Dark Sectors 2016

Theory and Visible Dark Photons Primer

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Prepared with Rouven Essig & Philip Schuster

Welcome!

Looking Back

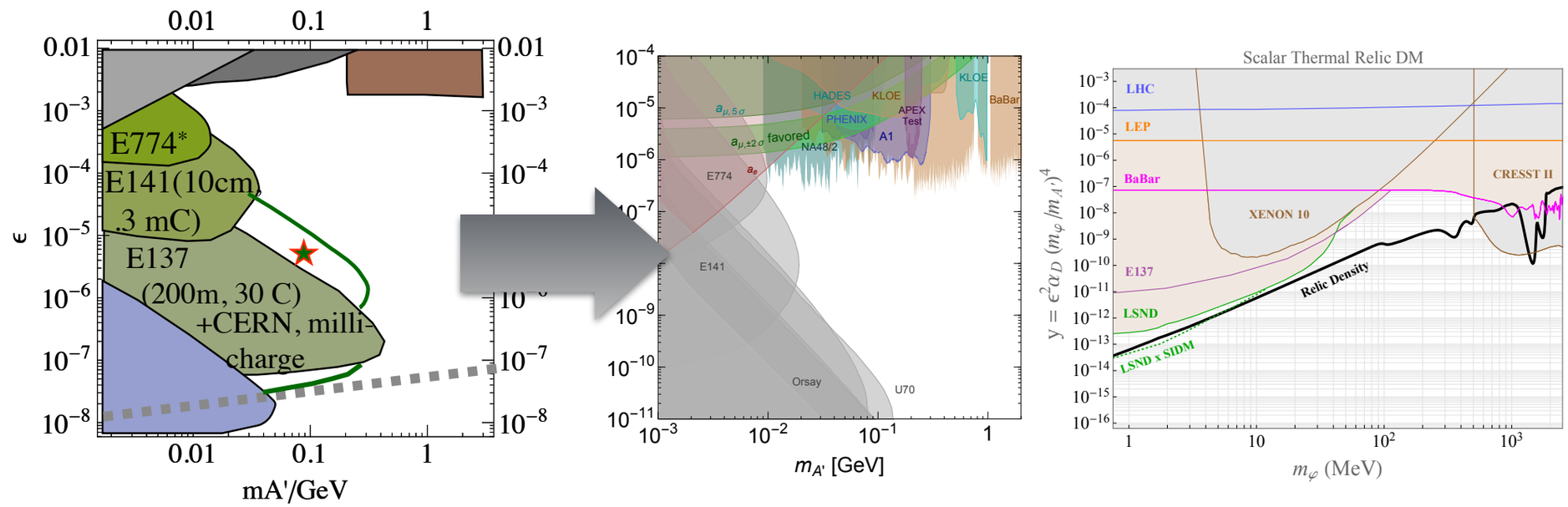
In 2009, SLAC held a “Dark Forces” workshop. At that time…


Dark Forces Workshop 2009

- Astrophysics data spurred renewed theoretical interest
- Re-analysis of data from multi-purpose detectors opened window to the dark sector
- First-generation experiments were starting to take shape.

Now is a great time!

Broad, international activity searching for dark sectors!



Many of the first-generation dedicated experiments are still ongoing. Their reach can be anticipated reliably, and it's clear what limits they run into.

It's a perfect time to ask: **Where do we go next?**
That's the focus of this workshop.

Next 3 talks: assessing the state of the field today, to set stage for these discussions.

Where to now?

- What new ideas will propel us past the obstacles found in designing the first-generation experiments?
- What important possibilities are we overlooking, that we should be searching for?
- What opportunities do we have with upcoming facilities and/or new technologies that didn't exist 7 years ago?
- What do we want this field to look like in 5-10 years? What is within reach? What should we focus on?

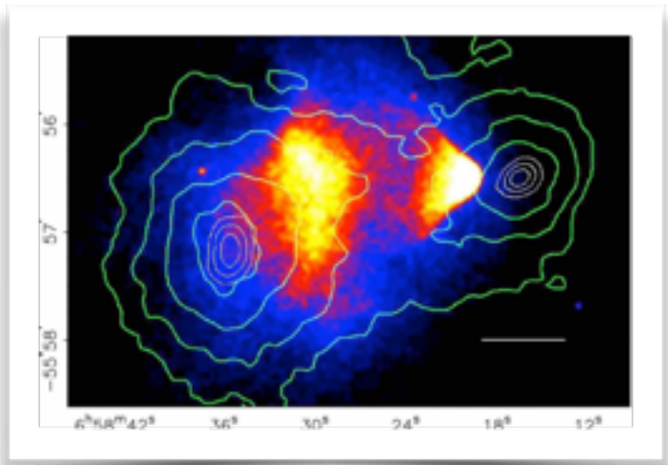
Outline

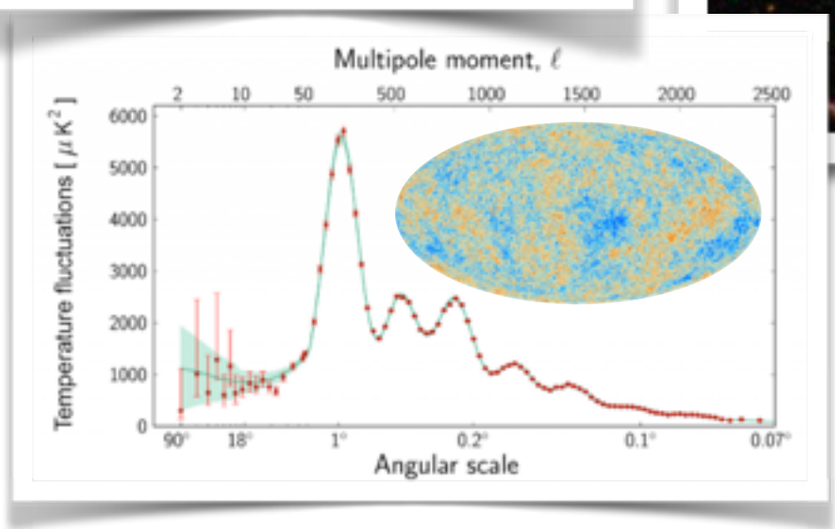
- Why Dark Sectors?
- Organizing Questions
- Visibly Decaying Dark Photon Searches
  - Properties
  - Search Strategies
  - Outstanding Challenges

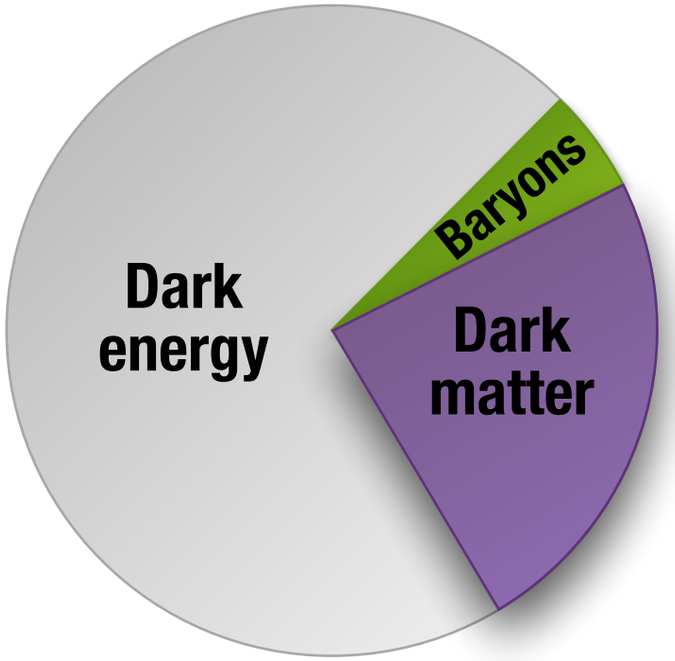
Why Dark Sectors?

- Nature seems well described by SU(3)xSU(2)xU(1) gauge theory
  - **We need to check this assumption!**
- Precedent in Standard Model for rare/subtle effects to be important (Radioactivity, Rutherford scattering, neutrinos, parity violation…)
- We ***already*** know we are missing something…

There is a dark sector!







- What is it?
- Where did it come from?

Theory Prejudice

Least addition of new particles?

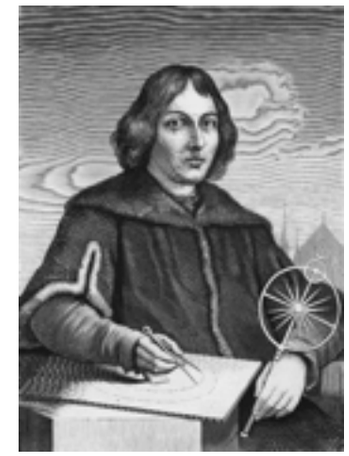
Motivates SM weak multiplet or axion

[SM itself is far from minimal in this sense]

Theory Prejudice

Least addition of new particles?

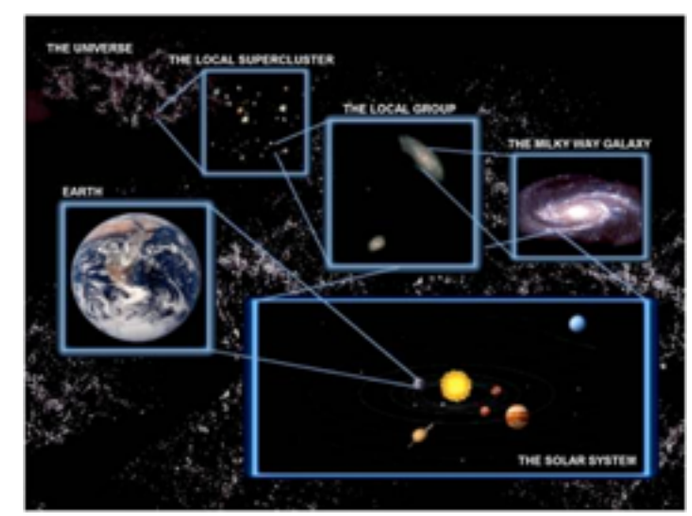
Motivates SM weak multiplet or axion



Parallel structure to Standard Model ⇒

*Motivates **weak coupling** searches at modest energy*

[SM itself is far from minimal in this sense]



Looking for Dark Sectors

Whatever is in the dark sector, only three sizeable interactions allowed by Standard Model symmetries:

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

New gauge interactions

Gauge Portal $g \sum_i q_i \bar{\psi}_i \bar{\sigma}^\mu \psi_i V_\mu$

A new vector can also couple to **anomaly-free global symmetries** of the Standard Model (or, with appropriate new matter, to anomalous symmetries)

e.g. B-L, L_μ-L_τ, ...

