RF6 Perspective on DM Complementarity

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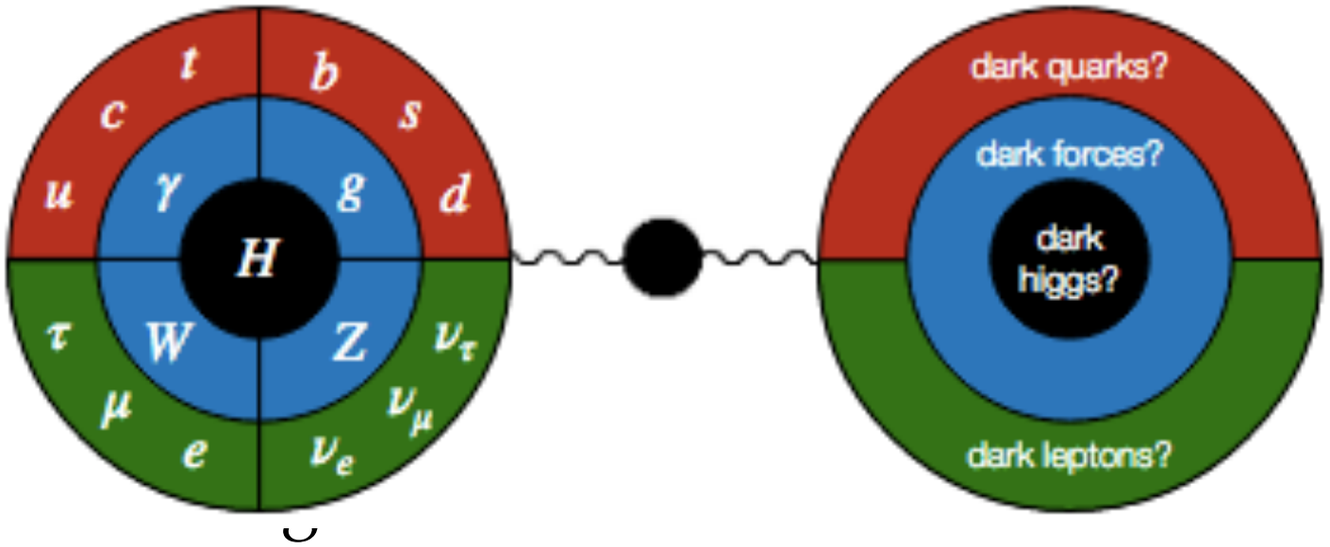
Outline

- Who is RF06 – Overall Scope, Vision, Priorities
- Dark Matter Scenarios and Signals
  - Cross-Cuts to CF, EF, and TF
- Goals for Working with Other Frontiers

RF6 – Dark sectors at Accelerators: Scope

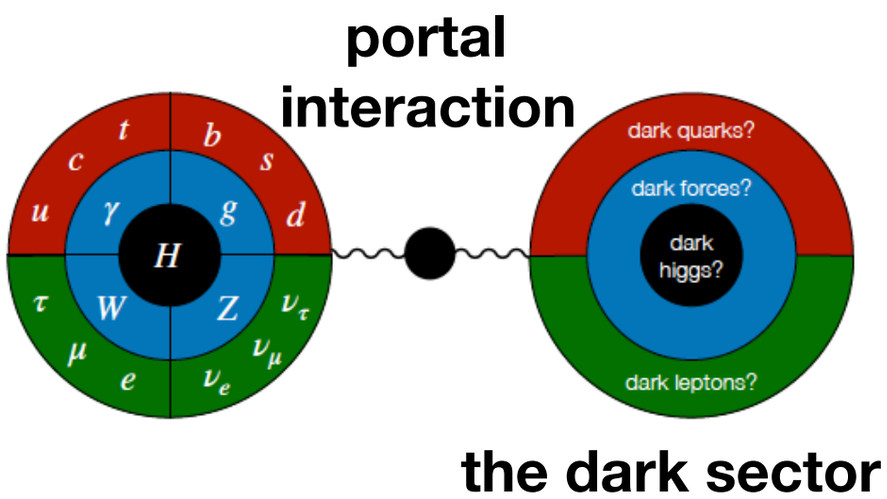


- **Using intensity-frontier experiments to probe low mass dark(hidden) sectors neutral under SM forces.**
  - Includes both dark matter proc
    (semi)-visible signals (produced dark sector particle decays into SM matter)
- **If DM is lighter than few GeV, it must be SM-neutral ⇒ dark sector framework**
- "Intensity Frontier" includes
  - analyses at existing flavor experiments (e.g. Belle II, LHCb)
  - beam-based searches and/or dedicated runs at neutrino experiments (overlaps NF3)
  - new small experiments
  - new auxiliary detectors at LHC (overlaps EF10)

- **Dark matter is a key motivation across all of these searches**

RF6 Vision

The existence of dark matter motivates a dark sector neutral under the SM forces



Dark sectors are a compelling possibility for new physics, with potential relevance to

lightness of SM neutrinos, baryon-antibaryon asymmetry,
hierarchy problem, strong-CP problem (e.g., axions, axion-like-particles),
anomalies in data

Dark sectors are generically weakly coupled to SM matter (via portal interactions) and can naturally have MeV-to-GeV masses.

➡ Only mild constraints from precision atomic physics & high-energy colliders

➡ Intensity-frontier experiments offer unique and unprecedented access to:

- Light dark matter production
- Systematic exploration of dark sector portals
- Searches for new flavors and rich structures in dark sectors

