RF6: Dark Sector Physics at High-Intensity Experiments

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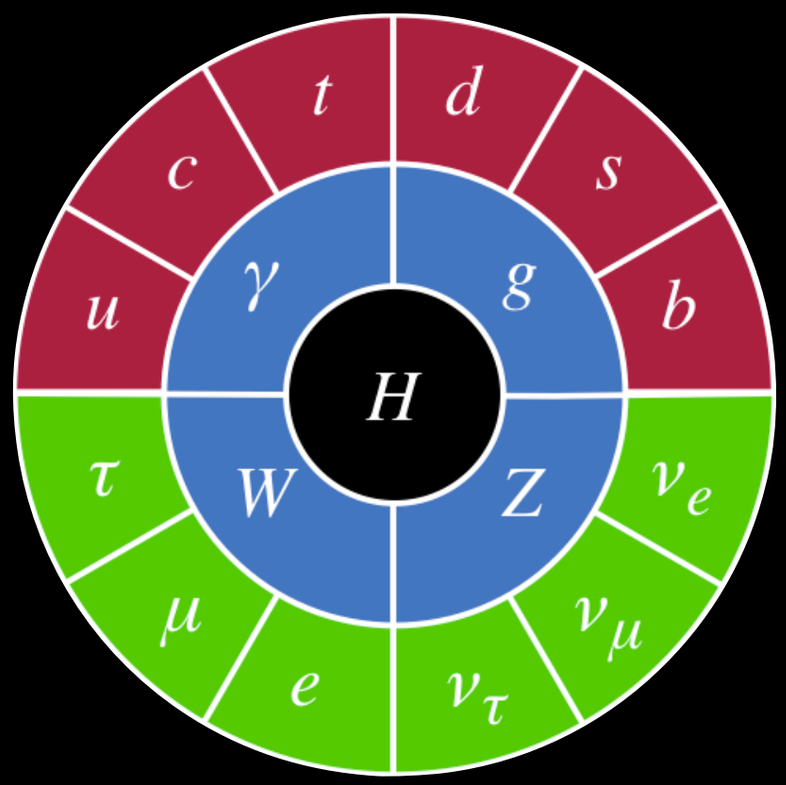
Dark (Hidden) Sectors

What if there is no connection between the SM and dark sector up to the Planck scale?
(Hidden sectors can result from a Grand Unified Theory (GUT) of nature, and are generic in string theory constructions.)



When things are at their blackest, I say to myself "Cheer up, things could get worse." And sure enough, they get worse. —Robert Asprin

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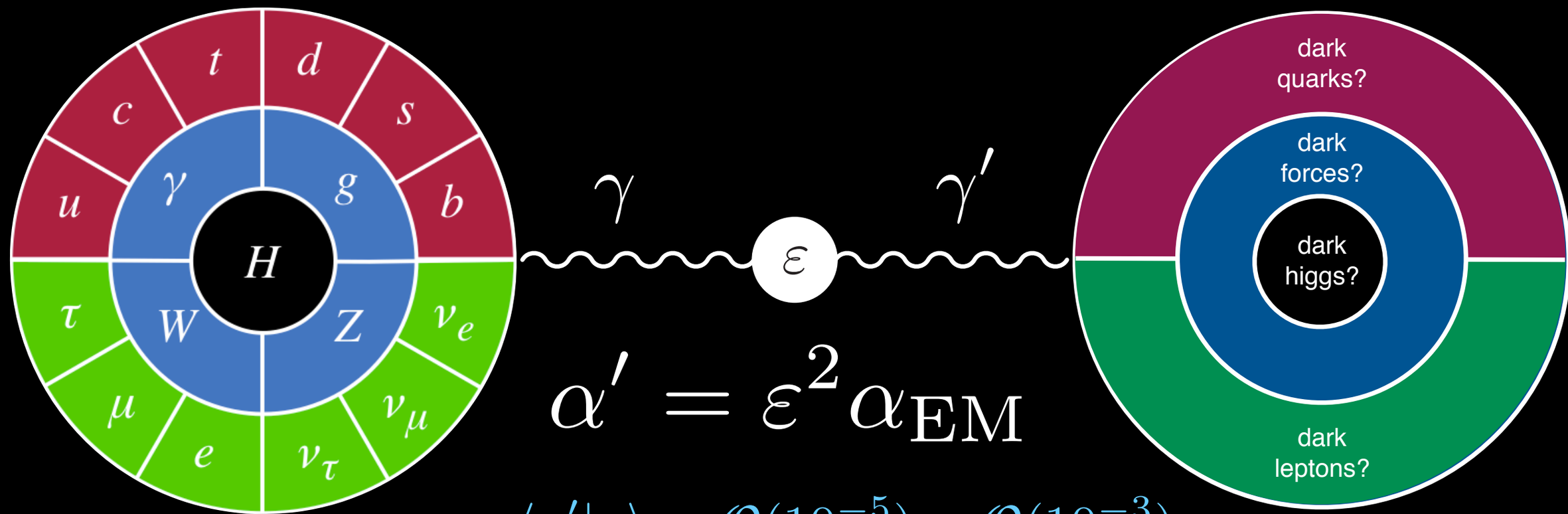


$$\alpha' = \varepsilon^2 \alpha_{\rm EM}$$

$$\varepsilon \equiv \langle \gamma' | \gamma \rangle \approx \mathcal{O}(10^{-5}) - \mathcal{O}(10^{-3})$$

If the sectors are connected at some scale (e.g. if they are both part of a GUT), then quantum mechanical mixing, e.g., between the photon and dark photon, will occur resulting in feeble interactions between ordinary and dark matter—opening the door for DM below the EW scale.