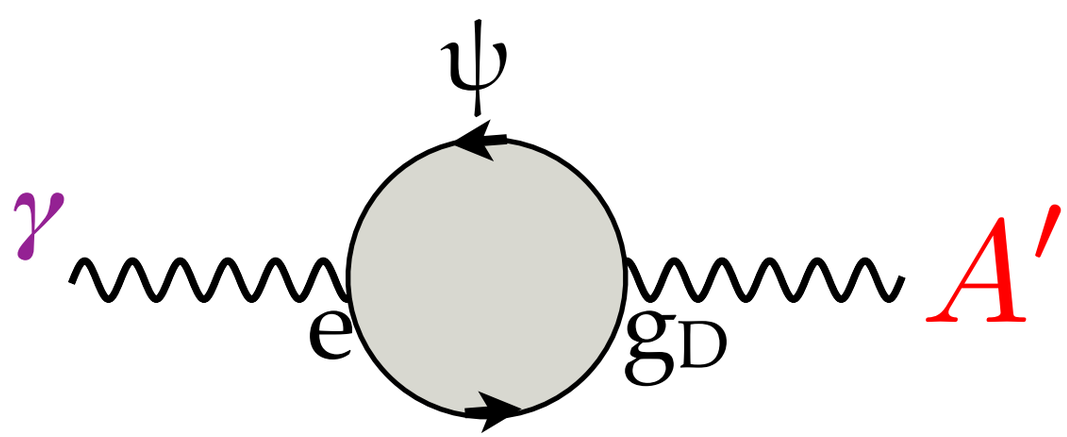
Looking for Dark Sectors

Whatever is in the dark sector, only three sizeable interactions allowed by Standard Model symmetries:

Vector Portal	$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$	*focus for this talk – big opportunity for low-energy experiments*
Higgs Portal	$\epsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$	exotic rare Higgs decays
Neutrino Portal	$\epsilon_\nu (hL)\psi$	not-so-sterile neutrinos
Gauge Portal	$g \sum_i q_i \bar{\psi}_i \bar{\sigma}^\mu \psi_i V_\mu$	sometimes “bycatch” in vector portal searches, but some interesting cases require dedicated searches!

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

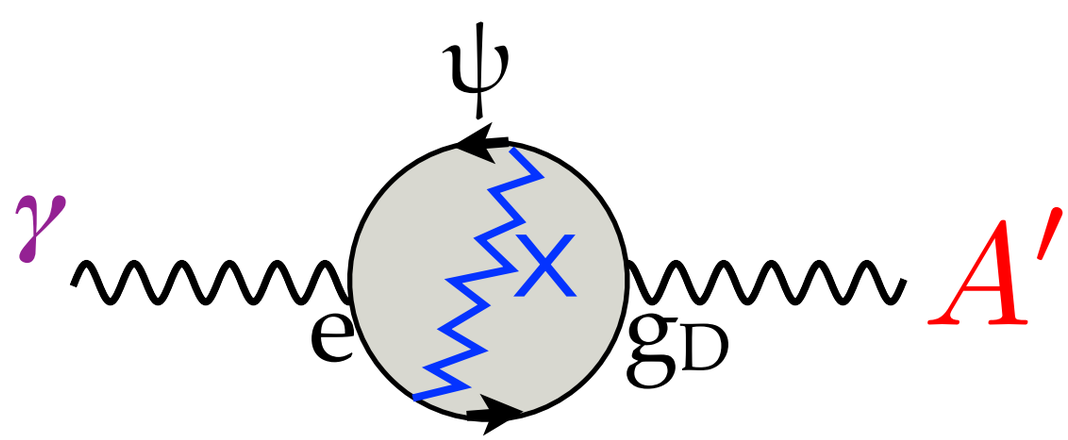
- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects
  - Simplest case: one heavy particle ψ with both EM charge & dark charge



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

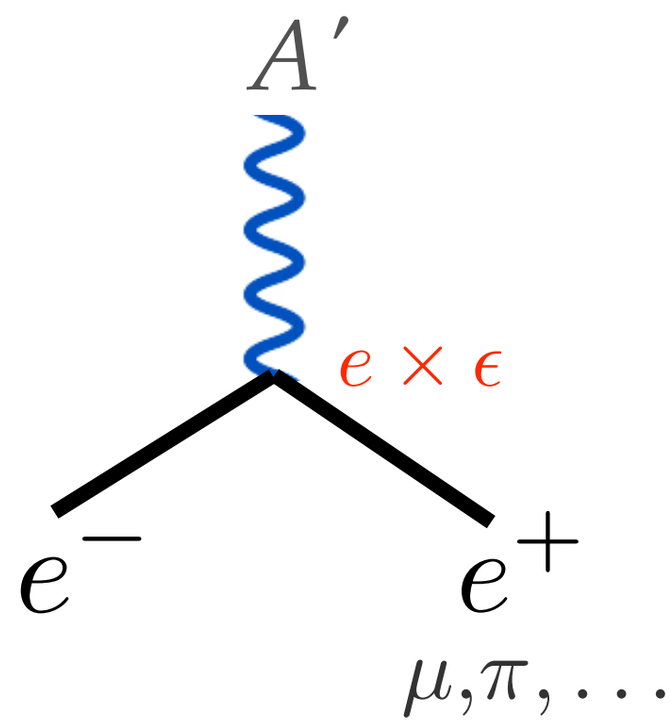


generating $\epsilon \sim 10^{-3} - 10^{-5}$

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

Effects of Kinetic Mixing

Regardless of where it comes from, **kinetic mixing can always be re-interpreted as (mainly) giving matter of electric charge qe an A′ coupling $\propto q\varepsilon e$**



Dark-sector matter can have an independent coupling g_D to A′

Hints of Dark Forces?

- High-energy cosmic ray anomalies
- Direct detection anomalies
- Muon g-2
- Muonic hydrogen Lamb shift
- ^{8}Be decay resonance
- Astrophysical hints of dark matter self-interaction?
- 511 keV line
- keV γ-ray excess
- Galactic center excess

Taxonomy of Dark Sectors

A few simple questions about the new physics…

1. What is the mediator?

   Kinetically mixed dark photon? *Scalar? Flavor gauge boson? SM dipole interaction?*

2. Is it lighter or heavier than…
   - any dark matter in dark sector? (invisible decays)
   - relevant SM particles? $2\,m_e$ (visible decays)
   - new unstable particles? ("rich" multi-body decays)

Taxonomy of Dark Sectors

If dark matter is relevant…

3. How is it produced?
   - Thermally (through annihilation to SM)?
   - Asymmetric?
   - Other?

     May imply constraints/relations among dark-sector couplings

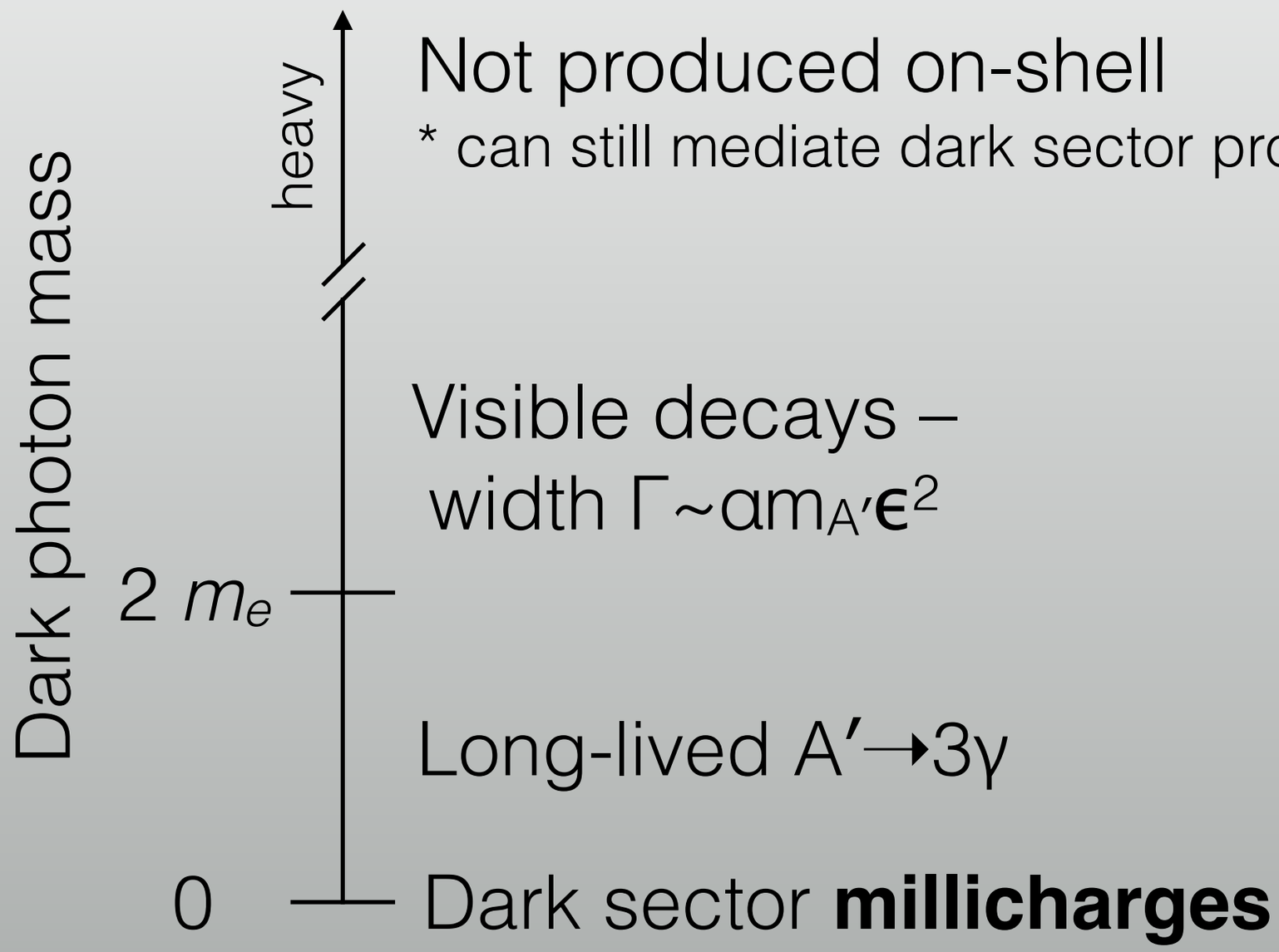
4. Fermion or scalar?

