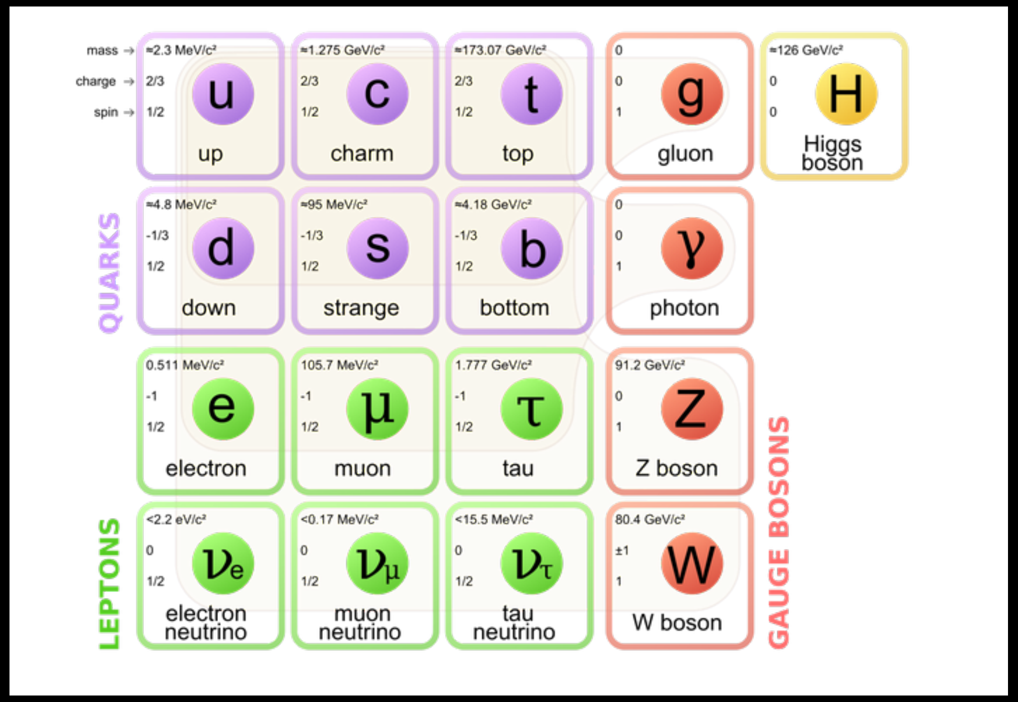
What is Dark Matter made of ?

$$\mathcal{L}_{\rm DM}\ ?$$

Disclaimer



$h_{\mu\nu}$ $\mathcal{L}_{\rm DM}$?

If the Dark Matter is a singlet it can naturally interact with the SM only gravitationally

DM can still be produced non-thermally

Hunting for DM in *non-gravitational* observables
one should keep in mind that there might be nothing to hunt for…

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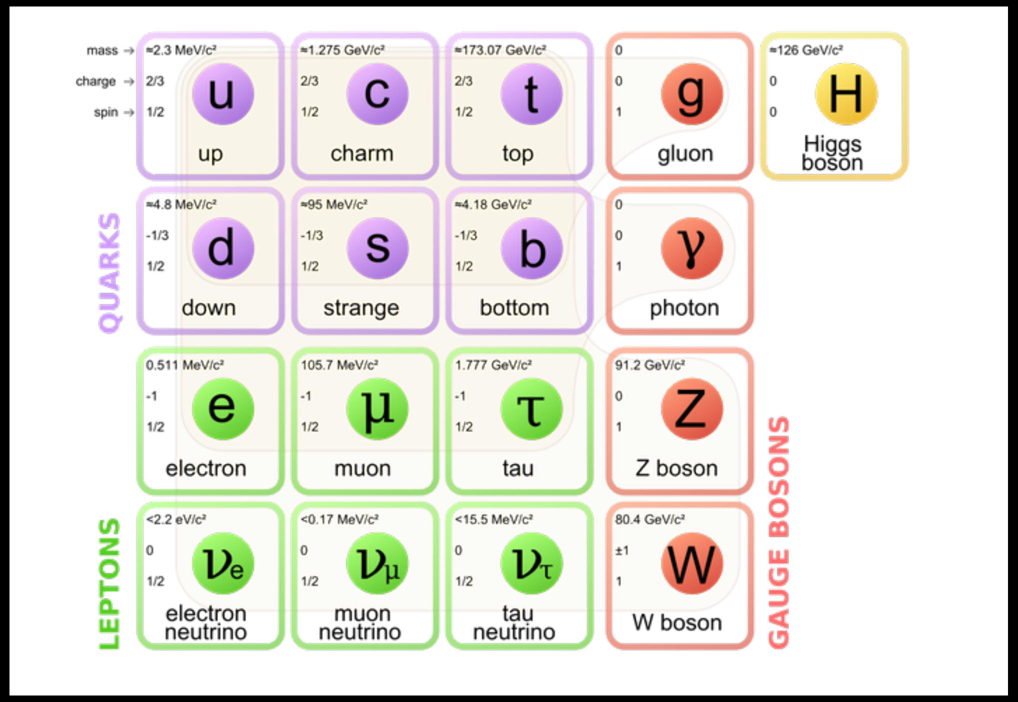

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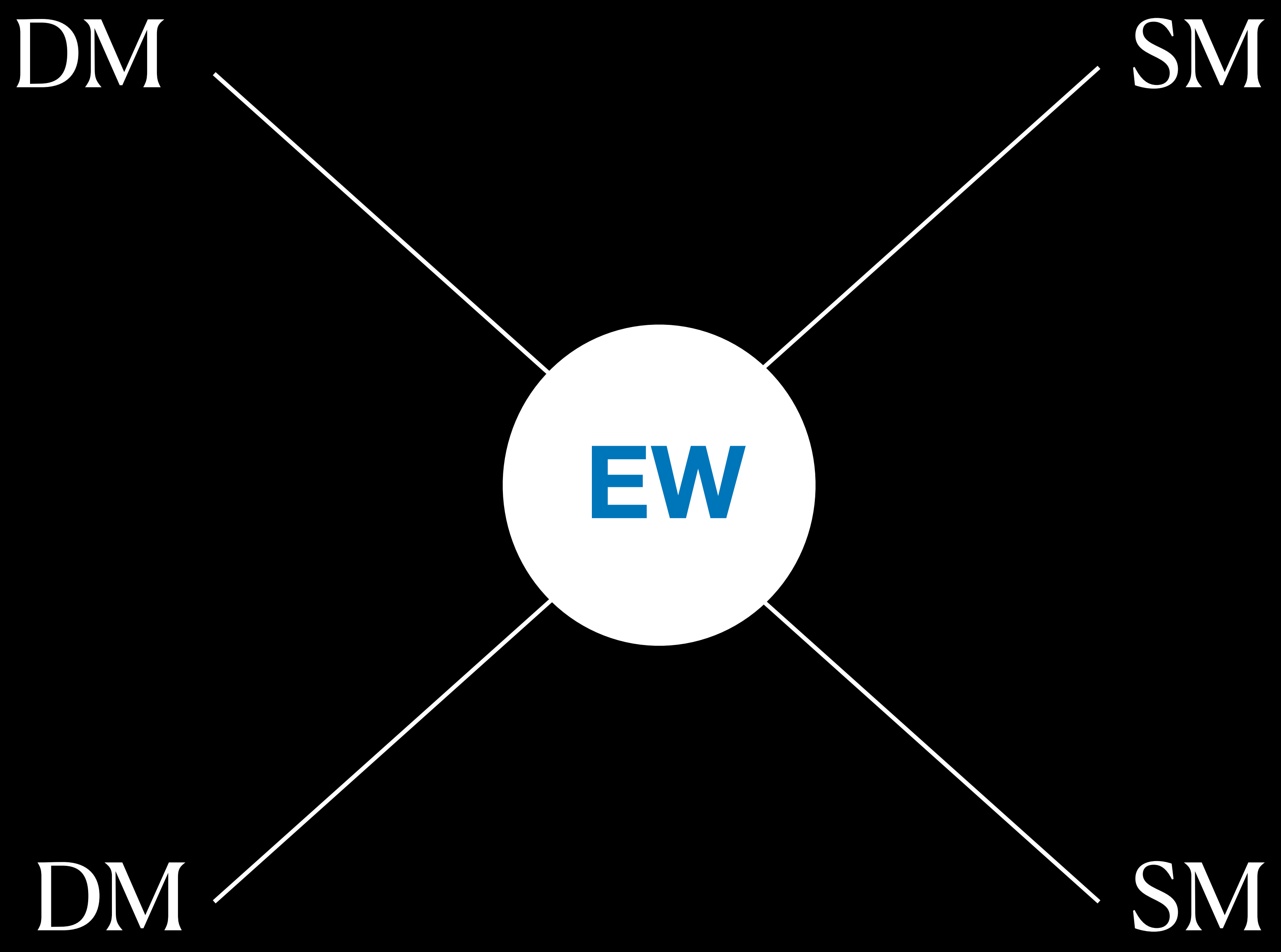
one should keep in mind that there might be nothing to hunt for…

Conversely the DM might be charged under the SM gauge group…

Is Dark Matter Electroweak?



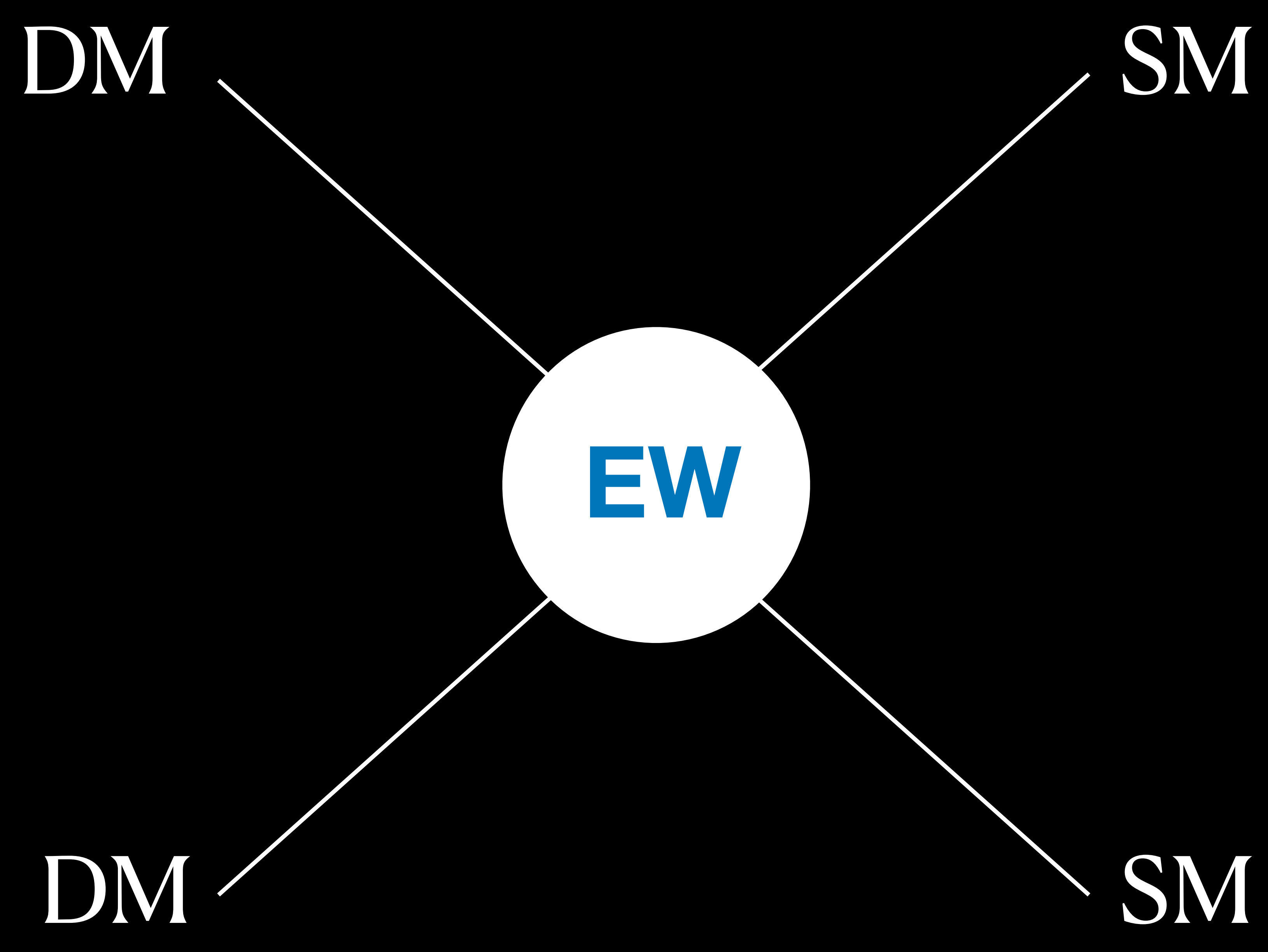
Assumptions* Cirelli, Fornengo, Strumia 2005

1) SM+DM up to a UV cutoff Λ_{UV}

2) 100% of DM in a single representation of SU(2)

$$\mathcal{L}_{DM} = \bar{\chi}(i\bar{\sigma}^{\mu}\partial_{\mu} - M_{\chi})\chi^{*}$$

Is Dark Matter Electroweak?



Assumptions* Cirelli, Fornengo, Strumia 2005

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$$\mathscr{L}_{\rm DM} = \bar{\chi}(i\bar{\sigma}^{\mu}\partial_{\mu} - M_{\chi})\chi^{*}$$

* 1)+2) make higher dimensional operators controlled by $\mathcal{O}(v/\Lambda_{\rm UV})$

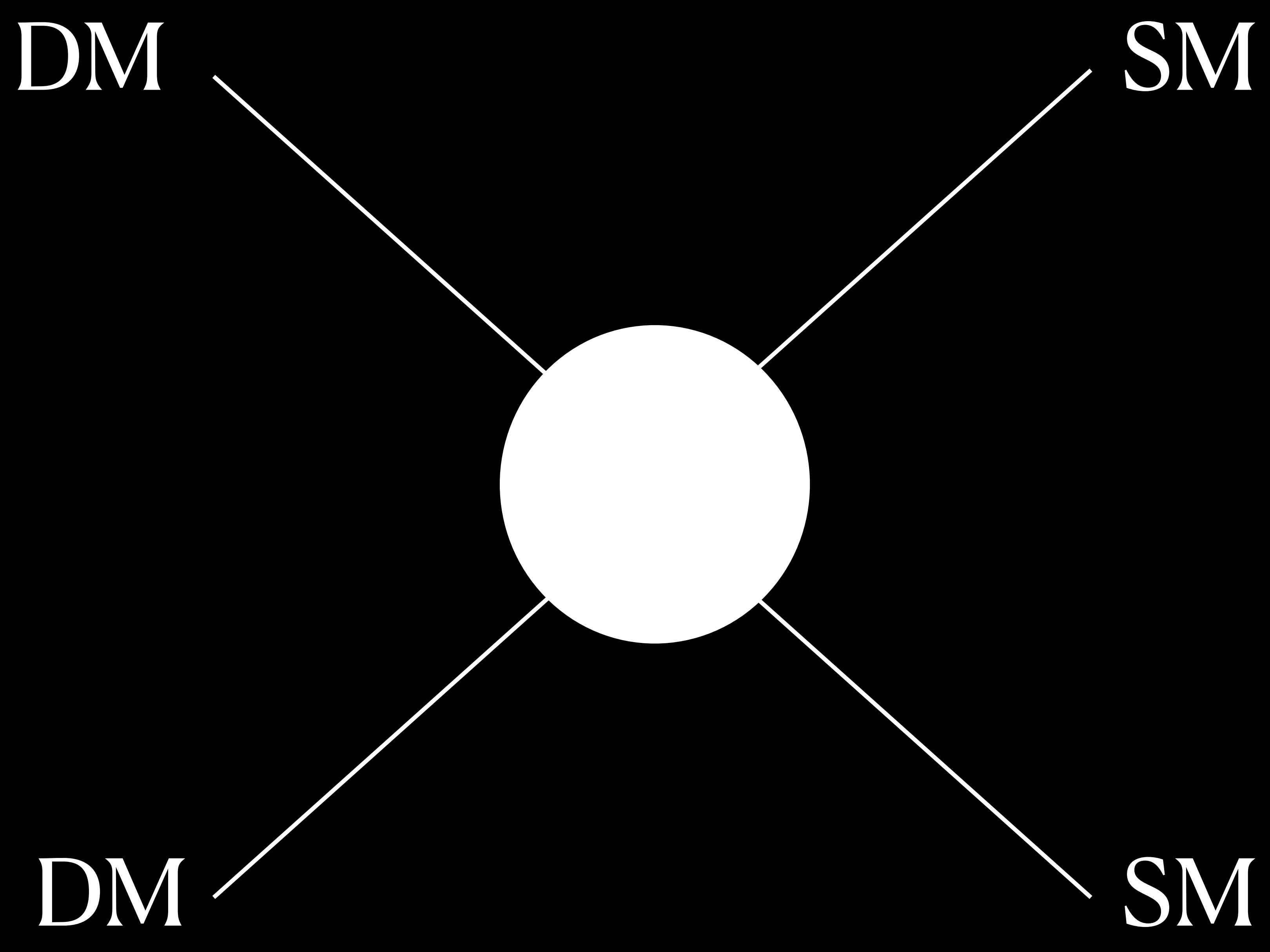
* I will focus on fermions but the same analysis was done for scalars

Plan

1) Classification of electroweak Dark matter	based on work with S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, L. Vittorio 2107.09688 + 2205.04486
2) Uncertainty in the theory Prediction	computed with S. Bottaro 2305.01680
3) Prospect for larg volume Xenon detectors	derived with I. Bloch, S. Bottaro, D.R. and L. Vittorio 2410.02723
4) Prospects for gamma ray telescopes	to appear with M. Baumgart, S. Bottaro, N. Rodd, T. Slatyer

Classification of EW Dark Matter

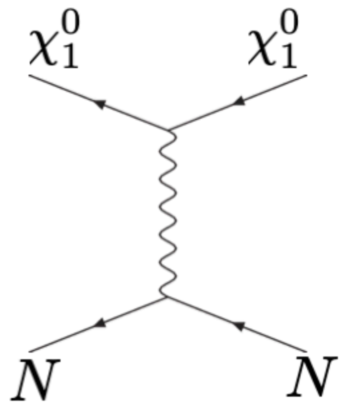
DM in a single representation of SU(2)



