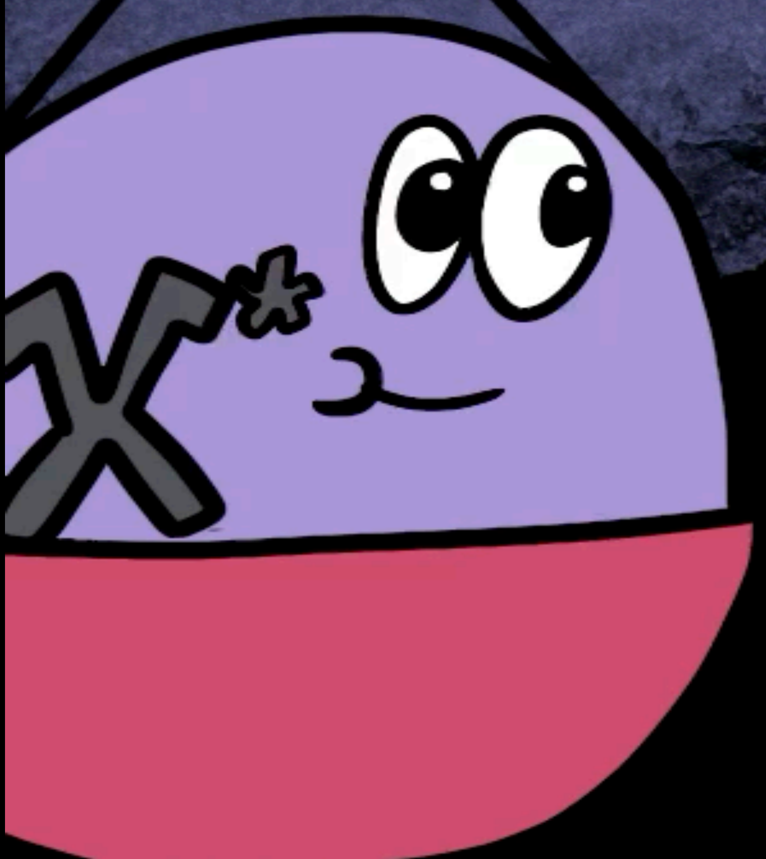
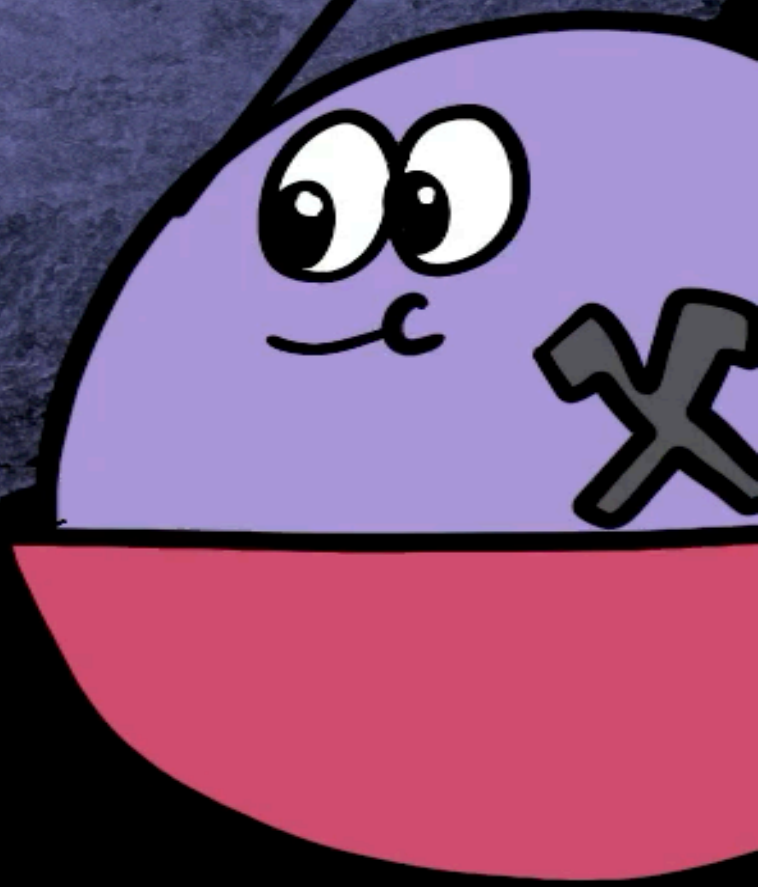
INELASTIC DARK MATTER THROUGH THE AGES

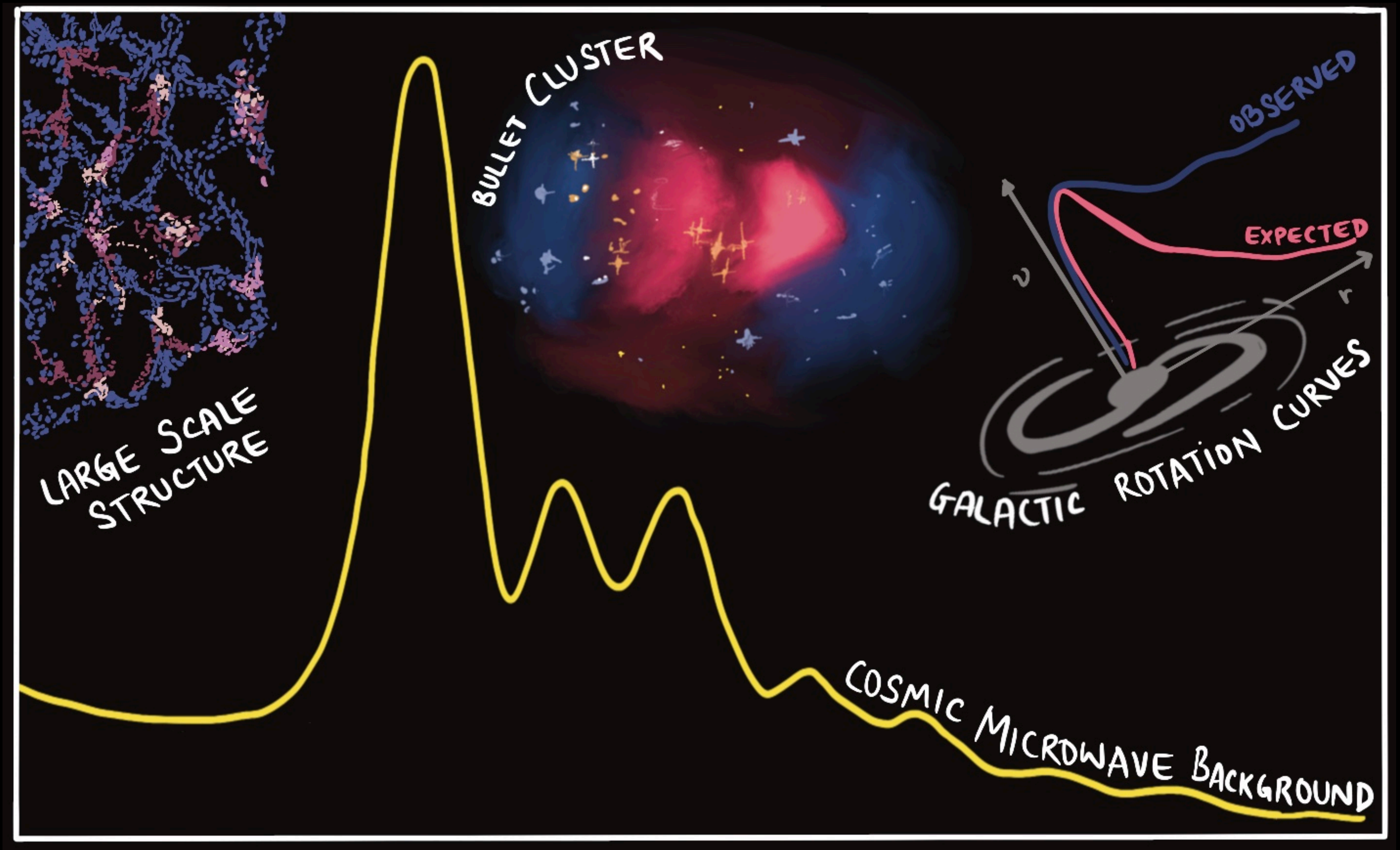
SANIYA HEEBA
TSI, McGILL U.

Based on:
2304.06072
(w/ Tongyan Lin & Katelin Schutz)

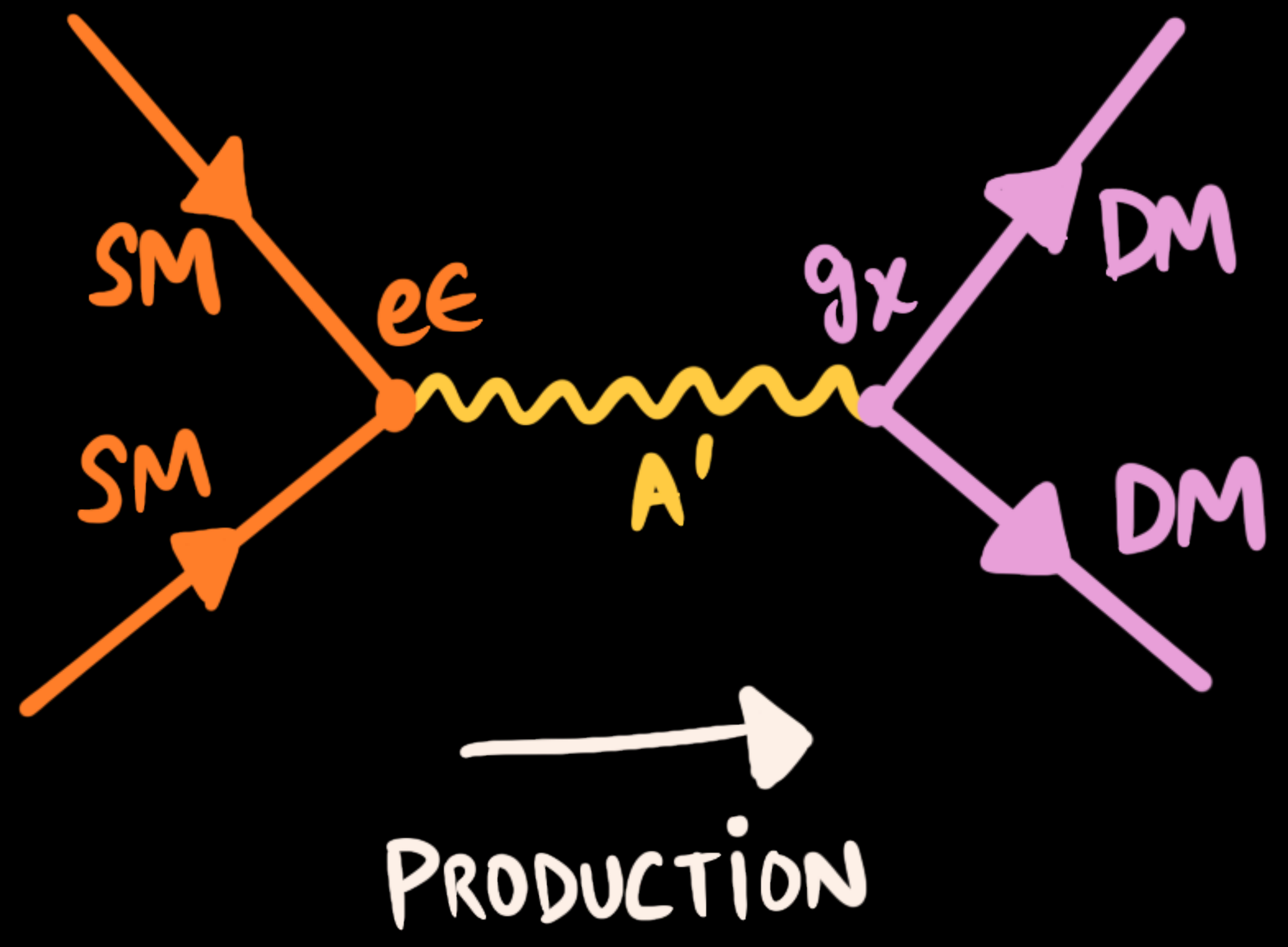




WE KNOW THAT DARK MATTER EXISTS



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



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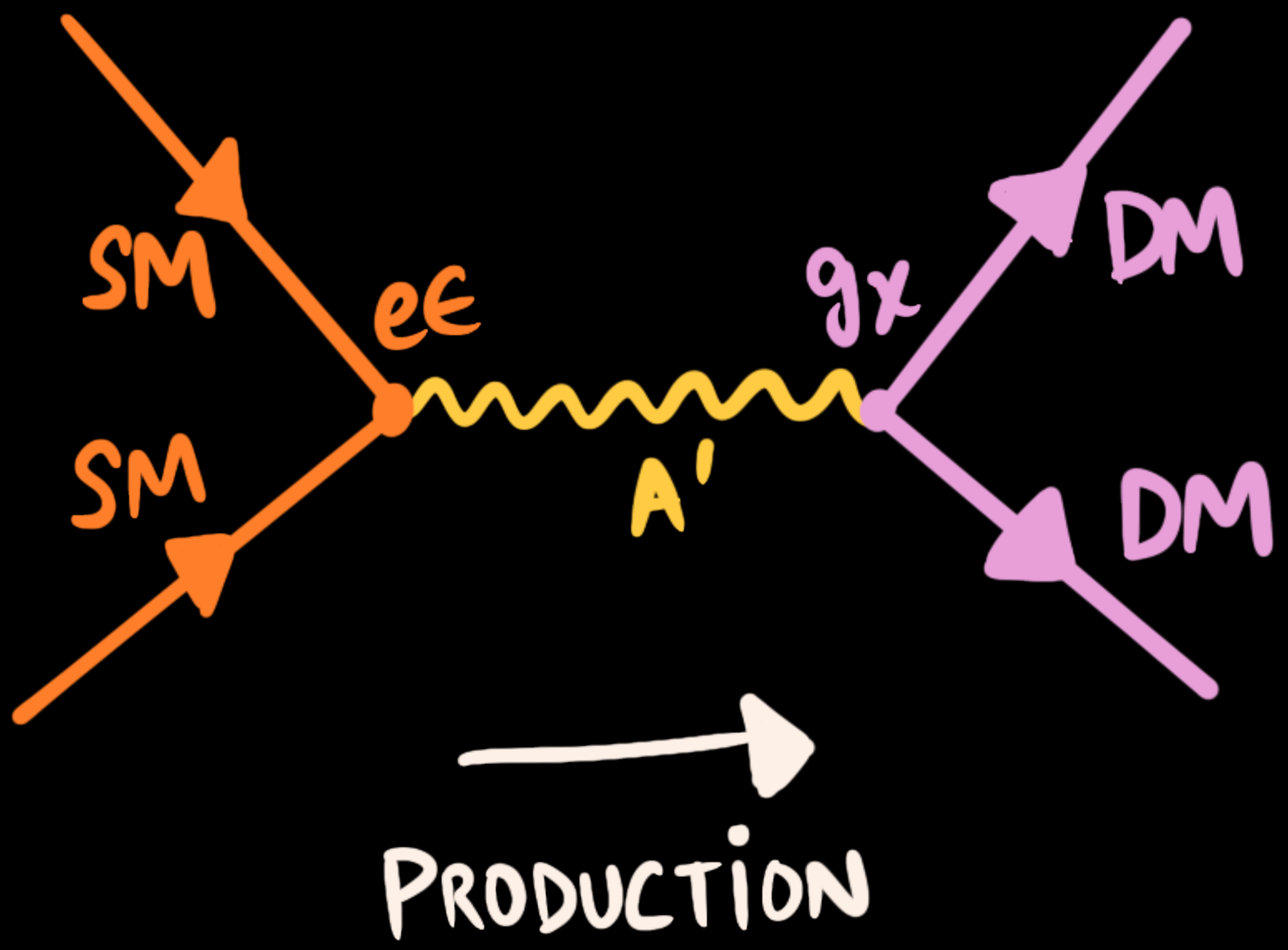

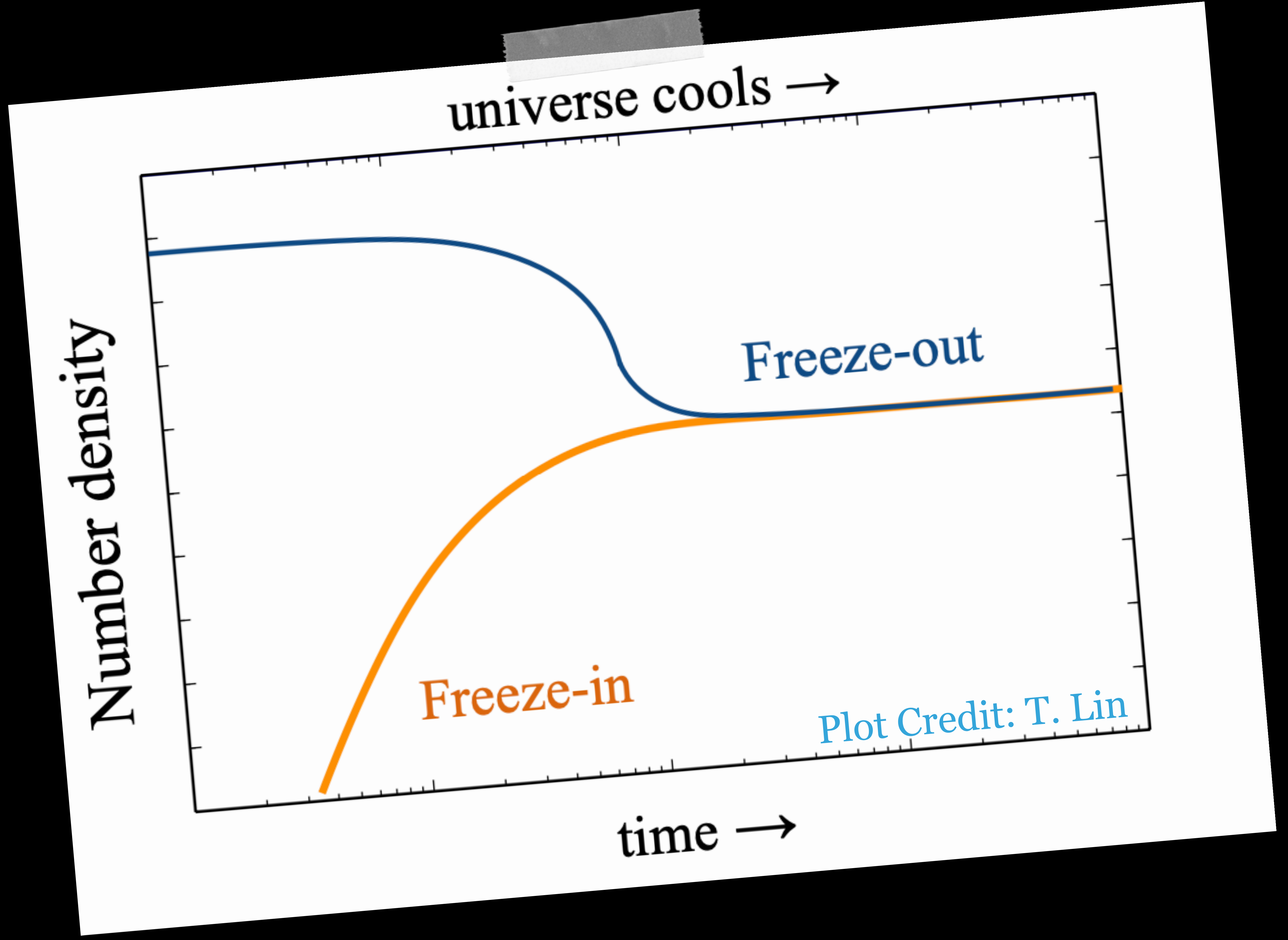

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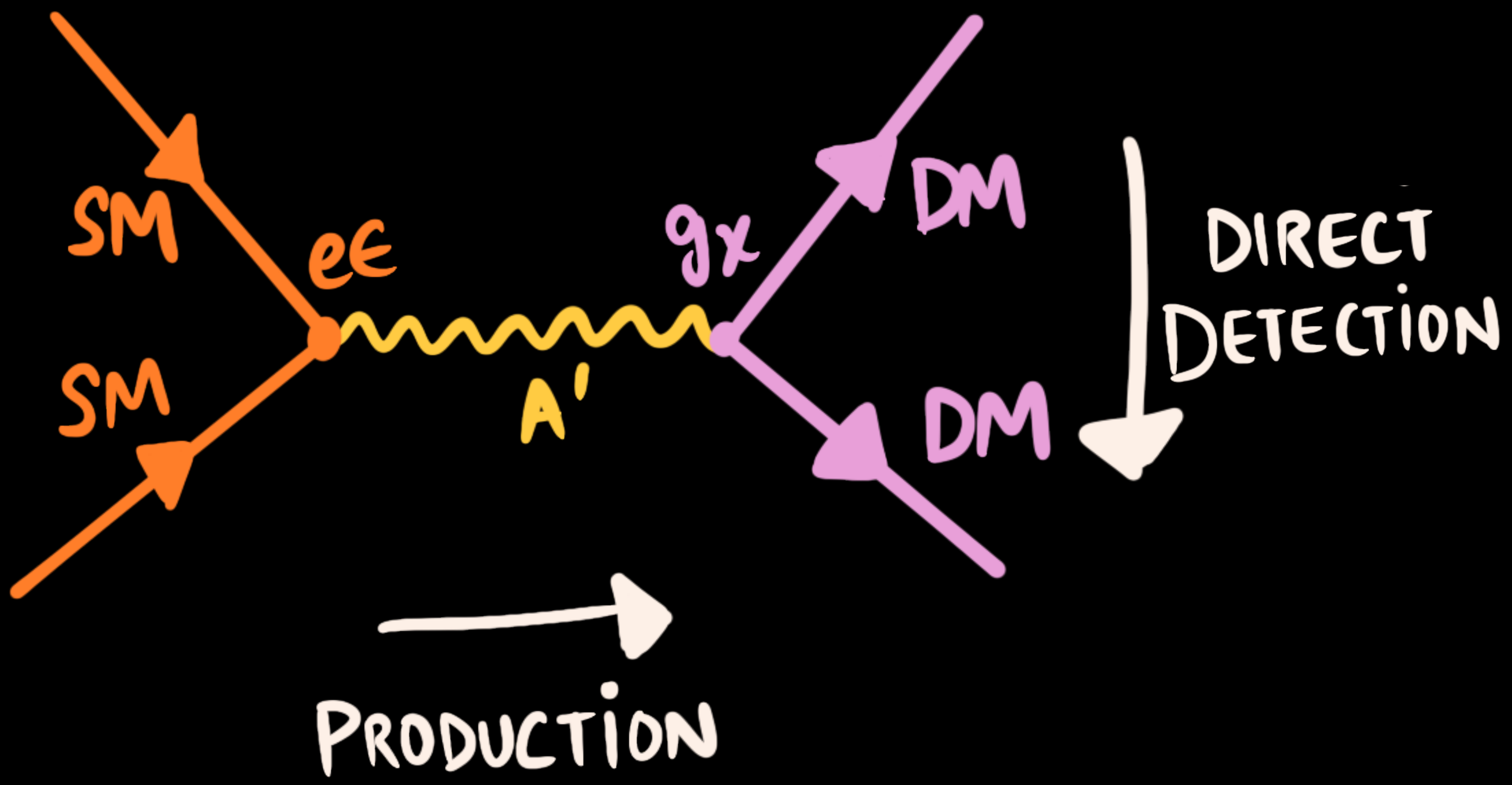