5. Elastic (mass-diagonal) or inelastic (mass-off-diagonal) interactions?

   Affect signals in various experiments and the comparisons among them

Taxonomy of Dark Sectors

Kinetically mixed dark photon decays to SM



Taxonomy of Dark Sectors

Kinetically mixed dark photon decays to SM

Dark photon mass

heavy

Not produced on-shell

* can still mediate dark sector production

Visible decays – width $\Gamma \sim \alpha m_{A'} \epsilon^2$

Visible & missing mass searches

$2\ m_e$

Long-lived $A' \rightarrow 3\gamma$

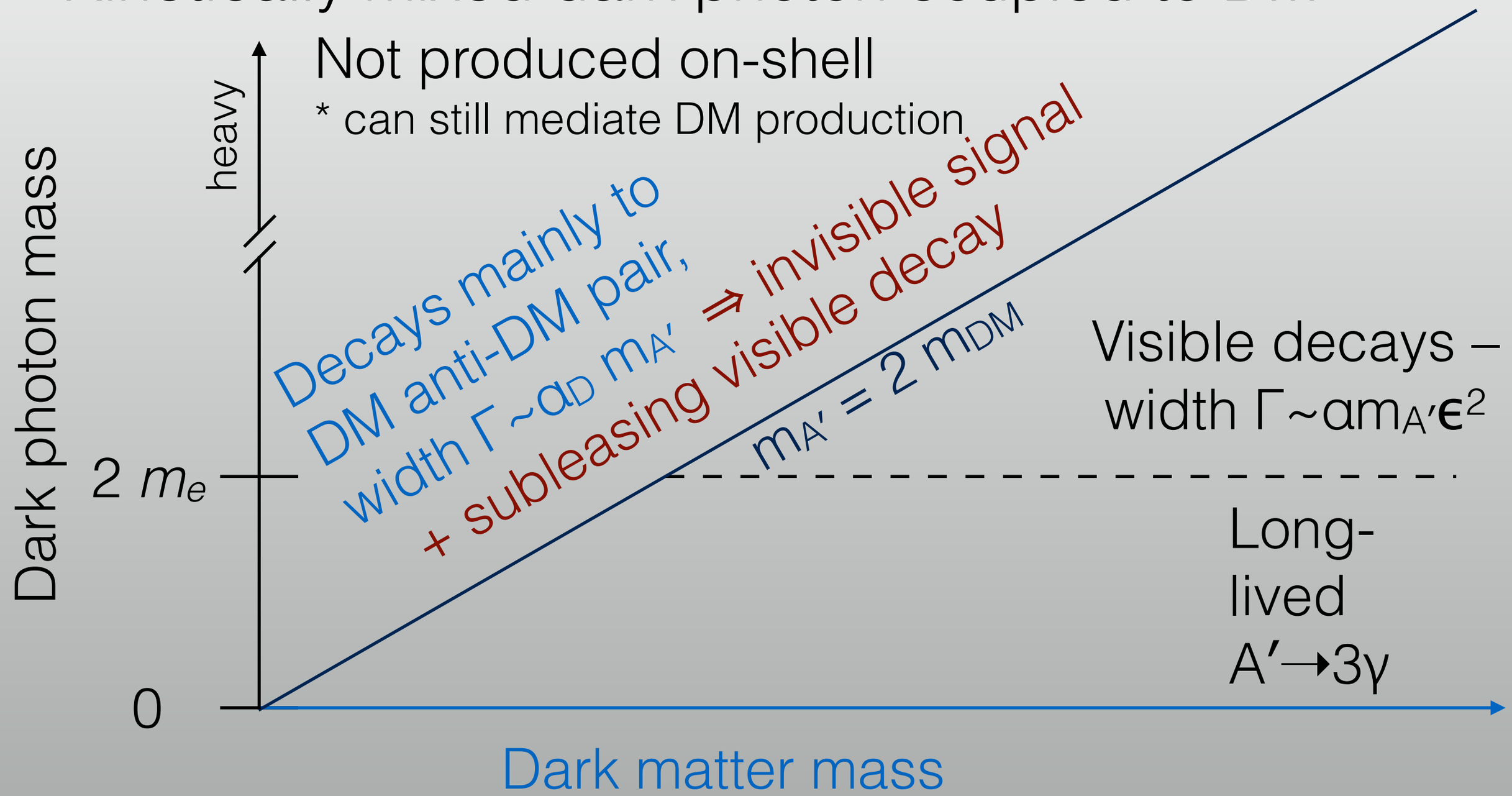
Cosmological & stellar bounds, solar production, light thru walls