Dark Sector Motivations

- Dark matter exists (and WIMP searches have thus far come up empty).
- Dark sectors can solve many experimental and/or theoretical puzzles, e.g. strong CP problem motivates axions and axion-like particles.
- Dark sector matter shares no charges with ordinary matter, hence is naturally dark.
- Dark-sector matter charged under a new interaction is inherently stable due to charge conservation in the dark sector (lightest dark-charged DM particle is stable).
- The inherently feeble interactions with ordinary matter provide a natural thermal-production origin for dark matter, extending the WIMP miracle to lower mass scales.
- Only a few options of how to couple a dark sector to ordinary matter that do not violate the symmetries of the SM (i.e. that do not invalidate the SM itself), which makes systematic exploration of dark sectors possible. (That said, the complexity in the dark sector could exceed that of the SM, resulting in a rich spectrum of possible phenomenologies.)
- Despite huge progress made in the past decade, much of the naturally most-interesting parameter space is still unexplored — though accessible in the next decade!

Portal Interactions

The gauge and Lorentz symmetries of the SM greatly restrict how the dark-sector mediators can couple to ordinary matter: (The dominant interactions between the SM and dark-sector mediators are naturally those with the lowest-dimensional SM gauge-singlet operators.)

- ***Vector Portal***: The dark photon, A', that mediates a dark U(1) force can obtain a small coupling to the EM current due to kinetic mixing between the SM hypercharge and A' field strength tensors.
- ***Higgs Portal***: A dark scalar coupled to the gauge-invariant Higgs mass operator can produce mass mixing between the Higgs and dark-scalar fields.
- ***Neutrino Portal***: A gauge-singlet fermion, referred to as a heavy neutral lepton (HNL), can be coupled to the gauge invariant operator formed of the SM lepton and Higgs doublets. Following EW symmetry breaking, the HNLs mix with the SM neutrinos.
- ***Axion Portal***: Axion-like particles (ALPs) are pseudoscalars whose couplings to the SM gauge bosons are highly suppressed at low energies by a large decay constant. ALPs are pseudo-Nambu-Goldstone bosons, and therefore, their masses are expected to be far below the dynamical scale.

The first three portals are renormalizable, while the axion portal is dimension 5 and suppressed by some high energy scale. Direct coupling of new gauge bosons to SM fermion vector currents are also possible, though most are anomalous; the few that are not (eg B-L) are viable.

This completes the list of possible dimension 5 and below interactions between a dark sector and the SM. This small list of possible interactions sharpens the focus of the experimental discovery effort.

RF6 Details

- Conveners: Stefania Gori (sgori@usc.edu) and Mike Williams (mwill@mit.edu)
- Email: SNOWMASS-RPF-06-DARK-SECTOR@fnal.gov
- Slack: #rpf-06-dark-sector
- Web: https://snowmass21.org/rare/dark

As part of the Snowmass process, we categorized the exploration of dark-sector physics by defining three ***Big Ideas***, each with associated ambitious — but achievable — goals for the next decade. We solicited a white paper on each of these, along with a fourth summarizing the experimental landscape:

- Big Idea 1: Dark matter production at intensity-frontier experiments, edited by Gordan Krnjaic and Natalia Toro (RF6 parallel session 11am Wednesday morning)
- Big Idea 2: Minimal portal interactions, edited by Brian Batell and Chris Hearty (RF6 parallel session 11am Tuesday morning)
- Big Idea 3: New flavors and rich structures in dark sectors, edited by Phil Harris, Philip Schuster, and Jure Zupan (RF6 parallel session 11.45am Wednesday morning)
- Experiments and facilities for accelerator-based dark sector searches, edited by Phil Ilten and Nhan Tran (RF6 parallel session 11.45am Tuesday morning)

All have circulated drafts for comment on slack. Please send any comments ASAP!

Benchmarks

initiated by N.Toro

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] m_χ vs.α_D [$m_{A'}/m_\chi$=3, y=y_{fo}] m_χ vs. m_A [α_D=0.5, y=y_{fo}] *Millicharge m vs. q*	$m_{A'}$ vs. ϵ [decay-mode agnostic] ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5] (anom connection)** **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L\,/\,\mu-\tau\,/\,B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. sinθ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. sinθ* [λ=0] *m_S vs. sinθ* [λ=s.t. Br(H→ss ~10^{-2})]?	Dark Higgssstrahlung (w/vector) scalar SIMP models Leptophilic/leptophobic dark Higgs
Neutrino	e/μ/τ a la1709.07001 Batell, Han, McKeen, Es Haghi	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasonable flavor structures	Sterile neutrinos with new forces
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* *m_a vs. f_w*	FV axion couplings

Focus: both the DM and the **mediator** are light (O(GeV) or less)

