



News from the dark

## Subhalos: the connection with simplified particle dark matter models

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1. Introduction : connection particle physics - clumps distribution
2. How to make the connection
3. The example of a single pseudo-scalar mediator
4. Conclusion

# 1. Introduction : connection particle physics - clumps distribution

## 1. General motivations

### Our global interest

- ▶ Sub-galactic structuring of Dark Matter (DM) particles
- ▶ DM makes clumps/mini halos inside the Milky Way
- ▶ Important to explain differences between simulations and observations
- ▶ Important to make precise predictions for detection experiment

### Our current tools

- ▶ Generic model for the clump distribution in Galaxies ([Stref+17](#))
- ▶ But need to set a **minimal mass for clumps** (free parameter of the model)

### Particle physics side

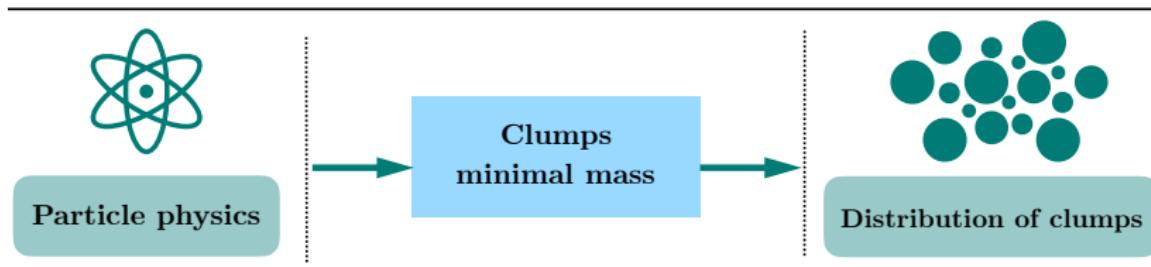
- ▶ Interest in generic models (e.g. low mass scalar mediator ([Winkler19](#)))

# 1. Introduction : connection particle physics - clumps distribution

## 1. General motivations

Our main goal in this study

Phenomenology of generic particle physics models for  
the distribution of clumps



# 1. Introduction : connection particle physics - clumps distribution

## 2. A generic dark matter model



Credits Sandbox Studio - Symmetry

### Our approach

- Thermally produced massive particles: WIMPs
- Generic model : bottom-up study

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### Our approach

- Thermally produced massive particles: **WIMPs**
- Generic model : bottom-up study

## Generic Lagrangian

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(1 + \zeta)\mathcal{L}_{\text{int}} + \tilde{\mathcal{L}}_{\text{int}} + \hat{\mathcal{L}}_{\text{int}} + \mathcal{L}_{\text{kin.}} + \mathcal{L}_{\text{mass}} + \mathcal{L}_{\text{SM}} \\ -\mathcal{L}_{\text{int}} &= \sum_{ijk} \left[ \lambda_{ijk}^s \bar{\psi}_\chi^i \psi_\chi^j \phi_s^k + i \lambda_{ijk}^p \bar{\psi}_\chi^i \gamma^5 \psi_\chi^j \phi_p^k + \bar{\psi}_\chi^i \gamma^\mu (a_{ijk} + b_{ijk} \gamma^5) \psi_\chi^j X_\mu^k \right] \\ -\tilde{\mathcal{L}}_{\text{int}} &= \sum_{ij} \left[ \tilde{\lambda}_{ij}^s \bar{\psi}_f^i \psi_f^j \phi_s^j + i \tilde{\lambda}_{ij}^p \bar{\psi}_f^i \gamma^5 \psi_f^j \phi_p^j + \bar{\psi}_f^i \gamma^\mu (\tilde{a}_{ij} + \tilde{b}_{ij} \gamma^5) \psi_f^j X_\mu^j \right] \\ -\hat{\mathcal{L}}_{\text{int}} &= v \sum_{ijk} \left[ \frac{1}{\mathcal{S}_{ijk}} c_{ijk} \phi_s^i \phi_s^j \phi_s^k + \frac{1}{\mathcal{S}_{jk}} d_{ijk} \phi_s^i \phi_p^j \phi_p^k \right] + v \sum_{ij} g_{ij} \phi_s^i X_\mu^j X^{j,\mu}\end{aligned}$$

