Searching for New Forces and Light Dark Matter with Electron Beams

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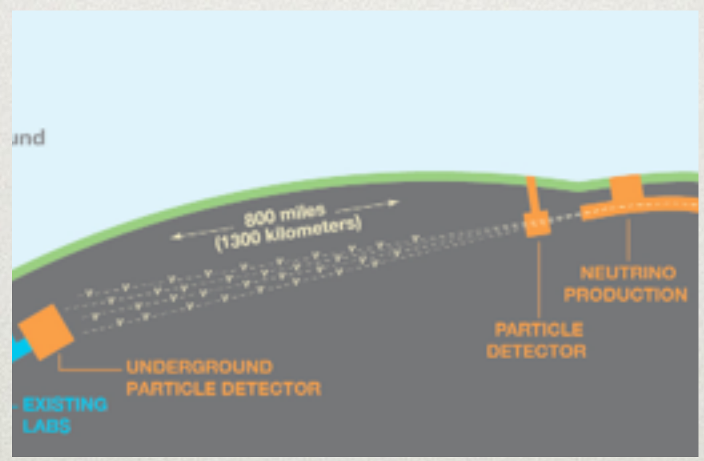
Dark Interactions 2016
October 4, 2016

What is a dark sector?

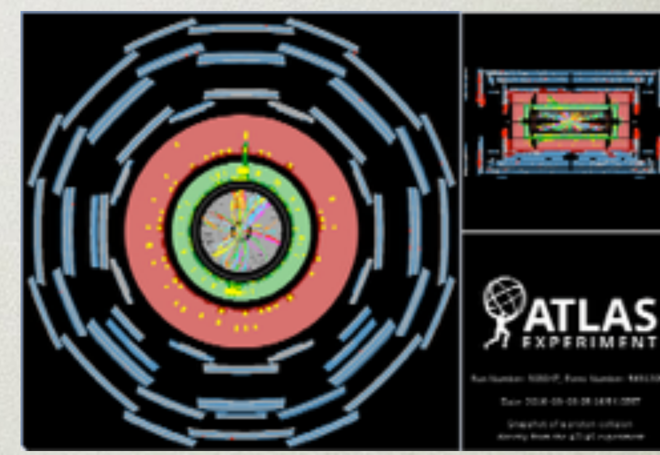
Most of our microscopic understanding of Nature has been learned through three basic forces:

EM

Weak

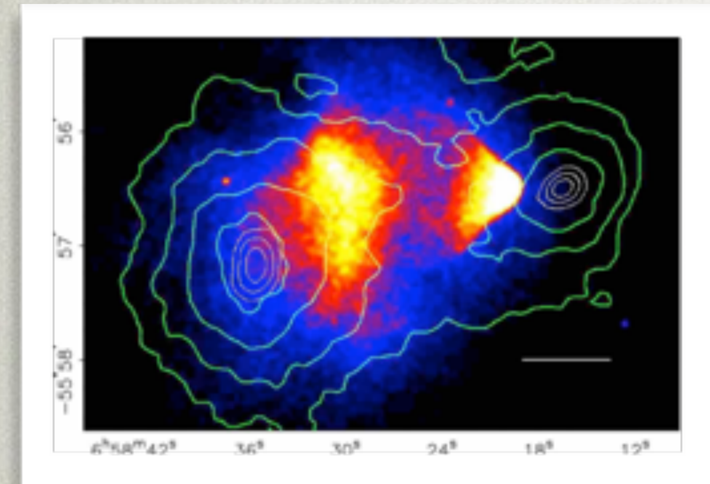


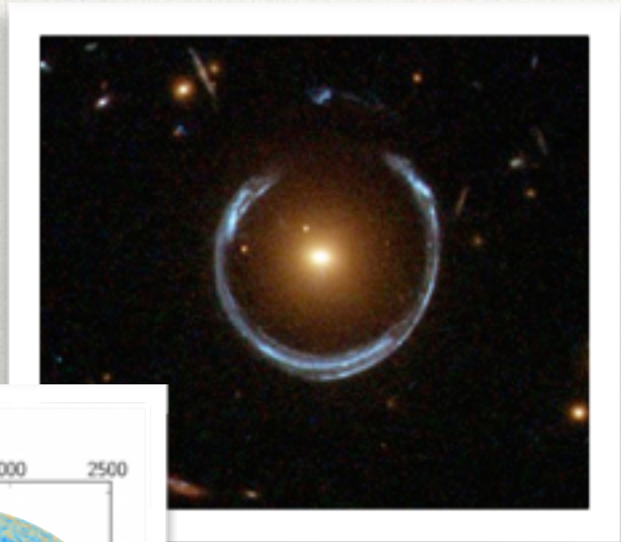
Strong

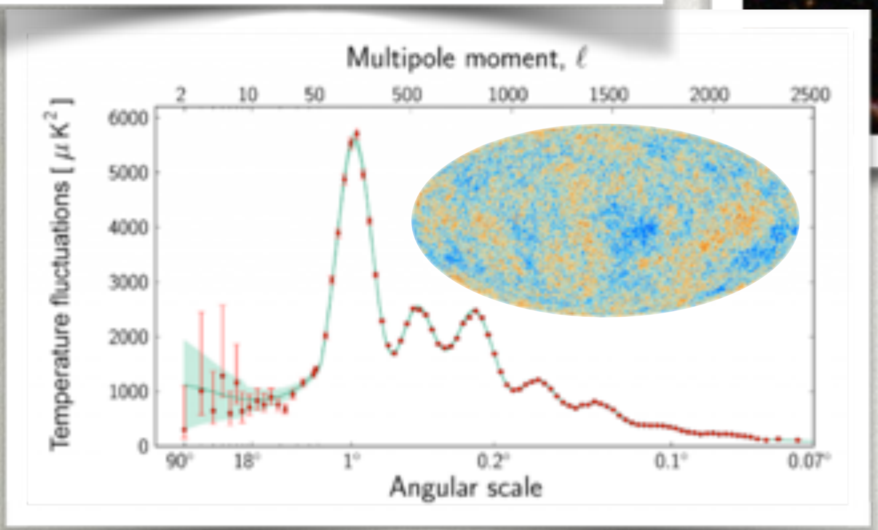


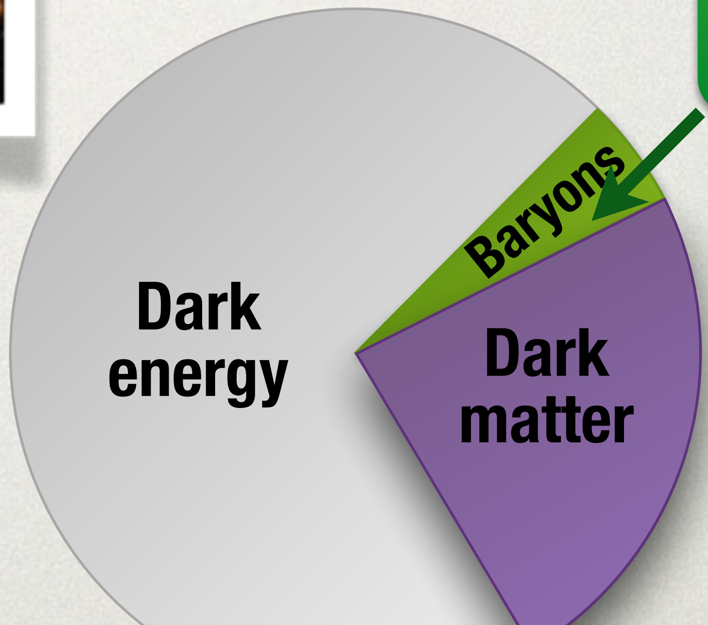
It would be easy to miss a **Dark Sector** – constituents of Nature that are neutral under these known forces.

Have we already found a dark sector?





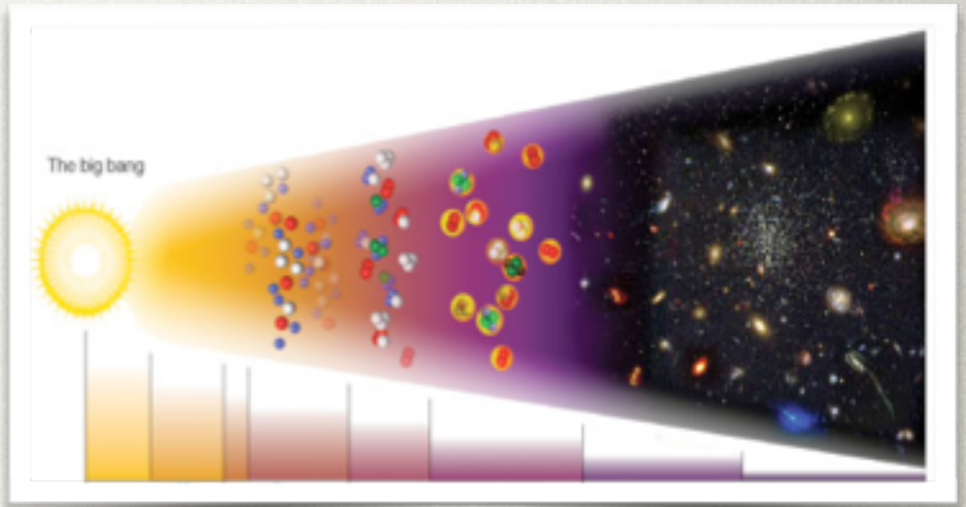




So far, dark matter has only been observed via gravity

- Its Standard Model interactions are tightly constrained
- Yet there is reason to think it interacts with us…

Thermal Dark Matter from a New Sector



- Thermal freeze-out is compelling motivation for non-gravitational interactions
- If DM is light, it **must** be SM-neutral and for thermal models, new force is required to mediate annihilation
  - W/Z/h-mediated annihilation over-produces DM (Lee-Weinberg)
  - Even with small couplings, scattering, annihilation & low-energy production xsec » weak interactions
- Sharp prediction of thermal DM annihilation rate gives important target for new force search

DM puzzle motivates comprehensive searches for Light DM + Light Mediators

Thermal Dark Matter from a New Sector

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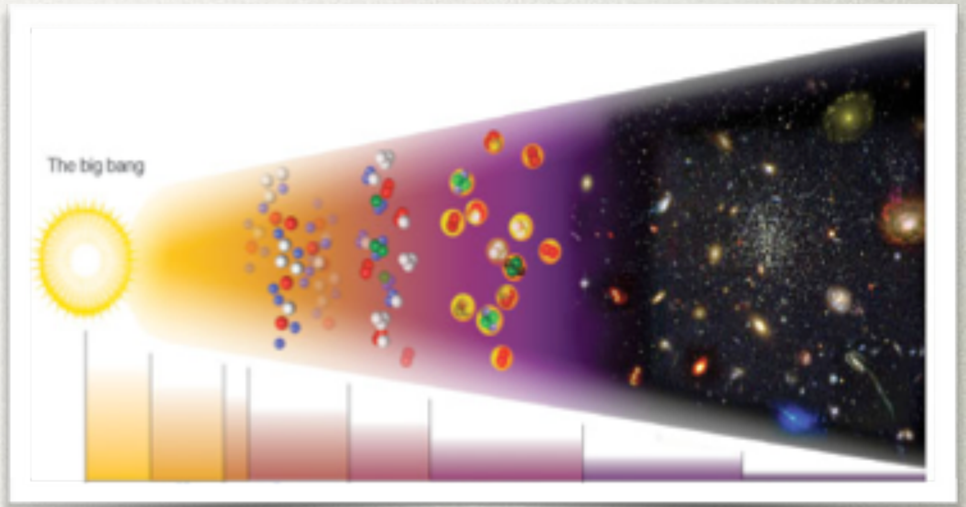

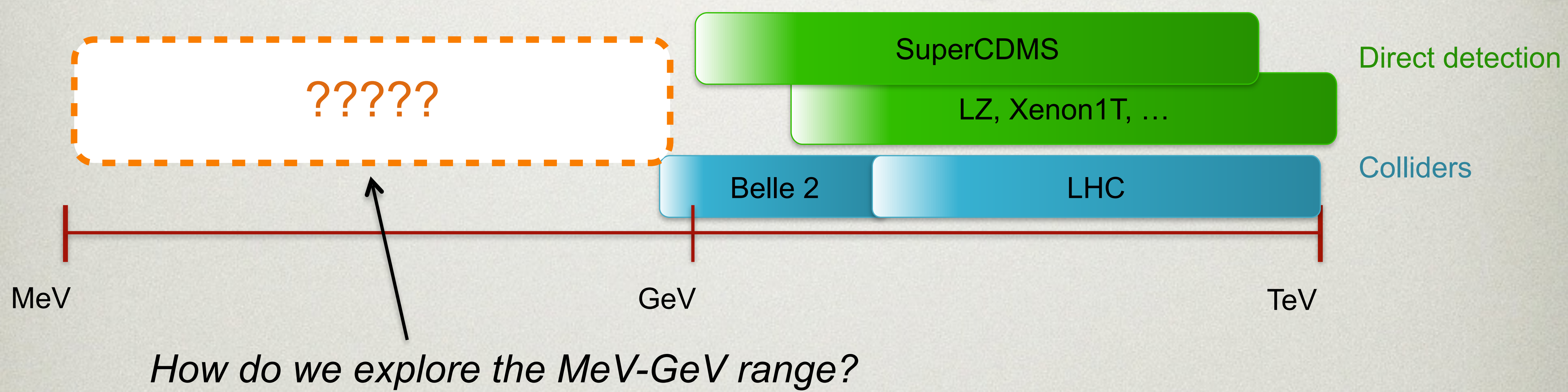

Exploring the Dark Sector

- Organizing the search for dark sectors
- Searching for new force-carriers decaying visibly
- Light dark matter parameter space and searches

How to look for dark sectors?

Even at low masses, dark sectors are easy to miss!

Most physics of the dark sector is insulated from SM by symmetries – leading interactions are suppressed by high mass scale

$$(\bar{\psi}_e \psi_e)_{SM} (\bar{\chi}\chi)_{new} / \Lambda^2$$

[analogous to approximate stability of proton in SM]

Even if χ is light, large $\Lambda \Rightarrow$ unobservable effect.

The first place to look for dark sector is by looking for particles that can interact **without** Λ-suppression.