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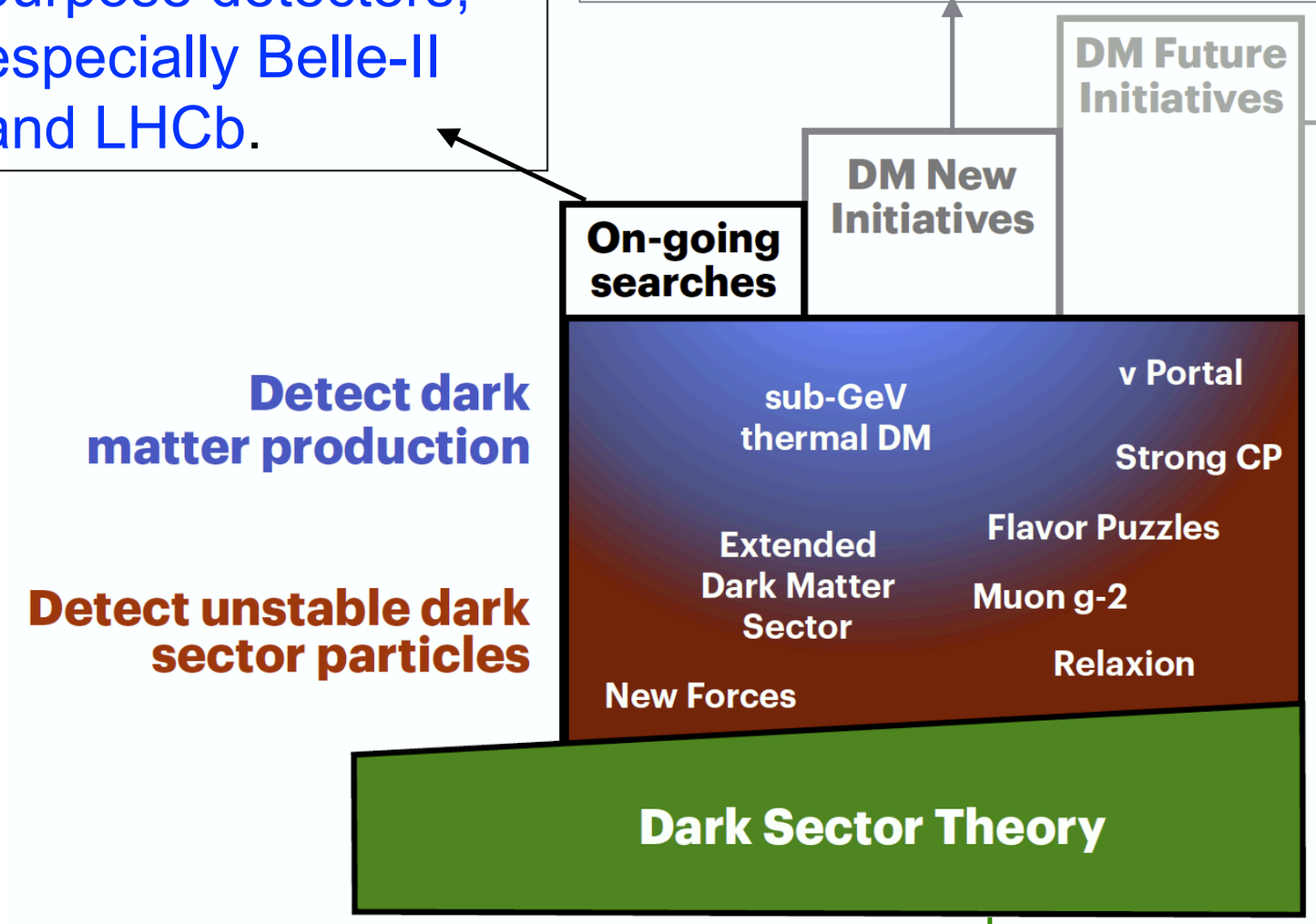
RF6 Strategy: To promote US leadership in dark sector studies

✱ Exploit the capabilities of existing multi-purpose detectors, especially Belle-II and LHCb.

✱ Invest in fully funding projects supported by "DM New Initiative" (*), LDMX and CCM

✱ Extend DMNI with focus on signals of visible decays of dark sector particles – proposals include proton and lepton beam-dump experiments, long-lived-particle detectors



✱ Support theory efforts to apply and explore dark sector and collaborate in dark-sector experiments – has been at the foundation of essentially all ongoing and planned experimental activities in this growing field.

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Dark Matter Science in RF6

Low-mass BSM physics should be SM-neutral → interactions through short list of ***portal*** couplings.

$$\epsilon F^{\mu\nu}\tilde{F}'_{\mu\nu}, \quad \kappa|H|^2 S^2, \quad yHLN, \quad \frac{1}{f}a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

DM abundance provides clues to DM interactions

DM production mechanisms that involve thermal equilibrium ⇒ accessible DM production at accelerators

- Most WIMP-like possibility: DM annihilates through mediator! Canonical benchmark model is freeze-out through *s*-channel dark photon – identified as high priority at BRN
  - Additional interesting models interact mainly with neutrinos

- Generalized freeze-out production mechanisms for light DM (e.g. SIMP, forbidden annihilation) often imply ***visible*** signals at accelerators – this was Thrust 2 of Accelerator PRD at the BRN and its importance is called out by RF6.

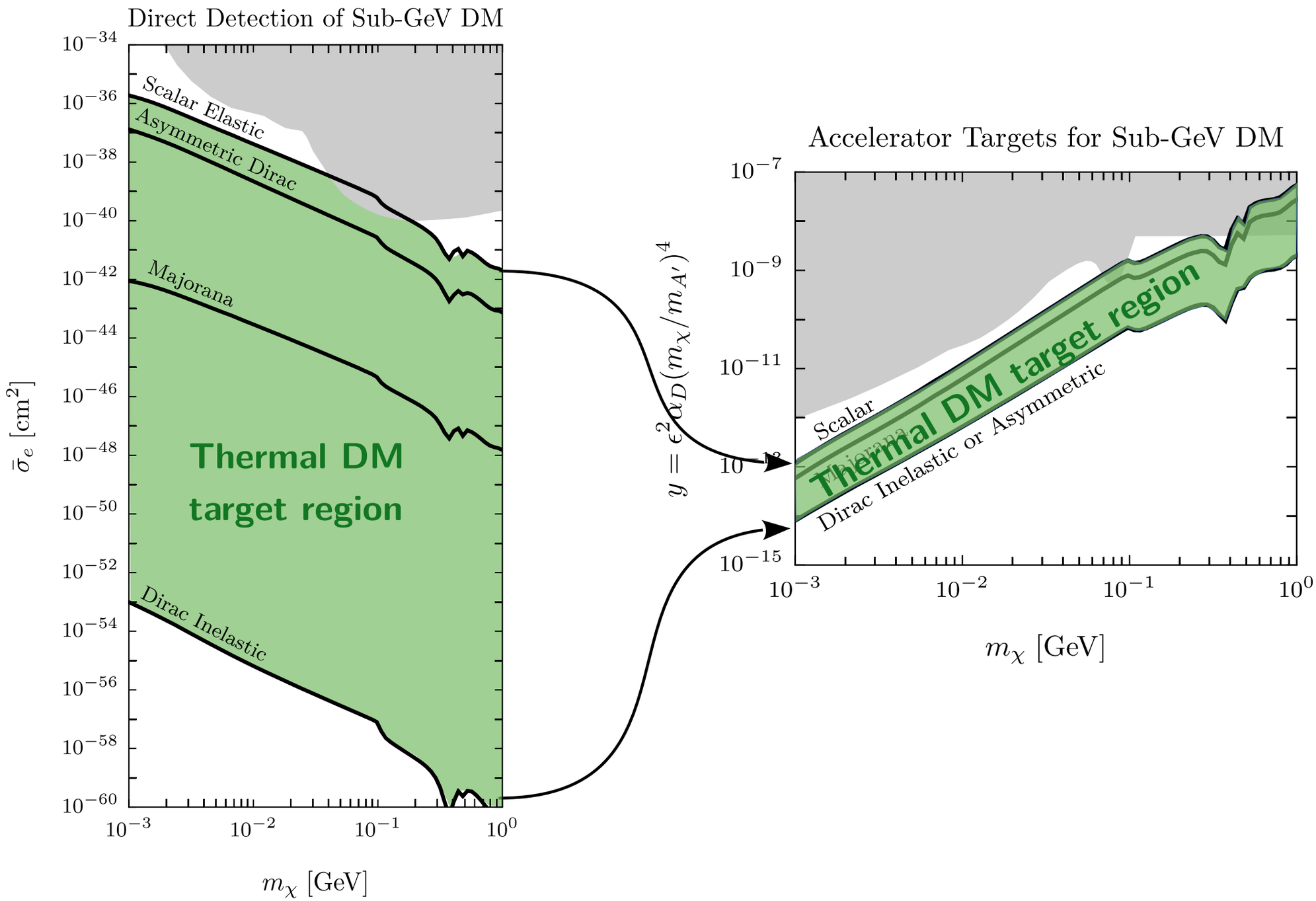
Complementarity of Accelerators and (In)Direct Detection

