Dark Matter and Dark Sector Searches at

FCC
hh ee he

Matthew McCullough

CERN

The Dark Side

Dark Matters

Evidence for dark matter is now overwhelming

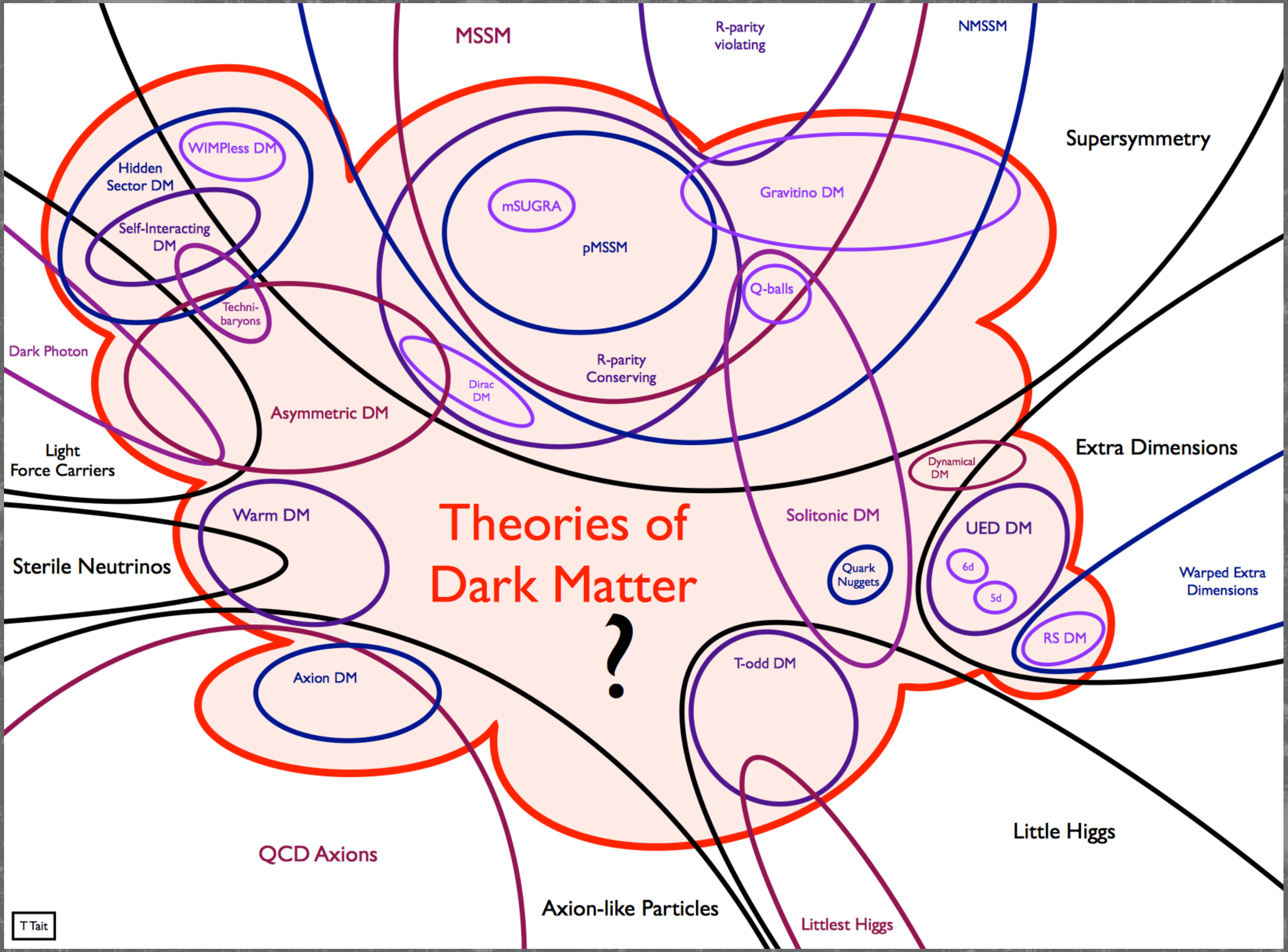
- Rotation curves
- CMB
- Large scale structure
- Velocity dispersions
- Gravitational lensing (Bullet Cluster)
- ....

Yet we have no clue what it is at the particle level!

?

