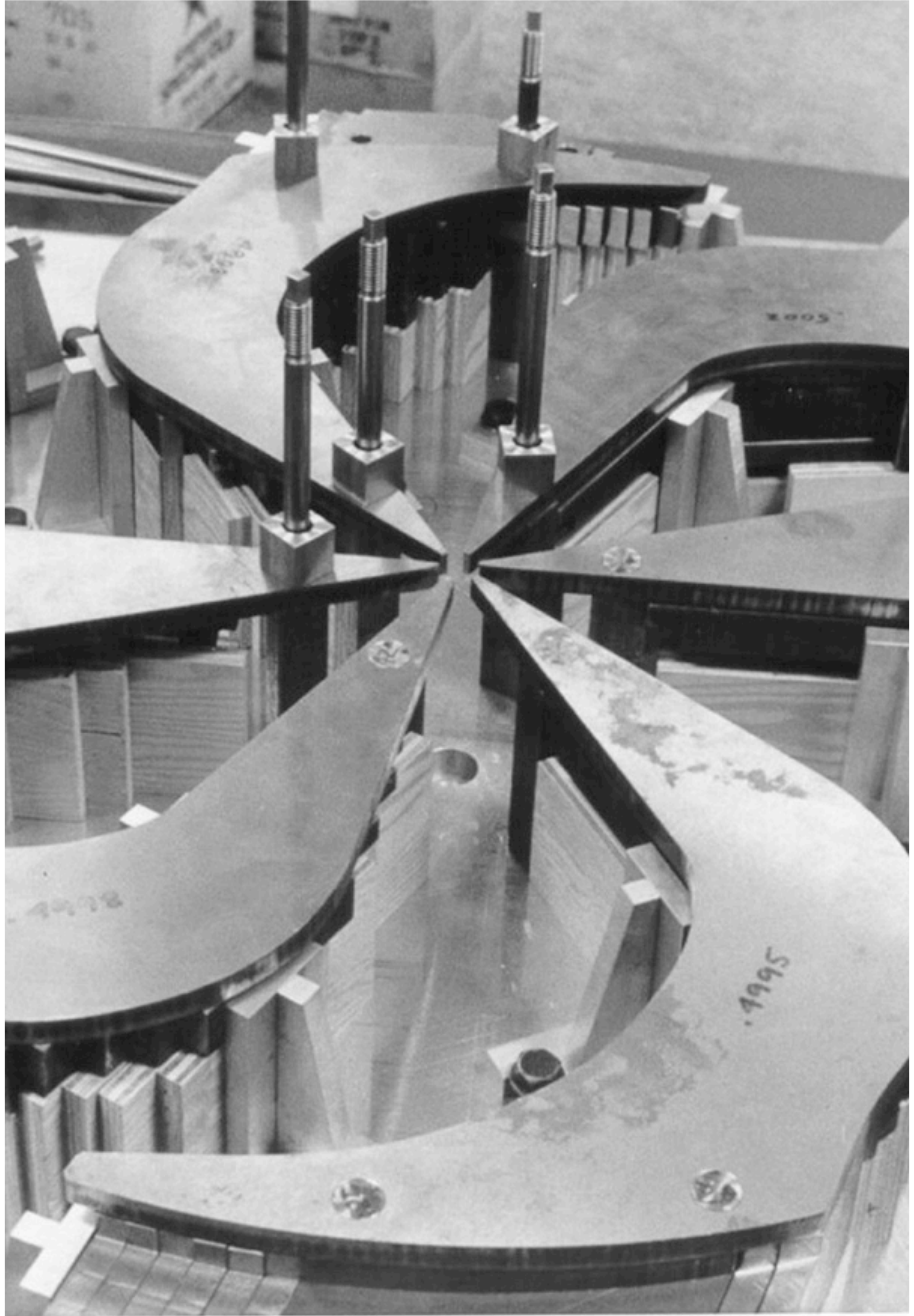
TRIUMF

DarkLight and the role of small experiments

Laura Miller

Physics Potential of Future Colliders
2024-09-19



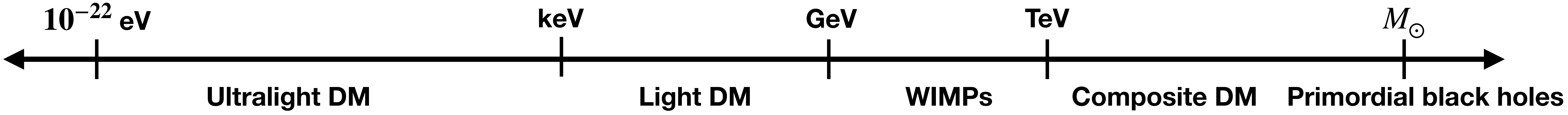
Discovery, accelerated

Introduction

