Feebly Interacting Particles (FIPs):

Conclusions

Outline of the items open for discussion

1. Dark Matter in the MeV-GeV range:
    - why in this range
    - current theoretical-phenomenological approach
    - current experimental results
    - future prospects

2. Heavy Neutral Leptons below EW scale
    - why in this range
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What do we know about MeV-GeV DM?

1. DM has to interact with SM particles:

Interactions with SM particles are necessary to provide mechanisms able to deplete the DM abundance in the early Universe to the levels known today in agreement with observations in standard cosmology.

1. To reproduce DM abundance sub-GeV DM has to interact with SM world via new forces

- to evade the Lee-Weinberg bound valid if interactions occur via weak force.

2. DM & mediators must be SM-neutral

- if the carry ew quantum numbers they would have been already observed at LEP, Tevatron and LHC

3. For s-wave annihilating DM, measurements of the CMB rule out $m_{DM} < o(10)$ GeV

Other viable options:

- DM annihilated in p-wave (hence the σv is v^2 suppressed, hence smaller at low-T (low-v)).
- Presence of a mechanism that cuts off late time annihilation, as eg. mass splitting in the $\chi - \bar{\chi}$ system
- other

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New IR degrees of freedom = light (e.g. sub-GeV) BSM states

Typical BSM model-independent approach is to include all possible BSM operators once very heavy new physics is integrated out:

$L_{SM+BSM} = -\, m_H^2\, (H^+_{SM} H_{SM}) +$ all dim 4 terms $(A_{SM}, y_{SM}, H_{SM}) +$
(W.coeff. $/L^2$) × Dim 6 etc $(A_{SM}, y_{SM}, H_{SM}) + \ldots$
all lowest dimension portals $(A_{SM}, y_{SM}, H, A_{DS}, y_{DS}, H_{DS})$ × portal couplings
\+ dark sector interactions (A_{DS}, y_{DS}, H_{DS})

SM = Standard Model
DS – Dark Sector

Golden rule of any EFT approach: first look at low-dim operators !

The Portal Framework

Expand the SM with the minimal set of operators of lowest dimension gauge-invariant and renormalizable (all but the pseudo-scalar).
This guarantees that the theoretical structure of the SM is preserved and any NP is just a simple (natural?) extension of what we already know..

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

They are representative of broad classes of models:
Each may predict distinct texture of New Physics interactions.

Direct annihilation: Vector mediator DM-SM:

Accelerator-based experiments

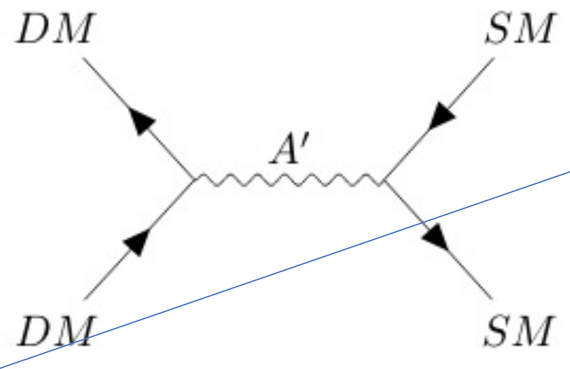
Production of DM at accelerators
(via SM (electron/proton/..) particles)

$$< \sigma v > \sim \alpha_D \varepsilon^2 \alpha \times \frac{m_{\rm DM}^2}{m_{A'}^4} \times m_{\rm DM}^2 \times \frac{1}{m_{\rm DM}^2}$$

y variable

DM Direct detection experiments

DM scattering with e/protons



$$\sigma(\chi f \to \chi f) \simeq \frac{16\pi\, \alpha_{\rm em}\, \epsilon^2\, \alpha_D\, \mu_{\chi f}^2}{(q^2 + m_{A'}^2)^2} \,,$$

Astroparticle, cosmology

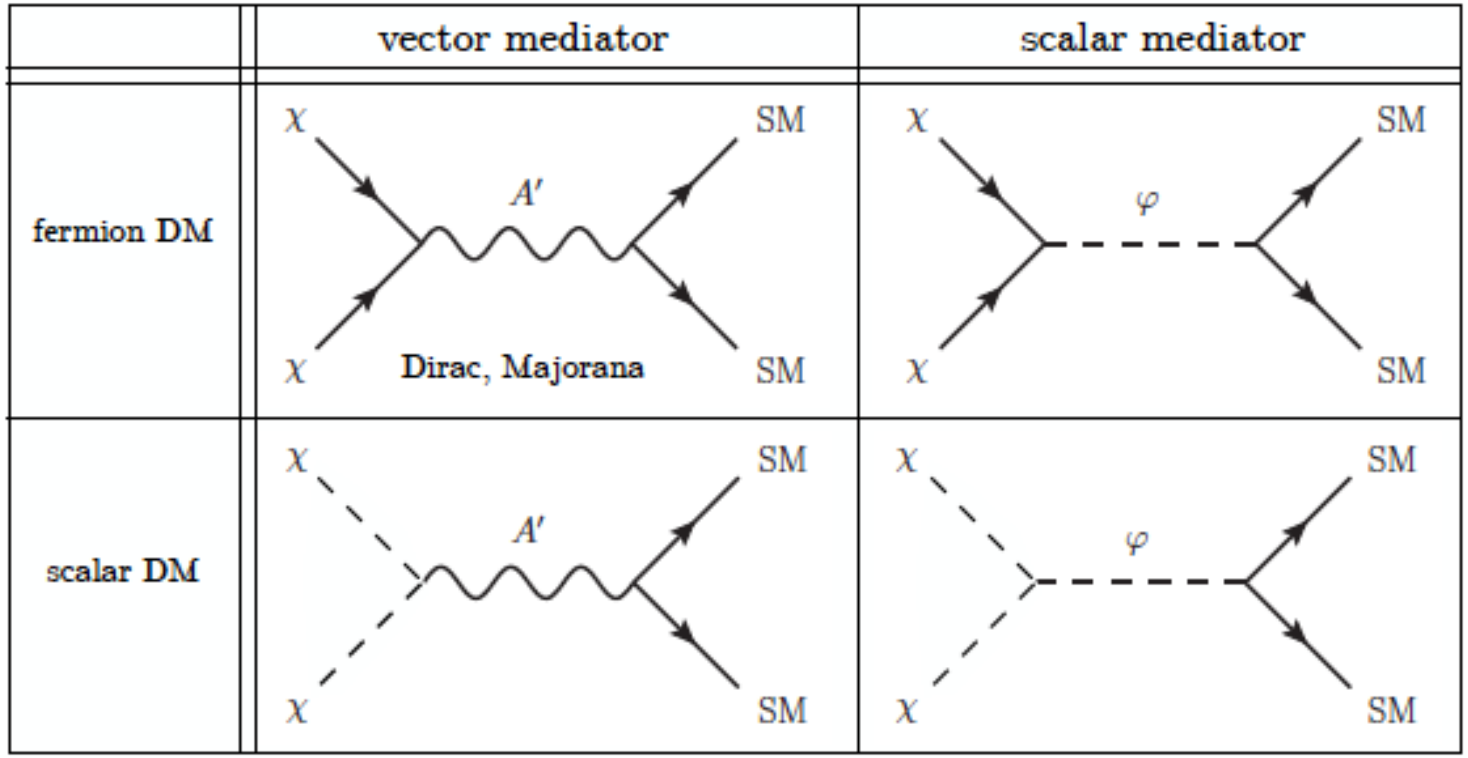
Direct DM annihilation
(main process to get the thermal relic abundance)

$$\Omega_{\rm DM} h^2 \sim \frac{10^9\ {\rm GeV}^{-1}}{M_{\rm pl}} \frac{1}{\langle \sigma v \rangle}$$

Within this framework we can interpret results from different fields.

Direct annihilation: Vector & Scalar mediators DM-SM:

different combinations are allowed in p- and s-wave.



Different phenomenology depending on the spin of DM and mediator

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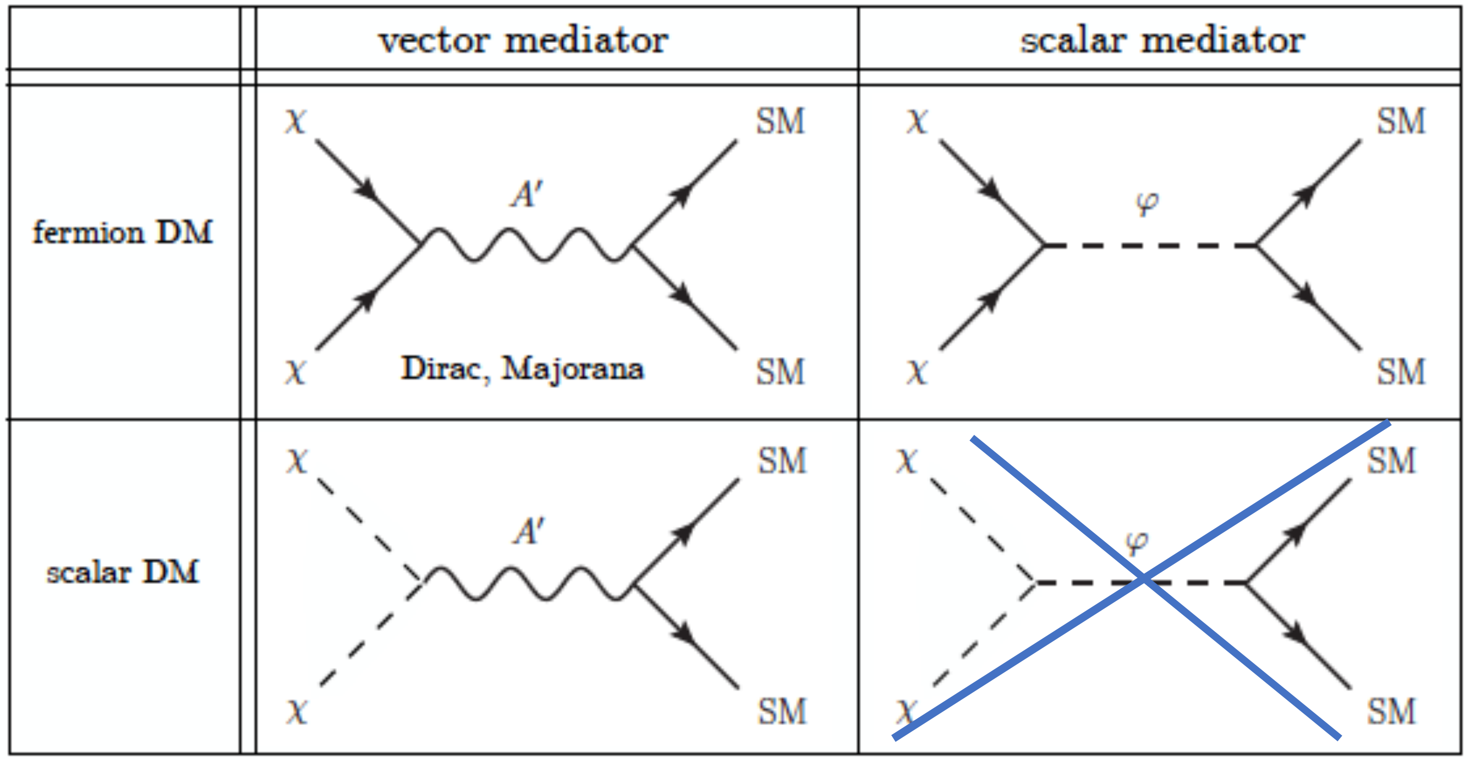

DM below 10 GeV annihilating in s-wave is excluded by CMB

Direct annihilation: Vector & Scalar mediators DM-SM:

