Workshop on Future Accelerators, Faliraki (Corfu) 28/04/2023

EW multiplets@μCollider

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Based on S. Bottaro *et al.*, Eur.Phys.J.C 82 (2022) 1, 31
and on S. Bottaro *et al.*, Eur.Phys.J.C 82 (2022) 11, 992

Plan of the Talk

WIMP Dark Matter

- ✦ Thermal Production mechanism
- ✦ Current phenomenological status

Main properties of EW multiplets

- Selection criteria
- Thermal mass w/ non-perturbative effects

Phenomenology of EW multiplets

- ★ Direct & Indirect detection
- ★ Signatures at the μCollider

Outlook & Discussions

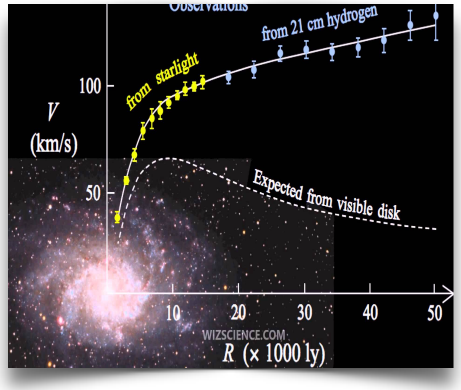
Dark Matter in the Universe

Compelling **macroscopic** evidence of Dark Matter

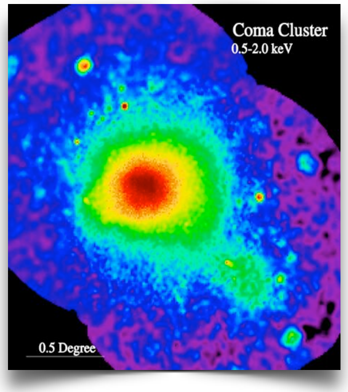
DM Exists !

80% of the matter
in the Universe is **DARK**

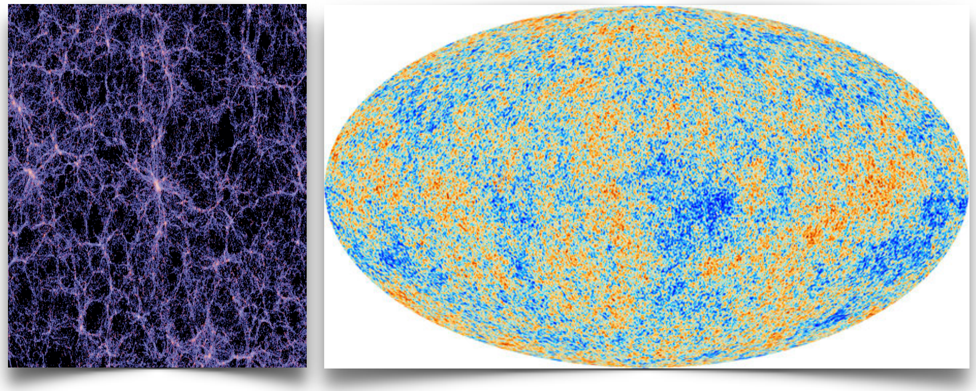
- **Stable**
- **Non-relativistic**
- **Weakly interacting**



Galaxy scale



Cluster scale



Cosmological scale

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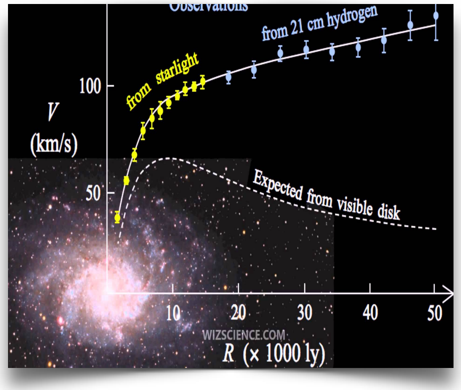

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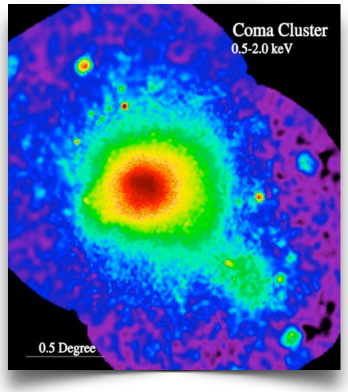

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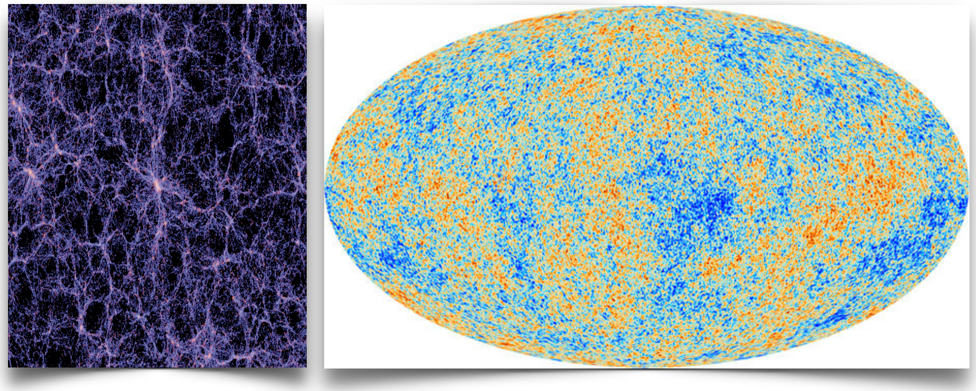


Cosmological scale

BUT ⇨ The DM **microphysics** is unknown

THEORY: Hidden sector theories, Supersymmetry, Technicolor, etc…

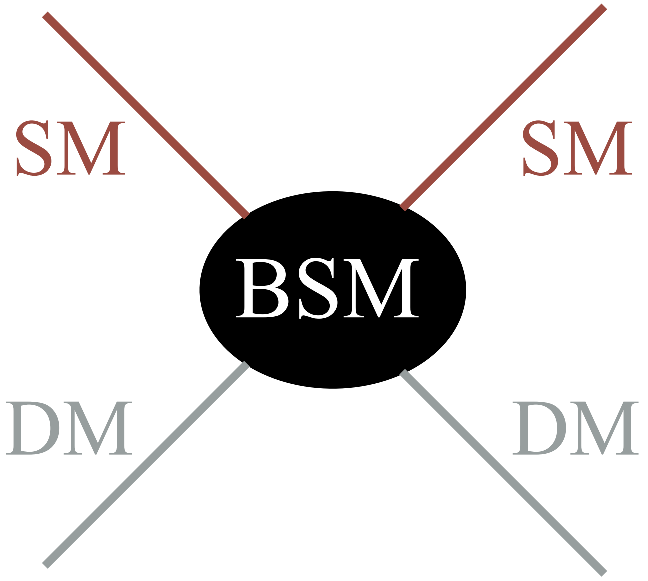
DM CANDIDATE: **axions, asymmetric DM, WIMP, primordial Black Holes**, etc…

DM DENSITY: cuspy DM density profiles **(e.g. NFW)** or cored profiles **(e.g. IsoT)**

Dark Matter Detection

Experimental strategies to identify the **DM microphysics**

Direct Detection



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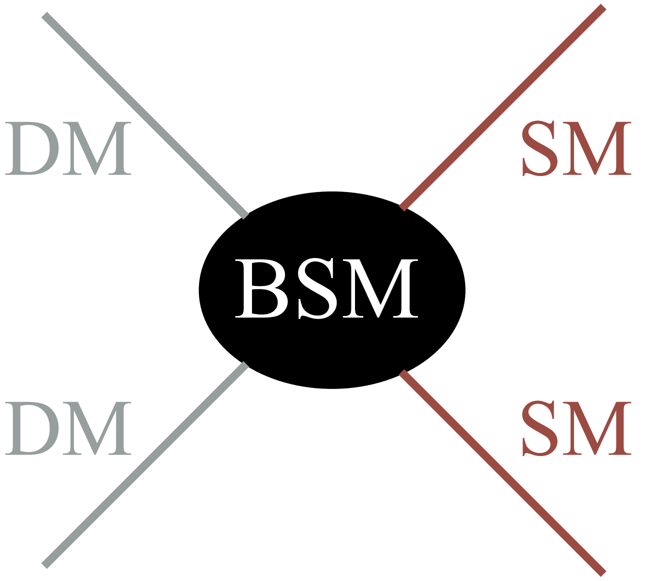
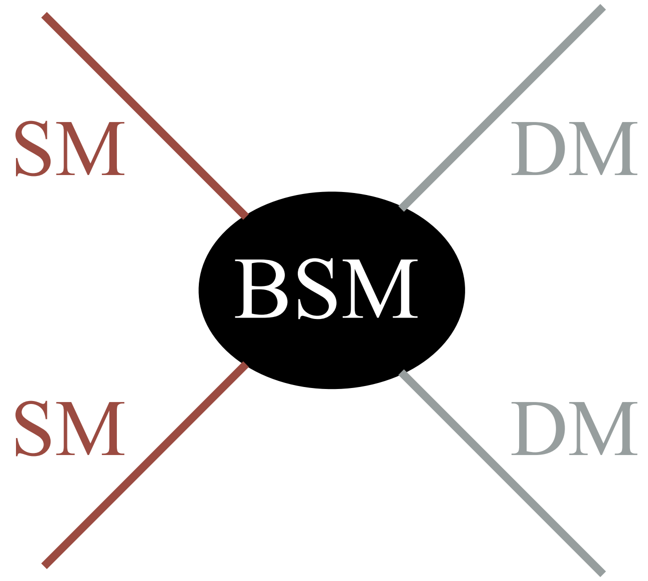


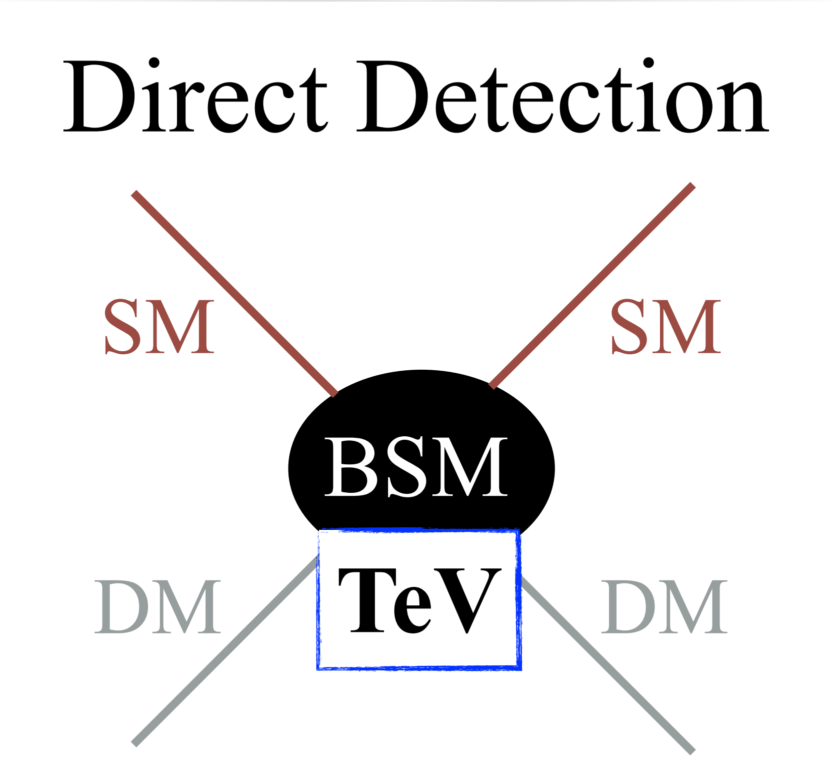
Colliders



Constrain the parameter space
Find several anomalies

Dark Matter Detection

Experimental strategies to identify the **DM microphysics**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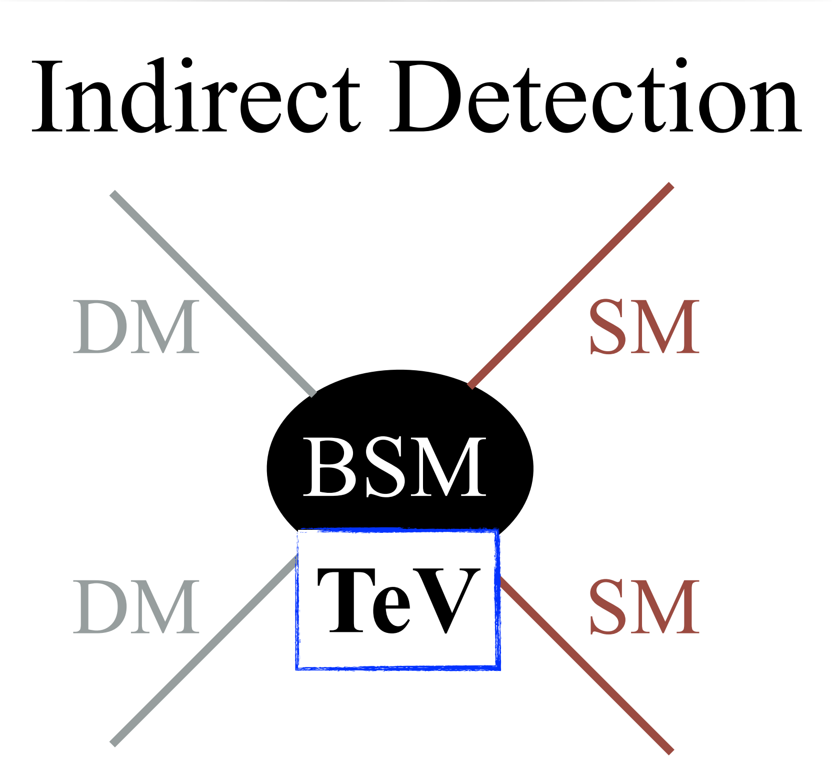
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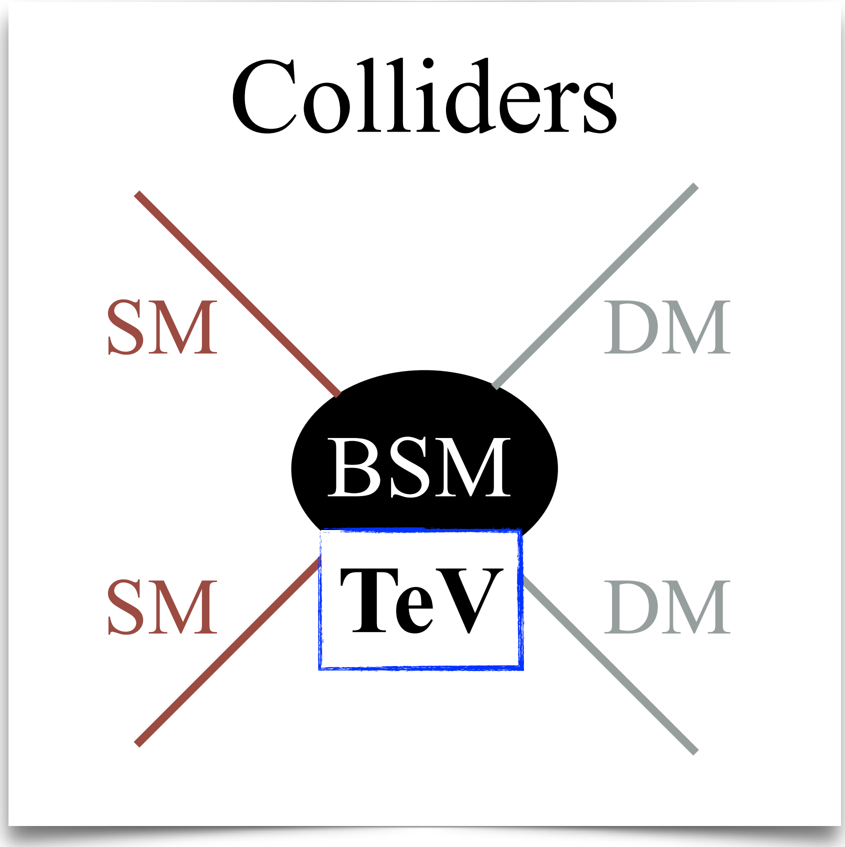
Colliders

2023 | 2025 | 2030 | 2035 | 2040

XENONnT & LZ
AMS-02 & H.E.S.S.
LHC Run 3

Next generation DD exps. (e.g. DARWIN)

Next generation ID exps. (e.g. CTA, LHAASO)

μCollider?

Approaching ***now*** the **TeV scale**

A new era has begun

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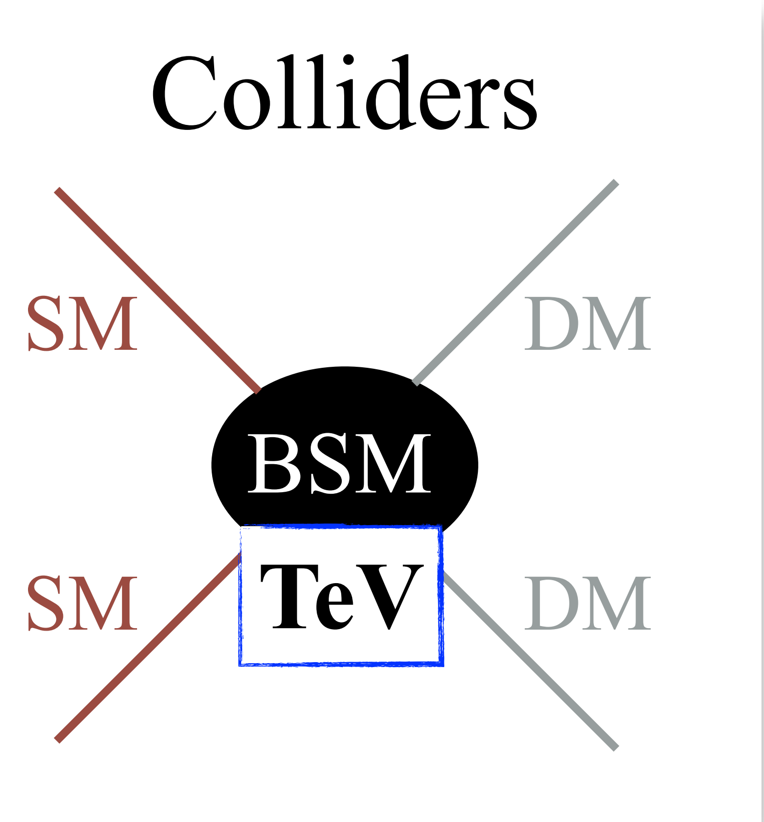

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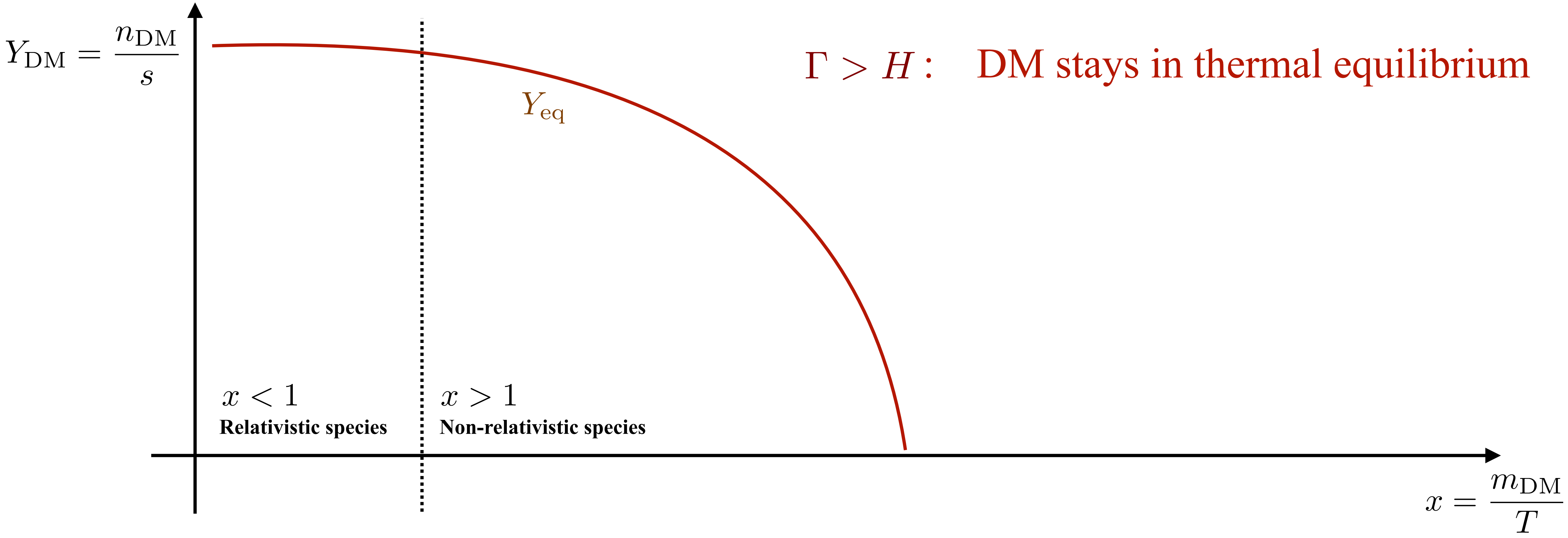

$\Gamma > H:$ DM stays in thermal equilibrium

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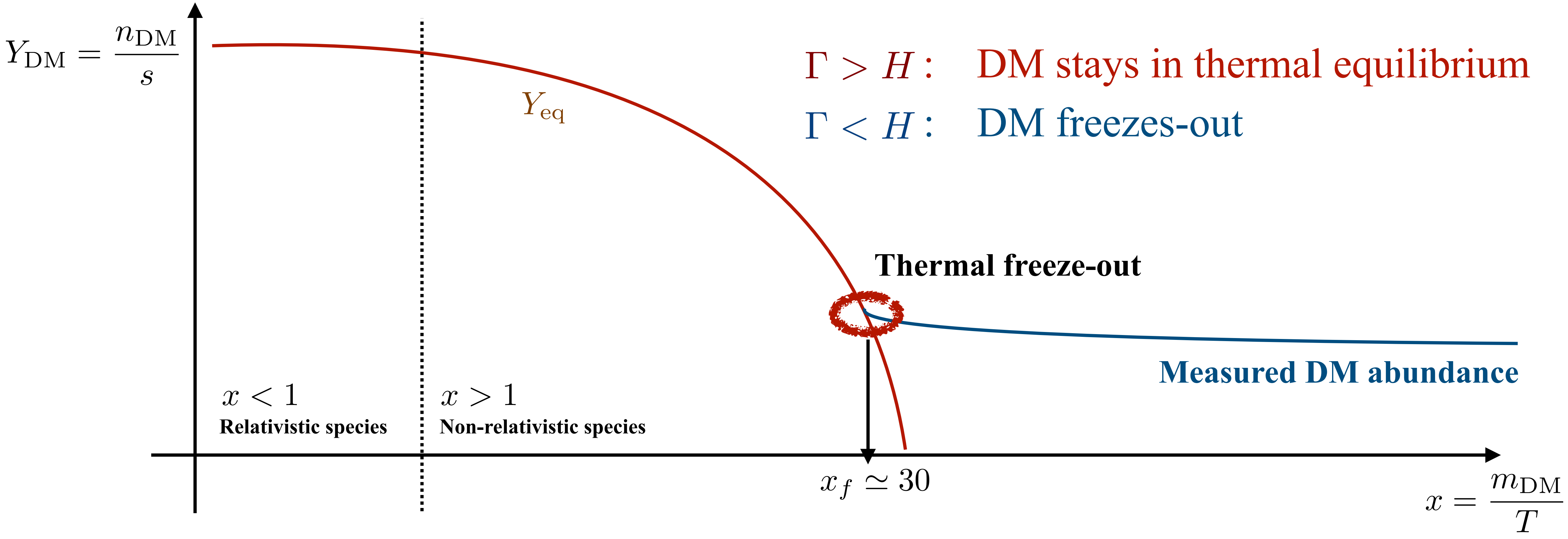

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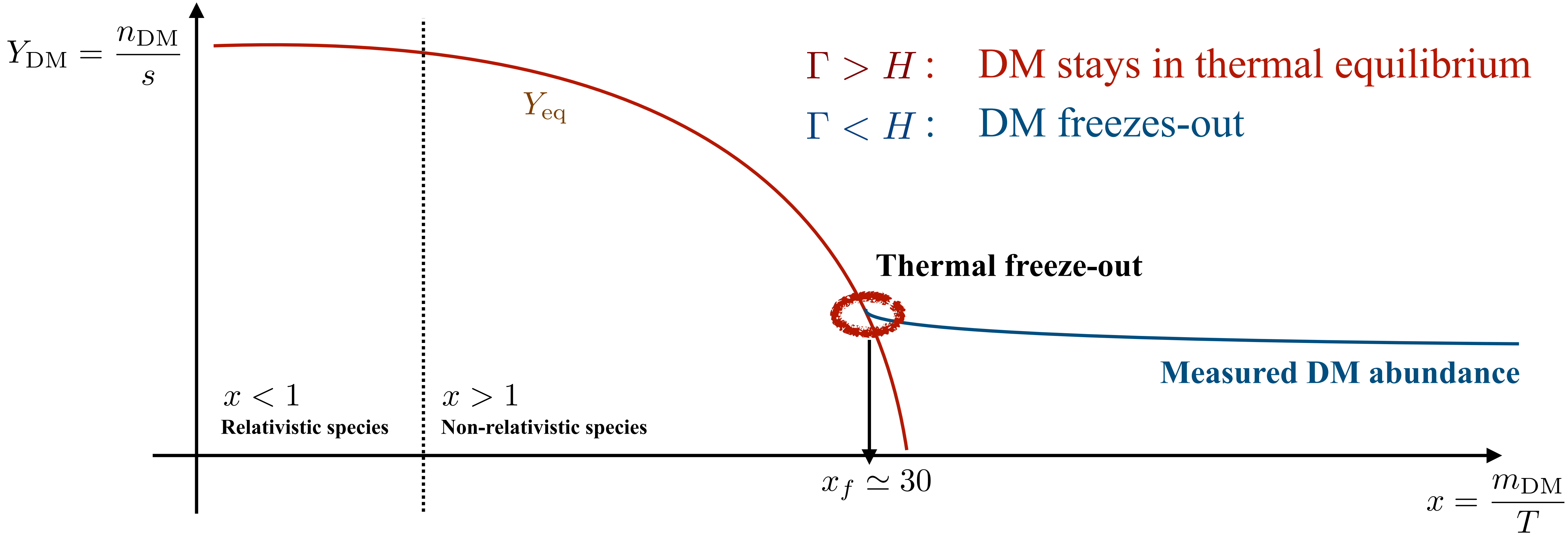

