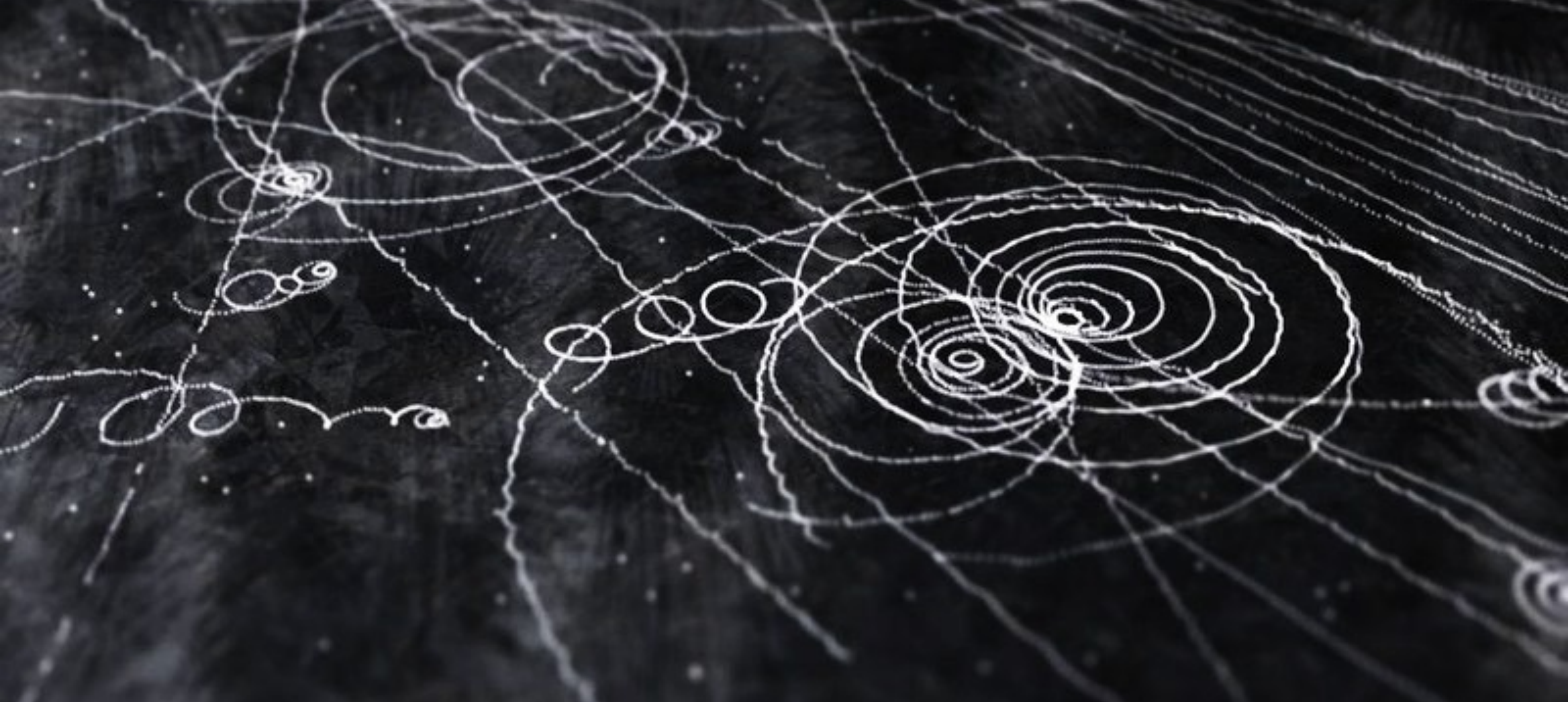


Dark Matter: status and prospects at FCC

Dario Buttazzo

Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

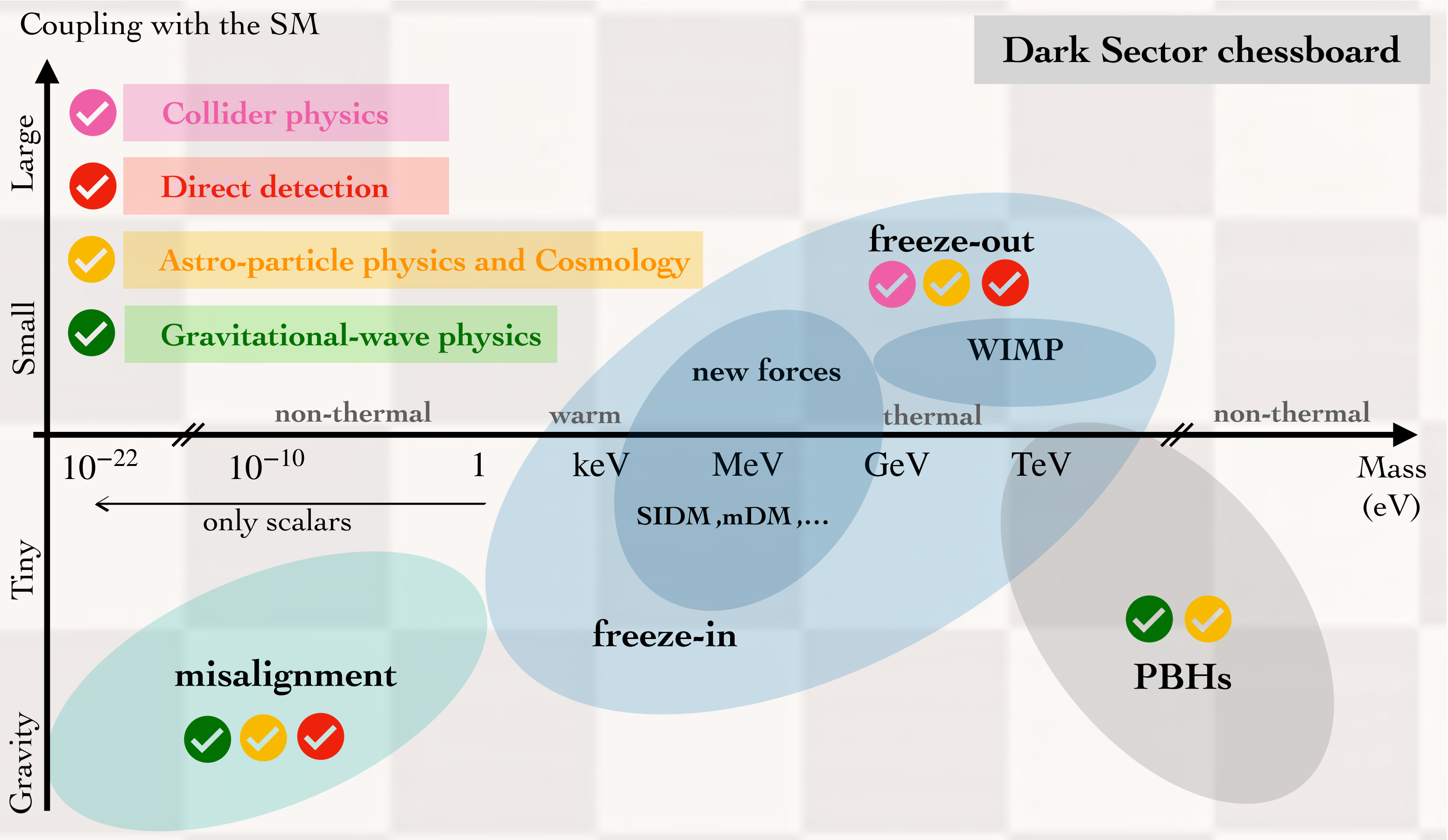
FCC France & Italy Workshop — Lyon, 22.11.2022

Motivation

- Dark Matter *exists*: the only direct evidence of physics beyond the Standard Model so far!

- One of the fundamental problems that the next large collider should be able to address

- Its fundamental nature is completely unknown: can span tens of orders of magnitude in mass and coupling

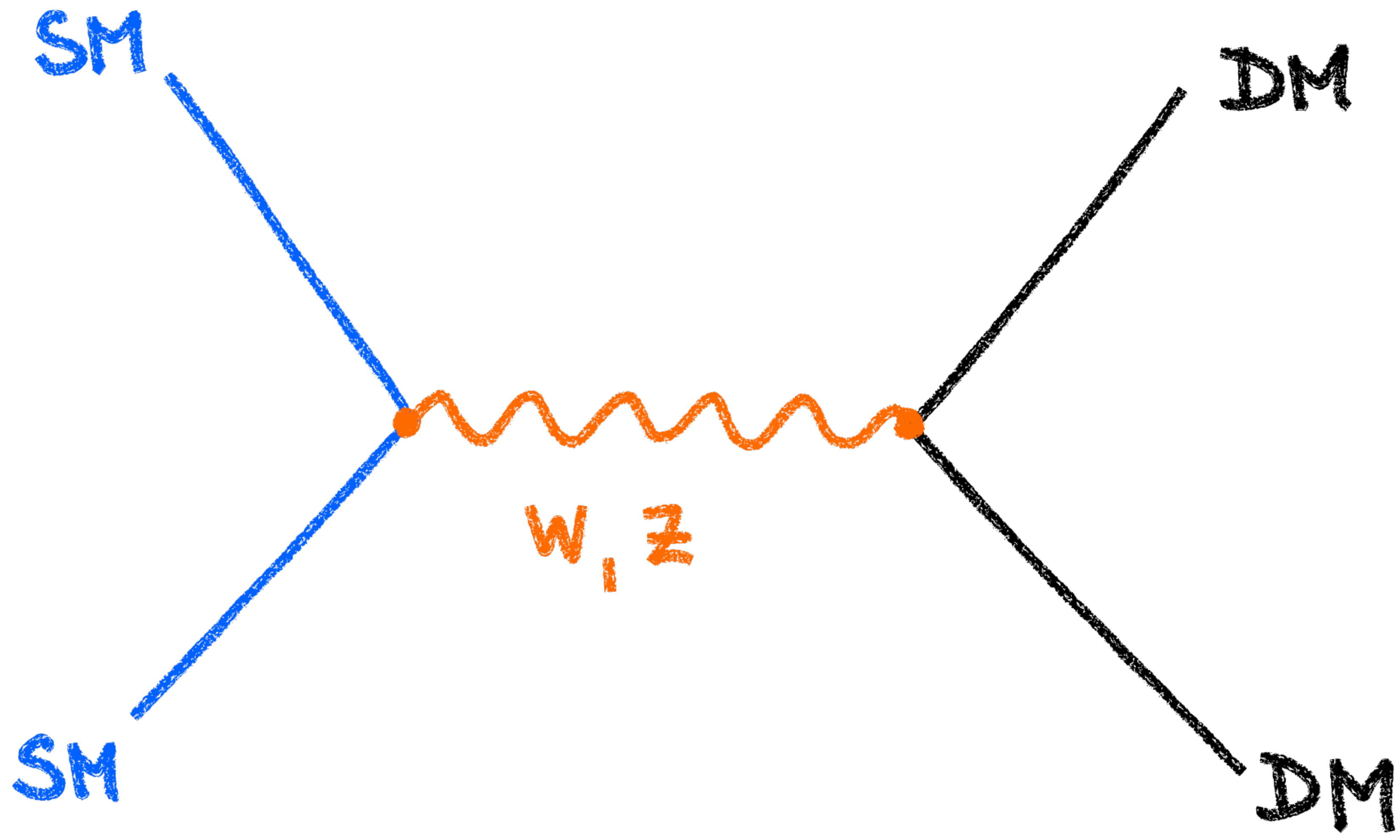


- The only measured quantity is the cosmological abundance $\Omega_{DM} \sim 0.26$

Motivation


LOOKING UNDER THE LAMPPOST
LOST YOUR KEYS?
YEAH,
I LOST THEM OVER THERE BUT THE LIGHT'S BETTER HERE

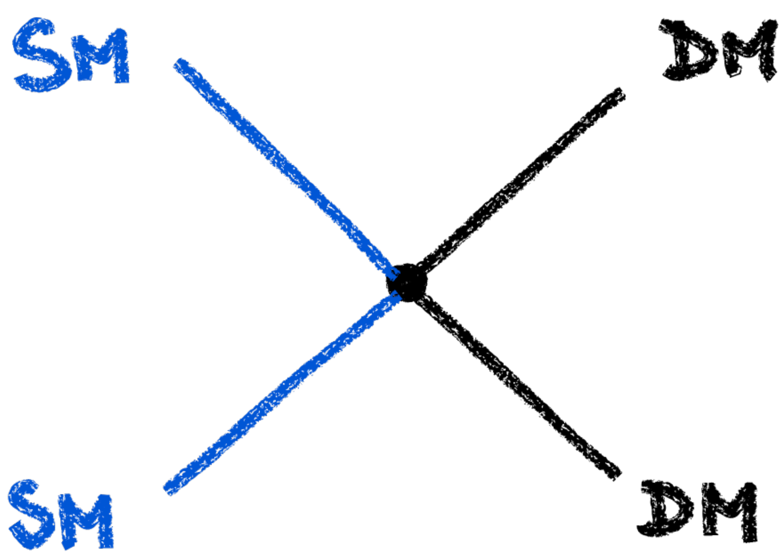
WIMP

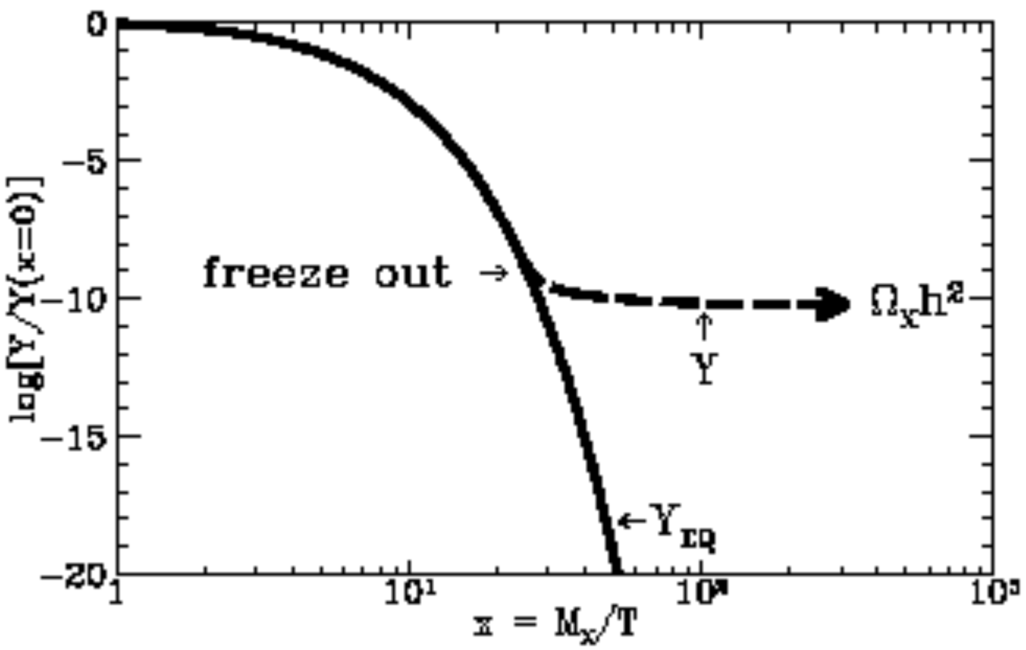


The case for WIMPs

- **WIMP miracle:** offers at the same time a simple explanation for the observed Dark Matter abundance (Ω_{DM} ~ 0.26) and a connection to naturalness of electroweak scale.

- Production in early Universe: thermal freeze-out of 2 → 2 scatterings





- For each value of the DM-SM coupling $g_\star$ DM mass is predicted.

☛ $g_\star \sim g_{EW} \Rightarrow M_{DM} \sim$ TeV

Ideal target for colliders!

