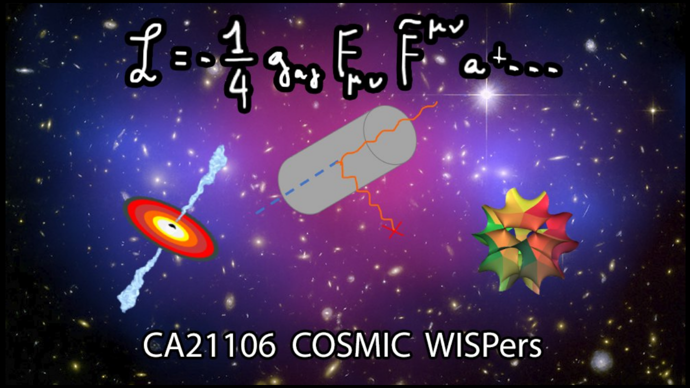
Searching for WISPs at the LHC with the MoEDAL-MAPP Experiment

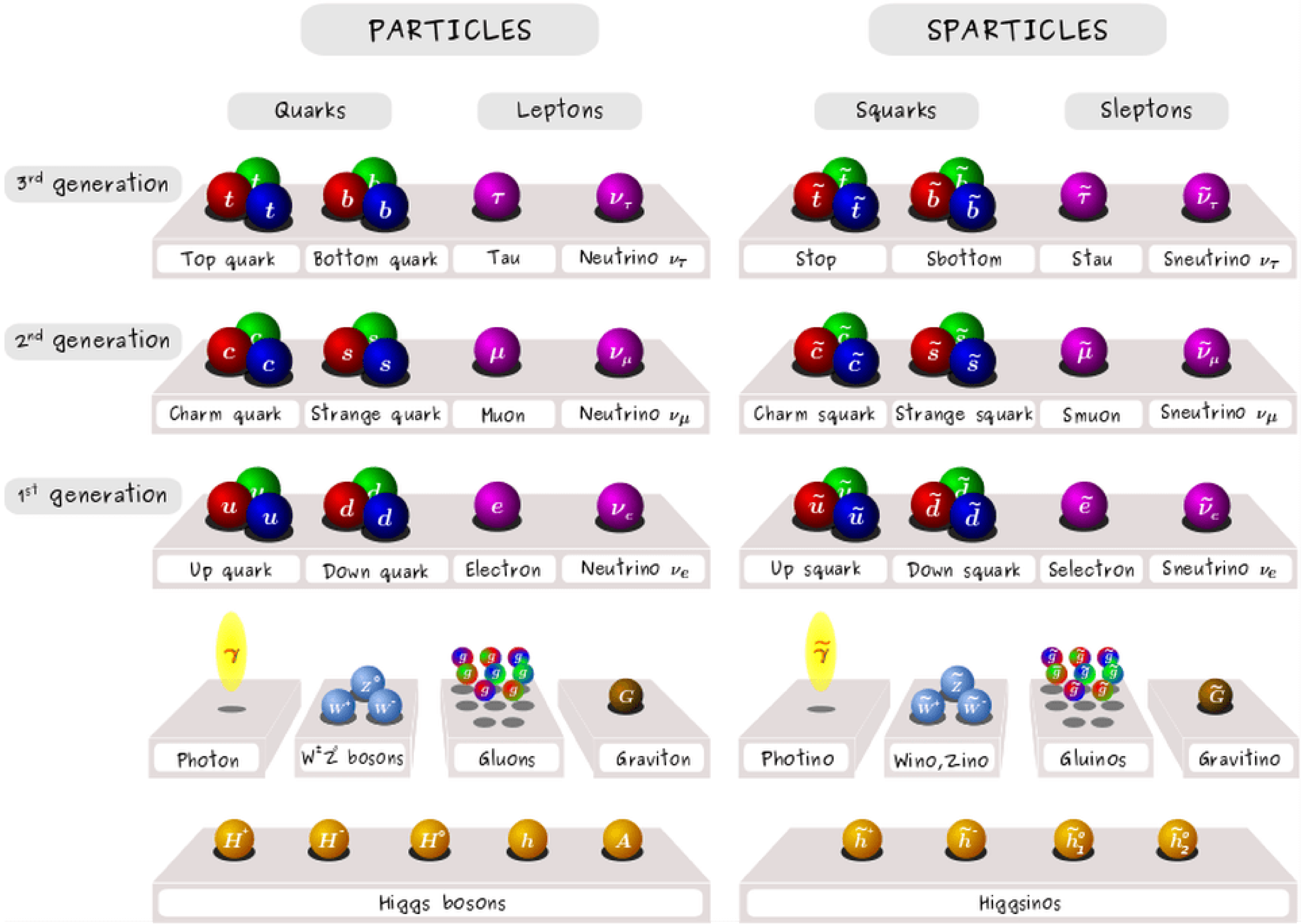
Michael Staelens (michael.staelens@ific.uv.es), Ph.D.
Instituto de Física Corpuscular (IFIC), CSIC–Universitat de València

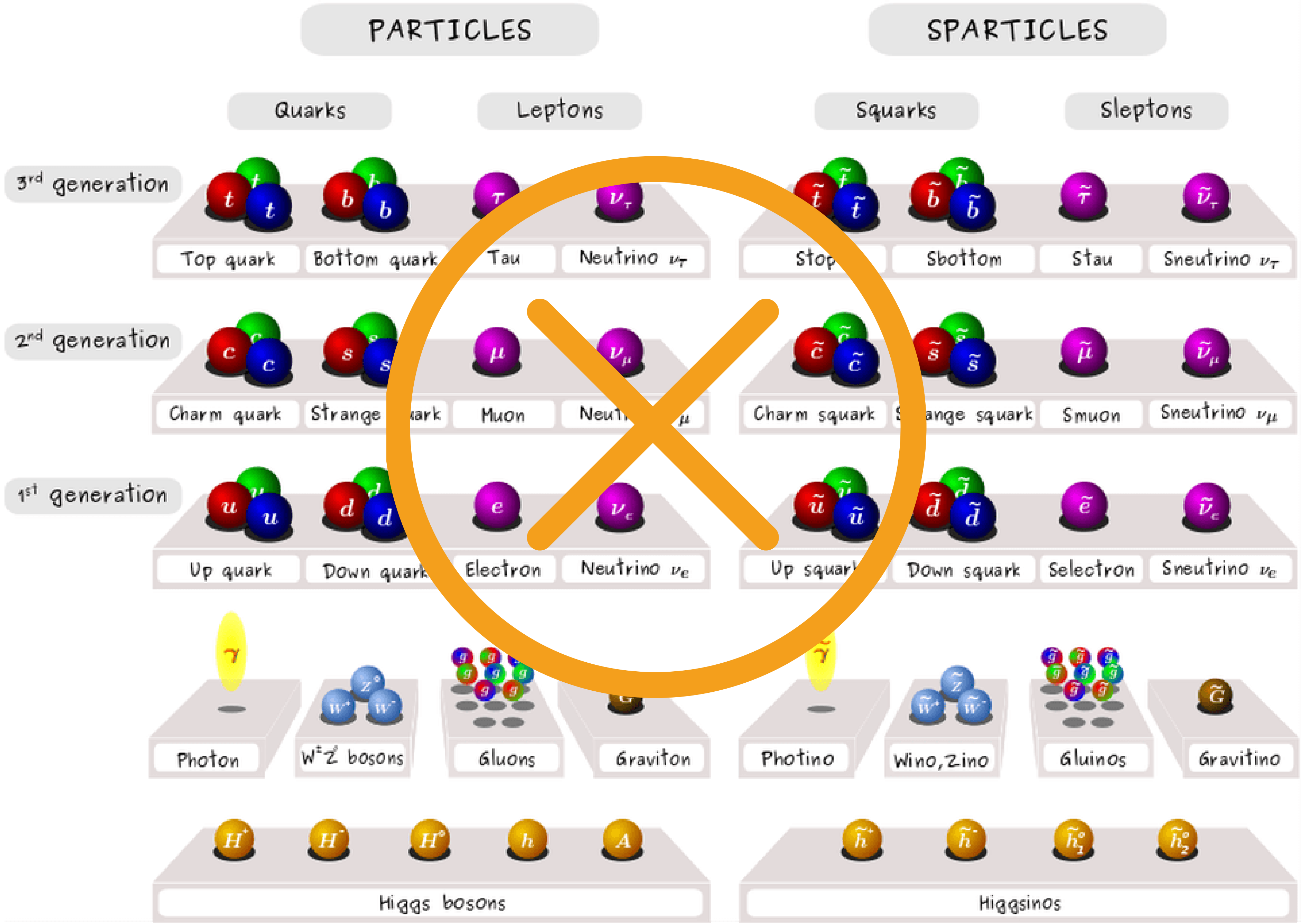


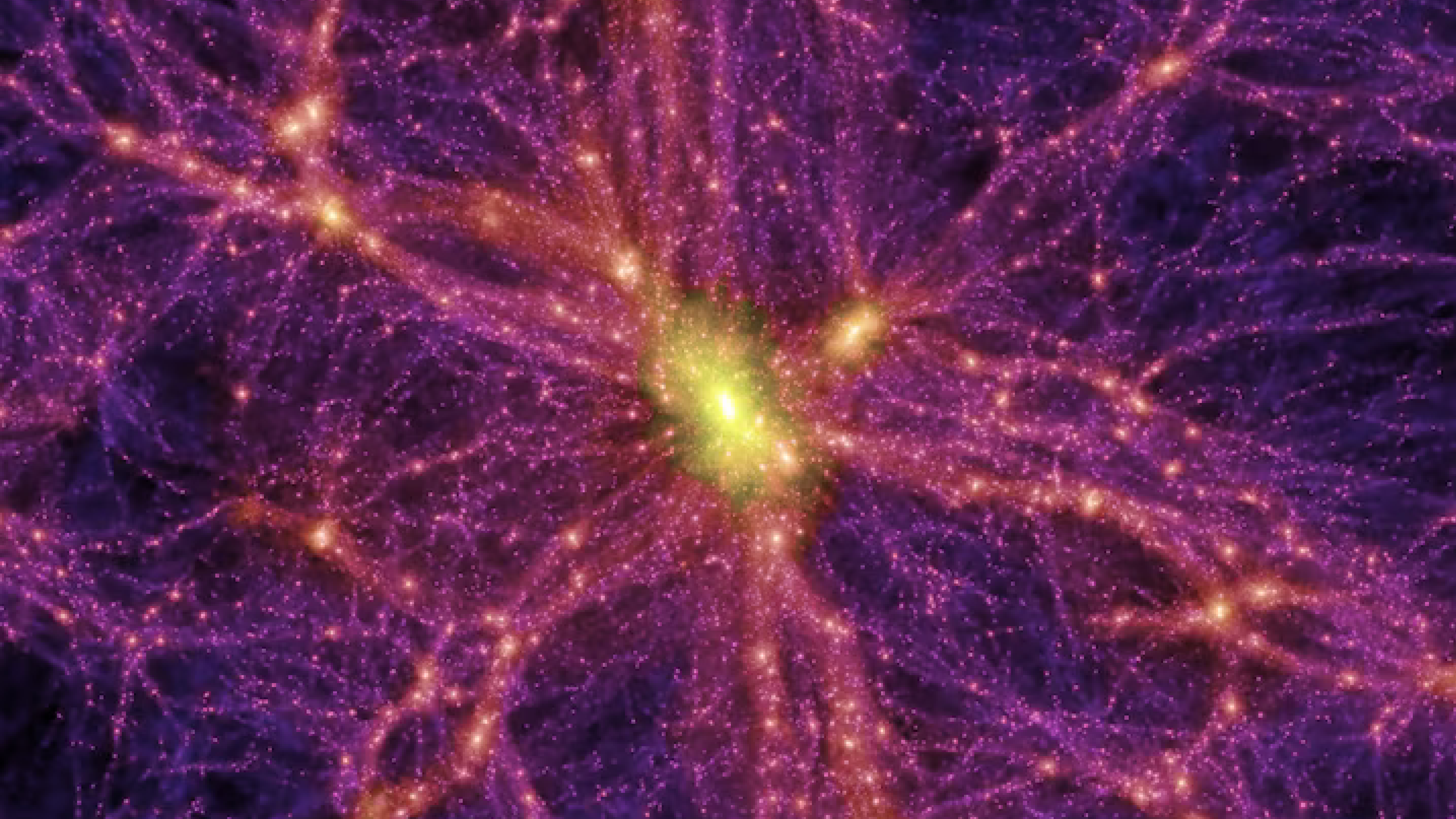
1

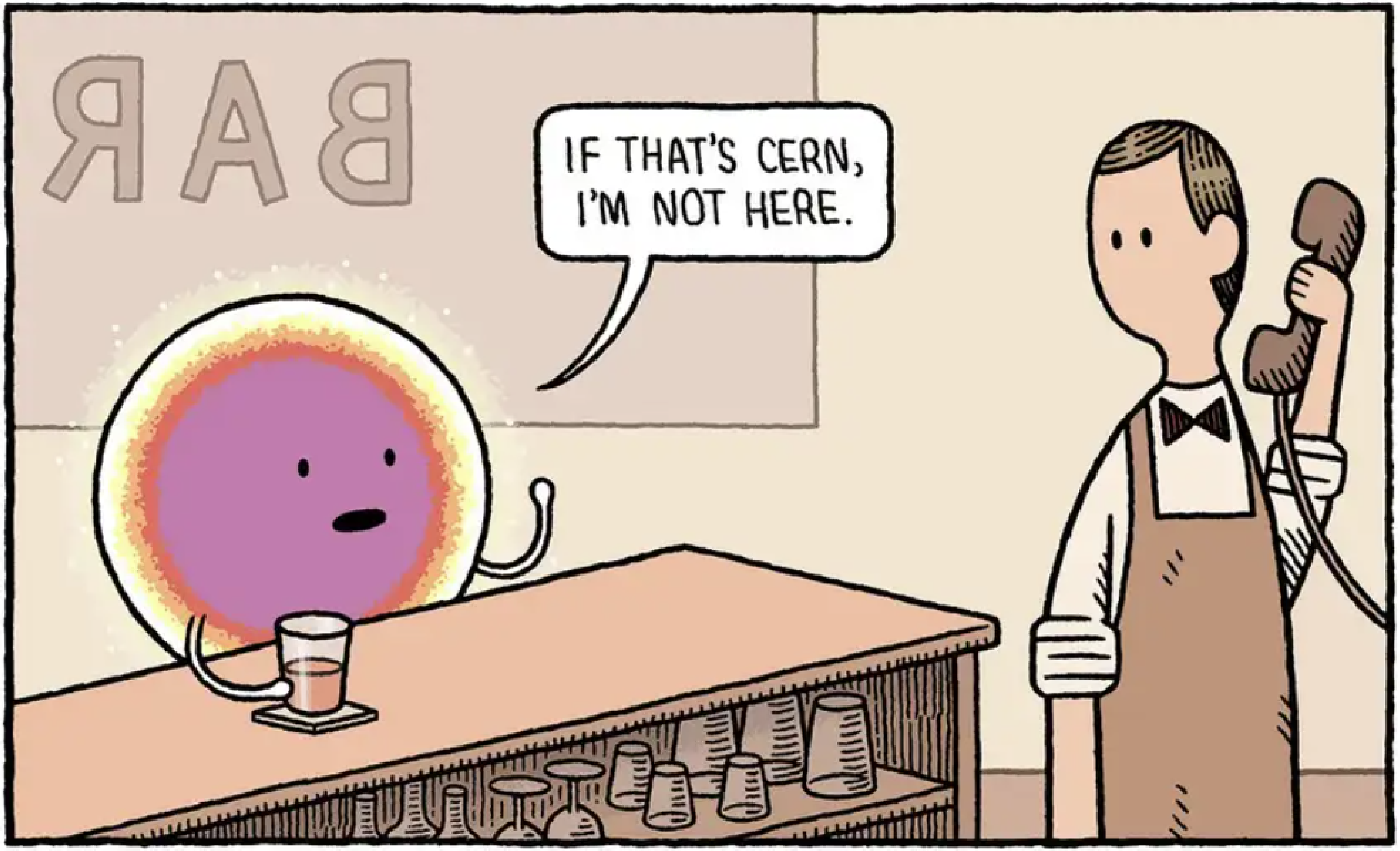
Beyond the Standard Model at the LHC

WISPs & Dedicated Search Experiments


PARTICLES
SPARTICLES
Quarks
Leptons
Squarks
Sleptons
3rd generation
Top quark
Bottom quark
Tau
Neutrino ντ
Stop
Sbottom
Stau
Sneutrino ντ
2nd generation
Charm quark
Strange quark
Muon
Neutrino νμ
Charm squark
Strange squark
Smuon
Sneutrino νμ
1st generation
Up quark
Down quark
Electron
Neutrino νe
Up squark
Down squark
Selectron
Sneutrino νe
Photon
W±Z0 bosons
Gluons
Graviton
Photino
Wino, Zino
Gluinos
Gravitino
Higgs bosons
Higgsinos


PARTICLES
SPARTICLES
Quarks
Leptons
Squarks
Sleptons
3rd generation
Top quark
Bottom quark
Tau
Neutrino ν_τ
Stop
Sbottom
Stau
Sneutrino ν_τ
2nd generation
Charm quark
Strange
Muon
Charm squark
Smuon
Sneutrino ν_μ
1st generation
Up quark
Down quark
Electron
Neutrino ν_e
Down squark
Selectron
Sneutrino ν_e
Photon
$W^\pm Z$ bosons
Gluons
Graviton
Photino
Wino, Zino
Gluinos
Gravitino
Higgs bosons
Higgsinos





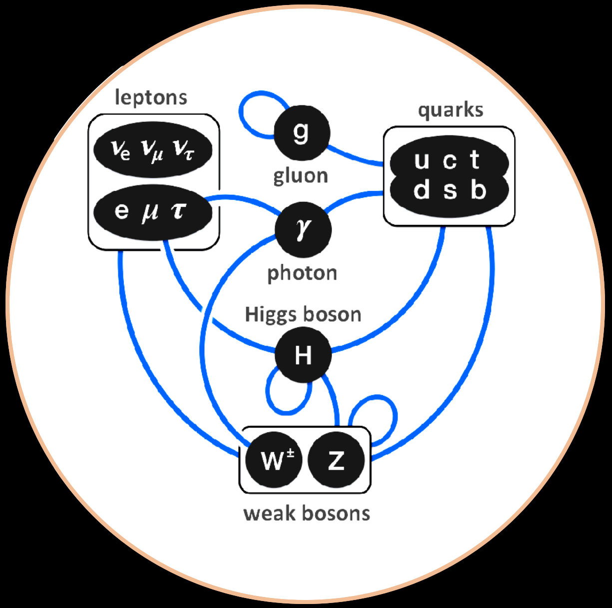
TOM GAULD for NEW SCIENTIST

Why No New Physics Yet at the LHC?