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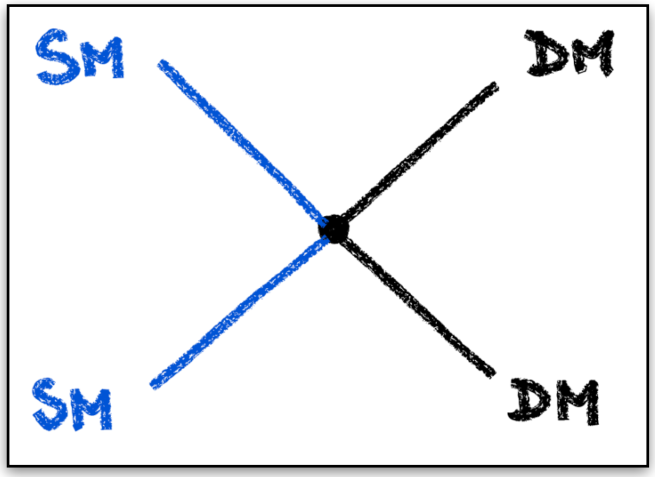

For $2 \rightarrow 2$ scatterings $\langle \sigma_{\rm th} v \rangle$ fully controls the abundance

For $\sigma_{\rm th} \simeq 1\,{\rm pb}$ DM freezes-out

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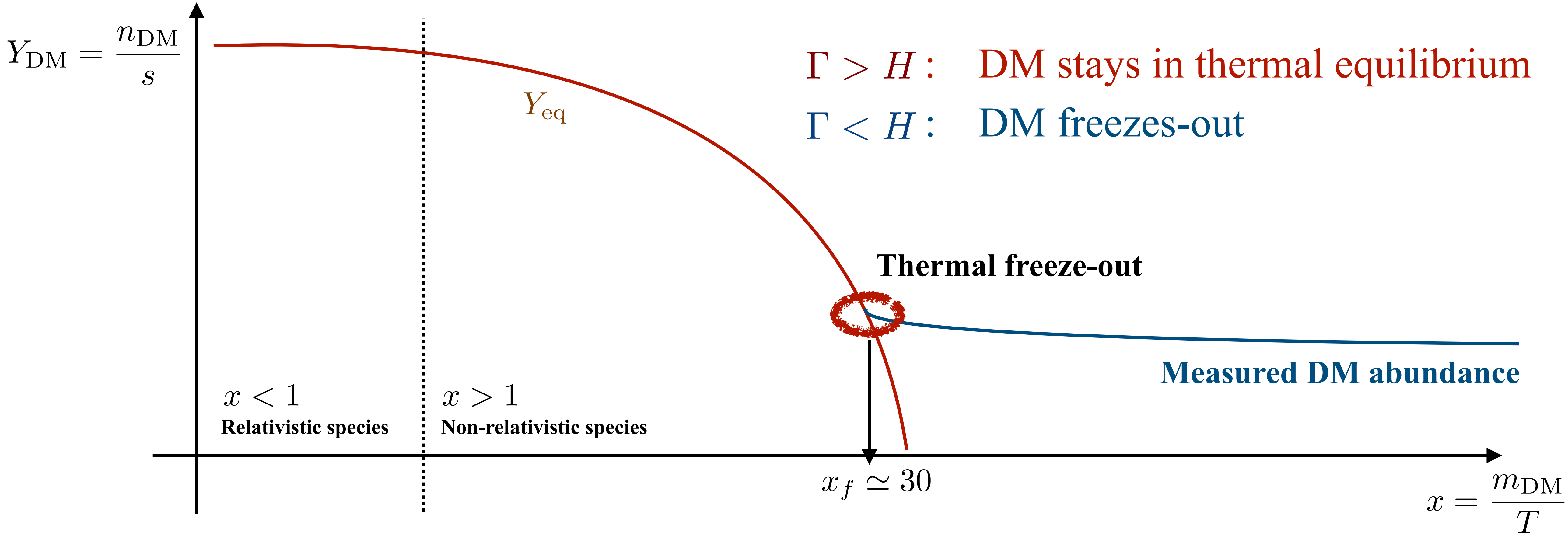

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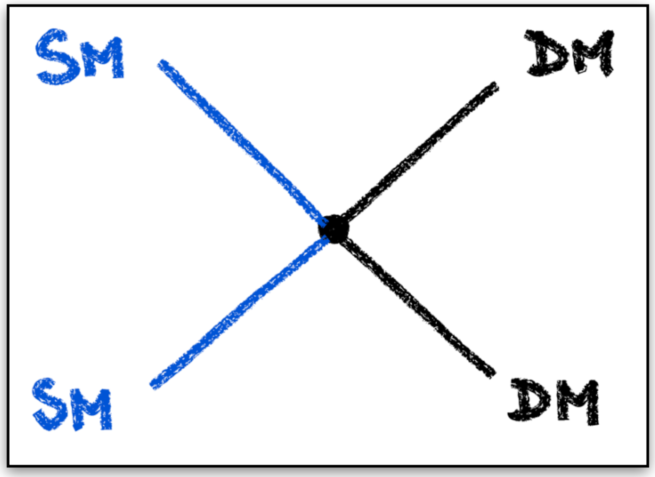

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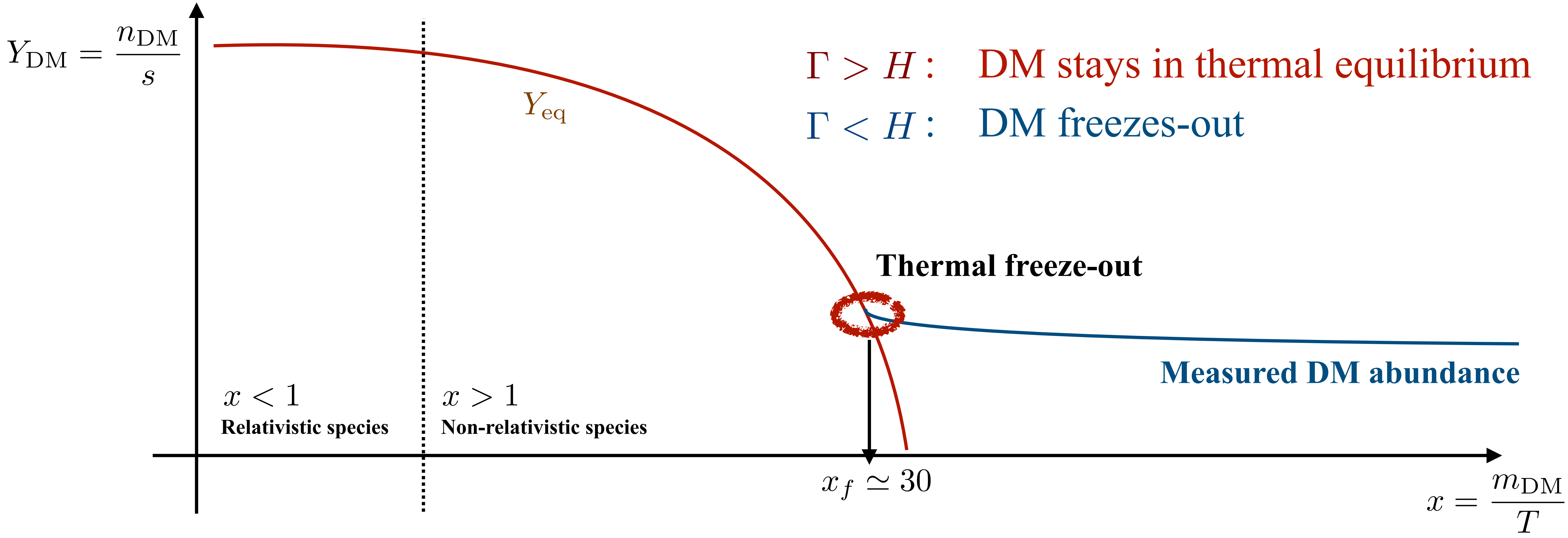

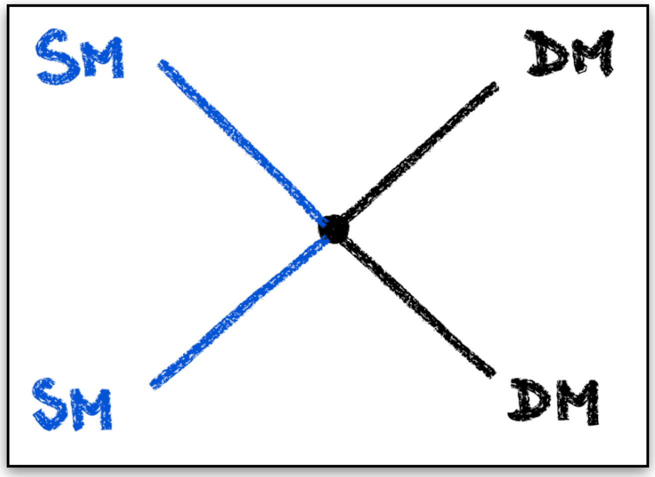

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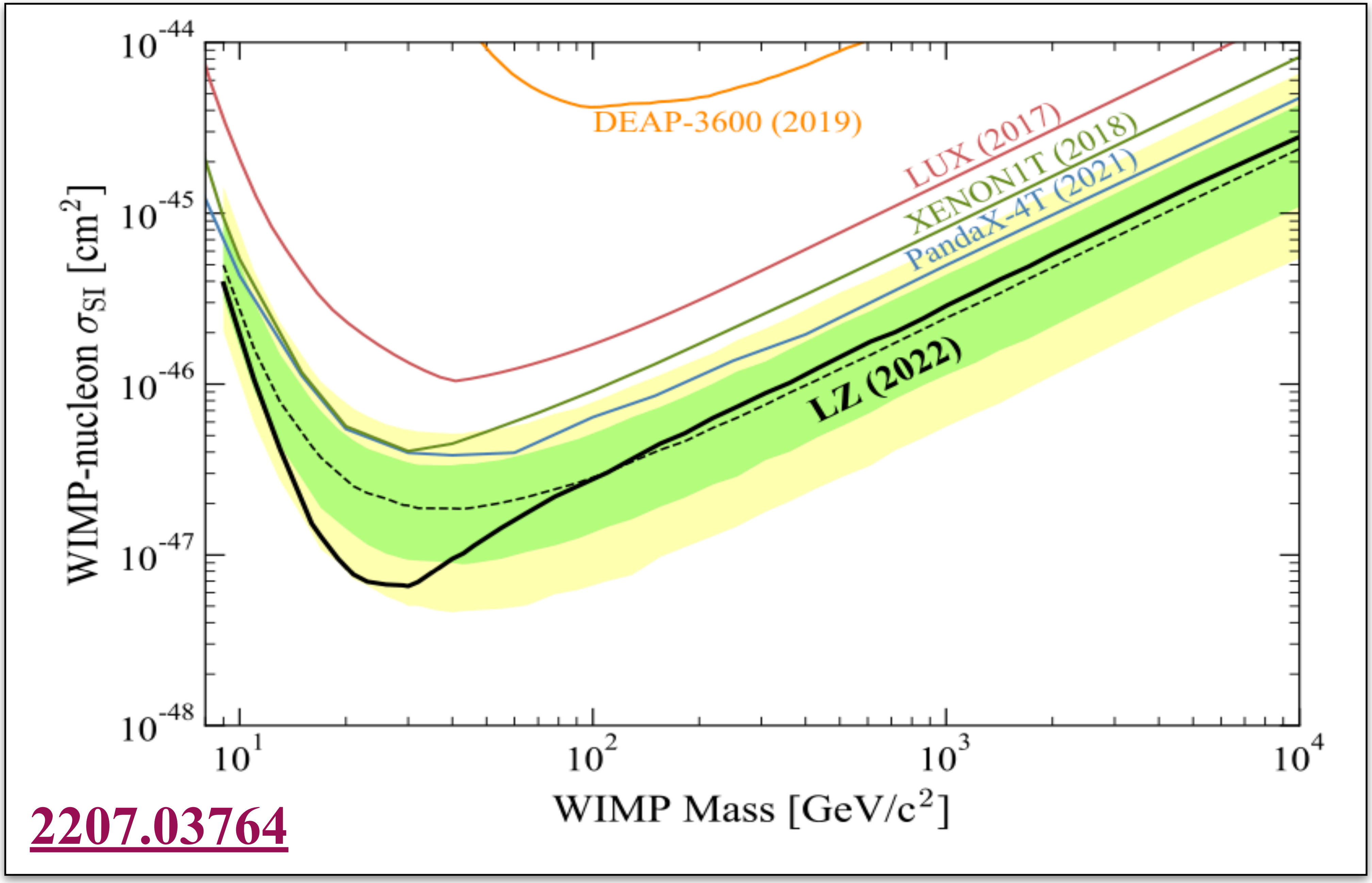
WIMP Miracle: Simple and robust explanation of the DM abundance and a connection to naturalness of EW scale

VERY REACH PHENOMENOLOGY

Direct Detection Bounds



2207.03764

Does it mean that WIMP are dead?

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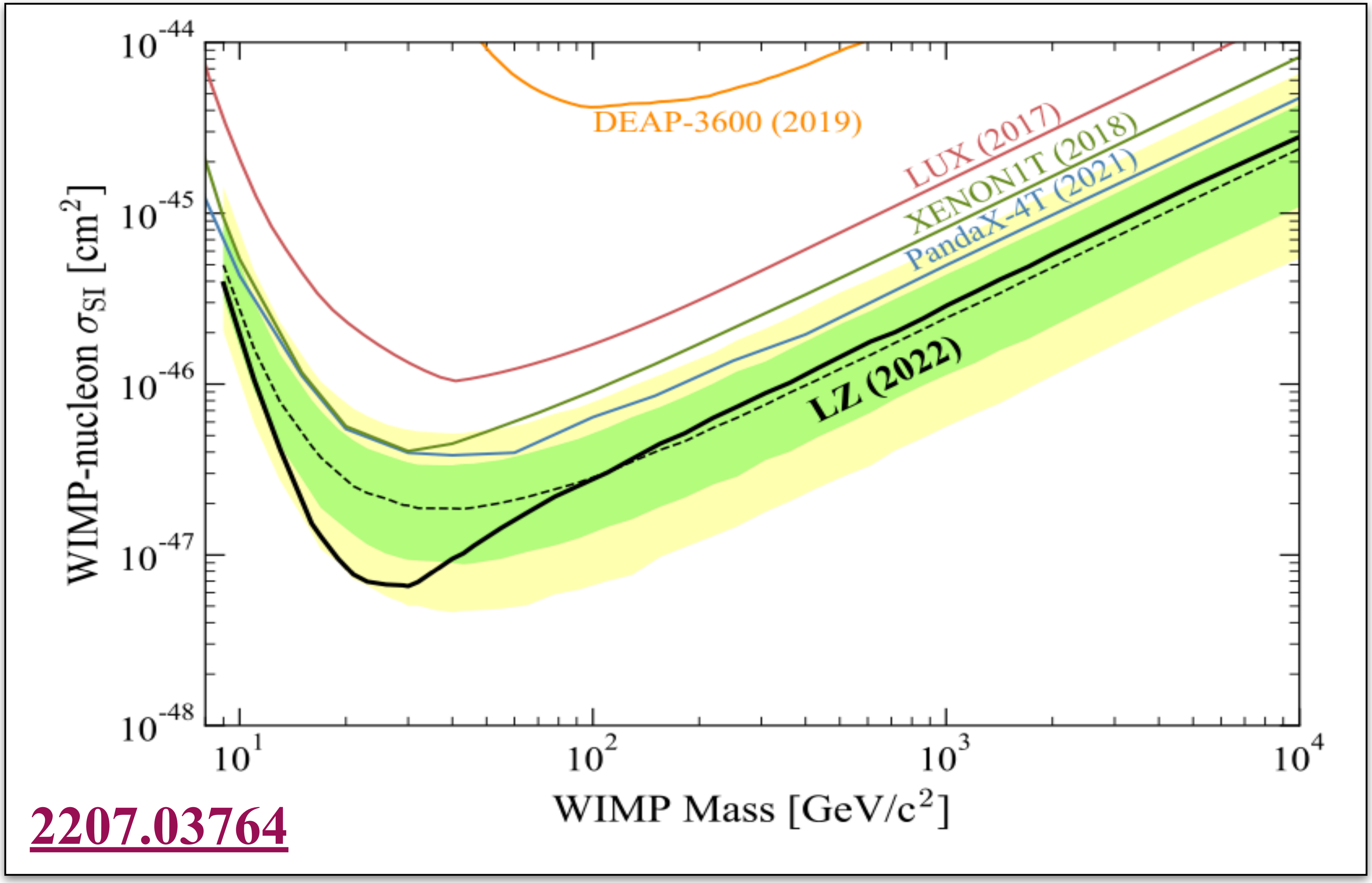

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- ✦ Energy entering in the scattering (few tens of **MeV**) is completely different with respect to the relevant one in the annihilation process (**TeV** and beyond)
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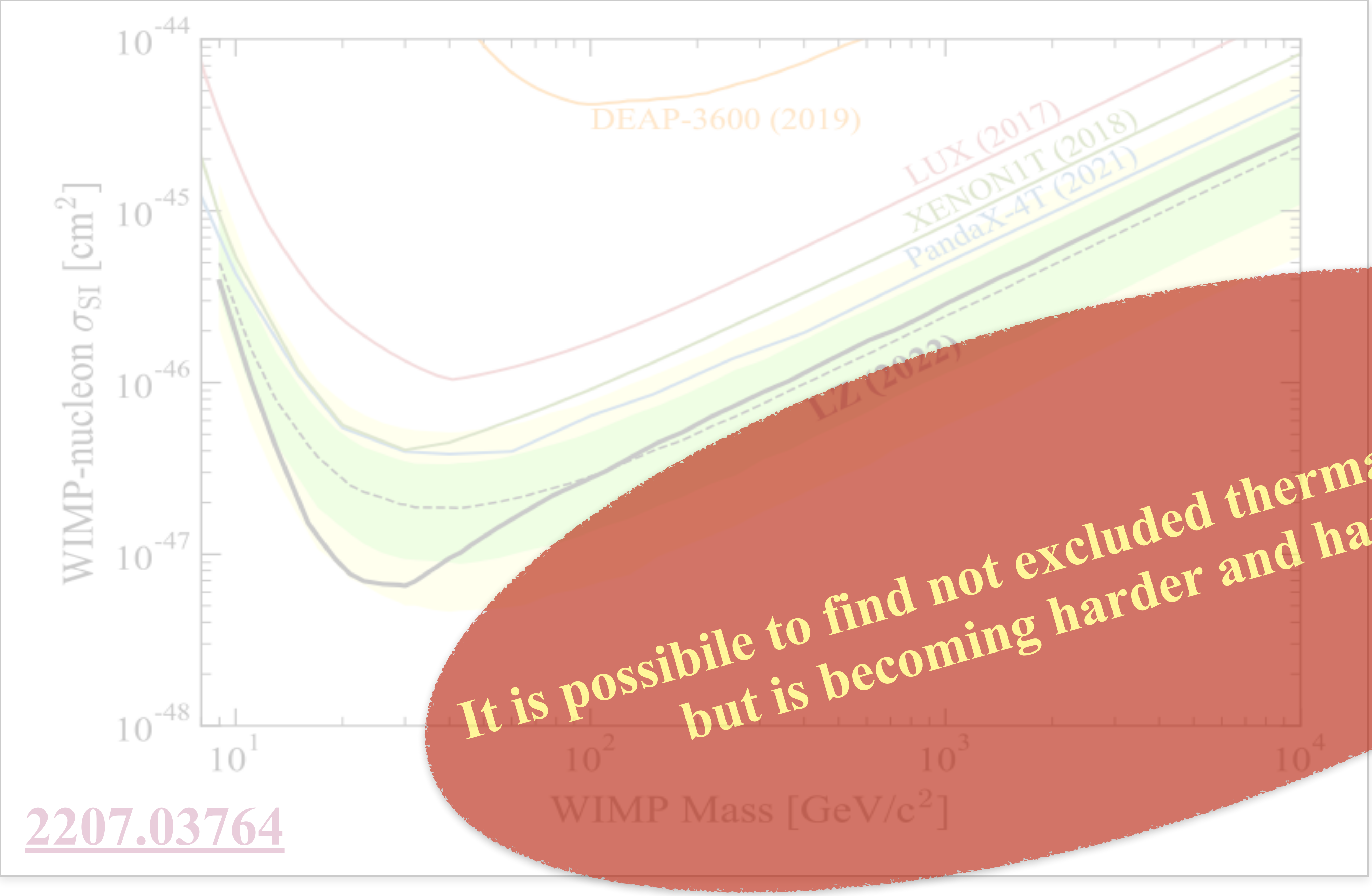

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It is possibile to find not excluded thermal DM models but is becoming harder and harder!

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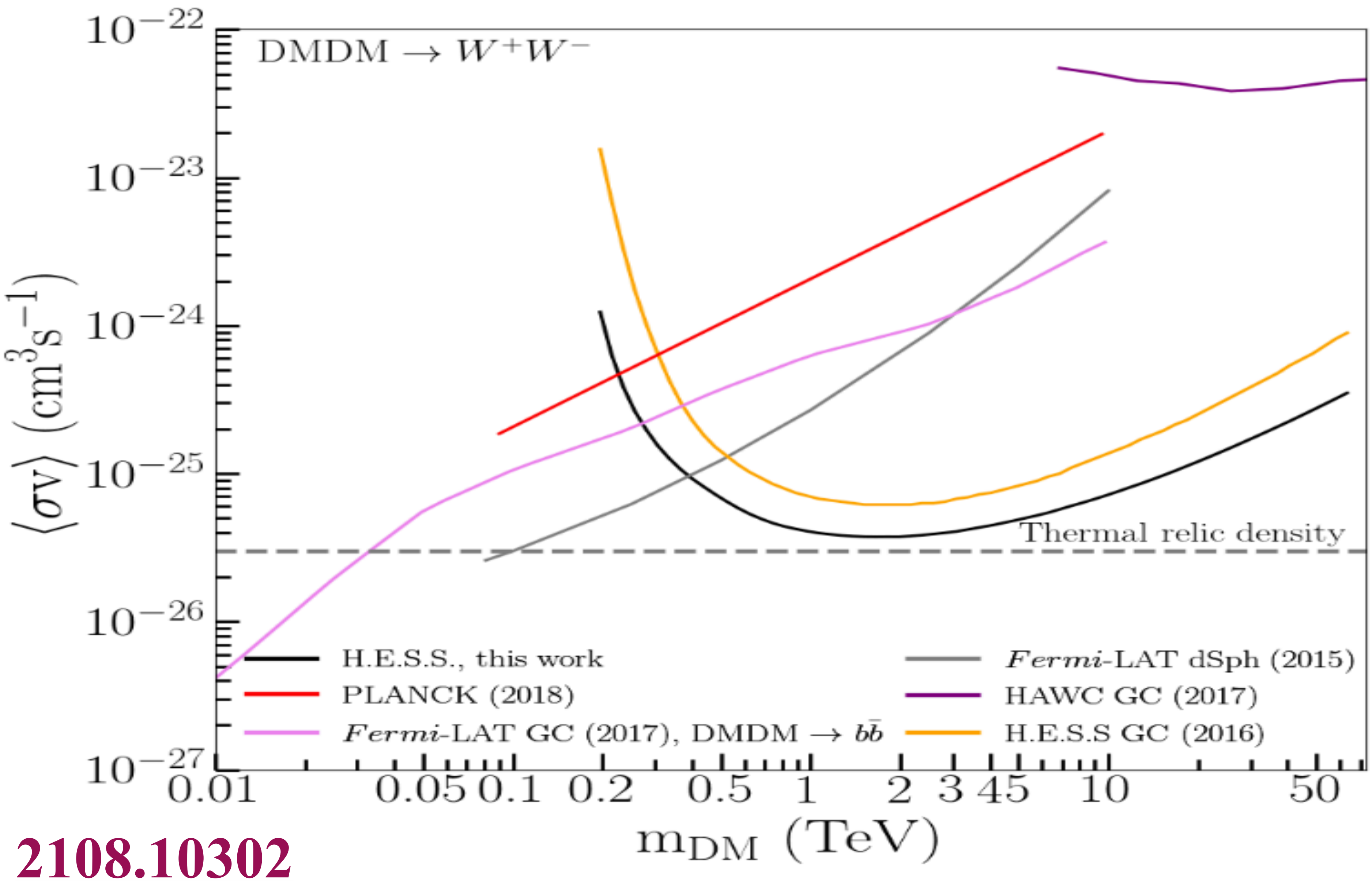

2108.10302

Thermal production is ruled out for light DM with *s*-wave annihilations

- Below 500 GeV the best limit to date is set by the observation of 15 dwarf by the FERMI satellite (**1503.02641**). **Stringent and robust exclusion**
- Above 500 GeV the best limit to date is set by an observation of the GC by the H.E.S.S. cherenkov telescope (**2108.10302**). Stringent exclusion but **NOT ROBUST**

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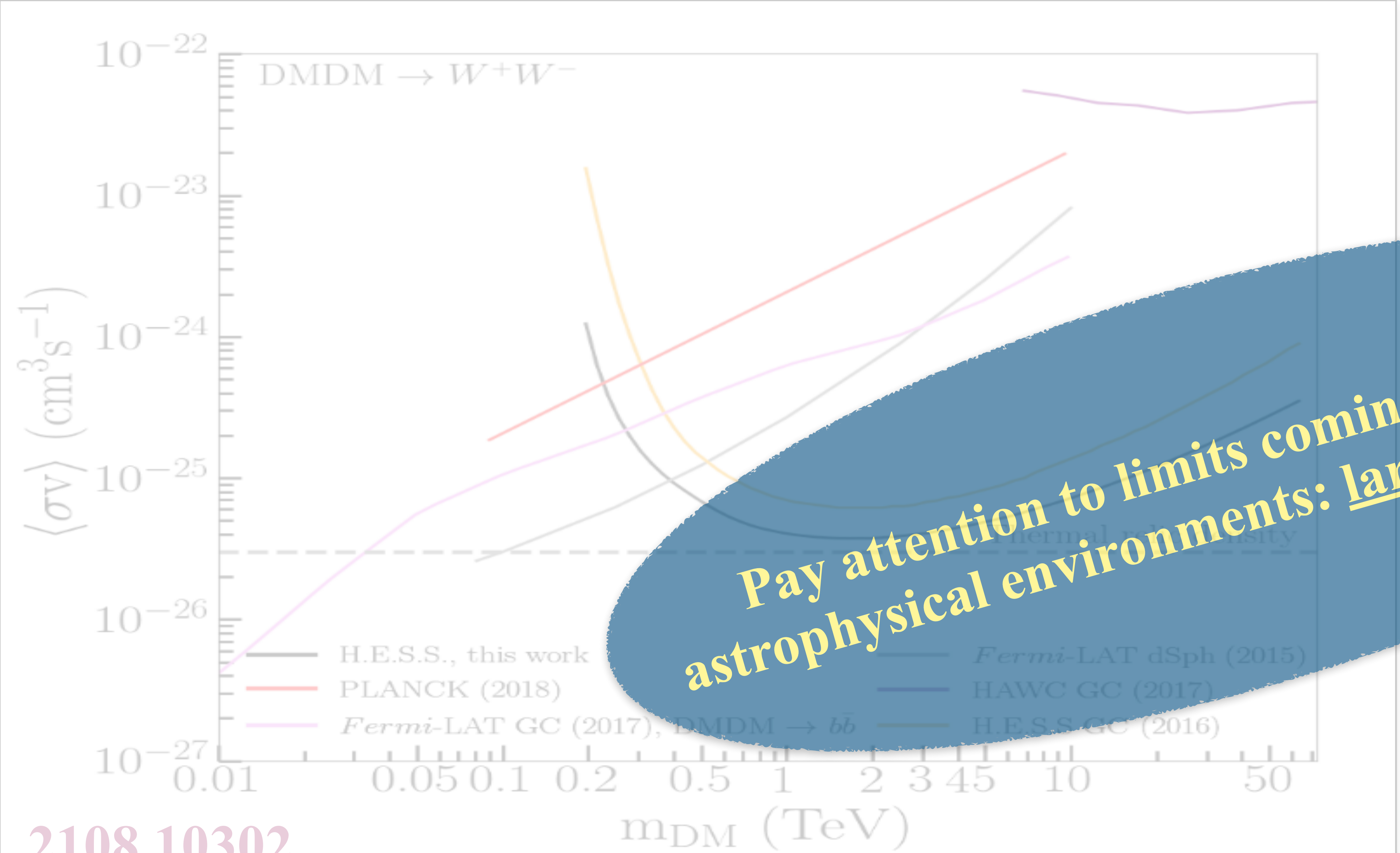

