“Future Accelerators Workshop 2024”,
Corfu, 22/05/2024

Dark Matter Phenomenology: a brief Status

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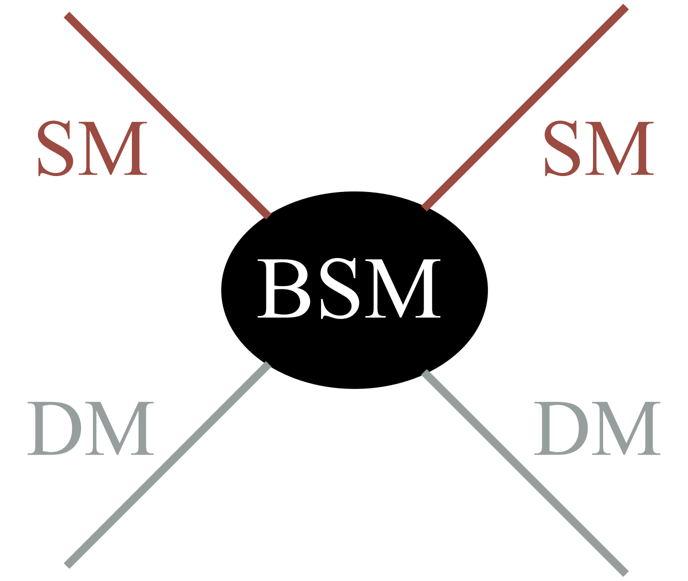
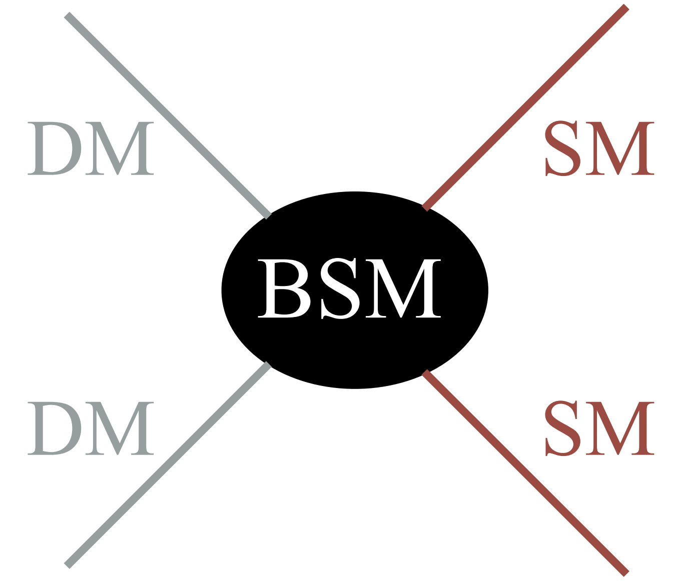
Dark Matter Detection

Experimental strategies to identify the **DM microphysics**

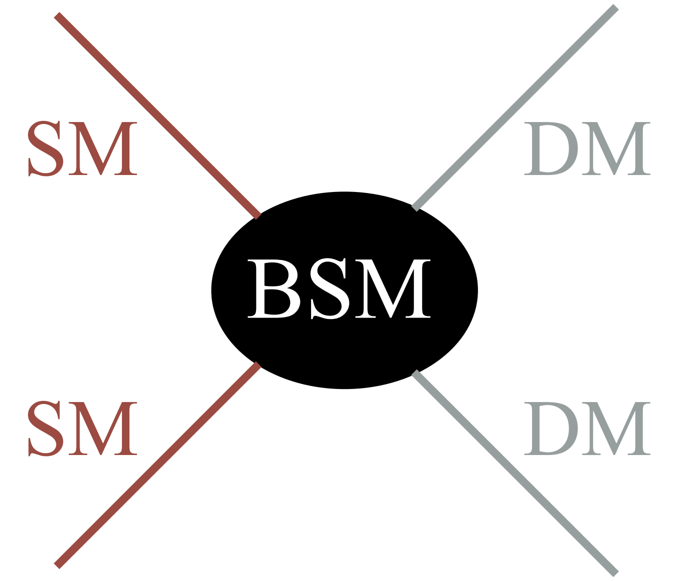
Direct Detection



Indirect Detection



Colliders

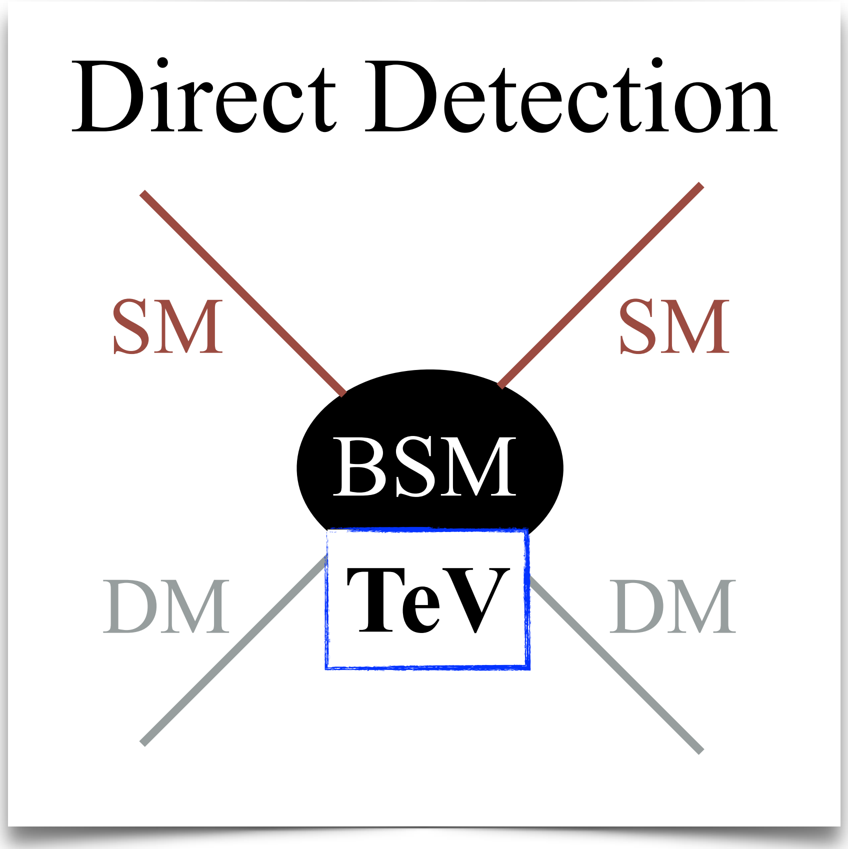


Constrain the parameter space
Find several anomalies

Dark Matter Detection

Experimental strategies to identify the **DM microphysics**

Direct Detection



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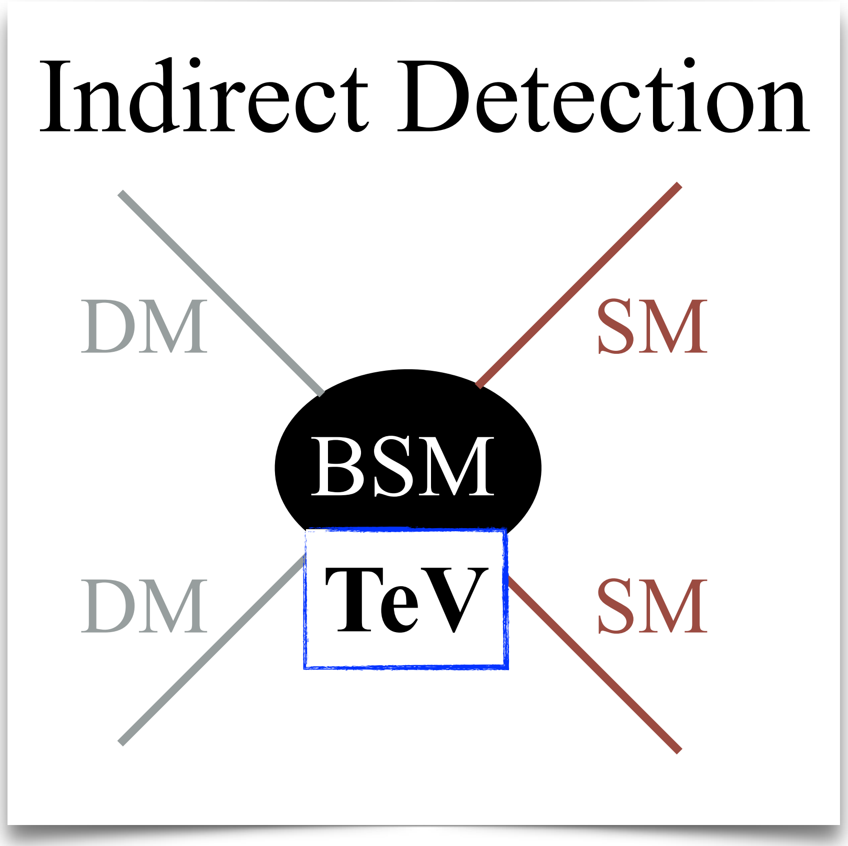

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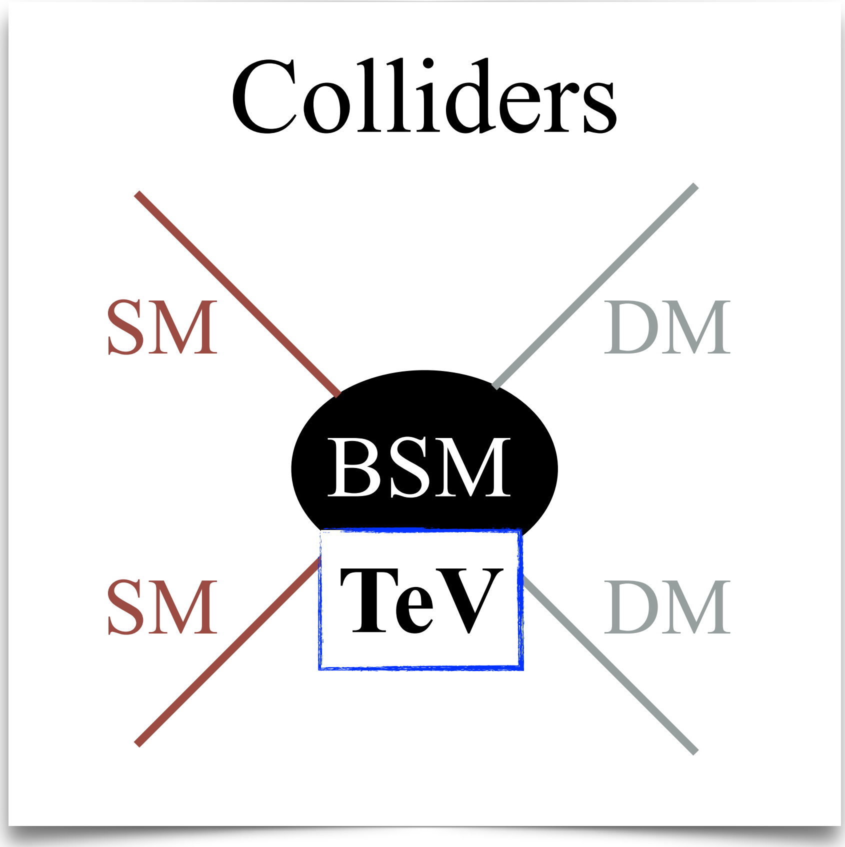


XENONnT & LZ
AMS-02 & H.E.S.S.
LHC Run 3

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

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

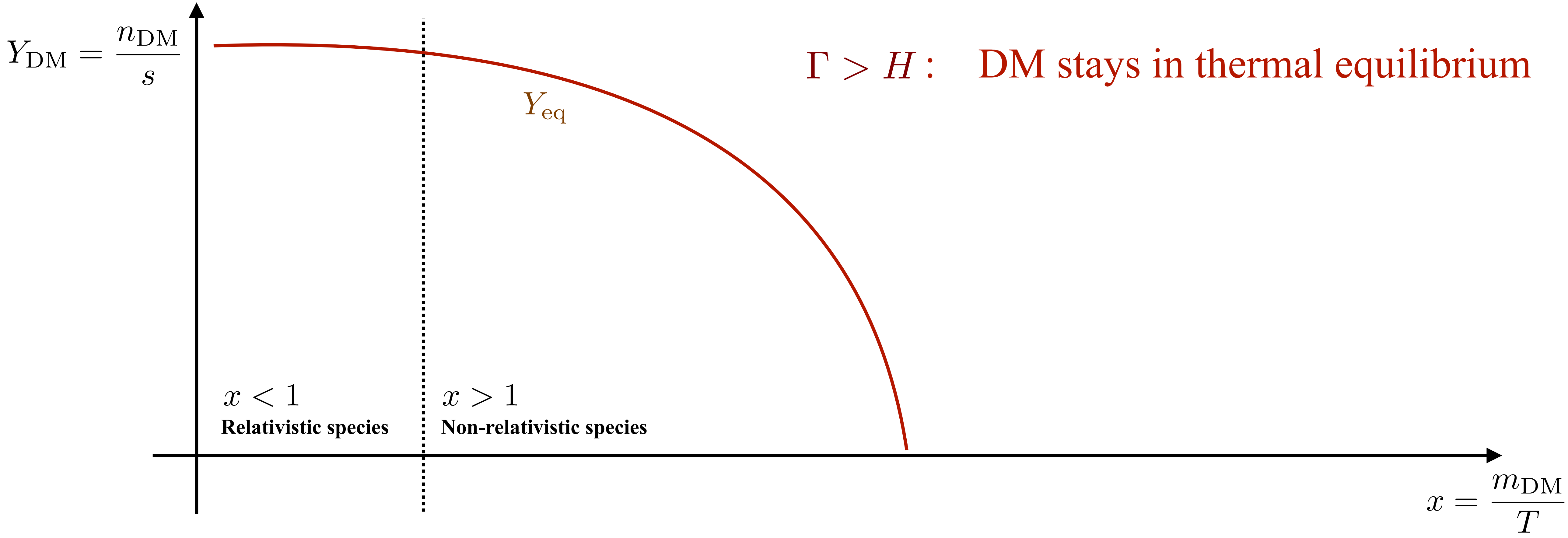
μCollider?

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

A new era has begun

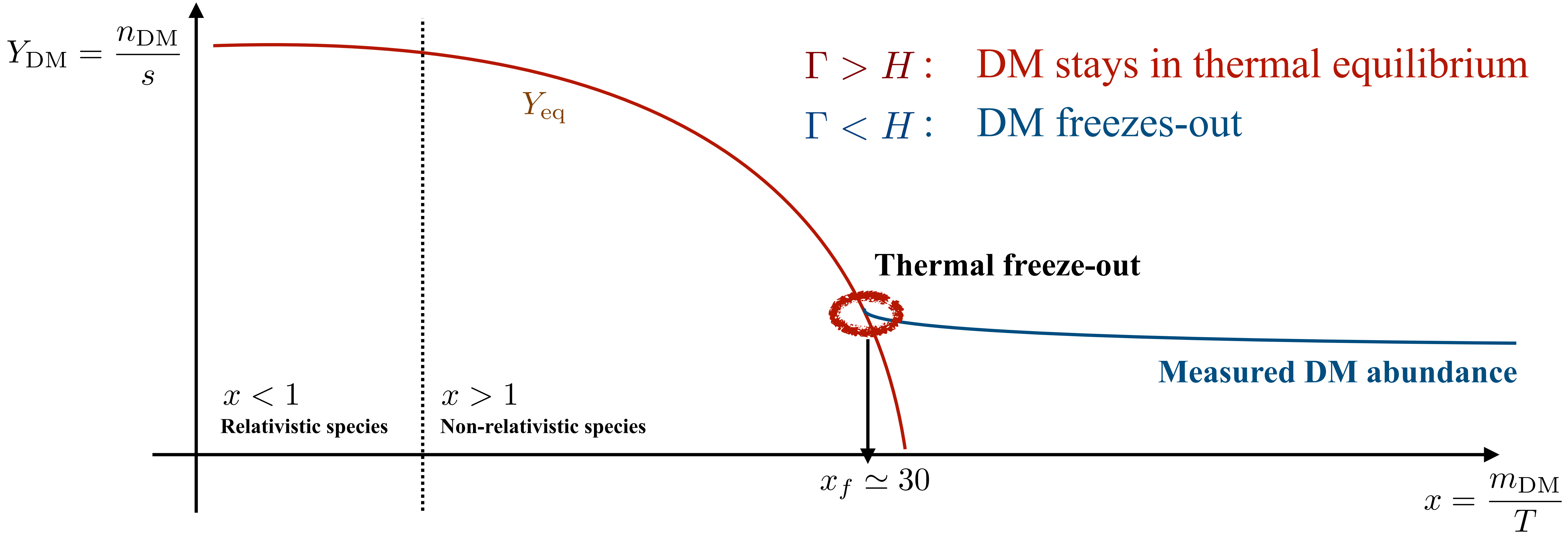
Thermal Freeze-out

Thermal Freeze-out



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

Thermal Freeze-out



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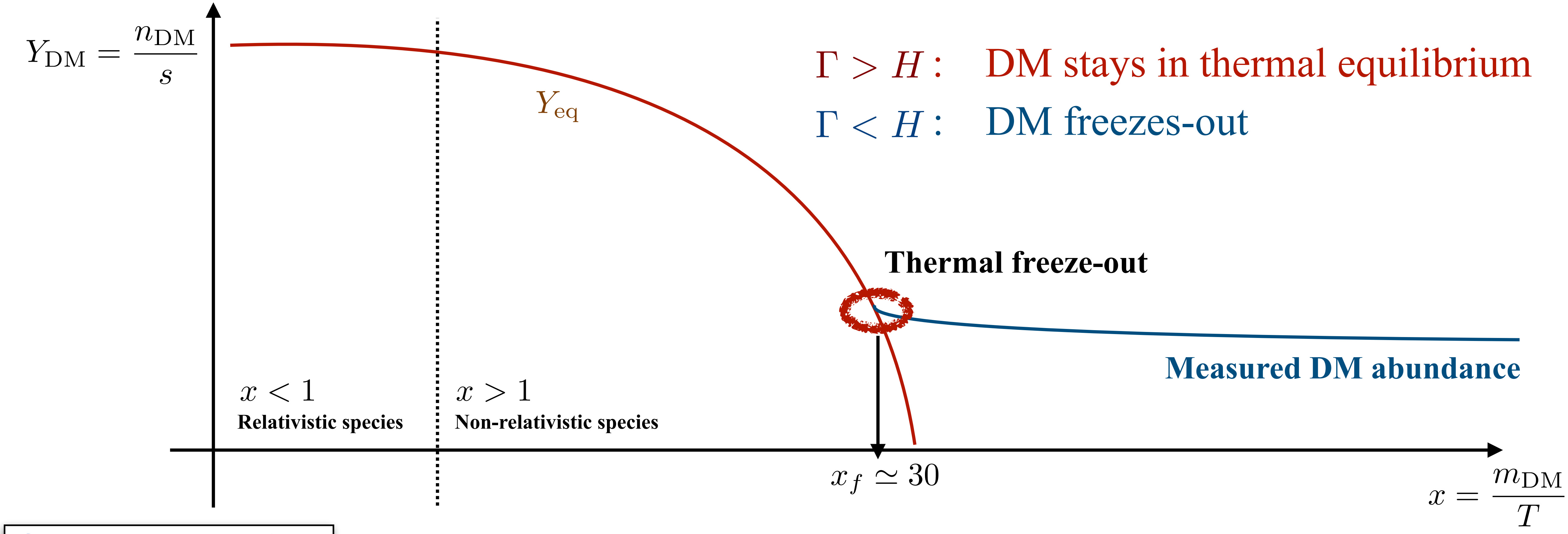
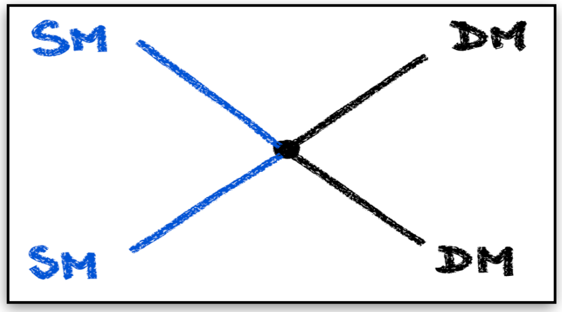
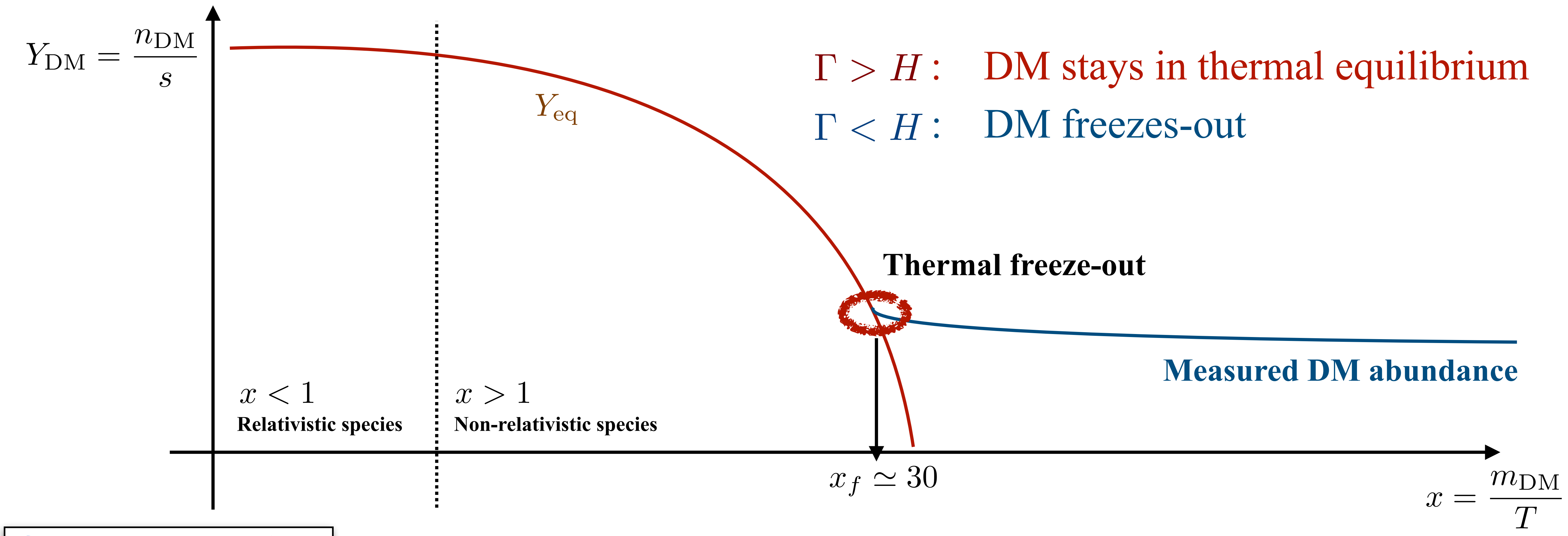




For 2 → 2 scatterings $\langle \sigma_{\rm th} v \rangle$ fully controls the abundance

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

Thermal Freeze-out



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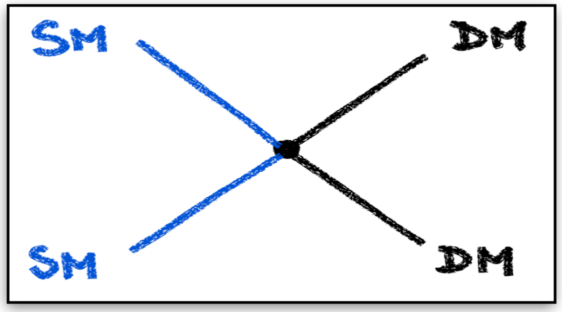
$\Gamma < H :$ DM freezes-out



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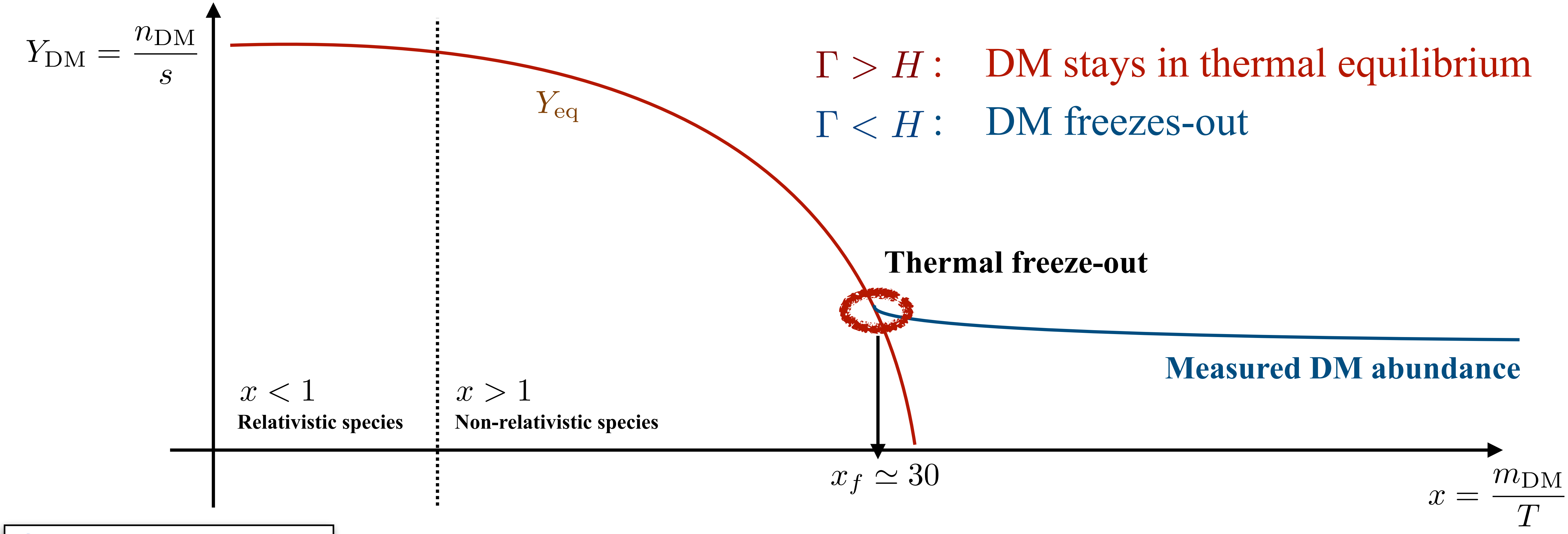

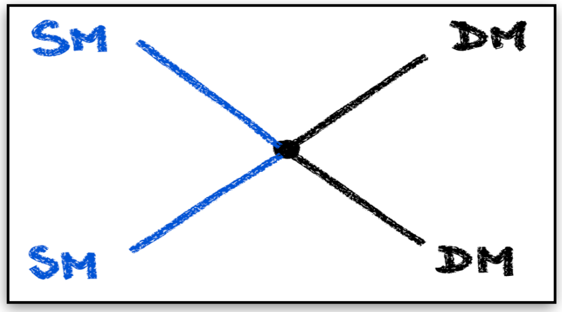

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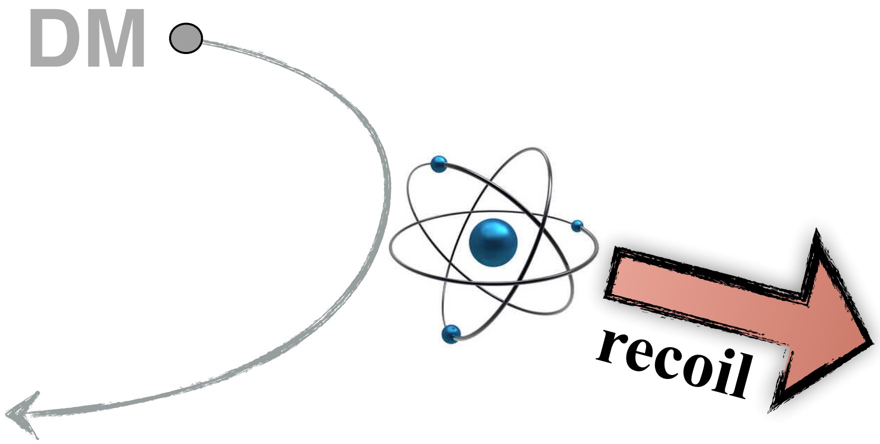
WIMP Miracle: Simple and robust explanation of the DM abundance and a connection to naturalness of EW scale

VERY REACH PHENOMENOLOGY

Direct Detection: overview



Elastic Scattering:

$$\mathrm{DM} + \mathcal{T}(A,Z)_{\mathrm{rest}} \longrightarrow \mathrm{DM} + \mathcal{T}(A,Z)_{\mathrm{recoil}}$$

Inelastic Scattering:

$$\mathrm{DM} + \mathcal{T}(A,Z)_{\mathrm{rest}} \longrightarrow \mathrm{DM}' + \mathcal{T}(A,Z)_{\mathrm{recoil}}$$

DM collisions are **very rare**
(less then 0.01 cpd/kg/keV)

- ☑ the detectors must **work deeply underground**
- ☑ they must **use active shields and very clean materials**
- ☑ they must **discriminate multiple scattering**

Direct Detection: overview

Tiny velocity ⇒ Collisions: **Non Relativistic regime**

$v_\odot \sim 10^{-3} c$

$$E_{\rm R} = \frac{1}{2} m_{\rm DM} v^2 \frac{4 m_{\rm DM} m_{\mathcal{T}}}{(m_{\rm DM} + m_{\mathcal{T}})^2} \frac{1}{2} \left(1 - \frac{v_t^2}{2v^2} - \sqrt{1 - \frac{v_t^2}{v^2}} \cos\theta \right)$$

DM kinetic energy

kinematic factor

threshold velocity kinematics

scattering angle

Direct Detection: overview

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RATE OF NUCLEAR RECOIL

$$\frac{\mathrm{d}R_{\mathcal{T}}}{\mathrm{d}E_{\mathrm{R}}} = N_{\mathcal{T}} \frac{\rho_\odot}{m_{\mathrm{DM}}} \int_{v_{\mathrm{min}}(E_{\mathrm{R}})}^{v_{\mathrm{esc}}} \mathrm{d}^3|\vec{v}| \; |\vec{v}| f_{\mathrm{DM}}(|\vec{v}|) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}}$$

total number of targets

Local DM number density

DM velocity distribution

Differential cross section

Direct detection: Uncertainties

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Local DM number density

DM velocity distribution

Differential cross section

Uncertainties from Astrophysics ⇒ i.e. local DM energy density & geometry of the halo

Uncertainties from Particle Physics ⇒ i.e. nature of the DM interaction & nuclear response functions

Uncertainties from Experimental side ⇒ i.e. background & detection efficiency close to lower threshold

Direct detection: Uncertainties

$$\frac{\mathrm{d}R_{\mathcal{T}}}{\mathrm{d}E_{\mathrm{R}}} = N_{\mathcal{T}} \frac{\rho_{\odot}}{m_{\mathrm{DM}}} \int_{v_{\mathrm{min}}(E_{\mathrm{R}})}^{v_{\mathrm{esc}}} \mathrm{d}^3|\vec{v}|\ |\vec{v}|\, f_{\mathrm{DM}}(|\vec{v}|)\, \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}}$$

Local DM number density

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Uncertainties from Particle Physics

i.e. nature of the DM interaction & nuclear response functions

Non-relativistic (NR) EFT

Deeply NR DM-nucleus scattering

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}} = \frac{1}{32\pi}\frac{1}{m_{\mathrm{DM}}^2 m_{\mathcal{T}}}\frac{1}{v^2}\left|\mathcal{M}_{\mathcal{T}}\right|^2$$

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DM-nucleon ME:
Galileian combination of NR d.o.f. $(\vec{q}, \vec{v}_\perp, \vec{s}_N, \vec{s}_{\mathrm{DM}})$

$$\mathcal{M}_N \equiv \sum_i \underbrace{\mathfrak{c}_i^N(\lambda, m_{\mathrm{DM}})}_{\substack{\textbf{NR coefficients} \\ \textbf{(details of the UV)}}} \underbrace{\mathcal{O}_i^{\mathrm{NR}}}_{\substack{\textbf{NR} \\ \textbf{operators}}}$$

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$$\begin{array}{ll}
\mathcal{O}_1^{\mathrm{NR}} \equiv \mathcal{I}_\chi \mathcal{I}_N \ , & \\
\mathcal{O}_3^{\mathrm{NR}} \equiv i\,\mathcal{I}_\chi \boldsymbol{s}_N \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp) \ , & \mathcal{O}_4^{\mathrm{NR}} \equiv \boldsymbol{s}_\chi \cdot \boldsymbol{s}_N \ , \\
\mathcal{O}_5^{\mathrm{NR}} \equiv i\,\mathcal{I}_N \boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp) \ , & \mathcal{O}_6^{\mathrm{NR}} \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{q}) \ , \\
\mathcal{O}_7^{\mathrm{NR}} \equiv \mathcal{I}_\chi \boldsymbol{s}_N \cdot \boldsymbol{v}^\perp \ , & \mathcal{O}_8^{\mathrm{NR}} \equiv \mathcal{I}_N \boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp \ , \\
\mathcal{O}_9^{\mathrm{NR}} \equiv i\,\boldsymbol{s}_\chi \cdot (\boldsymbol{s}_N \times \boldsymbol{q}) \ , & \mathcal{O}_{10}^{\mathrm{NR}} \equiv i\,\mathcal{I}_\chi \boldsymbol{s}_N \cdot \boldsymbol{q} \ , \\
\mathcal{O}_{11}^{\mathrm{NR}} \equiv i\,\mathcal{I}_N \boldsymbol{s}_\chi \cdot \boldsymbol{q} \ , & \mathcal{O}_{12}^{\mathrm{NR}} \equiv \boldsymbol{v}^\perp \cdot (\boldsymbol{s}_\chi \times \boldsymbol{s}_N) \ , \\
\mathcal{O}_{13}^{\mathrm{NR}} \equiv i(\boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp)(\boldsymbol{s}_N \cdot \boldsymbol{q}) \ , & \mathcal{O}_{14}^{\mathrm{NR}} \equiv i(\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{v}^\perp) \ , \\
\mathcal{O}_{15}^{\mathrm{NR}} \equiv [\boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)](\boldsymbol{s}_N \cdot \boldsymbol{q}) \ , & \mathcal{O}_{16}^{\mathrm{NR}} \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp)(\boldsymbol{s}_N \cdot \boldsymbol{v}^\perp) \ , \\
\mathcal{O}_{17}^{\mathrm{NR}} \equiv i[\boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)](\boldsymbol{s}_N \cdot \boldsymbol{v}^\perp) \ . &
\end{array}$$

Non-relativistic (NR) EFT

Deeply NR DM-nucleus scattering

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}} = \frac{1}{32\pi}\frac{1}{m_{\mathrm{DM}}^2 m_{\mathcal{T}}}\frac{1}{v^2}\left|\mathcal{M}_{\mathcal{T}}\right|^2$$

$$\Downarrow$$

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Experiments consider:

Spin independent

$$\mathcal{O}_1^{\mathrm{NR}} \equiv \mathcal{I}_{\mathrm{DM}}\mathcal{I}_N$$

Spin dependent

$$\mathcal{O}_4^{\mathrm{NR}} \equiv \vec{s}_{\mathrm{DM}} \cdot \vec{s}_N$$

Non-relativistic (NR) EFT

The nucleus is not point-like:

$$|\mathcal{M}_{\mathcal{T}}|^2 = \frac{m_{\mathcal{T}}^2}{m_N^2} \sum_{i,j} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} \underbrace{F_{i,j}^{(N,N')}(\vec{q}, \vec{v}_\perp, \vec{s}_N, \vec{s}_{\mathrm{DM}})}_{\text{NUCLEAR RESPONSES}}$$

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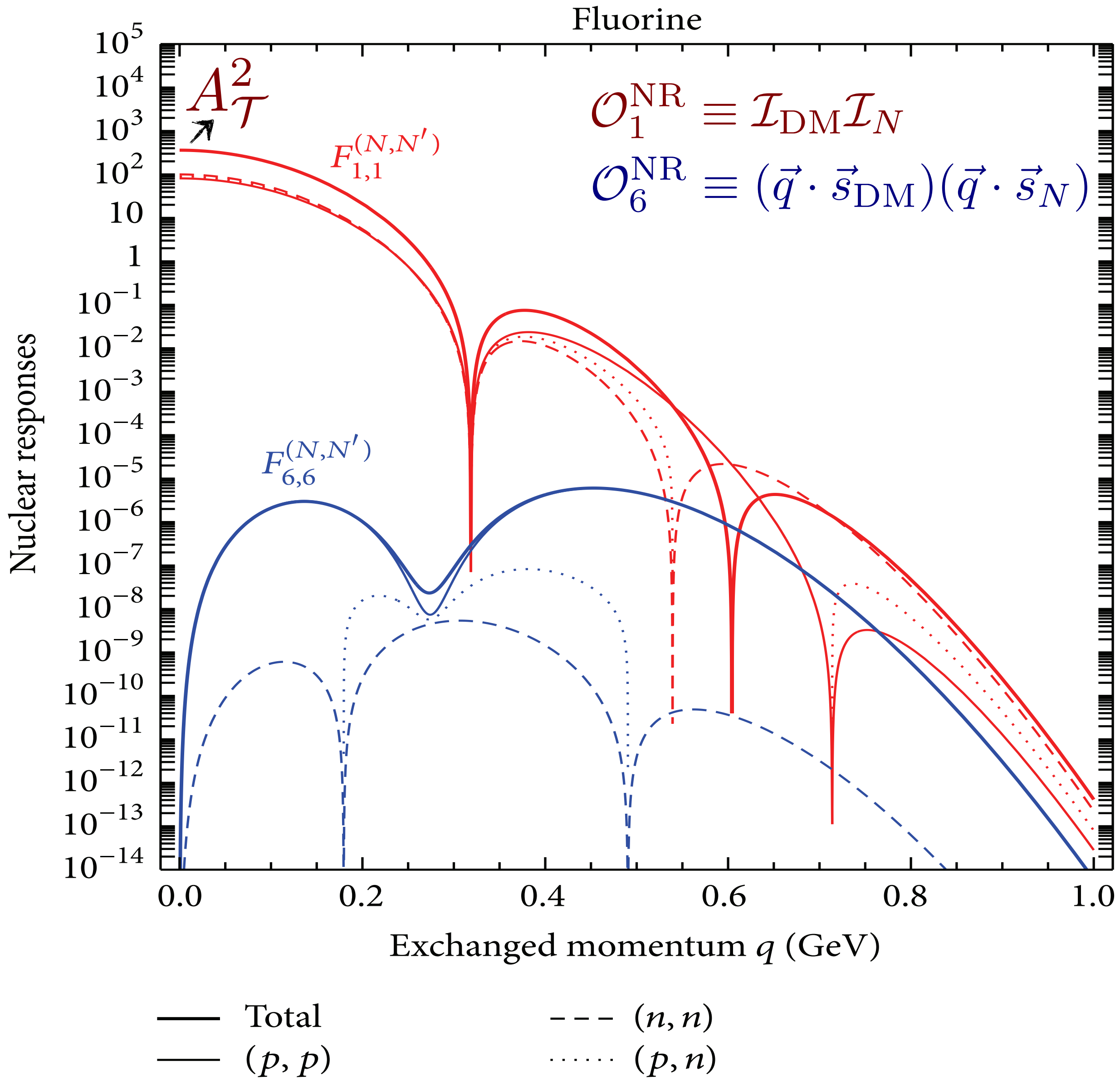
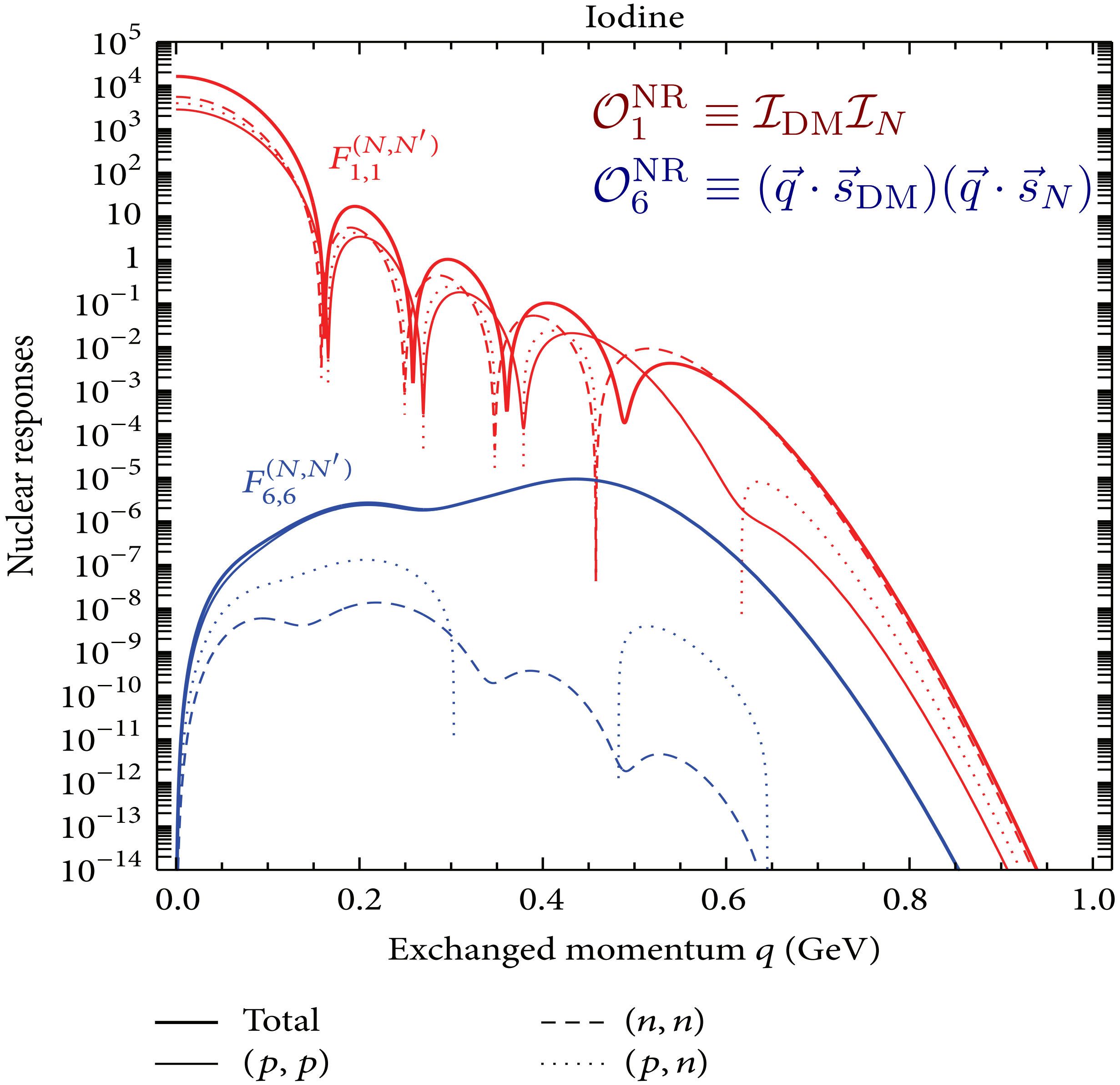
see e.g. **JCAP 1302 (2013) 004**





The rate of nuclear recoils

# of Events: in terms of **model independent form factor**

$$\mathcal{N}(\lambda, m_{\rm DM}) \propto \sum_{i,j} \sum_{N,N'=p,n} \underbrace{\mathfrak{c}_i^N(\lambda, m_{\rm DM})\mathfrak{c}_j^{N'}(\lambda, m_{\rm DM})}_{\text{PARTICLE PHYSICS}} \underbrace{\mathcal{F}^{ij}_{N,N'}(m_{\rm DM})}_{\text{MODEL INDEPENDENT}}$$

ME sensitives to Galileian combinations of NR d.o.f.

