Advancing Standards in Early Universe Physics: The Impact of Bound States & Thermal Effects

Julia Harz

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KEK Theory Meeting on Particle Physics Phenomenology

Cluster of Excellence PRISMA++ | Precision Physics, Fundamental Interactions and Structure of Matter

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
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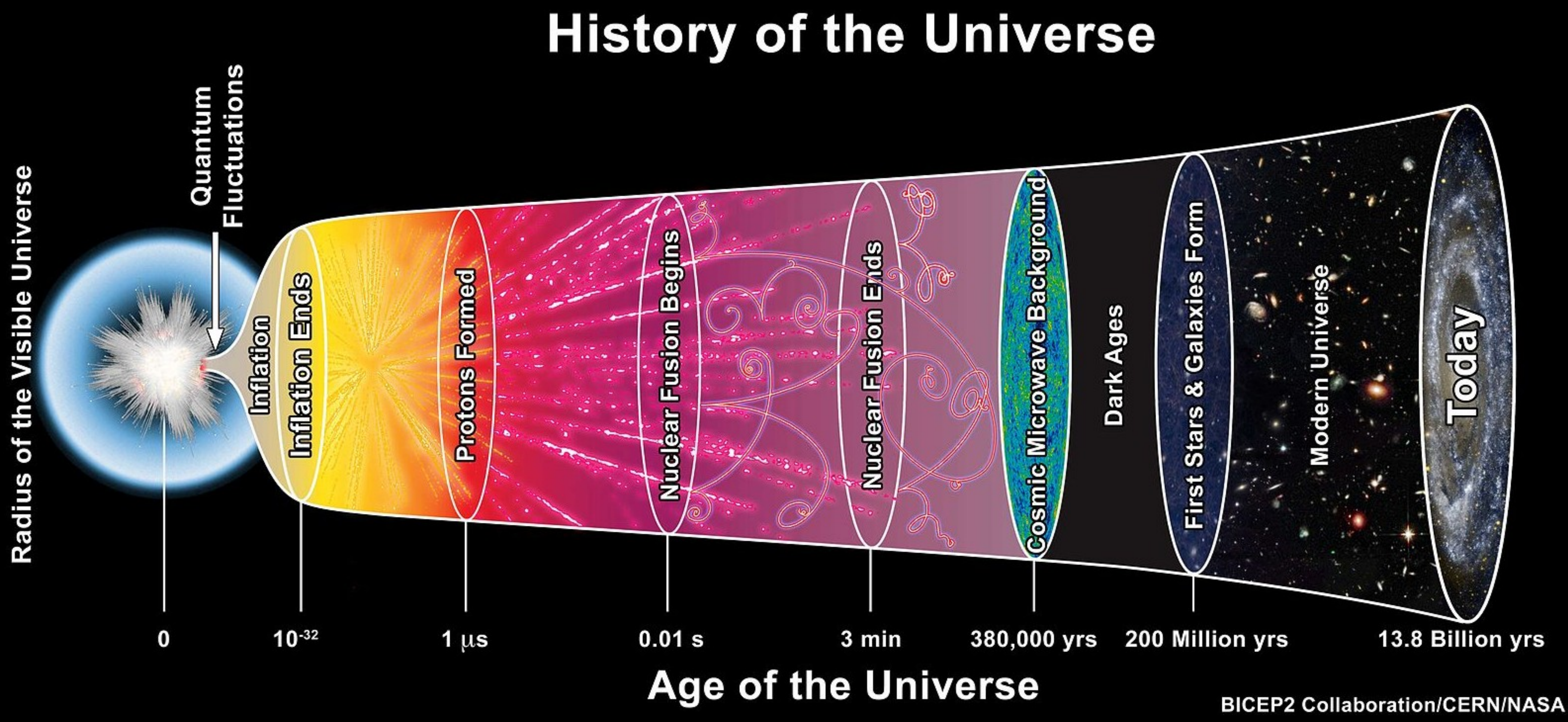
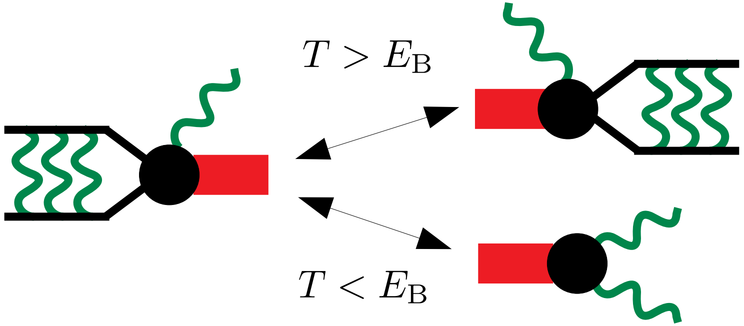
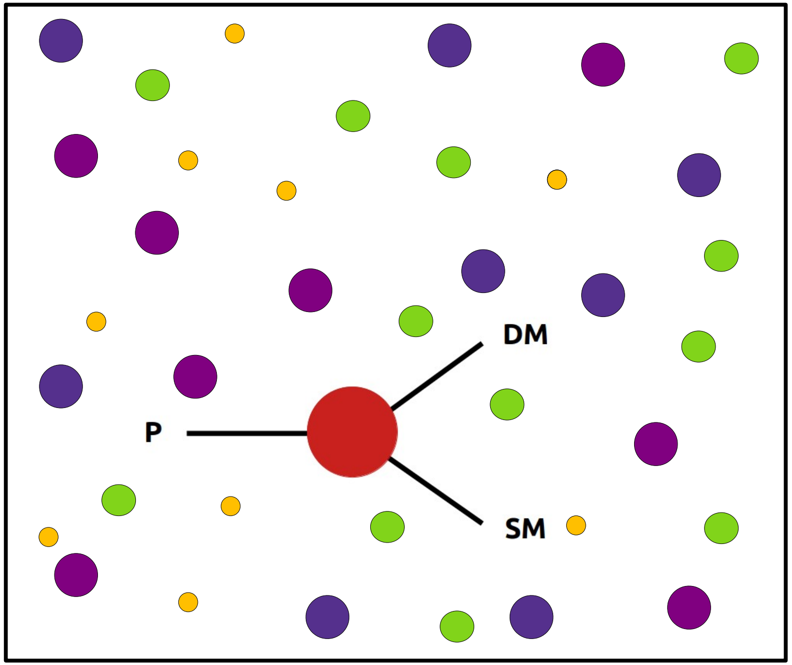

History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10-32
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA

Advancing Standards in Early Universe Physics



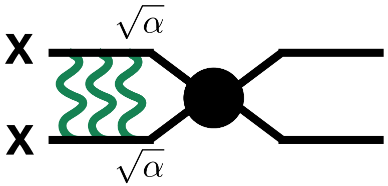


bound states formation

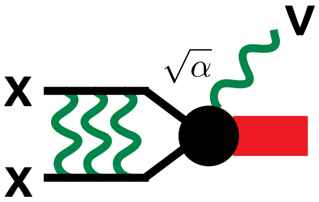
thermal plasma effects

Meta-stable Bound States in the Early Universe

If particles become non-relativistic, their annihilation cross-section can be affected by a Coulomb potential and form bound states via the emission of a gauge boson



Sommerfeld effect



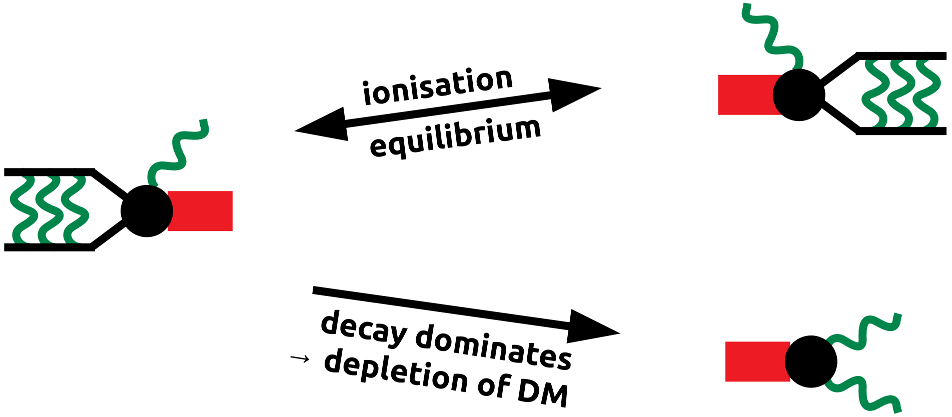
bound states formation

If $\alpha \sim v_{\rm rel}$, exchange of *n* light particles leads to

$$\left(\frac{\alpha}{v_{\rm rel}}\right)^n \sim 1$$ → resummation

Bound State Formation and Decay

Depending on the temperature, these bound states are in ionisation equilibrium or will decay



$T > E_{\mathrm{B}}$

$T < E_{\mathrm{B}}$

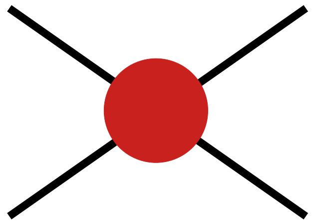
If bound states decay, hereby depleting the constituent particles, an effective new annihilation channel is generated

$$\langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle_{\mathrm{eff}} = \langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle \times \left(\frac{\Gamma_{\mathrm{dec}}}{\Gamma_{\mathrm{dec}} + \Gamma_{\mathrm{ion}}} \right)$$

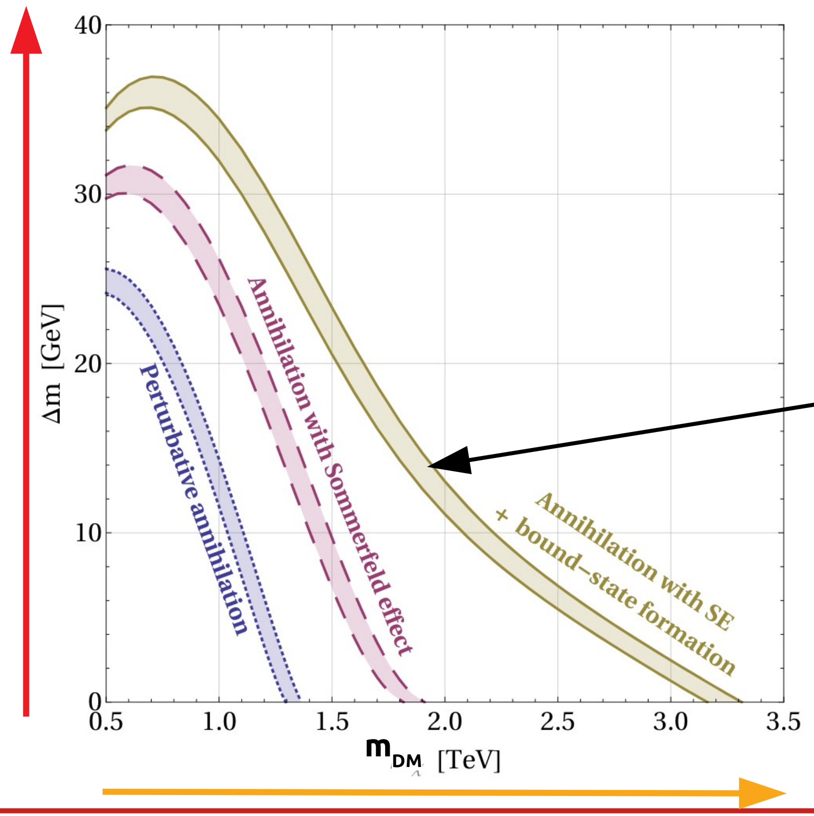
effective new annihilation channel

Impact of SE and BSF on the Theoretical Prediction

Assumption: Two, new dark particles with mass difference Δm



larger mass splitting
→ **multi-/mono-jet searches**



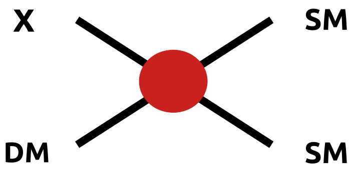
Relic abundance according to PLANCK

$$\Omega_{\mathrm{DM}} h^2 = 0.120 \pm 0.001$$

DM expected in multi-TeV regime
→ **future indirect detection experiments**

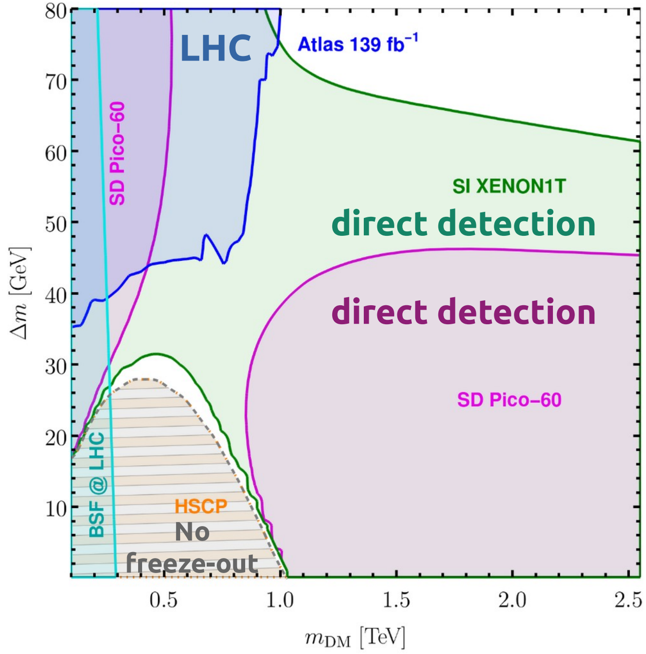
Petraki, JH (2018)

Impact on the Interpretation of Experimental Data



$$\mathcal{L} \supset g_{\mathrm{DM},ij} X_i^\dagger \bar{\chi} P_R q_j + h.c.$$

perturbative only



Exclusion of parameter space via

(1) experimental data and

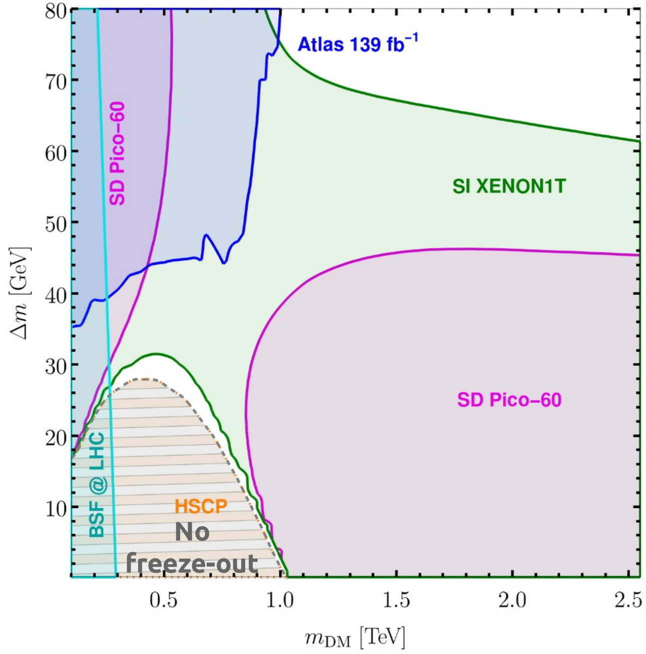
(2) preventing DM overproduction

experimental exclusion ↓ g_{DM} ↑ no DM overproduction

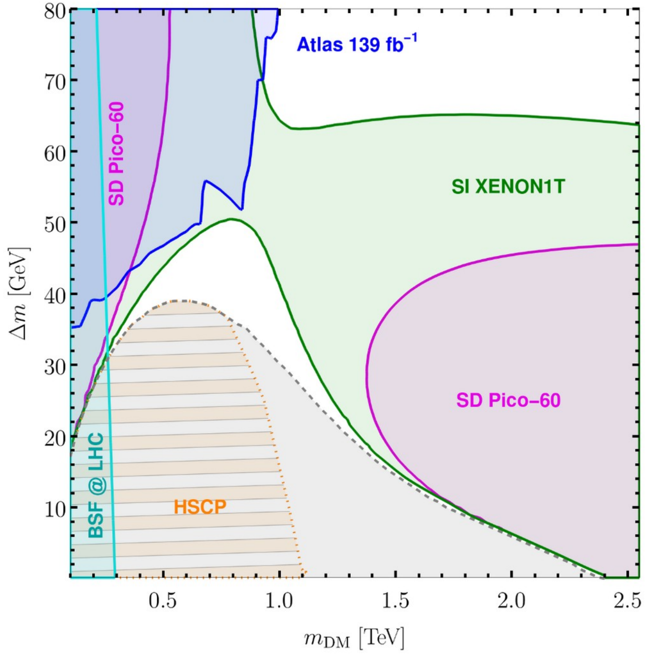
Becker, Copello, JH, Mohan, Sengupta (2022)