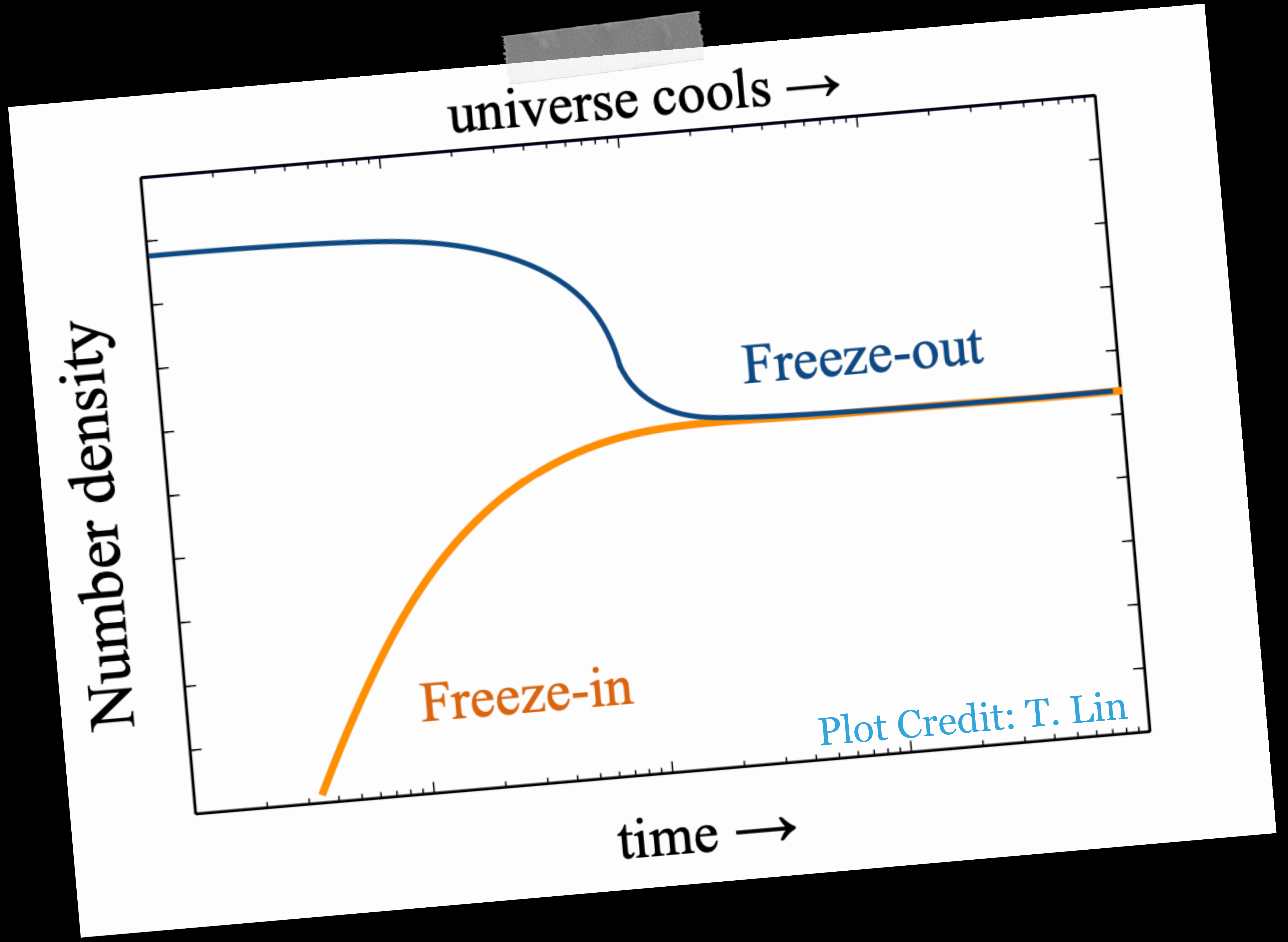

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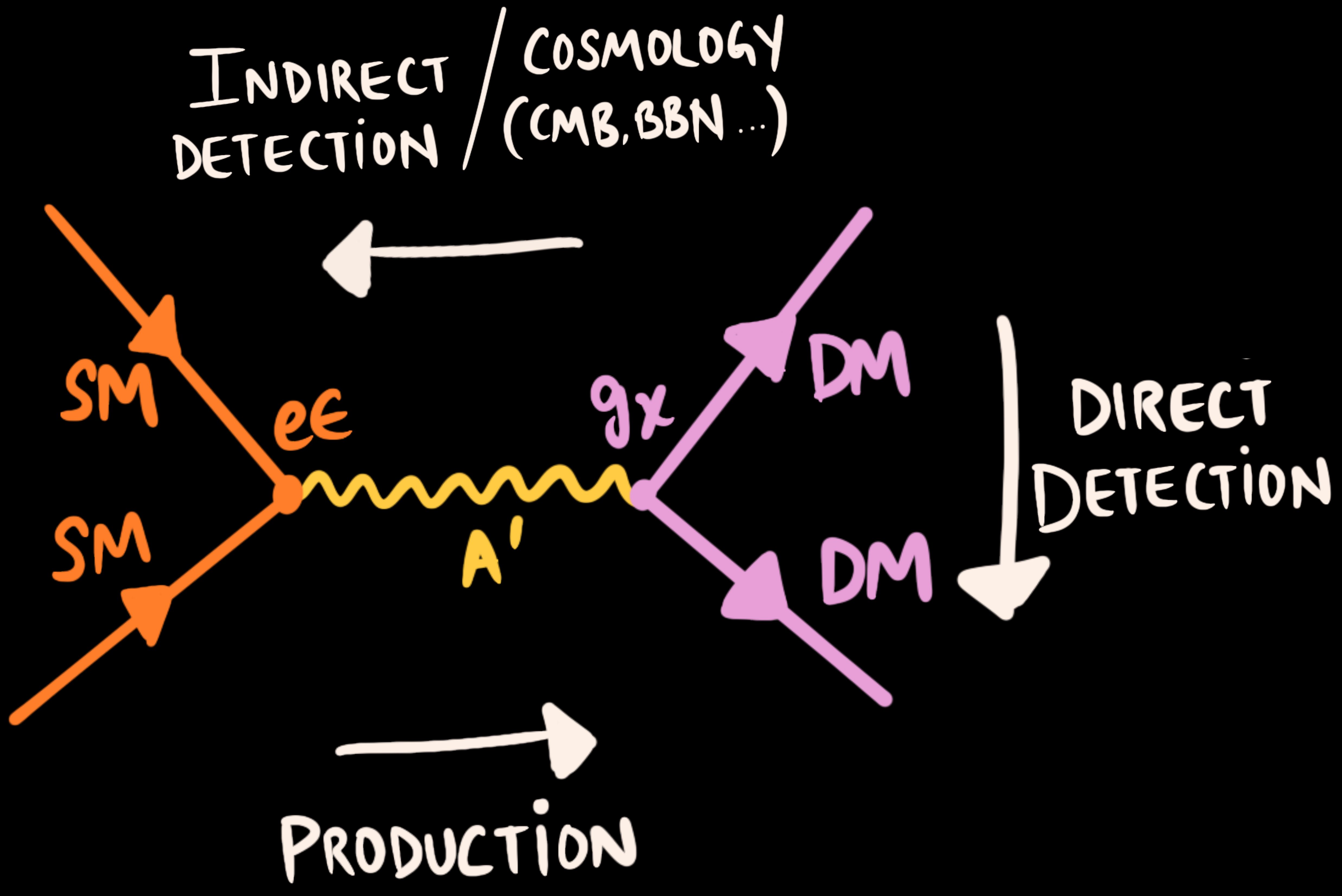

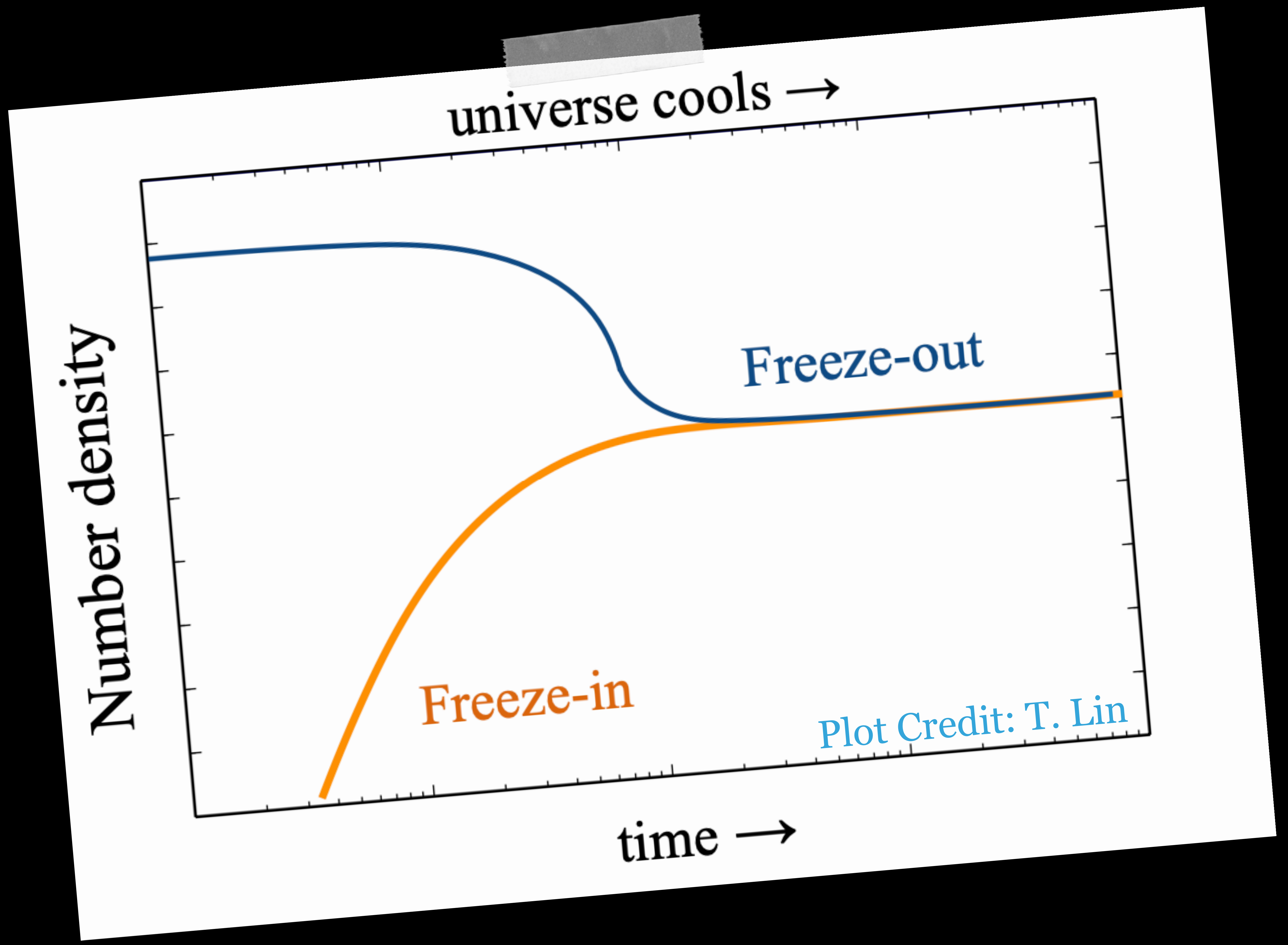

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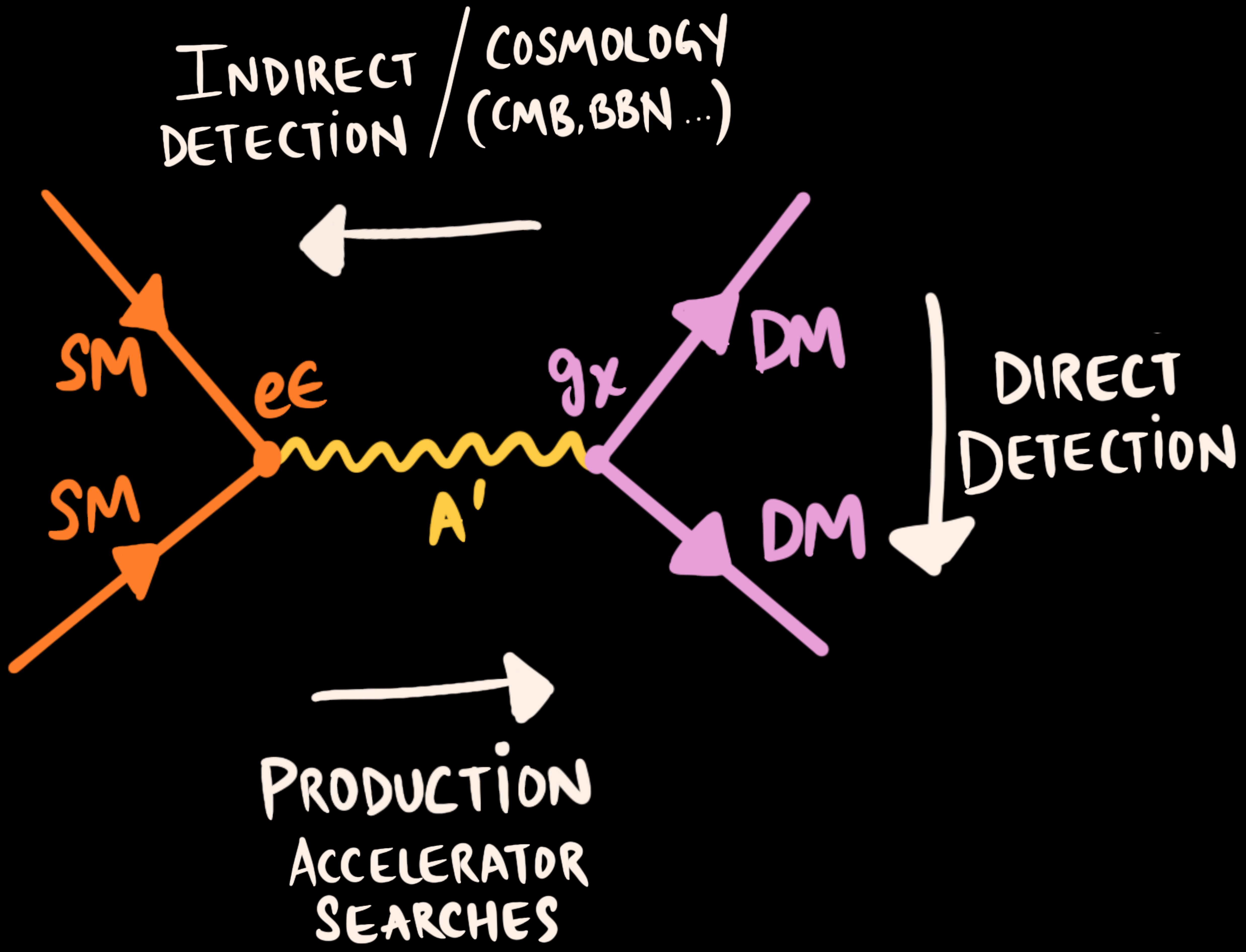
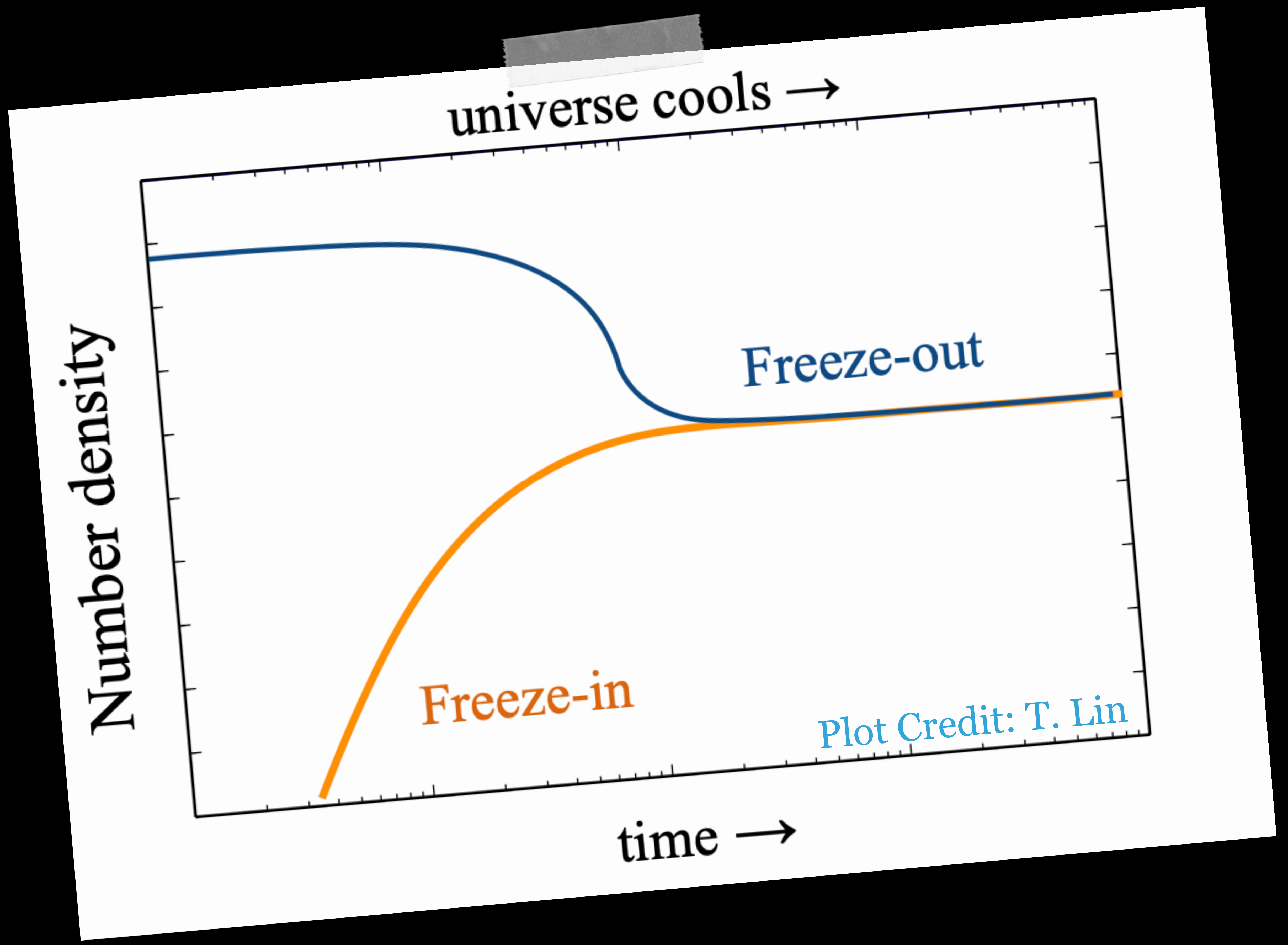
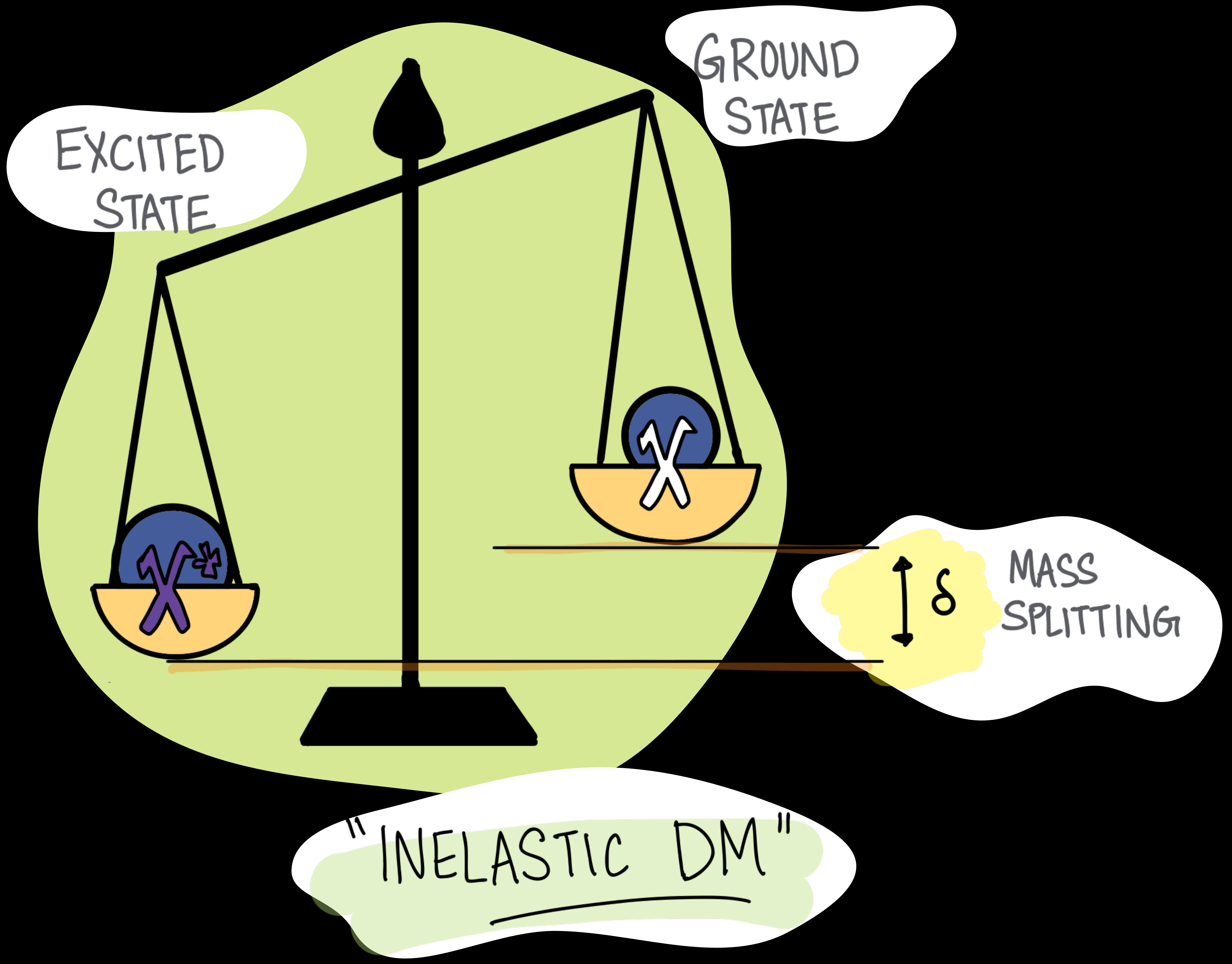