Going beyond the usual pictures (i.e. SI & SD interactions)

The standard interactions

SPIN INDEPENDENT **SPIN DEPENDENT**

The standard interactions

SPIN INDEPENDENT

SPIN DEPENDENT

Dimension-6 four fermion interactions

$$\lambda^N_{\mathrm{SI}}\, \bar{\chi}\gamma_\mu\chi\, \bar{N}\gamma^\mu N$$

$$\lambda^N_{\mathrm{SD}}\, \bar{\chi}\gamma_\mu\gamma_5\chi\, \bar{N}\gamma^\mu\gamma_5 N$$

The standard interactions

SPIN INDEPENDENT **SPIN DEPENDENT**

Dimension-6 four fermion interactions

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DM-nucleon ME $\mathcal{M}_{q^2\to0} \equiv \langle\chi N\,|\mathcal{L}|\,\chi' N'\rangle_{q^2\to0}$

$$\underbrace{4\lambda^N_{\mathrm{SI}} m_{\mathrm{DM}} m_N}_{\mathfrak{c}^N_1}\,\underbrace{\mathcal{I}_{\mathrm{DM}}\mathcal{I}_N}_{\mathcal{O}^{\mathrm{NR}}_1} \qquad \underbrace{-16\lambda^N_{\mathrm{SD}} m_{\mathrm{DM}} m_N}_{\mathfrak{c}^N_4}\,\underbrace{\vec{s}_{\mathrm{DM}}\cdot\vec{s}_N}_{\mathcal{O}^{\mathrm{NR}}_4}$$

The standard interactions

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Dimension-6 four fermion interactions

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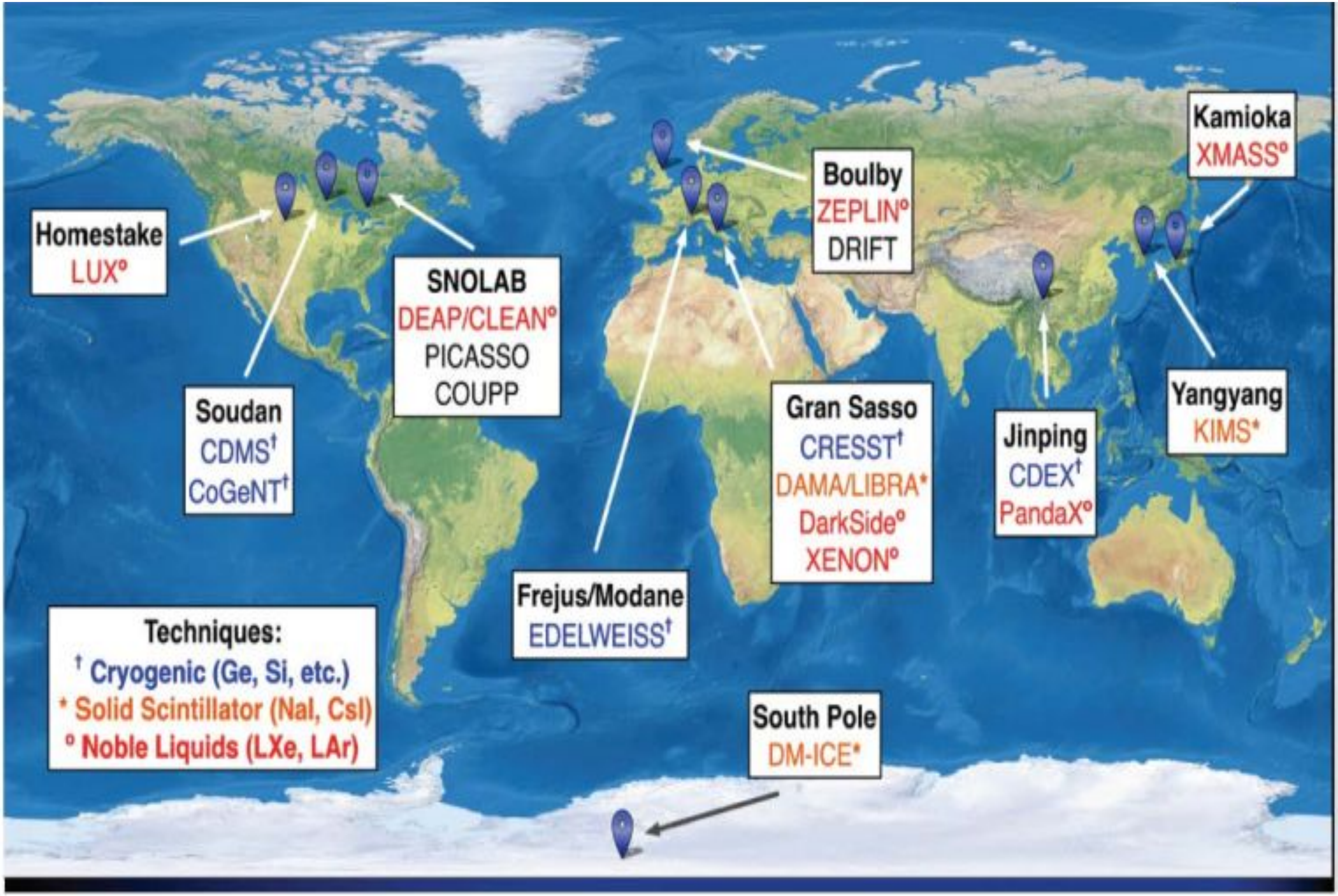
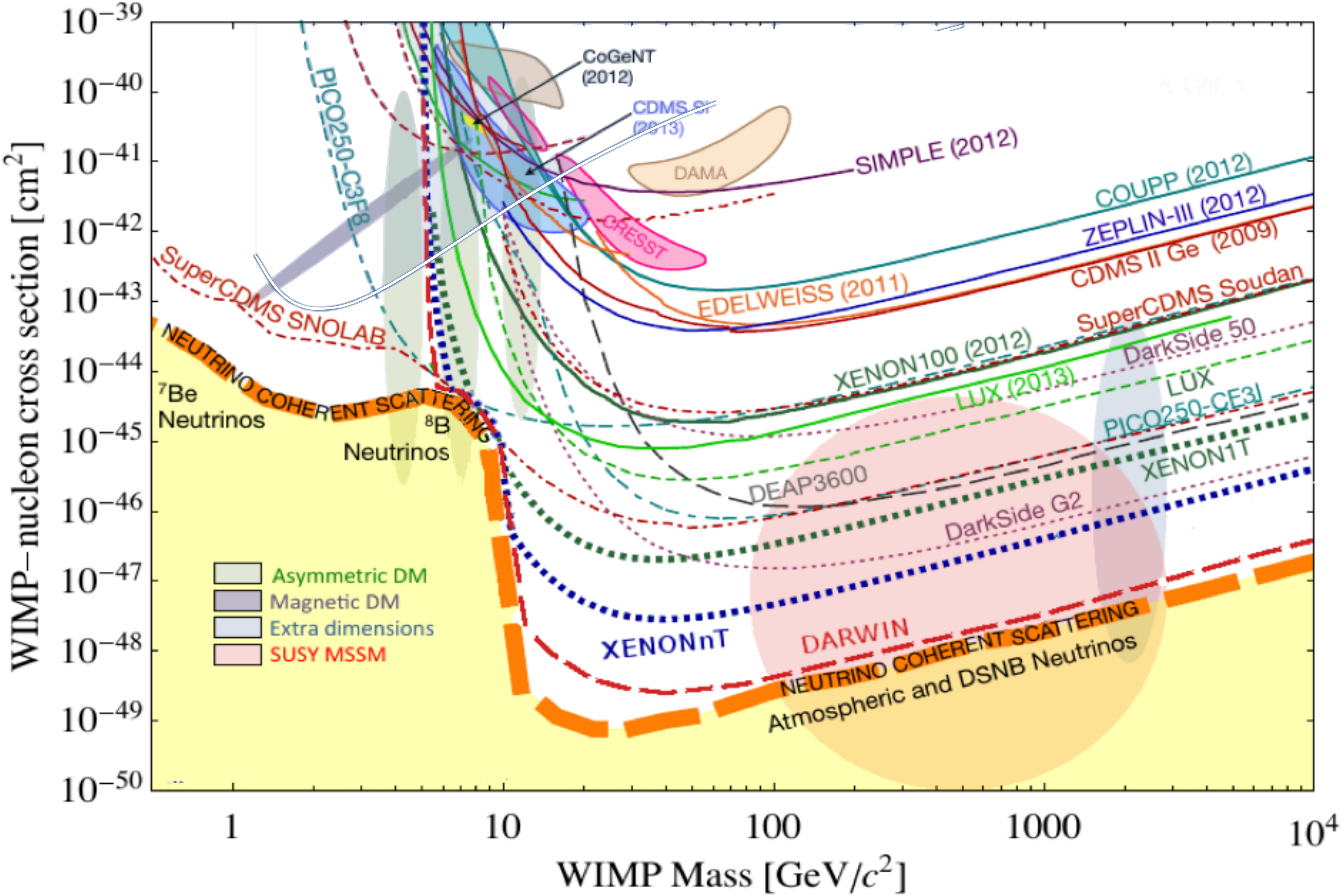
THE RATE

$$N_\mathcal{T}\frac{\rho_\odot}{m_\chi}\frac{m_\mathcal{T}}{2\mu^2_{\chi\mathcal{T}}}\begin{cases} \overset{\substack{\textbf{coherent}\\\textbf{factor}\\\nearrow}}{A^2_\mathcal{T}}\sigma^N_{\rm SI}\overset{\substack{\textbf{SI form}\\\textbf{factor}\\\nearrow}}{F^2_{\rm SI}(E_{\rm R})}\overset{\substack{\textbf{Halo function}\\\nearrow}}{\mathcal{H}(E_{\rm R})} & \text{with } \sigma^N_{\rm SI} = \dfrac{(\lambda^N_{\rm SI}\mu_{\chi N})^2}{\pi} \\ \underset{\substack{\searrow\\\textbf{Nuclear}\\\textbf{spin factor}}}{\langle J^2_\mathcal{T}\rangle}\sigma^N_{\rm SD}\underset{\substack{\searrow\\\textbf{SD form}\\\textbf{factor}}}{F^2_{\rm SD}(E_{\rm R})}\underset{\substack{\searrow\\\textbf{Halo function}}}{\mathcal{H}(E_{\rm R})} & \text{with } \sigma^N_{\rm SD} = \dfrac{3(\lambda^N_{\rm SD}\mu_{\chi N})^2}{\pi} \end{cases}$$

Worldwide DM searches



Spin independent: Status



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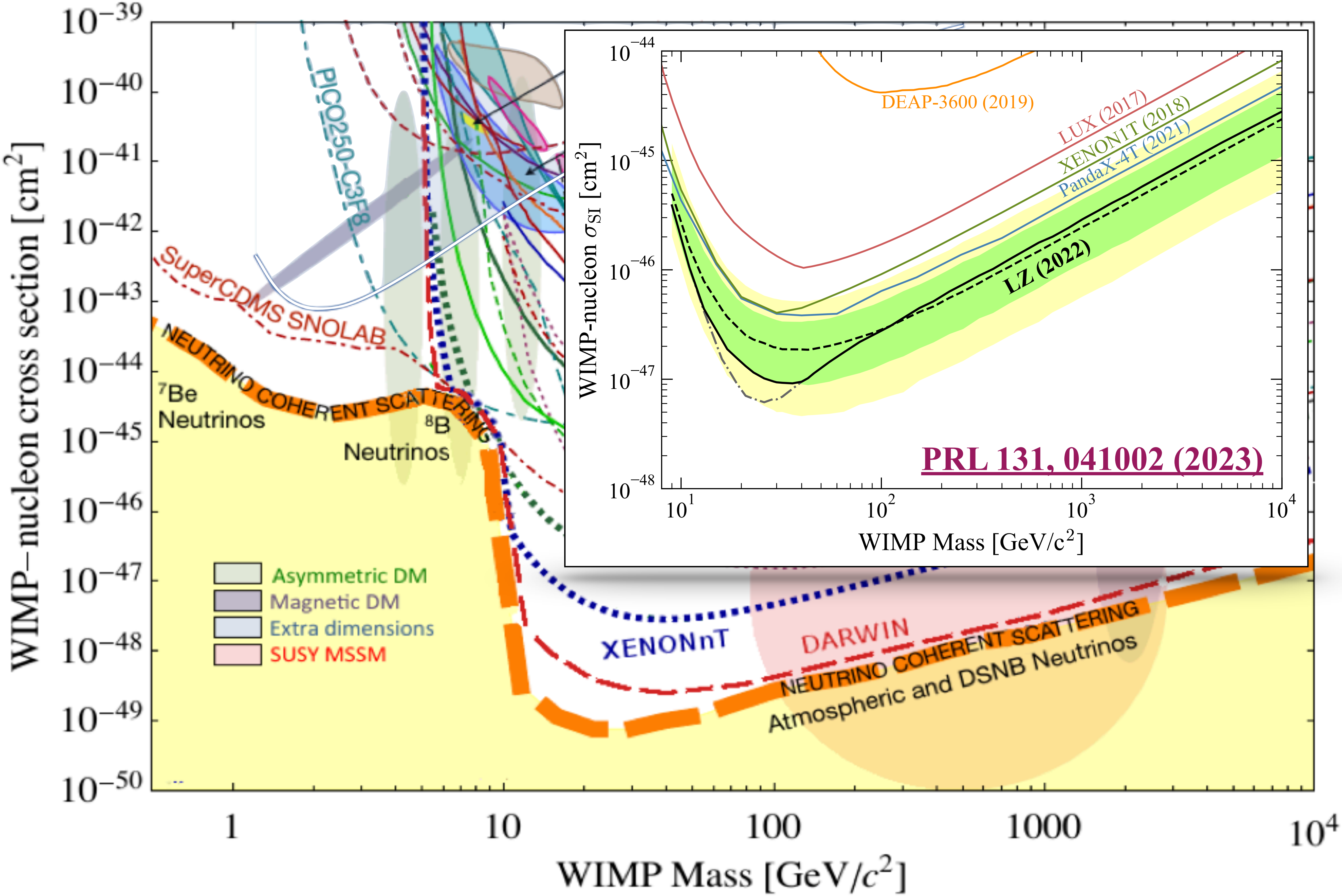

PRL 131, 041002 (2023)

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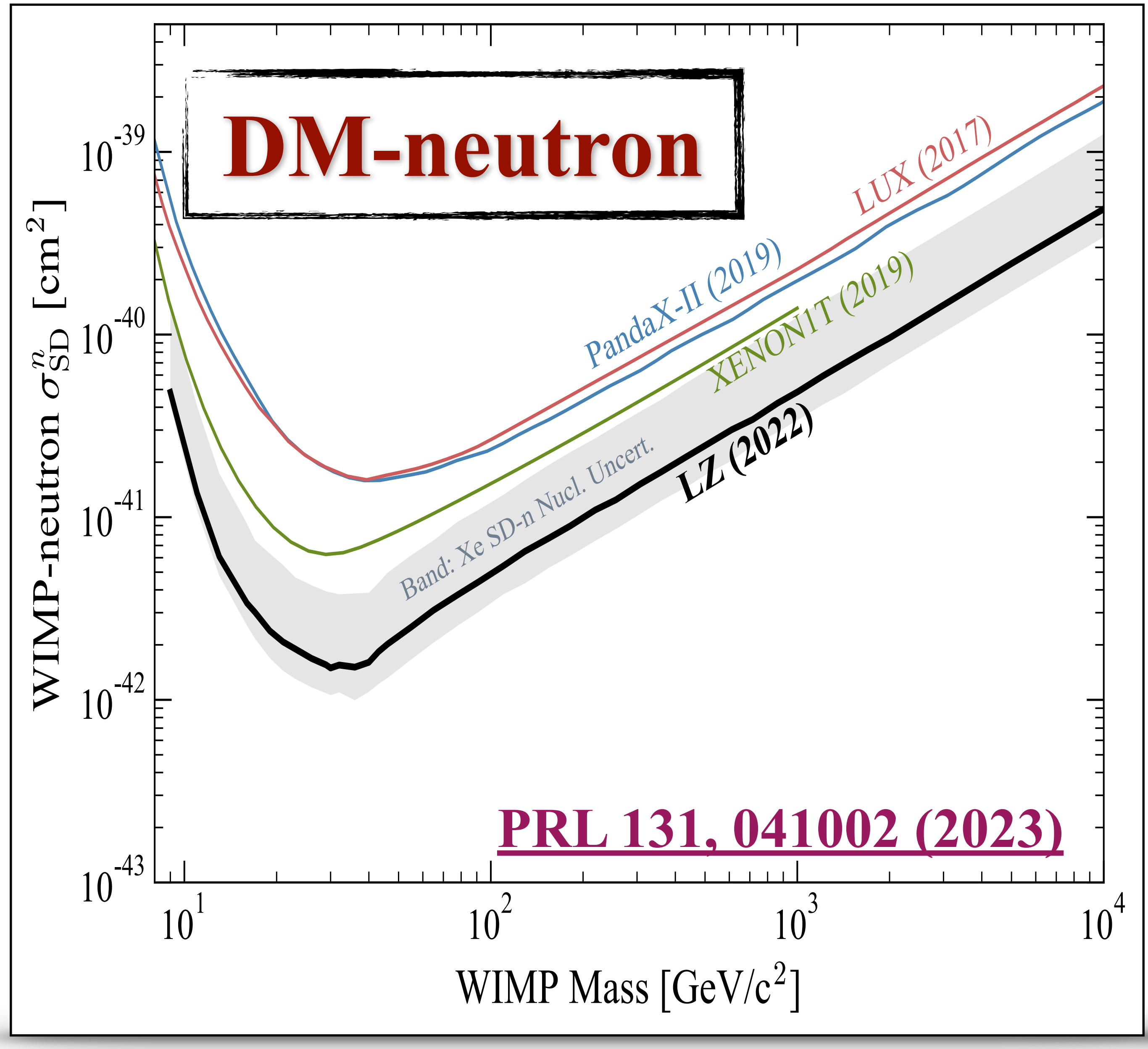

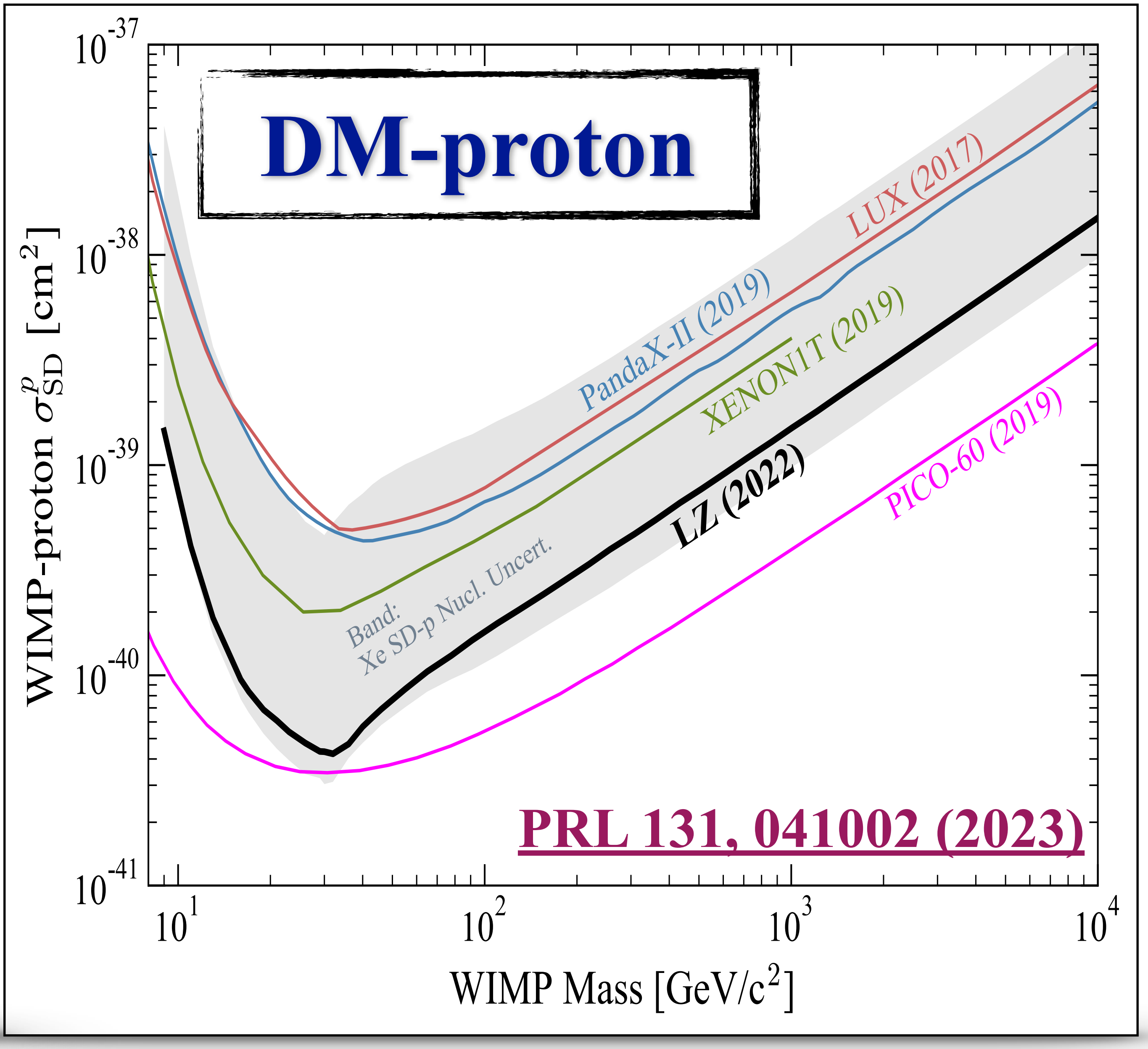

SENSITIVITIES:

unpaired neutrons in the outer nuclear shell (e.g. xenon): large **DM-*n* SD**

unpaired protons in the outer nuclear shell (e.g. fluorine): large **DM-*p* SD**

Direct detection *vs* WIMP paradigm

Tremendous progress in testing the properties of DM

The limits are well below $\sigma_{\rm th} \simeq 1\,{\rm pb}$

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Does it mean that WIMP are dead? **NOT REALLY!**

Direct comparison of the scattering and the thermal XS is not correct:

- **Different energy scale:** Energy entering in the scattering (few tens of **MeV**) is completely different with respect to the relevant one in the annihilation (**TeV** & beyond)
- **Different d.o.f.:** direct detection is only sensitive to light degrees of freedom (light quarks and gluons)

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

Indirect Detection: overview

Stable SM products (e^+, $\bar{p}$, .. ,γ) from annihilating/decaying DM

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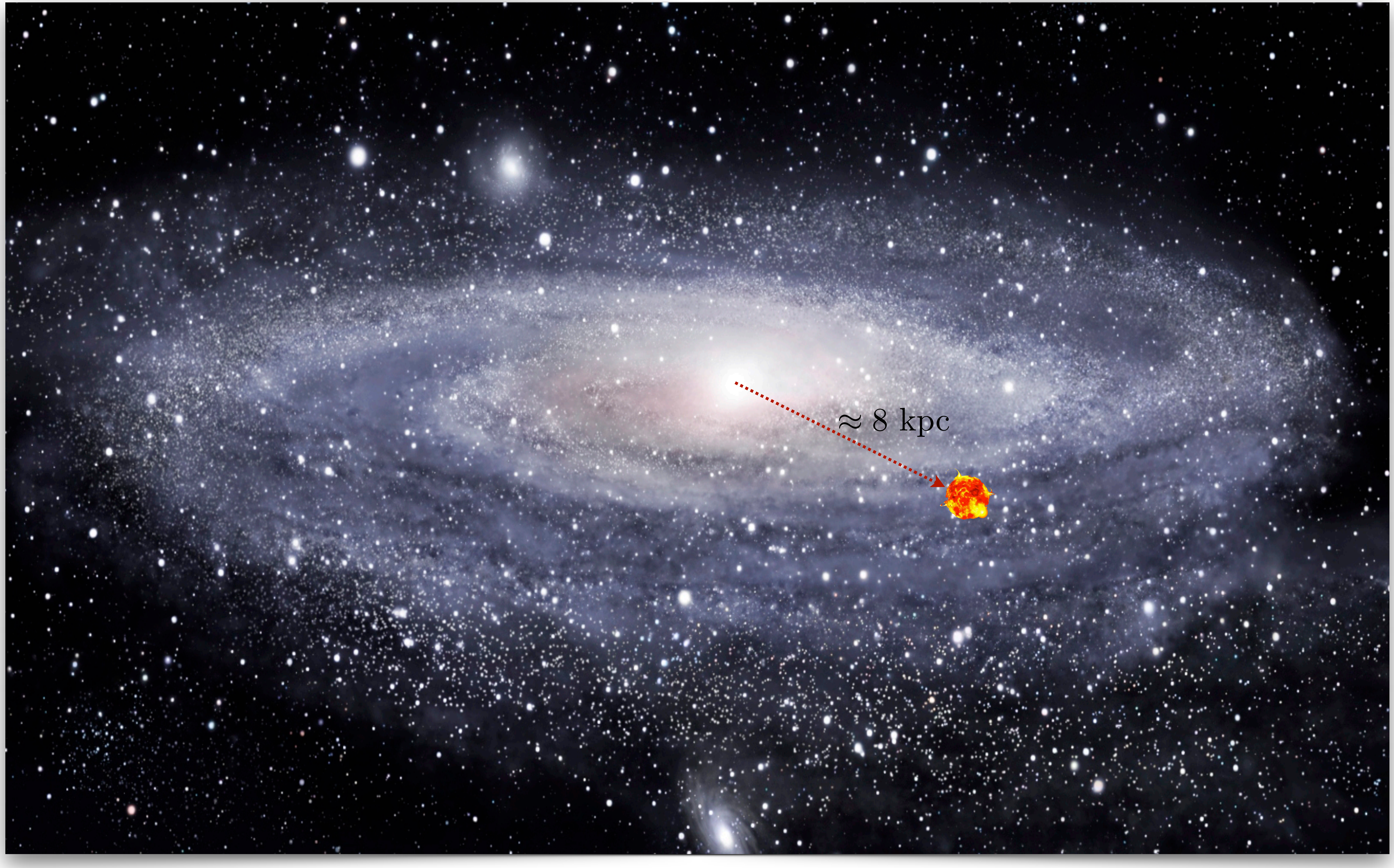
Stable SM products (e^+, $\bar{p}$, .. ,γ) from annihilating/decaying DM



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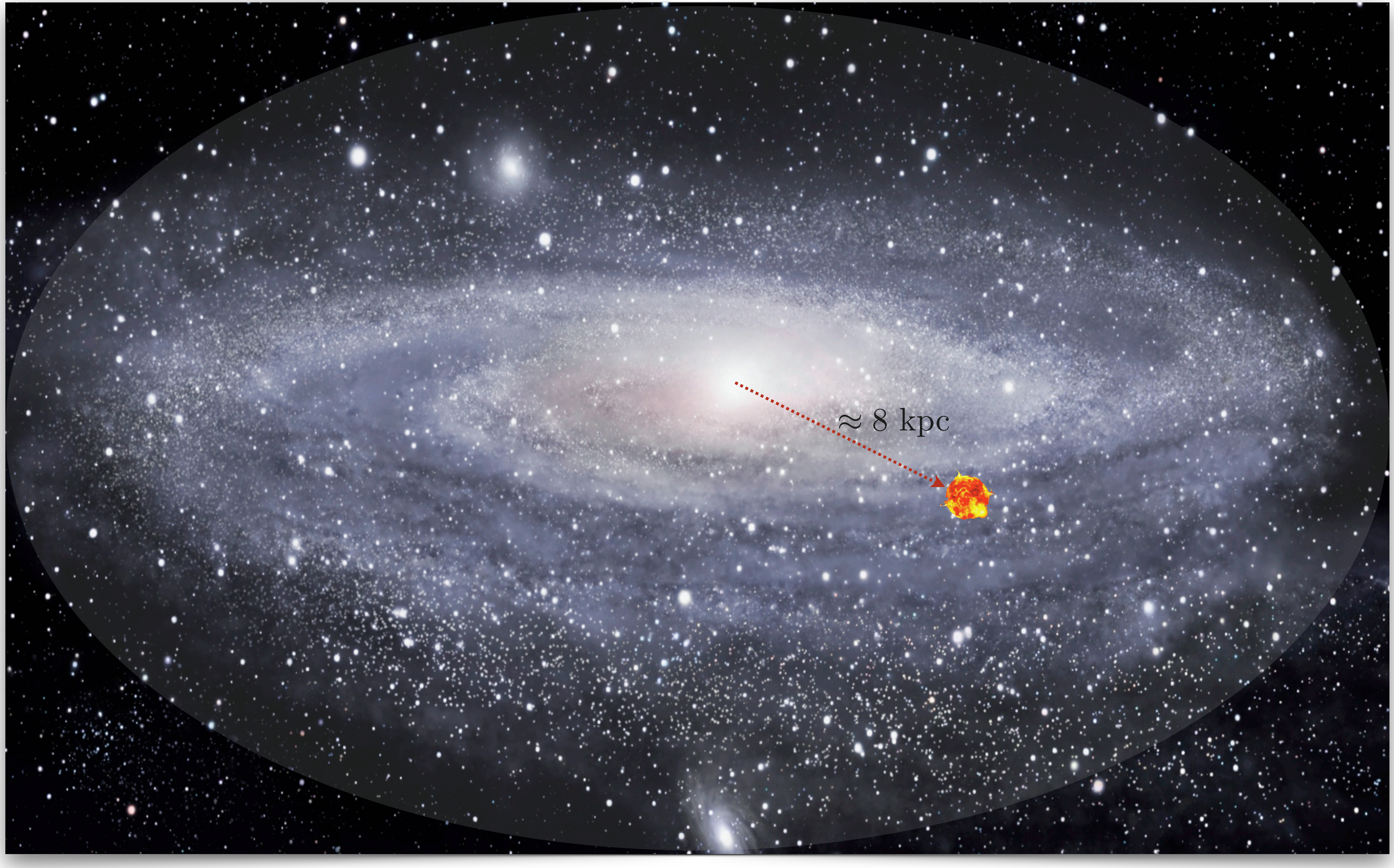

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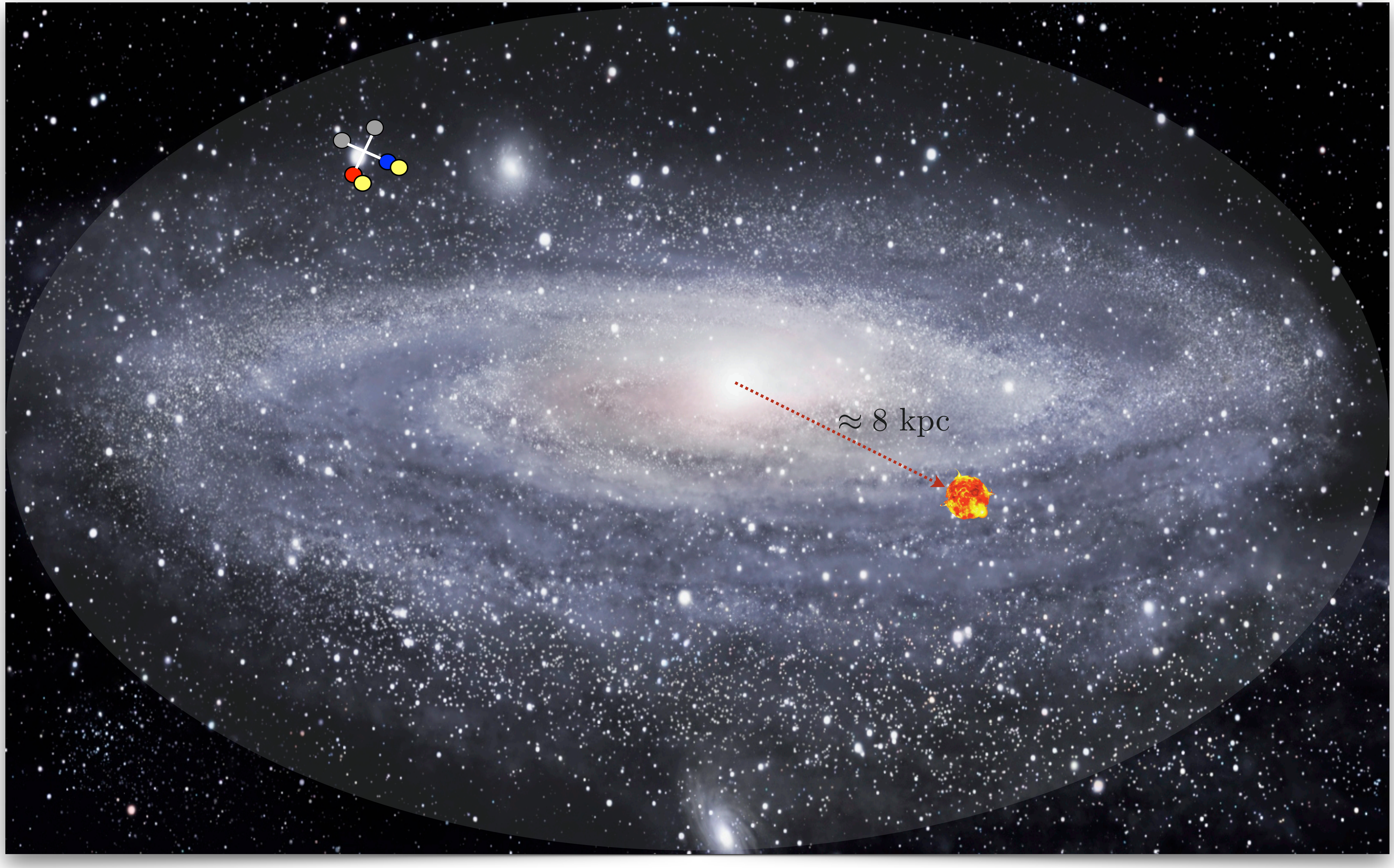
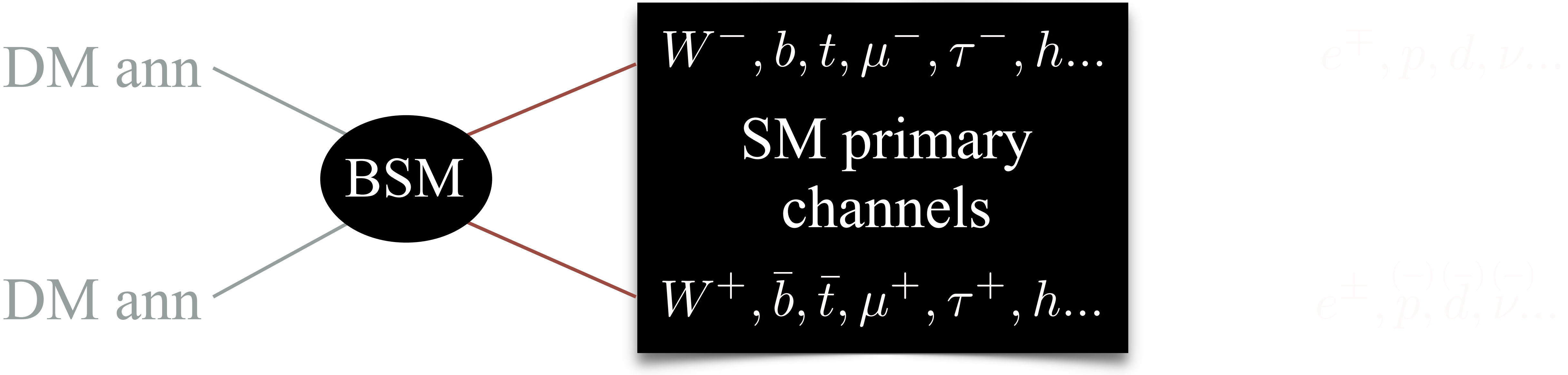


Fluxes @production

Stable SM products from annihilating/decaying DM



DM ann

DM ann

BSM

$W^-, b, t, \mu^-, \tau^-, h...$

SM primary channels

$W^+, \bar{b}, \bar{t}, \mu^+, \tau^+, h...$

$e^{\mp}, p, d, \nu...$

$e^{\pm}, \overset{(-)}{p}, \overset{(-)}{d}, \overset{(-)}{\nu}...$

Fluxes @production

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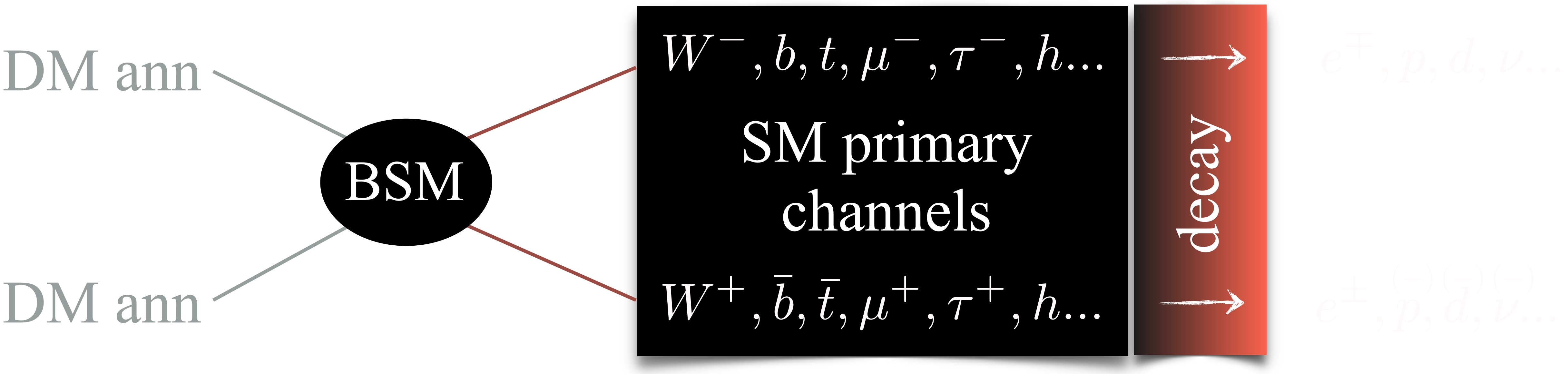

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$W^+, \bar{b}, \bar{t}, \mu^+, \tau^+, h...$