0

Dark sector **millicharges**

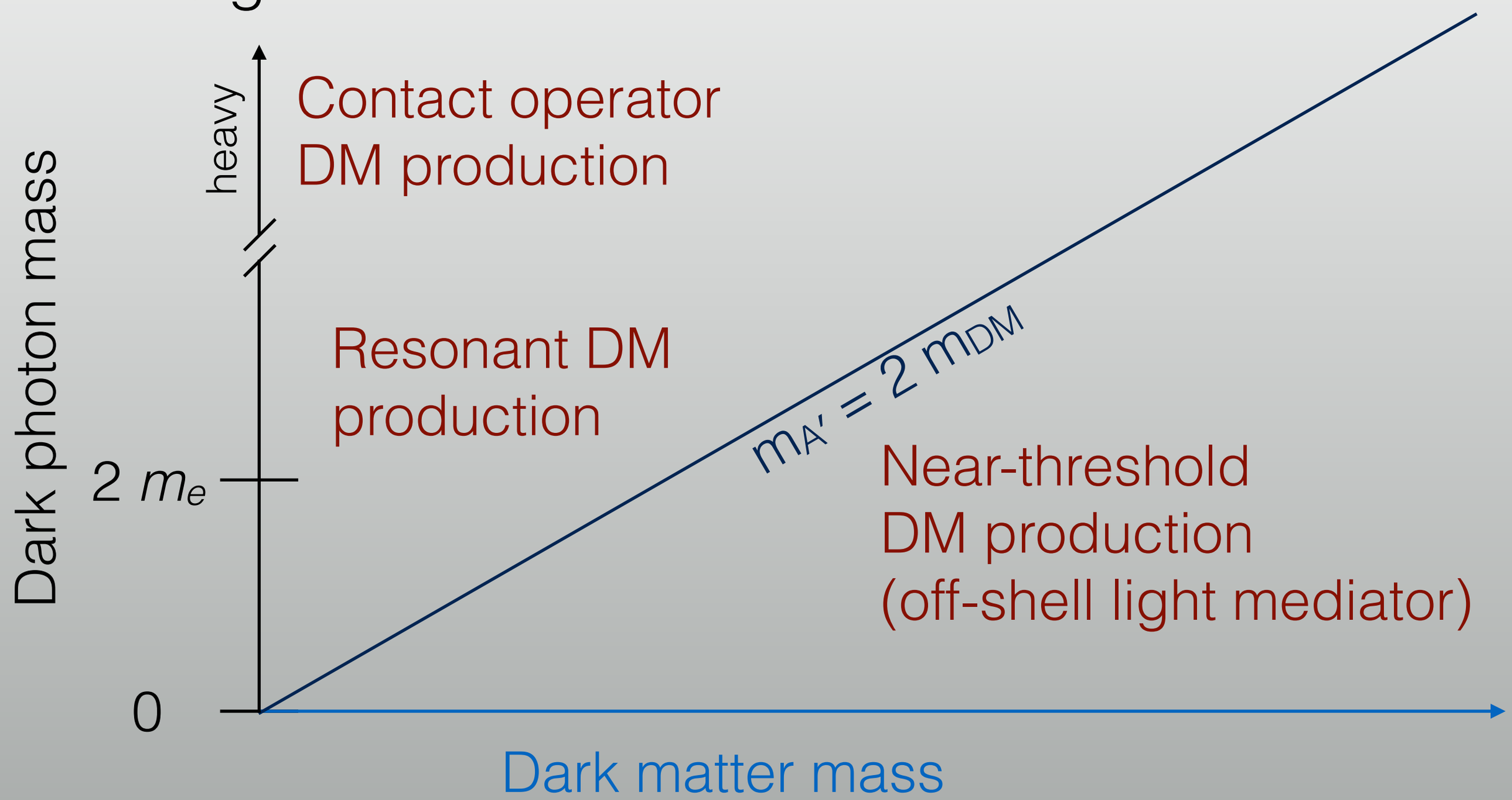
Taxonomy of Dark Sectors

Kinetically mixed dark photon coupled to DM

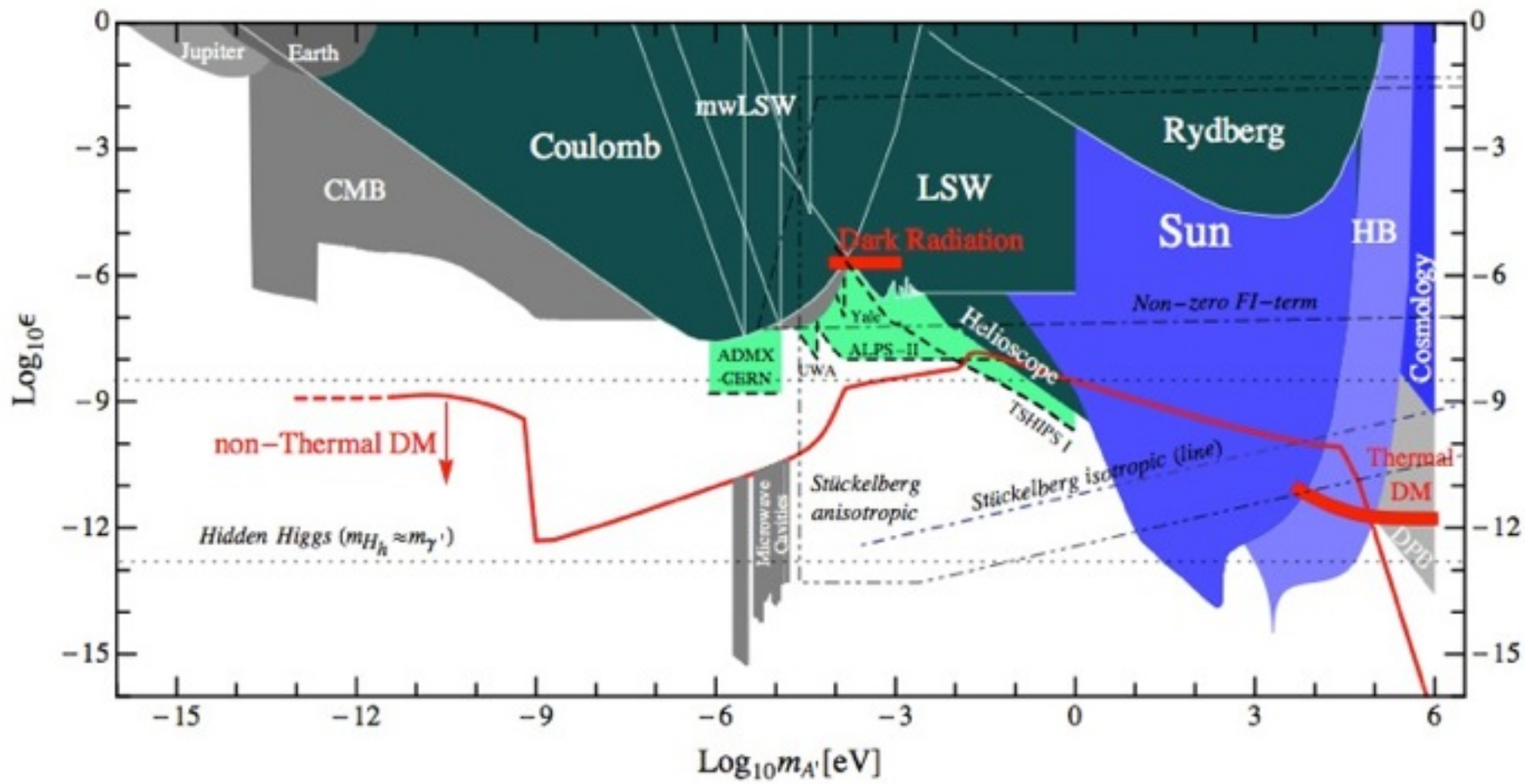


Taxonomy of Dark Sectors

DM Signals at colliders

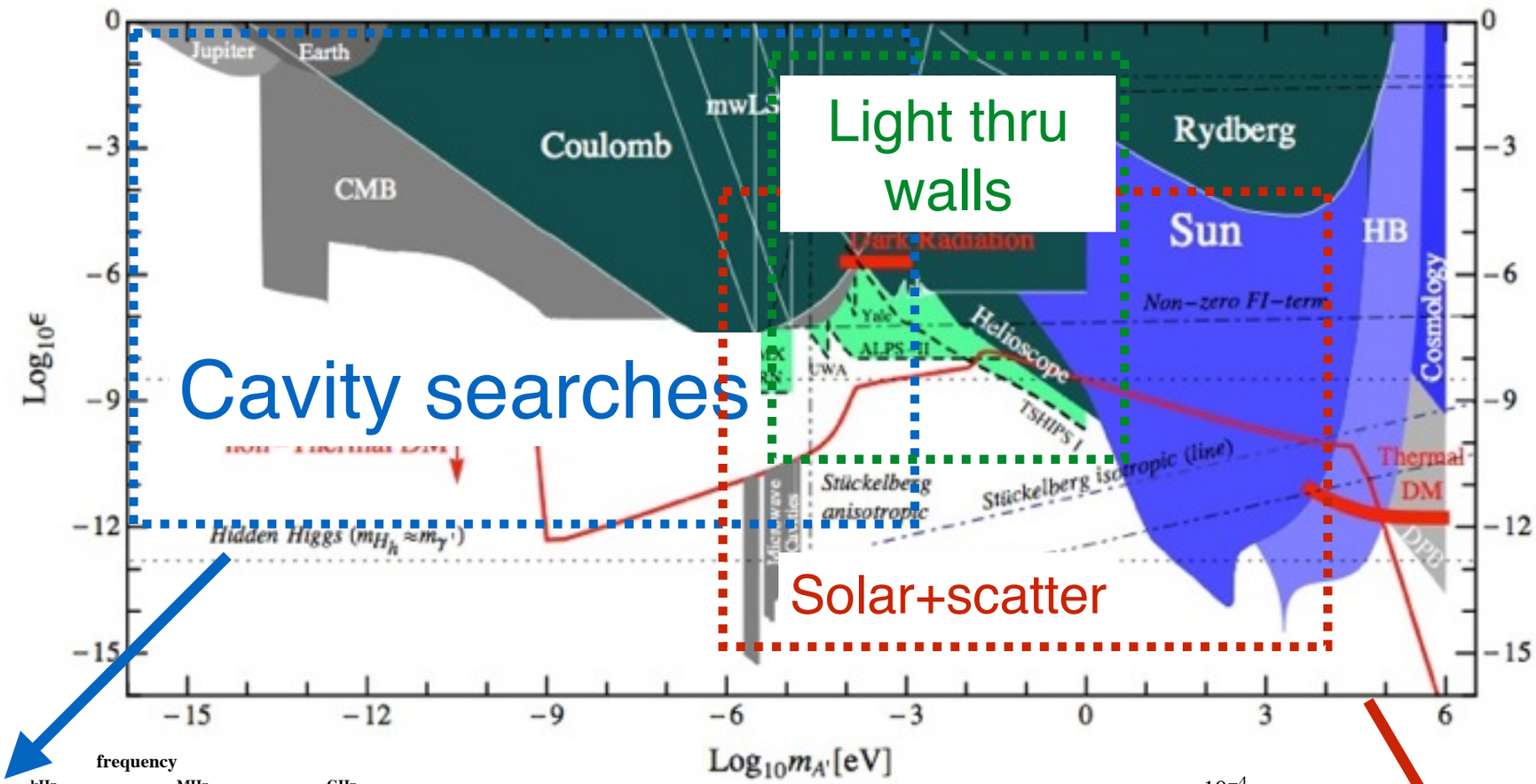


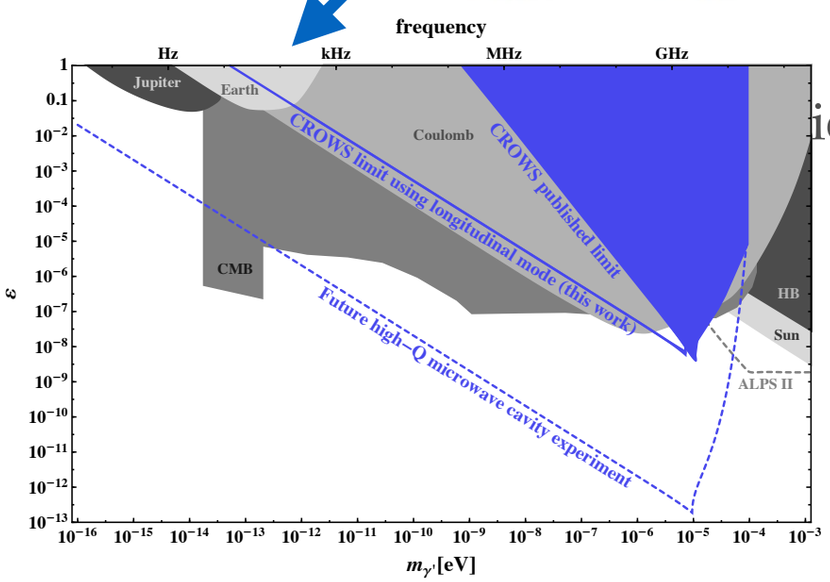
Sub-MeV Dark Photons



[Figure from 2013 Intensity Frontier report – Javier Redondo]