Complementarity with low-threshold DD:

- Probe different properties (particle properties @accel, combination w/ cosmic abundance at DD)
- Explore different kinematics ($v \ll c$ in DD, $v \sim c$ at accel)
  - Low-threshold DD has enhanced sensitivity to Coulombic scattering, as in light-mediator freeze-in
  - Accelerators are optimal for discovery of DM with suppressed interactions at low velocity, including freeze-out through dark photon with generic spin/mass structure.
- Where both are effective (e.g. elastic scalar thermal freeze-out), exciting opportunities for combined characterization of a signal

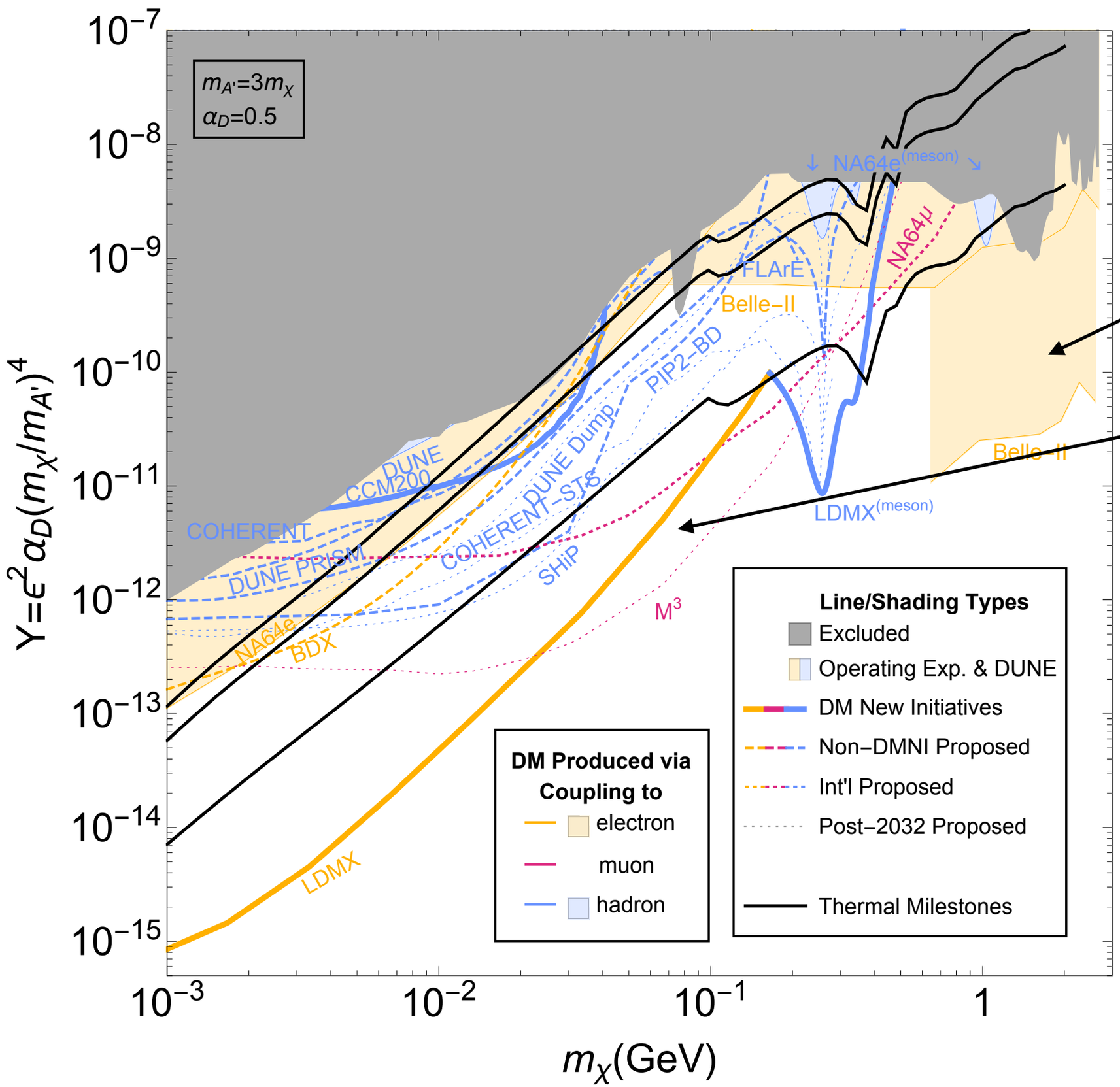
Viable light DM models have suppressed indirect detection signals or annihilate exclusively to neutrinos – in latter case, strong synergy with neutrino telescope ID

Velocity-dependence for thermal DM



Velocity-dependence of scattering spreads freeze-out models' direct detection signals over 20 decades of cross-section, while range of expected accelerator signals is compact. **Accelerator searches are necessary to test low-mass thermal scenarios.**

