Impact of bound states on non-thermal Dark Matter production

Albert-Ludwigs-Universität Freiburg

Julian Bollig

This talk is based on a paper with the same title by Julian Bollig and Stefan Vogl [2112.01491]

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Masse und Symmetrien nach der GRK 2044 Entdeckung des Higgs-Teilchens am LHC

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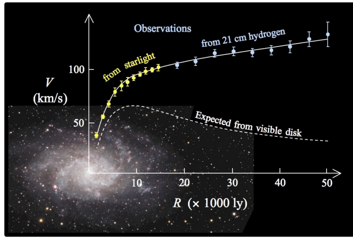
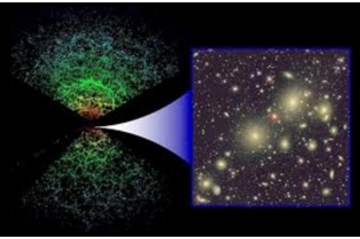
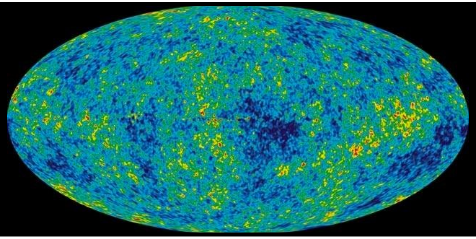
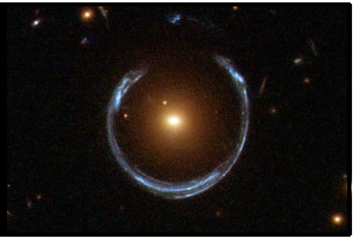


Galaxy Rotation curves

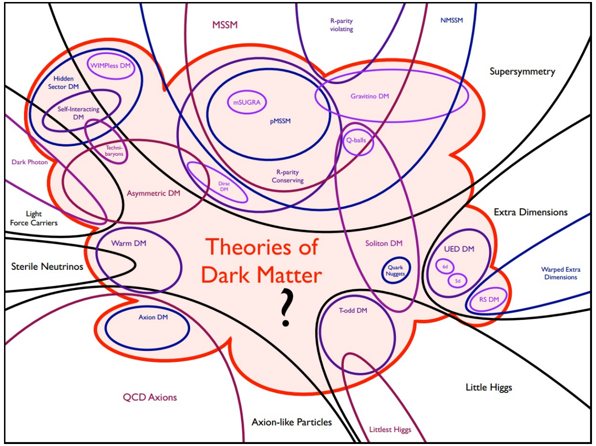

Large Scale Structures


CMB anisotropies

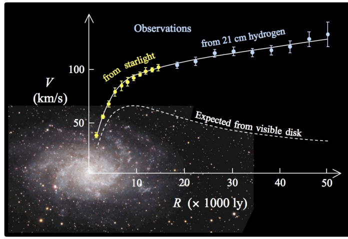

Gravitational lensing

Production mechanism are essential to understand the nature of Dark Matter (DM)

- Dark Matter is the most common explanation for many observations within the Standard Model of Cosmology
- <u>What it is</u> and <u>how it is produced</u> is a mystery
  - Even restricted to a particle nature, there are countless possible and plausible theories, which need to be investigated



[created by Tim Tait]



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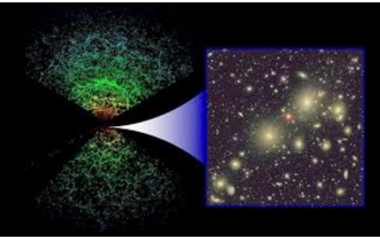

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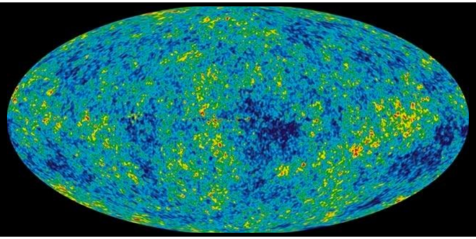

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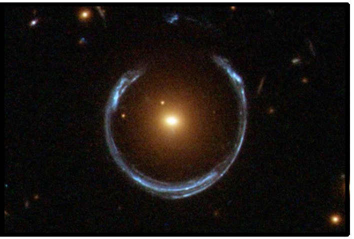

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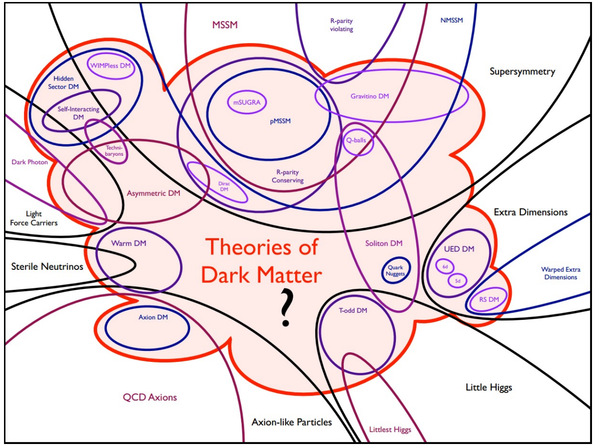
  → Simplified models



