Dark Photon mediated Inelastic Dark Matter in Cosmology, Astrophysics and Colliders

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Based on: arXiv:2602.1805

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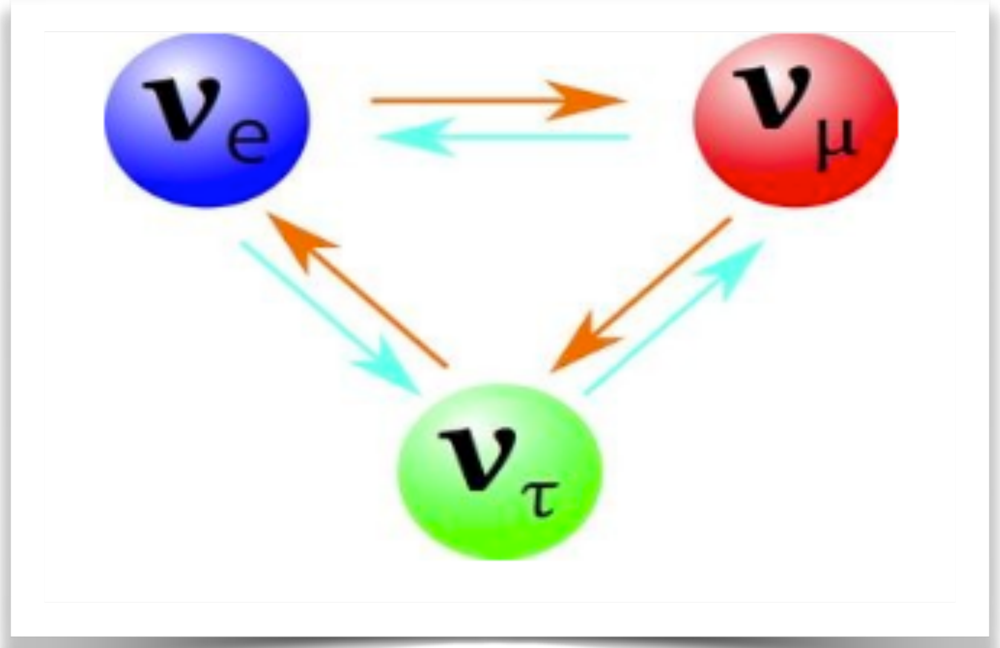
INTRODUCTION

Before the LHC started operating we all hoped for great discoveries ...

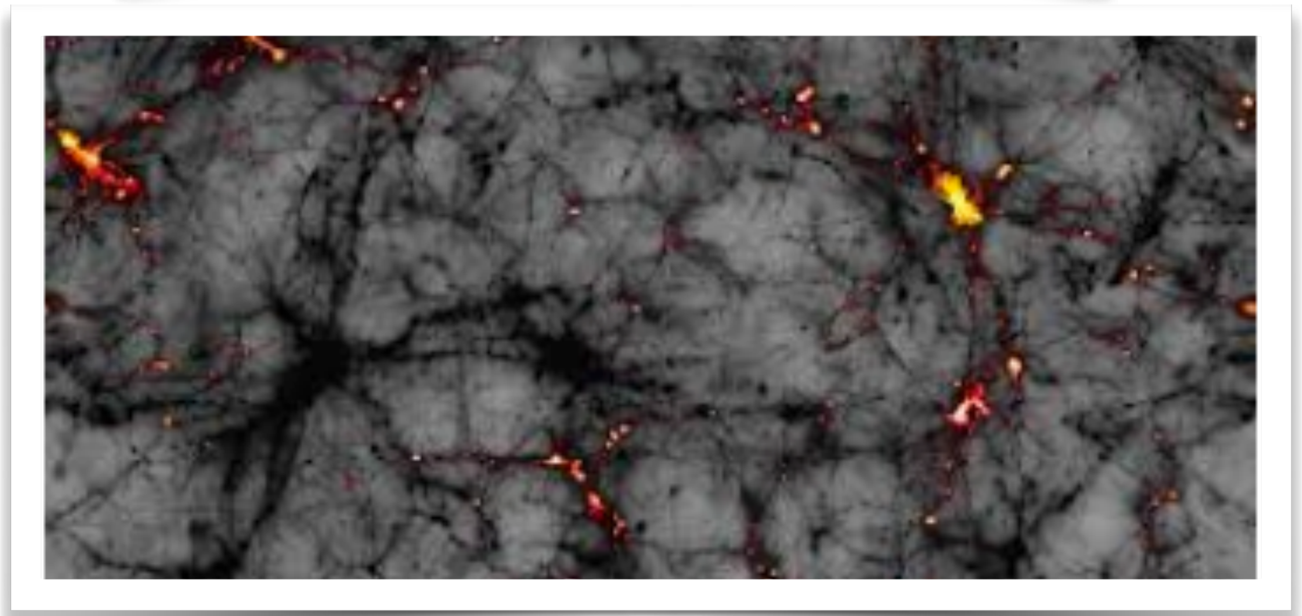

Microscopic
black holes
Extra dimensions
Supersymmetry
Compositeness
LHC expectations


LHC results...
125 GeV
palm tree

Do we have a good reason to go Beyond the Standard Model?

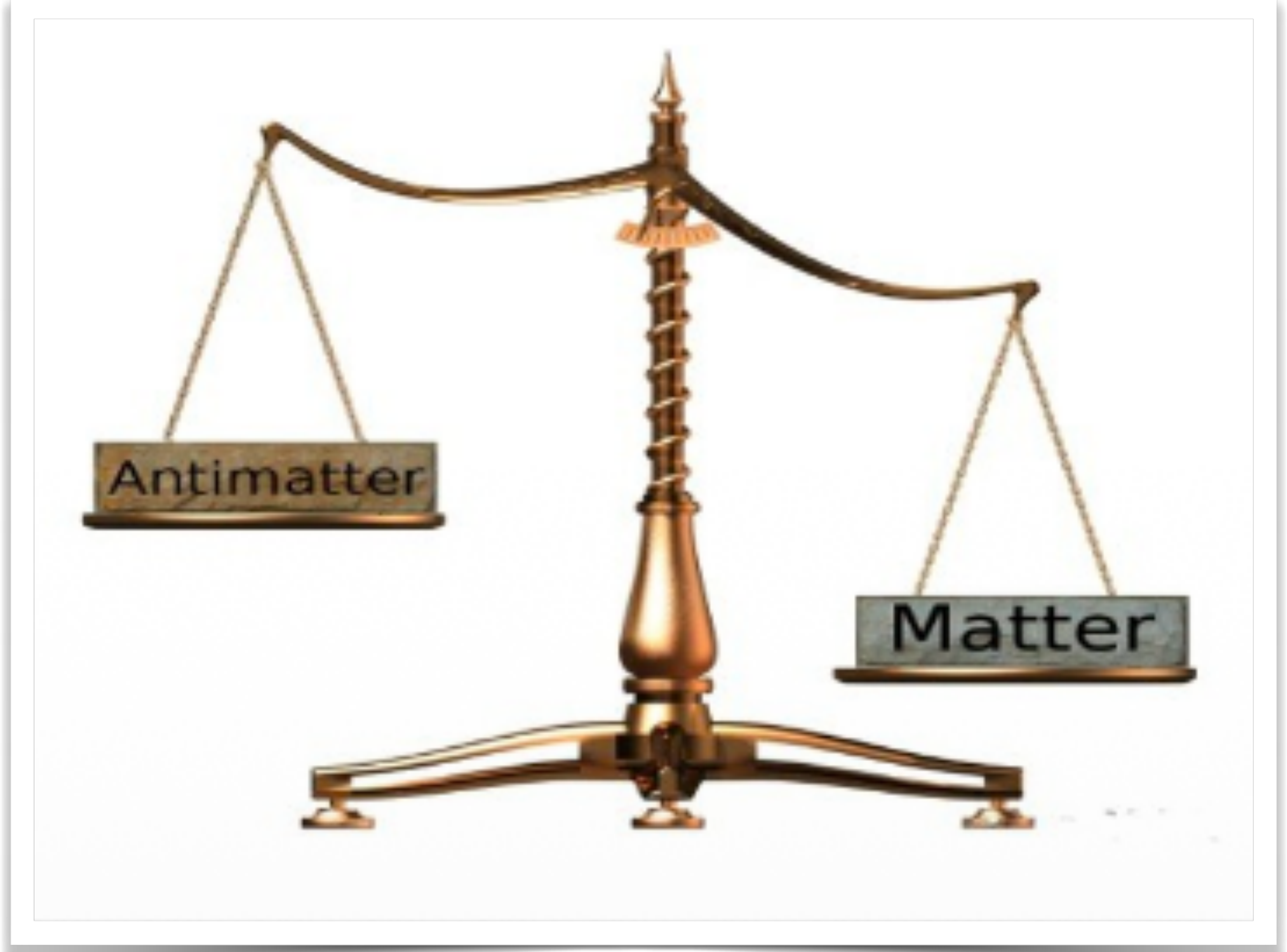


✤ SM fails to explain neutrino mass and mixing .



✤ SM doesn't have DM candidate.

✤ SM fails to explain observed baryon asymmetry.



Who can be a DM ?

✳ Should be massive

✳ Should be electrically neutral

✳ Should be present in early universe

✳ Should be stable or at least with half life greater than the age of the universe.