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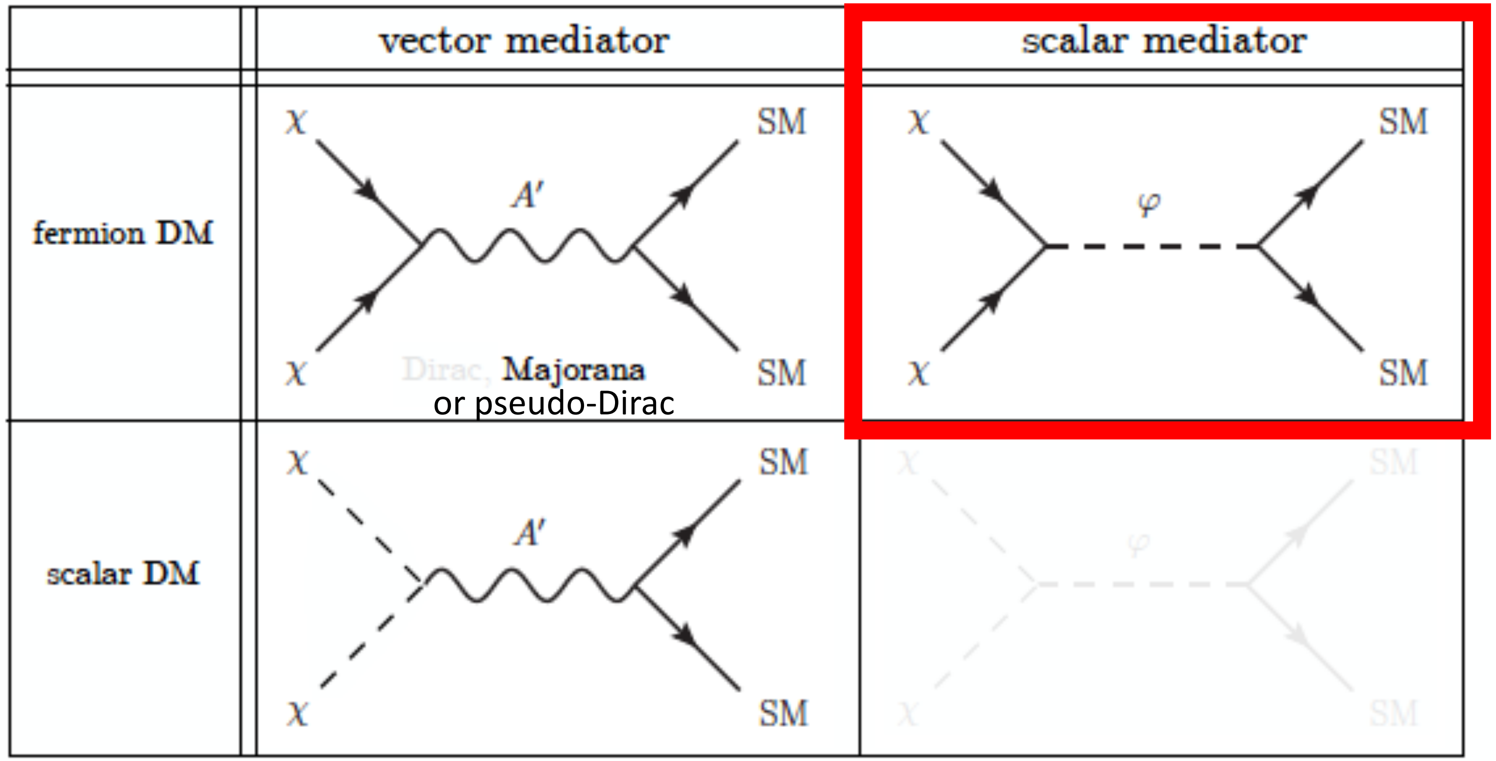
p-wave: $\sigma v \propto v^2$



Fermionic DM with a Scalar mediator

Berlin, FIPs 2020

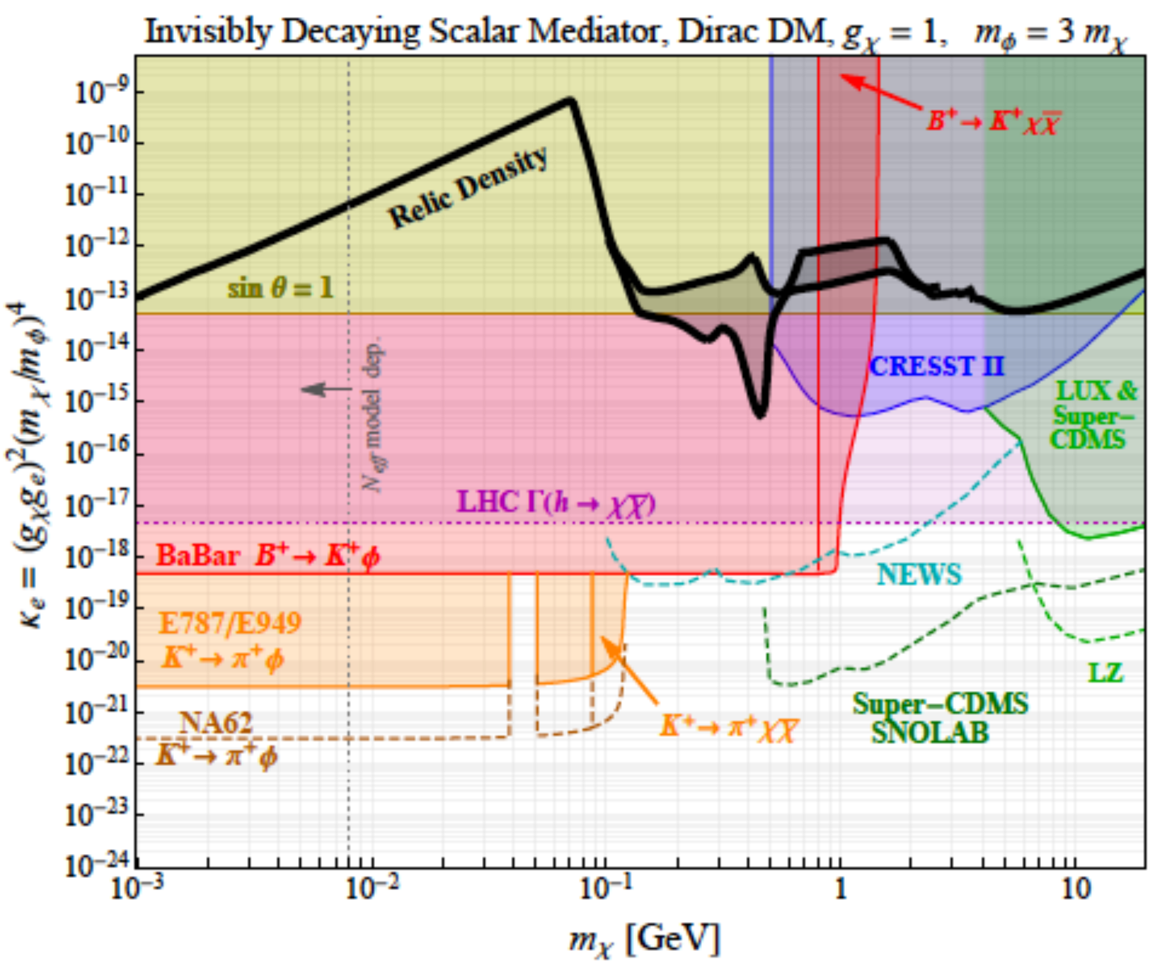
(non-relativistic) annihilation cross-section

$$\sigma v_{\mathrm{rel.}}(\chi\chi \to f\bar{f}) = \frac{g_\chi^2 g_f^2 m_\chi^2 v_{\mathrm{rel.}}^2}{8\pi(m_\phi^2 - 4m_\chi^2)^2} \propto g_\chi^2 g_f^2 \left(\frac{m_\chi}{m_\phi}\right)^4 \frac{1}{m_\chi^2}$$

Light Fermionic DM and scalar mediator:

experimental bounds and projections

G. Krnajic arXiv: 1512.04119



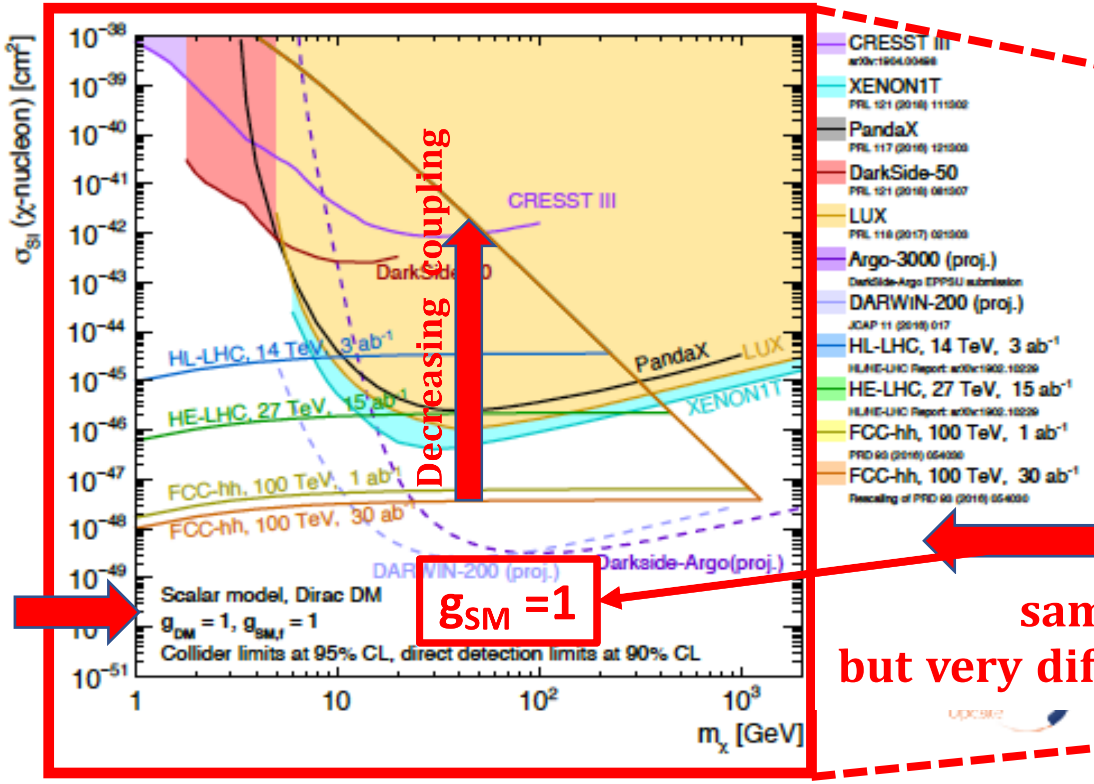
In case of scalar mediator and Dirac DM, for s-channel, p-wave annihilation, the DM thermal relic bound is saturated by low-energy and DD experiments below 10 GeV

Light Fermionic Dark Matter with scalar mediator

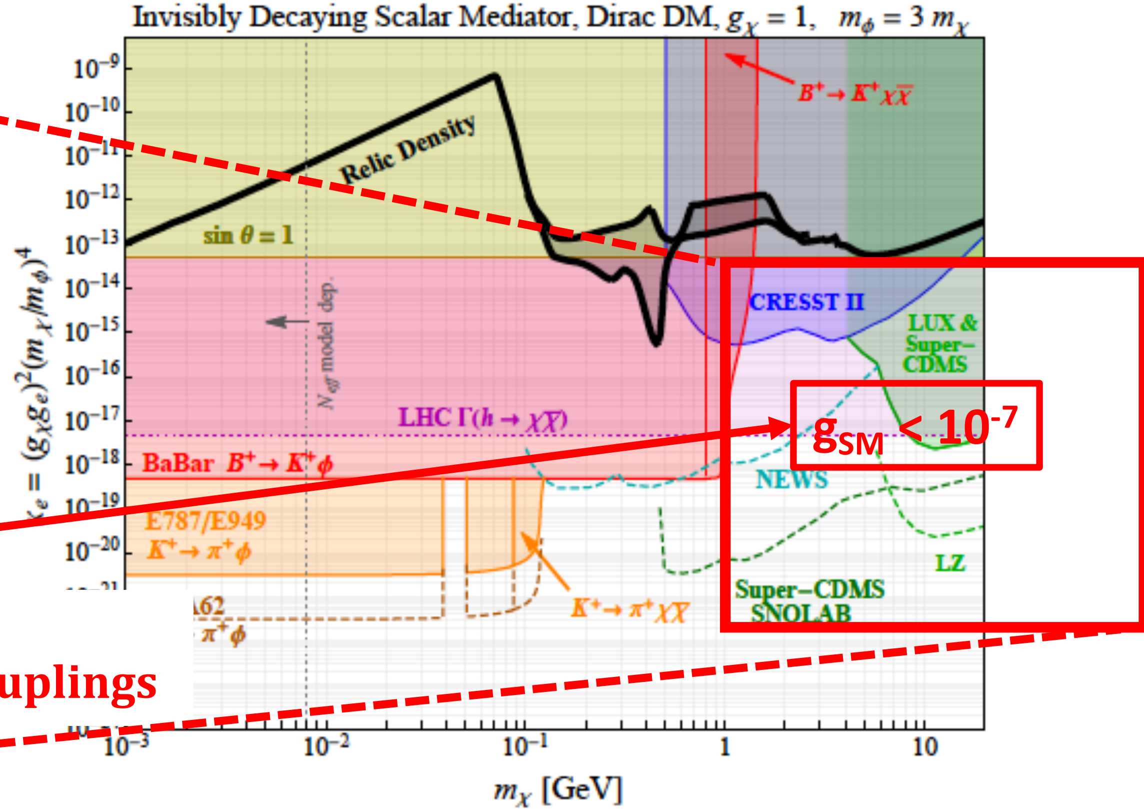
DM Direct Detection vs Colliders vs Extracted beams