- DarkLight@ARIEL is an ongoing experiment based here at TRIUMF
  - Some local flavour!
  - Fixed target experiment installing on the existing e-linac beam line
  - Dark photon search looking for low mass e^+e^- resonances
- Explore small dark photon experiments in the context of future collider proposals

Background

- Dark matter is one of the big unanswered questions of particle physics



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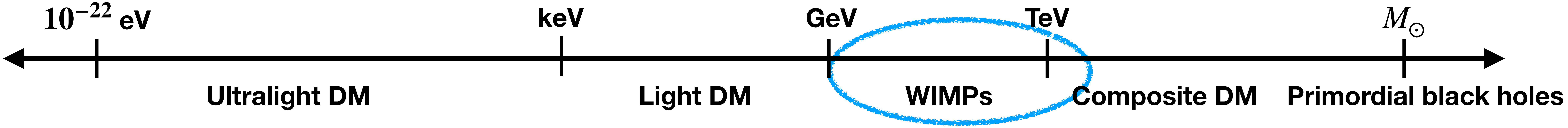
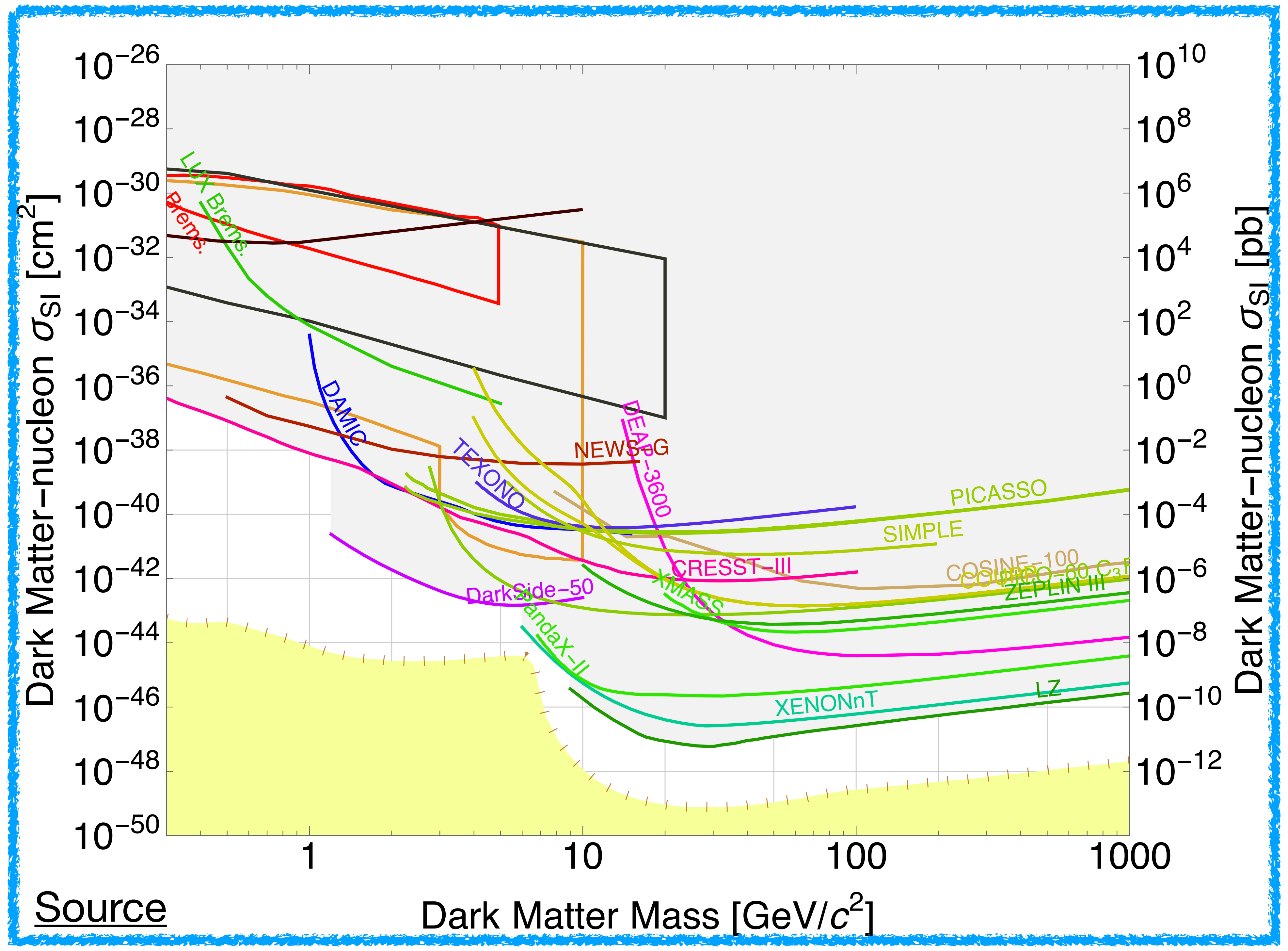


