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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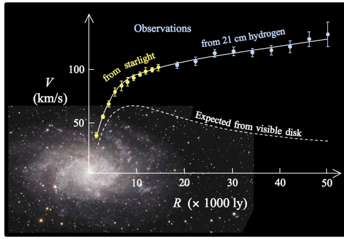
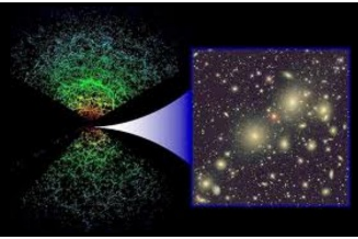
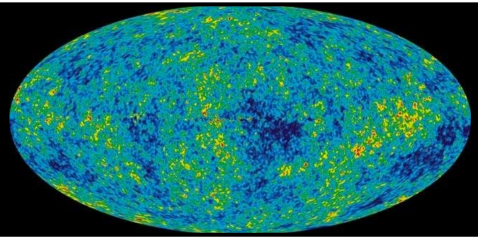


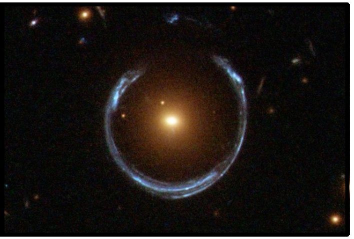
Galaxy Rotation curves



Large Scale Structures



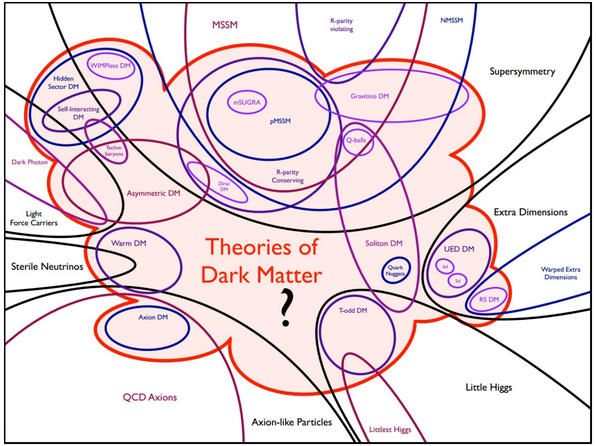
CMB anisotropies



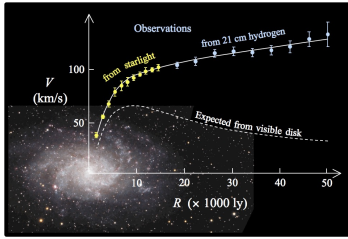
Gravitational lensing

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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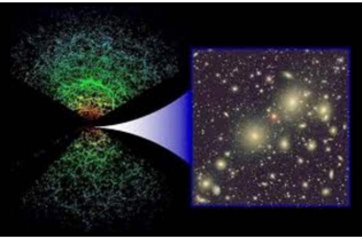

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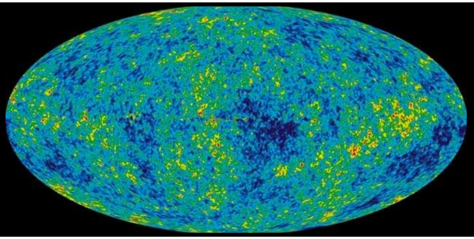

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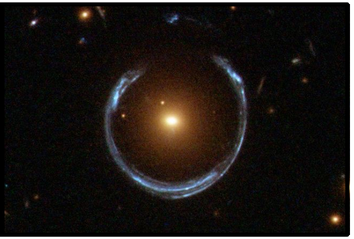

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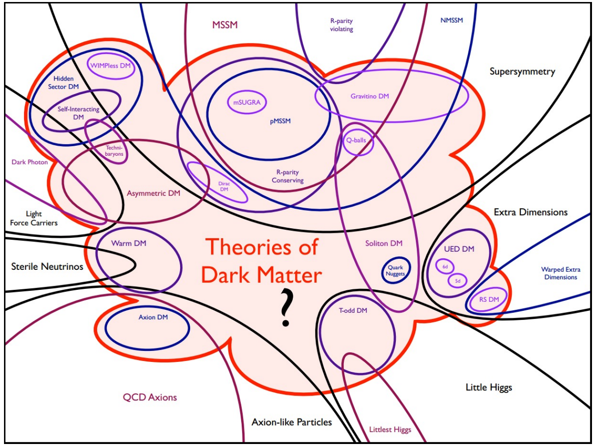
  → Simplified models