What are the possibilities?

Why No New Physics Yet at the LHC?

What are the possibilities?

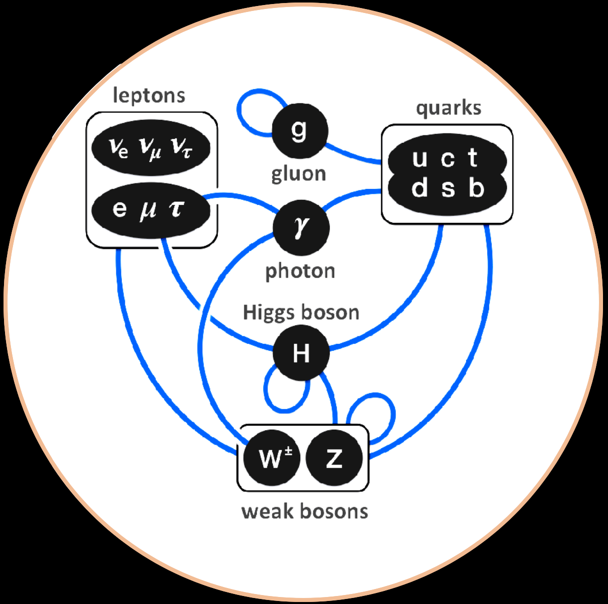


The Standard Model is it

There is no new physics

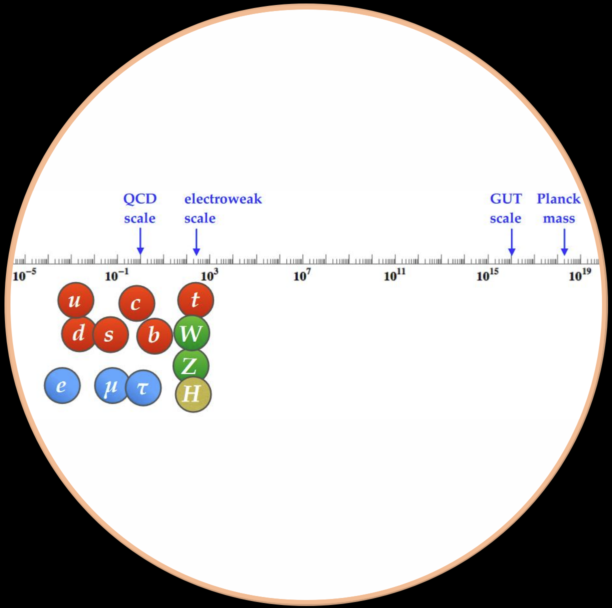
Why No New Physics Yet at the LHC?

What are the possibilities?



The Standard Model is it

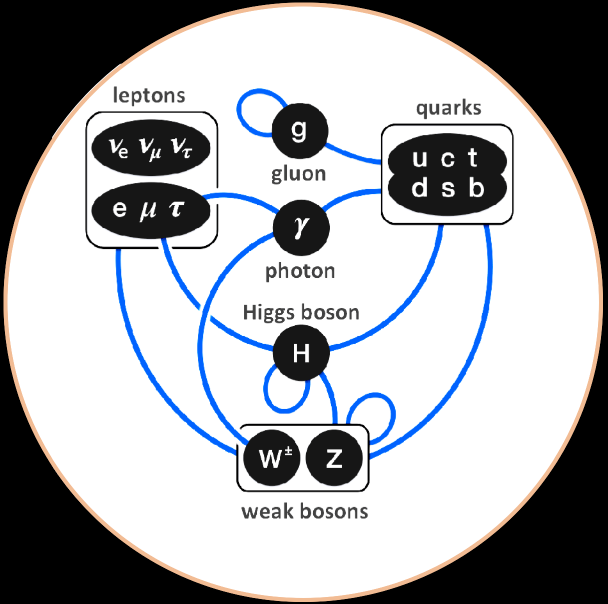
There is no new physics



New physics exists, but at a mass scale we can't ever reach

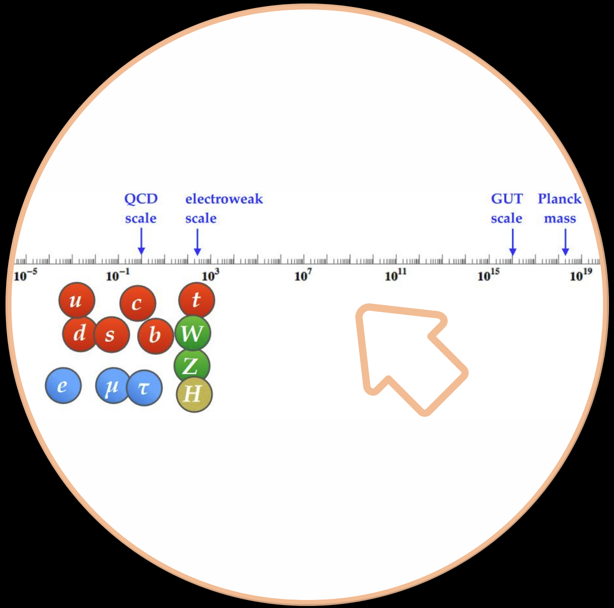
Why No New Physics Yet at the LHC?

What are the possibilities?



The Standard Model is it

There is no new physics

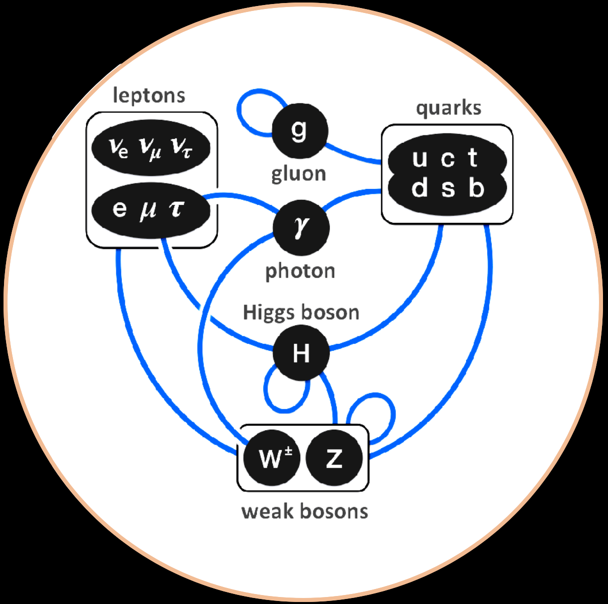


New physics exists, but at a mass scale we can't ever reach

MoEDAL MAPP

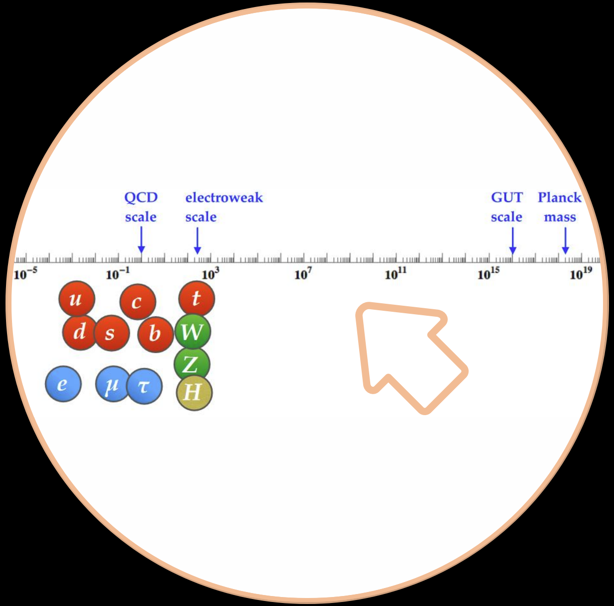
Why No New Physics Yet at the LHC?

What are the possibilities?

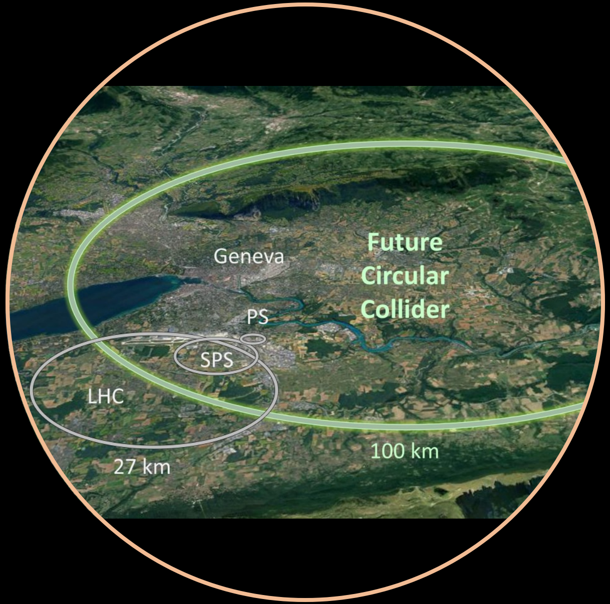


The Standard Model is it

There is no new physics



New physics exists, but at a mass scale we can't ever reach

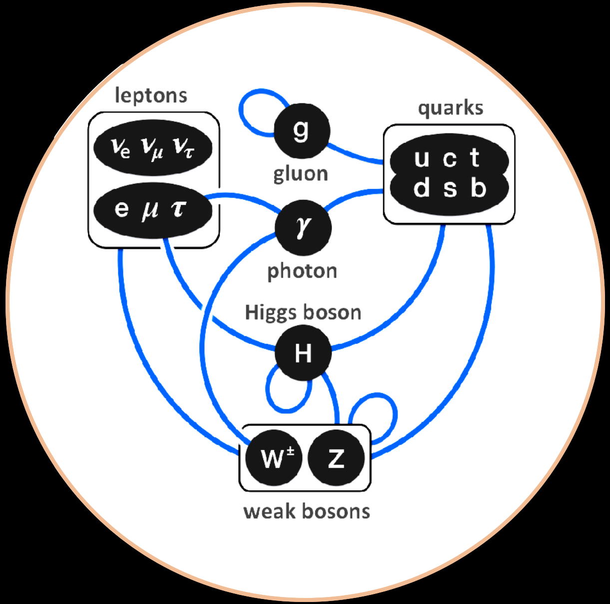


New physics exists, but we can only see something at a future collider

E.g., the FCC

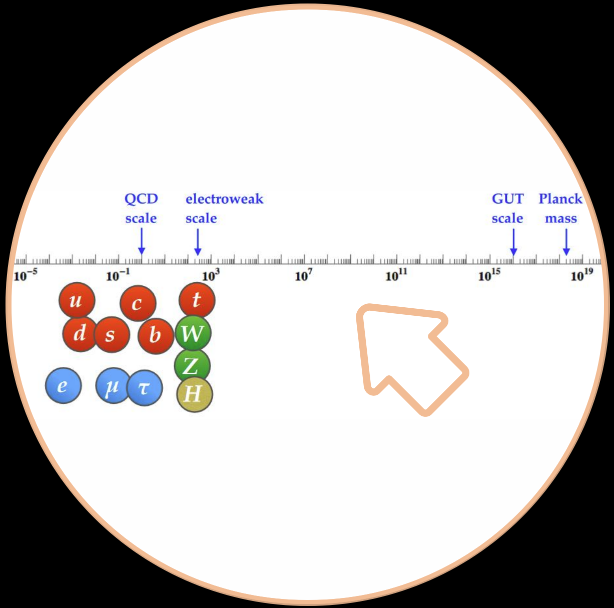
Why No New Physics Yet at the LHC?

What are the possibilities?

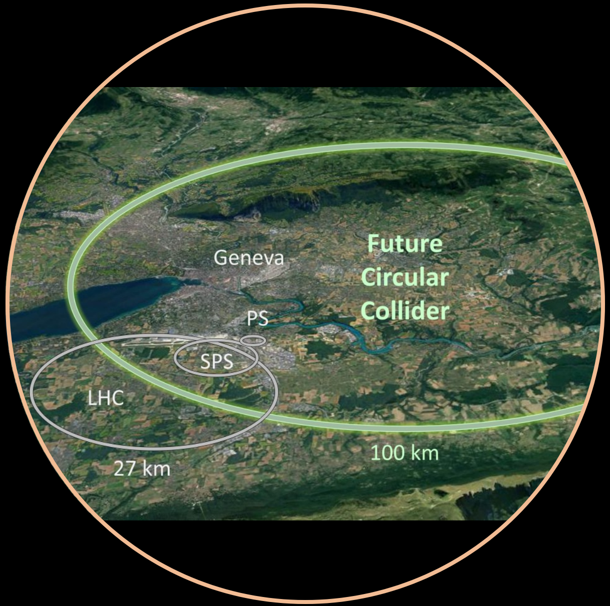


The Standard Model is it

There is no new physics



New physics exists, but at a mass scale we can't ever reach



New physics exists, but we can only see something at a future collider

E.g., the FCC

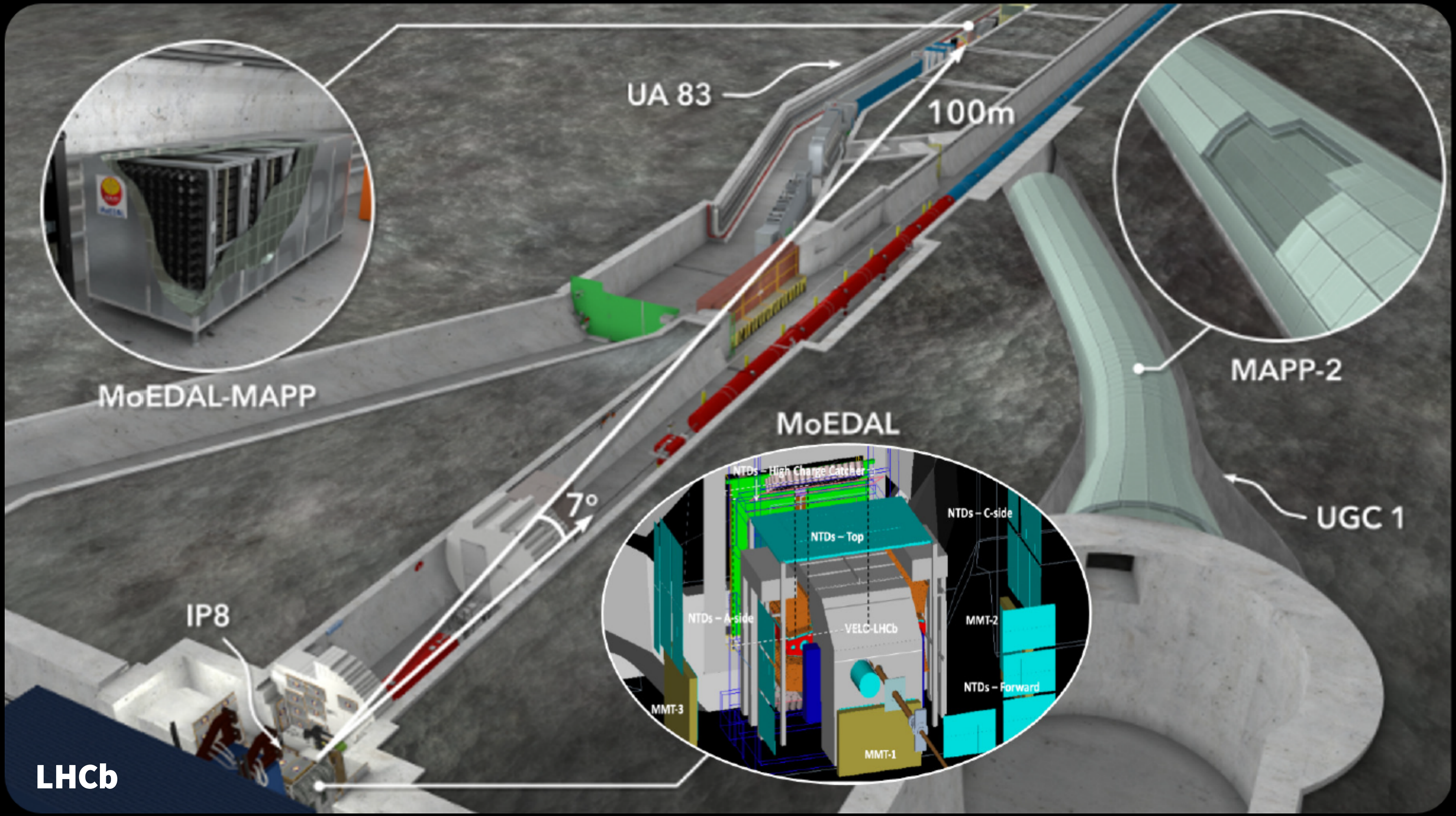
$$\sigma << 1\ \mathrm{ab}$$

New physics exists at our mass scale, but it has an extremely small cross-section

...or, perhaps new physics is right under our noses — but we can’t see it with our existing “standard” detectors

