Towards refined thermal decoupling descriptions of dark matter

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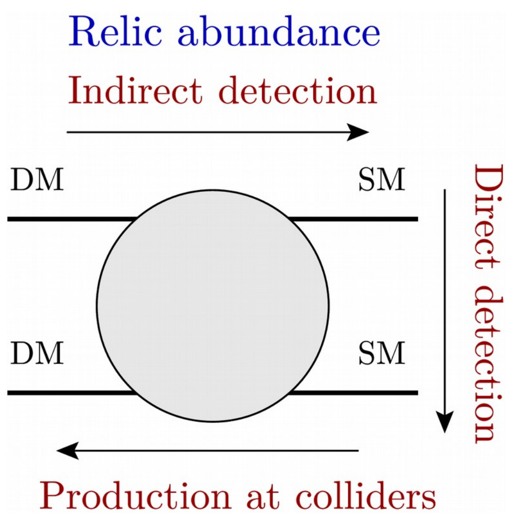
@ Kavli IPMU postdoc colloquium series (online)
27th November

Overview

- **Thermally produced dark matter**

  - ✔ Chemical decoupling (freeze-out) → observed abundance
  - ✔ Independent of initial conditions
  - ✔ Testable



(1) Thermal decoupling = chemical + ***kinetic decoupling !***

(2) Cosmological tensions as guiding principle for model building

(3) Heavy WIMPs

- (SM) interactions become long-ranged
- *require special relic abundance computation*

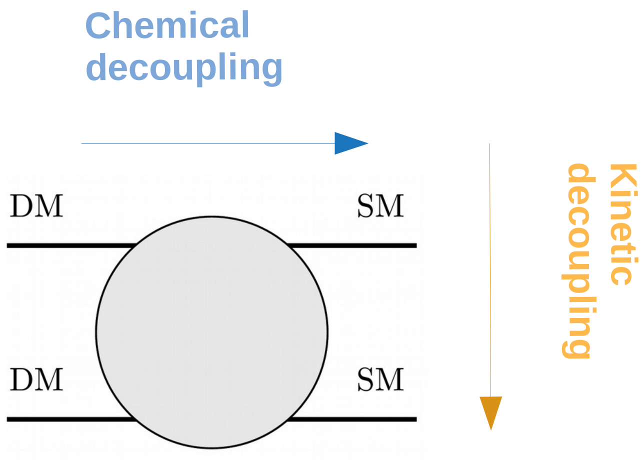
Thermal decoupling

$$\dot{n} + 3Hn = -\langle \sigma v \rangle \left[n^2 - n_{\rm eq}^2\right]$$

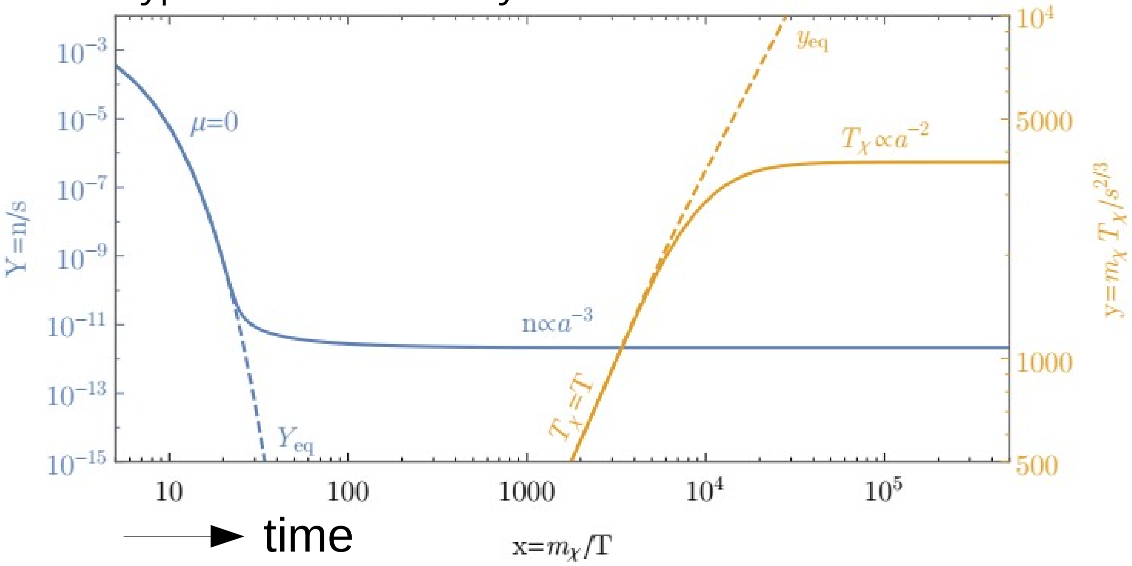
$$\Omega_\chi = \frac{m_\chi n}{\rho_{\rm cr}}\Big|_{T_{\rm CMB}}$$

- Lee-Weinberg equation
- DarkSUSY, micrOMEGAs, …
- ***Main assumption*:**

  kinetic equilibrium $(T_\chi = T)$ maintained during chemical decoupling



Typical thermal history



Three approaches

A) Boltzmann equation on phase-space density level

$$E(\partial_t - Hp\partial_p) f_\chi(t,p) = C_{\rm ann}[f_\chi] + C_{\rm el}[f_\chi]$$

B) Coupled system of momentum moments

$$\dot{n} + 3Hn = \langle C_{\rm ann} \rangle$$

$$\dot{T}_\chi + 2HT_\chi = \langle C_{\rm ann} \rangle_2 + \langle C_{\rm el} \rangle_2 + \ldots$$

Closure of Boltzmann hierarchy:

$$f_\chi(t,p) = \frac{n}{n^{\rm eq}(T_\chi)} e^{-E/T_\chi}$$

C) Standard (Lee-Weinberg eq.)

$$\dot{n} + 3Hn = \langle C_{\rm ann} \rangle$$

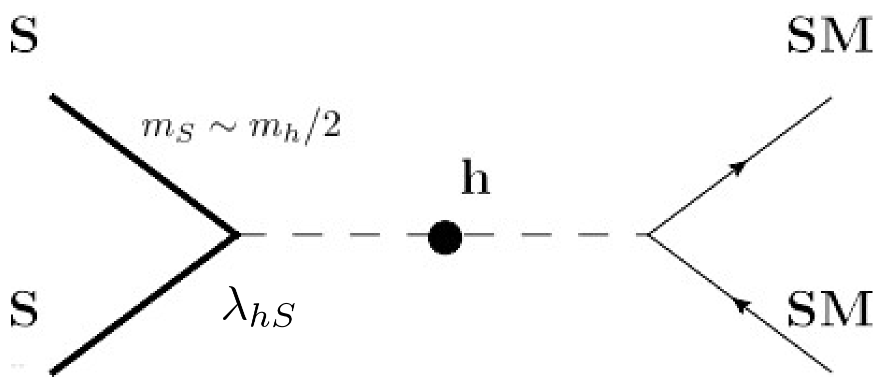
$$f_\chi(t,p) = \frac{n}{n^{\rm eq}(T)} e^{-E/T}$$

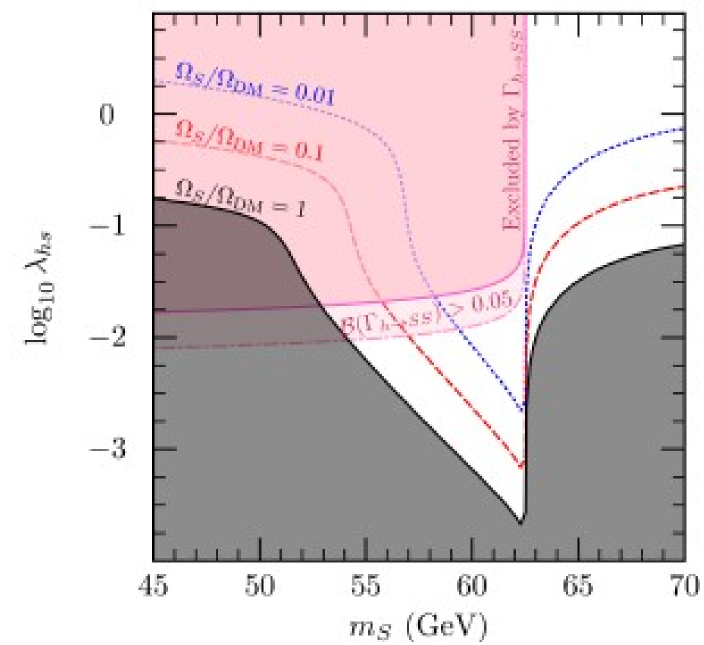
Scalar Singlet DM

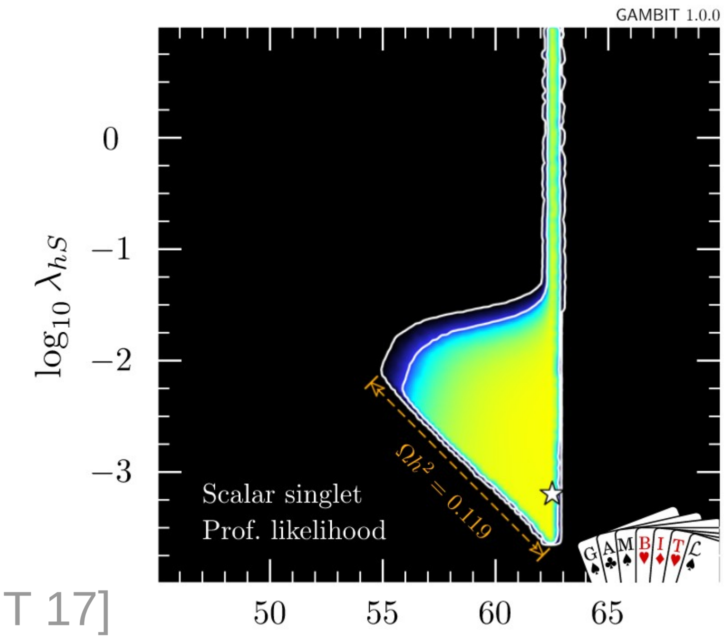
- **Silveira & Zee model**

$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S.$$

- **Renormalizable and minimal (2 parameter)**
- **Gained attraction after Higgs discovery**
- **Best fit in “resonance region”**



