



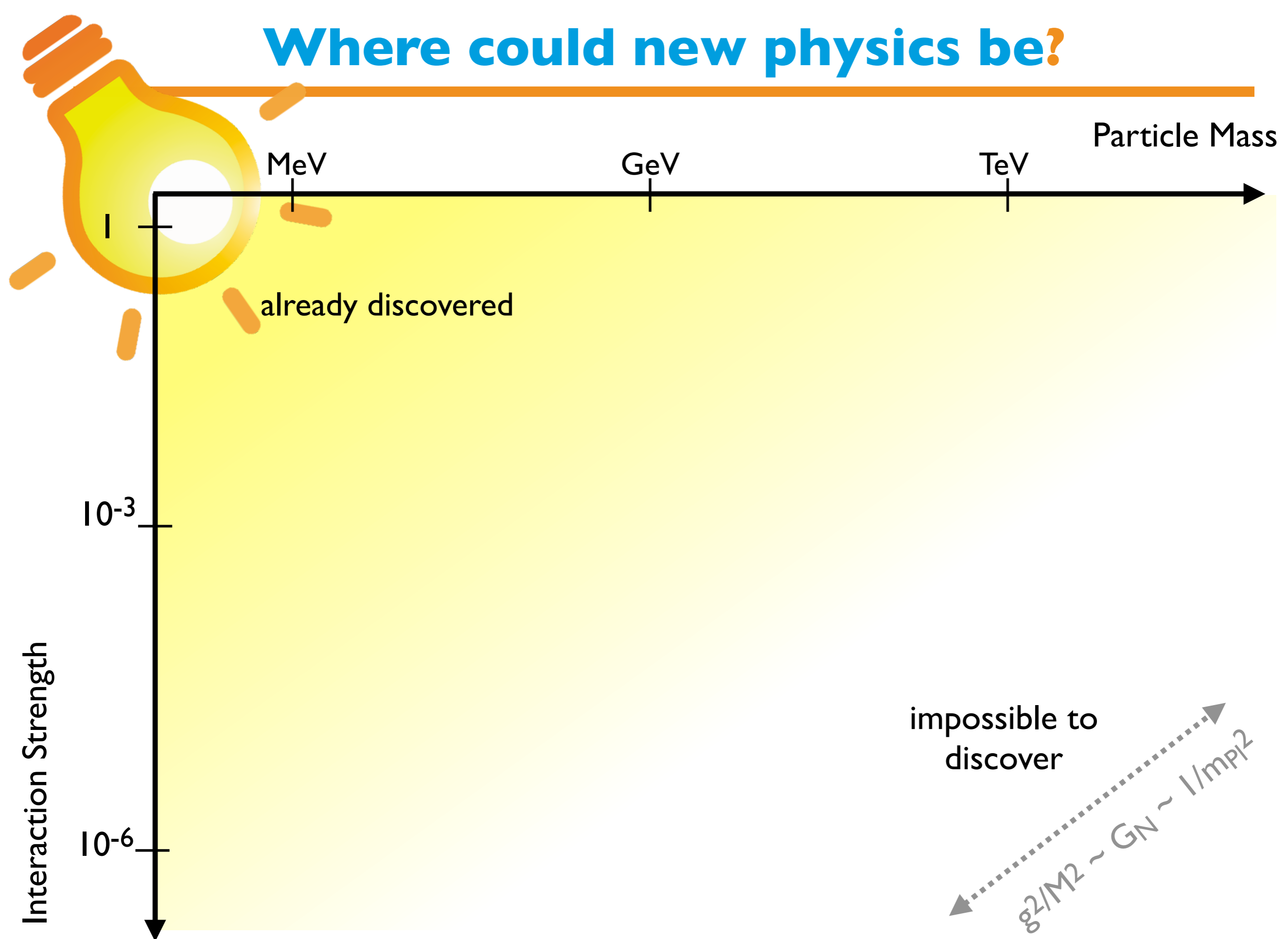
Testing the Dark Sector in the Laboratory

PASCOS 2022
July 29th 2022
Felix Kling

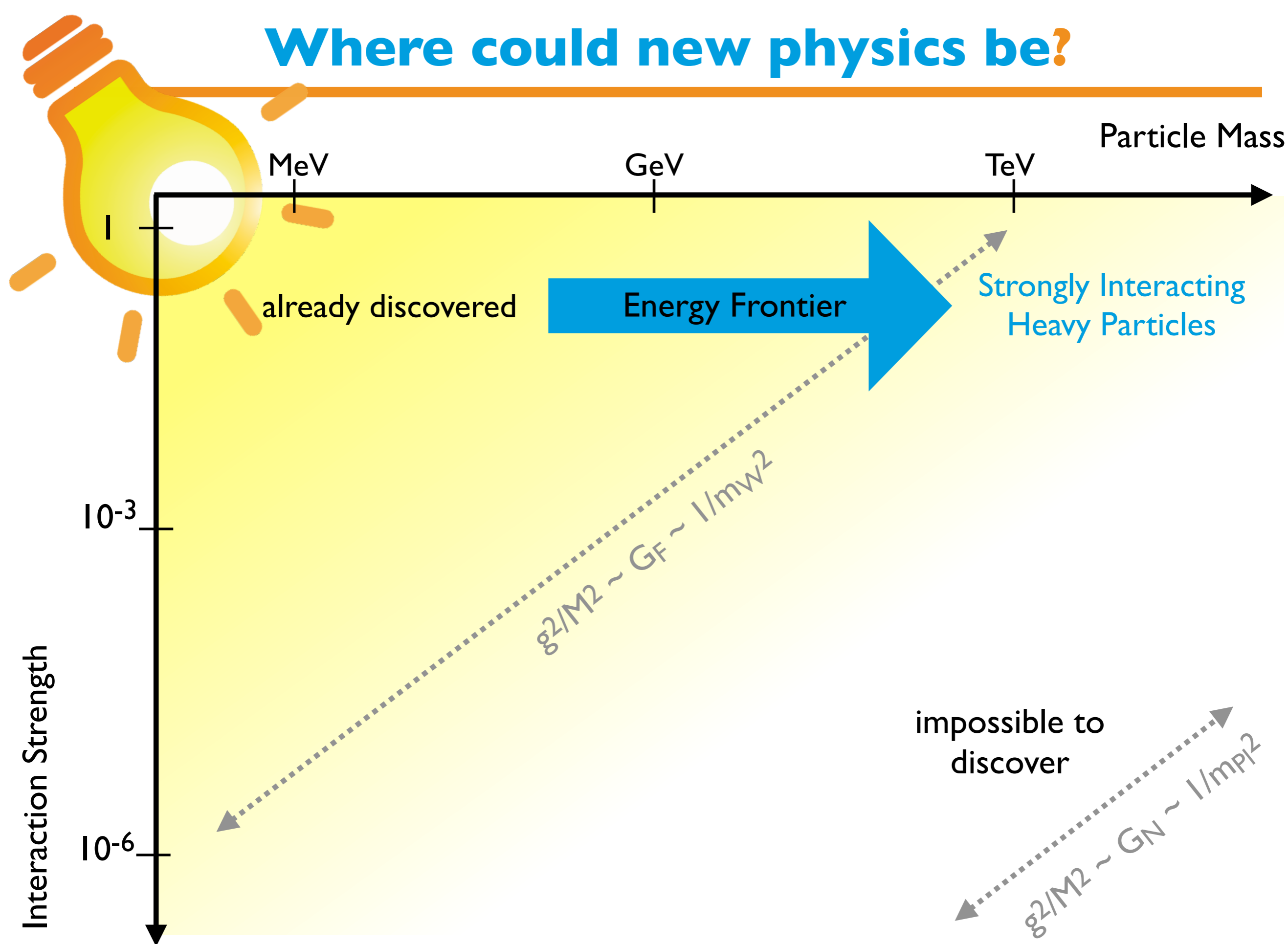


What is a dark sector?

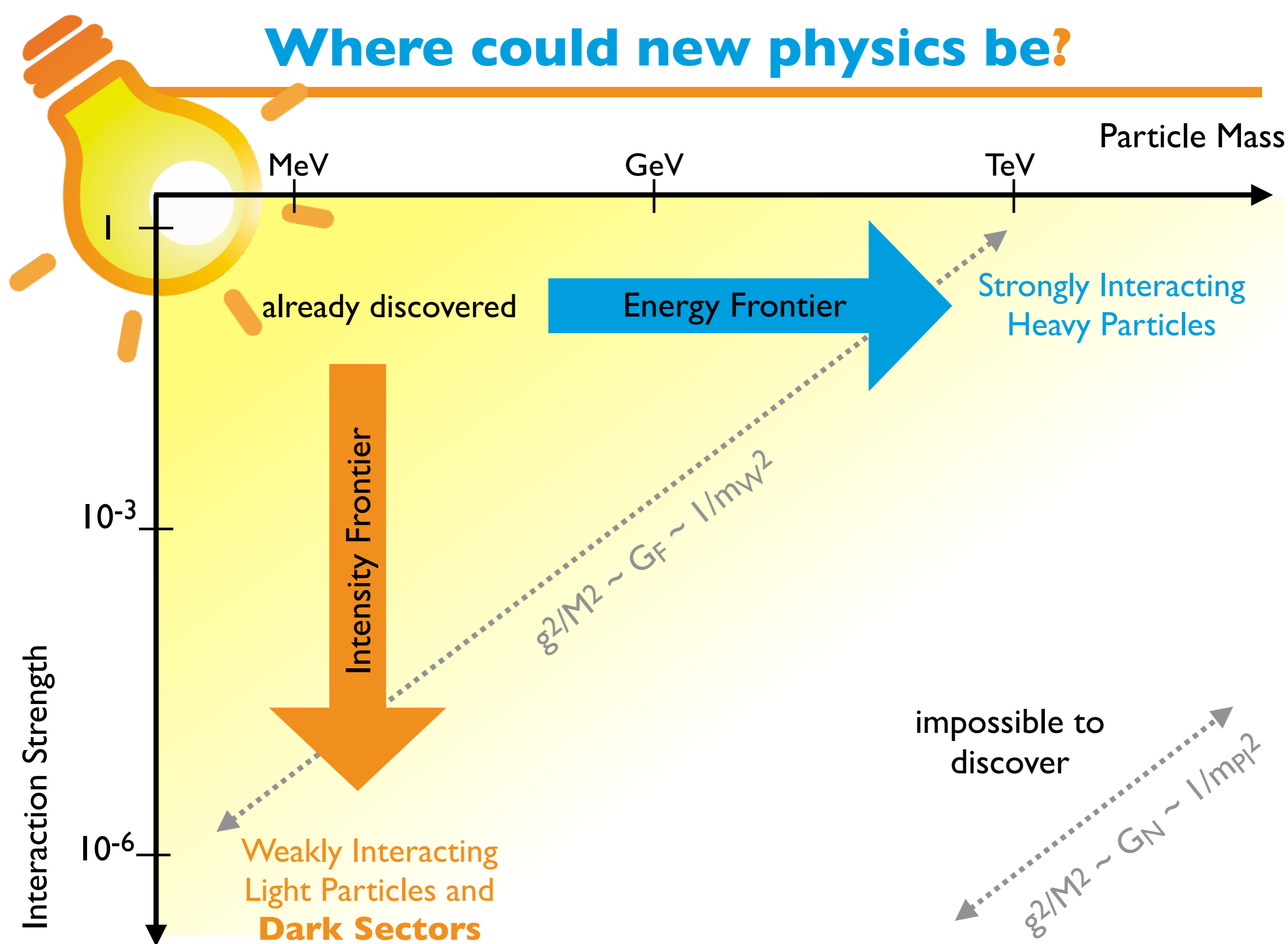
Where could new physics be?



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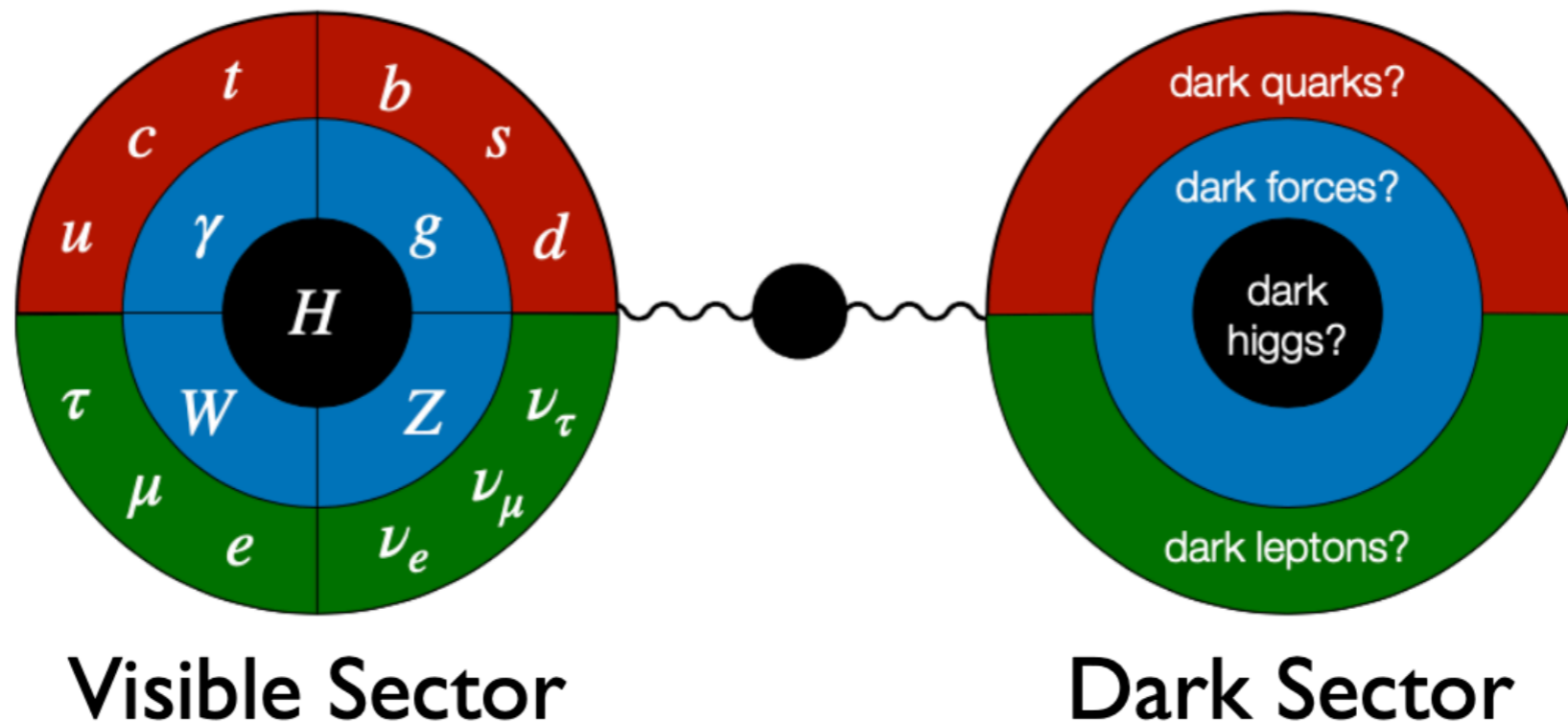


What is a dark sector?