Three "Portals" to Dark Sectors

Only three sizeable interactions allowed by Standard Model symmetries:

Vector Portal	$\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$	Most visible
Higgs Portal	$\epsilon_h \, \lvert h\rvert^2 \lvert\phi\rvert^2$	exotic rare Higgs decays rare meson decays
Neutrino Portal	$\epsilon_\nu \, (hL)\psi$	not-so-sterile neutrinos

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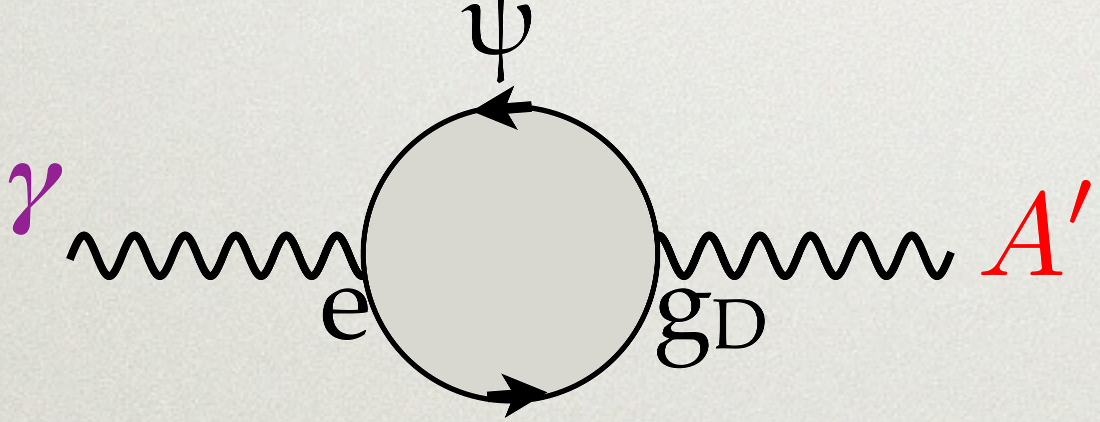
Sources and Sizes of Kinetic Mixing $\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$

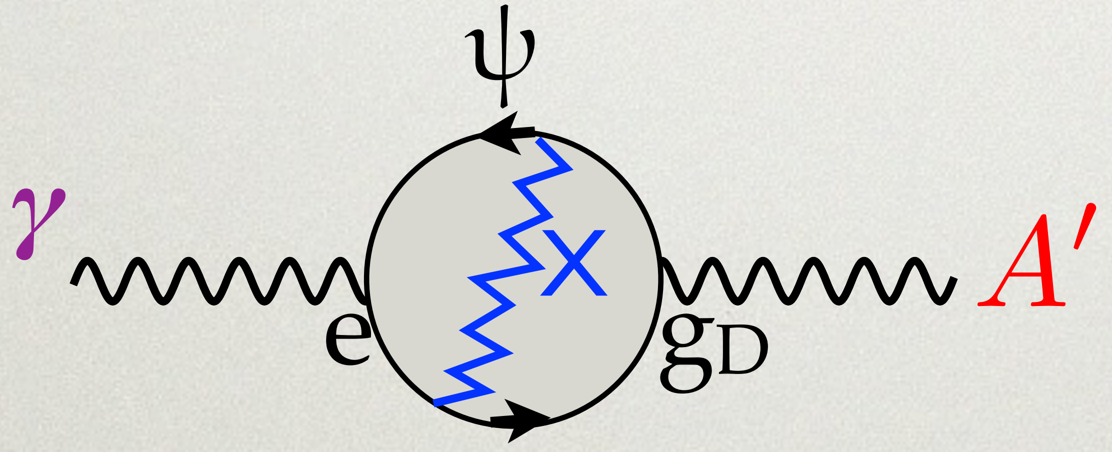
- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - Simplest case: one heavy particle ψ with both EM charge & dark charge



generates $\epsilon \sim \frac{e\, g_D}{16\pi^2} \log \frac{m_\psi}{M_*} \sim 10^{-2} - 10^{-4}$

Sources and Sizes of Kinetic Mixing $\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$

- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - In Grand Unified Theory, symmetry forbids tree-level & 1-loop mechanisms. GUT-breaking enters at 2 loops



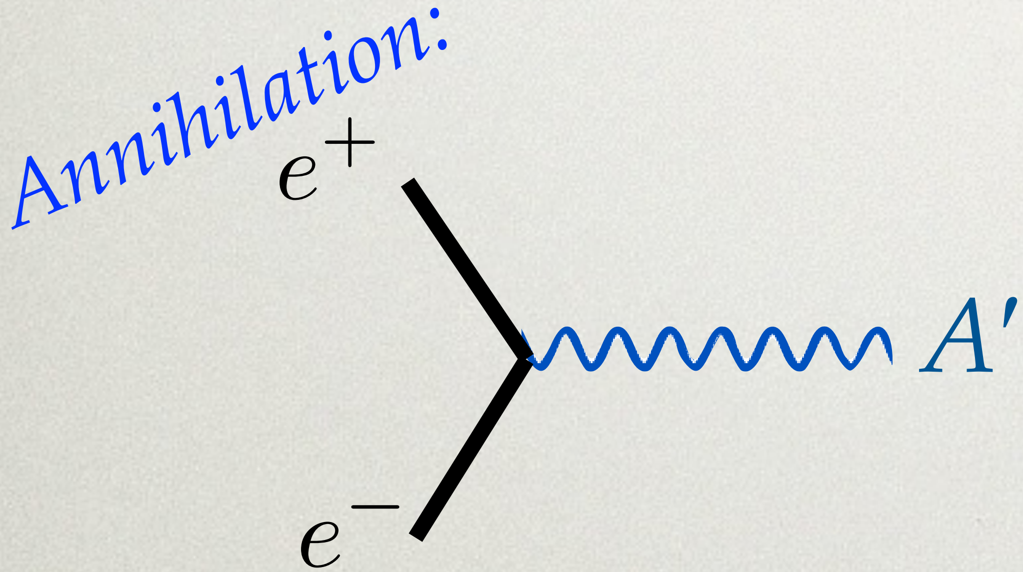
generating $\epsilon \sim 10^{-3} - 10^{-5}$

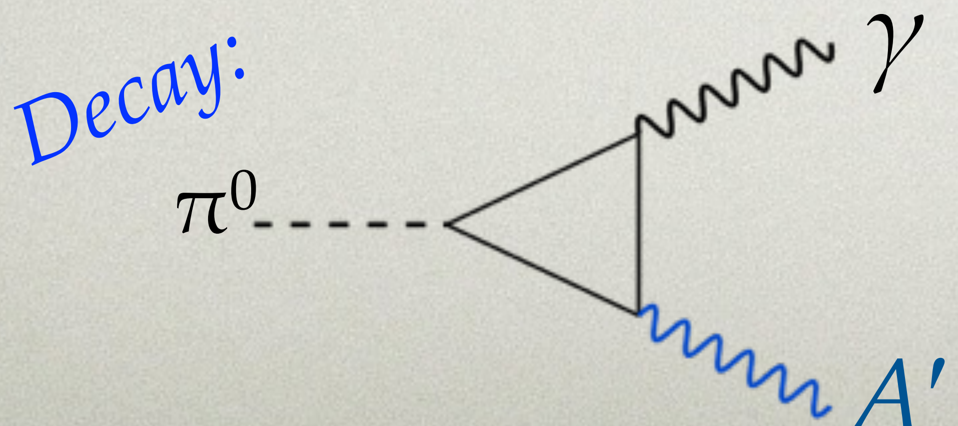
($\rightarrow 10^{-7}$ if both U(1)'s are in unified groups)

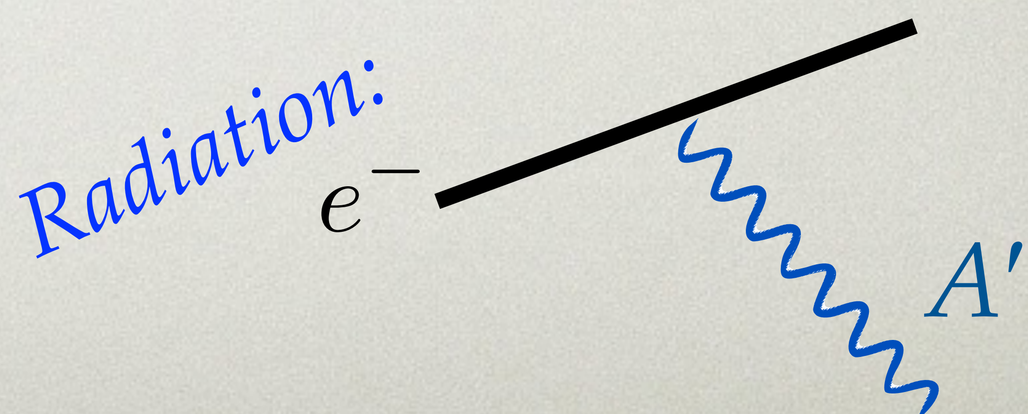
Dark Photon Production

Kinetic mixing effectively gives matter of electric charge qe an A′ coupling $\propto q\varepsilon e$

$\Rightarrow$ *Wherever there are photons (and sufficient phase space), there are dark photons*

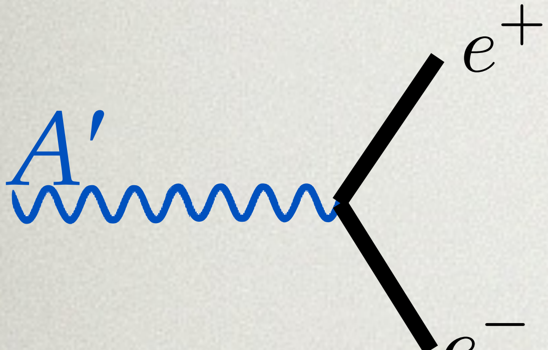






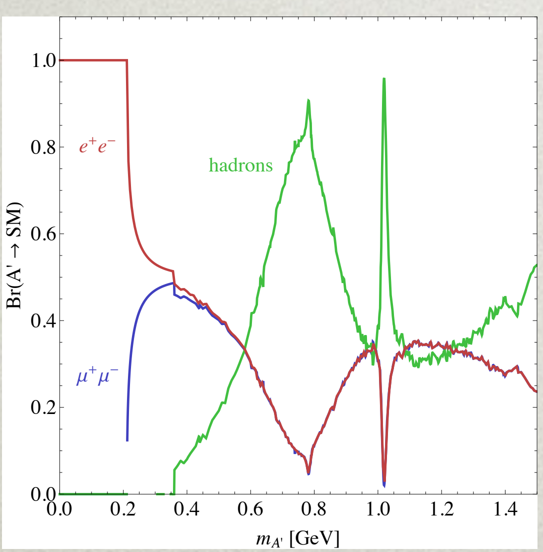
Dark Photon Decays
Two Simple Cases

"Minimal" Decay:

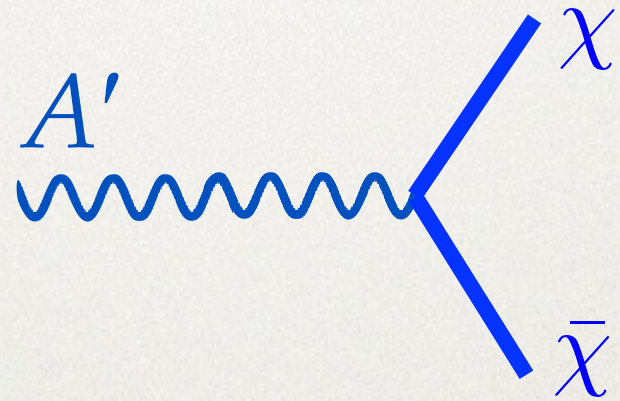


via same mixing operator as production ⇒ tiny width

$$\Gamma \sim \epsilon^2 \alpha m_{A'}$$



"Generic" Decay:



(not ε-supressed!)

If ***any*** *dark-sector matter χ has $m_\chi < 2m_{A'}$, this decay dominates*

Two cases:

– χ stable & invisible

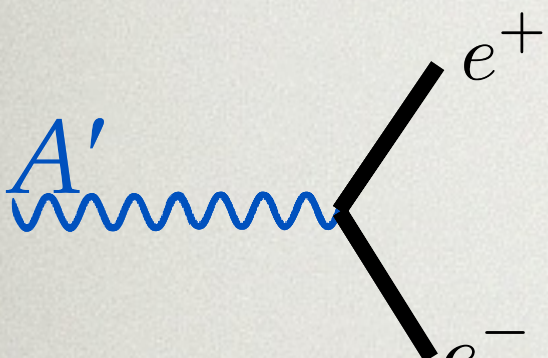
– χ decays into SM particles, A′→ >2 charged particles

searches at BaBar and KLOE

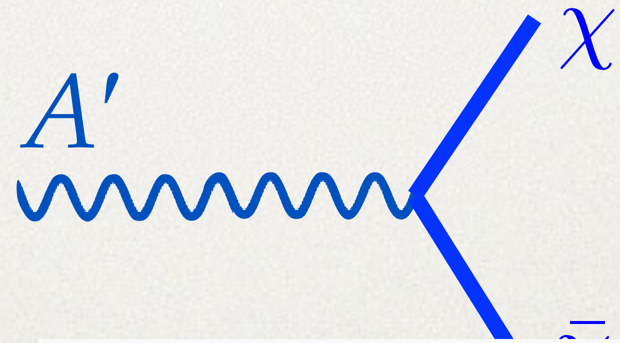
To test "dark sector" idea & maximize light thermal DM sensitivity, we need to search for both!

Dark Photon Decays
Two Simple Cases

"Minimal" Decay:



"Generic" Decay:



(not ε-supressed!)

*If **any** dark-sector matter χ has $m_\chi < 2m_{A'}$, this ...minates*

Major advances in last 5 years!

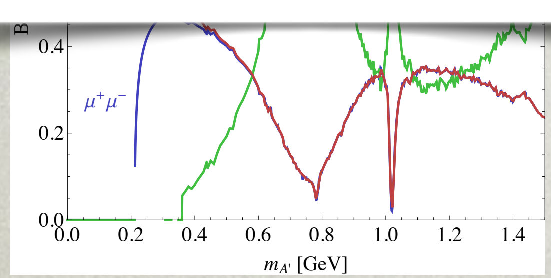
Huge upcoming opportunity!

Tw...

...cles,

$A' \to$ >2 charged particles

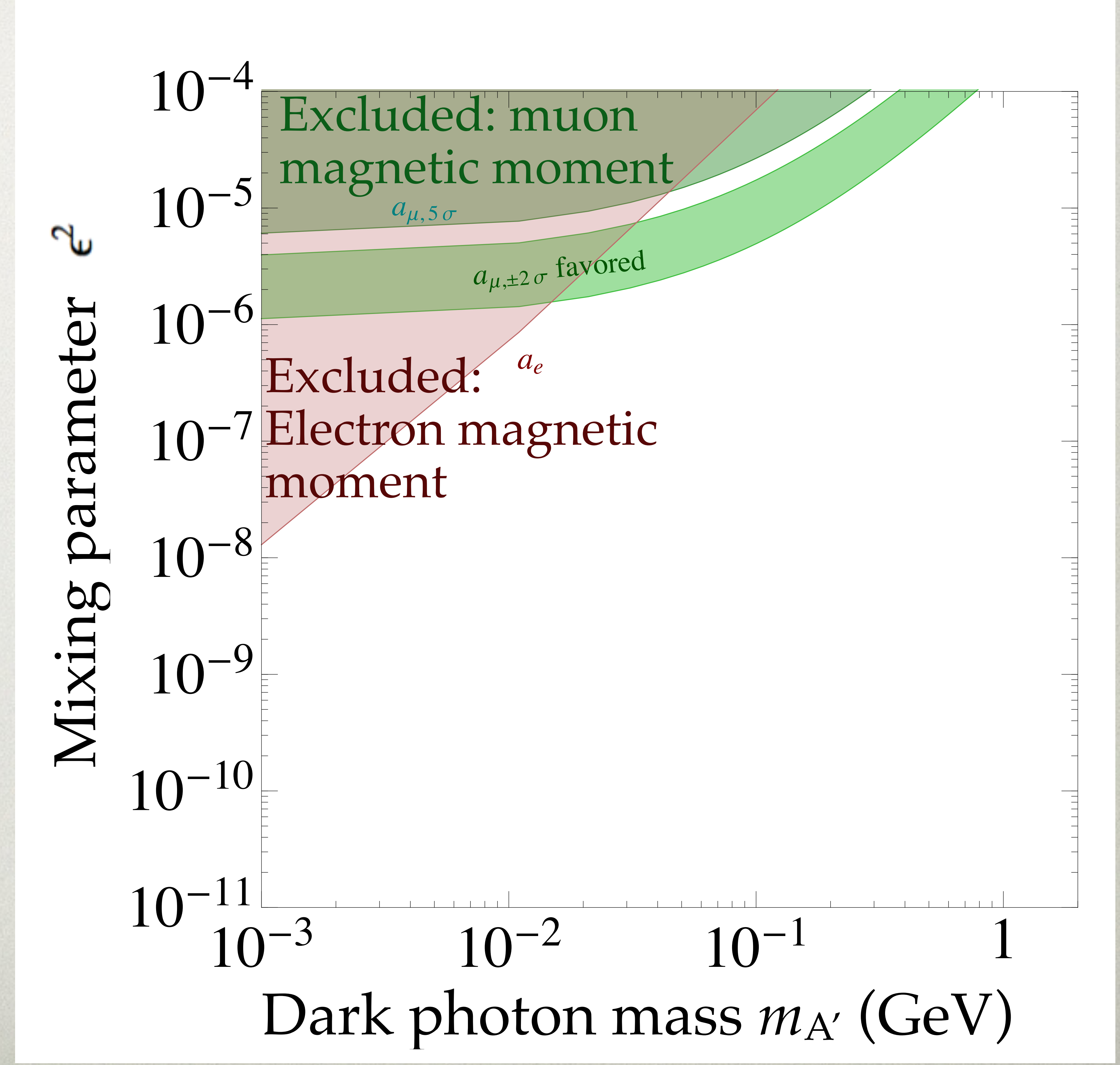
searches at BaBar and KLOE



To test "dark sector" idea & maximize light thermal DM sensitivity, we need to search for both!

