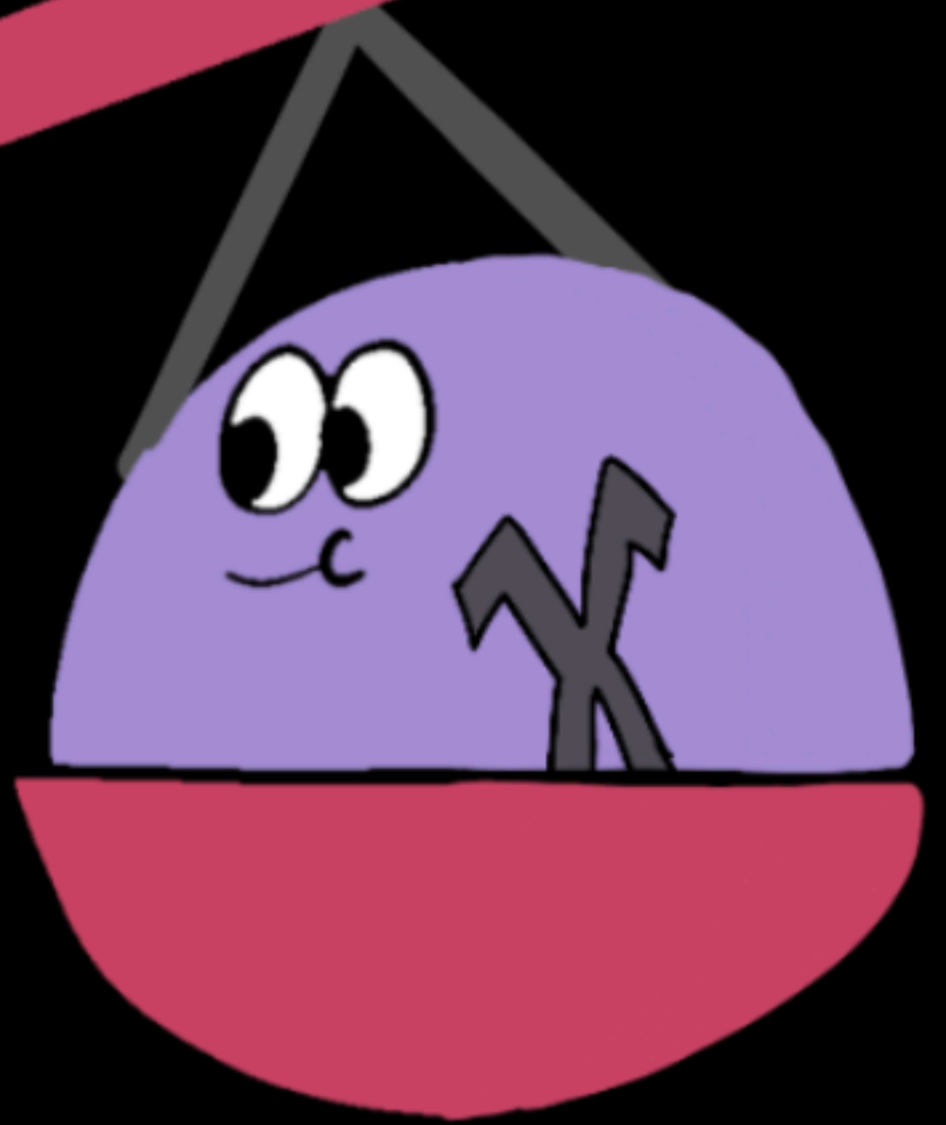
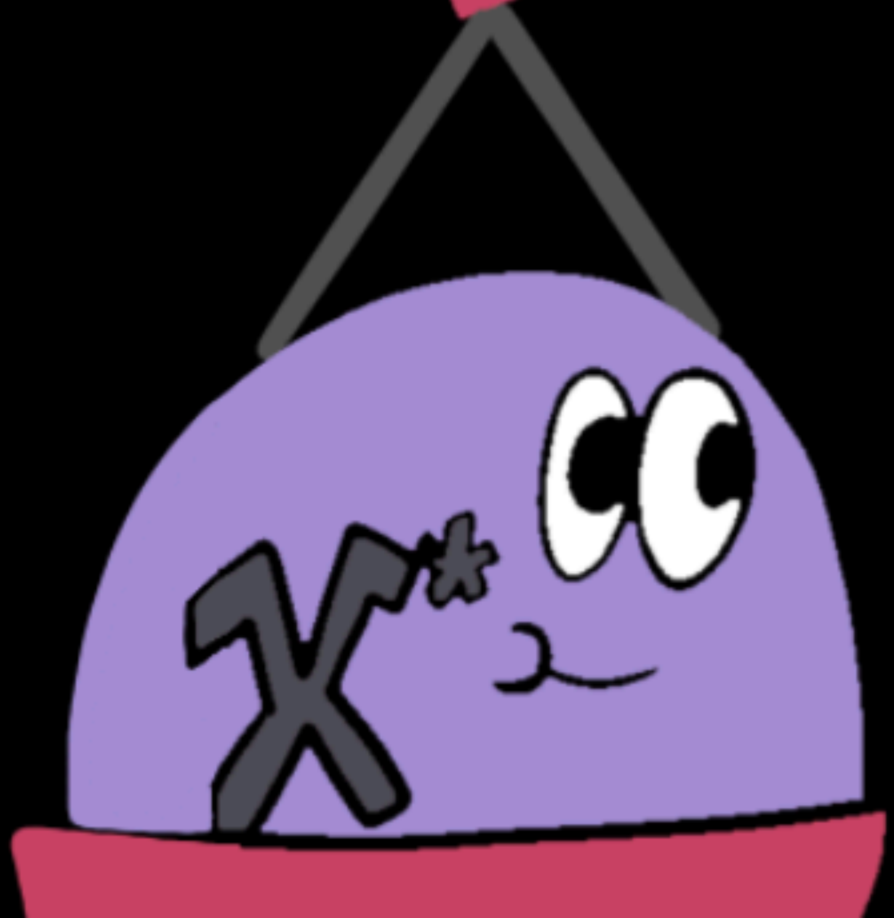
# INELASTIC DARK MATTER THROUGH THE AGES



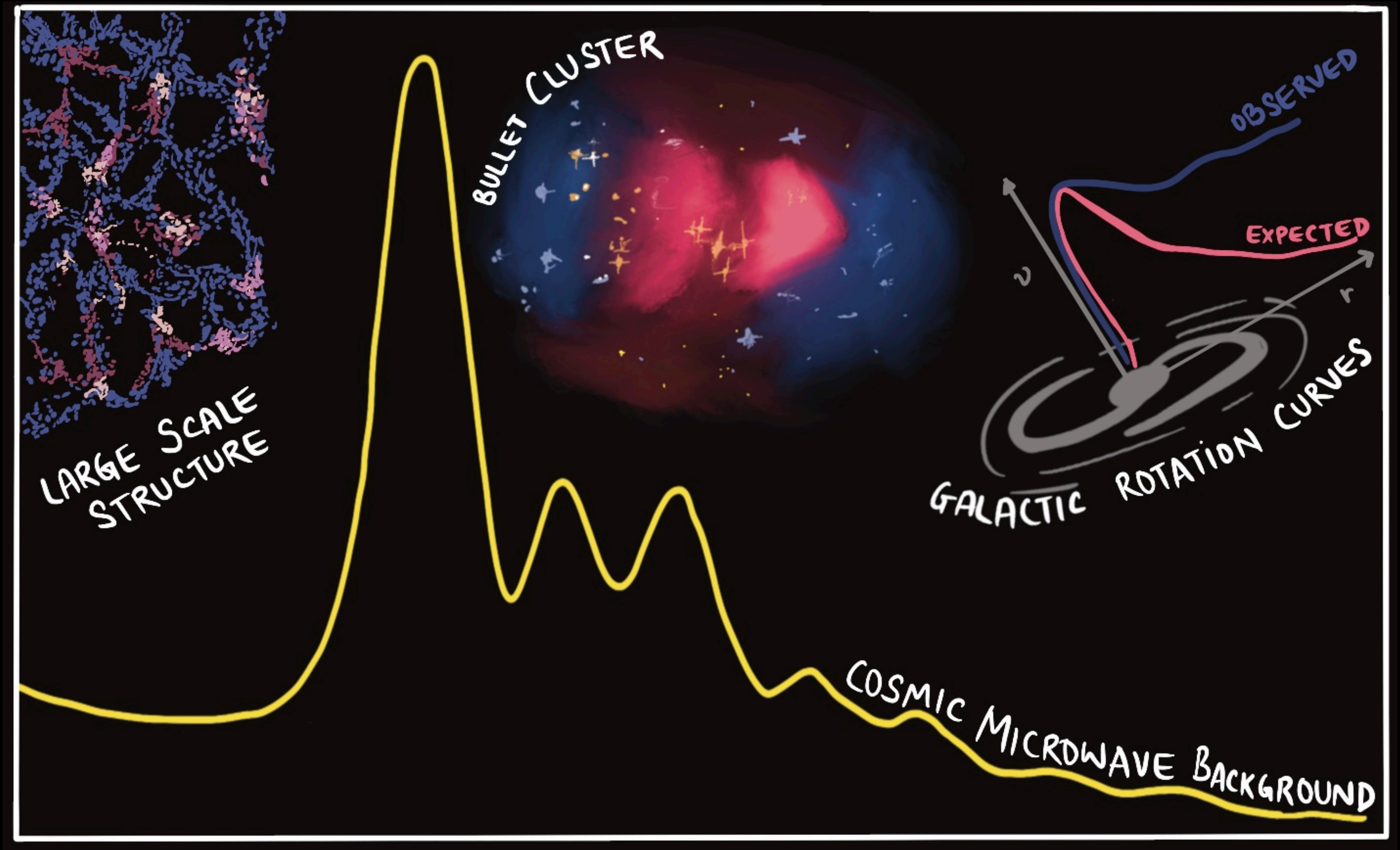


SANIYA HEEBA
TSI, McGILL U.

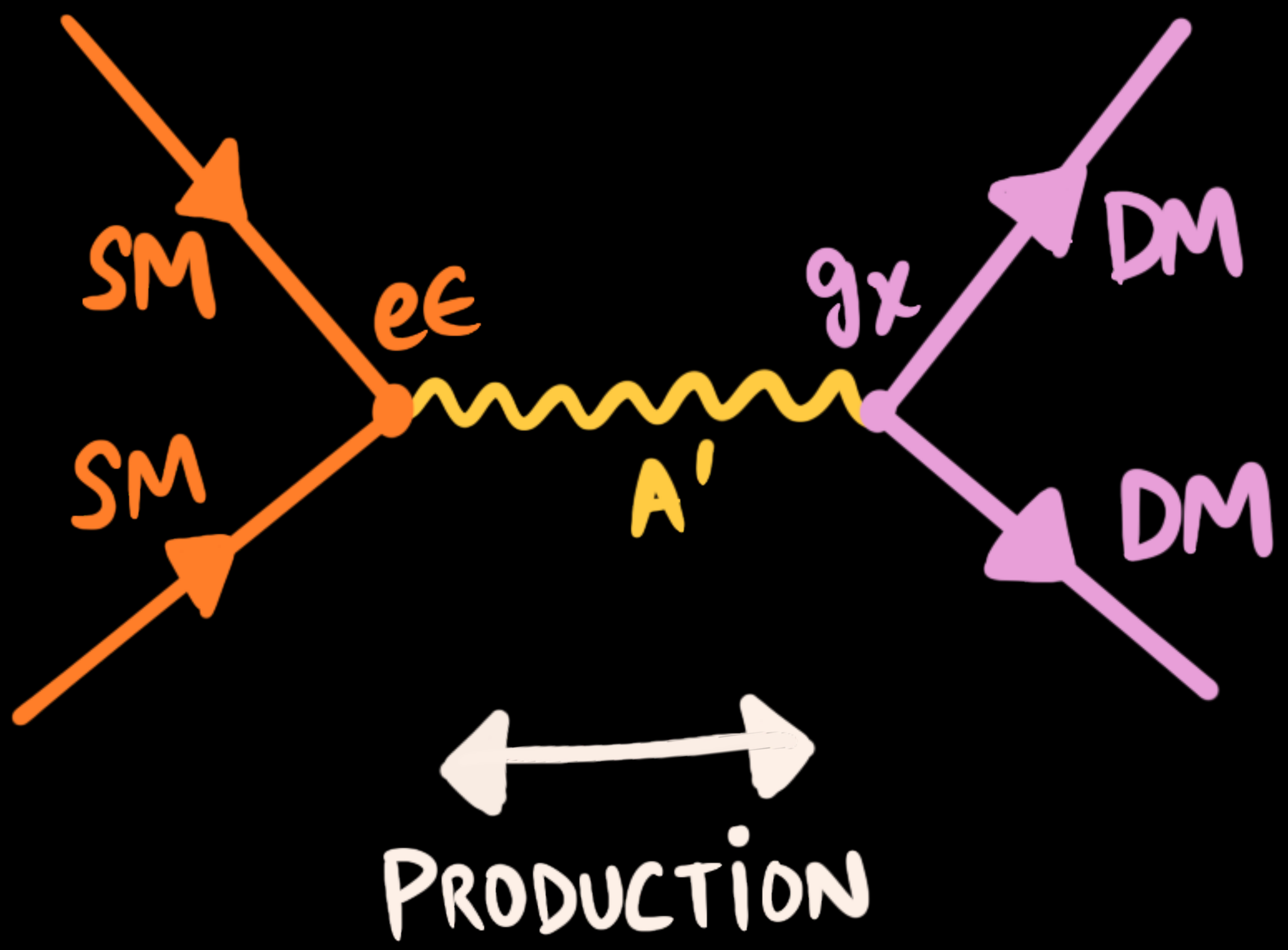
Based on: 2304.06072, 2308.01960
(w/ N. Brahma, T. Lin & K. Schutz)

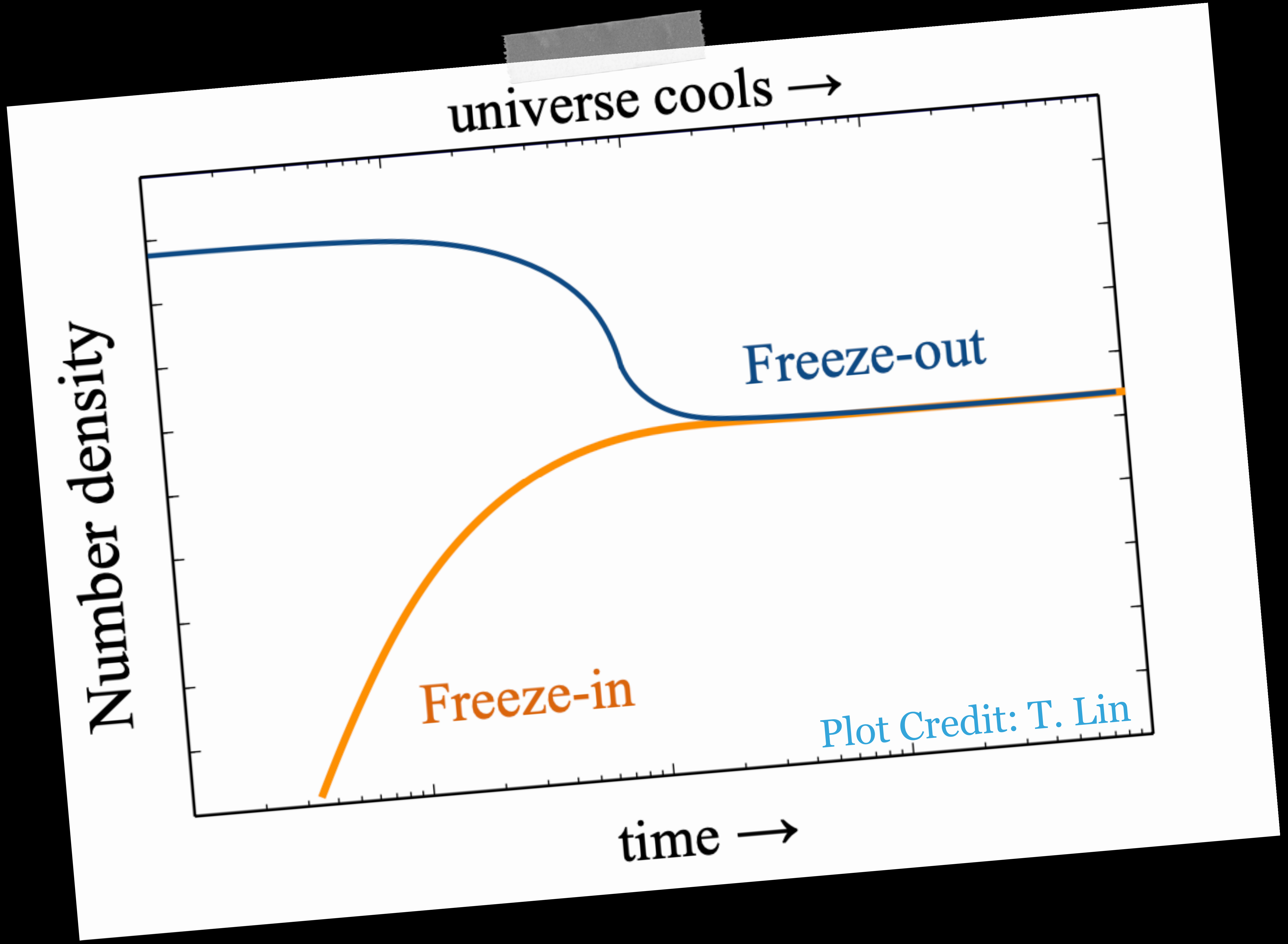
LIGHT DARK WORLD (2023), KARLSRUHE

# WE KNOW THAT DARK MATTER EXISTS

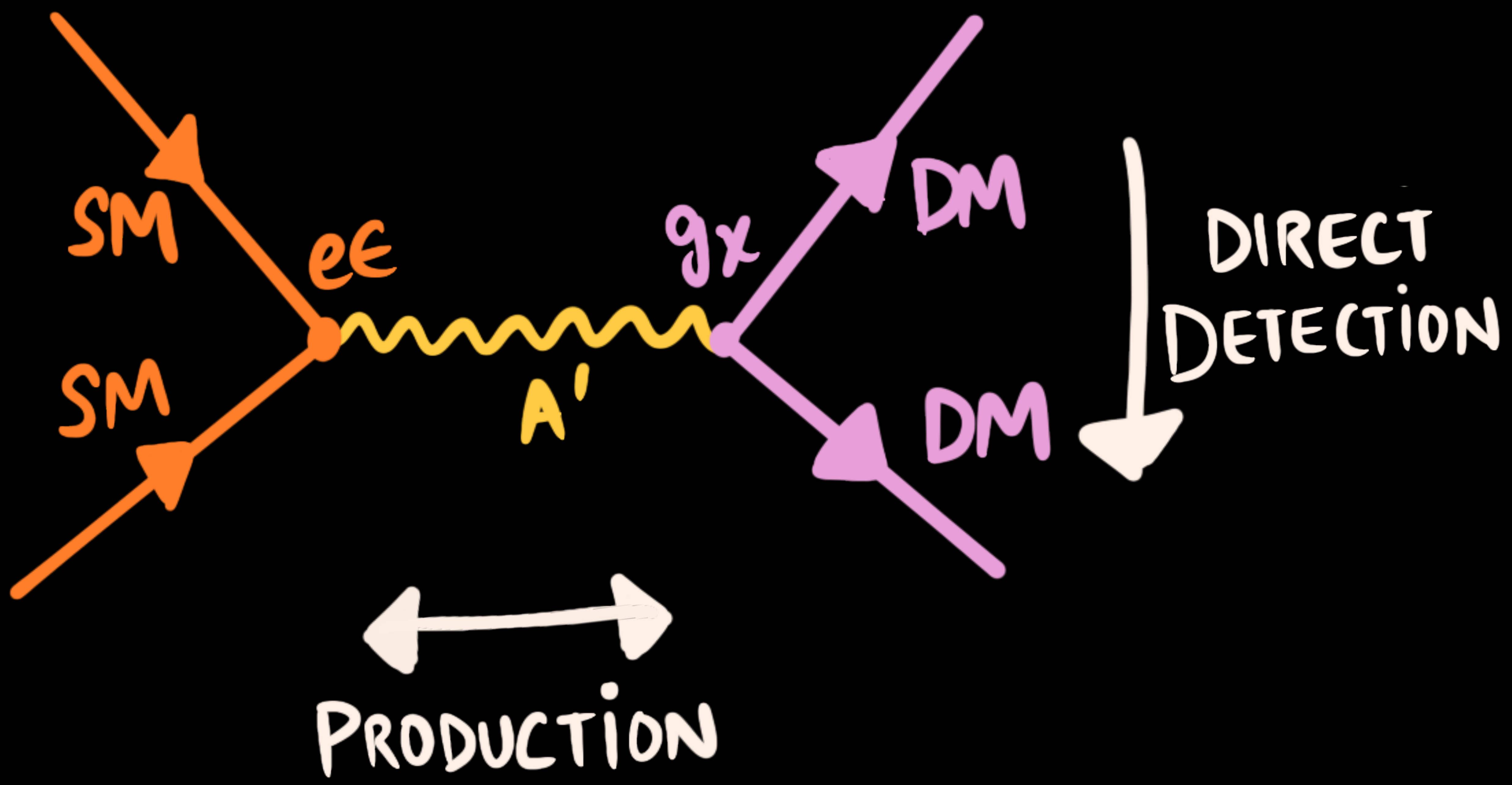


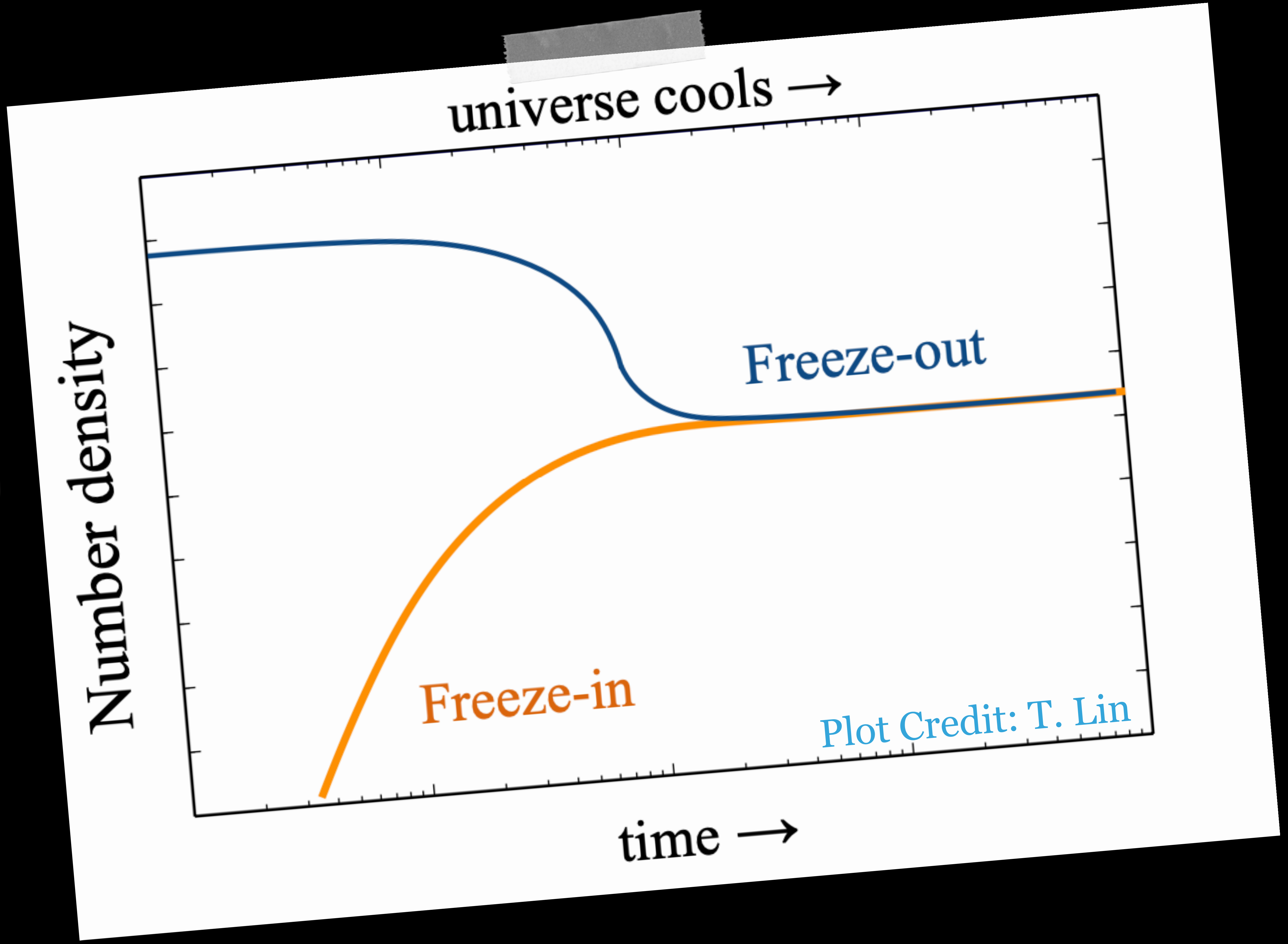
# To figure out where and what to look for, we exploit connections between DM behaviour at early and late times



# TO FIGURE OUT WHERE AND WHAT TO LOOK FOR, WE EXPLOIT CONNECTIONS BETWEEN DM BEHAVIOUR AT EARLY AND LATE TIMES



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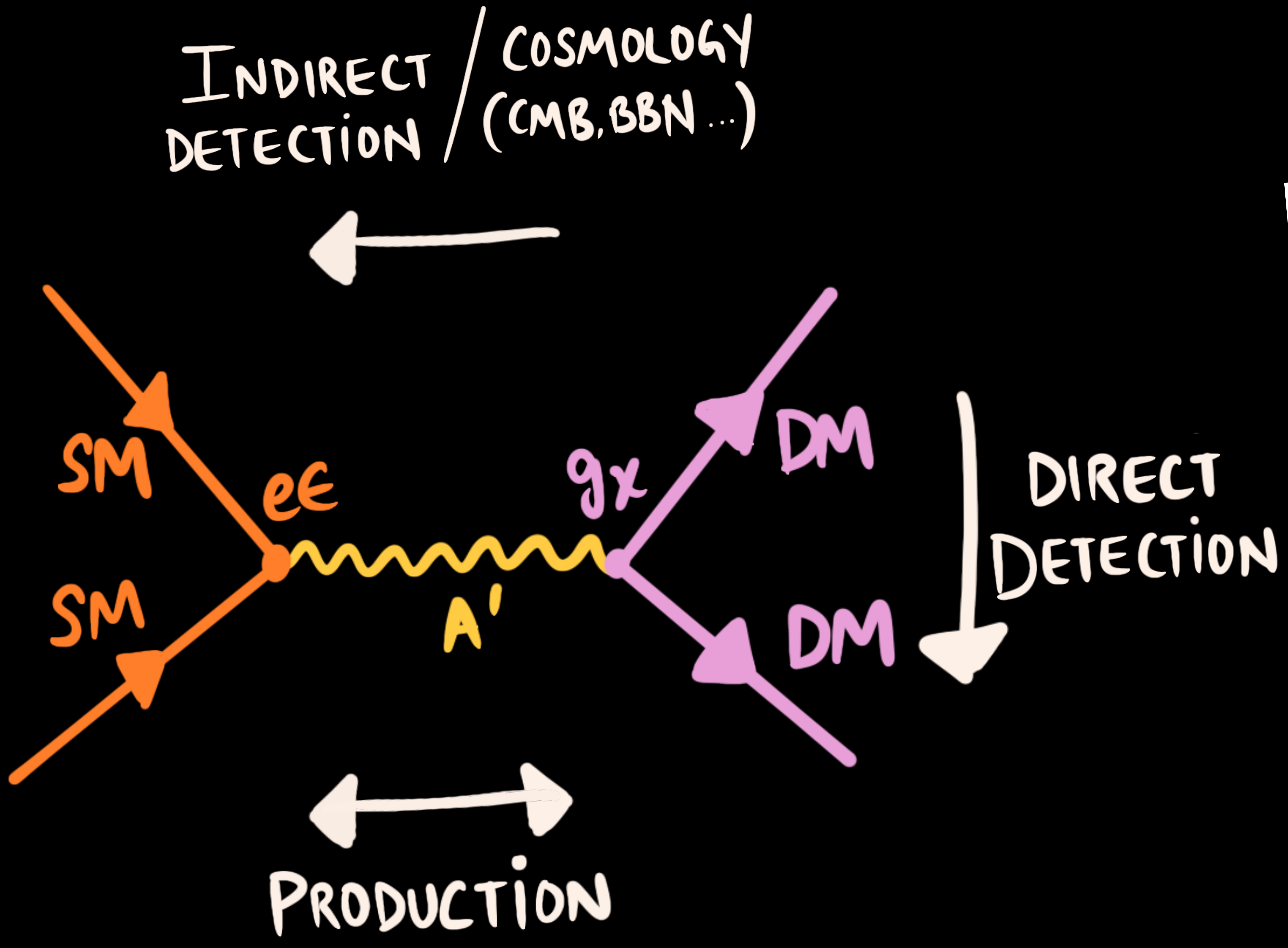