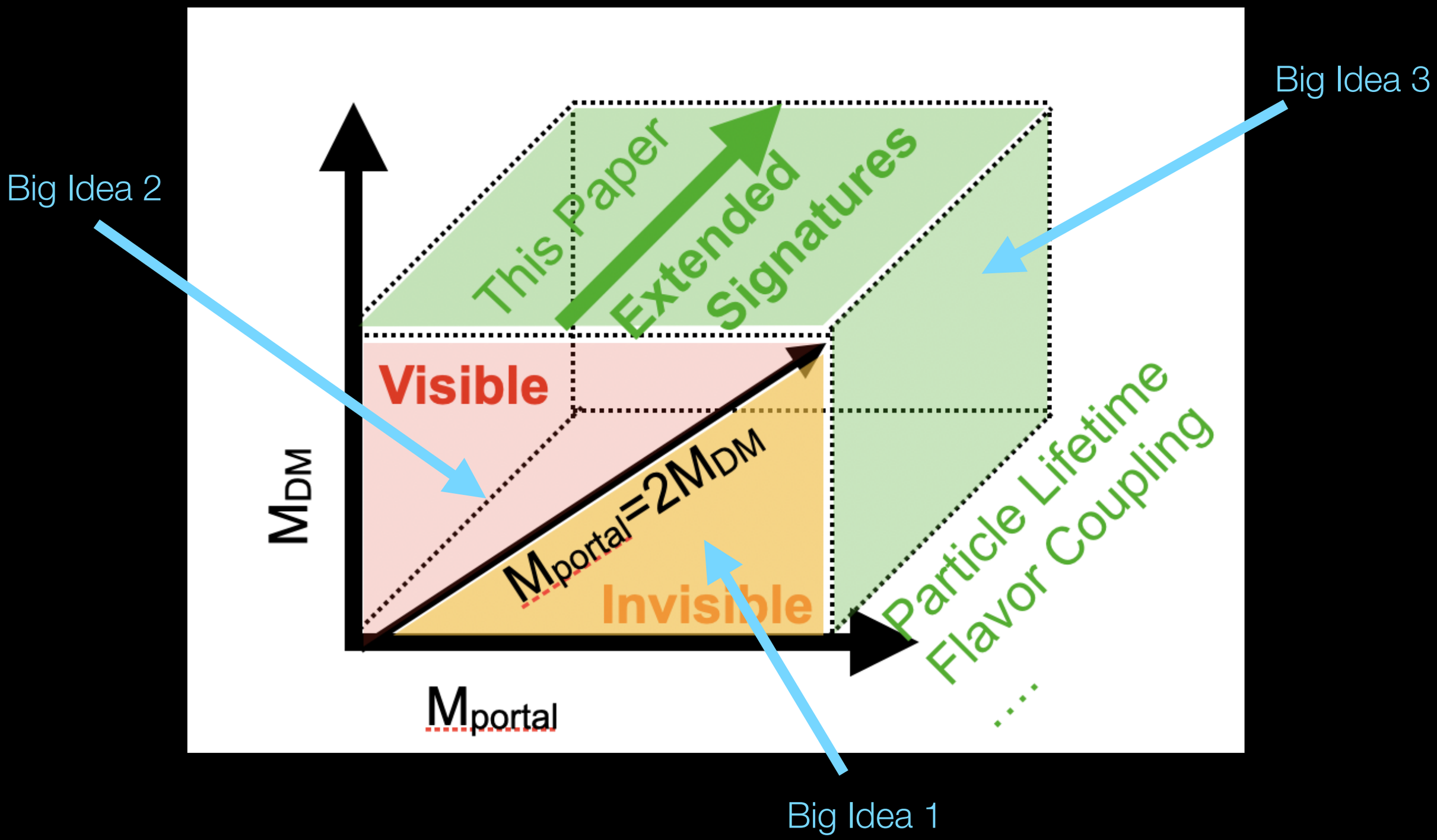
Bold = BRN benchmark, italic = PBC benchmark, others are new suggestions

BRN = basic research needs for DM small projects

N.b., DM is not the only motivation, especially for Big Ideas 2 and 3.