New Force Parameter Space

MeV – GeV mass



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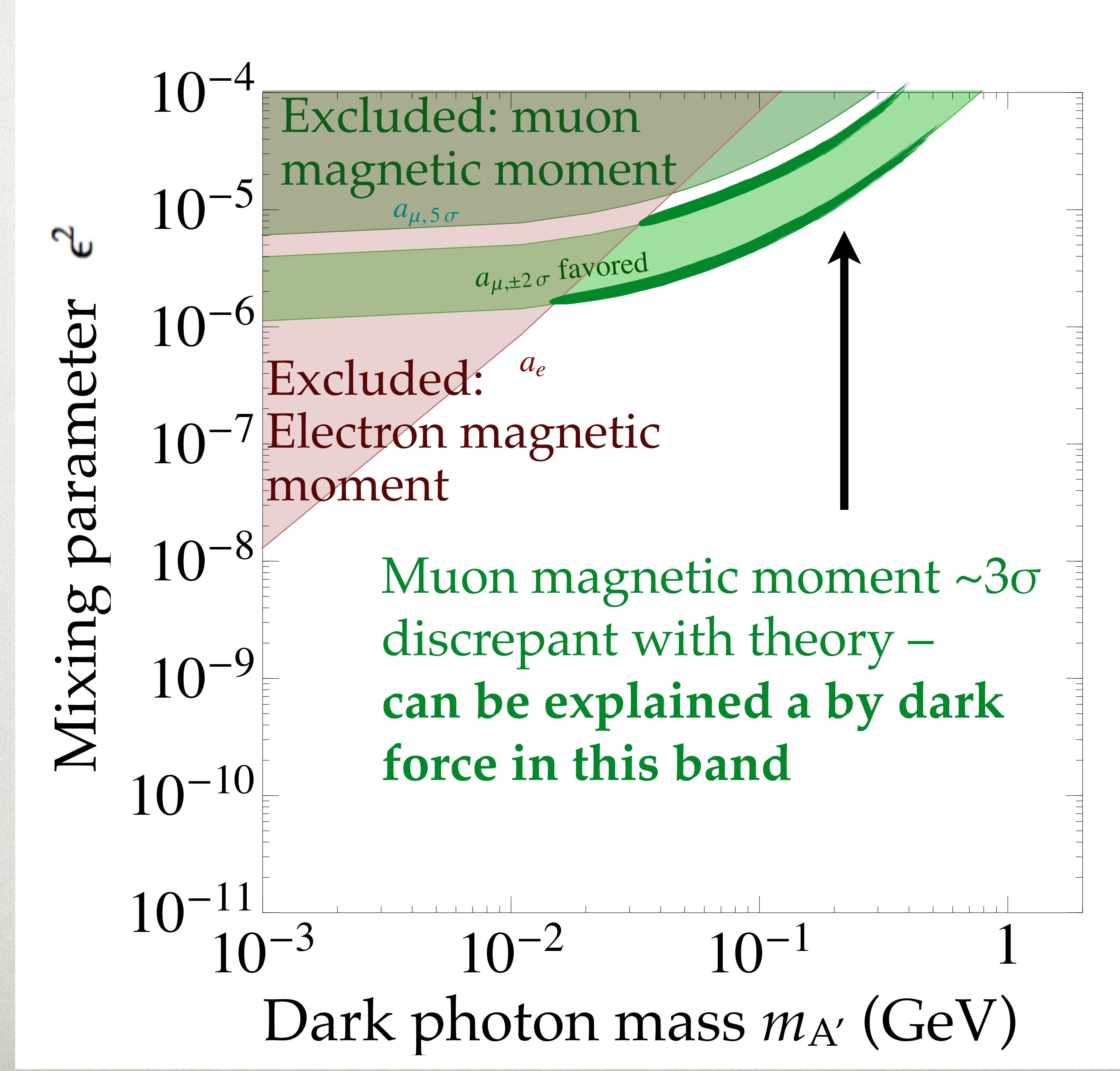

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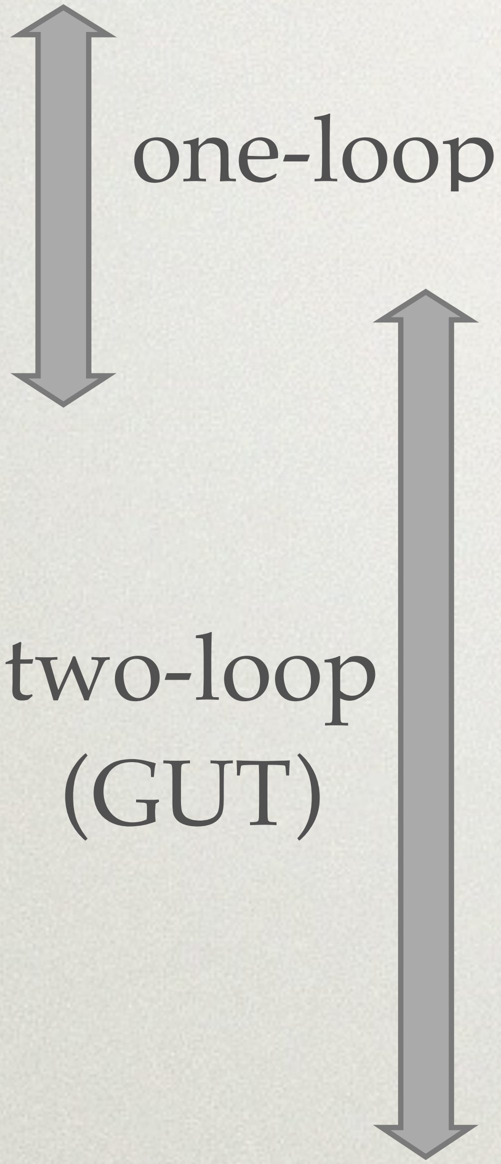
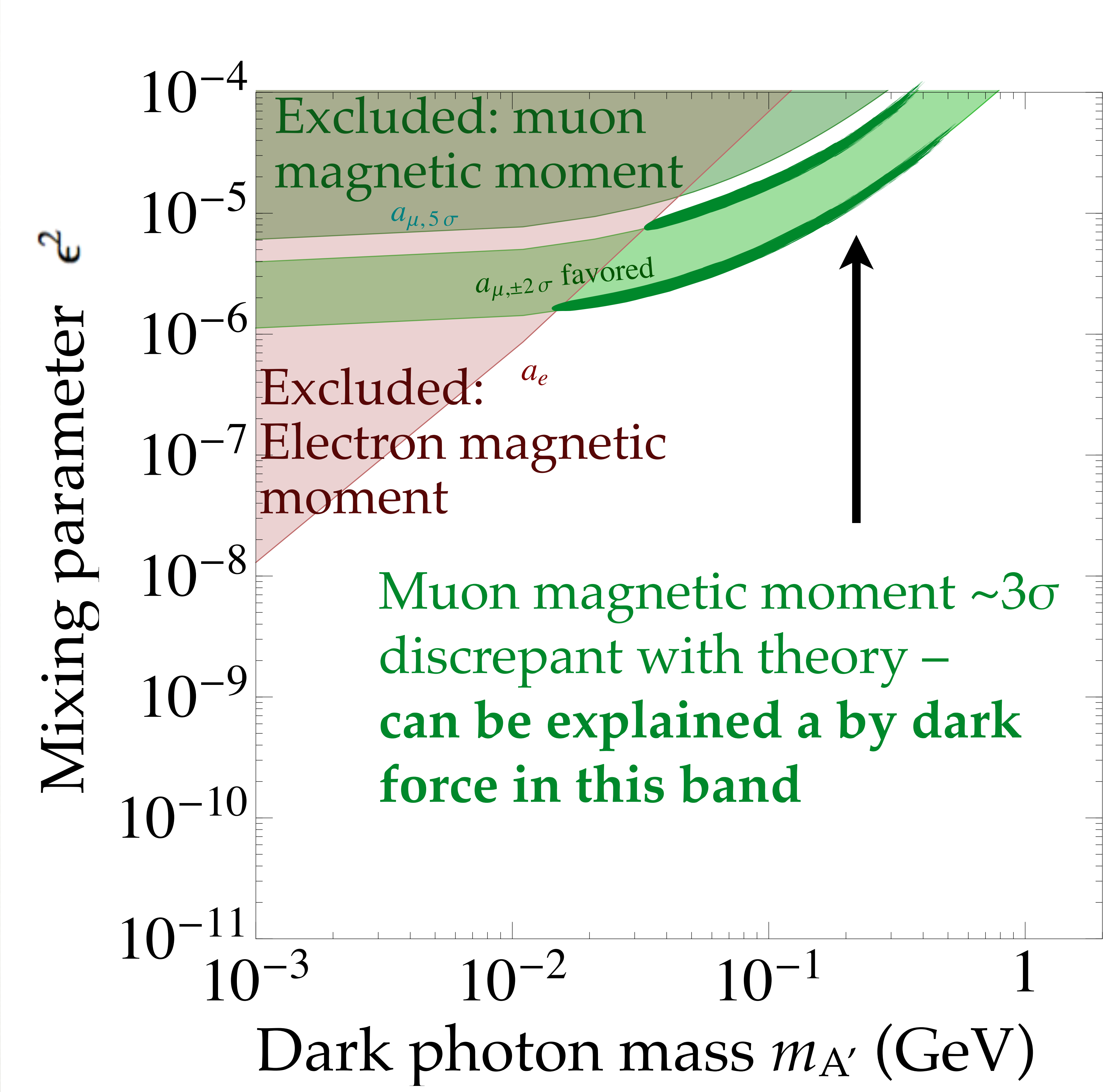




An Experimental Renaissance

A Forward-Looking Summary


arXiv:1608.08632v1 [hep-ph] 30 Aug 2016

Dark Sectors 2016 Workshop: Community Report

Jim Alexander (VDP Convener),[1] Marco Battaglieri (DMA Convener),[2] Bertrand Echenard (RDS Convener),[3] Rouven Essig (Organizer),[4,*] Matthew Graham (Organizer),[5,†] Eder Izaguirre (DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan Krnjaic (DMA Convener),[7] Jeremy Mardon (DD Convener),[8] David Morrissey (RDS Convener),[9] Tim Nelson (Organizer),[5,§] Maxim Perelstein (VDP Convener),[1] Matt Pyle (DD Convener),[10] Adam Ritz (DMA Convener),[11] Philip Schuster (Organizer),[5,6,¶] Brian Shuve (RDS Convener),[5] Natalia Toro (Organizer),[5,6,**] Richard G Van De Water (DMA Convener),[12] Daniel Akerib,[5,13] Haipeng An,[3] Konrad Aniol,[14] Isaac J. Arnquist,[15] David M. Asner,[15] Henning O. Back,[15] Keith Baker,[16] Nathan Baltzell,[17] Dipanwita Banerjee,[18] Brian Batell,[19] Daniel Bauer,[7] James Beacham,[20] Jay Benesch,[17] James Bjorken,[5] Nikita Blinov,[5] Celine Boehm,[21] Mariangela Bondí,[22] Walter Bonivento,[23] Fabio Bossi,[24] Stanley J. Brodsky,[5] Ran Budnik,[25] Stephen Bueltmann,[26] Masroor H. Bukhari,[27] Raymond Bunker,[15] Massimo Carpinelli,[28,29] Concetta Cartaro,[5] David Cassel,[1,5] Gianluca Cavoto,[30] Andrea Celentano,[2] Animesh Chaterjee,[31] Saptarshi Chaudhuri,[8] Gabriele Chiodini,[24] Hsiao-Mei Sherry Cho,[5] Eric D. Church,[15] D. A. Cooke,[18] Jodi Cooley,[32] Robert Cooper,[33] Ross Corliss,[34] Paolo Crivelli,[18] Francesca Curciarello,[35] Annalisa D'Angelo,[36,37] Hooman Davoudiasl,[38] Marzio De Napoli,[22] Raffaella De Vita,[2] Achim Denig,[39] Patrick deNiverville,[11] Abhay Deshpande,[40] Ranjan Dharmapalan,[41] Bogdan Dobrescu,[7] Sergey Donskov,[42] Raphael Dupre,[43] Juan Estrada,[7] Stuart Fegan,[39] Torben Ferber,[44] Clive Field,[5] Enectali Figueroa-Feliciano,[45] Alessandra Filippi,[46] Bartosz Fornal,[47] Arne Freyberger,[17] Alexander Friedland,[5] Iftach Galon,[47] Susan Gardner,[48,47] Francois-Xavier Girod,[17] Sergei Gninenko,[49] Andrey Golutvin,[50] Stefania Gori,[51] Christoph Grab,[18] Enrico Graziani,[52] Keith Griffioen,[53] Andrew Haas,[54] Keisuke Harigaya,[10,55] Christopher Hearty,[44] Scott Hertel,[10,55] JoAnne Hewett,[5] Andrew Hime,[15] David Hitlin,[3] Yonit Hochberg,[10,55,1] Roy J. Holt,[41] Maurik Holtrop,[56] Eric W. Hoppe,[15] Todd W. Hossbach,[15] Lauren Hsu,[7] Phil Ilten,[34] Joe Incandela,[57] Gianluca Inguglia,[58] Kent Irwin,[5] Igal Jaegle,[59] Robert P. Johnson,[60] Yonatan Kahn,[61] Grzegorz Kalicy,[62] Zhong-Bo Kang,[12] Vardan Khachatryan,[4] Venelin Kozhuharov,[63] N. V. Krasnikov,[49] Valery Kubarovsky,[17] Eric Kuflik,[1] Noah Kurinsky,[5,8] Ranjan Laha,[13,8] Gaia Lanfranchi,[35] Dale Li,[5] Tongyan Lin,[10,55] Mariangela Lisanti,[61] Kun Liu,[12] Ming Liu,[12] Ben Loer,[15] Dinesh Loomba,[64] Valery E. Lyubovitskij,[65,66,67] Aaron Manalaysay,[68] Giuseppe Mandaglio,[69] Jeremiah Mans,[70] W. J. Marciano,[38] Thomas Markiewicz,[5] Luca Marsicano,[2] Takashi Maruyama,[5] Victor A. Matveev,[49] David McKeen,[71] Bryan McKinnon,[72] Dan McKinsey,[10] Harald Merkel,[39] Jeremy Mock,[68] Maria Elena Monzani,[5] Omar Moreno,[5] Corina Nantais,[73] Sebouh Paul,[53] Michael Peskin,[5] Vladimir Poliakov,[74] Antonio D Polosa,[75,76] Maxim Pospelov,[6,11] Igor Rachek,[77] Balint Radics,[18] Mauro Raggi,[30] Nunzio Randazzo,[22] Blair Ratcliff,[5] Alessandro Rizzo,[36,37] Thomas Rizzo,[5] Alan Robinson,[7] Andre Rubbia,[18] David Rubin,[1] Dylan Rueter,[8] Tarek Saab,[78] Elena Santopinto,[2] Richard Schnee,[79] Jessie Shelton,[80] Gabriele Simi,[81,82] Ani Simonyan,[43] Valeria Sipala,[28,29] Oren Slone,[83] Elton Smith,[17] Daniel Snowden-Ifft,[84] Matthew Solt,[5] Peter Sorensen,[10,55] Yotam Soreq,[34] Stefania Spagnolo,[24,85] James Spencer,[5] Stepan Stepanyan,[17] Jan Strube,[15] Michael Sullivan,[5] Arun S. Tadepalli,[86] Tim Tait,[47] Mauro Taiuti,[2,87] Philip Tanedo,[88] Rex

