European Strategy for Particle Physics

Status and Open Questions Dark Matter and Sectors

Matthew McCullough (CERN)
For the ESPP 2026 WG on Dark Matter and Dark Sector

23-27 JUNE 2025 Lido di Venezia

The Special Investigators

Aaron Chou - Chicago
Caterina Doglioni* - Manchester
Emanuele Castorina - Milan
Francesca Calore – CNRS LAPTH
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Julia Katharina Vogel* – TU Dortmund
Maksym Ovchynnikov* - CERN
Monica D'Onofrio* - Liverpool
Paolo Agnes* – Gran Sasso Science Institute
Tina Pollmann – NIKHEF and Amsterdam
Yohei Ema* - CERN

The Submissions - 114

If yes, which benchmark models?
antimatter dark matter coupling, millicharged
light DM, sterile neutrinos (categorization was yes (more in 112)
sexaquark via pbar-He3 annihilation
QCD axion
QCD axion, sub-GeV indirect detection in MeV gap, more general WISPs
QCD axion via FLASH
QCD axion with GRAHAL and MADMAX, WIMPs and sub-GeV with DarkSide, XLZD, TESSERACT
WIMPs with XENONnT,XLZD
WIMPs with XLZD
WIMPs with colliders, indirect with CTAO, dark bosons with antimatter expts???
Heavy DM (CTA) - generic
ULDM, PBH, stochastic bkg
Phase transitions, w/ (heavy) and w/o portal. PBH, stochastic bkg
Light DM
Alps
generic support
Light DM, sterile neutrinos
heavy, ULDM, sub-GeV
heavy, ULDM, sub-GeV
YES (but just mentioned as science case for FCC)

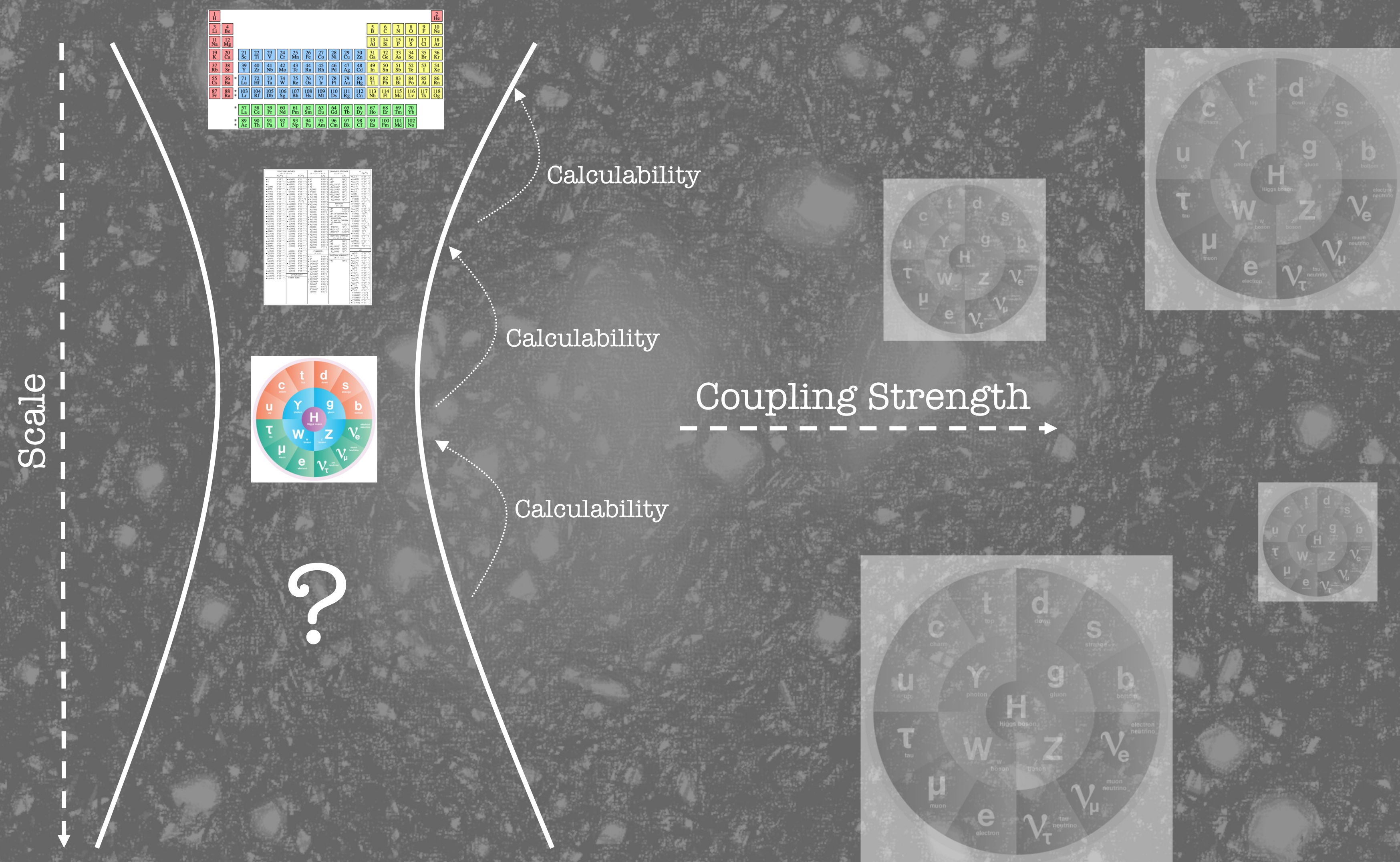
If yes, which benchmark models?
antimatter dark matter coupling, millicharged
YES (but just mentioned as general science case and for FCC)
YES (as national priority, generic)
YES (as national priority, generic)
YES (as national priority, generic)
YES (as consortium priority, generic)
heavy (WIMP),
super-heavy
light DM
YES (as national priority, generic)
super-heavy (exotic compact objects, PBHs), heavy, ULDM
YES (as consortium priority, generic)
no models, focus is complementarity/interplay with cevns
sub-GeV dark matter -- scalar dark matter and heavy neutral leptons via axion-like particle
refers to SBND publications on sensitivity to dark sector particles such as a Higgs-Portal scalar [15], heavy axion-like particles [16, 17] or dark photons that mediate interactions with light dark matter [18, 19]
no models, focus is describing scope of DRDs

If yes, which benchmark models?
antimatter dark matter coupling, millicharged
indirect detection from annihilation in sun
no models, national input
no models, focus is complementarity
no models, focus is compementarity
LDM and ULDM (no models)
ALPs, hidden sector (LDM, ULDM)
LDM (no details)
national input, generic (no models)
LDM (sterile neutrinos)
UDM (ALPs)
categorization was yes (indirect)
collider technology (categorization was yes (?))
LDM (plot with sensitivity to inelastic DM)
Lattice QCD calulations
QCD axion/ALPs
axion/ALP/dark photon
ULDM, WIMPs, sterile neutrino, FIPs, DP, Beamdump
Portals
LDM (BC2)
Portals

If yes, which benchmark models?
antimatter dark matter coupling, millicharged
LDM (inelastic DM)
Portals
Portals
LDM (inelastic DM)
Dark Higgs
Minimal DM, Portals, Alps
Minimal DM, Alps
Alps, UL DM
????
Yes, but superficial discussion.
Alps, light scalars
Light and heavy DM, dark photons
Alps, dark photons (categorization was yes, but superficial)
HNLs, light DM. (categorization was yes, but superficial)
Axion DM
Dark photons, ALPs
Yes, but summary of P5.
Yes, in supplementary material. See 2205.08553. WIMPs, scalar and lepton portal, simplified models.
Same models as 10 TeV COM lepton collider

Organised by relevance to benchmark models.

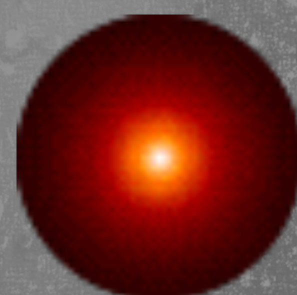
The Lessons We've Learned



Avoiding Modern-Day Heliocentrism

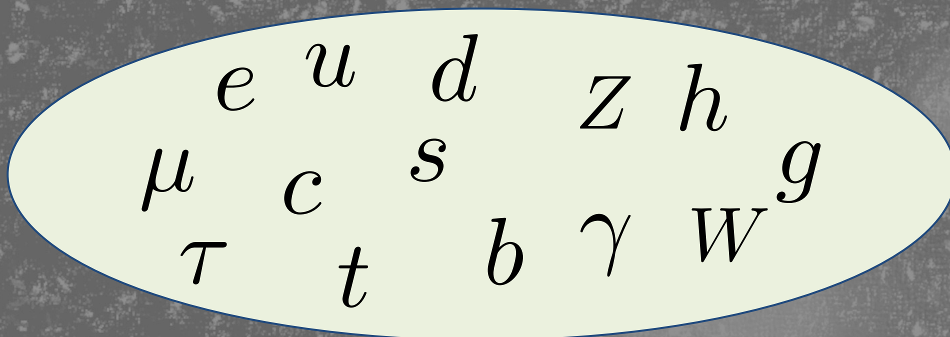
Visible Matters

Visible, baryonic matter makes up 16% of all the matter in our Universe. 73% of visible matter is Hydrogen. 25% is Helium. All the rest: 2%.

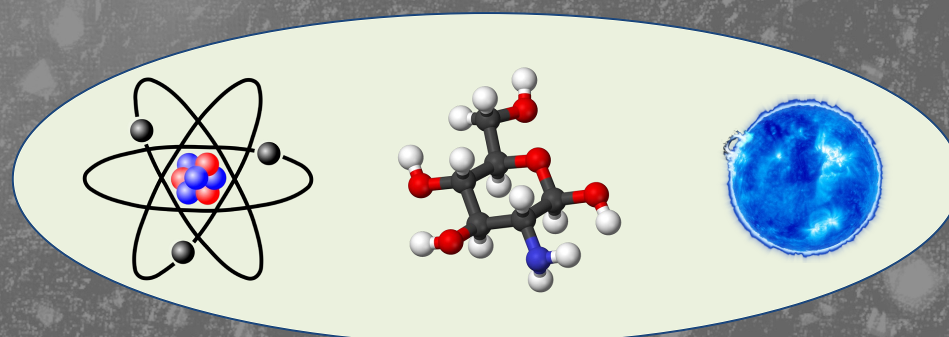


So, to a good approximation, the majority of visible matter is in relatively uninteresting atoms. Particularly hydrogen.

But the phenomenology of visible matter is not, to a good approximation, the phenomenology of hydrogen!



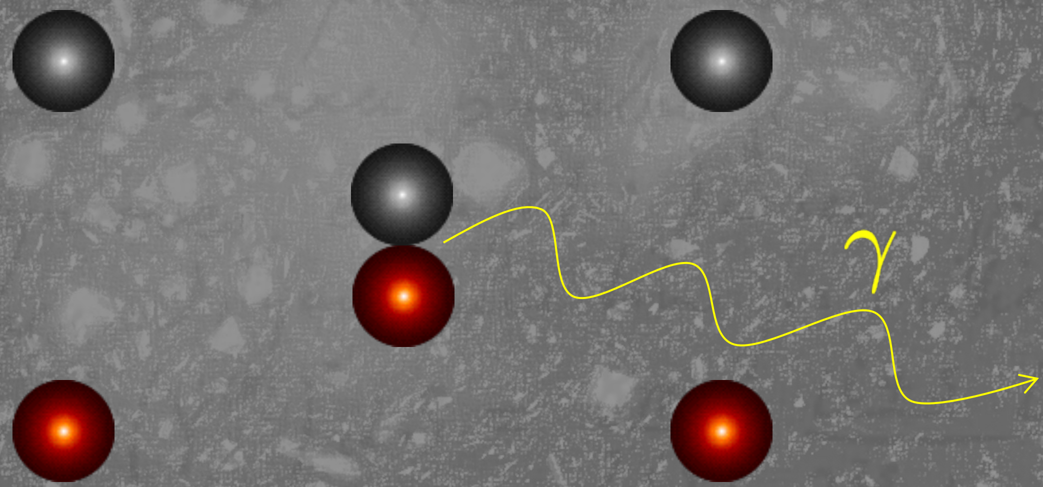
Within that visible 16% we observe extraordinary complexity.



