PLANCK 2025

Thermal Effects in Freeze-In Dark Matter Production

María José Fernández Lozano

JGU Mainz

arXiv:2506.xxxxx

in collaboration with

MATHIAS BECKER

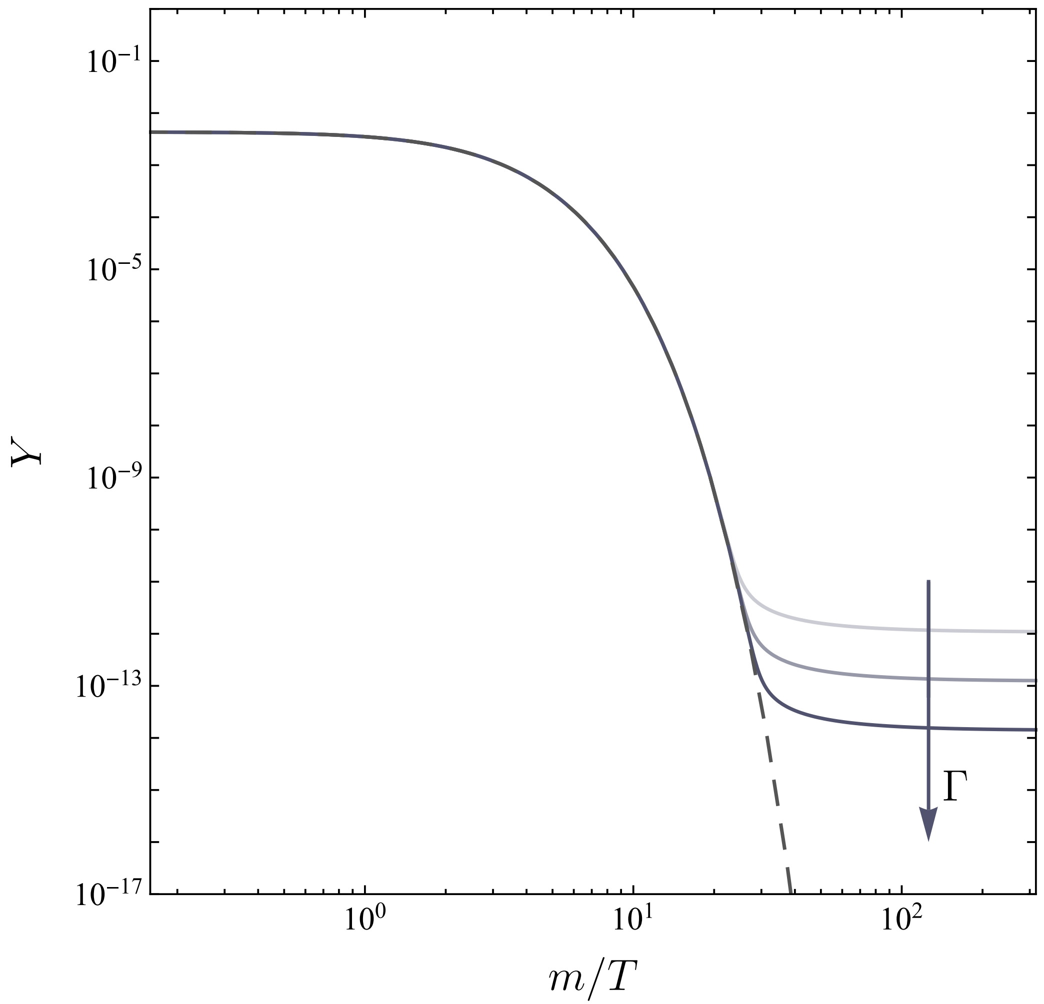
JULIA HARZ

CARLOS TAMARIT

JG|U

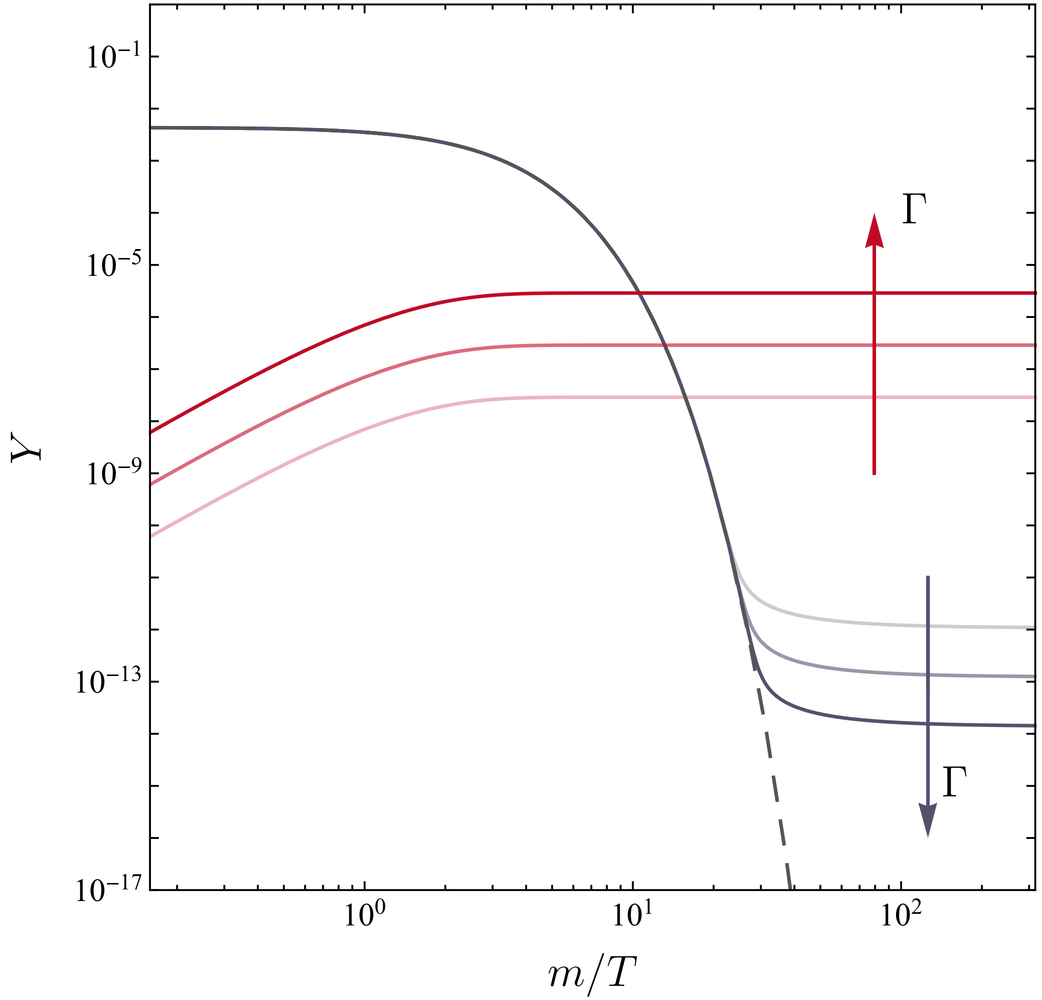
MPA MAINZ PHYSICS ACADEMY

DM Production Mechanisms



Freeze-out
(WIMPs)

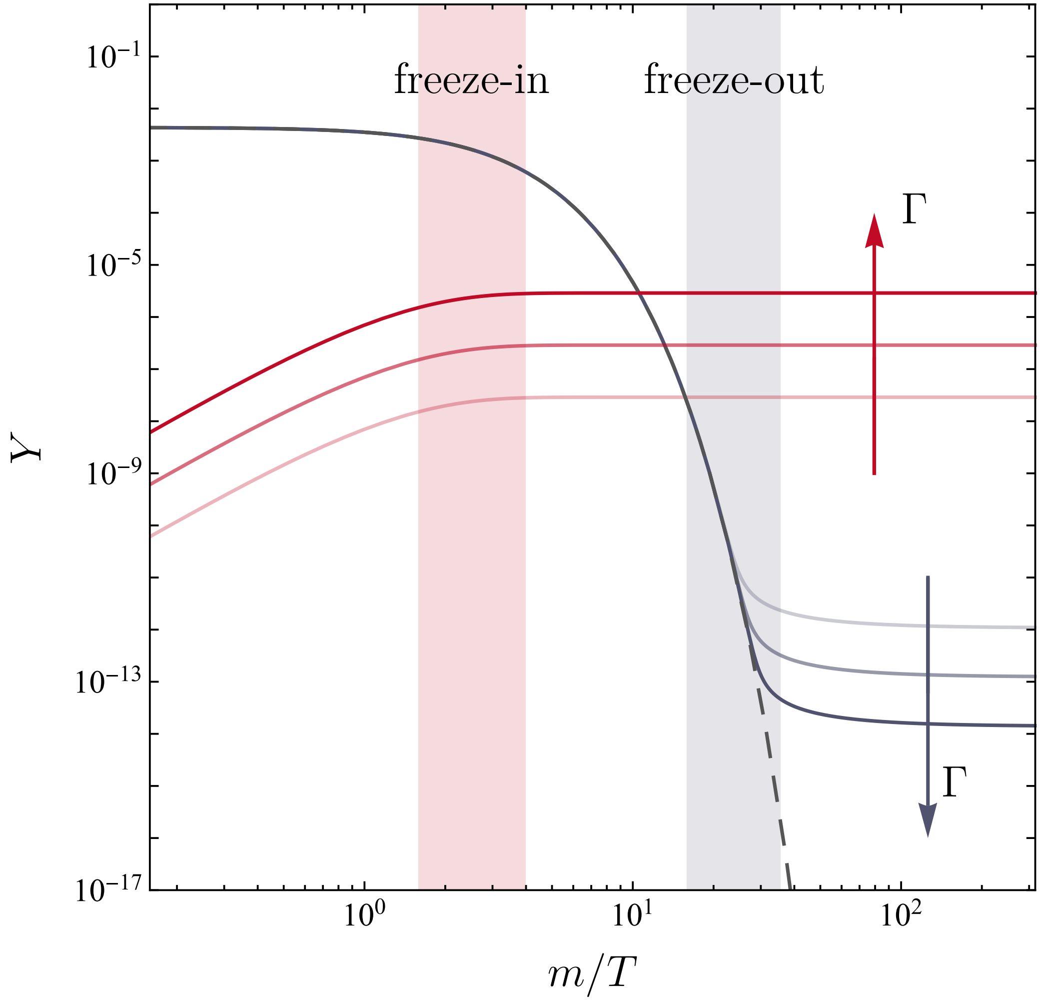
DM Production Mechanisms



Freeze-out
(WIMPs)

Freeze-In
(FIMPs)

DM Production Mechanisms



Freeze-out
(WIMPs)

Freeze-In
(FIMPs)

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

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?

OUTLINE

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

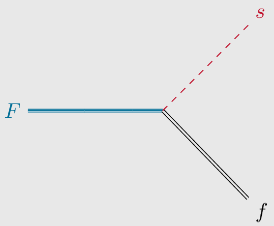
Thermal masses, modified distribution functions, off-shell effects, thermal widths, **multiple soft scatterings (LPM)**, …

OUTLINE

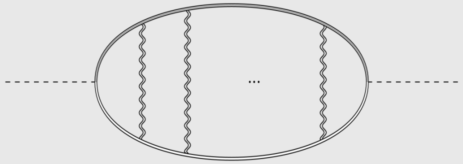
How does the thermal plasma affect the freeze-in mechanism?

