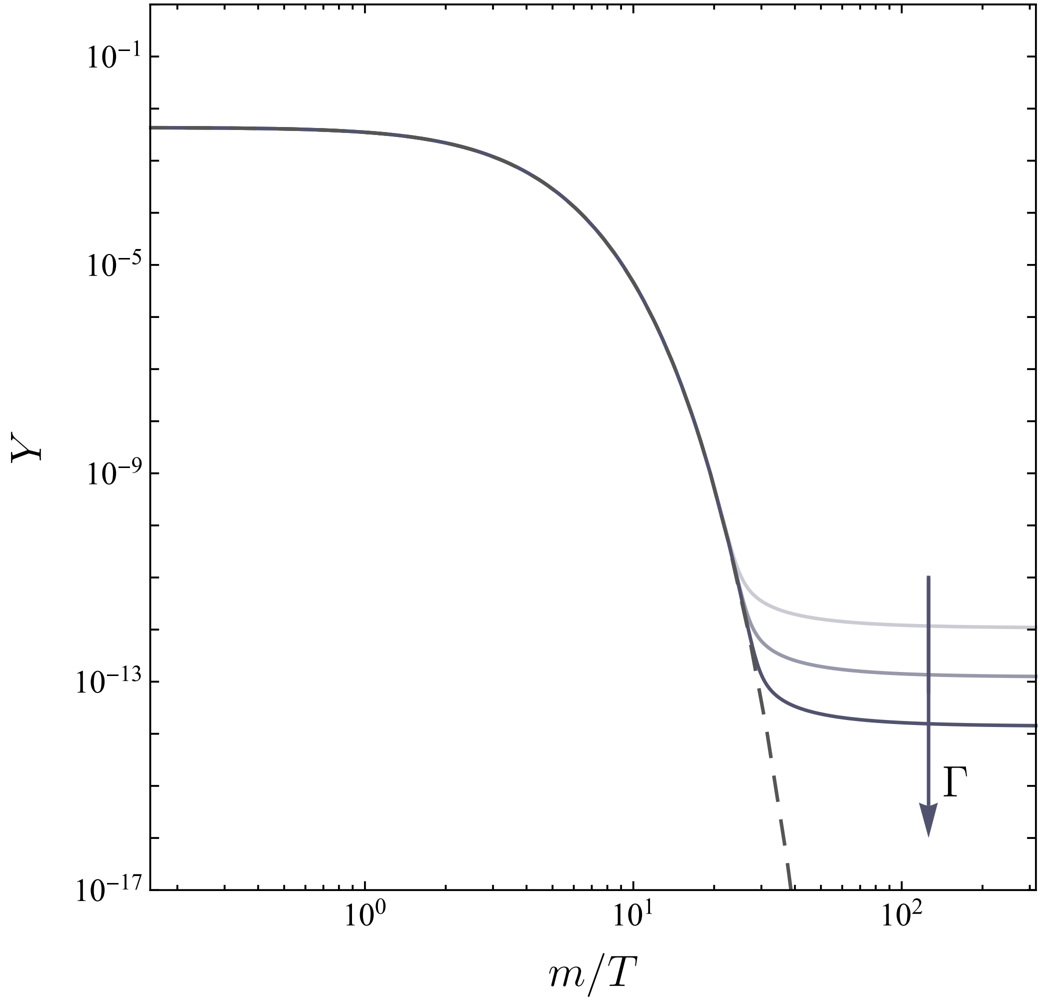
in collaboration with

Mathias Becker

Julia Harz

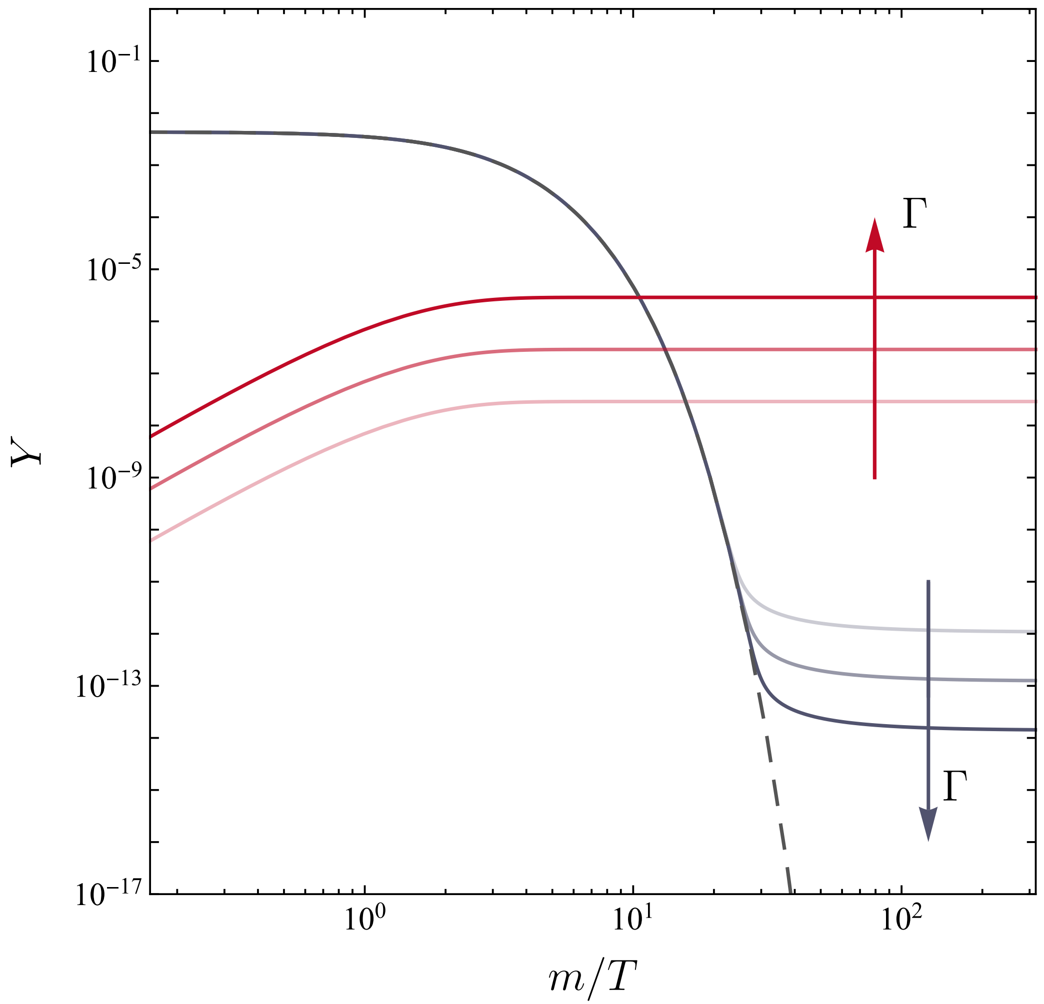
Carlos Tamarit

DM Production Mechanisms



Freeze-out
(WIMPs)

DM Production Mechanisms



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Freeze-In
(FIMPs)

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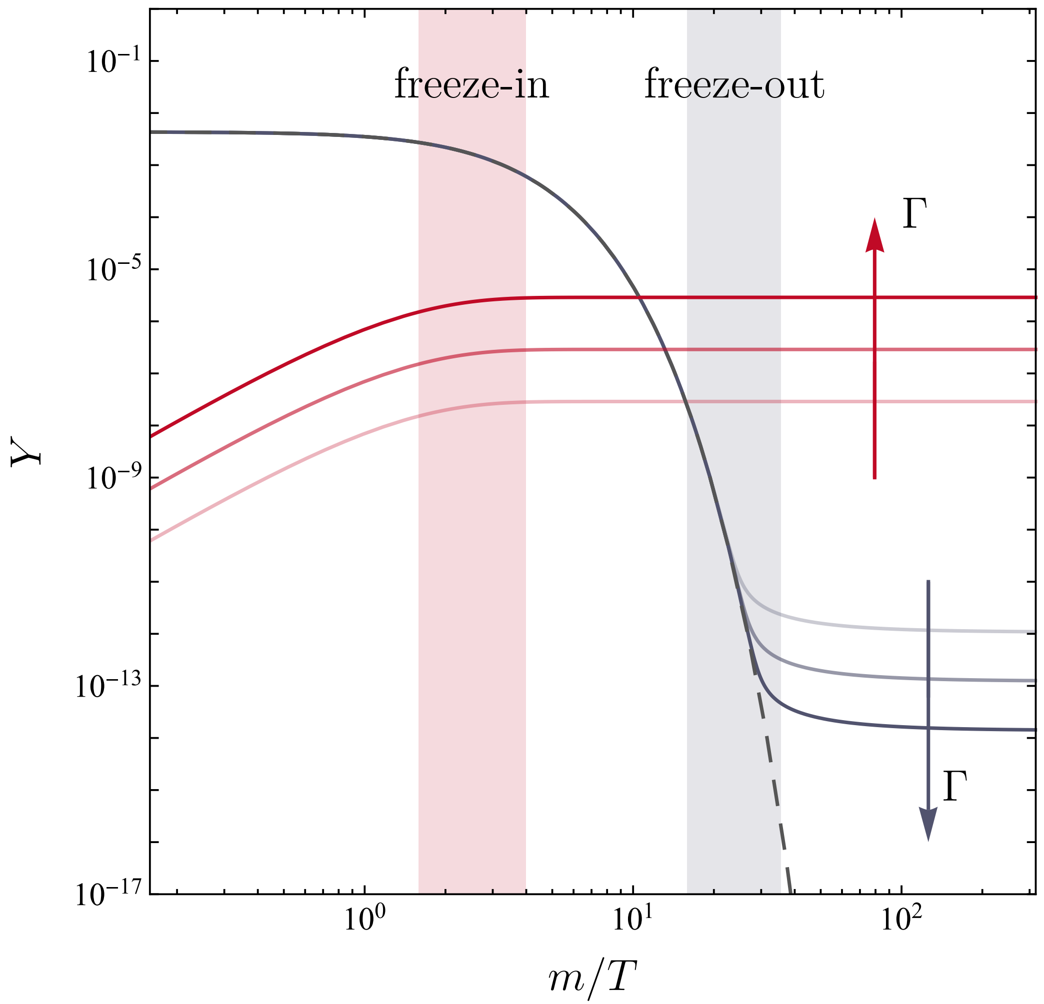