Sub-MeV Dark Photons





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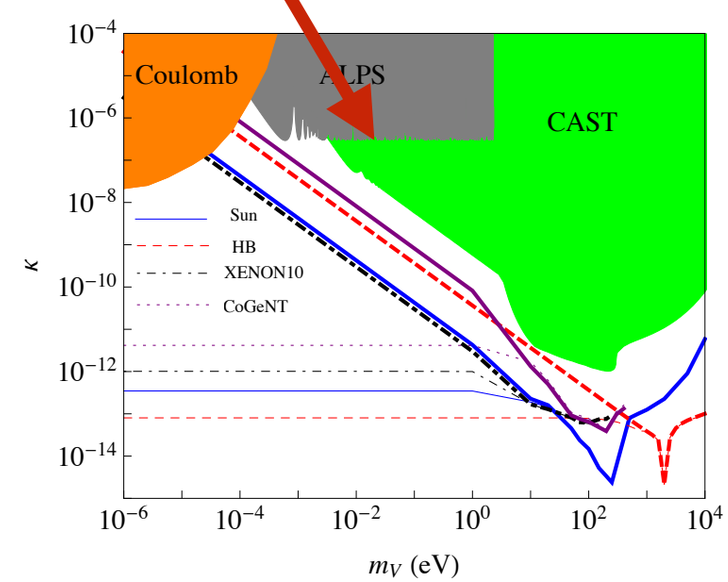
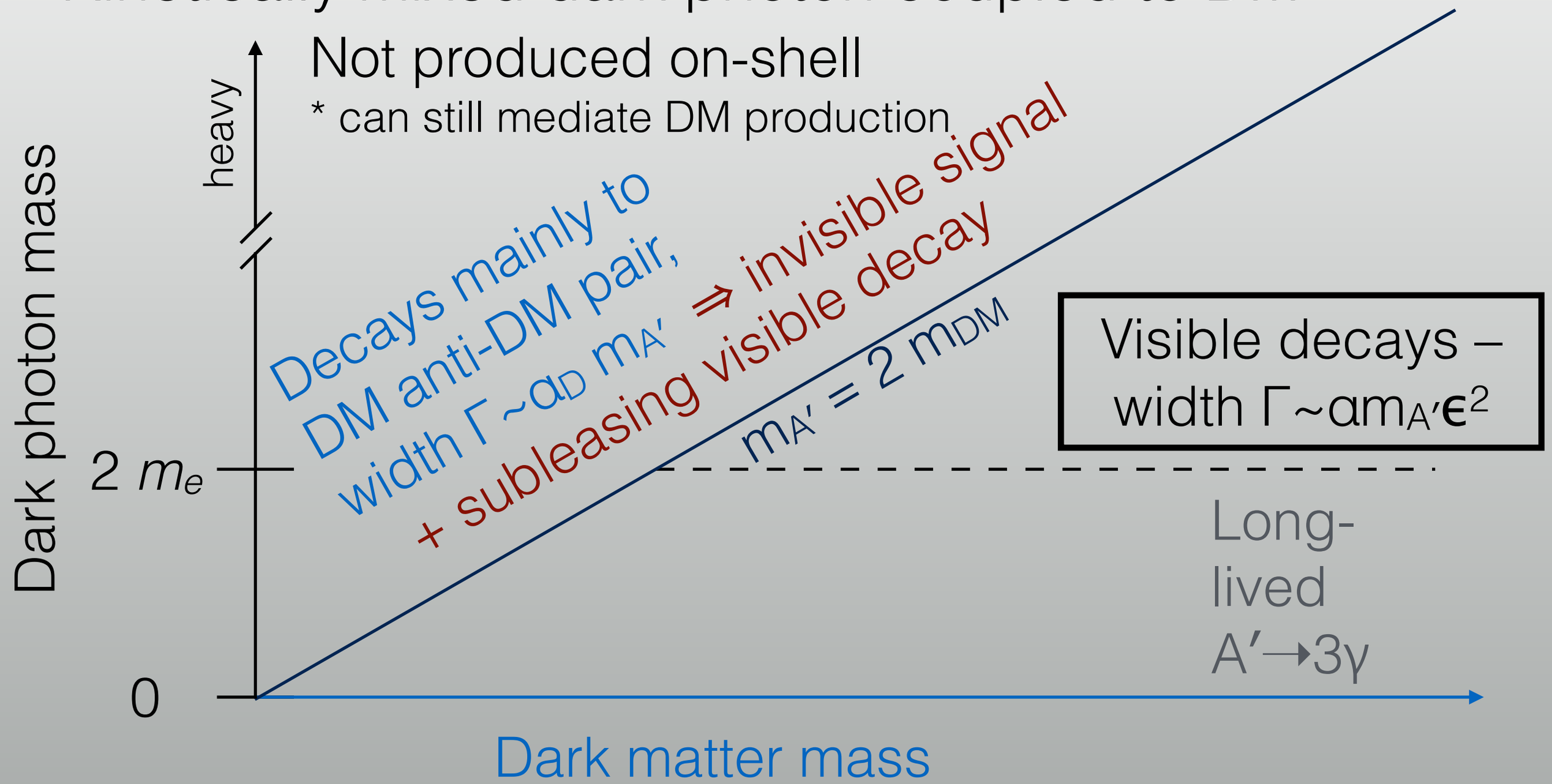
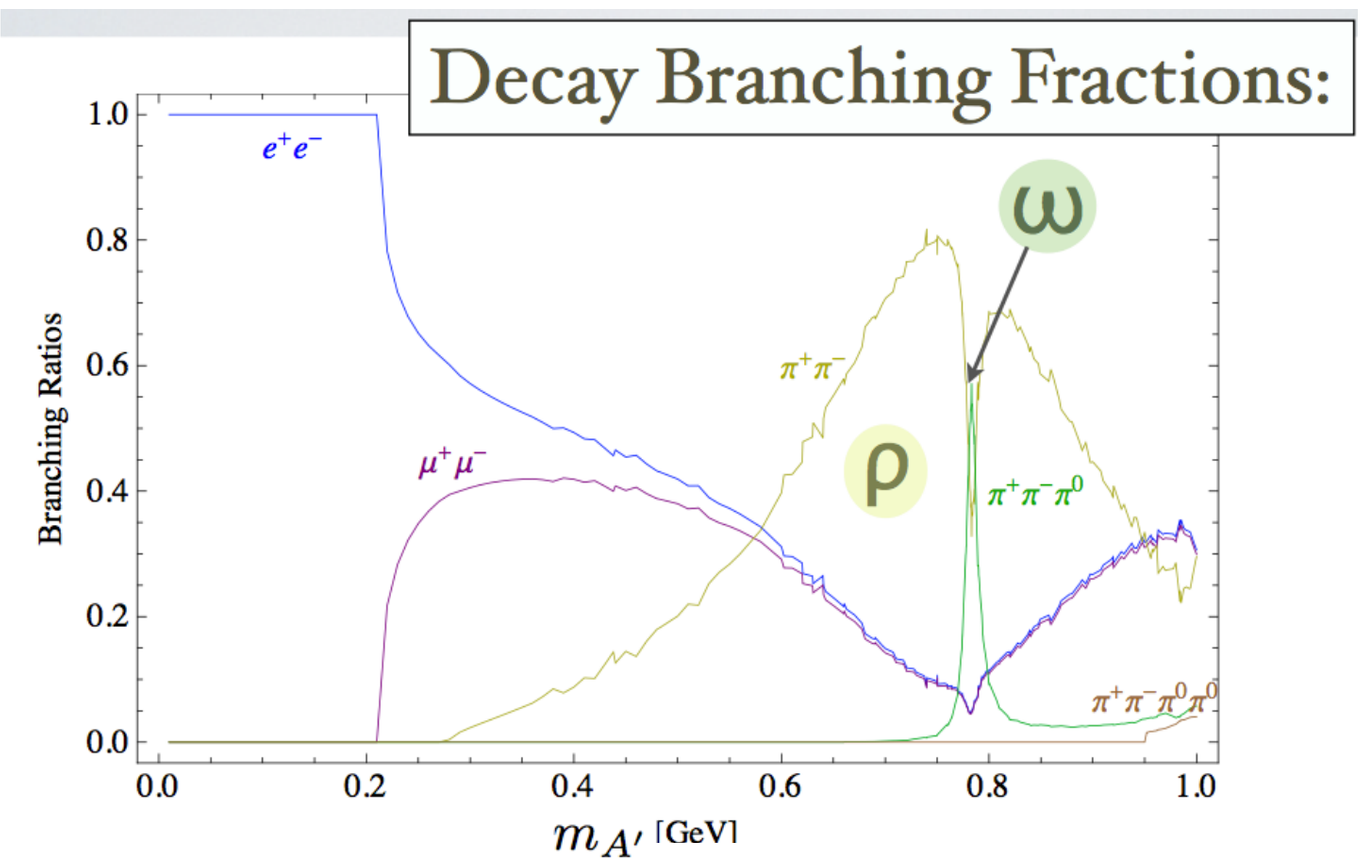


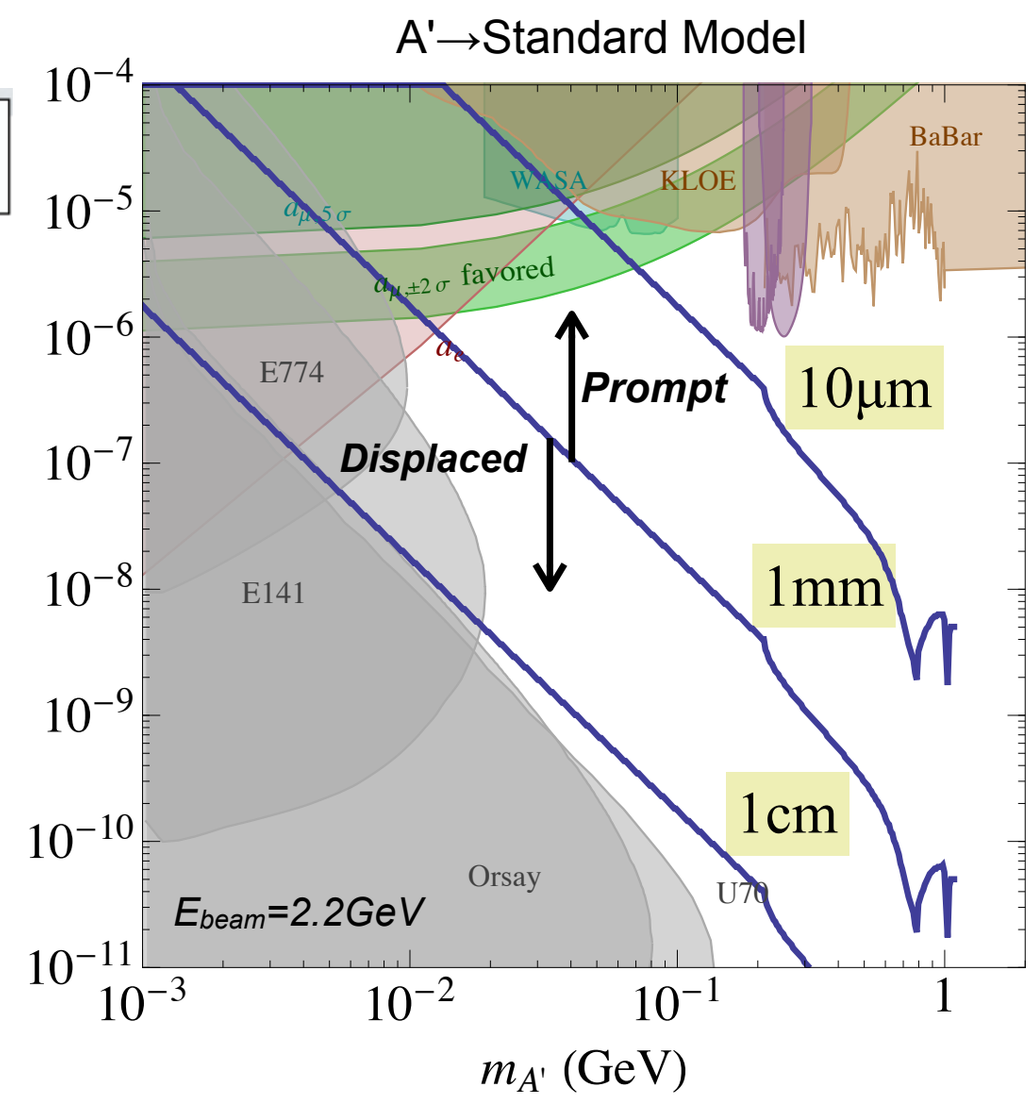
Taxonomy of Dark Sectors

Kinetically mixed dark photon coupled to DM



Decay Modes & Lifetimes





Far from Z-pole, same breakdown as e+e– annihilation modes

Visible Dark Photons

- Decay Modes and Lifetime
- **Search Strategies**
- Outstanding Challenges

Dark Photon Searches

Production Modes

- Electron-positron annihilation
- Meson Decays
- Drell-Yan (collider or fixed target)
- Bremsstrahlung

Detection Signatures

- Pair resonance
- Beam-dump late decay
- Inclusive missing mass
- Reconstructed displaced vertex

