Exploring the Dark Sector

Theoretical and Experimental Landscape

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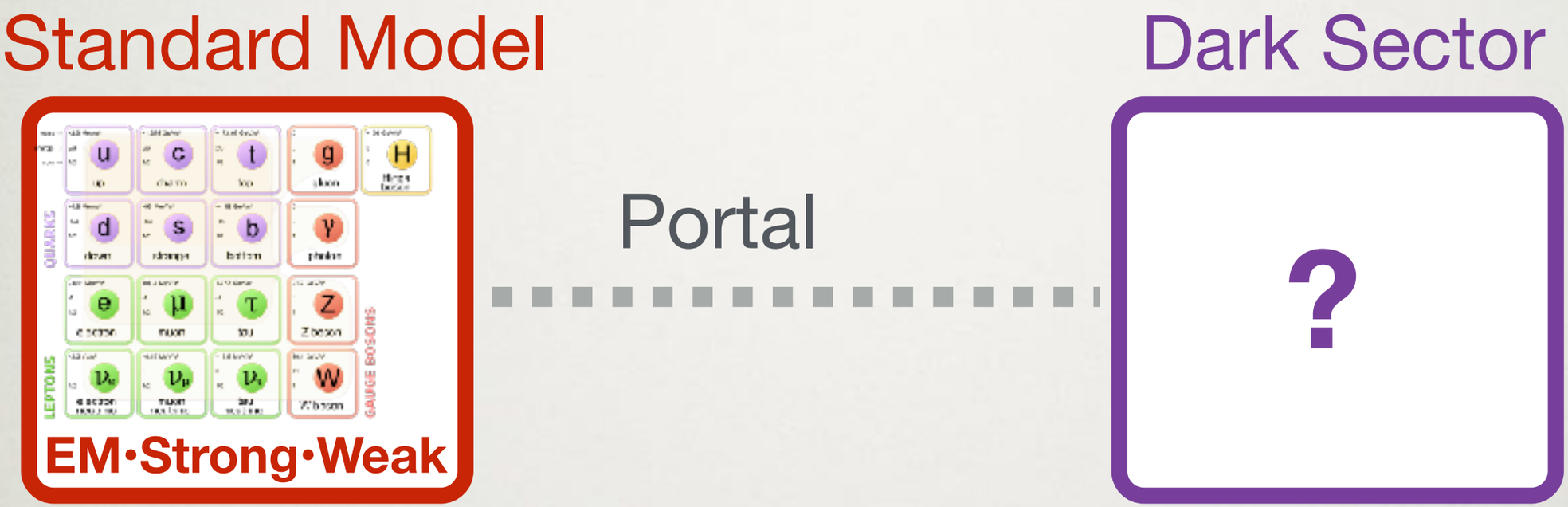
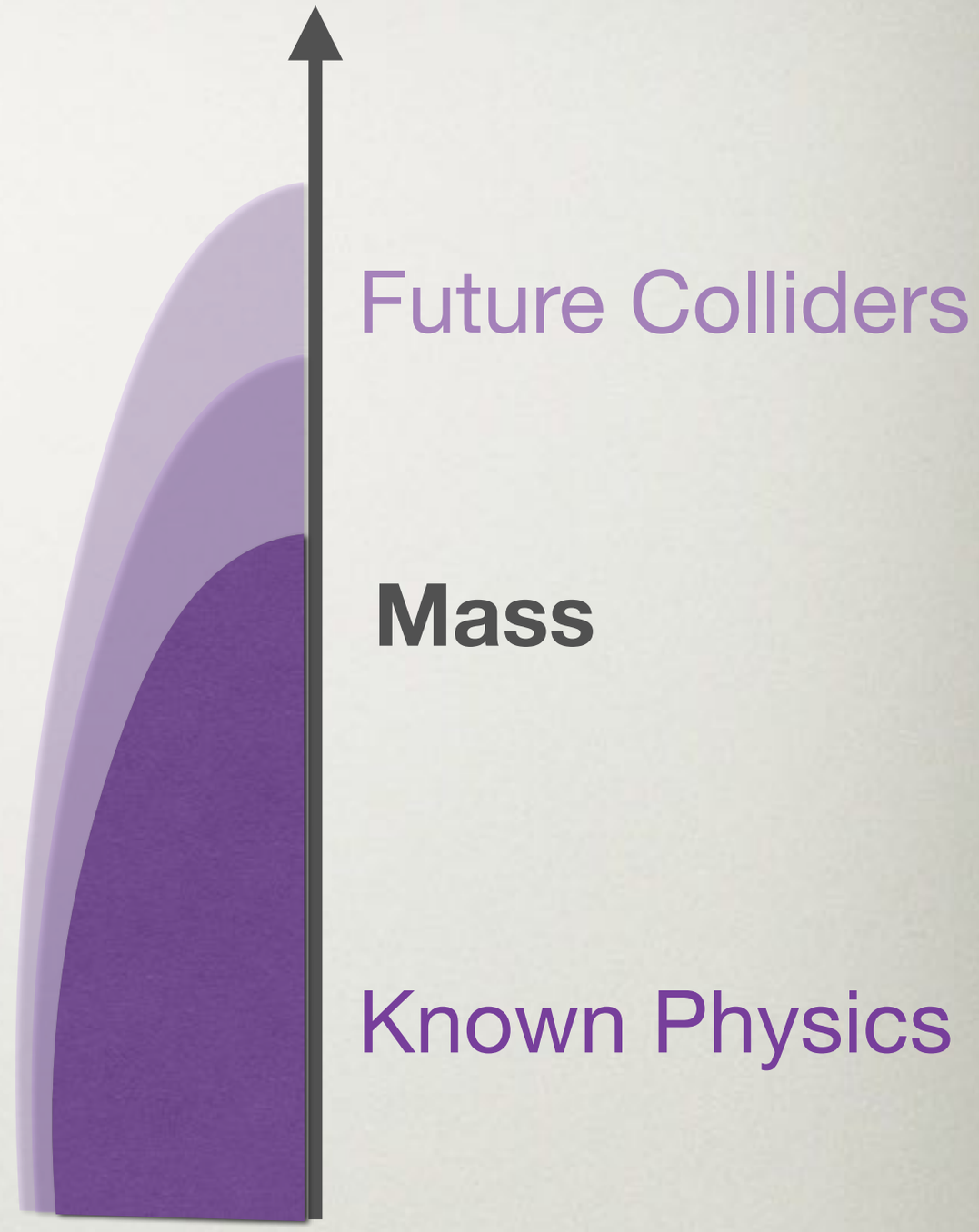
SLAC

Dark Sector Picture



- Anything neutral under Standard Model forces
  - Typically quite weakly coupled
    - Potentially hiding at mass scales we already consider “well explored” (e.g. lighter than proton)
  - Good candidate for dark matter

New Physics at Low Mass Scales?



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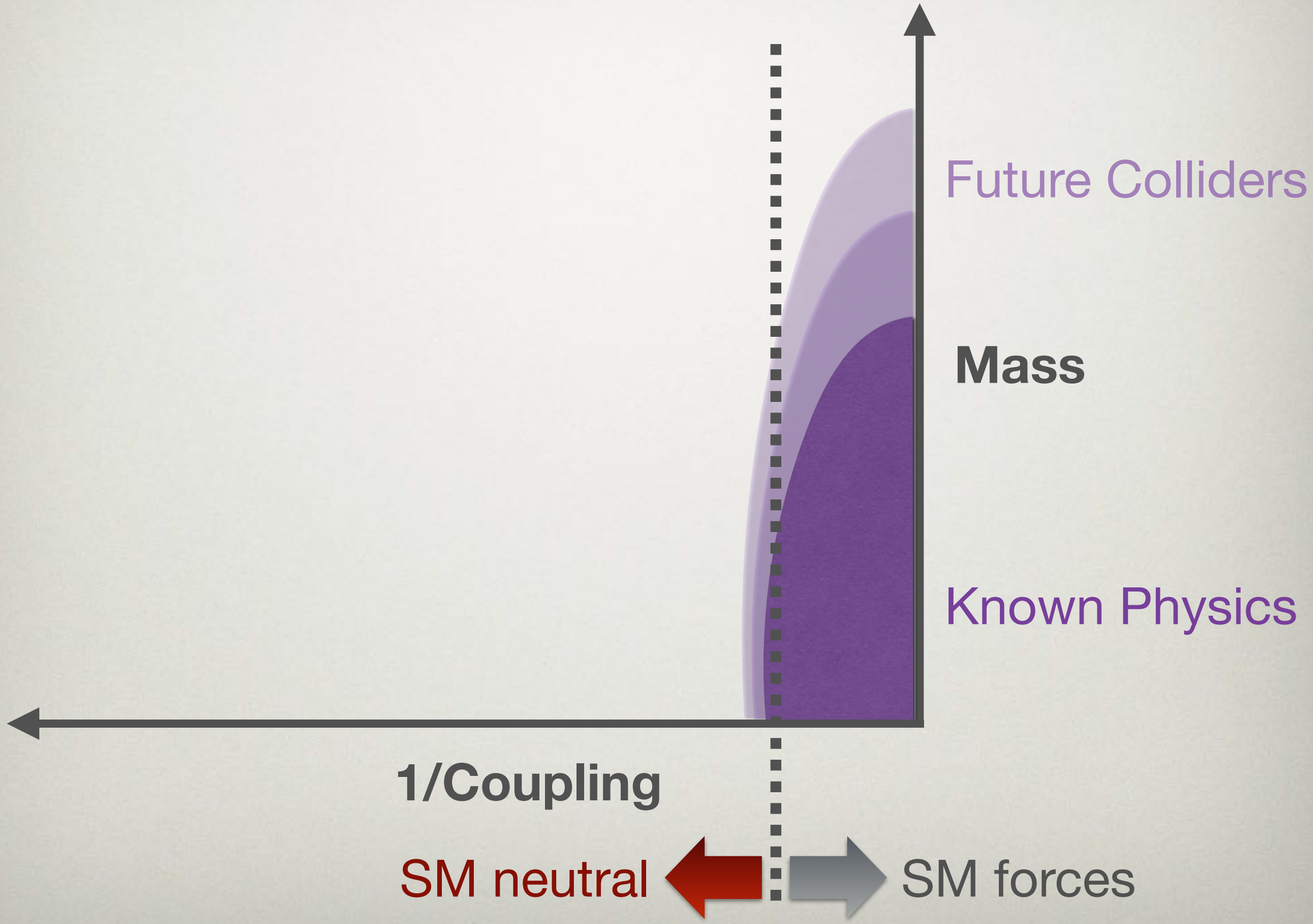

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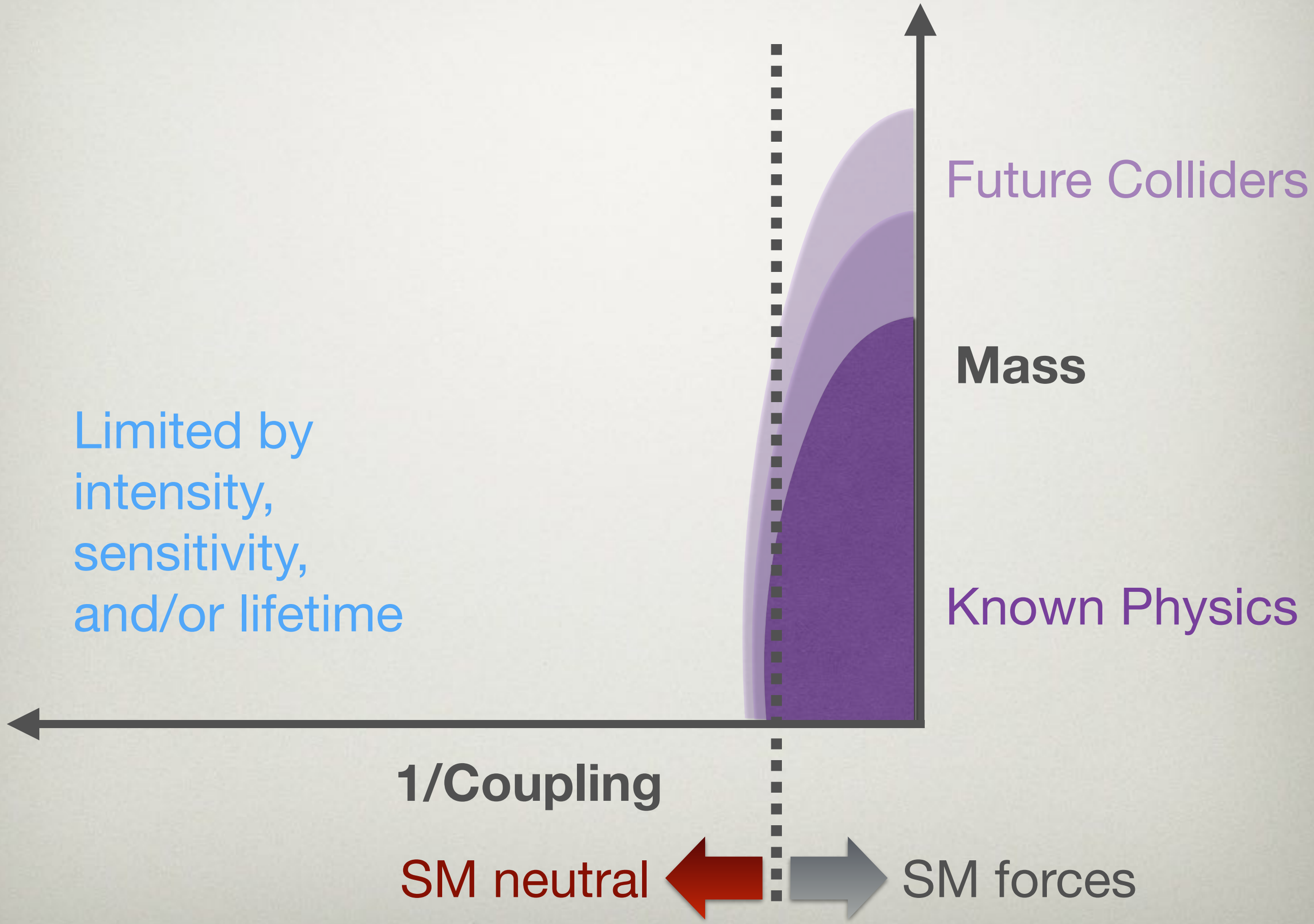