Direct Detection

excludes

tree-level Z-interactions



Elastic cross section

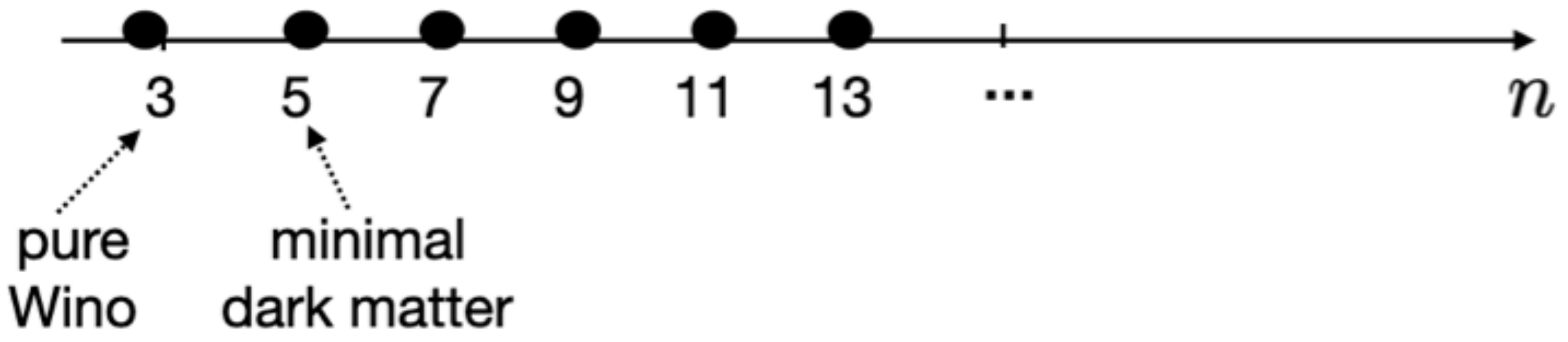
$$\sigma = \frac{G_F^2}{2\pi} \times \underbrace{m_N^2}_{m_\chi \gg m_N} \times Y_\chi^2 \times \underbrace{Y_{\rm Xe}^2}_{N-(1-4s^2_{\theta_{\rm w}})Z} \sim 7 \times 10^{-31} \times \left(\frac{A}{132}\right)^2 \times \left(\frac{Y_{X_e}}{70}\right)^2 \ \mathrm{cm}^2$$

Goodman and Witten 1985

The full list of EW survivors

* real representations with $Y = 0$

S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, D.R. and L. Vittorio 2021



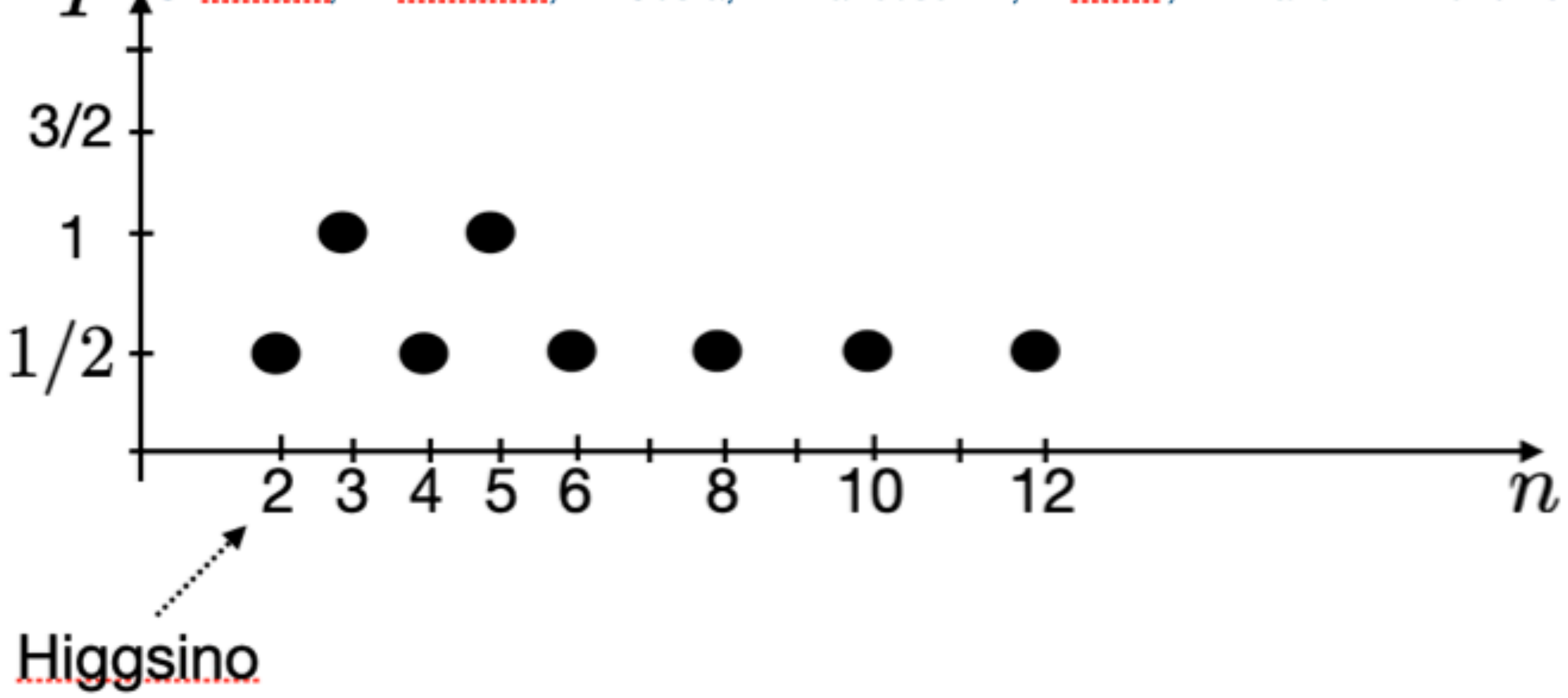
Cirelli, Fornengo, Strumia 2005

DM is Majorana

no tree level scattering with the SM

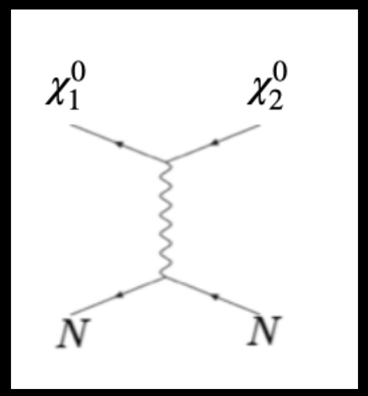
* complex representations $Y \neq 0$

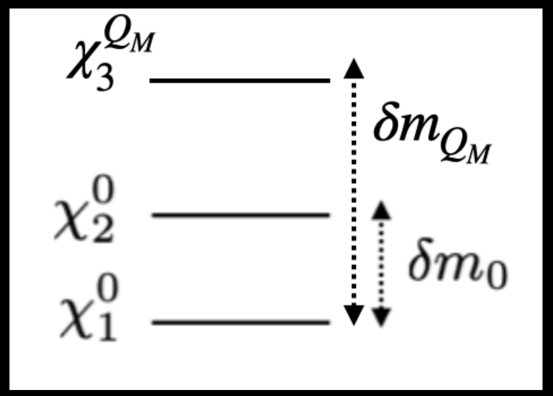
S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, D.R. and L. Vittorio 2022



DM is pseudo-Dirac

Inelastic scattering with the SM

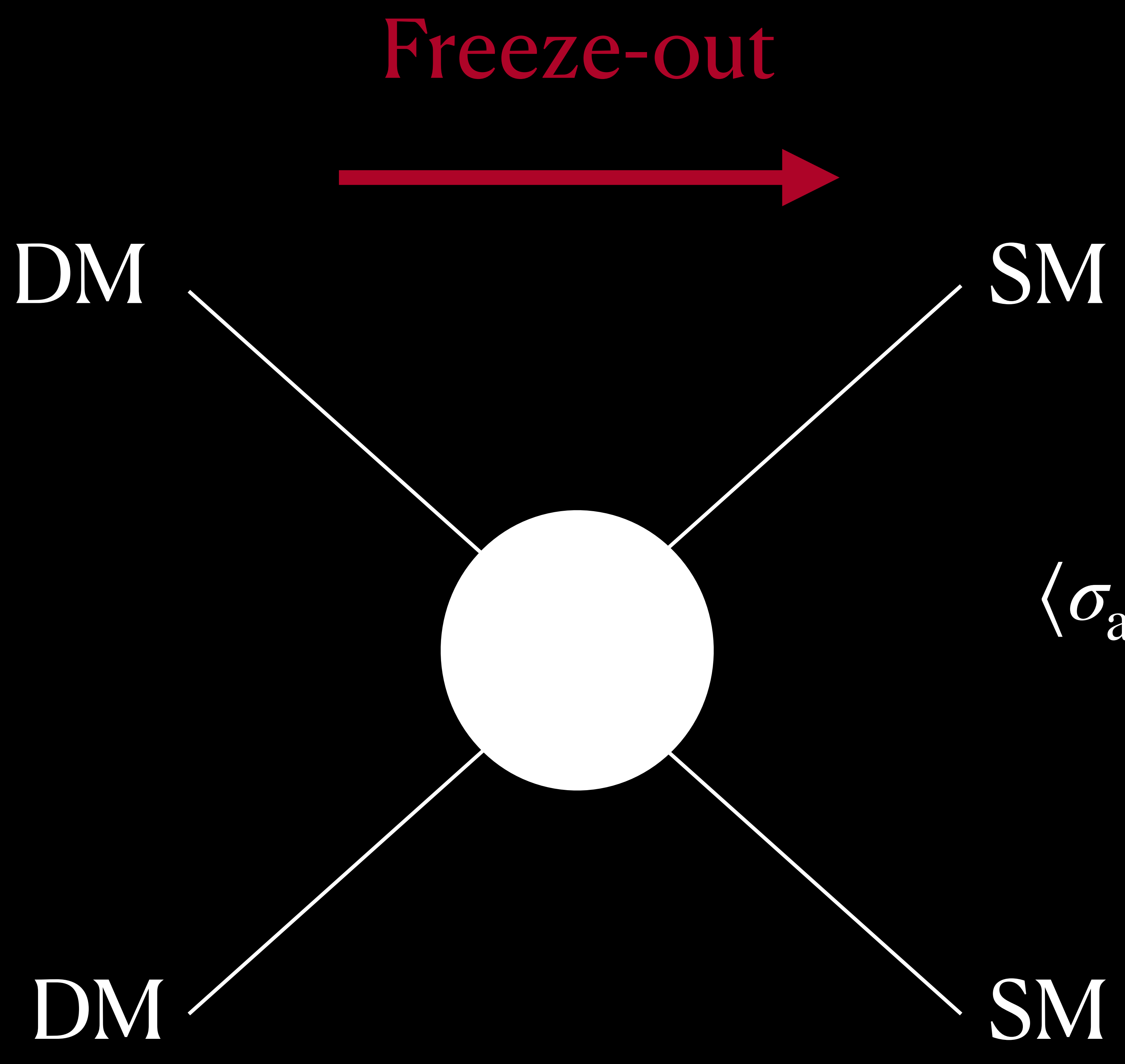




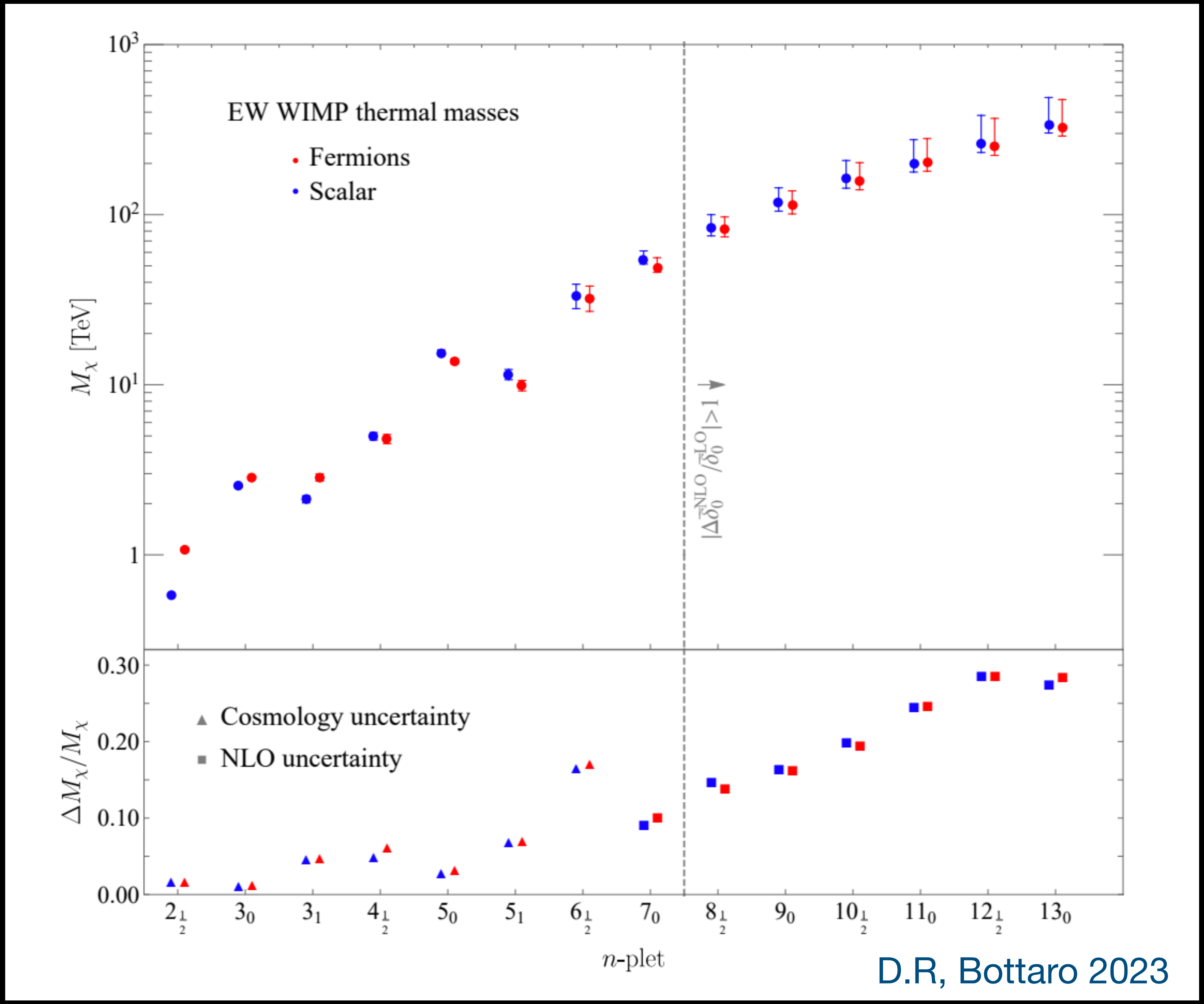
splittings bounded from *above* by direct detection (h-exc.)

below by direct detection (δm_0) and BBN (δm_{Q_M})

Freeze-out masses



$$\langle \sigma_{\text{ann.}} v \rangle \sim \# \frac{\pi^2 \alpha_2^3 n^5}{16 M_\chi^2}$$



fixes the mass necessary

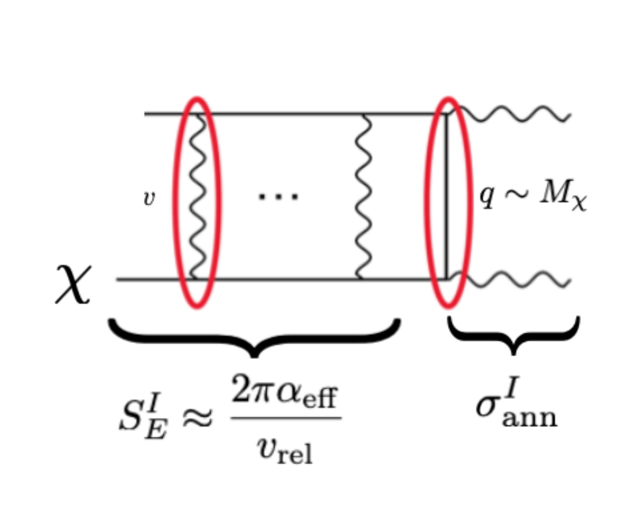
to get the observed DM abundance today

$$\Omega h^2 = 0.12 \leftrightarrow \langle \sigma_{\text{ann.}} v \rangle = 2.2 \cdot 10^{-26}\, \text{cm}^3\, \text{sec}^{-1}$$

Freeze-out uncertainties

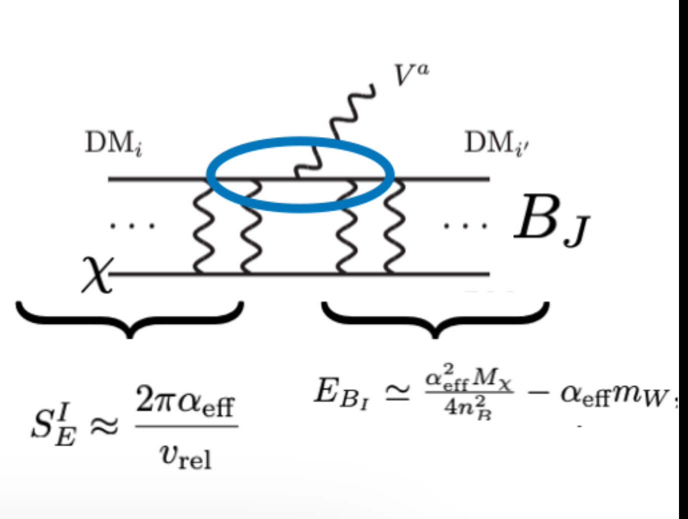
$$\langle \sigma_{\text{ann.}} v \rangle \sim \# \frac{\pi^2 \alpha_2^3 n^5}{16 M_\chi^2}$$

depends on Sommerfeld enhancement (SE)