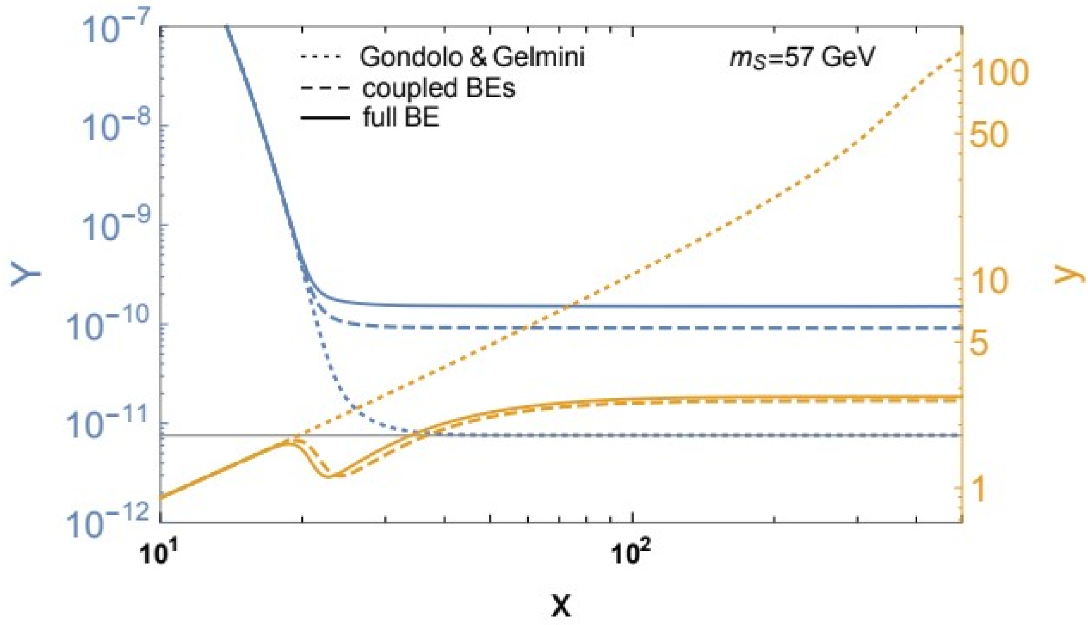




[Cline *et al.* 15, GAMBIT 17]

Early kinetic decoupling

[**TB**, Bringmann, Gustafsson, Hryczuk PRD 17]

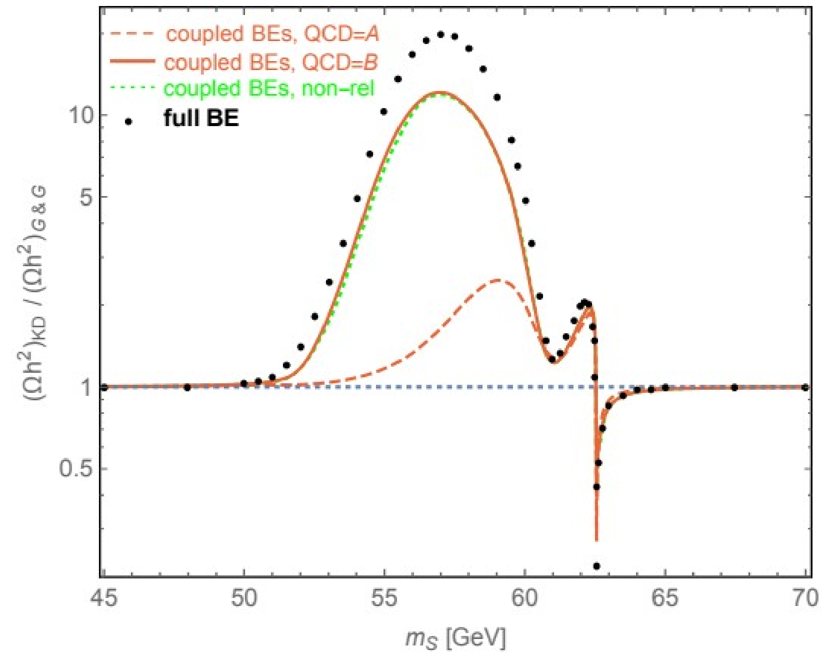


Early kinetic decoupling

- **Early KD for Scalar Singlet DM**

  [**TB**, Bringmann, Gustafsson, Hryczuk PRD 17]

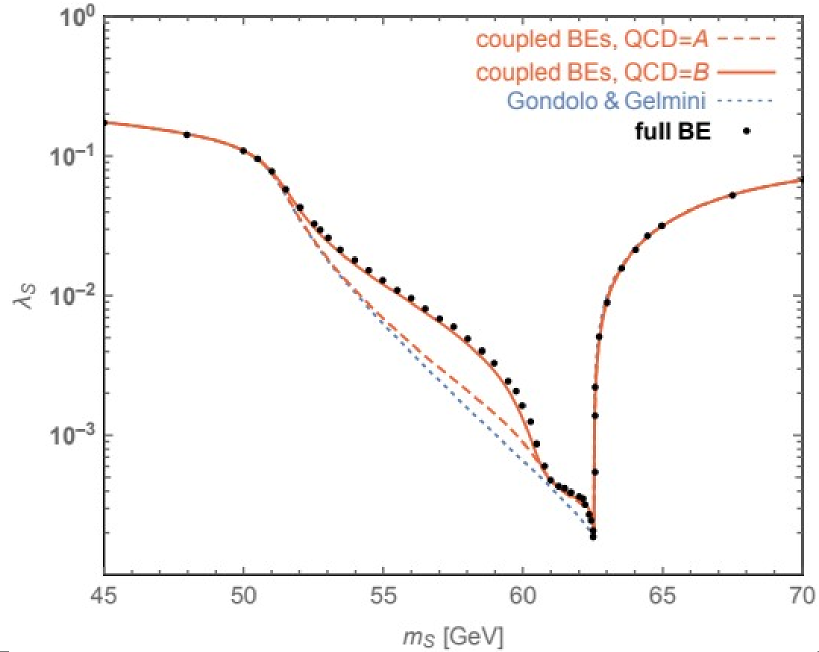
  - Standard computation fails by up to an order of magnitude
  - QCD modeling dominant error source
  - More parameter space probed by current and future Higgs-to-invisible searches
  - *Kinetic eq.* ***NOT*** *maintained in general*



- **DRAKE: Dark matter Relic Abundance beyond Kinetic Equilibrium**

  [**TB**, Bringmann, Gustafsson, Hryczuk (in prep.)]

  - Includes all 3 approaches
  - More examples (Resonance, Sommerfeld, Sub-threshold annihilation) for early KD
  - Output contains full phase-space density information → structure formation



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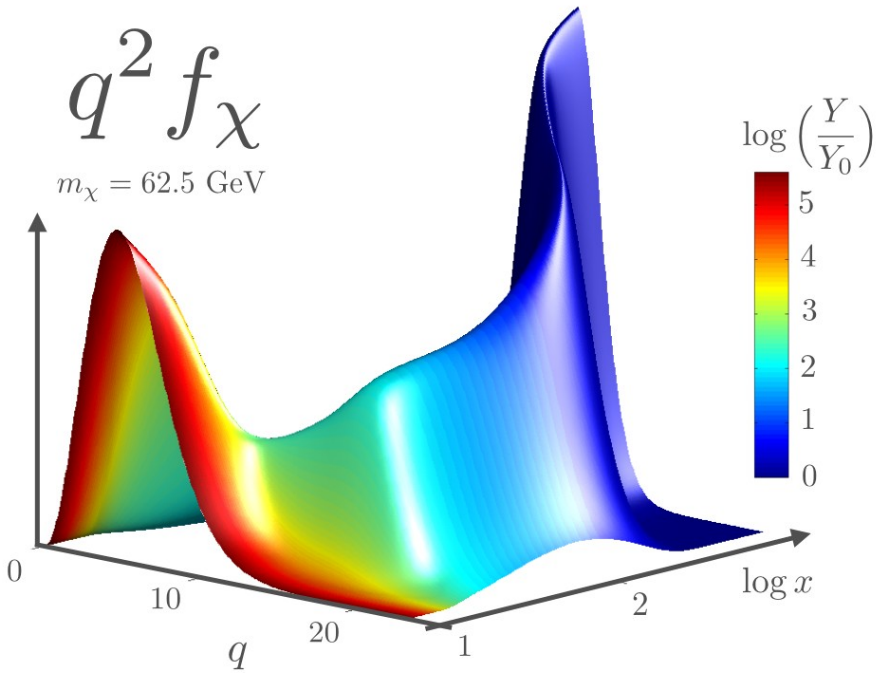
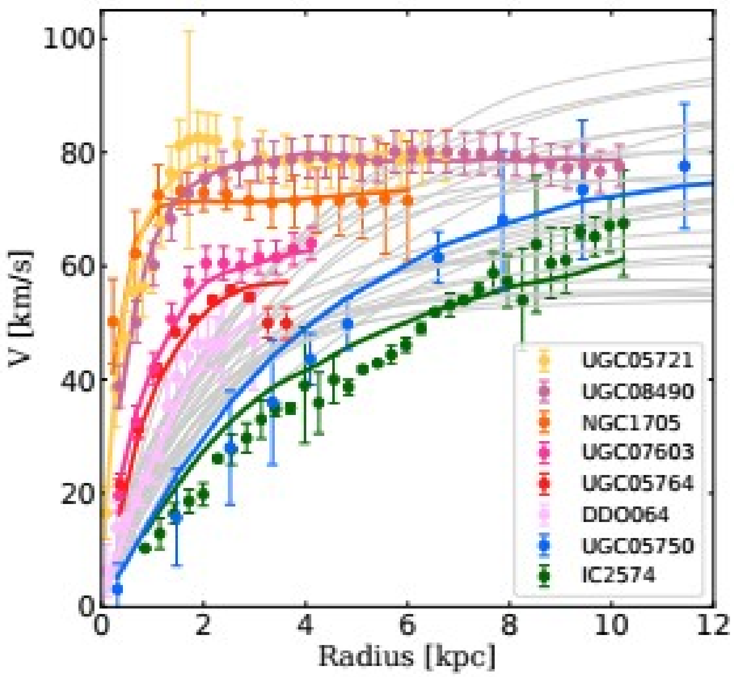


Cosmological tensions

- <u>**Inner halo density structure**</u>
  - **Diversity (Core and cusps)**
- **Halo abundance/mass**
  - **Missing satellites (?)**
- **Expansion rate today (H0 tension)**
  - **Early time extrapolation (CMB) vs.
    late time measurements (e.g. H0LiCOW)**



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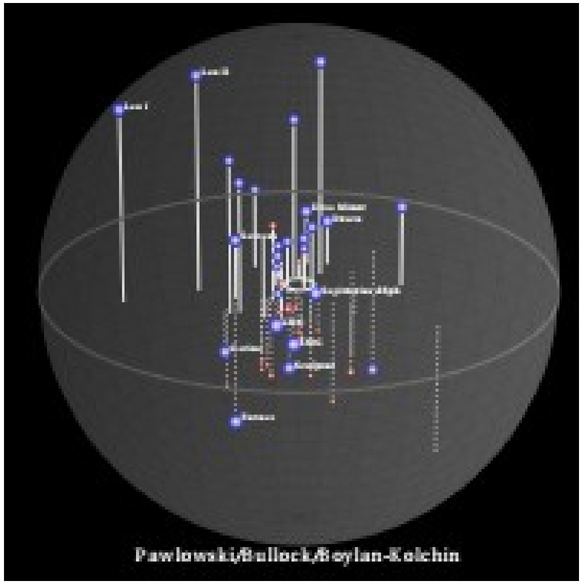

