

UNIVERSITÄT **BONN**



Bethe Center for
Theoretical Physics

LIGHT DARK MATTER: MODELS, MECHANISMS, PREDICTIONS

"A very subjective overview"

Patrick Foldenauer

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IFT (UAM-CSIC) Madrid

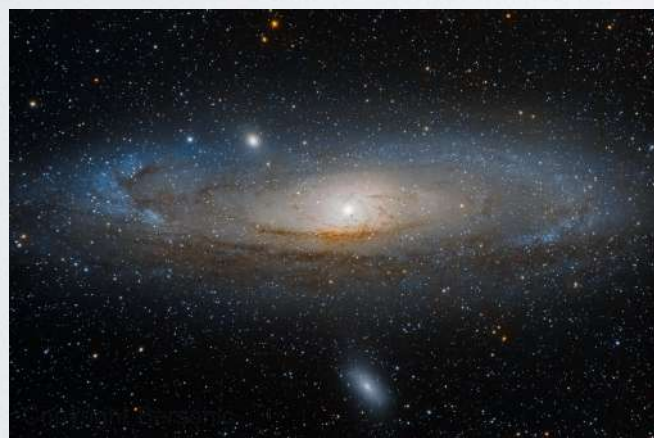
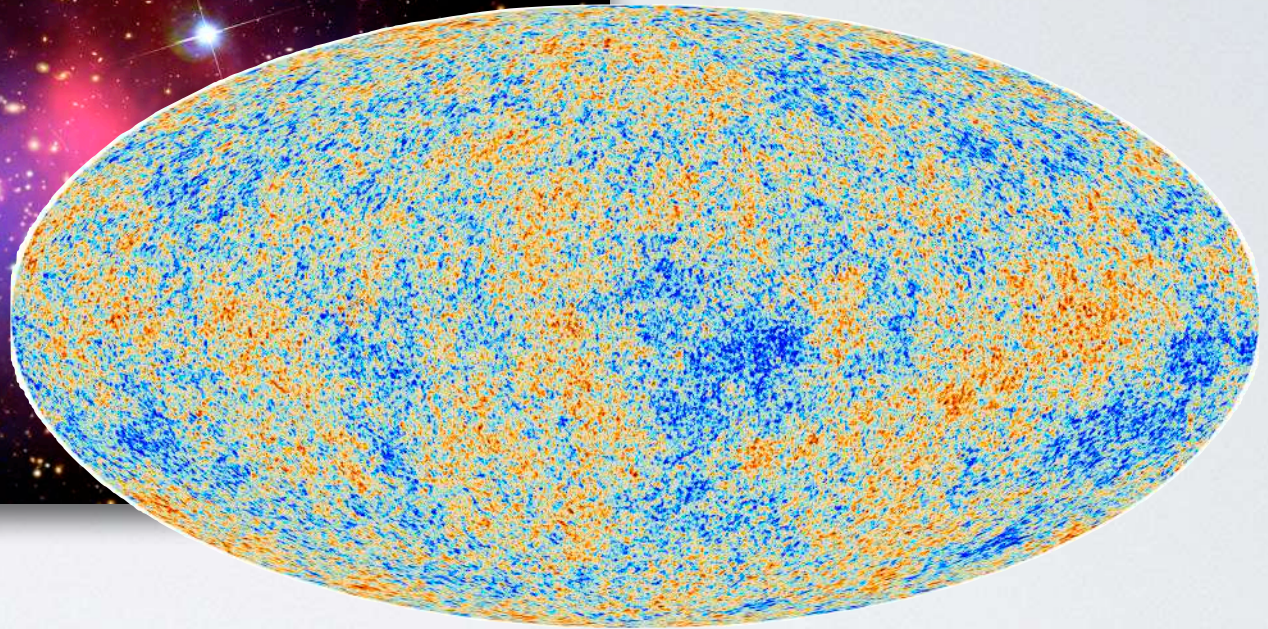
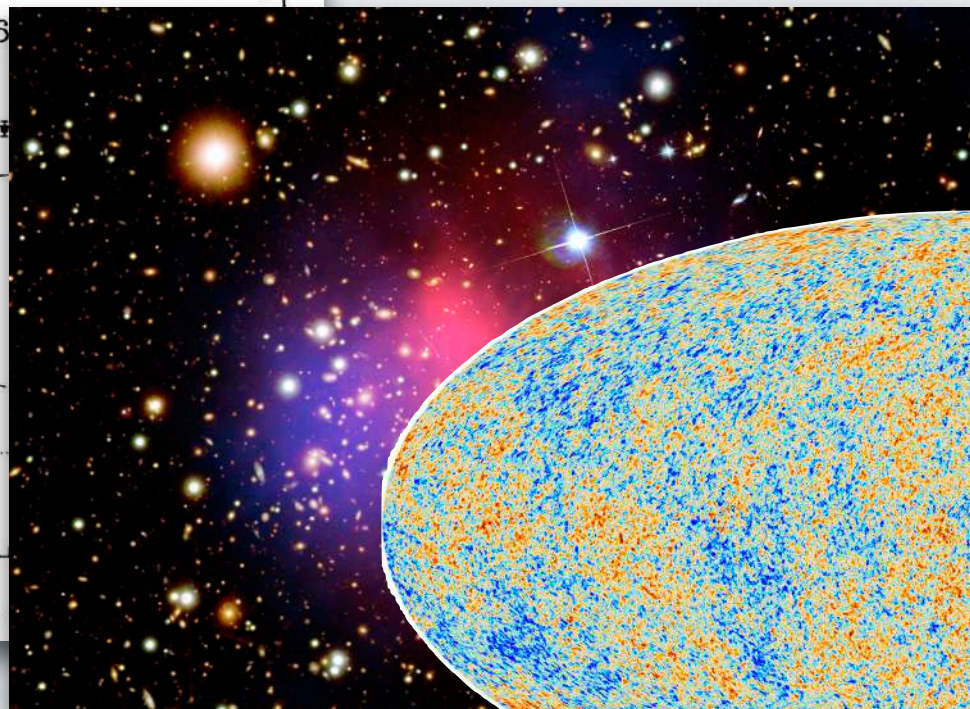
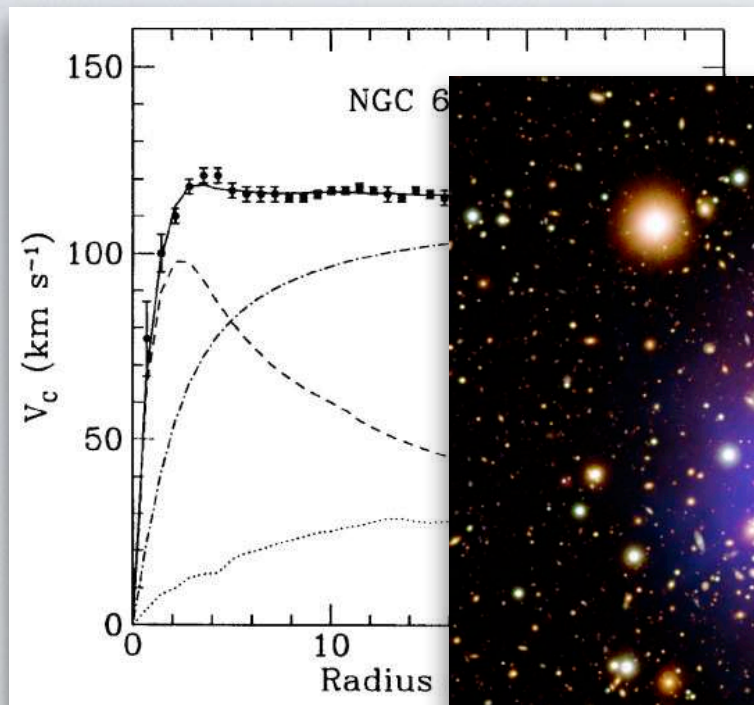


BCTP – Sep 30, 2026



"la Caixa" Foundation

THE QUEST FOR DARK MATTER



Galaxy formation

$$\lambda_{dB} = \frac{2\pi}{mv} \lesssim 100 \text{ kpc}$$

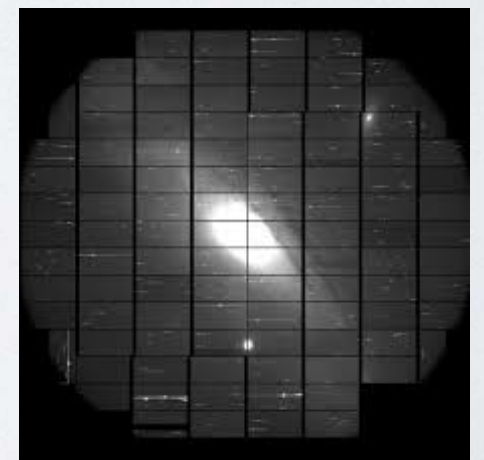
$$m \gtrsim 10^{-24} \text{ eV}$$

[Hlozek et al., PRD **91** (2015)]

[Niikura et al., Nat. Astr. 3 (2019) 6]

microlensing
searches of
PBHs

$$m \lesssim 10^{46} \text{ GeV}$$



10⁻³⁰

10⁻²⁰

10⁻¹⁰

10⁰

10¹⁰

10²⁰

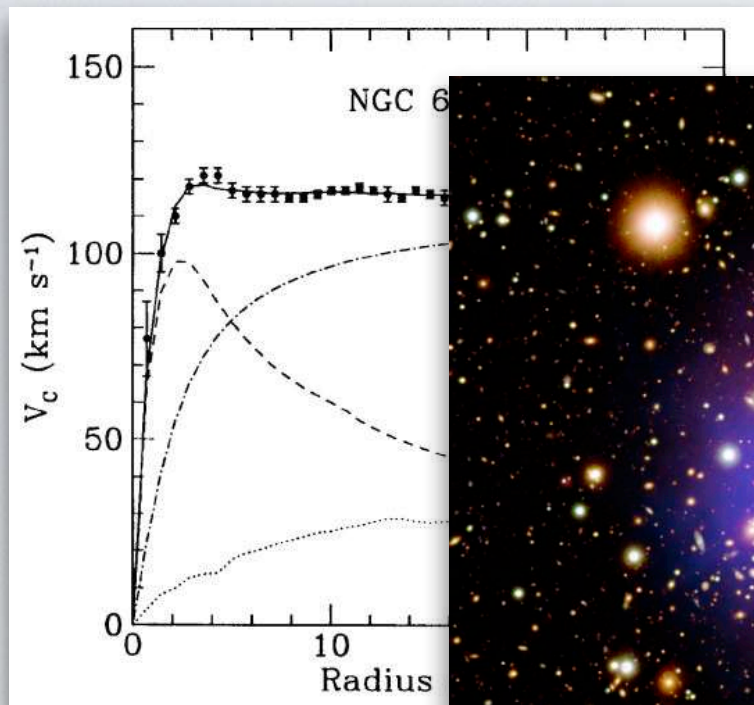
10³⁰

10⁴⁰

10⁵⁰

m [GeV]

THE QUEST FOR DARK MATTER

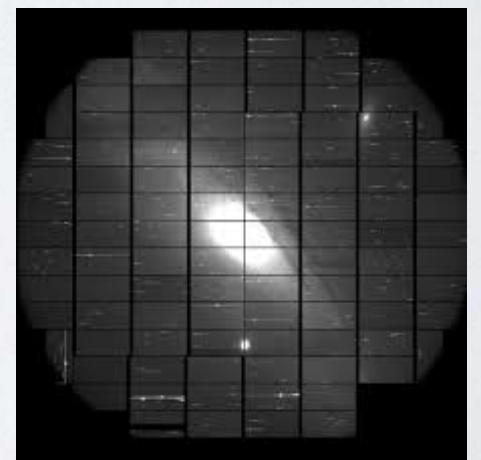


See excellent overview
by Kai!

[Niikura et al., Nat. Astr. 3 (2019) 6]

microlensing
searches of
PBHs

$$m \lesssim 10^{46} \text{ GeV}$$



[Hlozek et al., PRD **91** (2015)]

$$\sim 10^{-24} \text{ eV}$$

kpc

10^{-30}

10^{-20}

10^{-10}

10^0

10^{10}

10^{20}

10^{30}

10^{40}

10^{50}

$m [\text{GeV}]$

THE QUEST FOR

LIGHT DARK MATTER

Kai's
Wishlist

- new light mediator or additional dark-sector states
- sufficiently cold production
- consistency with BBN and N_{eff}
- suppression of late-time annihilation for thermal light DM
- sufficiently weak but experimentally relevant SM coupling

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Ingredients

- resonance
- p-wave or asymmetric DM
- forbidden or inelastic annihilation
- secluded annihilation
- freeze-in or modified reheating

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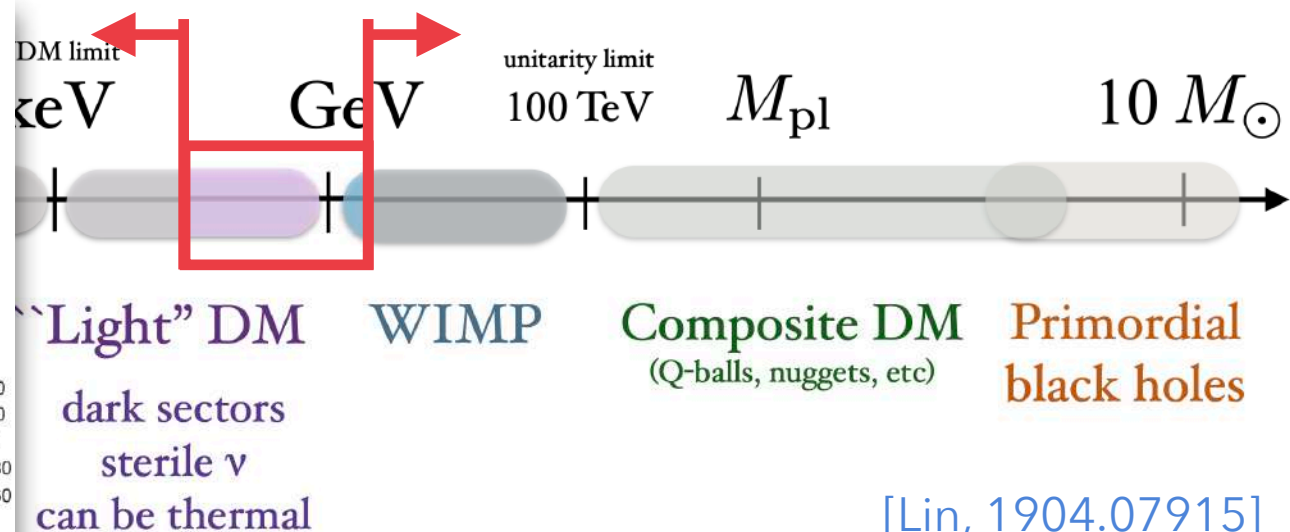
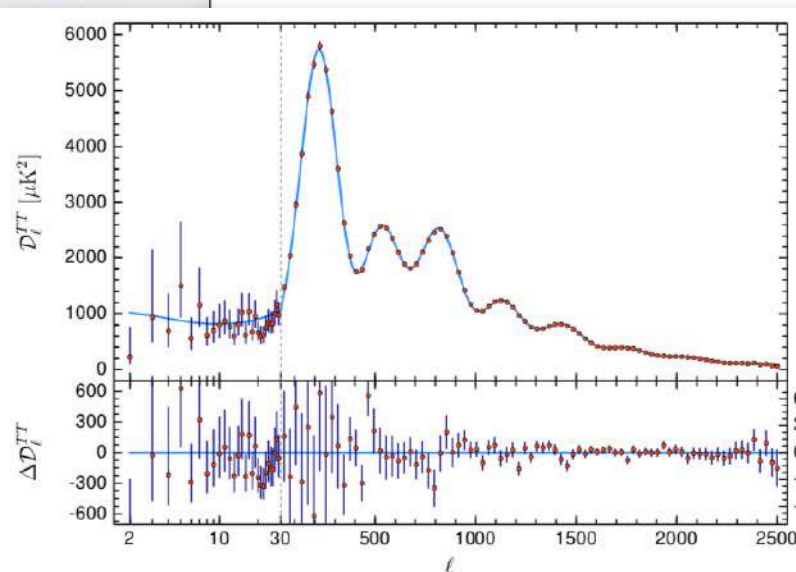
BBN and CMB

$$m_\chi \gtrsim 10 \text{ MeV}$$

**New
mediators!**

Lee-Weinberg

$$m_\chi \gtrsim 5 \text{ GeV} \quad \langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4}$$



[Lin, 1904.07915]

WHAT MAKES UP A LDM MODEL?

Particle content + mediator + thermal history $\Rightarrow$ observation

Particle content

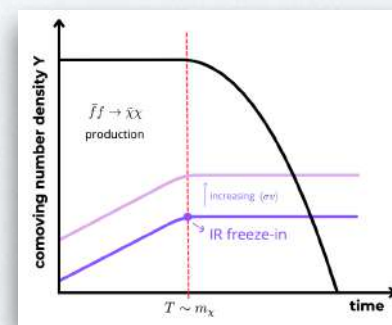
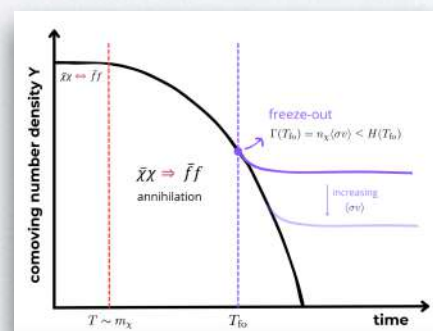
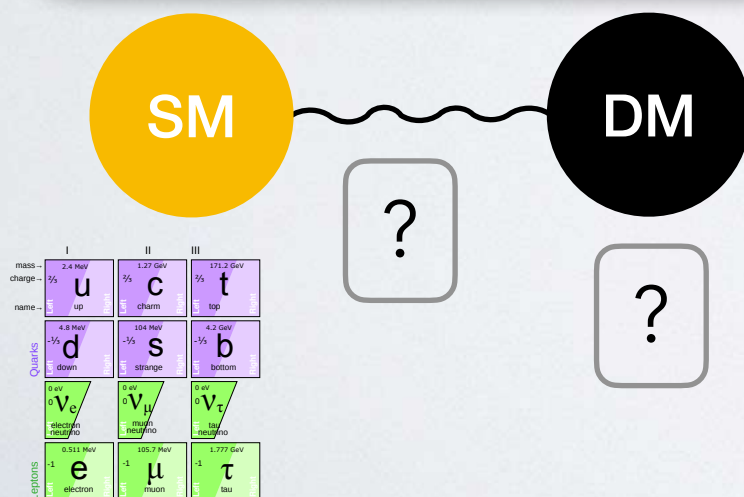
- DM spin and stability
- mediator spin and mass
- dark-sector spectrum

Production history

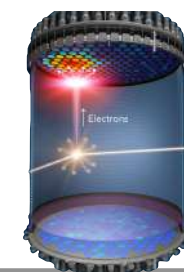
- freeze-out, freeze-in, coannihilation, ...
- one bath or separate dark temperature T'
- reheating and entropy injection

Observations

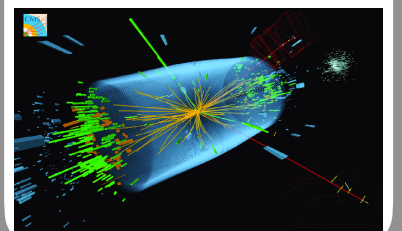
- accelerator production
- electron and nuclear recoils
- annihilation and decay
- self-interactions and structure



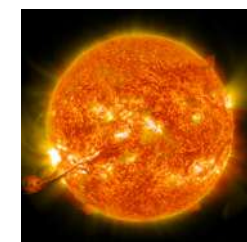
Direct Detection



Accelerators



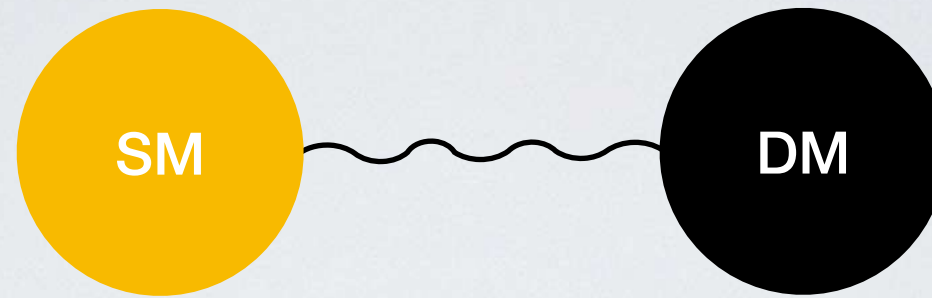
Astrophysics and Cosmo



Indirect detection



PORTAL INTERACTIONS



- Can build three renormalisable dim 4 portal interactions from the SM singlets $H^\dagger H$, $\bar{L}\tilde{H}$ and $B_{\mu\nu}$ by combining them with Dark Sector singlets

Higgs Portal

$$\lambda_{HS} S^\dagger S H^\dagger H$$

Neutrino Portal

$$-Y^N \bar{L}\tilde{H} N$$

Vector Portal

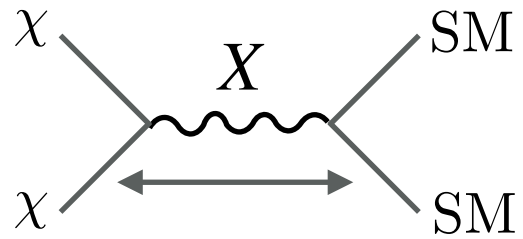
$$-\frac{\epsilon_Y}{2} B_{\mu\nu} X^{\mu\nu}$$

- Plus dim 5 axion portal

$$\frac{G_{agg}}{4} a \text{Tr}[G_{\mu\nu} \tilde{G}^{\mu\nu}]$$

PORTAL DOES NOT DEFINE RELIC DENSITY MECHANISM

Direct annihilation



- **One thermal bath**
- Abundance set via freeze-out

$$n_{\chi}^{\text{eq}}(T_f) \langle \sigma v \rangle \approx H(T_f)$$

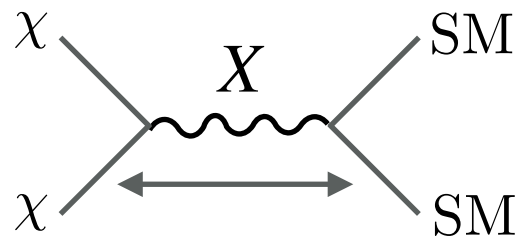
Production scaling:

$$\langle \sigma v \rangle_{\chi\chi \rightarrow ff} \propto \alpha_{\text{vis}} \alpha_D$$

$$\Omega h^2 \propto \langle \sigma v \rangle^{-1}$$

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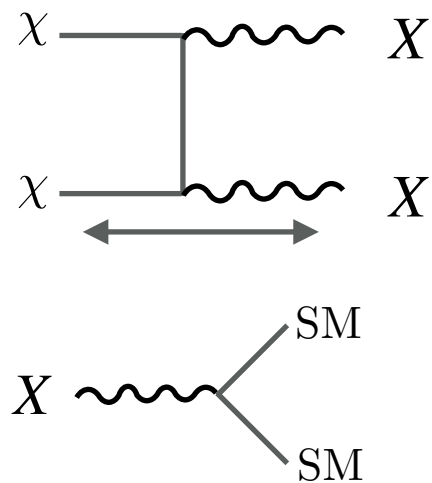
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Secluded annihilation



- Abundance set via
- $$n_{\chi}^{\text{eq}}(T'_f) \langle \sigma v \rangle \approx H(T_f)$$

$$m_{\text{DM}} > m_X$$

Production scaling:

$$\langle \sigma v \rangle_{\chi\chi \rightarrow ff} \propto \alpha_{\text{vis}} \alpha_D$$

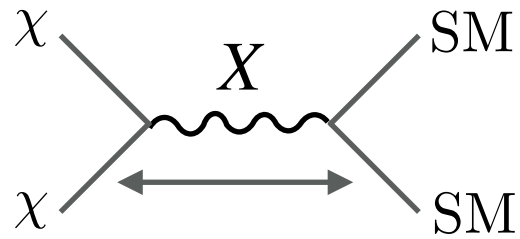
$$\Omega h^2 \propto \langle \sigma v \rangle^{-1}$$

$$\langle \sigma v \rangle_{\chi\chi \rightarrow XX} \propto \frac{\pi \alpha_D^2}{m_{\chi}^2}$$

$$\Omega h^2 \propto \alpha_D^{-2}$$

PORTAL DOES NOT DEFINE RELIC DENSITY MECHANISM

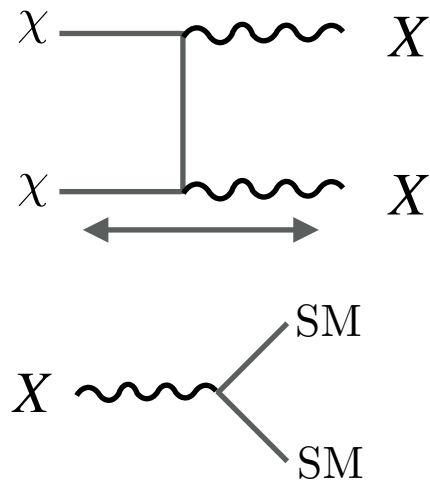
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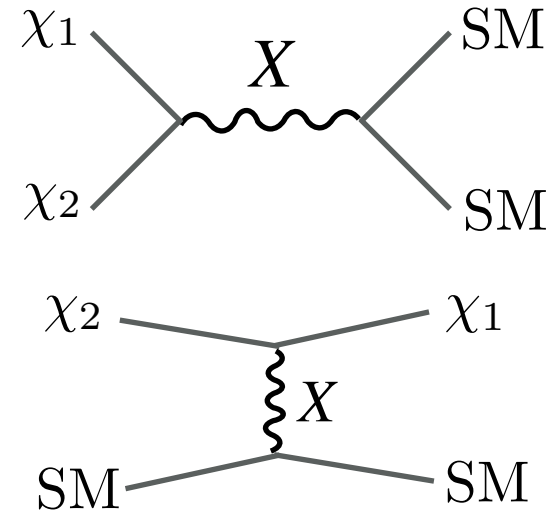
Secluded annihilation



- Abundance set via
- $$n_{\chi}^{\text{eq}}(T_f') \langle \sigma v \rangle \approx H(T_f)$$

$$m_{\text{DM}} > m_X$$

Inelastic/coannihilation



- Abundance set via
- $$n_{\chi}^{\text{eq}}(T_f) \langle \sigma v \rangle_{\text{coann}} \approx H(T_f)$$
- or
- $$\Gamma_{\chi_1 \leftrightarrow \chi_2}(T_{\text{conv}}) \approx H(T_{\text{conv}})$$

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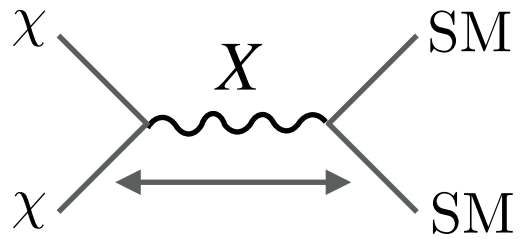
$$\Omega h^2 \propto \alpha_D^{-2}$$

$$\langle \sigma v \rangle_{\text{coann}} = \sum_{i,j} \langle \sigma_{ij} v \rangle \frac{n_i^{\text{eq}} n_j^{\text{eq}}}{(n^{\text{eq}})^2}$$

$$\frac{n_{\chi_2}^{\text{eq}}}{n_{\chi_1}^{\text{eq}}} \simeq \frac{g_2}{g_1} \left(1 + \frac{\Delta}{m_{\chi_1}} \right)^{3/2} e^{-\Delta/T}$$

PORTAL DOES NOT DEFINE RELIC DENSITY MECHANISM

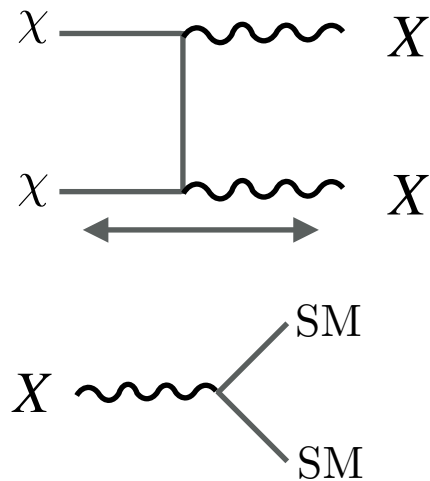
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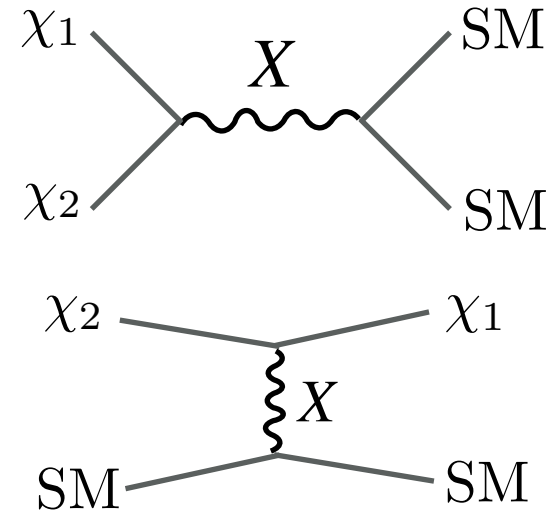
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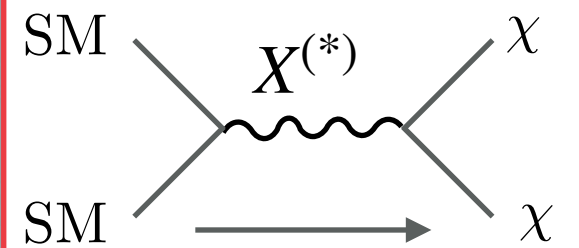
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Portal production



- **Never in equilibrium**
- Requires throughout

$$\Gamma_{\text{prod}}(T) < H(T)$$

Production scaling:

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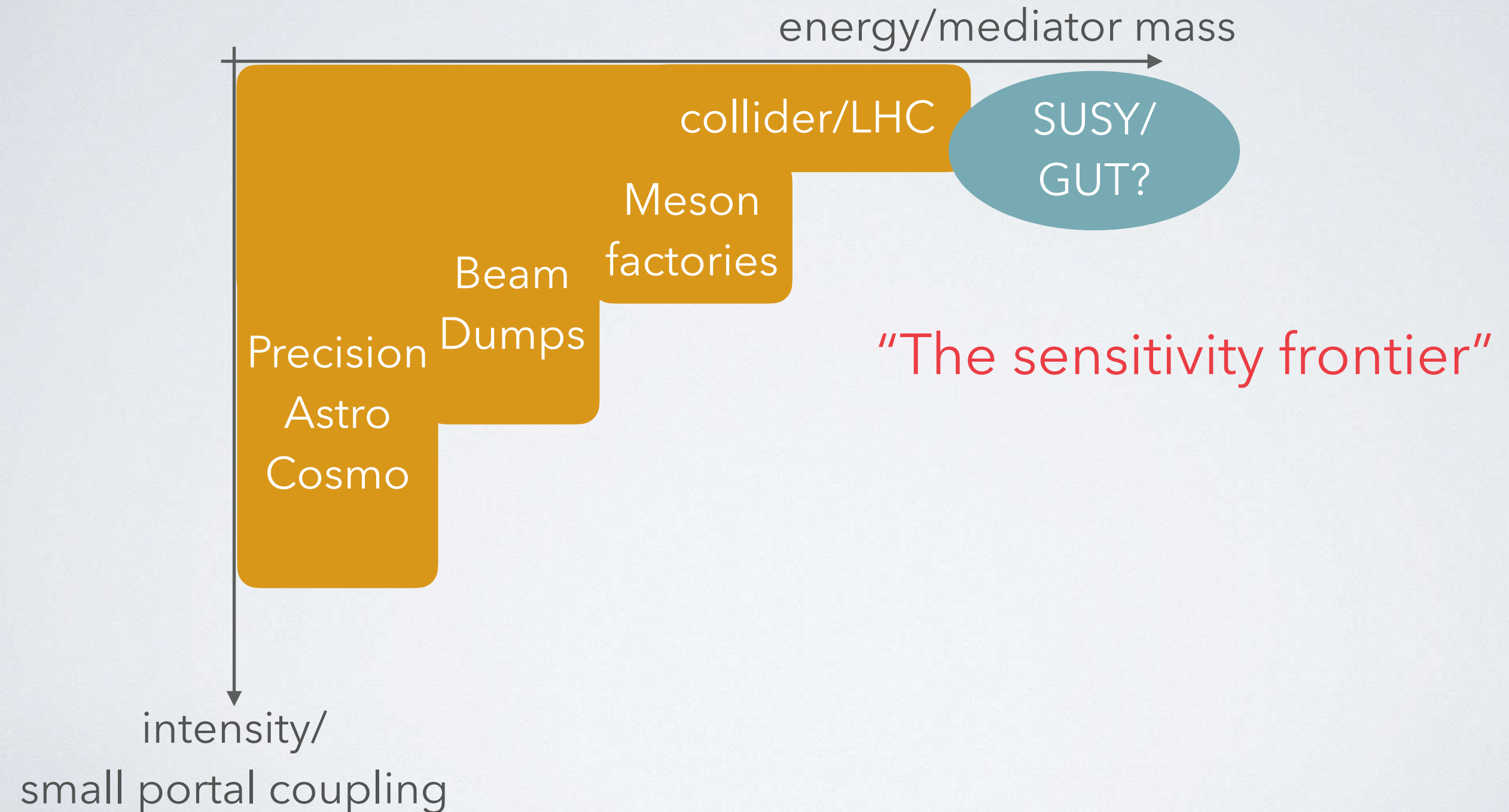
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$$Y_{\chi}^{\infty} = \int_{T_0}^{T_{\text{max}}} \frac{\gamma_{\text{prod}}(T)}{s(T)H(T)T} dT$$

$$Y_{\chi}^{\infty} \propto \alpha_{\text{vis}} \alpha_D$$

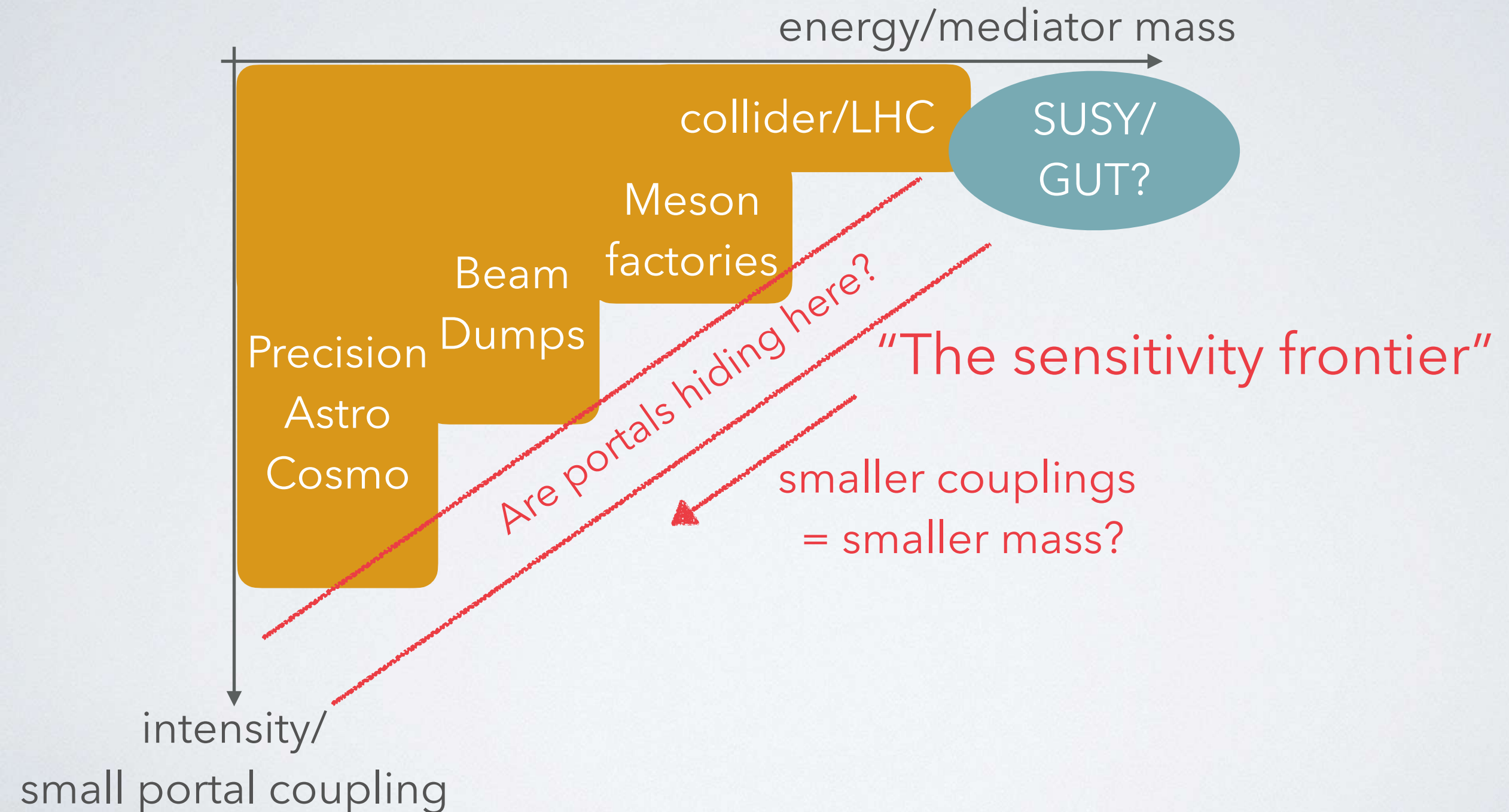
SEARCH FOR THE PORTAL

- Can search for the portal mediator independently through its visible sector interactions



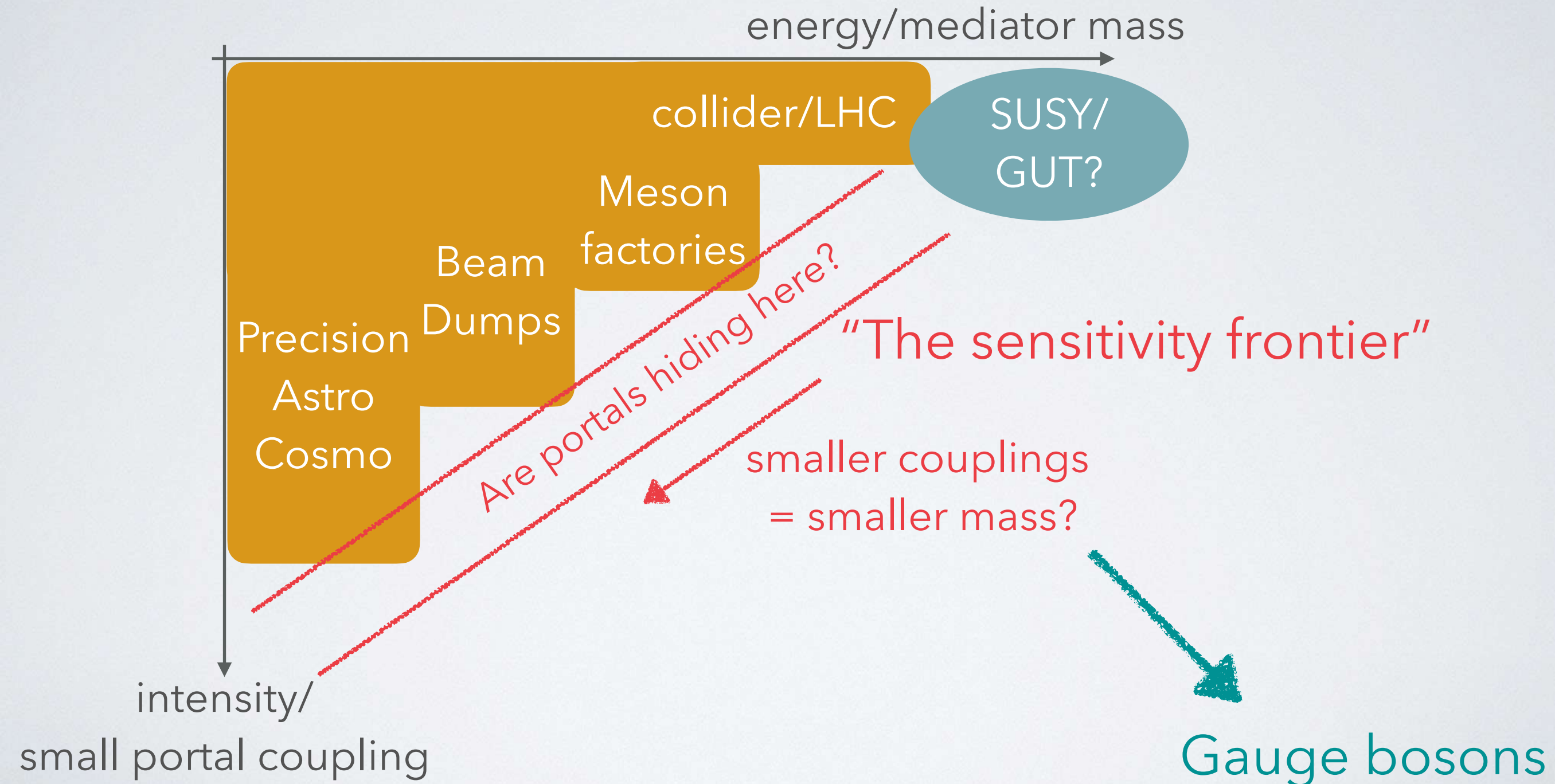
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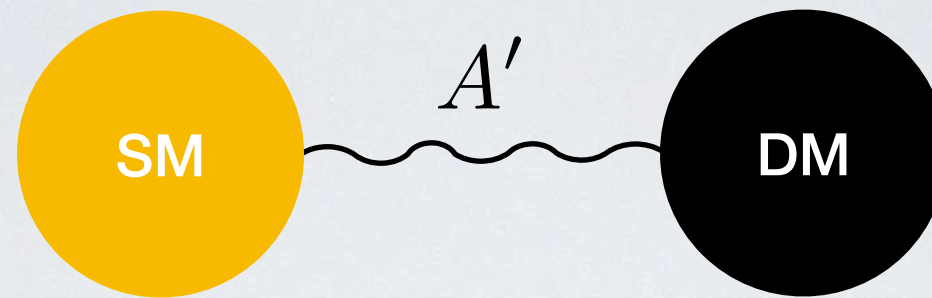


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DARK PHOTONS

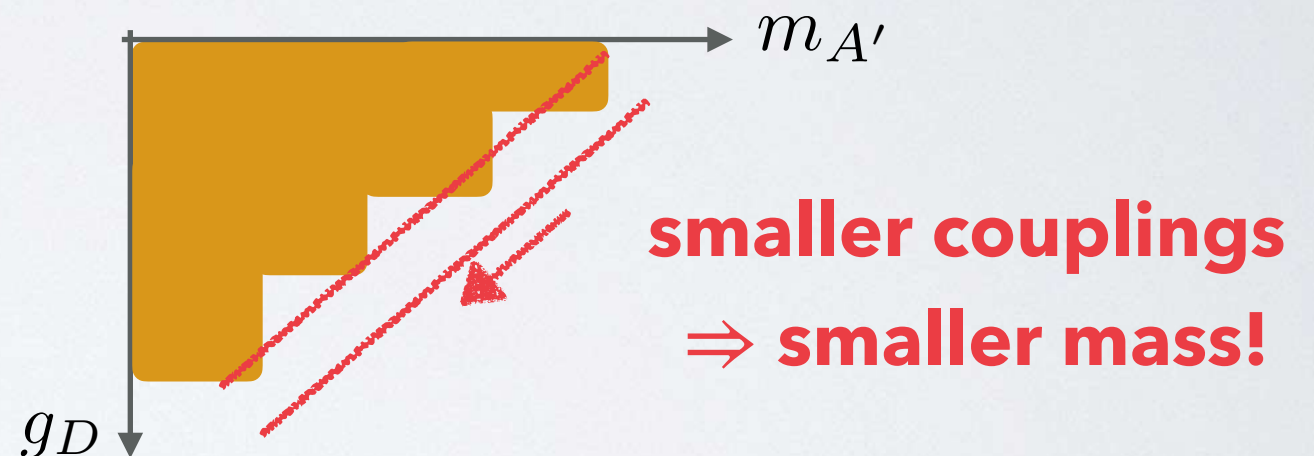


$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + g_D A'_\mu \bar{\chi}\gamma^\mu \chi$$

- If $U(1)_X$ broken by new scalar, mass is proportional to coupling

$$\mathcal{L} \supset (D_\mu S)^\dagger D^\mu S \rightarrow g_D^2 v_D^2 A'_\mu A'^\mu$$

$$\Rightarrow m_{A'} = g_D v_D$$



- Four-parameter theory $\{m_\chi, m_{A'}, \epsilon, g_D\}$ with two distinct regimes:

DARK PHOTONS

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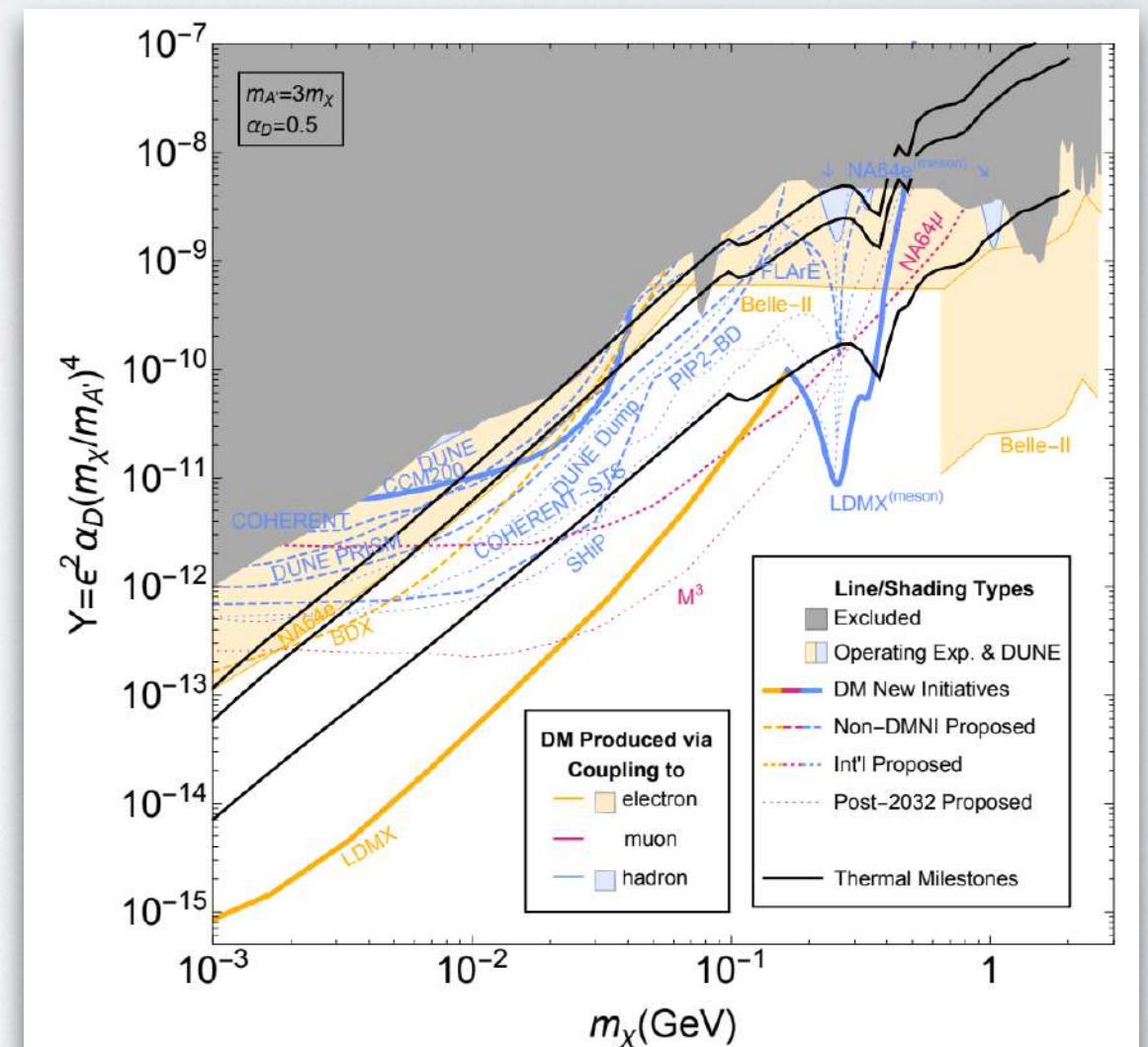
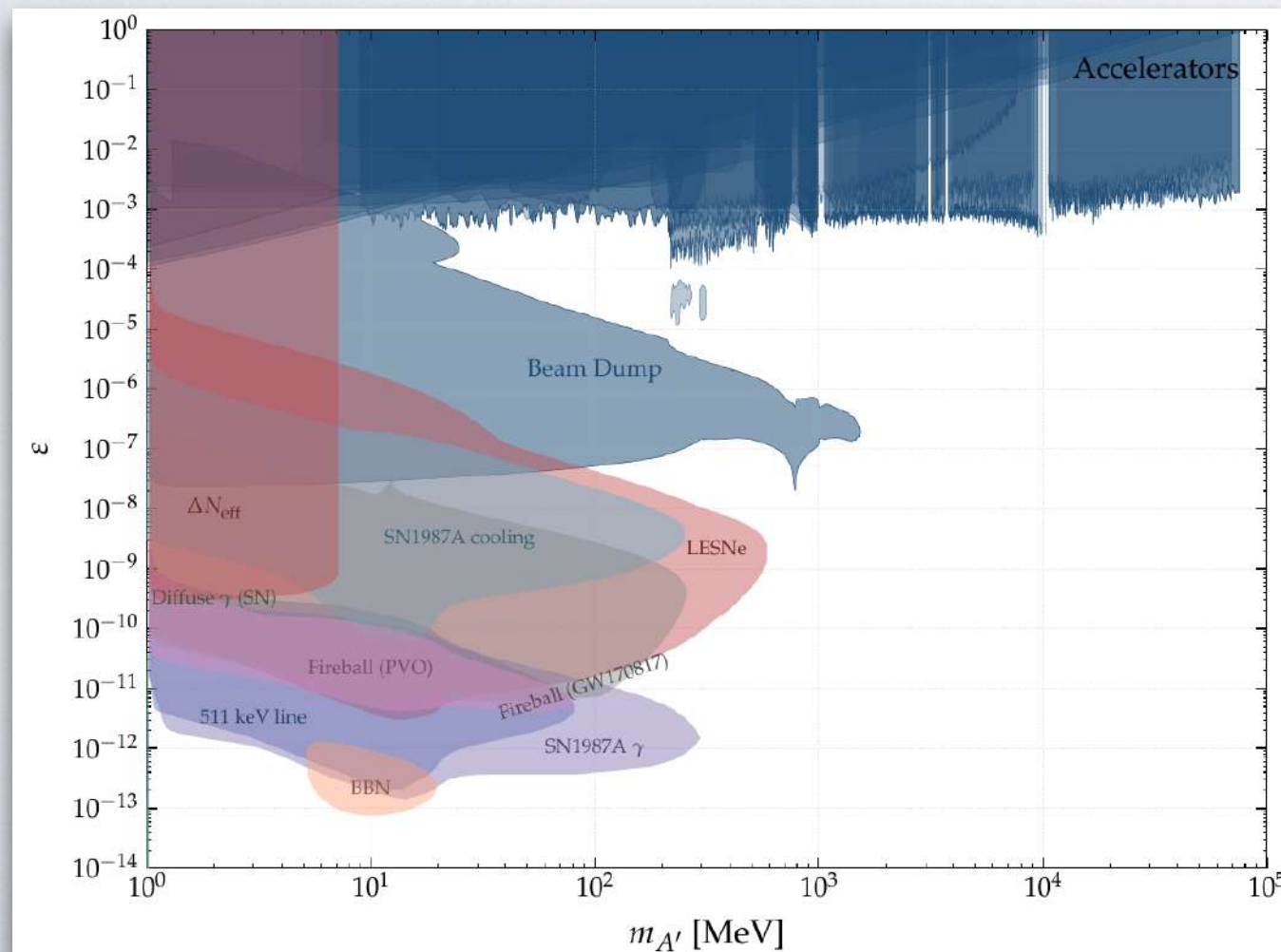
- There are two vastly different phenomenological regimes

visible:

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

invisible:

$$m_{A'} > 2m_\chi \quad A' \rightarrow \chi\chi$$



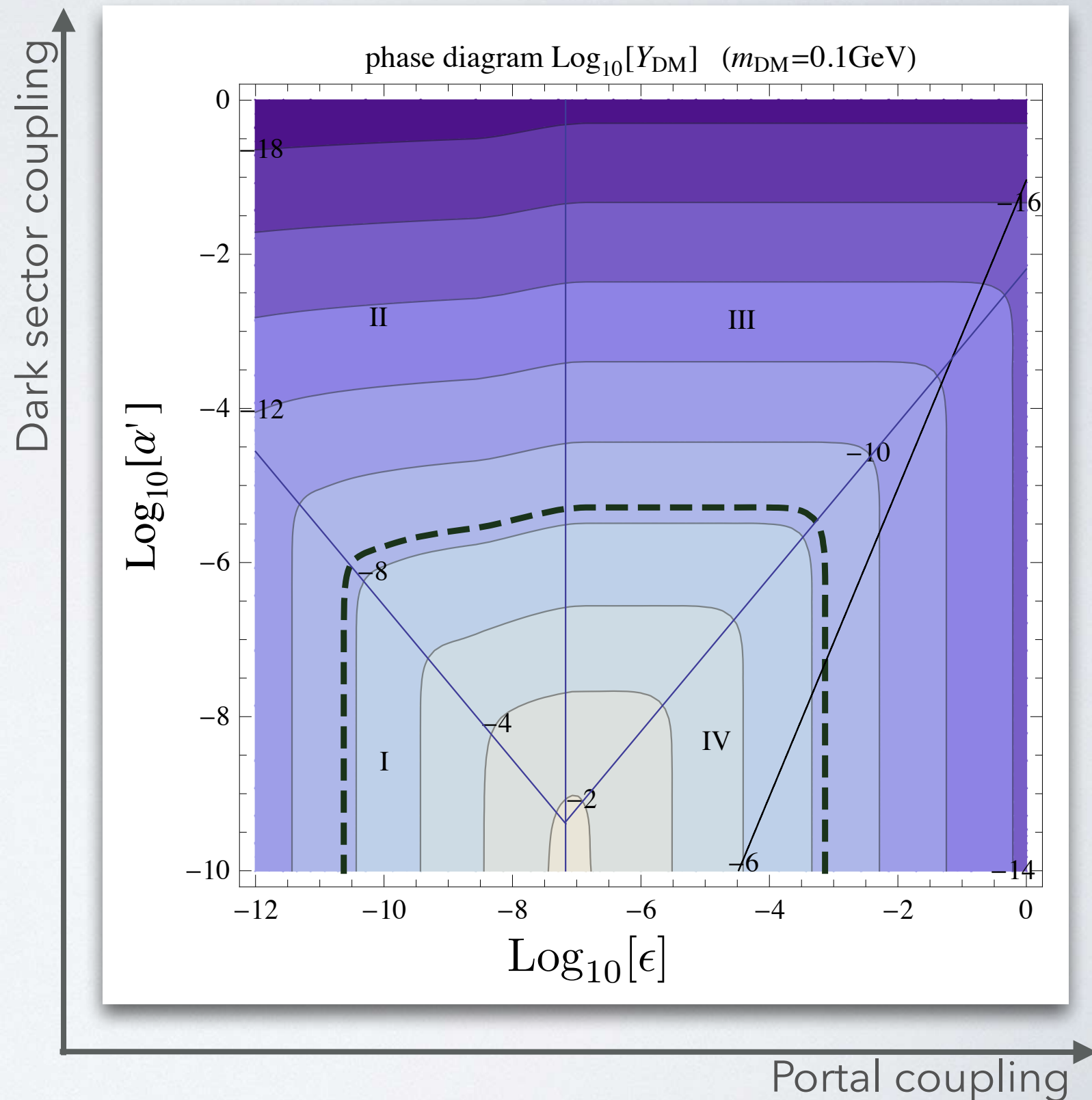
DM PHASE DIAGRAM

- Minimal dark photon portal has rich DM phenomenology
"Mesa" diagram

- DM production governed by

$$\frac{xH}{s} \frac{dY_\chi}{dx} = \langle \sigma_{\text{portal}} v \rangle [Y_{\text{eq}}^2(T) - Y_\chi^2] + \langle \sigma_{\text{DS}} v \rangle [Y_{\text{eq}}^2(T') - Y_\chi^2]$$

- Continuous deformation of the couplings connects:
I. Freeze-in
II. Reannihilation
III. Dark Freeze-out
IV. Freeze-out