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

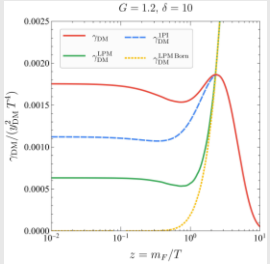
Framework



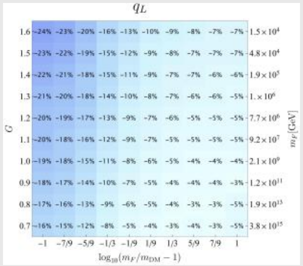
The LPM Effect



Complete Rate



Impact on Ωh^2



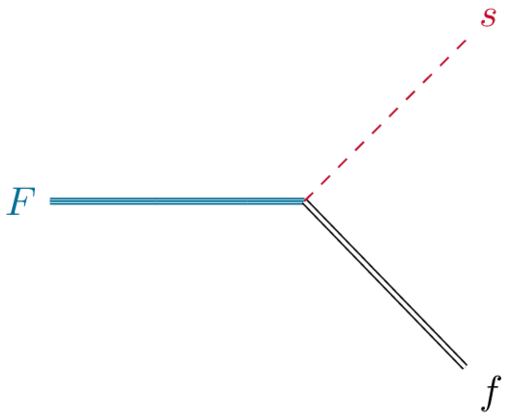
Vectorlike Scalar FIMP Model

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

portal coupling

dark mediator

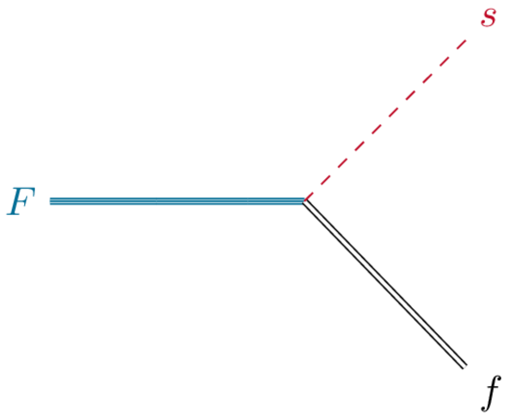
scalar dark matter particle



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



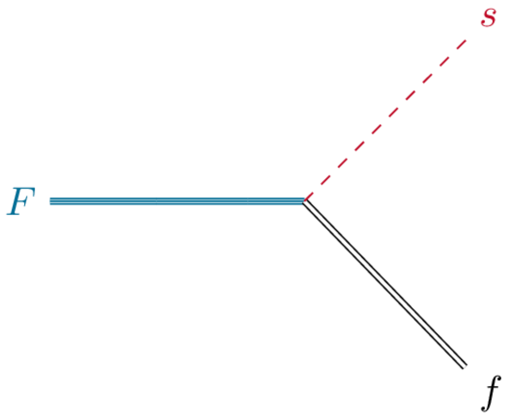
5 possible realizations of this model:

$$e_L, q_L, e_R, d_R, u_R$$

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



Parametrized with 4 quantities:

y_{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

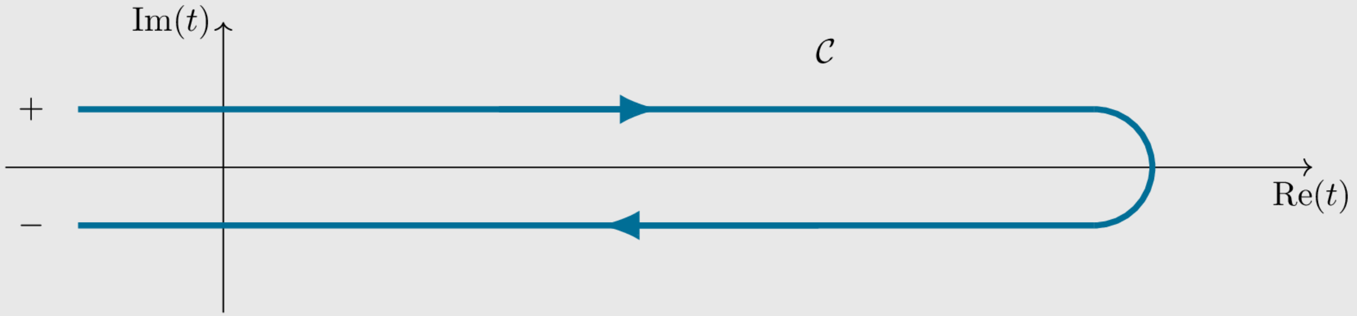
5 possible realizations of this model:

e_L, q_L, e_R, d_R, u_R

DM Rate Equation

CTP Formalism

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

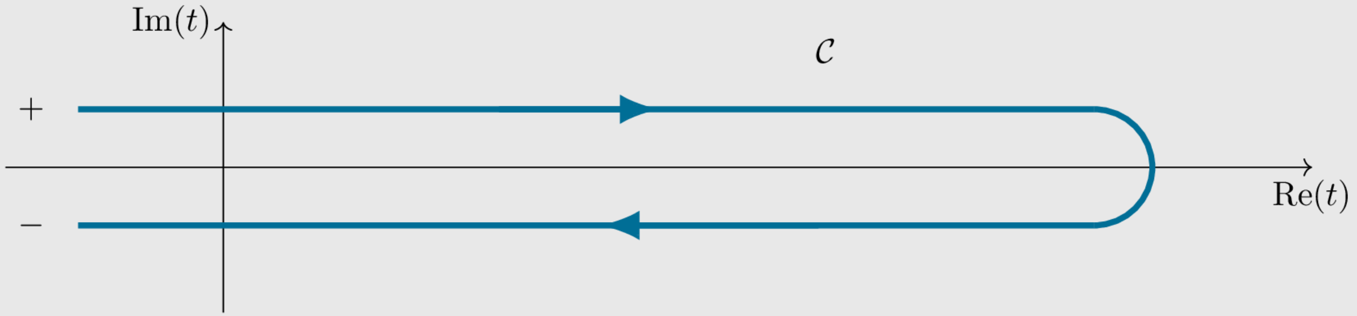


Advantage: allows for **non-equilibrium phenomena**

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**

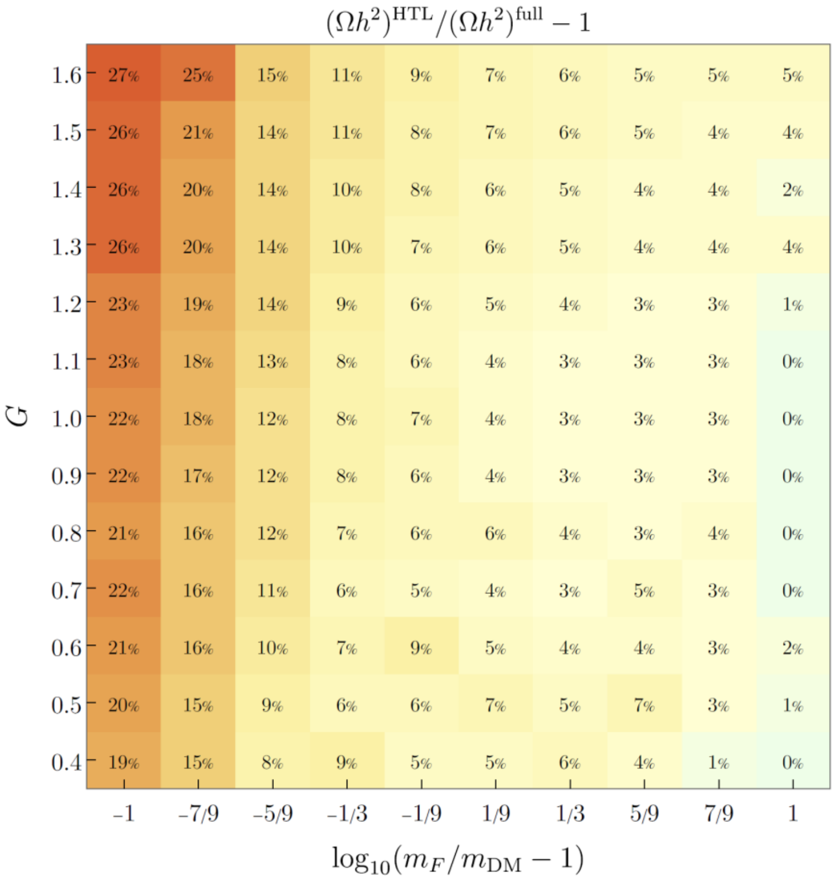
Equation for the DM production rate from the Kadanoff-Baym and CTP formalism

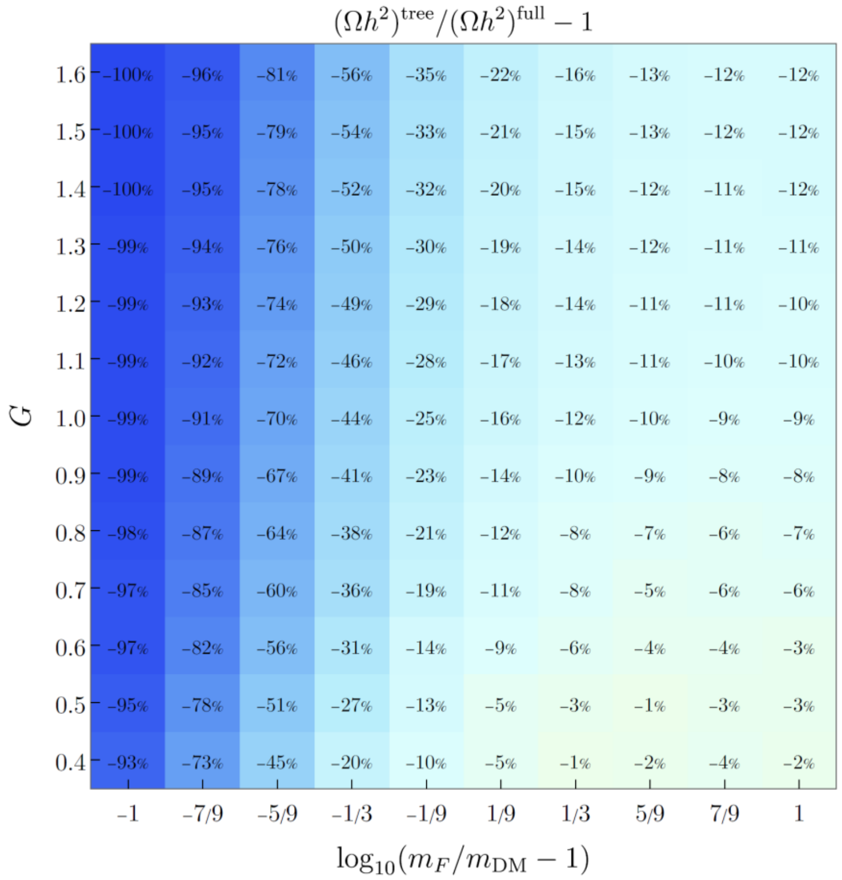
[Becker, Copello, Harz, Tamarit, 2312.17246]

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

Previous Work

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





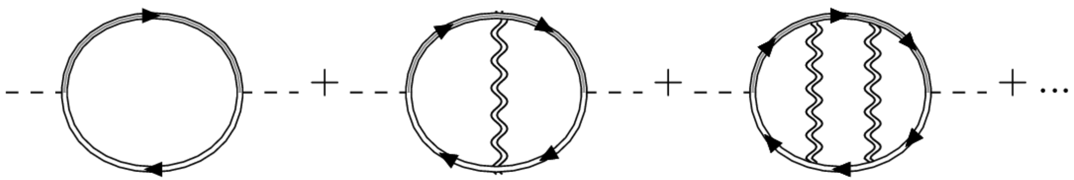
[Becker, Copello, Harz, Tamarit, 2312.17246]

Framework

Two key approximations:

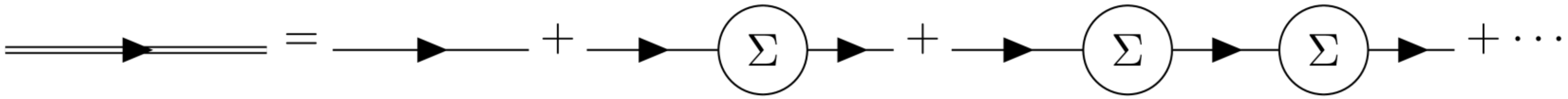
- Self-energy truncation:

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



- Propagator structure:

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

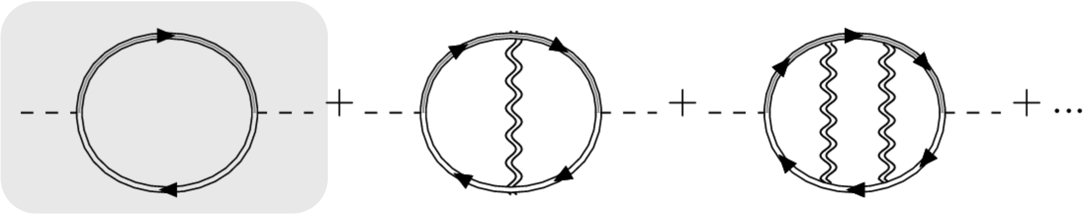


Framework

Two key approximations:

- Self-energy truncation:

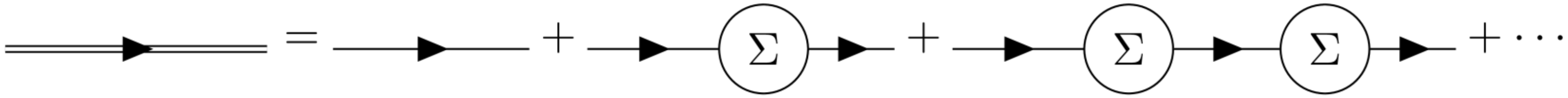
  whether we calculate $\Pi_s^{\mathcal{A}}$ at 1-loop, 2-loop...



