Future gamma-ray searches for light dark matter

Maíra Dutra

NASA Goddard Space Flight Center

mdutrava@mail.nasa.gov

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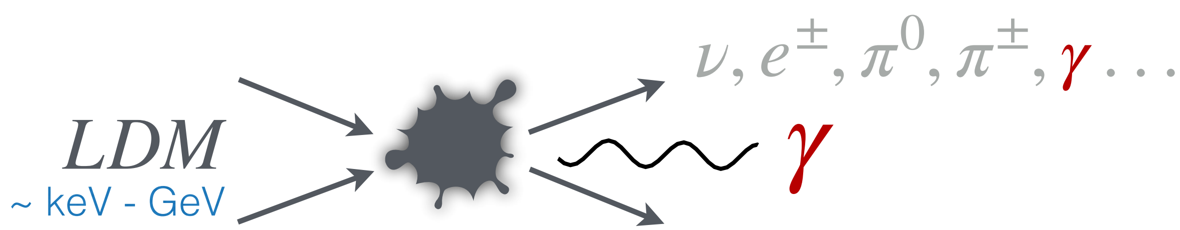
July 28th - July 31st
Carleton University
Ottawa, Canada

NASA Postdoctoral Program

MeV gamma rays from light dark matter



We can probe the masses of a light dark sector with MeV γ rays

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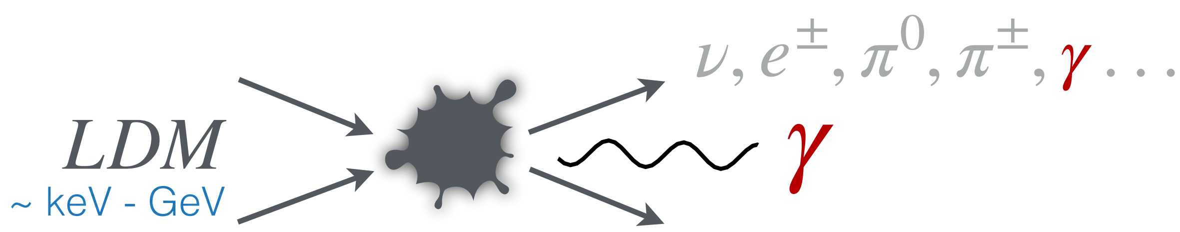

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- γ-ray lines at $E_\gamma = m_\chi(1 - m_N^2/(4m_\chi^2))$ from $\chi\bar{\chi} \to \gamma N$ (N: neutral state)
- γ-ray boxes w/ width $\Delta E_\gamma \approx \sqrt{m_\chi^2 - m_N^2}$ from N radiative decays
- Continuum emission from charged states: sharp cutoff at $E_\gamma = m_\chi$

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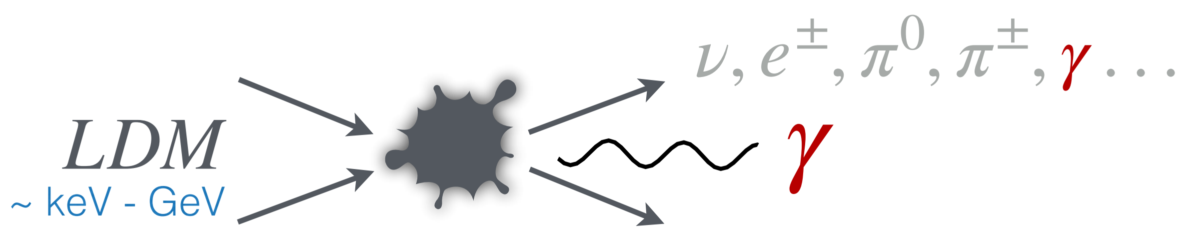

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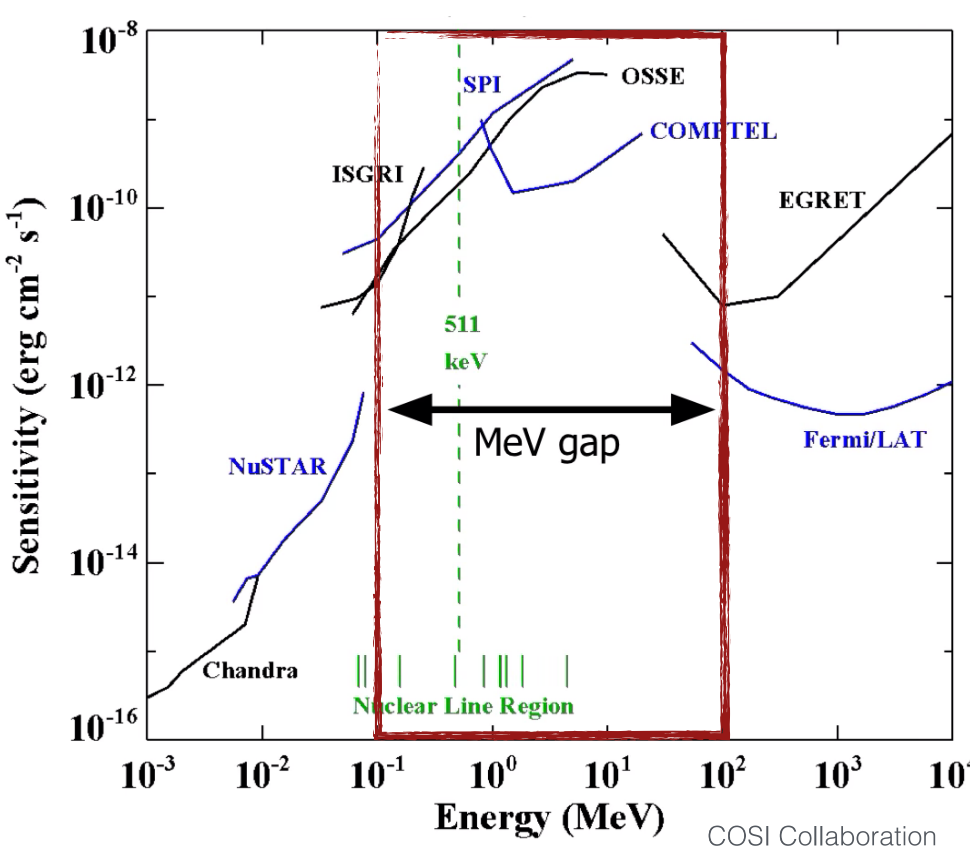

COSI Collaboration

COSI: upcoming MeV γ-ray telescope

- NASA Small Explorer satellite with a scheduled **launch in 2027**
- Compton telescope observing γ rays in the **0.2 - 5 MeV energy range**
- High-resolution Ge detectors: excellent **narrow-line sensitivity**

Some proposed γ-ray telescopes

AMEGO-X | GECCO | newASTROGAM | GRAMS

$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

Remnant Z_2
$\Rightarrow$ stable DM

$\langle \Phi_s \rangle_0 = \frac{v_s}{\sqrt{2}} \Rightarrow m_{Z'}, m_\chi, m_\nu \neq 0$

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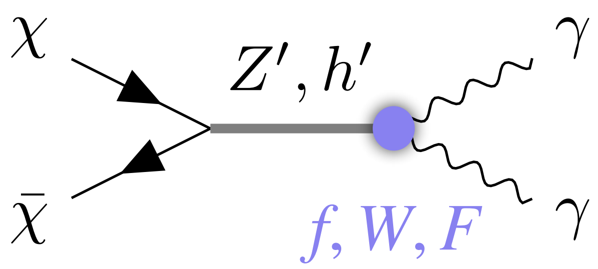
$\langle \Phi \rangle_0 = \frac{v}{\sqrt{2}} \Rightarrow m_Z, m_W, m_{f\pm} \neq 0$

$SU(3)_c \times U(1)_{em}$

A self-consistent vector-scalar portal for MeV γ-ray signals



γ-ray line

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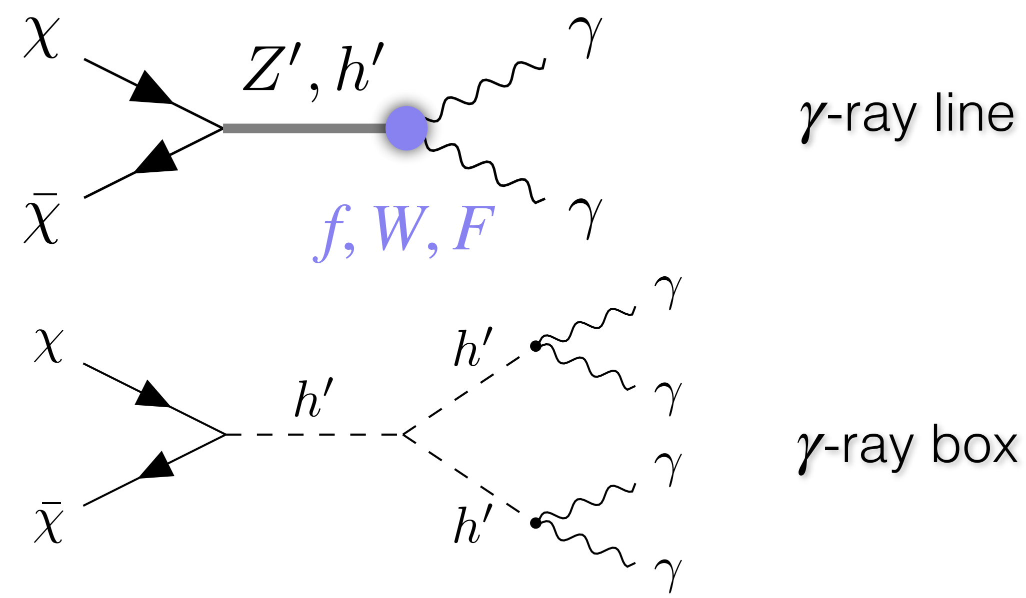

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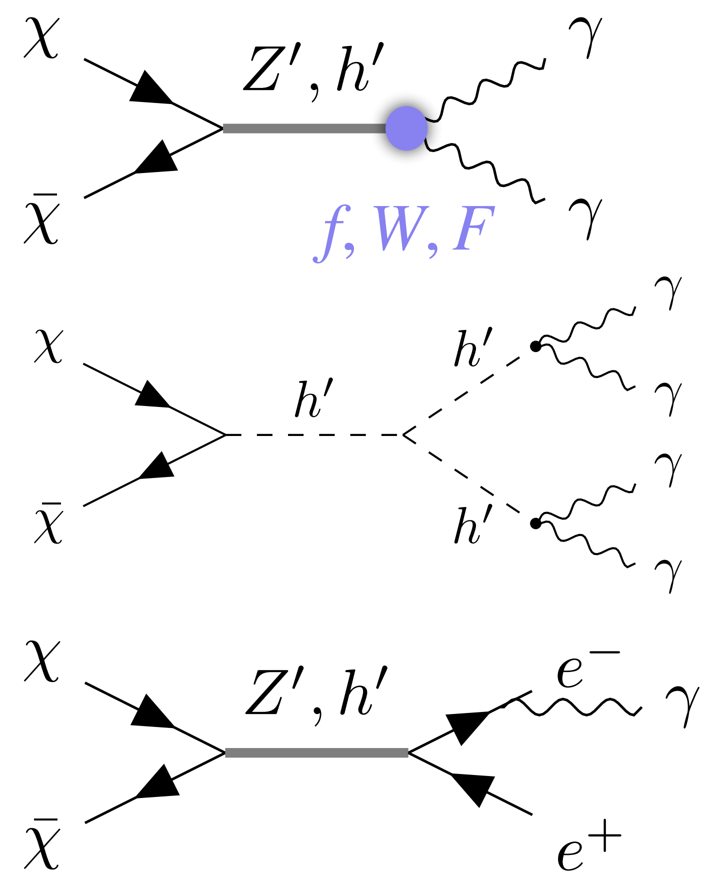

γ-ray line

γ-ray box

γ-ray continuum

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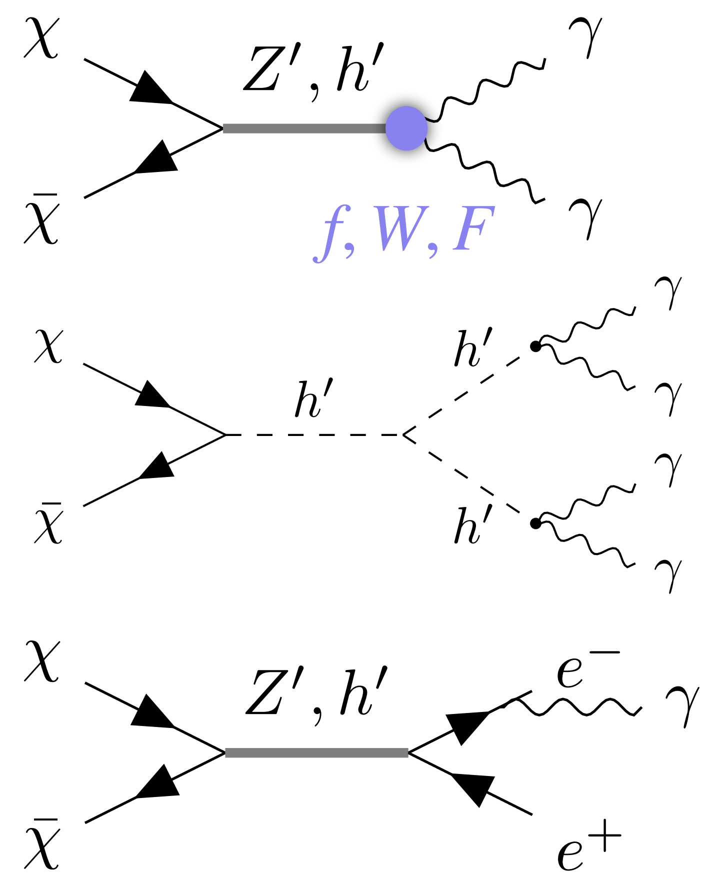


γ-ray line

γ-ray box

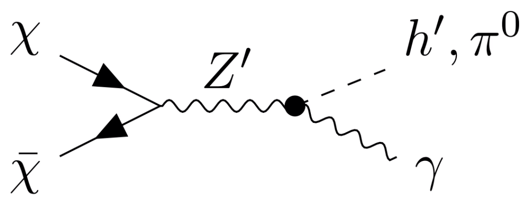
γ-ray continuum

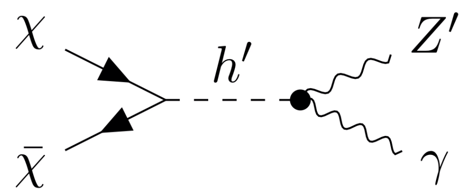
The same symmetry-breaking sector sets the DM mass and stability, and can generate strong γ-ray lines

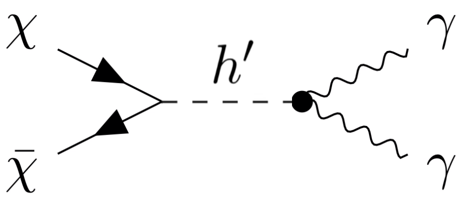
Constraining light dark matter in vector-scalar portals with COSI and AMEGO-X
M. Dutra, C. Siqueira, T. Venters
arXiv:**2508.15891**

The role of axial Z' couplings

Negligible γ-ray line cross sections:







p-wave

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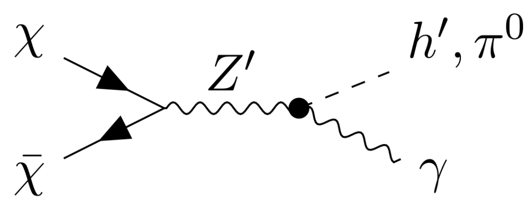
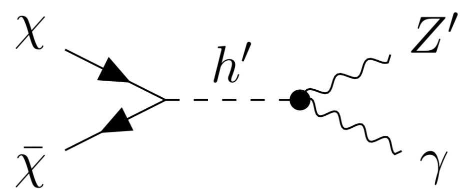
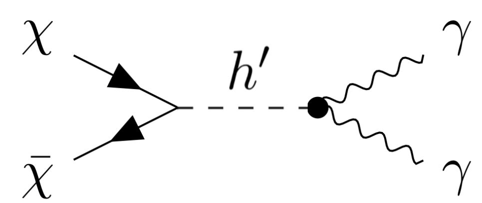