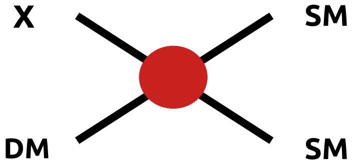
Impact on the Interpretation of Experimental Data

perturbative only



+ Sommerfeld effect
+ bound states





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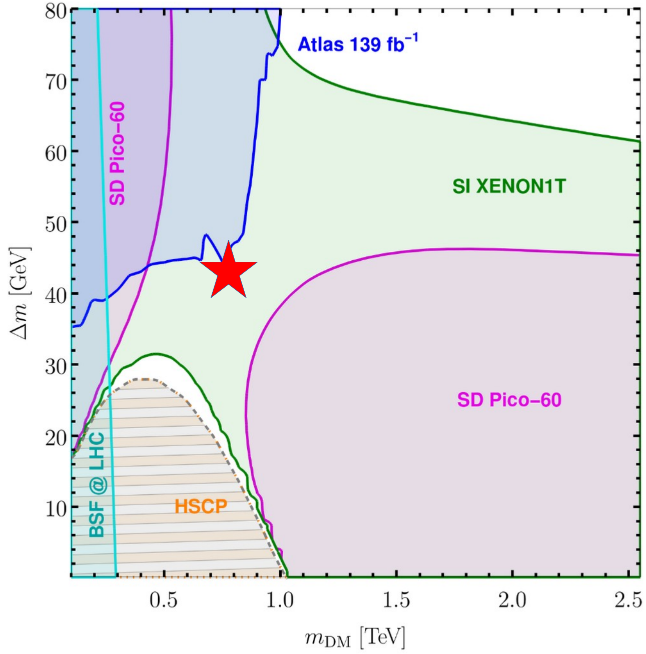

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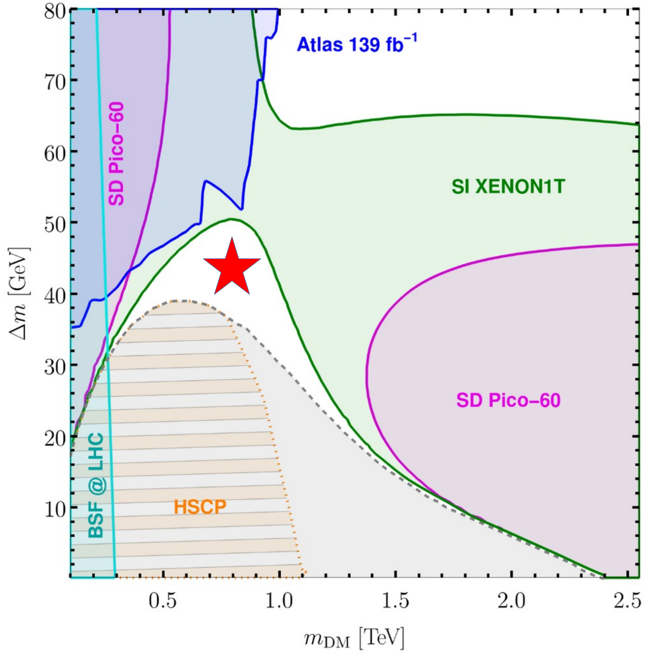
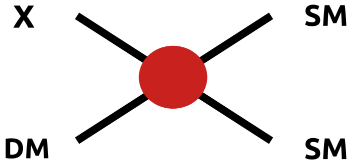


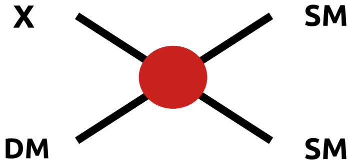


$$\mathcal{L} \supset g_{\mathrm{DM},ij} X_i^\dagger \bar{\chi} P_R q_j + h.c.$$

➡ **previously excluded parameter space is NOT yet excluded!**

Becker, Copello, JH, Mohan, Sengupta (2022)

Impact on the Interpretation of Experimental Data



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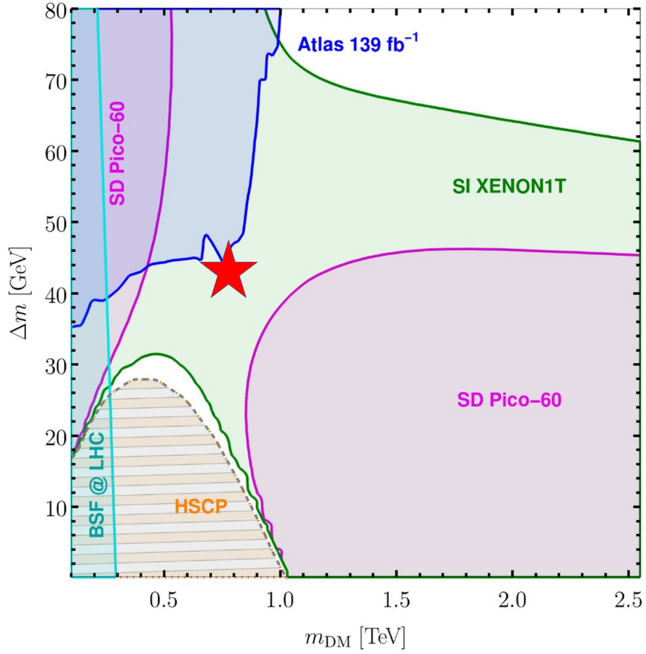

+ Sommerfeld effect
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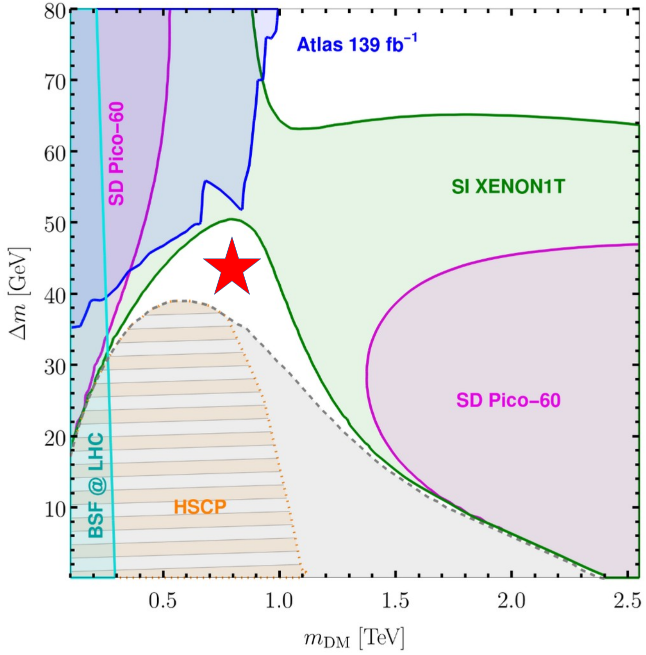


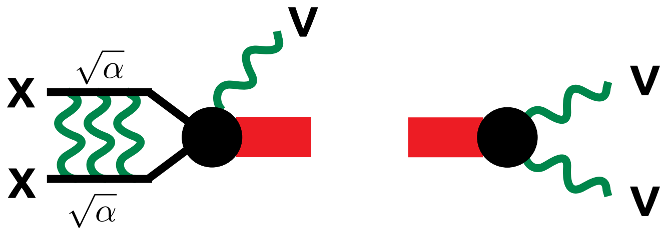
We studied further t-channel scenarios and provide code as plug-in for MicrOMEGAs!

SE+BSF4DM

Becker, Copello, JH, Napetschnig (2026)

Impact of Bound State Formation on Baryogenesis

Similarly, if particles in baryogenesis scenarios become non-relativistic, they can form bound states by the emission of a gauge boson



How can bound states effect baryogenesis and leptogenesis scenarios?

Becker, Fridell, JH, Hati (2024)

Bound States in Decay dominated Baryogenesis

Assume a toy model with X transforming in the adjoint representation of a non-abelian SU(N_D) with an associated gauge boson V with gauge strength g

$$|\mathcal{M}\,(X \to bb)\,|^2 = \lambda^2 m_X^2\,(1+\epsilon)$$
$$|\mathcal{M}\,\left(X \to \bar{b}\bar{b}\right)|^2 = \lambda^2 m_X^2\,(1-\epsilon)$$

B-L and CP-violating decays

Boltzmann equations taking into account bound states:

$$c\frac{Y_X}{z} = -\frac{\langle \Gamma_X \rangle}{z^2 s}\left(Y_X - Y_X^{\mathrm{eq}}\right) - \frac{2\langle \sigma v \rangle^{\mathrm{eff}}_{XX\to VV}}{z^2}\left(Y_X^2 - Y_X^{\mathrm{eq}\,2}\right)$$

X Yield

$$c\frac{Y_{\Delta b}}{z} = \epsilon\frac{\langle \Gamma_X \rangle}{z^2 s}\left(Y_X - Y_X^{\mathrm{eq}}\right) - 2\frac{Y_{\Delta b} Y_b^{\mathrm{eq}}}{z^2}\langle \sigma v \rangle_{bb\leftrightarrow\bar{b}\bar{b}}$$

B-L Yield

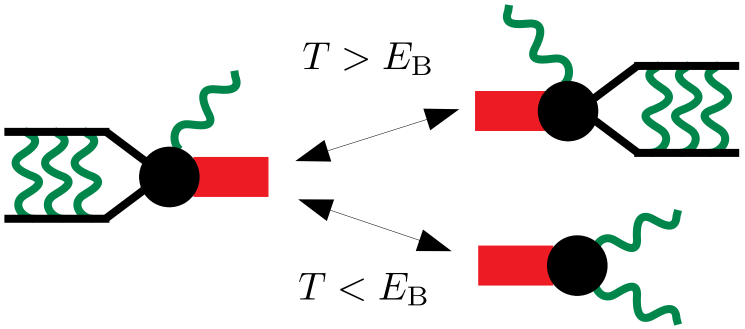
with

$$\langle \sigma v \rangle^{\mathrm{eff}}_{XX\to VV} = \langle \sigma v \rangle_{XX\to VV} + \langle \sigma v \rangle^{\mathrm{eff}}_{\mathcal{B}}$$

Becker, Fridell, JH, Hati (2024)

Bound States in Decay dominated Baryogenesis

Depending on the temperature, bound states will back-ionize or decay



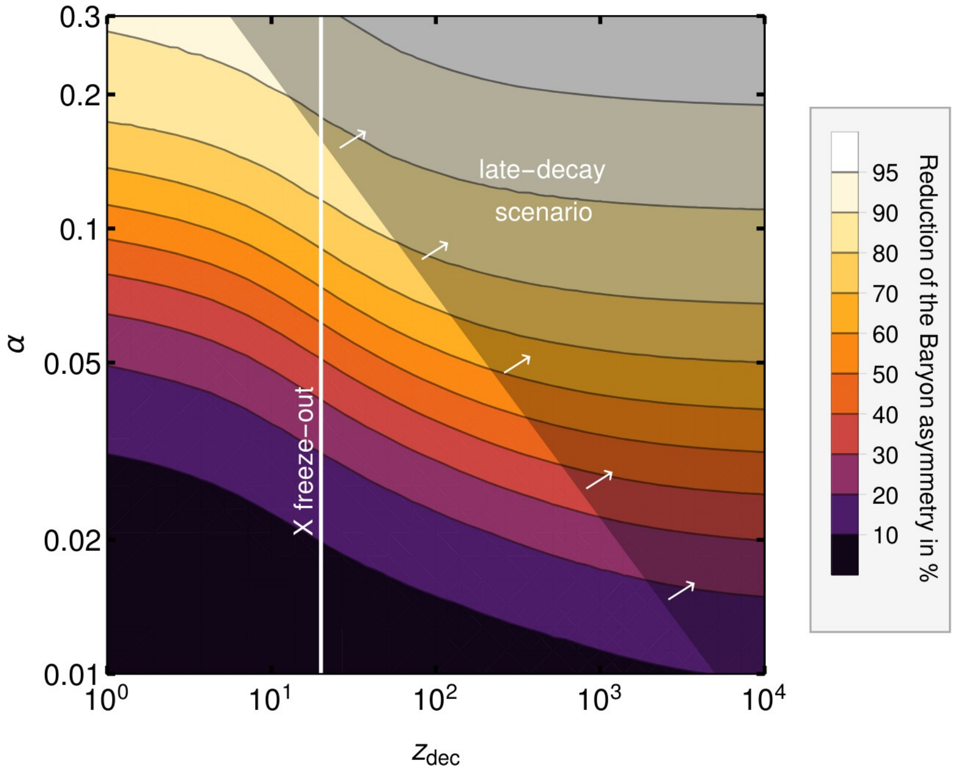
$$\langle \sigma v \rangle_{\mathcal{B}}^{\mathrm{eff}} = \frac{\langle \Gamma_{\mathcal{B}} \rangle}{\langle \Gamma_{\mathcal{B}} \rangle + \langle \Gamma_{\mathrm{ion}} \rangle} \langle \sigma v \rangle_{\mathcal{B}}$$

Bound state effects are mainly relevant for λ<<α, implying that $\mathcal{B} \to b\bar{b}$ is subdominant!

➡ **Late decay scenario: If bound states decay into mediators (z_{BSF}) before the asymmetry generation (z_{dec}), the yield of X changes, leading to a reduction of the asymmetry!**

Becker, Fridell, JH, Hati (2024)

Bound States in Decay dominated Baryogenesis

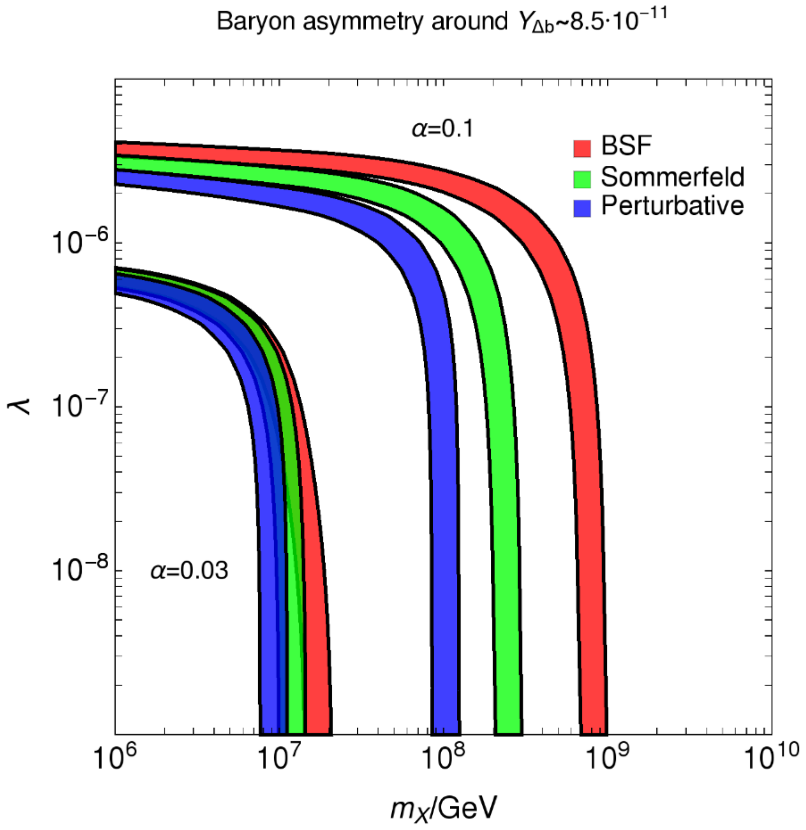


$$\epsilon = 0.1, m_b = 0.1 m_X, m_X = 10^6 \mathrm{GeV}$$

- **late decay scenario ($z_{BSF} < z_{dec}$):**
  BSF reduces the baryon asymmetry up to an order of magnitude
- **early decay scenario ($z_{dec} < z_{BSF}$):**
  correction mainly driven by Sommerfeld corrections, less significant

Becker, Fridell, JH, Hati (2024)