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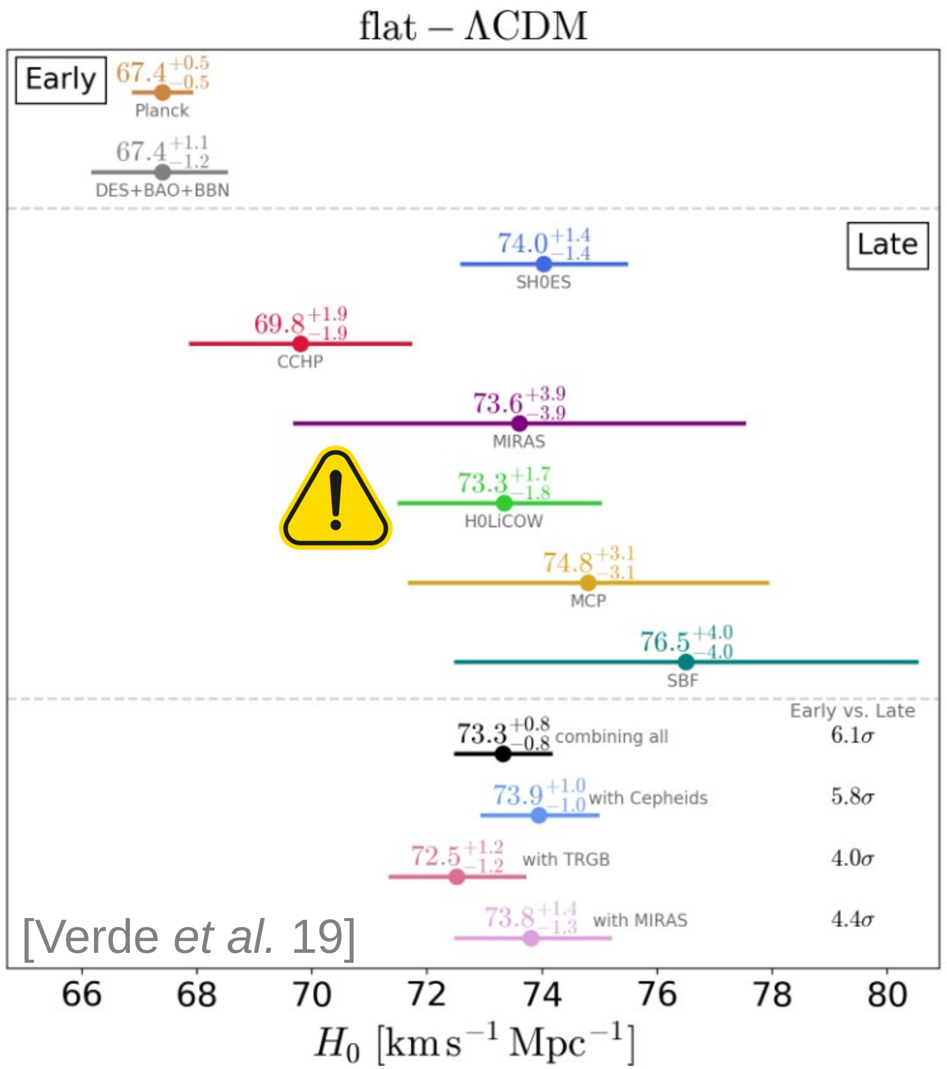

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Catch 22 problem for warm dark matter and fuzzy dark matter (ULAPs)

- **Expansion rate today (H0 tension)**
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Cosmological tensions

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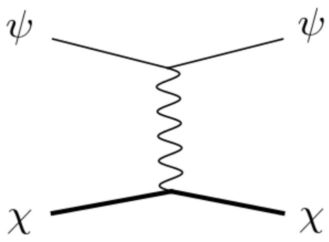
Decaying DM (post recombination) or Early Dark Energy (pre-recombination)

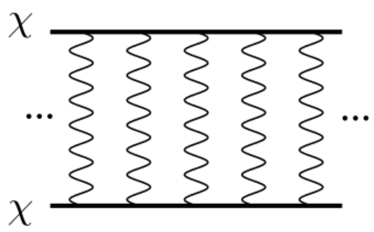
Dark MeV-scale mediators

$$\mathcal{L} \supset g\bar{\chi}\gamma^{\mu}\chi\phi_{\mu} + g\bar{\psi}\gamma^{\mu}\psi\phi_{\mu} \text{ or } \mathcal{L} \supset g\bar{\chi}\chi\phi + g\bar{\psi}\psi\phi, \text{ with } m_{\phi} \sim \text{MeV}$$

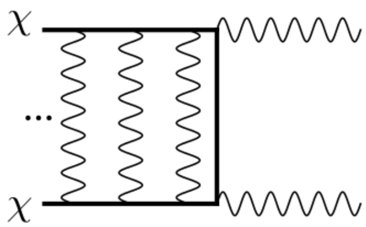
Scattering



Self-scattering



Annihilation



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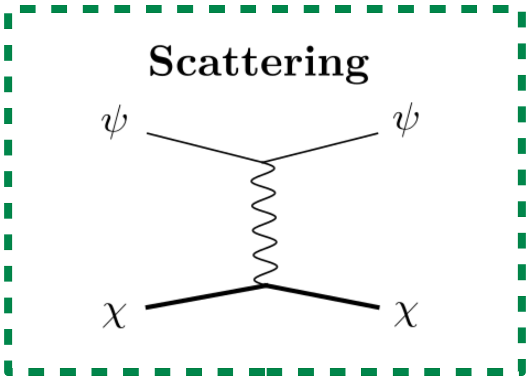
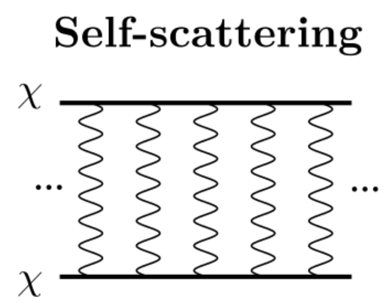
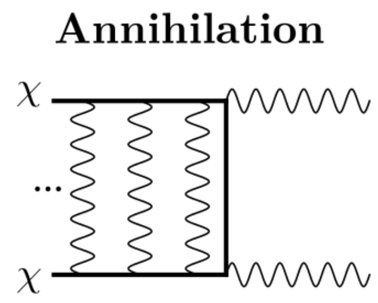




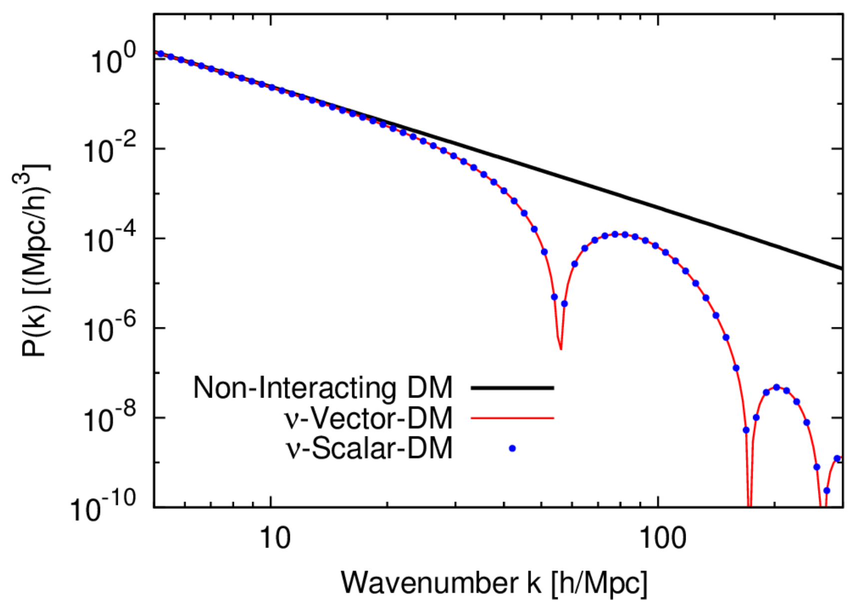


- Late kinetic decoupling:

  $\mathrm{M_{cut}} \sim 10^8 M_\odot$ possible

  ✔ Missing satellite ok

- Similar suppression for vector & scalar mediator (non-trivial)



[**TB**, Covi, Kamada, Murayama, Takahashi, Yoshida JCAP 16]

Dark MeV-scale mediators

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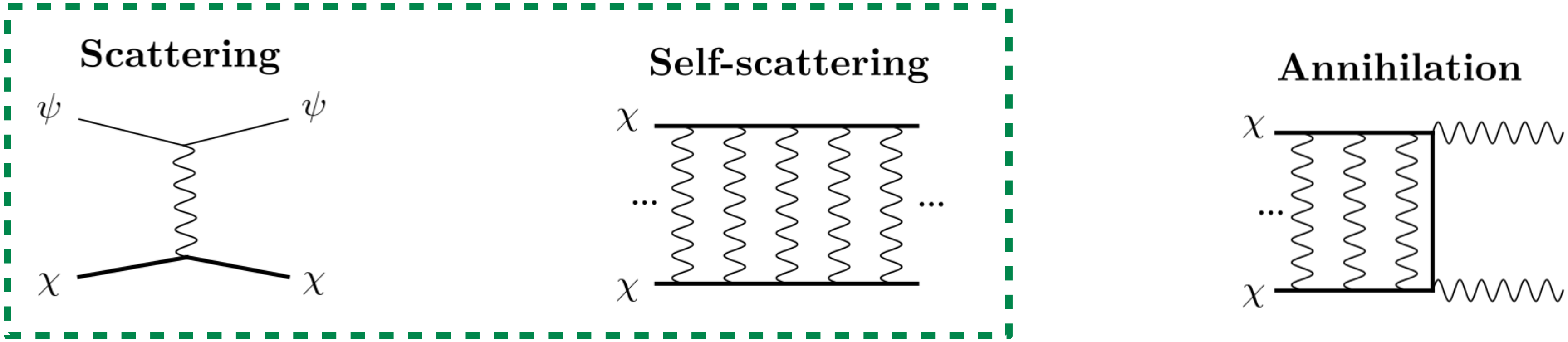
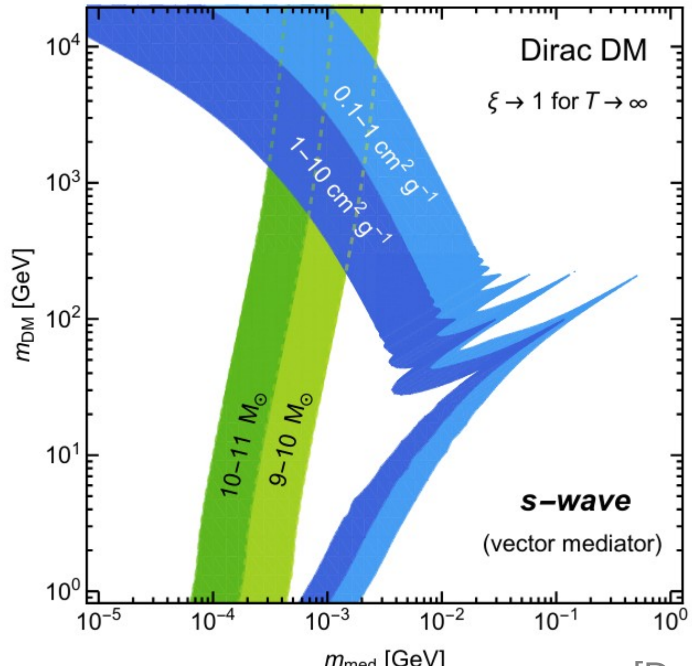
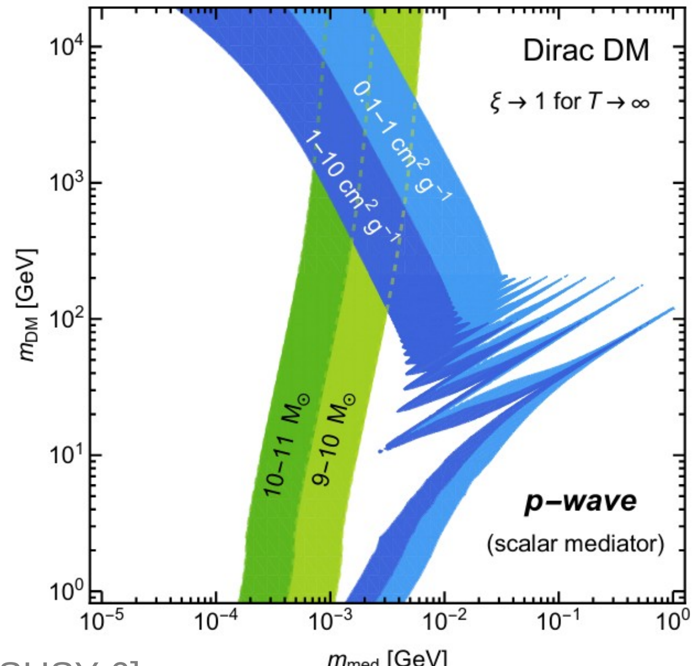