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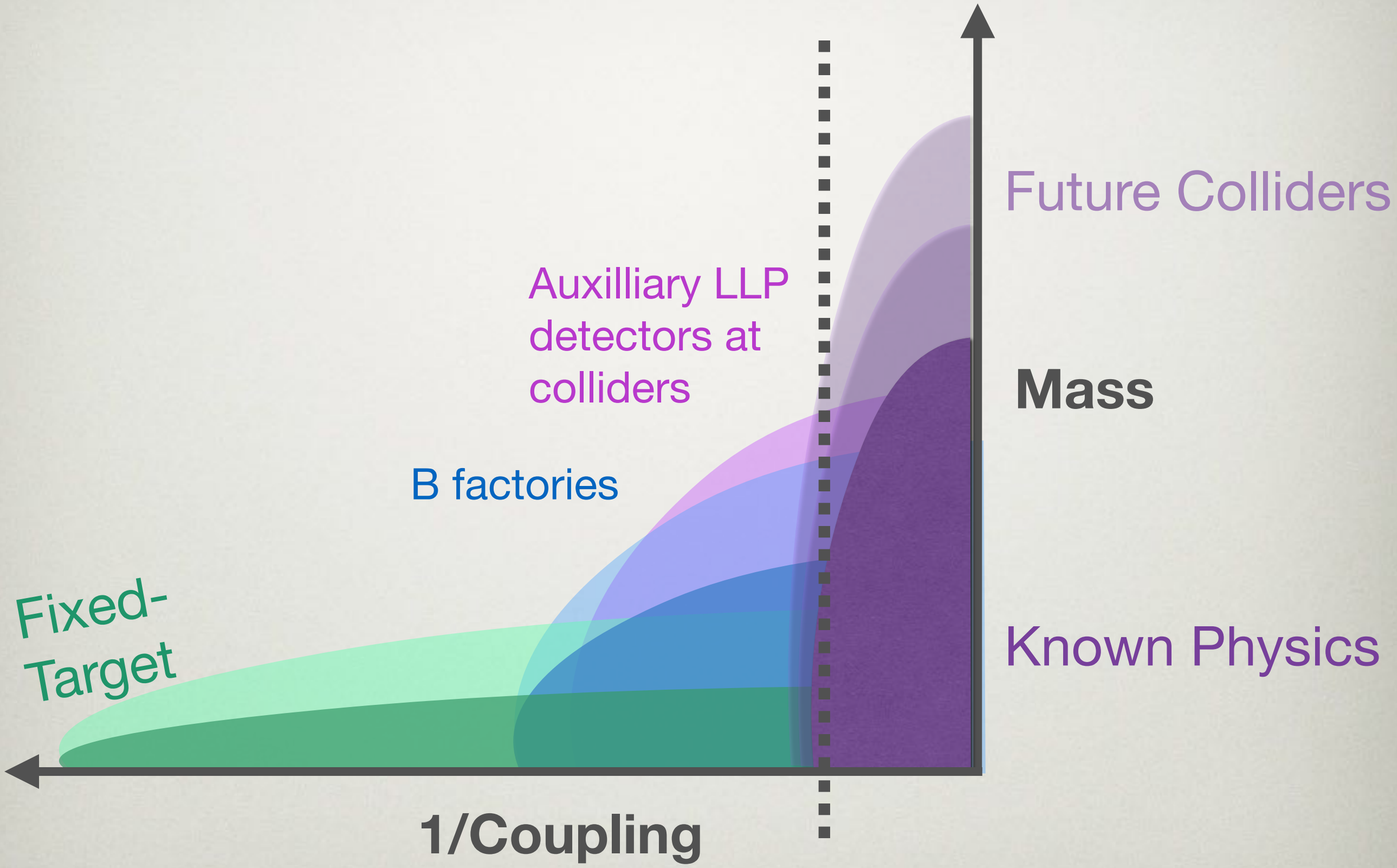
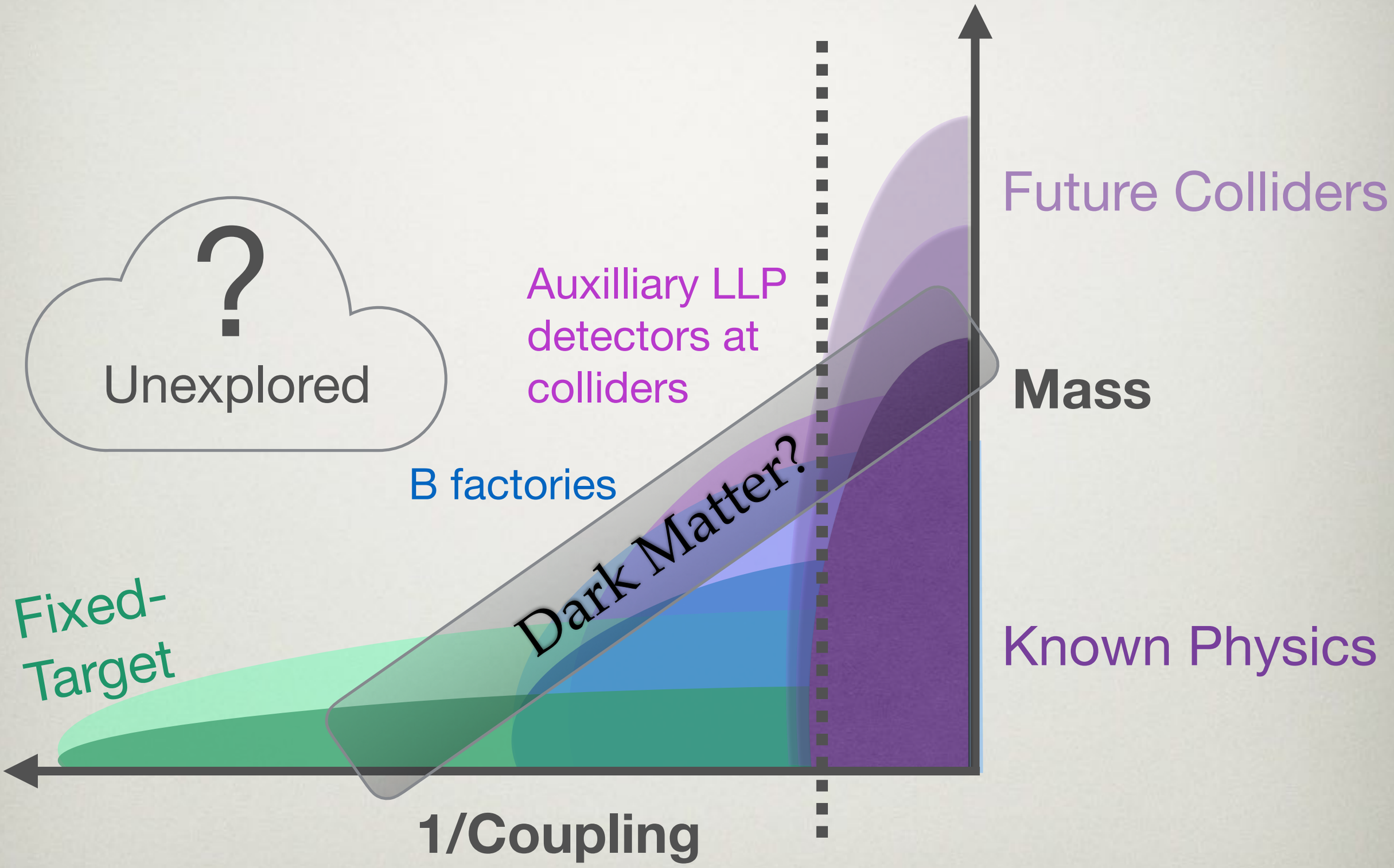


Need multiple experiments to explore this landscape broadly!

New Physics at Low Mass Scales?



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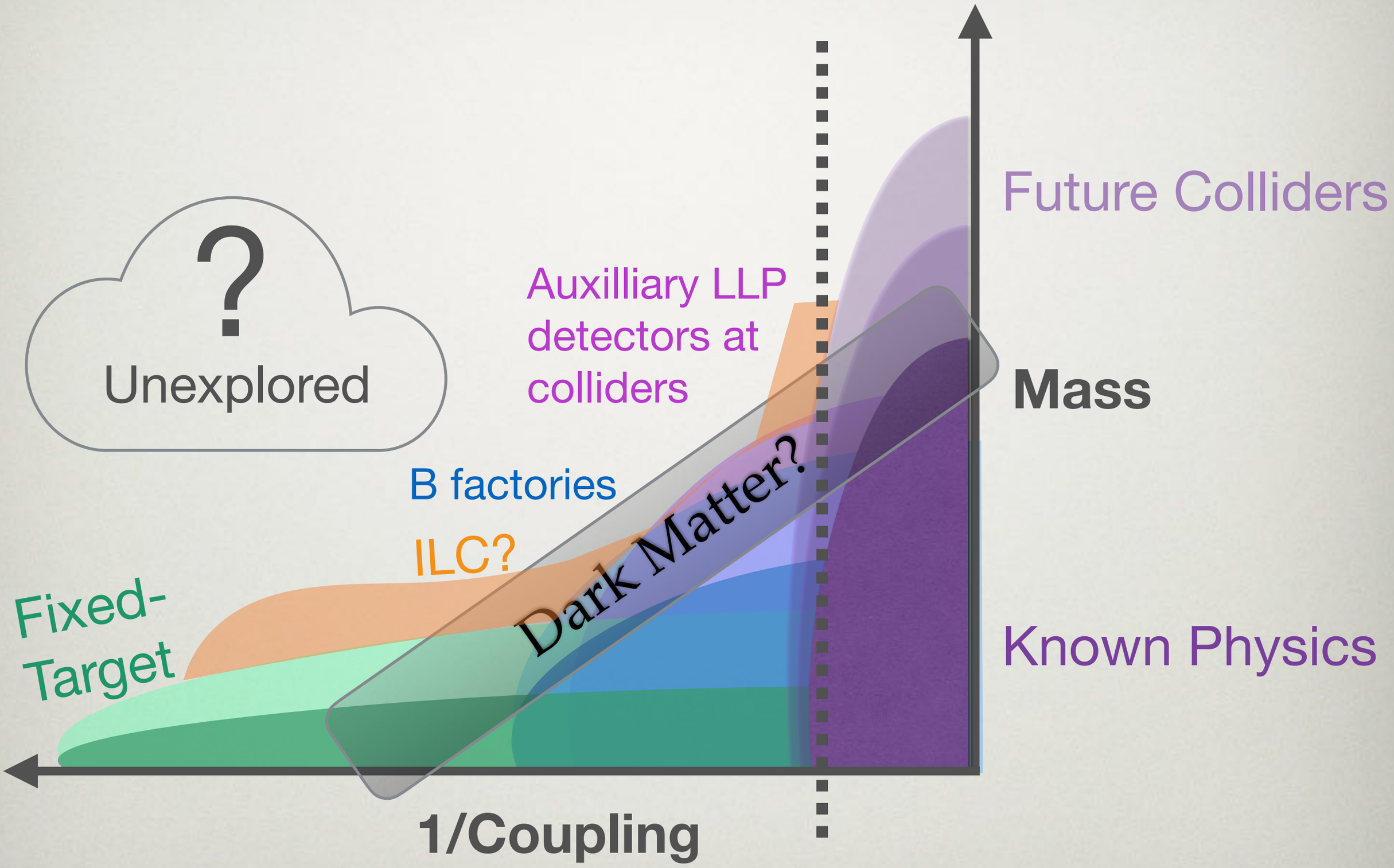


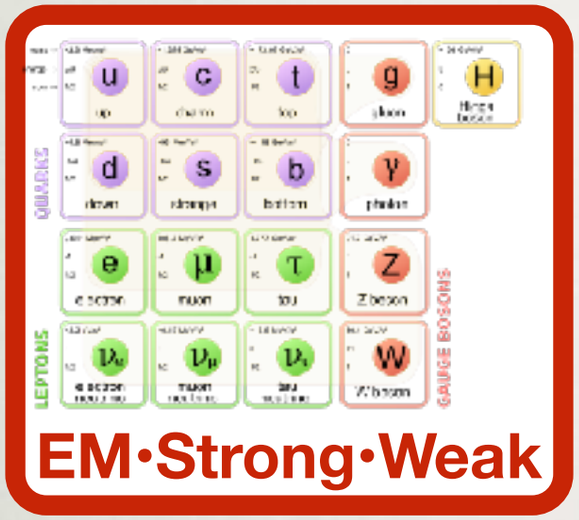
Need multiple experiments to explore this landscape broadly!

Outline

- ✦ Theoretical Ingredients
  - Portals to a Dark Sector
  - Thermal Dark Matter and other Milestones
  - Navigating the dark sector landscape
- ✦ Search Prospects at Existing Facilities
  - Dark Matter and Millicharge Production
  - Visible Decay searches for New Forces and Dark Sectors

Dark Sector Picture

Standard Model



Portal

Dark Sector

DM?
Other new particles?

- Interactions restricted by symmetries
  - Lorentz, SM gauge, dark sector gauge (if any)

- Interactions involving many fields/derivatives are suppressed by energy scale at which they originate → **Simplest symmetry-allowed interactions prevail at low energy**

The Portals

Interactions with **dimensionless** couplings dominate at low energy

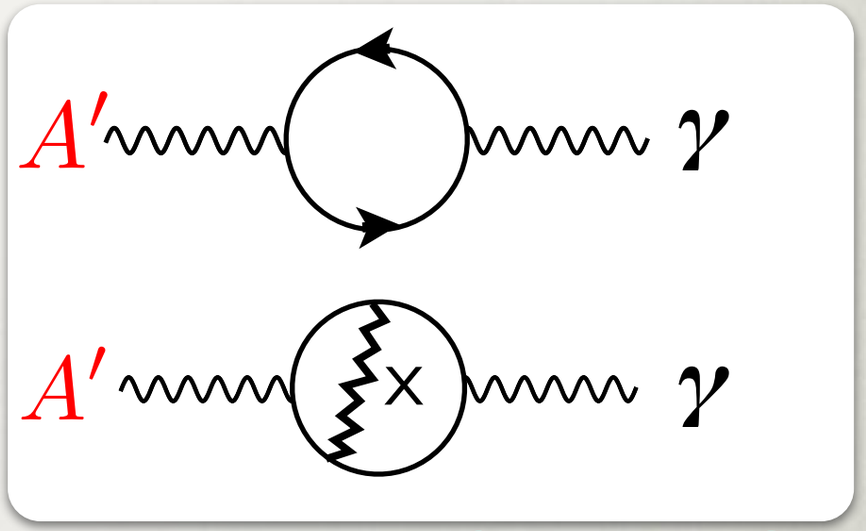
Vector Portal	$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$
Higgs portal[1]	$\epsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$
Higgs portal[singlet]	$A_h \lvert h\rvert^2 \phi$
Neutrino Portal	$\epsilon_\nu (hL)\psi$
Conserved currents	$\epsilon_V \bar{f}\gamma^\mu q_f f V_\mu$

Great working example: Compatible with cosmology in simple models, illustrative – focus here for most of my talk

How weakly Coupled?