Bound States in Decay dominated Baryogenesis



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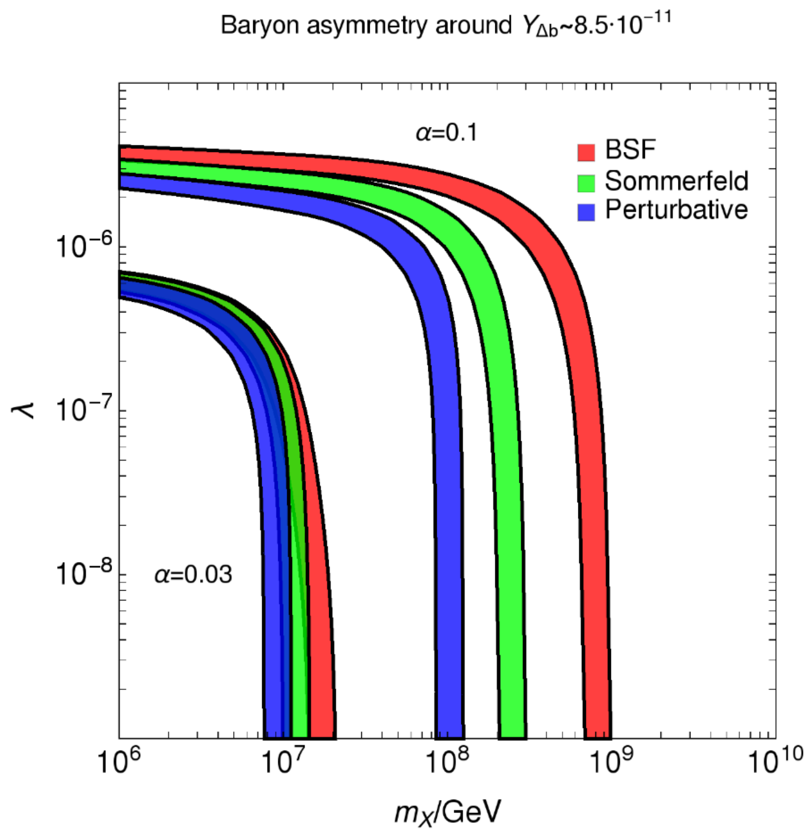
Becker, Fridell, JH, Hati (2024)

Bound States in Decay dominated Baryogenesis



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  correction mainly driven by Sommerfeld corrections, less significant

For scattering dominated baryogenesis see our paper or ask me later :-)

Becker, Fridell, JH, Hati (2024)

Summary: Impact of Bound States on Baryogenesis

Bound state can impact baryogenesis and leptogenesis scenarios threefold:

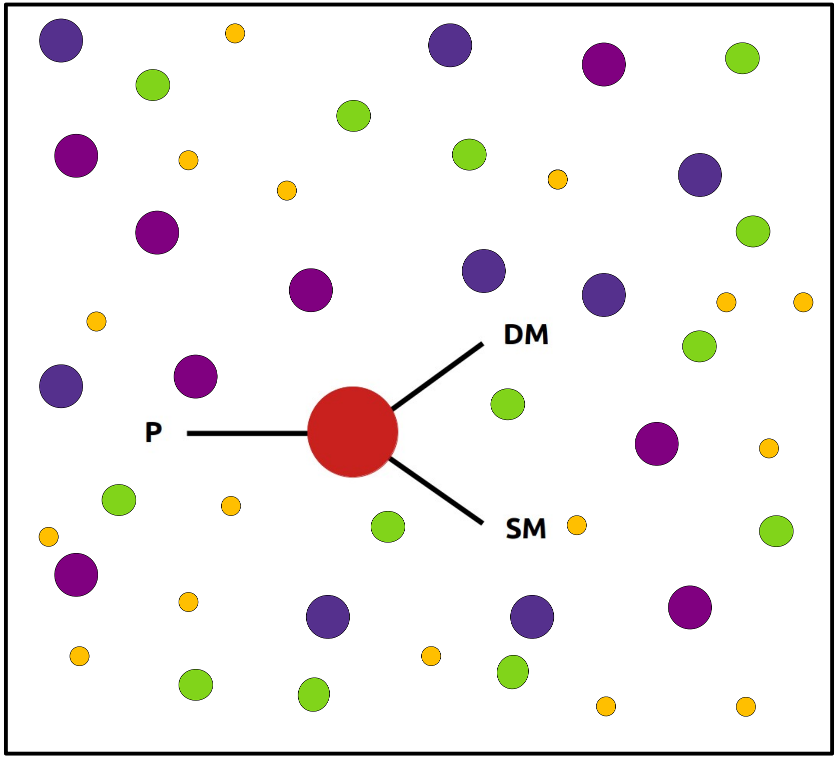
1. bound states that subsequently decay into gauge bosons lead to a more efficient depletion of the asymmetry generating particles and hence of the asymmetry itself

2. If bound states have CP and B-L violating decay modes, BSF with subsequent B-L decay can contribute to the asymmetry

3. The existence of (B-L)-violating decay modes leads to additional bound state mediated washout processes and their interferences

→ Next step: explore impact in specific model realizations

Becker, Fridell, JH, Hati (2024)



Thermal Effects for Early Universe Physics

Thermal Effects in Early Universe Physics

High-scale Leptogenesis:

- Numerous investigations in closed-time-path (CTP) and density matrix formalism

  → solving directly Schwinger-Dyson equations Garny, Kartavtsev, Hohenegger (2013), Iso, Shimada, Yamanaka (2014)
  → performing Wigner transform Garbrecht, Herranen (2012), Garbrecht, Gautier, Klaric (2014)
  → two-momentum picture Millington, Pilaftsis (2013), Bödeker, Schröder (2020)

- Investigations of IR convergence behaviour Beneke, Garbrecht, Herranen, Schwaller (2010), Garbrecht, Ramsey-Musolf (2014)

Low-scale Leptogenesis:

- Generalization of Sigl+Raffelt treatment of relativistic mixed neutrinos with additional heavy states
  Sigl, Raffelt (1993), Akhmedov, Rubakov, Smirnov (1998), Asaka, Shaposnikov (2005), Shaposnikov (2007, 2008), Shuve, Yavin (2014), Drewes, Garbrecht, Gueter, Klaric (2016), Ghiglieri, Laine (2016, 2019, 2020)

DM Freeze-out

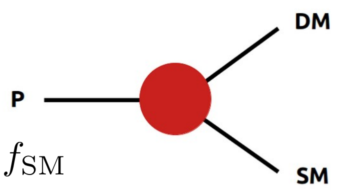
- Thermal effects at freeze-out temperatures for DM annihilation and Sommerfeld effect irrelevant
  Beneke, Dighera, Hryczuk (2016), Kim, Laine (2016)

- first description of bound state formation at NLO beyond ionisation equilibrium: bath particle scattering can be relevant for bound state formation Binder, Blobel, JH, Mukaida (2020)

The FIMP – Freeze-in of Dark Matter and LLP Signatures

- FIMPs feature a **feeble interaction with SM particles**

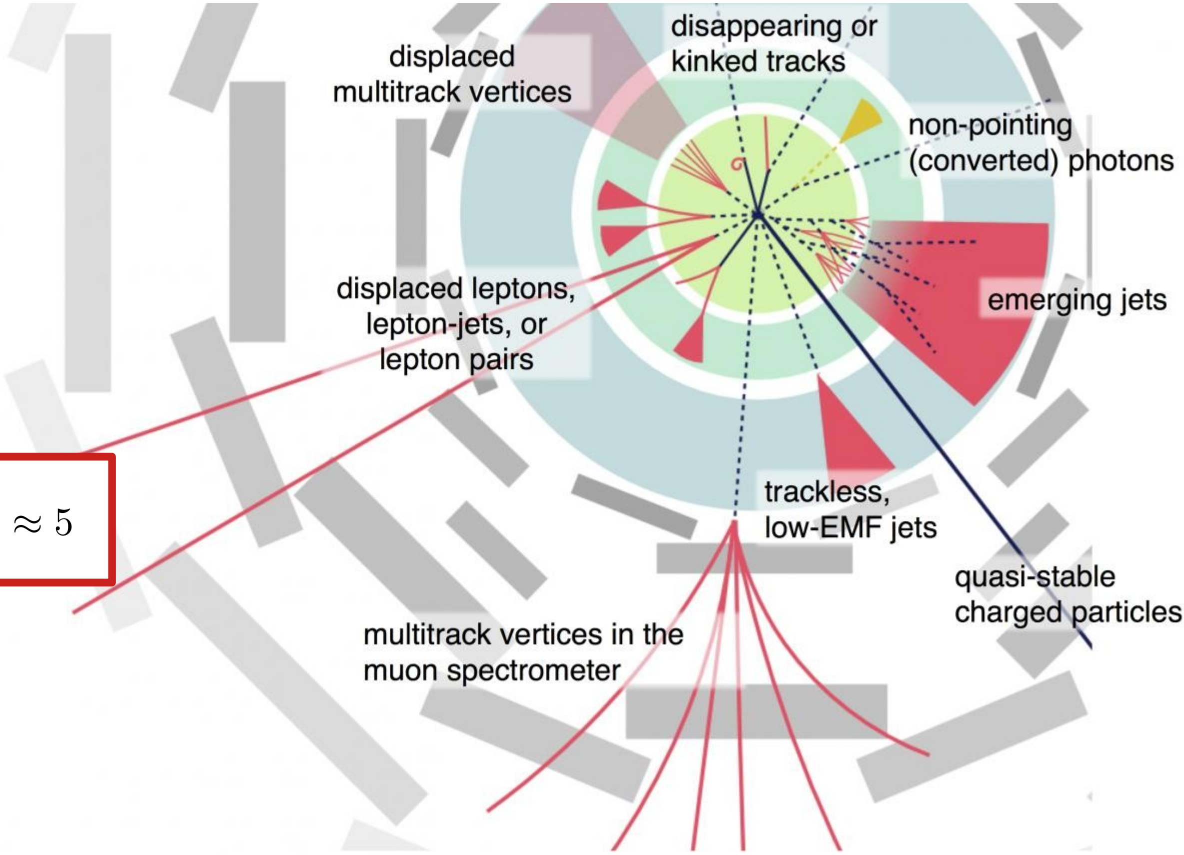
- FIMPs as DM are produced via the decay of a parent particle → **freeze-in**



$$y_{\mathrm{DM}}\, P\, \chi\, f_{\mathrm{SM}}$$

$$z_{\mathrm{FI}} = \frac{m_F}{T} \approx 5$$

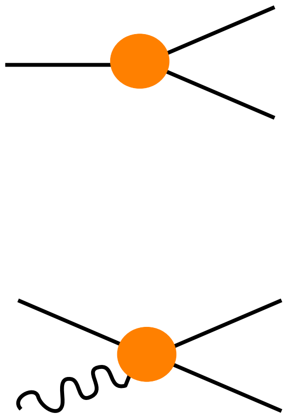
- Feeble interactions lead to **long life times** of the parent particles with characteristic signatures at the LHC

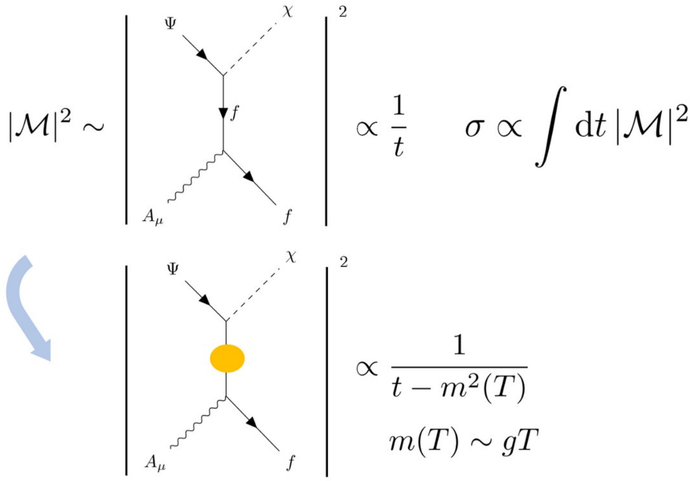


credits: Heather Russell from the LLP White Paper

Thermal Masses in Freeze-in Relic Abundance Calculations

Scattering with the thermal plasma





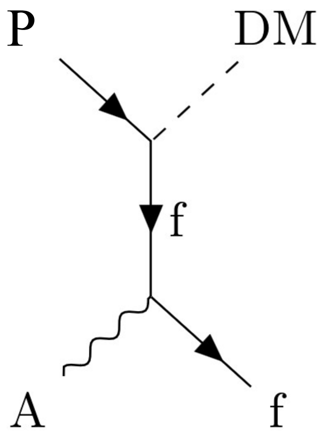
Credits: E. Copello

→ **divergence for massless particle in the t-channel propagator usually regularized with thermal mass**

Thermal Corrections to Freeze-in in the Literature

Different treatments can be found

- Boltzmann approach with decays in vacuum only
- Boltzmann approach with decays only including thermal masses
- Boltzmann approach with decays and scattering including thermal masses
- Non-equilibrium approach with tree-level propagators
- Non-equilibrium approach with HTL approximated propagators



→ **How do different treatments in the literature compare?**

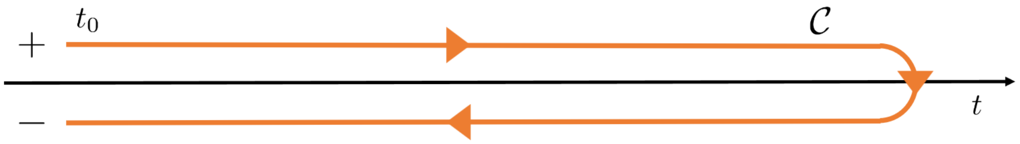
→ **What is phenomenologically the most recommended method?**

For comparing **thermal masses and quantum statistics** see Bringmann, Heeba, Kahlhoefer, Vangsnes (2021)
For production rate of scalar DM with real time formalism and **HTL approximation**, see Drewes, Kang (2015)
For fermionic DM with imaginary time formalism including **scattering** and **partially resummed propagators for decays** incl. **LPM effect**, see Biondini, Ghiglieri (2020)

DM Freeze-in in Non-Equilibrium Thermal QFT

- **S-matrix formalism (in-out) in vacuum for transition amplitudes between well-defined initial and final states**

- **CTP formalism (in-in) for time-dependent expectation values, e.g. the evolution of the statistical ensemble of a primordial plasma with continuously interacting fields**



$$iG^{ab}(x,y) = \langle T_C\, \phi(x^a)\bar{\phi}(y^b)\rangle$$

$$iG^{<} \equiv iG^{+-}$$

$$iG^{>} \equiv iG^{-+}$$

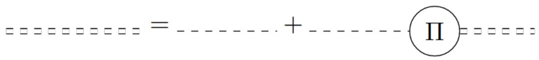
- **Number density** $$n_s = \int \frac{d^3p}{(2\pi)^3} f_s(\vec{p}) = \int \frac{d^3p}{(2\pi)^3} \int_0^\infty \frac{p^0}{\pi} p^0 i\Delta_s^<(p)$$

DM Freeze-in in Non-Equilibrium Thermal QFT

Derive evolution equation for the scalar self energy based on Schwinger-Dyson equations

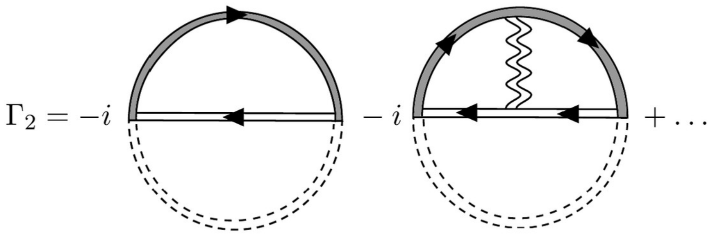
$$\partial_t f_s(t,|\vec{p}|) = \int_0^\infty \frac{p^0}{\pi}\,\frac{1}{2}\left[\left(i\Pi_s^<\right)\left(i\Delta_s^>\right) - \left(i\Pi_s^>\right)\left(i\Delta_s^<\right)\right]$$

$$i\Delta_0^{ab^{-1}}(x,y) = i\Delta^{ab^{-1}}(x,y) + i\Pi^{ab}(x,y)$$



We perform our calculation at LO in the loop expansion of the 2PI effective action

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



and include the fully 1PI-resummed propagators for fermions

Becker, Copello, JH, Tamarit (2023)

DM Freeze-in in Non-Equilibrium Thermal QFT

Derive evolution equation for the scalar self energy based on Schwinger-Dyson equations

$$\partial_t f_s(t, |\vec{p}|) = \int_0^\infty \frac{p^0}{\pi} \frac{1}{2} \left[\left(i\Pi_s^<\right) \left(i\Delta_s^>\right) - \left(i\Pi_s^>\right) \left(i\Delta_s^<\right) \right]$$

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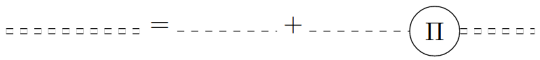