Pay attention to limits coming from dirty astrophysical environments: large uncertainties

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Consider a single ElectroWeak (EW) multiplet (n,Y)

in the same spirit of the original Minimal DM paper **hep-ph/0512090** and **1512.05353**

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Requirements:

- **NEUTRALITY:** DM must be the neutral component → $(\ldots, \chi^+, \chi_0, \chi^-, \ldots)$
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For a given *n* and Y the only free parameter is $m_{\rm DM}$
set by the requirement of thermal freeze-out

WIMP Prototypes

Real WIMPs: odd *n* and Y=0

Scalar $$\mathscr{L}_{\rm s} = \frac{1}{2}(D_\mu\chi)^2 - \frac{1}{2}M_\chi^2\chi^2 - \frac{\lambda_H}{2}\chi^2|H|^2 - \frac{\lambda_\chi}{4}\chi^4\,,$$

Fermion $$\mathscr{L}_{\rm f} = \frac{1}{2}\chi\,(i\bar\sigma^\mu D_\mu - M_\chi)\,\chi\,,$$

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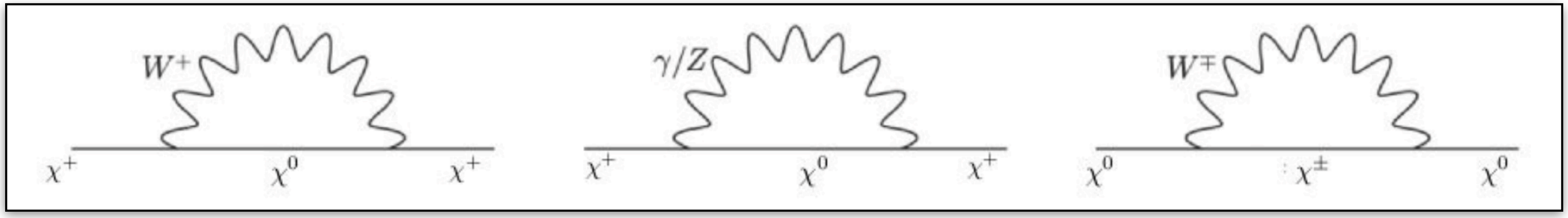
$$\Delta M_Q^{\text{EW}} = \delta_g Q^2 \simeq (167 \pm 4\,\text{MeV})\;Q^2$$

See *e.g.*
hep-ph/9811316
hep-ph/9904250
hep-ph/9904378
1212.5989
1712.00968



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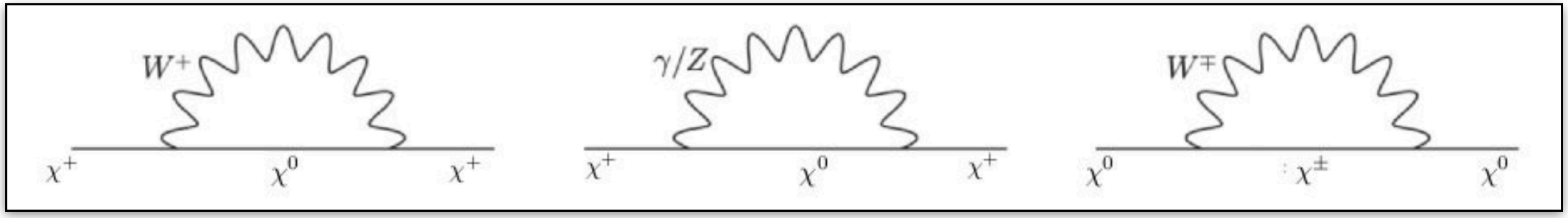
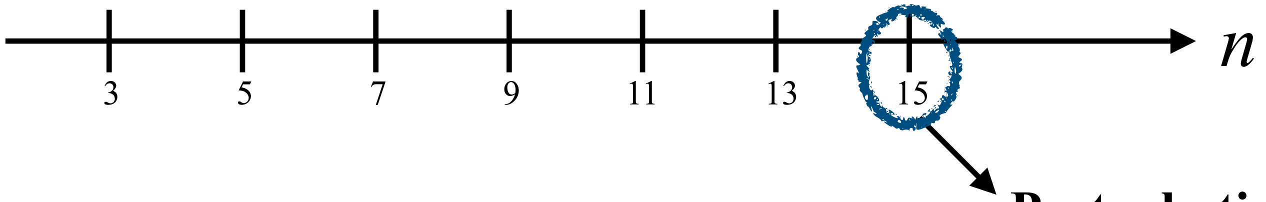


PERTURBATIVETY:



Perturbative Unitarity

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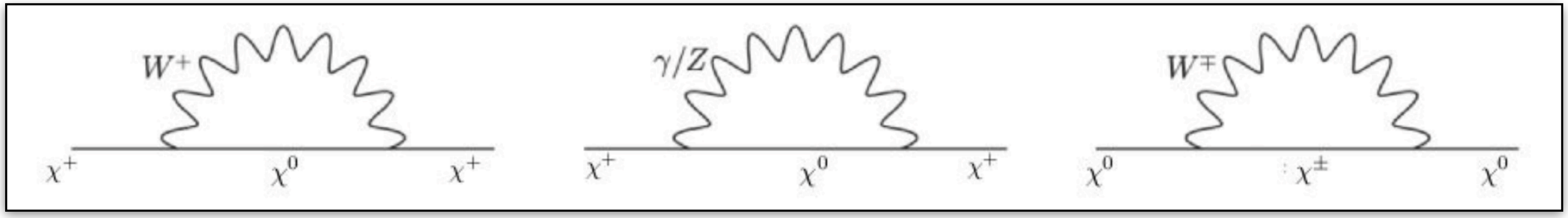

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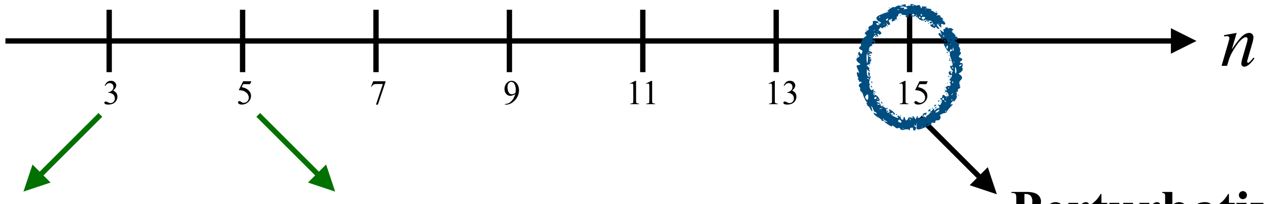

Wino

Minimal DM

Perturbative Unitarity

WIMP Prototypes

Complex WIMPs: any *n* and Y≠0

Dirac Fermion $\mathscr{L}_{\mathrm{D}} = \overline{\chi}\left(i\not{D} - M_\chi\right)\chi + \frac{y_0}{\Lambda_{\mathrm{UV}}^{4Y-1}}\mathcal{O}_0 + \frac{y_+}{\Lambda_{\mathrm{UV}}}\mathcal{O}_+ + \mathrm{h.c.}$

NOT MINIMAL: higher dimensional operators are needed

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$$\boxed{\mathcal{O}_0 = \frac{1}{2(4Y)!}\left(\overline{\chi}(T^a)^{2Y}\chi^c\right)\left[(H^{c\dagger})\frac{\sigma^a}{2}H\right]^{2Y}} \Longrightarrow \boxed{\begin{array}{c} \overset{\textbf{Dirac}}{\chi_{Q=0}} \to \overset{\textbf{Majorana}}{\chi_0, \chi_{\rm DM}} \\ \delta m_0 = 4 y_0 c_{nY0} \Lambda_{\rm UV}\left(\frac{v}{\sqrt{2}\Lambda_{\rm UV}}\right)^{4Y} \end{array}}$$

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This splitting is necessary to make the *Z*-mediated DM collision inelastic

$$\boxed{\mathscr{L}_Z = \frac{ieY}{\sin\theta_W\cos\theta_W}\overline{\chi}_0\not{Z}\chi_{\rm DM}}$$

⇨ Dynamically set to zero when $\frac{1}{2}\mu v_{\rm rel}^2 < \delta m_0$

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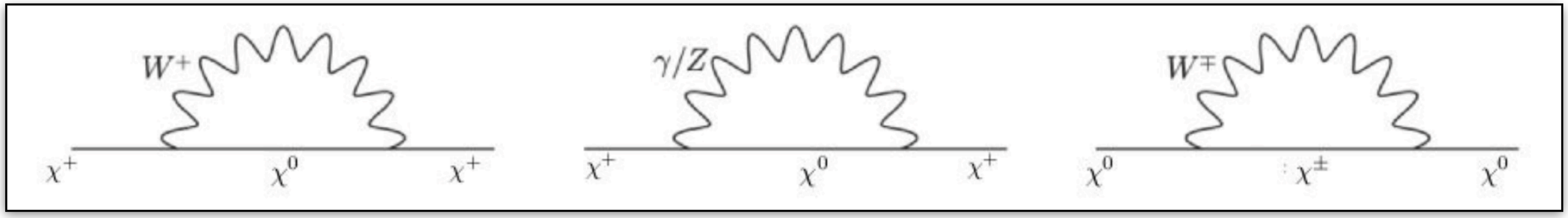
is necessary to make χ_0 the lightest state unless we choose multiplets with maximal *Y*

$$(1,n)_Y \begin{cases} \dots \\ \chi^+ \\ \updownarrow \delta_g \\ \chi_0 \\ \chi^- \\ \dots \end{cases}$$

$$\Delta M_Q^{\rm EW} = \delta_g\left(Q^2 + \frac{\boxed{2YQ}}{\cos\theta_W}\right)$$

It is negative if in the multiple are present states with negative charge *Q*=-*Y*



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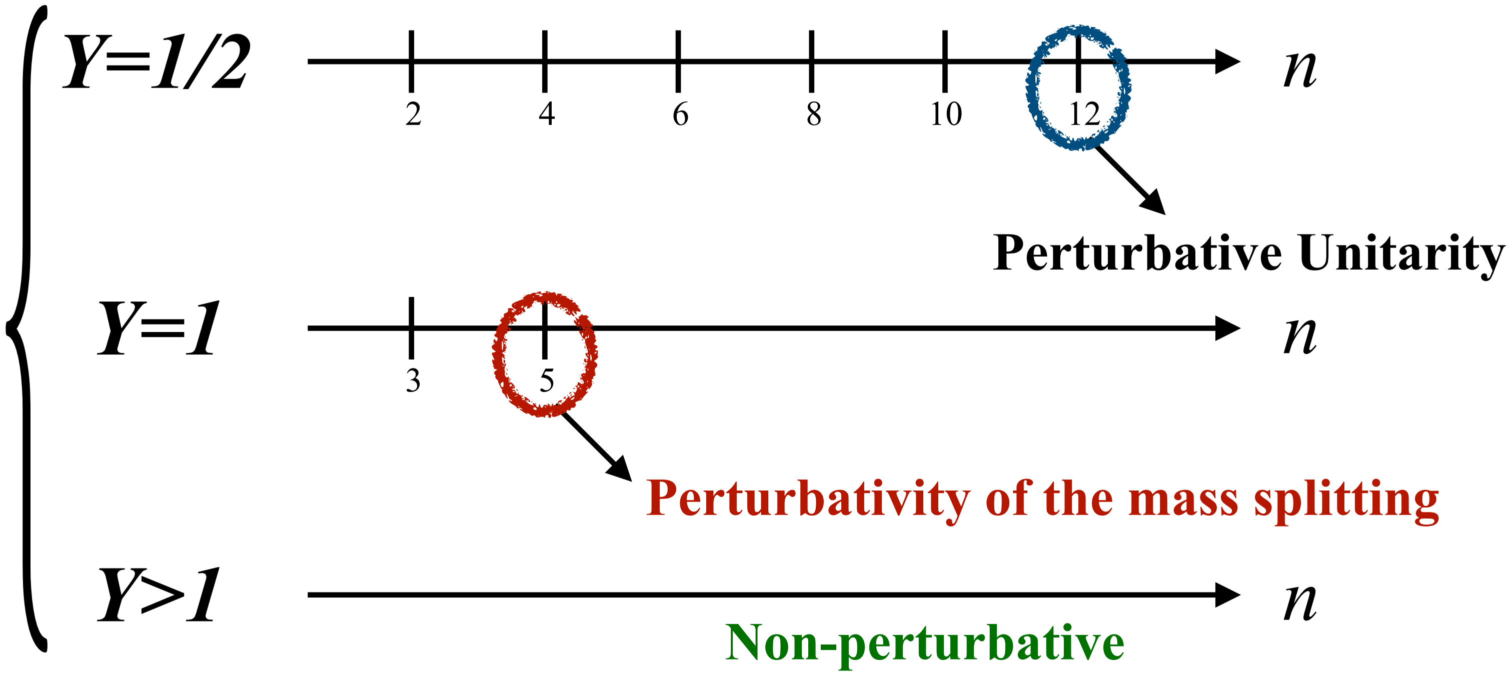


Perturbative Unitarity

Perturbativity of the mass splitting

Non-perturbative

WIMP Prototypes

Complex WIMPs: any *n* and Y≠0

Dirac Fermion $$\mathscr{L}_{\rm D} = \overline{\chi}\left(i\not{D} - M_\chi\right)\chi + \frac{y_0}{\Lambda_{\rm UV}^{4Y-1}}\mathcal{O}_0 + \frac{y_+}{\Lambda_{\rm UV}}\mathcal{O}_+ + \text{h.c.}$$

NOT MINIMAL: higher dimensional operators are needed

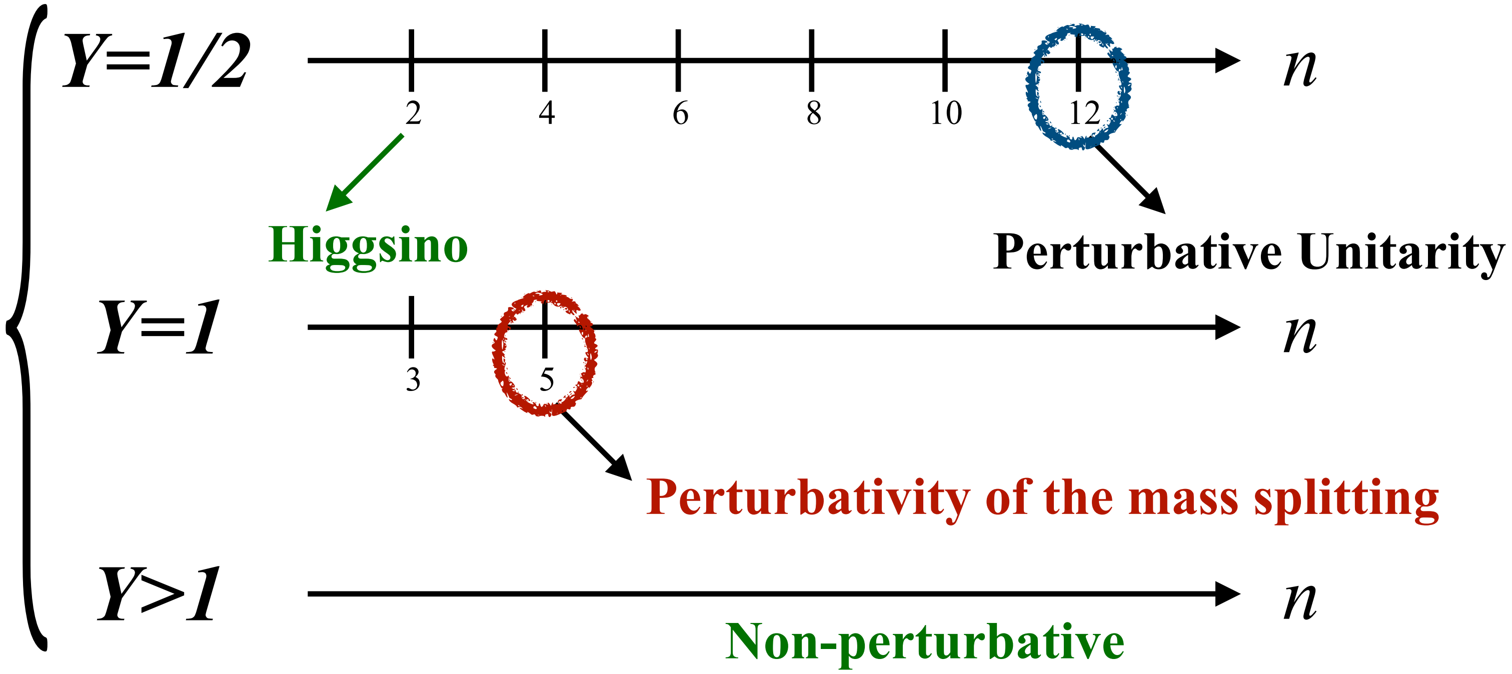
$$\boxed{\mathcal{O}_0 = \frac{1}{2(4Y)!}\left(\overline{\chi}(T^a)^{2Y}\chi^c\right)\left[(H^{c\dagger})\frac{\sigma^a}{2}H\right]^{2Y}}$$

is mandatory to make *Z*-mediated DM collision inelastic

$$\boxed{\mathcal{O}_+ = -\overline{\chi}T^a\chi H^\dagger\frac{\sigma^a}{2}H}$$

is necessary to make χ_0 the lightest state unless we choose multiplets with maximal *Y*

PERTURBATIVETY:



Thermal Production

For 2 to 2 processes $\langle \sigma_{\rm th} v \rangle$ fully controls the abundance

$$\frac{\mathrm{d}Y}{\mathrm{d}x} = -\frac{s(x)}{xH(x)}\boxed{\langle \sigma v \rangle}\left(1 - \frac{x}{3g_*(x)}\frac{\mathrm{d}g_*}{\mathrm{d}x}\right)\left(Y^2(x) - Y_{eq}^2(x)\right)$$

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WHICH CROSS SECTION?

Tree-level estimate:

(e.g. for majorana fermion)

$$\langle \sigma v \rangle_0 = \frac{\pi \alpha_2^2 (2n^4 + 17n^2 - 19)}{16 g_\chi M_\chi^2}$$

CORRECT…

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BUT INACCURATE!!

Important non-perturbative, non-relativistic effects are missing:

- Sommerfeld enhancement
- Bound States formation

Sommerfeld & BS formations

SE: long-range EW potentials deform the wave functions of the incoming particles

$$-\frac{\nabla^2\psi}{M_\chi}+V\psi=E\psi \qquad \langle\sigma v\rangle_0 \to \begin{cases}\langle\sigma v\rangle = S_{Som}(x)\langle\sigma v\rangle_0 \\ S_{Som}(x)\propto|\psi(0)|^2\end{cases}$$

The correction becomes more relevant at low velocity and saturate for $v_{\rm rel}\simeq 10^{-2}c$

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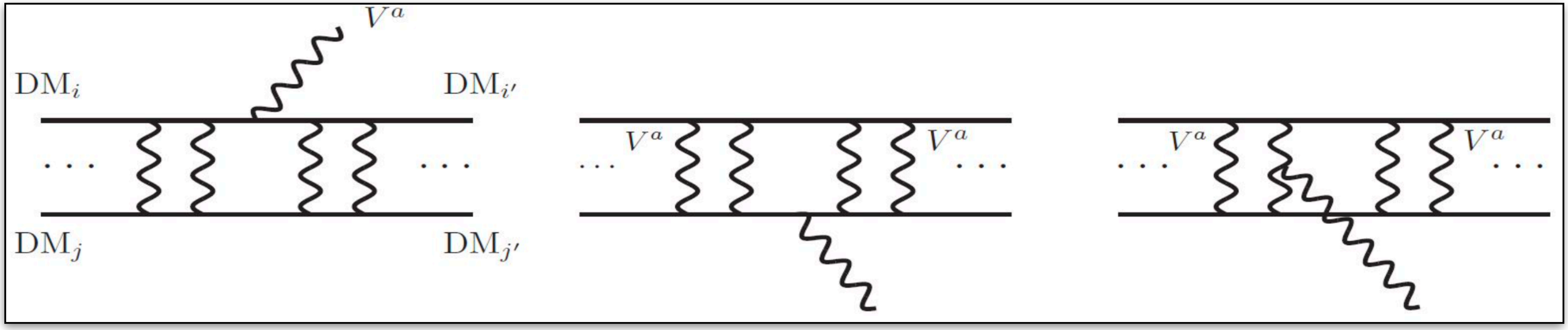
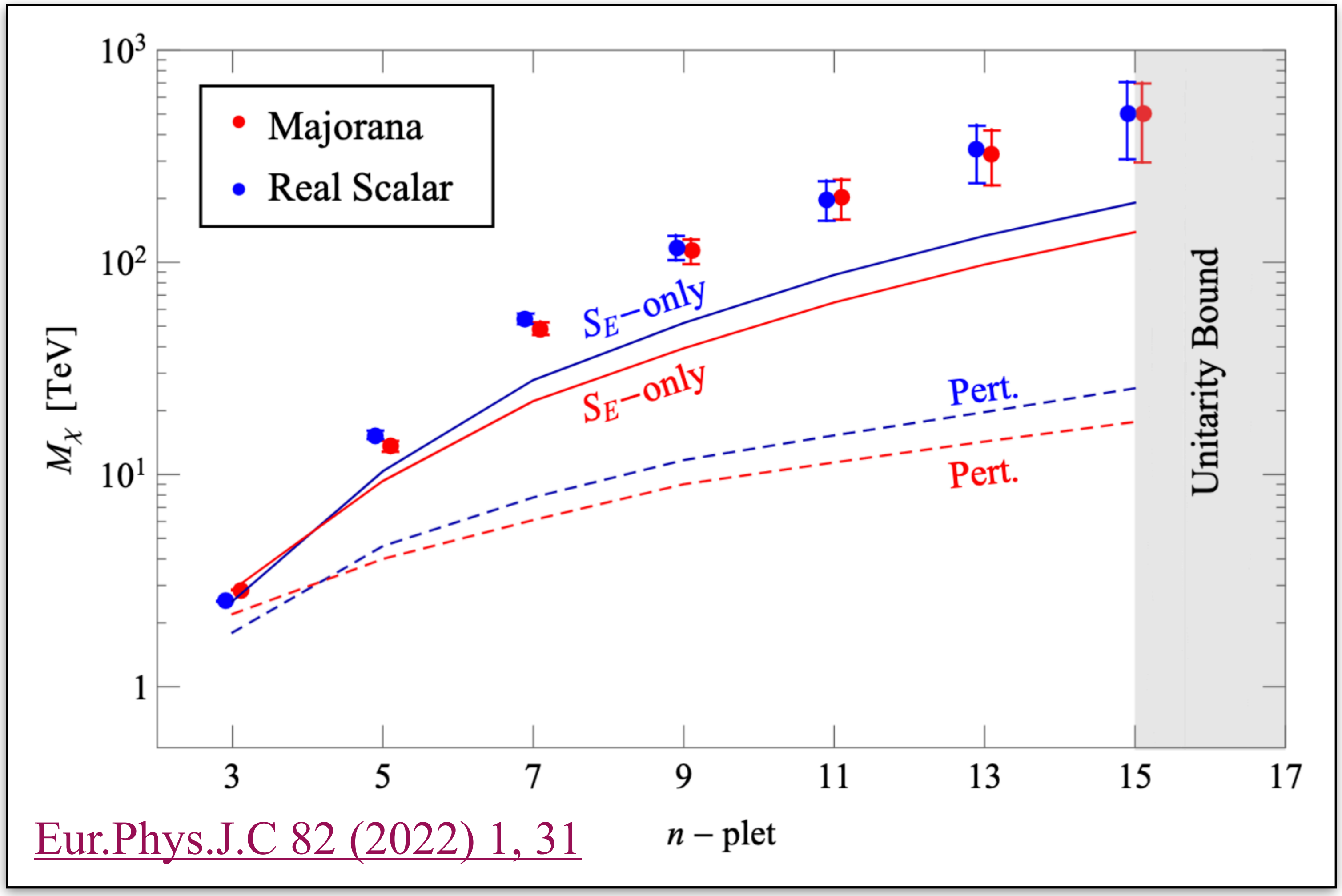
BS: Particle-antiparticle pair bind into a WIMPONIUM BS emitting a gauge boson



Annihilation enhancement: BS later annihilates into SM (see e.g. 1702.01141):

$$S(x) = S_{Som}(x) + \left[\frac{\langle\sigma v\rangle_0}{\langle\sigma_I v\rangle} + \frac{g_\chi^2\langle\sigma v\rangle_0 M_\chi^3}{2g_I\Gamma_{ann}}\left(\frac{1}{4\pi x}\right)^{\frac{3}{2}} e^{-xE_{B_I}/M_\chi}\right]^{-1}$$

