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JRJC

Confront resonant s-wave dark matter to cosmological and astrophysical constraints

25/11/2024

Margaux Jomain

Introduction

1. Thermal s-Wave Dark Matter: The cosmological context
2. Resonance
3. The constraints
4. Problems

The cosmological context

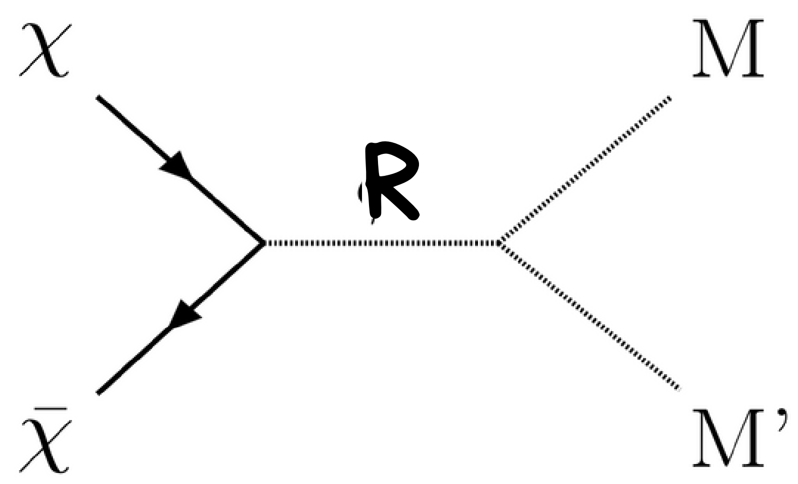
Thermal Dark Matter: Freeze-out

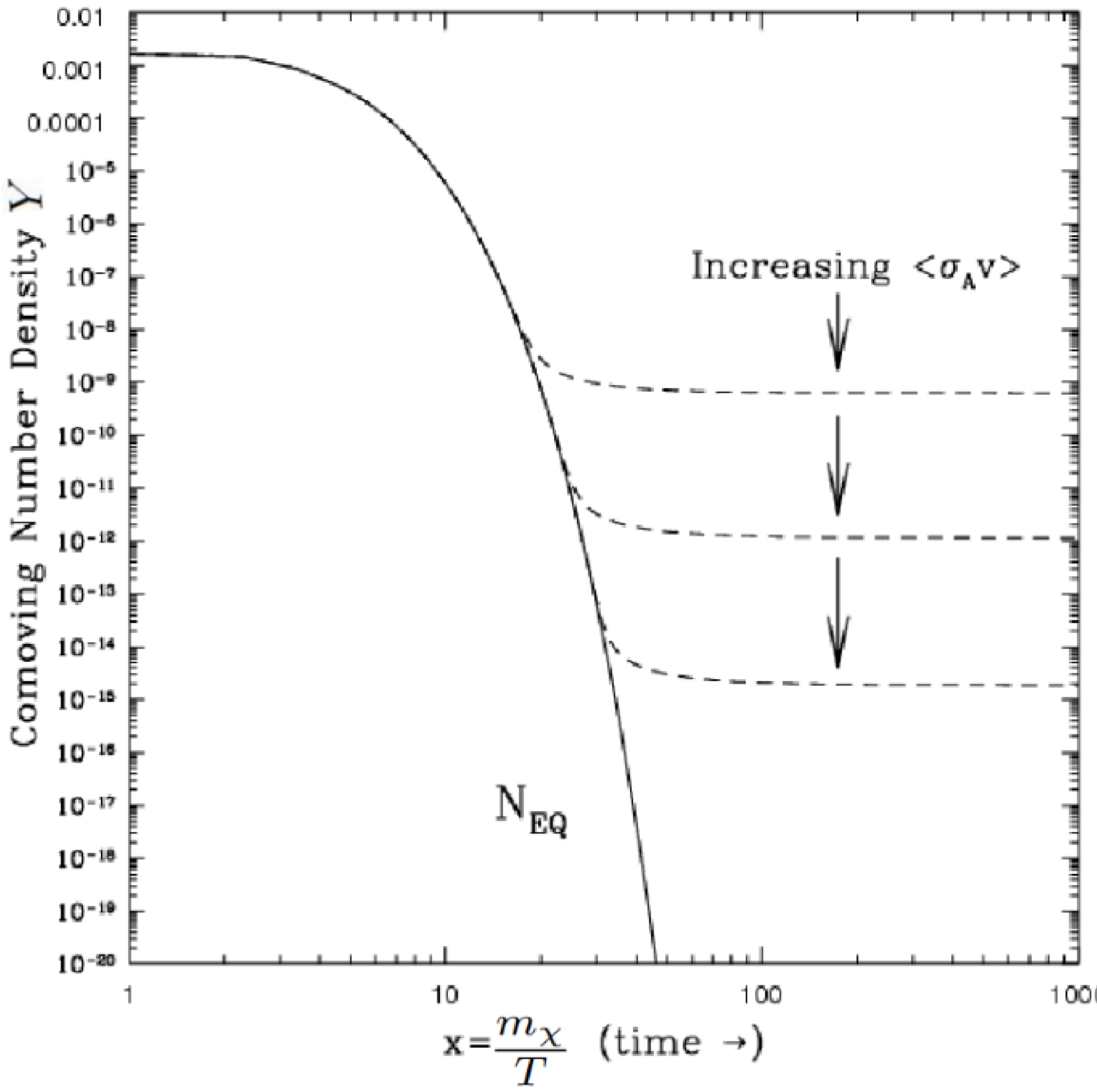
hypotheses:

FLRW metric

CP invariance

kinetic equilibrium





Boltzmann equation:

$$\frac{dY}{dx} = -\sqrt{\frac{\pi}{45G}}\frac{m}{x^2}g^{*1/2}\langle\sigma v_{M\phi l}\rangle\left(Y^2 - Y_{eq}^2\right)$$