Big Ideas

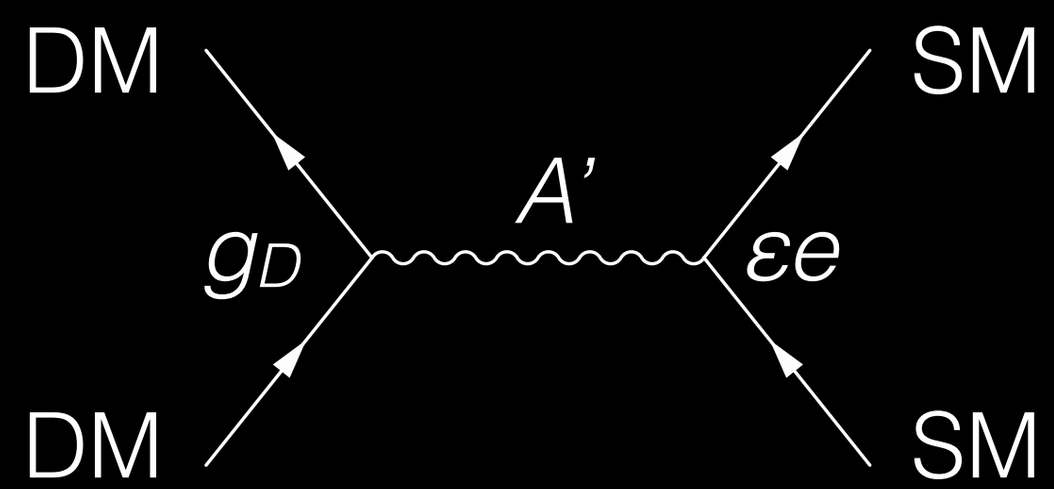
image from Big Idea 3 white paper

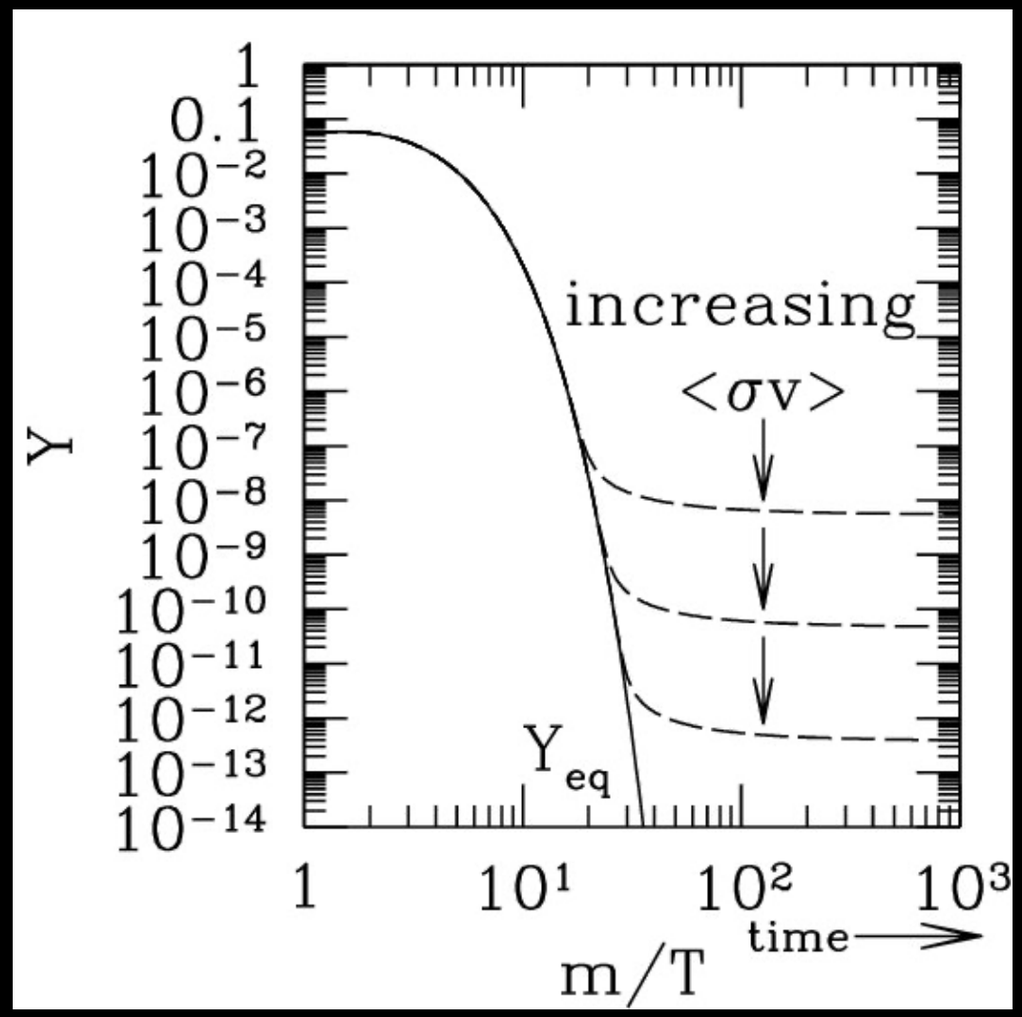


Big Idea 1: Dark matter production at intensity-frontier experiments

Thermal equilibrium of DM and ordinary matter in the early universe, followed by freeze-out of the DM, provides a simple explanation for the origin of the observed cosmological DM abundance.

For MeV-to-GeV DM, need light mediator and feeble coupling to SM of $O(10^{-6}—10^{-3})$, as expected from portal interactions.





If m(A') > 2 m(DM), A' decays to DM — we can produce DM in the lab via the A' portal!

Look for this either as missing momentum, mass, energy, or via subsequent rescattering of the DM in a downstream detector.

Edited by Gordan Krnjaic and Natalia Toro
(RF6 parallel session 11am Wednesday morning)

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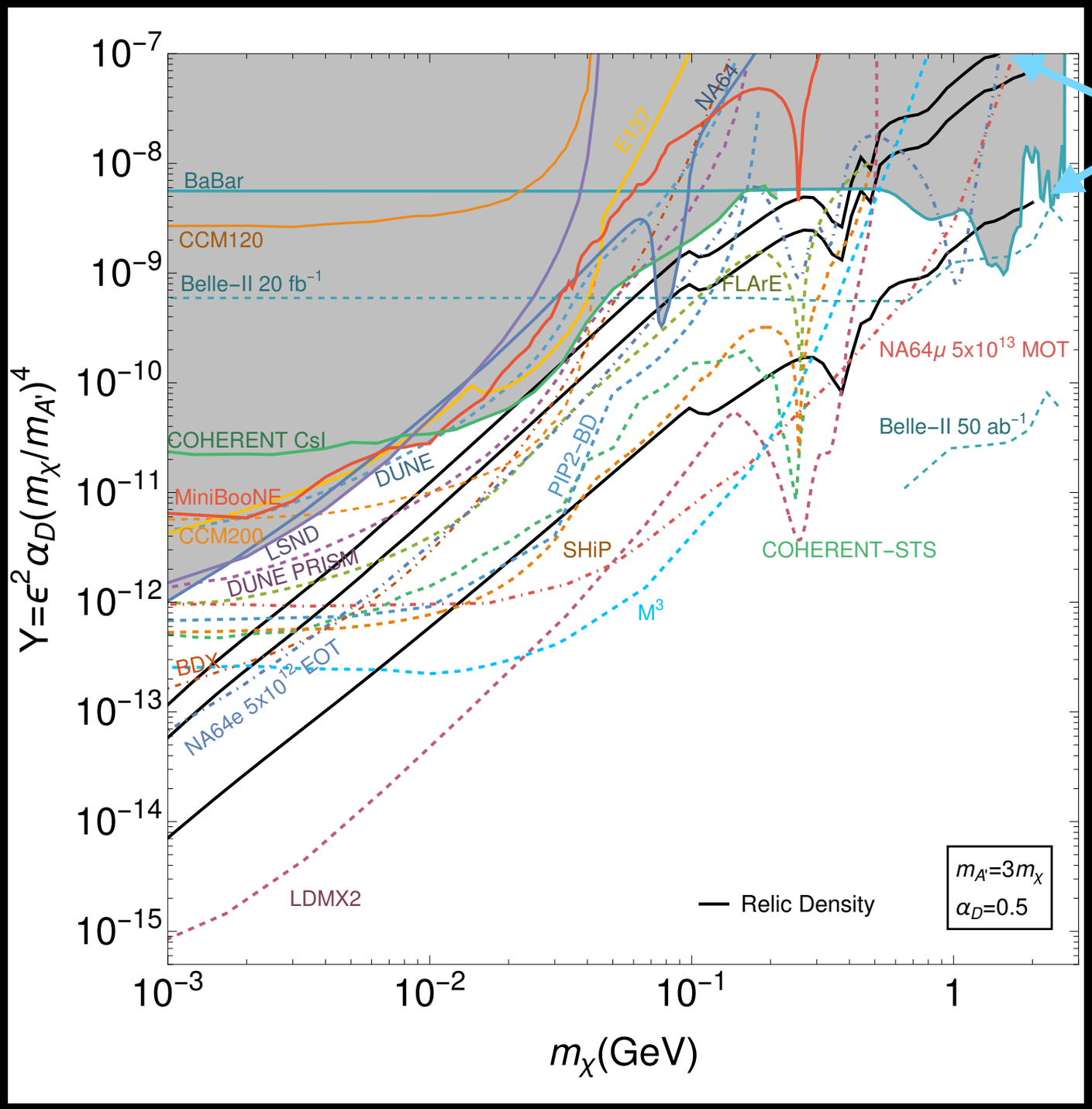

