Closing in on Vector Portals to Dark Matter

Patrick Foldenauer

patrick.foldenauer@csic.es

IFT (UAM-CSIC) Madrid

Instituto de Física Teórica UAM-CSIC

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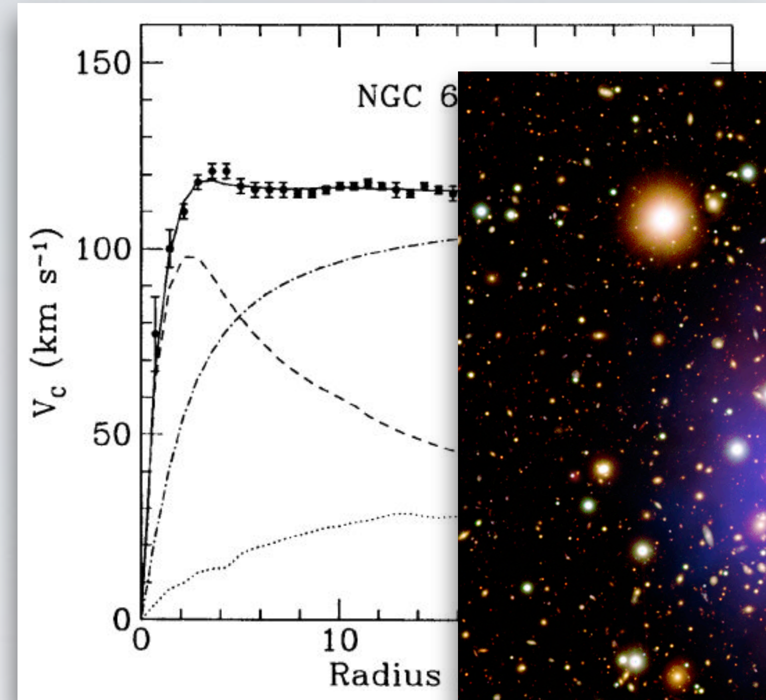
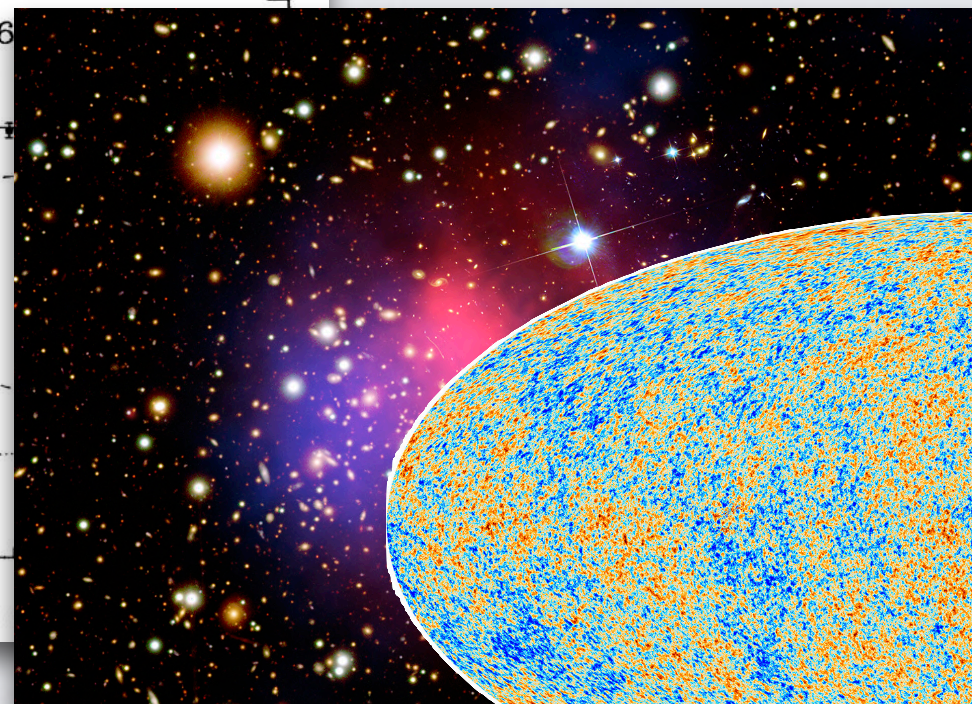
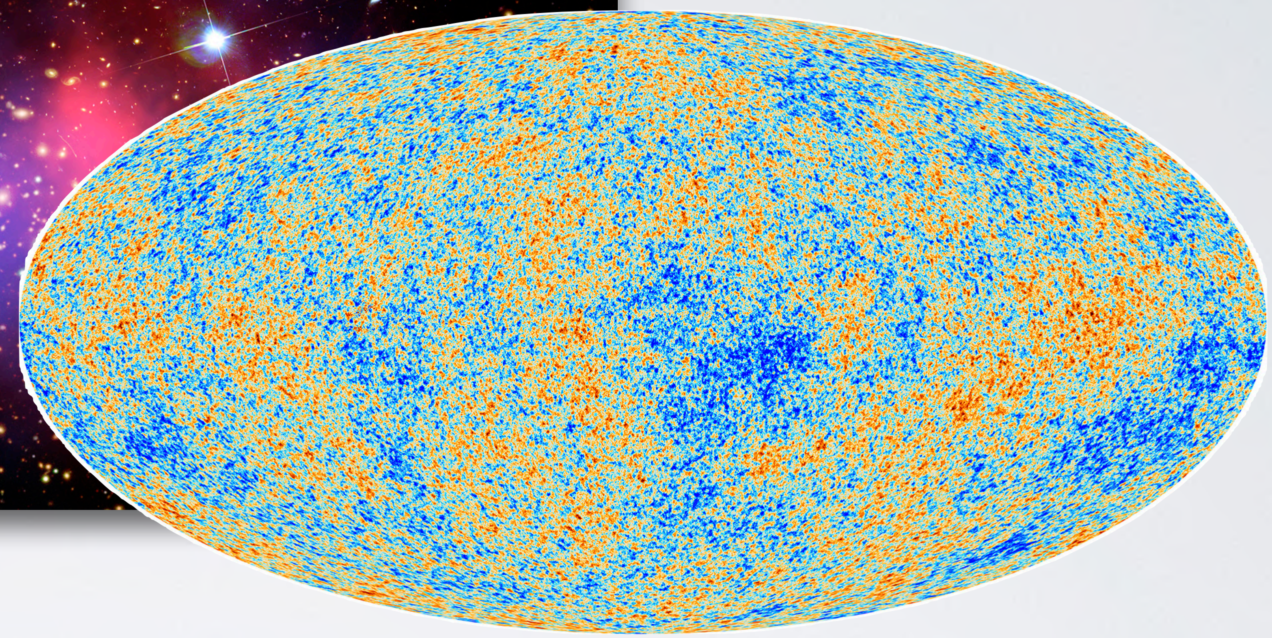
"la Caixa" Foundation

THE QUEST FOR DARK MATTER







Galaxy formation

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

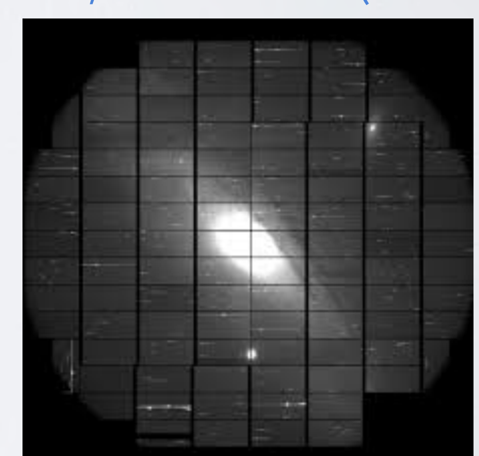
$$m \gtrsim 10^{-24}\,\text{eV}$$

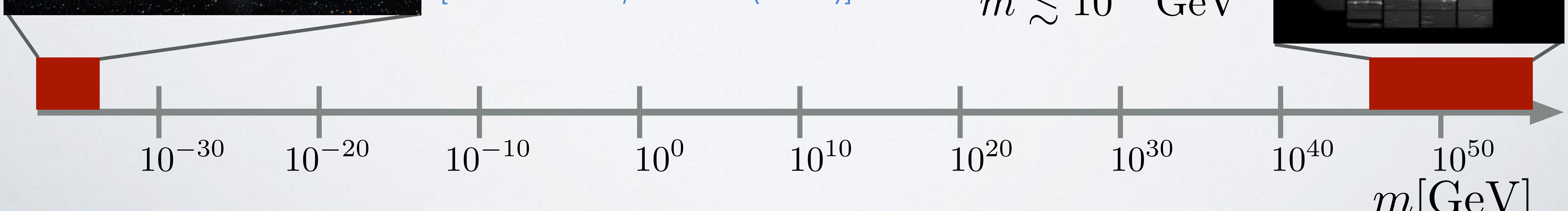
[Hlozek et al., PRD **91** (2015)]

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

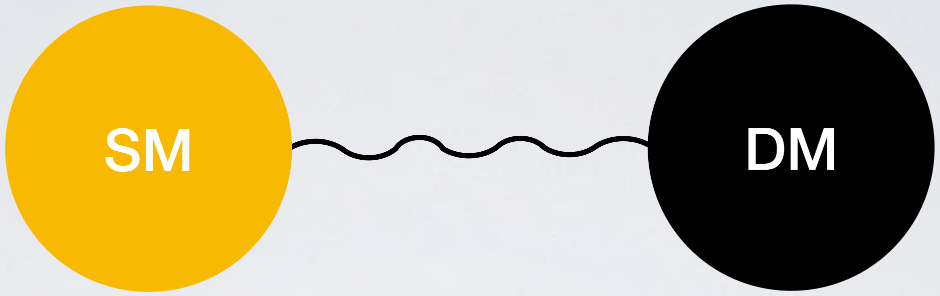
microlensing searches of PBHs

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





PORTAL INTERACTIONS

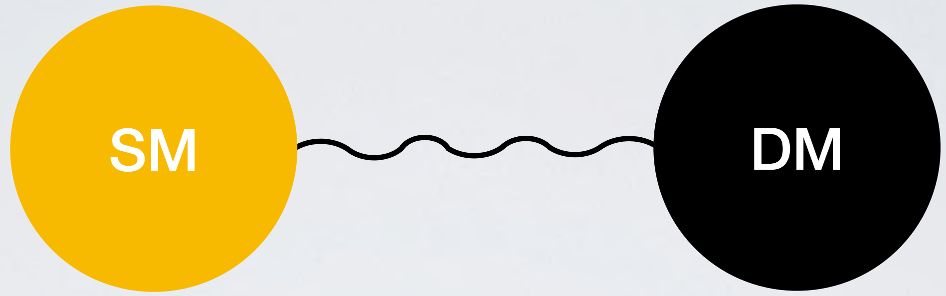


- Can build three renormalisable dim 4 portal interactions from the SM singlets $H^\dagger H$, $\bar{L}\tilde{H}$ and $B_{\mu\nu}$ by combining them with Dark Sector singlets

Higgs Portal	$\lambda_{HS} S^\dagger S H^\dagger H$
Neutrino Portal	$-Y^N \bar{L}\tilde{H} N$
Vector Portal	$-\frac{\epsilon_Y}{2} B_{\mu\nu} X^{\mu\nu}$

- Type of portal interaction can inform us on how to search for DM!

PORTAL INTERACTIONS



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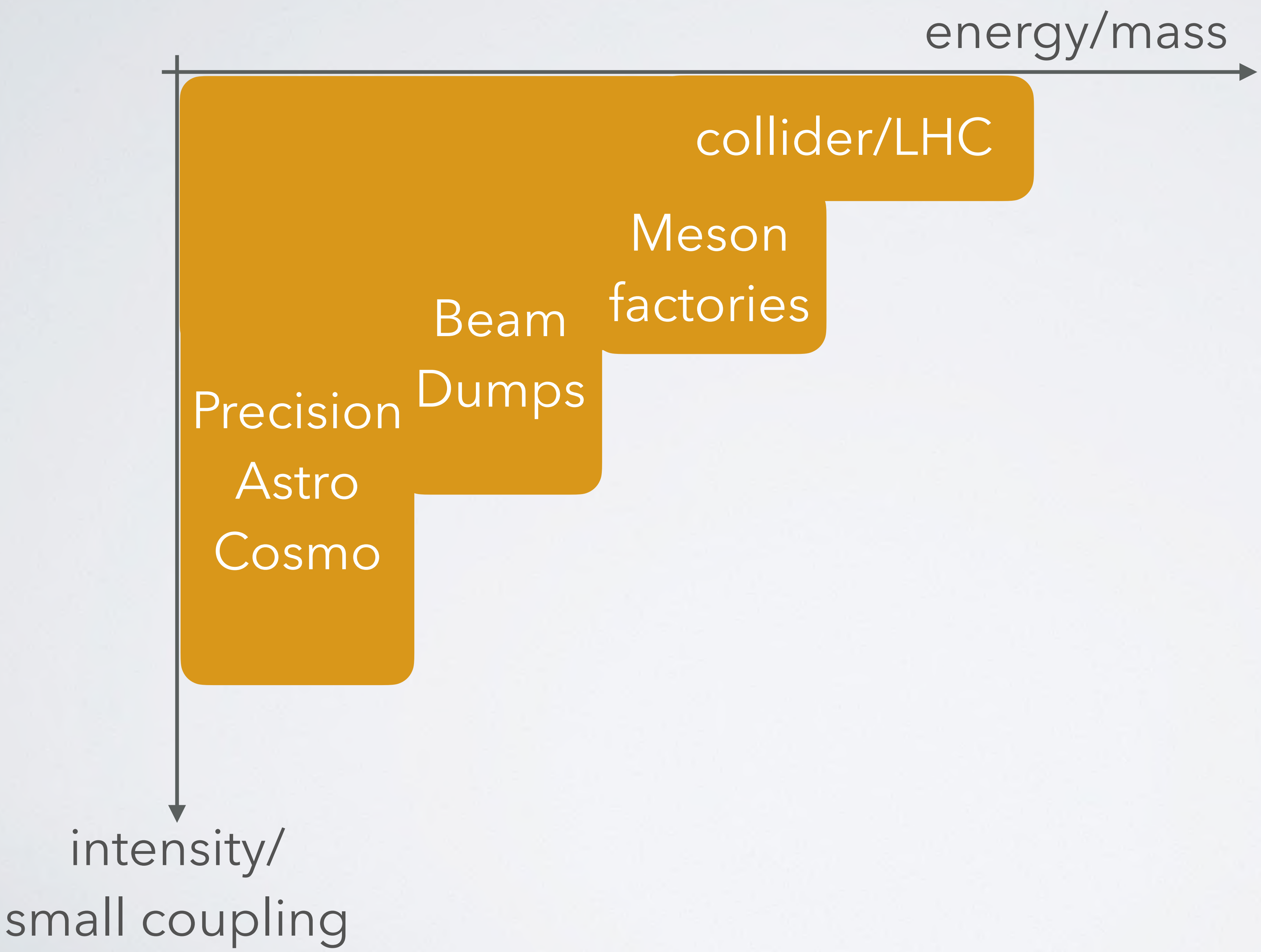
Requires new $U(1)$ gauge symmetry

- Type of portal interaction can inform us on how to search for DM!

WHERE TO SEARCH FOR DM?

- Experimental efforts to search for new particles give us an idea where BSM physics might hide



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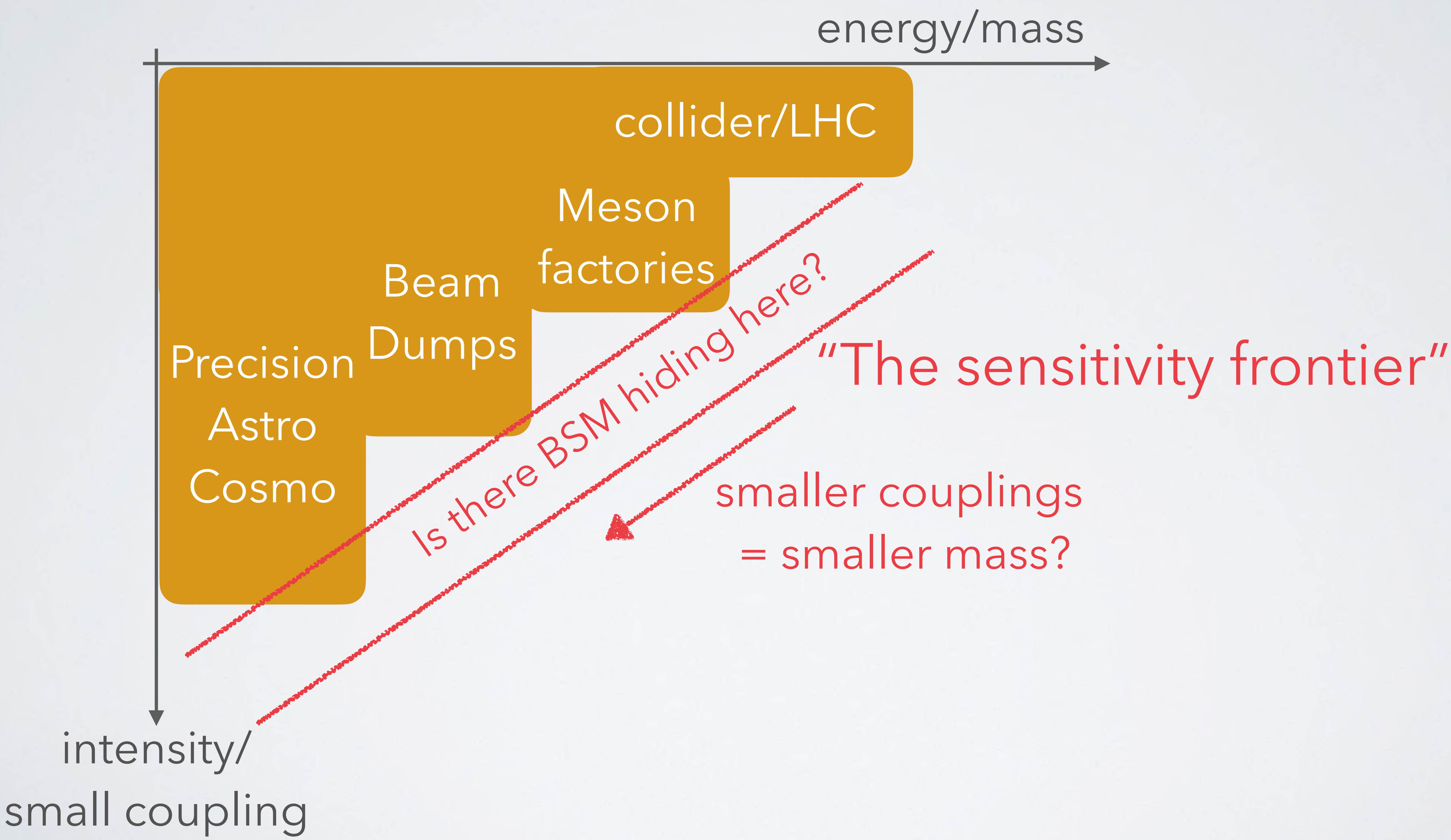

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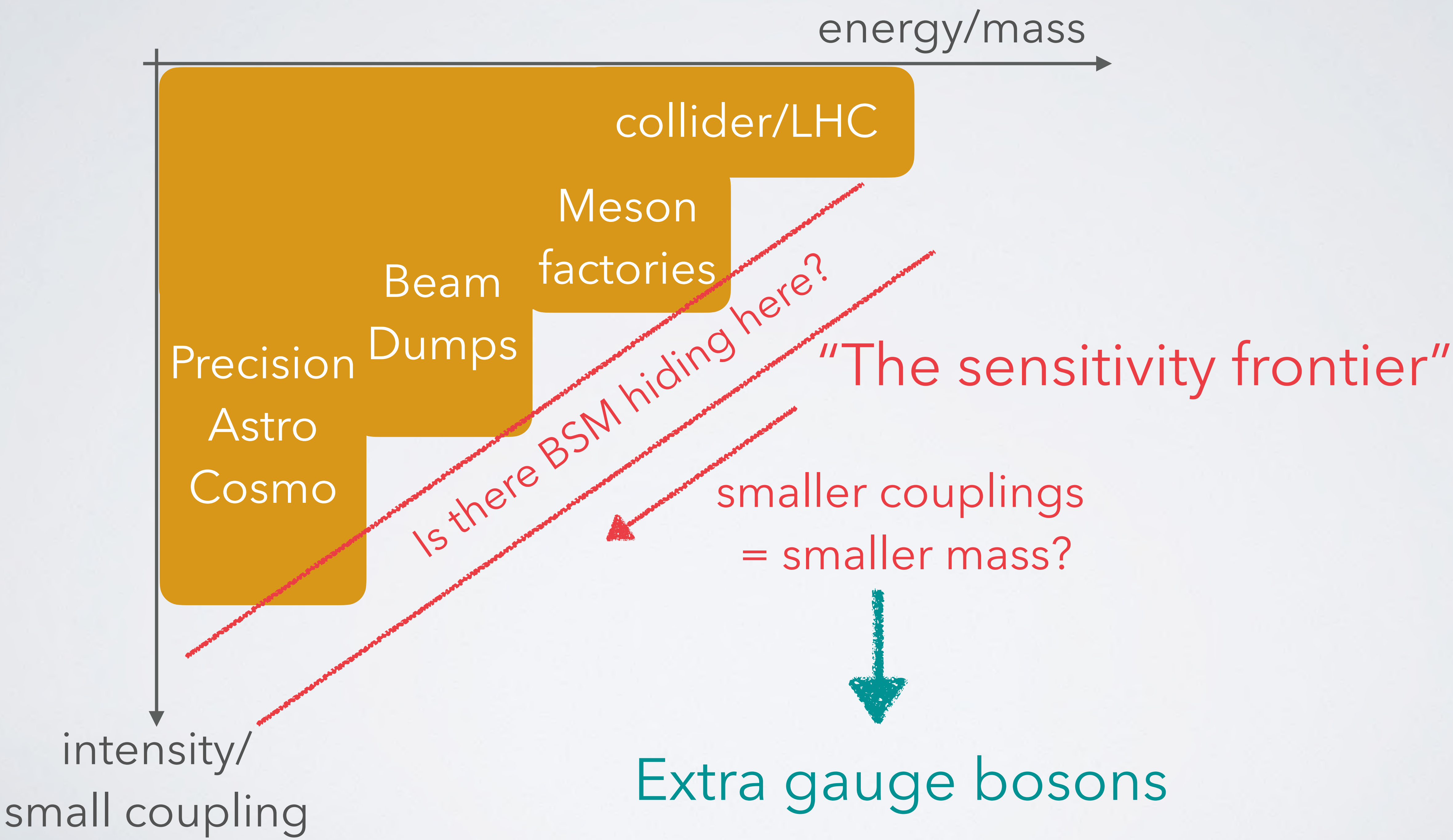
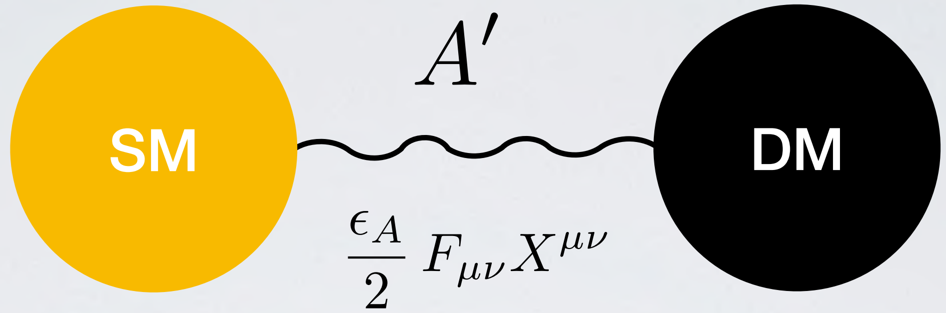


DARK PHOTONS

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

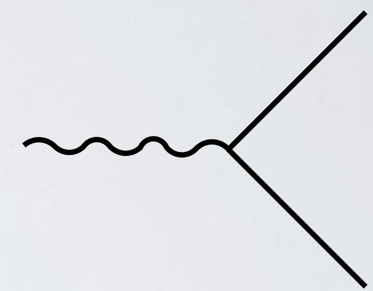


$U(1)_X$

See talk by Fuminobu Takahashi for mCPs

- For light **massive** mediators $M_X \ll M_Z$ kinetic terms can be diagonalised by simple field redefinition:

$$A^\mu \to A^\mu - \epsilon_A X^\mu \quad \rightarrow \quad e A_\mu J^\mu_{\mathrm{EM}} - \epsilon_A \, e X_\mu J^\mu_{\mathrm{EM}}$$



Coupling to EM current suppressed by ϵ_A, where typically $\epsilon_A \propto g_x/16\pi^2$