The visible sector is rich, whichever length scale you view it at.

Dark Matters

Historically assumed the phenomenology of the dark sector, including interactions with us, is also dominated by a single state.

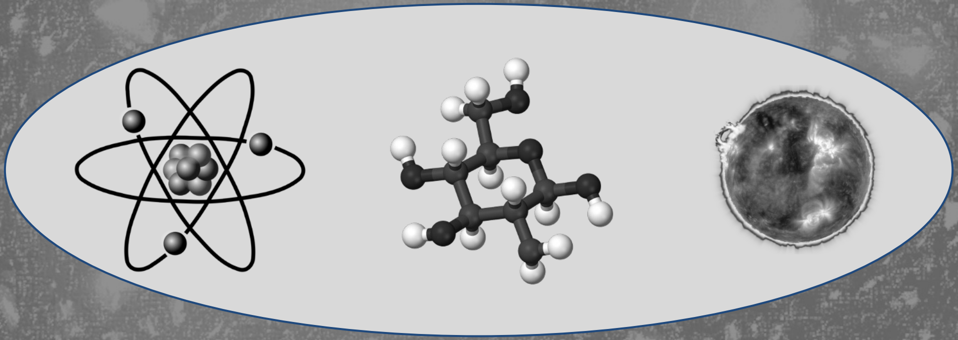


Consider the rich phenomenology of the visible sector. Why should the dark sector be simple?

An Evolving Landscape

Knowing the Unknown

What is increasingly appreciated is that the phenomena driving interactions with the dark sector could be rich, diverse, complex.



It's not that we don't know where to look. Rather we know there are many many places to look!

Knowing the Unknown

Theoretical perspectives now typically motivated by portals:

- Higgs
- Dark Photon
- ALP
- Neutrino

These portals aren't to be taken as fundamental theories. They are intended to capture the diverse phenomena that could be mediated from complex sectors. Consider the pion, for instance.

Windows

The standard model provides examples of neutral particles which can comfortably be light and have arbitrarily weak interactions:

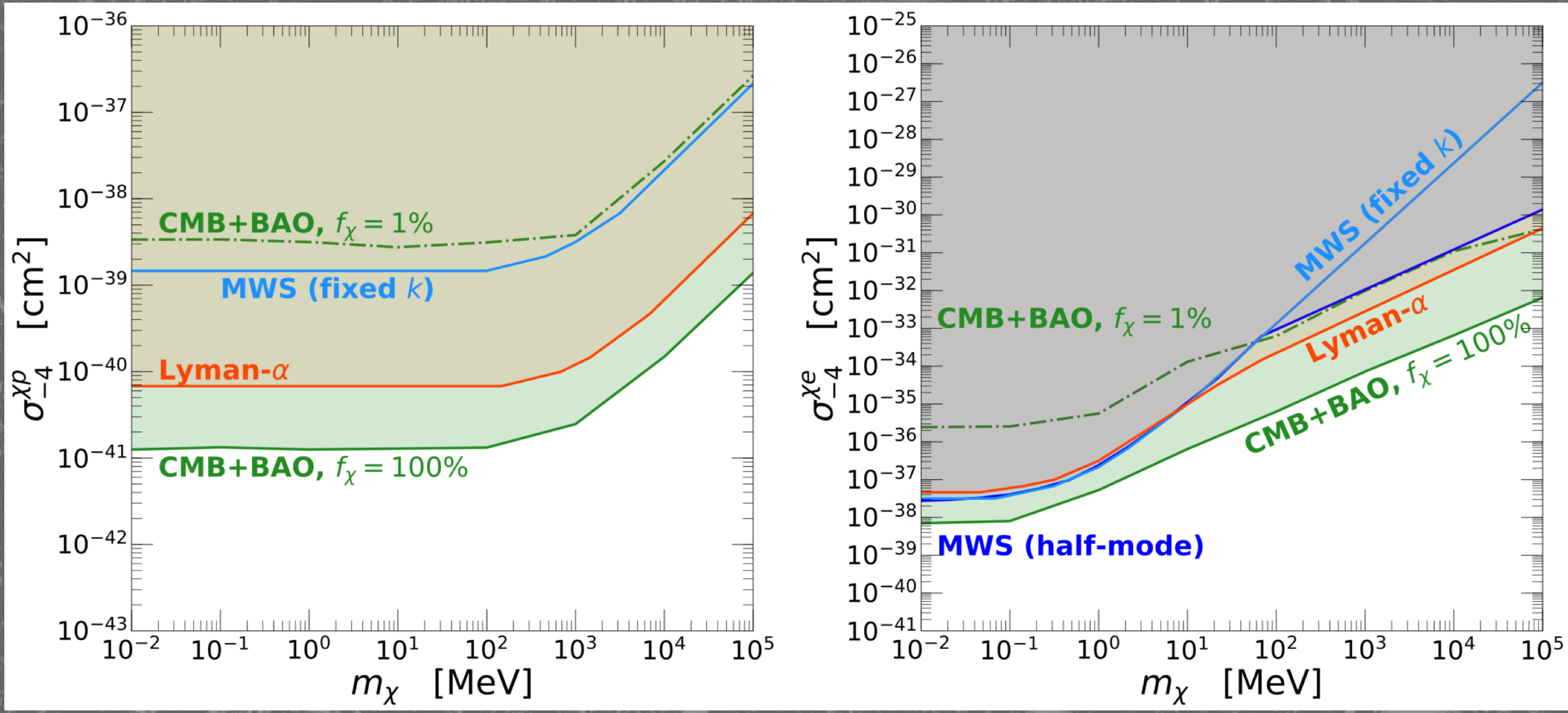
Standard Model	Dark Sector
Z	Z'
π	a
ν	χ

And a new, intriguing, portal...

$$(A\phi + \lambda\phi^2)|H|^2$$

Cosmic Horizons

Cosmology, such as structure formation, crucial to explore light dark sectors (Pradler).



Buen-Abad+ 2107.12377

Cosmic Horizons

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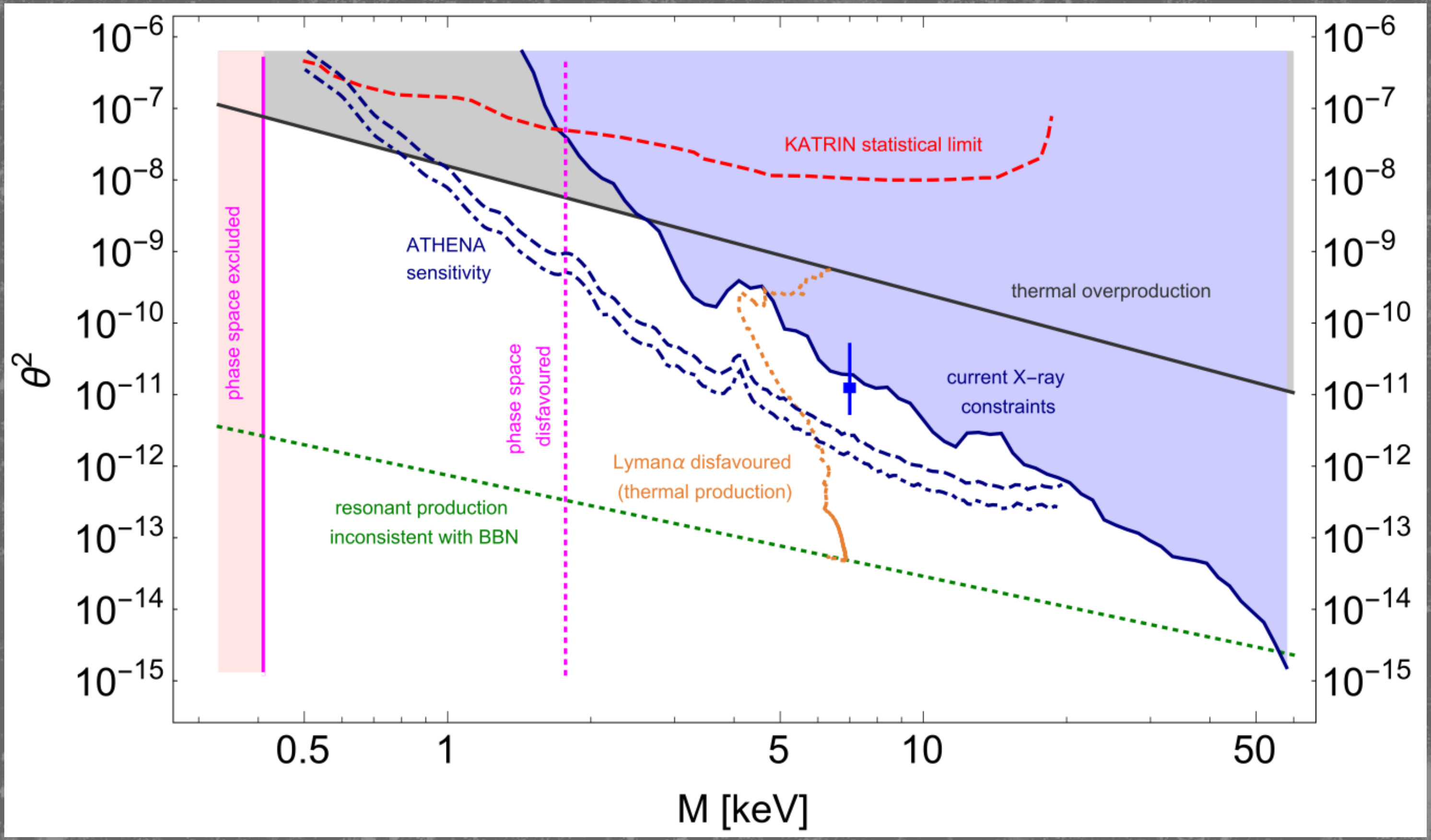
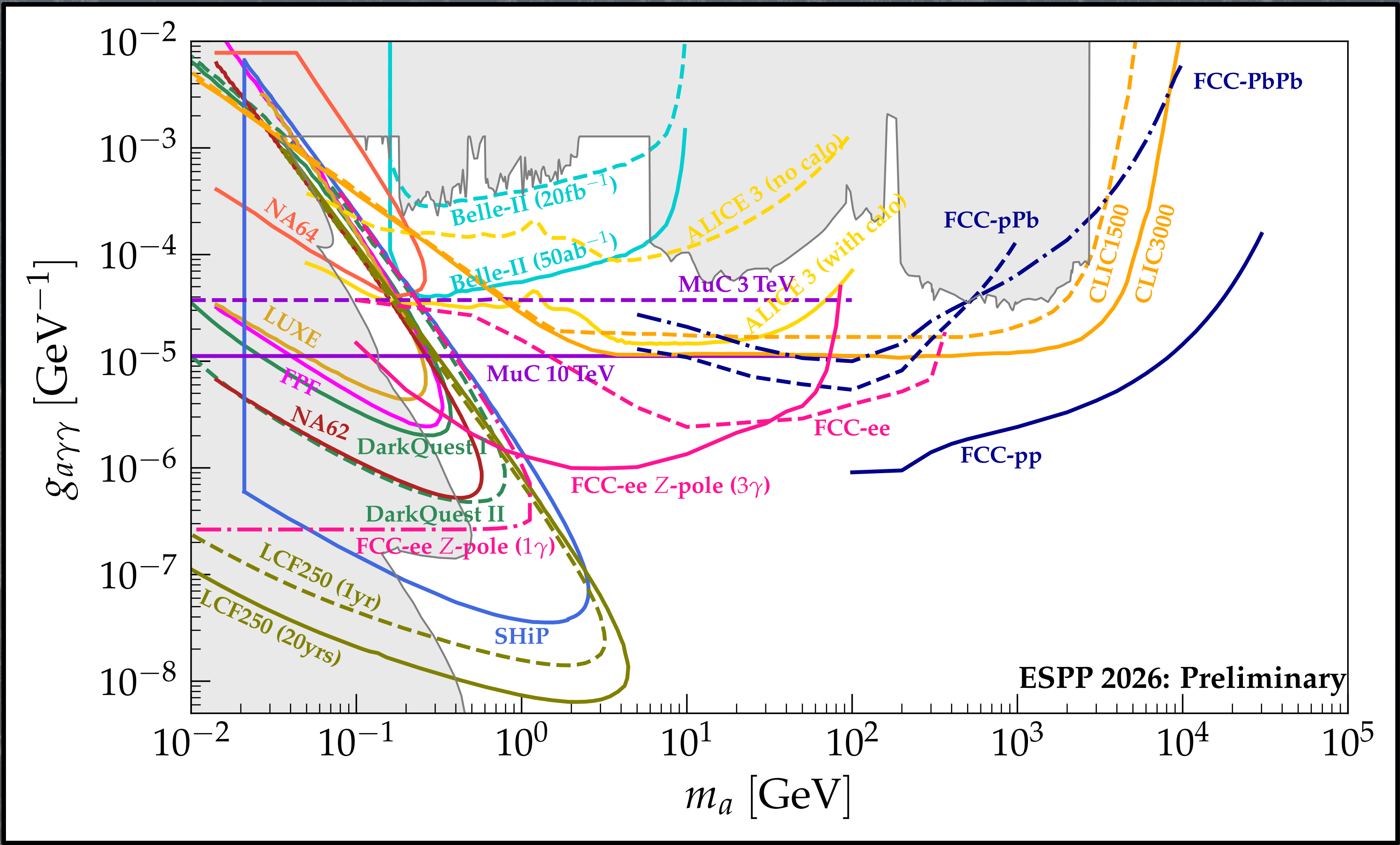