WHAT IF DM INTERACTIONS DON'T CONSERVE KINETIC ENERGY?



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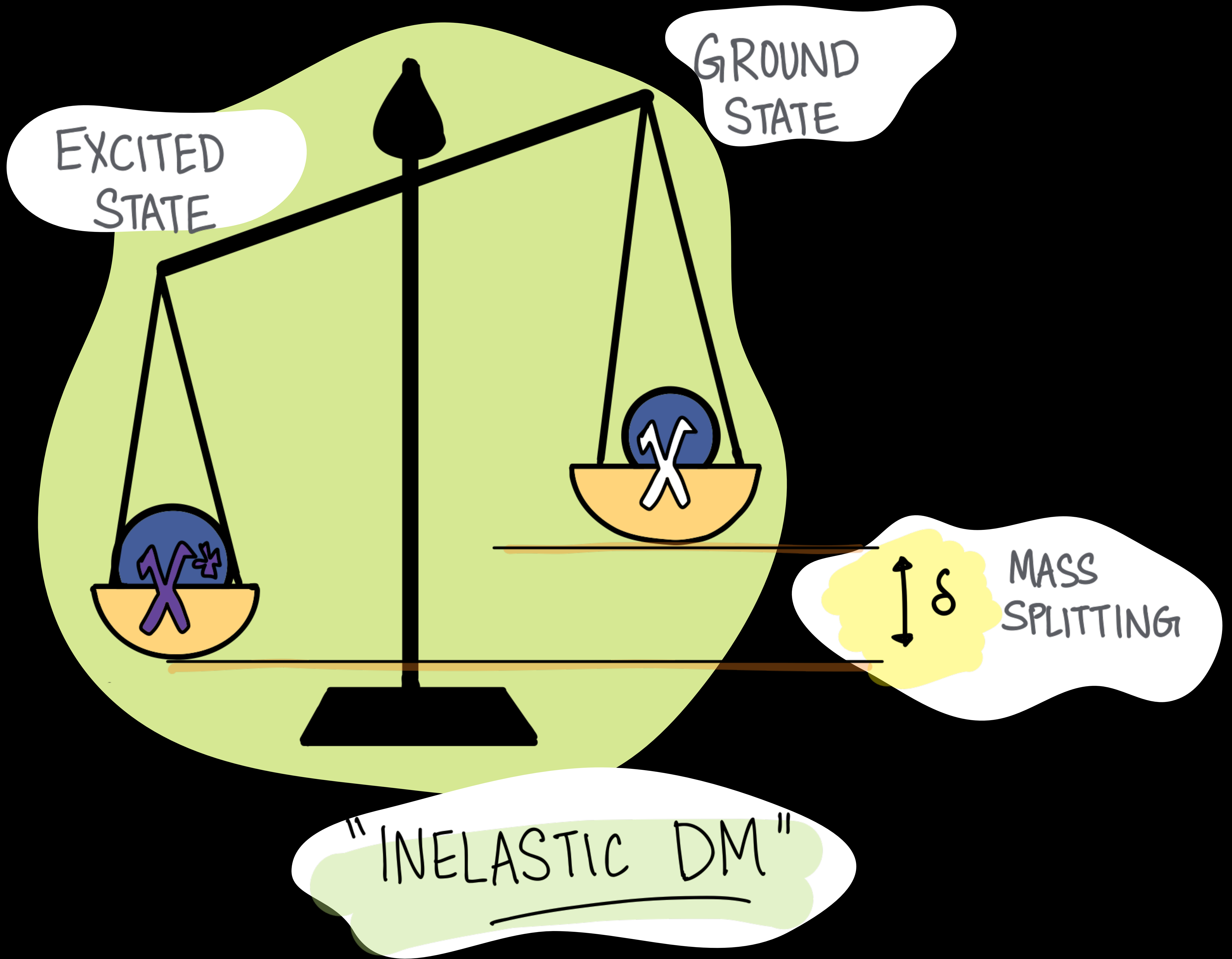
WHAT IF DM INTERACTIONS DON'T CONSERVE KINETIC ENERGY?

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



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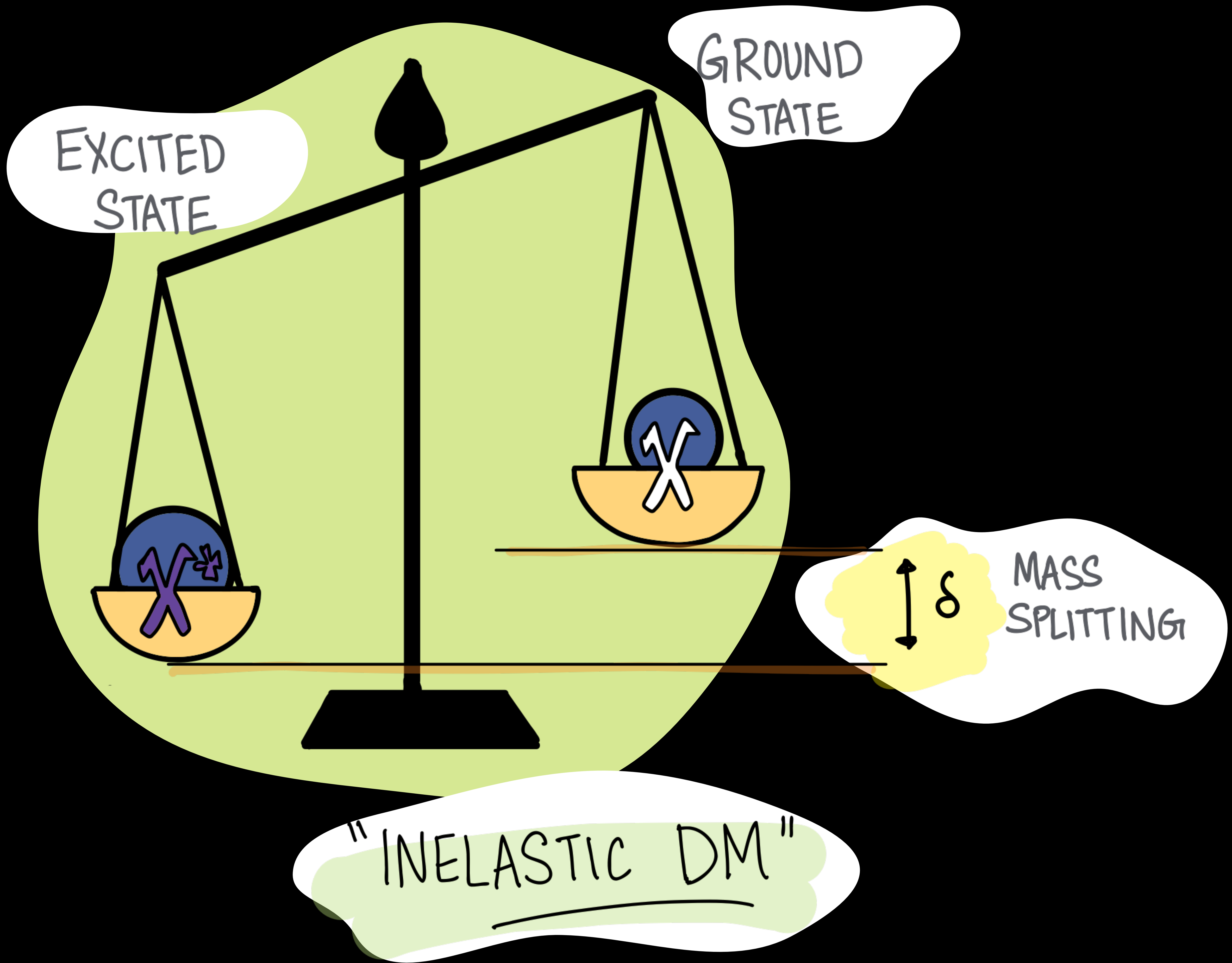
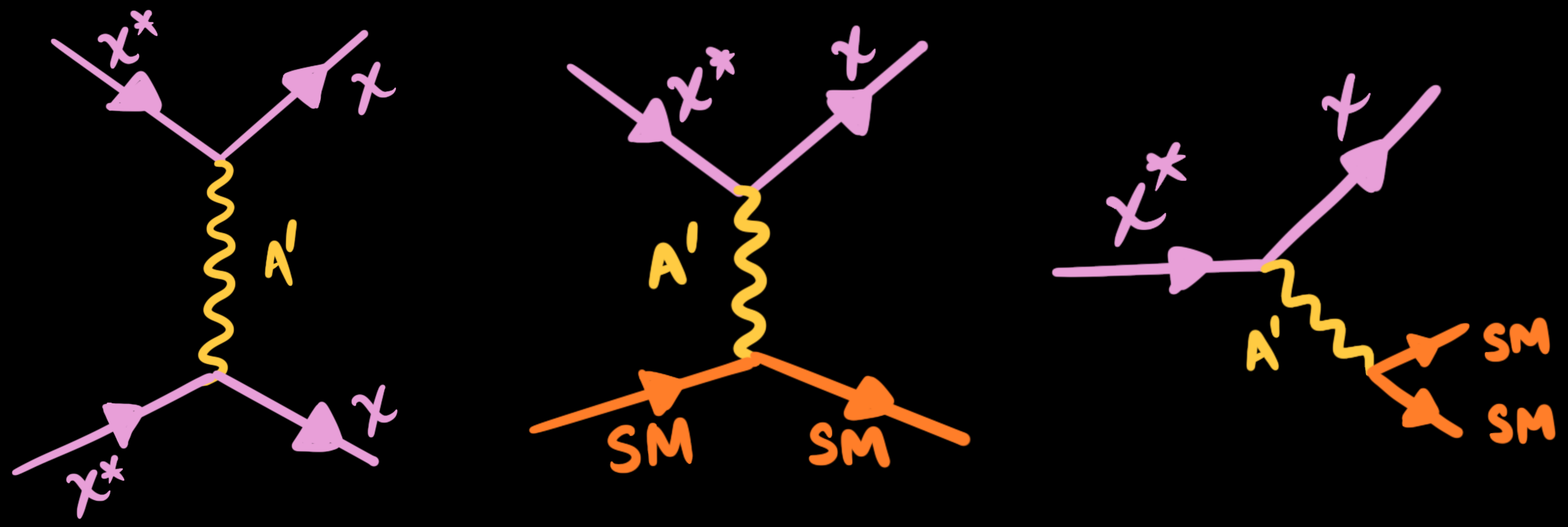


$$\mathcal{L} \supset i g_\chi A'_\mu \bar{\chi}^* \gamma^\mu \chi$$

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: 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)

INELASTIC DM: HOW CONTRIVED IS IT?

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NEW DARK HIGGS THAT PROVIDES THE DARK PHOTON MASS

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PORTAL TO THE STANDARD MODEL

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DARK FERMION CHARGED UNDER NEW U(1)

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GENERATES A MAJORANA MASS TERM FOR THE FERMION!

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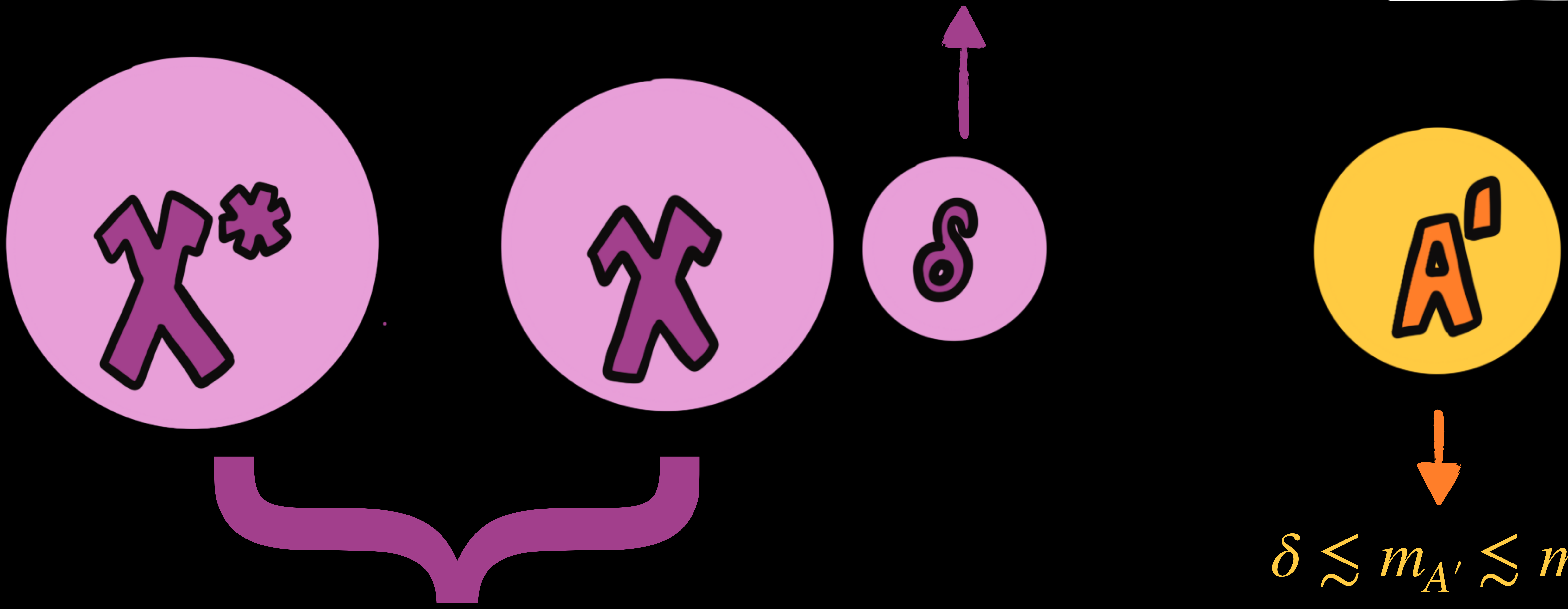
INELASTIC DM: PARAMETER SPACE