Specific model: SM SM ⟶ Dark Scalar ⟶ DM DM

Physics Briefing Book, 1910.11775, Fig.9.4, p.150



Phys.Rev. D94 (2016) no.7, 073009 arXiv: 1512.04119

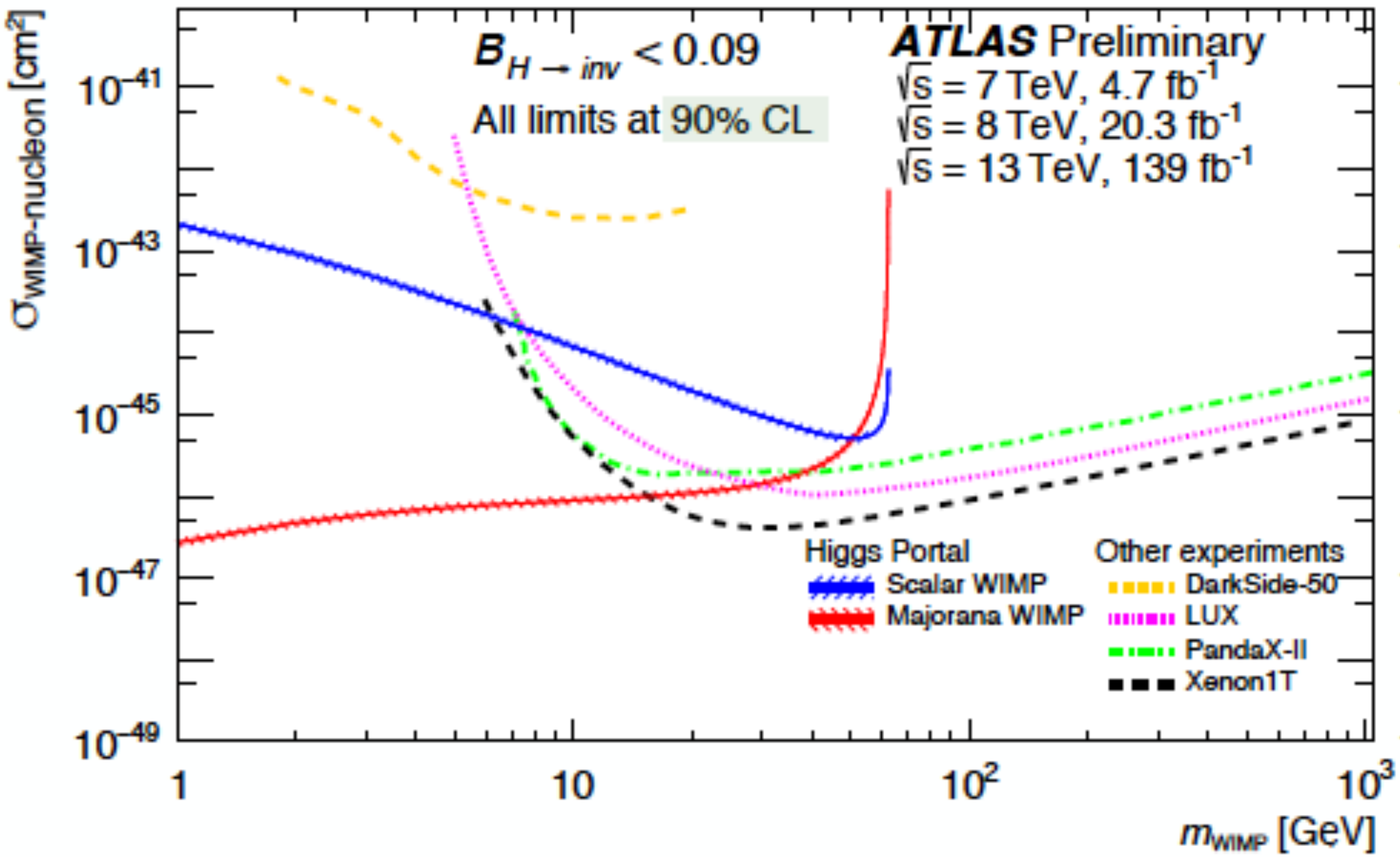


same model
but very different couplings

$$\sigma_{SI} \simeq 6.9 \times 10^{-43}\ \text{cm}^2 \cdot \left(\frac{g_q g_{DM}}{1}\right)^2 \left(\frac{125\ \text{GeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \text{GeV}}\right)^2$$

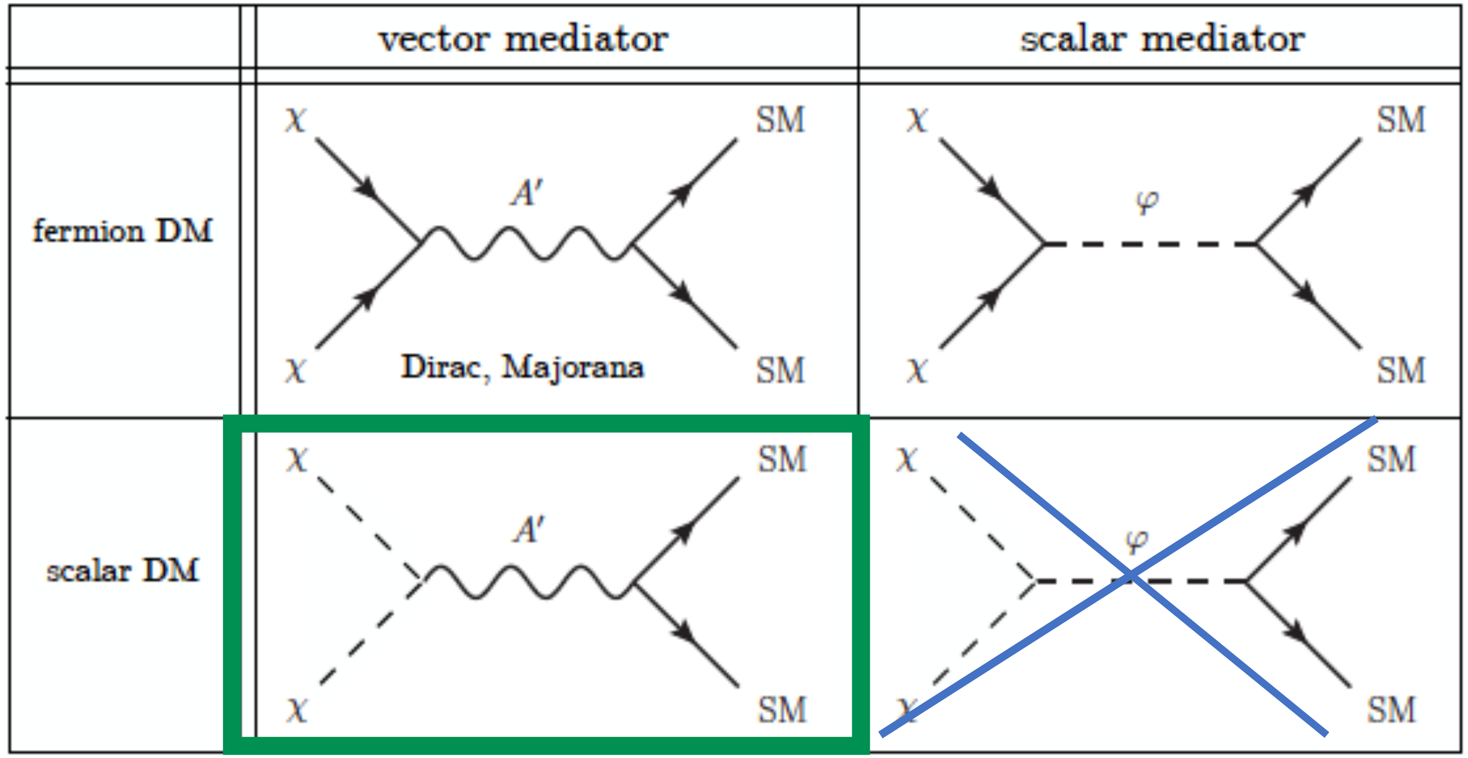
It would be important to test LHC sensitivity to much smaller couplings for mass ranges below 10 GeV

Search for Dark Matter through the invisible Higgs width



Very powerful method used at the LHC. Of course this is valid only if DM is Higgs-mediated.

Direct annihilation: Vector & Scalar mediators DM-SM:
different combinations are allowed in p- and s-wave.



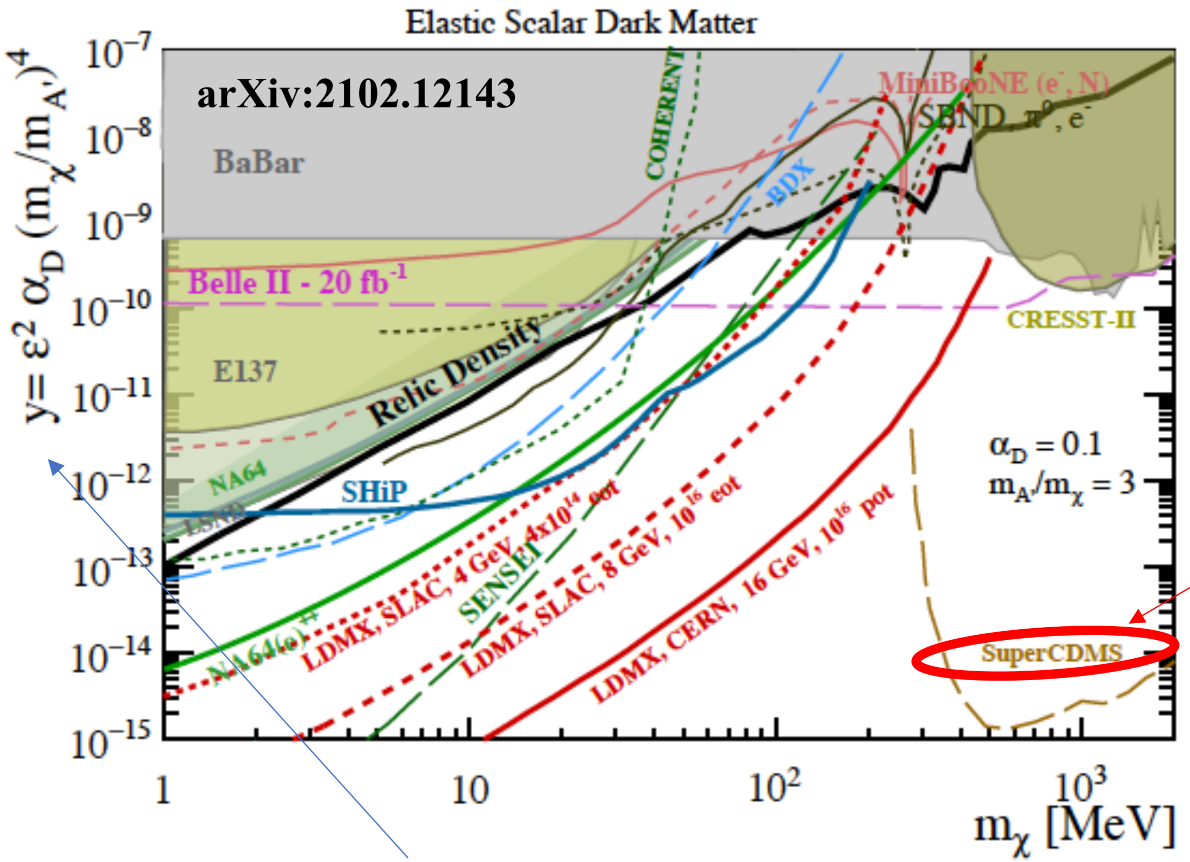
But p-wave ($\sigma v \sim v^2$) is compatible with cosmology (the annihilation rate is smaller at low T as the velocity redshifts with Hubble expansion). However this could be a problem for DD:

MeV scale DM: Kin. Energy = m v^2/2 ~ (10-3)^2 MeV ~ eV (below the ionization threshold! For Xe is 13 eV…)

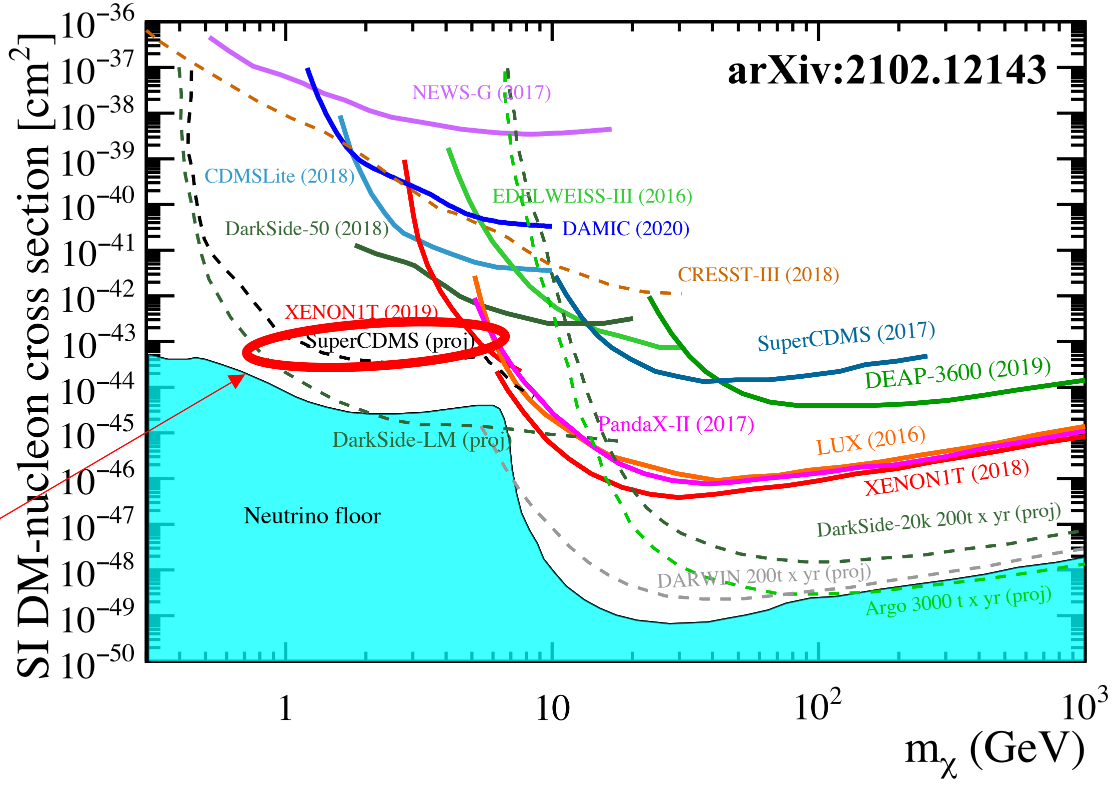
Scalar DM with Vector mediator

(a clear, predictive model to compare DD and accelerator-based experiment results).

Accelerator based:



Direct detection:



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$$\sigma(\chi f \to \chi f) \simeq \frac{16\pi\, \alpha_{\rm em}\, \epsilon^2\, \alpha_D\, \mu_{\chi f}^2}{(q^2 + m_{A'}^2)^2}\,,$$

NA64, DAMIC, XENON-nTon, SHiP, ….

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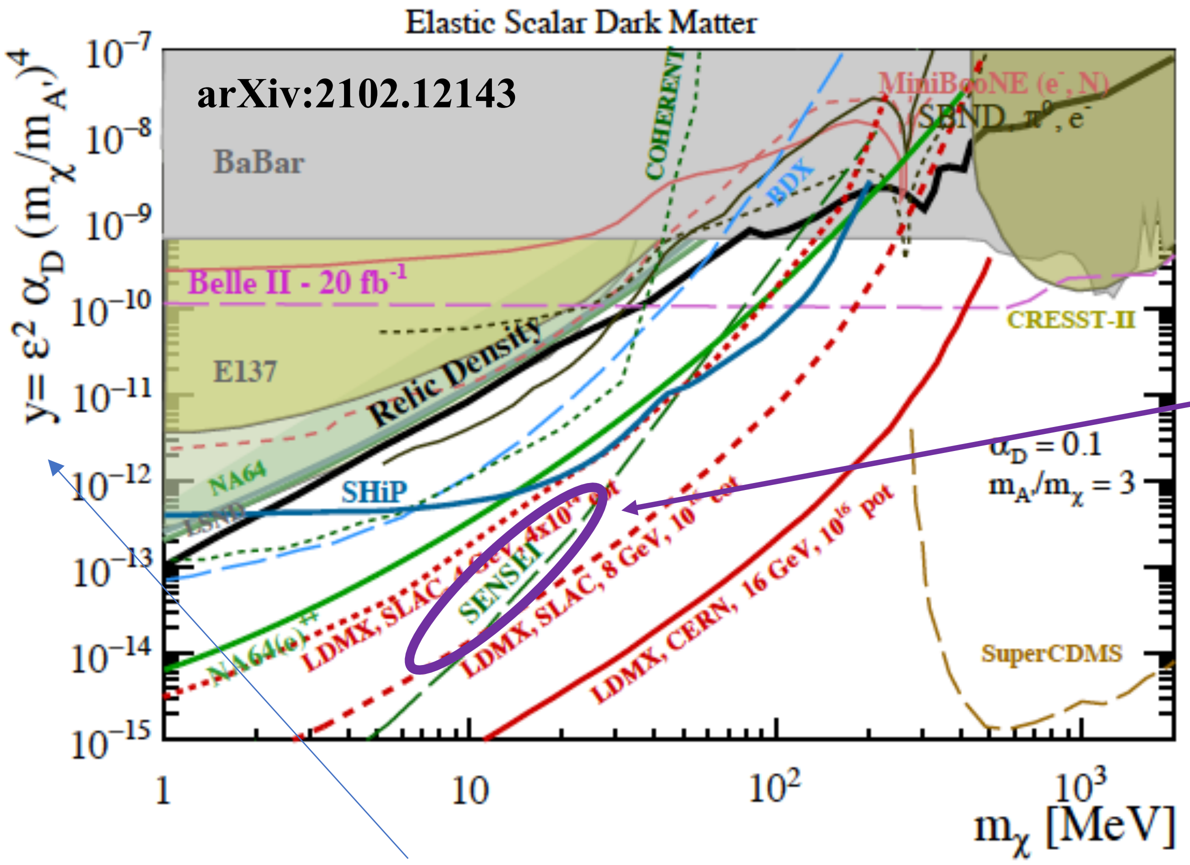

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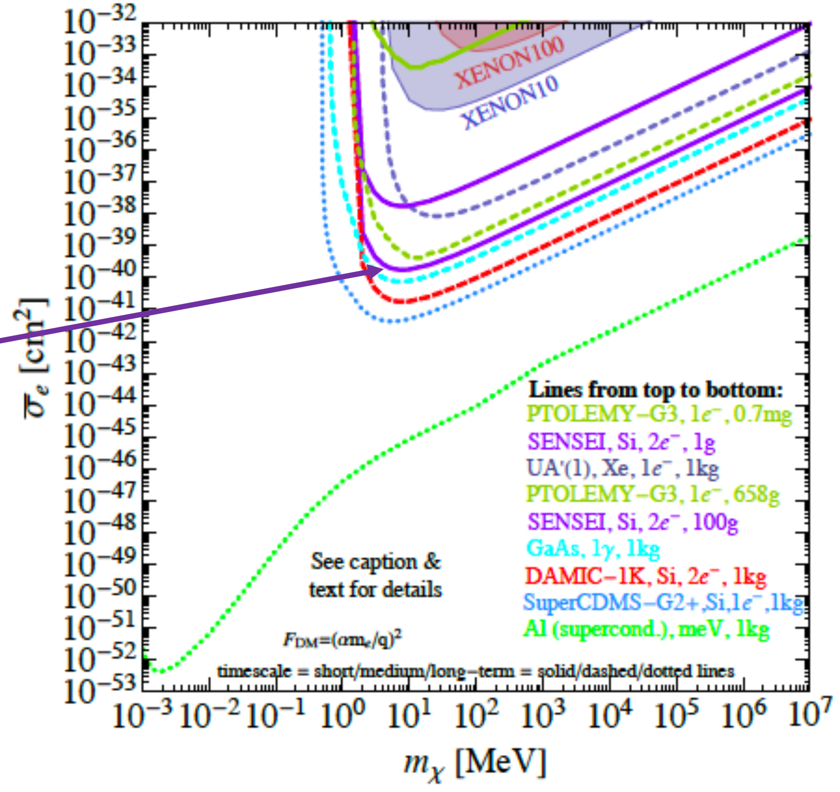

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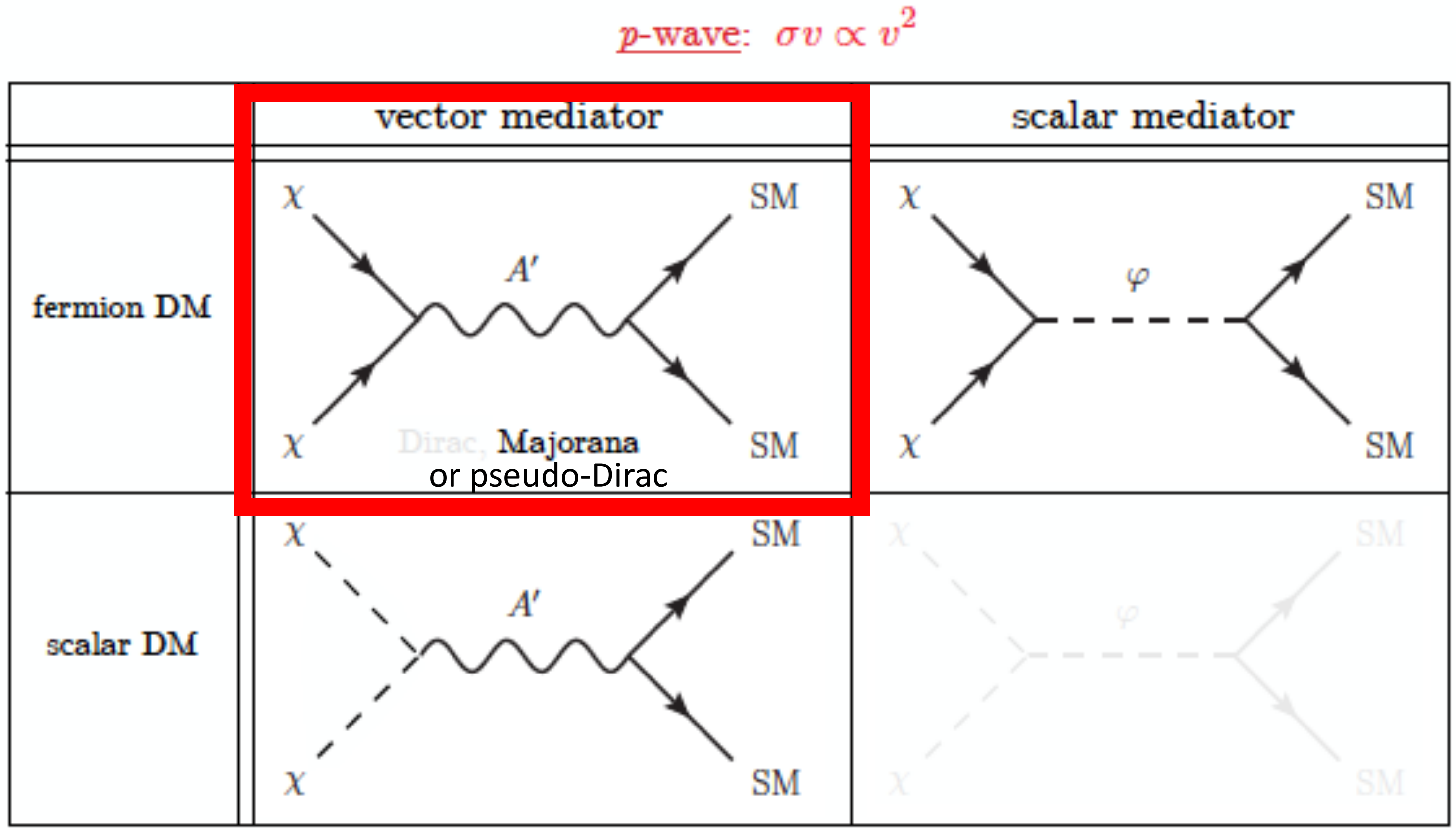
Direct annihilation: Vector & Scalar mediators DM-SM:

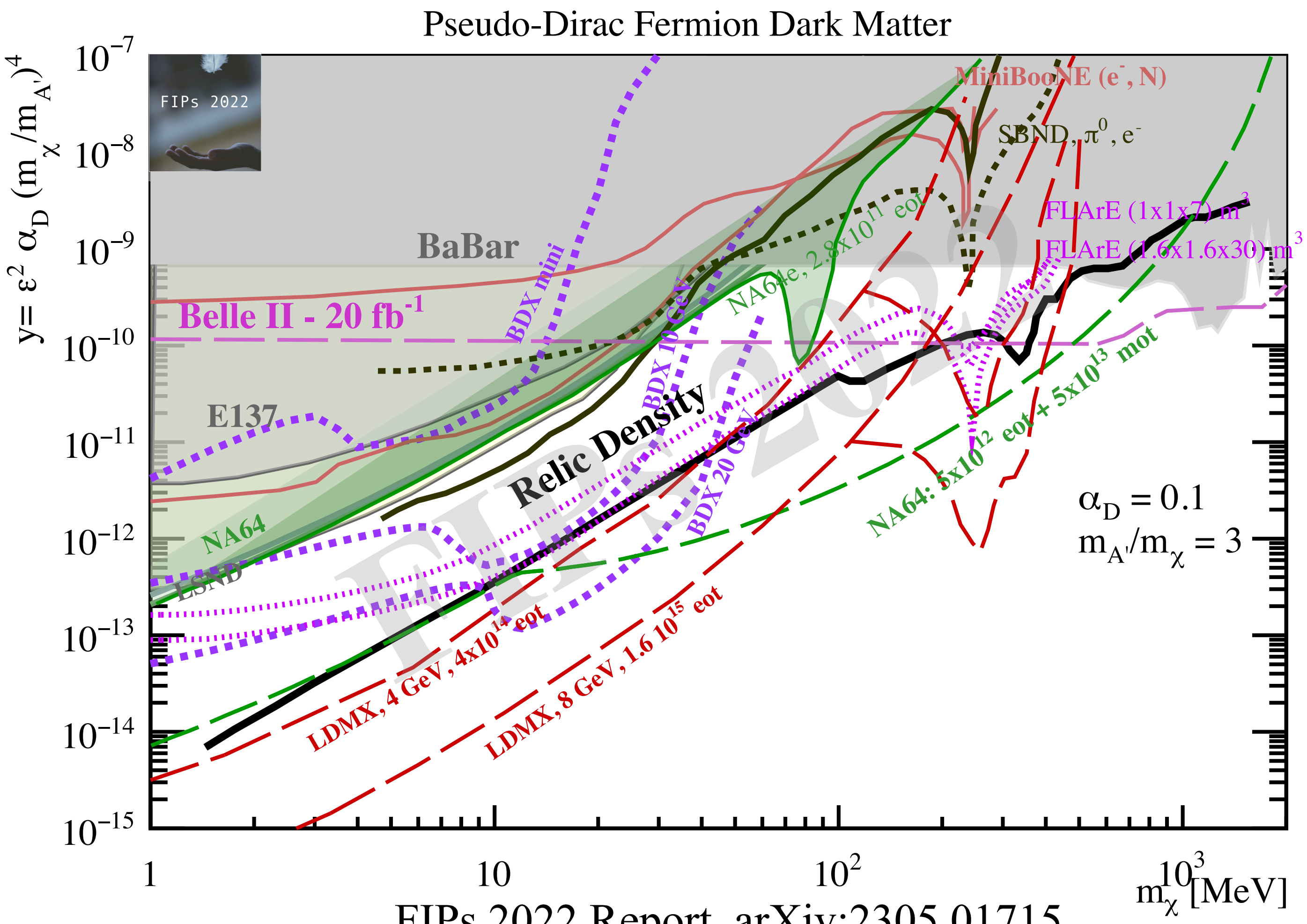
Berlin, FIPs 2020



Assume a pseudo-Dirac fermion with two components and Delta M = 10^{-3} M, M ~ MeV

During annihilation, for T = 0.1 m(chi) this Delta M does not play any role, but in the t-channel, for direct detection, the lightest particle can scatter into the heavier only if the kinetic energy transfer is larger than Delta M (keV) → hence the scattering can be quenched down.

Pseudo-Dirac DM with a Vector mediator



FIPs 2022 Report, arXiv:2305.01715

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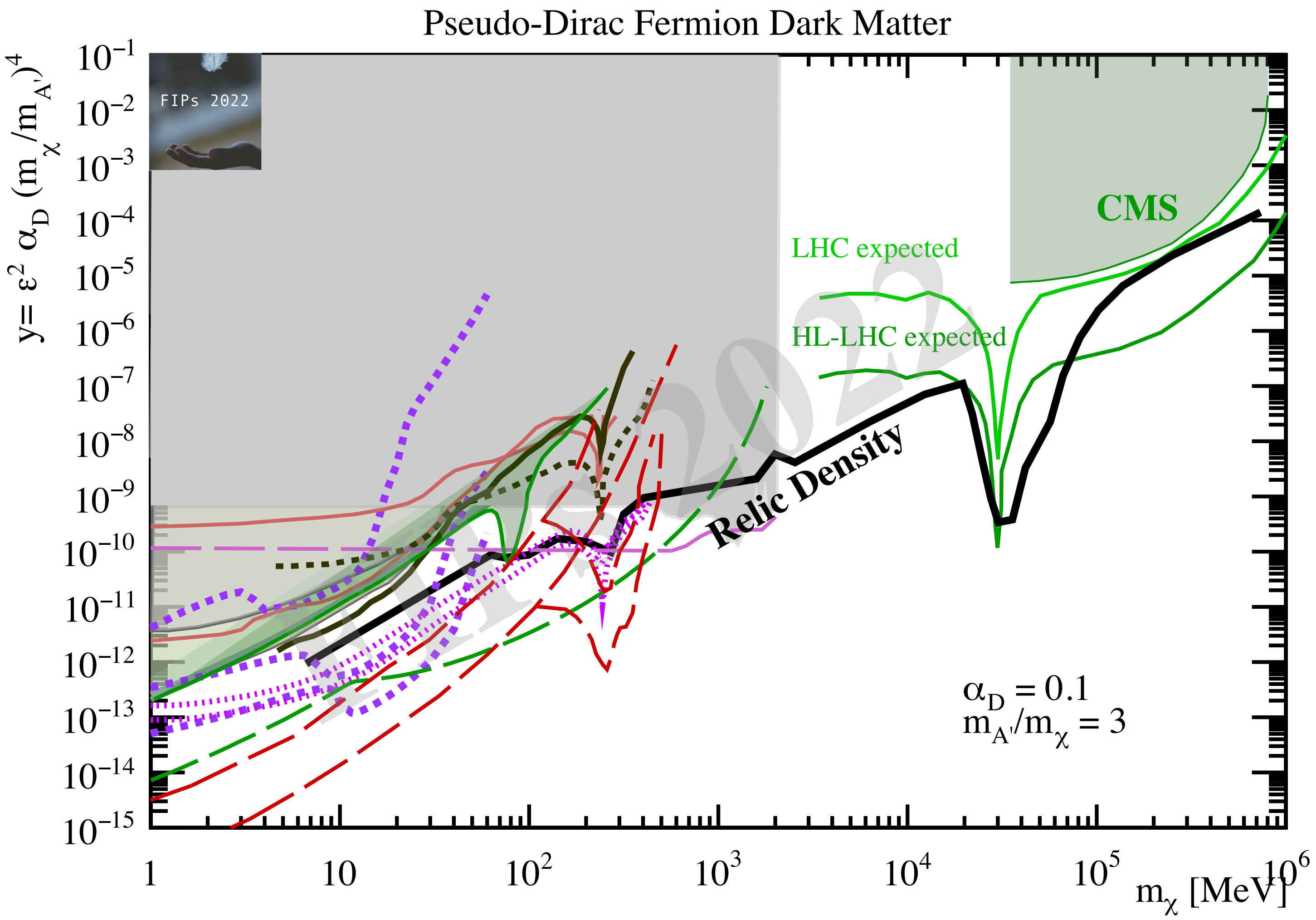
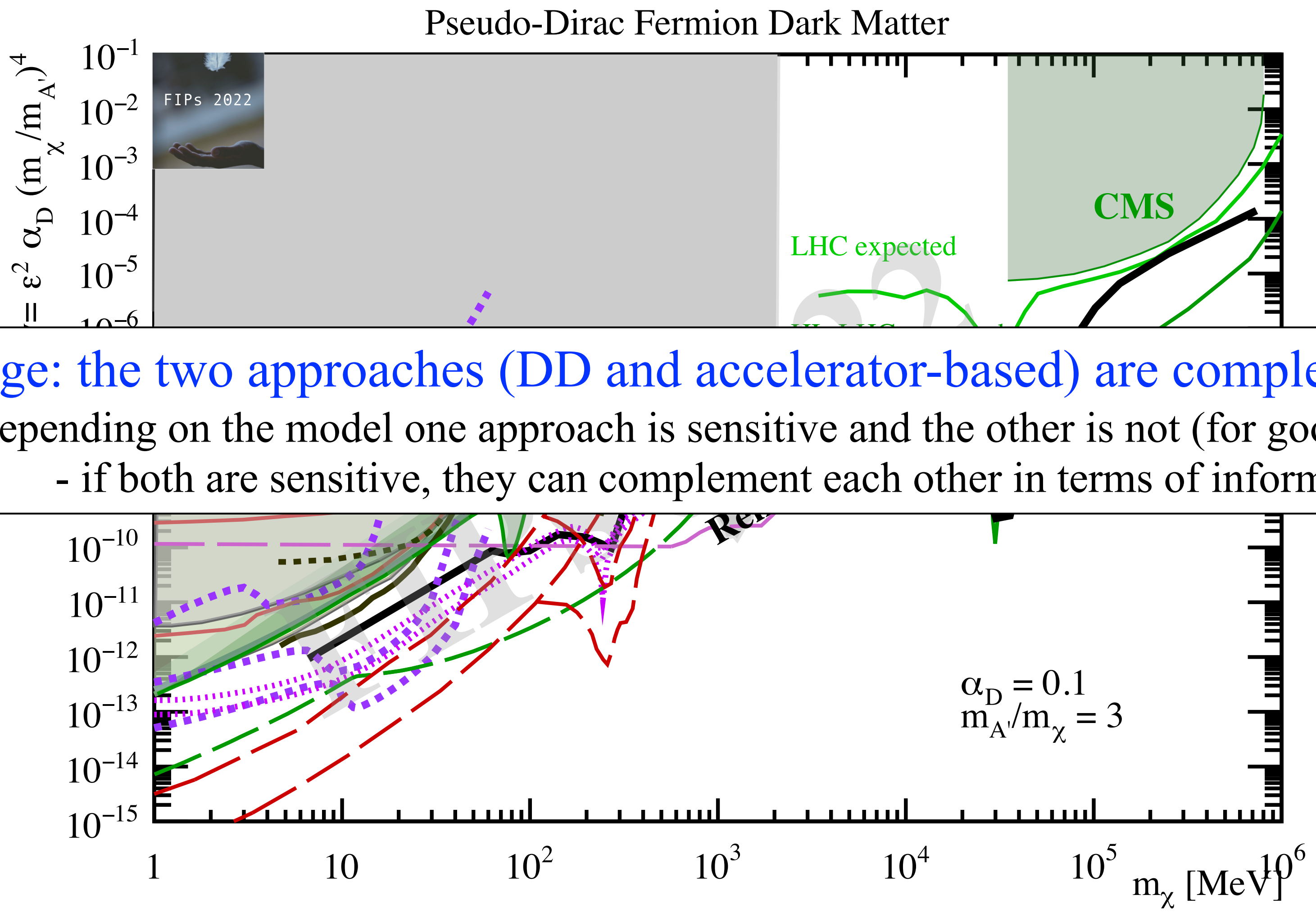


CMS, ATLAS, ….