[Becker, Copello, Harz, Tamarit, 2312.17246]

- Propagator structure:

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

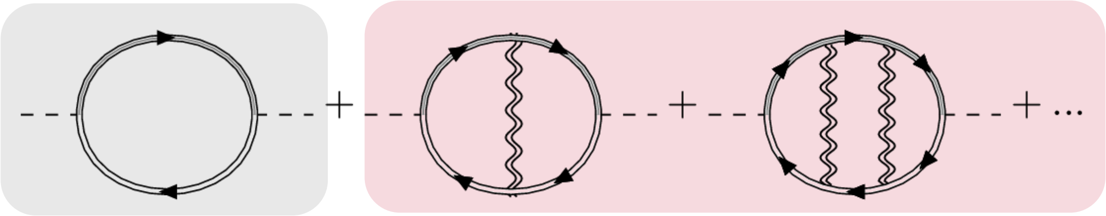


FRAMEWORK

Two key approximations:

- Self-energy truncation:

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

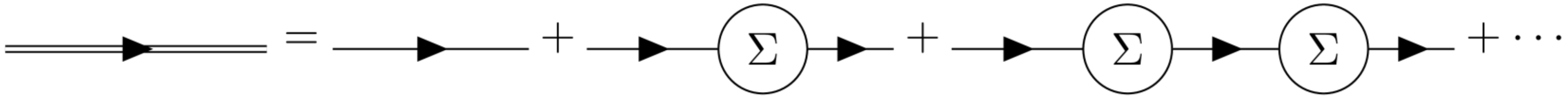


This work

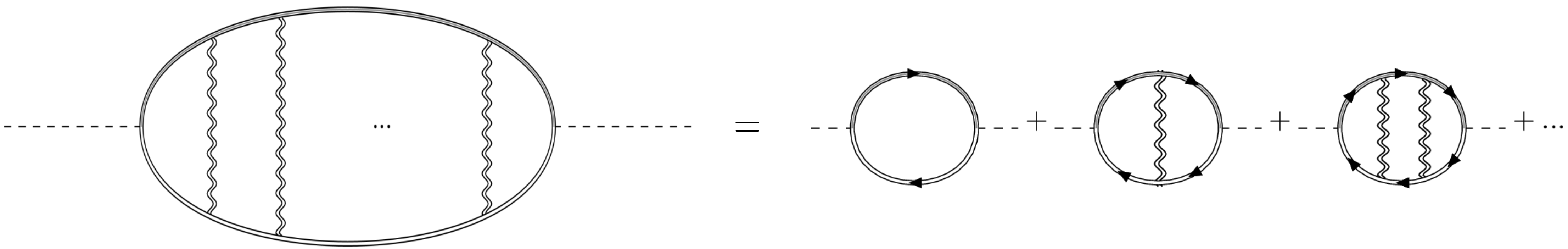
[Becker, Copello, Harz, Tamarit, 2312.17246]

- Propagator structure:

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



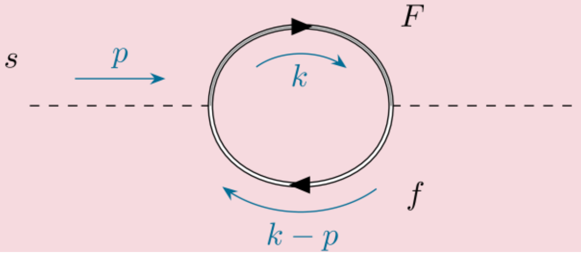
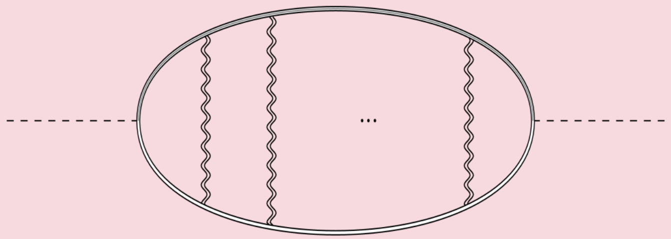
The Ladder Diagram



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

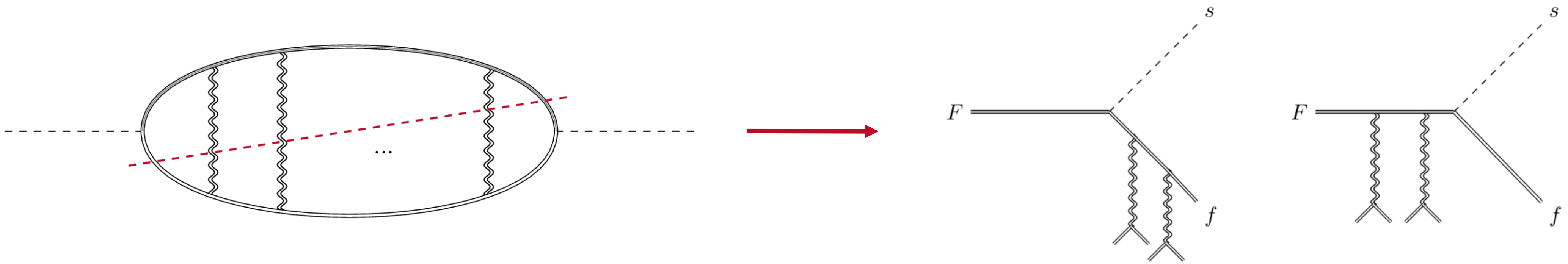
Discovered by **L**andau, **P**omeranchuk and **M**igdal (LPM) in the context of bremsstrahlung radiation.

[10.1103/PhysRev.103.1811]

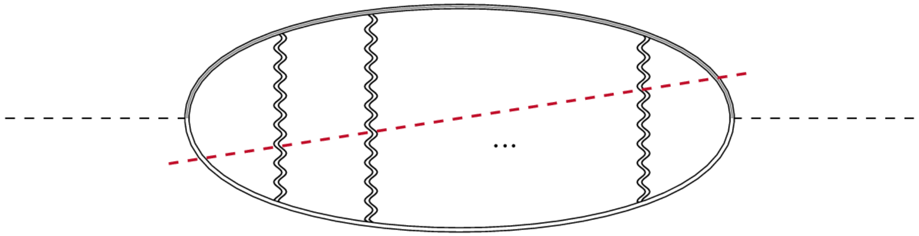
The LPM Effect

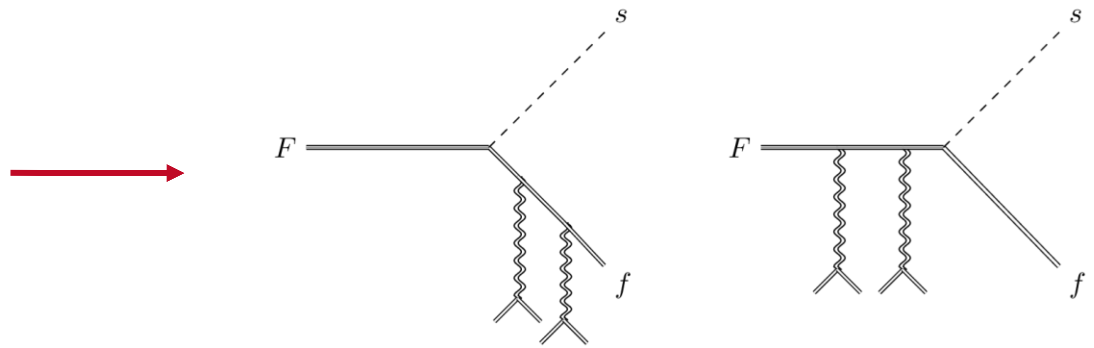
Discovered by **L**andau, **P**omeranchuk and **M**igdal (LPM) in the context of bremsstrahlung radiation.

[10.1103/PhysRev.103.1811]



Discovered by **L**andau, **P**omeranchuk and **M**igdal (LPM) in the context of bremsstrahlung radiation.
[10.1103/PhysRev.103.1811]

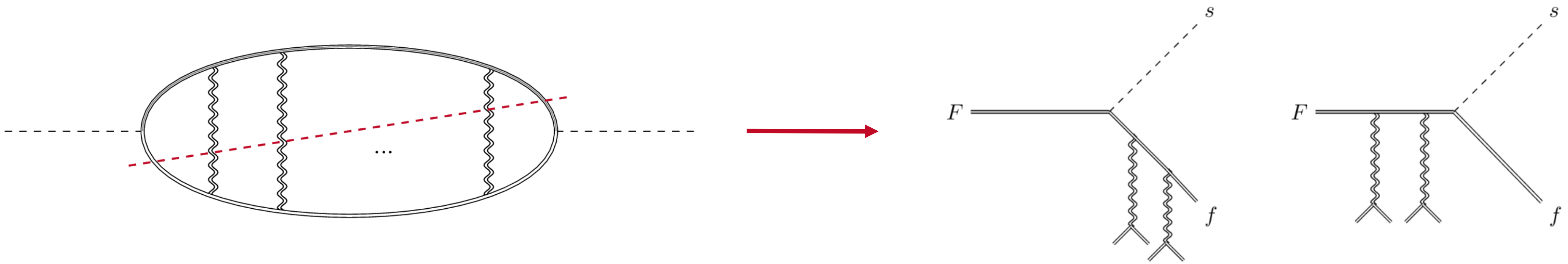




Multiple soft scattering of high-energy gauge bosons with the particles in a hot plasma.