- +Strong self-interactions
  - SIDM candidate
  - Diversity ok
  - Velocity dependence





[DarkSUSY 6]

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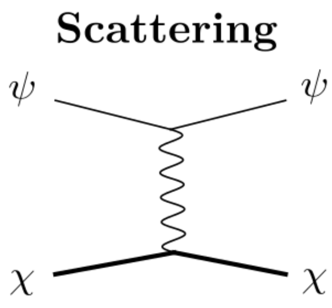
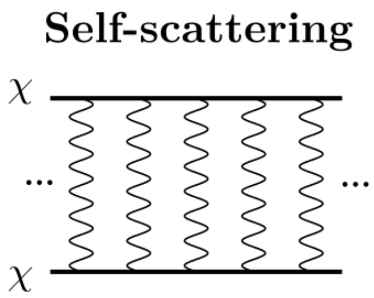
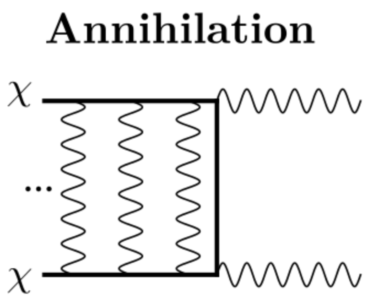
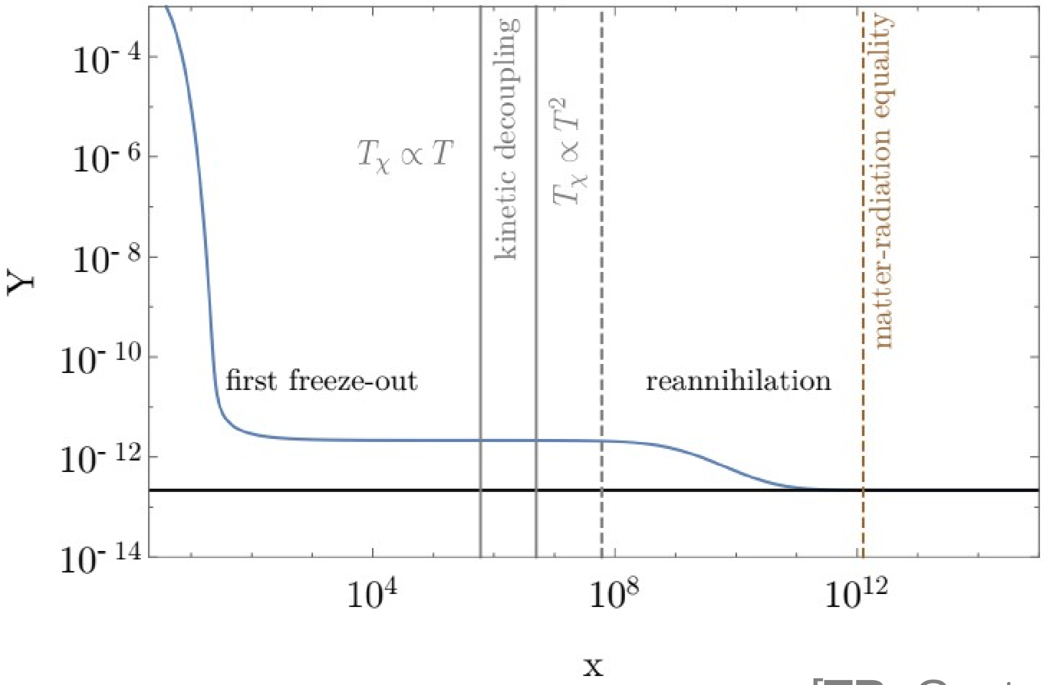








Reannihilation characterized by

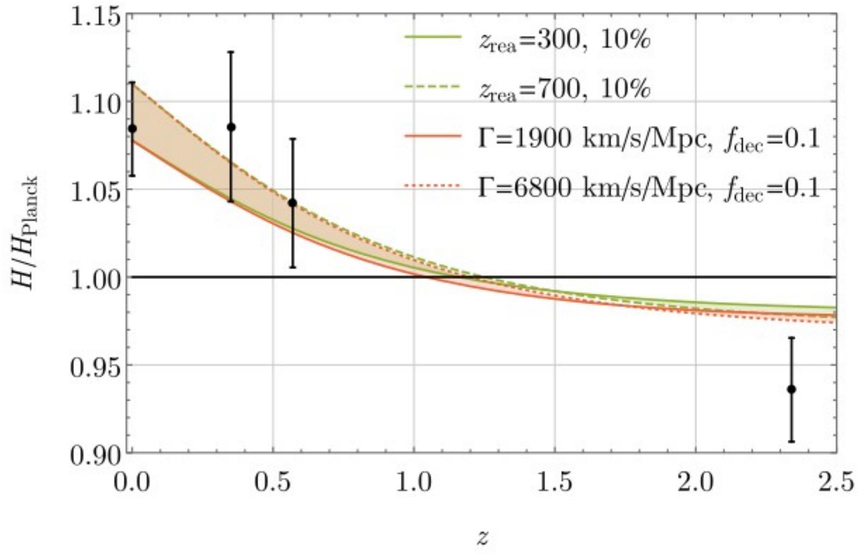
z_{rea}, amplitude

[**TB**, Gustafsson, Kamada, Sandner, Wiesner PRD 17]

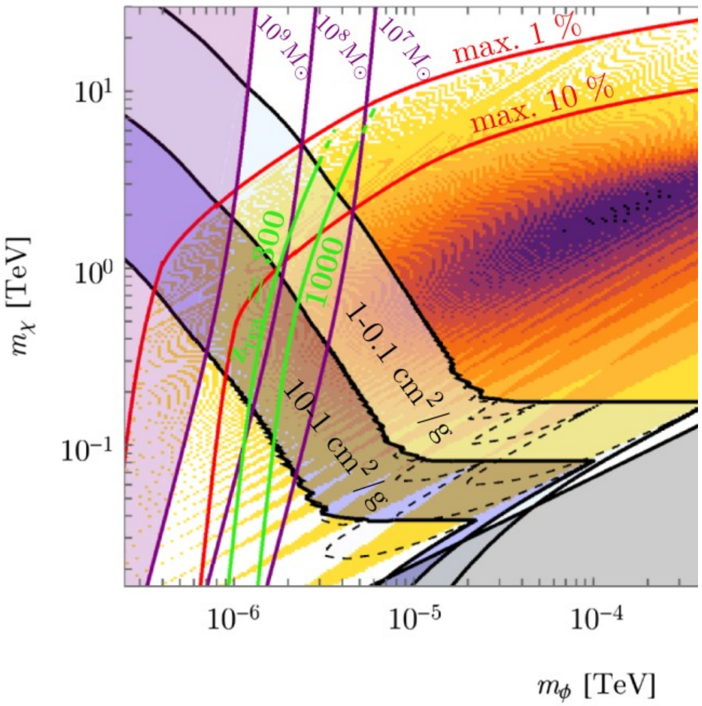
Alleviating cosmological tensions

[**TB**, Gustafsson, Kamada, Sandner, Wiesner PRD 17]

- **Reannihilation**
  - **Post-recombination solution to H0**
  - **5-10% change in DM abundance between z~1000-300**



- **Simultaneously solves:**
  - **H0**
  - **Missing satellite**
  - **diversity problem**



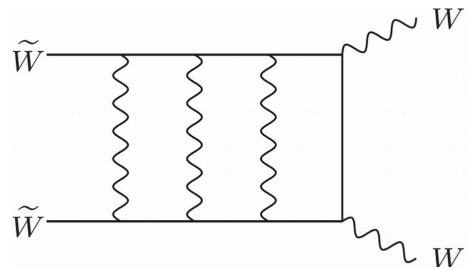
- **Embedding into SM challenging**

Heavy WIMPs

Prime example: Wino dark matter

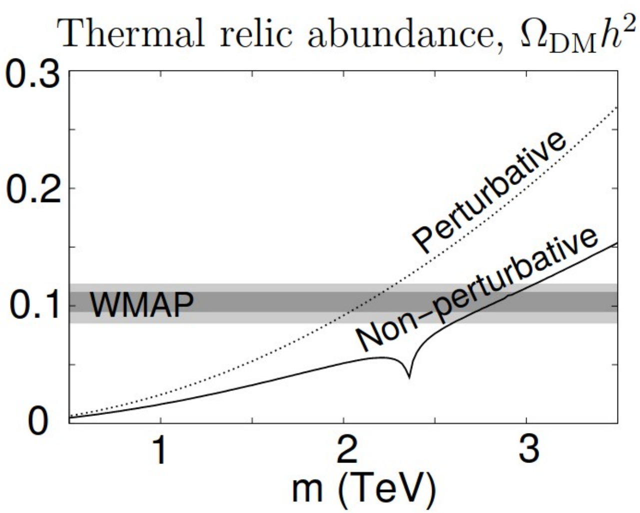
Wino:
- Majorana Fermion
- Triplet under SU(2)
- Hypercharge Y=0
- Most minimal DM!