Dark Matters

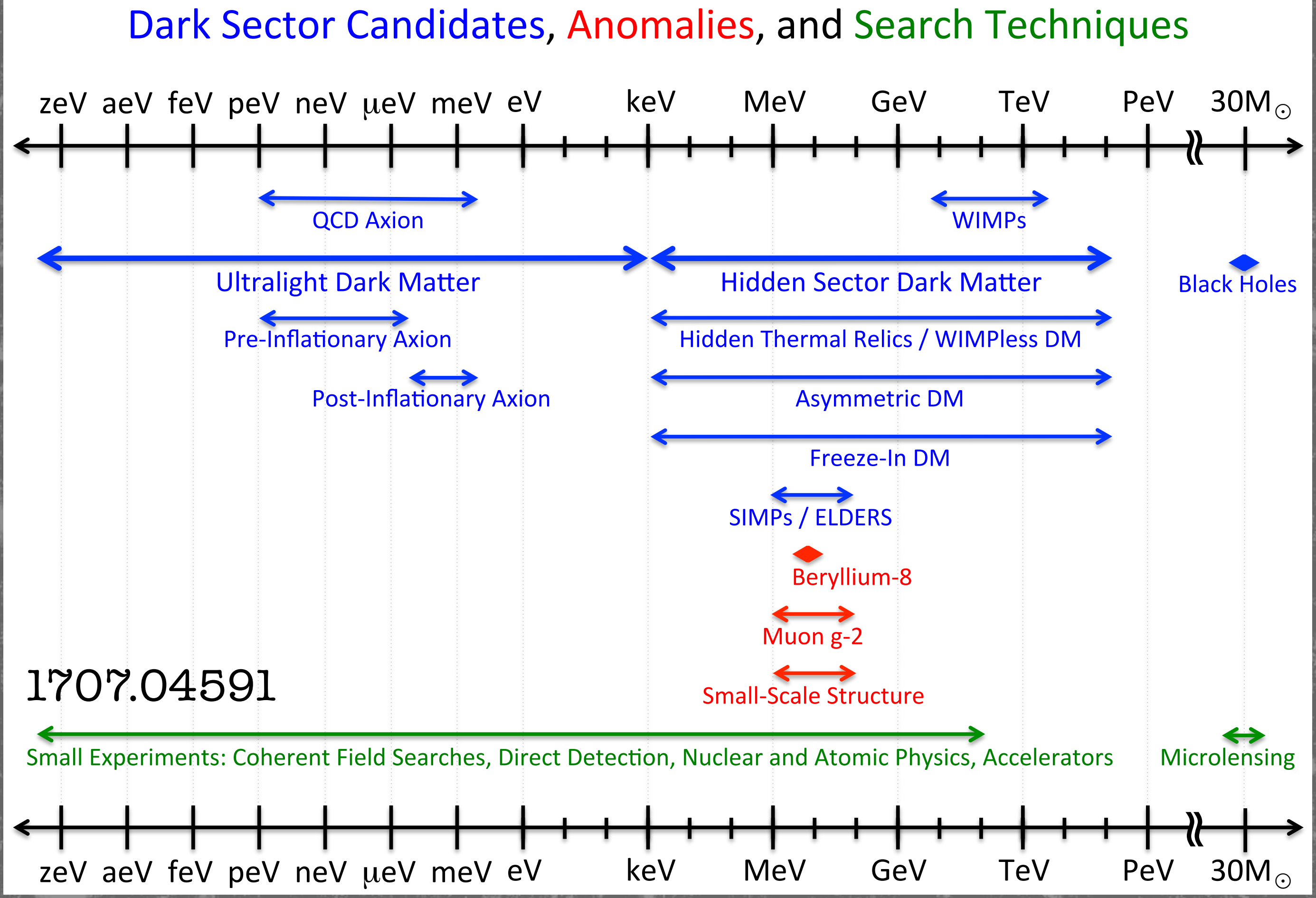
But there are some ideas…



Stolen from slides of Tim Tait

Dark Matters

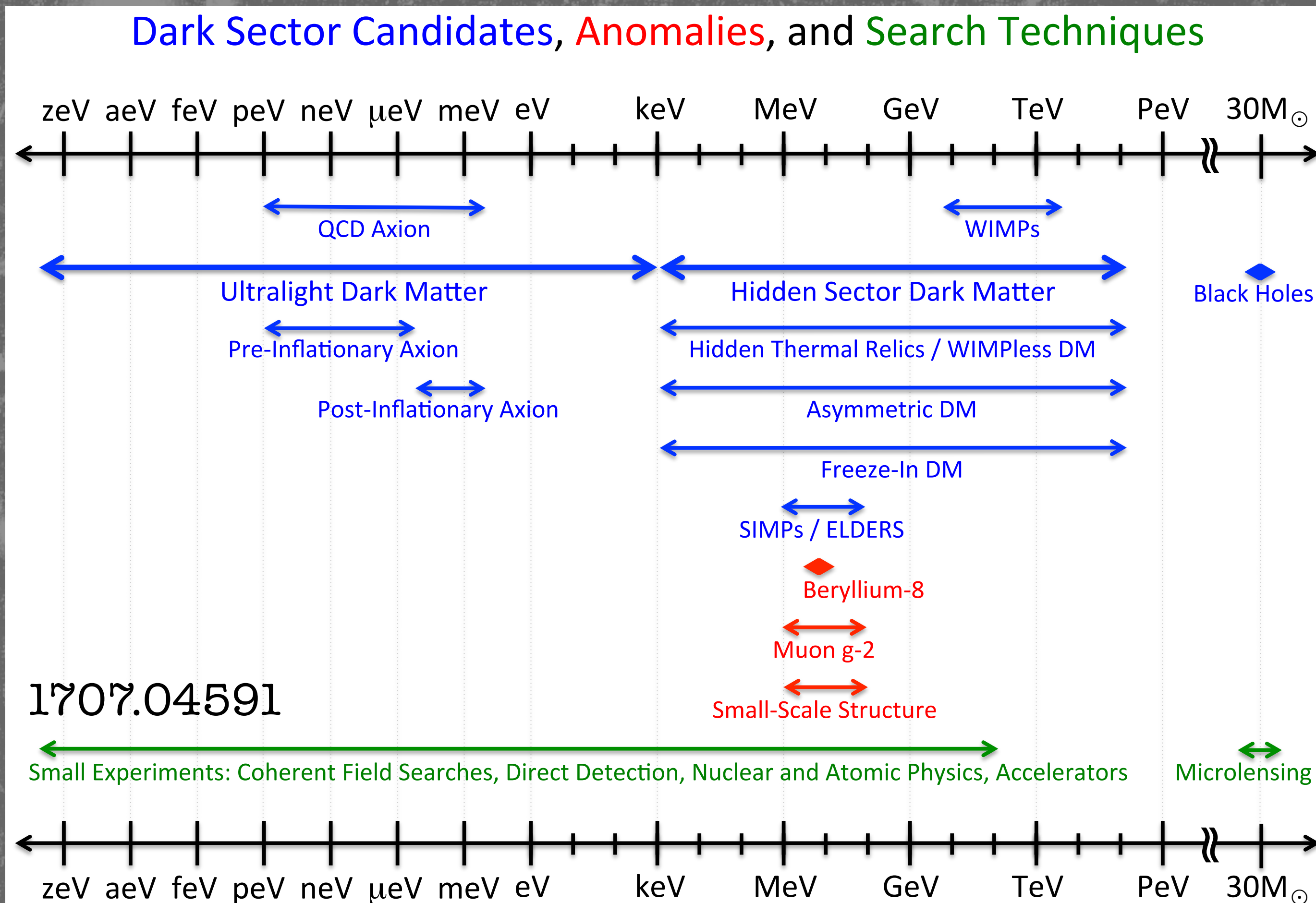
Our ignorance of the dark sector is logarithmic:



Experiments to cover every aspect of this plot should and will, hopefully, be undertaken.

Dark Matters

Our ignorance of the dark sector is logarithmic:



Only accelerators can create these particles in lab.

Dark Matters

Does cosmology give us any hint towards underlying particle physics scenarios?

Thermal Freeze-Out

For a given dark matter candidate, can trace the cosmological history from early times to present day.

For a given postulated interaction form, we can calculate the amount of dark matter left over.

Thermal Freeze-Out

Through this, cosmology provides a strong motivation for direct, indirect, and collider searches...

$$\Omega_{\rm DM} h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ \mathrm{TeV}}\right)^2 \left(\frac{0.3}{g_{\rm eff}}\right)^4$$

$$\Rightarrow$$

$$M_{DM} \sim \mathcal{O}(\text{few GeV}) \rightarrow \mathcal{O}(\text{10's TeV})$$

↑ Cosmological constraints

↑ Unitarity bounds

specifically, at TeV scale.

A Candle to light the dark?

This paradigm is very much still viable, and there are many many thermal freeze out models.... One class is Electroweak-Charged Massive Particles.*

Let us consider, as a standard candle, the WINO:

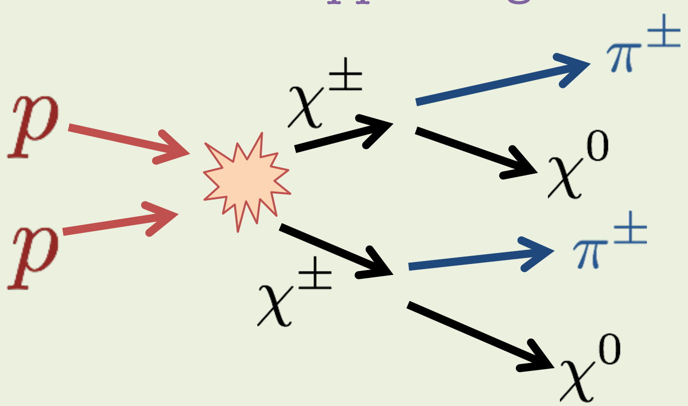
$$\mathcal{L} = \frac{1}{2} W^c \not{D} W - \frac{1}{2} M_W W^c W$$

* Also broadened to WIMPs.

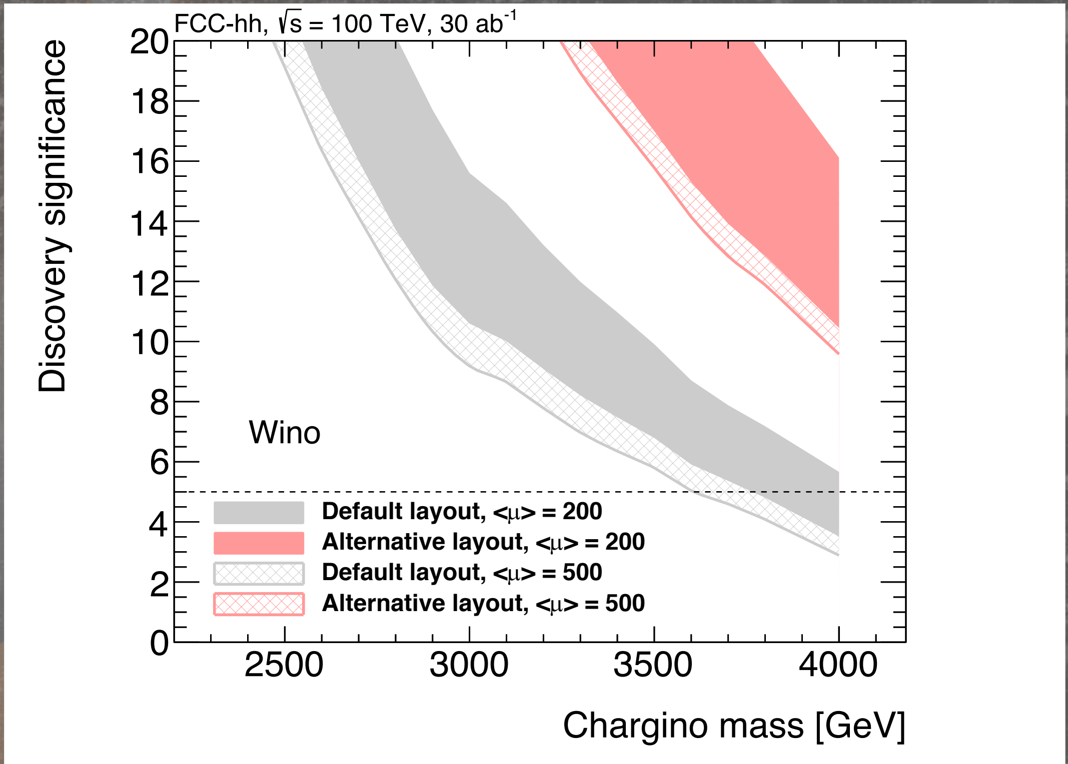
WINO Searches at FCC-hh

Disappearing Tracks

A promising search mode is for so-called “disappearing tracks”



The mass splitting is so small that the long-lived track essentially vanishes.