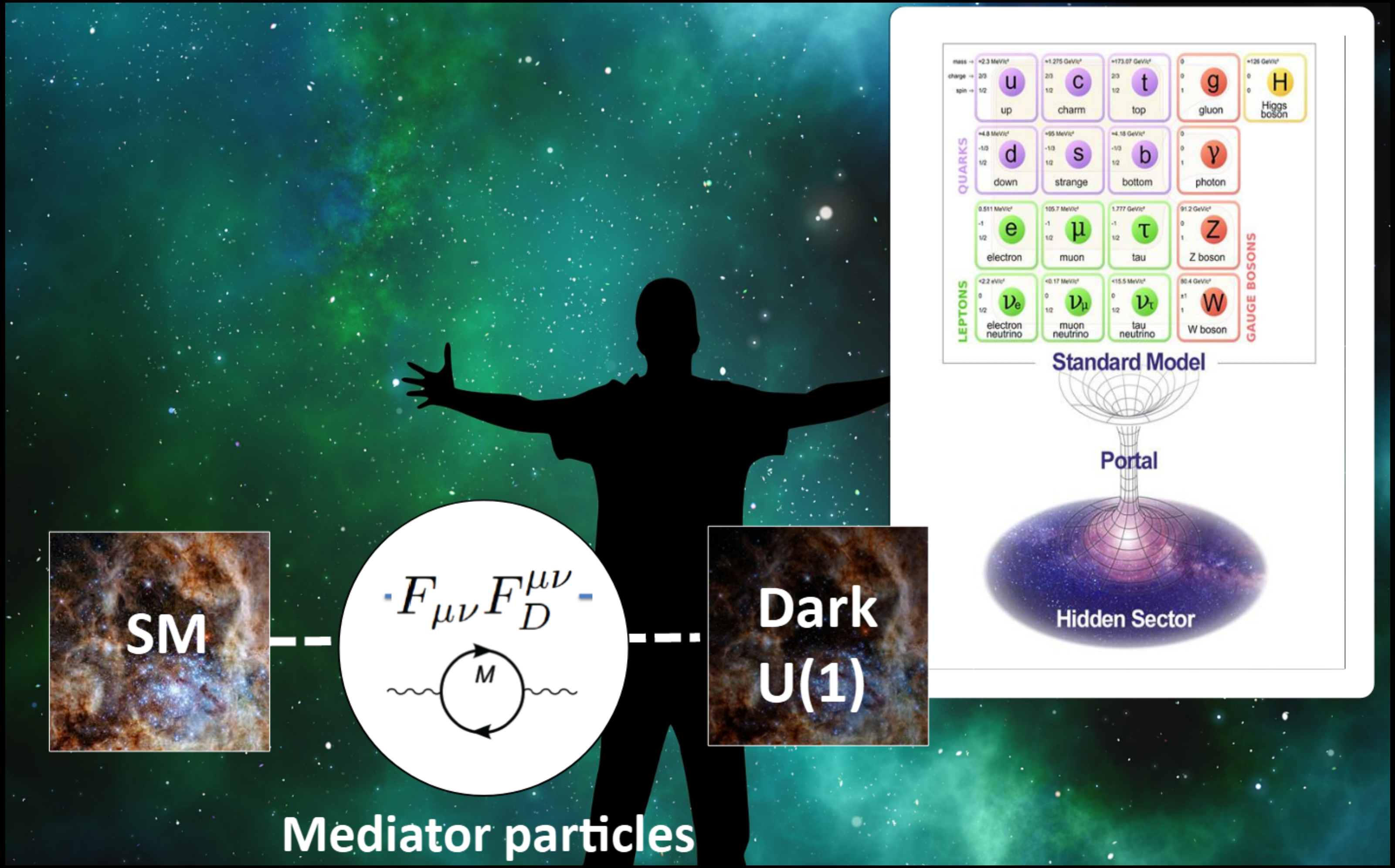
The MoEDAL-MAPP Dedicated Search Facility

Expanding the physics reach of MoEDAL beyond highly ionizing particles to include FIPs/WISPs



Particle Messengers From a Dark Sector

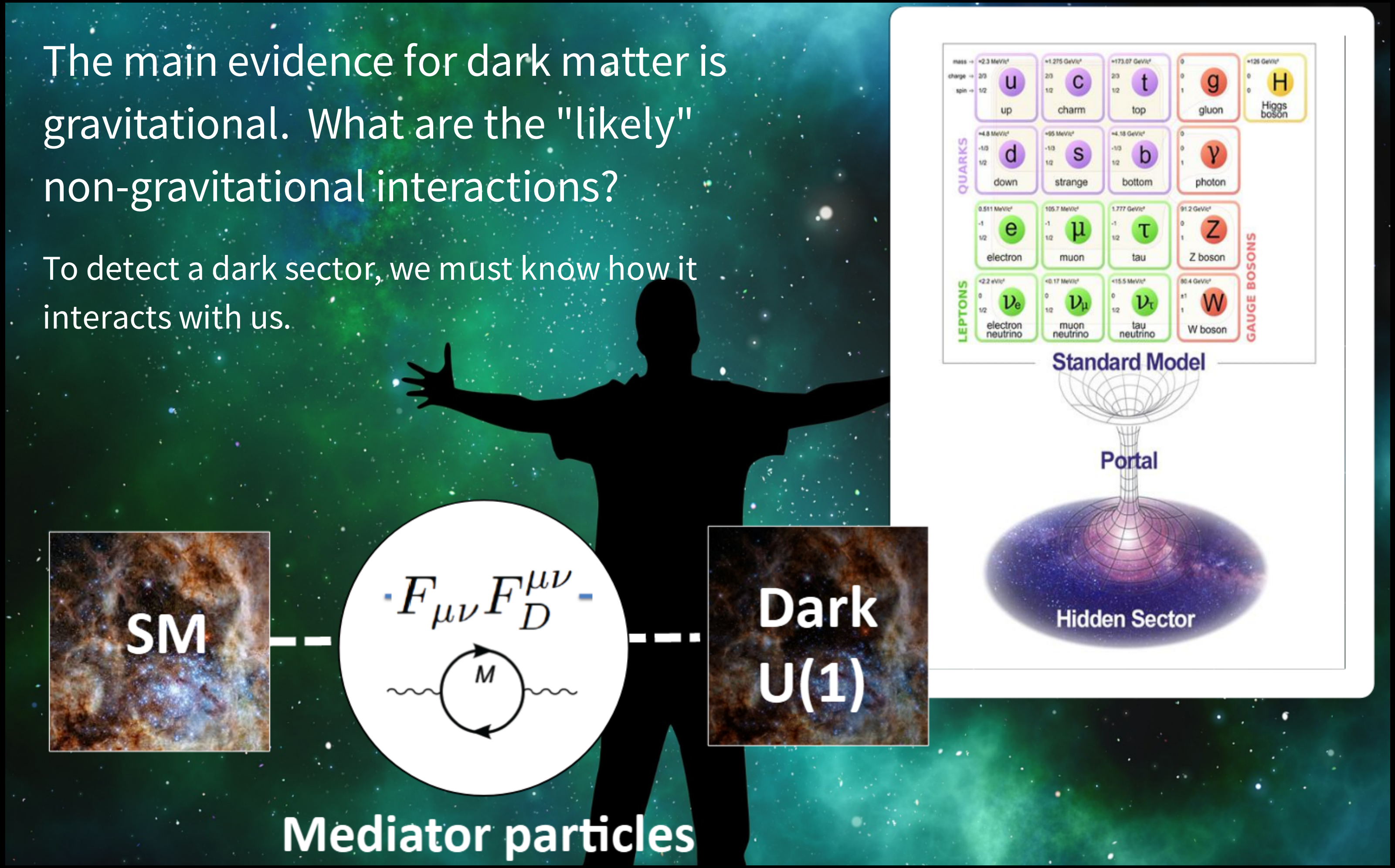
Particle Messengers From a Dark Sector



Particle Messengers From a Dark Sector

The main evidence for dark matter is gravitational. What are the "likely" non-gravitational interactions?

To detect a dark sector, we must know how it interacts with us.



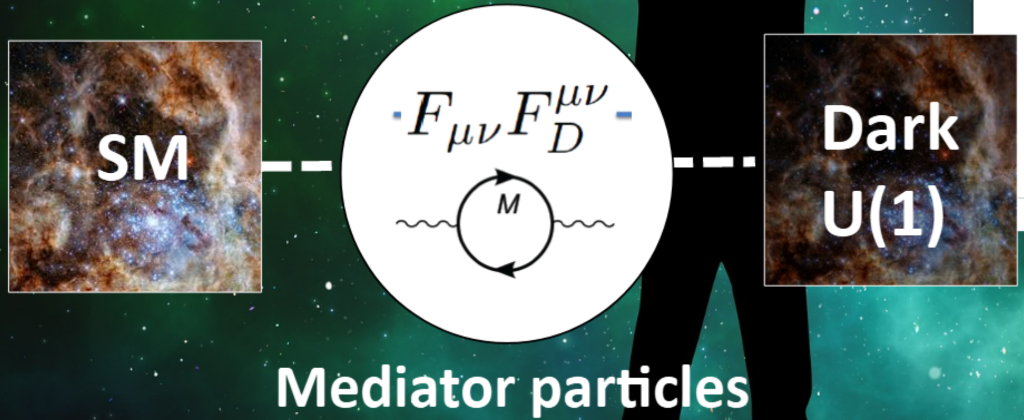
MAPP MoEDAL

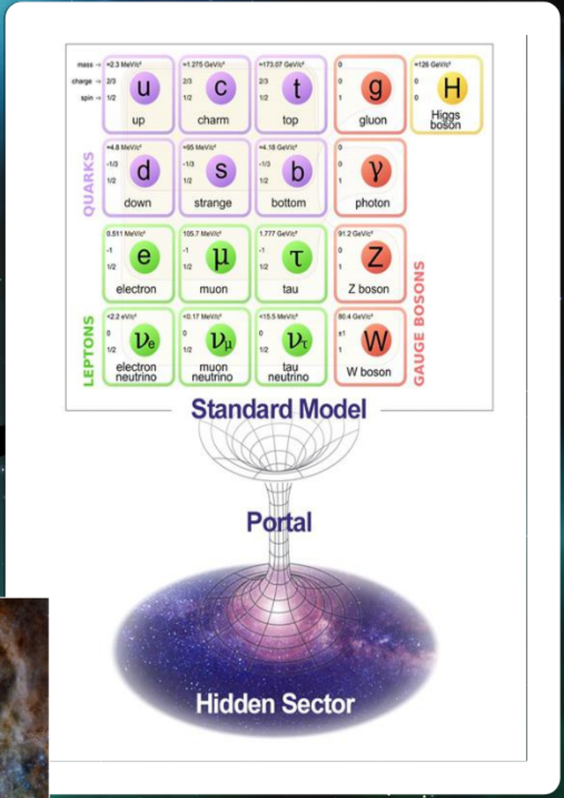
Particle Messengers From a Dark Sector

The main evidence for dark matter is gravitational. What are the "likely" non-gravitational interactions?

To detect a dark sector, we must know how it interacts with us.

- *Interactions between the two sectors are via mediator particles through so-called "portal interactions" — e.g., the vector portal:*



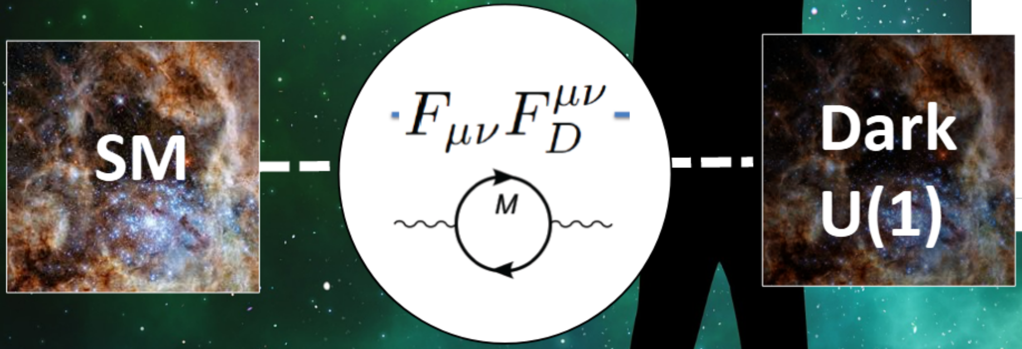


Particle Messengers From a Dark Sector

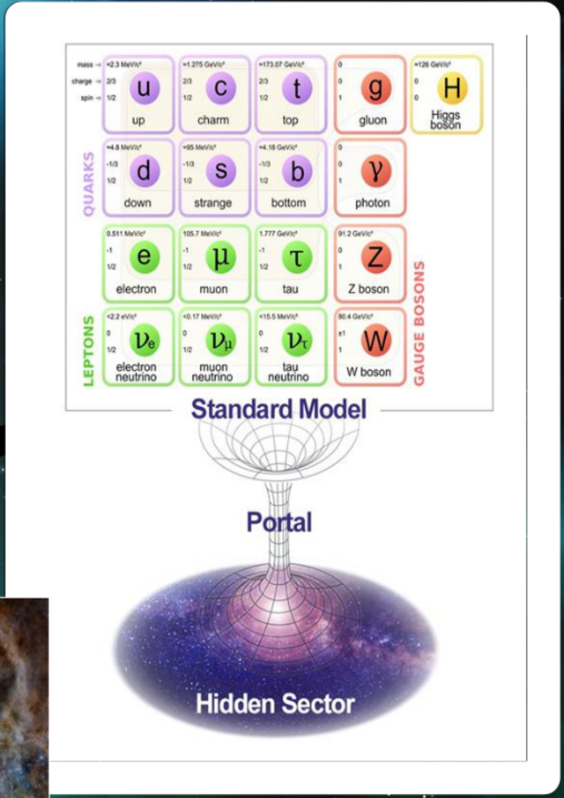
The main evidence for dark matter is gravitational. What are the "likely" non-gravitational interactions?

To detect a dark sector, we must know how it interacts with us.

- *Interactions between the two sectors are via mediator particles through so-called "portal interactions" — e.g., the vector portal:*



Mediator particles



$$\mathcal{L} \supset \epsilon_h |h^2||\phi_h^2|$$

$$\mathcal{L} \supset \epsilon_a a B^{\mu\nu}\tilde{B}_{\mu\nu}$$

$$\mathcal{L} \supset \epsilon_N L h N$$

$$\mathcal{L} \supset \epsilon_Y B^{\mu\nu}F'_{\mu\nu}$$

2

The Physics Program of MAPP

Dark Scalars

Why Dark Scalars?

Could potentially serve as mediators or constituents of dark matter

i.e., dark scalars provide a simple mechanism for DM's existence within particle physics frameworks.
see, e.g., *Phys. Rev. D* **94**, 073009 (2016).

Why Dark Scalars?

Could potentially serve as mediators or constituents of dark matter

i.e., dark scalars provide a simple mechanism for DM's existence within particle physics frameworks.
see, e.g., *Phys. Rev. D* **94**, 073009 (2016).

Connected to a variety of puzzles such as DM, inflation, and naturalness

e.g., inflationary models involving scalar fields, such as dark scalars, offer compelling explanations for the origin of primordial density fluctuations.
see, e.g., *JHEP* **2010**, 10 (2010).

Why Dark Scalars?

Could potentially serve as mediators or constituents of dark matter

i.e., dark scalars provide a simple mechanism for DM's existence within particle physics frameworks.
see, e.g., *Phys. Rev. D* **94**, 073009 (2016).

Connected to a variety of puzzles such as DM, inflation, and naturalness

e.g., inflationary models involving scalar fields, such as dark scalars, offer compelling explanations for the origin of primordial density fluctuations.
see, e.g., *JHEP* **2010**, 10 (2010).

Can provide a common new-physics-based explanation for the B anomalies

see, e.g., *Phys. Rev. D* **101**, 035010 (2020).

Dark Scalars in the Minimal Higgs-Portal Scenario

We consider a **dark/hidden sector model** where the **new interaction** is mediated by a **'Dark Higgs'**.

V. Gligorov et al., *Phys. Rev. D* **97**, 015023 (2018).

Dark Scalars in the Minimal Higgs-Portal Scenario

We consider a **dark/hidden sector model** where the **new interaction** is mediated by a **'Dark Higgs'**.

Introduce a **new light CP-even singlet scalar field**, *S*, that **mixes with the SM Higgs** with a mixing of **θ << 1**.

V. Gligorov et al., *Phys. Rev. D* **97**, 015023 (2018).

Dark Scalars in the Minimal Higgs-Portal Scenario

We consider a **dark/hidden sector model** where the **new interaction** is mediated by a **'Dark Higgs'**.

Introduce a **new light CP-even singlet scalar field**, *S*, that **mixes with the SM Higgs** with a mixing of **θ << 1**.

Dark sector interacts with the SM through the **Higgs-portal quartic scalar interaction**. In this way, we add to the SM Lagrangian, the following,

V. Gligorov et al., *Phys. Rev. D* **97**, 015023 (2018).

Dark Scalars in the Minimal Higgs-Portal Scenario

We consider a **dark/hidden sector model** where the **new interaction** is mediated by a **'Dark Higgs'**.

Introduce a **new light CP-even singlet scalar field**, ***S***, that **mixes with the SM Higgs** with a mixing of **θ << 1**.

Dark sector interacts with the SM through the **Higgs-portal quartic scalar interaction**. In this way, we add to the SM Lagrangian, the following,

$$\mathcal{L} = \mathcal{L}_{\mathrm{Kin}} + \mathcal{L}_{\mathrm{DS}} + \mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 + \mu^2 |H|^2 - \lambda |H|^4 - \epsilon_h S^2 |H|^2$$

V. Gligorov et al., *Phys. Rev. D* **97**, 015023 (2018).

Dark Scalars in the Minimal Higgs-Portal Scenario

We consider a **dark/hidden sector model** where the **new interaction** is mediated by a **'Dark Higgs'**.

Introduce a **new light CP-even singlet scalar field**, ***S***, that **mixes with the SM Higgs** with a mixing of **θ << 1**.

Dark sector interacts with the SM through the **Higgs-portal quartic scalar interaction**. In this way, we add to the SM Lagrangian, the following,

$$\mathcal{L} = \mathcal{L}_{\rm Kin} + \mathcal{L}_{\rm DS} + \mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 + \mu^2 |H|^2 - \lambda |H|^4 - \epsilon_h S^2 |H|^2$$

Proceeding with EWSB, one can **obtain the physical fields and their properties**. This **generates Yukawa-like couplings between the dark Higgs & fermions,**

V. Gligorov et al., *Phys. Rev. D* **97**, 015023 (2018).

Dark Scalars in the Minimal Higgs-Portal Scenario

We consider a **dark/hidden sector model** where the **new interaction** is mediated by a **'Dark Higgs'**.

Introduce a **new light CP-even singlet scalar field**, ***S***, that **mixes with the SM Higgs** with a mixing of **θ << 1**.

Dark sector interacts with the SM through the **Higgs-portal quartic scalar interaction**. In this way, we add to the SM Lagrangian, the following,

$$\mathcal{L} = \mathcal{L}_{\mathrm{Kin}} + \mathcal{L}_{\mathrm{DS}} + \mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 + \mu^2 |H|^2 - \lambda |H|^4 - \epsilon_h S^2 |H|^2$$

Proceeding with EWSB, one can **obtain the physical fields and their properties**. This **generates Yukawa-like couplings between the dark Higgs & fermions,**

$$\mathcal{L}_{\mathrm{eff}} = -m_{\phi_h}^2 \phi_h^2 - \sin\theta \frac{m_f}{v} \phi_h f \bar{f} - \lambda v h \phi_h \phi_h$$

V. Gligorov et al., *Phys. Rev. D* **97**, 015023 (2018).

MAPP
MoEDAL

Dark Scalars in the Minimal Higgs-Portal Scenario

We consider a **dark/hidden sector model** where the **new interaction** is mediated by a **'Dark Higgs'**.

Introduce a **new light CP-even singlet scalar field**, *S*, that **mixes with the SM Higgs** with a mixing of **θ << 1**.