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

$\delta \ll m_\chi$

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

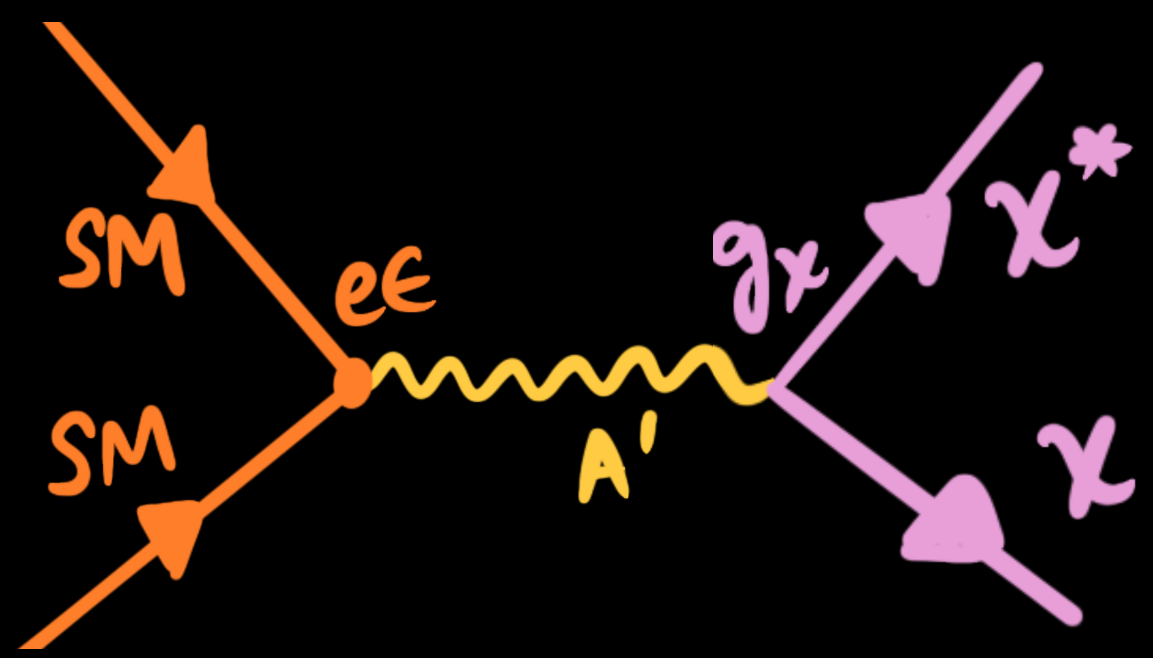


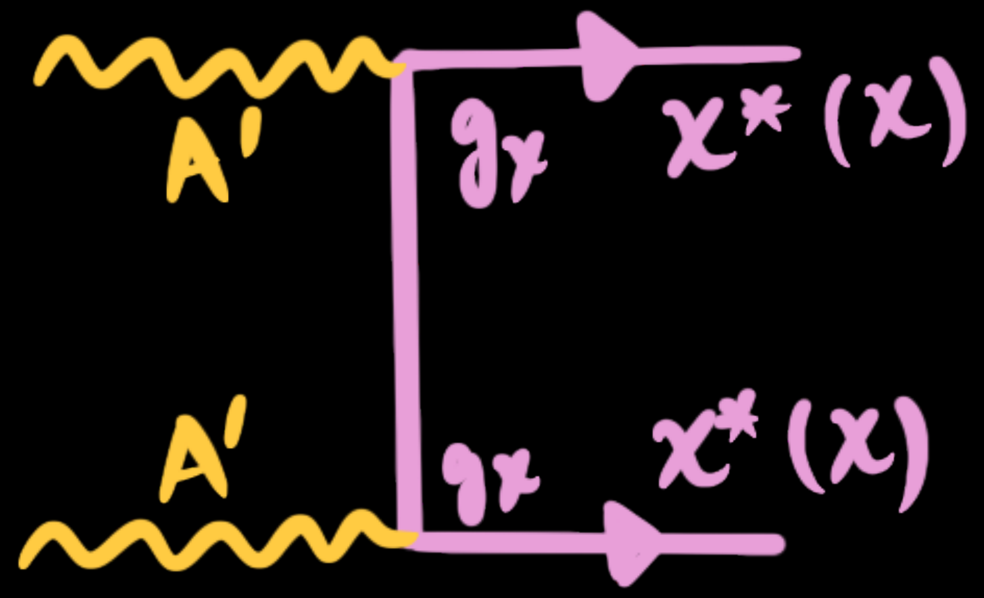
$m_\chi \sim \text{GeV} - \text{TeV}$

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

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

LETS MAKE SOME DARK MATTER





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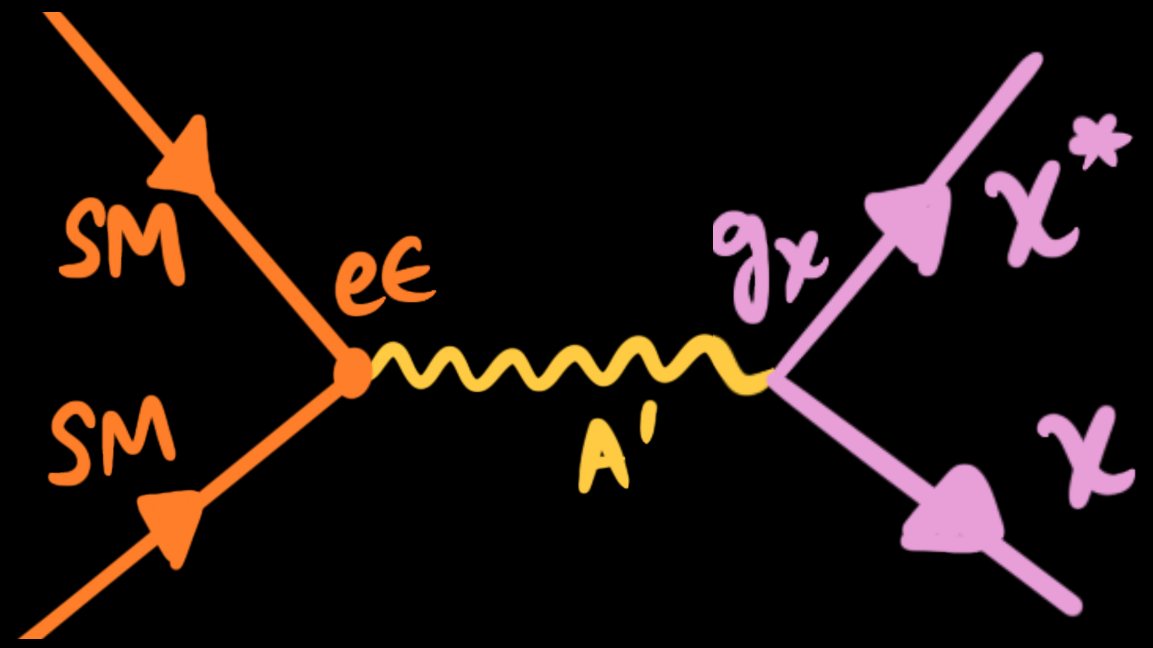
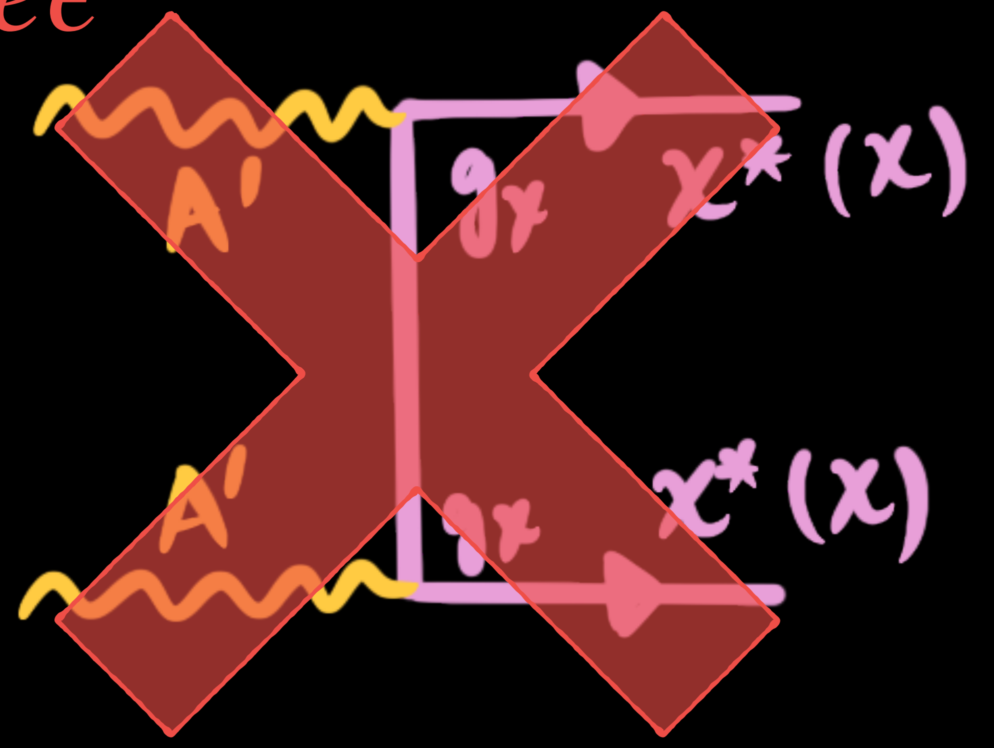


$g_\chi \lesssim e\epsilon$



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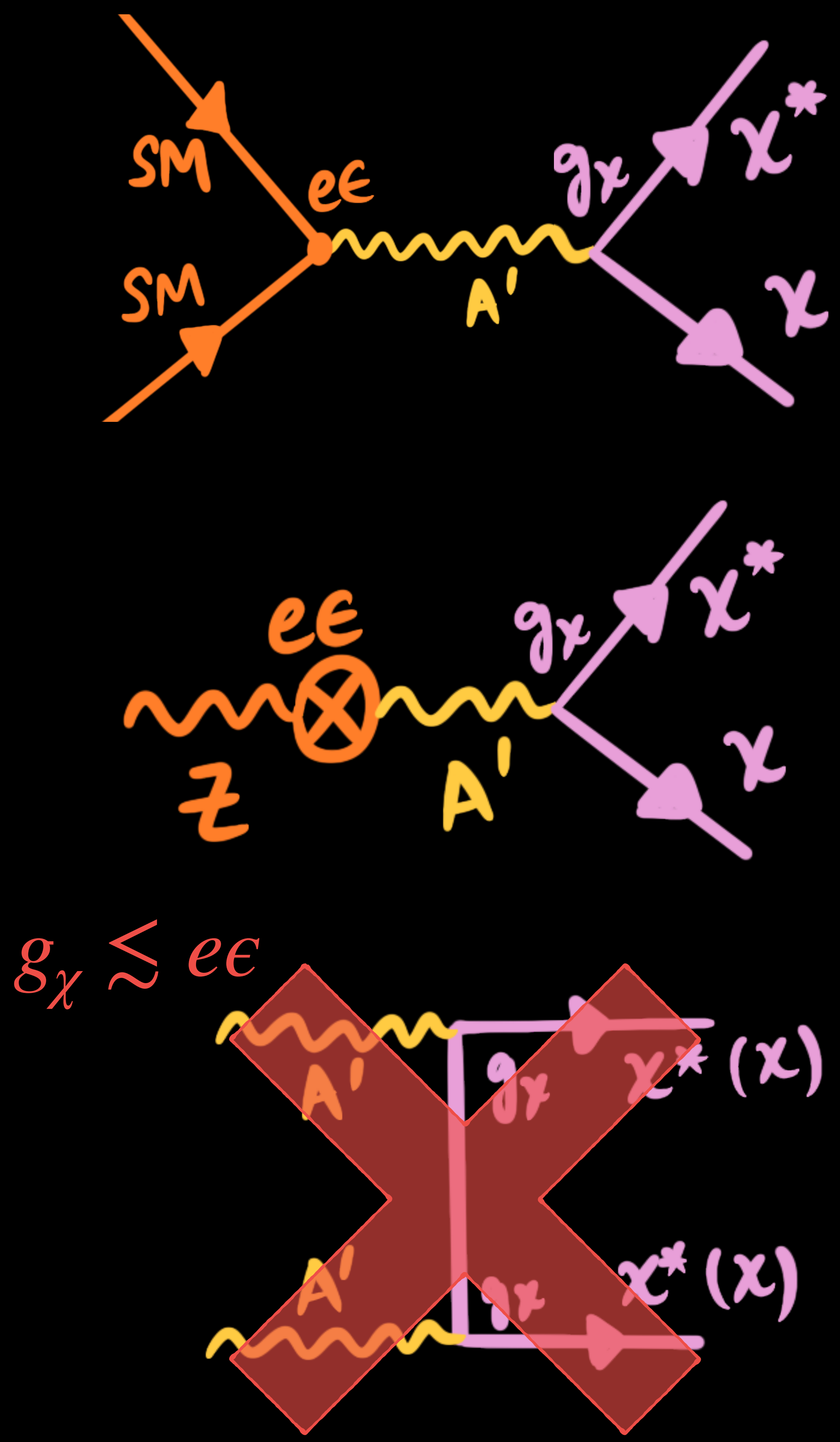

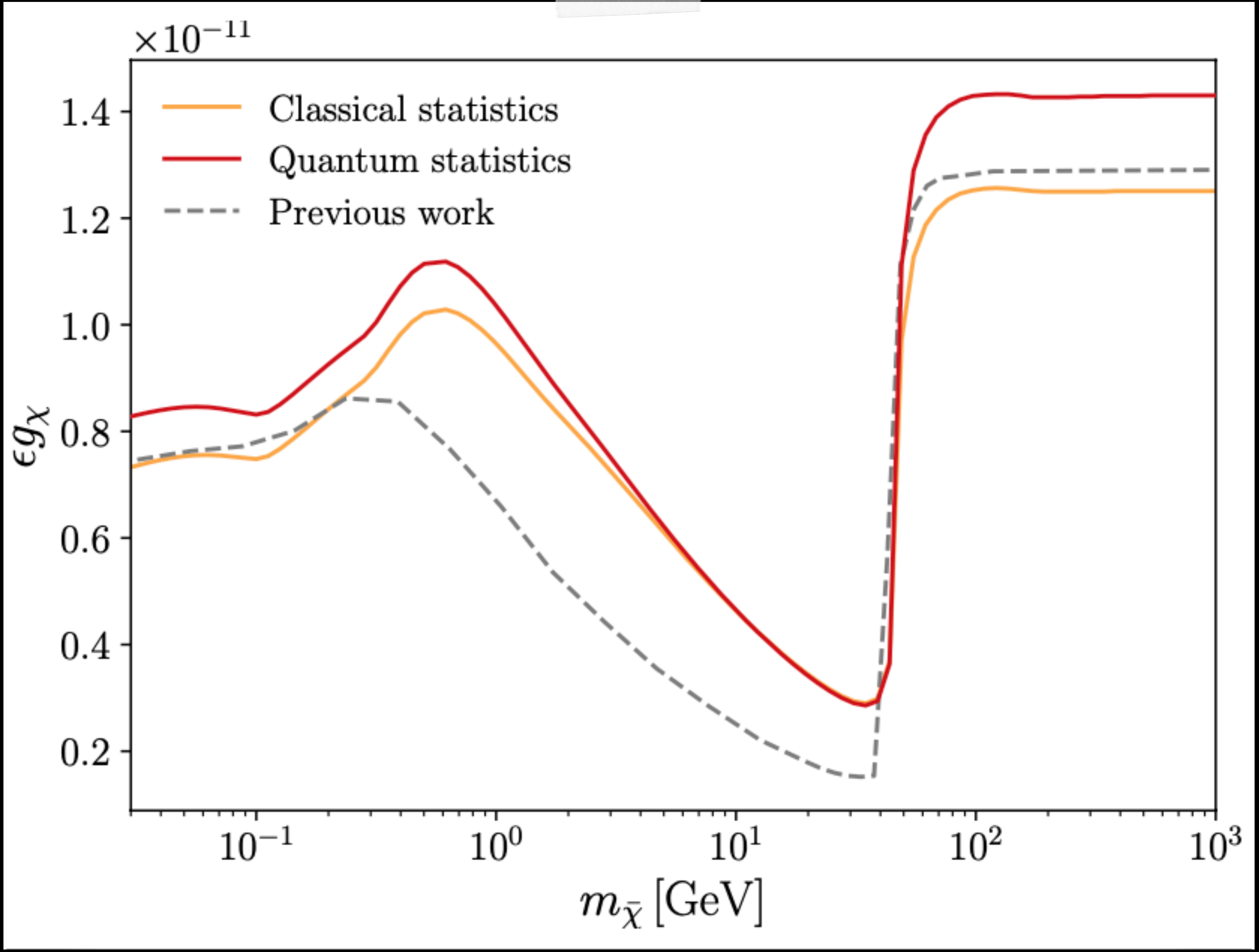

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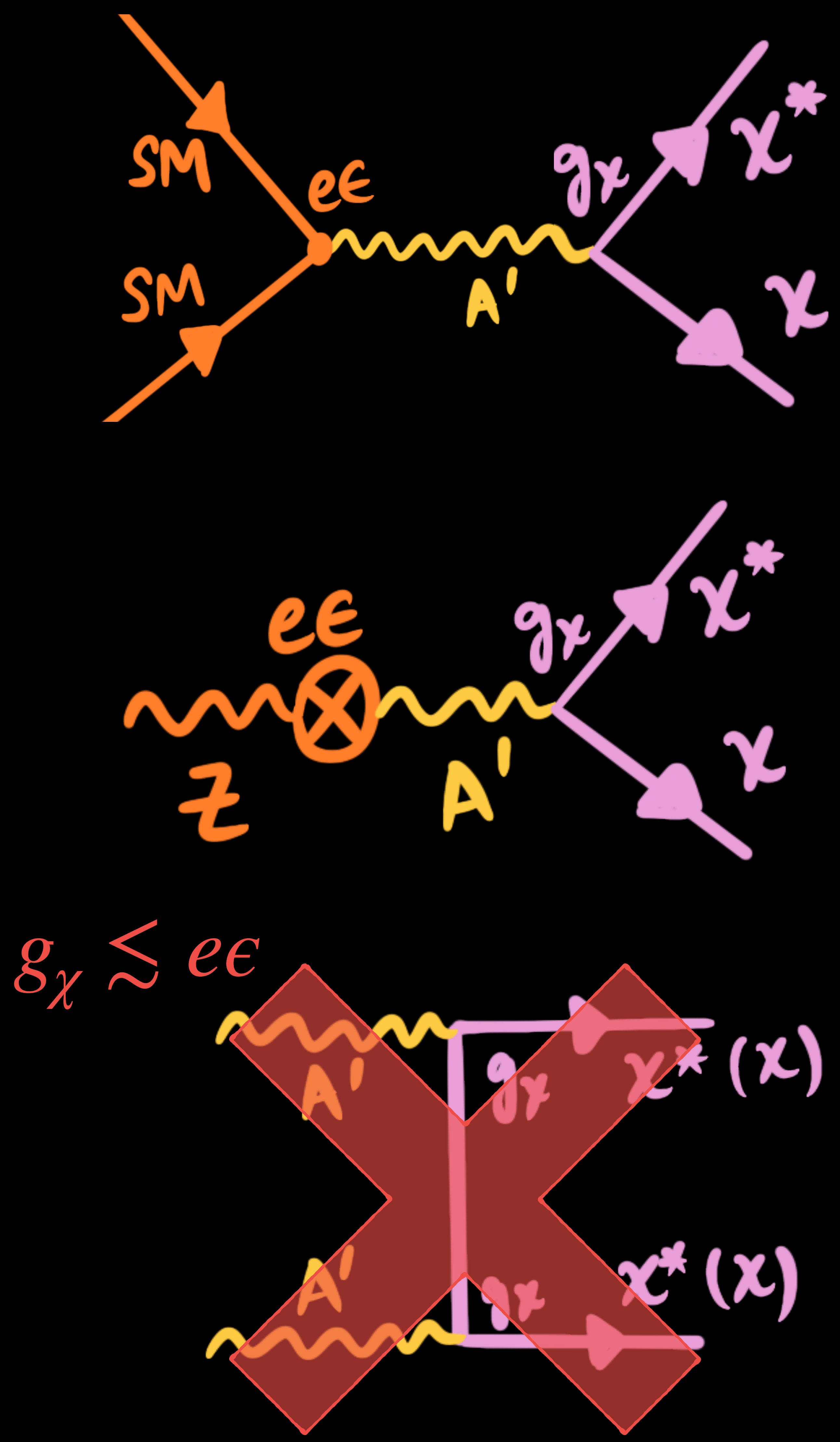

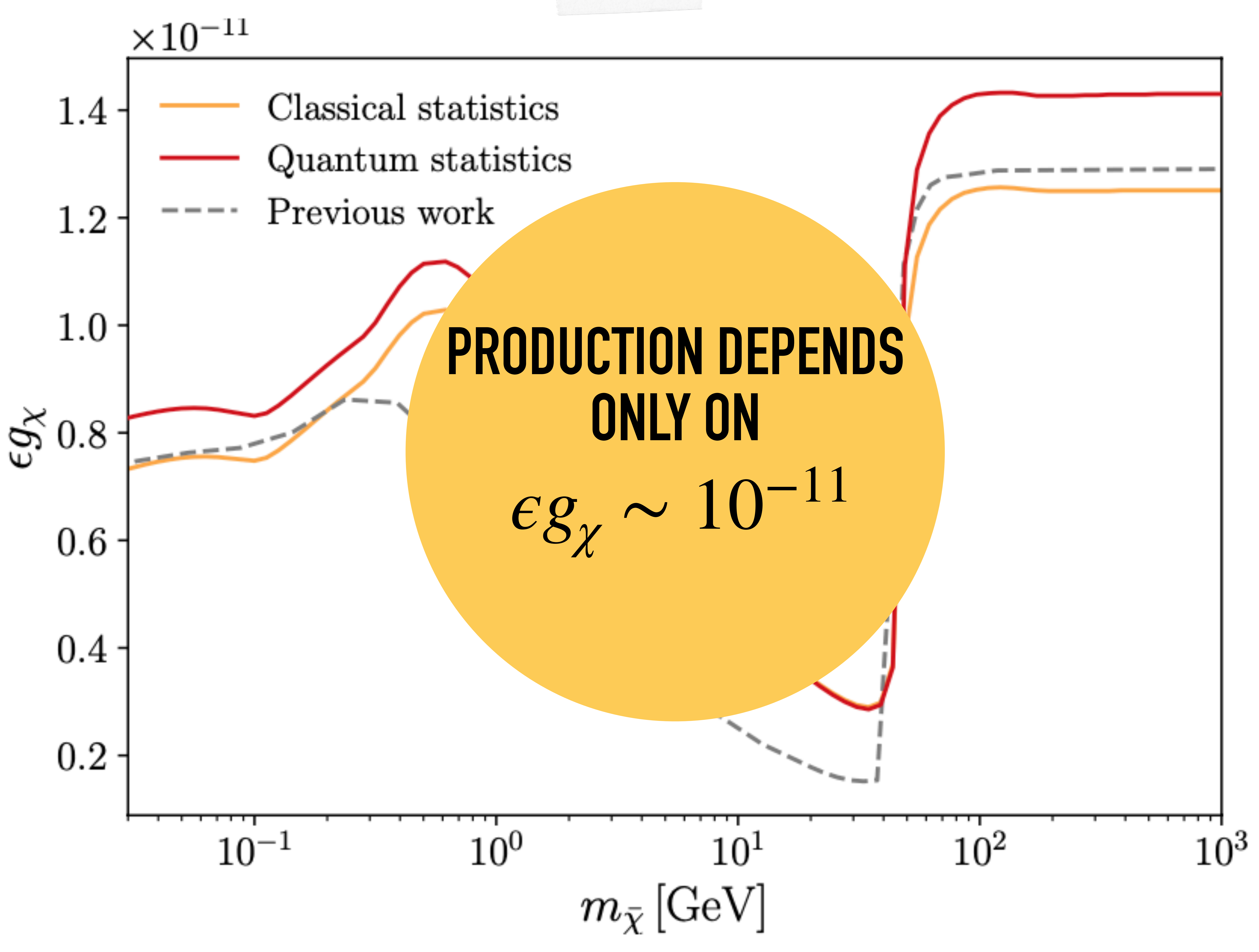

PRODUCTION DEPENDS ONLY ON

$$\epsilon g_\chi \sim 10^{-11}$$

IMPACT OF THE MASS SPLITTING

- Production: $\delta \ll$ freeze-in temperature. Ground and excited states symmetrically produced.
- Evolution: Because of tiny freeze-in couplings, all $2 \to 2$ up/downscattering processes are sub-Hubble