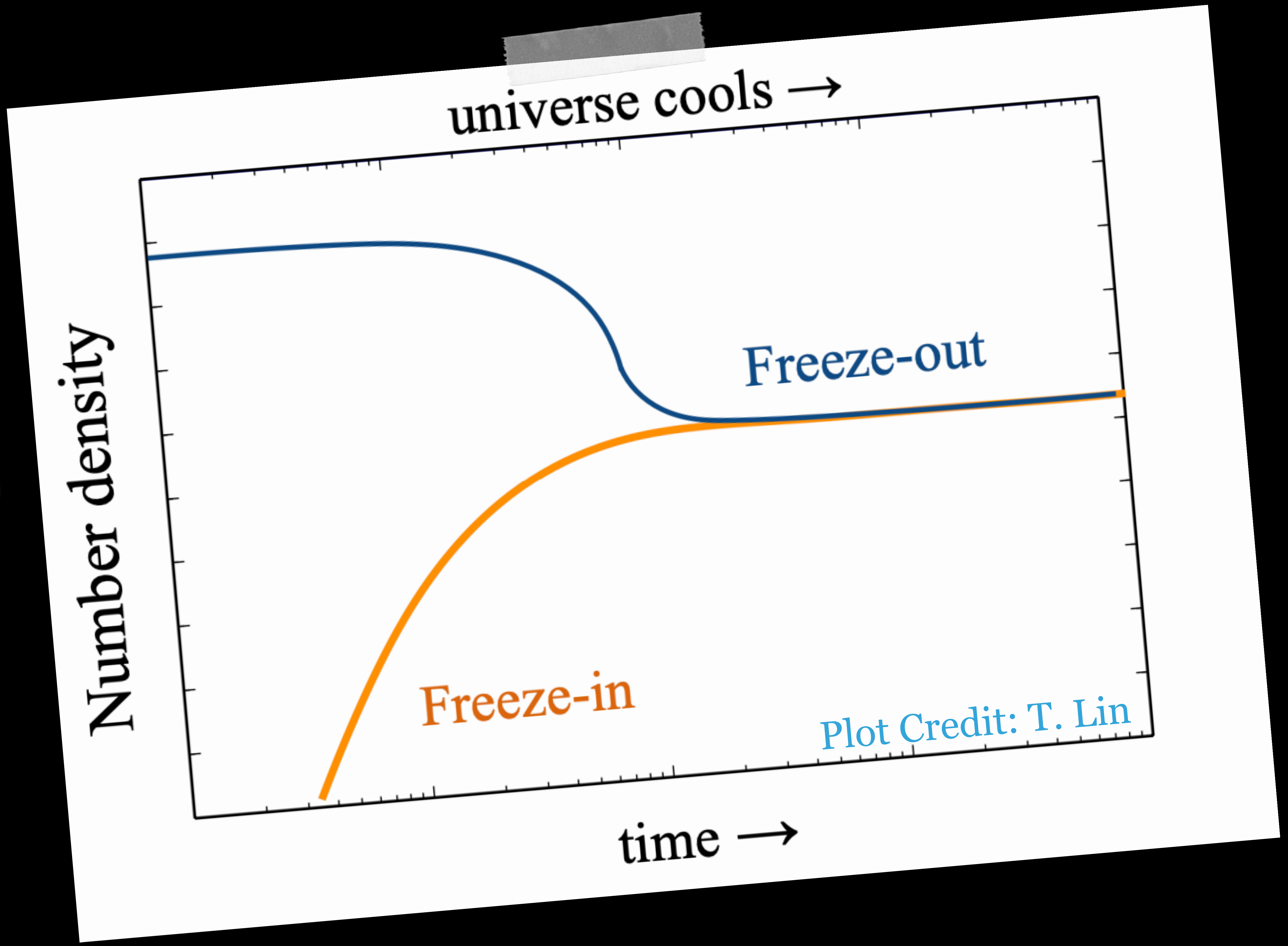

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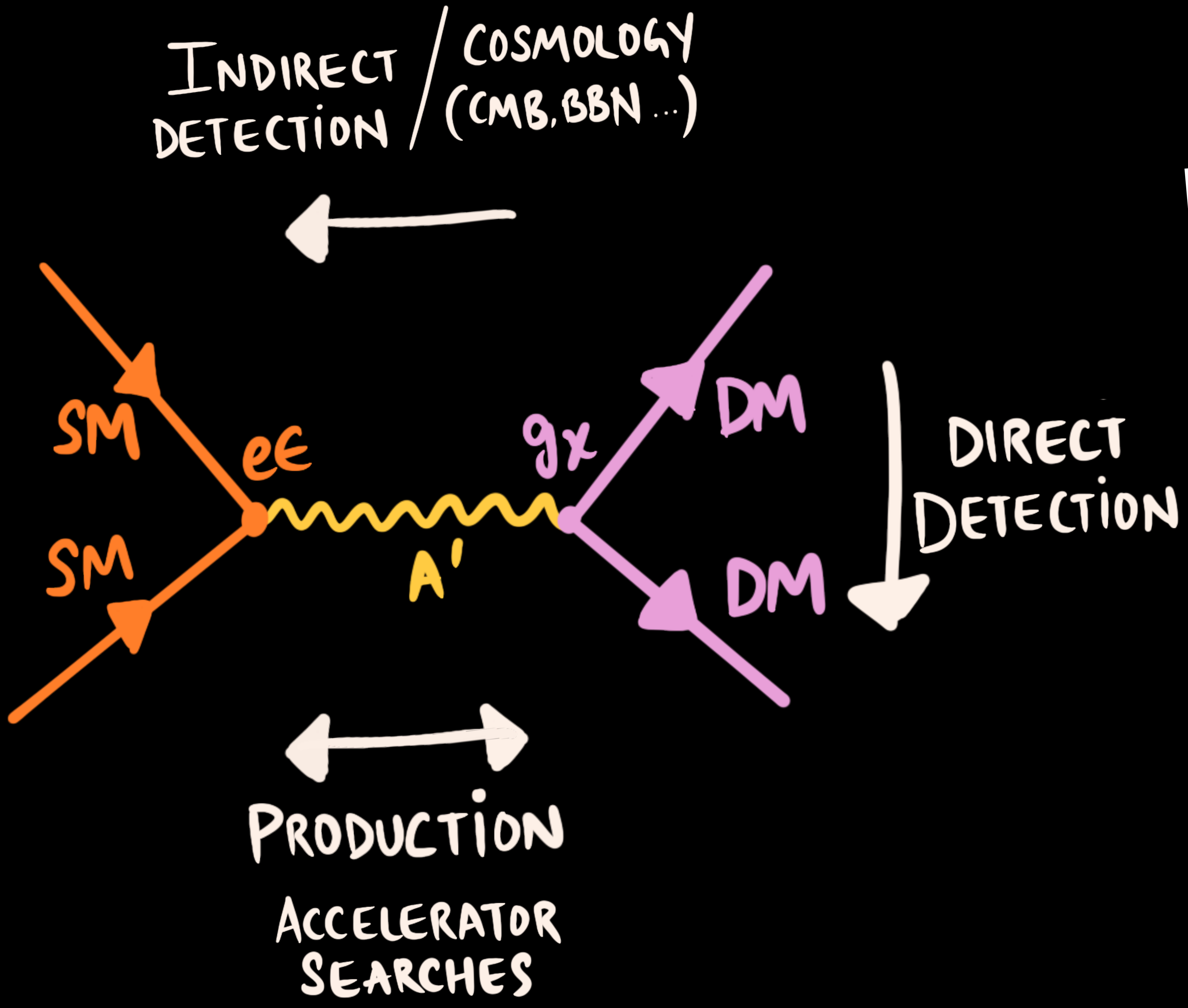


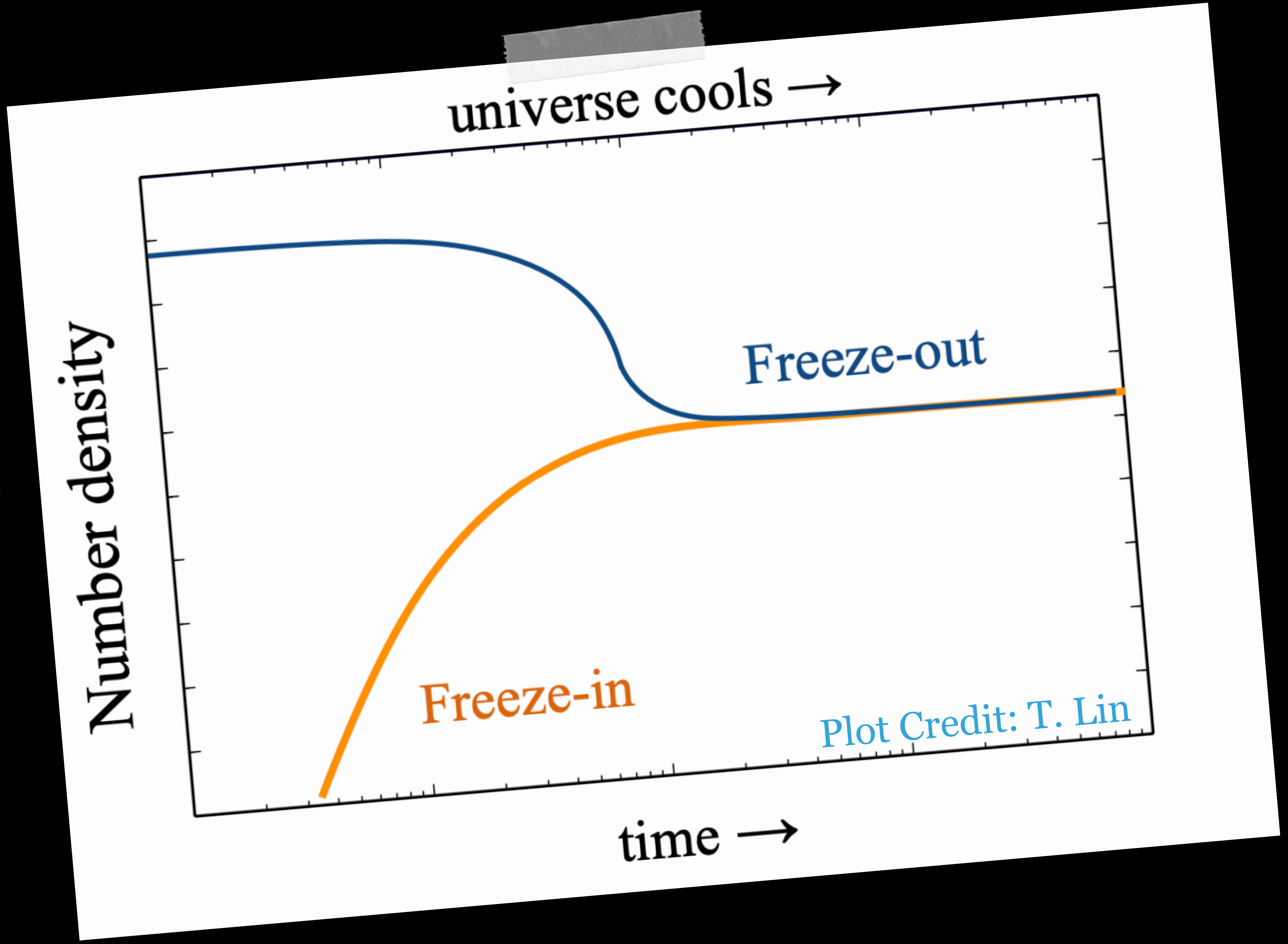

# WHAT IF DM INTERACTIONS DON'T CONSERVE KINETIC ENERGY?

D. Tucker-Smith & N. Weiner (2001)
D. P. Finkbeiner & N. Weiner (2007)
N. Arkami-Hamed et al (2008)
…

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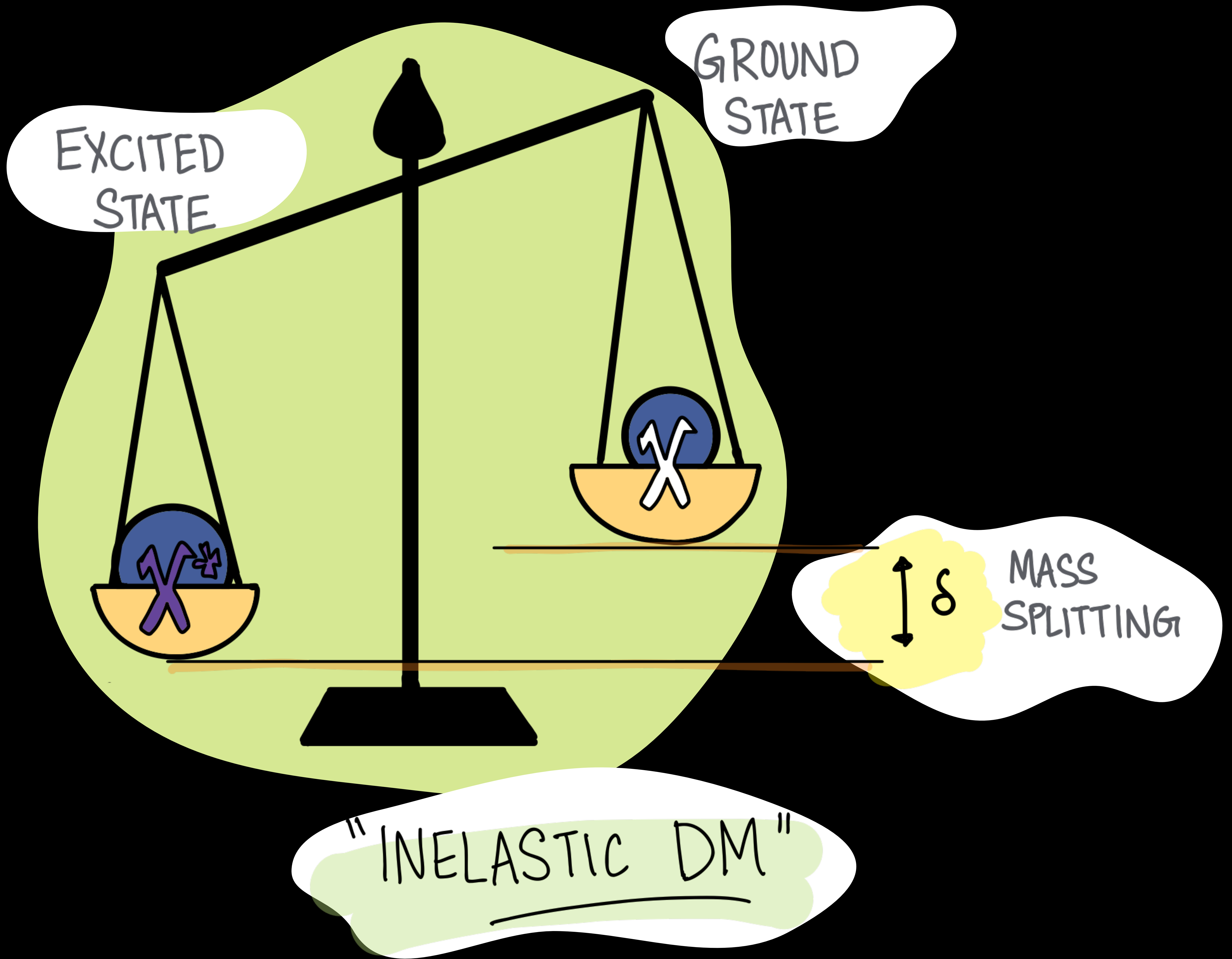


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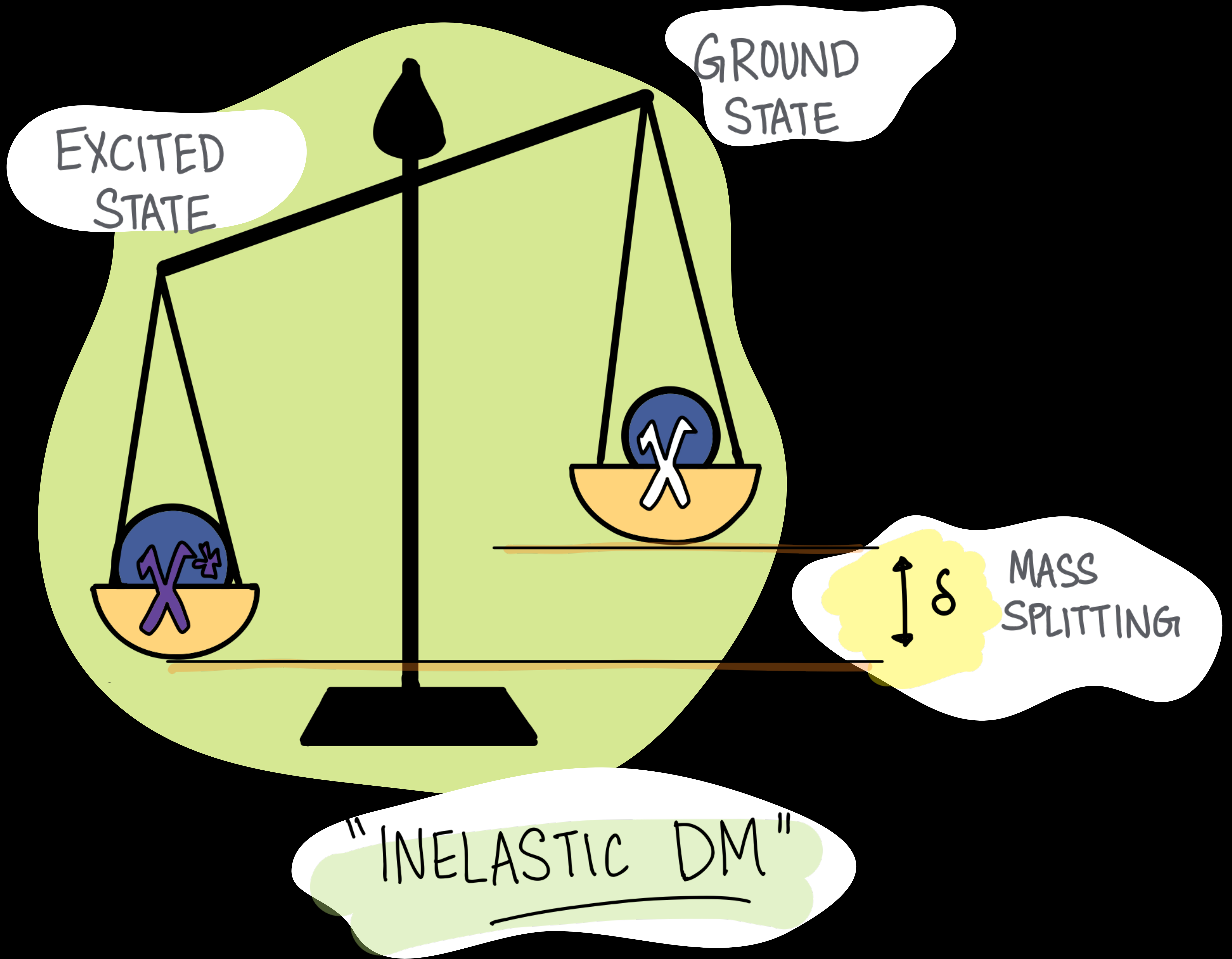
# WHAT IF DM INTERACTIONS DON'T CONSERVE KINETIC ENERGY?

$\mathcal{L} \supset i g_\chi A'_\mu \bar{\chi}^* \gamma^\mu \chi$

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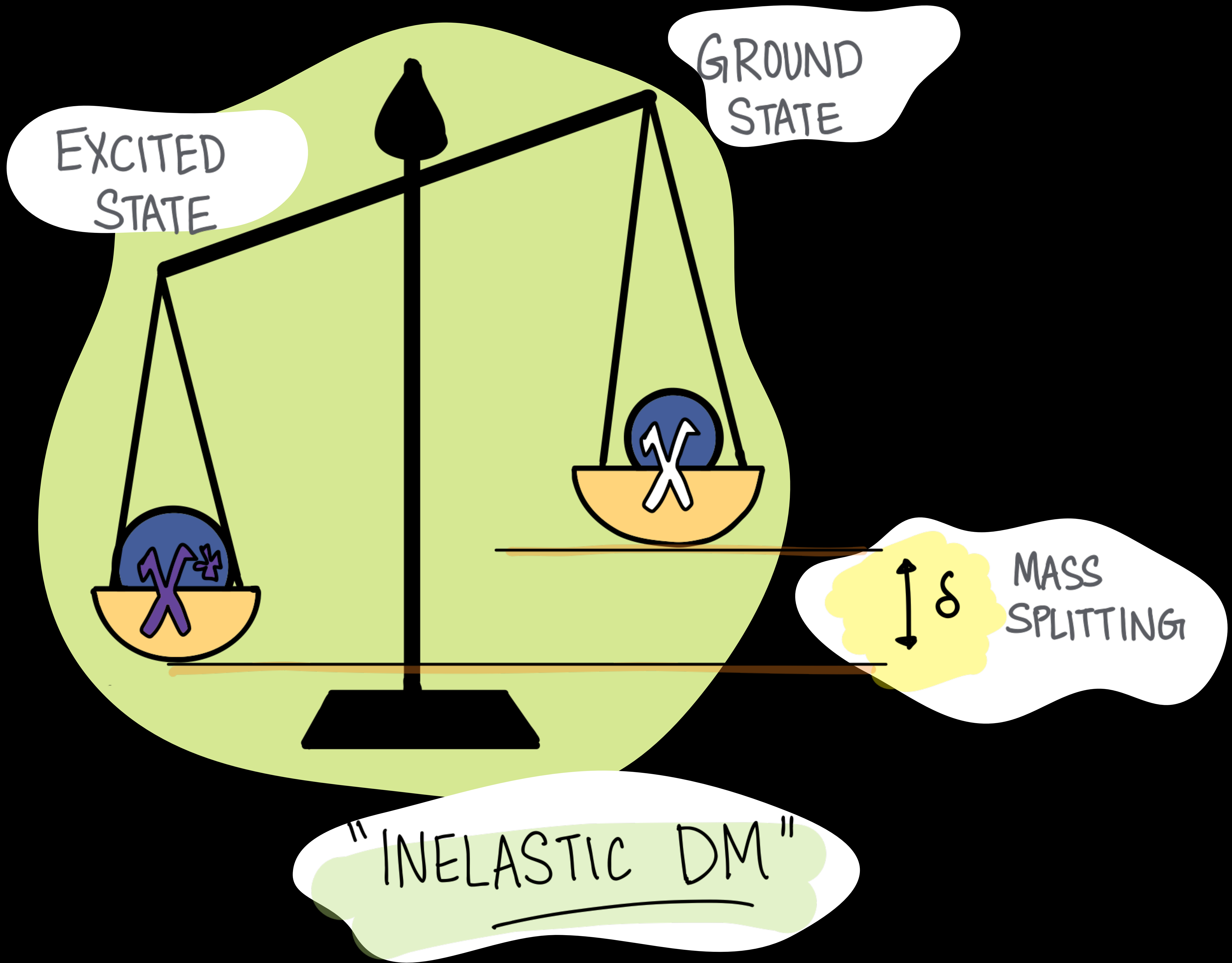
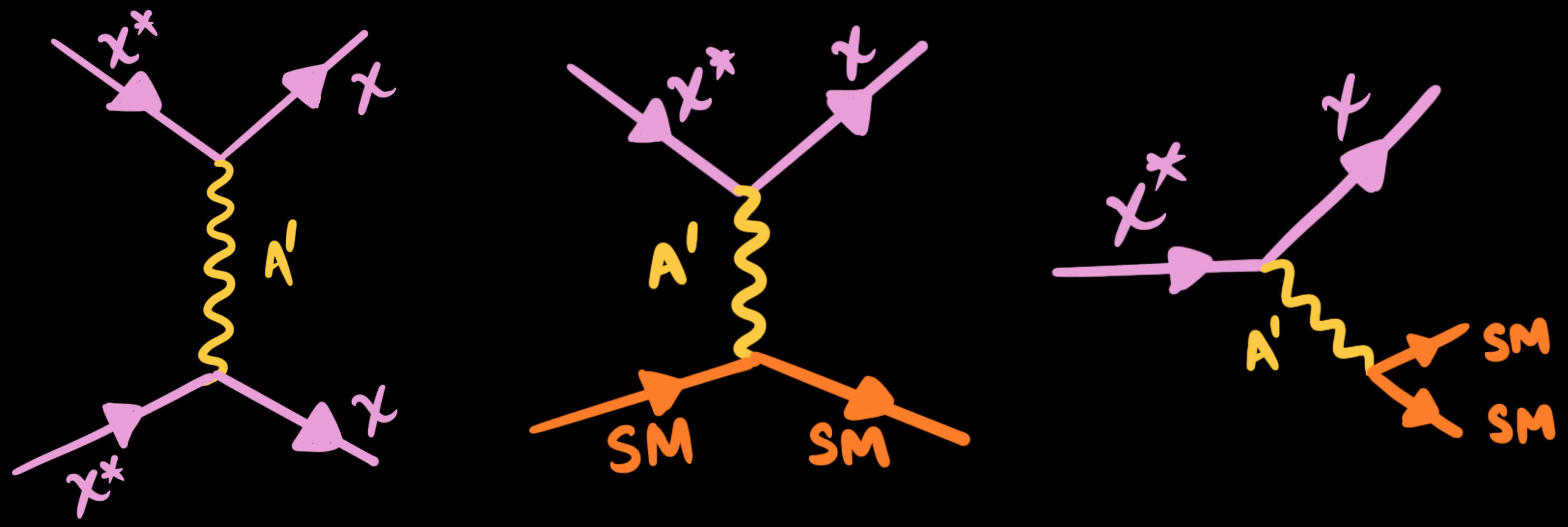



$$\mathcal{L} \supset i g_\chi A'_\mu \bar{\chi}^* \gamma^\mu \chi$$

Endothermic and exothermic reactions change DM phase space and result in unique signatures at different points in DM history





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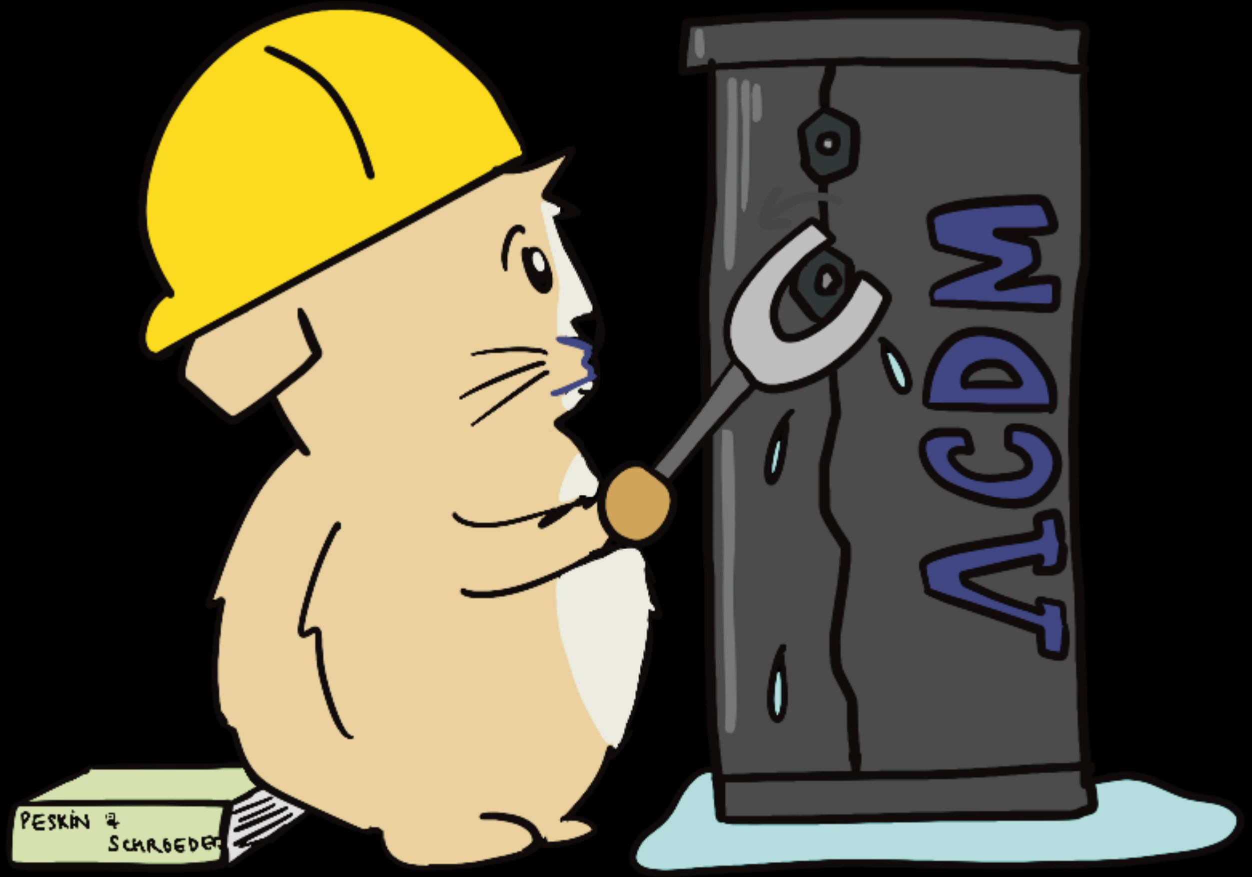
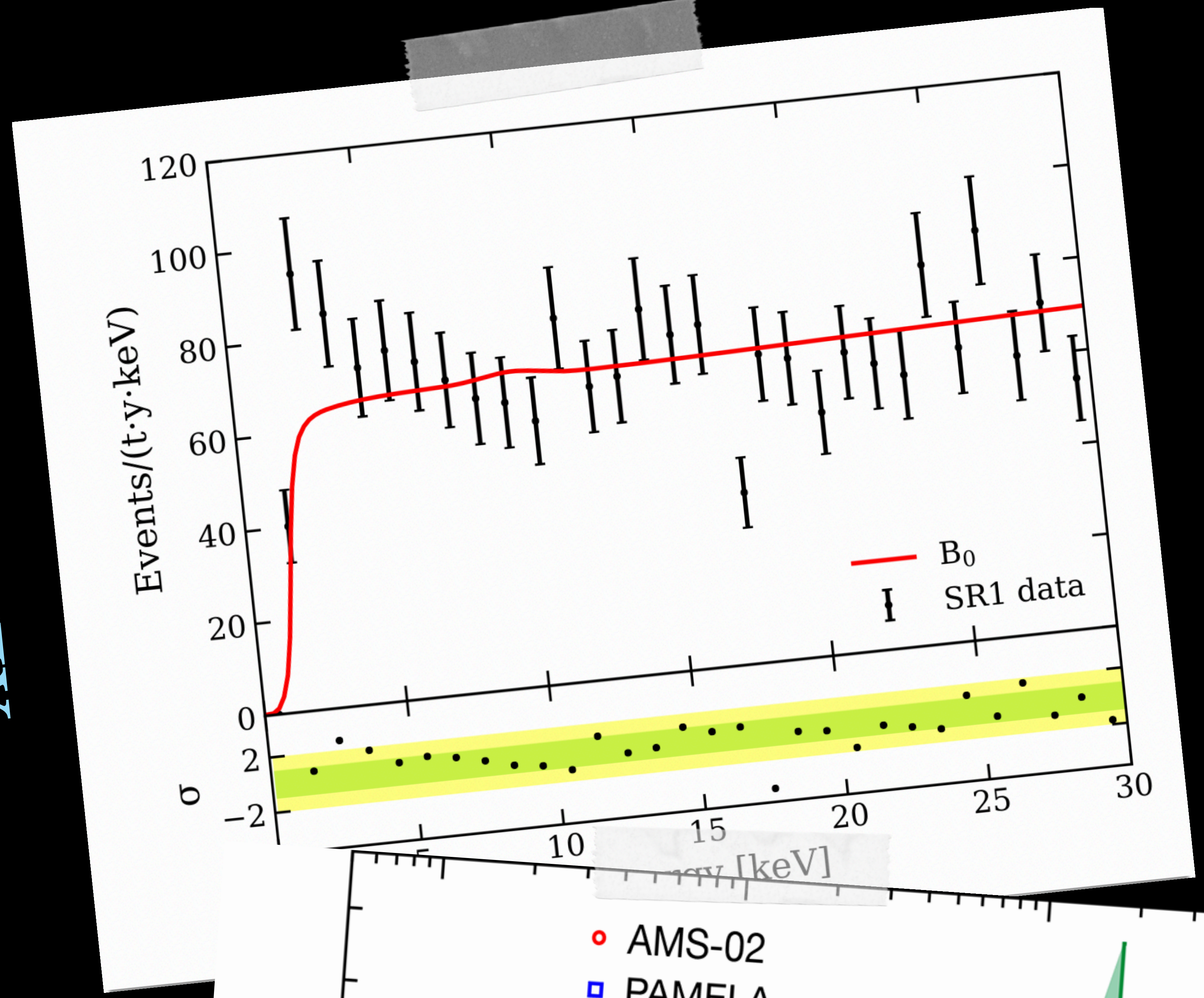
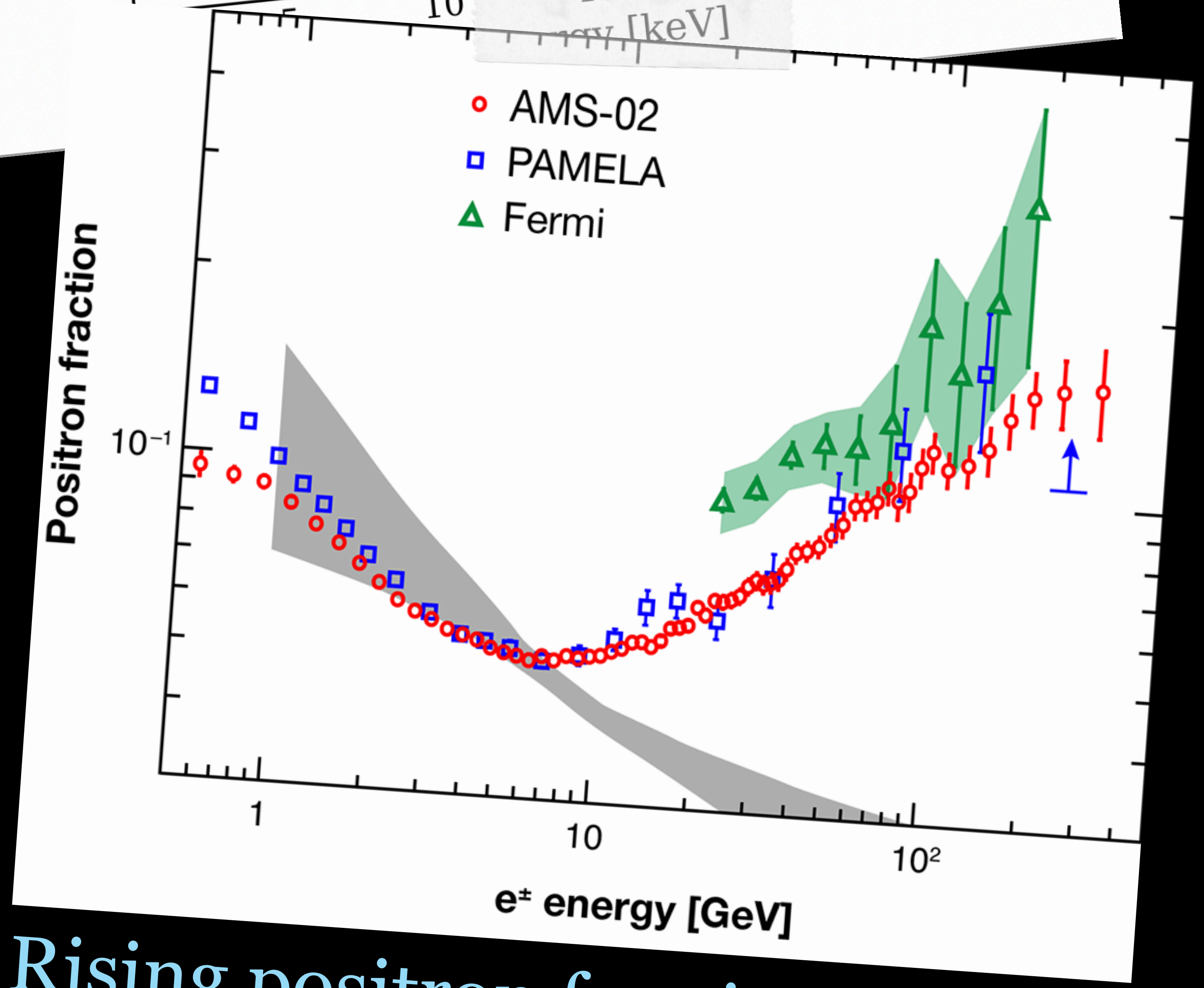
# INELASTIC DM AS ANOMALY FIXER