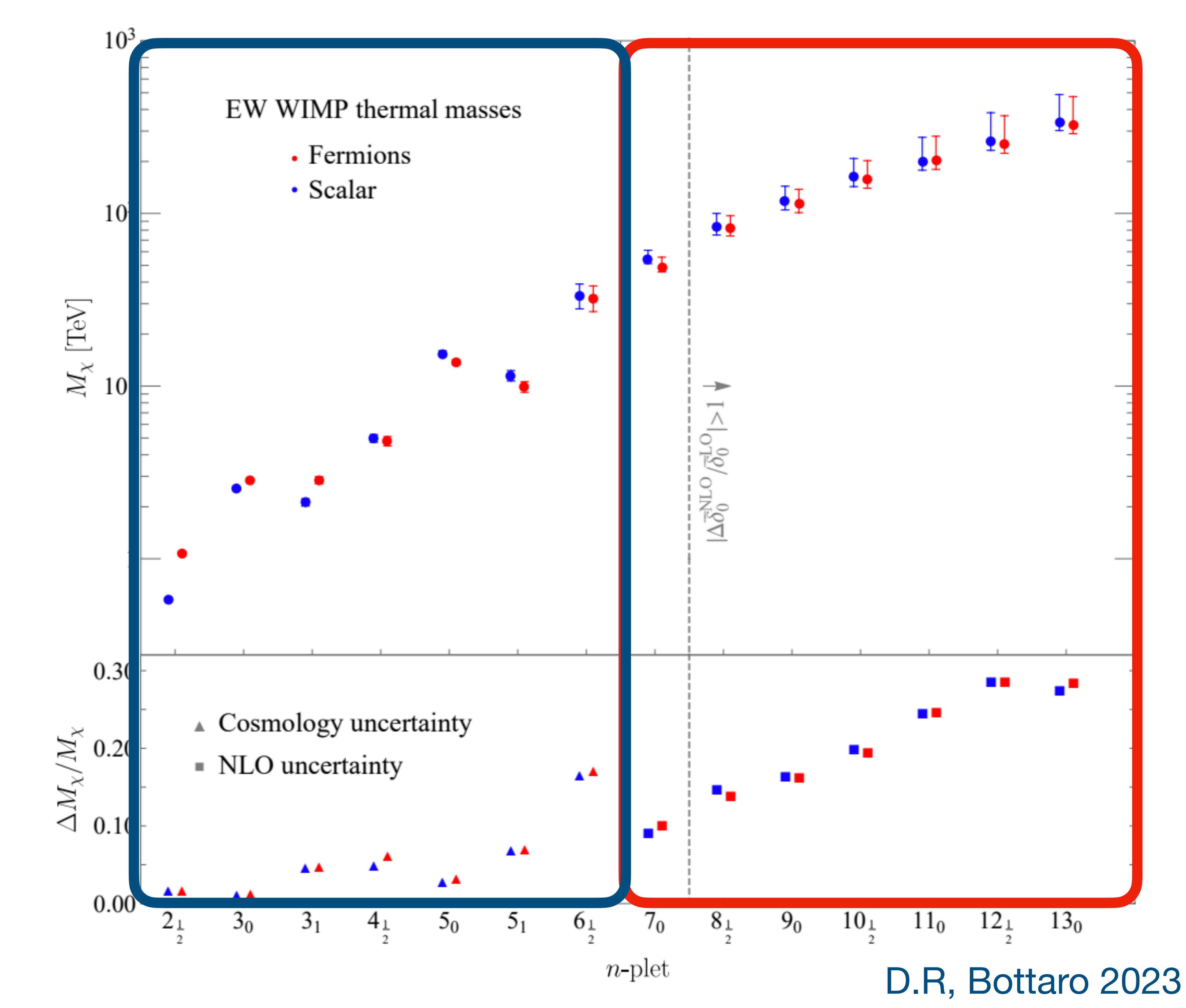


for $n \geq 7$ the uncertainty is dominated by UV NLO contribution to SE

+ bound state formation (BSF)



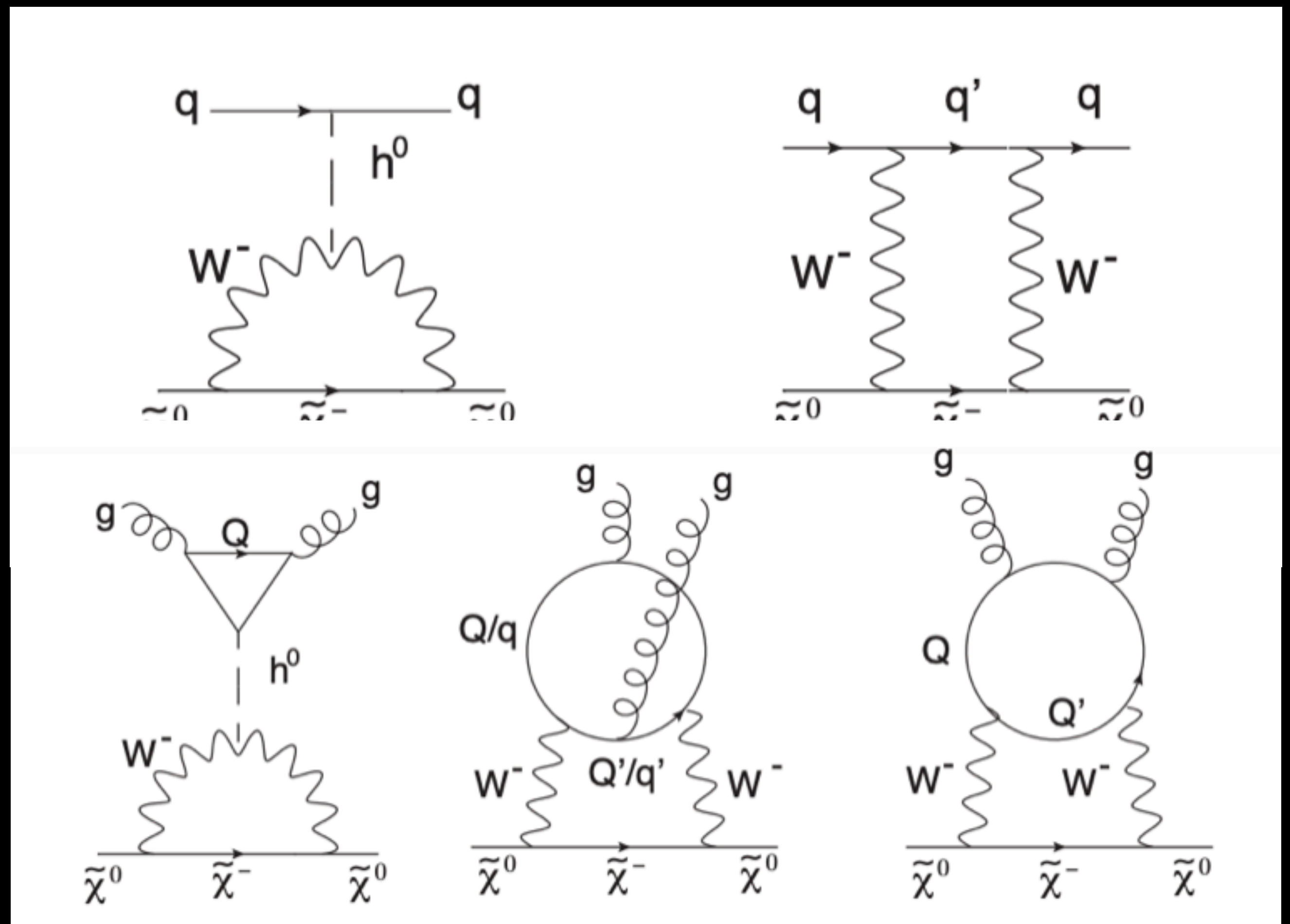
for $n < 7$ by the approximate treatment of BSF cosmology