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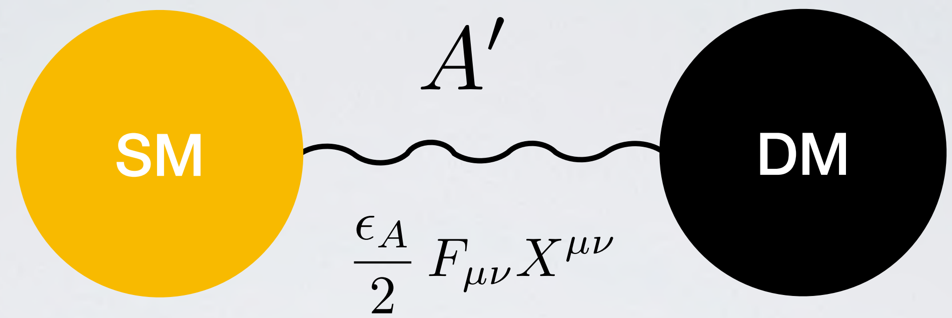

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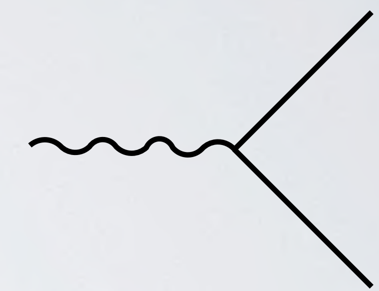
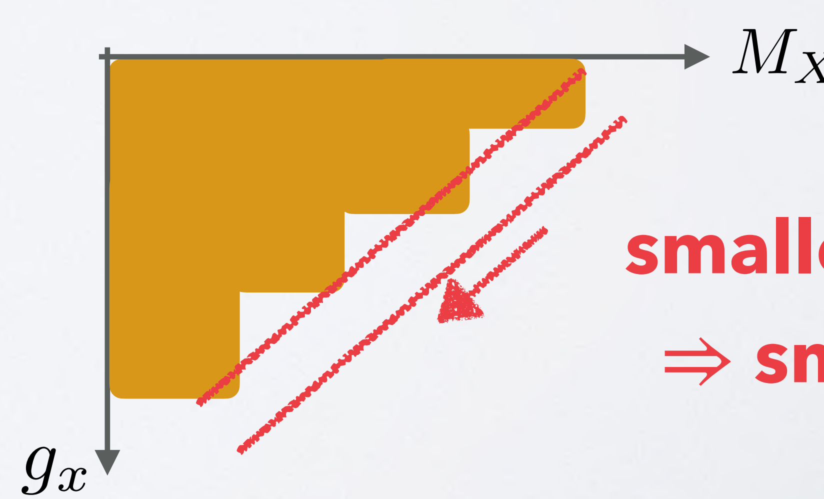


Coupling to EM current suppressed by ϵ_A, where typically $\epsilon_A \propto g_x/16\pi^2$

- If $U(1)_X$ is broken by VEV f of scalar, mass is related to coupling:

$$\mathcal{L} = (D_\mu S)^\dagger D^\mu S \supset g_x^2 f^2 \, X_\mu X^\mu$$

$$\Rightarrow \boxed{M_X = g_x f}$$

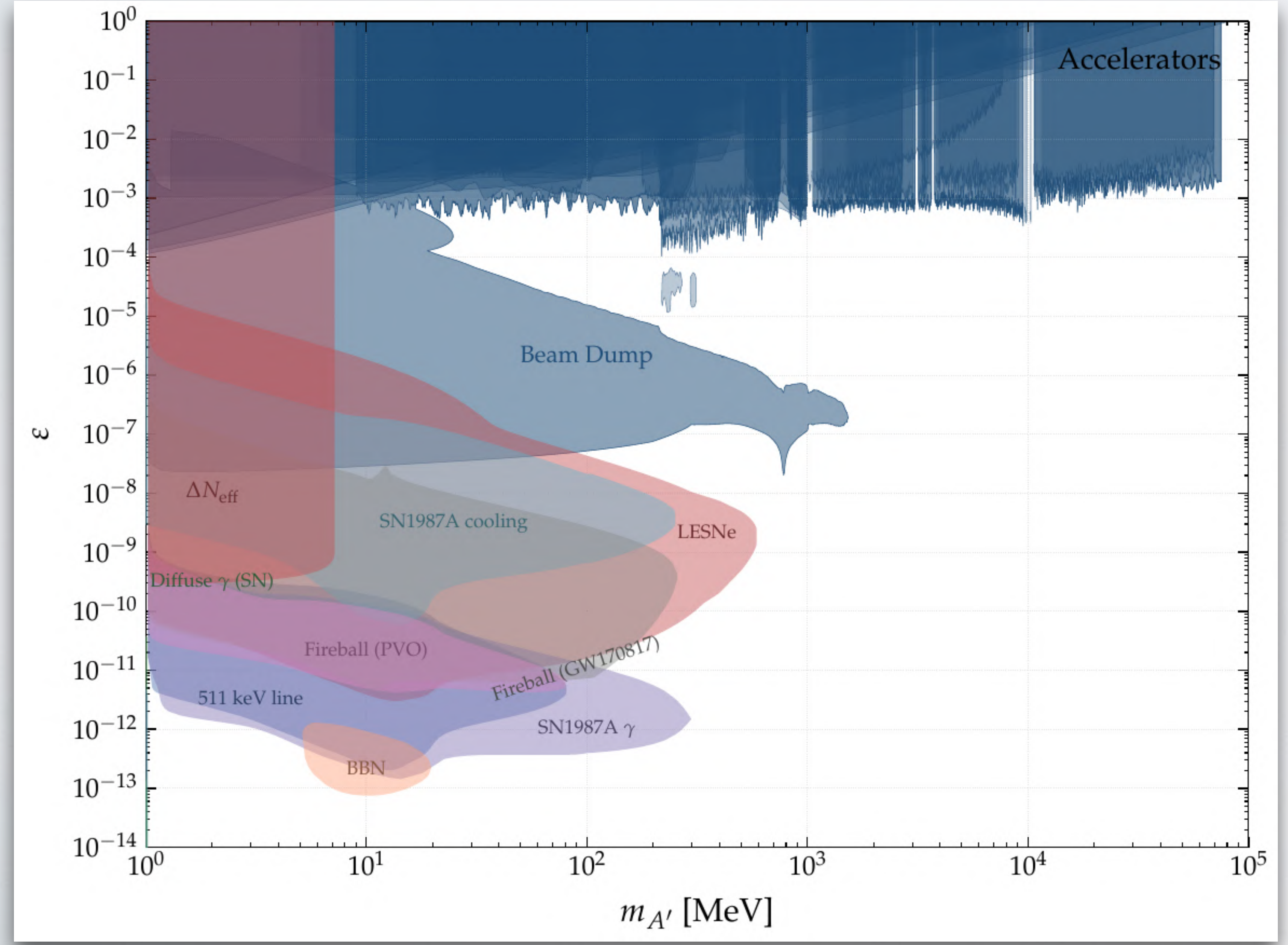


smaller couplings
$\Rightarrow$ smaller mass!

DARK PHOTONS

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\epsilon}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_X^2}{2} X_\mu \, X^\mu$$

- Past years have seen an extensive effort to search for MeV/GeV dark photon
- Constraints from **colliders, beam dumps, astrophysics, cosmology**

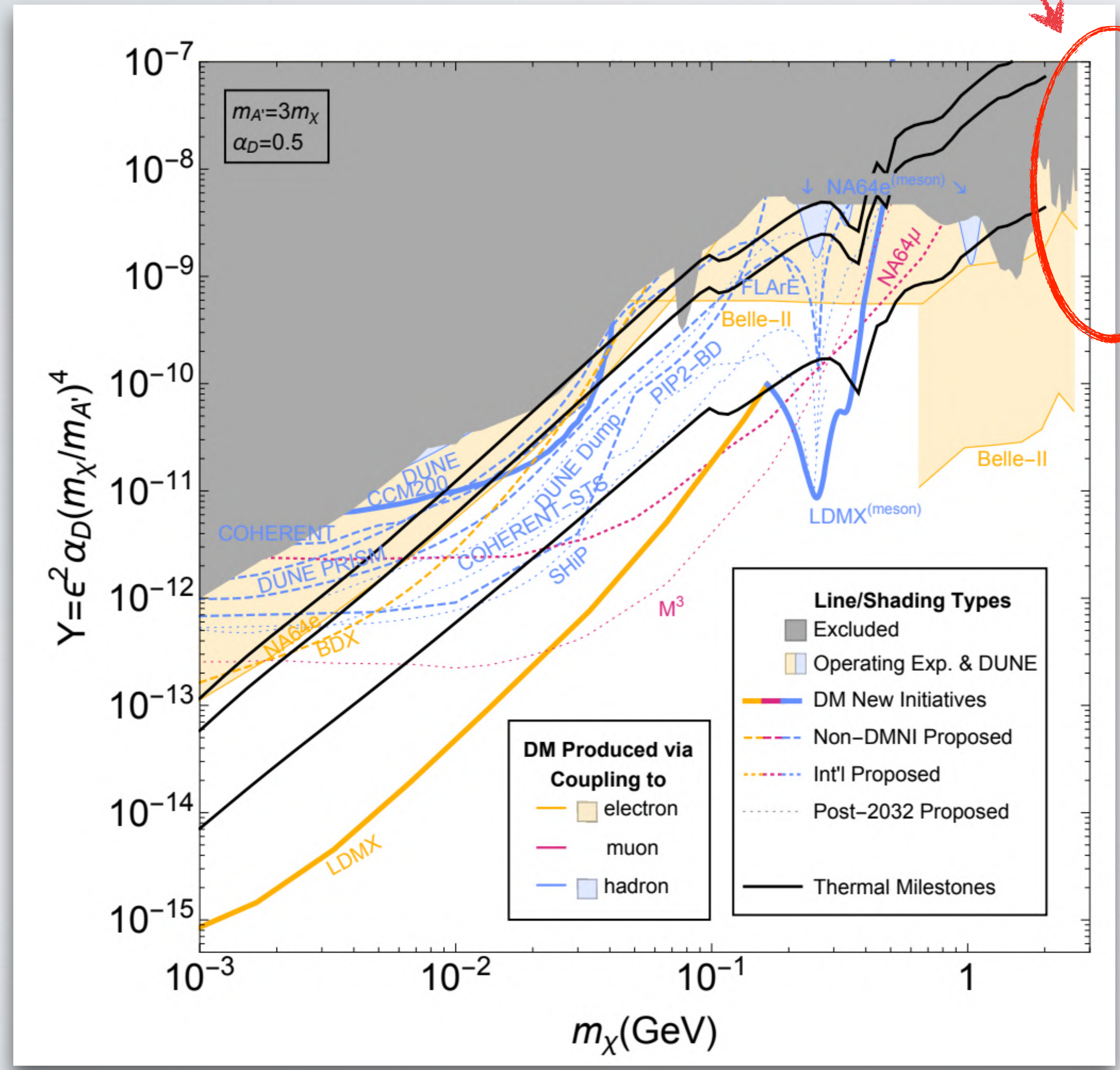


[Caputo, Essig; *2603.08430*]
[Kyselov, Ovchynnikov; *PRD 111, 015030*]
[Ilten et al., *JHEP* 06 (2018) 004]
[Bauer, **PF**, Jaeckel, *JHEP* 07 (2018) 094]

[many, many more …]

DARK PHOTONS AS MEDIATORS

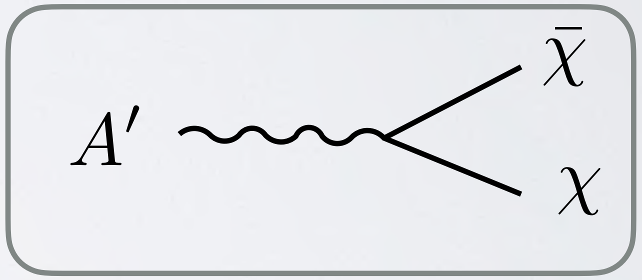
What happens here?



[Gori et al., *2209.04671*]

- Dark Photon can be **mediator to a dark sector**
- Simple example, vector-like fermion

$$\mathcal{L} = g_D\,\bar\chi\gamma^\mu\chi\;A'_\mu$$



- Assuming $g_D \gg \epsilon$ the HP will decay invisibly with

$$\mathrm{BR}(\mathrm{A}' \to \bar\chi\chi) \approx 1$$

THERMAL DM

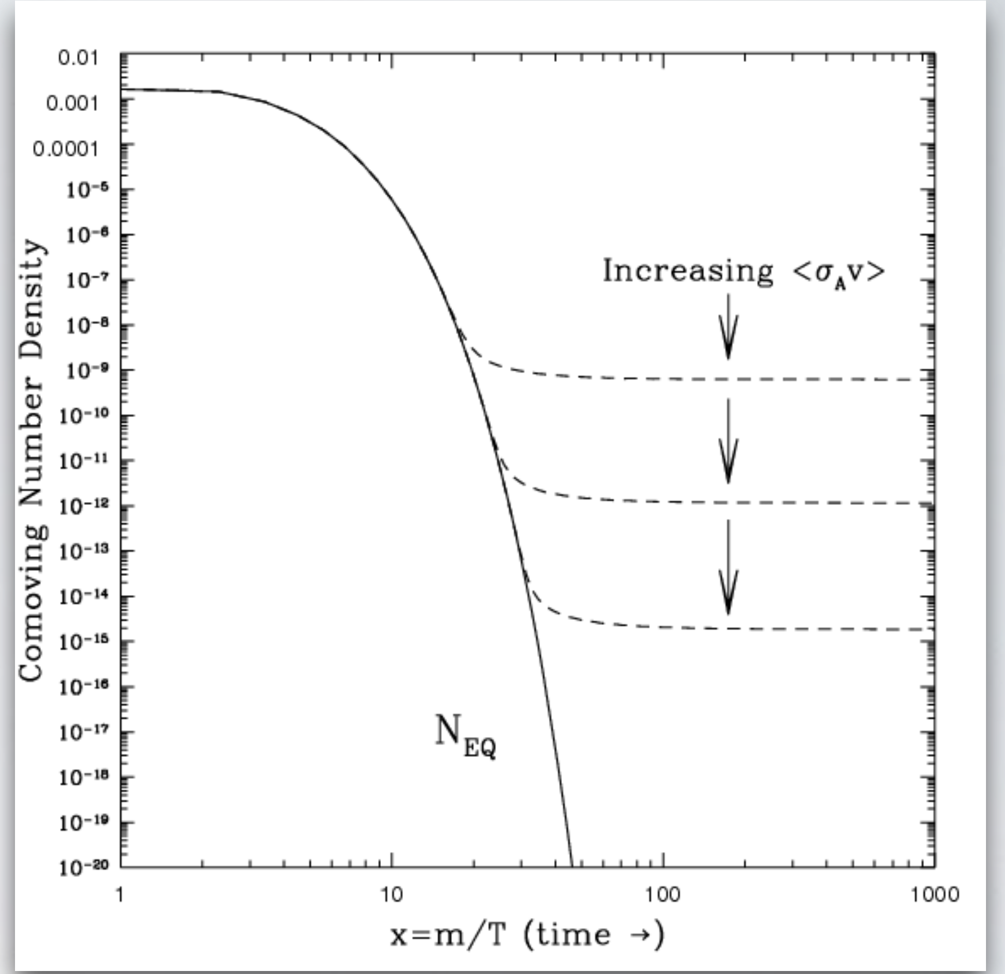
DM PRODUCTION

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

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

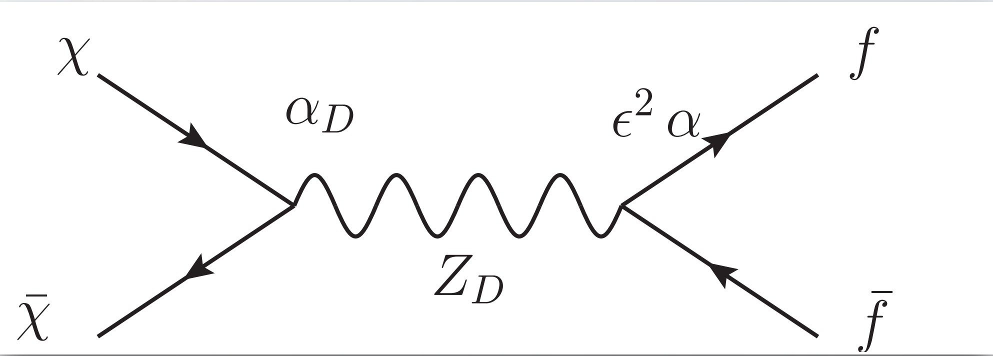
- **Freeze-out** abundance scales inversely with thermal cross section

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



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

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

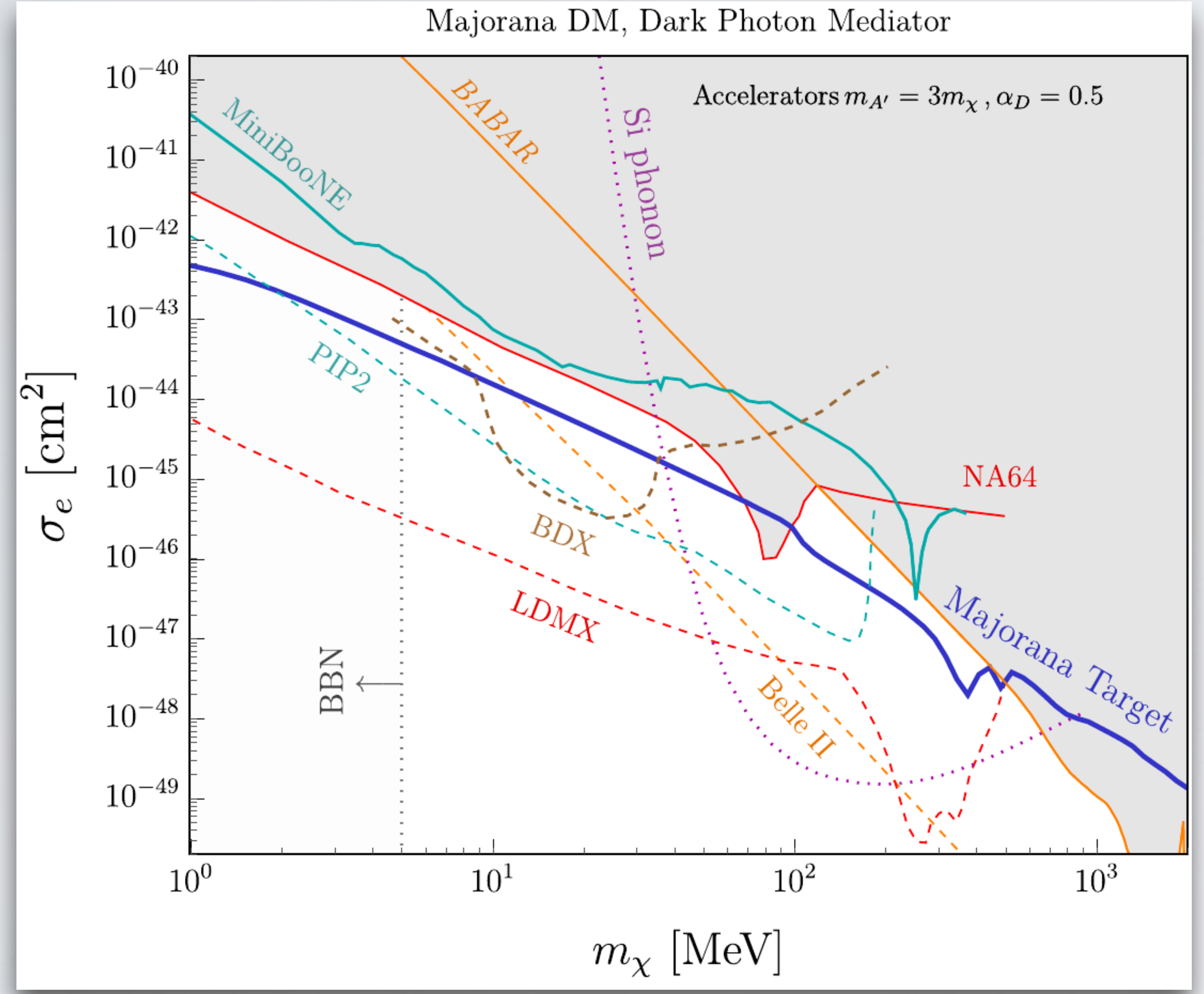


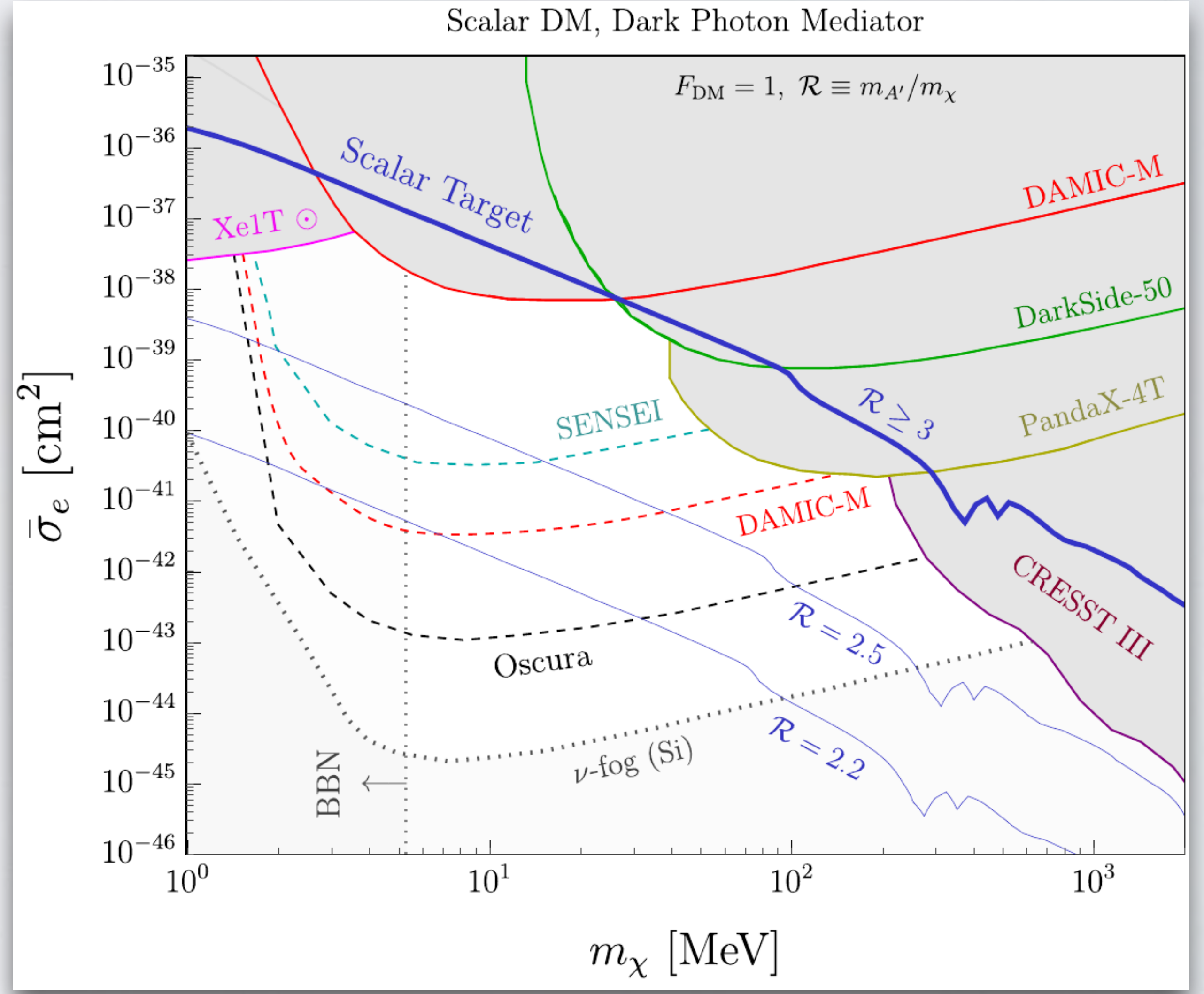
- Larger couplings ϵ and α_D yield smaller abundances!
- Resonance enhancement → can shift abundance to much smaller couplings

THERMAL BENCHMARKS

- DM coupled to a kinetically mixed vector mediator on the brink of being ruled out!

[Krnjaic, *2505.04626*]



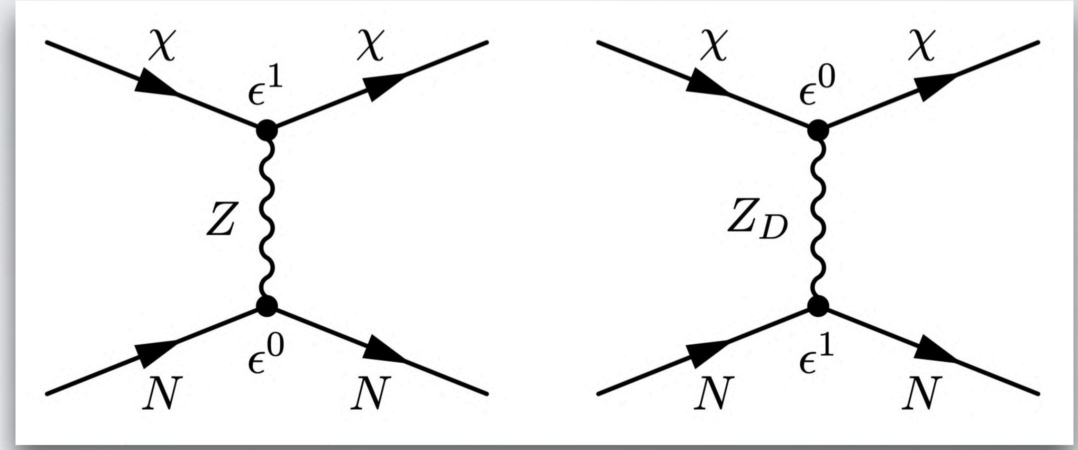


- Strongest constraints on MeV/GeV targets from **direct detection!**

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

BUT: No resonance enhancement in scattering!