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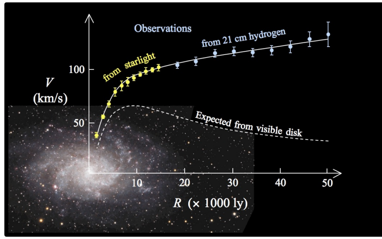

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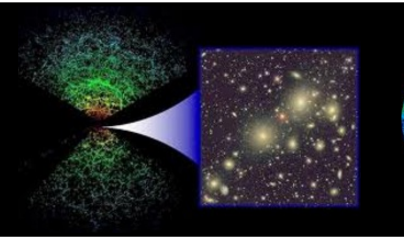
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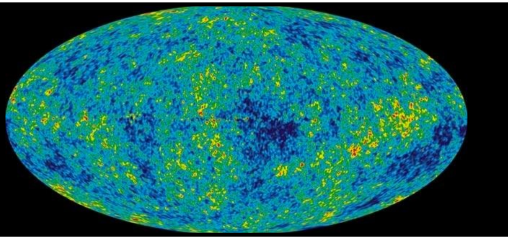
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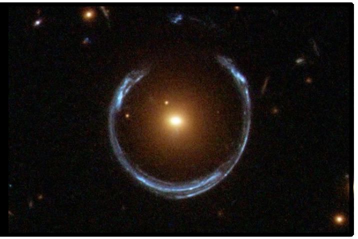
Gravitational lensing

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

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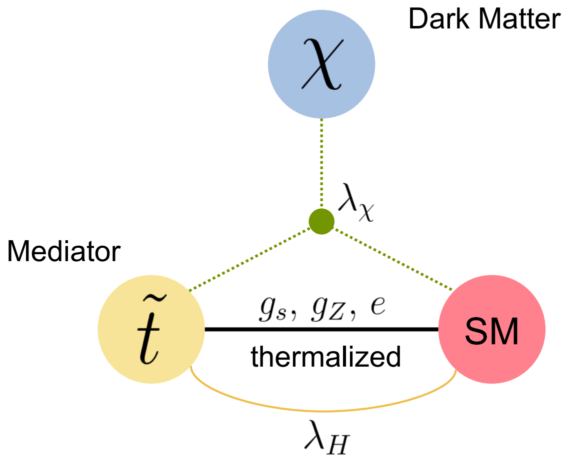
- We make use of a t-channel model with a color-charged mediator in the FIMP regime

$$\mathcal{L}_{\mathrm{DS}} = i\bar{\chi}\gamma^{\mu}\partial_{\mu}\chi - \frac{1}{2}m_{\chi}\bar{\chi}\chi - m_{\tilde{t}}^{2}\tilde{t}^{*}\tilde{t}$$
$$\mathcal{L}_{\mathrm{int}} = \left|D_{\mu}\tilde{t}\right|^{2} + \lambda_{\chi}\bar{t}_{R}\tilde{t}\chi + \lambda_{H}\tilde{t}\,\tilde{t}^{*}\left|\Phi\right|^{2} + h.c.$$