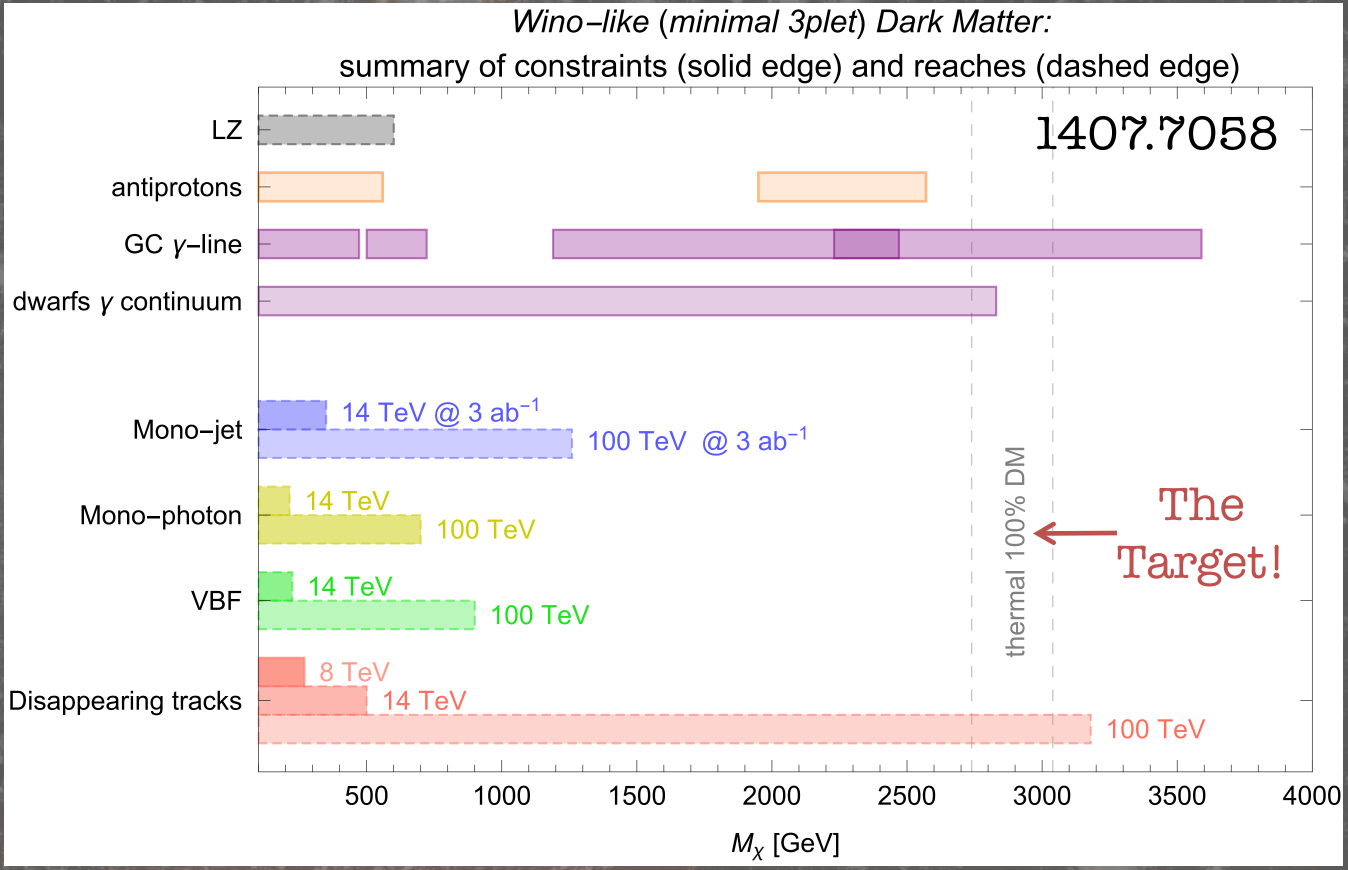


Reach extends far into target parameter space. In fact…

WINO Projection Summary

Direct, Indirect Detection

Collider Searches

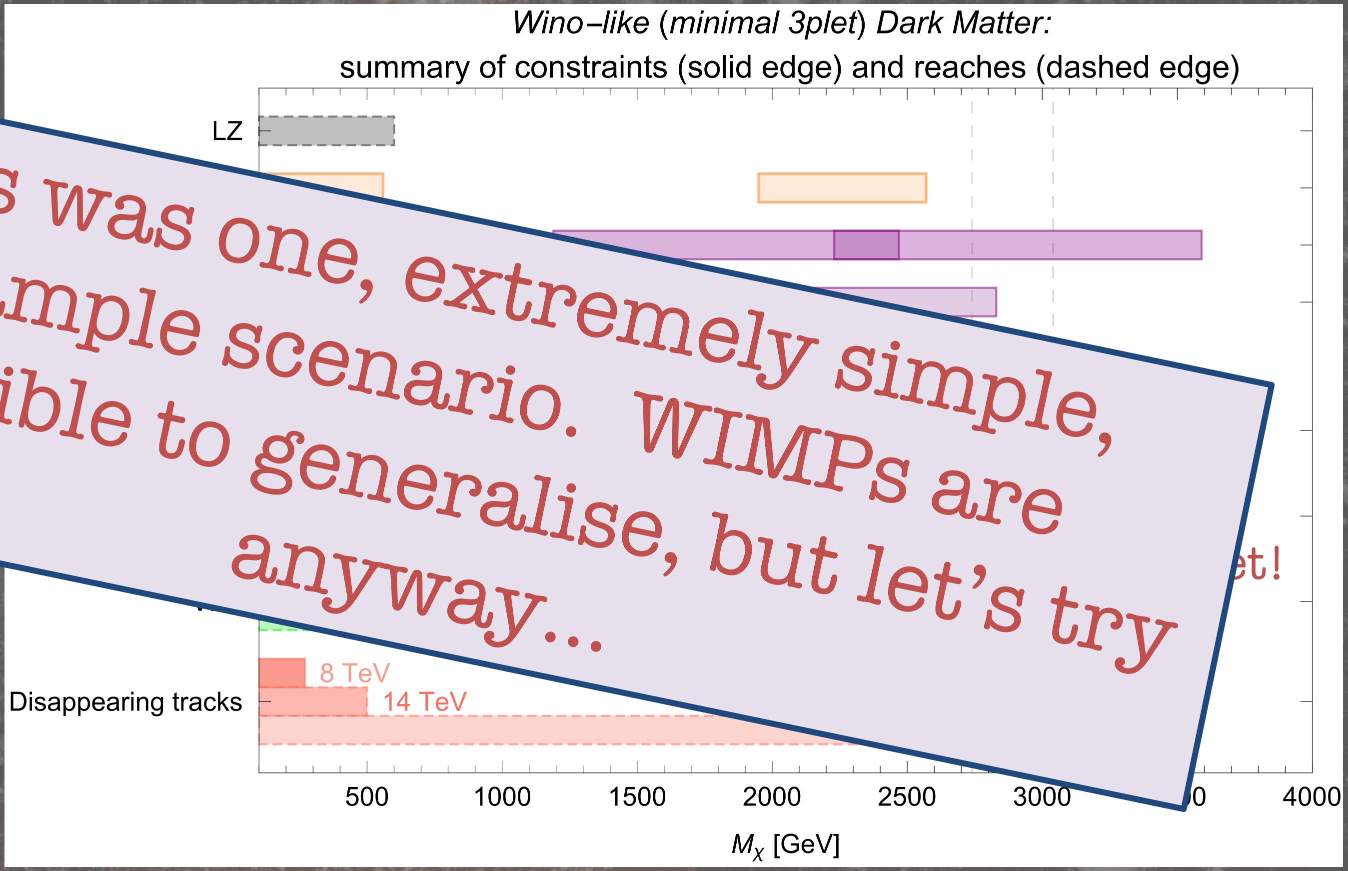


Only with FCC-hh can we unambiguously access the mass range where cosmology suggests we look.

WINO Projection Summary

Direc
Indir
Dete

Collider
Searches



This was one, extremely simple, example scenario. WIMPs are impossible to generalise, but let's try anyway…

Only with FCC-hh can we unambiguously access the mass range where cosmology suggests we look.

Simplified Dark Matter Models

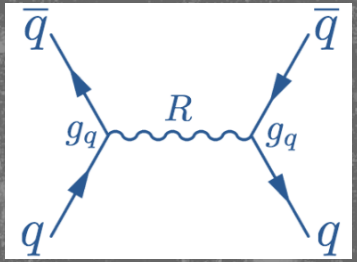
Write down simple models for dark matter interactions. Capture simplest experimental features.