Interaction strengths needed to explain relic abundance via thermal freeze out

Thermal targets are only a few orders of magnitude of current sensitivities — and will be accessible to the next generation of experiments!

Thermal targets also consistent with expected interaction strengths from kinetic mixing.

example: invisible A' decays

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Big Idea 2: Minimal Portal Interactions

Focus on minimal SM extensions with a single new light mediator coupled through one of the portals. DM is assumed to be heavy enough that the mediator can only decay to visible SM states. This implies that both the production and visible decay occur due to the portal interaction.

Portal	Decays
$\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu}$	$A' \to \ell^+\ell^-, \ldots$
$(\mu\phi + \lambda\phi^2) h^\dagger h$	$\phi \to \mu^+\mu^-, \pi^+\pi^-, KK, \ldots$
$y_N h L N$	$N \to \ell^-\pi^+, \ldots$
$\frac{a}{f_a}\left[c_{gg}\vec{G}_{\mu\nu} \cdot \vec{G}^{\mu\nu} + c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \ldots\right]$	$a \to \gamma\gamma, 3\pi, \eta\pi\pi, \ldots$

Dominant production modes are: (vector) EM, light meson decays, DY; (Higgs and ALP) B and K penguin decays; and (HNL) weak decays of leptons and mesons.

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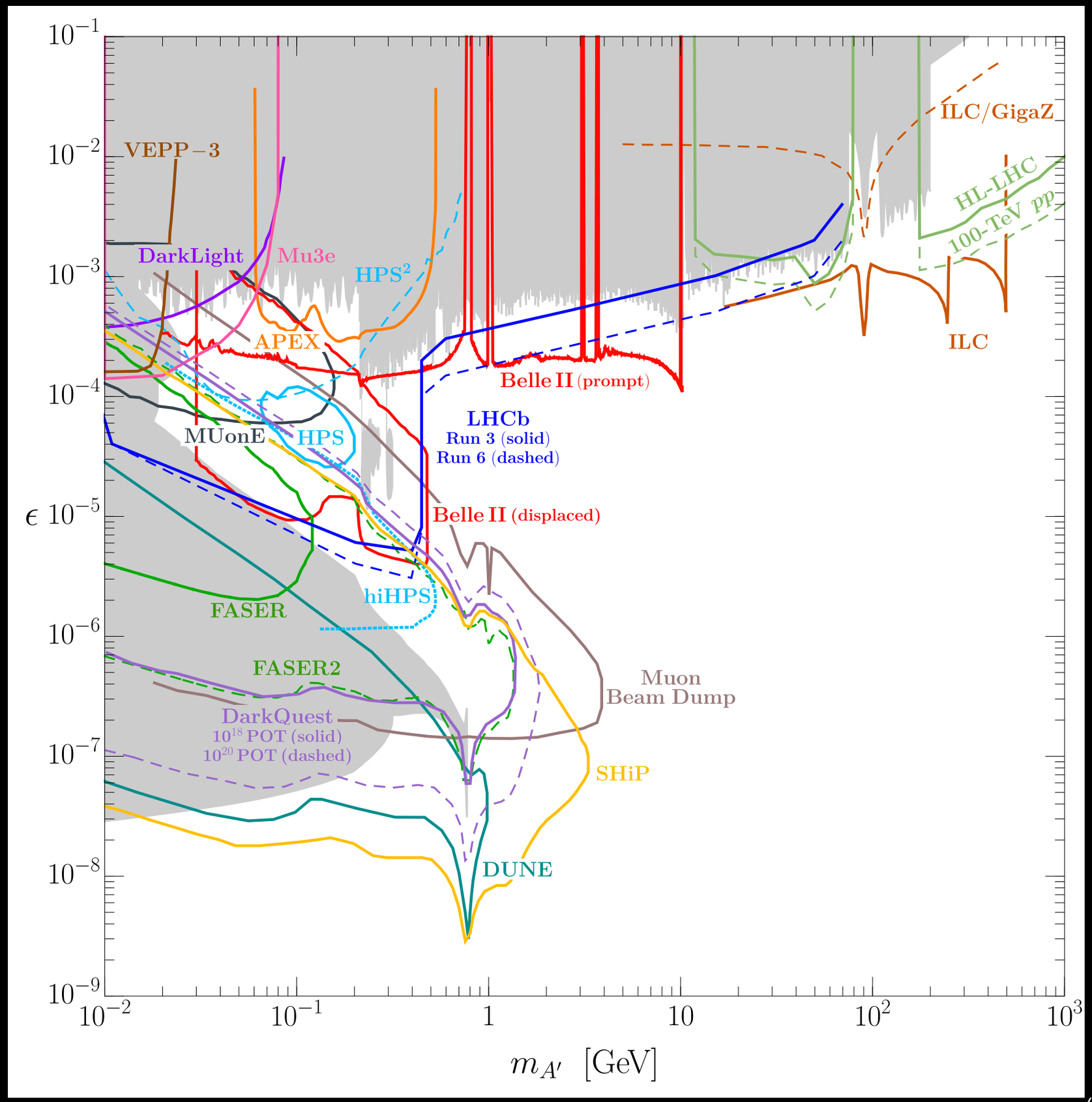

example: visible A' decays

Increasing production rate

Increasing A' lifetime

Need high intensity to produce dark sector particles

Detection strategy depends on the lifetime and mass

Complementarity between e or p fixed target, e+e-, meson and lepton factories, LHC, beam dumps, etc.