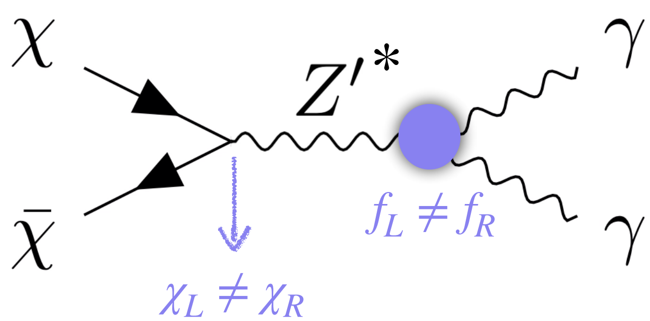




p-wave

Axial Z' couplings to both DM and SM fermions: sizable s-wave line

$A_\chi \equiv (X_{\chi_L} - X_{\chi_R})/2 \neq 0$



s-wave

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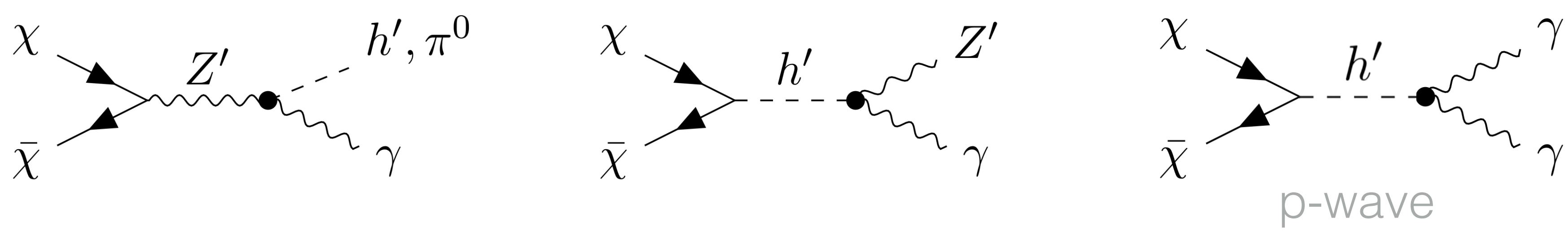

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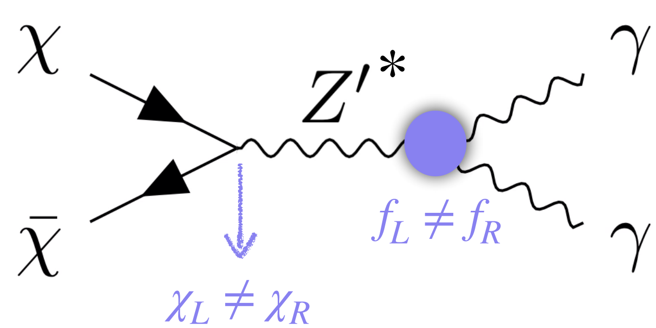

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s-wave

We consider two benchmark models:

- $U(1)_{B-L}$: vector couplings to SM fermions; anomaly-free w/ 3 RHNs; negligible lines far from h' resonances
- $U(1)_A$: low-energy axial benchmark; anomaly-free w/ heavy chiral fermions; sizable lines independent of scalar mixing

Axial couplings enable sizable present-day $\chi\bar{\chi} \to \gamma\gamma$

The role of the scalar portal

$A_\chi \neq 0$ forbids a gauge-invariant bare Dirac mass for χ

- In the minimal completion, χ acquires mass through a Yukawa coupling to the same singlet scalar whose VEV generates $m_{Z'}$

$$m_\chi \sim y_\chi \, v_s \ll v$$
$$m_{Z'} \sim X_{\Phi_s} \, g_X \, v_s \ll v$$

$$m_{h'} \sim \sqrt{\lambda_s} \, v_s$$

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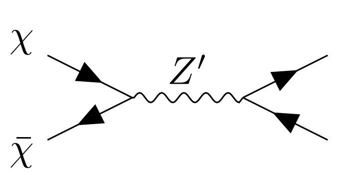
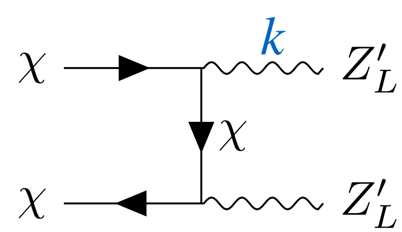
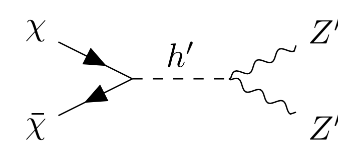
For $A_\chi \neq 0$, amplitudes involving longitudinal Z' bosons grow with energy

- Perturbative unitarity relates m_χ and $m_{Z'}$
- Scalar exchange cancels the high-energy growth and restores perturbative unitarity, so $m_{h'}$ is related to m_χ and $m_{Z'}$ $\Rightarrow$ light scalar for sizable couplings relevant for γ-ray phenomenology



@ $k \to \infty$ $\Rightarrow$ $\dfrac{m_{Z'}}{m_\chi} \gtrsim \sqrt{\dfrac{2}{\pi}}\, c_\xi g_X A_\chi$





@ $k \gg m_{Z'}$ $\Rightarrow$ $m_{h'} < \dfrac{\pi}{c_\xi^2 g_X^2 A_\chi^2} \dfrac{m_{Z'}^2}{m_\chi}$

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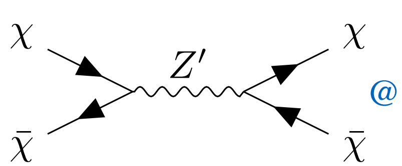

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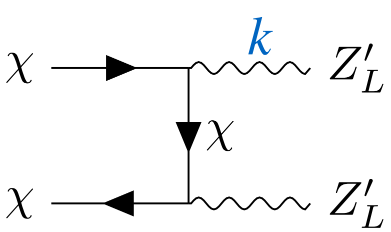

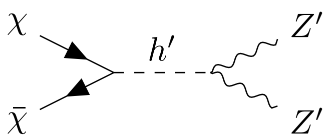

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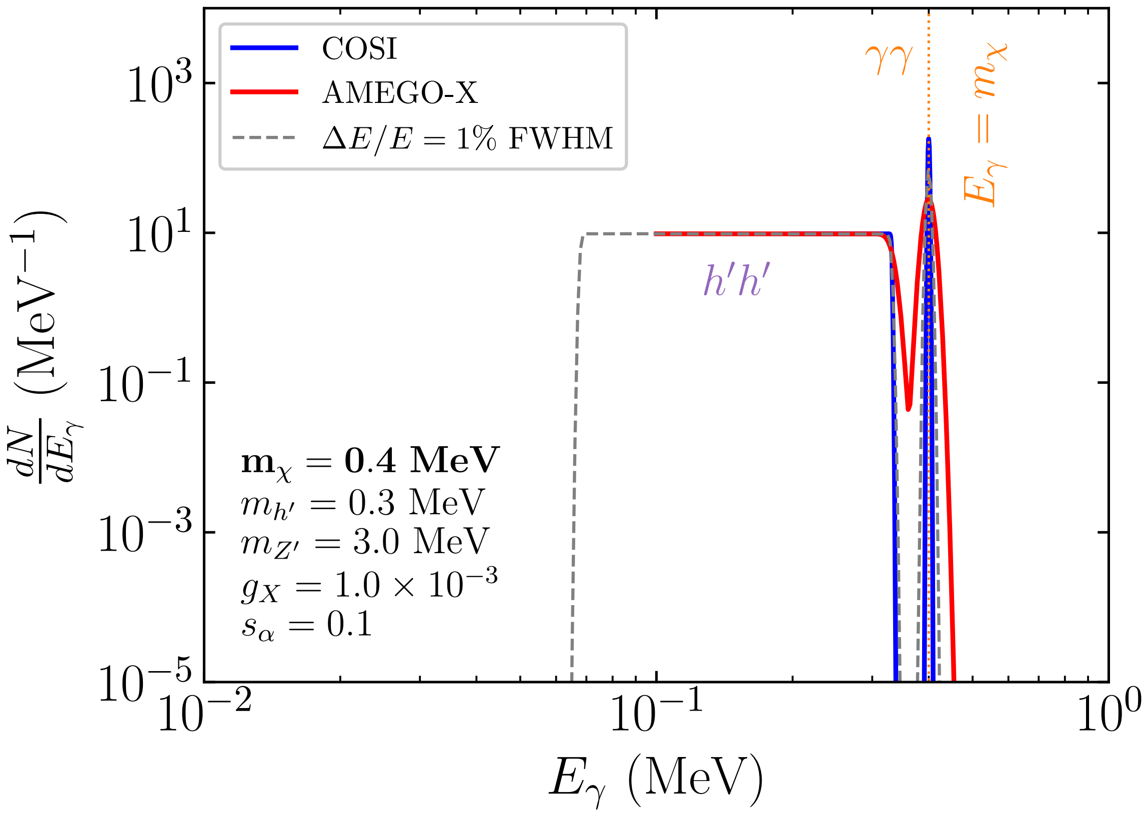
A minimal renormalizable framework with sizable MeV γ-ray lines contains light dark sector particles χ, Z', and h'

Gamma-ray spectroscopy of a light dark sector



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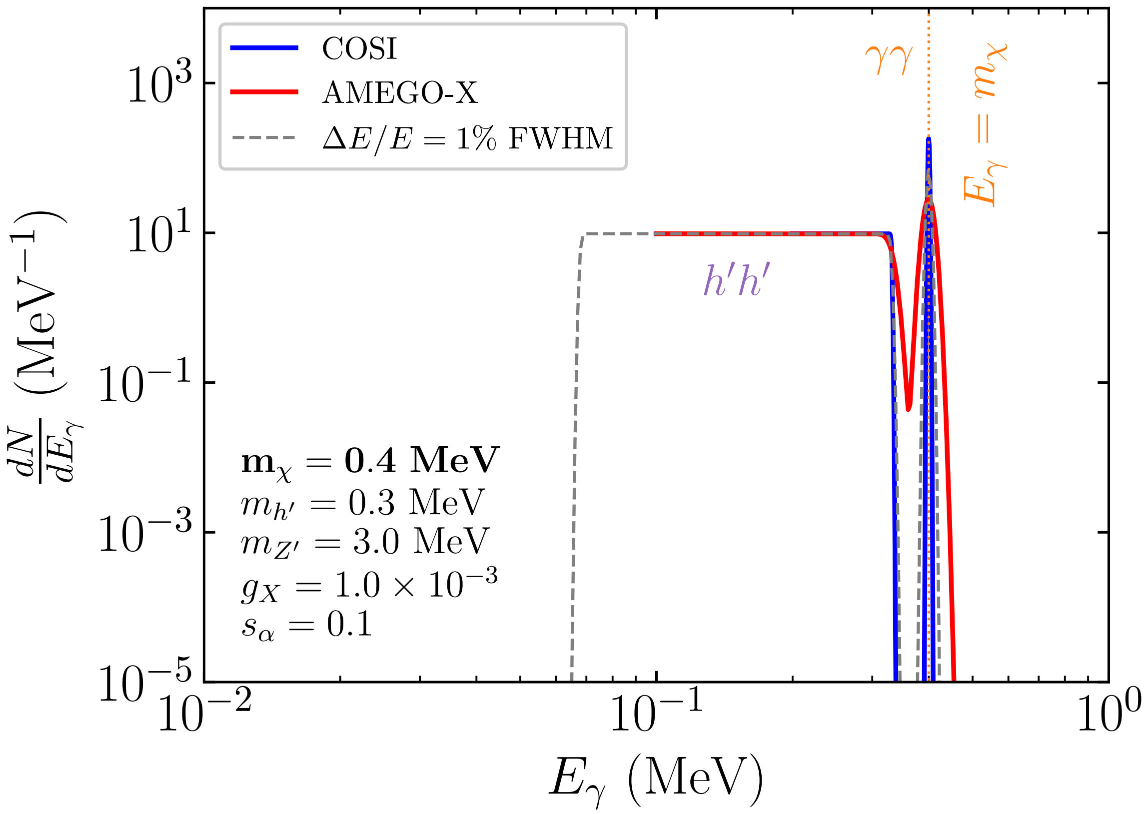

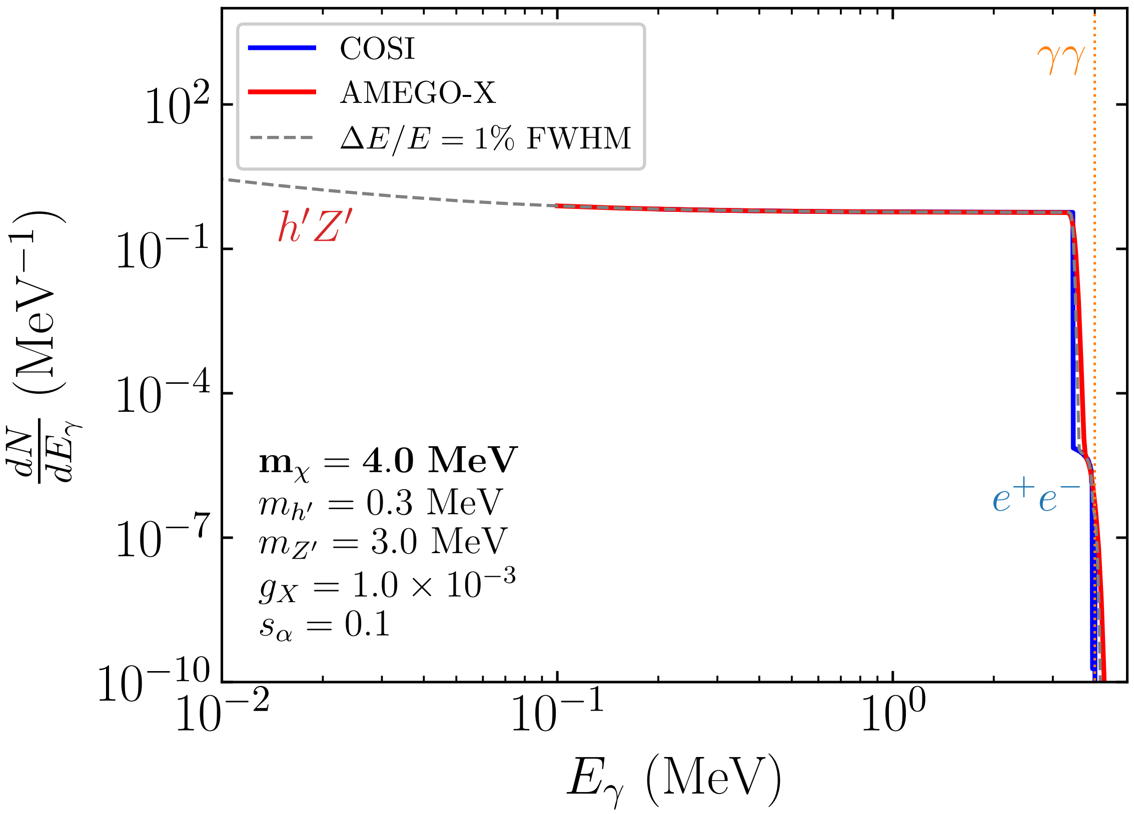

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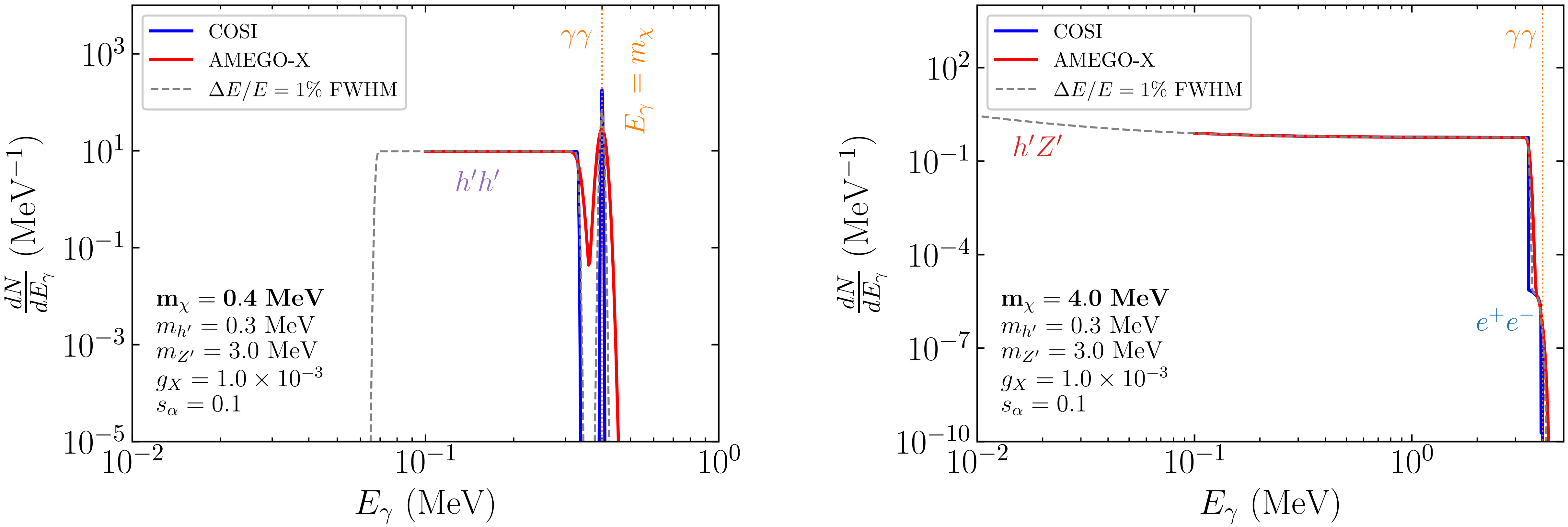