Dark sector interacts with the SM through the **Higgs-portal quartic scalar interaction**. In this way, we add to the SM Lagrangian, the following,

$$\mathcal{L} = \mathcal{L}_{\text{Kin}} + \mathcal{L}_{\text{DS}} + \mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 + \mu^2 |H|^2 - \lambda |H|^4 - \epsilon_h S^2 |H|^2$$

Proceeding with EWSB, one can **obtain the physical fields and their properties**. This **generates Yukawa-like couplings between the dark Higgs & fermions,**

$$\mathcal{L}_{\text{eff}} = -m_{\phi_h}^2 \phi_h^2 - \sin\theta \frac{m_f}{v} \phi_h f \bar{f} - \lambda v h \phi_h \phi_h$$

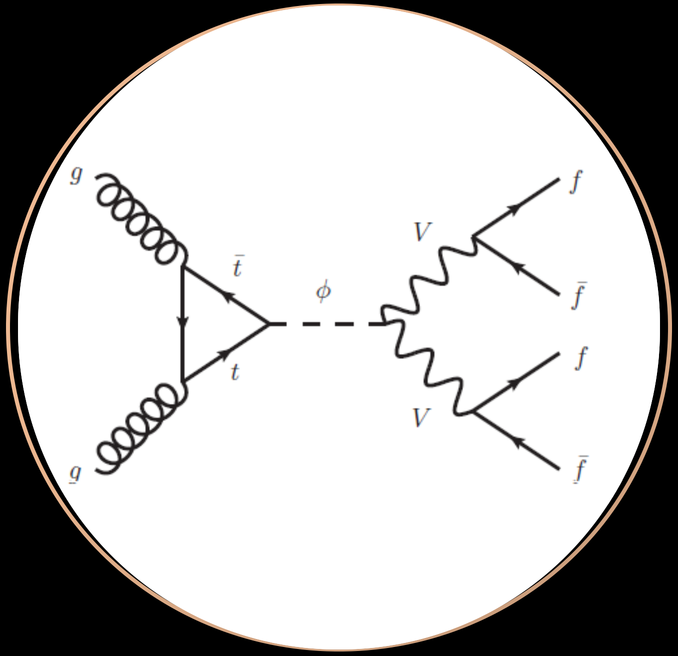
We use Pythia8, which can perform hadronization, to generate a *B* meson sample that decays inclusively to dark Higgs bosons: $B \to K\phi_h$

V. Gligorov et al., *Phys. Rev. D* **97**, 015023 (2018).

MAPP MoEDAL

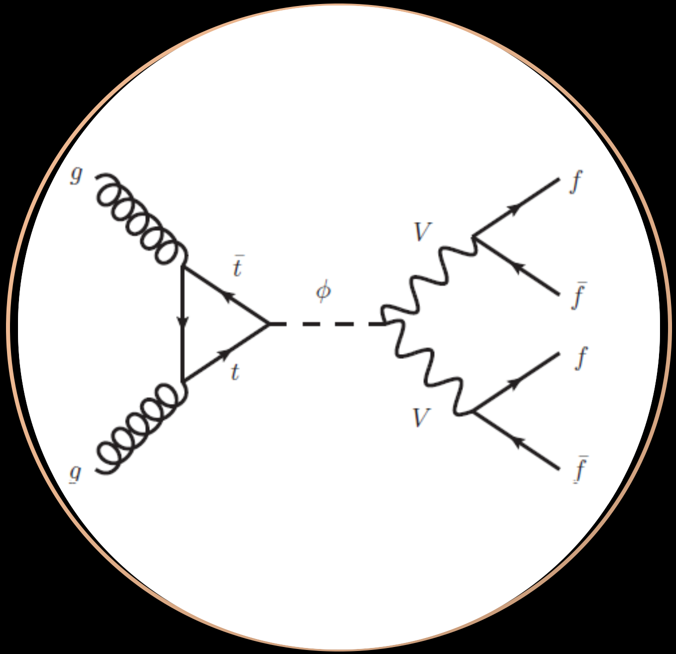
Some Dark Higgs Production Modes at Colliders

Some Dark Higgs Production Modes at Colliders

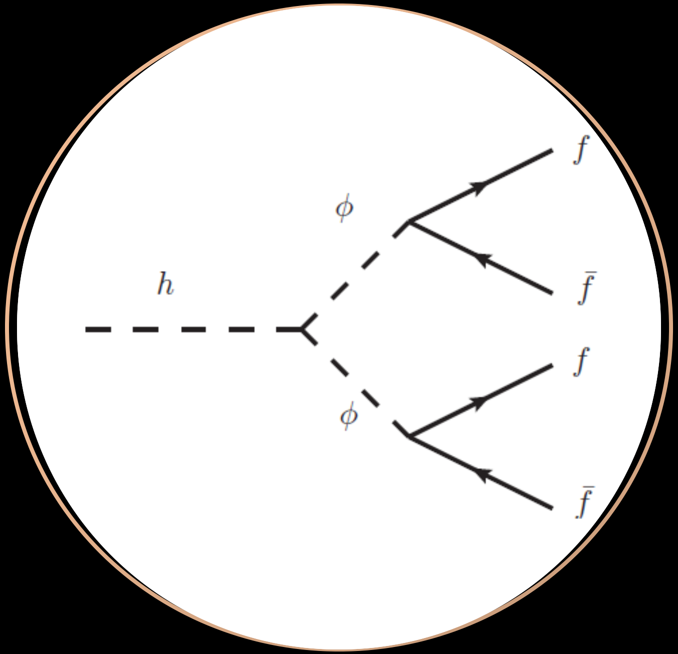


via **gluon fusion**

Some Dark Higgs Production Modes at Colliders

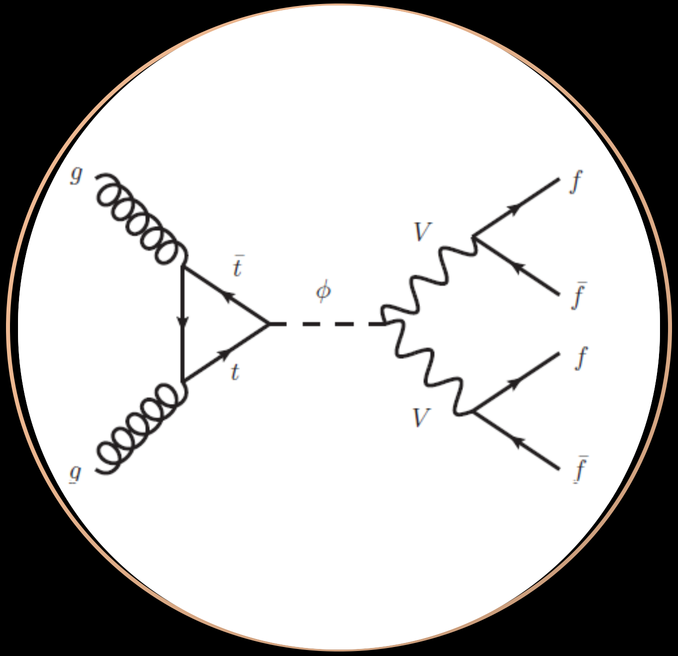


via **gluon fusion**

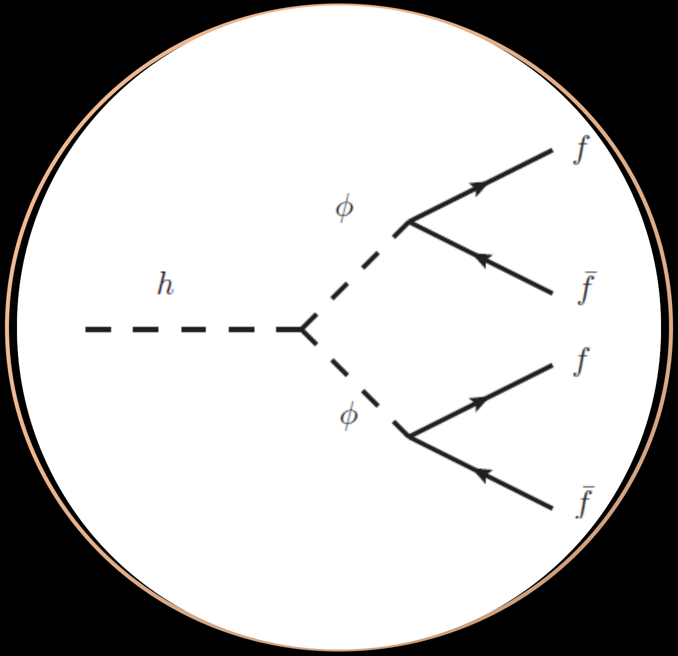


Decay of the SM-like Higgs boson

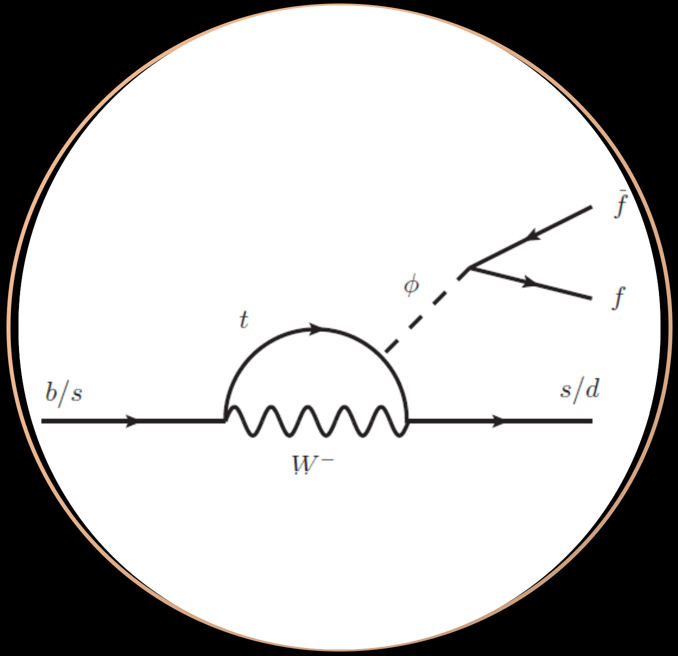
Some Dark Higgs Production Modes at Colliders



via **gluon fusion**



Decay of the SM-like Higgs boson



Rare *K* and *B* decays

Sensitivity of MAPP to Dark Higgs—Analysis & Results

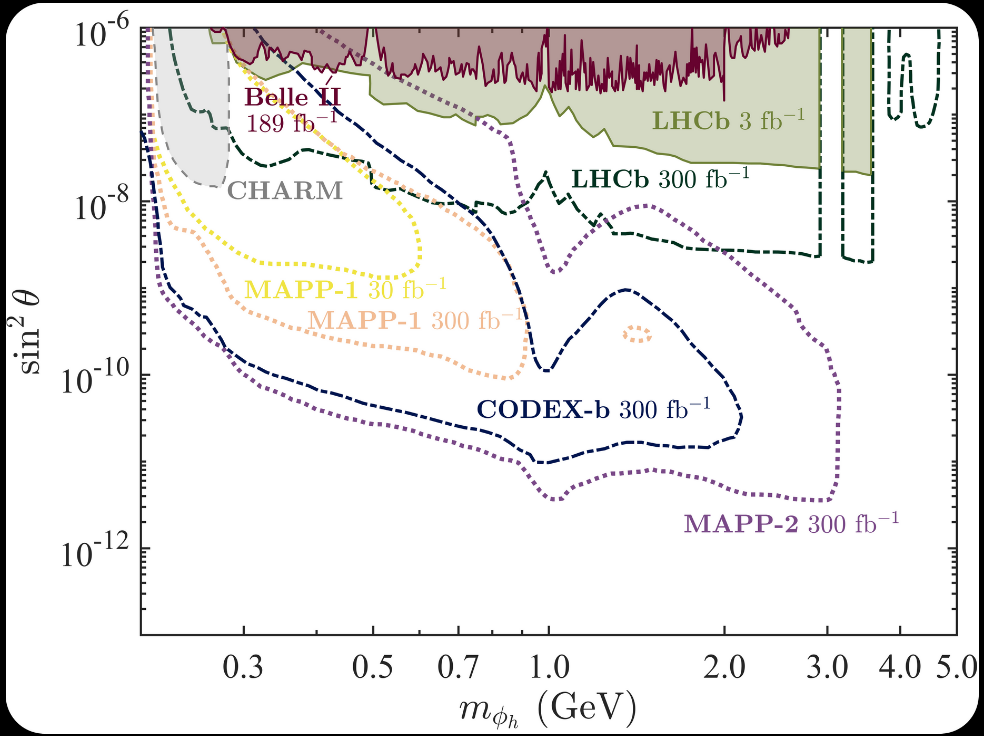
We use *Pythia8* **to perform hadronization and decays**.

- **An 'event'** was **defined as a dark Higgs decay to muons inside the MAPP-1/2 detector volume.**
- The **number of expected events in MAPP** was **estimated by the following equation,** $N_{\rm ev} = \sigma_{b\bar{b}} \times L^{\rm int}_{\rm LHCb} \times \mathcal{B}_{B\to X_s \phi_h} \times \epsilon_{\rm fid}$.
- We **obtain the fiducial efficiency of MAPP** by performing **MC simulations of *B* decays to dark Higgs bosons (*B* → *K* ϕ)** over the parameter space of interest.

V. Gligorov et al., *Phys. Rev. D* **97**, 015023 (2018).

Sensitivity of MAPP to Dark Higgs—Analysis & Results

95% C.L. exclusion bounds for dark Higgs produced in rare *B* decays at the LHC:



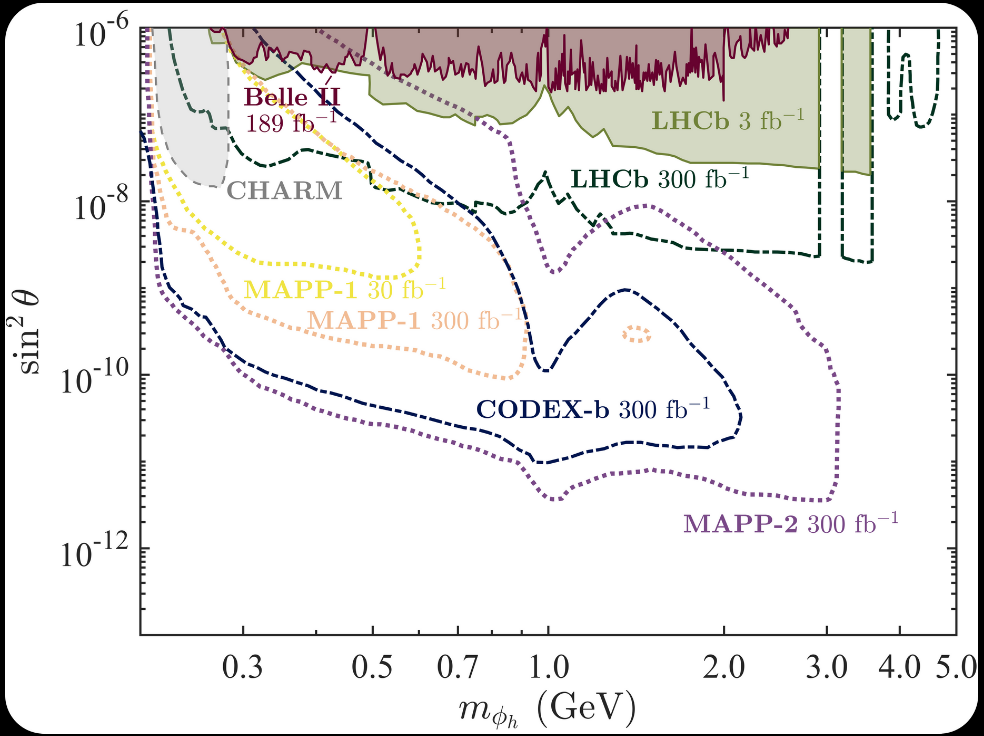
We use ***Pythia8*** **to perform hadronization and decays.**

- **An 'event'** was **defined as a dark Higgs decay to muons inside the MAPP-1/2 detector volume.**
- The **number of expected events in MAPP** was **estimated by the following equation,** $N_{\text{ev}} = \sigma_{b\bar{b}} \times L^{\text{int}}_{\text{LHCb}} \times \mathcal{B}_{B\to X_s\phi_h} \times \epsilon_{\text{fid}}$.
- We **obtain the fiducial efficiency of MAPP** by performing **MC simulations of *B* decays to dark Higgs bosons (*B* → *K* ϕ)** over the parameter space of interest.

V. Gligorov et al., *Phys. Rev. D* **97**, 015023 (2018).

Sensitivity of MAPP to Dark Higgs—Analysis & Results

95% C.L. exclusion bounds for dark Higgs produced in rare *B* decays at the LHC:



No BGs and an overall detector efficiency of 100% were assumed for ease of comparison.
(Simulations of detector response and efficiency are still ongoing.)

We use *Pythia8* **to perform hadronization and decays**.

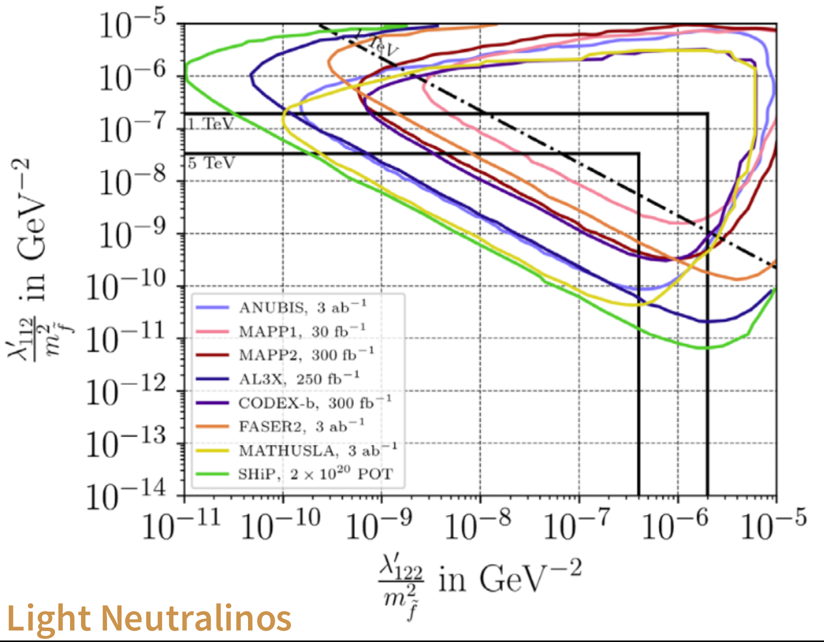
- **An 'event'** was **defined as a dark Higgs decay to muons inside the MAPP-1/2 detector volume.**
- The **number of expected events in MAPP** was **estimated by the following equation,** $N_{\rm ev} = \sigma_{b\bar{b}} \times L^{\rm int}_{\rm LHCb} \times \mathcal{B}_{B\to X_s\phi_h} \times \epsilon_{\rm fid}$.
- We **obtain the fiducial efficiency of MAPP** by performing **MC simulations of *B* decays to dark Higgs bosons (*B* → *K* ϕ)** over the parameter space of interest.