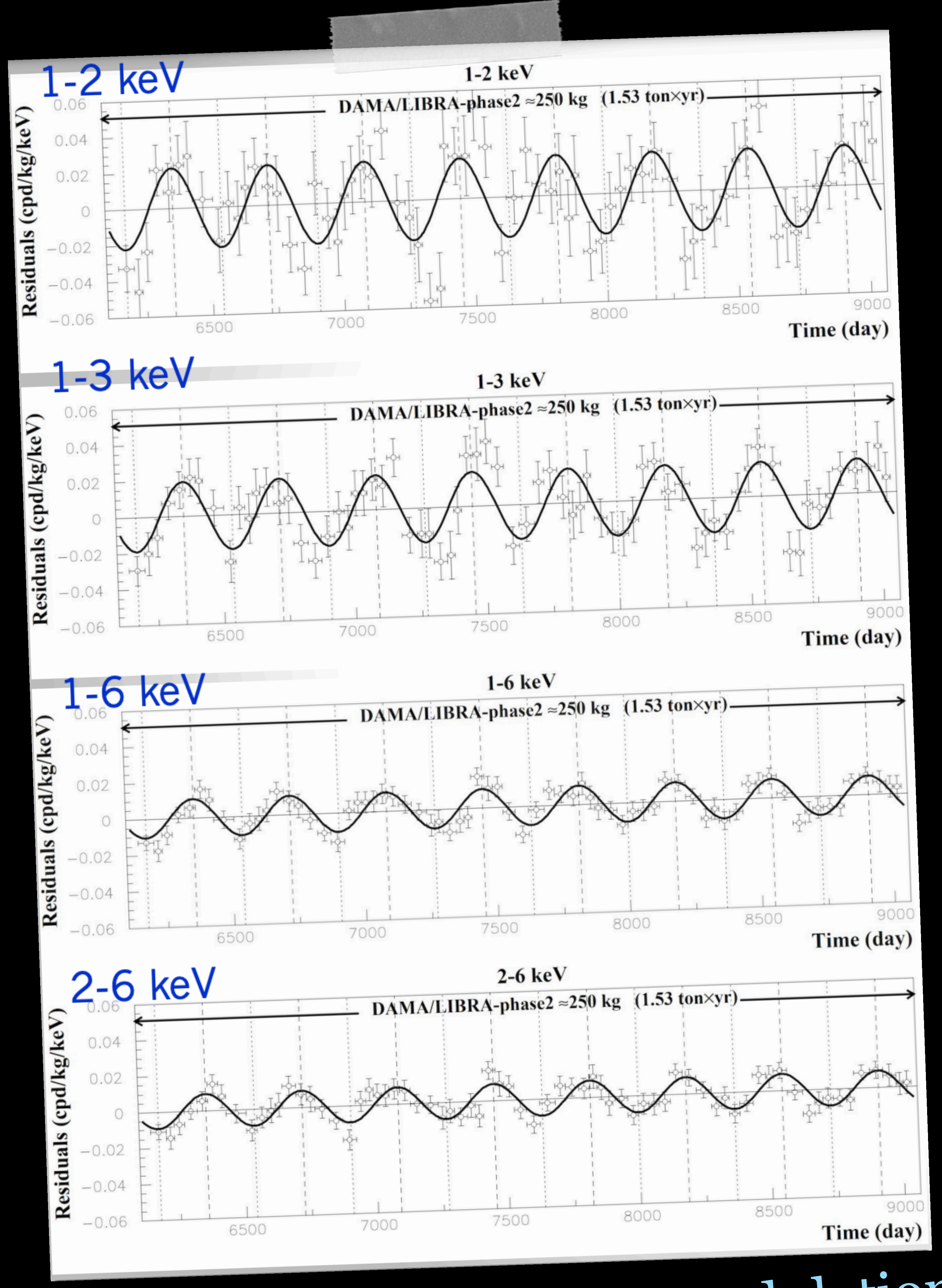



XENON1T Excess




Rising positron fraction at high energies




DAMA/LIBRA Annual modulation

# INELASTIC DM: HOW CONTRIVED IS IT?

$$\mathcal{L} \supset |D_\mu \phi_D|^2 + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + y_\chi \bar{\Psi} \Psi \phi_D + g_\chi A'_\mu \gamma^\mu \bar{\Psi} \Psi + m_\Psi \bar{\Psi} \Psi$$

Duerr, Ferber, Garcia-Cely et al (2020)
Elor, Liu, Slatyer et al (2018)

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DARK FERMION CHARGED UNDER NEW U(1)

Duerr, Ferber, Garcia-Cely et al (2020)
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PORTAL TO THE STANDARD MODEL

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NEW DARK HIGGS THAT PROVIDES THE DARK PHOTON MASS

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Duerr, Ferber, Garcia-Cely et al (2020)
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GENERATES A MAJORANA MASS TERM FOR THE FERMION!

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Duerr, Ferber, Garcia-Cely et al (2020)
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NEW DARK HIGGS THAT PROVIDES THE DARK PHOTON MASS

PORTAL TO THE STANDARD MODEL

GENERATES A MAJORANA MASS TERM FOR THE FERMION! → MASS SPLITTING

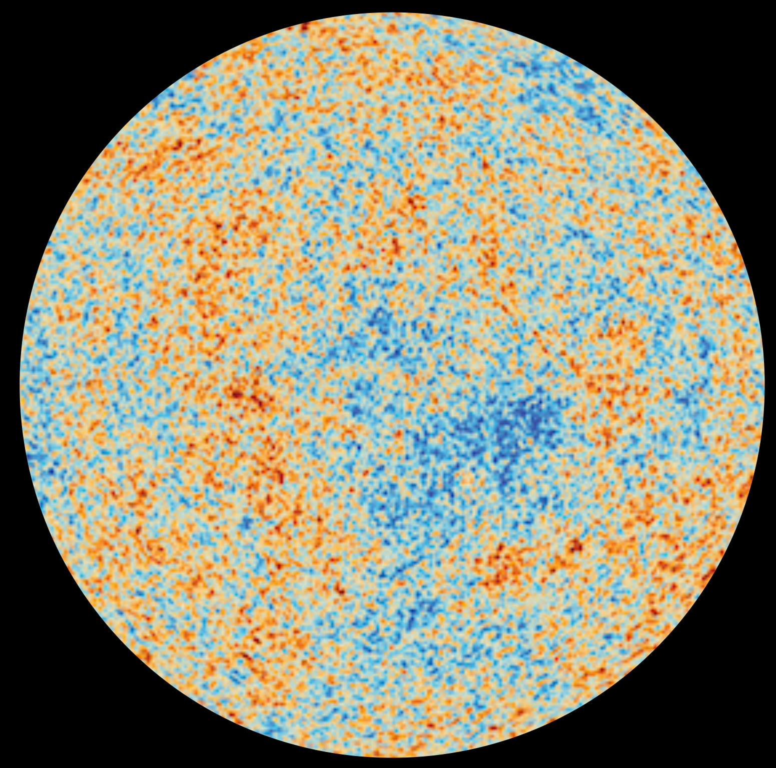
DARK FERMION CHARGED UNDER NEW U(1)

Duerr, Ferber, Garcia-Cely et al (2020)
Elor, Liu, Slatyer et al (2018)

**INELASTIC DARK MATTER MODELS ARE MINIMAL EXTENSIONS OF THE STANDARD MODEL WITH A DIVERSITY OF SIGNATURES.**

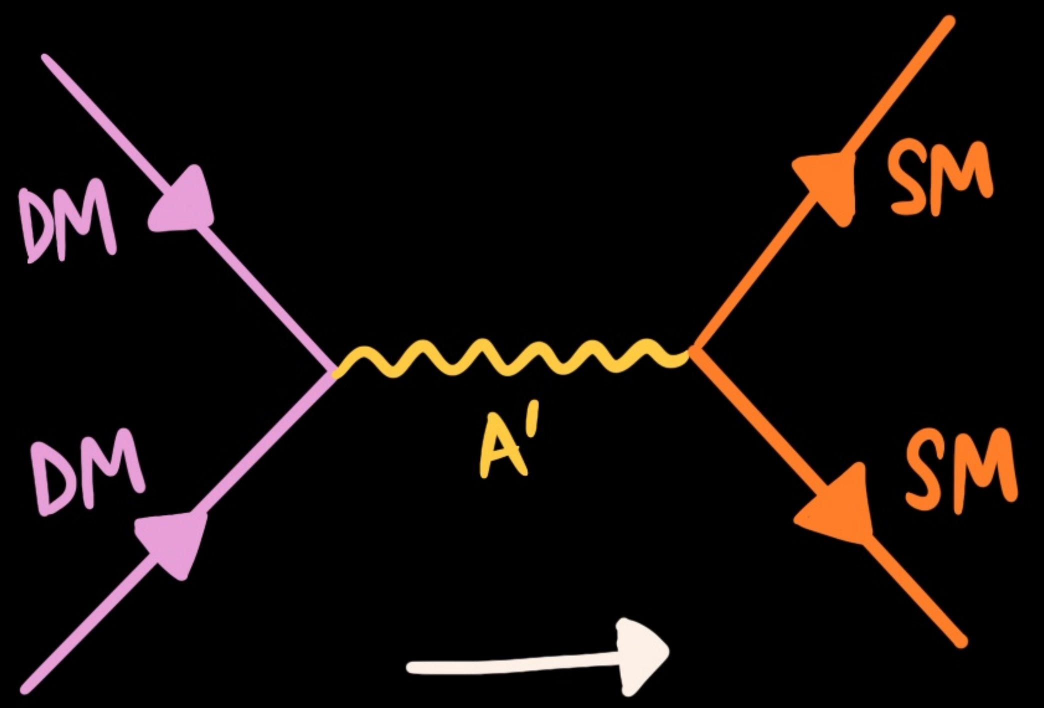
**HAVE WE EXHAUSTED THIS PARAMETER SPACE?**

# POTENTIAL THERMAL HISTORIES

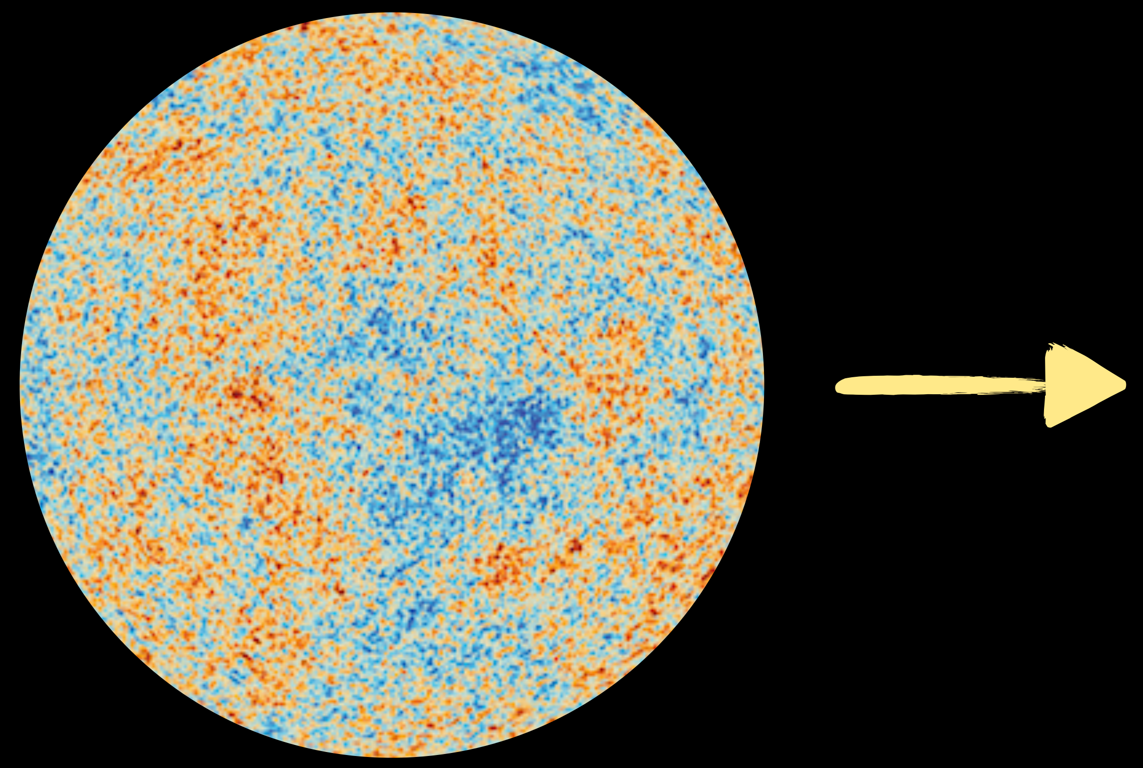


$\Omega_\chi h^2 = 0.12$

1. Thermal production: Freeze-out



# Potential Thermal Histories



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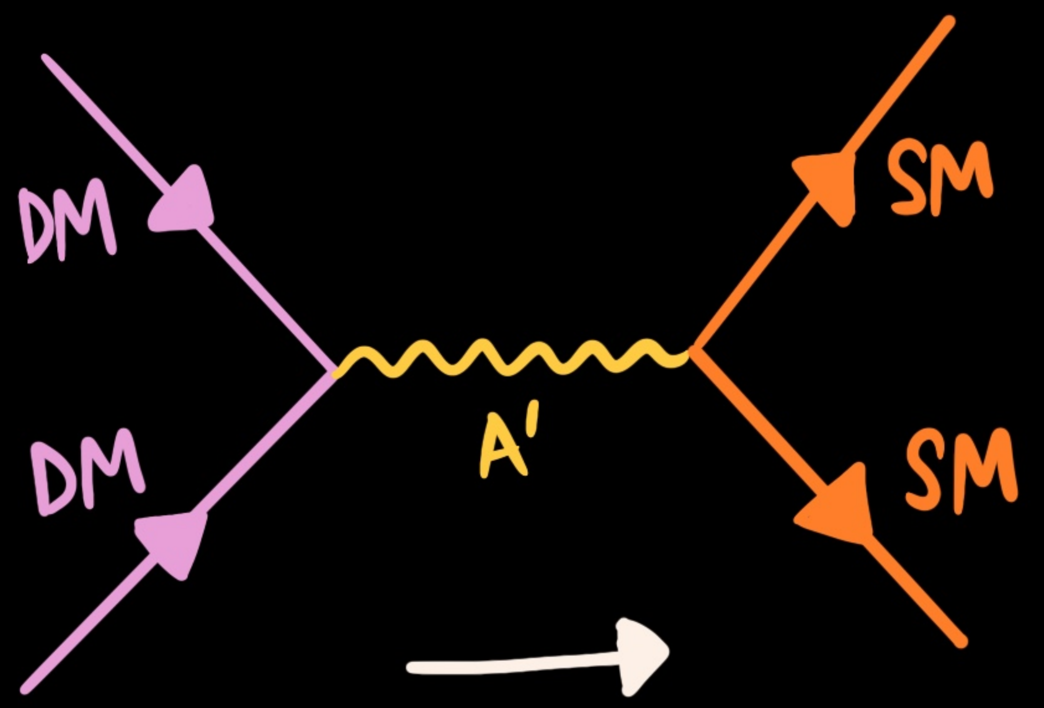
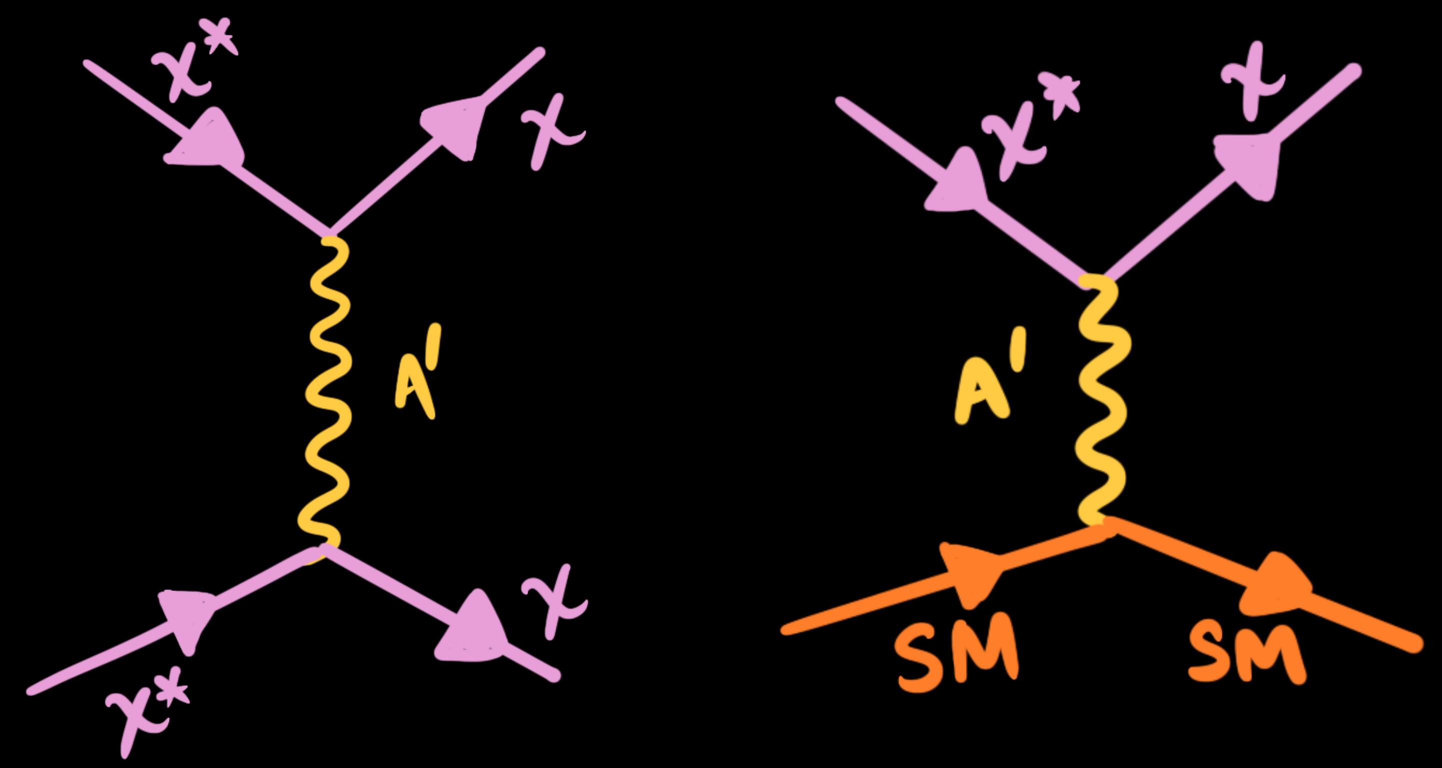


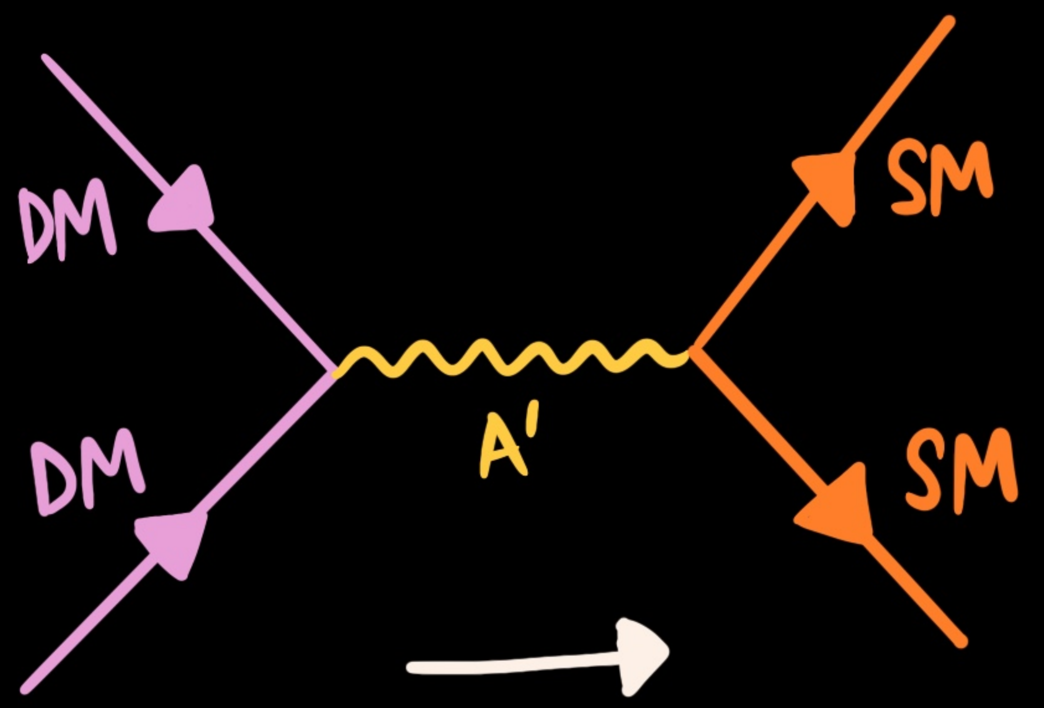

Excited state thermally depleted after production




$$n_{\chi^*} \sim e^{-\delta/T} n_\chi$$

# POTENTIAL THERMAL HISTORIES

1. Thermal production: Freeze-out

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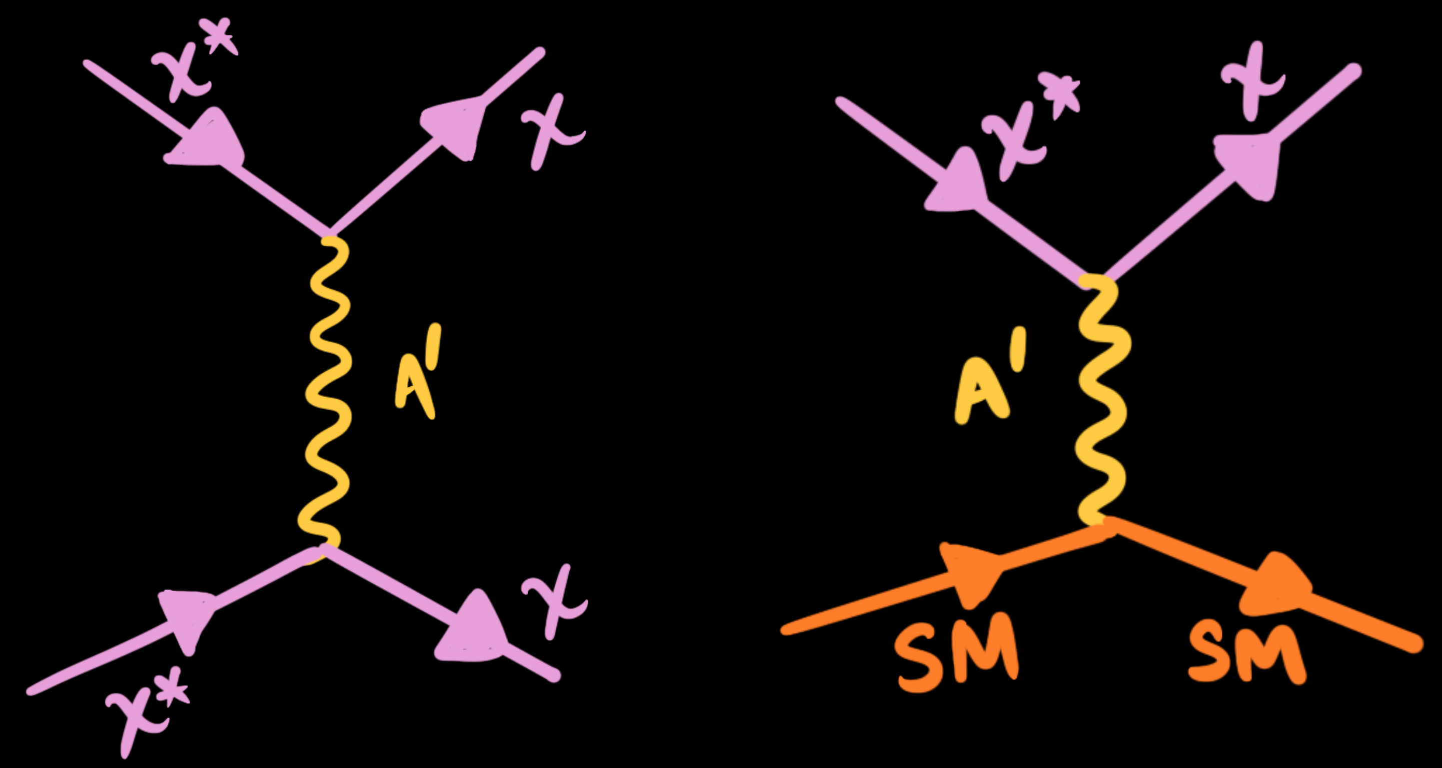


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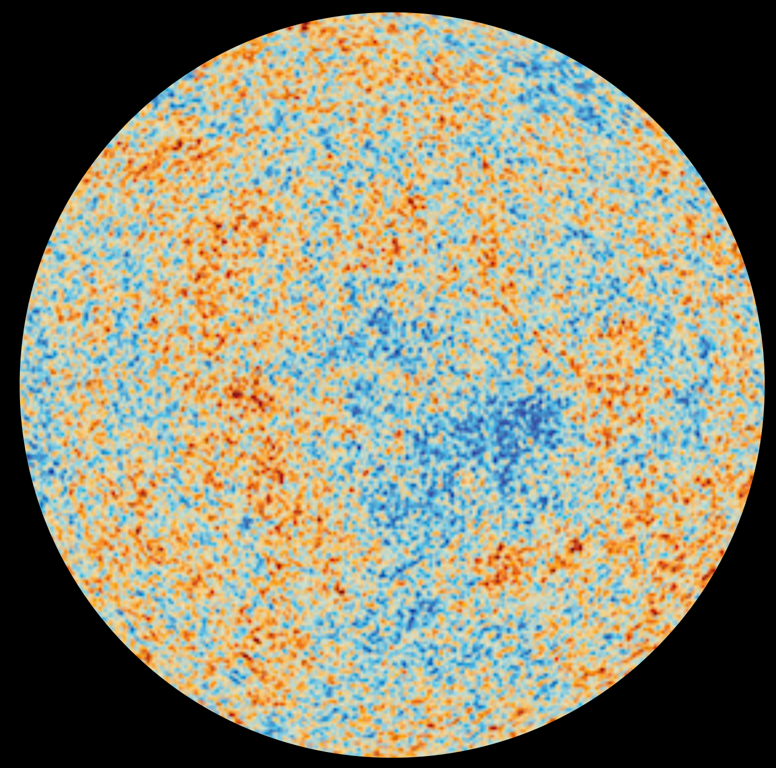
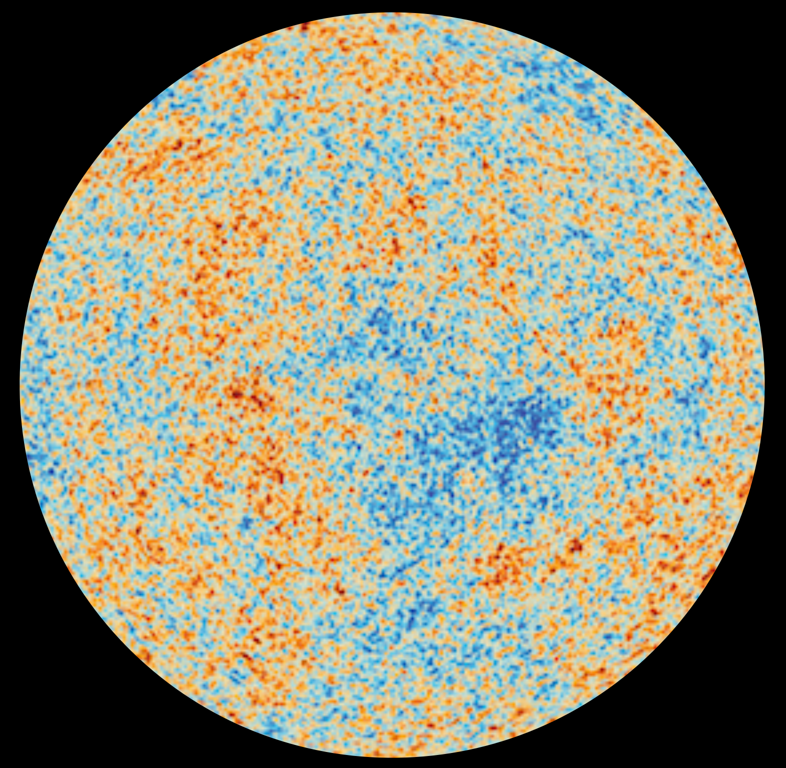


$$\Omega_\chi h^2 = 0.12$$

Benefit: Easy to evade CMB bounds coming from late-time DM annihilation into SM states.

Can make DM light!