Boyarsky+ 1807.07938

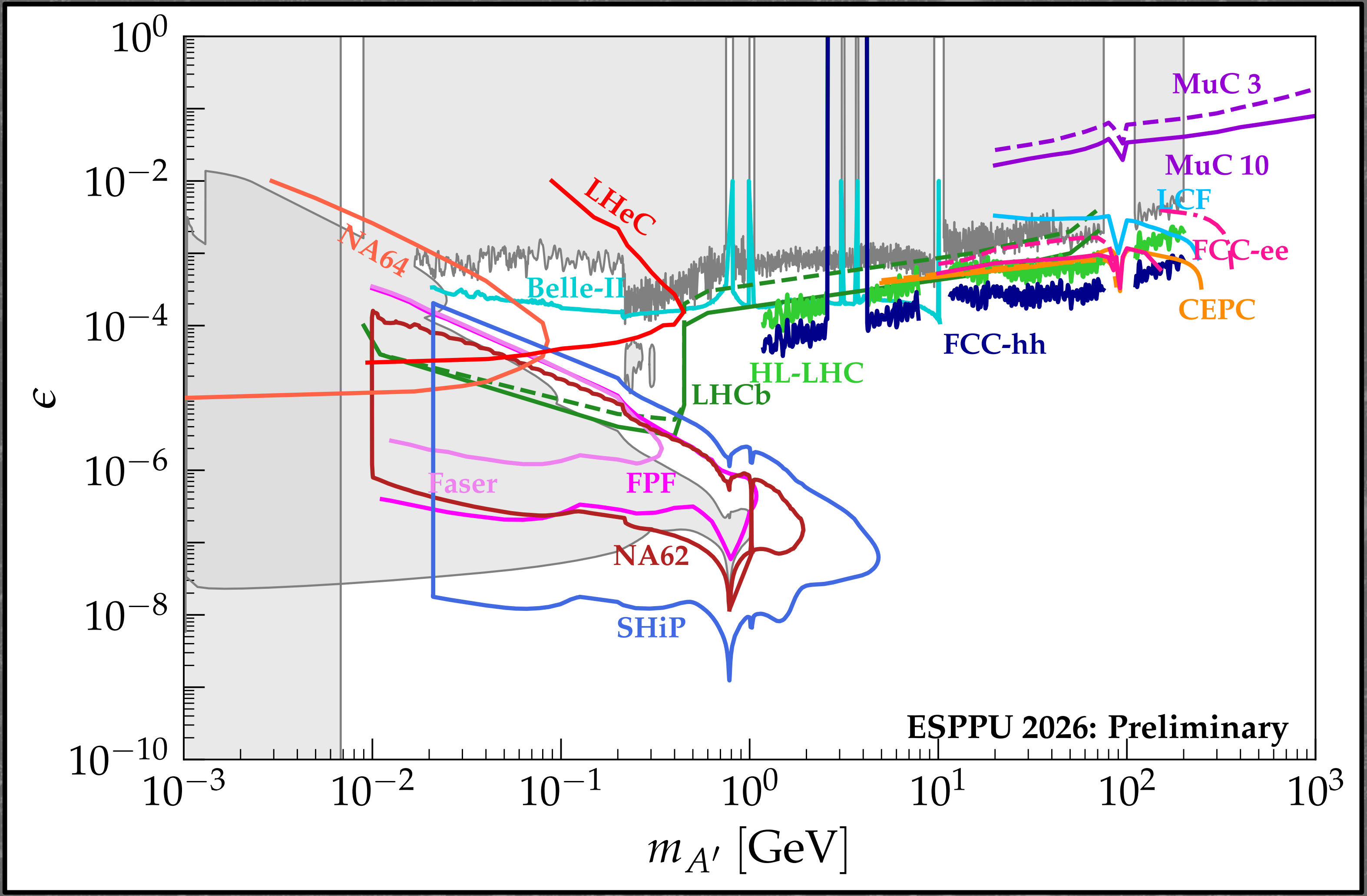
A Collision Course

ALPine Landscapes



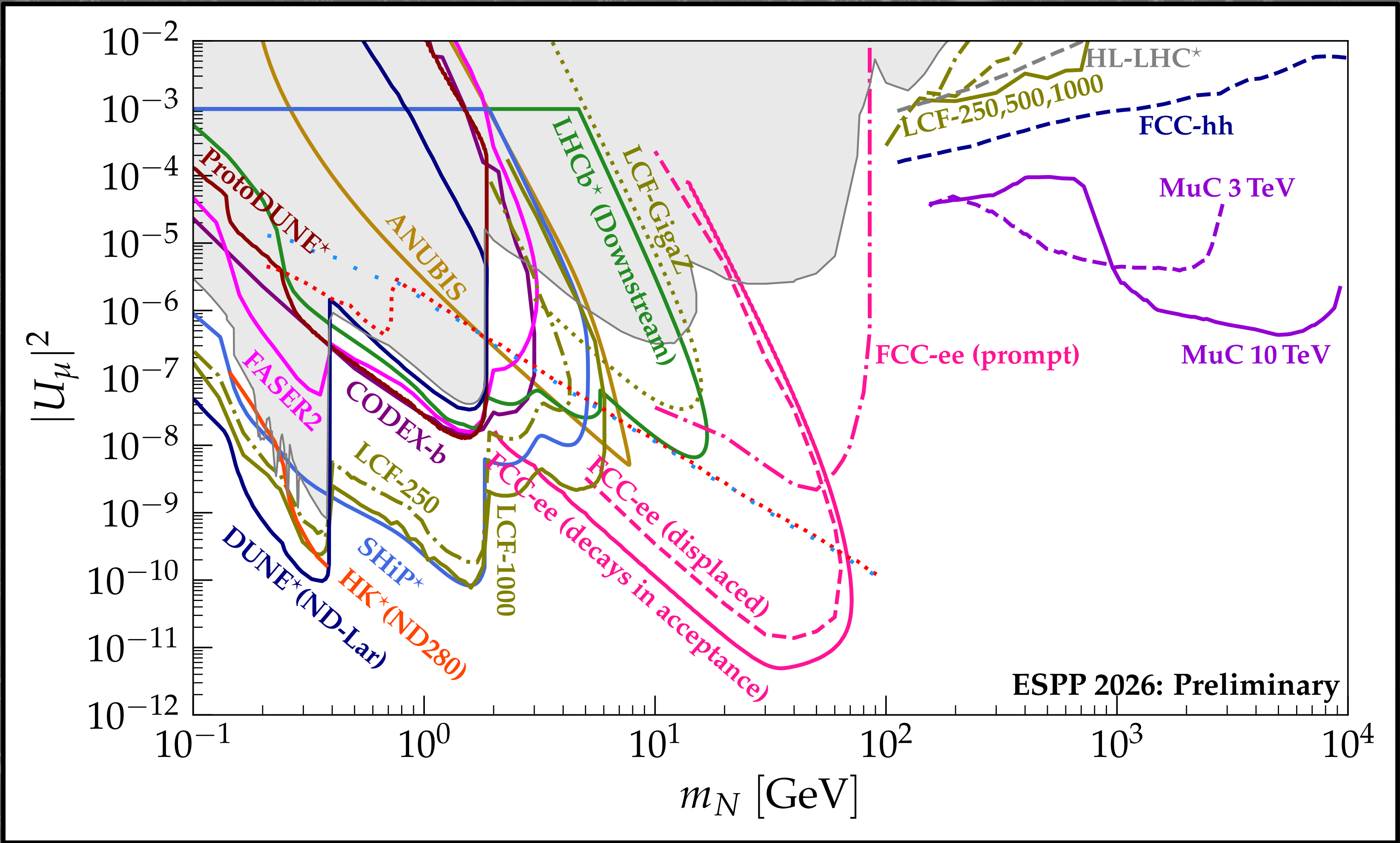
Vast array of probes. Future colliders extend intensity to new frontiers. EIC to be added.