The WIMP thermal masses



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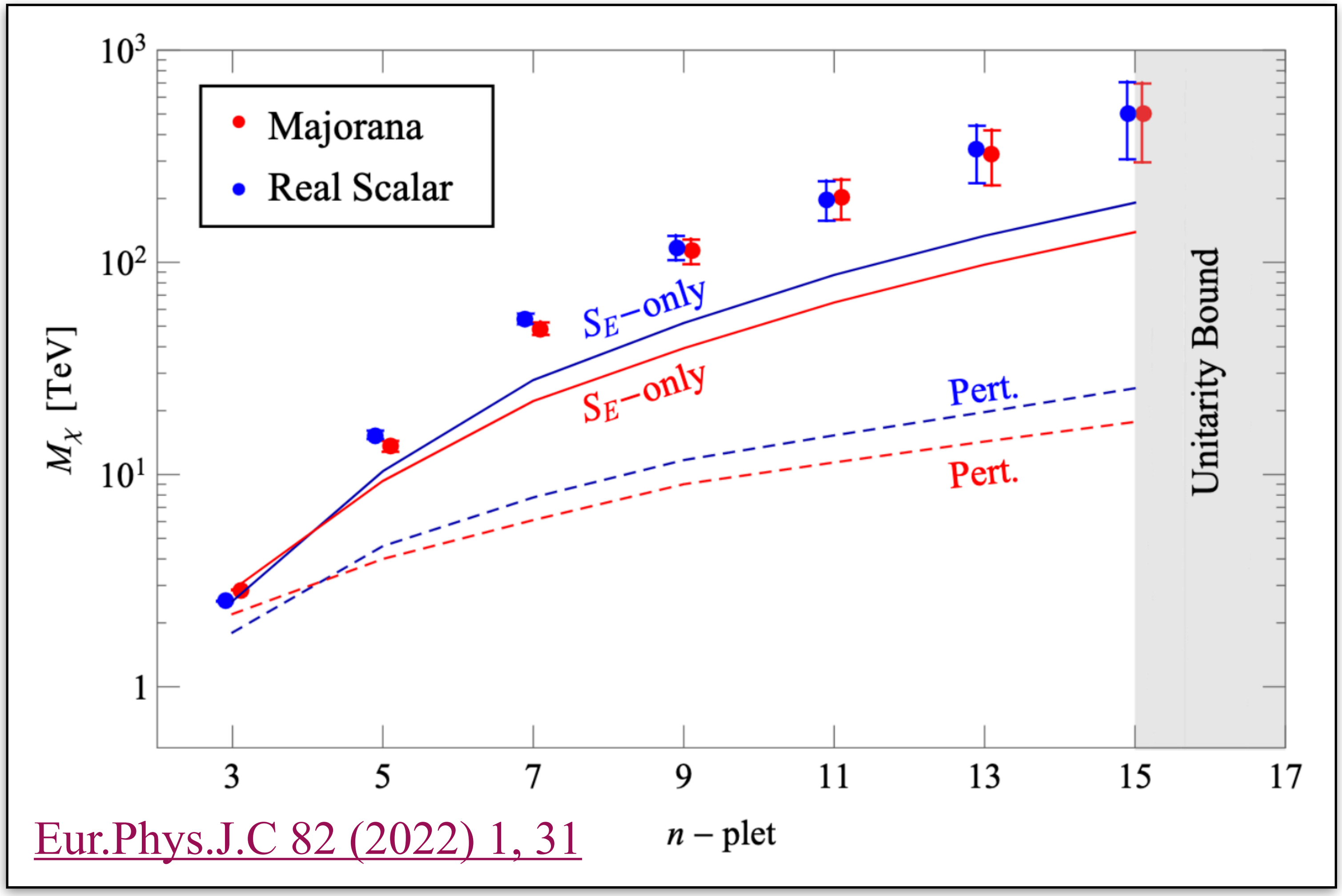

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(and similar for complex…)
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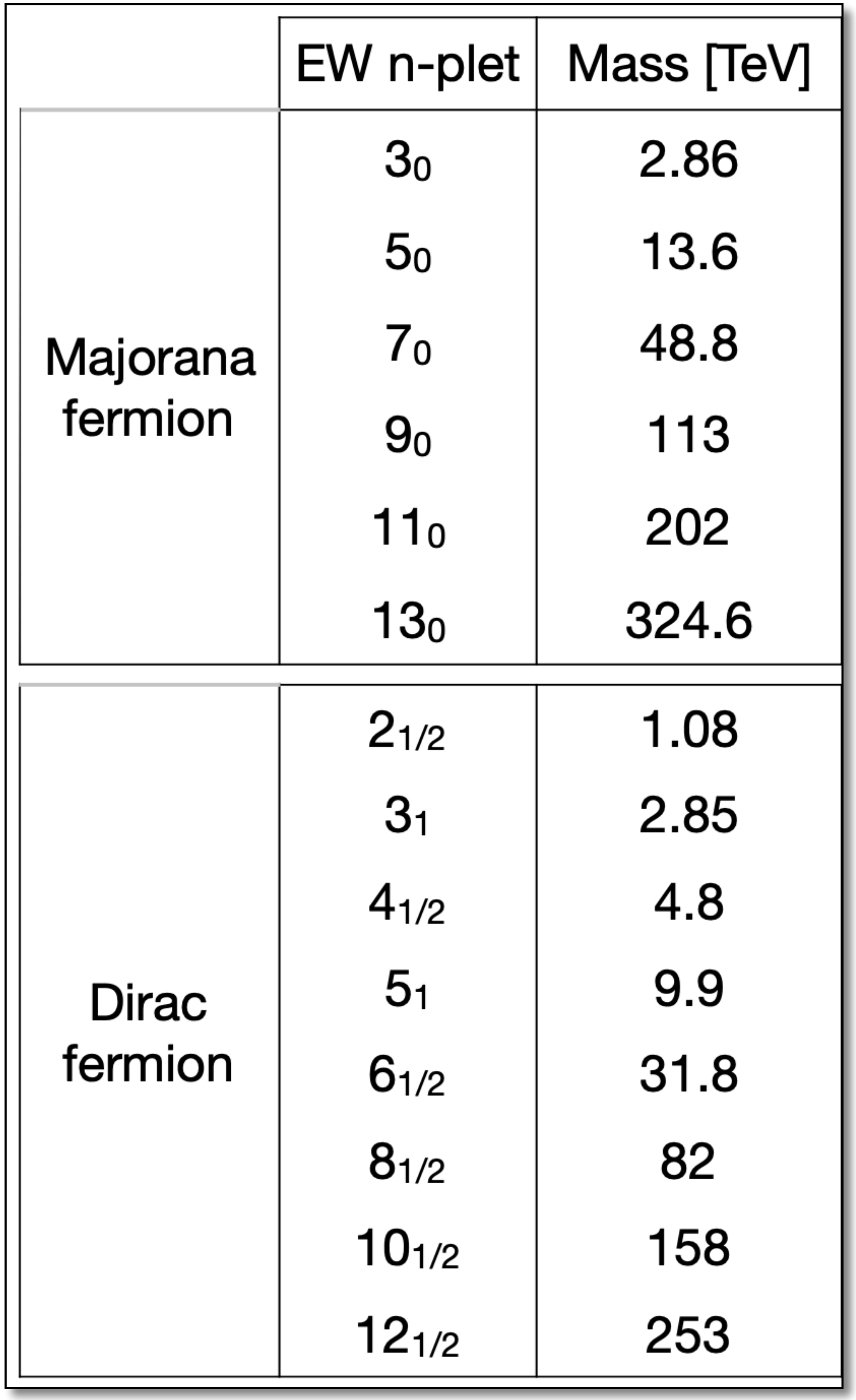

	EW n-plet	Mass [TeV]
Majorana fermion	3_0	2.86
	5_0	13.6
	7_0	48.8
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Dirac fermion	$2_{1/2}$	1.08
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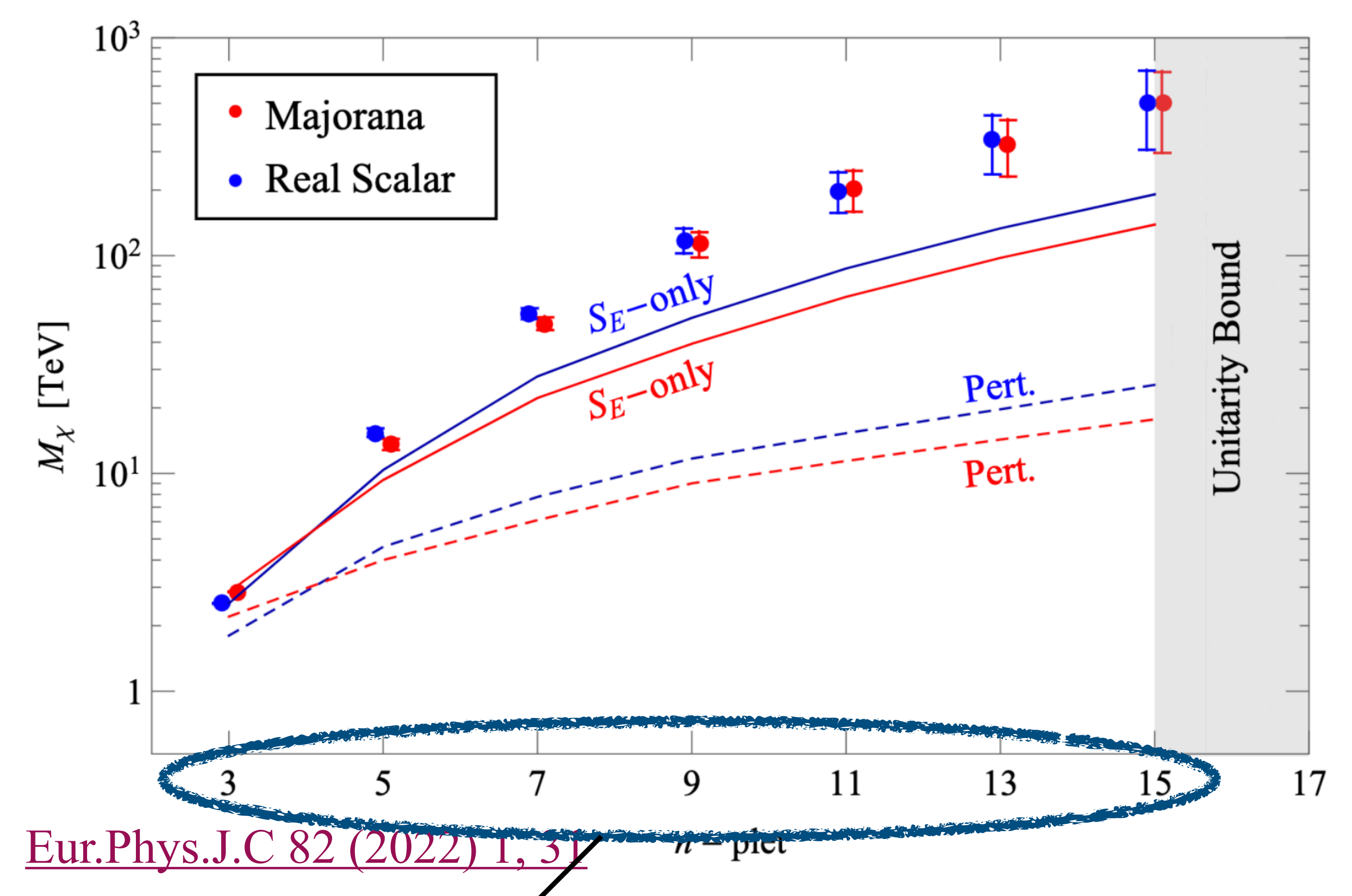
How do we probe these states?

The WIMP thermal masses



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DM Direct & Indirect detection

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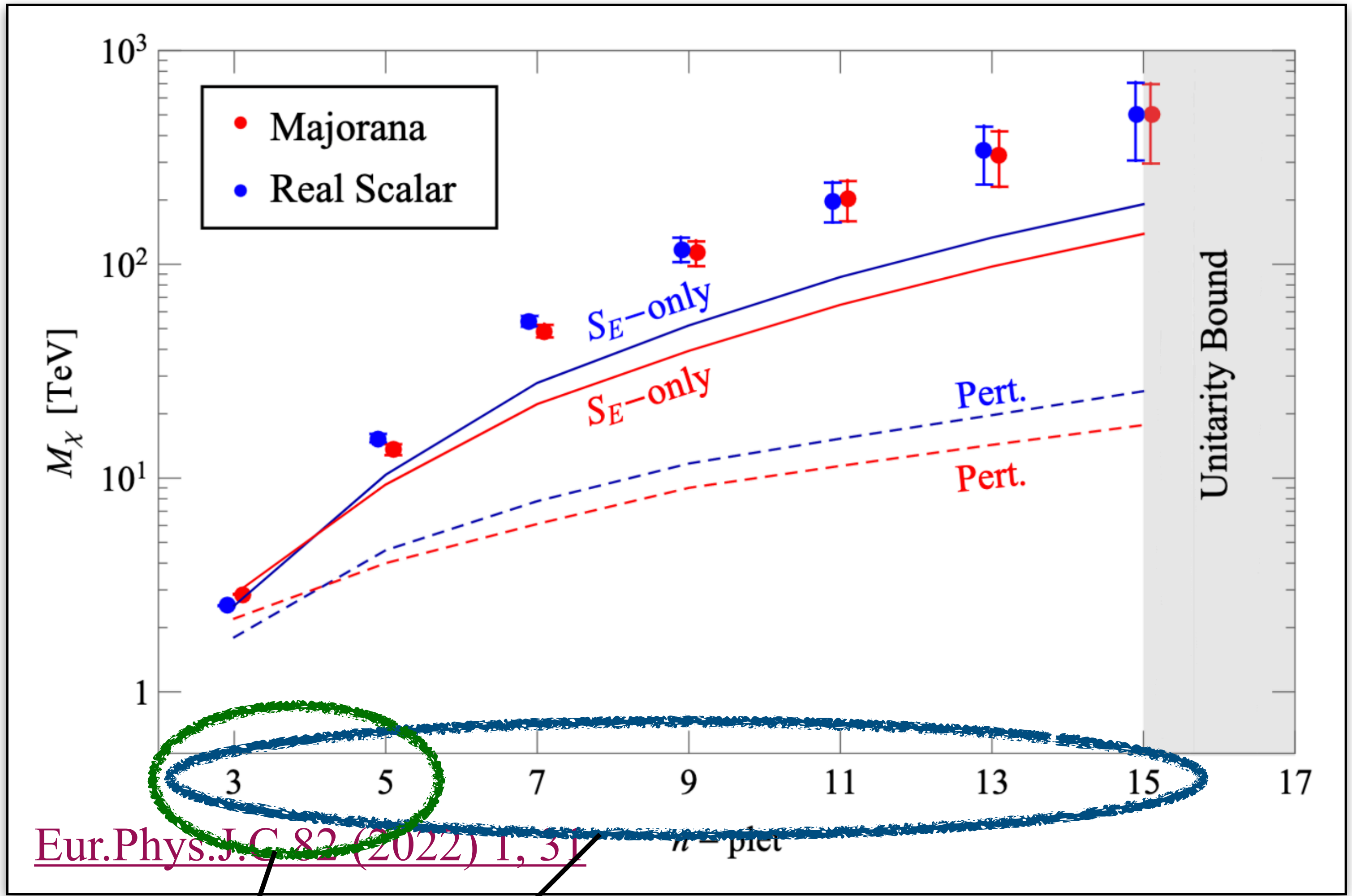

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μCollider?

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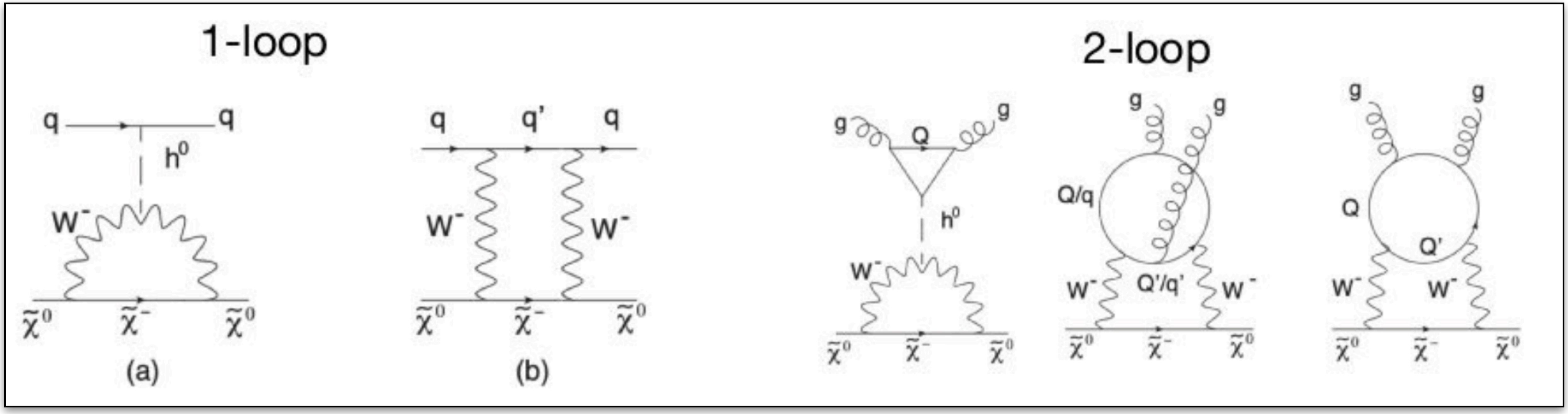
Direct Detection of EW multiplets

For EW multiplets the *Z*-mediated elastic DM-nucleon is forbidden



see e.g. Hisano *et al.* **hep-ph/0407168** and **1104.0228**

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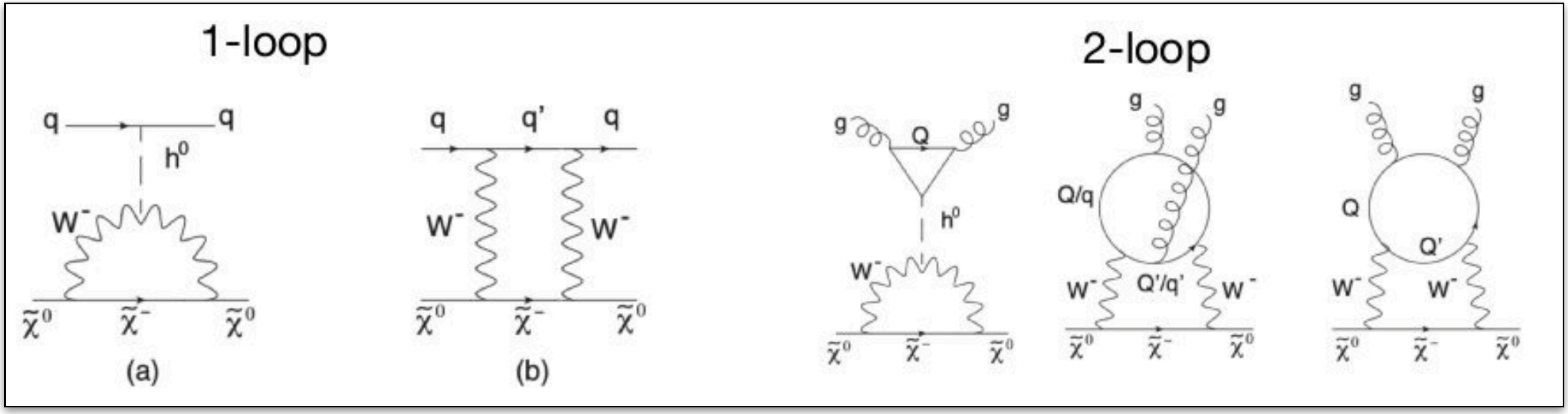

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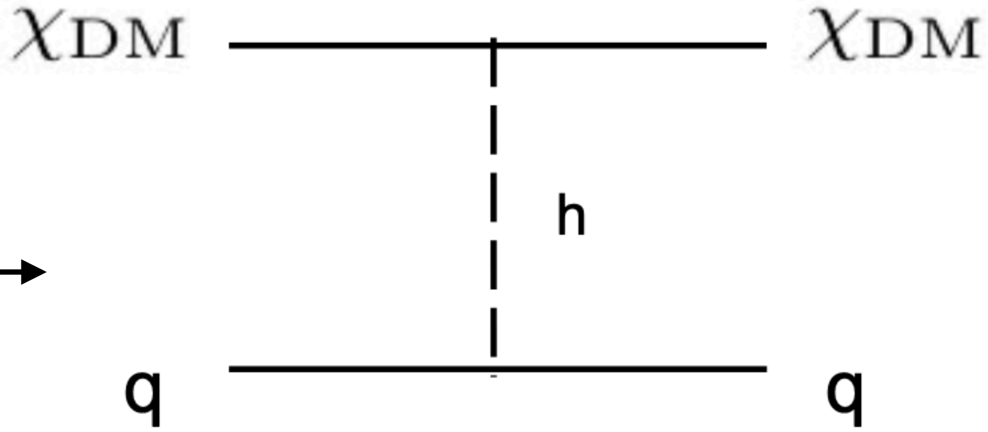
For complex EW multiplets: non minimal higgs portal can arise

Generate tree-level coupling
to the higgs

$$\mathcal{O}_0, \mathcal{O}_+ \longrightarrow$$



IRRELEVANT FOR MINIMAL SPLITTING!!

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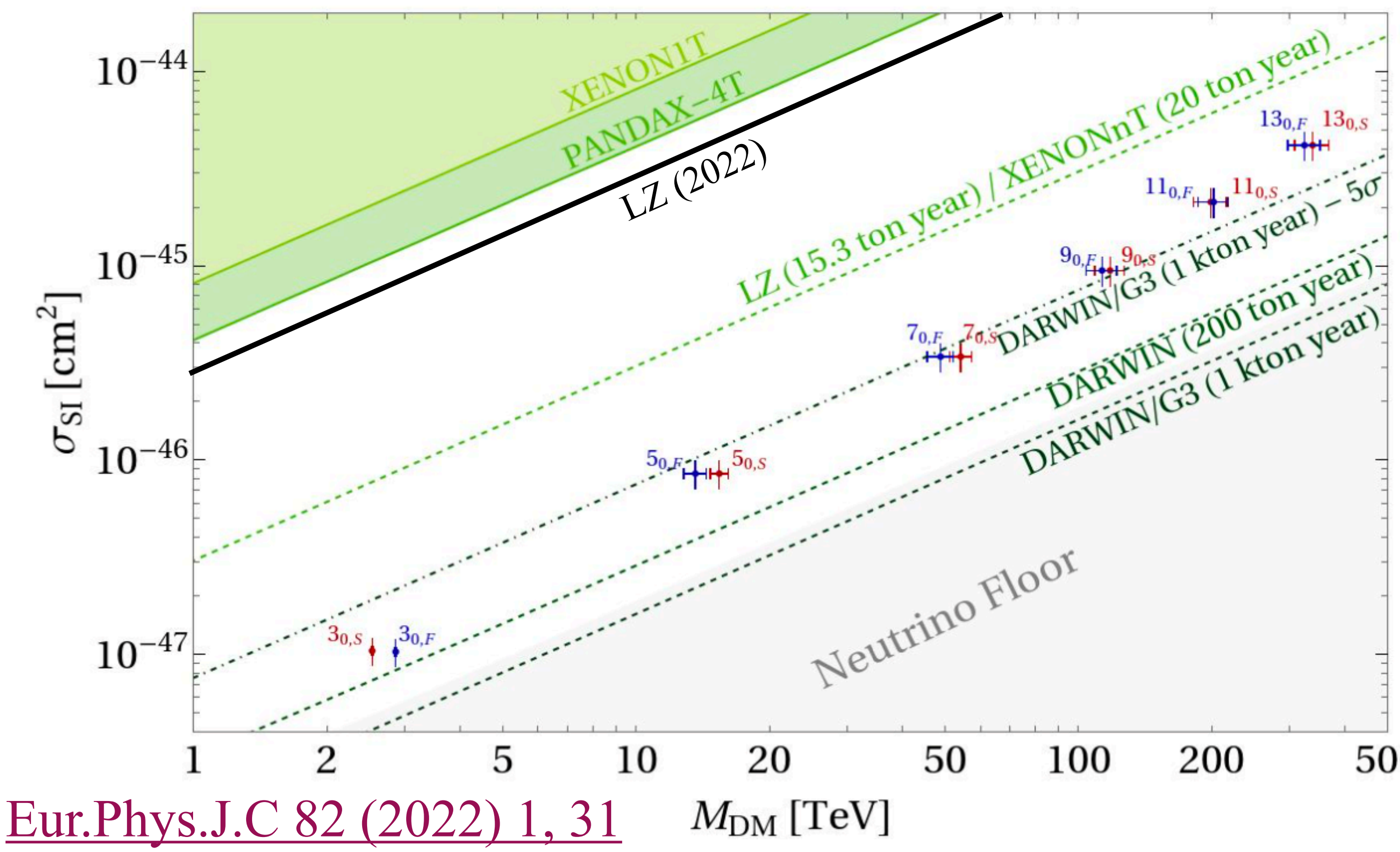

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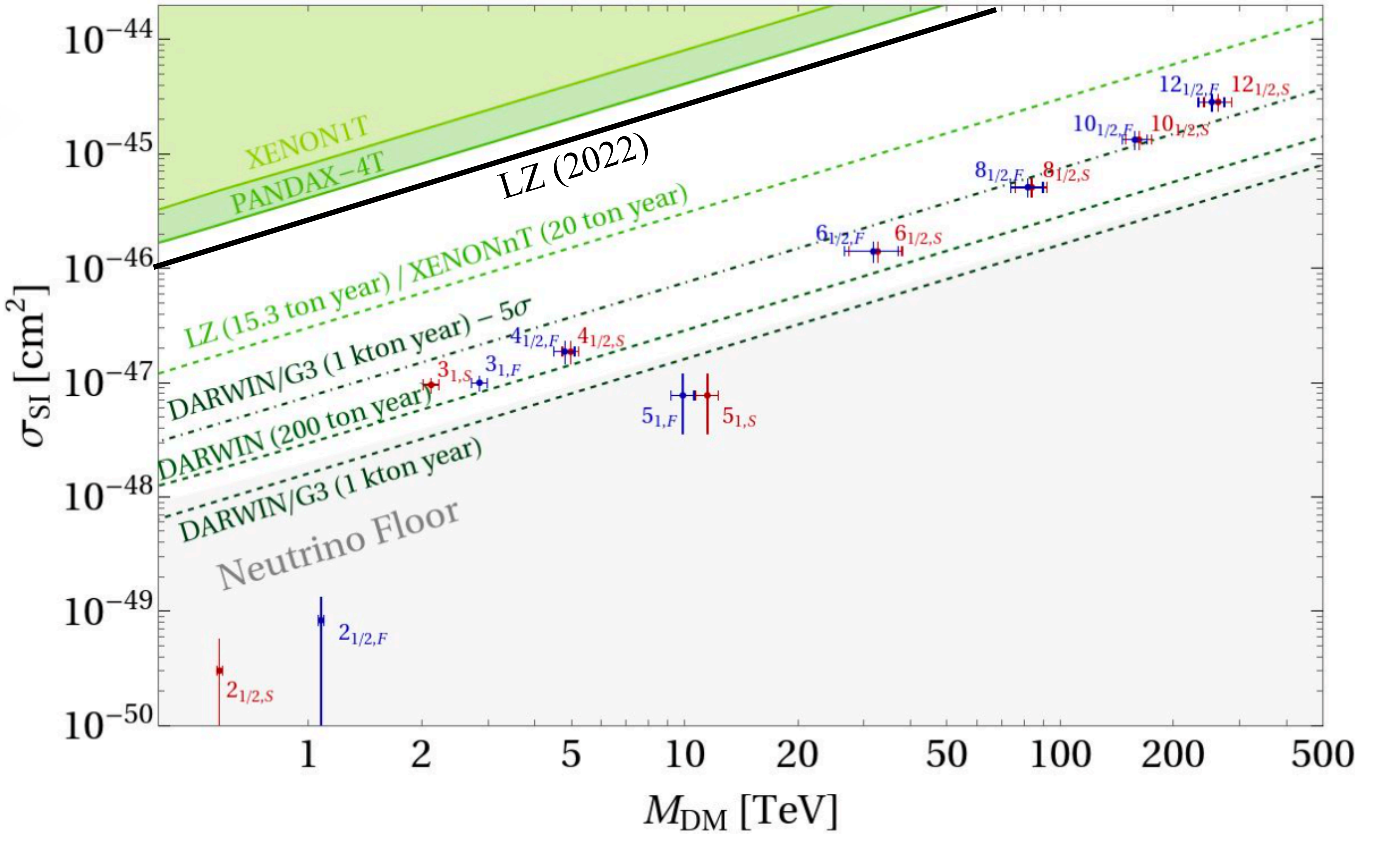
Real Multiplets