# POTENTIAL THERMAL HISTORIES



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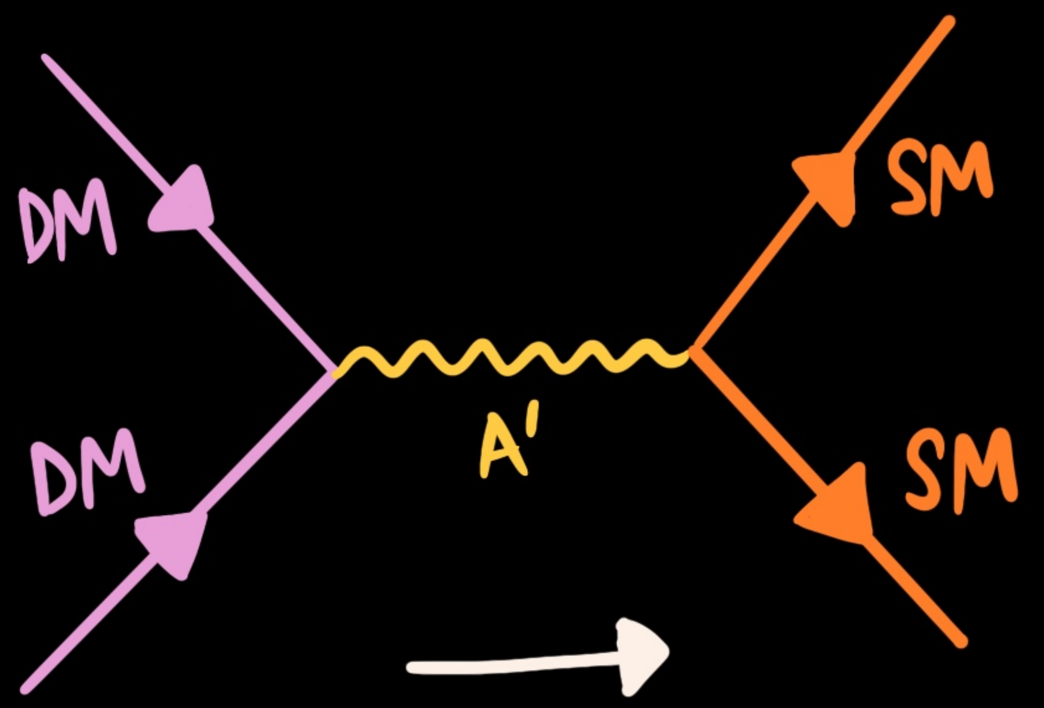
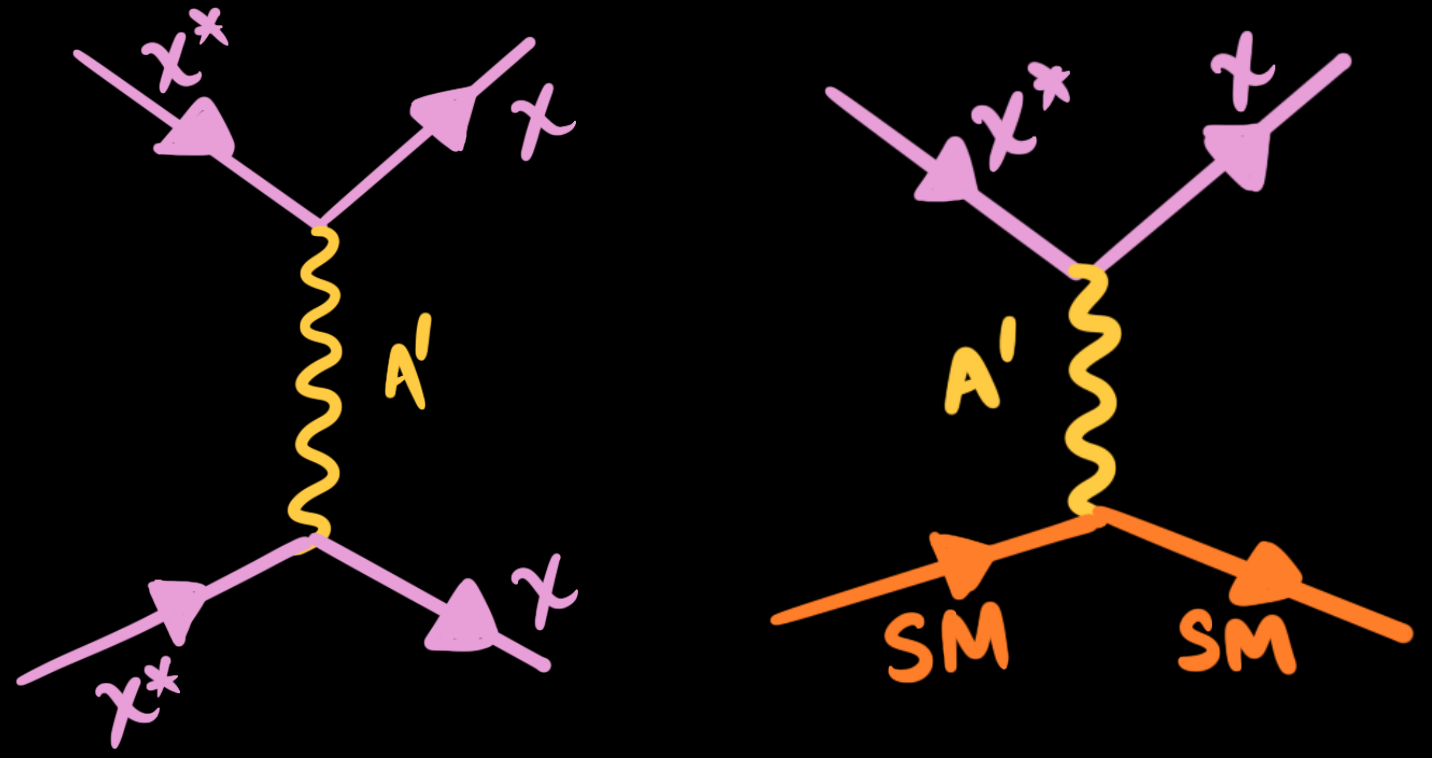



Excited state thermally depleted after production




$n_{\chi^*} \sim e^{-\delta/T} n_\chi$

Benefit: Easy to evade CMB bounds coming from late-time DM annihilation into SM states.
Can make DM light!

Downside: Lose sensitivity to direct and indirect detection searches that rely on the excited state

# THERMAL HISTORIES BEYOND FREEZE-OUT

## 1. EARLY KINETIC DECOUPLING

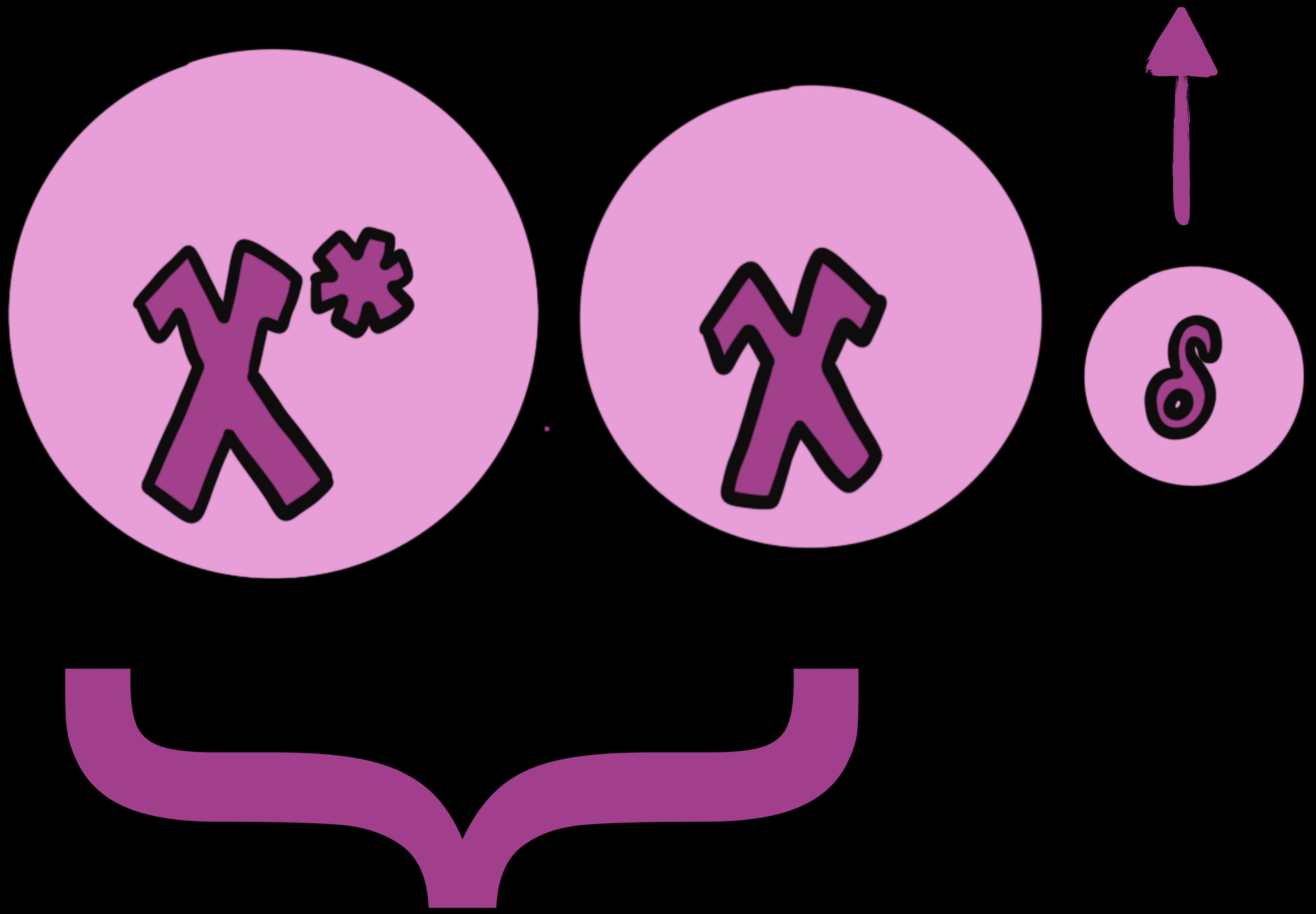
## (OR THERMALISH DARK MATTER)

# PARAMETER SPACE: RESONANT INELASTIC DM

$\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$

$\delta \ll m_\chi$

$\delta \sim \mathrm{eV} - \mathrm{keV}$




$m_\chi \sim \mathrm{MeV} - \mathrm{GeV}$

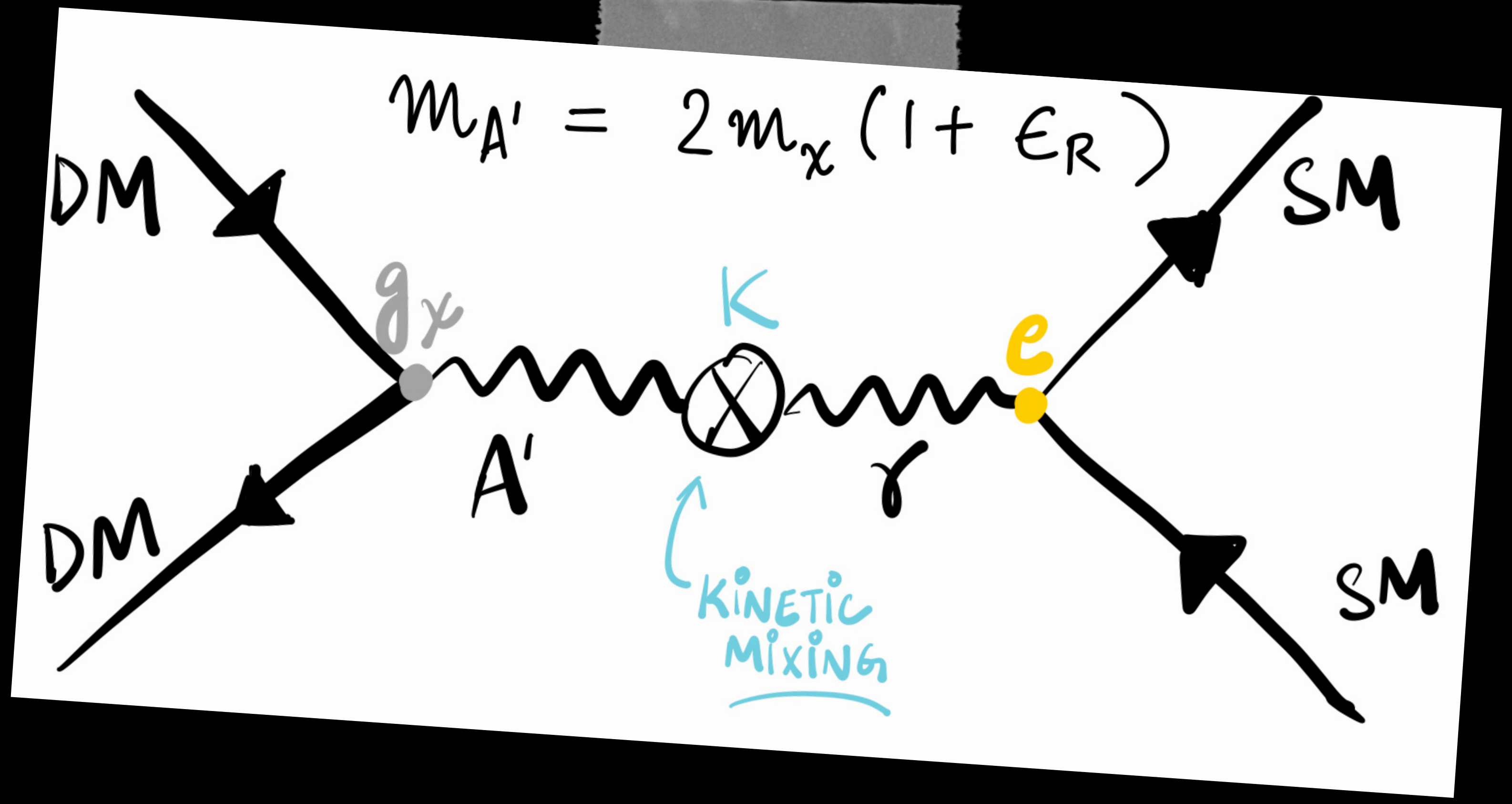

$m_{A'} \sim 2m_\chi$

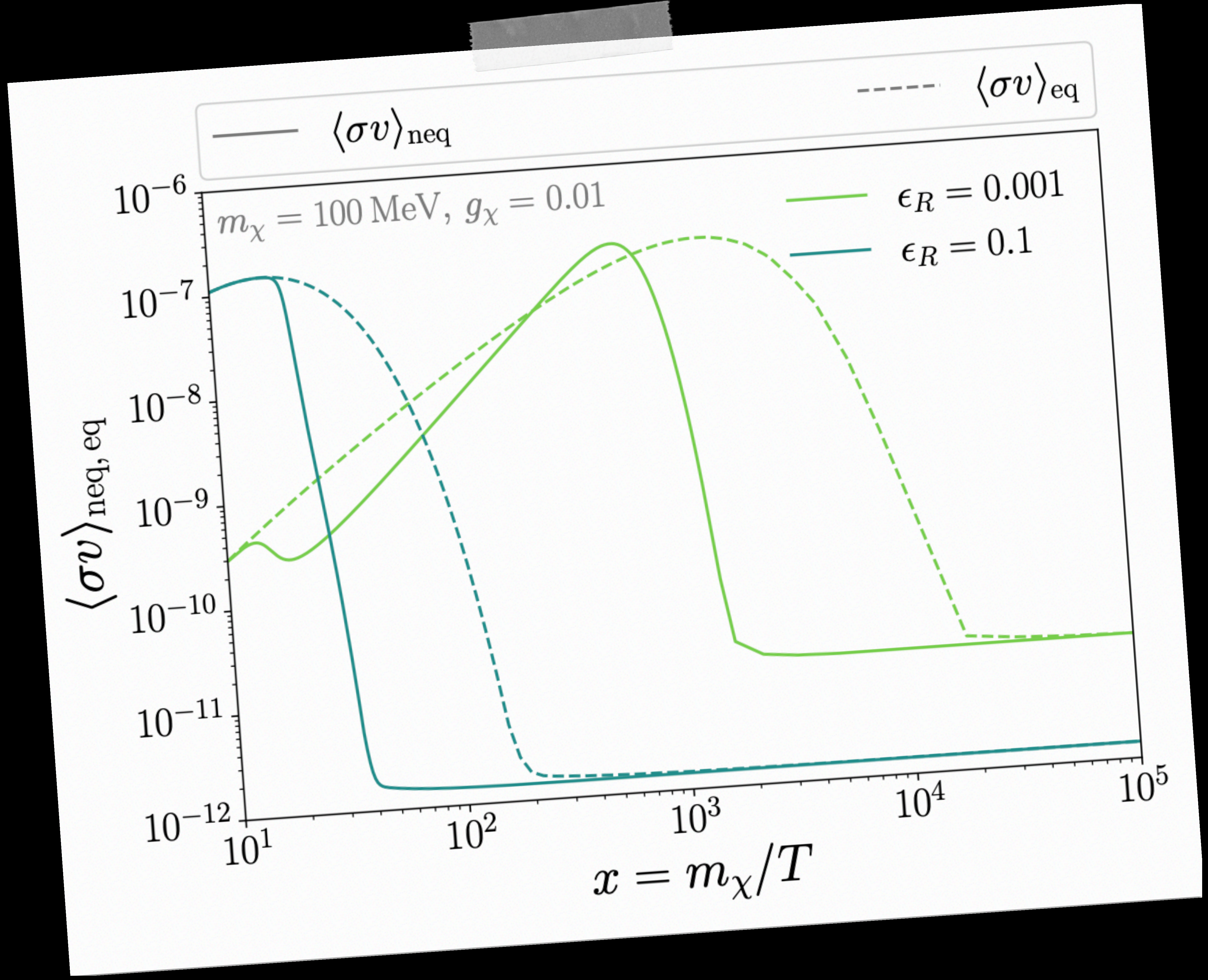
$m_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$

Brahma, **SH** & Schutz, arXiv: 2308.01960
Bernreuther, **SH** & Kahlhoefer, arXiv: 2010.14522

# RESONANT INELASTIC DM

A resonance in the theory, enhances the annihilation cross-section and reduces the couplings required to produce DM



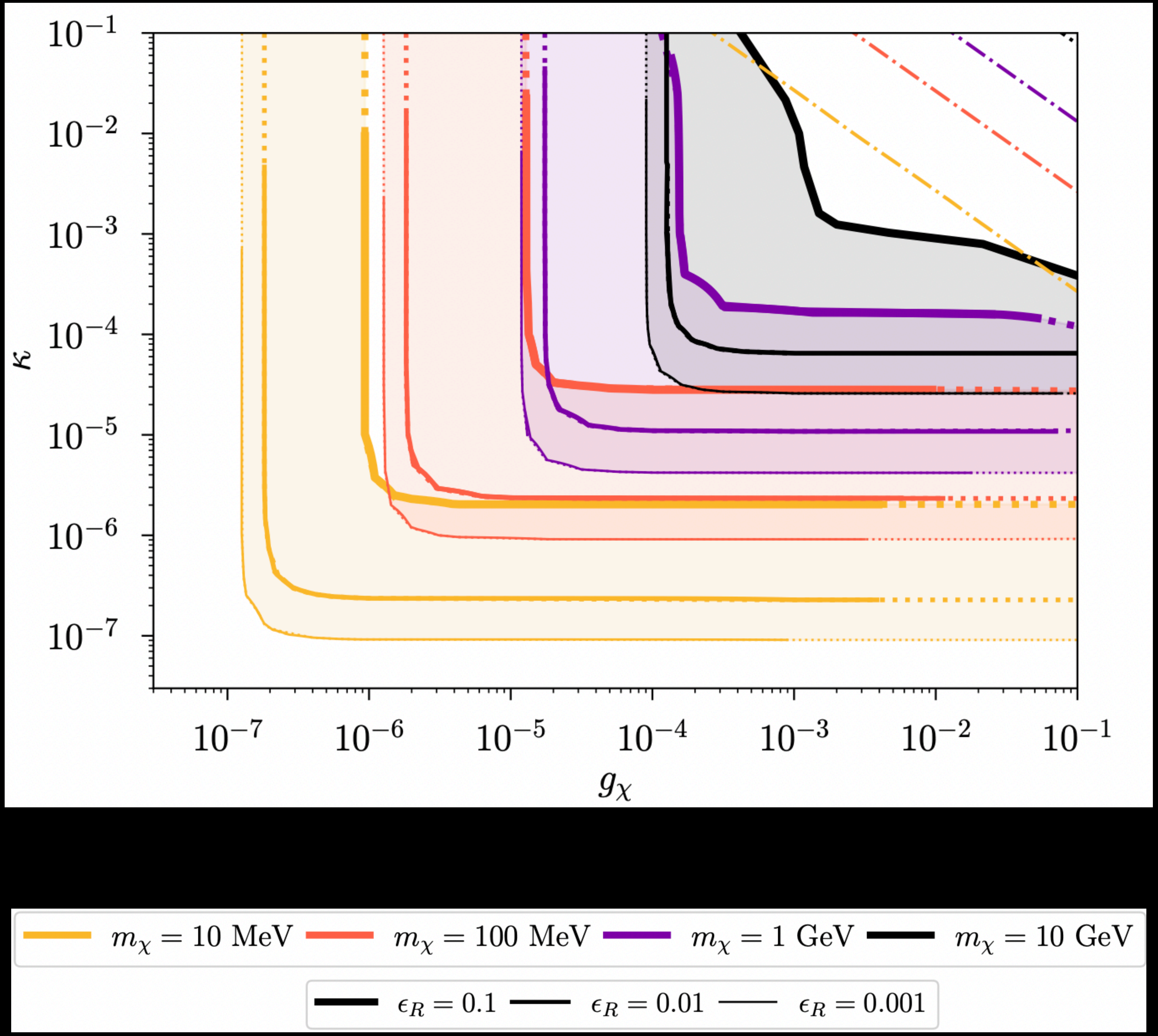

...but causes the DM to kinetically decouple

**Evades CMB bounds by reducing the cross-section at late times!**

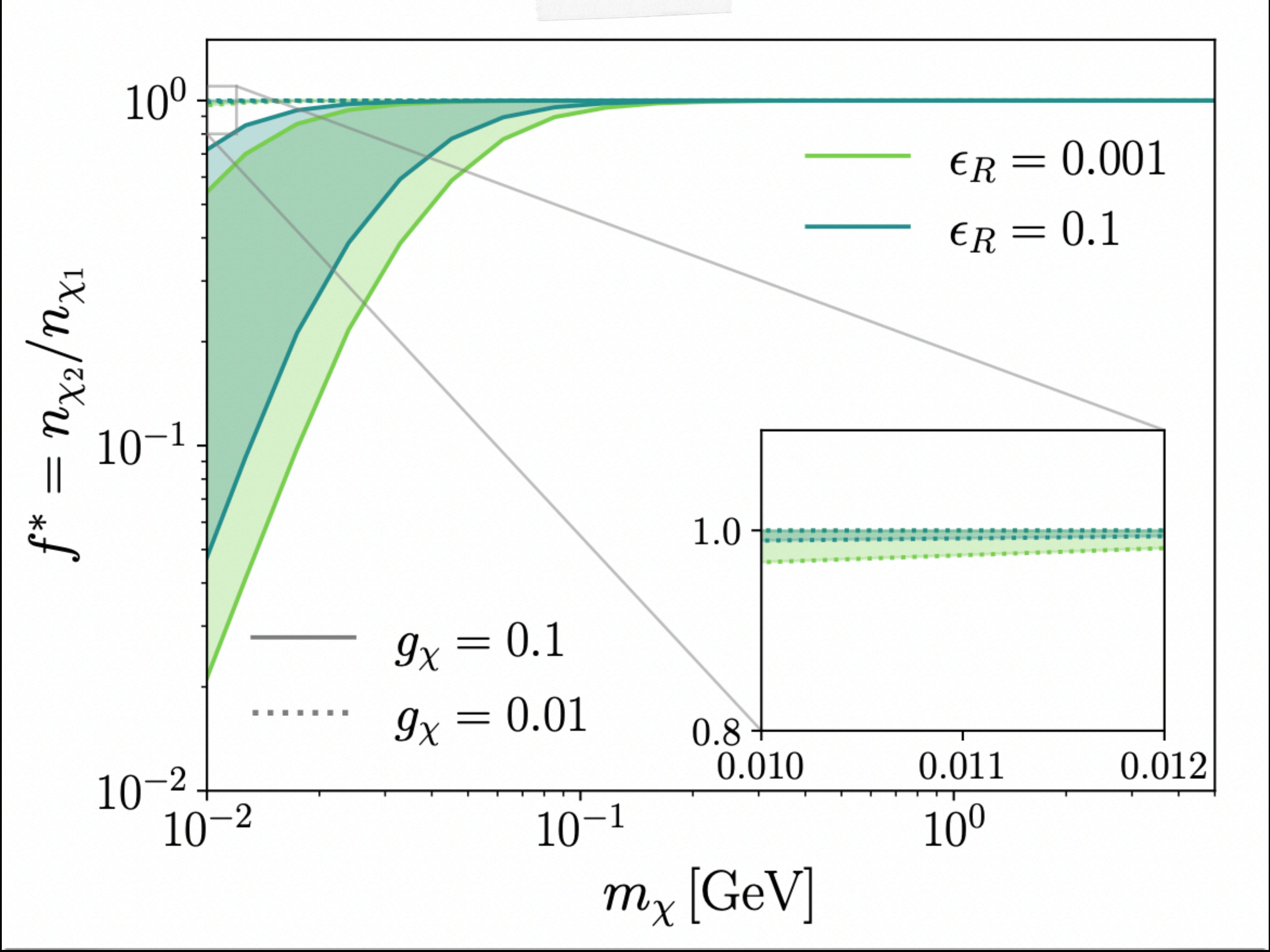
# SMALL COUPLINGS = EARLY KINETIC DECOUPLING

Solve coupled Boltzmann equations!

Binder et al, arXiv: 2103.01944

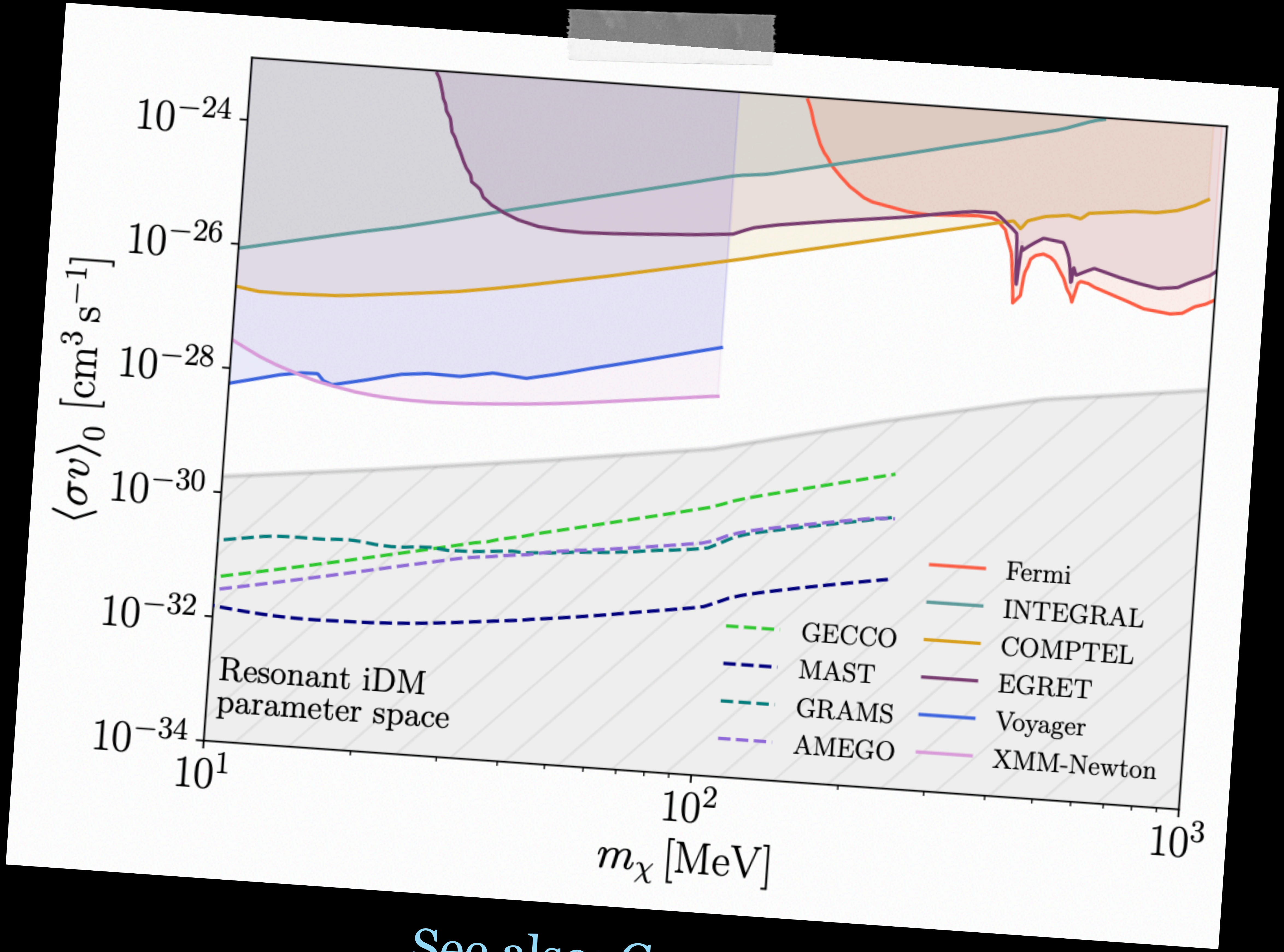


# ORDER ONE FRACTION OF THE EXCITED STATE AT LATE TIMES



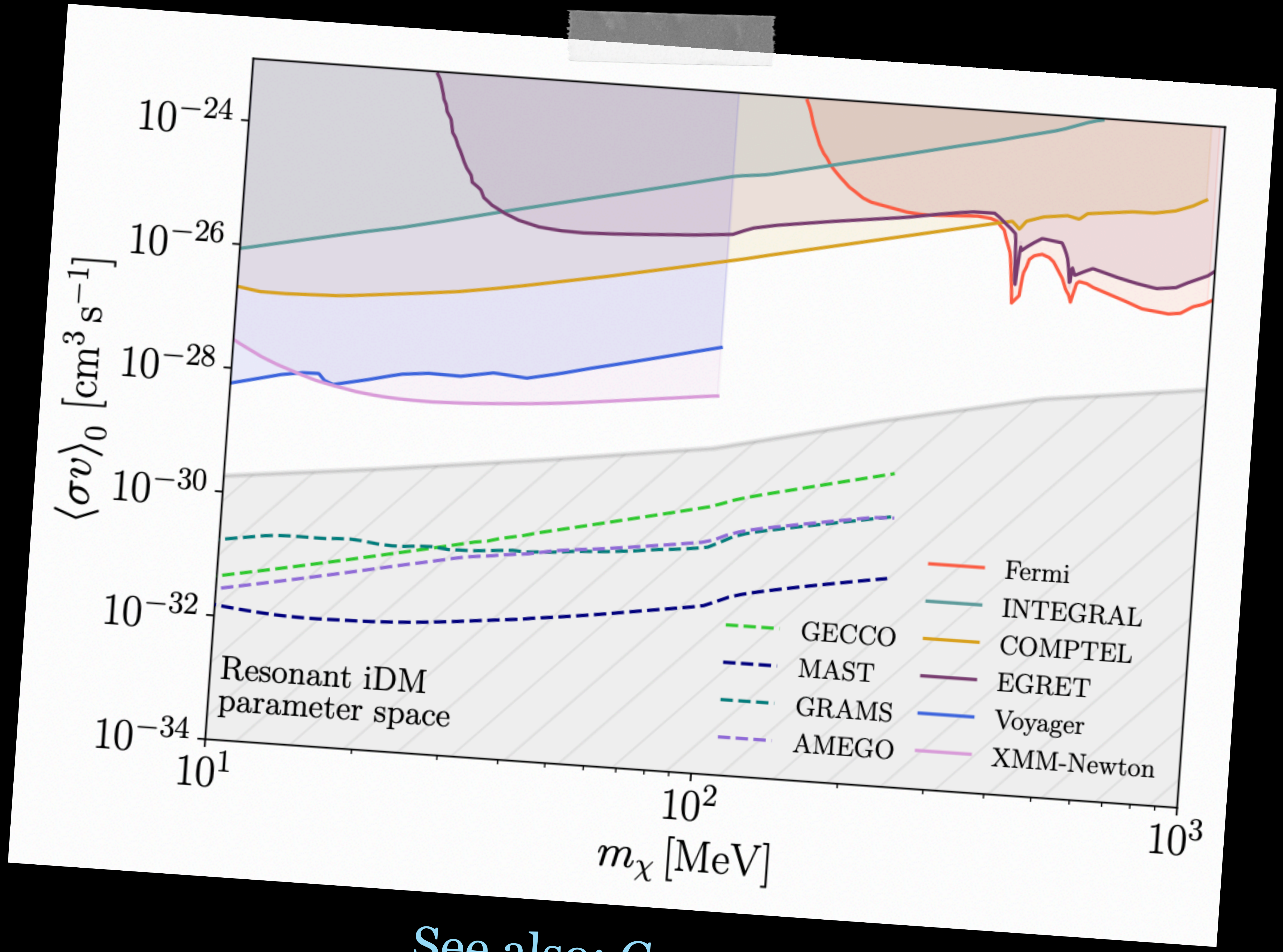

Safe from CMB for eV-scale mass splittings, because of small couplings!