Dark Lights



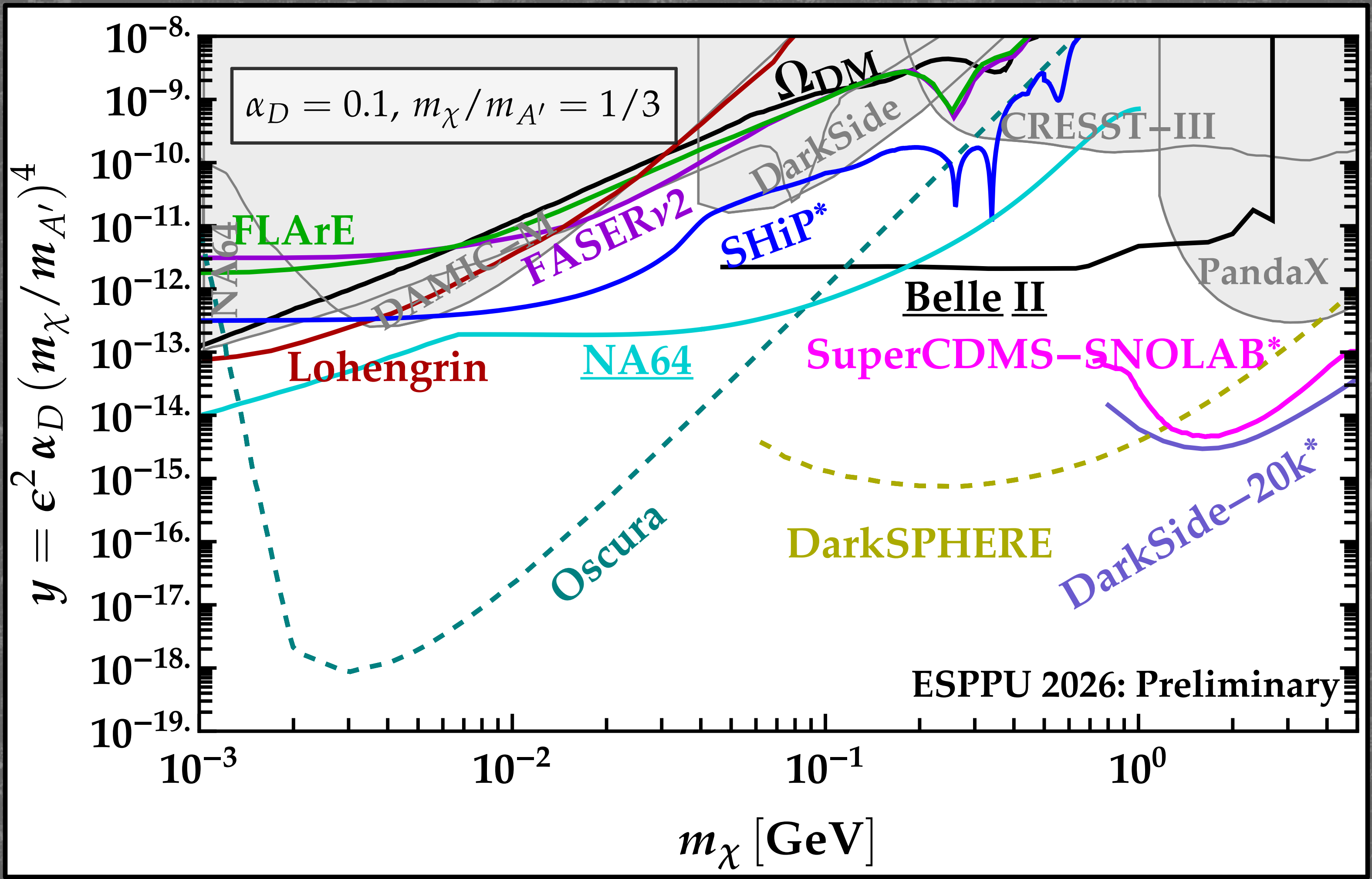
Vast array of probes. Future colliders extend intensity to new frontiers.

Neutrino Portal



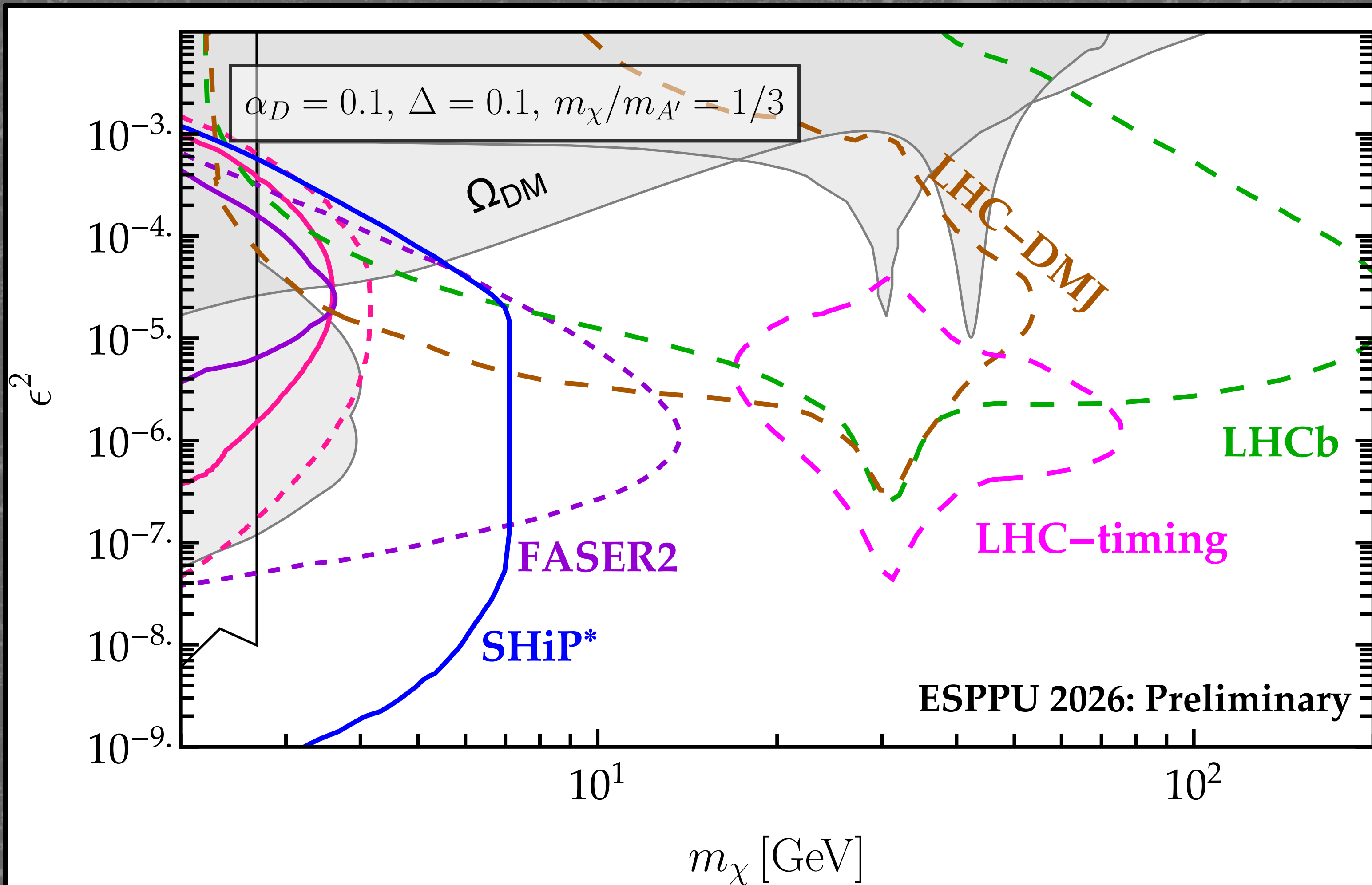
Vast array of probes. Future colliders extend intensity to new frontiers.

Elastic DM Photon Portal



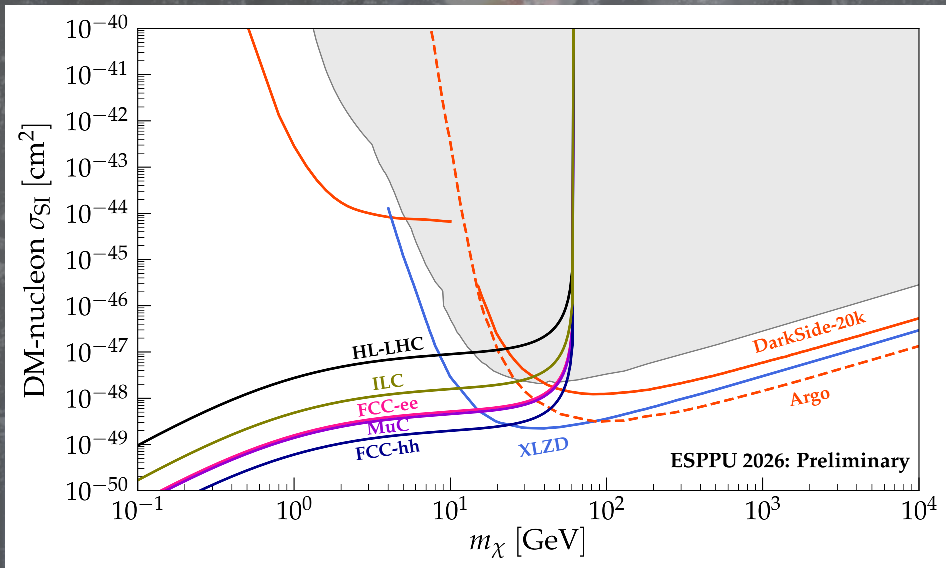
Vast array of probes. Future colliders extend intensity to new frontiers.

Inelastic DM Photon Portal

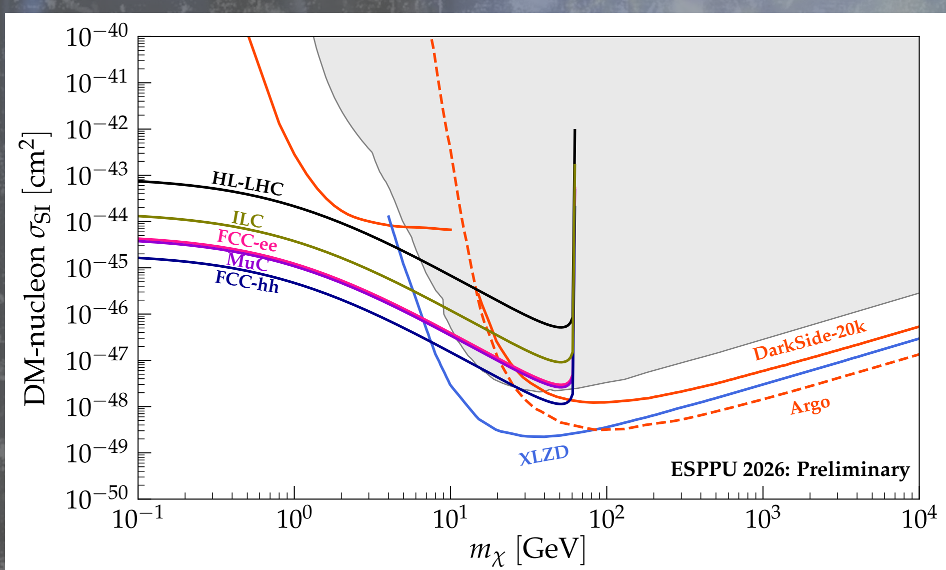


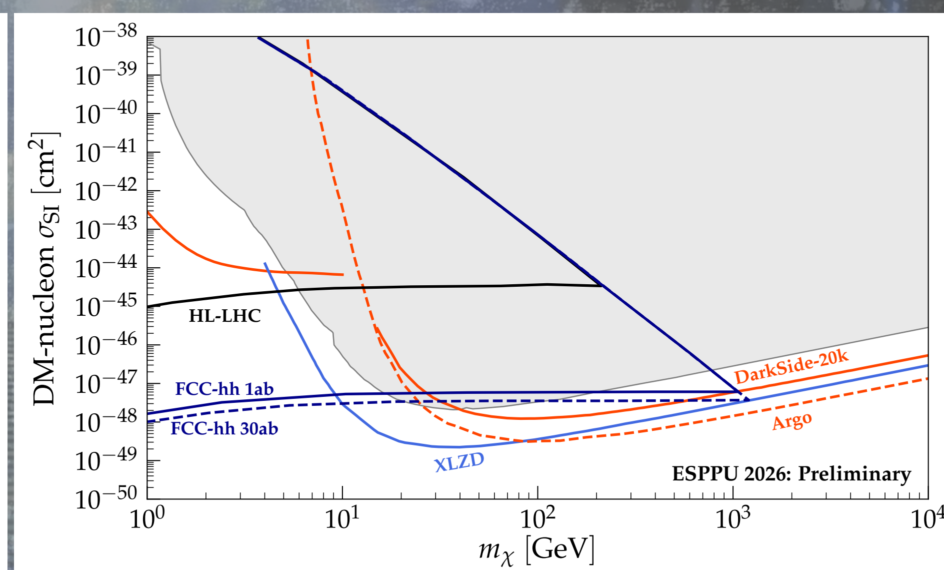
Vast array of probes. Future colliders extend intensity to new frontiers.