$$\begin{pmatrix} \widetilde{W}^+ \\ \widetilde{W}^0 \\ \widetilde{W}^- \end{pmatrix}$$

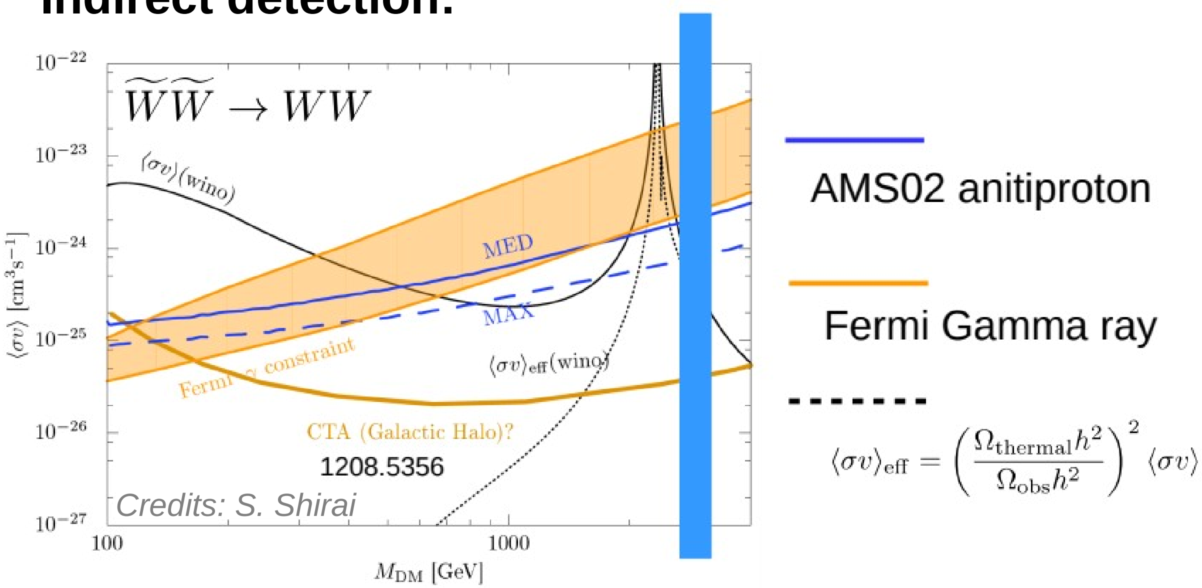


Seminal works by Hisano *et al.* '03, '05, '06

Predicted mass:

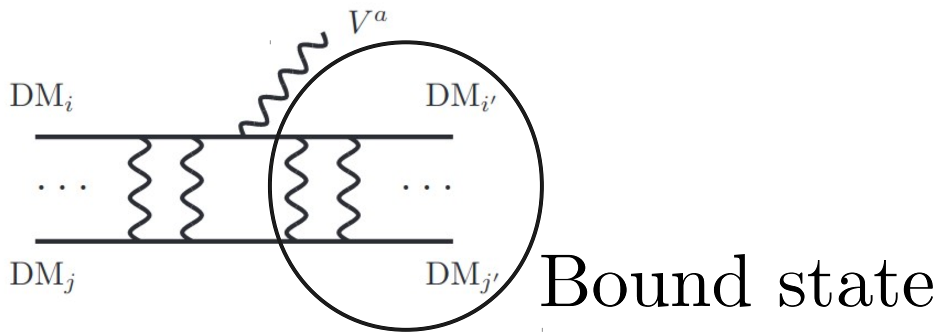


Indirect detection:

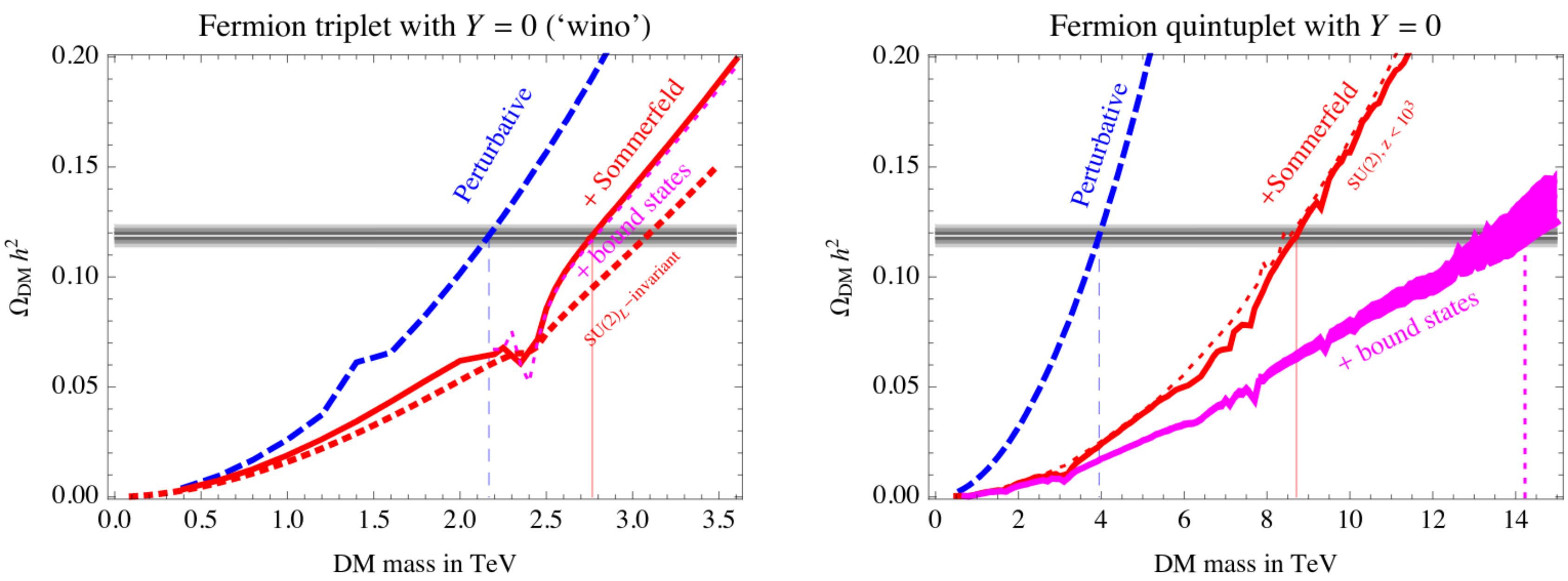


~10 % variation in the DM mass results in ~100 % change of the flux.

Bound-state implications in minimal DM

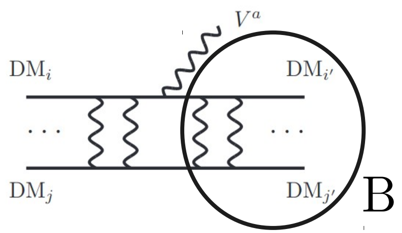


Meta-stable bound states contribute as an additional decay channel.



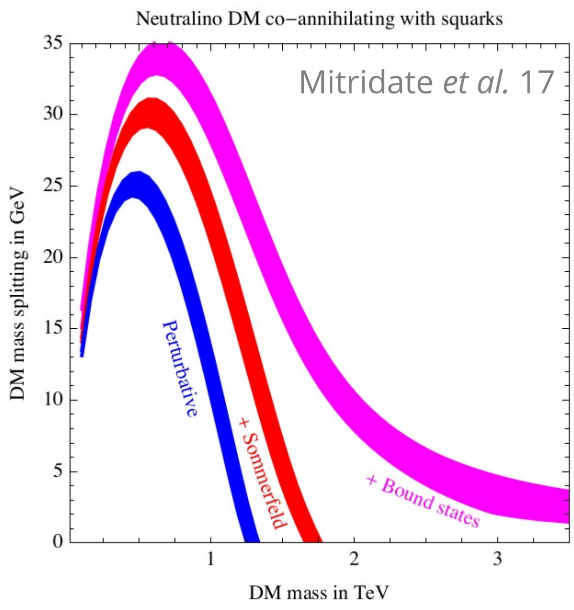
[Mitridate *et al.* 17]

Bound-state implications colored co-annihilation



- **<u>Co-annihilating partner charged under SU(3)</u>**
  - Squark (scalar triplet)
  - Gluino (fermion octet)

[Ellis *et al.* 15,
Liew&Luo 16,
Mitridate *et al.* 17]

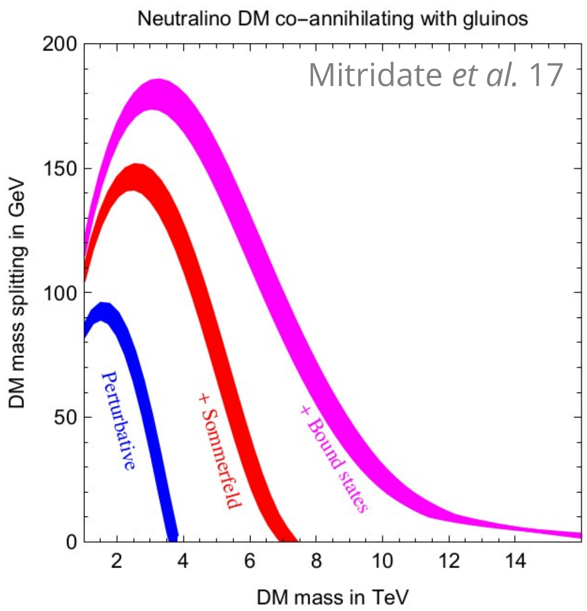


- **+ Higgs**
  - Additional attractive contribution
  - Order one corrections

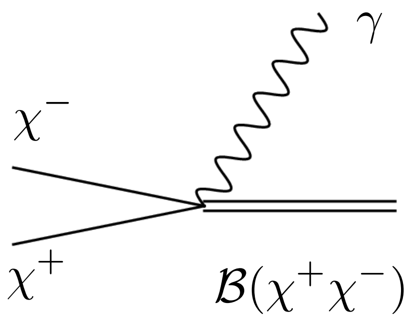
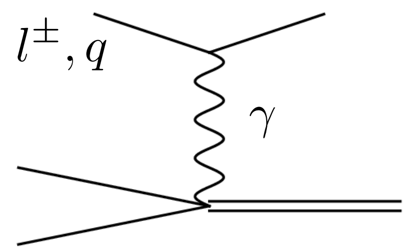
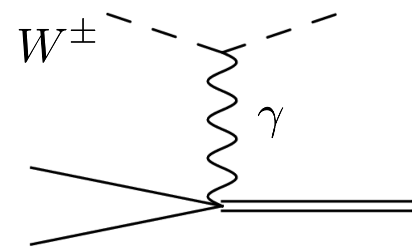
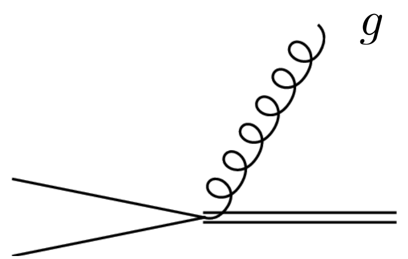
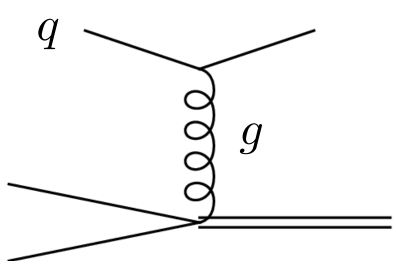
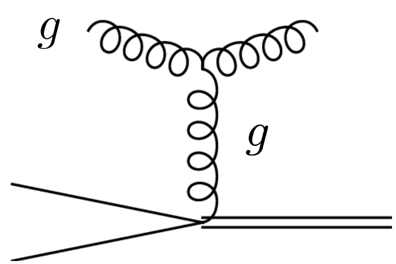
[Harz&Petraki 18,19]