Small couplings are **generic** if portal interactions generated radiatively

- Some portal interactions are further suppressed by small Yukawas

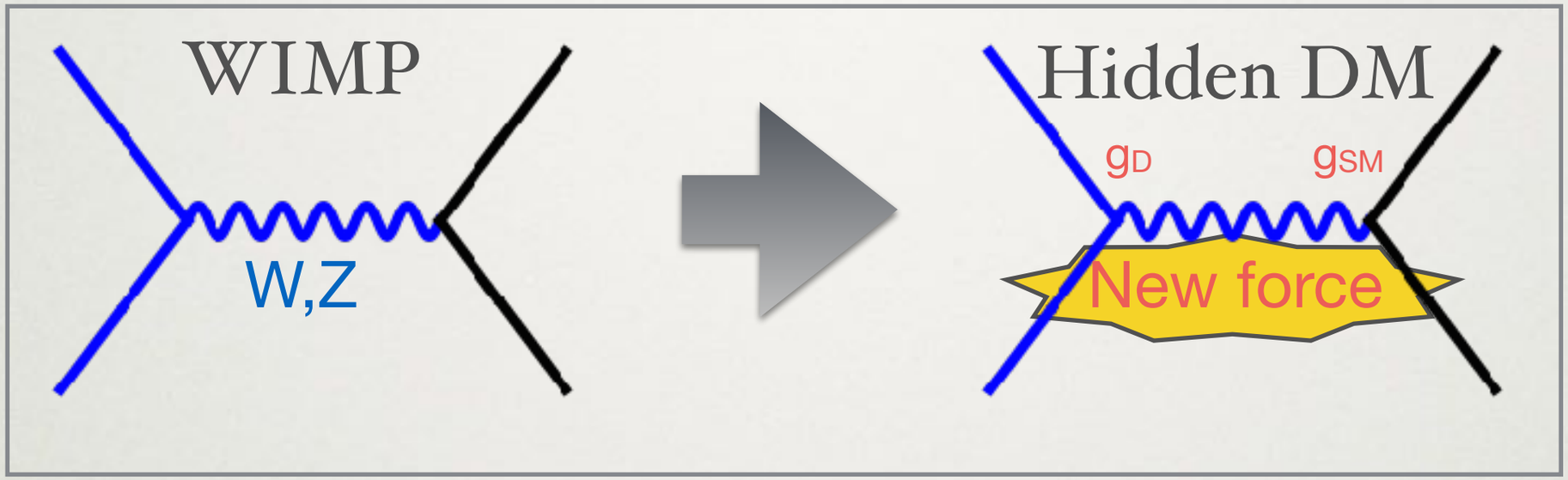


$$g_{\rm SM} \sim (10^{-6} - 10^{-2})e$$

Small couplings can motivate small masses, naturally (analogous to $\mathbf{m_{proton}}$, $\mathbf{m_{electron}} \ll \mathbf{m_{Weak}}$ in Standard Model)

A Small Step: Hidden Sector DM

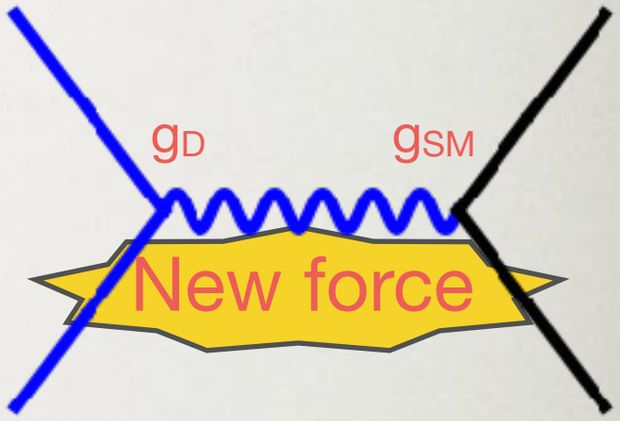
Dark Matter interacts with us through new portal force



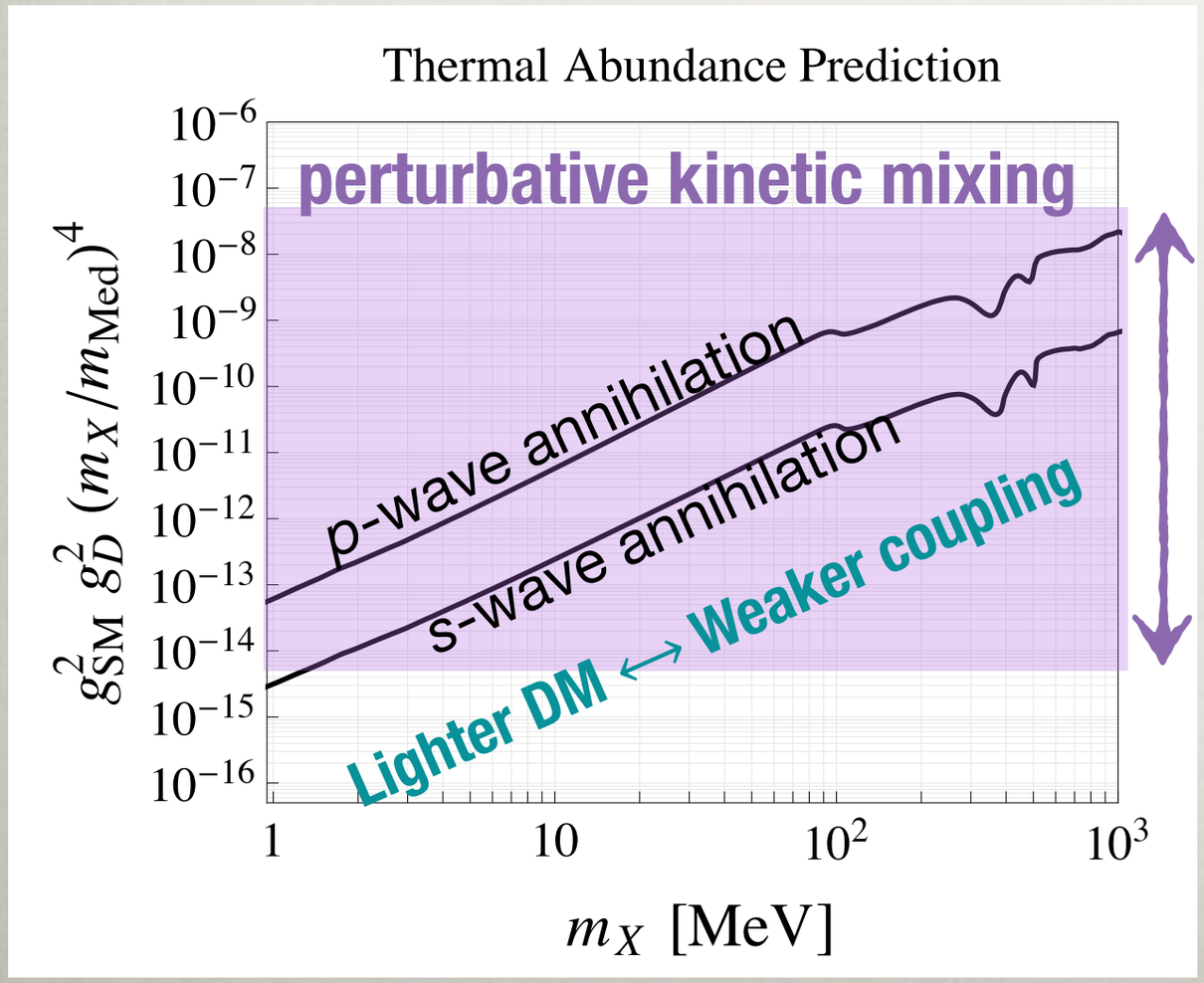
- ☑ Stable: Dark matter can be stabilized by new charge
- ☑ Dark: SM-neutral, interacts only through portal forces
- ☑ Abundance: Can arise from thermal freeze-out via portal force

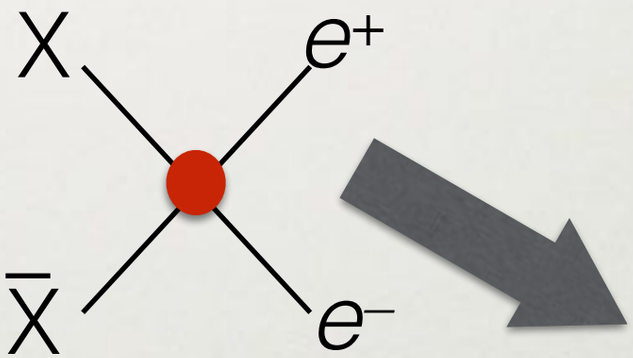
The WIMP-iest Hidden Sector Dark Matter

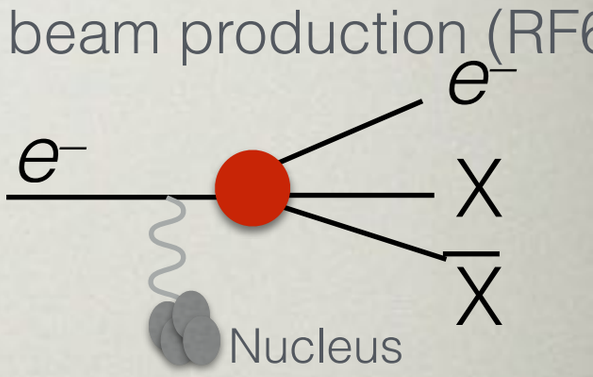
DM abundance ⇒ predicted strength of interaction



Low mass ⇒ annihilation lighter particles (*e*, in some models ν, γ)







⇒ Predicted rates for observables today

A Modest Extension

Dark sector ⇒ other light states. Multiple coupled Boltzmann equations can be relevant. e.g.

Secluded DM

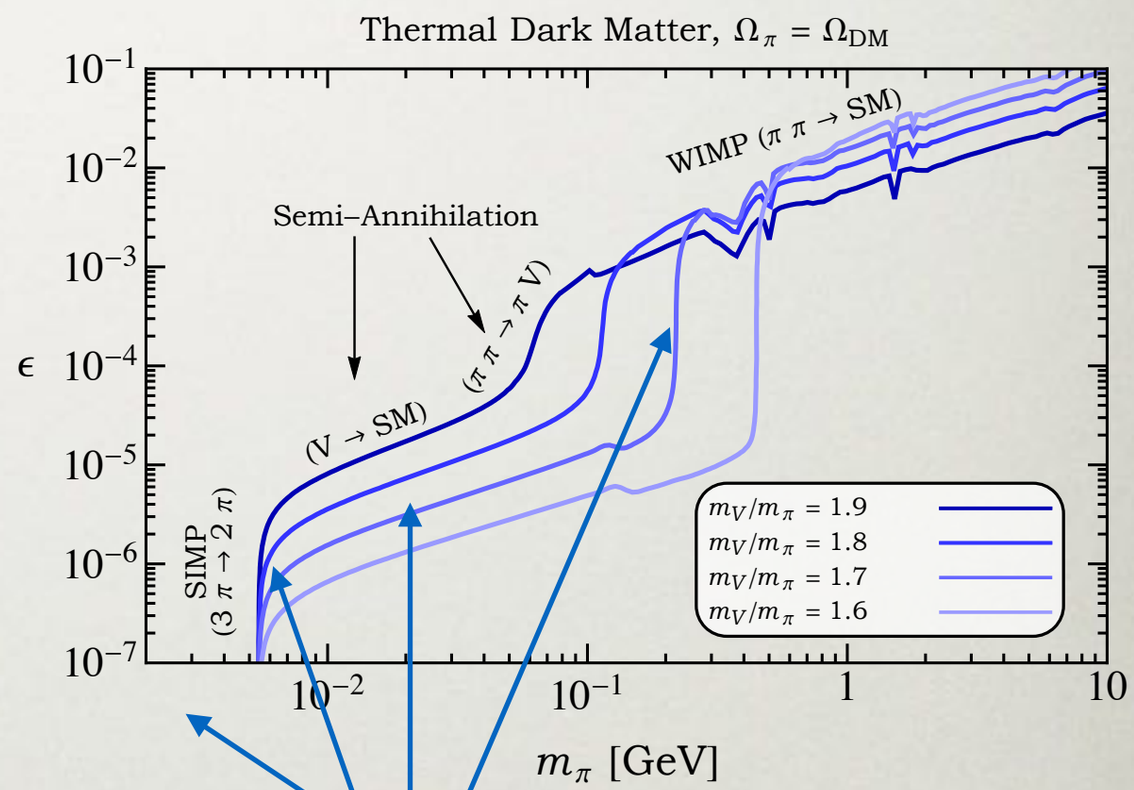
Annihilation
DM↔ϕ

Decay
ϕ↔SM

Decays maintain equilibrium with SM (allows a range of weaker couplings)

Strongly Interacting DM

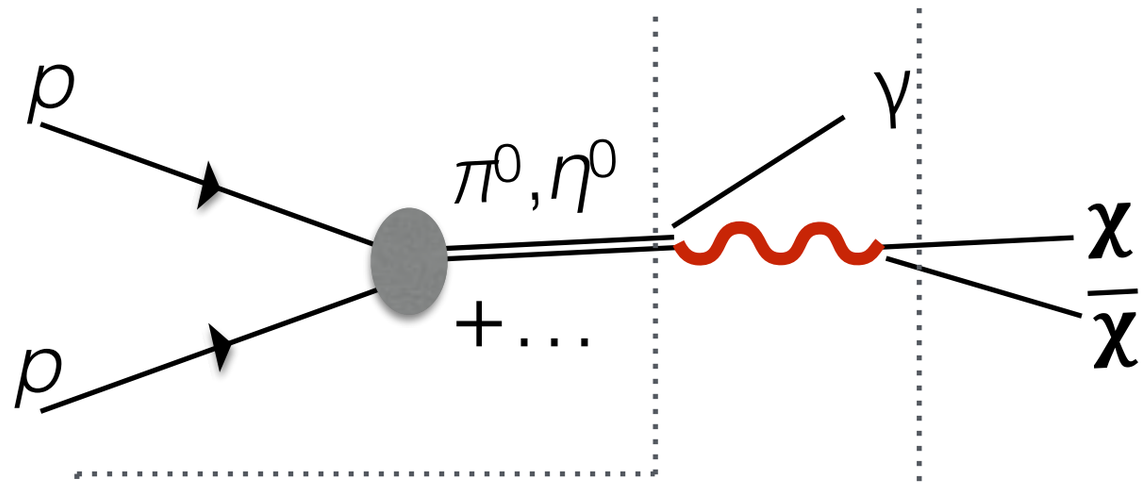
DM="pion" of confined dark sector.