Definition from Snowmass RF6 group: *Dark Sector Studies at High Intensities*
see Brian Batell's talk at [Seattle Snowmass Summer Meeting 2022](#)

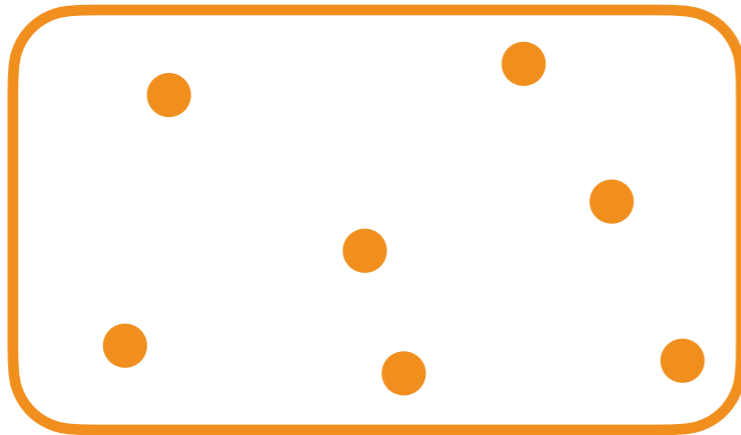
set of new particles, which do not experience known forces

weakly coupled to visible sector through a mediator or “portal”

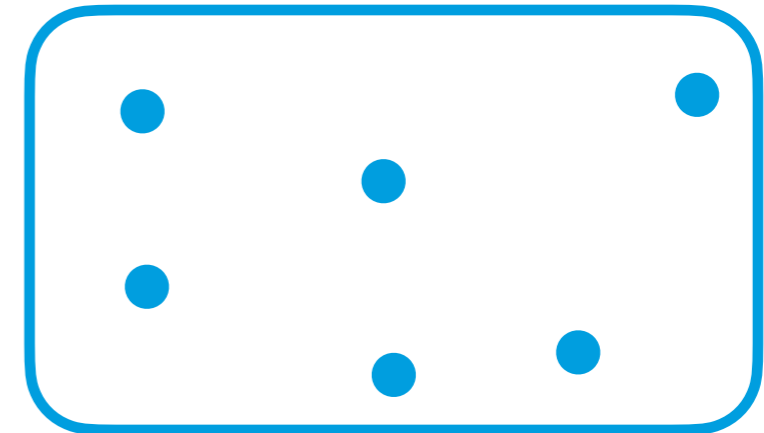


Example: dark photon portal.

visible sector



dark sector

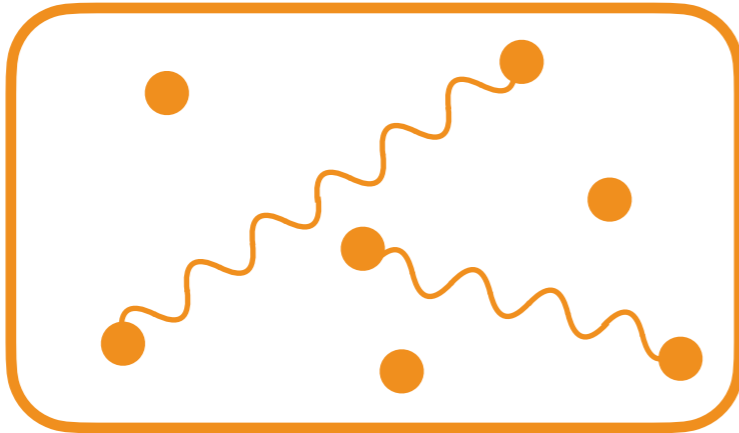


$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi.$$

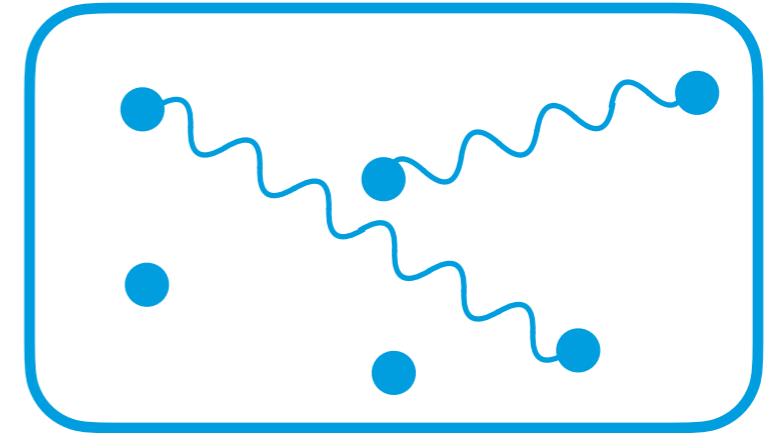
$$+i\bar{\chi}\gamma^\mu\partial_\mu\chi - m\bar{\chi}\chi$$

Example: dark photon portal.

visible sector



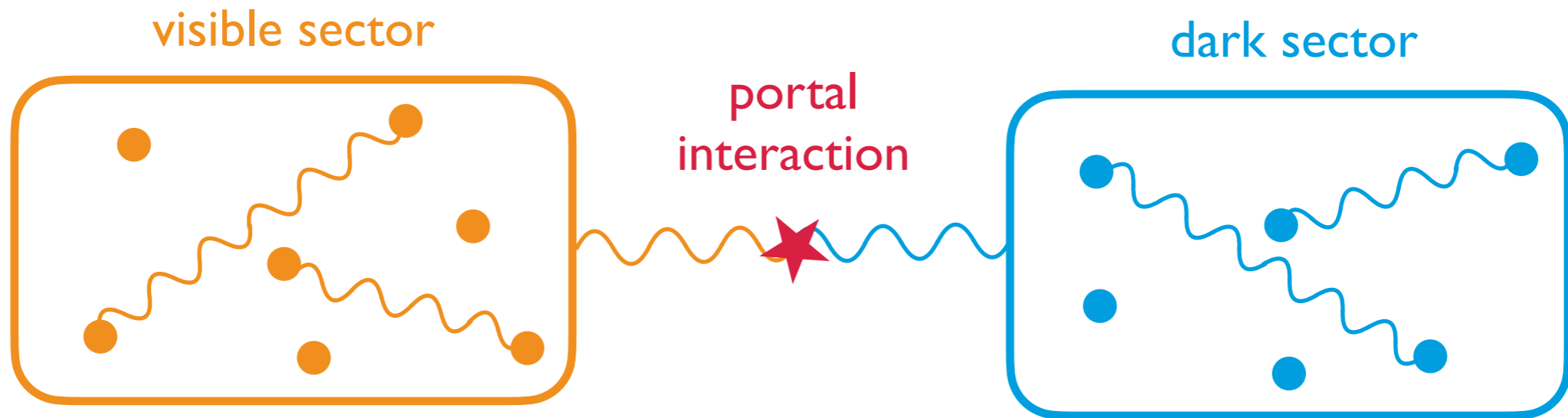
dark sector



$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + e\gamma^\mu\bar{\psi}A_\mu\psi.$$

$$+i\bar{\chi}\gamma^\mu\partial_\mu\chi - m\bar{\chi}\chi - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + e_D\gamma^\mu\bar{\chi}A'_\mu\chi.$$

Example: dark photon portal.



$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi.$$

$$-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + e\gamma^\mu\bar{\psi}A_\mu\psi.$$

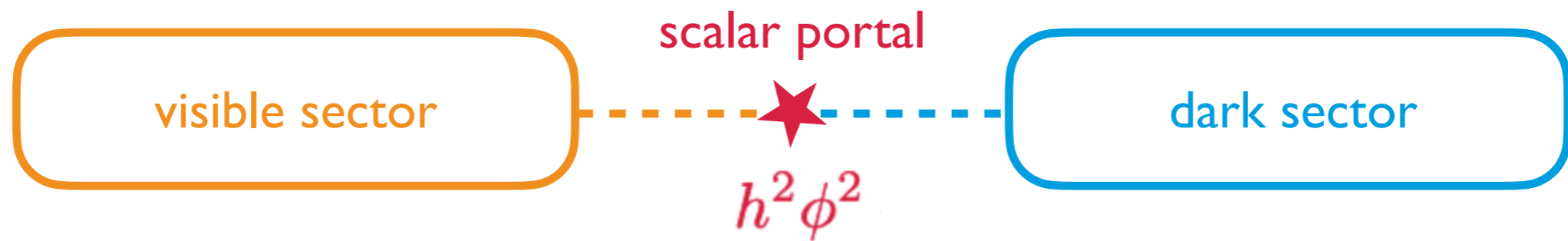
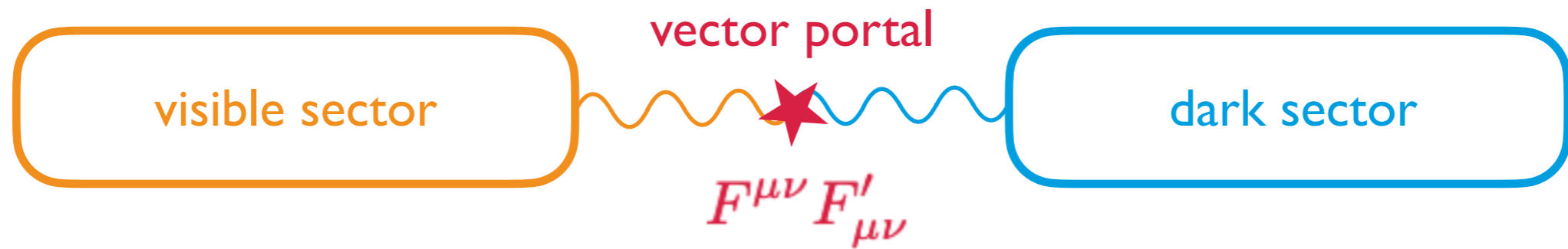
$$+i\bar{\chi}\gamma^\mu\partial_\mu\chi - m\bar{\chi}\chi$$

$$-\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + e_D\gamma^\mu\bar{\chi}A'_\mu\chi.$$

$$+\epsilon\frac{1}{4}F^{\mu\nu}F'_{\mu\nu}$$

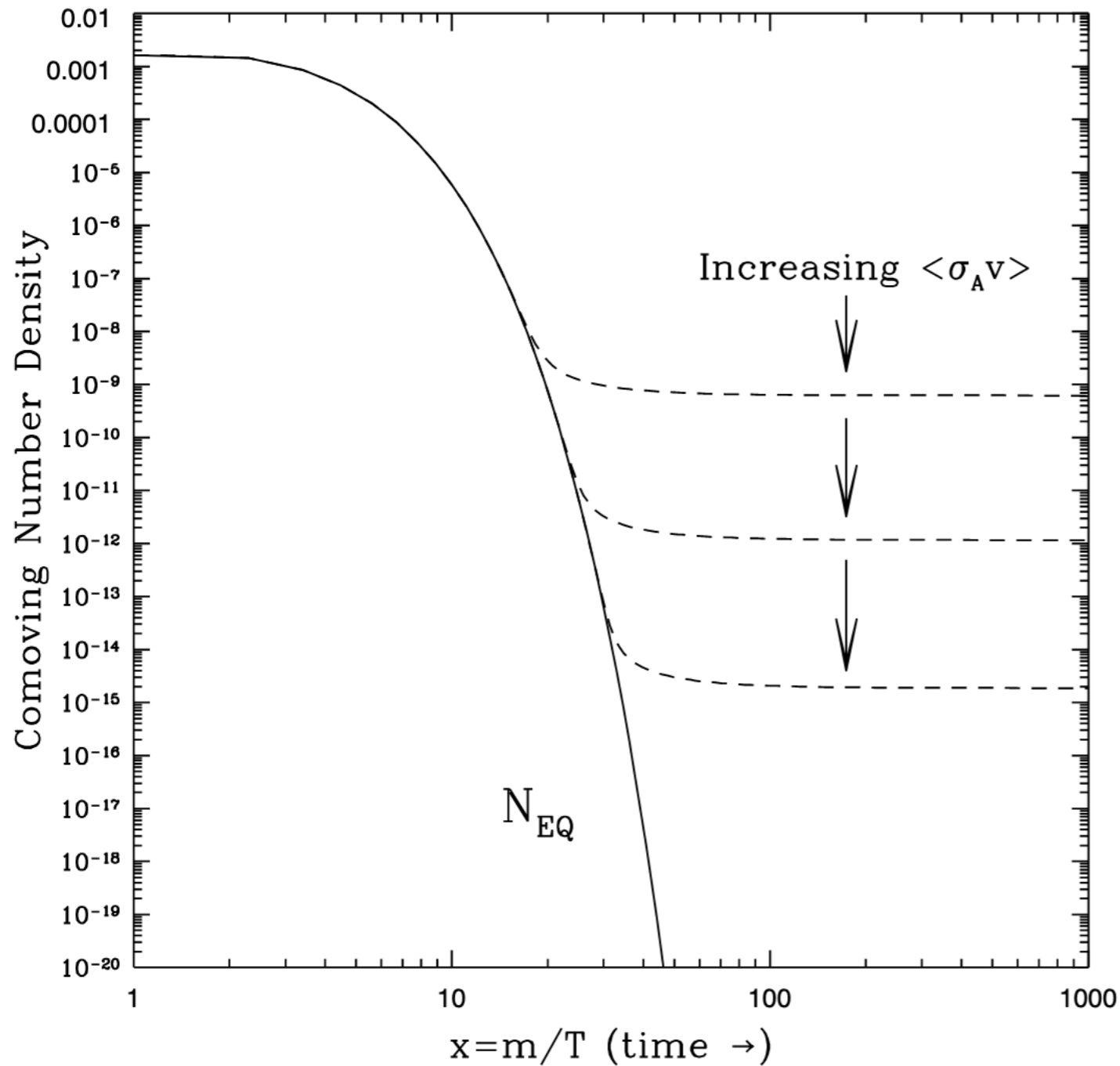
Other popular portals.

renormalizable portals



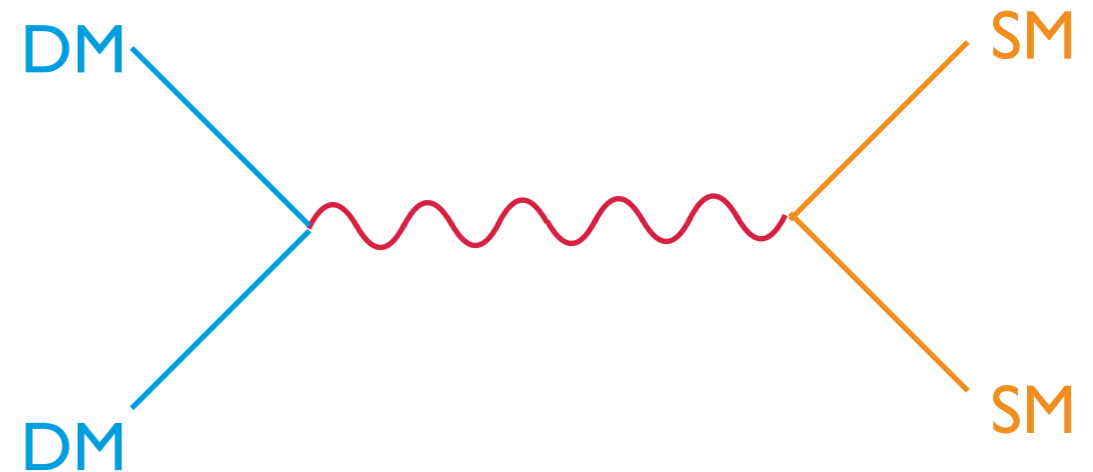
What do we care about dark sectors?

Motivation: dark matter.



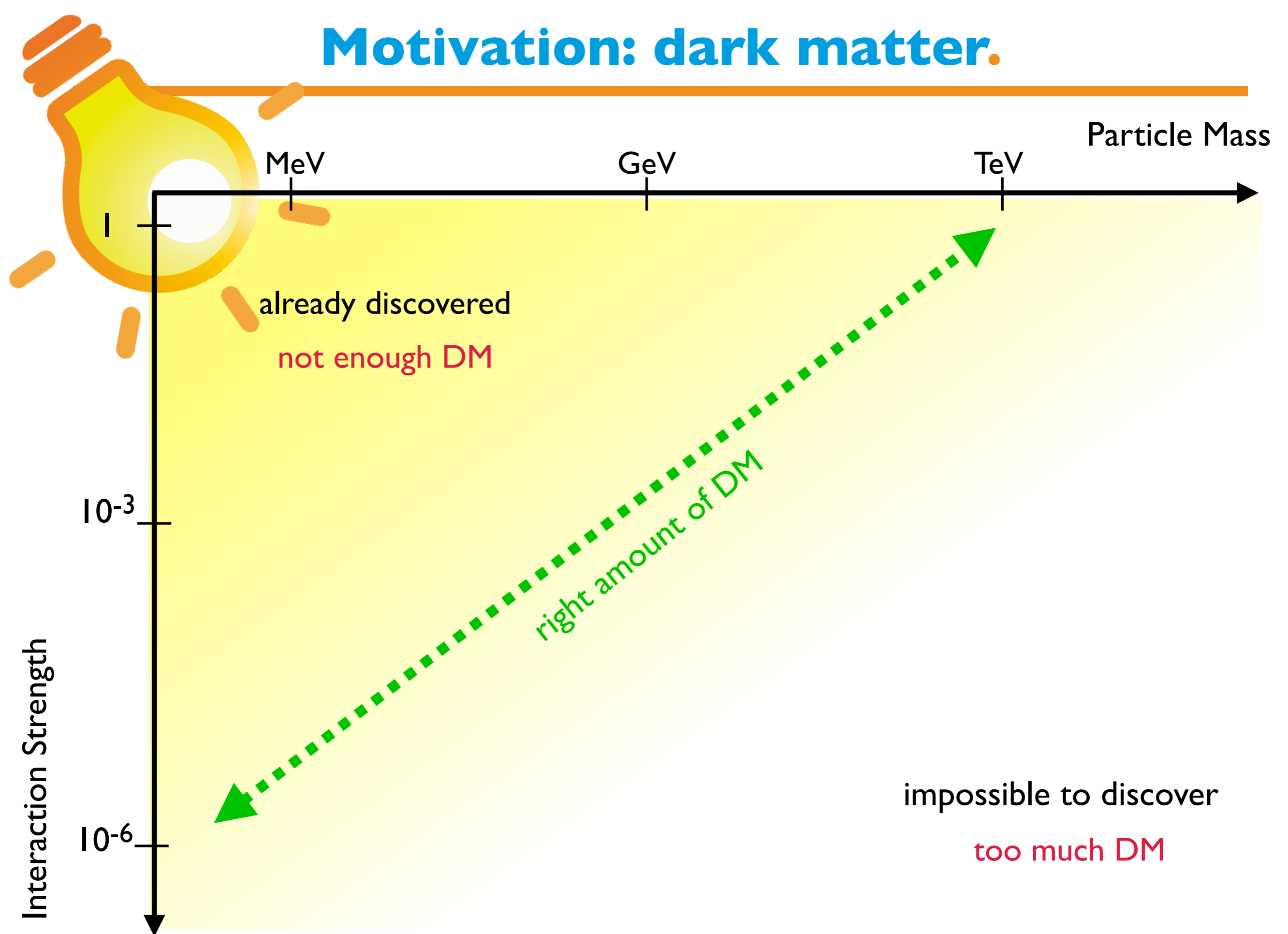
thermal freeze out:

$$\Omega_{DM} \sim 1/\langle \sigma v \rangle \sim m^2/g^4$$

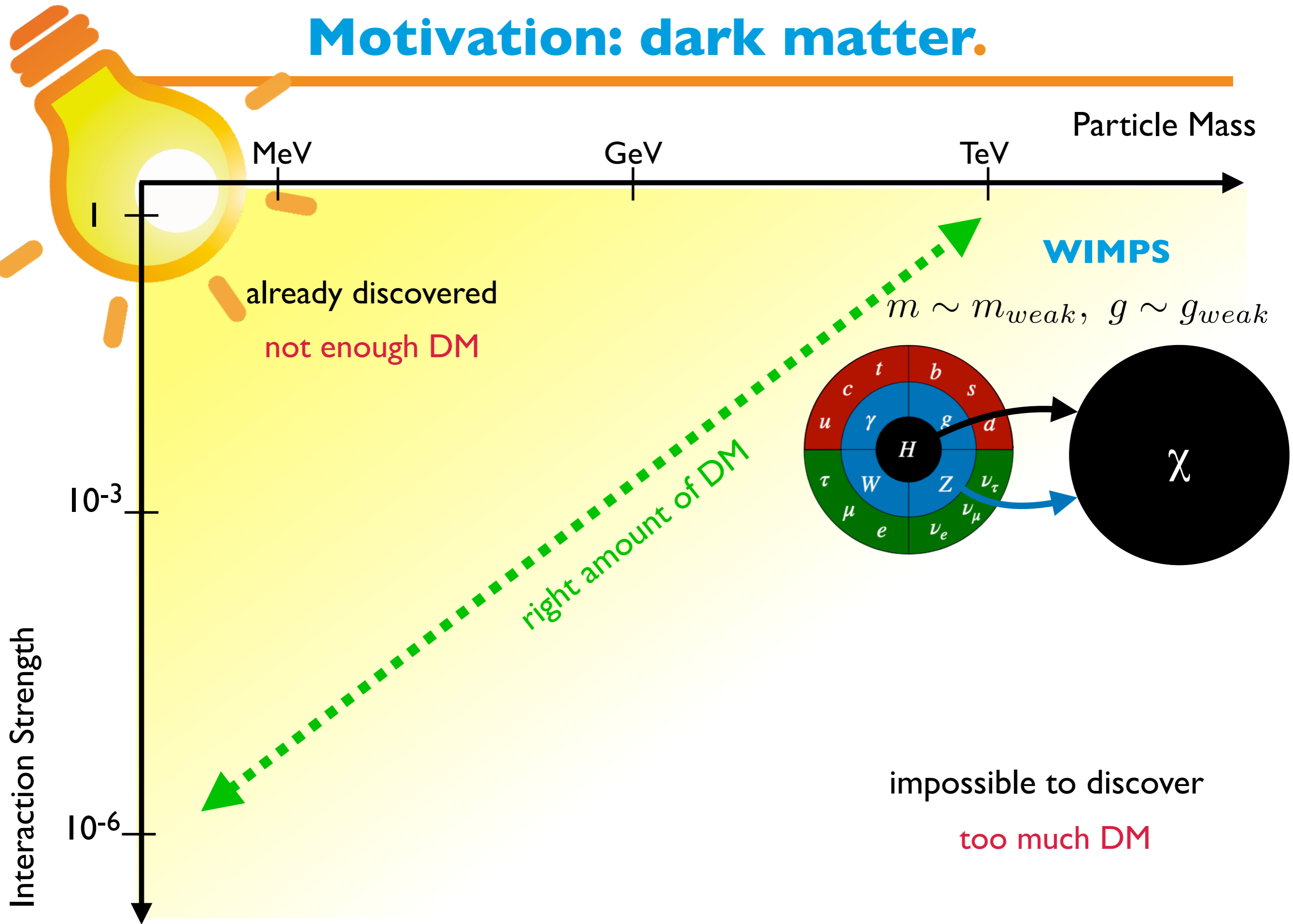


[TASI 2008 Lectures on Dark Matter
By Dan Hooper: [0901.4090](https://arxiv.org/abs/0901.4090)]

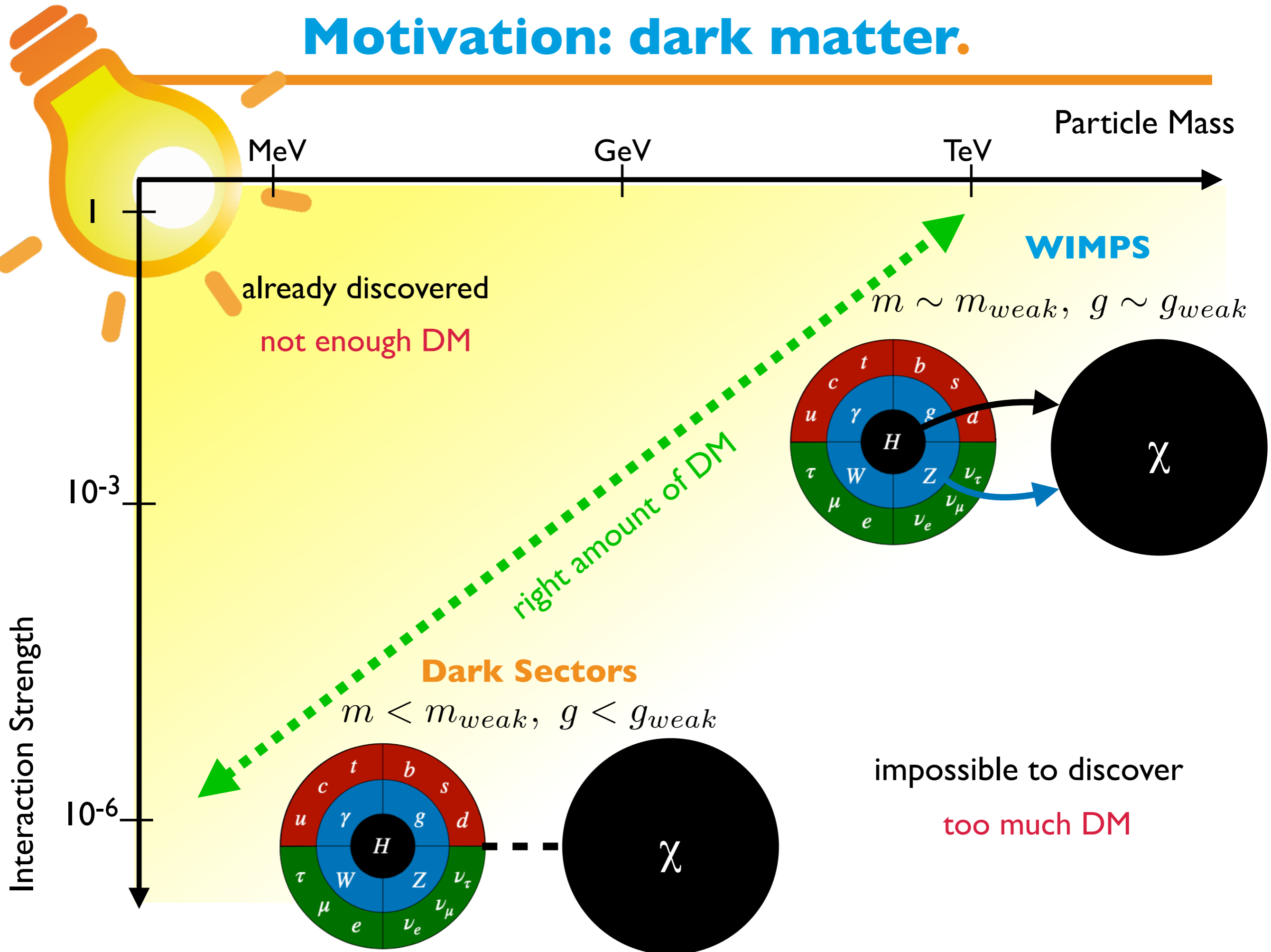
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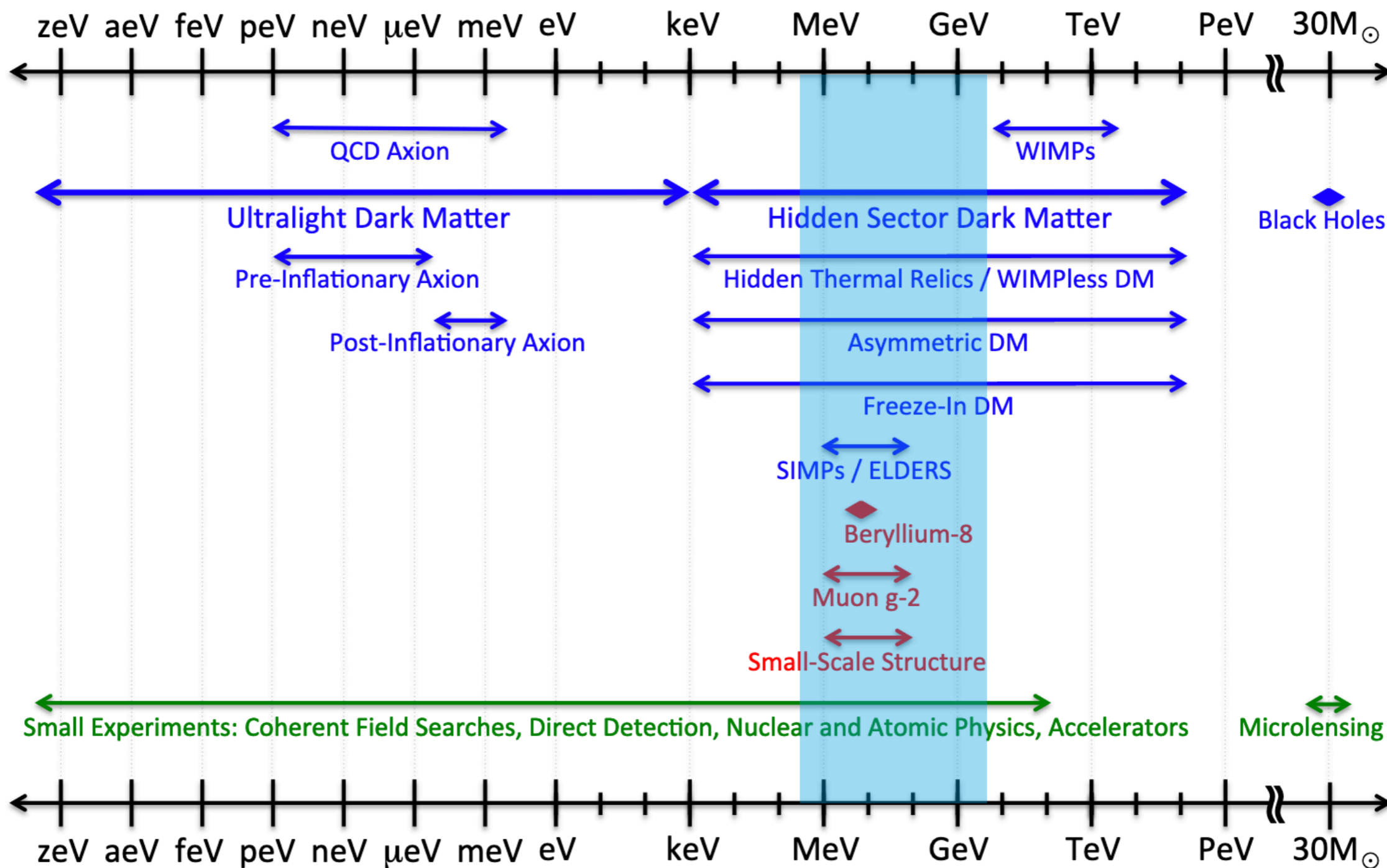


Motivation: dark matter.

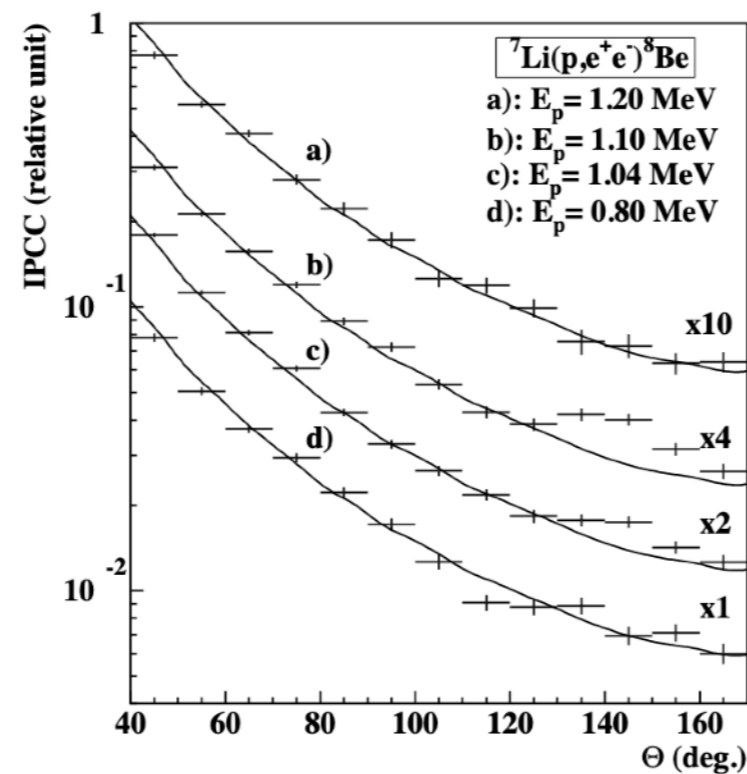
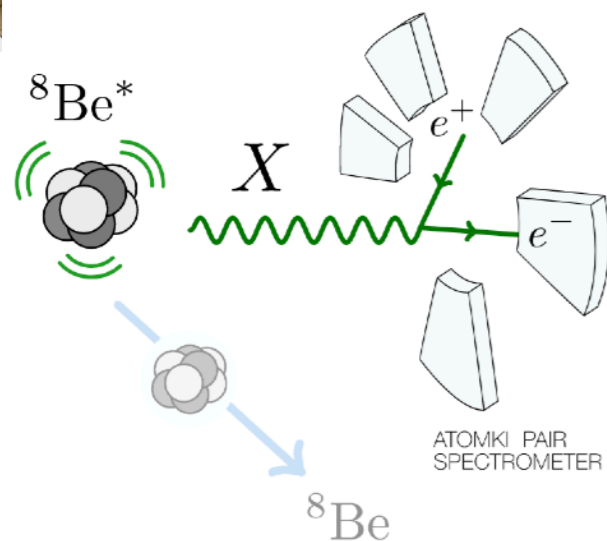
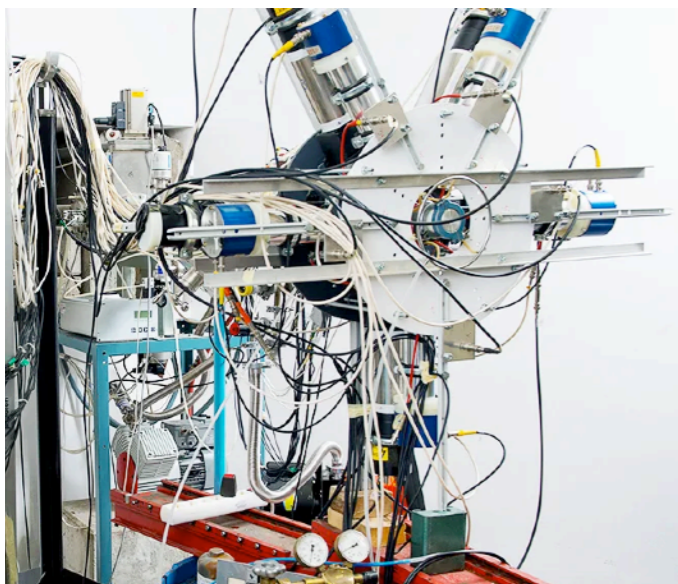


Motivation: anomalies.