Extension of sensitivity in the high mass region – LHC physics reach

Pseudo-Dirac DM with a Vector mediator



Take home message: the two approaches (DD and accelerator-based) are complementary and synergistic:

- depending on the model one approach is sensitive and the other is not (for good reasons).
- if both are sensitive, they can complement each other in terms of information.

CMS, ATLAS, ….

Extension of sensitivity in the high mass region – LHC physics reach

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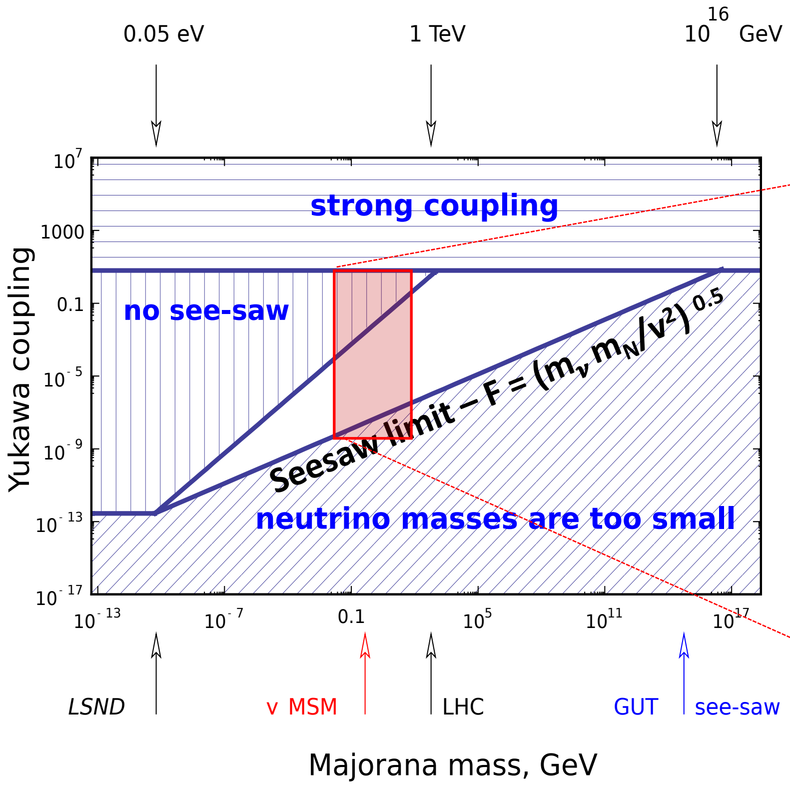
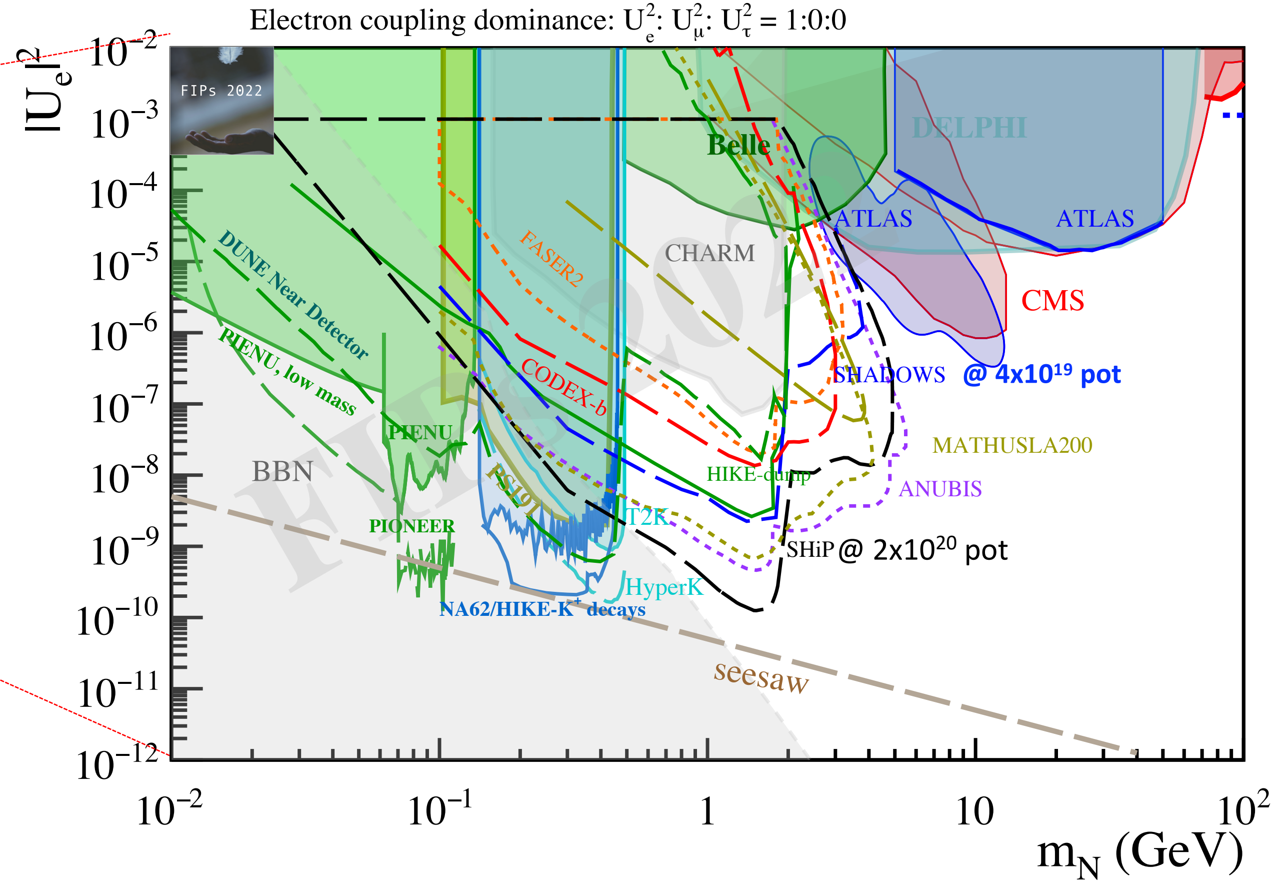
HNL searches: electron coupling



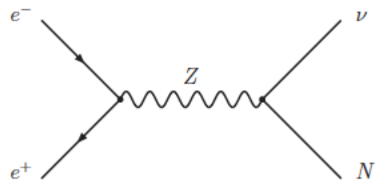


CMS, ATLAS, SHiP, HIKE, PIONEER,DUNE,HyperK….

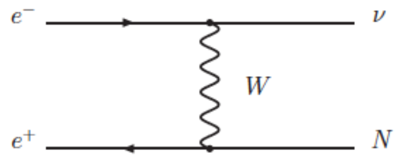
Fermion Portal: Heavy Neutral Leptons below/around EW scale

Prospects for FCC-ee : combination of data at the Z-pole (110 ab^{-1}), 2 m_W (7.5 ab^{-1}) and 240 GeV (5 ab^{-1}).

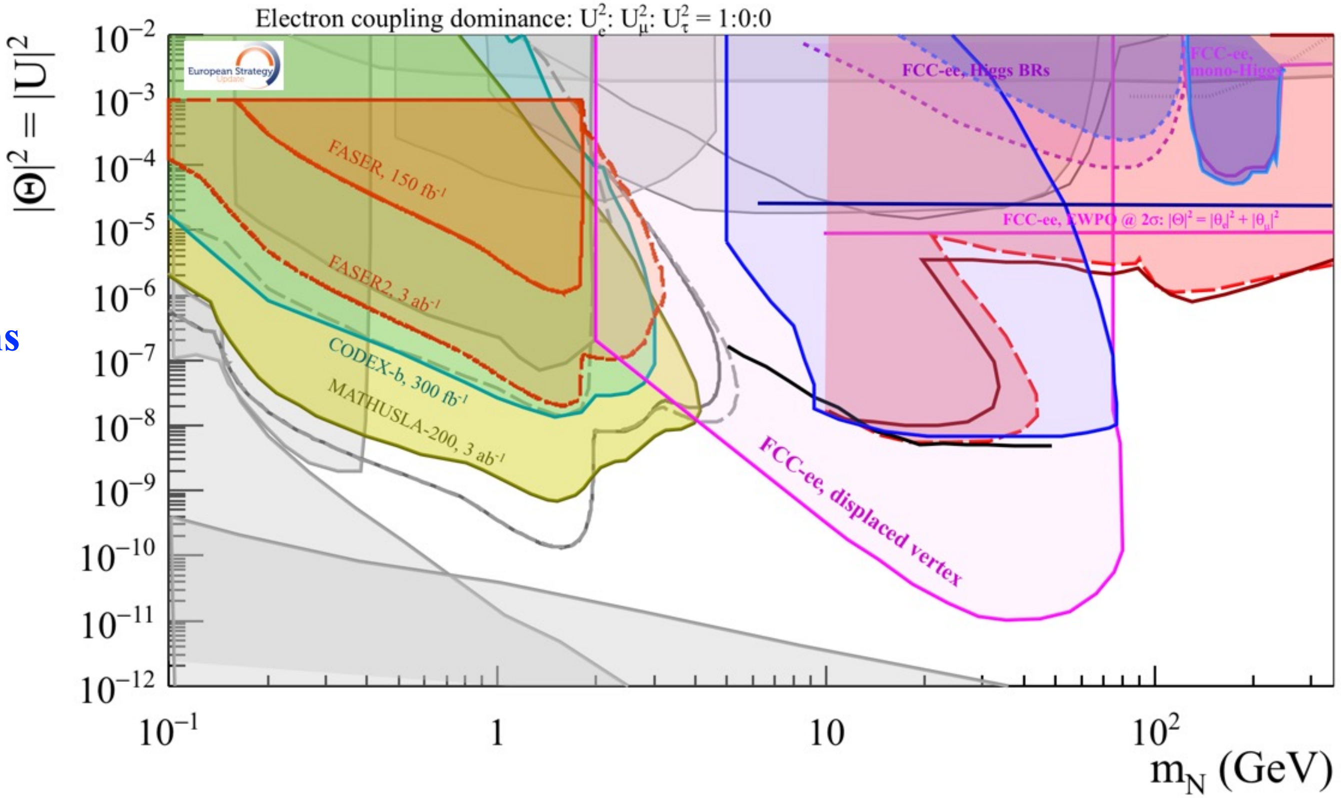
Production mechanisms at $e^+ e^-$ colliders:



production channel: $\mathbf{Z_s}$



production channel: $\mathbf{W_t}$



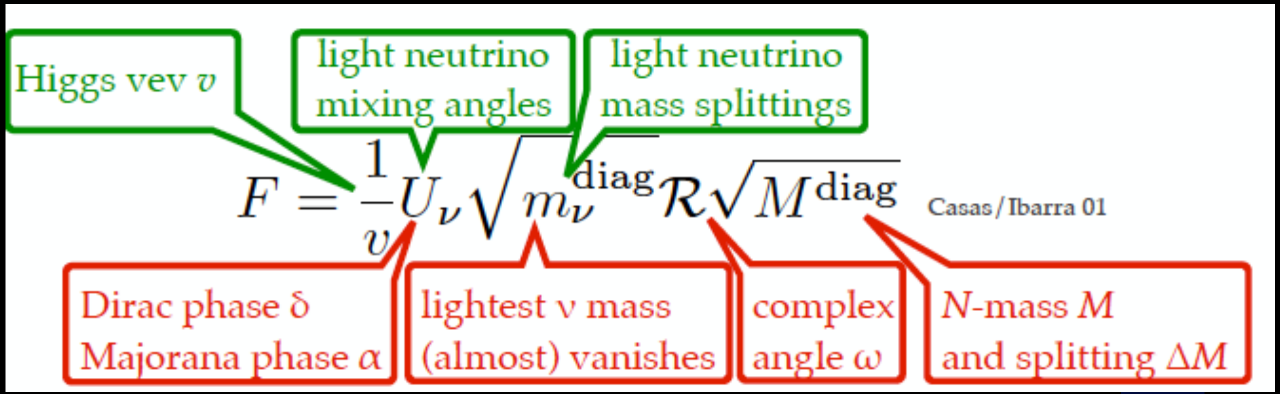
<u>Source</u>:
FCC report,
CERN-ACC-2018-0057
(based on Antusch et al., arXiv:1612.02728)

FCC-ee is highly competitive when running at the Z-pole

FCC-ee….