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



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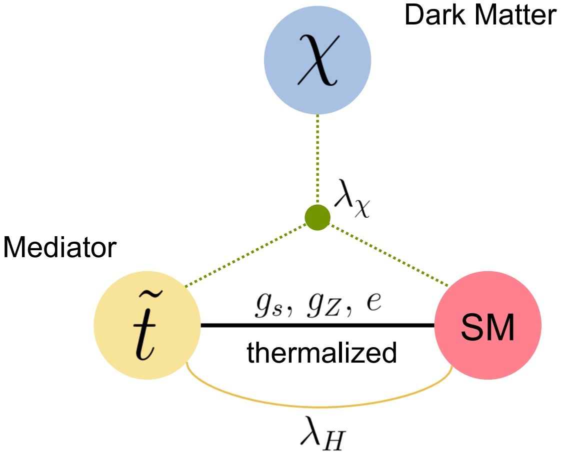
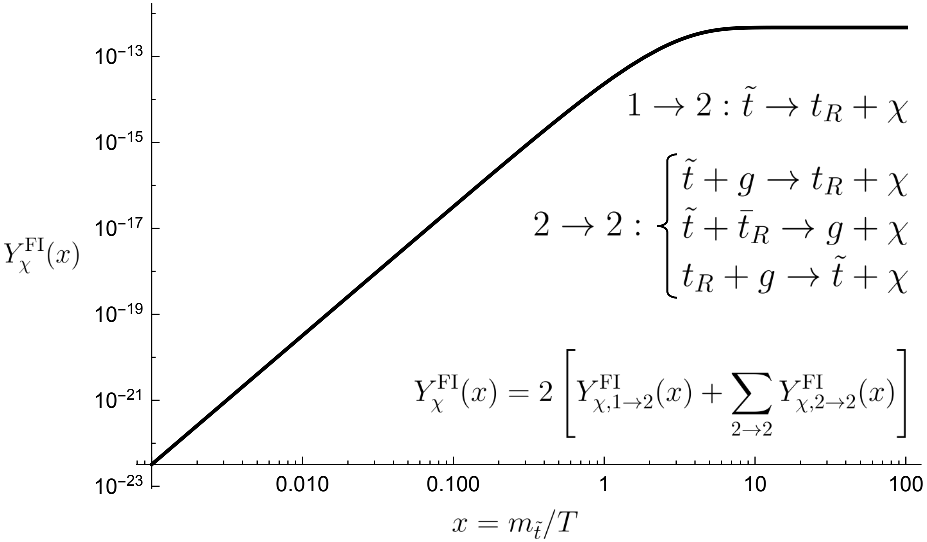
- Model parameters: $m_{\tilde{t}},\ m_\chi,\ \lambda_\chi,\ \lambda_H$

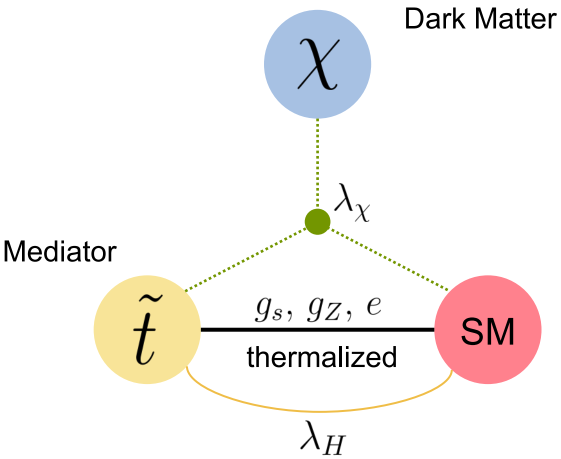
- If $\lambda_\chi \lesssim 10^{-8}$, DM can only be produced through non-thermal production mechanisms



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

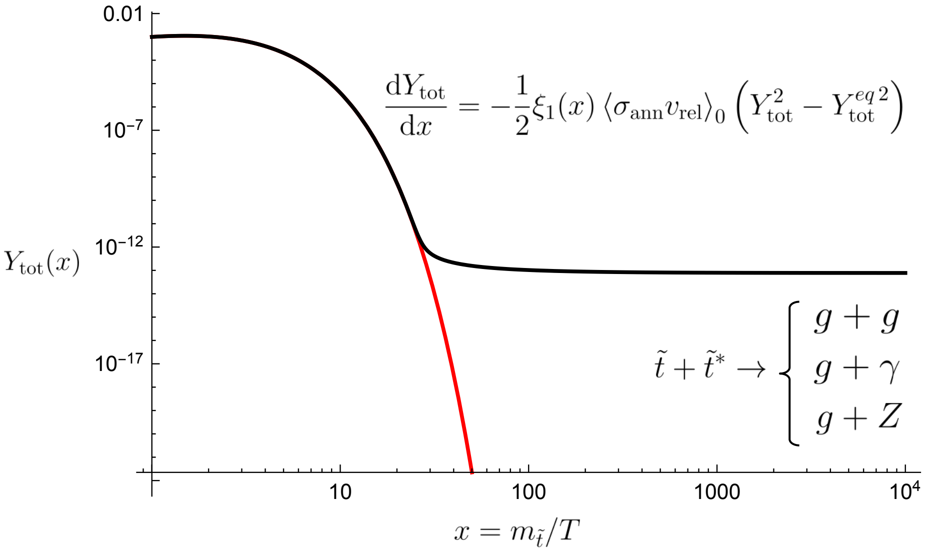
- For non-thermal production, two mechanisms become important
  - Freeze-in (dominant for $10^{-12} \lesssim \lambda_\chi \lesssim 10^{-8}$)