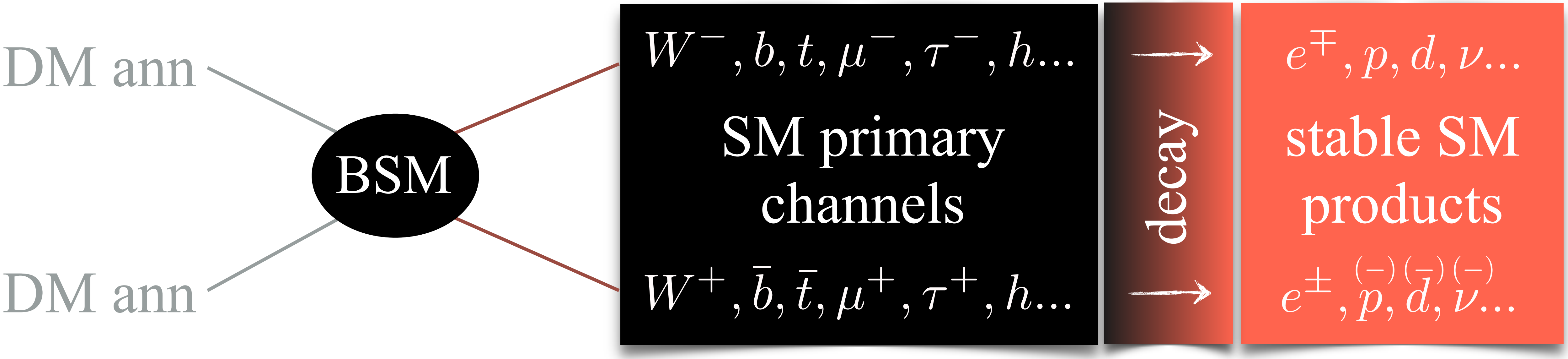
decay

$e^\mp, p, d, \nu...$

$e^\pm, \overset{(-)}{p}, \overset{(-)}{d}, \overset{(-)}{\nu}...$

Fluxes @production

Stable SM products from annihilating/decaying DM



DM ann

DM ann

BSM

$W^-, b, t, \mu^-, \tau^-, h...$

SM primary channels

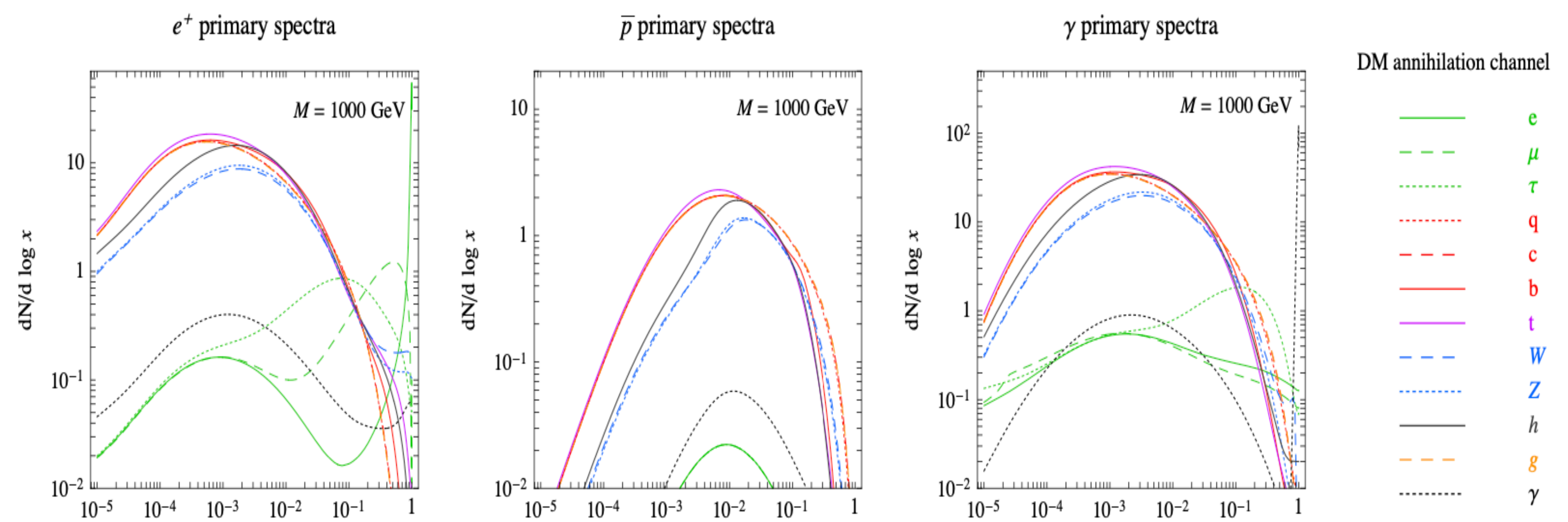
$W^+, \bar{b}, \bar{t}, \mu^+, \tau^+, h...$

decay

$e^\mp, p, d, \nu...$

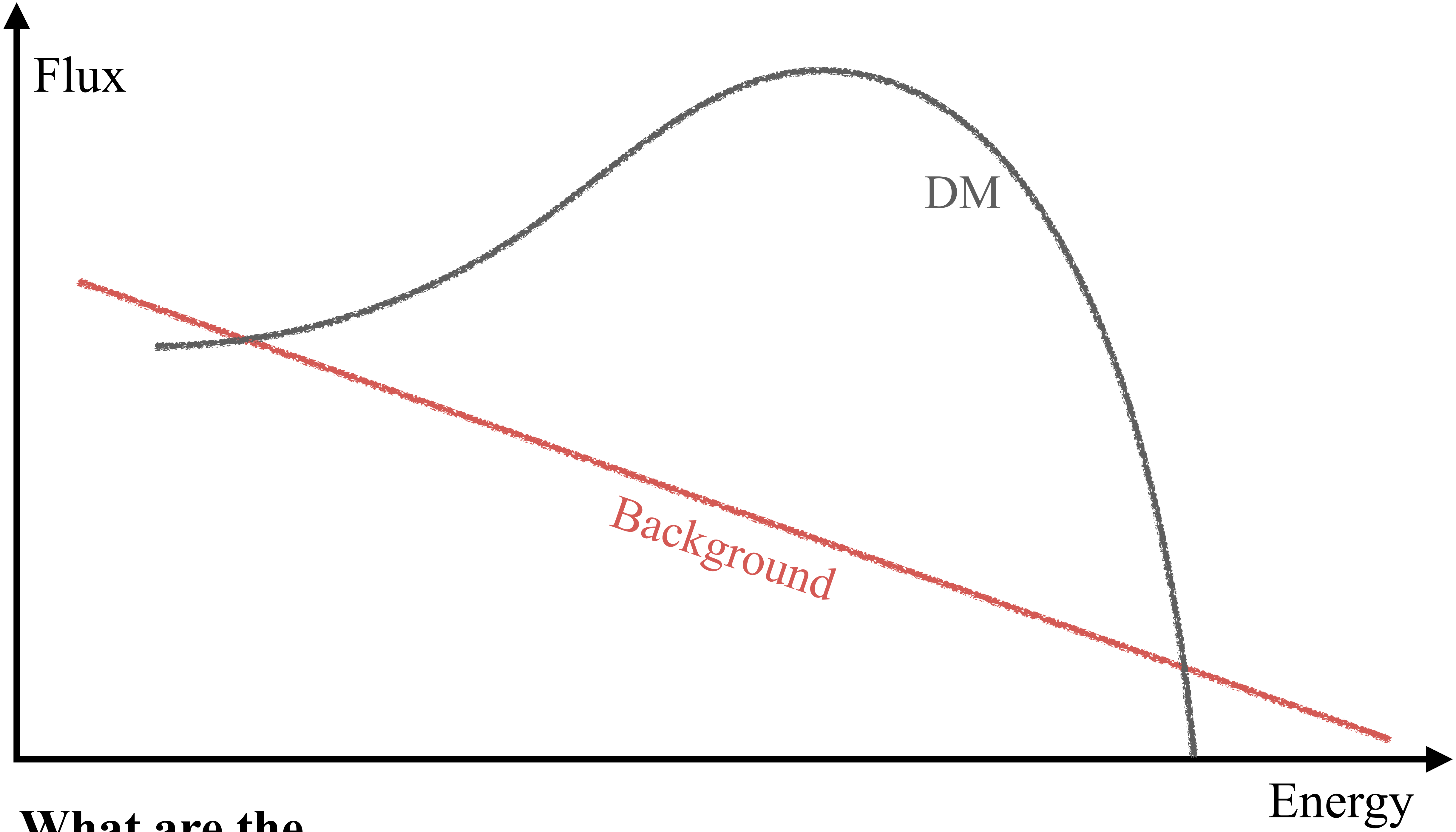
stable SM products

$e^\pm, \overset{(-)}{p}, \overset{(-)}{d}, \overset{(-)}{\nu}...$



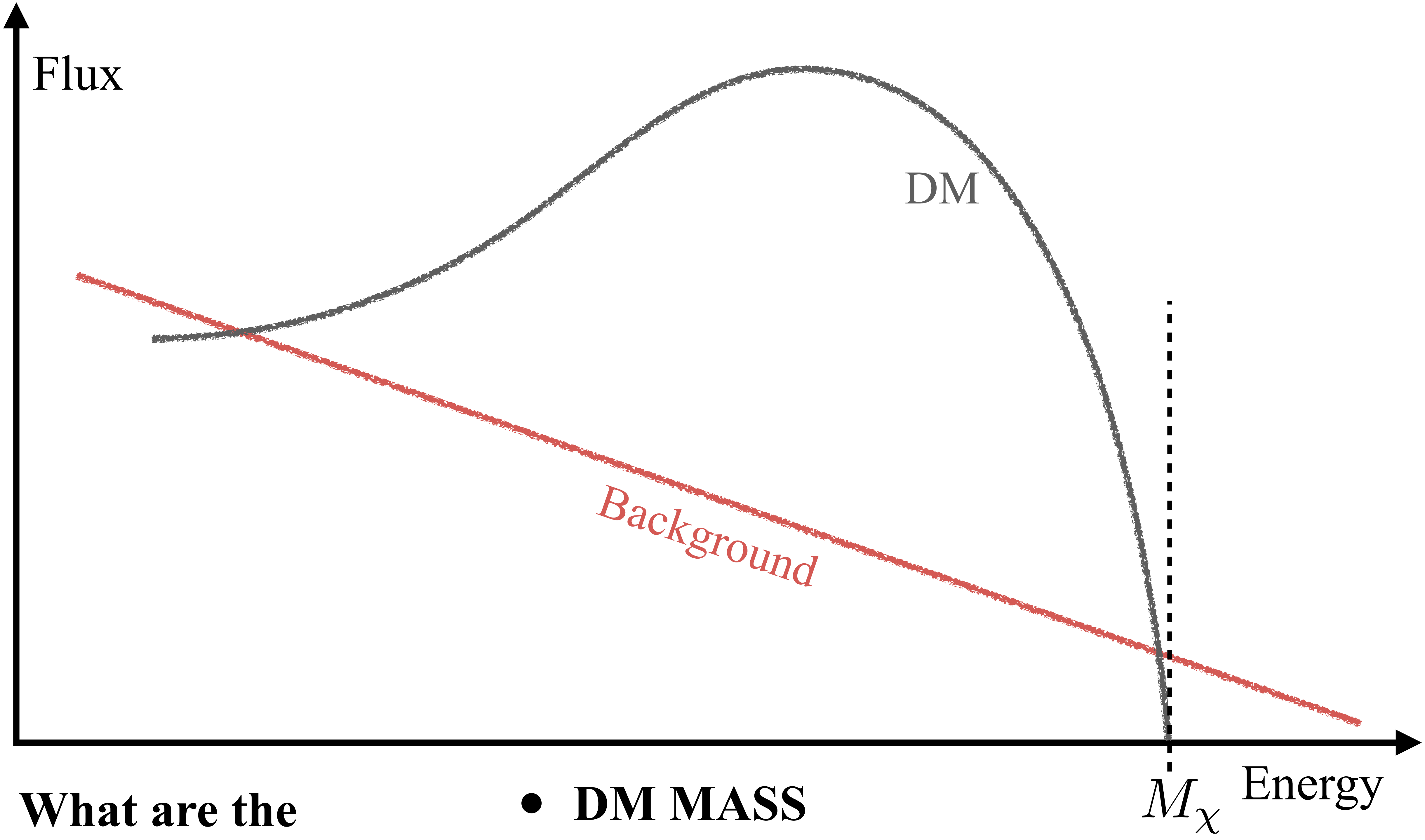
JCAP 1103 (2011) 051
JCAP 1103 (2011) 019

Fluxes @production



What are the particle physics parameters ?

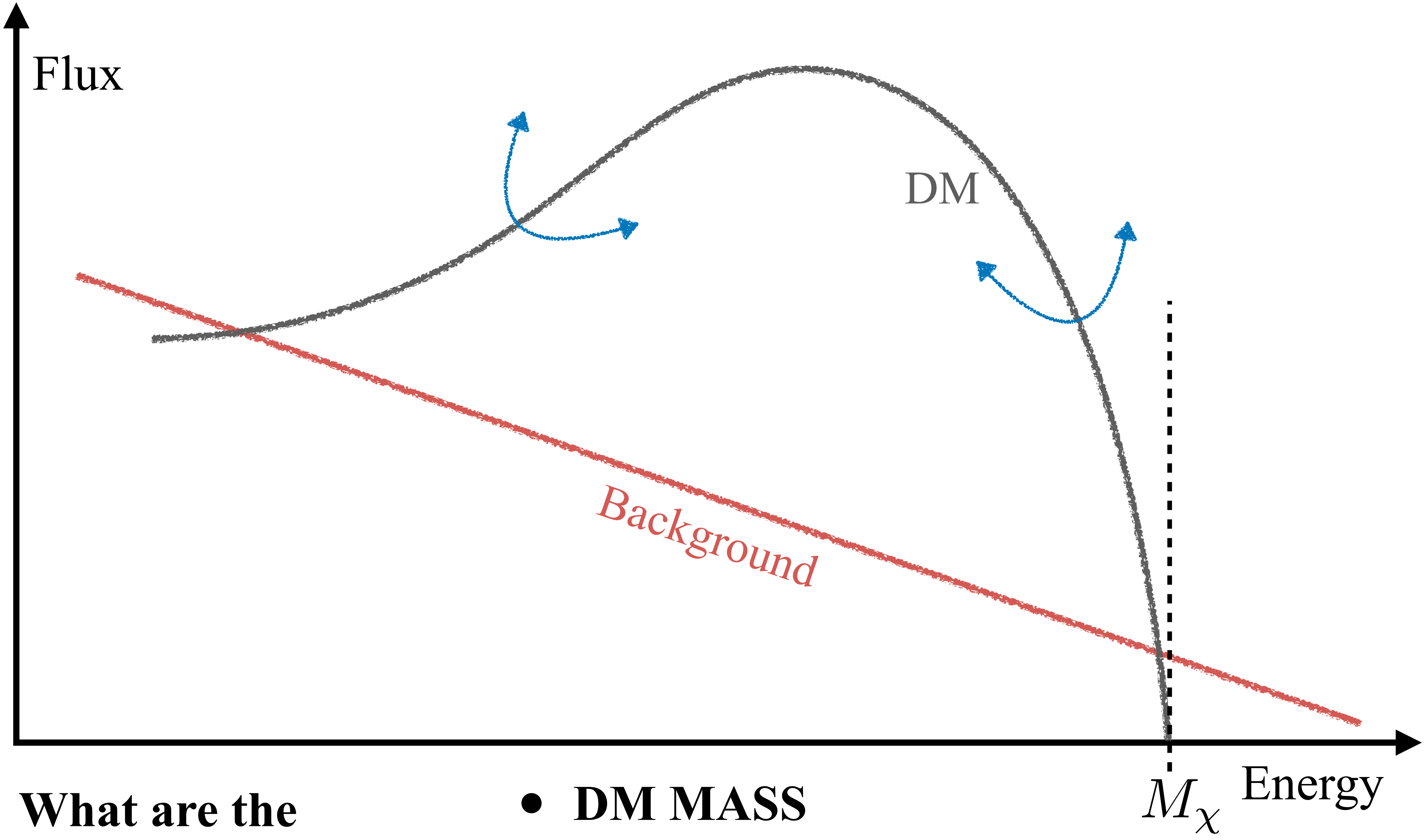
Fluxes @production



What are the particle physics parameters ?

- **DM MASS**

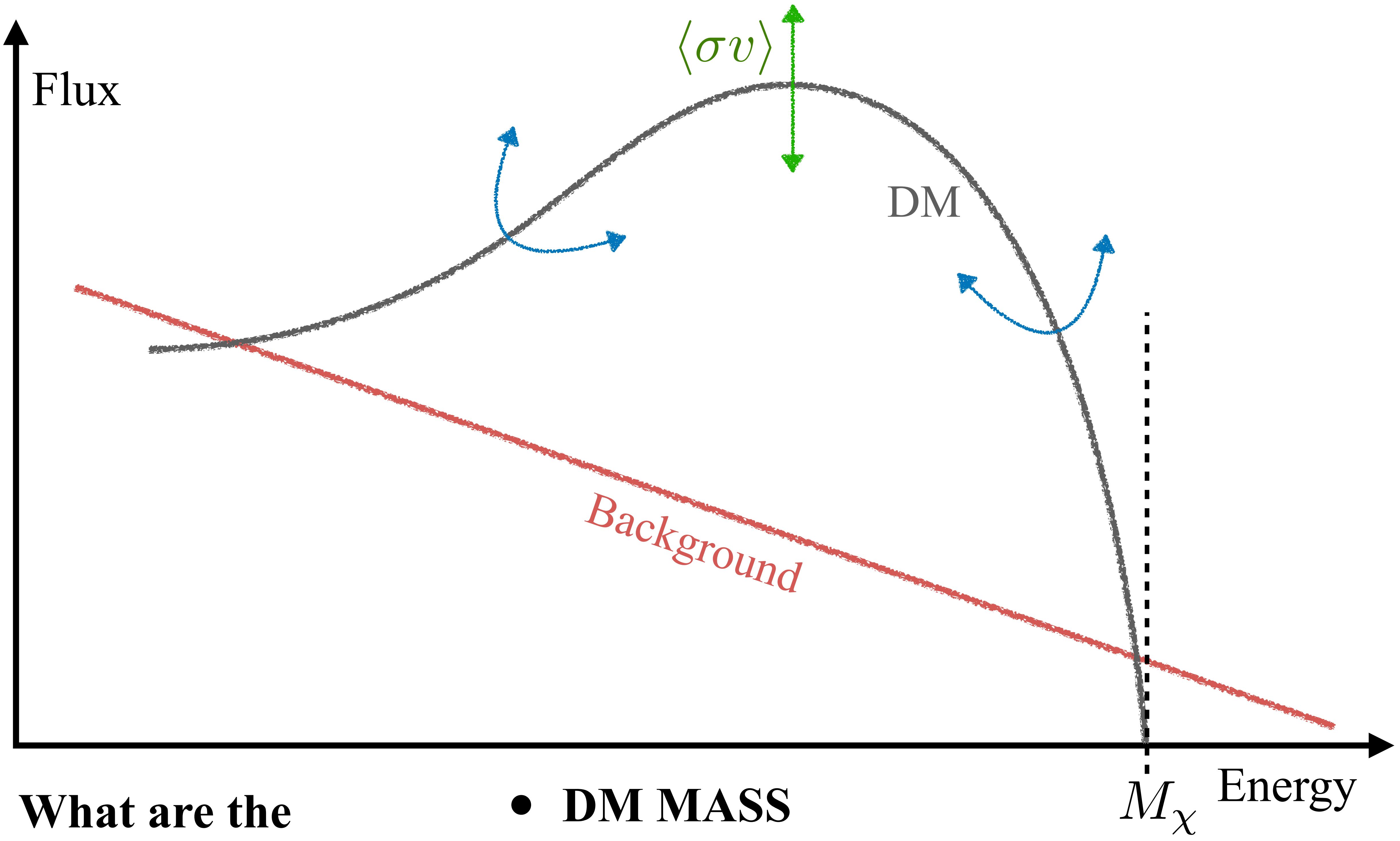
Fluxes @production



What are the particle physics parameters ?

- **DM MASS**
- **PRIMARY CHANNEL**

Fluxes @production



What are the particle physics parameters ?

- **DM MASS**
- **PRIMARY CHANNEL**
- **ANNIHILATION XS**

Prompt γ-ray fluxes @Earth

$$\frac{d\Phi_\gamma}{d\Omega\, dE} = \frac{1}{2}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{M_{\rm DM}}\right)^2 J \underbrace{\sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE}}_{\textbf{PARTICLE PHYSICS}}, \qquad J = \int_{\rm l.o.s.} \underbrace{\frac{ds}{r_\odot}\left(\frac{\rho(r(s,\theta))}{\rho_\odot}\right)^2}_{\textbf{ASTROPHYSICS}}$$

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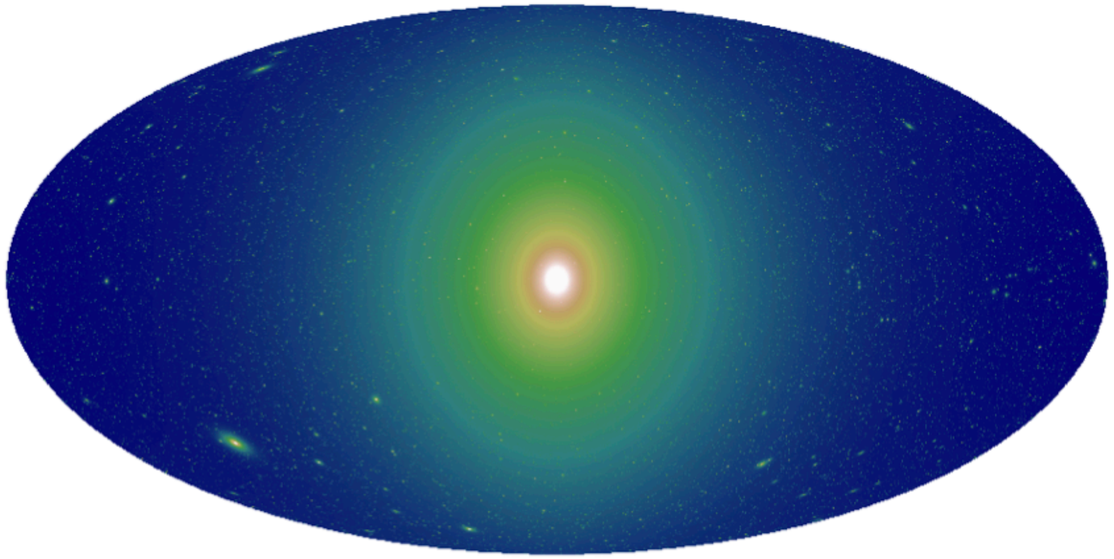
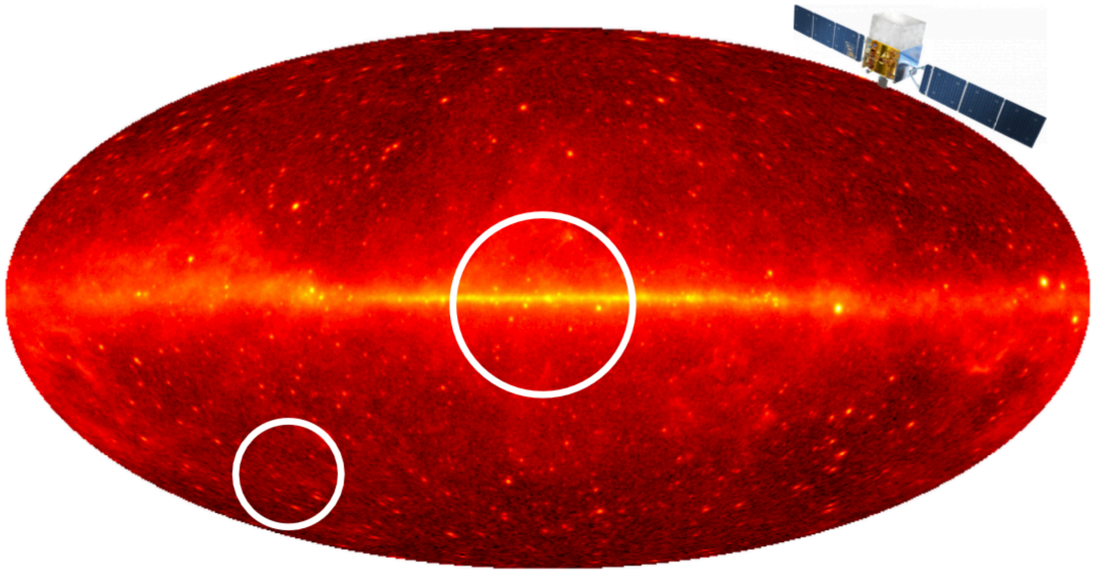
PARTICLE PHYSICS **ASTROPHYSICS**

DM diffuse γ-ray emission (MW-like)



FERMI-LAT γ-ray sky



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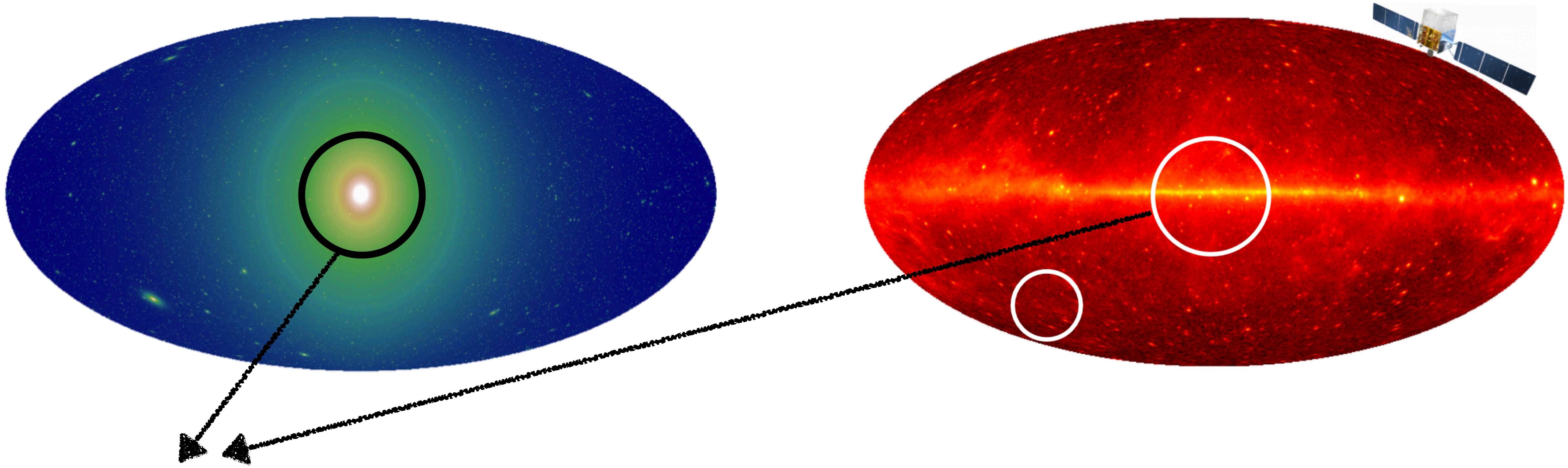

GALACTIC CENTER

- **Very bright**
- **Strong bkg**
- **Large uncertainties**

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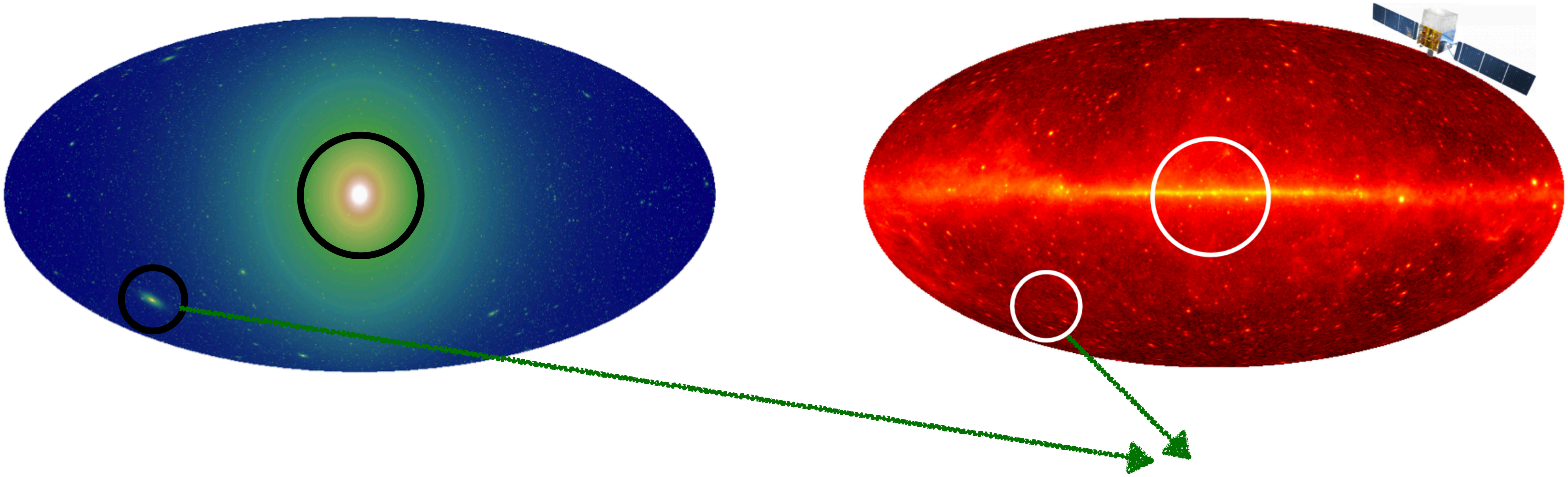

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MW DWARF GALAXIES

- **Clean environment**
- **Low bkg**
- **J-factor is measured**

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PARTICLE PHYSICS **ASTROPHYSICS**

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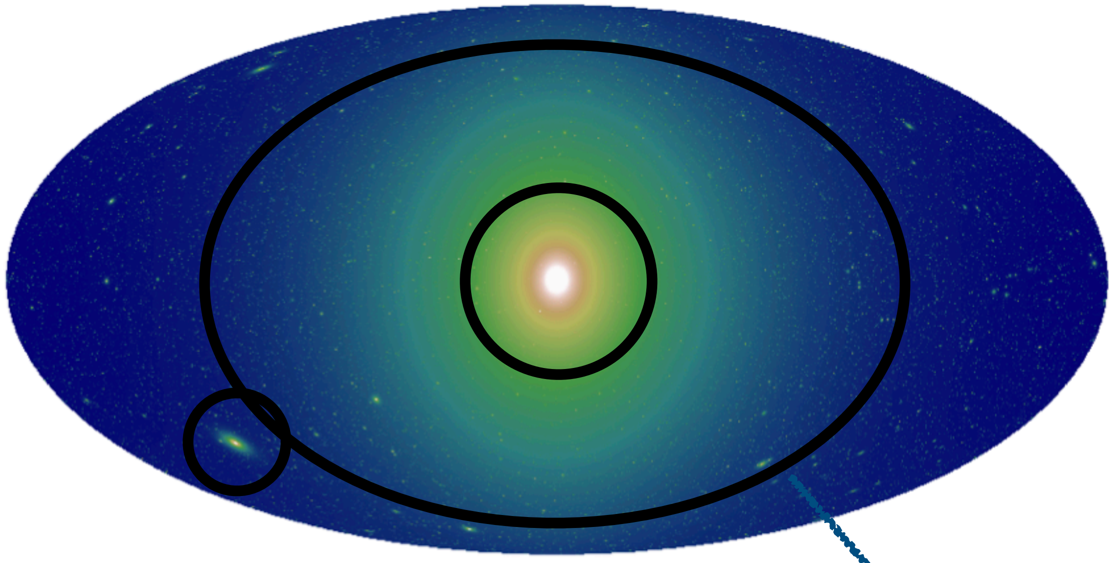
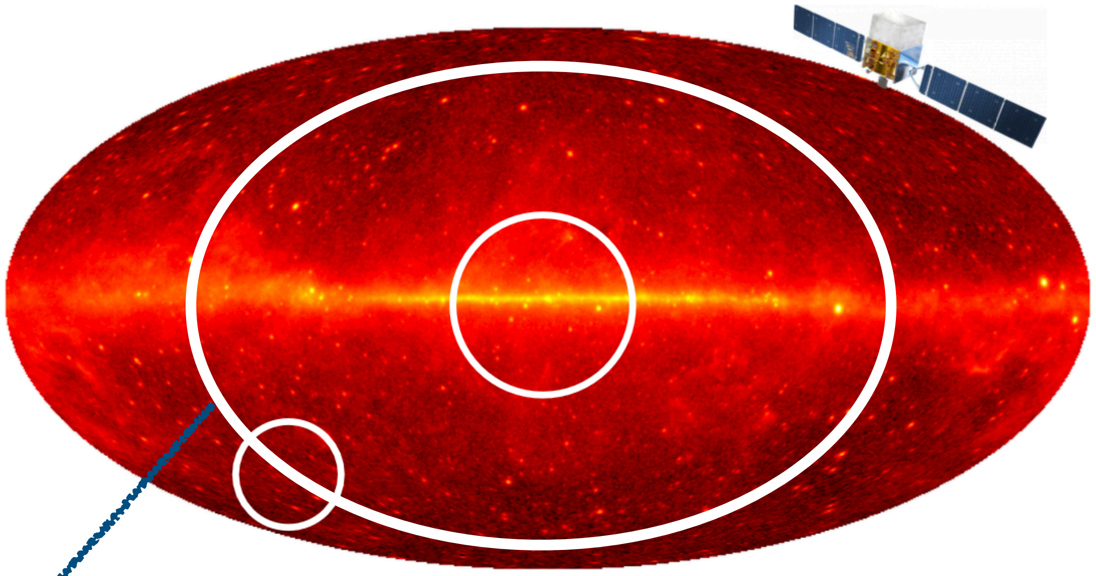


FERMI-LAT γ-ray sky



GALACTIC CENTER

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GALACTIC HALO

MW DWARF GALAXIES

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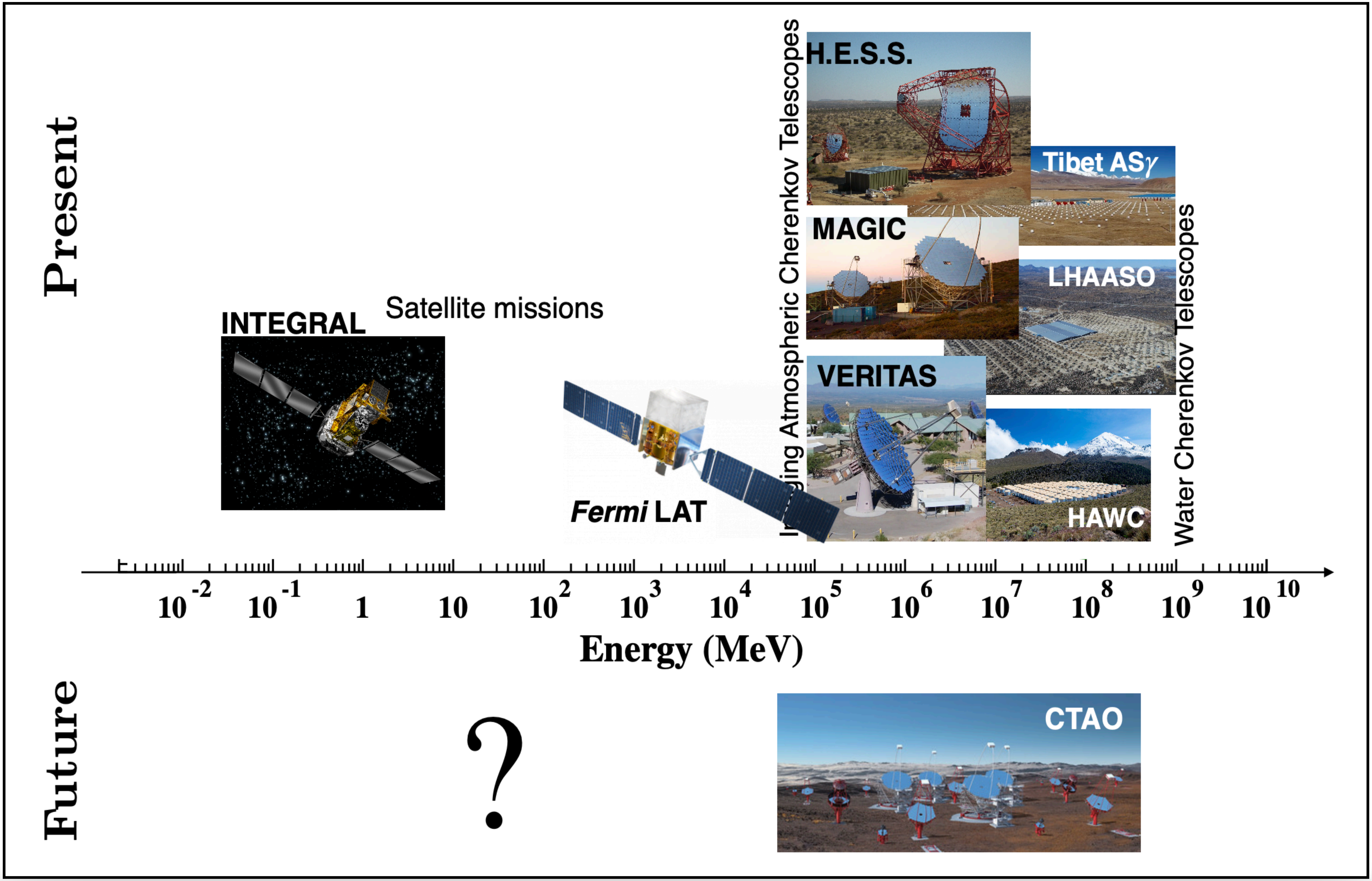
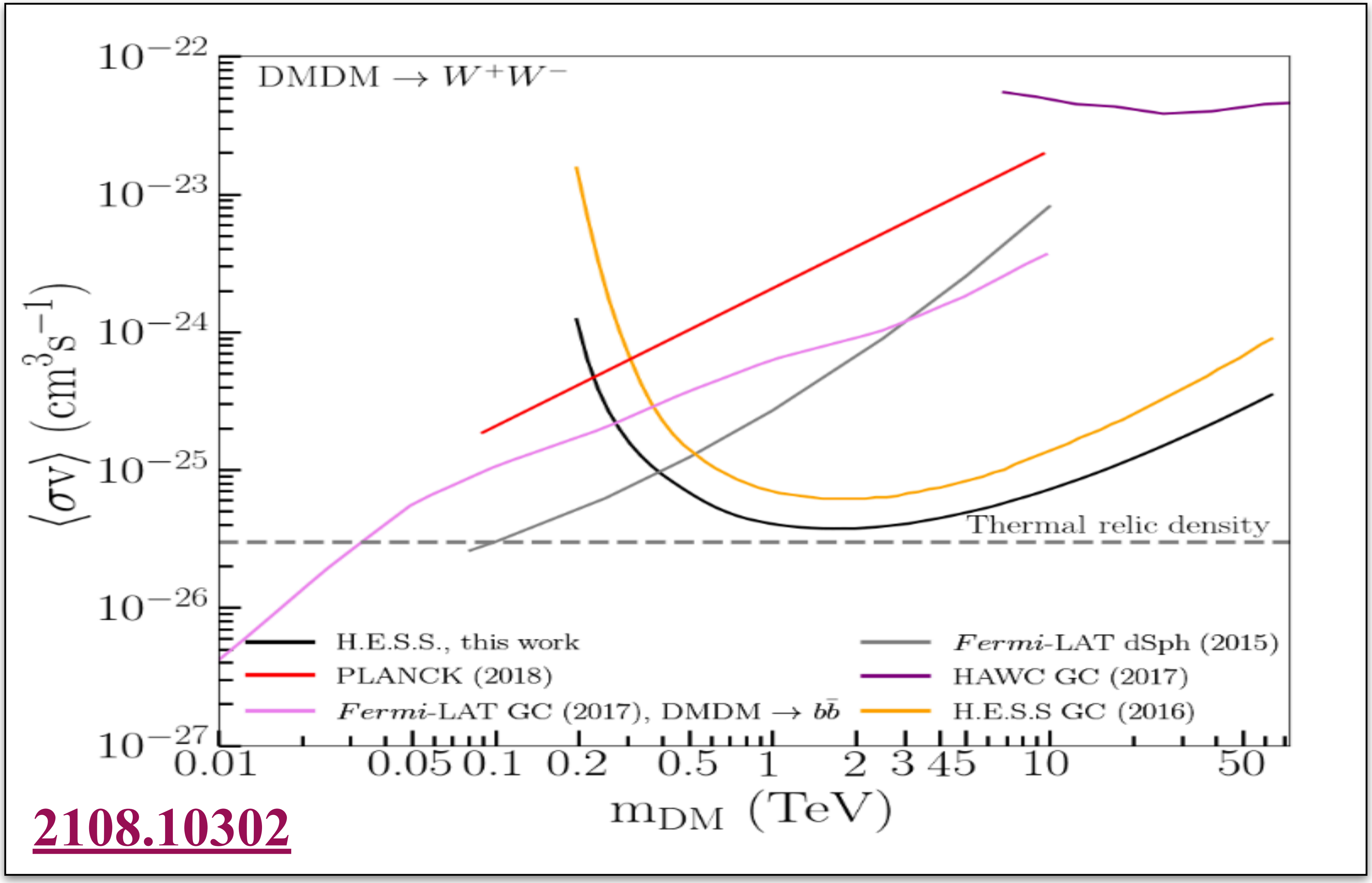
- **Low bkg**
- **J-factor is measured**