The LPM Effect

Discovered by **L**andau, **P**omeranchuk and **M**igdal (LPM) in the context of bremsstrahlung radiation.
[10.1103/PhysRev.103.1811]



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]

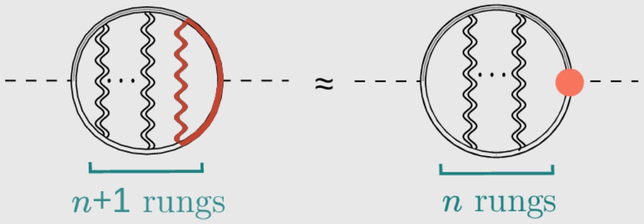
photon self energies

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

Calculation of the LPM rate

[Anisimov, Besak, Bodeker, 1202.1288]

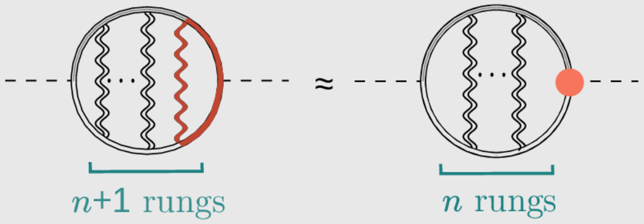
Recursion relation

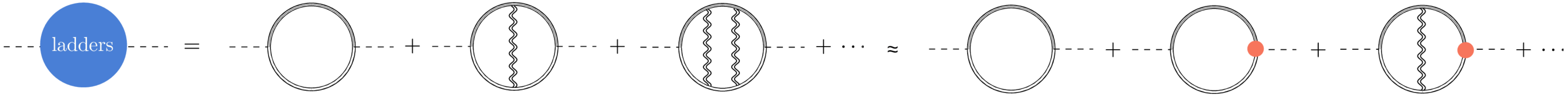


Calculation of the LPM rate

[Anisimov, Besak, Bodeker, 1202.1288]

Recursion relation

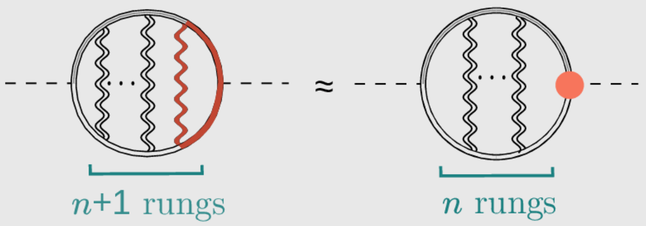


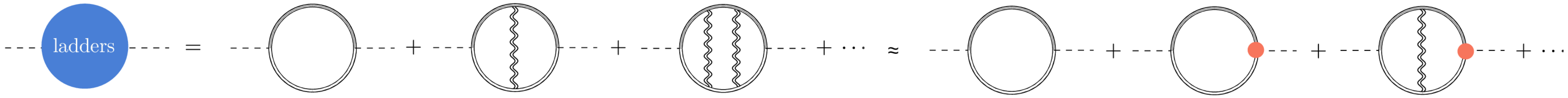


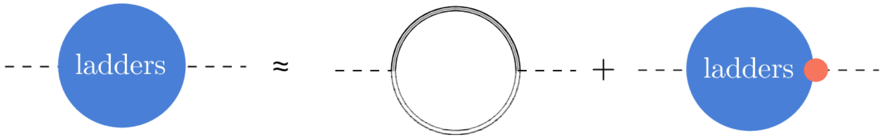
Calculation of the LPM rate

[Anisimov, Besak, Bodeker, 1202.1288]

Recursion relation





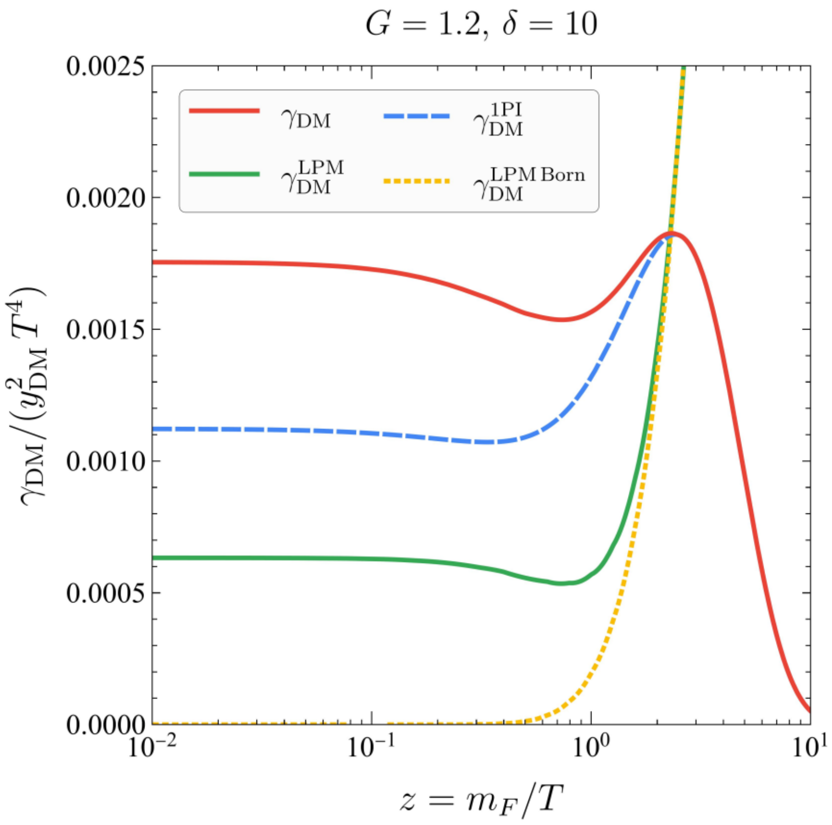


Switching Off the LPM Rate

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

[Biondini, Ghiglieri, 2012.09083]

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

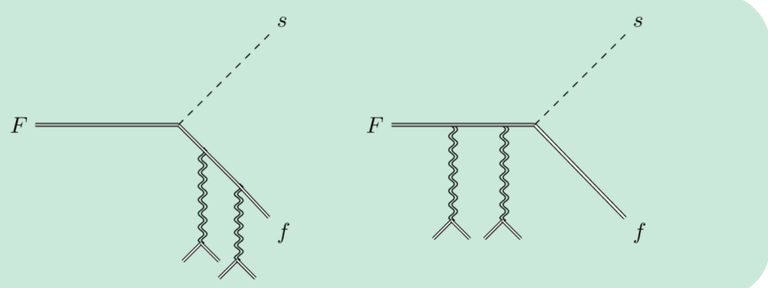


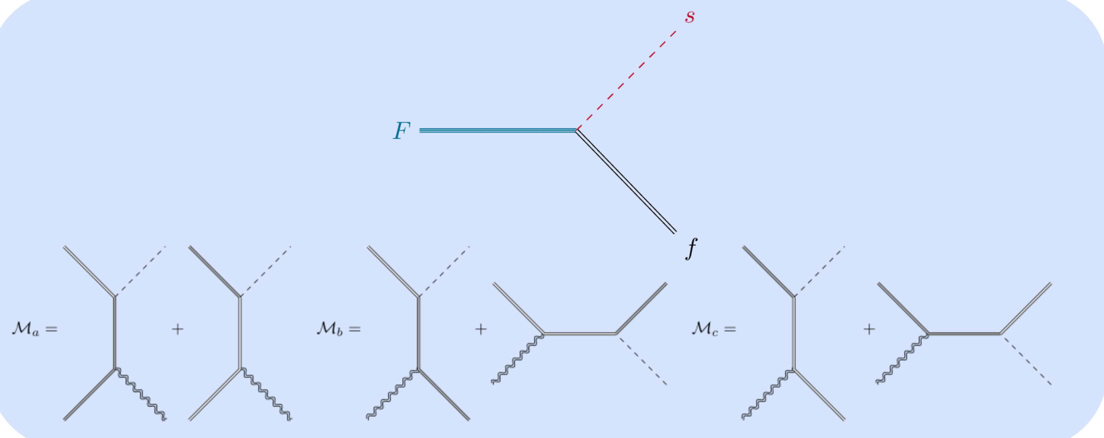
Switching Off the LPM Rate

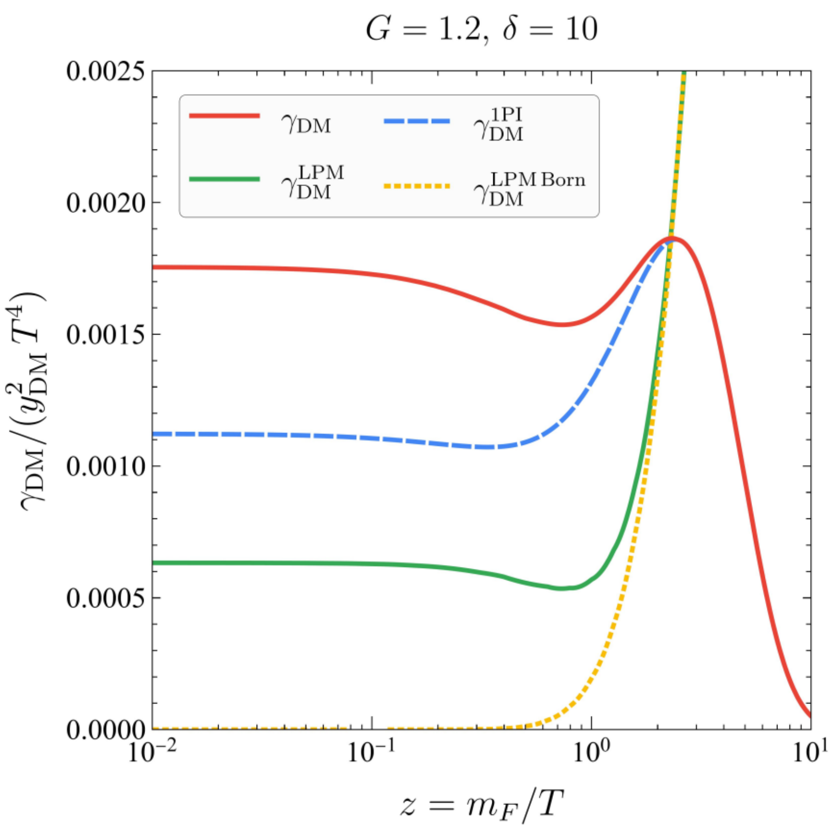
We have calculated the LPM rate in the ultrarelativistic regime. To move to non-relativistic, we use a simple prescription:

[Biondini, Ghiglieri, 2012.09083]

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







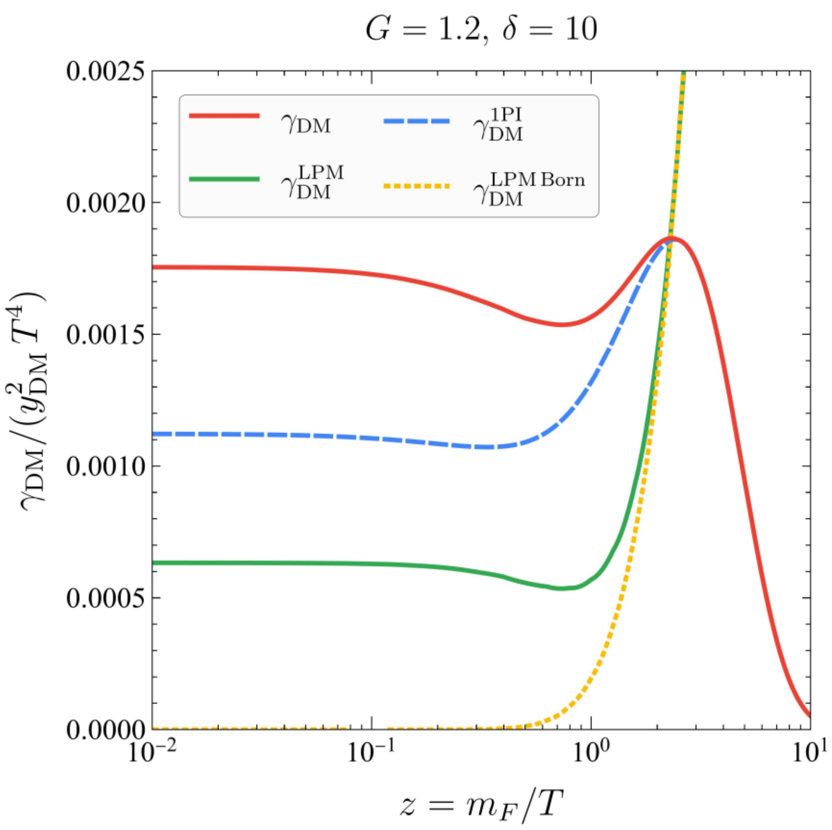
We have calculated the LPM rate in the ultrarelativistic regime. To move to non-relativistic, we use a simple prescription:

[Biondini, Ghiglieri, 2012.09083]

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

LPM Rate

Calculated in lightcone kinematics and valid for $m_F \ll T$



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]