- Weakly interacting massive particles (WIMPs) have been a focus of many past and proposed experiments

- No experimental evidence so far



Source

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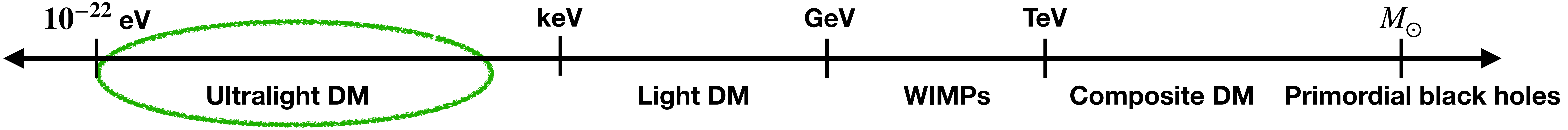
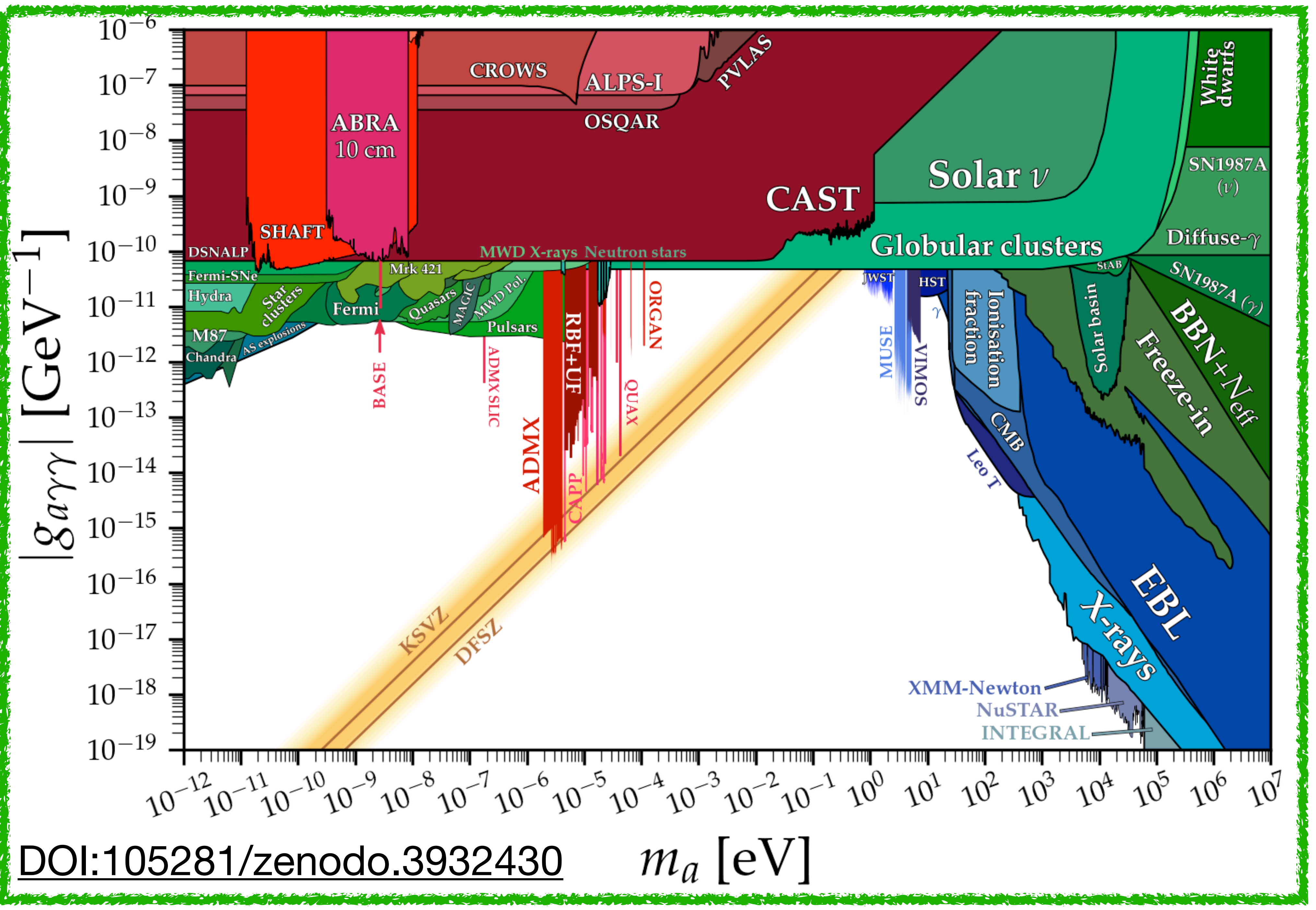
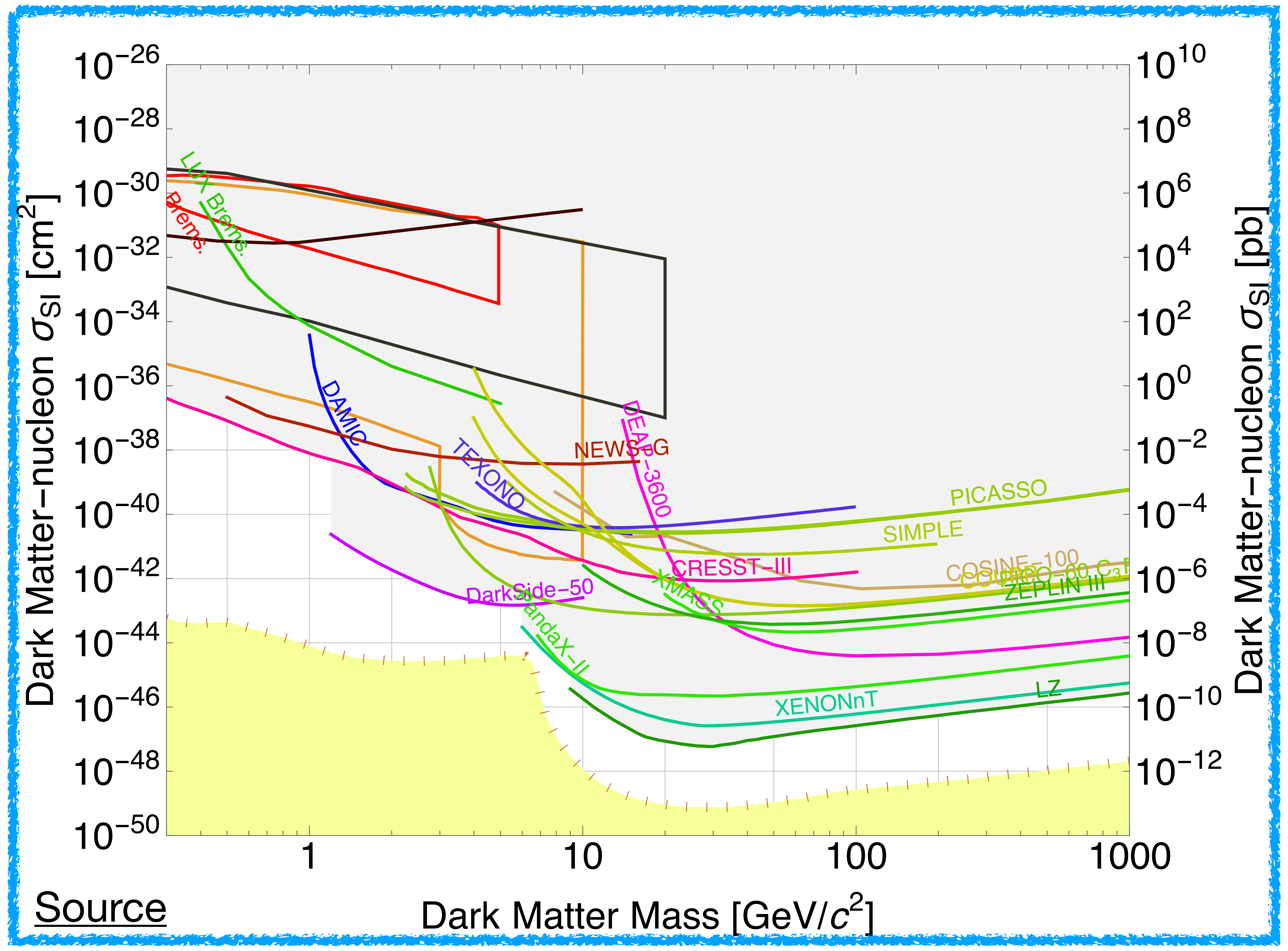