Zoology of γ-ray detection facilities



Indirect Detection Bounds: collection

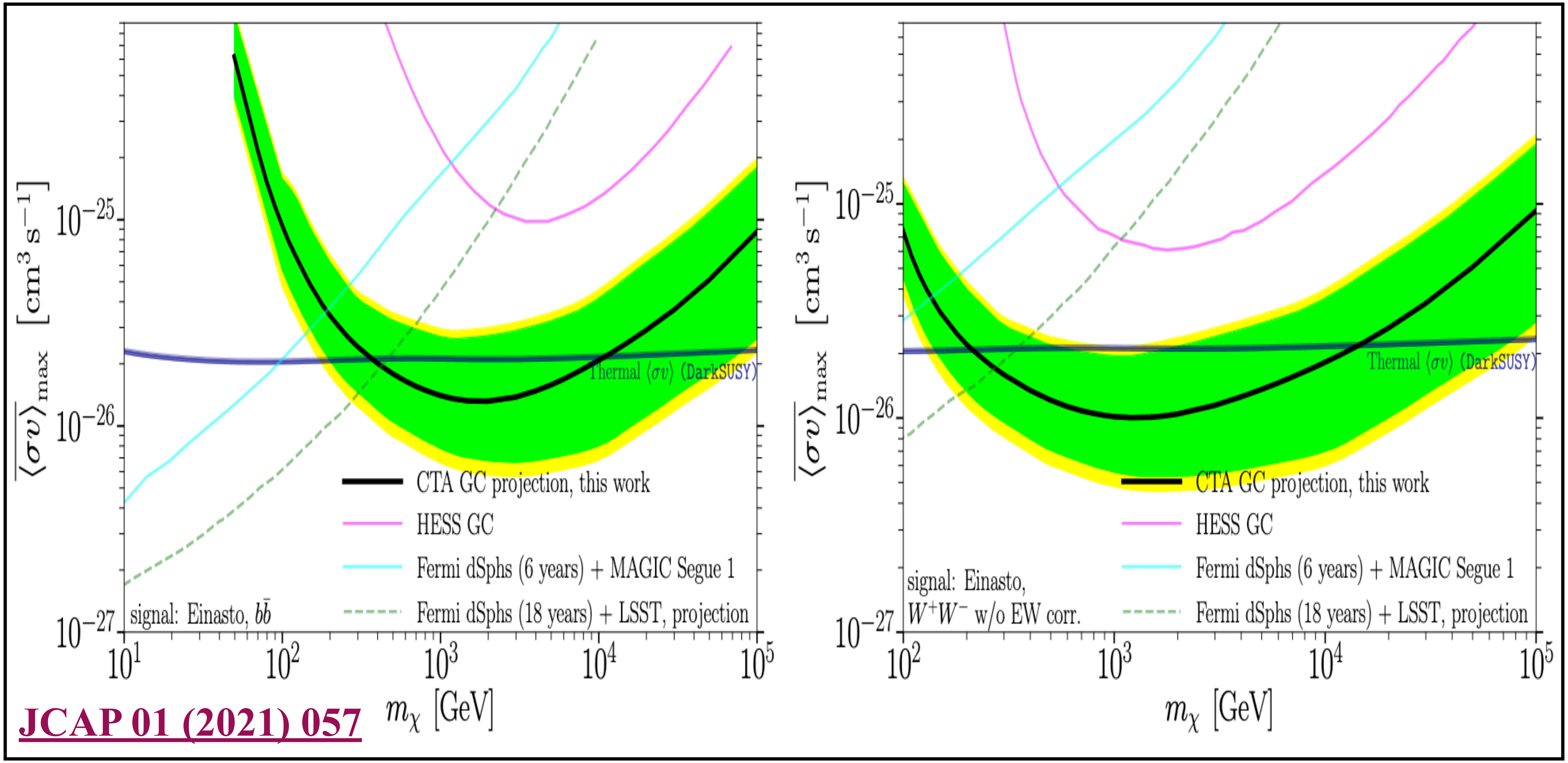


2108.10302

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**

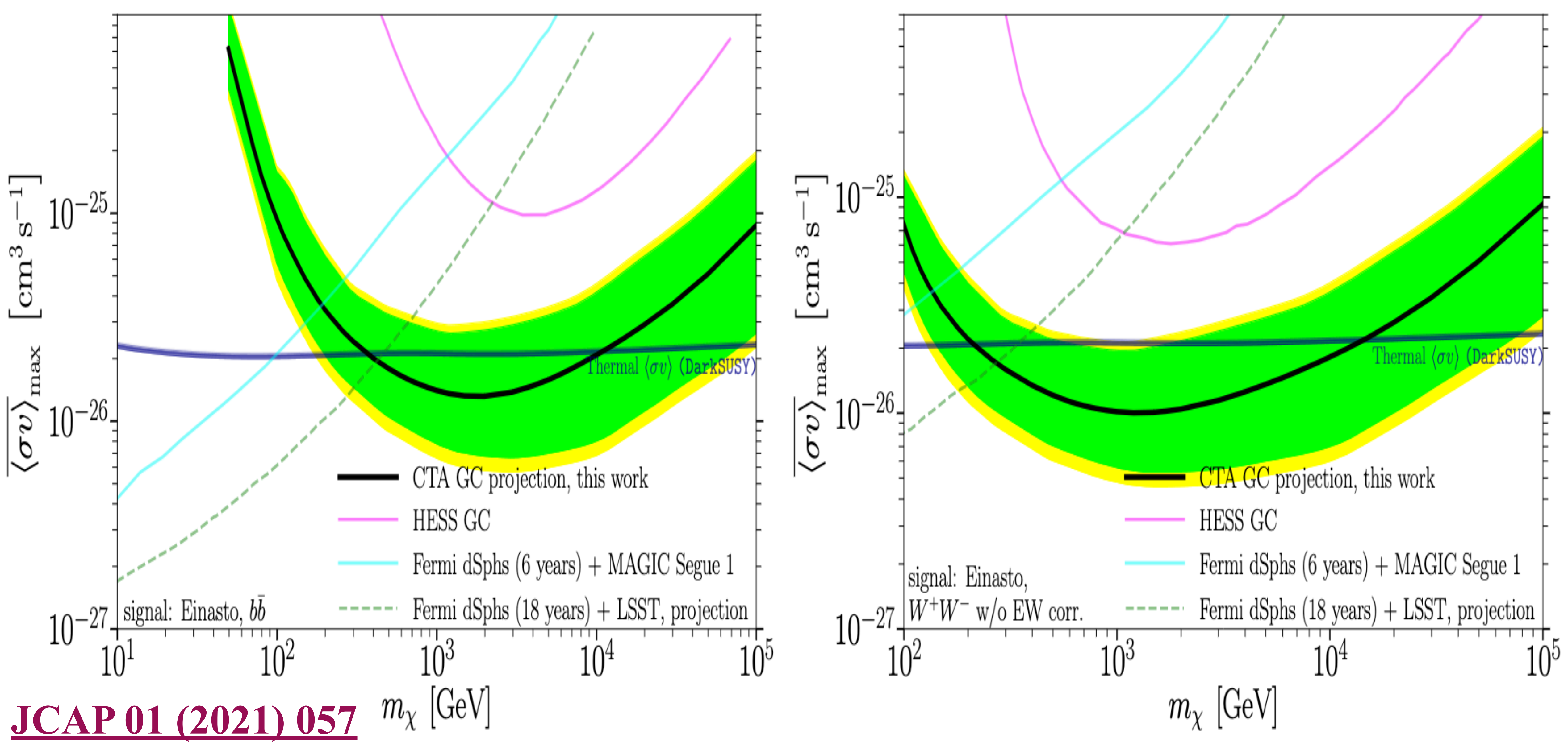
Indirect Detection with CTA: GC



JCAP 01 (2021) 057

FERMI & CTA can close the **Thermal window** for *s*-wave annihilations

Indirect Detection with CTA: GC



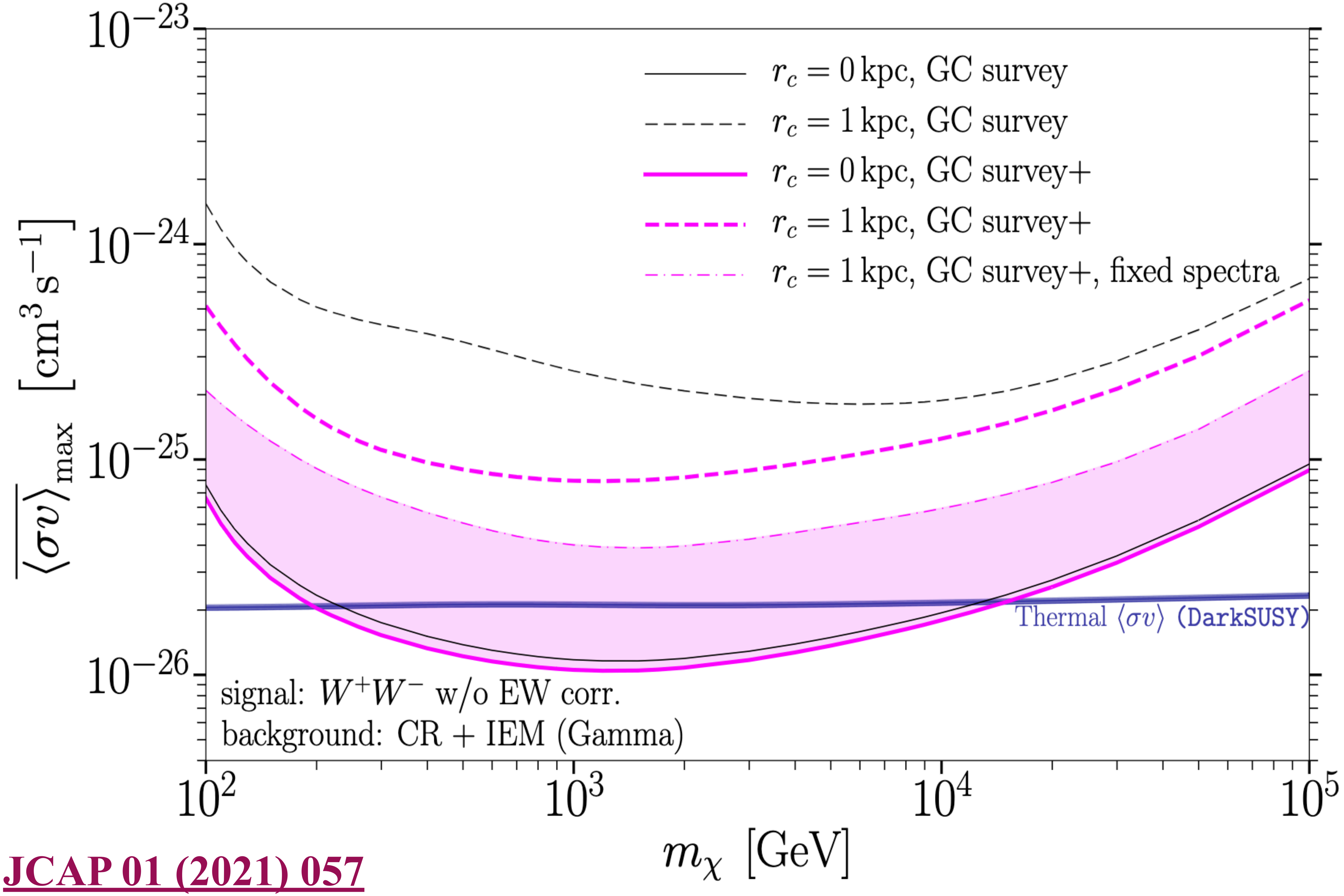
JCAP 01 (2021) 057

FERMI & CTA can close the **Thermal window** for *s*-wave annihilations

✦BE AWARE OF UNCERTAINTIES

Extensive DM cores are a blind spot for CTA (high degeneracy with the CR component).

Indirect Detection with CTA: GC



JCAP 01 (2021) 057

Indirect detection *vs* WIMP paradigm

FERMI & CTA can test the thermal DM production

➡ FERMI excludes the thermal production for light DM

➡ CTA will be sensitive to thermal DM in the multi-TeV mass range

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★ **Importantly:**

To draw robust conclusions it is preferable to utilize clean astrophysical environments

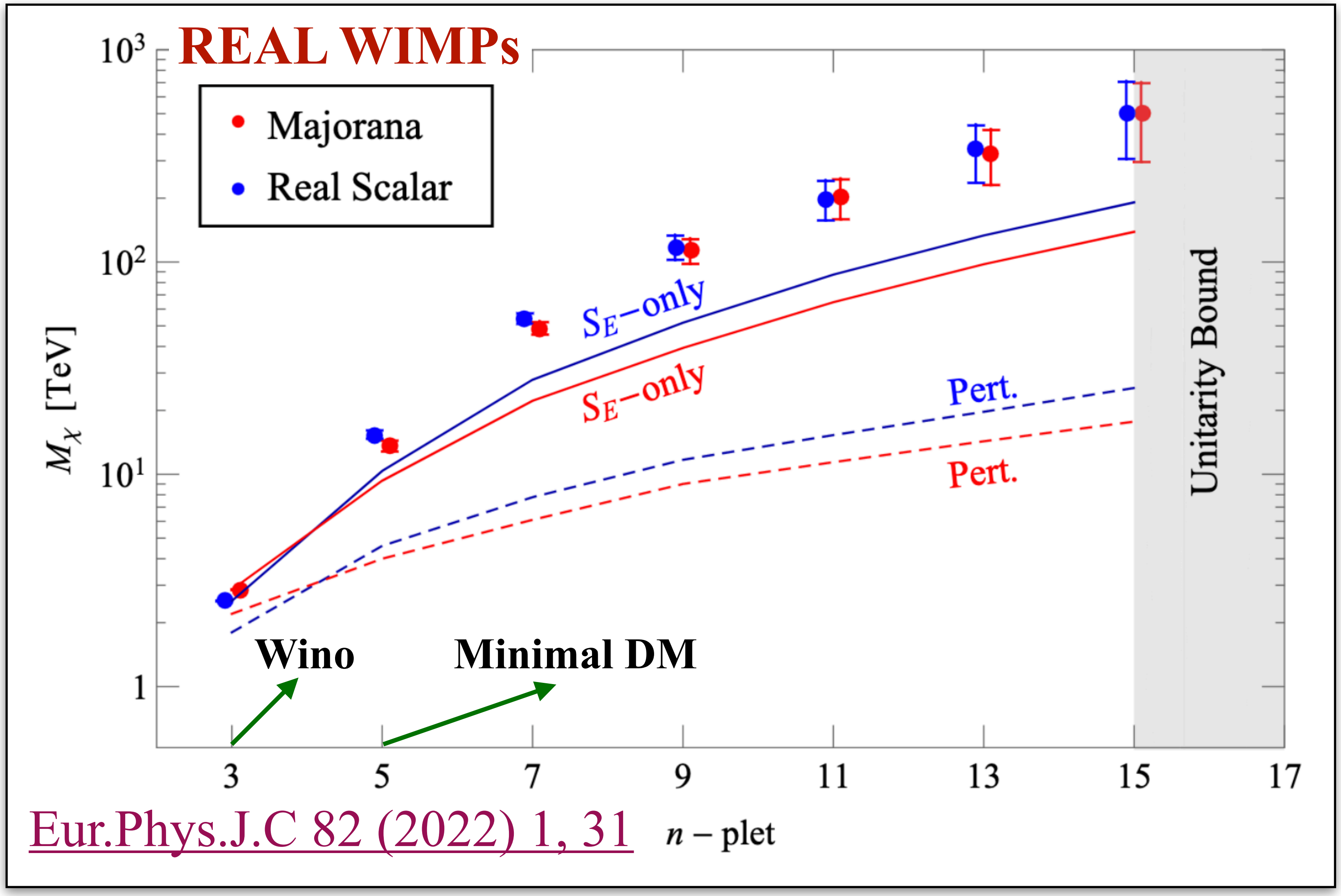
EW multiplets as DM candidates

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

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

- **Fully predicable**
- **The mass is set by the requirement of the relic abundance**

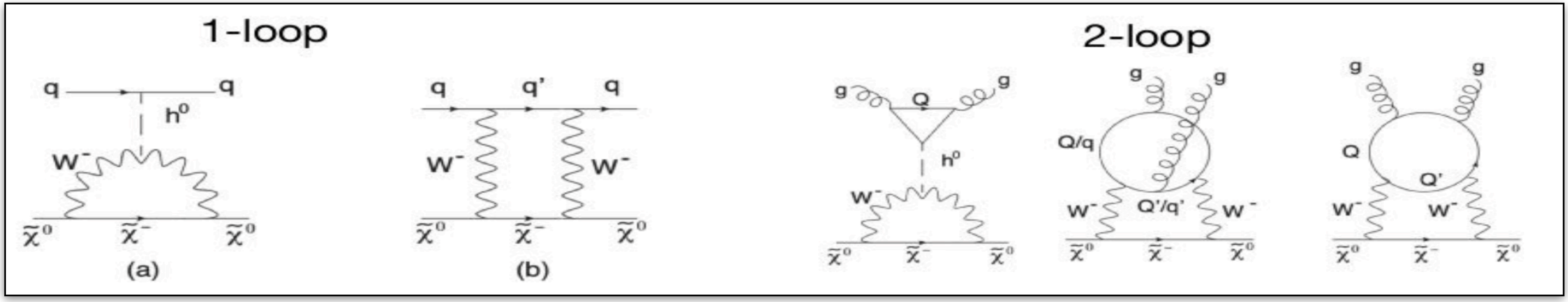
Thermal freeze-out points to multi-TeV mass scales

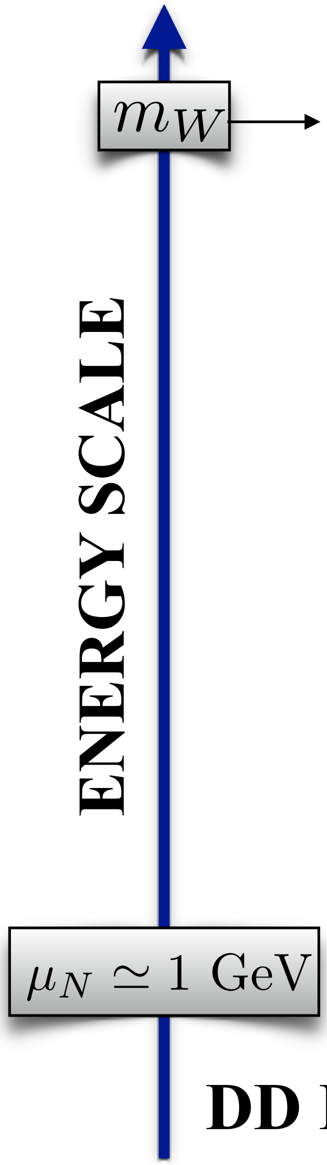


Eur.Phys.J.C 82 (2022) 1, 31

Direct Detection of EW multiplets

For EW multiplets Z-mediated elastic scattering is forbidden





$$m_W \longrightarrow \mathcal{L}_{\rm eff} = \bar{\chi}\chi\left(f_q m_q \bar{q}q + f_G G_{\mu\nu}G^{\mu\nu}\right) + \frac{g_q}{M_\chi}\bar{\chi} i\partial^\mu\gamma^\nu\chi\mathcal{O}^q_{\mu\nu} + d_q\left(\bar{\chi}\gamma^\mu\gamma_5\chi\right)\left(\bar{q}\gamma_\mu\gamma_5 q\right)$$

$$c^{(d)}_\alpha(m_W) \equiv \{f_q, f_G, g_q, d_q\}$$

coupling @mediator mass: functions of (*n*, *Y*)

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

ENERGY SCALE

$\mu_N \simeq 1$ GeV

DD EXPERIMENTS

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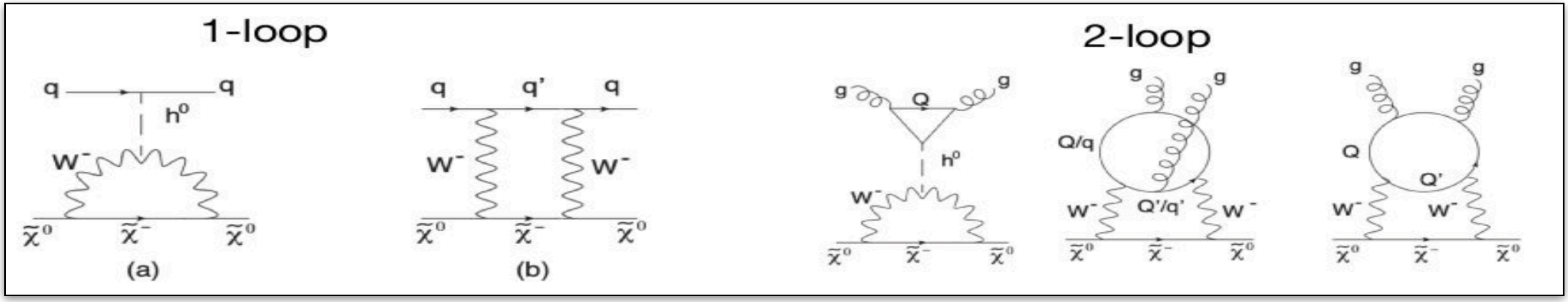

ENERGY SCALE

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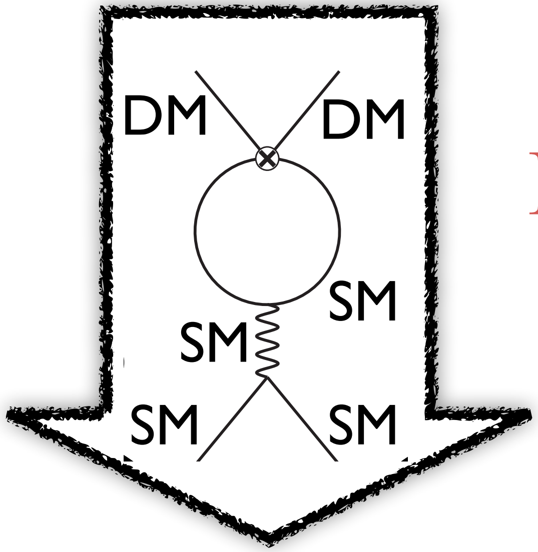

Renormalization Group Evolution

$\mu_N \simeq 1$ GeV — $c^{(d)}_\alpha(\mu_N)$

DD EXPERIMENTS

Direct Detection of EW multiplets

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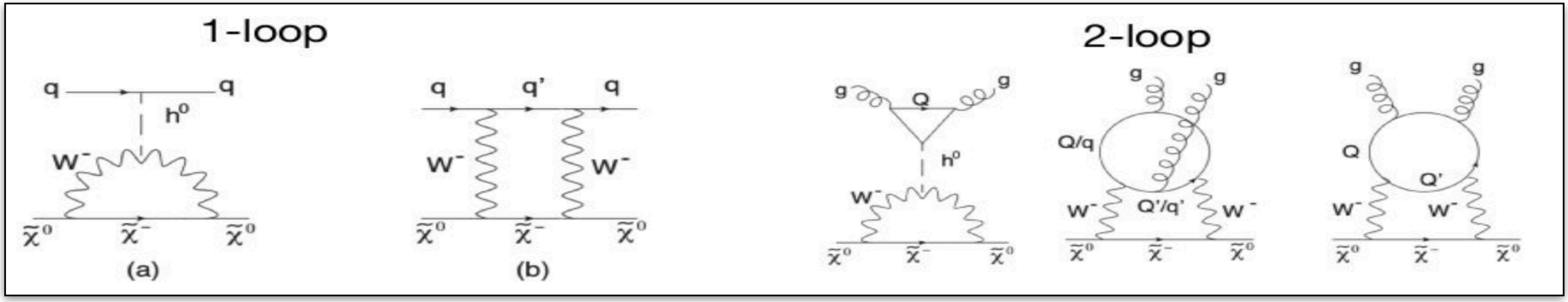

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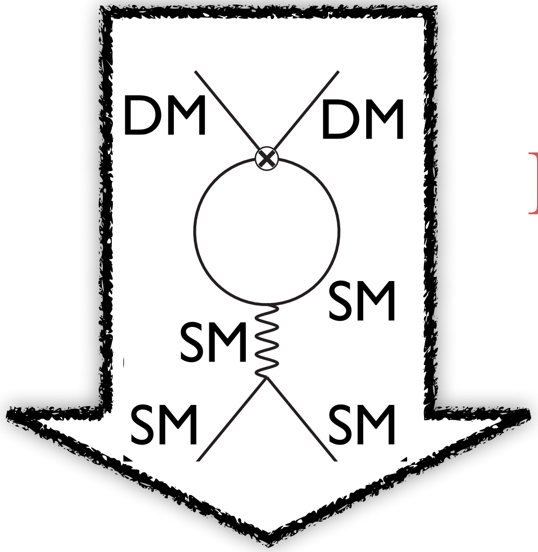

Renormalization Group Evolution

$\mu_N \simeq 1$ GeV — $c_\alpha^{(d)}(\mu_N)$ — **coupling @nuclear energy scale** → $\langle\chi N|\mathcal{L}^N_{\rm eff}(\mu_N)|N\chi\rangle$

DD EXPERIMENTS

Direct Detection of EW multiplets

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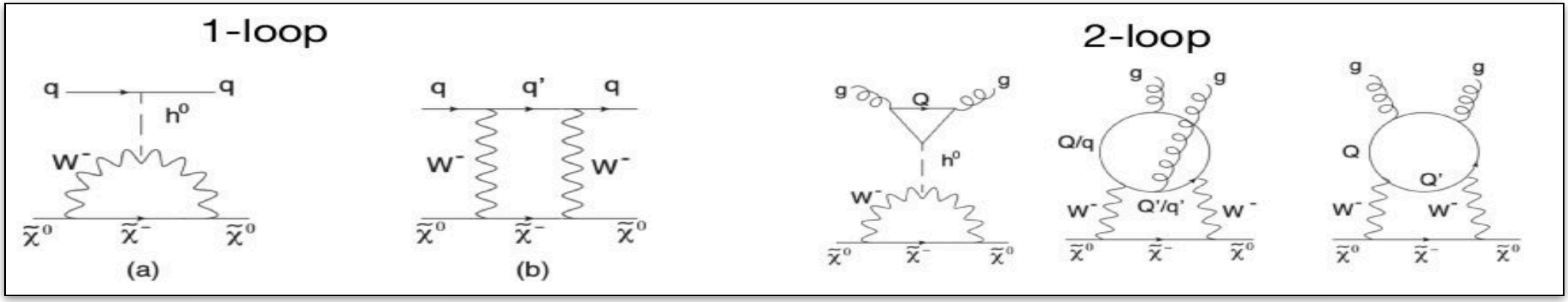


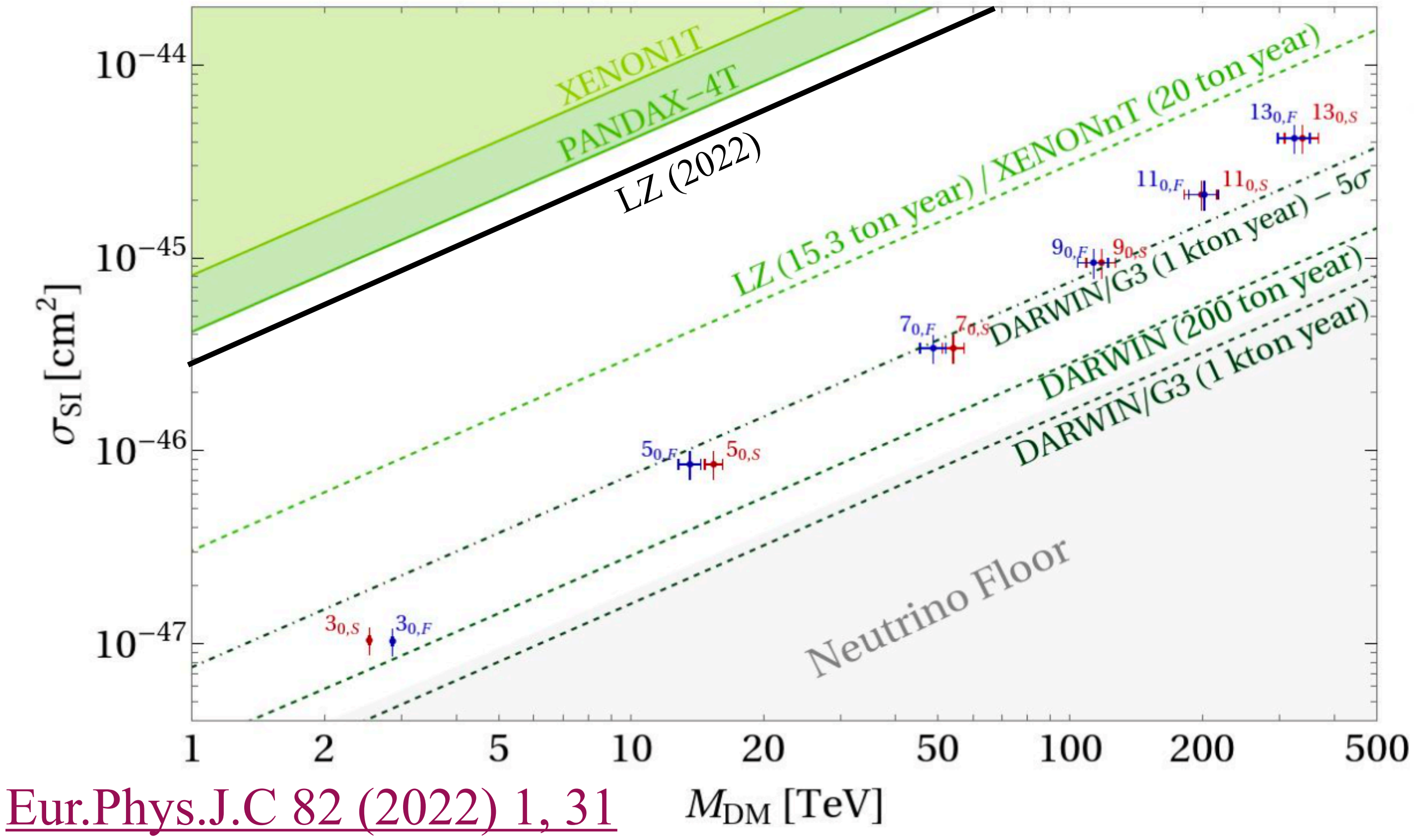
EW multiplets induce a DM-*n* SI interaction at loop-level

$$\sigma_{\rm SI} = \frac{4}{\pi} m_n^4 |k_n^{\rm EW}|^2 \simeq 10^{-49}{\rm cm}^2 \left(n^2 - 1 - \xi Y^2\right)^2 \qquad \text{with } \xi = 16.6 \pm 1.3$$

see e.g. Bottaro *et al.* **Eur.Phys.J.C 82 (2022) 1, 31** and **Eur.Phys.J.C 82 (2022) 11, 992**

- **Very small cross section:** The SI interaction occurs at loop-level
- **Accidental cancellation:** for specific choices of *n* and *Y* there is a cancellation: (e.g. $\left(n^2 - 1 - \xi Y^2\right)^2 \simeq 0$ for $2_{1/2}$ and 5_1)

Direct Detection of EW multiplets



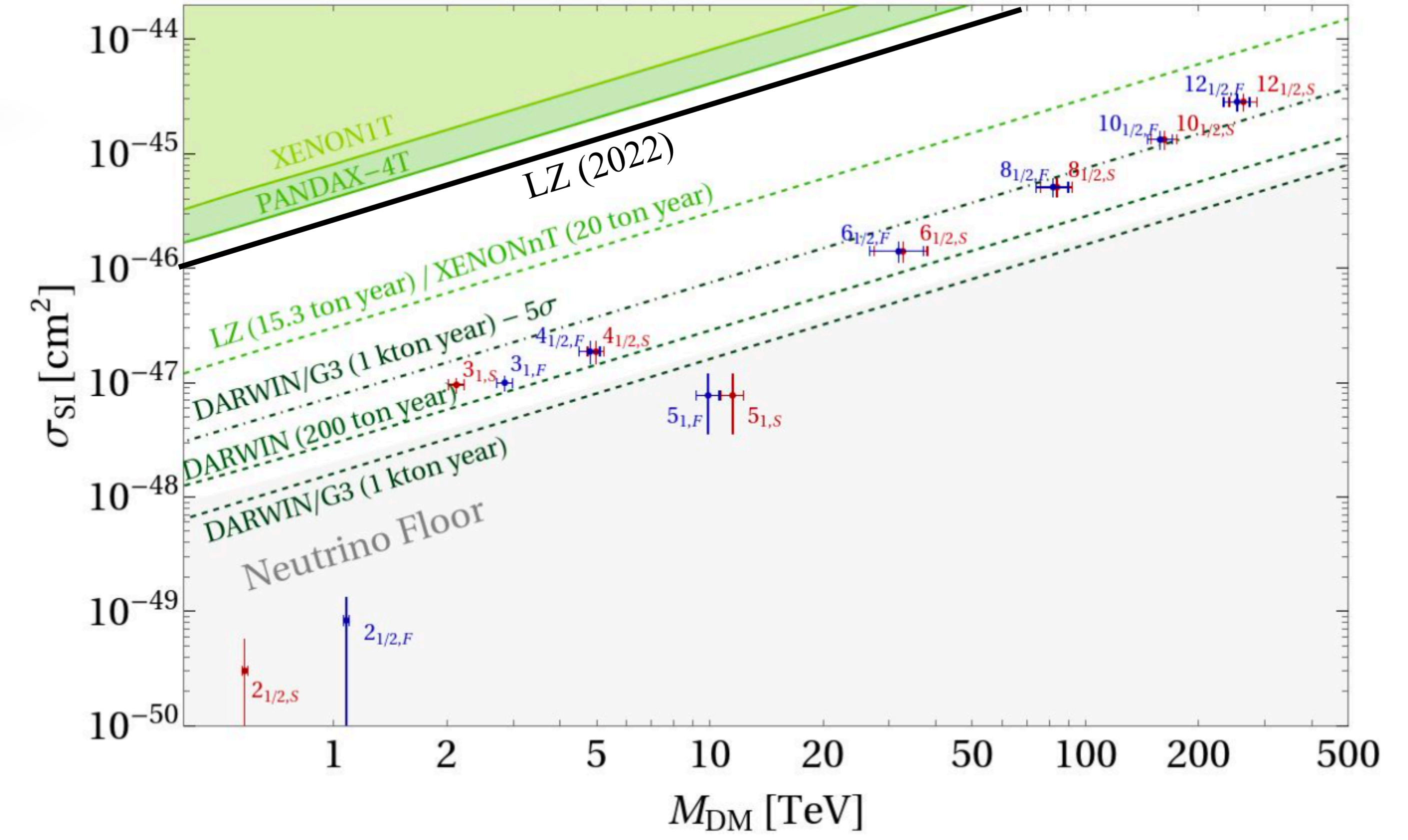
Eur.Phys.J.C 82 (2022) 1, 31

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)



Indirect Detection of EW multiplets

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

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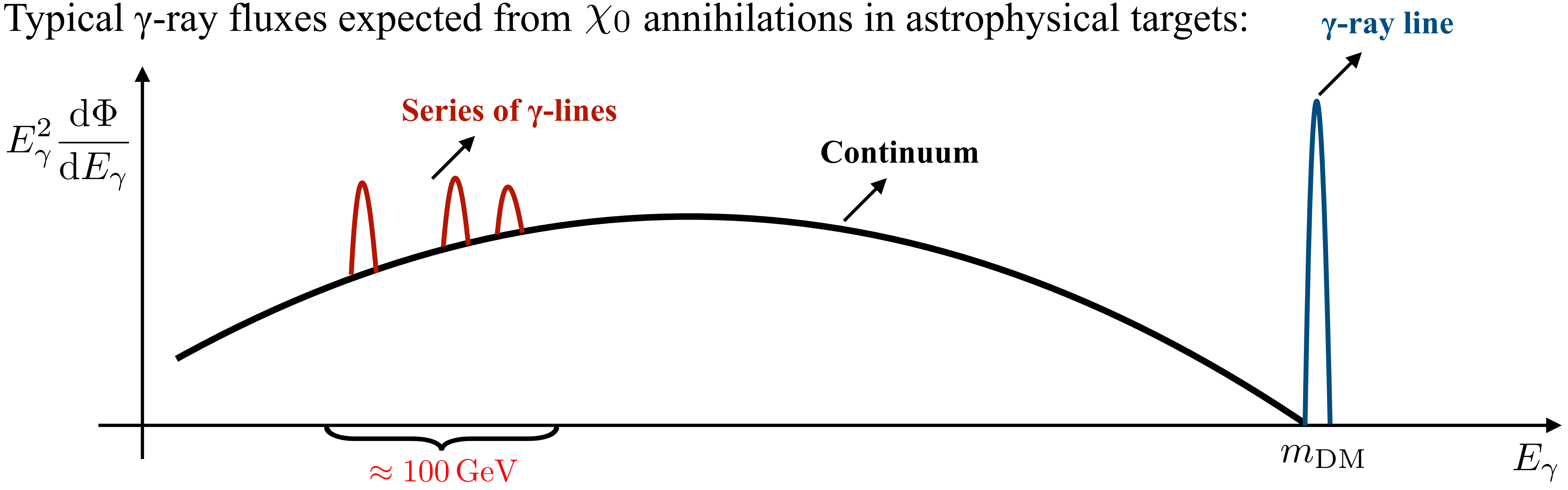
Typical γ-ray fluxes expected from χ_0 annihilations in astrophysical targets:



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

Indirect Detection of EW multiplets

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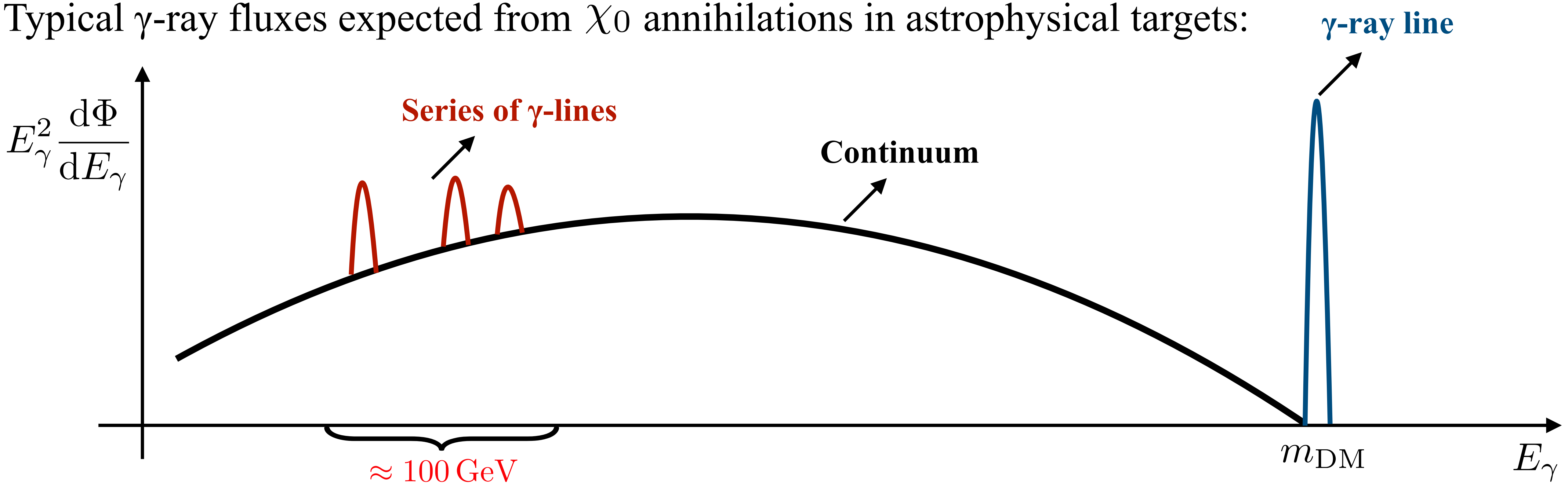


Continuum: from the decays and hadronization of heavy EW gauge bosons

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

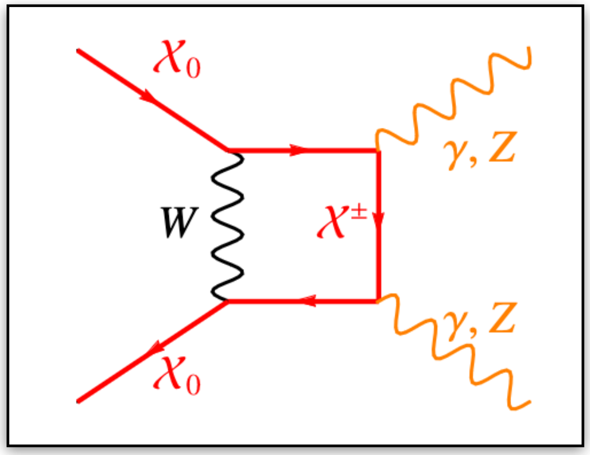
Series of γ-lines: Due to the formation of WIMPONIUM

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

➡ One can look for correlations of multiple lines!

