@ DM searches in the 2020s
12/11/19

Rapid bound-state formation of Dark Matter in the Early Universe

Tobias Binder

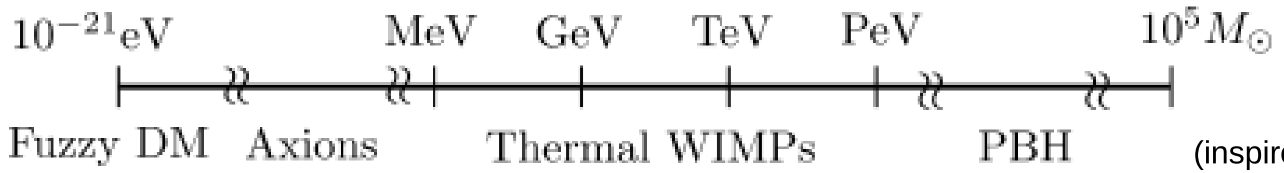
based on arxiv:**1910.11288**, arxiv:**1911.**[in prep.],

in collaboration with

Kyohei Mukaida and **Kalliopi Petraki**

[**Burkhard Blobel**, and **Julia Harz**].

Thermally produced dark matter



(inspired by S. Matsumoto's talk)

- One of the **leading hypothesis** for DM: Thermal WIMPs.

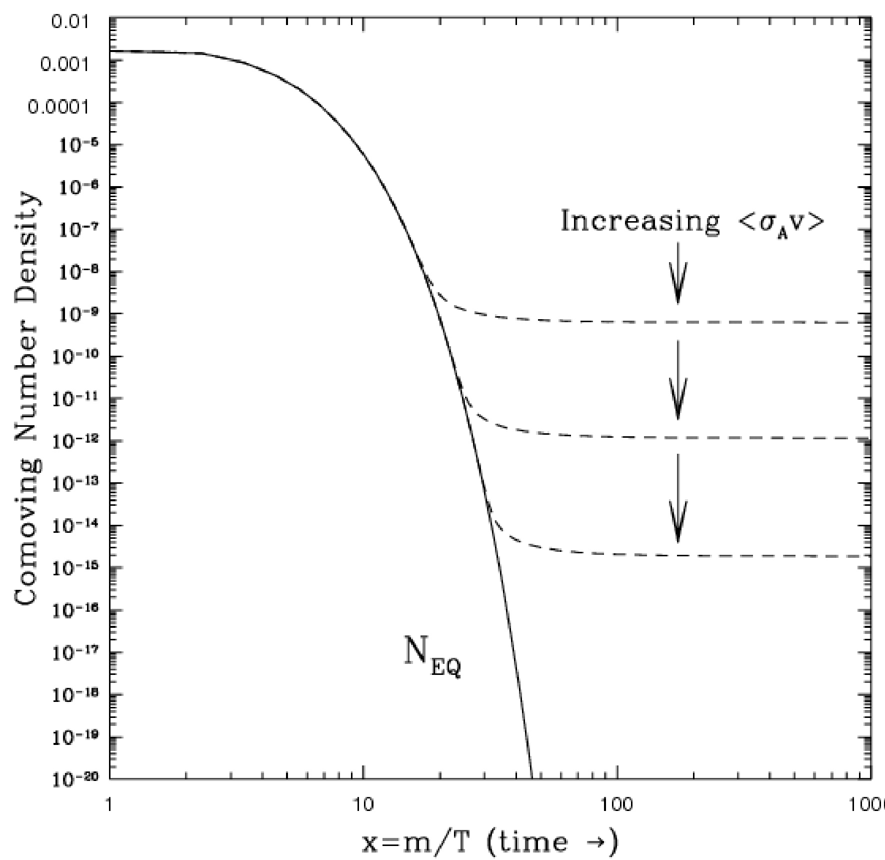
- **Testable** and final relic abundance **independent** of initial conditions.

- Strong constraints on coupling strength rule out many MeV-TeV mass realizations in thermal scenarios.
  (However: "WIMPs are not dead", G. Gelmini)

- TeV-scale and above still remains attractive and much less constrained.

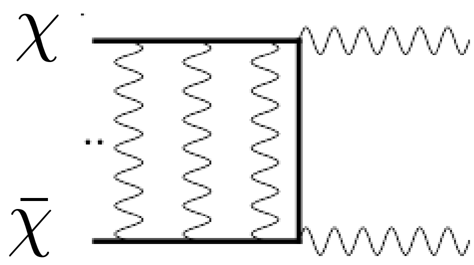
- ***How heavy WIMPs can be?***
  QM effects introduce theoretical uncertainties.

Thermal production mechanism



Quantum mechanical effects

QM effects induced by attractive long-range interactions:



- **Sommerfeld-enhanced annihilation**
  [J. Hisano *et al.* '03, '05, '06]

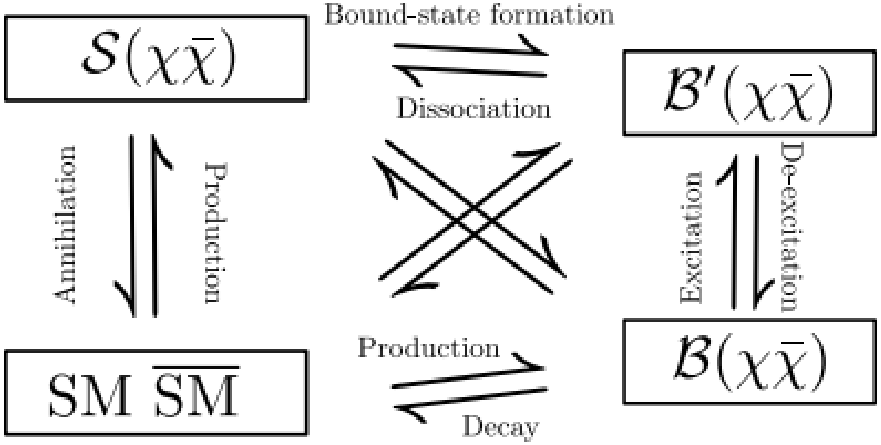
$$(\sigma v) = (\sigma v)_0 \times |\psi(r=0)|^2$$
$$\propto (\sigma v)_0 \, (\alpha / v) \, , \text{ for } v \lesssim \alpha .$$