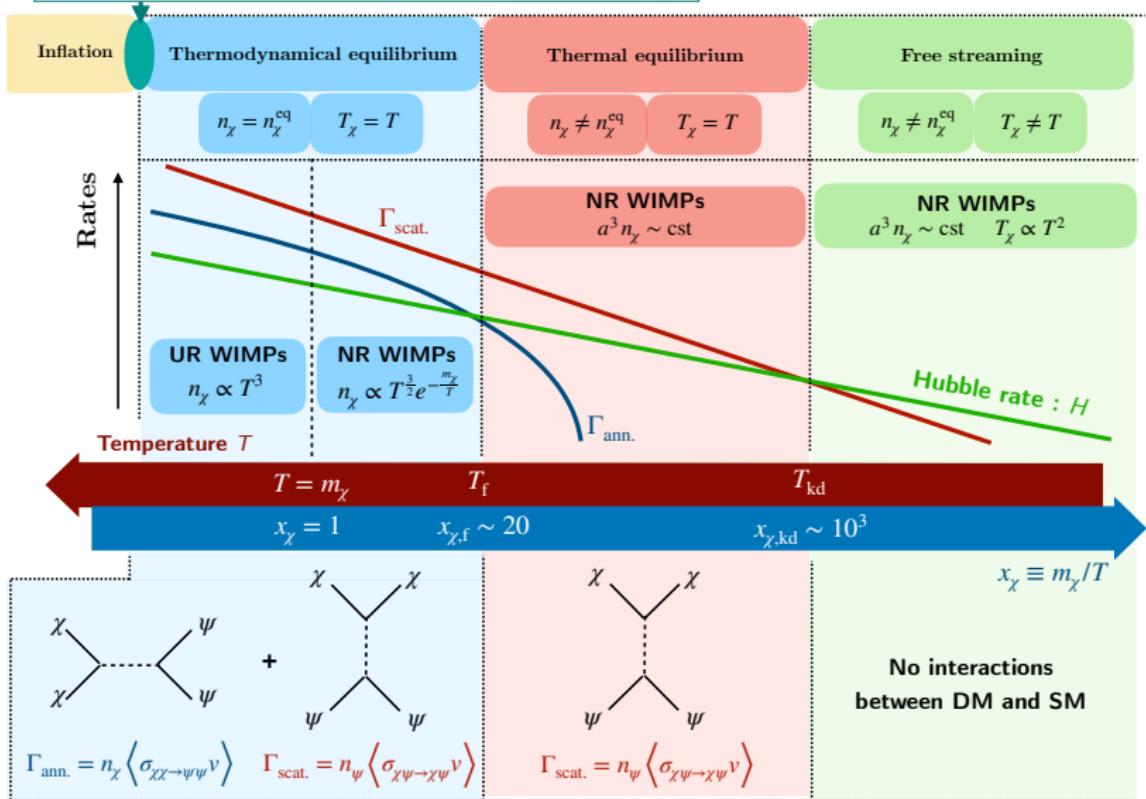
In this presentation we will focus on the case :

- ▶ A single species of majorana dark matter  $\zeta = 0$
- ▶ Free parameters:  $m_\chi, m_s, m_p, m_X, \lambda^s, \tilde{\lambda}^s, \lambda^p, \tilde{\lambda}^p, a, b, \dots$

# 1. Introduction : connection particle physics - clumps distribution

## 3. WIMP thermal history in the early Universe

End of the inflation era : thermal production of WIMPs and SM particles



# 1. Introduction : connection particle physics - clumps distribution

## 3. WIMP thermal history in the early Universe



### Radiation dominated era

### MD era

Thermodynamical equilibrium

Thermal equilibrium

Free streaming

Acoustic damping  
(collisional damping)

$$k > k_d \sim \frac{\sqrt{3}}{c} H(t_{kd})$$

Free streaming damping  
(collision-less damping)

$$k > k_{fs} = \frac{2\pi}{\lambda_{fs}} \sim \frac{2\pi}{a(t_{eq})} \left( \int_{t_{kd}}^{t_{eq}} \frac{v(t)}{a(t)} dt \right)^{-1}$$

Over-density field

$$\frac{\delta(k, t)}{\delta(k, t_i)} = \left( 1 - \frac{2}{3} \left( \frac{k}{k_{fs}} \right)^2 \right) \exp \left( - \left( \frac{k}{k_{fs}} \right)^2 - \left( \frac{k}{k_d} \right)^2 \right)$$