All real multiplets are above the neutrino floor

Complex Multiplets - minimal splitting

All complex multiplets are above the neutrino floor
(except doublets and 5-plets)



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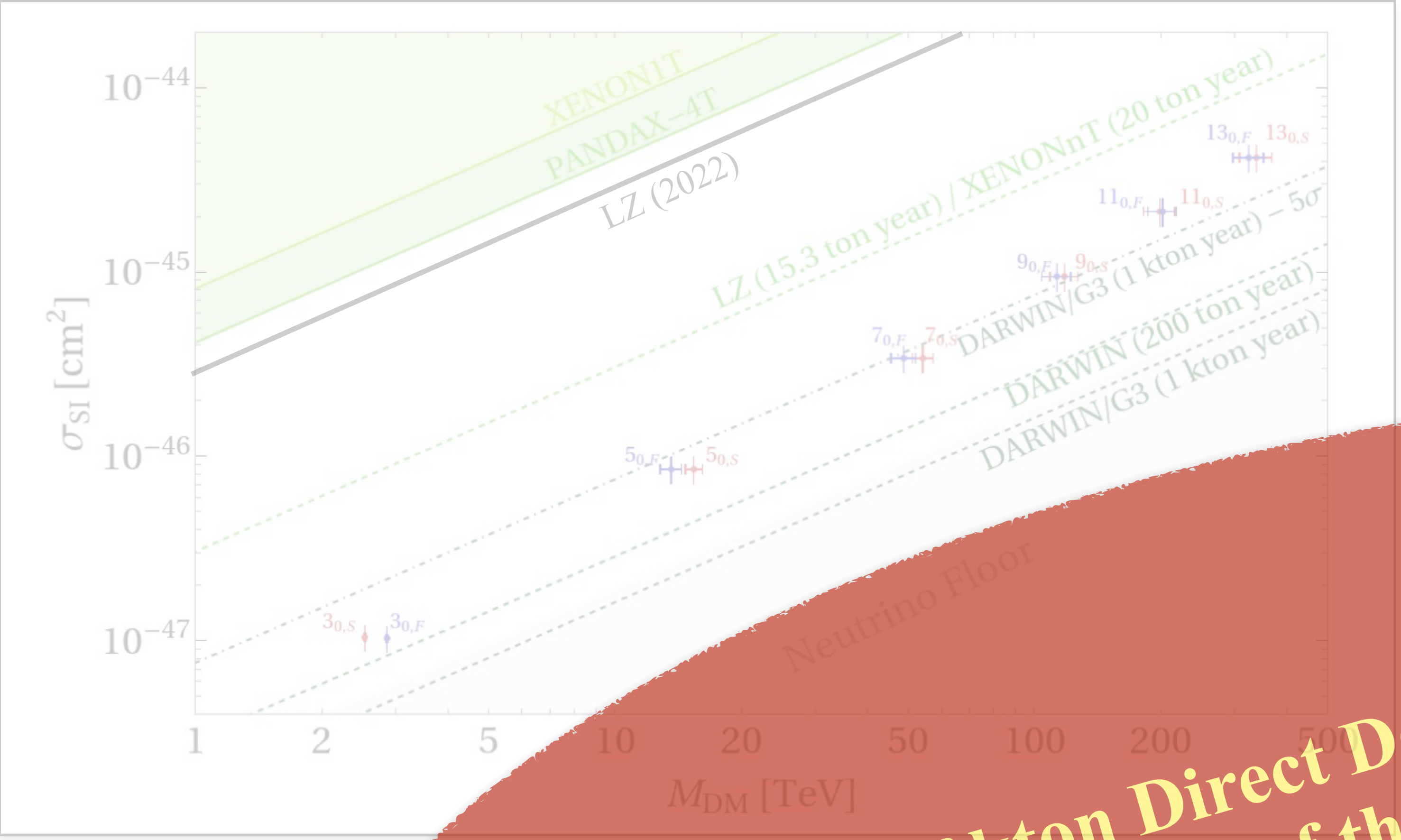

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Next generation of kton Direct Detection experiments can probe almost all of them in 30 years

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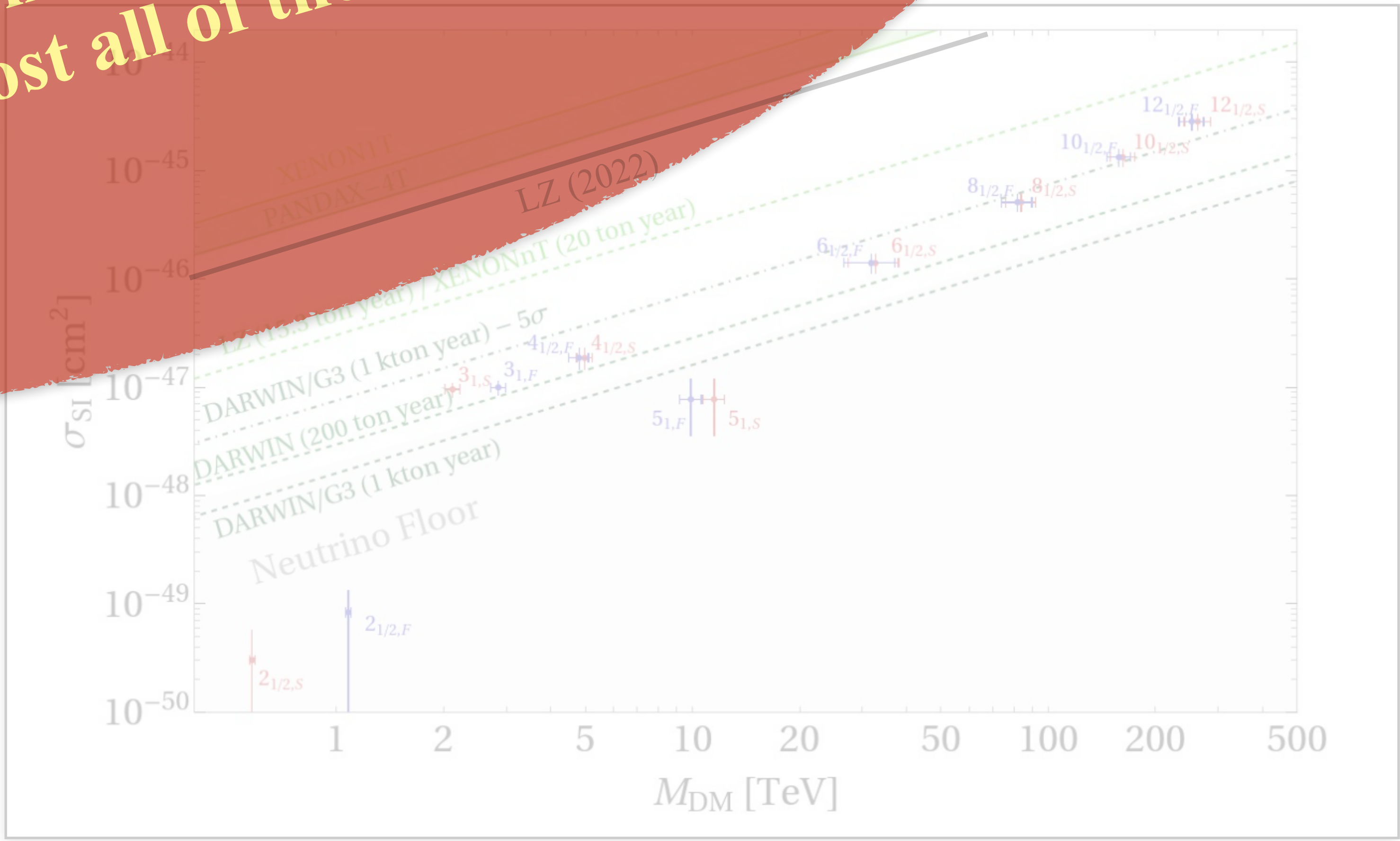

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Non-perturbative effects enhance $\langle \sigma v \rangle$ → all EW bosons in low velocity targets

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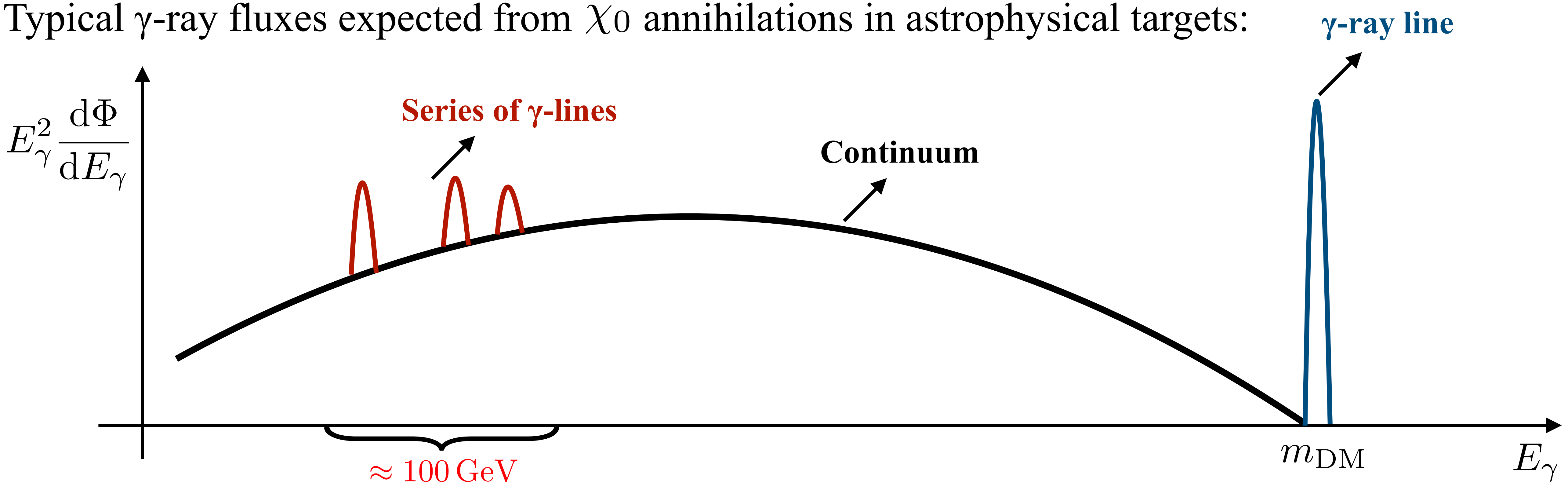
Typical γ-ray fluxes expected from χ_0 annihilations in astrophysical targets:



Continuum: from the decays and hadronization of heavy EW gauge bosons

γ-ray line: The Sommerfeld boost the loop-induced annihilation into γγ and γZ

Series of γ-lines: Due to the formation of WIMPONIUM

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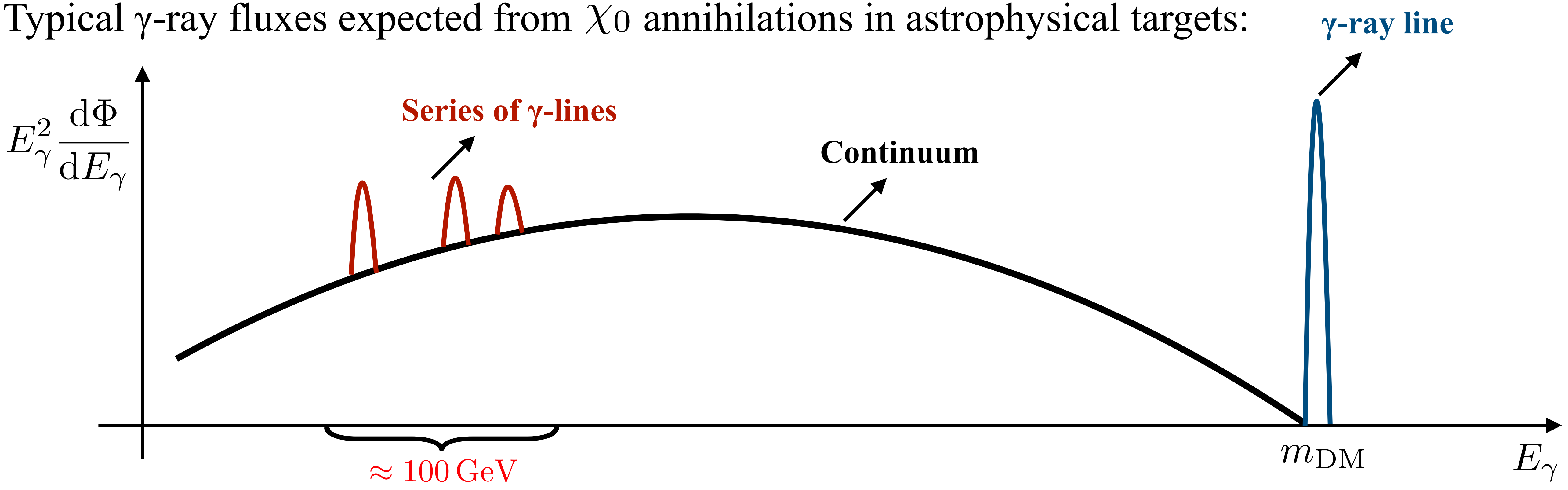

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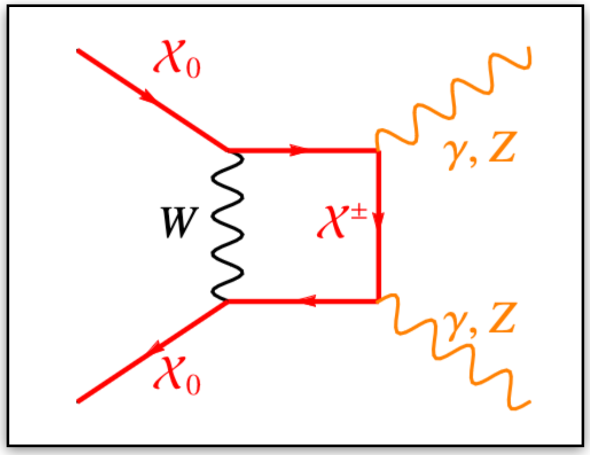
SMOKING GUN: Heavy EW multiplets are like atoms emitting in γ-rays.

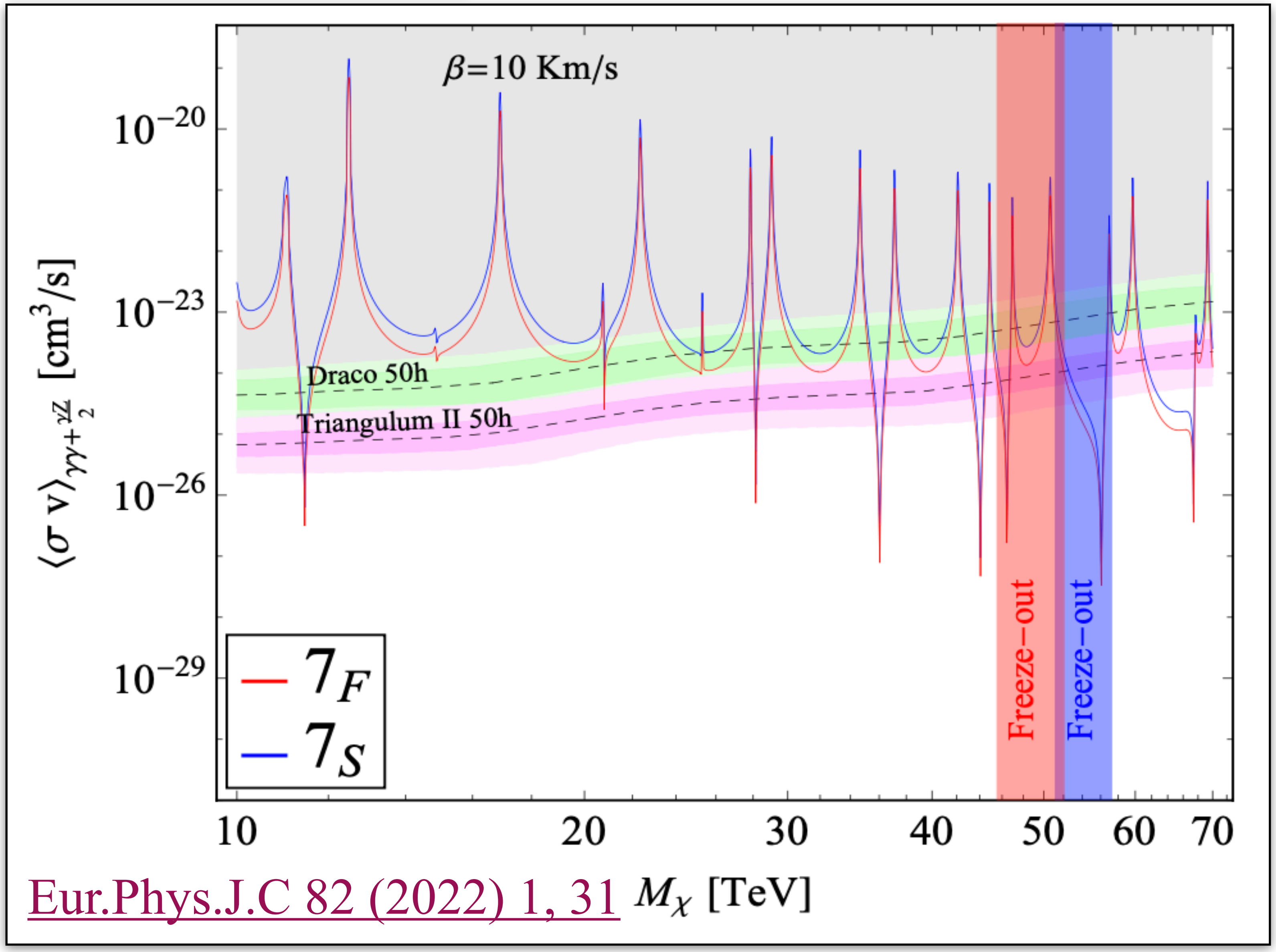
➡ One can look for correlations of multiple-lines!

Indirect Detection of EW multiplets

Loop-induced annihilations into $\gamma\gamma$ and γZ are largely boosted by the Sommerfeld



Look for γ-ray lines with CTA towards clean environments



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To be included:

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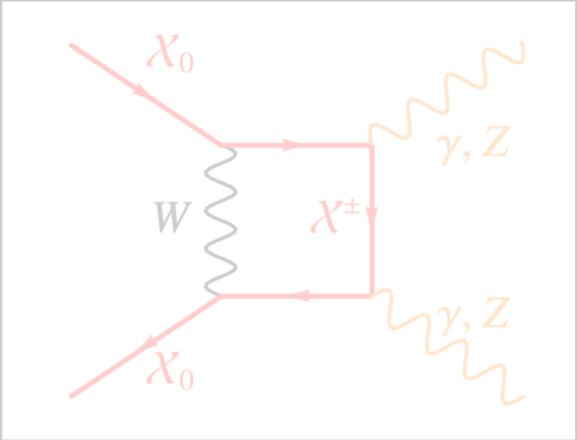

Look for γ-ray lines with CTA towards clean environments

Next generation of Cherenkov telescope can easily probe large multiplets due to increased annihilation cross sections

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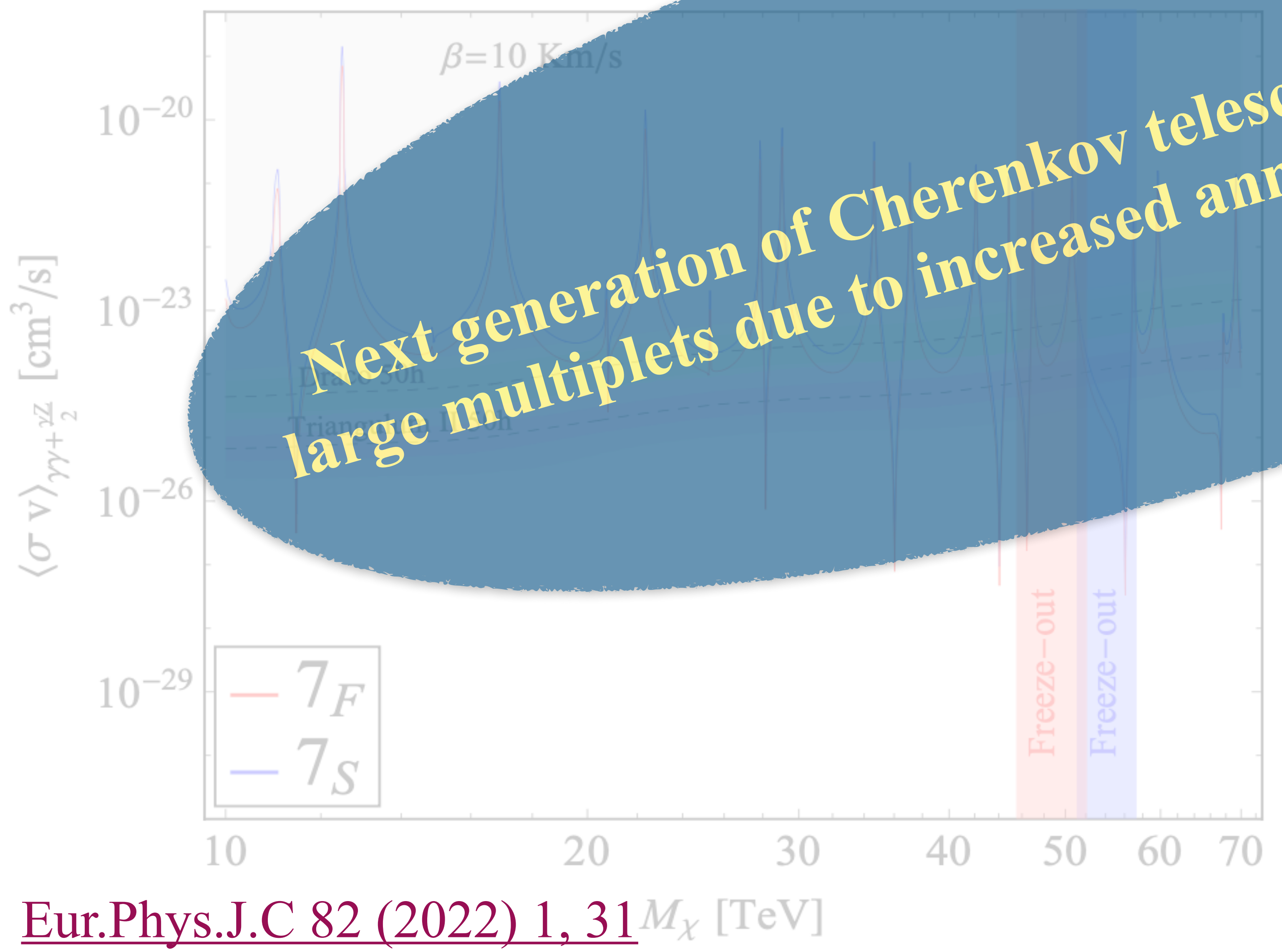

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Production @ Colliders

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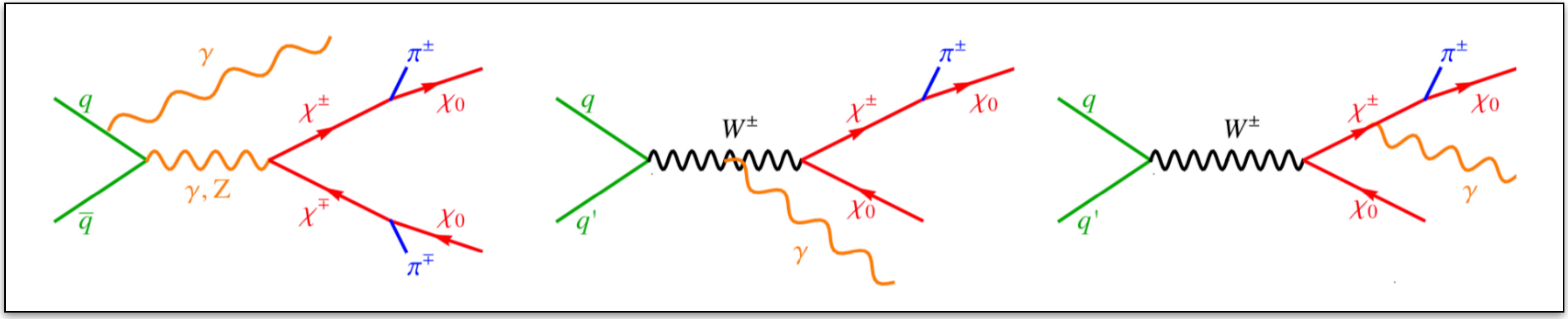
$2 \rightarrow 2$ production of invisible χ_0 pair + event tag, e.g. mono-γ



Very difficult at hadron colliders: large background, strong PDF suppression at high partonic c.o.m energies (large invariant mass)

- ✦ LHC sensitive to DM masses $\sim \mathcal{O}(200\,\mathrm{GeV})$
- ✦ Even at 100 TeV can't reach thermal freeze-out targets

See *e.g.* Sala *et al.* 1407.7058

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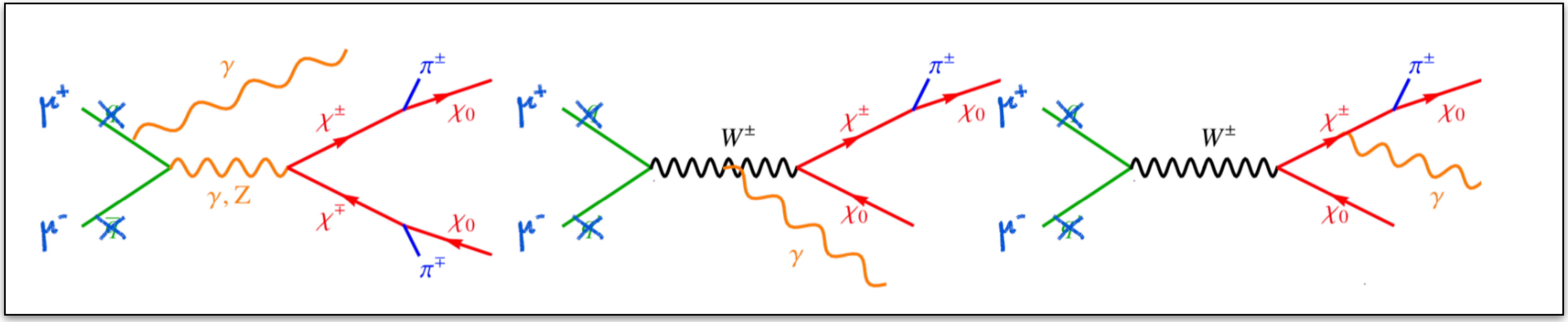