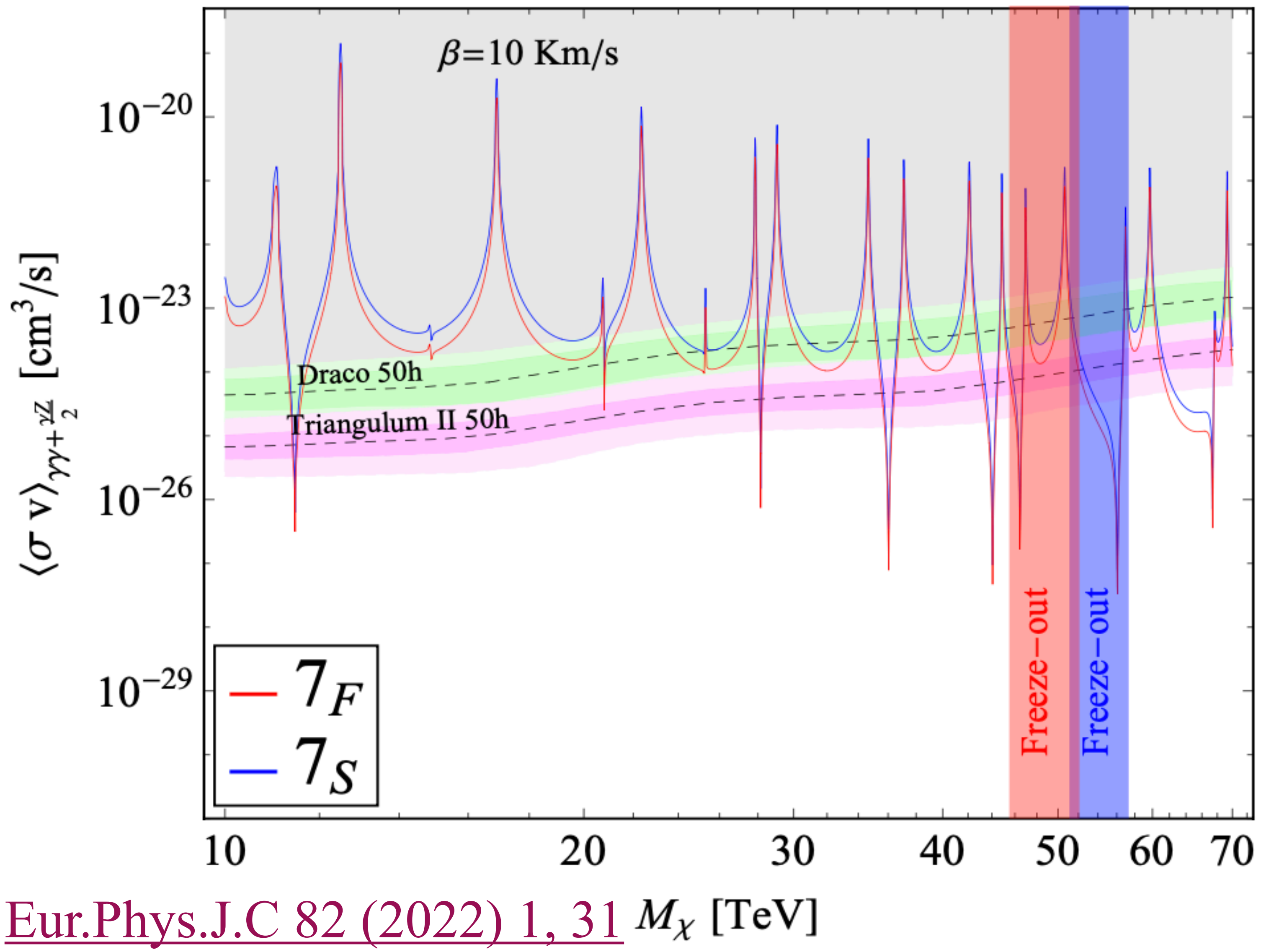
Indirect Detection of EW multiplets

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



CTA sensitivity of γ-ray lines towards clean environments

PRELIMINARY



Eur.Phys.J.C 82 (2022) 1, 31

To be included:

- continuum (small effect)
- BS formations
- Correlations of multiples lines

Conclusions & outlook

- I review the model independent signatures in both direct and indirect detection of heavy DM

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- Current and upcoming experiments are pushing previous searches to probe deeper the multi-TeV mass range

- We envisage a plan to say a final word on the EW nature of 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 (refer to **BUTTAZZO's talk**)

Backup slides

High-energy Operators

Effective operators for DM interactions with *q* and *g*

Matching onto
NR EFT

Produce bounds on the energy scale of such operators

J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait and H. -B. Yu, PRD 82 (2010) 116010, arXiv:1008.1783

P. J. Fox, R. Harnik, J. Kopp and Y. Tsai, PRD 84 (2011) 014028, arXiv:1103.0240

K. Cheung, P. -Y. Tseng, Y. -L. S. Tsai and T. -C. Yuan, JCAP 1205 (2012) 001, arXiv:1201.3402

J.-M. Zheng, Z.-H. Yu, J.-W. Shao, X.-J. Bi, Z. Li and H.-H. Zhang, NPB 854 (2012) 350, arXiv:1012.2022

Z.-H. Yu, J.-M. Zheng, X.-J. Bi, Z. Li, D.-X. Yao and H.-H. Zhang, NPB 860 (2012) 115, arXiv:1112.6052

and …

High-energy Operators

DIRAC DM

DIM-6 operators:
Constructed with neutral DM & SM quarks

$$\mathcal{O}_1^q = \bar{\chi}\chi\;\bar{q}q\,, \qquad \mathcal{O}_2^q = \bar{\chi}\,i\gamma^5\chi\;\bar{q}q\,,$$

$$\mathcal{O}_3^q = \bar{\chi}\chi\;\bar{q}\,i\gamma^5 q\,, \qquad \mathcal{O}_4^q = \bar{\chi}\,i\gamma^5\chi\;\bar{q}\,i\gamma^5 q\,,$$

$$\mathcal{O}_5^q = \bar{\chi}\gamma^\mu\chi\;\bar{q}\gamma_\mu q\,, \qquad \mathcal{O}_6^q = \bar{\chi}\gamma^\mu\gamma^5\chi\;\bar{q}\gamma_\mu q\,,$$

$$\mathcal{O}_7^q = \bar{\chi}\gamma^\mu\chi\;\bar{q}\gamma_\mu\gamma^5 q\,, \qquad \mathcal{O}_8^q = \bar{\chi}\gamma^\mu\gamma^5\chi\;\bar{q}\gamma_\mu\gamma^5 q\,,$$

$$\mathcal{O}_9^q = \bar{\chi}\,\sigma^{\mu\nu}\chi\;\bar{q}\,\sigma_{\mu\nu} q\,, \qquad \mathcal{O}_{10}^q = \bar{\chi}\,i\,\sigma^{\mu\nu}\gamma^5\chi\;\bar{q}\,\sigma_{\mu\nu} q\,,$$

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$$\mathcal{O}_3^q = \bar{\chi}\chi\,\bar{q}\,i\gamma^5 q\,, \qquad \mathcal{O}_4^q = \bar{\chi}\,i\gamma^5\chi\,\bar{q}\,i\gamma^5 q\,,$$
$$\mathcal{O}_5^q = \bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q\,, \qquad \mathcal{O}_6^q = \bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q\,,$$
$$\mathcal{O}_7^q = \bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu\gamma^5 q\,, \qquad \mathcal{O}_8^q = \bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q\,,$$
$$\mathcal{O}_9^q = \bar{\chi}\,\sigma^{\mu\nu}\chi\,\bar{q}\,\sigma_{\mu\nu}q\,, \qquad \mathcal{O}_{10}^q = \bar{\chi}\,i\,\sigma^{\mu\nu}\gamma^5\chi\,\bar{q}\,\sigma_{\mu\nu}q\,,$$

DIM-7 operators:
SM gauge invariant couple DM with gluons

$$\mathcal{O}_1^g = \frac{\alpha_s}{12\pi}\,\bar{\chi}\chi\,G^a_{\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{O}_2^g = \frac{\alpha_s}{12\pi}\,\bar{\chi}\,i\gamma^5\chi\,G^a_{\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{O}_3^g = \frac{\alpha_s}{8\pi}\,\bar{\chi}\chi\,G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\,, \qquad \mathcal{O}_4^g = \frac{\alpha_s}{8\pi}\,\bar{\chi}\,i\gamma^5\chi\,G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\,,$$

High-energy Operators

MAJORANA DM

DIM-6 operators:
Constructed with neutral DM & SM quarks

$$\mathcal{O}_1^q = \bar{\chi}\chi\,\bar{q}q\,, \qquad \mathcal{O}_2^q = \bar{\chi}\,i\gamma^5\chi\,\bar{q}q\,,$$

$$\mathcal{O}_3^q = \bar{\chi}\chi\,\bar{q}\,i\gamma^5 q\,, \qquad \mathcal{O}_4^q = \bar{\chi}\,i\gamma^5\chi\,\bar{q}\,i\gamma^5 q\,,$$

$$\mathcal{O}_5^q = \xcancel{\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q}\,, \qquad \mathcal{O}_6^q = \bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q\,,$$

$$\mathcal{O}_7^q = \xcancel{\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu\gamma^5 q}\,, \qquad \mathcal{O}_8^q = \bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q\,,$$

$$\mathcal{O}_9^q = \xcancel{\bar{\chi}\,\sigma^{\mu\nu}\chi\,\bar{q}\,\sigma_{\mu\nu}q}\,, \qquad \mathcal{O}_{10}^q = \xcancel{\bar{\chi}\,i\,\sigma^{\mu\nu}\gamma^5\chi\,\bar{q}\,\sigma_{\mu\nu}q}\,,$$

DIM-7 operators:
SM gauge invariant couple DM with gluons

$$\mathcal{O}_1^g = \frac{\alpha_s}{12\pi}\,\bar{\chi}\chi\,G^a_{\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{O}_2^g = \frac{\alpha_s}{12\pi}\,\bar{\chi}\,i\gamma^5\chi\,G^a_{\mu\nu}G^a_{\mu\nu}\,,$$

$$\mathcal{O}_3^g = \frac{\alpha_s}{8\pi}\,\bar{\chi}\chi\,G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\,, \qquad \mathcal{O}_4^g = \frac{\alpha_s}{8\pi}\,\bar{\chi}\,i\gamma^5\chi\,G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\,,$$

High-energy Operators

MAJORANA DM

DIM-6 operators:
Constructed with neutral DM & SM quarks

$$\mathcal{O}_1^q = \bar\chi\chi\,\bar q q\,, \qquad \mathcal{O}_2^q = \bar\chi\, i\gamma^5\chi\,\bar q q\,,$$

$$\mathcal{O}_3^q = \bar\chi\chi\,\bar q\, i\gamma^5 q\,, \qquad \mathcal{O}_4^q = \bar\chi\, i\gamma^5\chi\,\bar q\, i\gamma^5 q\,,$$

$$\mathcal{O}_5^q = \xcancel{\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q}\,, \qquad \mathcal{O}_6^q = \bar\chi\gamma^\mu\gamma^5\chi\,\bar q\gamma_\mu q\,,$$

$$\mathcal{O}_7^q = \xcancel{\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu\gamma^5 q}\,, \qquad \mathcal{O}_8^q = \bar\chi\gamma^\mu\gamma^5\chi\,\bar q\gamma_\mu\gamma^5 q\,,$$

$$\mathcal{O}_9^q = \xcancel{\bar\chi\,\sigma^{\mu\nu}\chi\,\bar q\,\sigma_{\mu\nu} q}\,, \qquad \mathcal{O}_{10}^q = \xcancel{\bar\chi\, i\,\sigma^{\mu\nu}\gamma^5\chi}\,\bar q\,\sigma_{\mu\nu} q\,,$$

DIM-7 operators:
SM gauge invariant couple DM with gluons

$$\mathcal{O}_1^g = \frac{\alpha_s}{12\pi}\,\bar\chi\chi\, G^a_{\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{O}_2^g = \frac{\alpha_s}{12\pi}\,\bar\chi\, i\gamma^5\chi\, G^a_{\mu\nu}G^a_{\mu\nu}\,,$$

$$\mathcal{O}_3^g = \frac{\alpha_s}{8\pi}\,\bar\chi\chi\, G^a_{\mu\nu}\tilde G^a_{\mu\nu}\,, \qquad \mathcal{O}_4^g = \frac{\alpha_s}{8\pi}\,\bar\chi\, i\gamma^5\chi\, G^a_{\mu\nu}\tilde G^a_{\mu\nu}\,,$$

LAGRANGIAN at the *q* & *g* level

$$\mathscr{L}_{\text{eff}} = \sum_{k=1}^{10}\sum_q c_k^q \mathcal{O}_k^q + \sum_{k=1}^{4} c_k^g \mathcal{O}_k^g\,,$$

c_k^q dim. of $[\text{mass}]^{-2}$

c_k^g dim. of $[\text{mass}]^{-3}$

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

STEP I:

dress the q and g operators to the nucleon level

$$\langle N(p')|\mathcal{O}_k^{(q,g)}|N(p)\rangle$$

DM-*nucleon* $\mathcal{L}$

$$\mathcal{L}_{\rm eff}^N = \sum_k c_k^N \mathcal{O}_k^N$$

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

STEP I:

dress the q and g operators to the nucleon level

$\langle N(p')|\mathcal{O}_k^{(q,g)}|N(p)\rangle$

DM-*nucleon* $\mathcal{L}$

$$\mathcal{L}_{\text{eff}}^N = \sum_k c_k^N \mathcal{O}_k^N$$

STEP II:

compute DM-*nucleon* ME & reduce it to NR operators

$\langle \chi N \,|\mathcal{L}_{\text{eff}}^N|\, \chi' N' \rangle_{q^2 \to 0}$

NR DM-*nucleon* ME

$$\sum_i \mathfrak{c}_i^N(\{c_{(q,g)}\}, m_\chi)\mathcal{O}_i^{\text{NR}}$$

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

STEP I:

dress the q and g operators to the nucleon level

$$\langle N(p')|\mathcal{O}_k^{(q,g)}|N(p)\rangle$$

DM-*nucleon* $\mathcal{L}$

$$\mathcal{L}_{\rm eff}^N = \sum_k c_k^N \mathcal{O}_k^N$$

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compute DM-*nucleon* ME & reduce it to NR operators

$$\langle \chi N\,|\mathcal{L}_{\rm eff}^N|\,\chi' N'\rangle_{q^2\to 0}$$

NR DM-*nucleon* ME

$$\sum_i \mathfrak{c}_i^N(\{c_{(q,g)}\}, m_\chi)\mathcal{O}_i^{\rm NR}$$

STEP III:

correct the DM-nucleon ME with the nuclear response

$$|\mathcal{M}_N|^2 \Rightarrow |\mathcal{M}_\mathcal{T}|^2$$

DM-Nucleus XS

$$\frac{d\sigma}{dE_{\rm R}} \propto \sum_{i,j}\sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} F_{i,j}^{(N,N')}$$

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

STEP I:

dress the q and g operators to the nucleon level

see e.g. J.R. Ellis, K. A. Olive, C. Savage,
PRD 77 (2008) **065026**, [arXiv: 0801.3656]

H.-Y. Cheng, C.-W. Chiang.
JHEP 07 (2012) **009**, [arXiv: 1202.1292]

F. Bishara, J. Brod, B. Grinstein, J. Zupan
JHEP 1711 (2017) **059**, [arXiv: 1707.06998]

☑

STEP II:

compute DM-*nucleon* ME & reduce it to NR operators

see e.g. M. Cirelli, E. Del Nobile, P. Panci,
JCAP 1310 (2013) **019**, [arXiv: 1307.5955]

F. Bishara, J. Brod, B. Grinstein, J. Zupan
[arXiv: 1708.02678]

☑

STEP III:

correct the DM-nucleon ME with the nuclear response

A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, Y. Xu,
JCAP 1302 (2013) **004**, [arXiv: 1203.3542]

☑

NR structure

$\mathcal{S}$-$\mathcal{S}$ $\quad c_1^q\,\bar{\chi}\chi\,\bar{q}q$

$\mathcal{V}$-$\mathcal{V}$ $\quad c_5^q\,\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q$

$\mathcal{S}$-GG $\quad \frac{\alpha_s}{12\pi}c_1^g\,\bar{\chi}\chi\,G^a_{\mu\nu}G_a^{\mu\nu}$

$$\mathcal{M}_N \propto \mathcal{I}_\chi \mathcal{I}_N$$

Contact SI

different coefficients
due to quark/gluon currents
dressing into *nucleons*

$\mathcal{AV}$-$\mathcal{AV}$ $\quad c_8^q\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q$

$\mathcal{T}$-$\mathcal{T}$ $\quad c_9^q\,\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{q}\sigma_{\mu\nu}q$

$$\mathcal{M}_N \propto \vec{s}_\chi \cdot \vec{s}_N$$

Contact SD

different coefficients
due to quark/gluon currents
dressing into *nucleons*

$\mathcal{PS}$-$\mathcal{PS}$ $\quad c_4^q\,\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$

$\mathcal{PS}$-$G\tilde{G}$ $\quad \frac{\alpha_s}{12\pi}c_4^g\,\bar{\chi}\gamma^5\chi G^a_{\mu\nu}\tilde{G}_a^{\mu\nu}$

$$\mathcal{M}_N \propto (\vec{q}\cdot\vec{s}_\chi)(\vec{q}\cdot\vec{s}_N)$$

Longitudinal SD

highly suppressed

$q^4/(m_N^2 m_\chi^2)$

The other 7 parity violating Operators

Matching onto NR EFT

SI & SD interaction

suppressed by

$(q^2/(m_{N,\chi}^2), v^2)$

NR Matching

Typical Dimension-6 Interactions

$$
\begin{aligned}
\mathcal{O}_1^N &= \bar{\chi}\chi\ \bar{N}N\,, & \mathcal{O}_2^N &= \bar{\chi}\, i\gamma^5\chi\ \bar{N}N\,,\\
\mathcal{O}_3^N &= \bar{\chi}\chi\ \bar{N}\, i\gamma^5 N\,, & \mathcal{O}_4^N &= \bar{\chi}\, i\gamma^5\chi\ \bar{N}\, i\gamma^5 N\,,\\
\mathcal{O}_5^N &= \bar{\chi}\gamma^\mu\chi\ \bar{N}\gamma_\mu N\,, & \mathcal{O}_6^N &= \bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{N}\gamma_\mu N\,,\\
\mathcal{O}_7^N &= \bar{\chi}\gamma^\mu\chi\ \bar{N}\gamma_\mu\gamma^5 N\,, & \mathcal{O}_8^N &= \bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{N}\gamma_\mu\gamma^5 N\,,\\
\mathcal{O}_9^N &= \bar{\chi}\,\sigma^{\mu\nu}\chi\ \bar{N}\,\sigma_{\mu\nu}N\,, & \mathcal{O}_{10}^N &= \bar{\chi}\, i\,\sigma^{\mu\nu}\gamma^5\chi\ \bar{N}\,\sigma_{\mu\nu}N\,,
\end{aligned}
$$

Galileian Invariant Operators

$$
\begin{aligned}
\mathcal{O}_1^{\rm NR} &= \mathbb{1}\ , & &\\
\mathcal{O}_3^{\rm NR} &= i\,\vec{s}_N\cdot(\vec{q}\times\vec{v}^\perp)\ , & \mathcal{O}_4^{\rm NR} &= \vec{s}_\chi\cdot\vec{s}_N\ ,\\
\mathcal{O}_5^{\rm NR} &= i\,\vec{s}_\chi\cdot(\vec{q}\times\vec{v}^\perp)\ , & \mathcal{O}_6^{\rm NR} &= (\vec{s}_\chi\cdot\vec{q})(\vec{s}_N\cdot\vec{q})\ ,\\
\mathcal{O}_7^{\rm NR} &= \vec{s}_N\cdot\vec{v}^\perp\ , & \mathcal{O}_8^{\rm NR} &= \vec{s}_\chi\cdot\vec{v}^\perp\ ,\\
\mathcal{O}_9^{\rm NR} &= i\,\vec{s}_\chi\cdot(\vec{s}_N\times\vec{q})\ , & \mathcal{O}_{10}^{\rm NR} &= i\,\vec{s}_N\cdot\vec{q}\,,\\
\mathcal{O}_{11}^{\rm NR} &= i\,\vec{s}_\chi\cdot\vec{q}\ , & \mathcal{O}_{12}^{\rm NR} &= \vec{v}^\perp\cdot(\vec{s}_\chi\times\vec{s}_N)\ .
\end{aligned}
$$

NR structure of the fermion bilinear

$$
\begin{aligned}
\bar{u}(p')u(p) &\simeq 2m\,,\\
\bar{u}(p')i\,\gamma^5 u(p) &\simeq 2i\,\vec{q}\cdot\vec{s}\,,\\
\bar{u}(p')\gamma^\mu u(p) &\simeq \begin{pmatrix} 2m \\ \vec{P}+2i\,\vec{q}\times\vec{s} \end{pmatrix}\ ,\\
\bar{u}(p')\gamma^\mu\gamma^5 u(p) &\simeq \begin{pmatrix} 2\vec{P}\cdot\vec{s} \\ 4m\,\vec{s} \end{pmatrix}\ ,\\
\bar{u}(p')\sigma^{\mu\nu}u(p) &\simeq \begin{pmatrix} 0 & i\,\vec{q}-2\vec{P}\times\vec{s} \\ -i\,\vec{q}+2\vec{P}\times\vec{s} & 4m\,\varepsilon_{ijk}s^k \end{pmatrix}\ ,\\
\bar{u}(p')i\,\sigma^{\mu\nu}\gamma^5 u(p) &\simeq \begin{pmatrix} 0 & -4m\vec{s} \\ 4m\vec{s} & i\,\varepsilon_{ijk}q_k-2P_is^j+2P_js^i \end{pmatrix}\ ,
\end{aligned}
$$

Match to NR operators

$$
\begin{aligned}
\langle\mathcal{O}_1^N\rangle = \langle\mathcal{O}_5^N\rangle &= 4m_\chi m_N\mathcal{O}_1^{\rm NR}\,,\\
\langle\mathcal{O}_2^N\rangle &= -4m_N\mathcal{O}_{11}^{\rm NR}\,,\\
\langle\mathcal{O}_3^N\rangle &= 4m_\chi\mathcal{O}_{10}^{\rm NR}\,,\\
\langle\mathcal{O}_4^N\rangle &= 4\mathcal{O}_6^{\rm NR}\,,\\
\langle\mathcal{O}_6^N\rangle &= 8m_\chi\left(+m_N\mathcal{O}_8^{\rm NR}+\mathcal{O}_9^{\rm NR}\right)\ ,\\
\langle\mathcal{O}_7^N\rangle &= 8m_N\left(-m_\chi\mathcal{O}_7^{\rm NR}+\mathcal{O}_9^{\rm NR}\right)\ ,\\
\langle\mathcal{O}_8^N\rangle = -\frac{1}{2}\langle\mathcal{O}_9^N\rangle &= -16\,m_\chi m_N\mathcal{O}_4^{\rm NR}\,,\\
\langle\mathcal{O}_{10}^N\rangle &= 8\left(m_\chi\mathcal{O}_{11}^{\rm NR}-m_N\mathcal{O}_{10}^{\rm NR}-4m_\chi m_N\mathcal{O}_{12}^{\rm NR}\right)
\end{aligned}
$$

How do we put limits?

➡ **The simplest method:**

assume the idealized case in which **only one operator** is active at a time

Scalar operators

$$\mathcal{O}_1^q = \bar{\chi}\chi\, \bar{q}q\,, \qquad \mathcal{O}_2^q = \bar{\chi}\, i\gamma^5\chi\, \bar{q}q\,,$$

$$\mathcal{O}_3^q = \bar{\chi}\chi\, \bar{q}\, i\gamma^5 q\,, \qquad \mathcal{O}_4^q = \bar{\chi}\, i\gamma^5\chi\, \bar{q}\, i\gamma^5 q\,,$$

Higgs-like couplings

$$c_i^q = \frac{m_q}{\Lambda^3}$$

Vector operators

$$\mathcal{O}_5^q = \bar{\chi}\gamma^\mu\chi\, \bar{q}\gamma_\mu q\,, \qquad \mathcal{O}_6^q = \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{q}\gamma_\mu q\,,$$

$$\mathcal{O}_7^q = \bar{\chi}\gamma^\mu\chi\, \bar{q}\gamma_\mu\gamma^5 q\,, \qquad \mathcal{O}_8^q = \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{q}\gamma_\mu\gamma^5 q\,,$$

Flavour-uni. couplings

$$c_i^q = \frac{1}{\Lambda^2}$$

Draw Bounds (V & AV)

Flavour-uni. couplings

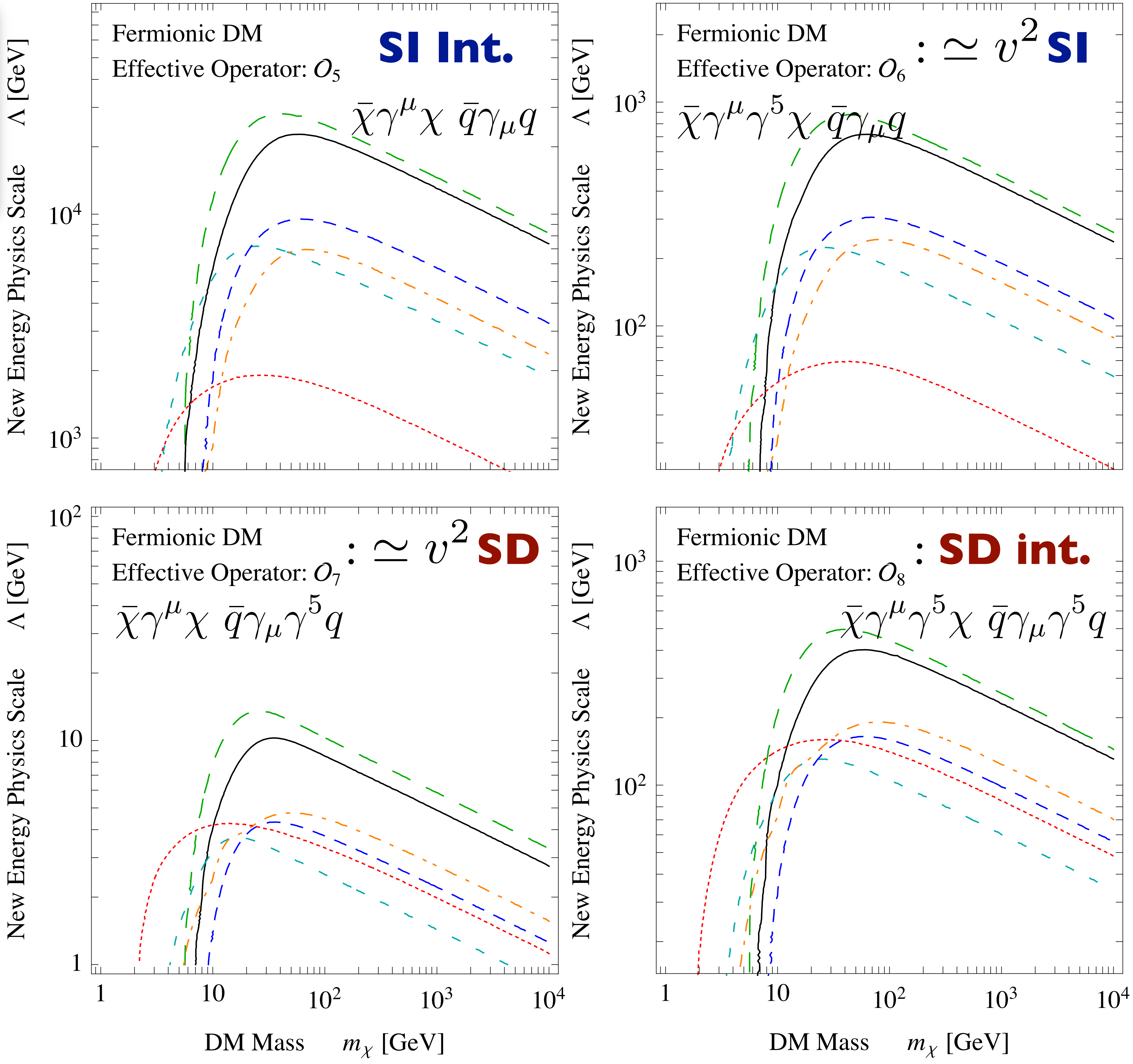
$$c_i^q = \frac{1}{\Lambda^2}$$

$\mathcal{O}_5^q$: **SI Int.**

$\mathcal{O}_6^q$: $\simeq v^2$ **SI Int.**

$\mathcal{O}_7^q$: $\simeq v^2$ **SD Int.**

$\mathcal{O}_8^q$: **SD Int.**



Draw Bounds (S & PS)

Higgs-like couplings

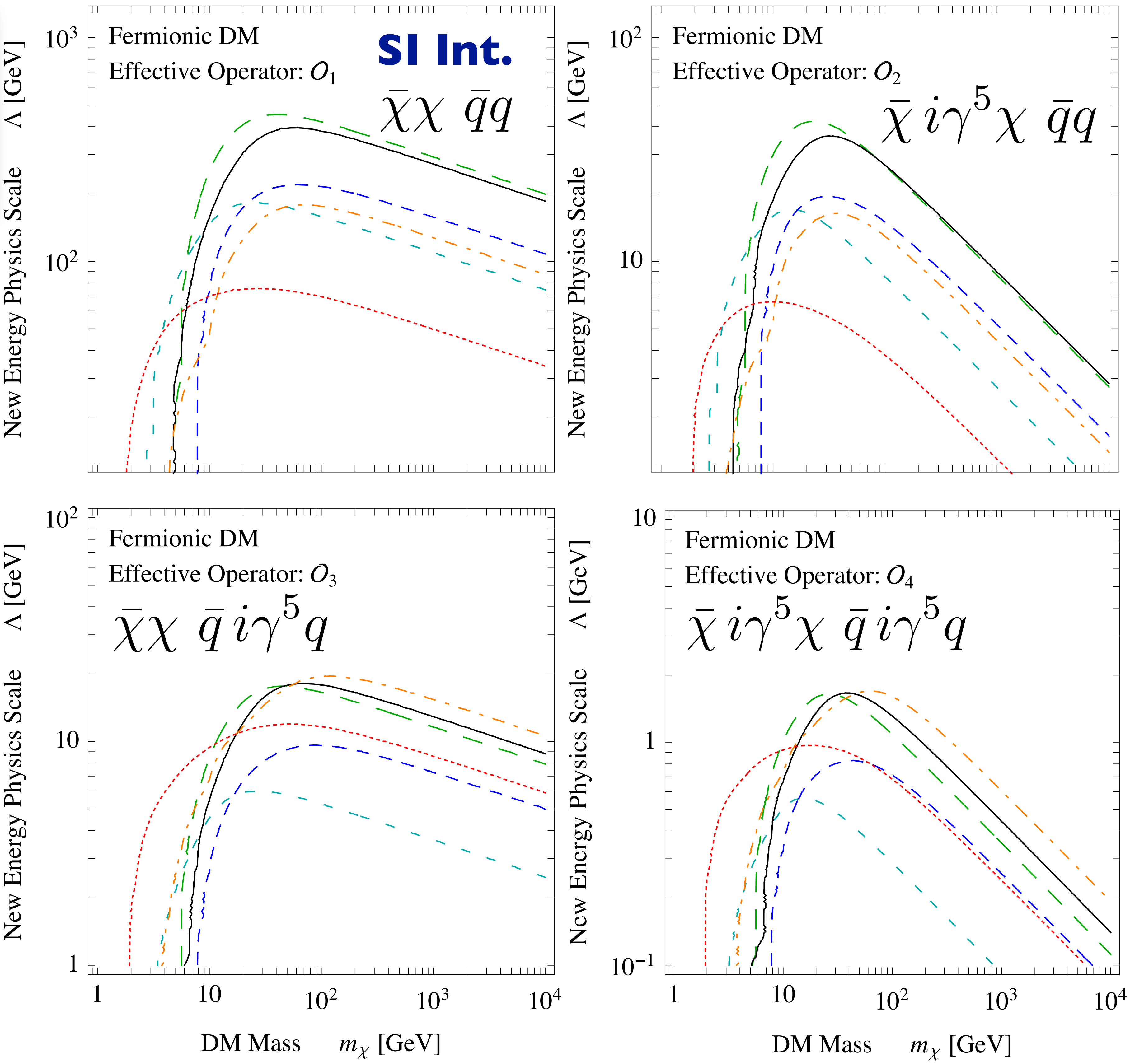
$$c_i^q = \frac{m_q}{\Lambda^3}$$

$\mathcal{O}_1^q$ **: SI Int.**

$\mathcal{O}_2^q$ **:** q^2/m_χ^2 **SI Int.**

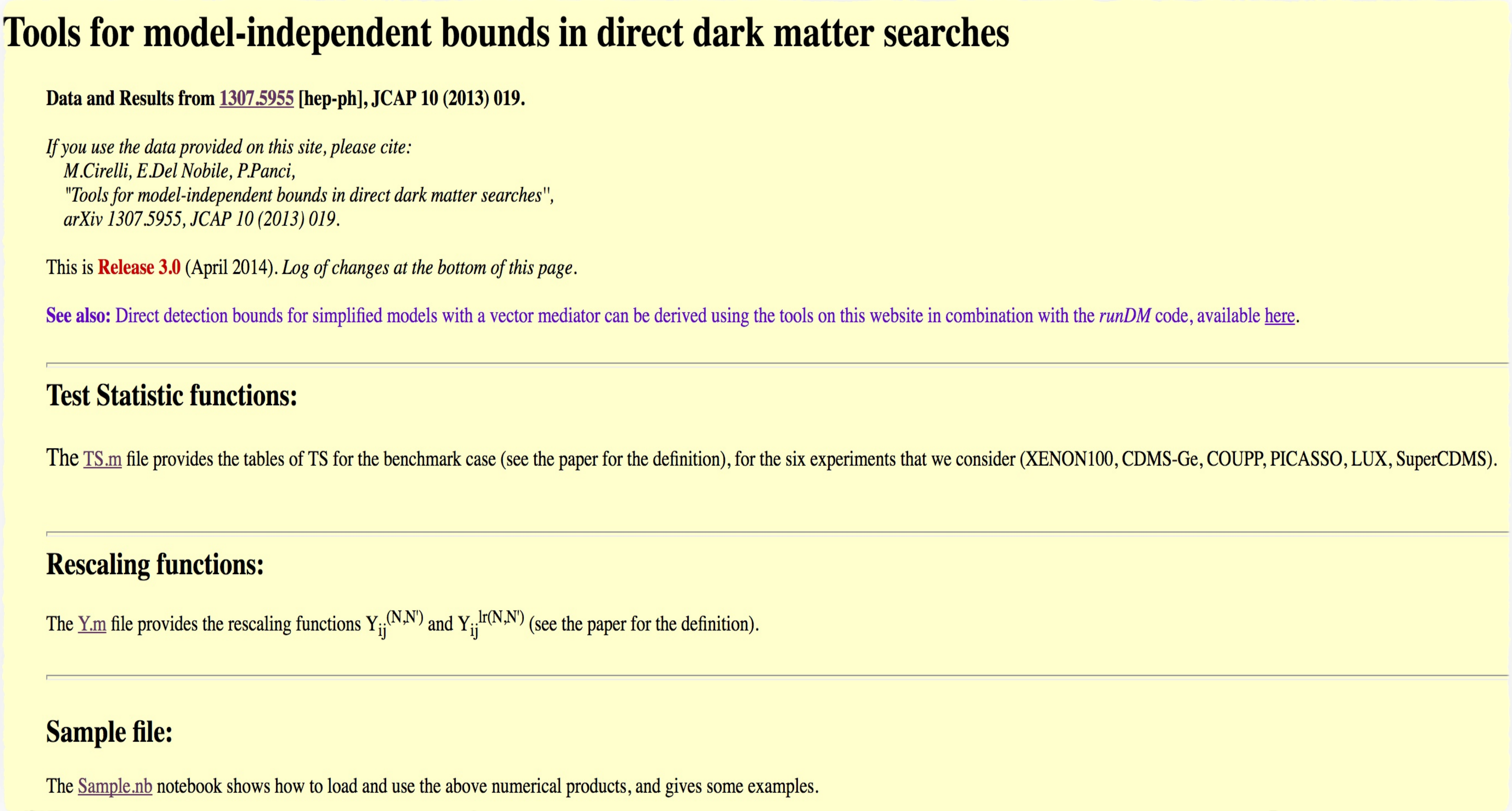
$\mathcal{O}_3^q$ **:** q^2/m_N^2 **SD Int.**

$\mathcal{O}_4^q$ **:** $q^4/(m_N^2 m_\chi^2)$ **SD Int.**



Direct detection tools

Interested in the limits from **all possible**
non-relativistic DM-nucleus elastic collisions?



Tools for model-independent bounds in direct dark matter searches

Data and Results from 1307.5955 [hep-ph], JCAP 10 (2013) 019.

If you use the data provided on this site, please cite:
M.Cirelli, E.Del Nobile, P.Panci,
"Tools for model-independent bounds in direct dark matter searches",
arXiv 1307.5955, JCAP 10 (2013) 019.

This is **Release 3.0** (April 2014). *Log of changes at the bottom of this page*.

See also: Direct detection bounds for simplified models with a vector mediator can be derived using the tools on this website in combination with the *runDM* code, available here.

Test Statistic functions:

The TS.m file provides the tables of TS for the benchmark case (see the paper for the definition), for the six experiments that we consider (XENON100, CDMS-Ge, COUPP, PICASSO, LUX, SuperCDMS).

Rescaling functions:

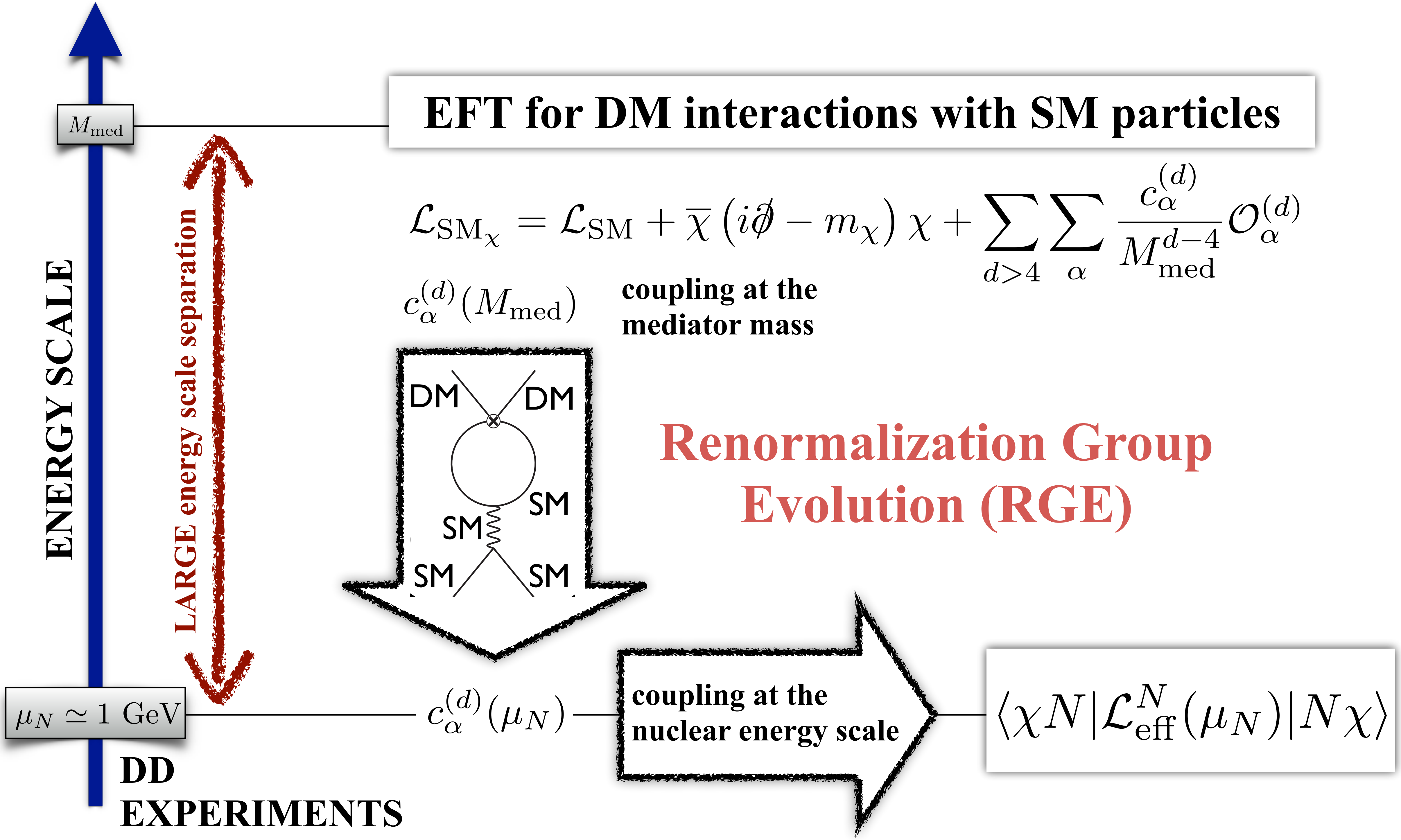
The Y.m file provides the rescaling functions $Y_{ij}^{(N,N')}$ and $Y_{ij}^{lr(N,N')}$ (see the paper for the definition).

Sample file:

The Sample.nb notebook shows how to load and use the above numerical products, and gives some examples.

Limitations of the naive matching

➡ In **UV Models several HE operators are generated** *with Wilson coefficients related in a non-trivial way*



EFT for DM interactions with SM particles

$$\mathcal{L}_{\mathrm{SM}_\chi} = \mathcal{L}_{\mathrm{SM}} + \overline{\chi}\left(i\not{\partial} - m_\chi\right)\chi + \sum_{d>4}\sum_{\alpha}\frac{c_\alpha^{(d)}}{M_{\mathrm{med}}^{d-4}}\mathcal{O}_\alpha^{(d)}$$

$c_\alpha^{(d)}(M_{\mathrm{med}})$ **coupling at the mediator mass**

Renormalization Group Evolution (RGE)

$c_\alpha^{(d)}(\mu_N)$ **coupling at the nuclear energy scale**

$\langle \chi N | \mathcal{L}_{\mathrm{eff}}^{N}(\mu_N) | N \chi \rangle$

III PART

Connect DM model to the nuclear energy scale

"You can hide but you have to run: Direct detection with vector mediator"

F. D’Eramo, B. J. Kavanagh, PP, JHEP 1608 (2016) **111**, [arXiv:1605.04917]

Why is RGE Relevant?

Should we worry about **loop corrections** in a pre-discovery era?

DM-nucleus collisions

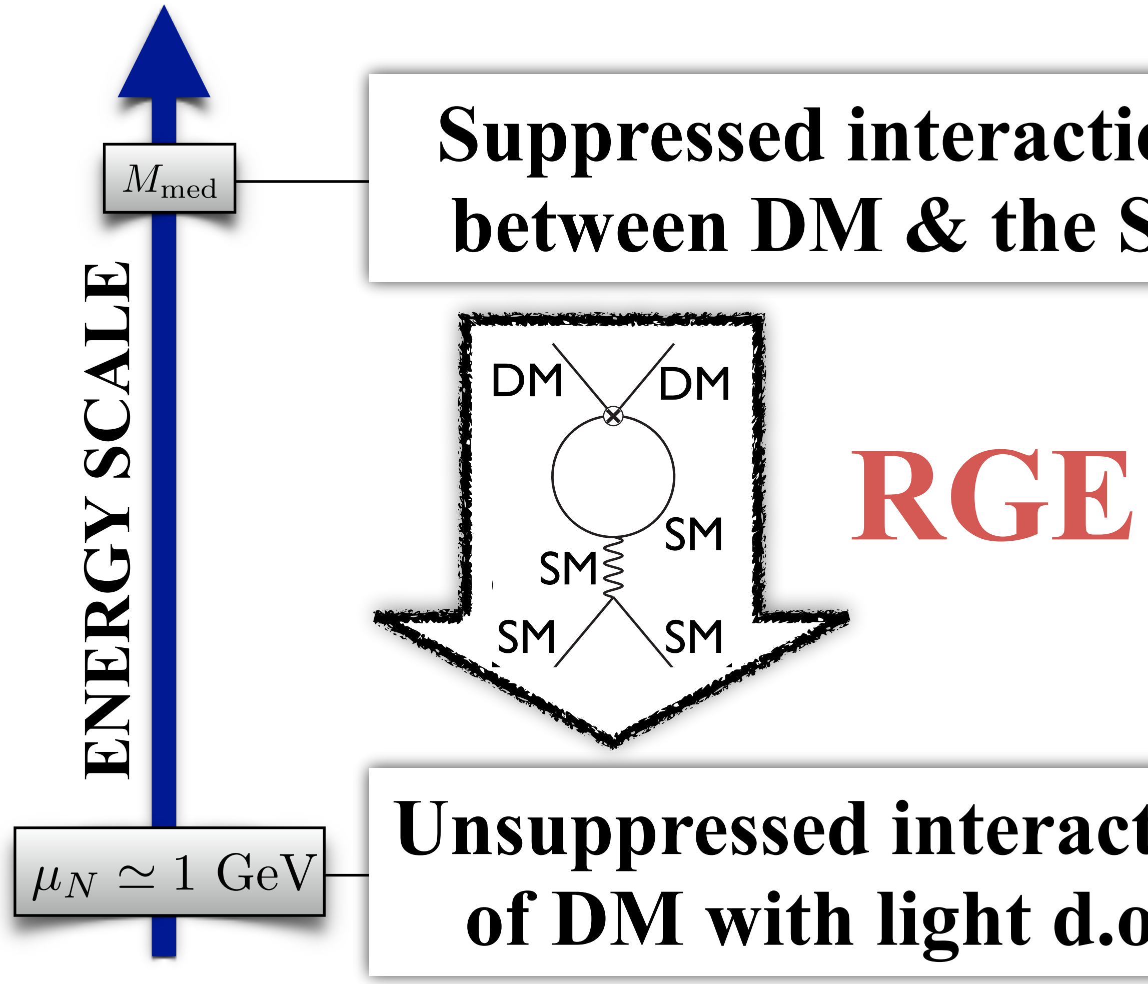
- only sensitive to **light degrees of freedom** (light *quarks* & *gluons*)
- particularly sensitive to the **Lorentz structure** of the HE operators

RGE Effects

- **change the size** of the Wilson coefficient of the HE operators
- **generate operator mixing** at low energy

Why is RGE Relevant?