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

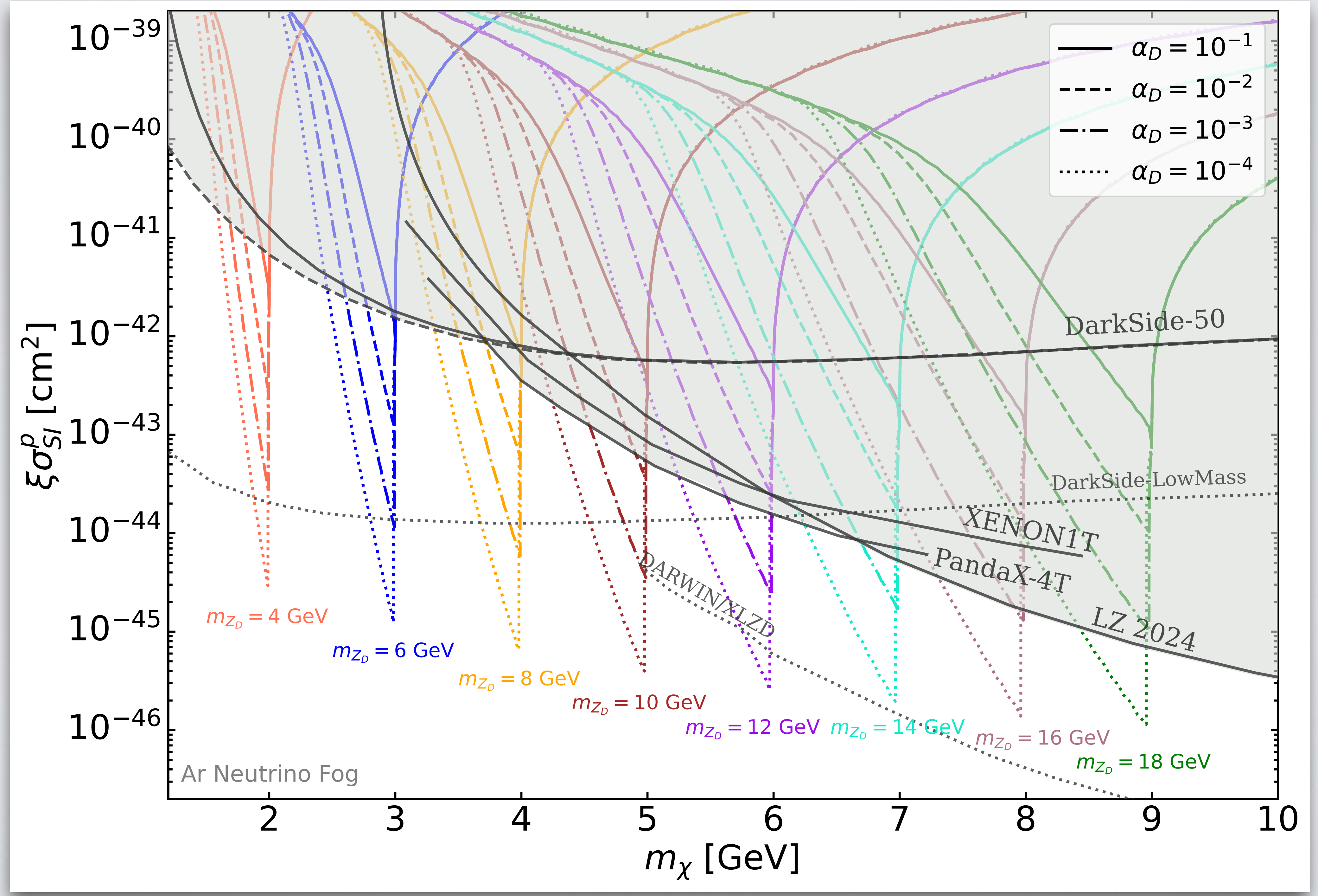
$$\rho_\chi \propto \frac{1}{\langle \sigma v \rangle} \Rightarrow \boxed{\frac{dR}{dE_R} \propto \frac{\sigma_{\chi T}}{\langle \sigma v \rangle} \propto \frac{\epsilon^2}{\epsilon^2} \frac{1}{(s - M_{Z_D}^2)^2 + \Gamma_{Z_D}^2 M_{Z_D}^2}}$$

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

DIRECT DETECTION

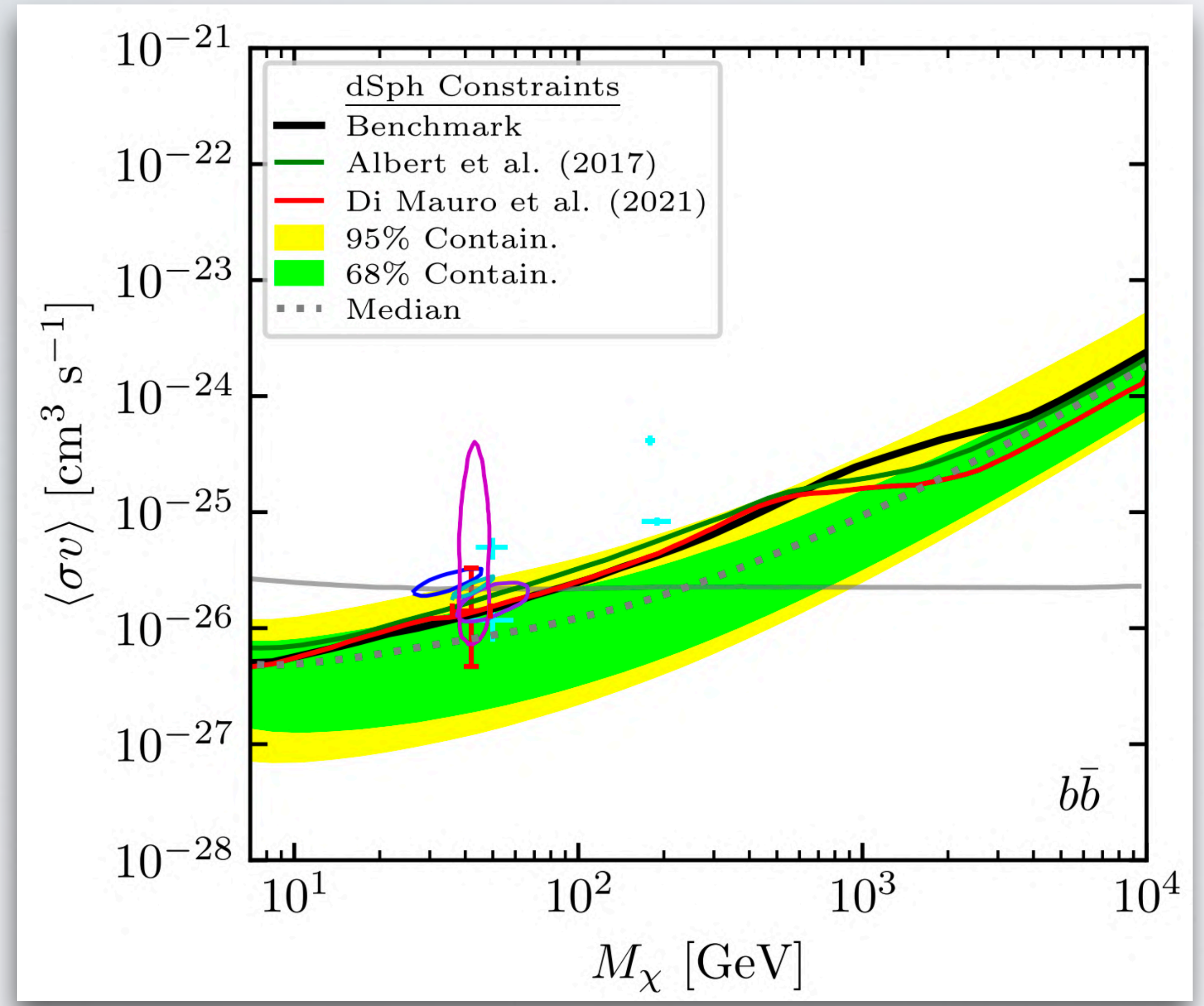
- GeV DM can avoid direct detection **close to resonance** for **small couplings α_D!**

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

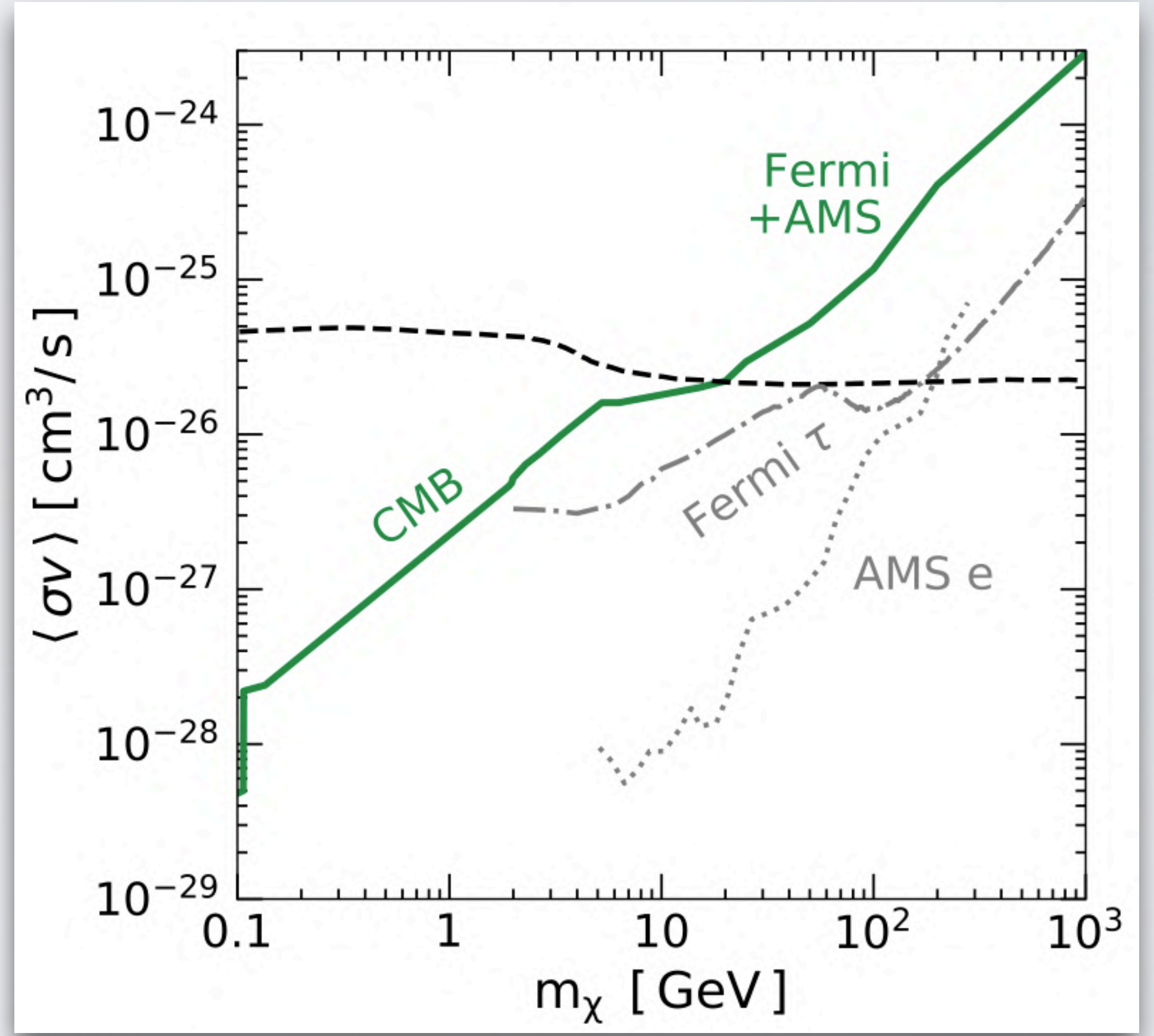


"MODEL-INDEPDENT" BOUNDS

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



[McDaniel+; PRD 109, 063024]

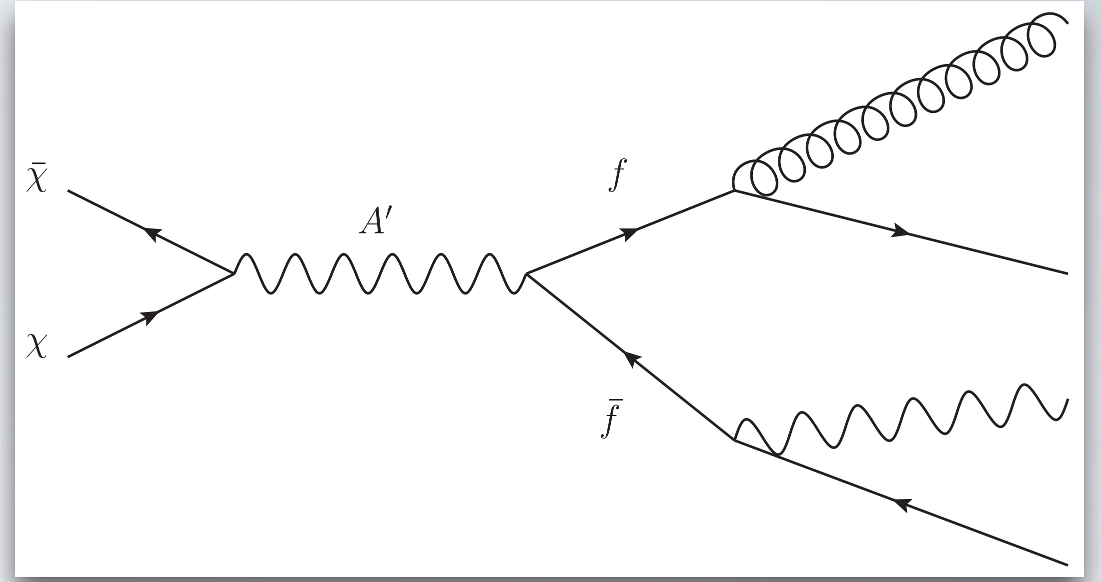


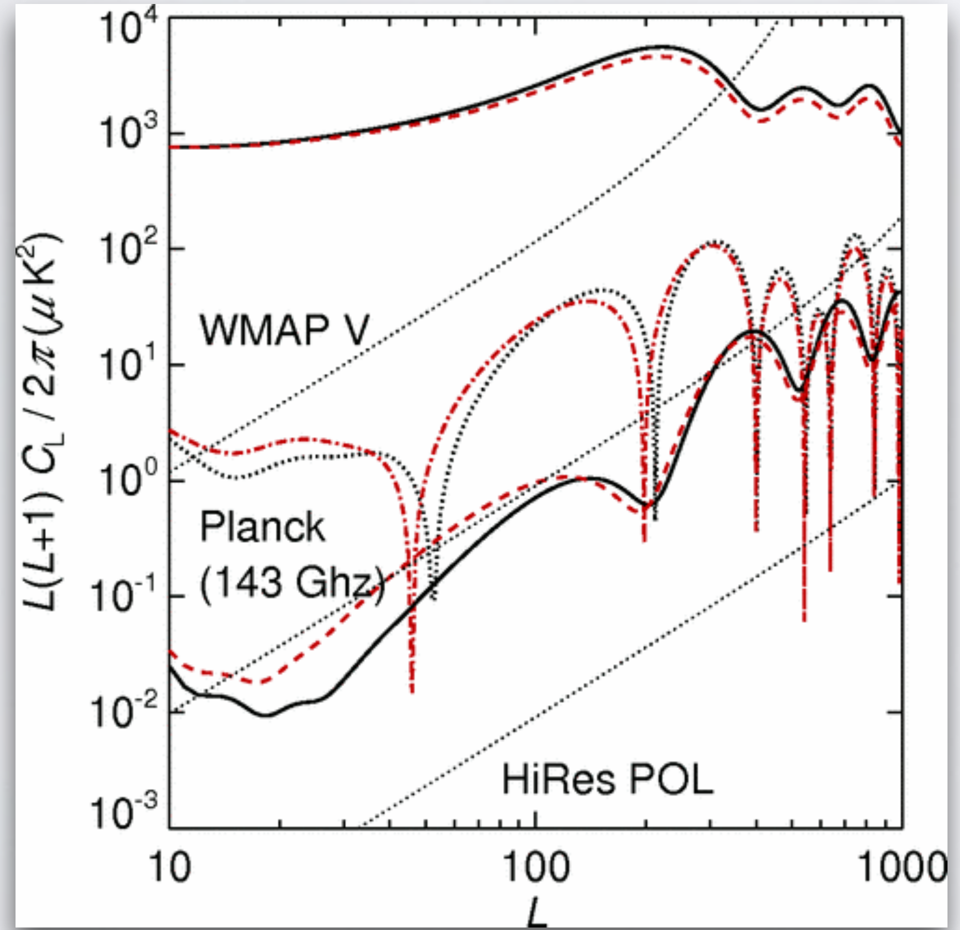
[Leane+; PRD 98, 023016]

- Is this really model independent? → Review simple benchmark

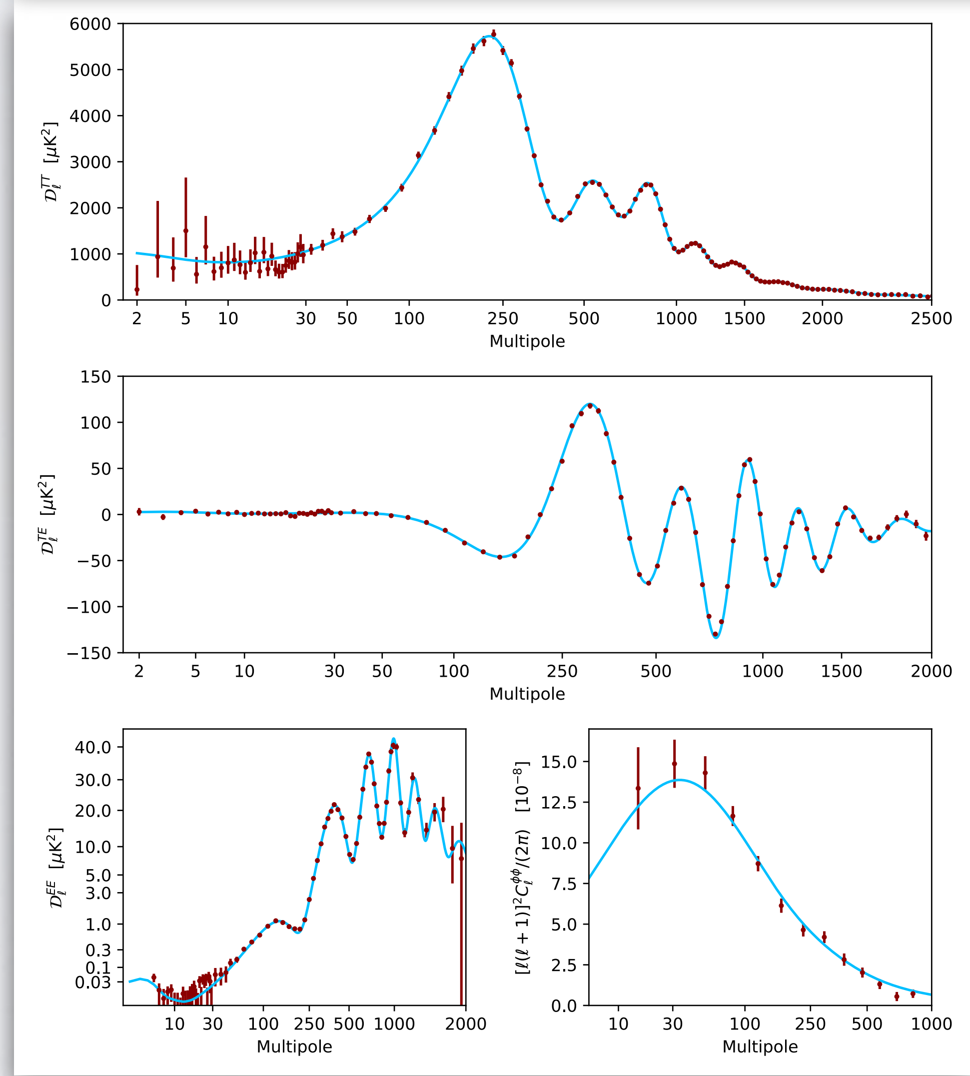
INDIRECT PROBES: CMB

- DM can annihilate into SM particles
- Energy injection into primordial plasma via cascade decays into secondary $p, e^{\pm}, \gamma$ and ν
- Extra ionization leads to distortions of TT, TE and EE coponents of CMB power spectra





[Padmanabahn, Finkbeiner; astro-ph/0503486]



[Planck; 1807.06209]

- **Planck** observations strongly constrain allowed extra ionisation @ $T_{\rm CMB}$!