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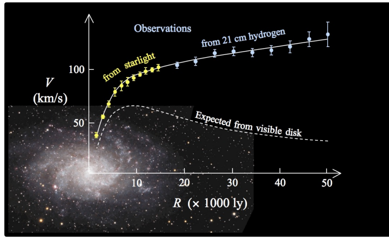

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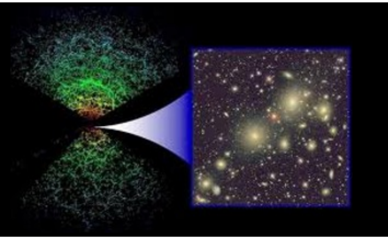

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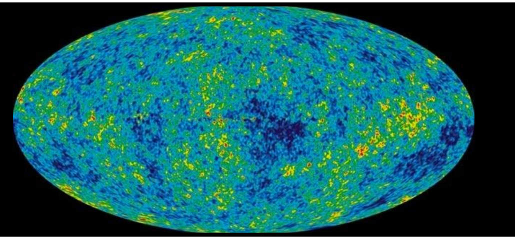

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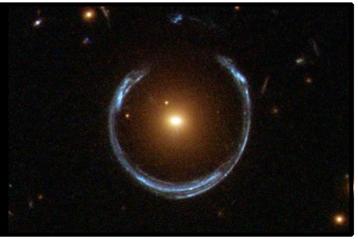

Gravitational lensing

In non-thermal production the DM particle is never in thermal equilibrium with the SM

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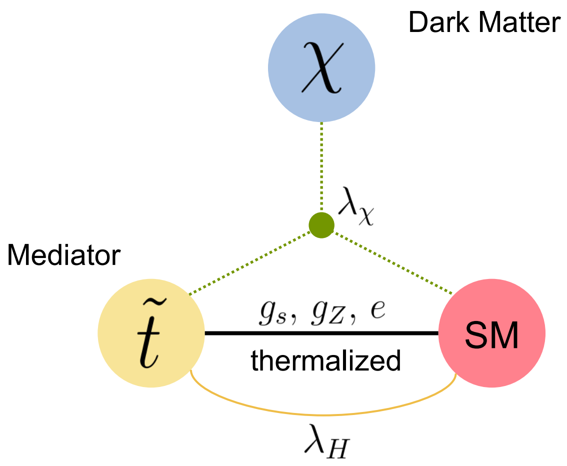
- We make use of a FIMP model with a color-charged mediator

$$\mathcal{L}_{\mathrm{DS}} = i\bar{\chi}\gamma^{\mu}\partial_{\mu}\chi - \frac{1}{2}m_{\chi}^{2}\bar{\chi}\chi - m_{\tilde{t}}^{2}\tilde{t}^{*}\tilde{t}$$

$$\mathcal{L}_{\mathrm{int}} = \left|D_{\mu}\tilde{t}\right|^{2} + \lambda_{\chi}\bar{t}_{R}\tilde{t}\chi + \lambda_{H}\tilde{t}\,\tilde{t}^{*}\left|\Phi\right|^{2} + h.c.$$