Freeze-out
(WIMPs)

Decoupling at
$T \sim m_\chi/25$

Freeze-In
(FIMPs)

Decoupling at
$T \sim m/5$

Freeze-in models are sensitive to thermal corrections

OUTLINE

How does the thermal plasma affect the freeze-in mechanism?

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Thermal masses, modified distribution functions, off-shell effects, thermal widths, **multiple soft scatterings (LPM)**, …

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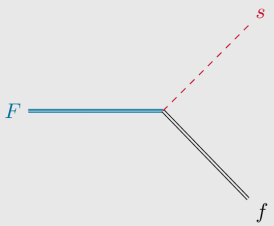
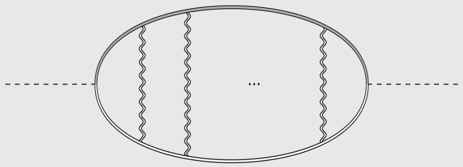
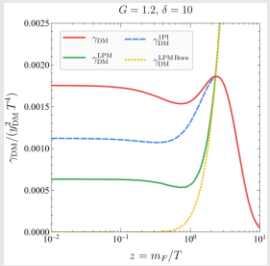


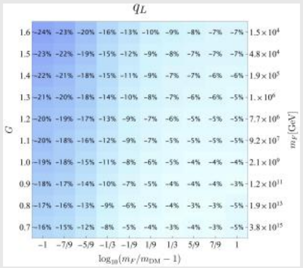
The LPM Effect



Complete Rate



Impact on Ωh^2



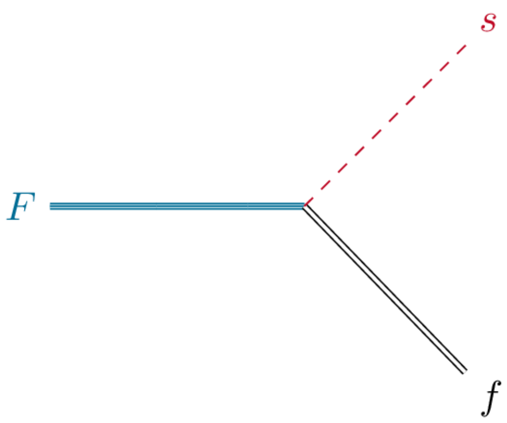
VECTORLIKE SCALAR FIMP MODEL

$$\mathcal{L}_{\text{int}} = -\left[y_{\text{DM}} \bar{F} f s + \text{h.c.}\right]$$

portal coupling

dark mediator

scalar dark matter particle



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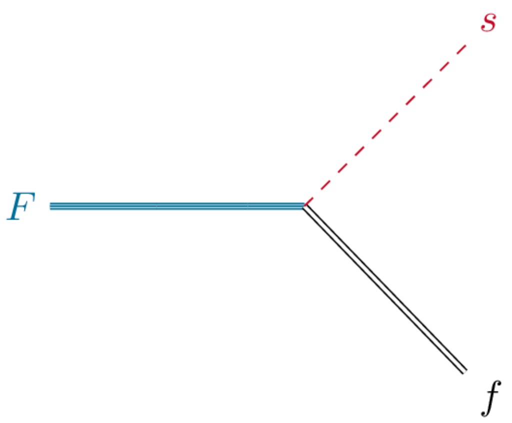

5 possible realizations of this model:

e_L, q_L, e_R, d_R, u_R

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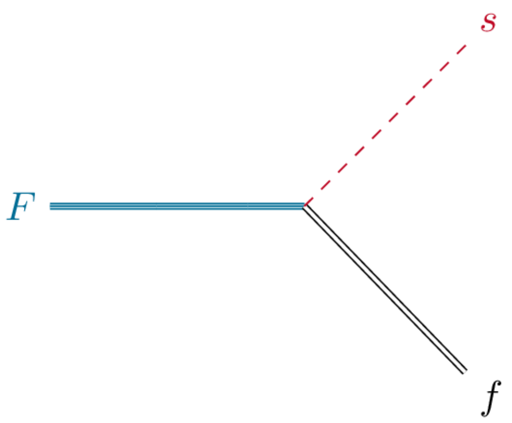
portal coupling — dark mediator — scalar dark matter particle



Parametrized with 4 quantities:

$$y_{\text{DM}}$$

$$G = Y^2 g_1^2 + C_2(\mathcal{R}_2)g_2^2 + C_2(\mathcal{R}_3)g_3^2$$

$$\delta = \frac{m_F - m_{\text{DM}}}{m_{\text{DM}}}$$

$$m_F$$

5 possible realizations of this model:

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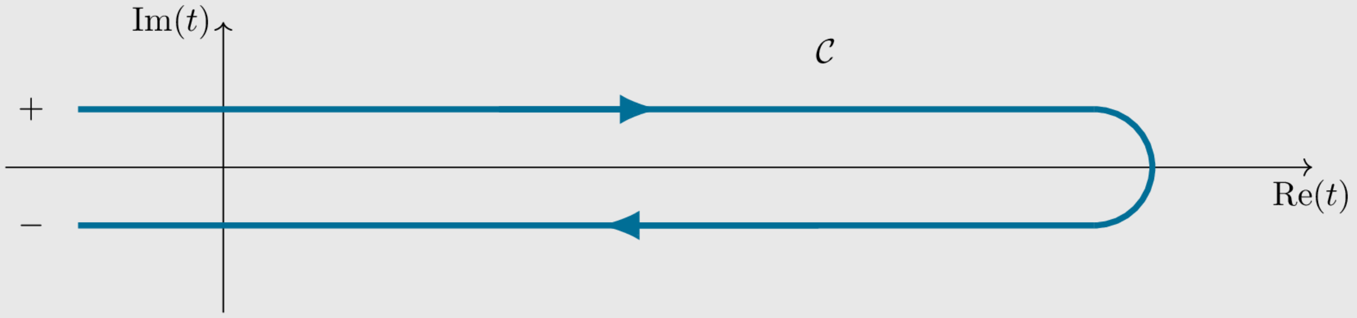
DM Rate Equation

CTP Formalism

Fields are defined on a complex time contour that doubly transverses the real-time axis



Advantage: allows for **non-equilibrium phenomena**

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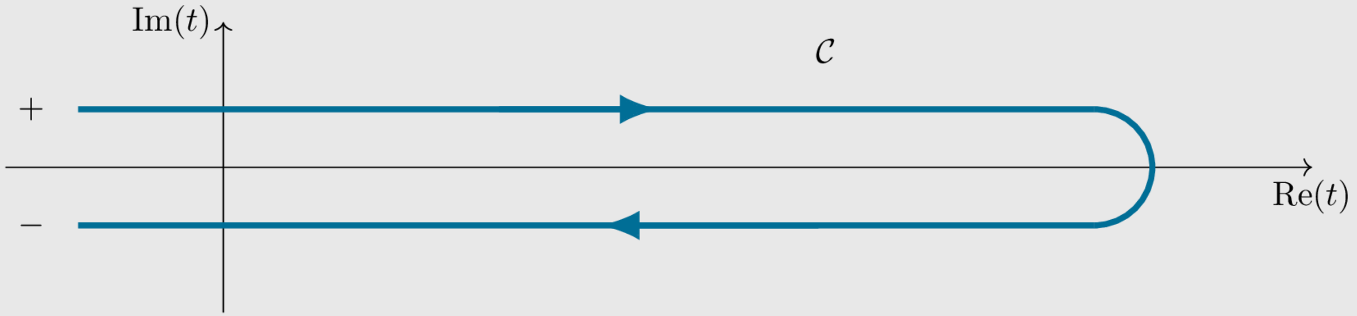