V. Gligorov et al., *Phys. Rev. D* **97**, 015023 (2018).

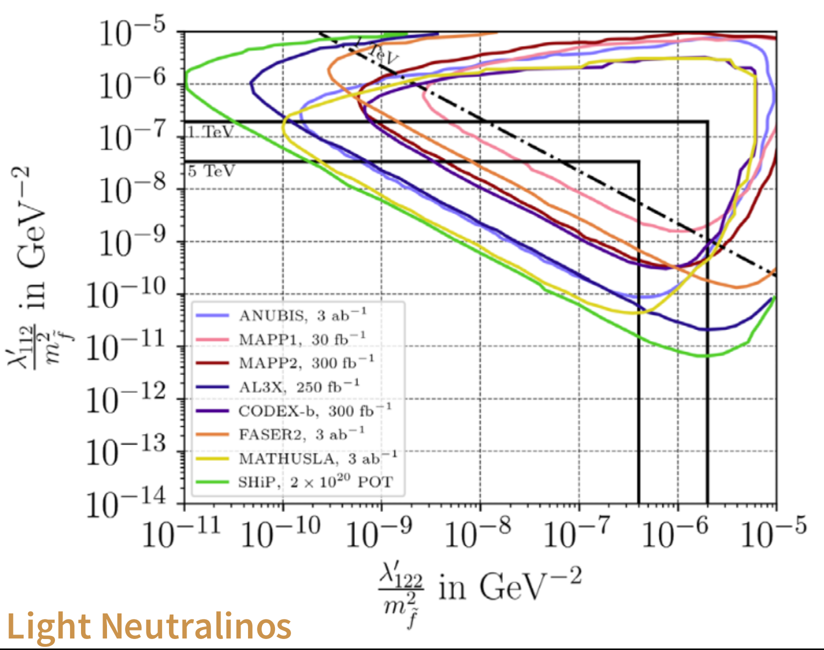
3

The Future of MoEDAL-MAPP

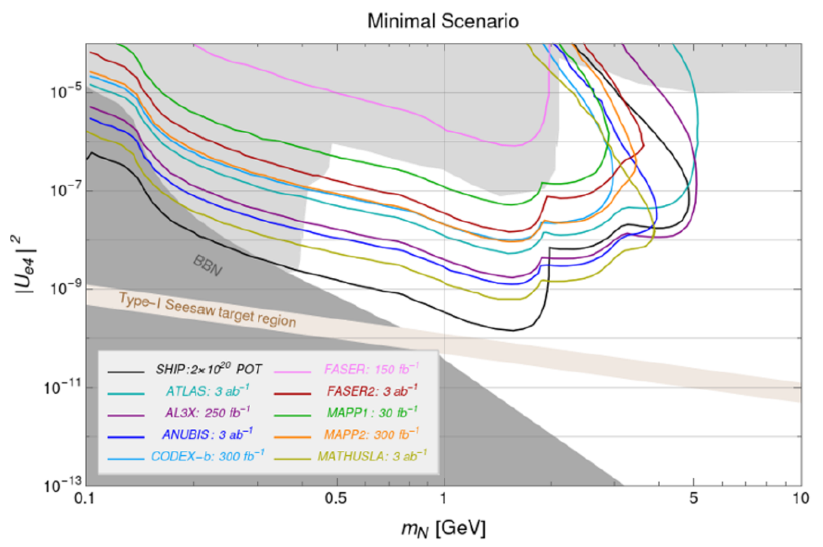
Progress and Prospects



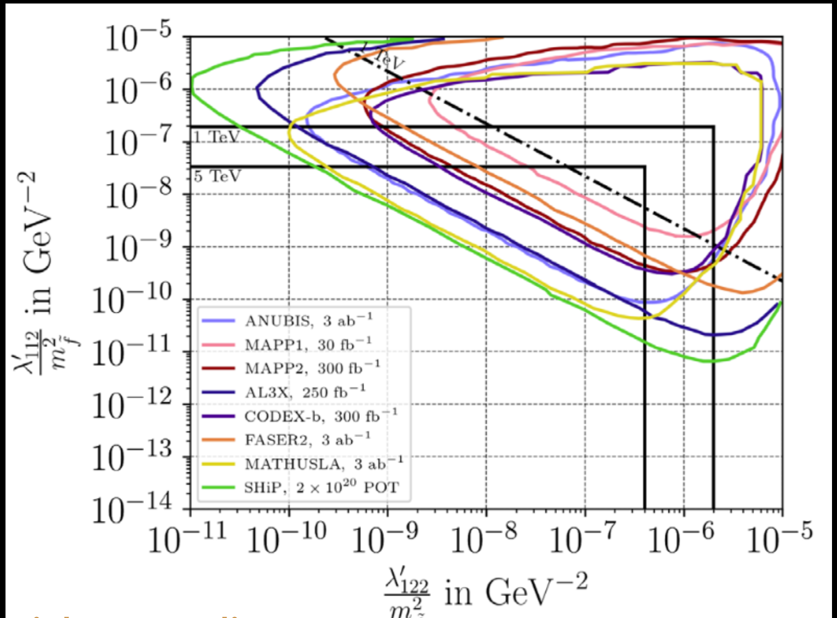
Light Neutralinos



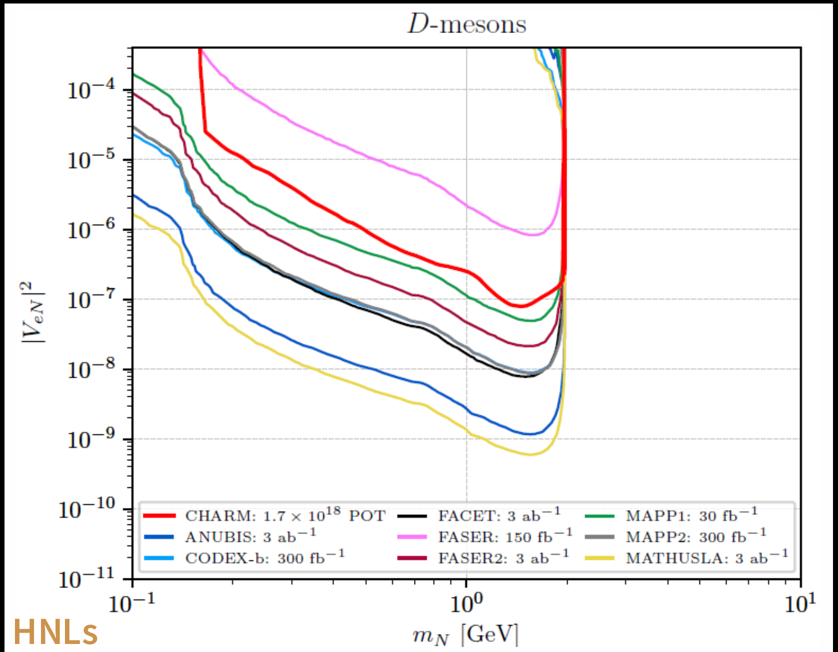
Light Neutralinos



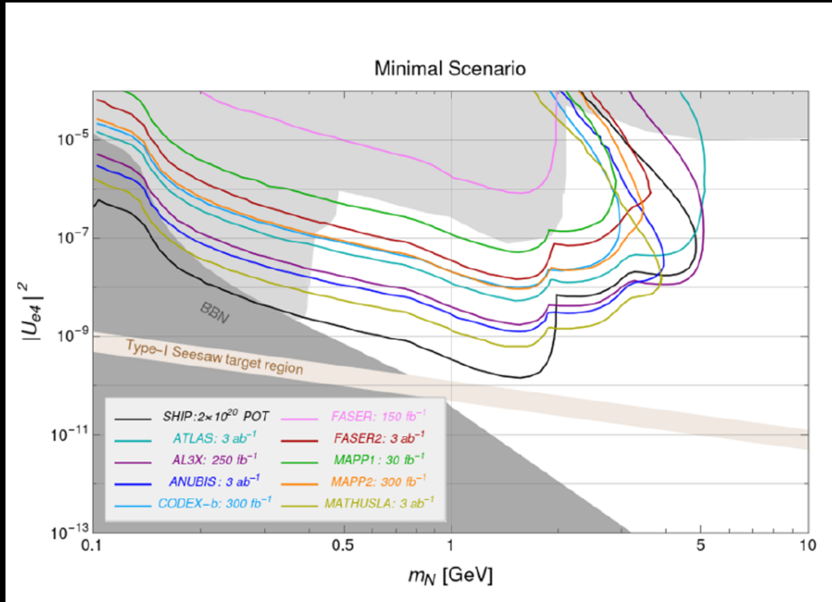
Sterile Neutrinos



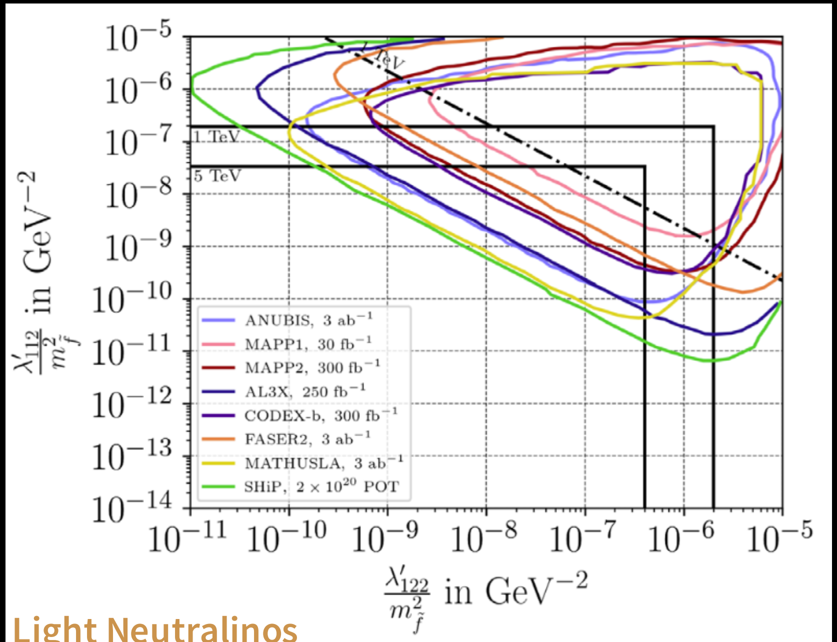
Light Neutralinos



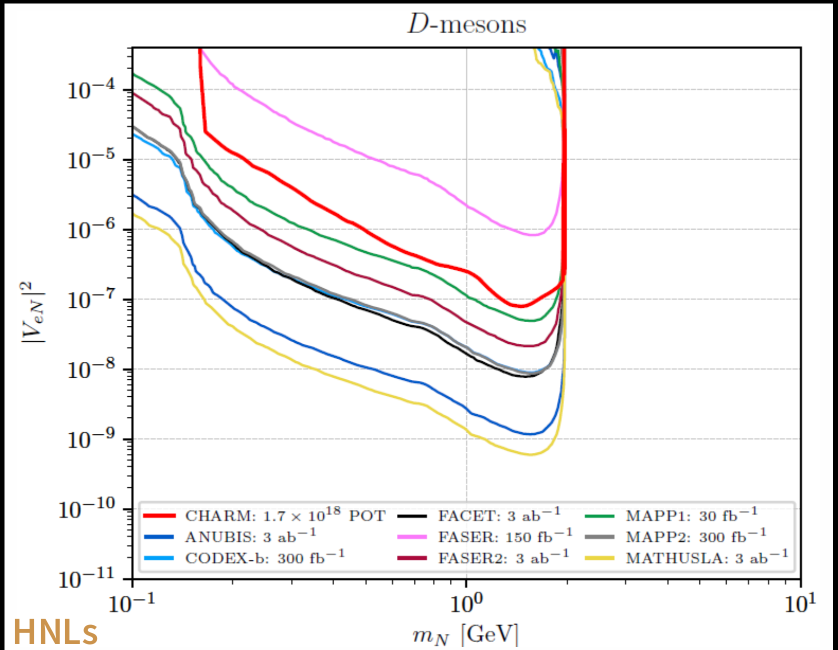
HNLs



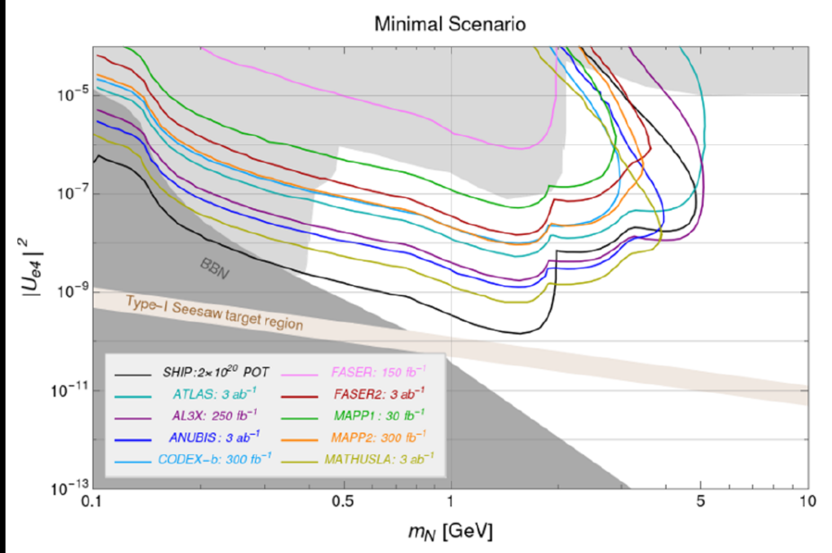
Sterile Neutrinos



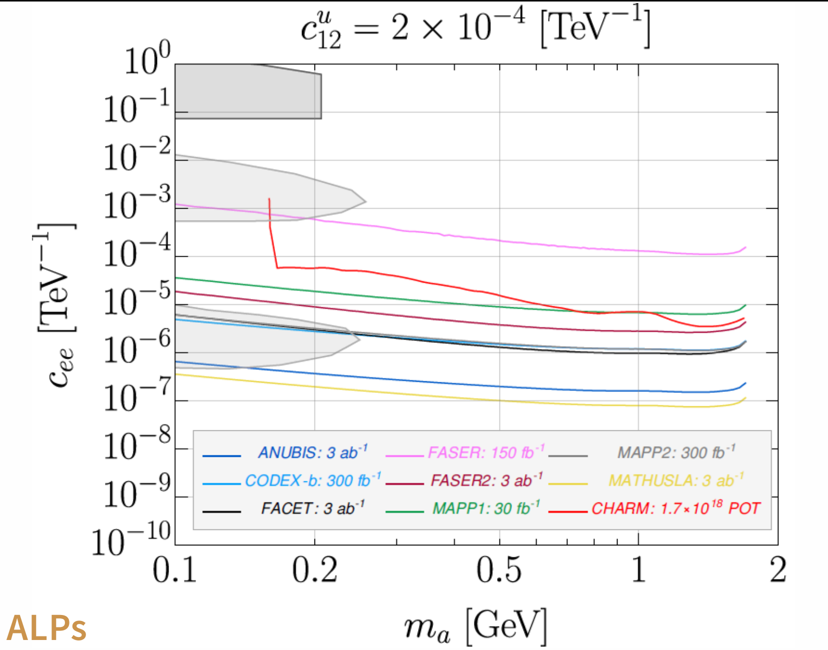
Light Neutralinos



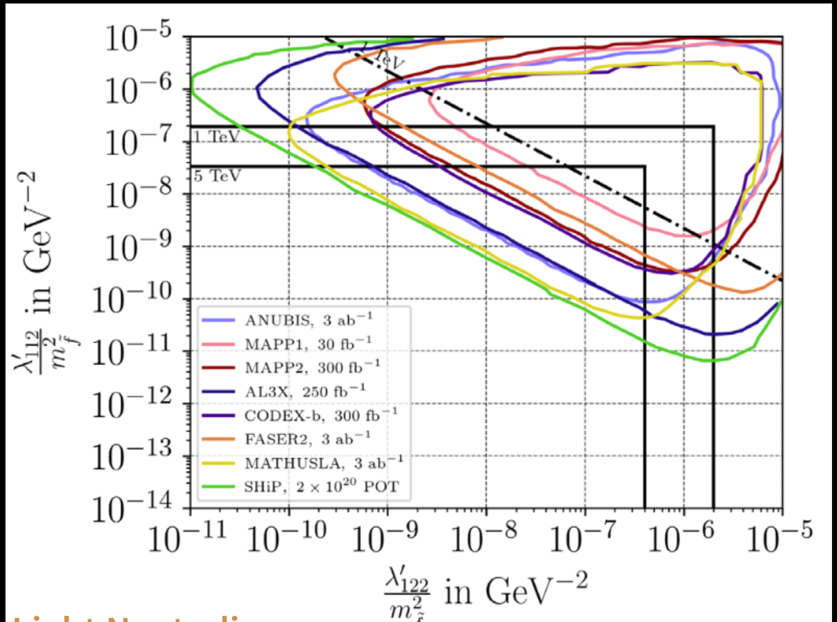
HNLs



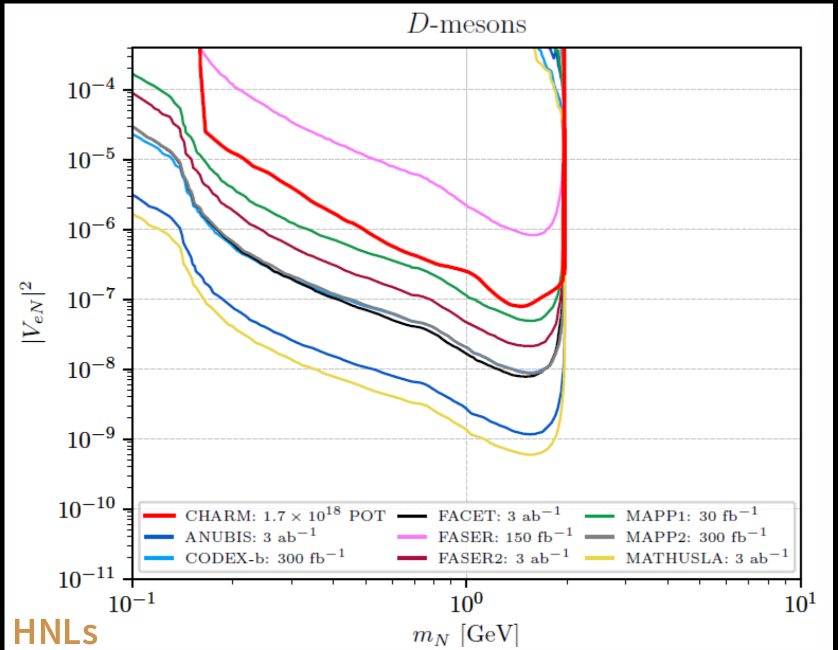
Sterile Neutrinos



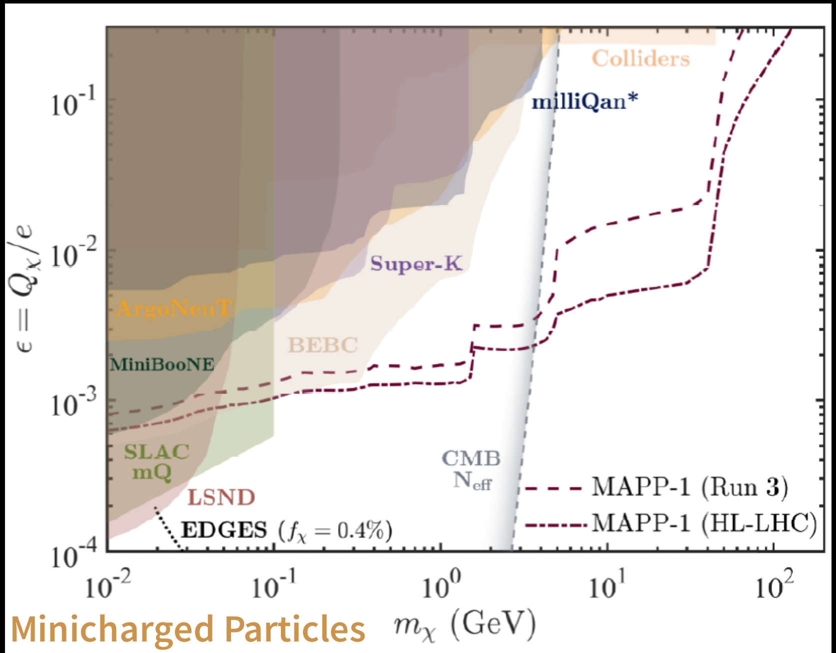
ALPs



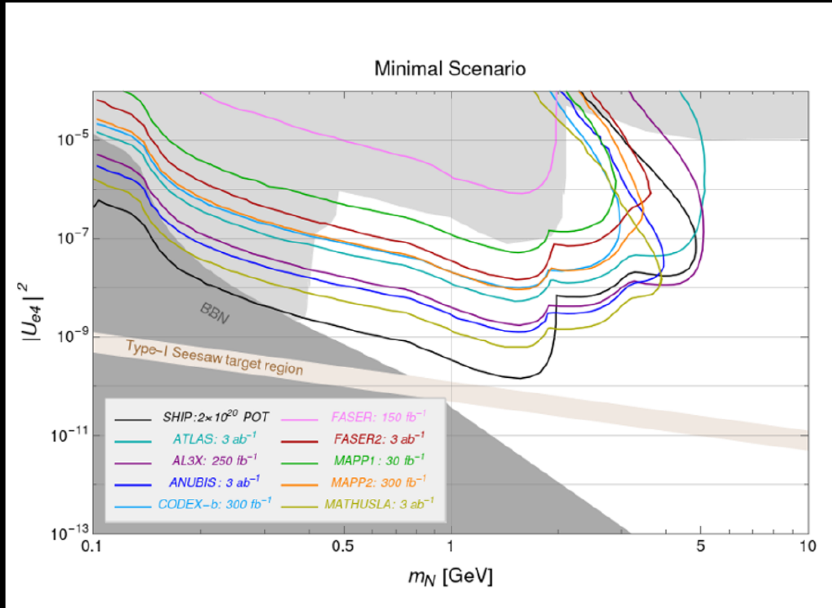
Light Neutralinos



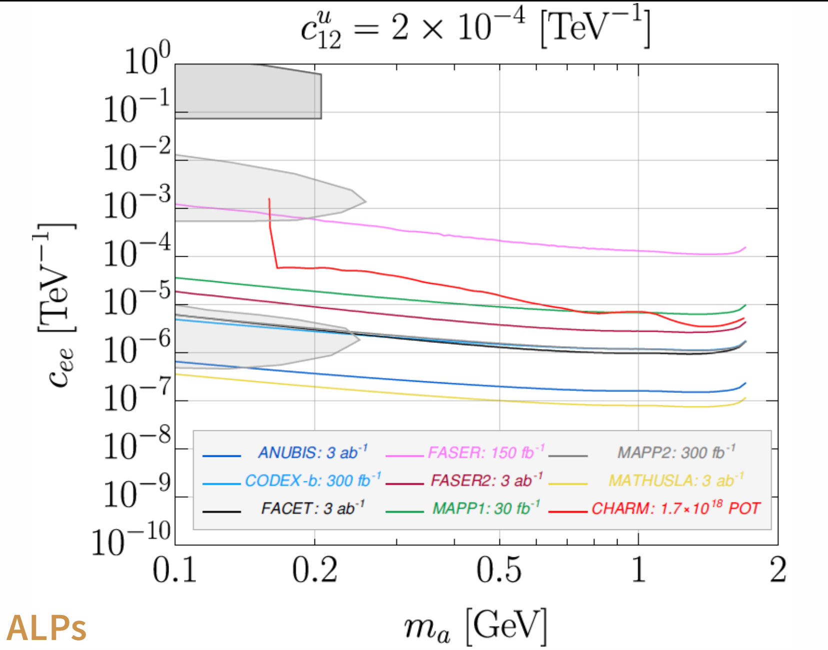
HNLs



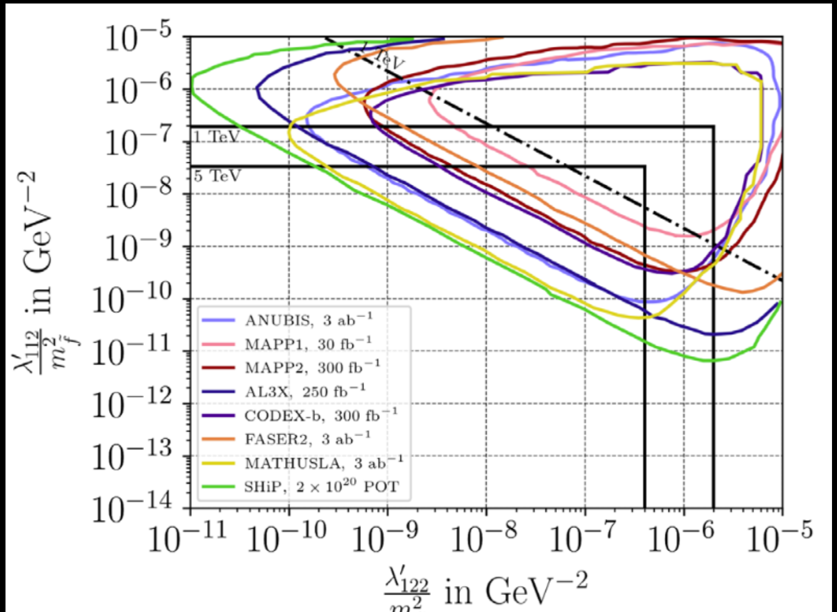
Minicharged Particles