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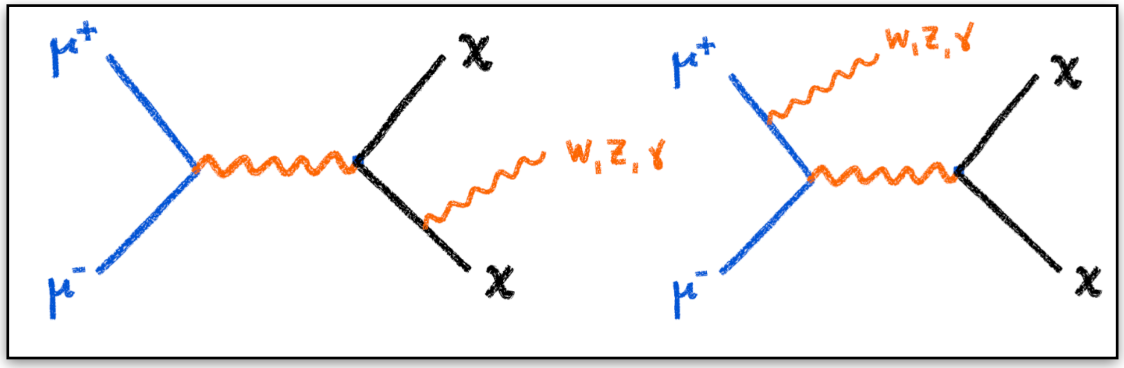
➡ **Try with a high-energy lepton collider**

μUON COLLIDER

Missing mass searches @ μCollider

Drell-Yan production of invisible χ_0 pair + event tag



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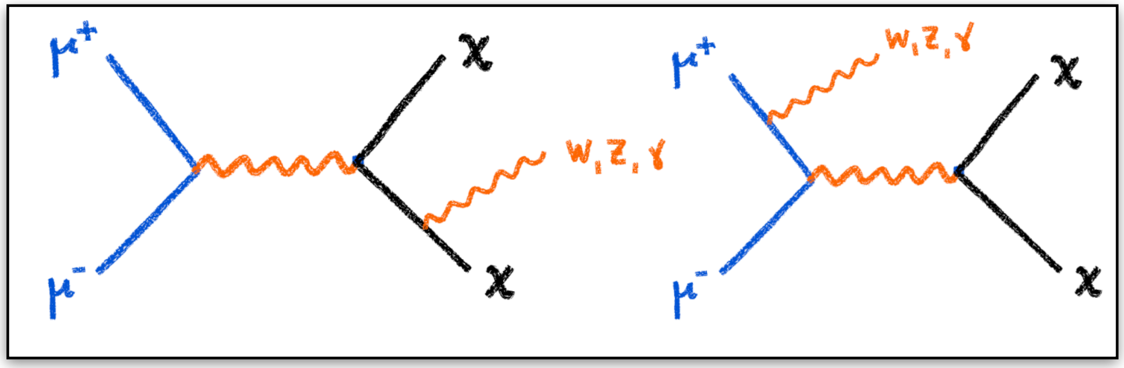

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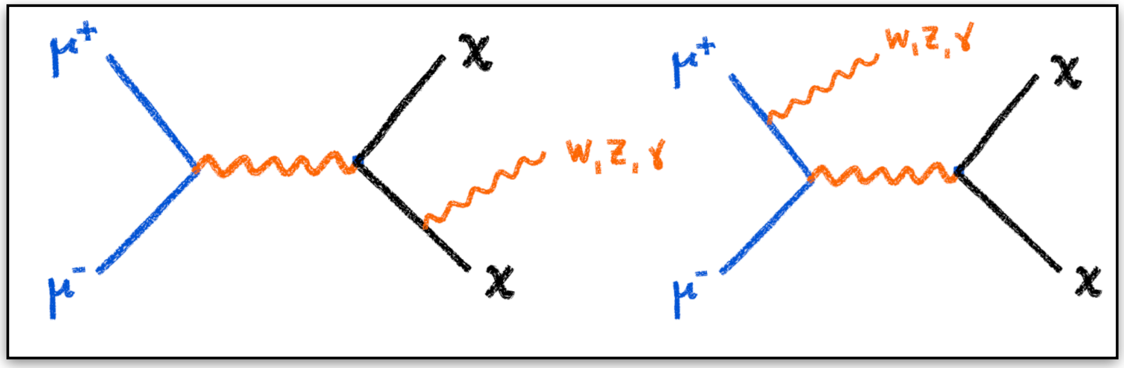

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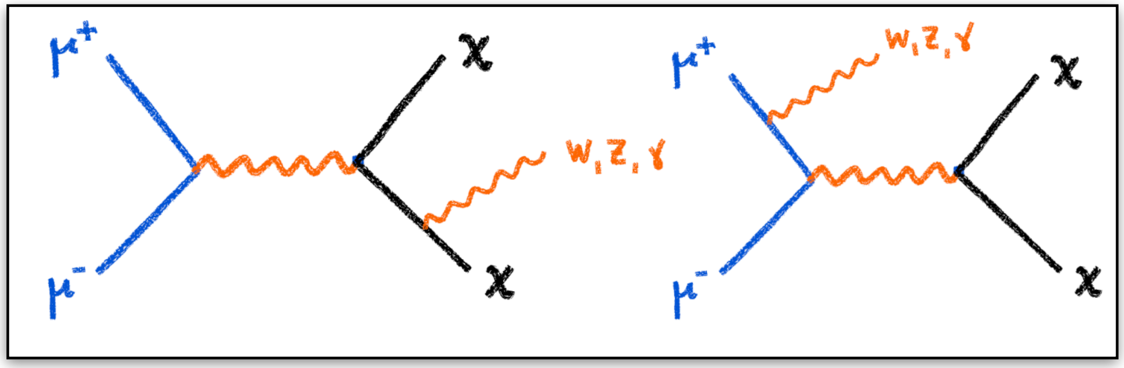

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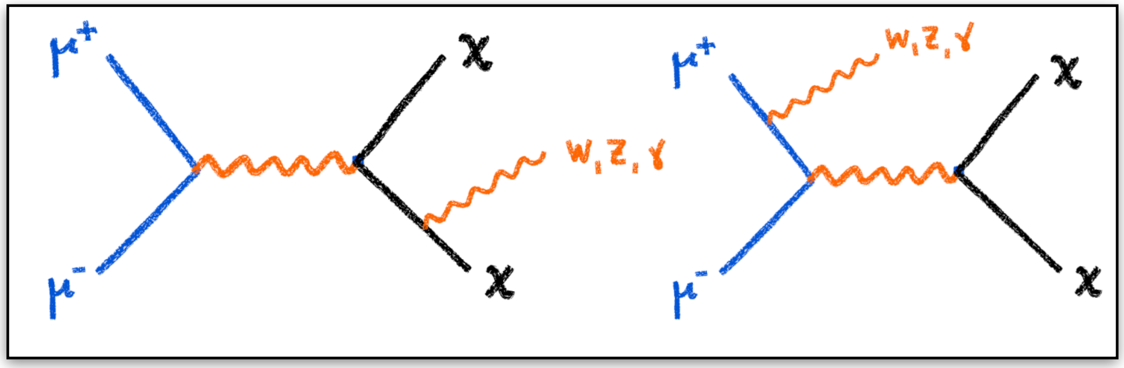

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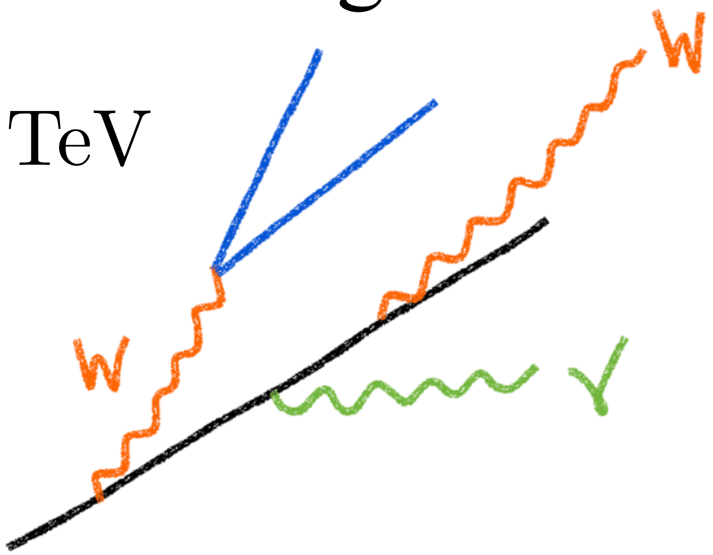
✳ **EW radiation** becomes important at multi-TeV energies!

Sudakov factor: $\frac{\alpha}{4\pi}\log^2(E/m_W) \approx 1 \;\text{ for }\; E \sim 10\,\text{TeV}$

➡ mono-γ, mono-*Z*, mono-*W*, are similar!

➡ multiple gauge bosons emission



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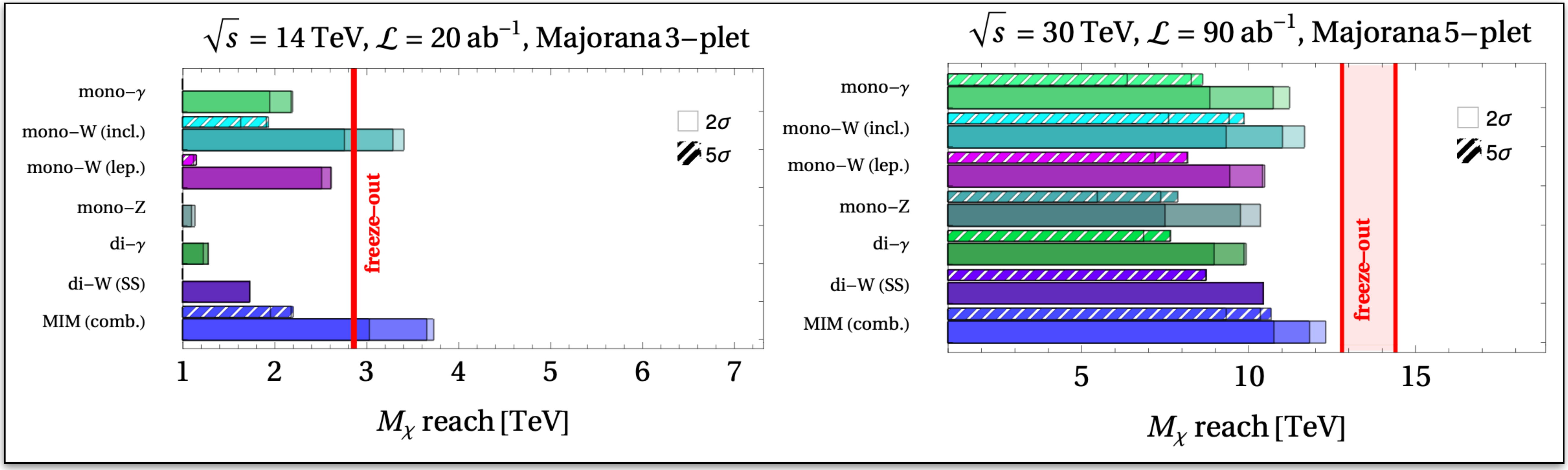

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typically low S/B → requires good control of systematics

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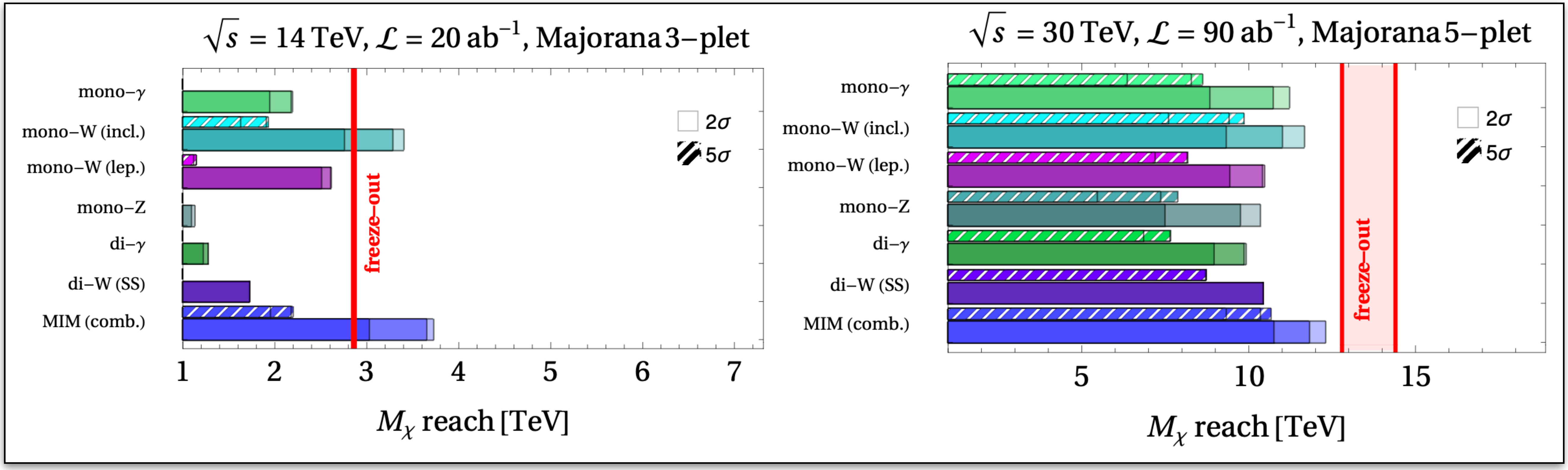

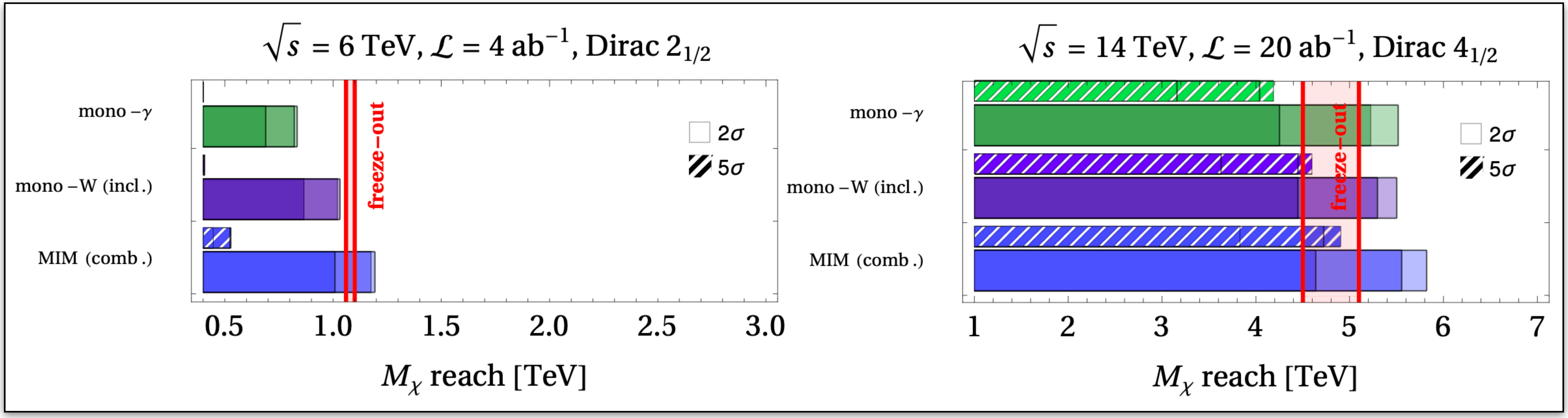

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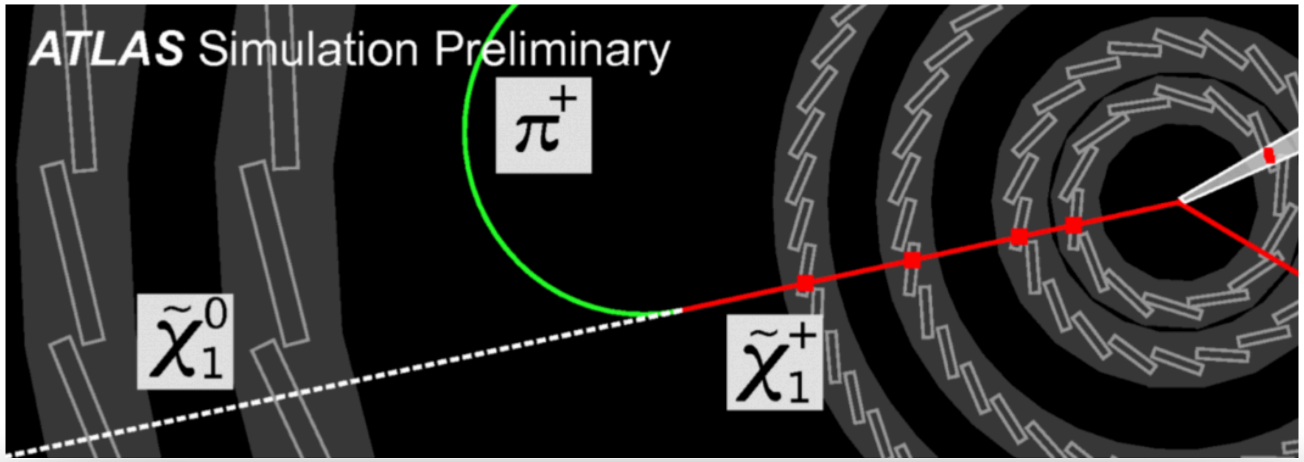
Mass splitting and DTs

Mass splitting and DTs

- ✳ DM is part of a multiplet that also includes charge states $(..., \chi^+, \chi_0, \chi^-, ...)$ $\chi^\pm$ **decays into DM inside the detector**

- ✳ Look for disappearing tracks of the charged particles to isolate the DM signals from the SM background (mainly neutrinos)



Recast of Capdevila *et al.* 2101.10334

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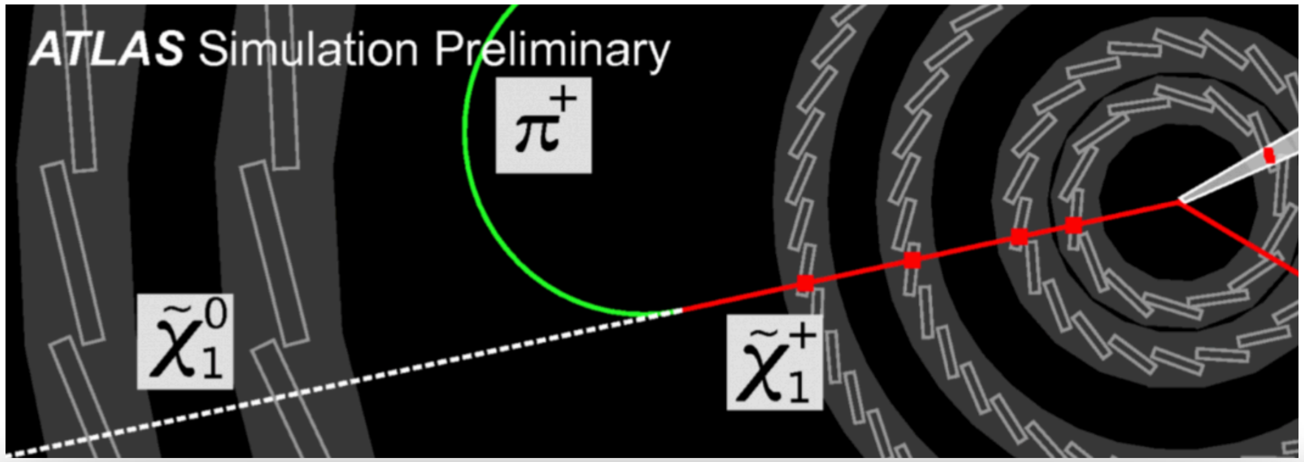

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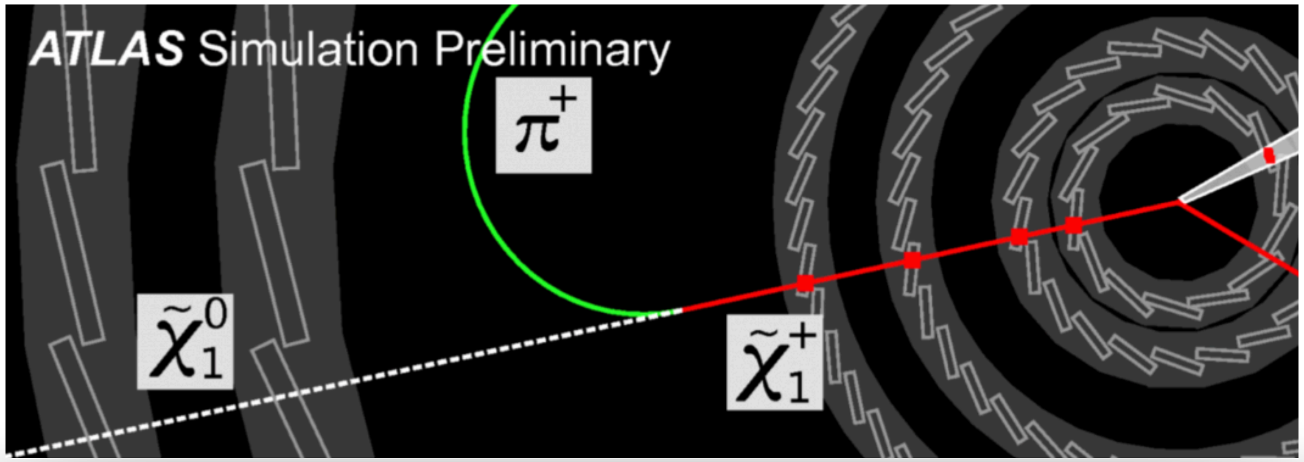

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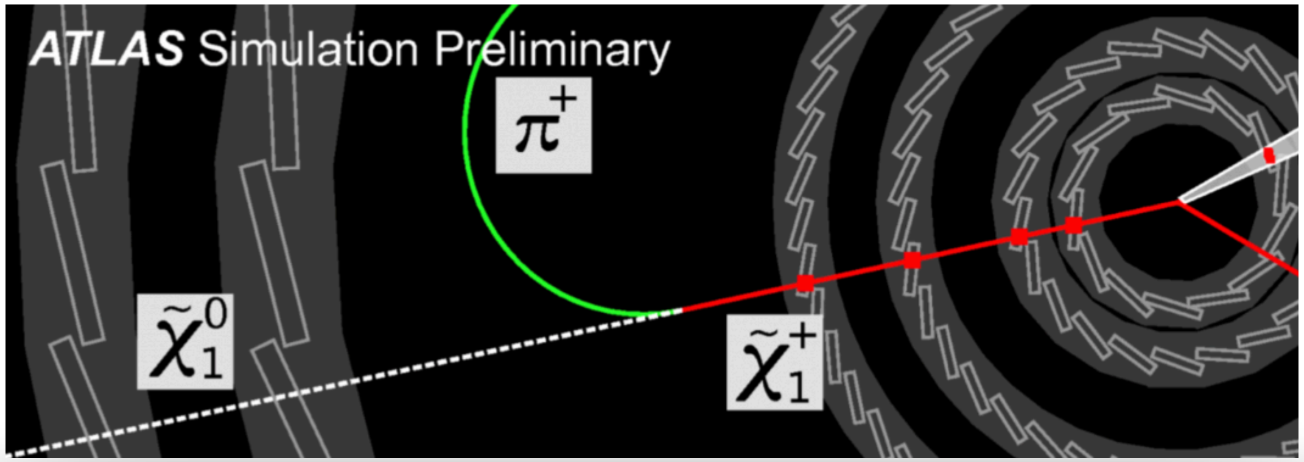

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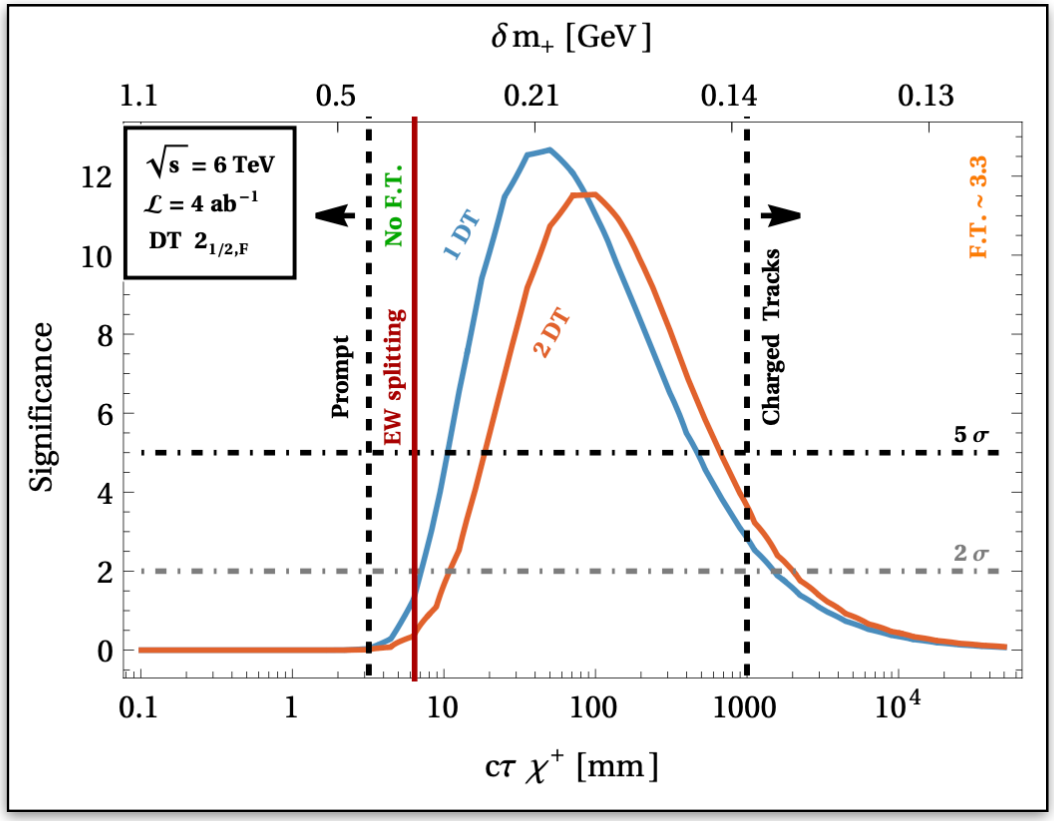