Advantage: allows for **non-equilibrium phenomena**

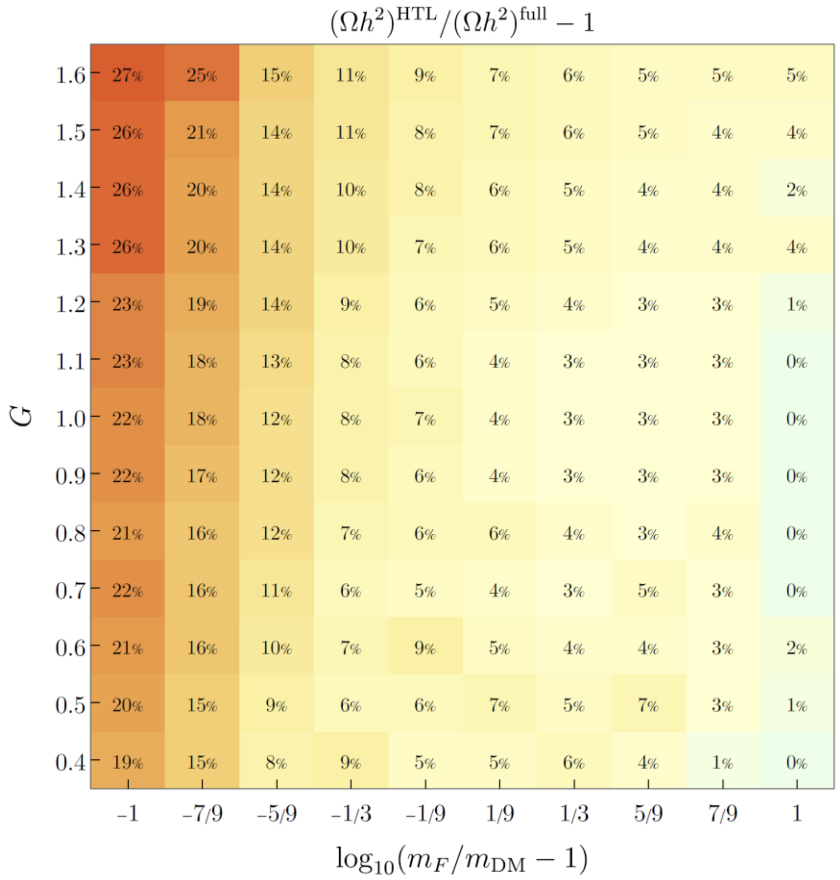
Equation for the DM production rate from the Kadanoff-Baym and CTP formalism

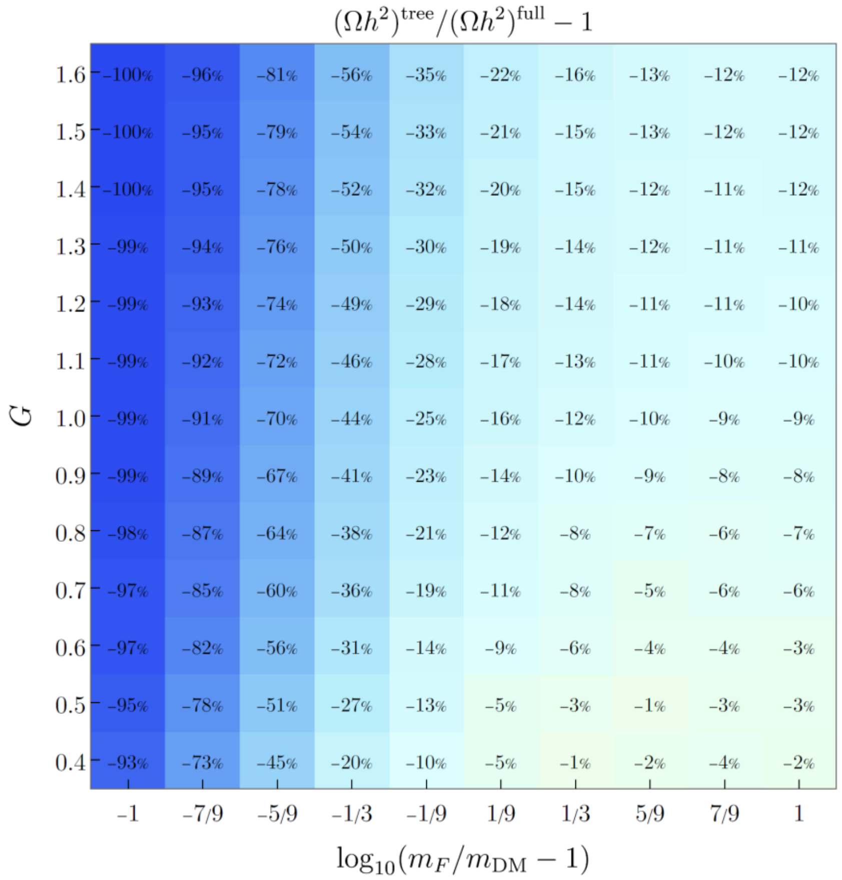
[Becker, Copello, Harz, Tamarit, 2312.17246]

$$\gamma_{\mathrm{DM}} \equiv \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{\Pi_s^{\mathcal{A}}(\omega_p, |\vec{p}|)}{\omega_p} f_{\mathrm{B}}(\omega_p)$$

Previous Work

Calculation with 1PI-resummed propagators provides a more accurate rate for freeze-in





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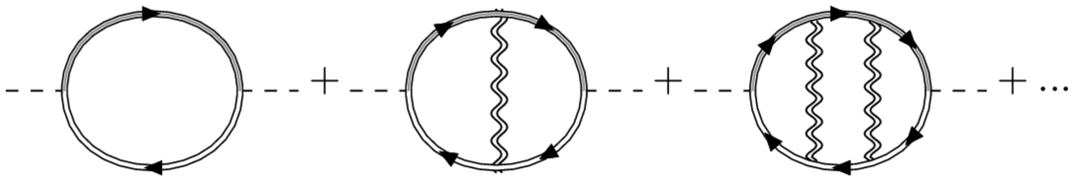
FRAMEWORK

Two key approximations:

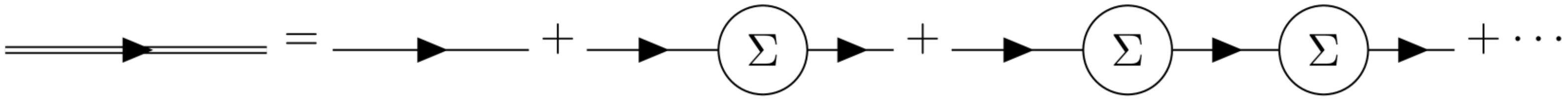
- Self-energy truncation:

  whether we calculate $\Pi_s^{\mathcal{A}}$ at 1-loop, 2-loop...



- Propagator structure:

  whether tree-level, HTL, or 1PI propagators are used inside $\Pi_s^{\mathcal{A}}$



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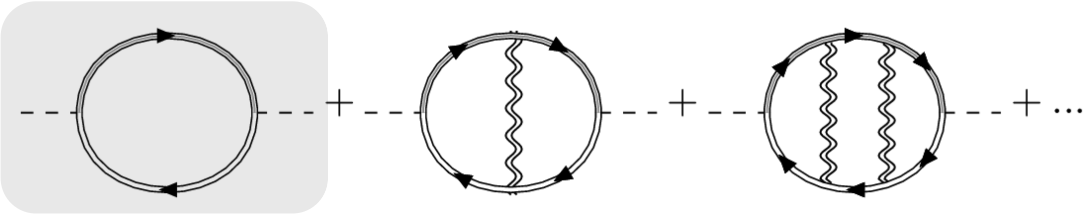

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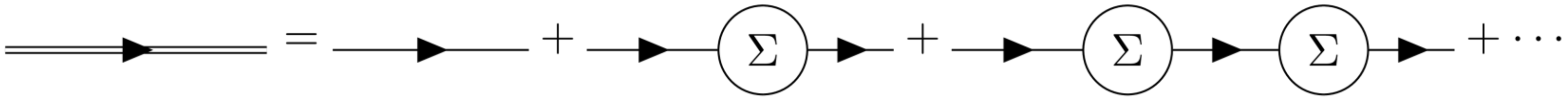