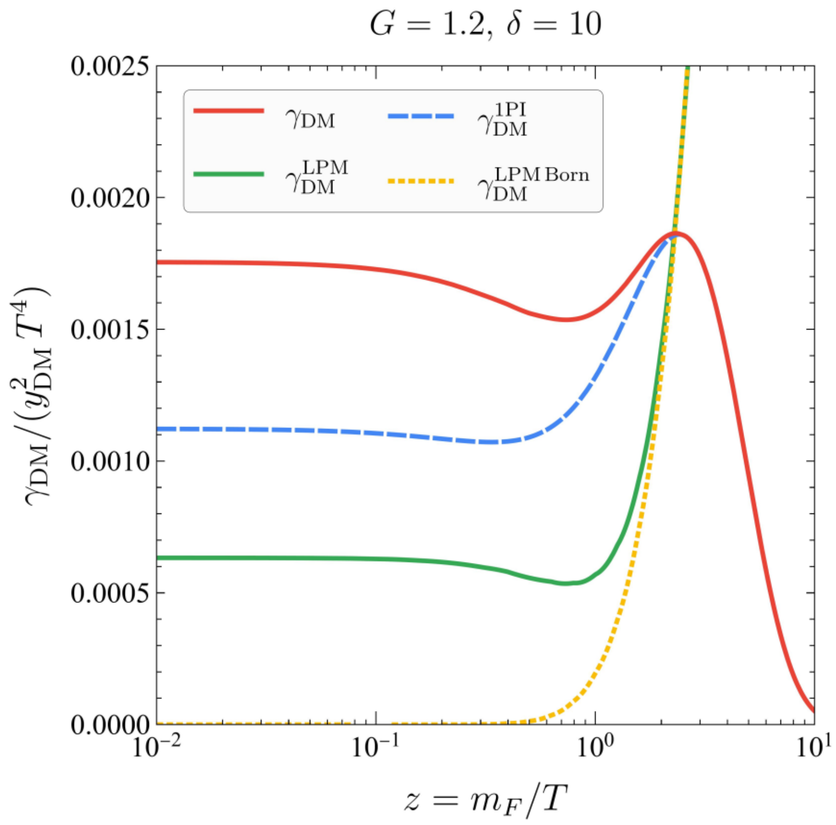
$$\gamma_{\rm DM} = \left(\gamma_{\rm DM}^{\rm LPM} - \gamma_{\rm DM}^{\rm LPMBorn}\right) f(m_F) + \gamma_{\rm DM}^{\rm 1PI}$$

LPM Rate

Calculated in lightcone kinematics and valid for $m_F \ll T$

LPM Born rate

Limit of vanishing soft scatterings. Removed to avoid double counting.



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]

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

LPM Rate

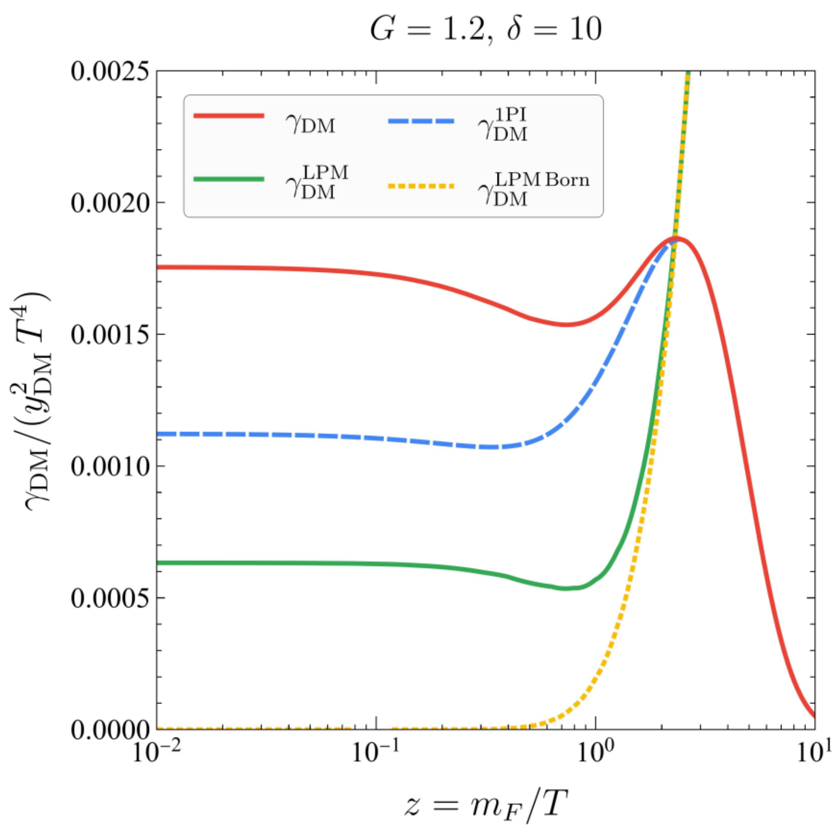
Calculated in lightcone kinematics and valid for $m_F \ll T$

LPM Born rate

Limit of vanishing soft scatterings. Removed to avoid double counting.

The 1PI rate

Obtained calculating the 1-loop self-energy with 1PI-resummed propagators



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]

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

LPM Rate

Calculated in lightcone kinematics and valid for $m_F \ll T$

LPM Born rate

Limit of vanishing soft scatterings. Removed to avoid double counting.