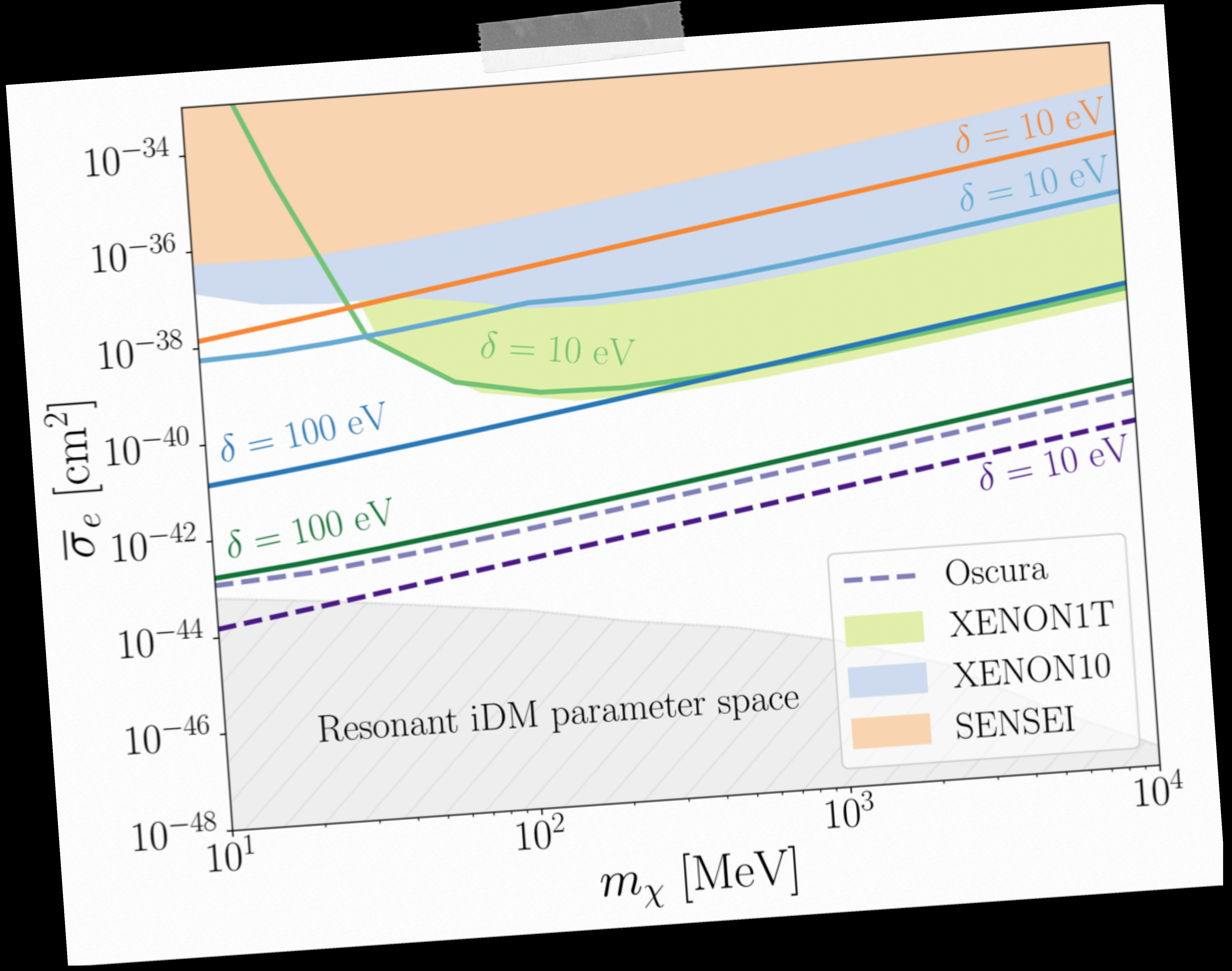
# SIGNATURES: DIRECT AND INDIRECT DETECTION




See also: Coogan et al, 2104.061682

# SIGNATURES: DIRECT AND INDIRECT DETECTION

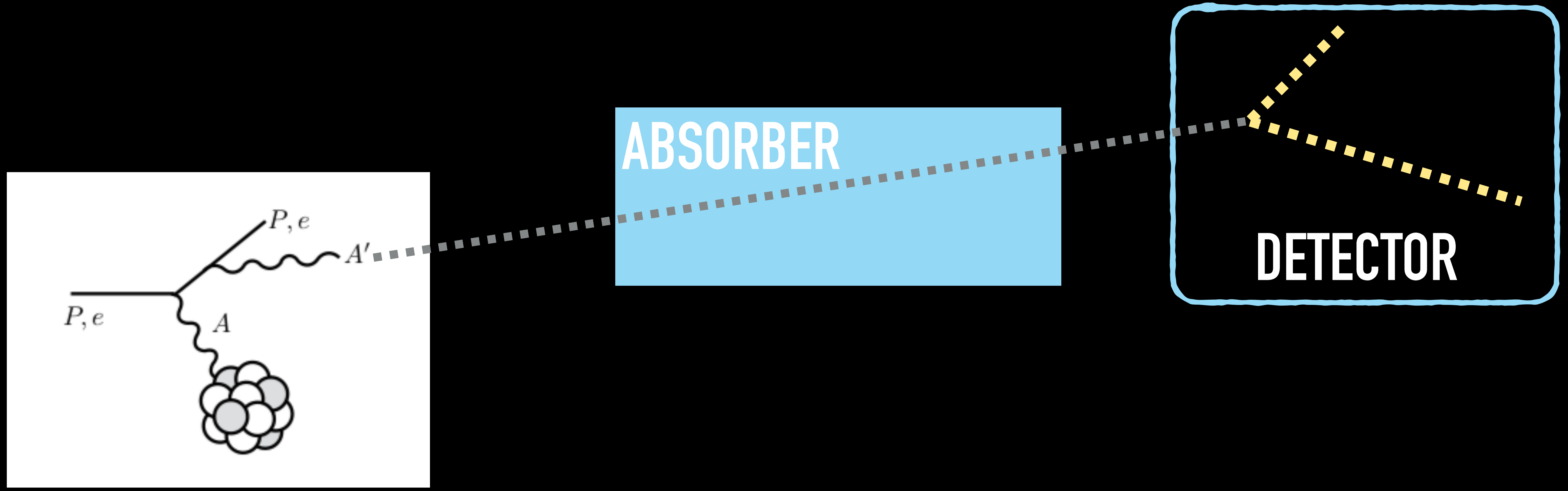


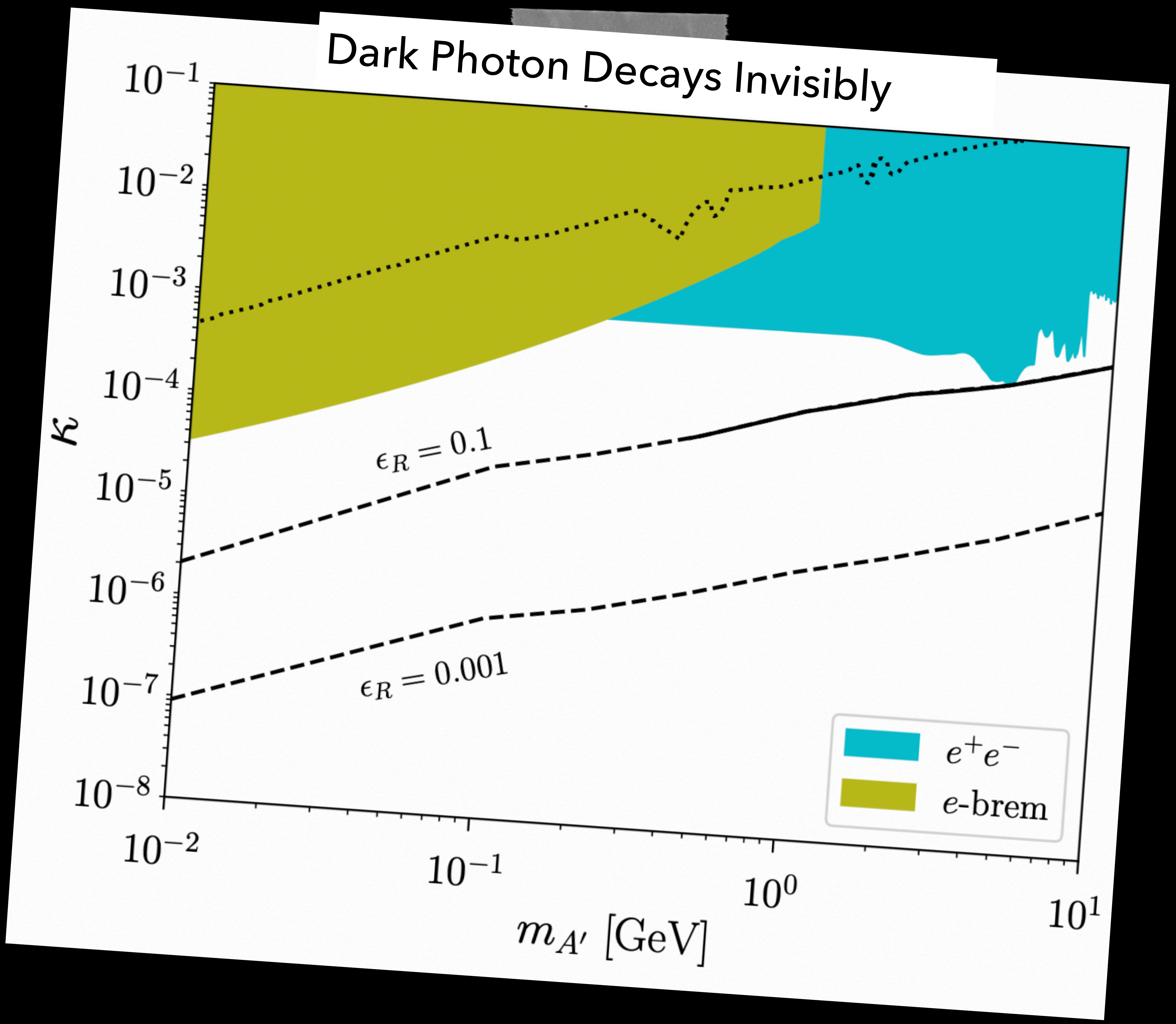



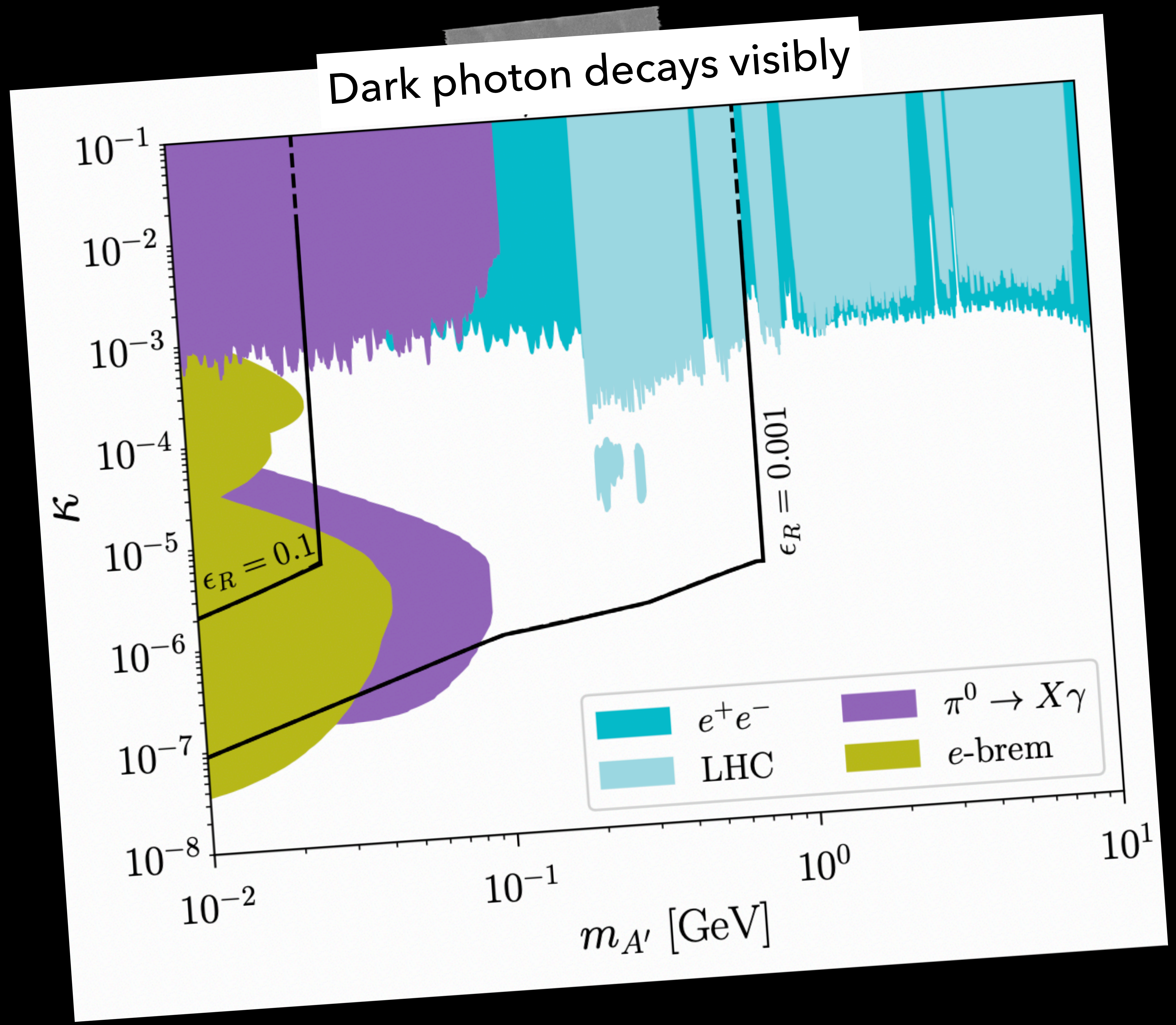

See also: Coogan et al, 2104.061682

# SIGNATURES: ACCELERATORS

Resonant sub-GeV DM as a thermal target

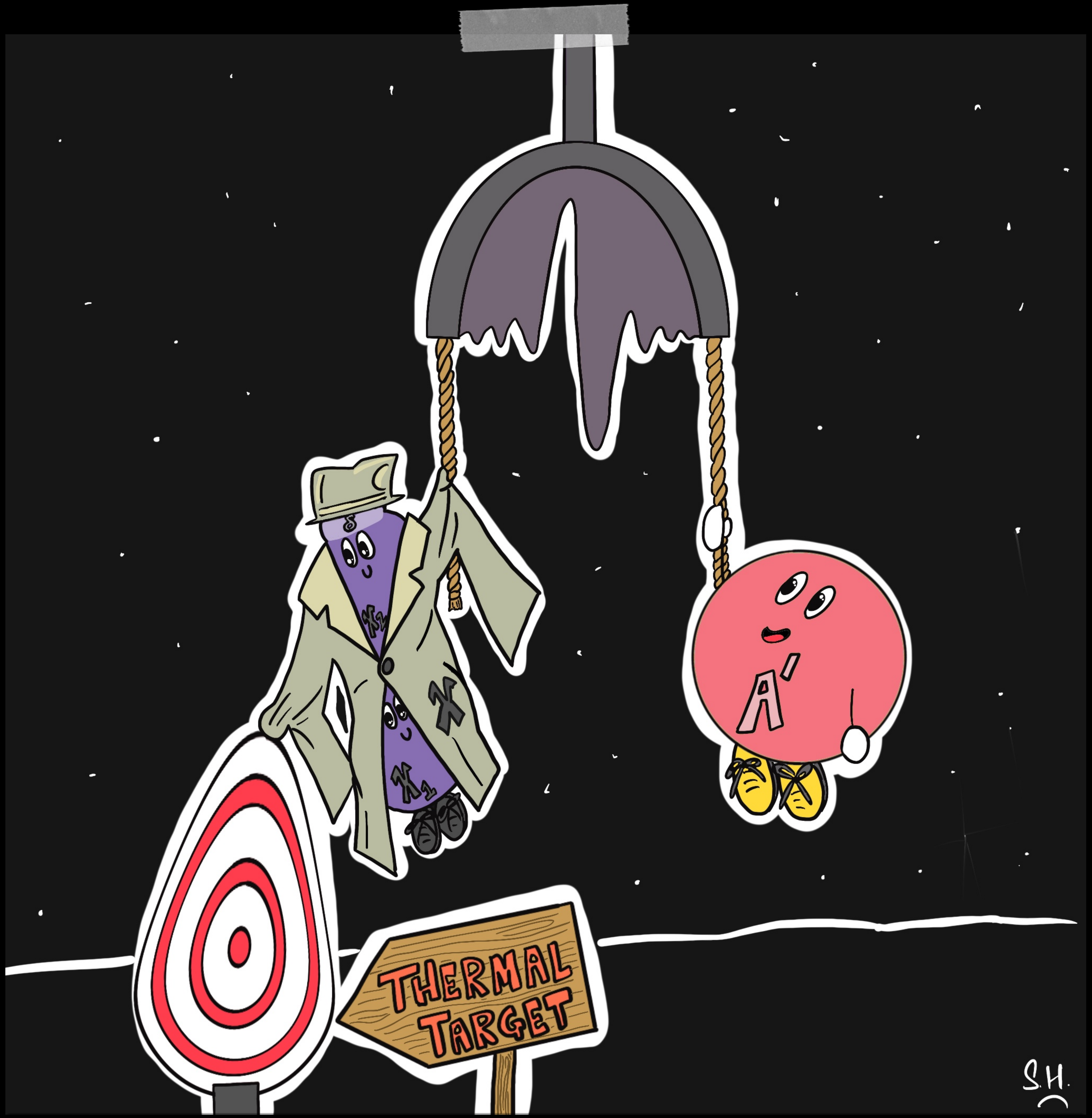


# TAKEAWAYS

RESONANT INELASTIC DARK MATTER BROADENS THE THERMAL TARGET, AND PROVIDES A WAY TO MAKE "LIGHT" DARK MATTER



# THERMAL HISTORIES BEYOND FREEZE-OUT

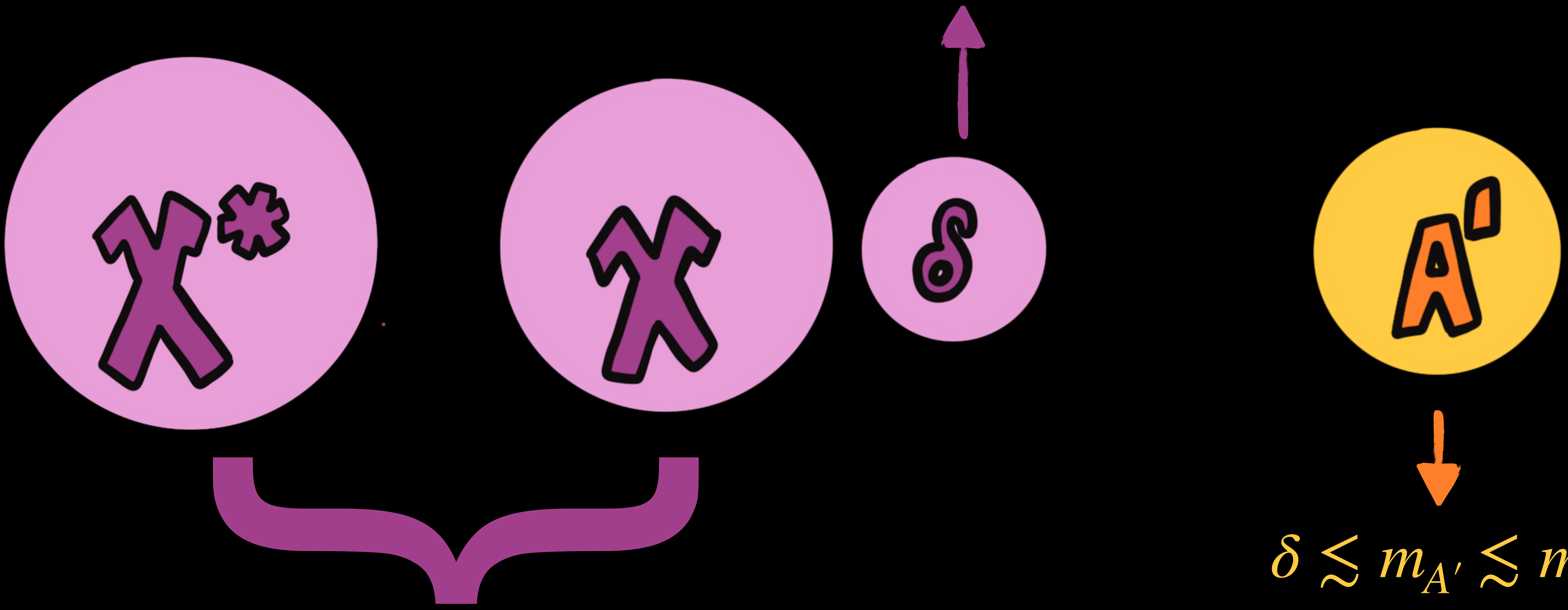
## 2. FREEZE-IN

# PARAMETER SPACE: INELASTIC FIMP DM

$$\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

$\delta \ll m_\chi$

$\delta \sim \text{MeV} - \text{GeV}$

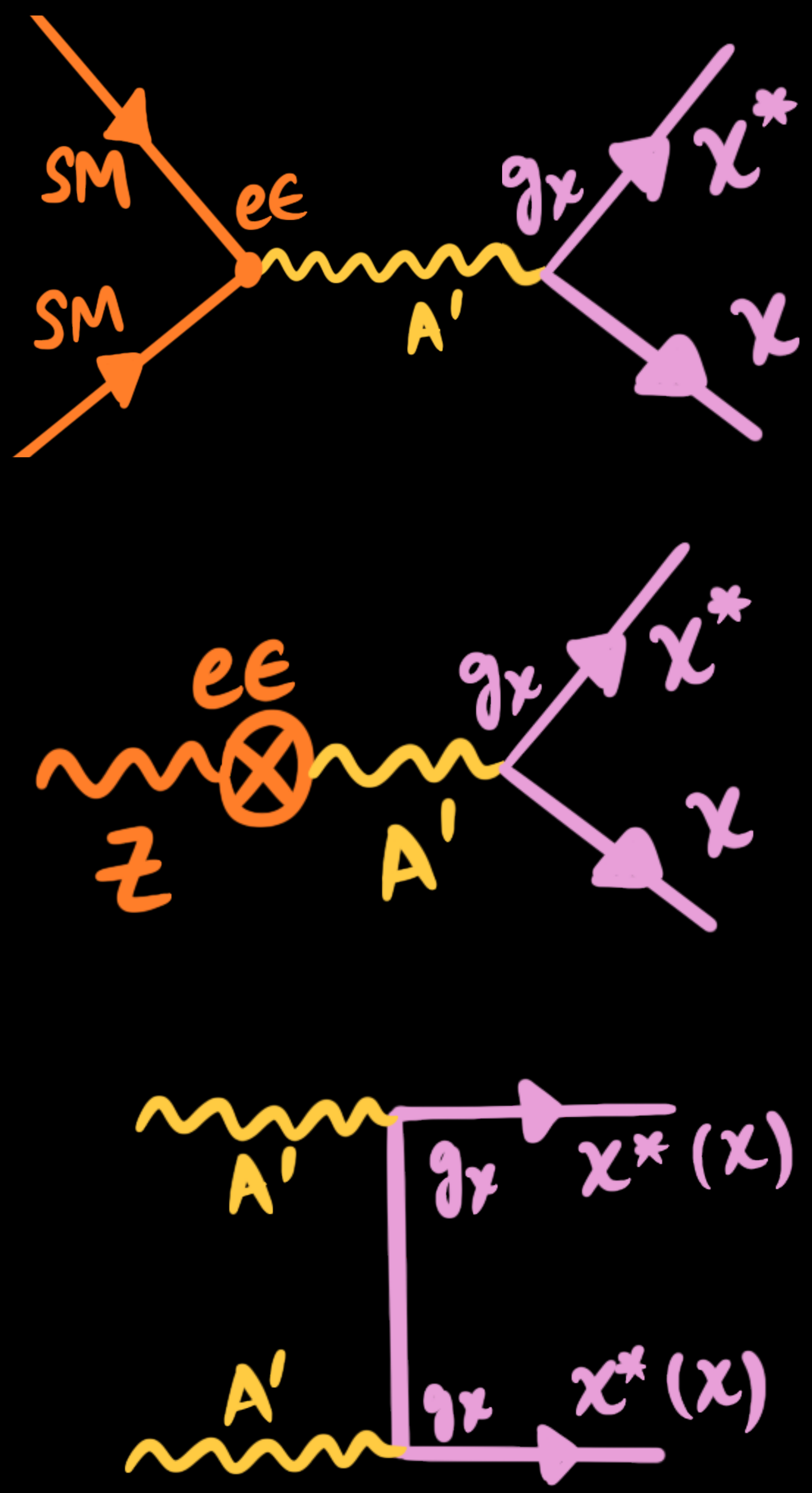


$m_\chi \sim \text{GeV} - \text{TeV}$

$\delta \lesssim m_{A'} \lesssim m_\chi$

$m_{A'} \sim \text{MeV} - \text{GeV}$

# INELASTIC FIMP DM



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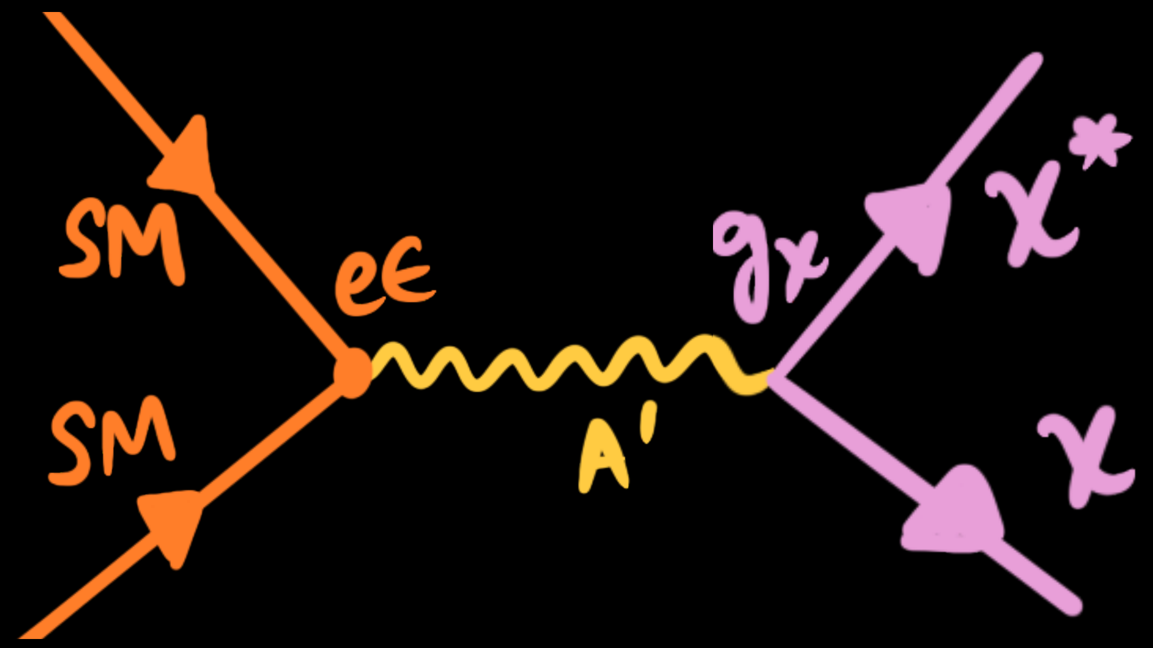
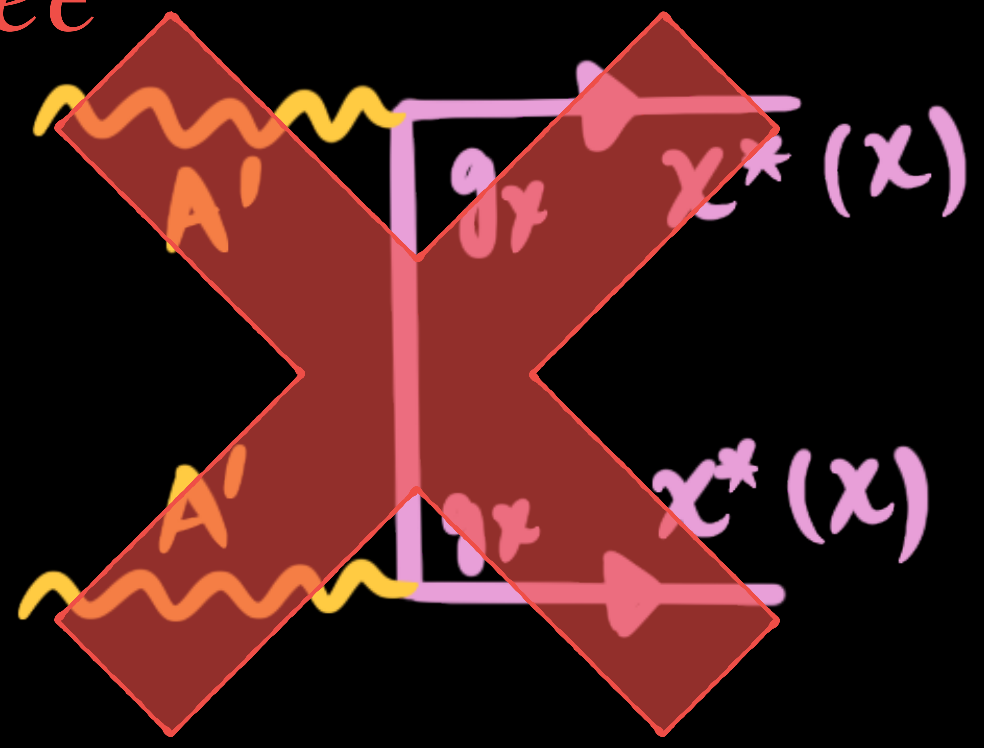




$g_\chi \lesssim e\epsilon$



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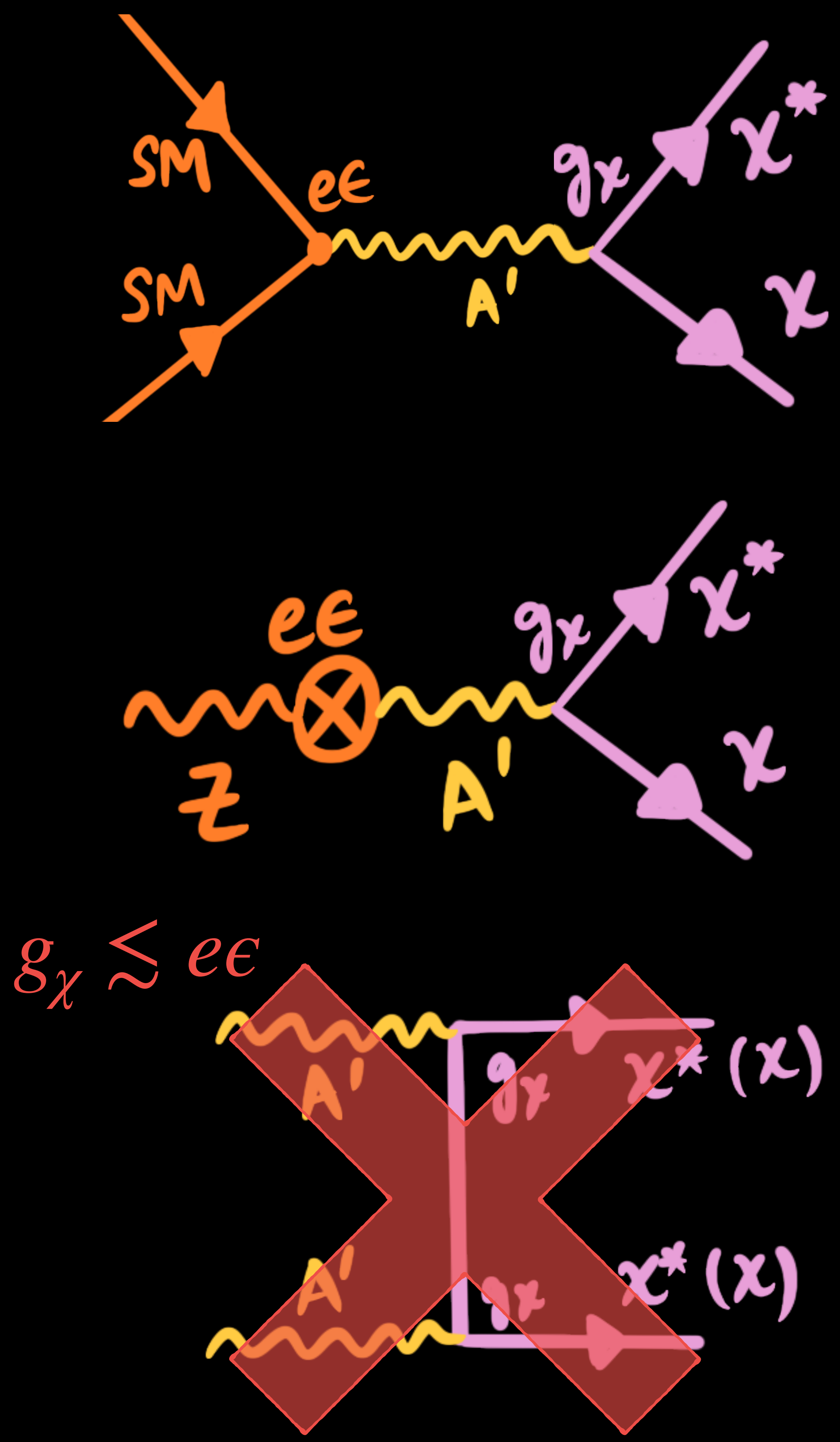