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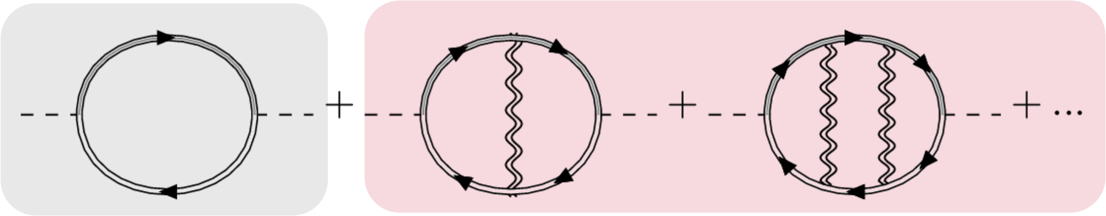

This work

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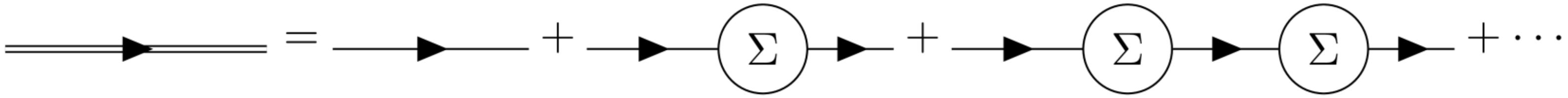
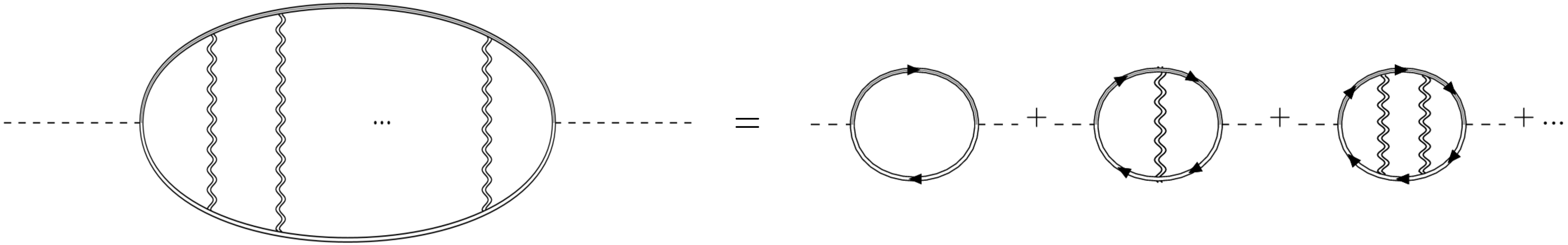


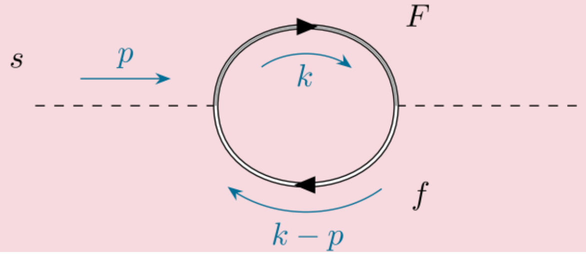
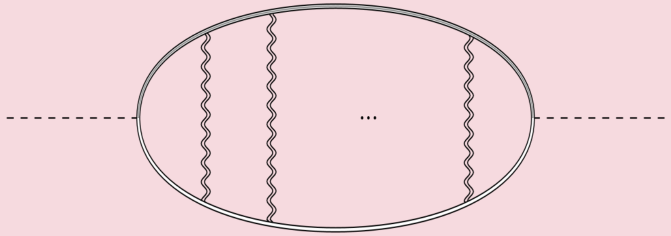
The Ladder Diagram



Power Counting

The ladder diagram is a LO process in the coupling constant in the kinematical regime

$$\underbrace{p \sim T, \quad k \sim T, \quad p^2 \sim g^2T^2, \quad k^2 \sim g^2T^2}_{\text{Lightlike}} \quad , \quad \underbrace{k \cdot p \sim g^2T^2}_{\text{Collinear}}$$

Fermion momenta		
Hard collinear	g^2T^2	g^2T^2
Hard non-collinear	g^2T^2	$g^{4n+2}T^2$

The LPM Effect

Discovered by **L**andau, **P**omeranchuk and **M**igdal (LPM) in the context of bremsstrahlung radiation.

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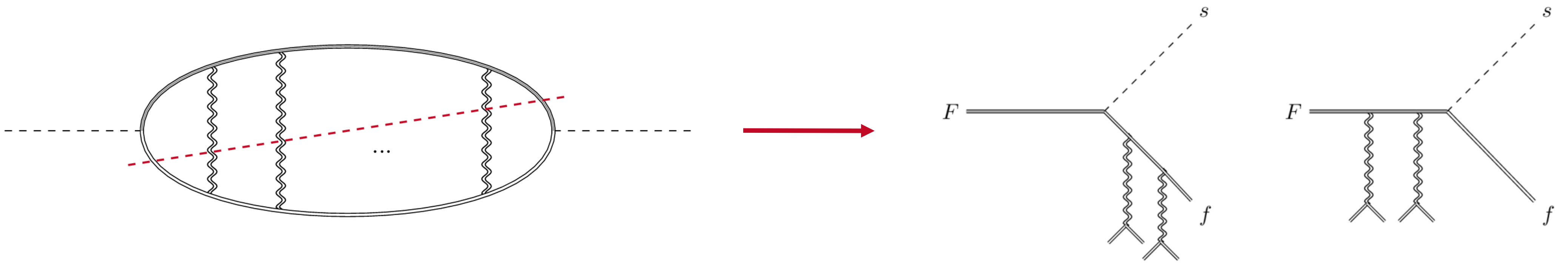

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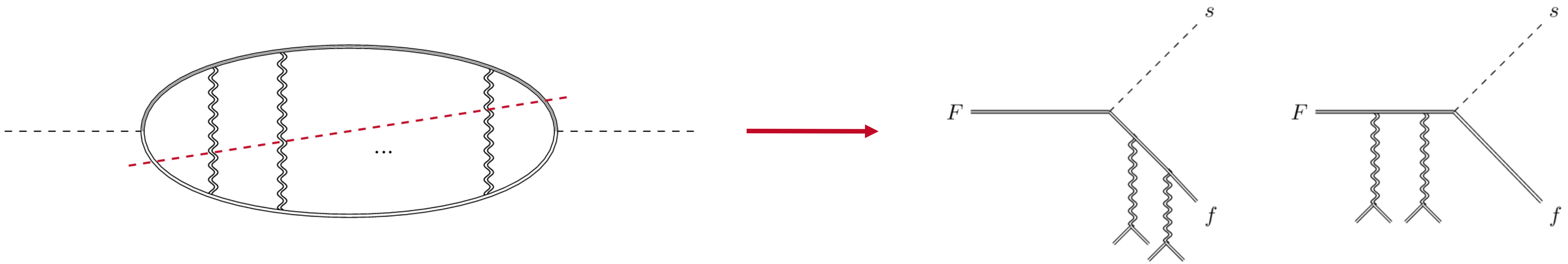

Multiple soft scattering of high-energy gauge bosons with the particles in a hot plasma.

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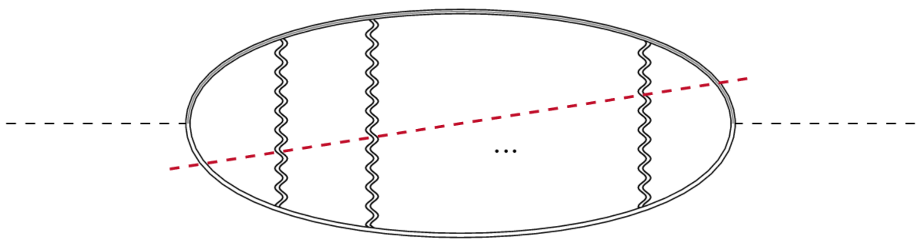
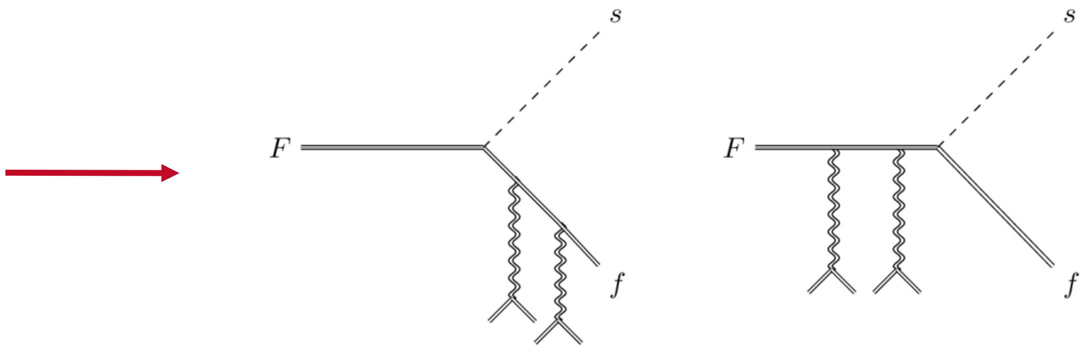




Multiple soft scattering of high-energy gauge bosons with the particles in a hot plasma.