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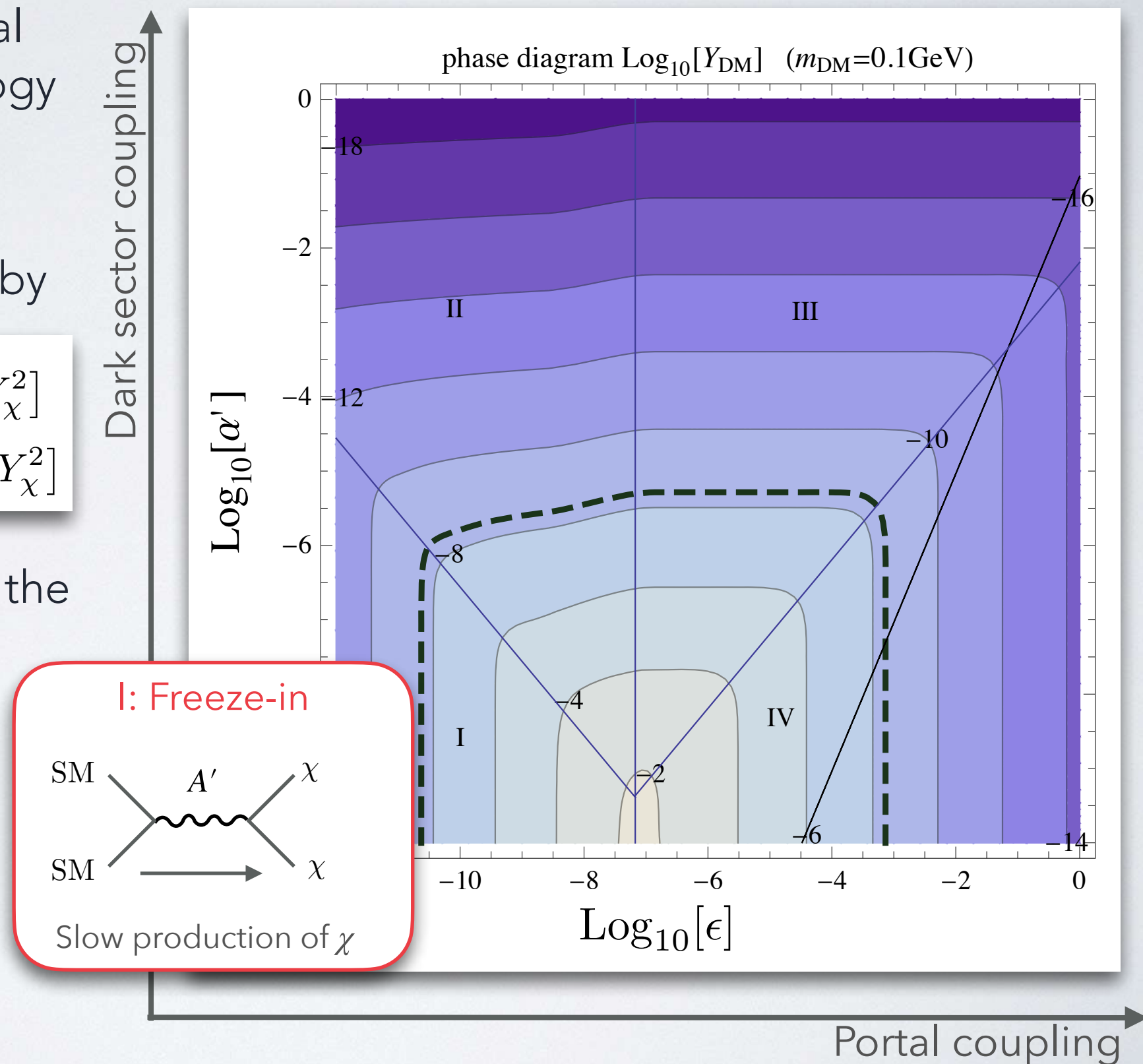
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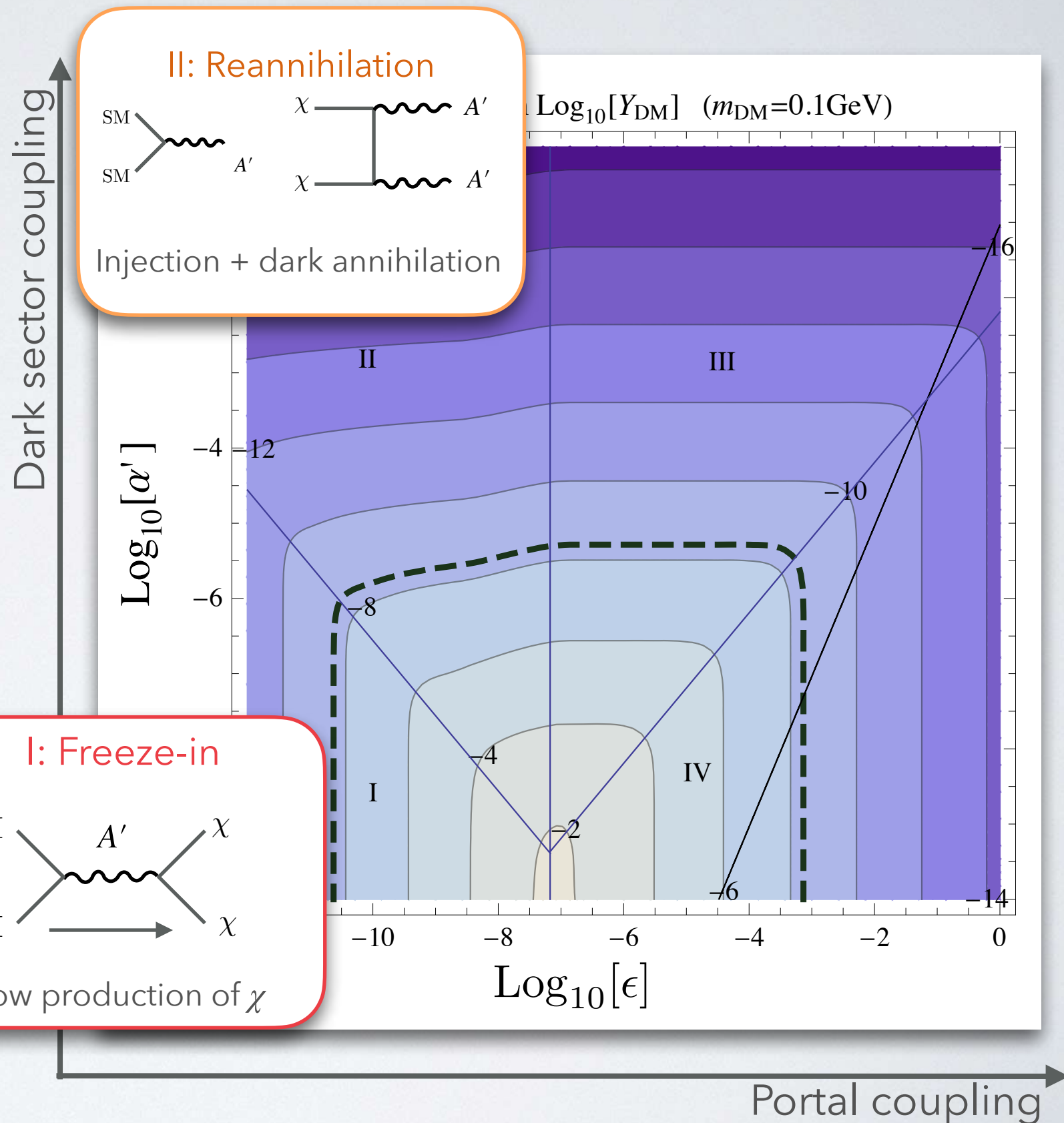
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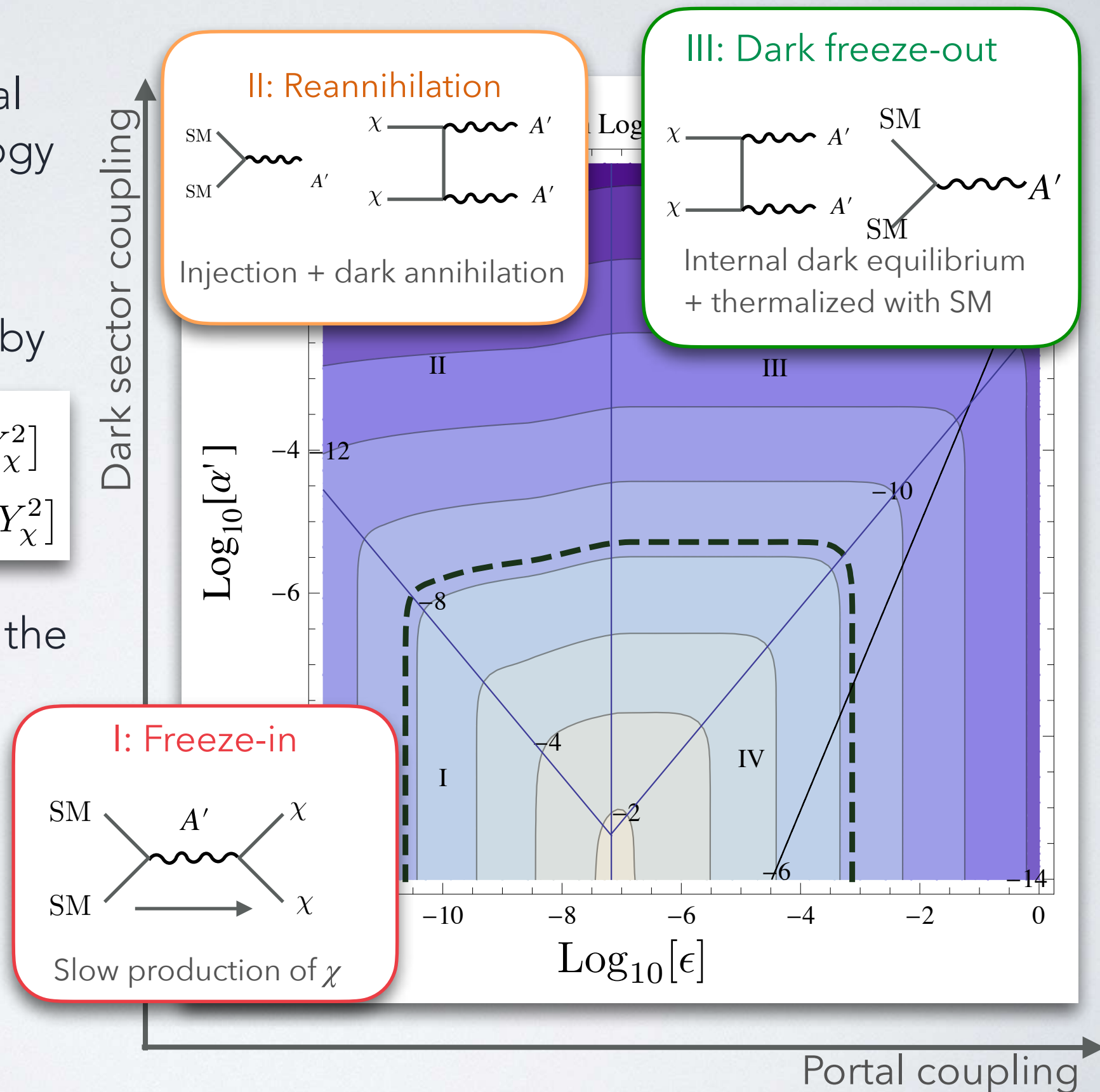
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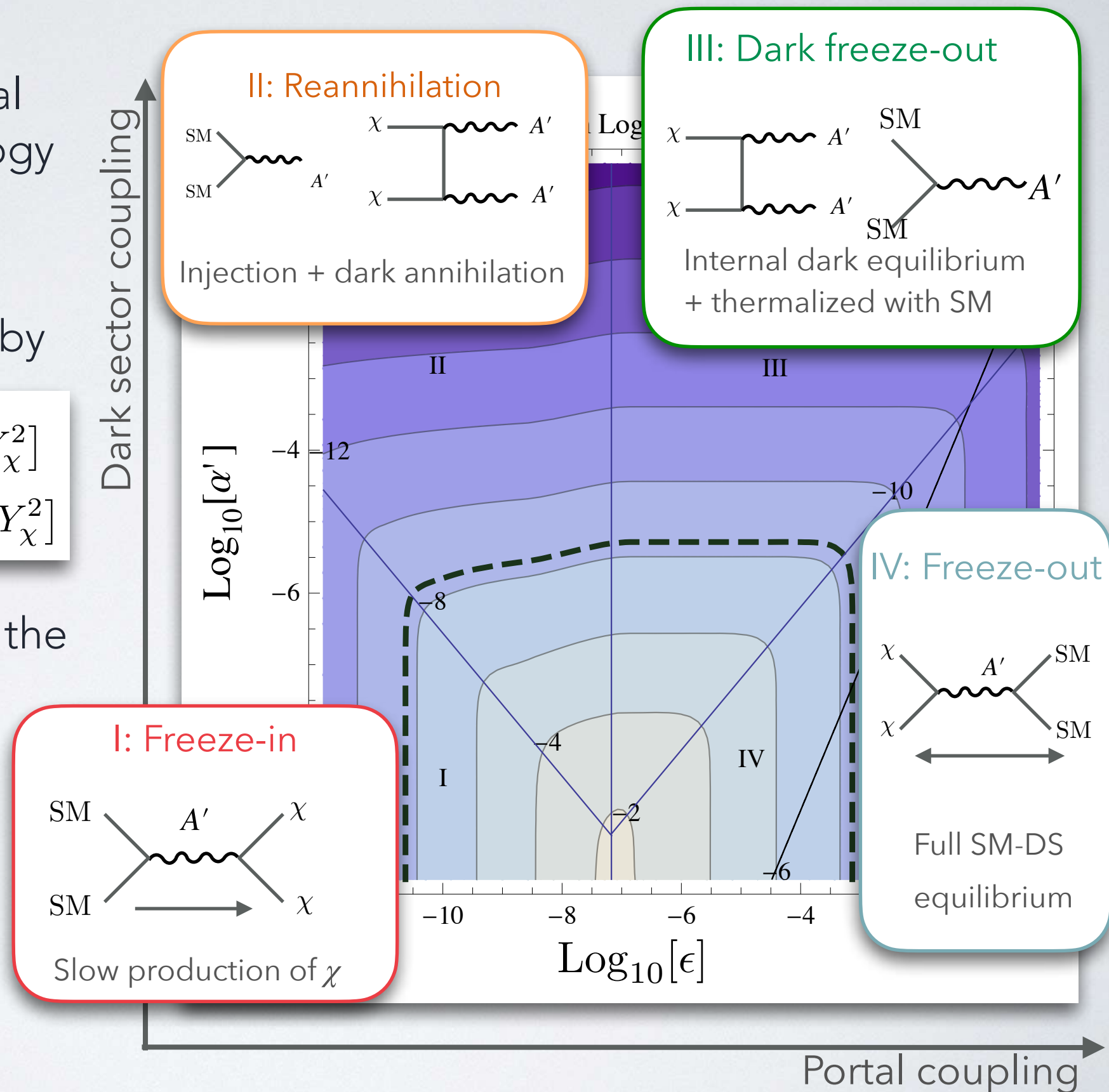
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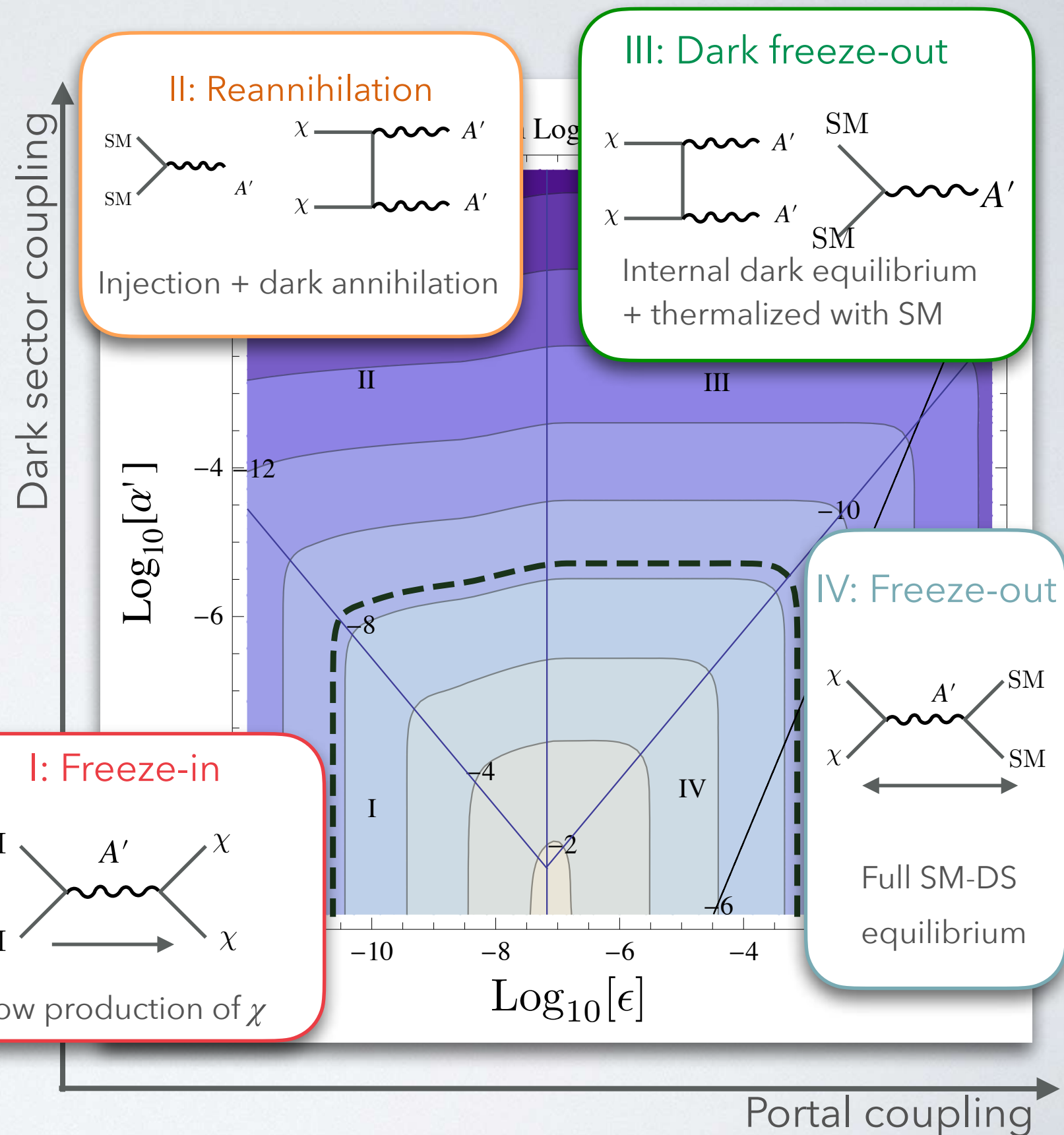
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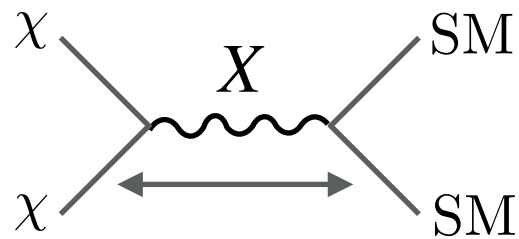
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$$Y_{\text{FI}} \propto \epsilon^2 \quad Y_{\text{FO}} \propto \epsilon^{-2}$$



TODAY: THREE EXAMPLES

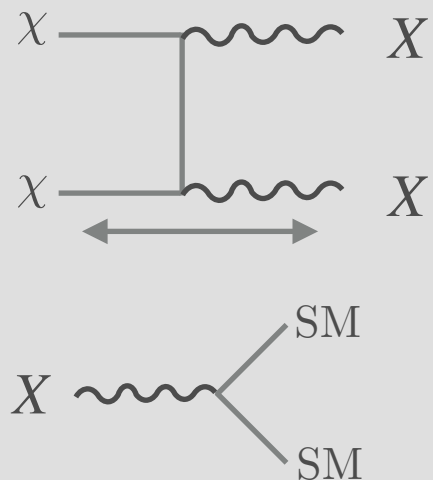
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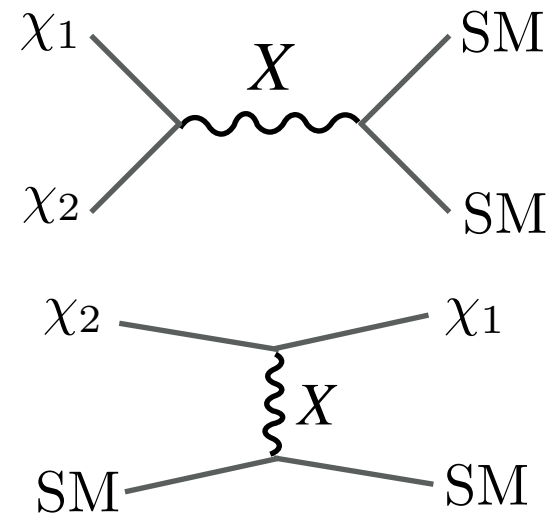
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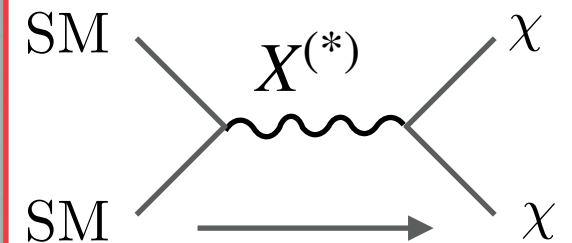
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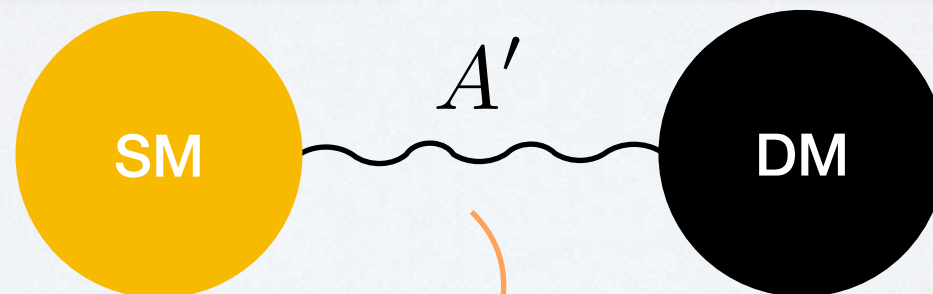
$$\Gamma_{\text{prod}}(T) < H(T)$$

Resonant Freeze-out

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

$$\Gamma_{\text{portal}}/H \gg 1$$

- Small portal couplings through s-channel enhancement



Inelastic/coannihilation

- Low q -enhanced scattering
- Sensitive to reheating T_{RH}
- Tiny interactions make it hard to test

Freeze-in

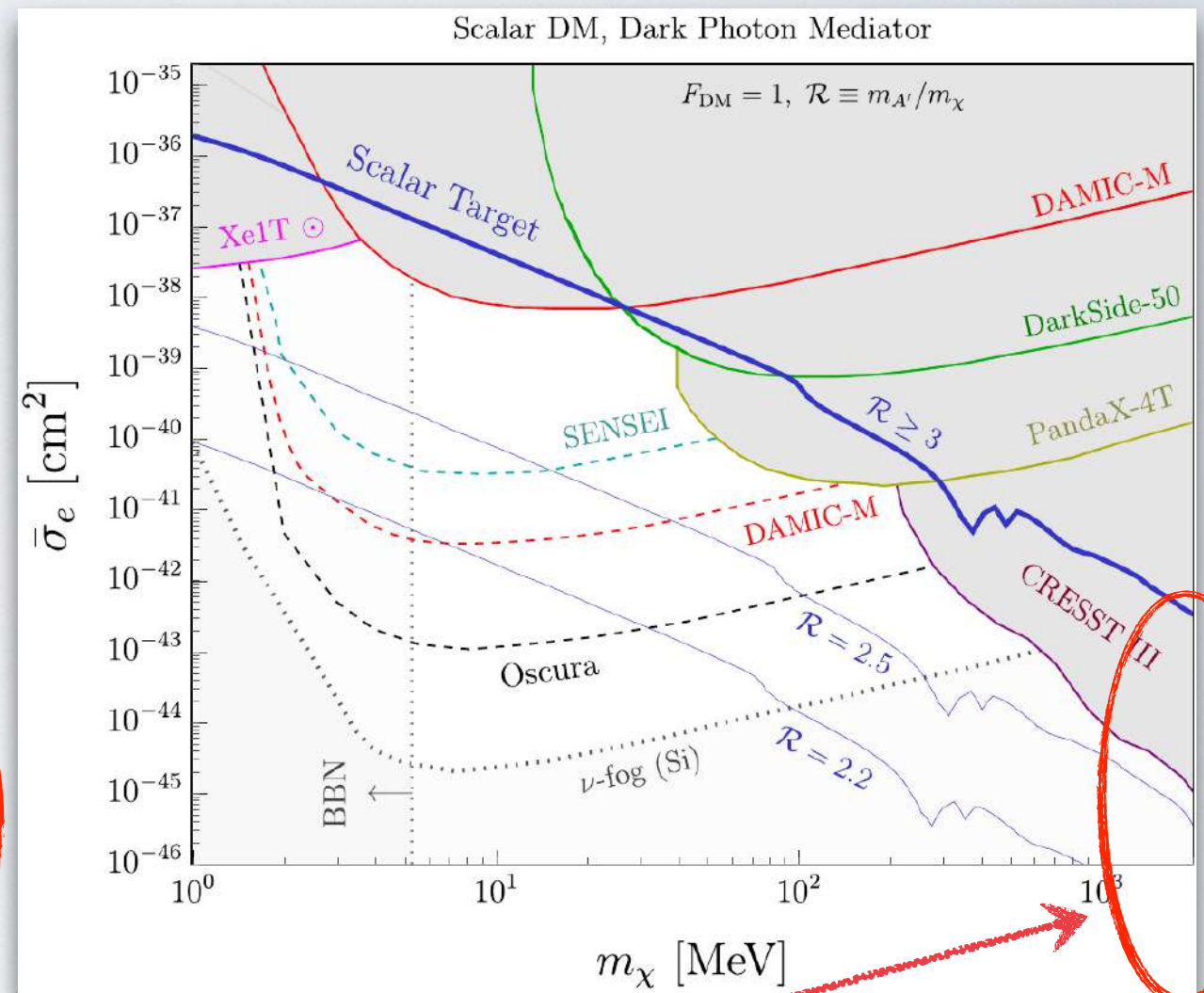
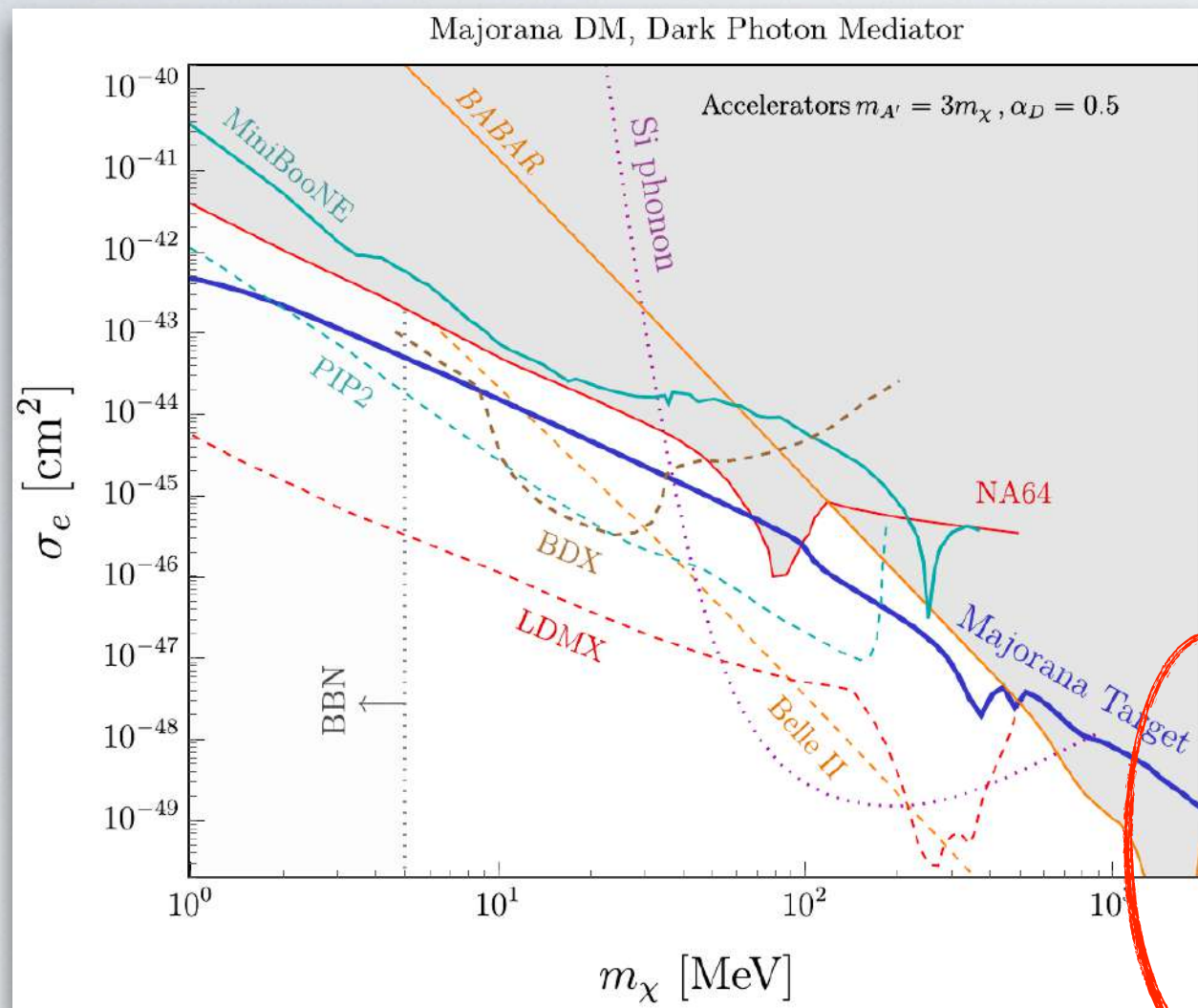
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RESONANT FREEZE-OUT

THERMAL BENCHMARKS

- Off-resonance direct-annihilation benchmarks are already strongly constrained

[Krnjaic, 2505.04626]



What happens here?



- But the map from relic abundance to detection rate is **model dependent**.

DM PRODUCTION

- If DM was in thermal equilibrium with SM bath, can be produced via **freeze out** described by simple Boltzman equation

$$\frac{dn}{dt} + 3Hn = \langle \sigma v \rangle (n_{eq}^2 - n^2)$$

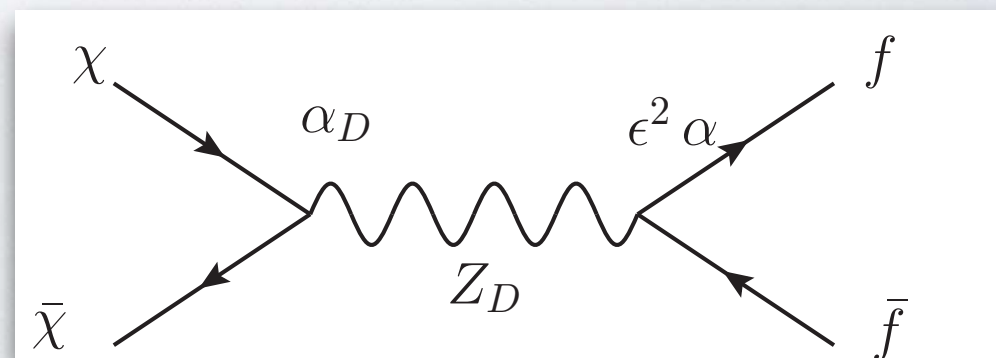
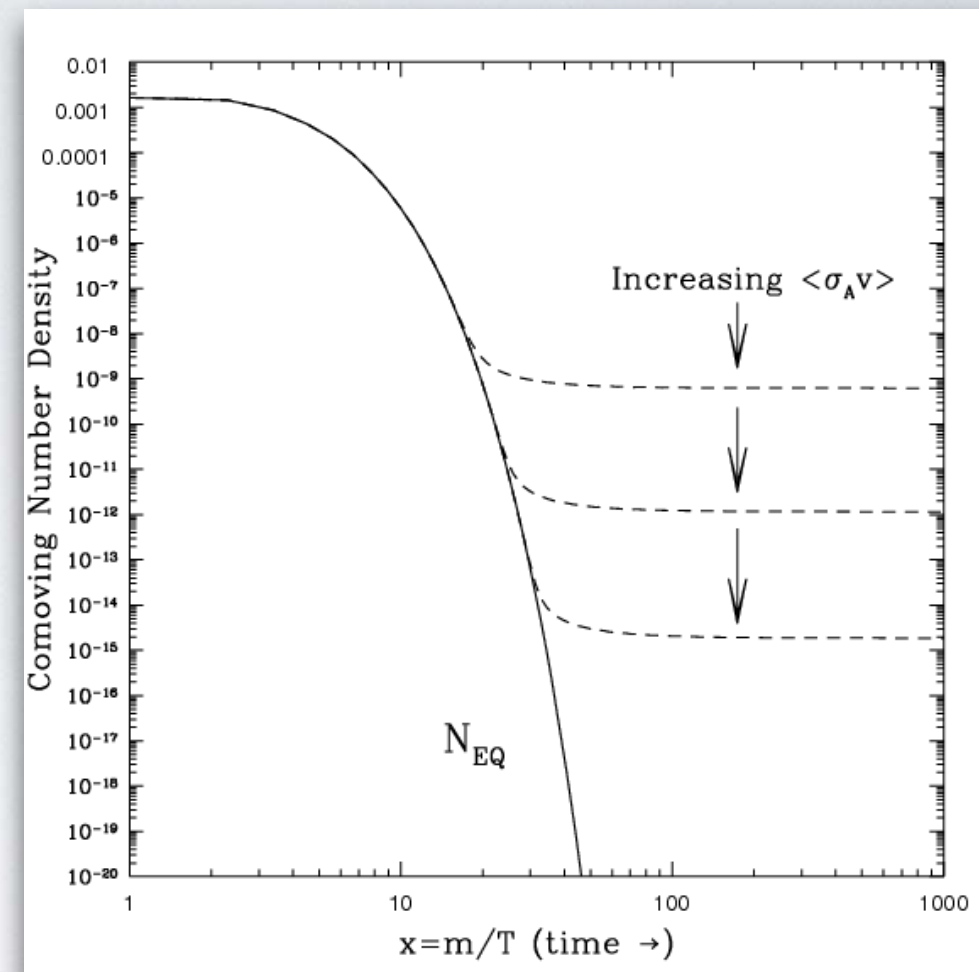
- Freeze-out** abundance scales inversely with thermal cross section

$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle}$$

- For $M_{Z_D} > m_{\chi'}$ simple s-wave annihilation

$$\sigma(\epsilon, \alpha_D, M_{Z_D}) \propto \frac{\epsilon^2 \alpha \alpha_D}{(s - M_{Z_D}^2)^2 + \Gamma_{Z_D}^2 M_{Z_D}^2}$$

- Larger couplings ϵ and α_D yield smaller abundances!
- Resonance enhancement** → can shift abundance to much smaller couplings

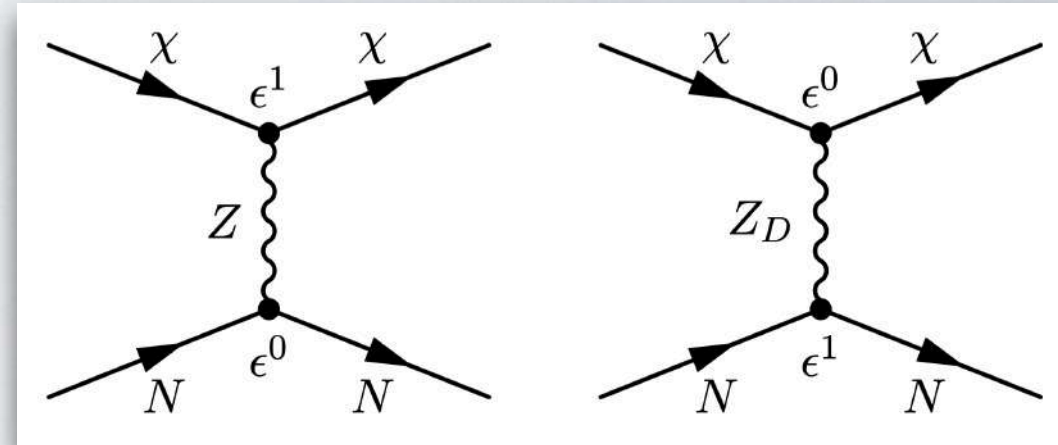


DIRECT DETECTION

- GeV-scale “WIMPs” strongly constrained by direct detection!

$$\sigma_{\chi T} \propto g_D^2 \epsilon^2 A^2 F^2(E_R) \left| \frac{f_n^{(Z_D)}}{m_{Z_D}^2} + \frac{f_n^{(Z)} s_W}{m_Z^2 - m_{Z_D}^2} \right|^2$$

with $f_n^{(X)} = \frac{1}{A} (Z (2g_{u,X} + g_{d,X}) + (A - Z) (g_{u,X} + 2g_{d,X}))$



BUT: No resonance enhancement in scattering!