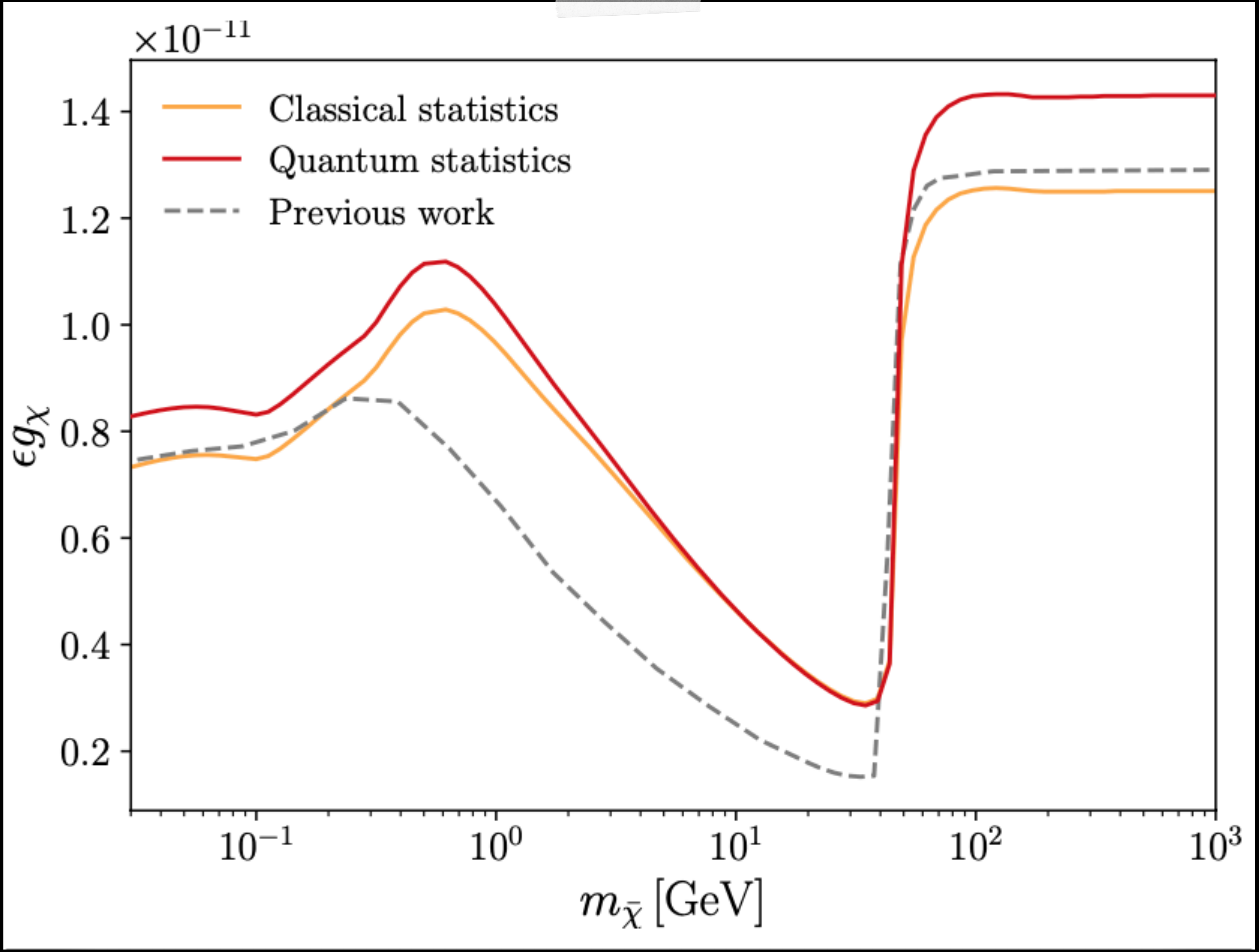

# SIGNATURES: COSMOLOGY

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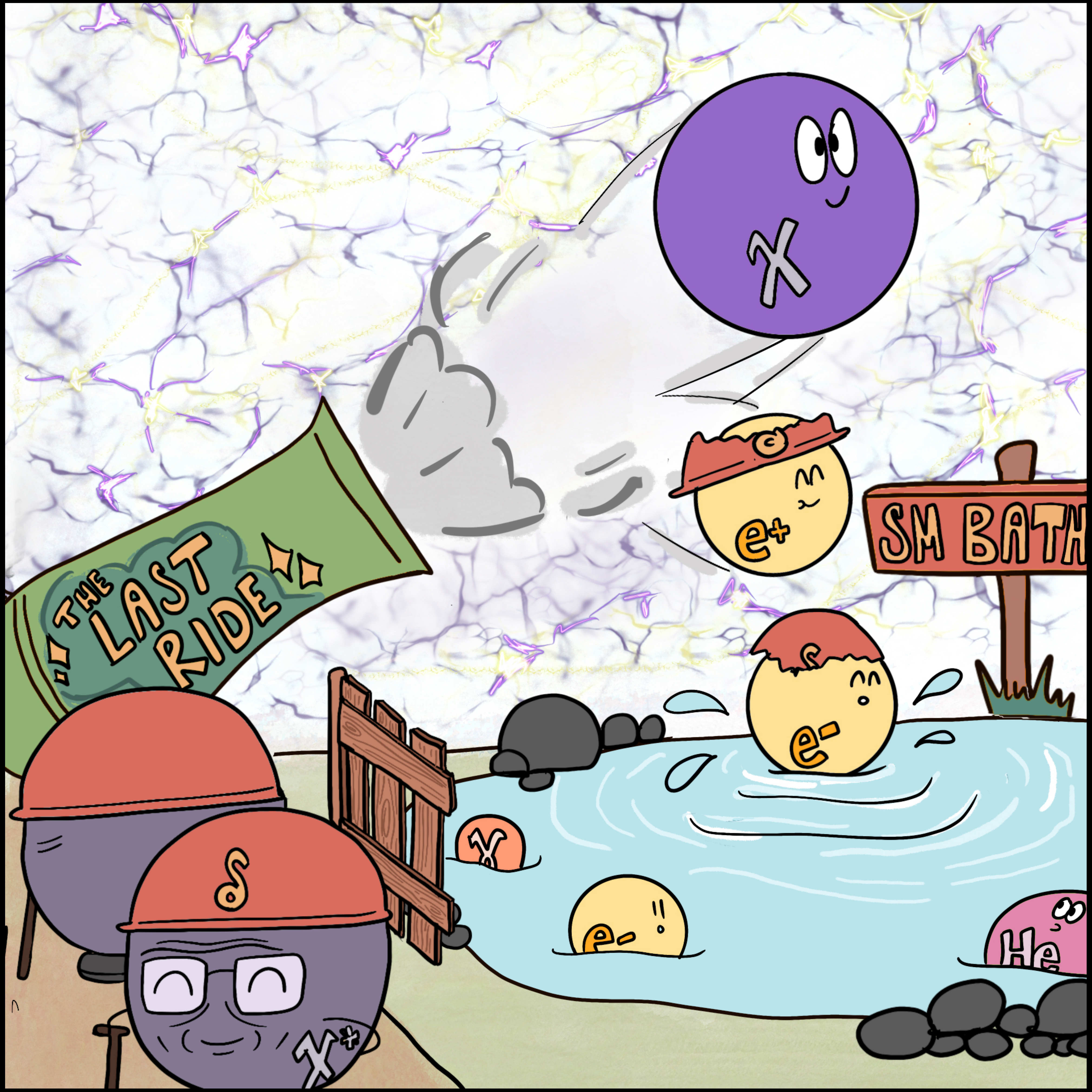
For $m_e < \delta \ll m_{A'}$ decays into $\ell^+\ell^-$ allowed.

Small freeze-in couplings result in long lived particles.

The coupling combination that sets the DM abundance also results in interesting late time cosmology

# SIGNATURES: COSMOLOGY



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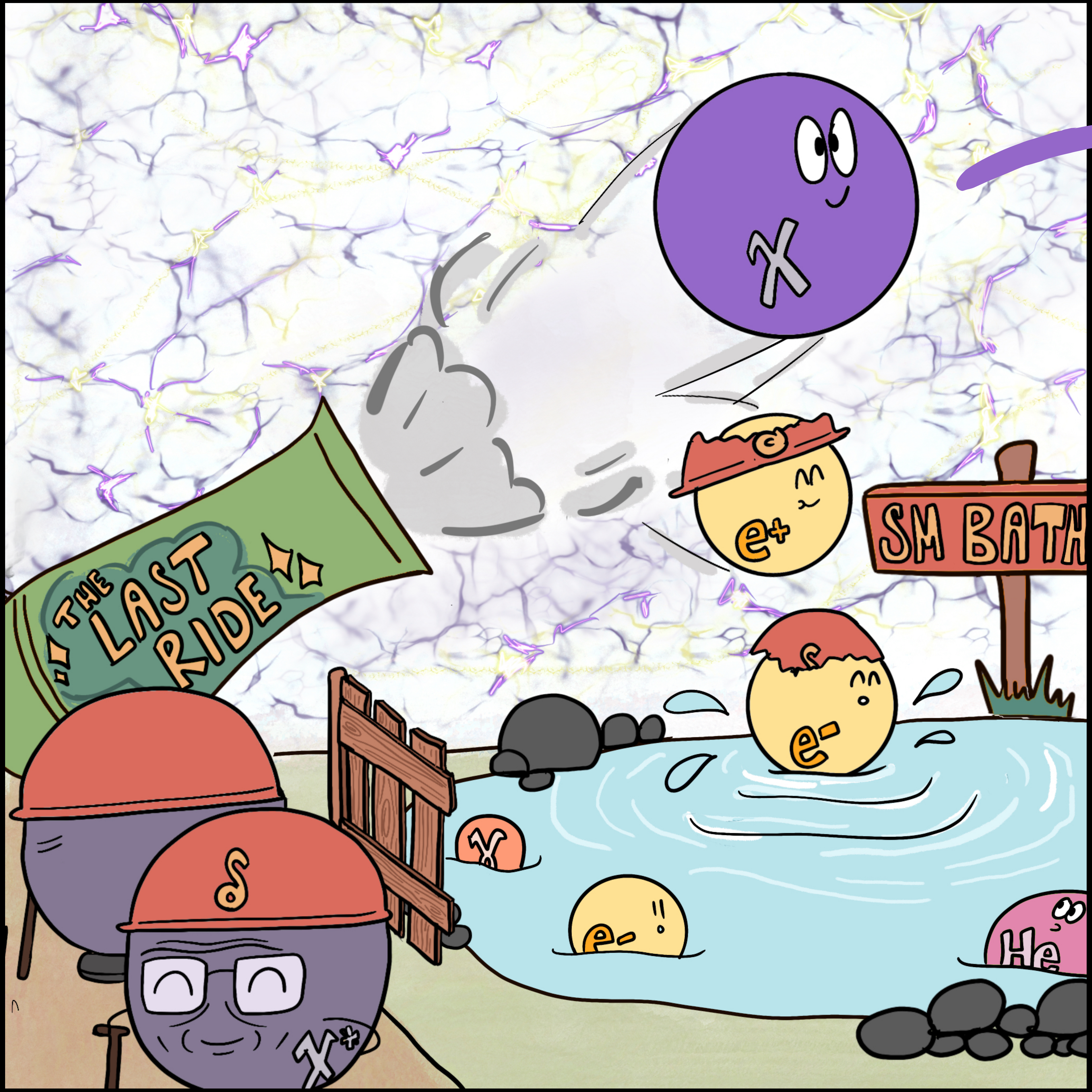
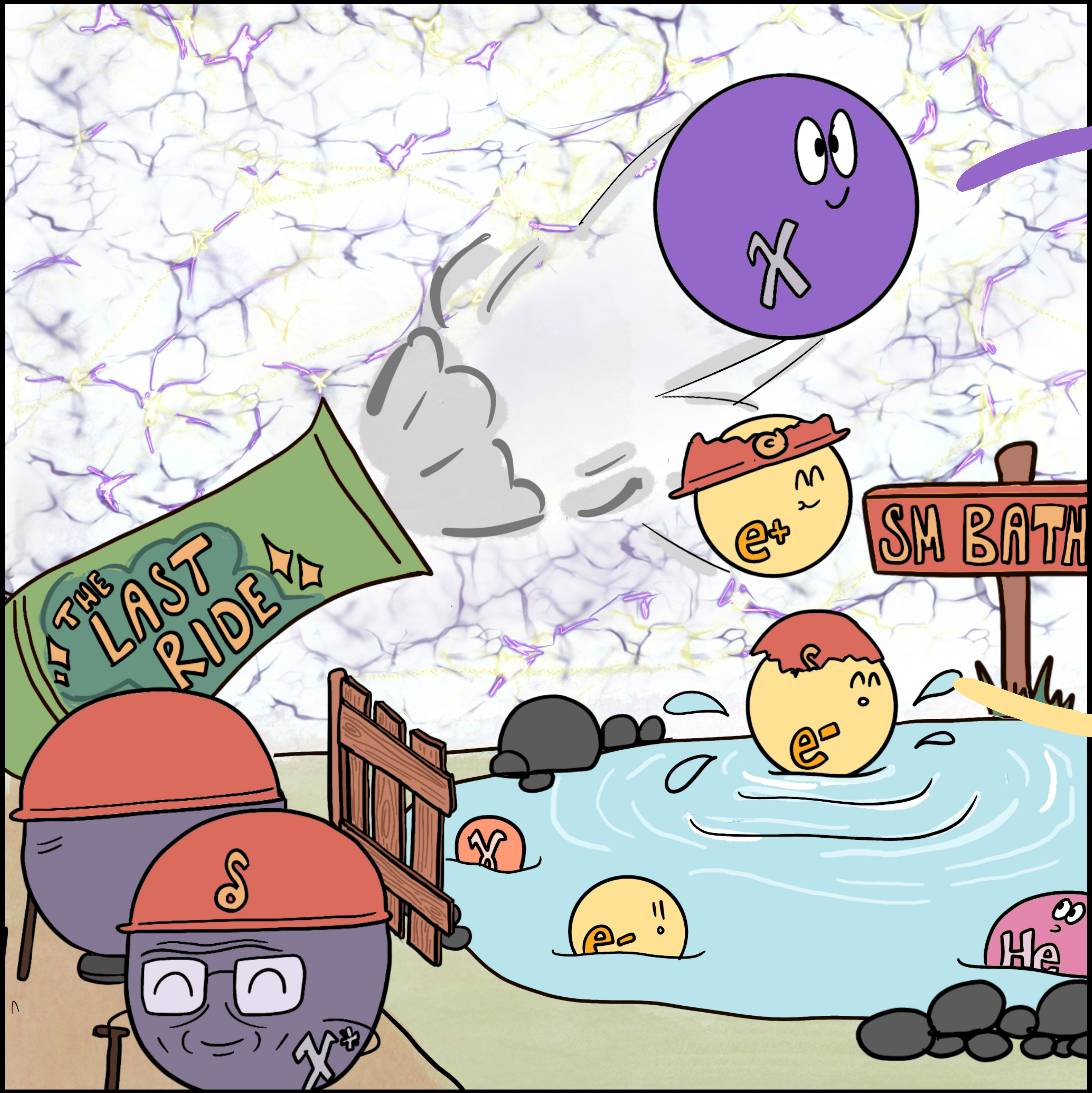



50% of the DM is warm (ish)

$$\langle v_{\mathrm{kick}} \rangle \approx \frac{\delta}{m_\chi}$$

# SIGNATURES: COSMOLOGY




50% of the DM is warm (ish)

$$\langle v_{\rm kick} \rangle \approx \frac{\delta}{m_\chi}$$

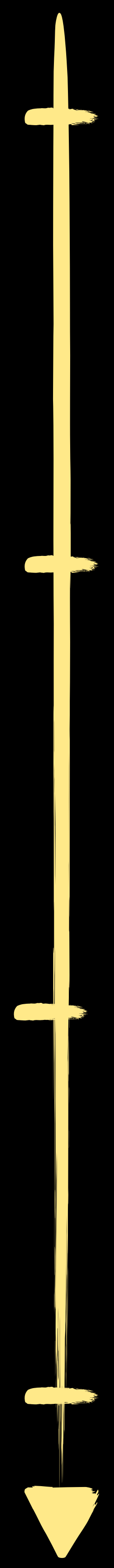
Extra energy injected into the SM plasma

$$\langle E_{e^+e^-} \rangle \approx \delta$$

# FOLLOWING THE LEPTONS

## When does the decay happen?

$$\tau \sim 10^7 \text{ seconds} \times \left(\frac{m_{A'}}{1 \text{ GeV}}\right)^4 \left(\frac{100 \text{ MeV}}{\delta}\right)^5$$



V. Poulin et al, arXiv: 1610.10051, M. Lucca et al, arXiv: 1910.04619, T.R. Slatyer & C. Wu, arXiv: 1610.06933, H. Liu et al, arXiv: 2008.01084

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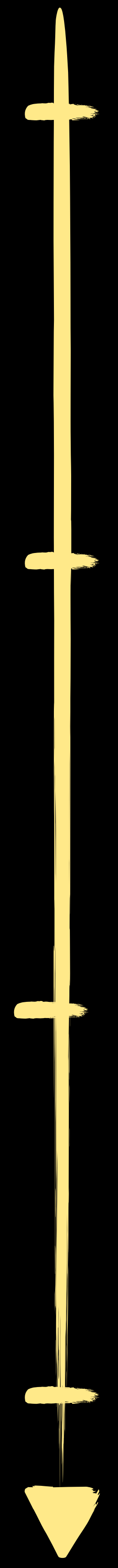

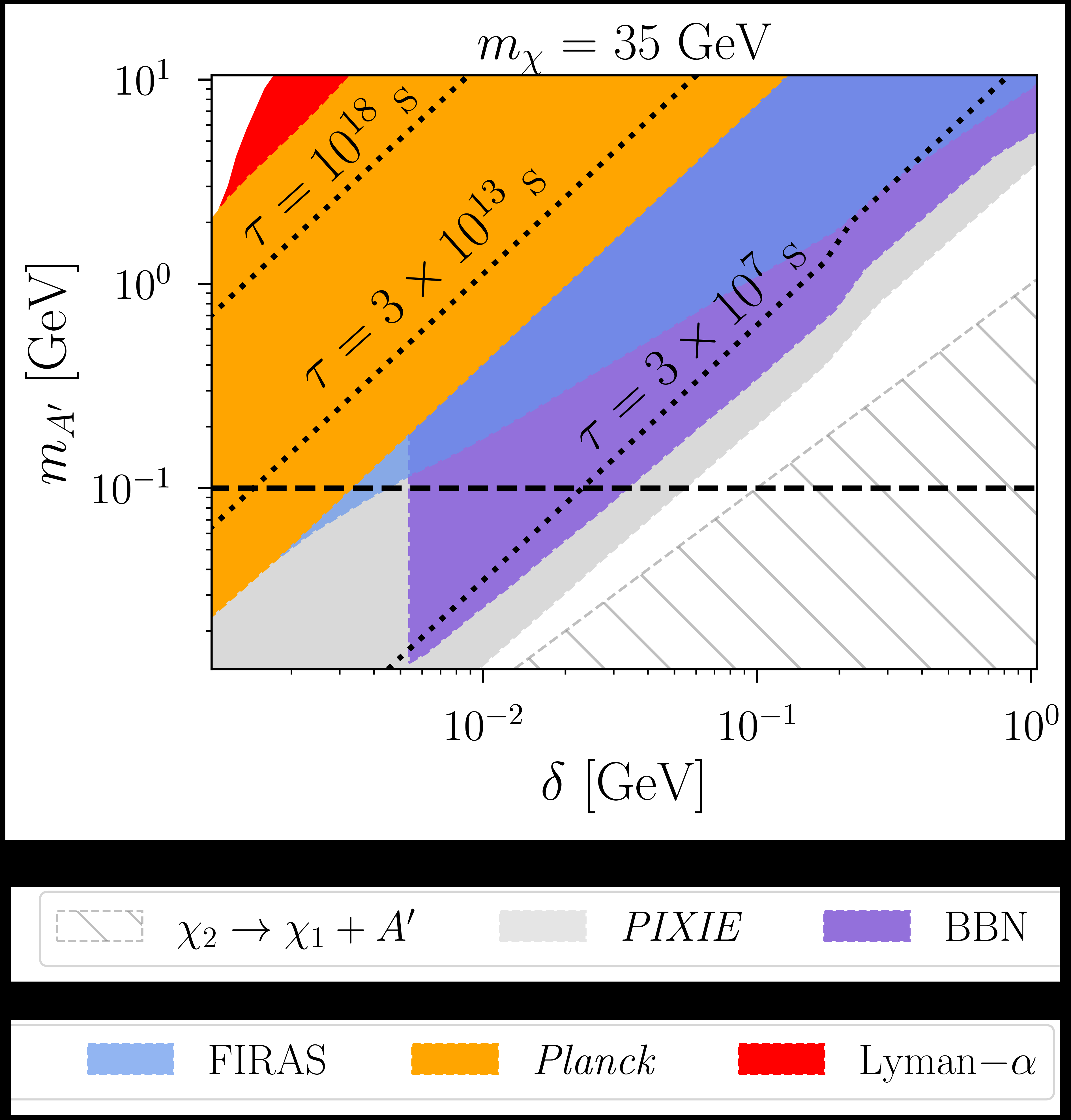


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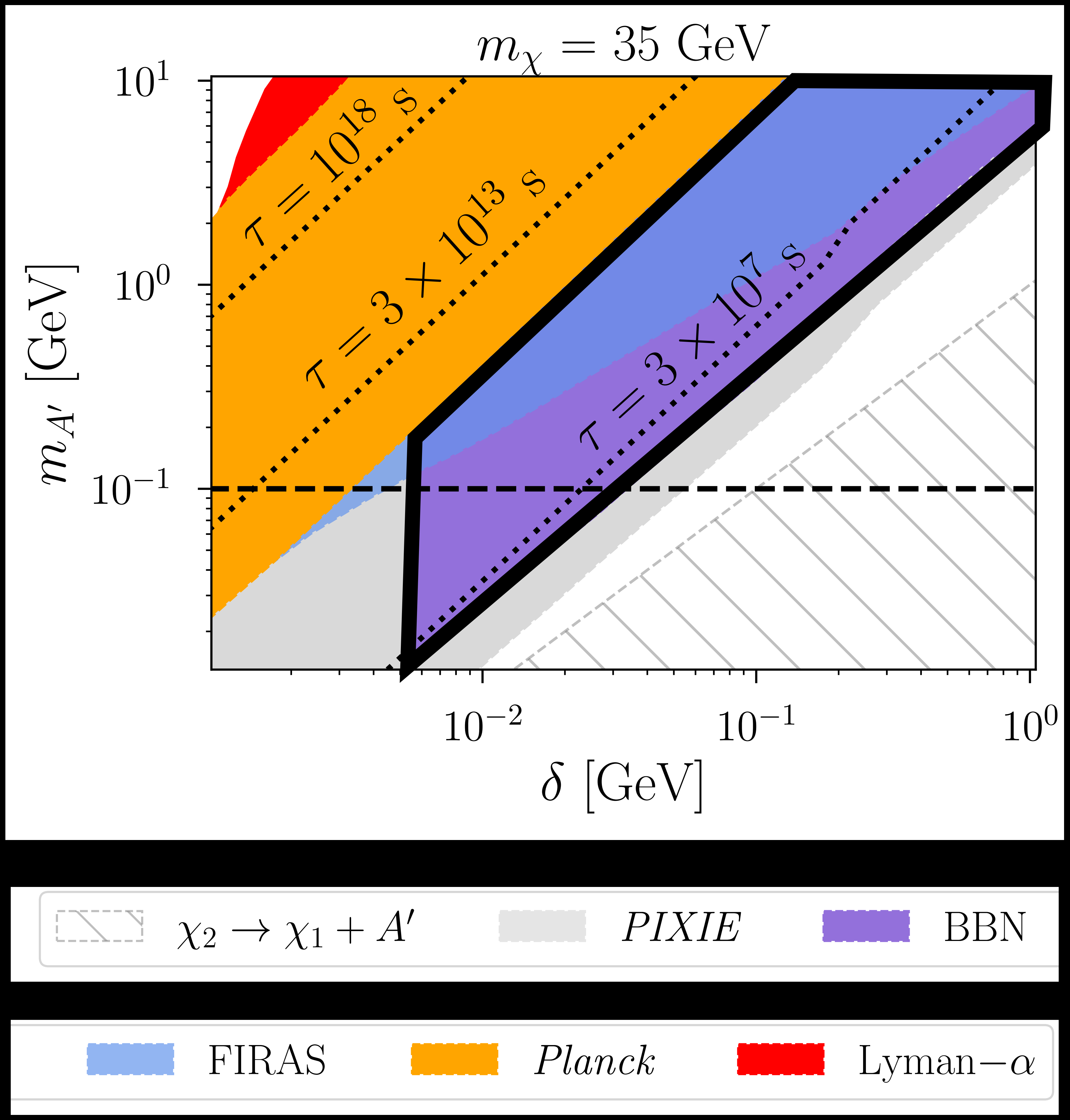
Destruction of light elements

$\tau \lesssim 10^{12}\,\text{s},\ \delta > 6\,\text{MeV}$

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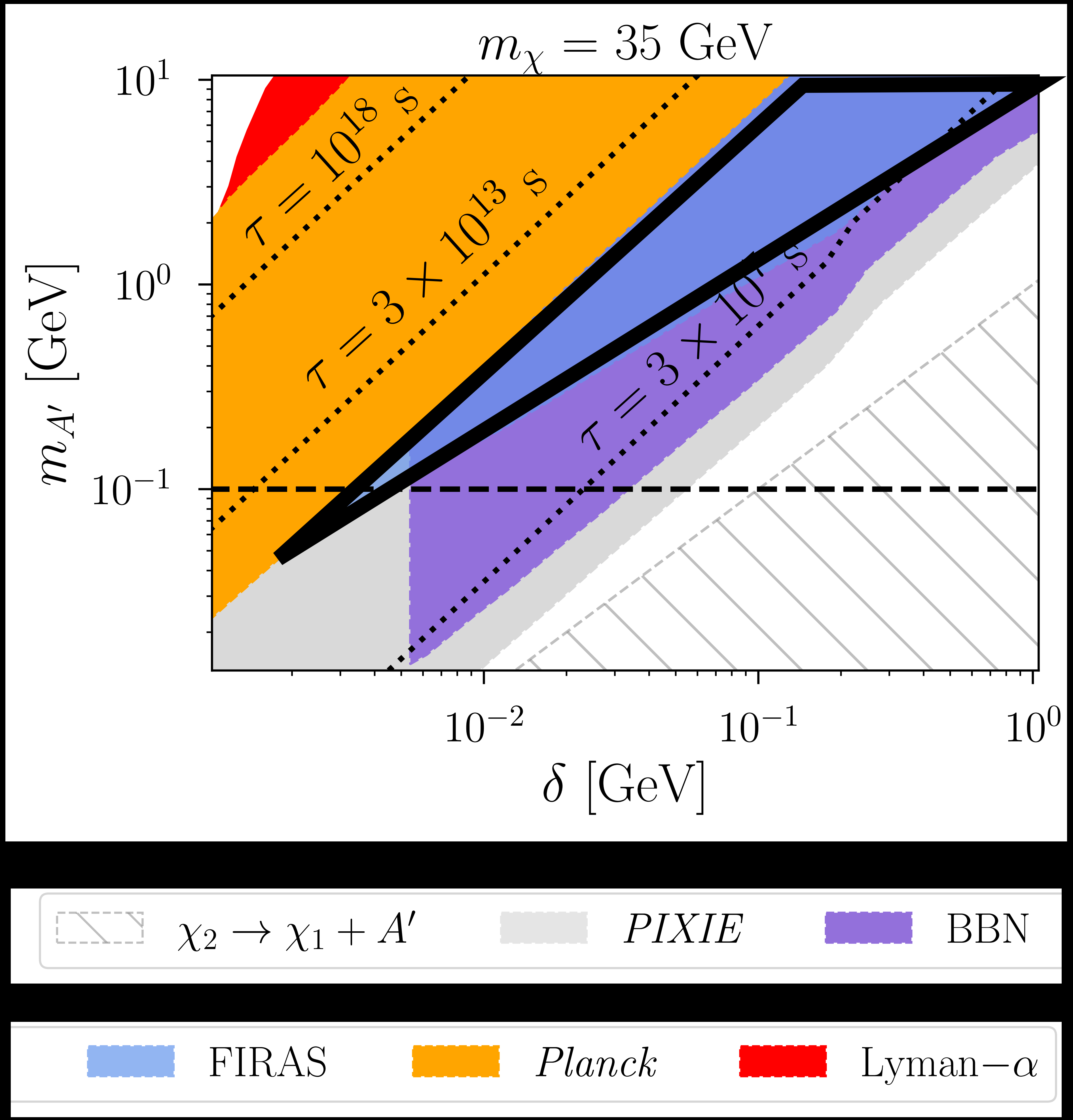
- CMB Spectral Distortions: $\tau \sim 10^7 - 10^{13}\,\text{s}$

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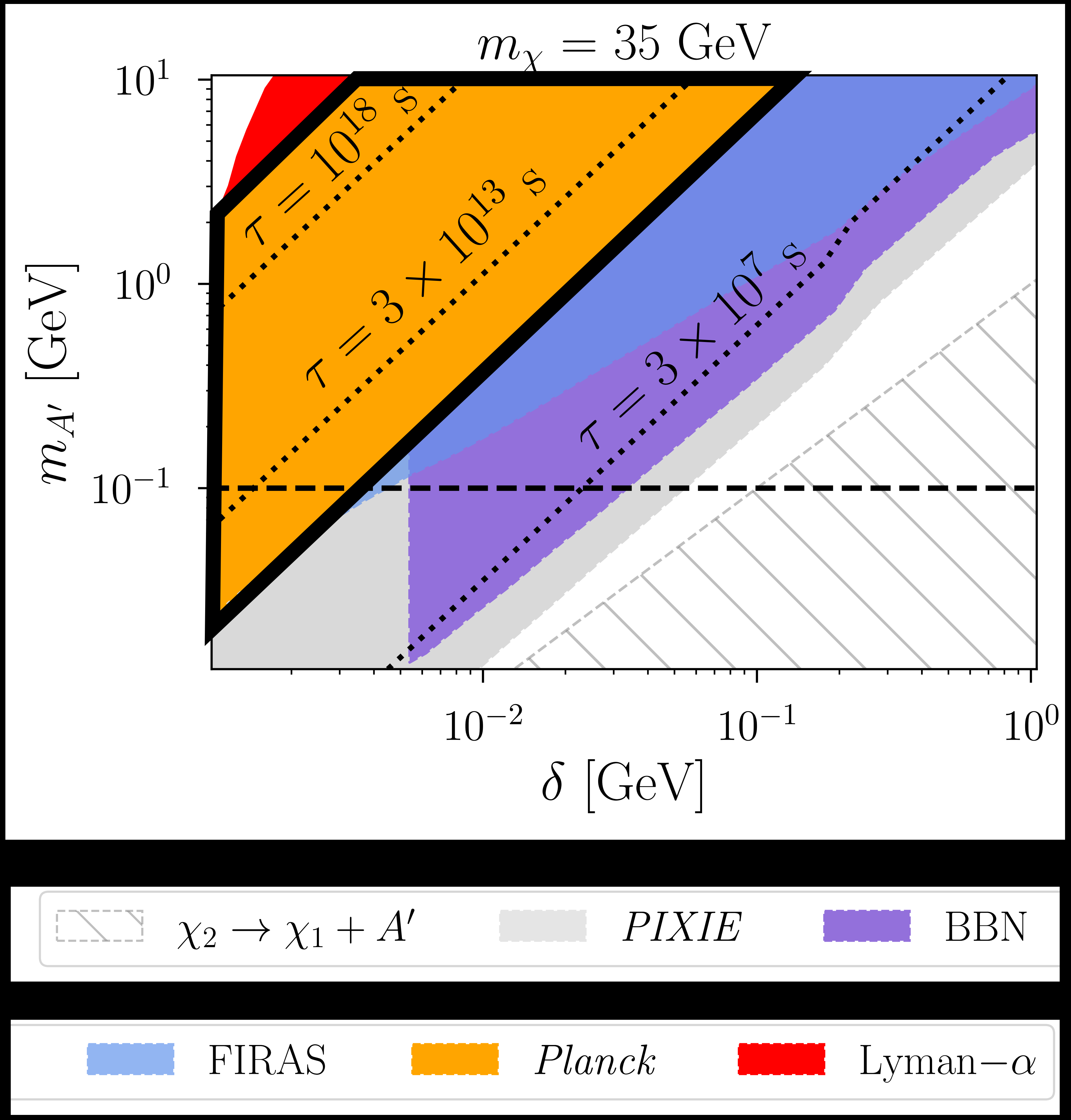