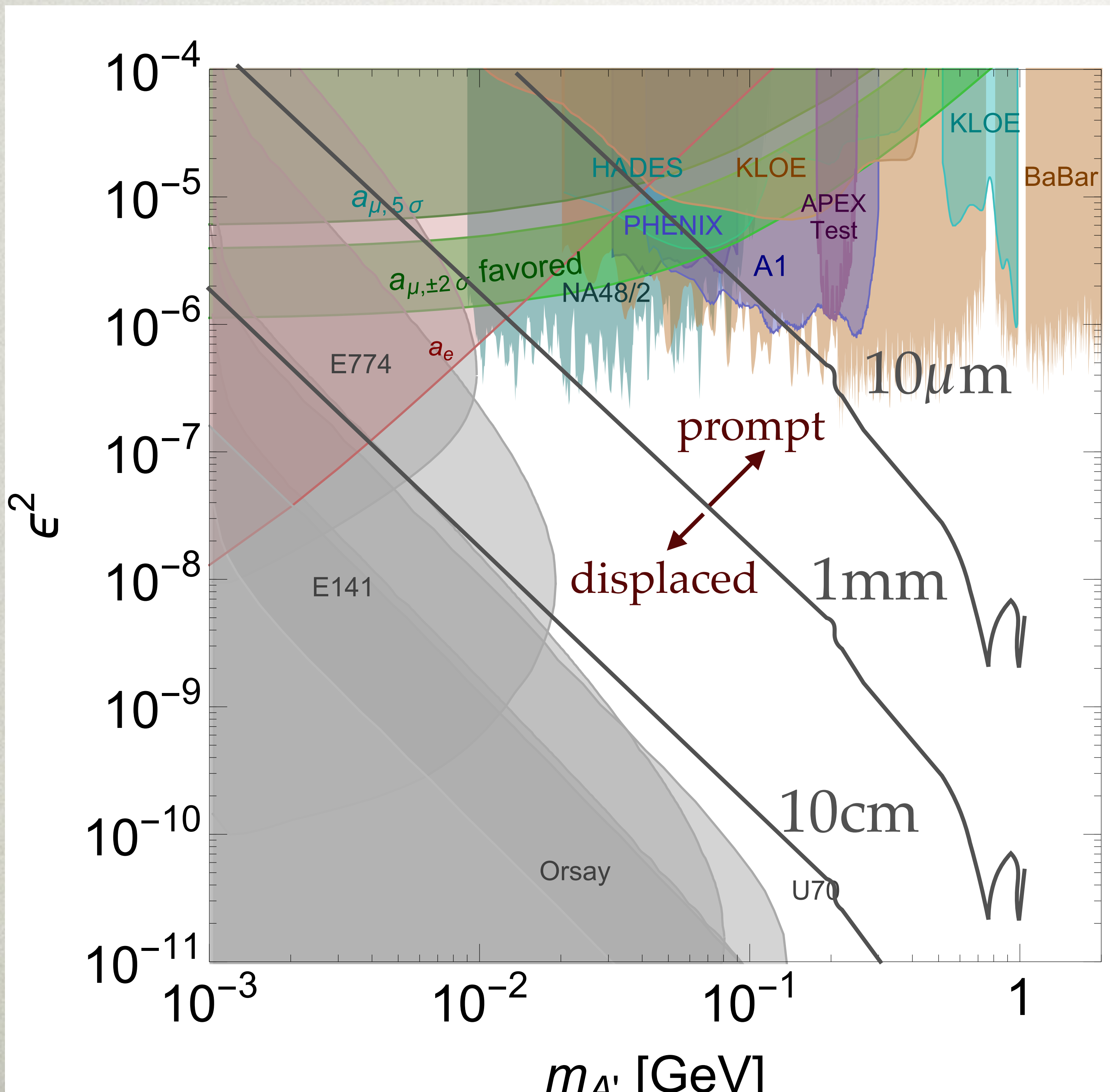
arXiV:1608.08632

Identified three key priorities:

- Extend searches for visibly decaying force carriers
- Search for light dark matter production to thermal relic target
- Low-mass direct detection

Summarizes ongoing experiments and proposals

Visible Dark Photons: Current Constraints

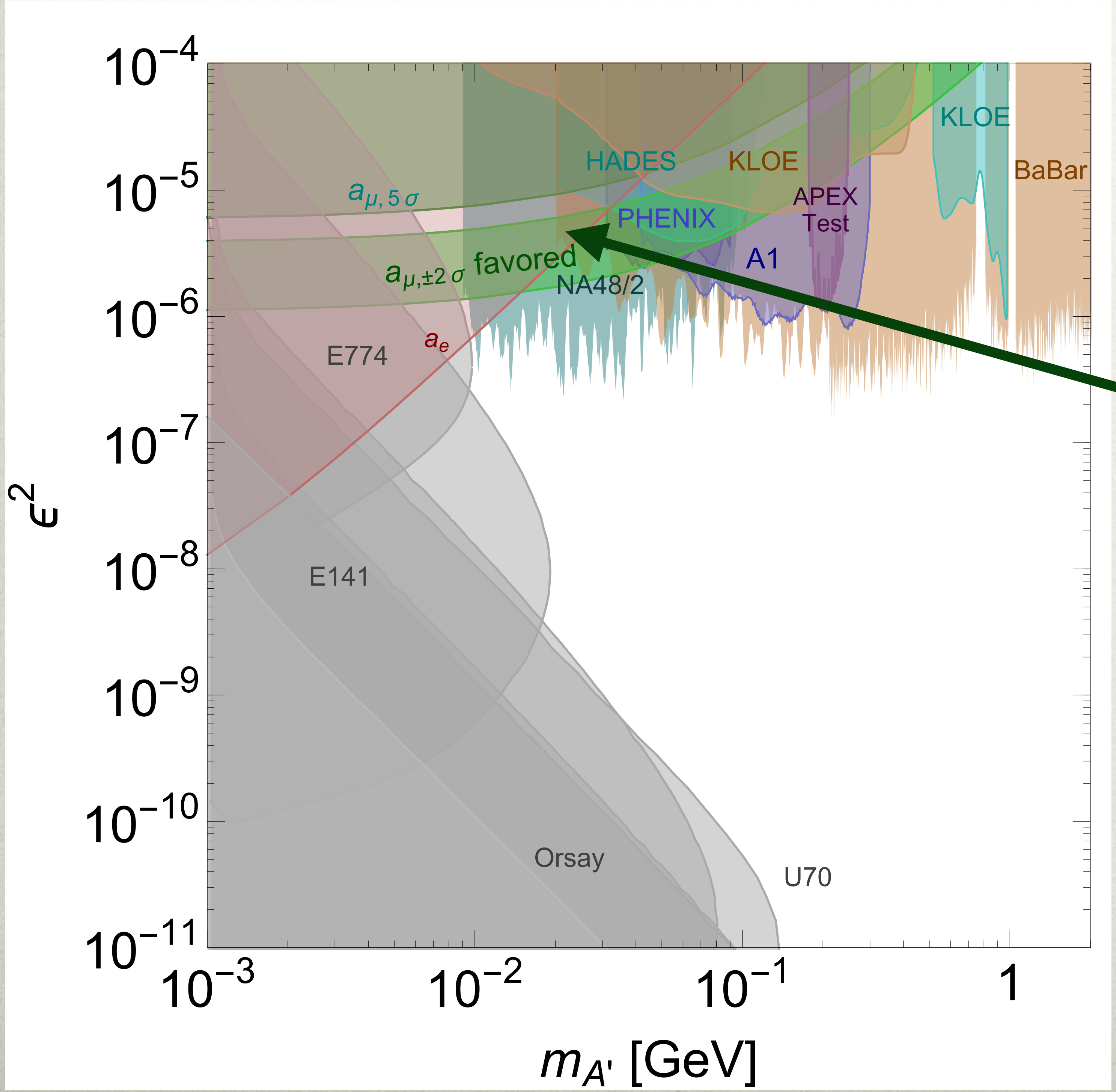


Red/green: e,μ anomalous dipole moments

All other colors: Pair resonance searches

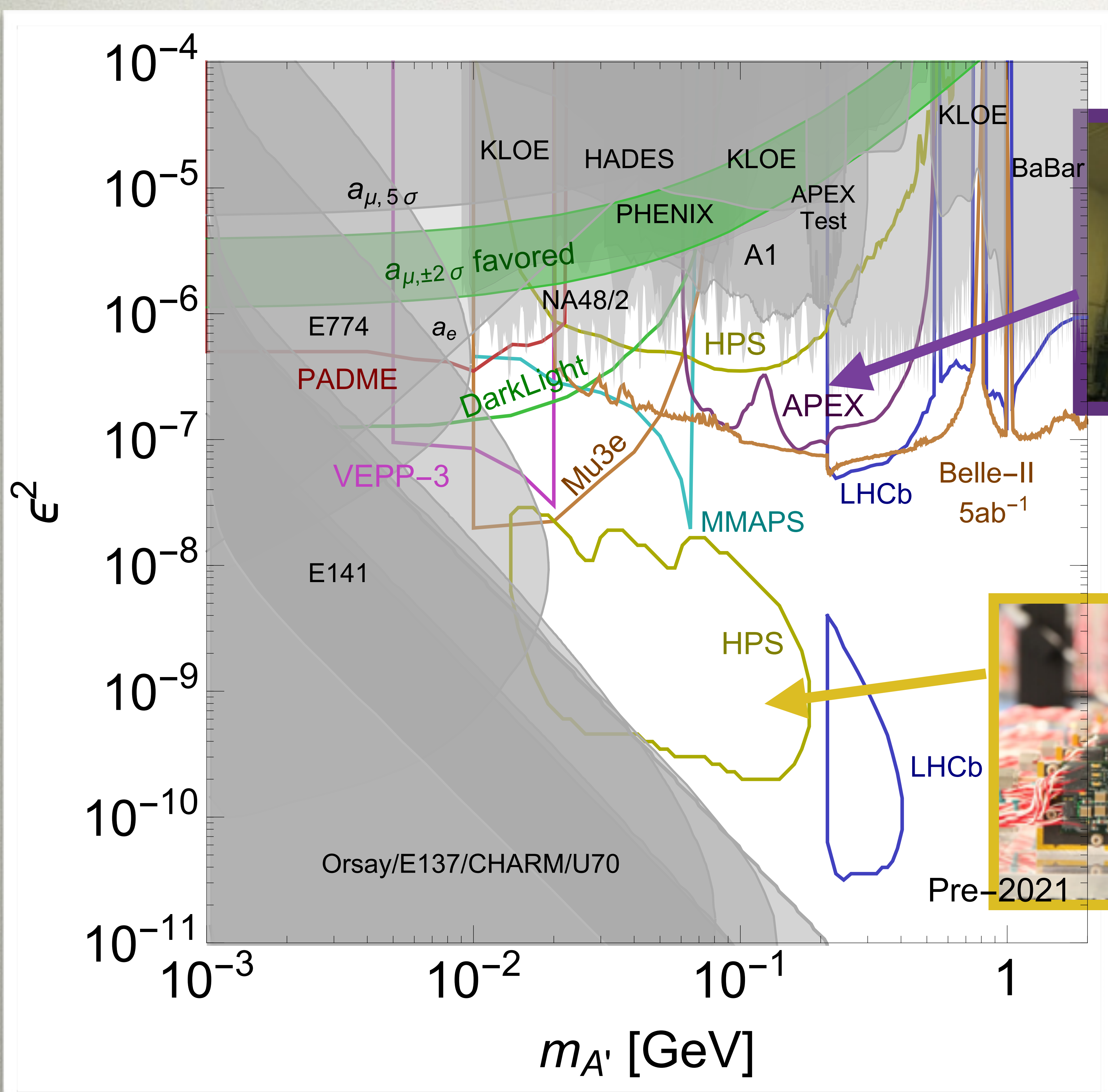
Gray: Beam Dump

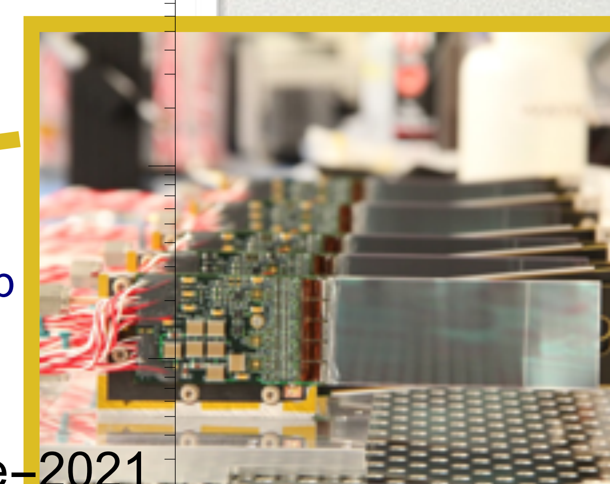
Visible Dark Photons: Current Constraints

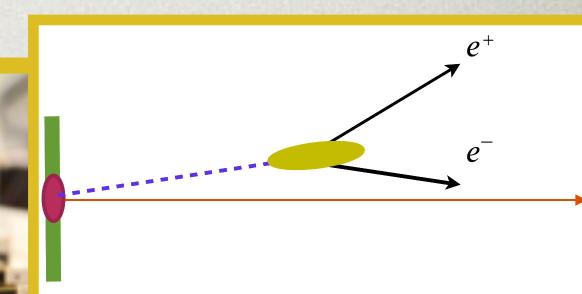


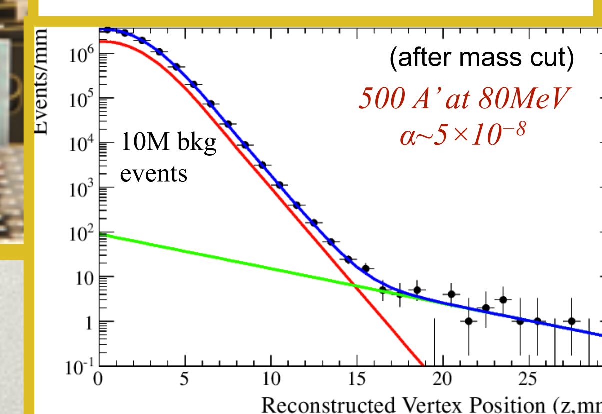
Recent experiments have tested interpretation of muon g-2 anomaly from dark photon — if it decays visibly!