Studied previously for

fermion self energies

- Leptogenesis [Besak, Bodeker, 1202.1288]
- Fermionic FIMPs [Biondini, Ghiglieri, 2012.09083]

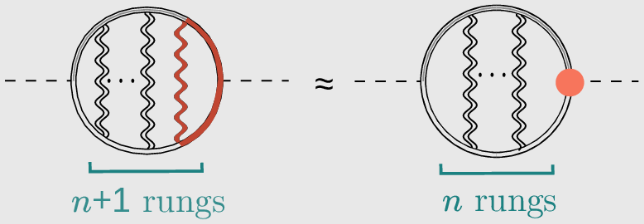
photon self energies

- QGP [Arnold, Moore, Yaffe, hep-ph/0111107]

Calculation of the LPM rate

[Anisimov, Besak, Bodeker, 1202.1288]

Recursion relation



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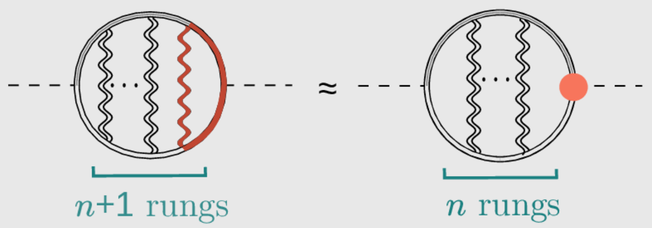

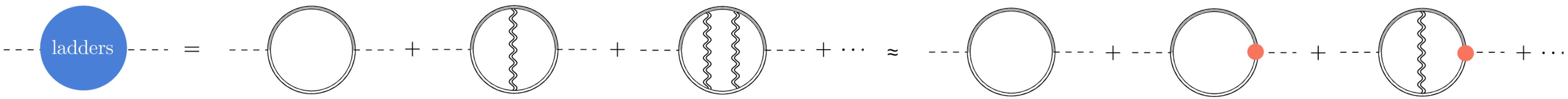

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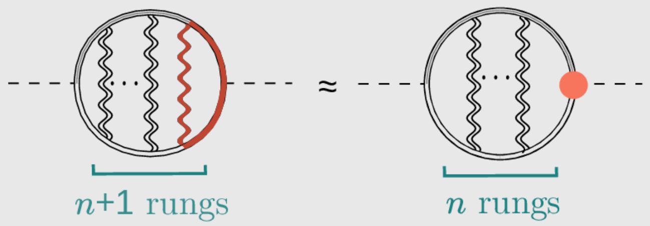
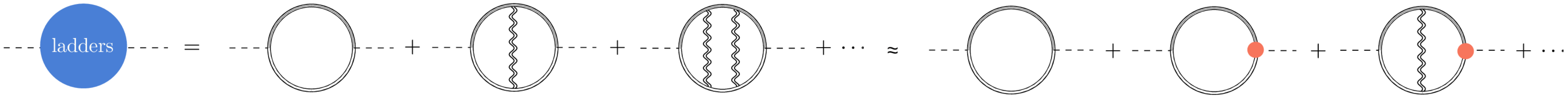
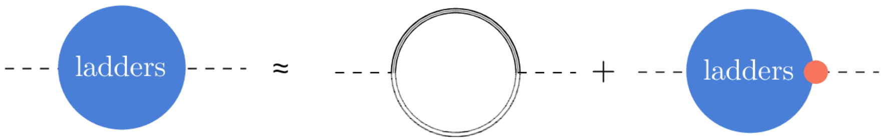




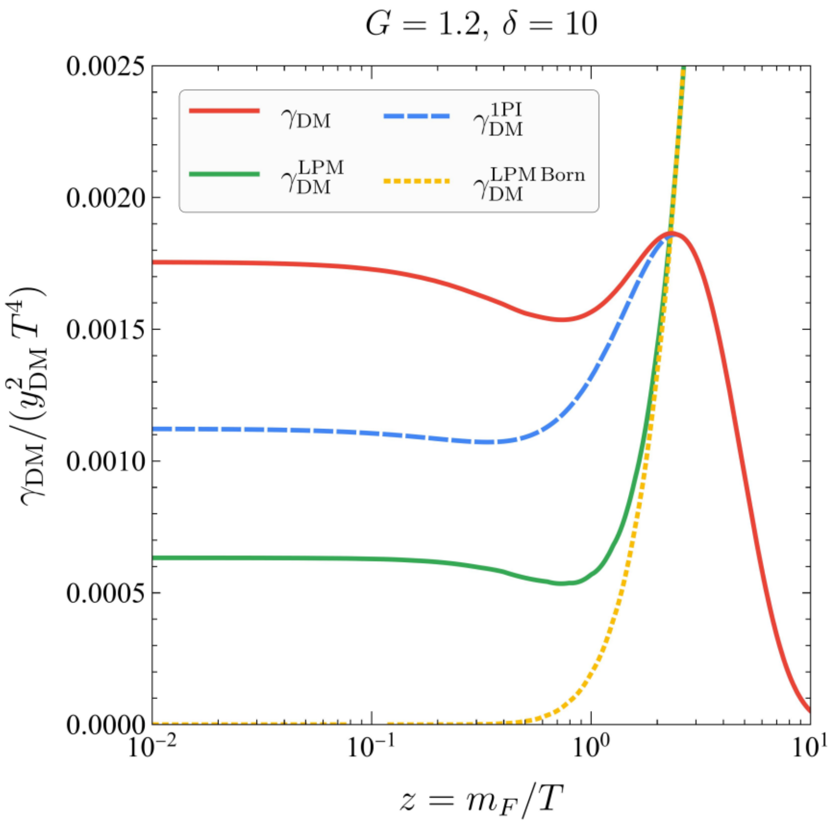


Switching Off the LPM Rate

We have calculated the LPM rate in the ultrarelativistic regime. To move to non-relativistic, we use a simple prescription:

[Biondini, Ghiglieri, 2012.09083]

$$\gamma_{\mathrm{DM}} = \left(\gamma_{\mathrm{DM}}^{\mathrm{LPM}} - \gamma_{\mathrm{DM}}^{\mathrm{LPMBorn}}\right) f(m_F) + \gamma_{\mathrm{DM}}^{\mathrm{1PI}}$$



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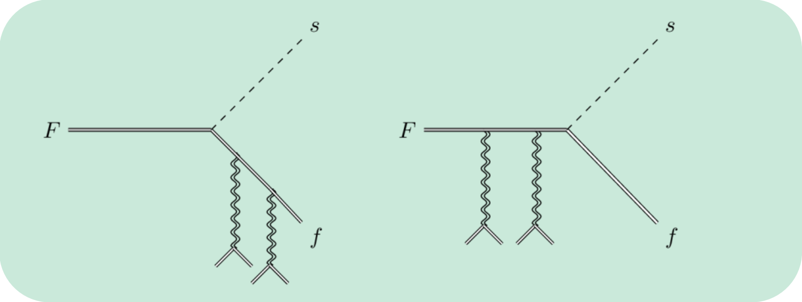