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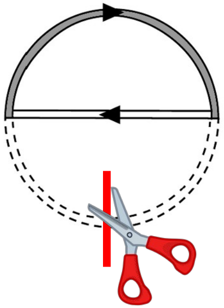
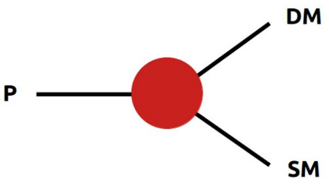
$\Gamma_2 = -i$ 

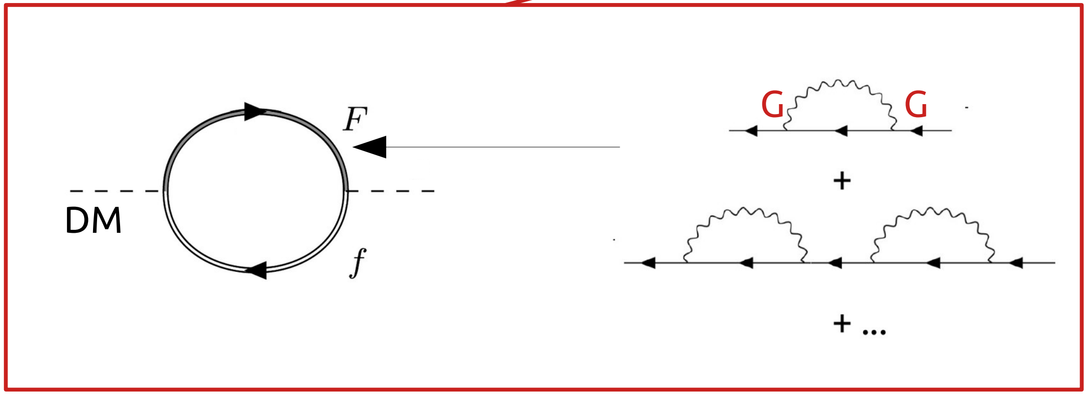
and include the fully 1PI-resummed propagators for fermions

Becker, Copello, JH, Tamarit (2023)

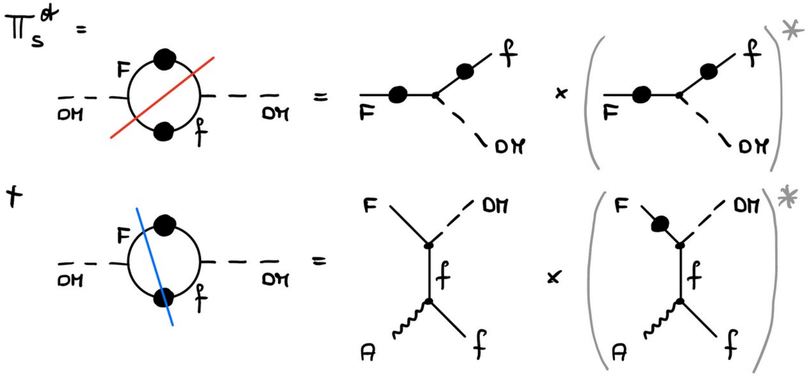
DM Freeze-in in Non-Equilibrium Thermal QFT

$$\dot{n}_s + 3Hn_s = \gamma_{\mathrm{DM}} \equiv \frac{1}{2\pi^2}\int d|\vec{p}|\,\frac{|\vec{p}|^2}{\omega_p}\,\Pi_s^A(\omega_p,|\vec{p}|)\,f_-(\omega_p)$$





Phenomenological interpretation:



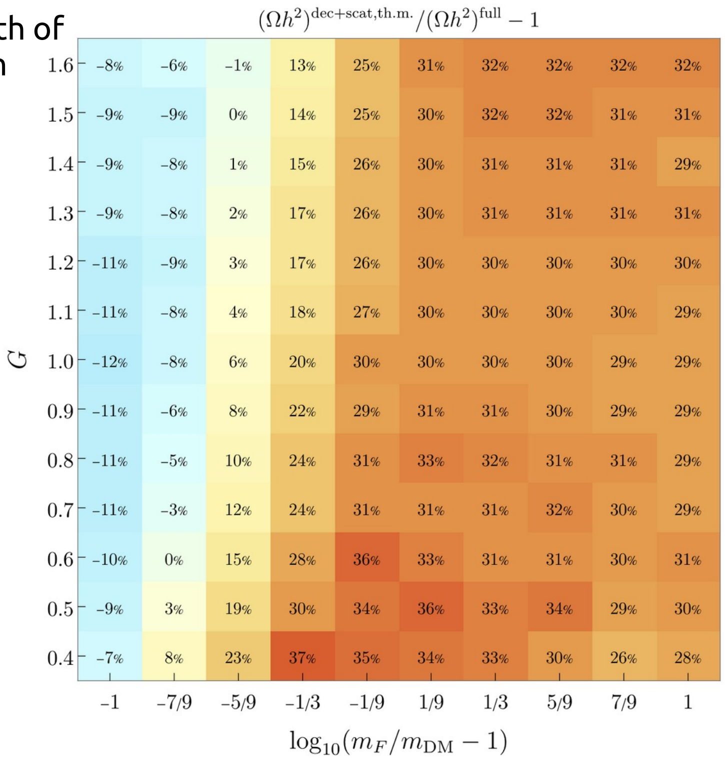
first consistent thermal calculation valid throughout all the relevant freeze-in regime
(HTL approximation breaks down in the important freeze-in regime $m_P \sim T$!)

Becker, Copello, JH, Tamarit (2023)

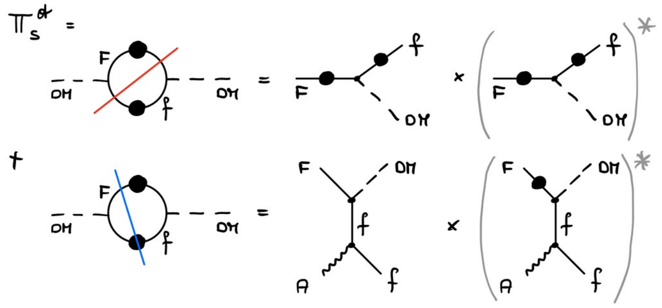
Impact of Thermal Corrections on Freeze-in DM

Compared to decays and scattering with thermal masses

interaction strength of P with the SM bath



Normalized relative mass difference between P and DM

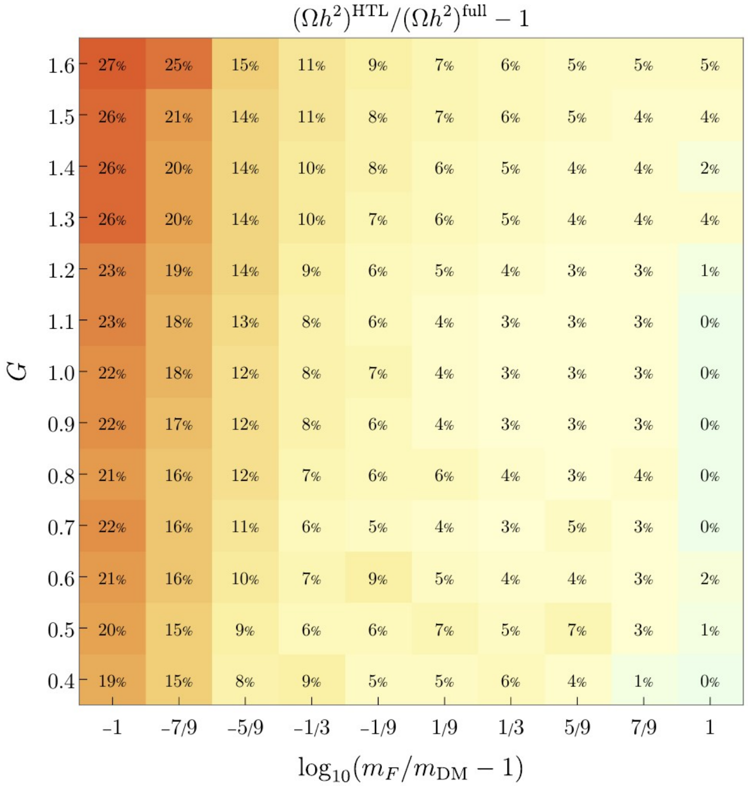


- Ω_{DM} **underestimated** for small mass splittings
- Ω_{DM} strongly **overestimated** for large mass splittings
- when including Fermi-Dirac / Bose-Einstein statistics in semi-classical BEQ, deviation reduces by approx. 50%

Becker, Copello, JH, Tamarit (2023)

Impact of Thermal Corrections on Freeze-in DM

Compared to HTL approximation

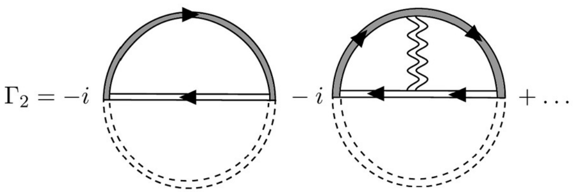


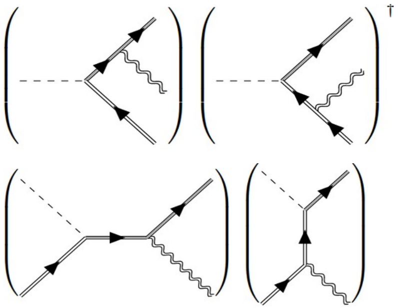
- Ω_{DM} **strongly overestimated** for small mass splittings (HTL overestimates scattering)
- Ω_{DM} **slightly overestimated** for large mass splittings (vanishing thermal width)
- Larger deviations for larger G
- **significant corrections on Ω_{DM} dependent on mass splitting and gauge coupling G**

Becker, Copello, JH, Tamarit (2023)

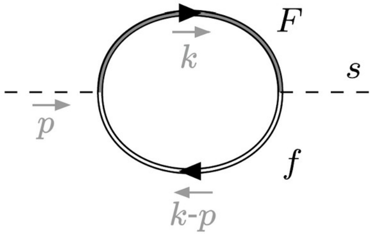
Going beyond LO in Expansion of 2PI Effective Action

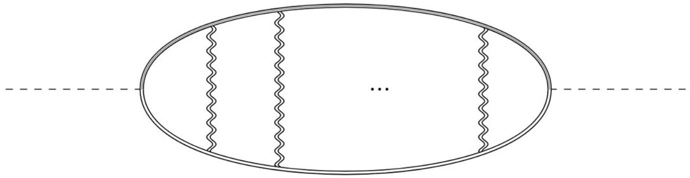
How relevant will be NLO contributions to 2PI effective action?





→ **Power counting** for soft gauge bosons for scalar self energy (for method see e.g. Arnold, Moore, Yaffe, 2001)





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

→ **multiple soft scatterings with thermal bath** for soft bosons and hard collinear fermions are **same order as LO**

→ **Landau-Pomeranschuk-Midgal (LPM) effect**

Going beyond LO in Expansion of 2PI Effective Action

LPM effect previously studied only for fermion self energies in the context of

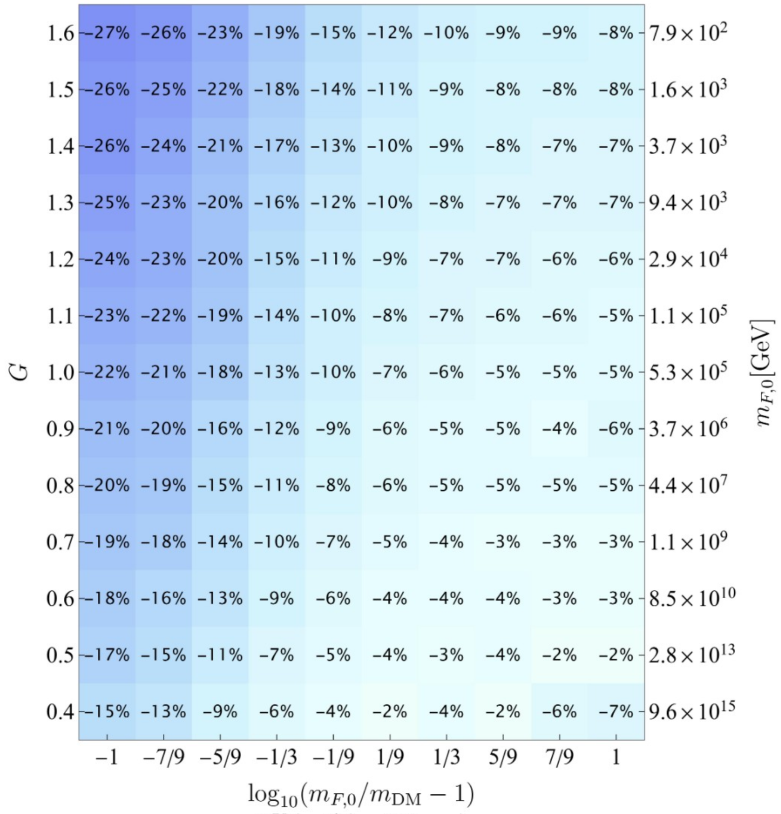
→ leptogenesis (Besak, Bödeker)

→ Fermionic FIMPs (Biondini, Ghiglieri)

➡ **First LPM resummation for scalar self energy**

➡ **Latest cutting-edge calculation for freeze-in DM production**

Rel. correction to result with 1PI-resummed propagators only



Becker, JH, Fernandez Lozano, Tamarit (2025)

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➡ **Latest cutting-edge calculation for freeze-in DM production**

$(\Omega h^2)^{\mathrm{dec+scat,th.m.}}/(\Omega h^2)^{\mathrm{full}}_{d_R} - 1$

G \ $\log_{10}(m_{F,0}/m_{\mathrm{DM}}-1)$	−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}

Becker, JH, Fernandez Lozano, Tamarit (2025)

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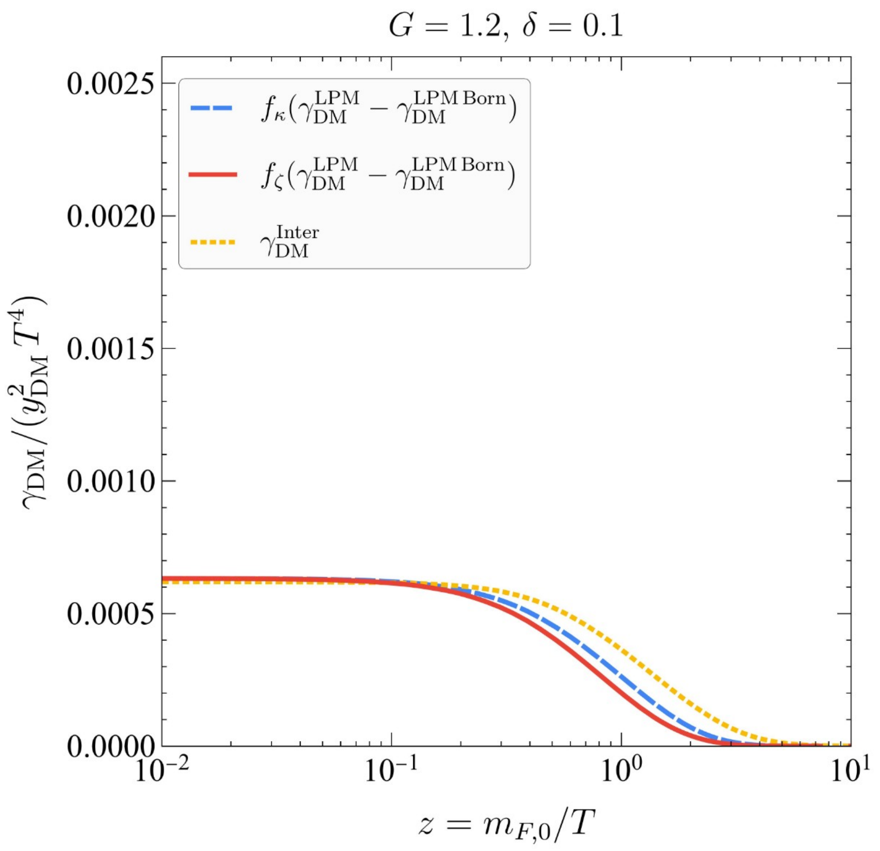
First LPM resummation for scalar self energy

Latest cutting-edge calculation for freeze-in DM production

Estimation of uncertainties based on different switch-off functions f(m_F)

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

We are currently developing a treatment of the LPM without switch-off function!