- Model parameters: $m_{\tilde{t}},\ m_{\chi},\ \lambda_{\chi},\ \lambda_{H}$



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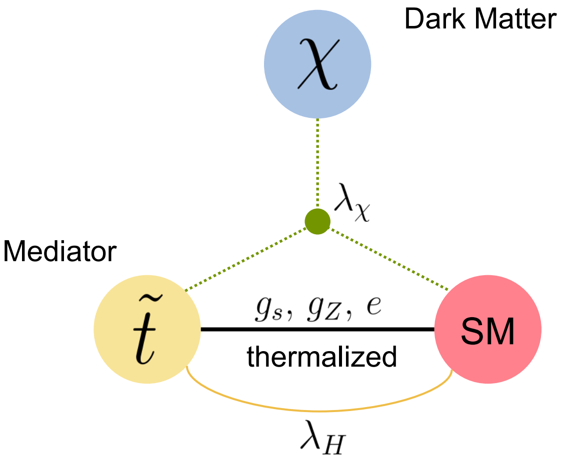
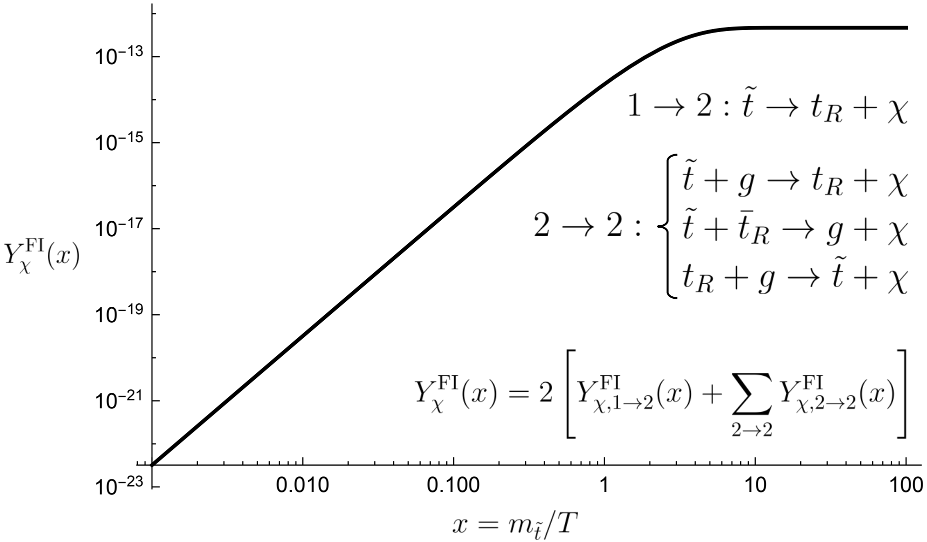
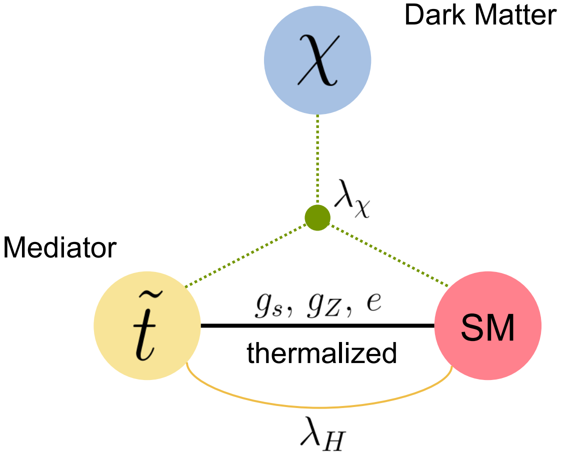
- Model parameters: $m_{\tilde{t}},\ m_{\chi},\ \lambda_{\chi},\ \lambda_{H}$
- If $\lambda_{\chi} \lesssim 10^{-8}$, DM can only be produced through non-thermal production mechanisms



In non-thermal production the DM particle is never in thermal equilibrium with the SM

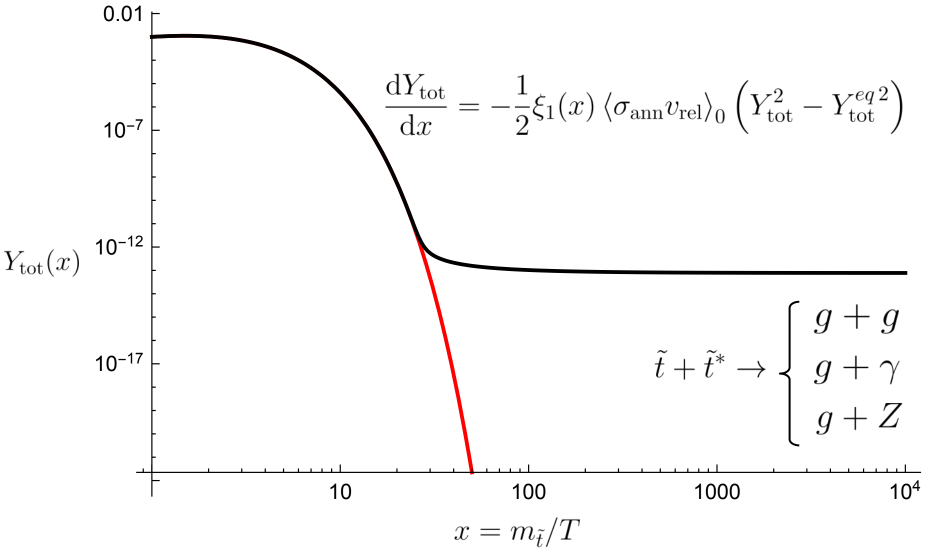
- For non-thermal production, two mechanisms become important
  - Freeze-in (dominant for $10^{-12} \lesssim \lambda_\chi \lesssim 10^{-8}$)

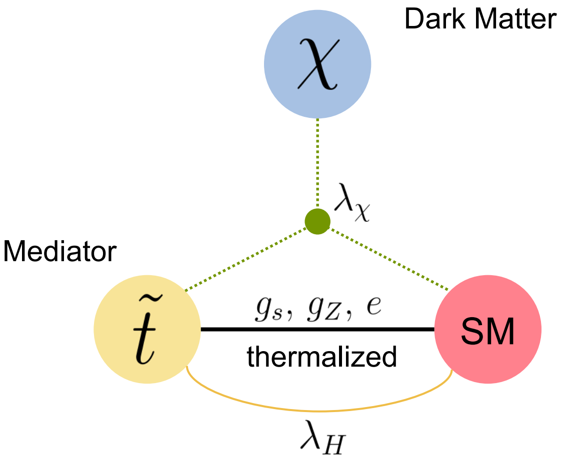




In non-thermal production the DM particle is never in thermal equilibrium with the SM

- For non-thermal production, two mechanisms become important
  - Freeze-in (dominant for $10^{-12} \lesssim \lambda_\chi \lesssim 10^{-8}$)
  - SuperWIMP (dominant below $\lambda_\chi \lesssim 10^{-12}$)