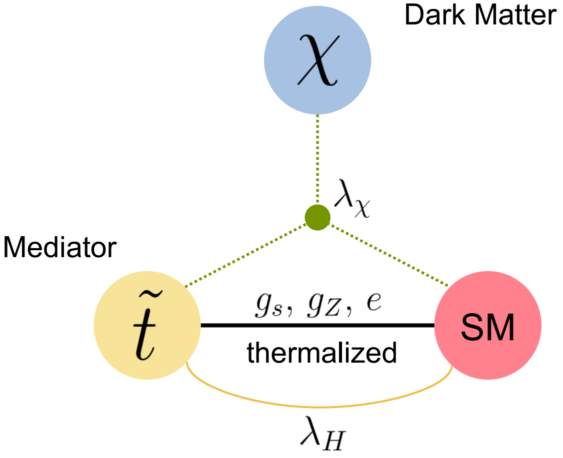




In non-thermal production the DM particle is never in thermal equilibrium with the SM

- 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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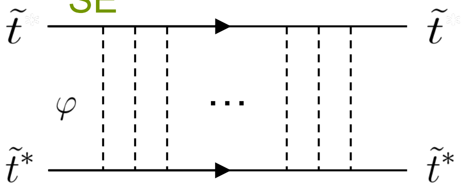
- Long ranged potentials influence the in- and outgoing wavefunctions (Sommerfeld Effect - SE) and lead to Bound State Formation (BSF) of the mediator

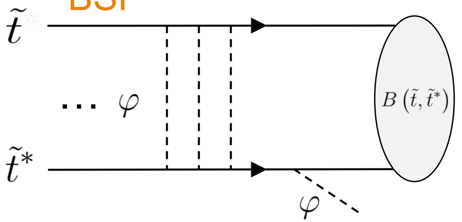
$$\left[-\frac{1}{2\mu}\nabla^2 + V(\vec{r})\right] \phi_{\vec{q}}(\vec{r}) = \mathcal{E}_{\vec{q}}\, \phi_{\vec{q}}(\vec{r})$$

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

SE



BSF



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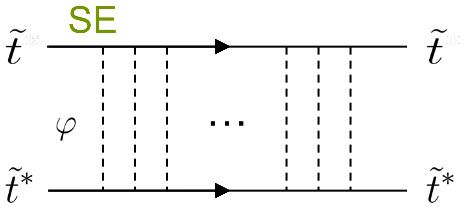
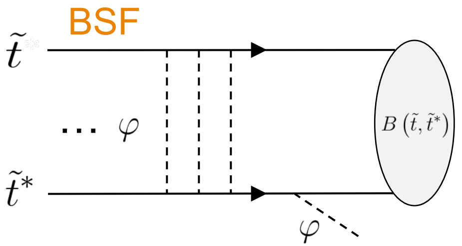




$$\frac{\mathrm{d}Y_{\mathrm{tot}}}{\mathrm{d}x} = -\frac{1}{2}\xi_1(x)\left\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}}\right\rangle_0 \left(Y_{\mathrm{tot}}^2 - Y_{\mathrm{tot}}^{eq\,2}\right)$$