Should we worry about **loop corrections** in a pre-discovery era?



Suppressed interactions between DM & the SM

Unsuppressed interactions of DM with light d.o.f.

RGE Effects

- **change the size** of the Wilson coefficient of the HE operators
- **generate operator mixing** at low energy

Vector mediator

SIMPLIFIED MODEL

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM} V_\mu + J^\mu_{\rm SM} V_\mu$$

Frandsen, Kahlhoefer, Preston, Sarkar, K. Schmidt-Hoberg, JHEP07 (2012), arXiv:1204.3839

Buchmueller, Dolan, McCabe, JHEP01 (2014), arXiv:1308.6799

Alves, Profumo, Queiroz, JHEP04 (2014), arXiv:1312.5281

Arcadi, Mambrini,Tytgat, Zaldivar, JHEP03 (2014), arXiv:1401.0221

Lebedev, Mambrini, PLB734 (2014), arXiv:1403.4837

Buchmueller, Dolan, Malik, McCabe, JHEP01 (2015), arXiv:1407.8257

Harris, Khoze, Spannowsky,Williams, PRD91 (2015), arXiv:1411.0535

Alves, Berlin, Profumo, Queiroz, PRD92 (2015), arXiv:1501.03490

Jacques, Nordström, JHEP06 (2015), arXiv:1502.05721

Chala, Kahlhoefer, McCullough, Nardini, Schmidt-Hoberg, JHEP07 (2015), arXiv:1503.05916

Powerful tool to study LHC phenomenology and **complementary** among DM searches

Vector mediator

SIMPLIFIED MODEL

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DM}} + \mathcal{L}_{V} + J^{\mu}_{\mathrm{DM}} V_{\mu} + J^{\mu}_{\mathrm{SM}} V_{\mu}$$

Kinetic term for both scalar (complex) and fermion DM (Dirac & Majorana)

$$\mathcal{L}_{\mathrm{DM}} = \begin{cases} |\partial_{\mu}\phi|^2 - m_{\phi}^2 \, |\phi|^2 & \quad \text{scalar DM} \\ \mathcal{K}_{\chi} \, \overline{\chi} \left(i\not{\partial} - m_{\chi} \right) \chi & \quad \text{fermion DM} \end{cases}$$

$$\mathcal{K}_{\chi} = \begin{cases} 1 & \text{Dirac} \\ 1/2 & \text{Majorana} \end{cases}$$

Vector mediator

SIMPLIFIED MODEL

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^{\mu}_{\rm DM} V_\mu + J^{\mu}_{\rm SM} V_\mu$$

Kinetic term for the spin 1 massive mediator

$$\mathcal{L}_V = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + \frac{1}{2} m_V^2 V^\mu V_\mu$$

We do not consider **mass and kinetic mixing**
with the *Z* boson since they depend
on the **details of the UV theory**

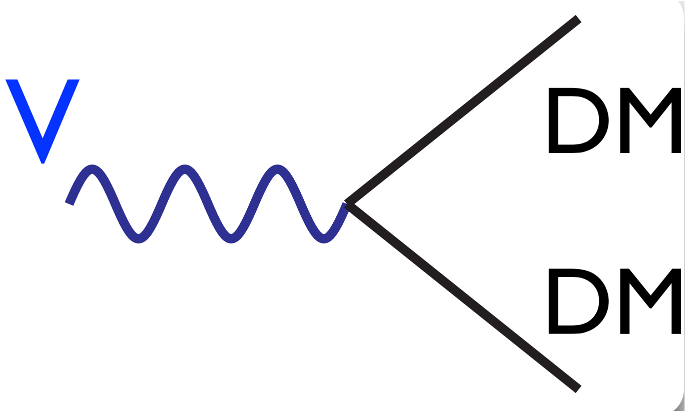
Vector mediator

SIMPLIFIED MODEL

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DM}} + \mathcal{L}_V + J^\mu_{\mathrm{DM}} V_\mu + J^\mu_{\mathrm{SM}} V_\mu$$

Mediator coupled with spin 1 DM currents

$$J^\mu_{\mathrm{DM}} = \begin{cases} c_\phi \, \phi^\dagger \overleftrightarrow{\partial}_\mu \phi & \text{scalar DM} \\ \mathcal{K}_\chi \left(c_{\chi V} \, \overline{\chi} \gamma^\mu \chi + c_{\chi A} \, \overline{\chi} \gamma^\mu \gamma^5 \chi \right) & \text{fermion DM} \end{cases}$$



Vector mediator

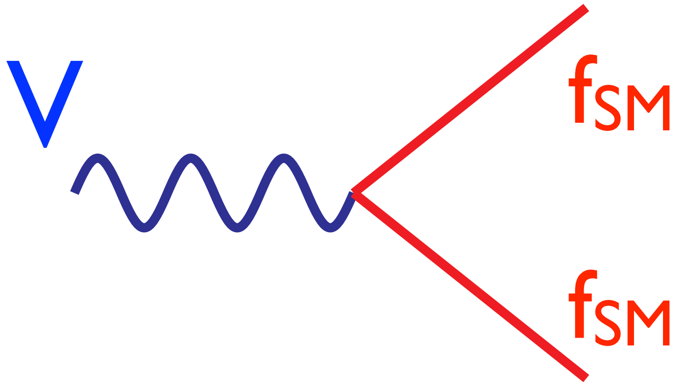
SIMPLIFIED MODEL

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM} V_\mu + J^\mu_{\rm SM} V_\mu$$

Mediator coupled with spin 1 currents of SM fermions

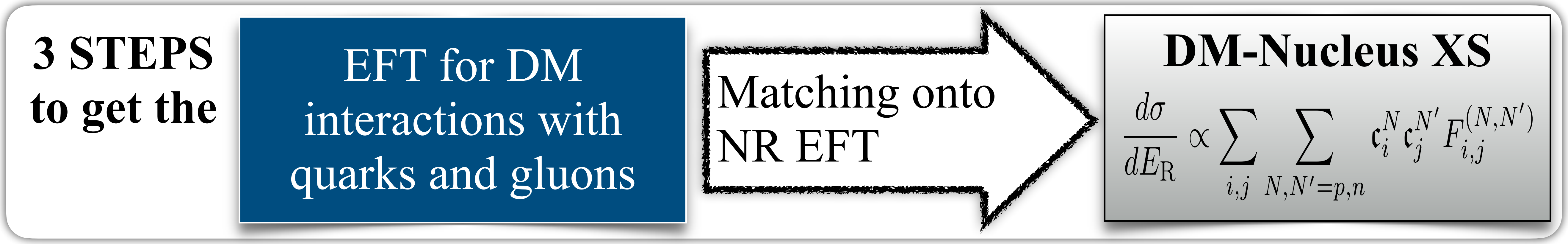
$$J^\mu_{\rm SM} = \sum_{i=1}^{3} \left[c_q^{(i)} \; \overline{q_L^i} \gamma^\mu q_L^i + c_u^{(i)} \; \overline{u_R^i} \gamma^\mu u_R^i + c_d^{(i)} \; \overline{d_R^i} \gamma^\mu d_R^i + c_l^{(i)} \; \overline{l_L^i} \gamma^\mu l_L^i + c_e^{(i)} \; \overline{e_R^i} \gamma^\mu e_R^i \right]$$

15 independent SU(2) x U(1) gauge invariant couplings to SM fermions



Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**



3 STEPS to get the

EFT for DM interactions with quarks and gluons

Matching onto NR EFT

DM-Nucleus XS

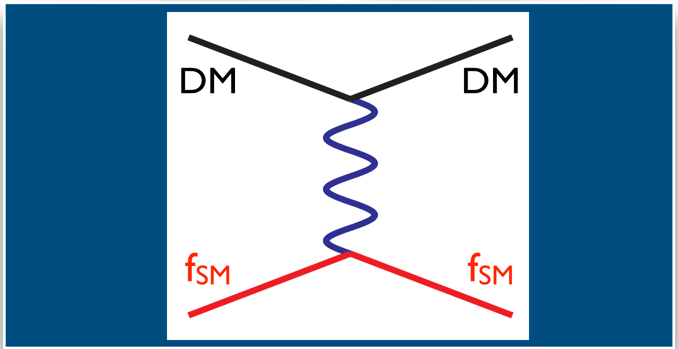
$$\frac{d\sigma}{dE_{\rm R}} \propto \sum_{i,j} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} F_{i,j}^{(N,N')}$$

Main steps to NR cross section

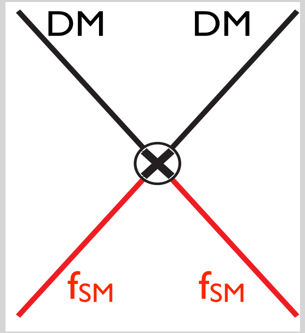
DM-nucleus collisions: **deeply NR regime**

STEP I:

integrate-out the mediator



$$\frac{1}{q^2 - m_V^2} \simeq -\frac{1}{m_V^2}$$



EFT
DM contact
interactions

3 STEPS to get the

EFT for DM interactions with quarks and gluons

Matching onto NR EFT

DM-Nucleus XS

$$\frac{d\sigma}{dE_R} \propto \sum_{i,j} \sum_{N,N'=p,n} c_i^N c_j^{N'} F_{i,j}^{(N,N')}$$

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

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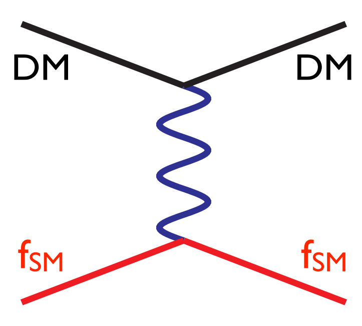
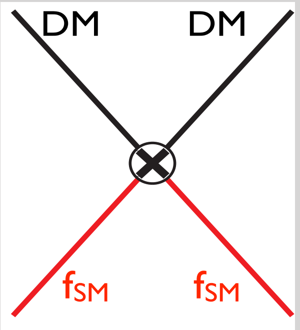


$$\frac{1}{q^2 - m_V^2} \simeq -\frac{1}{m_V^2}$$

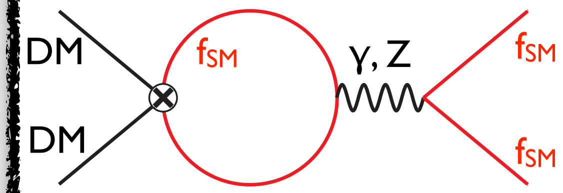


EFT
DM contact interactions

STEP II:

connecting energy scale

EFT
coupling at the mediator mass



NUCLEAR SCALE

➡ size couplings changed

➡ **New interactions** are generated (mixing)

3 STEPS to get the

EFT for DM interactions with quarks and gluons

Matching onto NR EFT

DM-Nucleus XS

$$\frac{d\sigma}{dE_R} \propto \sum_{i,j} \sum_{N,N'=p,n} c_i^N c_j^{N'} F_{i,j}^{(N,N')}$$

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

STEP I:

integrate-out the mediator

straightforward for vector mediator

☑

STEP II:

connecting energy scale

complete **one loop RGE analysis** for Spin 1 mediator can be found in

F. D’Eramo, M. Procura, JHEP 1504 (2015), [arXiv:1411.3342]
F. Bishara, J. Brod, B. Grinstein, J. Zupan, [arXiv:1809.03506]

☑

3 STEPS to get the

EFT for DM interactions with quarks and gluons

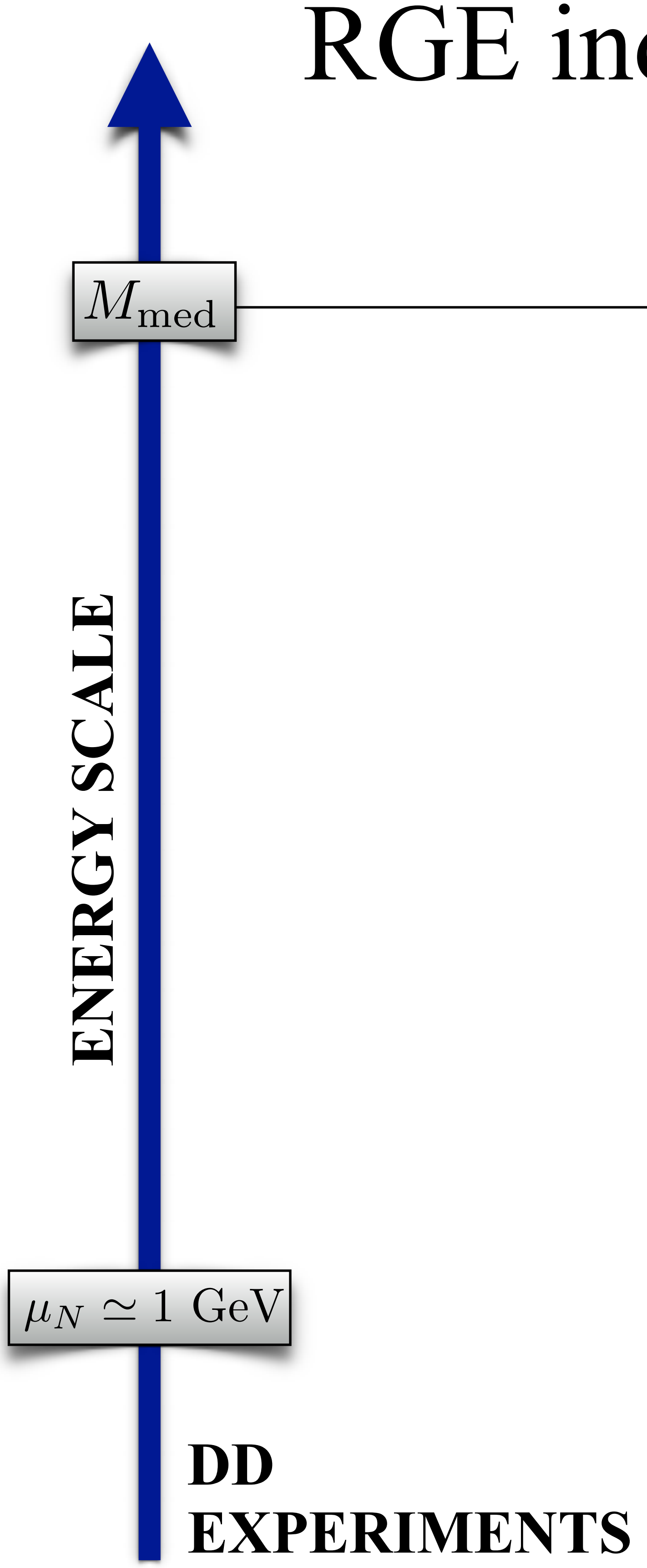
Matching onto NR EFT

DM-Nucleus XS

$$\frac{d\sigma}{dE_{\rm R}} \propto \sum_{i,j} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} F_{i,j}^{(N,N')}$$

RG Effects

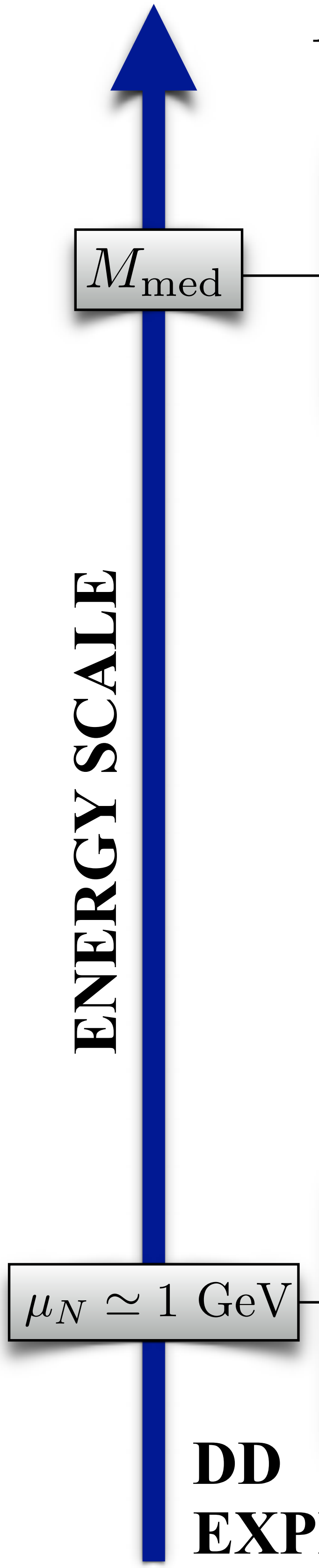
RGE induces currents with light quarks



Approximate solution

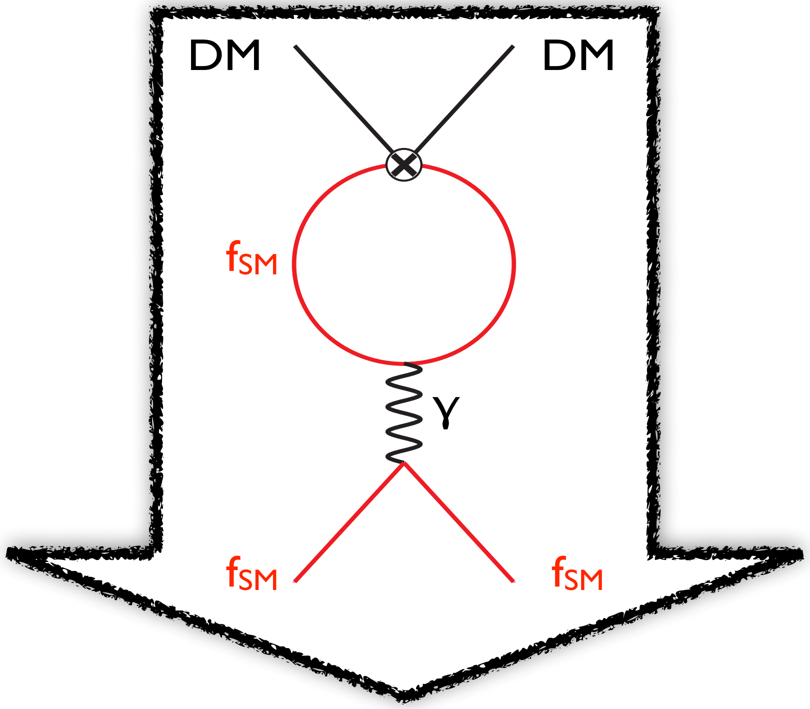
RG Effects

RGE induces currents with light quarks



V coupled to ***vector currents*** of SM fermions

Approximate solution



Important if *V* is not coupled to light quarks

(e.g. leptons or heavy quarks)

Otherwise 1% corrections

RGE only induces ***vector current*** of light quarks

$$\Delta c_V \simeq \frac{e^2}{16\pi^2} \ln(m_V/\mu_N)$$

RG Effects

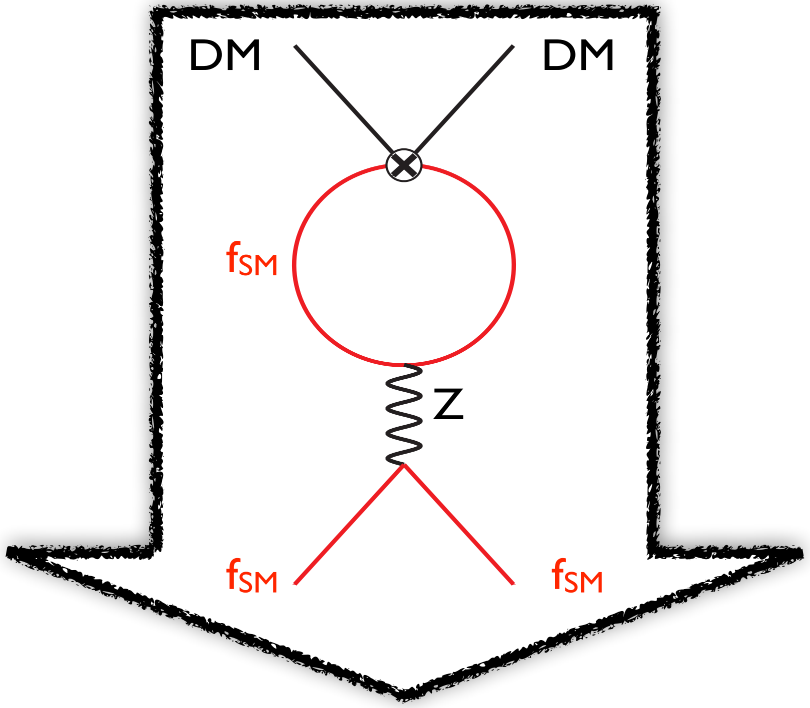
RGE induces currents with light quarks

ENERGY SCALE

$M_{\rm med}$

V coupled to ***axial-vector currents*** of SM fermions

Approximate solution



Phenomenologically very important
(operator mixing)

Dominated by heavy SM fermions (prop to Yukawa)

$\mu_N \simeq 1$ GeV

RGE induces ***vector & axial current*** of light quarks

$$\Delta c_{V,A} \simeq \frac{\lambda_f^2}{16\pi^2} \ln(m_V/\mu_N)$$

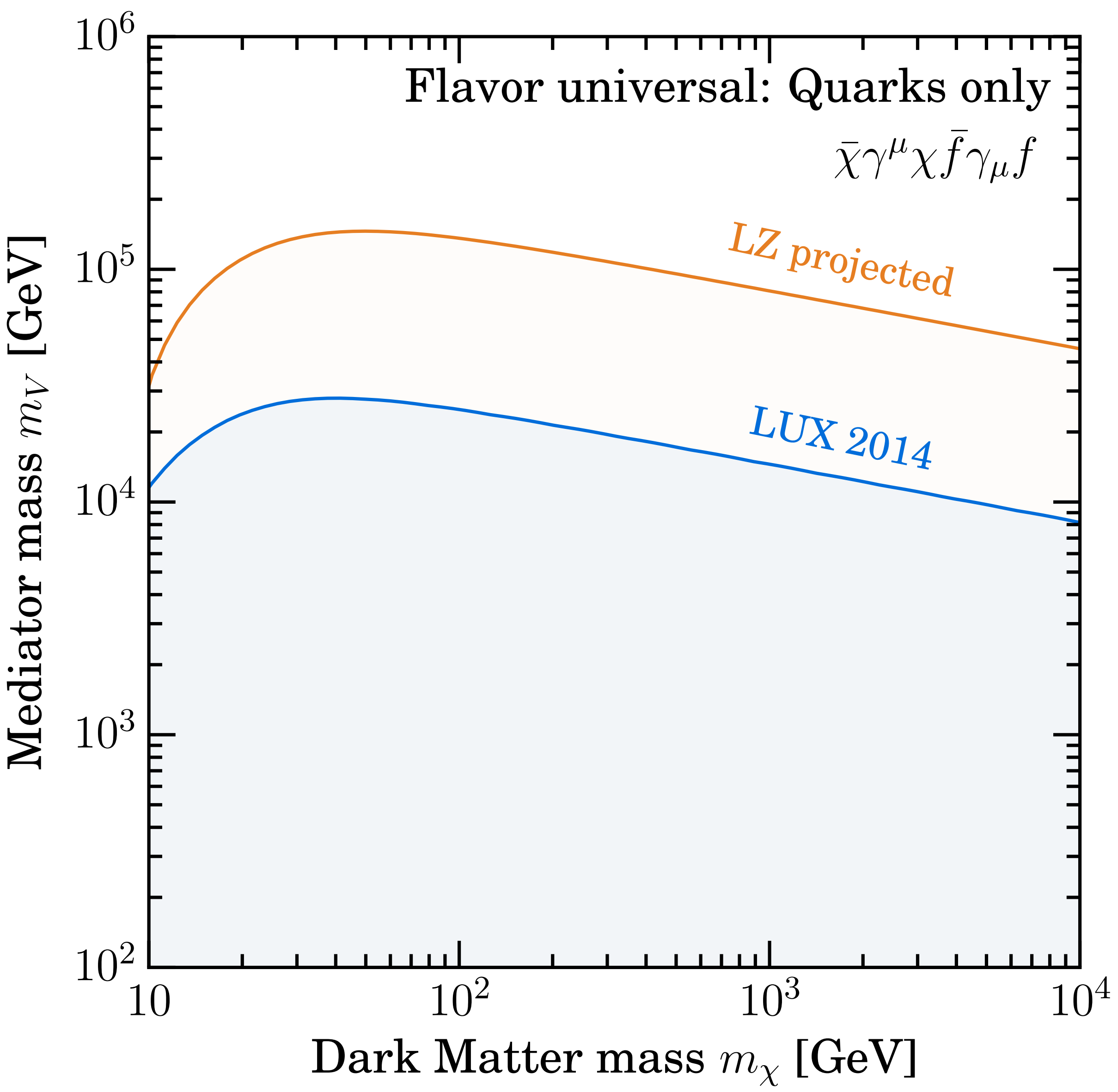
DD EXPERIMENTS

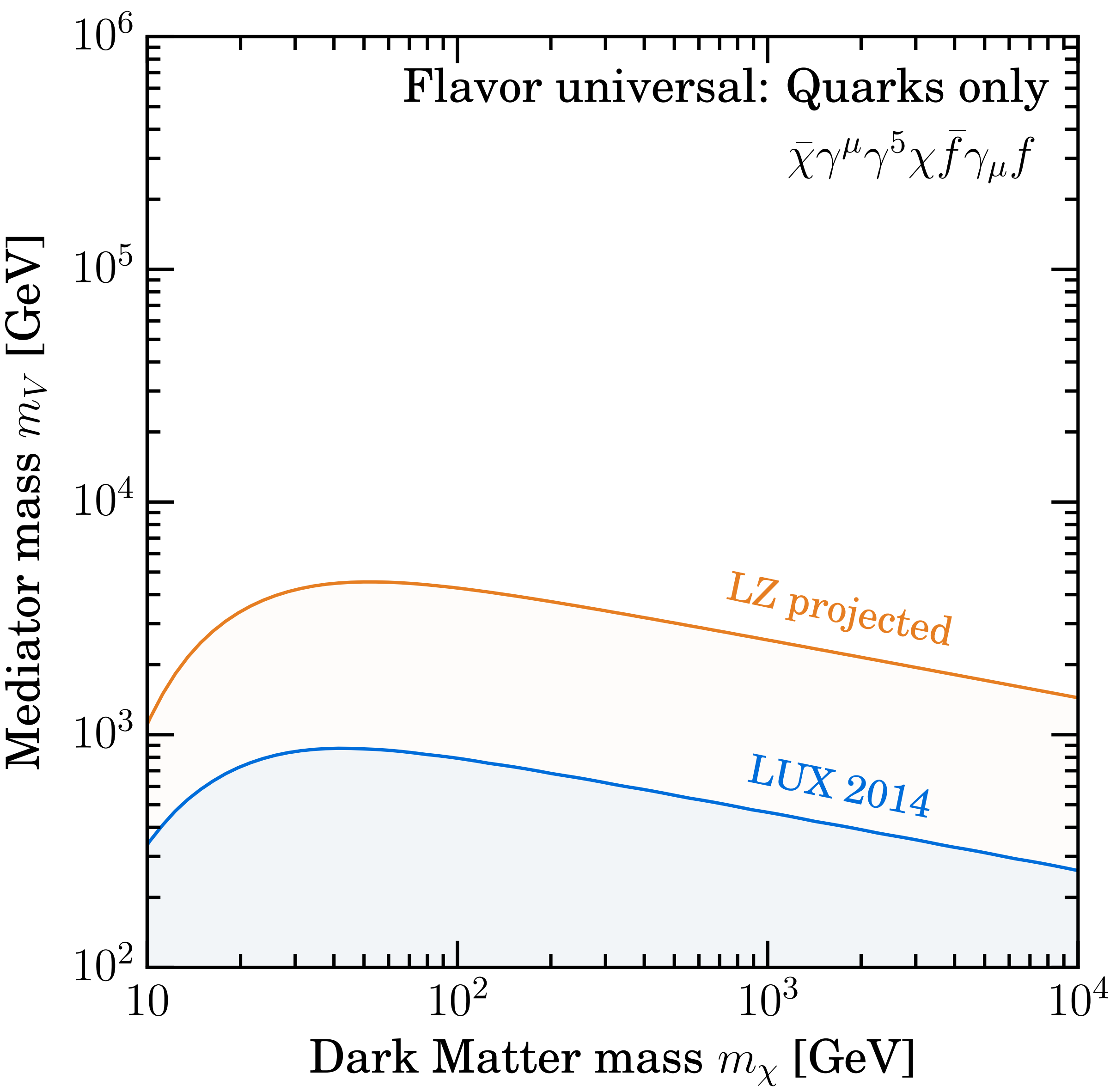
Some Results: Quark Vector

Mediator coupled FU with ***vector currents*** *of quarks*

$$= -\frac{1}{m_V^2} J_{\mathrm{DM}\,\mu} \sum_{i=1}^{3} \left[\overline{u^i}\gamma^\mu u^i + \overline{d^i}\gamma^\mu d^i\right]$$

RGE driven by loops of **electromagnetic currents (<u>no mixing</u>)**



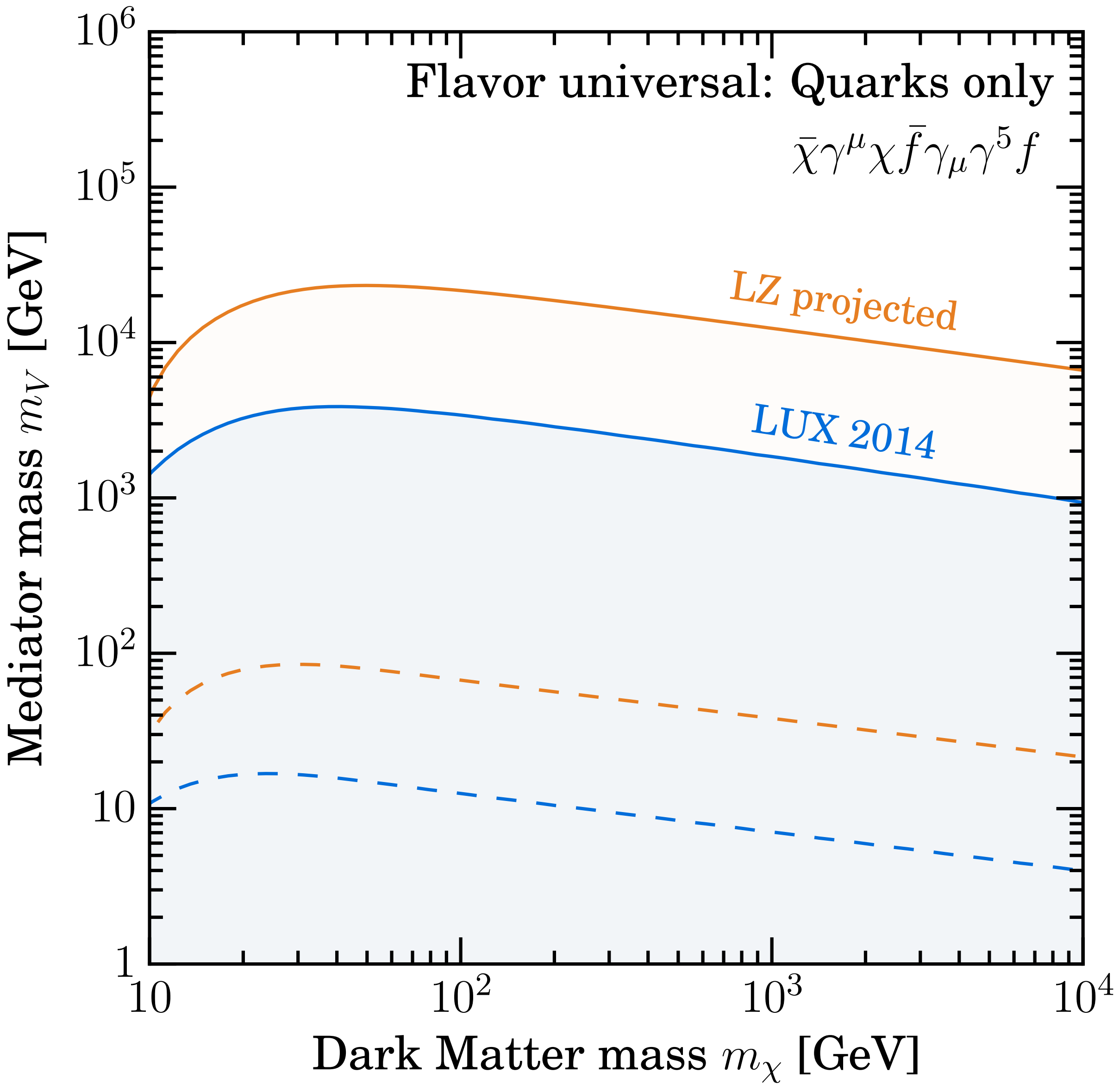


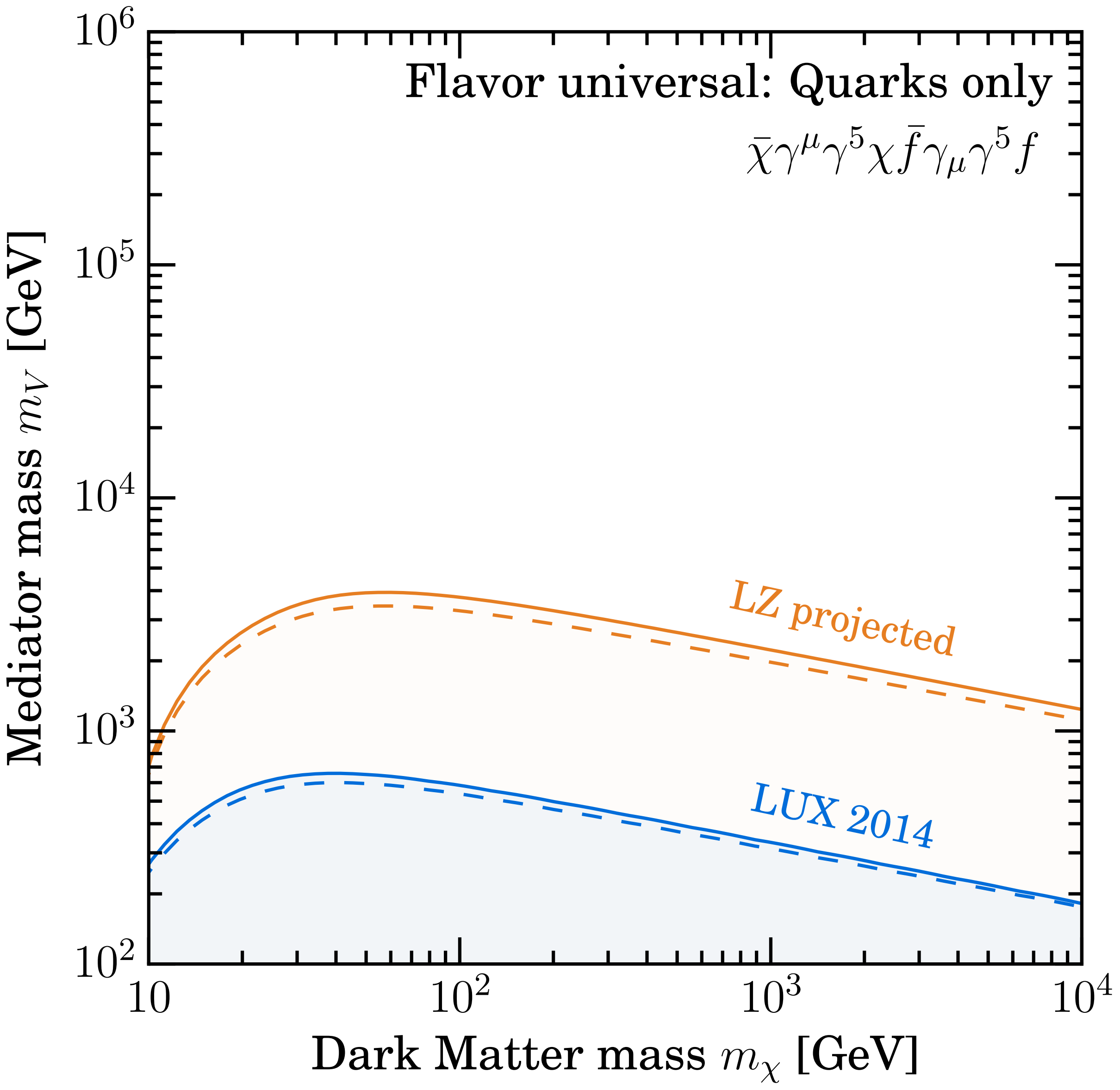
Some Results: Quark Axial

Mediator coupled FU with ***axial currents*** *of quarks*

$$= -\frac{1}{m_V^2} J_{\mathrm{DM}\,\mu} \sum_{i=1}^{3} \left[\overline{u^i}\gamma^\mu\gamma^5 u^i + \overline{d^i}\gamma^\mu\gamma^5 d^i \right]$$

RGE driven by **Yukawa couplings** alter the rate **(<u>mixing</u>)**

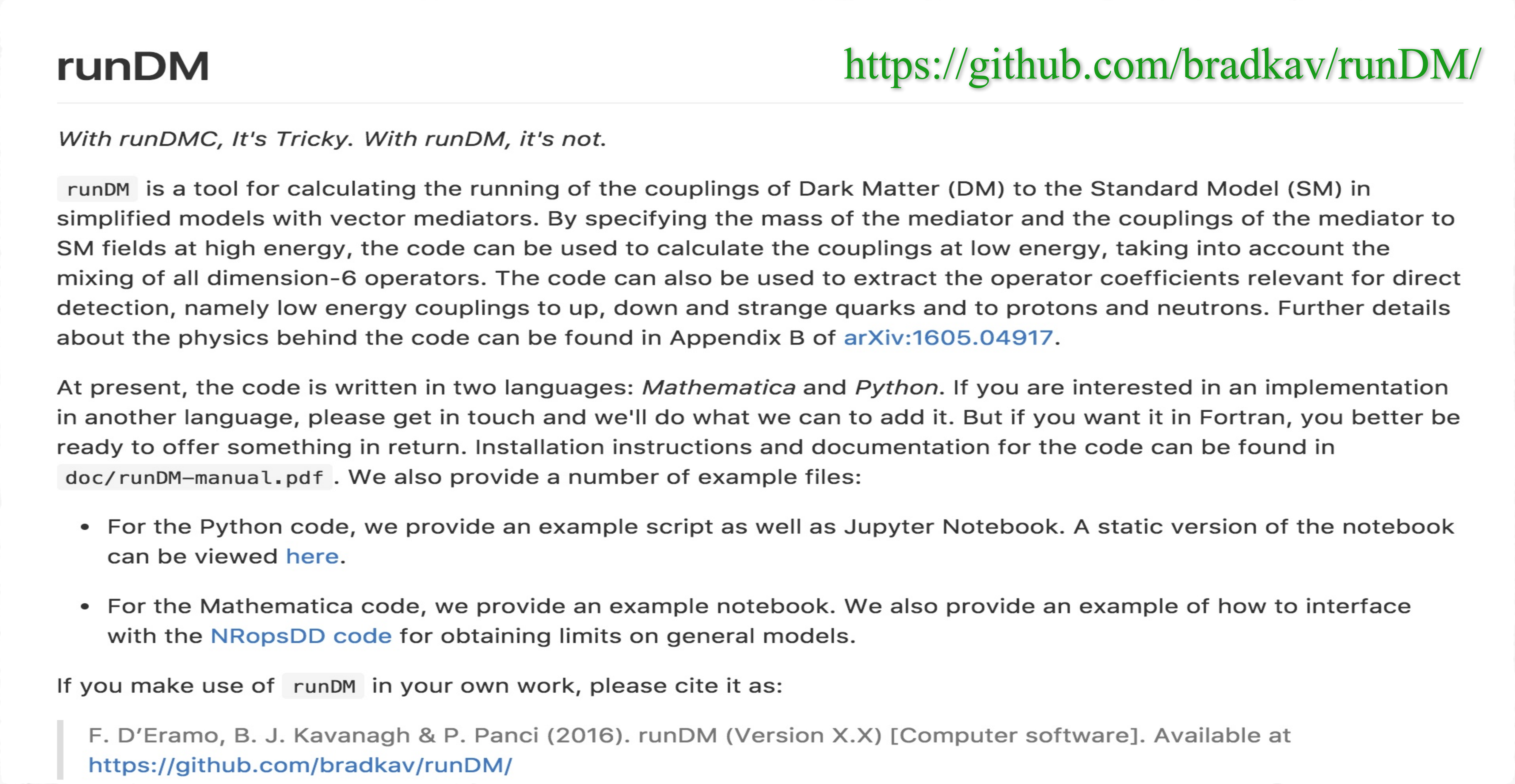




runDM: general RGE

Interested in the **RGE** of the 15 gauge invariant couplings from high energy to low energy ?

Exhaustive study for other cases in JHEP 1608 (2016) **111**, [arXiv: 1605.04917]



runDM

https://github.com/bradkav/runDM/

With runDMC, It's Tricky. With runDM, it's not.