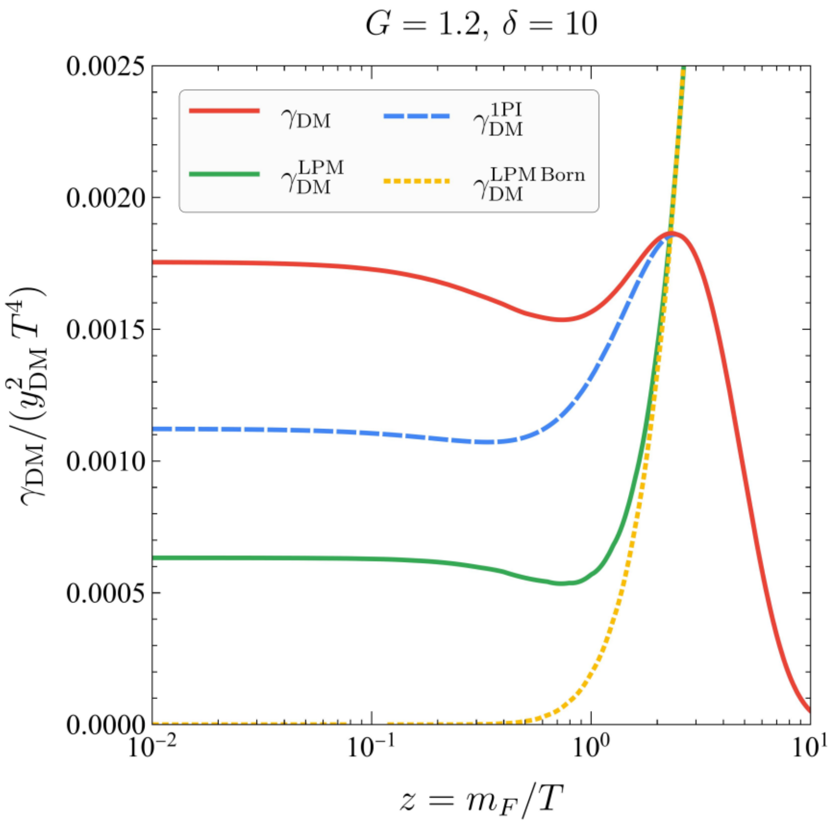
The 1PI rate

Obtained calculating the 1-loop self-energy with 1PI-resummed propagators

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

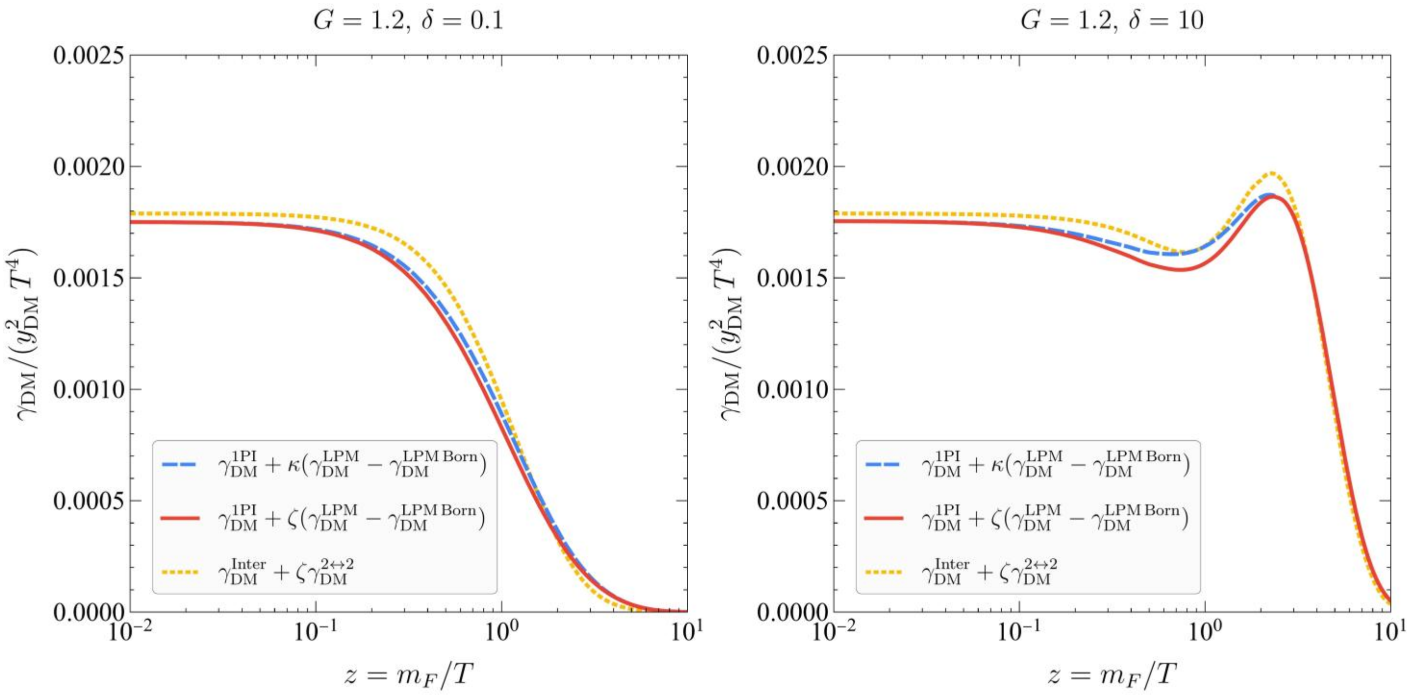
Thermal function

+ Captures 1PI behaviour
+ Most conservative approach

Smooth interpolation

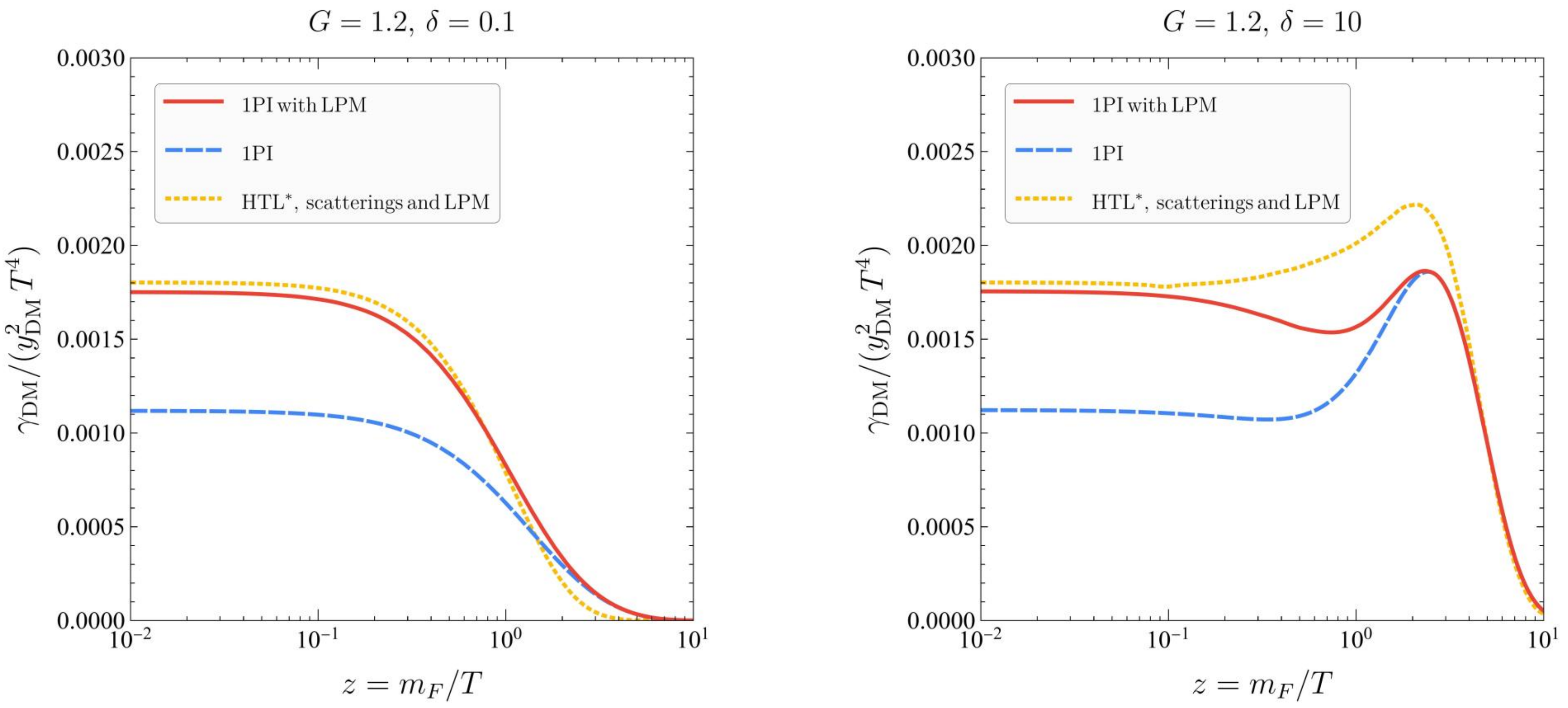
[Ghiglieri, Laine 2110.07149]

- Scatterings must be added manually
- Decay peak is overestimated



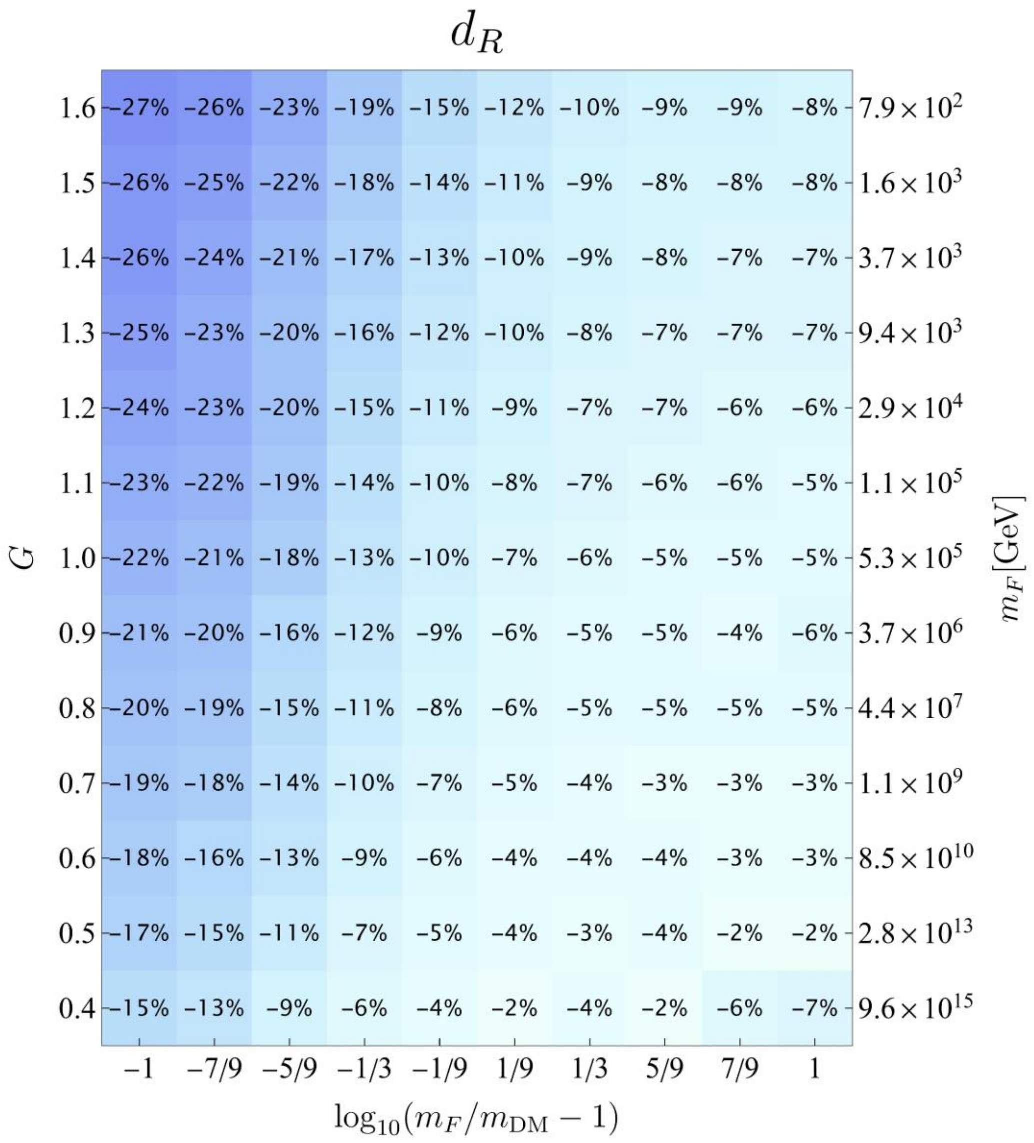
Discrepancies of ~30% and ~5% at the Ωh^2 level

The Final DM Rate



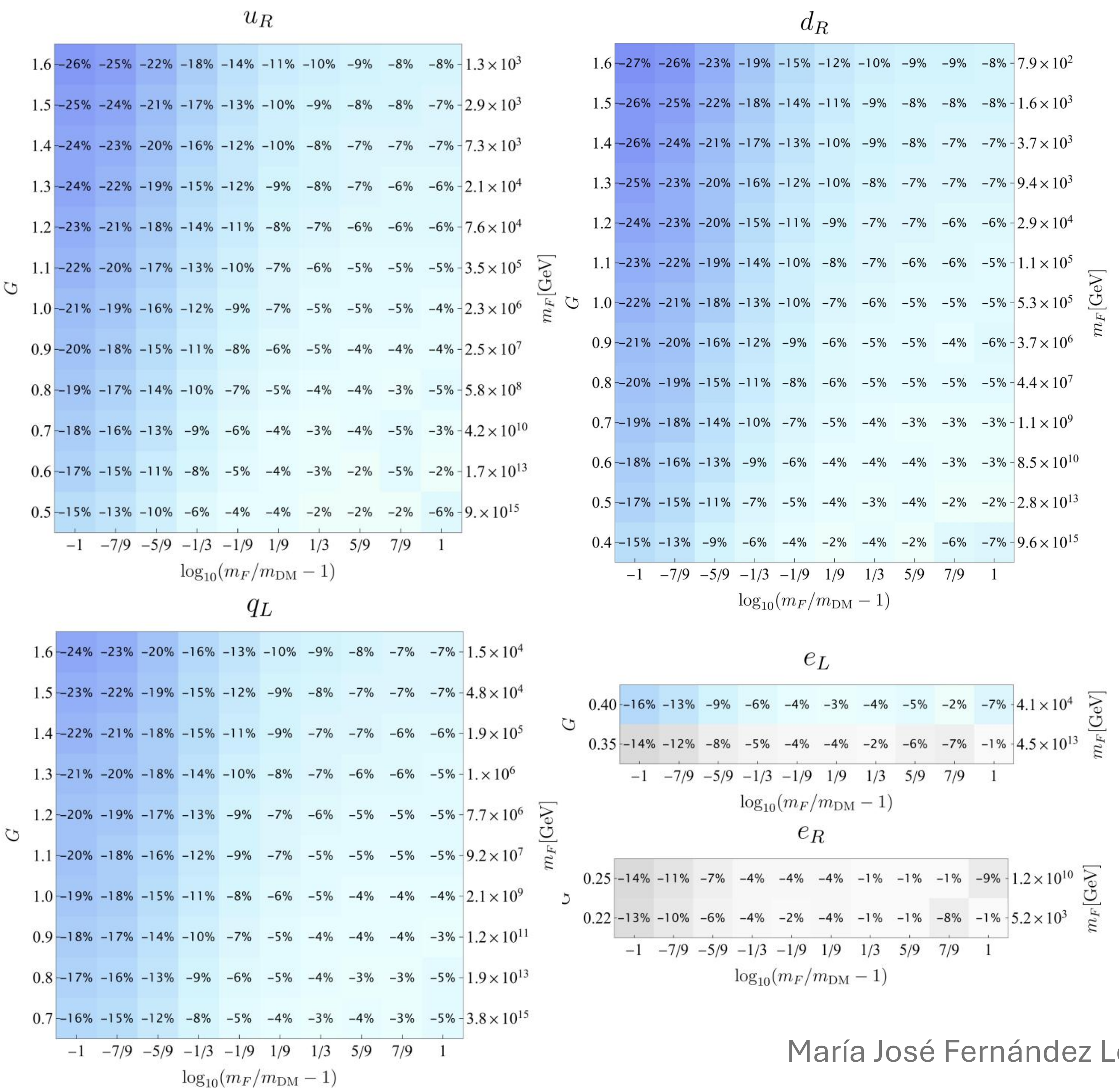
We provide a fitting of the LPM in the ultrarelativistic limit $\gamma_{\rm DM}^{\rm LPM}/(y_{\rm DM}^2 T^4)\Big|_{z=0.01} = a + bG$

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



PRiSMA+

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

Comparison to Simplified Methods

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

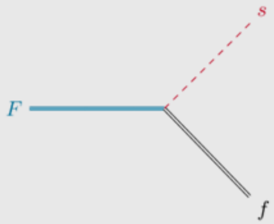
G \ $\log_{10}(m_{F,0}/m_{\text{DM}}-1)$	−1	−7/9	−5/9	−1/3	−1/9	1/9	1/3	5/9	7/9	1	$m_{F,0}$[GeV]
1.6	-100%	-96%	-81%	-56%	-33%	-19%	-12%	-8%	-8%	-7%	7.9×10^{2}
1.5	-100%	-95%	-79%	-53%	-31%	-17%	-10%	-8%	-6%	-6%	1.6×10^{3}
1.4	-99%	-95%	-77%	-51%	-29%	-15%	-9%	-6%	-5%	-6%	3.7×10^{3}
1.3	-99%	-94%	-75%	-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}

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

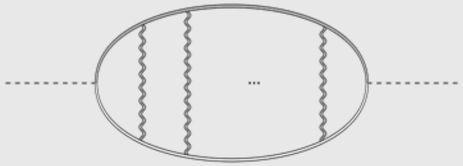
G \ $\log_{10}(m_{F,0}/m_{\text{DM}}-1)$	−1	−7/9	−5/9	−1/3	−1/9	1/9	1/3	5/9	7/9	1	$m_{F,0}$[GeV]
1.6	-33%	-31%	-24%	-8%	7%	16%	19%	20%	21%	21%	7.9×10^{2}
1.5	-33%	-32%	-22%	-6%	8%	16%	20%	21%	20%	21%	1.6×10^{3}
1.4	-32%	-30%	-20%	-5%	10%	17%	20%	21%	21%	20%	3.7×10^{3}
1.3	-32%	-30%	-19%	-2%	11%	18%	20%	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