- Axion searches have also failed to produce any experimental evidence of dark matter



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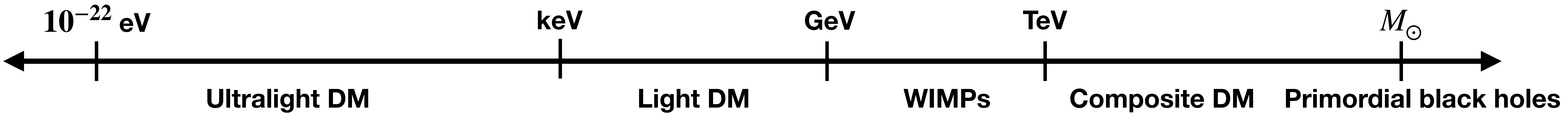
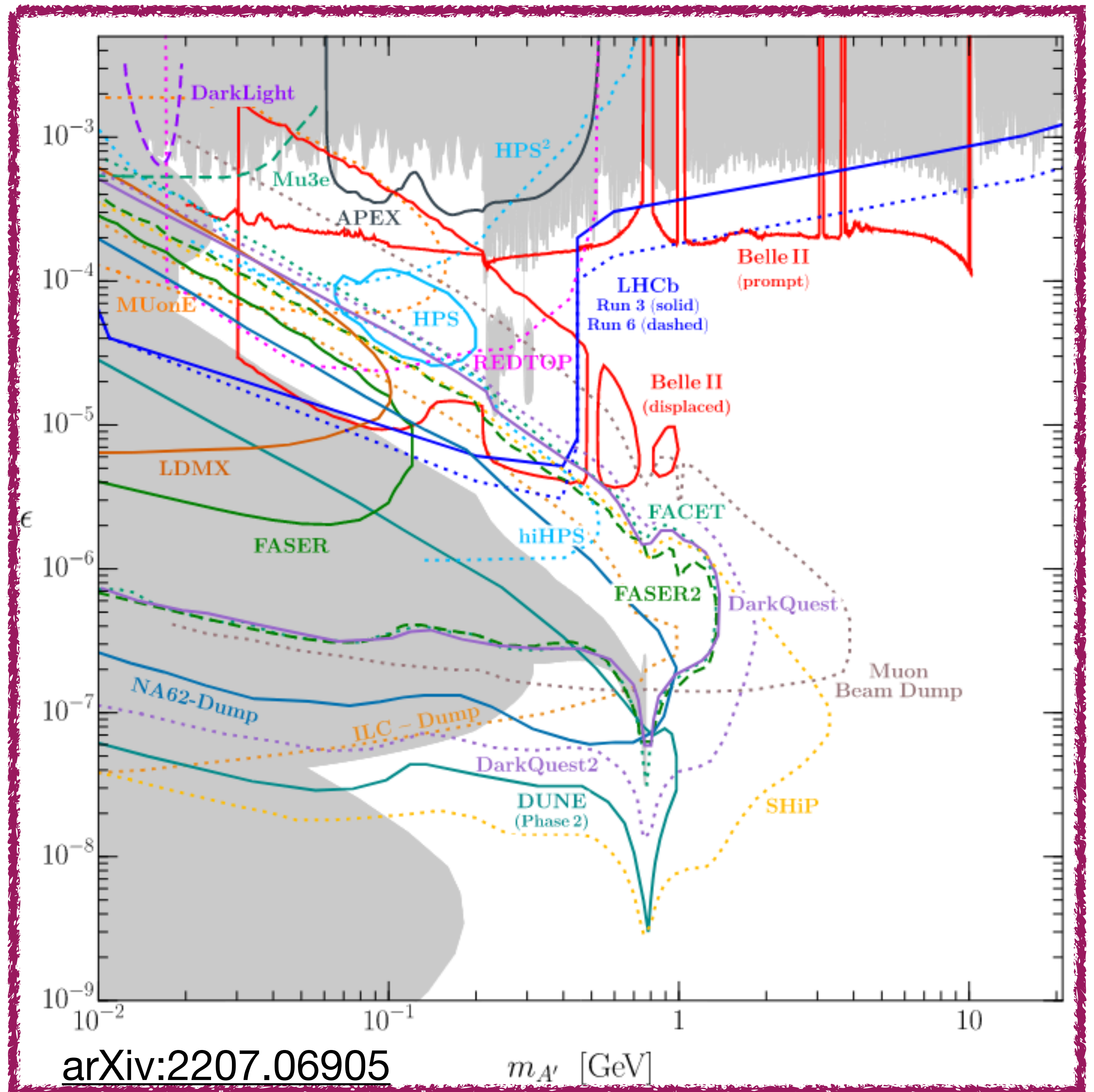