CONSISTENT CMB BOUND

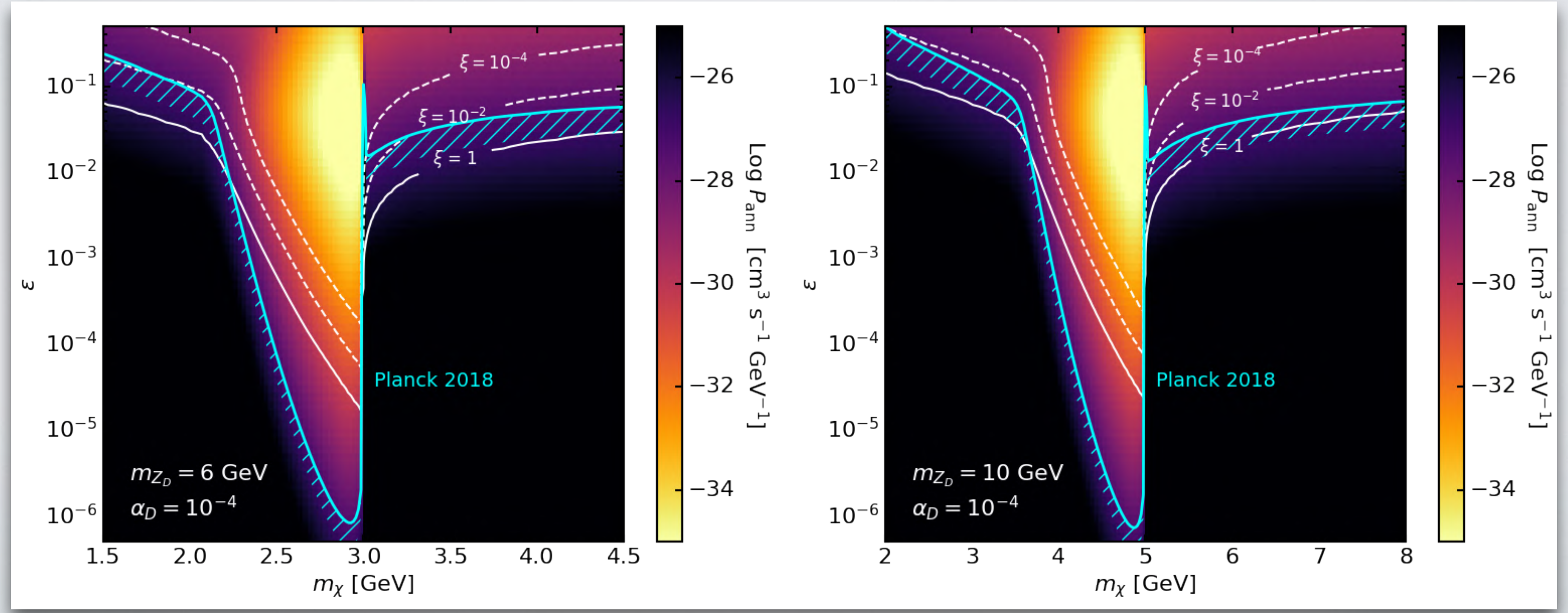
- Rate of energy released into heating and ionisation

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

with annihilation parameter $\boxed{P_{\rm ann}(m_\chi) = \xi^2 \sum_i f_i(m_\chi)\,\frac{\langle\sigma v\rangle_i}{m_\chi}}$, dilution: $\xi = \frac{\rho_\chi}{\rho_{\rm DM}}$

- Planck constraint: $P_{\rm ann} < 3.5 \times 10^{-28}\ {\rm cm^3\,s^{-1}\ GeV^{-1}}$ [Planck; 1807.06209]

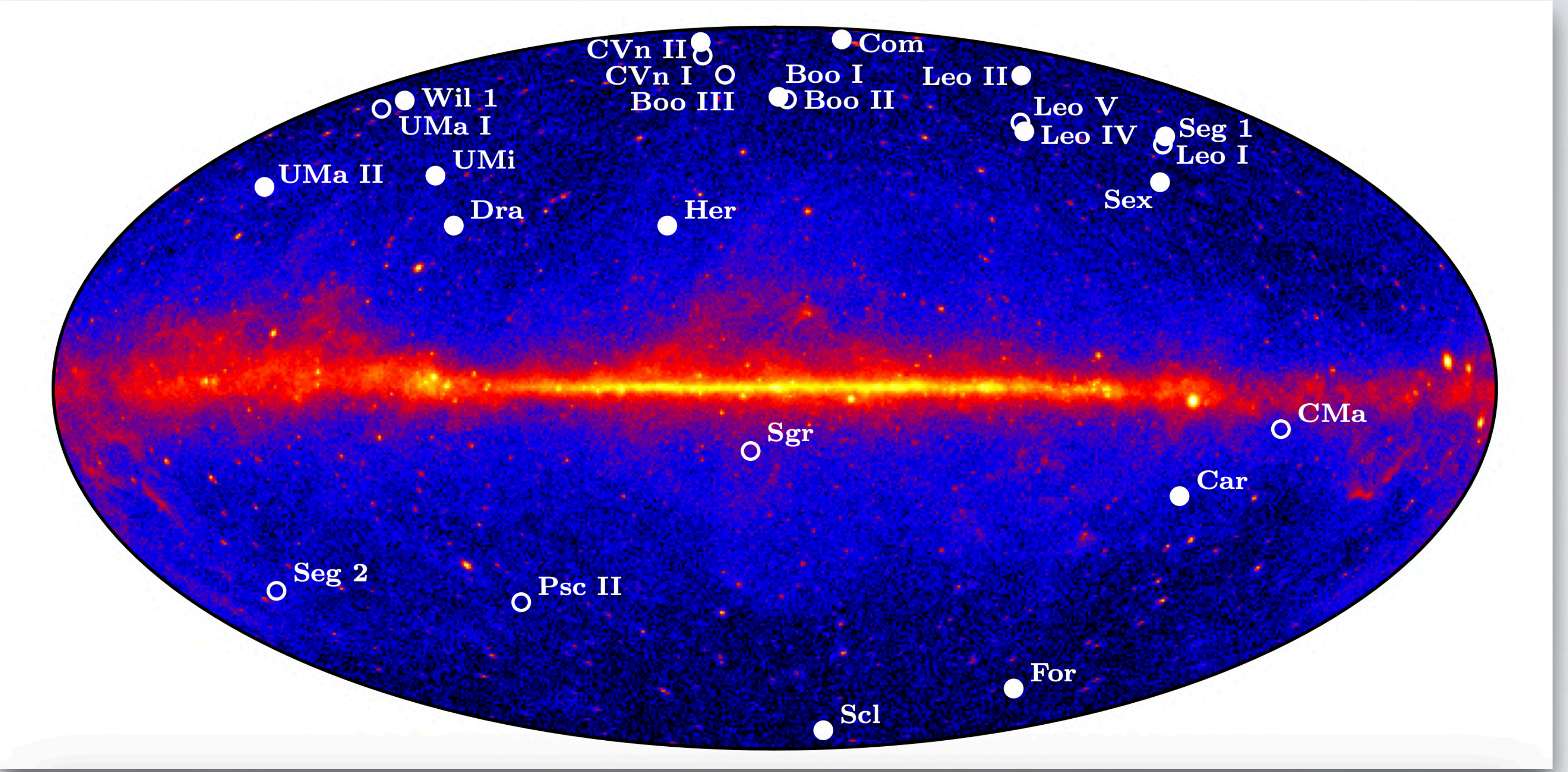
- Larger ξ^2 at samller ϵ, we get a **lower bound on ϵ!** [Alonso-González, Cerdeño, **PF**, No; 2507.11376]



DWARF SPEHROIDALS

- **Dwarf galaxies** are some of **most DM-rich environments** in our universe

- FermiLAT observed Milky Way dSphs for over 15 years in γ-rays [Fermi-LAT, *PRD 89, 042001]*



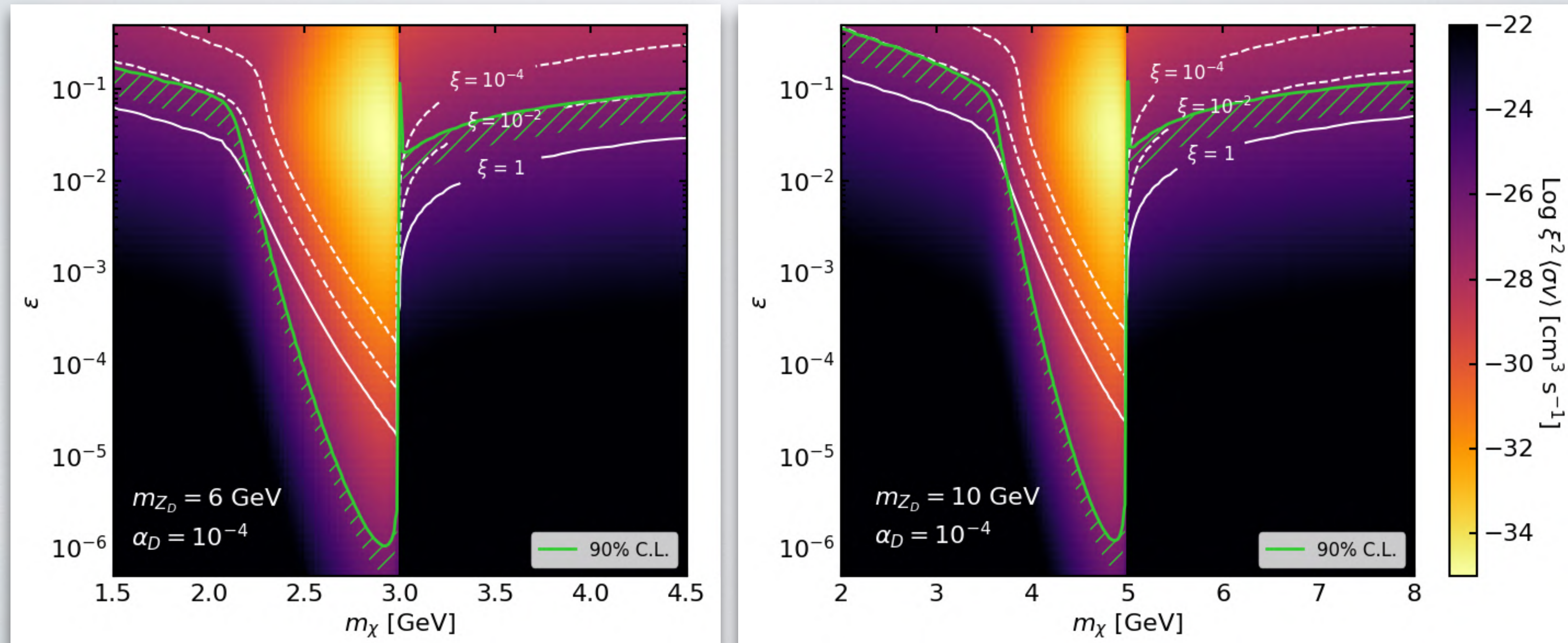
- Expected differential flux due to DM annihilation

Note: $\rho_\chi = \xi \times \rho_{\rm CDM}$

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

CONSISTENT FERMI BOUND

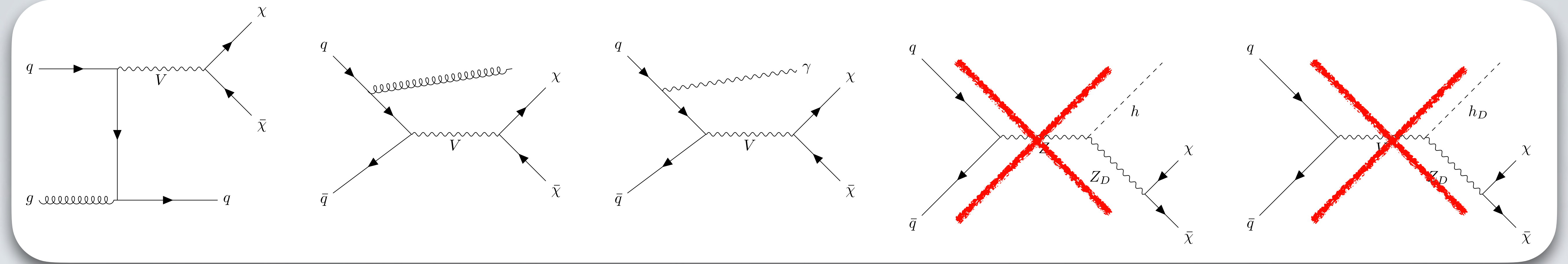
- FermiLAT legacy analysis provides single-source, binned likelihood profiles $\mathscr{L}(d\phi/dE, E) \rightarrow$ derive upper limits [McDaniel+, *PRD 109 063024*]
- Gamma ray flux sensitiviely depends on $\xi^2 \sum \frac{\langle \sigma v \rangle}{m_\chi^2}$
- As for CMB, we get a lower bound on ϵ!



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

COLLIDER CONSTRAINTS - I

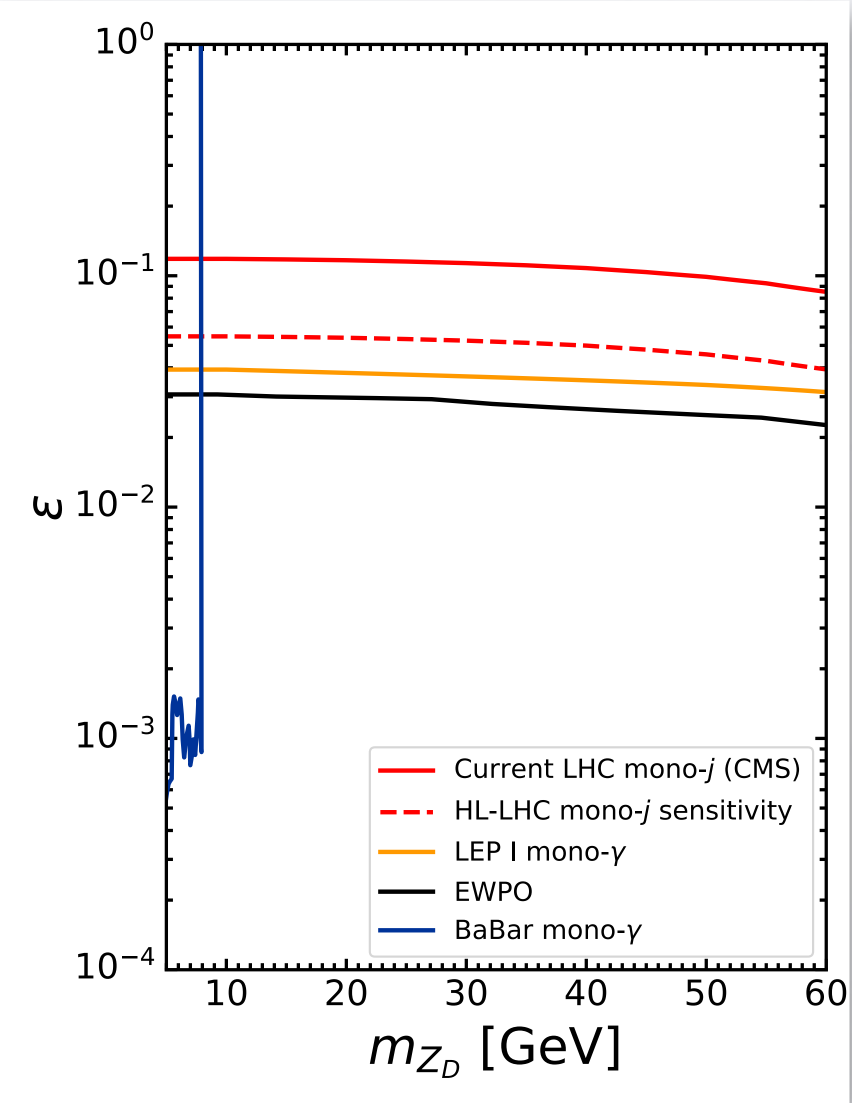
- **Invisible regime ($m_\chi < m_{Z_D}/2$): mono-X signatures**



- In this mass range leading bound given by **BaBar mono γ, EWPO**

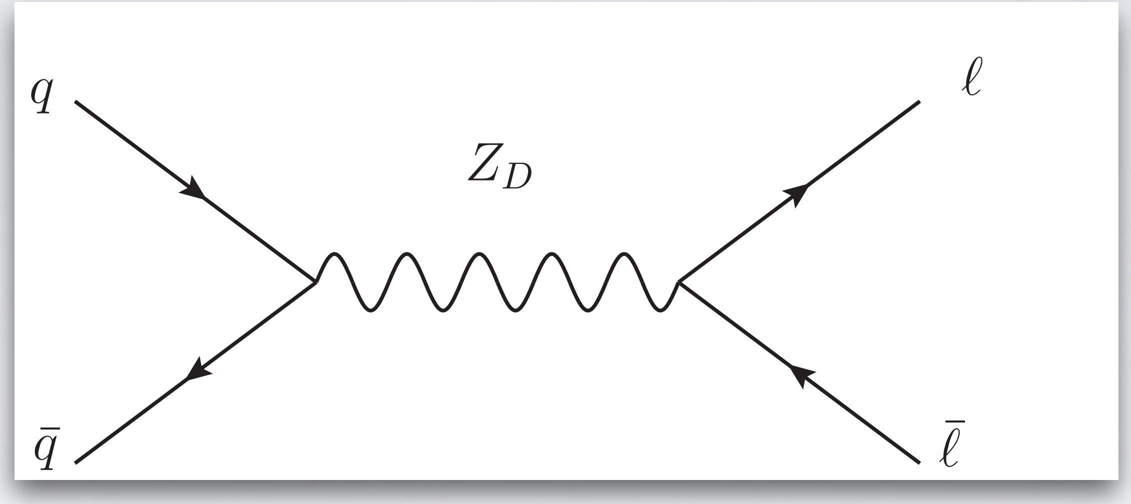
- HL-LHC could give competitive constraints

- Mono-Higgs no competitive bounds



COLLIDER CONSTRAINTS - II

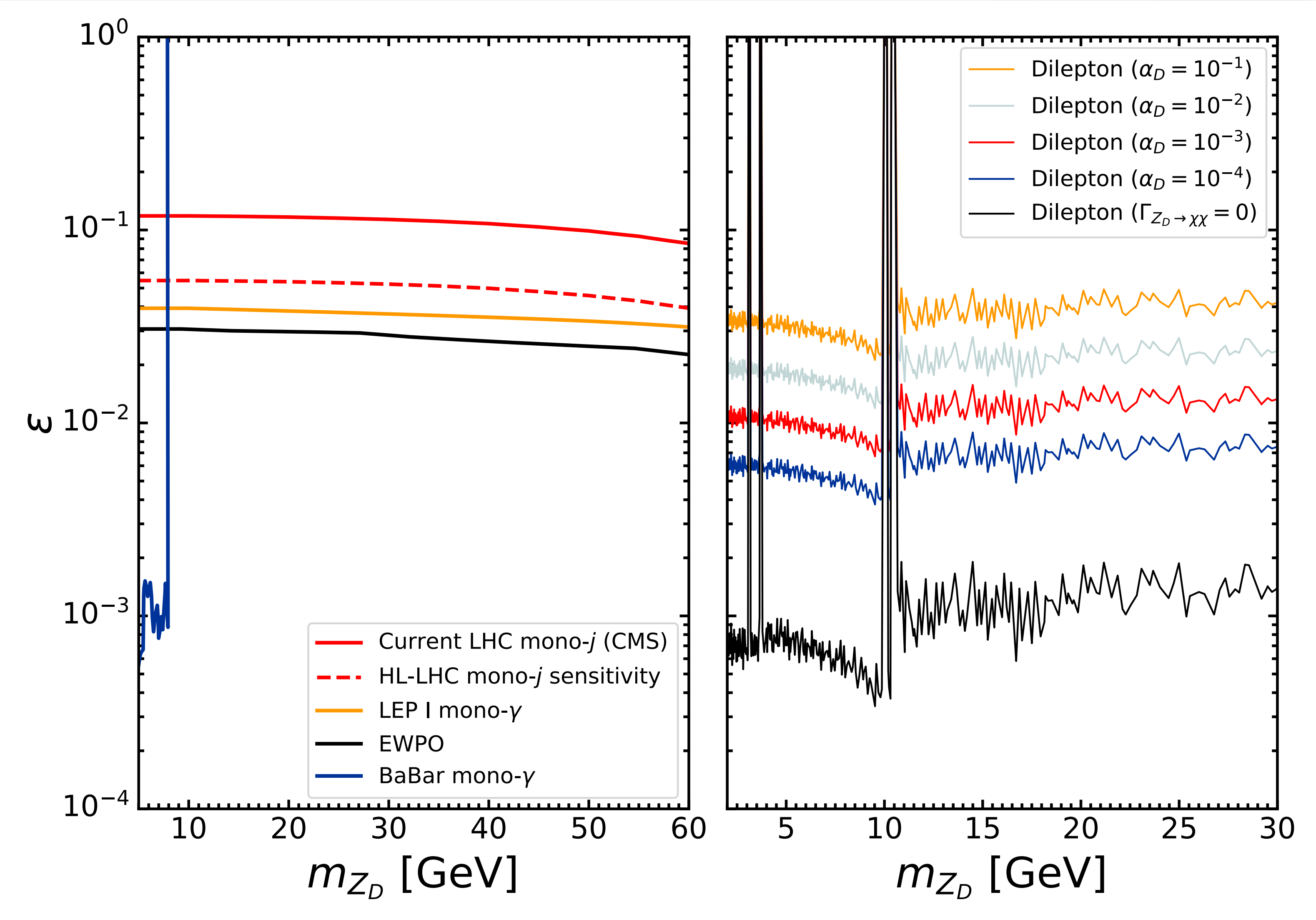
- **Visible regime ($m_\chi > m_{Z_D}/2$): dilepton signatures**



- 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:

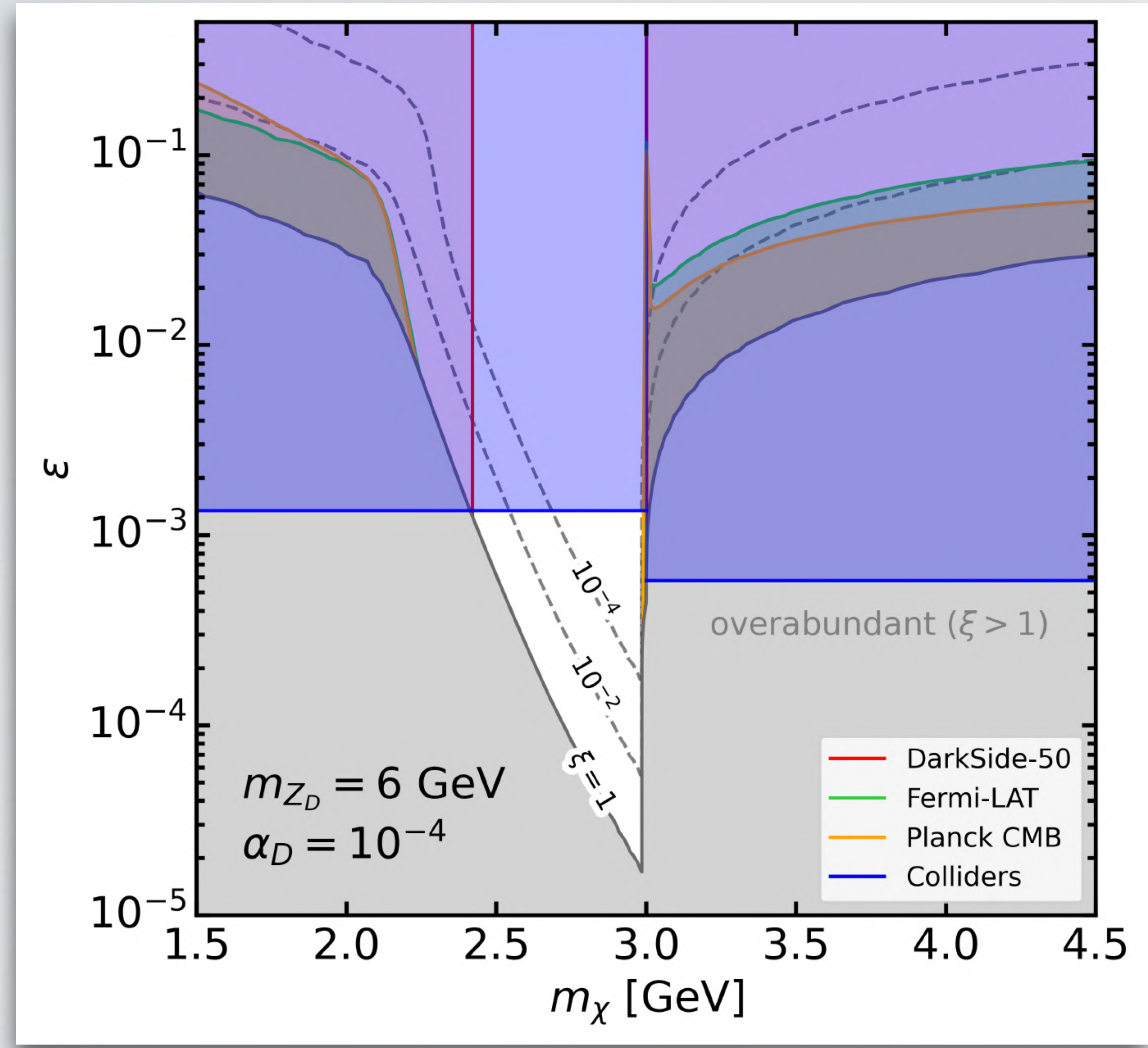
$$\epsilon_{90}^{\ell\ell} \times \sqrt{\frac{\Gamma_{Z_D \to \mathrm{SM}} + \Gamma_{Z_D \to \chi\chi}}{\Gamma_{Z_D \to \mathrm{SM}}}}$$