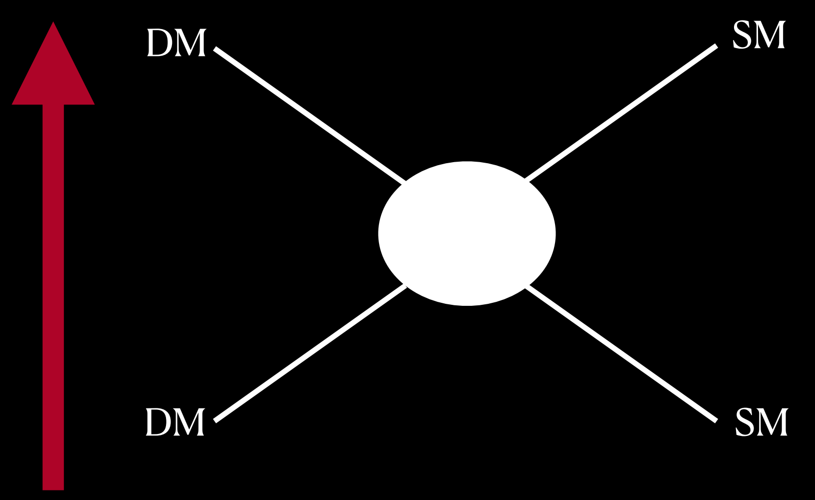
D.R, Bottaro 2023

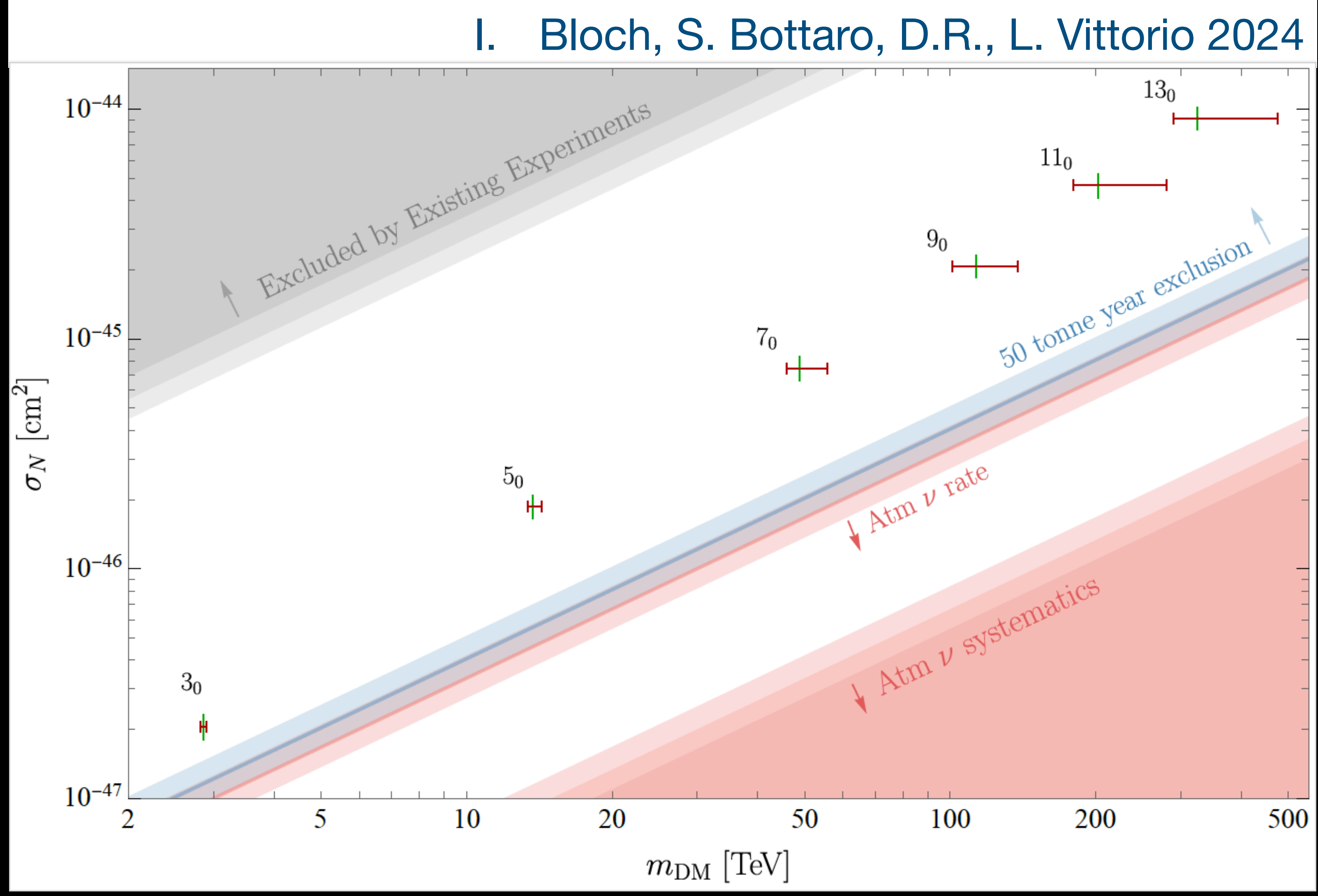
The real multiplets

1-loop +2 loop scattering with nucleons



Hisano, Matsumoto, Nojiri, Saito 2005
Hisano, Ishiwata, Nagata 2010





Heavy real WIMPs

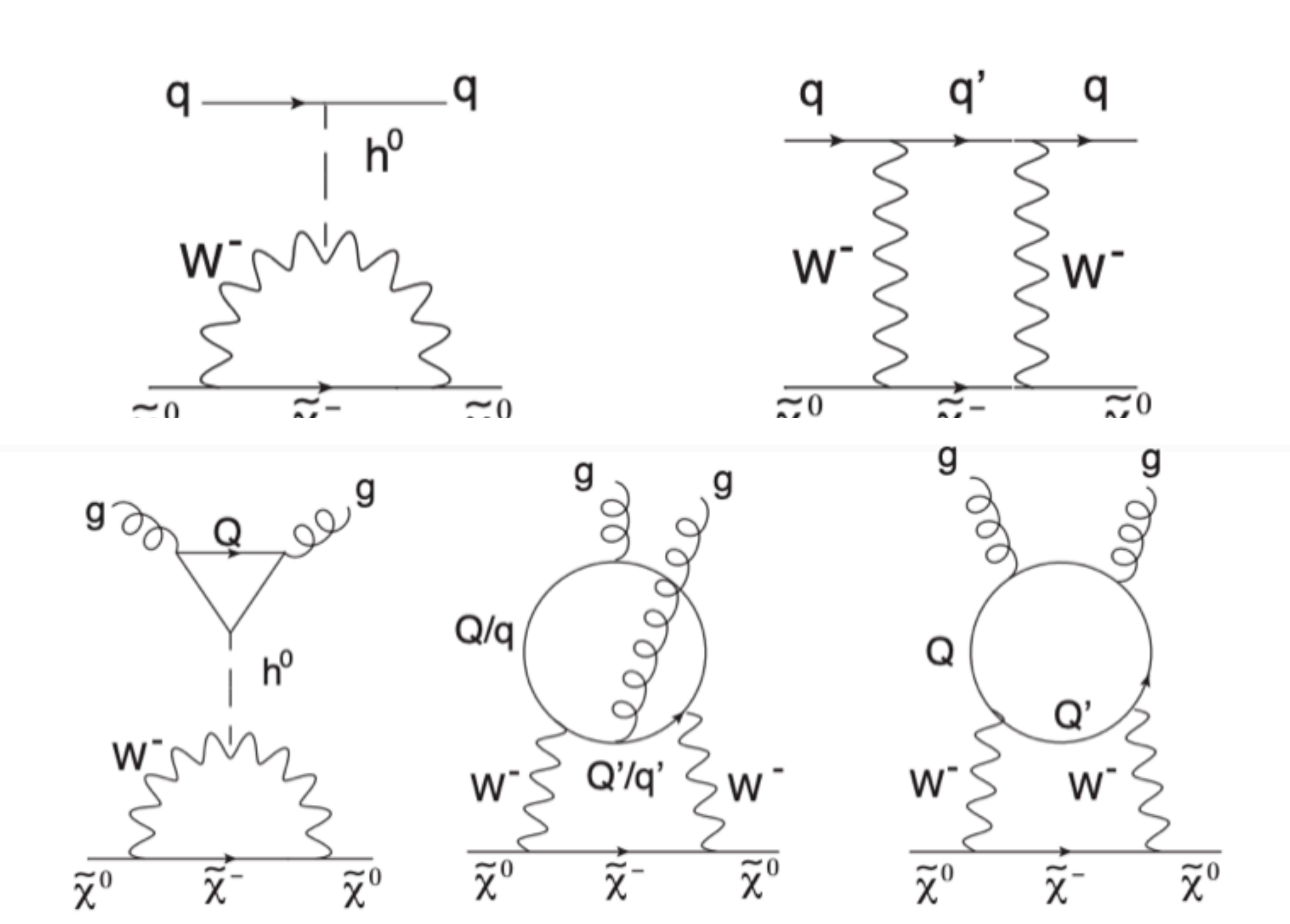
can be tested

with 50 tonne of Xenon

CHALLENGE
suppress noise sources

The real multiplets

1-loop +2 loop scattering with nucleons



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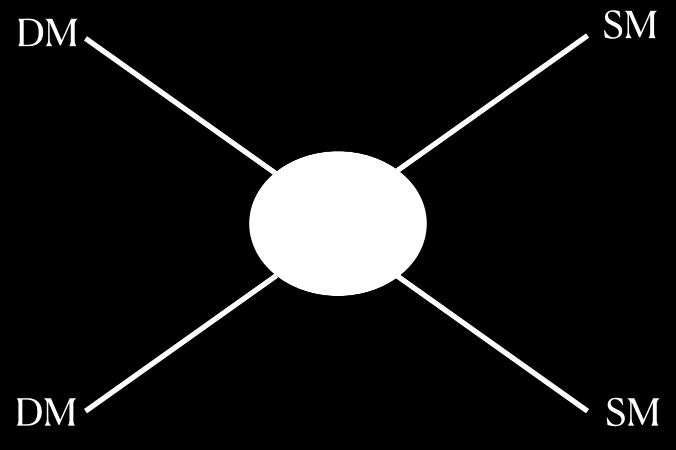
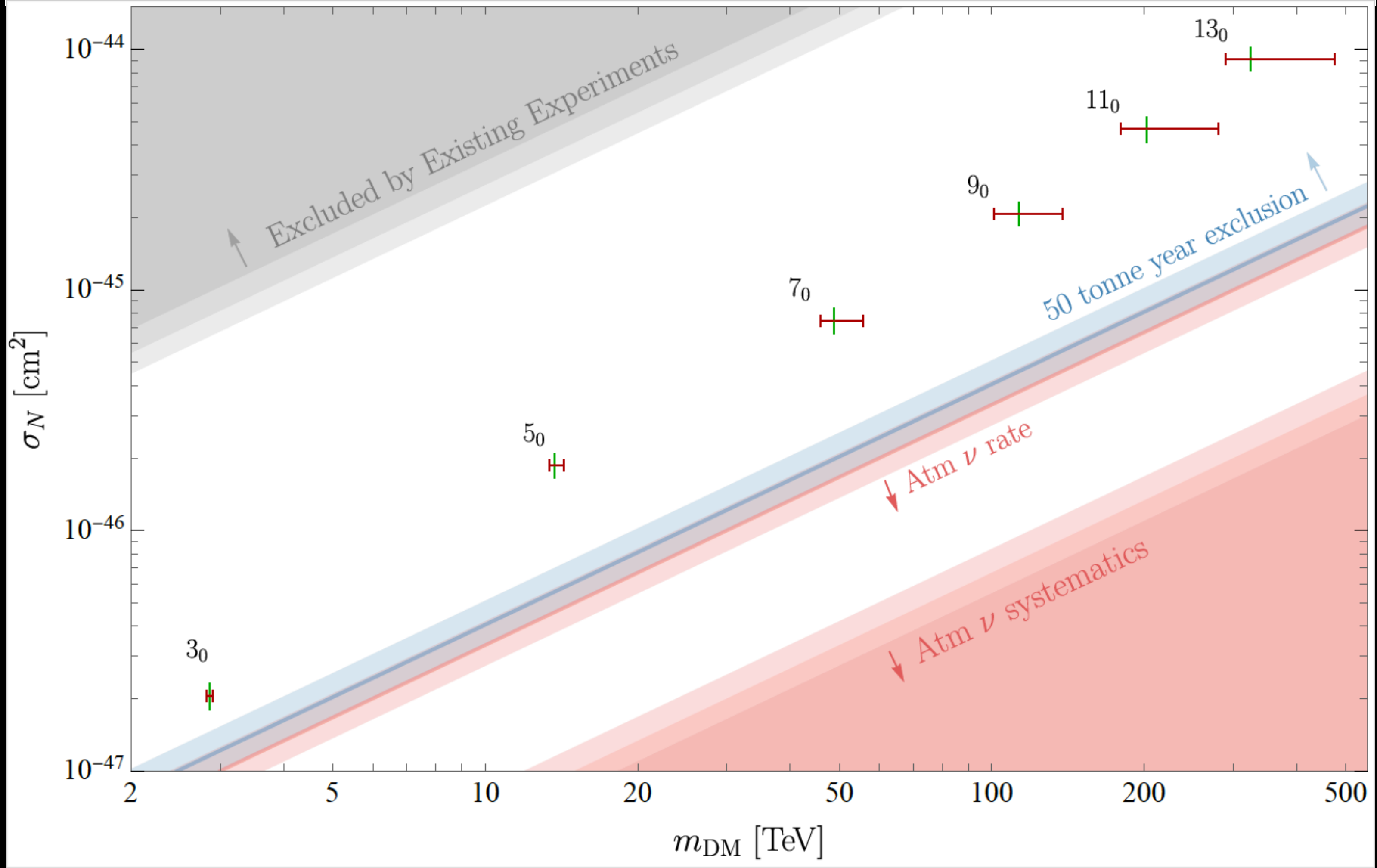


I. Bloch, S. Bottaro, D.R., L. Vittorio 2024



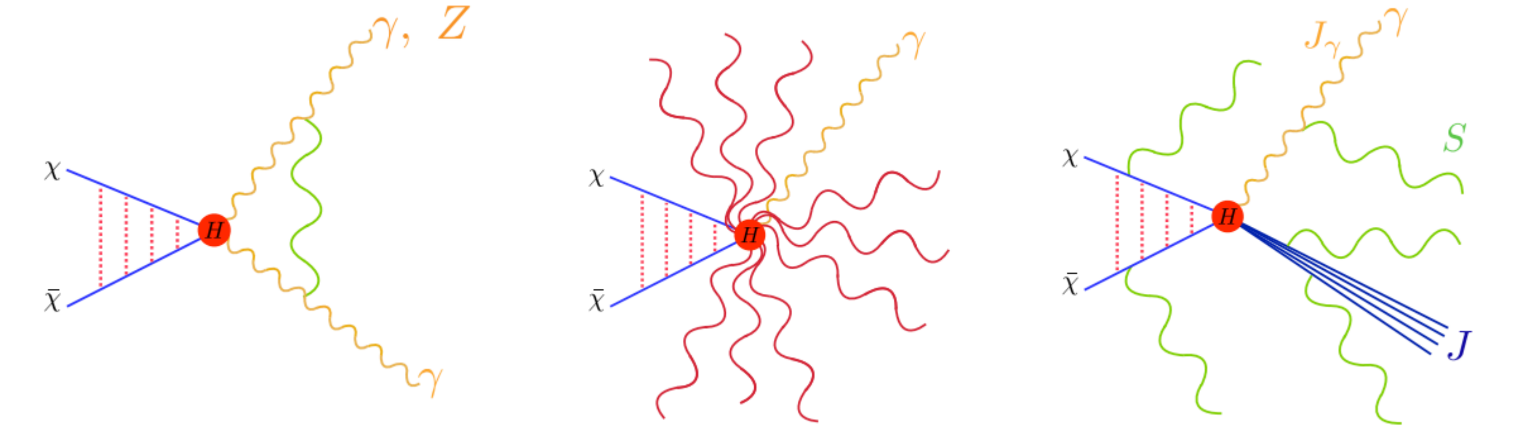
Heavy real WIMPs

can be tested

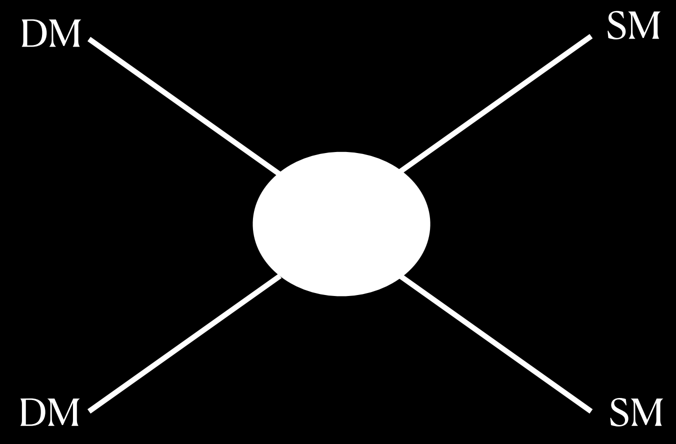
with 50 tonne of Xenon

CHALLENGE
suppress noise sources

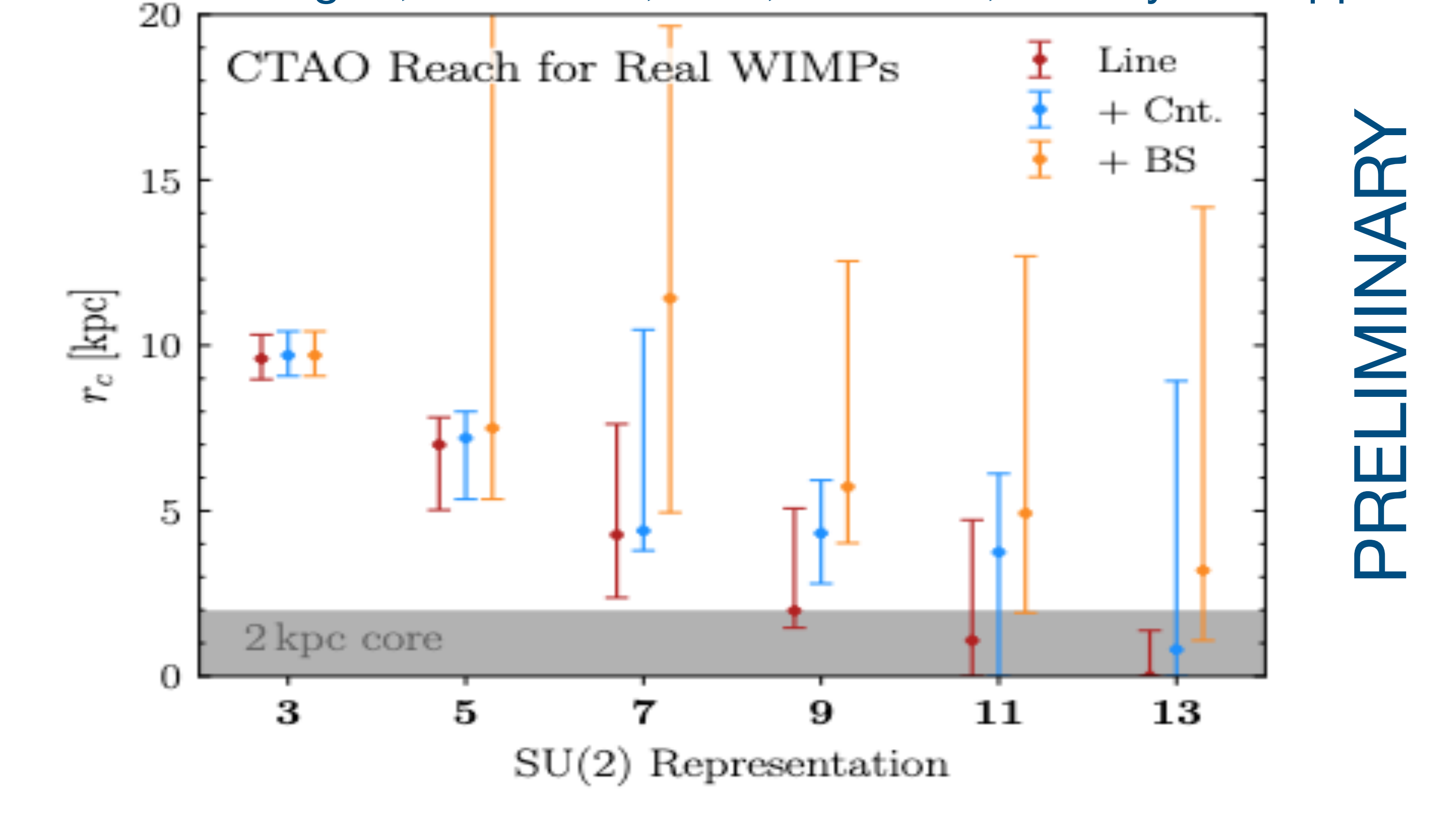
Annihilation into photons: $\chi\chi \to \gamma + X$



M. Baumgart, T. Cohen, I. Moult, N. L. Rodd,
T. R. Slatyer, M. P. Solon, I. W. Stewart and V. Vaidya 2017



M. Baumgart, S. Bottaro, D.R., N. Rodd, T. Slatyer to appear



Light real WIMPs

can be tested

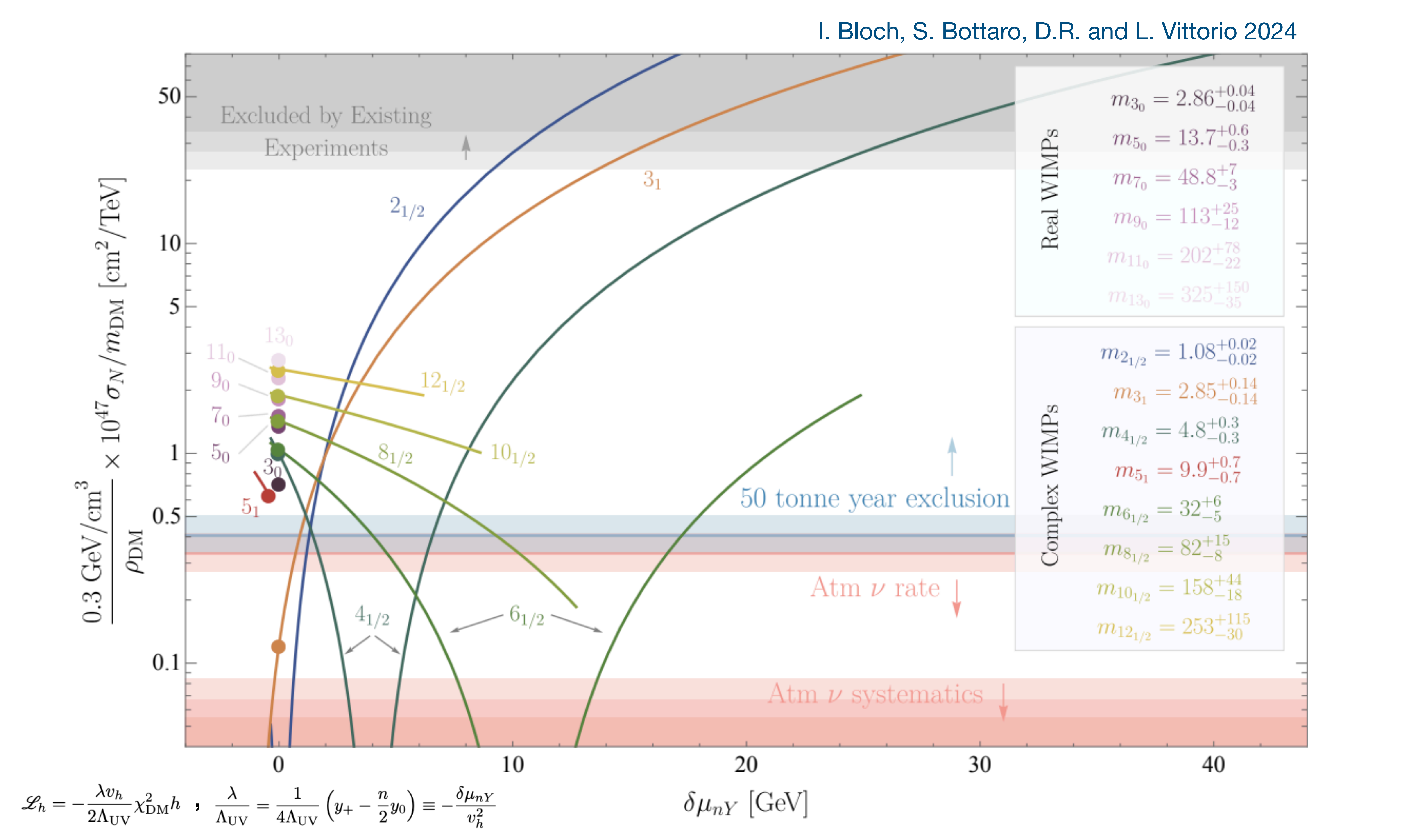
@ CTA (line reach is robust)

Heavy real WIMPs

are affected by large

background systematics

The complex multiplets



The $2_{1/2}$ and the 3_1 have a EW xsec in direct detection which is below the neutrino floor

For the $4_{1/2}$,$6_{1/2}$,$8_{1/2}$ the EW contribution can cancel against the Higgs contribution.

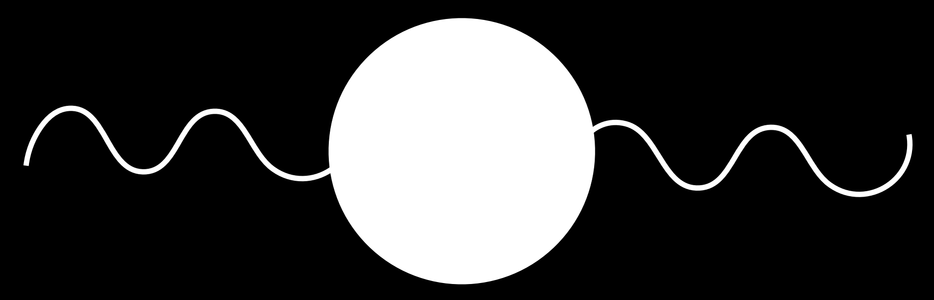
For the 5_1,$10_{1/2}$,$12_{1/2}$ can be tested by direct detection with less than 50 tonne-year

Complex WIMPs are a target for future colliders

Indirect effects:

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{c_{WW}}{2g^2v^2}(DW)^2 + \frac{c_{BB}}{2g'^2v^2}(DB)^2$$

Barbieri, Pomarol, Rattazzi Strumia 2004



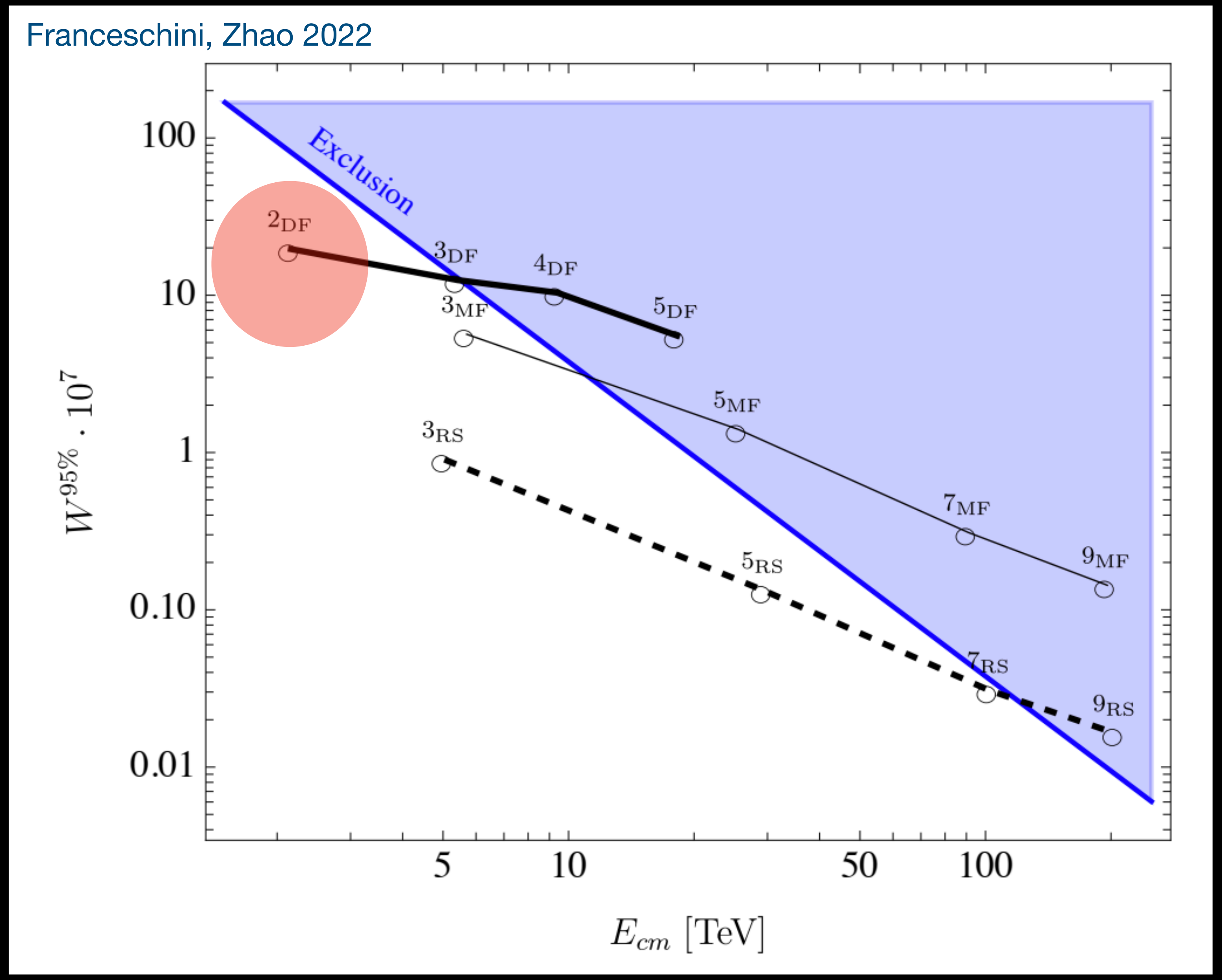
Future muon collider reach on deviation in

$$\mu^+\mu^- \to f\bar{f} + X, \mu^+\mu^- \to ff' + X,\ \mu^+\mu^- \to Zh/W^+W^- + X$$

$$\hat{W} = \frac{\alpha_{\rm em}}{180\pi}\frac{m_Z^2}{M_{\rm DM}^2}\kappa n(n^2-1) \simeq 8\kappa \times 10^{-7}\left(\frac{1\ \rm TeV}{M_{\rm DM}}\right)^2\left(\frac{n}{2}\right)^3$$

$$\hat{Y} = \frac{\alpha_{\rm em}}{15\pi}\frac{m_Z^2}{M_{\rm DM}^2}\kappa n Y^2 \simeq 5\kappa \times 10^{-7}\left(\frac{Y}{1/2}\right)^2\left(\frac{1\ \rm TeV}{M_{\rm DM}}\right)^2\left(\frac{n}{2}\right)$$