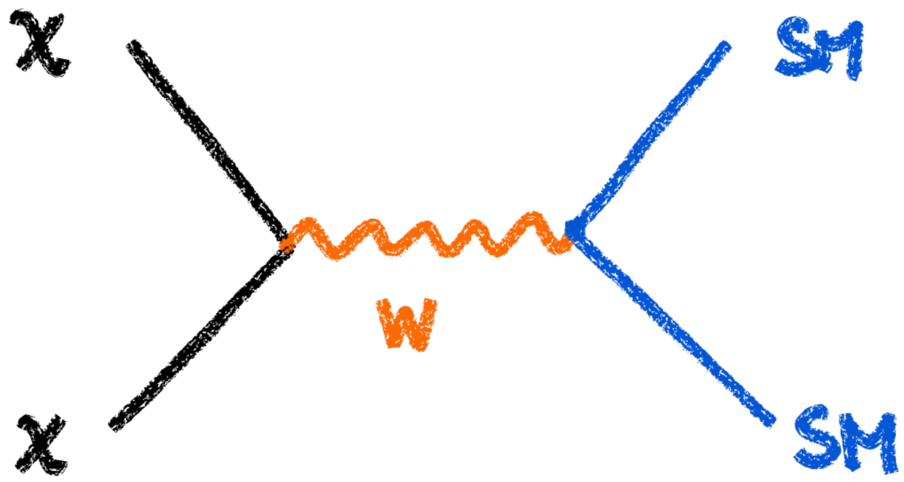
Which WIMP?

- Consider generic EW multiplet: interacts w/ SM through W, Z

  DM is the neutral component $\chi_n = (\cdots, \chi^-, \chi^0, \chi^+, \cdots)$

  "Minimal Dark Matter": Cirelli, Fornengo, Strumia 2005

- DM needs to be stable
- Strong bounds from Direct Detection: No Z coupling @ tree-level
  - Real multiplet: Y = 0, *n* odd
  - Complex multiplet: Y ≠ 0,
    (mass splittings from higher-dimensional operators needed)
- Single parameter sets the DM abundance: mass M_{DM}

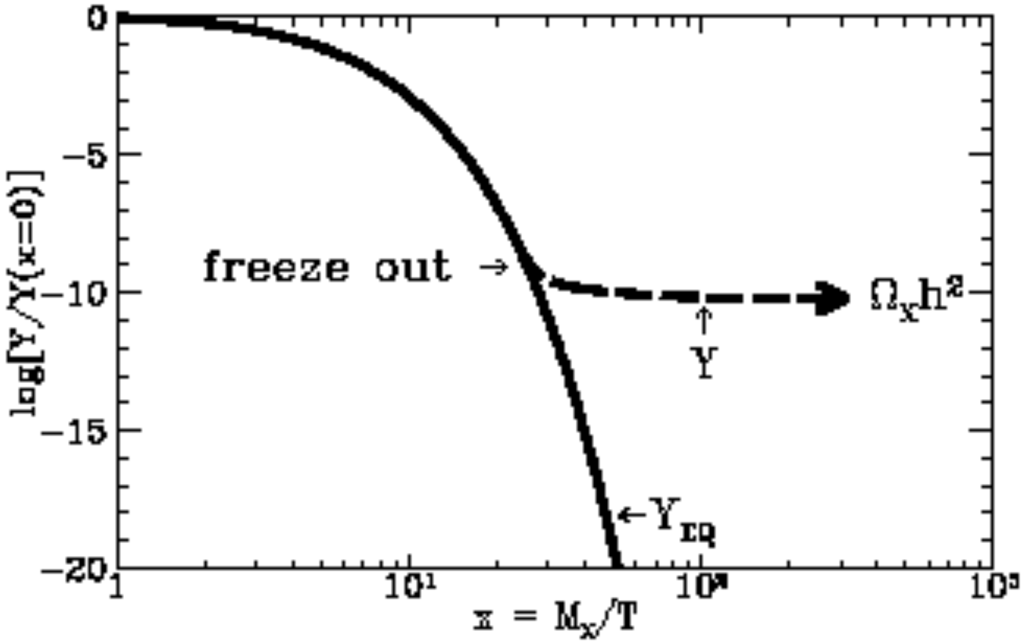


Which WIMP?

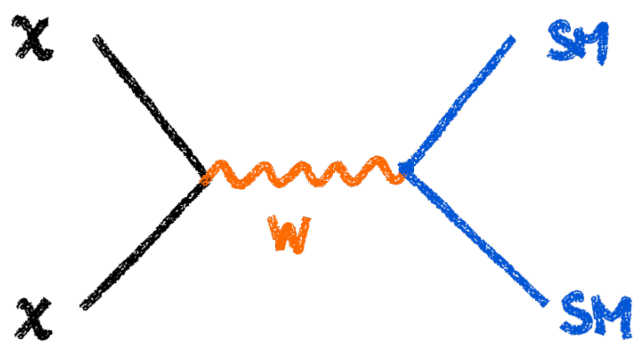
- Consider generic EW multiplet: interacts w/ SM through W, Z

$$\frac{dY}{dx} \propto \langle \sigma v \rangle (Y^2 - Y_{\rm eq}^2)$$

which cross-section?



- Tree-level EW cross-section…



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

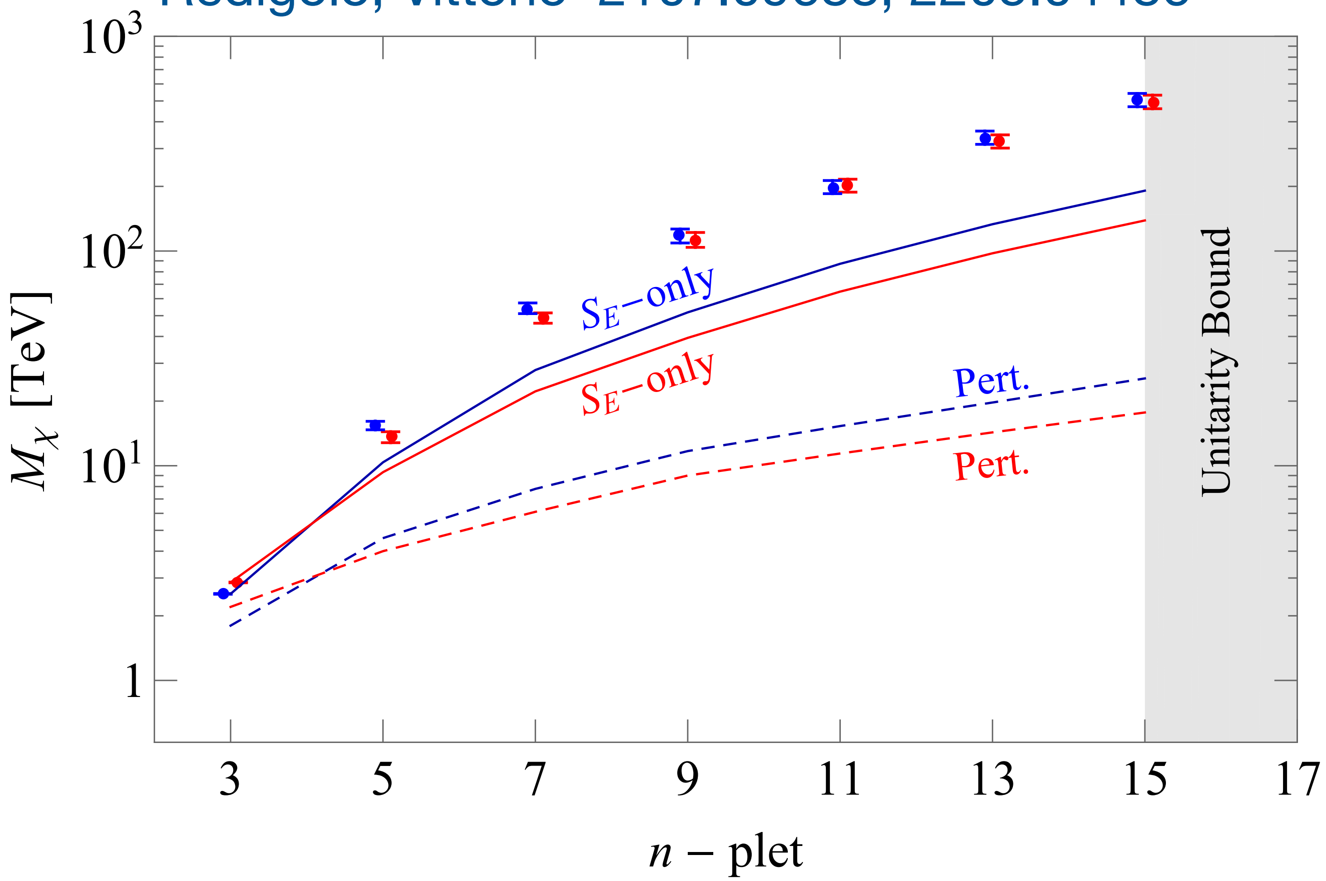
… is inaccurate!

- Sommerfeld enhancement
- Bound states formation

Large non-perturbative, non-relativistic effects

Thermal freeze-out masses

Bottaro, DB, Costa, Franceschini, Panci, Redigolo, Vittorio 2107.09688, 2205.04486



(and similar for scalars)

	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

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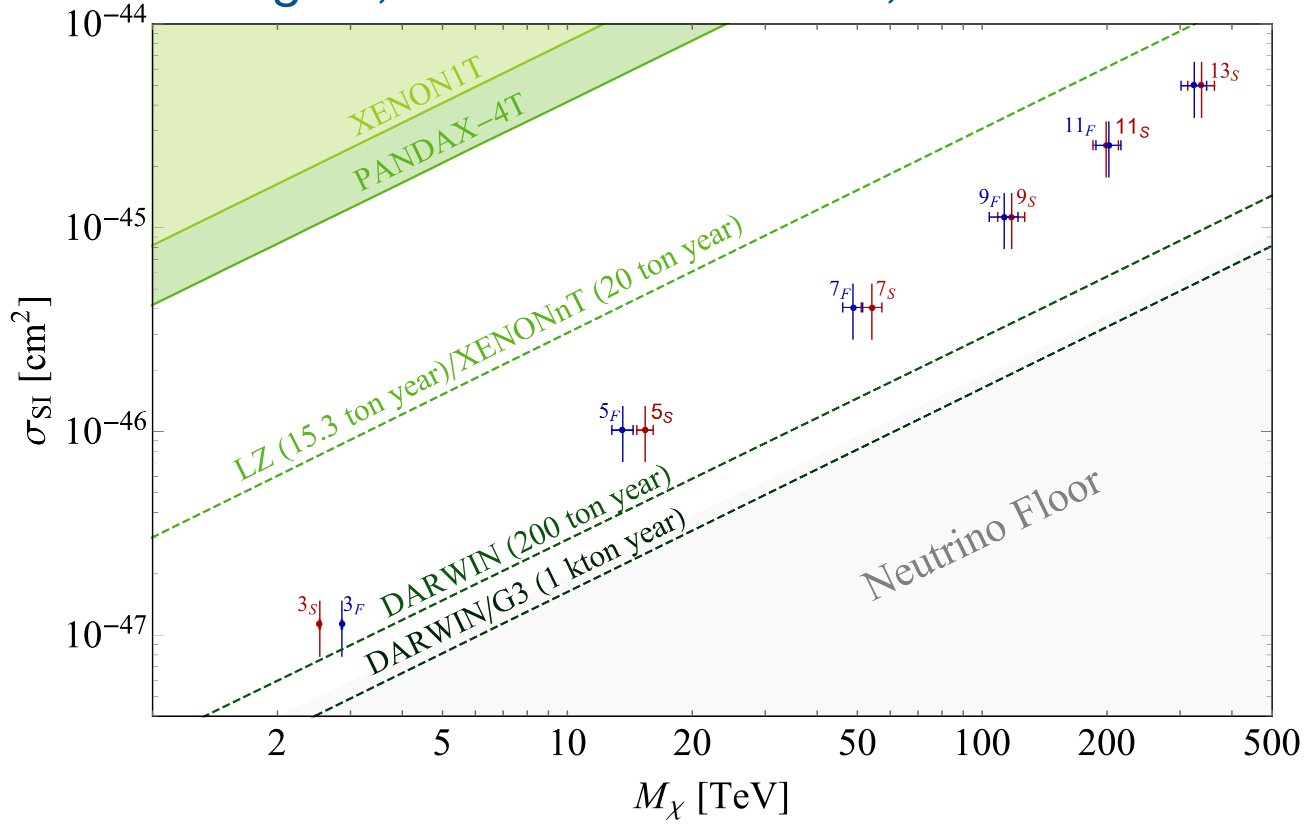

Direct Detection challenging…

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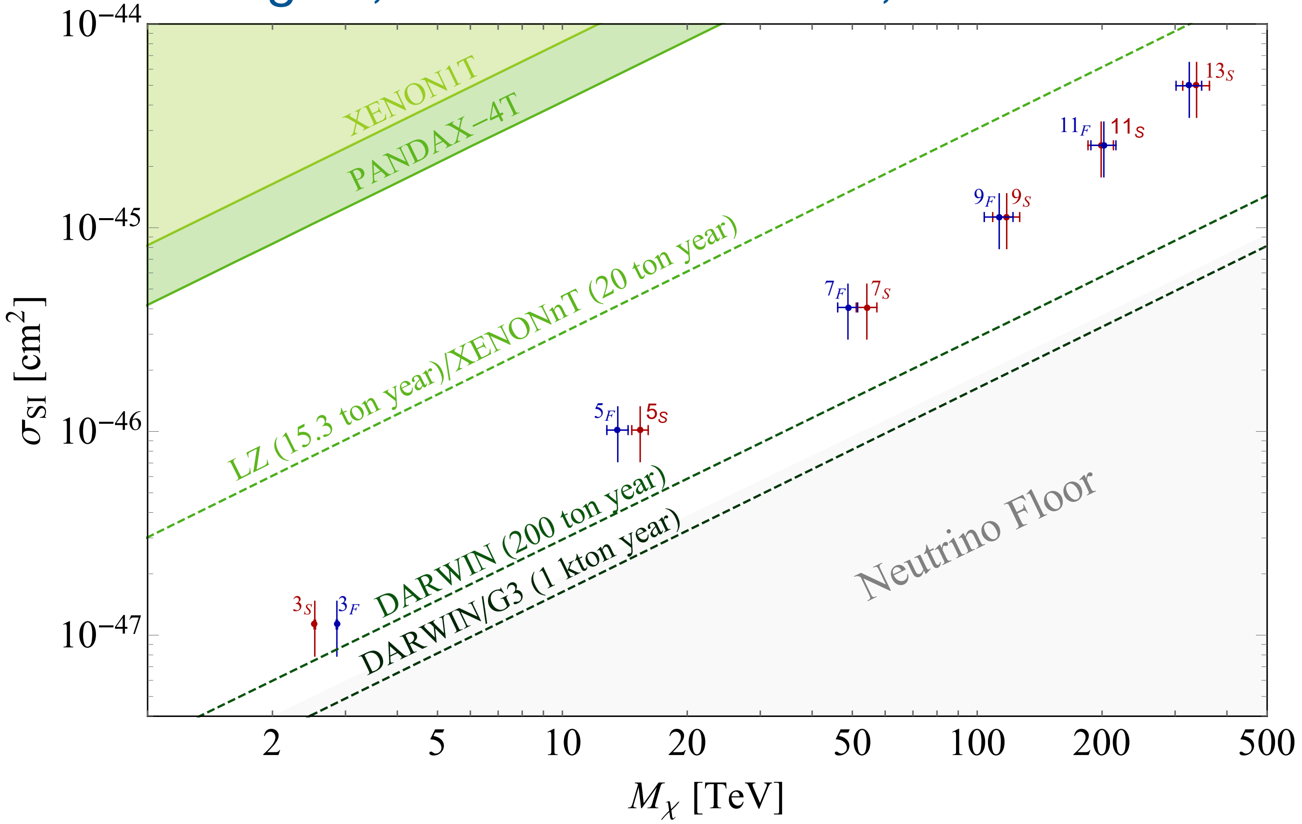

Direct Detection challenging...

Potentially in reach of a high-energy collider!