Constraints on Dark Matter

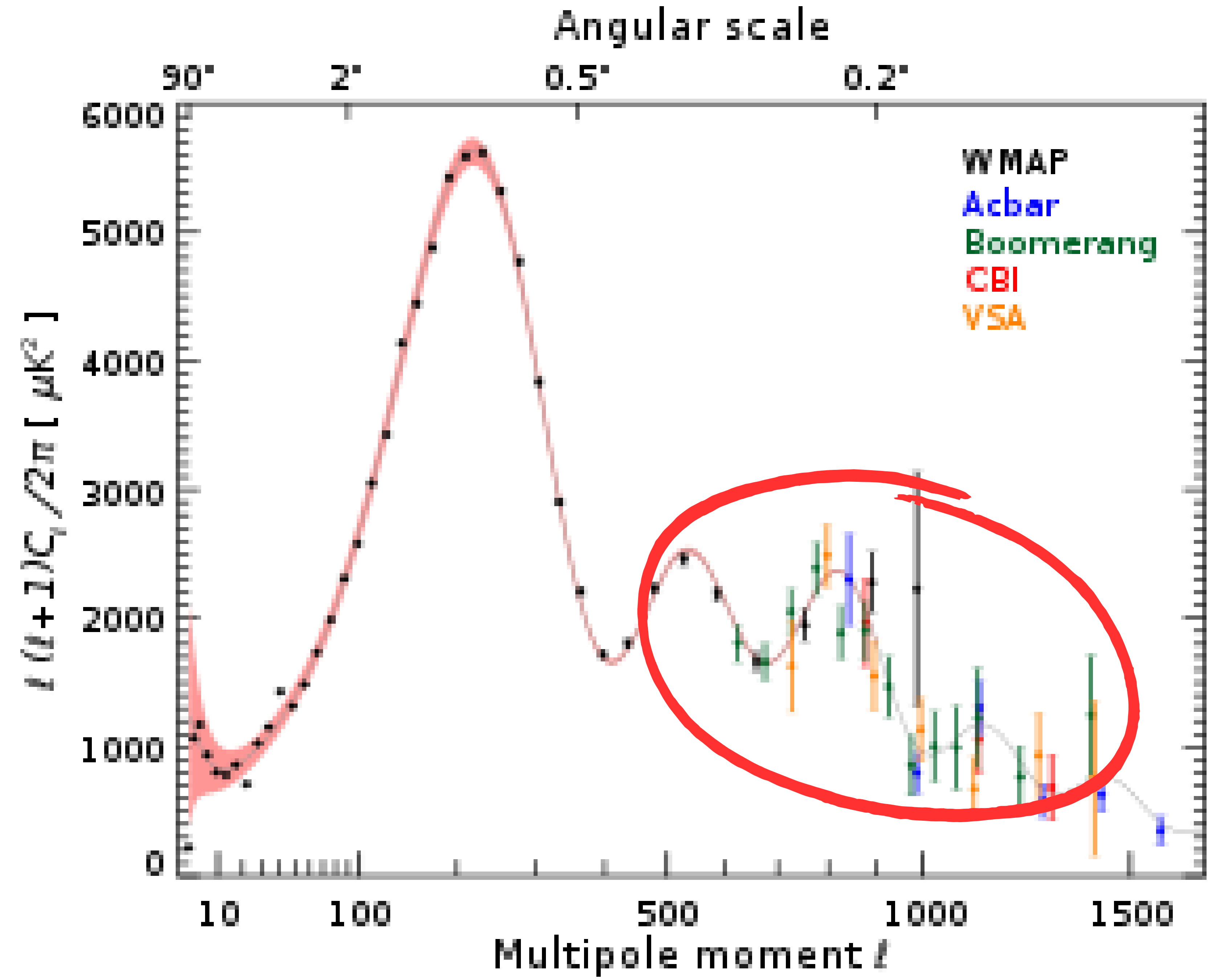
CMB Constraints

Dark Matter annihilation

energy injection

re-ionization of plasma

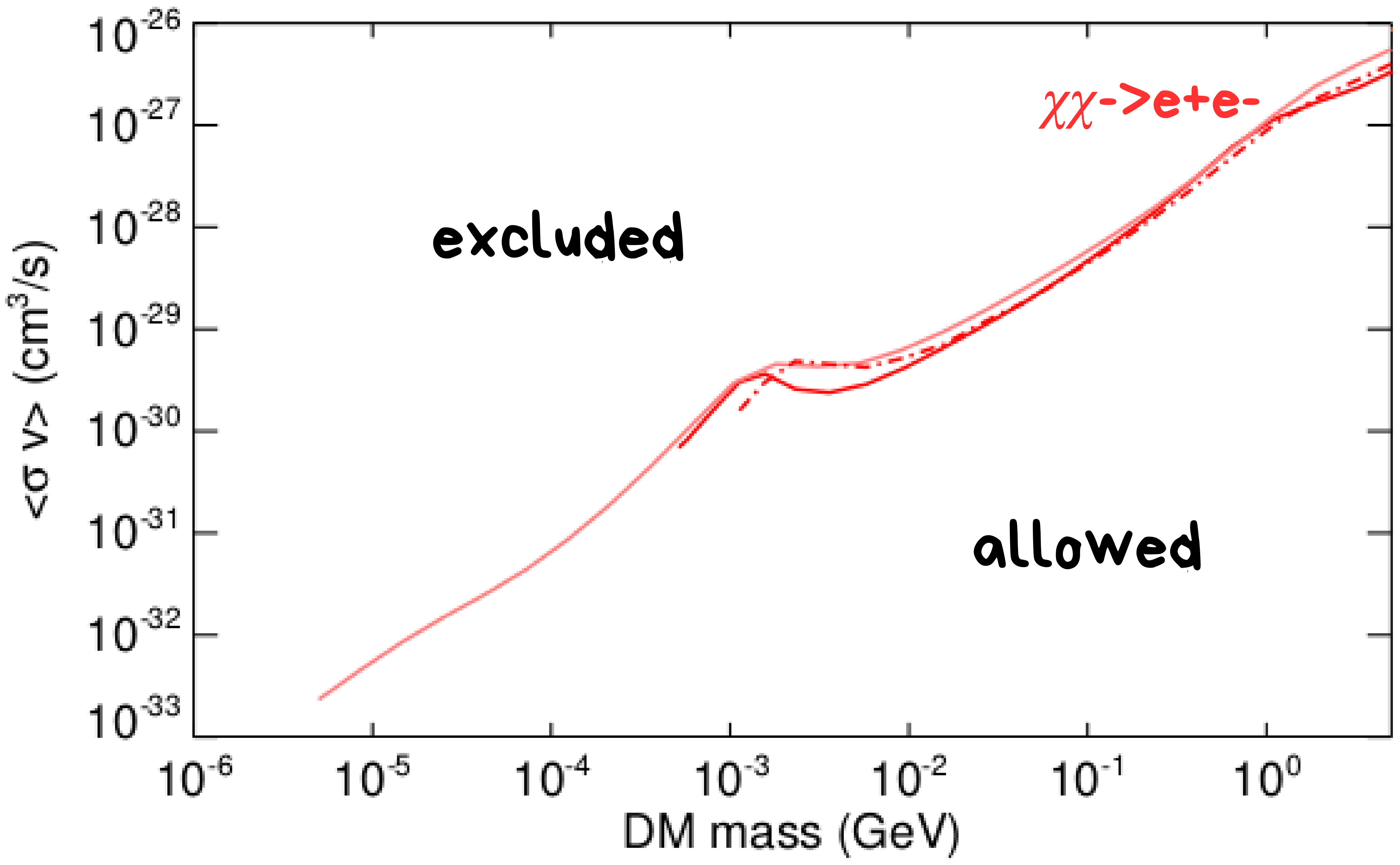
interaction photon/ionized plasma



Constraints on Dark Matter

CMB Constraints

Indirect Dark Matter Signatures in the Cosmic Dark Ages I.
Generalizing the Bound on s-wave Dark Matter Annihilation from Planck



My krampouz and me

s-wave annihilation cross section

velocity dispersion

$$\langle \sigma v \rangle = c_0 + c_1 v^2 + c_2 v^4 + \ldots + c_n v^{2n}$$

s-wave annihilation cross section

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$= 0 \rightarrow$ p-wave

$\neq 0 \rightarrow$ s-wave

s-wave annihilation cross section

velocity dispersion

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$= 0 \rightarrow$ p-wave

$\neq 0 \rightarrow$ s-wave

$$v_{\rm halos} \simeq 10^{-3} c$$
$$v_{\rm CMB} \simeq 10^{-8} c$$

CMB -> strong constraints on annihilation cross section

s-wave annihilation cross section not suppressed during CMB epoch.

Almost every s-wave model excluded

CMB -> strong constraints on annihilation cross section

s-wave annihilation cross section not suppressed during CMB epoch.

Almost every s-wave model excluded

Resonant models can evade

Goal of this work

Being model independant, we want to find the properties that a resonant model must have to evade the actual constraints

- Relic density constraint
- CMB constraints
- Indirect Detection constraints


My krampouz and me
watching a movie

Resonance

$$\sigma v \propto \frac{1}{\left(s - m_R^2\right)^2 + m_R^2 \Gamma^2}$$

$$4m^2 \left(1 + v^2 + v^4 + o(v^6)\right)$$

Resonance

$$\sigma v \propto \frac{1}{(s - m_R^2)^2 + m_R^2 \Gamma^2}$$

$= 0$ for $m_R^2 = 4m^2 \left(1 + v^2\right)$

$4m^2 \left(1 + v^2 + v^4 + o(v^6)\right)$

<=> $\frac{m_R^2 - 4m^2}{4m^2} = v^2$

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$\iff \frac{m_R^2 - 4m^2}{4m^2} = v^2$

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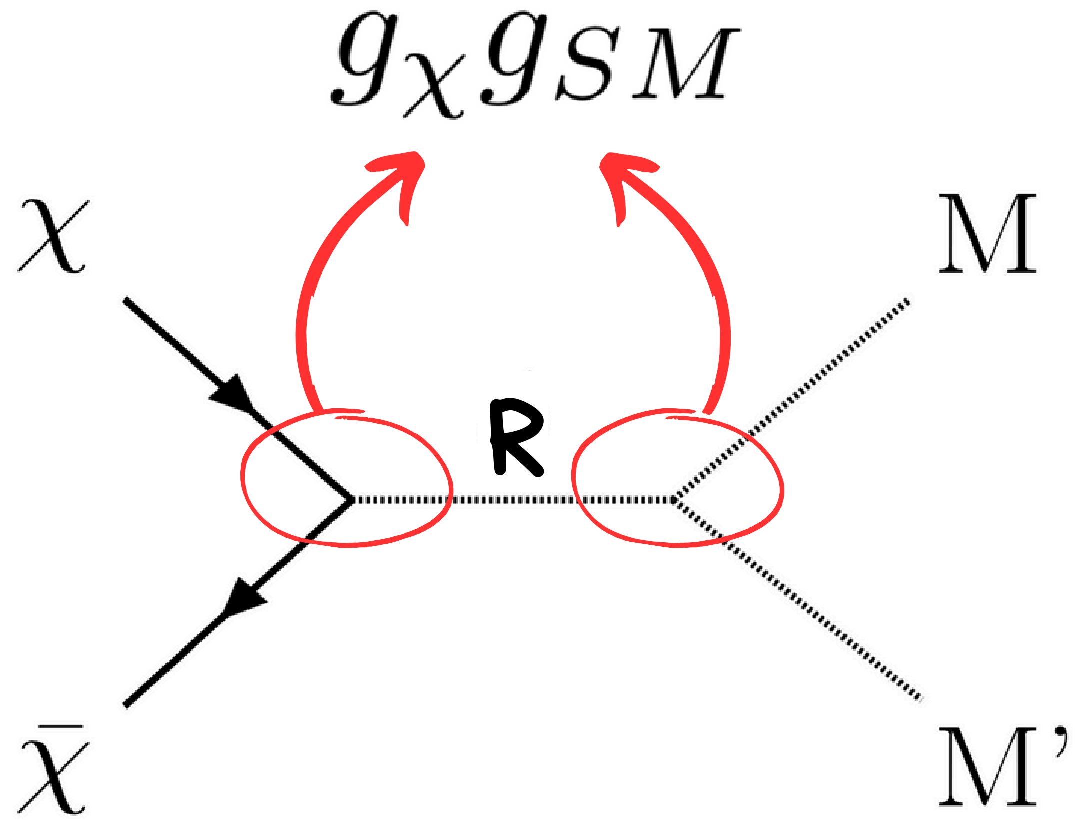
Resonance

$$\frac{1}{\Omega h^2} \propto \int \sigma \equiv \int \bar{\sigma} \; (g_\chi g_{SM})$$