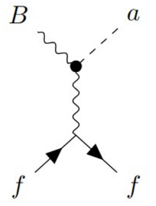


Becker, JH, Fernandez Lozano, Tamarit (2025)

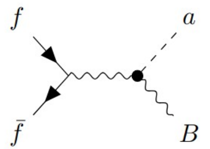
Another Application: Ly-α Limits on Freeze-in of ALP DM

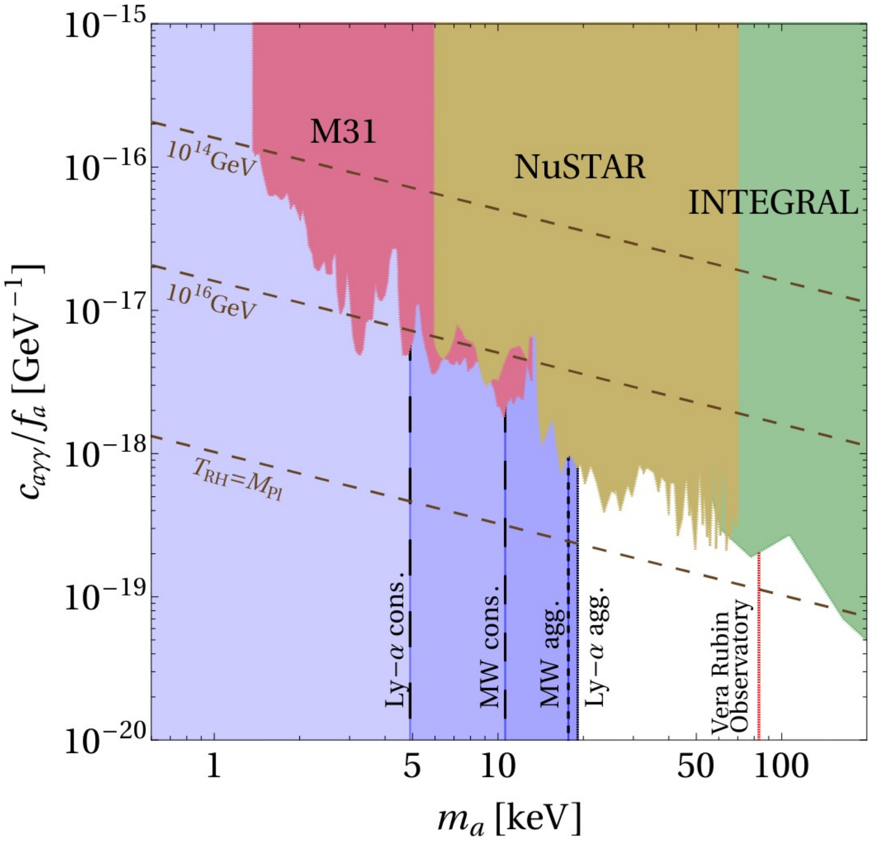
- **Photophilic ALP DM freezes-in via scattering processes**

$f\,V \to f\,a$



$f\,\bar{f} \to V\,a$





Baumholzer, Brdar, Morgante (2021)

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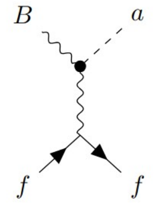

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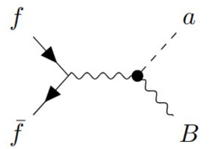


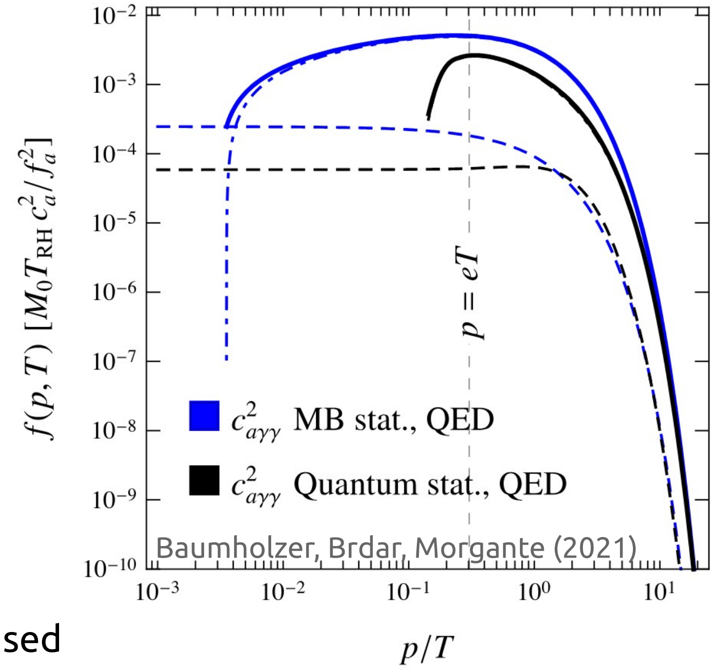
- **Limit from Lyman-α on free-streaming length as warm DM**

$$\lambda_{\rm fs} \propto \frac{\langle p \rangle / T}{m_a} \qquad \langle p \rangle = \frac{\int dp\, p^3 f_a(p)}{\int dp\, p^2 f_a(p)} \qquad \langle p/T \rangle_{\rm cut} = 3.24$$

- **T-channel divergence in f V → f a diagram**

Introduce cut-off scale k_* below which HTL resummed propagator is used

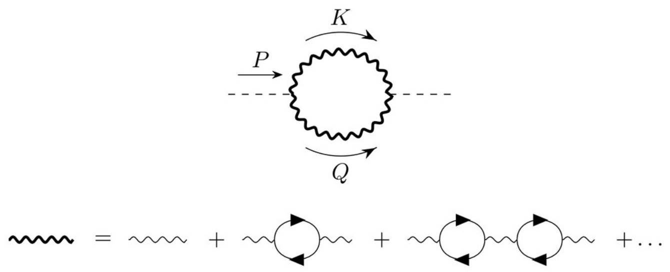
$gT \ll k_\star \ll T$, only valid for $p_a > gT$ Braaten, Yuan (1991); Bolz, Brandenburg, Buchmuller (2001)



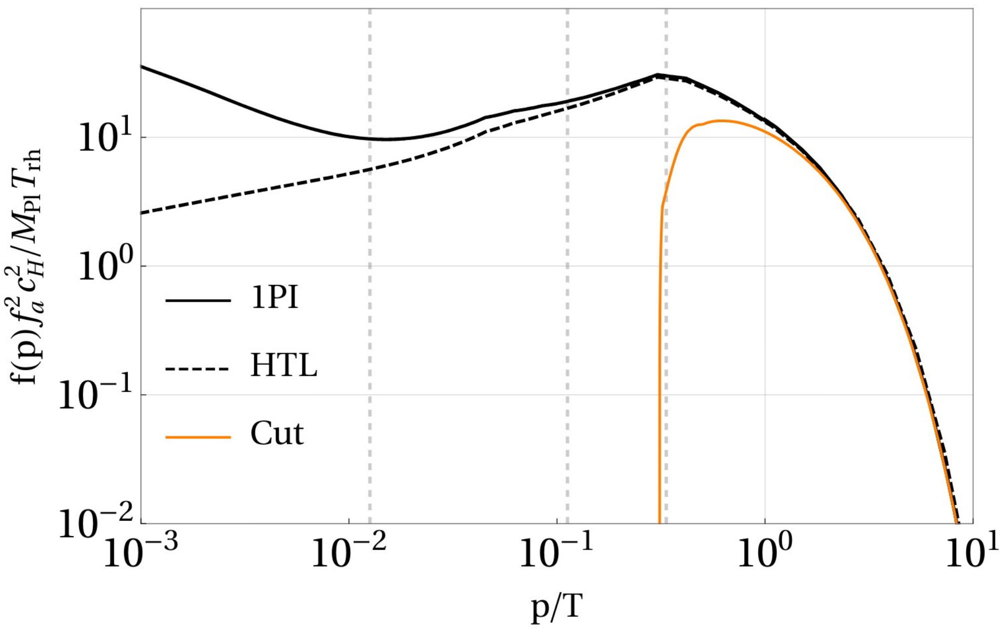
→ Momentum distribution functions turn negative for soft ALP momenta!

Another Application: Ly-α Limits on Freeze-in of ALP DM

- **Calculate distribution functions using CTP including fully 1PI-resummed propagators**



HTL solves negative rates already



Becker, JH, Morgante, Puchades-Ibanez, Schwaller (2025)

For different approach for non-abelian theories, see Bouzoud and Ghiglieri (2024)

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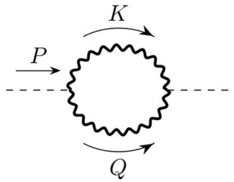
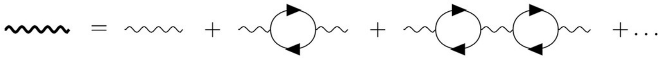




HTL solves negative rates already

1PI-resummed propagators show previously neglected TT contribution for low momenta

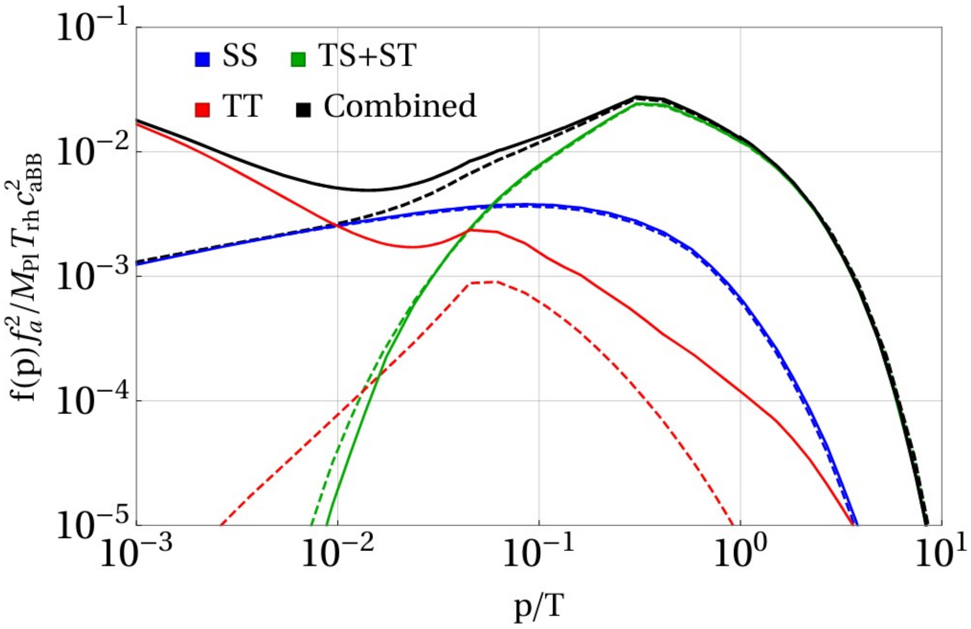
- **Impacts directly Lyman-α constraints**

$$\lambda_{\rm fs} \propto \frac{\langle p\rangle/T}{m_a}$$

$$\langle p/T\rangle_{\rm cut} = 3.24$$

$$\langle p/T\rangle_{\rm HTL} = 3.19$$

$$\langle p/T\rangle_{\rm Full} = 3.08$$



Becker, JH, Morgante, Puchades-Ibanez, Schwaller (2025)

For different approach for non-abelian theories, see Bouzoud and Ghiglieri (2024)

Conclusions

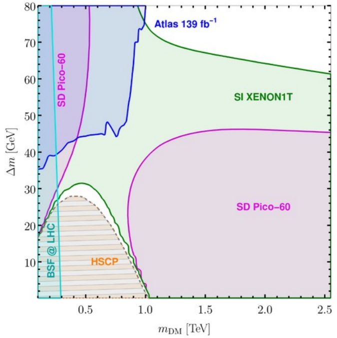
- **Cutting-edge methods needed for precise theory predictions and accurate experimental interpretation**

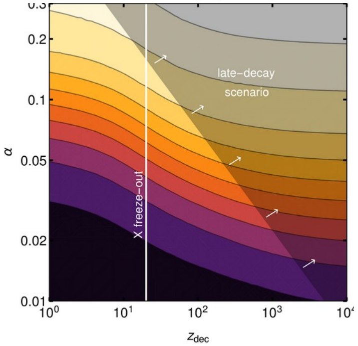
Bound states

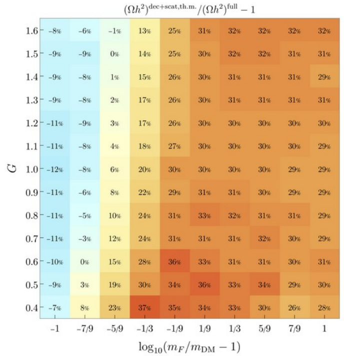
- **Sommerfeld effect and BSF can impact significantly freeze-out DM production and baryogenesis**

Thermal plasma effects

- **Interactions with the thermal bath can have sizeable impact on freeze-in production**



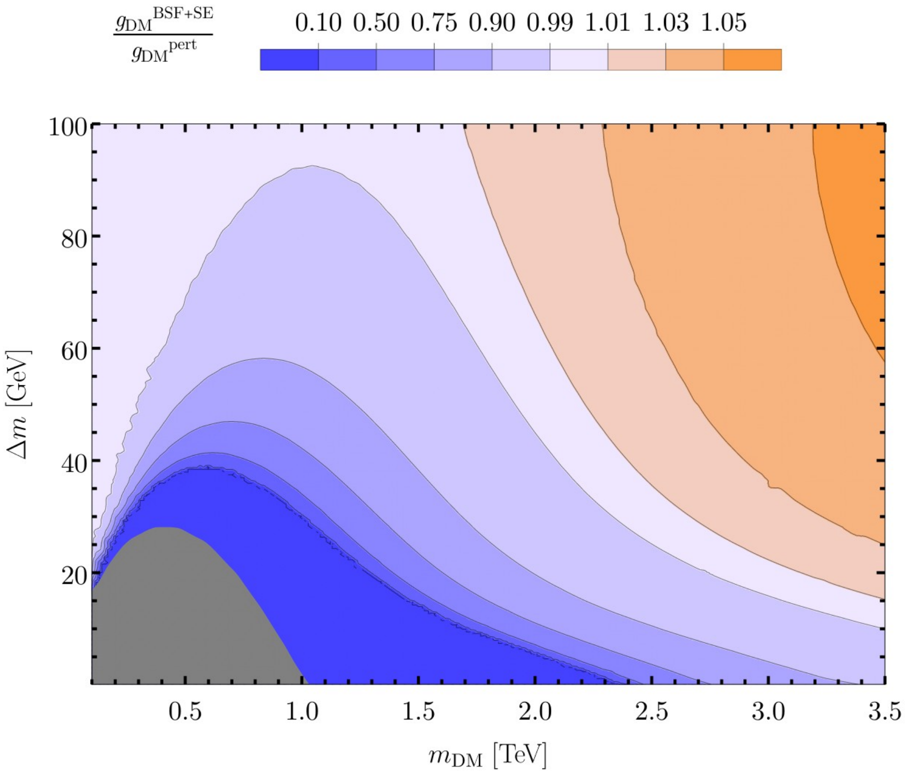




Thank you for your attention!