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Impact of the mass splitting

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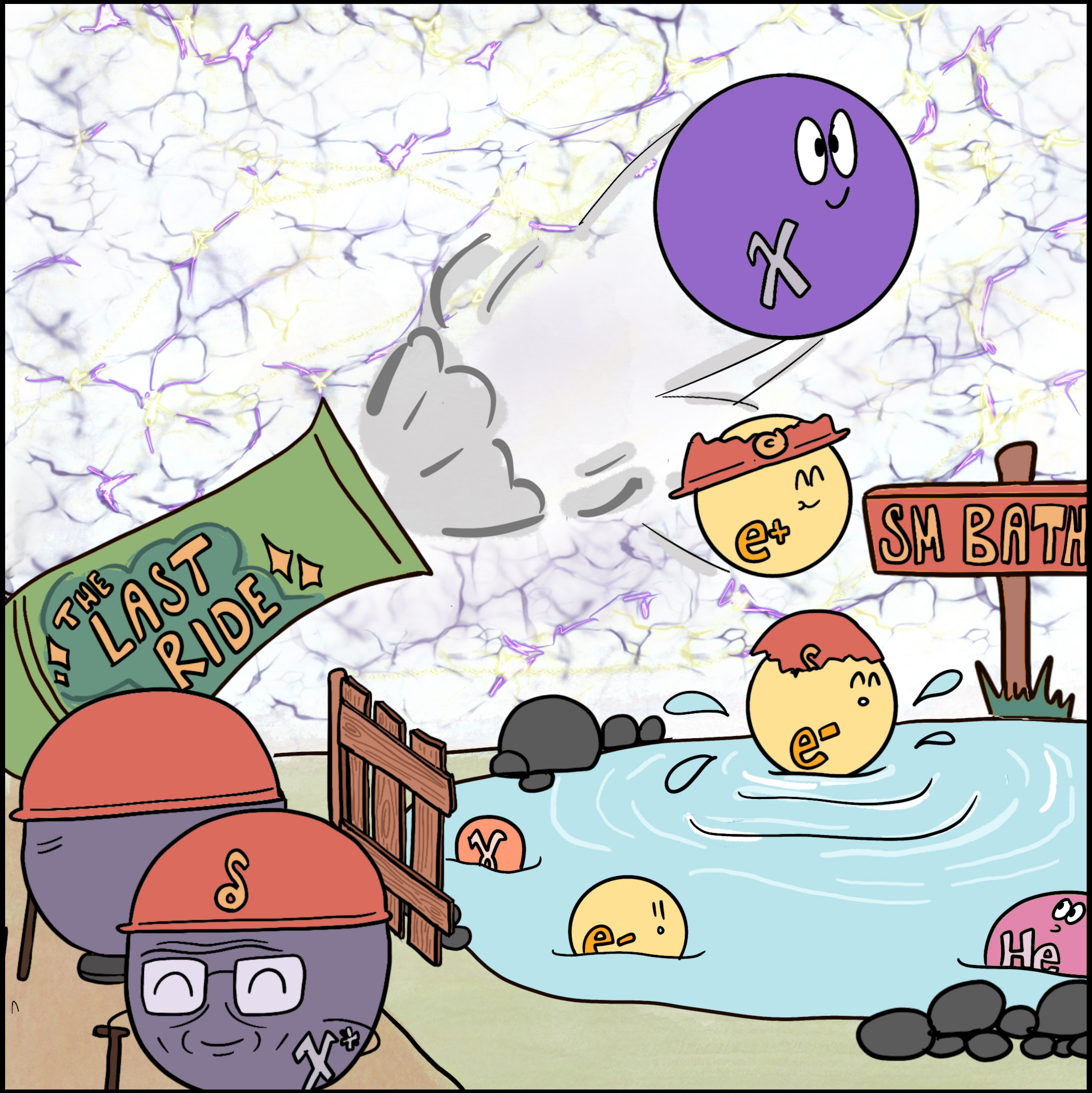
- **Evolution:** Because of tiny freeze-in couplings, all $2 \to 2$ up/downscattering processes are sub-Hubble

For $m_e < \delta$ 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

IMPACT OF THE MASS SPLITTING



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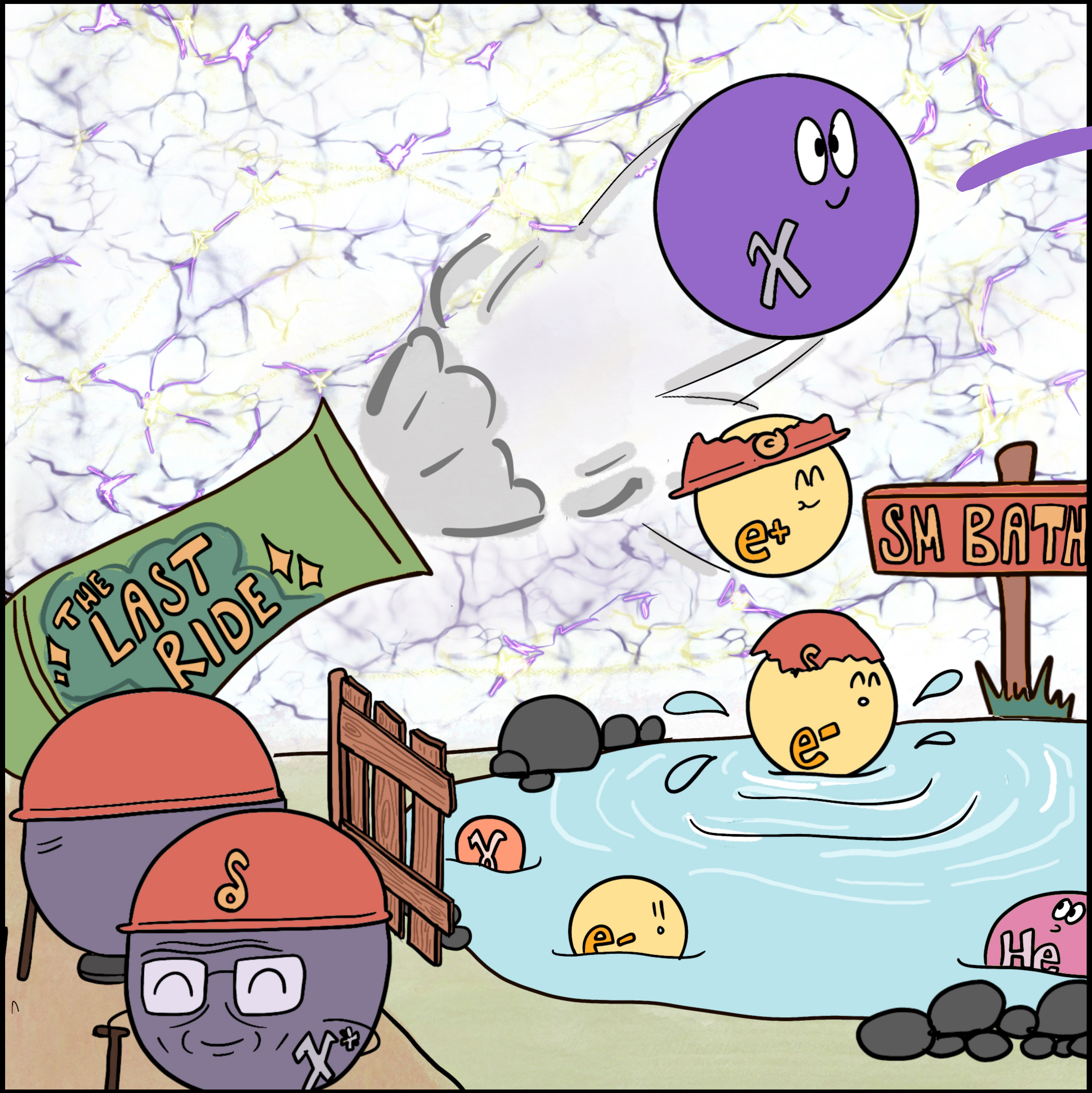

50% of the DM is warm (ish)

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

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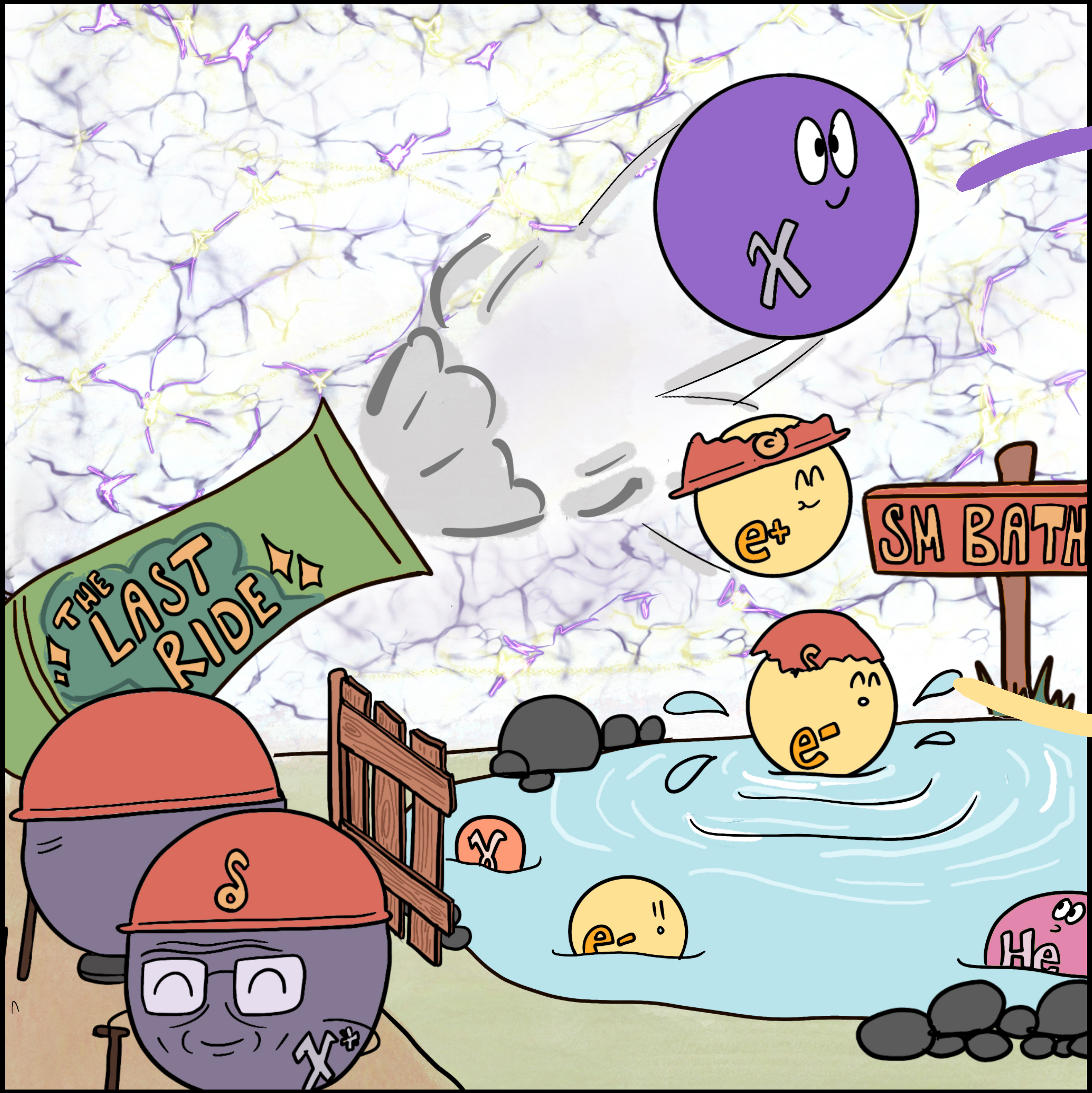

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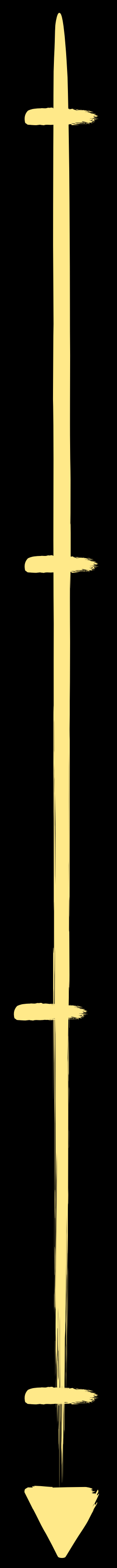
Extra energy injected into the SM plasma*

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

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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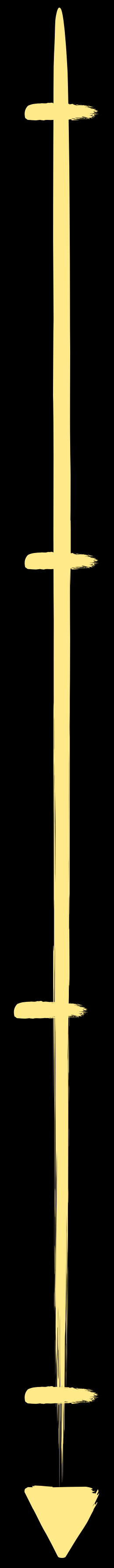

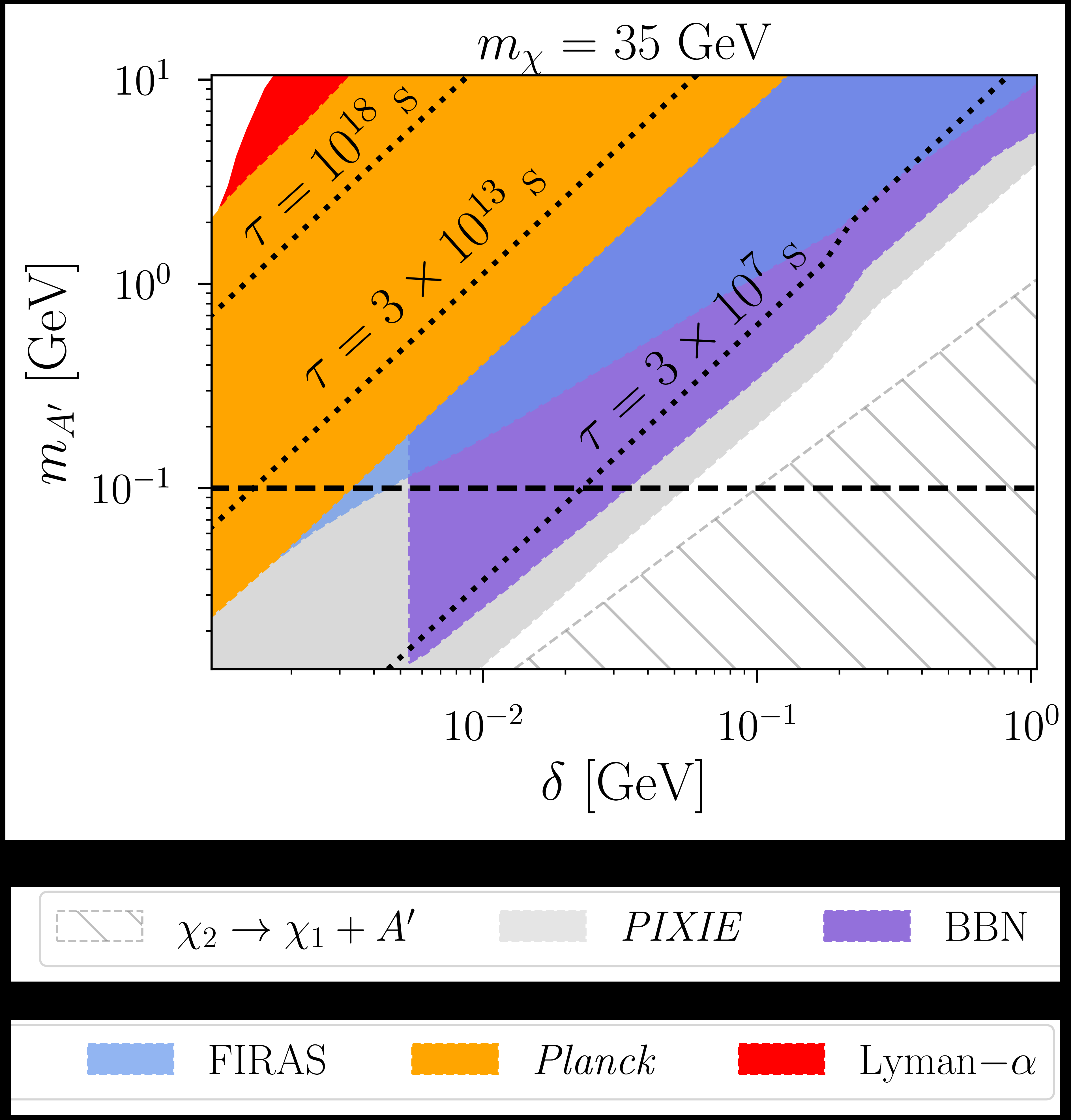

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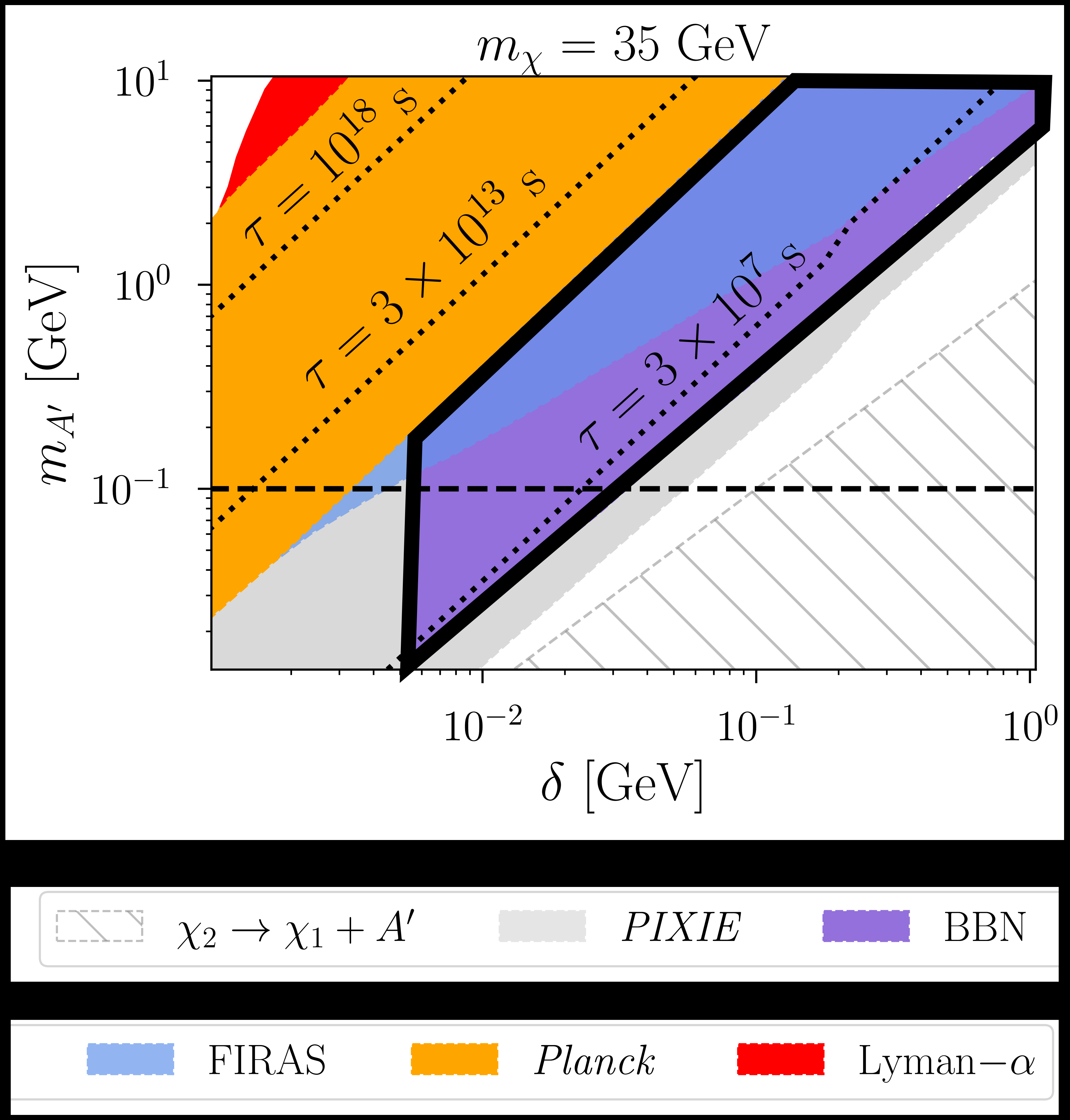
$\tau \lesssim 10^{12}\,\text{s},\ \delta > 6\,\text{MeV}$