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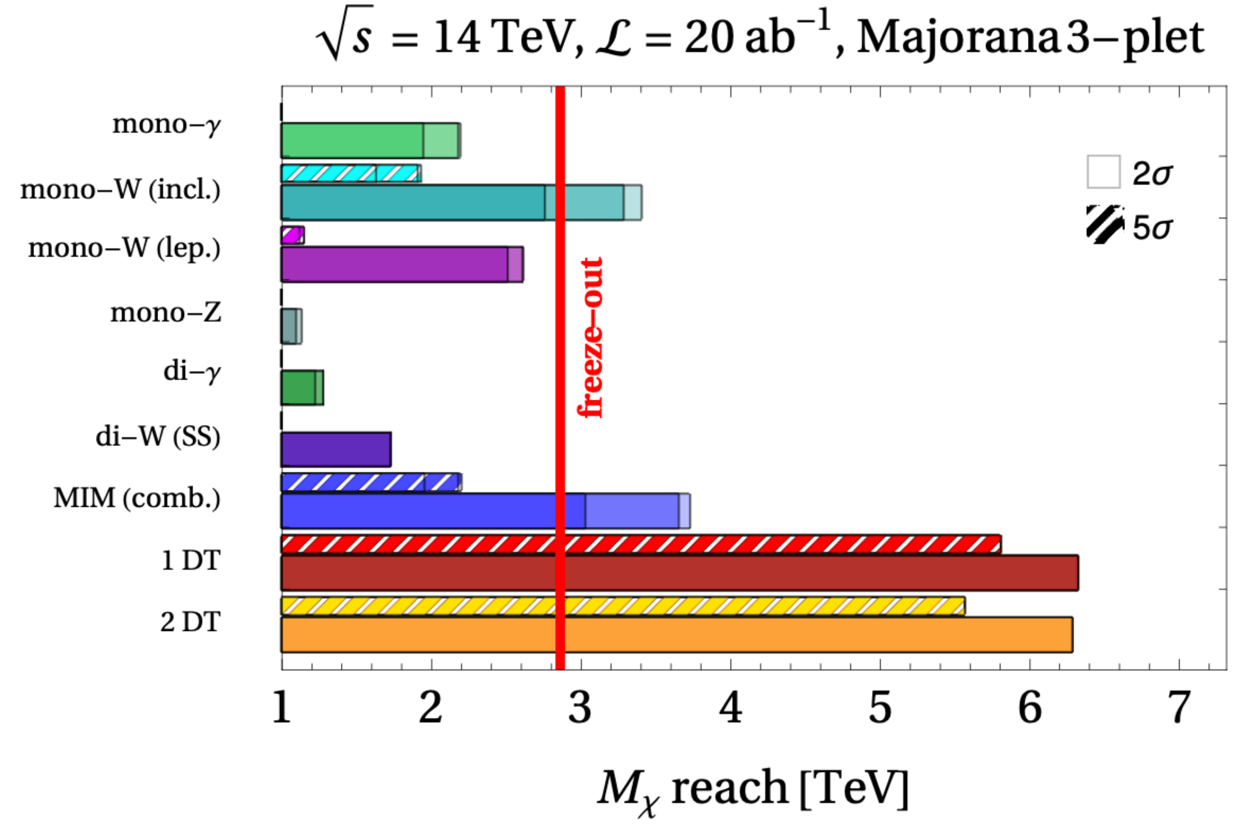
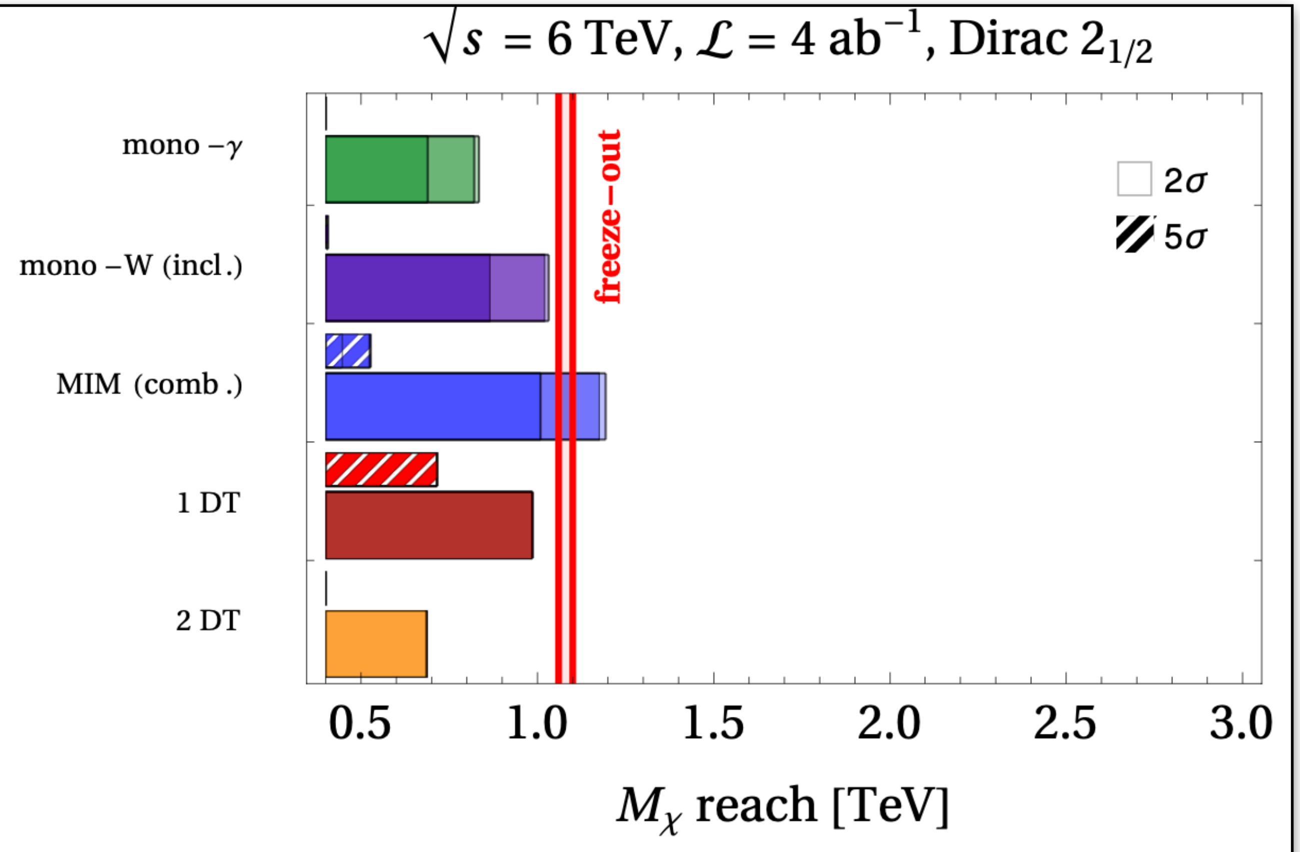
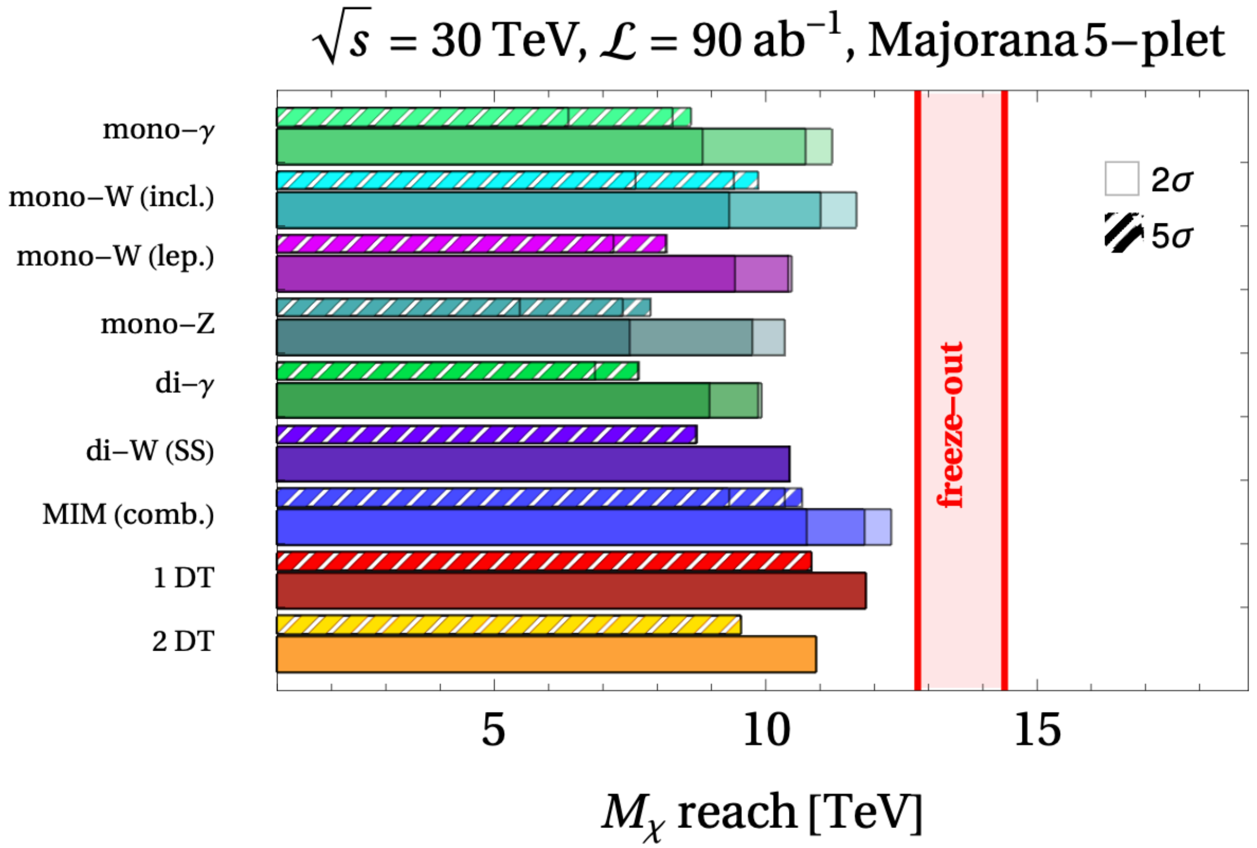
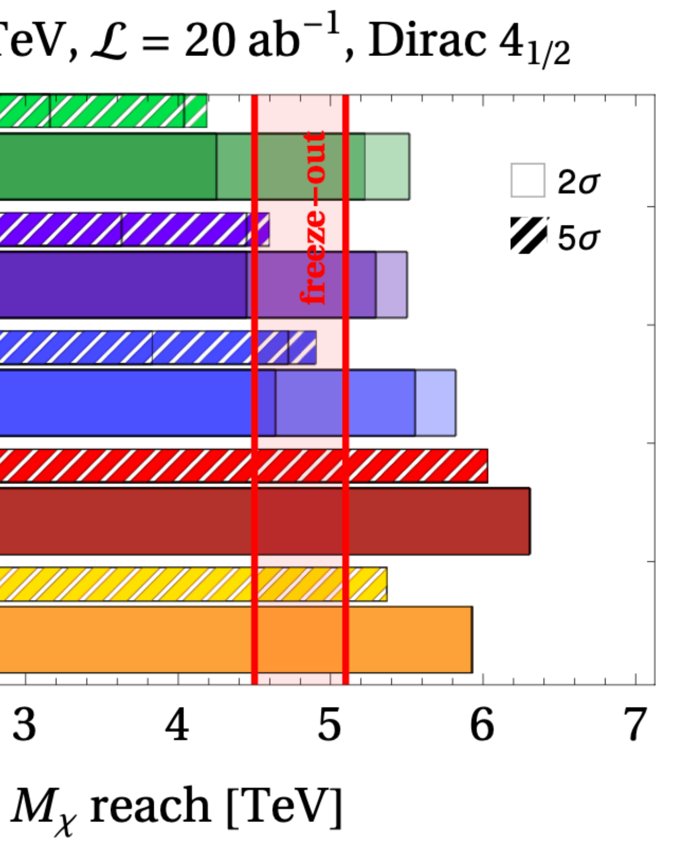
Disappearing tracks @ μCollider



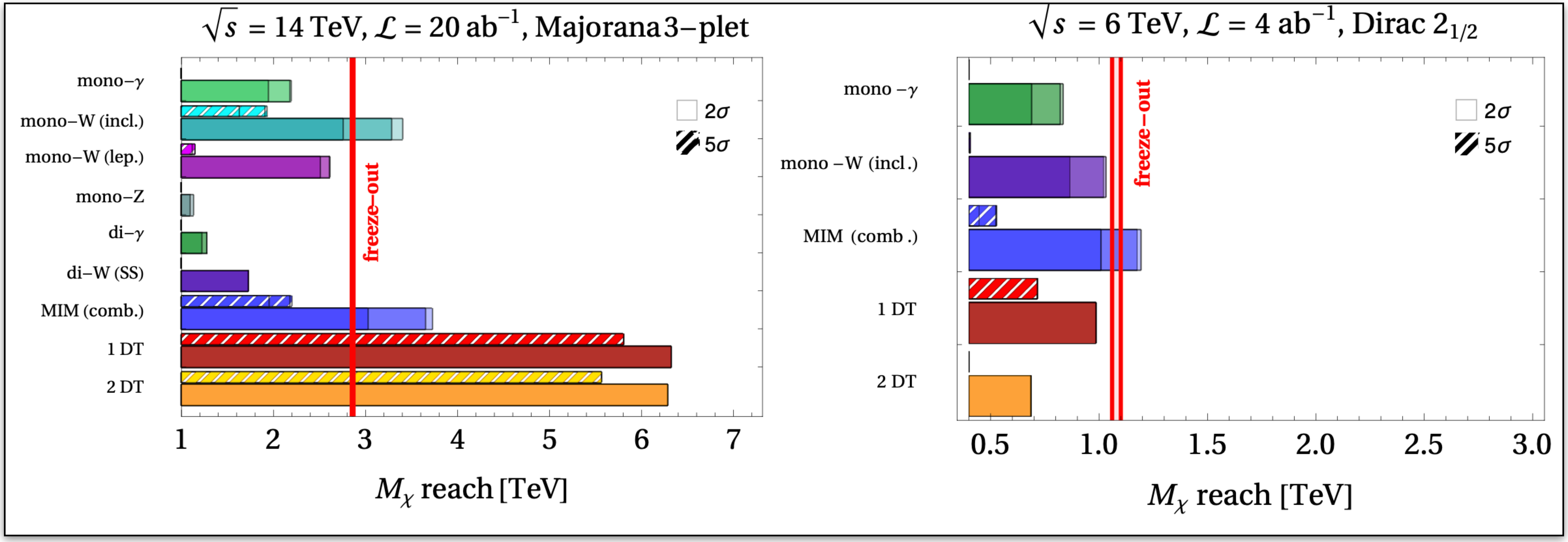


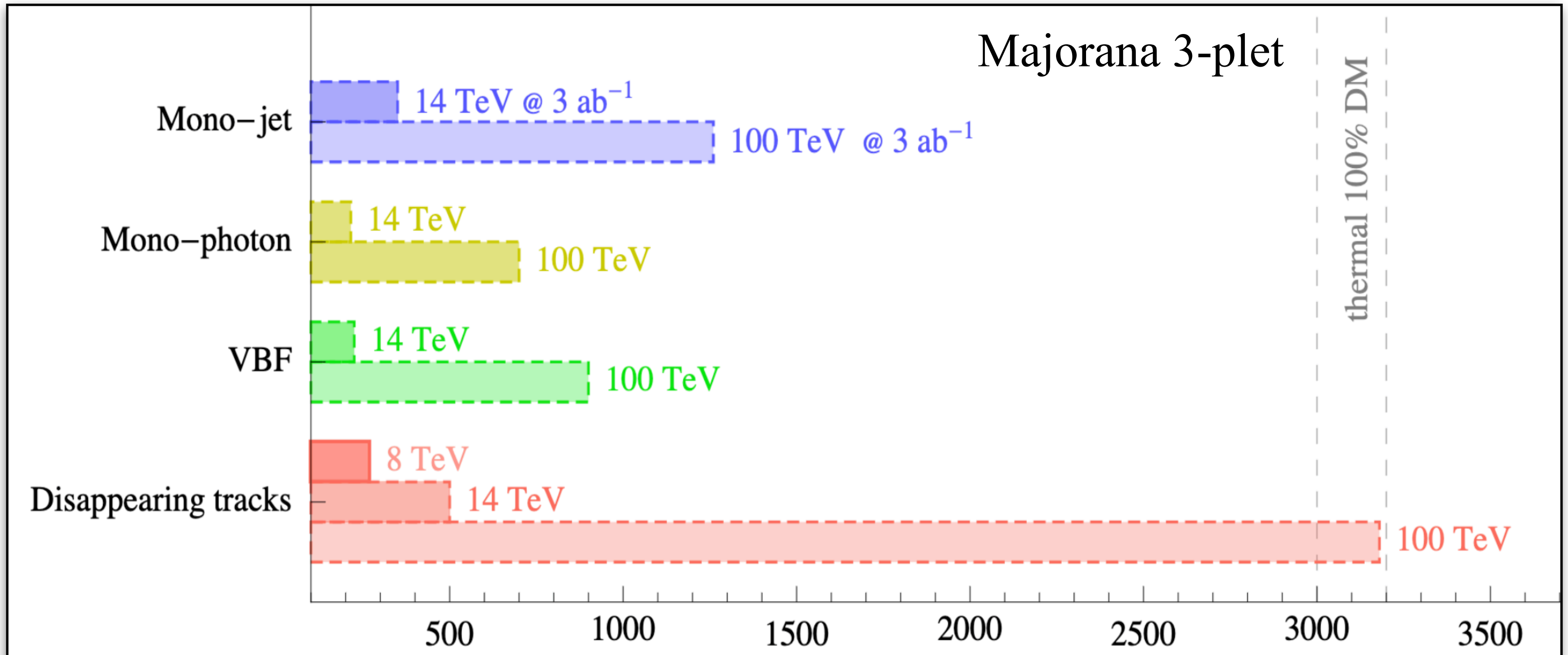




Minimal splitting

Disappearing tracks @ Colliders





Sala *et al.* 1407.7058

*Disappearing tracks allow
to probe the Wino also at FCC-hh

Conclusions

We review the phenomenology of EW multiples which are the **prototype of WIMP DM**

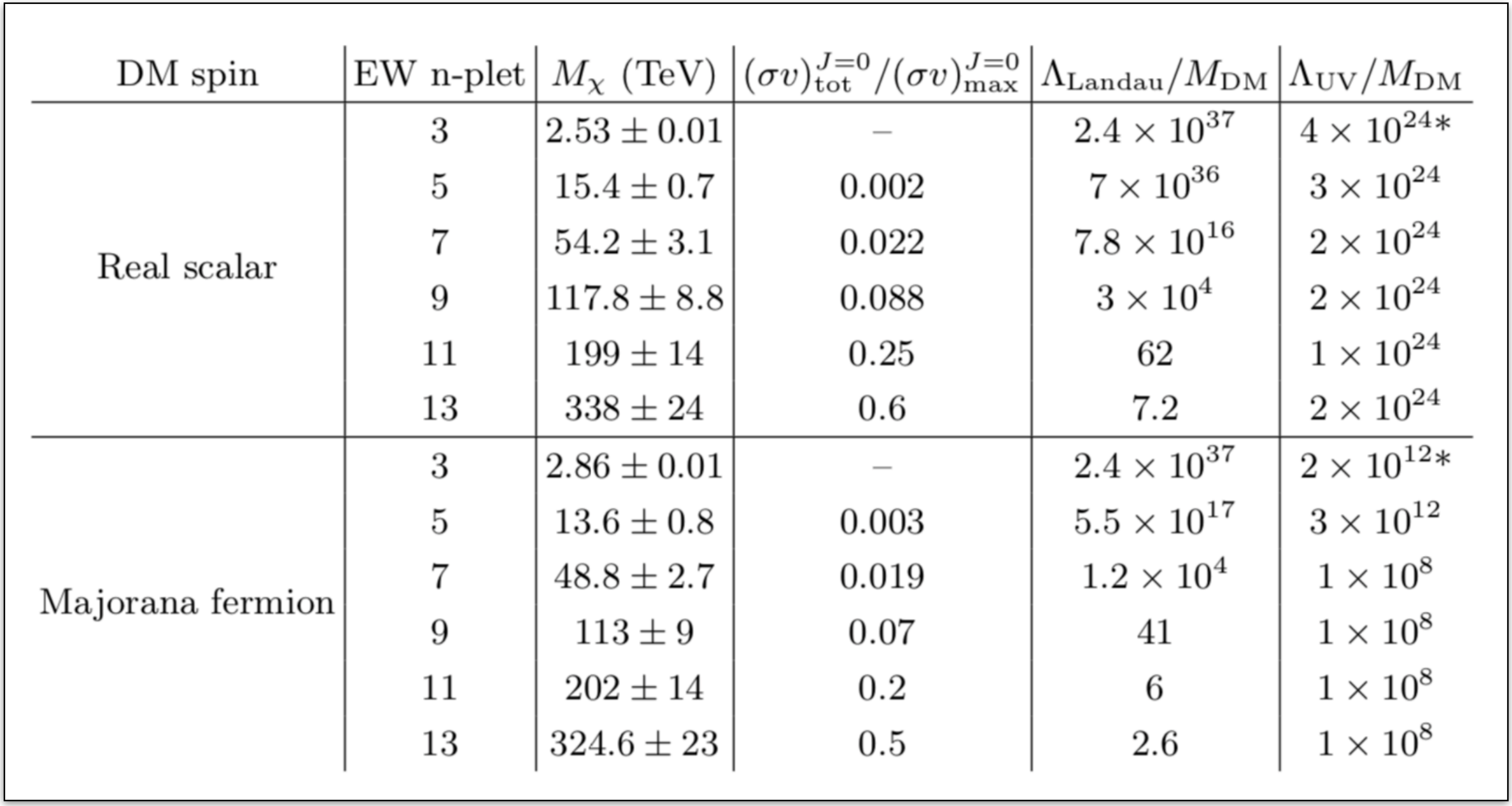
Thermal freeze-out points to multi-TeV mass scales. **Not probed yet!**

We envisage a plan to say a final word on WIMP DM in the upcoming 30 years

- Indirect detection: can test large EW multiplets due to the enhanced annihilation cross sections in low velocity environments
- kTon Direct detection exp.: can probe basically all the candidates except the complex doublet and 5plet
- 14 TeV μCollider: is needed to probe small multiplets like the supersymmetric higgsino and the Wino

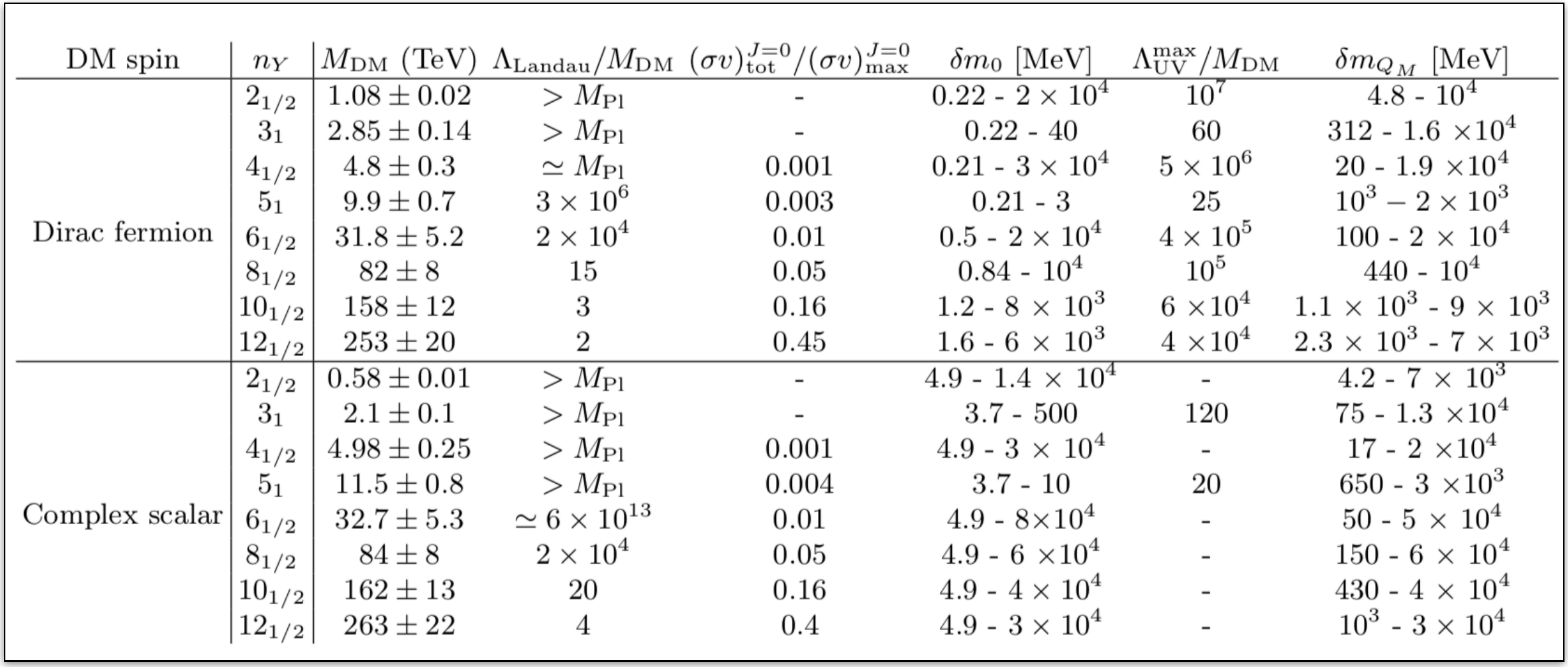
BACKUP

Results: Real WIMPs



DM spin	EW n-plet	M_χ (TeV)	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	$\Lambda_{\rm Landau}/M_{\rm DM}$	$\Lambda_{\rm UV}/M_{\rm DM}$
Real scalar	3	2.53 ± 0.01	–	2.4×10^{37}	$4 \times 10^{24}*$
	5	15.4 ± 0.7	0.002	7×10^{36}	3×10^{24}
	7	54.2 ± 3.1	0.022	7.8×10^{16}	2×10^{24}
	9	117.8 ± 8.8	0.088	3×10^{4}	2×10^{24}
	11	199 ± 14	0.25	62	1×10^{24}
	13	338 ± 24	0.6	7.2	2×10^{24}
Majorana fermion	3	2.86 ± 0.01	–	2.4×10^{37}	$2 \times 10^{12}*$
	5	13.6 ± 0.8	0.003	5.5×10^{17}	3×10^{12}
	7	48.8 ± 2.7	0.019	1.2×10^{4}	1×10^{8}
	9	113 ± 9	0.07	41	1×10^{8}
	11	202 ± 14	0.2	6	1×10^{8}
	13	324.6 ± 23	0.5	2.6	1×10^{8}