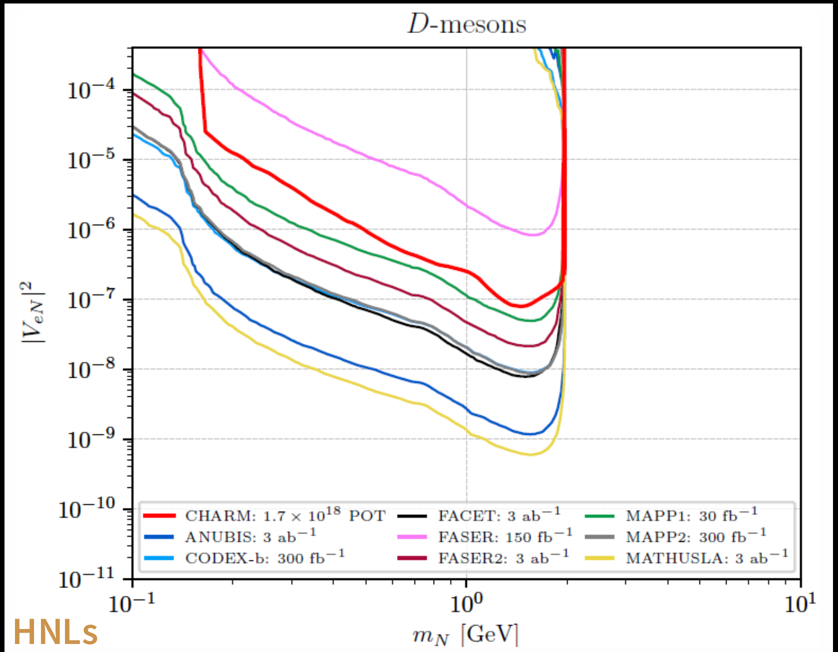
Sterile Neutrinos



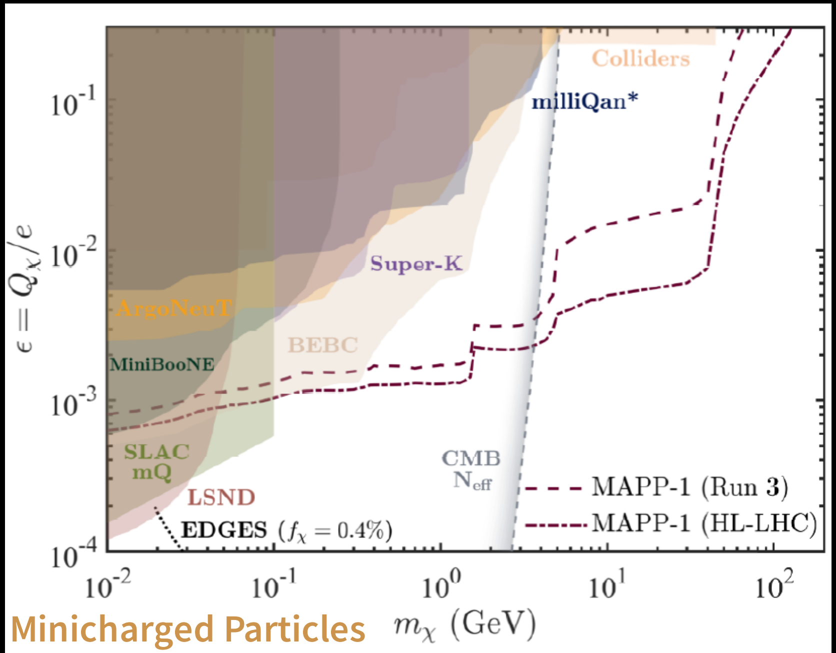
ALPs



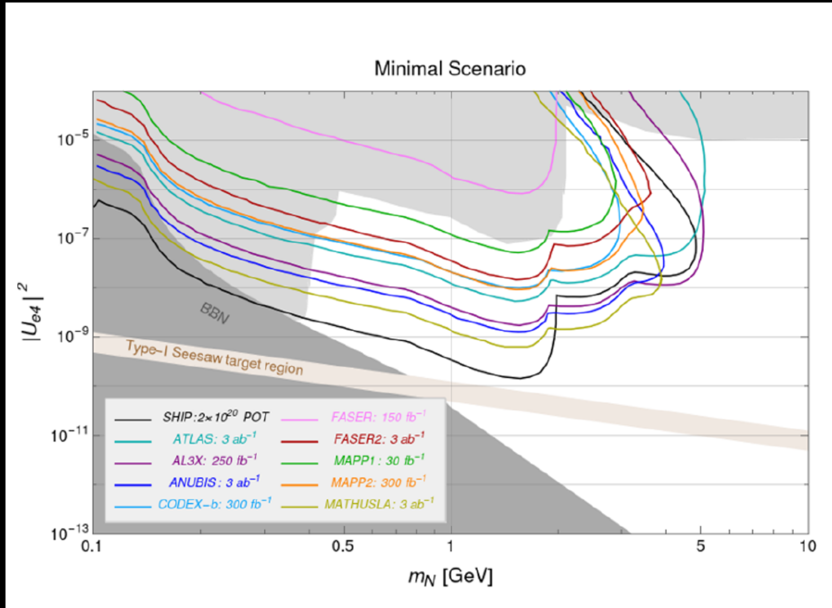
Light Neutralinos



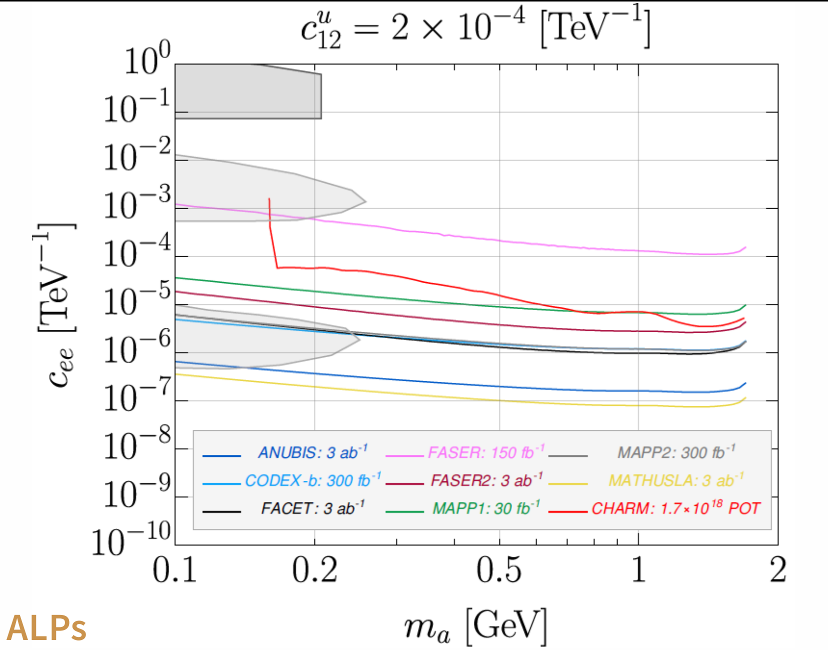
HNLs



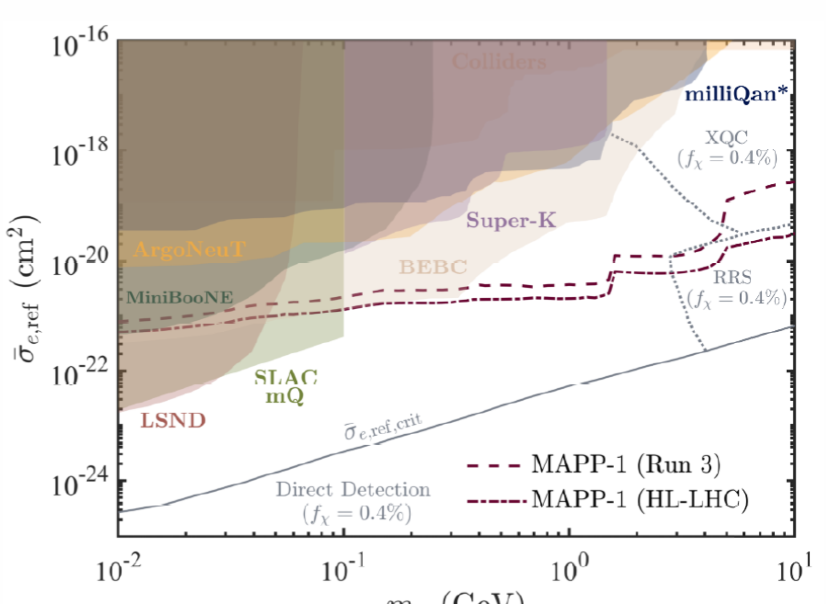
Minicharged Particles



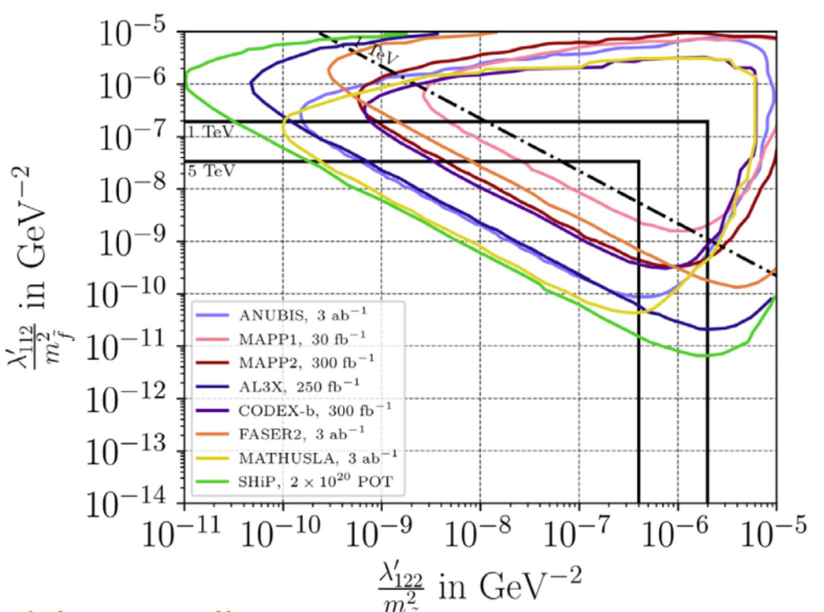
Sterile Neutrinos



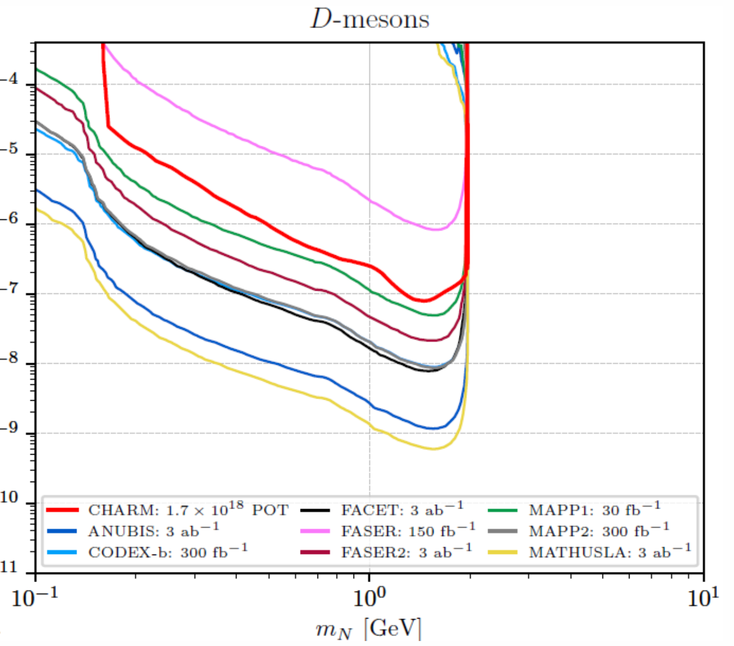
ALPs



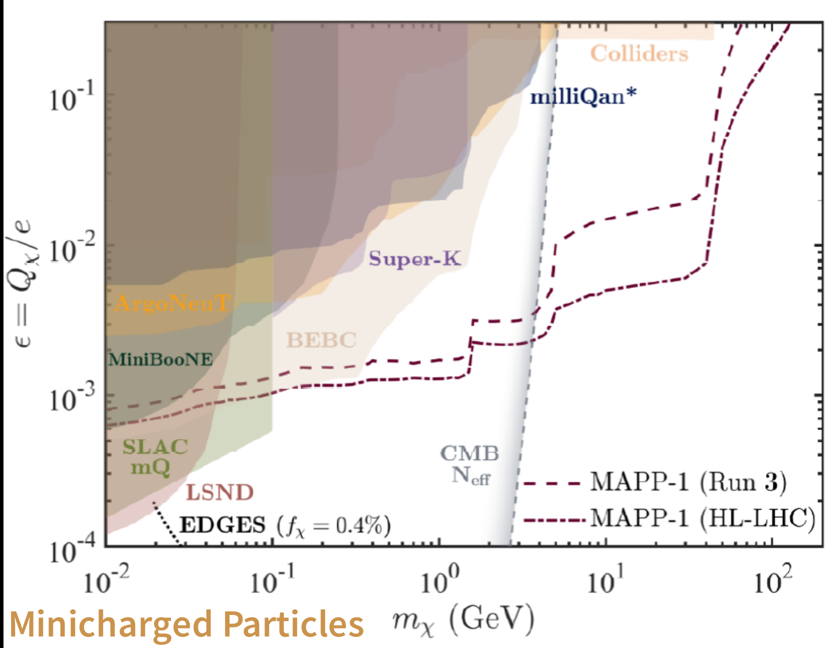
Minicharged SIDM



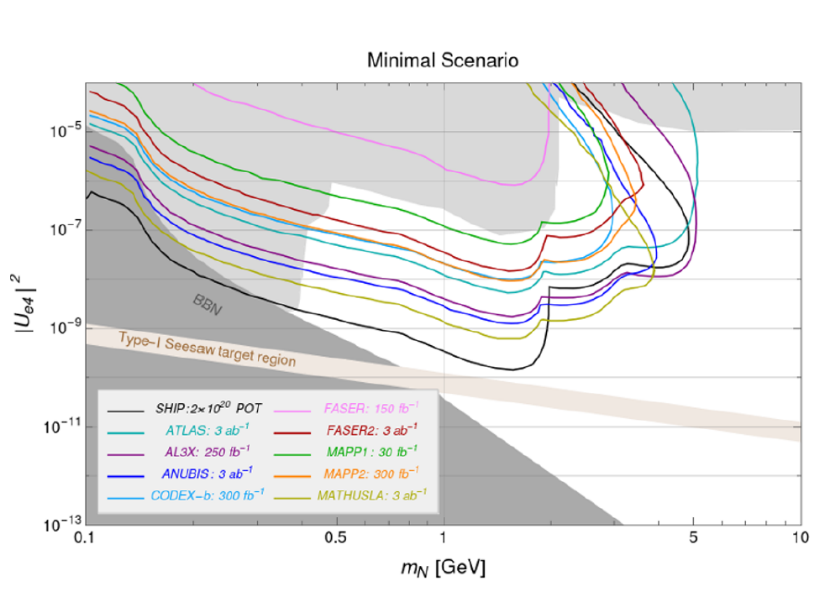
Light Neutralinos



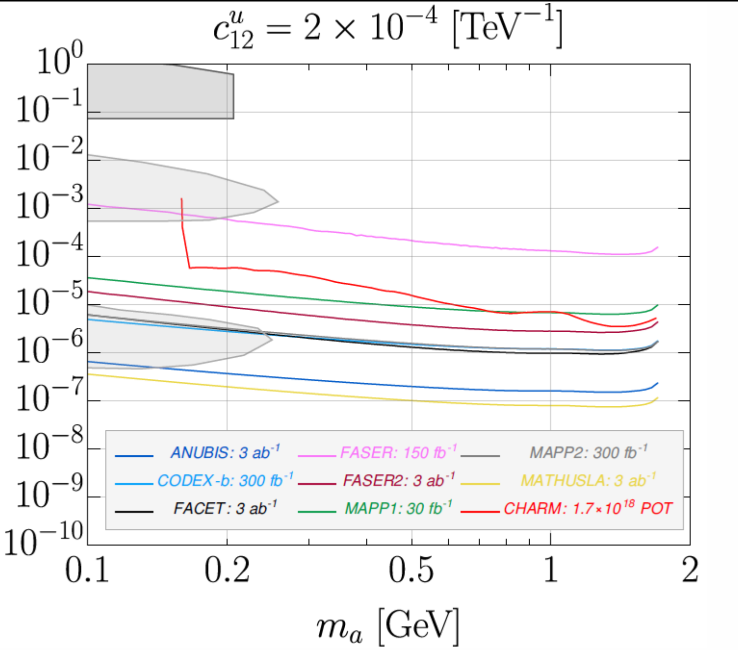
HNLs



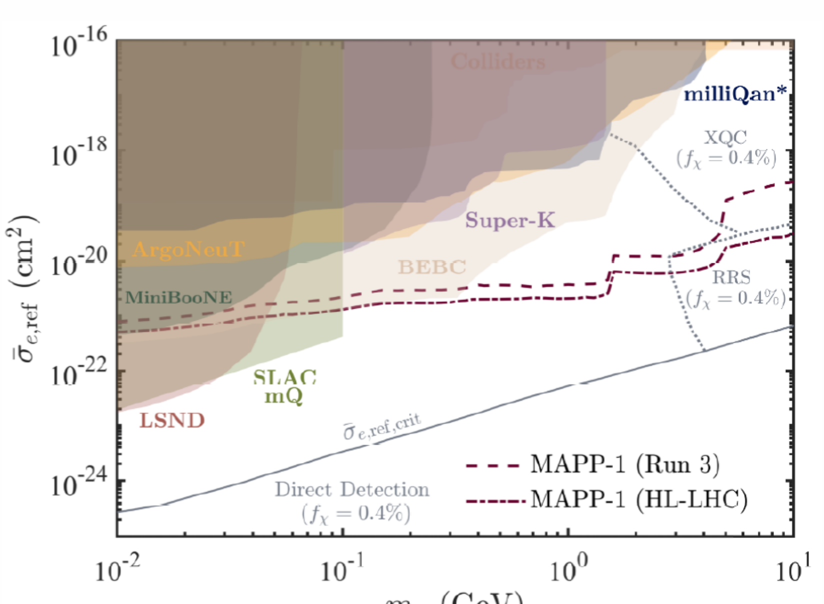
Minicharged Particles



Sterile Neutrinos



ALPs



Minicharged SIDM

Phys. Rev. D **103**, 075013 (2021); *JHEP* **2021**, 148 (2021); *JHEP* **2023**, 31 (2023); *JHEP* **2024**, 137 (2024)

Future Directions

GEANT4 modeling of the MAPP-2 detector is underway; various designs of the detector planes are currently being studied