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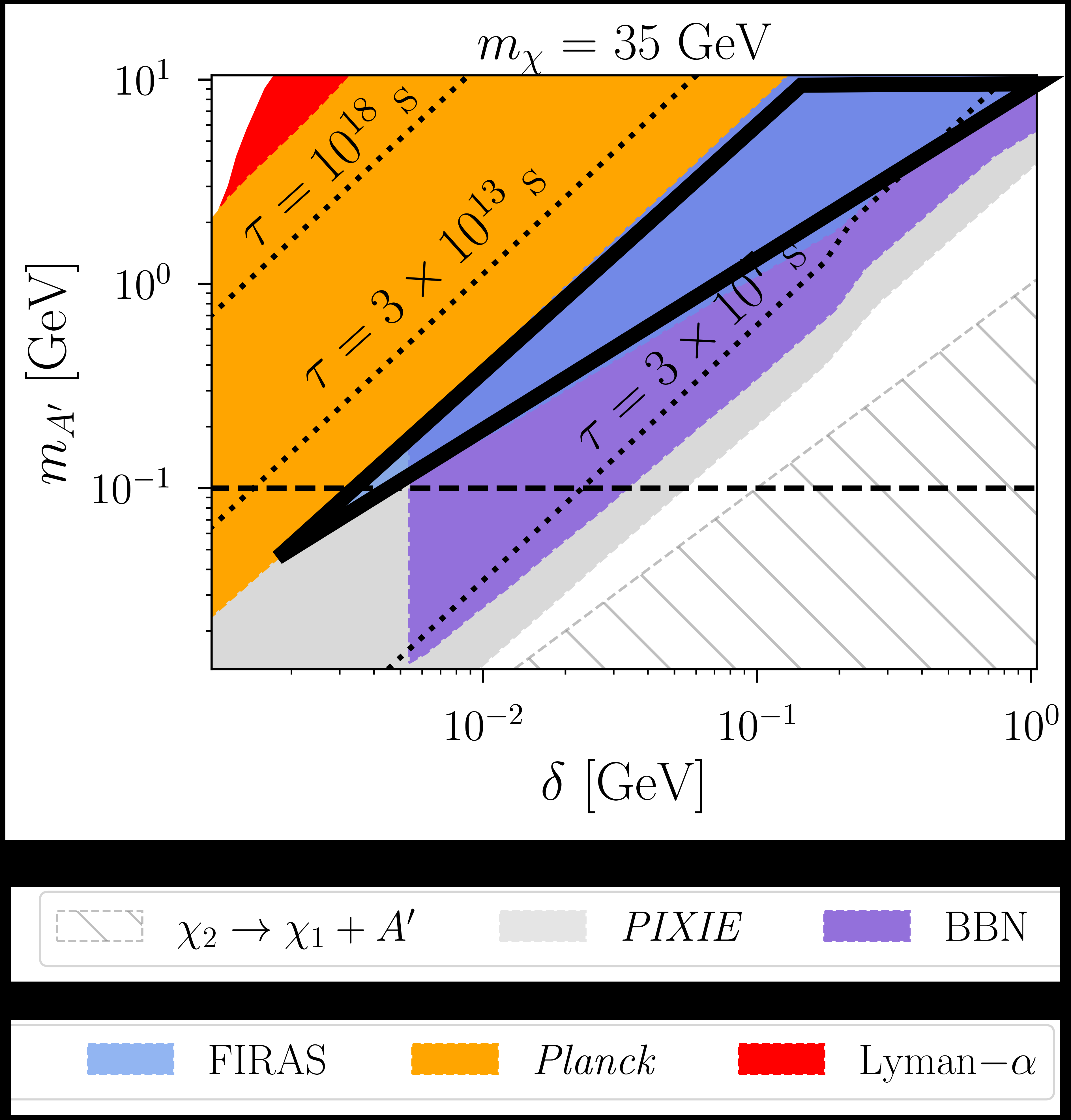
- Destruction of light elements — $\tau \lesssim 10^{12}\,\text{s},\ \delta > 6\,\text{MeV}$
- CMB Spectral Distortions — $\tau \sim 10^7 - 10^{13}\,\text{s}$



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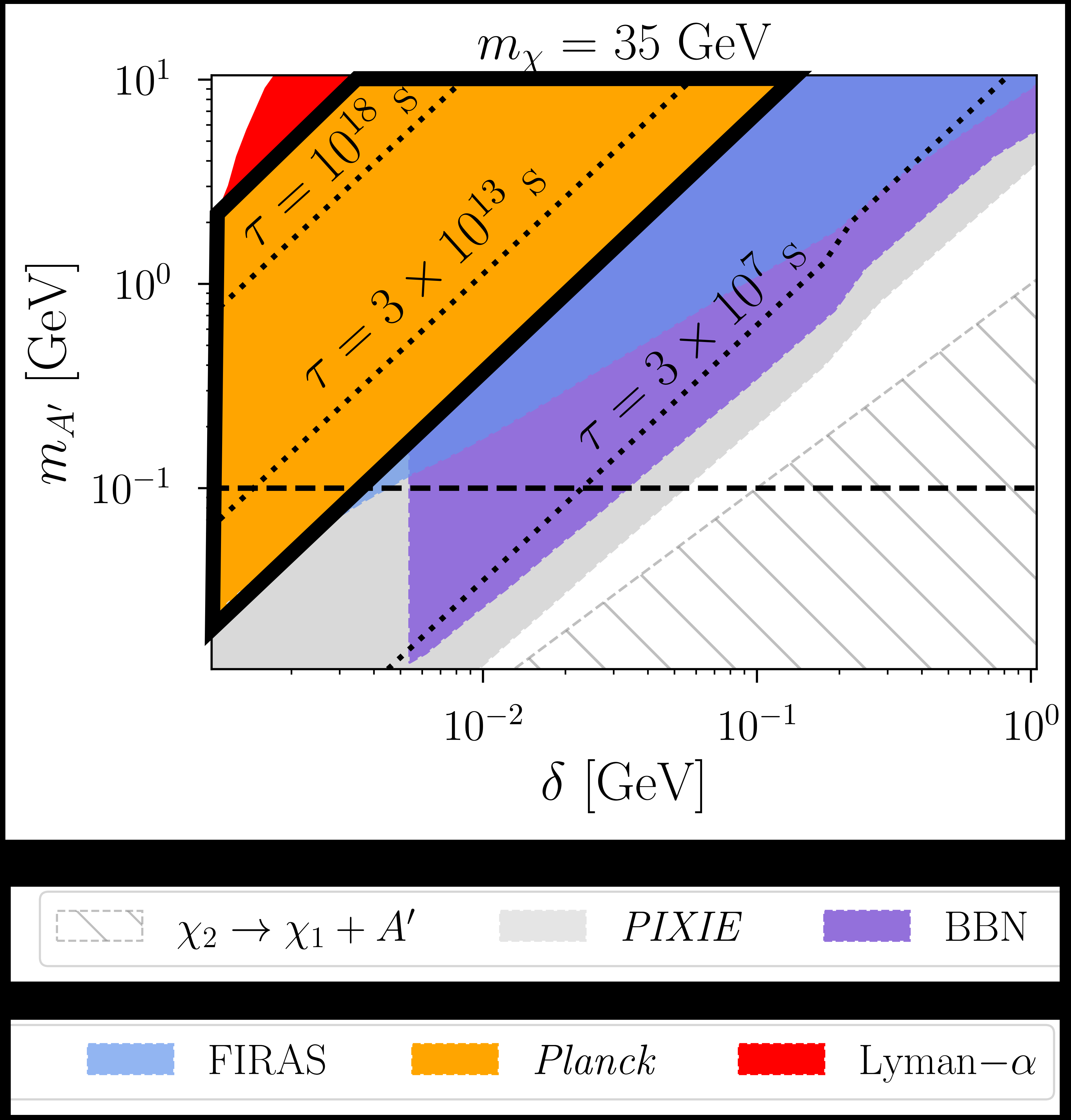
CMB Anisotropies — $\tau \gtrsim 10^{13}\,\text{s}$



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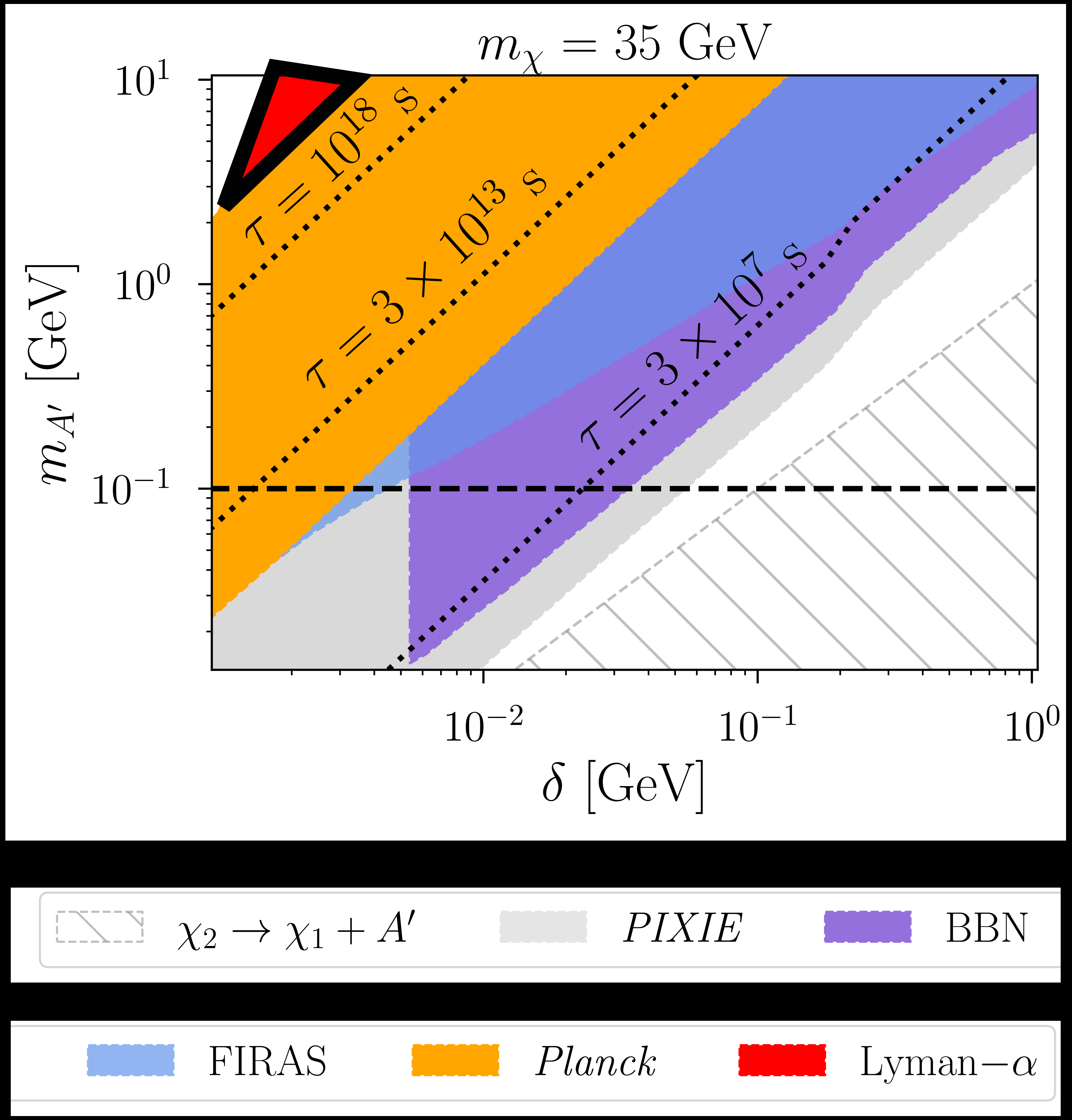
- Lyman-α $\tau \sim 10^{16}\,\text{s}$



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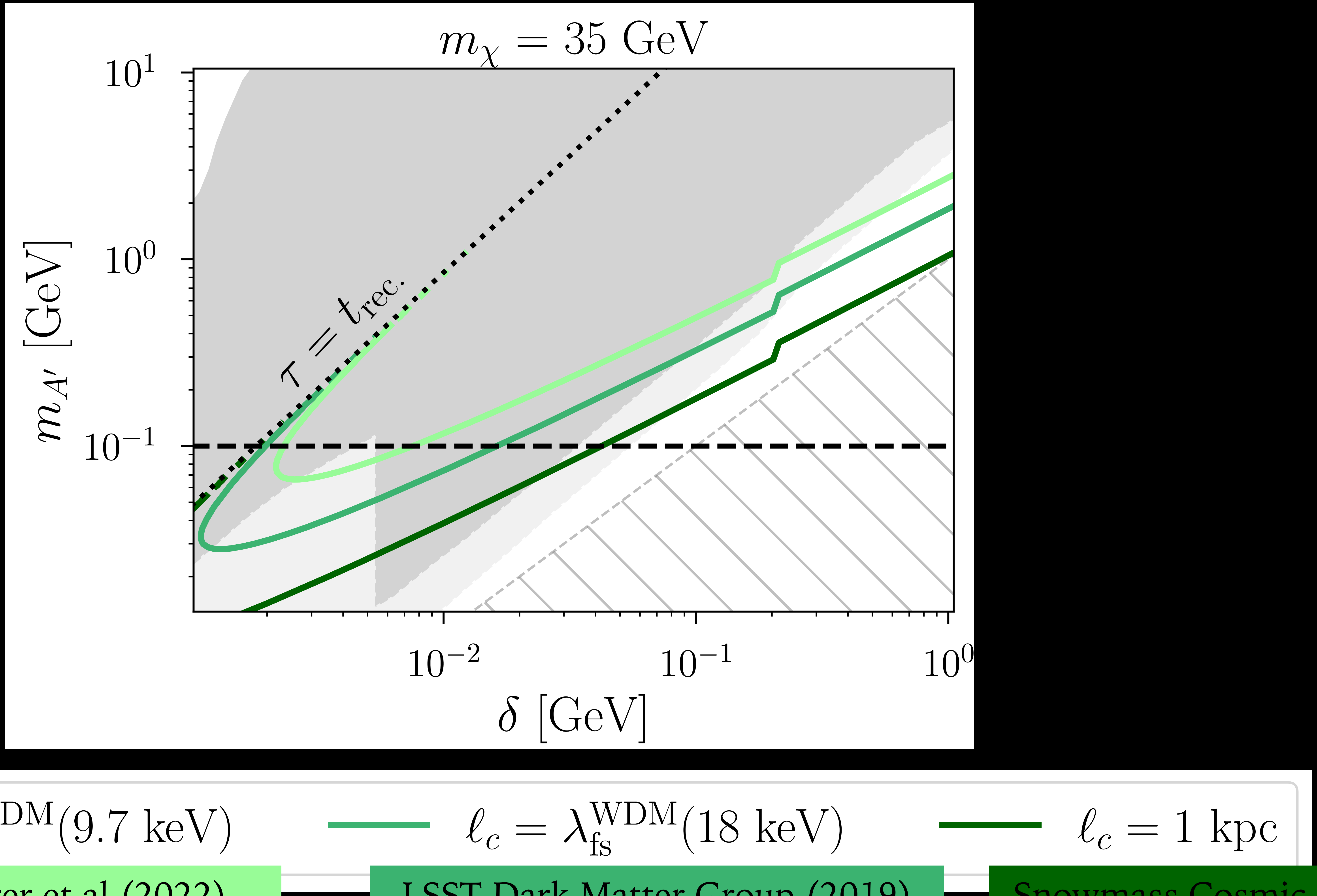
FOLLOWING THE GROUND STATE

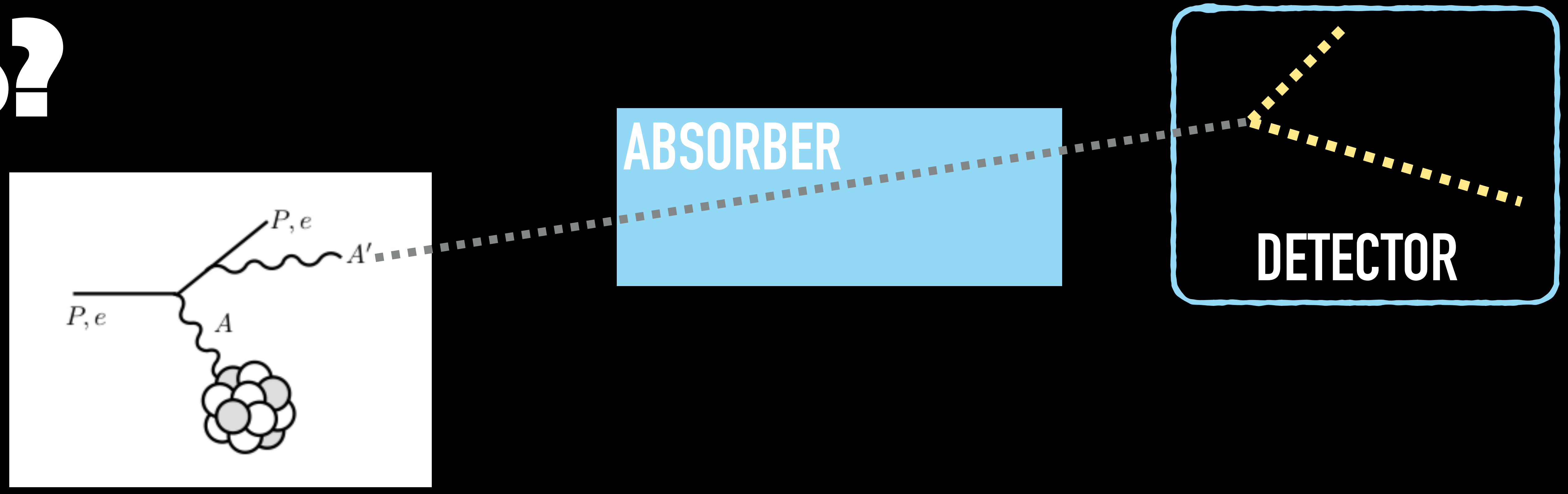
Compare the free-streaming length to Warm Dark Matter



Nadler, Birrer et al (2022) LSST Dark Matter Group (2019) Snowmass Cosmic Frontier (2021)

FREEZE-IN AT COLLIDERS?