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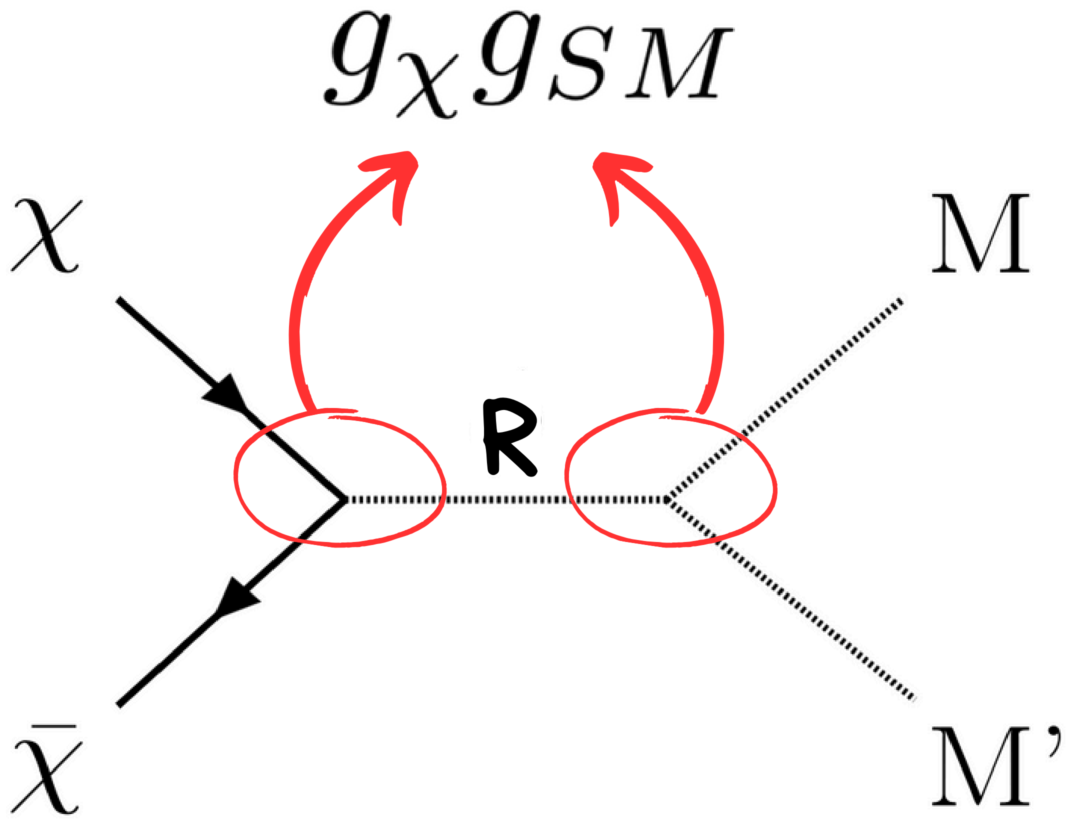

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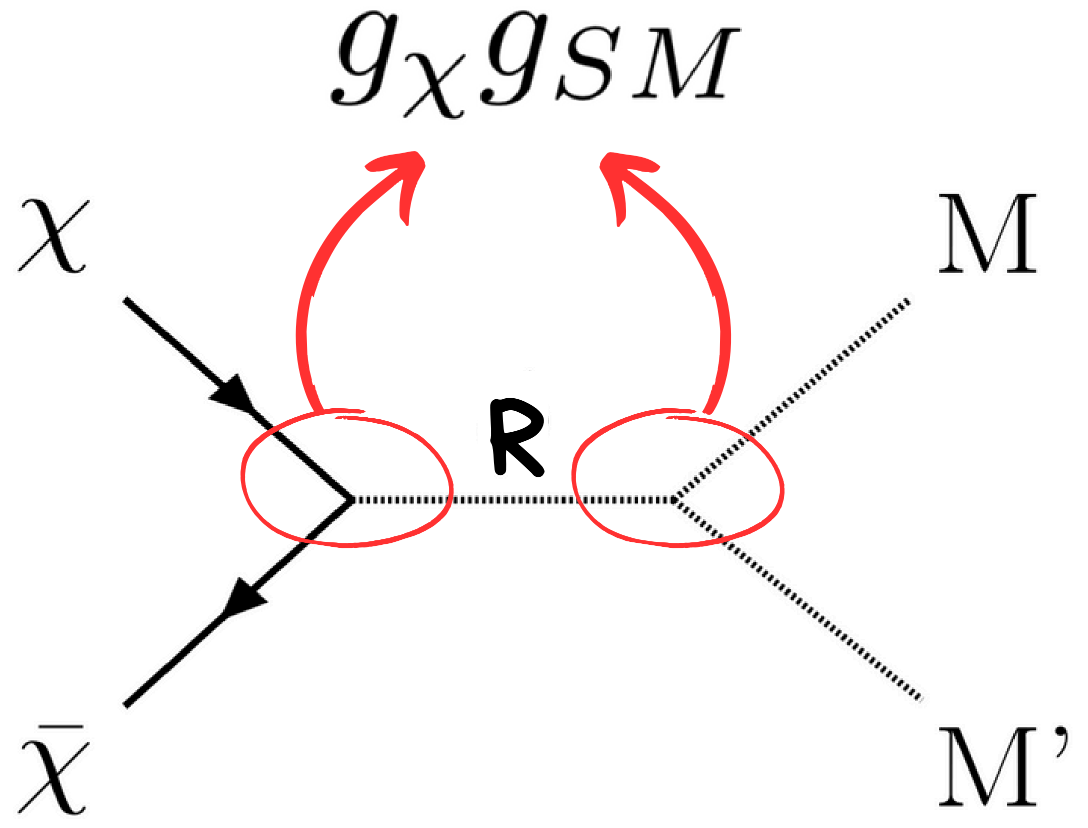

Resonance

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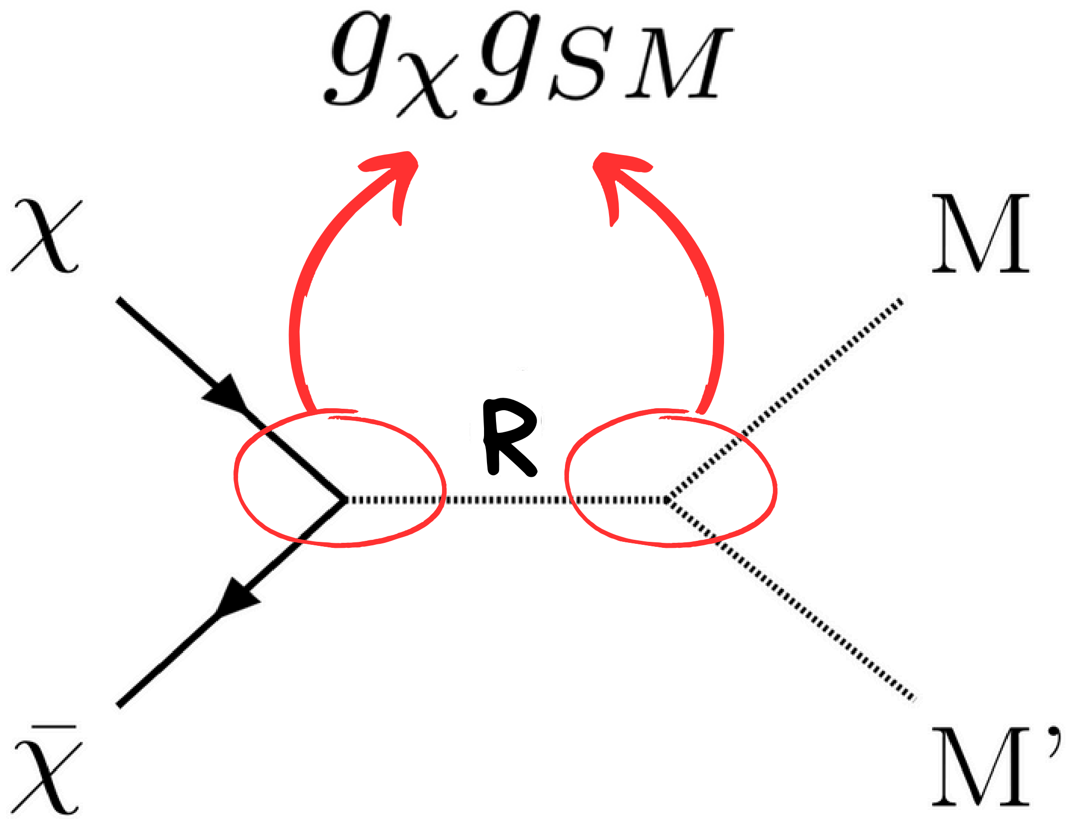