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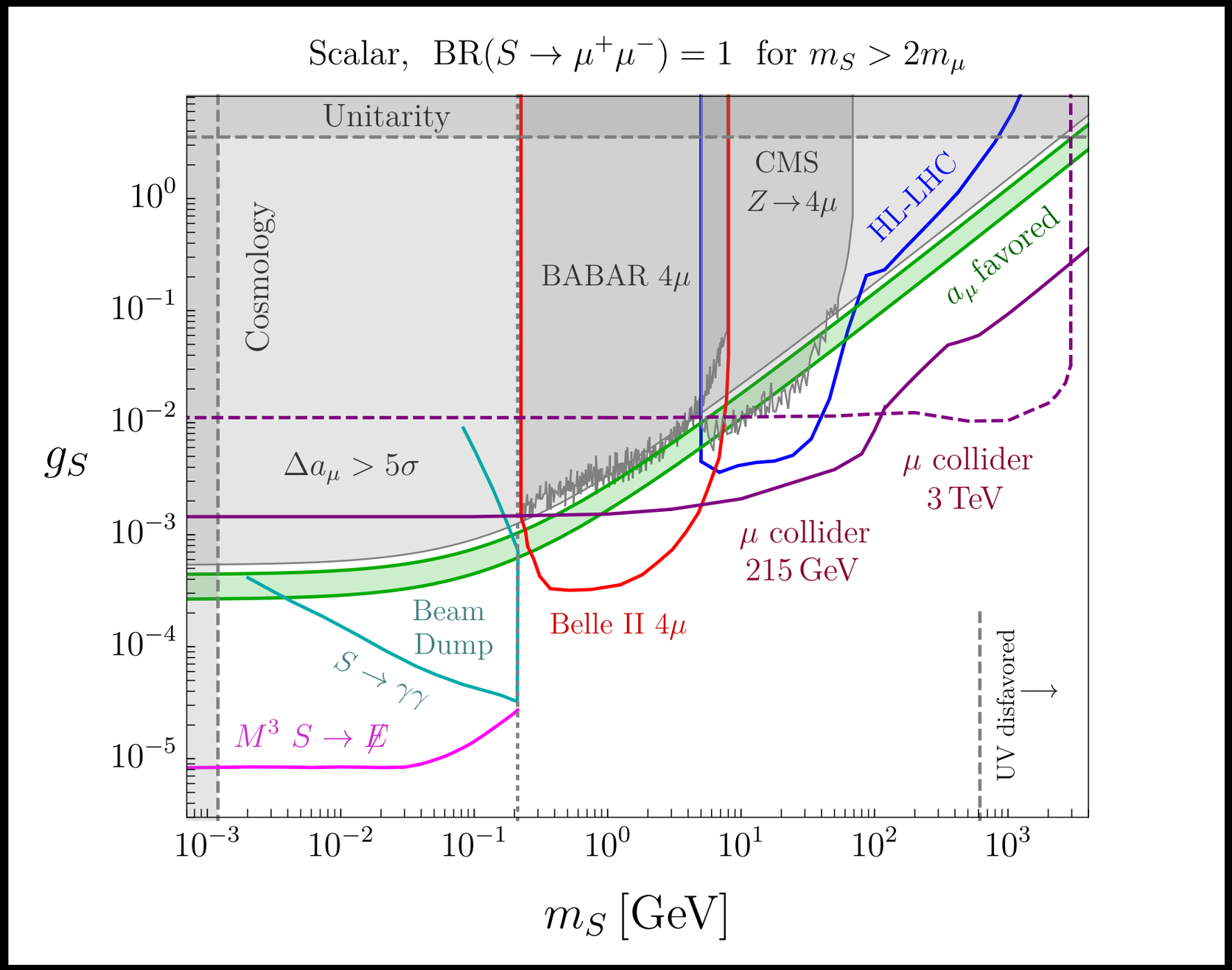
Big Idea 3: New flavors and rich structures in dark sectors

- Richer structure in the dark sector could lead to richer phenomenology, which could require a rethinking of experimental approaches.
- Anomalies in data motivate many of these efforts, e.g. (g-2), flavor anomalies, etc.
- One class of examples involves taking the minimal benchmark models and going beyond minimality in the couplings (e.g. flavor violating ALPs).
- Another class of models are dark quarks charged under a confining dark strong force, which leads to phenomenology similar to QCD (dark mesons, etc).
- Inelastic DM models posit a spectrum of dark states with the heavier ones unstable (we can search for their decays, which are semi-visible).