Modified Boltzmann Equation

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

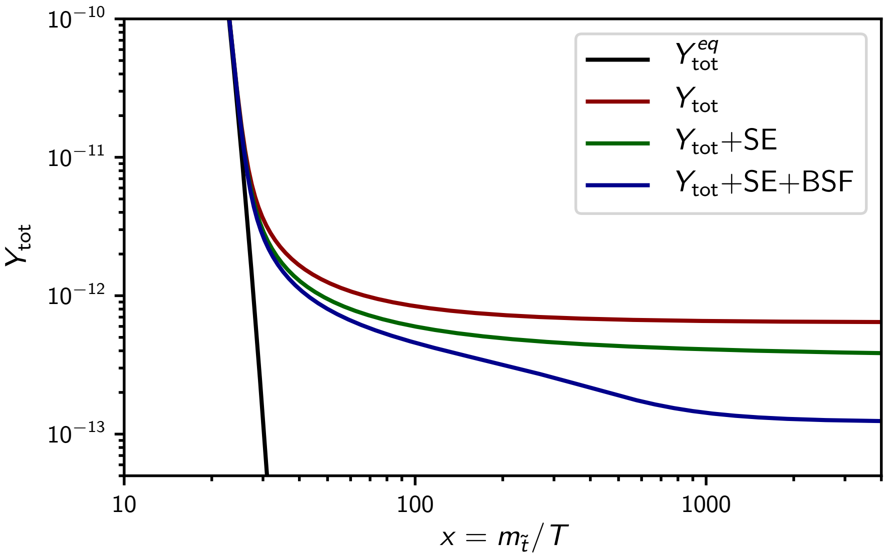
$$\frac{\mathrm{d}Y_B}{\mathrm{d}x} = -\xi_2(x)\left\langle \Gamma_{\mathrm{dec}}\right\rangle \left(Y_B - Y_B^{eq}\right) + \frac{1}{4}\,\xi_1(x)\left\langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}}\right\rangle Y_{\mathrm{tot}}^2 - \xi_2(x)\left\langle \Gamma_{\mathrm{ion}}\right\rangle Y_B$$

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

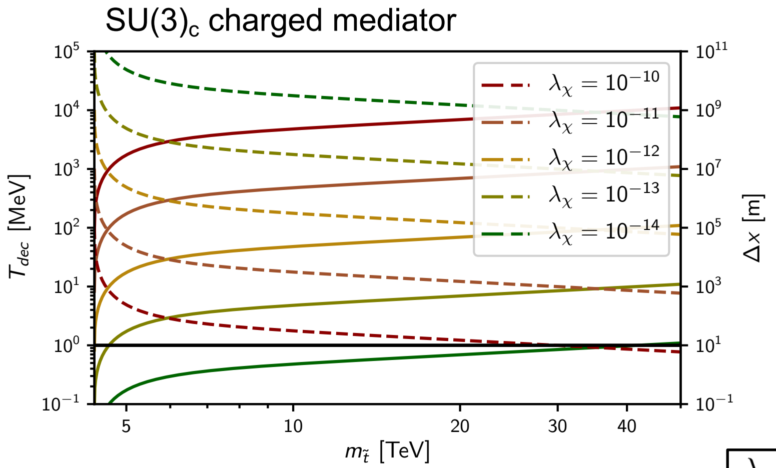
- The total mediator abundance after freeze-out changes considering
  - SE alone by ~ 40-50%
  - SE and BSF by ~ 80-90%

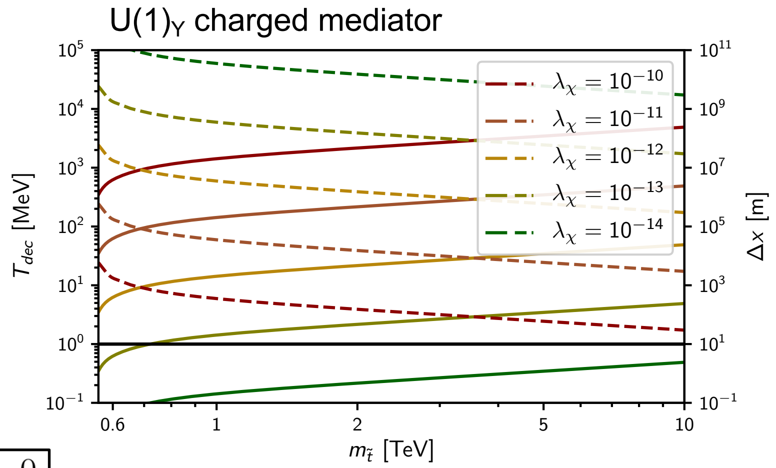
→ This allows for higher mediator masses in LHC searches

- Two important questions remain:
  - Does the late decay of the mediator spoil BBN?
  - Is the mediator detector-stable for ATLAS and CMS searches?