Turning Weakness Into Strength



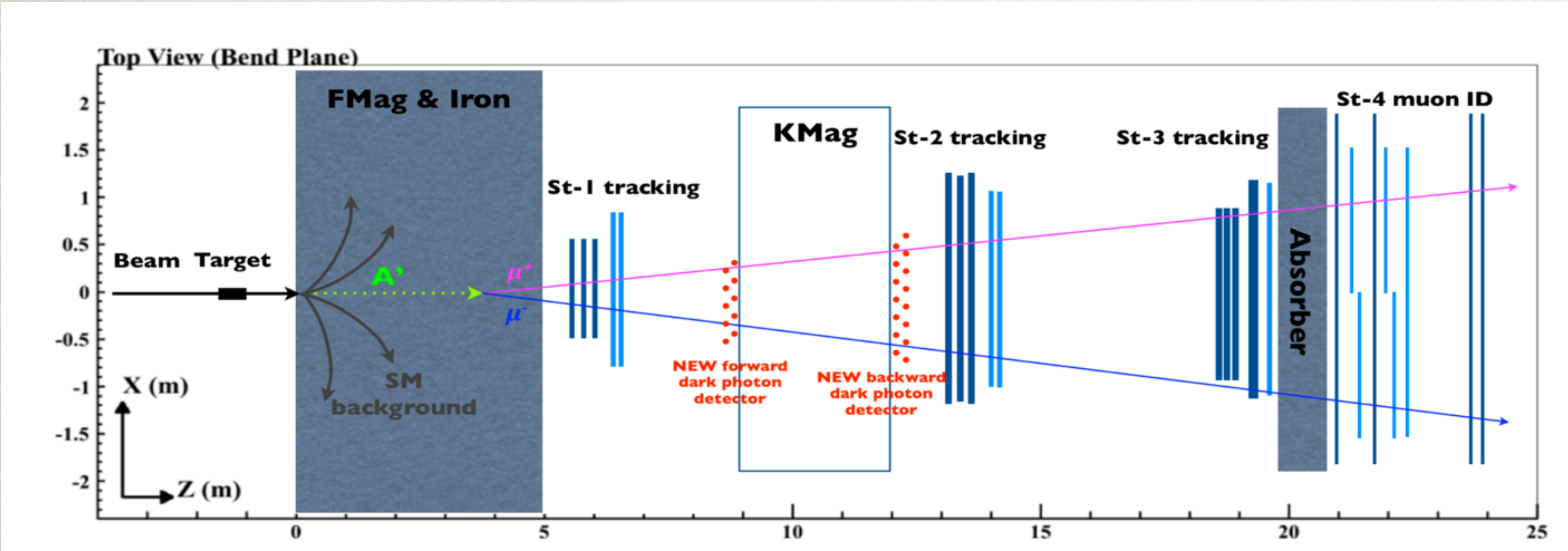




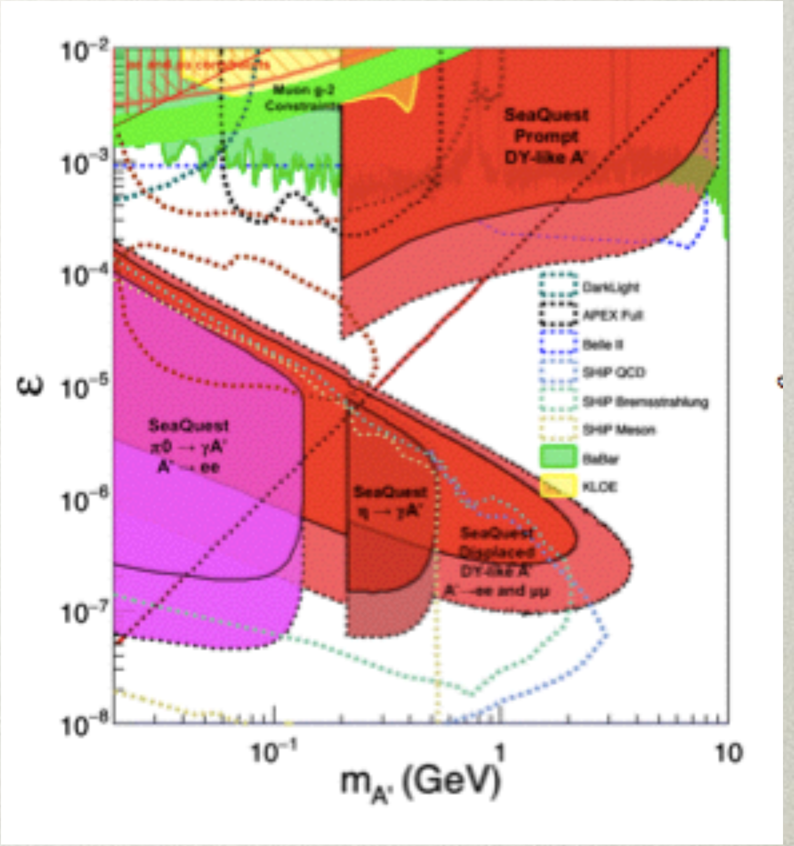


Results soon from 2015-16 first run

A New Opportunity: SeaQuest [Talk to Ming!]



2017+



Proton beam incident on a "medium" dump – high yield, but penetrable by muons & long-lived dark photons.

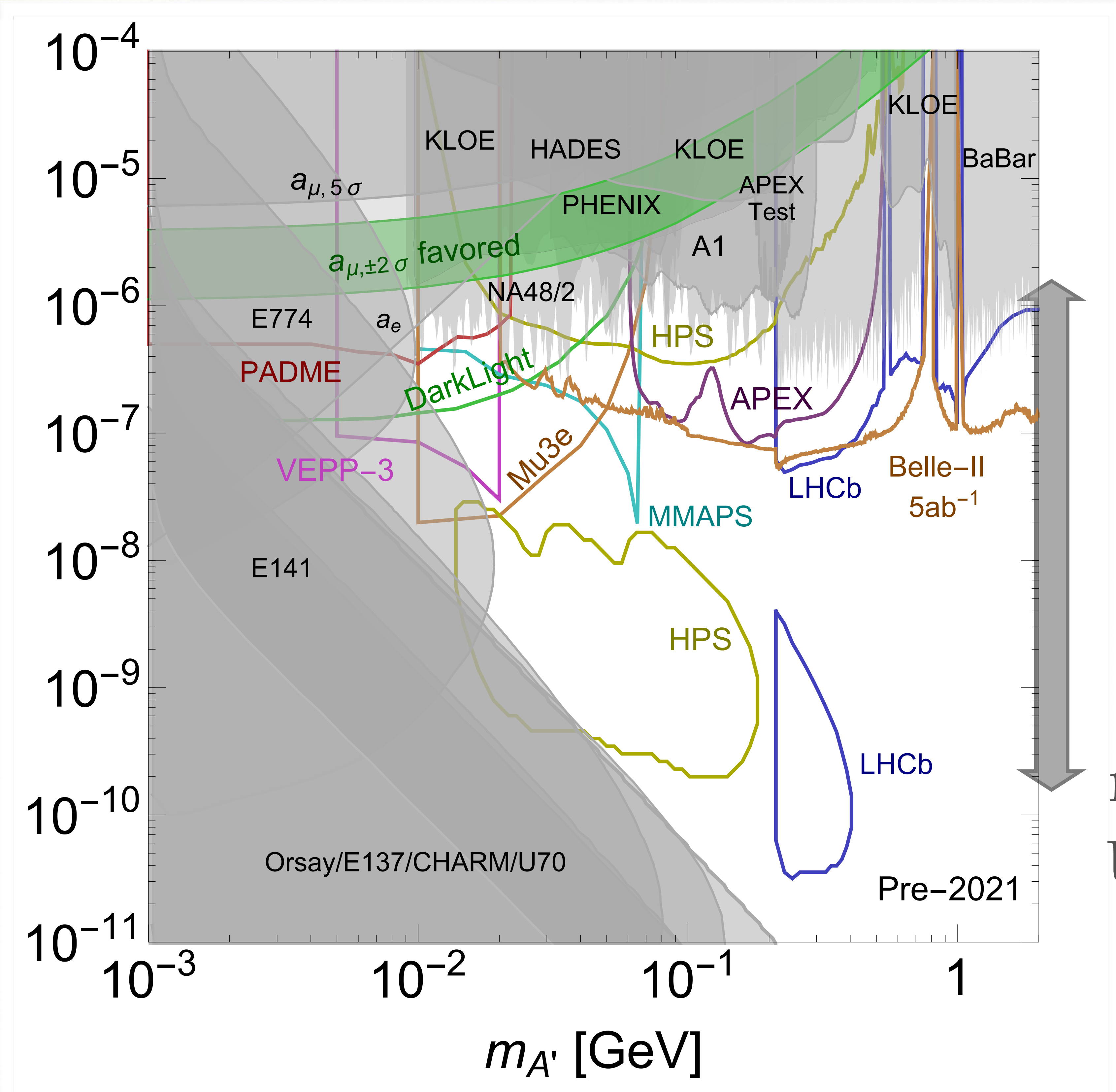
– Muon pair resonance search
– Muon pair displaced vertex search

} *Degraded resolution @ low masses from mult. scattering?*

– Electron pair displaced vertex search (with detector upgrade)
– Also sensitive to dark higgs and probably more!

ongoing work with S. Gori, P. Schuster

PROJECTIONS FOR 2016-20

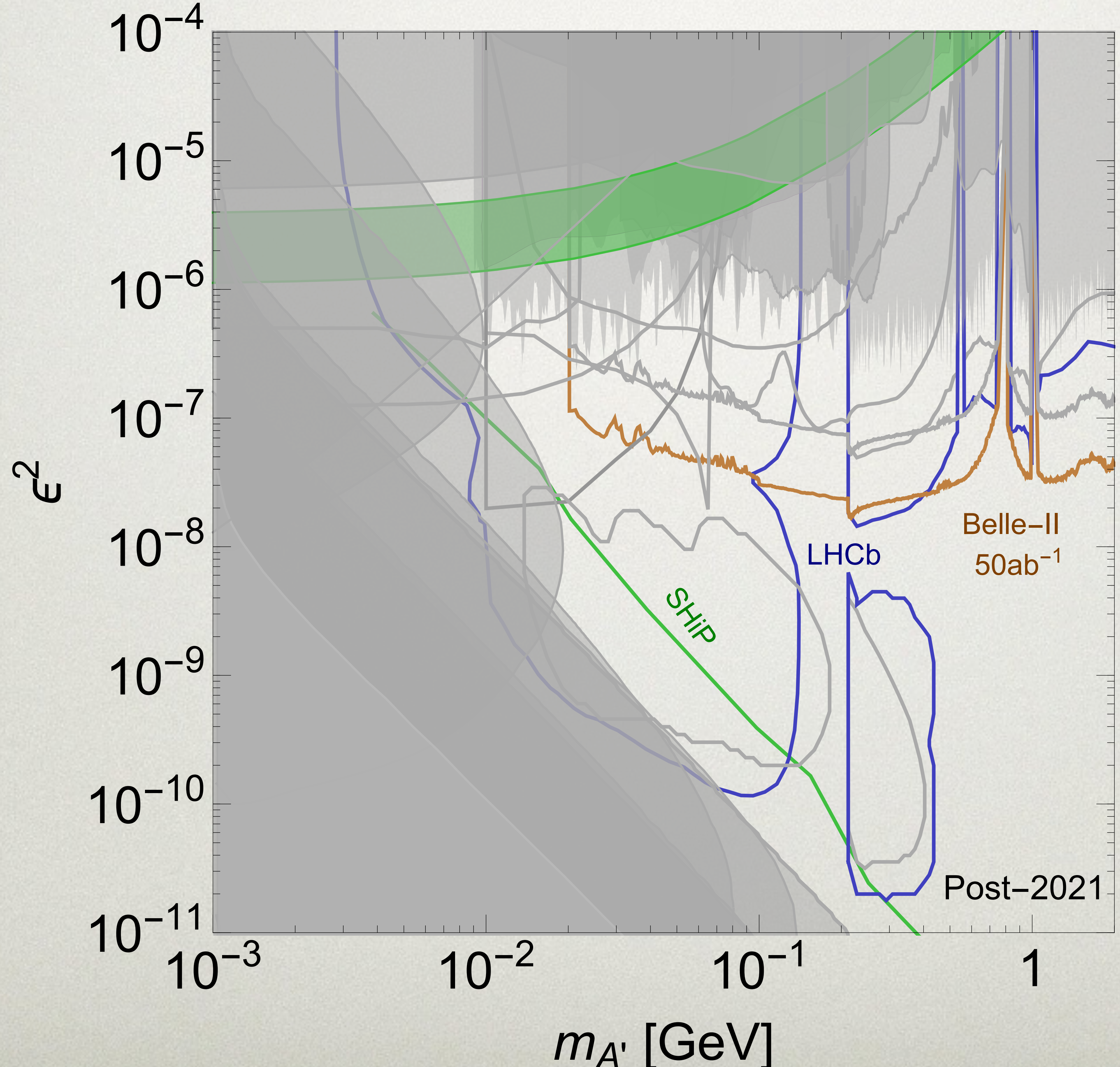


Upcoming experiments will make first forays into GUT-compatible region, from both above and below

mixing in Grand Unified Theories

Projections for 2020's

New opportunities from LHCb upgrades, Belle-II, SHiP

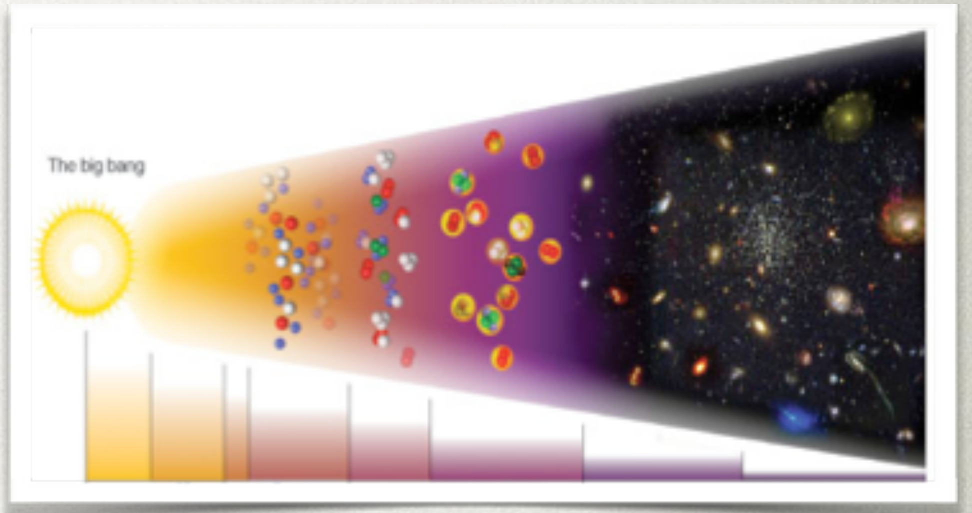


Visible Dark Photon Searches

- In last 7 years, searches have
  - Explored most of the territory for 1-loop mixing below a GeV
  - Pioneered new vertexing technique & extended bump hunt sensitivity dramatically
  - Tested **visible** A' interpretation of muon g-2 anomaly
- Planned experiments over next 5–10 years will almost fully explore two-loop (GUT) kinetic mixing below a GeV

Thermal Dark Matter from a New Sector

- Beyond theoretical appeal, a new sector (or at least new force carrier) is **necessary** for consistent models of thermally produced dark matter below a few GeV.

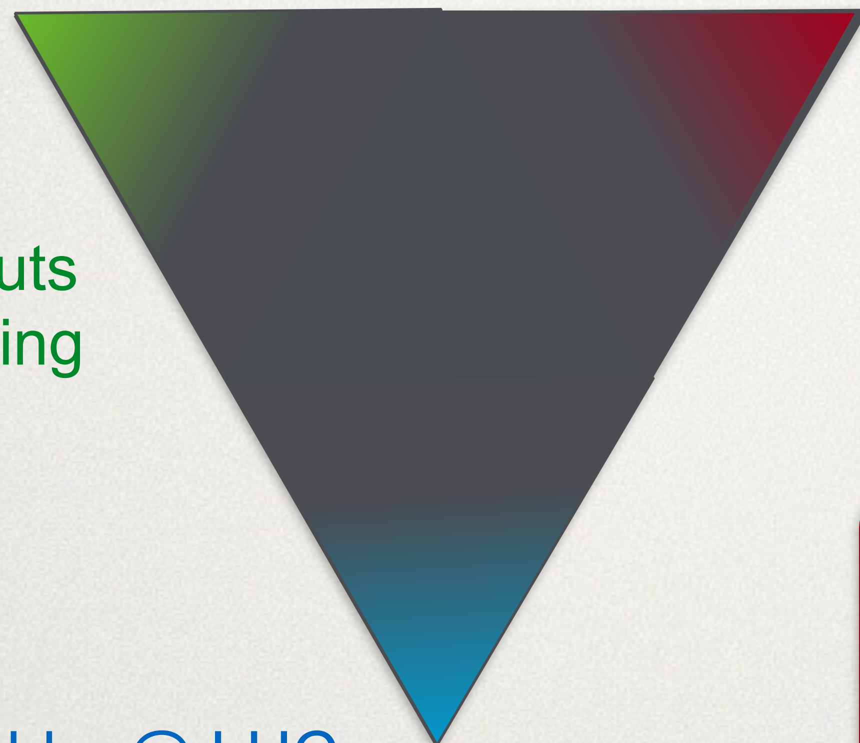


- The same physics that gives dark photon mass typically induces mass splitting of DM states
  - Leading interaction is inelastic
  - Important consequences for all approaches to DM detection