Consider a scenario where dark matter interacts via a new Z' boson:

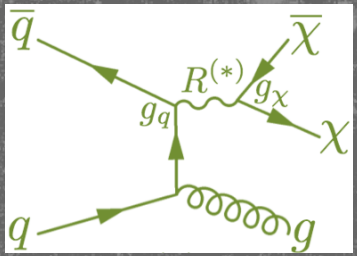
$$\mathcal{L} = -\, g_q \sum_q Z'^{\mu}\, \bar{q}\gamma_\mu q - \frac{g_{\rm DM}}{2} Z'^{\mu}\, \bar{\chi}\gamma_\mu\gamma^5\chi$$

These interactions, combined with the particle masses, let us calculate basic features.

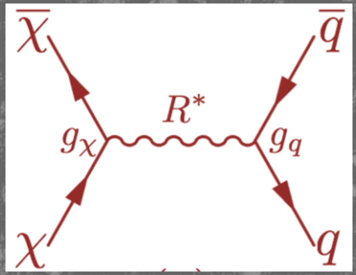
Dijet Resonances



Missing Energy



Relic Density

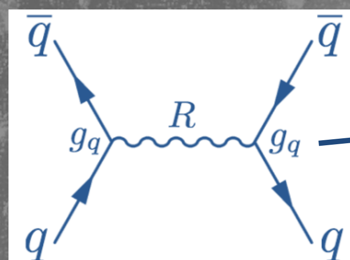


Simplified Dark Matter Models

Consider a scenario where dark matter interacts via a new Z' boson:

1606.00947

Dijet Resonances



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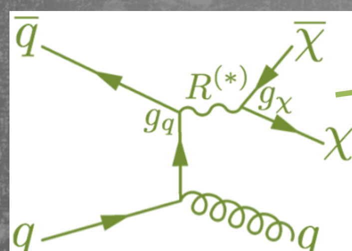

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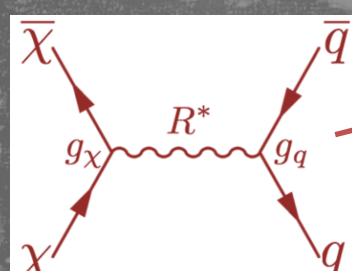
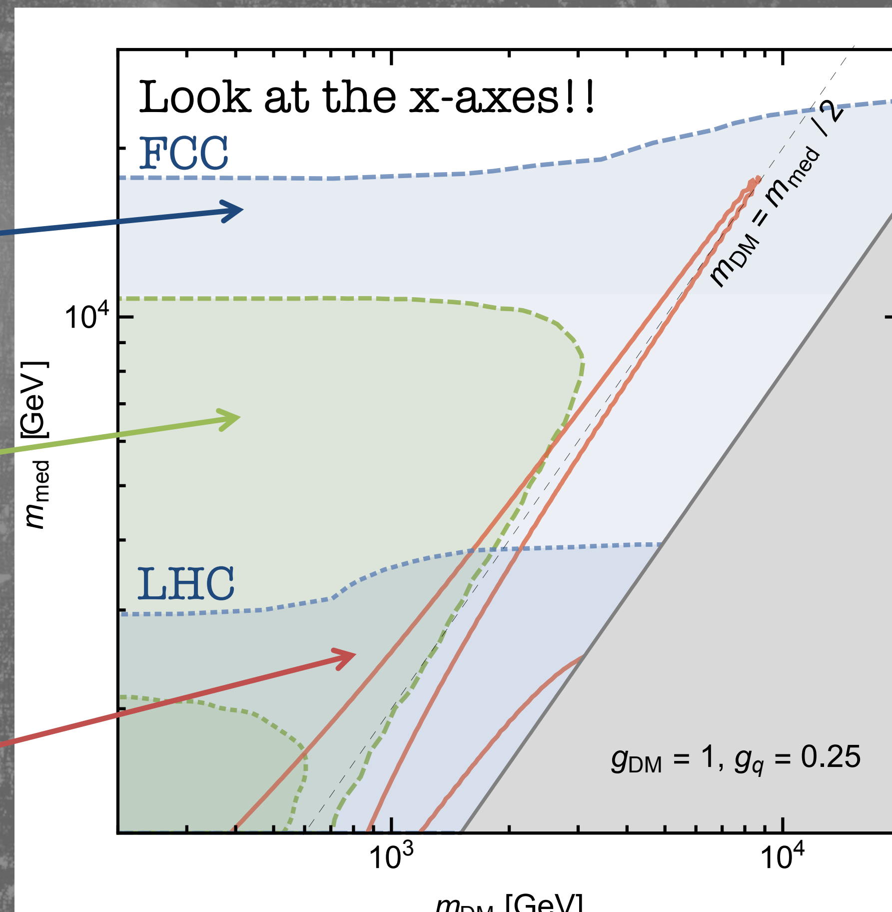




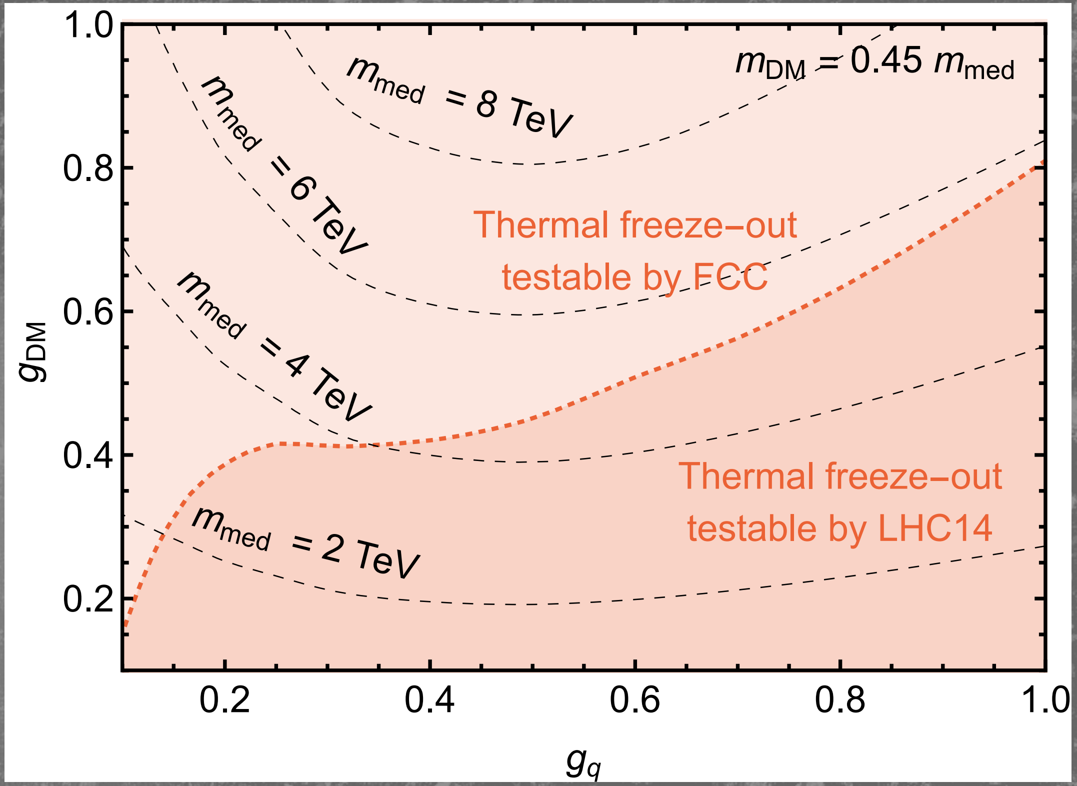
Simplified Dark Matter Models

1606.00947

This model has four parameters.

$$\mathcal{L} = -\, g_q \sum_q Z'^{\mu}\, \bar{q}\gamma_\mu q \; - \frac{g_{\rm DM}}{2} Z'^{\mu}\, \bar{\chi}\gamma_\mu\gamma^5\chi$$

Two couplings and two masses. For illustration, set a ratio between mediator and DM mass, and always picking mass that gives the right relic density.