The mediator is detector-stable and decays fast enough in the considered parameter space





$\lambda_H = 0$

Decay temperature:

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

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

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

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

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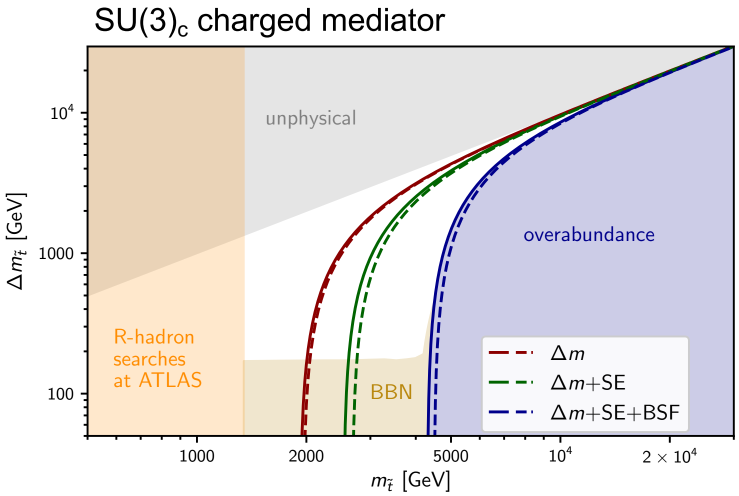


- The coupling strength λ_χ at each point is given by the cosmological DM abundance

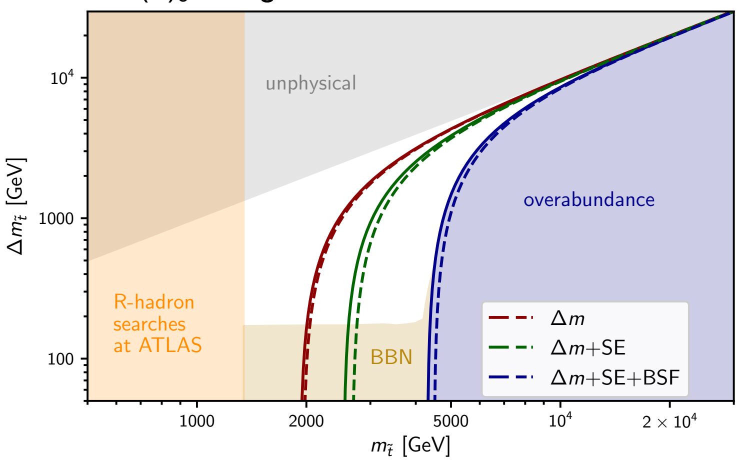
$$\Omega_{\rm DM}h^2 = \Omega_{\rm DM}^{\rm FI}h^2 + \Omega_{\rm DM}^{\rm sW}h^2 = 0.12$$

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

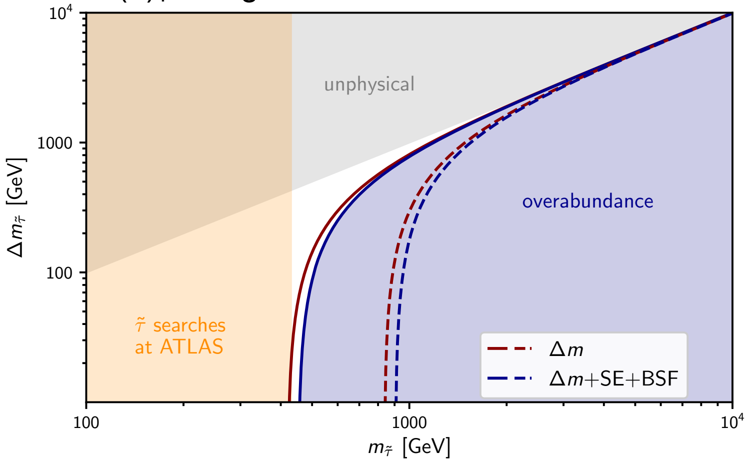
Masse und Symmetrien nach der Entdeckung des Higgs-Teilchens am LHC — GRK 2044

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

SU(3)$_c$ charged mediator



U(1)$_Y$ charged mediator



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

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

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

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- SE and BSF have a large impact on the DM abundance in the sWIMP regime and should be considered in future calculations
  - *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 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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Masse und Symmetrien nach der