- **+ Non-perturbative effects**
  - Relevant for mass splittings below QCD confining scale
  - Up to 1 PeV DM possible

[Gross *et al.* 18,
Fukuda&Luo&Shirai 18]



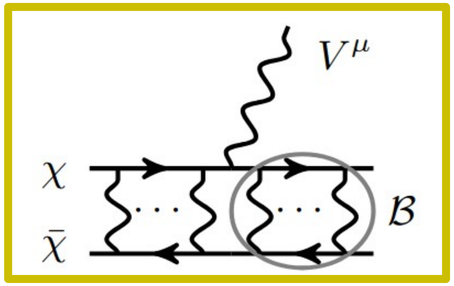
Bound-state formation at higher order

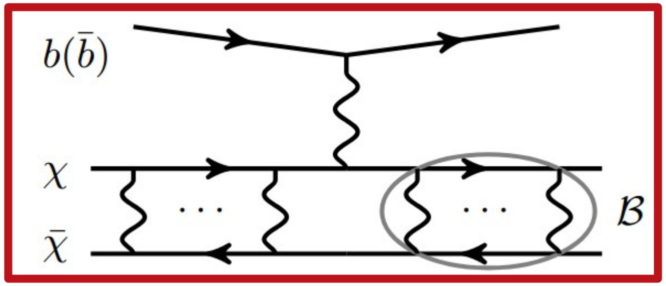
	BSF via on-shell mediator emission	**BSF via bath-particle scattering**	
Chargino co-annihilation			
Colored co-annihilation			

$(H, W^\pm, Z^0$ analog$)$

(...) no kinematical block!

BSF via bath-particle scattering





Dark (broken) U(1) toymodel parametrically resembles:

Wino-like

Colored-coannihilation-like

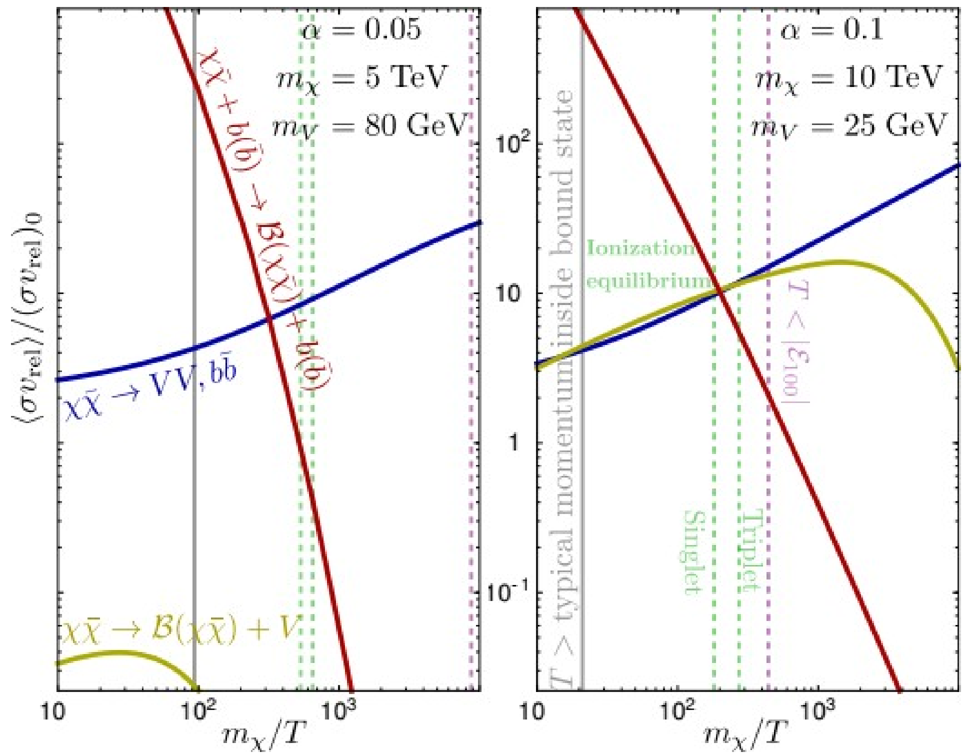
- **Proof of concept:**

  bound-state formation via bath-particle scattering ***can entirely dominate***

- **Implication**

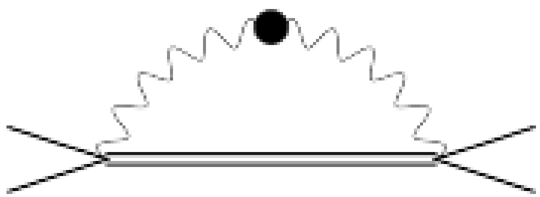
  - Phase of maximum depletion maintained longer
  - Specific examples show up to 20% relic abundance corrections
    → DM could be heavier than expected

no kimenatical block

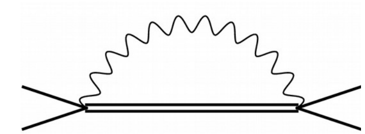


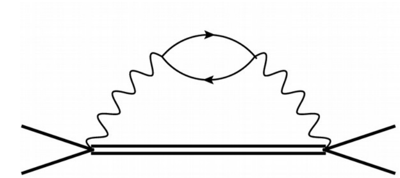
[TB, Mukaida, Petraki PRL 19]

Massless mediator

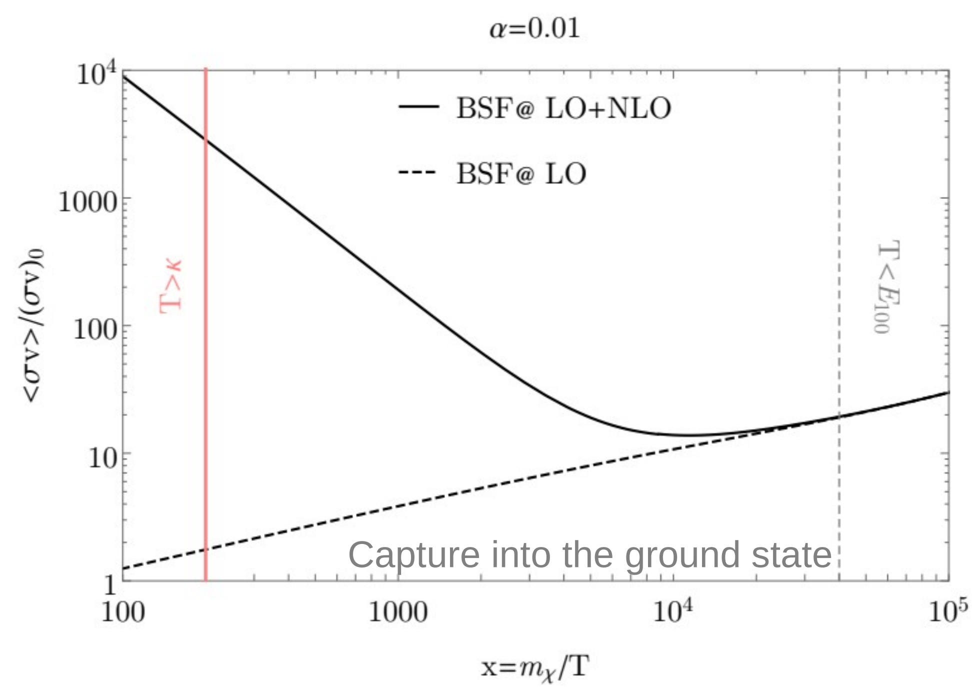


$$\sigma^{\rm BSF}_{nlm} v_{\rm rel} = \int \frac{{\rm d}^3 p}{(2\pi)^3} D^{-+}_{\mu\nu}(\Delta E, \mathbf{p}) \mathcal{T}^{\mu}_{\mathbf{k},nlm}(\Delta E, \mathbf{p}) \mathcal{T}^{\nu\star}_{\mathbf{k},nlm}(\Delta E, \mathbf{p}).$$

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

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

- BSF cross section in terms of thermal correlators
- **Complete** NLO QED computation.
- Proof for cancellation of collinear divergences.
- Finite T NLO starts to dominate over LO for $\mathrm{T} \gtrsim |E_B|$



[TB, Blobel, Harz, Mukaida JHEP 20 & in progress]

Annihilation/decay at finite temperature

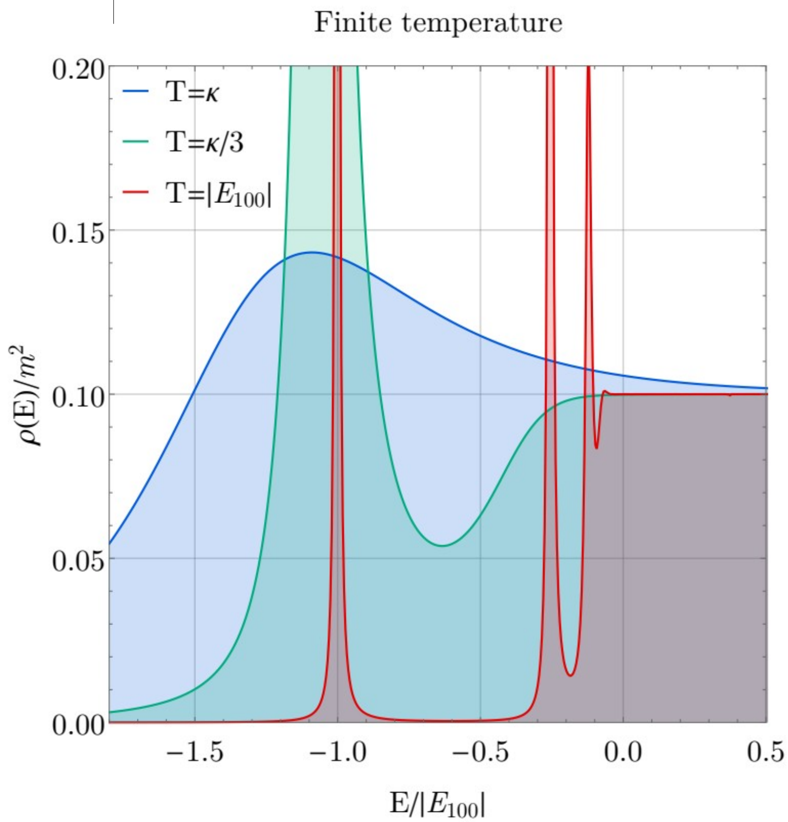
[TB, Covi, Mukaida PRD 18]