To test light thermal DM: Search for Light DM + Light Mediator

robust to inelastic splitting

Experimental Status

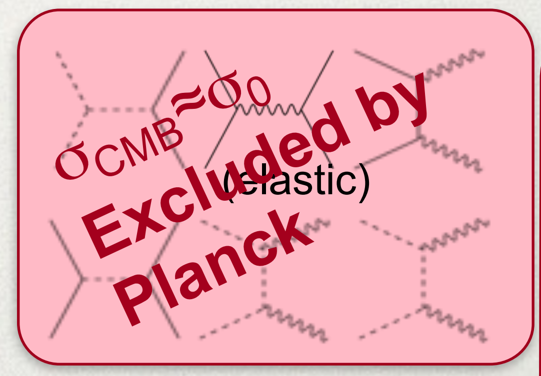


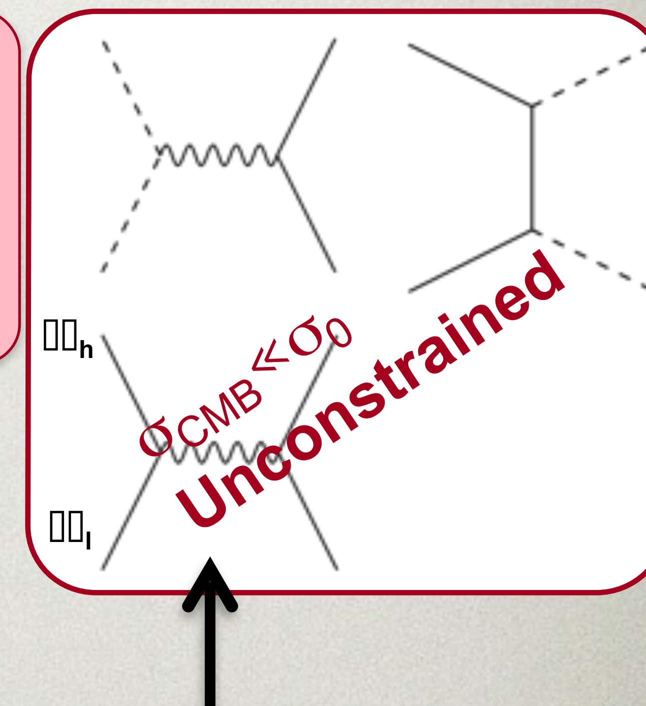
Direct detection:

- Below experiments' energy thresholds
- Inelastic splitting shuts off tree-level scattering

Annihilation:

- CMB energy injection excludes **some models** of light thermal DM (those with $\sigma_{CMB} \approx \sigma_{freeze\text{-}out}$), sharpening target for other searches

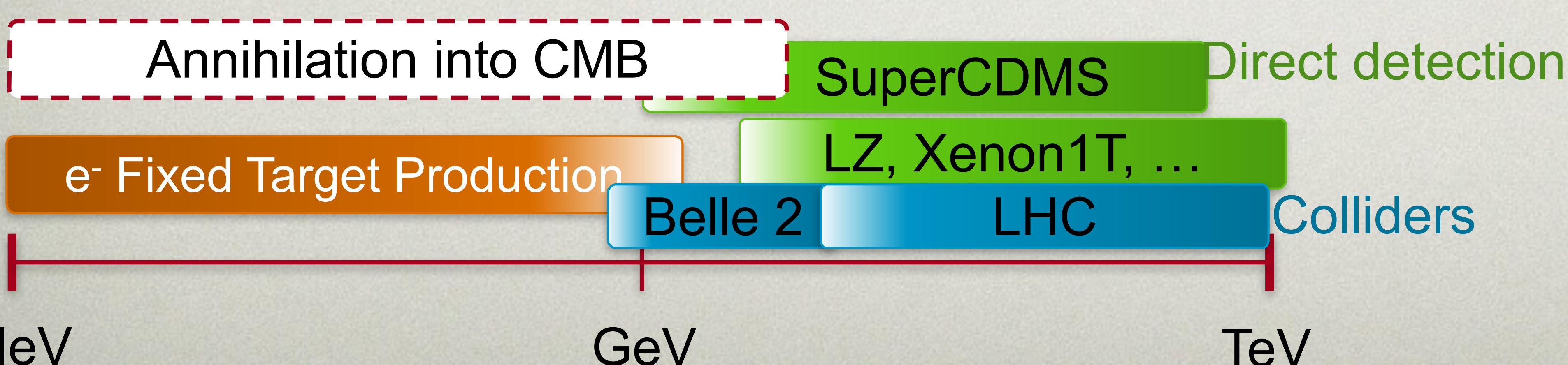




Motivate **minimum** coupling of new gauge boson to Standard Model

DM production:

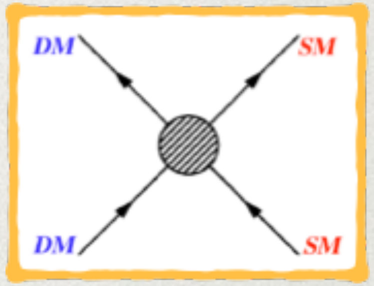
- Low rate & buried in bkg @ LHC and even BaBar
- Unique opportunity for fixed-target searches



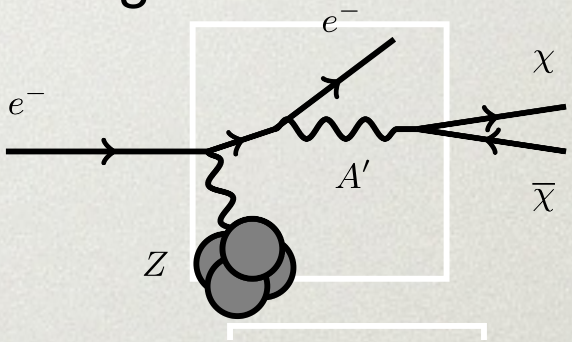
A Sharp Target

Interactions between dark and familiar matter maintain thermal equilibrium as Universe cools, until critical density below which dark matter annihilation “freezes out”

Observed DM density fixes particle annihilation cross-section – this tells us a lot about its interactions!



1. DM lighter than a few GeV would annihilate **too little** through W/Z/h interactions
   → light force carrier
   → DM production at accelerators through new force

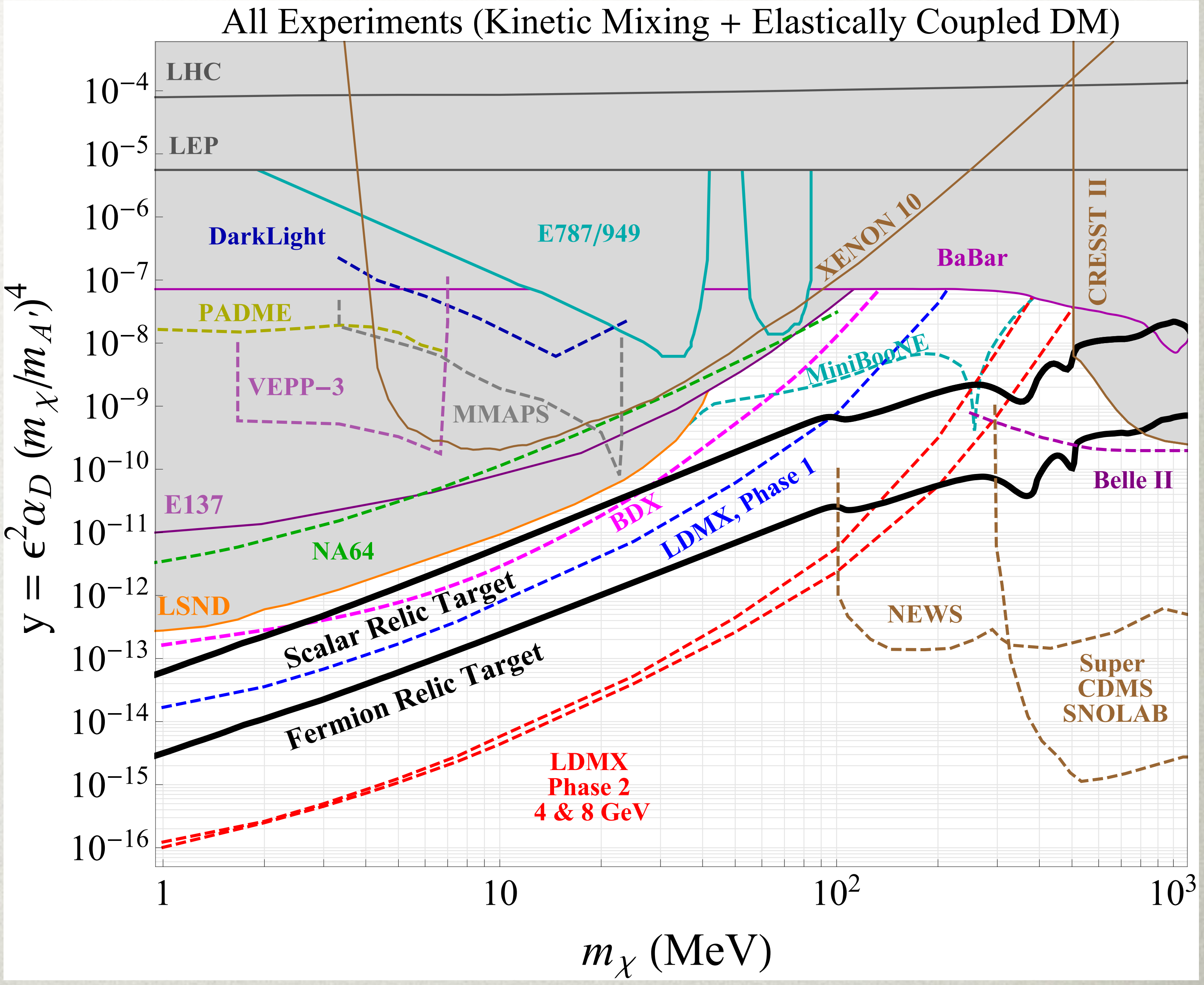


2. Also implies minimum coupling for new force
   → **minimum lab production cross-section for given DM mass (thermal relic target)**

Reaching this target sensitivity = decisively testing a broad class of low-mass thermal dark matter models.

A Sharp Target

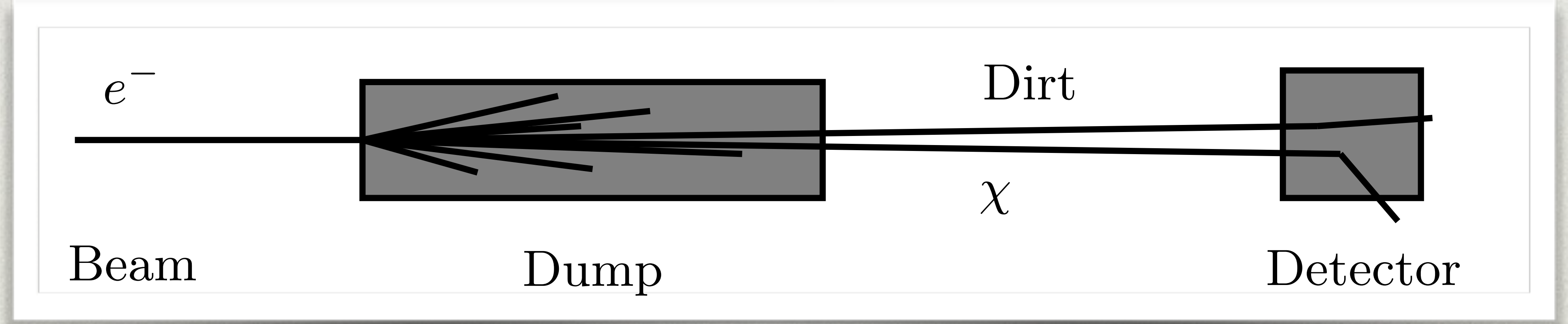
Best-motivated models of light thermal DM are beyond reach of Direct Detection and Colliders, but motivate a sharp & testable target for fixed-target DM production experiments



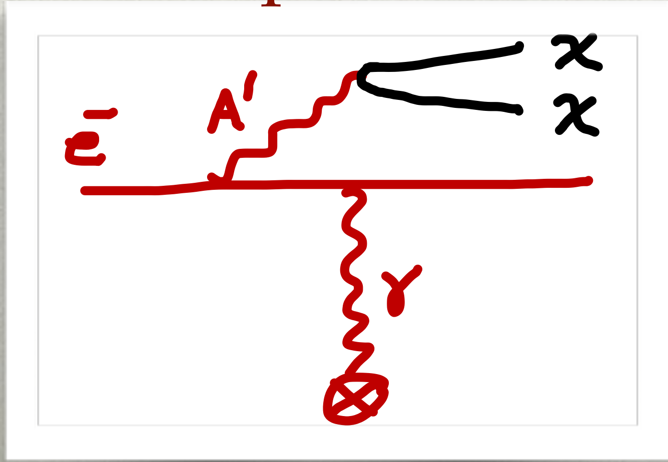
Light Dark Matter Searches
at beam dumps

Dark Matter interacts weakly

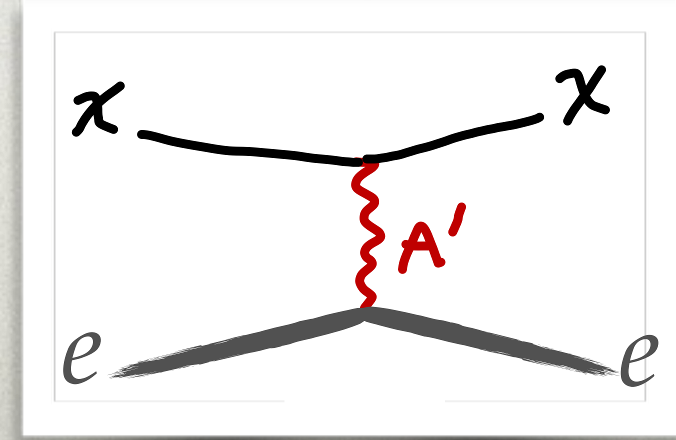
$\Rightarrow$ passes through anything!