4 new domains where different reactions control abundance [ELDER not shown in plot]

+ (not)forbidden, co-scattering, KINDER, …

Many Faces of Dark Sectors



People & facilities naturally organize by **initial-state**…

- e^+e^- collider/FT
- pp collider/FT
- e^-N FT

x Theories naturally organize by **intermediate-state** "portals"

x Scientific impact closely aligned with whether **final-state** is SM, non-SM, or mixed

All three axes are important, both in mapping the physics and understanding detector design and capabilities.

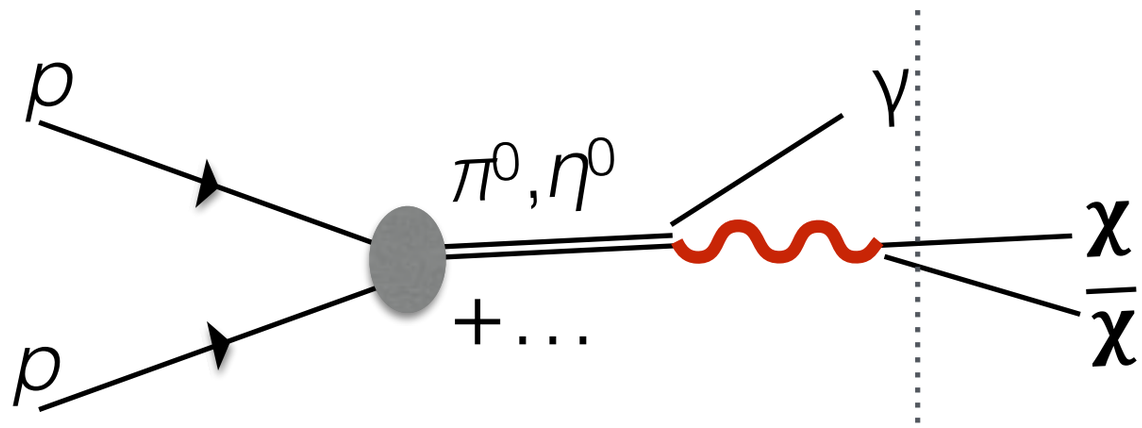
Dark Sectors Are Everywhere

[table is assuredly incomplete]

	e/μ missing energy/ momentum	e± thin target	e±/μ beam dump	p far beam dump (incl. NF)	p near beam dump	Kaon factories	e+e− collider	EF Multi-Purpose Experiments	EF Dedicated Experiments
	NA64, LDMX, M3	HPS, APEX, DarkLight, PADME, μ3e, MAMI, MAGIX, JLab, MMAPS	BDX, BDX-DRIFT, DarkMESA, *E137*	Fermini, SUBMET, MiniBooNE-DM, COHERENT, BNB, *LSND, DUNE*	Dark**Quest, SHIP, *CHARM...*	NA62, KOTO, KLEVER...	Belle II, BES-3, *BaBar, Belle*	ATLAS, CMS, LHCb	FASER, CODEX-b, milliQan, MATHUSLA
Low-Inv-Mass Dark Matter Production	✔		✔	✔		✔	✔		
Dark Photons and other Vectors→SM	✔	✔	✔		✔	✔	✔	✔	✔
Millicharges	✔		✔	✔	✔	✔	✔	✔	✔
Dark Scalars		✔			✔	✔	✔	✔	✔
ALPs		✔			✔	✔	✔	✔	✔
Neutral Heavy Leptons				✔	✔	✔		✔	✔
Semi-Visible & Cascades	✔	✔	✔	✔	✔	✔	✔	✔	✔

I will try to give a sampling of the field, but can't cover everything (biased towards e± beams).

The Final-State Axis



"Once you get in to the dark sector, what do you look for?"

non-SM

Dark Matter Production

Producing stable particles that could be (all or part of) the Dark Matter

SM

Portal-Mediator Decays to SM

Systematically explore the minimal couplings of SM to dark sectors

mixed

Structure of the Dark Sector

There could be a rich sector of new physics under our noses

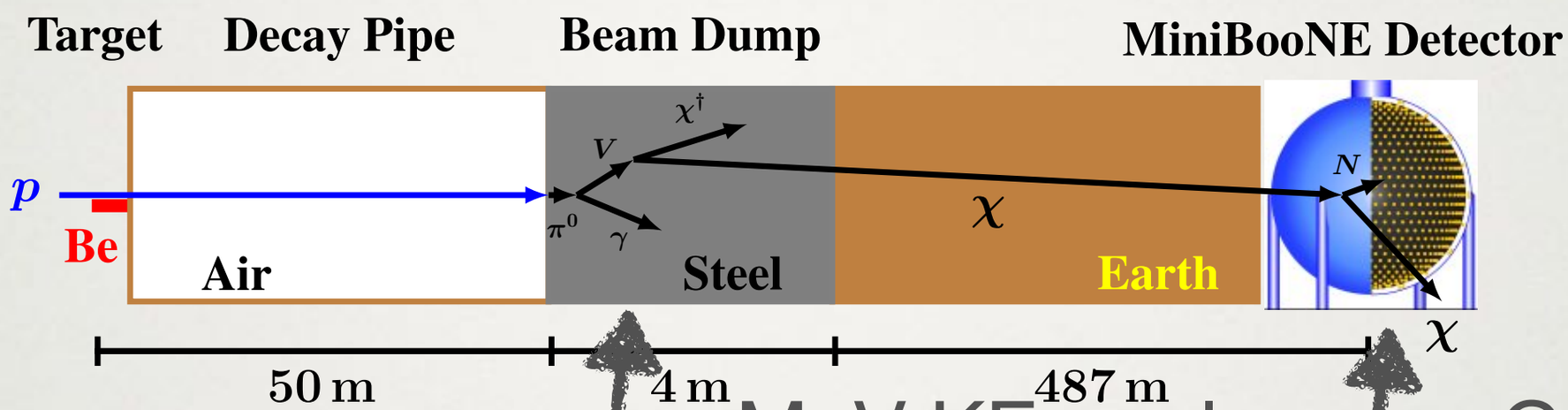
These 3 possibilities are well aligned with what makes dark sectors viscerally exciting!

Dark Matter Production

Overviews of planned and proposed experiments can be found in
US Cosmic Visions Dark Matter report (US-focused)
CERN Physics Beyond Colliders report (EU-focused)

I will not try to be exhaustive but survey some of the broad ideas

Dark Matter from Beam Dumps

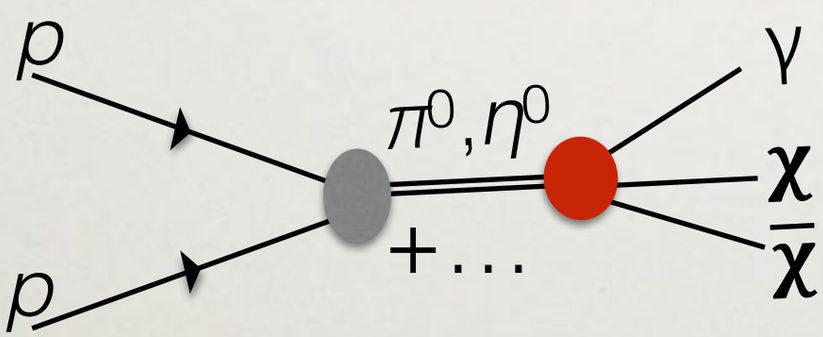


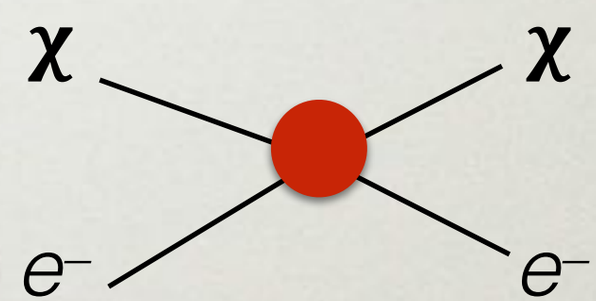
arXiv:1807.06137

~MeV KE nucleons, ~GeV electr

Produce dark matter in dump

Look for (relativistic) scatter in detector





Similar approach for millicharges (softer recoil spectrum)

Powerful constraints already from LSND, E137, MiniBooNE

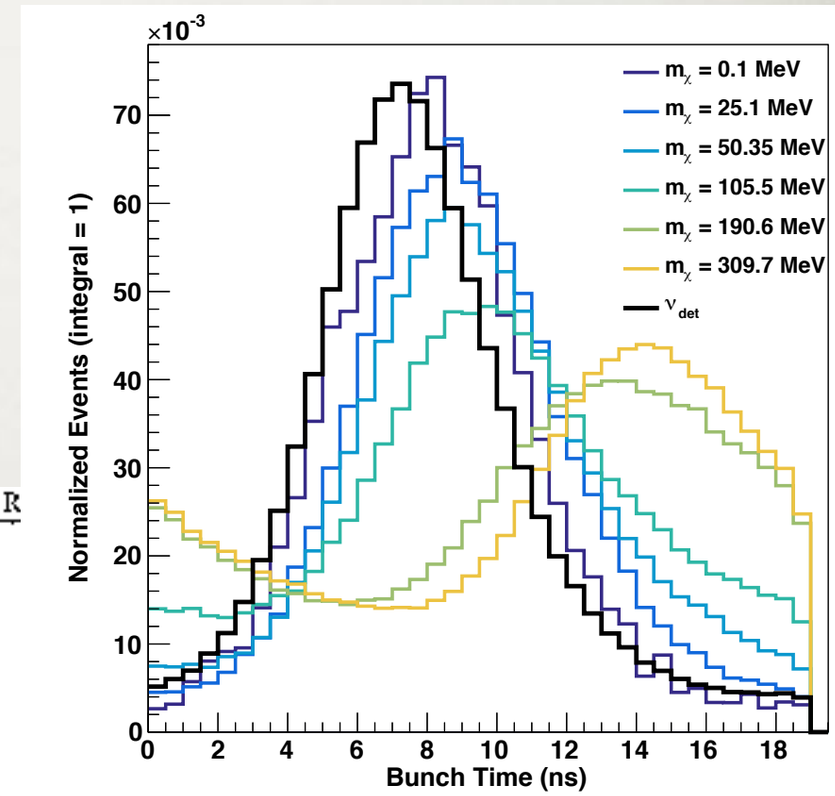
Experiment Design Factors

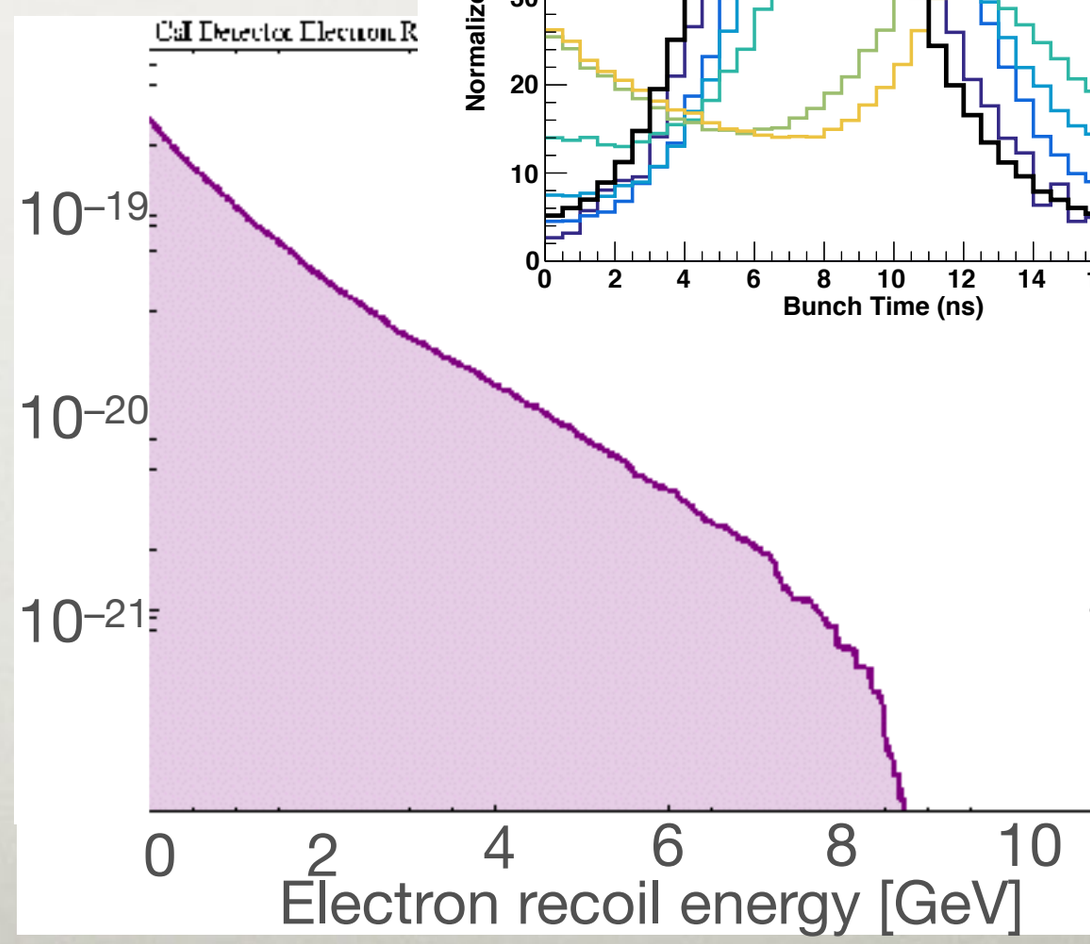
Benefits from highest possible luminosity!