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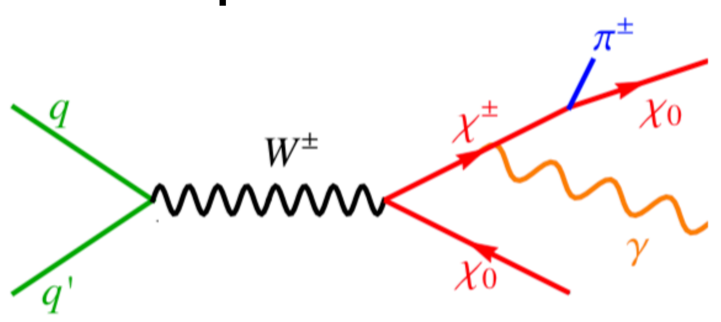
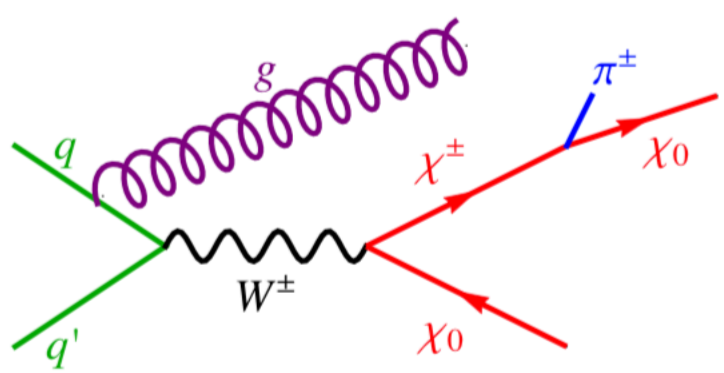
Electroweak triplet: missing energy searches

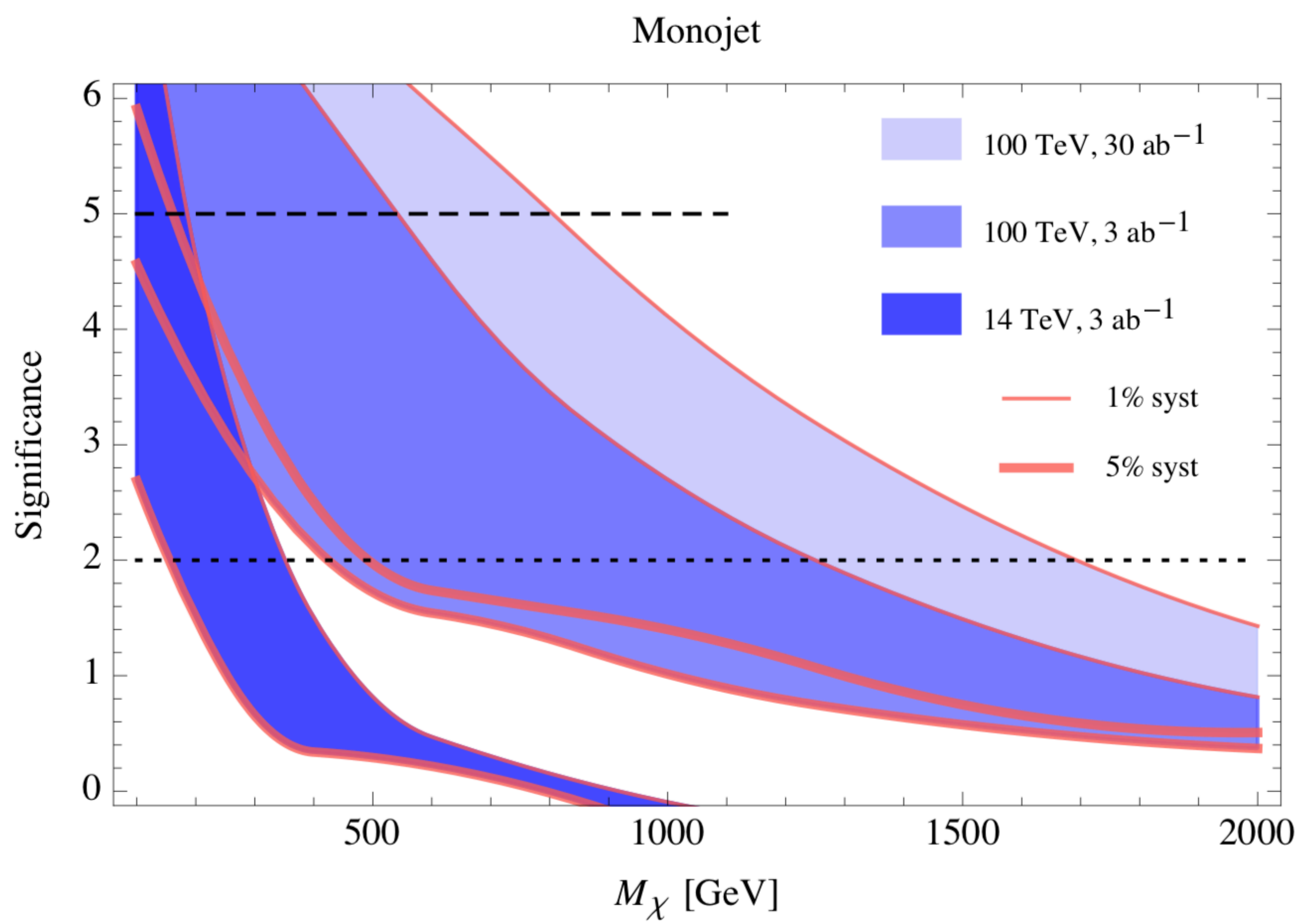
$$\mathscr{L} = \frac{1}{2}\bar{\chi}\left(iD_\mu\gamma^\mu - M_\chi\right)\chi, \qquad \chi = (\chi^-, \chi^0, \chi^+) \sim \mathbf{3}$$

- $2 \to 2$ production of invisible χ pair + event tag
  - Mono-photon:



  - Mono-jet





Cirelli, Sala, Taoso 1407.7058

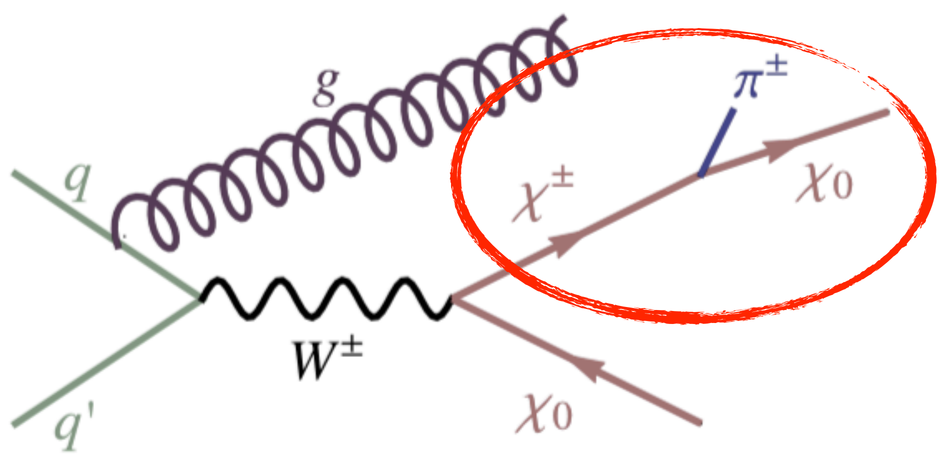
- Main background from Z → neutrinos
- Requires good control of systematics

Thermal freeze-out mass: 2.86 TeV ✘

Electroweak triplet: disappearing tracks

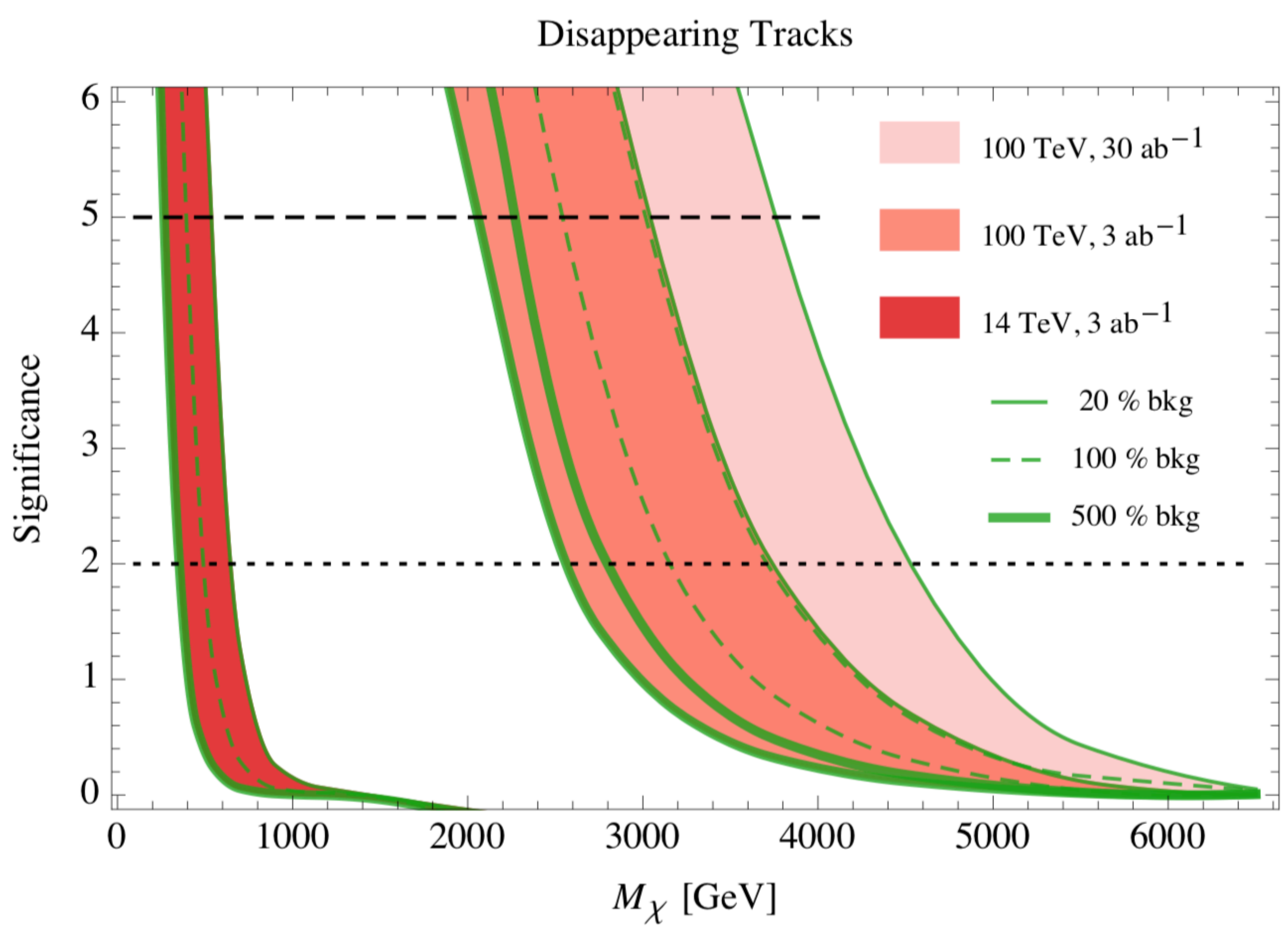
$$\mathscr{L} = \frac{1}{2}\bar{\chi}\left(iD_\mu\gamma^\mu - M_\chi\right)\chi, \qquad \chi = (\chi^-, \chi^0, \chi^+) \sim \mathbf{3}$$

- $2 \to 2$ production of invisible χ pair + event tag
- Can look for the tracks of charged χ^+ decaying to χ^0 DM:



- Real WIMPS: lifetime is fixed by EW interactions

$$c\tau \approx 50\,\mathrm{cm}/(n^2-1)$$



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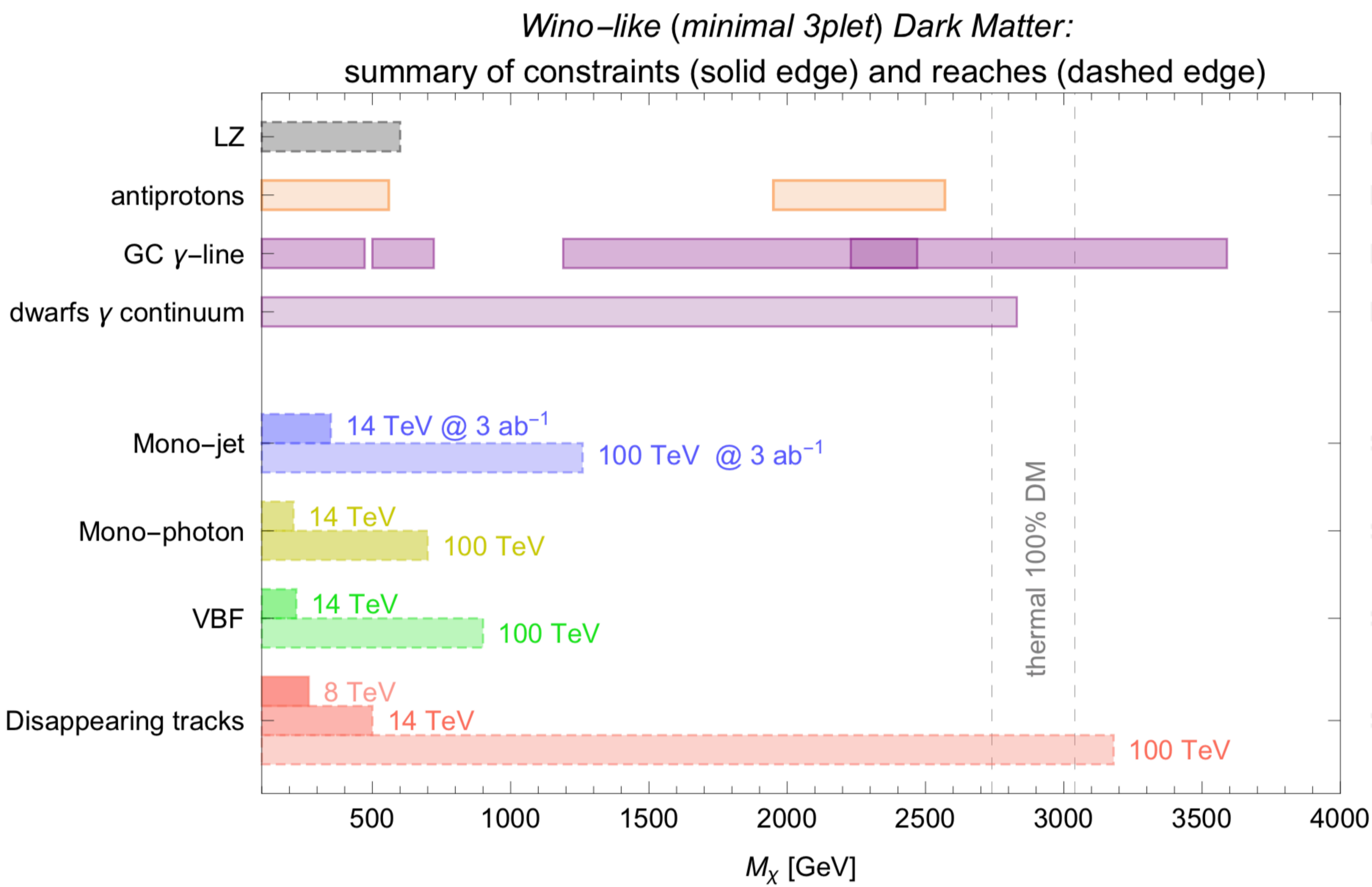
Cirelli, Sala, Taoso 1407.7058