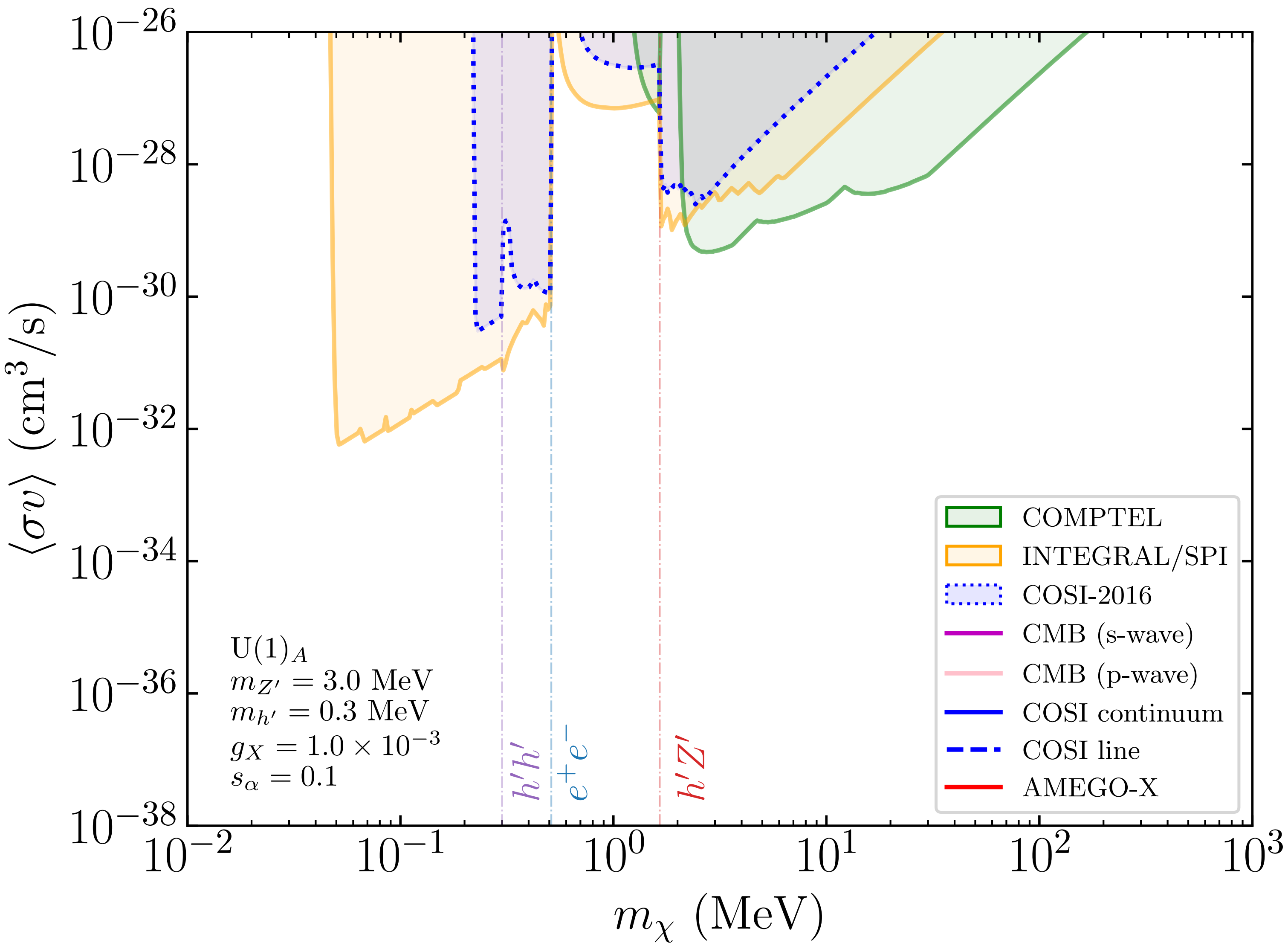
Measuring the soft γ-ray spectrum with good energy resolution is a way of probing the mass spectrum of a light dark sector

HAZMA

Hazma: a python toolkit for studying indirect detection of sub-GeV dark matter
Coogan, Morrison, Profumo **arXiv:1907.11846**

Implementation of a generic vector-scalar portal model in Hazma

Current limits and projected reach



- **Excluded by MeV γ-ray telescopes:** values of $\langle \sigma v \rangle$ for which $\Phi_\gamma|_{\bar{\chi}\chi}$ exceeds the diffuse γ-ray emission measured by existing telescopes

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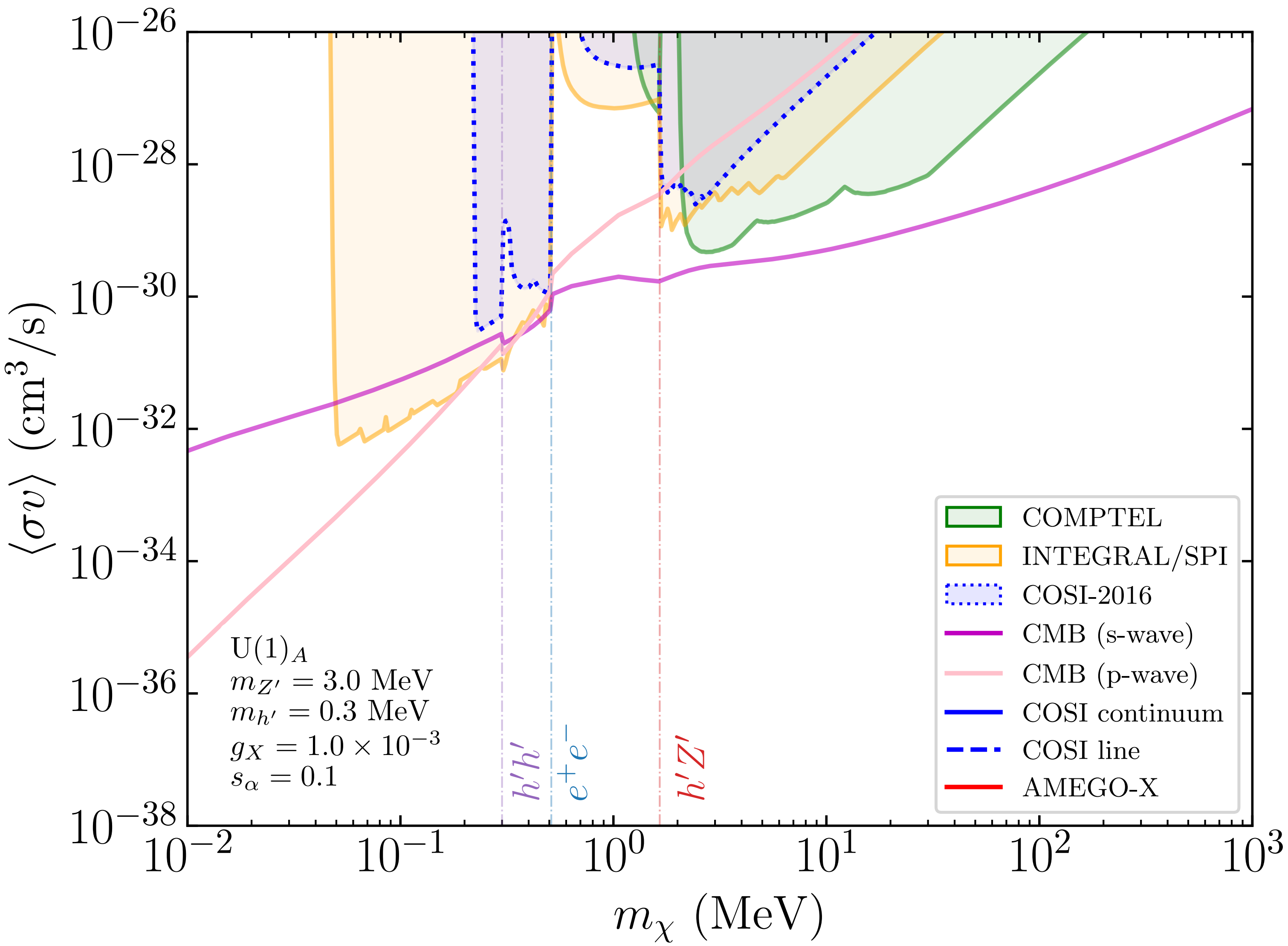

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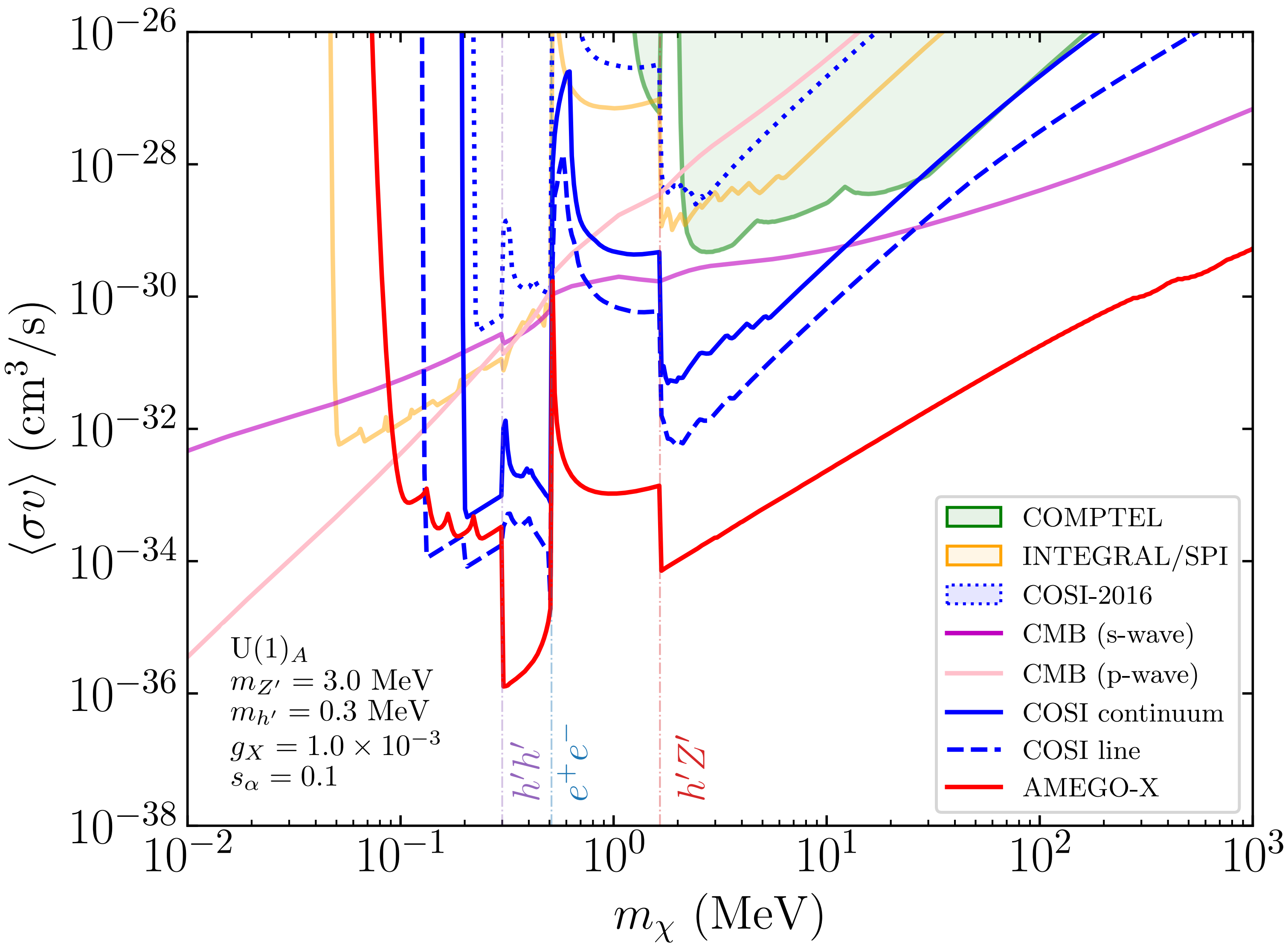

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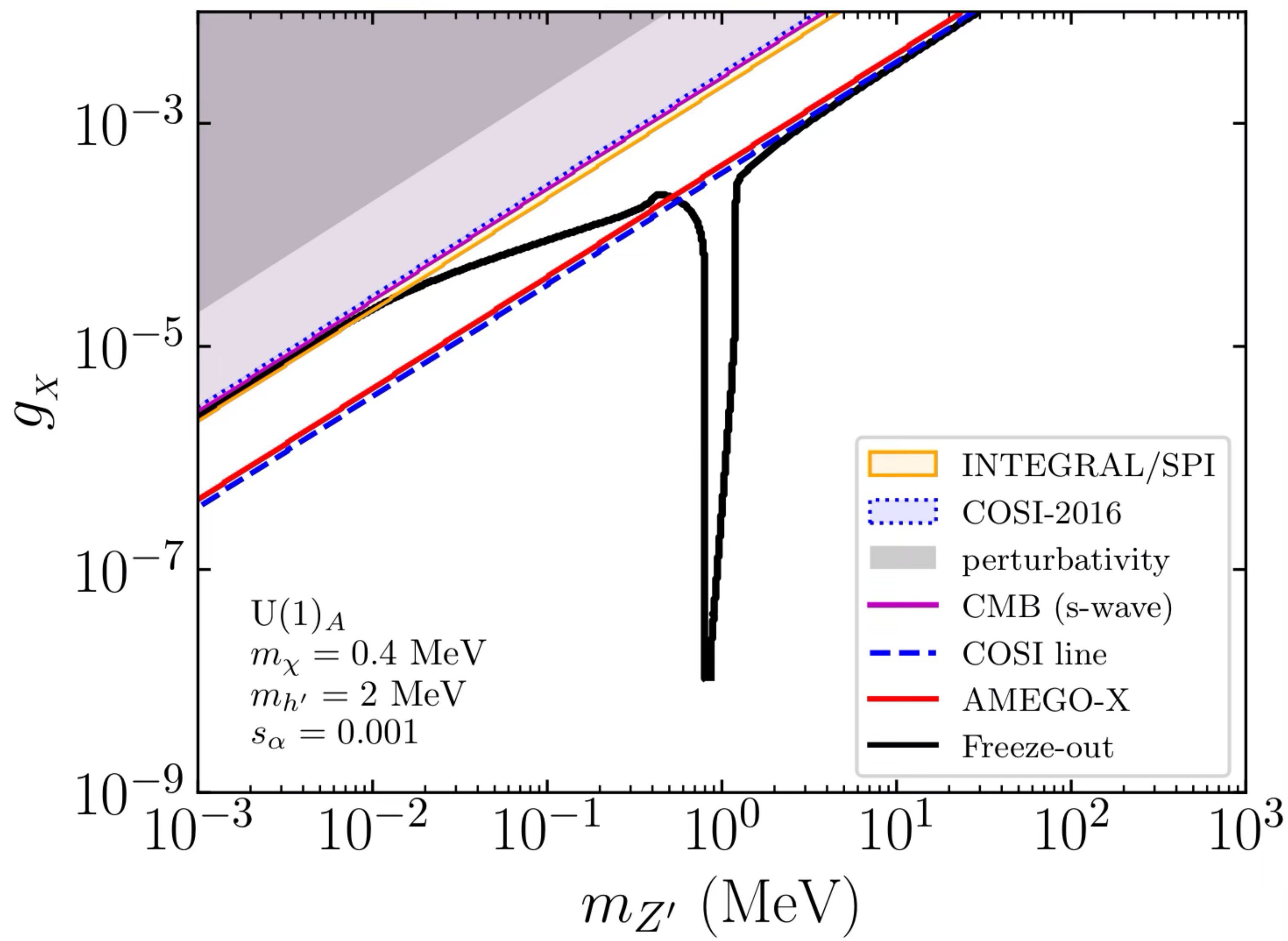
- **Projected reach for future γ-ray telescopes:** values of $\langle \sigma v \rangle$ for which $\Phi_\gamma|_{\bar{\chi}\chi}$ exceeds the expected sensitivity of COSI (line and continuum) and AMEGO-X (continuum)

The future reach shown here is an indicative sensitivity estimate based on published point-source sensitivities rescaled to a 10˚ Galactic Center disk.

A full response-level likelihood analysis for COSI is ongoing!