- **Consistent with Boltzmann equations in zero temperature limit**
- **Finite temperature corrections modify two-particle spectrum**
- **Formalism advantages**
  - ✔ Sommerfeld-enhanced annihilation
  - ✔ **ALL** bound states included
  - ✔ Finite temperature corrections
  - ✔ Simple number density equation
- **Limitation**
  - Hard-Thermal-Loop resummation (ok for |E|<T)
  - Ionization equilibrium

$$\dot{n} + 3Hn = -2(\sigma v)_0 G_4^{++--}\big|_{\mathrm{eq}} \left[e^{\beta 2\mu} - 1\right],$$

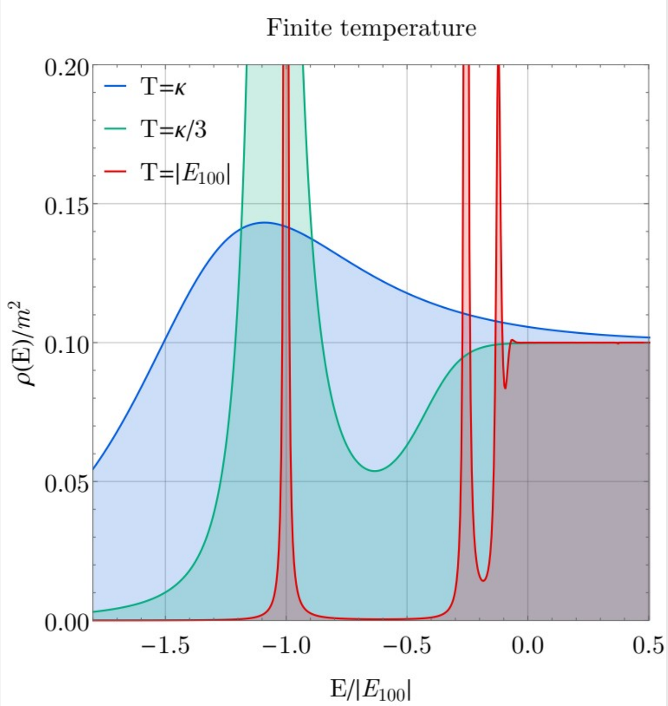
$$G_4^{++--}\big|_{\mathrm{eq}} \propto \int_{-\infty}^{\infty} \frac{\mathrm{d}E}{(2\pi)} e^{-\beta E} \rho(E).$$

$$V(r) = -\alpha m_D - \frac{\alpha}{r} e^{-m_D r} - i\alpha T \phi(m_D r)$$

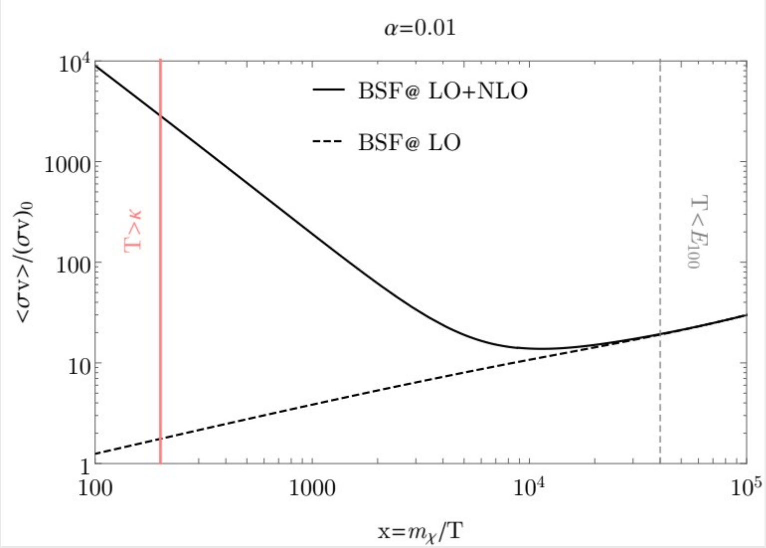


More complete freeze-out picture

High T



Low T

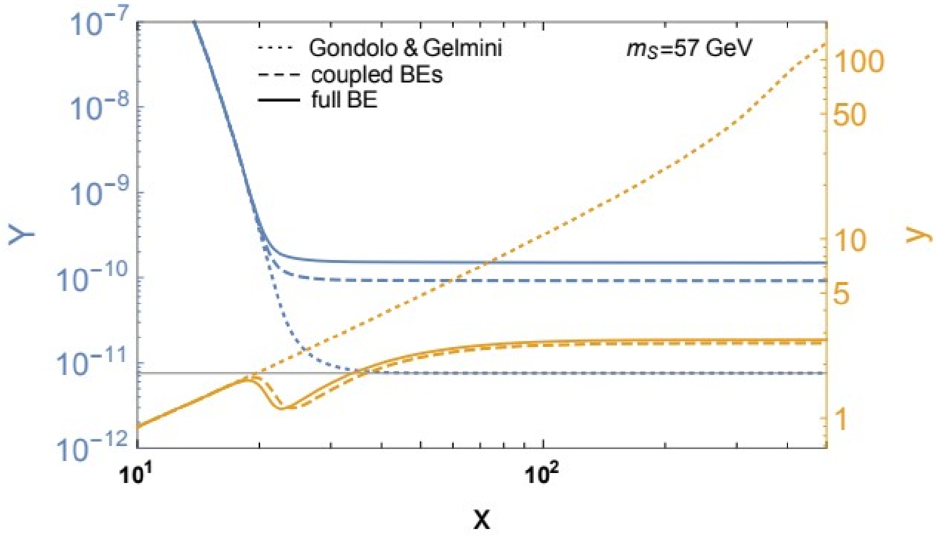


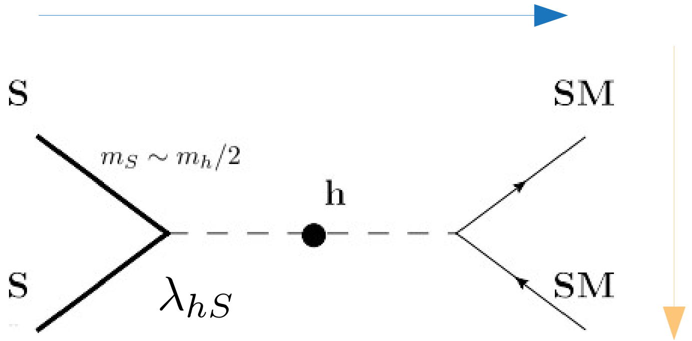
Summary and conclusion

- Thermally produced DM remain attractive candidates.
- Thermal decoupling = chemical + kinetic decoupling !
- Kinetic equilibrium not maintained in general during freeze-out.

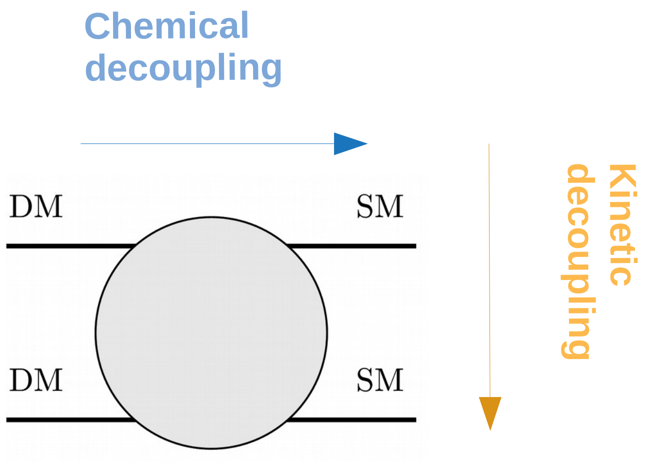
  (But remains rather an exception)
- Cosmological tensions → new physics needed ?
- Bound-state contribution can play crucial role for mass prediction.
- Theoretical basis set for heavy WIMP finite temperature corrections.

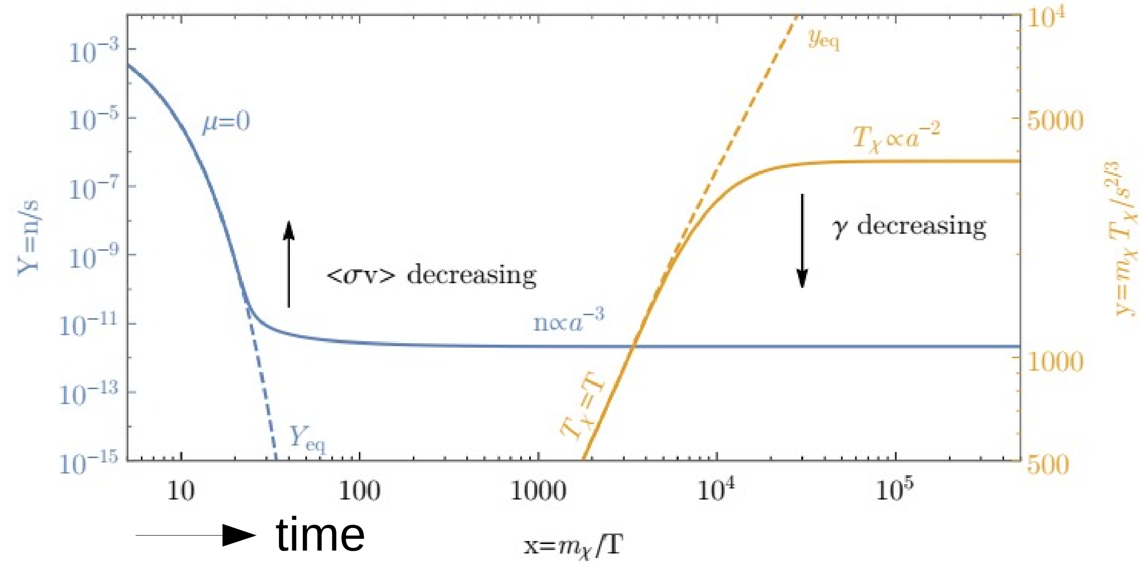
Early kinetic decoupling





Thermal decoupling of annihilating DM





$$\dot{n} + 3Hn = -\langle \sigma v \rangle \left[n^2 - n_{\rm eq}^2 \right]$$

$$\Omega_\chi = \frac{m_\chi n}{\rho_{\rm cr}} \Big|_{T_{\rm CMB}}$$

- Relic abundance often most important observable in global (likelihood) analysis
- Public codes guarantee high accuracy → DarkSUSY, micrOMEGAs, ...
- ***Main assumption*:** **kinetic equilibrium maintained**

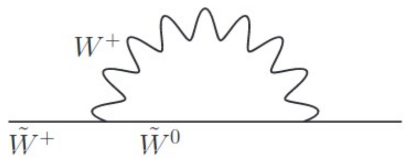
$$\dot{T}_\chi + 2HT_\chi = -\gamma(T)\left[T_\chi - T\right]$$

$$\mathrm{M}_{\rm cut} = \mathrm{Max}[M_{\rm fs}(T_{\rm kd}), M_{\rm ao}(T_{\rm kd})]$$