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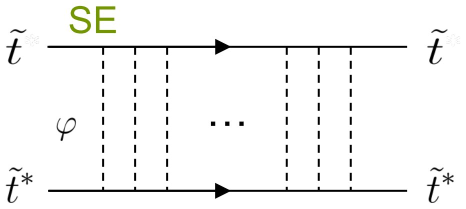
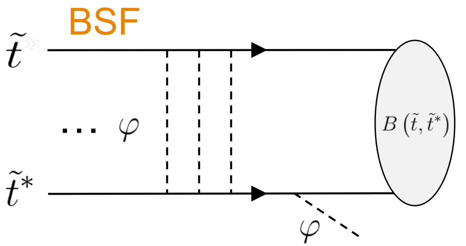
$$\left[-\frac{1}{2\mu}\nabla^2 + V(\vec{r})\right] \phi_{\vec{q}}(\vec{r}) = \mathcal{E}_{\vec{q}}\,\phi_{\vec{q}}(\vec{r})$$

$$\left[-\frac{1}{2\mu}\nabla^2 + V(\vec{r})\right] \psi_{nlm}(\vec{r}) = \mathcal{E}_n\,\psi_{nlm}(\vec{r})$$





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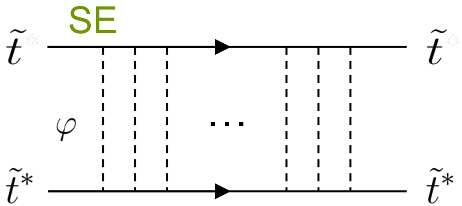

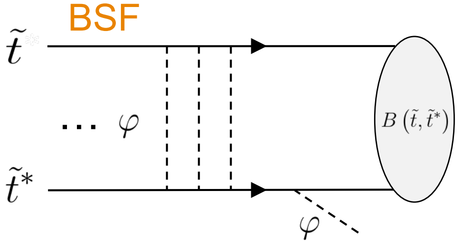

$$\frac{\mathrm{d}Y_{\text{tot}}}{\mathrm{d}x} = -\frac{1}{2}\xi_1(x)\langle\sigma_{\text{ann}}v_{\text{rel}}\rangle_0 \left(Y_{\text{tot}}^2 - Y_{\text{tot}}^{eq\,2}\right)$$

Modified Boltzmann Equation

$$\frac{\mathrm{d}Y_{\text{tot}}}{\mathrm{d}x} = -\frac{1}{2}\,\xi_1(x)\,\langle\sigma_{\text{ann}}v_{\text{rel}}\rangle \left(Y_{\text{tot}}^2 - Y_{\text{tot}}^{eq\,2}\right) - \frac{1}{2}\,\xi_1(x)\,\langle\sigma_{\text{BSF}}v_{\text{rel}}\rangle\, Y_{\text{tot}}^2 + 2\,\xi_2(x)\,\langle\Gamma_{\text{ion}}\rangle\, Y_B$$

$$\frac{\mathrm{d}Y_B}{\mathrm{d}x} = -\xi_2(x)\,\langle\Gamma_{\text{dec}}\rangle\,(Y_B - Y_B^{eq}) + \frac{1}{4}\,\xi_1(x)\,\langle\sigma_{\text{BSF}}v_{\text{rel}}\rangle\, Y_{\text{tot}}^2 - \xi_2(x)\,\langle\Gamma_{\text{ion}}\rangle\, Y_B$$