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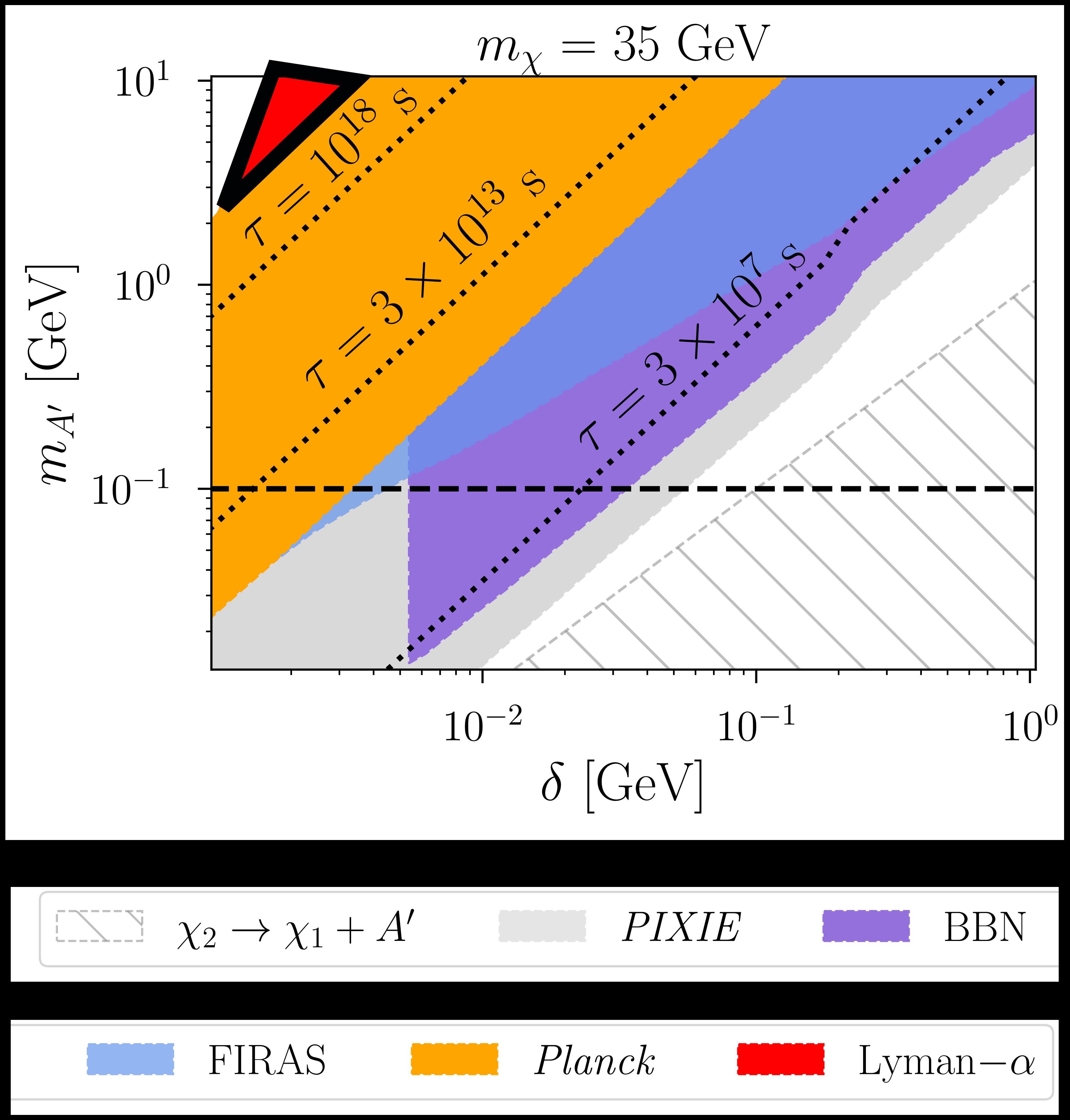
- Lyman-$\alpha$ — $\tau \sim 10^{16}\,\text{s}$

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# FOLLOWING THE GROUND STATE

Compare the free-streaming length to Warm Dark Matter

# Following the Ground State

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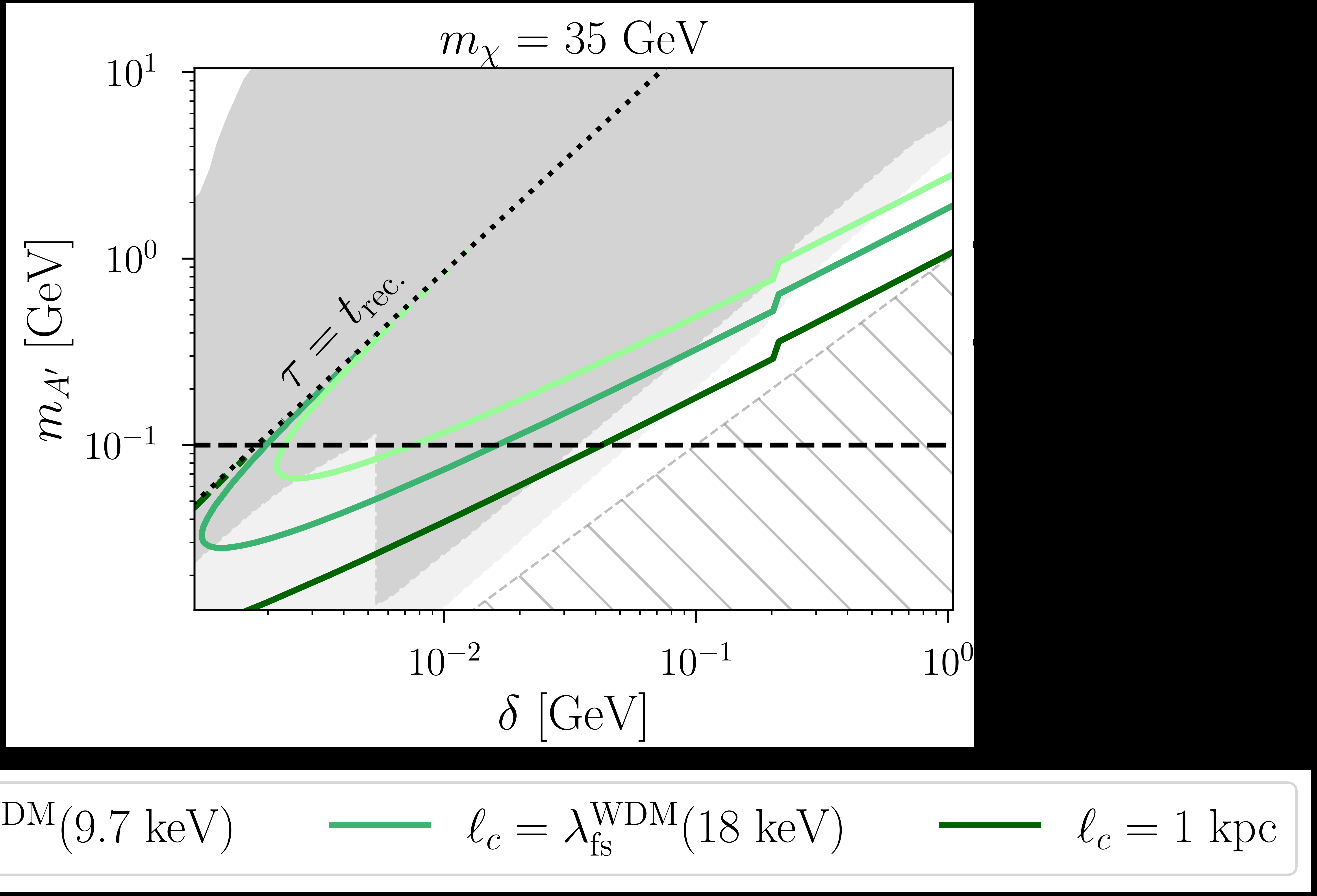

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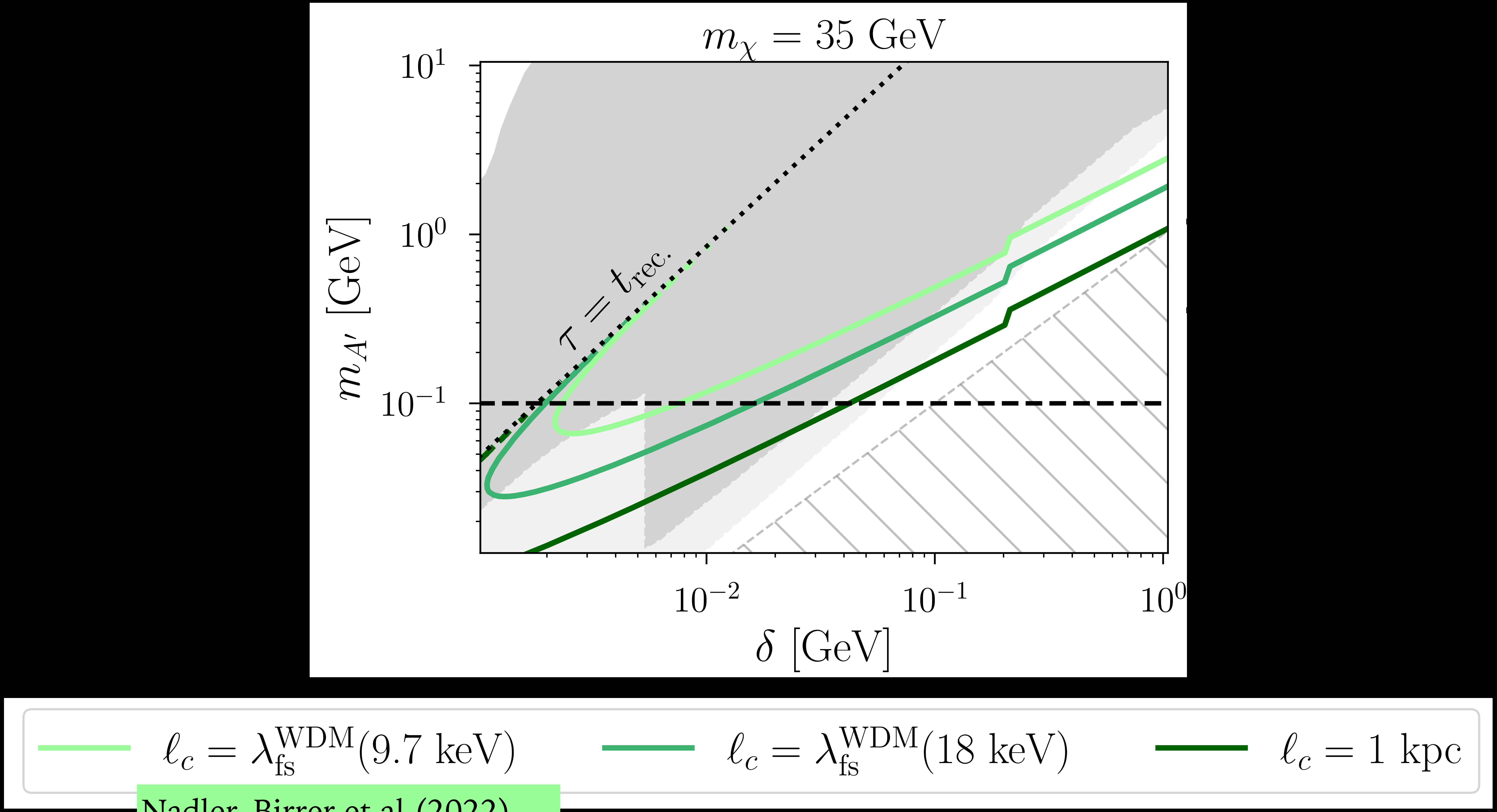


Nadler, Birrer et al (2022)

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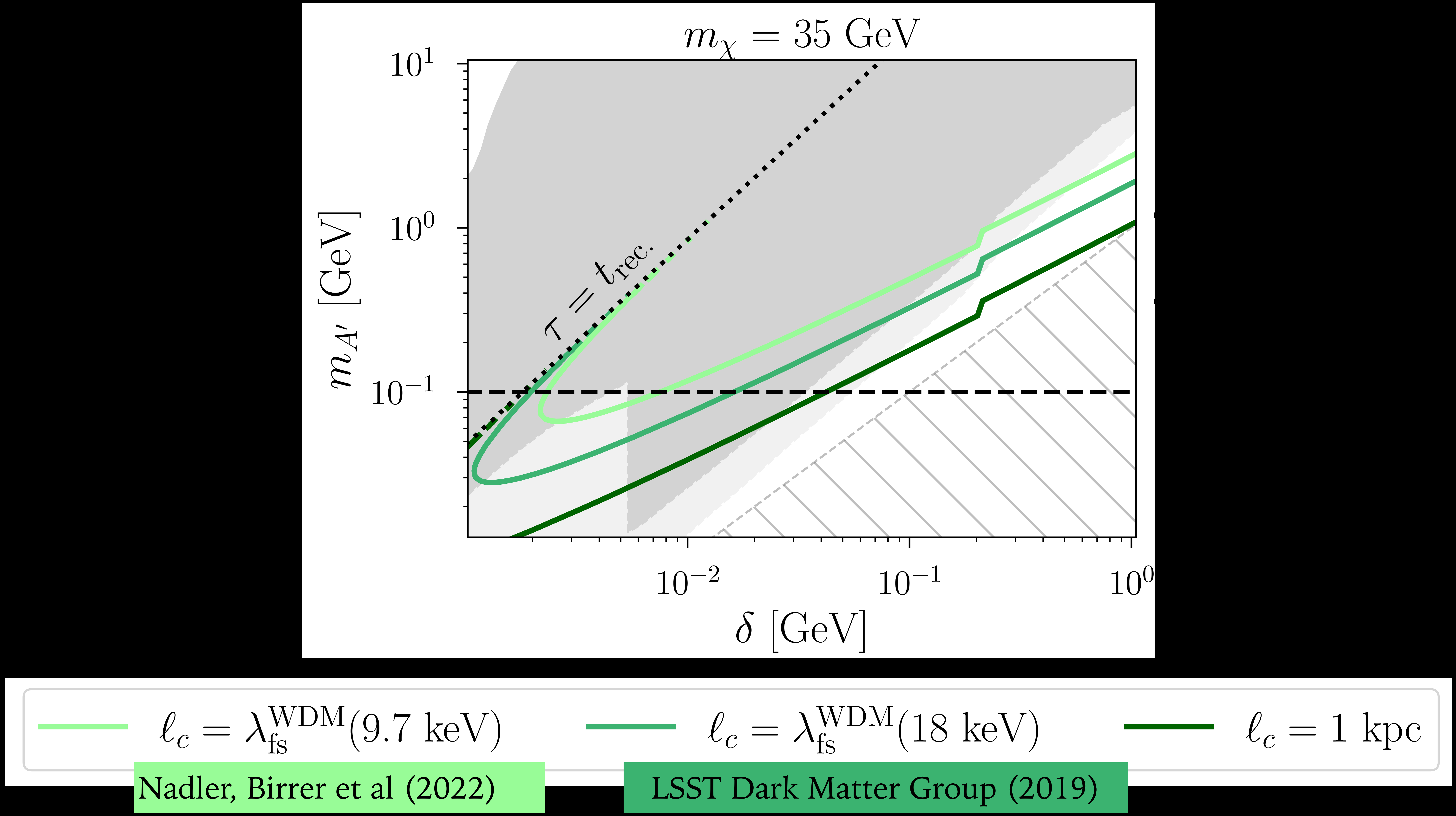

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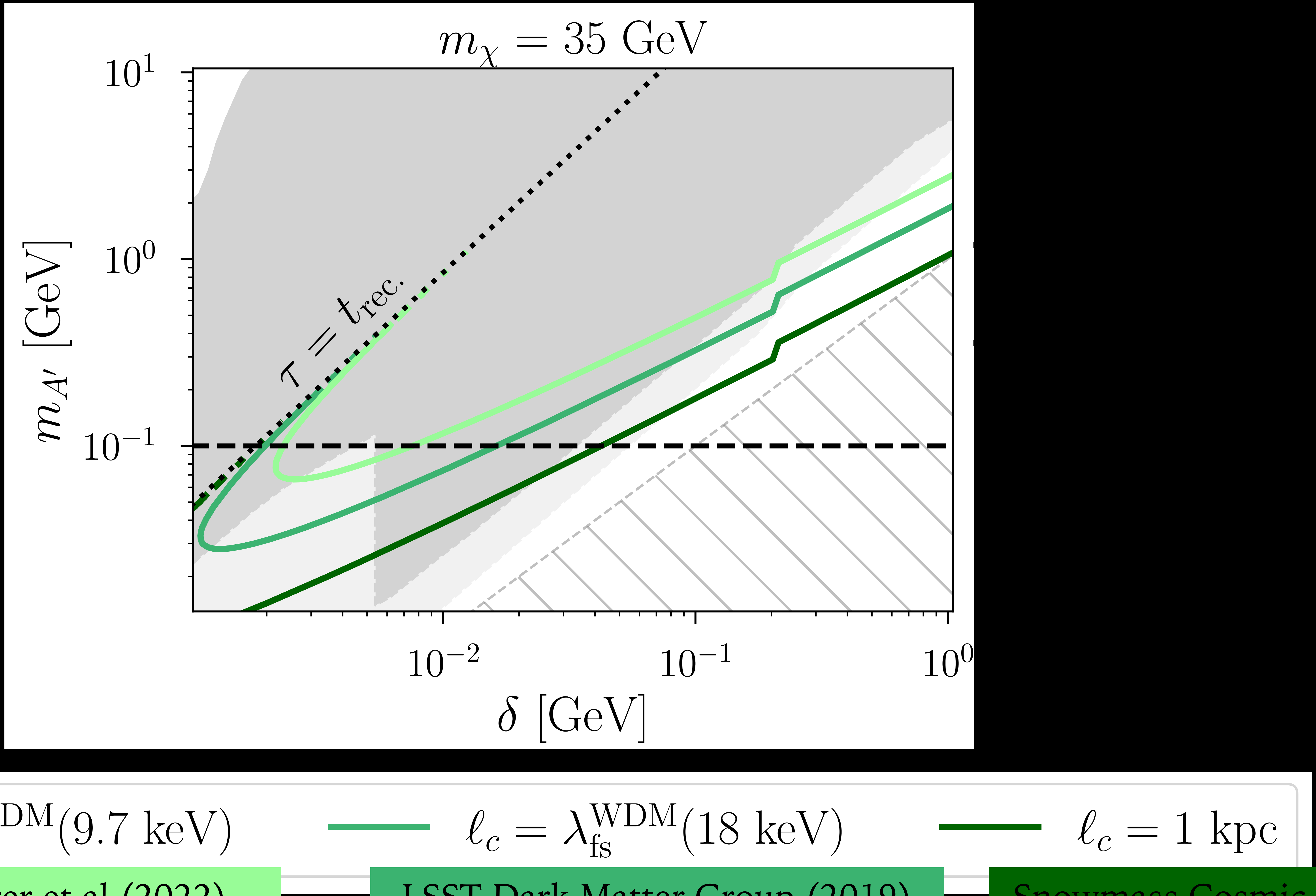


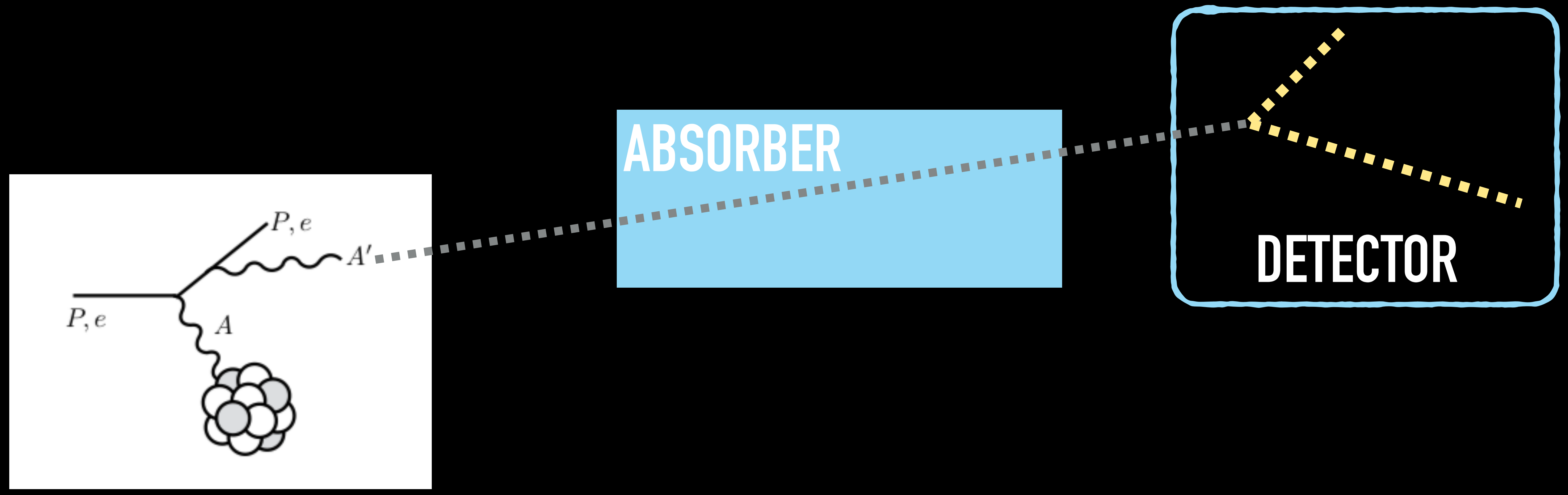

Nadler, Birrer et al (2022)

LSST Dark Matter Group (2019)

Snowmass Cosmic Frontier (2021)

# FREEZE-IN AT COLLIDERS?

Independently constrain the dark photon



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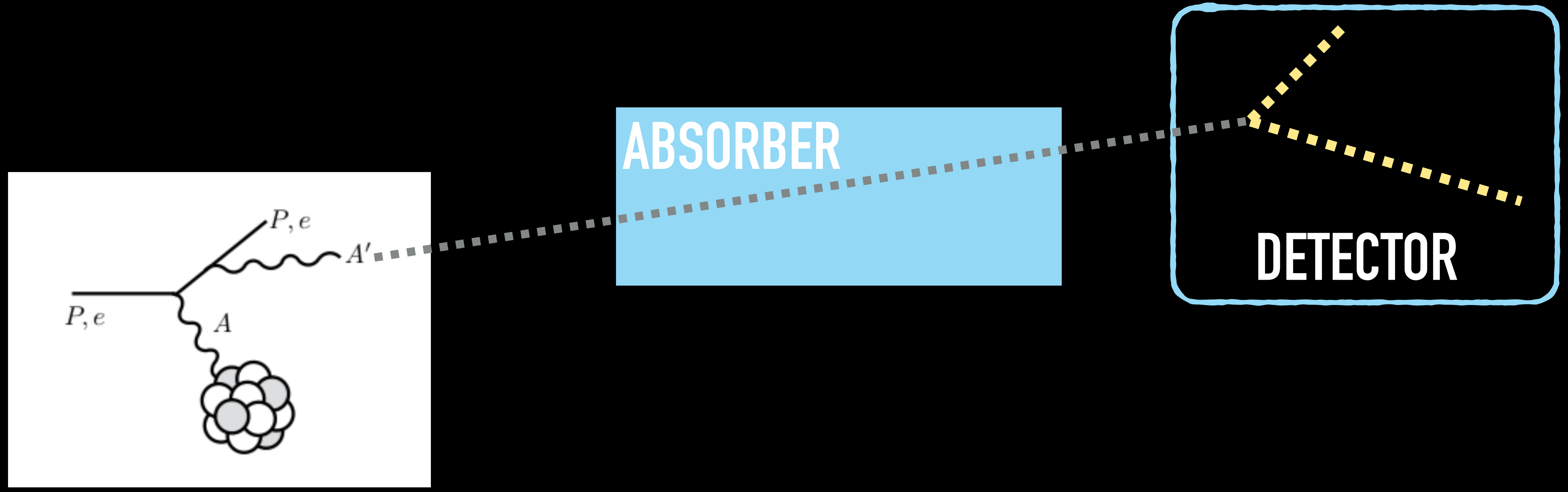


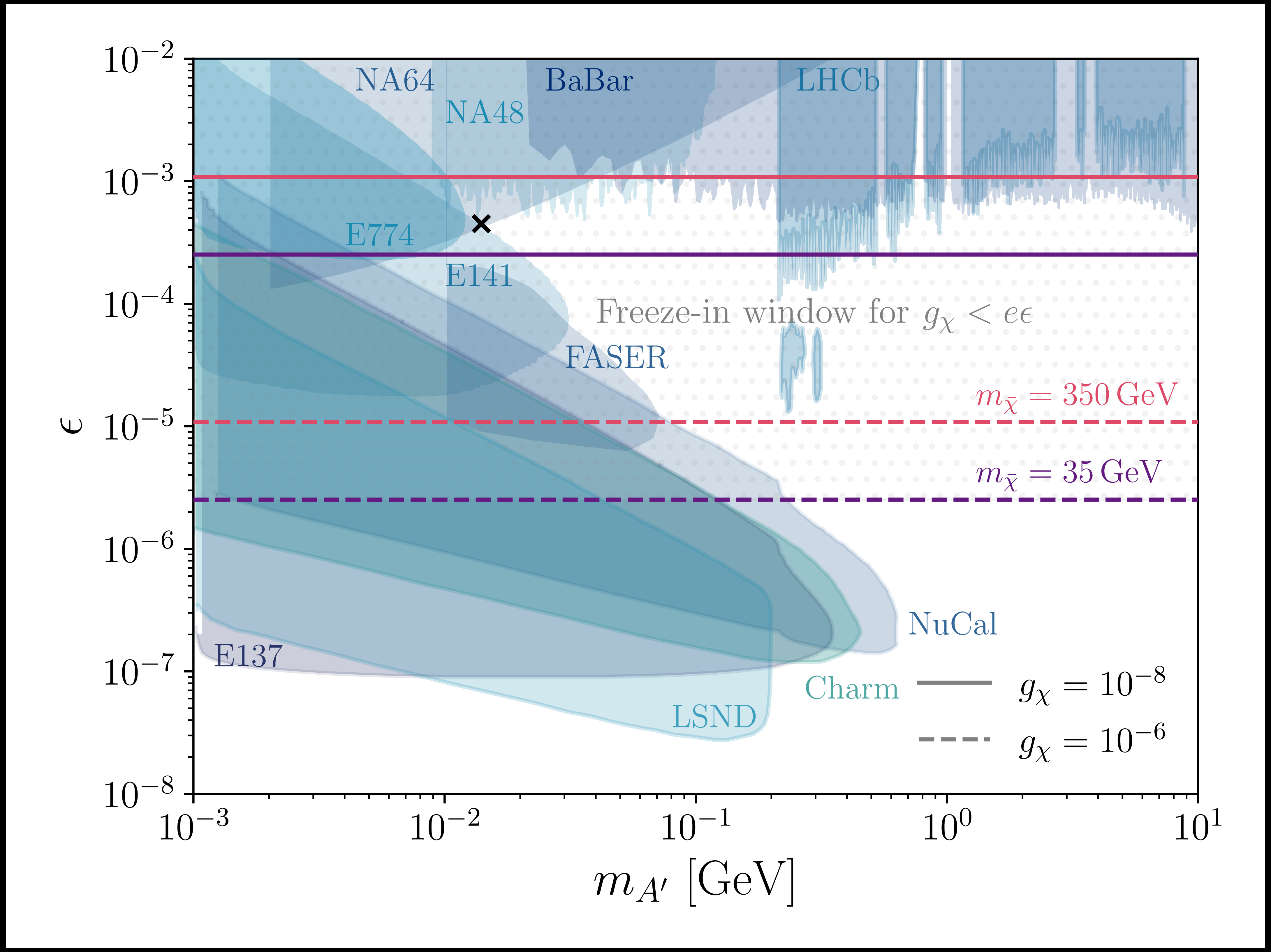

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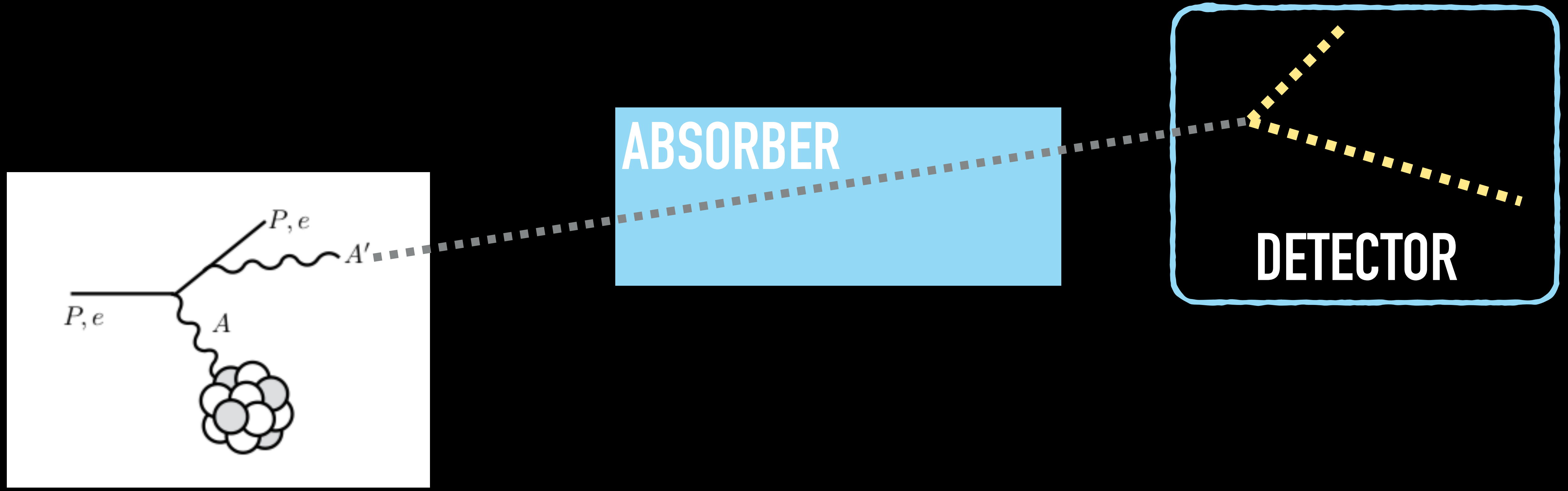