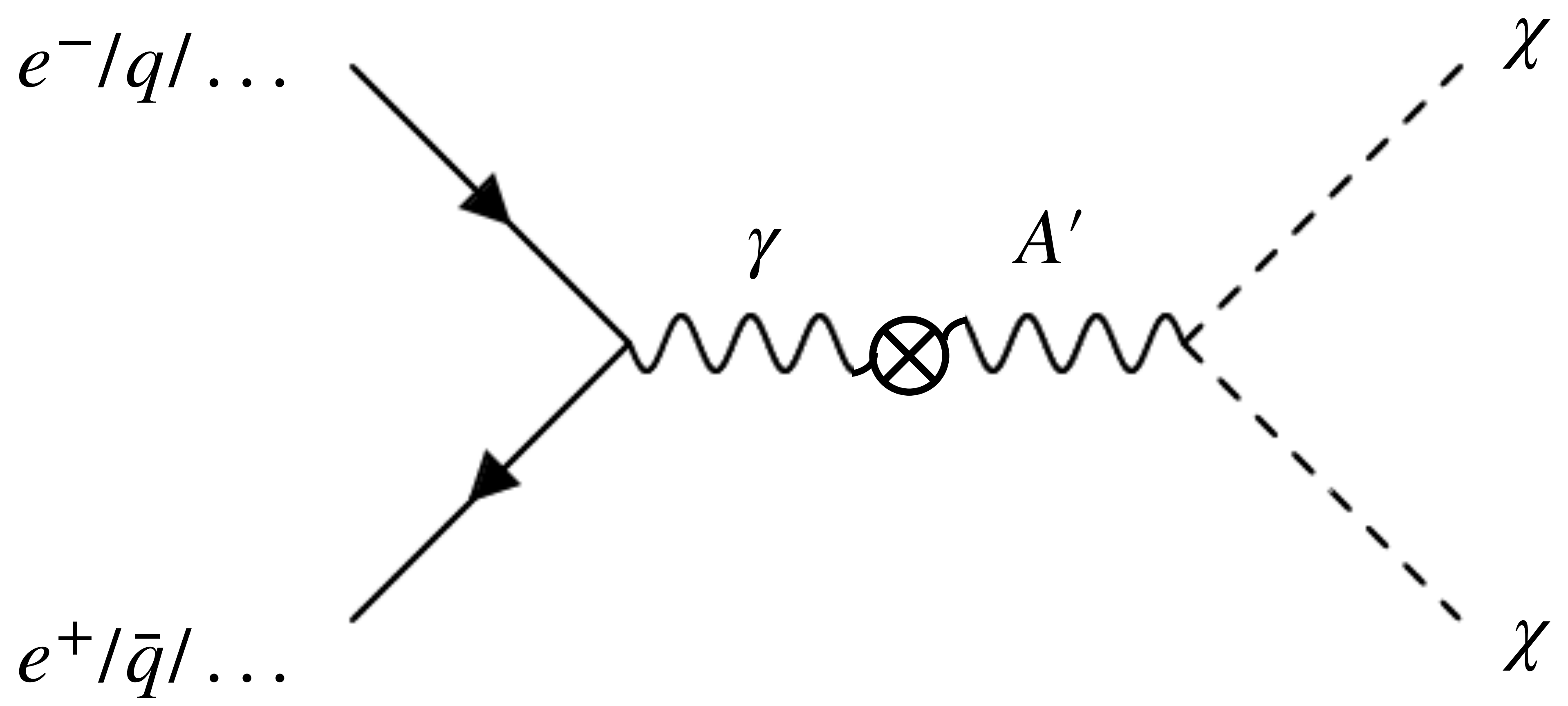
arXiv:2207.06905

- Recently more interest in DM candidates on the MeV scale

- Includes dark sector models

Dark Photon

- Posits a dark sector not charged under an SM gauge group, where interactions with the SM are facilitated by an intermediary particle
- Dark photon implies an additional U(1) gauge group
- Most basic model: kinetic mixing with the SM photon $\mathscr{L}_{\text{int}} = e\varepsilon J_\mu A'^\mu$