Timing: DM mass → reduced velocity → increased TOF (MiniBooNE, ~500 m baseline)

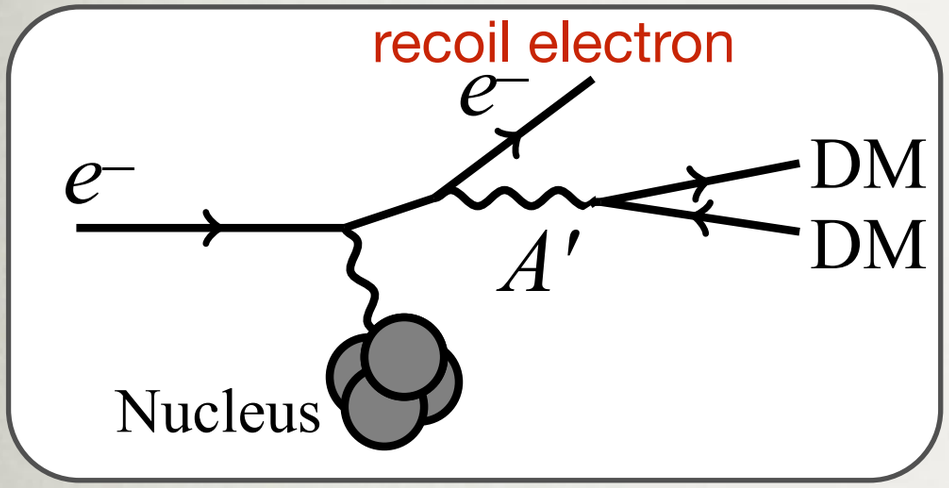
Benefits from low energy thresholds for detection of recoiling nucleons and/or electrons

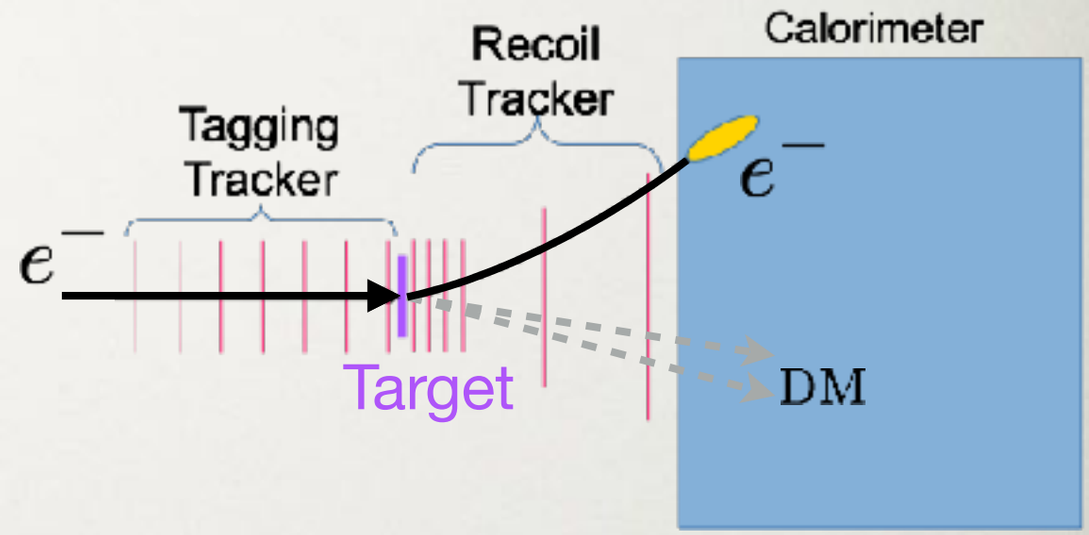
Flux ~1/(baseline)^2

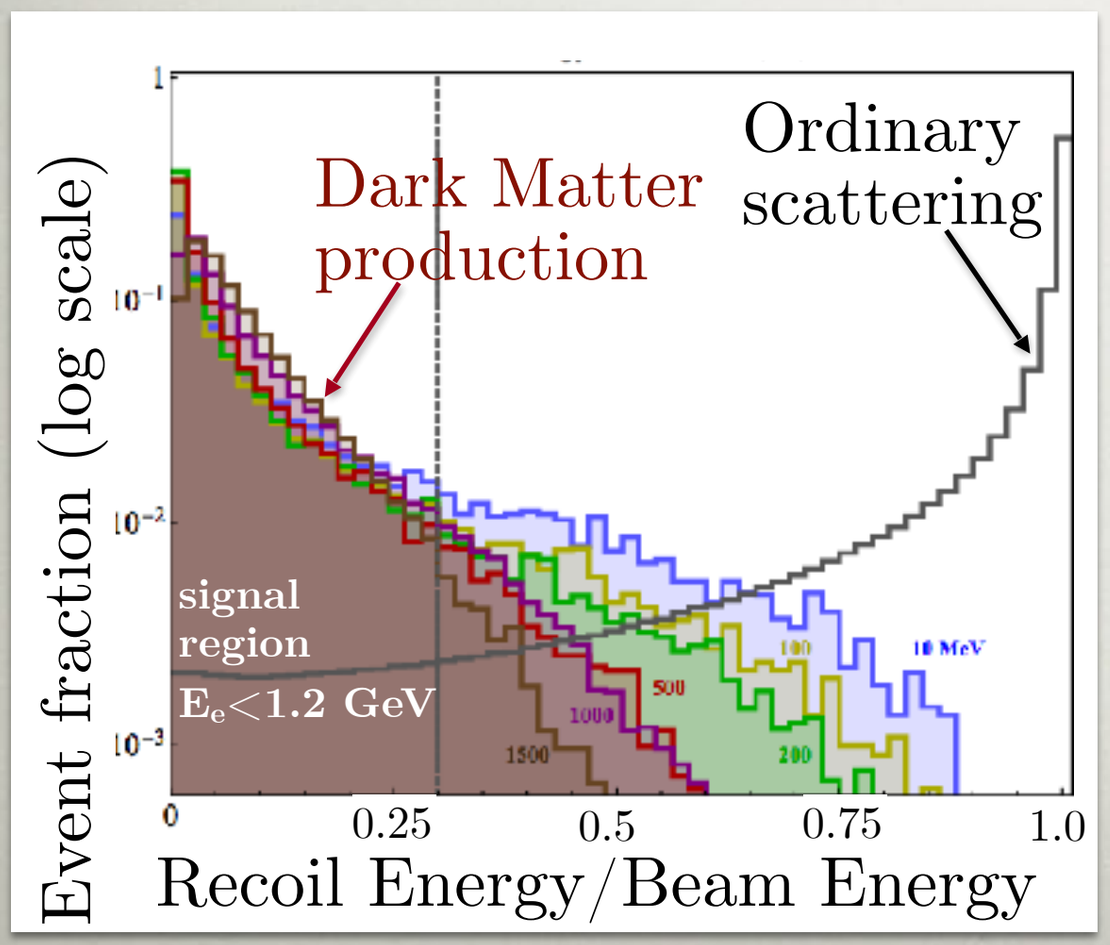




Kinematic ID of Dark Matter Production







DM production characterized by:

- Low ECal energy deposition
- No HCal energy deposition
- Sizable electron pT
- Only one EM shower matched to track
- No additional ECal features

Missing Energy (NA64)

Missing Momen-tum (LDMX)

Experiment Design Factors

Only feasible with 1-to-few electrons at a time.

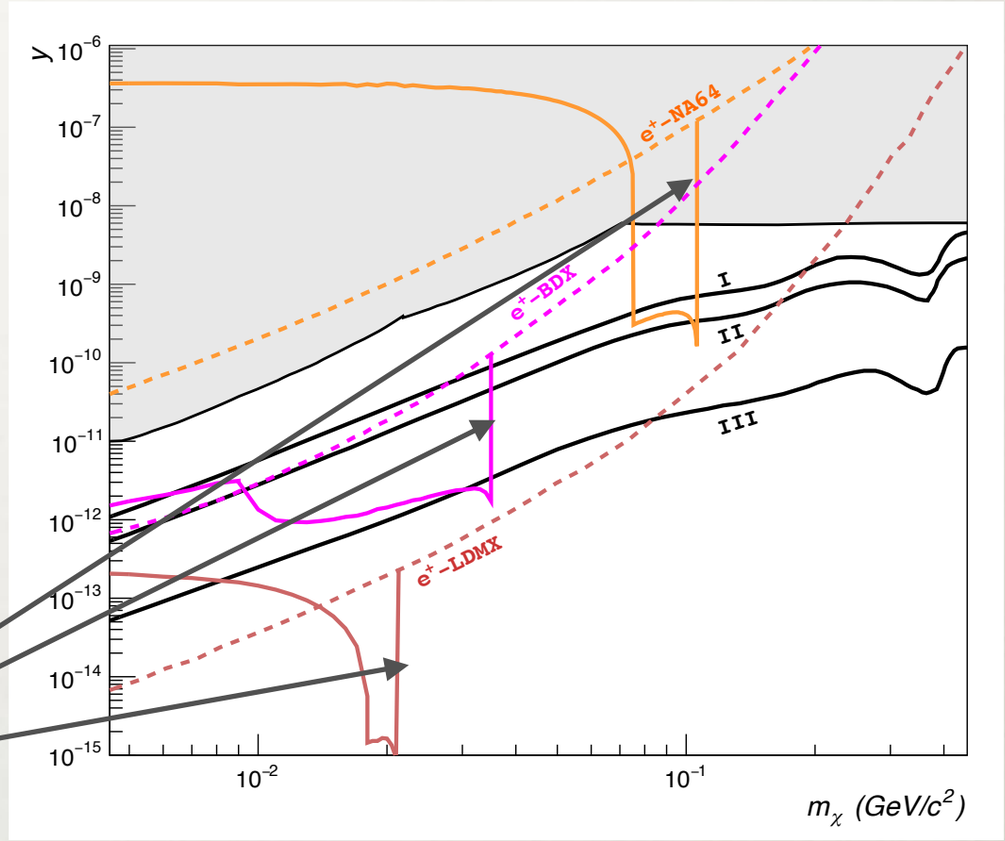
Competitive sensitivity requires $\gtrsim 10^{14}$ electrons

Rate limited by beam repetition rate and duty factor, as well as detector response time and radiation tolerance.

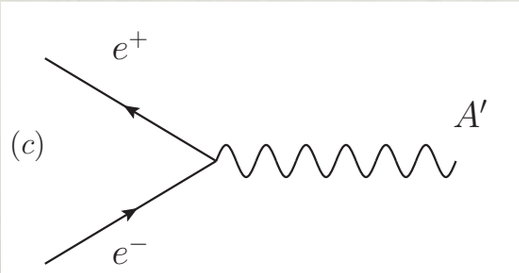
Impact of Beam Energy

Generally, these experiments rely on dark-photon bremsstrahlung

→ yield improves modestly at high energies (at least in mass range where the experiments do well)