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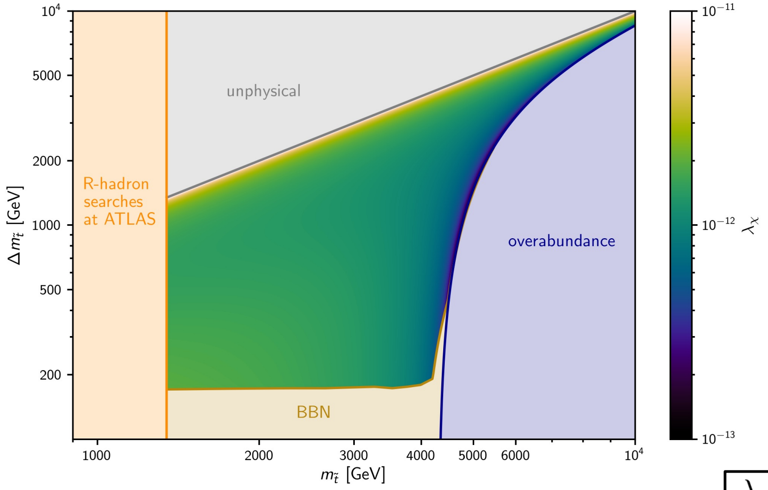
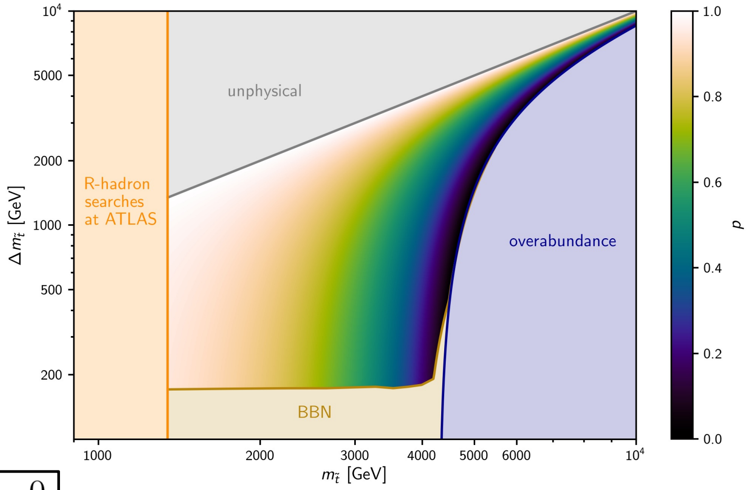
Entdeckung des Higgs-Teilchens am LHC

Backup

Trilinear coupling in the parameter space

SU(3)$_c$ charged mediator





$$\lambda_H = 0$$

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

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

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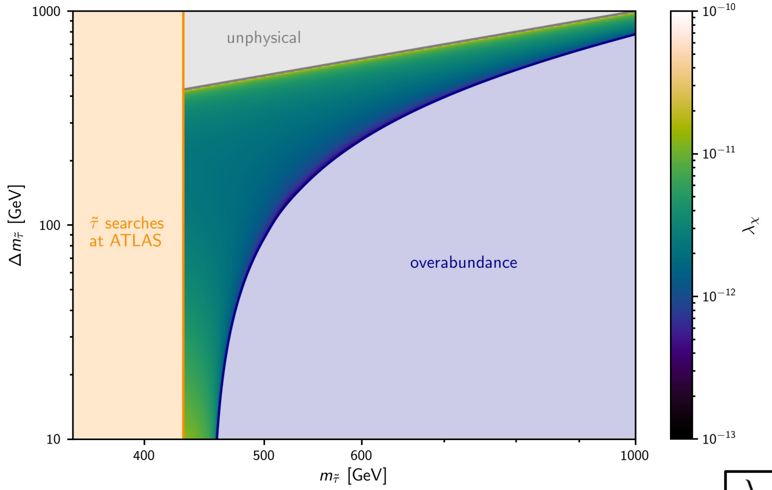