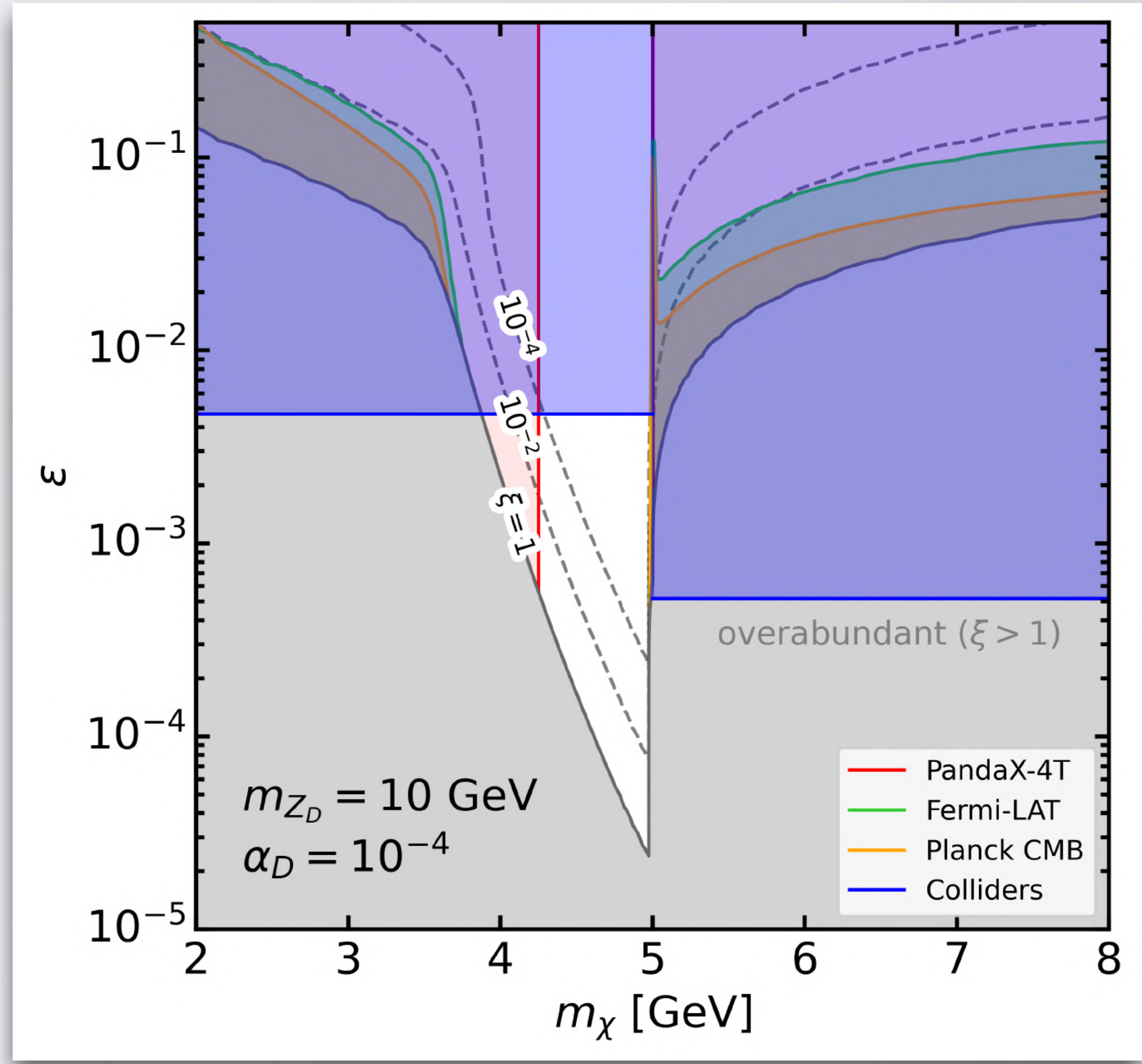


THE GEV WINDOW

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

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





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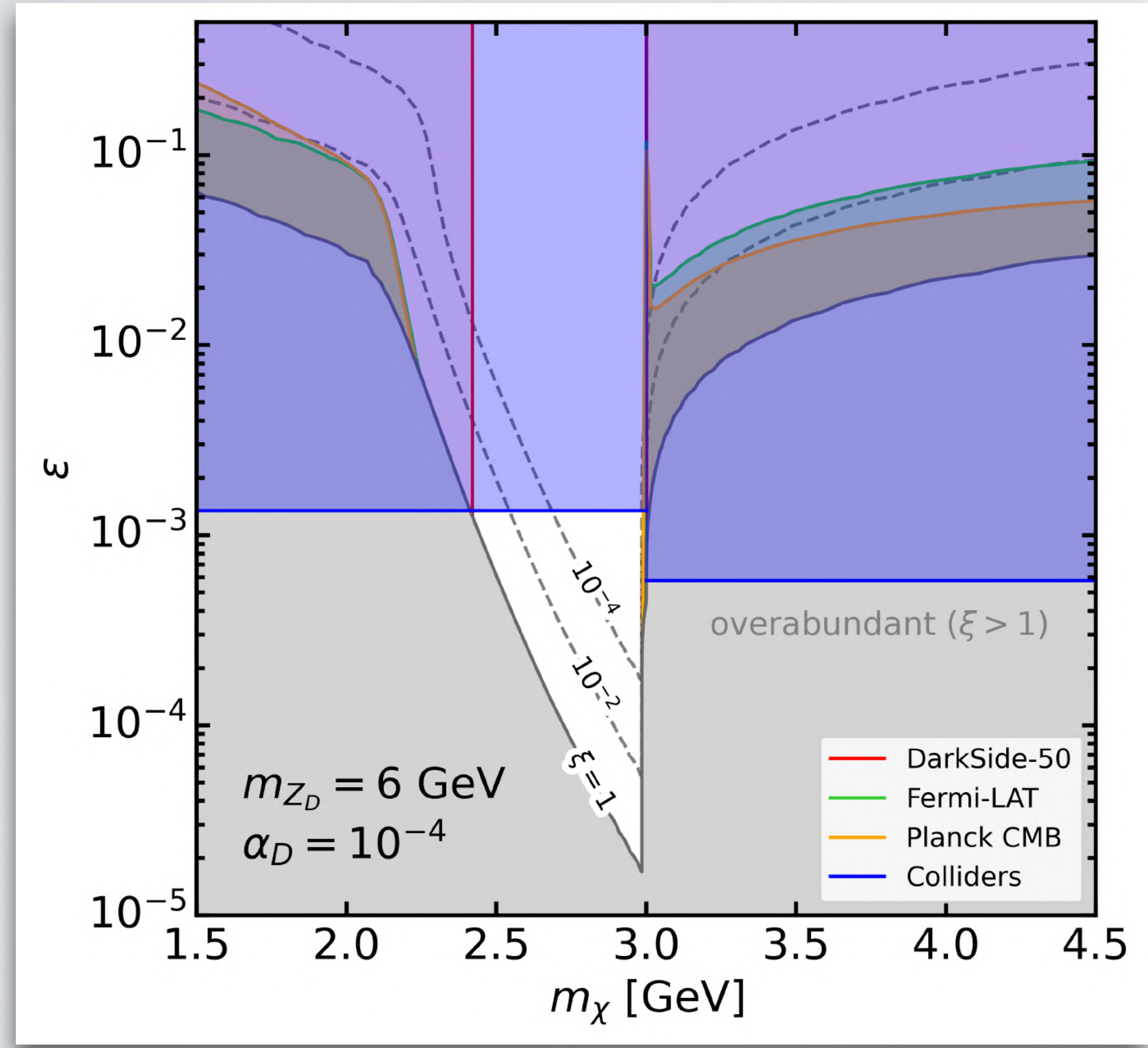
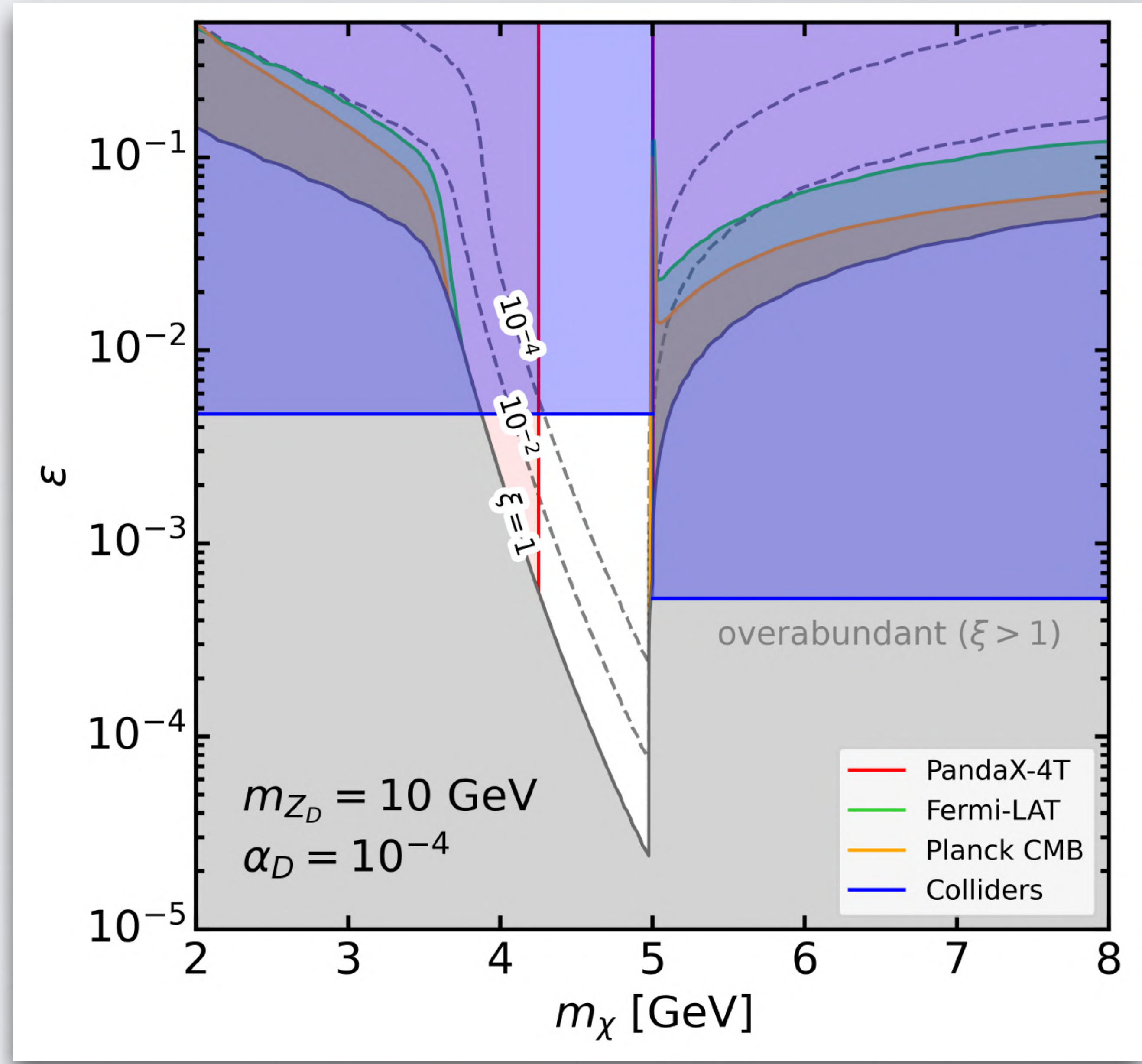




- **What about alternative production mechanisms?**

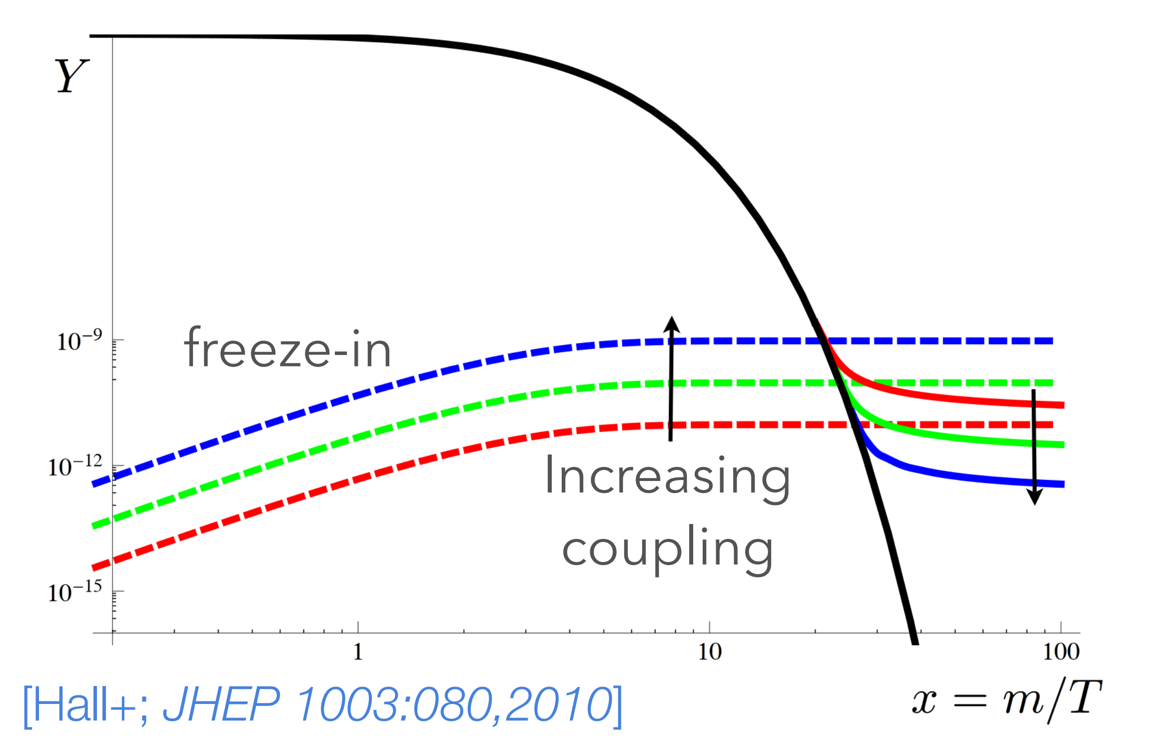
FREEZE-IN

FREEZE-IN PRODUCTION

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

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

- PROBLEM: Tiny interactions typically hard to probe!



[Hall+; *JHEP 1003:080,2010*]

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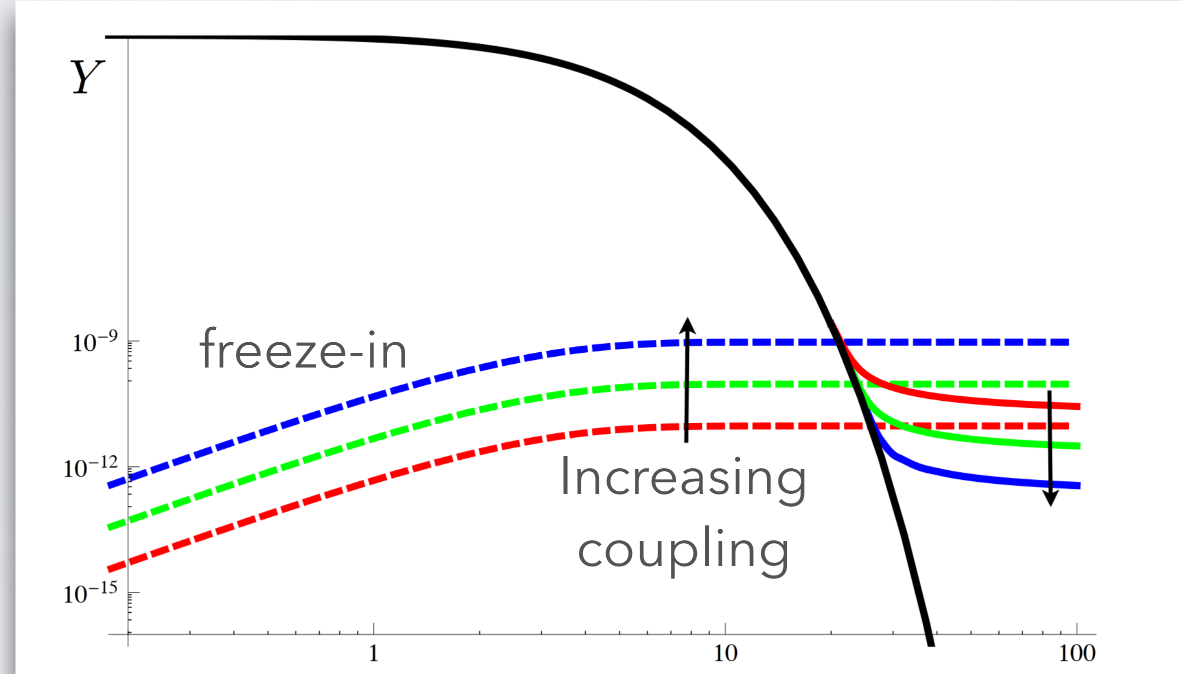
- PROBLEM: Tiny interactions typically hard to probe!

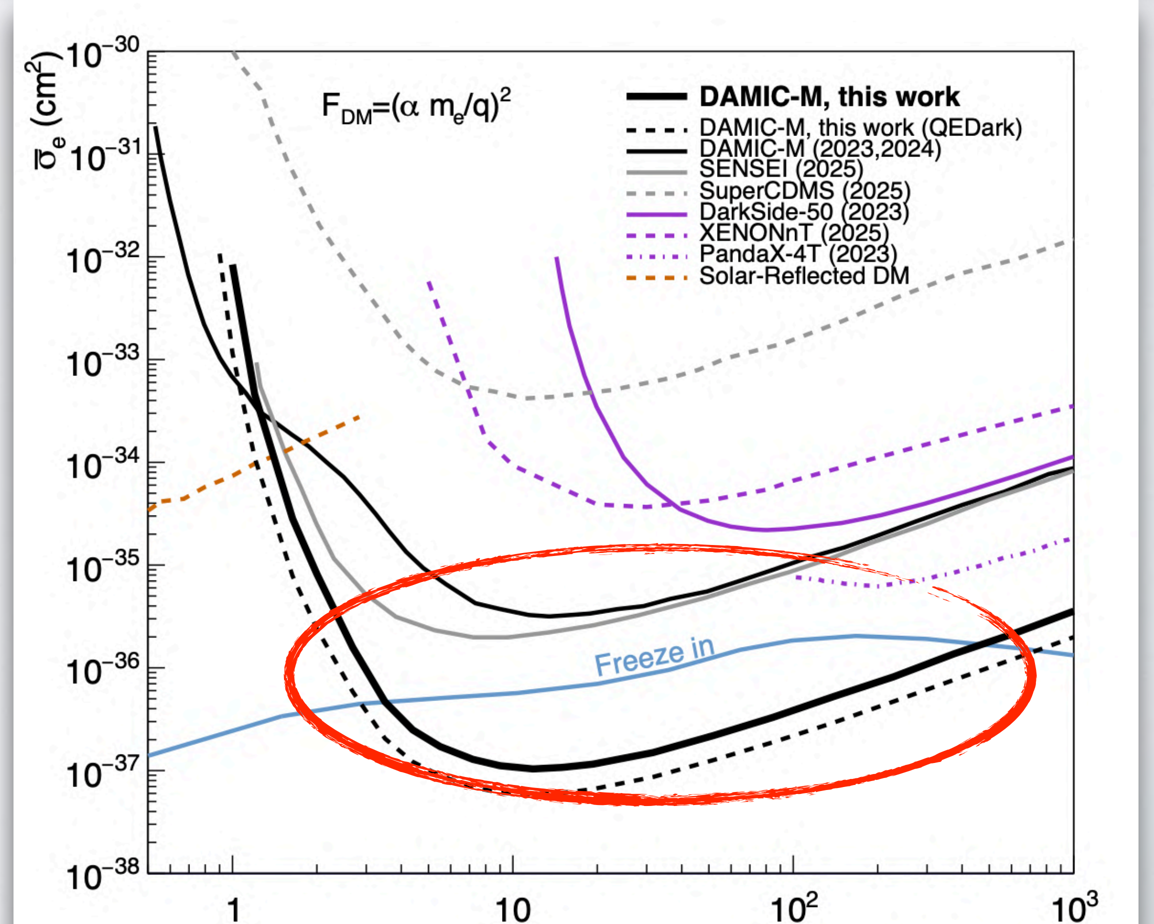
- **BUT:** New (ultra-)light mediators can significantly enhance cross section!

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

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



[Hall+; *JHEP 1003:080,2010*]



[DAMIC-M; *PRL 135 071002*]

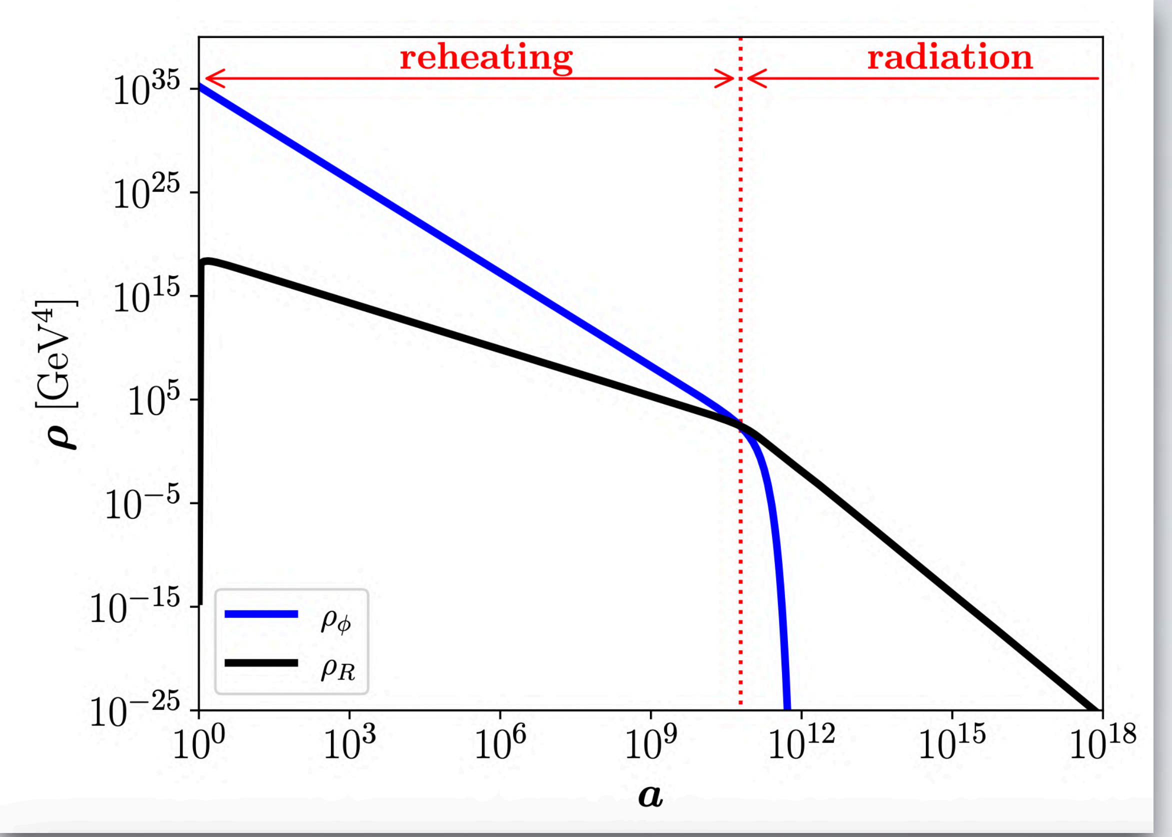
A SUBTLETY — LOW REHEATING

[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 $\rho_\phi(T_{\rm rh}) = \rho_R(T_{\rm rh})$



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)**

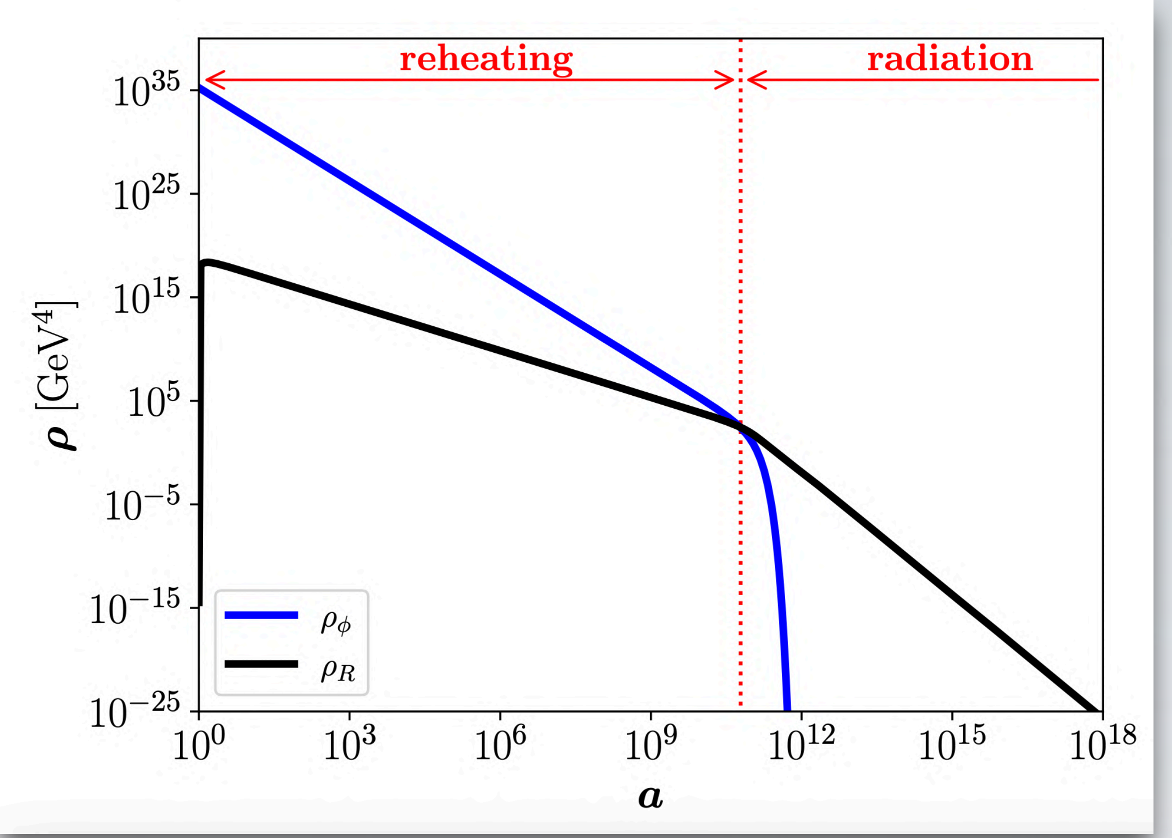
  $\Rightarrow$ **Entropy injection into SM bath**