Masse und Symmetrien nach der Entdeckung des Higgs-Teilchens am LHC
GRK 2044

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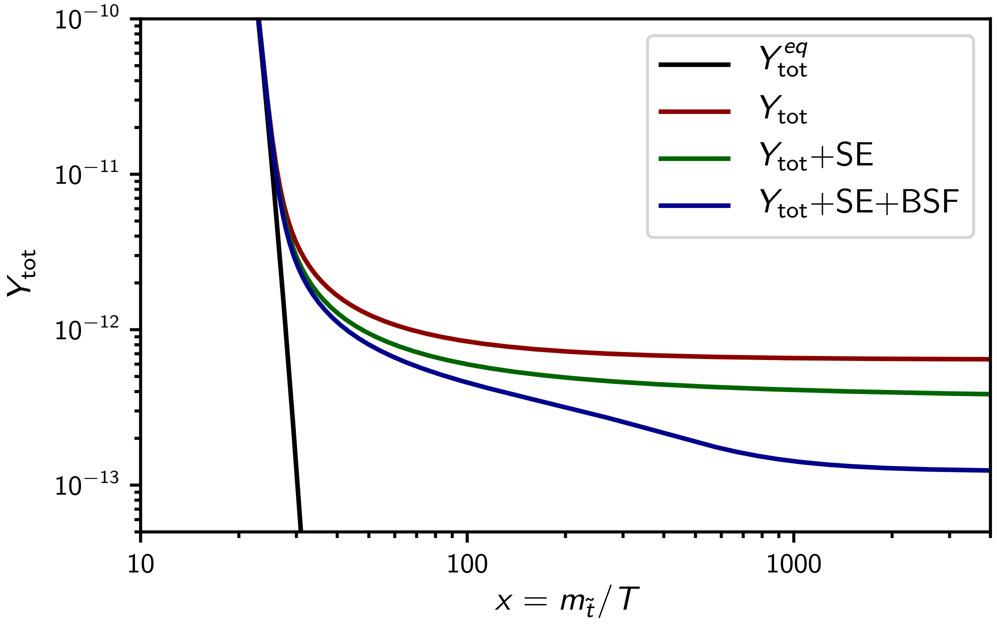
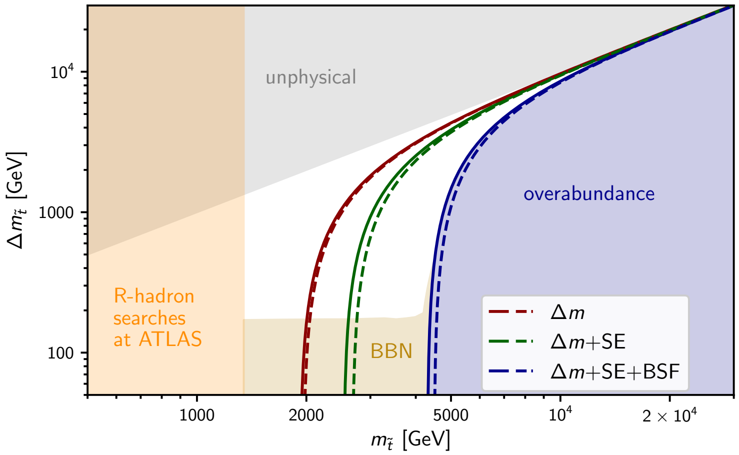
We have found large deviations in the DM abundance caused by non-perturbative effects

- the total mediator abundance after freeze-out changes considering
  - SE alone by ~ 40-50%
  - SE and BSF by ~ 80-90%



Including non-perturbative effects broadens the parameter space for LHC searches

SU(3)$_c$ charged mediator



- The coupling strength λ_χ at each point is given by the cosmological DM abundance

$$\Omega_{\rm DM} h^2 = \Omega_{\rm DM}^{\rm FI} h^2 + \Omega_{\rm DM}^{\rm sW} h^2 = 0.12$$

$\lambda_H = 0$	solid lines
$\lambda_H = 0.3$	dashed lines

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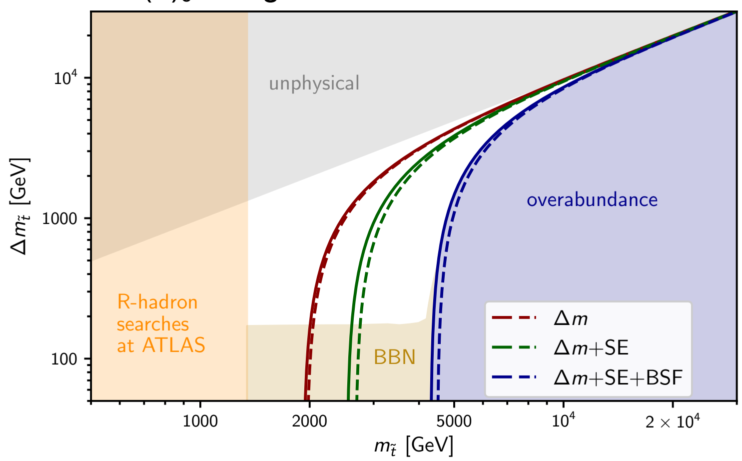
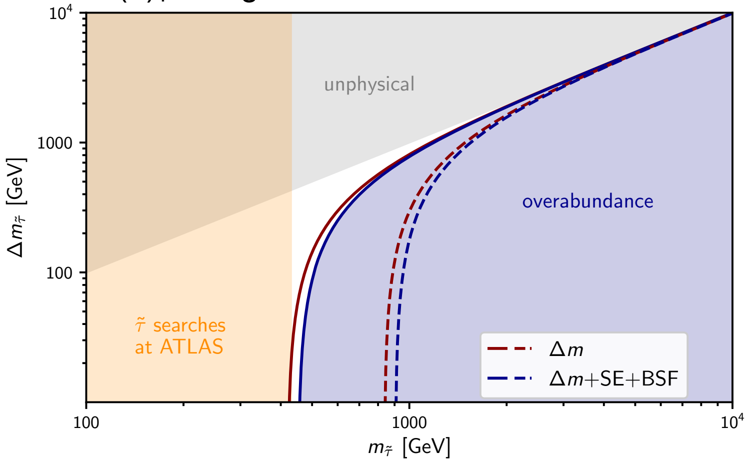


U(1)$_Y$ charged mediator



- The coupling strength λ_χ at each point is given by the cosmological DM abundance

$$\Omega_{\rm DM}h^2 = \Omega_{\rm DM}^{\rm FI}h^2 + \Omega_{\rm DM}^{\rm sW}h^2 = 0.12$$

- For a purely U(1)$_Y$ charged mediator, the Higgs portal becomes important

$\lambda_H = 0$	solid lines
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Non-perturbative effects are important for DM production in t-channel mediator models

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  - *the effect has also been observed in other coupling regimes (e.g. [2112.01499] for conversion driven freeze-out or [2203.04326] for WIMP freeze-out)*

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- The parameter space of non-thermal DM with a $SU(3)_c$ charged mediator in the FI and sWIMP regime is significantly larger than initially thought

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  - *the effect has also been observed in other coupling regimes (e.g. [2112.01499] for conversion driven freeze-out or [2203.04326] for WIMP freeze-out)*

- The Higgs portal coupling becomes very important for a $U(1)_Y$ charged mediator and should not be neglected

Thank you for your attention!