Need a symmetry like $\mathbb{Z}_2, \mathbb{Z}_3$ etc

Singlet Scalar

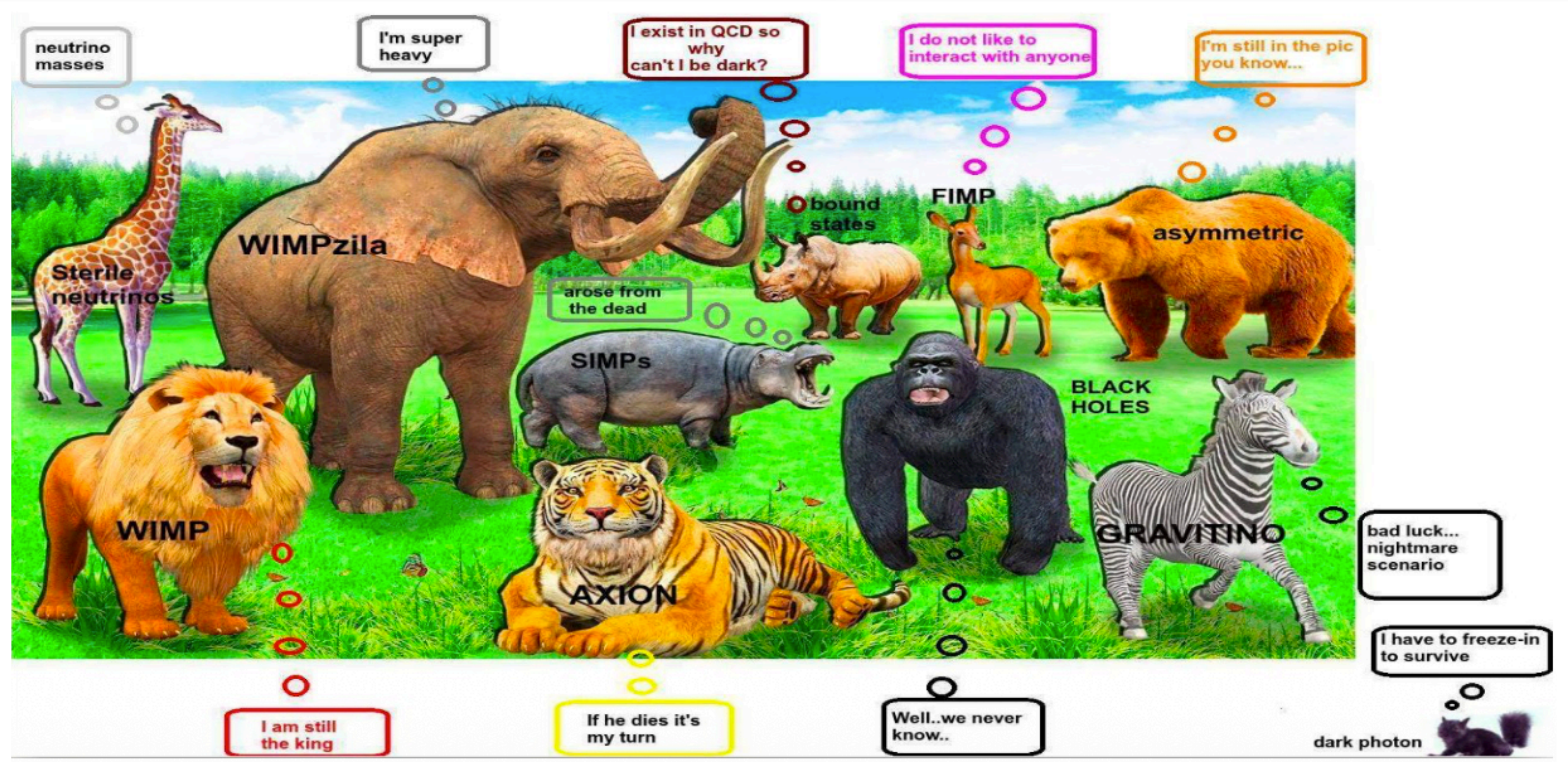
Singlet Fermion

Scalar in triplet repn

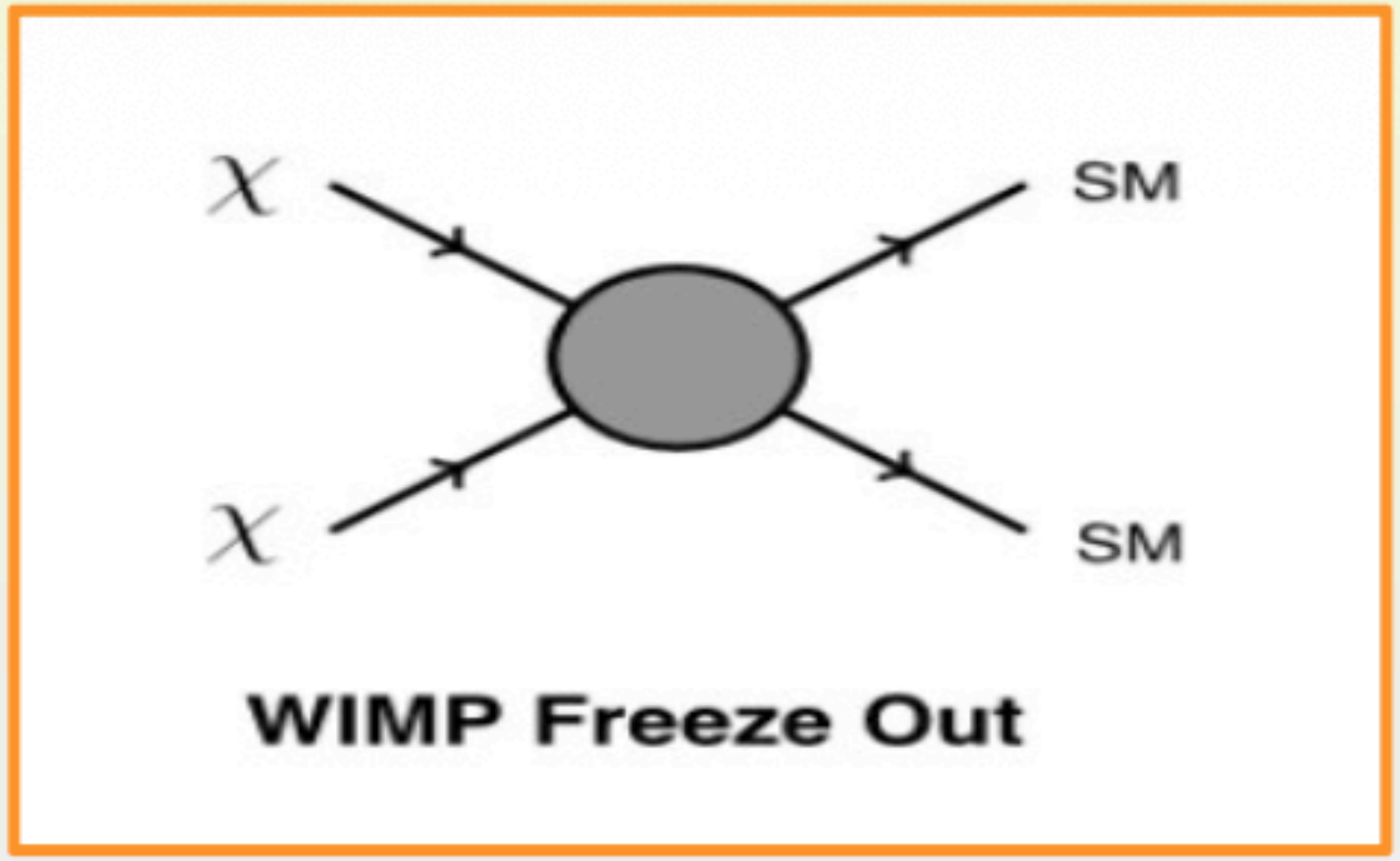
Fermion in triplet repn

...and many more

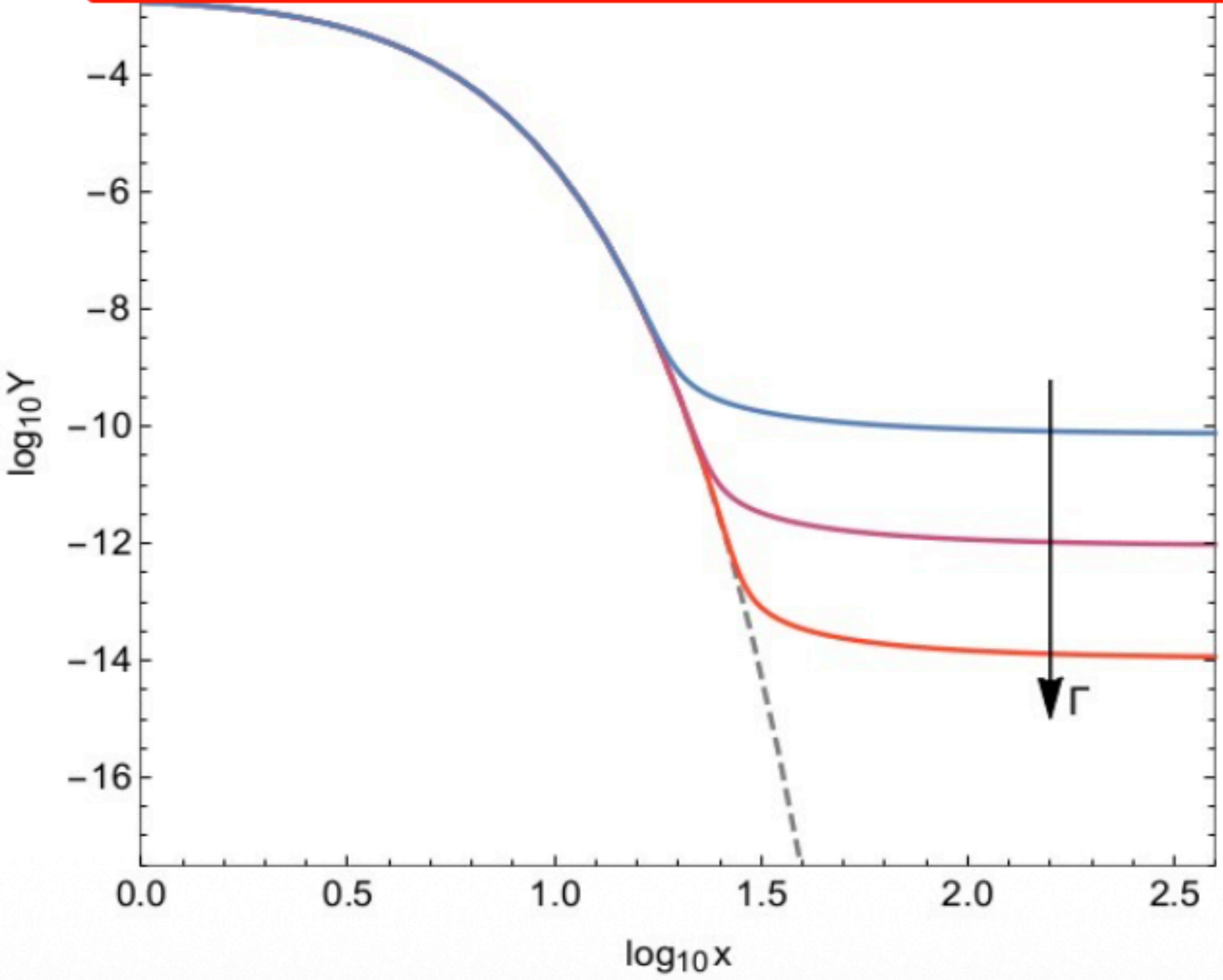
Zoo of Dark Matter Candidates



Overview WIMP Mechanism



$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{eq})^2\right]$$



Classic WIMP Paradigm

- Initially in **thermal equilibrium** with the SM plasma.
- Relic abundance set by **freeze-out** via pair annihilation

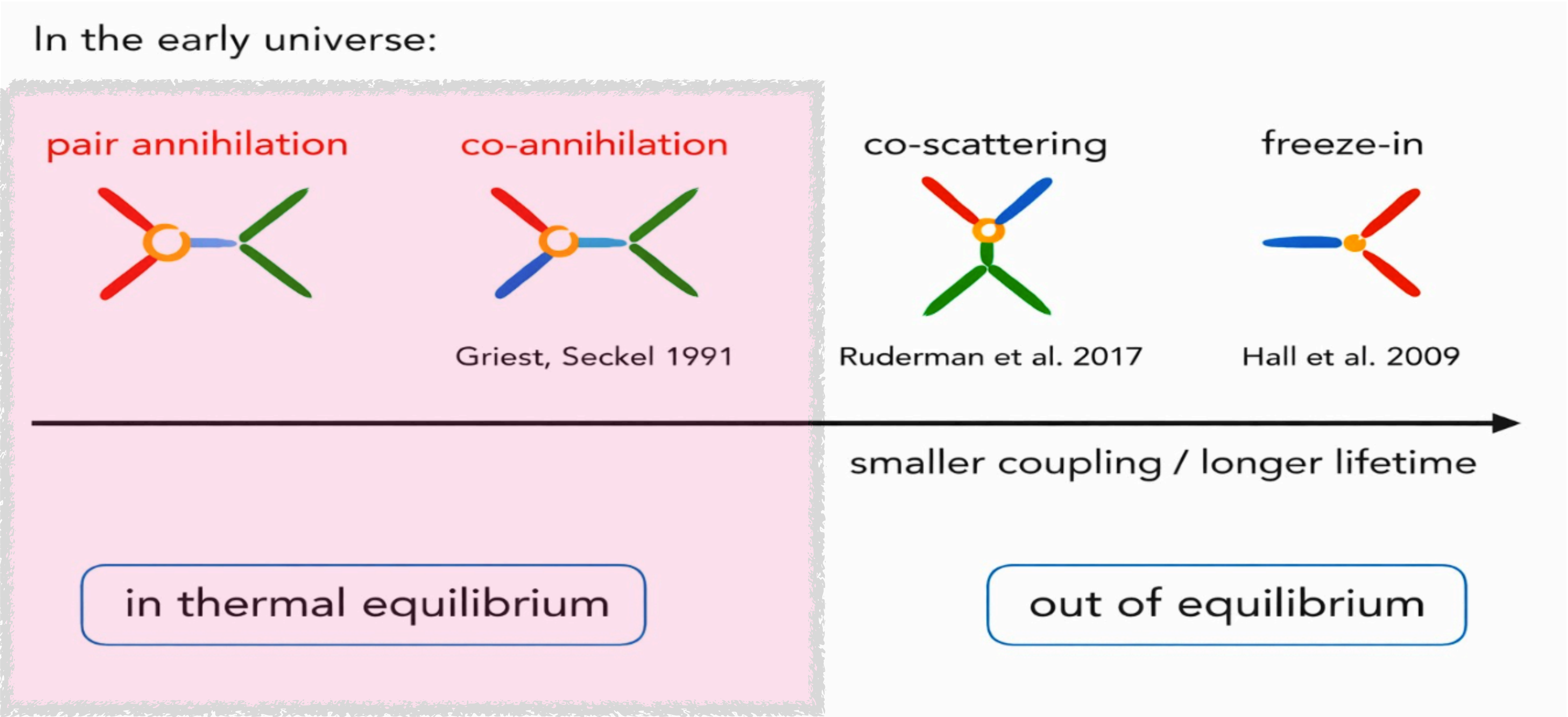
$$\chi\chi \to \mathrm{SM\ SM}$$

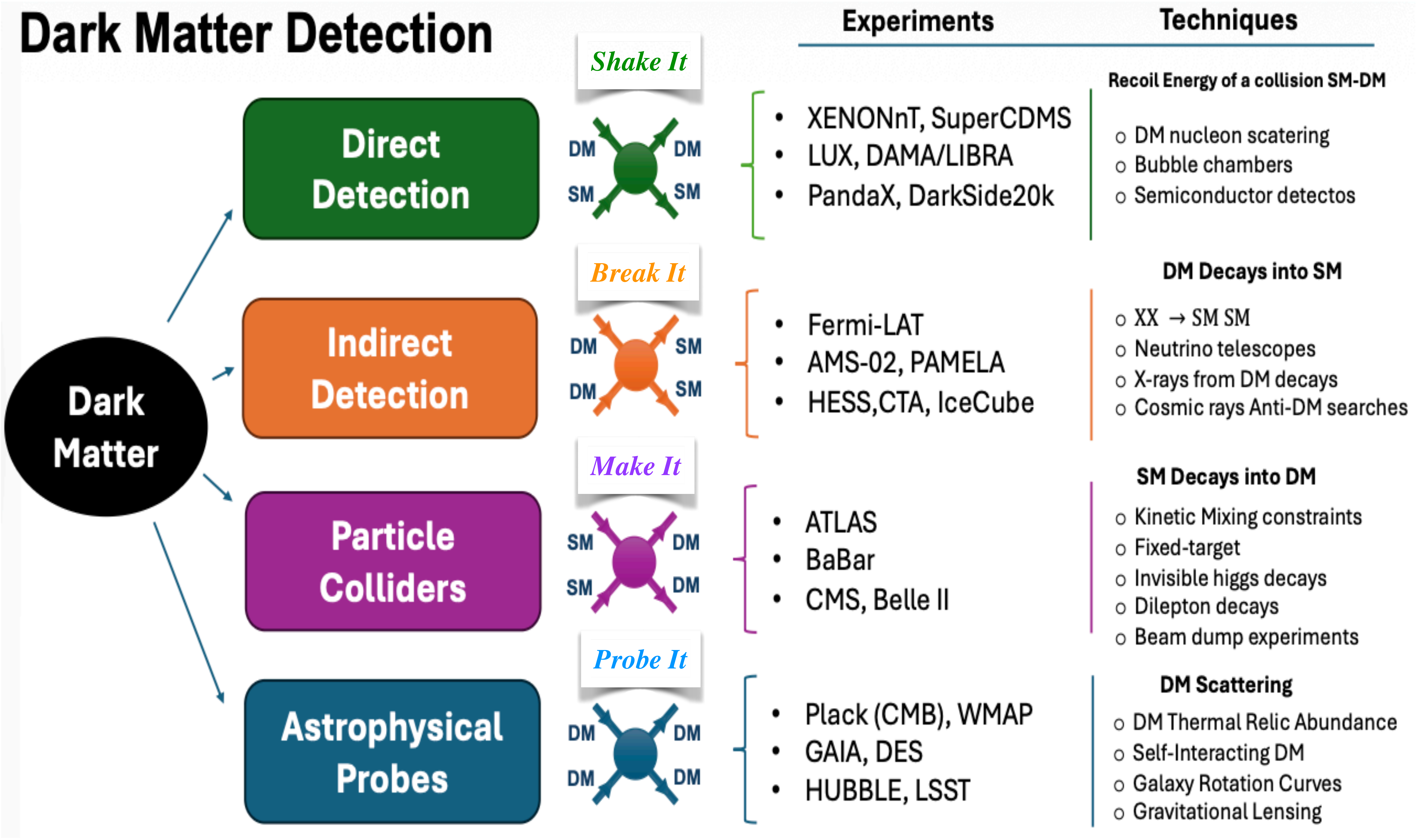
- Predicts the canonical thermal relic cross section

$$\langle \sigma v\rangle \sim 3\times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

- Strongly constrained by **direct and indirect detection experiments**.

Overview WIMP Mechanism

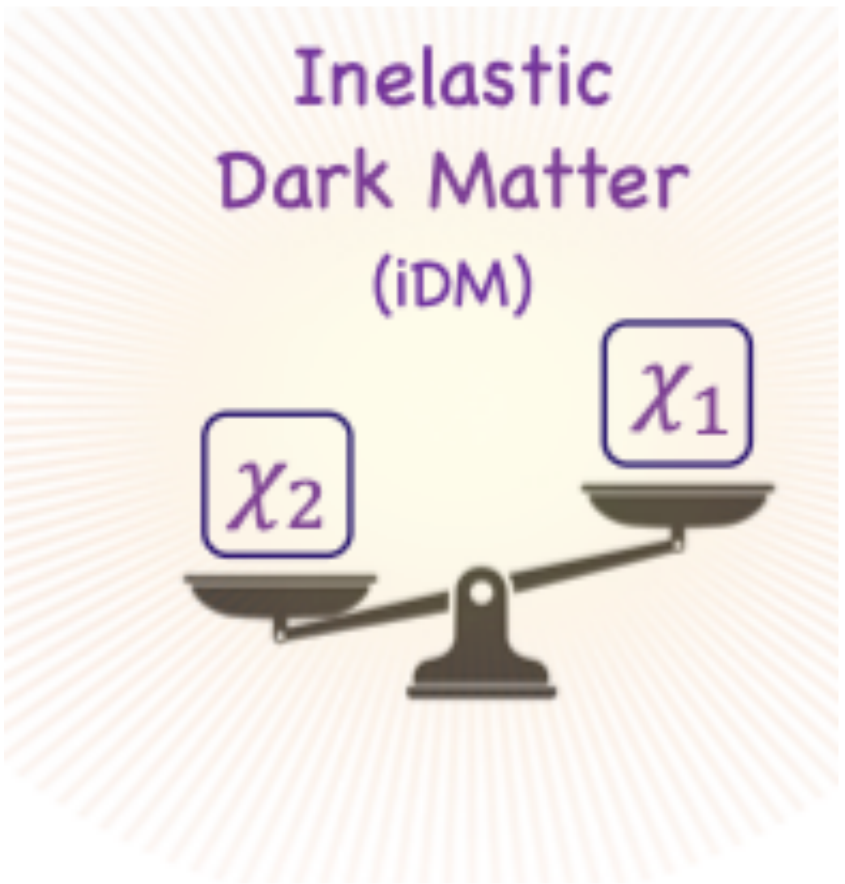



Dark Matter Detection
Experiments
Techniques
Dark Matter
Shake It
Direct Detection
DM
DM
SM
SM
XENONnT, SuperCDMS
LUX, DAMA/LIBRA
PandaX, DarkSide20k
Recoil Energy of a collision SM-DM
DM nucleon scatering
Bubble chambers
Semiconductor detectos
Break It
Indirect Detection
DM
SM
DM
SM
Fermi-LAT
AMS-02, PAMELA
HESS,CTA, IceCube
DM Decays into SM
XX → SM SM
Neutrino telescopes
X-rays from DM decays
Cosmic rays Anti-DM searches
Make It
Particle Colliders
SM
DM
SM
DM
ATLAS
BaBar
CMS, Belle II
SM Decays into DM
Kinetic Mixing constraints
Fixed-target
Invisible higgs decays
Dilepton decays
Beam dump experiments
Probe It
Astrophysical Probes
DM
DM
DM
DM
Plack (CMB), WMAP
GAIA, DES
HUBBLE, LSST
DM Scattering
DM Thermal Relic Abundance
Self-Interacting DM
Galaxy Rotation Curves
Gravitational Lensing


Dark Matter Portals
Portal
Mediator Particle
Operator
Dark Sector
Portal
Standard Model
Vector
Dark Photon
$\mathcal{L} \supset -\frac{\varepsilon}{2} B_{\mu\nu} F'^{\mu\nu}$
Axion
Pseudoscalars
$\mathcal{L} \supset \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i\mu\nu}\tilde{G}_i^{\mu\nu}, \ldots$
Higgs
Dark scalars
$\mathcal{L} \supset (\mu\phi + \lambda\phi^2)H^\dagger H$
Neutrino
Sterile neutrinos
$\mathcal{L} \supset y_N LHN$

Inelastic Dark Matter (iDM)

Theoretical Framework



Dark Sector

Dirac Pair

Two-component Weyl fermions forming a Dirac pair splitting into a **pseudo-Dirac pair** (χ_1, χ_2)