During CMB epoch, not boosted !

$$\bar{\sigma}_{\text{CMB}}(g_\chi g_{SM})$$

Resonance

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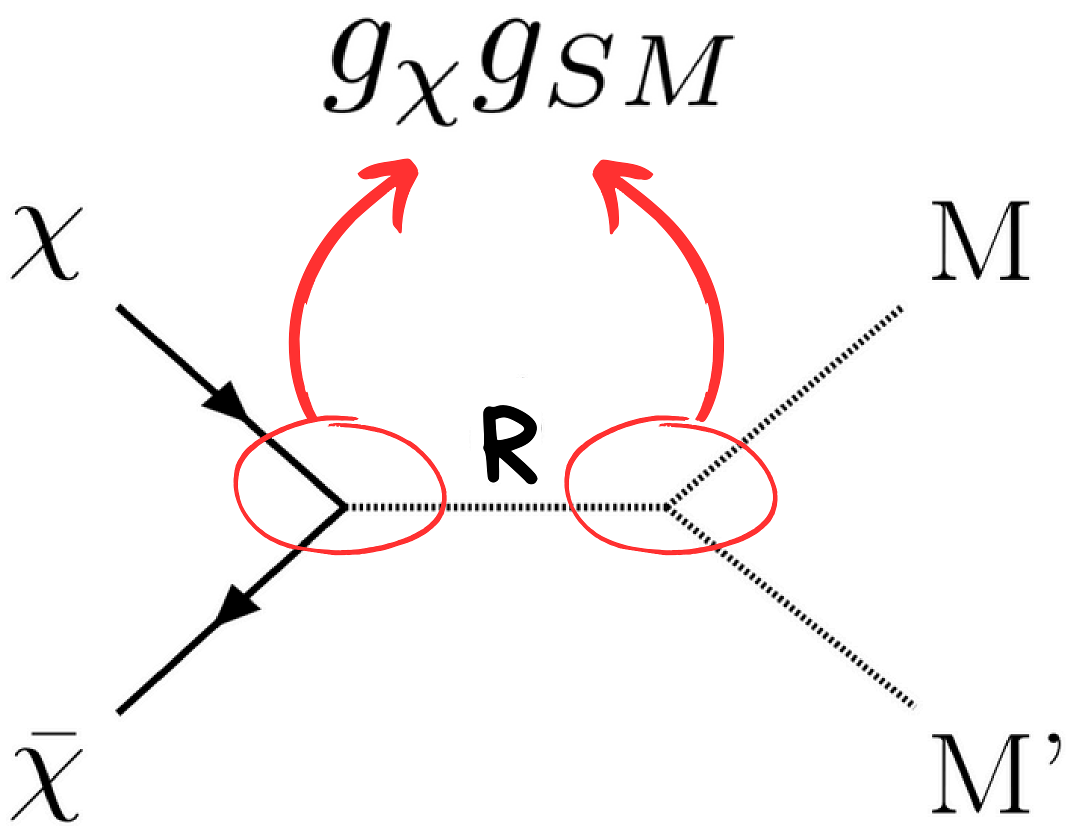

During CMB epoch, not boosted !

$$\bar{\sigma}_{\text{CMB}}(g_\chi g_{SM})$$

Can escape the constraint


My krampouz and me drinking beer

4 parameters to describe a model:

$$m_\chi^2$$

Mass of Dark Matter

$$\epsilon_R \equiv \frac{m_R^2}{4m_\chi^2} - 1$$

Deviation from the exact resonant position

Width of the resonance

$$\gamma_R \equiv \frac{m_R \Gamma_R}{4m_\chi^2}$$

Branching ratio of resonant particle into DM

$$b_R \equiv \omega \bar{B}_\chi (1 - \bar{B}_\chi)$$

3 Constraints

$$\Omega_\chi h^2 \simeq 5.5 \times 10^{-13} N_\chi \frac{m_{\chi\mathrm{GeV}}^2 \epsilon_R^{1/2}}{b_R \gamma_R \bar{g}_*^{1/2}}$$

Relic density

3 Constraints

$$\Omega_\chi h^2 \simeq 5.5 \times 10^{-13} N_\chi \frac{m^2_{\chi\mathrm{GeV}} \epsilon_R^{1/2}}{b_R \gamma_R \bar{g}_*^{1/2}}$$

Relic density

$$\langle \sigma v \rangle_{\mathrm{CMB}} \simeq \frac{8\pi b_R \gamma_R}{m_\chi^2 \epsilon_R^{1/2} (\gamma_R^2 + \epsilon_R^2)}$$

CMB constraint

3 Constraints

$$\Omega_\chi h^2 \simeq 5.5 \times 10^{-13} N_\chi \frac{m^2_{\chi\mathrm{GeV}} \epsilon_R^{1/2}}{b_R \gamma_R \bar{g}_*^{1/2}}$$

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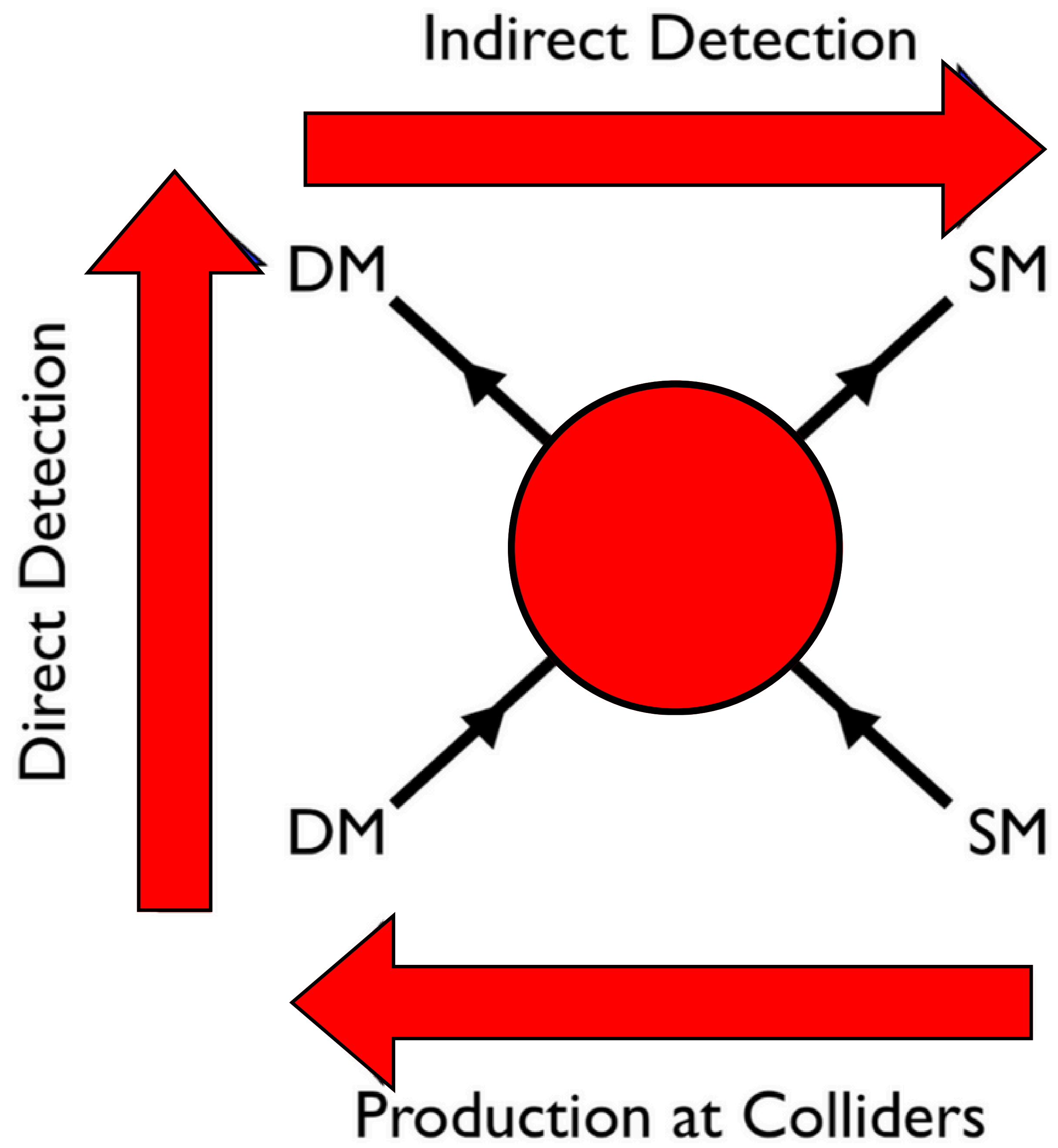
CMB constraint

$$\langle \sigma v \rangle_{\mathrm{halo}} \simeq \frac{16\pi^{3/2} b_R \gamma_R}{m^2_{\mathrm{DM}}} x^{3/2}_{\mathrm{halo}} e^{-x_{\mathrm{halo}} \epsilon_R}$$