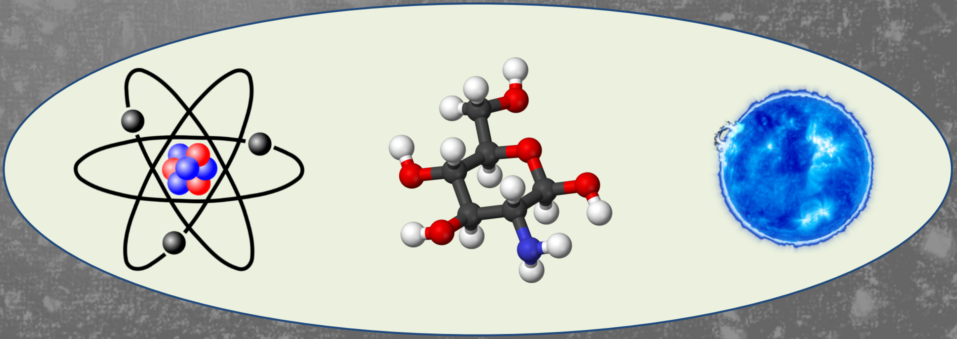
FCC covers swathes of new parameter space with reasonable couplings.

Dark Sectors

Only 18% of all matter in Universe is visible.

e u d Z h μ c s g τ t b γ W

Within that 18% we observe extraordinary complexity.



The photon, despite not being matter itself, gave us our first tool to explore the visible sector.

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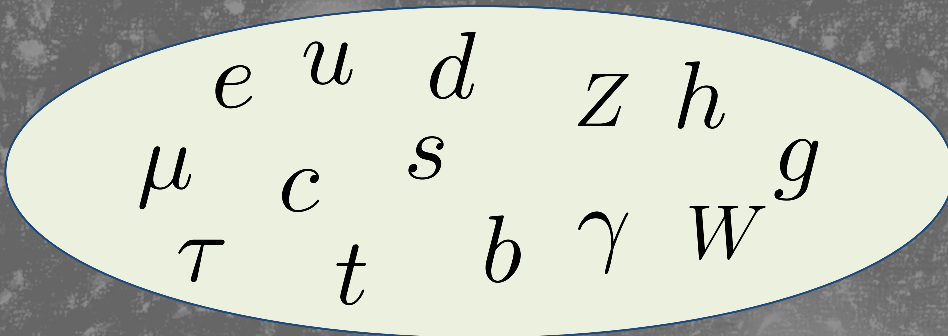

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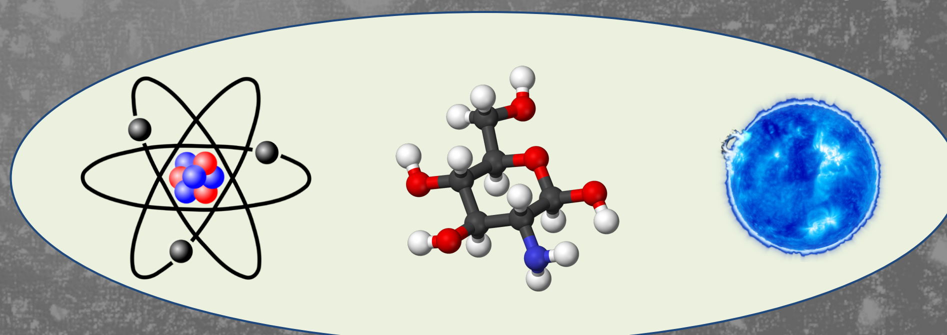


Similarly, it may be the light mediators, or other states, that open the window to the dark sector.

ALPs

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

Standard Model	Dark Sector
Z	Z'
π	a

ALPs

We will here focus on this case:

π — Standard Model

a — Dark Sector

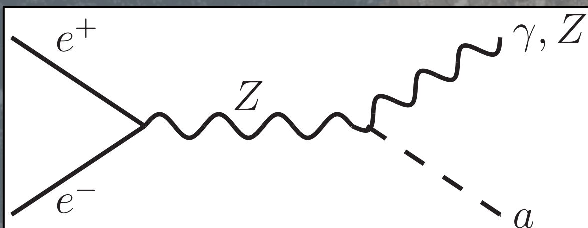
Pseudo-Goldstone Bosons can be naturally light.
Typically called "Axion-Like Particles (ALPs)".

$$\mathcal{L}_{\text{eff}} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}$$

Many possible interactions, but focus on these.

ALPs: FCC-ee

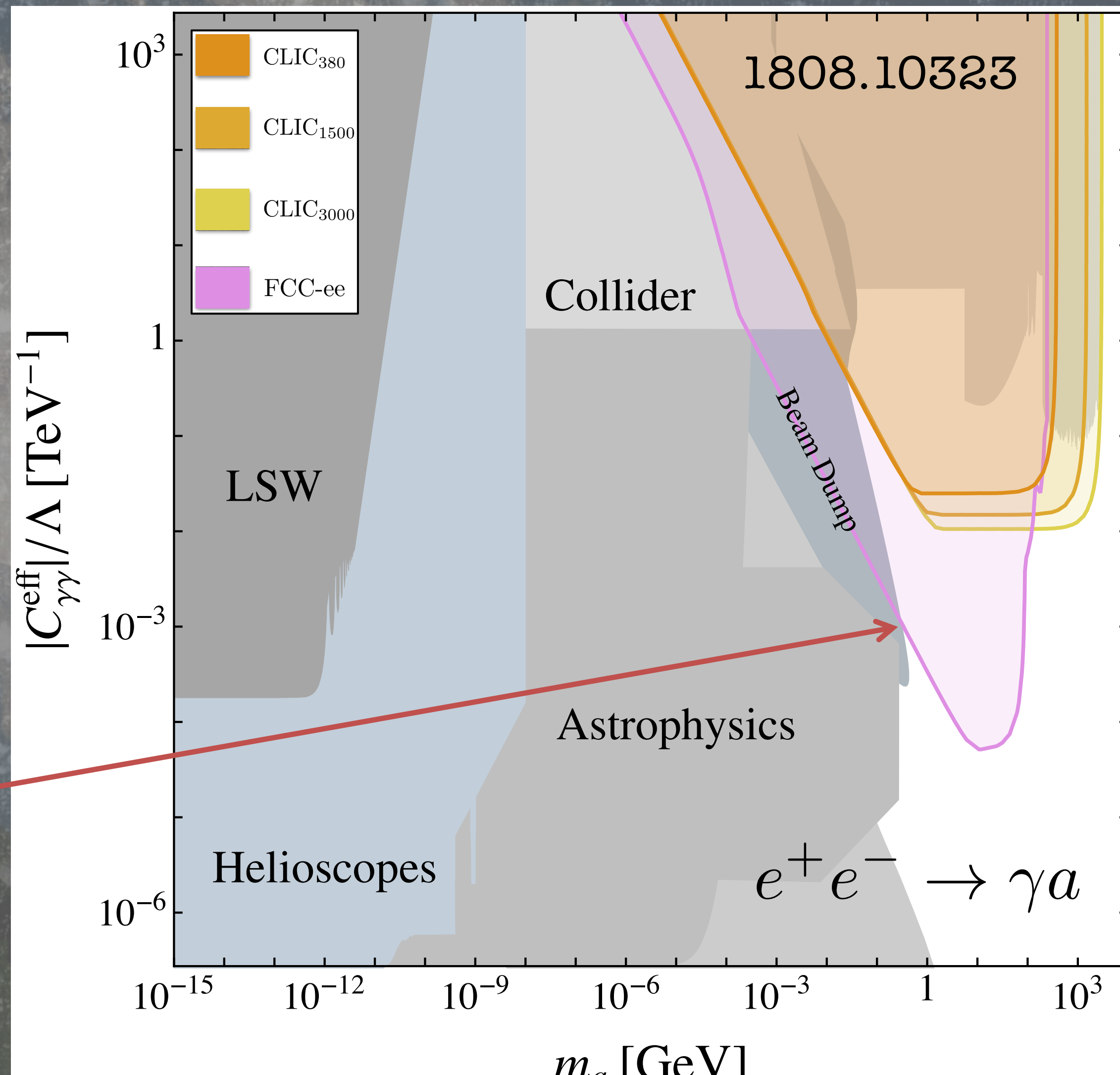
Key production channel:



Followed by:

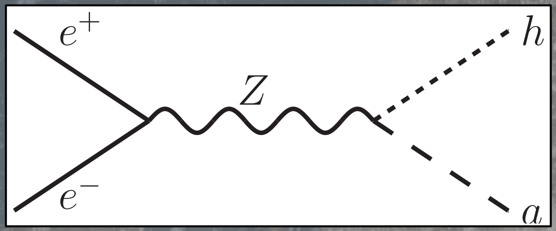
$$a \to \gamma\gamma$$

FCC-ee is an <u>intensity frontier</u> machine!!!