Mediator

New vector mediator A' arising from a spontaneously broken abelian gauge symmetry $U(1)_D$

$$\mathcal{L}_{int} \supset \frac{\epsilon}{2\cos\theta_W} A'^{\mu\nu} B_{\mu\nu},$$

$$\mathscr{L} \supset -M_D \psi_1 \psi_2 - \frac{1}{2}\left(\delta_1 \psi_1^2 + \delta_2 \psi_2^2\right) + h.c., \text{with } \delta_{1,2} \ll \mathrm{M_D}$$

Dirac Majorana

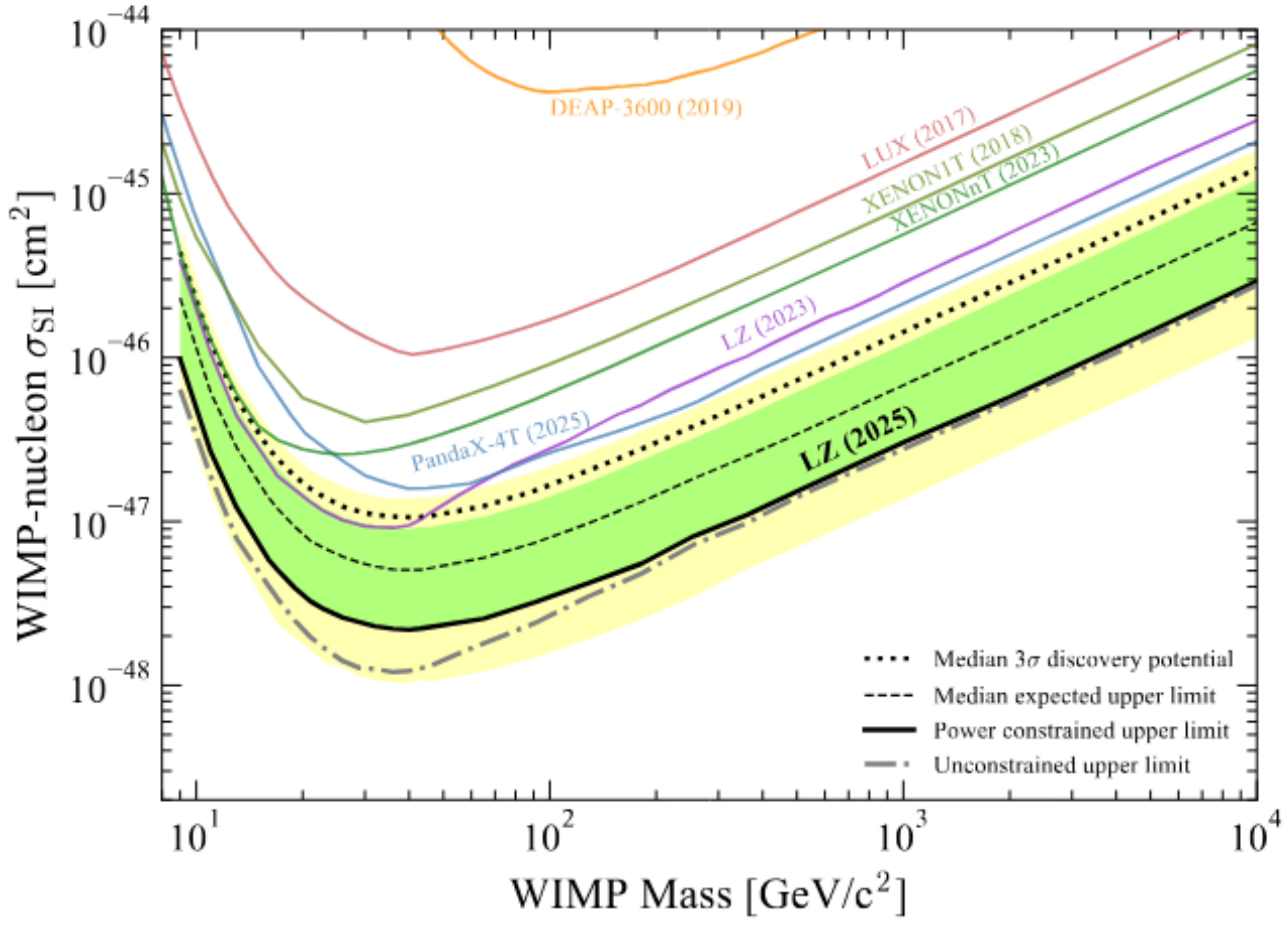
⇒ mass eigenstates

$$\chi_1 \simeq \frac{i}{\sqrt{2}}\left(\psi_1 - \psi_2\right)$$

$$\chi_2 \simeq \frac{1}{\sqrt{2}}\left(\psi_1 + \psi_2\right)$$

$$M_{\chi_2,\chi_1} = M_D \pm \frac{1}{2}\left(\delta_1 + \delta_2\right), \qquad \delta = M_{\chi_2} - M_{\chi_1} = \delta_1 + \delta_2$$

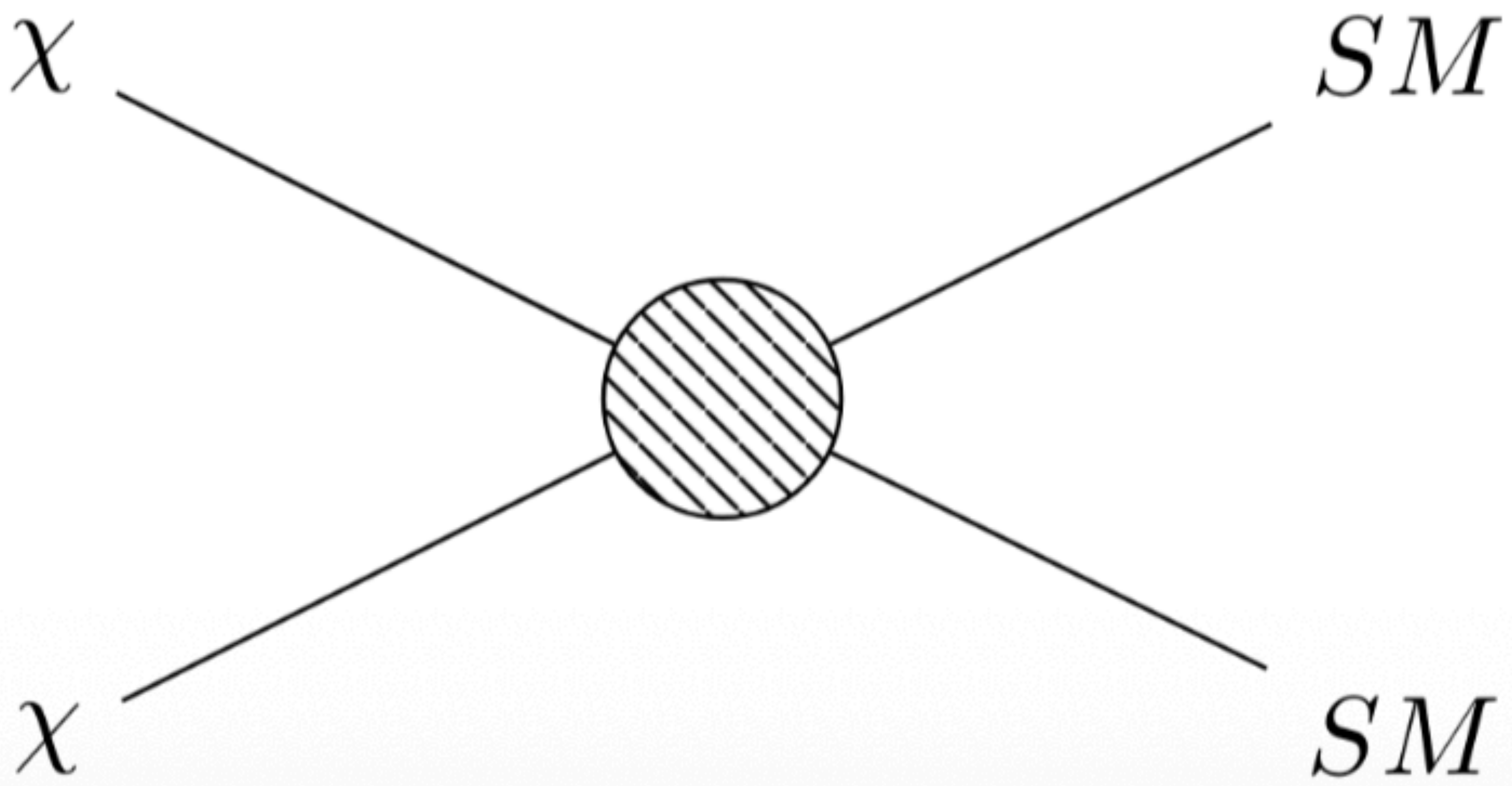
Direct detection puts strong bounds on thermal dark matter



Direct detection puts strong bounds on thermal dark matter

Self-annihilation

Elastic scattering



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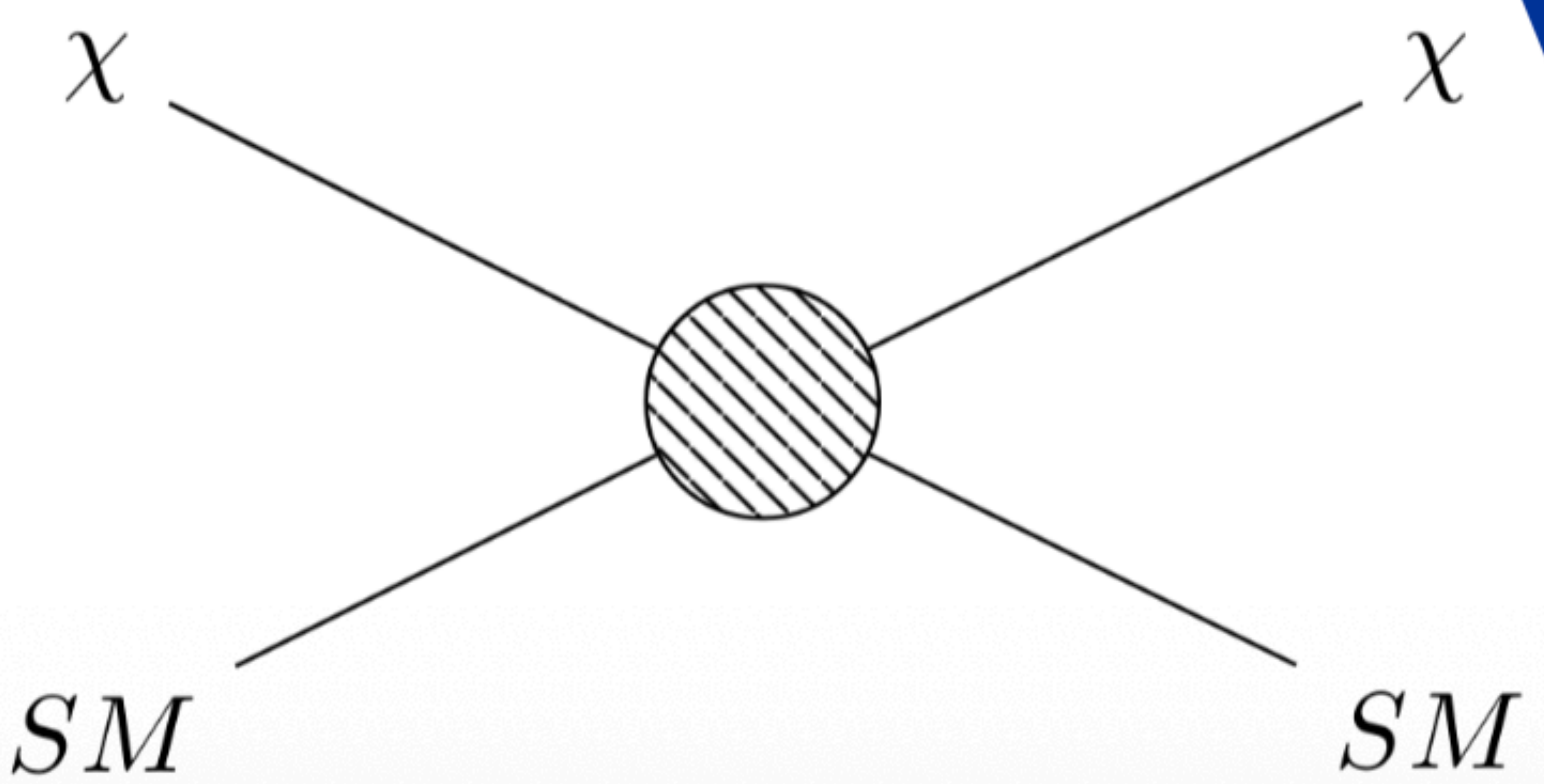
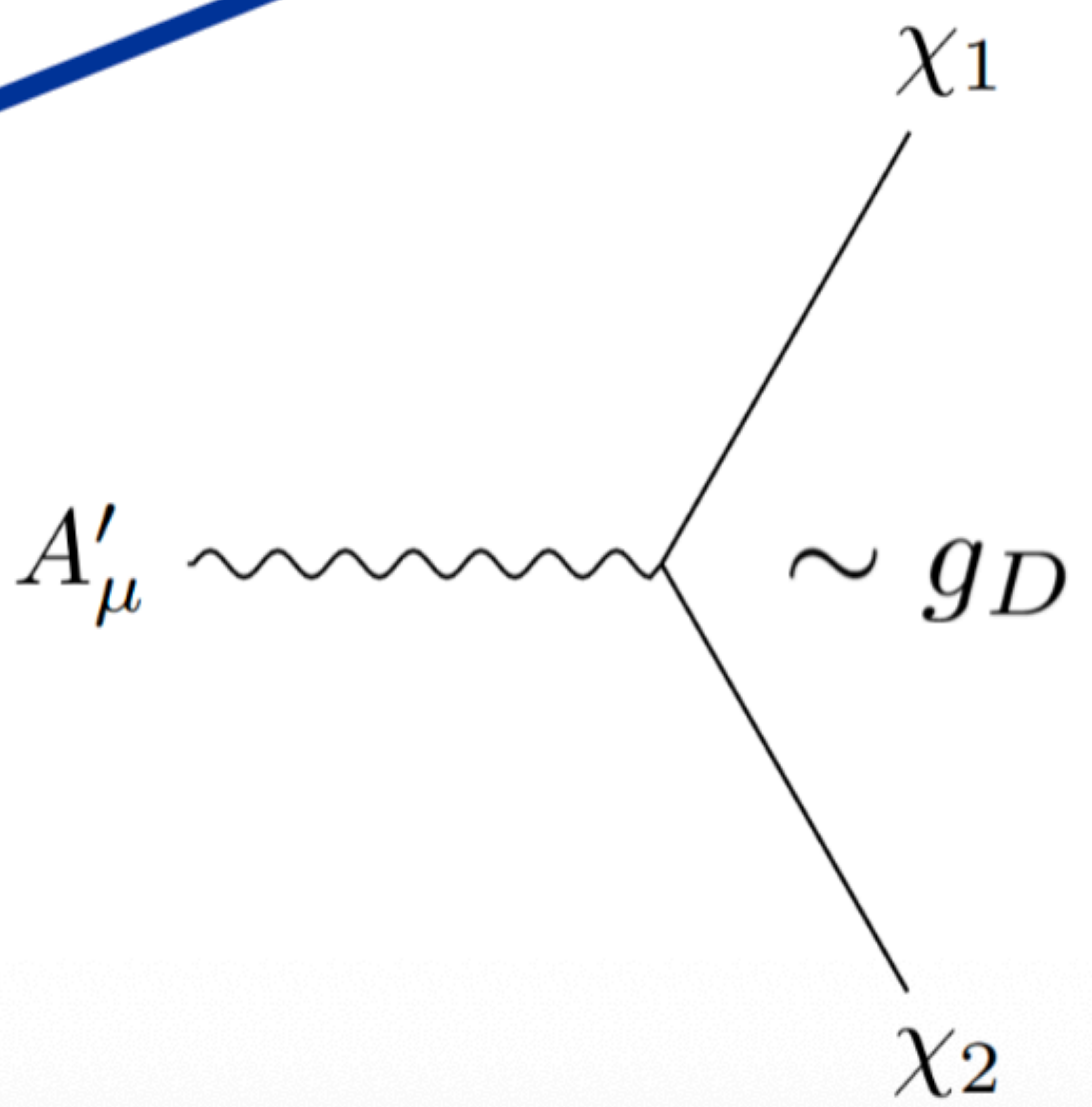