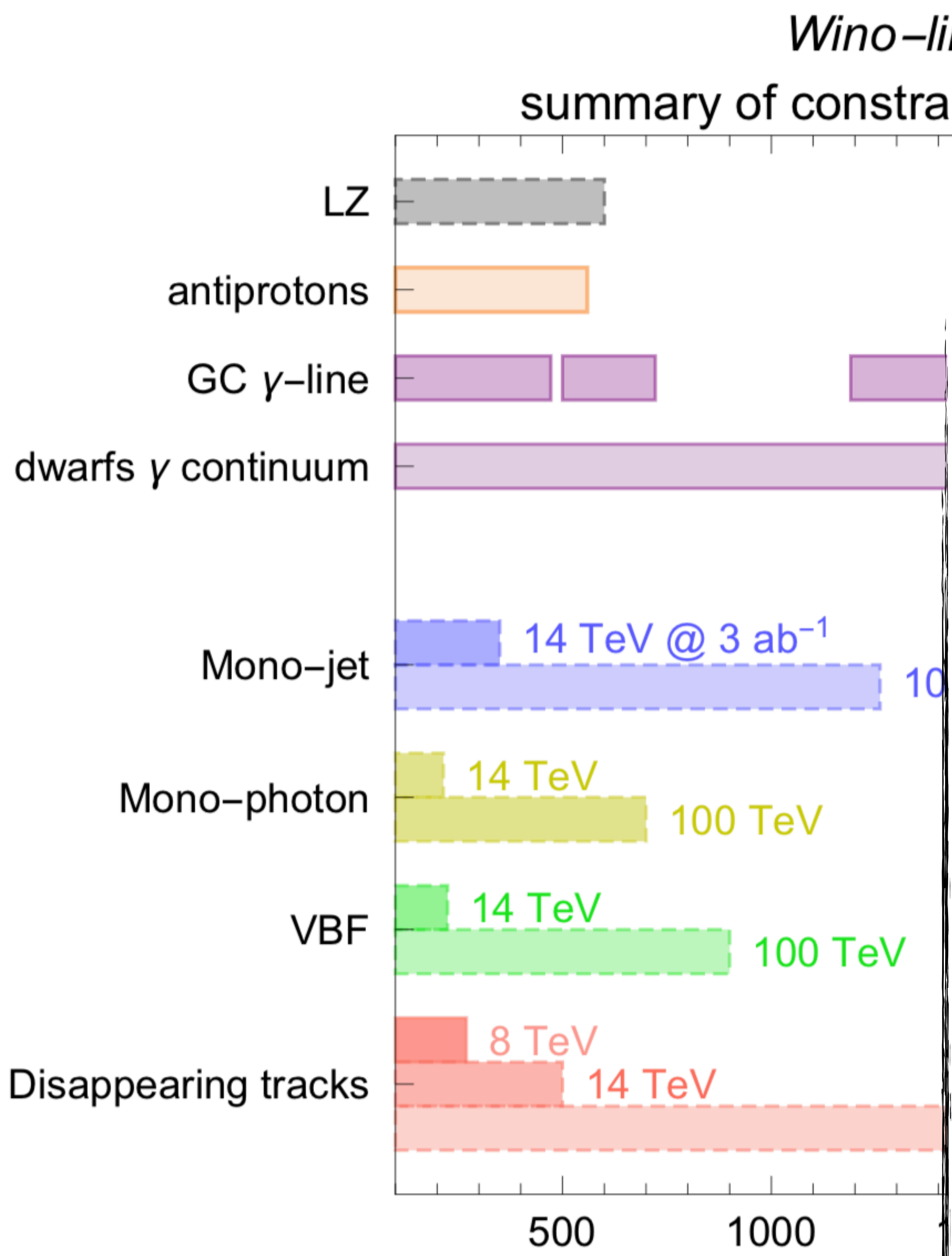
Electroweak triplet @ FCC-hh

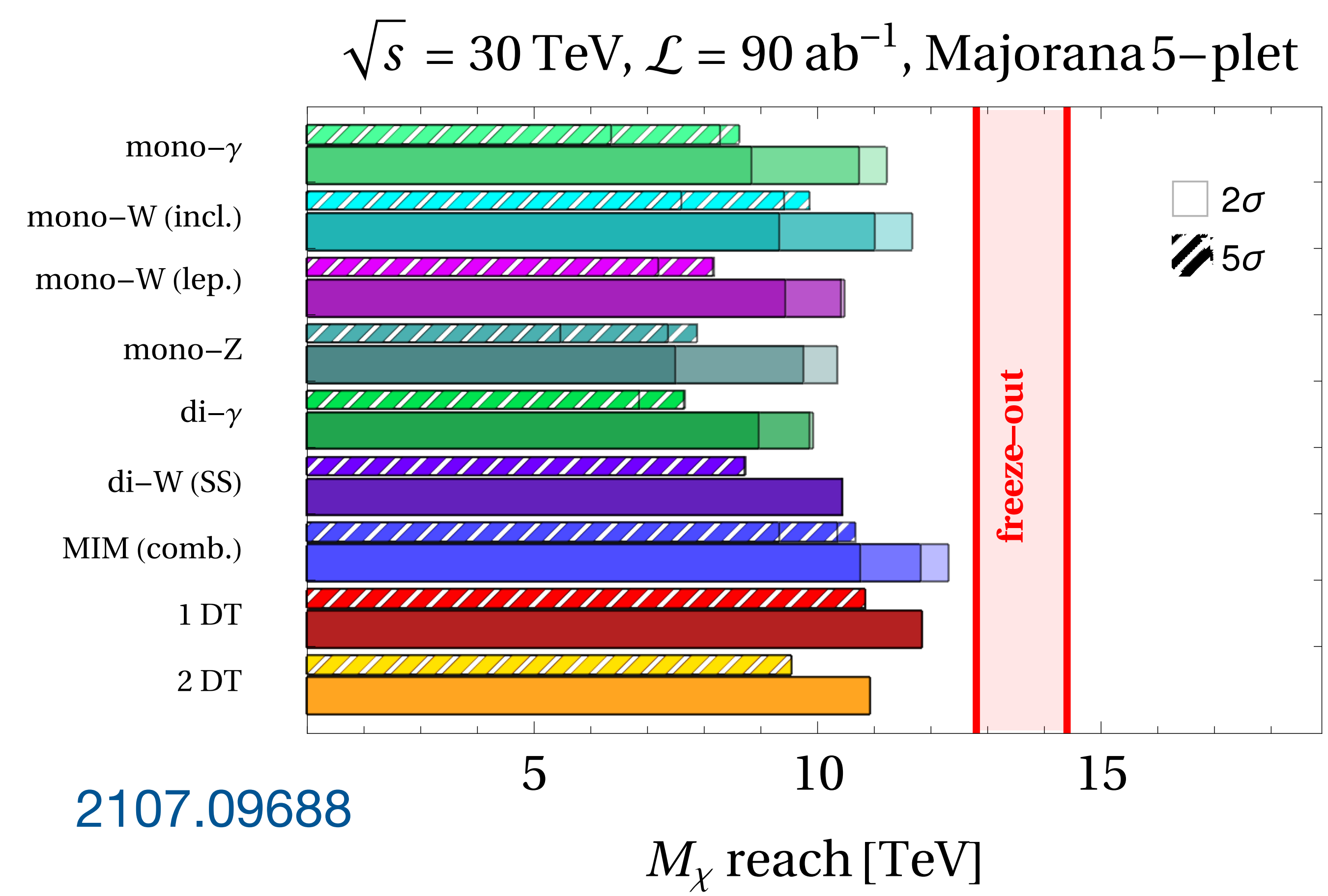


Cirelli, Sala, Taoso 1407.7058

FCC Physics Opportunities

Electroweak triplet @ FCC-hh





2107.09688

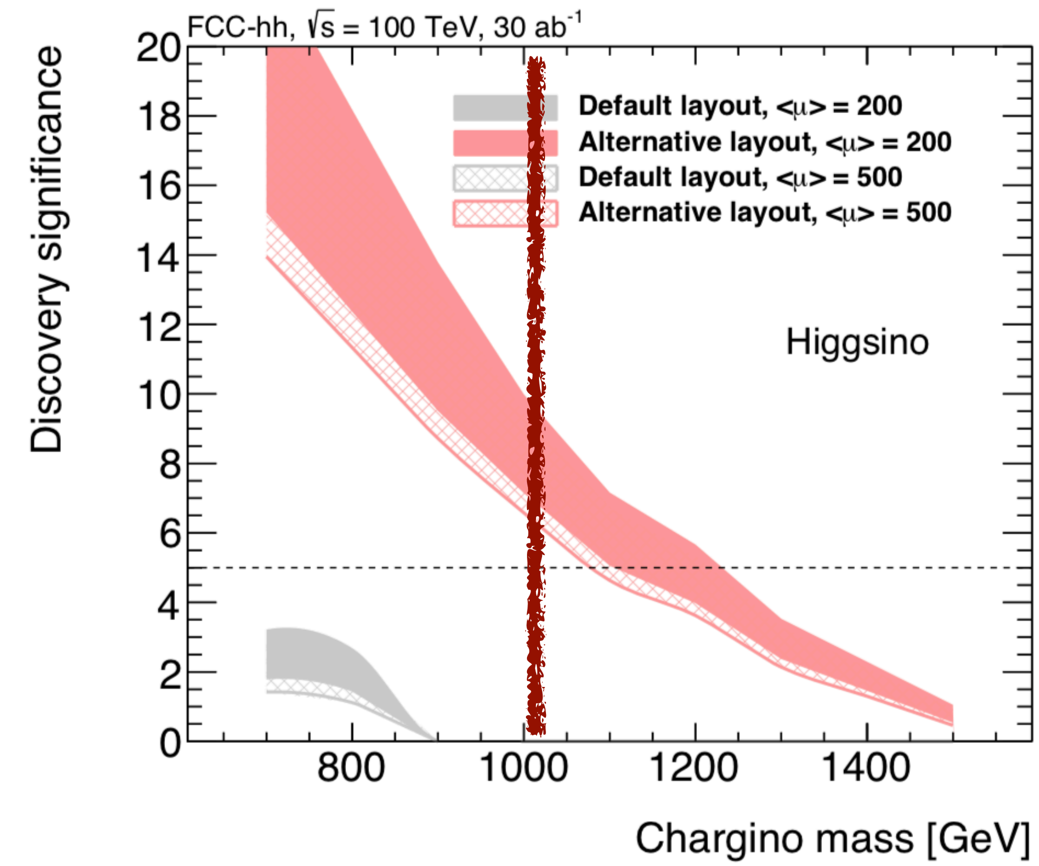
- Many other channels possible (EW radiation important at high energy)
- Can be combined to improve limits and reduce impact of systematics

Cirelli, Sala, Taoso 1407.7058
FCC Physics Opportunities

Other EW multiplets

- Doublet (Higgsino) and triplet (Wino) fully probed at FCC-hh
  - Results strongly depend on the detector layout!

    Terashi, Sawada, Saito, Asai (2018)



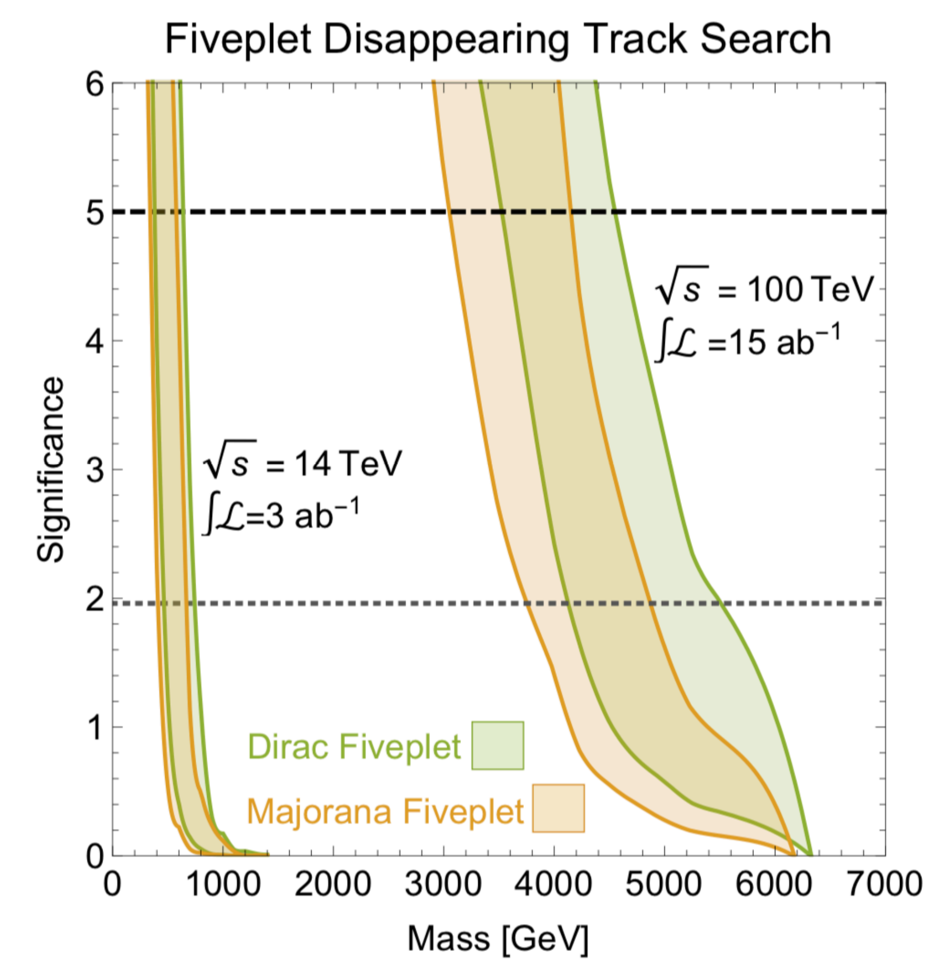
- Larger EW multiplets:

😊 Larger cross-section due to big EW charges

😣 Much larger thermal masses, $M_{DM} \sim n^{5/2}$

😣 Shorter lifetime of charged components, disappearing tracks less effective

n ≥ 5 not testable at FCC



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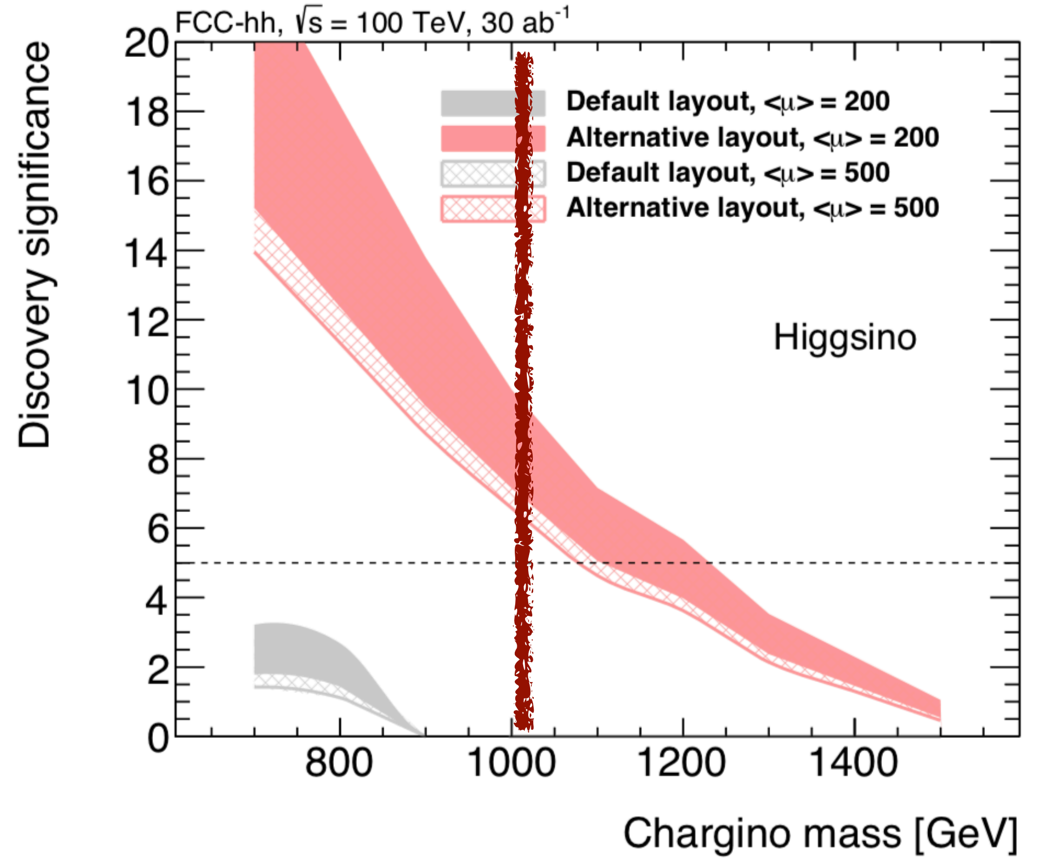