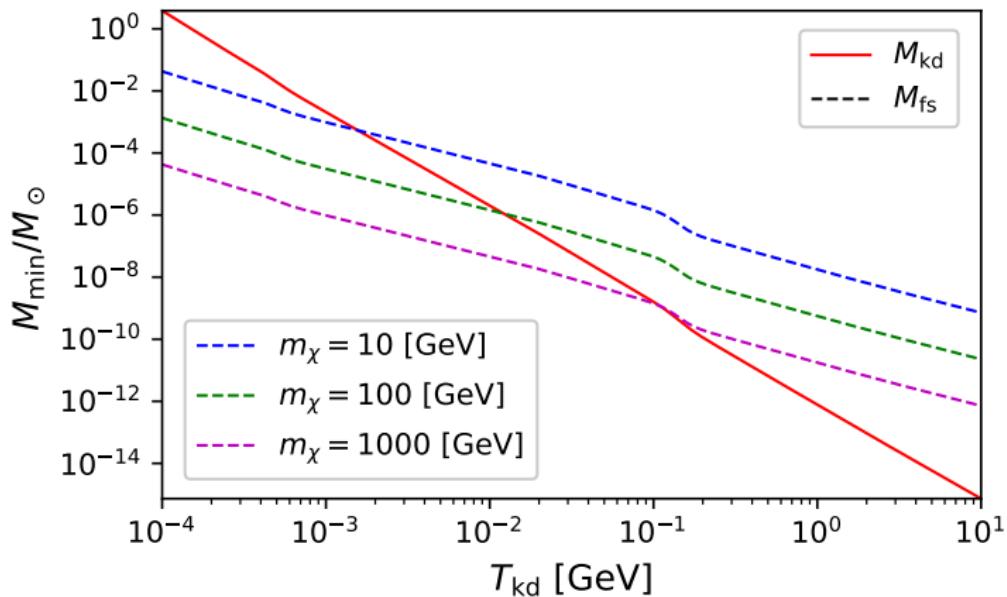
$$M_{halo} > \max \left[ \frac{4\pi}{3} \bar{\rho}_m(t_{kd}) \left( \frac{2\pi}{k_d} \right)^3, \frac{4\pi}{3} \bar{\rho}_m(t_{eq}) \left( \frac{2\pi}{k_{fs}} \right)^3 \right]$$

Perturbations growth

(Green+05, Loeb+05, Gondolo+12, ...)

# 1. Introduction : connection particle physics - clumps distribution

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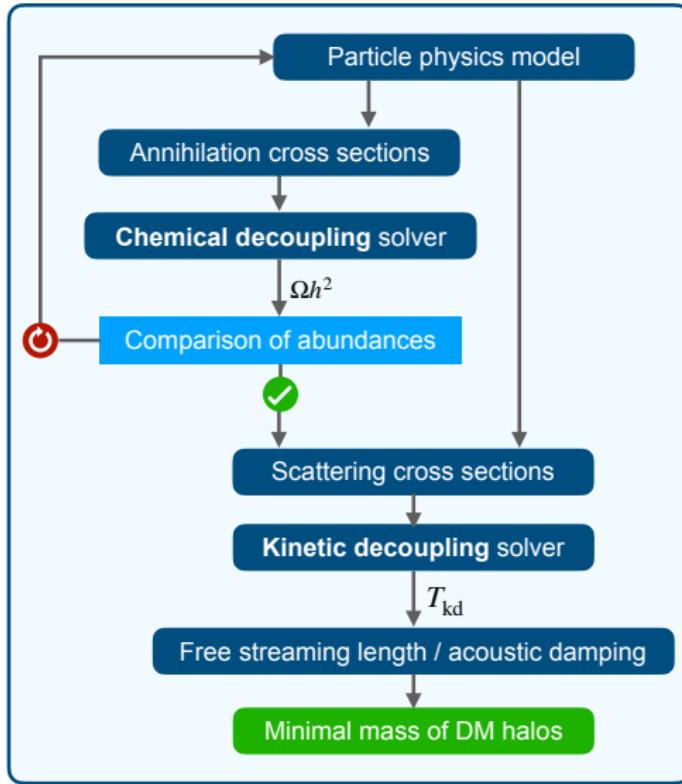


Particle physics model  $\rightarrow T_{\text{kd}} \rightarrow M_{\text{min}}$

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## 2. How to make the connection

### 1. A consistent resolution



## 2. How to make the connection

### 2. Kinetic and microscopic description

#### Liouville theorem

$$\omega = - \det(g_{\mu\nu}) dx^0 \wedge dx^1 \wedge dx^2 \wedge dx^3 \wedge dp^0 \wedge dp^1 \wedge dp^2 \wedge dp^3$$

$\mathcal{L}_X(\omega) = 0$ , with  $X$  generator of the geodesics

**Distribution function in phase space**  $f_\chi$  :  $N_\chi = g_\chi f_\chi(x^\mu, p^\mu) \omega$

$\mathcal{L}_X(f_\chi) = 0$  for collisionless particles

#### Boltzmann equation

$$\mathcal{L}_X(f_\chi) = \hat{C}[f_\chi] \quad \text{with } \hat{C} \text{ collision operator}$$