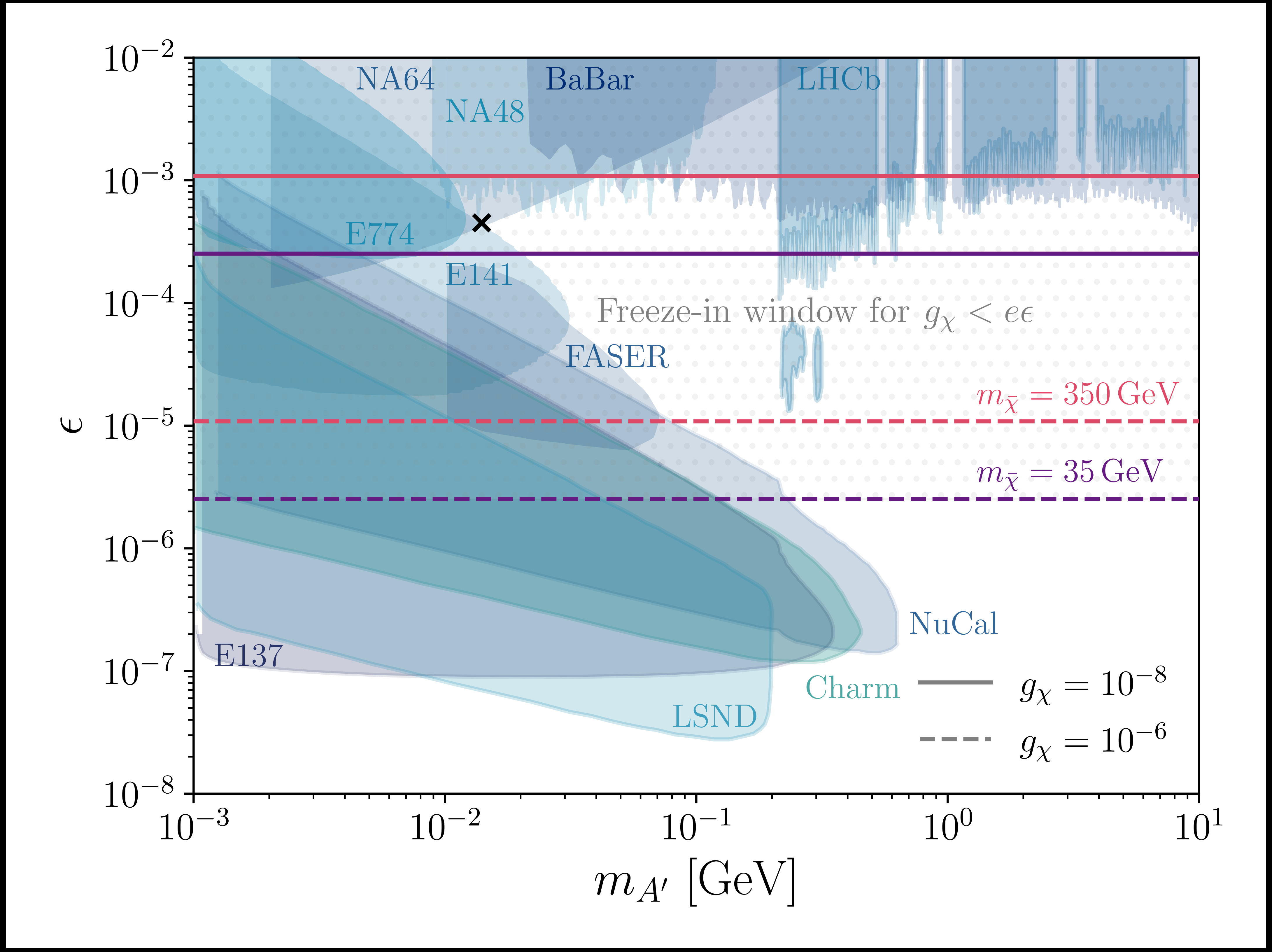


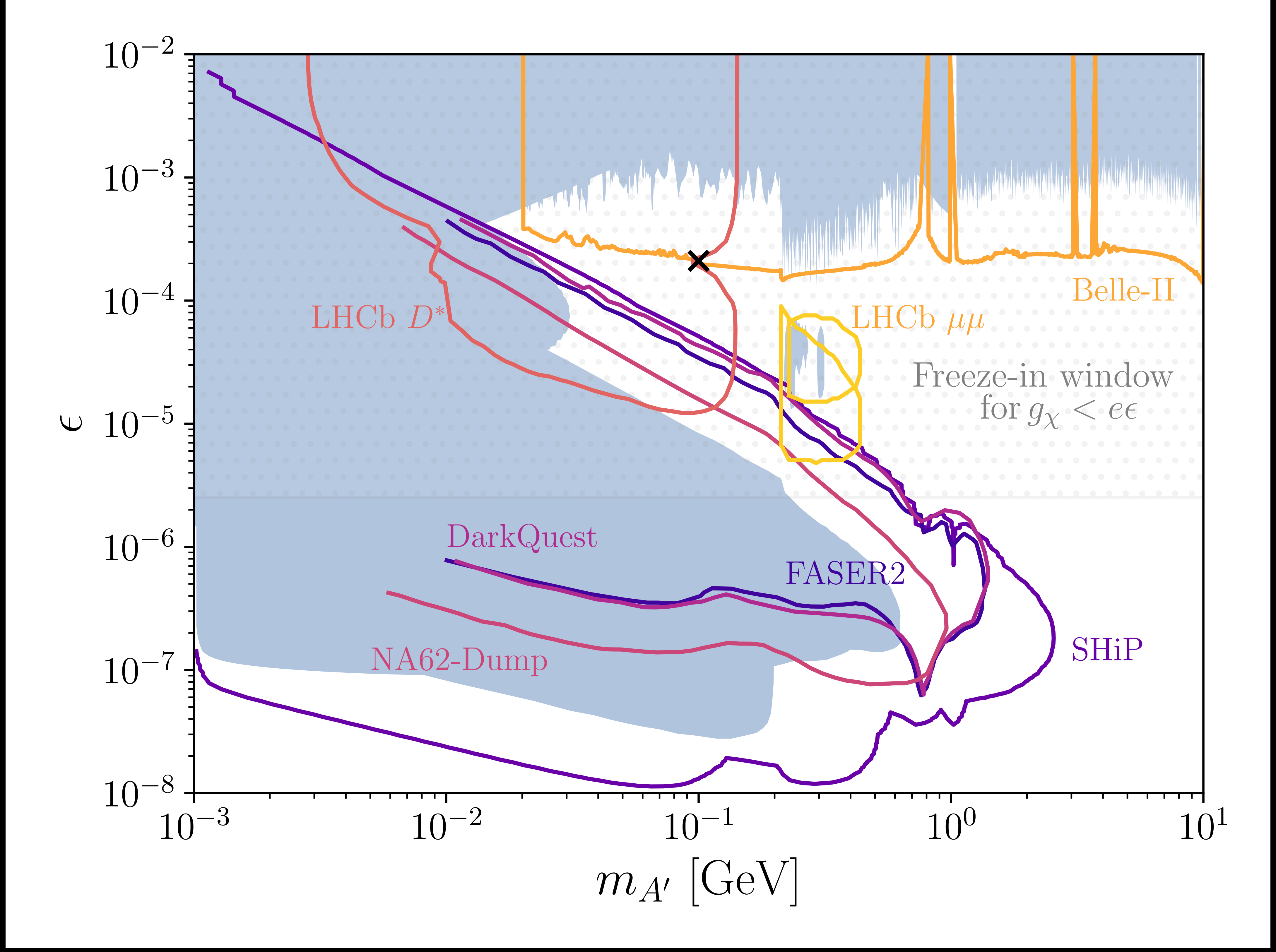

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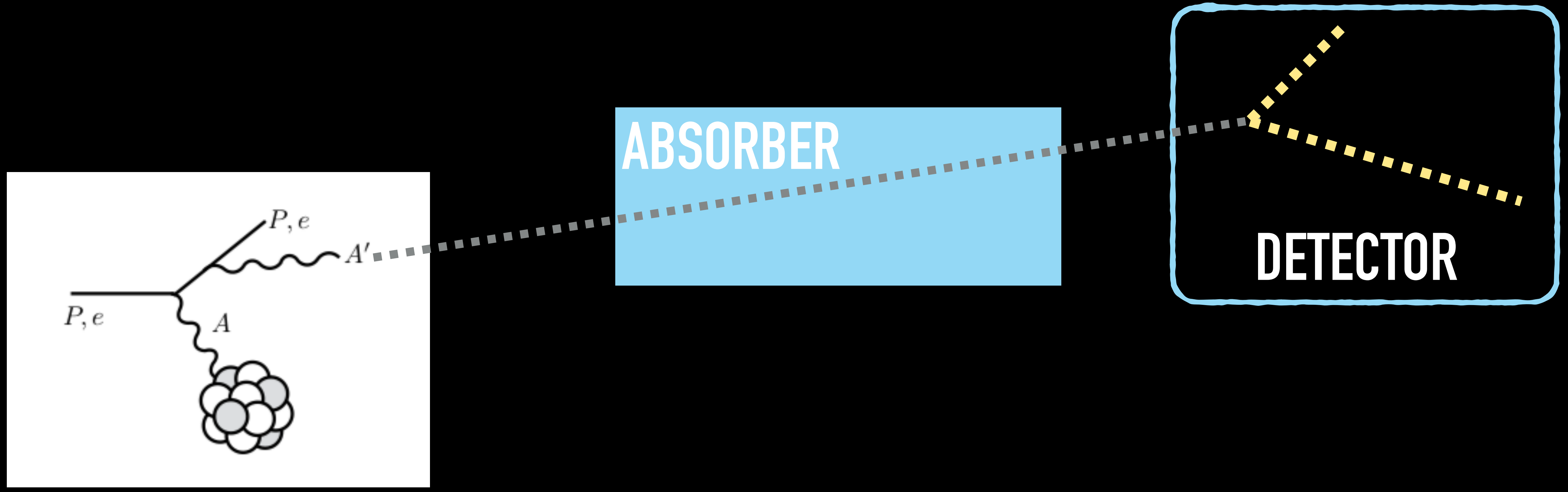
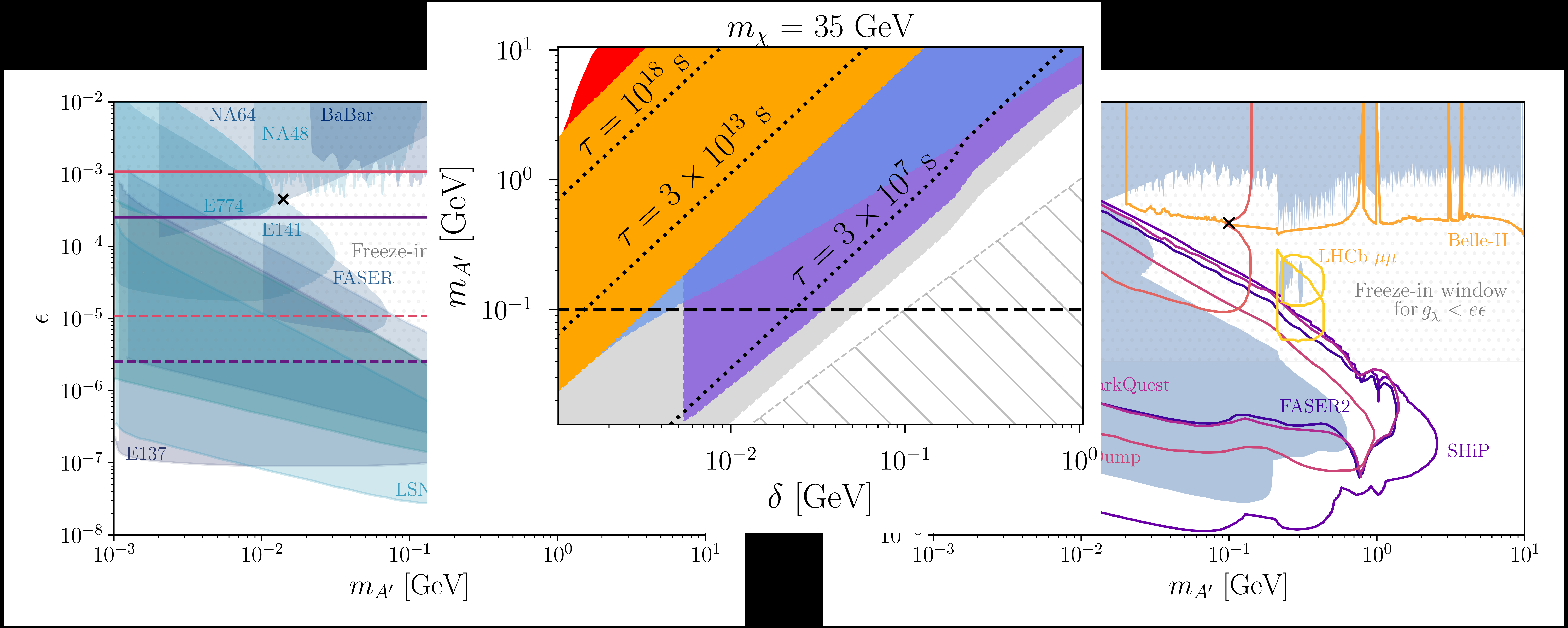
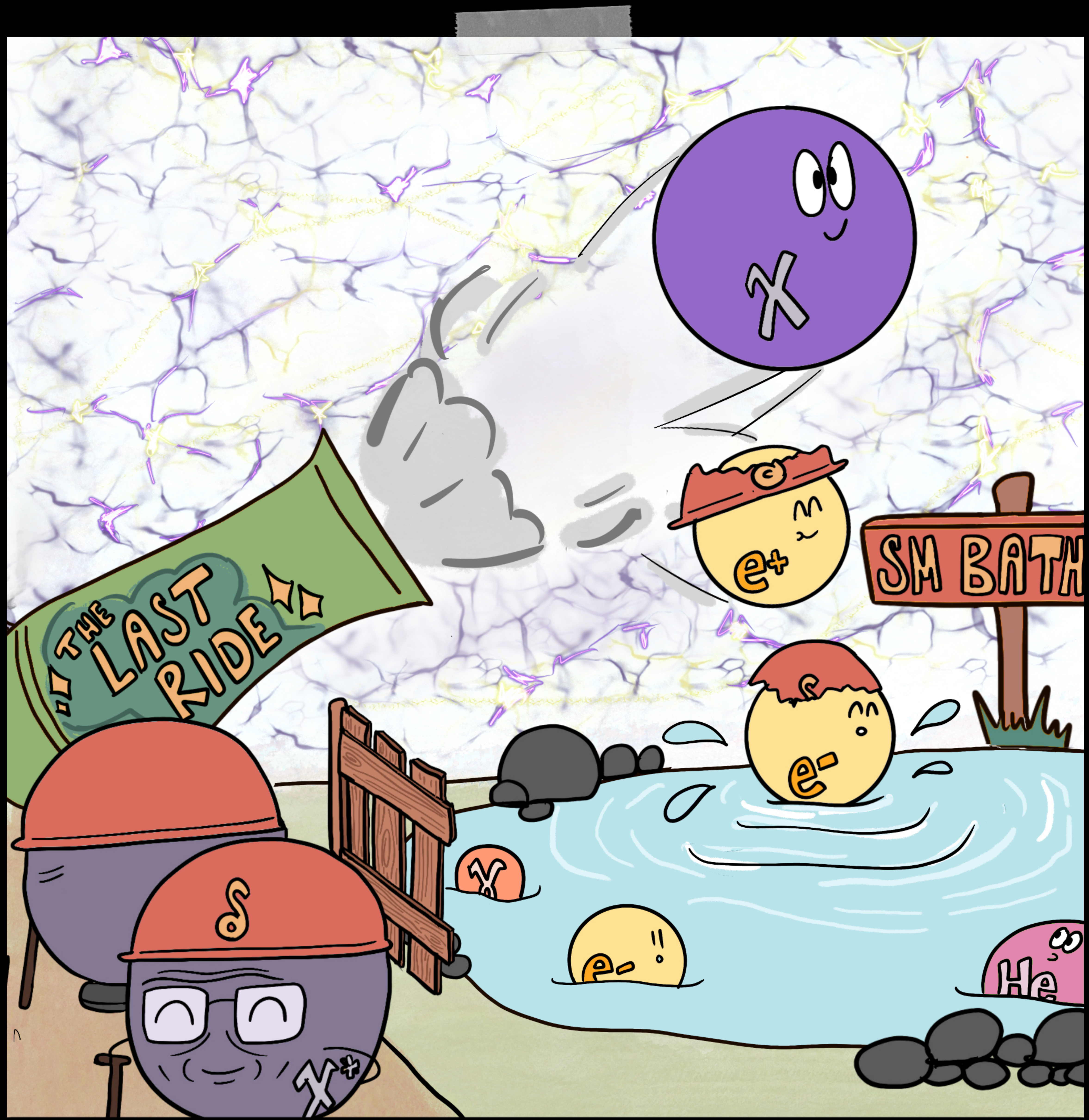


# TAKEAWAYS:

INELASTIC FREEZE-IN GIVES A CONSISTENT THERMAL HISTORY FOR DM PRODUCTION AT DECAY, AND PROVIDES A TARGET FOR COSMOLOGICAL AND COLLIDER SEARCHES FOR DARK MATTER



# TLDR

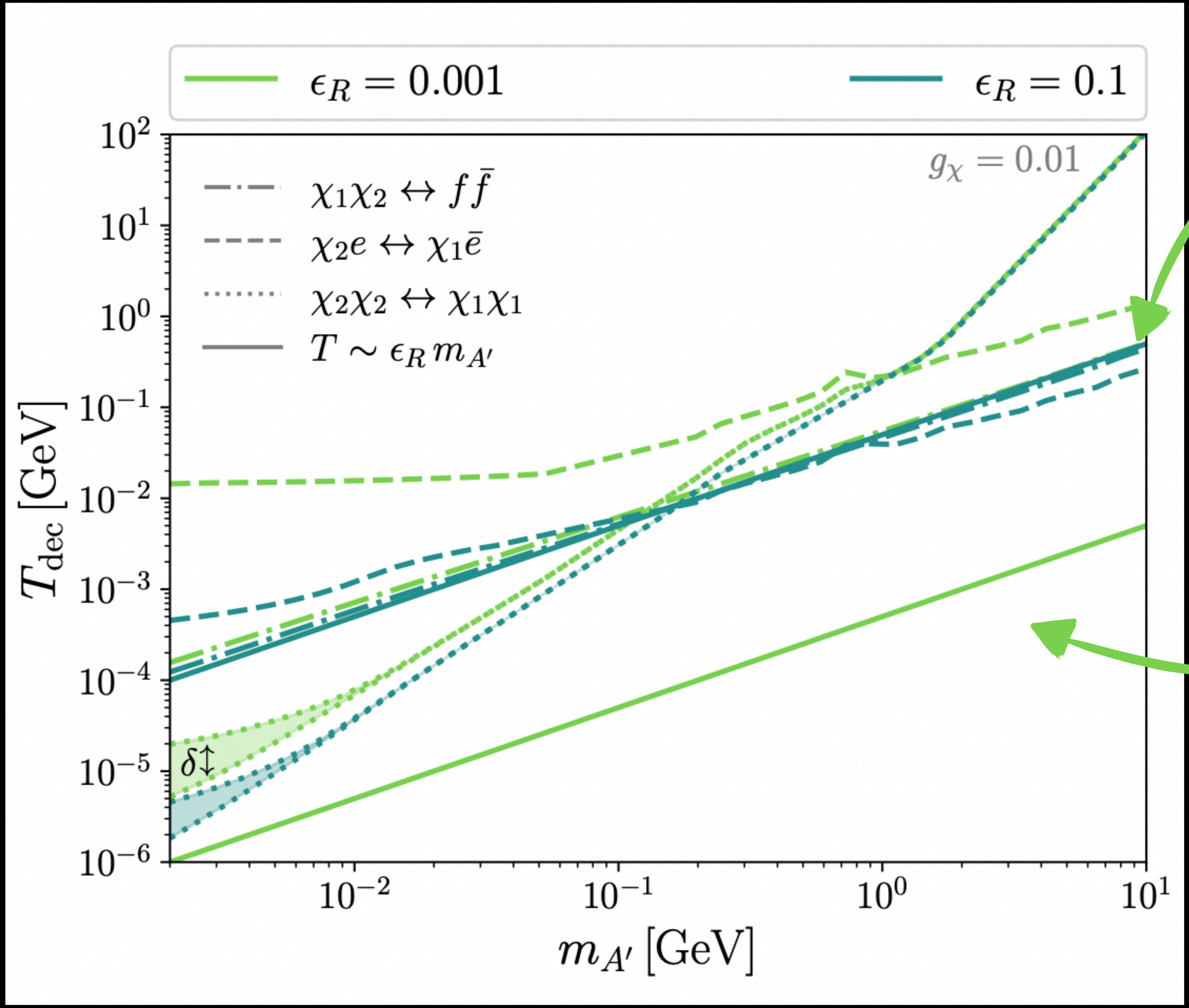
BY RELATING EARLY AND LATE TIME DM BEHAVIOUR, THE UNIVERSE CAN BE USED AS A GIANT LABORATORY TO CONSTRAIN DM

INELASTIC DM IS A SIMPLE EXTENSION OF THE SM THAT GIVES QUALITATIVELY NEW SIGNATURES AT A RANGE OF SCALES

THE PHENOMENOLOGY OF INELASTIC DM BEYOND FREEZE-OUT IS YET TO BE CONSISTENTLY MAPPED OUT!

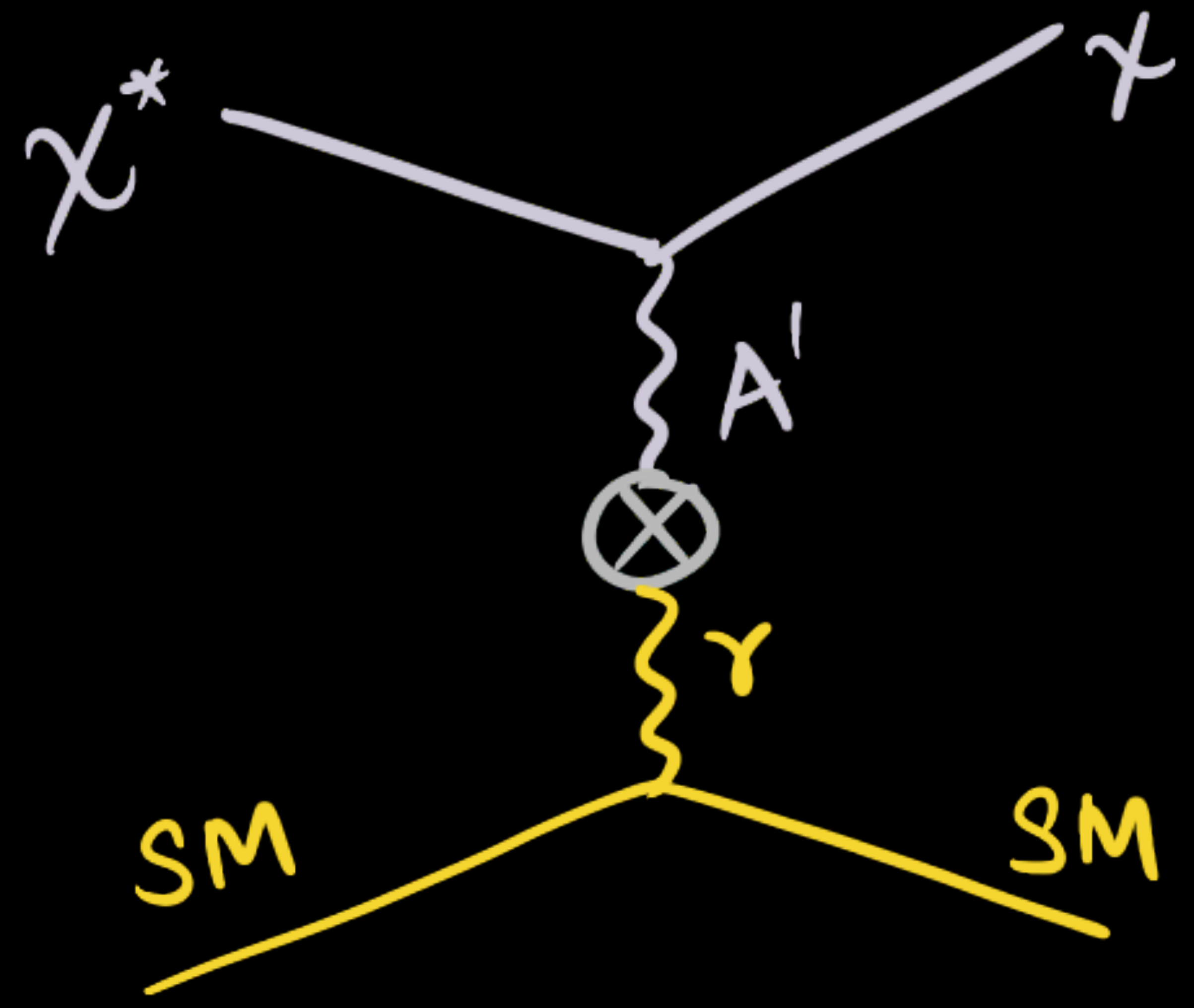
# APPENDIX

# EARLY KINETIC DECOUPLING

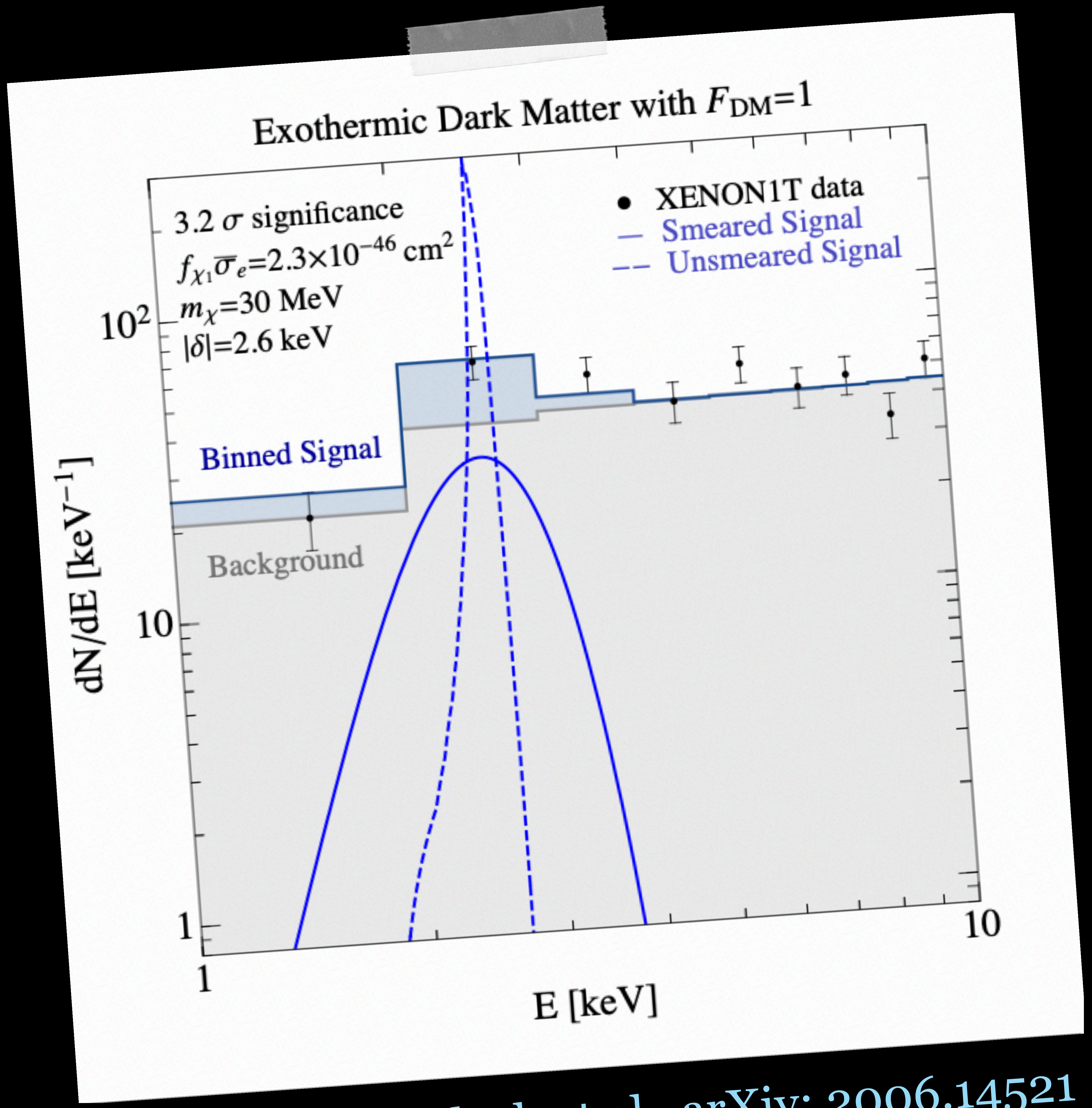



Annihilations become resonant!

# SUCH INTERACTIONS HAVE A UNIQUE PHENOMENOLOGY

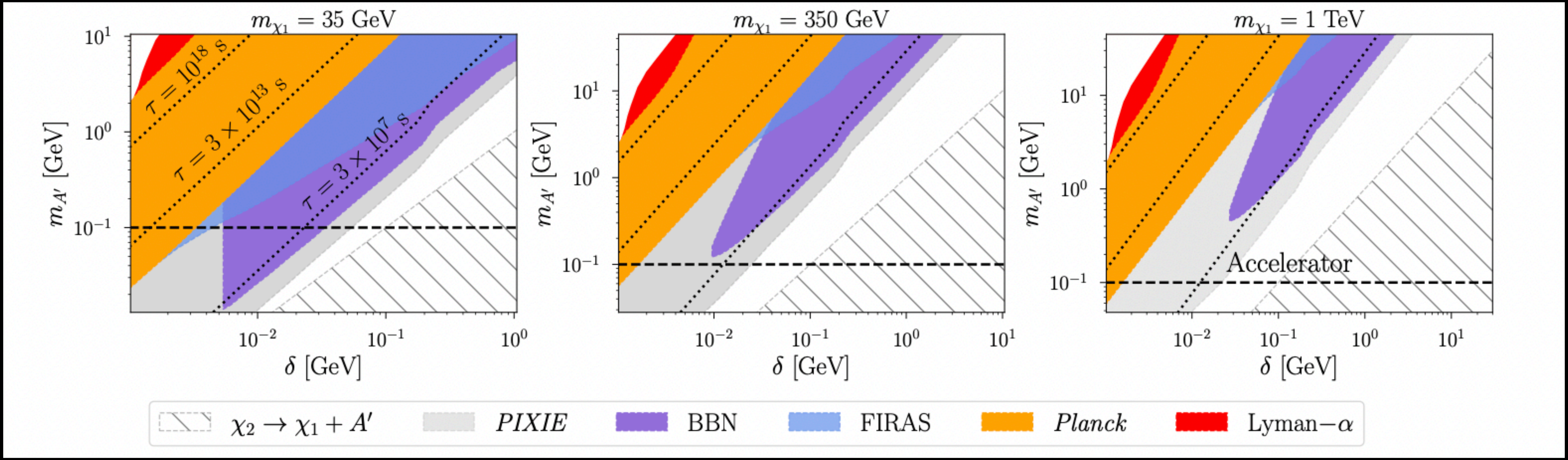

Sensitive to the fraction of excited state at late times




Bloch et al , arXiv: 2006.14521

See also: Emken, Frerik, SH & Kahlhoefer, arXiv: 2112.06930

# MASS SCALING



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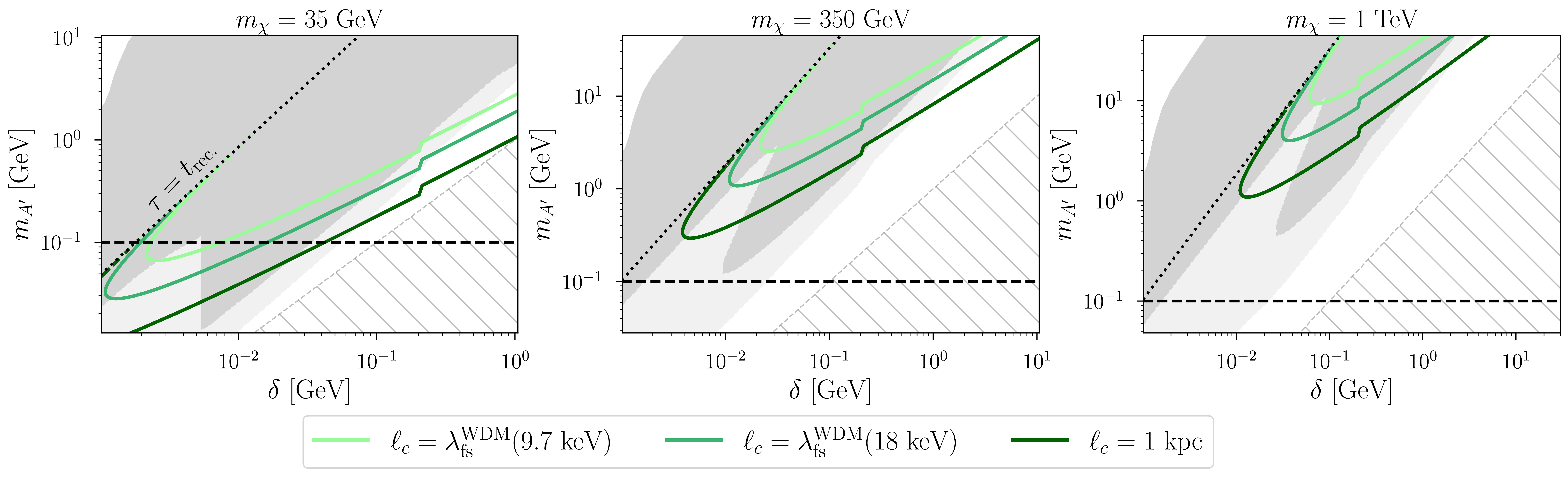

# PARAMETER SPACE

Simple UV completing with a dark Higgs symmetry breaking:

$$m_{A'} = 2g_\chi v_D, \quad \delta = 2\sqrt{2} y_\chi v_D, \quad m_{\chi_{1,2}} = m_D \mp \sqrt{2} y_\chi v_D, \quad m_{h_D} = \sqrt{2\lambda_D} v_D \,.$$

Assumptions:

- Dark Higgs heavier than everything else, $m_{h_D} \gg \mathrm{TeV}$
- Dark photon in the MeV-GeV range and DM in the GeV-TeV range
- Dark photon **not** in thermal equilibrium at early times
- Everything satisfied for $g_\chi \lesssim e\epsilon$ and freeze-in couplings under consideration

# OTHER SIGNATURES: STRUCTURE


O'Neil, Vogelsberger, **SH,** Schutz et al (2022)
Simulations done in the Born regime for self-scattering