Independently constrain the dark photon mass and lifetime



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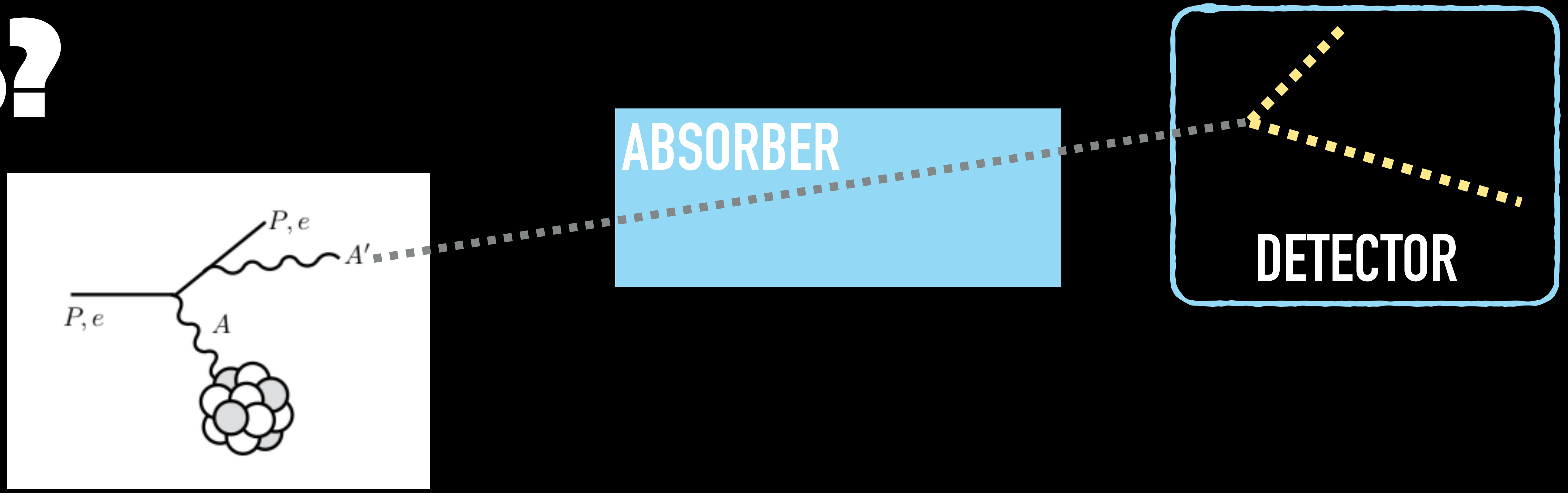

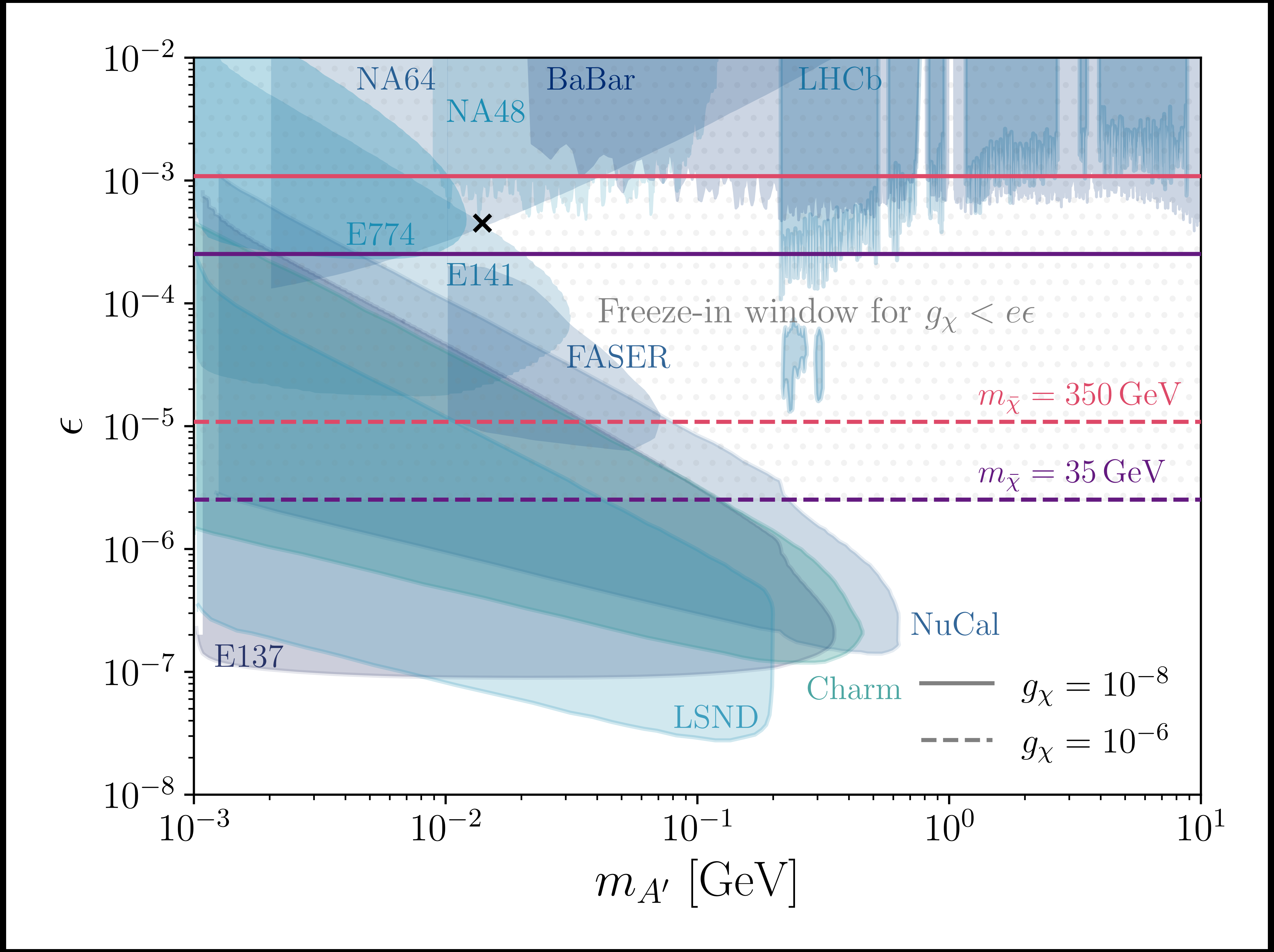

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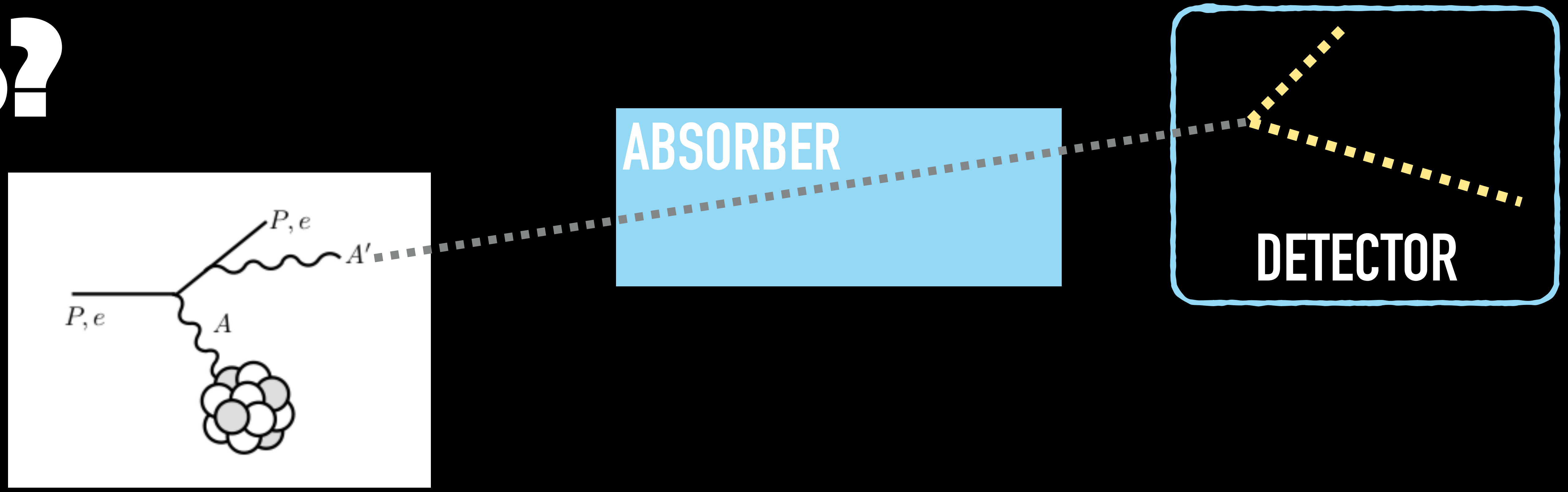

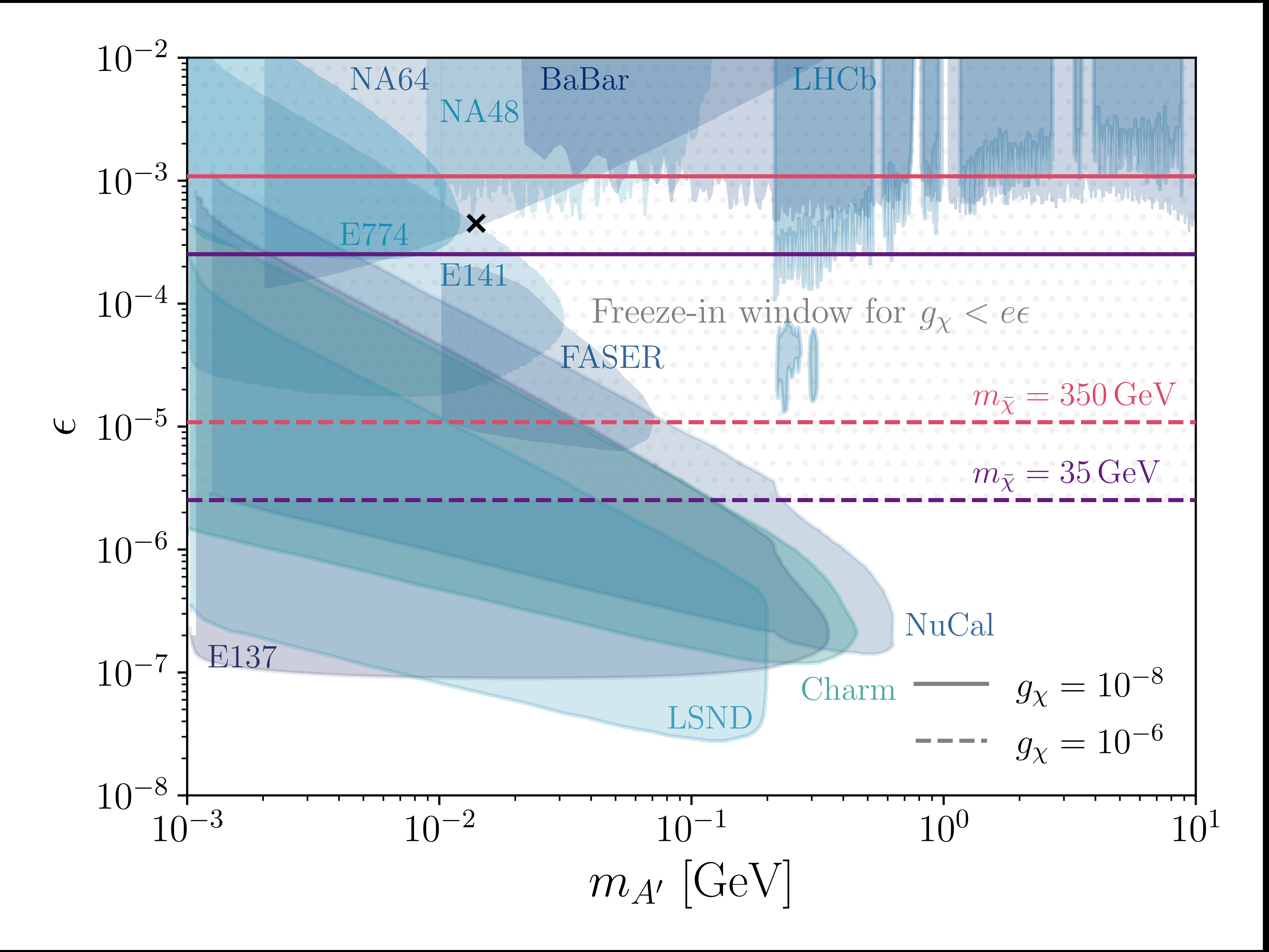

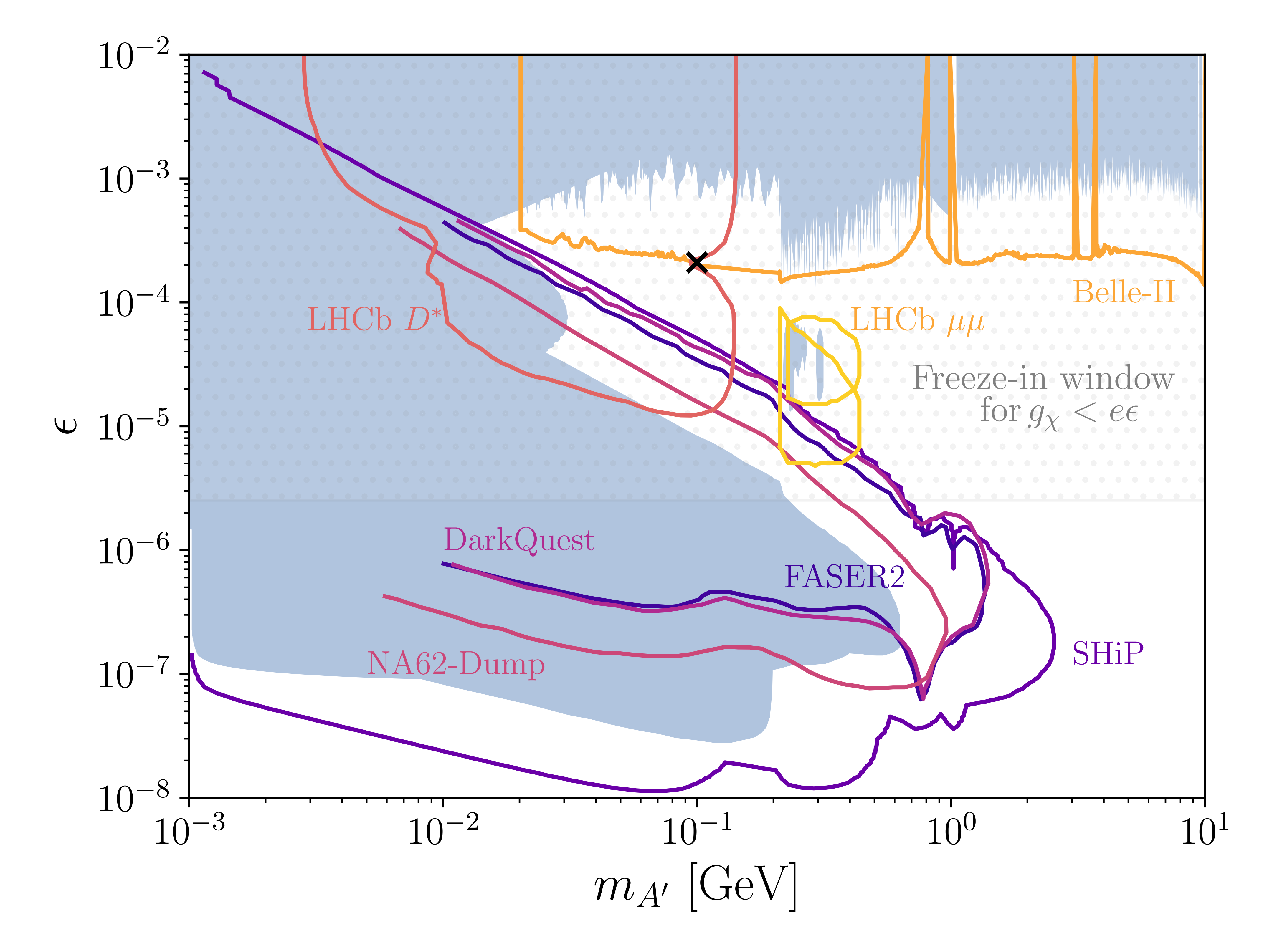

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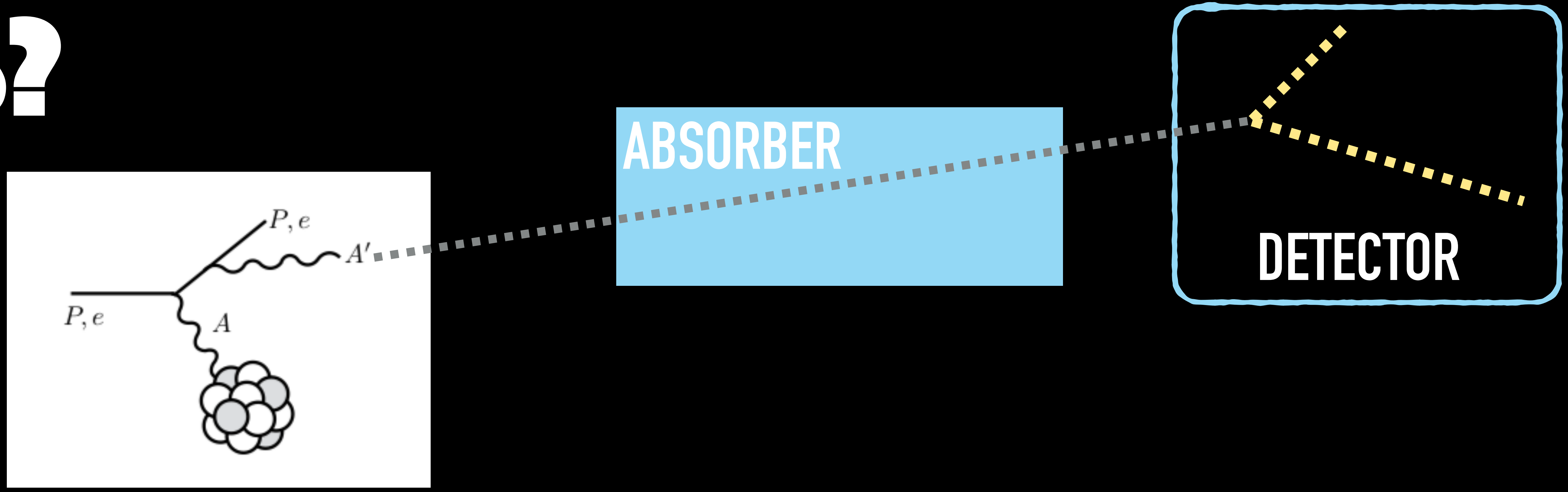
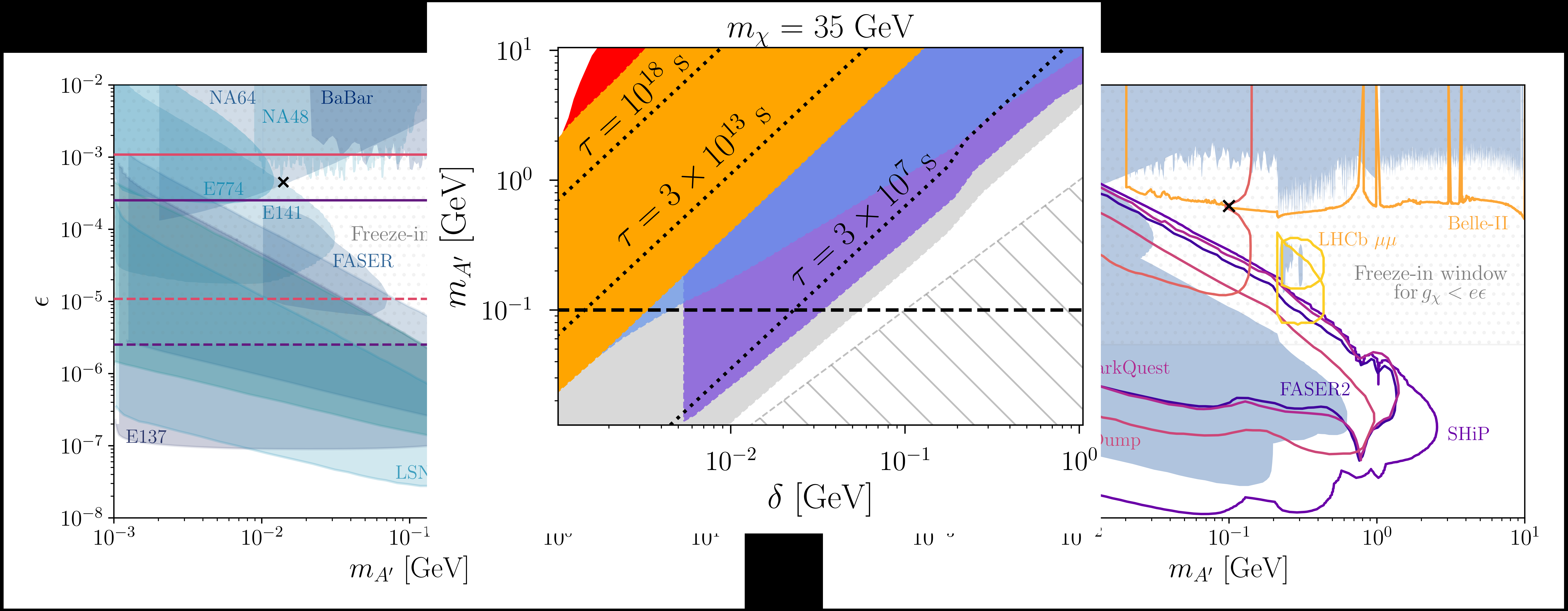