- Zeroth moment gives evolution equation for  $n_\chi$

$$\int \mathcal{L}_X(f_\chi) \frac{1}{E_\chi(\mathbf{p})} \frac{d^3\mathbf{p}}{(2\pi)^3} = \int \hat{C}[f_\chi] \frac{1}{E_\chi(\mathbf{p})} \frac{d^3\mathbf{p}}{(2\pi)^3}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle \sigma_{\text{ann}} v \rangle ((n_\chi^{\text{eq}})^2 - n_\chi^2), \quad \Gamma_{\text{ann}} = n_\chi \langle \sigma_{\text{ann}} v \rangle$$

## 2. How to make the connection

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#### Boltzmann equation

$$\mathcal{L}_X(f_X) = \hat{C}[f_X] \quad \text{with } \hat{C} \text{ collision operator}$$

► Second moment gives evolution equation for  $T_\chi = \langle p^2 \rangle / (3m_\chi)$

$$\int \mathcal{L}_X(f_\chi) \frac{p^2}{E_\chi(\mathbf{p})} \frac{d^3\mathbf{p}}{(2\pi)^3} = \int \hat{C}[f_\chi] \frac{p^2}{E_\chi(\mathbf{p})} \frac{d^3\mathbf{p}}{(2\pi)^3}$$

$$\frac{dT_\chi}{dt} + 2HT_\chi = \gamma(T)(T - T_\chi), \quad \Gamma_{\text{scatt.}} = \gamma(T)$$

## 2. How to make the connection

### 3. Main equations and code implementation

Equations numerically solved

Introduce two new quantities : (with  $s$  entropy density )

- Comoving number density of WIMPs :  $Y_\chi = n_\chi/s$
- Dimensionless "temperature" :  $y_\chi = m_\chi T_\chi s^{-2/3}$

$$\frac{dY_\chi}{dx_\chi} = \left(\frac{\pi}{45}\right)^{1/2} \frac{m_\chi m_{\text{Pl}}}{x_\chi^2} g_\star^{1/2} \langle \sigma_{\text{ann}} v \rangle \left( (Y_\chi^{\text{eq}})^2 - Y_\chi^2 \right)$$

$$\Omega_{\text{DM}}^{0,\text{th}} h^2 = \frac{m_\chi n_\chi^0}{\rho_{\text{cri}}} \propto m_\chi \lim_{x_\chi \rightarrow \infty} Y_\chi(x_\chi)$$

$$\frac{d \ln y_\chi}{d \ln x_\chi} = - \left( 1 + \frac{d \ln (h_{\text{eff}}(T))}{3 d \ln (T)} \right) \frac{\gamma(T)}{H} \left( 1 - \frac{y_\chi^{\text{eq}}}{y_\chi} \right)$$

$$T_{\text{kd}} s^{-3/2} (T_{\text{kd}}) = \frac{1}{m_\chi} \lim_{x_\chi \rightarrow \infty} y_\chi(x_\chi)$$

- Chemical decoupling : ([Lee+77](#), [Bernstein+85](#), [Gondolo+91](#), [Edsjo+97](#))
- Kinetic decoupling : ([Bertschinger+06](#), [Bringmann+09](#), [Binder+16-17](#))

## 2. How to make the connection

### 3. Main equations and code implementation



#### Our numerical tools

- ▶ Can evaluate any annihilation tree level cross-section analytically
- ▶ Can evaluate any scattering tree level cross-section analytically
- ▶ Evaluate the different propagators width consistently with the model
- ▶ Can solve the two main equations with different numerical schemes
- ▶ Can deal with an arbitrary amount of new mediators
- ▶ Can consistently compute the sum over the relativistic degrees of freedom
- ▶ Can/Will evaluate certain annihilation cross section into photons through triangle diagrams (even at low DM mass where perturbative QCD may break down - [Domingo+17](#), [Winkler+19](#))

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### 3. The example of a single pseudo-scalar mediator

#### 1. The correct universal coupling



Consider now **universal couplings  $\lambda$  and a single pseudo-scalar mediator**

- One DM particle of mass  $m_\chi$  + one pseudo-scalar mediator of mass  $m_p$

### 3. The example of a single pseudo-scalar mediator

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$$-\mathcal{L}_{\text{int}} = \frac{1}{2} \lambda \bar{\psi}_\chi \gamma^5 \psi_\chi \phi_p + \lambda \sum_i \bar{\psi}_f^i \gamma^5 \psi_f^i \phi_p$$