Opening The Higgs Portal

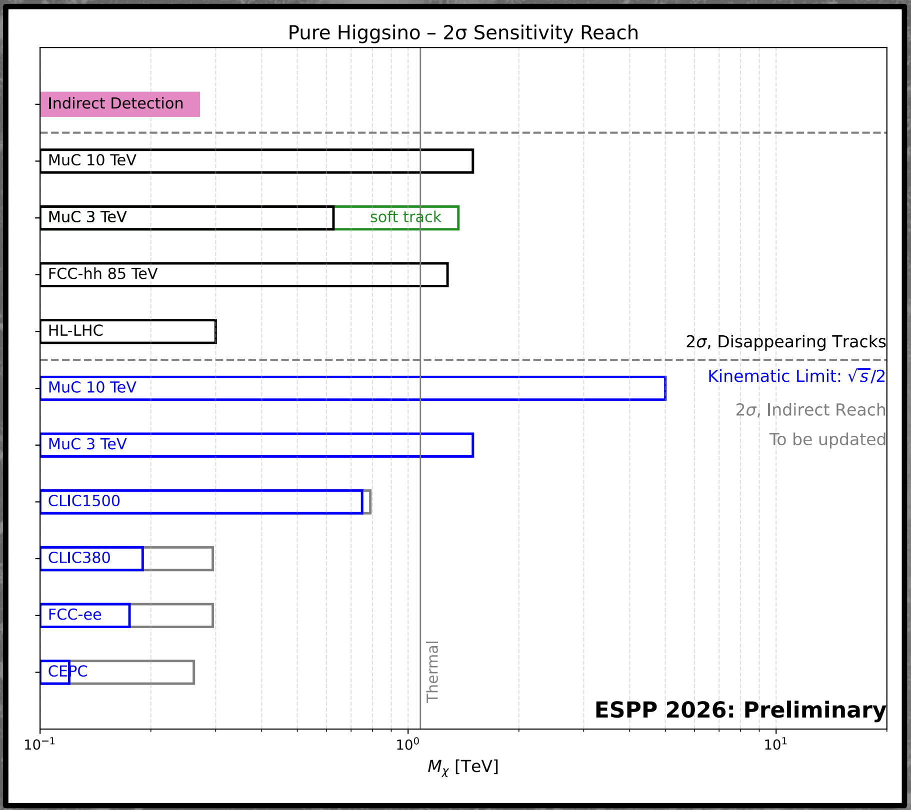


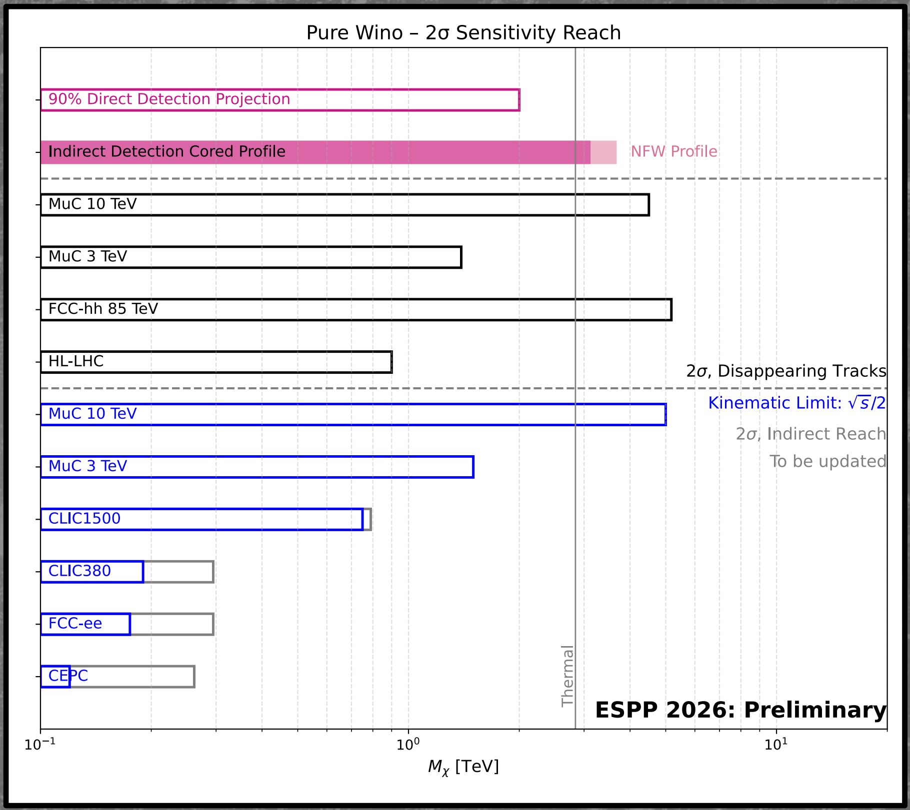
Great deal of complementarity between colliders and direct/indirect detection.





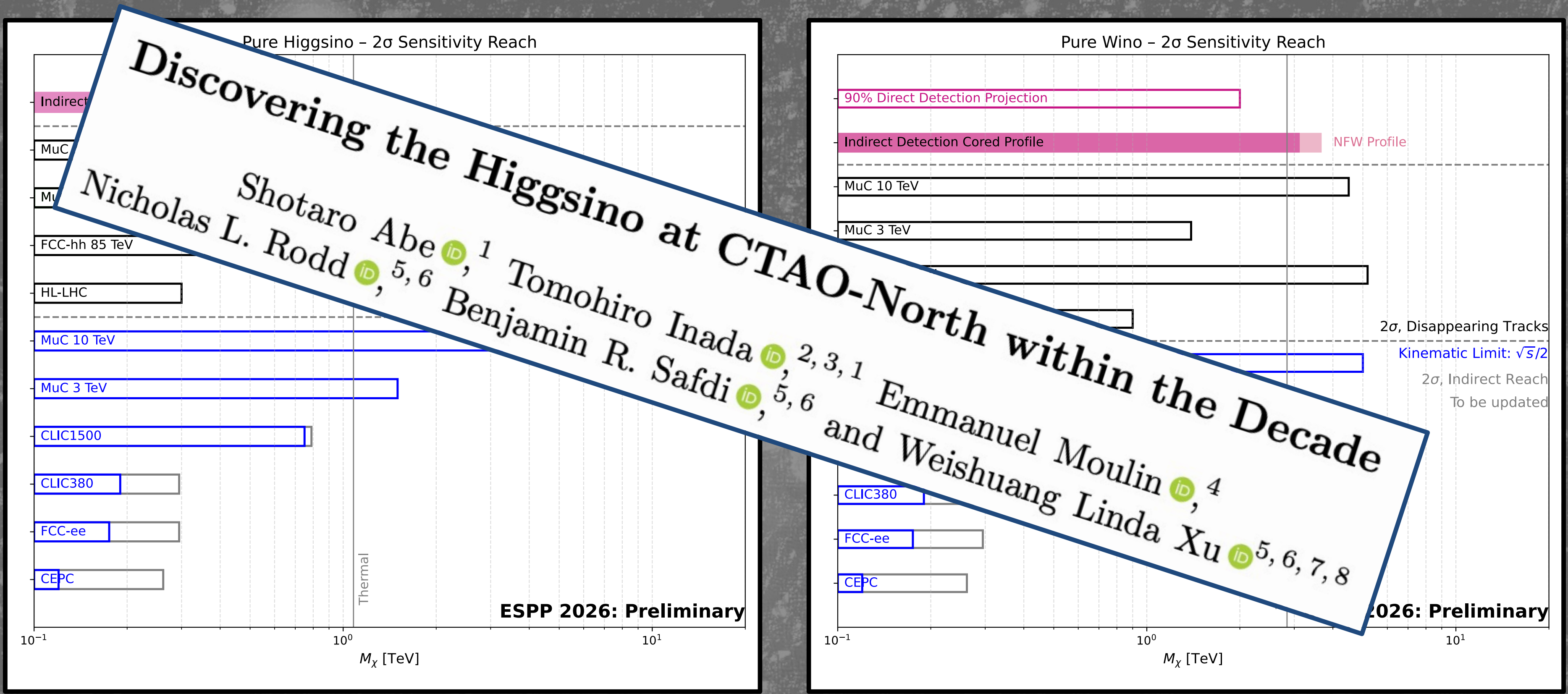
Fate of the Ino





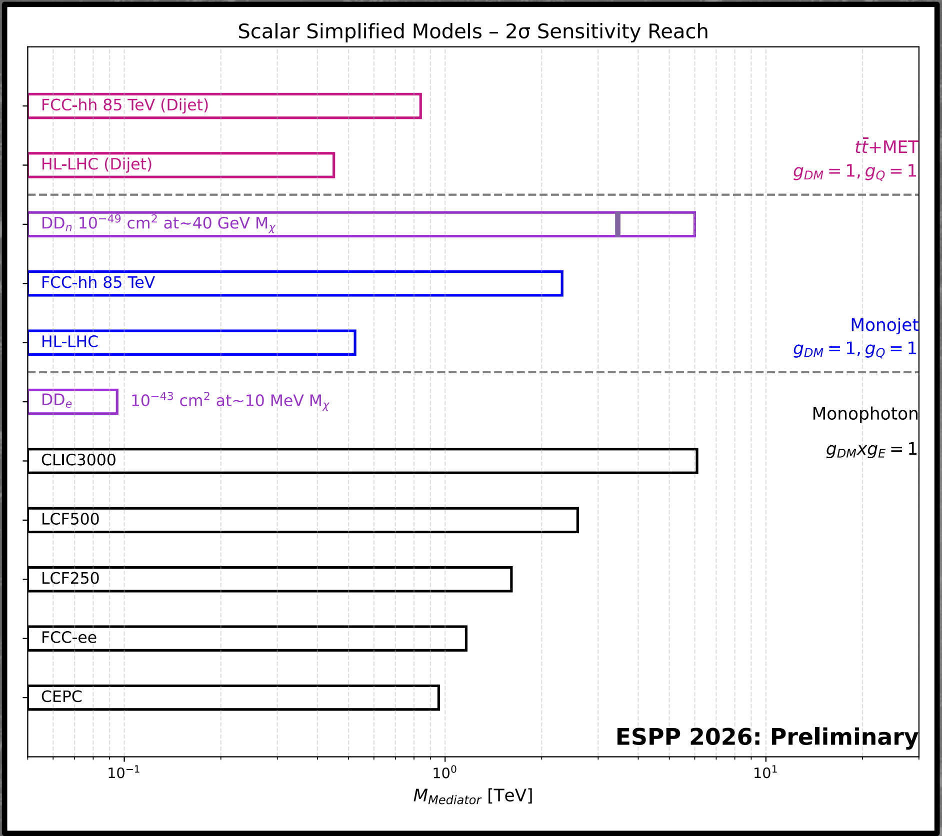
Great deal of complementarity between colliders and (present) indirect detection. Long live the Ino?