Produce DM through the portal…



…detect its scattering downstream

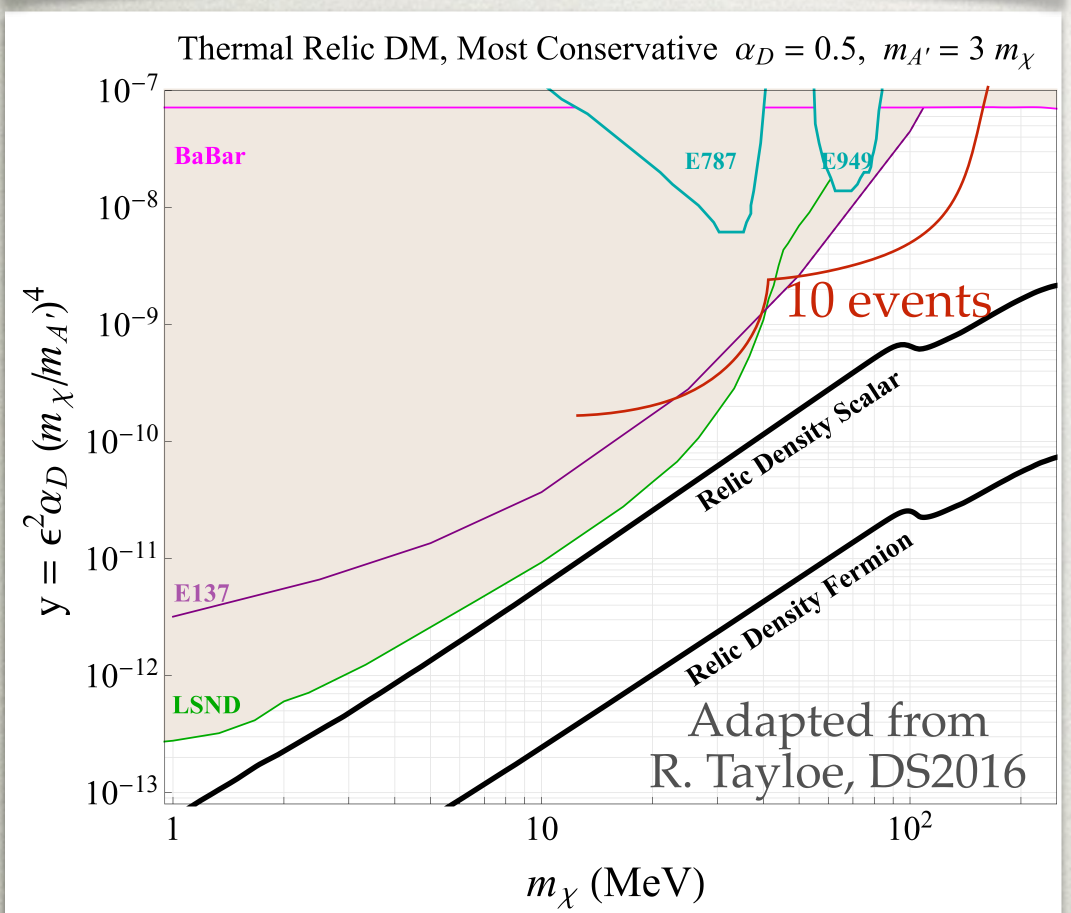


Izaguirre, Krnjaic, Schuster & NT PRD.88.114015 and 1403.6826

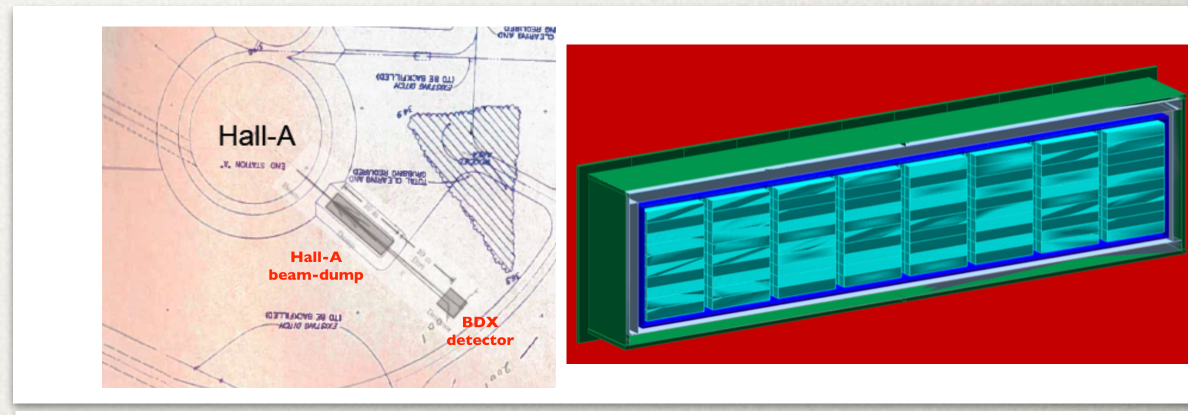
Beam Dump Opportunities

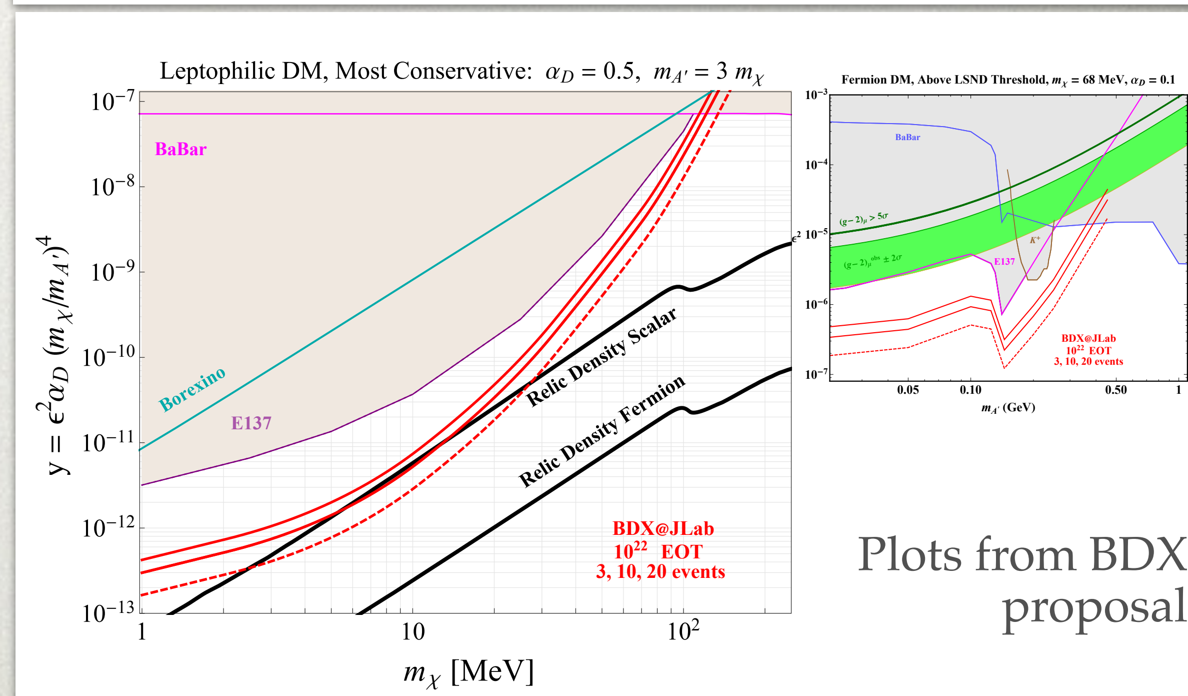
MiniBoone run in dump mode (enhance $\pi^0 \to A'\gamma$ relative to $\pi^\pm \to \nu\mu$) completed 2015; analysis ongoing

BDX proposal (parasitic behind JLab Hall A dump) to PAC44



Adapted from R. Tayloe, DS2016



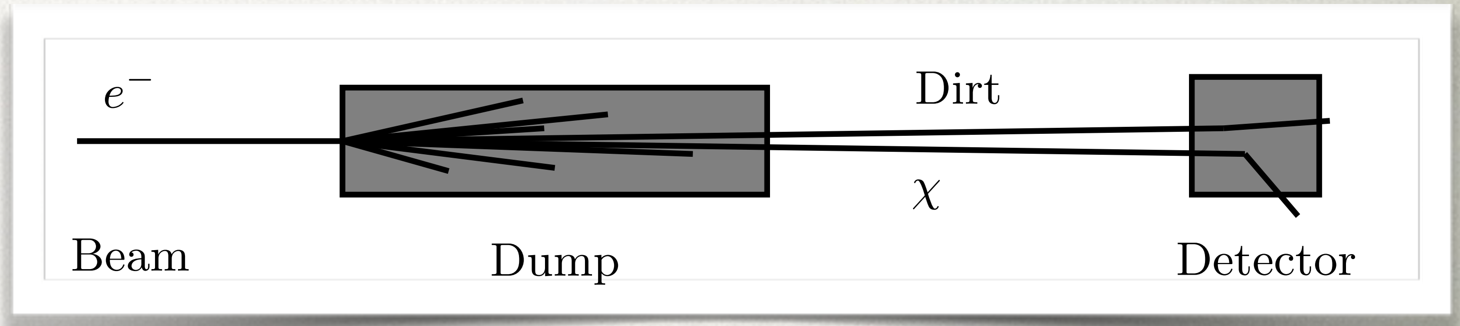


Plots from BDX proposal

How to Test the Thermal Relic Target?

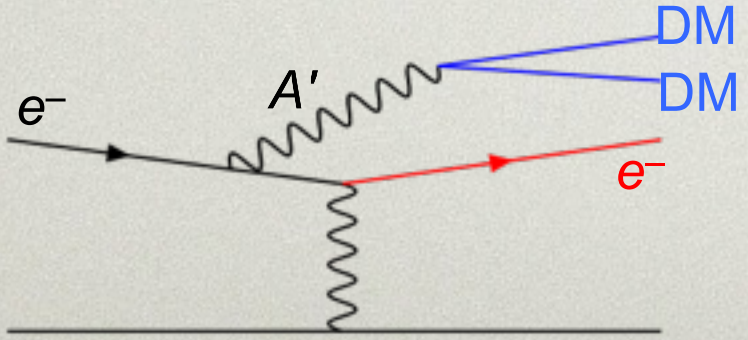
Dump signal:

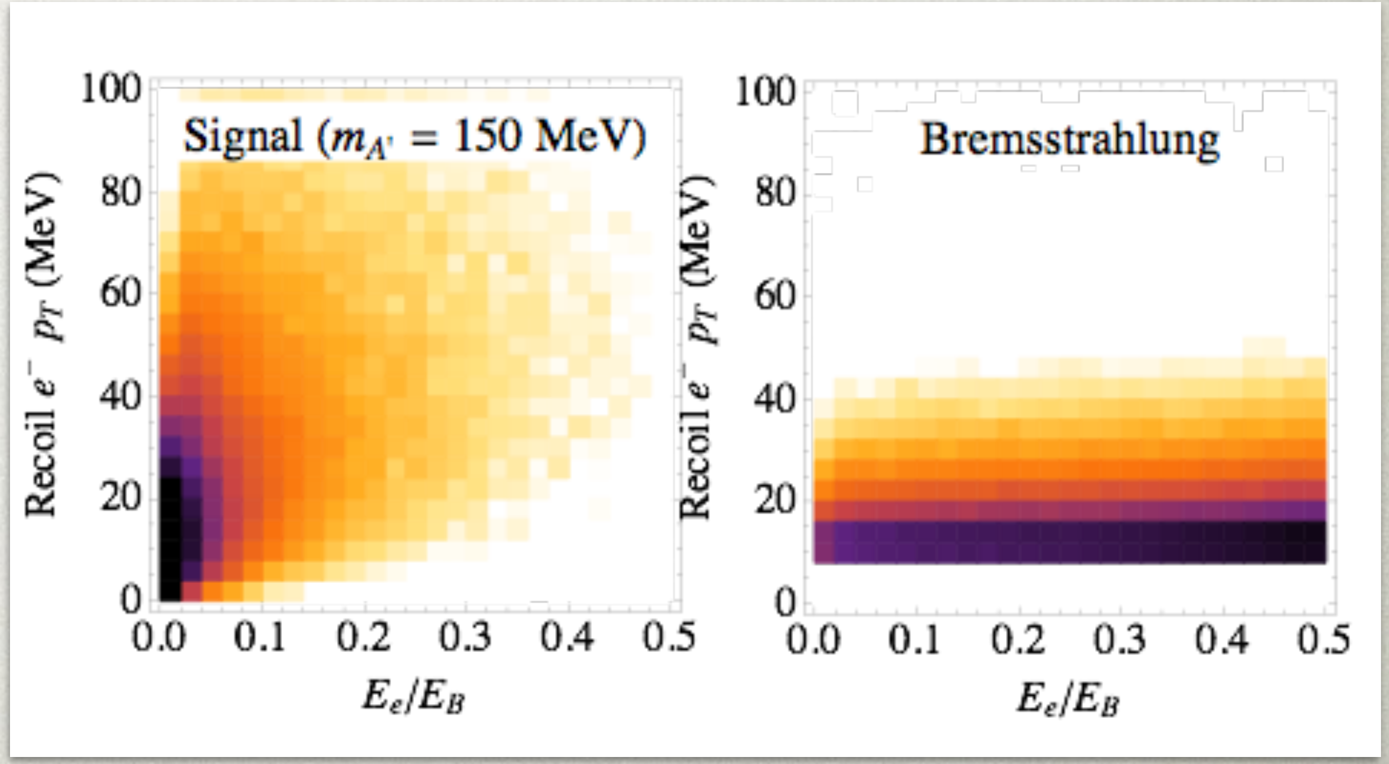
product of two rare processes
scales as (coupling)^4
$\Rightarrow$ slow improvement with
flux & detector volume



Alternate approach:

Detect DM bremsstrahlung
using ***recoil e⁻*** kinematics
& ***veto*** on additional particles

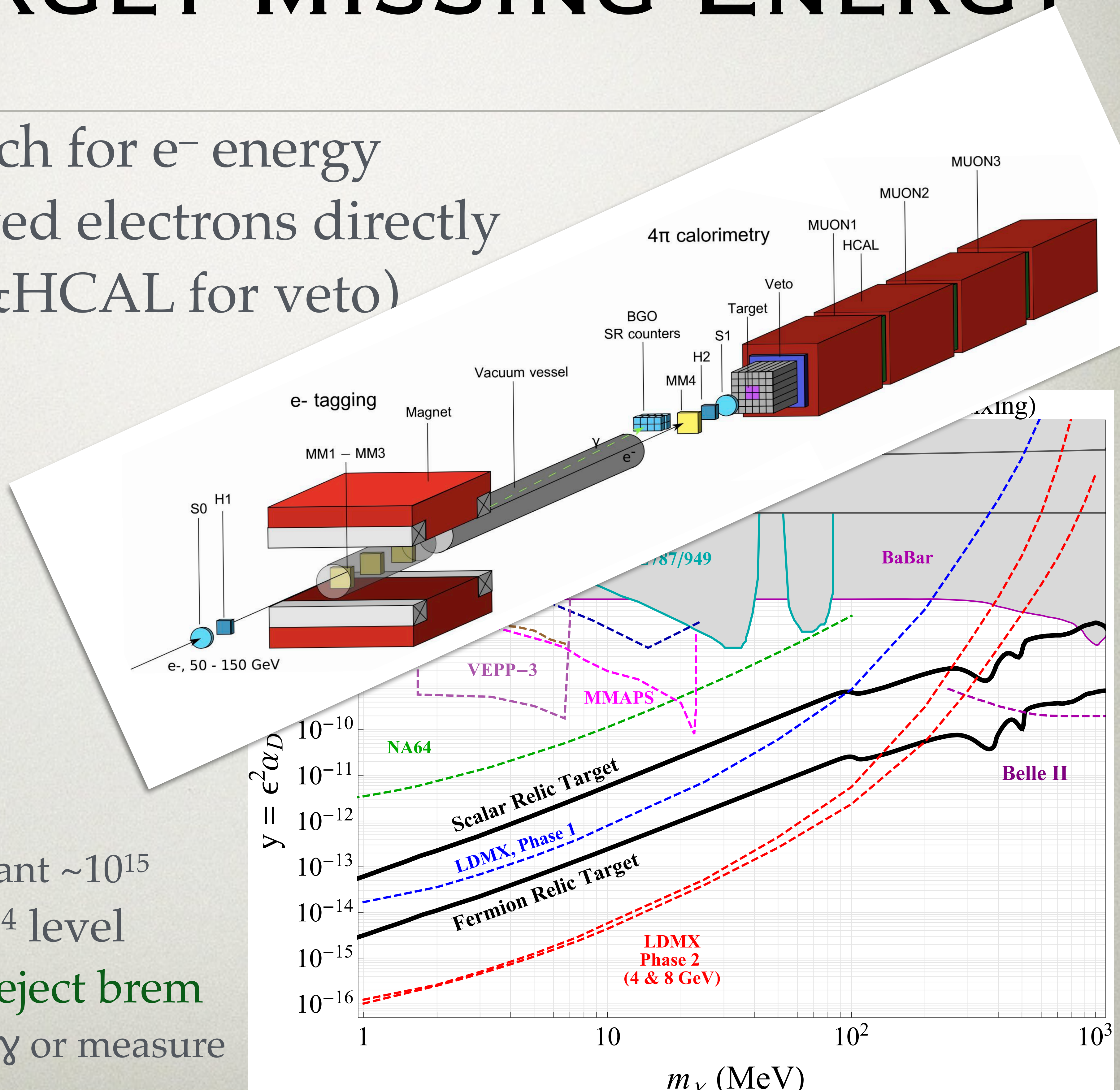




O(pb) x-section≫ ν pair production

Fixed-Target Missing Energy

NA64 @ CERN: search for e⁻ energy loss by running tagged electrons directly into ECAL (+muon&HCAL for veto)