Inelastic Dark Matter

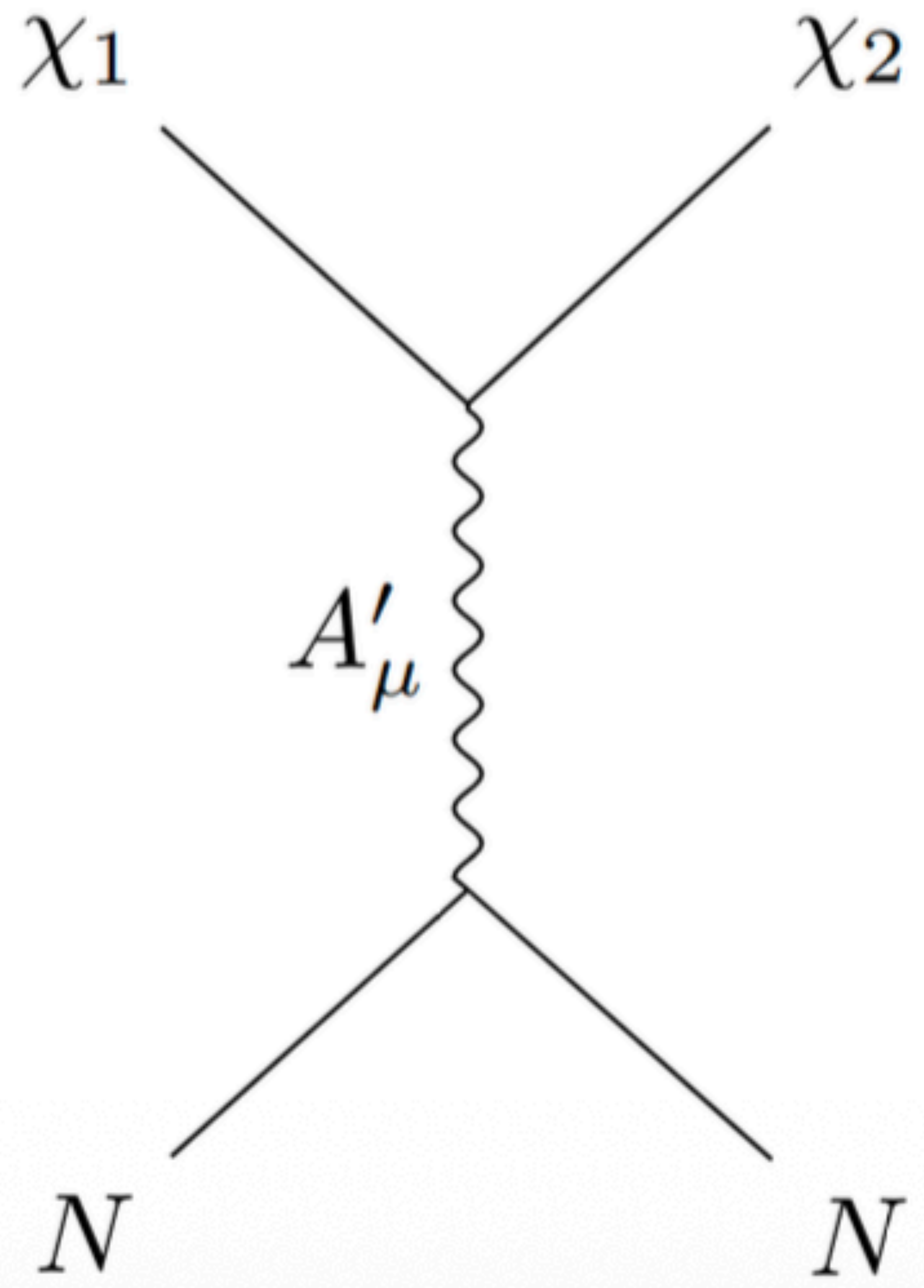


Dark fermions couple mainly off-diagonally with dark photon

Weaker direct detection bound

Thermal through co-annihilation

Inelastic Dark Matter



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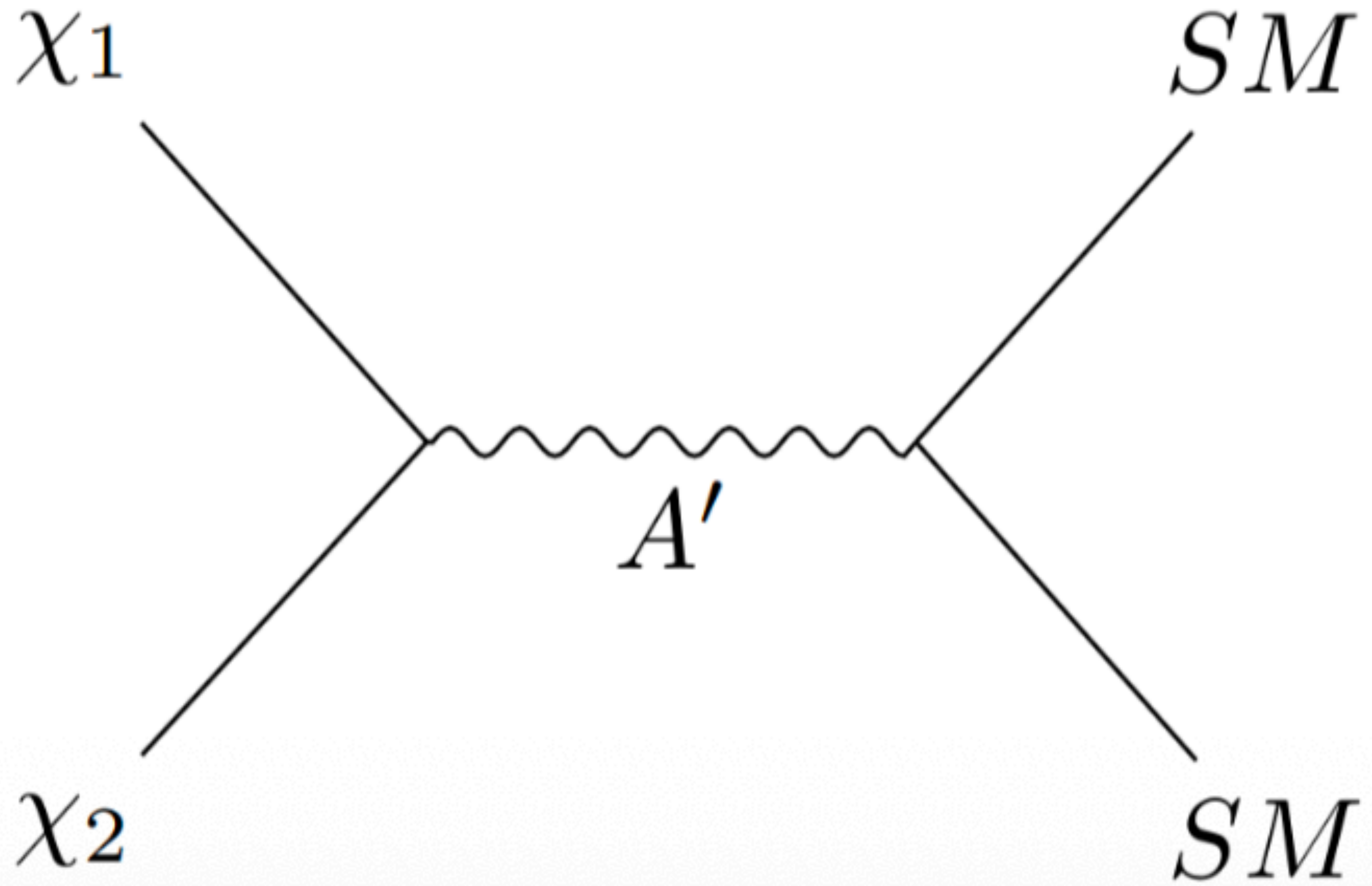
Inelastic Dark Matter



Dark fermions couple mainly off-diagonally with dark photon

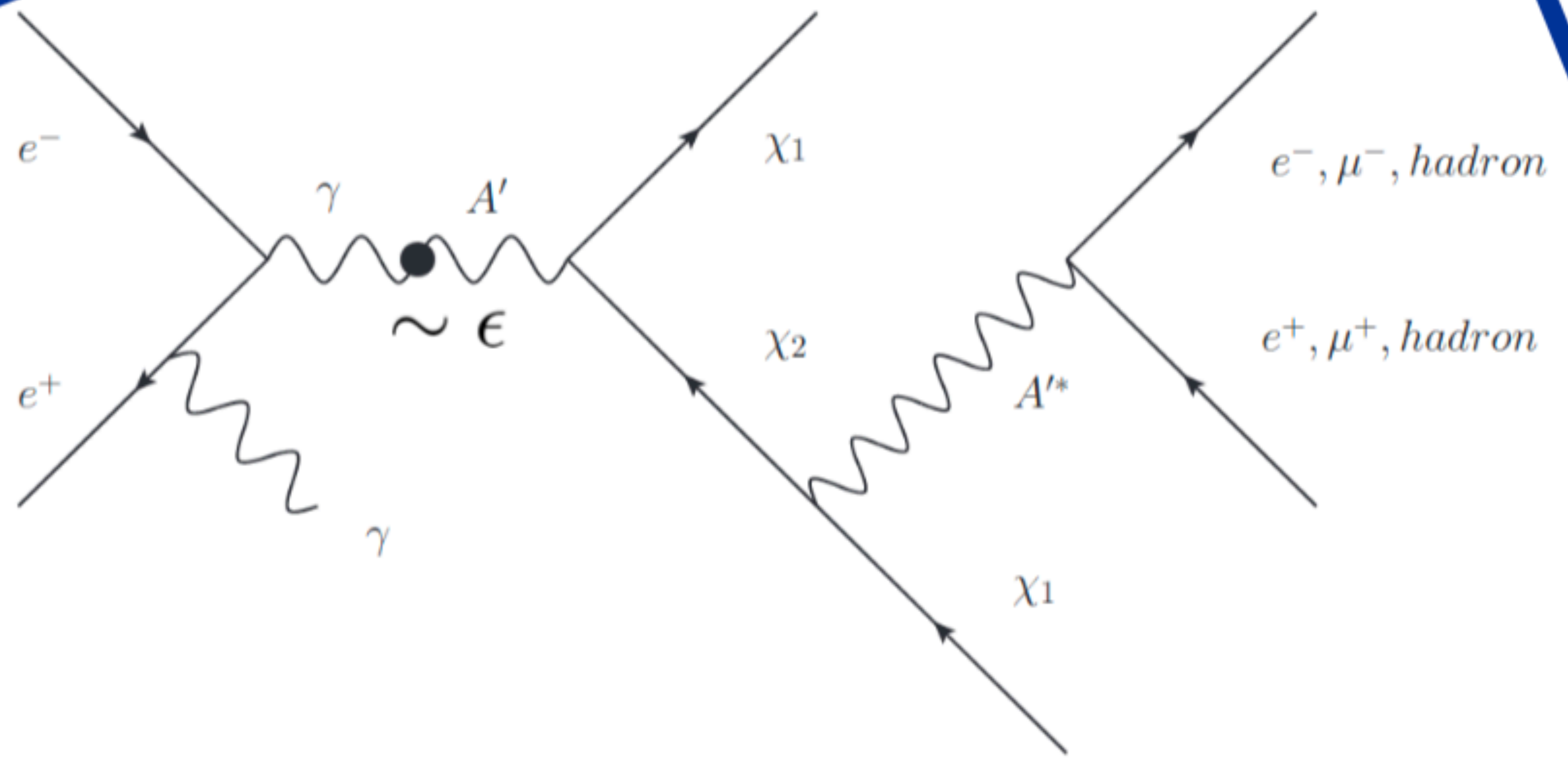
Weaker direct detection bound

Thermal through co-annihilation

Inelastic DM detection

Colliders

- Displaced signature
- Mono-photon

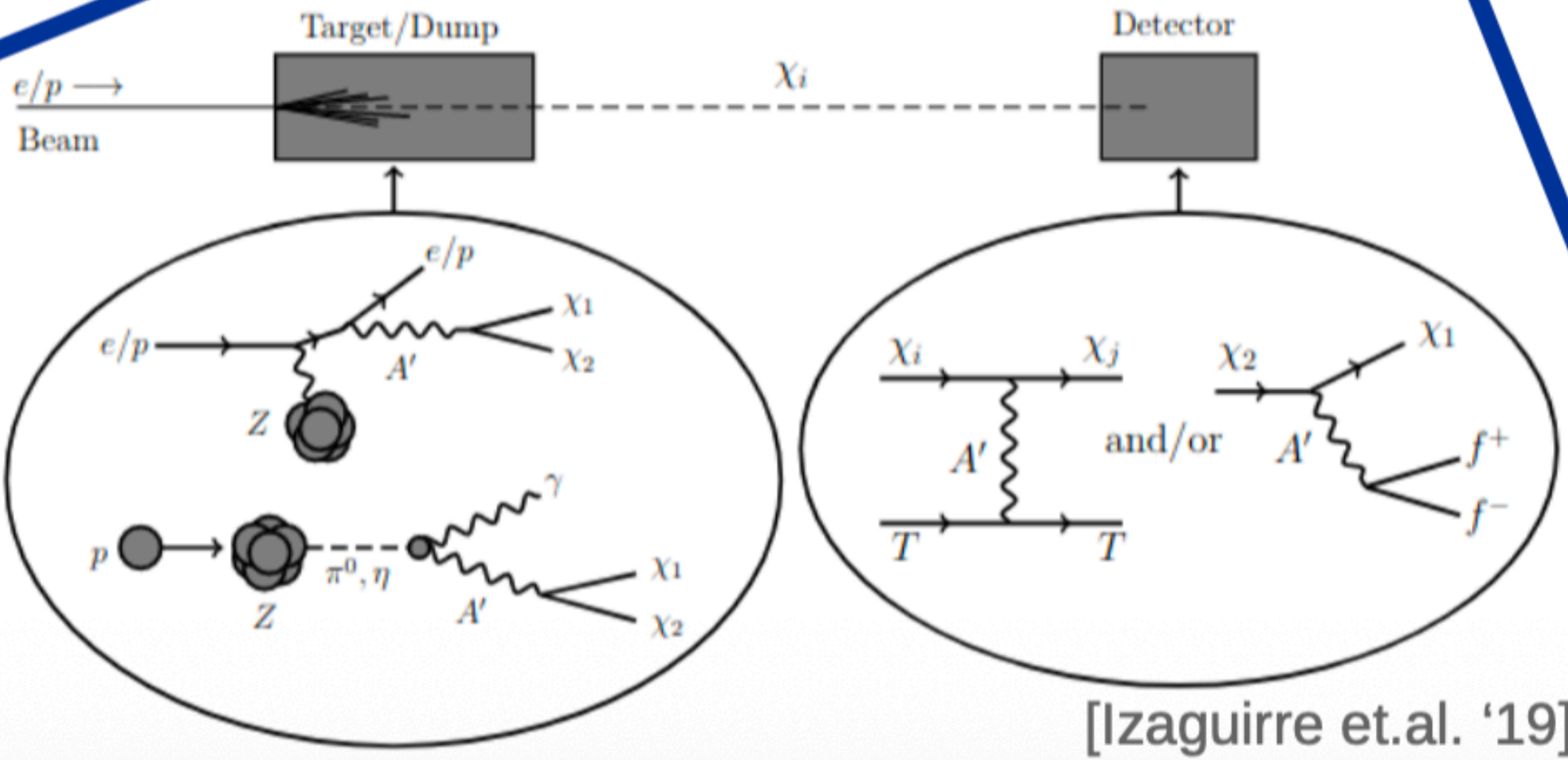


Inelastic DM detection

Colliders

Beam-dump

- Scattering
- Decay



[Izaguirre et.al. ‘19]

From arXiv:2005.01515

Massive Dark Photon

Limits on **visible decays** (dilepton resonances)