- **Formation and decay of bound states**

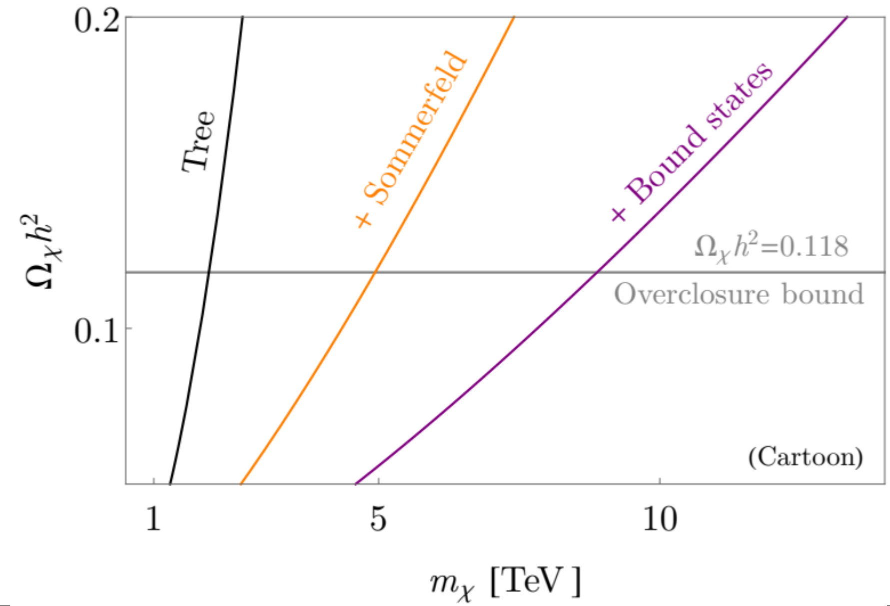
$$\Gamma_n = (\sigma v)_0 \times |\psi_n(r=0)|^2$$

QM effects not included in any public relic density solver. (In progress…)

Complex chemical network:

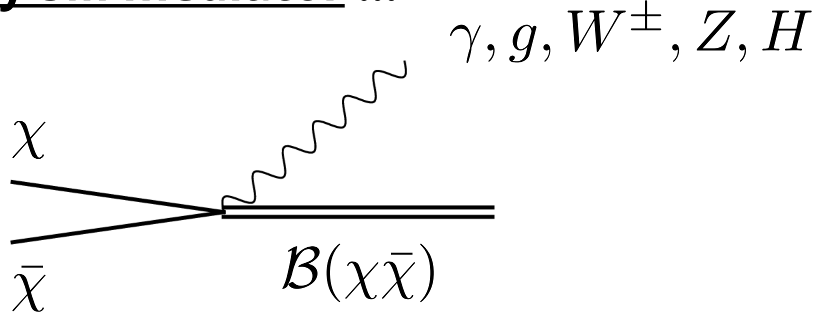


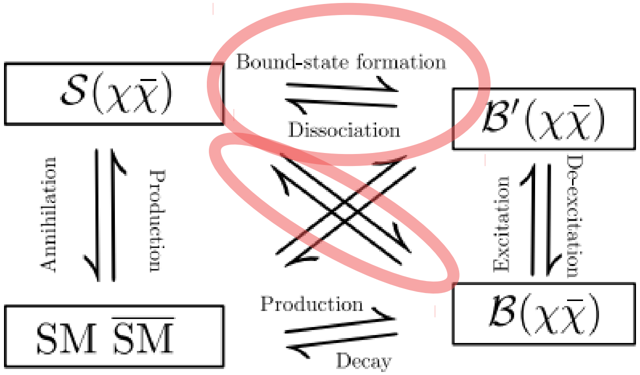
QM effects allow for **larger DM masses**:



Bound-state formation: model examples

For <u>every SM mediator</u> …

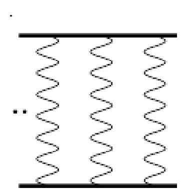




…, possible DM models have been found where QM effects are relevant to include:

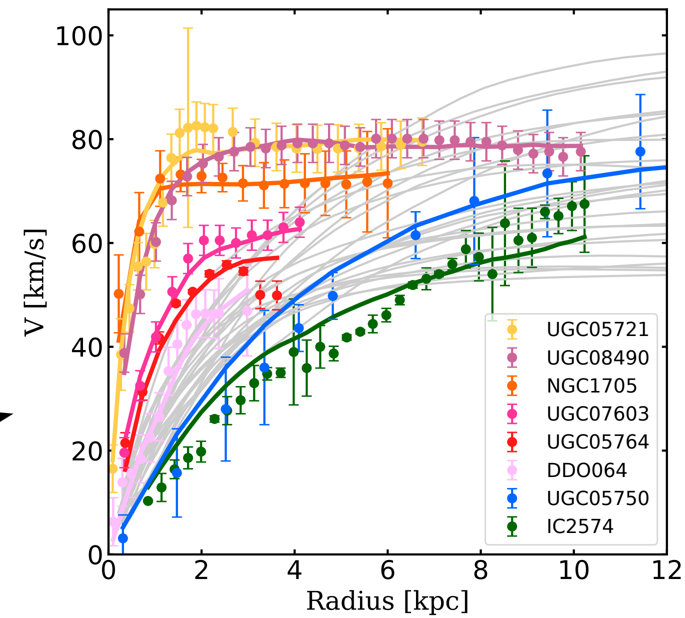
- Minimal DM (includes Wino)
  …, [Cirelli *et al.* '07], [Mitridate *et al.* '17]
- Co-annihilation with color-charged particles
  [J. Ellis *et al.* '16], [Kim&Laine '17],….
  , [Harz&Petraki '18], [S. Biodini *et al.* '19,'19,'19],…
- Higgs mediated bound states
  [Harz&Petraki '18], [S. Biodini '18],…

Or <u>bottom-up motivated</u> scenarios with <u>exotic mediators</u>:



- **S**elf-**I**nteracting **DM** with light mediators
  [J. L. Feng *et al.* '10], [von Harling&Petraki '14], … [many]

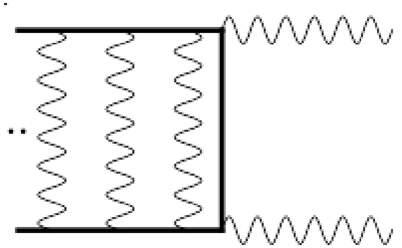
SIDM solves Diversity problem:
[Kamada *et al.* '16],…, [Kaplinghat *et al.* '19]