`runDM` is a tool for calculating the running of the couplings of Dark Matter (DM) to the Standard Model (SM) in simplified models with vector mediators. By specifying the mass of the mediator and the couplings of the mediator to SM fields at high energy, the code can be used to calculate the couplings at low energy, taking into account the mixing of all dimension-6 operators. The code can also be used to extract the operator coefficients relevant for direct detection, namely low energy couplings to up, down and strange quarks and to protons and neutrons. Further details about the physics behind the code can be found in Appendix B of arXiv:1605.04917.

At present, the code is written in two languages: *Mathematica* and *Python*. If you are interested in an implementation in another language, please get in touch and we'll do what we can to add it. But if you want it in Fortran, you better be ready to offer something in return. Installation instructions and documentation for the code can be found in `doc/runDM-manual.pdf`. We also provide a number of example files:

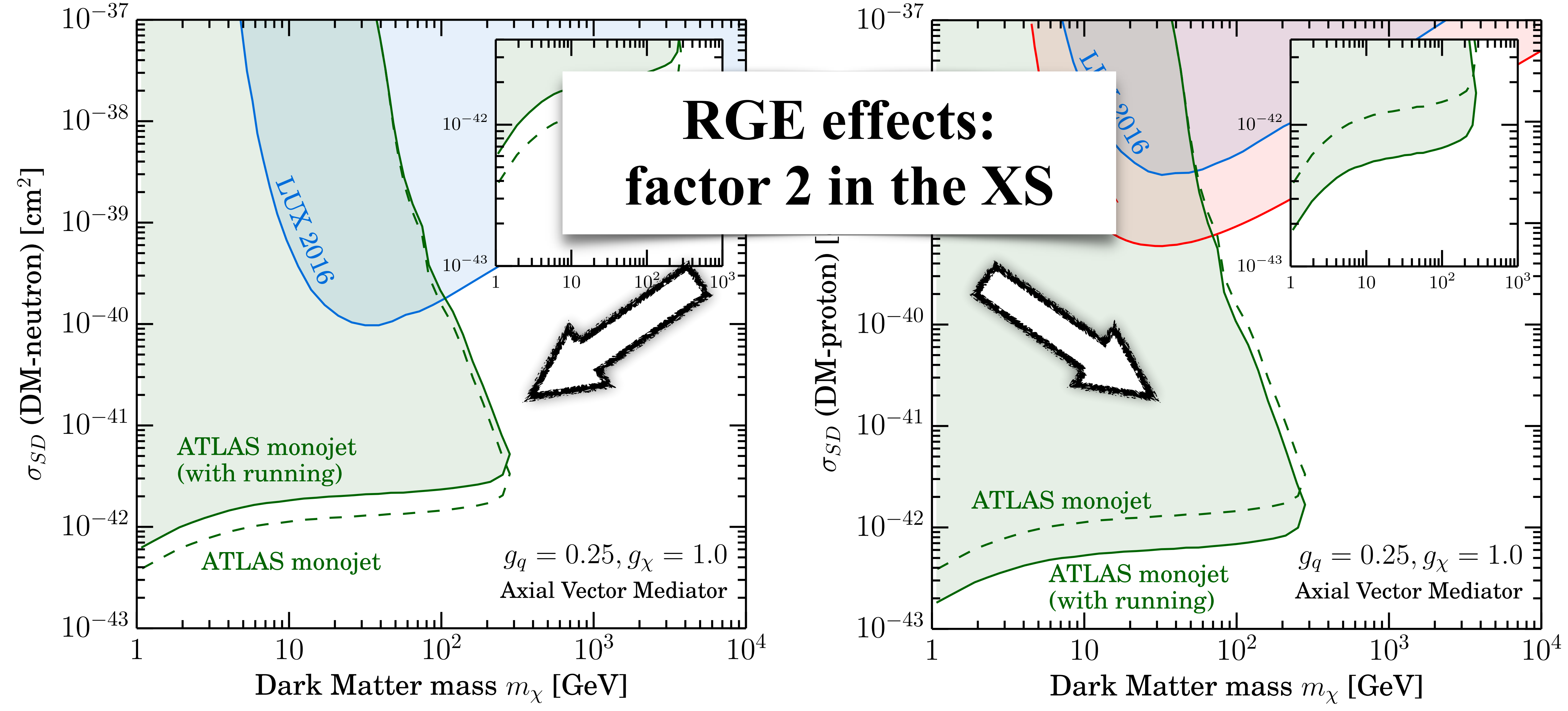
- For the Python code, we provide an example script as well as Jupyter Notebook. A static version of the notebook can be viewed here.
- For the Mathematica code, we provide an example notebook. We also provide an example of how to interface with the NRopsDD code for obtaining limits on general models.

If you make use of `runDM` in your own work, please cite it as:

> F. D'Eramo, B. J. Kavanagh & P. Panci (2016). runDM (Version X.X) [Computer software]. Available at https://github.com/bradkav/runDM/

DD vs LHC (Axial-Axial)

using **simplified DM model** is possible to **map** the **LHC constraints** on the V mass onto the **(m_χ, σ) plane**



RGE effects:
factor 2 in the XS

See e.g. XENON1T [arXiv: 1902.03234]; LUX [arXiv: 1602.03489]; PICO-2L [arXiv: 1601.03729]; ATLAS [arXiv: 1604.01306], etc…..

Backup slides EW DM

WIMP Prototypes

Two approaches:

Top-down approach: Electroweak multiplets (EW) naturally arise in several BSM theories that primarily aim to address the naturalness problem of the EW scale

Refer for instance to ***Hisano's talk*** at the previous edition of this workshop

Bottom-up approach: EW multiplets are chosen by imposing general requirements that all DM candidates must satisfy, without specifying the theory in which they are embedded

In this talk I will follow this approach

WIMP Prototypes

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

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

Requirements:

- **NEUTRALITY:** DM must be the neutral component → $(..., \chi^+, \chi_0, \chi^-, ...)$
- **STABILITY:** DM must be stable → χ_0 is the lightest component of the multiplet
- **NOT EXCLUDED:** by direct detection → χ_0 must not be coupled at tree-level with the *Z* boson
- **PERTURBATIVITY:** of the annihilation cross section. This requirement is needed to select the maximal value of *n*

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

Fermion $$\mathscr{L}_f = \frac{1}{2}\chi\left(i\bar{\sigma}^\mu D_\mu - M_\chi\right)\chi ,$$

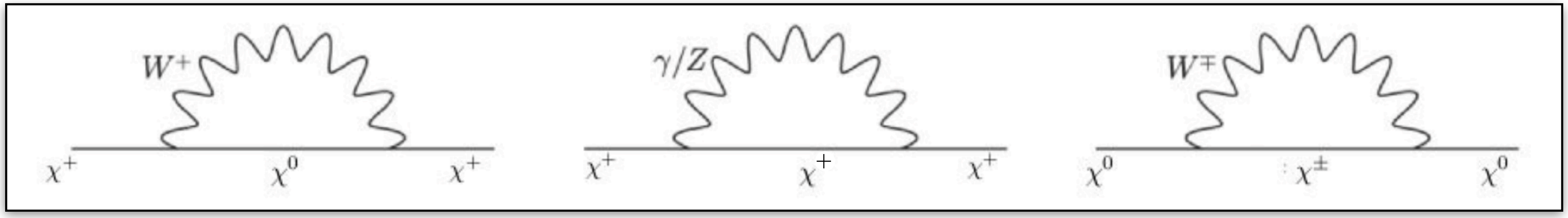
For such multiplets χ_0 is

- automatically the lightest
- not coupled at tree-level with the *Z*

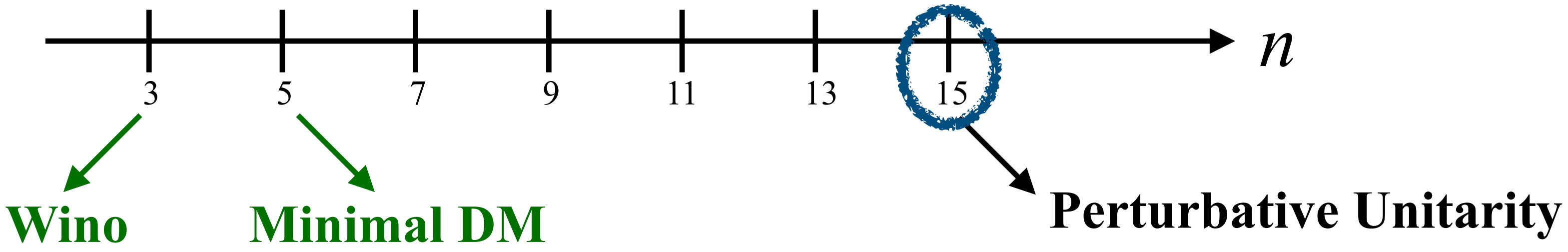
$$(1,n)_0 \begin{cases} \dots \\ \chi^+ \\ \chi_0 \\ \chi^- \\ \dots \end{cases} \qquad \updownarrow \delta_g$$

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

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



PERTURBATIVETY:



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

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

⇨

Dirac **Majorana**

$$\chi_{Q=0} \to \chi_0, \chi_{\mathrm{DM}}$$

$$\delta m_0 = 4 y_0 c_{nY0}\Lambda_{\mathrm{UV}}\left(\frac{v}{\sqrt{2}\Lambda_{\mathrm{UV}}}\right)^{4Y}$$

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

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

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

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

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

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

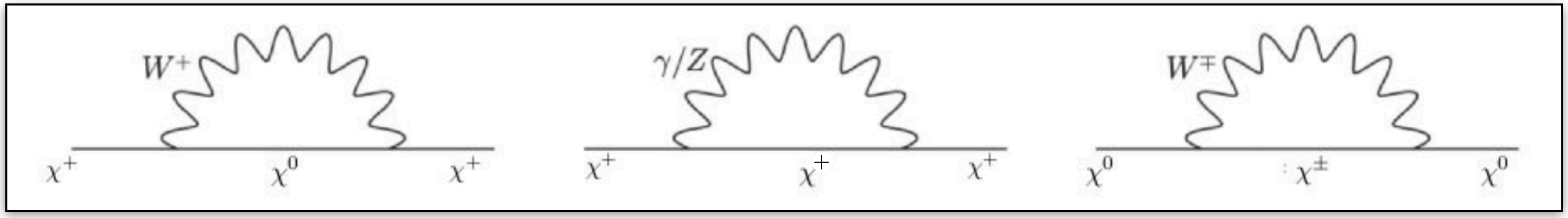
$$\boxed{\mathcal{O}_+ = -\overline{\chi}T^a\chi H^\dagger\frac{\sigma^a}{2}H}$$

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

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

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

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



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

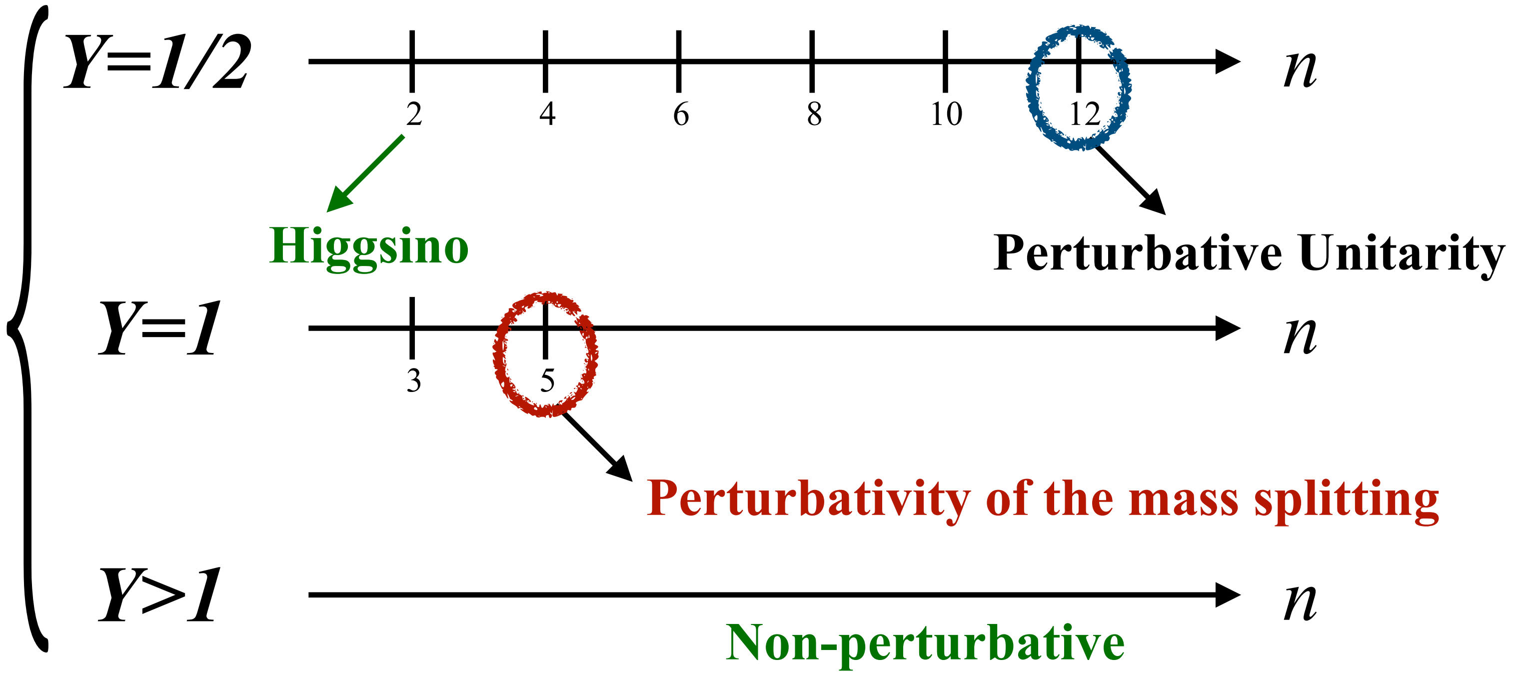
$$\boxed{\mathcal{O}_0 = \frac{1}{2(4Y)!}\left(\overline{\chi}(T^a)^{2Y}\chi^c\right)\left[(H^{c\dagger})\frac{\sigma^a}{2}H\right]^{2Y}}$$

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:



Higgsino

Perturbative Unitarity

Perturbativity of the mass splitting

Non-perturbative

Thermal Production

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

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

WHICH CROSS SECTION?

Tree-level estimate:
(e.g. for majorana fermion)

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

CORRECT…

BUT INACCURATE!!

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

- ✦ Sommerfeld enhancement
- ✦ Bound States formation

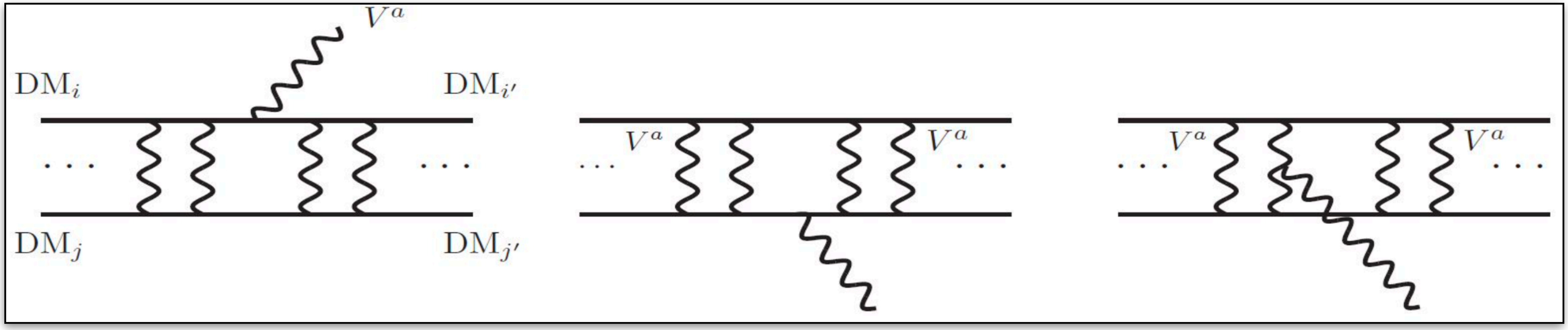
Sommerfeld & BS formations

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 $v_{\rm rel} \simeq 10^{-2}c$

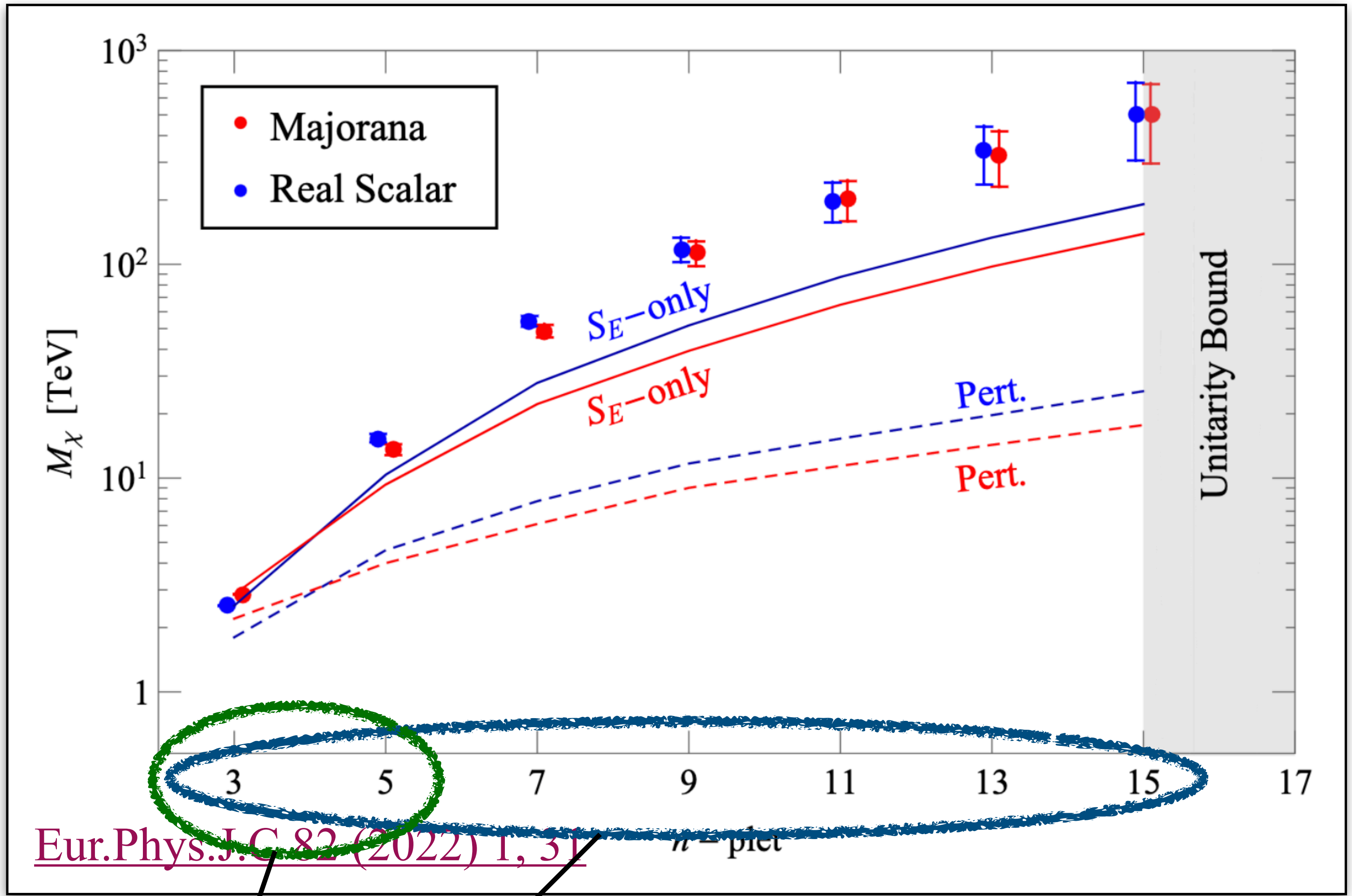
BS: Particle-antiparticle pair bind into a WIMPONIUM BS emitting a gauge boson



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

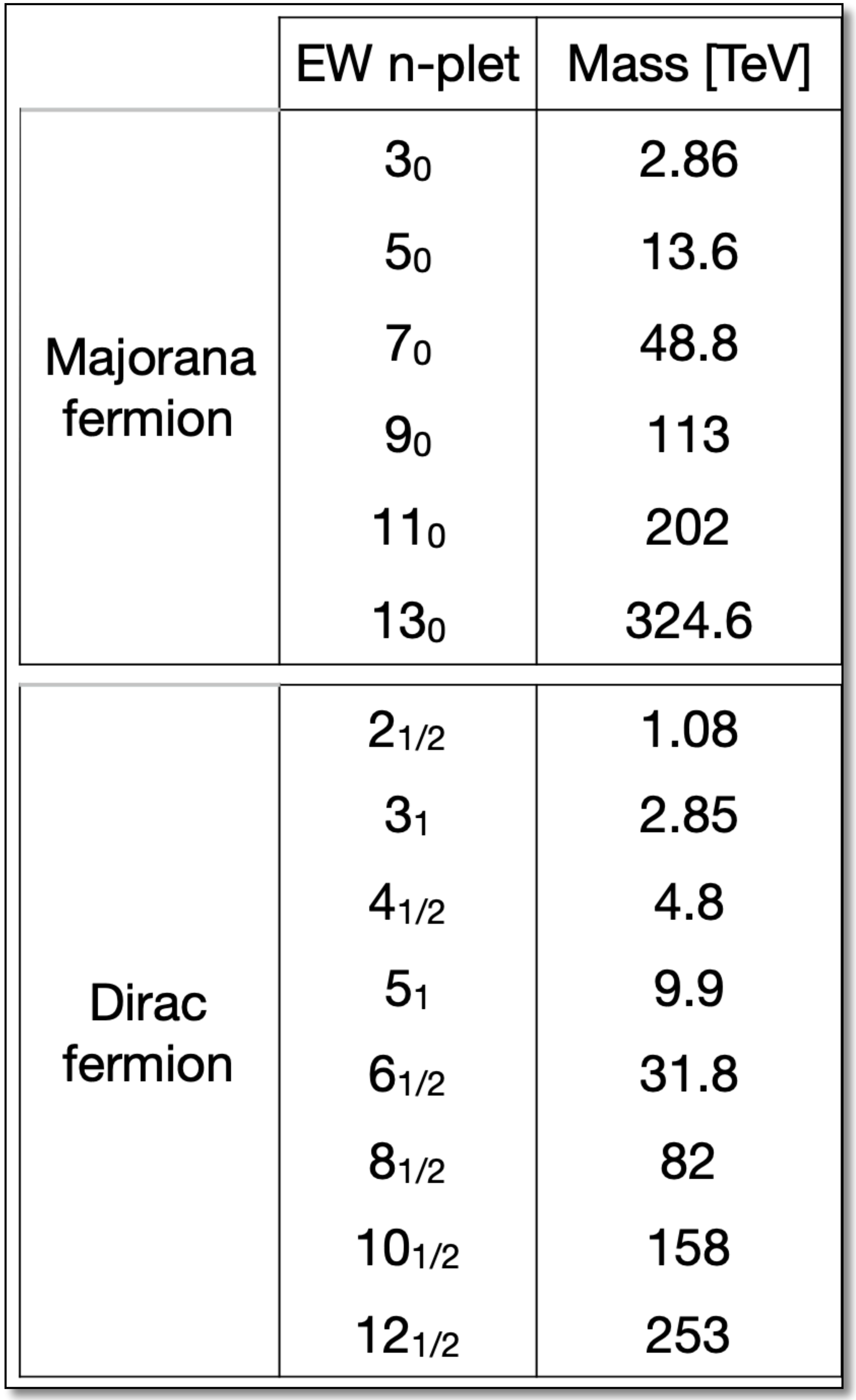


Eur.Phys.J.C 82 (2022) 1, 31

DM Direct & Indirect detection

μCollider?

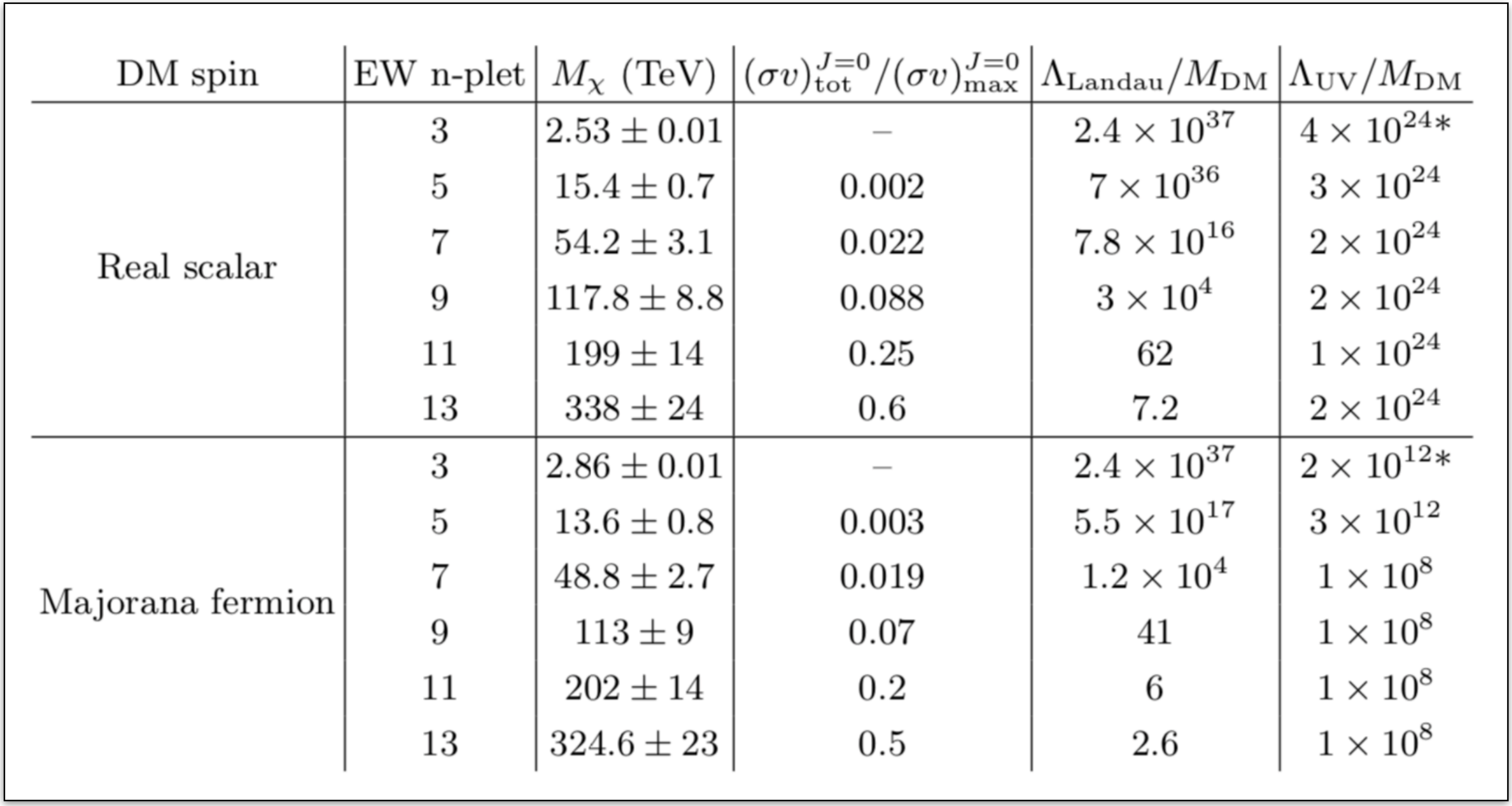
(and similar for complex…)
Eur.Phys.J.C 82 (2022) 11, 992



	EW n-plet	Mass [TeV]
Majorana fermion	3_0	2.86
	5_0	13.6
	7_0	48.8
	9_0	113
	11_0	202
	13_0	324.6
Dirac fermion	$2_{1/2}$	1.08
	3_1	2.85
	$4_{1/2}$	4.8
	5_1	9.9
	$6_{1/2}$	31.8
	$8_{1/2}$	82
	$10_{1/2}$	158
	$12_{1/2}$	253

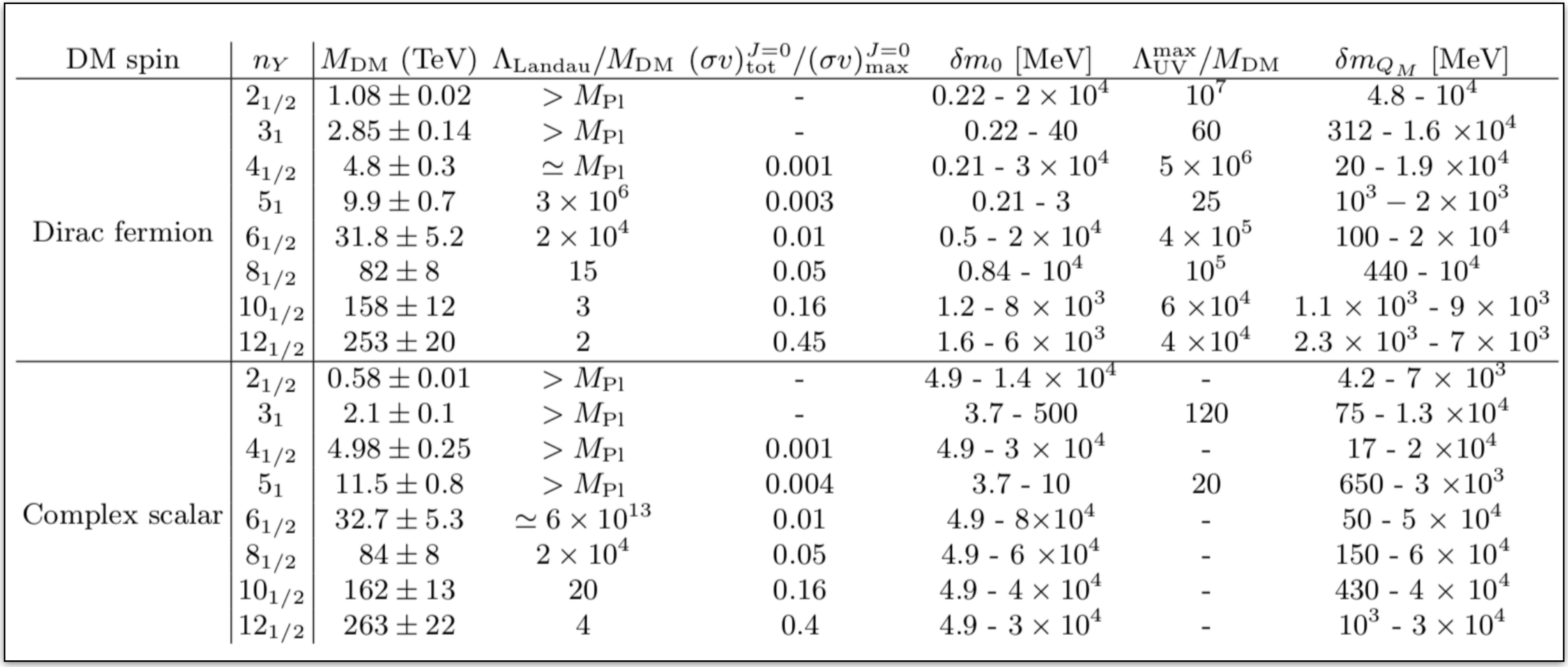
How do we probe these states?

Results: Real WIMPs



DM spin	EW n-plet	M_χ (TeV)	$(\sigma v)^{J=0}_{\text{tot}}/(\sigma v)^{J=0}_{\text{max}}$	$\Lambda_{\text{Landau}}/M_{\text{DM}}$	$\Lambda_{\text{UV}}/M_{\text{DM}}$
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}

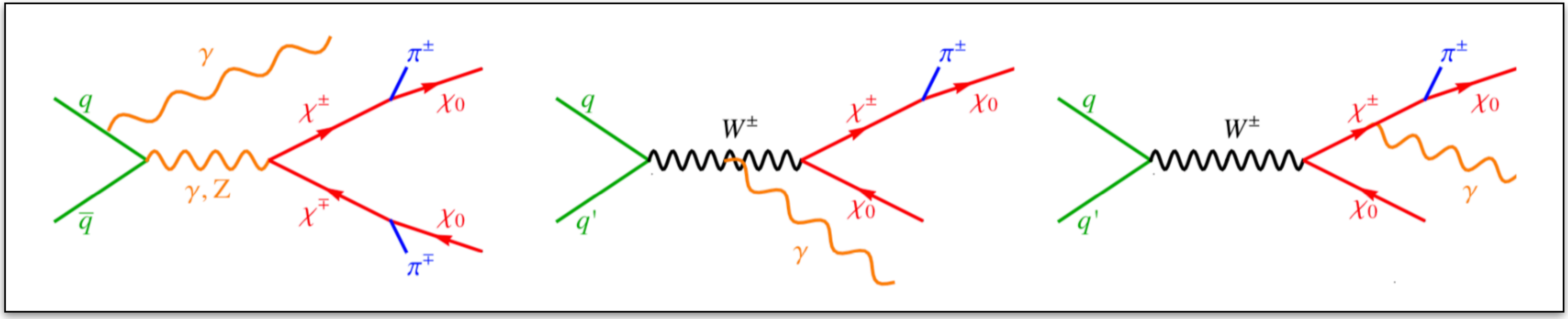
Results: Complex WIMPs



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

Production @ Colliders

$2 \to 2$ 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

Production @ Colliders

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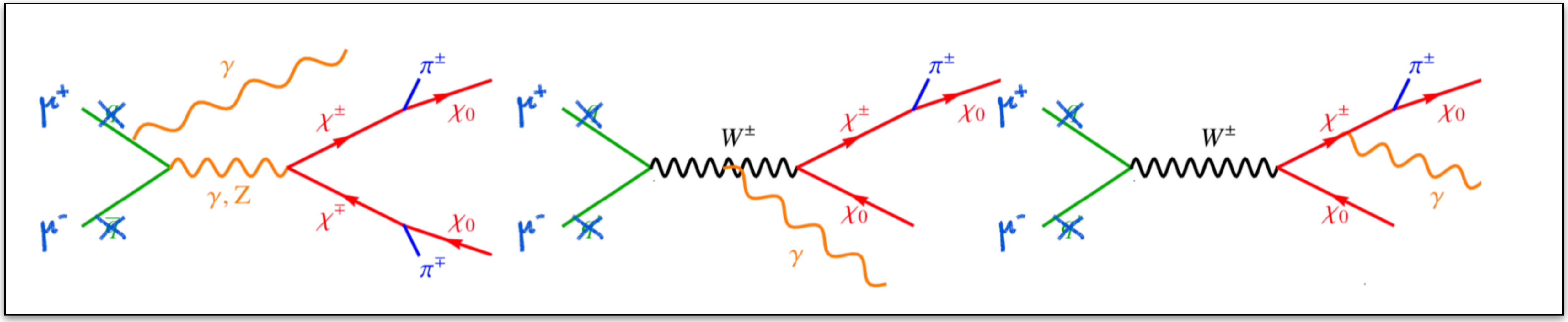

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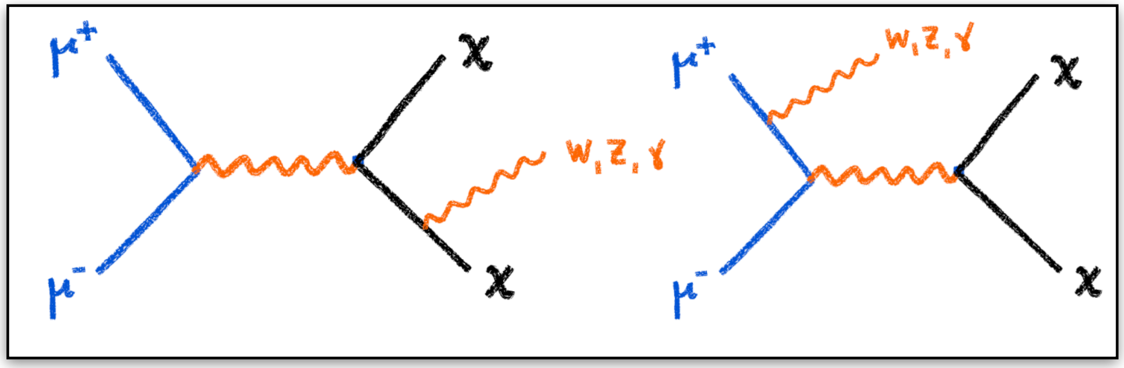
➡ Try with a high-energy lepton collider

μUON COLLIDER

Missing mass searches @ μCollider

Drell-Yan production of invisible χ_0 pair + event tag



✴ Full energy available in the c.o.m.