Dark Photon Model: RF6 Message

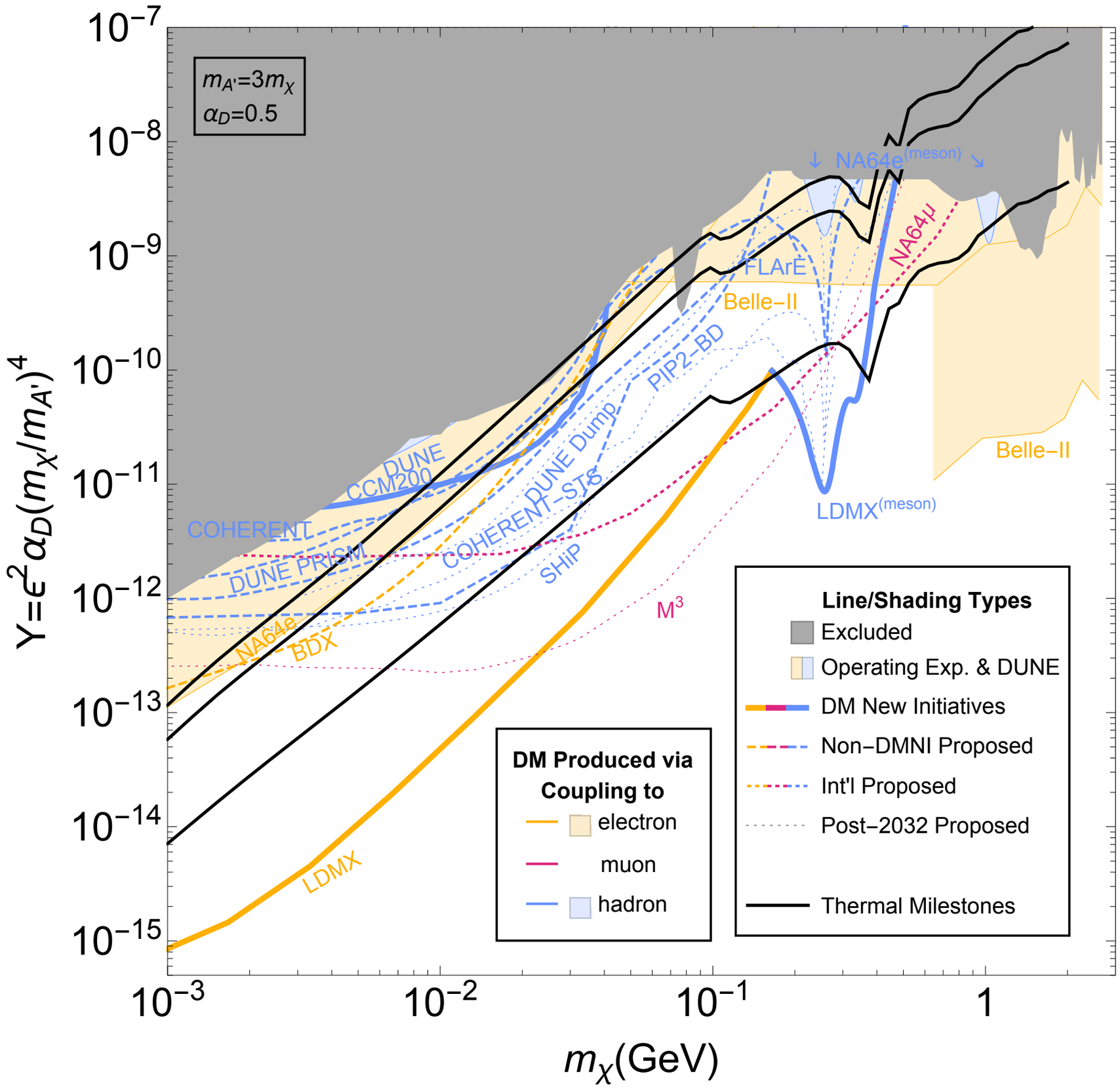


Example of 3 experimental "prongs" in action:

Multi-purpose experiments and **DMNI program** both needed to cover thermal production milestones.

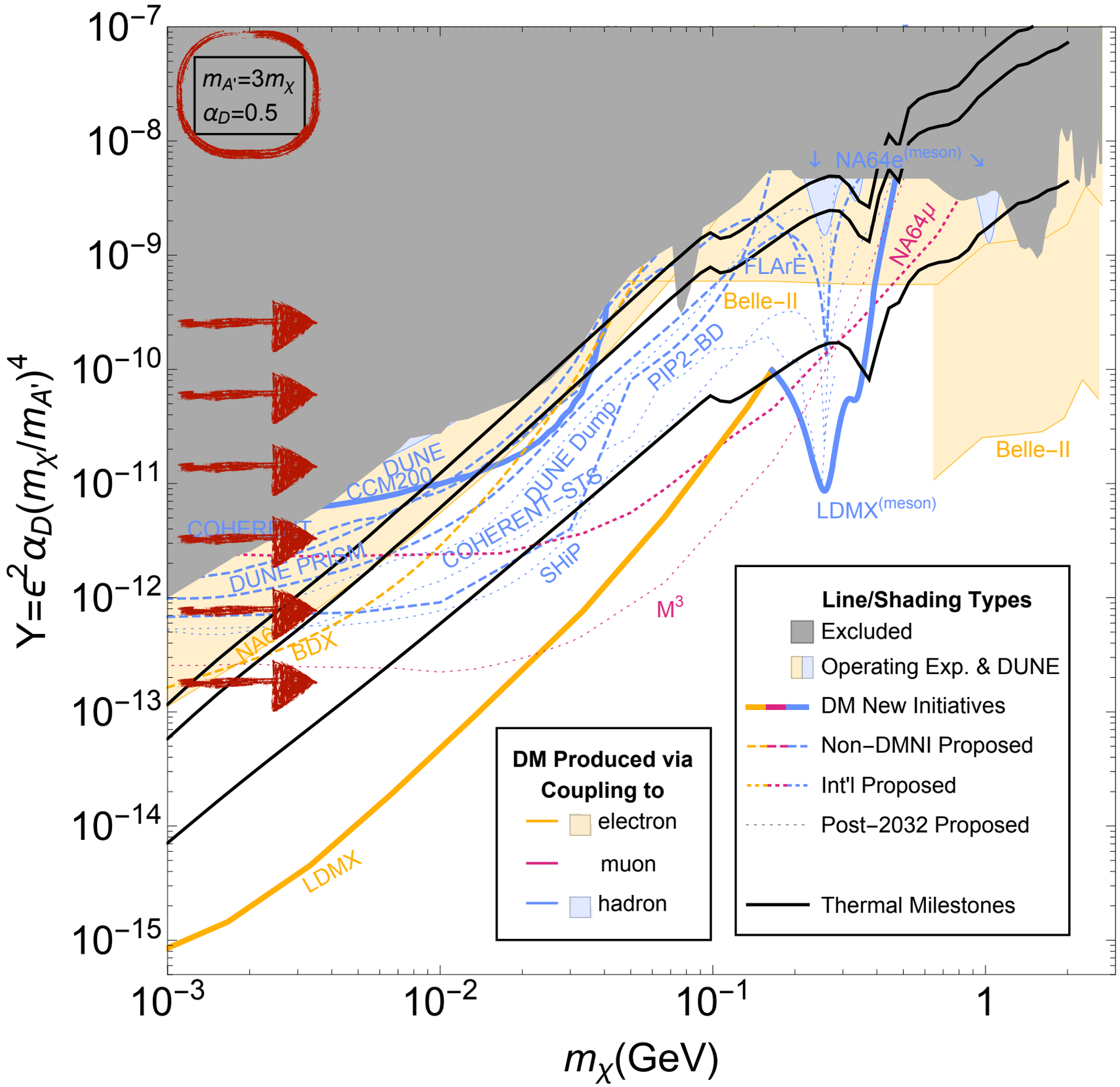
For this signal, **moving beyond DMNI-funded scope** buys sensitivity to models that don't couple to electrons & complementary measurement

Dark Photon Model: Complementarity



EF10 complementarity: LHC searches for similar models at higher (mediator and / or DM) mass scales

Dark Photon Model: Complementarity



CF3 complementarity:

Halo properties constrain DM self-interactions

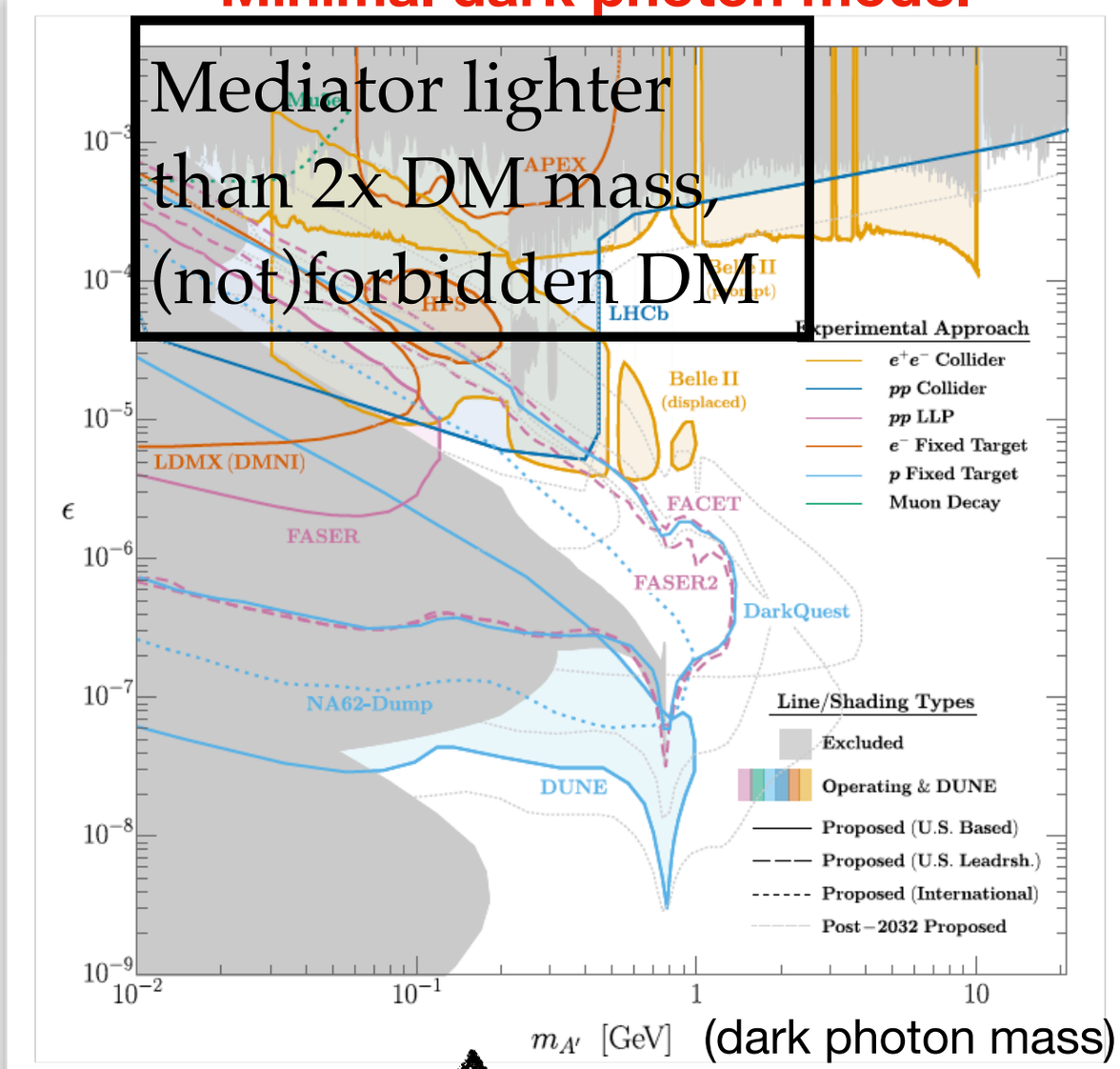
Light dark sectors can affect N_{eff}

Combination w/ RF6 → more powerful coverage of dark sector models

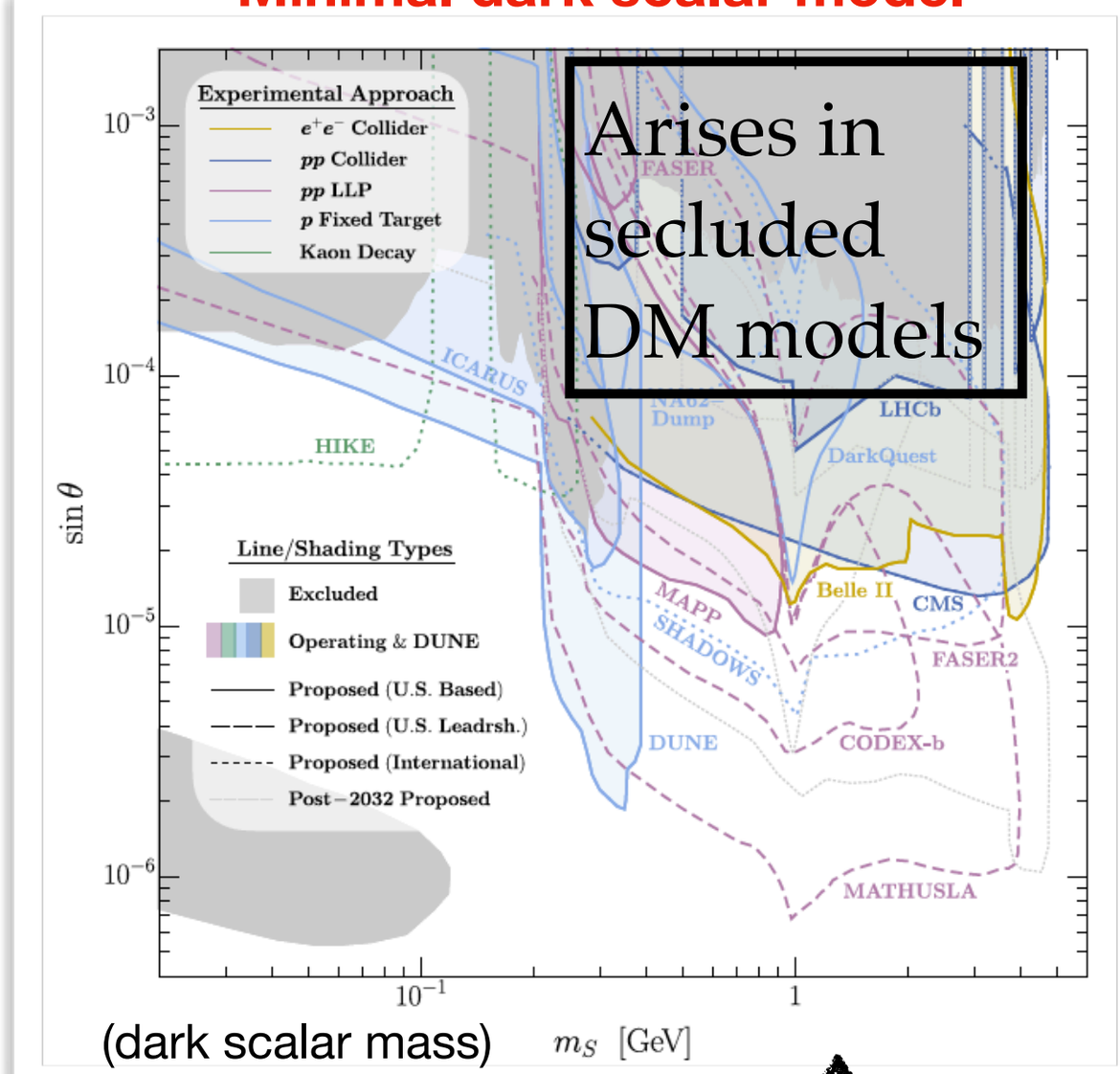
Unstable Dark Sector Particles and Dark Matter