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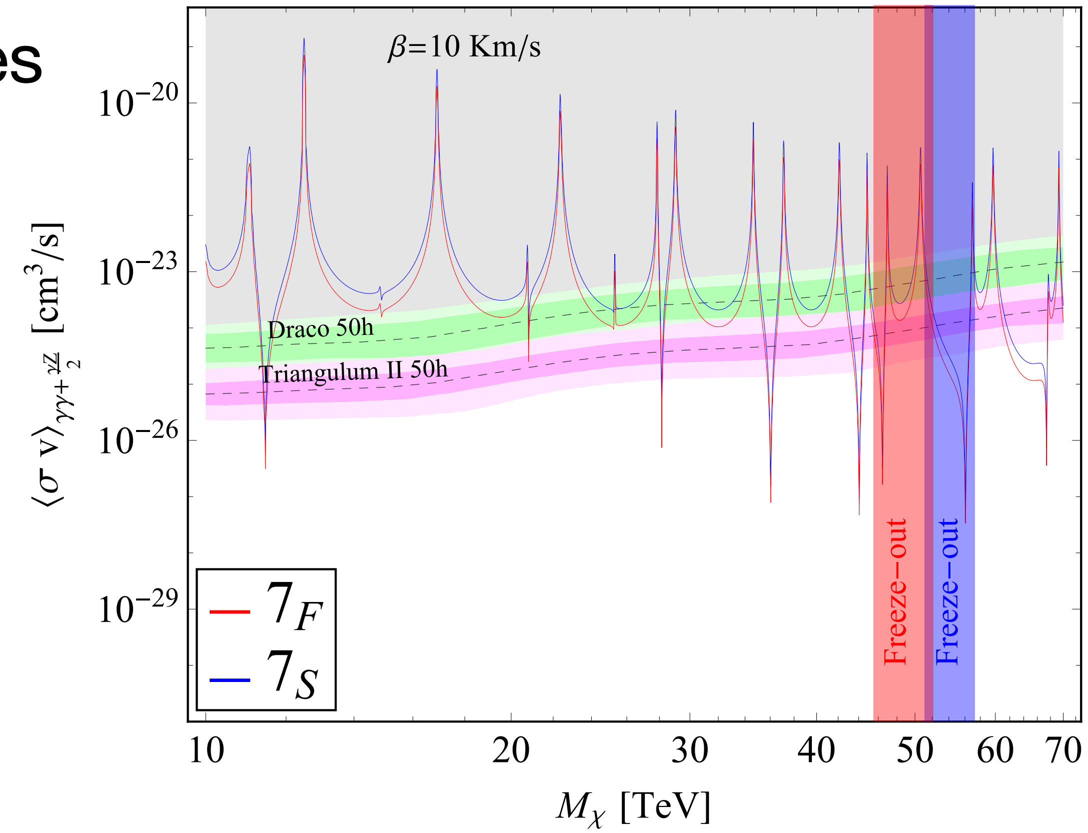
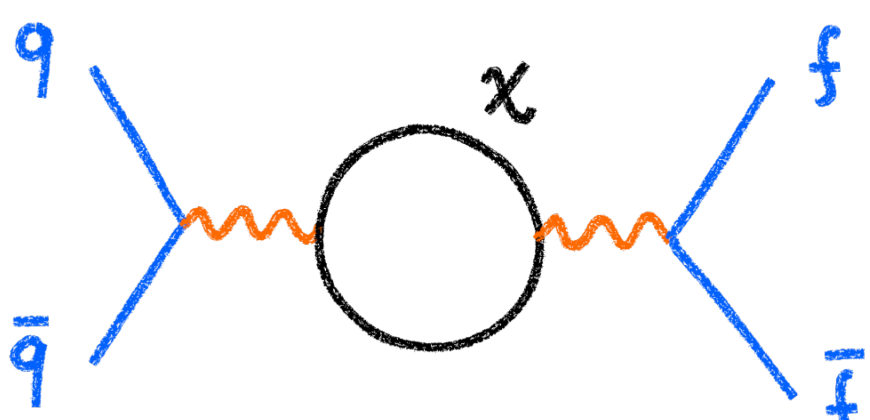
Signals in Indirect Detection!

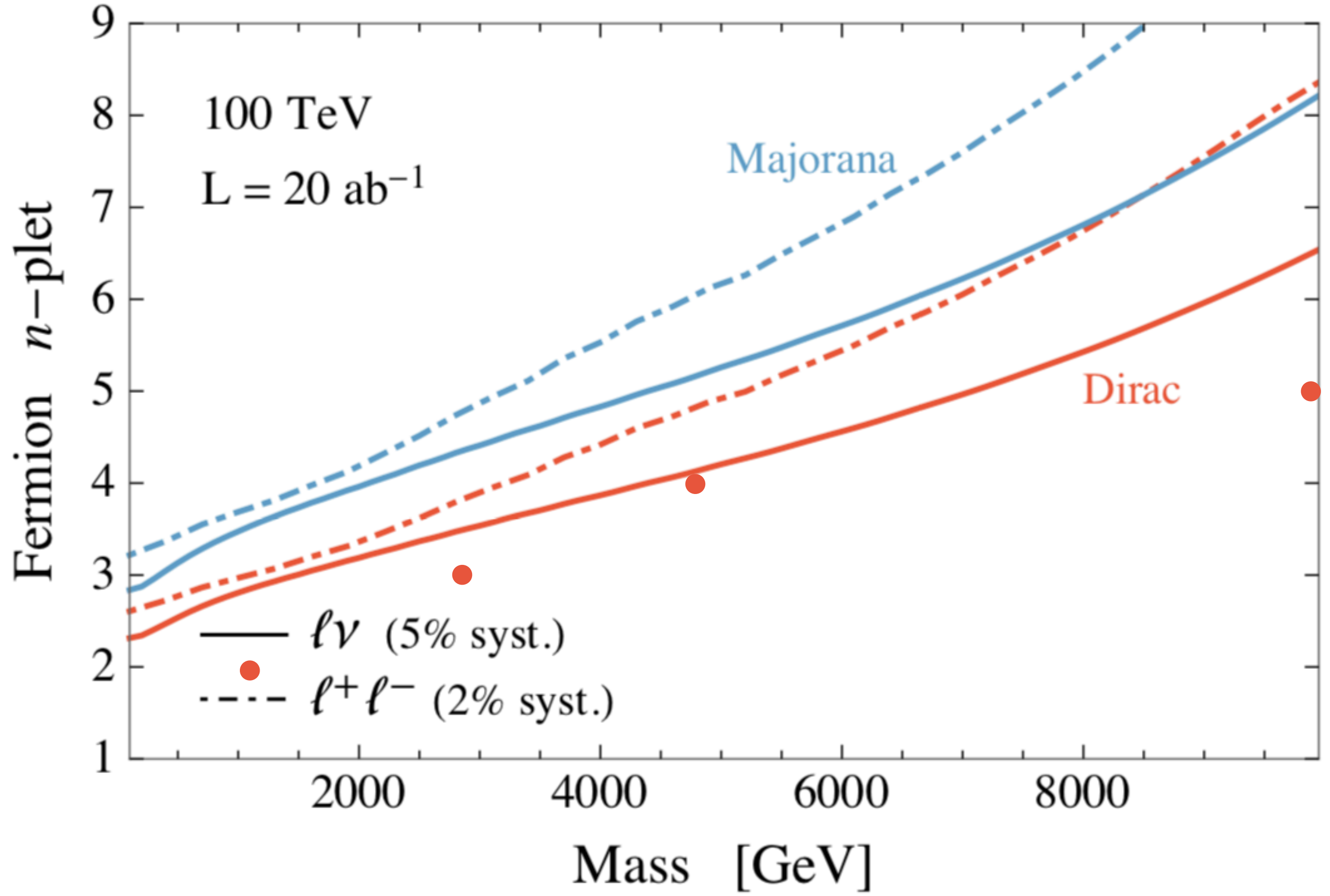


Indirect effects at colliders

- All EW multiplets give universal contributions to high-energy 2 → 2 fermion scattering (W, Y parameters)



Di Luzio, Gröber, Panico 1810.10993



These effects grow with energy, can be tested at FCC-hh

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

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

Indirect effects at colliders

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

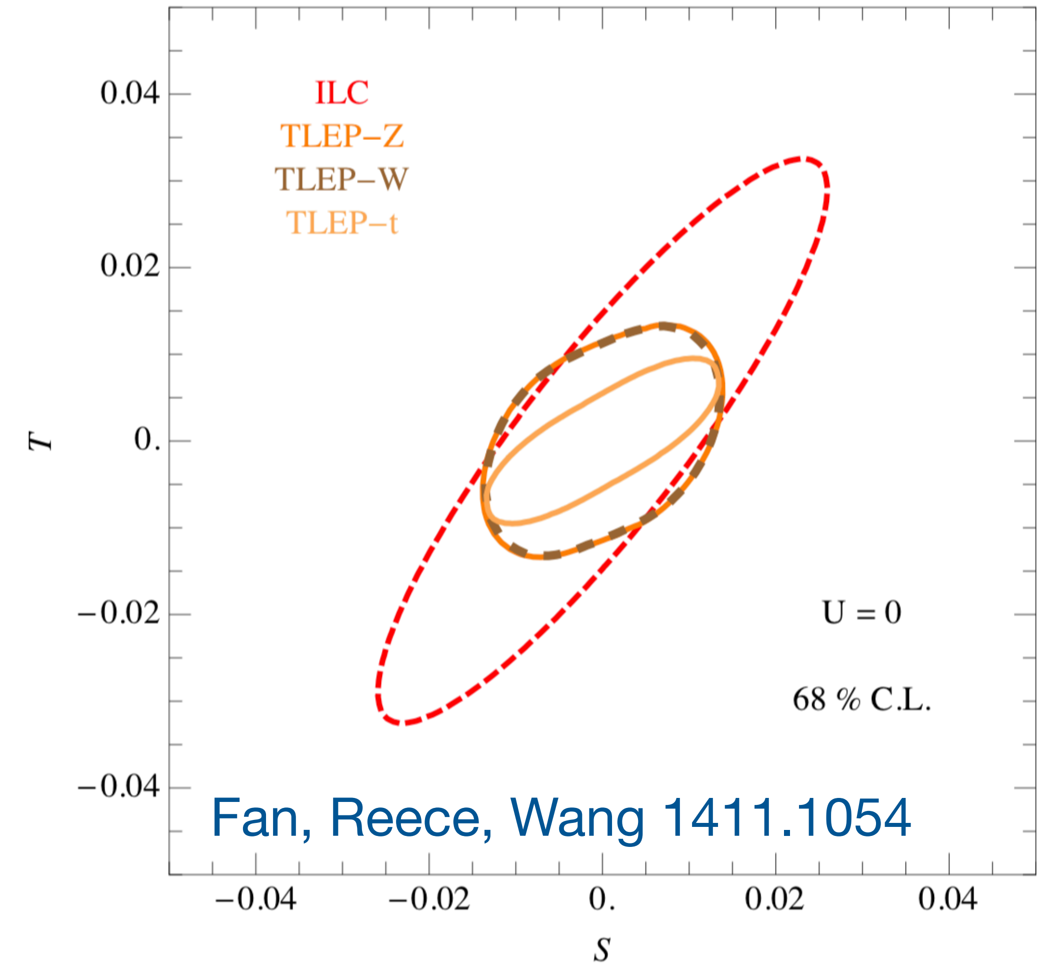
- Contribution to S, T parameters

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

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

Bottaro, DB, Costa, Franceschini, Panci, Redigolo, Vittorio 2205.04486

Di Luzio, Gröber, Kamenik, Nardecchia 1505.00359

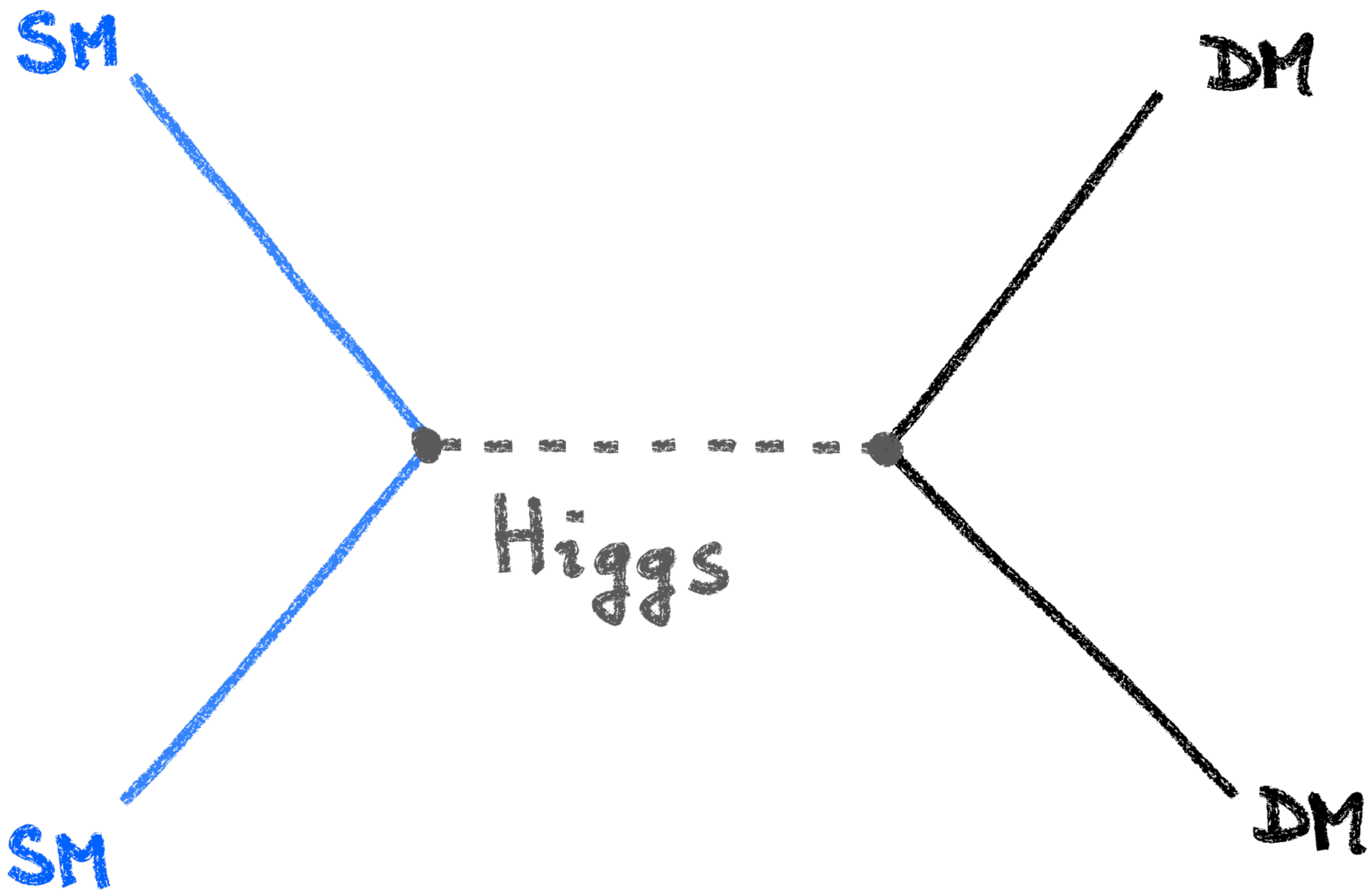


Fan, Reece, Wang 1411.1054

- FCC-ee sensitivity: $\hat{S}, \hat{T} \lesssim \text{few} \times 10^{-5}$

could probe larger EW multiplets

Higgs portal

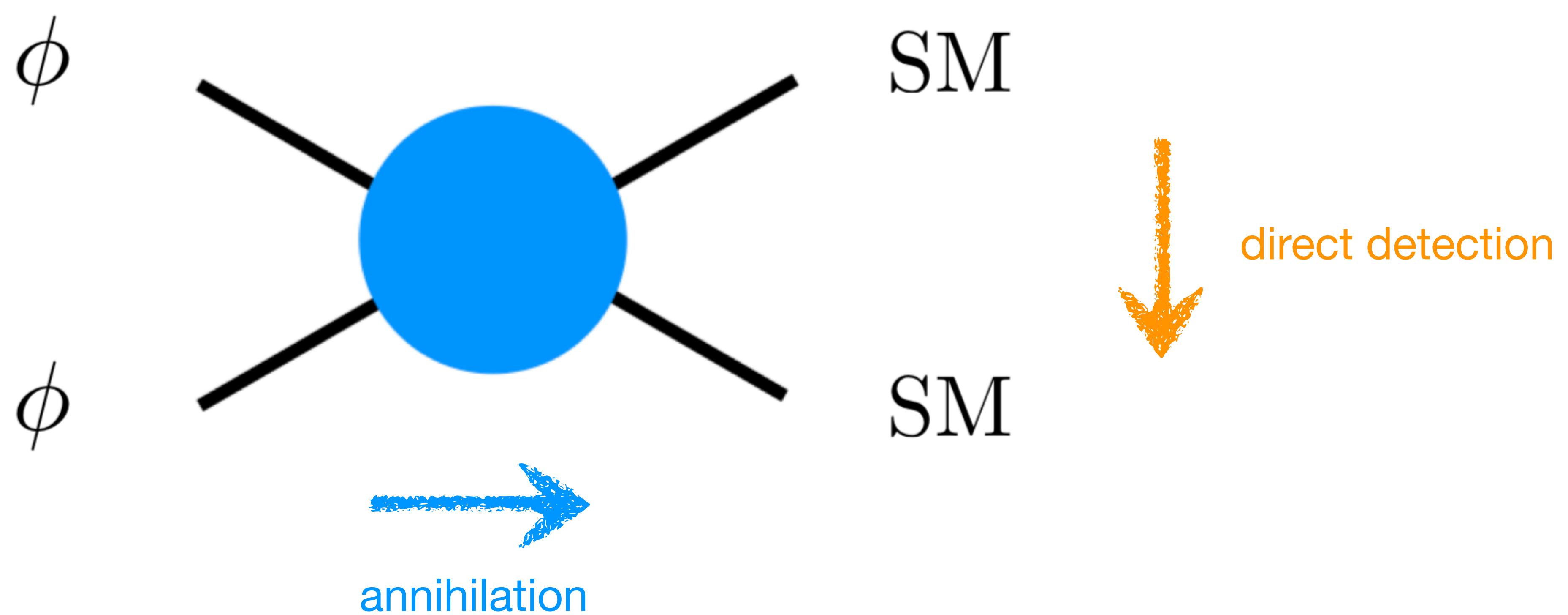


Higgs portal

- Singlet scalar coupled through Higgs portal:

  one of the simplest thermal DM scenarios beyond EW interactions

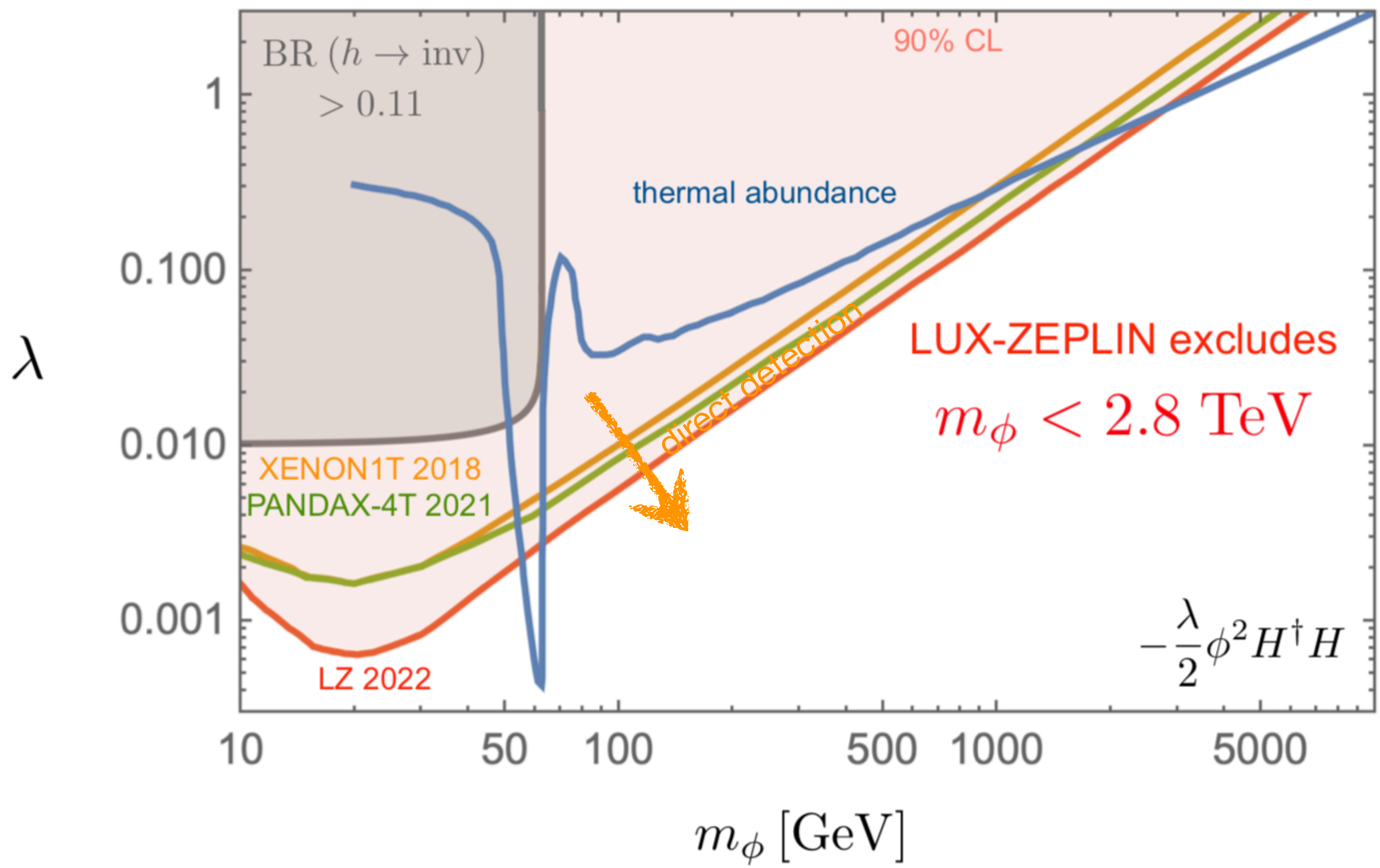
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{1}{2}M_\phi^2\phi^2 - \frac{\lambda}{2}\phi^2 H^\dagger H$$



Freeze-out: $\Omega_\phi h^2 \propto \frac{1}{\langle\sigma v\rangle} \approx 0.1\left(\frac{0.1}{\lambda}\right)^2\left(\frac{M_\phi}{100\,\mathrm{GeV}}\right)^2$

Higgs portal

- Masses below few TeV strongly constrained by Direct Detection

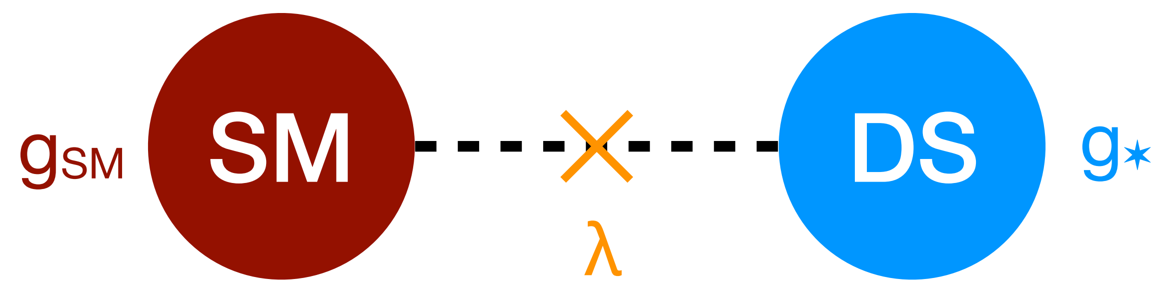


Good example of the “WIMP **vs** direct detection” tension

E. Salvioni
@ Higgs2022

Higgs portal

- Higgs portal to a *Dark Sector:* decouple freeze-out and direct detection



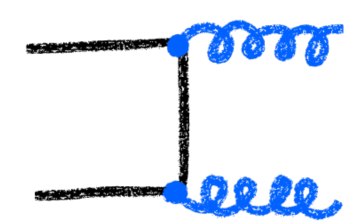
  - freeze-out is controlled by a coupling $g_\star$ in the dark sector
  - portal coupling $\lambda |H|^2 |\phi|^2$ can be made small

☛ Unitarity: if g ~ 4π, m_{DM} ~ 100 TeV

Examples

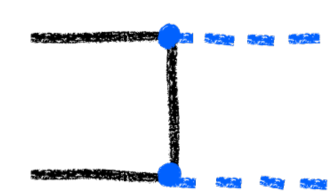
- Dark Matter + dark gauge field

$$\mathscr{L} = -\frac{1}{4}\mathscr{F}^a_{\mu\nu}\mathscr{F}^a_{\mu\nu} + |D_\mu \phi|^2 - m_\phi^2 |\phi|^2 - \lambda\, \phi^2 (H^\dagger H)$$



- Majorana fermion + singlet scalar

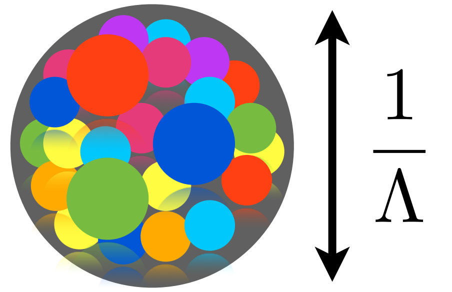
$$\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{m_\phi^2}{2}\phi^2 + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - g_\chi \phi \chi\chi - \lambda\, \phi^2 (H^\dagger H)$$

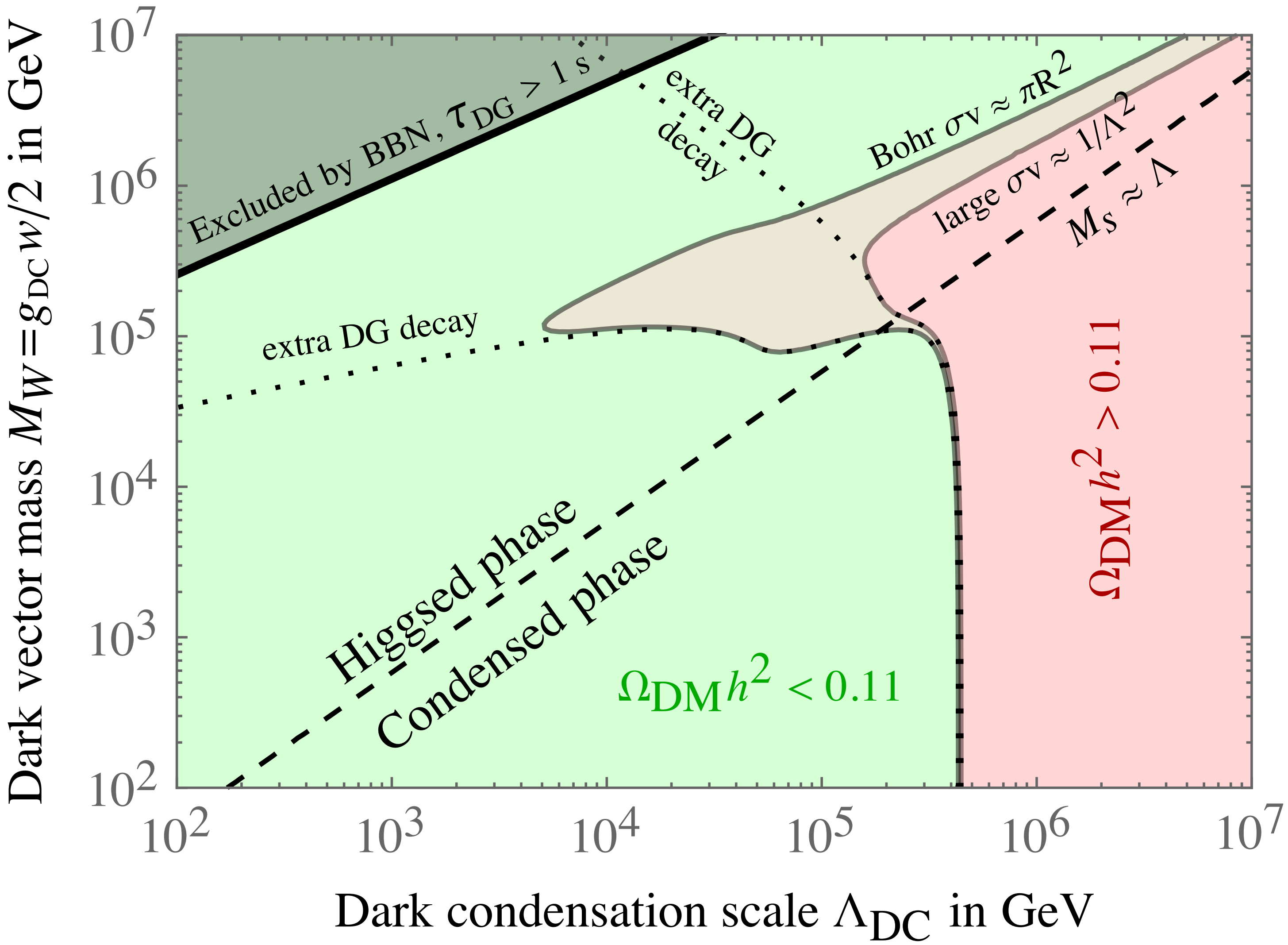


Composite Dark Matter

- If dark group confines, Dark Matter is bound state of strong “dark force” at Λ ~ few × (1 – 100 TeV)

- Stable thanks to accidental “dark baryon number”





constituents can be fermions

Strassler, Zurek 2006
Antipitin, Redi, Strumia, Vigiani 2015
… many more…

or scalars

Hambye 2008
DB, Di Luzio, Landini, Strumia, Teresi 2019

✘ Thermal mass ~ few × 100 TeV: not directly testable at colliders

Scalar singlets

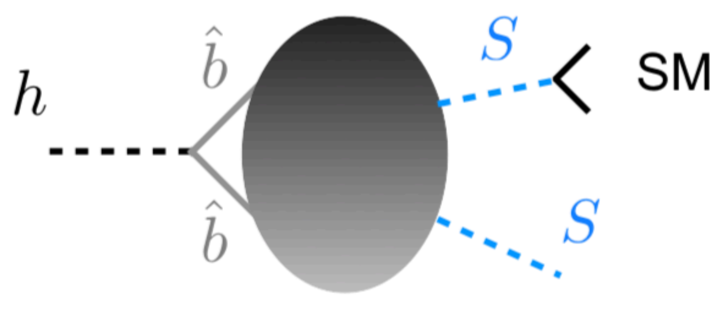
- Can test the portal interaction with the singlet sector

$$\mathcal{L}_\phi = -\frac{1}{2}m_\phi^2\phi^2 - V(\phi) - \mu\phi H^\dagger H - \frac{\lambda}{2}\phi^2 H^\dagger H$$

induces mixing between Higgs and scalar singlet ($\phi \to -\phi$ symmetry is not exact)

controls BR(h $\to \phi\phi$), or BR($\phi \to$ hh)

- ϕ can be e.g. Goldstone, or glueball of dark gauge interactions…



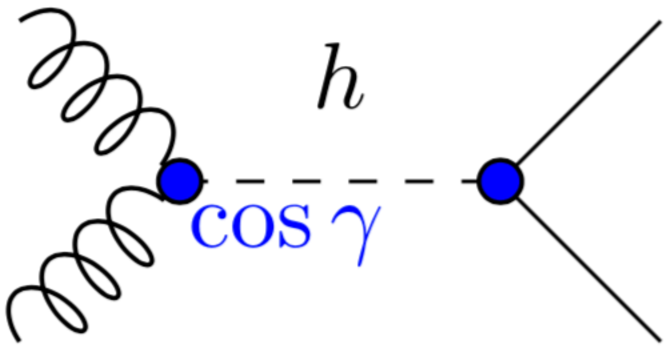
- ϕ can mediate DM freeze-out if $M_{DM} > M_\phi$

$$\mathcal{L}_{\rm DM} = y_\chi \phi \chi \chi$$

Scalar singlets @ FCC

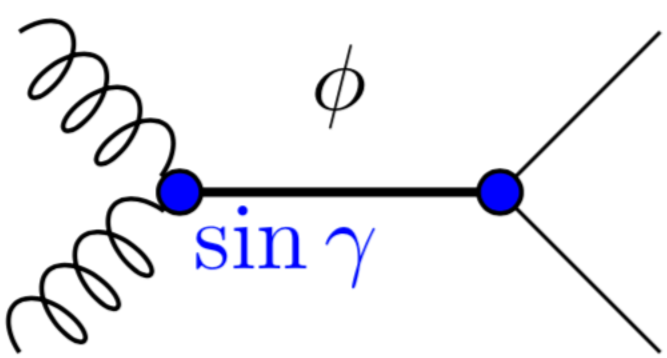
- Two complementary ways to look for the singlet at colliders:

Higgs signal strengths



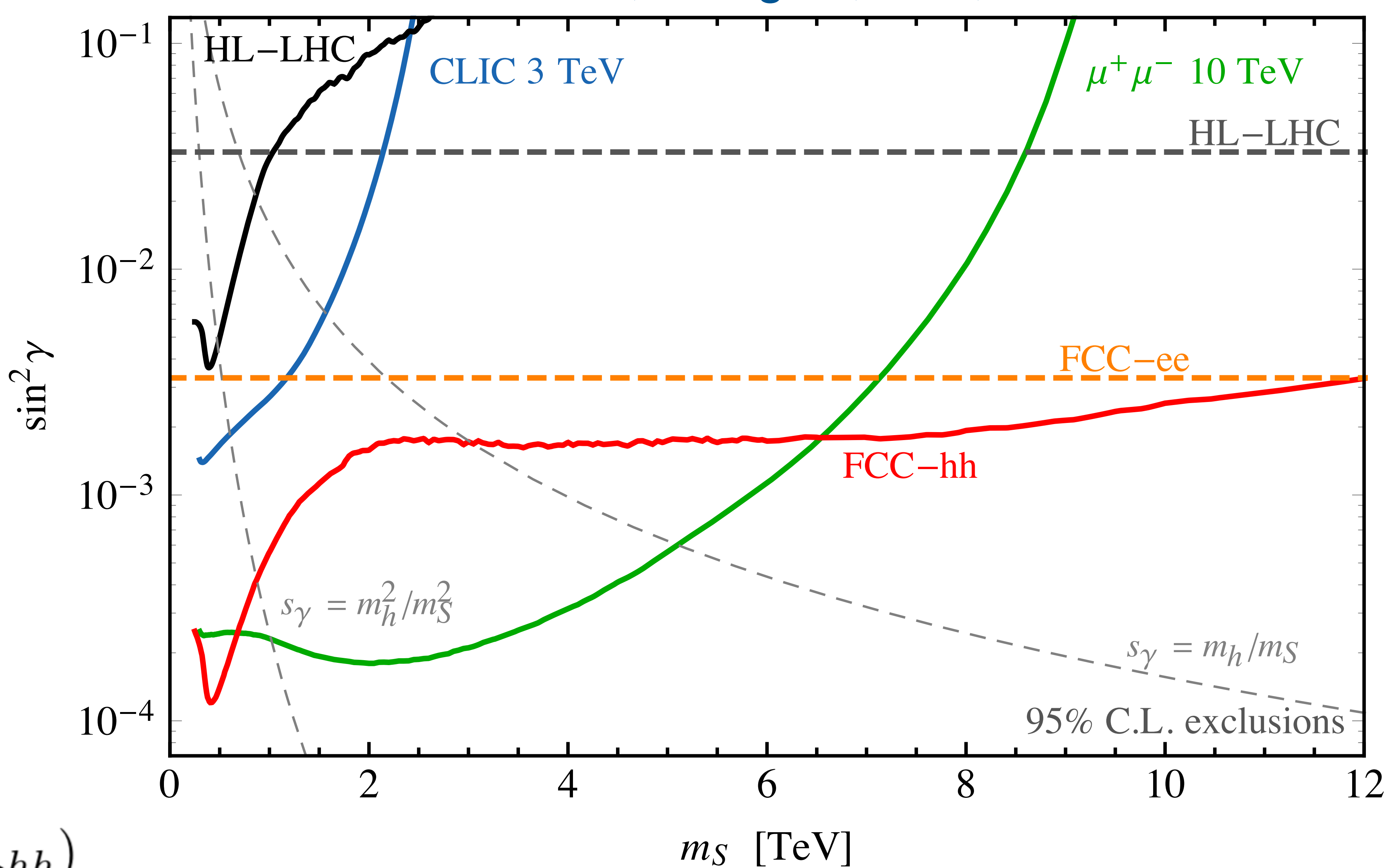
$$\mu_h = c_\gamma^2 \mu_{\rm SM}$$

Direct searches



$$\mu_\phi = s_\gamma^2 \mu_{\rm SM} \times (1 - {\rm BR}_{\phi\to hh})$$

DB, Sala, Tesi 1505.05488
DB, Redigolo, Sala, Tesi 1807.04743

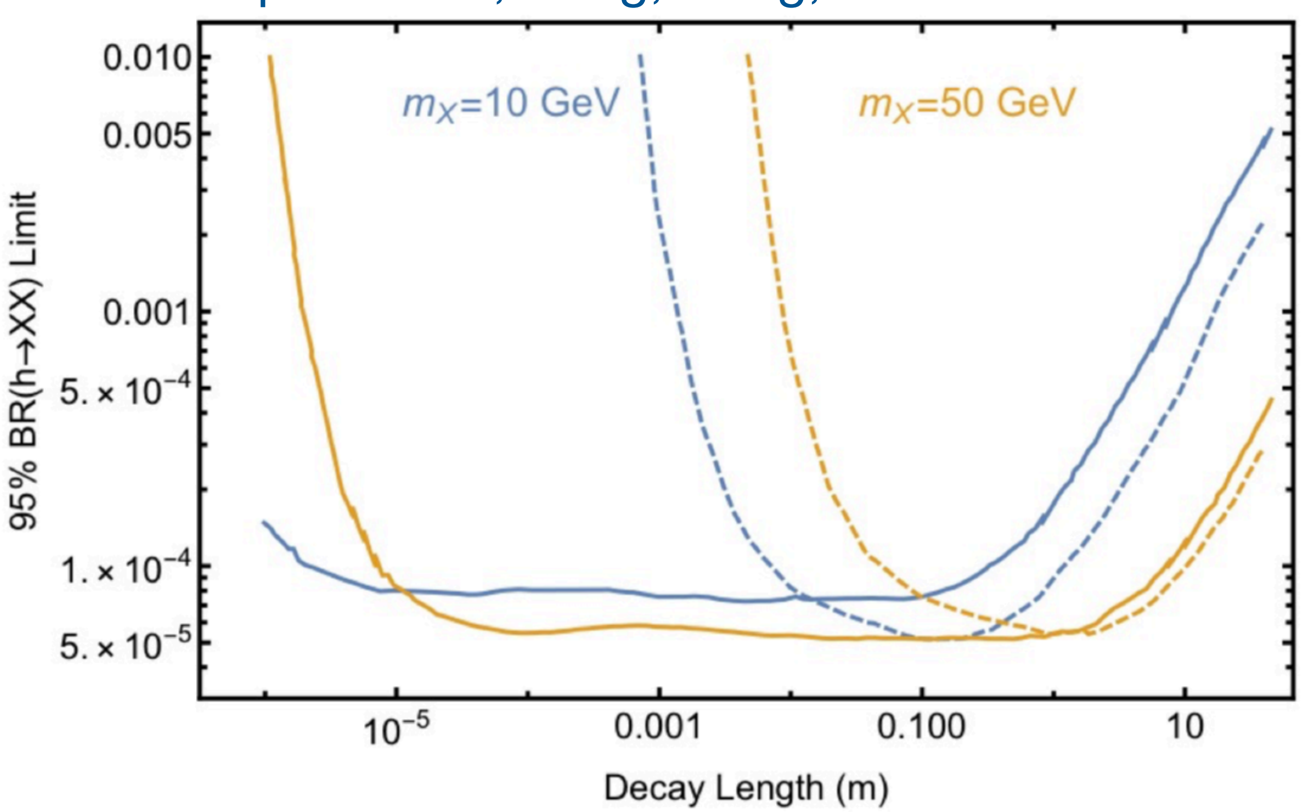


Light singlets

- If singlet is light, it can be produced in Higgs decays, indep. of mixing
- Light scalar: mostly hadronic decays, long lifetime
  - dedicated triggers and searches for light particles

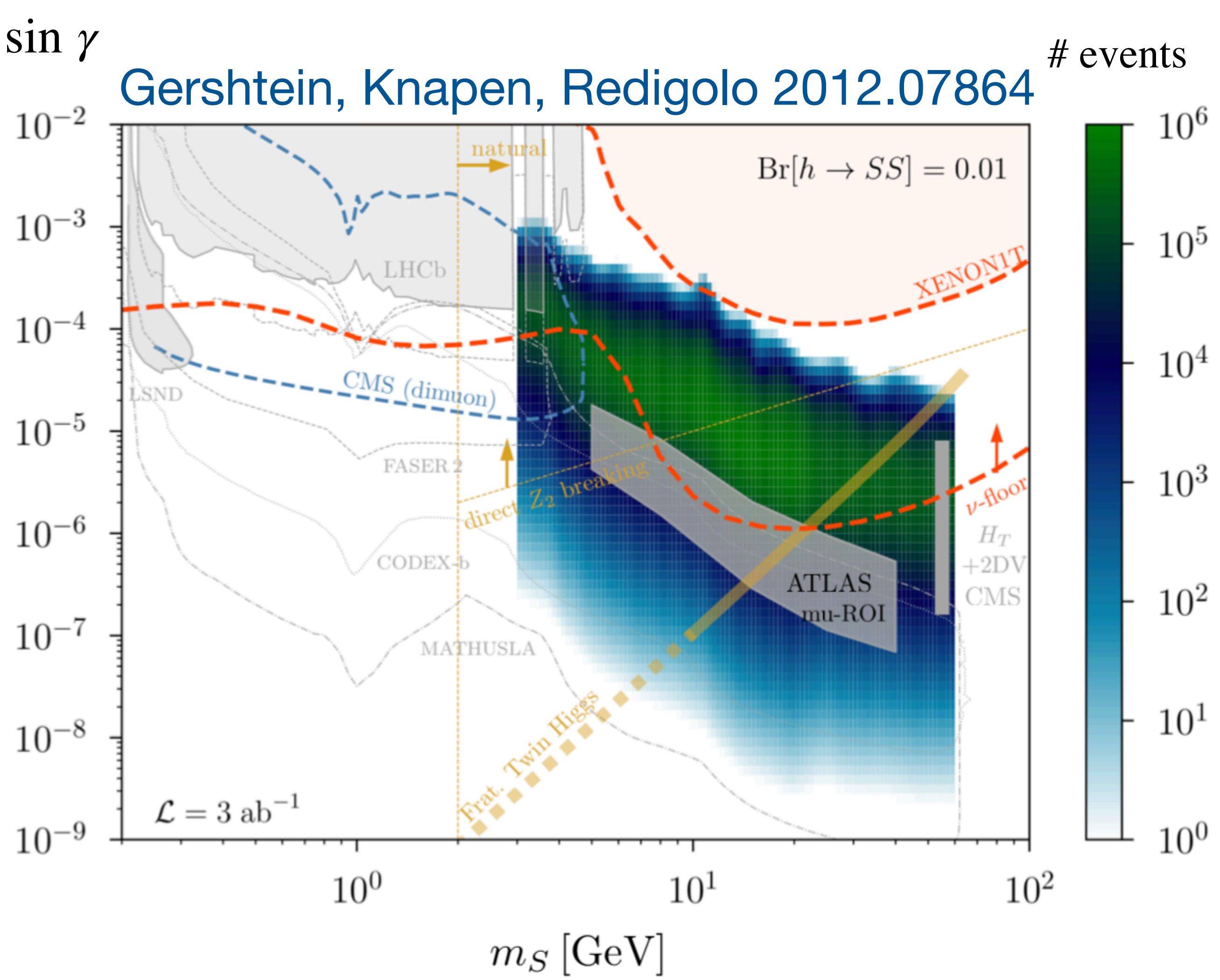
FCC-ee:

Alipour-Fard, Craig, Jiang, Koren 1812.05588



LHC:

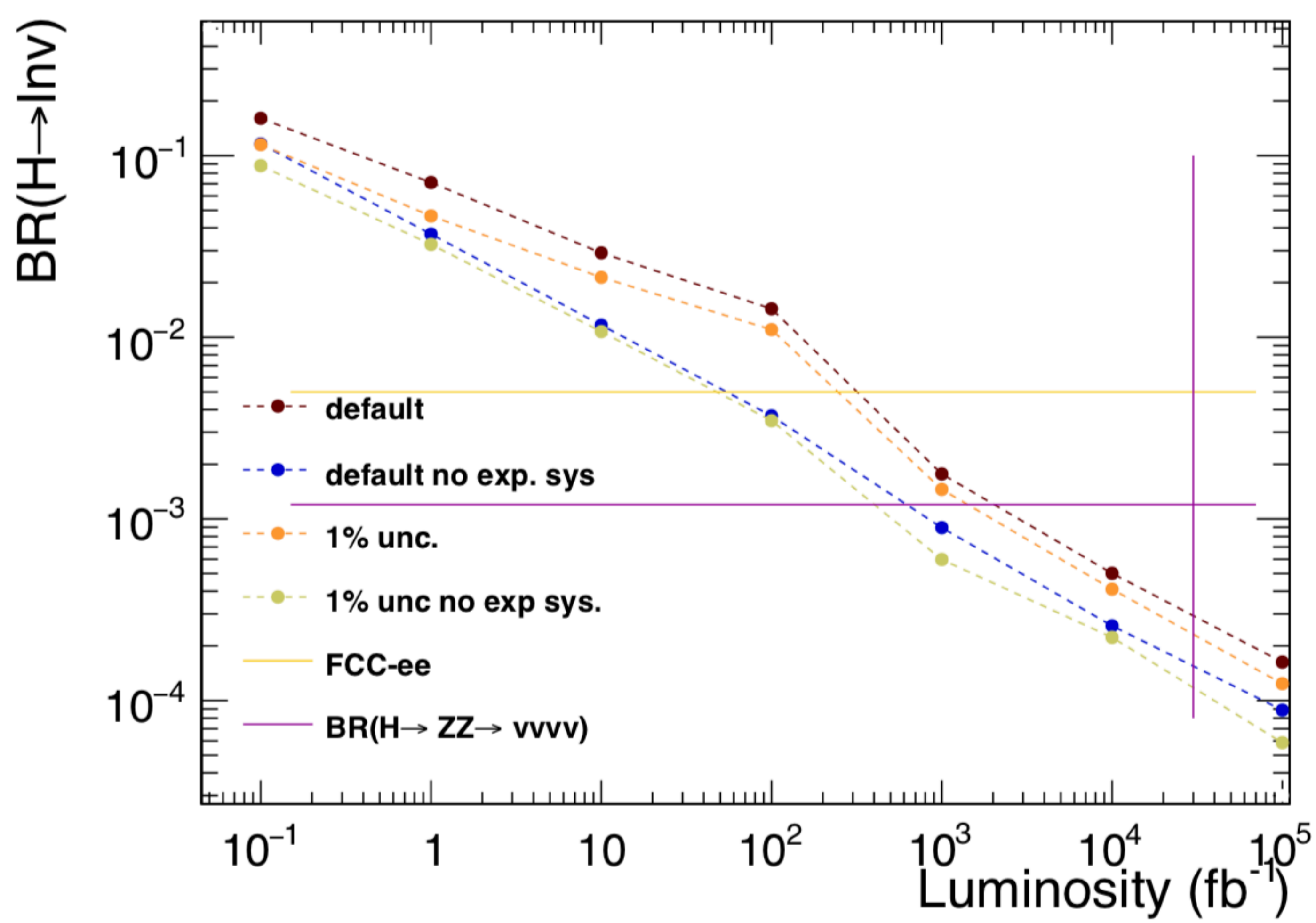
Gershtein, Knapen, Redigolo 2012.07864

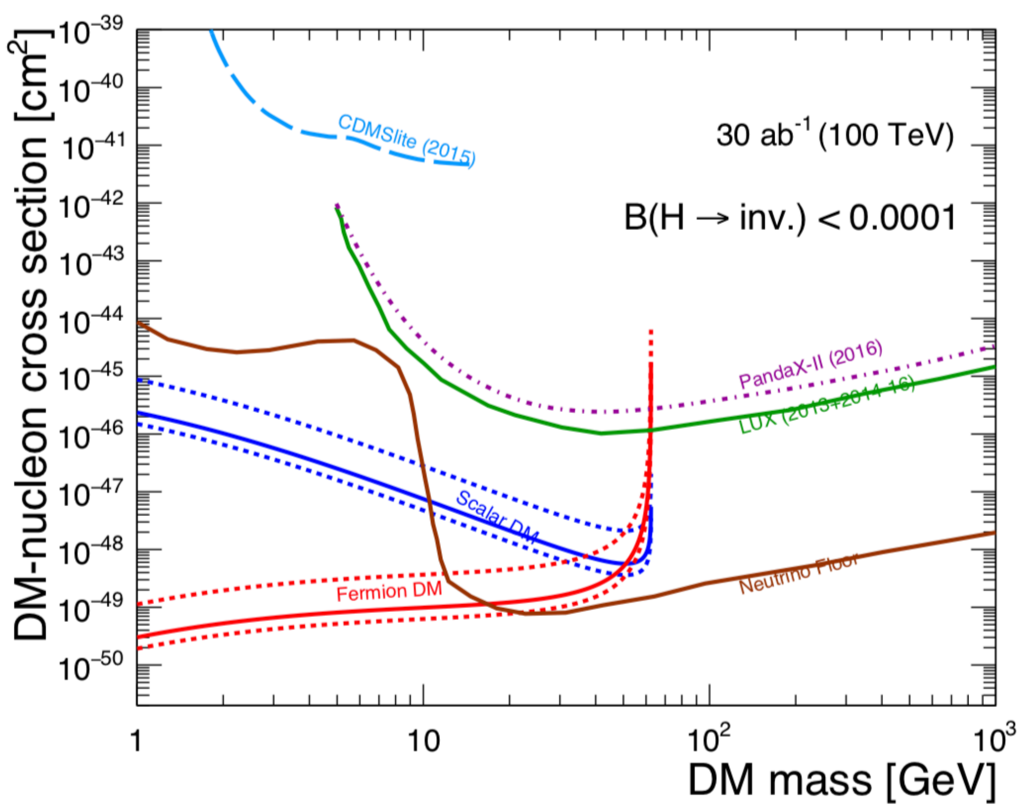


Light singlets: invisible Higgs

- In the zero-mixing limit the singlet is invisible
  - BR(h → inv) < few × 10^{-3} (missing mass @ FCC-ee)
  - BR(h → inv) < few × 10^{-4} from Higgs p_T distribution in VBF or ttH @ FCC-hh

CERN-ACC-2018-0045





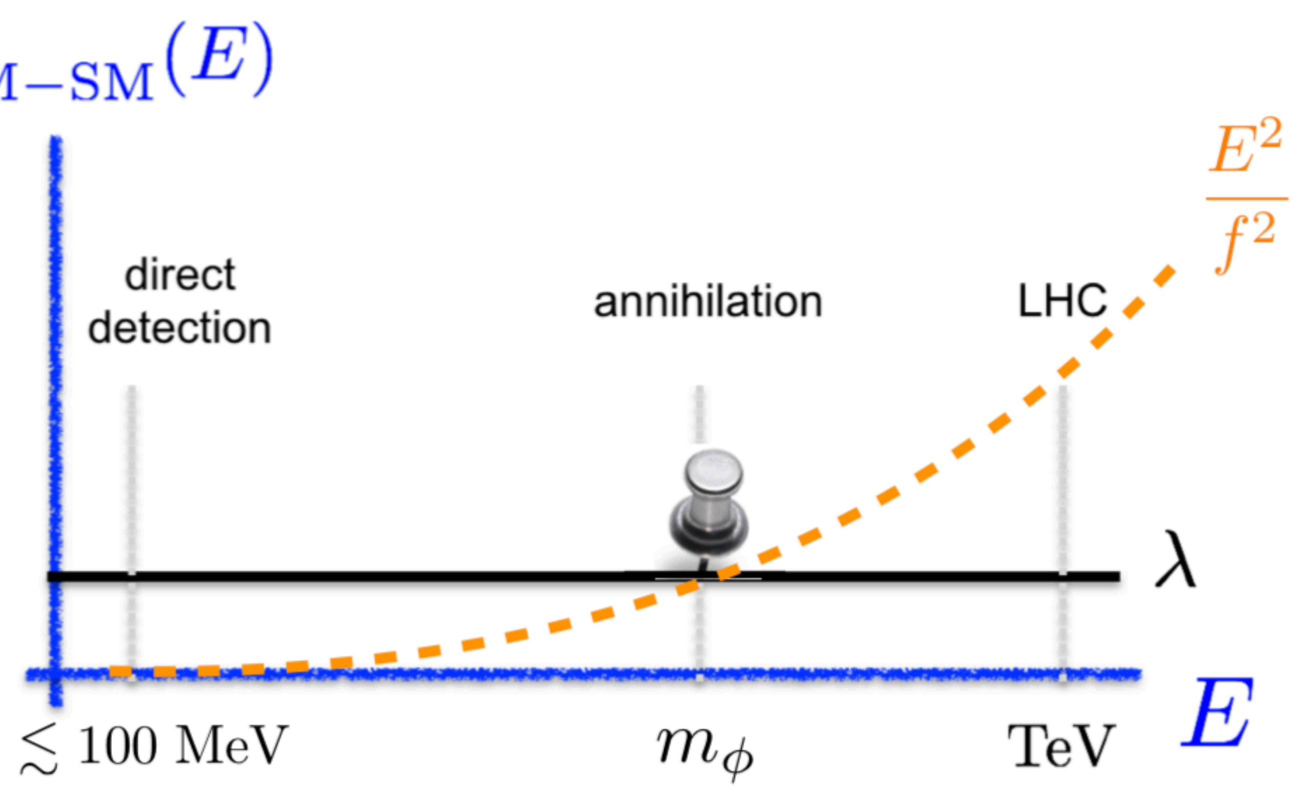
- No Higgs-singlet mixing: singlet is stable, can be identified with DM

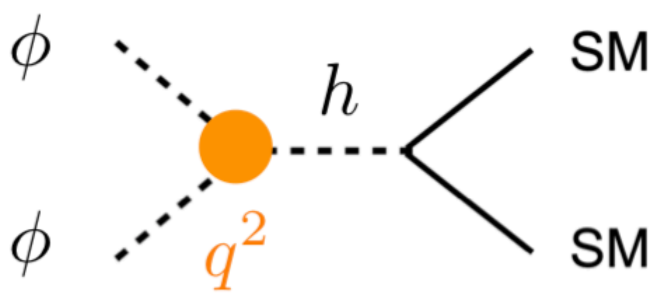
  stronger than Direct Detection prospects for low mass DM

Derivative Higgs portal

A viable alternative:

$$\mathcal{L} \supset \frac{1}{2f^2}\partial_\mu(\phi^2)\partial^\mu(H^\dagger H)$$





annihilation $q^2 \sim m^2_{\rm DM}$

scattering

$q^2 \sim m^2_{\rm DM} v^2_{\rm DM}$

$v_{\rm DM} \sim 10^{-3}$

For the derivative Higgs portal,

direct detection is automatically suppressed

E. Salvioni @ Higgs2022

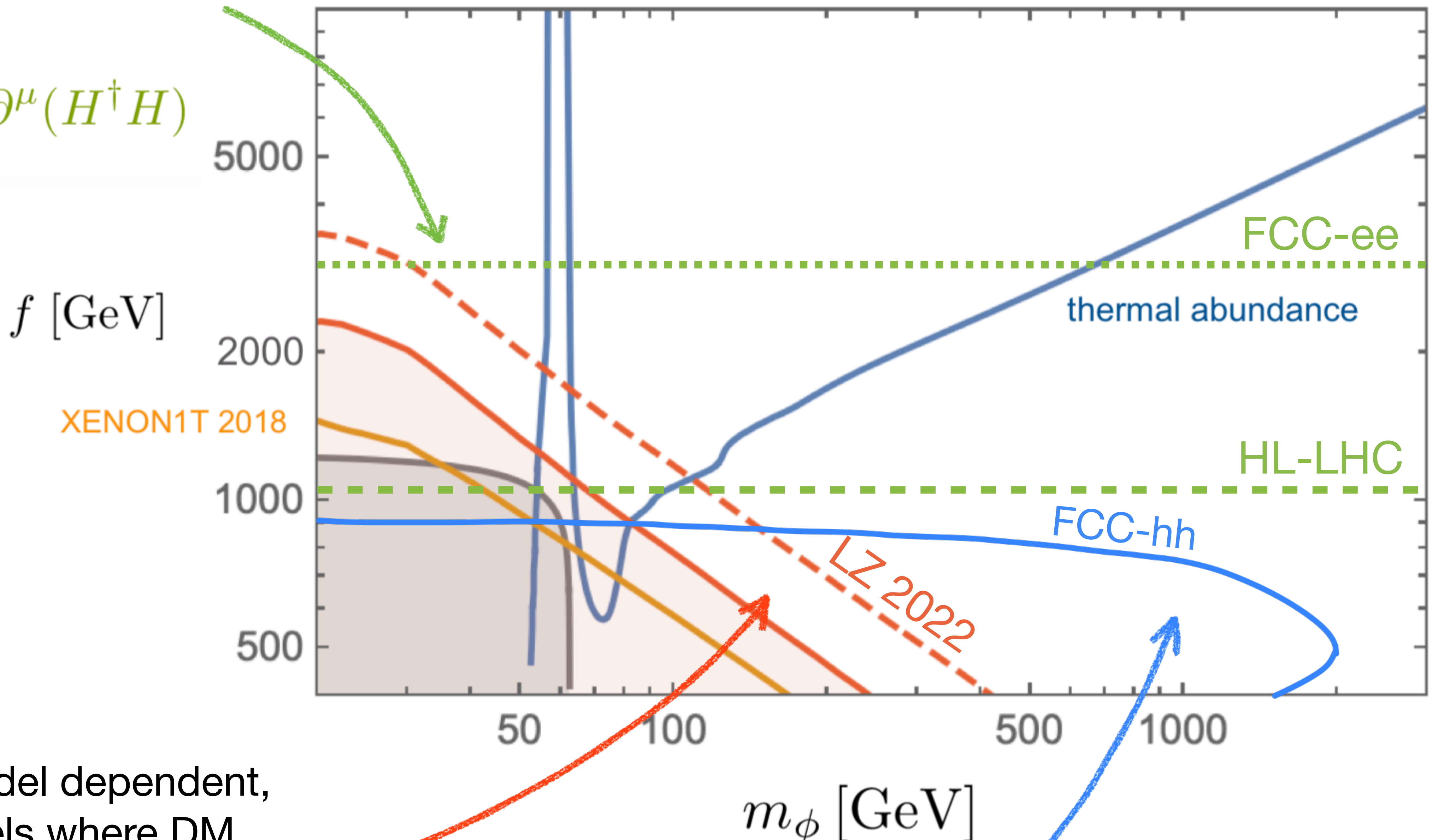
Ruhdorfer, Salvioni, Weiler 1910.04170

Derivative Higgs portal

Higgs couplings: model dependent, e.g. composite models where DM and Higgs are pNGB

$$\mathcal{L} \supset \frac{1}{2f^2}\partial_\mu (H^\dagger H)\partial^\mu (H^\dagger H)$$

Ruhdorfer, Salvioni, Weiler 1910.04170

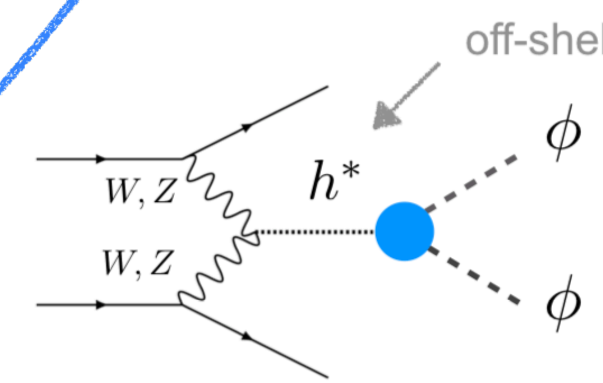


Direct Detection: model dependent, e.g. composite models where DM mass arises from down quark loops

$$\mathcal{L} \supset y_d \bar{q}_L H d_R \frac{\phi^2}{2f^2}$$

Vector boson fusion

$$\mathcal{L} \supset \frac{1}{2f^2}\partial_\mu (\phi^2)\partial^\mu (H^\dagger H)$$

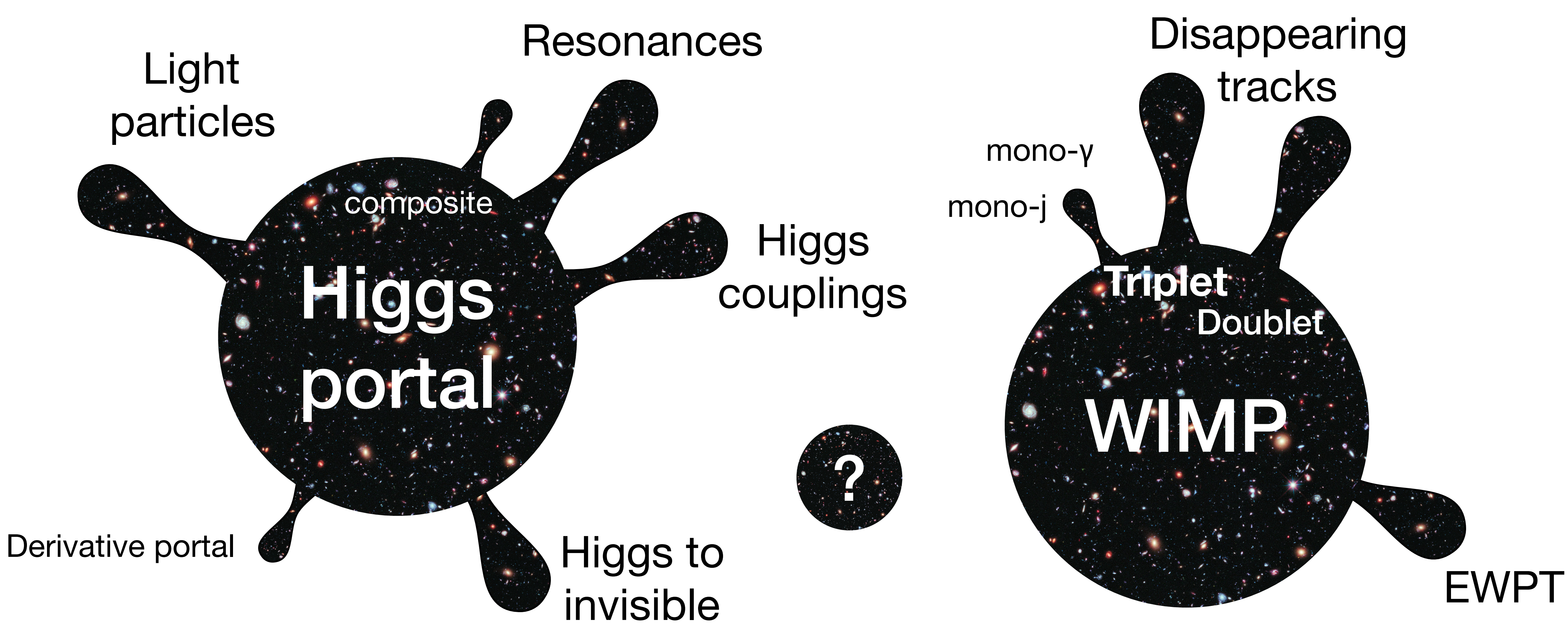


Summary

Searches for motivated DM candidates are difficult (EW states, singlets…)

Many viable models… Not everything can be probed at FCC.

High energy + precision: excellent prospects in many interesting cases.



Complementary information will come from ID and DD in the coming years