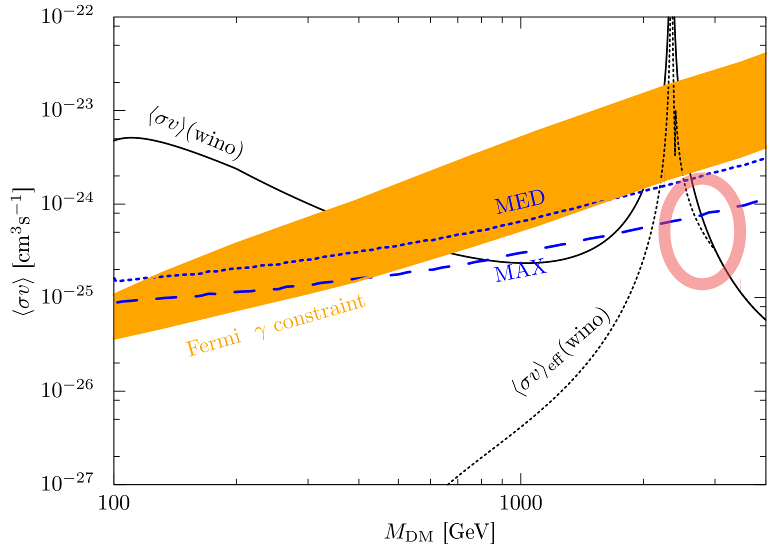


One particular motivation: Wino

For traditional Wino neutralino, bound states exist!

[J. Hisano *et al.* '03, '05,'06]





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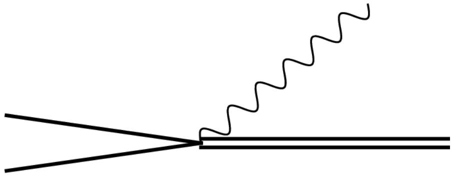
- Indirect detection **sensitive to DM mass** due to Sommerfeld resonances. For constraining WIMPs reliably, we need to theoretical predict the relic abundance precisely!

  (10% change in the mass would result in 100 % change in the flux! see Satoshi's talk)

- **BSF via on-shell mediator emission** has essentially

  no impact on the traditional Wino relic abundance.

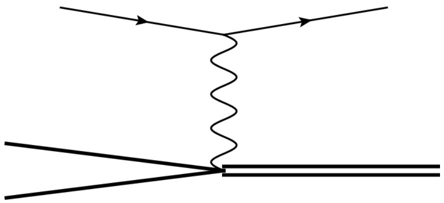
  (*see "Cosmological implications of dark matter bound states"* **[Mitridate *et al.* '17]**)



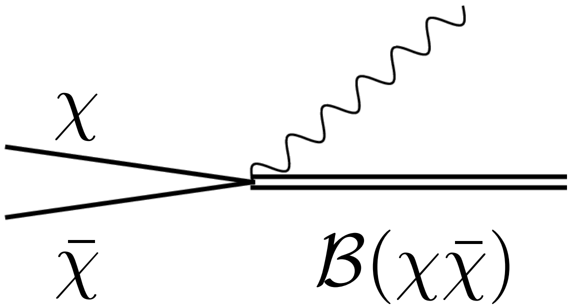
- **Virtual mediator** contributions?

  E.g.: **BSF via bath particle scattering.**

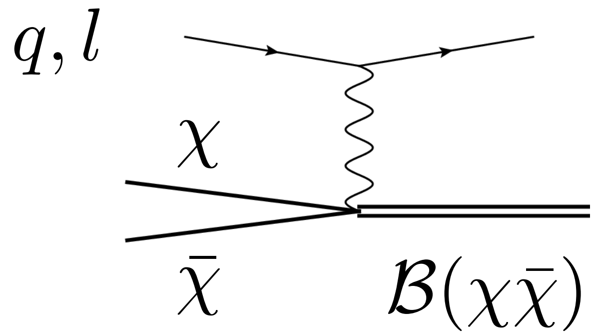
  (no kinematic block, no phase-space suppression, number-density dependent)



BSF: On-shell or off-shell mediator?



vs.



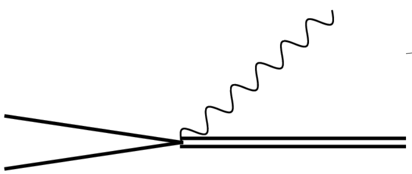
<u>Which one dominates in the Early Universe?</u>

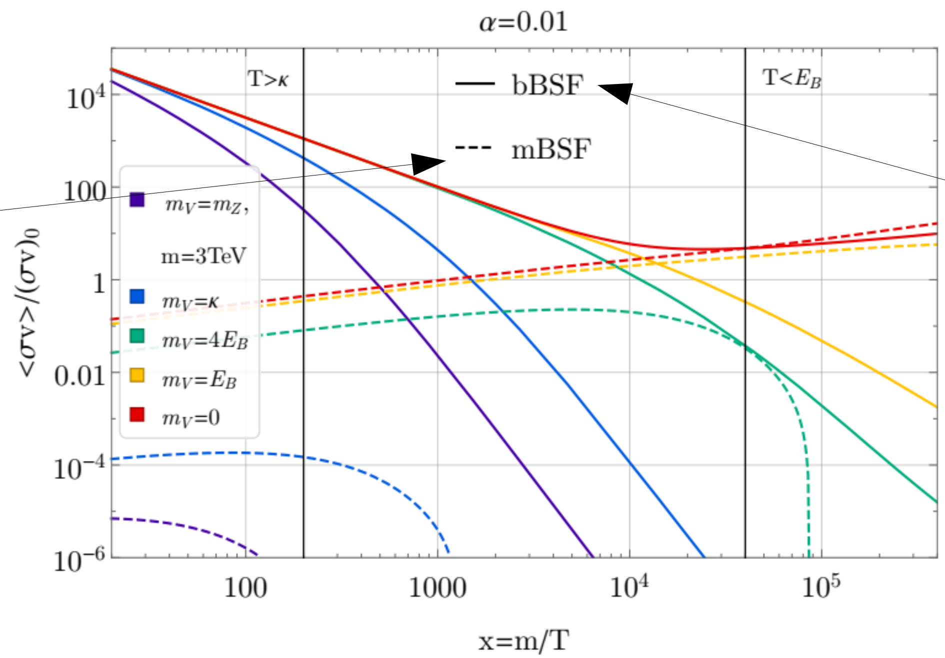
- On-shell scenario resembles situation of SM neutral hydrogen recombination in matt. dom. era.
- Heavy Quarkionia in quark-gluon plasma:

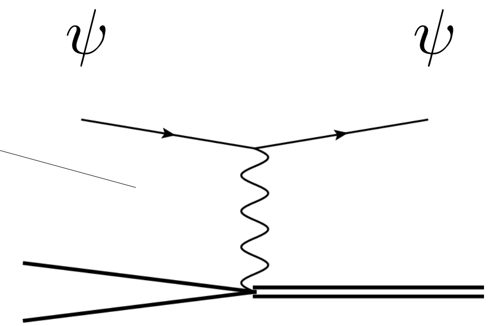
  Parton dissociation dominates on-shell gluon absorption for temperature larger than binding energy.
- By argument of detailed balance: **BSF via parton scattering must dominate** as well!
- Heavy Quarkionia system similar to DM in the Early Universe (>100 rel. d.o.f).
- This insight might already have profound implications for models where light or massless mediators in co-annihilation scenarios are involved.

First estimate: Capture into the ground state

Toy model: $\mathcal{L} \supset g\bar{\chi}\gamma^\mu\chi V_\mu + g\bar{\psi}\gamma^\mu\psi V_\mu$







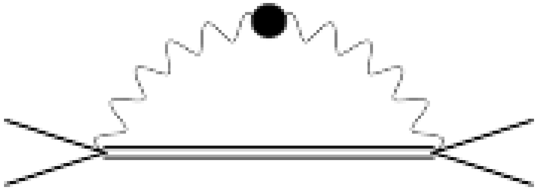
- <u>Proof of concept:</u>

  BSF via bath particle scattering can dominate over on-shell mediator emission.

- Forward scattering divergence regularized by **Debye screening mass**.
- HTL resummation **not applicable** for temperature smaller than binding energy!

➡ Requires **thermal field theory analysis**.

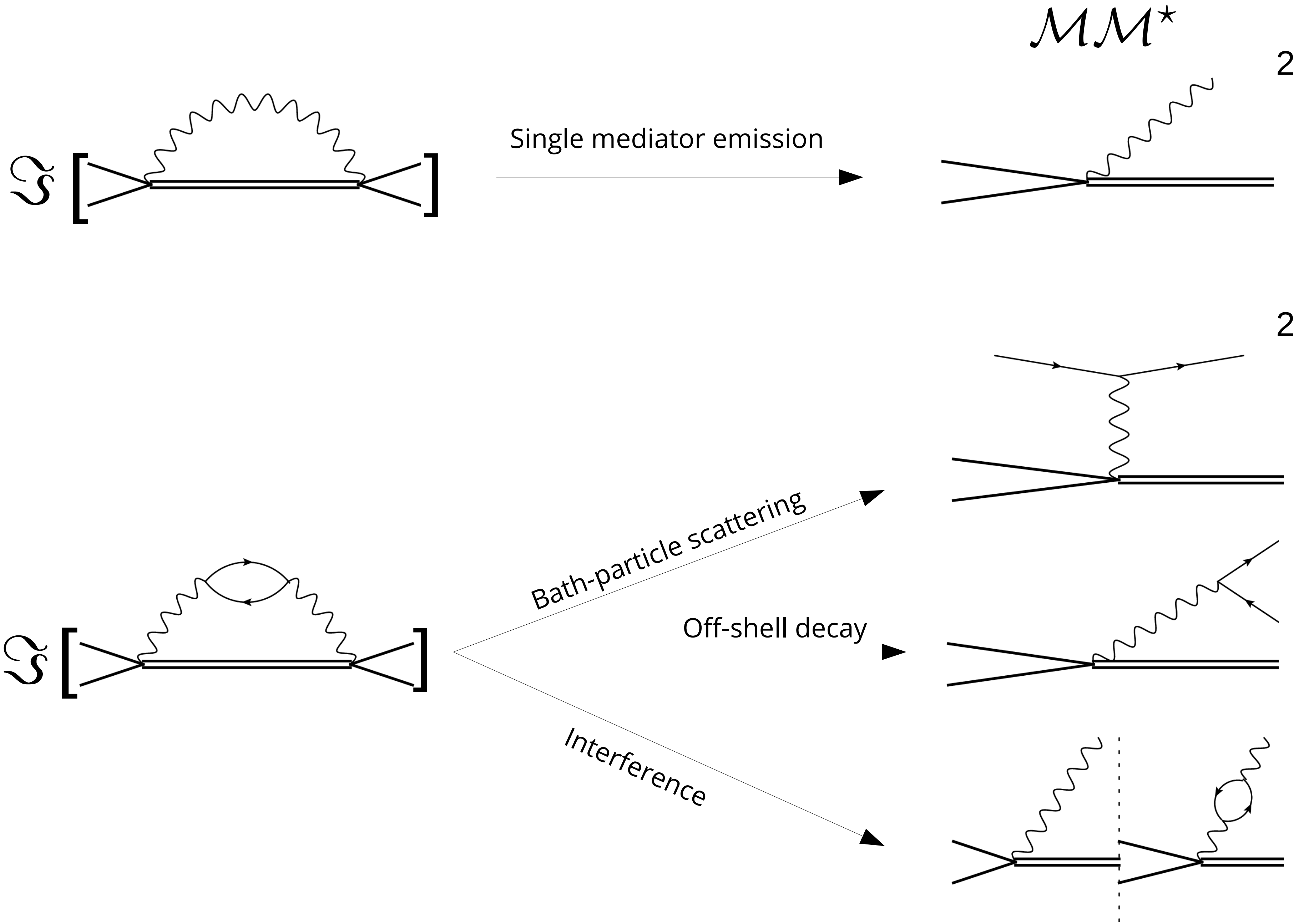
Generalized bound-state formation cross section



$$\sigma^{\rm BSF}_{nlm} v_{\rm rel} = \int \frac{{\rm d}^3 p}{(2\pi)^3} D^{-+}_{\mu\nu}(\Delta E, \mathbf{p}) \sum_{\rm spins} \mathcal{T}^{\mu}_{\mathbf{k},nlm}(\Delta E, \mathbf{p}) \mathcal{T}^{\nu\star}_{\mathbf{k},nlm}(\Delta E, \mathbf{p}).$$

arxiv:**1911.**(in prep.)