Cirelli, Fornengo, Strumia 2005



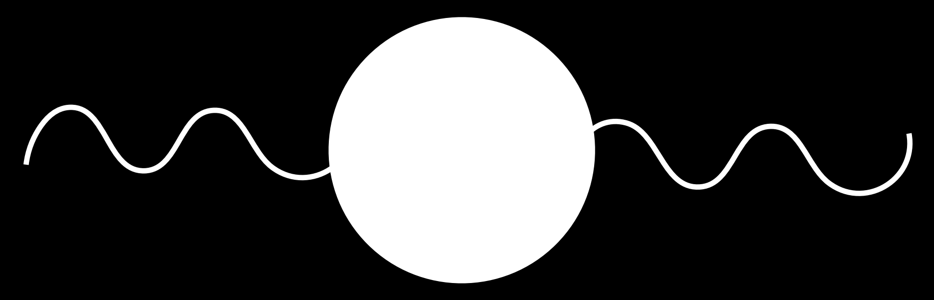
$$\mathscr{L} = 10{\rm ab}^{-1}\left(\frac{E_{\rm cm}}{10{\rm TeV}}\right)^2$$

the $2_{1/2}$ can't be tested indirectly

Complex WIMPs are a target for future colliders

Indirect effects:

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{c_H}{v^2}|H^\dagger D H|^2 + \frac{c_{WB}}{g g' v^2}(H^\dagger T^a H) W^a B$$



Lavoura, Li 1994

$$\hat{S}_F = -\frac{\alpha_{\rm em} Y n^3}{9\pi s_{2W} M_{\rm DM}} \delta\mu_{Q_M} \simeq 1.2 \times 10^{-5} \left(\frac{n}{2}\right)^3 \left(\frac{1\ {\rm TeV}}{M_{\rm DM}}\right) \left(\frac{\delta\mu_{Q_M}}{10\ {\rm GeV}}\right),$$

$$\hat{T}_F = -\frac{\alpha_{\rm em}}{18\pi s_{2W}^2} n^3 \frac{\delta\mu_{Q_M}^2 + \delta\mu_0^2}{m_Z^2} \simeq 1.6 \times 10^{-5} \left(\frac{n}{2}\right)^3 \frac{\delta\mu_{Q_M}^2 + \delta\mu_0^2}{100\ {\rm GeV}^2},$$

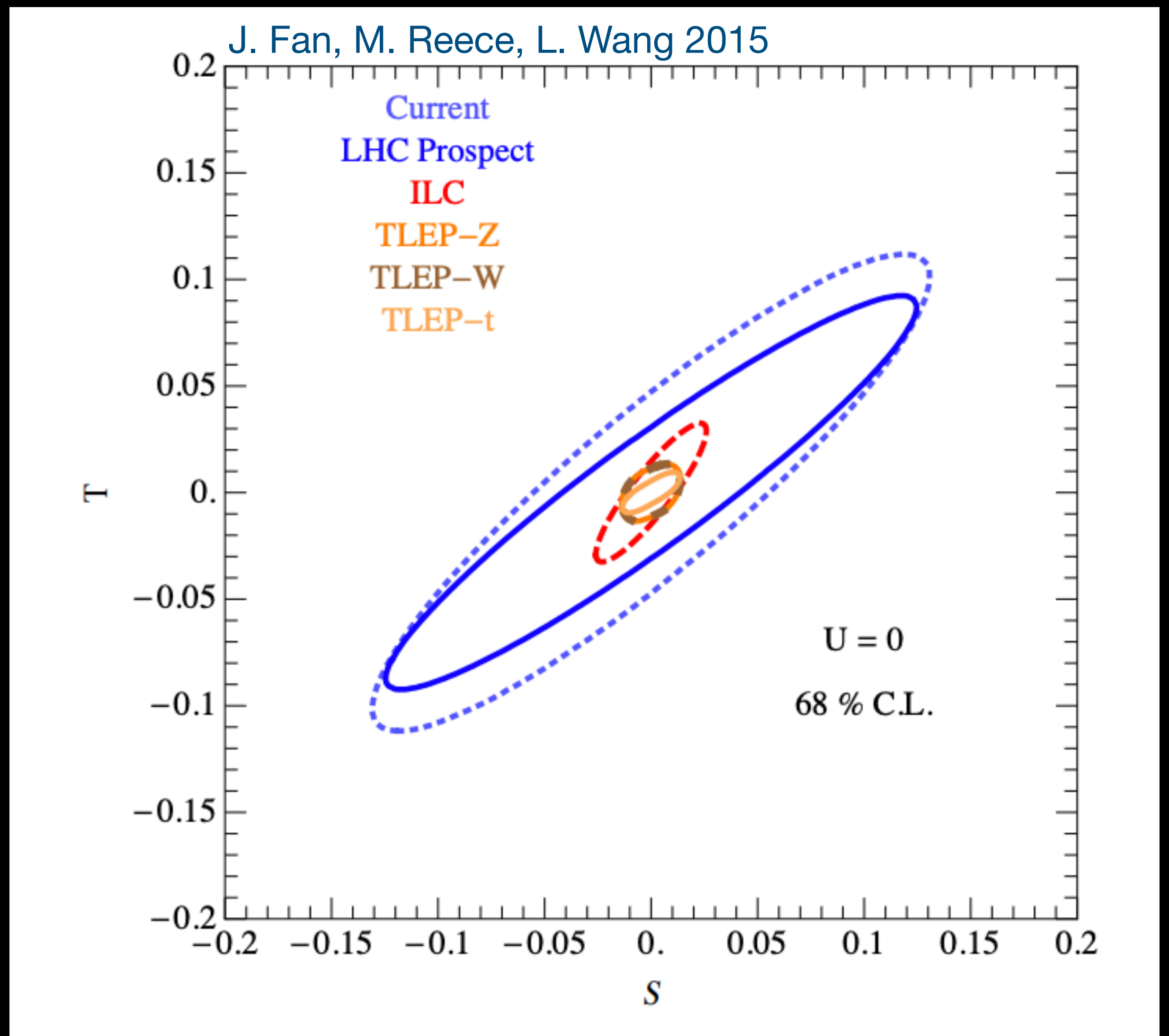
Breaking of

Custodial symmetry

No sensitivity on S

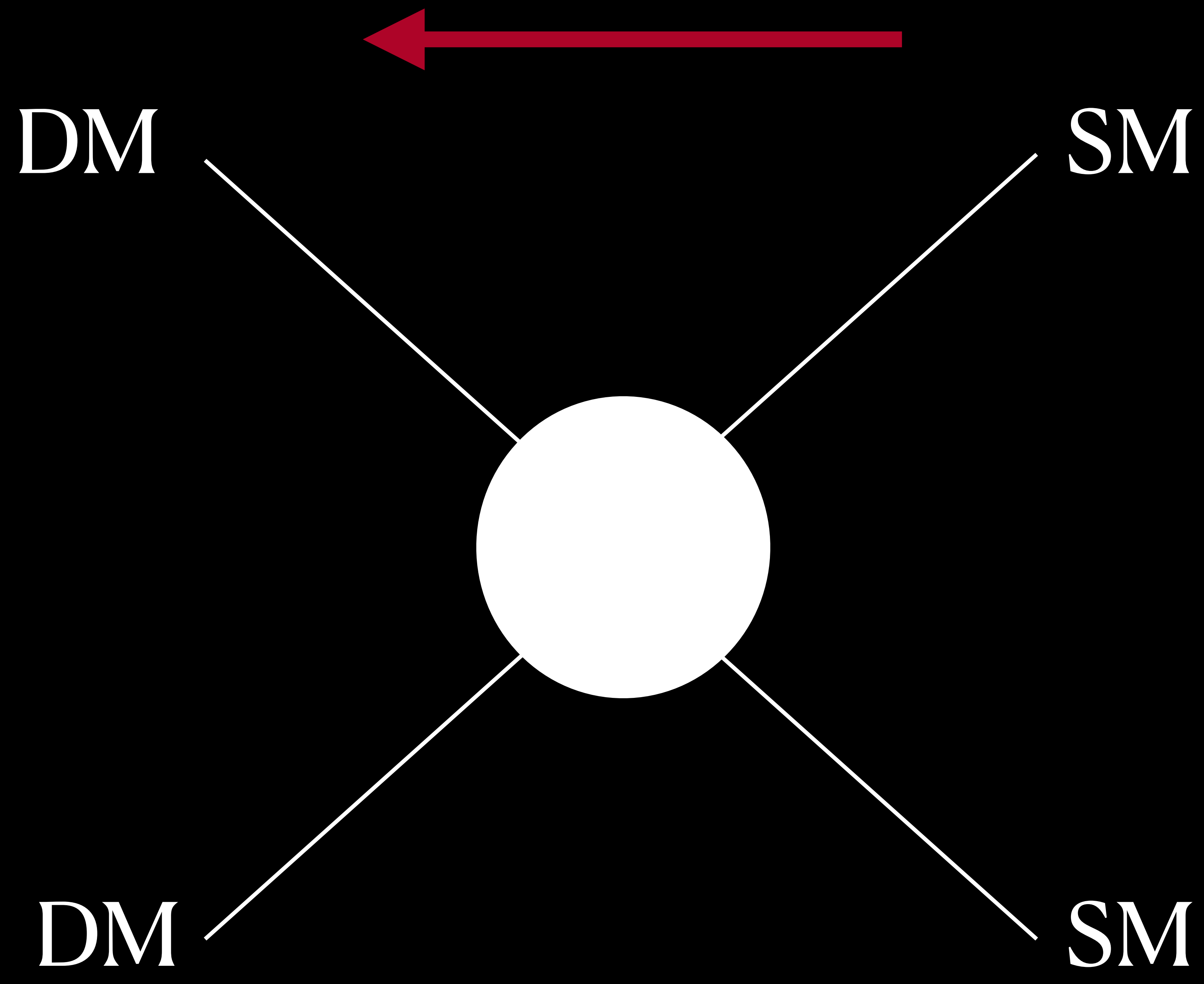
Sensitivity @ FCC-ee on T because of the enhancement for large n

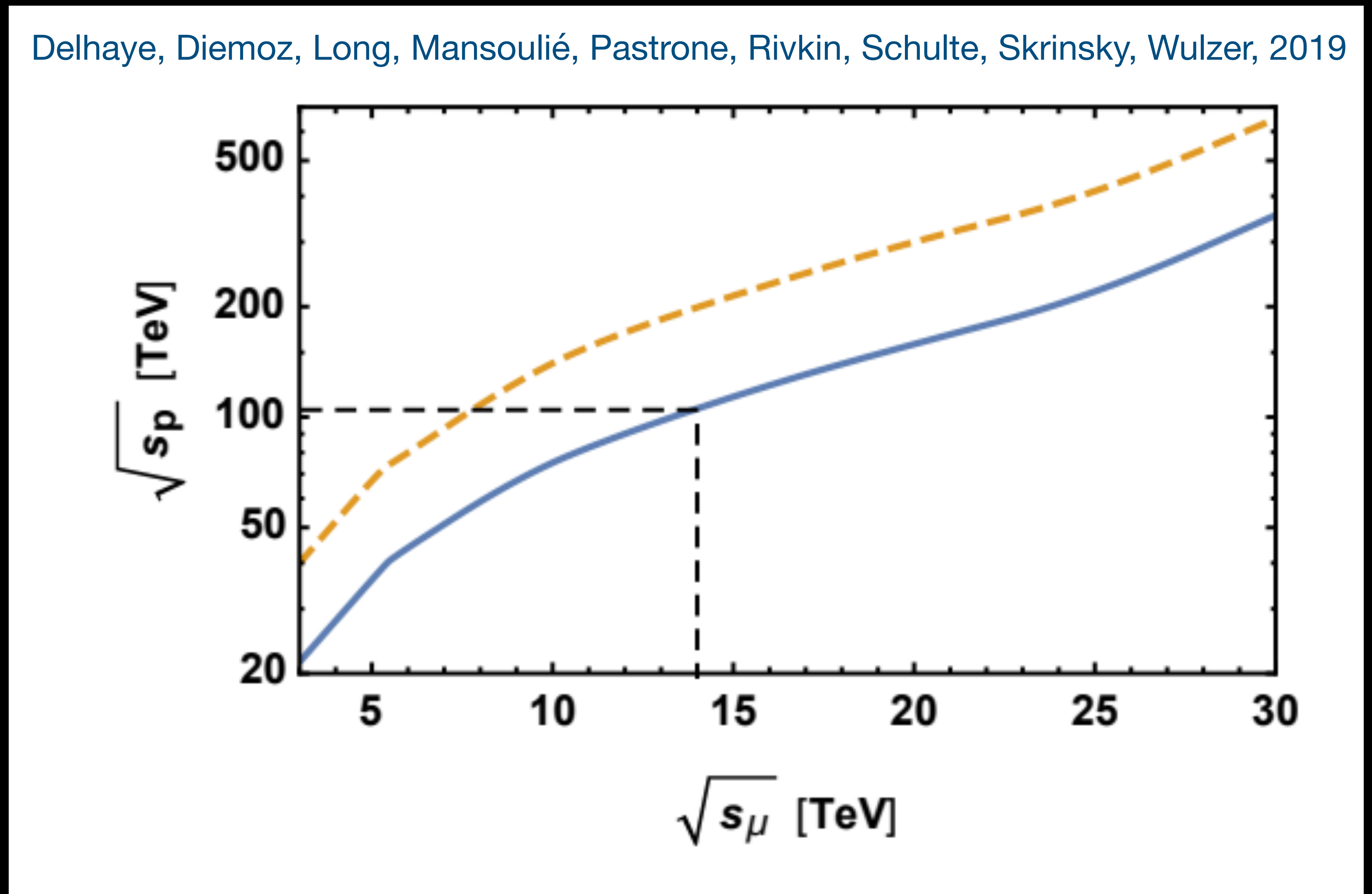
This seems something one can do with ~Tera-Z (systematics?)