Dark Sector Candidates, Anomalies, and Search Techniques



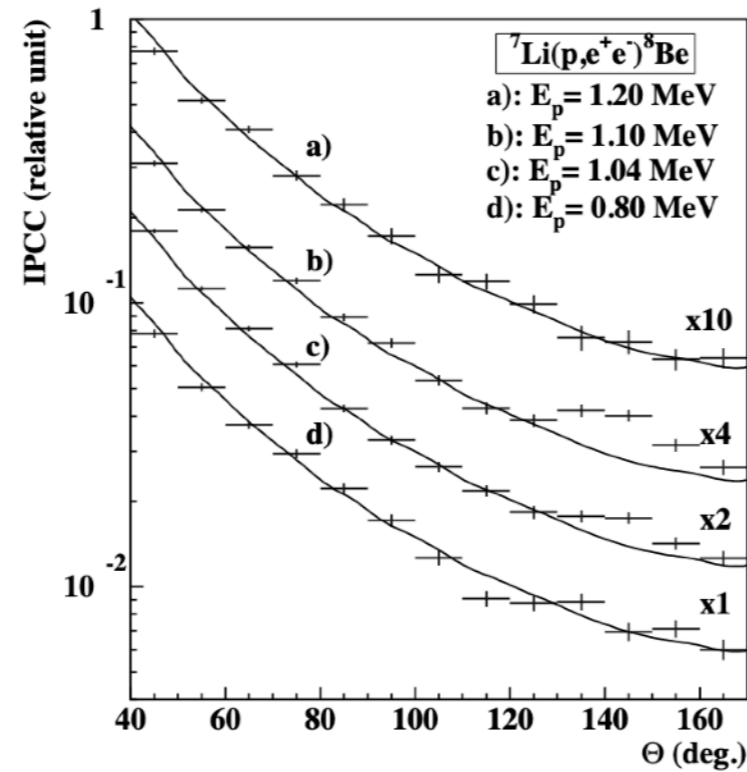
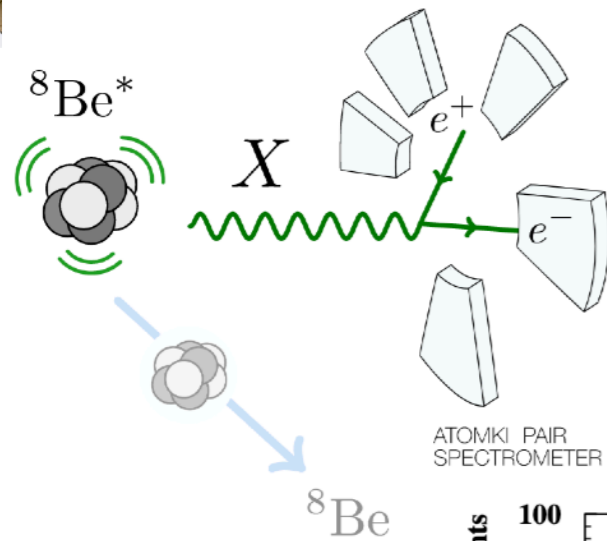
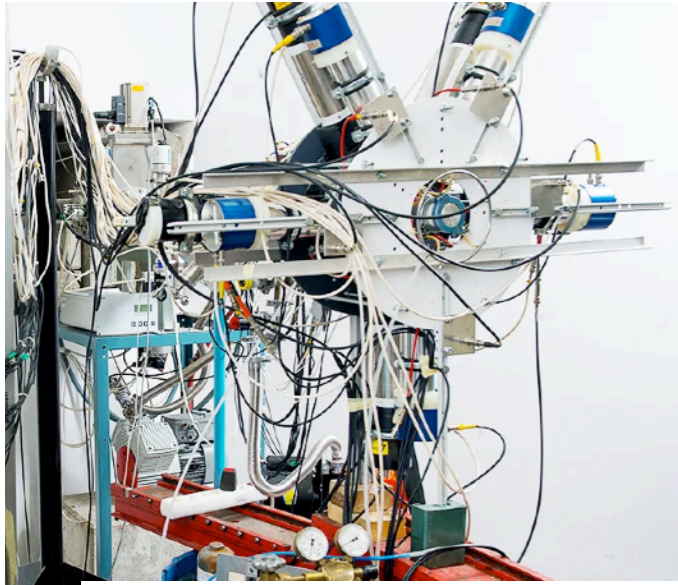
Motivation: Be8 and He4 anomalies.



2015: ATOMKI group reported a 7σ excess in rare Be decays

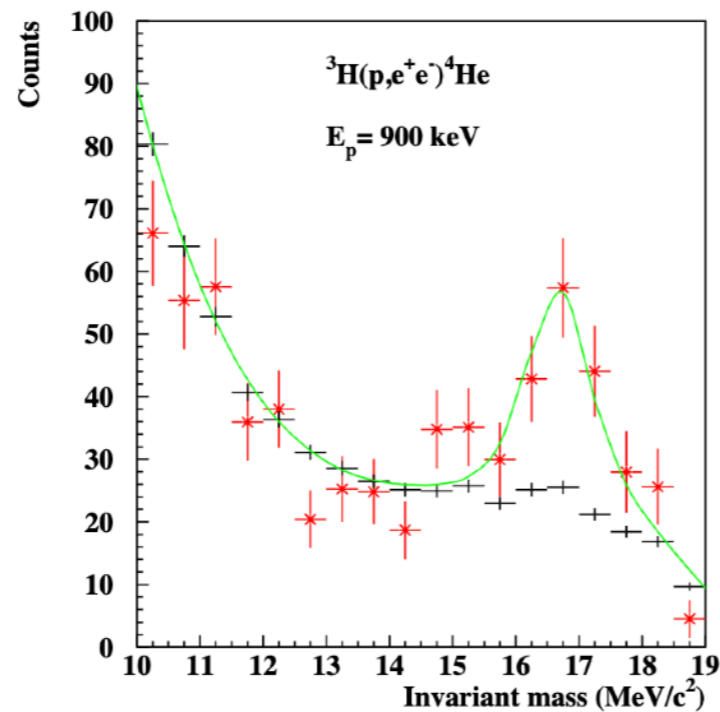
[ATOMKI, [1504.01527](#)]

Motivation: Be8 and He4 anomalies.

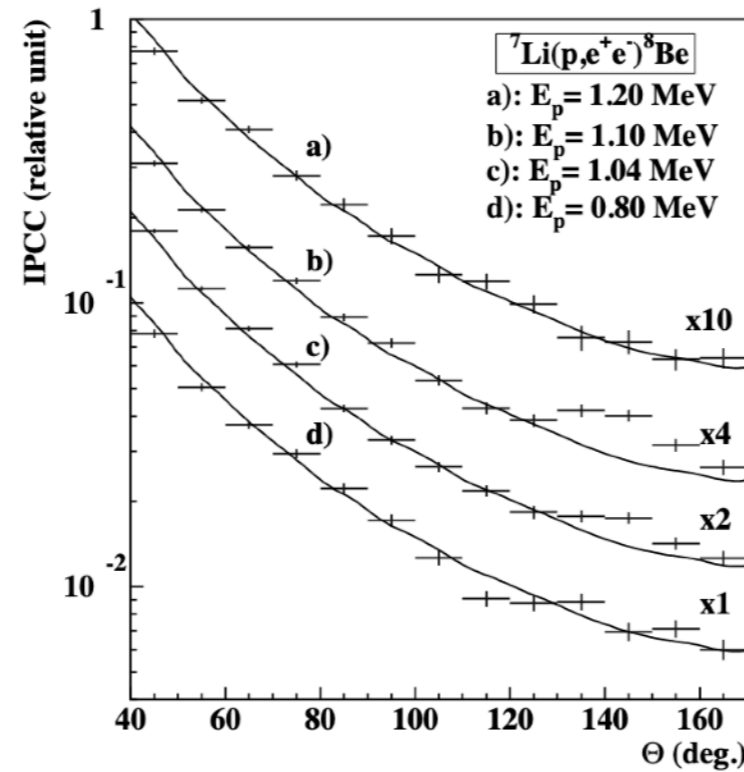
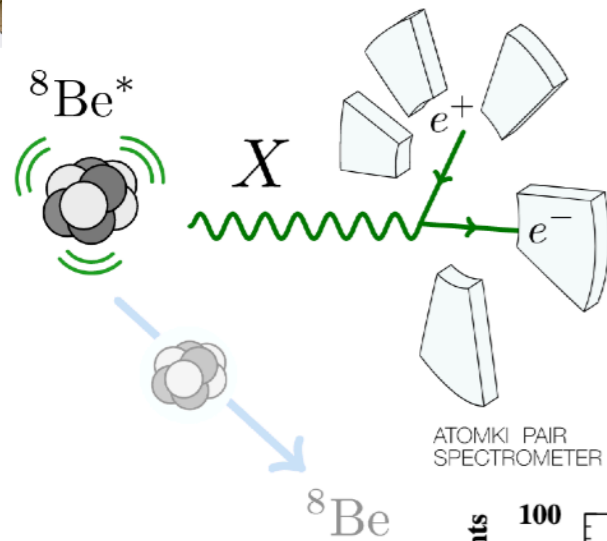
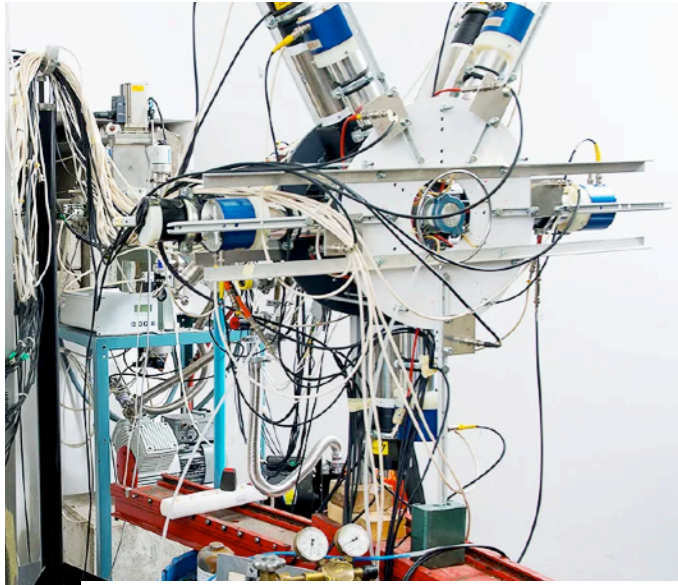


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2019: also excess in He decays
 [ATOMKI, [1910.10459](#)]



Motivation: Be8 and He4 anomalies.

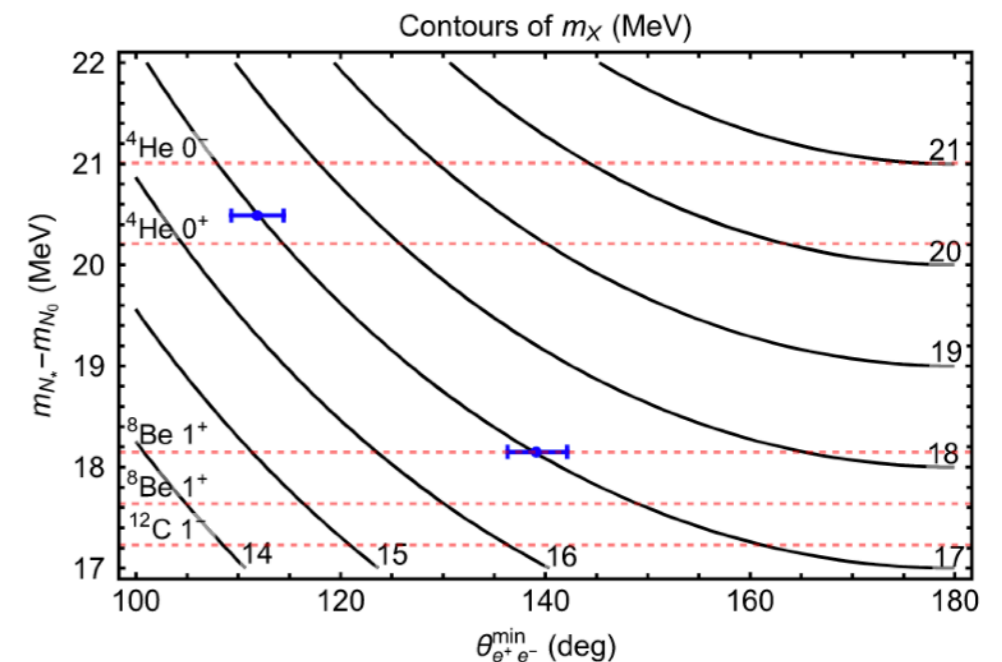
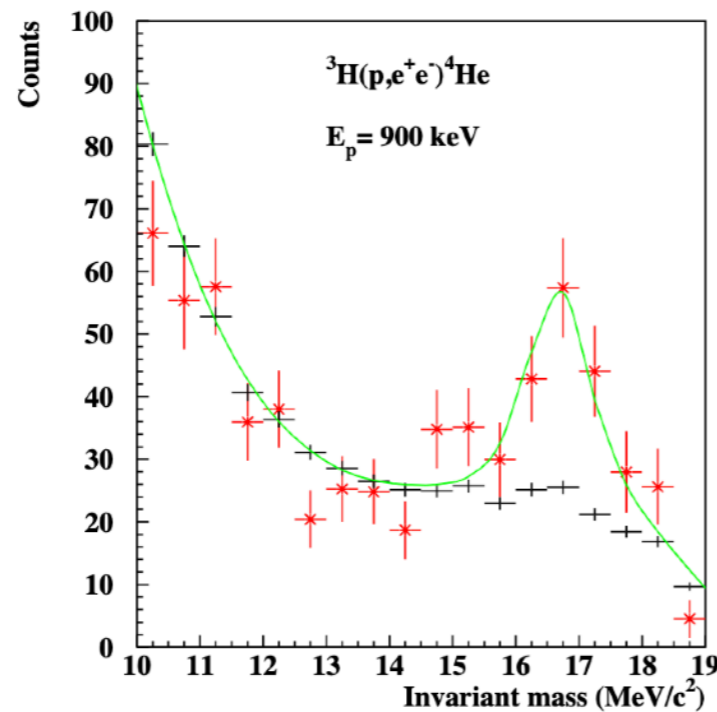


2015: ATOMKI group reported a 7σ excess in rare Be decays
 [ATOMKI, [1504.01527](#)]

Possible solution: new photophobic vector boson with 17 MeV mass

[Feng et al, [1608.03591](#)]
 [Feng et al, [2006.01151](#)]

2019: also excess in He decays
 [ATOMKI, [1910.10459](#)]



How can we look for them in the lab?

How to test dark sectors in the lab?