Non-equilibrium QFT approach

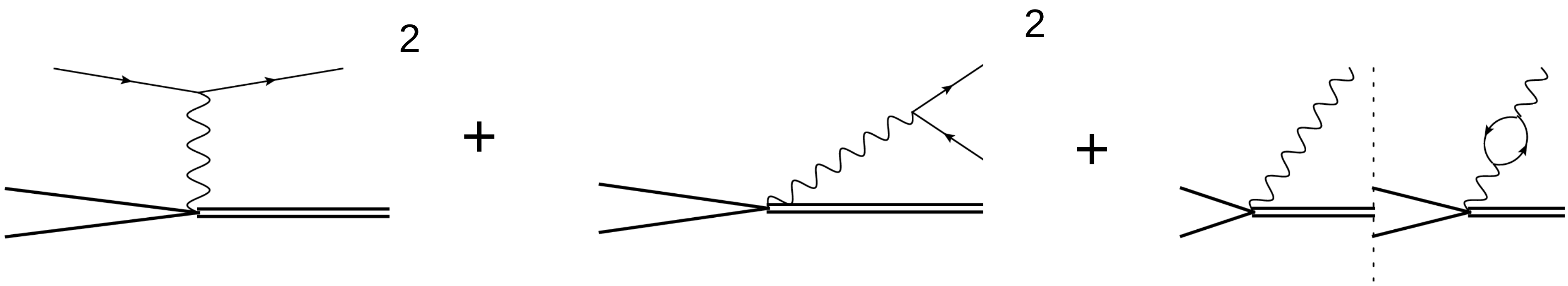


NLO contributions

UV finite, collinear divergent.

UV finite, collinear divergent.

Vacuum part UV divergent, collinear divergent.



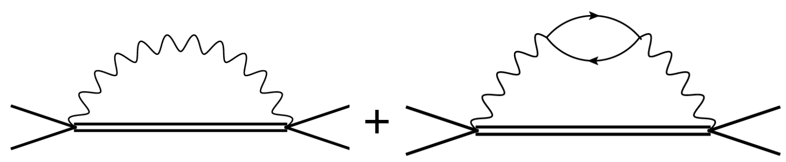
= Finite in collinear direction, and UV finite after vacuum renormalization.

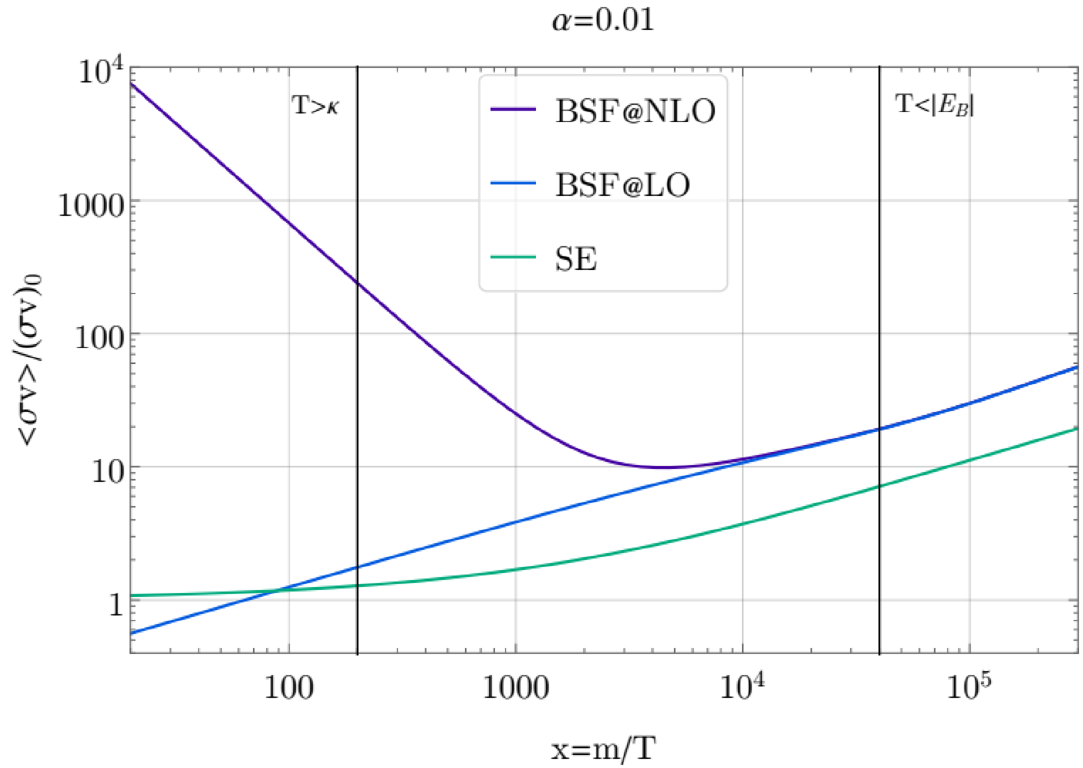
- Provide mathematical proof for cancellation of collinear divergences.
- Holds even for arbitrary phase-space distribution of bath particles, i.e. bath particles do not have to be in thermal equilibrium in order to guarantee finiteness in the forward scattering direction.
- (Bloch-Nordsieck theorem does not help here)

arxiv:**1911.**(in prep.)

Bound-state formation at NLO: massless case

- Interference terms **cancel collinear divergences,** resulting in a finite cross section.
- At high temperature $(T \gtrsim E_B)$ BSF via bath particle scattering **dominates** over single mediator emission.
- Variation of renormalization scale between DM mass and binding energy doesnt affect plot visually, hence Log-contributions are under control.

$(\sigma v)^{\rm NLO}_{\rm BSF} \equiv \Im\Big[$  $\Big]$



arxiv:**1911.**(in prep.)