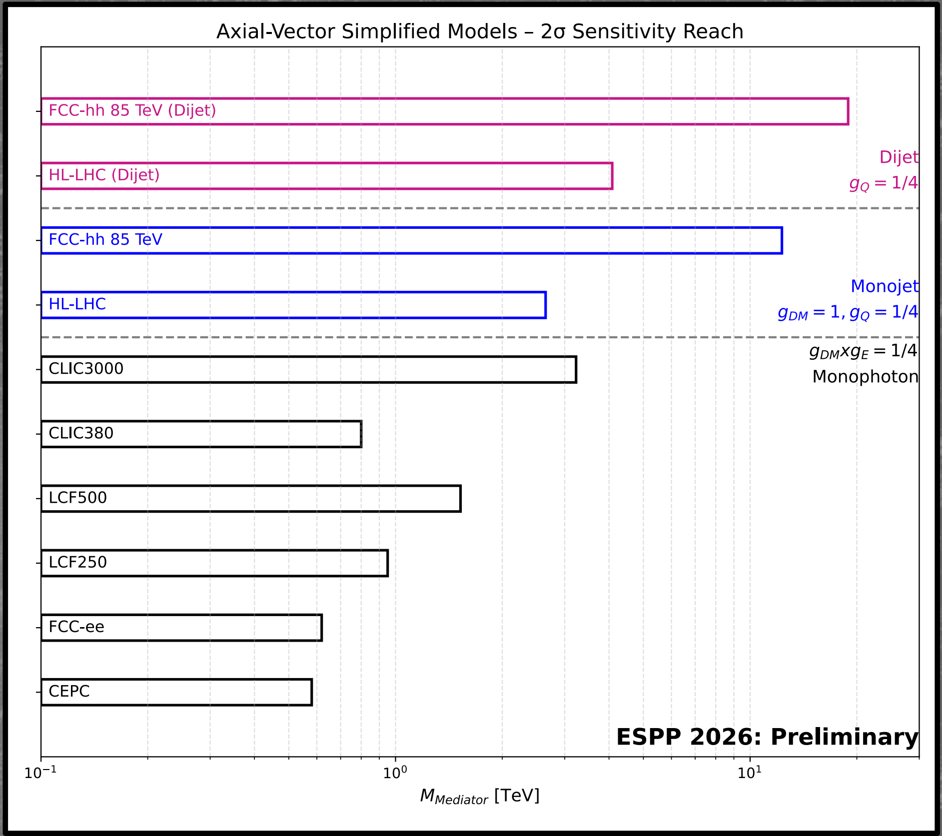
Fate of the Ino



Great deal of complementarity between colliders and (present) indirect detection. Long live the Ino?

Simplified Models





Great deal of complementarity between colliders and direct detection, but comparison nuanced…. DD: Long term: XLZD, Oscura. Near: DarkSide and DAMIC. Muon collider yet to be added.

Conclusions

The theoretical landscape is maturing.

- More open-minded, less anthropocentric.
- Portals attempt to capture diverse phenomena.
- Need to hedge, through breadth of programme, for **future evolution** of pheno landscape.

It's not that we don't know where to look. It's that we do know there are many places we **should** look.

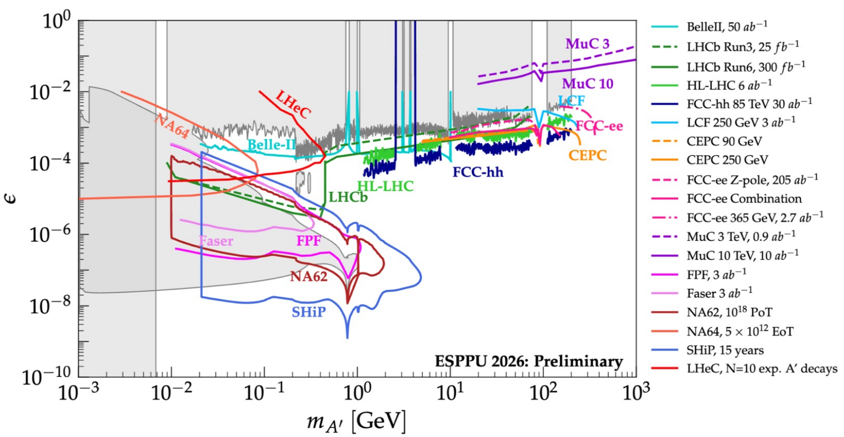
Let's look forward to a dark future together!

Backup

Beam Dump experiments

A' production

- **Bremsstrahlung** $e^-Z \to e^-ZA'$ and $pZ \to pZA'$ (NA62, NA64, Faser, FPF, SHiP)
- **Light mesons decays** $M \to A'\gamma$ (NA62, Faser 2, SHiP)
- **Meson mixing** (NA62)



90% CL exclusion limits for Dark Photons in the plane mixing parameter ε versus Dark Photon mass. HL-LHC, CEPC, FCC-ee and FCC-hh curves correspond to 95% CL exclusion limits. LHeC curve correspond to N=10 expected A' decays and 0 background. The sensitivity of future colliders, mostly covers the large-mass, large-coupling range, and is fully complementary to the the low-mass, very low- coupling regime where beam-dump and fixed-target experiments are most sensitive. Belle II and LHCb upgrade provide additional coverage in the medium-mass, high-coupling region.

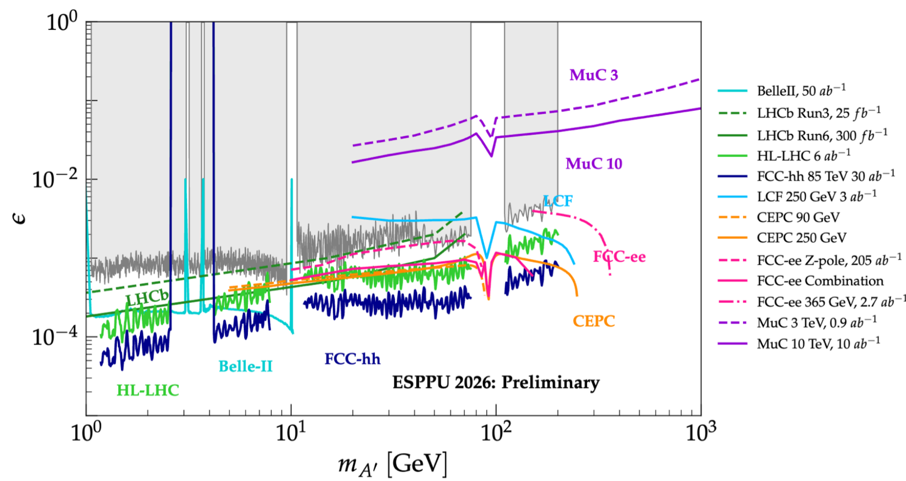
Theoretical Uncertainties: models in low-mass, low-coupling region affected by sizeable Th. Unc., which are treated in different ways by experiments

Backup

Collider experiments

A’ production

- **Radiative return**, $e^-e^+/\mu^-\mu^+ \to A'\gamma$ (MuC, FCC-ee, CEPC, ILC)
- **Drell-Yan**, $q\bar{q} \to A'$ (HL-LHC, LHCb, FCC-hh)
- **Associated production**, $\mu^+\mu^- \to A'\mu^+\mu^-$, (MuC
- **Z decays**, $Z \to A'\mu^+\mu^-$ (FCC-ee, CEPC)
- **Heavy meson decays**, $D^* \to DA'$ (LHCb)

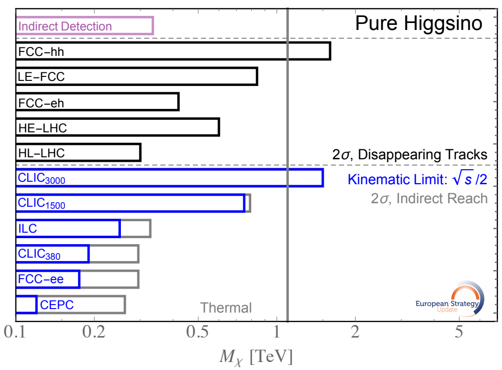


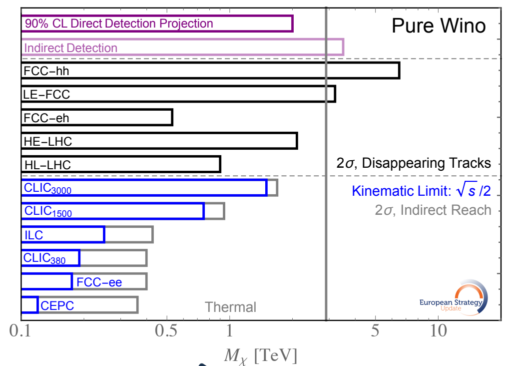
High dark photon mass region: 90% CL exclusion limits for Dark Photons in the plane mixing parameter ε versus Dark Photon mass. HL-LHC, CEPC, FCC-ee and FCC-hh curves correspond to 95% CL exclusion limits. The sensitivity of future colliders mostly covers the large-mass, large-coupling range. Belle II and LHCb upgrade provide additional coverage in the medium-mass, high-coupling region.

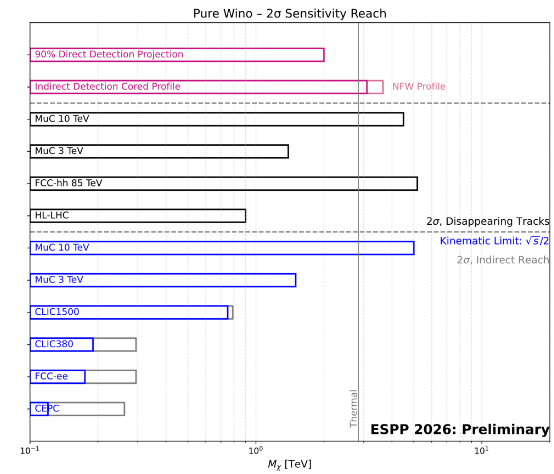
Annapaola’s Slides BSM

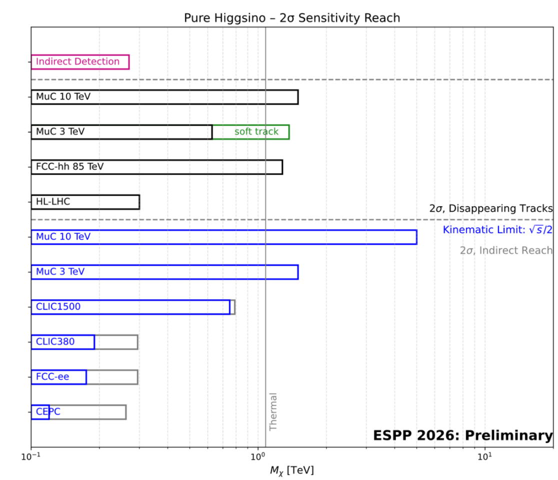
Then versus now. Thanks Monica!!!