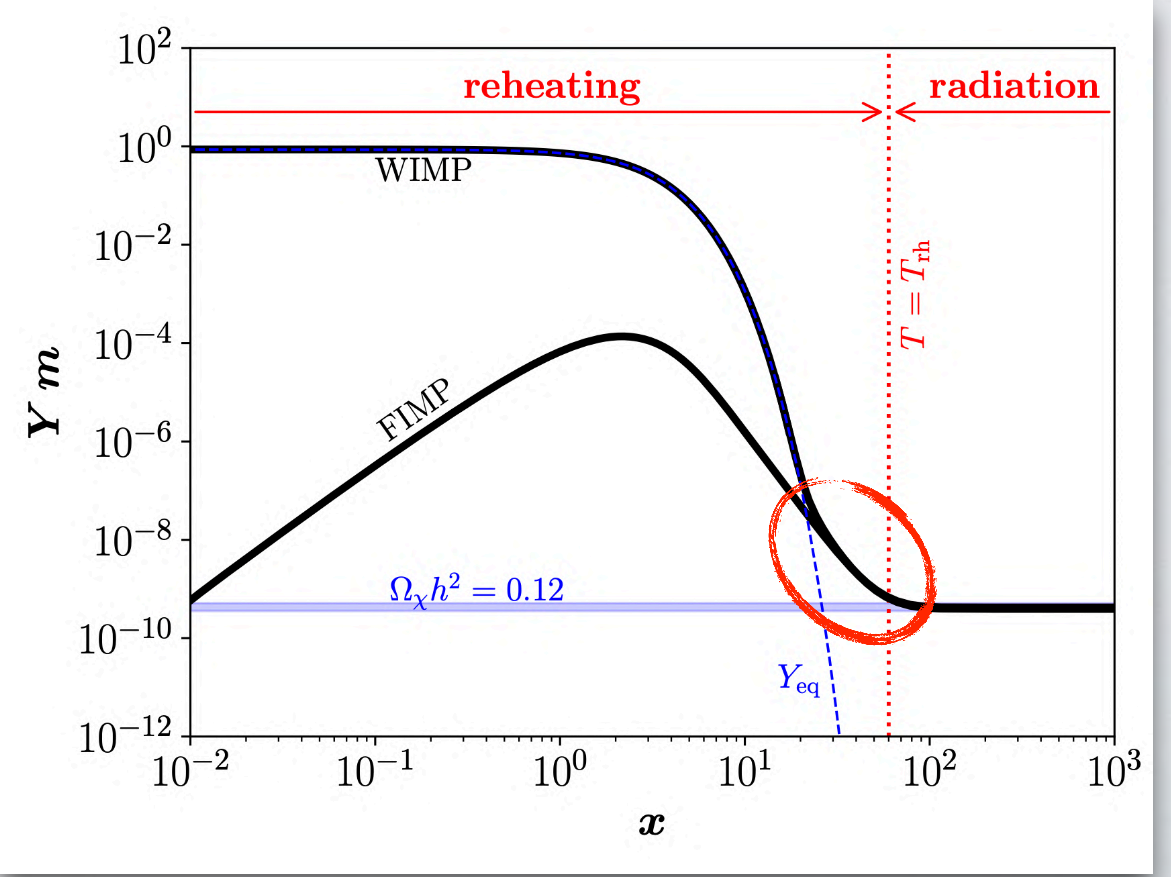
- End of reheating reached at onset of SM radiation domination for $\rho_\phi(T_{\rm rh}) = \rho_R(T_{\rm rh})$

- 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





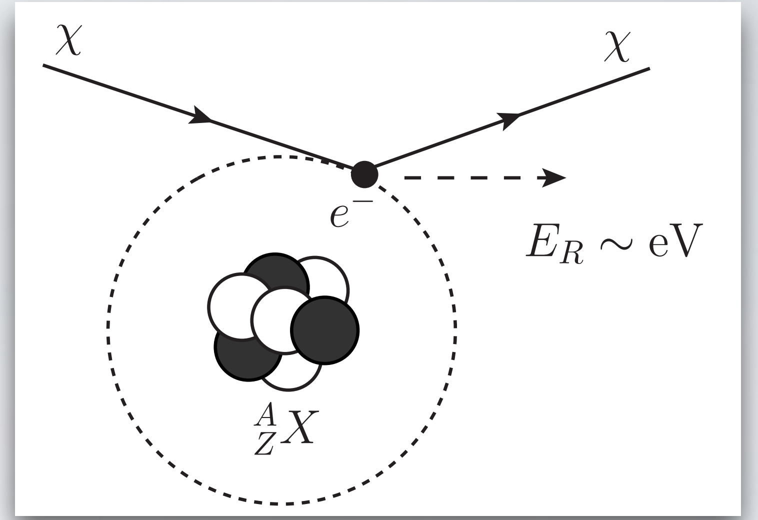
TESTS OF DP FREEZE IN

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

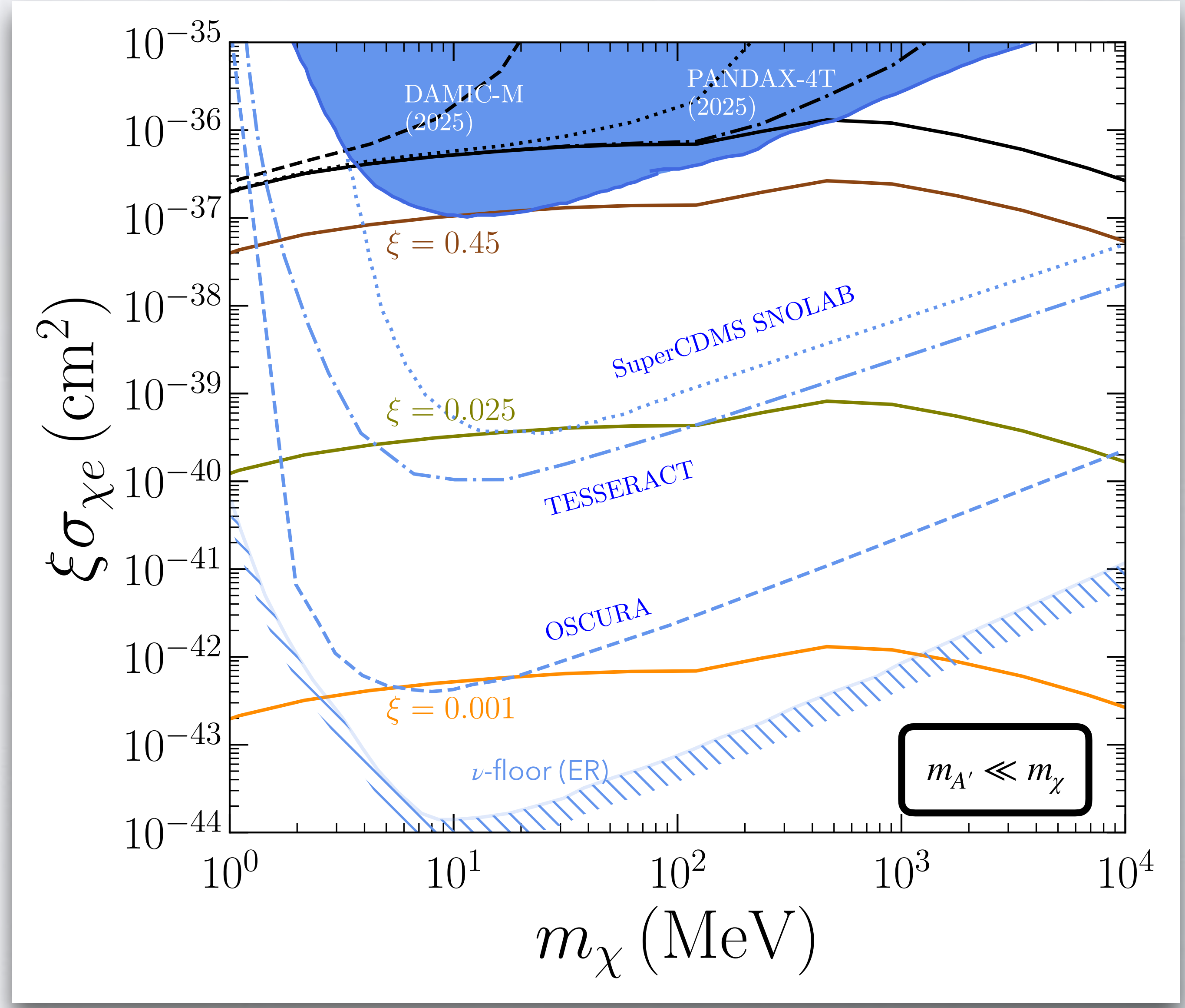
$$\sigma_{\chi e} = \frac{\mu_{\chi e}^2}{\pi} \frac{g_D^2\, g_{eX}^2}{\left(\alpha_{\rm EM}^2 m_e^2 + m_{A'}^2\right)^2}$$

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

[DAMIC-M; *PRL 135 071002*]
[PandaX; *PRL 135 211001*]



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



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 $\xi = 0.001$**

REALISTIC SCENARIO

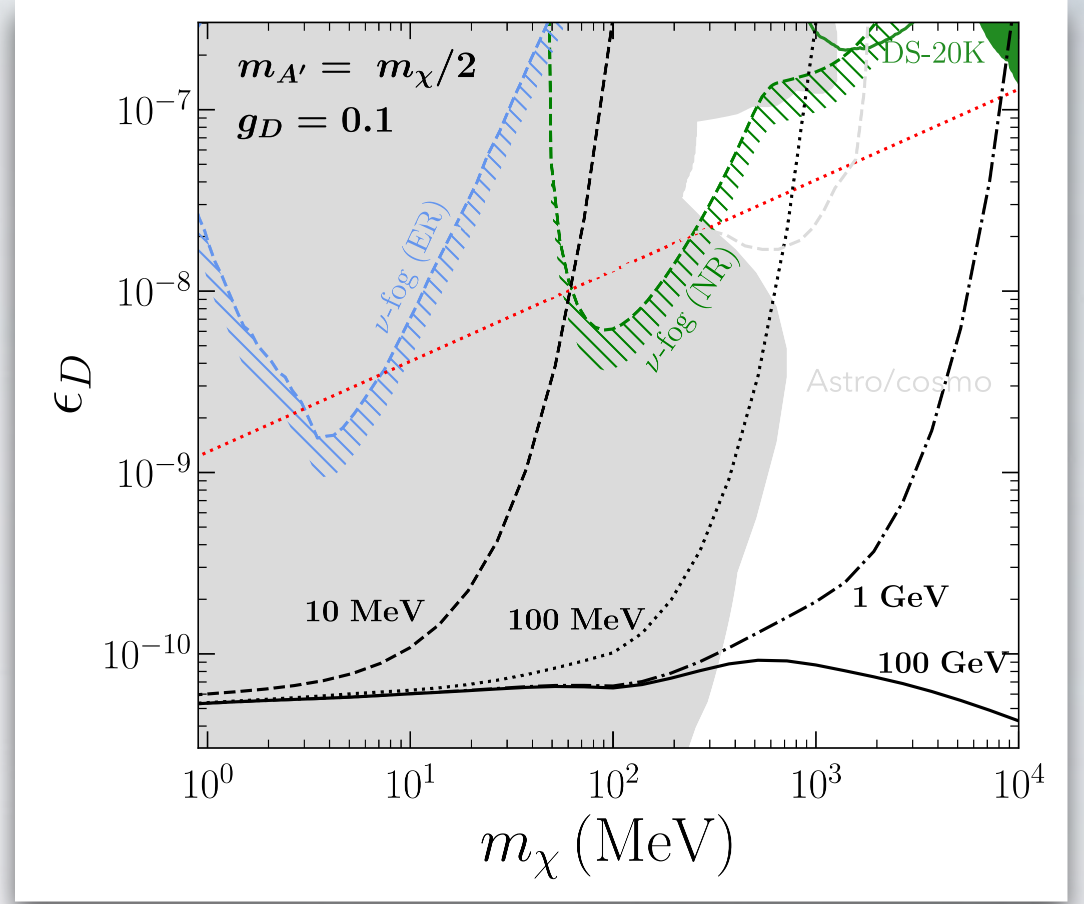
- Consider **massive vector mediator** scenario with comparable masses

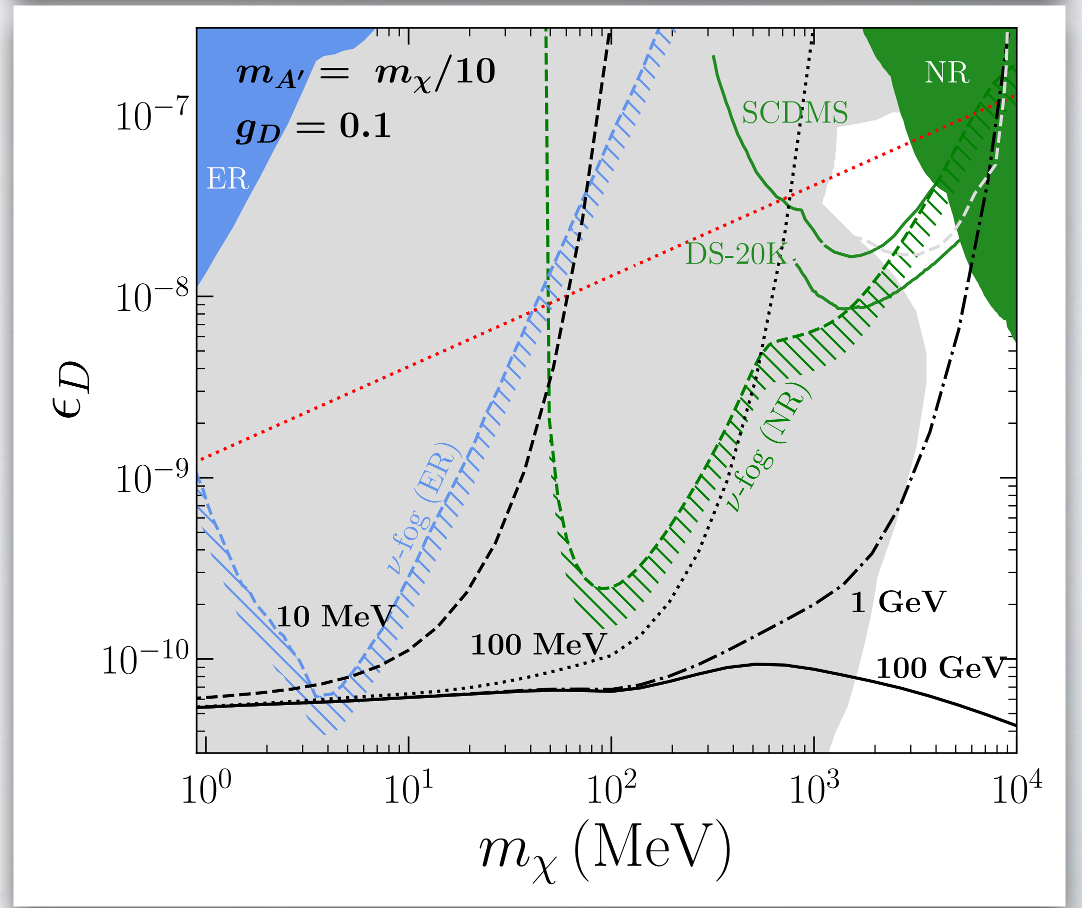
- MeV dark photons **severely constrained** from beam dump searches, astrophysics, and cosmology (gray)

- High reheating freeze-in lines completely buried in the neutrino floor

- **Low reheating scenarios with $T_{\rm rh} \sim$ 100 MeV - 1 GeV in reach of future direct detection experiments!**

- Consistent dark photon signal in fixed target experiments like **SHiP**





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

ANOMALY-FREE PORTALS

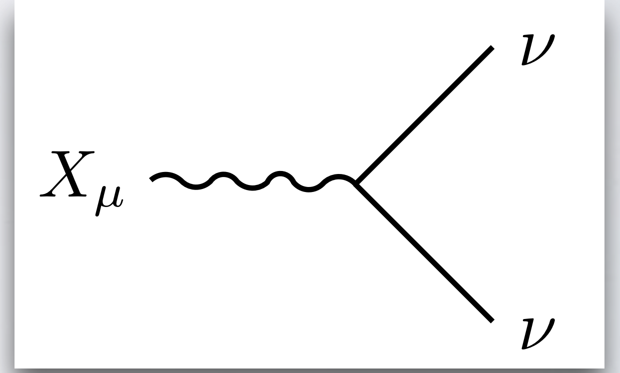
- Beyond kinetic mixing, $U(1)_X$ can be coupled to SM by gauge interactions

SM fields

$$J_X^\mu = \sum_\psi \bar{\psi}\, Q_\psi\, \gamma^\mu \psi \qquad \text{with } \psi = Q, L, u, d, \ell, \nu$$

- Infinite family of **anomaly-free U(1) with SM field content**. Simple examples are:

$B-L$	$L_\mu - L_e$	$L_e - L_\tau$	$L_\mu - L_\tau$
charging quarks & leptons	charging 1st & 2nd generation leptons	charging 1st & 3rd generation leptons	charging 2nd & 3rd generation leptons

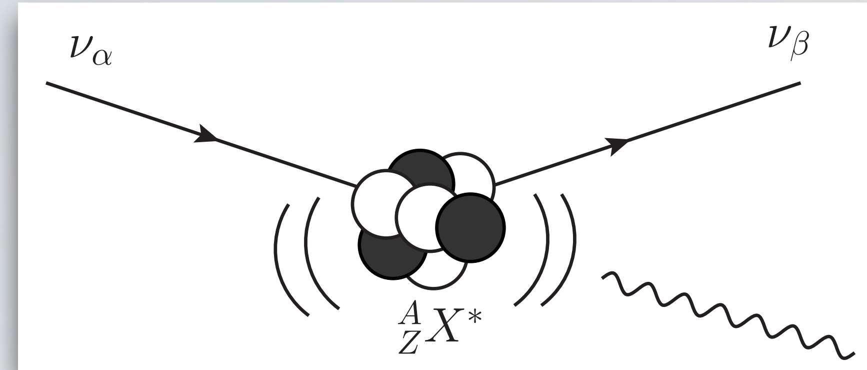


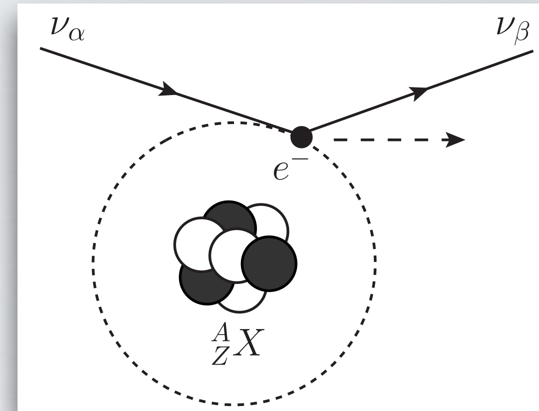
- Effectively induces neutrino non-standard interactions (NSI)

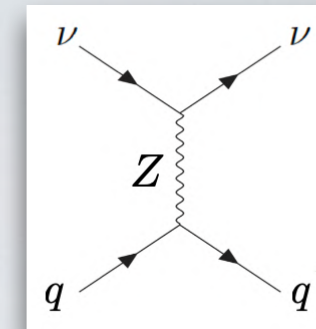
$$\varepsilon_{\alpha\alpha}^{fP}(E_R) = \frac{g_f\, g_\nu}{2\sqrt{2}G_F\,(2m_f E_R + M_X^2)}$$

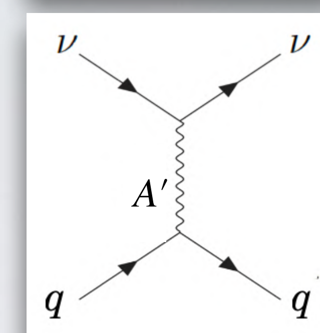
⇒ **Solar neutrino scattering will be enhanced in direct detection!**

MODIFIED NEUTRINO FLOOR









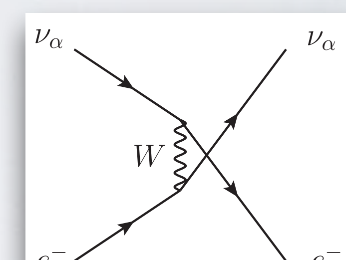
CEvNS

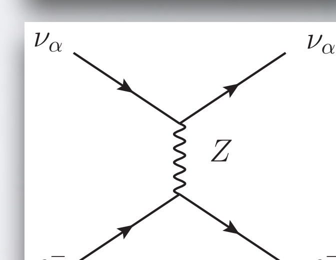
(for universal vector couplings)

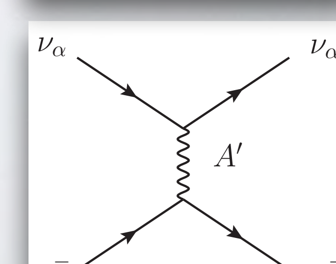
$$\frac{d\sigma_{\nu_\alpha N}}{dE_R} = \frac{G_F^2 M_N}{\pi}\left(1-\frac{M_N E_R}{2E_\nu^2}\right) \times \left\{\underbrace{\frac{Q_{\nu N}^2}{4}}_{\text{SM}} + \underbrace{\frac{g_{xN}\, g_{x\nu}}{\sqrt{2}G_F\left(2M_N E_R + M_{A'}^2\right)} + \frac{g_{xN}^2\, g_{x\nu}^2}{2G_F^2\left(2M_N E_R + M_{A'}^2\right)^2}}_{\text{BSM}}\right\}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

EvES

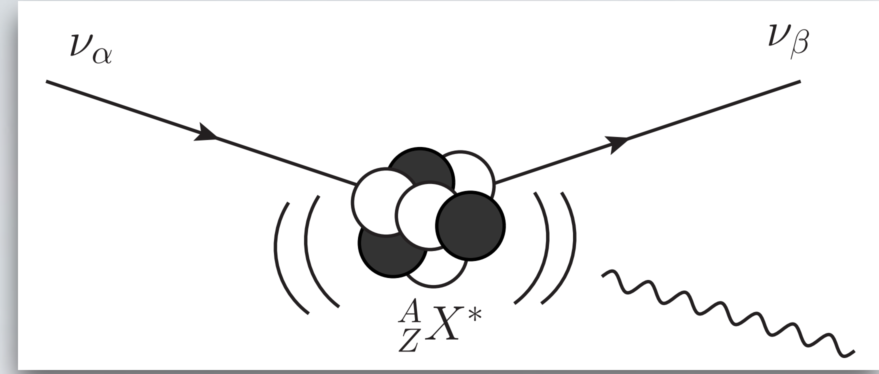
$$\frac{d\sigma_{\nu_\alpha e}}{dE_R} = \frac{2G_F^2 m_e}{\pi}\left\{\underbrace{\left[{g_L^e}^2 + {g_R^e}^2\left(1-\frac{E_R}{E_\nu}\right)^2 - g_L^e g_R^e \frac{m_e E_R}{E_\nu^2}\right]}_{\text{SM}} \right.$$
$$\left. \underbrace{+ \frac{g_{xe}\, g_{x\nu}}{\sqrt{2}G_F\left(2E_R m_e + M_{A'}^2\right)}\left[\left(g_L^e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