Below the electron threshold: lines



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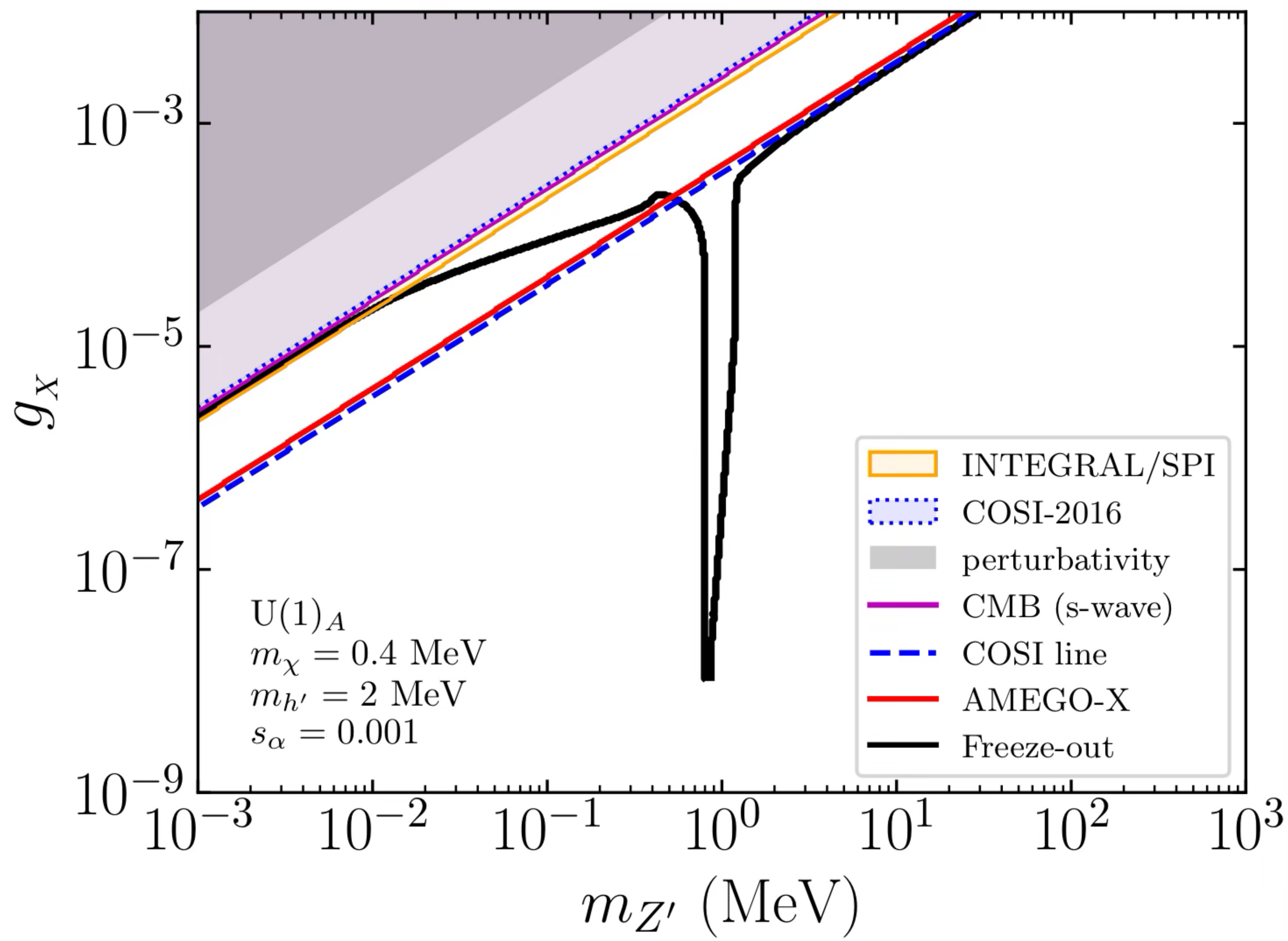

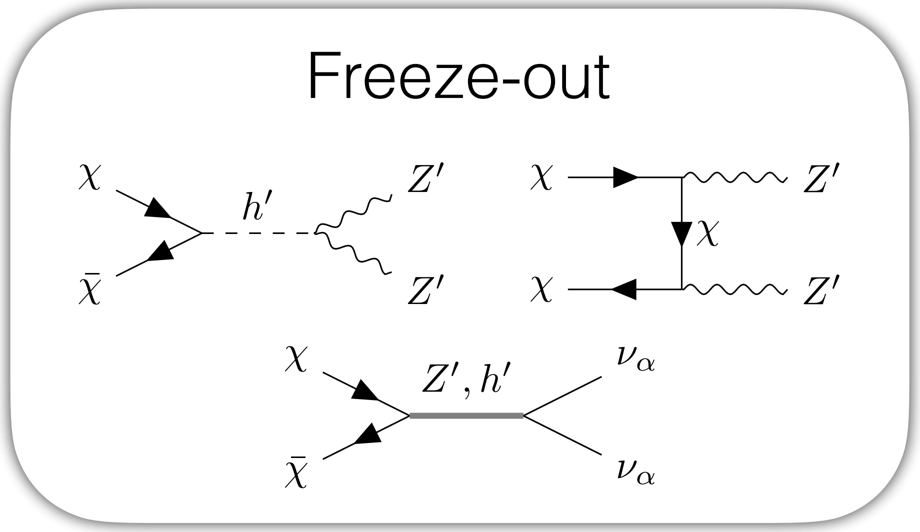

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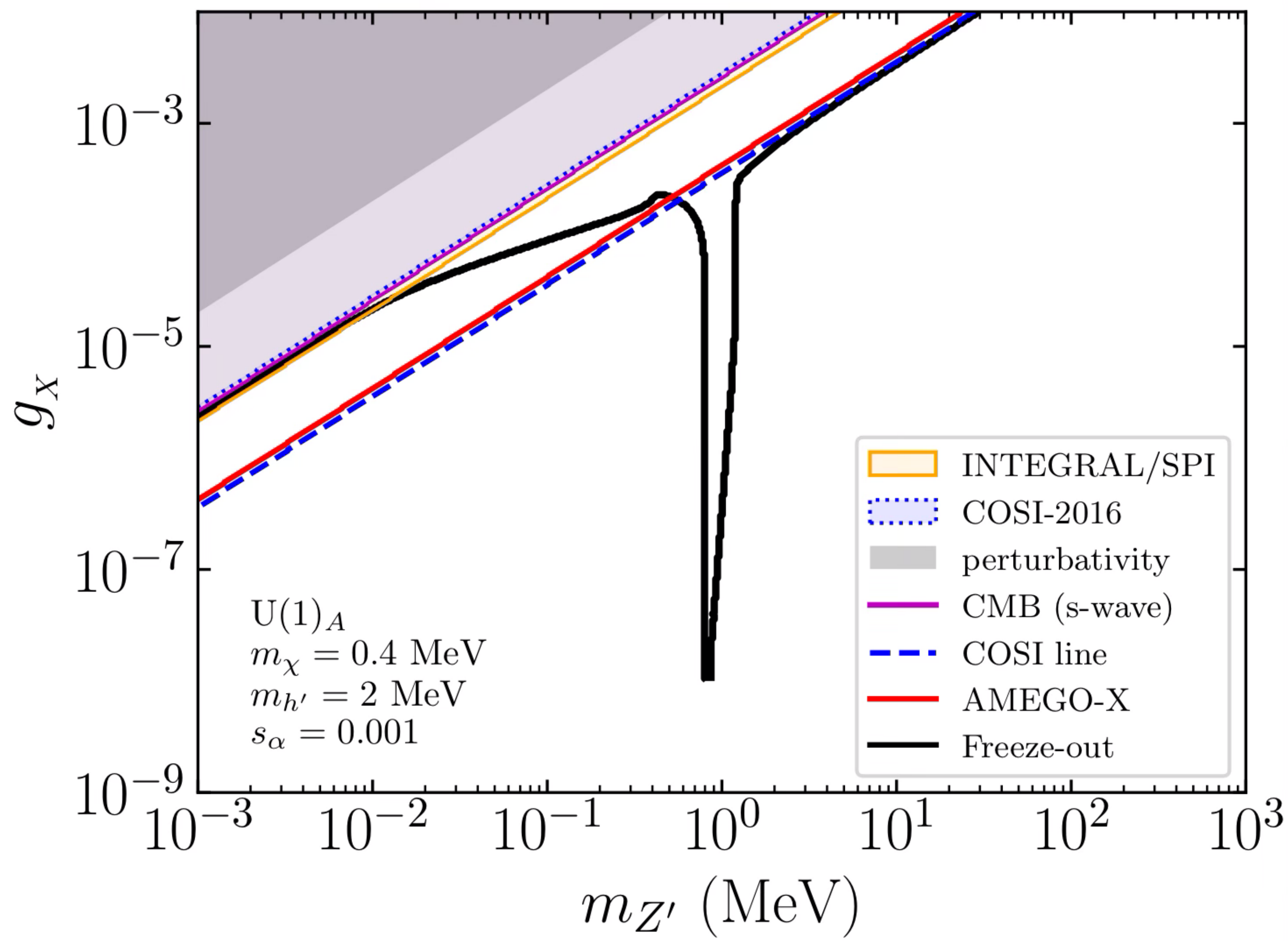
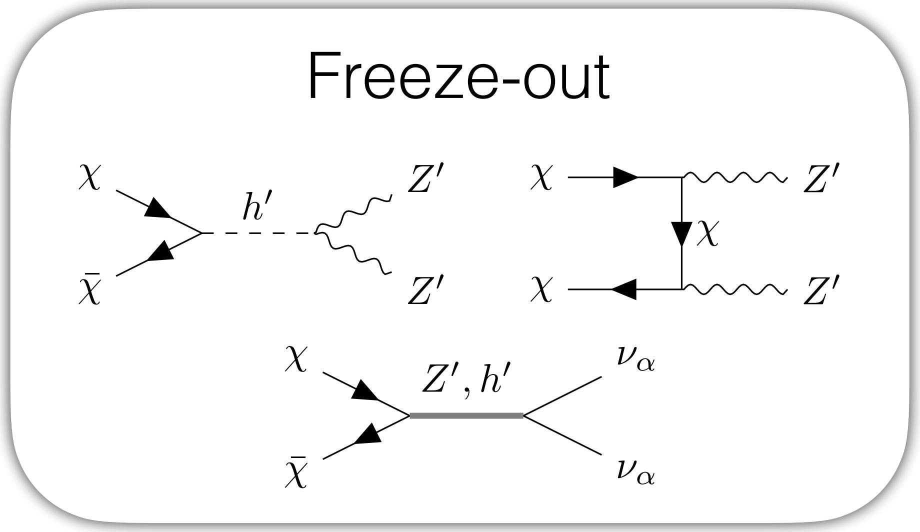
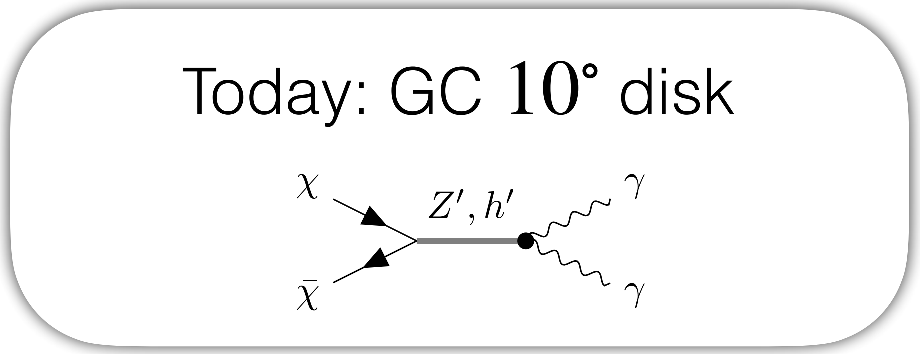
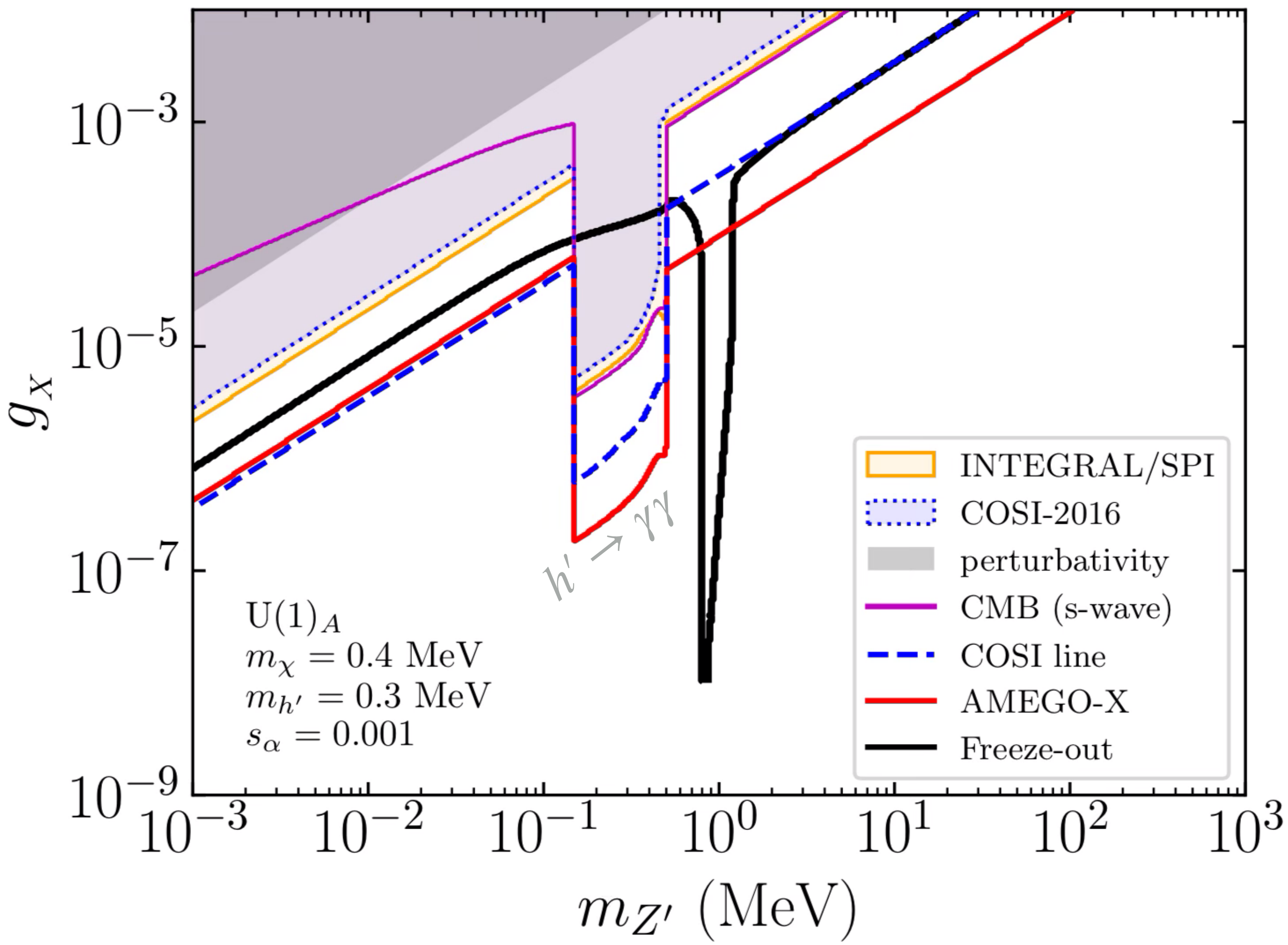


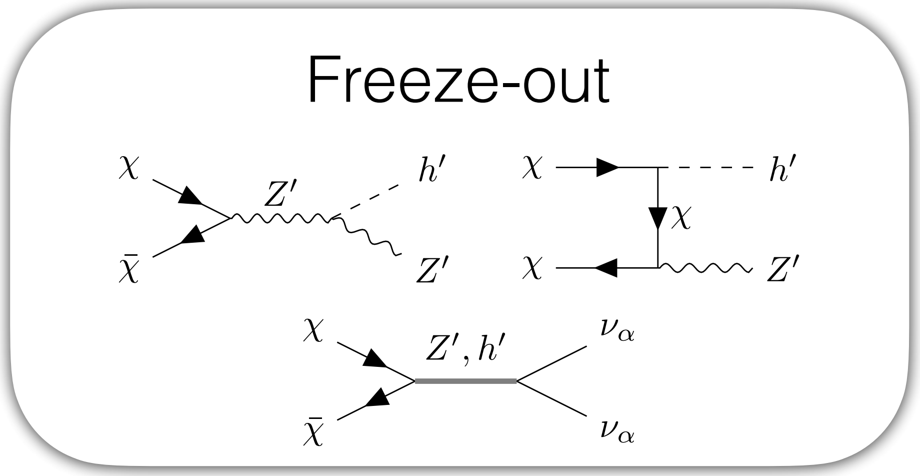


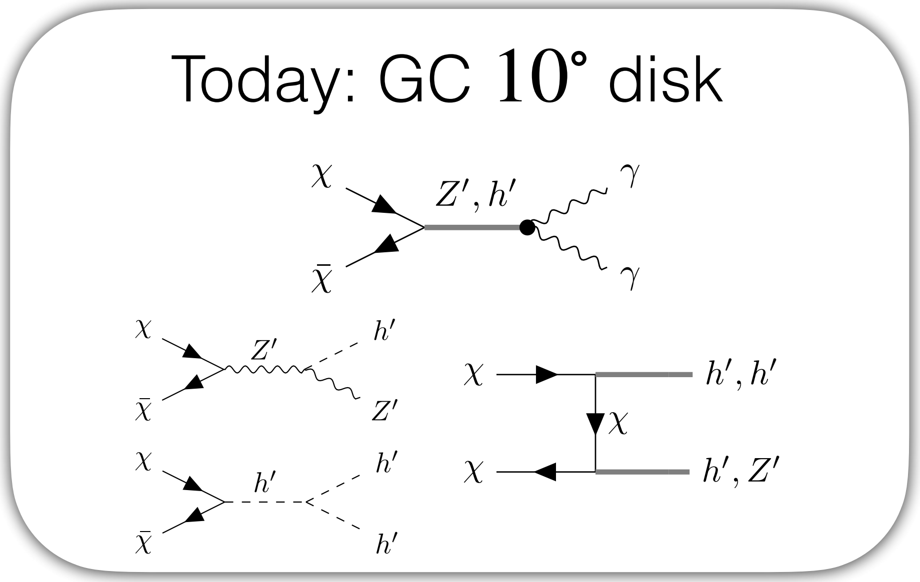


- We assume freeze-out in standard cosmology (going beyond that motivates improved limits!)
- The current ID limits exclude the viable parameter space for $m_{Z'} \lesssim 10$ MeV in this benchmark
- COSI is projected to probe the remaining viable parameter space beyond CMB bounds, except for the resonance region