Edited by Phil Harris, Philip Schuster, Jure Zupan
(RF6 parallel session 11.45am Wednesday morning)

Big Idea 3: New flavors and rich structures in dark sectors

example: scalar coupled to muons



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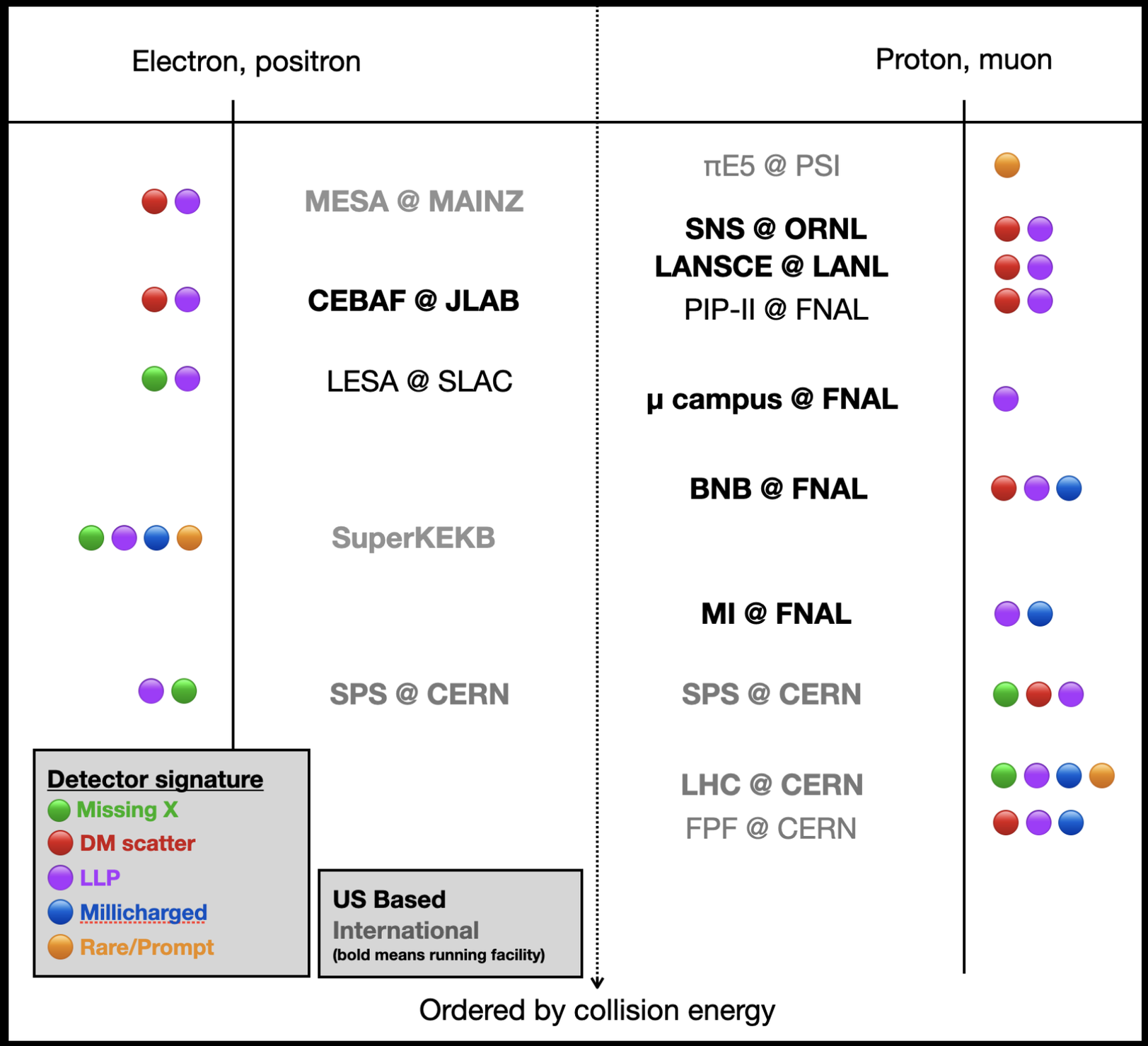
Experiments & Facilities

Impressive array of experiments and facilities searching and/or planning to search for dark sectors!



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Accelerators vs Direct Detection

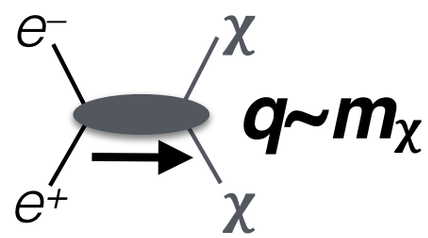
- Direct detection explores cosmic abundance, which accelerators cannot do directly.
- Accelerators can explore the entire dark sector — or even multiple dark sectors — whereas direct detection can only explore the cosmologically stable parts.
- Vastly different kinematics: Direct detection explores non-relativistic scattering, while accelerator production is highly relativistic.