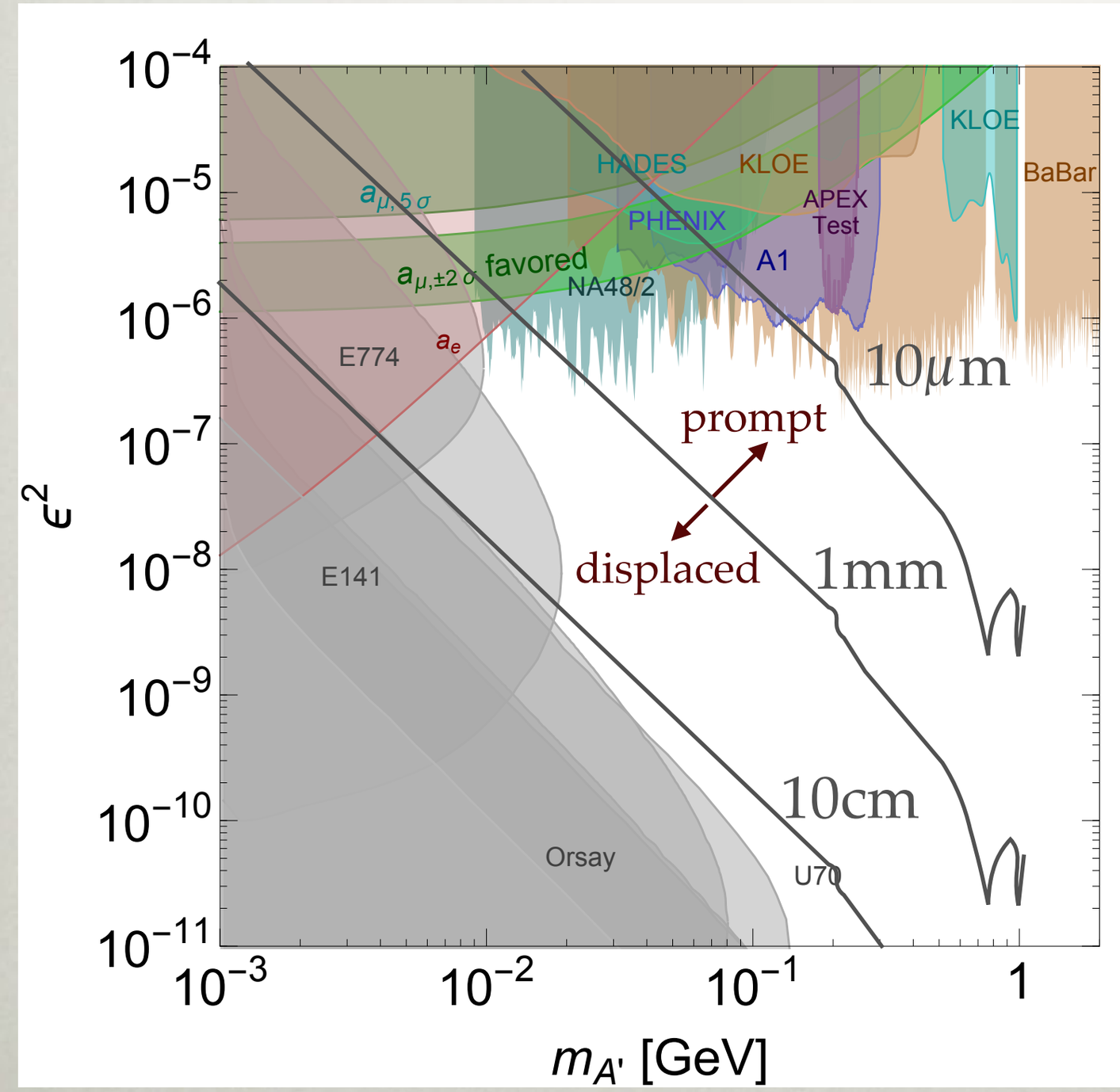


Interesting exception: Resonant positron annihilation on atomic electrons



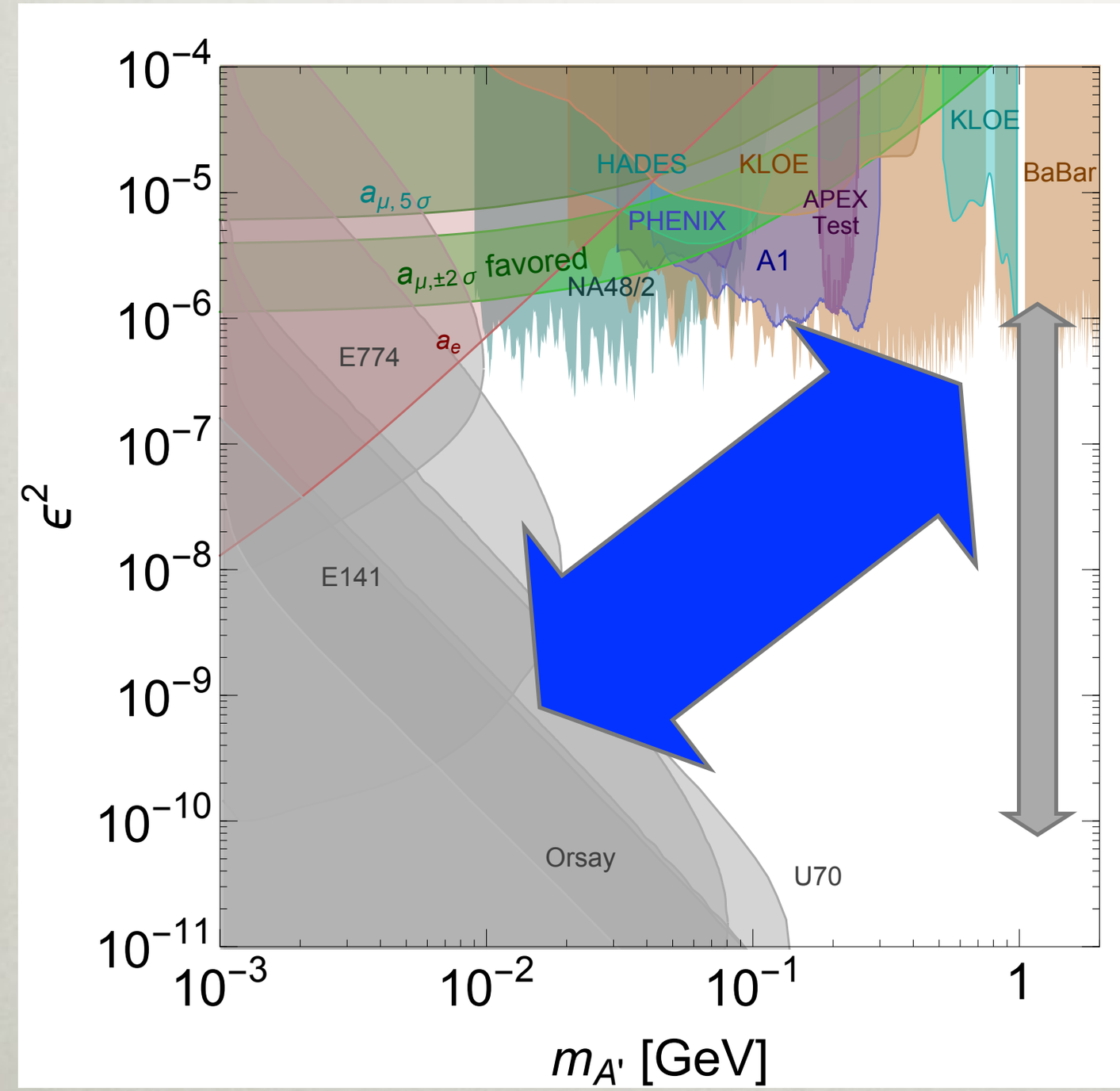
Potentially very well-suited to ILC?

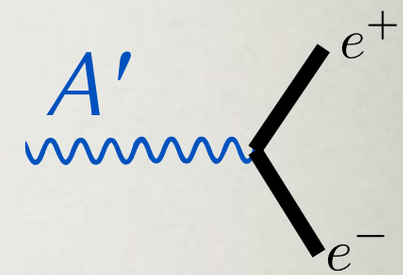
Visible Decays of Portal Mediatorss



Natural parameter space has wide range of production rates & lifetimes

Visible "Dark Photons"