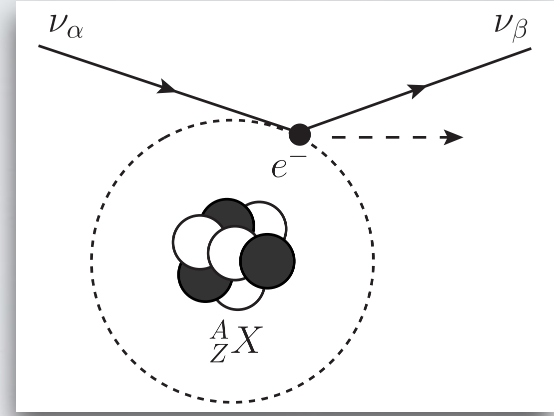




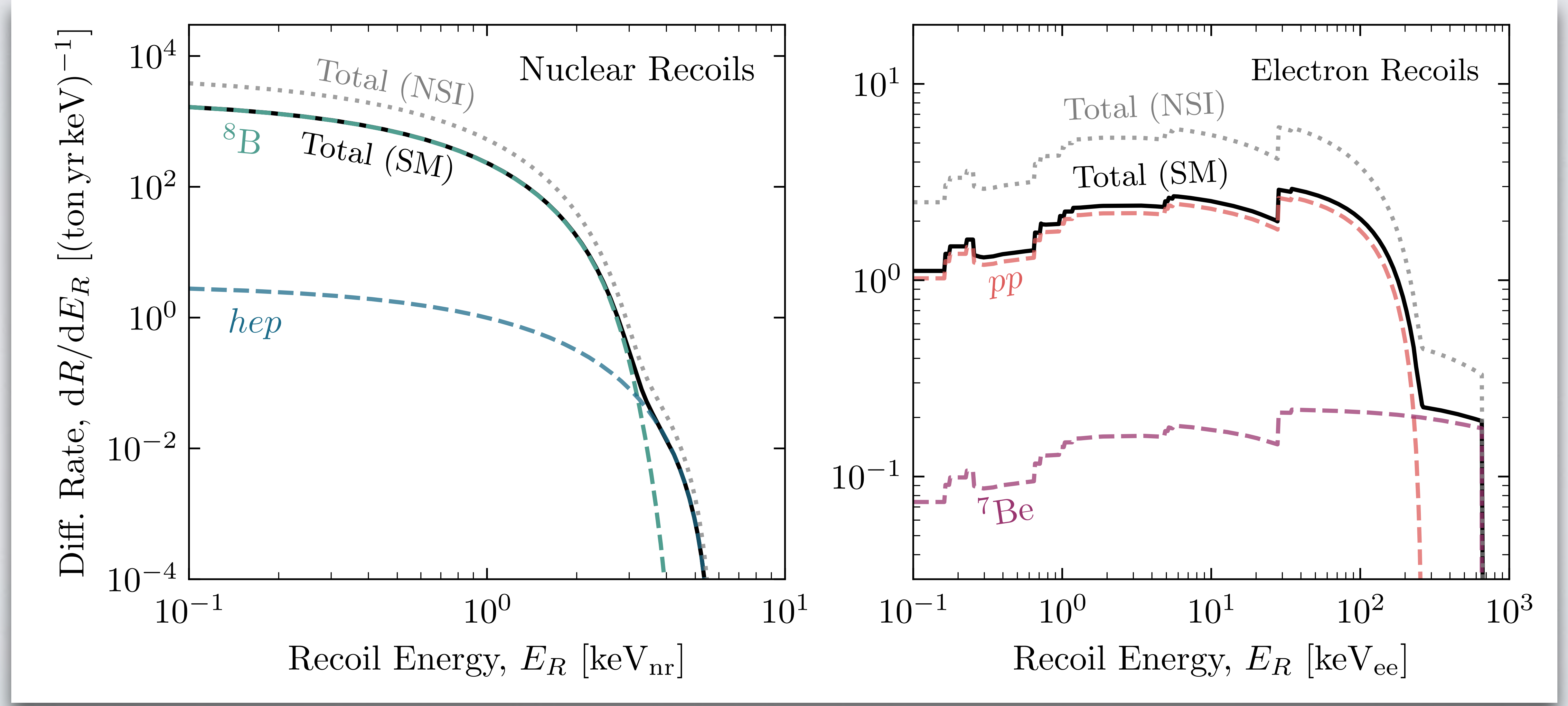


SOLAR NEUTRINO SCATTERING





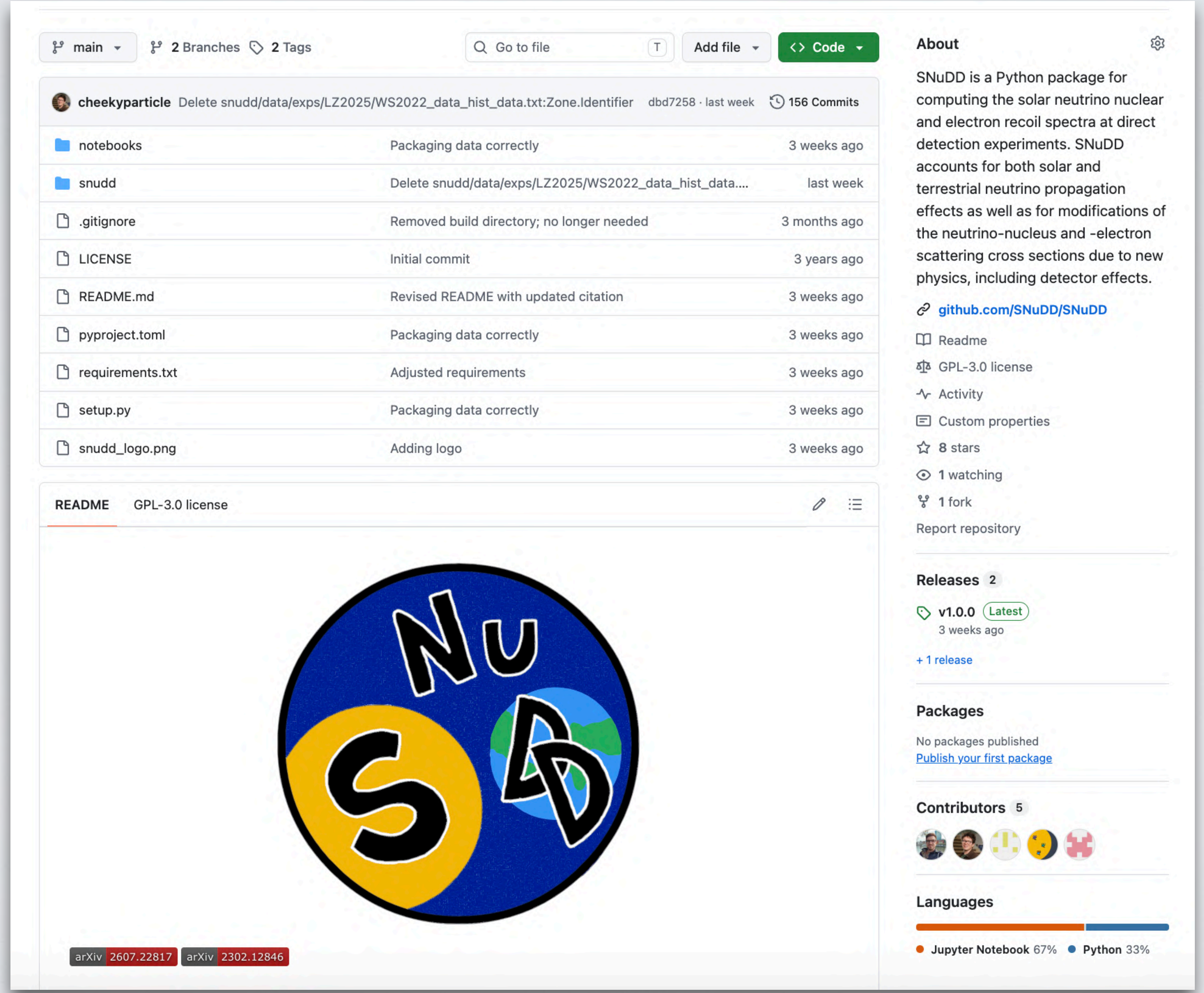
- Can compute solar neutrino **scattering rate including NSI in propagation and scattering:**



[Amaral, Cerdeno, Cheek, Costa, **PF**; 2607.22817]

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

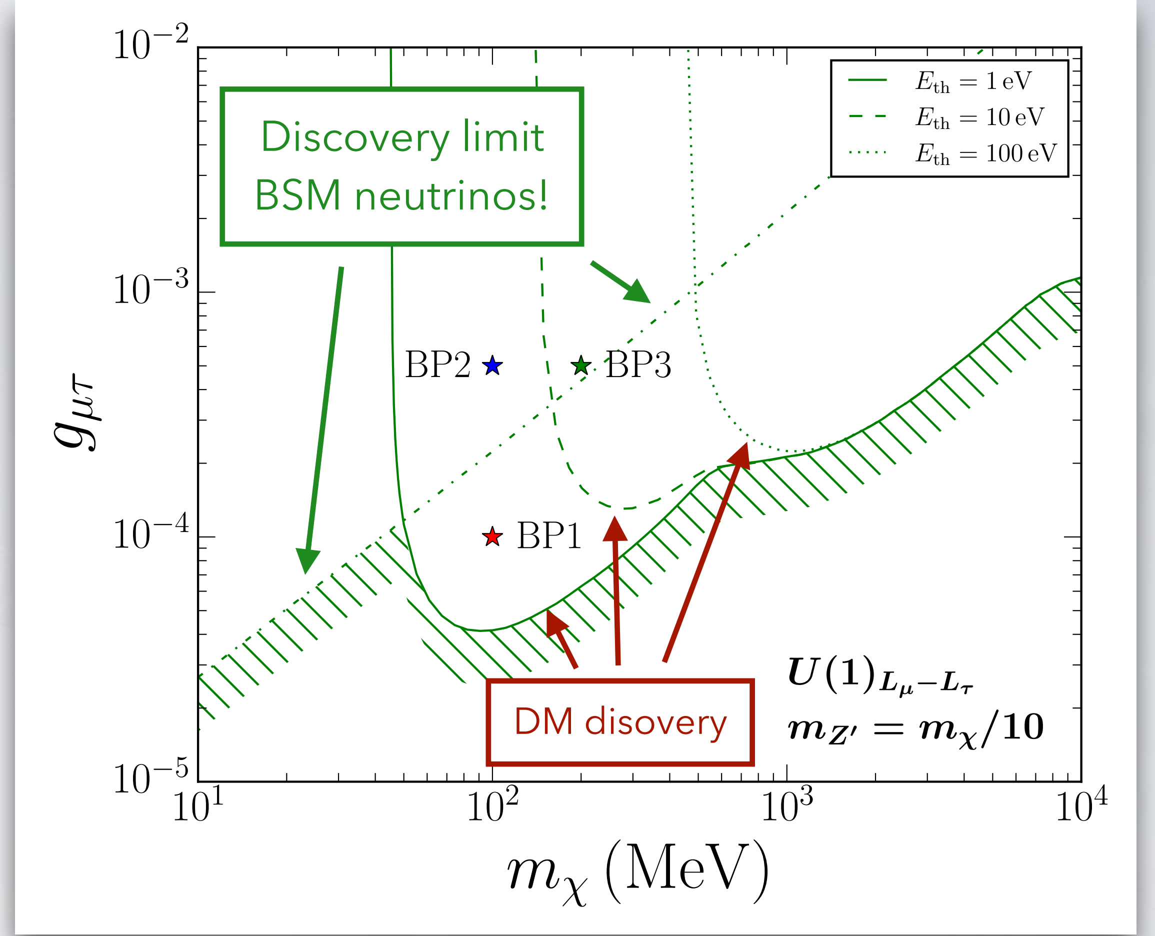


MODIFIED NEUTRINO FLOOR

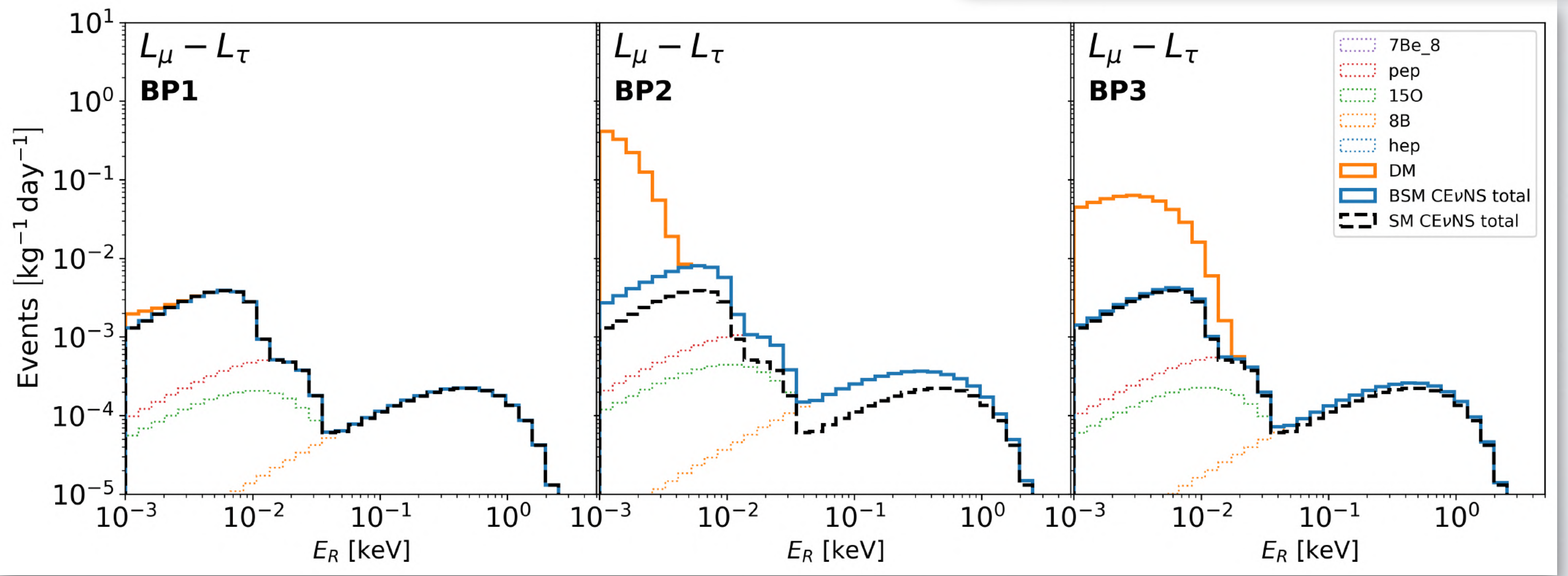
- Leptophilic mediators lead to **simultaneous DM and neutrino signal**

- DM discovery limit (neutrino floor) depends on **experimental threshold** $E_{\rm th}$

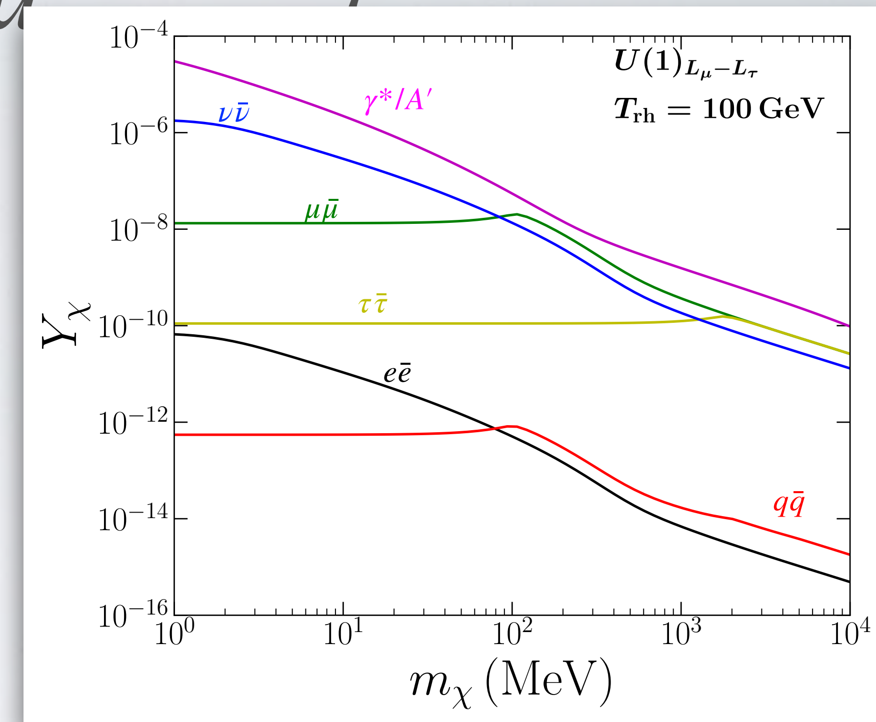
- Signal discrimination via spectral information $\Rightarrow$ need statistics (**exposure, background**)



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

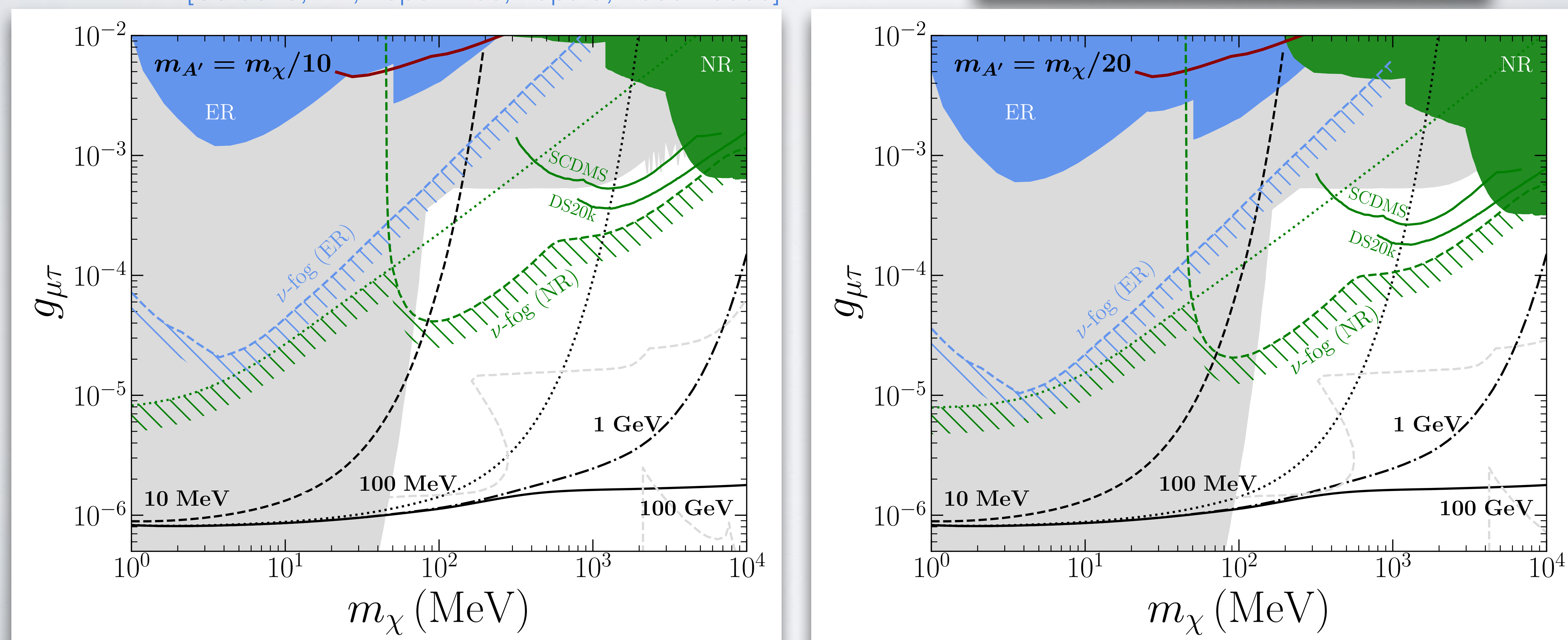


FREEZE IN - $L_\mu - L_\tau$



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

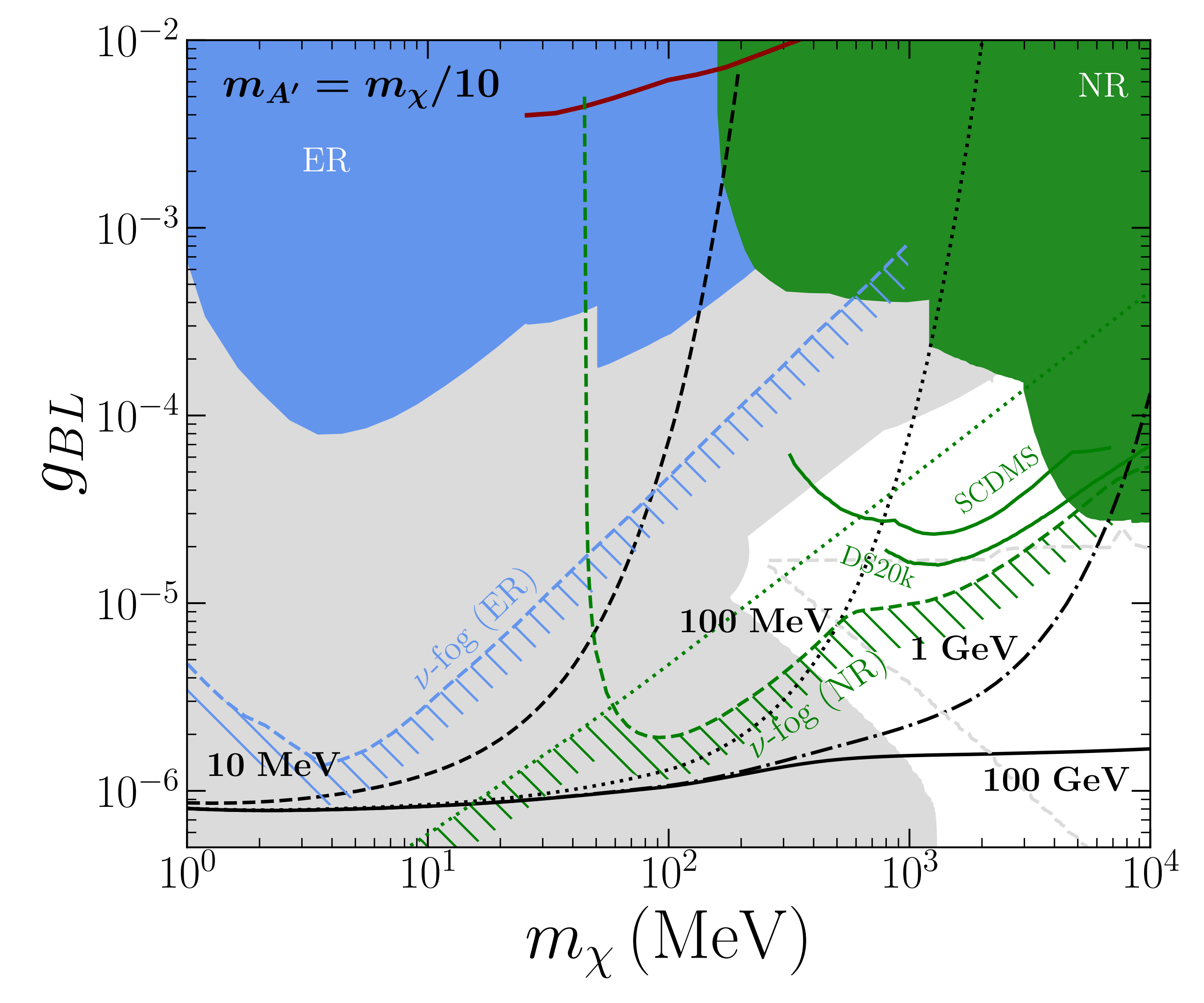
[Cerdeño, **PF**, López Noé, Zapata; 2603.16863]

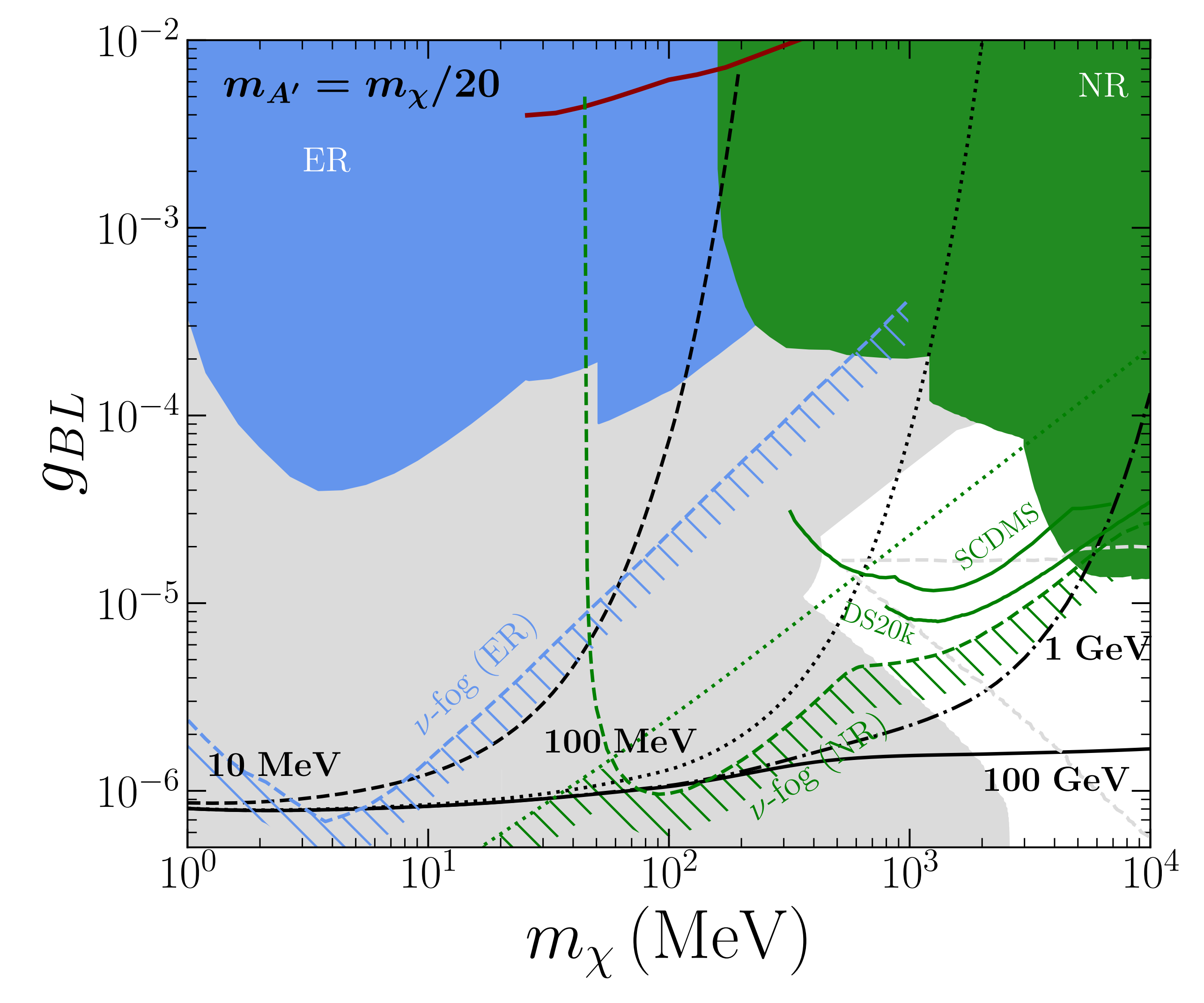


FREEZE IN - $B - L$

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

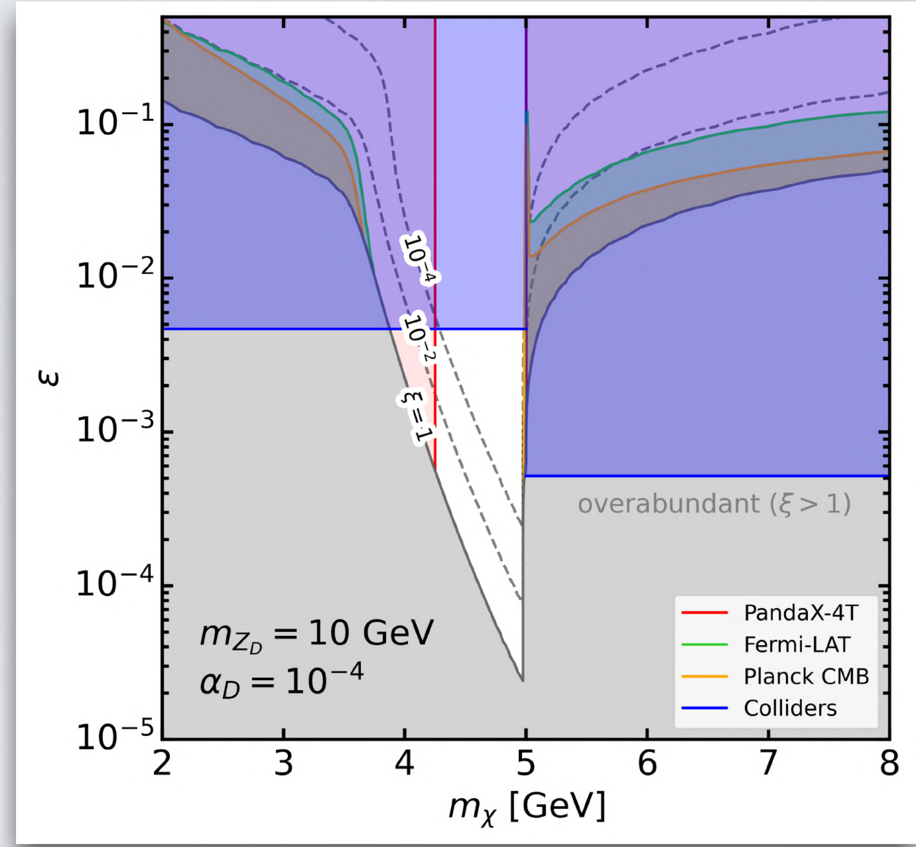
[Cerdeño, **PF**, López Noé, Zapata; 2603.16863]