- Scaling of the DM signal rate $\frac{dR}{dE_R} = \frac{\rho_\chi}{m_T m_\chi} \int_{v_{\min}} d^3v v f(\vec{v}) \frac{d\sigma_{\chi T}}{dE_R}$

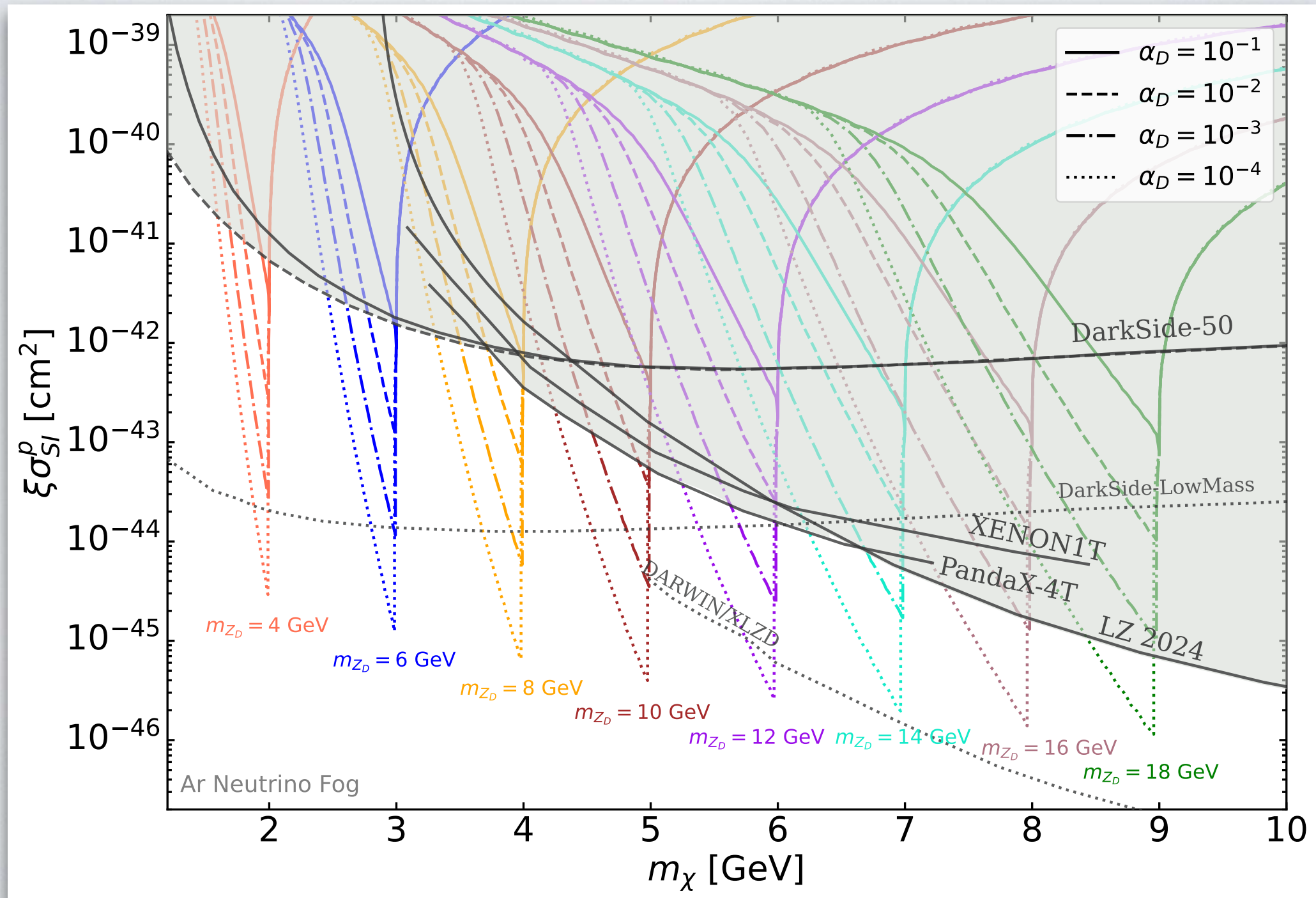
$$\rho_\chi \propto \frac{1}{\langle \sigma v \rangle} \Rightarrow \frac{dR}{dE_R} \propto \frac{\sigma_{\chi T}}{\langle \sigma v \rangle} \propto \frac{\epsilon^2}{\epsilon^2} \frac{1}{(s - M_{Z_D}^2)^2 + \Gamma_{Z_D}^2 M_{Z_D}^2}$$

In the resonance can **suppress DD independently of ϵ !**

DIRECT DETECTION

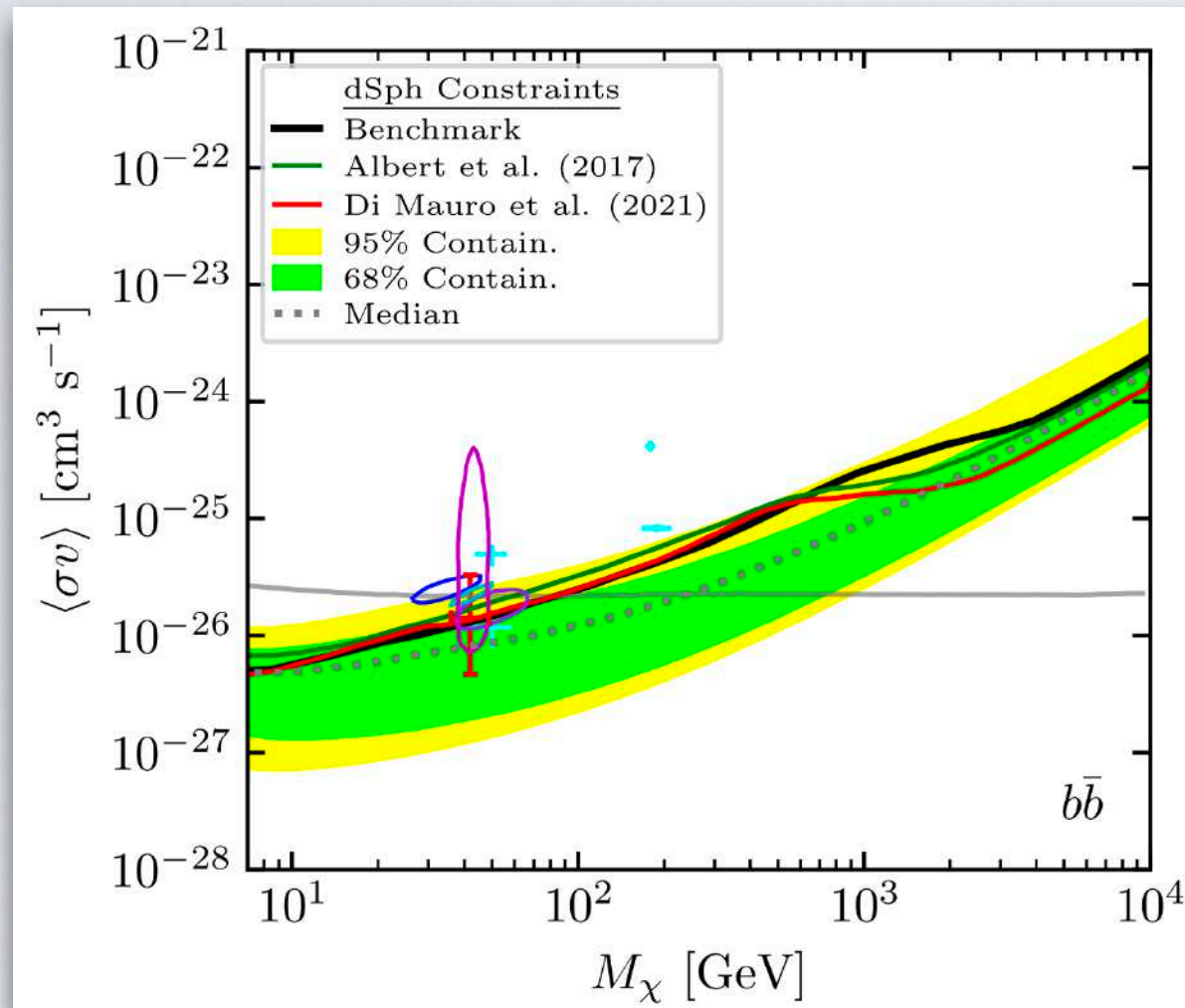
- GeV DM can avoid direct detection **close to resonance** for **small couplings α_D** !

[Alonso-González, Cerdeno, **PF**, No; 2507.11376]

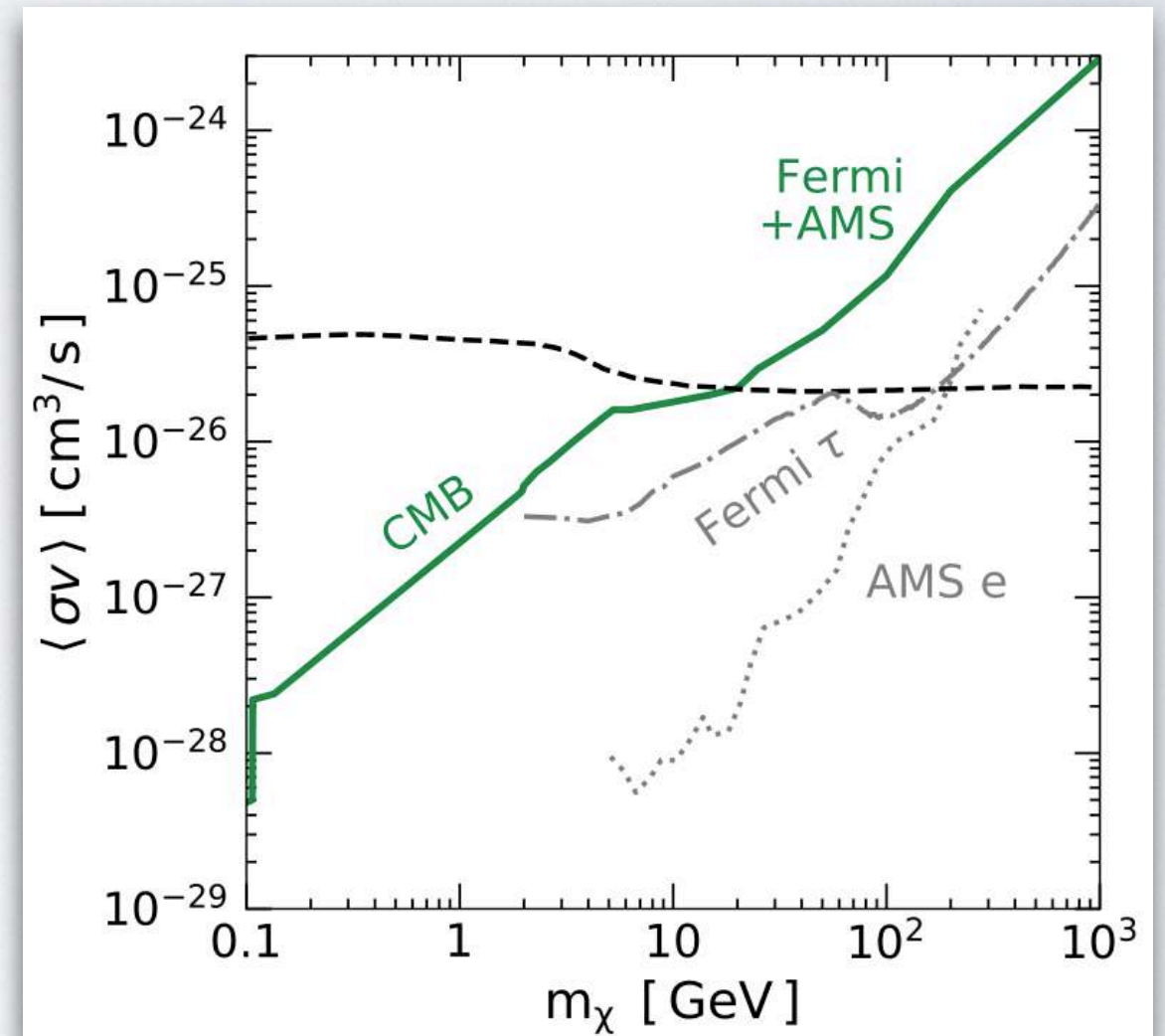


"MODEL-INDEPENDENT" BOUNDS

- The common lore is that GeV-scale WIMPS are ruled out by **indirect detection**



[McDaniel+; PRD 109, 063024]



[Leane+; PRD 98, 023016]

- Is this really model independent? $\rightarrow$ Review simple benchmark

CONSISTENT CMB BOUND

- Rate of energy released into heating and ionisation

$$\frac{d^2 E}{dV dt} = \rho_\chi^2 (1+z)^6 \sum_i f_i(z) \frac{\langle \sigma v \rangle_i}{m_\chi} = \rho_{\text{DM}}^2 (1+z)^6 P_{\text{ann}}(z)$$

with annihilation parameter

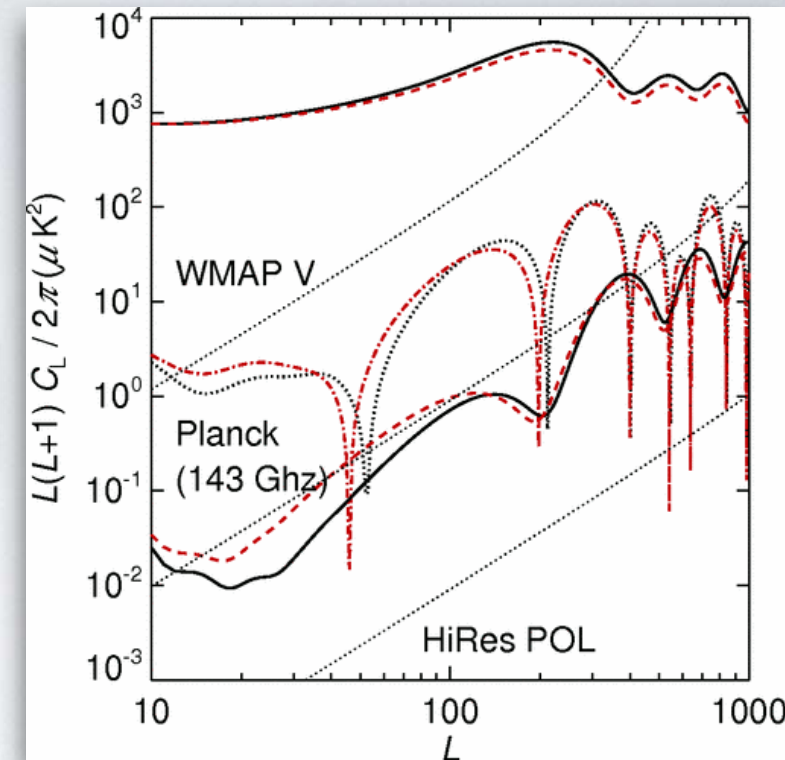
$$P_{\text{ann}}(m_\chi) = \xi^2 \sum_i f_i(m_\chi) \frac{\langle \sigma v \rangle_i}{m_\chi}$$

- Planck: $P_{\text{ann}} < 3.5 \times 10^{-28} \text{ cm}^3 \text{ s}^{-1} \text{ GeV}^{-1}$

[Planck; 1807.06209]

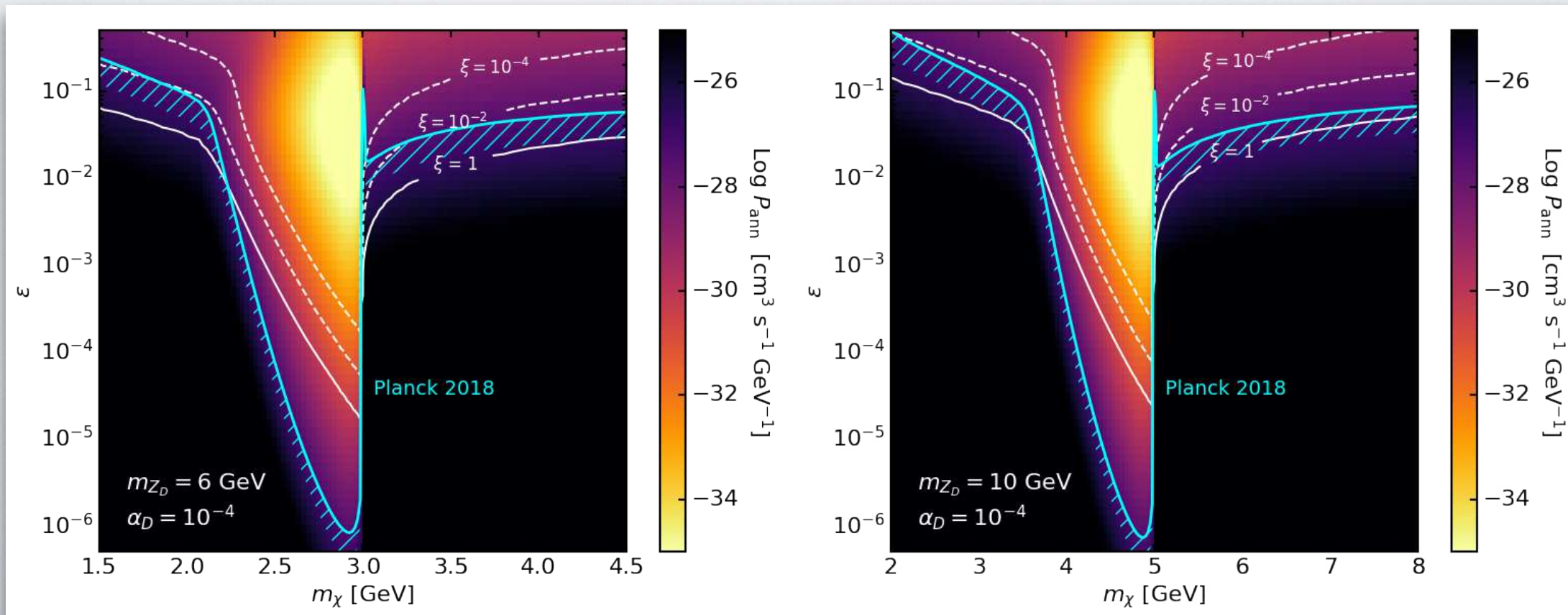
Dilution factor

$$\xi = \frac{\rho_\chi}{\rho_{\text{DM}}}$$



[Padmanabhan, Finkbeiner;
astro-ph/0503486]

[Alonso-González, Cerdano, **PF**, No; 2507.11376]



CONSISTENT FERMILAT BOUND

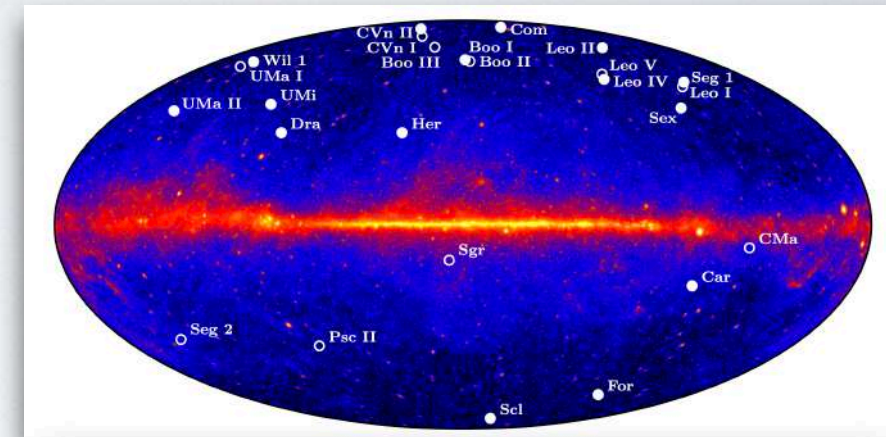
- FermiLAT legacy analysis provides single-source, binned likelihood profiles $\mathcal{L}(d\phi/dE, E)$ on gamma ray flux

[McDaniel+, PRD 109 063024]

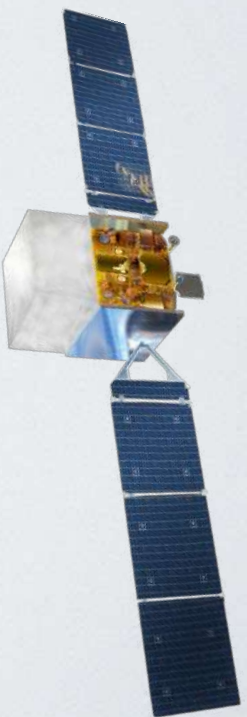
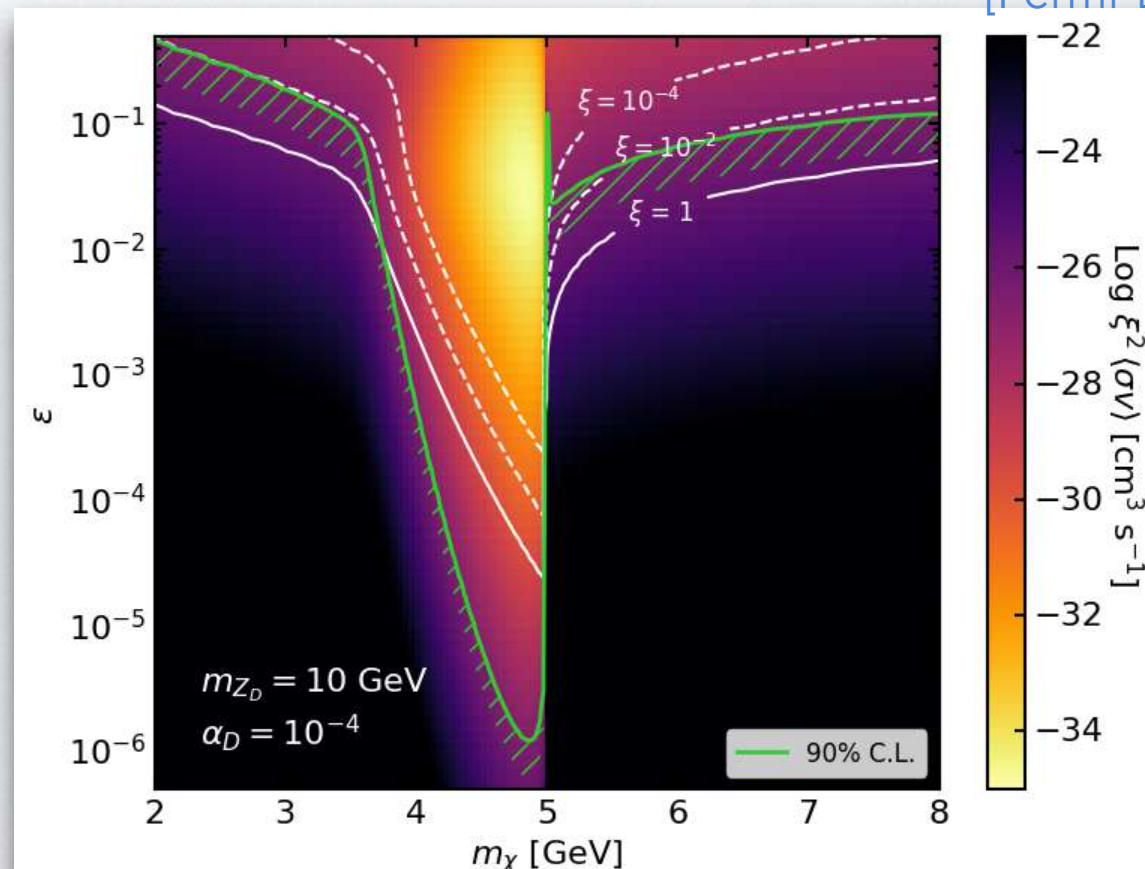
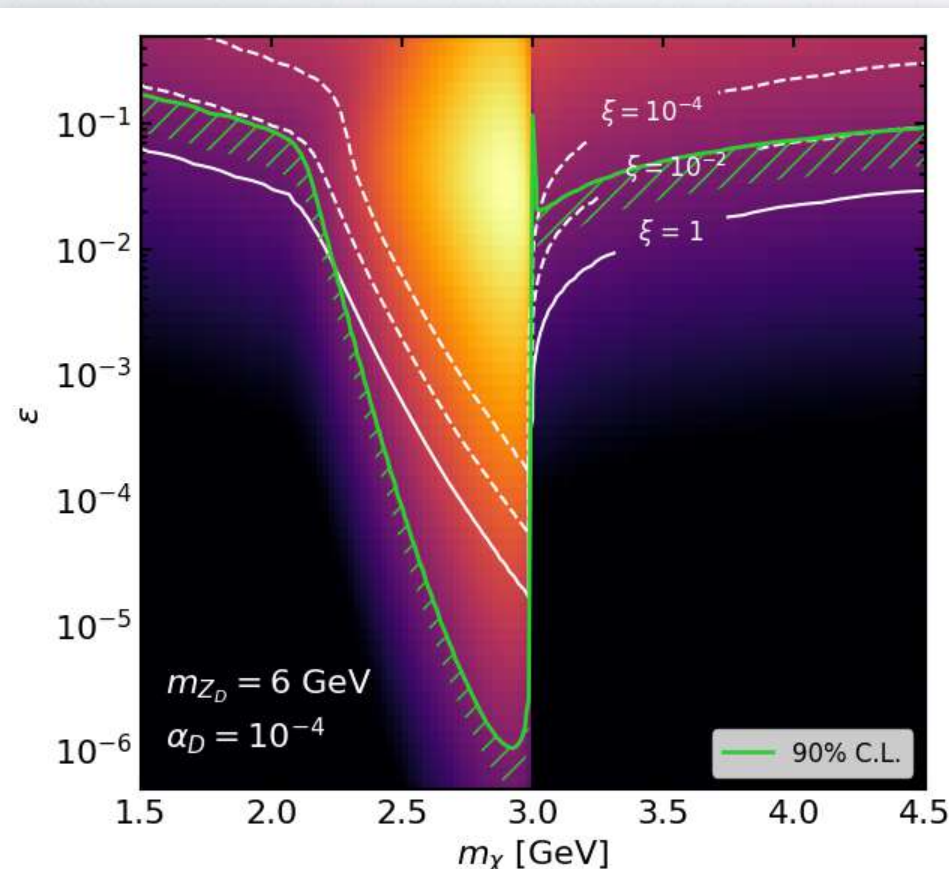
$$\frac{d\phi}{dE}(\Delta\Omega) = \frac{1}{4\pi} \sum_f \frac{\langle\sigma v\rangle_f}{2m_\chi^2} \frac{dN_\gamma^f}{dE} \underbrace{\int_{\Delta\Omega} d\Omega \int d\ell \rho_{\text{DM}}(r)^2}_{J\text{-factor}} \quad \text{Note: } \rho_\chi = \xi \times \rho_{\text{CDM}}$$

- Gamma ray flux sensitively depends on $\xi^2 \sum \frac{\langle\sigma v\rangle}{m_\chi^2}$
- As for CMB, we get a lower bound on ϵ !