Wino and higgsino: old vs new





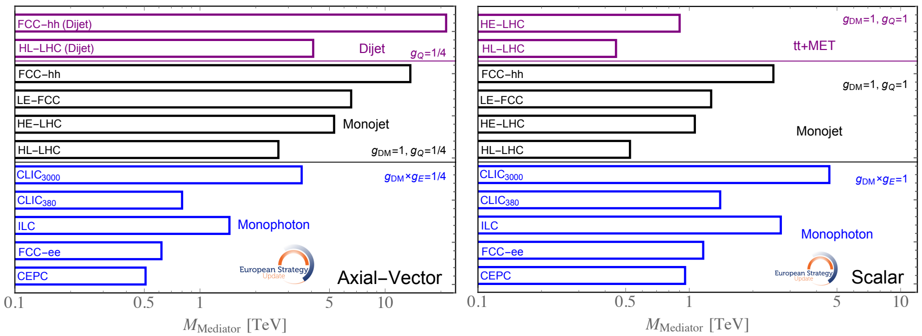


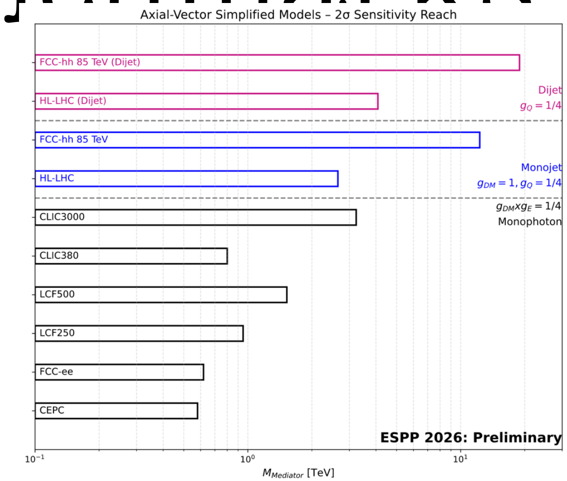


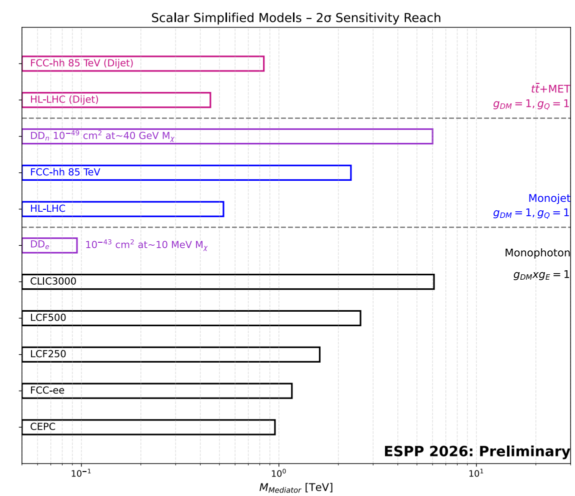
From ESPP2020 to ESPP2026

- A reduced com energy for FCC-hh still make it possible the discovery of a higgsino DM
  - CTAO could discard or discover it much sooner indirectly
  - Indirect searches already in tension with wino hypothesis
- MuC results now available:
  - MuC higgsino in reach also for MC 3 TeV with new soft-track based feasibility studies

Simplified model benchmarks







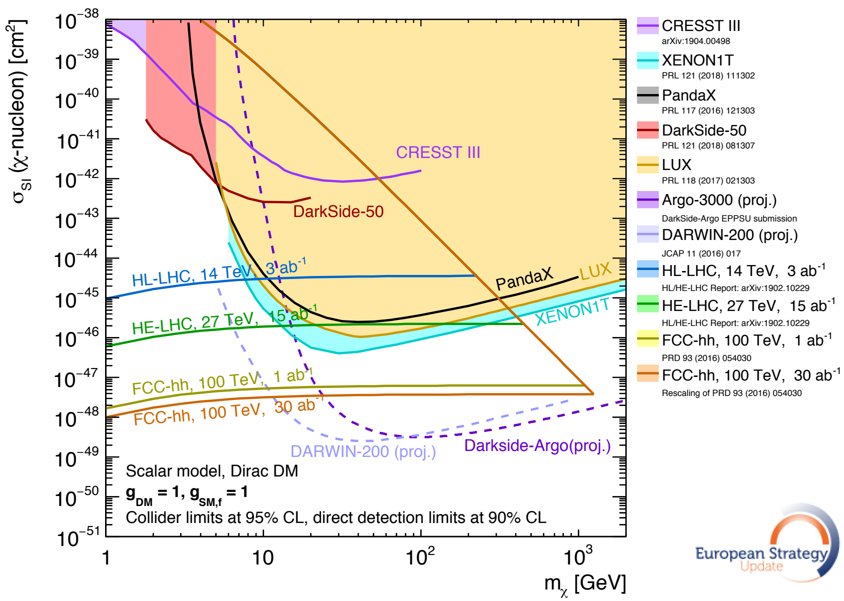
From ESPP2020 to ESPP2026

- Minor impact from reduced com energy for FCC-hh
- MuC results now available but not yet in the plot:

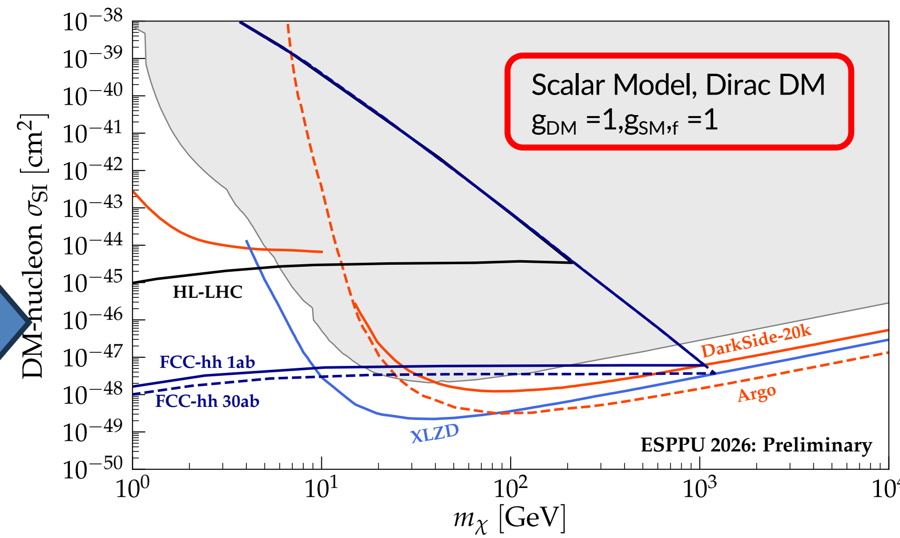
Simplified models: scalar mediators

From ESPP2020 to ESPP2026

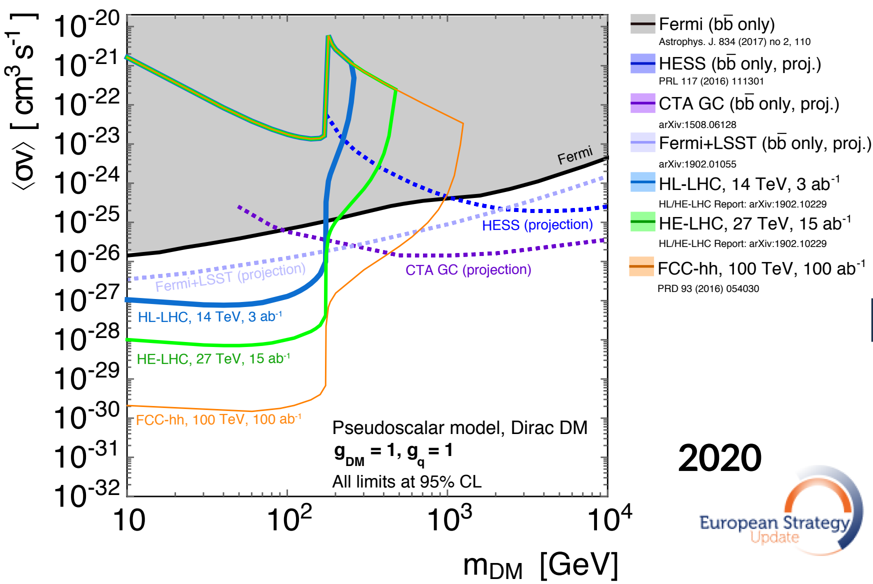
- Main changes in reach of DD – complementarity still very clear