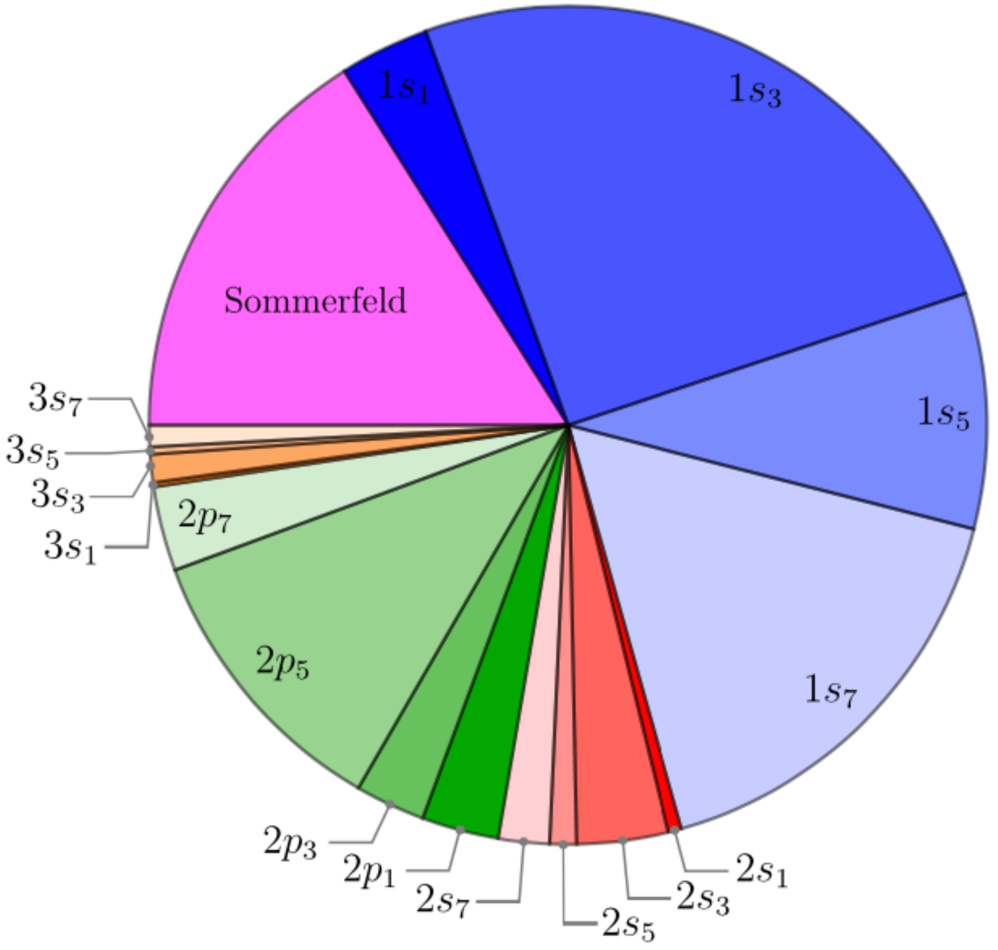
Results: Complex WIMPs

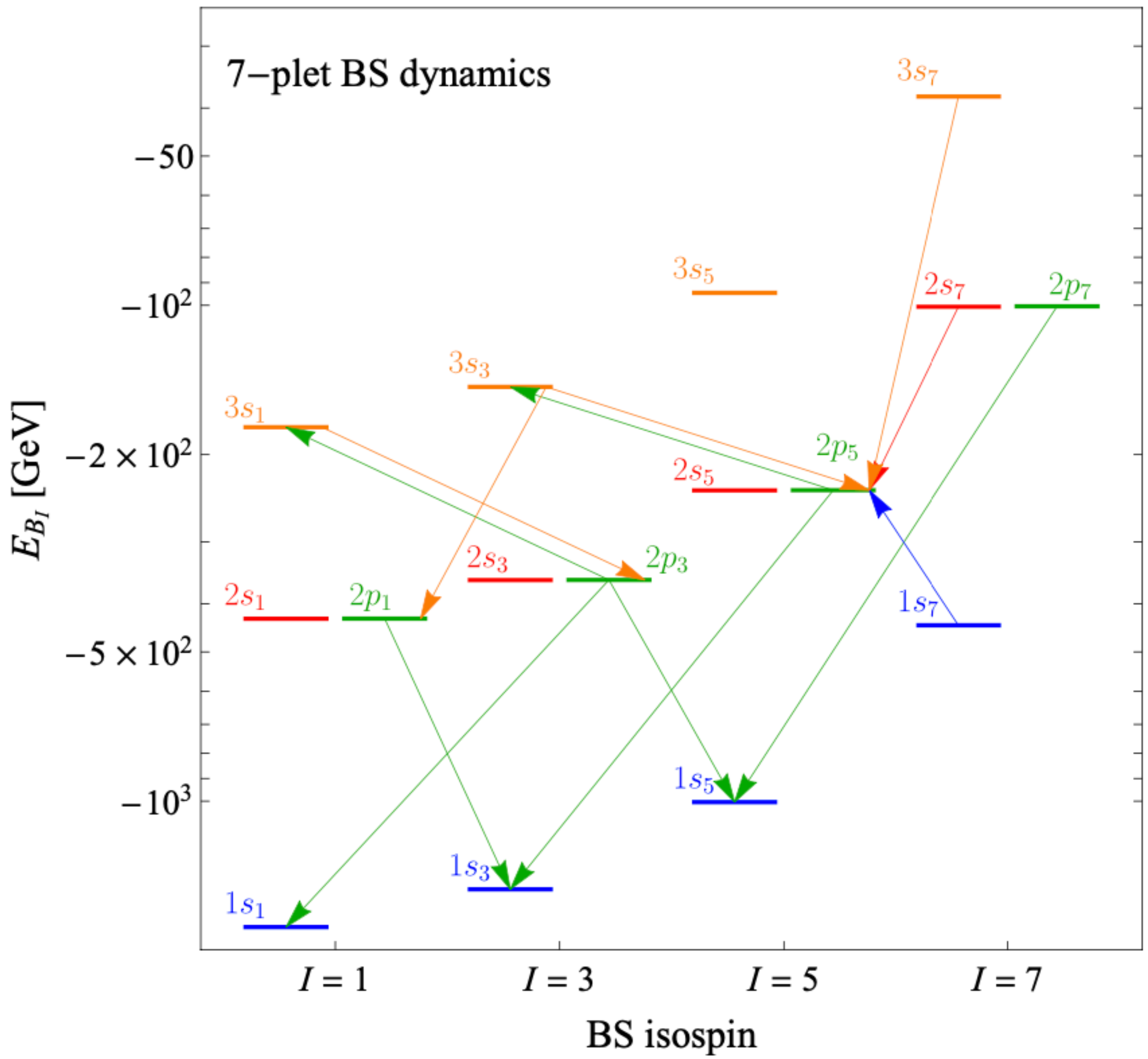


DM spin	n_Y	$M_{\rm DM}$ (TeV)	$\Lambda_{\rm Landau}/M_{\rm DM}$	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	δm_0 [MeV]	$\Lambda^{\rm max}_{\rm UV}/M_{\rm DM}$	δm_{Q_M} [MeV]
Dirac fermion	$2_{1/2}$	1.08 ± 0.02	$> M_{\rm Pl}$	-	0.22 - 2×10^4	10^7	4.8 - 10^4
	3_1	2.85 ± 0.14	$> M_{\rm Pl}$	-	0.22 - 40	60	312 - 1.6×10^4
	$4_{1/2}$	4.8 ± 0.3	$\simeq M_{\rm Pl}$	0.001	0.21 - 3×10^4	5×10^6	20 - 1.9×10^4
	5_1	9.9 ± 0.7	3×10^6	0.003	0.21 - 3	25	$10^3 - 2 \times 10^3$
	$6_{1/2}$	31.8 ± 5.2	2×10^4	0.01	0.5 - 2×10^4	4×10^5	100 - 2×10^4
	$8_{1/2}$	82 ± 8	15	0.05	0.84 - 10^4	10^5	440 - 10^4
	$10_{1/2}$	158 ± 12	3	0.16	1.2 - 8×10^3	6×10^4	1.1×10^3 - 9×10^3
	$12_{1/2}$	253 ± 20	2	0.45	1.6 - 6×10^3	4×10^4	2.3×10^3 - 7×10^3
Complex scalar	$2_{1/2}$	0.58 ± 0.01	$> M_{\rm Pl}$	-	4.9 - 1.4×10^4	-	4.2 - 7×10^3
	3_1	2.1 ± 0.1	$> M_{\rm Pl}$	-	3.7 - 500	120	75 - 1.3×10^4
	$4_{1/2}$	4.98 ± 0.25	$> M_{\rm Pl}$	0.001	4.9 - 3×10^4	-	17 - 2×10^4
	5_1	11.5 ± 0.8	$> M_{\rm Pl}$	0.004	3.7 - 10	20	650 - 3×10^3
	$6_{1/2}$	32.7 ± 5.3	$\simeq 6 \times 10^{13}$	0.01	4.9 - 8×10^4	-	50 - 5×10^4
	$8_{1/2}$	84 ± 8	2×10^4	0.05	4.9 - 6×10^4	-	150 - 6×10^4
	$10_{1/2}$	162 ± 13	20	0.16	4.9 - 4×10^4	-	430 - 4×10^4
	$12_{1/2}$	263 ± 22	4	0.4	4.9 - 3×10^4	-	10^3 - 3×10^4

Bound States dynamics

Example: n=7



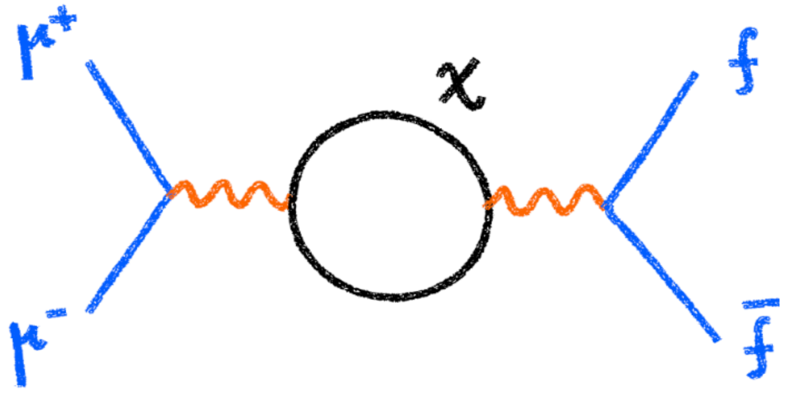


Indirect effets at colliders

From BUTTAZZO's talk @ Moriond

- All EW multiplets contribute to high-energy 2 → 2 fermion scattering: effects that grow with energy, can be tested at μ collider or FCC-hh

Di Luzio, Gröber, Panico 1810.10993



$$\hat{W} \approx 10^{-7} \times \left(\frac{1\,\text{TeV}}{M_{\text{DM}}}\right)^2 n^3 \propto 1/n^2$$

$$\hat{Y} \approx 10^{-7} \times \left(\frac{1\,\text{TeV}}{M_{\text{DM}}}\right)^2 Y^2 n \propto 1/n^4$$

- Complex multiplets need mass splittings from higher dim. operators
  - Charged-neutral splitting (to make DM stable): $\left(\bar{\chi} T^a \chi\right)\left(H^\dagger \sigma^a H\right)$
  - Inelastic splitting (suppress Z-induced scattering): $\left(\bar{\chi} (T^a)^{2Y} \chi^c\right)\left(H^{\dagger c} \sigma^a H\right)^{2Y}$

$$\hat{S} \approx 10^{-5} \times \left(\frac{1\,\text{TeV}}{M_{\text{DM}}}\right)\left(\frac{\delta M}{10\,\text{GeV}}\right) n^3, \qquad \hat{T} \approx 10^{-5} \times \left(\frac{\delta M}{10\,\text{GeV}}\right)^2 n^3$$

can be tested at FCC-ee

Di Luzio, Gröber, Kamenik, Nardecchia 1505.00359

μCollider

2303.08533
2210.02591
2209.01318
2203.07256
2203.07261
2103.14043
1901.06150

2203.07964
2203.08033
2203.07224

International
MUON Collider
Collaboration

+ many more…

www.redbubble.com/people/muon-collider

➡ Try with a high-energy lepton collider

MUON COLLIDER

Main SM backgrounds

MIM + mono-V

$$\begin{array}{ll}\text{mono-}\gamma\ \text{bkg:} & \ell^+\ell^- \to \gamma\nu\bar{\nu}\ , \\ \text{mono-}Z\ \text{bkg:} & \ell^+\ell^- \to Z\nu\bar{\nu}\,, \\ \text{mono-}W\ \text{bkg:} & \ell^+\ell^- \to W^{\mp}\nu\ +\ \ell^{\pm}(\text{lost})\end{array}$$

mono-W requires a lost charge along the beam

Dominated by VBF

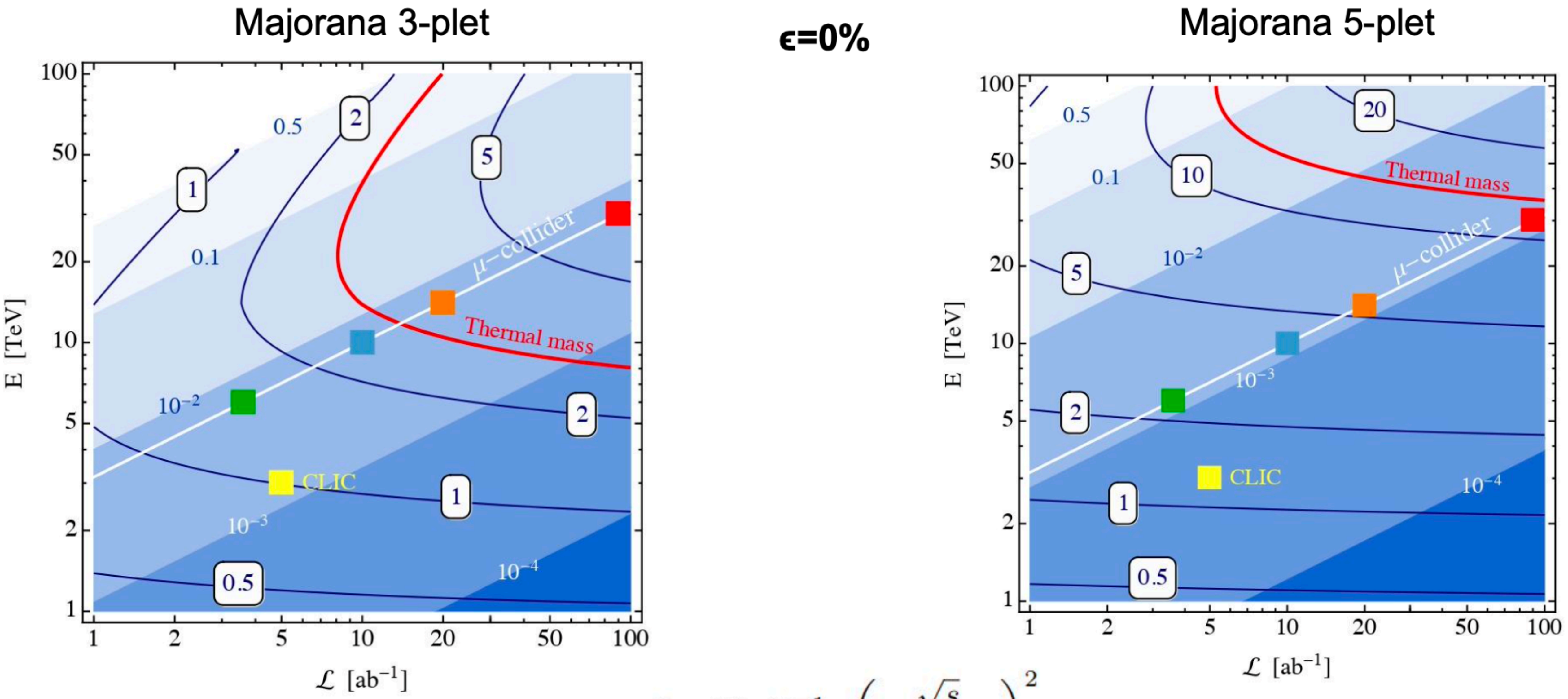
Di-V

Possible SM backgrounds:

$$\ell^+\ell^- \to W^-W^-W^+W^+$$

$$\begin{array}{l}\ell^+\ell^- \to W^-W^+(\text{mistag})\ \nu\bar{\nu}\ , \\ \ell^+\ell^- \to W^-W^+(\text{mistag})\ \ell^+\ell^-\end{array}$$

Lumi vs Energy (Mono-W)



$$\mathcal{L} \simeq 10\ \text{ab}^{-1} \cdot \left(\frac{\sqrt{s}}{10\ \ \text{TeV}}\right)^2$$

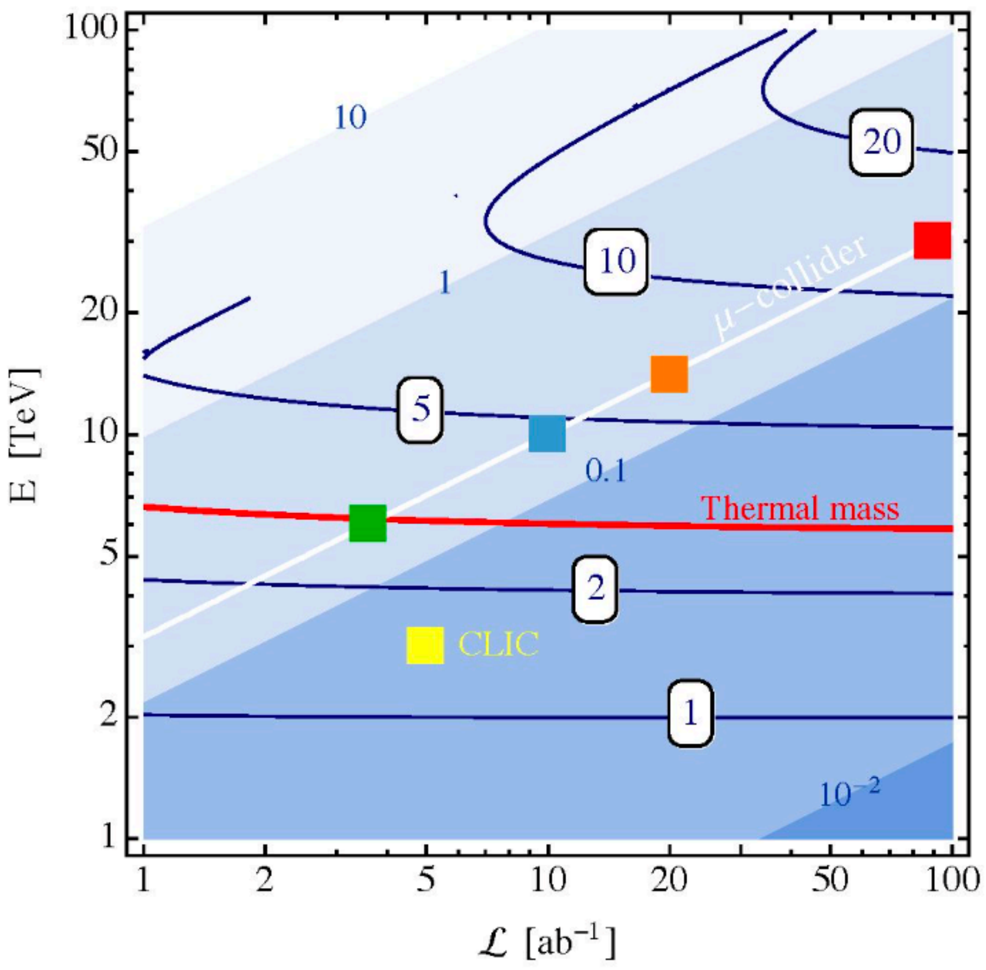
2σ: 12 TeV

2σ: 35 TeV

Lumi vs Energy (DTs)

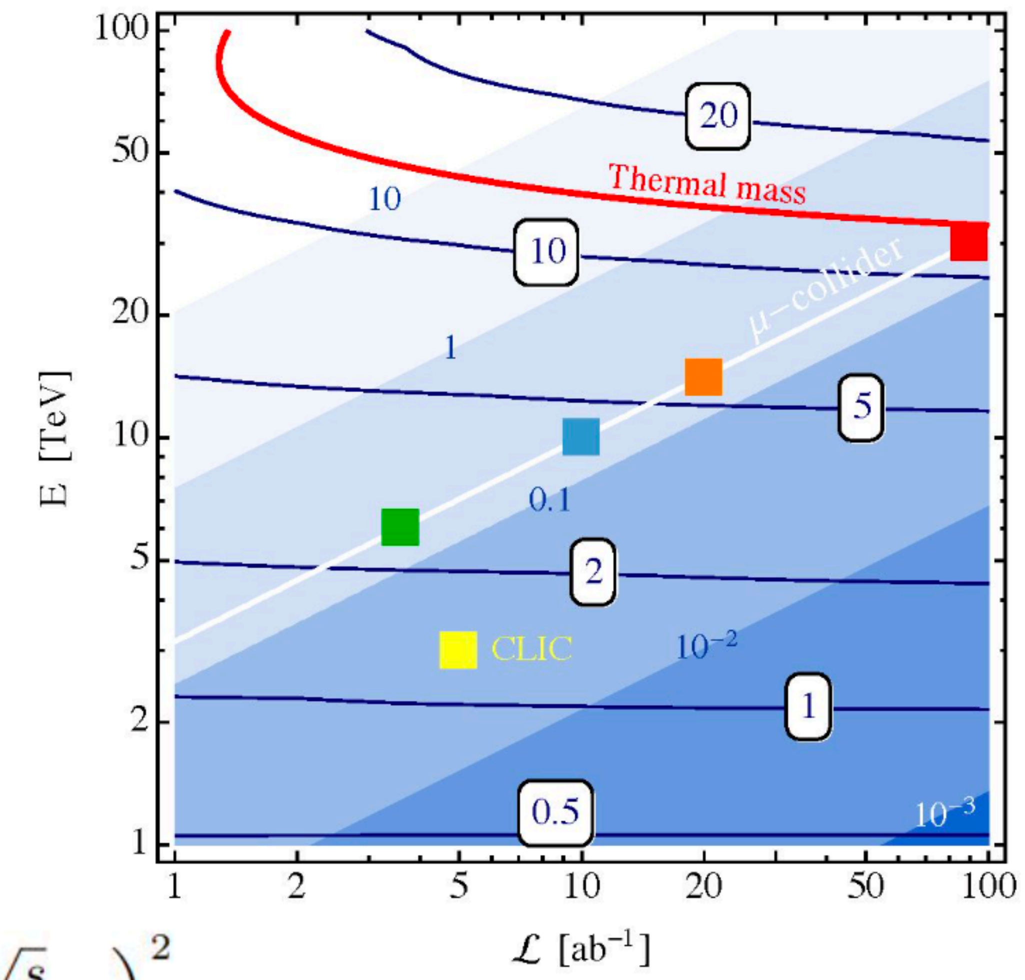
ϵ=0%

Majorana 3-plet



2σ: 6 TeV

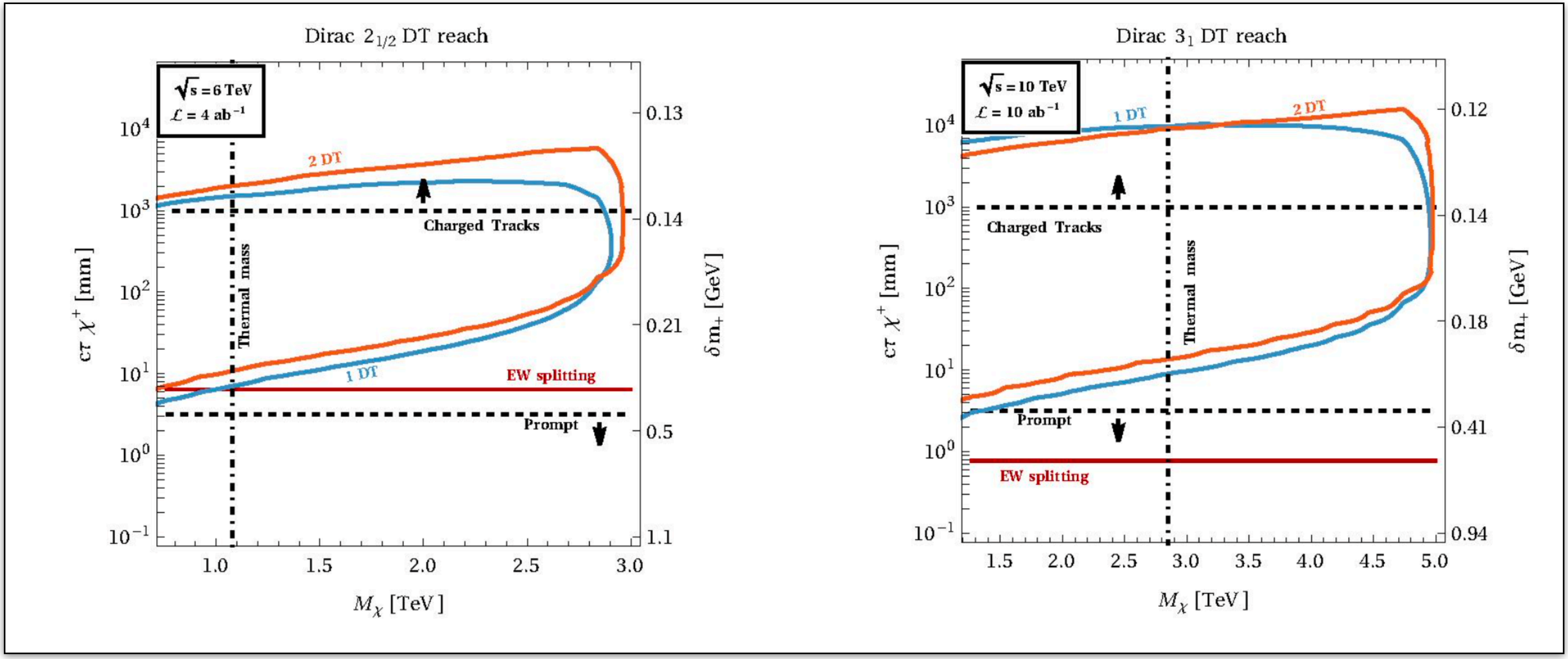
Majorana 5-plet



2σ: 35 TeV

$$\mathcal{L} \simeq 10 \text{ ab}^{-1} \cdot \left(\frac{\sqrt{s}}{10 \text{ TeV}}\right)^2$$

Disappearing Tracks Reach



Results: Scalar WIMPs

Scalar WIMPs have lower cross sections