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Annihilation cross section : small temperatures expansion

$$\langle \sigma_{\text{ann}} v_{\text{Møl}} \rangle = \sum_{n=0}^{\infty} a_n \left( \frac{T}{m_\chi} \right)^n = \sum_{n=0}^{\infty} a_n x_\chi^n$$

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In our example here we have, (with i SM fermions of mass  $m_i < m_\chi$ )

$$a_0 = \frac{\lambda^4}{2\pi} \sum_i \frac{m_\chi (m_\chi^2 - m_i^2)^{1/2}}{(m_p^2 - 4m_\chi^2)^2 + m_p^2 \Gamma_p^2}$$

In the limit  $m_i \ll m_\chi$  for all fermions  $i$  such that  $m_i < m_\chi$

$$a_0 \sim N \frac{\lambda^4}{2\pi} \frac{m_\chi^2}{(m_p^2 - 4m_\chi^2)^2 + m_p^2 \Gamma_p^2}$$

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$$\langle \sigma_{\text{ann}} v_{\text{M}\emptyset\text{l}} \rangle = \sum_{n=0}^{\infty} a_n \left( \frac{T}{m_\chi} \right)^n = \sum_{n=0}^{\infty} a_n x_\chi^n$$

Since the abundance satisfies

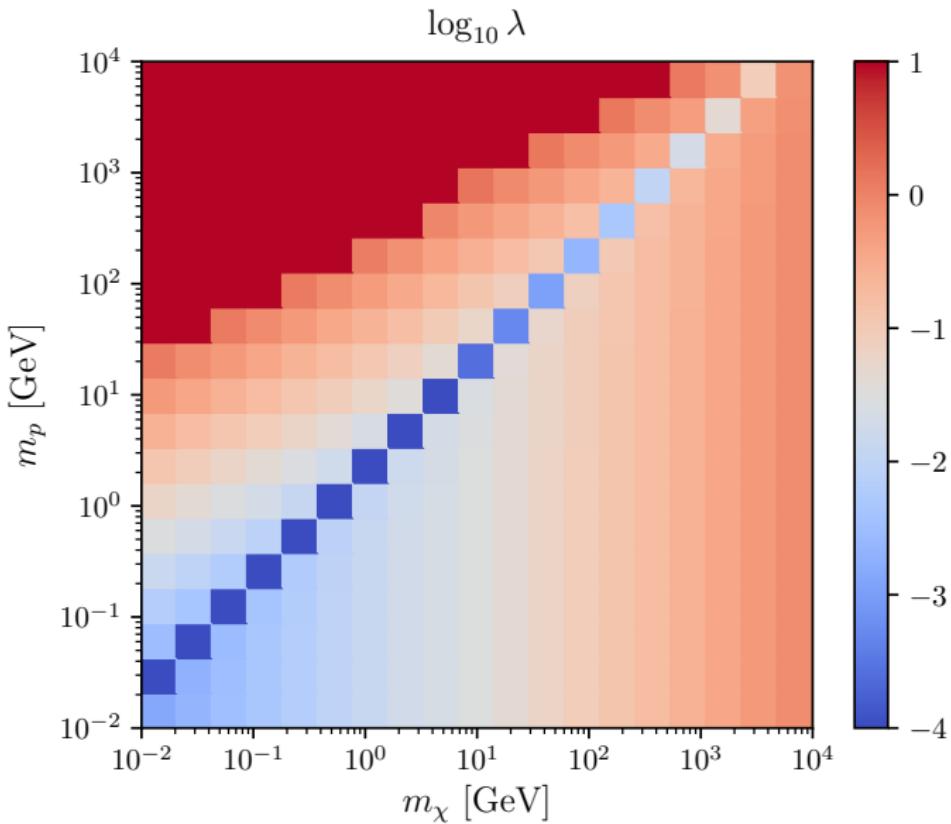
$$\Omega_\chi^0 h^2 \sim \frac{1}{\langle \sigma_{\text{ann}} v_{\text{M}\emptyset\text{l}} \rangle}$$

if we fix its value to be  $\Omega_\chi^0 h^2 = 0.1188$  ([Ade+15](#)) we expect to have

$$\lambda \propto \frac{1}{a_0^{1/4}} \propto \left( \frac{(m_p^2 - 4m_\chi^2)^2 + m_p^2}{m_\chi^2} \right)^{1/4} \propto \begin{cases} m_p m_\chi^{1/2} & \text{if } m_\chi \ll m_p \\ m_\chi^{-1/2} & \text{if } m_\chi \gg m_p \end{cases}$$