Dark Photon Searches

Production Modes

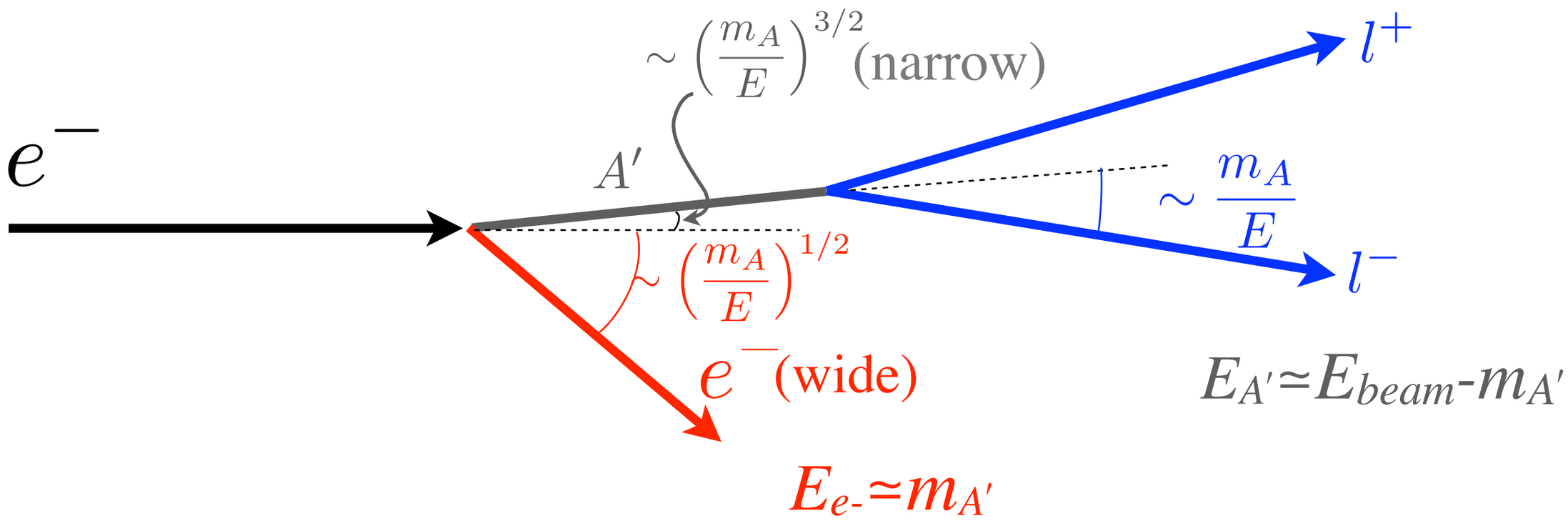
- Electron-positron annihilation
- Meson Decays
- Drell-Yan (collider or fixed target)
- Bremsstrahlung

~constant yield up to threshold

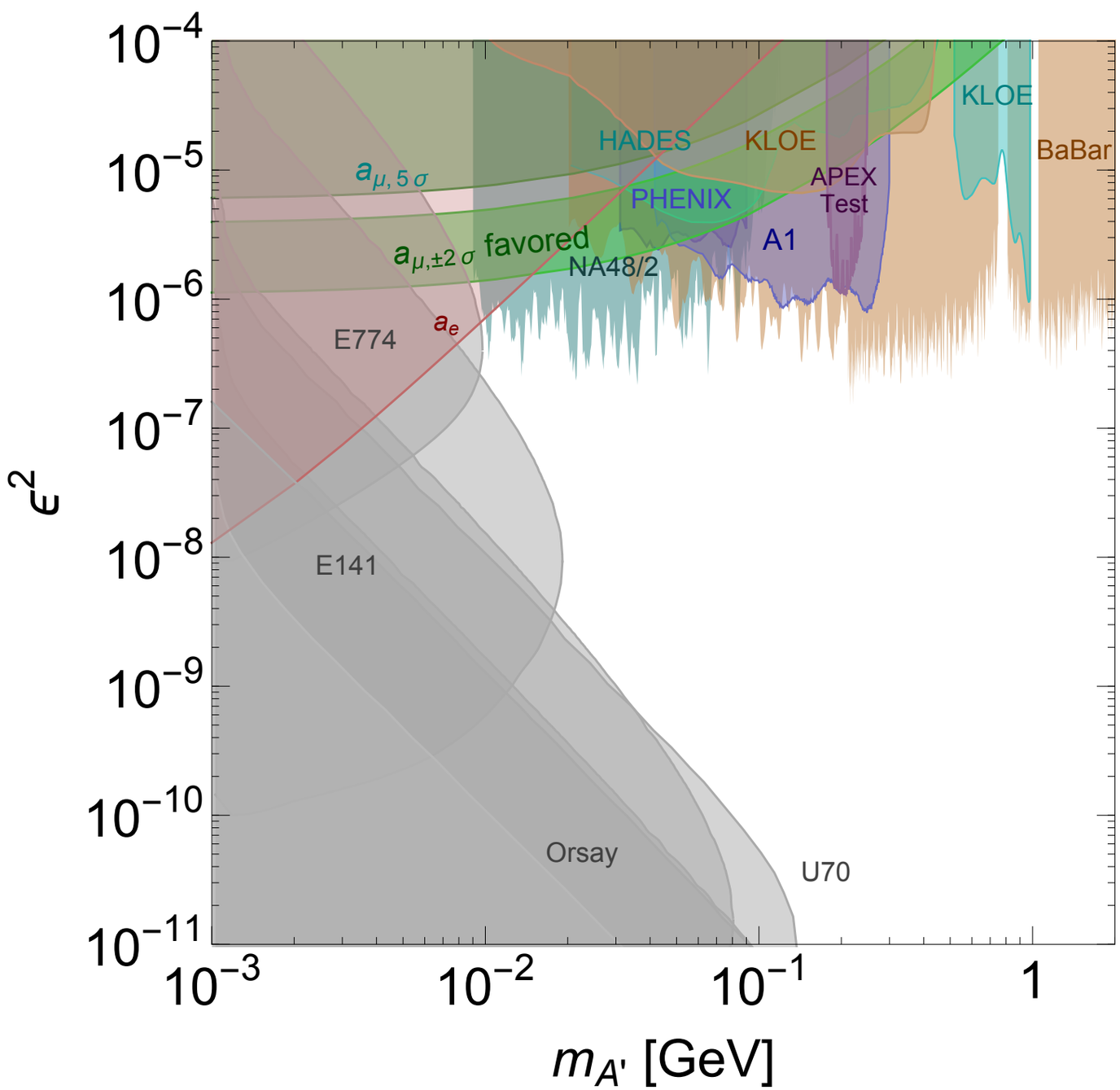
Yield falls steeply with mass

Production: e^- bremsstrahlung

Distinctive kinematics: for $m_e \ll m_{A'} \ll E_{beam}$, A′ carries most of beam energy & very forward-peaked



Dark Photon Search: Current Constraints



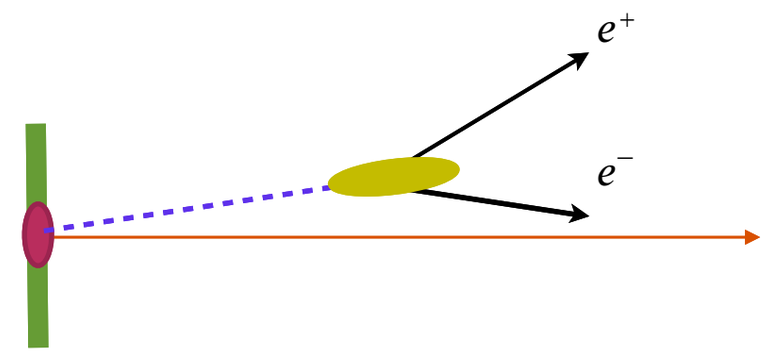
Red/green: e,μ anomalous dipole moments

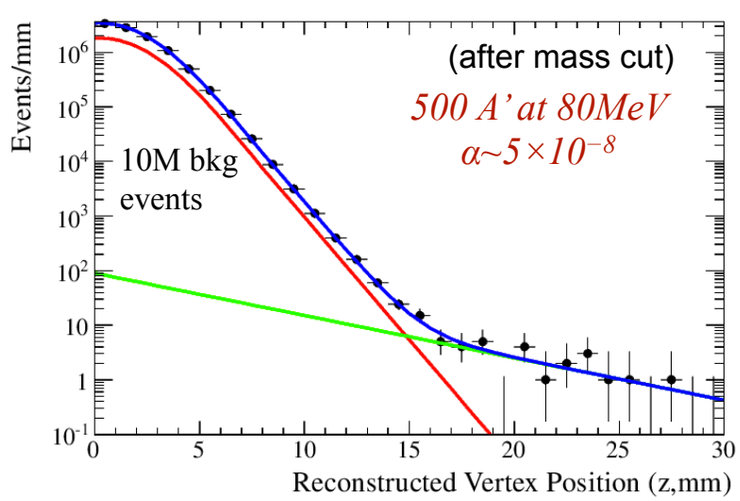
All other colors: Pair resonance searches

Gray: Beam Dump

New Dark Photon Searches: Visible Vertex Searches

Look for A′ decay displaced from target by reconstructing final-state tracks

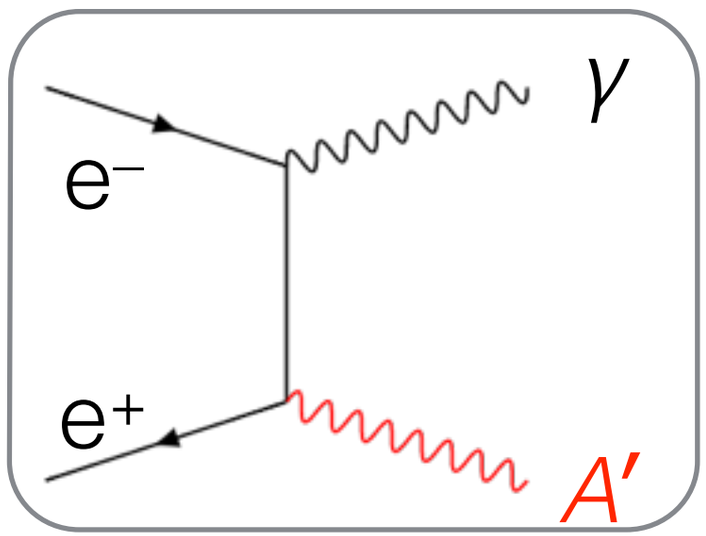




Enables substantial background reduction → sensitivity to lower ϵ (assuming no other decays that broaden A′ resonance)