Currently working on **optimizing efficiency and displaced-vertex reconstruction resolution vs. cost.**

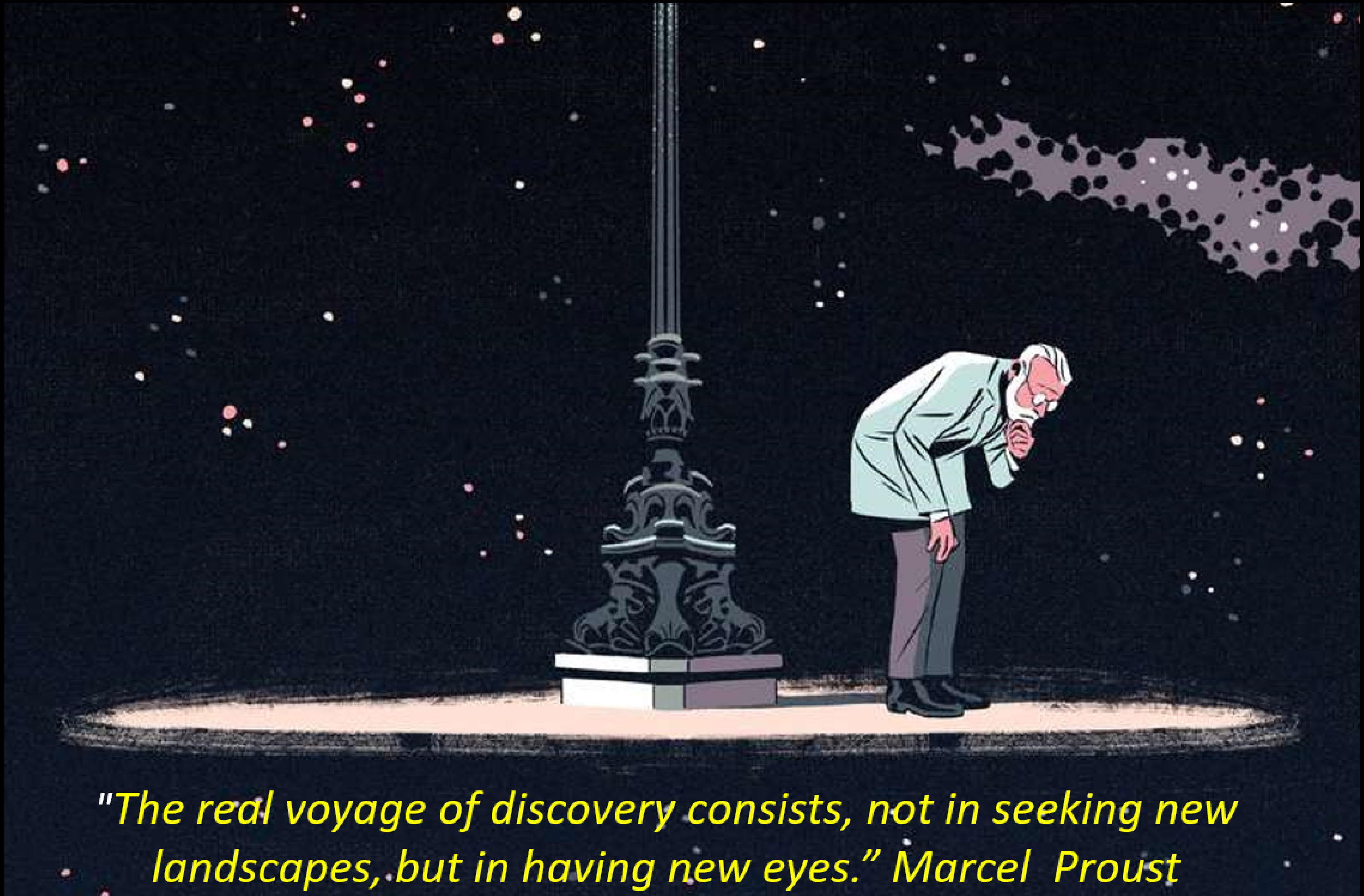
Modeling and analysis of MAPP's sensitivity to other scenarios such as long-lived "mirror mesons" and "dark jets".

Modeling is currently in progress.

Revised dark Higgs (and other) limits that include GEANT4 simulations of detector efficiency and BGs are in the pipeline

Comprehensive study of BGs is currently underway.

Concluding Remarks



Thank you!

Questions?

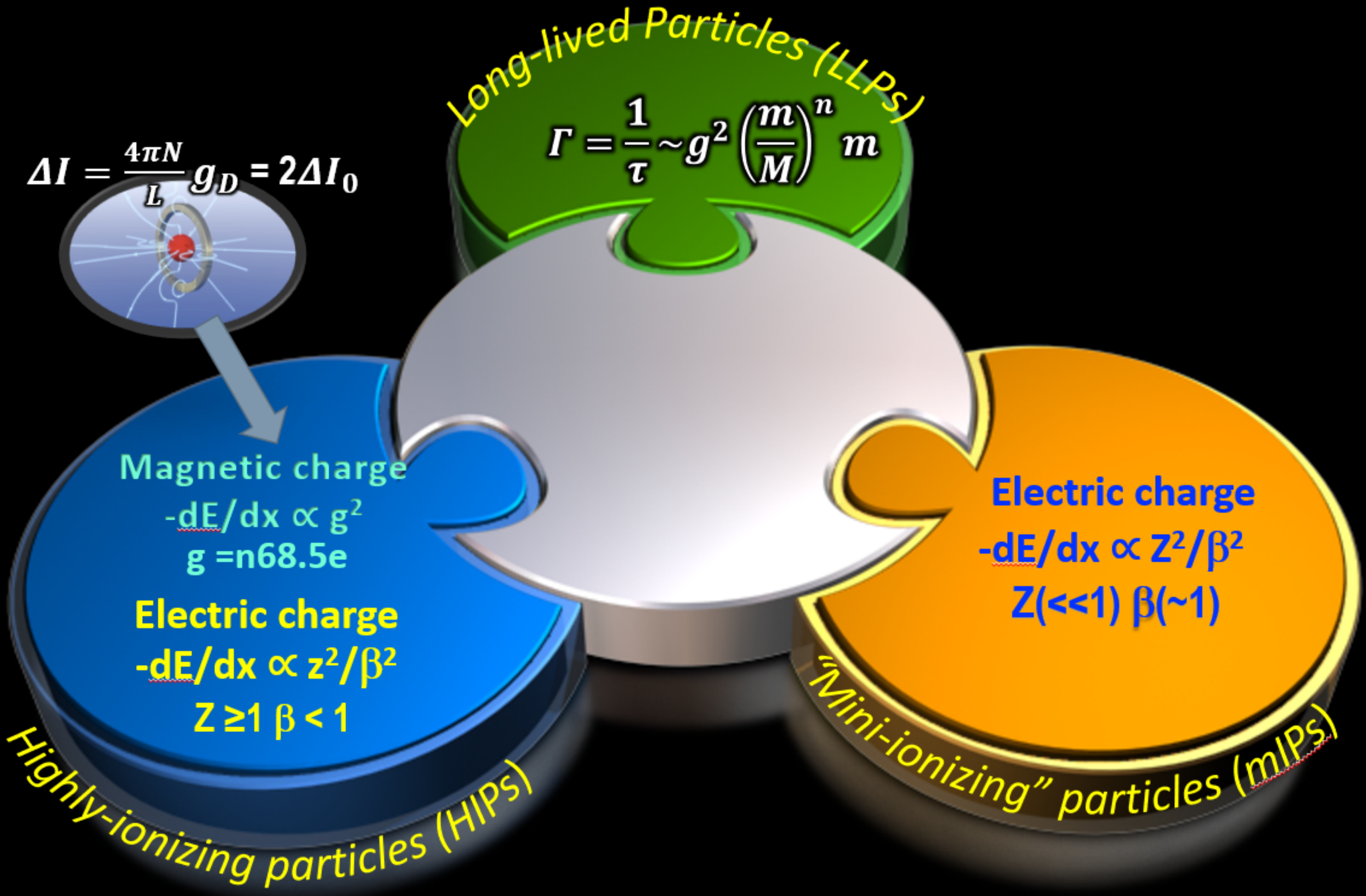
Backup Slides

The MoEDAL-MAPP Collaboration

Currently >70 physicists contributing!

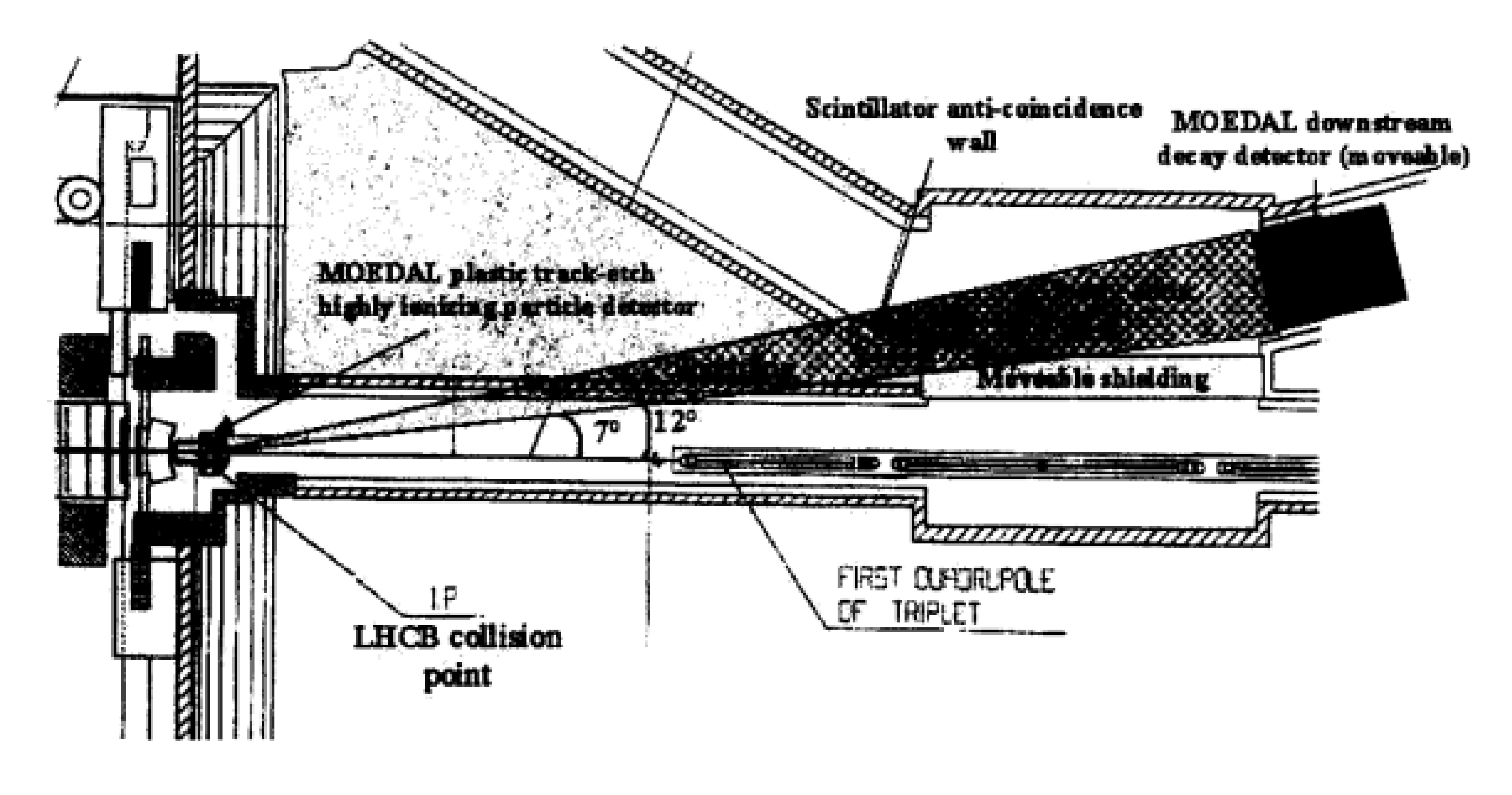
The Avatars of New Physics Targeted by MoEDAL-MAPP

For which ATLAS & CMS are not optimized



MAPP's Origins

The original MoEDAL LOI (1999) for the nominal MoEDAL detector also included a new downstream feebly interacting particle (FIP) detector.