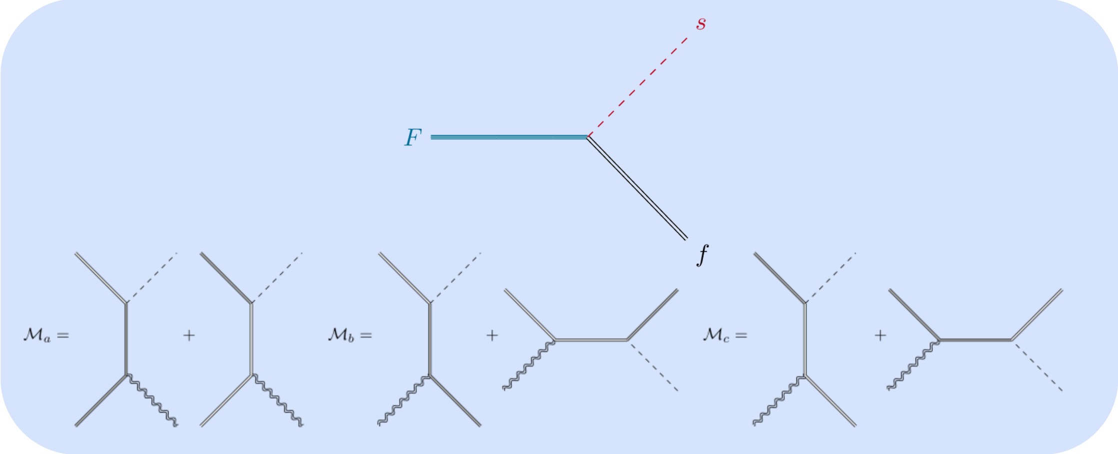

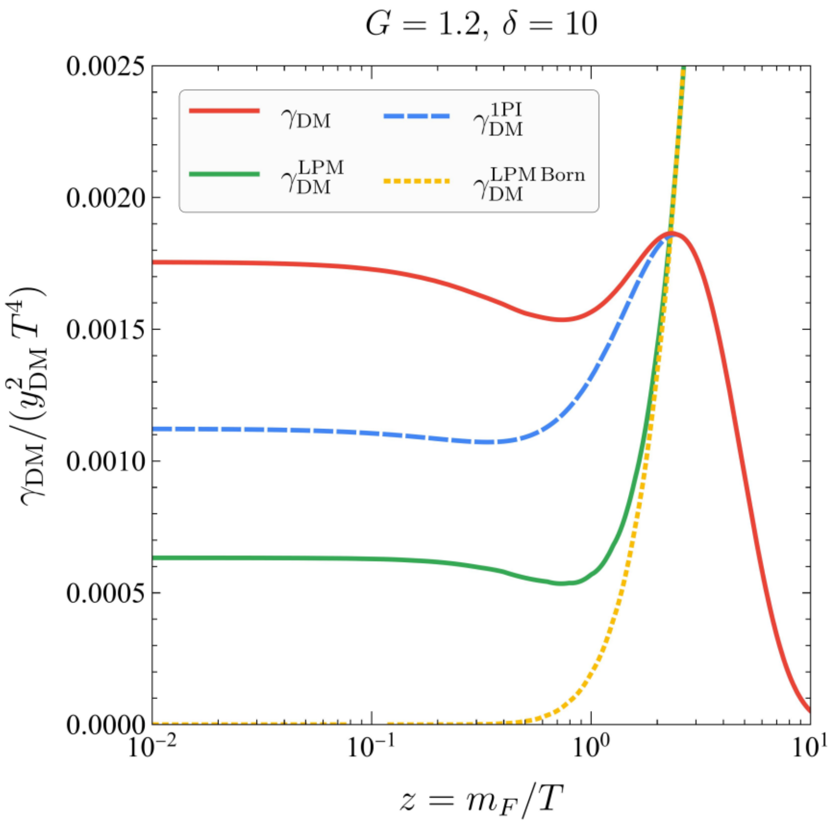

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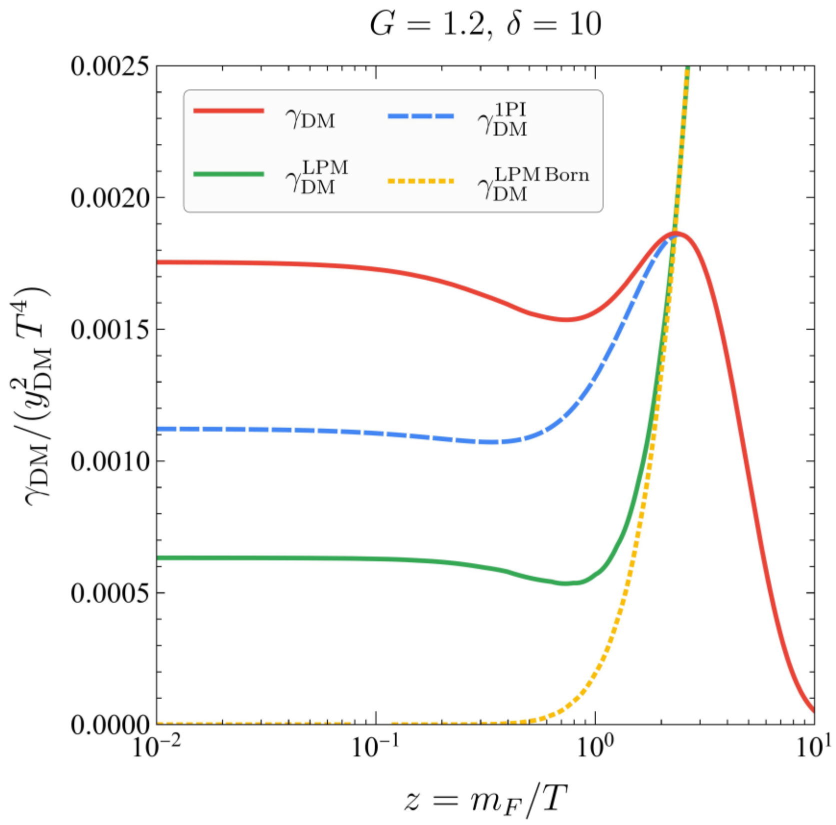
Switch-off function

Switches off the unphysical rate. Must satisfy

$$f(\tfrac{m_F}{T} \to 0) = 1, f(\tfrac{m_F}{T} \to \infty) = 0$$



Different Switch-off Procedures

Susceptibility function [Ghiglieri, Laine, 1605.07720]

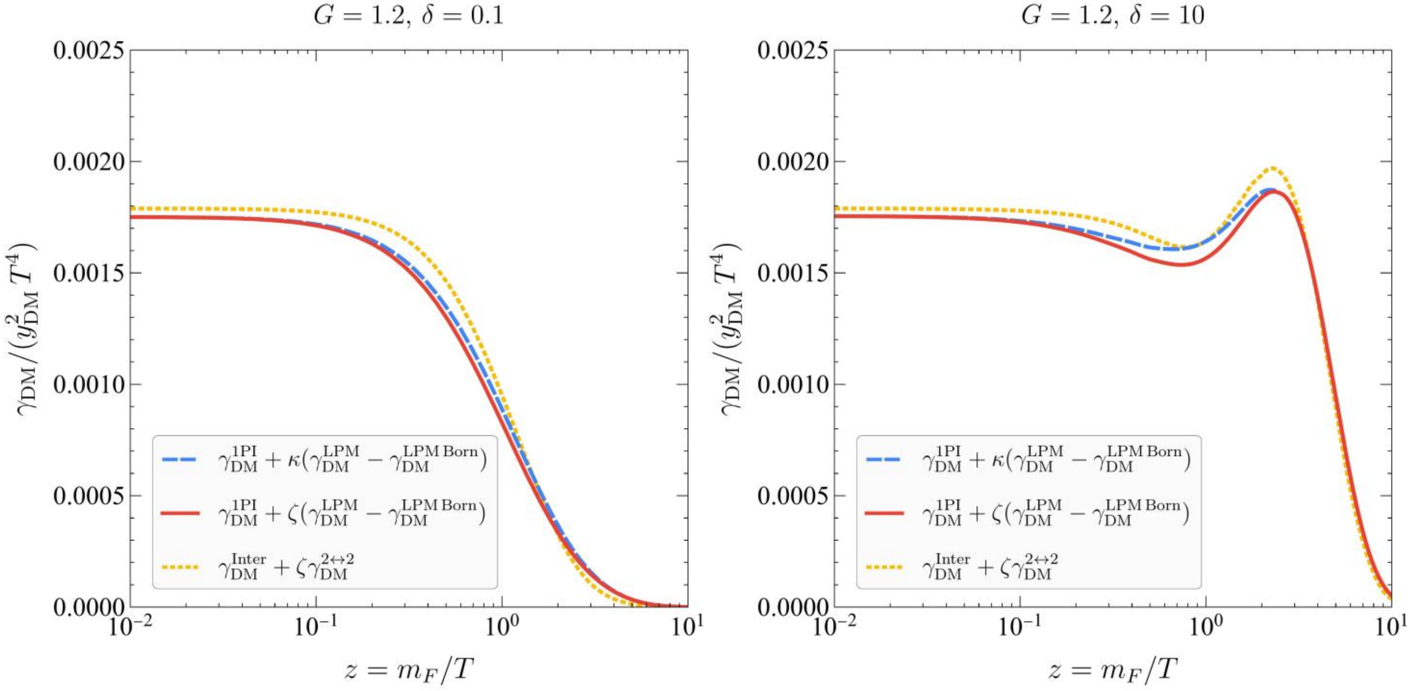
- Slower switch-off might lead to DM overestimation
- Doesn't switch-off scatterings fast enough