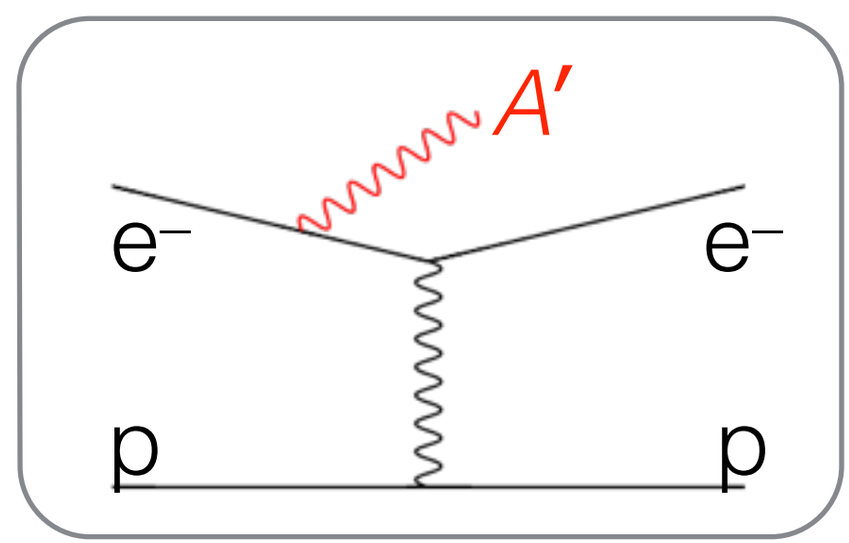
New Dark Photon Searches:
Fixed Target Missing Mass Searches

New technique, being pursued by several proposed experiments:



"Easier" missing mass: e^+ beam on atomic e^-: measure γ [e.g. MMAPS, VEPP-3]

"Harder" missing mass: e^- beam on H, reconstruct e– & [e.g. DarkLight, in conjunction with visible resonance or veto to reject background]



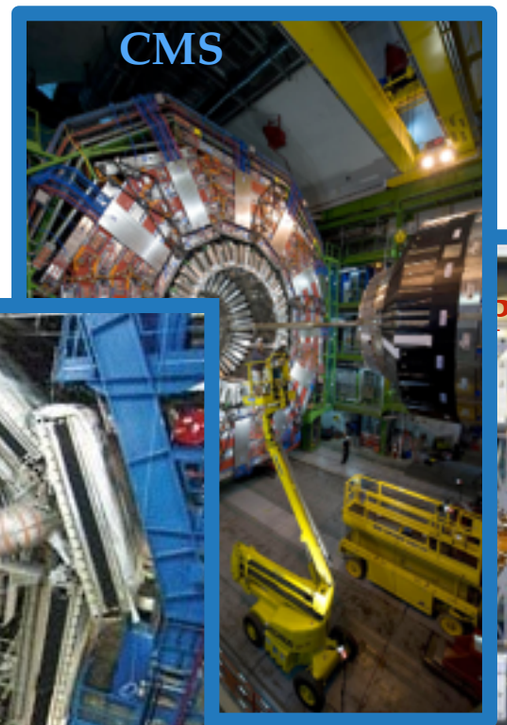
Ongoing Efforts

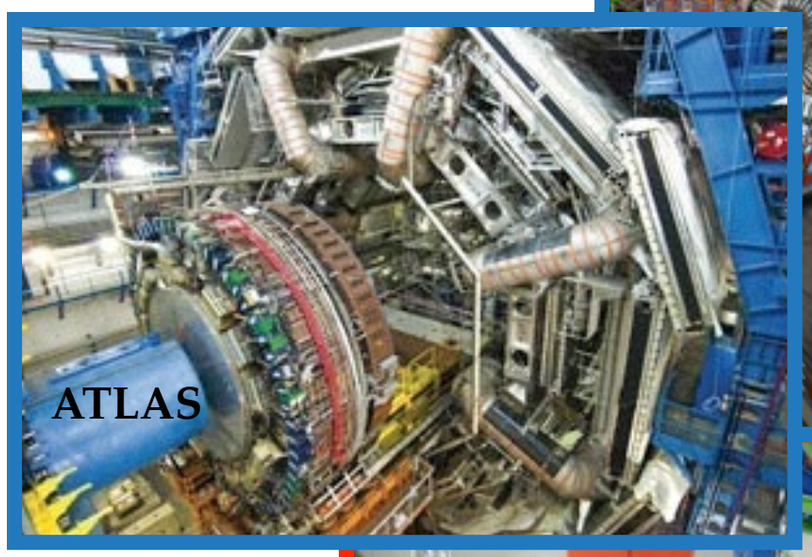
Broad worldwide effort to search for dark forces!
(this is the list of **ongoing** searches for **visible** dark photons)

- DarkLight
- APEX
- HPS
- CMS & ATLAS lepton jets & exotic Higgs decays
- LHCb
- Belle II
- MMAPS
- VEPP-3
- MESA
- Future MAMI-A1
- SHiP
- SeaQuest
- KLOE-II
- NA64
- **????**

Ongoing Efforts

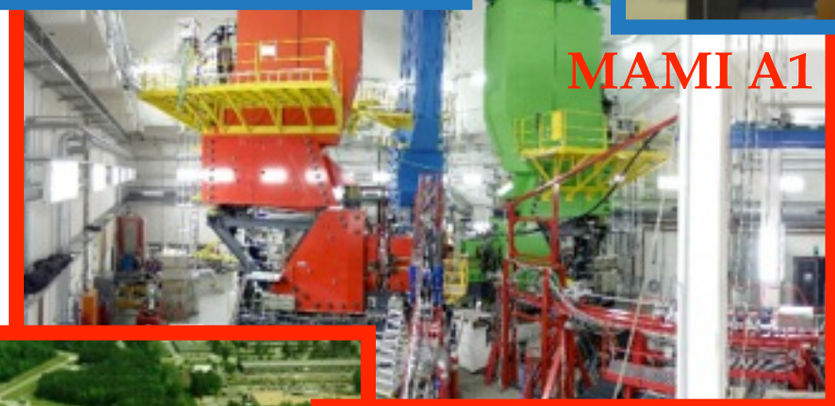
High-energy colliders

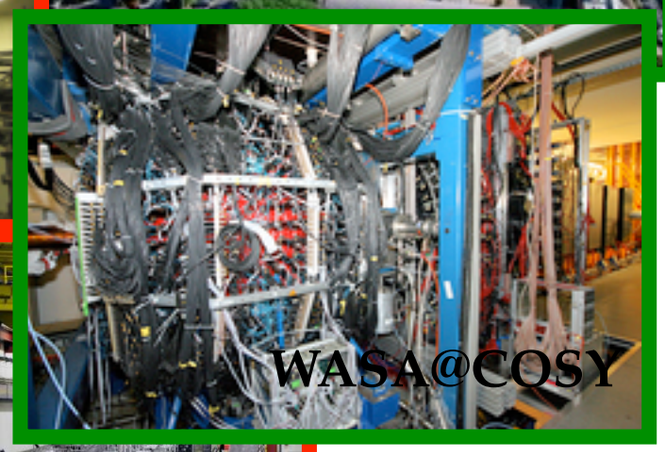


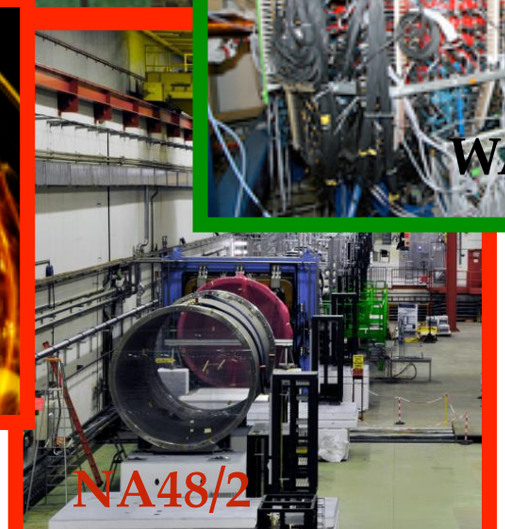


High intensity colliders

Fixed Target







What Next?

- Opportunities
  - Are these lists missing something? Can we combine them in new and exciting ways?

Production Modes

- Electron-positron annihilation
- Meson Decays
- Drell-Yan (collider or fixed target)
- Bremsstrahlung