Simple Model: dark matter charged under $U(1)_D$

$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m_{A'}^2 A'^2 - m_\chi^2 \chi^2 + e_D \bar{\chi} A' \chi$$

phenomenology depends on masses

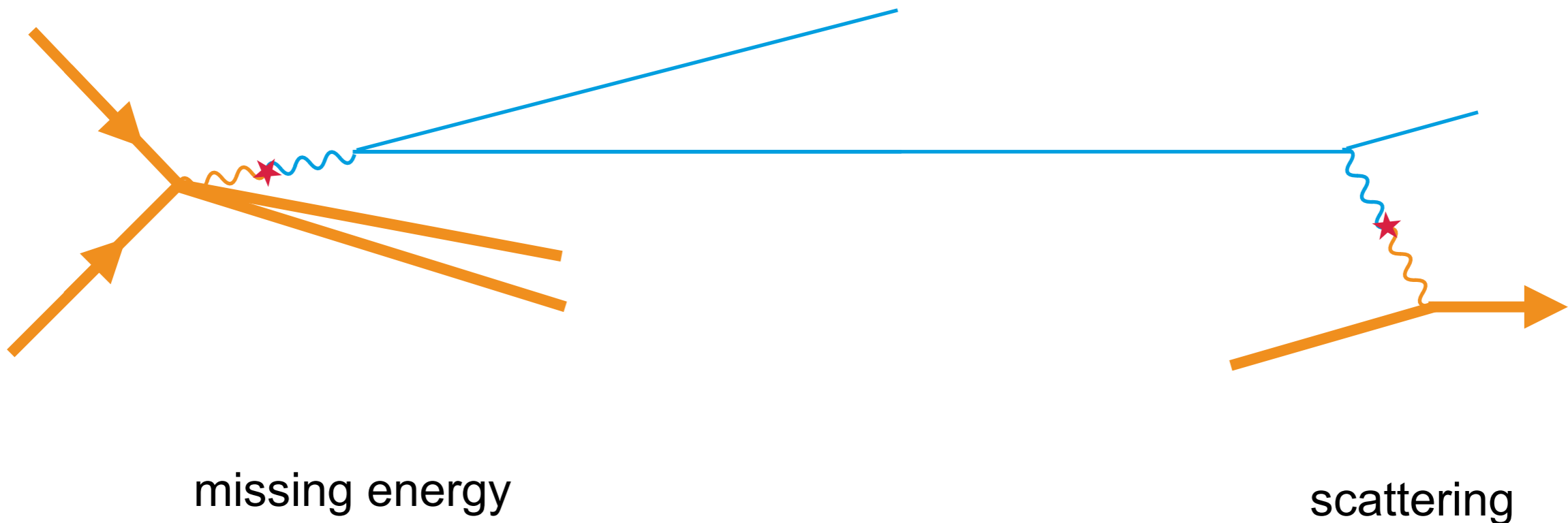
$m_{A'} > 2m_\chi$:
 $A' \rightarrow \chi\chi$

$m_{A'} < 2m_\chi$:
 $A' \rightarrow \text{SM SM}$

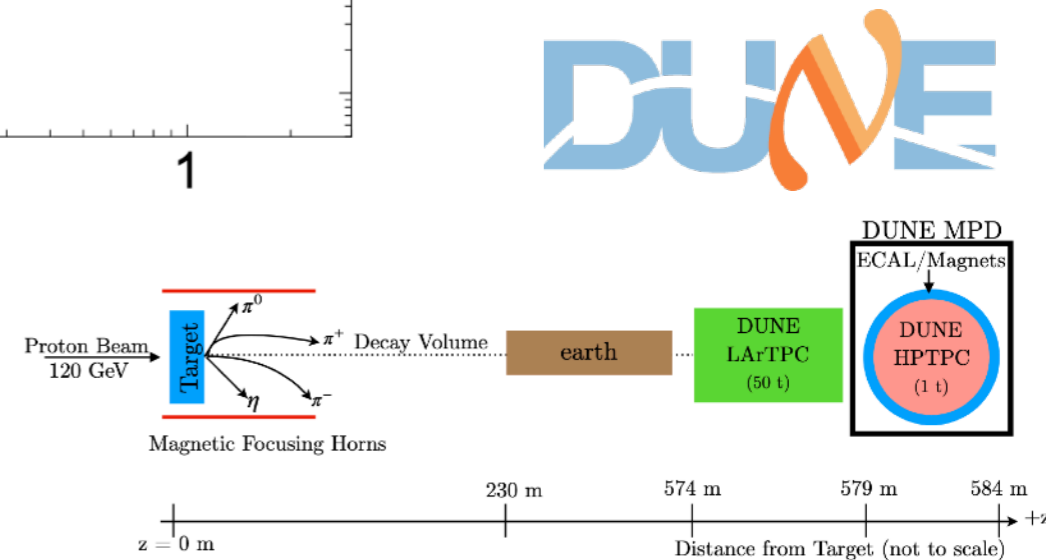
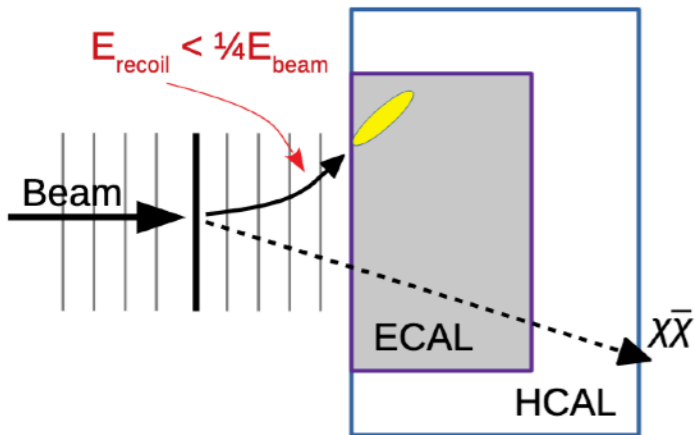
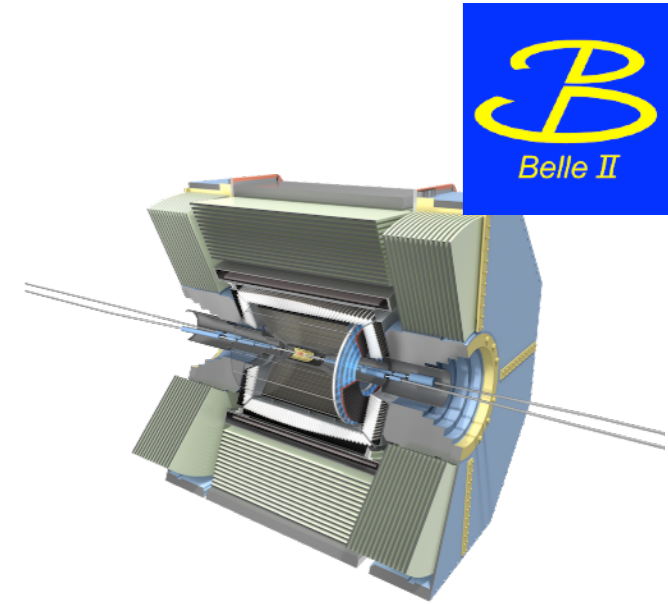
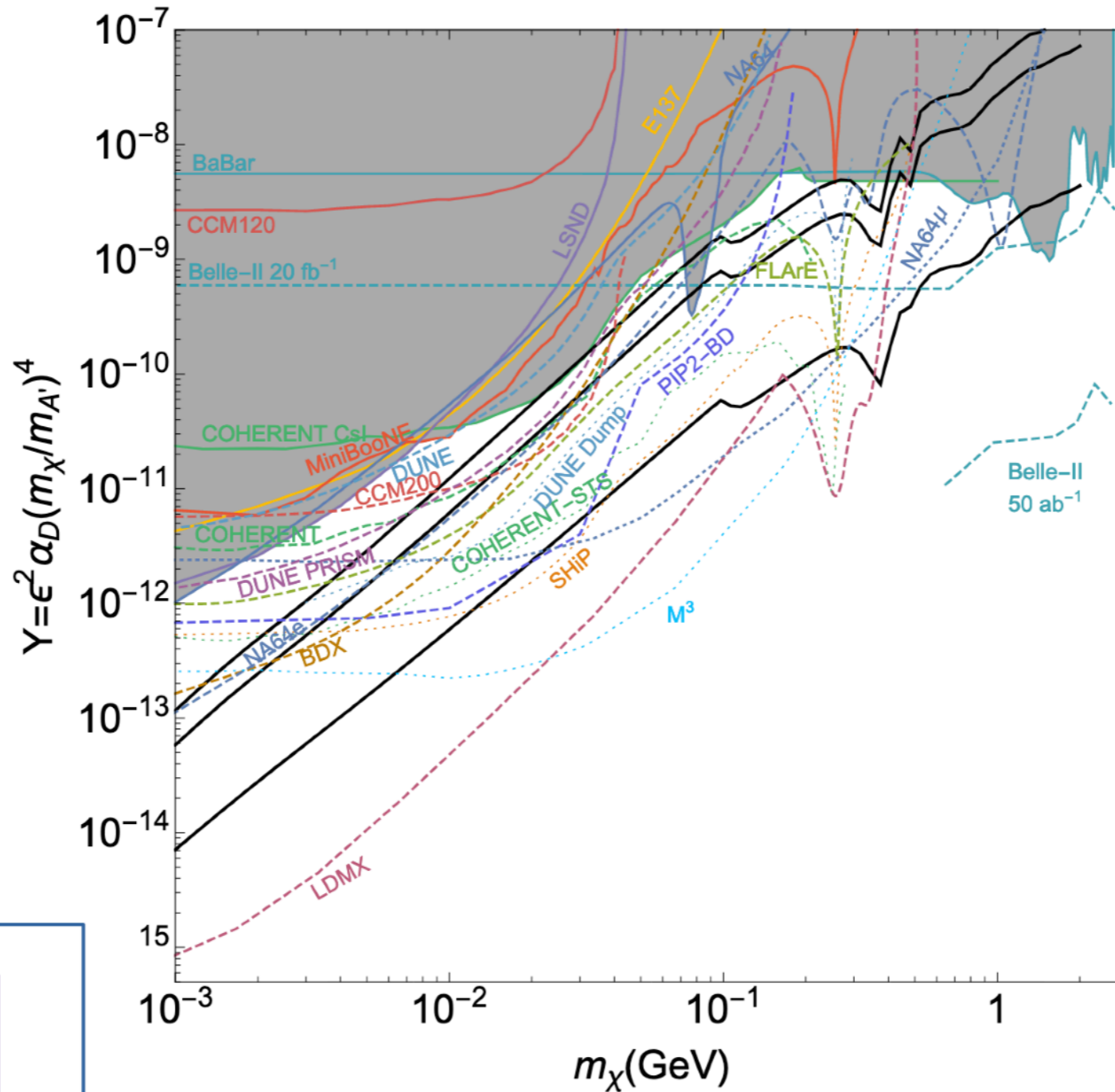
$m_{A'} = 0$:
milli-charged χ

many possible signatures

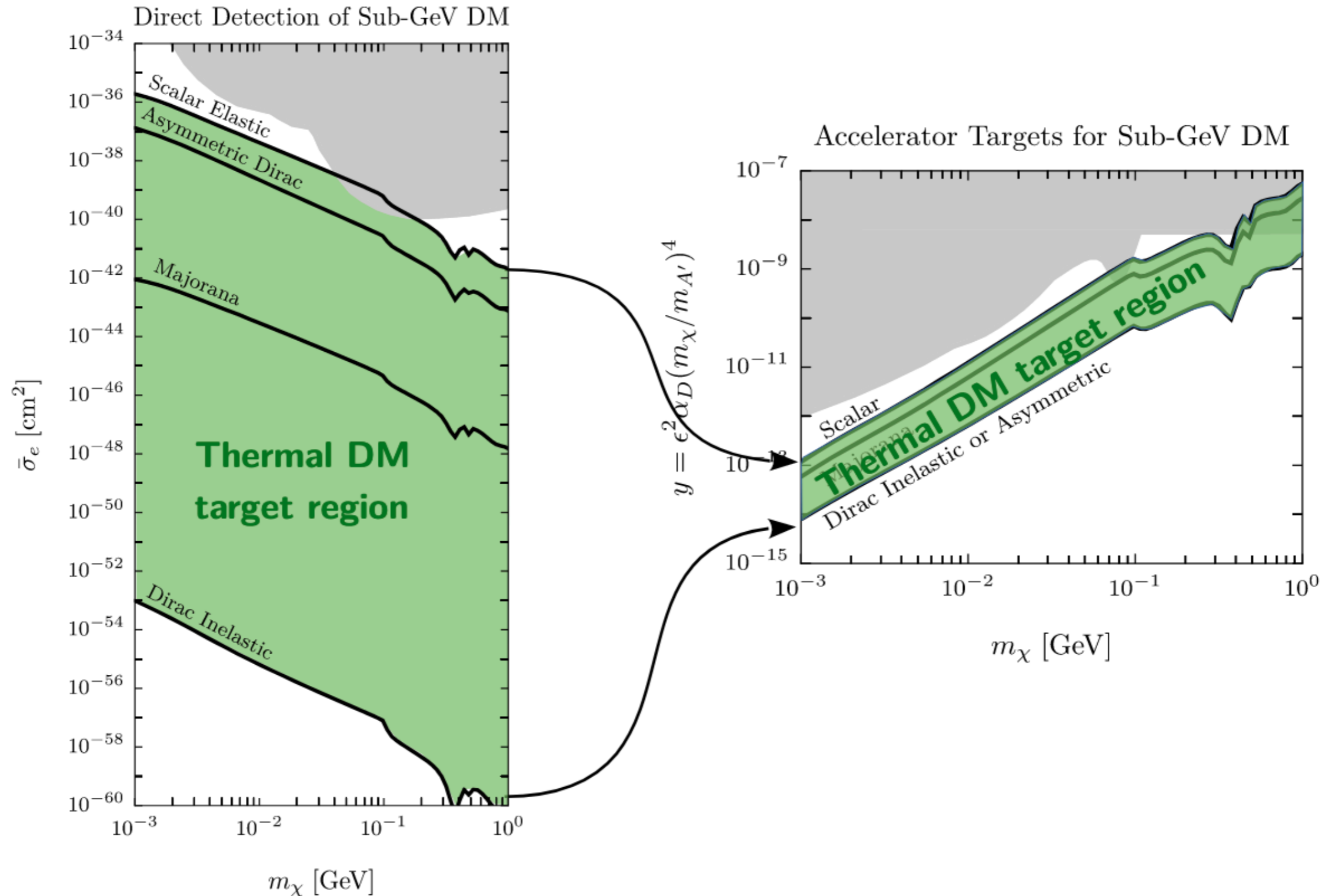
Signature with invisible decays.



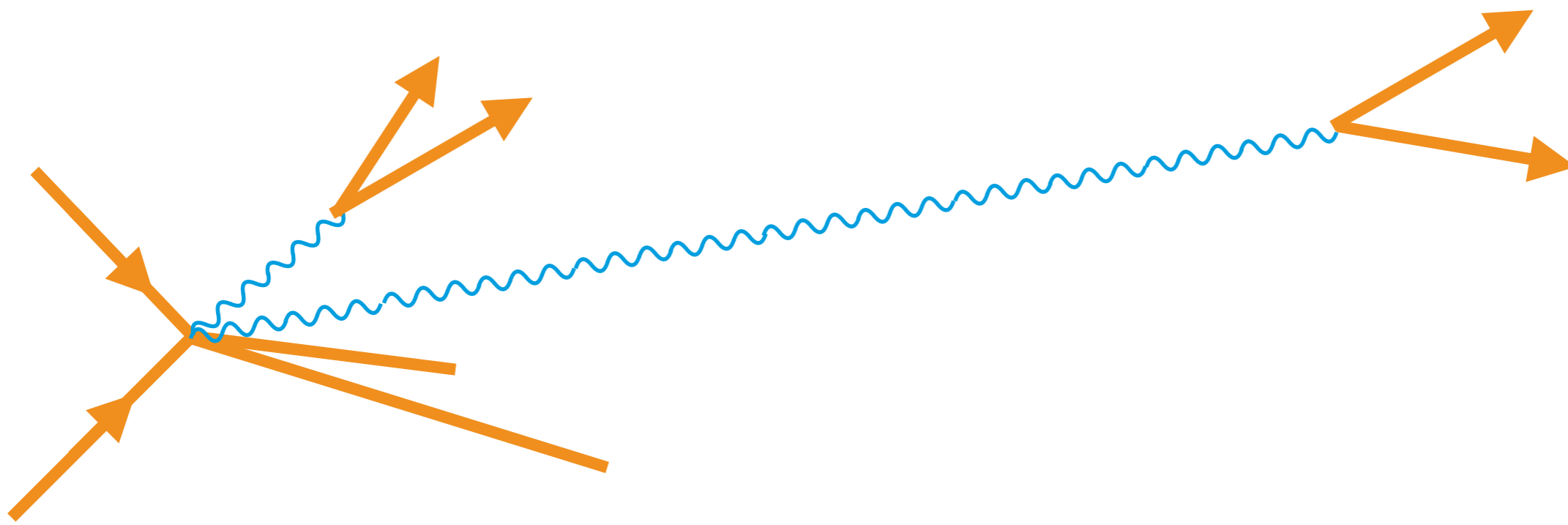
Signature with invisible decays.



Complementarity to Direct Detection.



Signature with visible decays.