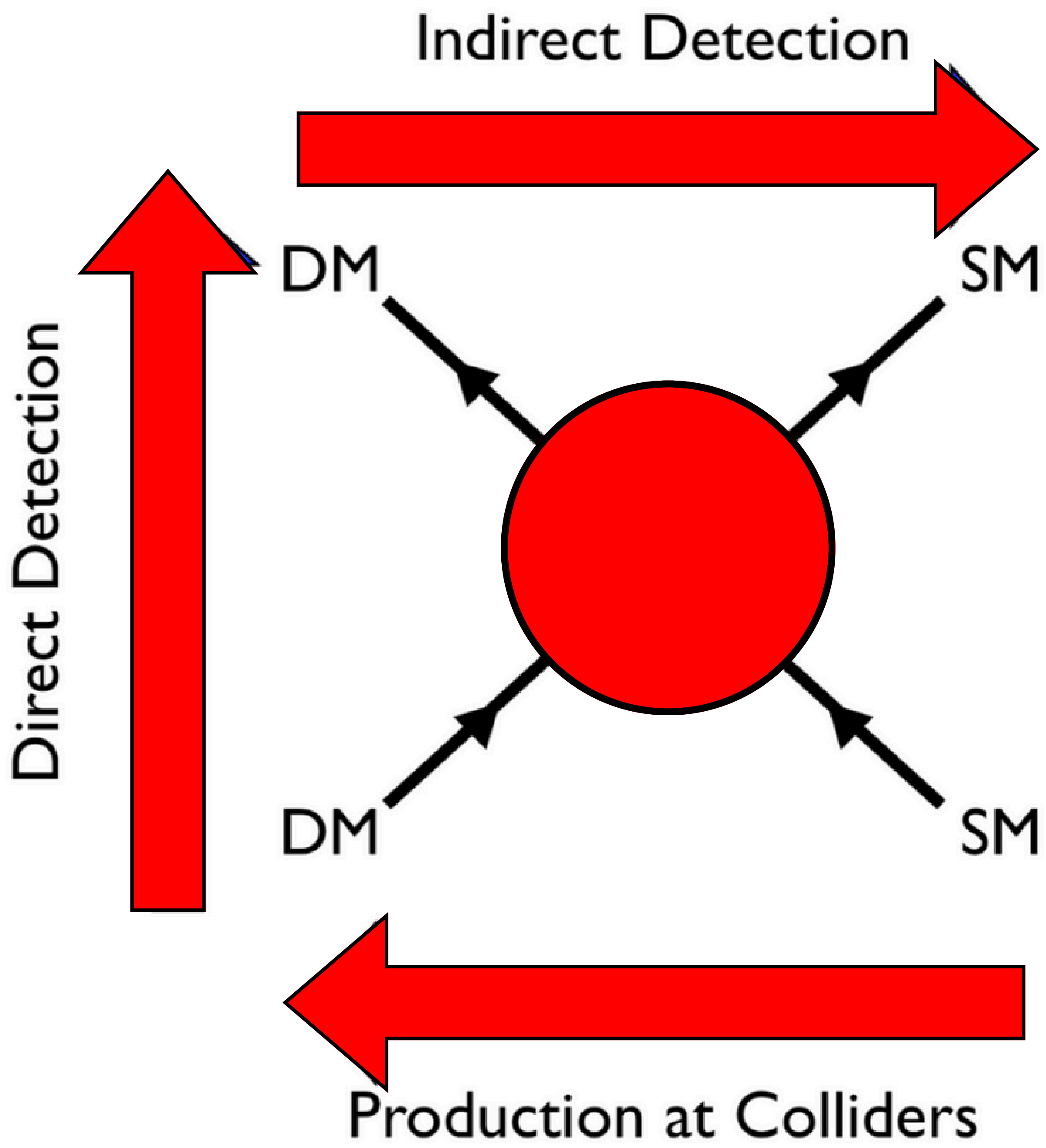
Indirect Detection constraint

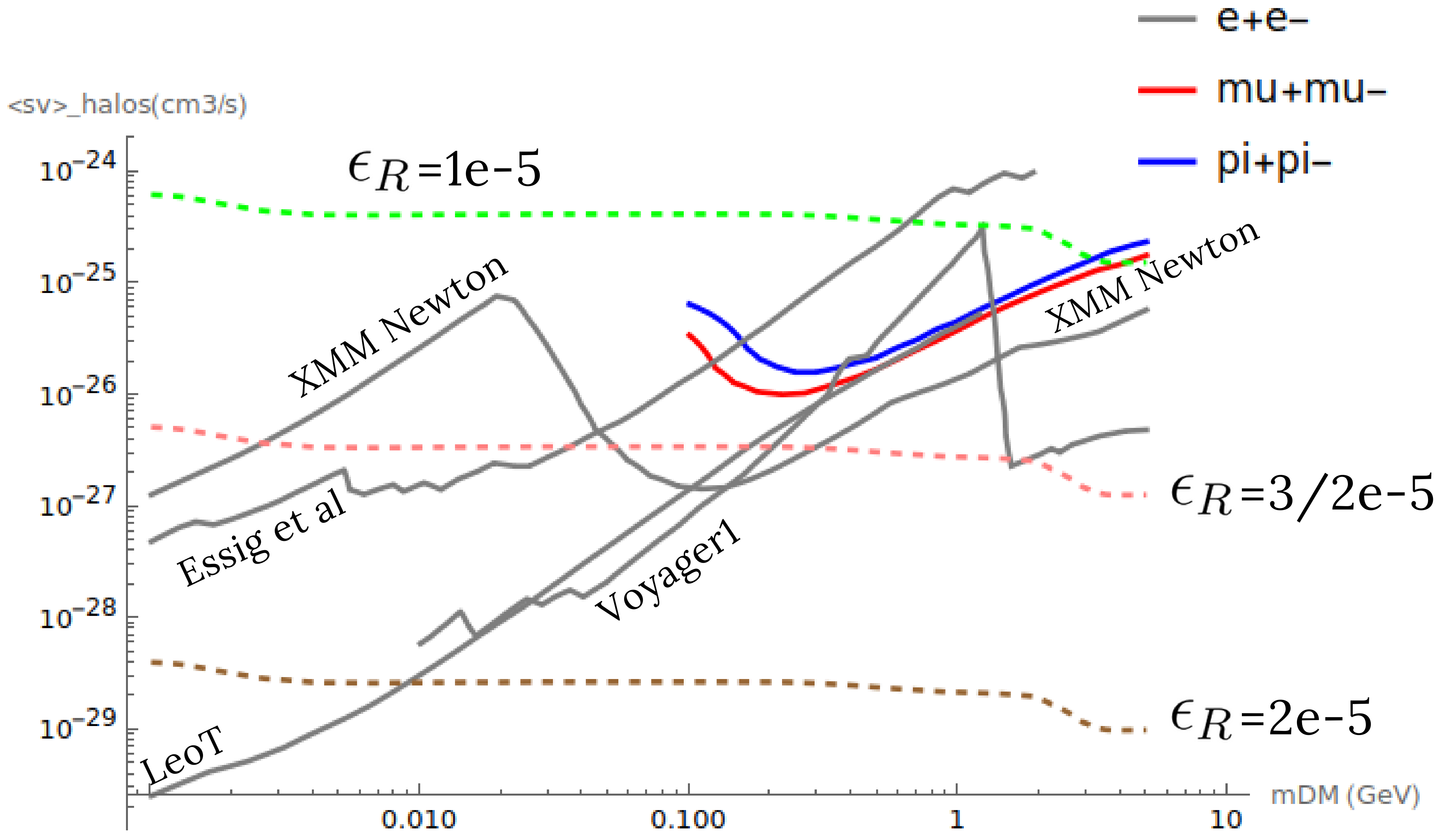
My krampouz and me quarreling

Indirect Detection



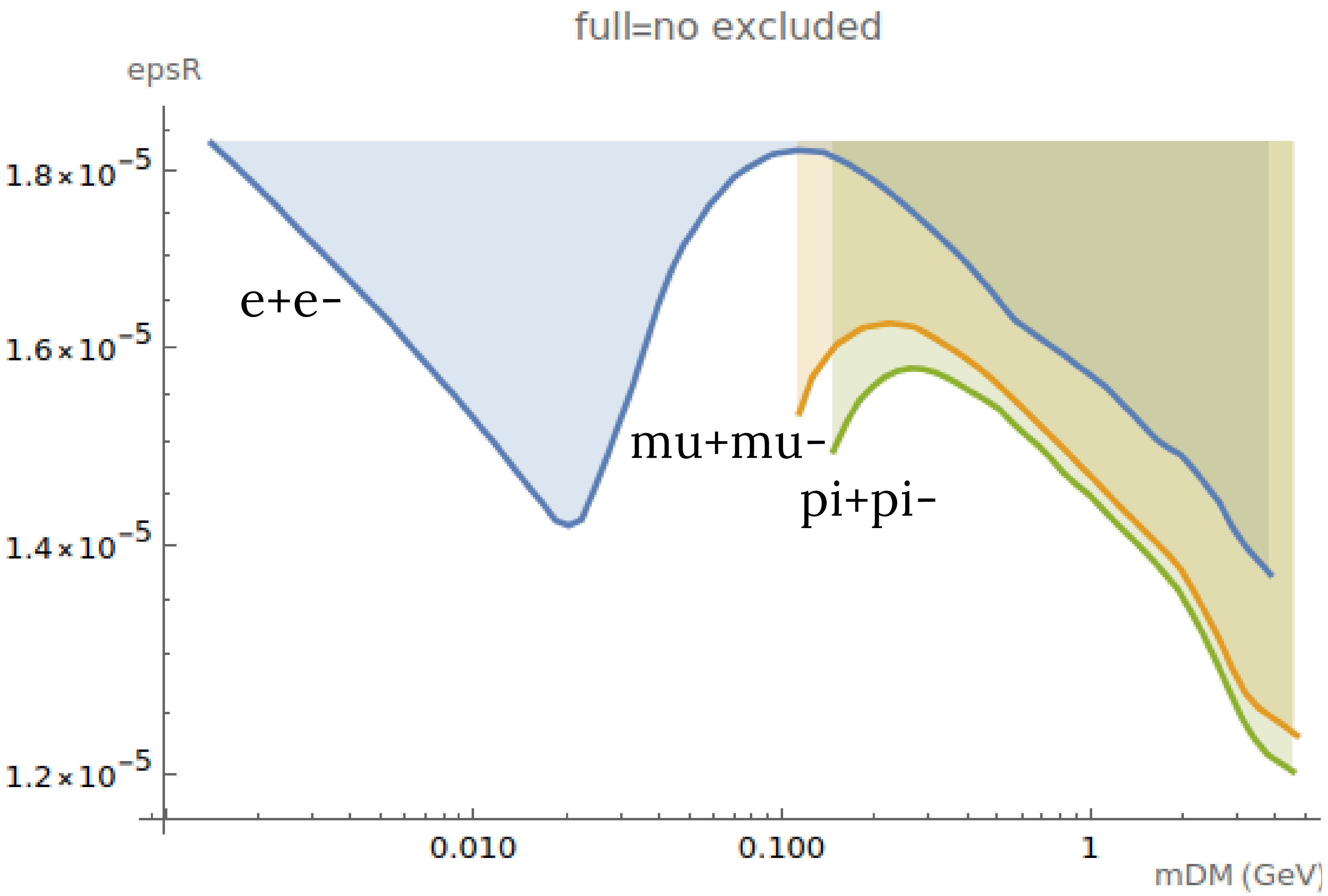
Indirect Detection



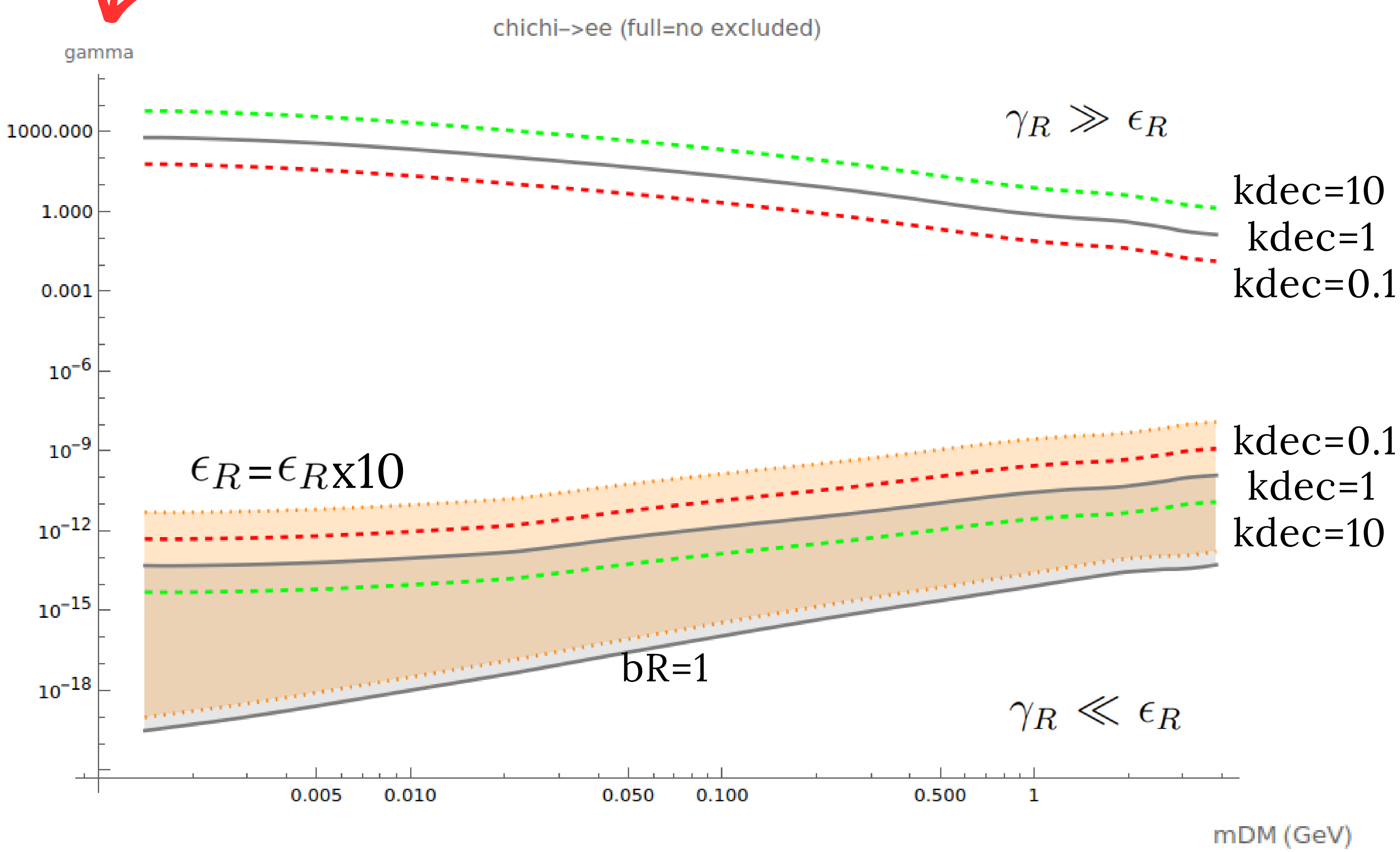


arXiv:2007.11493v5 [hep-ph] 5 Jul 2022

Properties of the resonance



Width of the resonance