Current limits

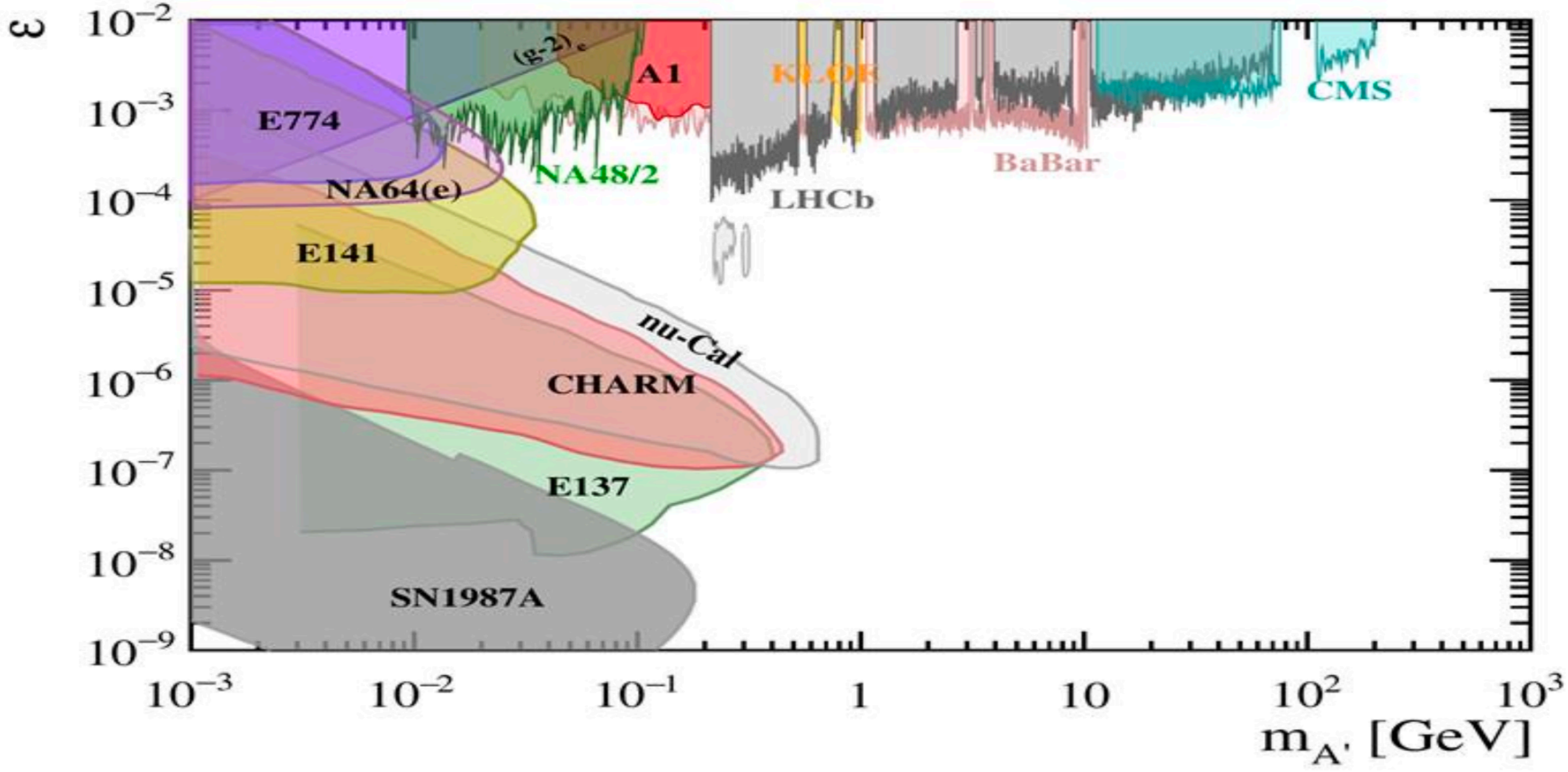


Figure 3.3: Existing limits on the massive dark photon for $m_{A'} > 1$ MeV from di-lepton searches at experiments at collider/fixed target (A1 [176], LHCb [177], CMS [178], BaBar [179], KLOE [180, 181, 182, 183], and NA48/2 [184]) and old beam dump: E774 [185], E141 [186], E137 [187, 188, 189]), ν-Cal [190, 191], and CHARM (from [192]. Bounds from supernovae [193] and $(g-2)_e$ [194] are also included.

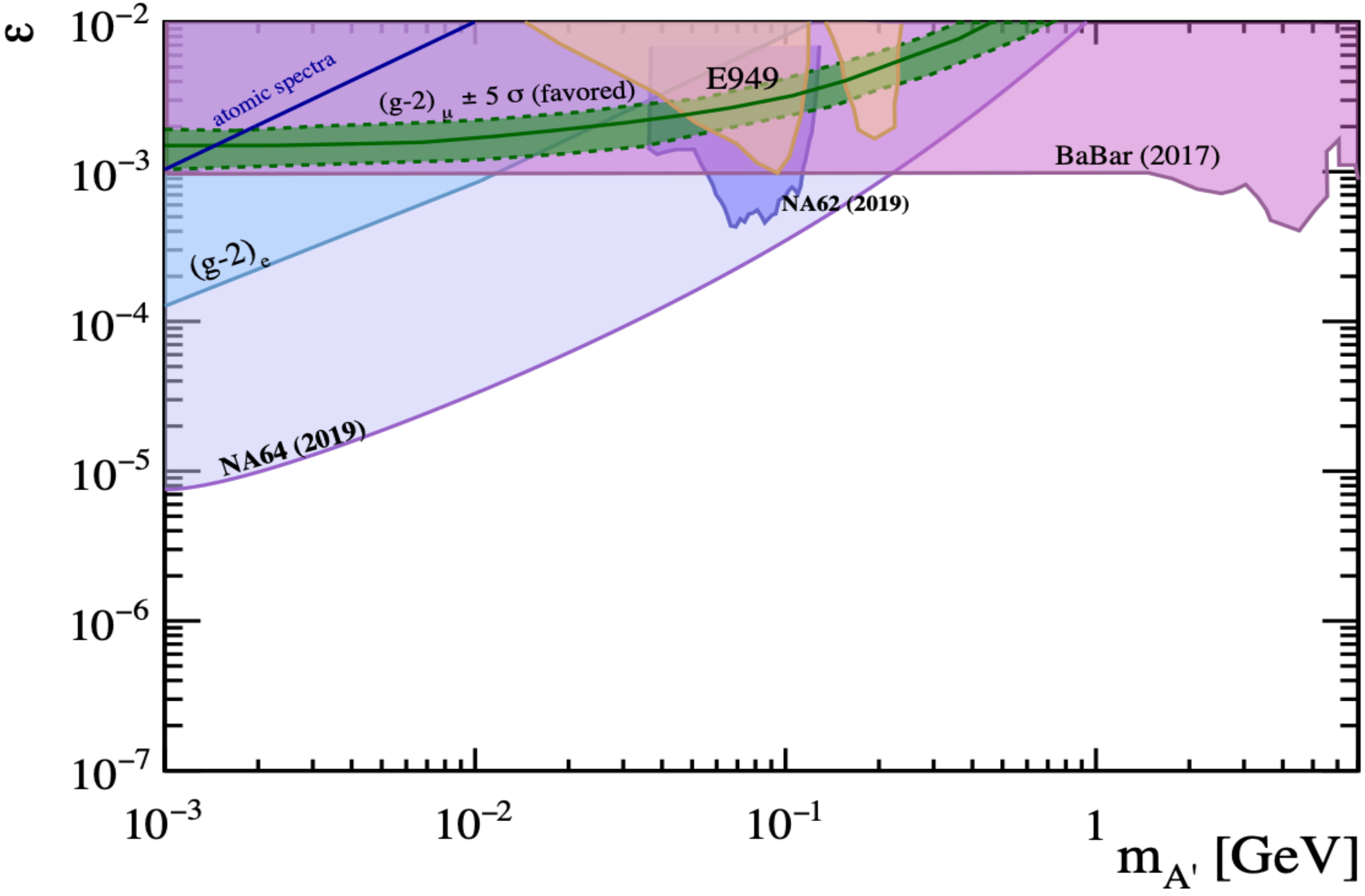
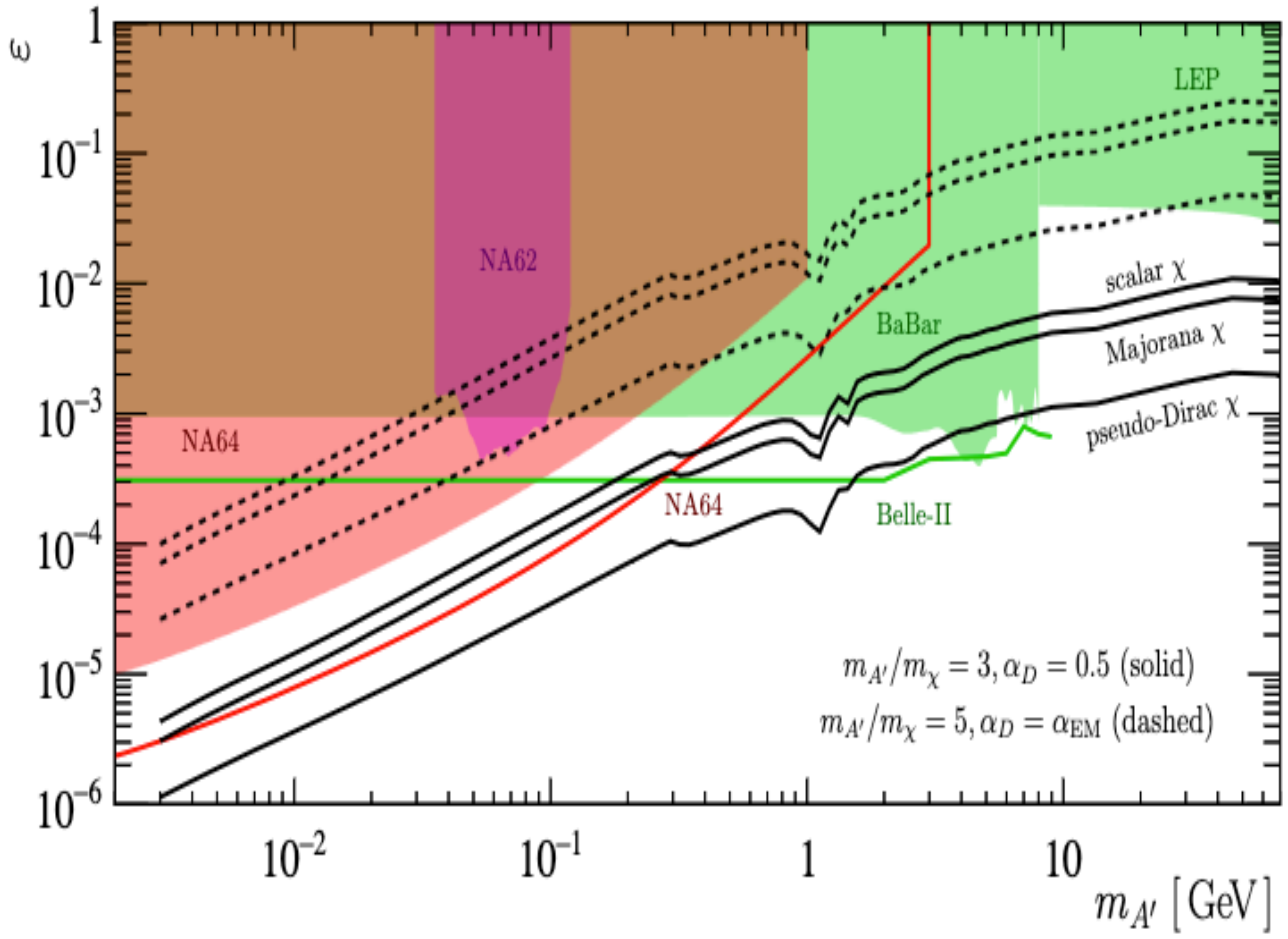
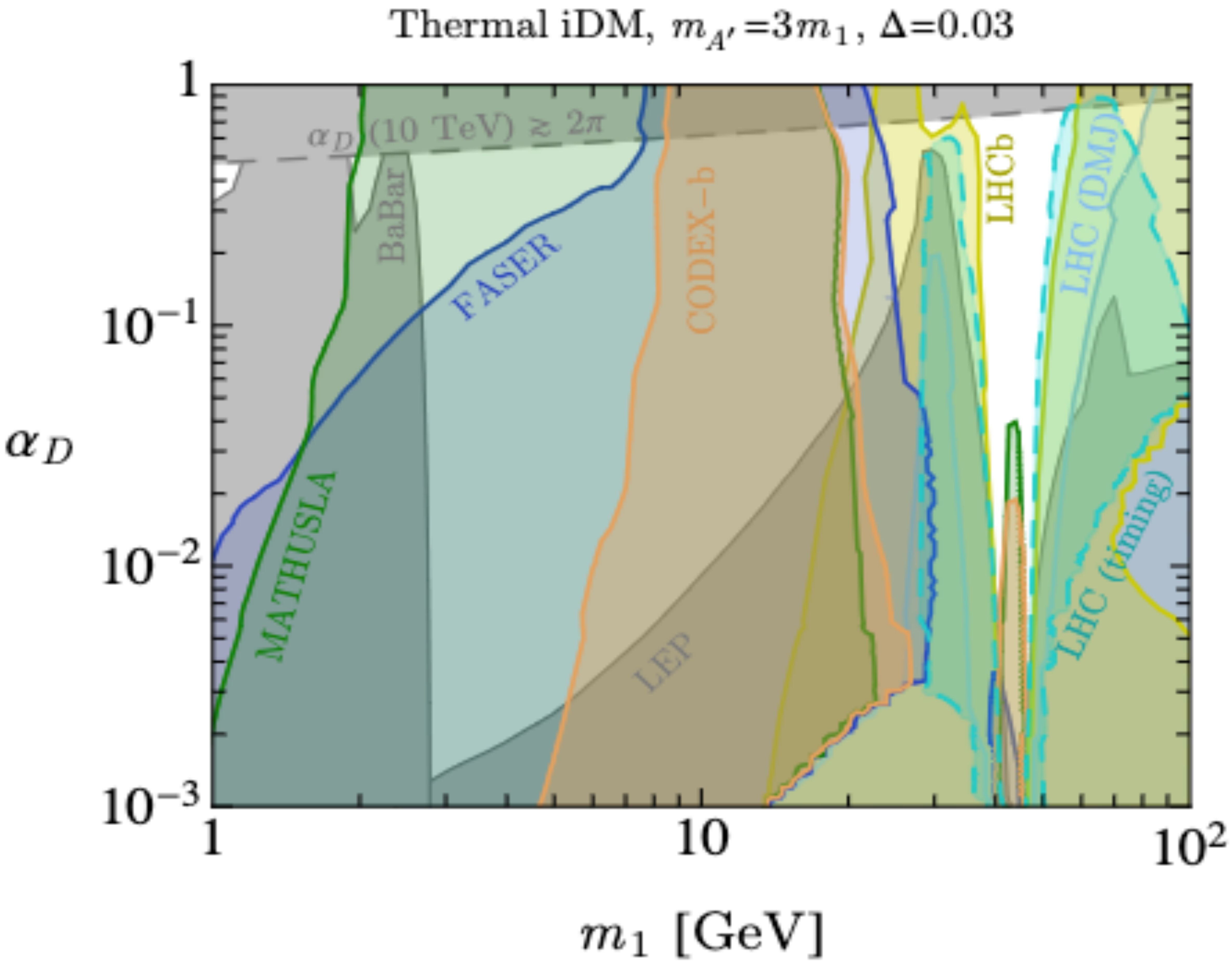


Figure 3.5: Existing limits for a massive dark photon going to invisible final states ($\alpha_D >> \alpha\varepsilon^2$). Existing limits from Kaon decay experiments (E787 [222], E949 [223], NA62 [224]), BaBar [225], and NA64(e) [226]. The constraints from $(g-2)_\mu$ [115] and $(g-2)_e$ are also shown.