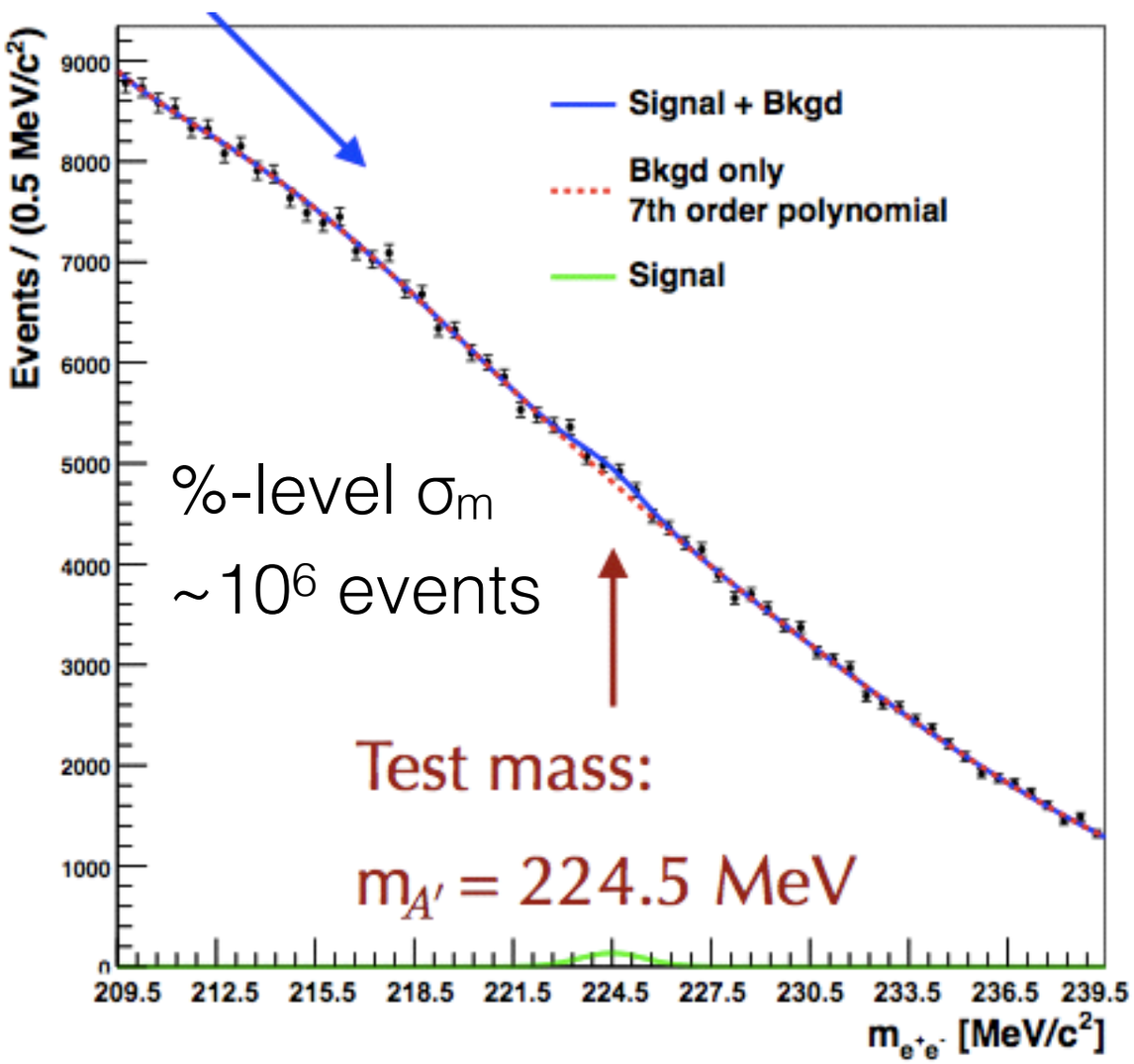
Detection Signatures

- Pair resonance
- Beam-dump late decay
- Inclusive missing mass
- Reconstructed displaced vertex

- Challenges
  - What do present experiments teach us about obstacles we'll have to confront to go further?
  - What milestones do we really want to hit?

The Limit to Bump Hunts?

This is what a signal looked like in APEX test run



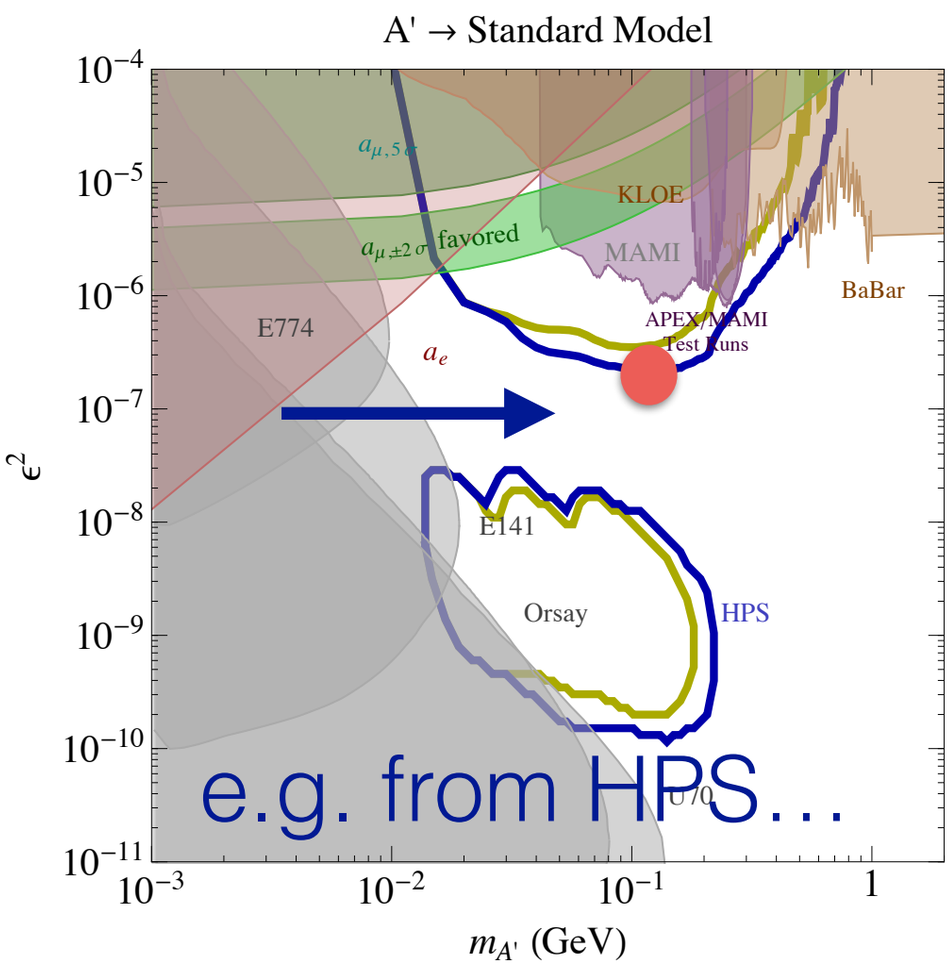
Detection requires excellent **statistics & mass resolution** and exquisite **bkg model**

theory & exp uncertainties → most analyses parametrize bg

Not unique challenge (cf h→γ γ), but future dark photon searches push it even further.

What's the ultimate limit?

Closing “Mont’s” Vertexing Gap



Closing from above (bump hunt) runs into systematics

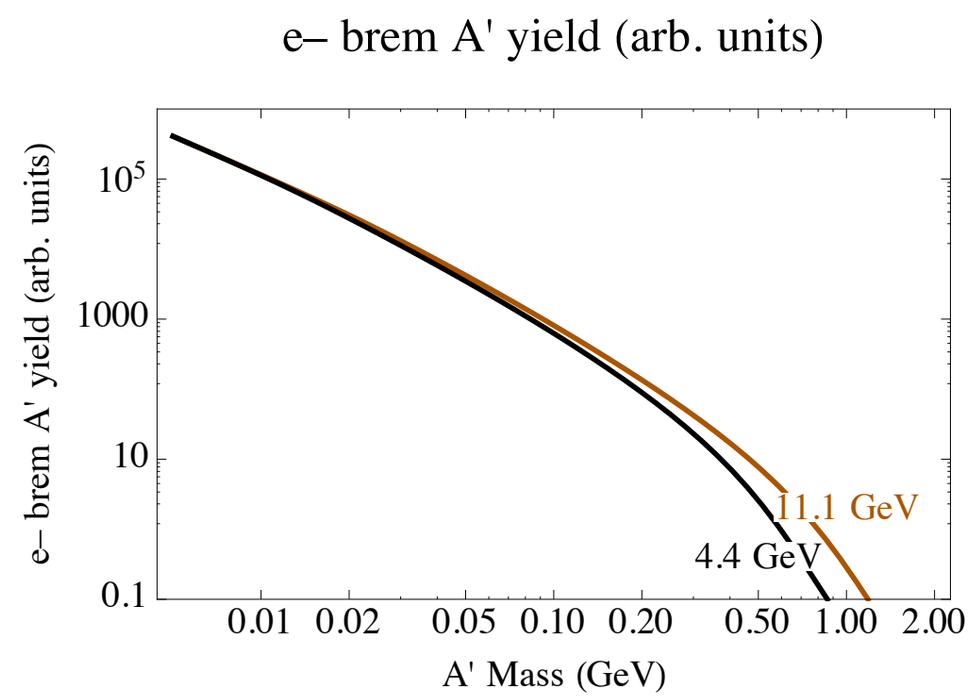
Closing from below requires great vertex resolution in high luminosity environment

1/5 B meson lifetime
1/50 the energy
orders of magnitude lower S/B

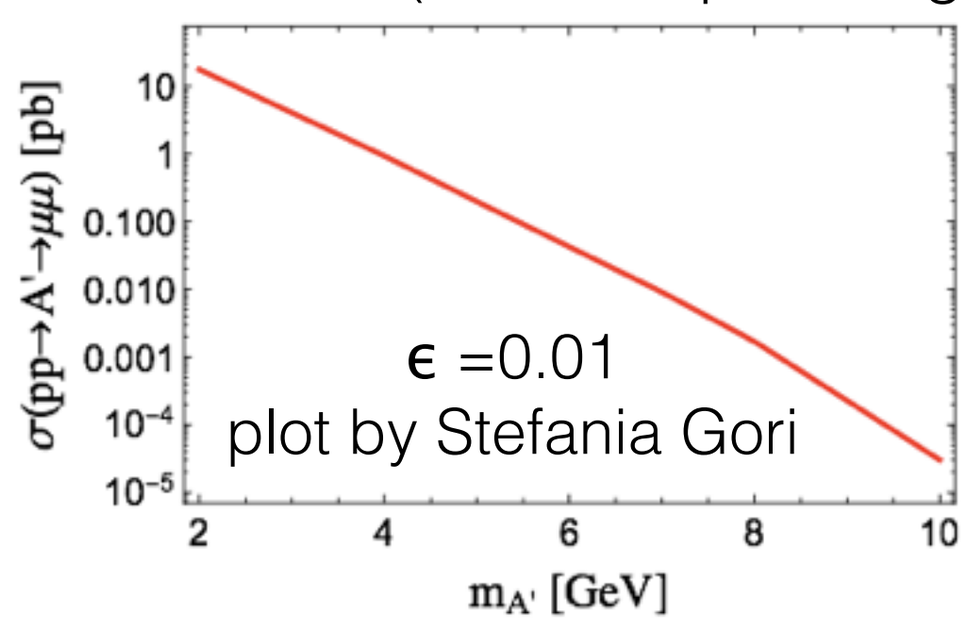
Extending to Higher Masses

How to reach lower ϵ at O(GeV) masses?

- Yield…
  - Fixed-target yields falling precipitously (form factors, pdfs, …)
  - Still mostly "low-pT" for LHC
  - Is Belle II best we can do?
- Hadronic channels start to dominate branching ratios



Drell-Yan (120 GeV p on target)



Conclusion

- Exploring Dark Sectors is an important and growing element of physics beyond the Standard Model
  - Requires searching for several complementary signatures (more in subsequent primer talks)
  - A wealth of exciting ongoing experiments (more in WGs)
  - Important hurdles to surpass for the next generation of experiments (more in WGs)
- Workshop aims to stimulate thinking about the next steps. Thanks for coming!