Impact on minimal dark matter coupling strength

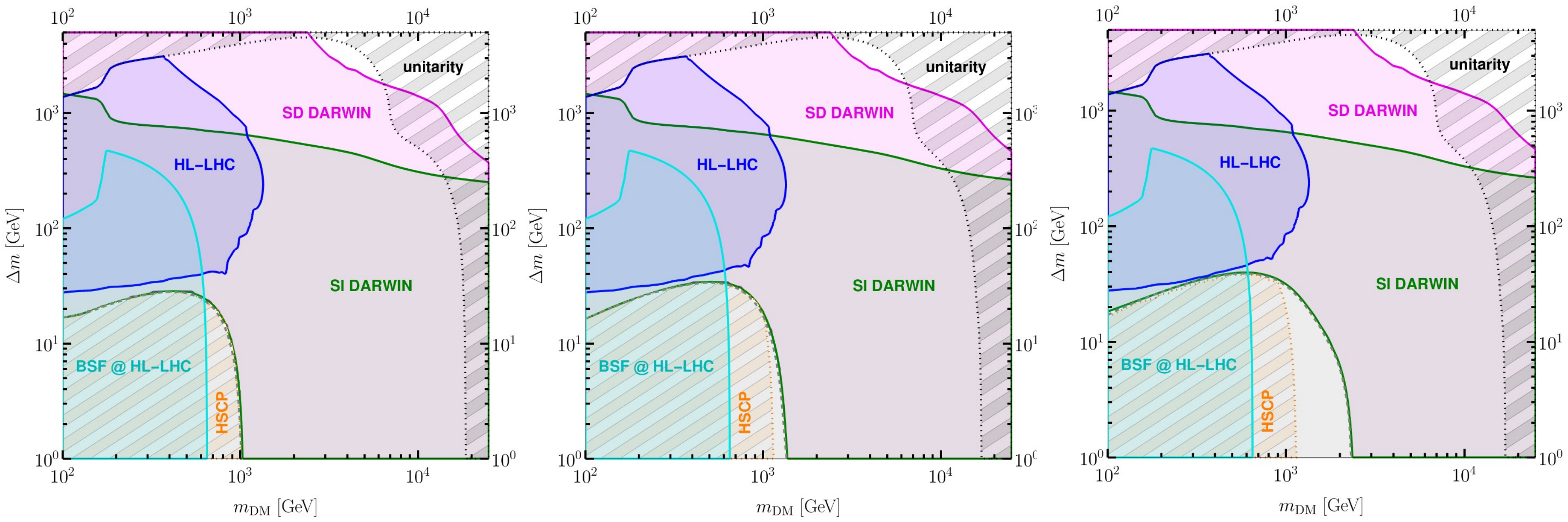
Identify lower bound on g_{DM} in order not to overproduce DM



- **Non-perturbative effects result in corrections on minimal g_{DM}**
- **Depending on parameter space: positive or negative correction**

Becker, Copello, JH, Mohan, Sengupta (2022)

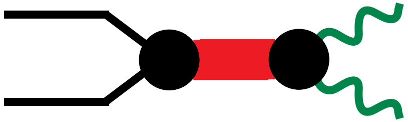
Future prospects



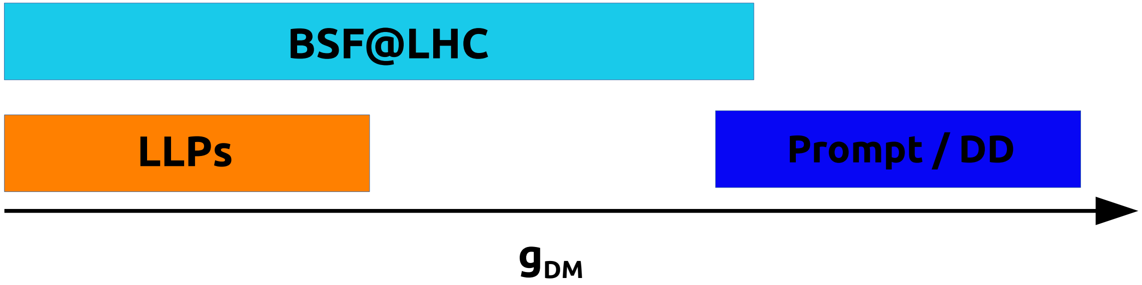
- **HSPC not strict exclusion limit (BSF@LHC is!)**
- **Highly testable: parameter space can be almost entirely probed**
- **BSF effects enlarge parameter range that still needs to be tested**

Becker, Copello, JH, Mohan, Sengupta (2022)

Potential of Bound State Formation at Colliders



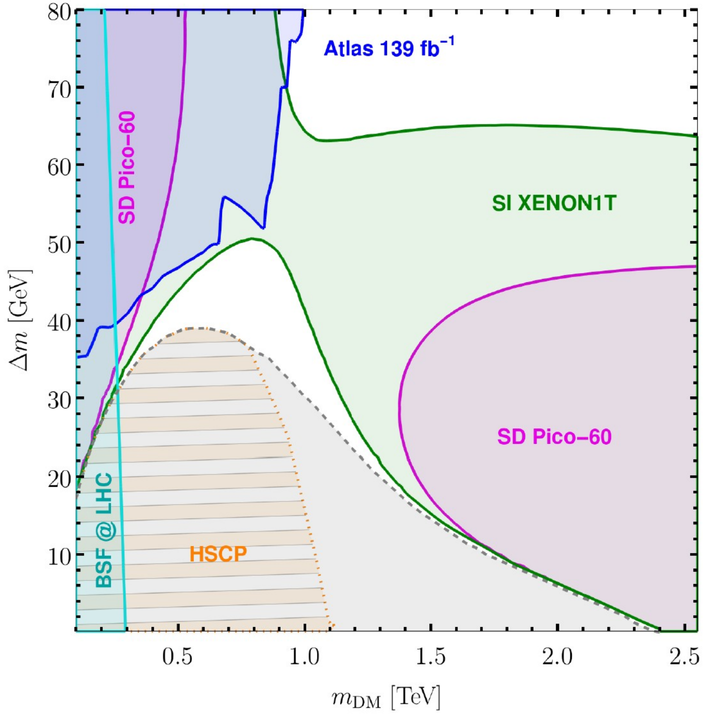
- production of bound state and subsequent decay (e.g. into photons)
- Dedicated searches, see e.g. *ATLAS coll. Phys. Lett. B 775 (2017) 105*
- Efficient for large range of g_{DM}, as long as $\Gamma_X < E_B$

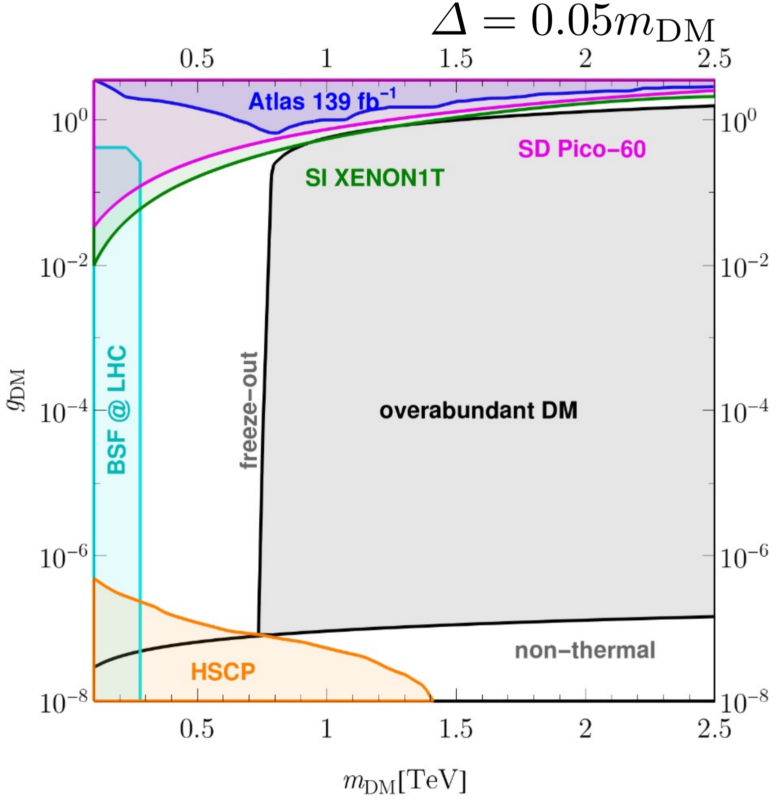


Becker, Copello, JH, Mohan, Sengupta (2022)

Potential of Bound State Formation at Colliders

$$\mathcal{L} \supset g_{\mathrm{DM},ij} X_i^\dagger \bar{\chi} P_R q_j + h.c.$$





→ **BSF@LHC closes gap between prompt and LLP (HSCP) searches**

Becker, Copello, JH, Mohan, Sengupta (2022)

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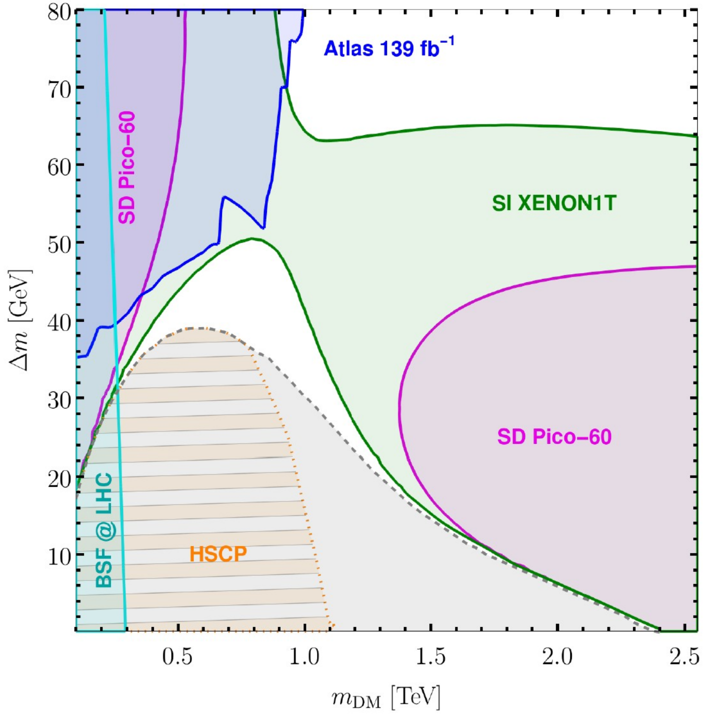
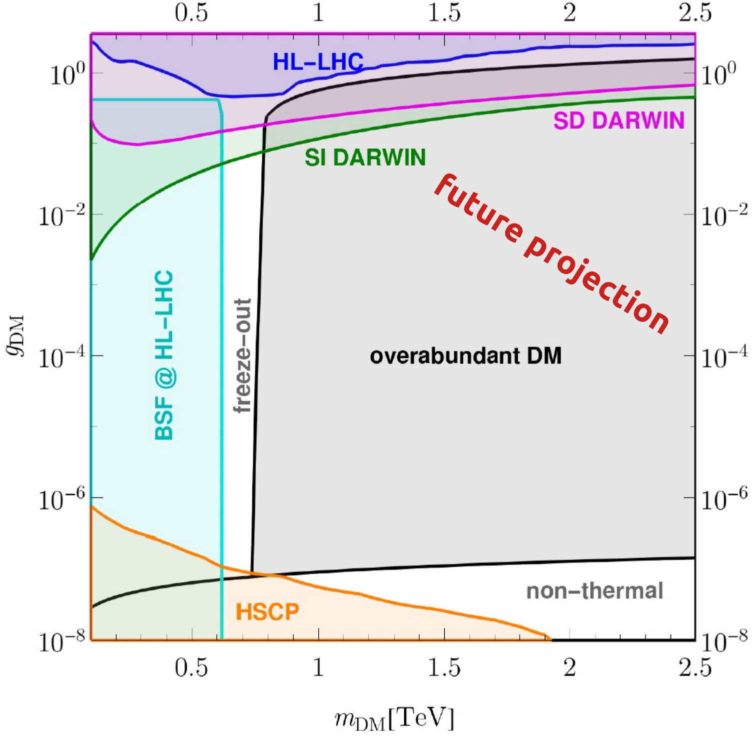


$\Delta = 0.05 m_{\mathrm{DM}}$



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Becker, Copello, JH, Mohan, Sengupta (2022)

Bound States in Scattering dominated Baryogenesis

Assume toy model with Φ transforming in the adjoint representation of an non-abelian SU(N_D) with associated gauge boson V and with gauge strength g

$$|\mathcal{M}(\phi\phi \to bb)|^2 = |\lambda_1|^2 (1+\epsilon)$$
$$|\mathcal{M}(\phi\phi \to \bar{b}\bar{b})|^2 = |\lambda_1|^2 (1-\epsilon)$$

B-L and CP-violating scatterings with quartic coupling λ_1

$$|\mathcal{M}(bb \to \bar{b}\bar{b})|^2 = |\lambda_2|^2 \left(1 + \frac{|\lambda_1|^2}{|\lambda_2|^2}\epsilon\right)$$
$$|\mathcal{M}(\bar{b}\bar{b} \to bb)|^2 = |\lambda_2|^2 \left(1 - \frac{|\lambda_1|^2}{|\lambda_2|^2}\epsilon\right)$$

B-L and CP-violating scatterings with quartic coupling λ_2

Boltzmann equations taking into account bound states:

$$c\frac{Y_\phi}{z} = -\frac{2}{z^2}\left[\langle\sigma v\rangle^{\rm tot}_{\phi\phi\to bb} + \langle\sigma v\rangle^{\rm eff}_{\phi\phi\to VV}\right]\left(Y_\phi^2 - \left(Y_\phi^{\rm eq}\right)^2\right)$$

$$c\frac{Y_{\Delta b}}{z} = \frac{2}{z^2}\epsilon\left[\langle\sigma v\rangle^{\rm tot}_{\phi\phi\to bb} + \langle\sigma v\rangle^{\rm asy}_{\mathcal{B}}\right]\left(Y_\phi^2 - \left(Y_\phi^{\rm eq}\right)^2\right) - \frac{Y_{\Delta b}}{Y_b^{\rm eq} z^2}\left[\left(Y_\phi^{\rm eq}\right)^2\langle\sigma v\rangle^{\rm tot}_{\phi\phi\to bb} + 2\left(Y_b^{\rm eq}\right)^2\langle\sigma v\rangle^{\rm tot}_{bb\leftrightarrow\bar{b}\bar{b}} + \left(Y_b^{\rm eq}\right)^2\langle\sigma v\rangle^{\rm tot}_{bb\leftrightarrow VV}\right]$$

Becker, Fridell, JH, Hati (2024)

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$$\langle\sigma v\rangle^{\rm eff}_{\phi\phi\to VV} = \langle\sigma v\rangle_{\phi\phi\to VV} + \langle\sigma v\rangle^{\rm eff}_{\mathcal{B}}$$

$$\langle\sigma v\rangle^{\rm asy}_{\mathcal{B}} = \langle\sigma v\rangle_{\mathcal{B}}\frac{\langle\Gamma_{\mathcal{B}}\rangle\left(Br_b + Br_{\bar{b}}\right)}{\langle\Gamma_{\mathcal{B}}\rangle + \langle\Gamma_{\rm ion}\rangle}$$

bound states as intermediate states

Becker, Fridell, JH, Hati (2024)

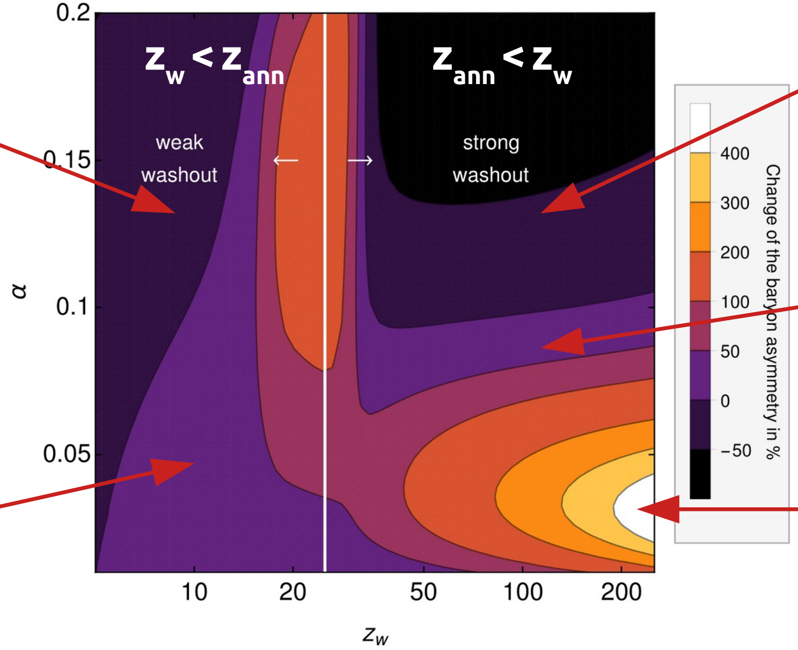
Bound States in Scattering dominated Baryogenesis

Sommerfeld enhanced washout processes become dominant

$\langle \sigma v \rangle^{\text{tot}}_{\phi\phi\to bb}$ > $\langle \sigma v \rangle^{\text{tot}}_{bb\leftrightarrow \bar{b}\bar{b}}$

Sommerfeld effect keeps Φ closer to equilibrium and enhances asymmetry generation

$\langle \sigma v \rangle^{\text{tot}}_{\phi\phi\to bb}$



$\epsilon = 0.1, m_\phi = 10^4\text{GeV}, \lambda_1 = 0.1$

bound states lead to higher depletion of Φ

$\langle \sigma v \rangle^{\text{eff}}_{\phi\phi\to VV}$

Sommerfeld effect increases asymmetry

$\langle \sigma v \rangle_{\phi\phi\to VV}$

Interplay of asymmetry generation from bound states, late washout freeze-out, and depletion of Φ via bound states

Becker, Fridell, JH, Hati (2024)