[Alonso-González, Cerdeño, PF, No; 2507.11376]

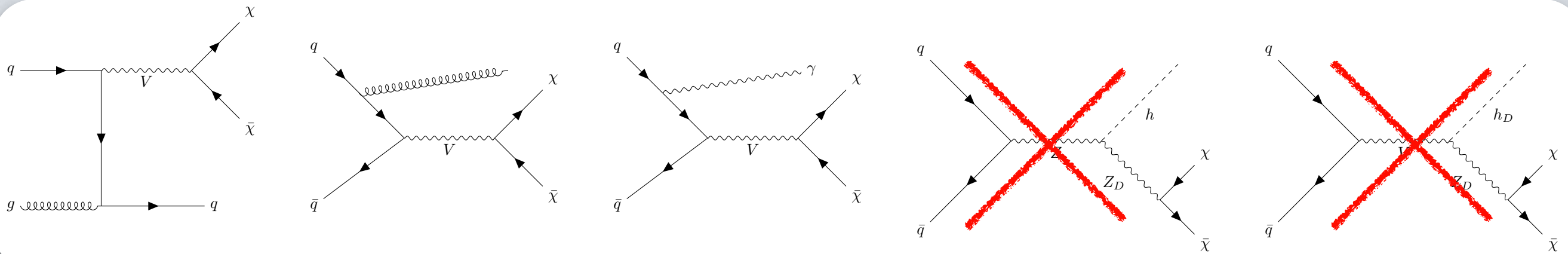


[Fermi-LAT, PRD 89, 042001]

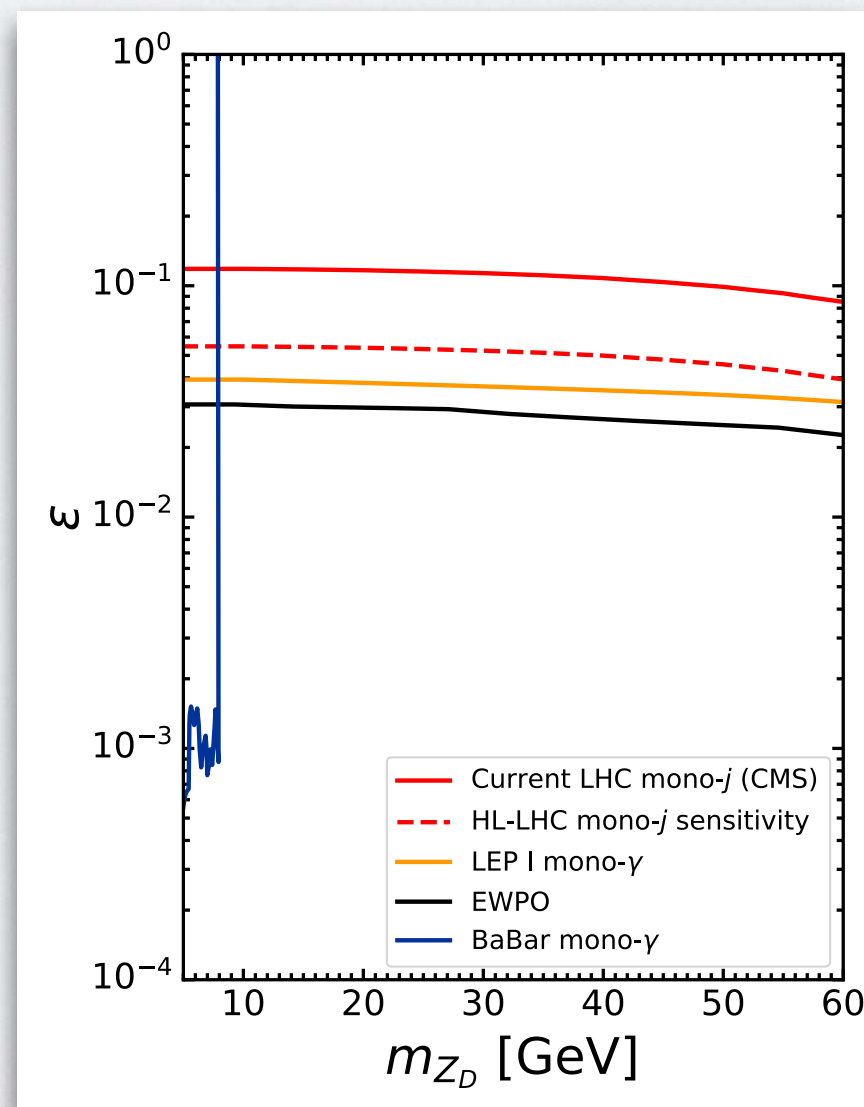


COLLIDER CONSTRAINTS - I

- Invisible regime ($m_\chi < m_{Z_D}/2$): mono-X signatures**

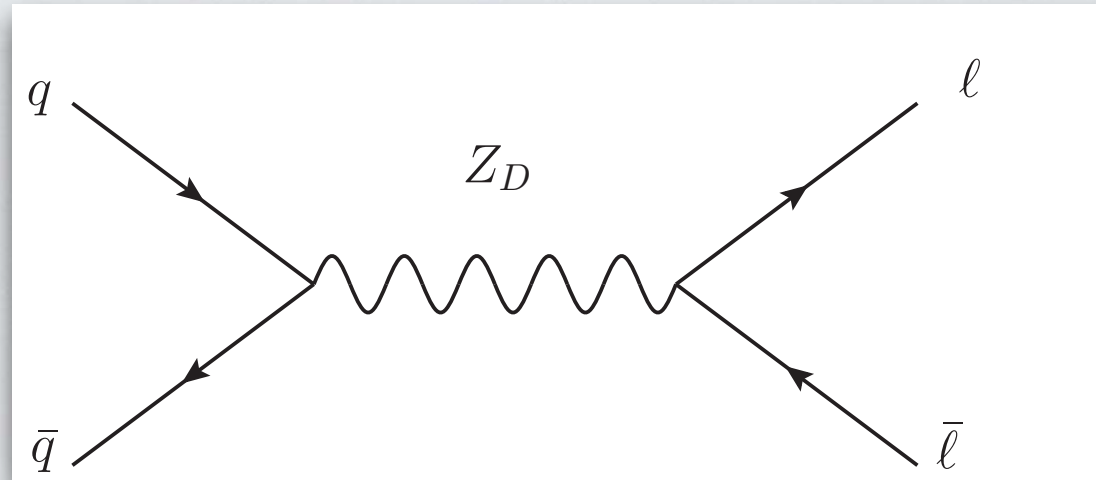


- In this mass range leading bound given by **BaBar mono γ , EWPO**
- HL-LHC could give competitive constraints
- Mono-Higgs no competitive bounds



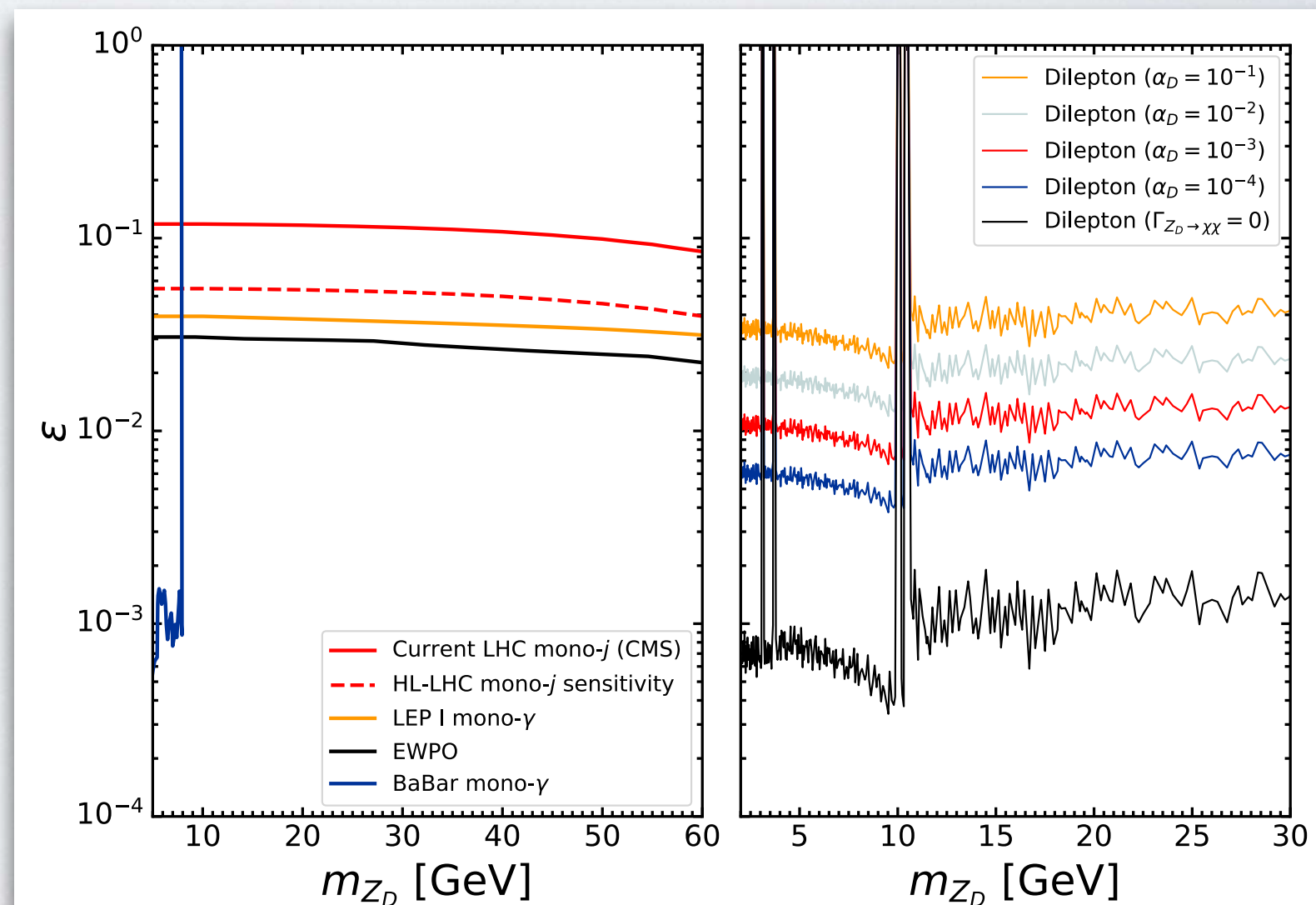
COLLIDER CONSTRAINTS - II

- Visible regime ($m_\chi > m_{Z_D}/2$): dilepton signatures



- Already get significant visible decays for small gauge couplings $\alpha_D \lesssim \epsilon^2$
- We have to rescale the dilepton limit with the relevant branching ratio:

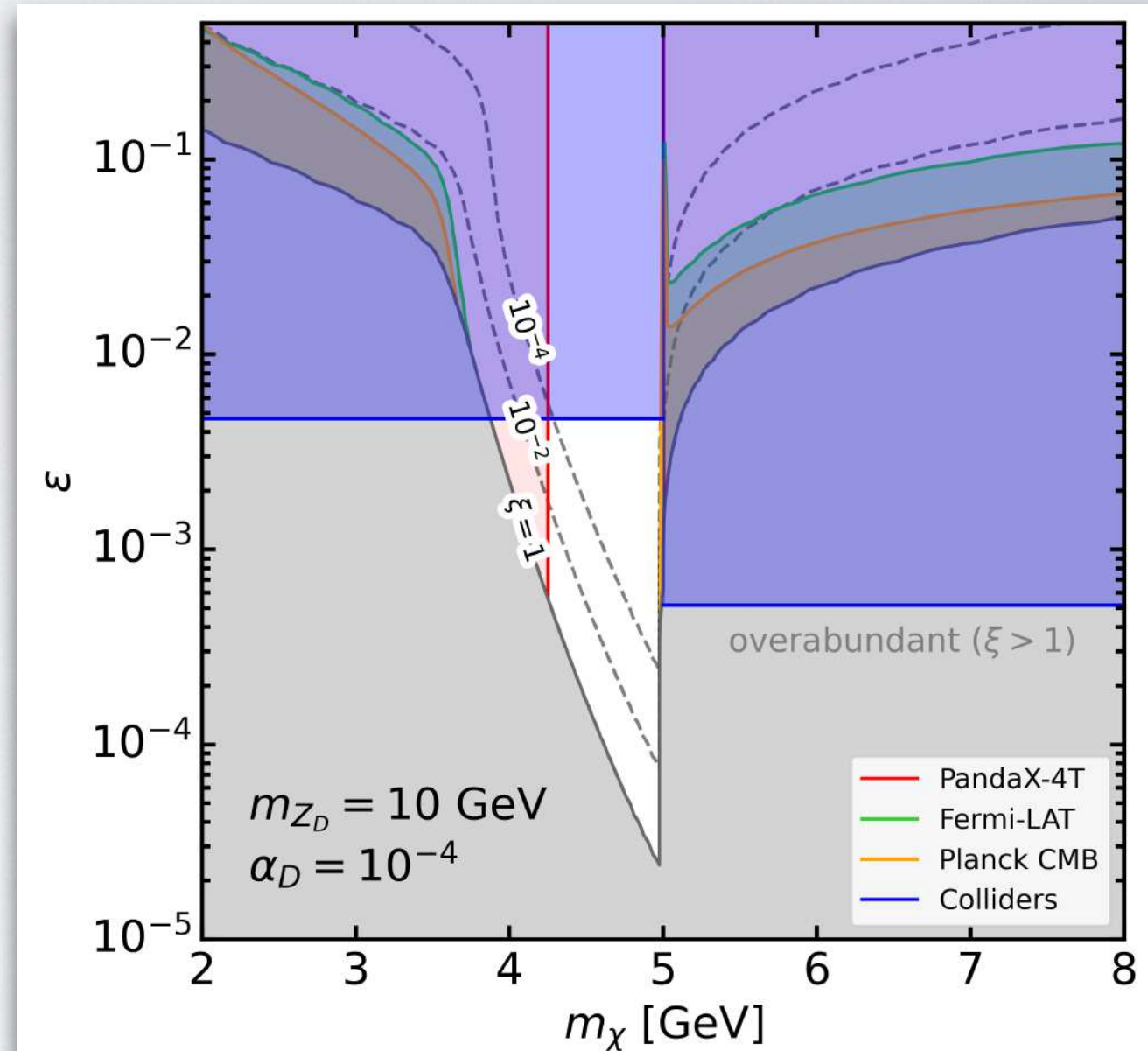
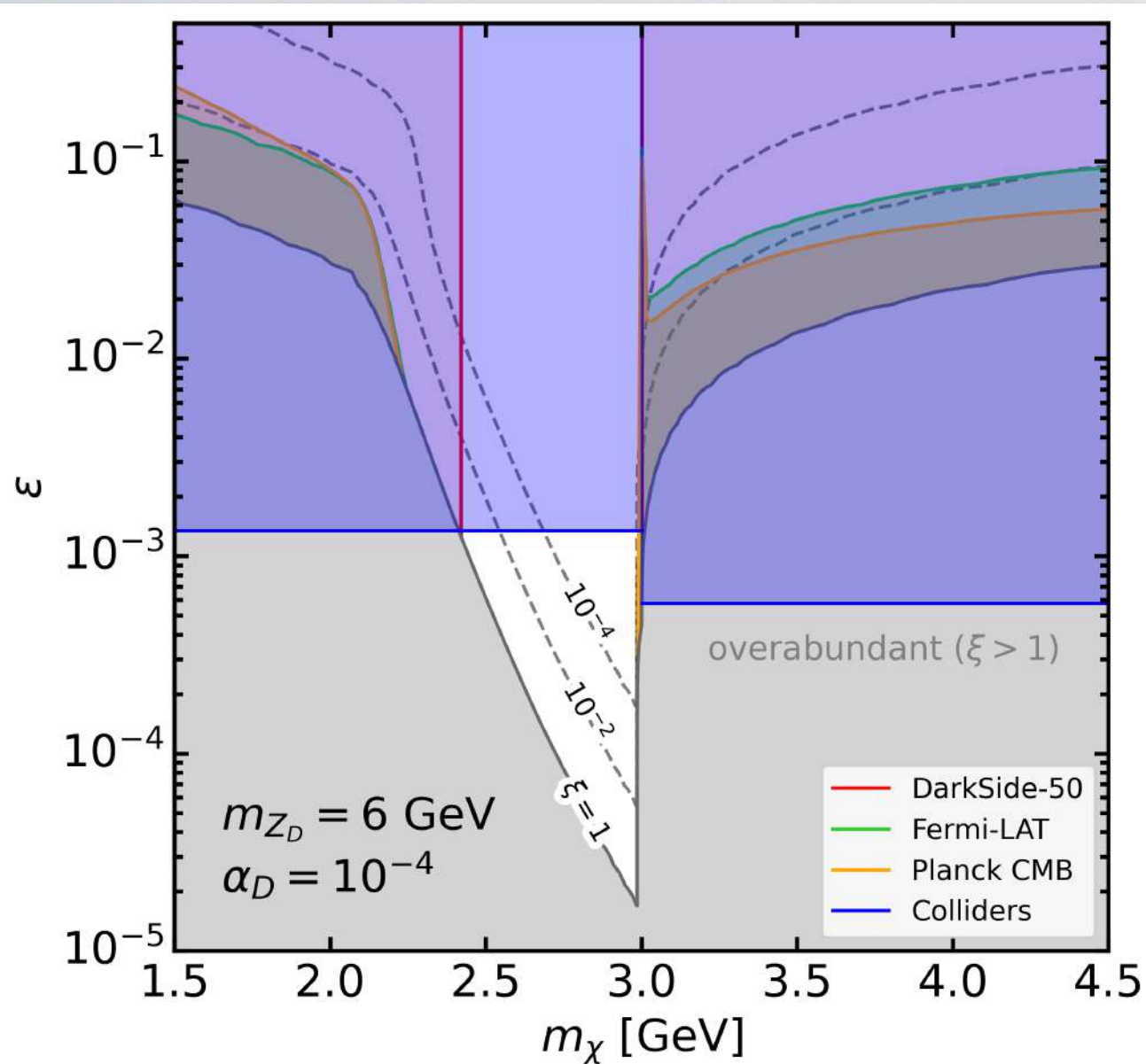
$$\epsilon_{90}^{\ell\ell} \times \sqrt{\frac{\Gamma_{Z_D \rightarrow \text{SM}} + \Gamma_{Z_D \rightarrow \chi\chi}}{\Gamma_{Z_D \rightarrow \text{SM}}}}$$



THE GEV WINDOW

- **GeV DM** only viable in the **resonance regime**
- Complementary constraints for **direct detection** and **colliders**!

[Alonso-González, Cerdeno, **PF**, No; 2507.11376]



SUCCESSFULL LDM REALIZATION

- What are the ingredients to realize LDM with resonant production?

Kinematics

- resonance affects freeze-out and late annihilation differently
- scattering probes spacelike momentum transfer $\rightarrow$ no resonance!

Abundance

- subcomponent fraction ξ rescales DD by ξ
- annihilation signals scale as ξ^2

Tests

- DD continues to narrow down resonance parameter space
- accelerators test the portal without assuming the cosmological abundance

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- **What if portal to feeble to ever establish equilibrium?**

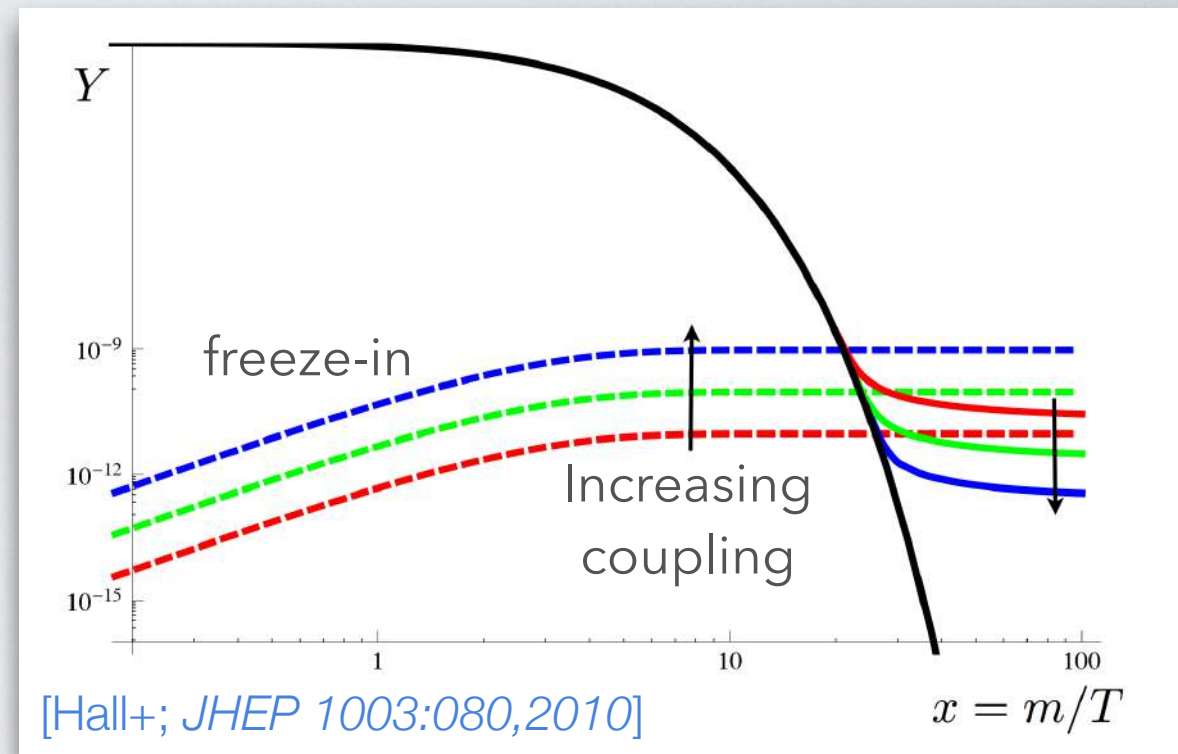
FREEZE-IN

FREEZE-IN PRODUCTION

- Very **feebly coupled DM is never thermalized** with SM bath

$$\frac{dn}{dt} + 3Hn = \langle \sigma v \rangle (n_{eq}^2 - n^2)$$

- PROBLEM: Tiny interactions typically hard to probe!



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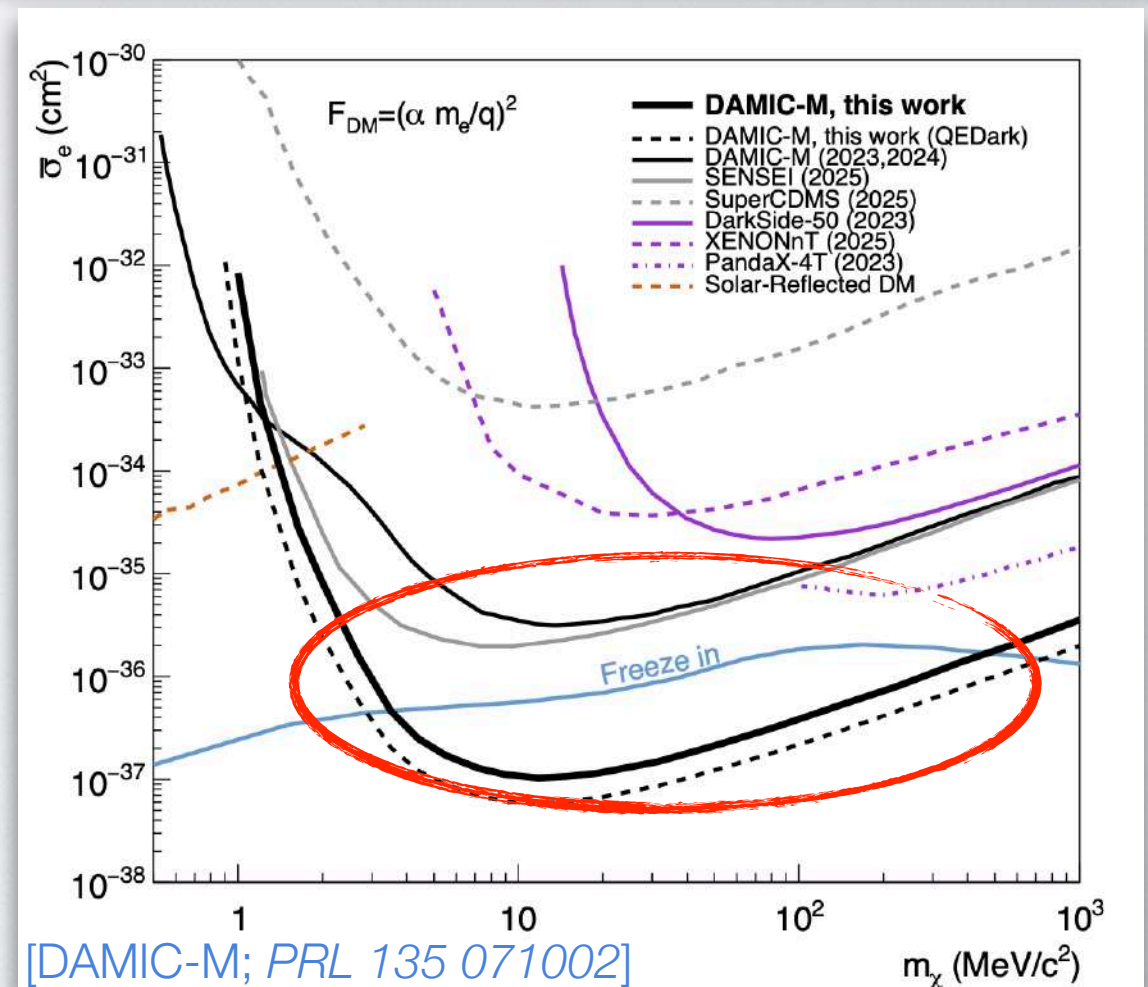
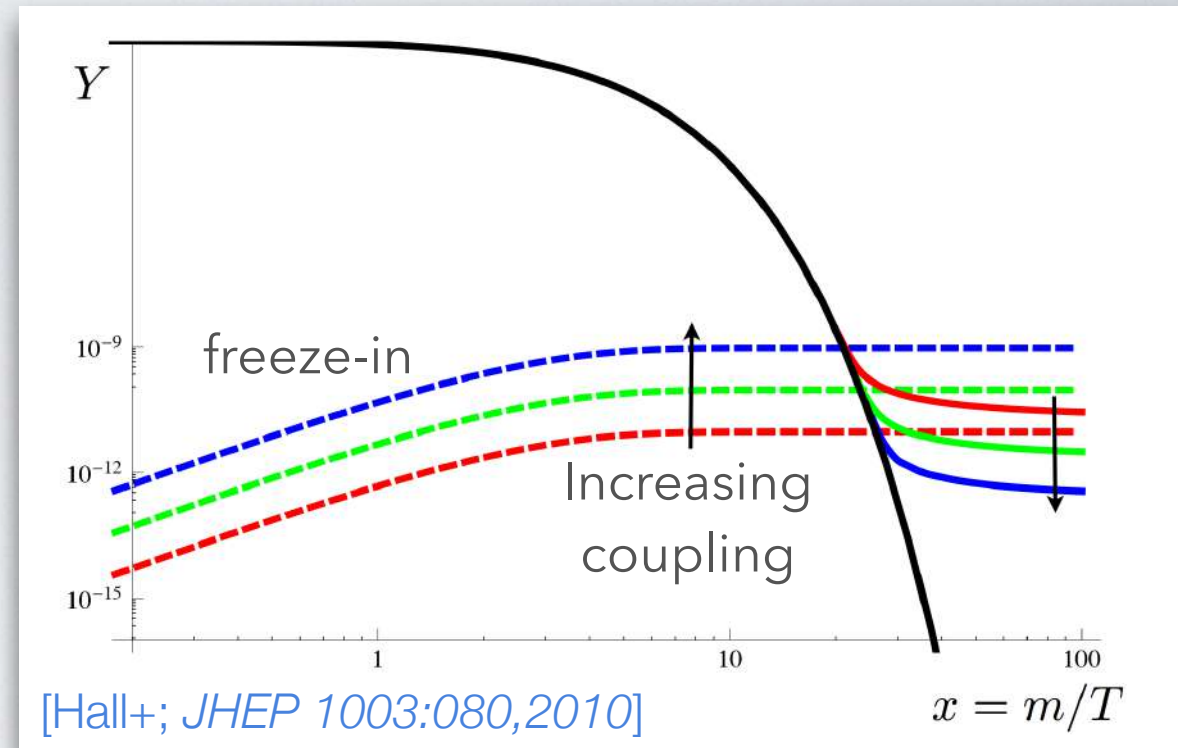
$$\frac{dn}{dt} + 3Hn = \langle \sigma v \rangle (n_{eq}^2 - \cancel{n^2})$$

- PROBLEM: Tiny interactions typically hard to probe!

- **BUT:** New (ultra-)light mediators can significantly enhance cross section!

$$\sigma \sim \frac{g_D^4}{m_\chi^2} \left(\frac{s}{s - m_{A'}^2} \right)^2 \sim \frac{g_D^4}{m_\chi^2}$$

- **Direct detection is already testing freeze-in with a light mediator!**



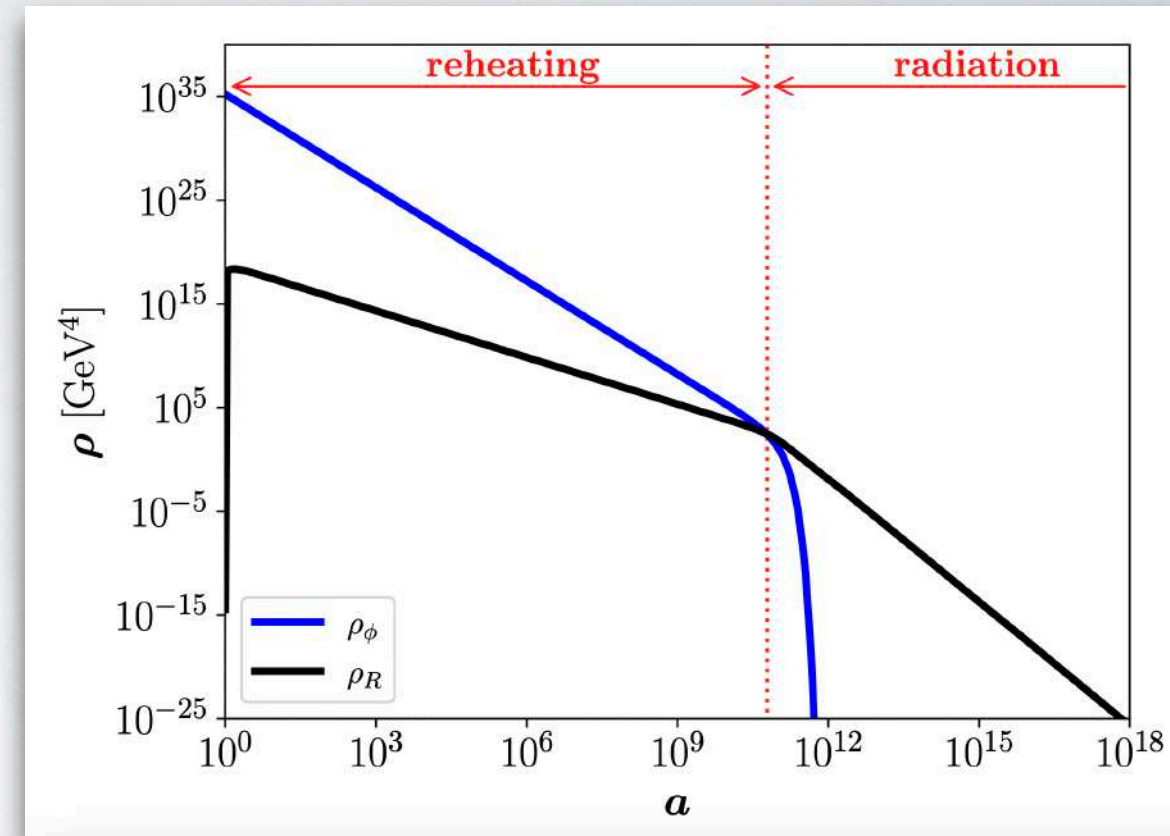
A SUBTLETY — LOW REHEATING

[Bélanger, Bernal, Pukhov; *JHEP* 03 (2025) 079]

- At the end of inflation, decay of the inflaton ϕ sources thermal population SM bath
(reheating)

⇒ **Entropy injection into SM bath**

- End of reheating reached at onset of SM radiation domination for $\rho_\phi(T_{\text{rh}}) = \rho_R(T_{\text{rh}})$



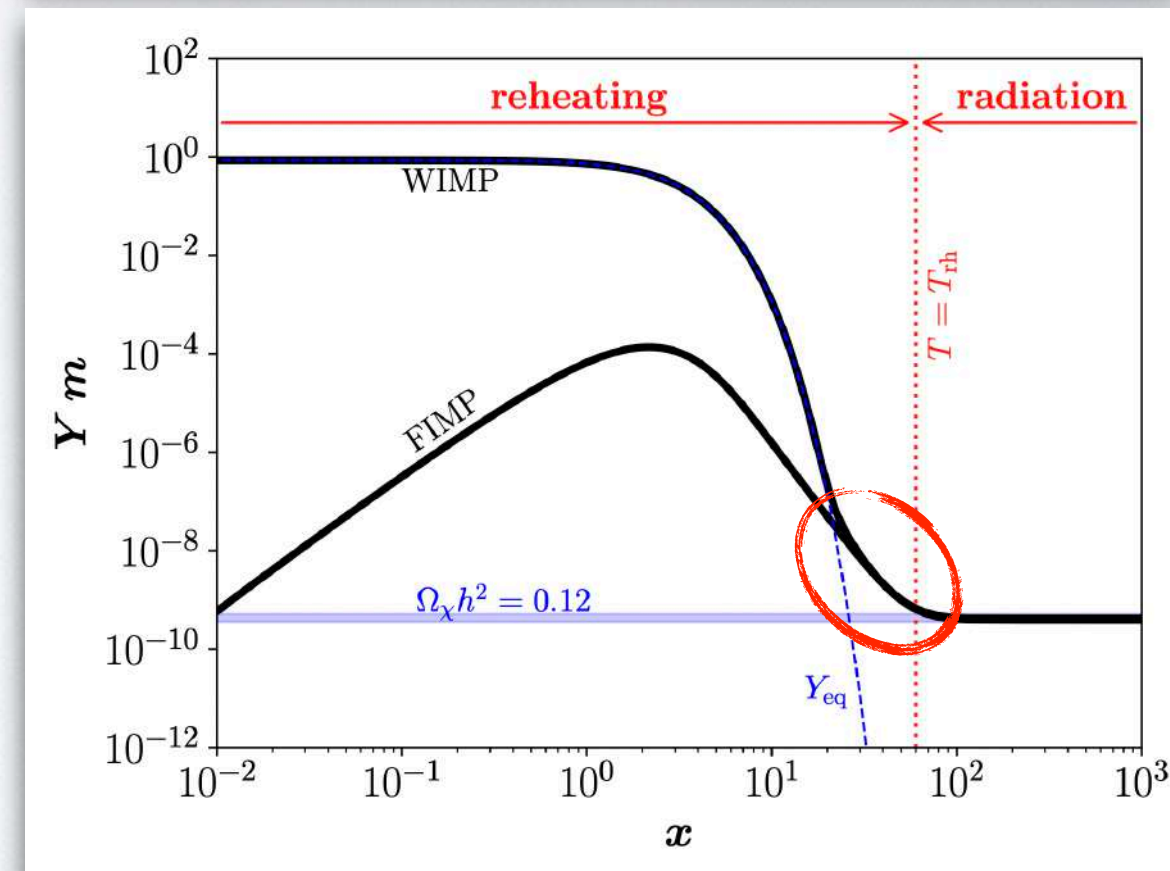
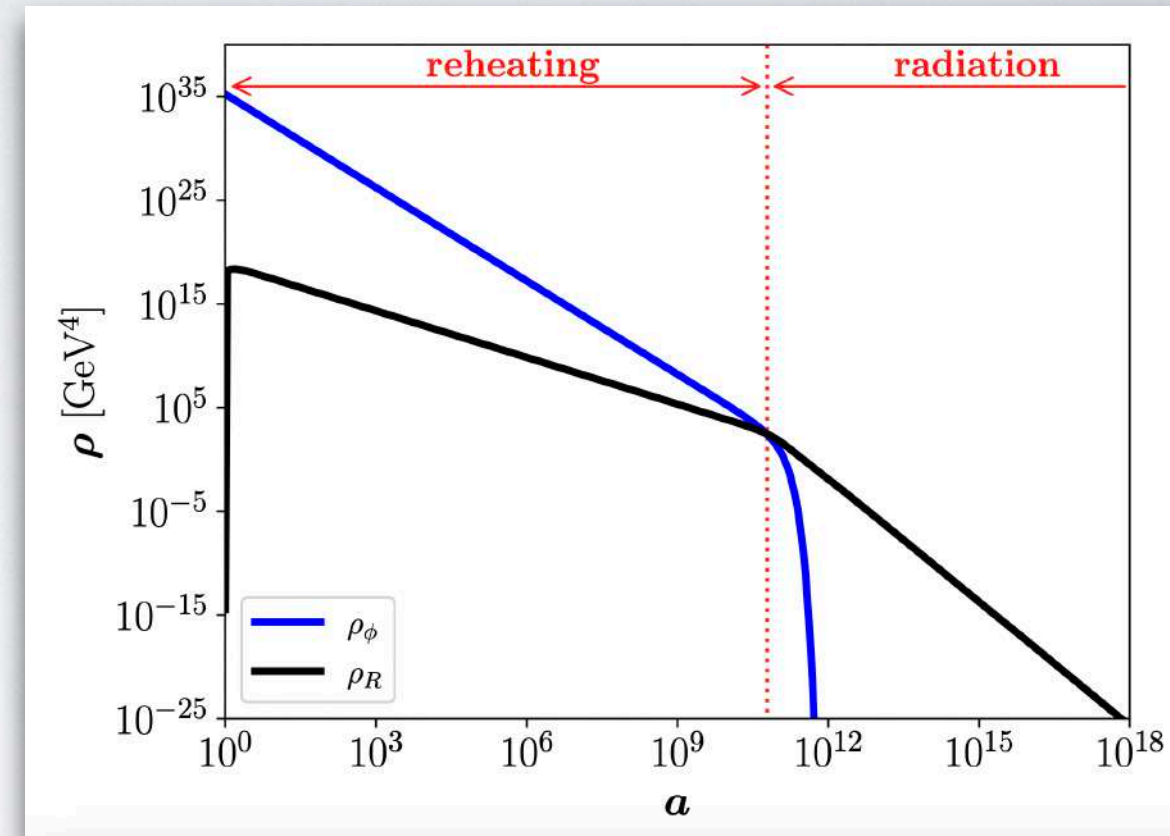
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⇒ **Entropy injection into SM bath**