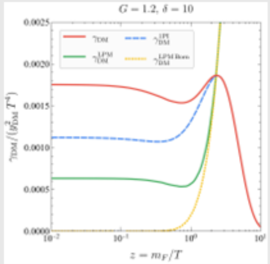
Framework



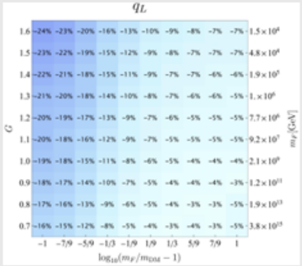
The LPM Effect



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

Rate Equation

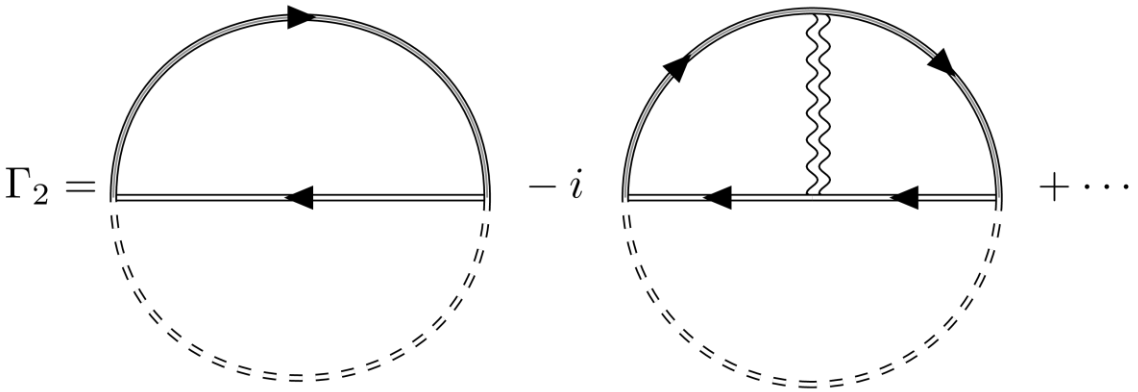
Equation for the DM production rate from the Kadanoff-Baym and CTP formalism

$$\frac{d}{dt}n_{s,\mathrm{ph}}(t) + 3Hn_{s,\mathrm{ph}} = \int \frac{d^3\vec{p}}{(2\pi)^3}\frac{\Pi_s^{\mathcal{A}}(\omega_p,|\vec{p}|)}{\omega_p} f_{\mathrm{B}}(\omega_p) \equiv \gamma_{\mathrm{DM}}$$

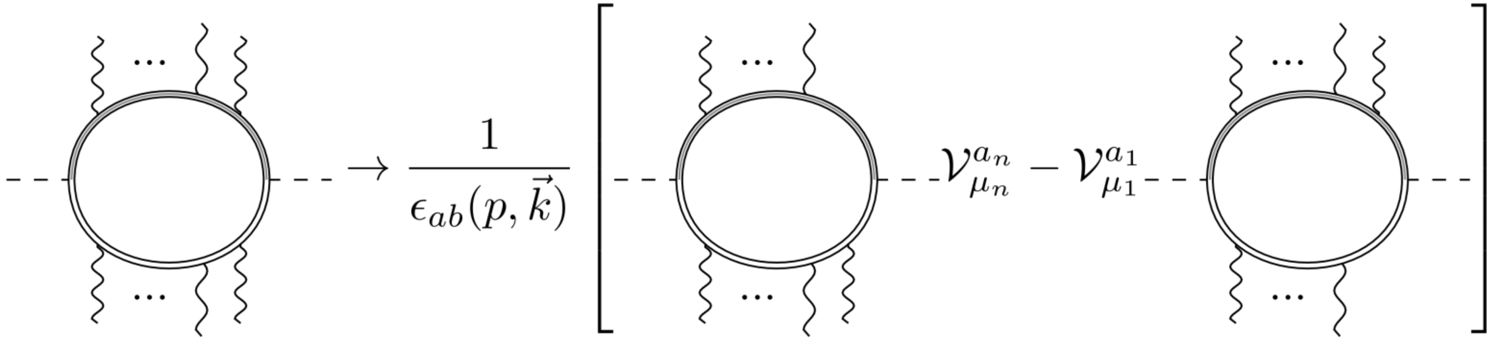
[M. Becker, E. Copello, J. Harz, C. Tamarit (2023)]

The self-energy is given by the functional derivative of the 2PI effective action

$$\Pi^{ab}(x,y) = iab\frac{\delta\Gamma_2[\Delta,S]}{i\delta\Delta^{ba}(y,x)}$$



Strategy of the Calculation



1. In the CTL regime, relate the n-point function to the (n-1)-point function where only one gauge boson was removed
2. Define a current by integrating over all external momenta and contracting with external fields
3. Integrate out the soft gauge boson background, so that external gauge bosons appear as rungs or in the self-energy insertions

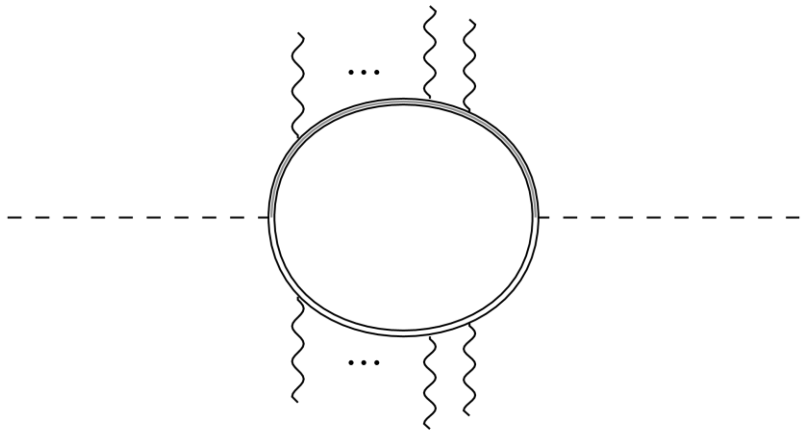
D.Besak (2010)

$$\hat{\Pi}_\phi(P, k_{||}, \vec{k}_\perp) = \frac{1}{\epsilon_{ab}(P, \vec{k})} \Big\{ d(r)\mathcal{C}_\phi(K, P) + ig^2 C_2(r) T \int \frac{\mathrm{d}^2 q_\perp}{(2\pi)^2} \mathcal{K}(\vec{q}_\perp) \Big[\hat{\Pi}_\phi(P, k_{||}, \vec{k}_\perp) - \hat{\Pi}_\phi \left(P, k_{||}, \vec{k}_\perp - \vec{q}_\perp\right) \Big] \Big\}$$

KINEMATICS

External and internal momenta are collinear and in the near-lightcone scale.

$$p \sim T, p^2 \sim g^2T^2, p \cdot k \sim g^2T^2$$



We can define the lightlike coordinates through a lightlike vector $V^\mu = (1, \hat{v})$

$$p_{\parallel}, k_{\parallel} \sim \mathcal{O}(T)$$
$$\vec{p}_\perp, \vec{k}_\perp \sim \mathcal{O}(gT)$$

Finite temperature analogue of Soft Collinear Effective Theory (SCET)

$$p_\pm = p_0 \pm p_{\parallel}$$

$$p^\mu \sim (p_+, p_-, \vec{p}_\perp)$$

$$p_+ \sim T, \vec{p}_\perp \sim gT, p_- \sim g^2T$$

	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

The LPM Effect

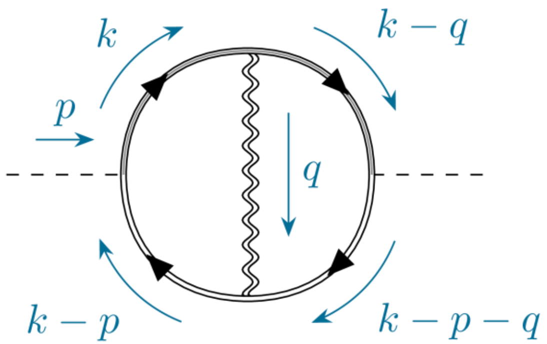
If all masses are thermal masses,

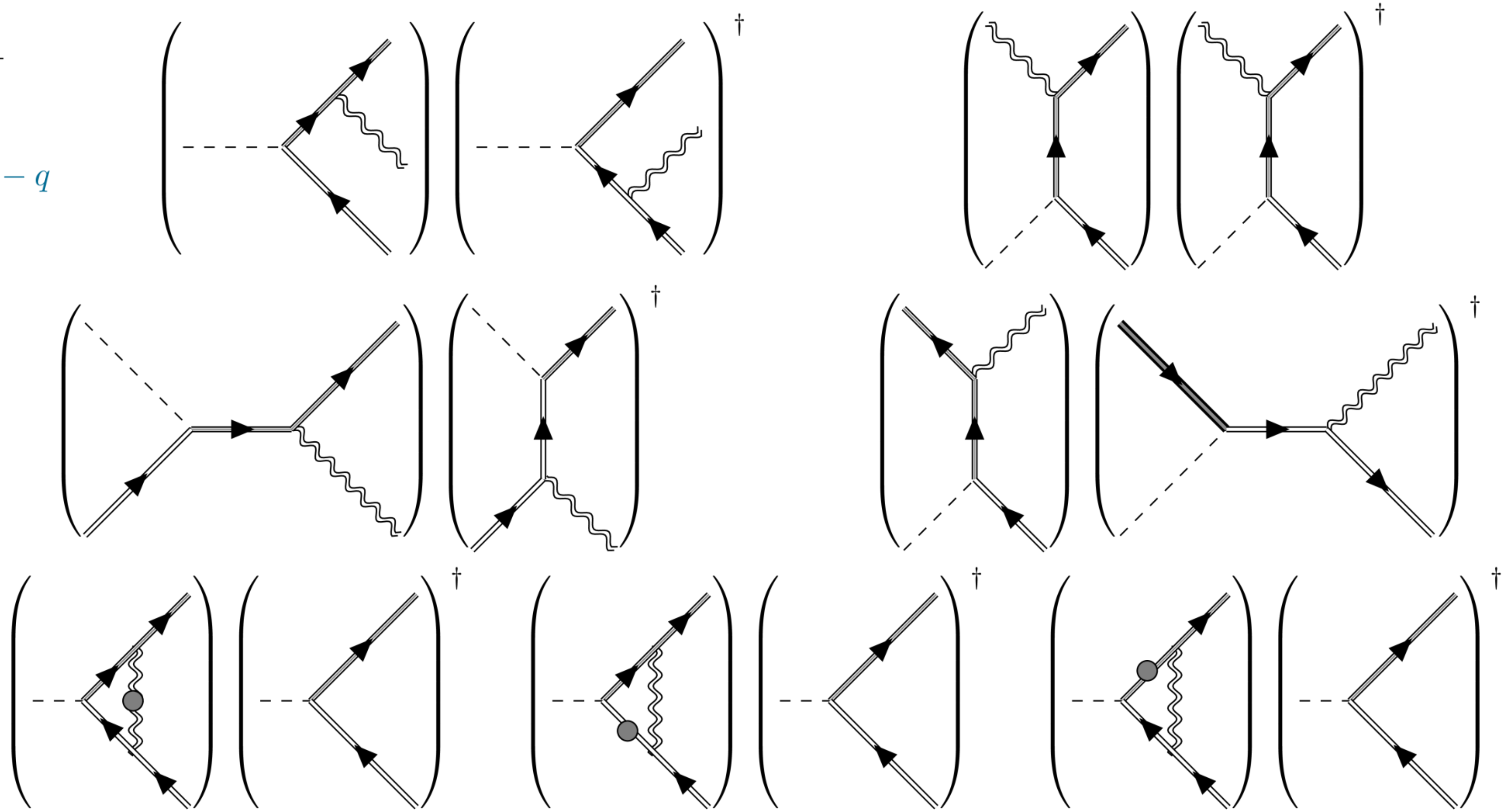
$$k^2 = m_F^2 = (p+q)^2 = m_{\mathrm{DM}}^2 + m_f^2 + 2pq$$