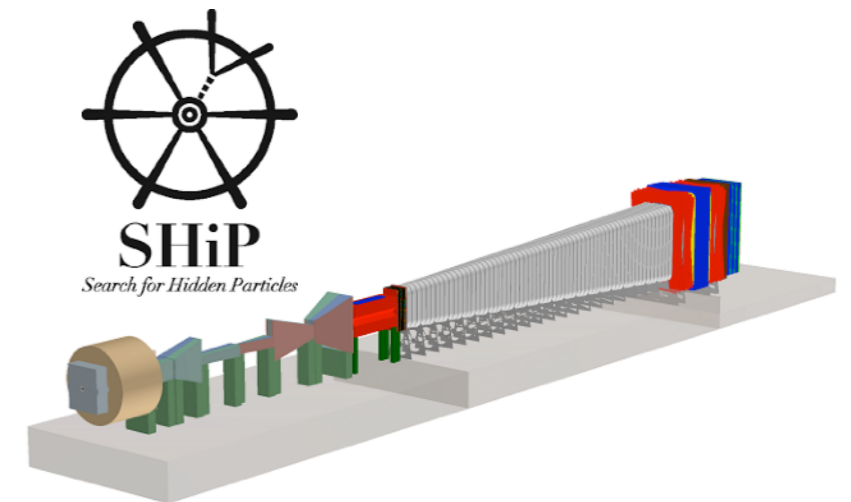
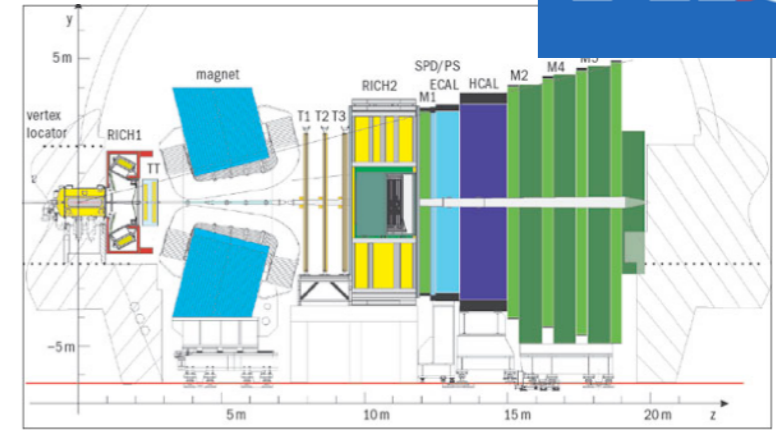
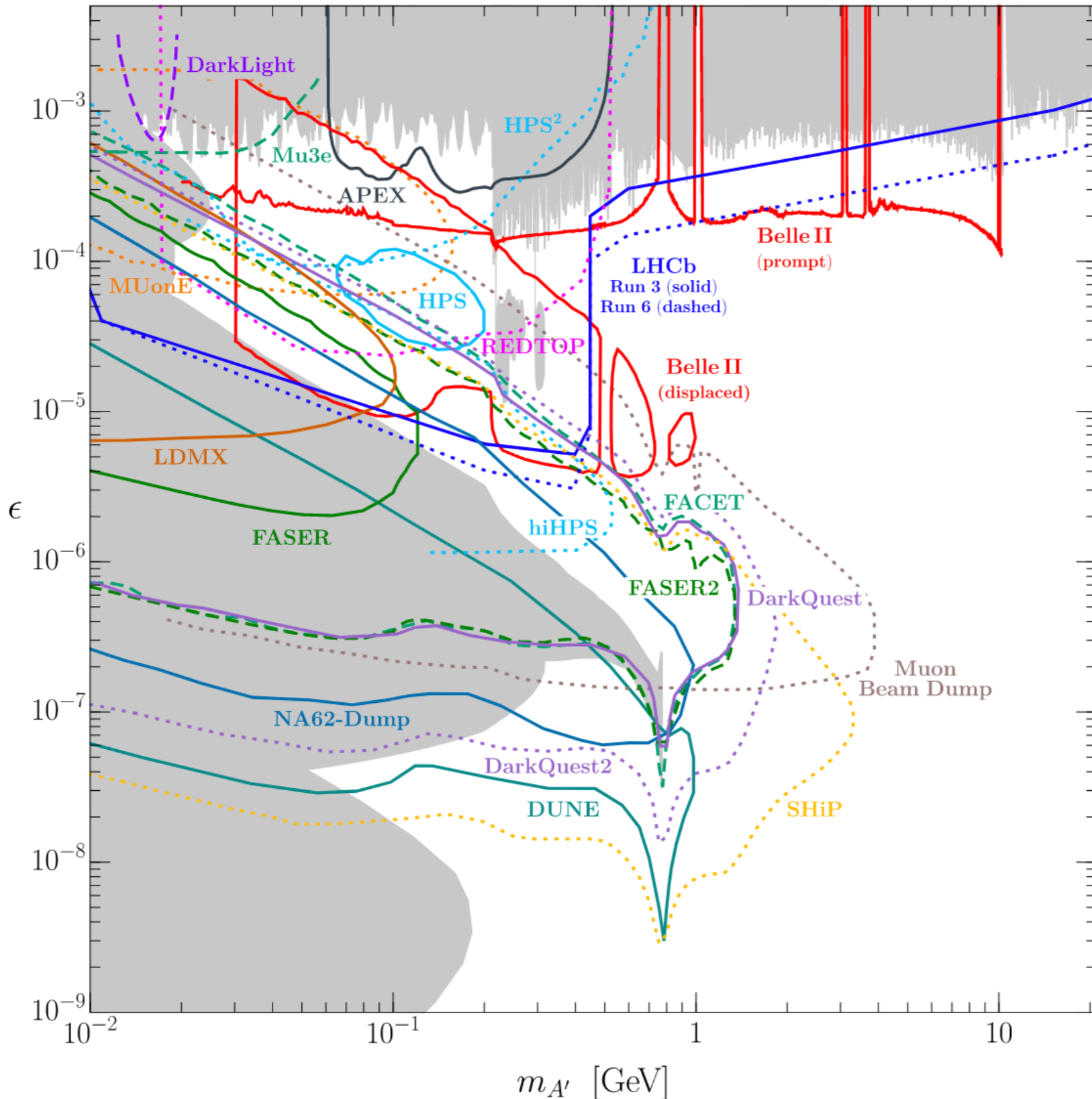
prompt resonances

$$c\tau \ll m$$

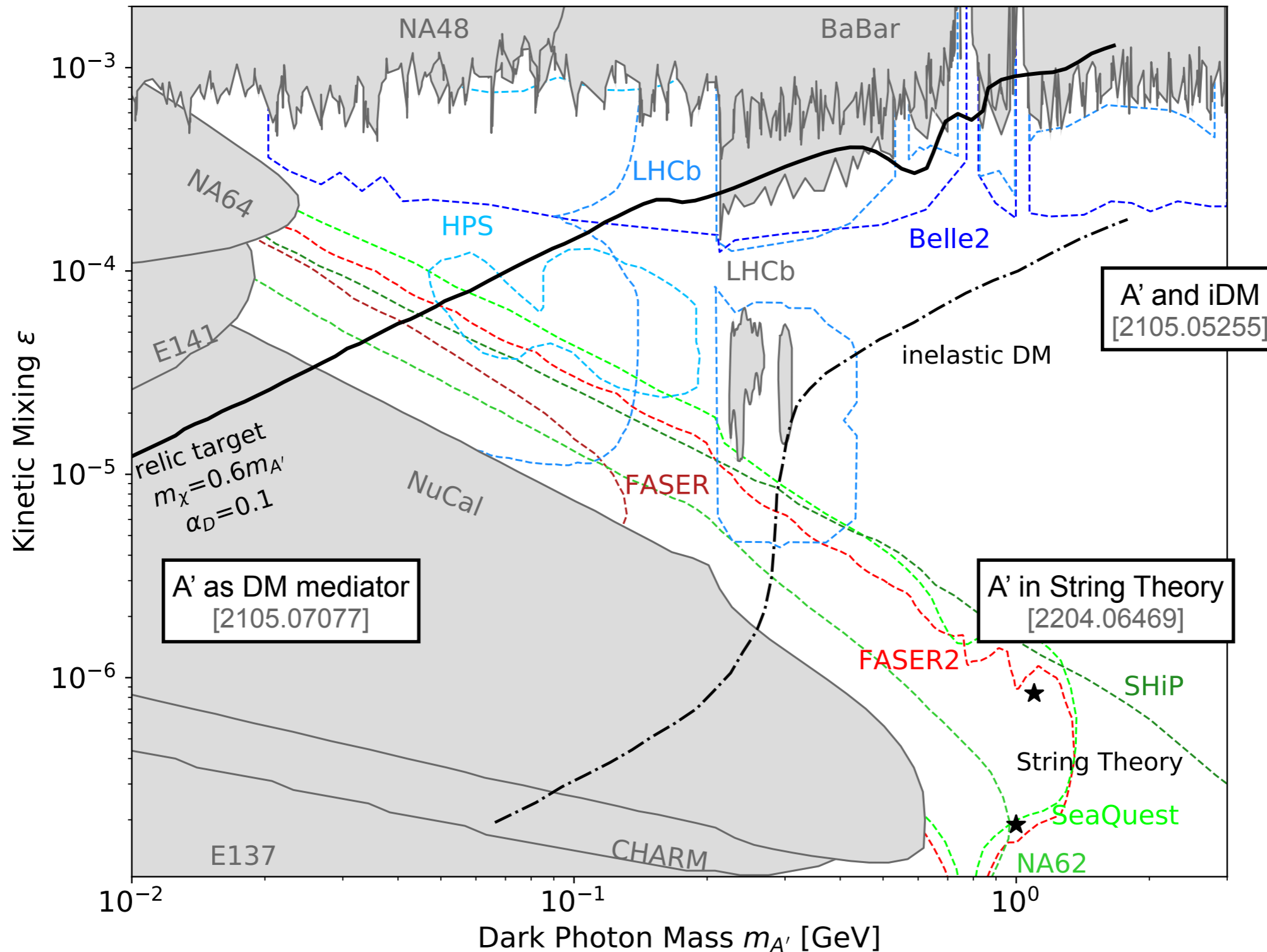
long-lived particle

$$c\tau \gg m$$

Signature with visible decays.



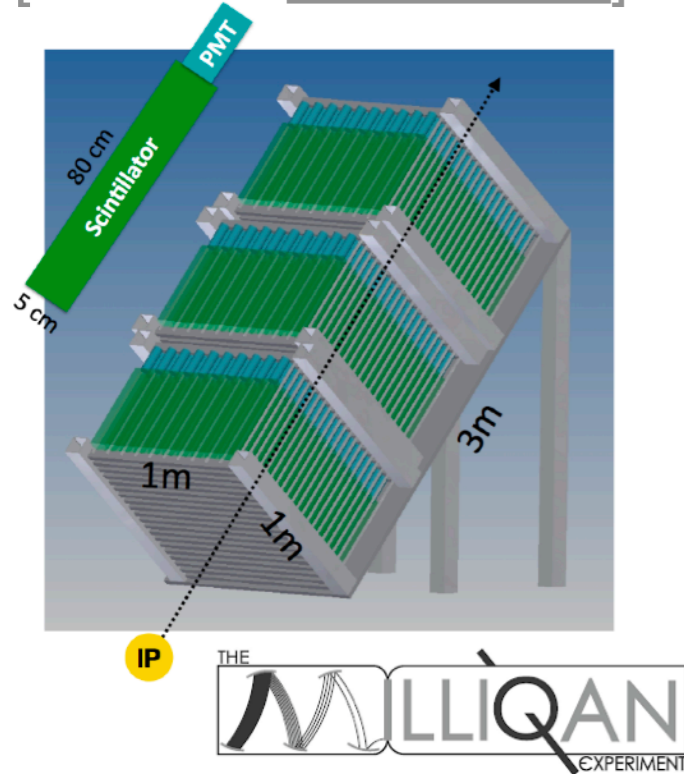
Signature with visible decays.



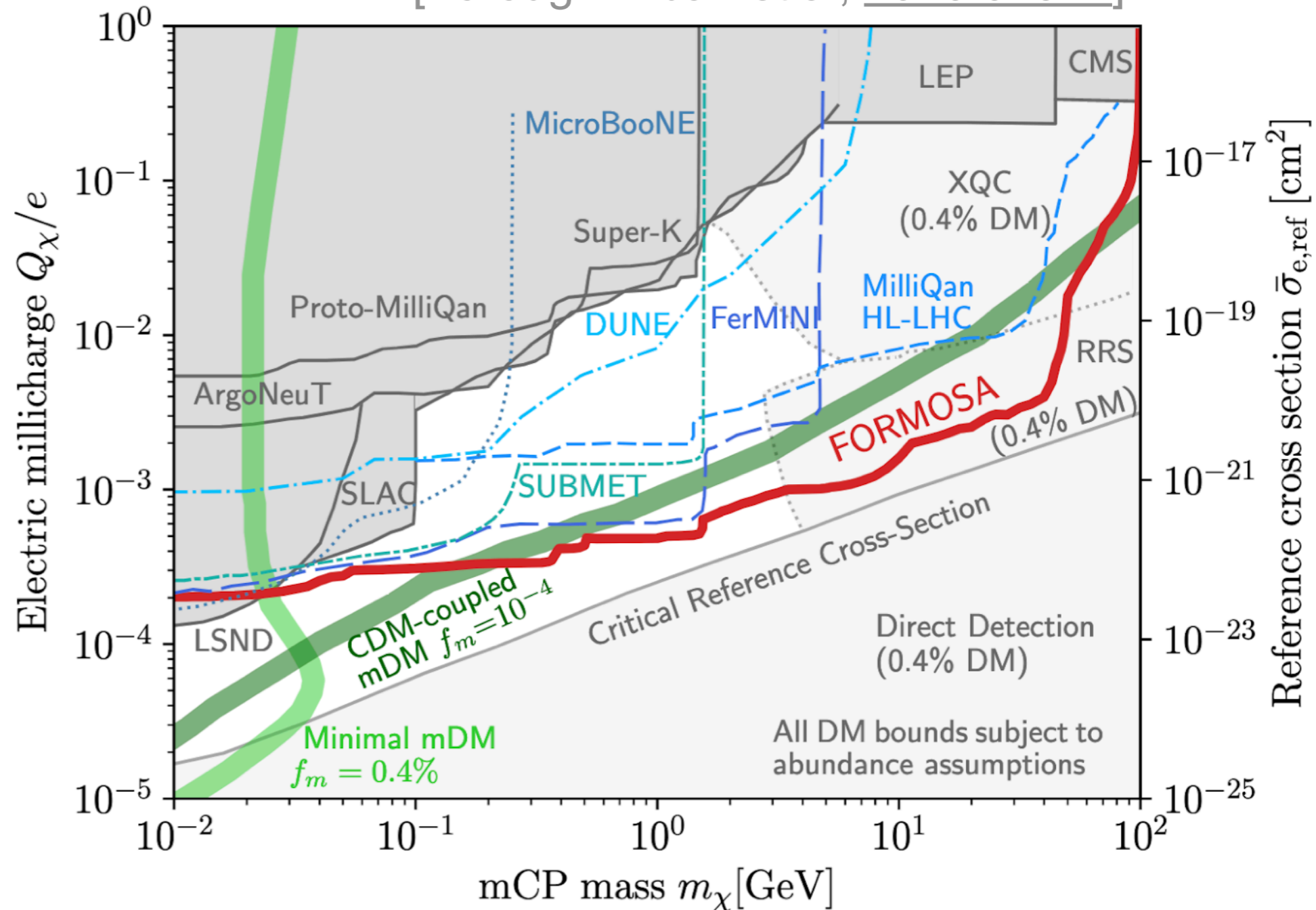
Signatures of Millicharged Particles.