Below the electron threshold: lines and boxes







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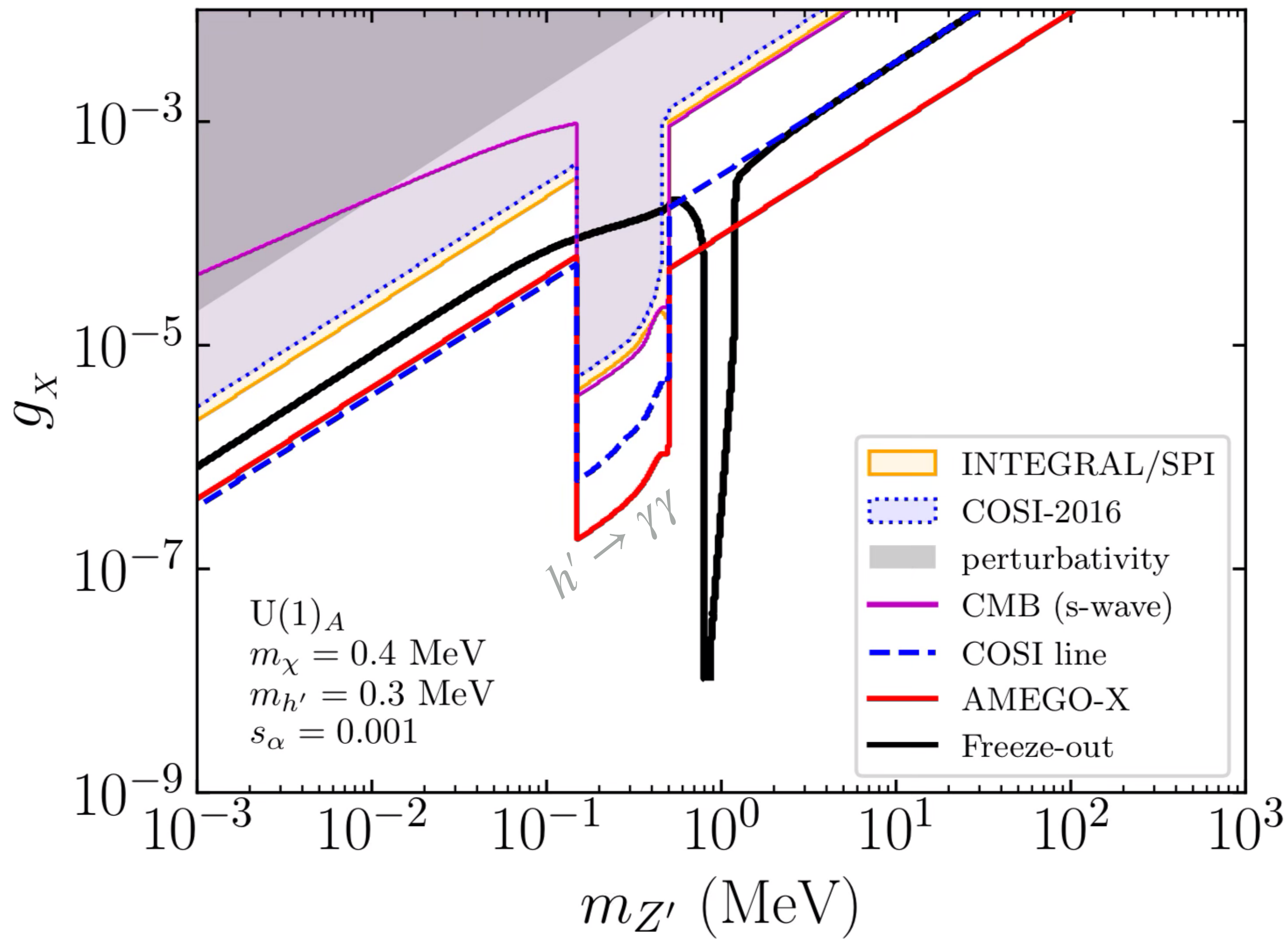
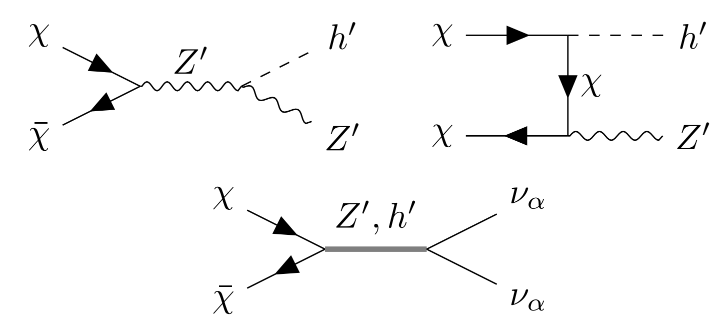
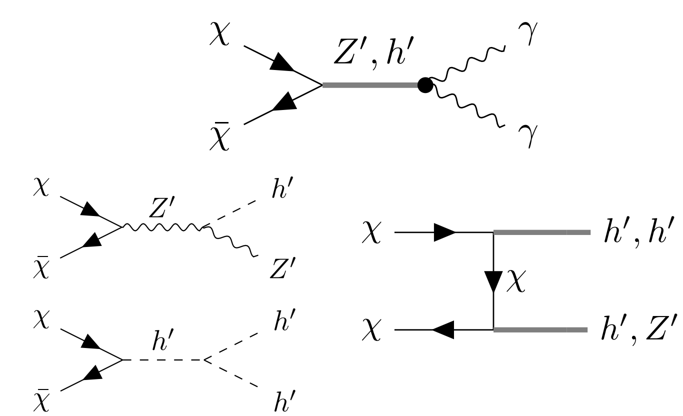


Freeze-out



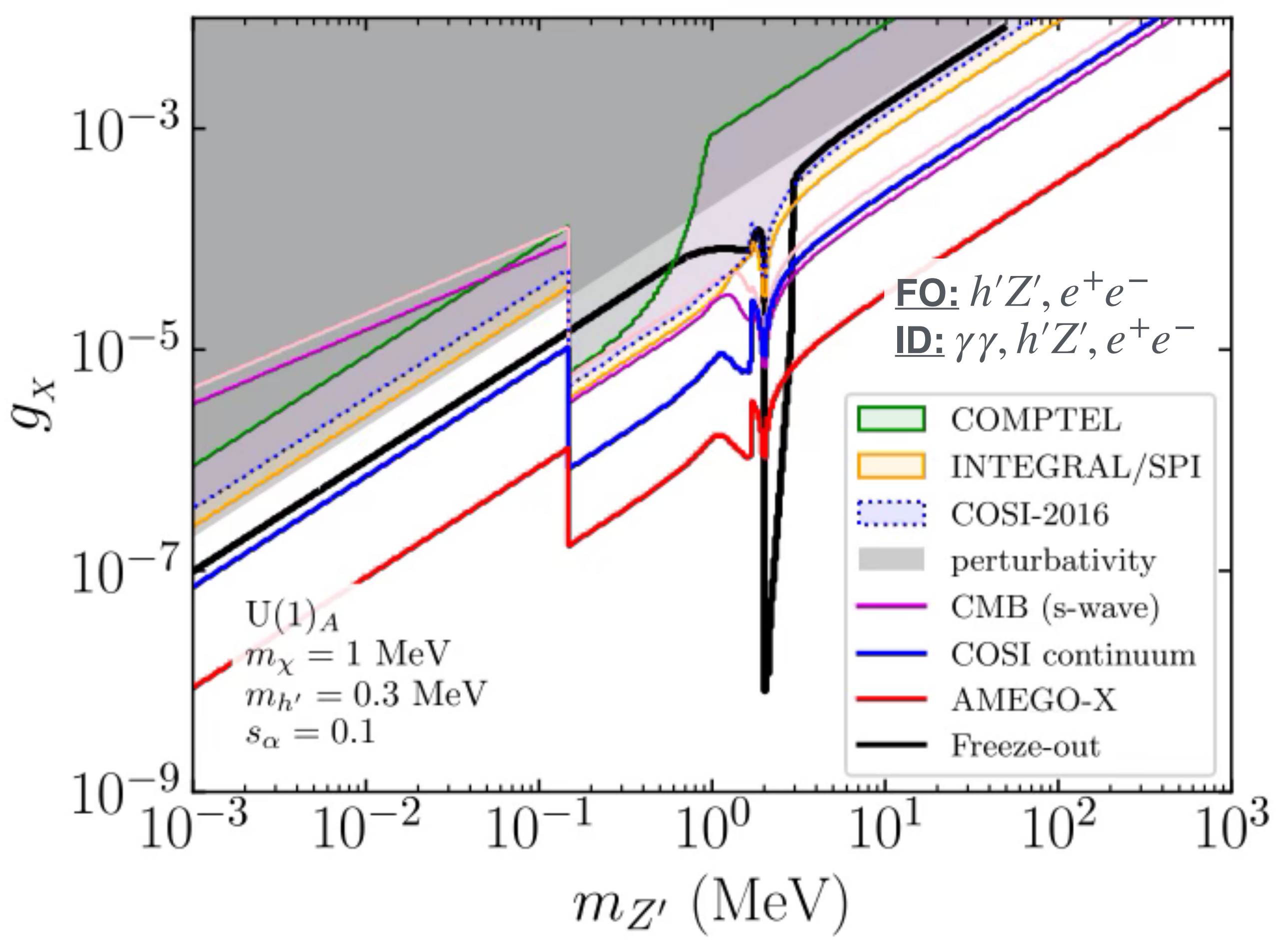
Today: GC 10° disk



- A light scalar changes significantly the MeV γ-ray phenomenology
- In this benchmark, for $m_{h'}/2 < m_{Z'} < 2m_\chi - m_{h'}$, the γ-ray boxes from the $h'Z'$ channel are strongly enhanced, ruling out the viable parameter space
- COSI will probe the remaining viable parameter space, except for the resonance region, beyond CMB bounds

Above the electron threshold: CMB vs continuum

$m_{h'} < m_\chi$



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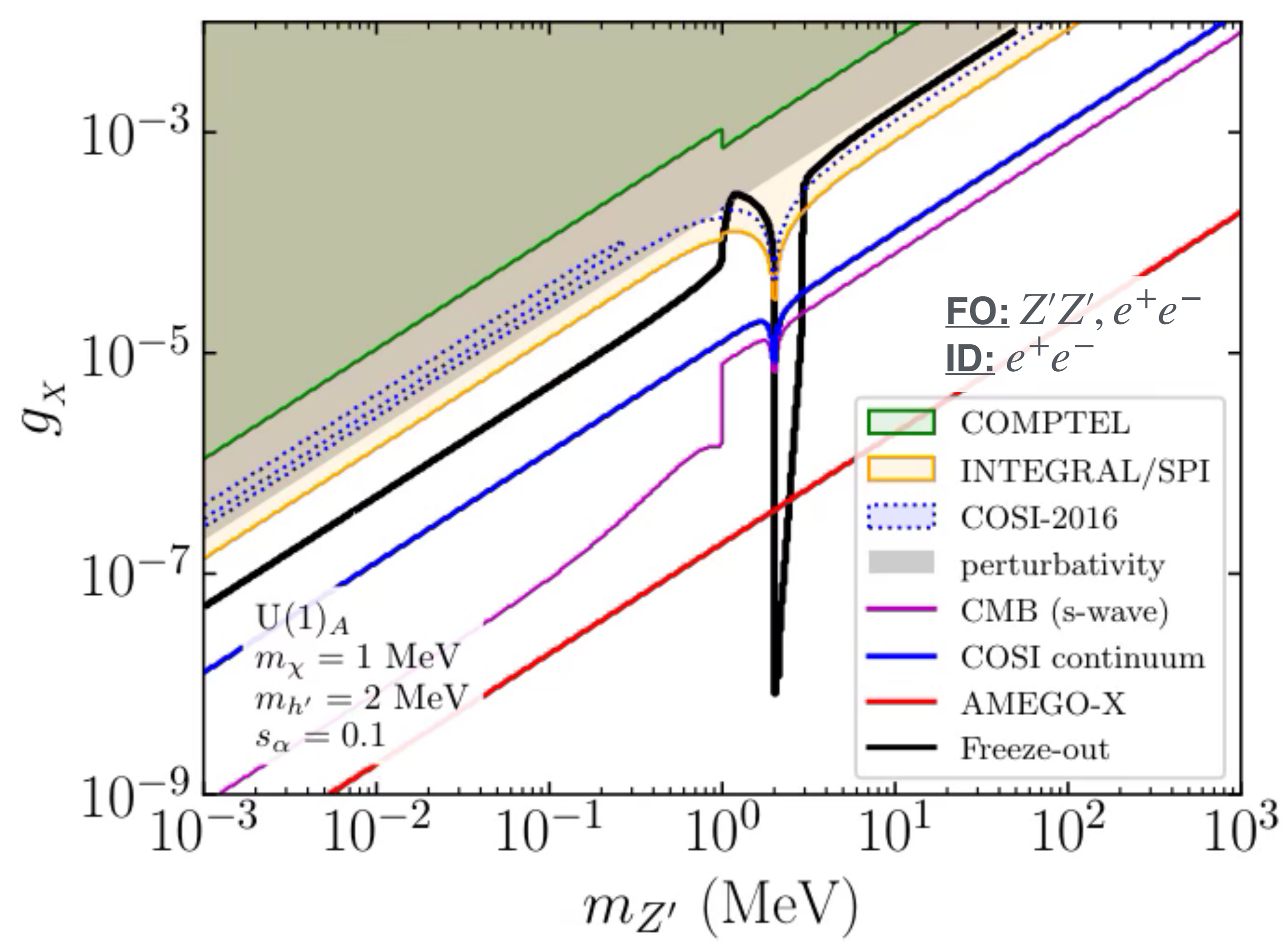

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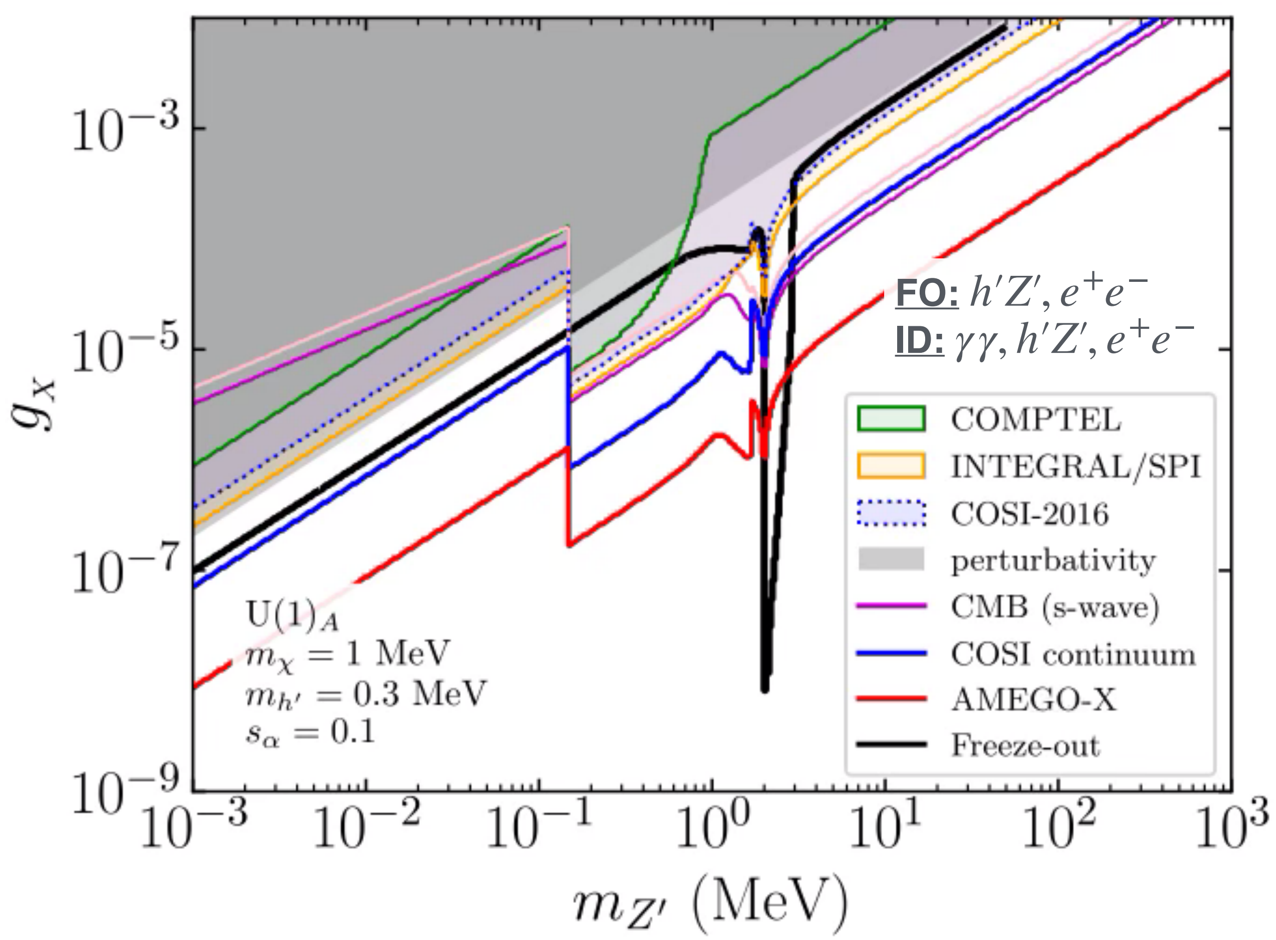