My krampouz and me being upset
after the quarrel

Summary

Can we evade the CMB constraints being s-wave ?

In a case of a resonance, YES

We saw the properties that must have this resonance, being model-independant

Summary

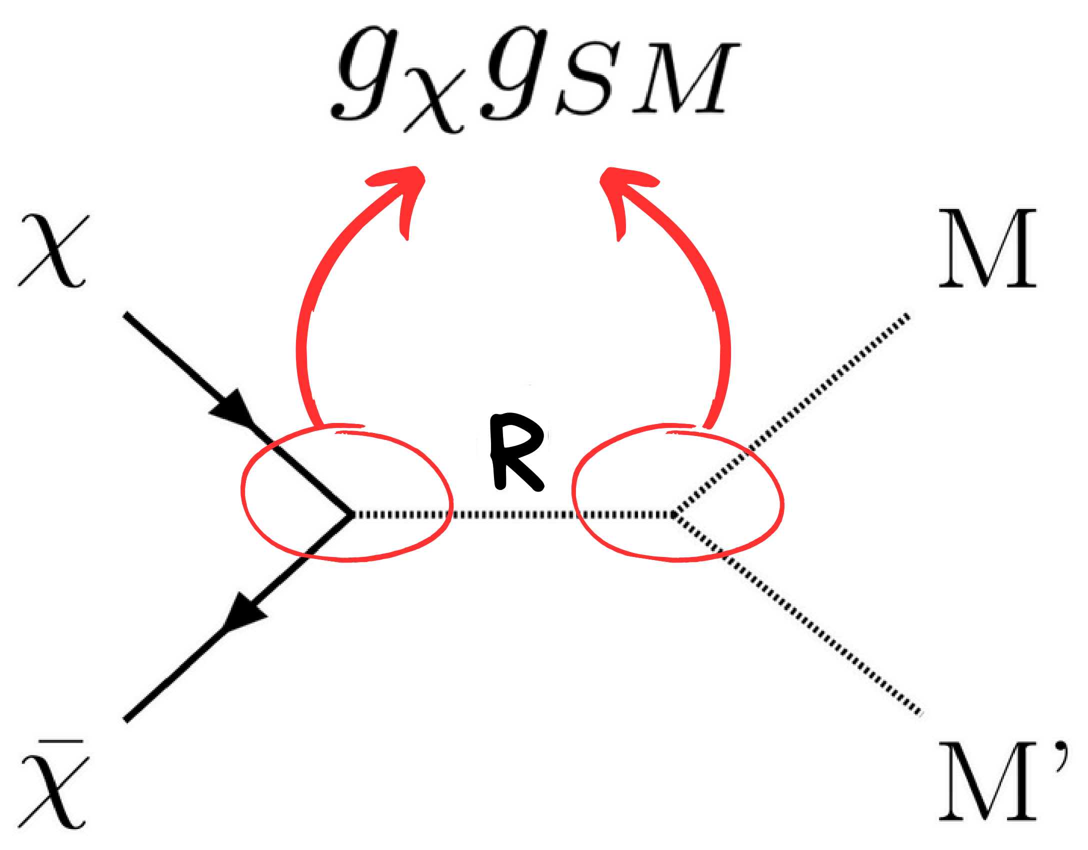
We cannot exclude all s-wave models for thermal DM with indirect detection, even improving the experiments