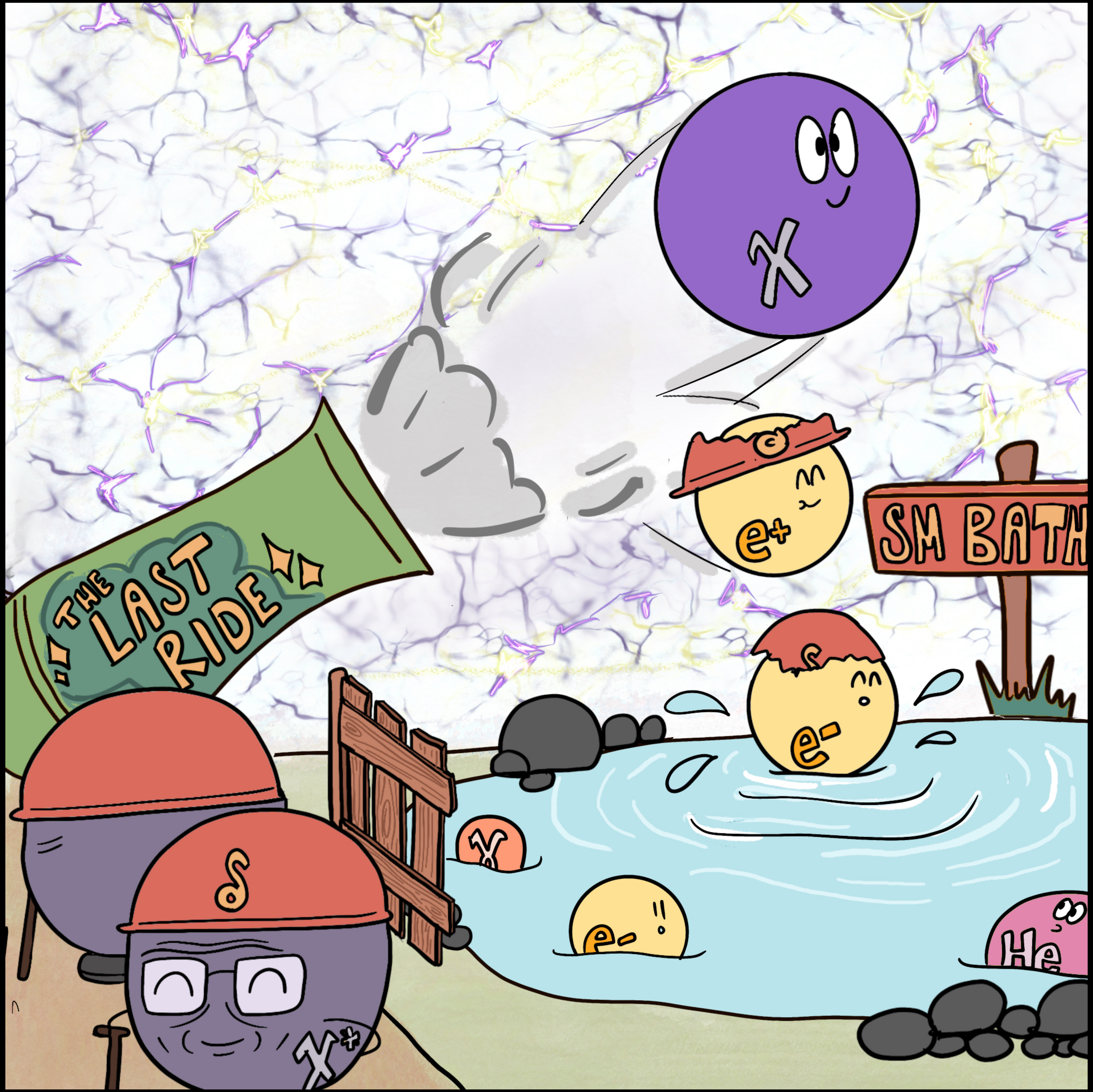


TAKEAWAYS:

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

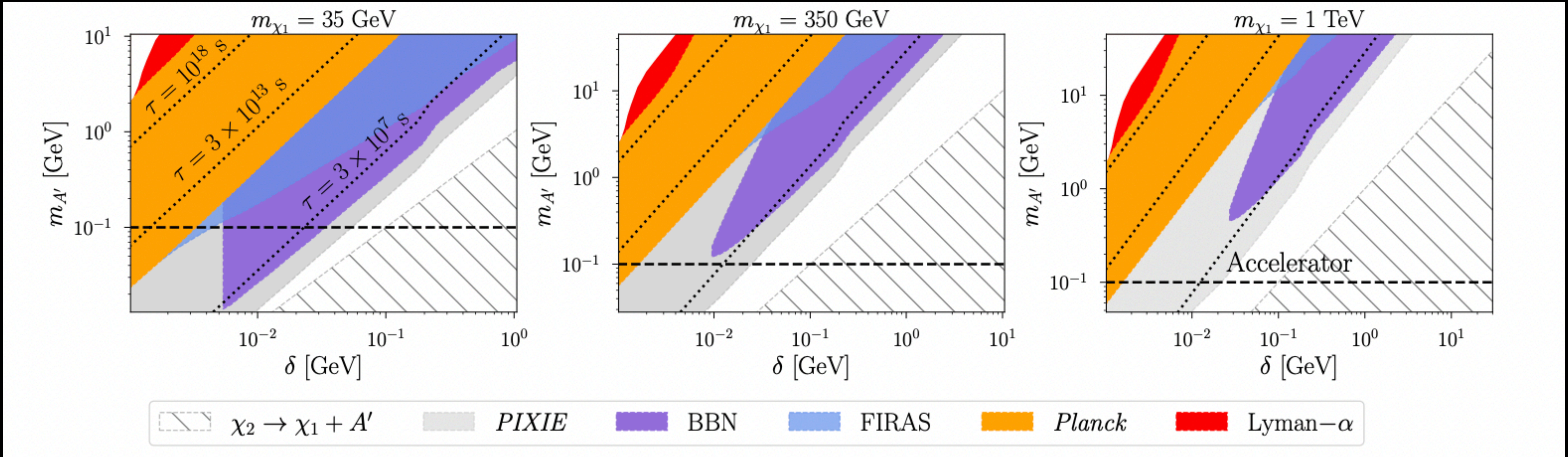
INELASTIC DM IS A SIMPLE EXTENSION OF THE SM THAT GIVES QUALITATIVELY NEW SIGNATURES AT A RANGE OF SCALES

INELASTIC FREEZE-IN GIVES A CONSISTENT THERMAL HISTORY FOR DM PRODUCTION AT DECAY

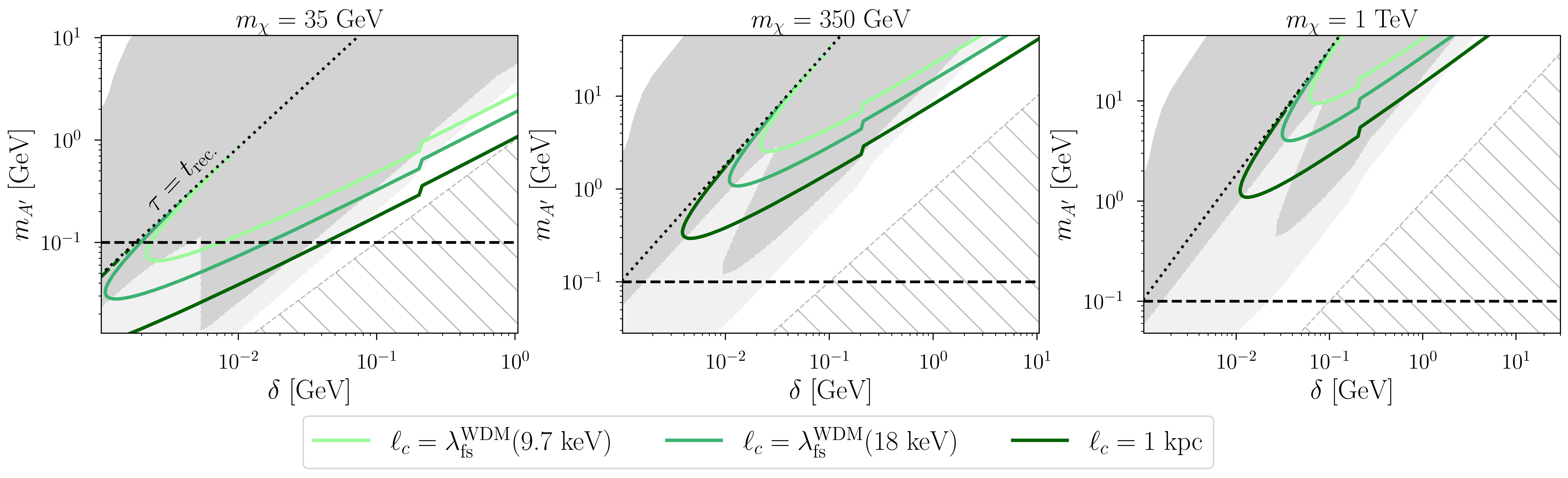


BACKUP

MASS SCALING



MASS SCALING



PARAMETER SPACE

Simple UV completing with a dark Higgs symmetry breaking:

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

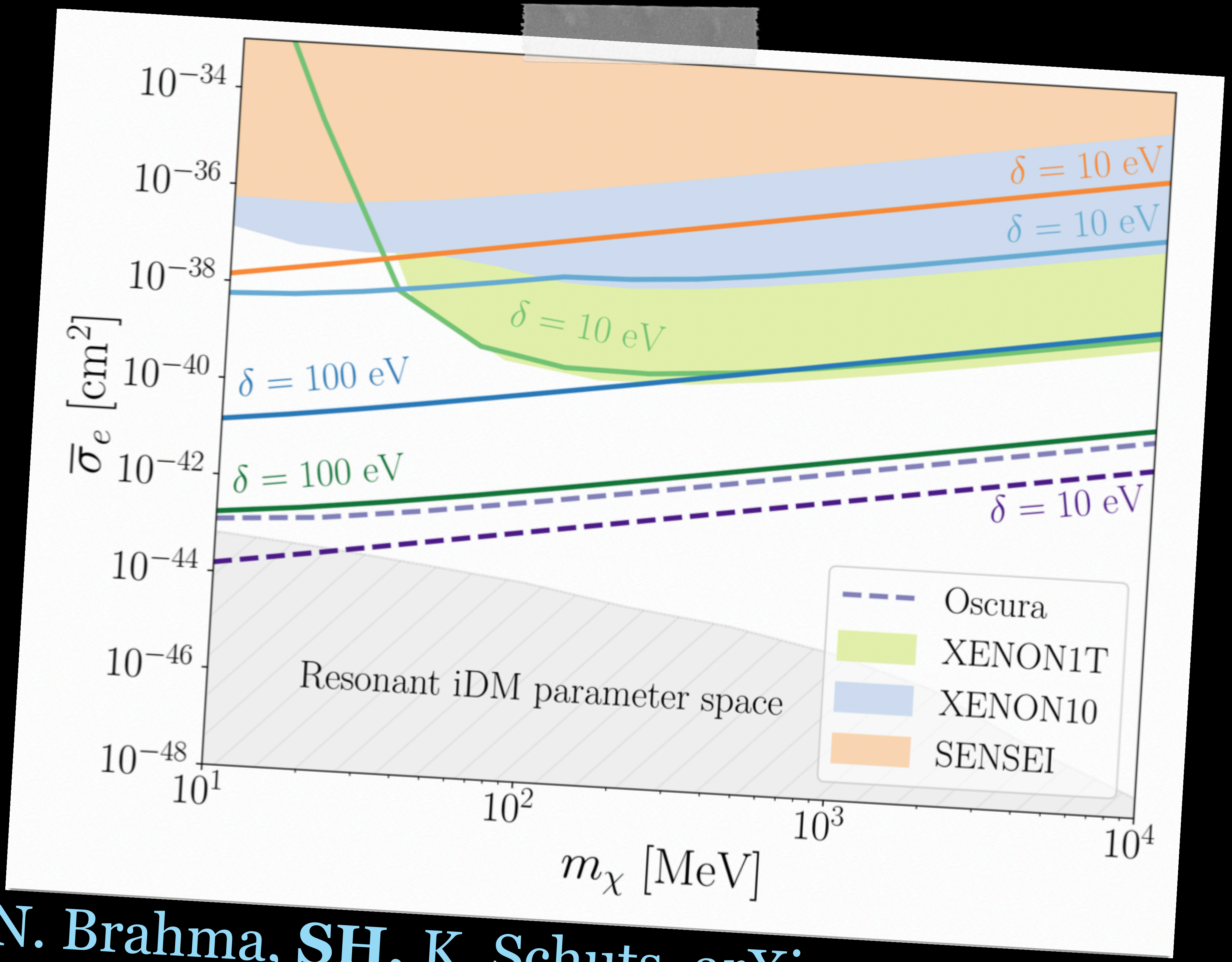
Assumptions:

- Dark Higgs heavier than everything else, $m_{h_D} \gg$ 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

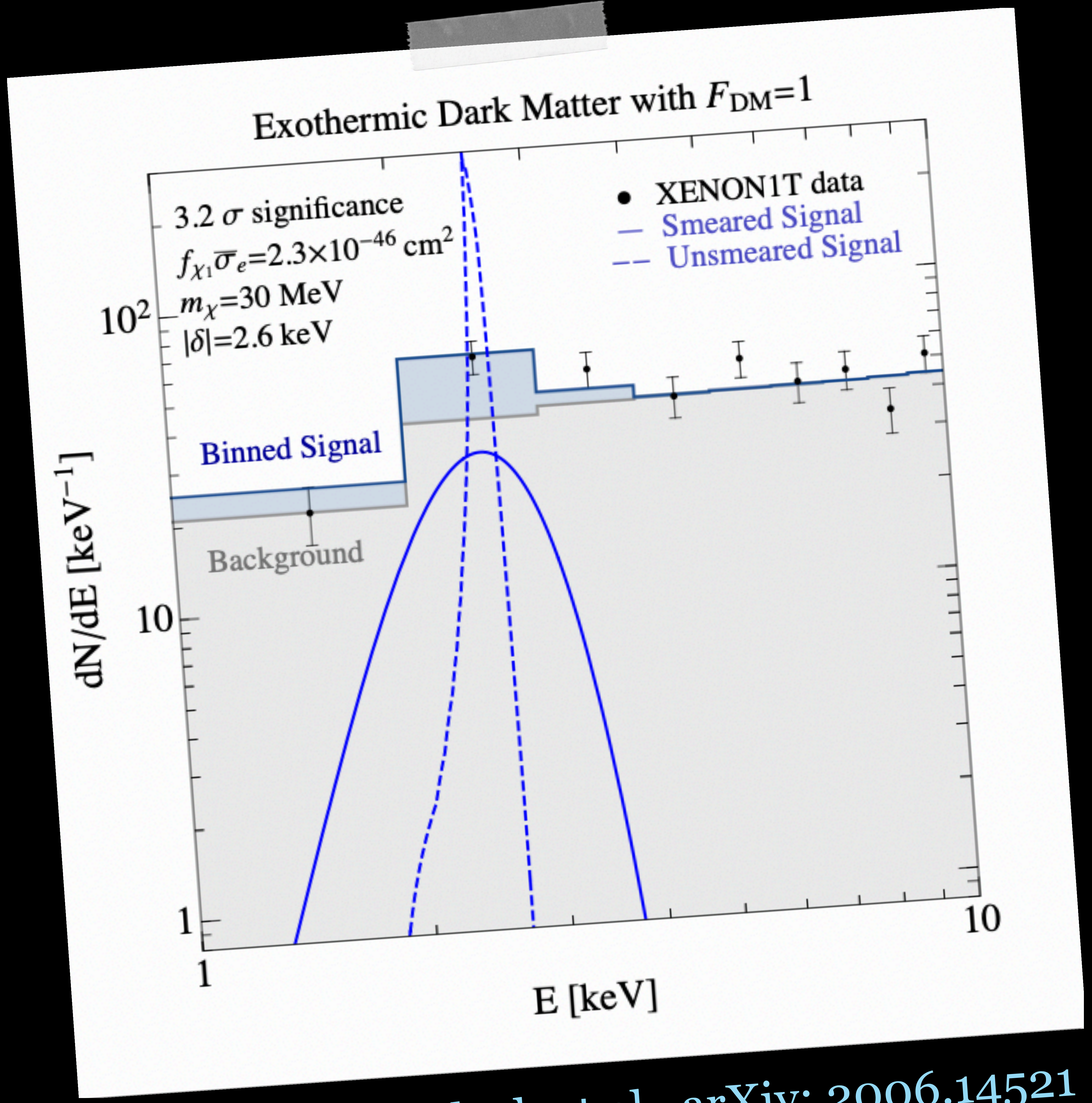
DIRECT DETECTION



N. Brahma, **SH**, K. Schuts, arXiv: 2308.01960.

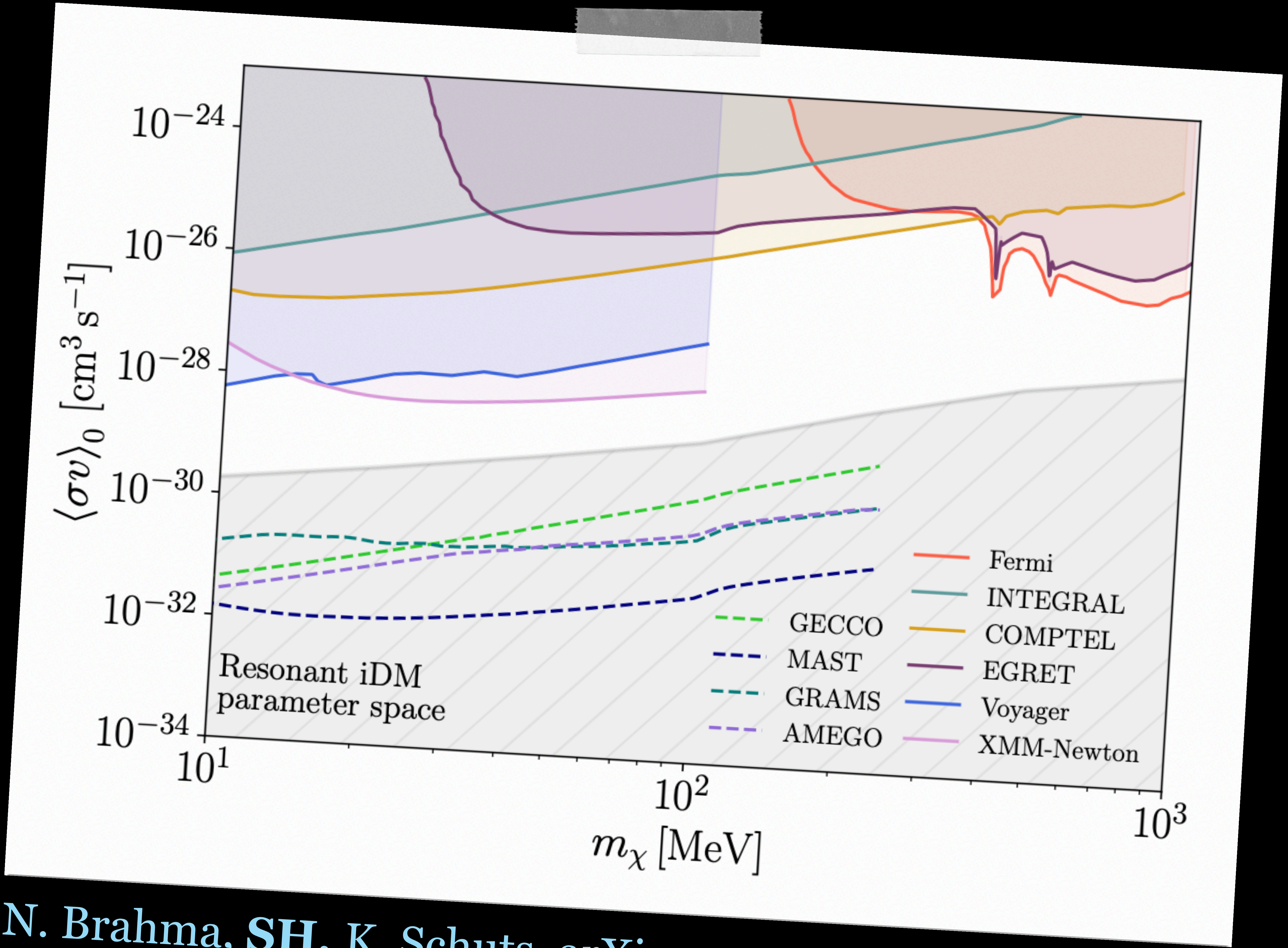
Sensitive to the fraction of excited state at late times: for thermally produced DM, this is very small!

See also: H. An & D. Yang , arXiv: 2006.15672
M. C. Gonzalez & N. Toro, arXiv: 2108.13422



Bloch et al , arXiv: 2006.14521

INDIRECT DETECTION



N. Brahma, **SH**, K. Schuts, arXiv: 2308.01960.

Despite the small couplings, with an appreciable relic excited state fraction, resonant Pseudo-Dirac DM is an exciting target for future telescopes!