- Generic WIMP: $\mathrm{M}_{\rm cut} = 10^{-11} - 10^{-3} M_\odot$
- Late kinetic decoupling: $\mathrm{M}_{\rm cut} \lesssim 10^8 M_\odot$ see DarkSUSY & ETHOS
- ***Main assumption*:** **conserved co-moving number density**

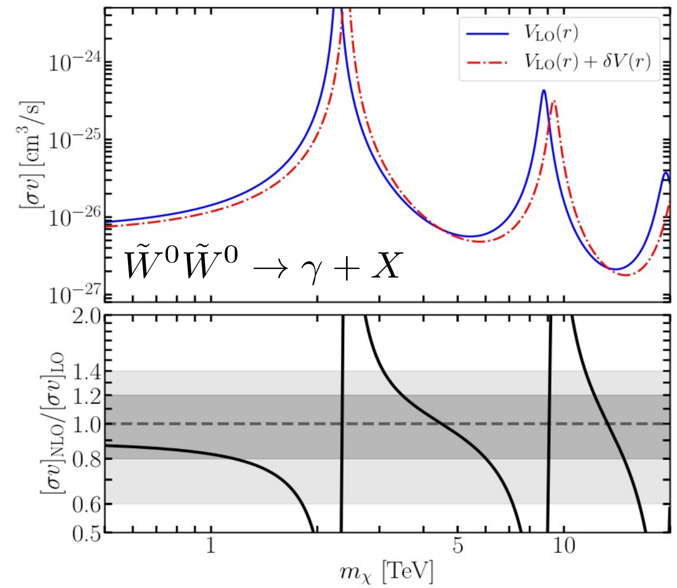
Precision Wino

- **Mass splitting** [Ibe,Matsumoto,Sato 12]
  - ✓ $m_{\tilde{W}^\pm} - m_{\tilde{W}^0} \simeq 165\ \mathrm{MeV}$

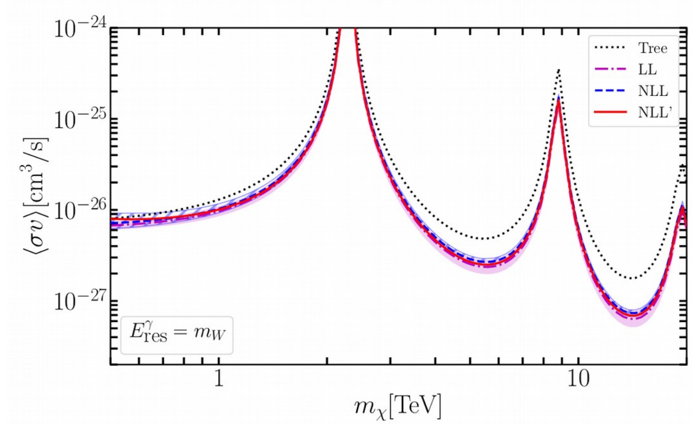


+...

- **Potential at NLO (zero T)** [Beneke *et al.* 19, 20]
  - Real part corrections shift resonance
  - Mildly affects predicted mass
  - 40 % *enhancement* of predicted flux (~ 3 TeV Wino)



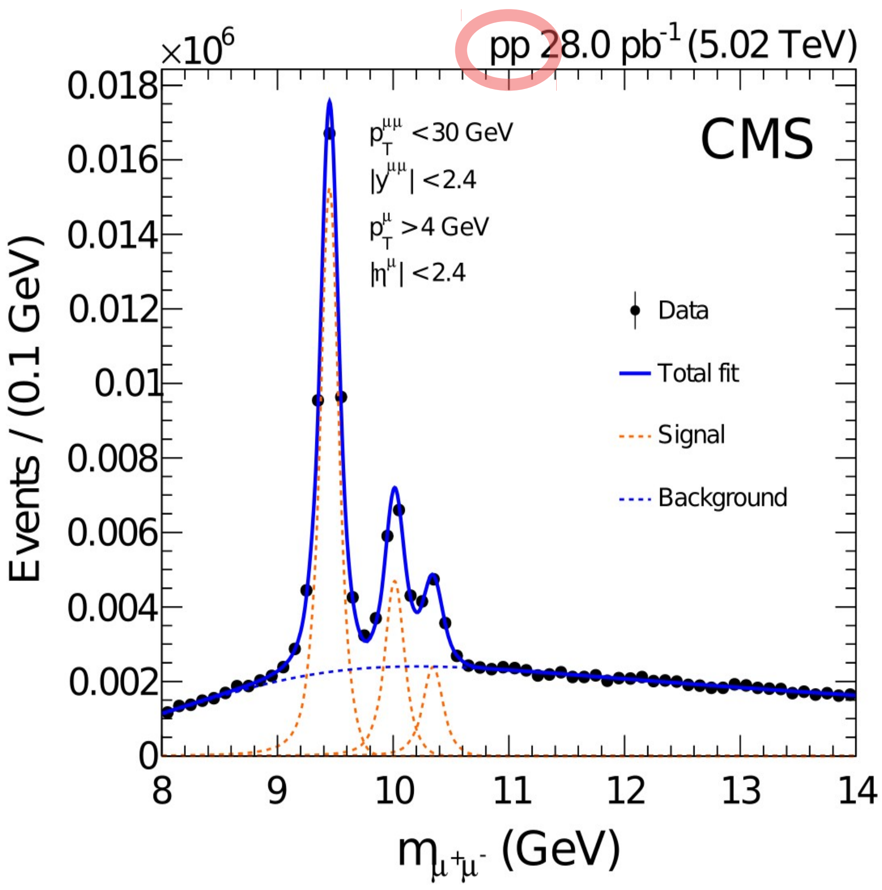
- **Final state corrections** [Beneke *et al.* 20]
  - Large electroweak (Sudakov) Logs
  - 30-40% *suppression* of predicted flux

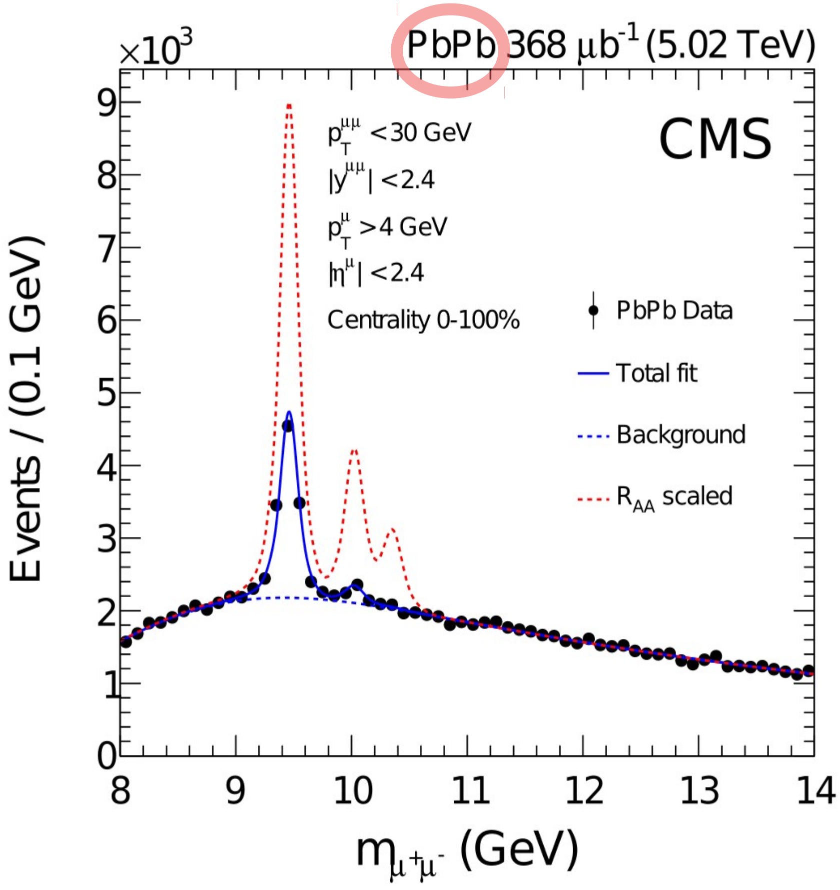


- **Other potential uncertainties:**
  - **Astrophysical (e.g. J factor)**
  - **Bound states (?)**
  - **Thermal corrections (?)**

Data

Sequential melting of b-bbar bound states inside QGP plasma observed.





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

Non-equilibrium QFT approach

[TB, Covi, Mukaida PRD 18]

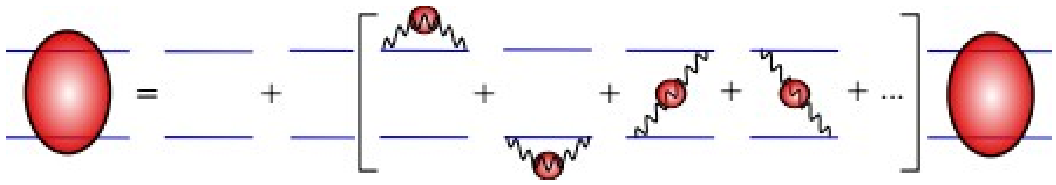
In-medium potential + dynamics from Keldysh-Schwinger-Formalism

Scheme:

I Non-relativistic effective action

II Number density equation from EoM of 2-point correlation function

III Resummation of 4-point correlator



(potential shows thermal width, consistent with quarkonia literature, e.g. Laine *et al.* 2007)

Theory

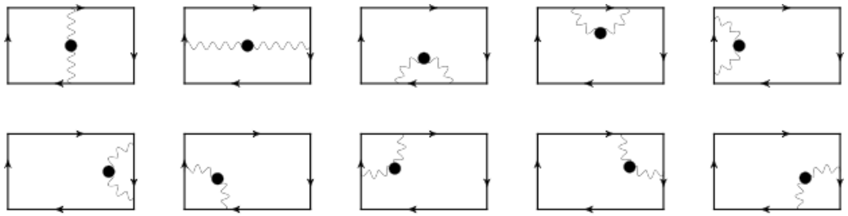
Heavy Quarkonia in QGP

- **Matsui & Satz 1986**
  - J/Psi suppression in QGP due to screening effect
  - In-medium potential from **2** Polyakov loop (Wilson line)

$$V(\mathbf{r}) = -\frac{\alpha}{r}e^{-m_D r},\ m_D \propto gT$$

Debye screening

- **Laine *et al.* 2007**
  - **4** Polyakov loop method



$$V(\mathbf{r}) = -\alpha m_D - \frac{\alpha}{r}e^{-m_D r} - i\alpha T\phi(m_D r)$$

Salpeter correction

Thermal width

Heavy DM in primordial plasma

- **Cirelli *et al.* 2007 (Minimal DM)**
  - Debye screened Sommerfeld enhancement
  - (Wino mass lowered)

- **Bödeker & Laine 2012**
  - First dynamical formulation based on “linear response theory”

[see follow-ups by Biondini & Kim & Laine]