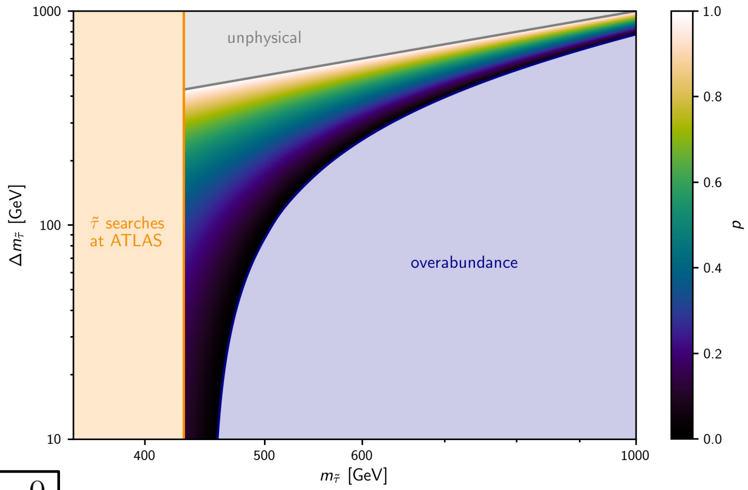

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Potentials and Bound state formation limits

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]

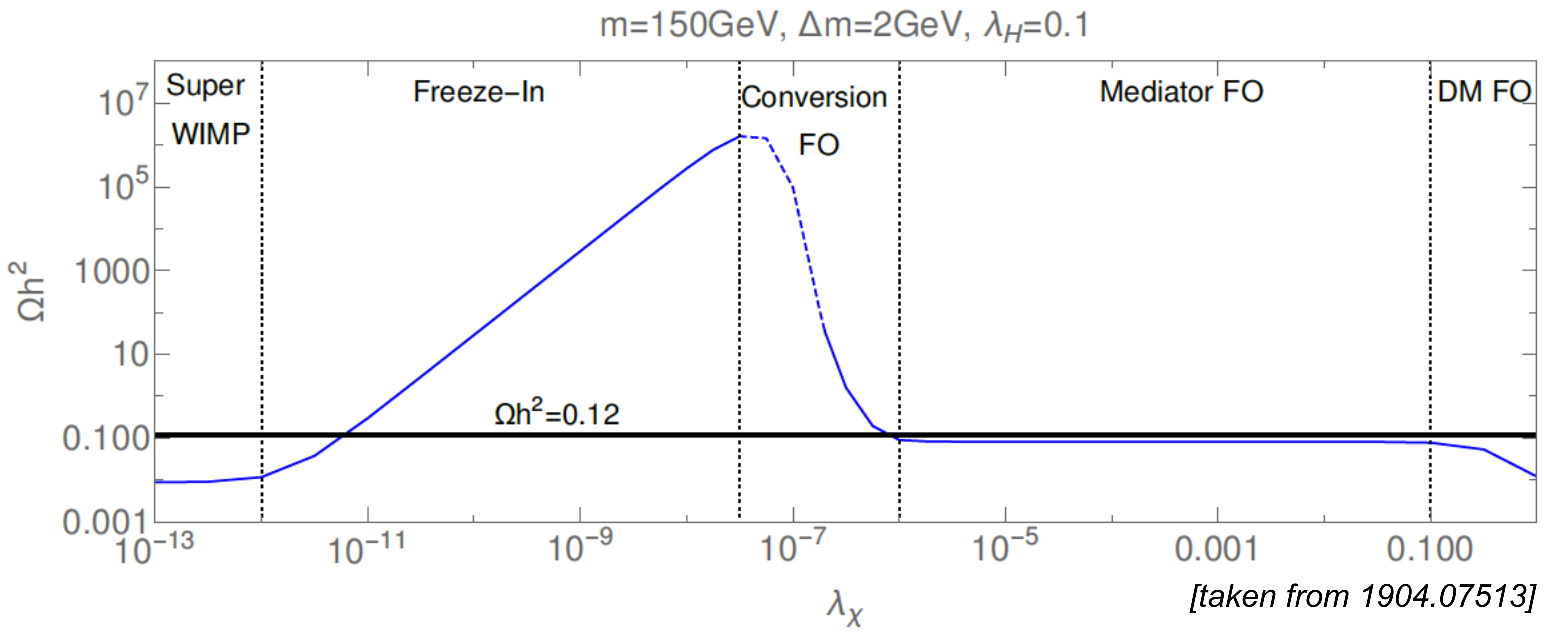
Dark sector particles

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]