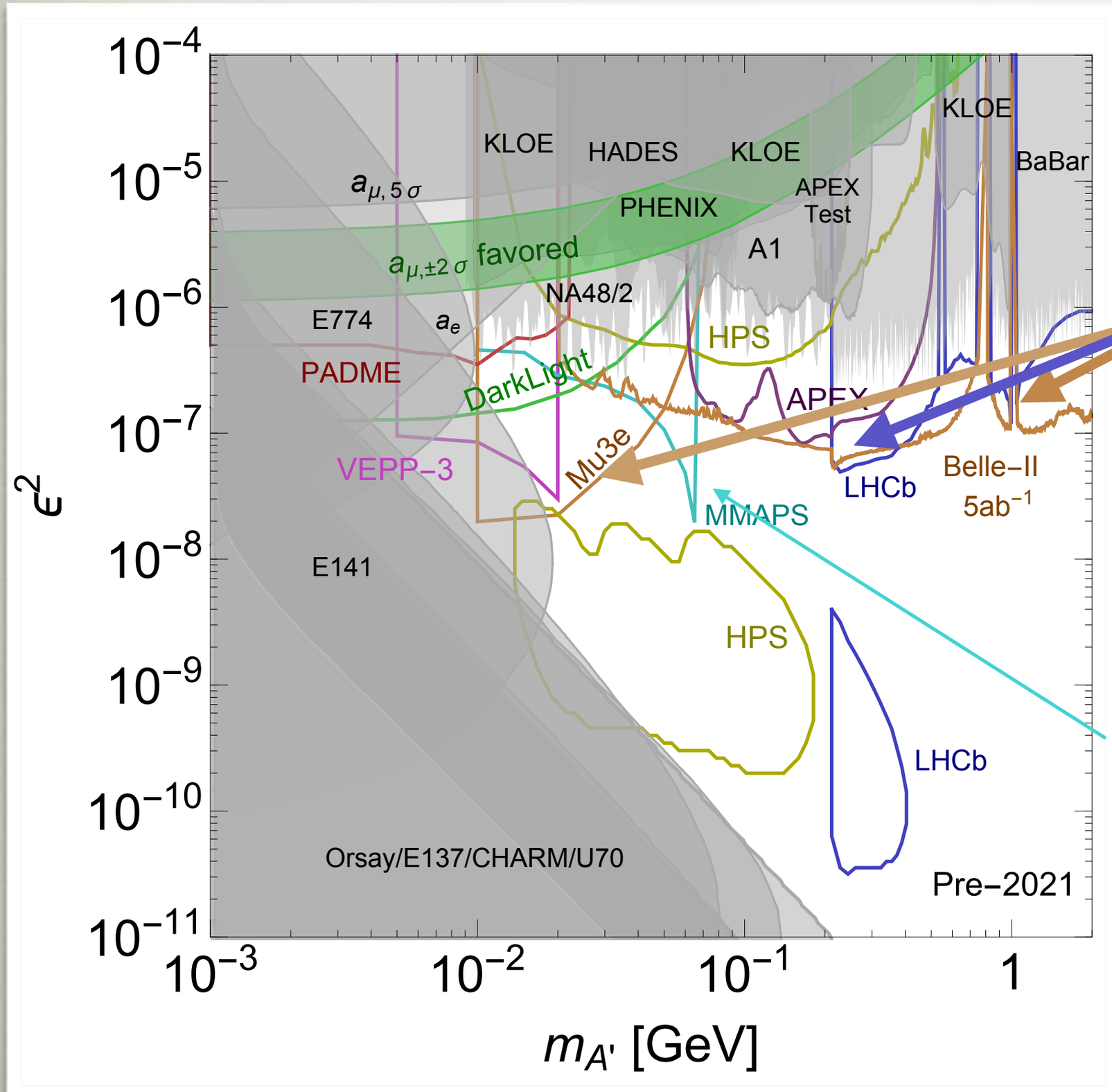


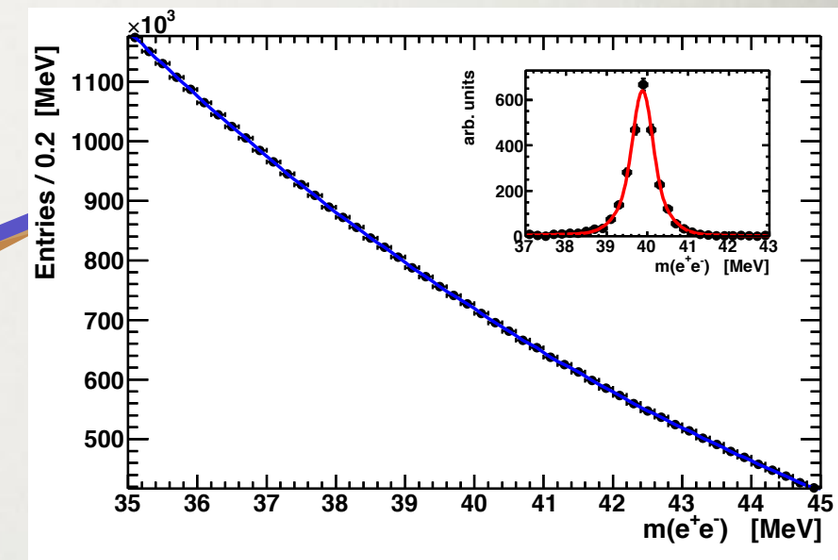
Mixing in Grand Unified Theories

sub-GeV mass scale compatible with radiative Higgs mixing or hidden valley

Small Bumps

Look for tiny resonance on very high-statistics background

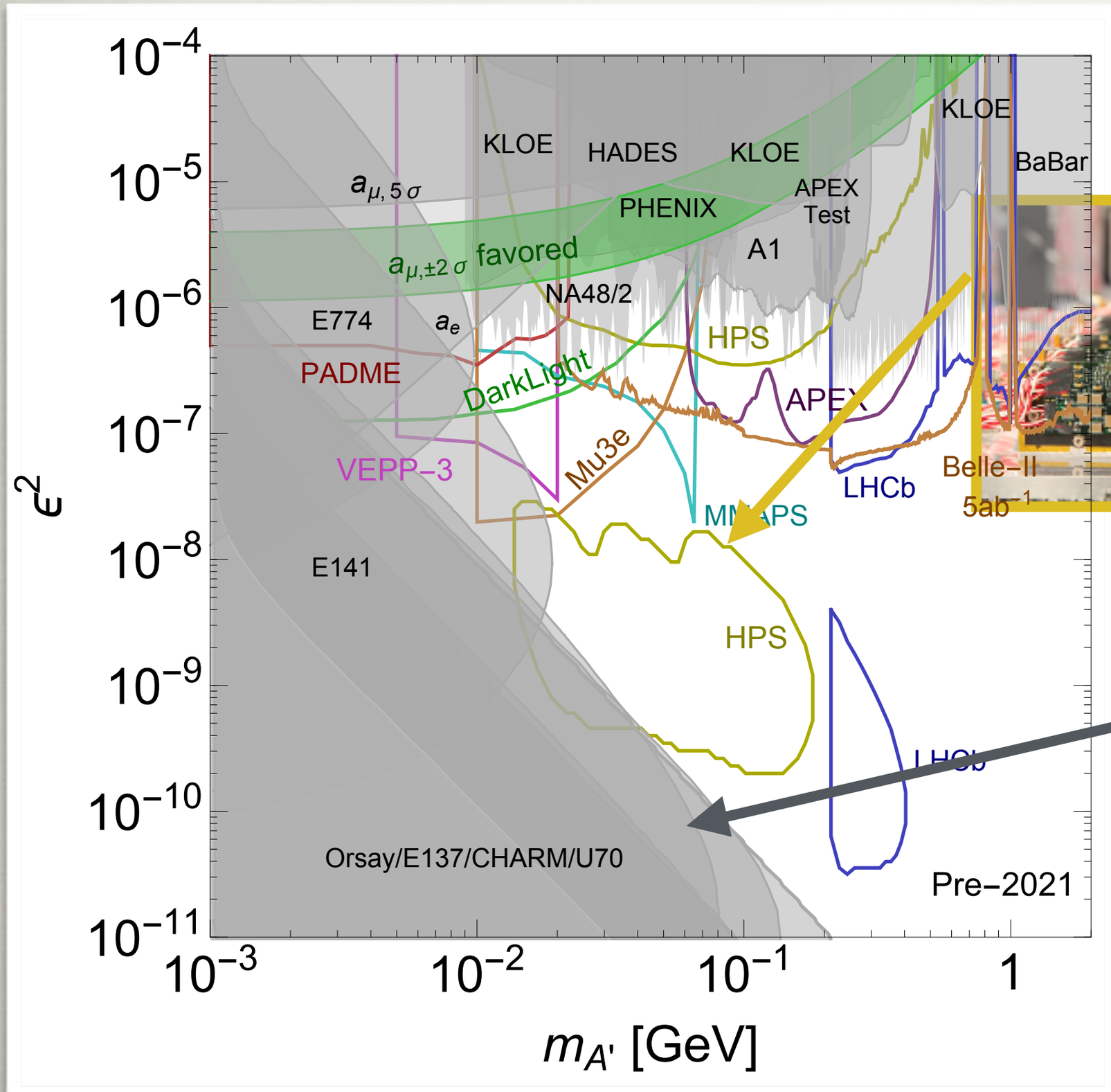




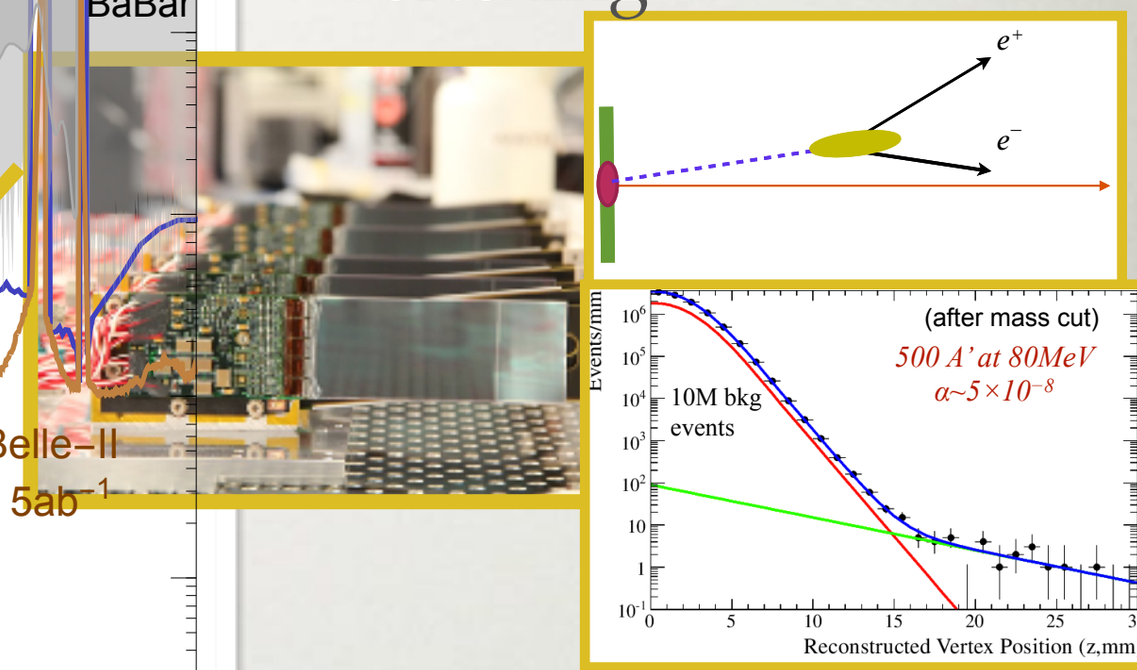
Echenard, Essig, Zhong 1411.1770

Positron annihilation
Potential improvement from ILC energies

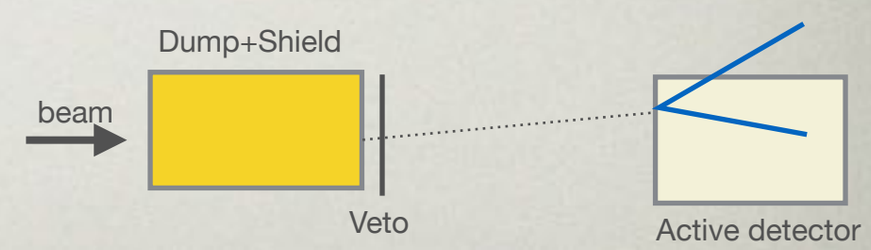
Displaced Decays



Vertexing

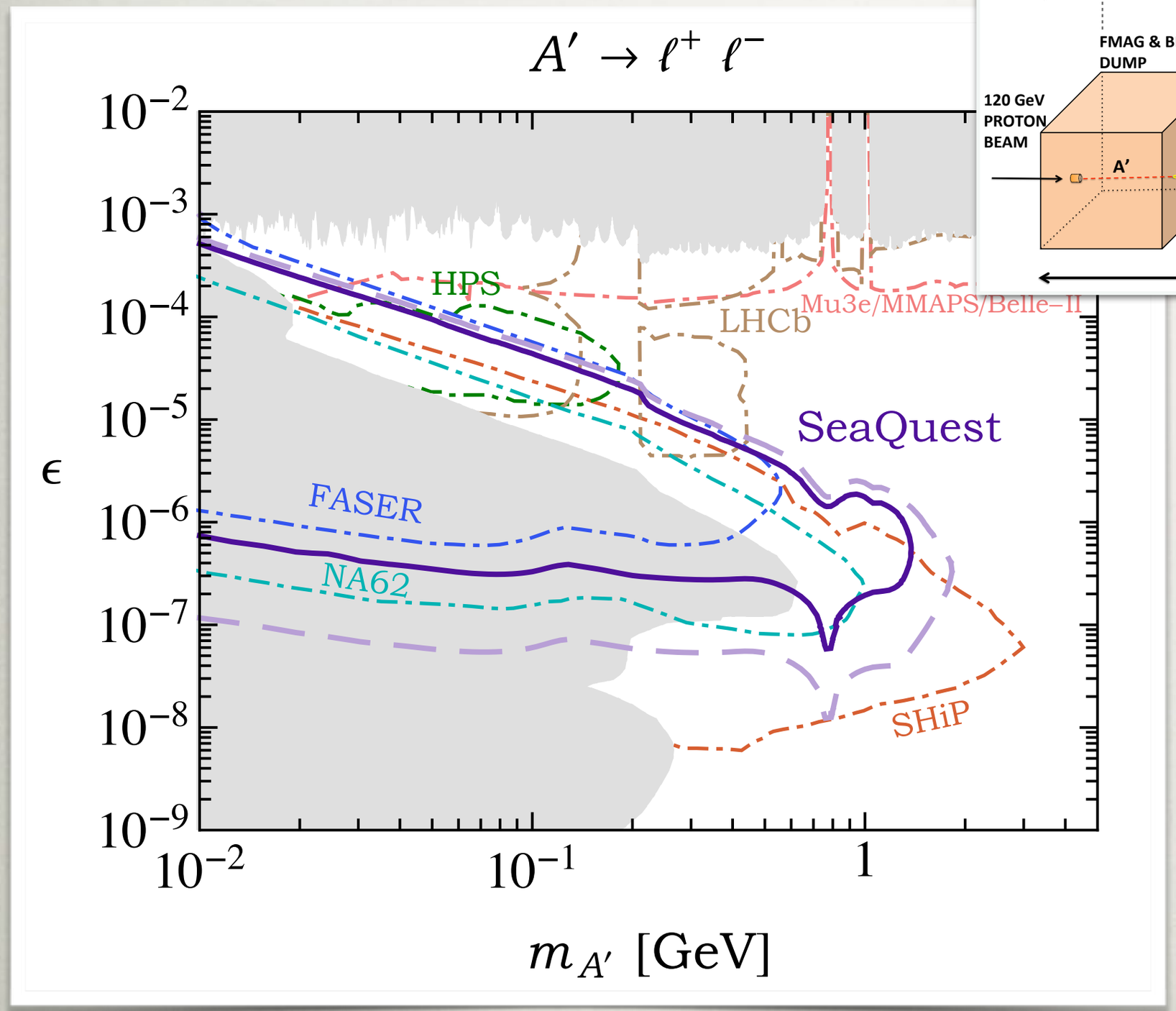


Decay search at Beam Dump

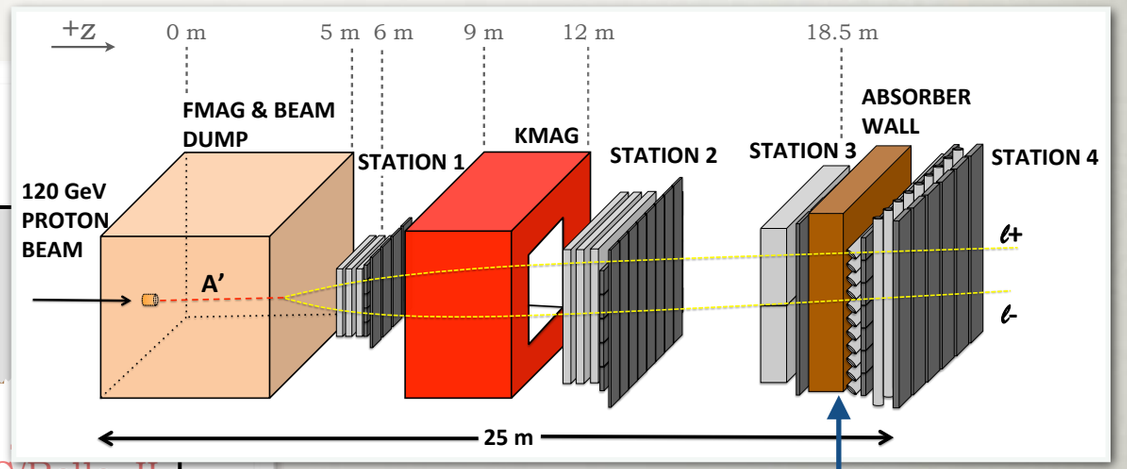


Vertexing Behind a Short Dump

10^{18-20} protons at 120 GeV



SeaQuest→DarkQuest



ECal goes here

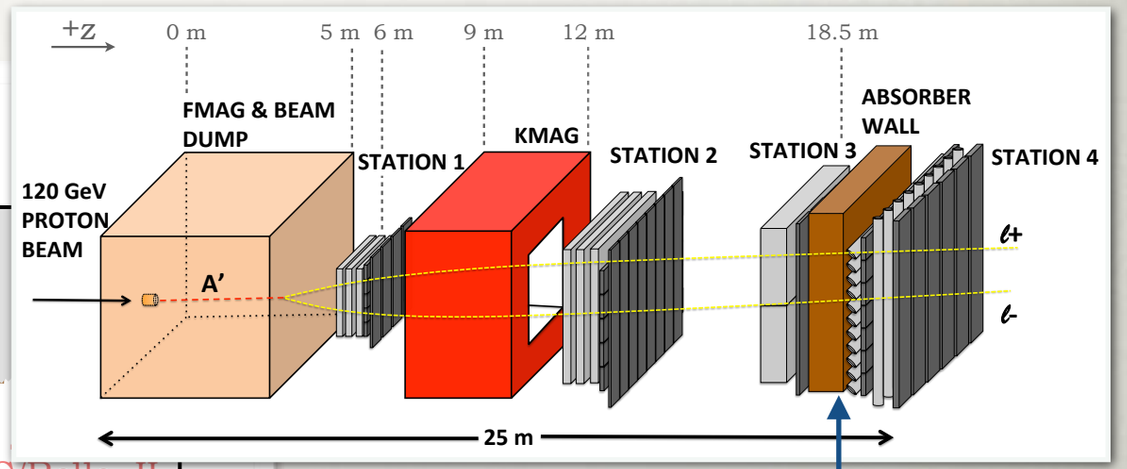
Further instrumentation upgrades possible.

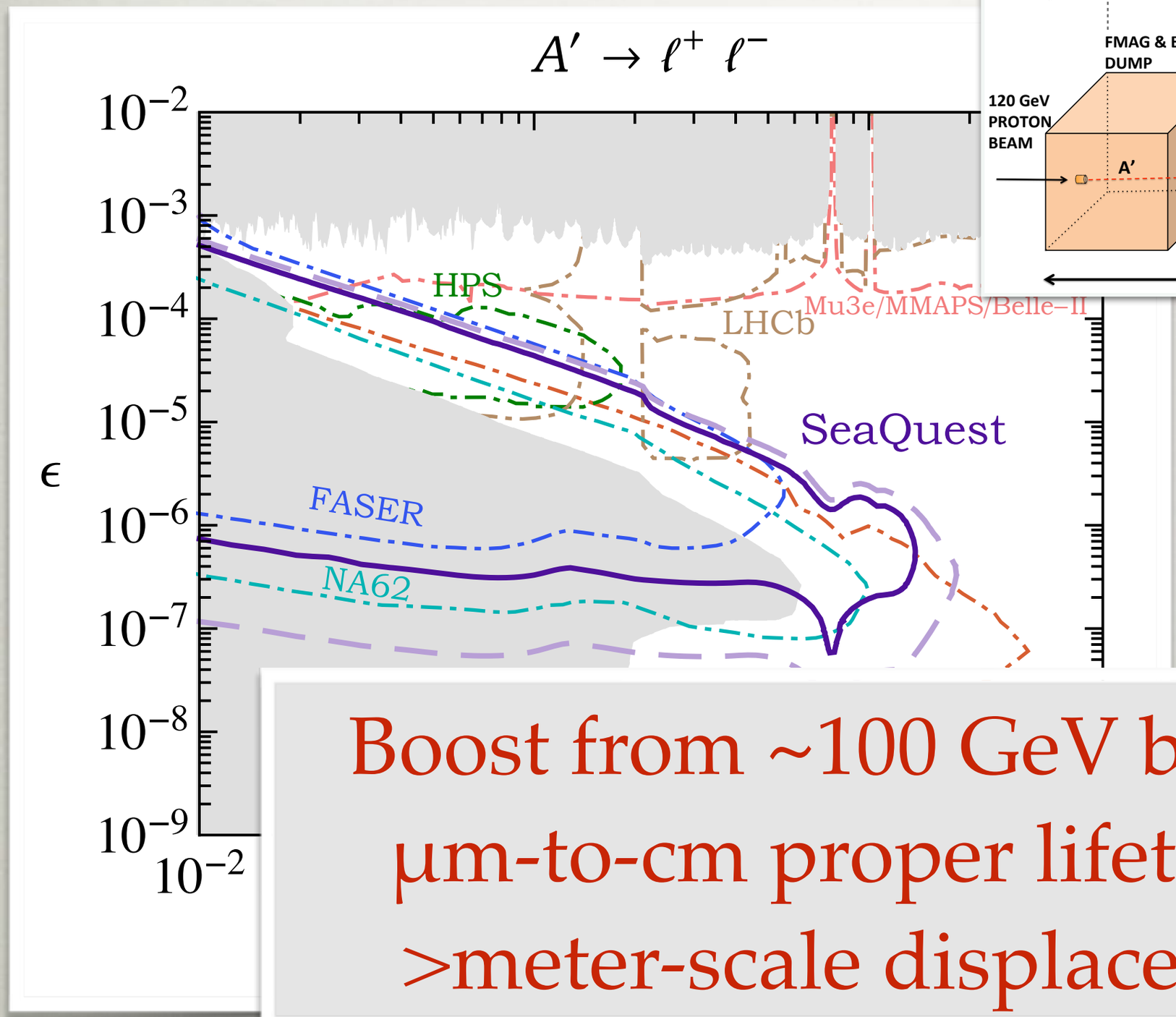
Berlin, Gori, Schuster, NT 1804.00661
building on Gardner, Holt, Tadepalli 1509.00050