Albert-Ludwigs-Universität Freiburg

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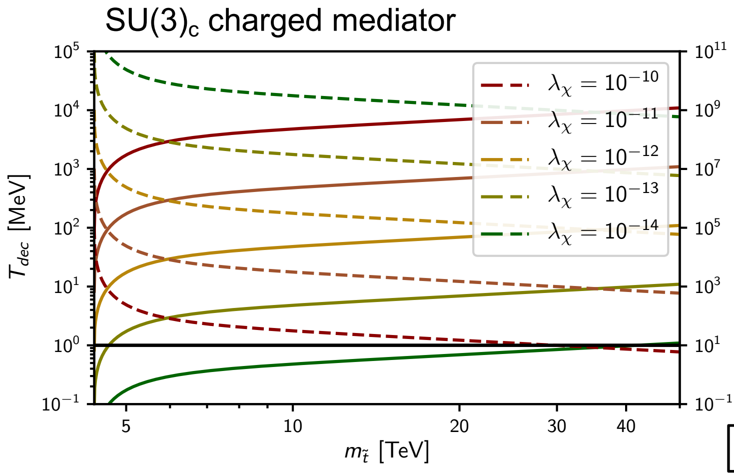
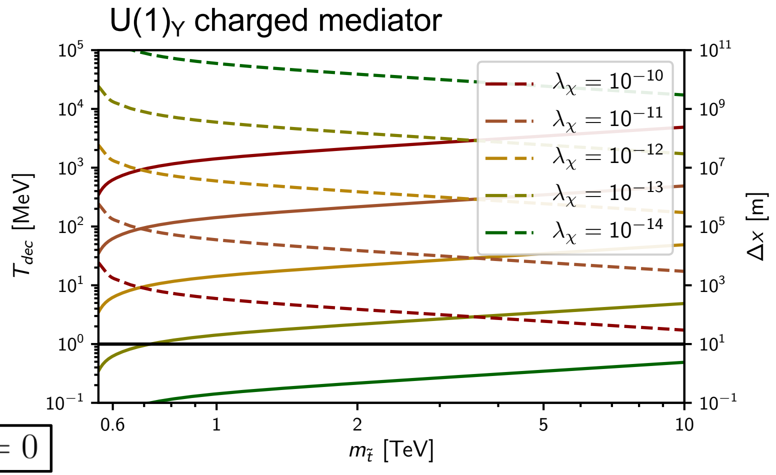
Backup

Decay temperature and decay length



$\lambda_H = 0$



$$T_{\rm dec} \simeq \sqrt{0.301 g_*^{1/2} M_{\rm Pl} \Gamma_{\tilde{t}}(m_{\tilde{t}}, m_\chi, \lambda_\chi)}$$

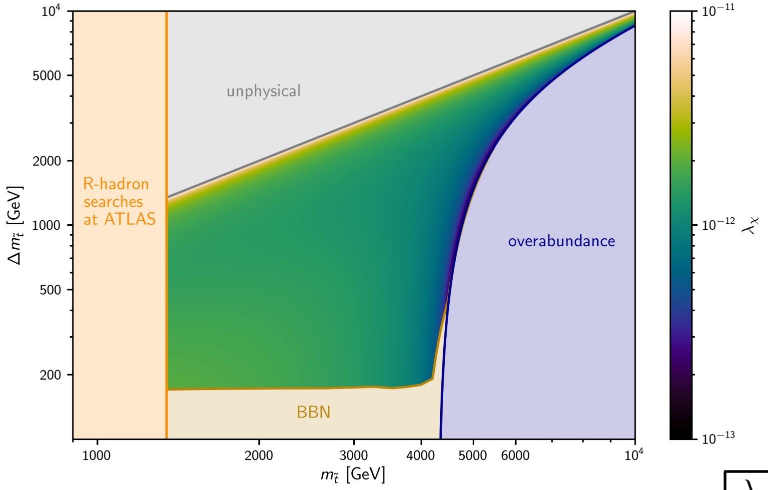
$$\Delta x \simeq \frac{\hbar c}{\Gamma_{\tilde{t}}} \beta_{\rm lab} \gamma$$