Big idea 2. Producing and detecting unstable dark particles

Minimal dark photon model



Minimal dark scalar model



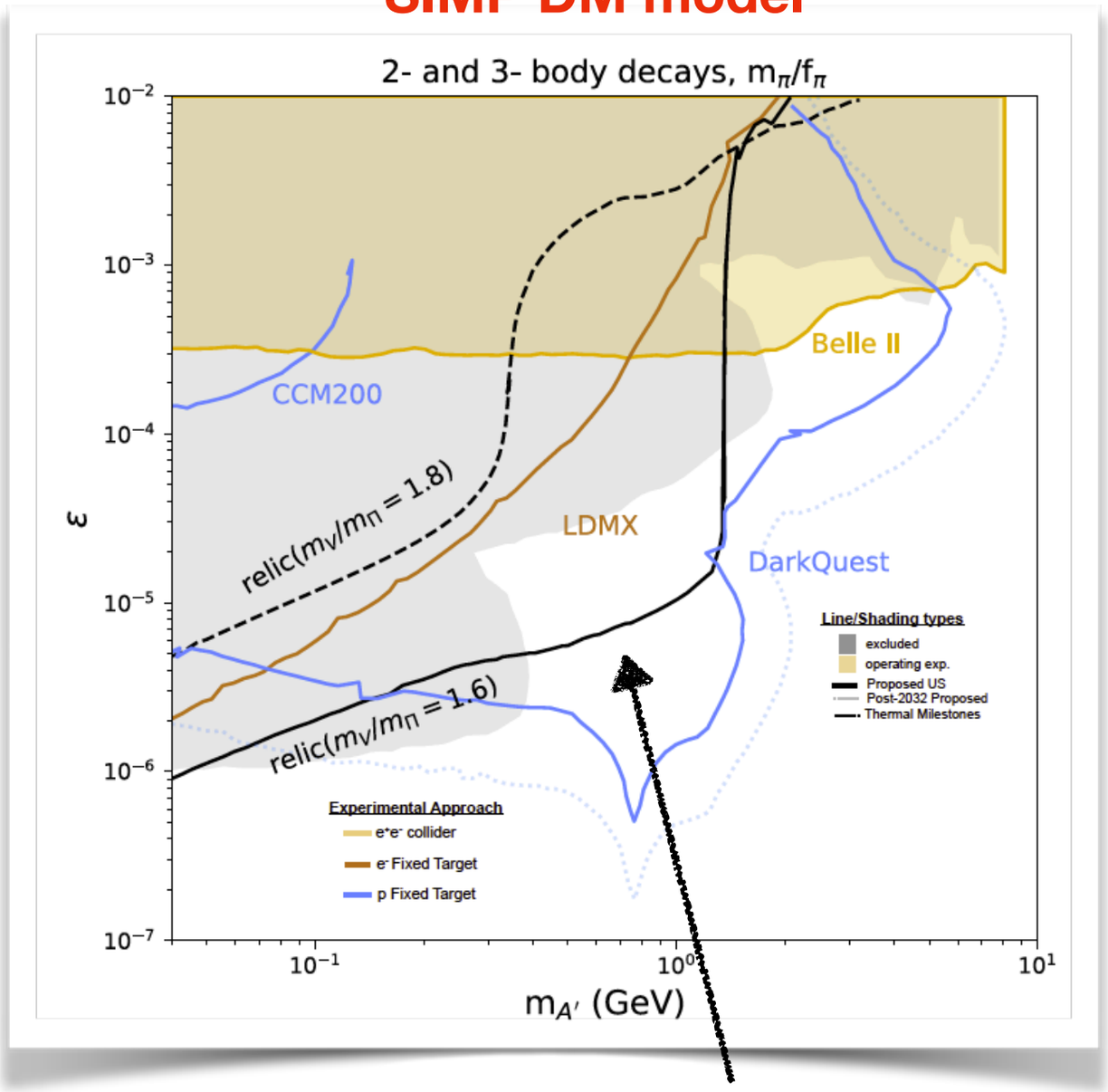
The mediator decays **visibly** to SM particles

This entire parameter space predicts a dark sector in thermal equilibrium with the SM

Unstable Dark Sector Particles and Dark Matter

Big idea 3. Beyond minimal models

SIMP DM model

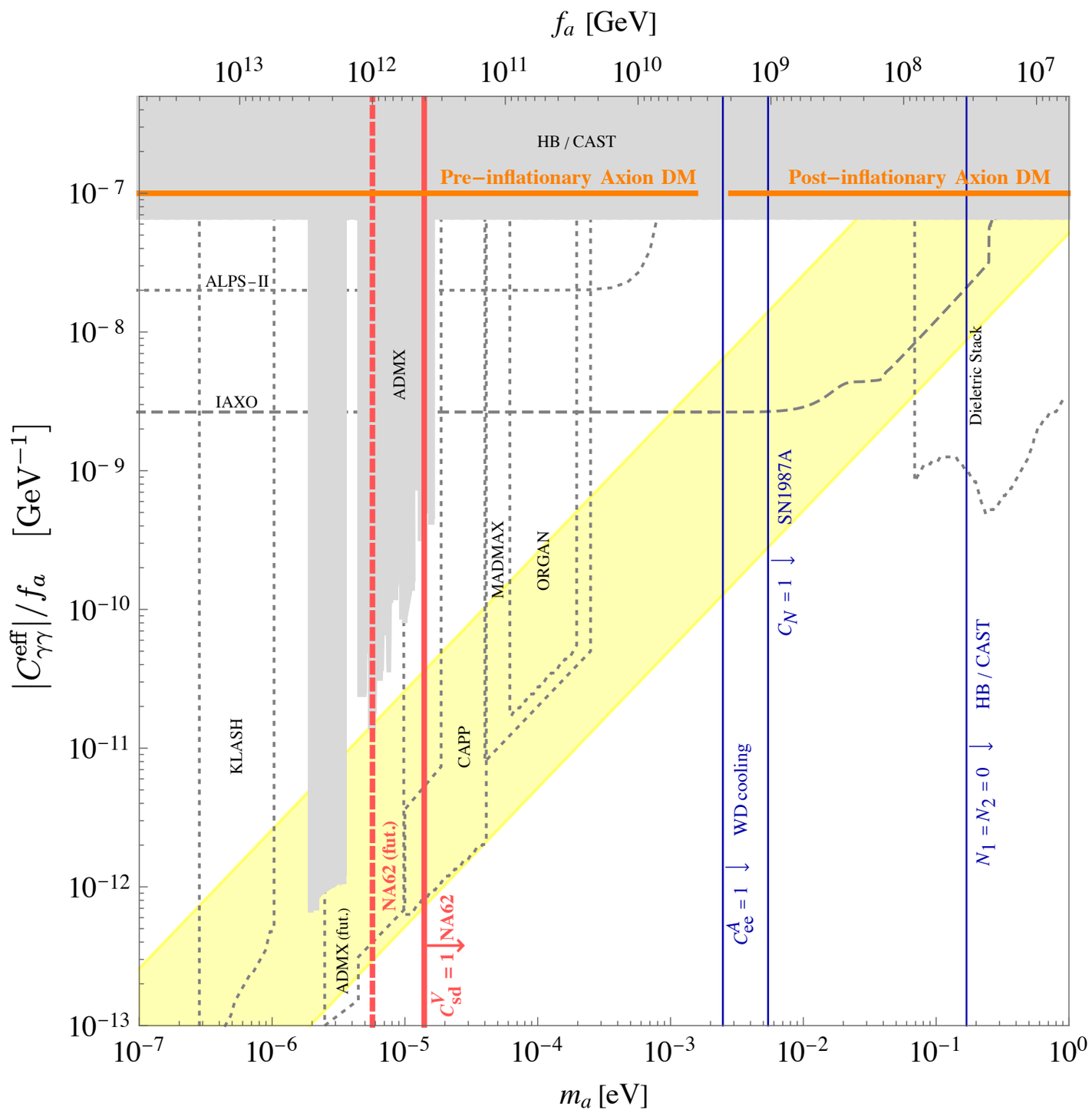


benchmarks for thermal DM

Broad theme
Accelerators can probe the detailed physics of the dark sector.