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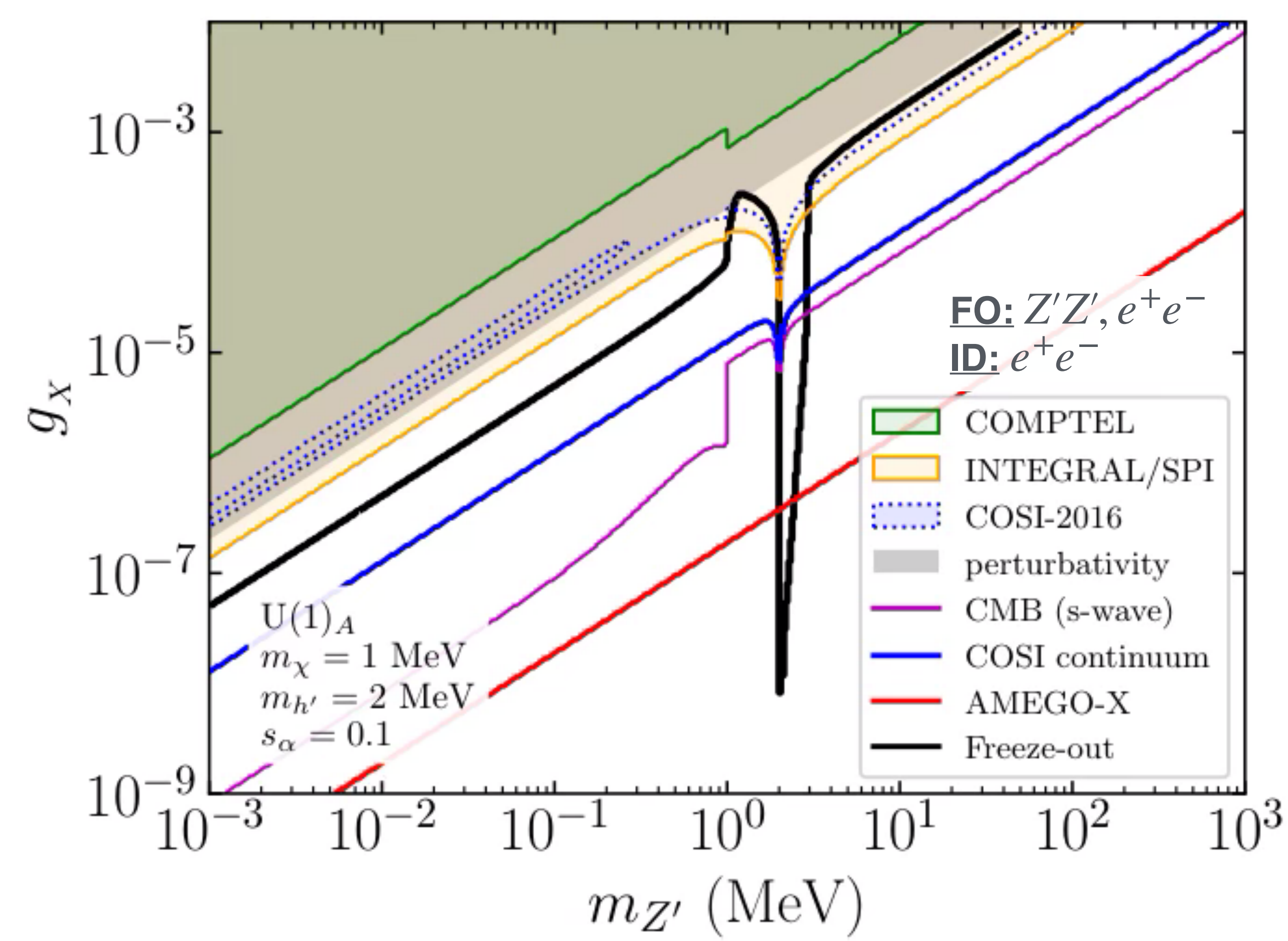
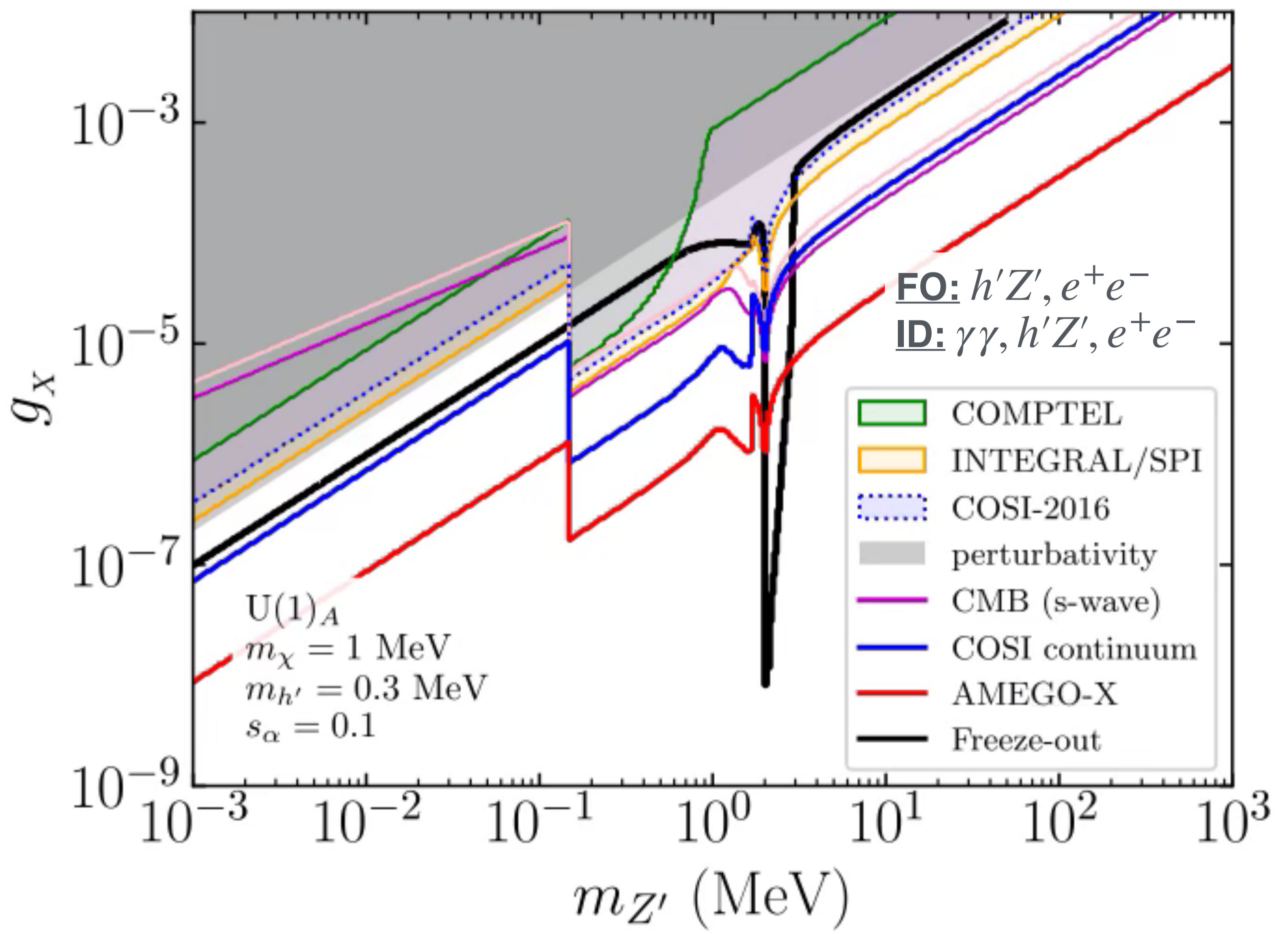


- In this benchmark, the current ID limits exclude the viable parameter space with $m_{Z'} \gtrsim m_{h'}/2$, except near the Z' resonance
- Mediator final states generate boxes and cascade FSR, improving the projected reach

Above the electron threshold: CMB vs continuum

$m_{h'} < m_\chi$



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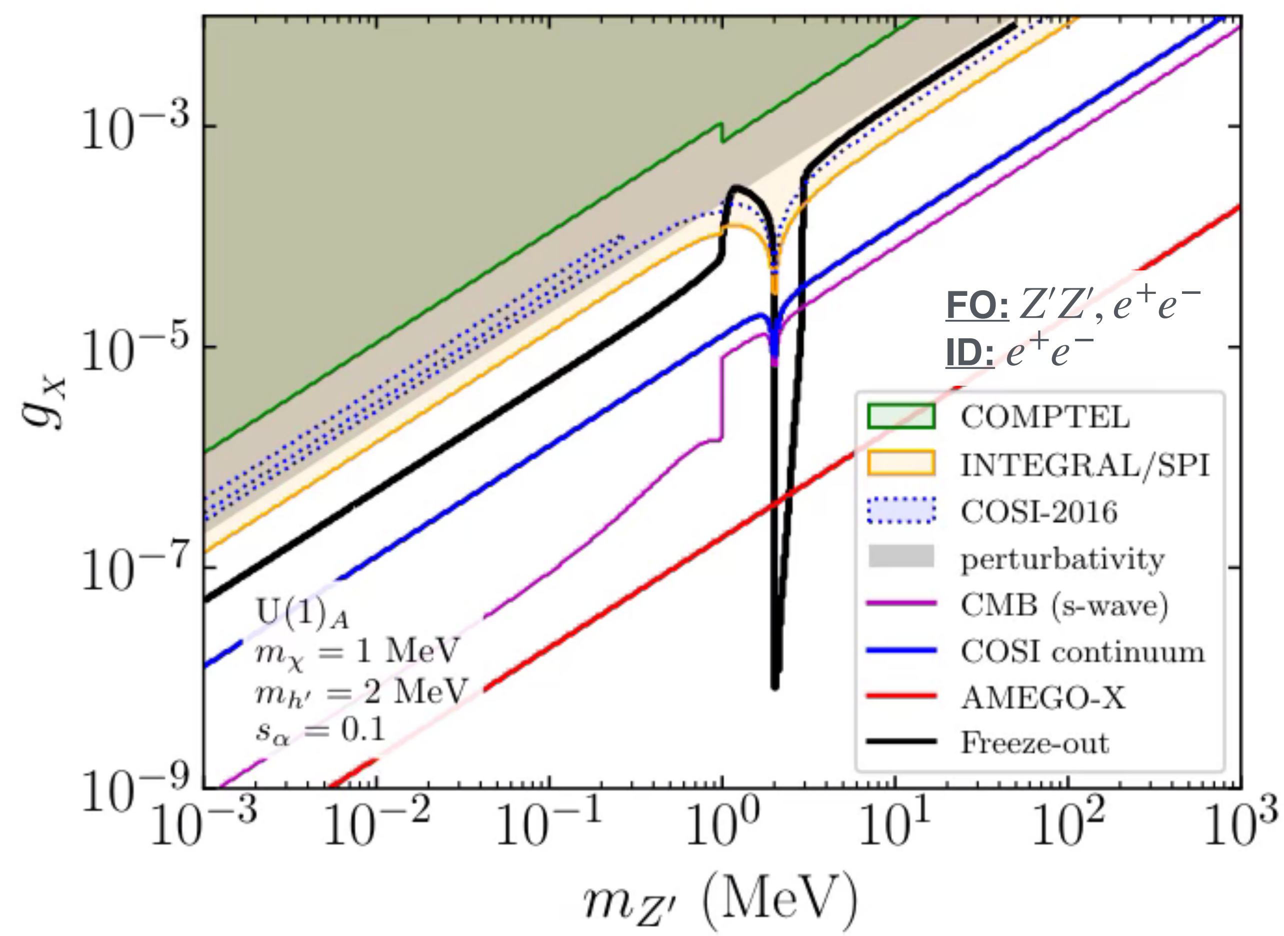

- In this benchmark, the current ID limits exclude the viable parameter space with $m_{Z'} \gtrsim m_{h'}/2$, except near the Z' resonance
- Mediator final states generate boxes and cascade FSR, improving the projected reach

- The CMB bound excludes all the viable parameter space except for the resonance region
- The continuum FSR from the e^+e^- channel is so strong that AMEGO-X can probe very small g_X (freeze-in motivated)

Take-home messages

- A sizable present-day $\gamma\gamma$ line points to dark matter annihilation via light axial Z' bosons; a minimal renormalizable completion requires a $U(1)_X$-breaking scalar.

- In the case of a light h' scalar, vector-scalar portals predict correlated γ-ray lines, boxes, and continuum emission while opening new thermal-relic parameter space in agreement with CMB bounds.

- COSI and proposed MeV γ-ray telescopes will probe complementary spectral features; the present projected reach is indicative, and a response-level COSI analysis is ongoing

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COSI is scheduled to launch in 2027. Get ready!

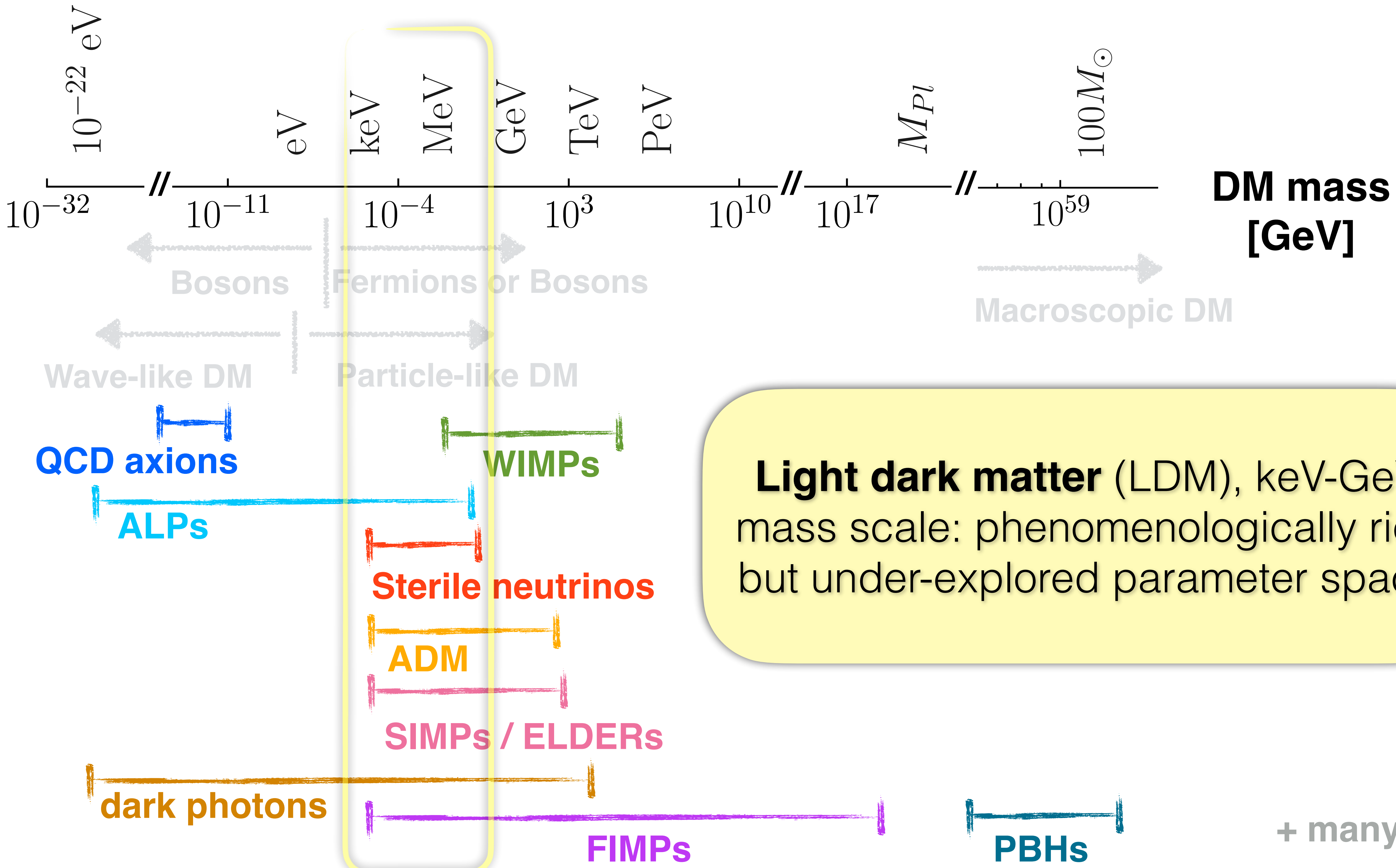
DM @ COSI
Data Challenge 4

Obrigada!