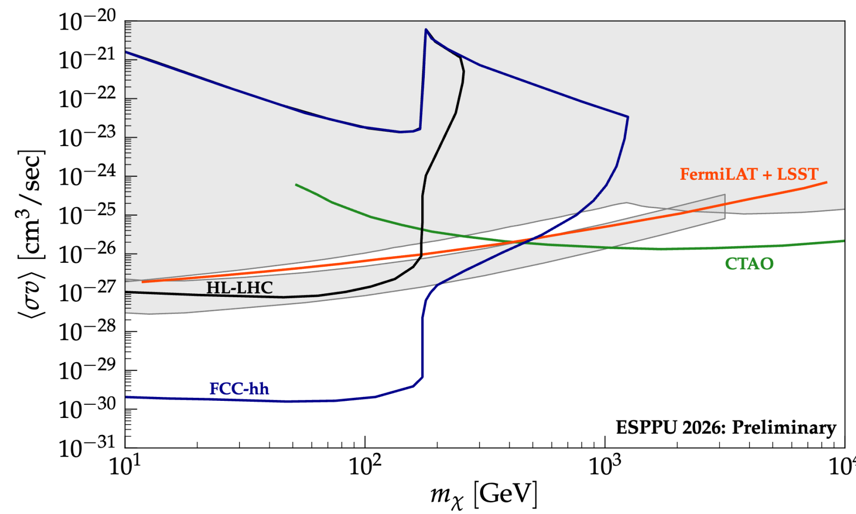
European Strategy Update



Simplified models: scalar mediators



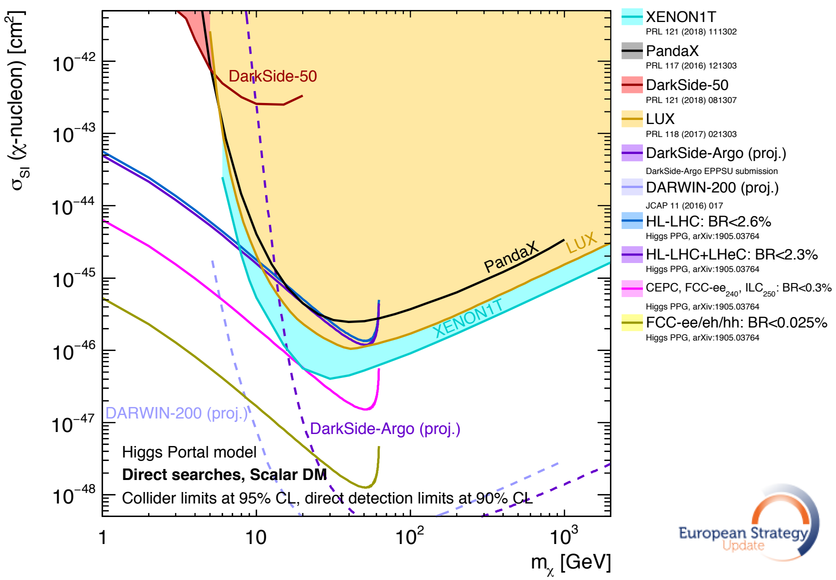
2020

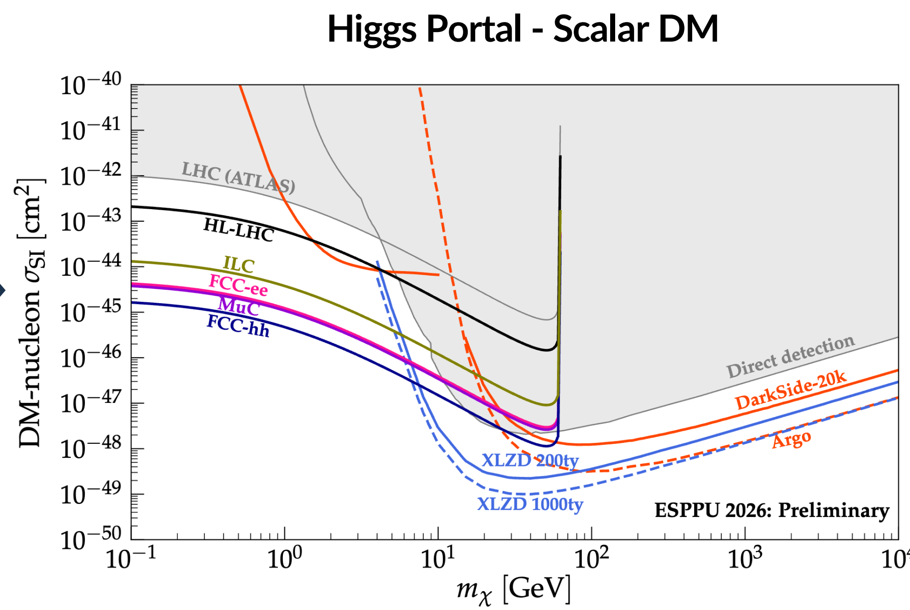


New: 2025

Higgs portal models

- Colliders do not change much
- Current LHC results cover regions at low mass

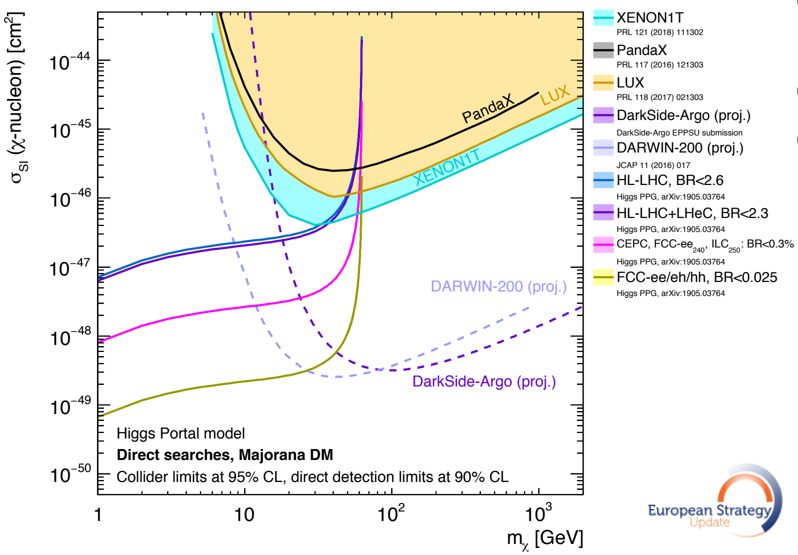


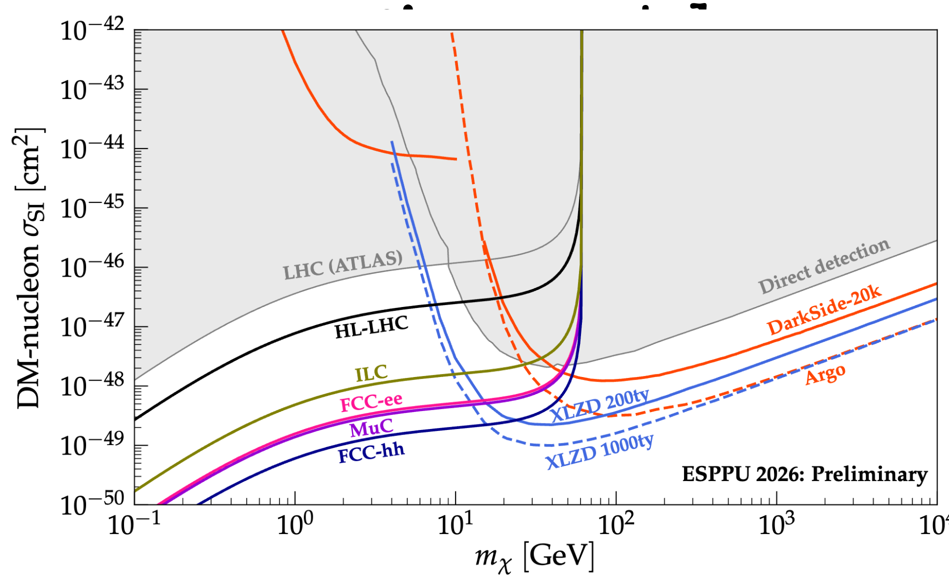


Higgs portal models

Higgs Portal - Majorana DM

- Colliders do not change much





Minimal models: Dark photons

– Some improved analyses from LHCb covering regions in the low

diate couplings

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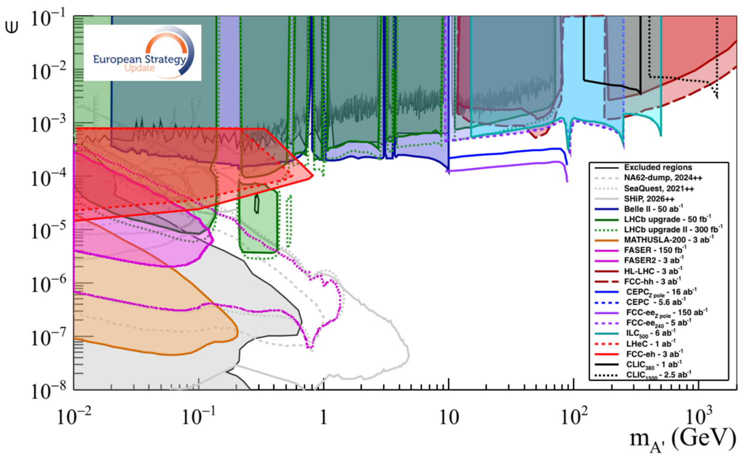
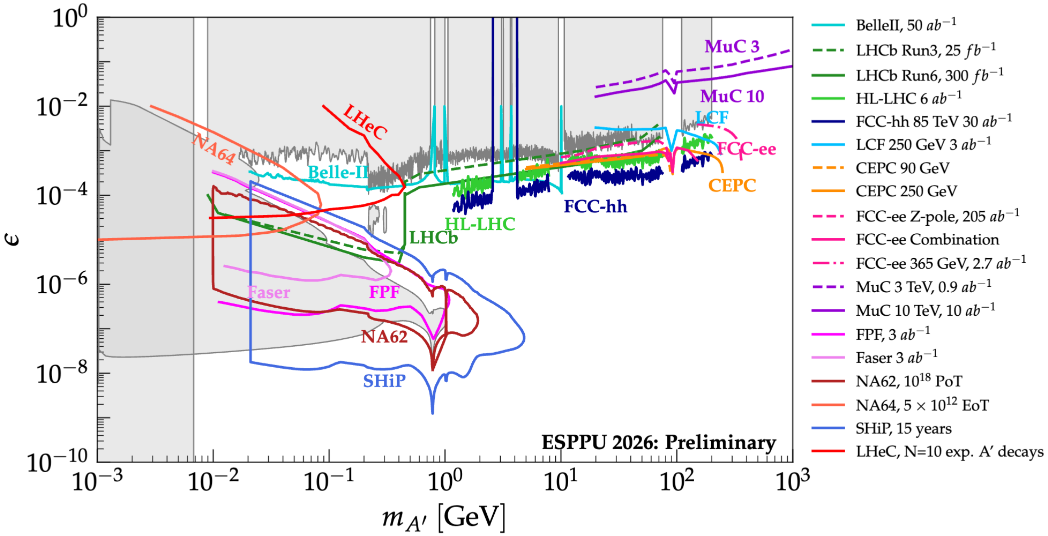
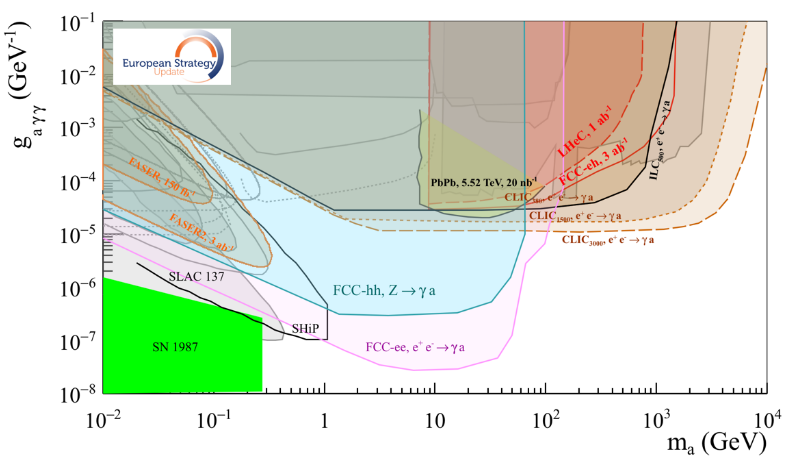
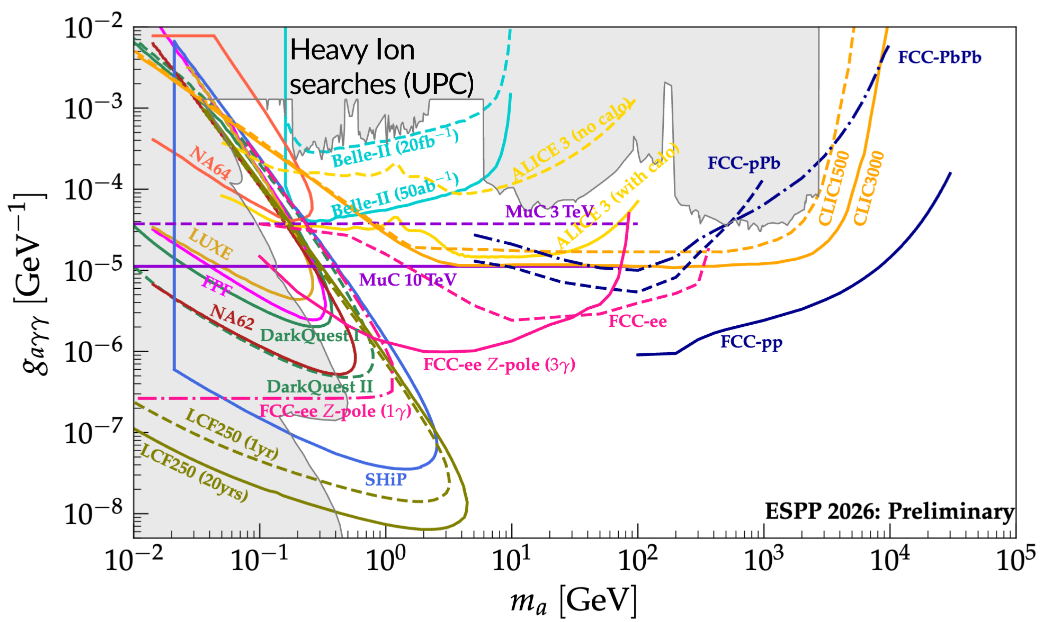




Minimal models: ALPs

- ALPs searches at colliders very diverse depending on couplings
  - Improvements from FCC-hh new analysis, Exploitation of light-by-light UP collisions at high mass/intermediate couplings
  - New studies from FCC-ee Z-pole and LCF in low mass/low coupling are





Minimal models: Heavy Neutral Leptons

- ESPP2020 – electron dominance; ESPP2026 – muon dominance
comp