- End of reheating reached at onset of SM radiation domination for $\rho_\phi(T_{\text{rh}}) = \rho_R(T_{\text{rh}})$
- Typical freeze-in production ceases at $T \sim \max(m_{A'}, m_\chi)$
- If the reheating temperature is lower than the DM/mediator mass, further **entropy injection dilutes produced freeze-in abundance!**
- Exponential suppression of $\langle\sigma v\rangle$** since only kinematic tail of particles have enough energy to produce DM



TESTS OF DP FREEZE IN

- Direct detection with **electron scattering** has potential to test smaller couplings

$$\sigma_{\chi e} = \frac{\mu_{\chi e}^2}{\pi} \frac{g_D^2 g_{eX}^2}{(\alpha_{\text{EM}}^2 m_e^2 + m_{A'}^2)^2}$$

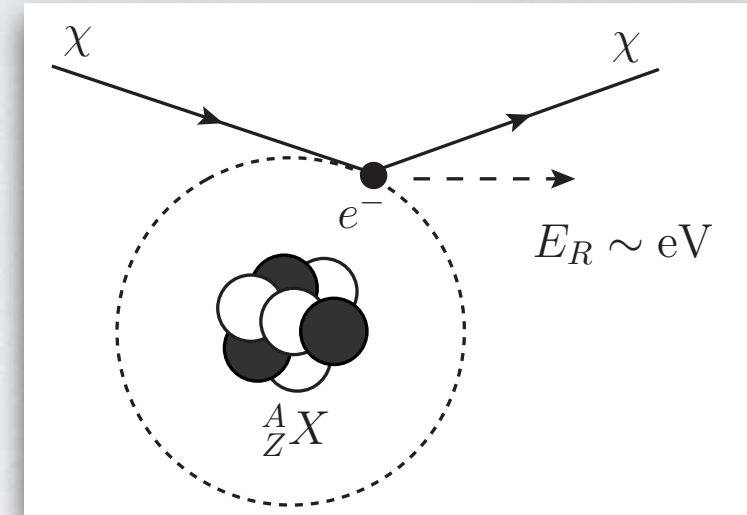
- Recently, **DAMIC-M** and **PandaX-4T** published first results excluding freeze-in cross section

[DAMIC-M; PRL 135 071002]

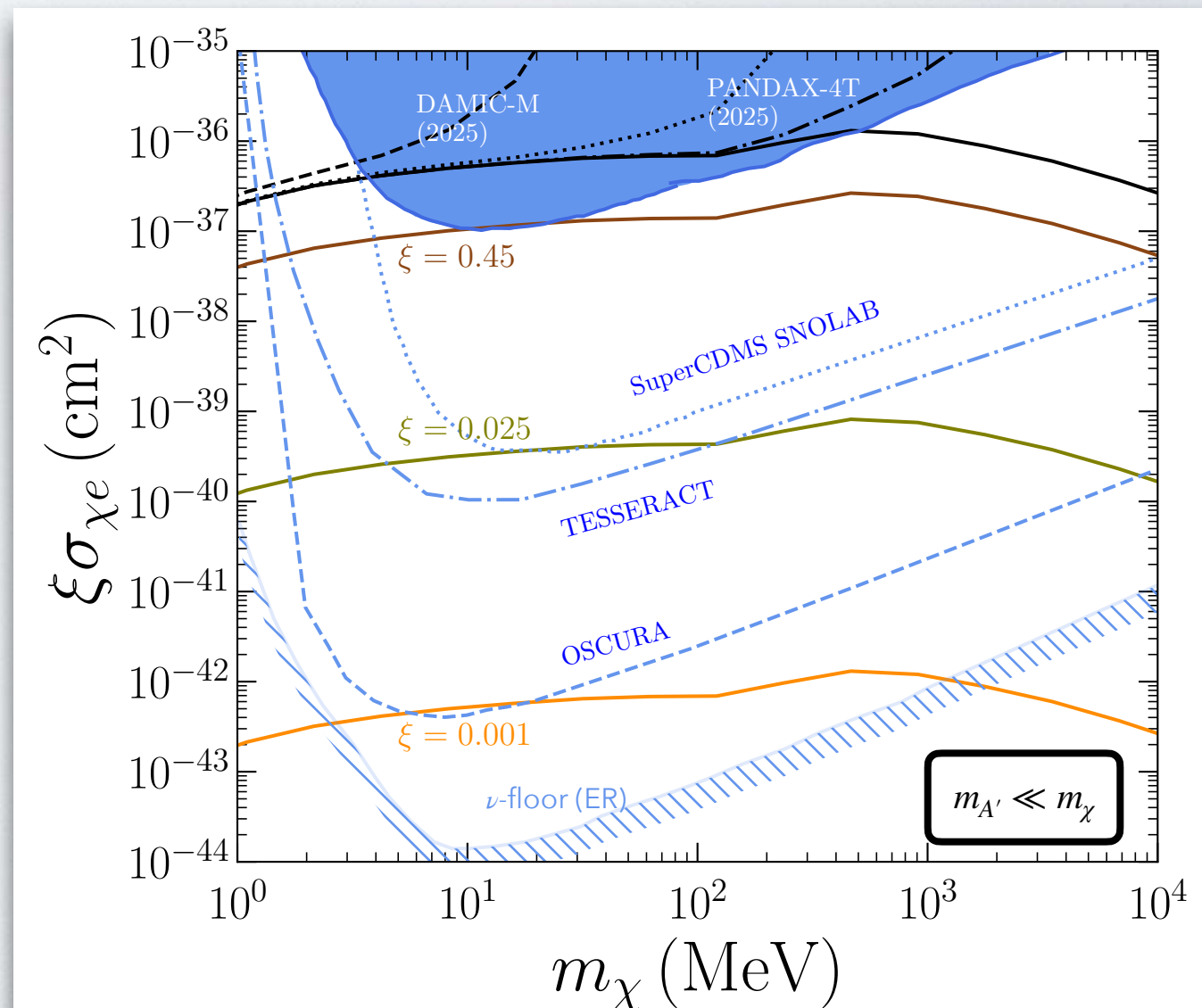
[PandaX; PRL 135 211001]

Ultralight mediator

- Large parts of **massless** mediator scenario for $m_\chi \sim [3, 400]$ MeV excluded
- Low reheating temperature scenarios excluded**
- Future searches test underabundance down to $\xi = 0.001$**

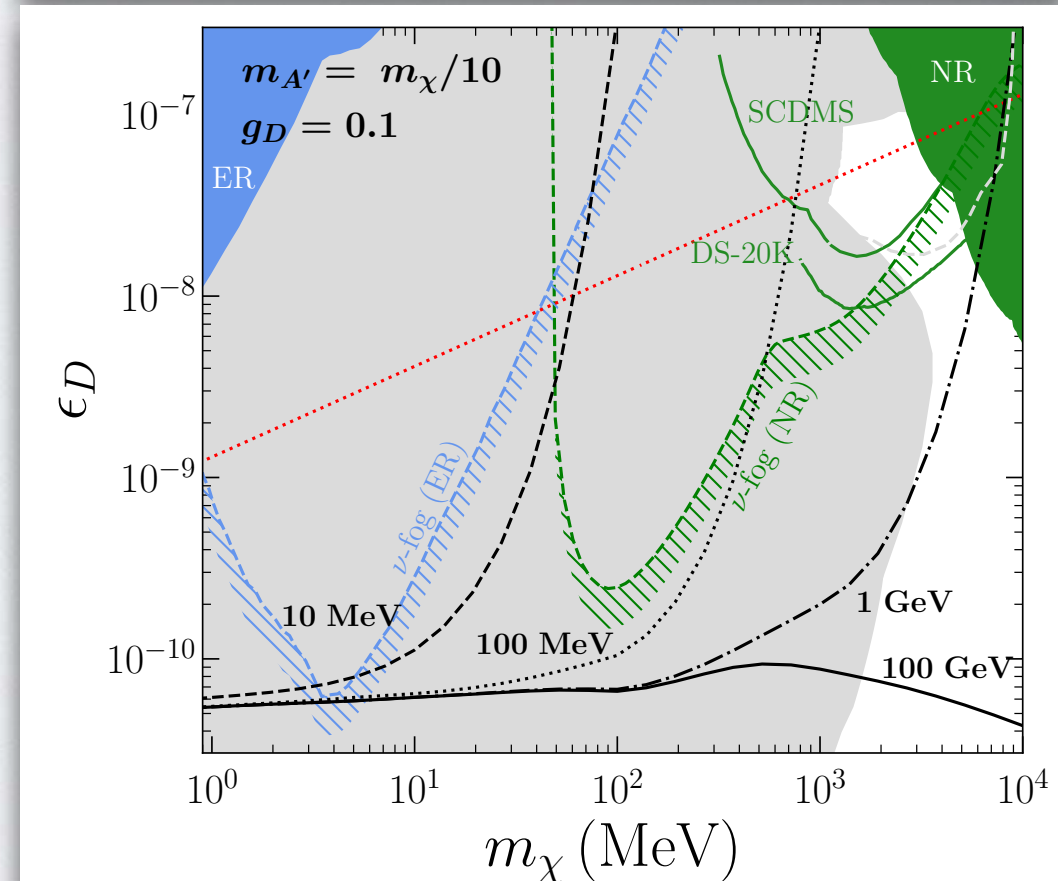
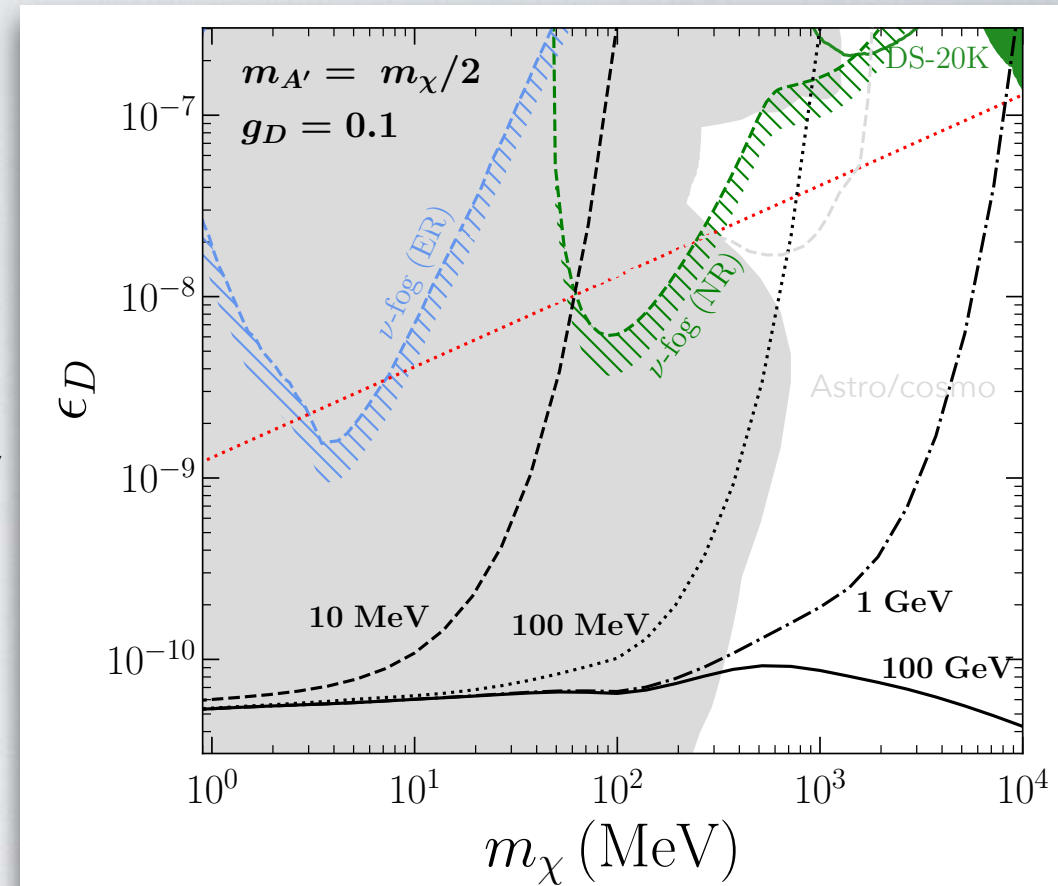


[Cerdeño, PF, López Noé, Zapata; 2603.16863]



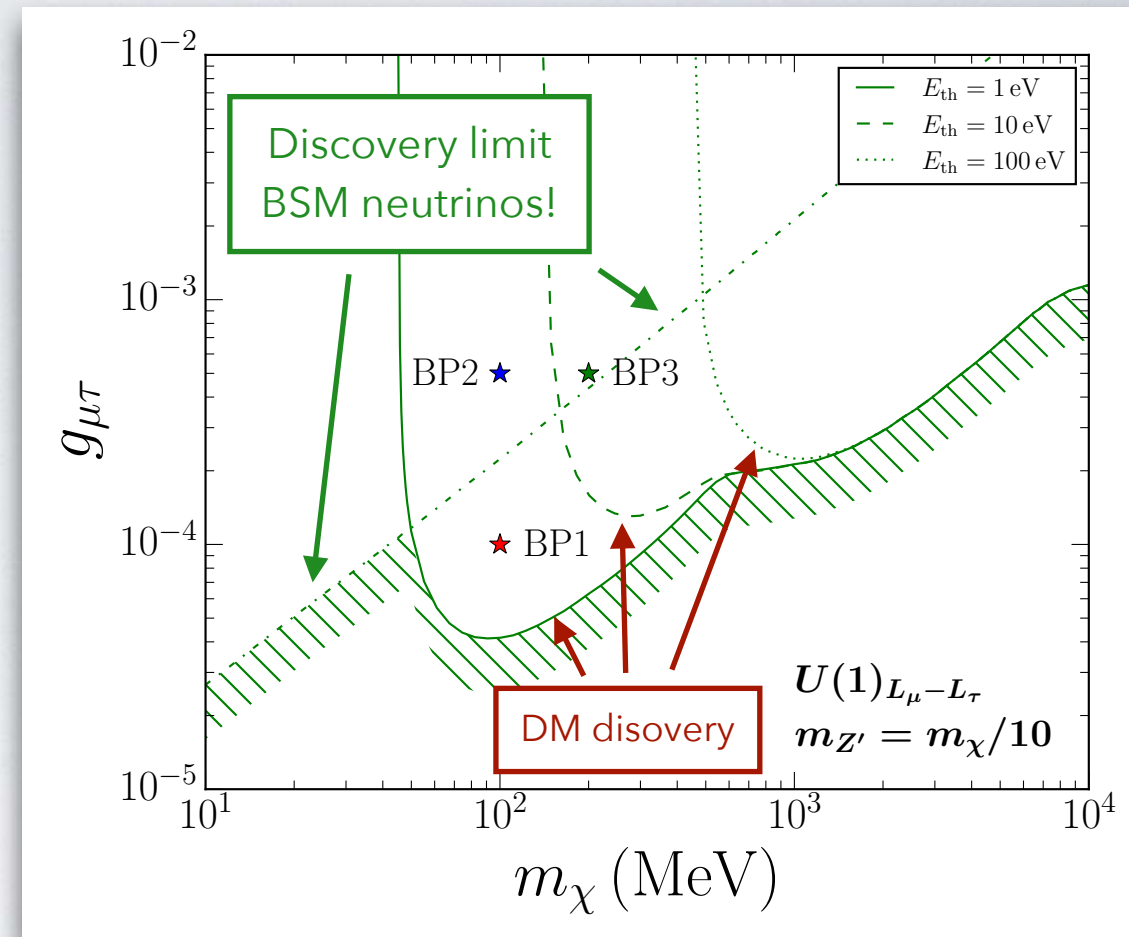
REALISTIC SCENARIO

- Consider **massive vector mediator** scenario with comparable masses
- MeV dark photons **severely constrained** from beam dump searches, astrophysics, and cosmology (gray)
- High reheating freeze-in lines completely buried in the neutrino floor
- Low reheating scenarios with $T_{\text{rh}} \sim 100 \text{ MeV} - 1 \text{ GeV}$ in reach of **future direct detection experiments!**
- Consistent dark photon signal in fixed target experiments like **SHiP**

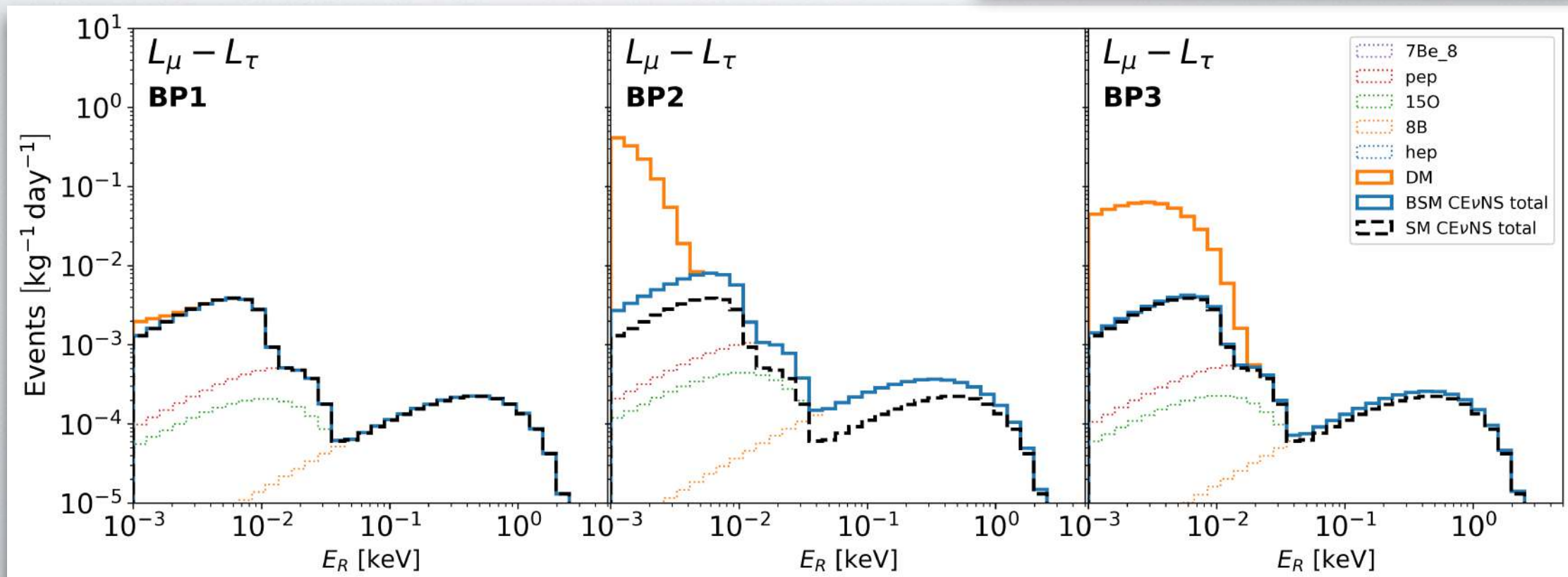


MODIFIED NEUTRINO FLOOR

- Leptophilic mediators lead to **simultaneous DM and neutrino signal**
- DM discovery limit (neutrino floor) depends on **experimental threshold** E_{th}
- Signal discrimination via spectral information
 $\Rightarrow$ need statistics (**exposure, background**)



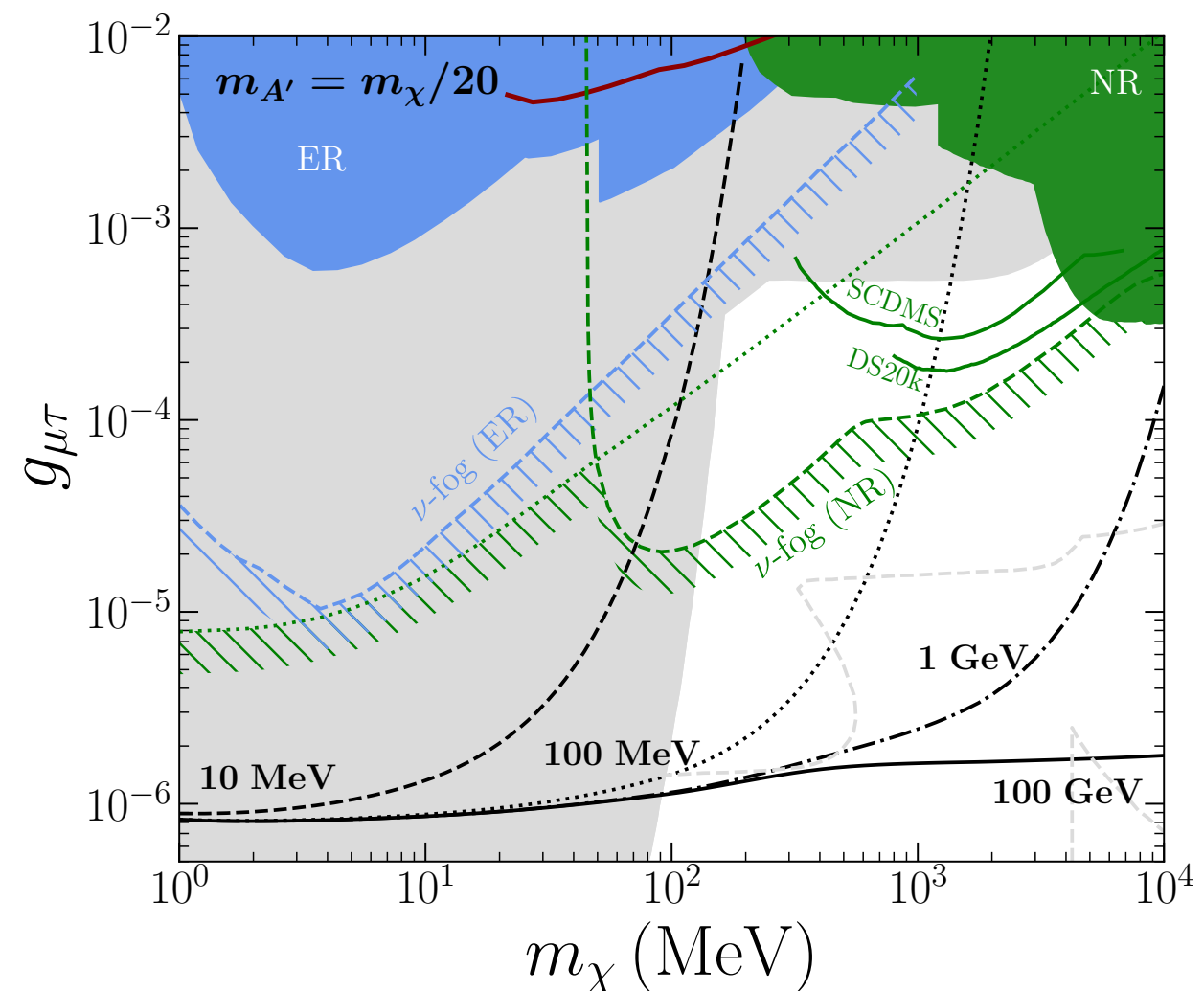
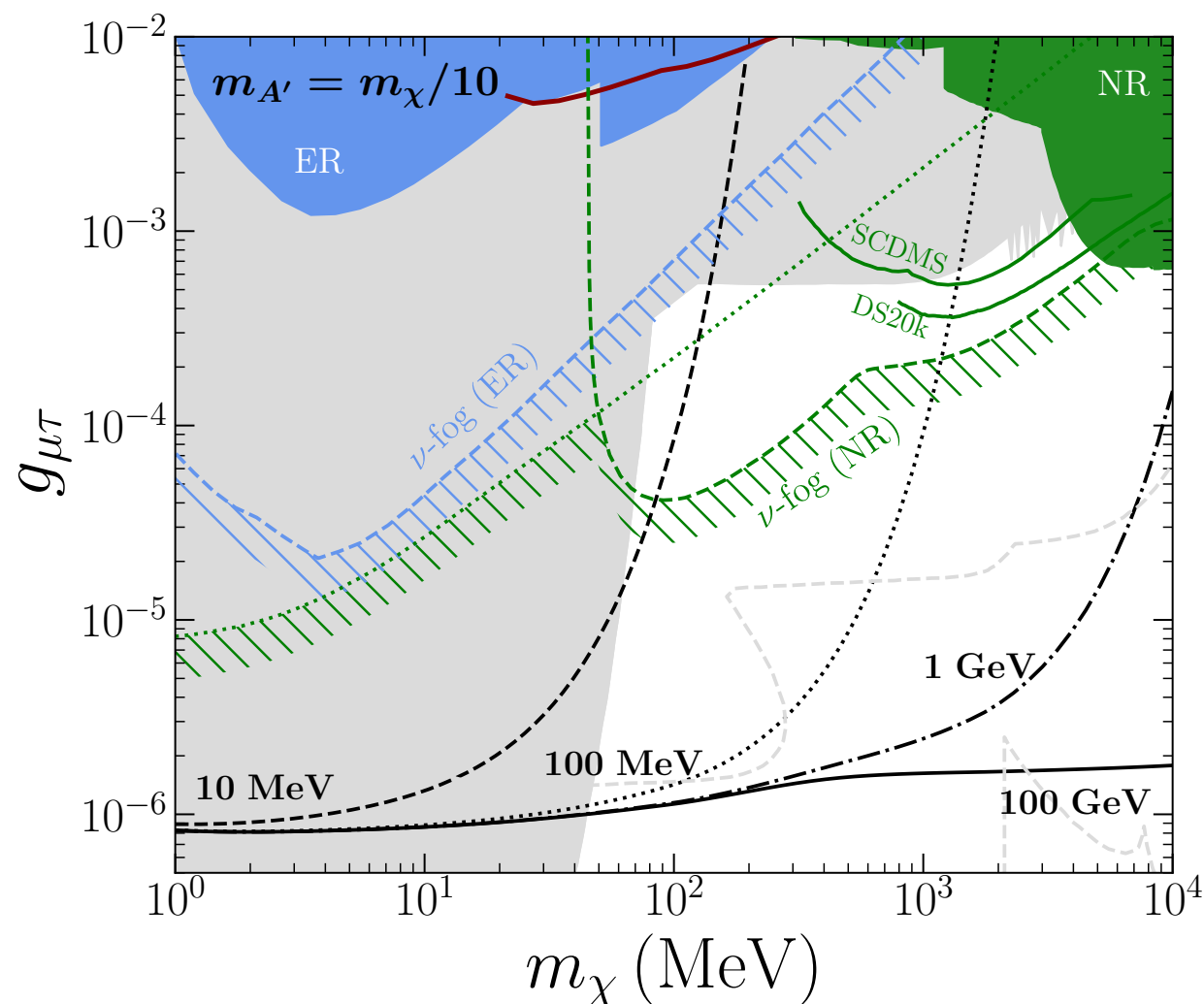
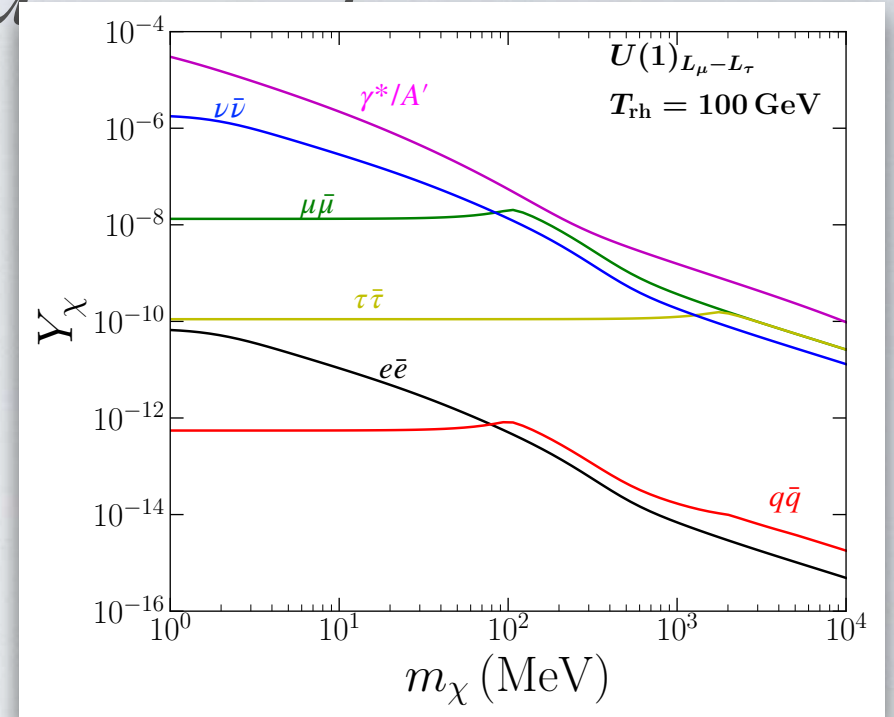
[Cerdeño, **PF**, López Noé, Zapata; 2603.16863]