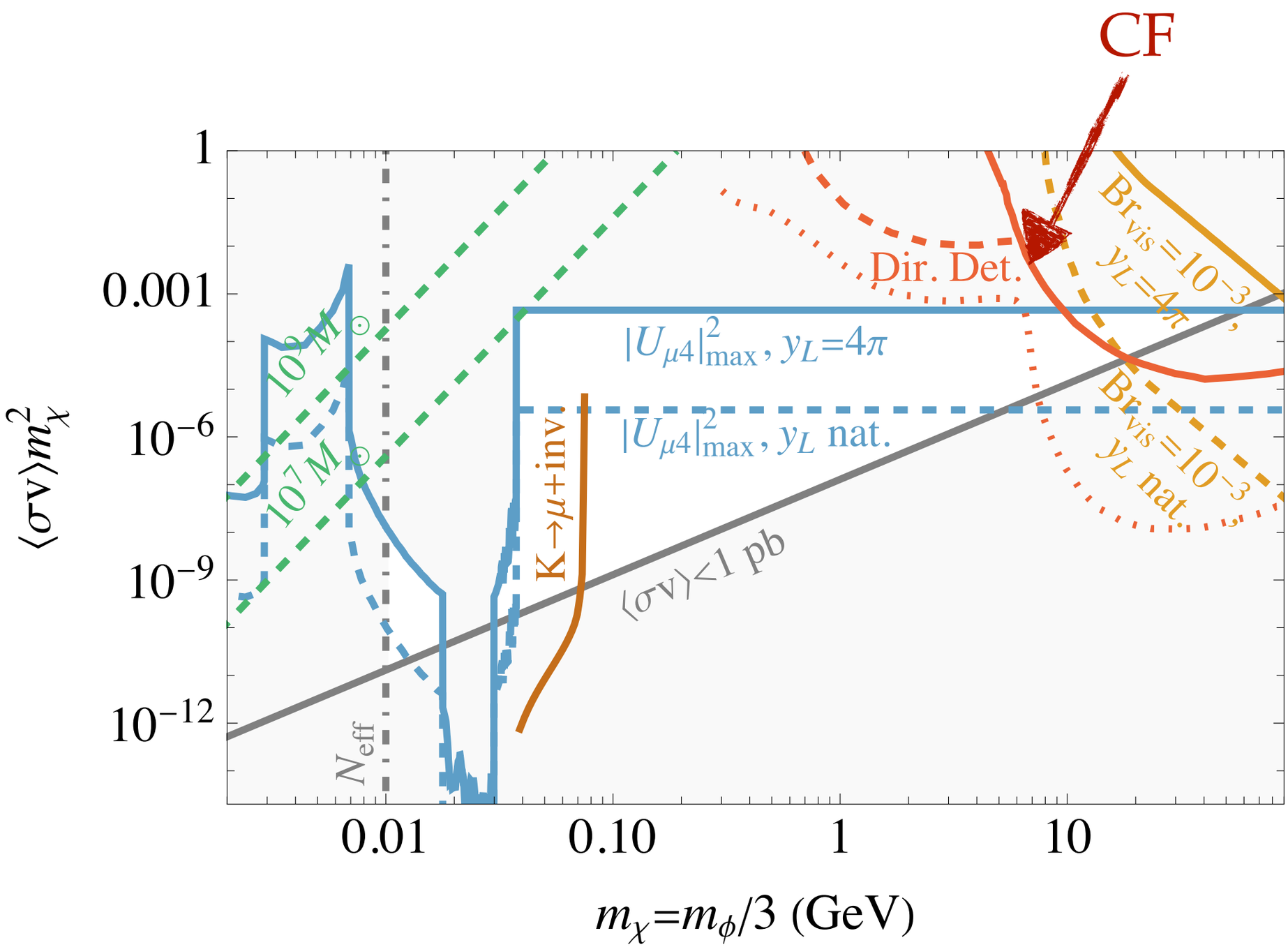
Unstable Dark Sector Particles and Dark Matter

Big idea 3. Beyond minimal models



Axion-quark couplings with new flavor structure are powerfully constrained by kaon decays – **CF2 complementarity**