Vertexing Behind a Short Dump

$10^{18\text{–}20}$ protons at 120 GeV

SeaQuest→DarkQuest





ECal goes here

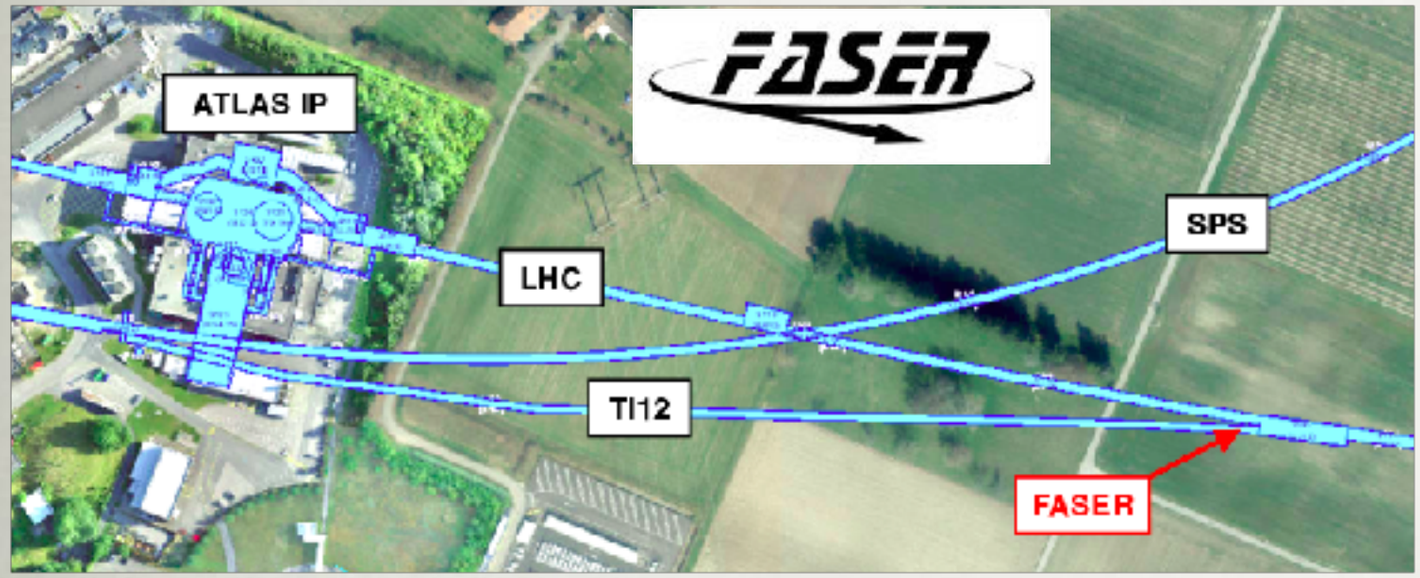
Further instrumentation upgrades possible.

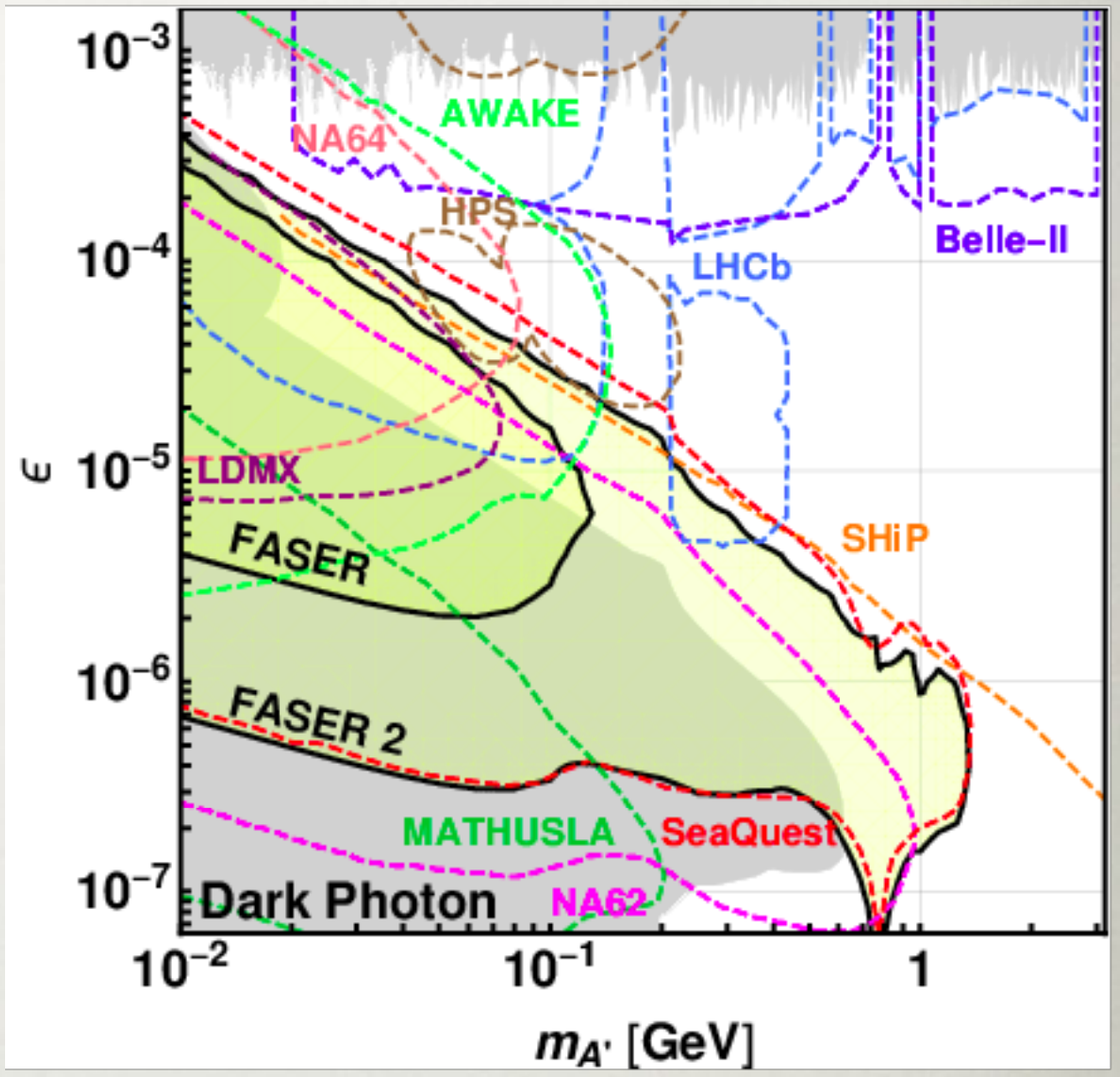
Boost from ~100 GeV beam turns μm-to-cm proper lifetimes into >meter-scale displaced decays

Berlin, Gori, Schuster, NT 1804.00661
building on Gardner, Holt, Tadepalli 1509.00050

Collider-auxiliary LLP detectors

Take advantage of boost and large interaction rates at LHC

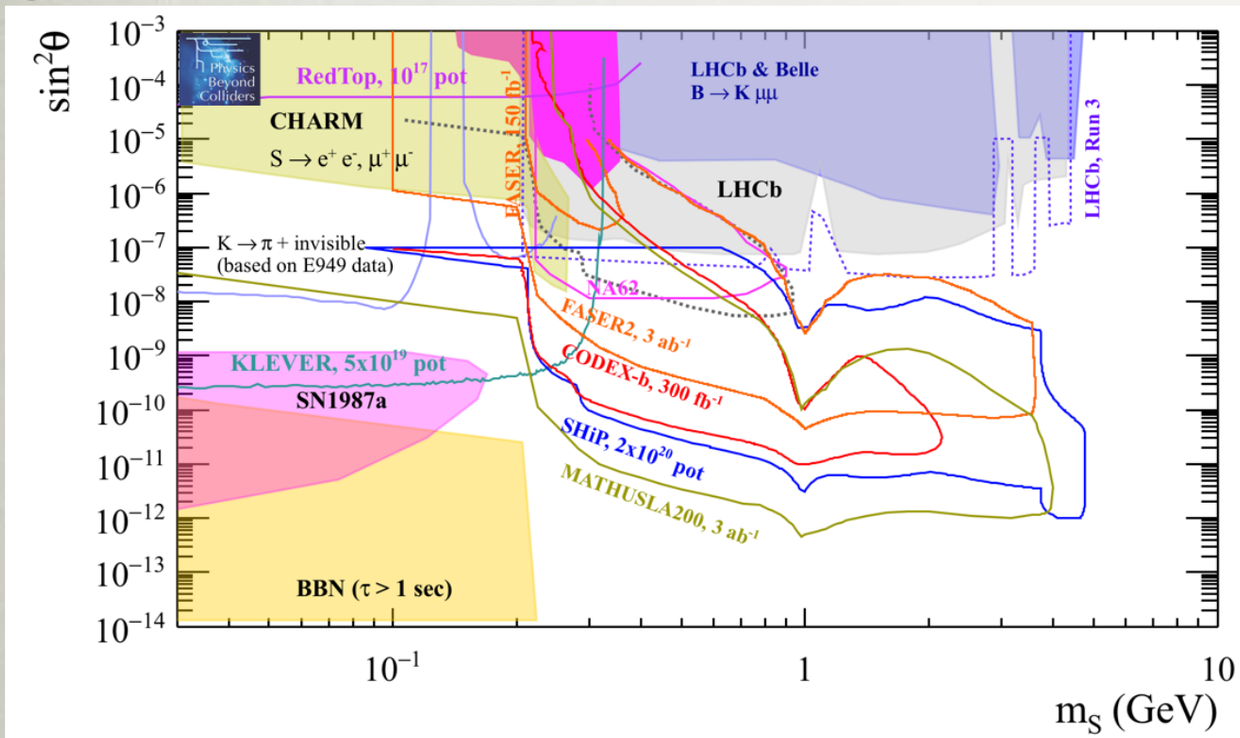




Also:
Millicharge detector proposals
GAZELLE proposal at Belle-II
Physics case less explored at high-energy e^+e^- machines

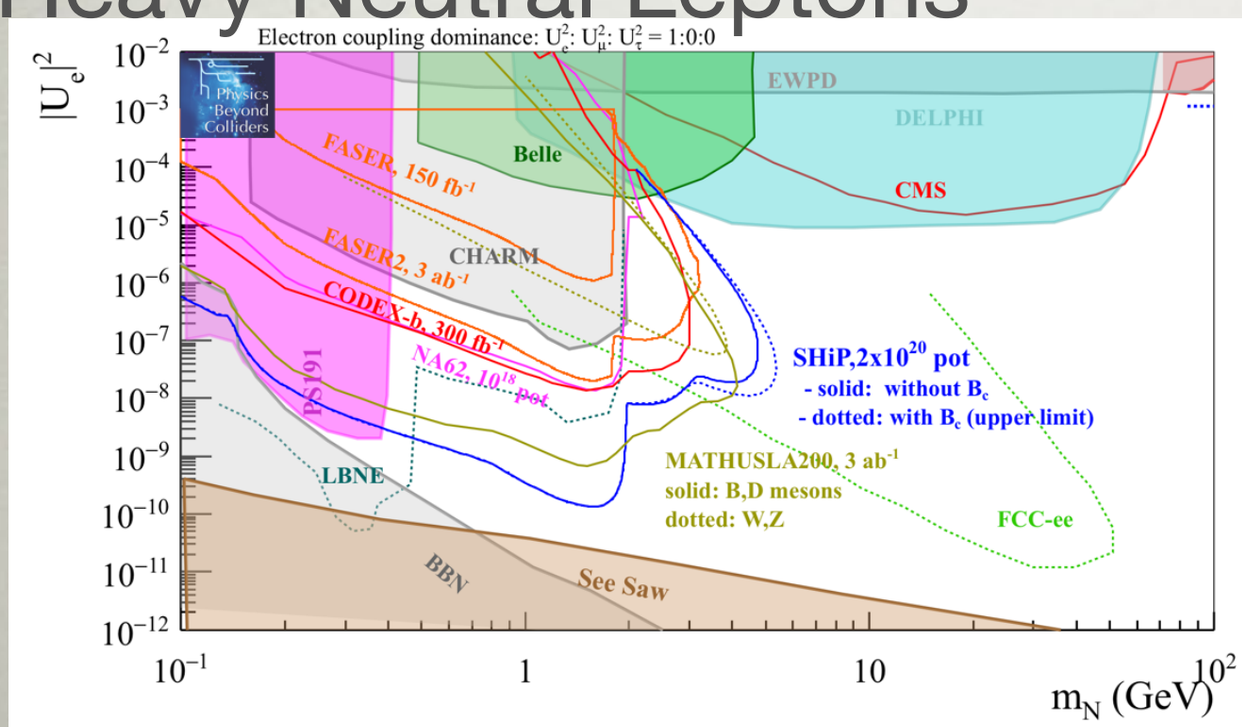
Other Dark Sectors

Scalar Portal



Probably favors proton beams, meson decays.

Heavy Neutral Leptons



Maybe interesting at ILC?

Conclusions

- ✦ Hidden sector science:
  - ✦ Potential to discover new physics by studying familiar mass scales with unprecedented precision
  - ✦ A strong candidate for the nature of dark matter
- ✦ A world-wide program of (mostly small) experiments motivated by these possibilities, both in fixed-target experiments and at colliders
- ✦ The combination of ~100 GeV beam energies with lepton beams has not yet been well explored