BSF via bath-particle scattering: massive case

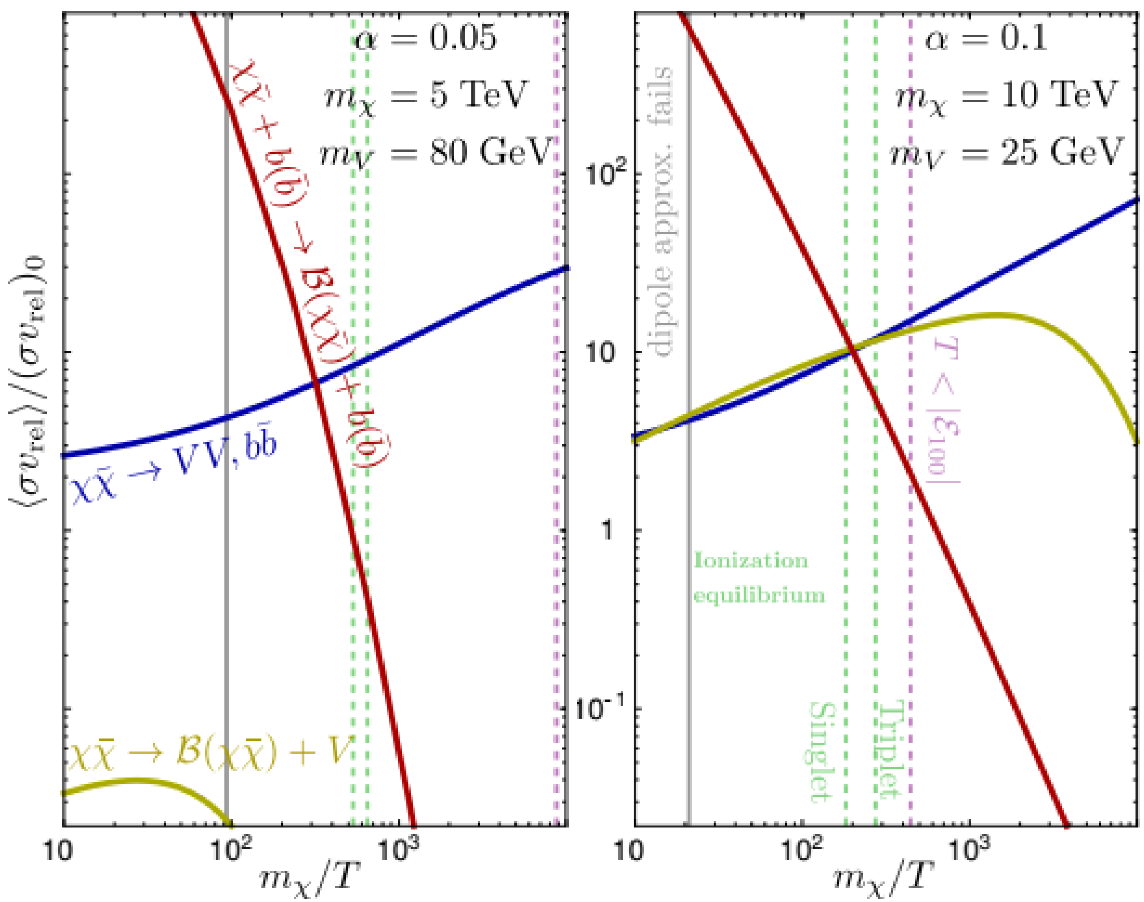
arxiv:**1910.11288**

Parametrically resembles:

no kimenatical block

Wino

Co-annihilation with
colored charged particles



Summary and conclusion

Formal achievements:

- Non-equilibrium QFT analysis shows that **collinear divergences cancel** in the case of a massless mediator, even for arbitrary phase-space distributions of bath particles.
- Combining with previous lit., we achieved more **complete description** of the DM freeze-out, ranging from melting effects of bound states at high T down to far below the decoupling from ionization equilibrium.

Phenomenological results and their implications:

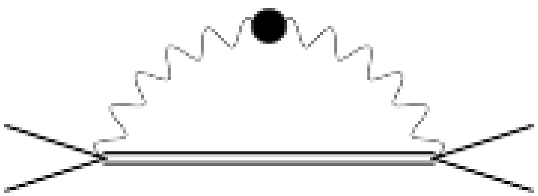
- **Previous literature** considered BSF via **on-shell mediator emission** only.
- For temperature larger binding energy, we find in the massless case that the **dominant BSF channel** is **via bath-particle scattering** (in agreement with lit. about heavy quarkonia in QGP).
- BSF cross section via bath-particle scattering can exceed the single mediator emission by many orders of magnitude.
- Statement expected to be true also for non-abelian gauge or Yukawa theories.
- **Consequently, DM mass could be heavier than previously expected.**

(Eventually informs indirect searches and construction of future colliders)

Ready to (re-)analyse multi-TeV scale thermal relics!

Thank you!

Generalized bound-state formation cross section



$$\sigma^{\rm BSF}_{nlm} v_{\rm rel} = \int \frac{{\rm d}^3 p}{(2\pi)^3} D^{-+}_{\mu\nu}(\Delta E, \mathbf{p}) \sum_{\rm spins} \mathcal{T}^{\mu}_{\mathbf{k},nlm}(\Delta E, \mathbf{p}) \mathcal{T}^{\nu\star}_{\mathbf{k},nlm}(\Delta E, \mathbf{p}).$$

arxiv:**1911.**(in prep.)

$$\mathcal{L} \supset g\bar{\chi}\gamma^{\mu}\chi V_{\mu} + g\bar{\psi}\gamma^{\mu}\psi V_{\mu}$$

arxiv:**1910.11288**

Interacting two-point correlation fct.:

$$D^{-+}_{\mu\nu}(x,y) \equiv \langle V_{\mu}(x) V_{\nu}(y) \rangle$$

$$\langle \ldots \rangle = {\rm Tr}[e^{-H_{\rm env}/T} \ldots]$$

Kubo-Martin-Schwinger relation:

$$D^{-+}_{\mu\nu}(\Delta E, \mathbf{p}) = [1 + f^{\rm eq}_V(\Delta E)]\, D^{\rho}_{\mu\nu}(\Delta E, \mathbf{p})$$

$$D^{\rho}_{\mu\nu} = 2\Im \left[i D^{R}_{\mu\nu} \right]$$

$$D^{R}_{\mu\nu} = D^{R,0}_{\mu\nu} + D^{R,0}_{\mu\alpha} \Pi^{\alpha\beta}_{R} D^{R,0}_{\beta\nu} + \ldots$$

S-B transition matrix elements:

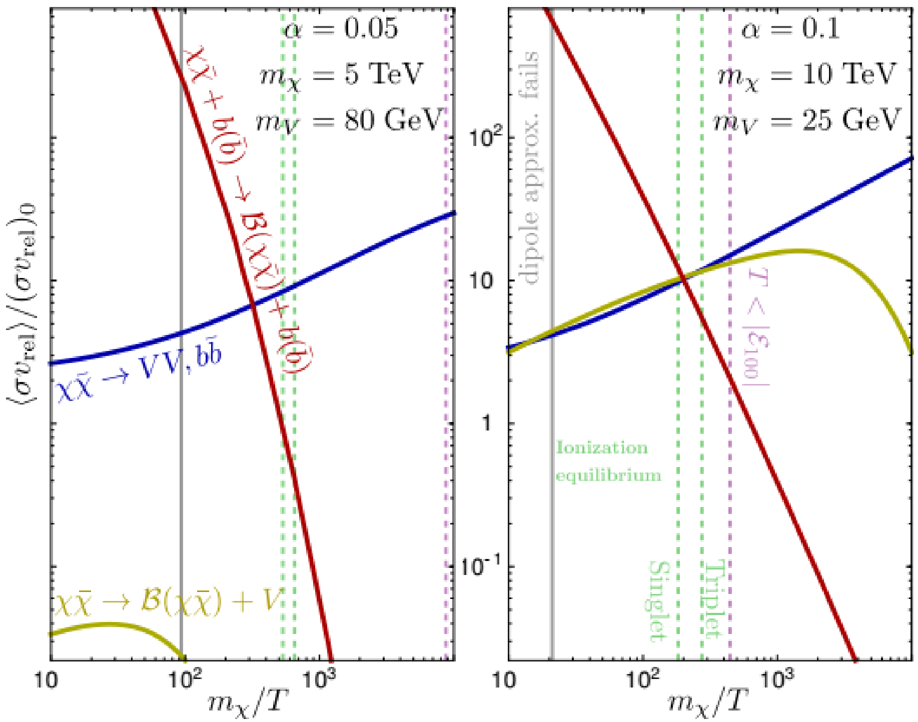
$$\mathcal{T}^{\mu}_{\mathbf{k},nlm}(P) \equiv (g_{\chi} g_{\bar{\chi}} 4 m_{\chi}^2 2M)^{-1/2} \mathcal{M}^{\mu}_{\mathbf{k},nlm}\Big|^{\rm NR}_{\rm dip}$$

$$\delta^4 \mathcal{M}^{\mu}_{\mathbf{k},nlm} = \int {\rm d}^4 x\, e^{iPx} \langle \mathcal{B}_{nlm} |\, g\bar{\chi}(x)\gamma^{\mu}\chi(x)\, | \mathcal{S}_{\mathbf{k}} \rangle$$

Well developed, see, e.g., Kallias works.

Implications of strongly enhanced BSF

arxiv:**1910.11288**



Approx. number density eq. **[von Harling&Petraki '14]**:

$$\dot{n}_s + 3Hn_s = -\left[\langle\sigma v\rangle_{\rm an} + \frac{\Gamma_1\langle\sigma v\rangle_{\rm BSF}}{\Gamma_1 + \Gamma_{1\to s}}\right]\left(n_s^2 - n_s^{\rm eq} n_s^{\rm eq}\right)$$

$$\Gamma_{1\to s} = \langle\sigma v\rangle_{\rm BSF}\frac{n_s^{\rm eq} n_s^{\rm eq}}{n_1^{\rm eq}}$$

$$\Gamma_1 \ll \Gamma_{1\to s}$$

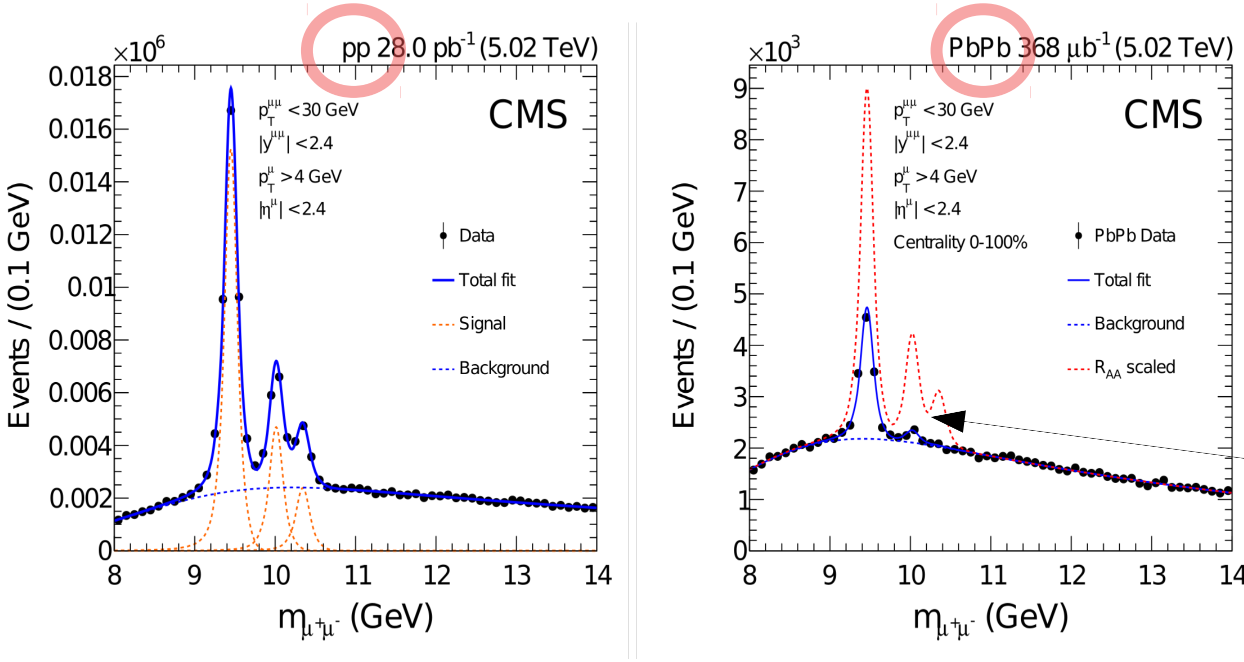
(Saha-) Ionization equilibrium [TB, Covi, Mukaida '18]:

$$\dot{n}_s + 3Hn_s = -\left[\langle\sigma v\rangle_{\rm an} + \Gamma_1\frac{n_1^{\rm eq}}{n_s^{\rm eq} n_s^{\rm eq}}\right]\left(n_s^2 - n_s^{\rm eq} n_s^{\rm eq}\right)$$