Thermal function

+ Captures 1PI behaviour
+ Most conservative approach

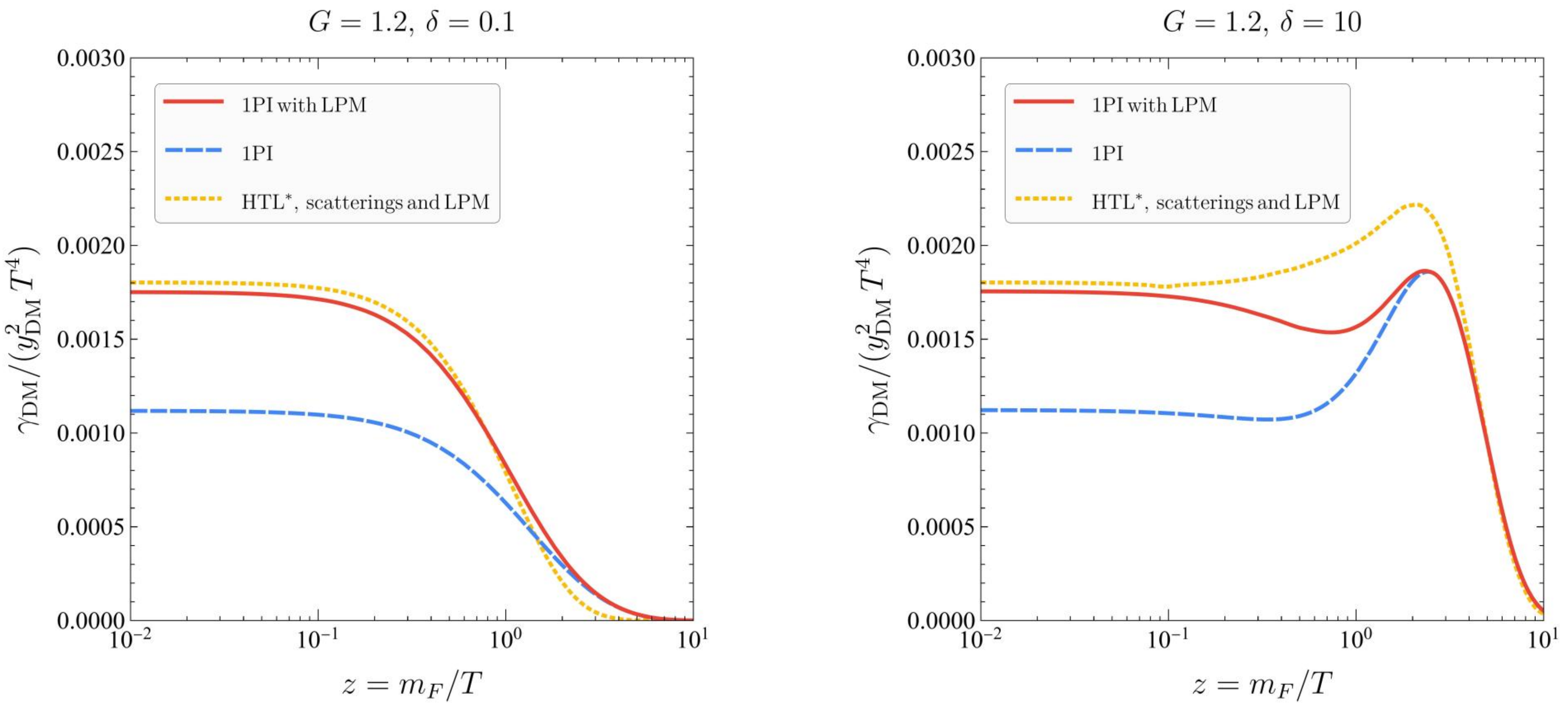
Smooth interpolation [Ghiglieri, Laine 2110.07149]

- Scatterings must be added manually
- Decay peak is overestimated



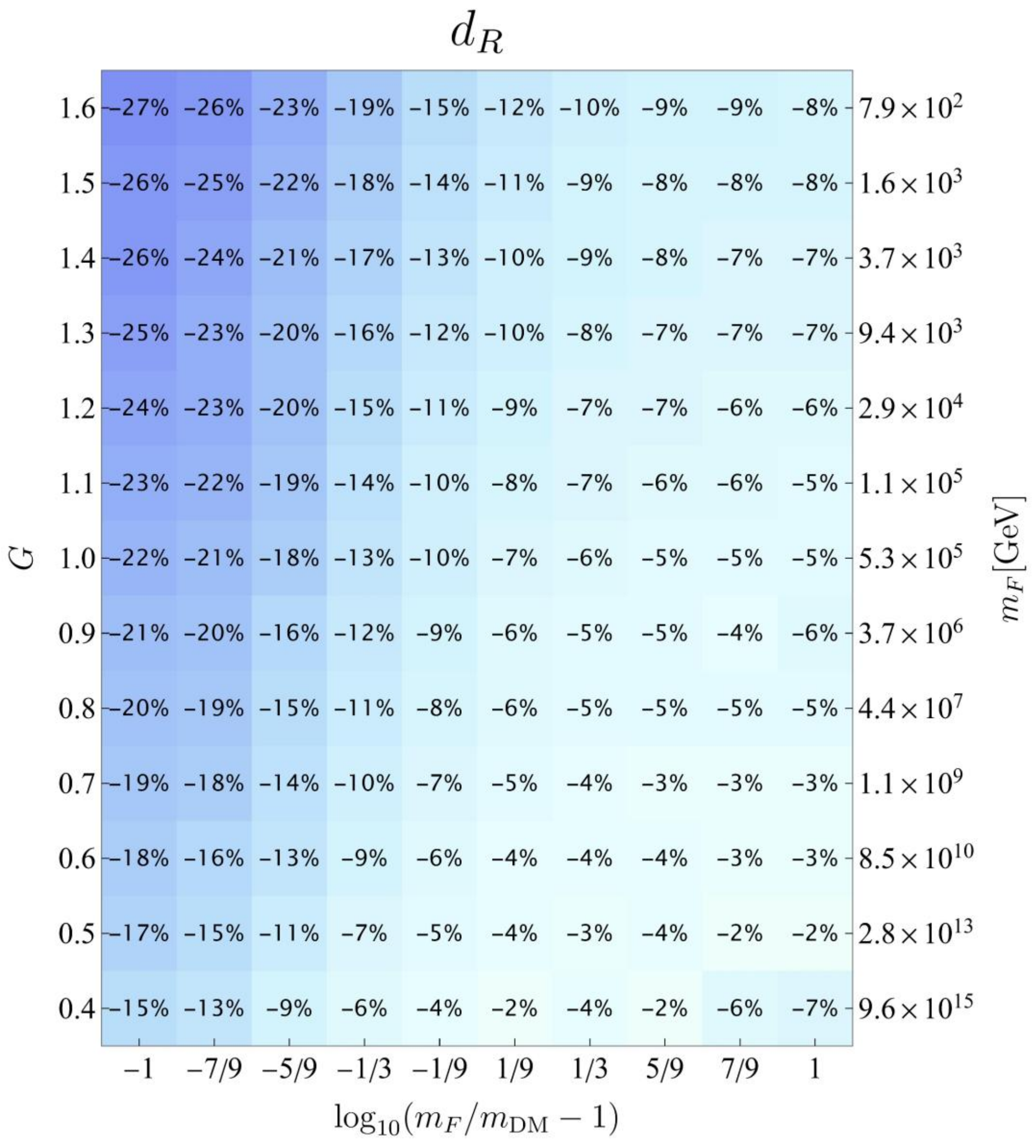
Discrepancies of ~30% and ~5% at the Ωh^2 level