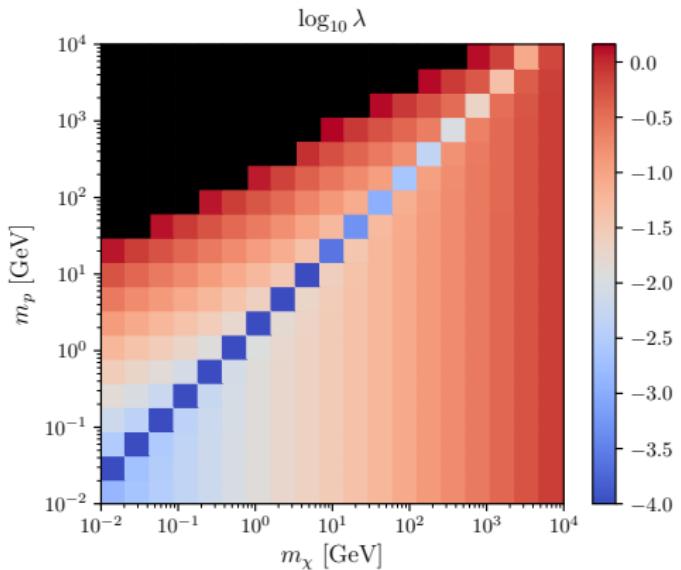
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#### 1. The correct universal coupling