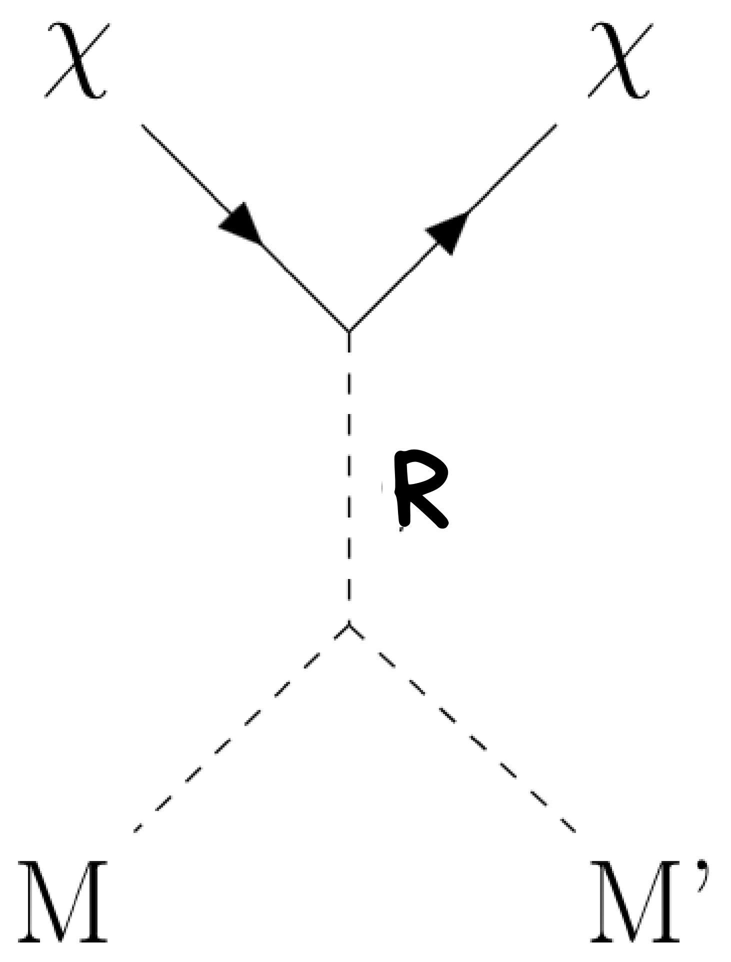
Dark zone: kinetic decoupling


My krampouz and me reconciling

Kinetic decoupling

$$\frac{1}{\Omega h^2} \propto \int \sigma \equiv \int \bar{\sigma}\,(g_\chi g_{SM})$$

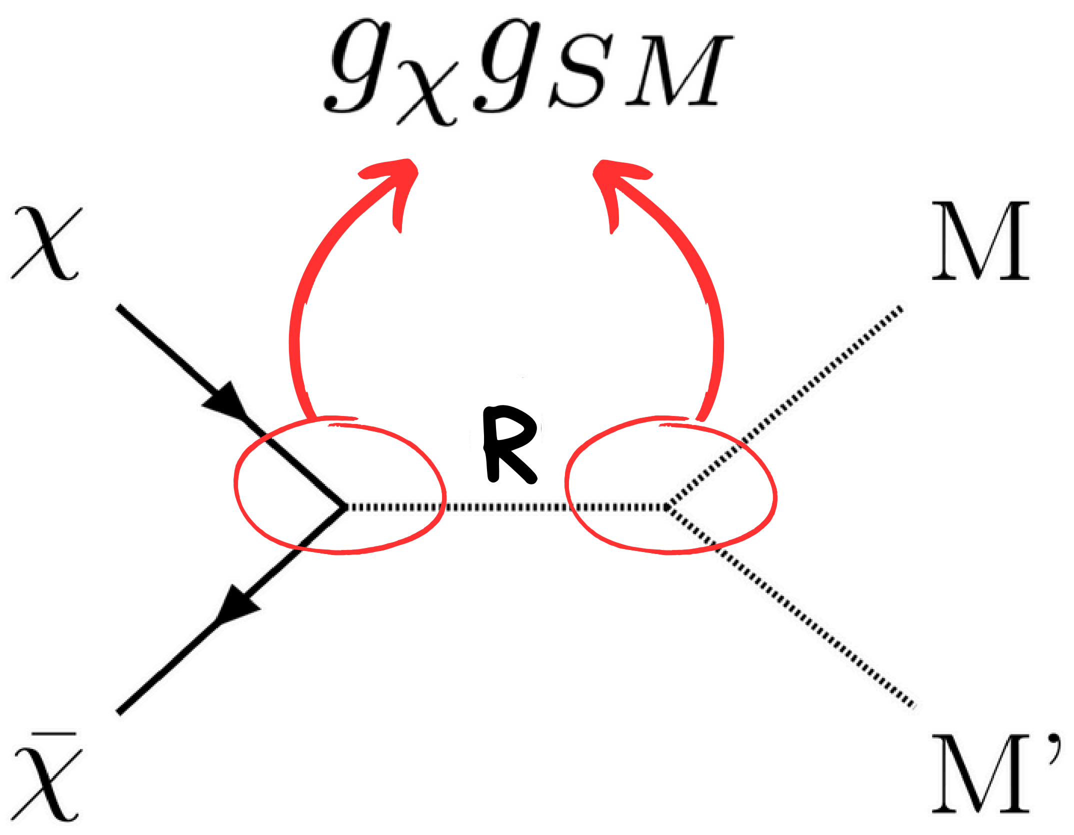




$$\bar{\sigma}_{\text{Bis}}(g_\chi g_{SM})$$

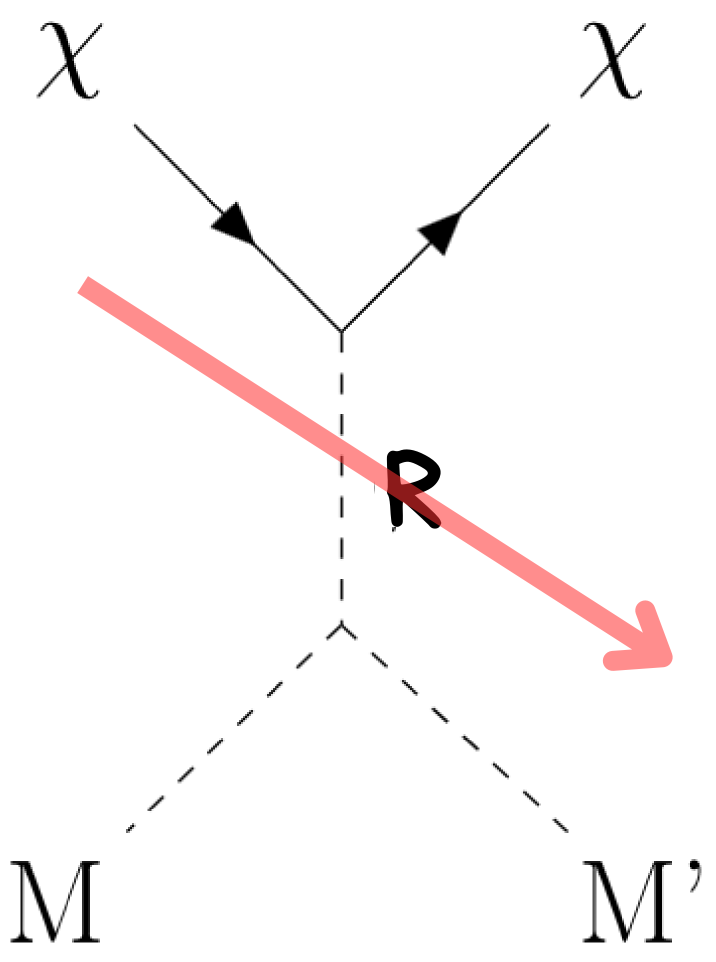
Kinetic decoupling

$$\frac{1}{\Omega h^2} \propto \int \sigma \equiv \int \bar{\sigma} \left(g_\chi g_{SM} \right)$$