Clues of New Physics: origin of the neutrino masses and oscillations

Close connection with the physics of active neutrinos

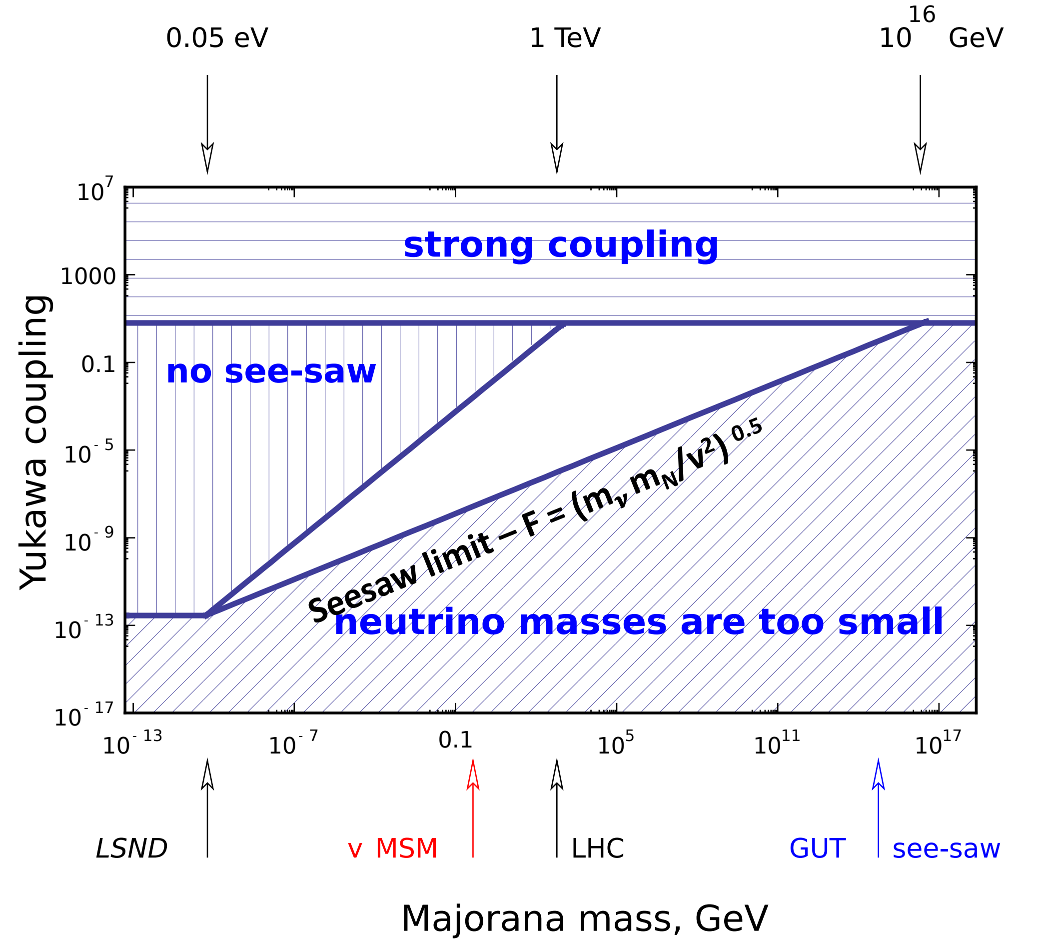


In case of one generation the seesaw formula holds:

$U^2 = v^2F^2/m_N^2$

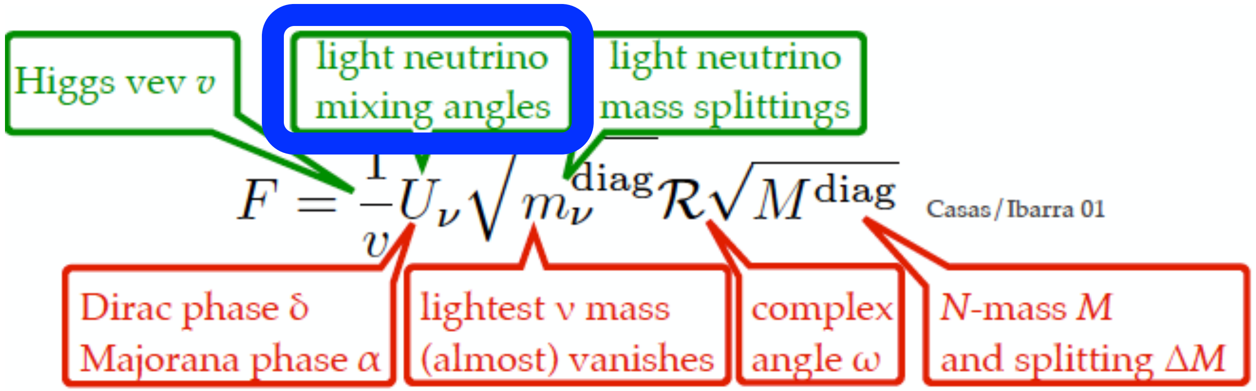
For m_N= 2 GeV , $U^2 \sim 10^{-8}$

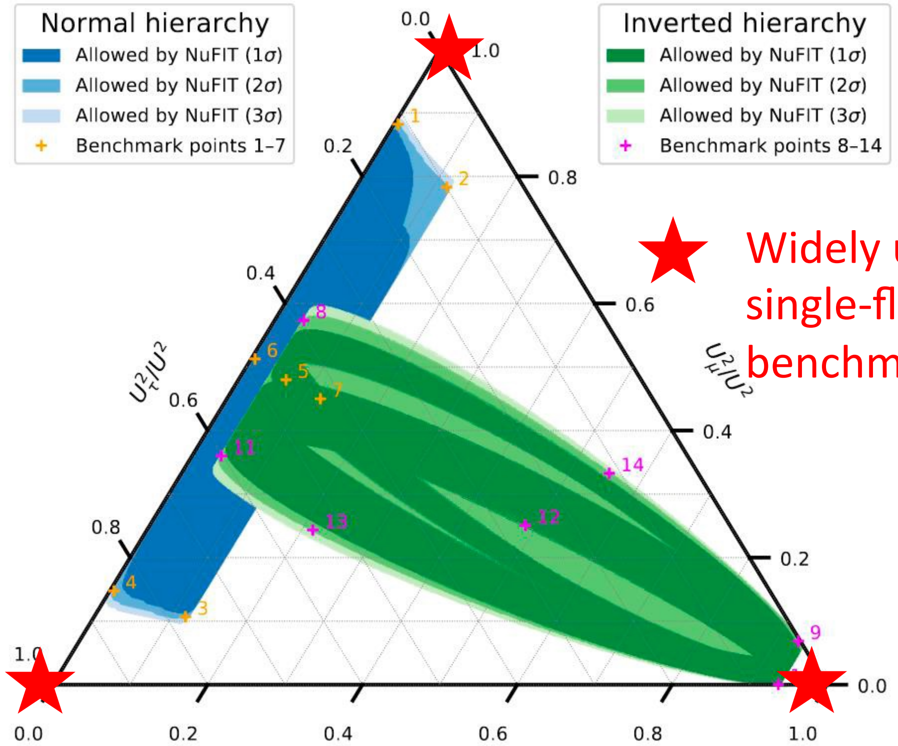
→ Yukawa coupling ~ 10^{-6} (like the electron…)



HNL-active neutrino mixing angles and PMNS non unitarity

The present status of neutrino oscillation experiments allows to do some quantitative analysis.
One can use the statistical information about the light neutrino parameters gathered in various neutrino oscillation experiments to obtain a **probability distribution for the U^2_a/U^2**.





Widely used single-flavor benchmark

2 RHN coupled to active neutrinos

In case of one generation the seesaw formula holds:
$U^2 = v^2F^2/m_N^2$

We cannot know absolute values of couplings to the three active neutrino generations but we can constrain the ratios.

HNL-active neutrino mixing angles and δ_{CP}

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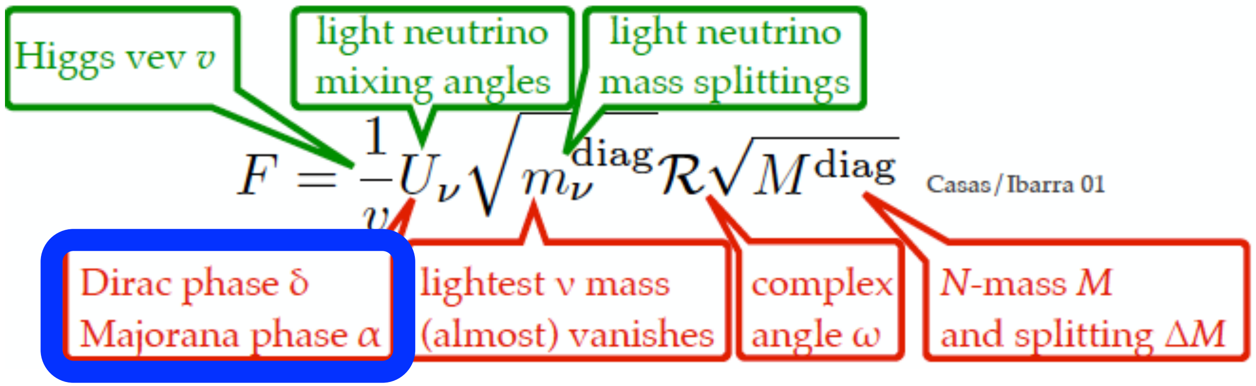

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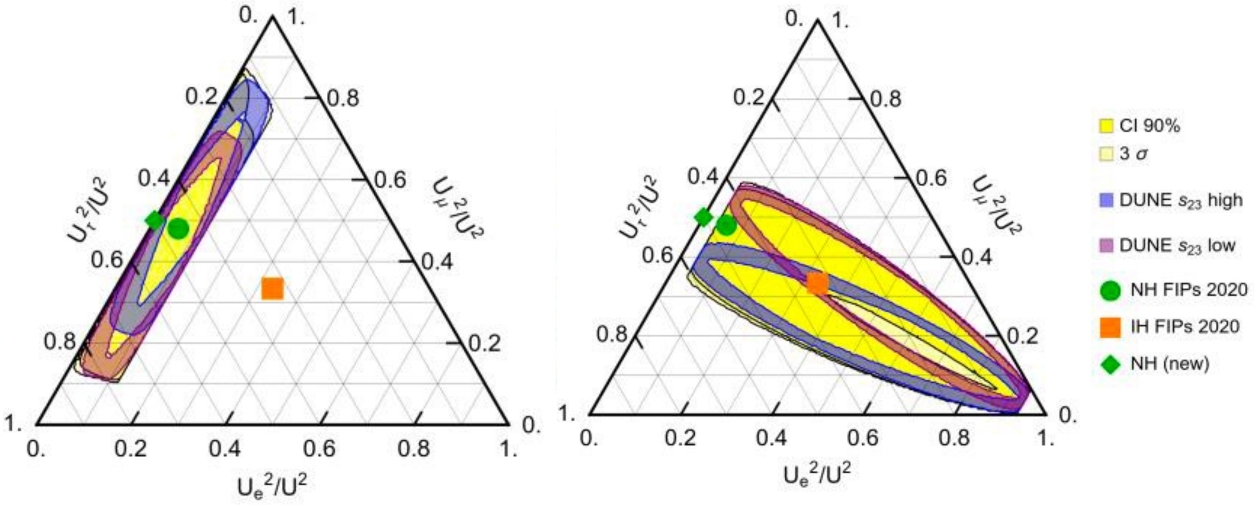
Normal ordering **Inverted ordering**