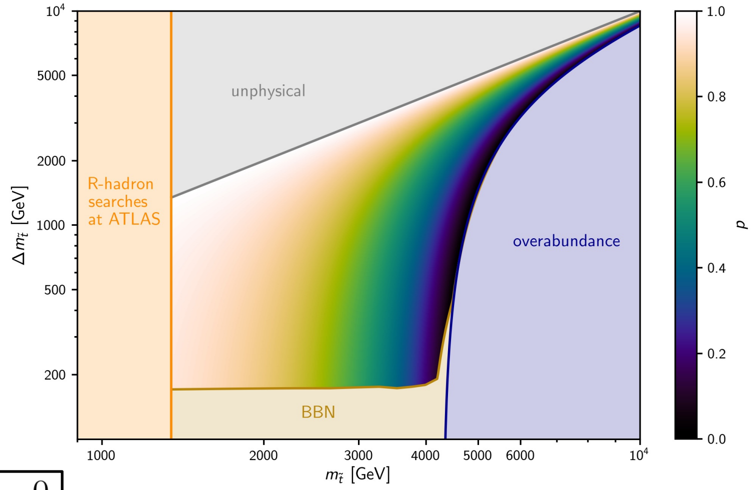
with

$$\Gamma_{\tilde{t} \to t_R \chi} = \lambda_\chi^2 \frac{\sqrt{\lambda(m_{\tilde{t}}^2, m_t^2, m_\chi^2)}(m_{\tilde{t}}^2 - m_\chi^2 - m_t^2)}{16\pi m_{\tilde{t}}^3}$$

Trilinear coupling in the parameter space

SU(3)$_c$ charged mediator





$$\lambda_H = 0$$

$$\lambda_\chi = \sqrt{\frac{\frac{\Omega_{\mathrm{DM}} h^2 \rho_{crit,0}}{m_\chi s_0} - Y^{\mathrm{sW}}_{\chi,\infty}}{Y^{\mathrm{FI}}_{\chi,\infty}}}$$

$$p = 1 - \frac{m_\chi Y^{\mathrm{sW}}_{\chi,\infty} s_0}{\Omega_{\mathrm{DM}} h^2 \rho_{crit,0}}$$

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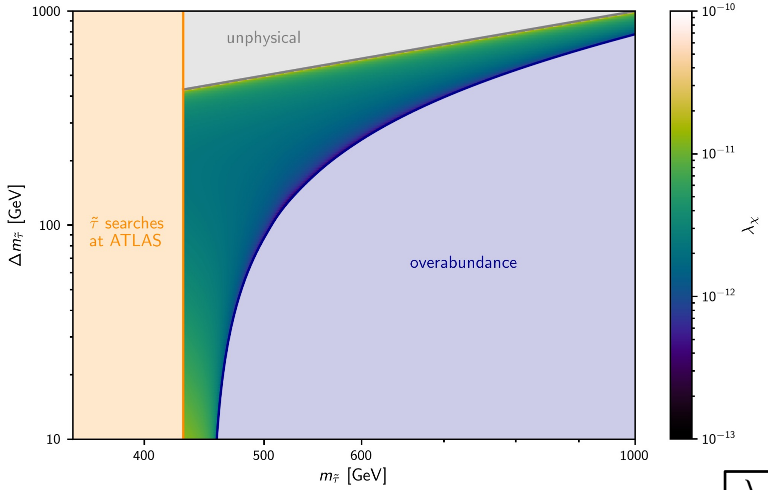

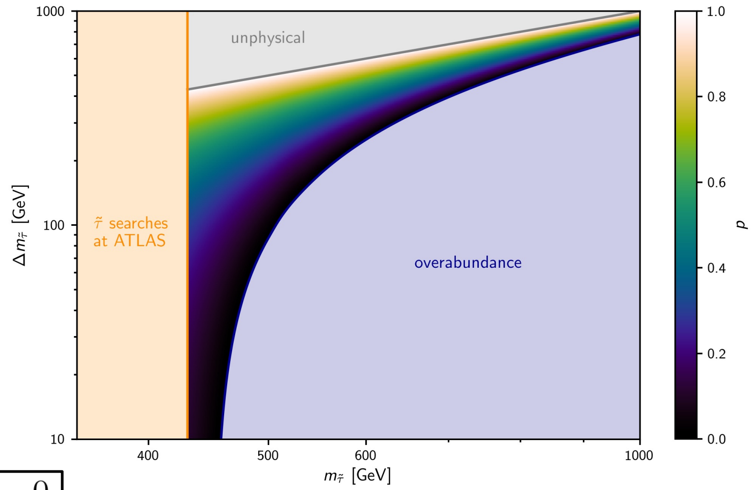

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$$p = 1 - \frac{m_\chi Y_{\chi,\infty}^{\mathrm{sW}} s_0}{\Omega_{\mathrm{DM}} h^2 \rho_{crit,0}}$$

Potentials and Bound state formation limits

Bound state formation limit from Debye screening:

$$m_{\tilde{t}} \geq \frac{1.68 m_X}{\alpha}$$

For a Z-boson:

$$m_{\tilde{t}} \gtrsim 68\,\mathrm{TeV}$$

For a Higgs-boson:

$$m_{\tilde{t}} < m_H$$

even for $\lambda_H \sim \mathcal{O}(1)$

TABLE II. Attractive potentials and fine structure constants for color-charged $\tilde{t} - \tilde{t}^*$ mediator interactions ($Q_{\rm em} = 2/3$). For lepto-philic $\tilde{\tau} - \tilde{\tau}^*$ mediator interactions, the results for γ, Z and H exchange remain the same with $Q_{\rm em} = -1$.