ALPs: FCC-ee

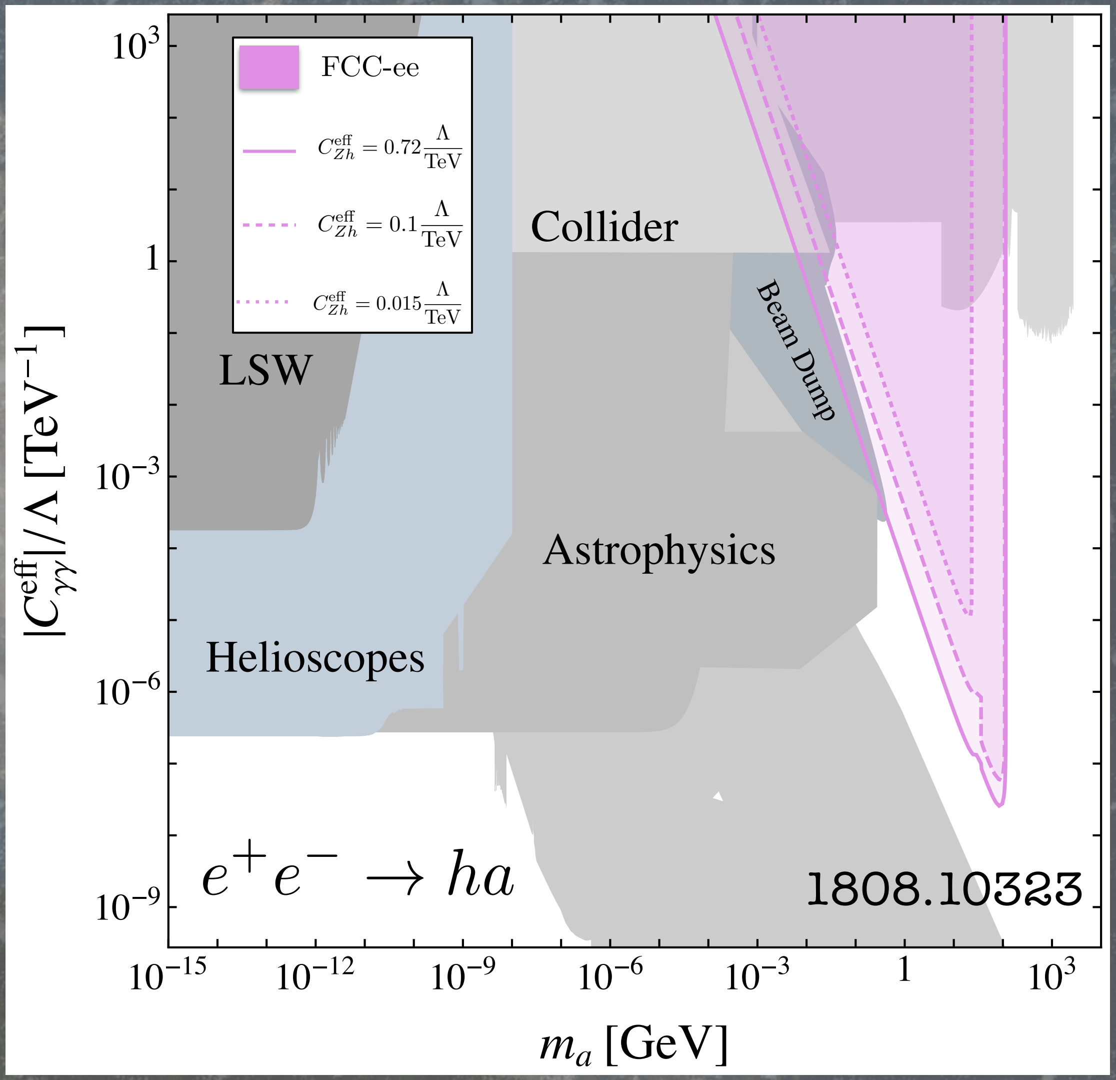
The Higgs is a key player:



Followed by:

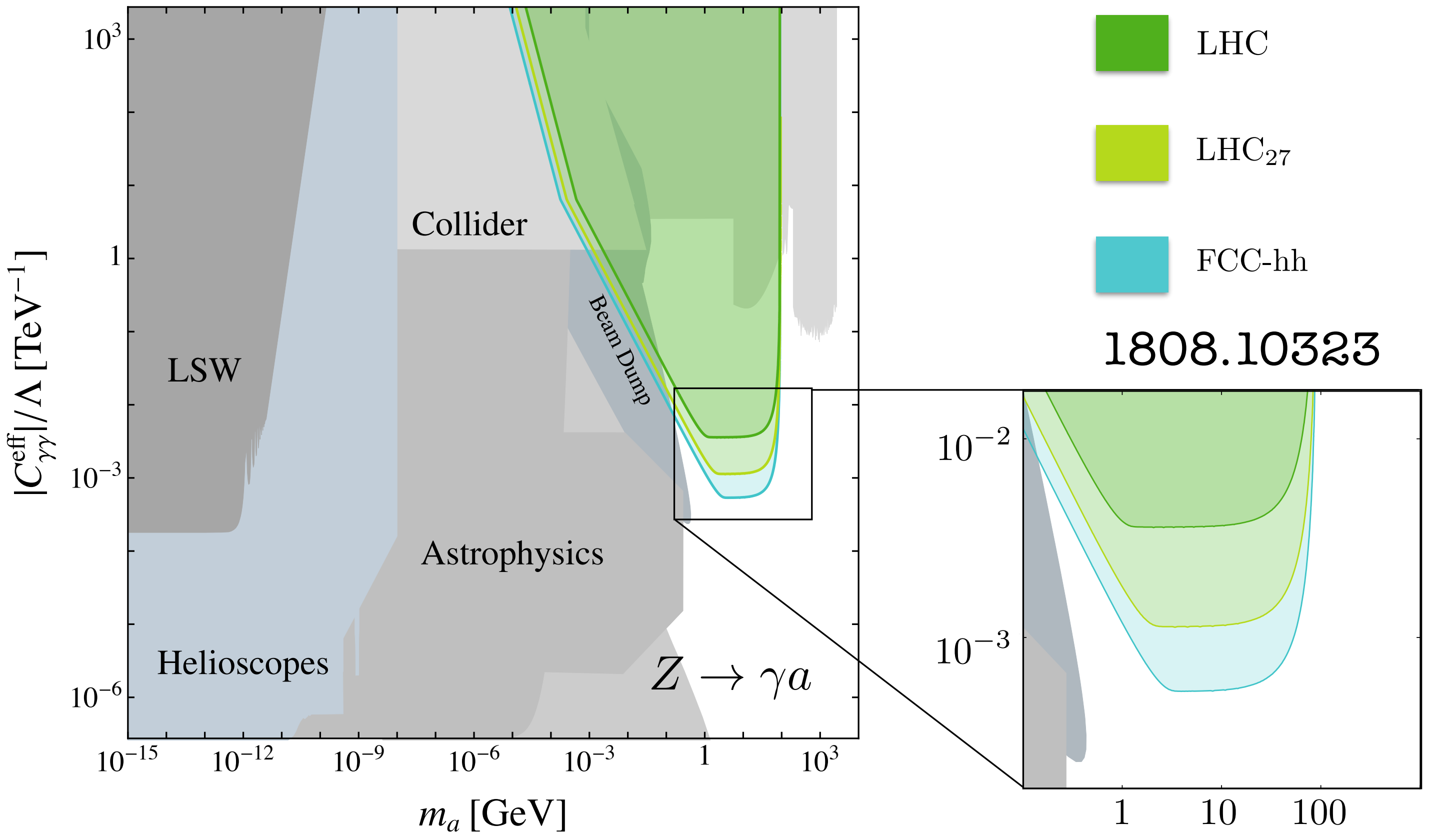
$$a \to \gamma\gamma$$

FCC-ee can probe extremely high scales through the Higgs.