arXiv: 2104.10280



arXiv: 1810.01879

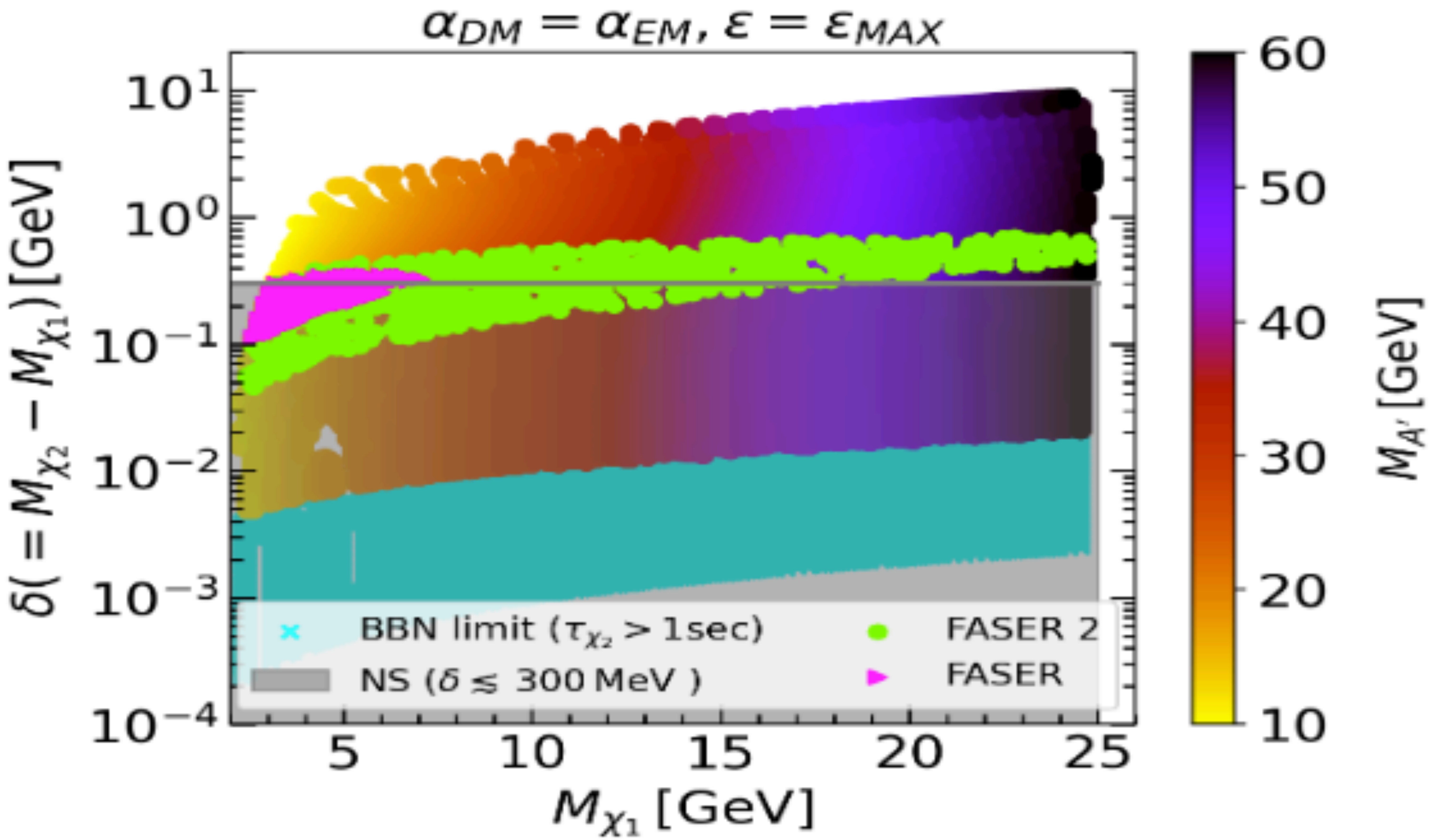


Previous studies demonstrates that $\alpha_D = \alpha_{EM}$ **is phenomenologically disfavored.**

Results

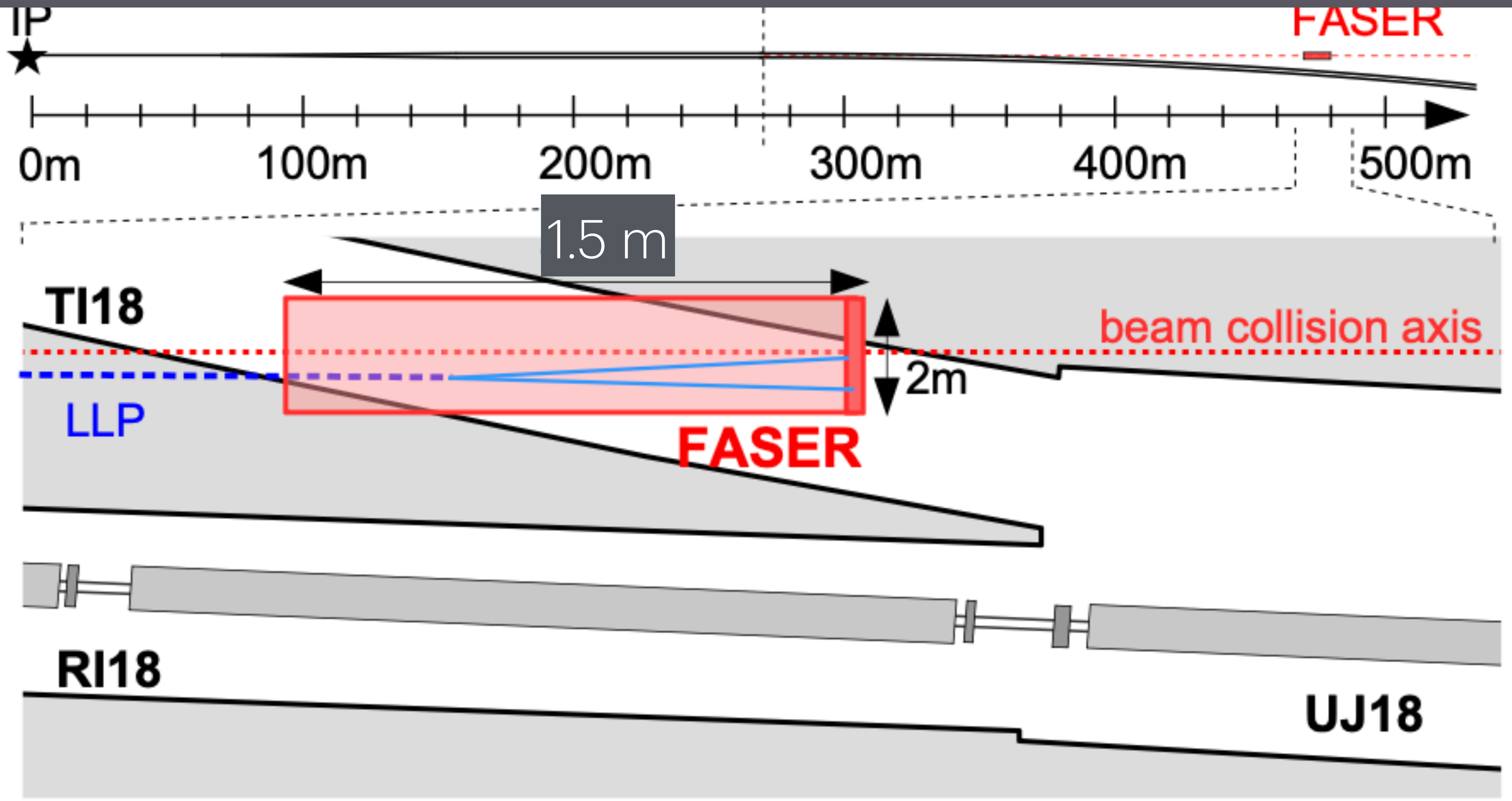
Parameter	Scanned range
M_{χ_1} [GeV]	[1 , 30]
δ [GeV]	$[10^{-4}$, 20]
$M_{A'}$ [GeV]	[10 , 60]
ϵ	$\epsilon_{\max}(M_{A'})$
α_D	α_{EM}

Max allowed by LEP



Contrary to suggestions from previous studies, we demonstrates that $\alpha_D = \alpha_{EM}$ **is not phenomenologically disfavored.**

FASER (ForwArd Search ExpeRiment)



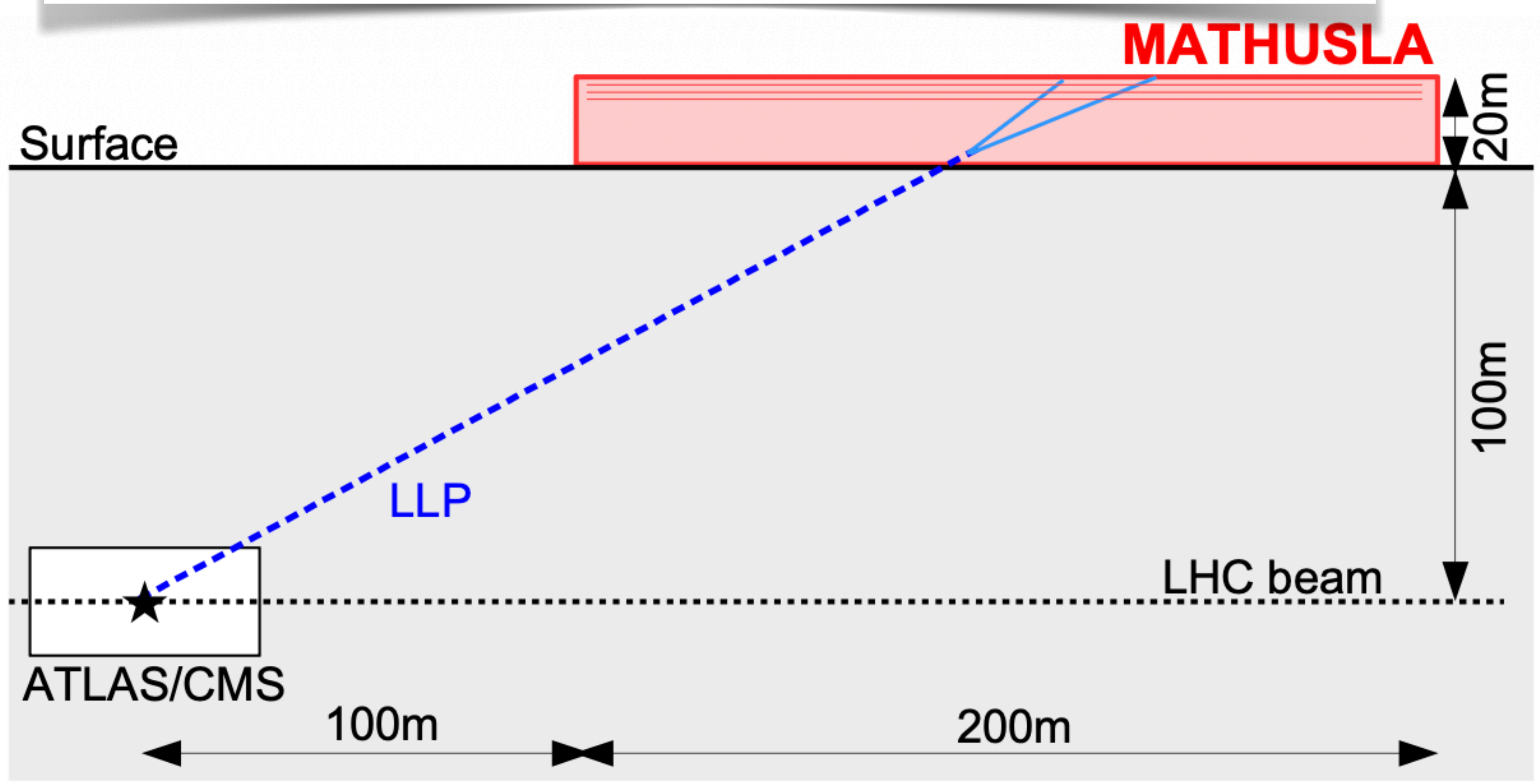
✤ **FASER** is a dedicated forward experiment at the LHC, located O(100) **m downstream of the ATLAS interaction point (IP1)**

✤ It searches for **light, weakly interacting long-lived particles (LLPs)** produced in proton-proton collisions that travel along the beam collision axis.

✤ Provides a **low-background and cost-effective** approach to exploring physics beyond the Standard Model.

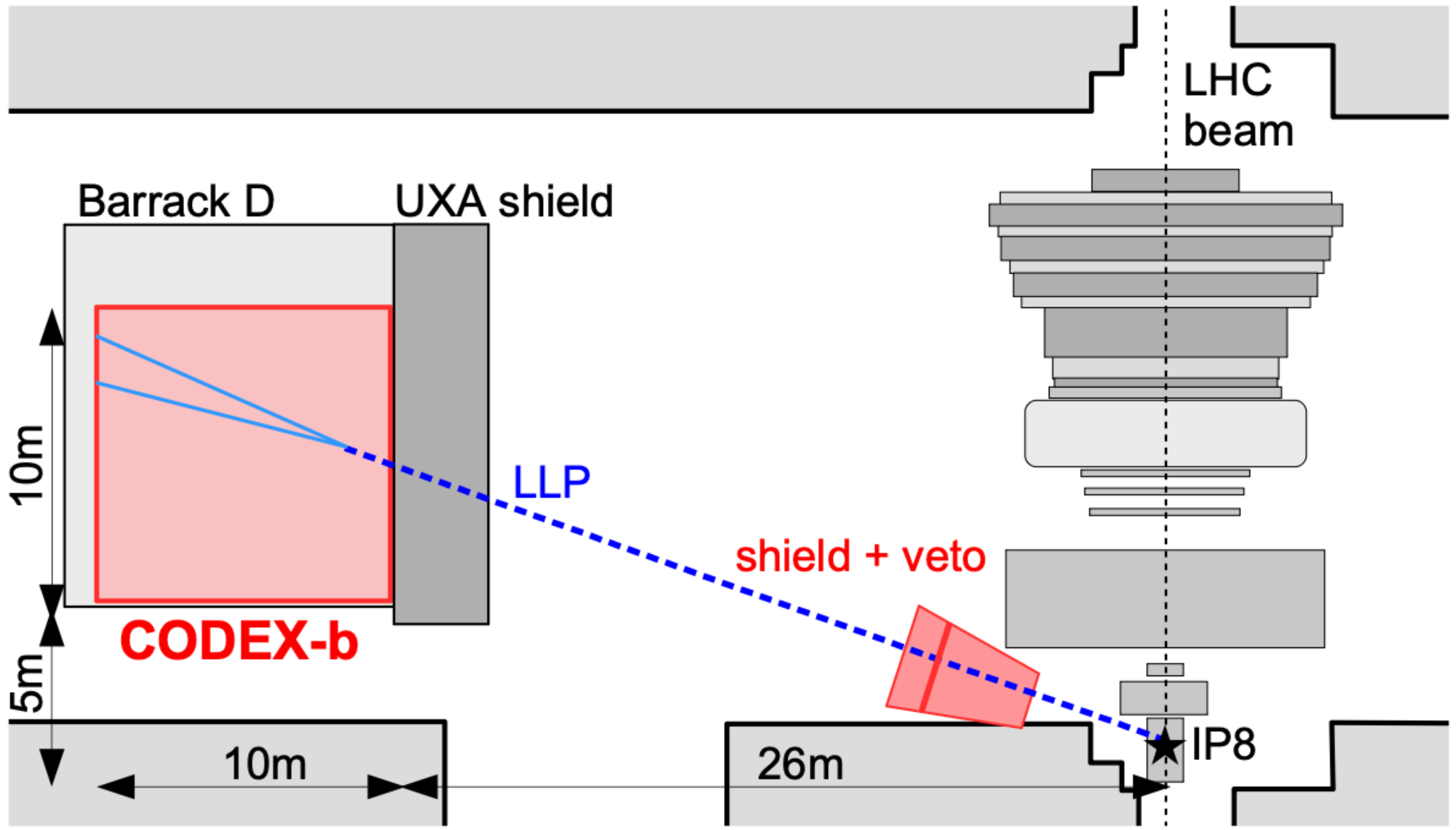
arXiv: 1810.01879

MAssive Timing Hodoscope for Ultra-Stable neutral pArticles (MATHUSLA)



- Large surface detector proposed above the LHC for **long-lived particle (LLP)** searches.
- Detects **displaced decays** in a nearly background-free environment.
- Extends sensitivity to **very long lifetimes**, complementing **ATLAS, CMS, and FASER**.

CODEX-b (COmpact Detector for EXotics at LHCb)



- CODEX-b is a proposed long-lived particle (LLP) detector located in a shielded cavern ~25 m from the LHCb interaction point (IP8).
- It searches for **neutral LLPs** that travel through the shielding and decay inside a **10 m × 10 m × 10 m** instrumented decay volume, providing a **very low-background environment**.
- Shielding suppresses Standard Model backgrounds, enabling a low-background search for long-lived particle decays.