M. Drewes et al., 1801.04207

Inclusion of knowledge of δ_{CP} and two values of s_{23}

HNL-active neutrino mixing angles and $0\nu\beta\beta$ decay

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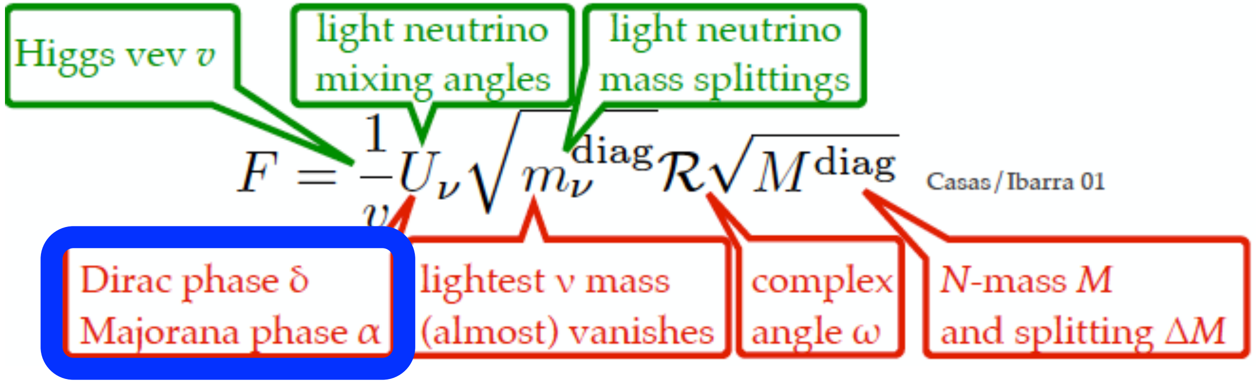

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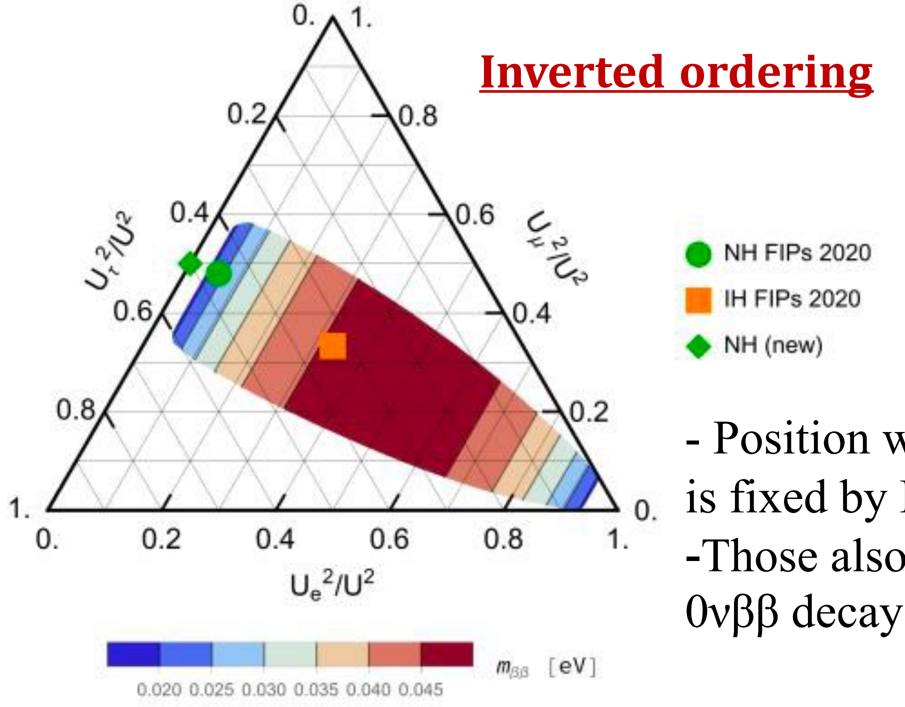
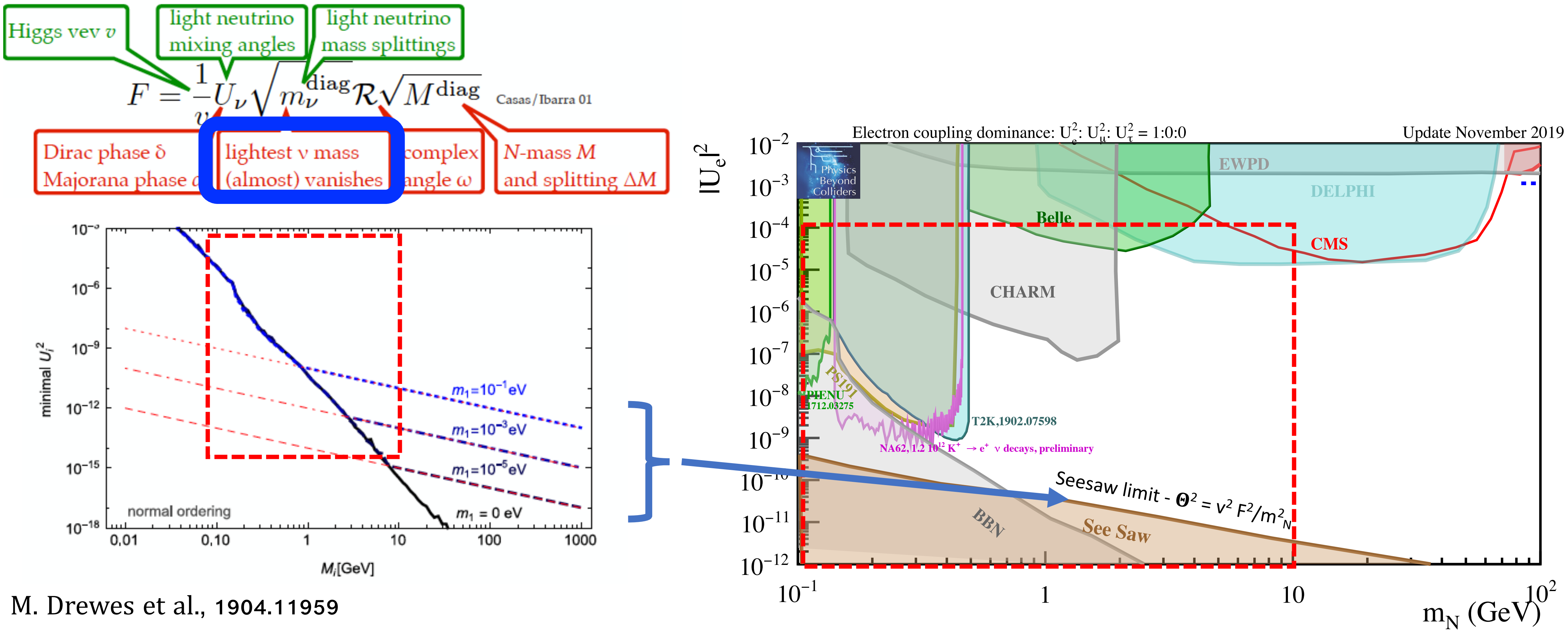


- Position within the triangle is fixed by PMNS phases
-Those also fix the rate of $0\nu\beta\beta$ decay

Value of $m_{\beta\beta}$ within the current 3σ regions

HNLs mixing parameters: lower limit from lightest active neutrino



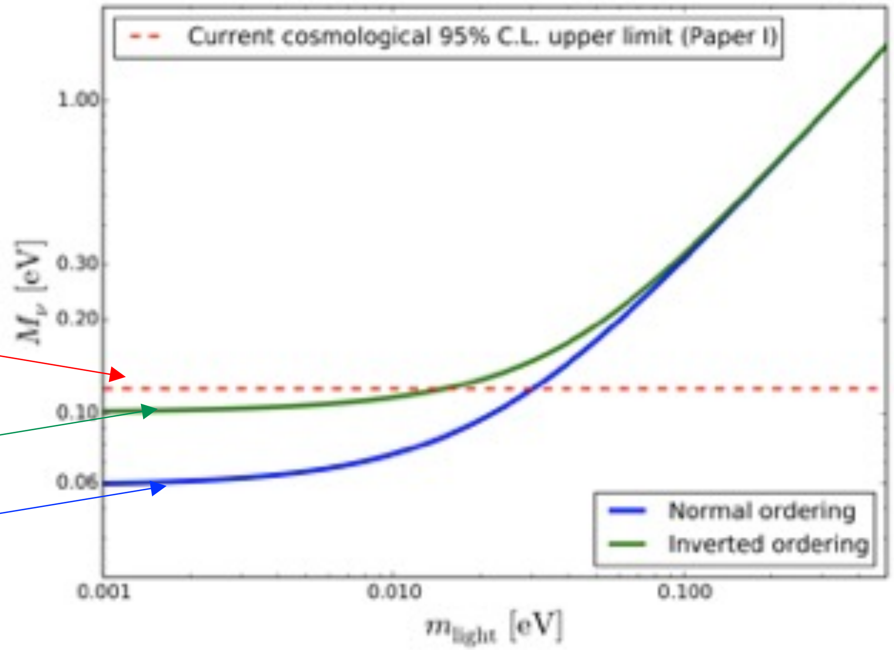
M. Drewes et al., 1904.11959

Lower boundary depends on the mass of the lightest active neutrino

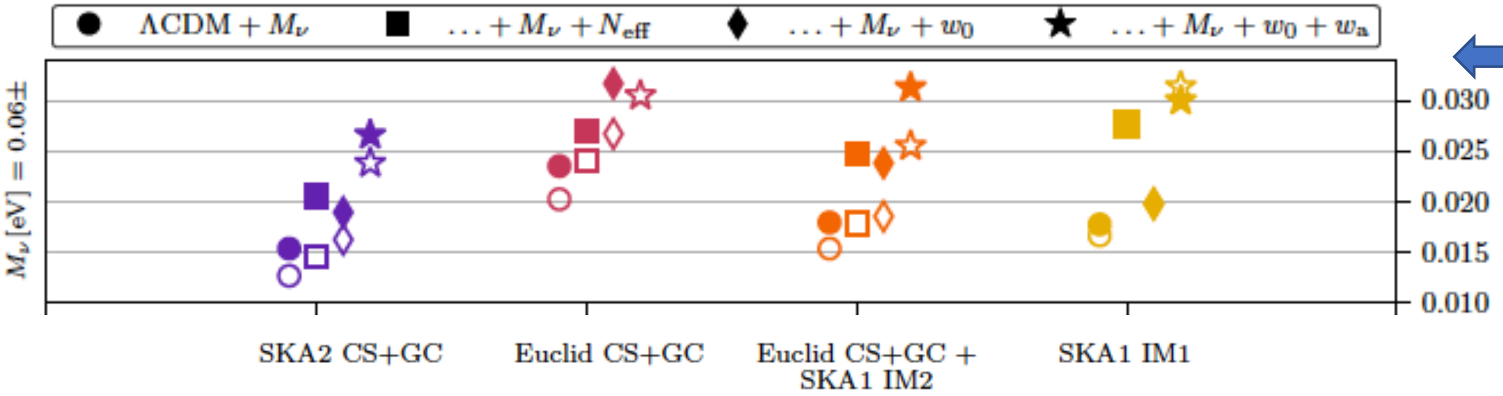
Current knowledge on the absolute active neutrino masses

Current cosmological limits on the sum of neutrino masses is between 0.12 - 0.14 eV, (depending on what dataset you use).

From oscillations we know that
$\sum m_\nu$ >= 0.10 eV for Inverted Ordering
$\sum m_\nu$ >= 0.06 eV for Normal Ordering.



Sprenger et al., 1801.08331



New data from Euclid and Square Km Array (SKA) will be able to bring the cosmological limit down to $\sum m_\nu$ <= 0.06 ± 0.02 eV and shed light on the value of the mass of the lightest neutrino
(and the seesaw limit of HNLs…)

Conclusions

- Feebly interacting particles are a blooming field touching many aspects of the current physics landscape:
  - light Dark Matter, Heavy Neutrinos, axions, ALPs, etc.

- Many experiments can contribute to the field, in different manners:
  via direct searches or providing indirect contraints.

- A first list of experimental efforts from CHIPP, contains:
  NA64, NA62/HIKE, SHiP, mu3e, PIONEER, DUNE, HyperK, FCC-ee, DAMIC, XENON, exotic atoms related experiments, FASER, SND, FPF,… and of course theory.

This is a moving target where more inputs, from experiments and theory, is expected to come in the coming years.