no longer efficient
exchange of energy

$$\bar{\sigma}_{\text{Bis}} \left(g_\chi g_{SM} \right)$$



Kinetic decoupling

Binder, Tobias ; Bringmann, Torsten ; Gustafsson, Michael ; Hryczuk, Andrzej

DRAKE: Dark matter relic abundance beyond kinetic equilibrium

full Boltzman equation:

$$
\begin{aligned}
E\left(\partial_t - Hp\partial_p\right) f_\chi = & \frac{1}{2g_\chi}\int\frac{d^3\tilde{p}}{(2\pi)^3 2\tilde{E}}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}} \\
& \times(2\pi)^4\delta^{(4)}(\tilde{p}+p-\tilde{k}-k) \\
& \times\left[|\mathcal{M}|^2_{\bar{\chi}\chi\leftarrow\bar{f}f}\, g(\omega)g(\tilde{\omega}) - |\mathcal{M}|^2_{\bar{\chi}\chi\rightarrow\bar{f}f}\, f_\chi(E)f_\chi(\tilde{E})\right] \\
+ & \frac{1}{2g_\chi}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}}\int\frac{d^3\tilde{p}}{(2\pi)^3 2\tilde{E}} \\
& \times(2\pi)^4\delta^{(4)}(\tilde{p}+\tilde{k}-p-k)|\mathcal{M}|^2_{\chi f\leftrightarrow\chi f} \\
& \times\left[\left(1\mp g^{\pm}(\omega)\right) g^{\pm}(\tilde{\omega}) f_\chi(\tilde{E}) - (\omega\leftrightarrow\tilde{\omega},\, E\leftrightarrow\tilde{E})\right]
\end{aligned}
$$

annihilation term (first three lines)

elastic scattering term (last three lines)

Kinetic decoupling

Binder, Tobias ;
Bringmann, Torsten ;
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Hryczuk, Andrzej

DRAKE: Dark matter relic abundance beyond kinetic equilibrium

C KONPLIKÉ

full Boltzman equation:

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annihilation term

$$+ \frac{1}{2g_\chi}\int \frac{d^3k}{(2\pi)^3 2\omega} \int \frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}} \int \frac{d^3\tilde{p}}{(2\pi)^3 2\tilde{E}} \times (2\pi)^4 \delta^{(4)}(\tilde{p} + \tilde{k} - p - k)|\mathcal{M}|^2_{\chi f\leftrightarrow\chi f} \times \left[\left(1 \mp g^\pm(\omega)\right) g^\pm(\tilde{\omega}) f_\chi(\tilde{E}) - (\omega \leftrightarrow \tilde{\omega}, E \leftrightarrow \tilde{E})\right]$$

elastic scattering term

Kinetic decoupling

$$\Omega h^2_{\text{real}} = k_{\text{dec}} \Omega h^2_{\text{simplified}}$$

Kinetic decoupling

$$\Omega h^2_{\text{real}} = k_{\text{dec}} \Omega h^2_{\text{simplified}}$$

Conclusion

s-Wave Thermal
Dark Matter

Conclusion

s-wave Thermal
Dark Matter

Freeze-out
scenario

Conclusion

s-wave Thermal Dark Matter

Freeze-out scenario

CMB constraints

Indirect Detection constraints

Conclusion

s-Wave Thermal Dark Matter

Freeze-out scenario

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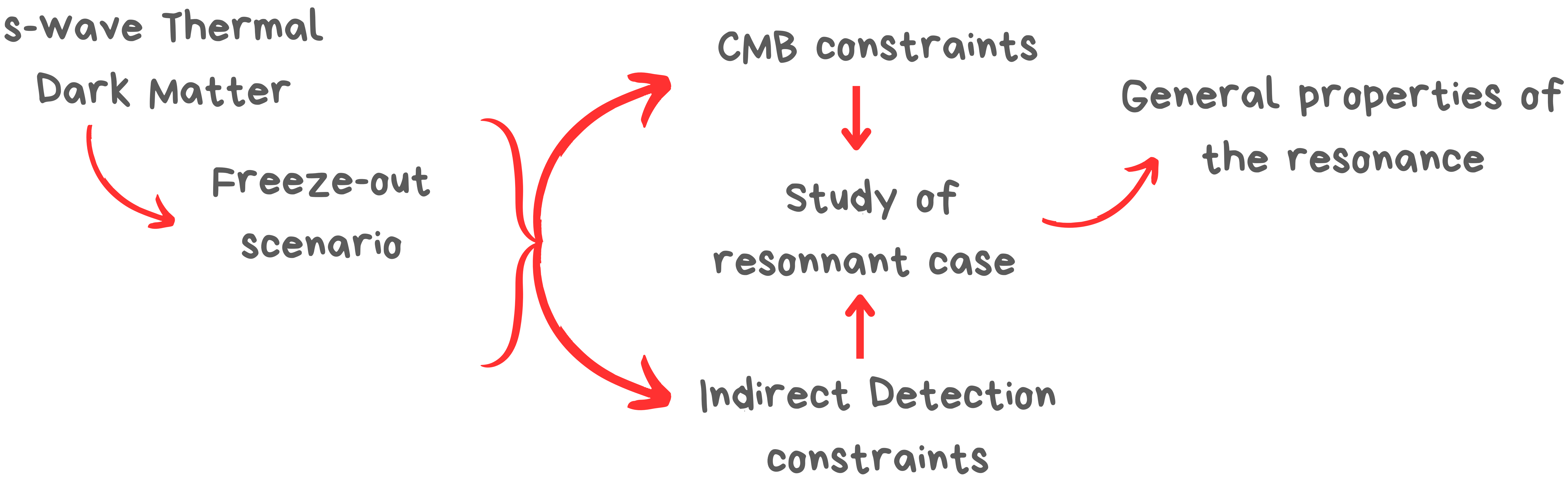
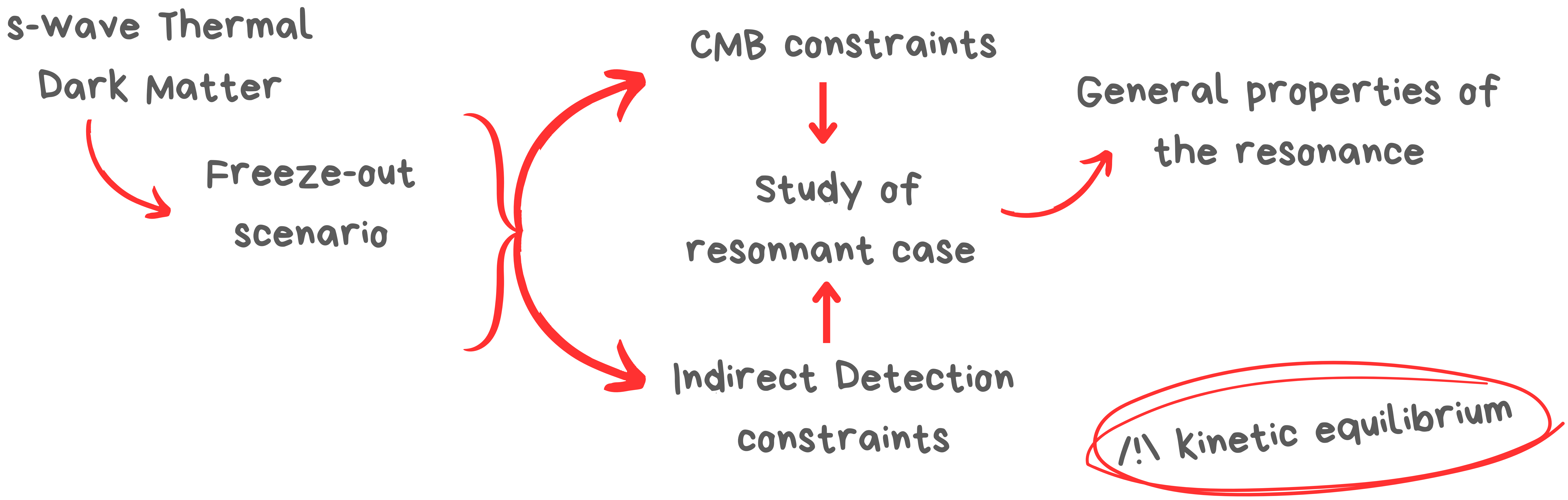
Study of resonnant case

Indirect Detection constraints

Conclusion


s-wave Thermal Dark Matter
Freeze-out scenario
CMB constraints
Study of resonnant case
Indirect Detection constraints
General properties of the resonance

Conclusion


s-wave Thermal
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/!\ kinetic equilibrium

My krampouz and loving each other forever

Thanks