Impact of thermal plasma in ultrarelativistic regime

- **Interpolation with susceptibility needed to bridge between ultrarelativistic and (non)relativistic regime**

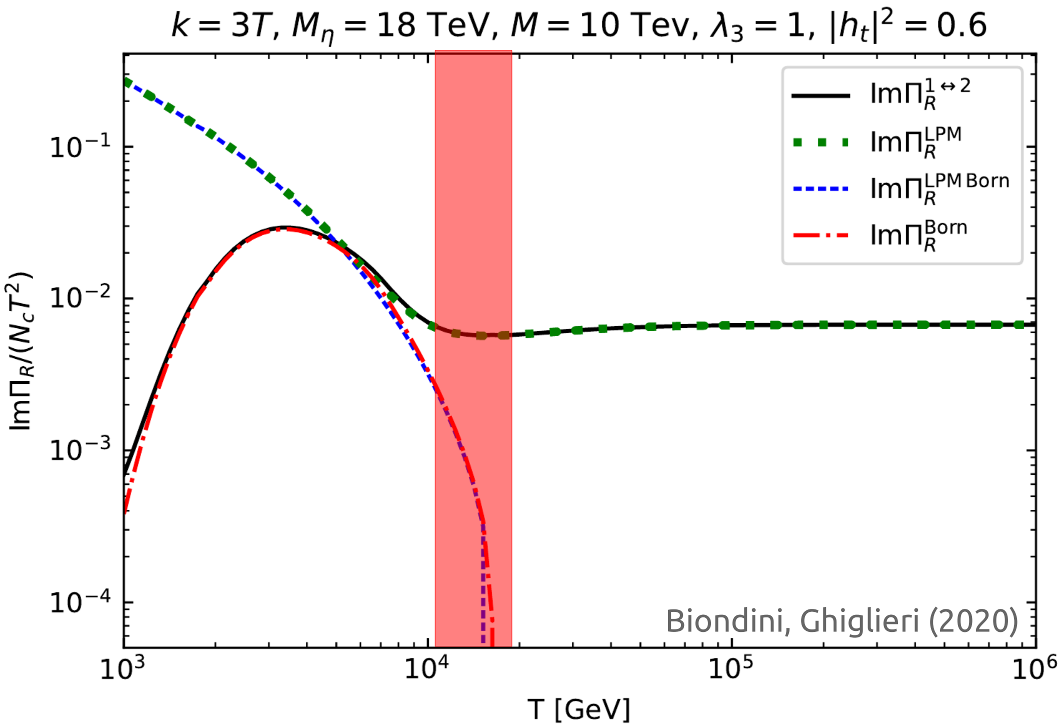
$$\mathrm{Im}\Pi_R^{\mathrm{tot}} = \mathrm{Im}\Pi_R^{1\leftrightarrow 2} + \mathrm{Im}\Pi_R^{2\leftrightarrow 2}$$

$$\mathrm{Im}\Pi_R^{1\leftrightarrow 2} = (\mathrm{Im}\Pi_R^{\mathrm{LPM}} - \mathrm{Im}\Pi_R^{\mathrm{LPM\ Born}})\kappa(M_\eta) + \mathrm{Im}\Pi_R^{\mathrm{Born}}$$

$$z_{\mathrm{FI}} = \frac{m_F}{T} \approx 5 \qquad m_{F,0}^2 + G\frac{T^2}{4} \approx 25T^2$$

$$m_{F,0} \approx \mathcal{O}(T)$$

- **pure HTL approximation breaks down**



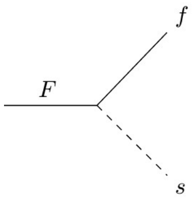
→ freeze-in highly dependent on regime when parent particle becomes non-relativistic

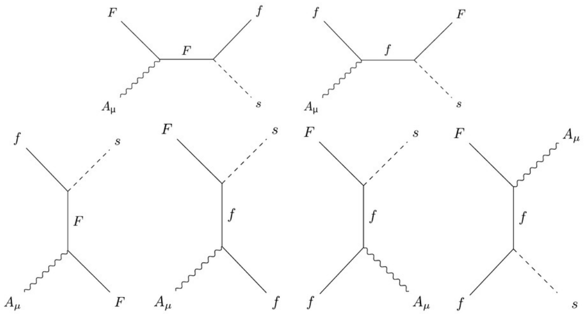
DM freeze-in in the Closed Time Path (CTP) formalism

GOAL: Calculate freeze-in within non-equilibrium framework (**closed time path formalism**) with **1PI-resummed propagators** at **LO in the loop expansion of the 2PI effective action** and compare with other approaches

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu s)^2 - \frac{1}{2}m_s^2 s^2 - V(s,H) + \bar{F}\left(i\not{D} - m_F\right)F - \left[y_{\rm DM}\bar{F}fs + h.c.\right]$$

Free parameters: $\delta = \frac{m_F - m_{\rm DM}}{m_{\rm DM}}$ $\quad y_{\rm DM}$ $\quad z = \frac{m_F}{T}$ $\quad G = Y^2 g_1^2 + C_2(\mathcal{R}_2)\, g_2^2 + C_2(\mathcal{R}_3)\, g_3^2$





	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**	$\frac{g_1^2}{9} + \frac{4g_3^2}{3}$	2.0	1.2	0.8	0.6

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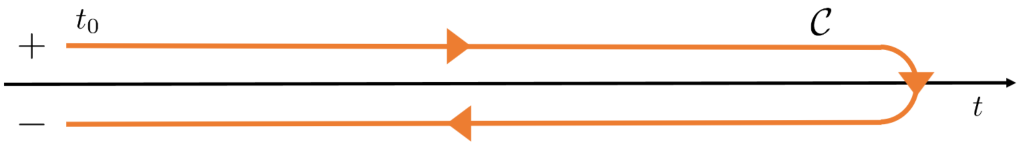
The CTP formalism I

CTP formalism (in-in) for time-dependent expectation values, e.g. the evolution of the statistical ensemble of a primordial plasma with continuously interacting fields



$$iG^{ab}(x,y) = \langle T_C\, \phi(x^a)\bar{\phi}(y^b)\rangle$$

- Hermitian and anti-hermitian (spectral) propagator

$$G^H \equiv \frac{1}{2}\left(G^{++} - G^{--}\right) \qquad iG^< \equiv iG^{+-}$$

$$G^A \equiv \frac{i}{2}\left(iG^> - iG^<\right) \qquad iG^> \equiv iG^{-+}$$

- **spectral propagator** for free scalar field

$$\Delta_0^A(p) = \pi\,\mathrm{sign}(p^0)\delta(p^2 - m^2)$$

- free scalar **Wightman functions** in equilibrium

$$i\Delta_0^{\mathrm{eq},<}(p) = 2\Delta_0^{\mathrm{eq},\mathcal{A}}(p)\, f_-(p^0)$$

- **Number density**

$$n_s = \int \frac{d^3p}{(2\pi)^3}\, f_s(\vec{p}) = \int \frac{d^3p}{(2\pi)^3} \int_0^\infty \frac{p^0}{\pi}\, p^0 i\Delta_s^<(p)$$

The CTP formalism II

Finally, we obtain an evolution equation for the number density of the scalar particle

$$\dot{n}_s + 3Hn_s = \gamma_{\rm DM} \equiv \frac{1}{2\pi^2}\int d|\vec{p}|\frac{|\vec{p}|^2}{\omega_p}\Pi_s^{\mathcal{A}}(\omega_p, |\vec{p}|) f_-(\omega_p)$$

With the reaction density

$$\gamma_{\rm DM} = \frac{y_{\rm DM}^2}{4\pi^5}\int d|\vec{p}|\, dk^0\, d|\vec{k}|\, d\cos\theta\, \frac{|\vec{k}|^2|\vec{p}|^2}{\omega_p} tr\left\{P_L \not{S}_F^{\mathcal{A}}(k) P_R \not{S}_f^{\mathcal{A}}(k-p)\right\} f_-(\omega_p)\left[1 - f_+(k^0) - f_+(\omega_p - k^0)\right]$$

And the spectral propagators

$$\not{S}_F^{\mathcal{A}}(k) = \left(\not{k} - \not{\Sigma}_F^{\mathcal{H}}(k) + m_F\right)\frac{\Gamma_F(k)}{\Omega_F^2(k) + \Gamma_F^2(k)} - \not{\Sigma}_F^{\mathcal{A}}(k)\frac{\Omega_F(k)}{\Omega_F^2(k) + \Gamma_F^2(k)}$$

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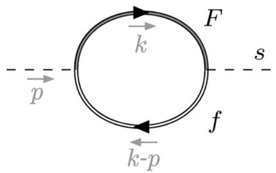
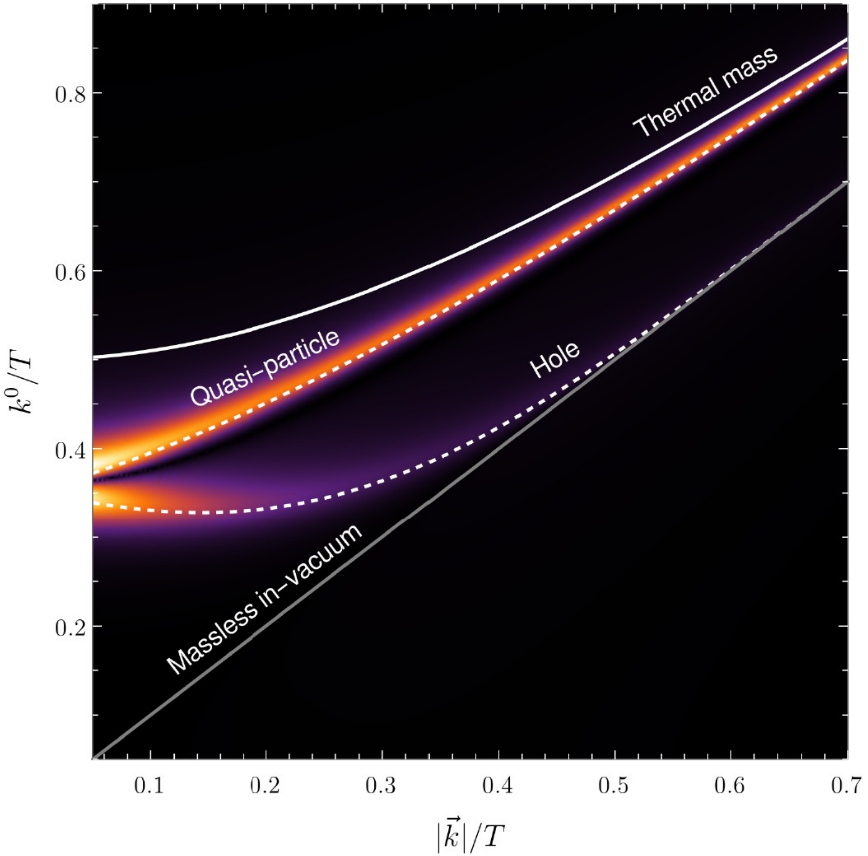
Comparing methods – spectral propagator





- **In vacuum** $\not{S}^{\mathcal{A}} \sim \delta(k^2 - m_0^2)$
- **With thermal masses** $\not{S}^{\mathcal{A}} \sim \delta(k^2 - m_{\text{th}}^2)$
- **1PI resummed**

$$\not{S}_F^{\mathcal{A}}(k) = \left(\not{k} - \not{\Sigma}_F^{\mathcal{H}}(k) + m_F\right) \frac{\Gamma_F(k)}{\Omega_F^2(k) + \Gamma_F^2(k)} - \not{\Sigma}_F^{\mathcal{A}}(k) \frac{\Omega_F(k)}{\Omega_F^2(k) + \Gamma_F^2(k)}$$

→ thermal width broadens the spectrum

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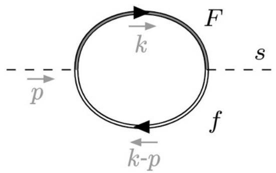
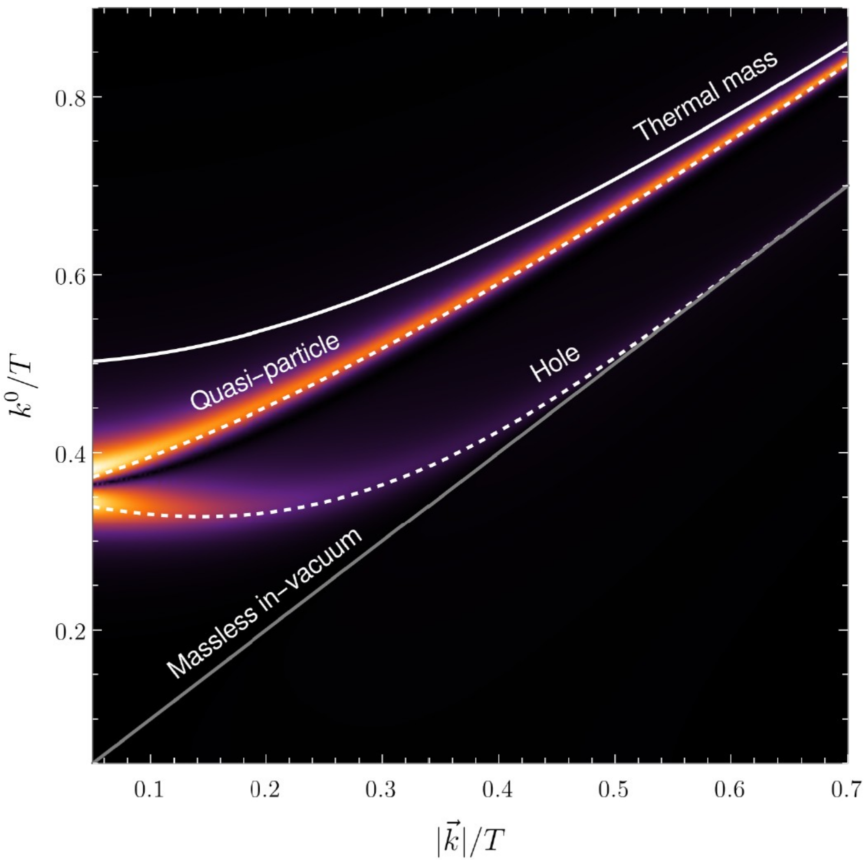
Comparing methods – spectral propagator





- **Tree-level CTP approximation**
  - Thermal widths identically zero
  - Dispersion relation with momentum-independent thermal masses and vacuum mass

$$\not{S}_F^{\mathcal{A}}(k) = \pi\delta(k^2 - m_F^2)(\not{k} + m_F)\,\mathrm{sign}(k^0)$$

  - Corresponds to DM decay from on-shell F including in-vacuum masses and thermal masses by accounting for the proper quantum statistics

$$\Pi_s^{\mathcal{A}}(p) = \frac{y_{\mathrm{DM}}^2}{16\pi\,|\vec{p}|}\left|p^2 - m_F^2 - m_f^2\right| \int_{\mathcal{B}} k_0 \left[1 - f_+(k_0) - f_+(p_0 - k_0)\right]$$

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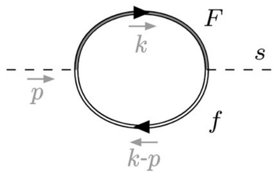
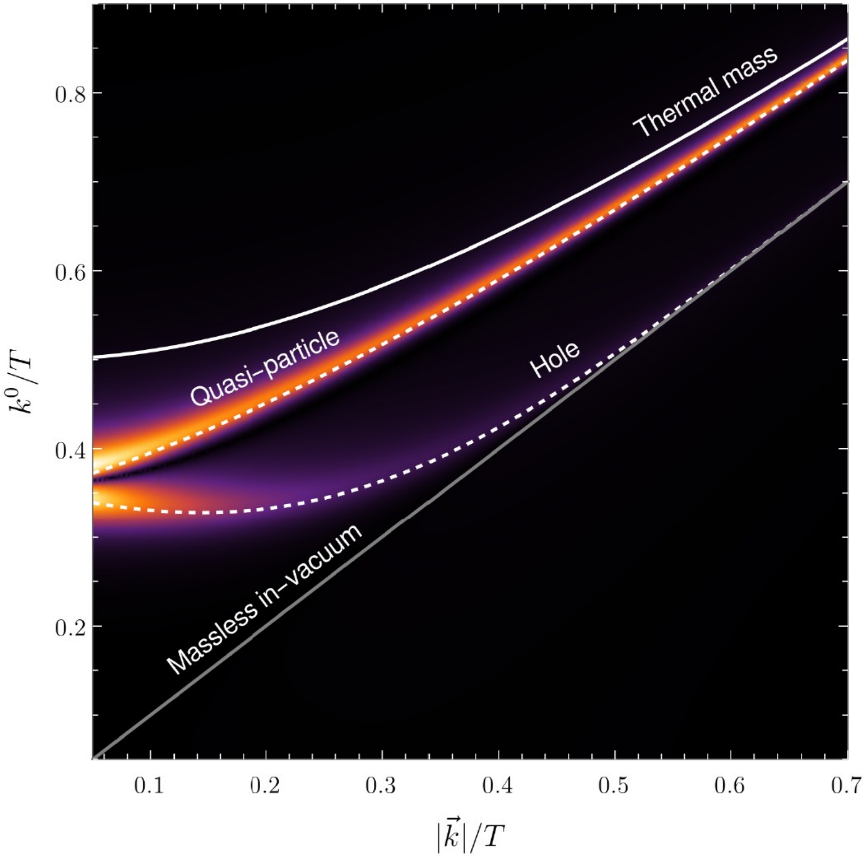
Comparing methods – spectral propagator