Approved by CERN RB after 2015 test run

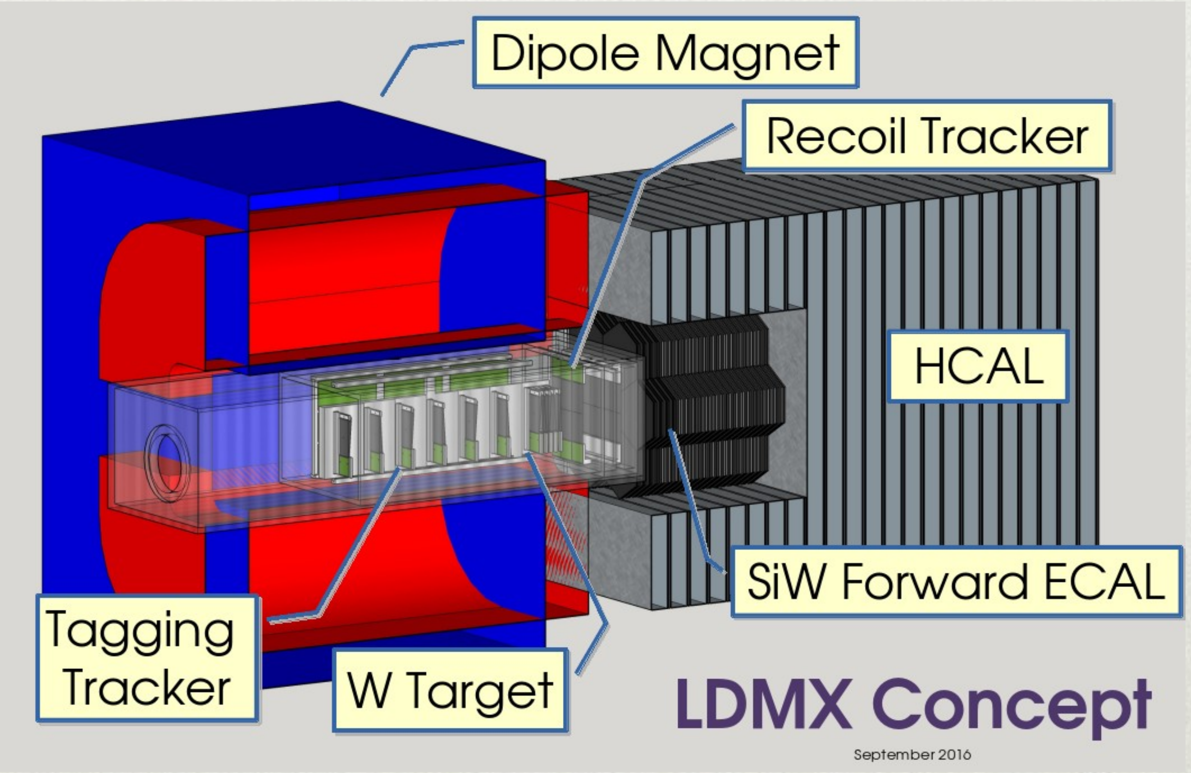
- Test beam – low lumi ($<10^{12}$ e⁻/ 20 nb^{-1})

  for decisive experiment want ~10^{15}
- Neutrino+ɣ bkg at 10^{-14} level
- Only one variable to reject brem

  can't discriminate e⁻ from ɣ or measure recoil p_T

Fixed-Target Missing Energy-Momentum

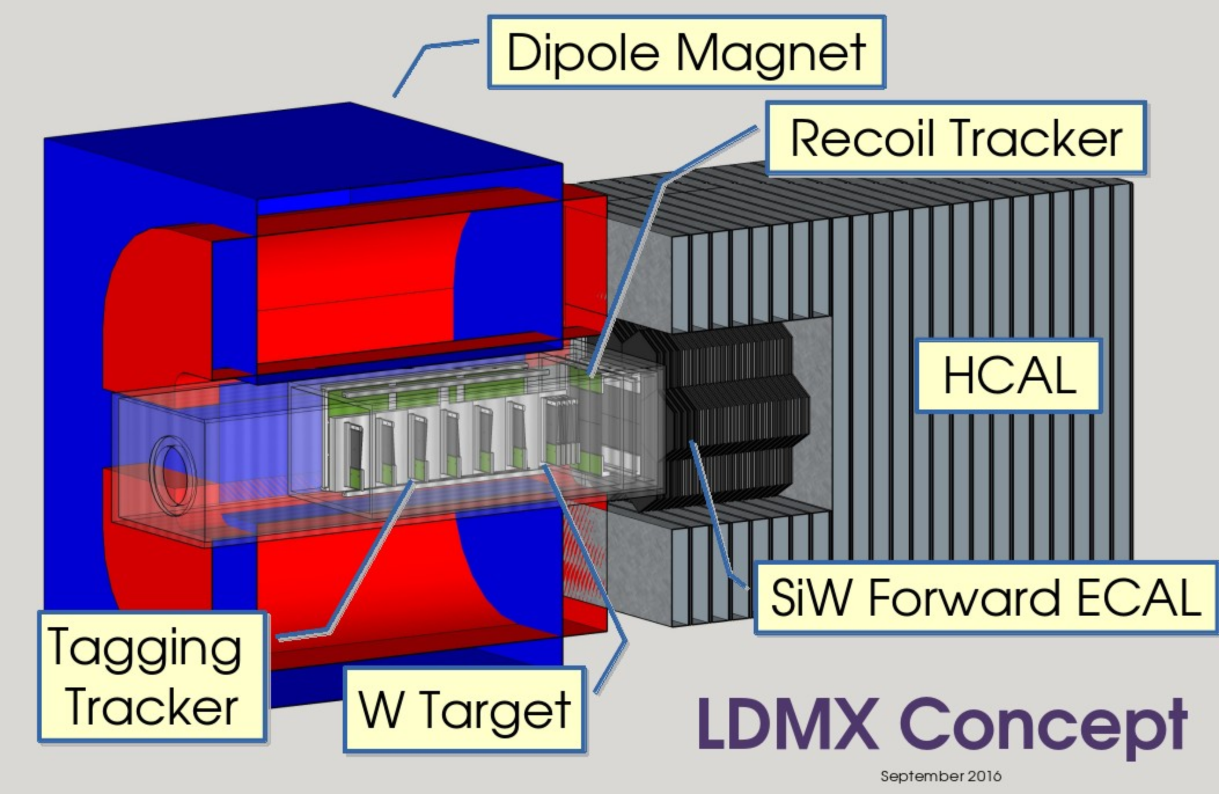
- Reaching thermal relic sensitivity requires
  - Higher-intensity e^- beam: low-current CW with O(1) e^- / ns
  - qualitatively new detector design w/ target & tracker upstream of ECAL to
    - discrimnate e/ɣ (veto neutrino and trident-like bkg)
    - Measure recoil e^- p_T



- Main physics bkg: hard brem + photo-nuclear (small EM shower & few hadrons)
  - photon/hadron veto & e^- p_T give 2 handles to reject this background

Light Dark Matter experiment (LDMX)

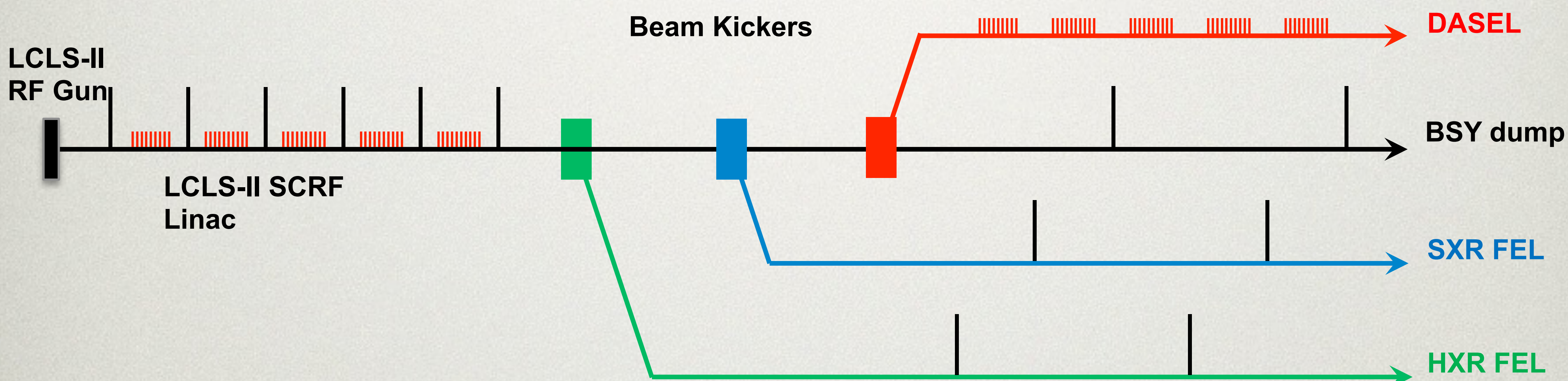
- Evolving design and growing collaboration – SLAC, UCSB, Minnesota, FNAL, UCSC, Caltech
- Current concept
  - Tracker design based on HPS forward tracking (SLAC, UCSC)
  - Si calorimeter based on prototype for CMS HL-LHC forward calorimeter (UCSB & U. Minnesota)
  - HCAL design being developed by FNAL collaborators



- Detection & analysis challenge: high veto efficiency for photonuclear reactions in tracker or in ECAL, and for wide-angle scattering in target
- Accelerator challenge: where to get ultra-low-current, multi-GeV CW e^- beam?

CW Electrons, Parasitically
Dark Sector Experiments at LCLS-II (DASEL)

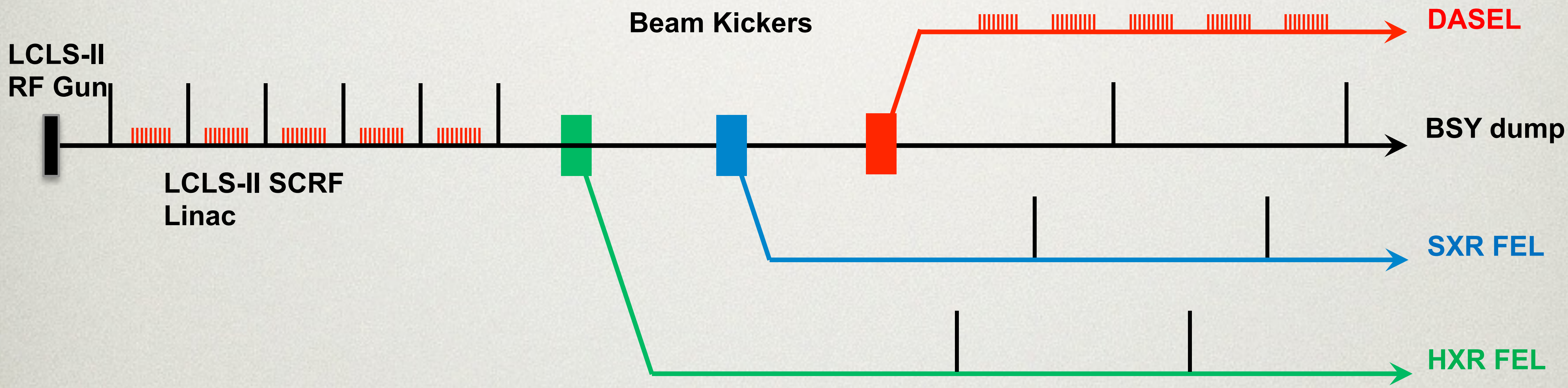
- Linac delivers 4 GeV electrons (62 μA) for LCLS-II spaced every 1.1μs
- Gun laser, RF gun, and linac all operate at higher frequencies (multiples of 46.5 MHz)



- Idea: use the higher-frequency bunches to power a low-current CW beam to End Station A

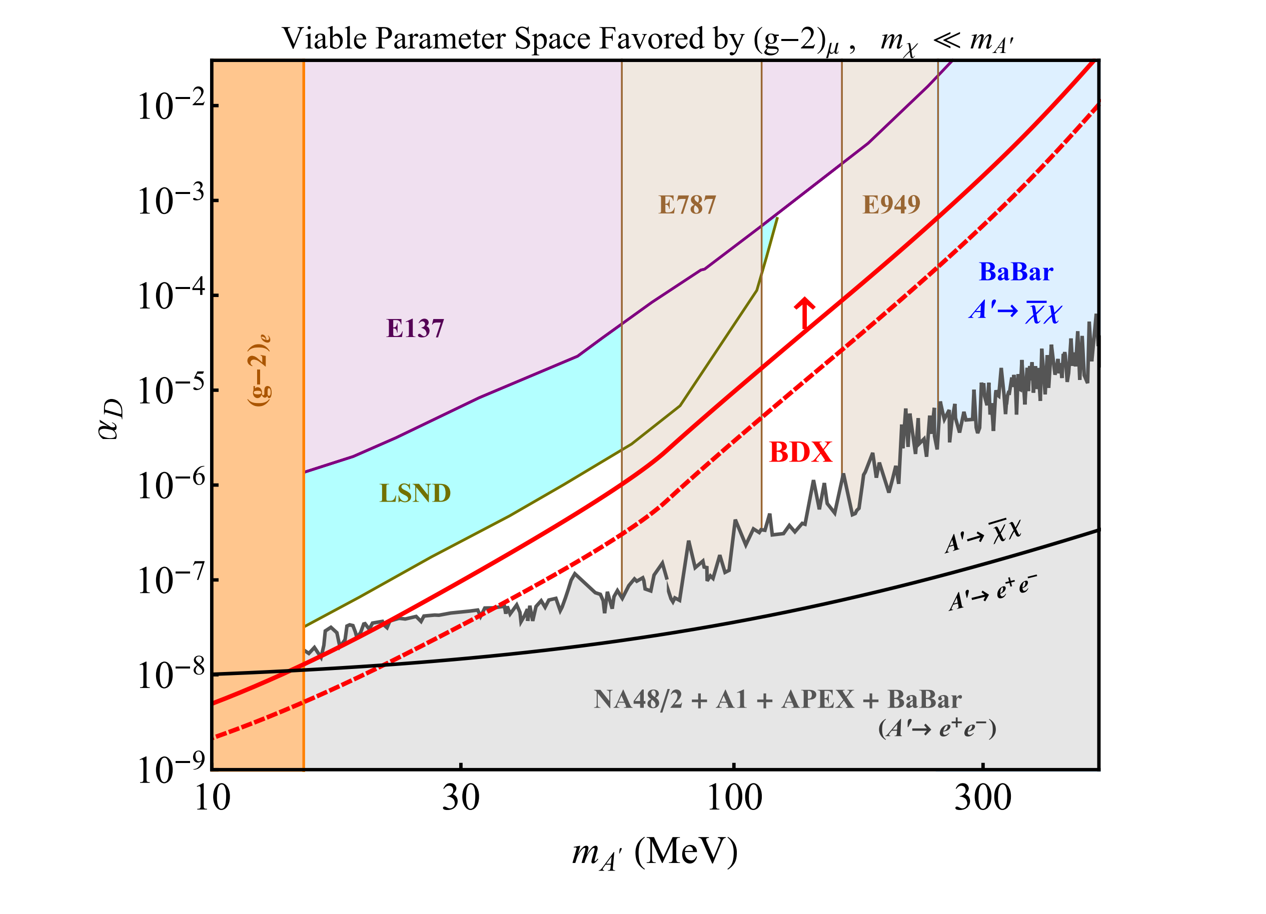
CW Electrons, Parasitically
Dark Sector Experiments at LCLS-II (DASEL)

- First phase: 4 GeV, 46 MHz, ~25 nA in accelerator → spoiled sub-nA beam with 10 cm^2 spot for LDMX
- Possible upgrades: increase rep rate to 186 MHz, 8 GeV beam, current up to ~1 μA

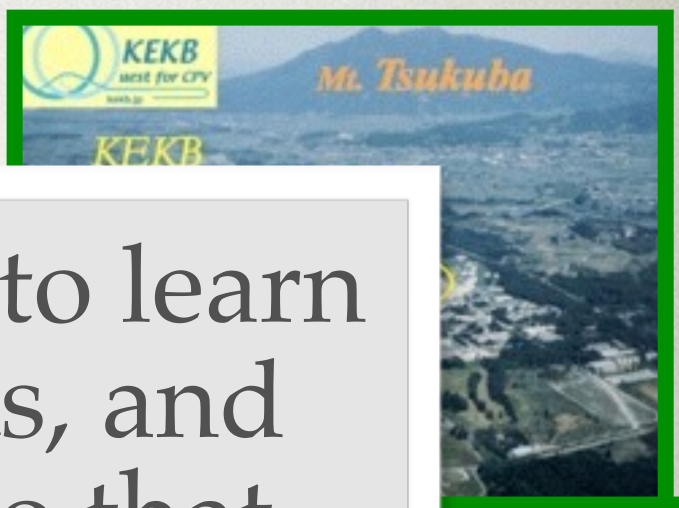


Light Dark Matter Searches

- Active and diverse program of accelerator experiments searching for light DM
- LDMX can fully explore the window for light DM annihilating through vector portal
- These experiments will also more fully close muon g-2 window (allowing for arbitrary mix of invisible & SM decays)



The Future Ahead



- Rich experimental opportunities to learn what dark matter is, how it works, and how the physics we know fits into that larger picture
  - Experiments in next few years with dramatic new sensitivity to new forces
  - Opportunity to decisively probe one of the few ways that dark matter can interact with the Standard Model