1. **The transverse momentum of χ2 originates mainly from the decay of the dark photon and therefore peaks around :** $p_{T,\chi_2} \simeq \dfrac{\sqrt{m_{A'}^2 - 4m_1^2}}{2}$

2. **Angle with respect to the beam axis:** $\theta_{\chi_2} \simeq \dfrac{\sqrt{m_{A'}^2 - 4m_1^2}}{2\,p_{\chi_2}}$

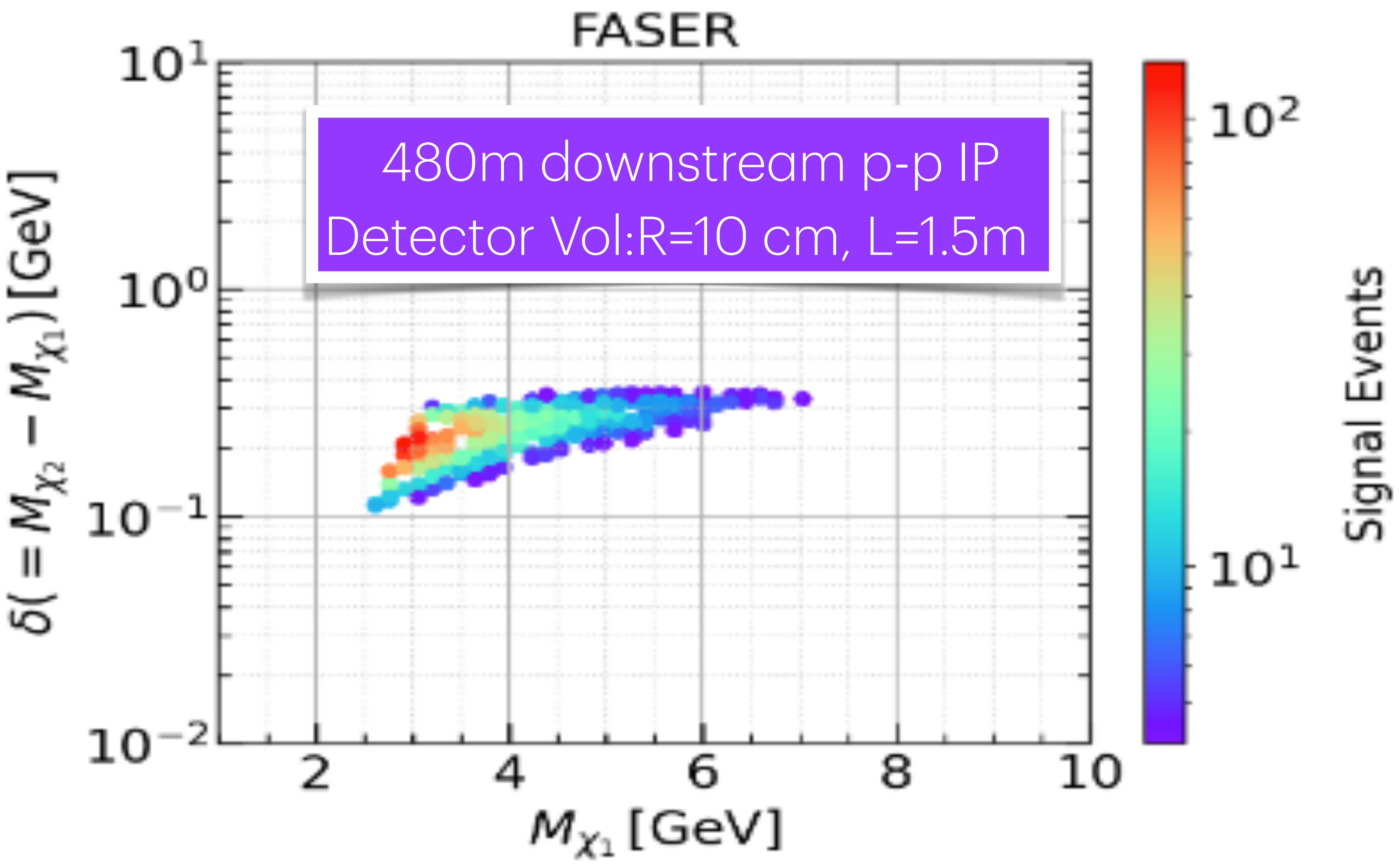
LLPs reaching FASER are highly boosted and produced at very small angles (≲ few mrad), making forward detectors particularly sensitive to long-lived particles.

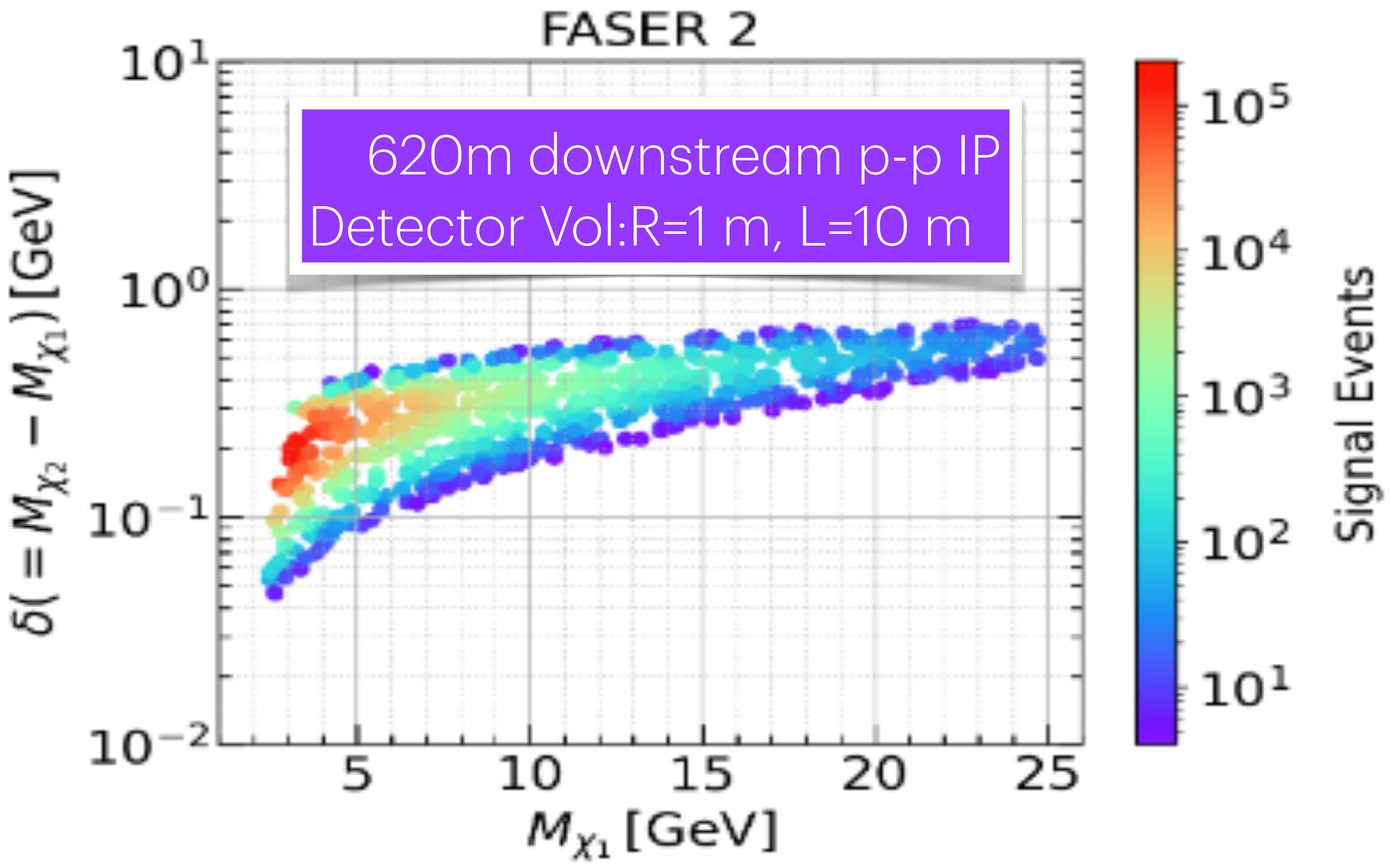
Collider Signal

$$pp \to \chi_1\chi_2;\ \chi_2 \to \chi A'^* \to \chi_1 f\bar{f}$$

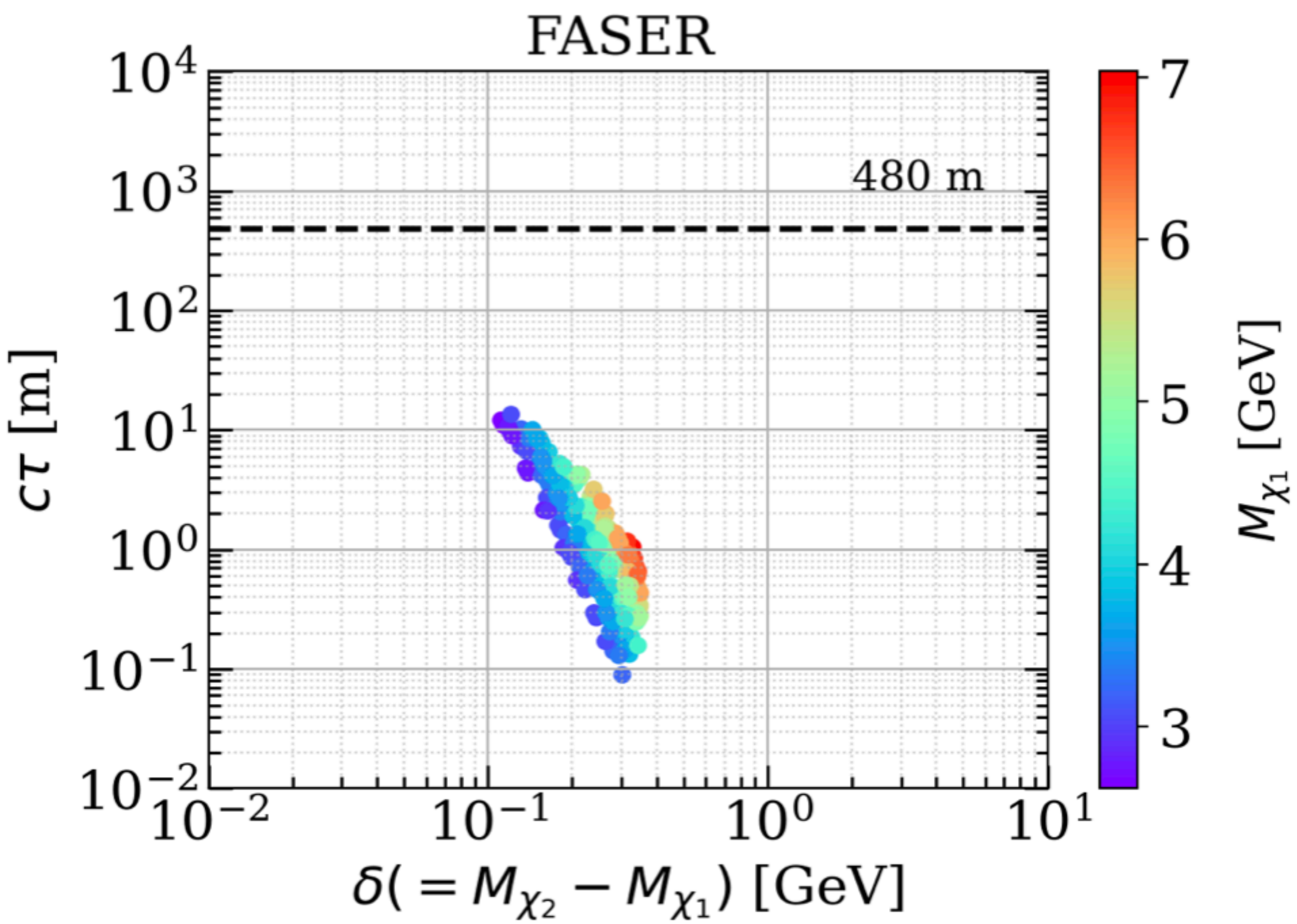
$$\mathcal{N}_{\rm signal} = \mathcal{L}\sigma P_{\rm decay}\epsilon_{\rm det}$$

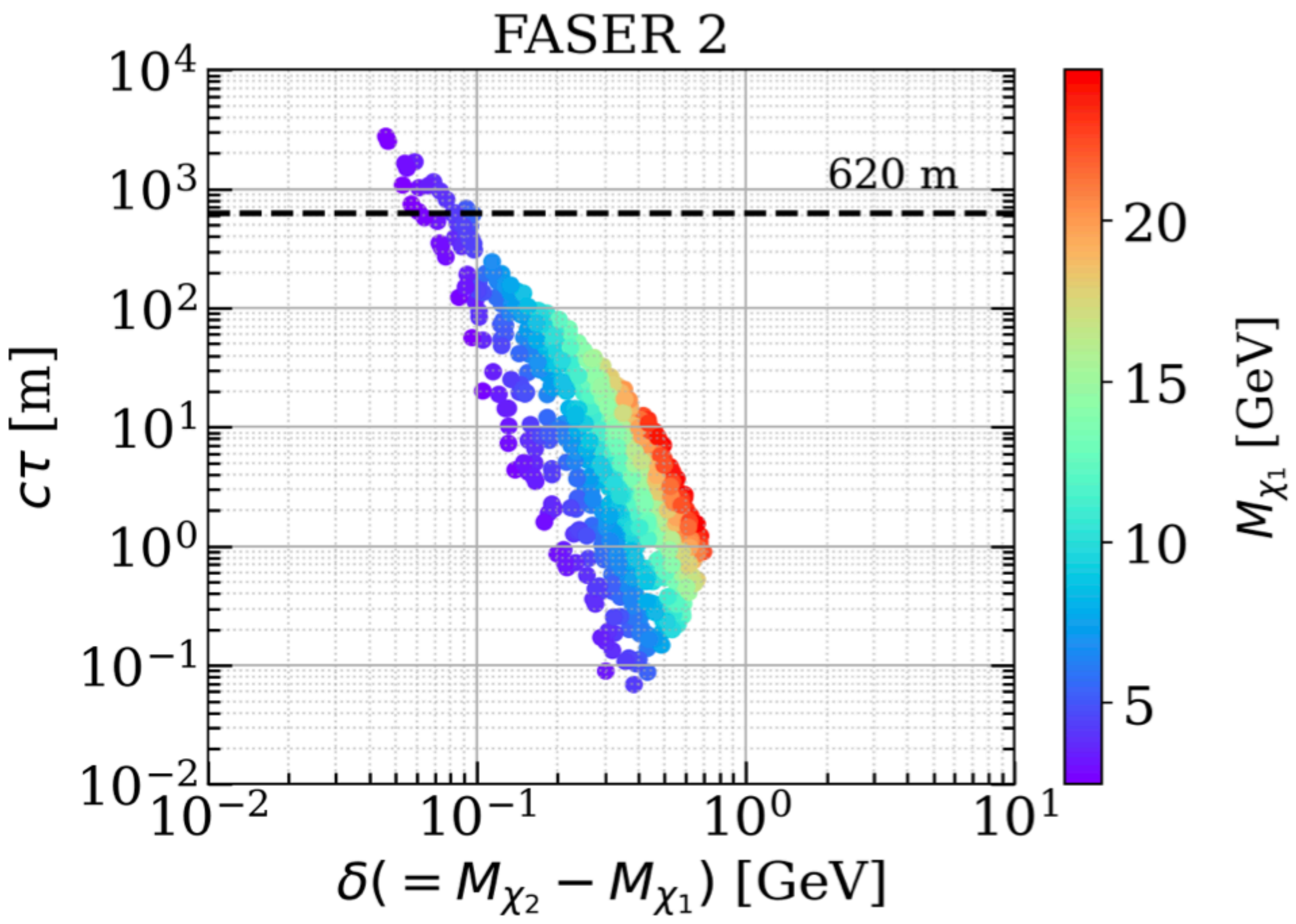
$E_{vis} > 100\,\mathrm{GeV}$





Collider Signal





1. FASER $c\tau$ is smaller than the detector distance, but the large longitudinal boost allows the χ_2 to decay within the detector volume.
2. Even for $c\tau$ larger than the detector distance, FASER 2 retains sensitivity owing to production cross sections large enough