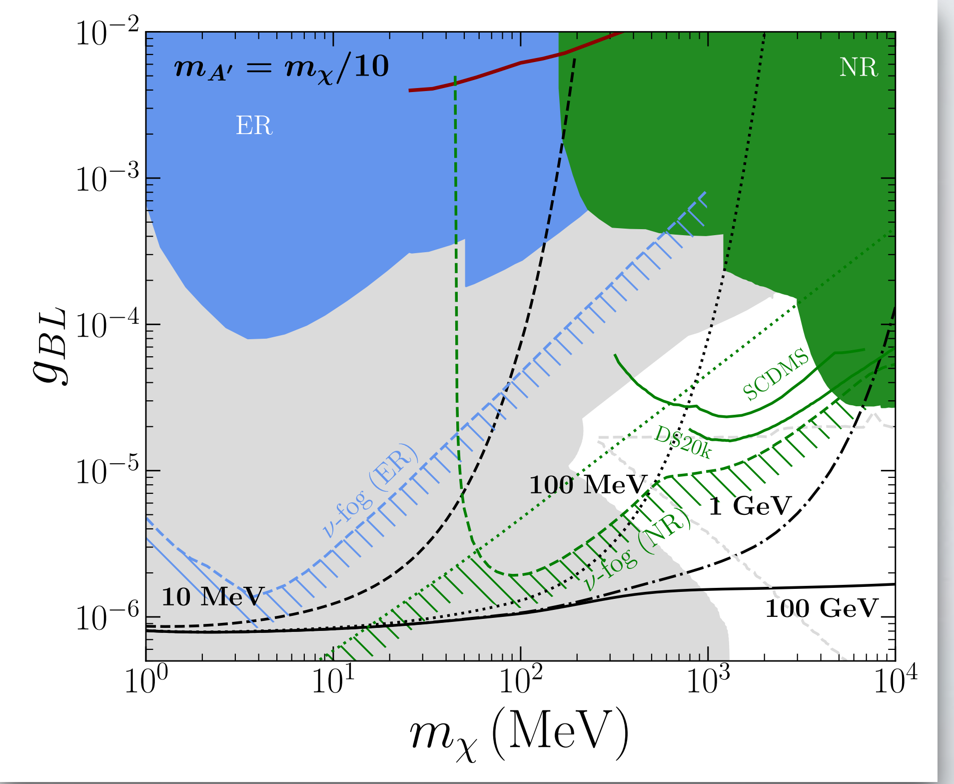




CONCLUSIONS

- GeV WIMPs are cornered, but **still alive!**
- **Direct detection** experiments and **colliders** are most promising to further close the **resonance window**
- **Freeze-in** option is still viable in large class of vector mediator models
- Upcoming direct detection experiments cant **test low reheating regime**
- **Leptophilic vector mediators** can induce simultaneous **DM and neutrino** signal at direct detection

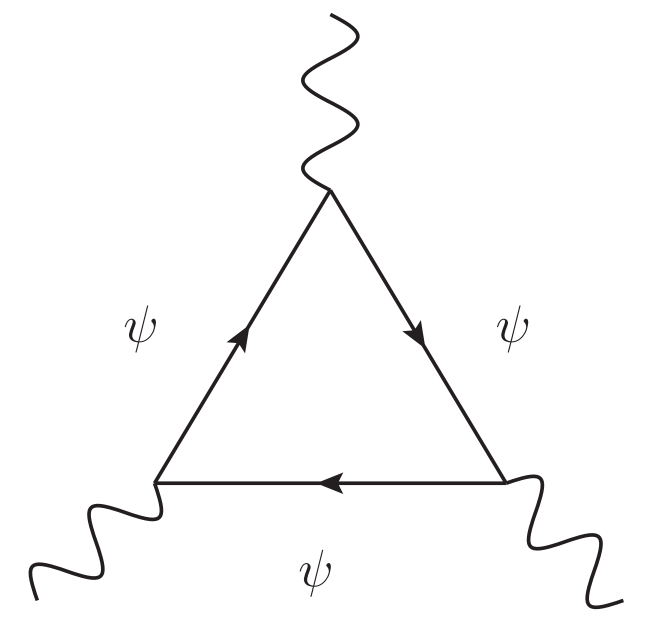




BACKUP

CONSISTENT ANOMALY-FREE MODELS

- Constraints on possible charge assignments of SM fields plus 3 RH neutrinos from **anomaly cancellation:**



$$J_X^\mu = \sum_\psi \bar{\psi}\, Q_\psi\, \gamma^\mu \psi \qquad \text{with} \quad \psi = Q, L, u, d, \ell, \nu$$

Define sum of family charges $\quad X_\psi^n = \sum_i^3 (Q_{\psi_i})^n$

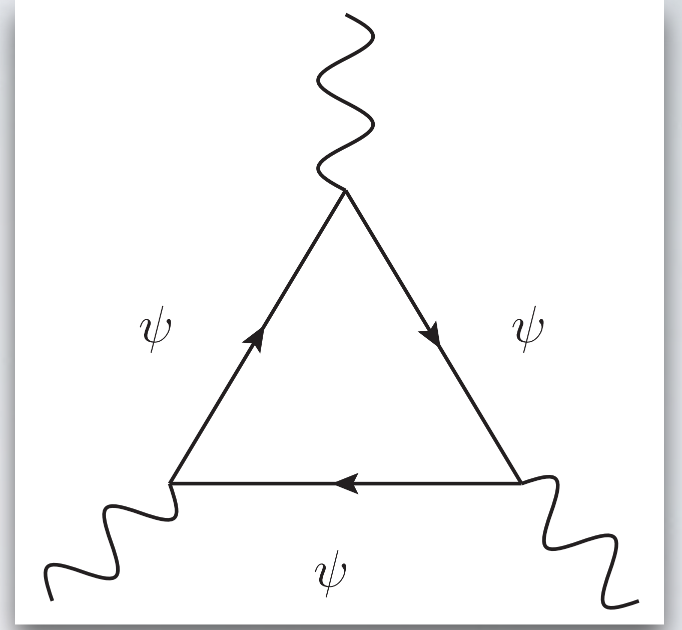
Anomaly	Charge combinations
$U(1)_X^3$	$2X_L^3 + 6X_Q^3 - X_\ell^3 - X_\nu^3 - 3(X_u^3 + X_d^3)$
$U(1)_X^2 U(1)_Y$	$2Y_L X_L^2 + 6Y_Q X_Q^2 - Y_\ell X_\ell^2 - Y_\nu X_\nu^2 - 3(Y_u X_u^2 + Y_d X_d^2)$
$U(1)_X U(1)_Y^2$	$2Y_L^2 X_L + 6Y_Q^2 X_Q - Y_\ell^2 X_\ell - Y_\nu^2 X_\nu - 3(Y_u^2 X_u + Y_d^2 X_d)$
$SU(3)^2 U(1)_X$	$2X_Q - X_u - X_d$
$SU(2)^2 U(1)_X$	$2X_L + 6X_Q$
$\text{grav}^2 U(1)_X$	$2X_L + 6X_Q - X_\ell - X_\nu - 3(X_u + X_d)$

CONSISTENT ANOMALY-FREE MODELS

- Constraints on possible charge assignments of SM fields plus 3 RH neutrinos from **anomaly cancellation:**

$$J_X^\mu = \sum_\psi \bar{\psi}\, Q_\psi\, \gamma^\mu \psi \qquad \text{with} \quad \psi = Q, L, u, d, \ell, \nu$$

Define sum of family charges $\quad X_\psi^n = \sum_i^3 (Q_{\psi_i})^n$



- Additional constraints from SM **Yukawa terms** since they must respect $U(1)_X$

$$\mathcal{L}_Y = \frac{v}{\sqrt{2}} \sum_\psi \bar{\psi} y_\psi \psi$$

Anomaly	Charge combinations	with Yukawa constraints
$U(1)_X^3$	$2X_L^3 + 6X_Q^3 - X_\ell^3 - X_\nu^3 - 3(X_u^3 + X_d^3)$	$X_L^3 - X_\nu^3$
$U(1)_X^2 U(1)_Y$	$2Y_L X_L^2 + 6Y_Q X_Q^2 - Y_\ell X_\ell^2 - Y_\nu X_\nu^2 - 3(Y_u X_u^2 + Y_d X_d^2)$	0
$U(1)_X U(1)_Y^2$	$2Y_L^2 X_L + 6Y_Q^2 X_Q - Y_\ell^2 X_\ell - Y_\nu^2 X_\nu - 3(Y_u^2 X_u + Y_d^2 X_d)$	$-\frac{1}{2}(X_L + 3X_Q)$
$SU(3)^2 U(1)_X$	$2X_Q - X_u - X_d$	0
$SU(2)^2 U(1)_X$	$2X_L + 6X_Q$	$2X_L + 6X_Q$
$\text{grav}^2 U(1)_X$	$2X_L + 6X_Q - X_\ell - X_\nu - 3(X_u + X_d)$	$X_L - X_\nu$

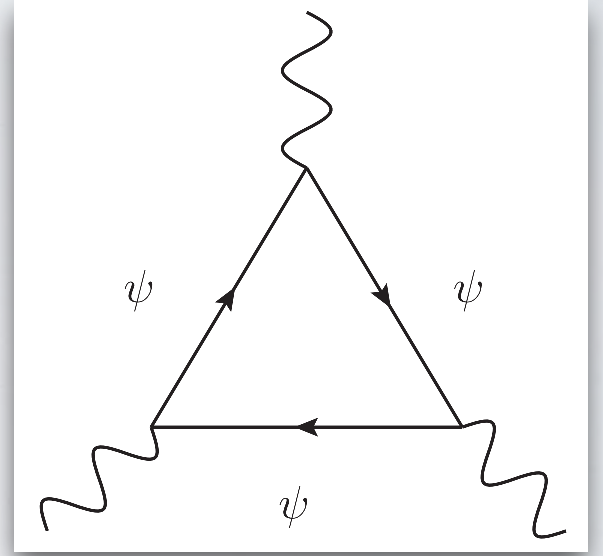
WHY IS THIS INTERESTING?

- Can build anomaly free gauge groups out of accidental local symmetries of SM

$$U(1)_B \qquad U(1)_{L_e} \qquad U(1)_{L_\mu} \qquad U(1)_{L_\tau}$$

- Four simple anomaly-free combinations are:

$B-L$	$L_\mu - L_e$	$L_e - L_\tau$	$L_\mu - L_\tau$
charging quarks & leptons	charging 1st & 2nd generation leptons	charging 1st & 3rd generation leptons	charging 2nd & 3rd generation leptons



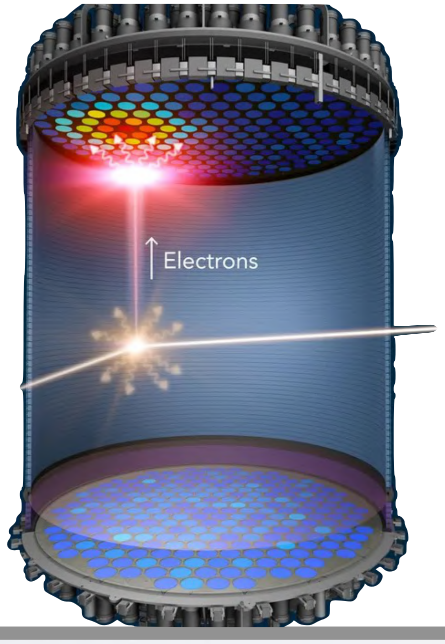
- These models have rich phenomenology
  $\Rightarrow$ Gauge coupling with **neutrinos!**

- **How do these work as portals to DM?**

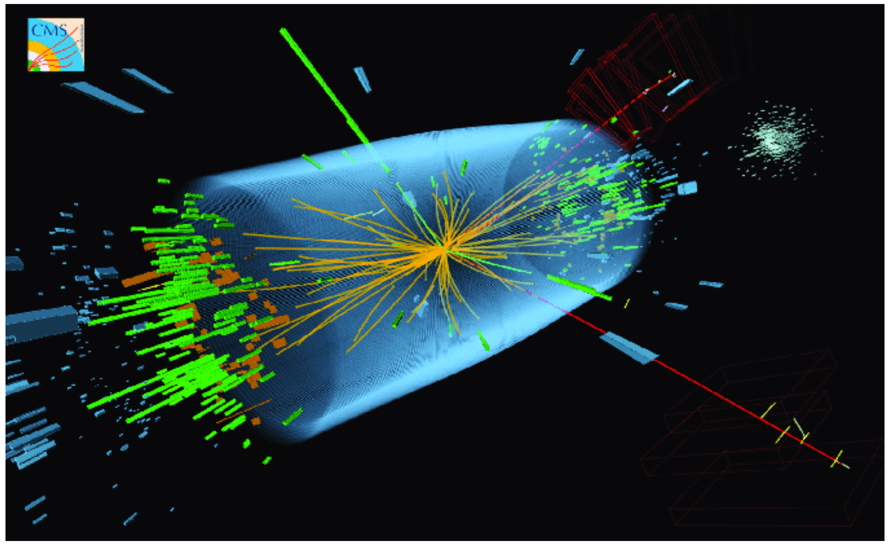
HOW TO SEARCH FOR DM?

- Complementary strategies testing different aspects of DM

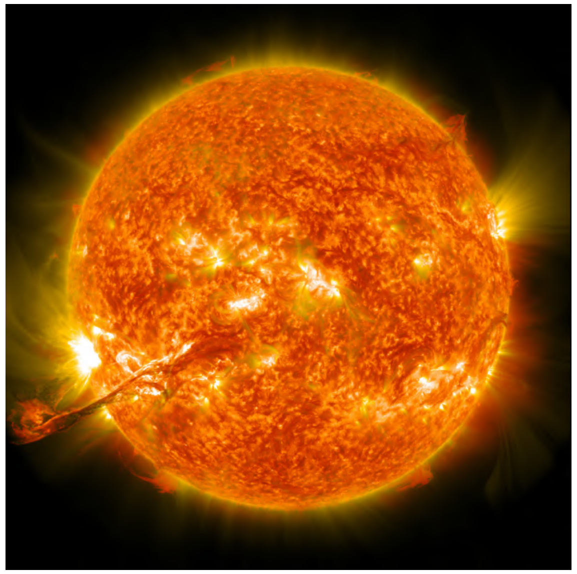
Direct Detection
(Dispersion)



Accelerators
(Production)

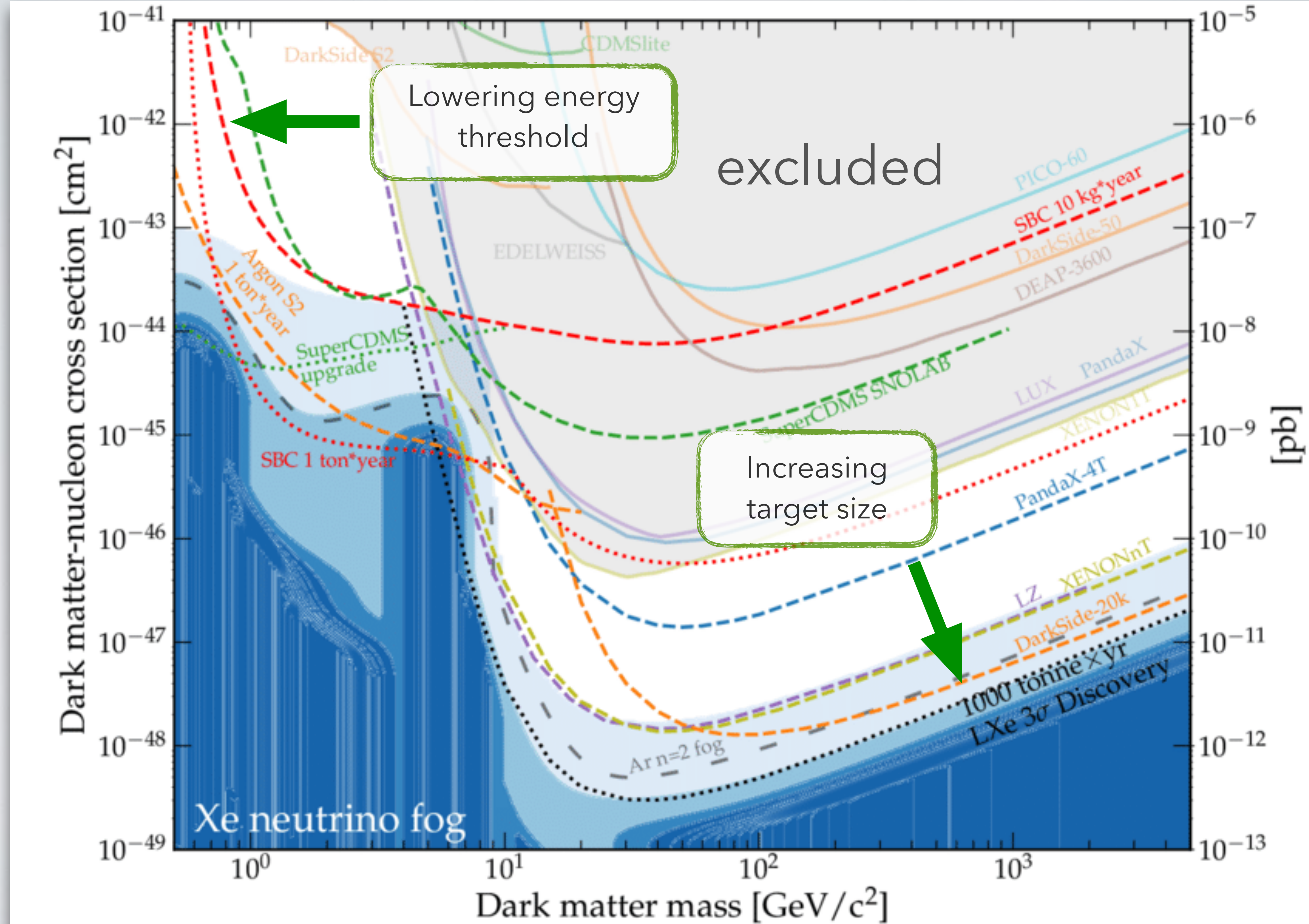


Astrophysics and Cosmo
(Production)



Indirect detection
(Annihilation and decay)

DIRECT DETECTION LANDSCAPE



[Snowmass2021; 2203.08084]

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

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

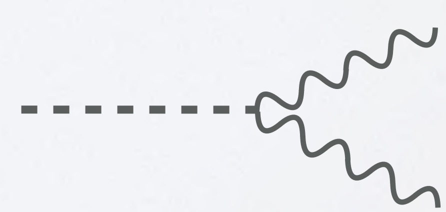
- This leads to a mixed scalar mass matrix and scalar mixing

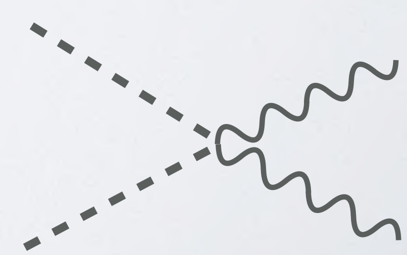
$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda v^2 & \lambda_m v w \\ \lambda_m v w & 2\lambda_s w^2 \end{pmatrix} \qquad \Rightarrow \qquad \begin{pmatrix} h_{125} \\ h_D \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

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

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

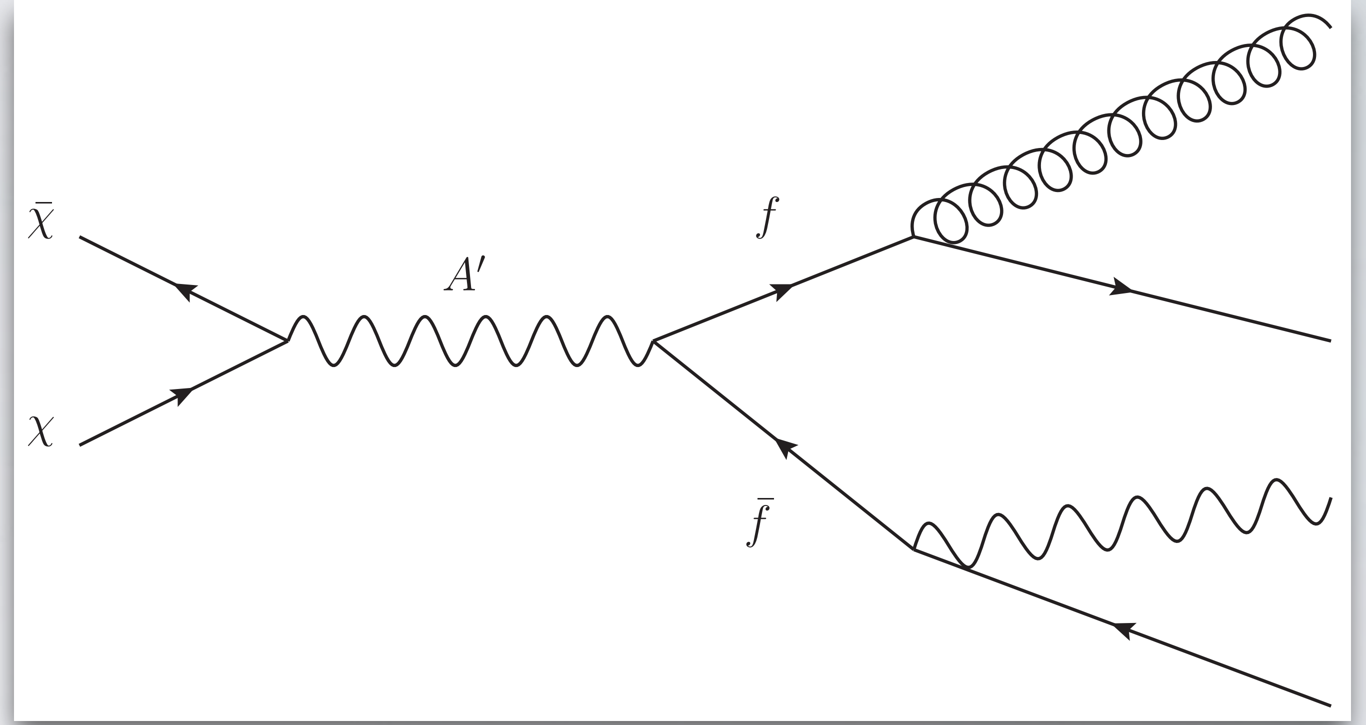
$$\boxed{M_X = g_x\, q_x\, w}$$





INDIRECT DETECTION

- DM can inject energy into primordial plasma via cascade decays into secondary $p, e^{\pm}, \gamma$ and ν



- Secondary particles can also heat and ionize IGM, alter post-recombination ionization fraction