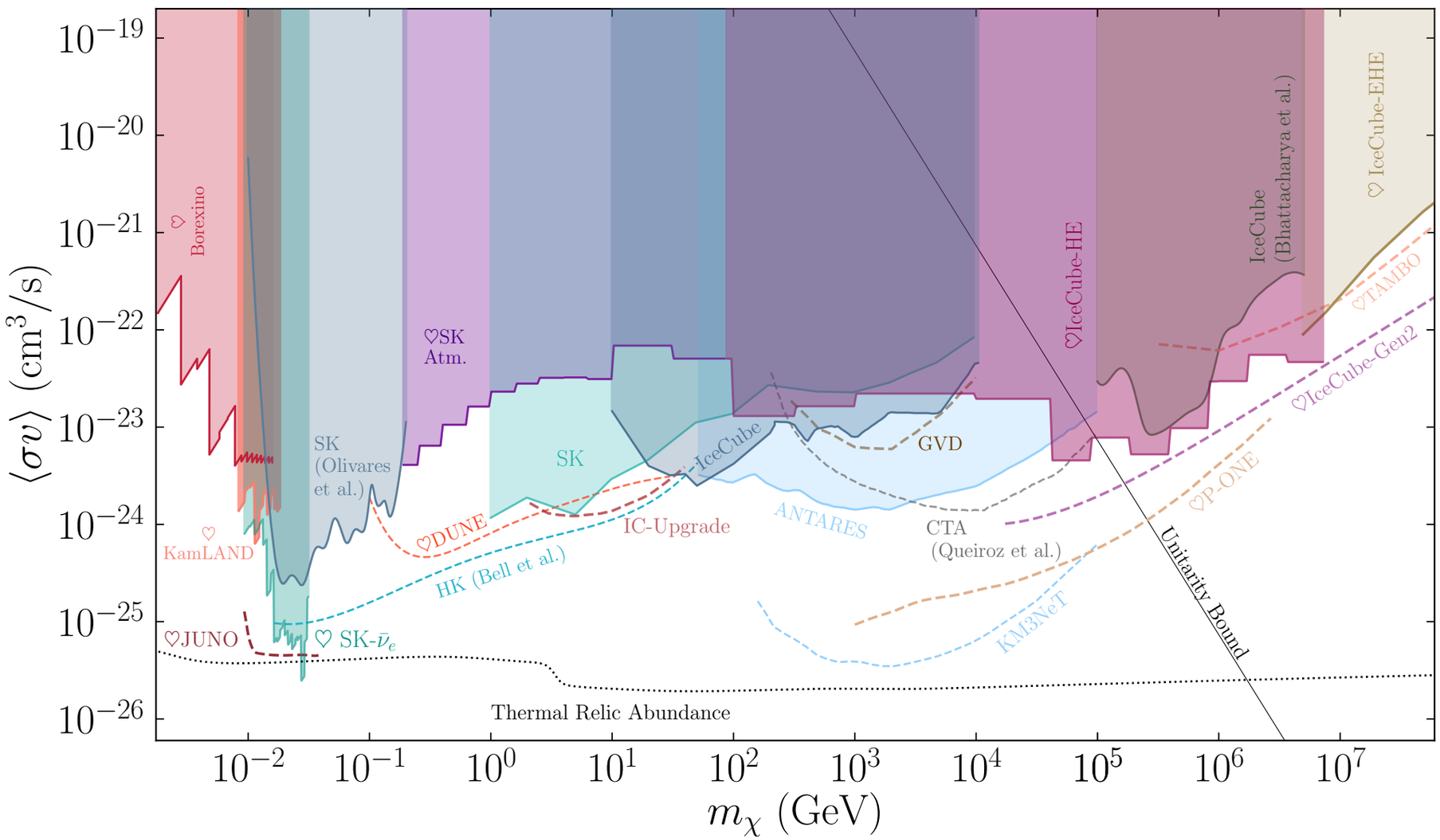
Neutrino-Coupled Models



t-channel annihilation, muon flavor mixing

Neutrino-Coupled Models

s-channel annihilation, tau flavor mixing



Complementarity between accelerator-based neutrinos, cosmogenic neutrinos, CTA

Cross-Frontier Goals and Synergies: Specific Science Opportunities

- Direct detection and accelerators probe similar interactions; We need both because
  - ***different kinematics*** $\Rightarrow$ ***complementary discovery reach***
  - each approach ***answers different questions***

- Cosmic probes and DM self-interaction constraints are highly complementary, unique window on ***dark-sector-only interactions*** – especially at 1-20 MeV masses ($\sigma/m \sim 1/m^3$)

- DM-neutrino interactions can be explored via indirect detection, neutrino program (accel+natural), and flavor

- Flavor experiments and CF2 offer complementary windows on axions/ALPs, which can have flavor-violating interactions

Cross-Frontier Goals and Synergies: Program

Completion and future continuation of DM New Initiatives is essential to realize opportunities across CF1, CF2, RF6, NF3.

- Current DMNI is supporting compelling science – following through is important
- There are more exciting opportunities along this path than could be achieved in one round – the program should continue (with eventual rejuvenation to refresh priorities & factor in new ideas)
- Beyond specific science, IMO support for small projects is also essential to the health the overall HEP ecosystem.

We also need to **support new DM science that is not small projects** – e.g. CF3, research, upgrades – these are highly leveraged investments with great returns!

Cross-Frontier Goals and Synergies: Theory

Support for DM theory is essential and should be multi-faceted: developing new models, understanding interplay between complementary probes, and supporting small experiments are all vital.

Cross-Frontier Goals and Synergies: Theory Interface

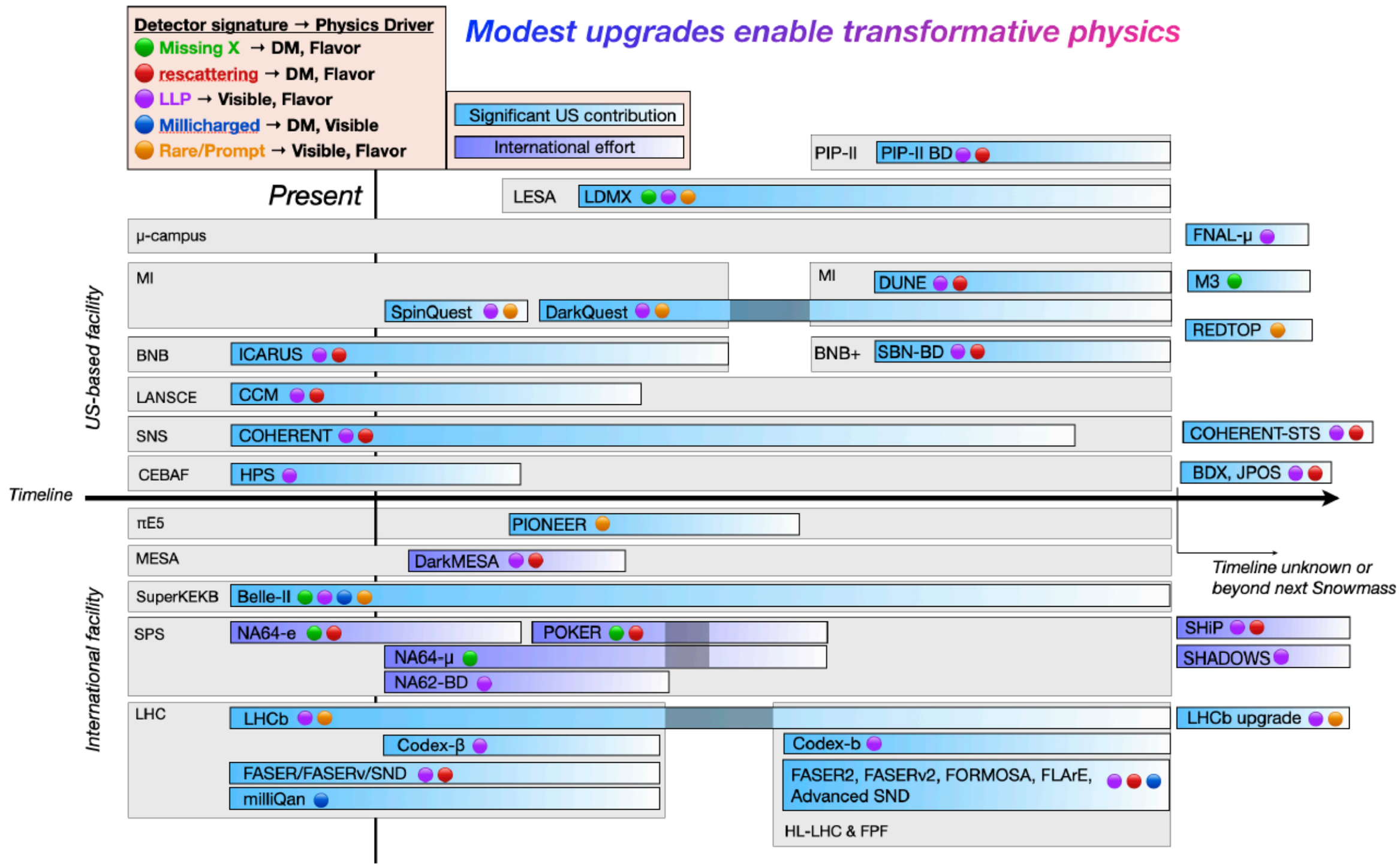
Great opportunities have been found at theory-experiment-instrumentation interface; there is surely untapped potential

- Especially important for DM, where the field of possibilities is so vast
- Infrequent dialogue, different technical dialects, and funding challenges can be obstacles
- So is insufficient appreciation of the potential (e.g. no Theory-Instrumentation liaison at Snowmass)
- **We should tell this story**

Discussion …

Backup

Experiments/facilities



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