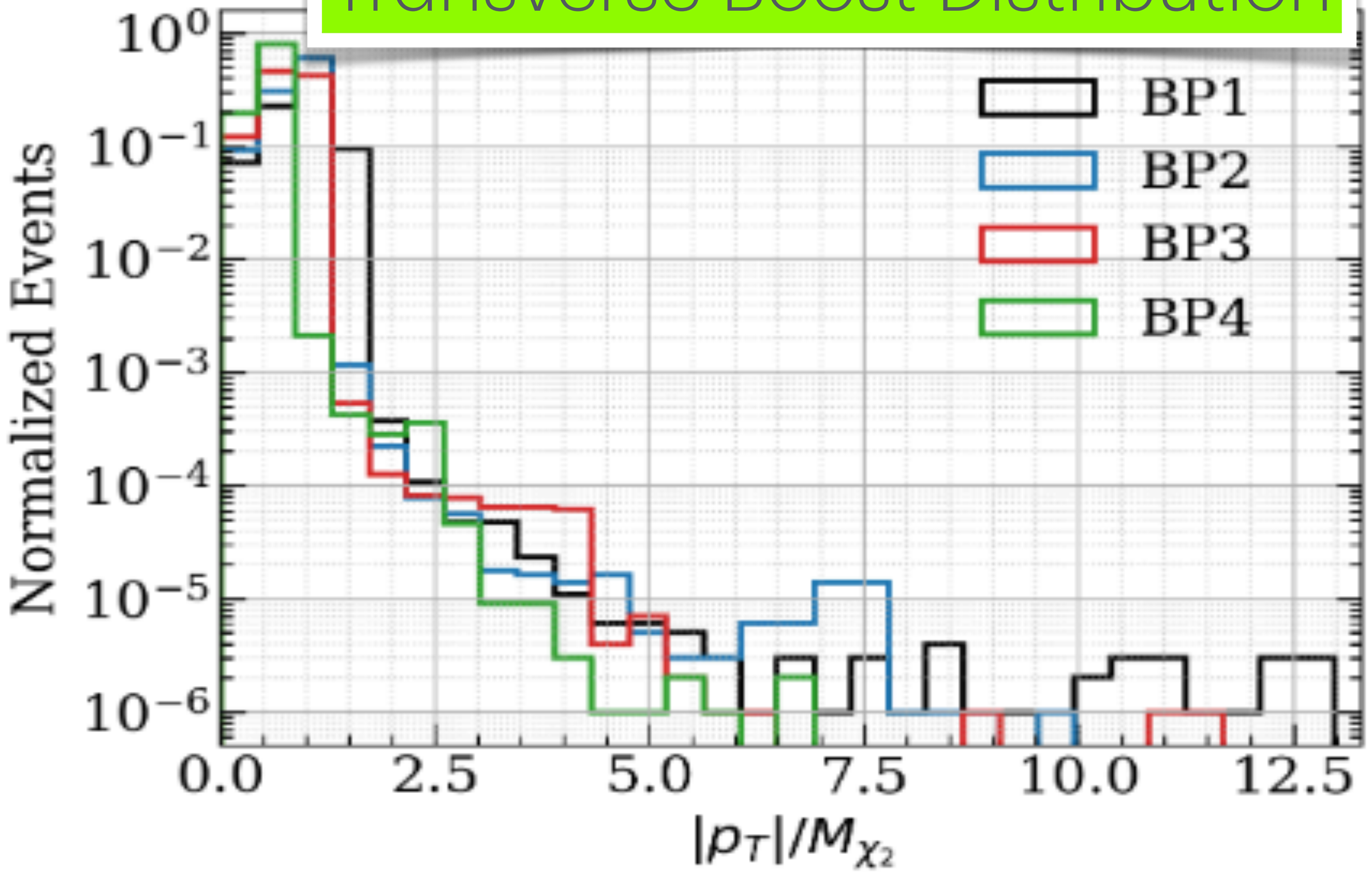
Benchmark Points Results

BP1: $M_{\chi_1} = 3.35$ GeV, $\delta = 0.21$ GeV, $M_{A'} = 11.60$ GeV,
BP2: $M_{\chi_1} = 5.56$ GeV, $\delta = 0.32$ GeV, $M_{A'} = 17.62$ GeV,
BP3: $M_{\chi_1} = 10.71$ GeV, $\delta = 0.27$ GeV, $M_{A'} = 30.45$ GeV,
BP4: $M_{\chi_1} = 16.15$ GeV, $\delta = 0.56$ GeV, $M_{A'} = 41.68$ GeV.

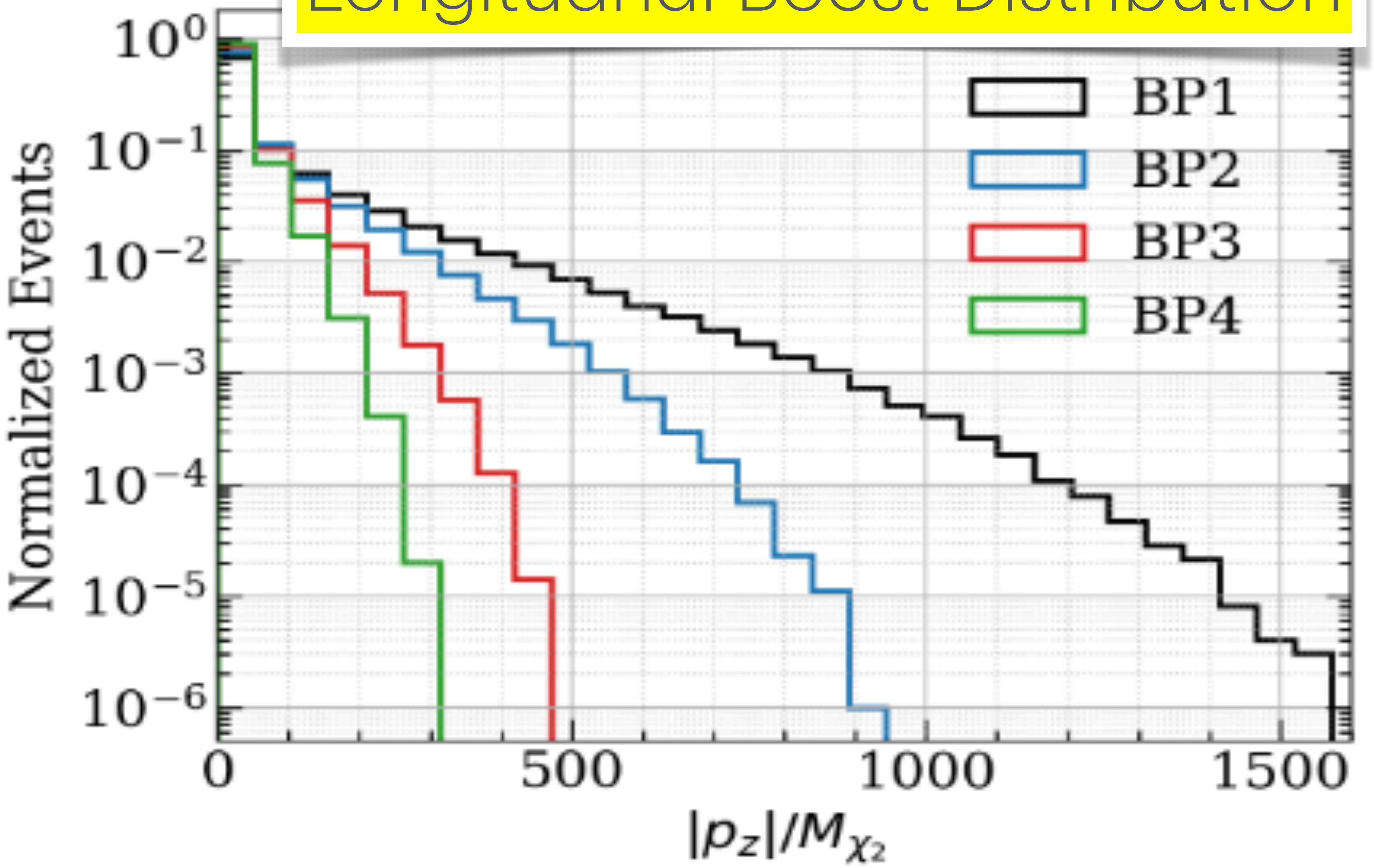
Decay length in LHC frame: $L_{\chi_2} = \beta\gamma c\tau_{\chi_2}$

$$\beta\gamma = \frac{|p|}{M_{\chi_2}}$$

Transverse Boost Distribution



Longitudnal Boost Distribution



BP1: $c\tau = 0.94$ m, $\sigma = 1332$ pb, signal events = 64 (138474),
BP2: $c\tau = 0.57$ m, $\sigma = 549$ pb, signal events = 9 (14643),
BP3: $c\tau = 11.32$ m, $\sigma = 139$ pb, signal events = 0 (228),
BP4: $c\tau = 0.86$ m, $\sigma = 75$ pb, signal events = 0 (69).

signal events in FASER (FASER 2)

Astrophysical Objects Can Capture Dark Matter

- As astrophysical objects move within the DM halo, they sweep DM particles along their path.
- Gravitational forces accelerate DM particles toward these objects.
- If the particles lose enough kinetic energy, they become captured.
- The captured DM particles can contribute to neutrino emission, leading to the formation of black holes within the objects, and increasing their temperatures.
- The temperature increase occurs through the deposition of DM kinetic energy into the objects and via DM annihilation.
- Neutron stars could accelerate DM particles to relativistic velocities. They could deposit their kinetic energy into neutron stars and heat them up.
- Neutron stars are an ideal target for studying inelastic DM because they can accelerate infalling DM to relativistic velocities.

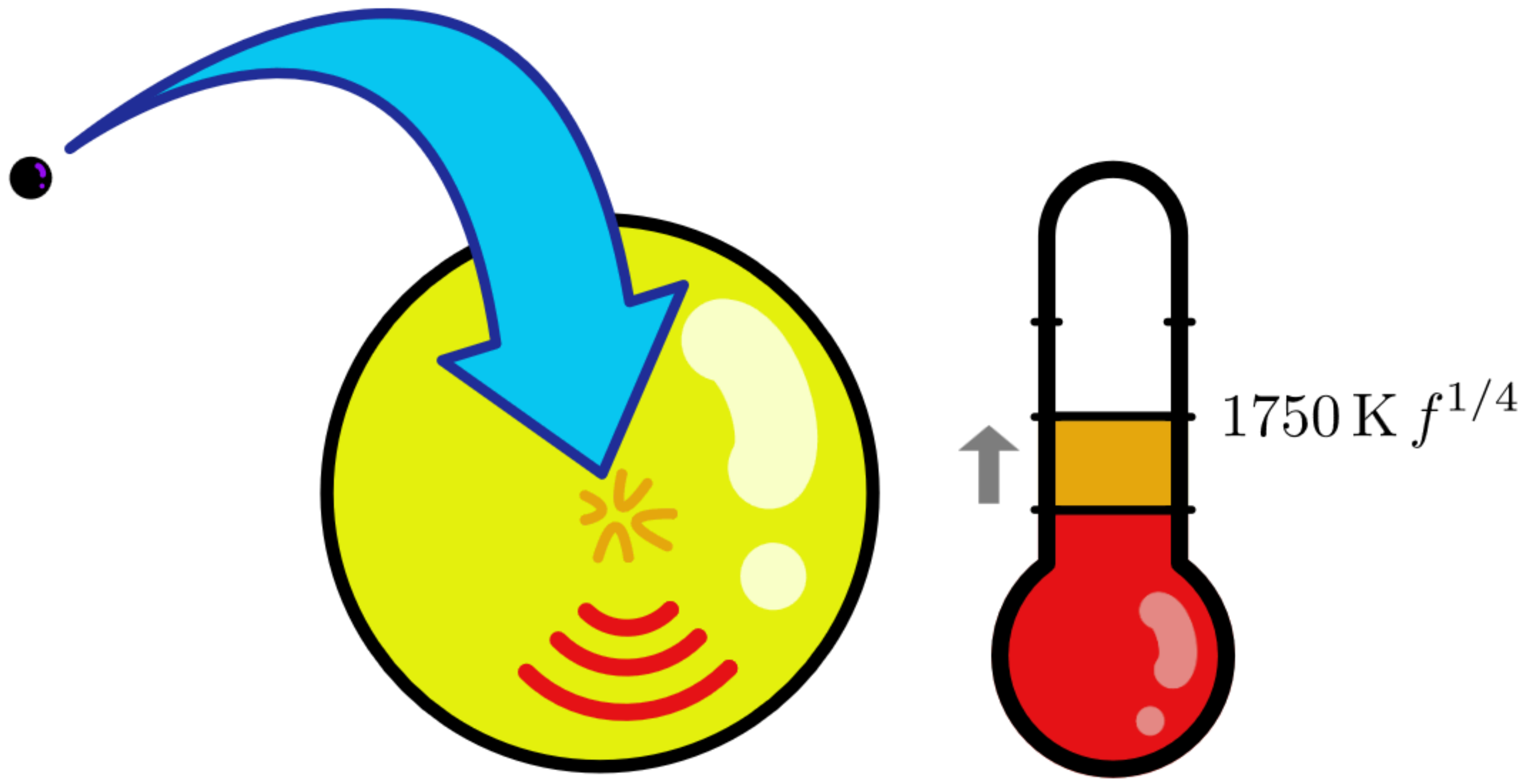
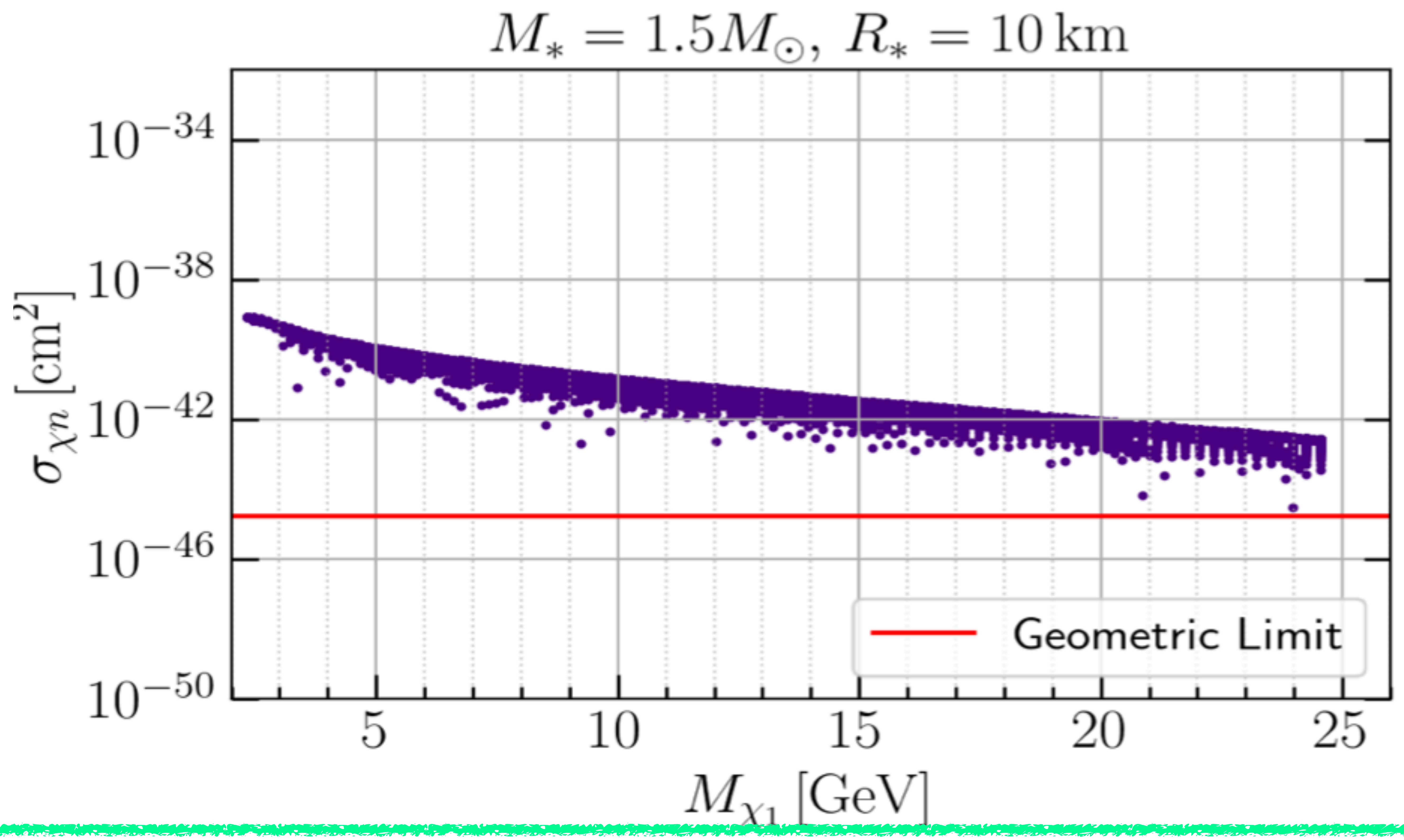


Figure 1. Ambient dark matter is accelerated as it approaches a neutron star. This flux of kinetic energy is deposited into the star as heat, predicting a warmer neutron star temperature than in the absence of a dark matter–Standard Model interaction.



Geometric Capture: NS acts as a vacuum clean

Summary

- In this work we consider dark photon A' portal between the Dark Sector and the SM.

- Contrary to suggestions from previous studies, we demonstrates that $\alpha_D = \alpha_{EM}$ **is not phenomenologically disfavored.**

- We also parameter space accessible via accelerator LLP searches partially overlaps with the region probed by χ_1 capture in neutron stars.

Any Questions ??