- **HTL approximation**

$$\Gamma_F^{\mathrm{HTL}} \propto \theta\left(-k^2\right)\frac{G}{\pi}8|\vec{k}|T^2$$

  - Thermal width non-zero only for space-like momenta k → continuum (“Landau damping”)
  - For time-like momenta k, vanishing thermal width and recovery of particle-like dispersion relation

$$\not{S}^{\mathcal{A}}_{F/f}(k) = \pi\,\mathrm{sign}(k^0)\left(\not{k} - m_{F/f} - \not{\Sigma}^{\mathcal{H},\mathrm{HTL}}_{F/f}(k)\right)\delta\left(\left[k - \Sigma^{\mathcal{H},\mathrm{HTL}}_{F/f}(k)\right]^2 - m^2_{F/f}\right)$$

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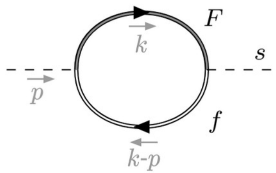
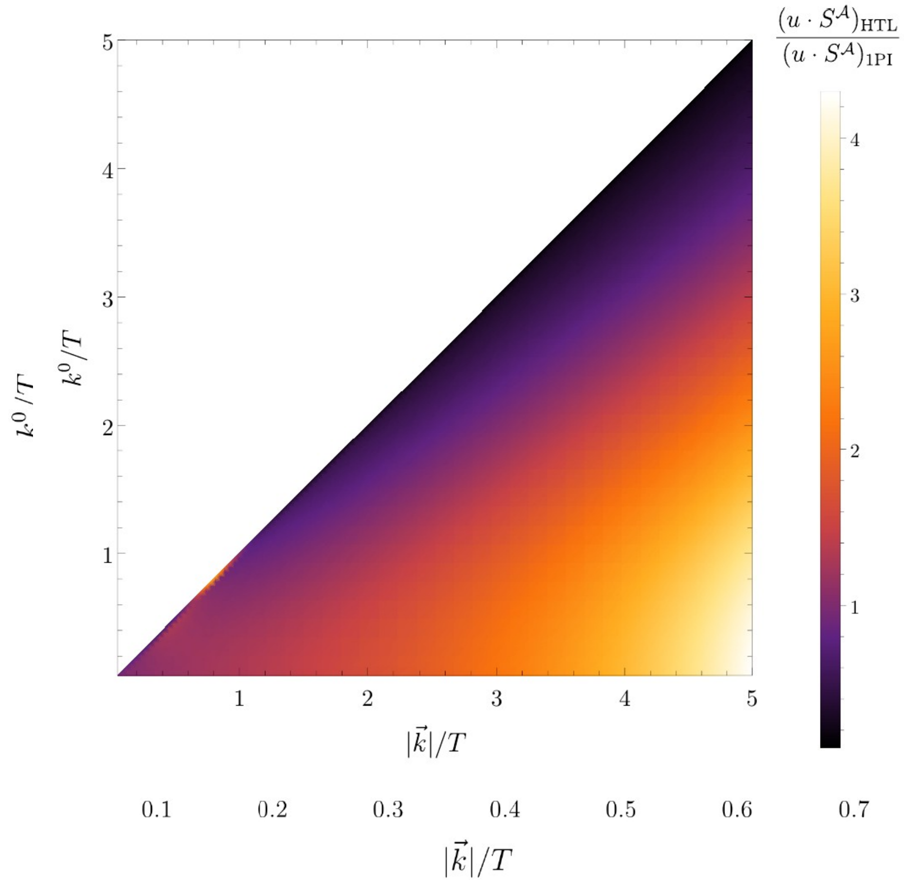
Comparing methods – spectral propagator





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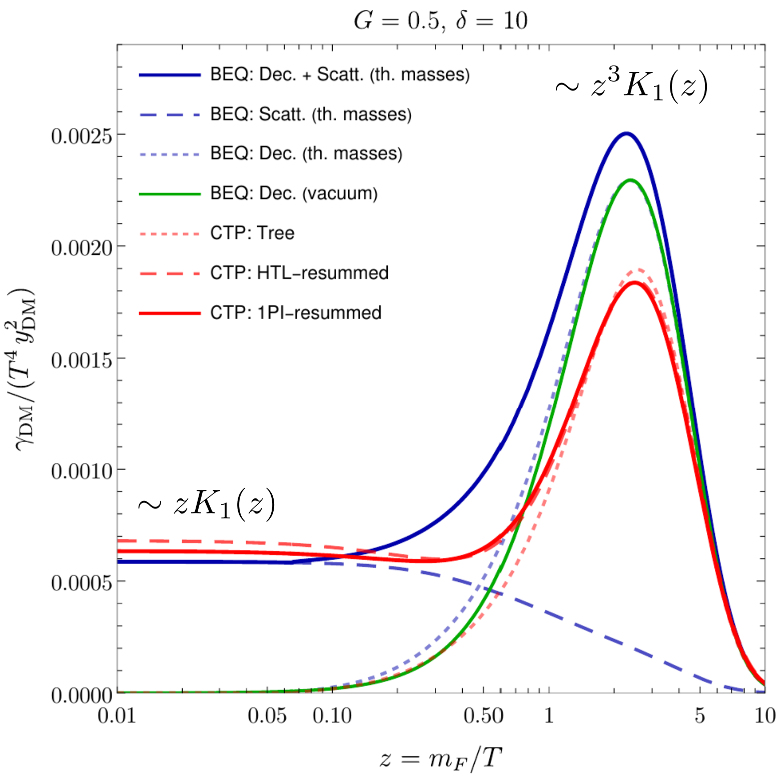
Comparing methods – interaction rate density



- **Scatterings** dominate for small z (plateau)
- **Decays** start to dominate for large z

$$z > \sqrt{G}\,\frac{m_{\rm DM} m_F}{m_F^2 - m_{\rm DM}^2}$$

- Relative mass difference δ sets **height** of the **decay peak**

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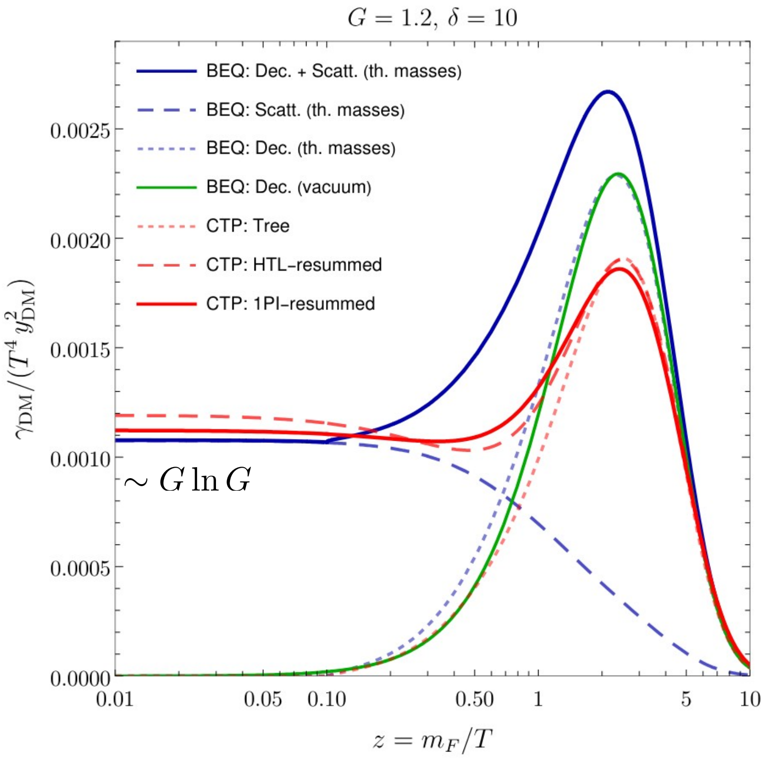
Comparing methods – interaction rate density



- **Scatterings** dominate for small z (plateau)
- **Decays** start to dominate for large z

$$z > \sqrt{G}\frac{m_{\mathrm{DM}} m_F}{m_F^2 - m_{\mathrm{DM}}^2}$$

- Relative mass difference δ sets **height** of the **decay peak**
- Gauge coupling G sets the **height** of the **plateau**

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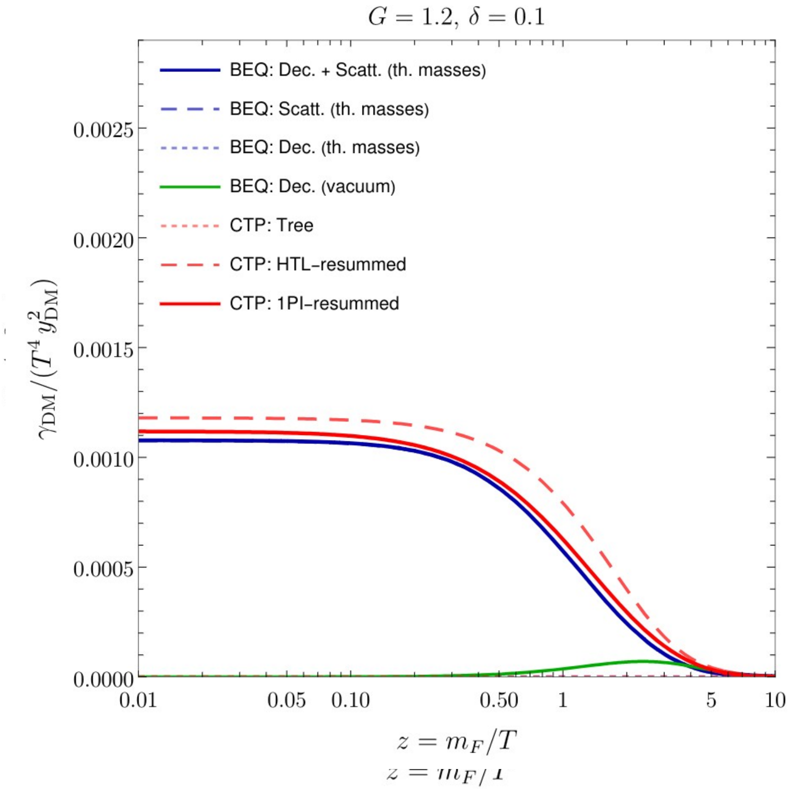
Comparing methods – interaction rate density



- **Scatterings** dominate for small z (plateau)
- **Decays** start to dominate for large z

$$z > \sqrt{G}\frac{m_{\rm DM} m_F}{m_F^2 - m_{\rm DM}^2}$$

- Relative mass difference δ sets **height** of the **decay peak**
- Gauge coupling G sets the **height** of the **plateau**
- For smaller δ, decays become less relevant due to **phase space suppression**

$$z > \sqrt{G}\frac{1-\delta}{2\delta - \delta^2}$$

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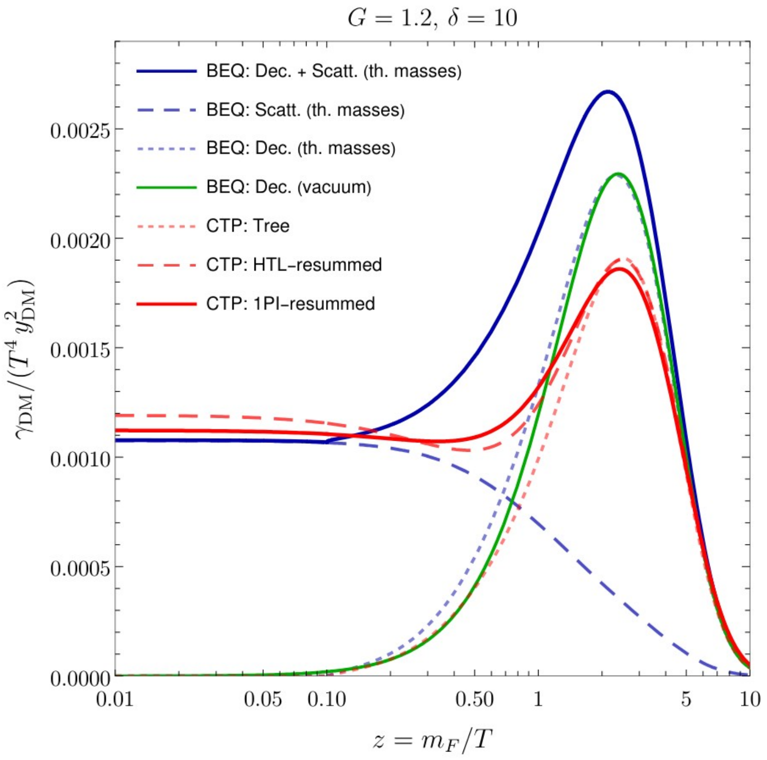
Comparing methods – interaction rate density



BEQ with decay only (vacuum masses)

- Heavily **underestimates** production for **small z** (missing scatterings)
- **Overestimates** production for **large z** due to missing quantum statistics

BEQ with decay and scatterings (incl. thermal masses)

- General differences due to missing quantum statistics
- Decay **overestimated** due to higher thermal mass, earlier closure of the decay window, larger and longer contribution from BEQ than for 1PI resummed

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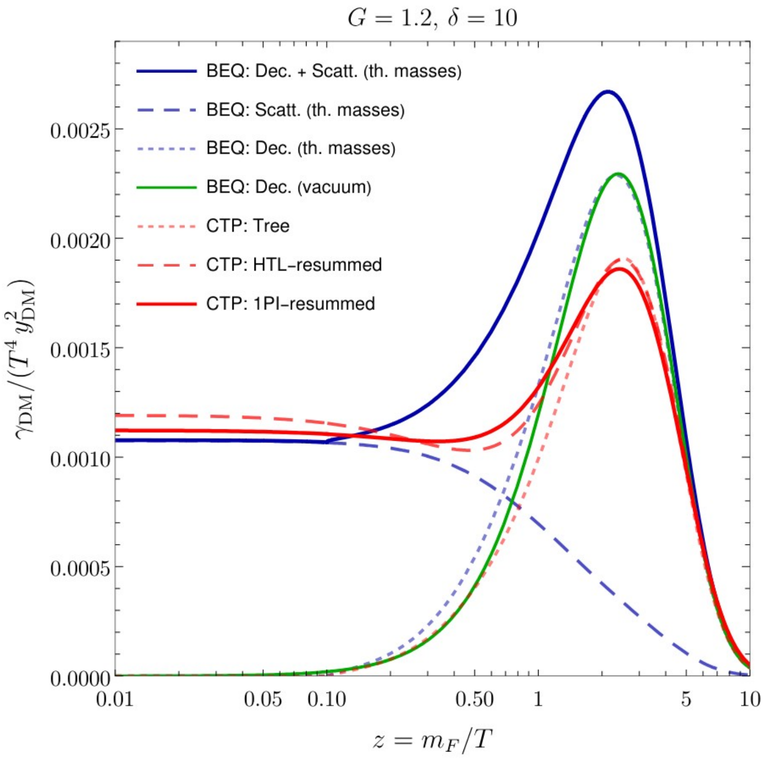
Comparing methods – interaction rate density



CTP with tree-level propagators

- Accounts for **decays with thermal masses** and proper **quantum statistics** while neglecting scatterings
- Comparable with **HTL for decays**

CTP with HTL approximation

- For **small z**, HTL overestimates, as dominated by **ST**-contributions that lack suppression by vacuum mass for large space-like momenta
- Decay contribution kicks in later, as HTL-propagator is delta function for time-like momenta in contrast to 1PI-resummed one
- For **large z**, **HTL overestimates** decays as finite width in 1PI-resummed propagators smear out quasi-particle solution

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