FREEZE IN - $L_\mu - L_\tau$

- Dominant production via (thermalized) A' and $\nu_{\mu,\tau}$ annihilation
- Freeze-in @ low reheating in reach of future experiments for $T_{\text{rh}} \sim 10 - \mathcal{O}(\text{few}) 100 \text{ MeV}$
- Predicts consistent signature in **nuclear recoils** and future **fixed target** experiments

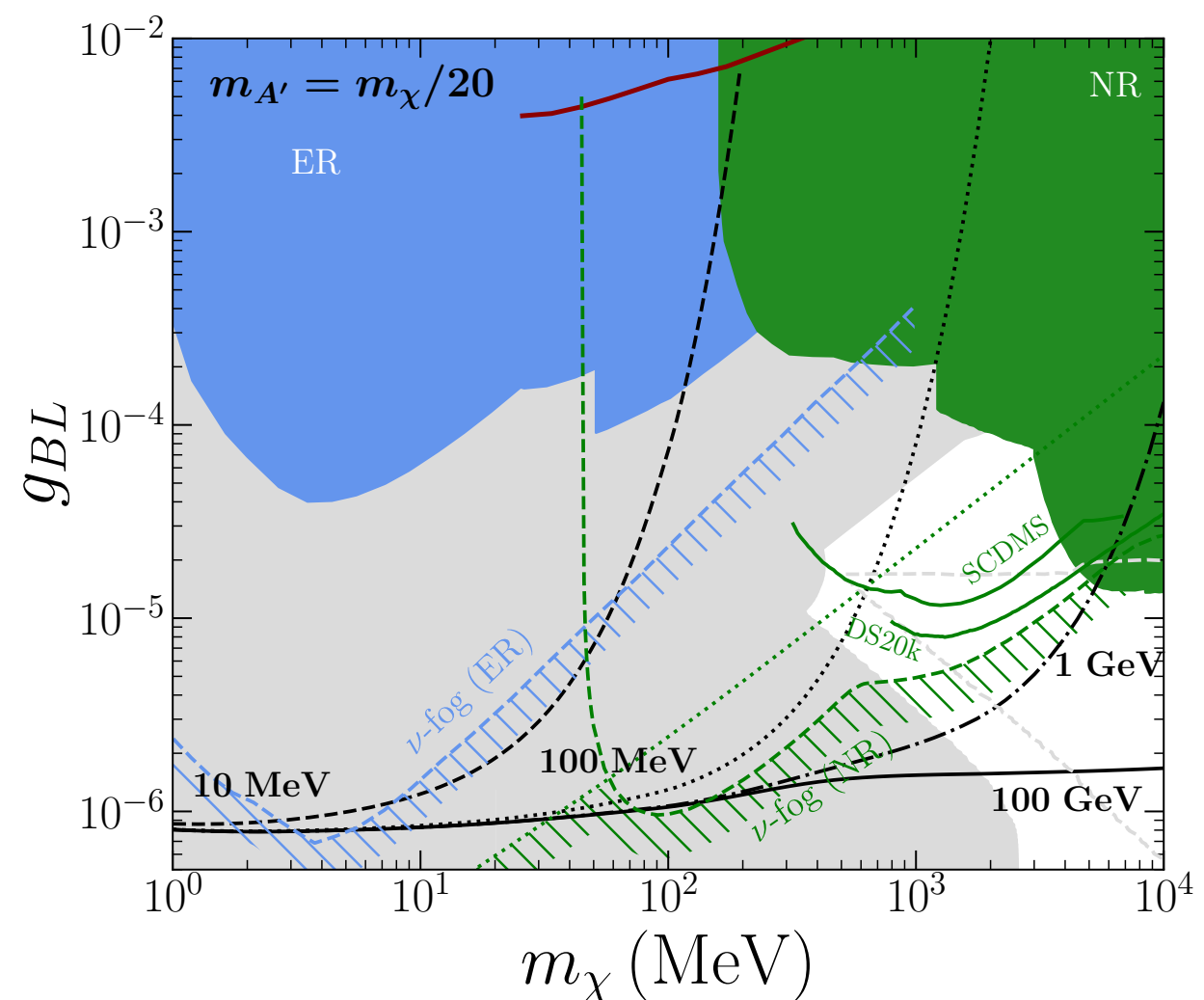
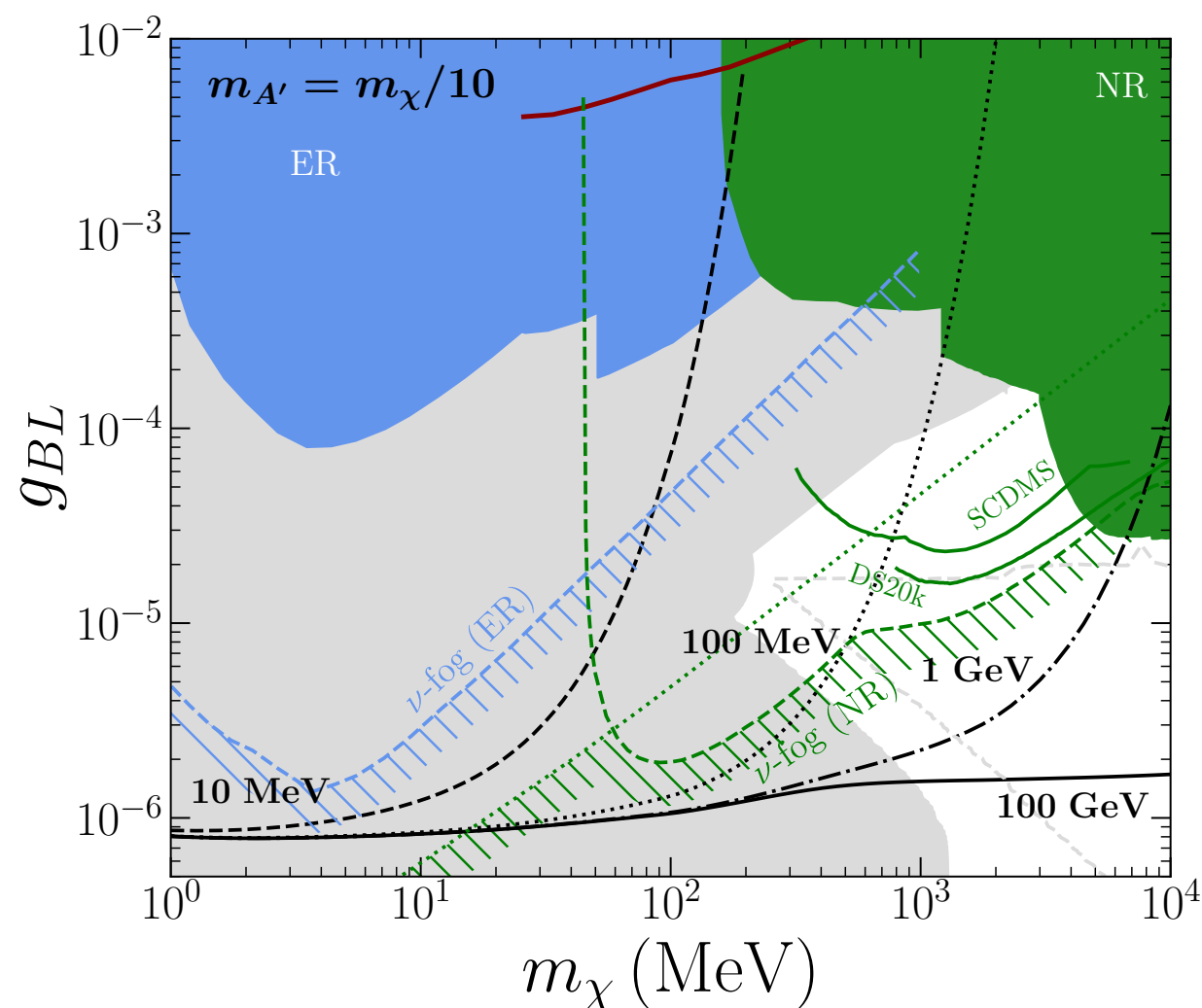
[Cerdeño, **PF**, López Noé, Zapata; 2603.16863]



FREEZE IN - $B - L$

- Due to direct gauge coupling with nucleons, nuclear recoils more sensitive $\rightarrow$ sensitive to larger region of parameter space
- Significant sensitivity to **BSM neutrino signal** alone!

[Cerdeño, **PF**, López Noé, Zapata; 2603.16863]



INELASTIC DARK MATTER

INELASTIC VECTOR PORTAL

- Two oppositely charged Weyl components of Dirac fermion $\psi^T = (\eta, \xi)$
- Small Majorana masses m_η, m_ξ split the states into two Majorana particles

$$\mathcal{L}_{\text{mass}} \supset -m_D \eta \xi - \frac{1}{2} m_\eta \eta \eta - \frac{1}{2} m_\xi \xi \xi + \text{h.c.}$$

$$m_{1,2} \simeq m_D \mp \frac{m_\eta + m_\xi}{2} \quad \Rightarrow \quad \Delta = m_\eta + m_\xi$$



Parameters: $\{m_\chi, \Delta, m_{A'}, g_D, g_{SM}\}$

Off-diagonal vector interactions

Dirac basis:

$$\mathcal{L}_{\text{int}} \supset -g_D (\eta^\dagger \bar{\sigma}^\mu \eta - \xi^\dagger \bar{\sigma}^\mu \xi) A'_\mu$$



Mass basis:

$$\mathcal{L}_{\text{int}} \supset -g_D \bar{\chi}_2 \gamma^\mu \chi_1 A'_\mu + \text{h.c.}$$

+ diagonal terms suppressed by mass ratios

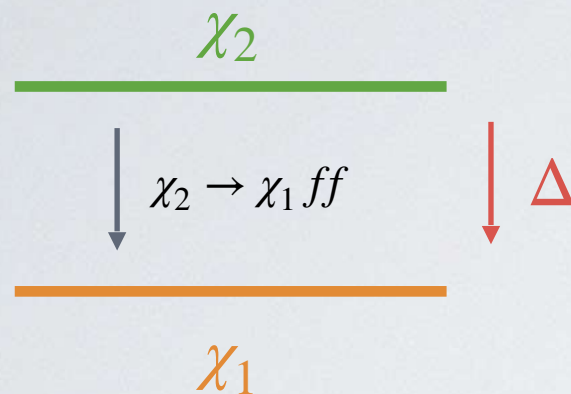
**Core
idea**

Vector mediator mainly converts $\chi_2 \leftrightarrow \chi_1$

Freeze-out involves χ_2 . Present-day halos contain only χ_1 .

SPLITTING SUPPRESSES SIGNALS

Thermal history



$$T_{FO} \gtrsim \Delta \gtrsim E_{\text{kin halo}}$$

χ_2 populated at freeze-out, but depleted and kinematically inaccessible today.

Thermal abundance without the usual present-day s-wave and elastic-scattering signals

Thermal relic freezes out

$$\chi_2 \chi_1 \rightarrow A'^* \rightarrow f f$$

$$\frac{n_{\chi_2}^{\text{eq}}}{n_{\chi_1}^{\text{eq}}} \simeq \frac{g_2}{g_1} \left(1 + \frac{\Delta}{m_{\chi_1}} \right)^{3/2} e^{-\Delta/T}$$

Coannihilation active if Δ is not much larger than freeze-out temp T_f

CMB/Indirect signal suppression

Leading annihilation off-diagonal

$$\Gamma_{\text{ann}} = n_1 n_2 \langle \sigma_{12} \rangle$$

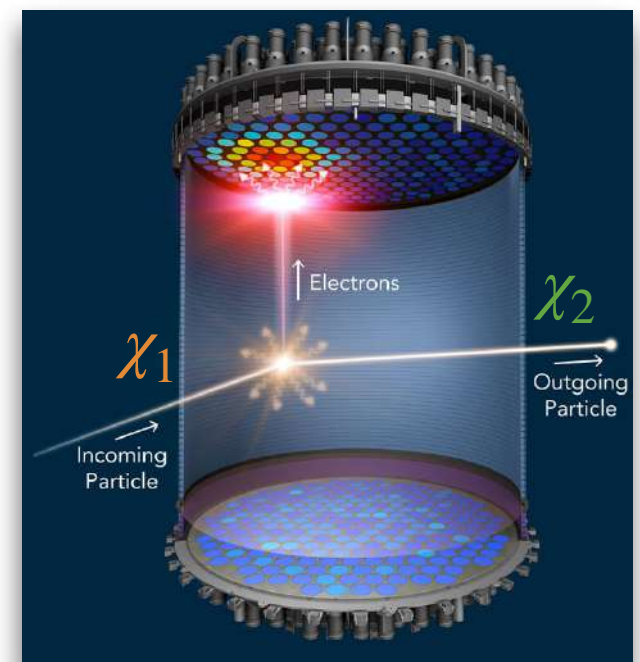
At late times, χ_2 depleted through decays ($n_2 \rightarrow 0$), energy injection strongly suppressed

Inelastic scattering

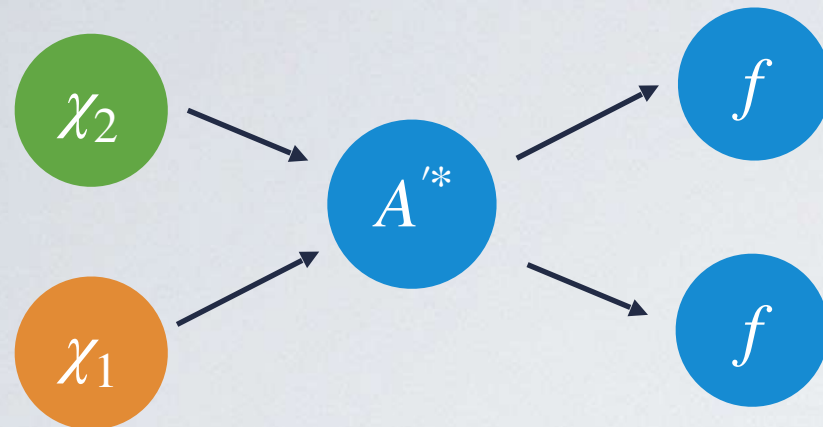
$$\chi_1 T \rightarrow \chi_2 T \quad \text{requires up-scattering}$$

$$\text{Need } v_{\min} = \frac{m_T E_R / \mu_{\chi T} + \Delta}{\sqrt{2m_T E_R}}$$

If Δ exceeds the available halo kinetic energy, the event is forbidden. Splittings of order 10-100 keV can strongly suppress nuclear recoils.



RELIC DENSITY SET BY COANNIHILATION



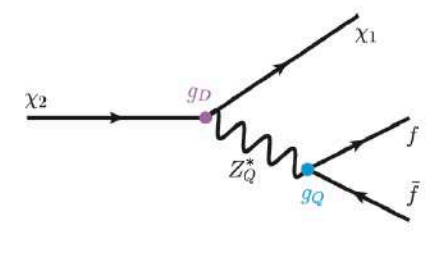
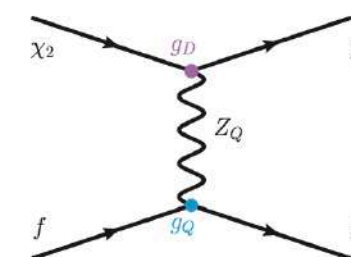
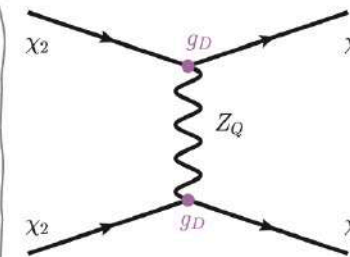
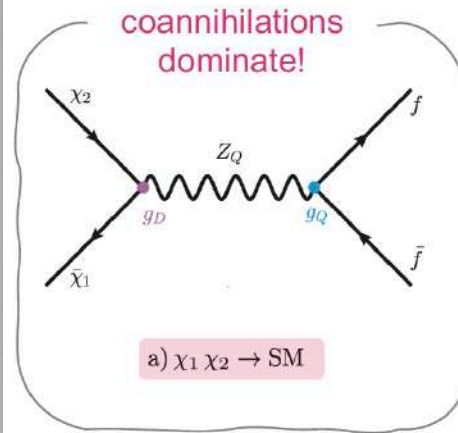
Freeze-out condition

$$n^{\text{eq}}(T_f) \langle \sigma v \rangle_{\text{coann}} \approx H(T_f)$$

Boltzmann Equation

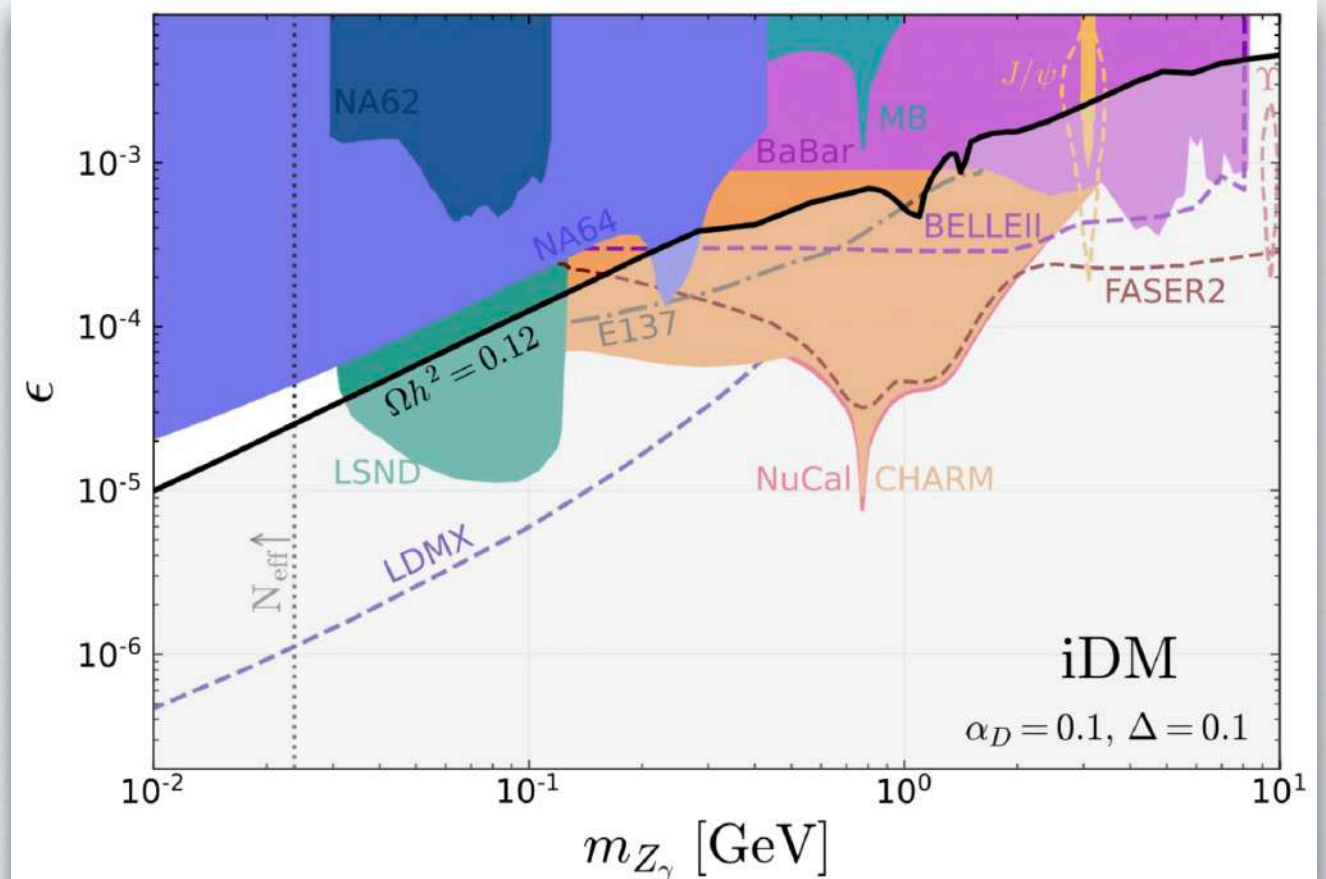
Credit: A.L. Foguel

$$\frac{dY_{1,2}}{dx} = \frac{s}{Hx} \left[-\langle \sigma v \rangle_{12 \rightarrow ff} (Y_1 Y_2 - Y_1^{\text{eq}} Y_2^{\text{eq}}) \pm 2 \langle \sigma v \rangle_{22 \rightarrow 11} \left((Y_2)^2 - \left(Y_1 \frac{Y_2^{\text{eq}}}{Y_1^{\text{eq}}} \right)^2 \right) \right. \\ \left. \pm \left(\langle \sigma v \rangle_{2f \rightarrow 1f} Y_f^{\text{eq}} + \frac{1}{s} \langle \Gamma \rangle_{2 \rightarrow 1ff} \right) \left(Y_2 - Y_1 \frac{Y_2^{\text{eq}}}{Y_1^{\text{eq}}} \right) \right],$$



44

- Coannihilation $\chi_2 \chi_1$ typically dominates effective rate (for compressed spectra)
- Light inelastic DM in minimal dark photon model **strongly constrained** by searches for mediator



INELASTIC DM BEYOND MINIMAL

- Going beyond minimal kinetic mixing, including direct SM charges

$$\mathcal{L}_{\text{int}} \supset -g_Q \sum_f Q_F \bar{f} \gamma^\mu f A'_\mu - g_D \bar{\chi}_2 \gamma^\mu \chi_1 A'_\mu + \text{h.c.}$$

- Charge assignment changes production, visible branching ratios and accelerator constraints.
- **Opens up thermal relic parameter space; sensitivity of future experiments like FASER, LDMX, etc.**

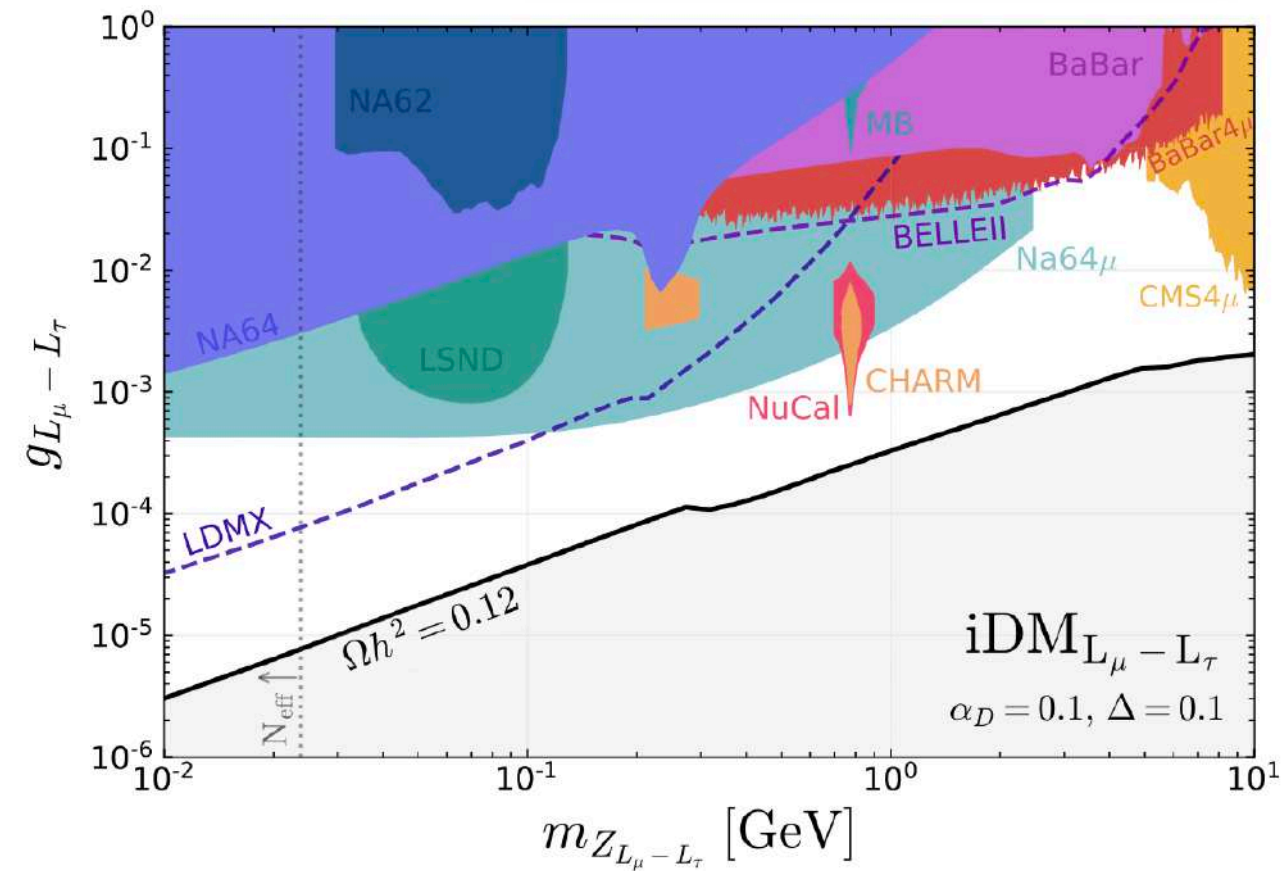
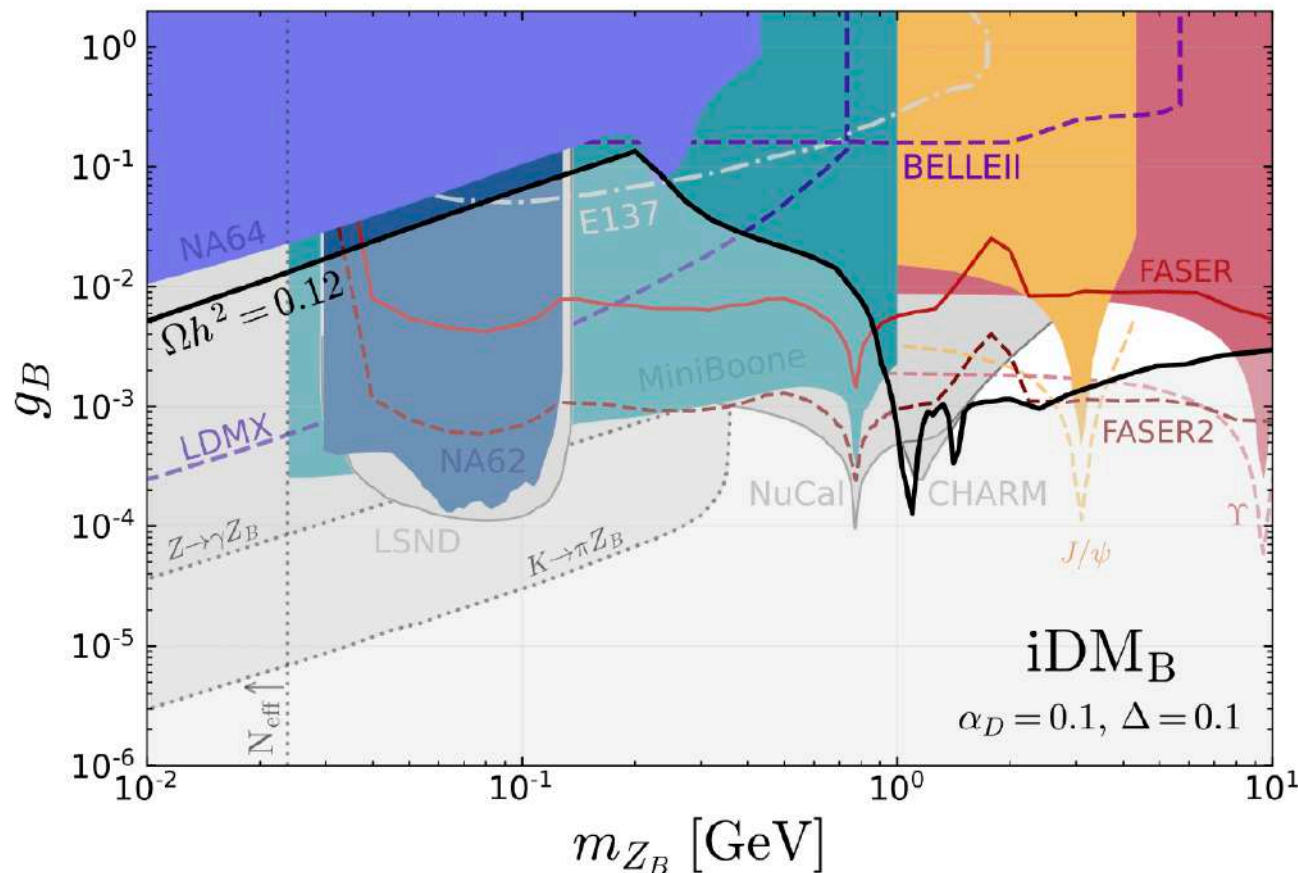
$$Q = x_B B - x_e L_e - x_\mu L_\mu - x_\tau L_\tau$$

x_B	x_e	x_μ	x_τ	Q	q_Q^f			
					quarks	e/ν_e	μ/ν_μ	τ/ν_τ
1	1	1	1	$B-L$	$\frac{1}{3}$	-1	-1	-1
1	0	0	3	$B-3L_\tau$	$\frac{1}{3}$	0	0	-3
1	0	0	0	B	$\frac{1}{3}$	0	0	0
0	0	-1	1	$L_\mu - L_\tau$	0	0	1	-1

Benchmarks

$$m_{A'}/m_\chi = 3;$$

A' decay to $\chi_1 \chi_2$ forbidden



CONCLUSIONS

Mechanism	Required feature	Characteristic prediction
Resonant freeze-out	$m_{A'} \approx 2 m_\chi$	DD / accelerator complementarity
Low-Trh freeze-in	$T_{\text{RH}} \lesssim m_\chi, m_{A'}$	larger, testable portal coupling
Inelastic/coannihilation	$T_F \gtrsim \Delta \gtrsim E_{\text{kin halo}}$	suppressed CMB and elastic direct-detection signals

- What can we extract from a potential DM signal?