If $m_A' = 0$: X is effectively **milli-charged** with $Q = \epsilon e$
 search for minimum ionizing particle with very small dE/dx

[MilliQan: 1607.04669]

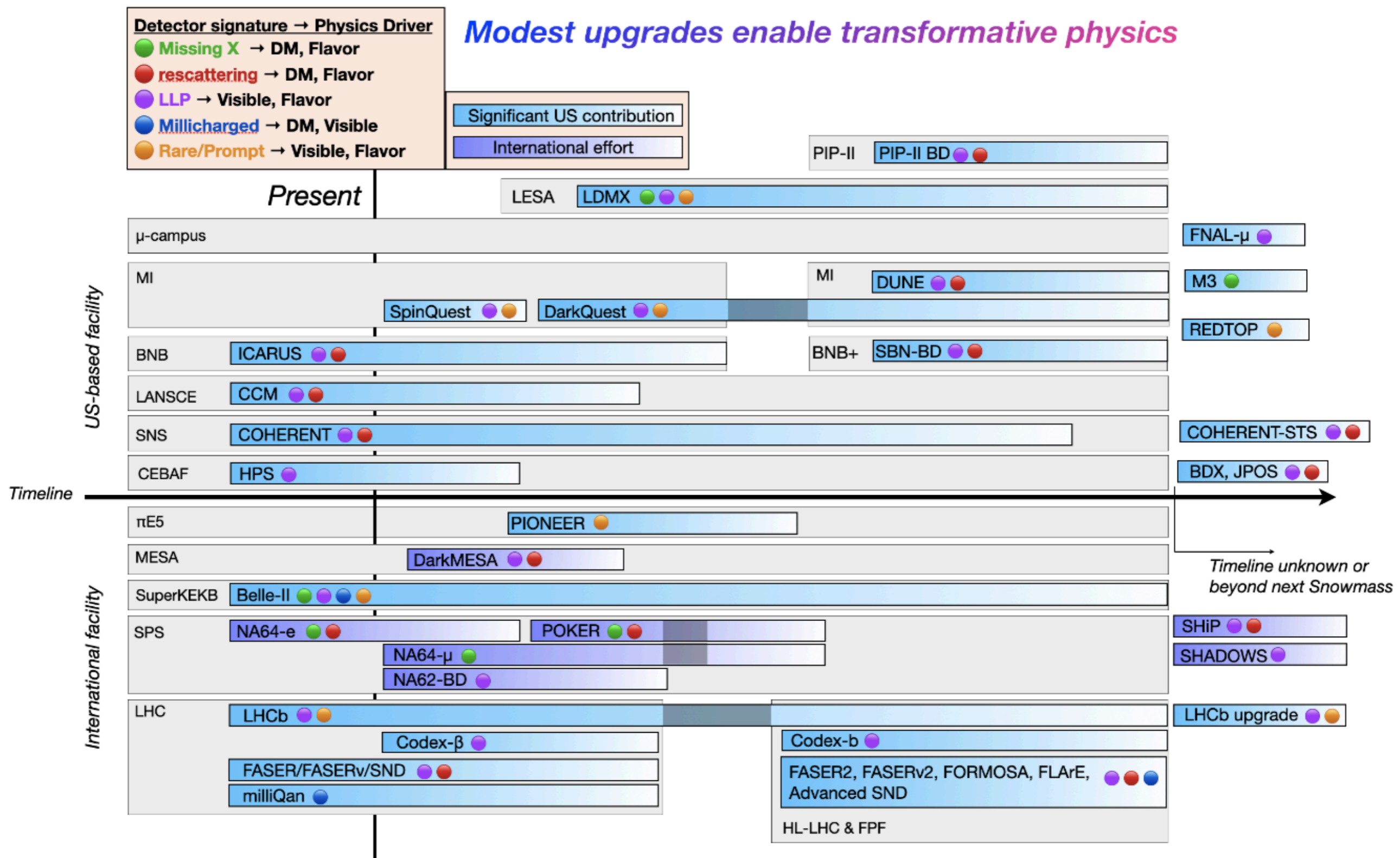


[Foroughi-Abari et al, 2010.07941]



Who is looking?

Experiments and Facilities



FASER: Idea.

The LHC produces an **intense** and strongly **collimated** beam of highly **energetic** particles in the forward direction.

10^{17} π^0 , 10^{16} η , 10^{15} D , 10^{13} B within 1 mrad of beam

Can we do something with that?

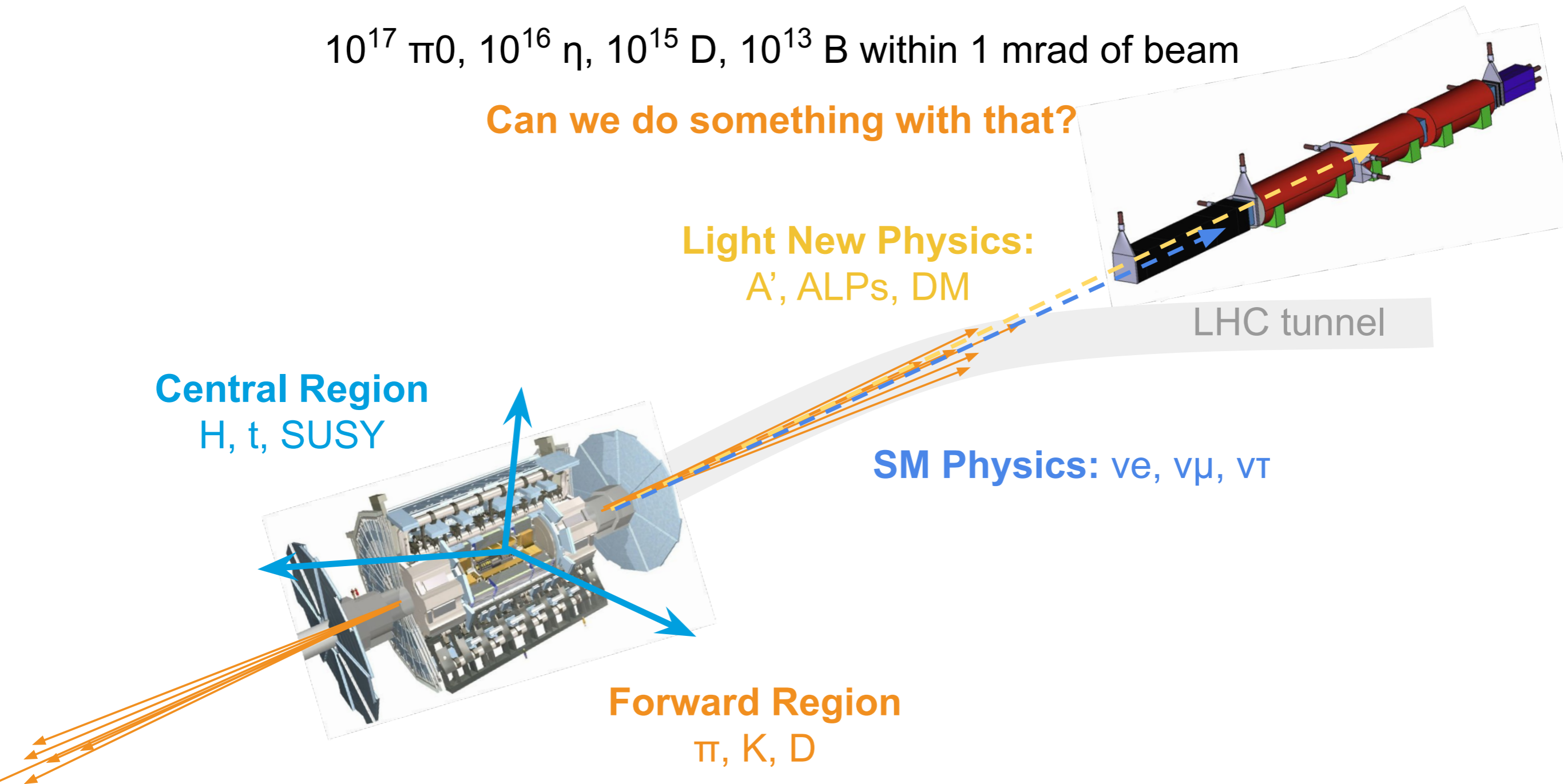
Light New Physics:
 A' , ALPs, DM

LHC tunnel

Central Region
 H , t , SUSY

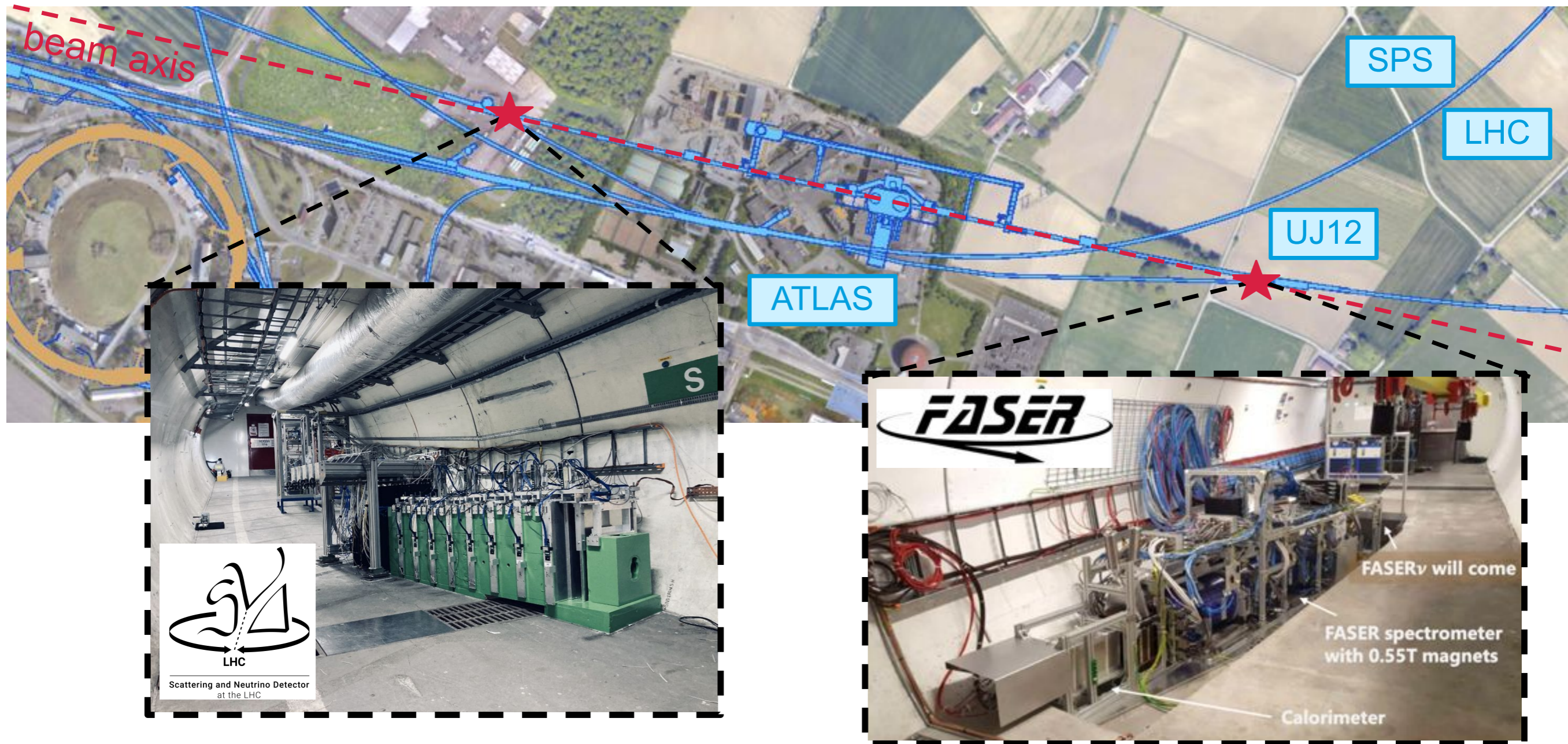
SM Physics: ν_e , ν_μ , ν_τ

Forward Region
 π , K , D

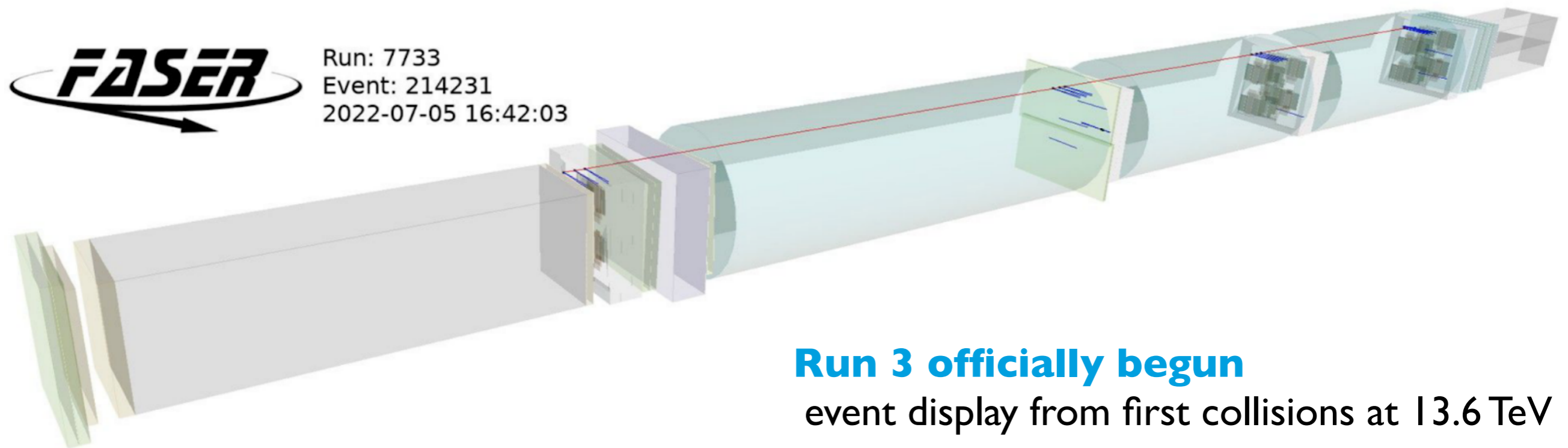
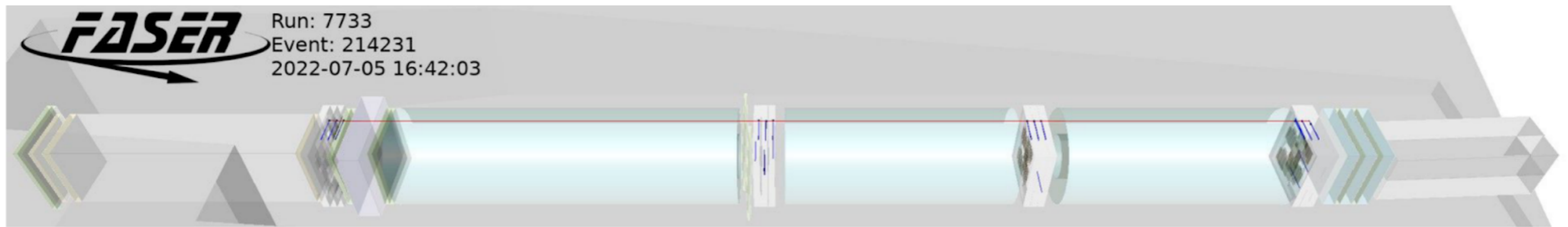


FASER: Location.

Two new experiments will exploit this potential during run 3 of the LHC:
SND@LHC and FASER.



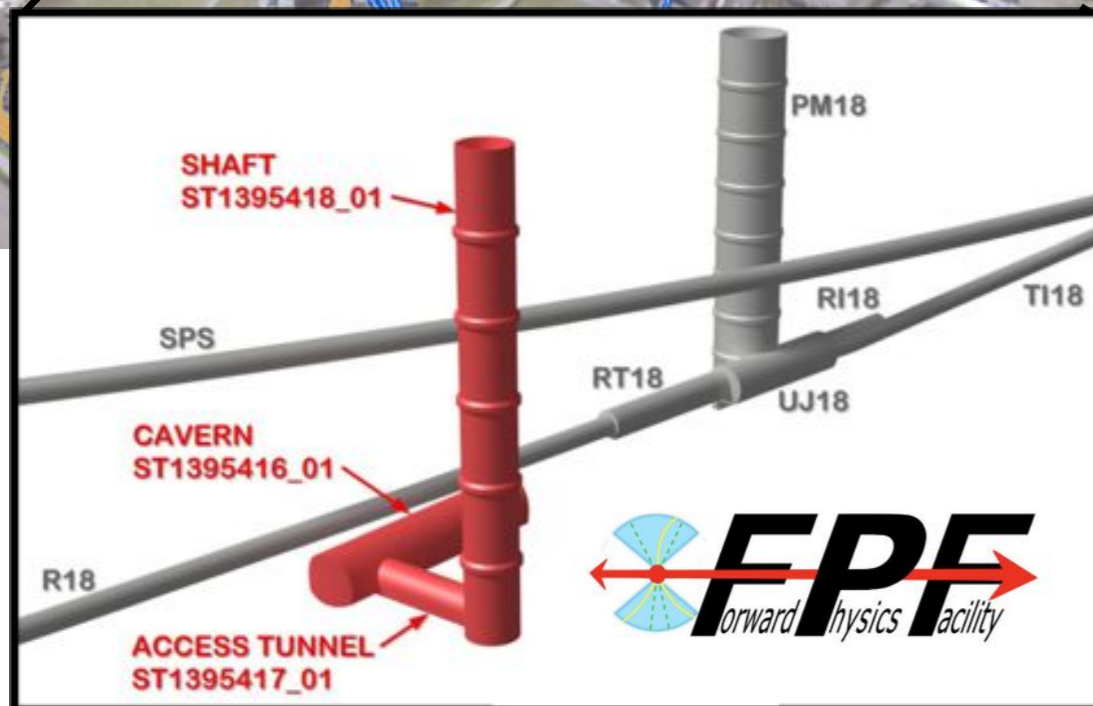
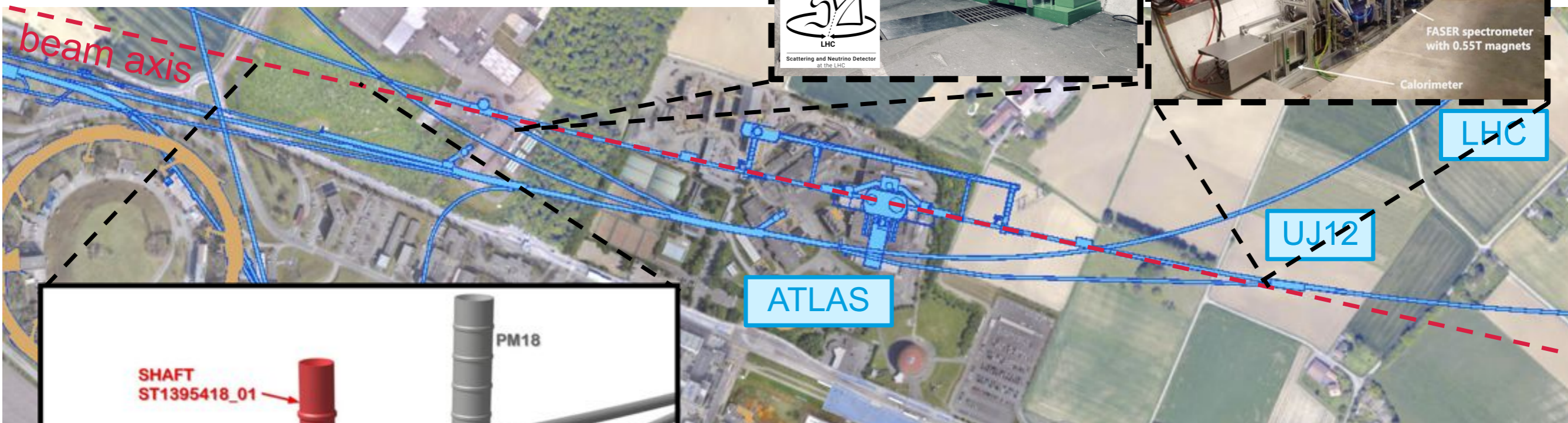
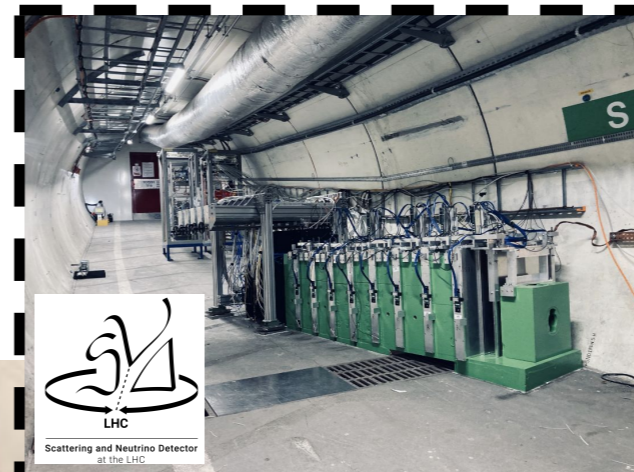
FASER: First Events.