then the emission occurs collinearly $\theta \sim g$

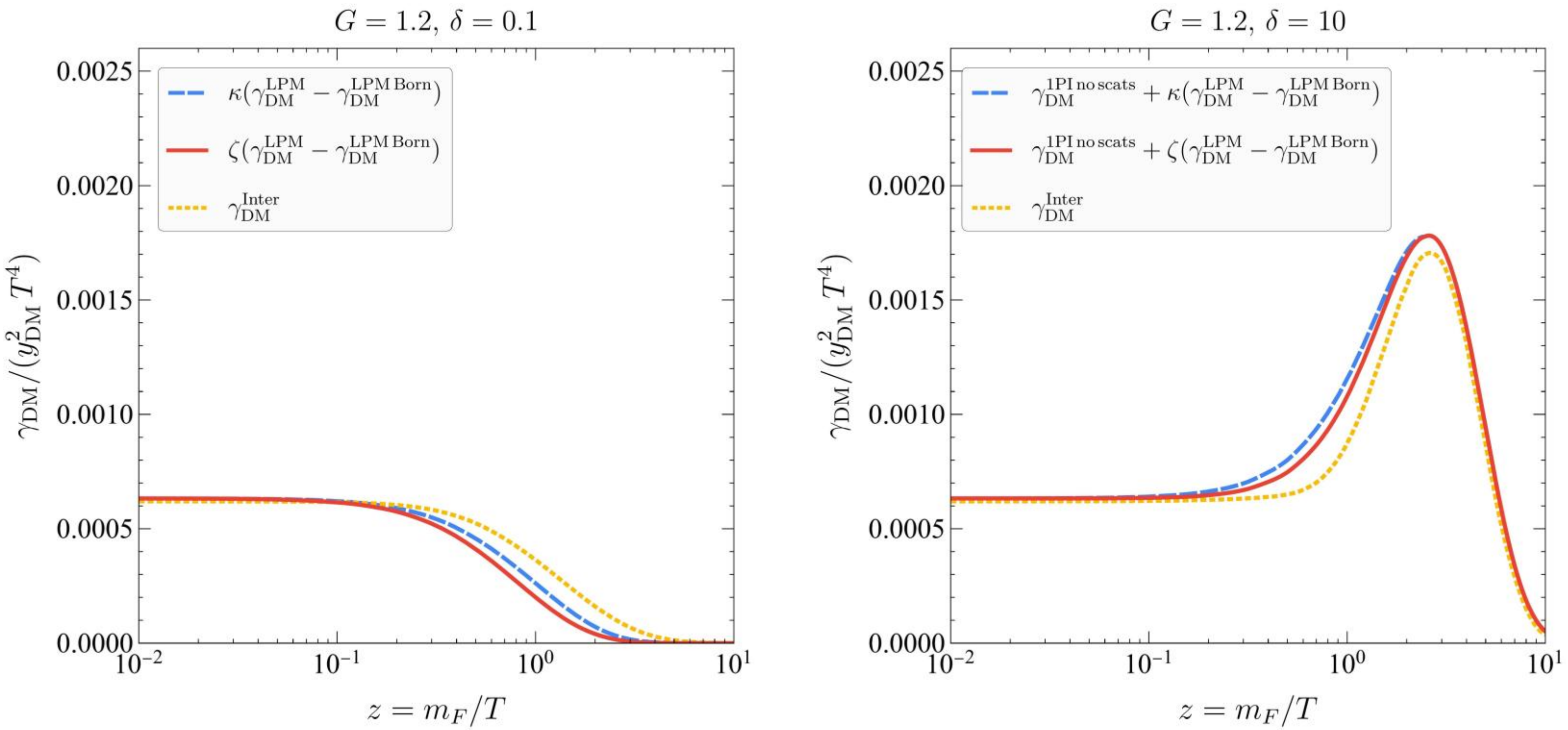
$$pq = |\vec{p}||\vec{q}|\,(1-\cos\theta) \sim g^2 T^2$$

The mean free time between collisions is of the same order as particle formation.
It is impossible to treat emission and scatterings as independent processes.

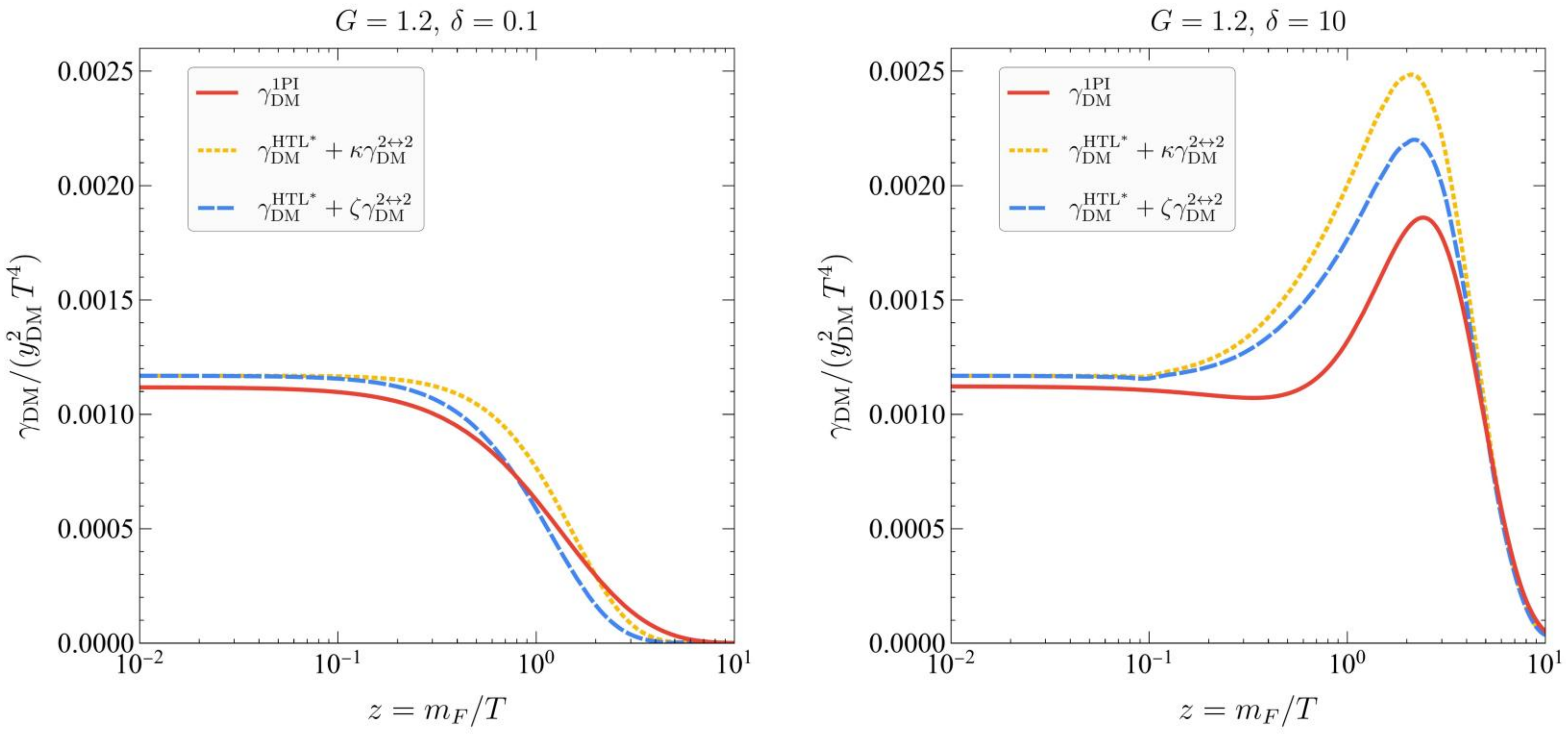

k
$k-q$
p
q
$k-p$
$k-p-q$

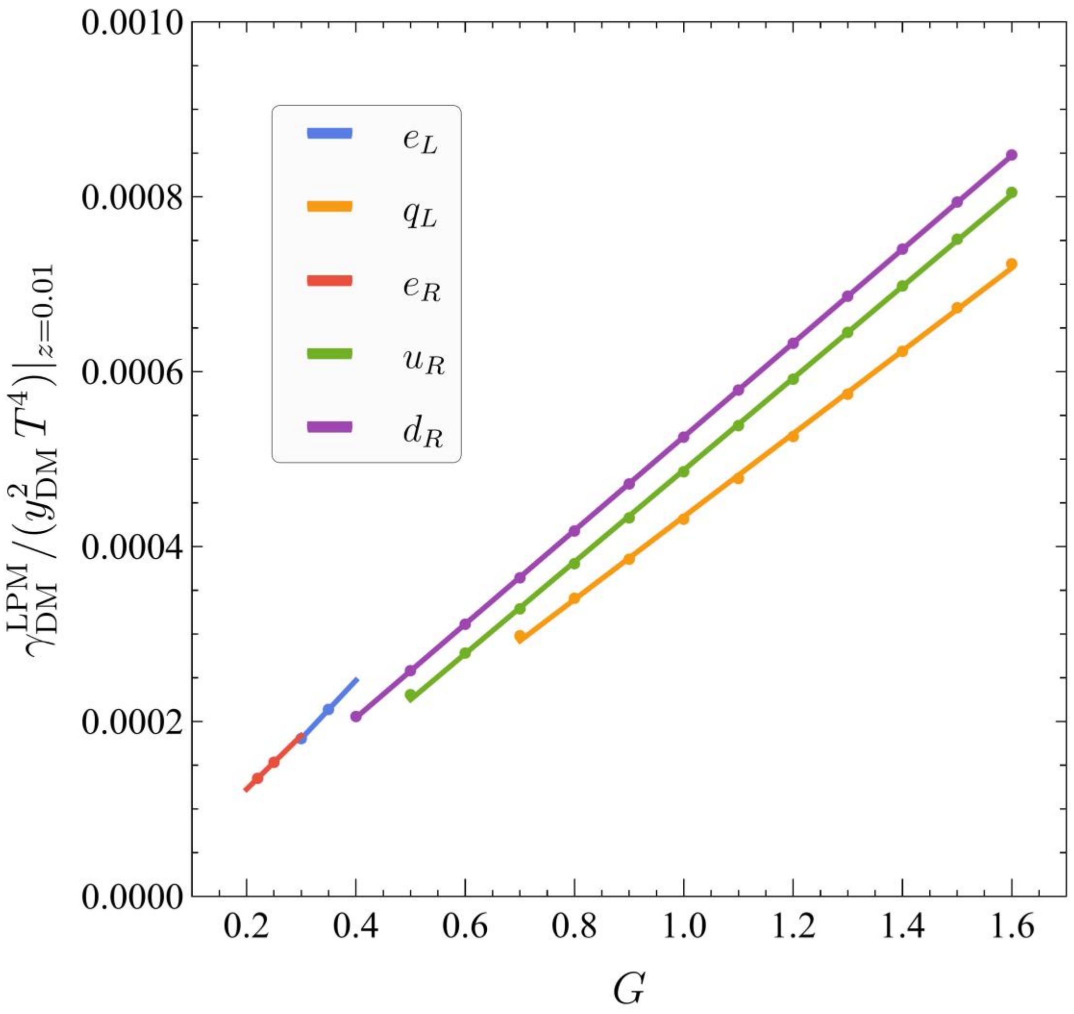

†
†
†
†
†
†
†

Prescriptions. Rate without Scatterings



Prescriptions. Rate without LPM.




0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
$\gamma_{\rm DM}^{\rm LPM}/(y_{\rm DM}^2 T^4)|_{z=0.01}$
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6
G
e_L
q_L
e_R
u_R
d_R