Light complex WIMPs can be produced directly

Direct production





A hypothetical muon collider is the best machine to pair produce heavy new states

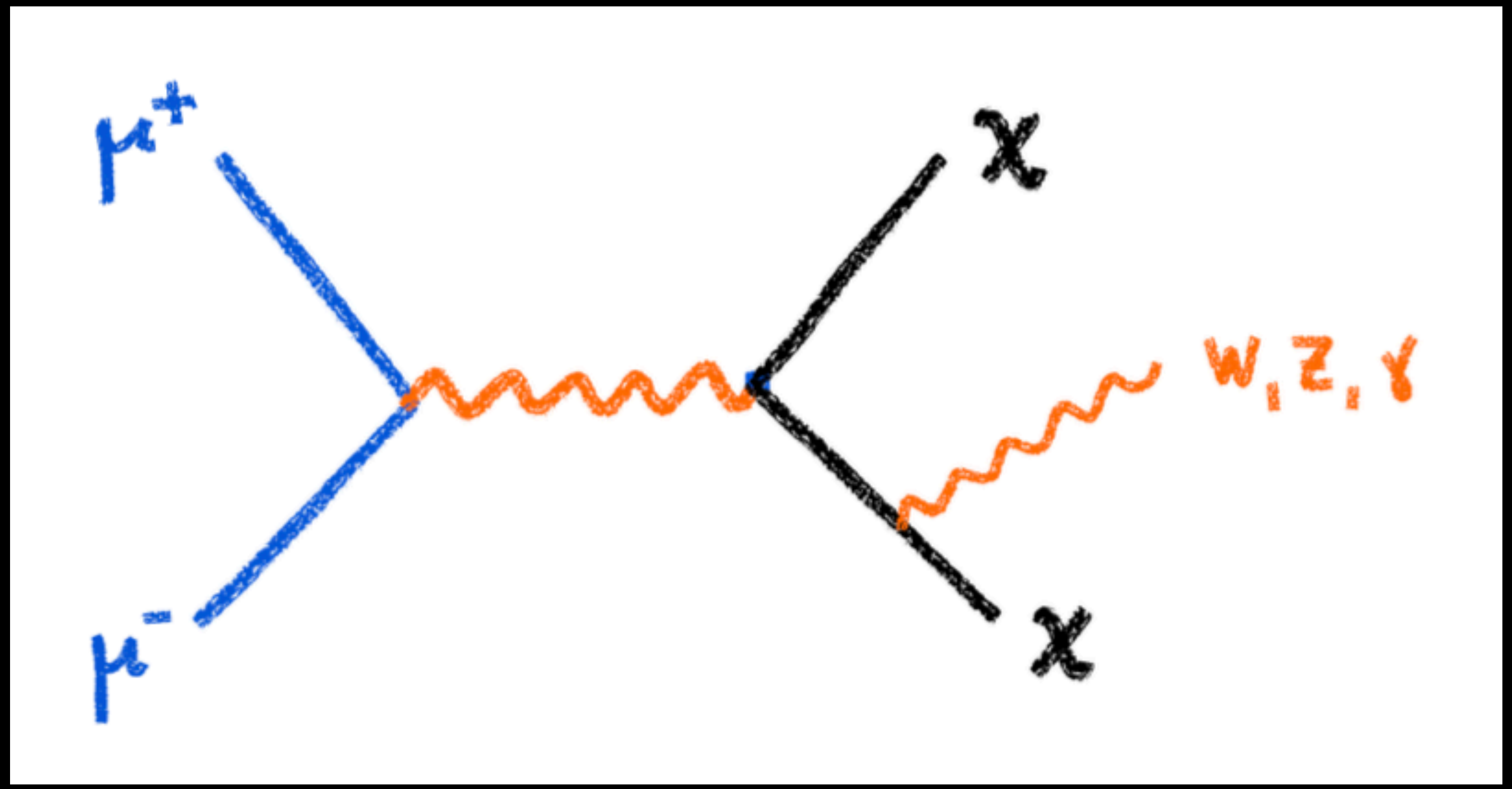
The muons are elementary so all the energy is available for hard scattering

Colored particles:
14 TeV μμ ~ 100 TeV pp

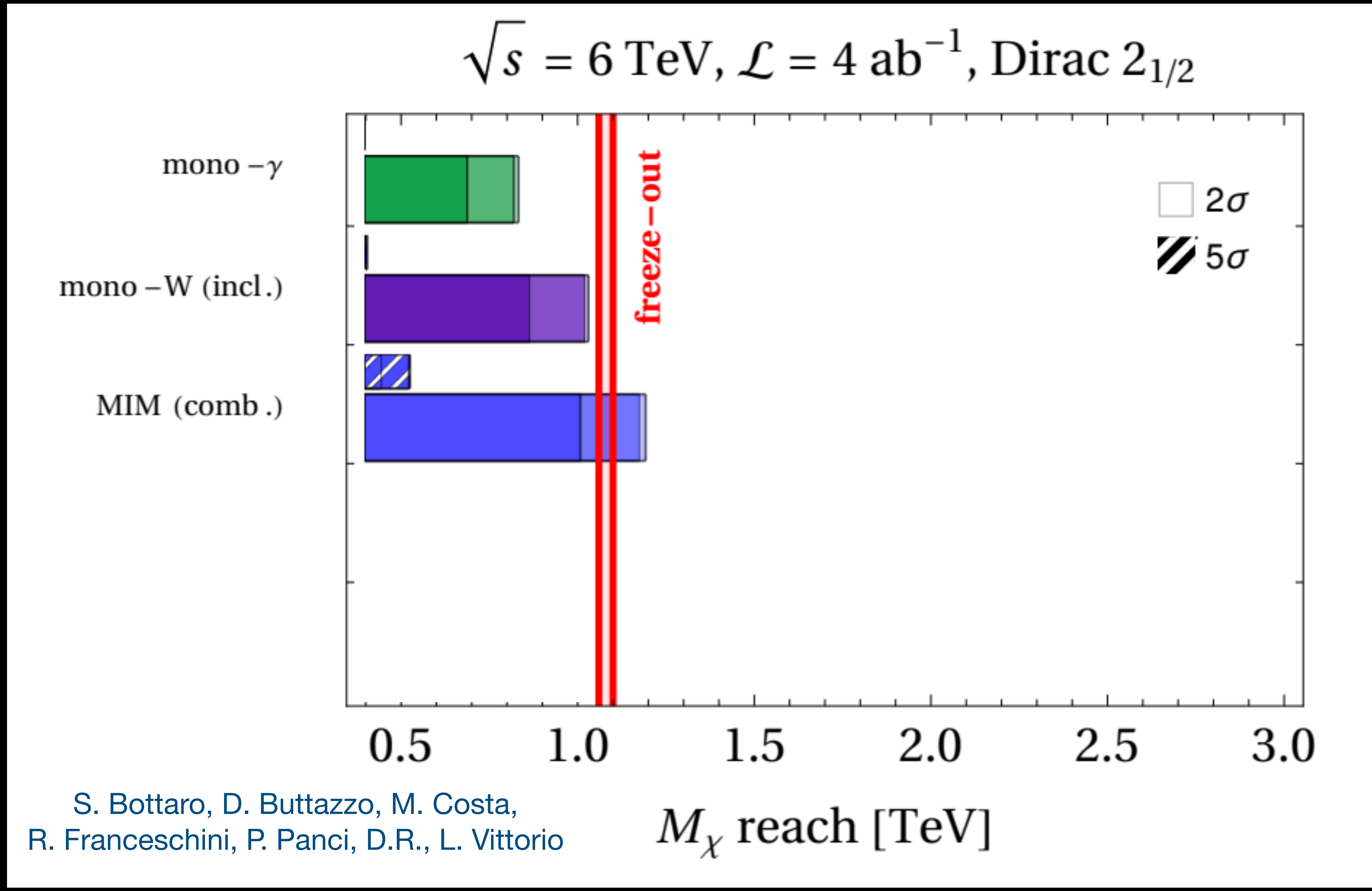
EW particles:
14 TeV μμ ~ 200 TeV pp

Light complex WIMPs can be produced @ colliders

Direct production



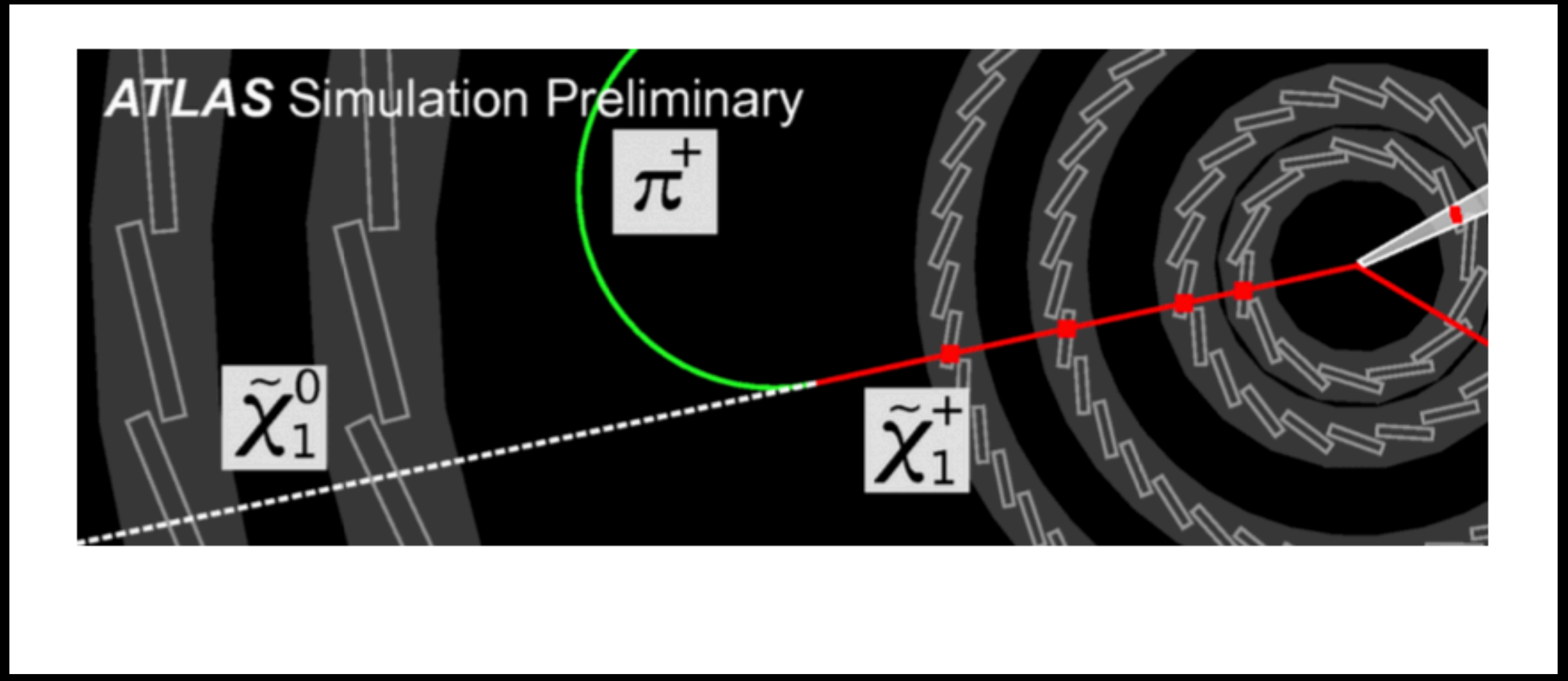
MET searches



A 6 TeV muon collider can exclude Higgsino DM combining the MET channels

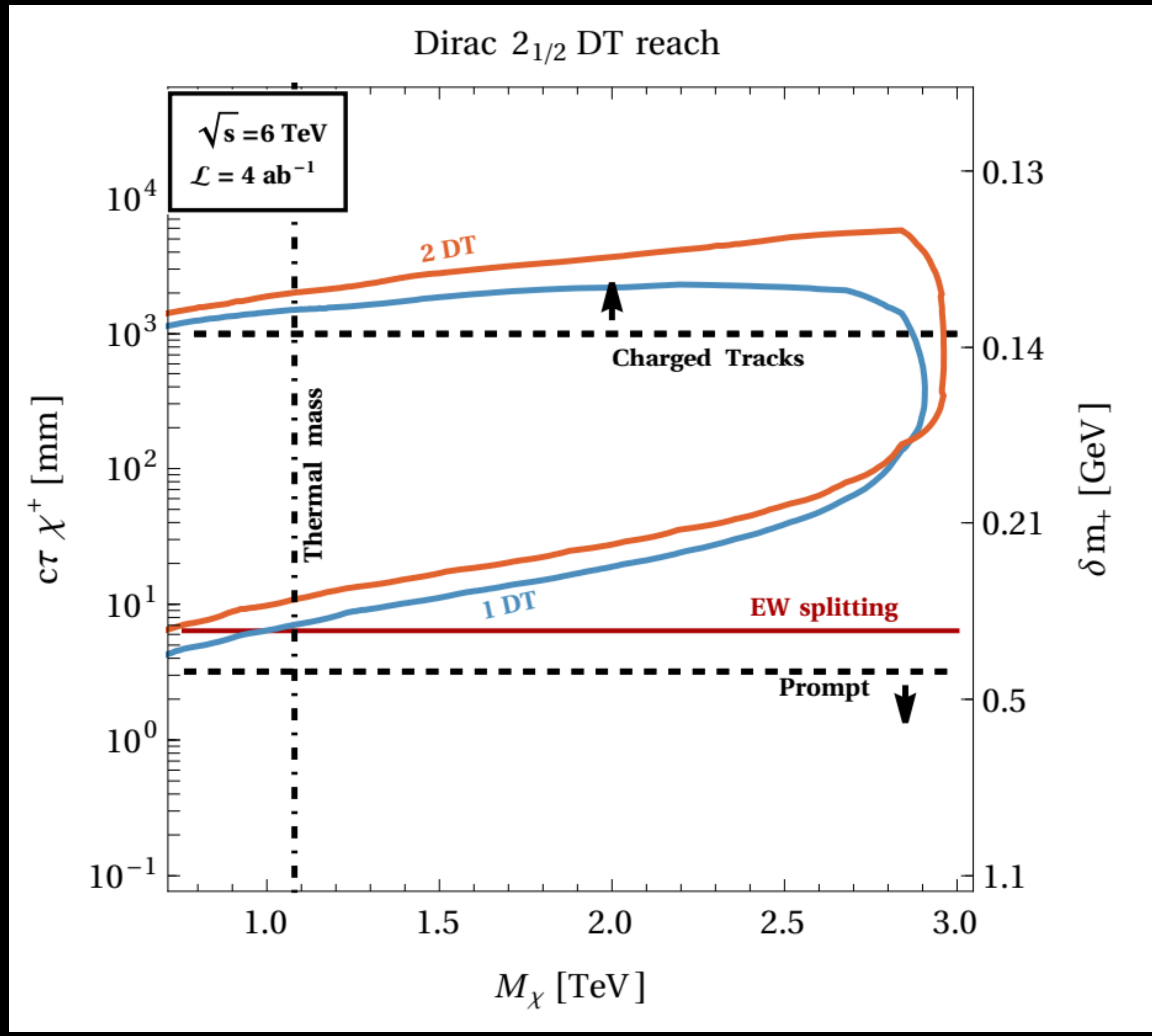
Light complex WIMPs are a target for colliders

Direct production

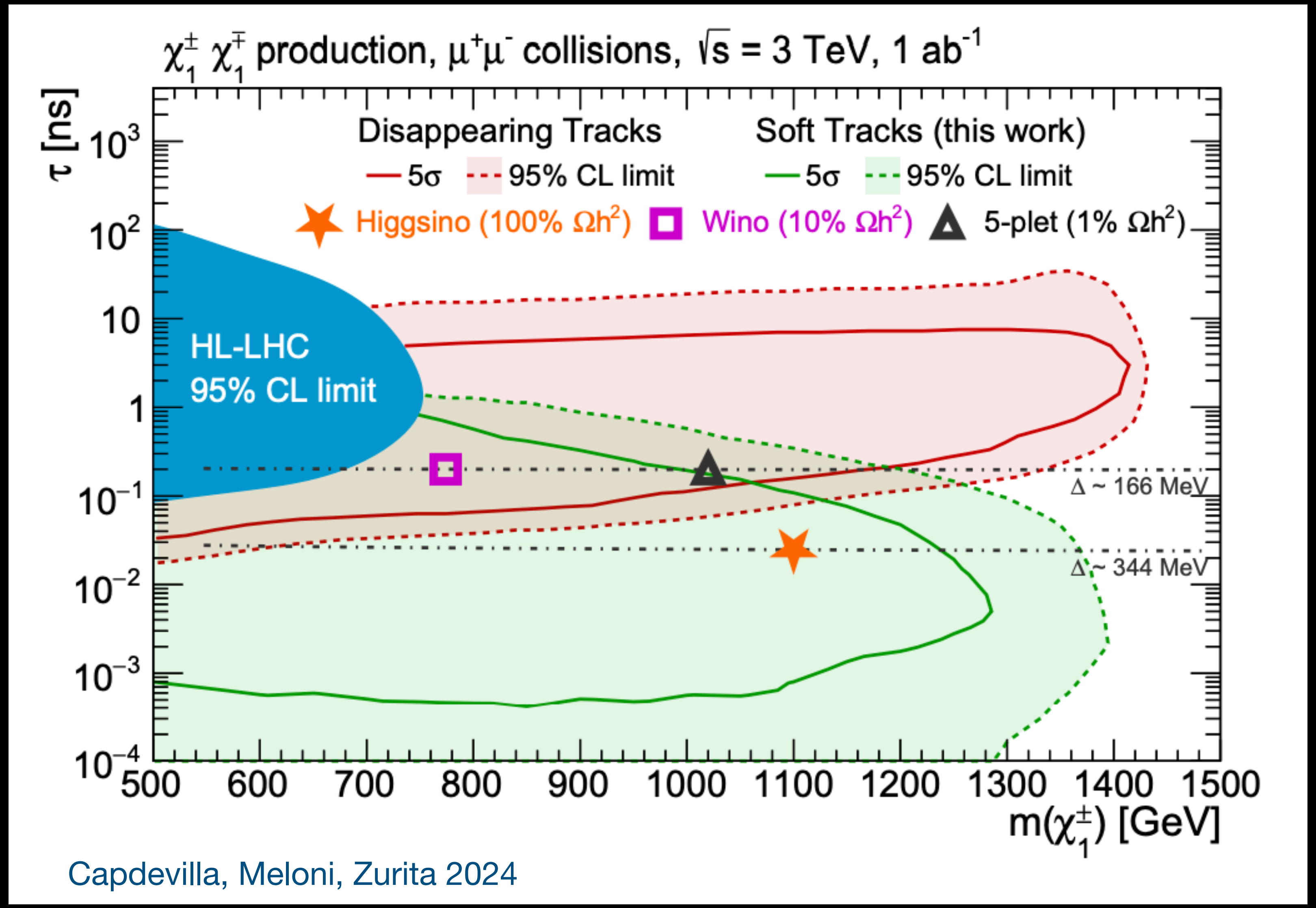


$$\chi_2^+ \to \pi^+ + \chi_1^0$$

Disappearing Track



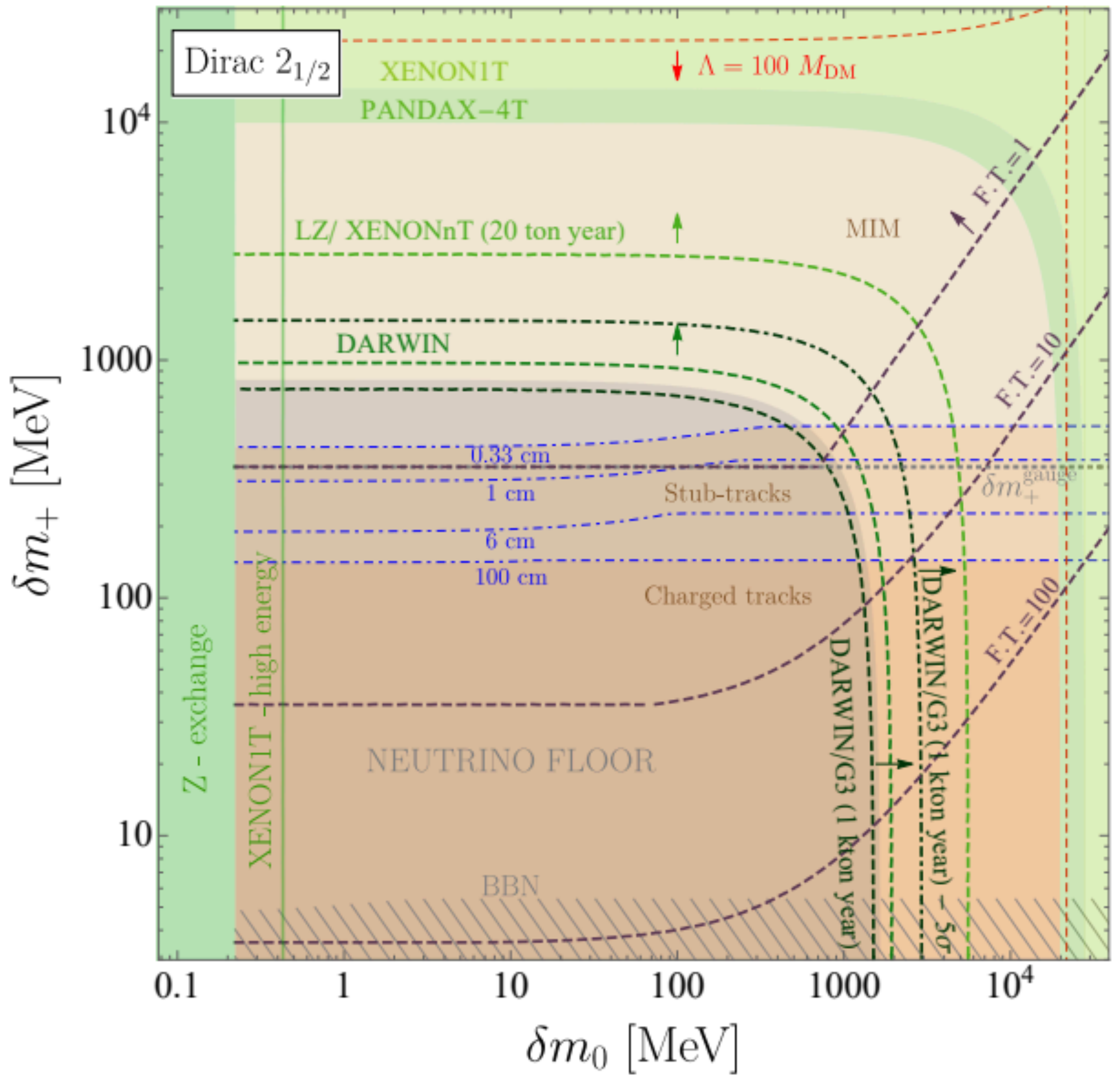
Soft Tracks



Disappearing and soft track can test the full range of lifetimes for χ^+

Higgsino parameter space

S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, L. Vittorio 2022



Direct Detection + BBN

make the splitting parameter space compact

Charge tracks + disappearing track

+ missing energy (+soft tracks)

can fully test the available Higgsino parameter space

Is the Dark Matter Electroweak?