### 3. The example of a single pseudo-scalar mediator

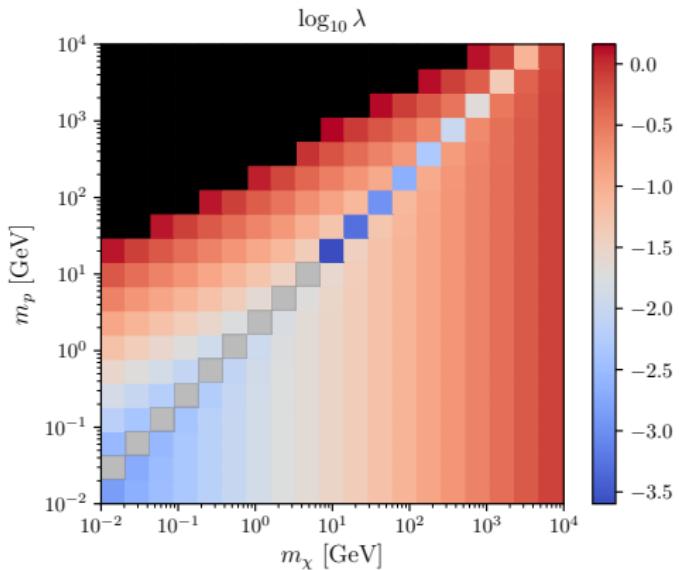
#### 1. The correct universal coupling



Remove the points when  
→  $\lambda > 10$

### 3. The example of a single pseudo-scalar mediator

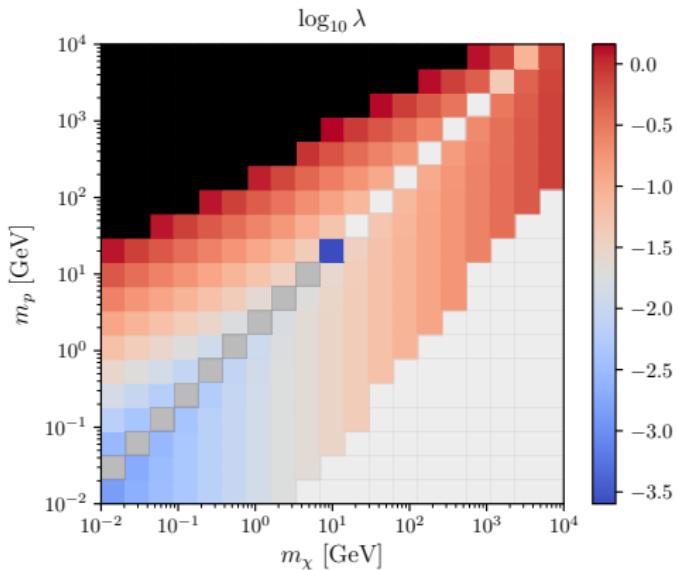
#### 1. The correct universal coupling



Remove the points when  
•  $\lambda > 10$   
• numerical integration fails

### 3. The example of a single pseudo-scalar mediator

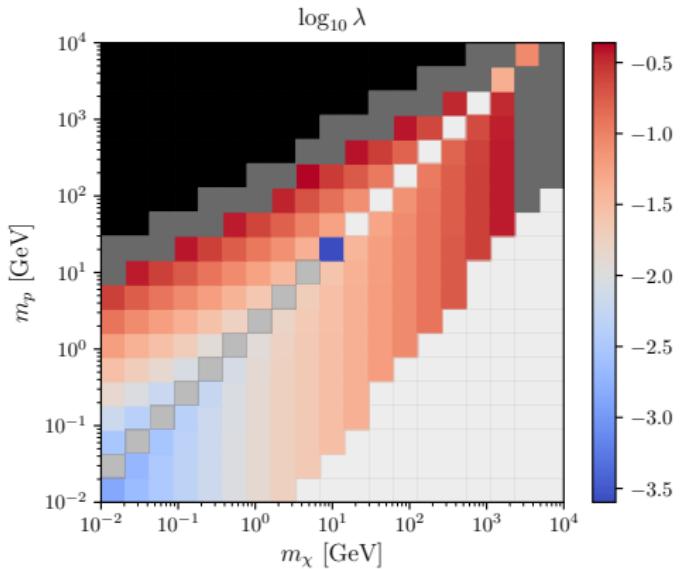
#### 1. The correct universal coupling



- Remove the points when
  - $\lambda > 10$
  - numerical integration fails
  - $x_{\text{kd}} < 2x_f$  is returned
  - kd evaluation fails

### 3. The example of a single pseudo-scalar mediator

#### 1. The correct universal coupling

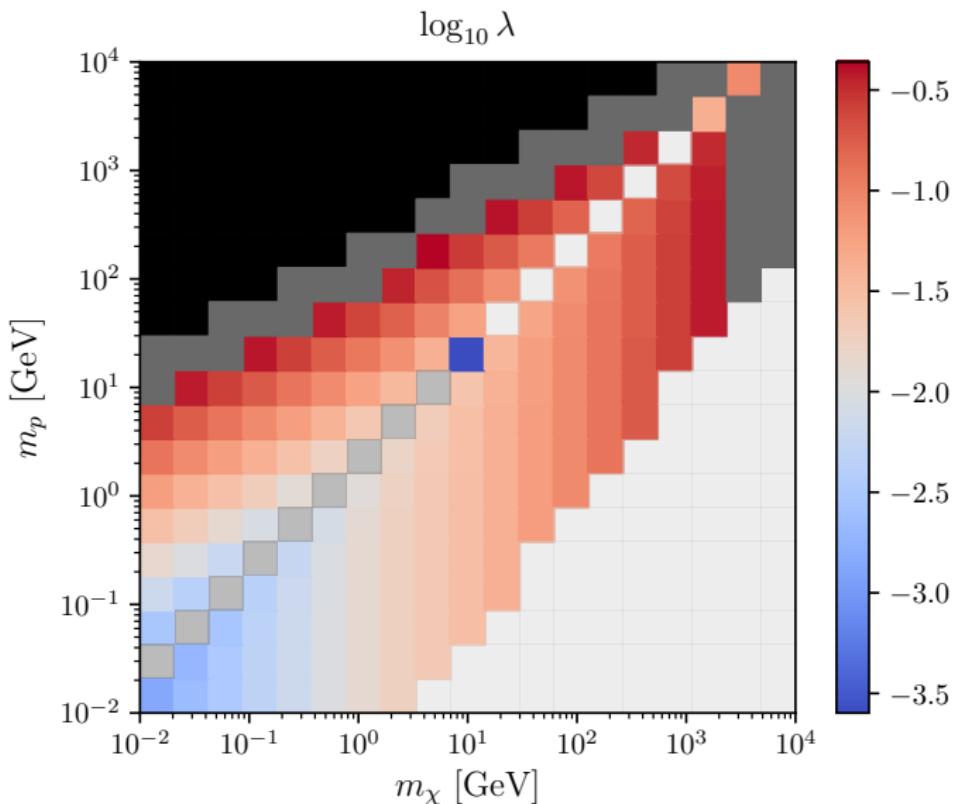


Remove the points when

- ▶  $\lambda > 10$
- ▶ numerical integration fails
- ▶  $x_{\text{kd}} < 2x_f$  is returned
- ▶ kd evaluation fails
- ▶  $\Gamma_p > 0.1m_p$