Nucl. Phys. B Proc. Suppl. **78**(1–3):52–57, 1999

However, only the passive MoEDAL detector was approved for data taking during LHC Run 2

Nov. 2021: MAPP receives unanimous approval from the LHC Experiments Committee

MoEDAL gets a new detector

The new detector, known as MAPP, will increase the physics reach of the MoEDAL experiment and the Large Hadron Collider

28 MARCH, 2022 | By Ana Lopes

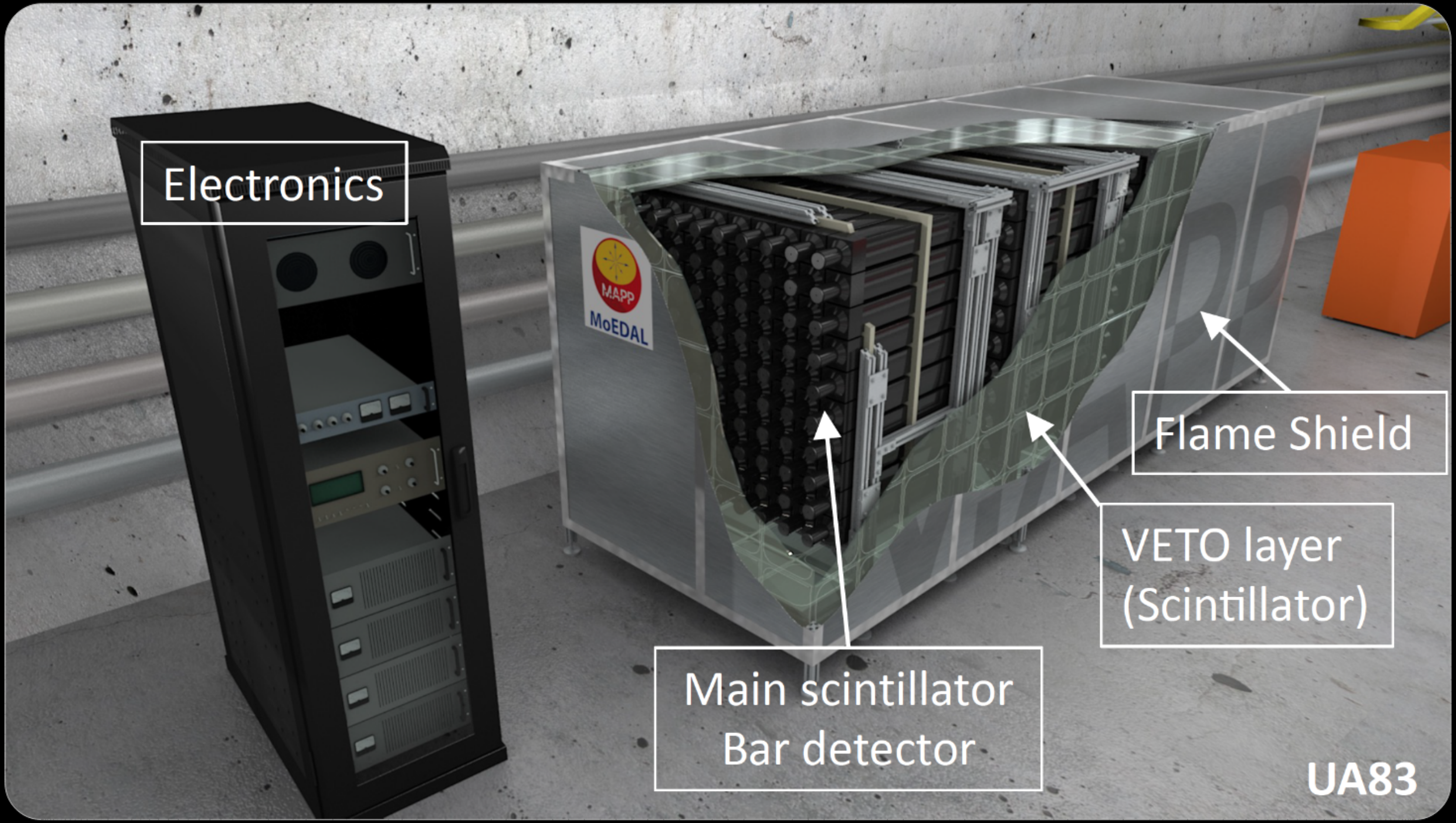
Installation of the support structure for the MAPP detector components. (Image: CERN)

The MoEDAL collaboration at the Large Hadron Collider (LHC) is adding a new detector to its experiment, in time for the start of the next run of the collider this coming summer. Named as the MoEDAL Apparatus for Penetrating Particles, or MAPP for short, the new detector will expand the physics scope of MoEDAL to include searches for minicharged particles and long-lived particles.

MAPP
MoEDAL

The Phase-1 MAPP Detector (MAPP-1)

400 scintillator bars (10 × 10 × 75 cm) in 4 sections readout by coincident PMTs & protected by a hermetic VETO system



Installation of MAPP-1

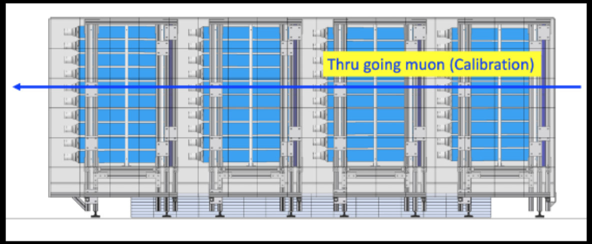
In the LHC's UA83 gallery

Electronics rack

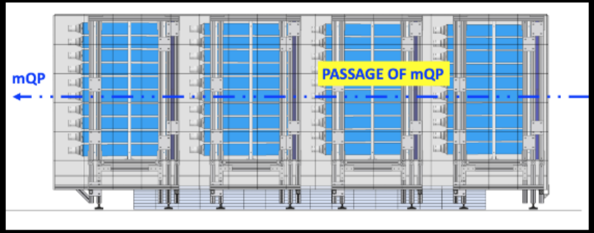
MAPP-1 with flame shield

One sector of MAPP-1

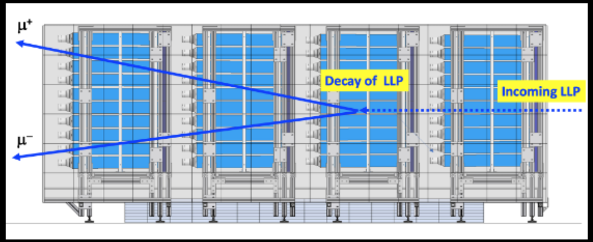
MAPP-1 — Modes of Detection



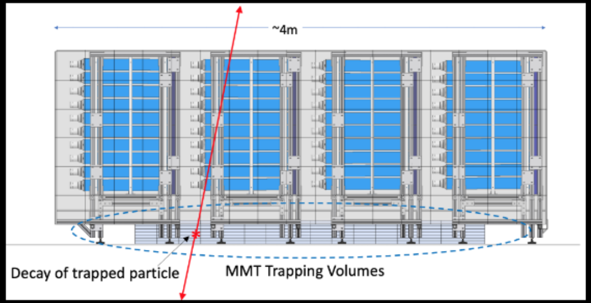
Muons from IP (Calibration)



Millicharged particle detection

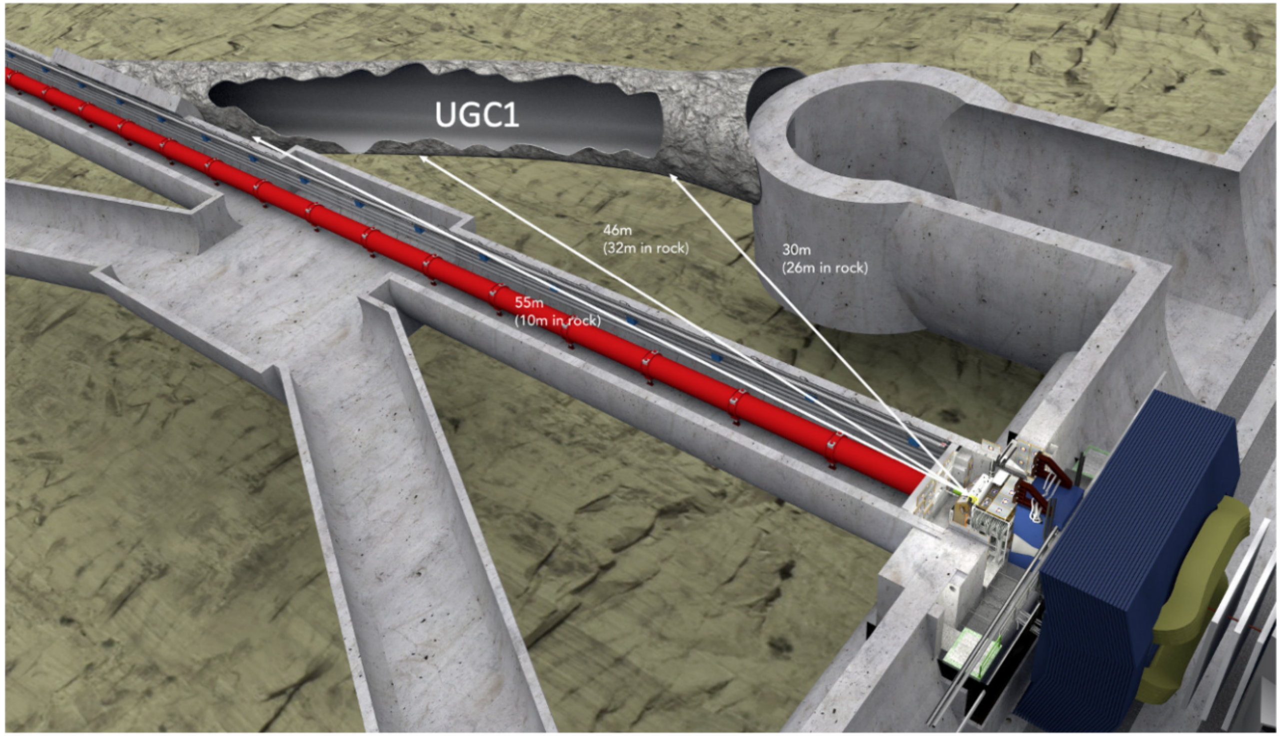


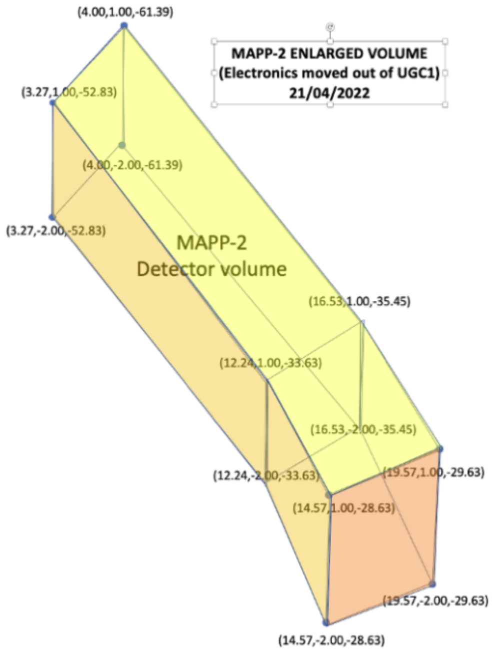
Neutral LLP Detection



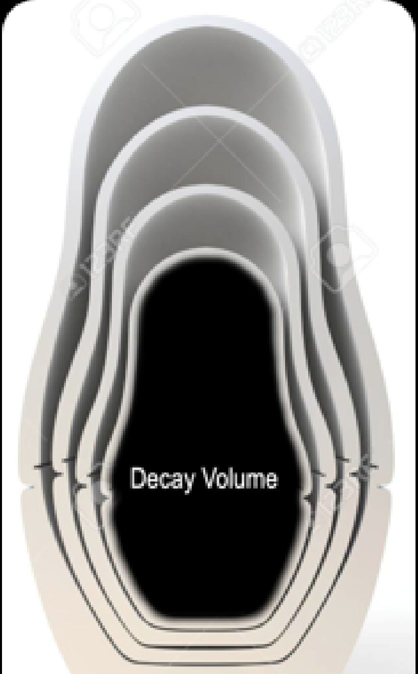
Charged LLP Detection
(In conjunction with MoEDAL)

The MAPP-2 Detector Volume





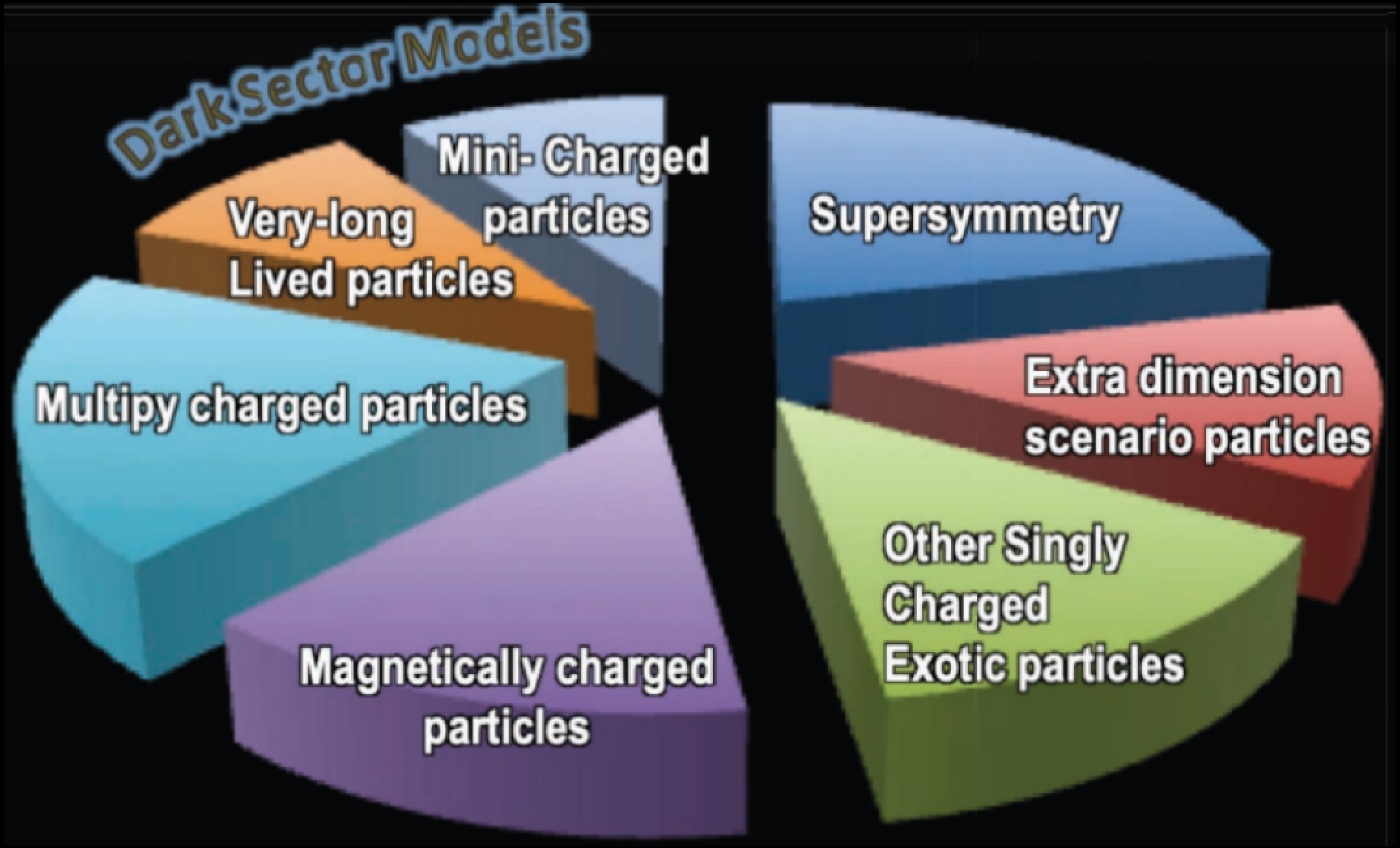
Dimensions in metres (Max. FV ~1400 m^3)



"Russian doll" configuration of scintillator walled boxes

MoEDAL-MAPP's Physics Program

MoEDAL—highly ionizing particle (HIP) searches; MAPP—feebly interacting particle (FIP) searches



The Physics Program of the MAPP Experiment

Searching for feebly interacting particles at the LHC

Particle Class	New Physics Scenario
Anomalously Ionizing Particles	Fermionic minicharged particles (Holdom phase)
	Fermionic minicharged particles (mixed phase)
	Fermionic minicharged strongly-interacting DM
	Scalar minicharged particles (“pion-like” DM)
	Heavy neutrinos w/ large EDMs
	Mini-magnetically charged particles
	Magneticons (magnetic charge $g = e$)
Long-Lived Neutral Particles	Dark Higgs (scalar portal)
	Dark photon (vector portal)
	Axion-like particles (pseudoscalar portal)
	‡Heavy neutral leptons in the minimal “$3+1$” scenario
	‡RH Majorana neutrinos in the $U(1)_{B-L}$ model
	‡Light neutralinos in RPV-SUSY
	‡Sterile neutrinos in νSMEFT
	‡Inelastic dark matter states (fermionic & scalar)
	Binos
	Higgsinos
	Mirror mesons

‡ = sensitivity study performed by an external group

Yellow text = study not yet performed or still ongoing

A total of 11 different scenarios have been studied so far!

MAPP MoEDAL