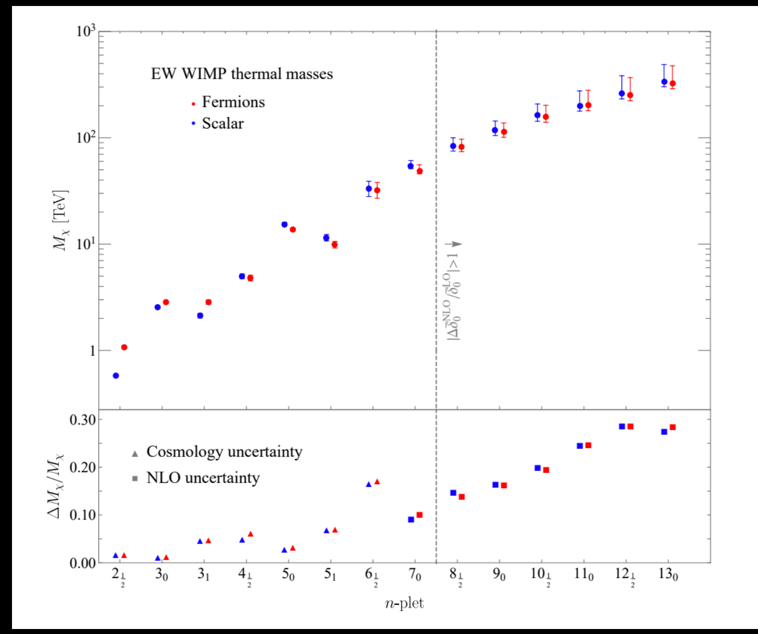
multi-ton Xenon + CTA + 6 TeV muon collider

have the potential to test them *all* the EW WIMPs

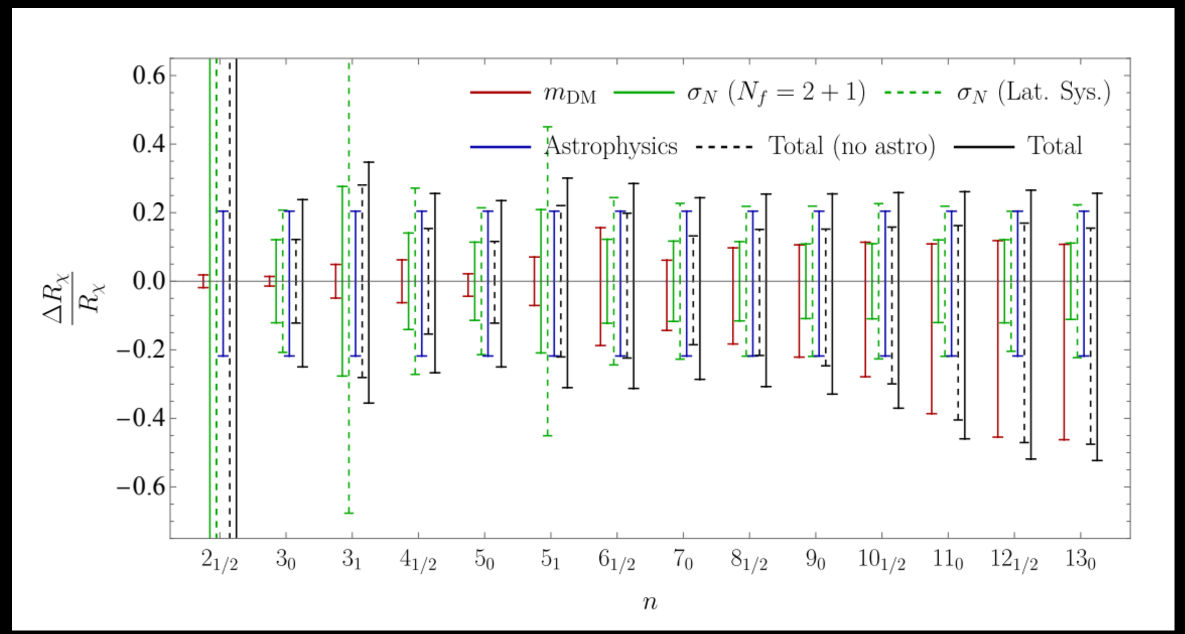
(big experimental challenge)

Many theory computations to be improved:

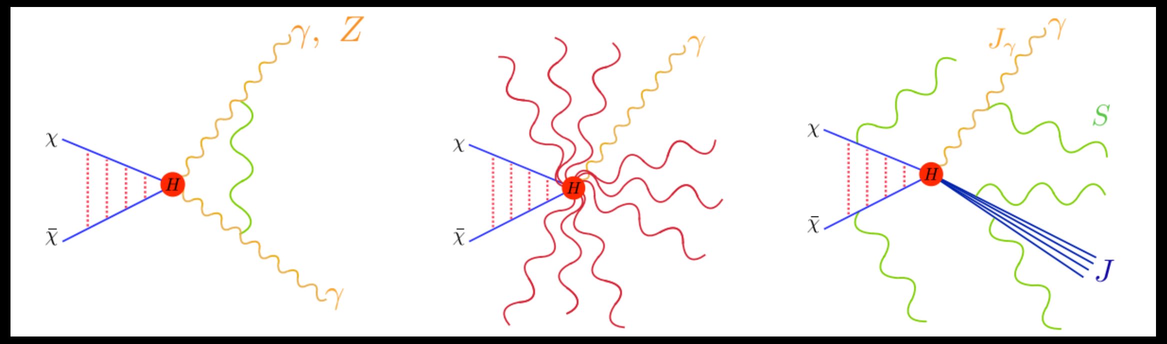
refining the freeze-out predictions



form factors in direct detection

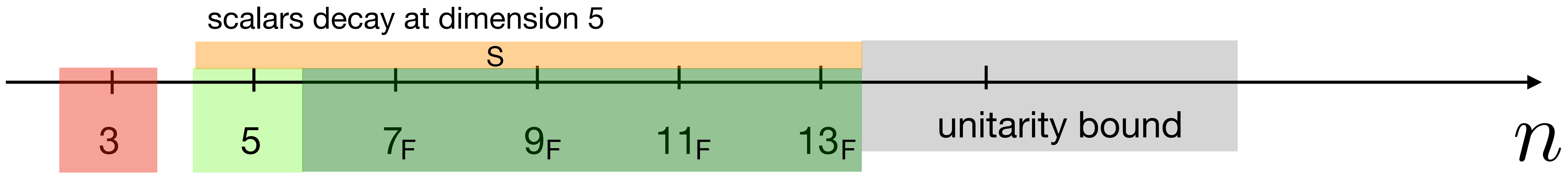


EW+Higgs radiation in ID



BACKUP

More on real WIMPs



$$\mathcal{L}_f = \frac{1}{2}\chi(i\bar{\sigma}^\mu D_\mu - M_\chi)\chi$$

*Neutral component naturally lighter

$\chi^\pm$ ——— ↕ ΔM
χ^0 ———

$$\Delta M_{\rm IR} = (167 \pm 4)\ \text{MeV}$$

1-loop: $\frac{\alpha_{\rm em} m_W}{2(1+c_{\rm w})}$

2-loops: $\sim \frac{\alpha_2^2}{16\pi^2} m_t$

$\Delta M_{\rm UV} \sim v^4/\Lambda_{\rm UV}^3$

UV splitting heavily suppressed

*Splitting UV independent $\quad c\tau_{\chi^+} \simeq \frac{120\ \text{mm}}{T(T+1)} \quad 2T+1 = n \quad$ macroscopic lifetimes for n small

*Accidental stability in field theory (for fermions n>3)

5_F decay at dimension 6 $\quad (\chi HLW\ , \dots)$

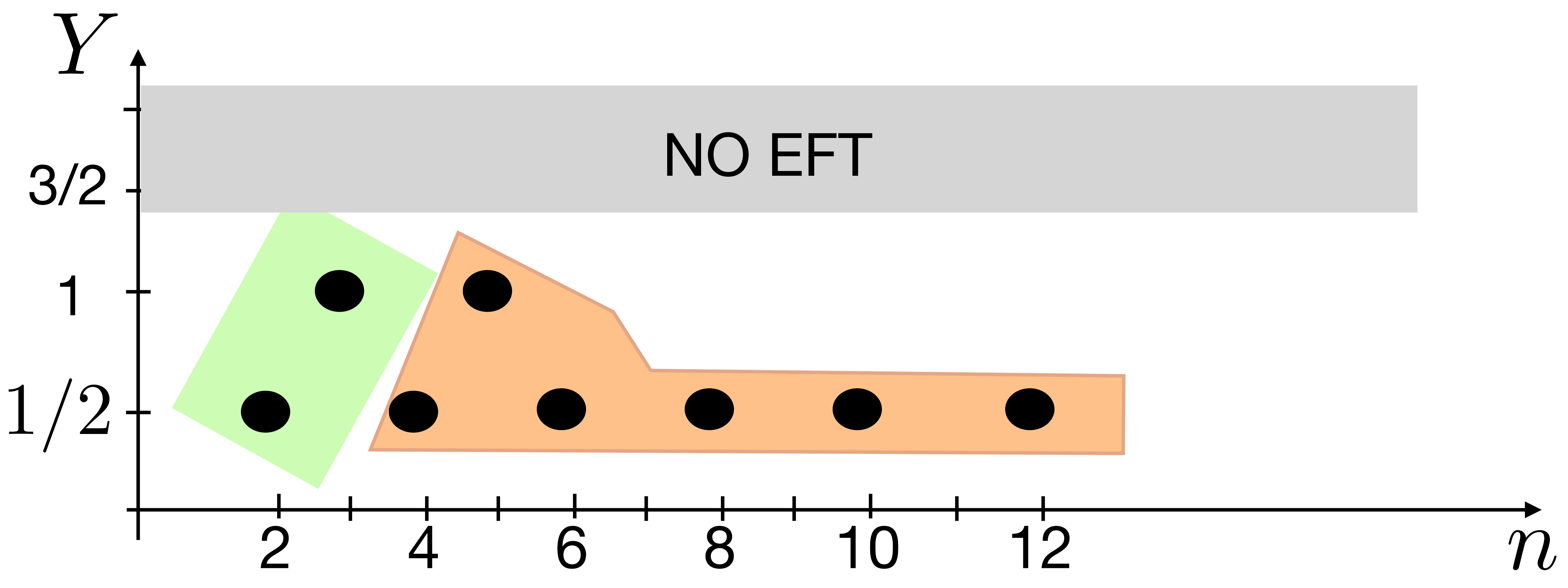
n_F decay at dimension 7 $\quad (\chi^3 HL, \dots)$

*Perturbativity

5_F Landau pole > stability cut-off

n_F Landau pole < stability cut-off

More on complex WIMPs



*Neutral component naturally lighter in multiplets with maximal hypercharge: $2_{1/2}, 3_1$

otherwise a UV splitting beyond EW corrections is required for stability $-\frac{y_+}{2\Lambda}\left[\bar{\chi}T^a\chi\right]\left[H^\dagger\sigma^a H\right]$

$$\delta m_Q = 166\ \text{MeV}\left(Q^2 + \frac{2YQ}{\cos\theta_W}\right) - \frac{y_+ v^2 Q}{4\Lambda}$$

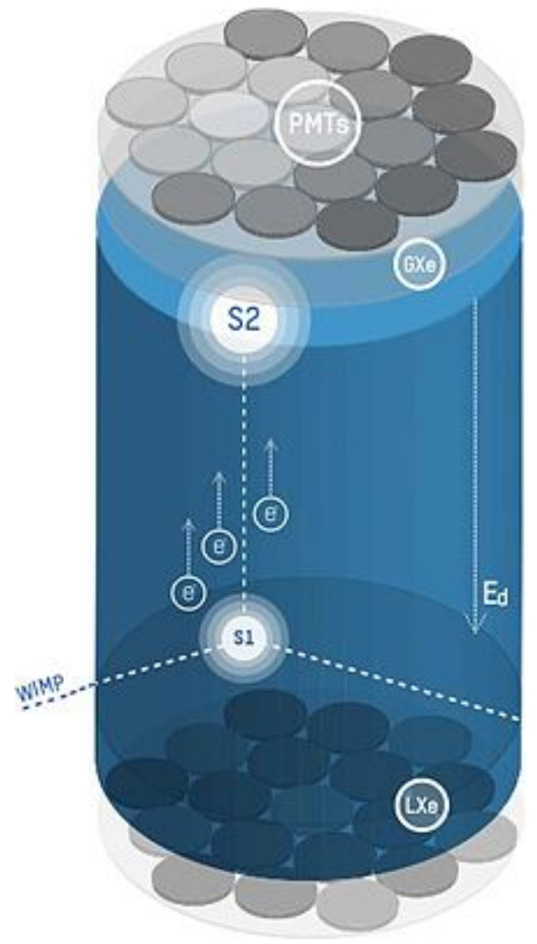
*Splitting required to make the tree-level Z scattering inelastic

$$\frac{y}{2(4Y)!\Lambda^{4Y-2}}\left[\chi^\dagger (T^a)^{2Y}\chi^c\right]\left[(H^{c\dagger})\frac{\sigma^a}{2}H\right]^{2Y} + \text{h.c.} \longrightarrow \delta m_0 \simeq \frac{2yv^2}{\Lambda}\times\left(\frac{v}{\Lambda}\right)^{4Y-2}$$

$\delta m_0 >$ BBN + direct detection limits the allowed candidates

Direct Detection reach

Signal rate:



The scattering rate per energy per unit detector mass

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{\min}}^{v_{\max}} d^3v \frac{d\sigma}{dE_R} v \tilde{f}(\vec{v}, t)$$

- N_T: # targets/unit mass
- ρ_χ: DM number Density
- $\frac{d\sigma}{dE_R}$: xsec averaged on the velocity distr.