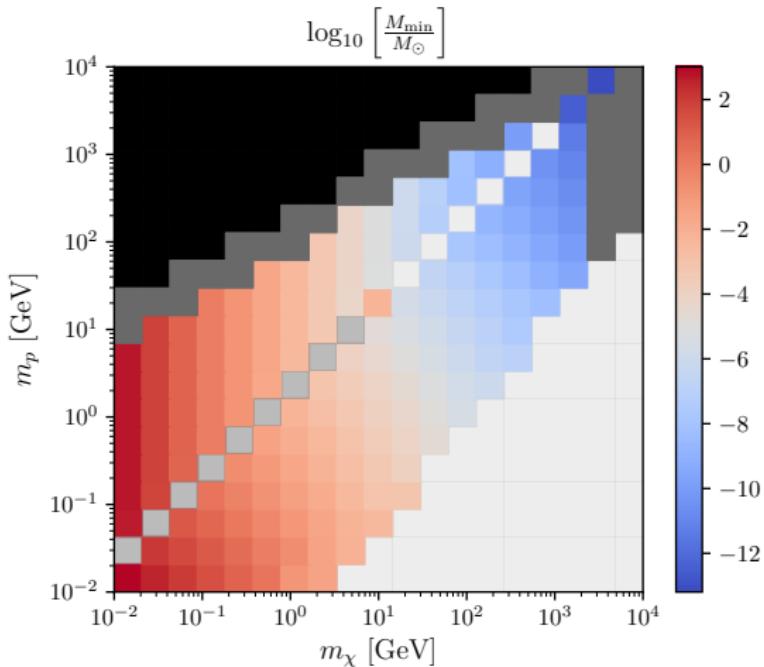
### 3. The example of a single pseudo-scalar mediator

#### 1. The correct universal coupling



### 3. The example of a single pseudo-scalar mediator

#### 2. Subhalos minimal mass



Dominant effect (since free-streaming mass dominates) :  
smaller  $m_\chi \rightarrow$  higher speed at  $k d \rightarrow$  smaller  $k_{\text{fs}}$   $\rightarrow$  higher minimal mass

### 3. The example of a single pseudo-scalar mediator

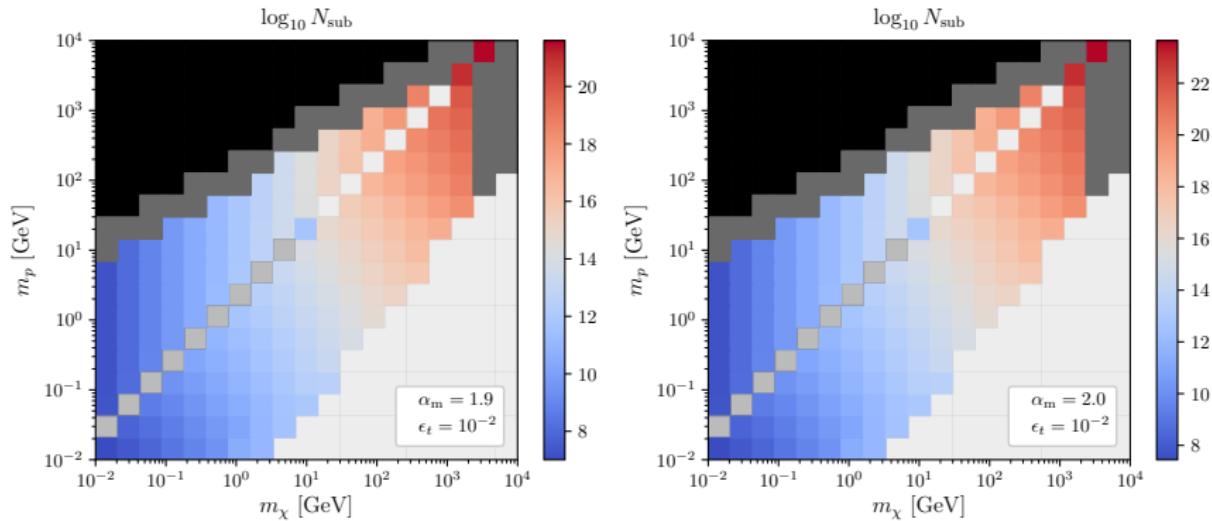
#### 2. Subhalos minimal mass

##### Limits of the current resolution

- ▶ Freeze-in production mechanism instead of freeze-out
- ▶ Chemical and kinetic decoupling happening simultaneously (Binder+17)
- ▶ Importance of the self-interaction (for large couplings)
- ▶ Sommerfield enhancement

### 3. The example of a single pseudo-scalar mediator

#### 3. Impacts on the clump distribution



Number of subhalos in the Milky Way  $N_{\text{sub}}$   
( $\alpha_m$  : mass index,  $\epsilon_t$  : disruption parameter)

(Using [Stref+17](#) model)

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### Conclusion on this study

- ▶ Numerical implementation still needs some improvements
- ▶ Phenomenological study of the impact of **microscopic** properties on **minimal mass** of **macroscopic** mini-halos using constraints from **abundance**
- ▶ Important for CDM predictions and model constraints (influence on the number of clumps, the boost factor, etc.)

## 4. Conclusion