ALPs: FCC-hh

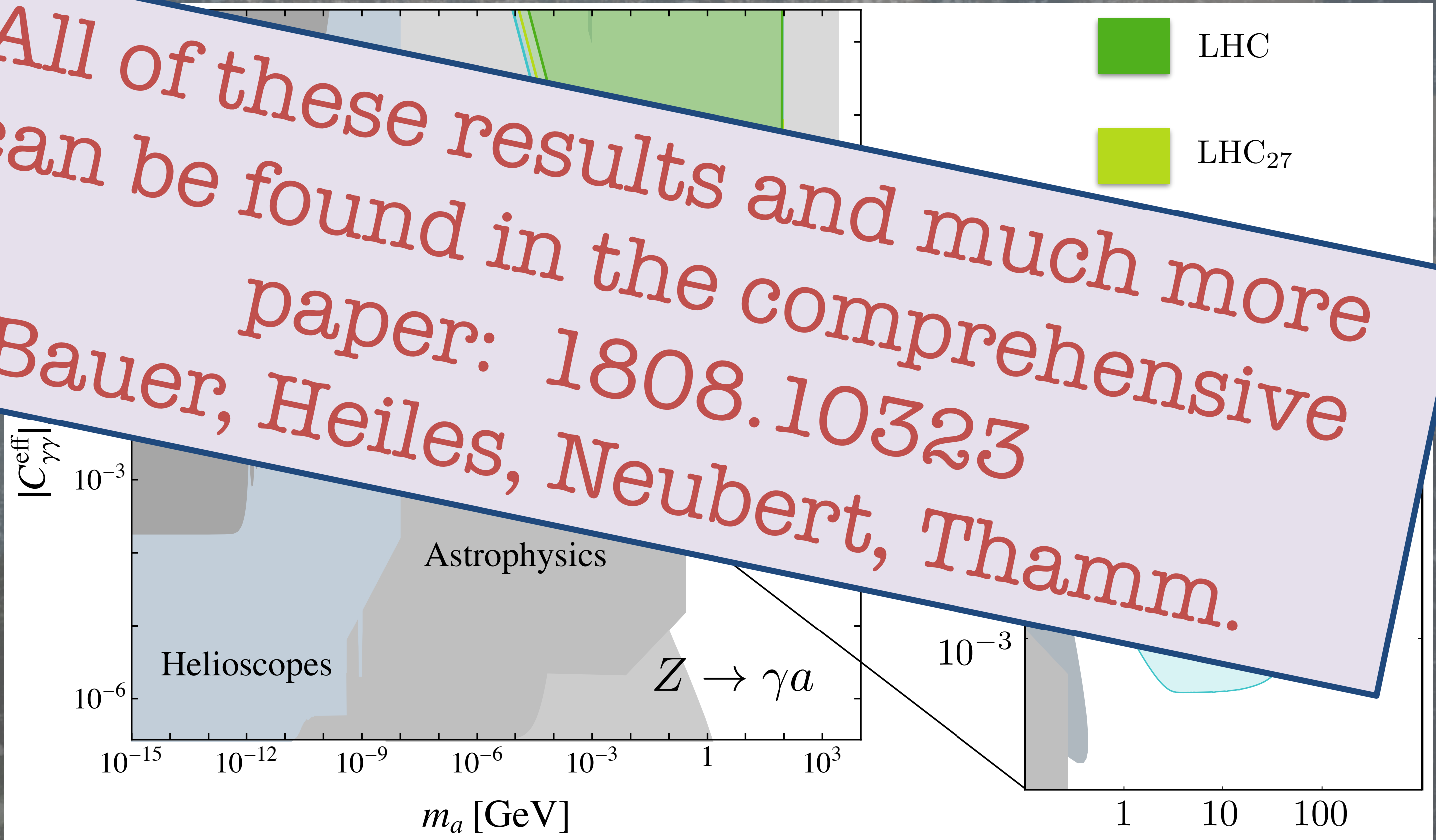
Future proton colliders can also reach intensity frontier levels:



Again here searching for the decay: $a \to \gamma\gamma$

ALPs: FCC-hh

Future proton colliders can also reach intensity frontier levels:

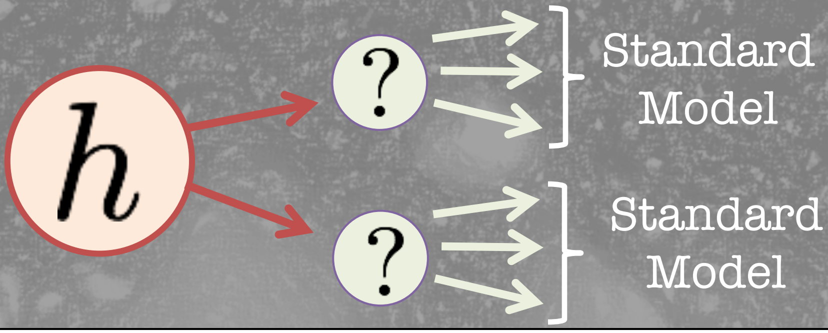


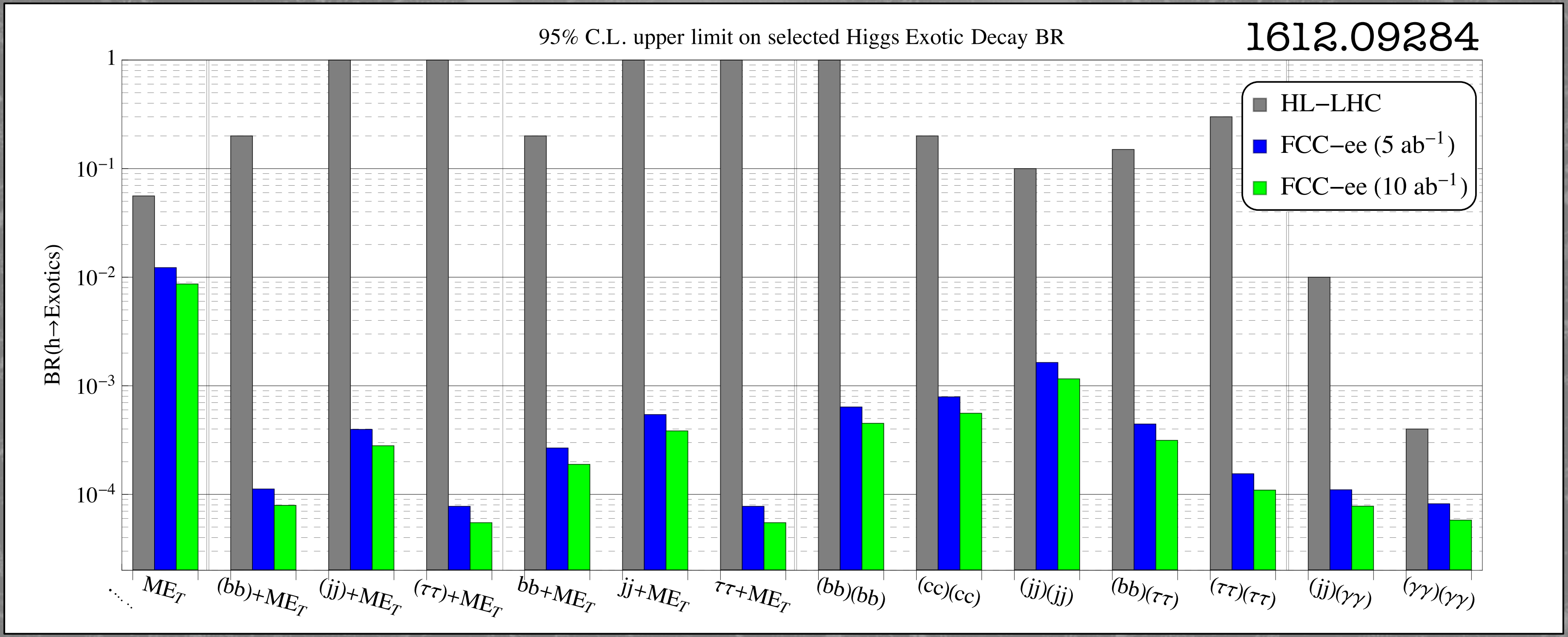
All of these results and much more can be found in the comprehensive paper: 1808.10323
Bauer, Heiles, Neubert, Thamm.