→

The total rate in the (S1,S2) channels in Xenon

$$\mathcal{R}(S_1, S_2) = \text{Exp} \cdot \int \frac{dR}{dE_R} \cdot \epsilon(E_R) \cdot \mathcal{P}(S_1, S_2 | E_R) dE_R$$

- Exp: Exposure (ton · year)
- $\epsilon(E_R)$: Efficiency*
- $\mathcal{P}(S_1, S_2 | E_R)$: Probability of S1,S2 events for given recoil energy*

* These are computed using NEST

Backgrounds:

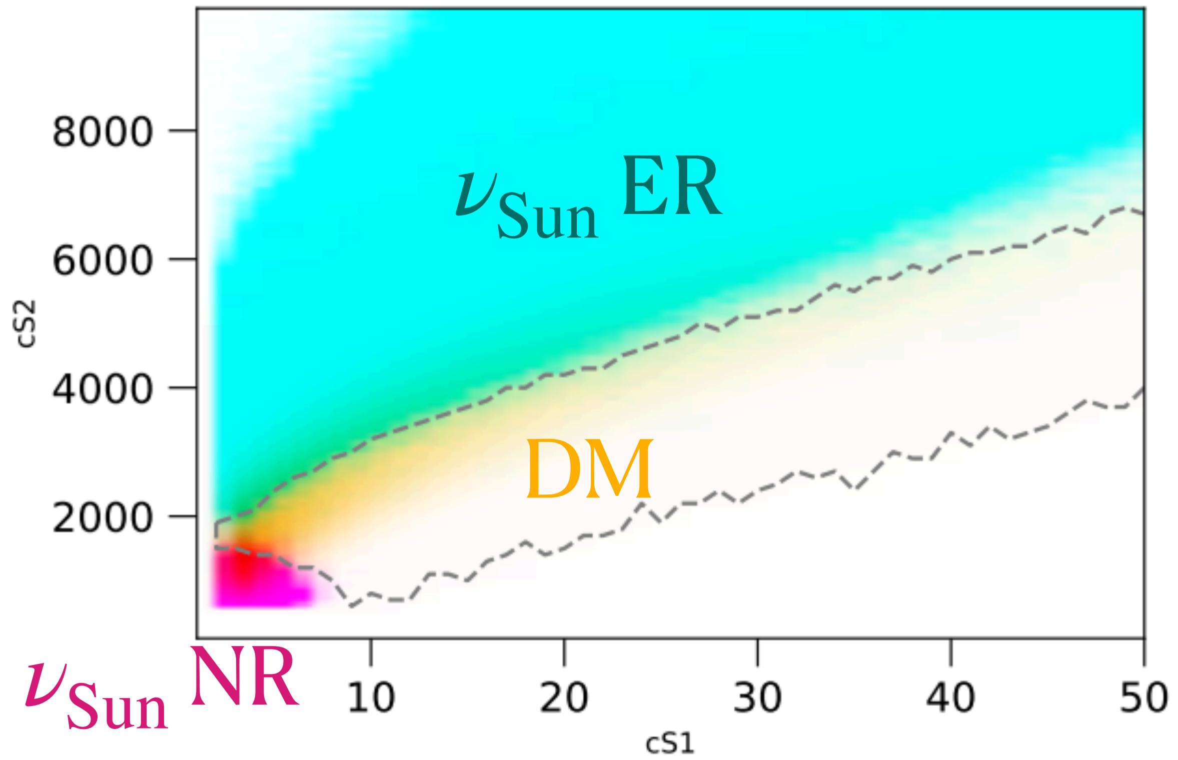
At present noise sources dominate the background (main problem is Radon contamination)

LZ 2207.03764

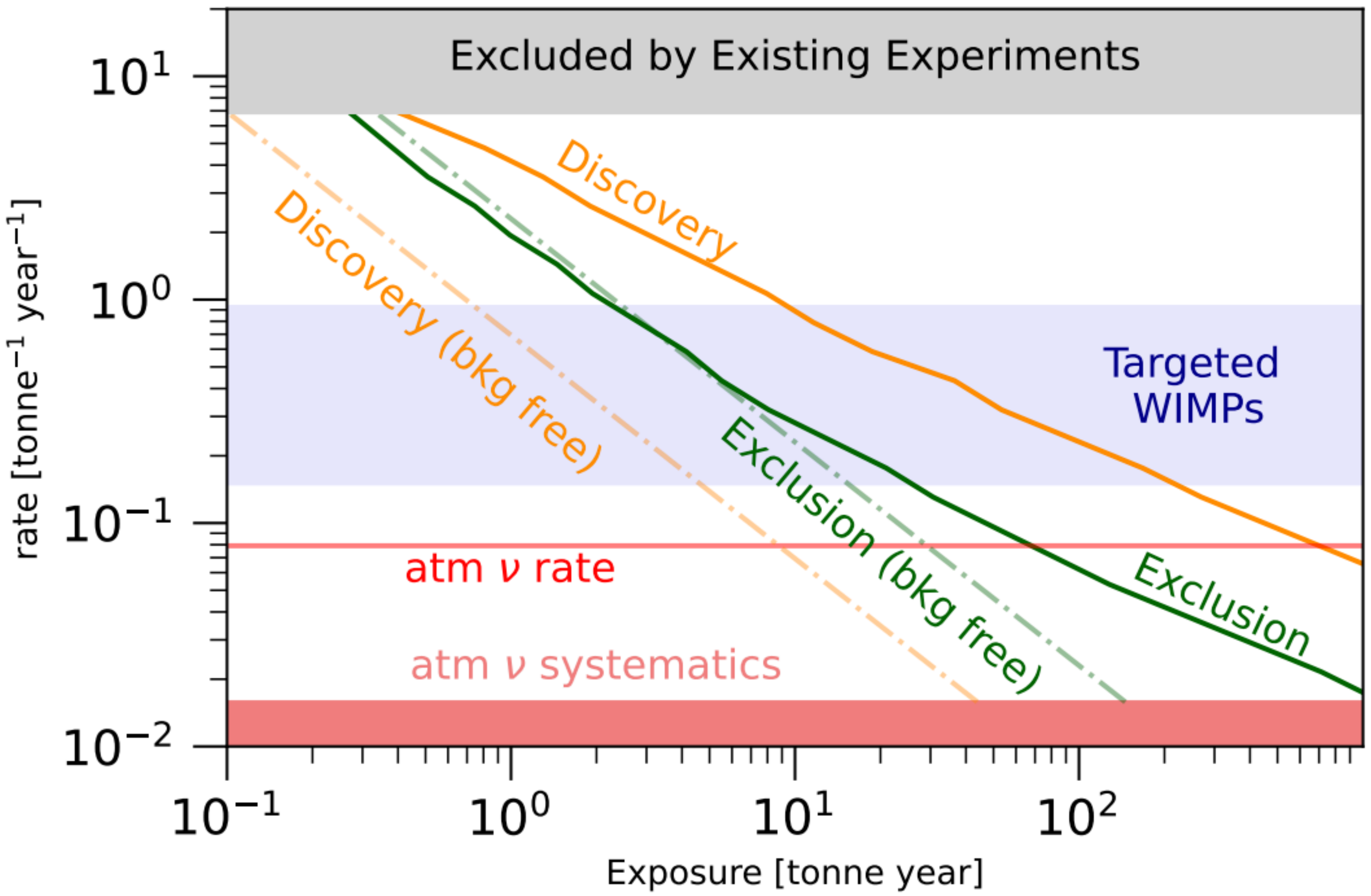
Source	Expected Events	Fit Result
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6

crystalline Xenon? S. Kravitz, H. Chen, R. Gibbons, S. J. Haselschwardt, Q. Xia, and P. Sorensen 2022

The solar neutrino electron recoil events leak into the signal region!



Expected exclusion/discovery



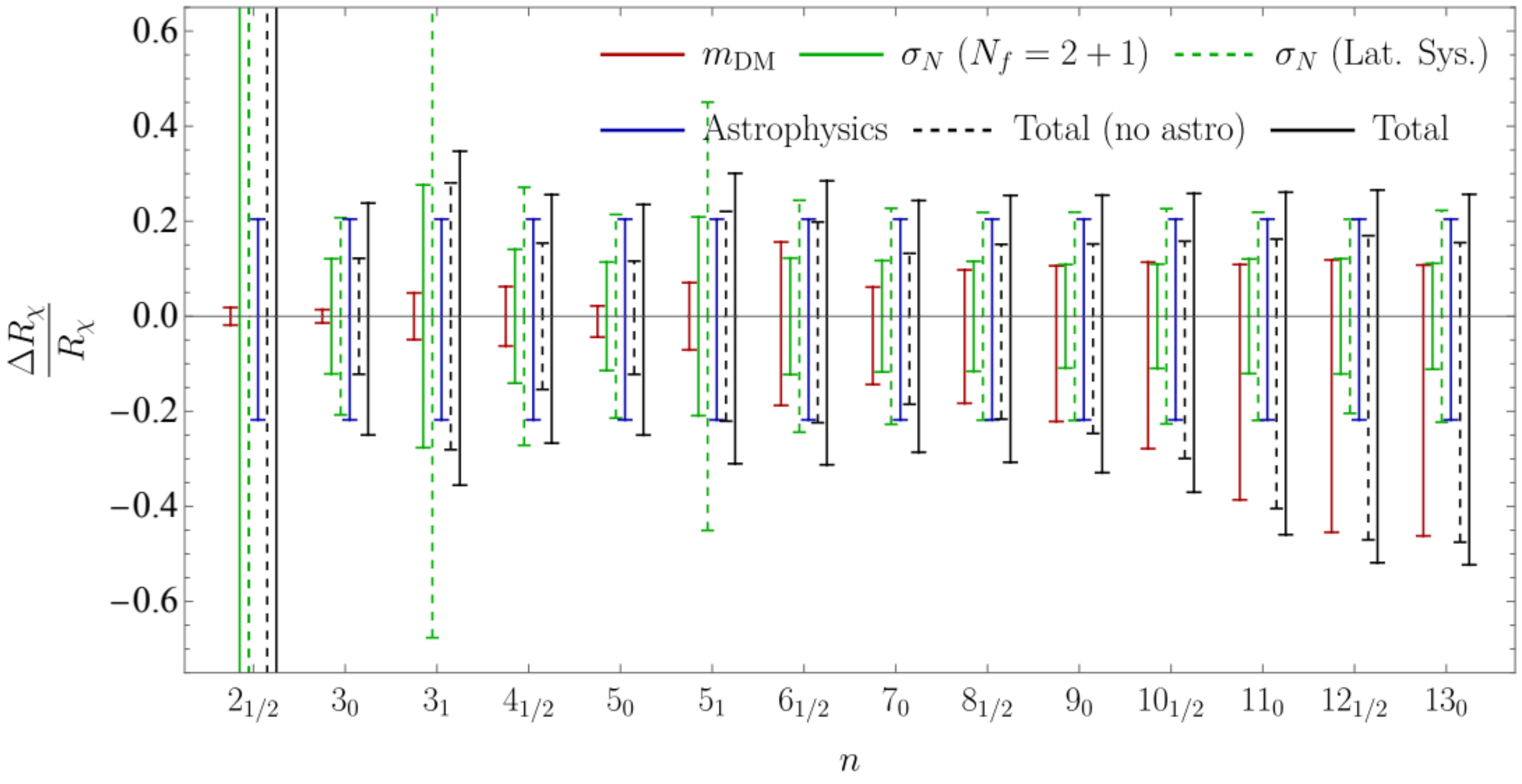
The standard neutrino floor irreducible background from atmospheric and DSN neutrinos lies below the electron recoil fog from solar neutrinos

Accounting for the electron recoil fog for the WIMPs makes the required exposure for exclusion/discovery much larger*

This effect is especially important for discovery and gives $O(1)$ factor in exposure for exclusion

* this effect is well know to Xenon experimentalists but somehow was never accounted for in the theory projections

Direct Detection rates uncertainties

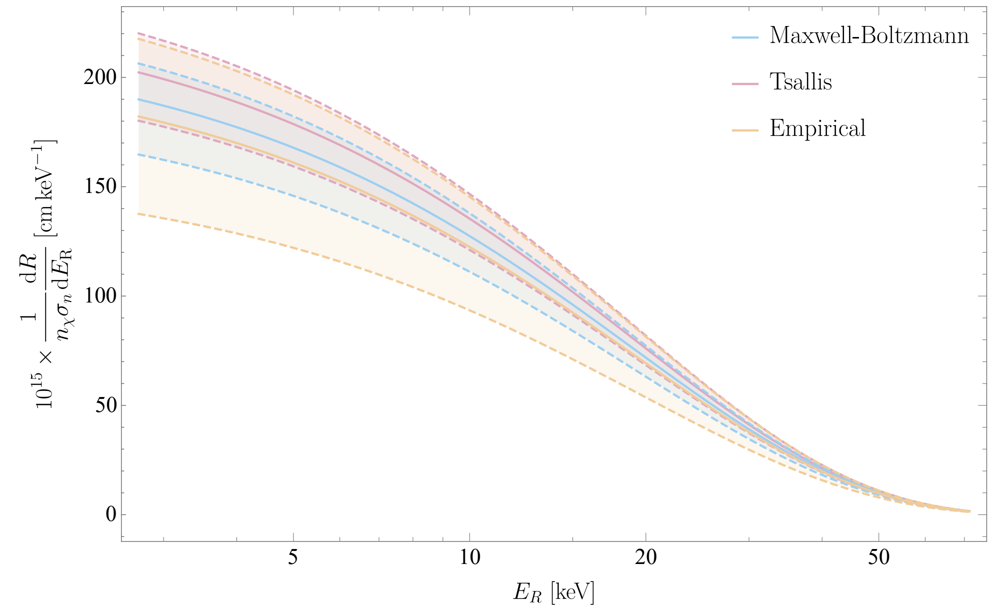


The uncertainty on the cross section coming from lattice

is of the same order of a generous

Astrophysical uncertainty

obtained by marginalising over the parameters of three different velocity distributions



Large systematics (dashed line) originating from a tension in lattice data

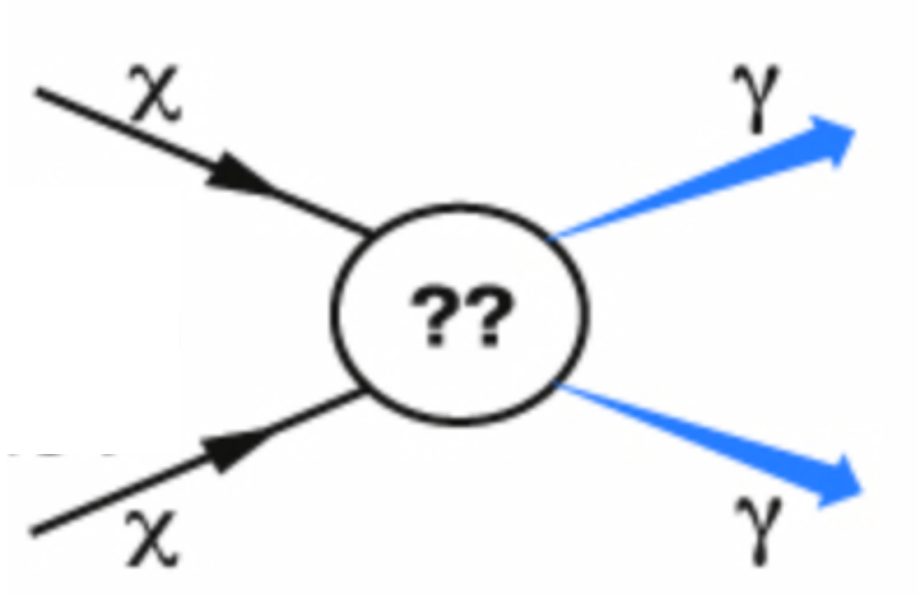
	$N_f = 2+1+1$			$N_f = 2+1$		
Method	Ref.	$\sigma_{\pi N}$	σ_s	Ref.	$\sigma_{\pi N}$	σ_s
MEC	[62]	—	$0.44(8)(5)\ \times m_s$	[61]	45.9(7.4)(2.8)	40.2(11.7)(3.5)
				[62]	—	$0.637(55)(74)\ \times m_s$
FHA	[64]	64.9(1.5)(13.2)	—	[60]	38(3)(3)	105(41)(37)
				[63]	—	48(10)(15)
				[59]	$39(4)(^{18}_{7})$	$67(27)(^{55}_{47})$

$$\frac{\sigma_{\pi N}}{m_N} \equiv (f_{Tu} + f_{Td}) \qquad \langle N | m_q \bar{q} q | N \rangle = m_N f_{T_q}$$

2 computation schemes: * Direct computation of the matrix element (MEC)

* $\sigma_{\pi N} \approx m_\pi^2 \frac{\partial m_N}{\partial m_\pi^2}$ this is sensitive to the functional shape of $m_N(m_\pi^2)$ extracted from baryonic chPT

Indirect Detection reach



EW Dark Matter annihilating in our surroundings generate a high energy photon flux

$$\frac{d\Phi}{dE} = \frac{J(r_c)}{8\pi M_\chi^2}\frac{d\langle\sigma v\rangle}{dE}$$

The annihilation cross section has three components

$$\frac{d\langle\sigma v\rangle}{dz} = 2\langle\sigma v\rangle_{\rm line}\delta(1-z) + \left.\frac{d\langle\sigma v\rangle}{dz}\right|_{\rm EP} + \left.\frac{d\langle\sigma v\rangle}{dz}\right|_{\rm cont}$$

Line — End-point — Continuum

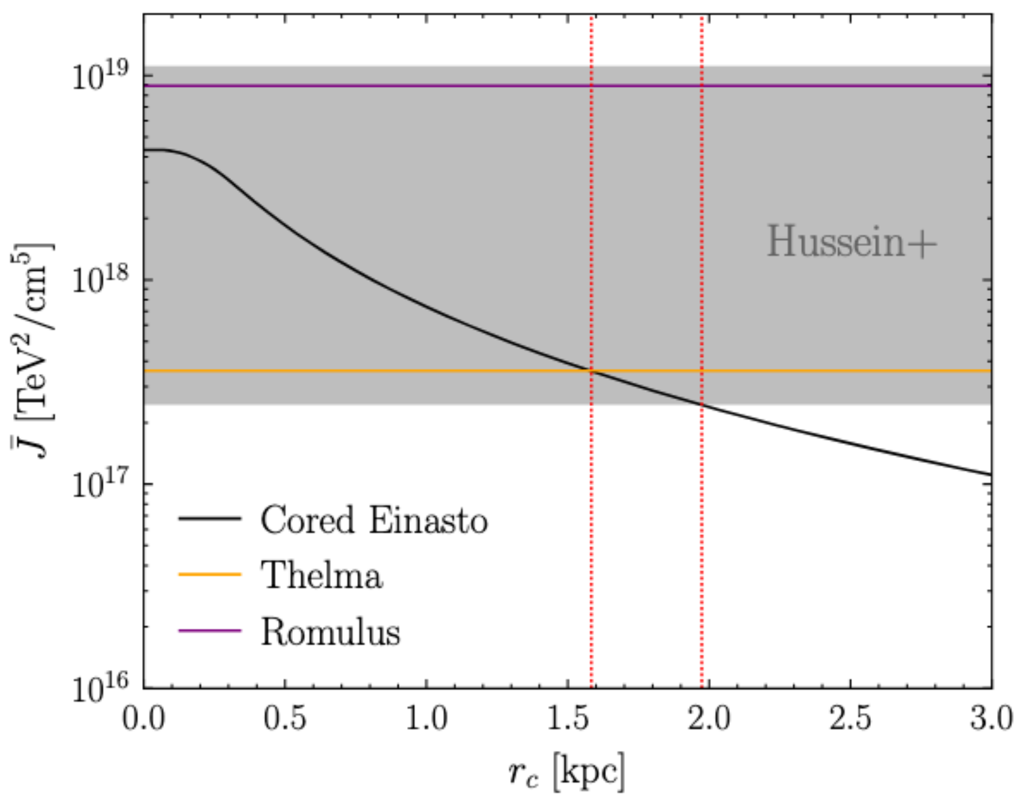
see previous papers by Baumgart Rodd, Statyer et al.

The final flux depends on the DM distribution in the galaxy*

*focus on the Galactic Center

$$J(r_c) = \int_{\Omega_{\rm ROI}} ds\, d\Omega\, \rho^2(r(s,\Omega), r_c)$$

$$\Omega_{\rm ROI} \begin{cases} \theta < 5^\circ \\ |b| < 0.3^\circ \end{cases}$$



Details of the Higgsino reach