Run 3 officially begun
event display from first collisions at 13.6 TeV

The Forward Physics Facility.

FASER and SND@LHC are highly constrained by 1980's infrastructure that was never intended to support experiments



The proposal: create a dedicated Forward Physics Facility (FPF) for the HL-LHC.

The Forward Physics Facility.

The FPF would house a suite of experiments that will greatly enhance the LHC's physics potential for **BSM physics searches**, **neutrino physics** and **QCD**.

FASER2

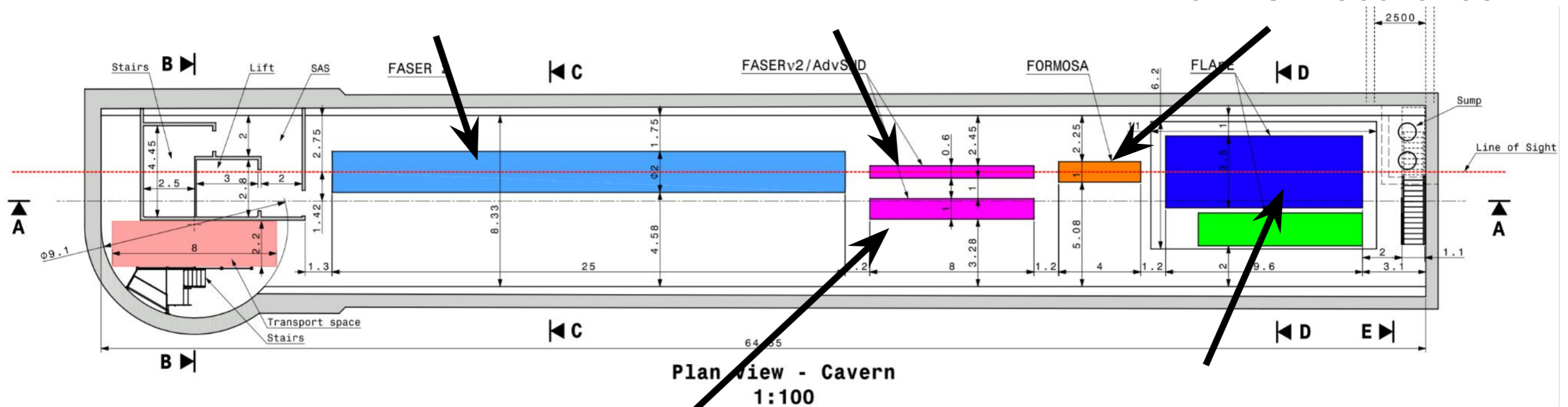
magnetized spectrometer
for BSM searches

FASERv2

emulsion-based
neutrino detector

FORMOSA

plastic scintillator array
for BSM searches



AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

The Forward Physics Facility.

FPF workshop series:
[FPF1](#), [FPF2](#), [FPF3](#), [FPF4](#)

FPF Paper:
[2109.10905](#)

~75 pages, ~80 authors

Snowmass Whitepaper:
[2203.05090](#)

~450 pages, ~250 authors

The Forward Physics Facility: Sites, Experiments, and Physics Potential

Luis A. Anchordoqui,^{1,*} Akitaka Ariga,^{2,3} Tomoko Ariga,⁴ Weidong Bai,⁵ Kincso Balazs,⁶ Brian Batell,⁷ Jamie Boyd,⁶ Joseph Bramante,⁸ Adrian Carmona, Francesco G. Celiberto,^{11,12,13} Grigorios Chachamis,¹⁴ Matthew Citre, Albert de Roeck,⁶ Hans Dembinski,¹⁸ Peter B. Denton,¹⁹ Anton Milind V. Diwan,²⁰ Liam Dougherty,²¹ Herbi K. Dreiner,²² Yong Yasaman Farzan,²⁵ Jonathan L. Feng,^{26,†} Max Fieg,²⁶ Patric Foroughi-Abari,²⁸ Alexander Friedland,^{29,*} Michael Fucilla,³⁰ Maria Vittoria Garzelli,^{33,†} Francesco Giuli,³⁴ Victor P. Gonca, Francis Halzen,³⁷ Juan Carlos Helo,^{38,39} Christopher S. Hill,⁴ Ameen Ismail,⁴² Sudip Jana,⁴³ Yu Seon Jeong,⁴⁴ Krzysztof Jo Kumar,²⁰ Kevin J. Kelly,⁴⁶ Felix Kling,^{29,47,‡} Rafal Maciula, Abraham,⁴¹ Julien Manshanden,³³ Josh McFayden,⁴⁹ Mohammed Pavel M. Nadolsky,^{50,*} Nobuchika Okada,⁵¹ John Osborne,⁶ Hic Pandey,^{52,46,*} Alessandro Papa,^{30,31} Digesh Raut,⁵³ Mary Hall R Adam Ritz,²⁸ Juan Rojo,⁵⁵ Ina Sareevic,^{56,*} Christiane Scherb Holger Schulz,⁵⁹ Dipan Sengupta,⁶⁰ Torbjörn Sjöstrand,^{61,*} Tyler B. Anna Stasto,⁶² Antoni Szczurek,⁴⁸ Zahra Tabrizi,⁶³ Sebastia Yu-Dai Tsai,^{26,46} Douglas Tucker,⁶⁶ Martin W. Winkler,⁶⁷ Kepin

The Forward Physics Facility (FPF) is a proposal to create a infrastructure to support a suite of far-forward experiments at during the High Luminosity era. Located along the beam collision interaction point by at least 100 m of concrete and rock, the F that will detect particles outside the acceptance of the existing L will observe rare and exotic processes in an extremely low-background work, we summarize the current status of plans for the FPF, its civil engineering in identifying promising sites for the FPF; the L envisioned to realize the FPF's physics potential; and the many physics topics that will be advanced by the FPF, including search probes of dark matter and dark sectors, high-statistics studies of flavors, aspects of perturbative and non-perturbative QCD, and physics.

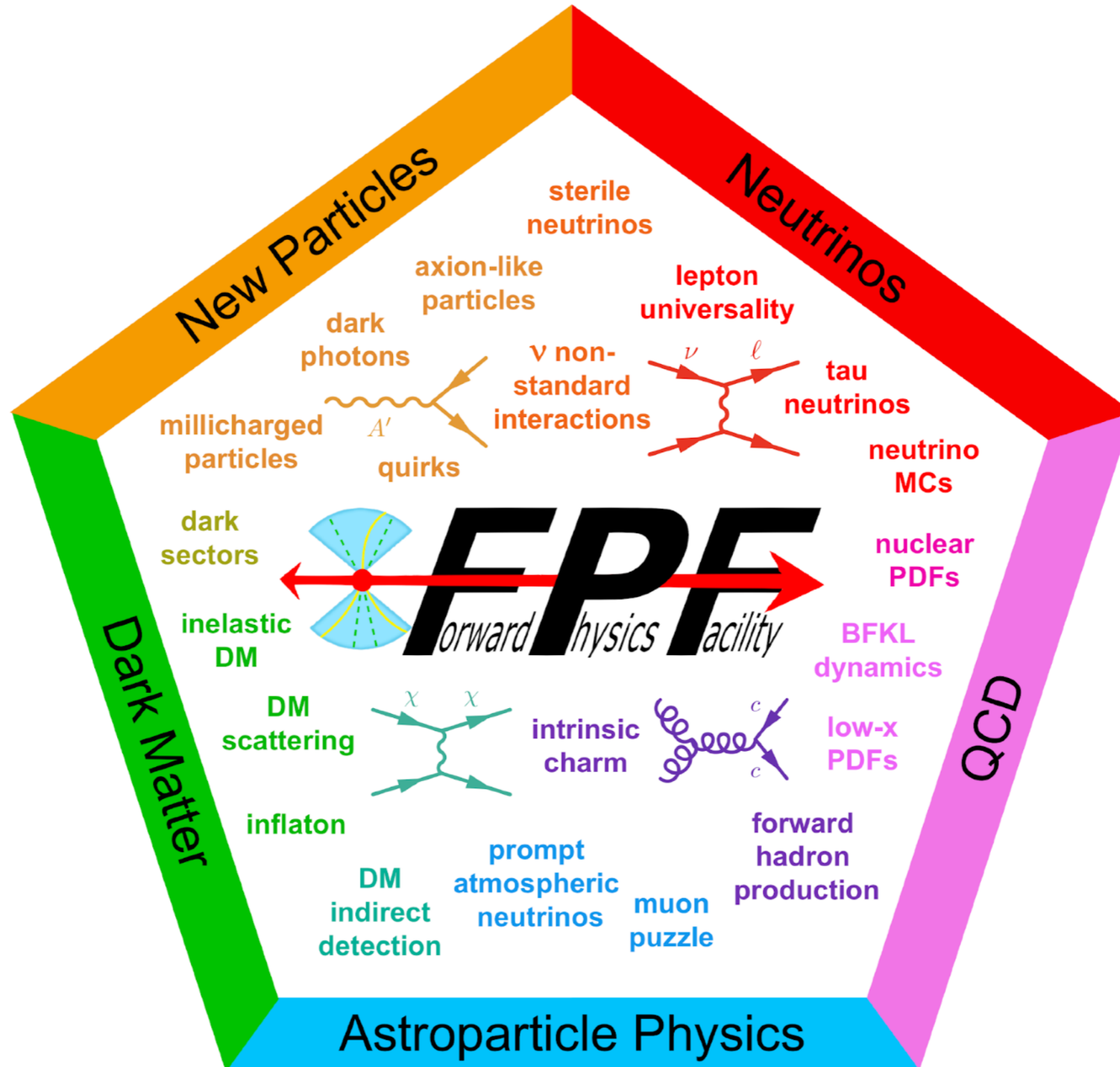
Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)



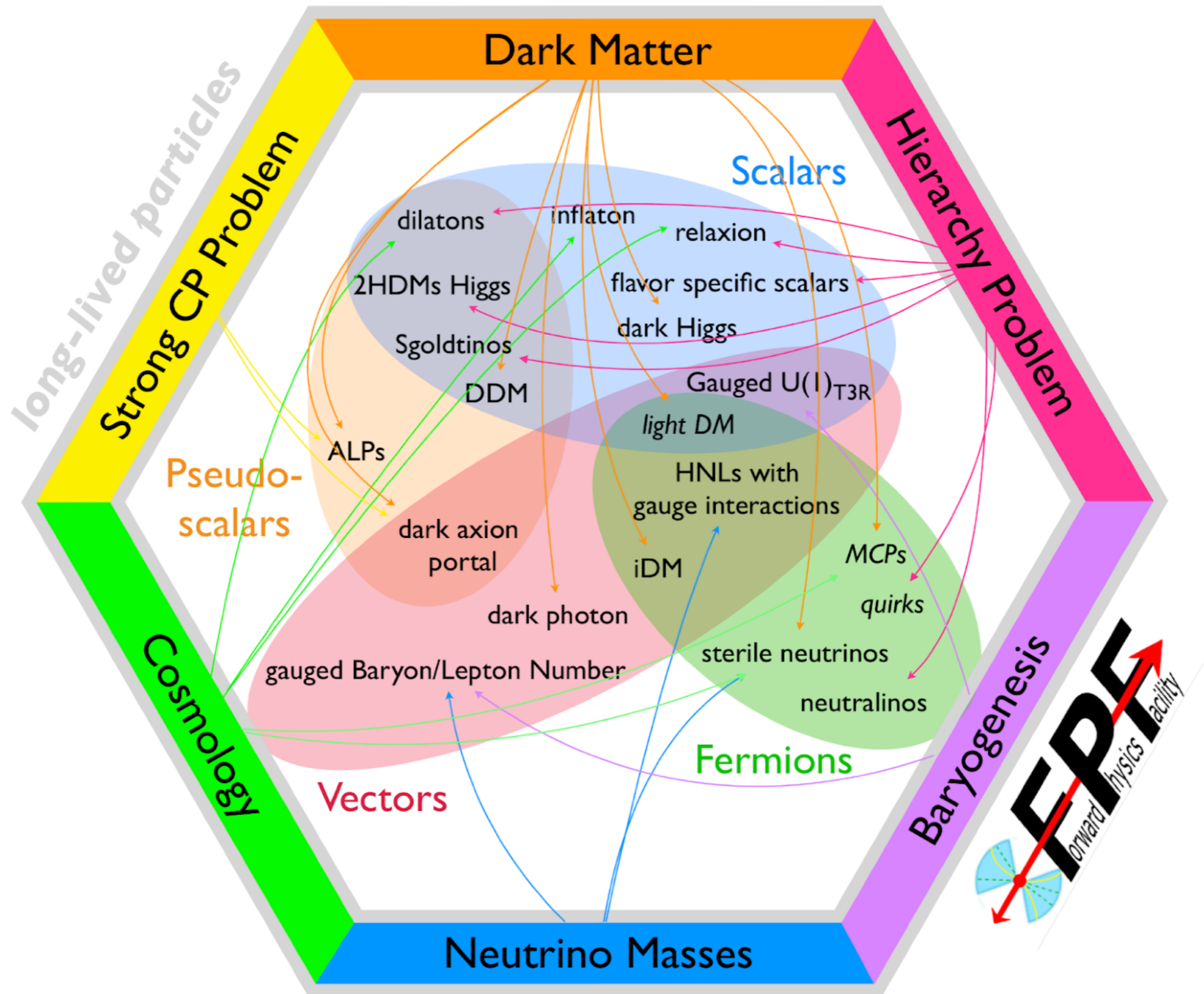
The Forward Physics Facility at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from an LHC interaction point and shielded by concrete and rock, will host a suite of experiments to probe standard model processes and search for physics beyond the standard model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from standard model expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will trace back to fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector and simulation studies, and on future directions to realize the FPF's physics potential.

The Forward Physics Facility.



The Forward Physics Facility.



Summary.

What is a dark sector?

- set of new particles, which do not experience known forces
- weakly coupled to visible sector through a mediator or “portal“

Why are we interested in dark sector?

- dark matter, other theoretical puzzles, experimental anomalies

What can laboratory experiments do?

- intensity frontier experiments probe small portal couplings
- upcoming experiments have great potential to discover dark sectors

→ **Next decade will be exciting**