Again here searching for the decay: $a \to \gamma\gamma$

Higgs

The Higgs is totally different from other particles and could be our new window to the dark sector:





Higgs

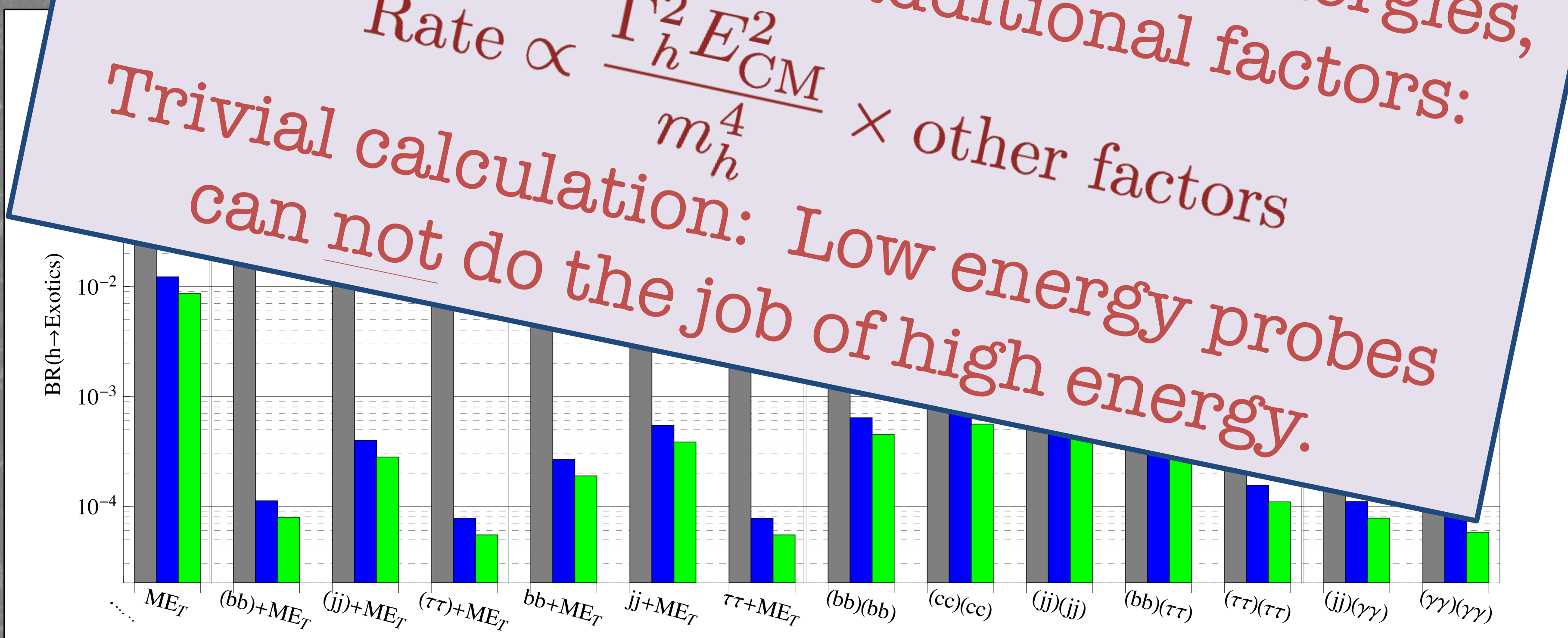
The … is totally different from other particles and … window to the dark sector:

Standard

The only way to search for such scenarios is with a Higgs boson. At lower energies, suppressed by tiny additional factors:

$$\text{Rate} \propto \frac{\Gamma_h^2 E_{\text{CM}}^2}{m_h^4} \times \text{other factors}$$

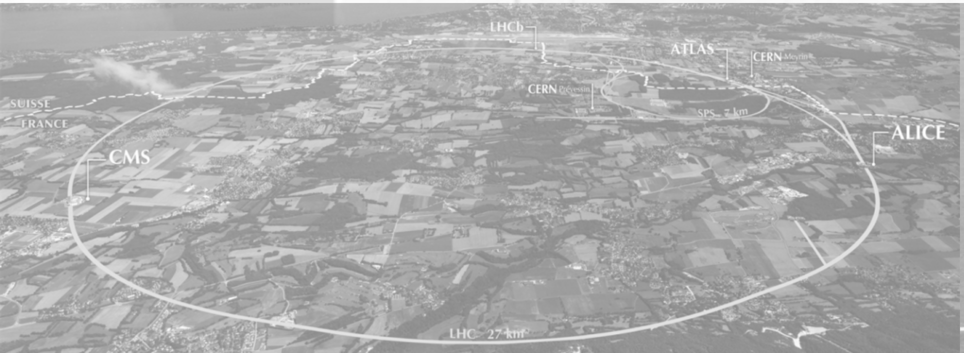
Trivial calculation: Low energy probes can not do the job of high energy.

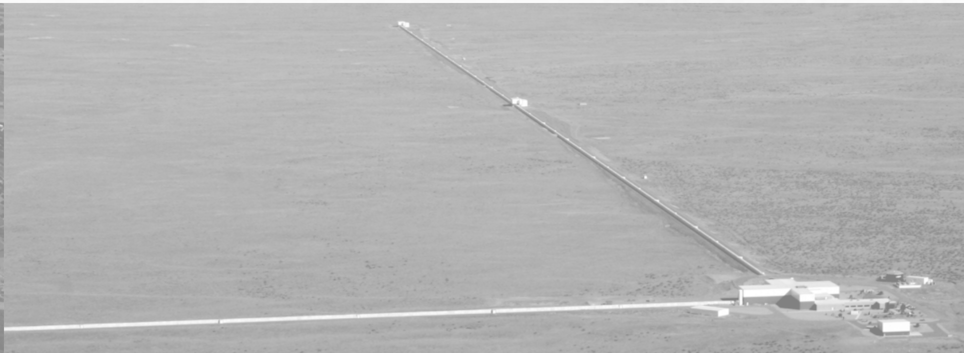


Summary

Fundamental advances come when experimental measurements challenge theoretical ideas.

The dark matter puzzle is arguably the most significant question in fundamental physics. We must deploy <u>every tool</u> to uncover the fundamentals of the dark sector.

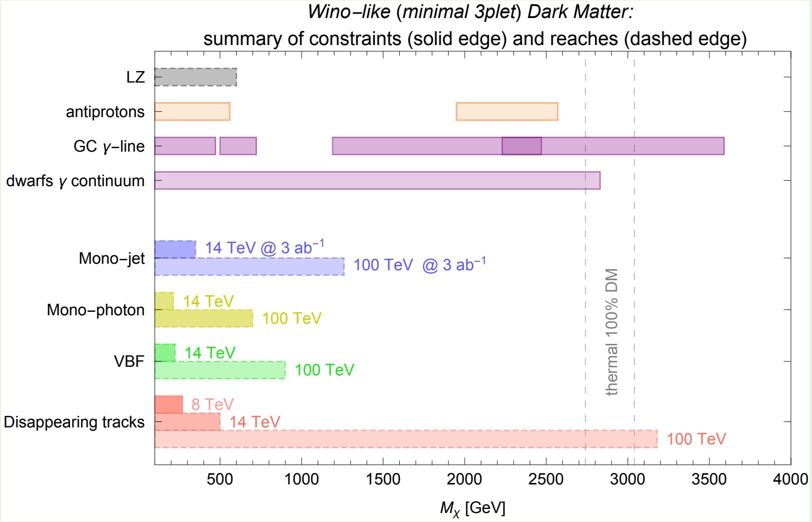




Summary

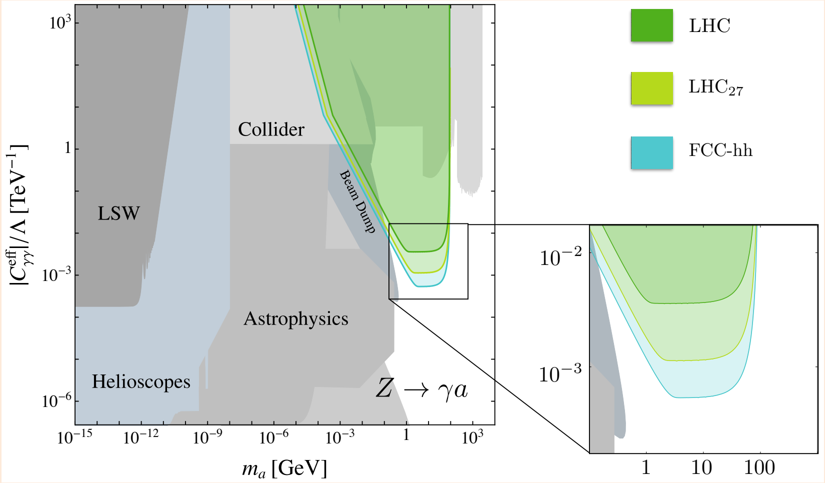
By the end of the HL-LHC era we will have:

Impressive...



but incomplete, exploration of electroweak scale dark matter candidates.

Early exploration of hidden sector particles at weak scale...



but not yet as a high energy component to intensity frontier programme.

Summary

Future Circular Colliders

FCC
hh ee he

Offer:

- Unprecedented exploration of the dark sector, from light dark matter to above the TeV scale.
- An indispensable high-energy component to the intensity-frontier hunt for new, weakly-coupled, hidden sector particles.