The Final DM Rate



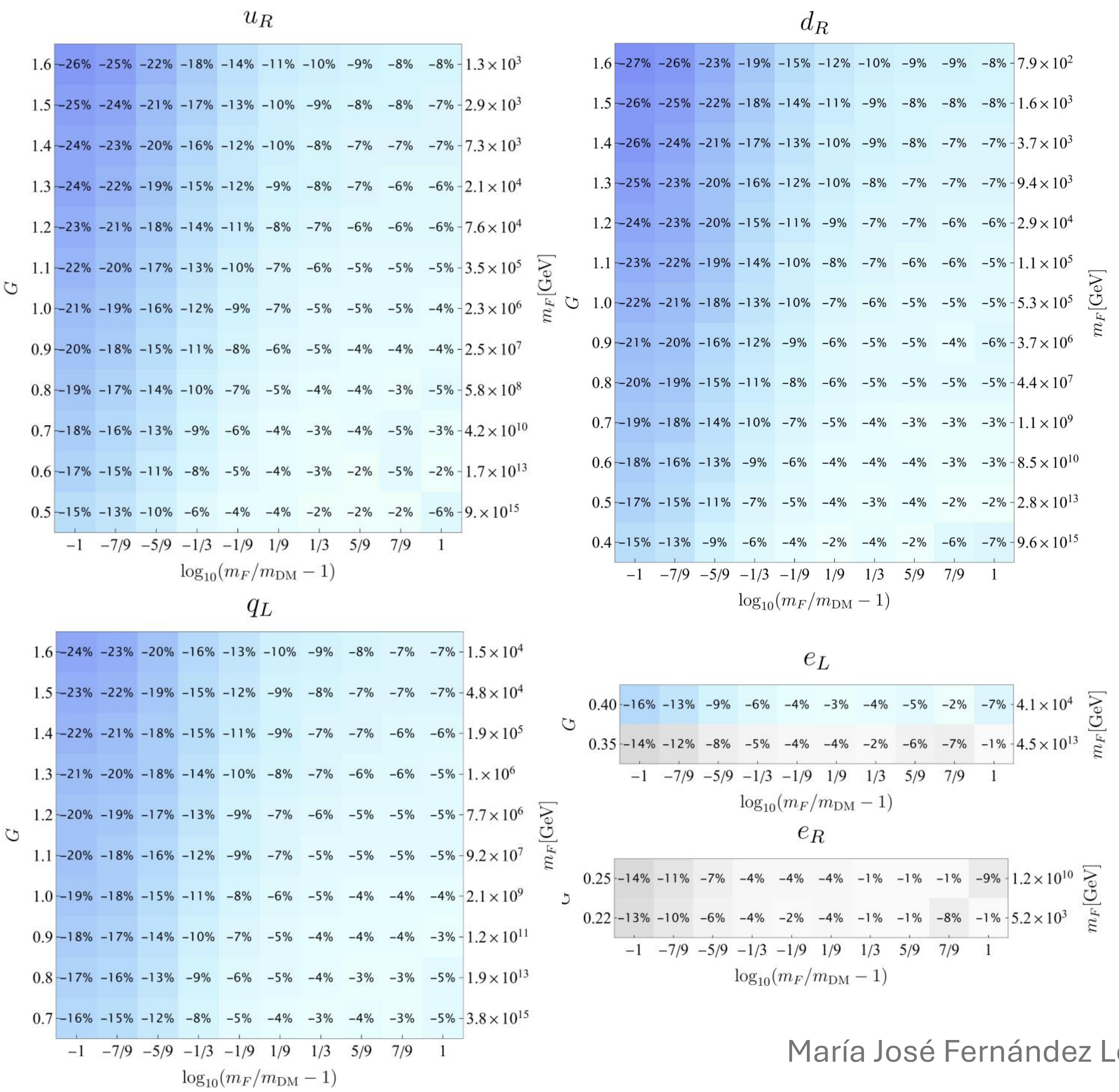
We provide a fitting of the LPM in the ultrarelativistic limit $\left.\gamma_{\rm DM}^{\rm LPM}/(y_{\rm DM}^2 T^4)\right|_{z=0.01} = a + bG$

DM Relic Abundance Ωh^2



The amount of DM that is underestimated if one does not take the LPM into account

- Greater G leads to bigger LPM effect
- Smaller δ leads to bigger LPM effect (no decay contribution)
- Five possible realizations of DM mediator



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Comparison to Simplified Methods

$(\Omega h^2)^{\text{dec,th.m.}}/(\Omega h^2)^{\text{full}}_{dR}$

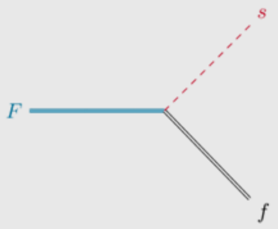
G \ $\log_{10}(m_{F,0}/m_{\text{DM}}-1)$	−1	−7/9	−5/9	−1/3	−1/9	1/9	1/3	5/9	7/9	1	$m_{F,0}$[GeV]
1.6	-100%	-96%	-81%	-56%	-33%	-19%	-12%	-8%	-8%	-7%	7.9×10^2
1.5	-100%	-95%	-79%	-53%	-31%	-17%	-10%	-8%	-6%	-6%	1.6×10^3
1.4	-99%	-95%	-77%	-51%	-29%	-15%	-9%	-6%	-5%	-6%	3.7×10^3
1.3	-99%	-94%	-75%	-48%	-26%	-13%	-7%	-4%	-3%	-3%	9.4×10^3
1.2	-99%	-93%	-73%	-46%	-24%	-12%	-5%	-4%	-2%	-2%	2.9×10^4
1.1	-99%	-91%	-70%	-42%	-21%	-9%	-4%	-2%	-1%	-1%	1.1×10^5
1.0	-98%	-90%	-67%	-38%	-17%	-7%	-2%	-1%	1%	1%	5.3×10^5
0.9	-98%	-88%	-63%	-34%	-14%	-4%	0%	2%	2%	1%	3.7×10^6
0.8	-98%	-86%	-59%	-30%	-10%	0%	4%	4%	4%	2%	4.4×10^7
0.7	-97%	-83%	-54%	-25%	-7%	2%	4%	8%	7%	7%	1.1×10^9
0.6	-96%	-79%	-48%	-19%	1%	6%	7%	8%	9%	10%	8.5×10^{10}
0.5	-94%	-74%	-40%	-13%	3%	11%	12%	12%	12%	12%	2.8×10^{13}
0.4	-91%	-65%	-31%	-2%	7%	13%	13%	14%	7%	7%	9.6×10^{15}

$(\Omega h^2)^{\text{dec+scat,th.m.}}/(\Omega h^2)^{\text{full}}_{dR}$

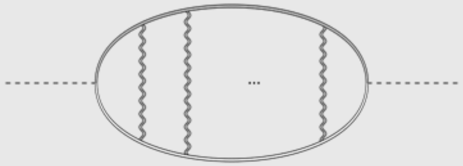
G \ $\log_{10}(m_{F,0}/m_{\text{DM}}-1)$	−1	−7/9	−5/9	−1/3	−1/9	1/9	1/3	5/9	7/9	1	$m_{F,0}$[GeV]
1.6	-33%	-31%	-24%	-8%	7%	16%	19%	20%	21%	21%	7.9×10^2
1.5	-33%	-32%	-22%	-6%	8%	16%	20%	21%	20%	21%	1.6×10^3
1.4	-32%	-30%	-20%	-5%	10%	17%	20%	21%	21%	20%	3.7×10^3
1.3	-32%	-30%	-19%	-2%	11%	18%	20%	22%	22%	22%	9.4×10^3
1.2	-32%	-29%	-17%	-1%	12%	19%	21%	21%	22%	22%	2.9×10^4
1.1	-31%	-28%	-15%	1%	14%	20%	21%	22%	23%	22%	1.1×10^5
1.0	-32%	-27%	-13%	4%	17%	21%	22%	23%	23%	23%	5.3×10^5
0.9	-30%	-25%	-10%	7%	18%	23%	24%	24%	23%	22%	3.7×10^6
0.8	-29%	-23%	-7%	10%	21%	25%	26%	25%	24%	22%	4.4×10^7
0.7	-28%	-20%	-4%	12%	22%	24%	25%	27%	26%	25%	1.1×10^9
0.6	-26%	-16%	1%	17%	28%	28%	26%	25%	27%	28%	8.5×10^{10}
0.5	-24%	-12%	6%	21%	28%	31%	30%	28%	26%	27%	2.8×10^{13}
0.4	-21%	-6%	12%	29%	29%	31%	28%	28%	19%	19%	9.6×10^{15}

Conclusions and Outlook

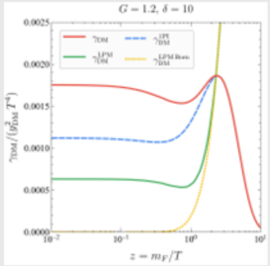
Framework



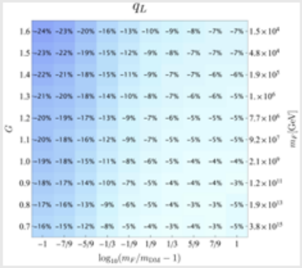
The LPM Effect



Complete Rate



Impact on Ωh^2



- Multiple soft scatterings give up to a 27% (8%) contribution for mass splittings of $\delta = 0.1 (\delta = 10)$
- We calculate for the first time the LPM effect for scalar DM
- We provide the most accurate state-of-art calculation

BACKUP SLIDES

	Y	SU(2)	SU(3)	G	$\mu = M_Z$	10^4 GeV	10^7 GeV	10^{10} GeV
e_L	$-1/2$	2	1	$\frac{g_1^2}{4} + \frac{3g_2^2}{4}$	0.38	0.4	0.46	0.52
q_L	$+1/6$	2	3	$\frac{g_1^2}{36} + \frac{3g_2^2}{4} + \frac{4g_3^2}{3}$	2.3	1.6	1.2	1.0
e_R	-1	1	1	g_1^2	0.21	0.22	0.24	0.26
u_R	$+2/3$	1	3	$\frac{4g_1^2}{9} + \frac{4g_3^2}{3}$	2.1	1.3	0.9	0.7
d_R	$-1/3$	1	3	$\frac{g_1^2}{9} + \frac{4g_3^4}{3}$	2.0	1.2	0.8	0.6