Accelerators vs Direct Detection

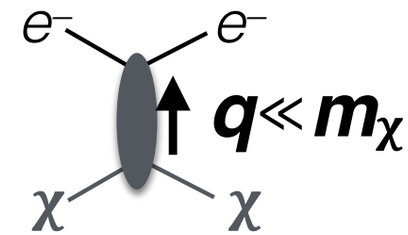
slide by Natalia Toro

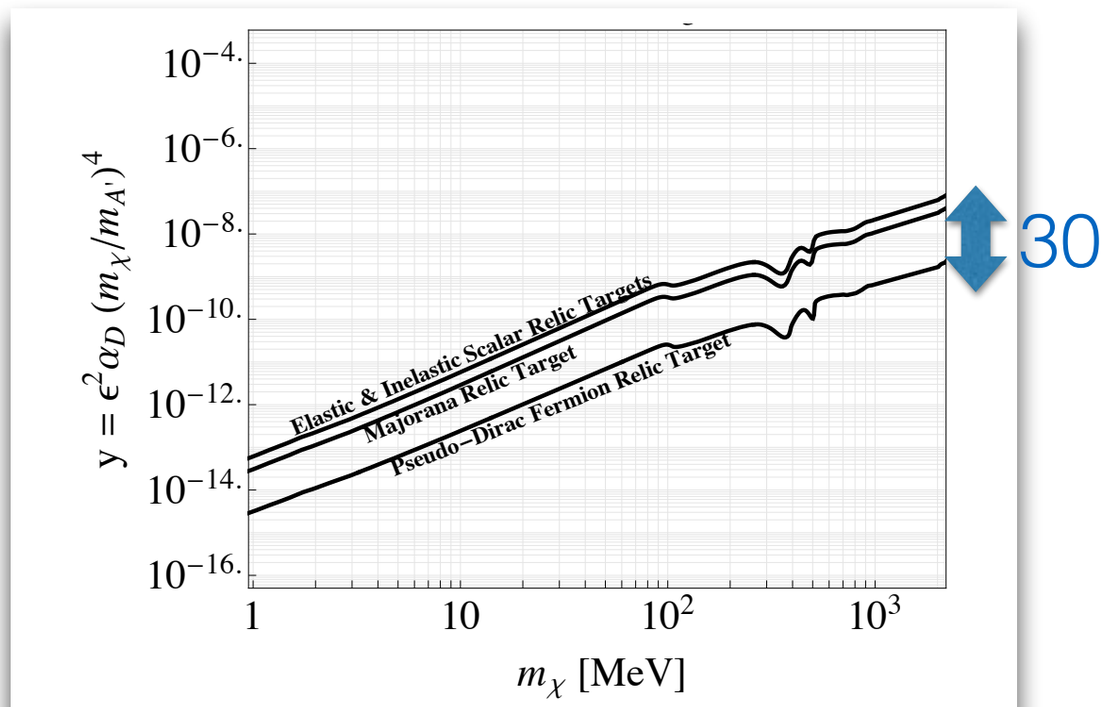
Kinematics Matters

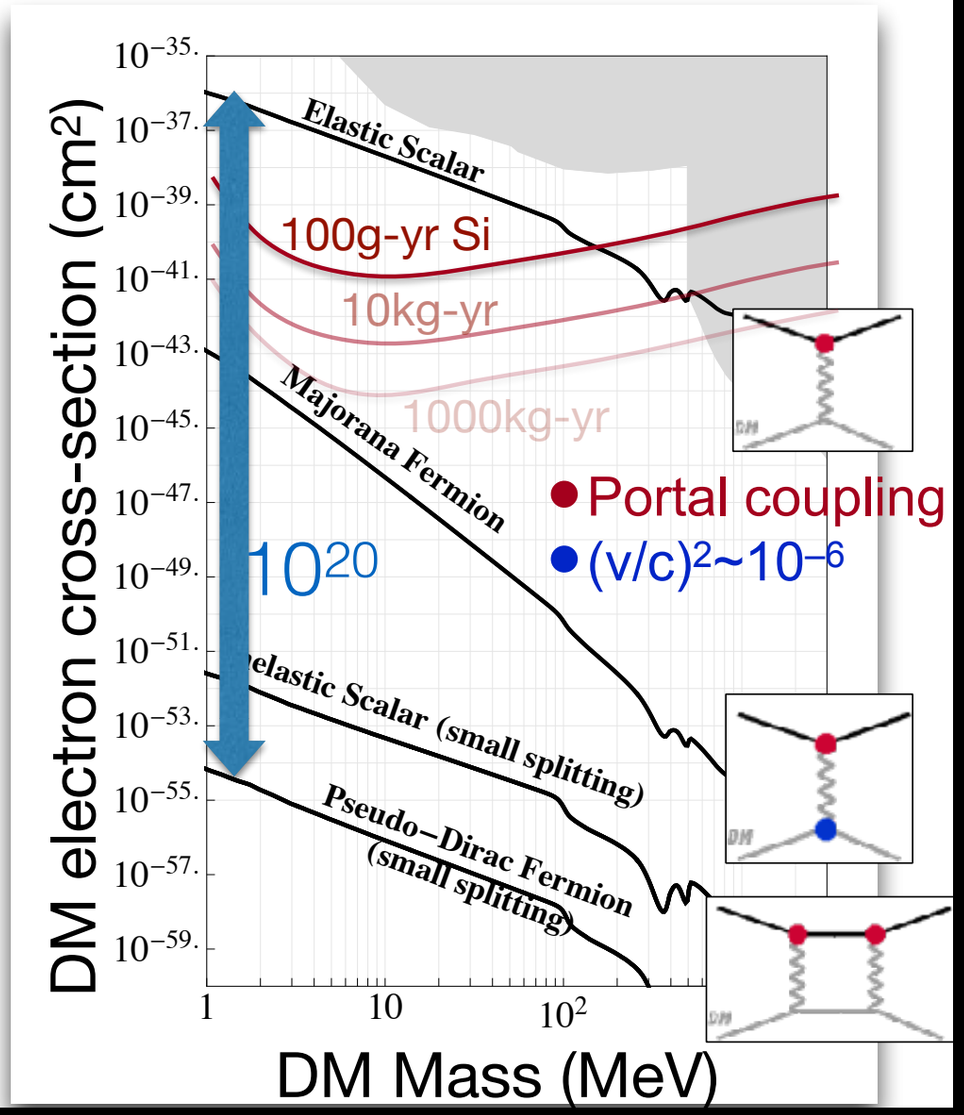
Accelerator Production



Direct Detection







Kinematic similarity to freeze-out temperature ⇒ narrow band

But note $q \ll m_\chi$ **enhances** other models' signals ⇒ need both!

39

Scientific Opportunities & Roadmap

The goals of the three Big Ideas are complementary and must be pursued in parallel to fully explore the physics of dark sectors. Realizing them requires simultaneously:

- exploiting the capabilities of existing large multi-purpose detectors, including near-future upgrades;
- investing in specialized small-scale experiments, and in facilities that can deliver high-intensity beams;
- and supporting the theory community to further develop the theory of dark-sector physics.

Collectively, these activities provide a roadmap for the US dark-sectors program for the next decade.

Discovering a dark sector would not only shed light on the enigma of dark matter and possibly several additional open issues in particle physics—but would revolutionize our understanding of the universe and open an entire new pathway to studying nature.

Following the roadmap outlined here will secure the leadership role of the US dark-sectors community.