(ability to discover particles up to $\sqrt{s}/2$)

✴ Full event reconstruction: **missing invariant mass** (not just pT)

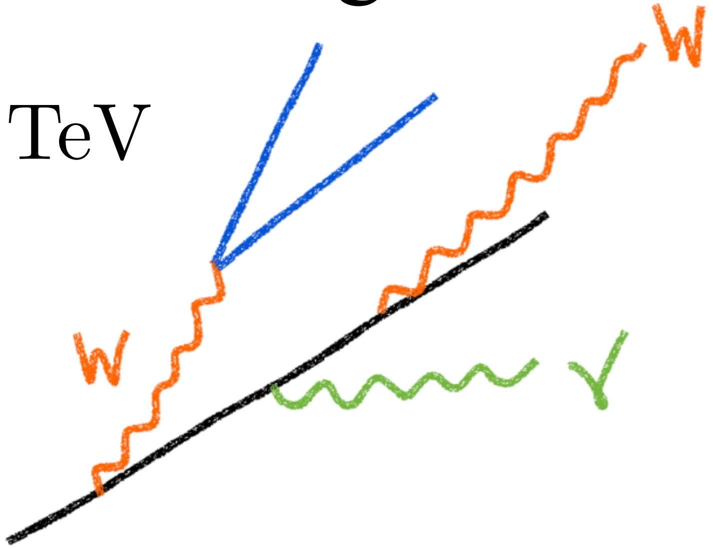
✴ No QCD background: **ideal for EW physics**

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

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

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

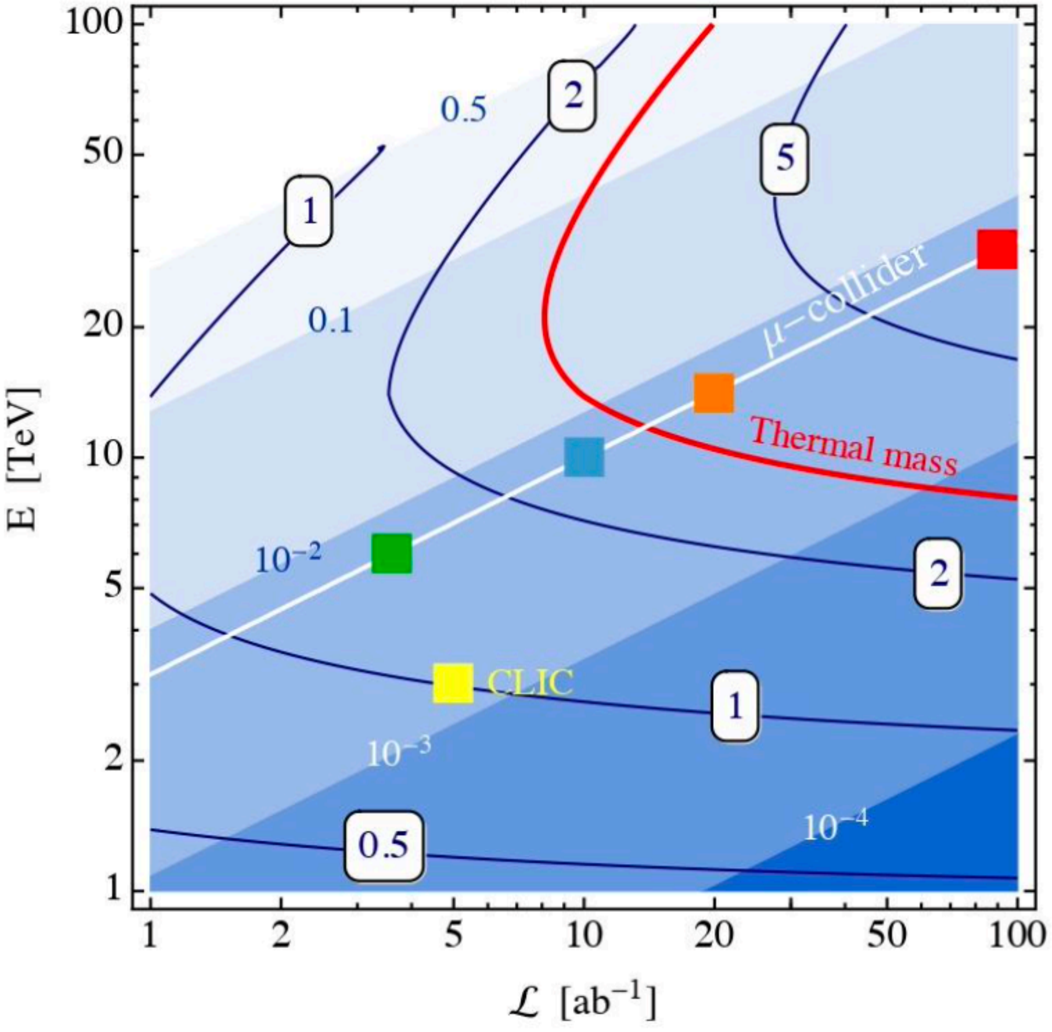
➡ multiple gauge bosons emission



Lumi vs Energy (Mono-W)

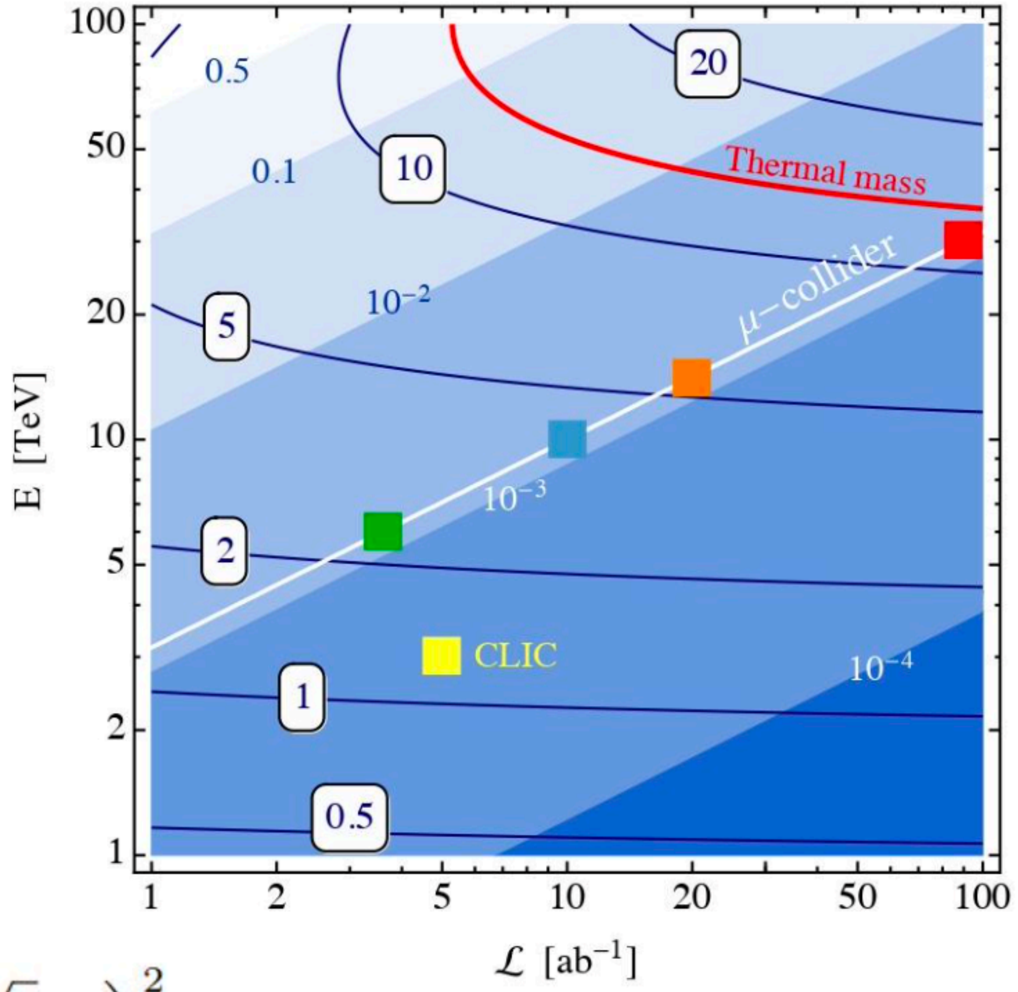
ϵ=0%

Majorana 3-plet



2σ: 12 TeV

Majorana 5-plet



2σ: 35 TeV

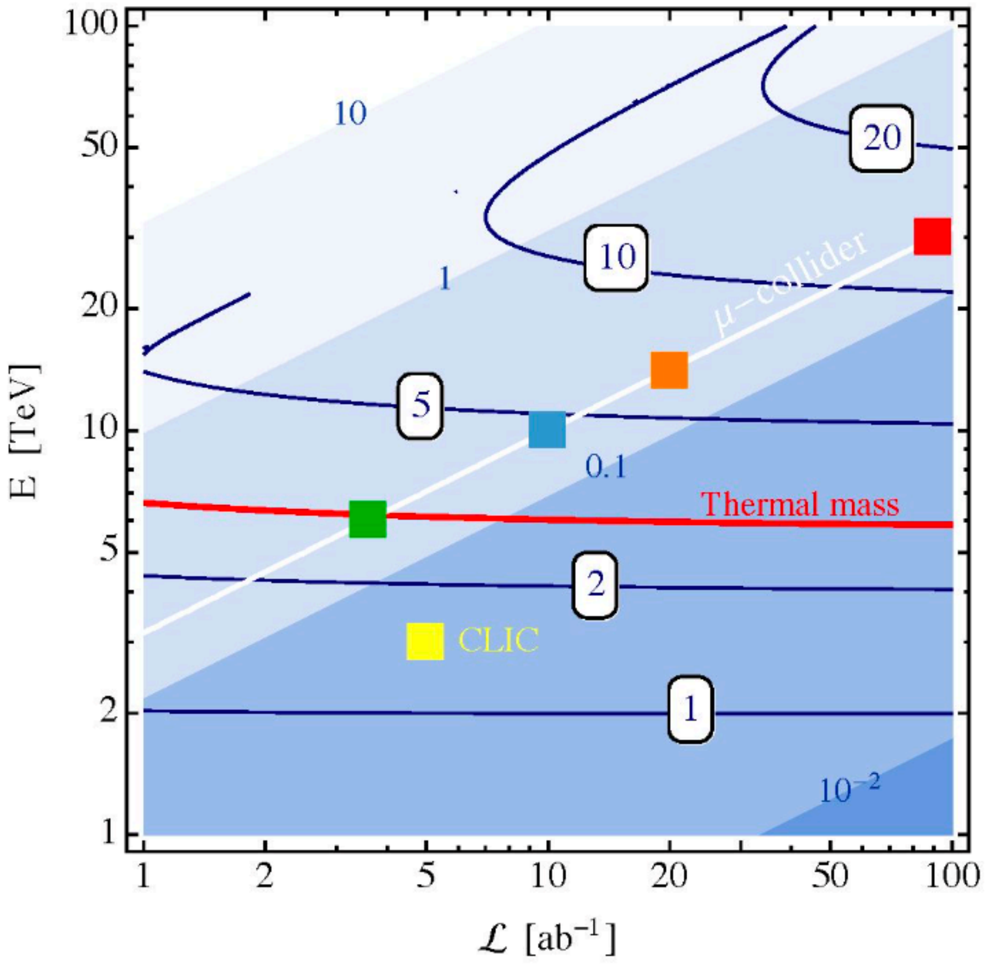
$$\mathcal{L} \simeq 10\ \text{ab}^{-1} \cdot \left(\frac{\sqrt{s}}{10\ \ \text{TeV}}\right)^2$$

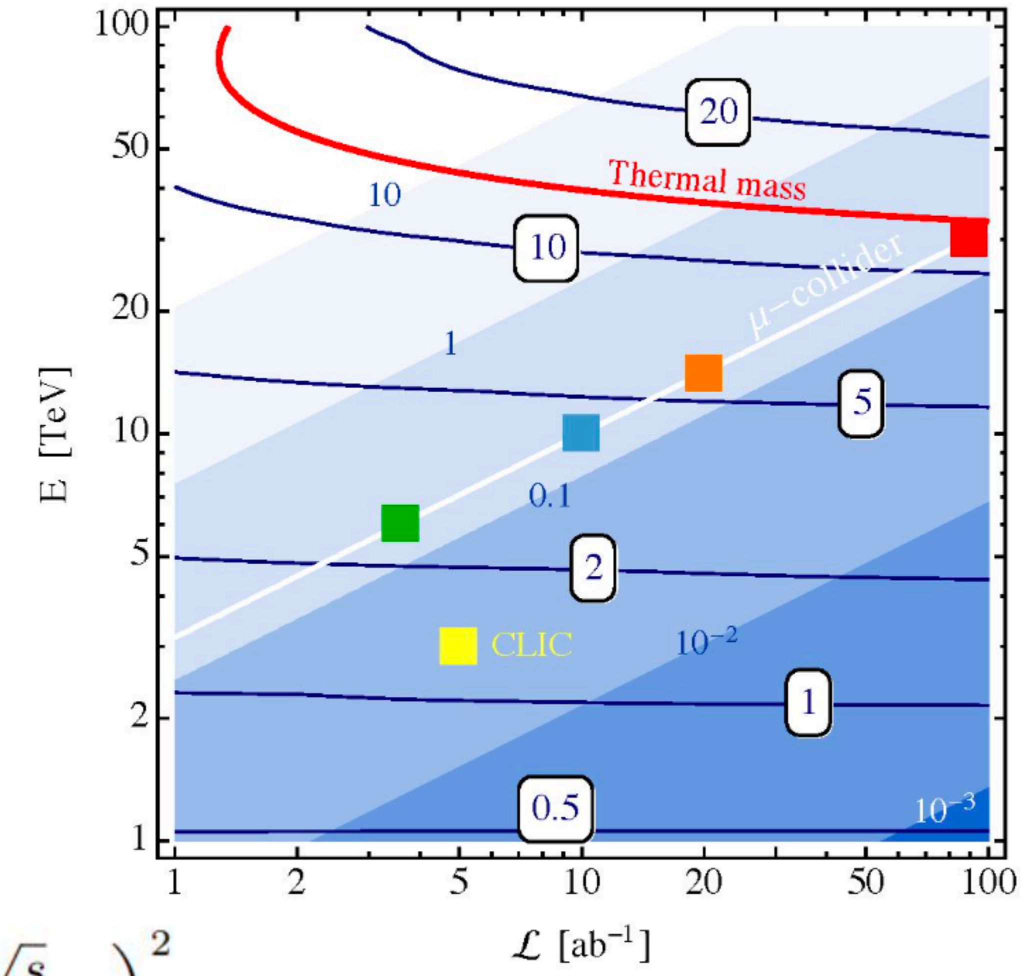
Lumi vs Energy (DTs)

Majorana 3-plet

ϵ=0%

Majorana 5-plet



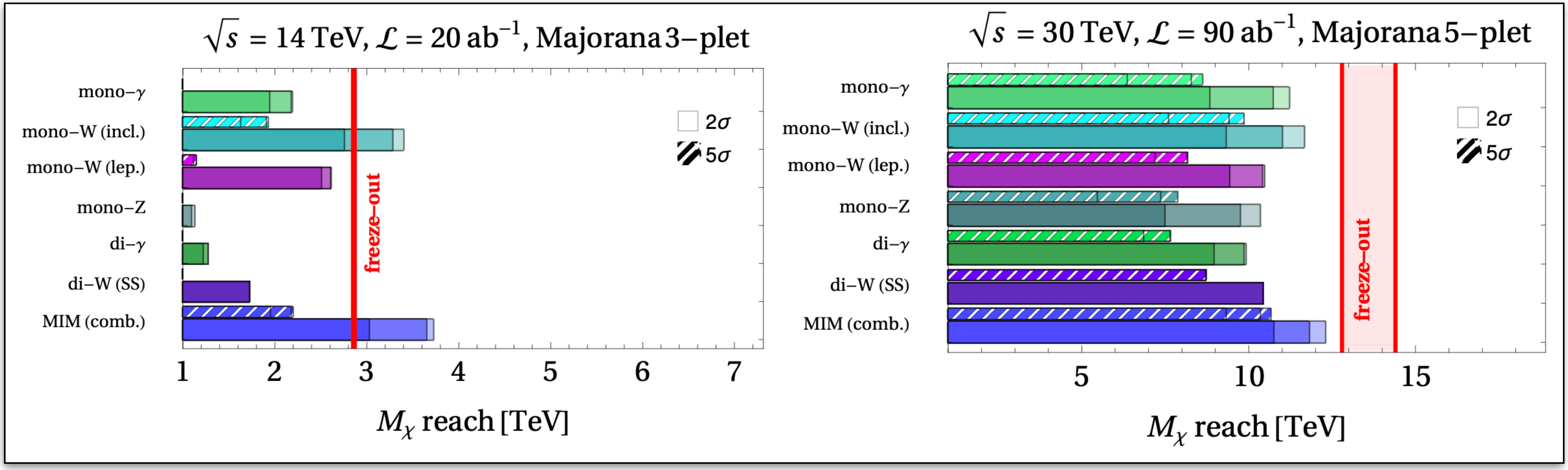


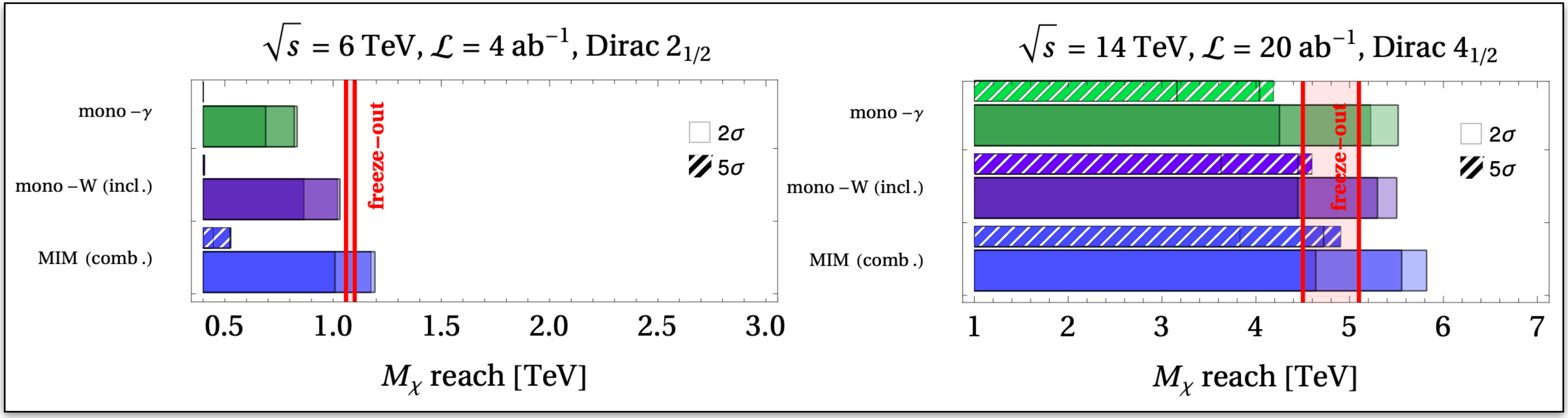
$$\mathcal{L} \simeq 10\ \text{ab}^{-1} \cdot \left(\frac{\sqrt{s}}{10\ \text{TeV}}\right)^2$$

2σ: 6 TeV

2σ: 35 TeV

Missing mass searches @ μCollider



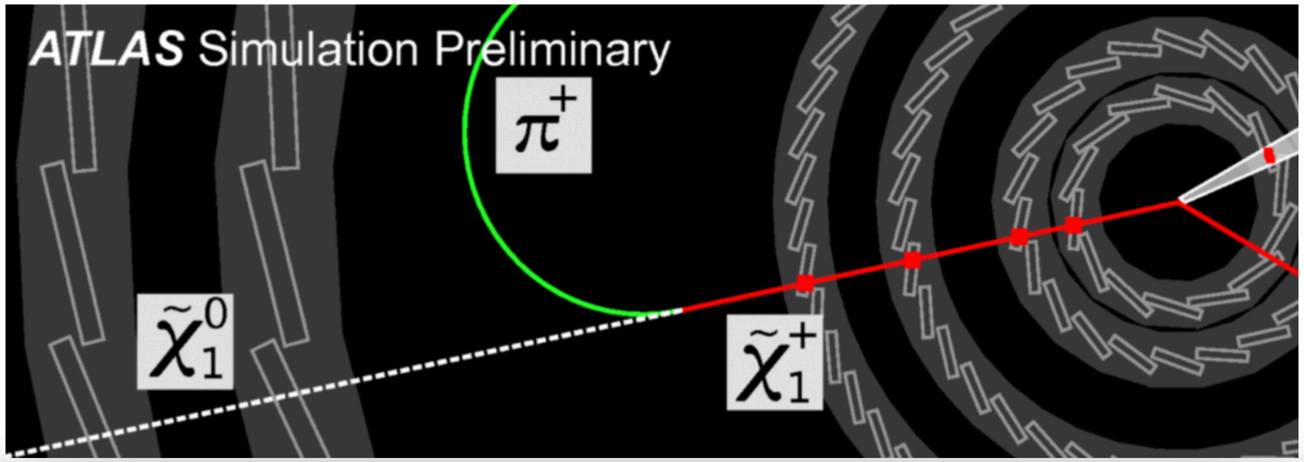


* shadings=different assumptions about systematic errors
typically low S/B → requires good control of systematics

Mass splitting and DTs

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

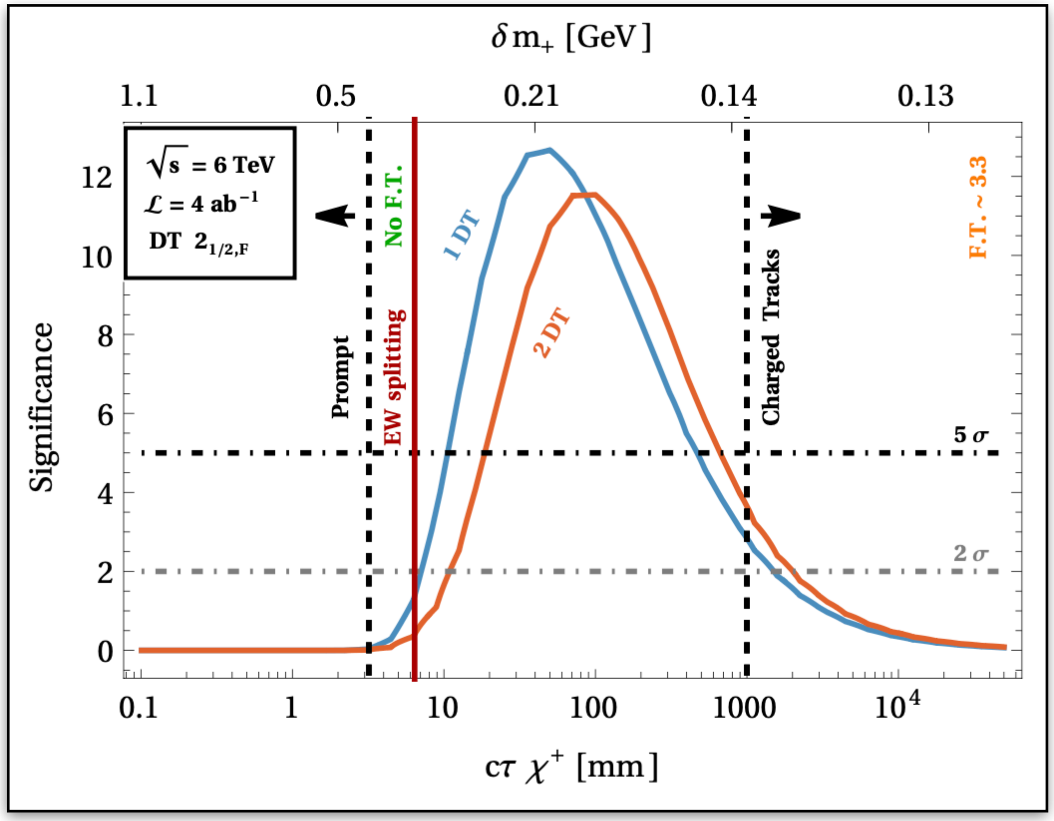
- ✳ Look for disappearing tracks of the charged particles
  to isolate the DM signals from the SM background (mainly neutrinos)



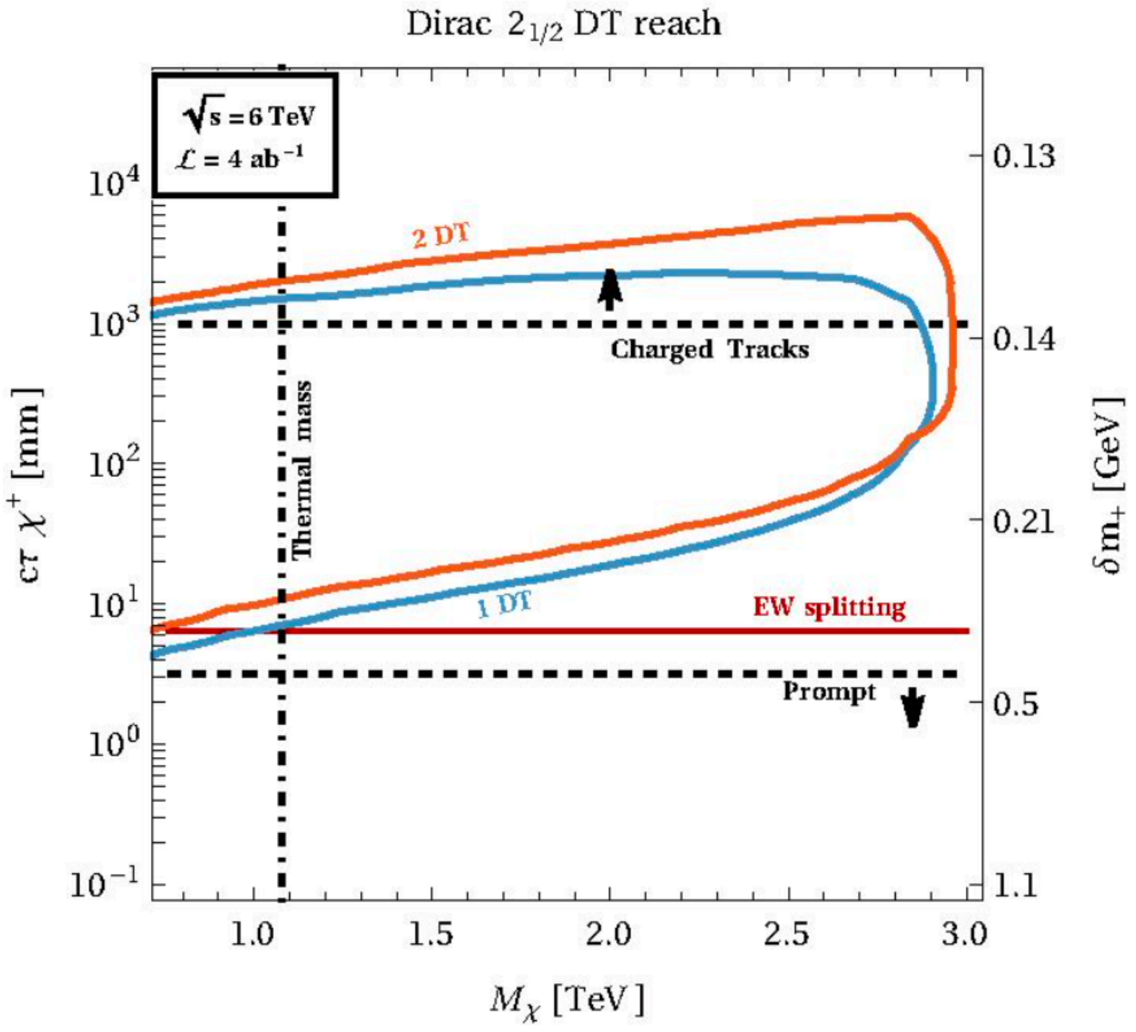
Recast of Capdevila *et al.* 2101.10334

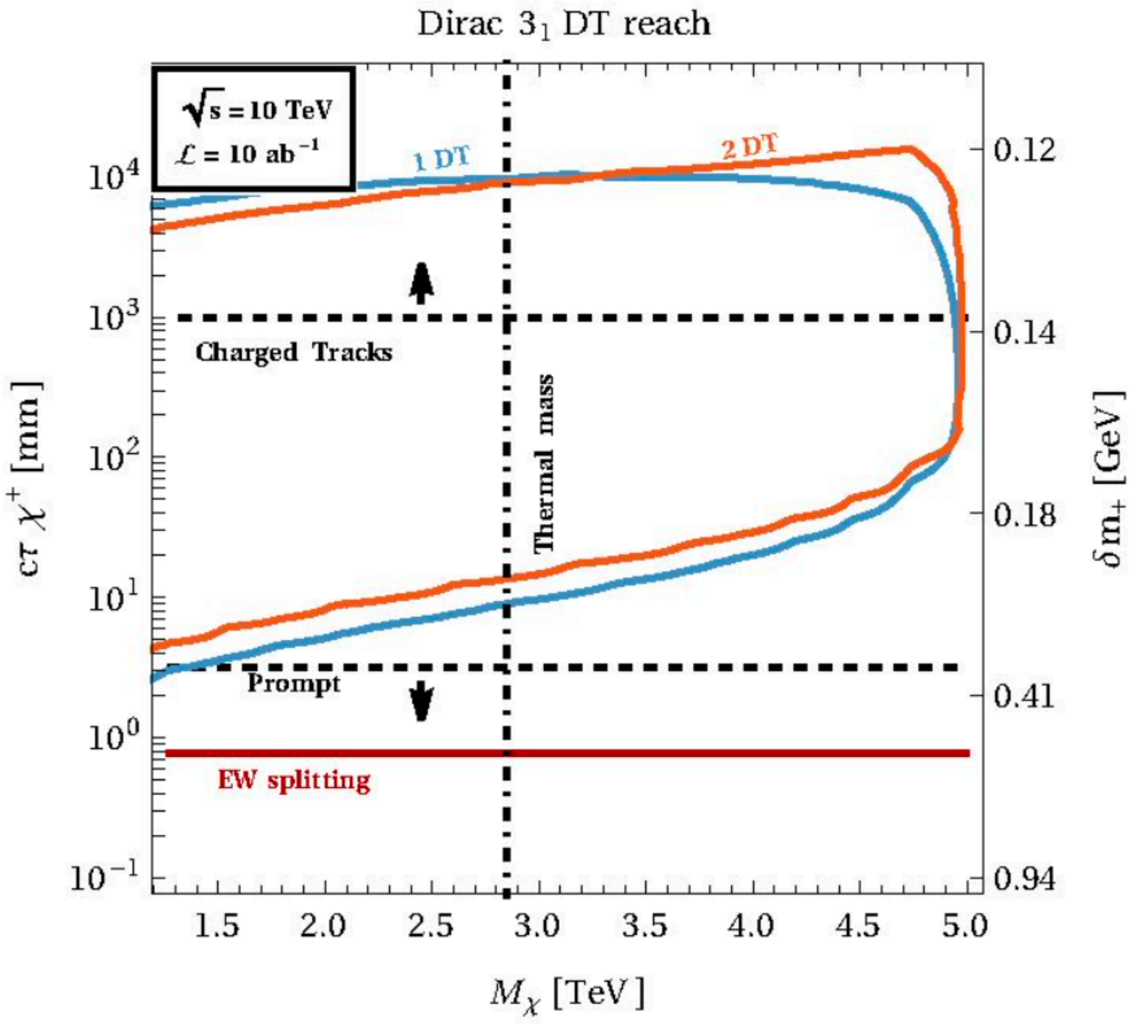
- ✳ For real WIMPs with Y=0
  mass splitting is fixed: $c\tau_{\chi^\pm} \approx 50\,\mathrm{cm}/(n^2-1)$

- ✳ For complex WIMPs with Y≠0:
  mass splitting is fixed by gauge interactions only for multiplets with maximal Y

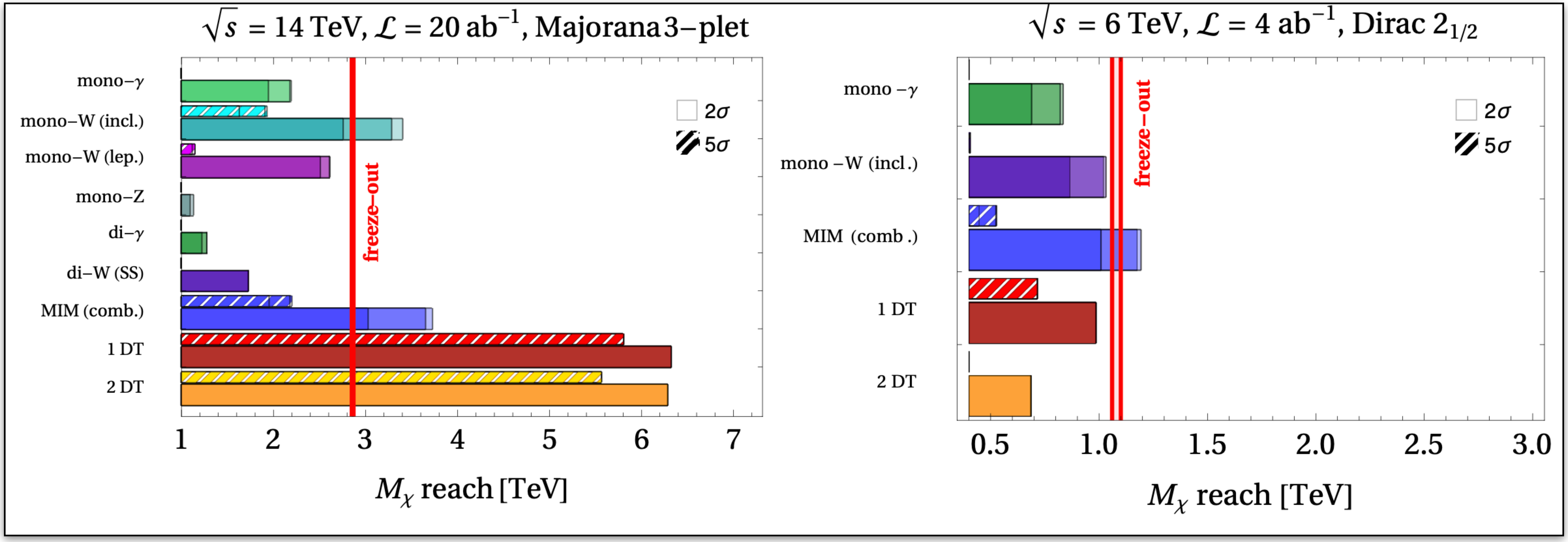


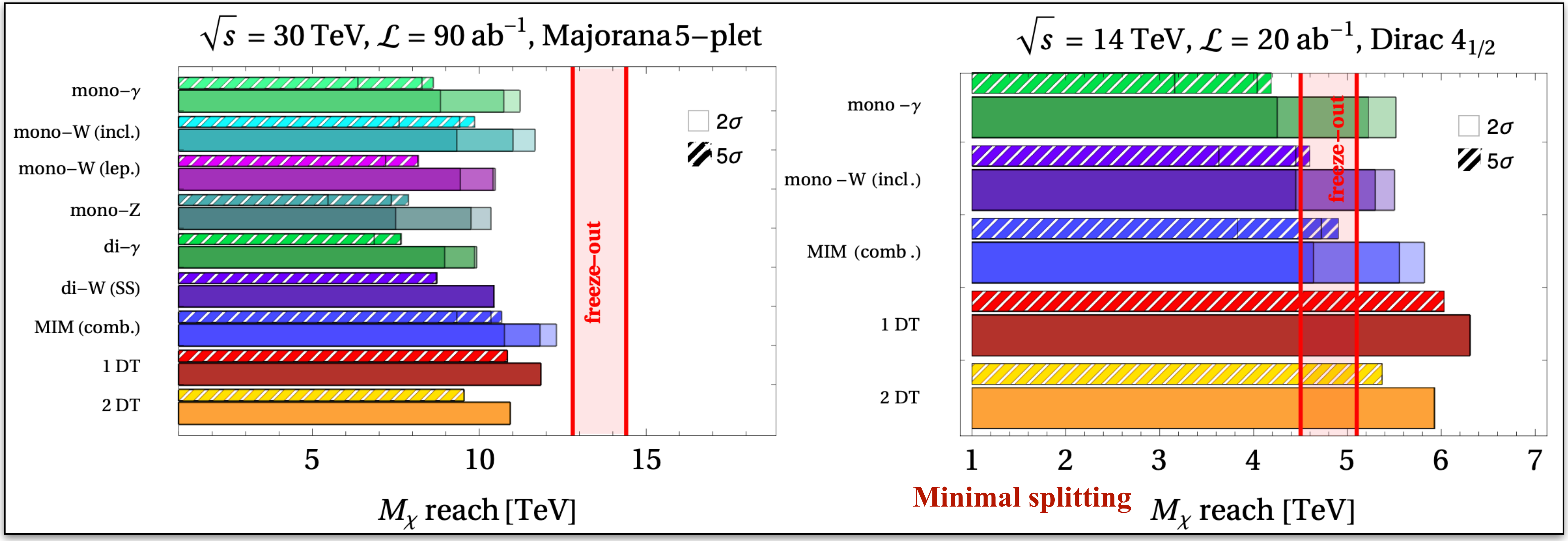
Disappearing Tracks Reach





Disappearing tracks @ μCollider

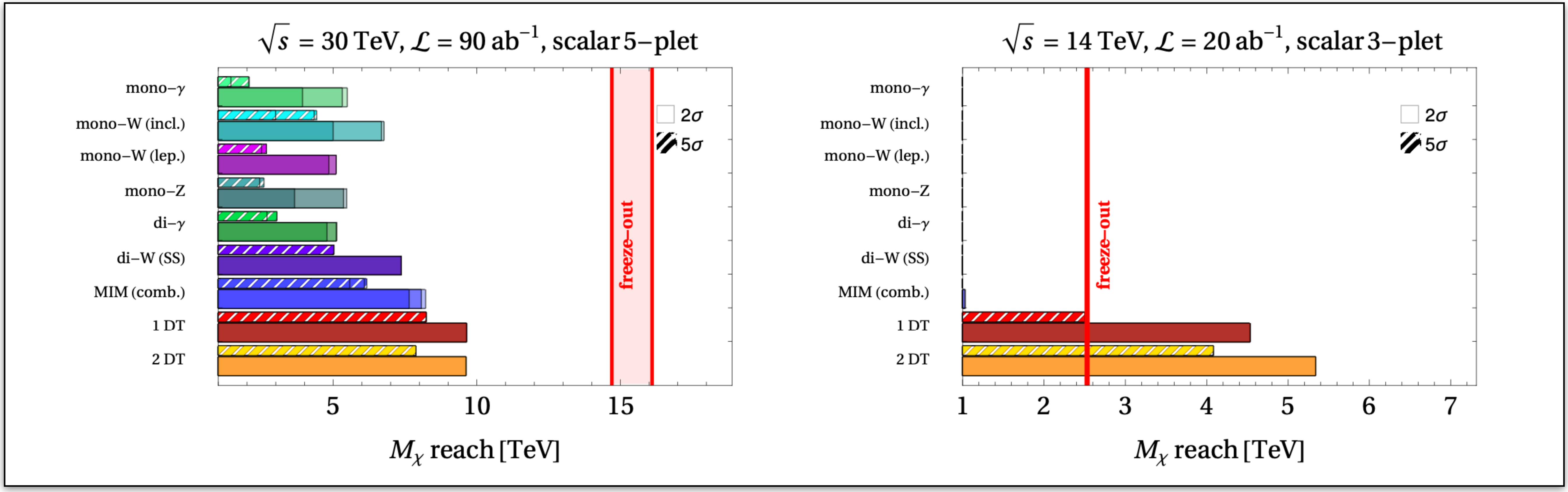




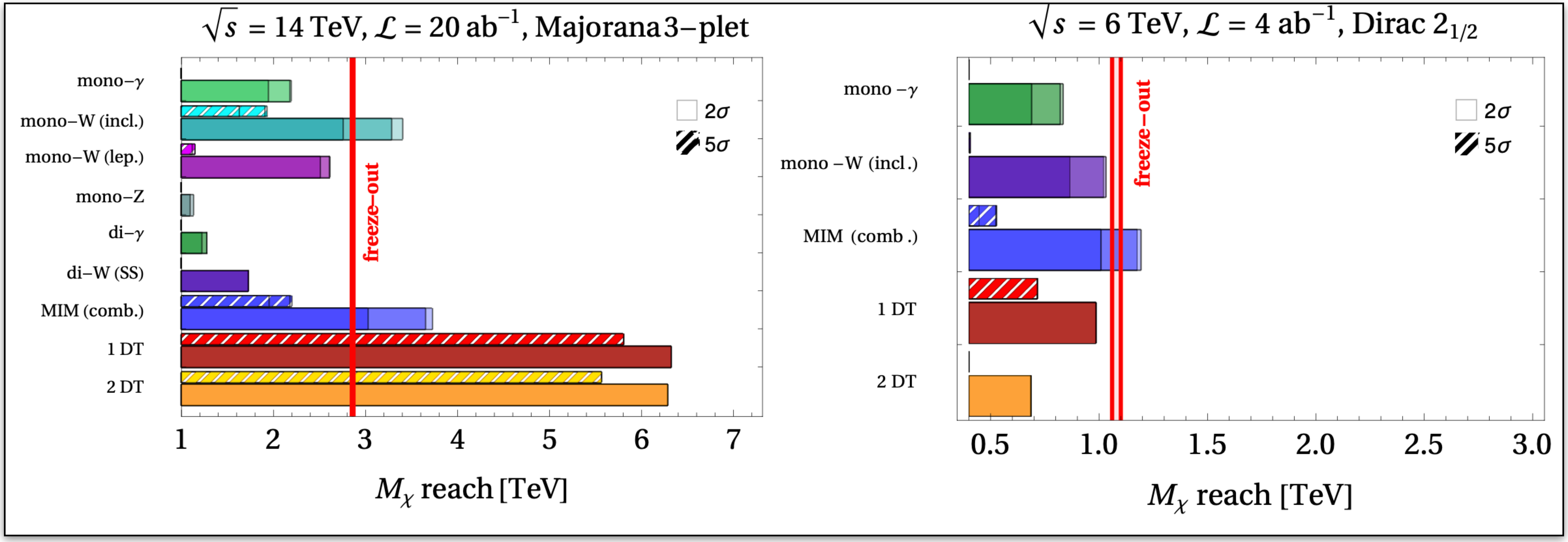
Minimal splitting

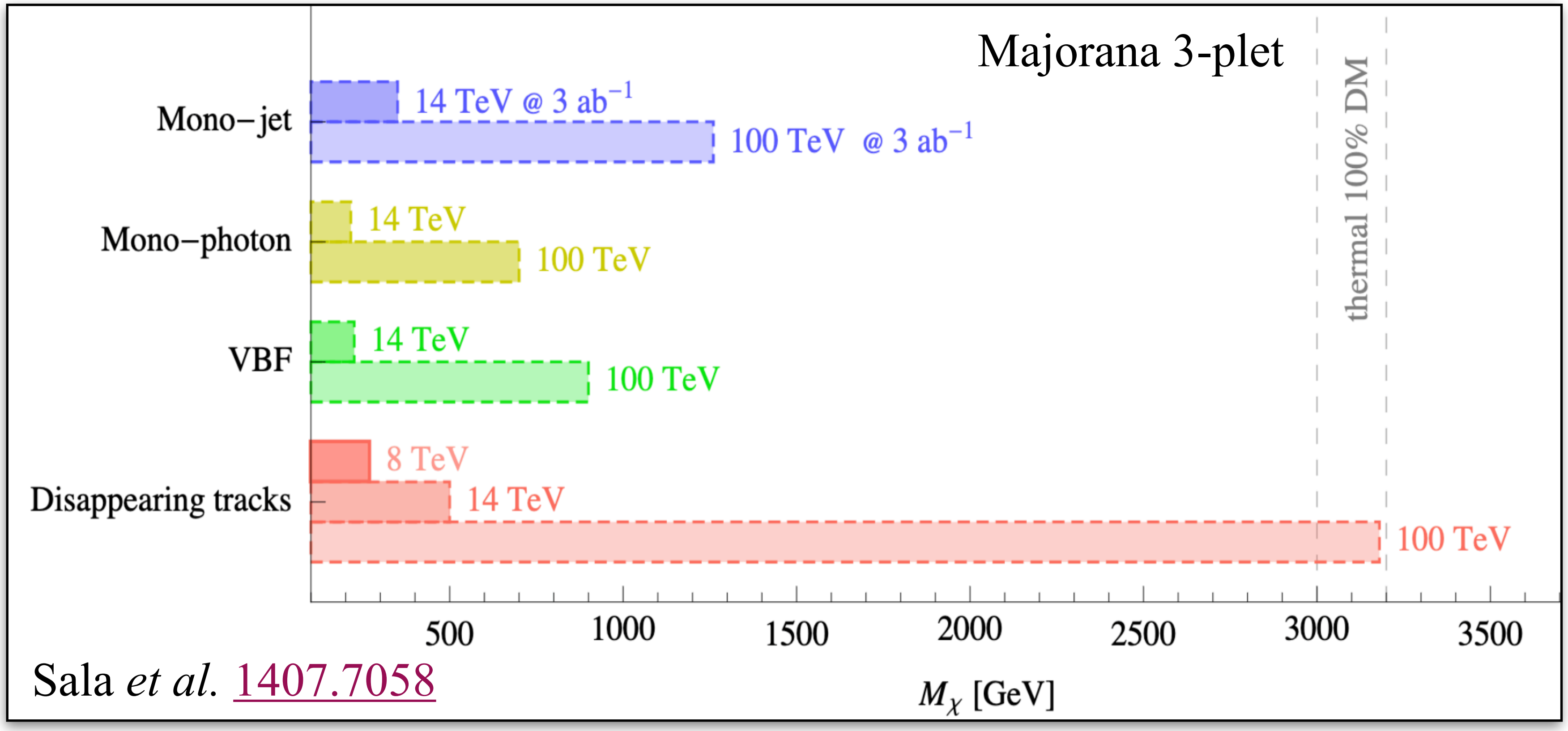
Results: Scalar WIMPs

Scalar WIMPs have lower cross sections



Disappearing tracks @ Colliders





Sala *et al.* 1407.7058

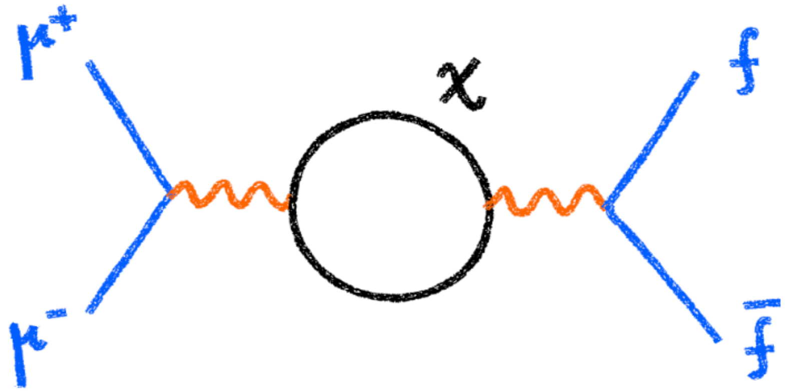
*Disappearing tracks allow to probe the Wino also at FCC-hh

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