gauge boson	$V(r)$	α
Gluon	$V_g(r) = -\frac{\alpha_{g,[\mathbf{1}]}}{r}$	$\alpha_{g,[\mathbf{1}]} = \frac{4}{3}\alpha_s$
Photon	$V_\gamma(r) = -\frac{\alpha_\gamma}{r}$	$\alpha_\gamma = Q_{\rm em}^2 \alpha_{\rm em}$
Z-boson	$V_Z(r) = -\frac{\alpha_Z}{r} e^{-m_Z r}$	$\alpha_Z = Q_{\rm em}^2 \tan^2\theta_W \alpha_{\rm em}$
Higgs	$V_H(r) = -\frac{\alpha_H}{r} e^{-m_H r}$	$\alpha_H = \frac{\lambda_H^2 v^2}{16\pi m_{\tilde{t}}^2}$

[taken from arXiv: 2112.01491]

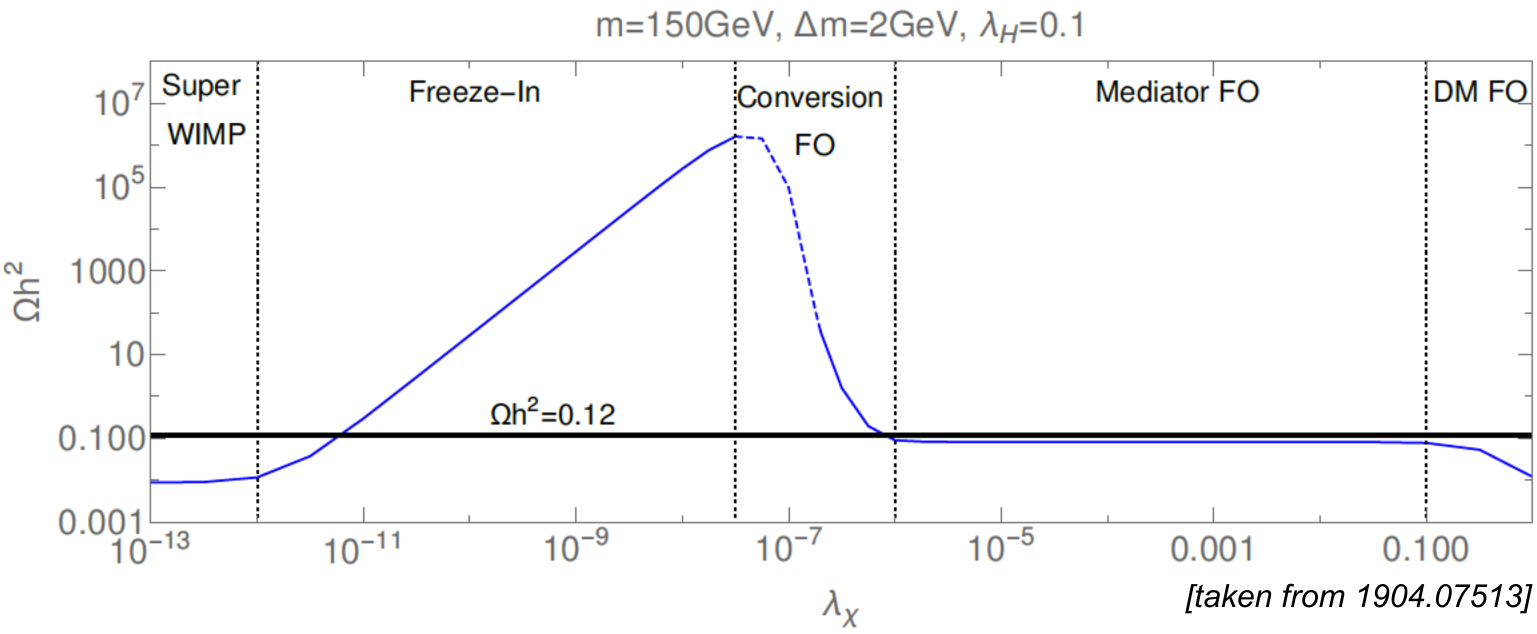
Dark sector particles

TABLE I. Summary of all new fields introduced in the simplified models considered. Besides their displayed type and charges under the SM gauge group, all these particles are odd under an additional $\mathbb{Z}_2$ symmetry.

new particles	type	$SU(3)_c \times SU(2)_L \times U(1)_Y$
$\tilde{t}$	bosonic scalar	$(\mathbf{3}, \mathbf{1}, 4/3)$
$\tilde{\tau}$	bosonic scalar	$(\mathbf{1}, \mathbf{1}, -1)$
χ	Majorana fermion	$(\mathbf{1}, \mathbf{1}, 0)$

[taken from arXiv: 2112.01491]

Dominating regimes in the FIMP model



[taken from 1904.07513]