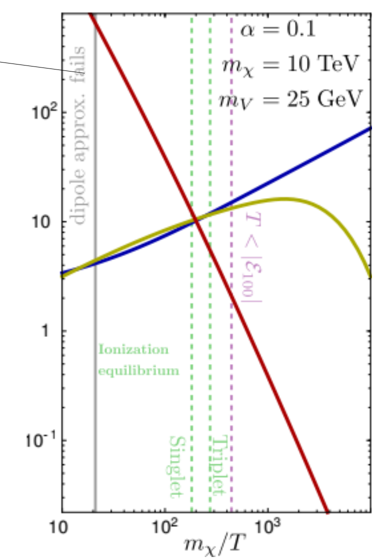
Strongly enhanced BSF via bath-particle scattering leads to **ionization equilibrium,** where i) collision term is **independent of BSF cross section and DISS rate**, and ii) **effective depletion cross section takes maximum value** for fixed T.

Limitation

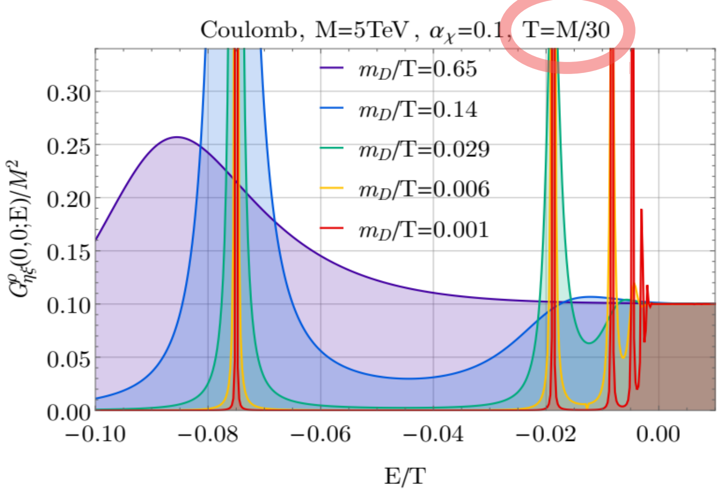
CMS collaboration, Phys.Lett. **B790** (2019) 270-293

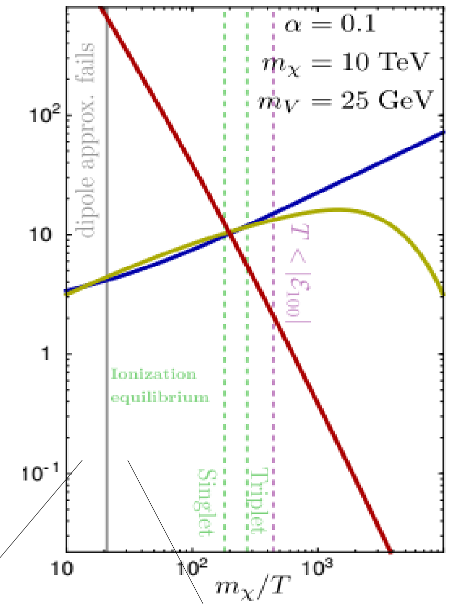


Melting of bound states inside plasma environment observed.



Complete picture





[TB, Covi, Mukaida '18]

$$\dot{n} + 3Hn = -2(\sigma v)_0 G^{++--}_{\eta\xi}(x,x,x,x)\big|_{\rm eq}\left[e^{\beta 2\mu} - 1\right],$$

$$G^{++--}_{\eta\xi}\big|_{\rm eq} = e^{-2\beta M}\int \frac{d^3\mathbf{P}}{(2\pi)^3} e^{-\beta \mathbf{P}^2/(4M)} \int_{-\infty}^{\infty} \frac{dE}{(2\pi)} e^{-\beta E} G^\rho_{\eta\xi}(\mathbf{0},\mathbf{0};E).$$

arxiv:**1911.**(in prep.)

arxiv:**1910.11288**

$$\sigma^{\rm BSF}_{nlm} v_{\rm rel} = \int \frac{d^3 p}{(2\pi)^3} D^{-+}_{\mu\nu}(\Delta E, \mathbf{p}) \sum_{\rm spins} \mathcal{T}^{\mu}_{\mathbf{k},nlm}(\Delta E, \mathbf{p}) \mathcal{T}^{\nu\star}_{\mathbf{k},nlm}(\Delta E, \mathbf{p}).$$

Backup

1 BS+R.h.s of BS equation vanishes

$$\dot{n}_s + 3Hn_s = -\left[\langle\sigma v\rangle_{\rm an} + \frac{\Gamma_1\langle\sigma v\rangle_{\rm BSF}}{\Gamma_1+\Gamma_{1\to s}}\right]\left(n_s^2 - n_s^{\rm eq}n_s^{\rm eq}\right)$$

Coupled BEs:

$$\begin{aligned}\dot{n}_s + 3Hn_s =& -\langle\sigma v\rangle_{\rm an}\left[n_s^2 - (n_s^{\rm eq})^2\right]\\ &- \sum_i \langle\sigma^i v\rangle_{\rm BSF}\left[n_s^2 - n_i (n_s^{\rm eq})^2/n_i^{\rm eq}\right],\\ \dot{n}_i + 3Hn_i =& -\Gamma_i\left[n_i - n_i^{\rm eq}\right]\\ &+ \langle\sigma^i v\rangle_{\rm BSF}\left[n_s^2 - n_i (n_s^{\rm eq})^2/n_i^{\rm eq}\right]\\ &- \sum_j \Gamma_{i\to j}\left[n_i - n_j n_i^{\rm eq}/n_j^{\rm eq}\right]\end{aligned}$$

$\Gamma_1 \ll \Gamma_{1\to s}$

Radiative processes much faster than total number violating processes -> ionization equilibrium

[TB, Covi, Mukaida ’18]

$$\dot{n} + 3Hn = -\left[\langle\sigma v\rangle_{\rm an} + \sum_i \Gamma_i \frac{n_i^{\rm eq}}{n_s^{\rm eq}n_s^{\rm eq}}\right]\left(\alpha^2 n^2 - n_s^{\rm eq}n_s^{\rm eq}\right)$$