Backup slides

Light dark matter: candidates

Based on all the evidence we have, dark matter is most likely made of **gravitationally interacting particles**



Light dark matter (LDM), keV-GeV mass scale: phenomenologically rich but under-explored parameter space

+ many more

Benchmark charge assignments and their completions

	L_L	l_R	Q_L	u_R	d_R	Φ	Φ_s	χ_L	χ_R
$SU(3)_c$	1	1	3	1	1	1	1	1	1
$SU(2)_L$	2	1	2	1	1	2	1	1	1
$U(1)_Y$	-1	-2	1/3	4/3	-2/3	1	0	0	0
$U(1)_{B-L}$	-1	-1	1/3	1/3	1/3	0	2	4	2
$U(1)_A$	1/3	-1/3	1/3	-1/3	-1/3	2/3	2	4	2

Relevant parameter space

g_X, s_α gauge coupling and scalar mixing angle

$m_\chi, m_{Z'}, m_{h'}$ masses of new particles

$X_\Phi, X_{\Phi_s}, X_{Q_L}, X_{L_L}, X_{\chi_L}$

charges under $U(1)_X$ (set by choice of symmetry)

$U(1)_{B-L}$ gauge symmetry:

- One of the simplest anomaly-free setups for a new gauge symmetry
- RHNs cancel the anomalies and enable seesaw
- Gauge invariance requires $X_\Phi = 0 \Rightarrow$ no Z-Z' mass mixing
- Pure vector couplings of SM fermions ($X_{f_L} = X_{f_R}$)

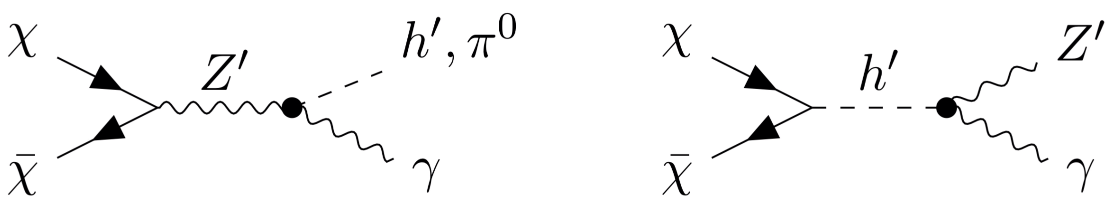
$U(1)_A$ gauge symmetry:

- Phenomenologically motivated (GC GeV excess, SD direct detection, MeV anomalies)
- Requires additional chiral fermions for anomaly cancellation and an extended Higgs sector for gauge-invariant SM Yukawa sector
- Gauge invariance requires $X_\Phi = 2/3 \Rightarrow$ Z-Z' mass mixing
- Pure axial-vector couplings of SM fermions ($X_{f_L} = -X_{f_R}$)

Z' mediated dark matter models for the Galactic Center Gamma-ray Excess
D. Hooper **arXiv:1411.4079**

Axial vector Z' and Anomaly Cancellation
Ismail, Keung, Tsao, Unwin **arXiv:1609.02188**

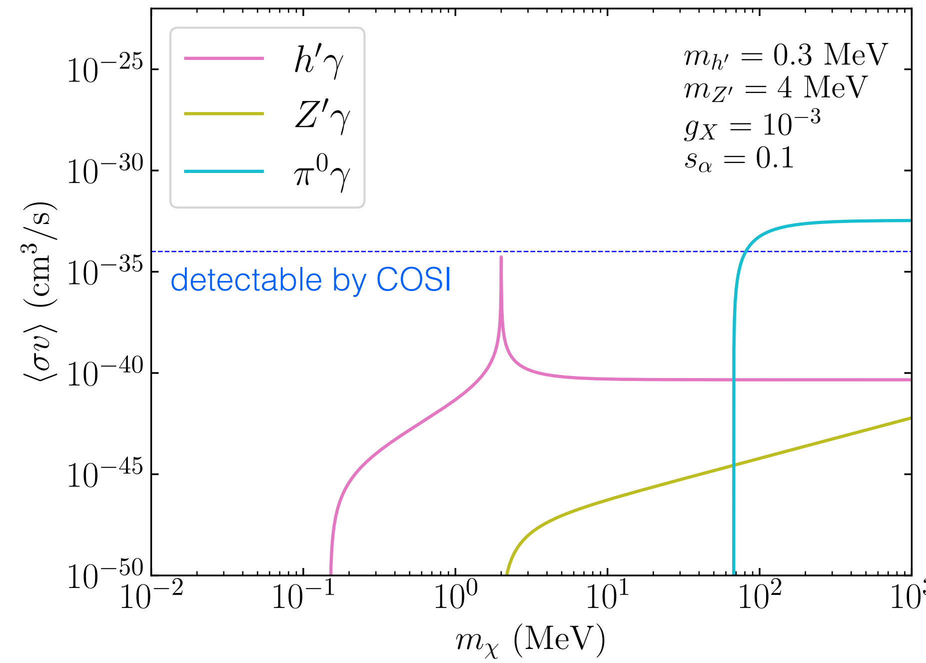
How to generate strong γ-ray lines at the MeV scale?

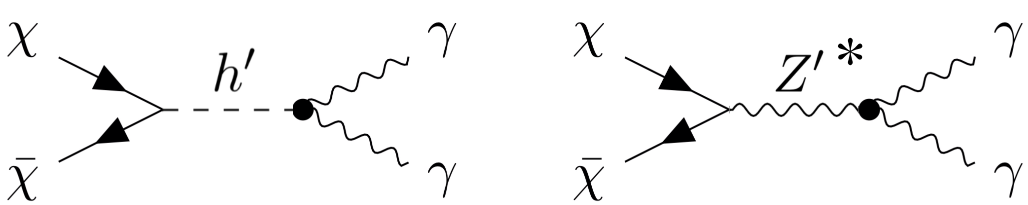


- Negligible cross-sections

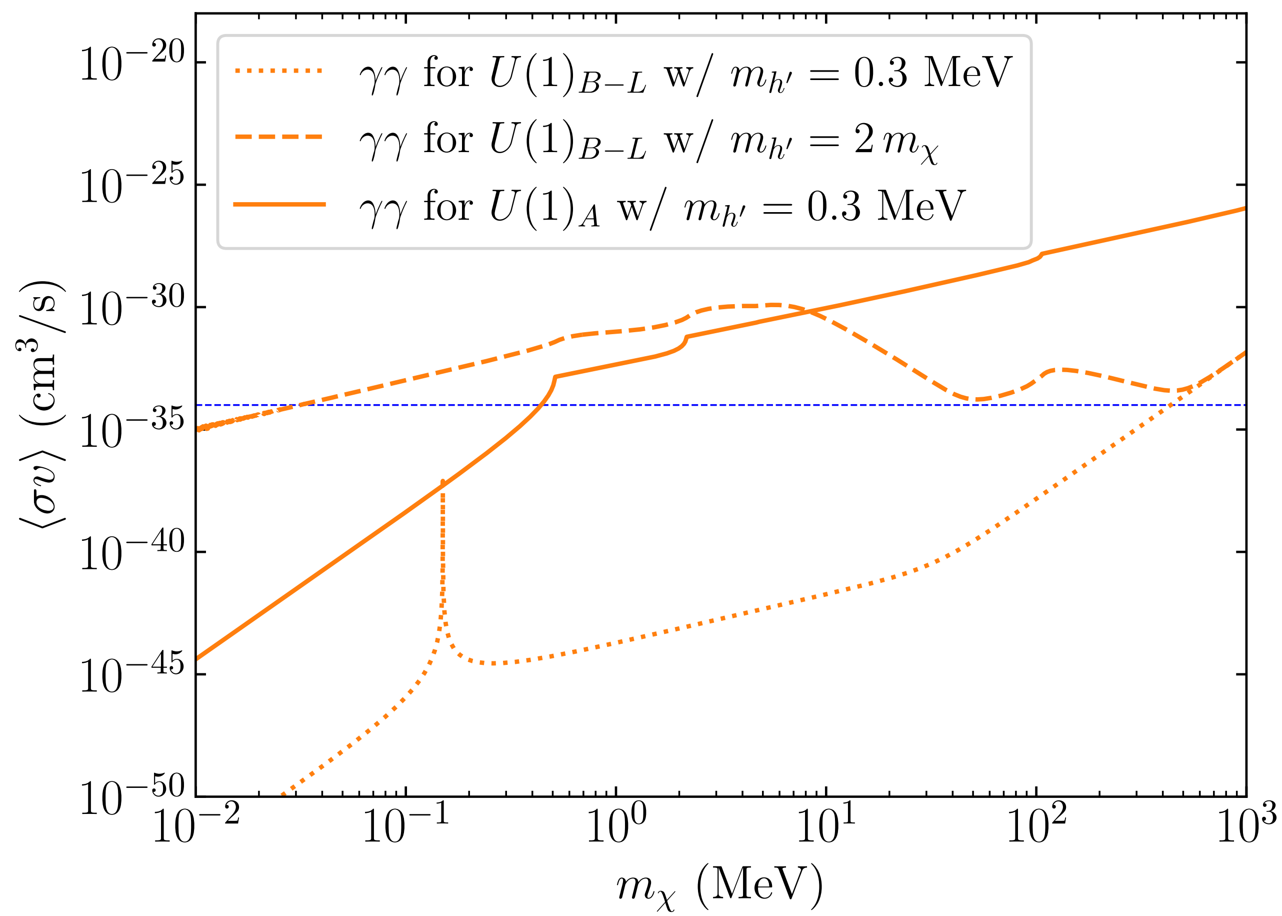
$$\sigma_{\pi\gamma} \propto \alpha_{em}\, g_X^4/f_\pi^2 \qquad \sigma_{Z'\gamma} \propto \alpha_{em} G_F^2 m_W^2 s_W^2\, m_\chi^2/v_s^2$$

$$\sigma_{h'\gamma} \propto \alpha_{em} G_F^2 m_W^2 s_W^2 g_X^2$$



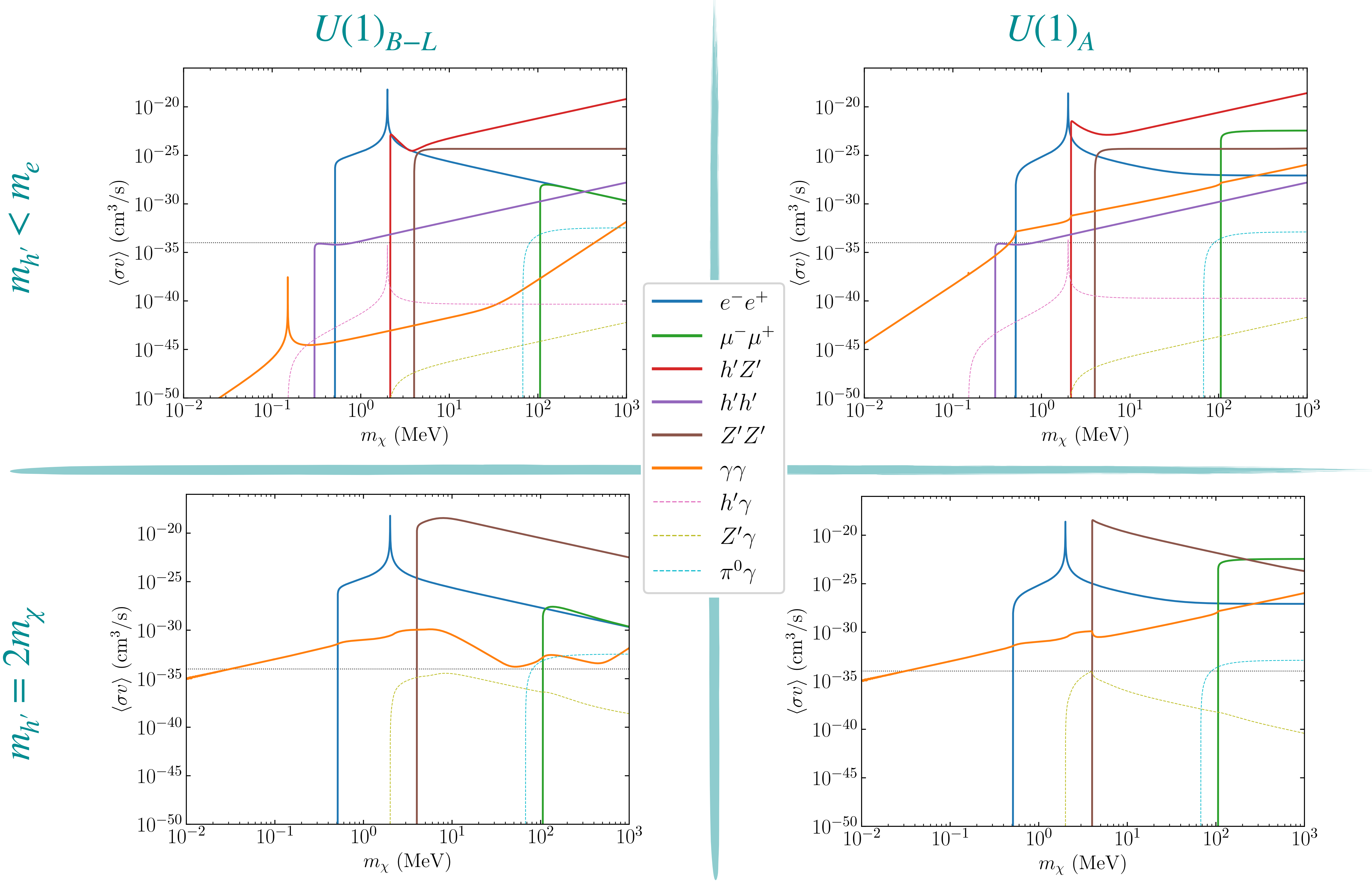


Landau-Yang forbids
$Z'_{on-shell} \to \gamma\gamma$



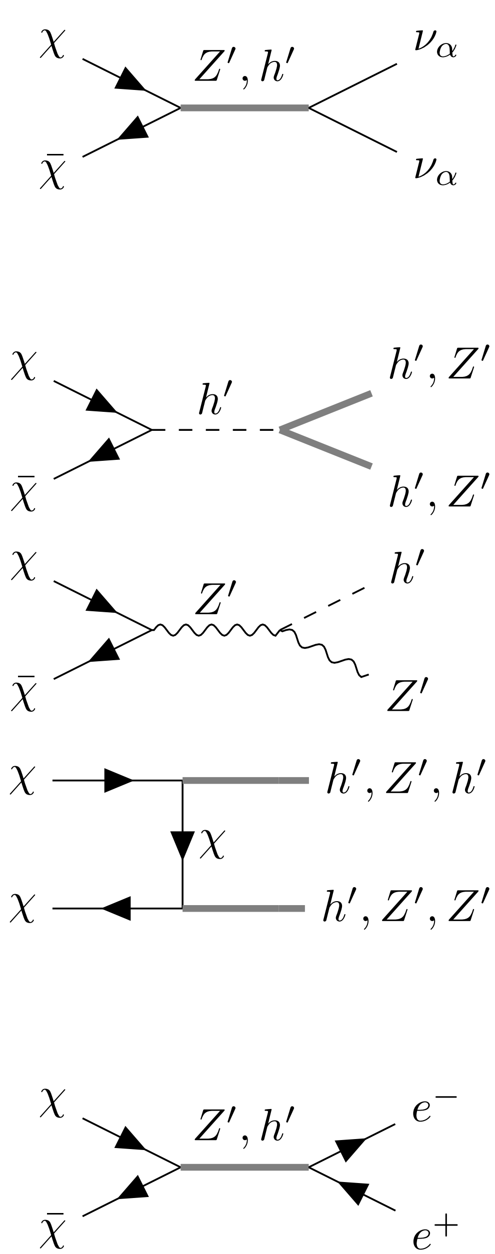
- Scalar portal: negligible cross-section (p-wave and Yukawa suppressed) outside resonance region
- Vector portal: possible if $X_{\chi_L, f_L} \neq X_{\chi_R, f_R}$; sizable cross-section (s-wave)