Relatively robustly

- mediator mass from a visible resonance
- recoil-spectrum momentum dependence
- visible branching ratios and decay channels

Cosmology dependent

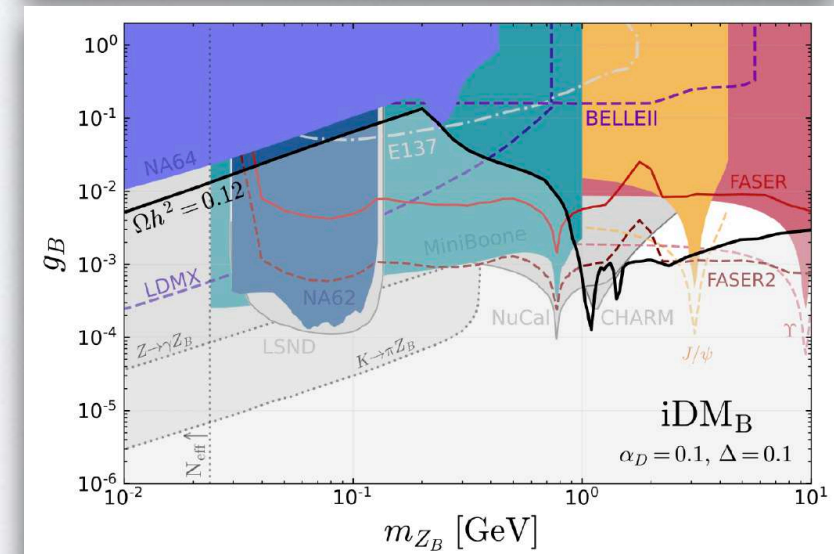
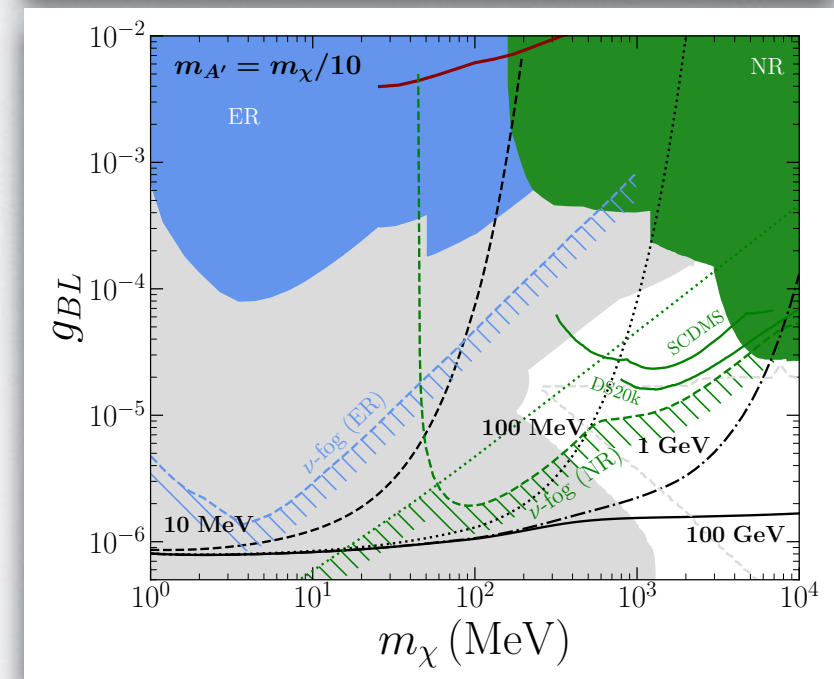
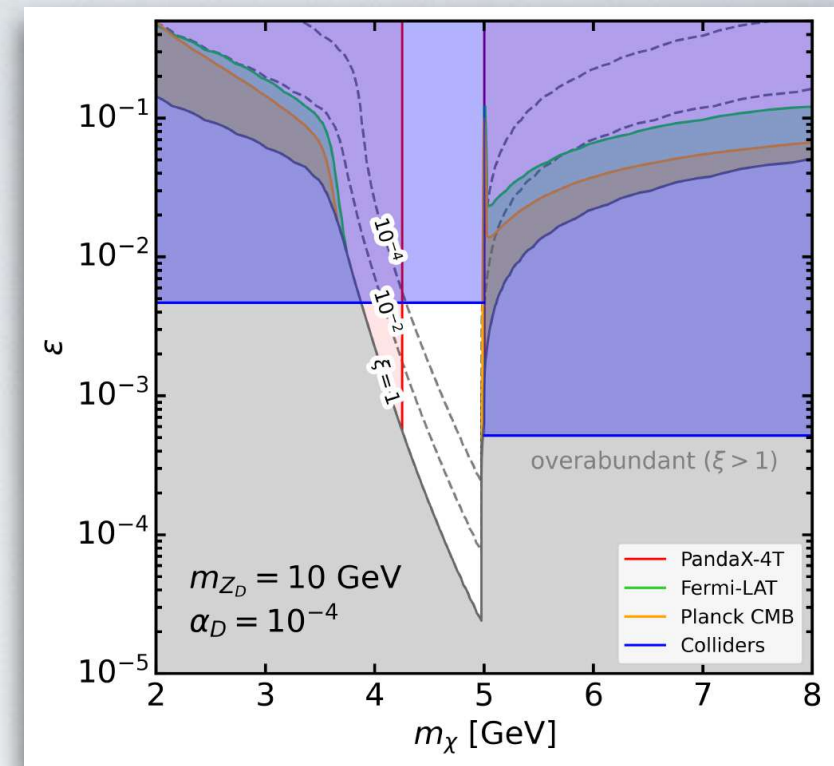
- mapping couplings to the relic abundance
- reheating temperature
- excited-state abundance and lifetime

Model dependent

- dark charge assignment
- mass splitting Δ and dark-state spectrum
- stability symmetry and additional dark states

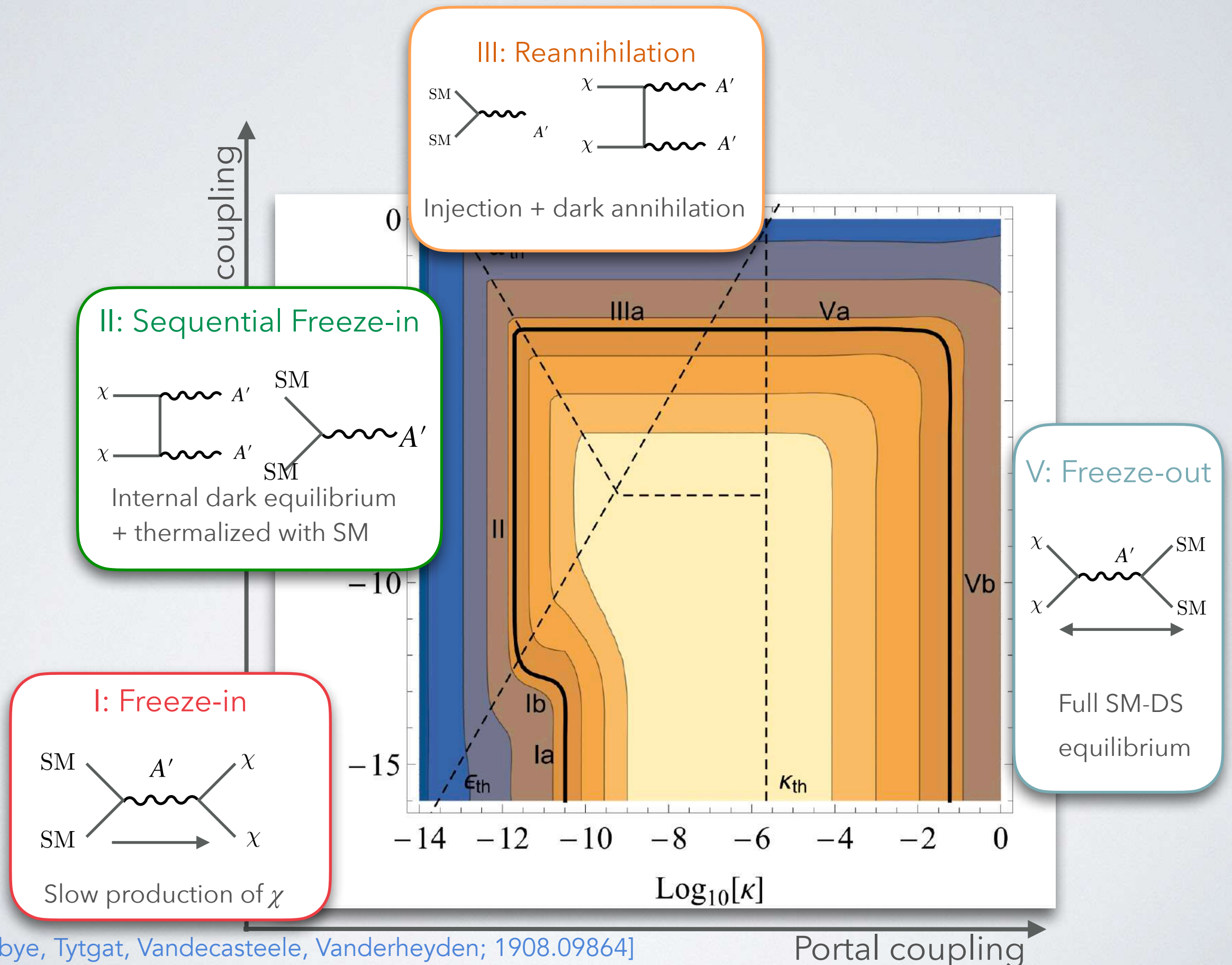
CONCLUSIONS

- GeV thermal DM still viable in resonance
- **Direct detection** experiments and **colliders** are most promising to further close the GeV **resonance window**
- **Freeze-in** option is still viable in large class of vector mediator models
- Upcoming direct detection experiments can **test low reheating regime**
- **Leptophilic vector mediators** can induce simultaneous **DM and neutrino** signal at direct detection
- Minimal inelastic DM strongly constrained!
- General anomaly-free iDM models **open up thermal relic space; testable at future experiments**

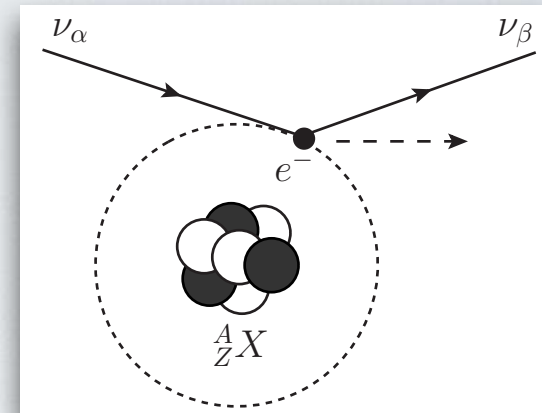
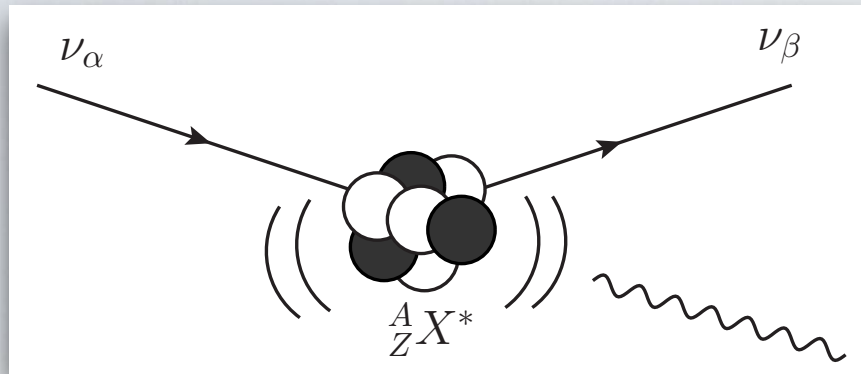


BACKUP

DM PHASE DIAGRAM: MOORING BOLLARD



MODIFIED NEUTRINO FLOOR



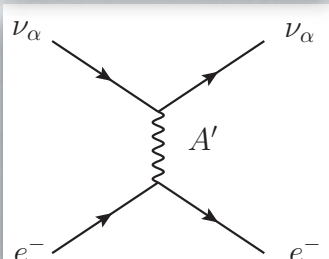
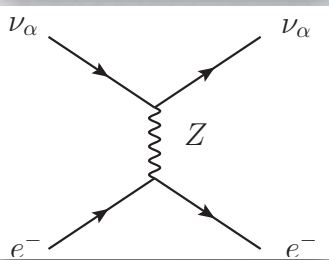
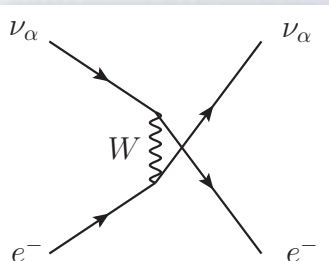
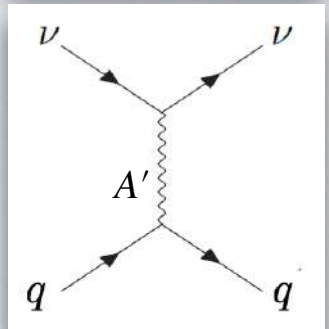
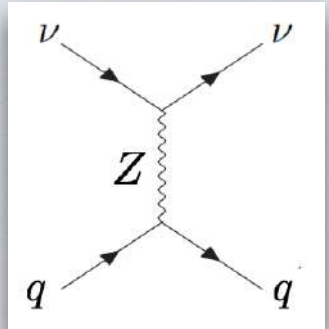
CEvNS

(for universal vector couplings)

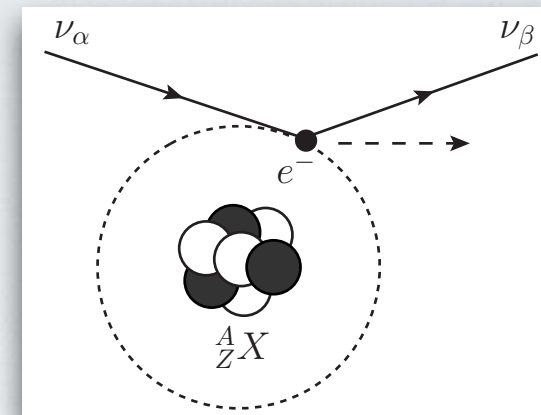
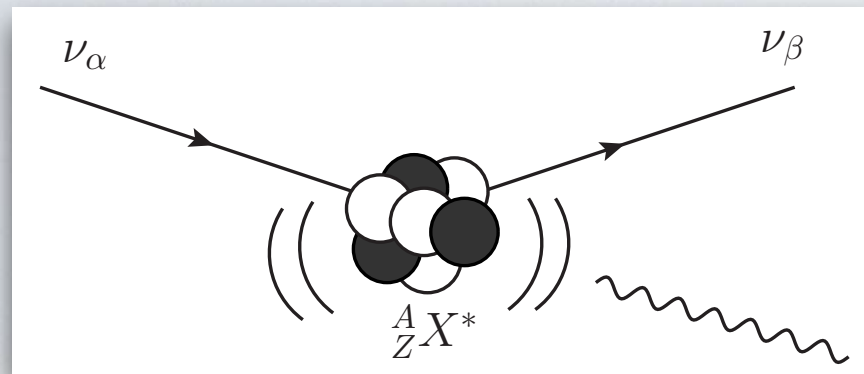
$$\frac{d\sigma_{\nu_{\alpha}N}}{dE_R} = \frac{G_F^2 M_N}{\pi} \left(1 - \frac{M_N E_R}{2E_\nu^2} \right) \times \left\{ \underbrace{\frac{Q_{\nu N}^2}{4}}_{\text{SM}} + \underbrace{\frac{g_{xN} g_{x\nu}}{\sqrt{2}G_F (2M_N E_R + M_{A'}^2)} + \frac{g_{xN}^2 g_{x\nu}^2}{2G_F^2 (2M_N E_R + M_{A'}^2)^2}}_{\text{BSM}} \right\} F^2(E_R)$$

EvES

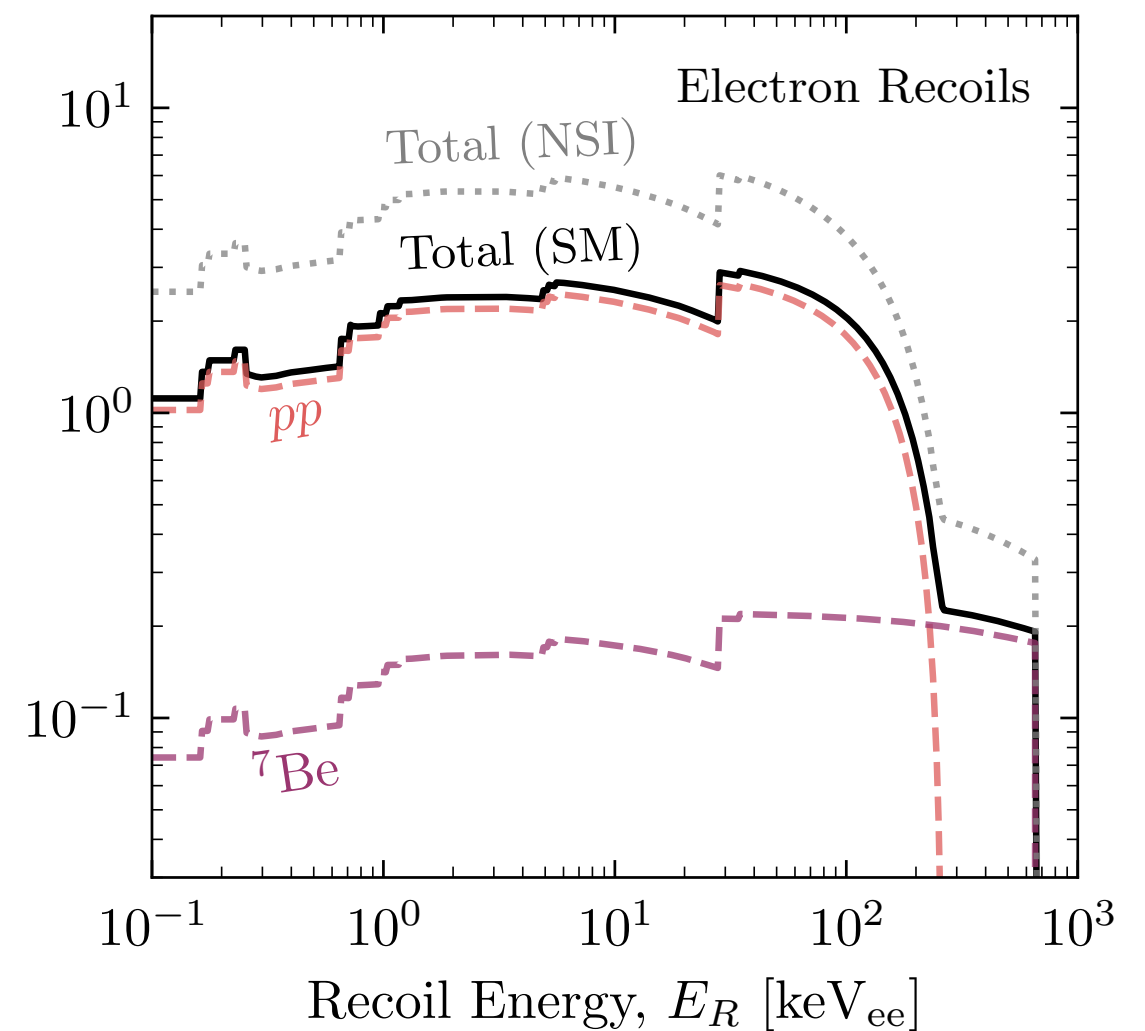
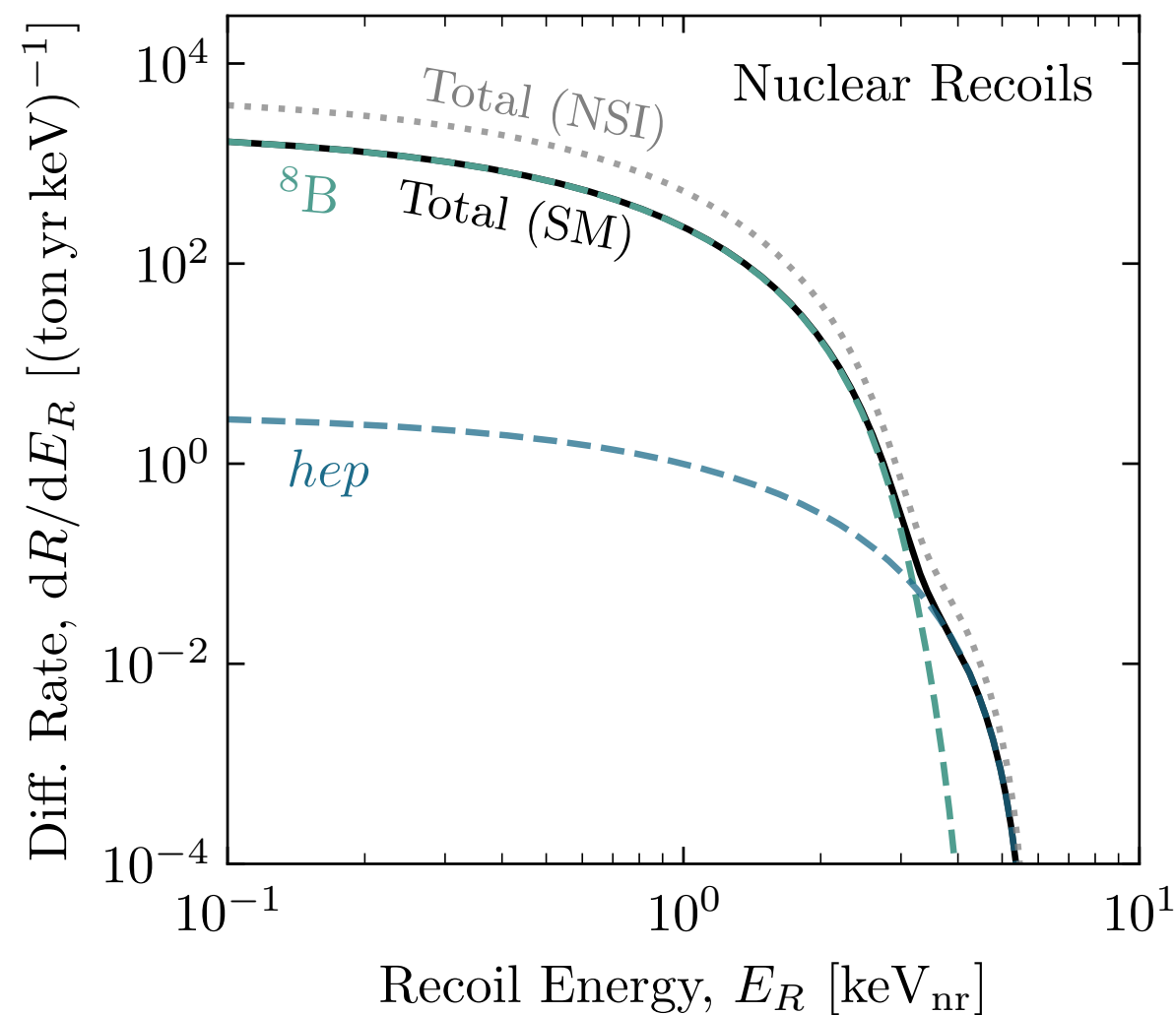
$$\frac{d\sigma_{\nu_{\alpha}e}}{dE_R} = \frac{2G_F^2 m_e}{\pi} \left\{ \underbrace{\left[g_L^e{}^2 + g_R^e{}^2 \left(1 - \frac{E_R}{E_\nu} \right)^2 - g_L^e g_R^e \frac{m_e E_R}{E_\nu^2} \right]}_{\text{SM}} + \underbrace{\frac{g_{xe} g_{x\nu}}{\sqrt{2}G_F (2E_R m_e + M_{A'}^2)} \left[(g_L^e + g_R^e) \left(1 - \frac{m_e E_R}{2E_\nu^2} \right) - g_R^e \frac{E_R}{E_\nu} \left(2 - \frac{E_R}{E_\nu} \right) \right] + \frac{g_{xe}^2 g_{x\nu}^2}{4G_F^2 (2E_R m_e + M_{A'}^2)^2} \left[1 - \frac{E_R}{E_\nu} \left(1 - \frac{E_R - m_e}{2E_\nu} \right) \right]}_{\text{BSM}} \right\}$$



SOLAR NEUTRINO SCATTERING



- Can compute solar neutrino **scattering rate including NSI in propagation and scattering**:



SNUDD

- Implemented the full chain of **propagation**, **scattering** plus **detector effects** for **NSI** in solar ν in open-source **Python** package: <https://github.com/SNuDD/SNuDD.git>

The screenshot shows the GitHub repository for SNUDD. The repository is owned by 'cheekyparticle' and has 2 branches and 2 tags. The file list includes notebooks, snudd, .gitignore, LICENSE, README.md, pyproject.toml, requirements.txt, setup.py, and snudd_logo.png. The README section is visible, featuring a logo with 'Nu' in white on a blue background, 'S' in white on a yellow background, and 'DD' in white on a blue background with a globe. The right sidebar shows the 'About' section, stating that SNUDD is a Python package for computing solar neutrino nuclear and electron recoil spectra. It also lists the license as GPL-3.0, the number of stars (8), and the number of forks (1). The 'Releases' section shows version v1.0.0 as the latest release, published 3 weeks ago. The 'Packages' section indicates no packages are published. The 'Contributors' section shows 5 contributors. The 'Languages' section shows Jupyter Notebook at 67% and Python at 33%.

main 2 Branches 2 Tags

Go to file Add file Code

cheekyparticle Delete snudd/data/exps/LZ2025/WS2022_data_hist_data.txt:Zone.Identifier dbd7258 · last week 156 Commits

notebooks	Packaging data correctly	3 weeks ago
snudd	Delete snudd/data/exps/LZ2025/WS2022_data_hist_data....	last week
.gitignore	Removed build directory; no longer needed	3 months ago
LICENSE	Initial commit	3 years ago
README.md	Revised README with updated citation	3 weeks ago
pyproject.toml	Packaging data correctly	3 weeks ago
requirements.txt	Adjusted requirements	3 weeks ago
setup.py	Packaging data correctly	3 weeks ago
snudd_logo.png	Adding logo	3 weeks ago

README GPL-3.0 license

arXiv 2607.22817 arXiv 2302.12846

About

SNUDD is a Python package for computing the solar neutrino nuclear and electron recoil spectra at direct detection experiments. SNUDD accounts for both solar and terrestrial neutrino propagation effects as well as for modifications of the neutrino-nucleus and -electron scattering cross sections due to new physics, including detector effects.

github.com/SNuDD/SNuDD

Readme

GPL-3.0 license

Activity

Custom properties

8 stars

1 watching

1 fork

Report repository

Releases 2

v1.0.0 Latest 3 weeks ago

+ 1 release

Packages

No packages published

[Publish your first package](#)

Contributors 5

Languages

Jupyter Notebook 67% Python 33%

MASS GENERATION

- The Dark Photon mass can be dynamically generated by a **new complex scalar** S

$$V(H, S) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2 - \mu_s^2 S^* S + \lambda_s(S^* S)^2 + \lambda_m S^* S H^\dagger H$$

- Once the scalars acquire a VEV they will break the symmetries

$$H = \frac{1}{\sqrt{2}}(v + h) \quad , \quad S = \frac{1}{\sqrt{2}}(w + s)$$

- This leads to a mixed scalar mass matrix and scalar mixing

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda v^2 & \lambda_m v w \\ \lambda_m v w & 2\lambda_s w^2 \end{pmatrix} \Rightarrow \begin{pmatrix} h_{125} \\ h_D \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- Kinetic term of S generates DP mass and scalar-vector couplings if charged under $U(1)_X$

$$(D_\mu S)^* (D^\mu S) \supset \frac{g_x^2 q_x^2}{2} w^2 X_\mu X^\mu + g_x^2 q_x^2 w s X_\mu X^\mu + \frac{g_x^2 q_x^2}{2} s^2 X_\mu X^\mu$$

$$M_X = g_x q_x w$$

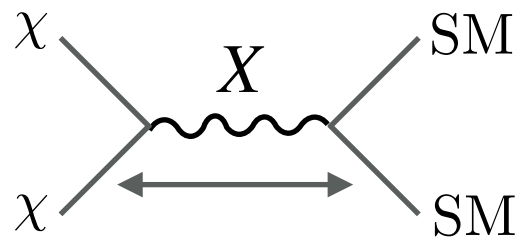


PORTAL VS. PRODUCTION MECHANISM

- Same portal operator can lead to different relic-density mechanisms

Exchange for reannihilation?

Direct annihilation



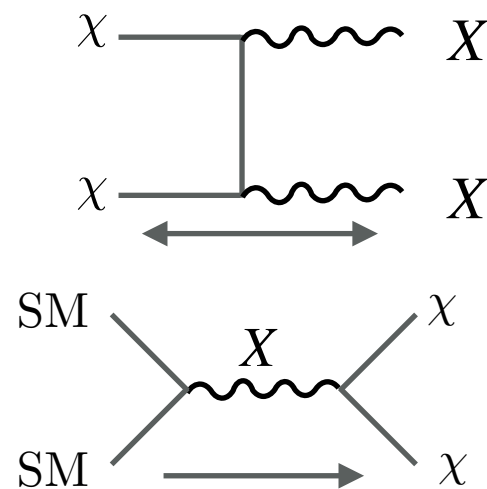
- One thermal bath**
- Abundance set via freeze-out

$$n_{\chi}^{\text{eq}}(T_f) \langle \sigma v \rangle \approx H(T_f)$$

$$\langle \sigma v \rangle_{\chi\chi \rightarrow ff} \propto \alpha_{\text{vis}} \alpha_D$$

$$\Omega h^2 \propto \langle \sigma v \rangle^{-1}$$

Reannihilation

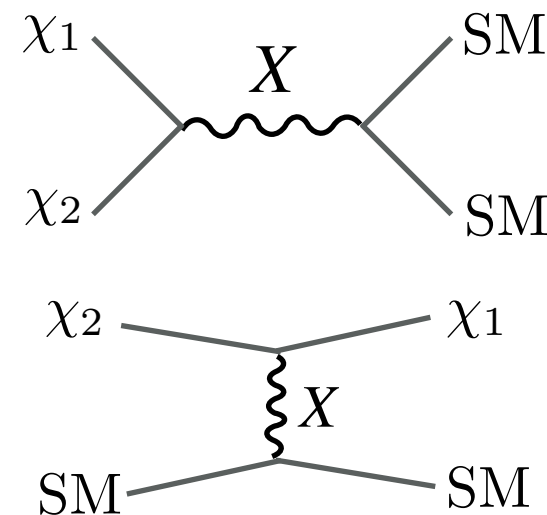


- Abundance set via

$$n_{\chi}^{\text{QSE}}(T) \langle \sigma v \rangle_{\chi\chi \rightarrow XX} \approx H(T)$$

$$n_{\chi}^{\text{QSE}} \approx \sqrt{\frac{\gamma_{SM \rightarrow \chi\chi}}{\langle \sigma v \rangle_{\chi\chi \rightarrow XX}}}$$

Inelastic/coannihilation



- Abundance set via

$$n^{\text{eq}}(T_f) \langle \sigma v \rangle_{\text{coann}} \approx H(T_f)$$

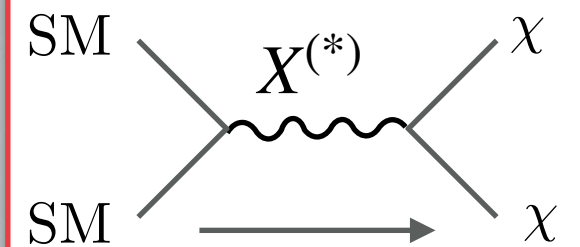
or

$$\Gamma_{\chi_1 \leftrightarrow \chi_2}(T_{\text{conv}}) \approx H(T_{\text{conv}})$$

$$\langle \sigma v \rangle_{\text{coann}} = \sum_{i,j} \langle \sigma_{ij} v \rangle \frac{n_i^{\text{eq}} n_j^{\text{eq}}}{(n^{\text{eq}})^2}$$

$$\frac{n_{\chi_2}^{\text{eq}}}{n_{\chi_1}^{\text{eq}}} \simeq \frac{g_2}{g_1} \left(1 + \frac{\Delta}{m_{\chi_1}} \right)^{3/2} e^{-\Delta/T}$$

Portal production



- Never in equilibrium**
- Requires throughout

$$\Gamma_{\text{prod}}(T) < H(T)$$

$$Y_{\chi}^{\infty} = \int_{T_0}^{T_{\text{max}}} \frac{\gamma_{\text{prod}}(T)}{s(T)H(T)T} dT$$

$$Y_{\chi}^{\infty} \propto \alpha_{\text{vis}} \alpha_D$$