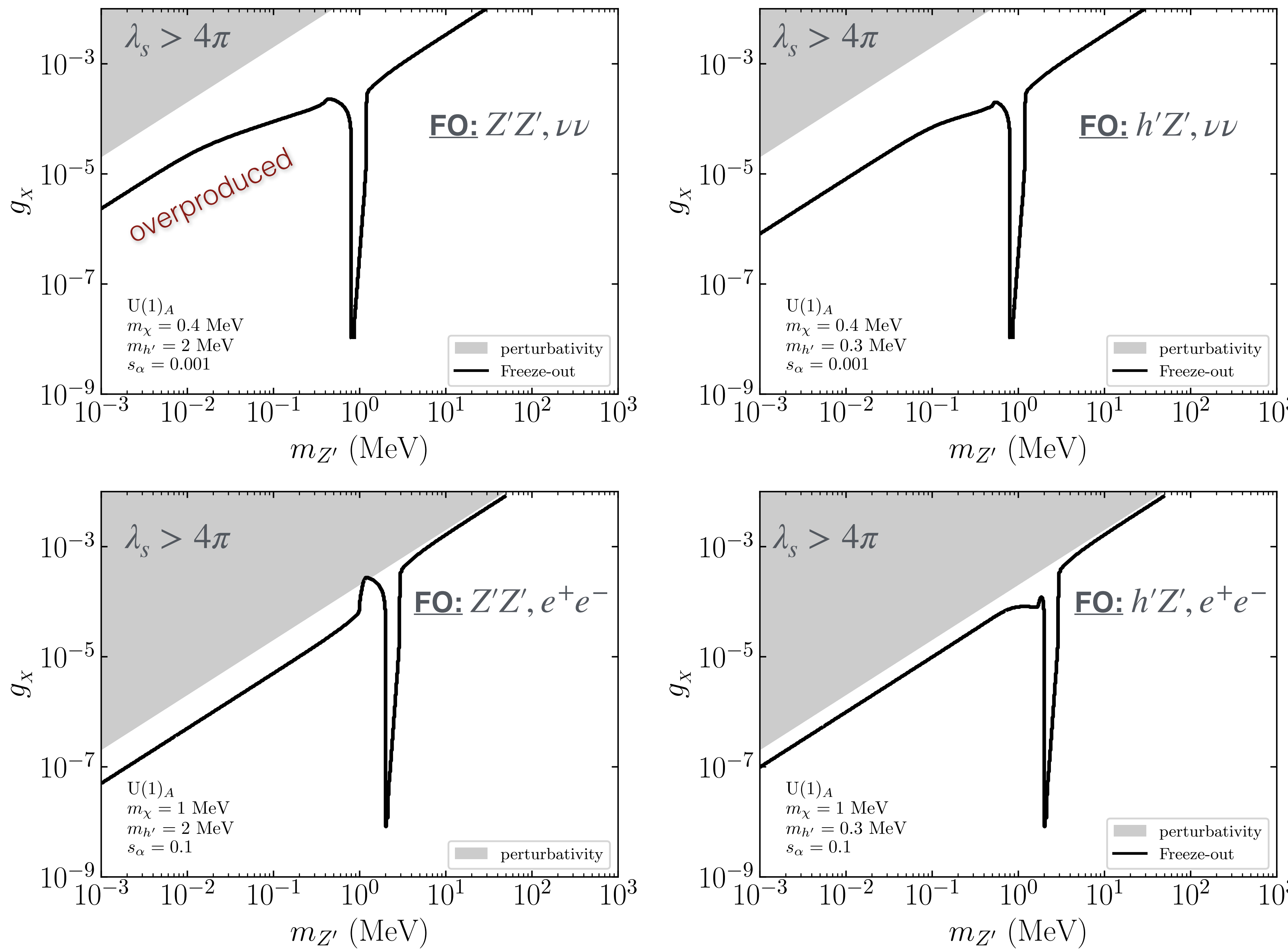
Annihilation channels



Freeze-out of LDM in vector-scalar portal

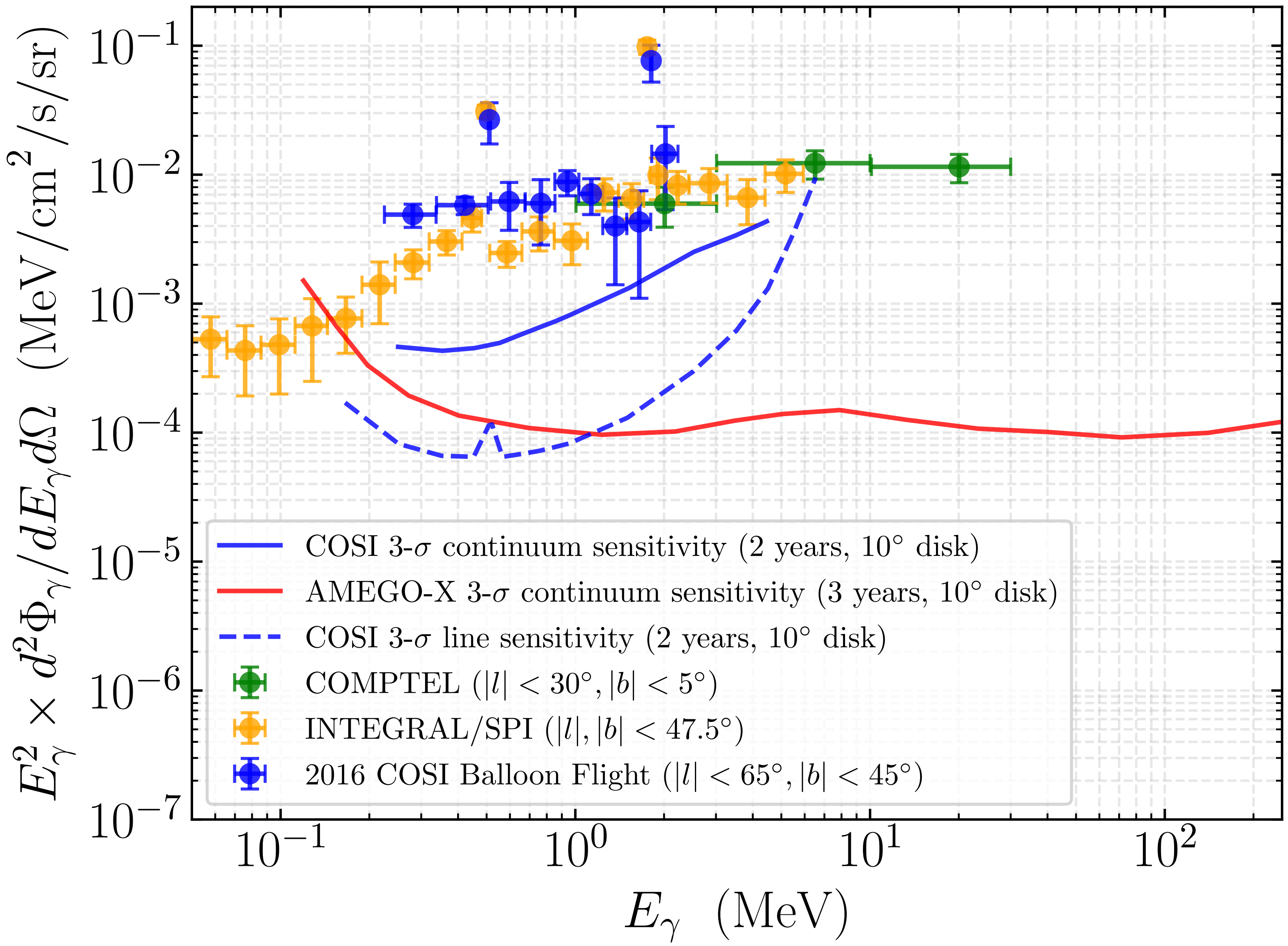
We consider the freeze-out production of sub-GeV DM in standard cosmology





Indirect detection of light dark matter

Excluded/probed region in the DM parameter space:



Differential γ-ray flux from DM annihilation:

$$\left.\frac{d\Phi_\gamma}{dE_\gamma}\right|_{\chi\bar{\chi}} = \frac{\Delta\Omega}{16\pi}\bar{J}(\Delta\Omega)\frac{\langle\sigma v\rangle}{m_\chi^2}\sum_f B_f \frac{dN^f}{dE_\gamma}$$

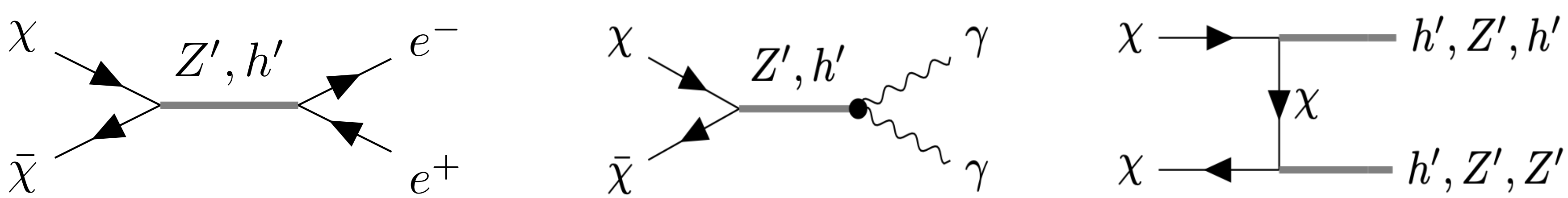
$\bar{J}$: line-of-sight integral of the square DM density, averaged over $\Delta\Omega$ (**signal morphology**)

$\langle\sigma v\rangle$: total velocity-averaged DM annihilation cross-section

$\frac{dN^f}{dE_\gamma}$: γ-ray spectrum from final state f w/ annihilation branching fraction B_f

Model-dependent CMB bounds

DM annihilation into e.m. particles around and after recombination can modify the ionization history and therefore the CMB temperature and polarization anisotropies



$$f_{eff}\frac{\langle\sigma v\rangle_{CMB}}{m_\chi} < 3.5\times 10^{-31}\text{cm}^3/\text{s}/\text{MeV}$$ (95% Planck TT, TE, EE + lowE)

Efficiency of energy deposition from DM annihilation in medium:

$$f_{eff} = \frac{1}{E_{cm}}\int_0^{E_{cm}/2} dE\, E\left(f_{eff}^{\gamma}\frac{dN}{dE_\gamma}(E) + 2f_{eff}^{e^+}\frac{dN}{dE_{e^+}}(E)\right)$$

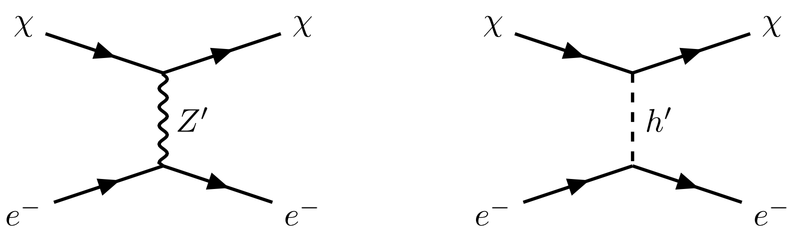
All relevant model-dependent spectra were considered

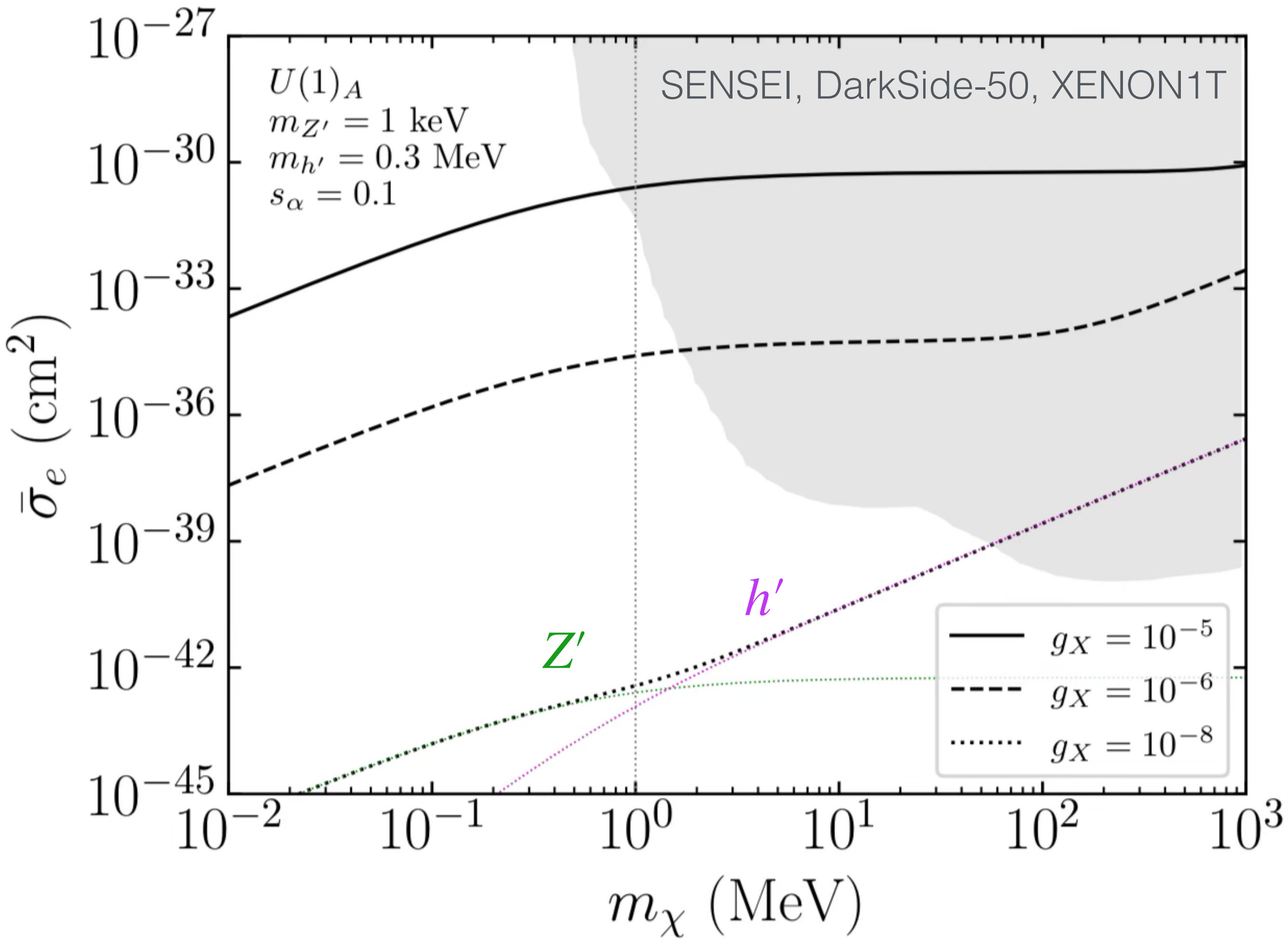
s-wave limit: $\langle\sigma v\rangle^0 = \langle\sigma v\rangle^{CMB}$

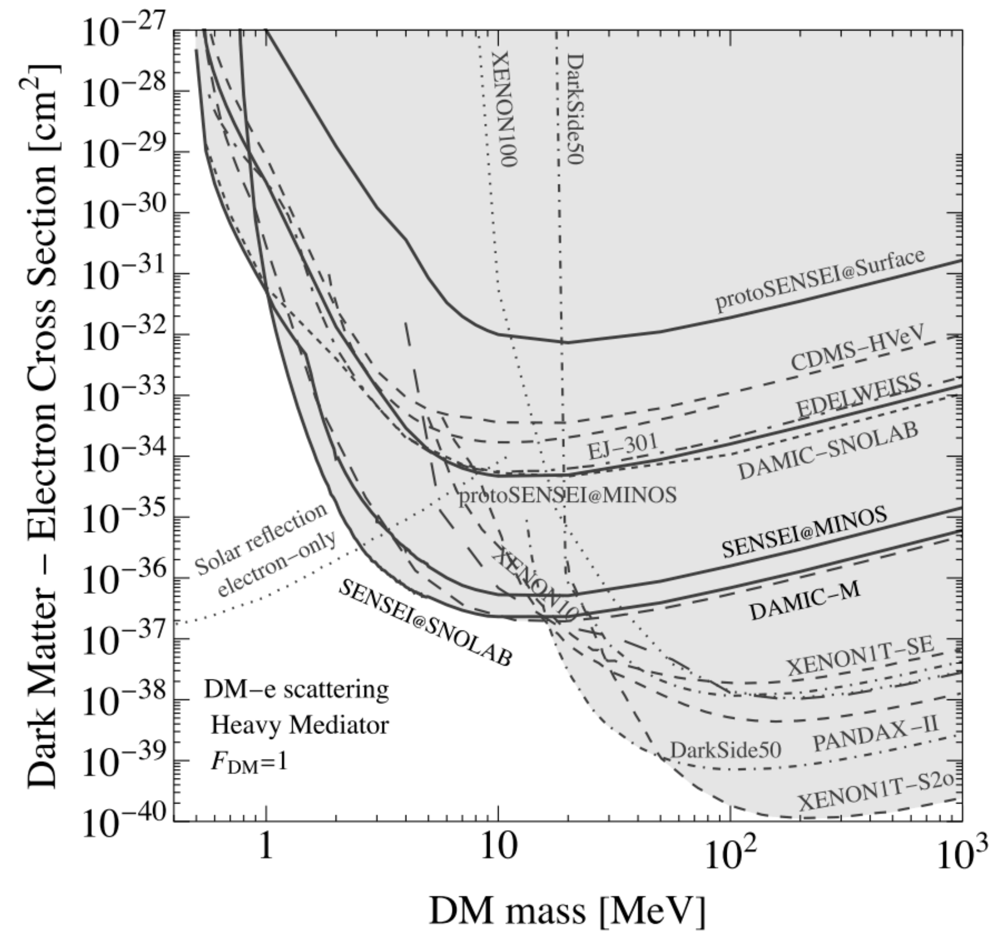
p-wave limit: $\langle\sigma v\rangle^0 = \langle\sigma v\rangle^{CMB}(v_0/v_{CMB})^2$

v_{CMB} depends on kinetic decoupling assumptions

Direct detection of LDM







Some progress & challenges for the direct-detection of sub-GeV dark matter
R. Essig **Nucl. Phys. B 1003 (2024) 116484**

- The largest values of $\bar{\sigma}_e$ for $m_\chi \sim 1$MeV are obtained for $g_X \sim 10^{-5}$. This region is currently allowed by DD, but already excluded by ID and theoretical limits
- It is interesting to have in mind that for DM in the MeV-GeV range, we will be able to explore the complementarity between AMEGO-X and future DD experiments