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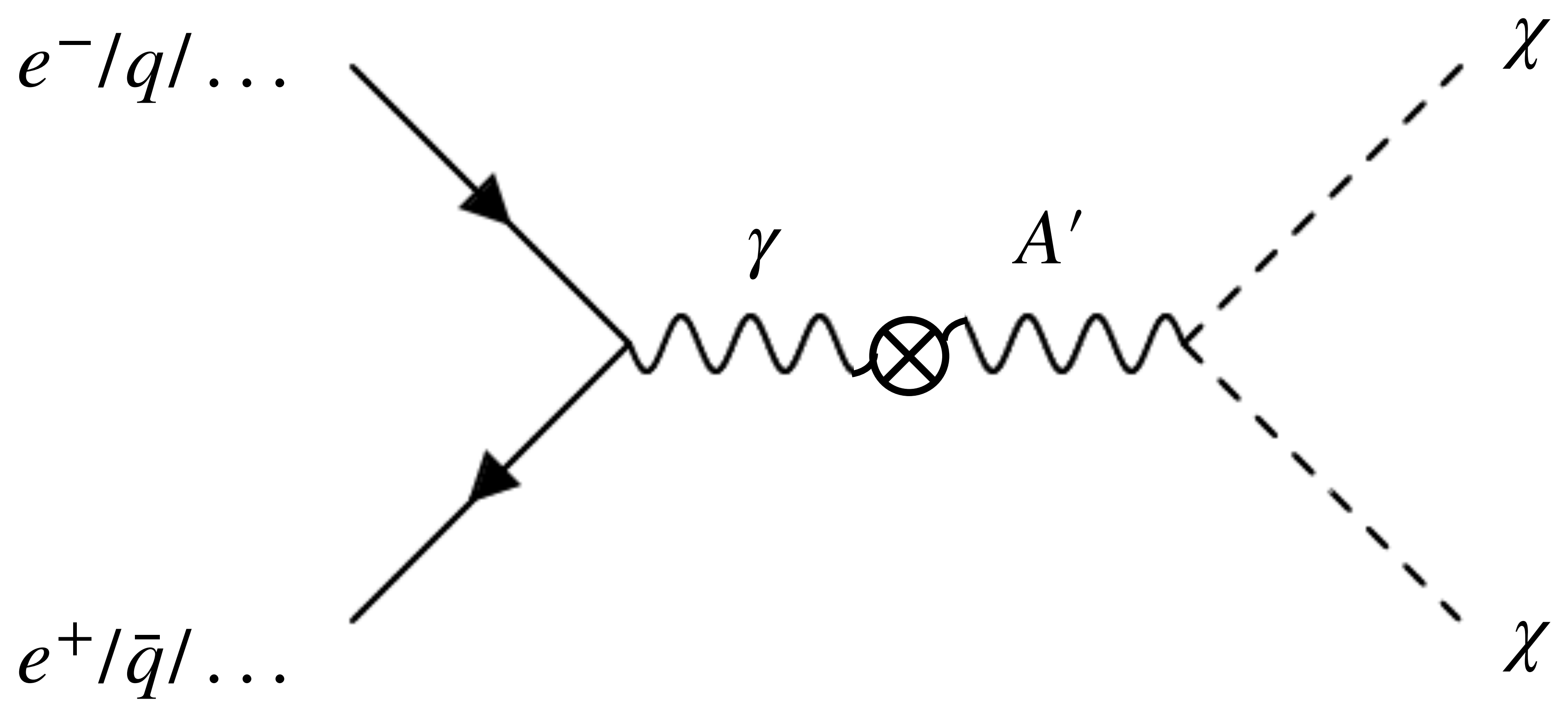
$$\mathscr{L}_{\text{int}} = e\varepsilon J_\mu A'^\mu$$

Kinetic mixing strength (ε)

SM QED current (J_μ)

Dark photon (A'^μ)



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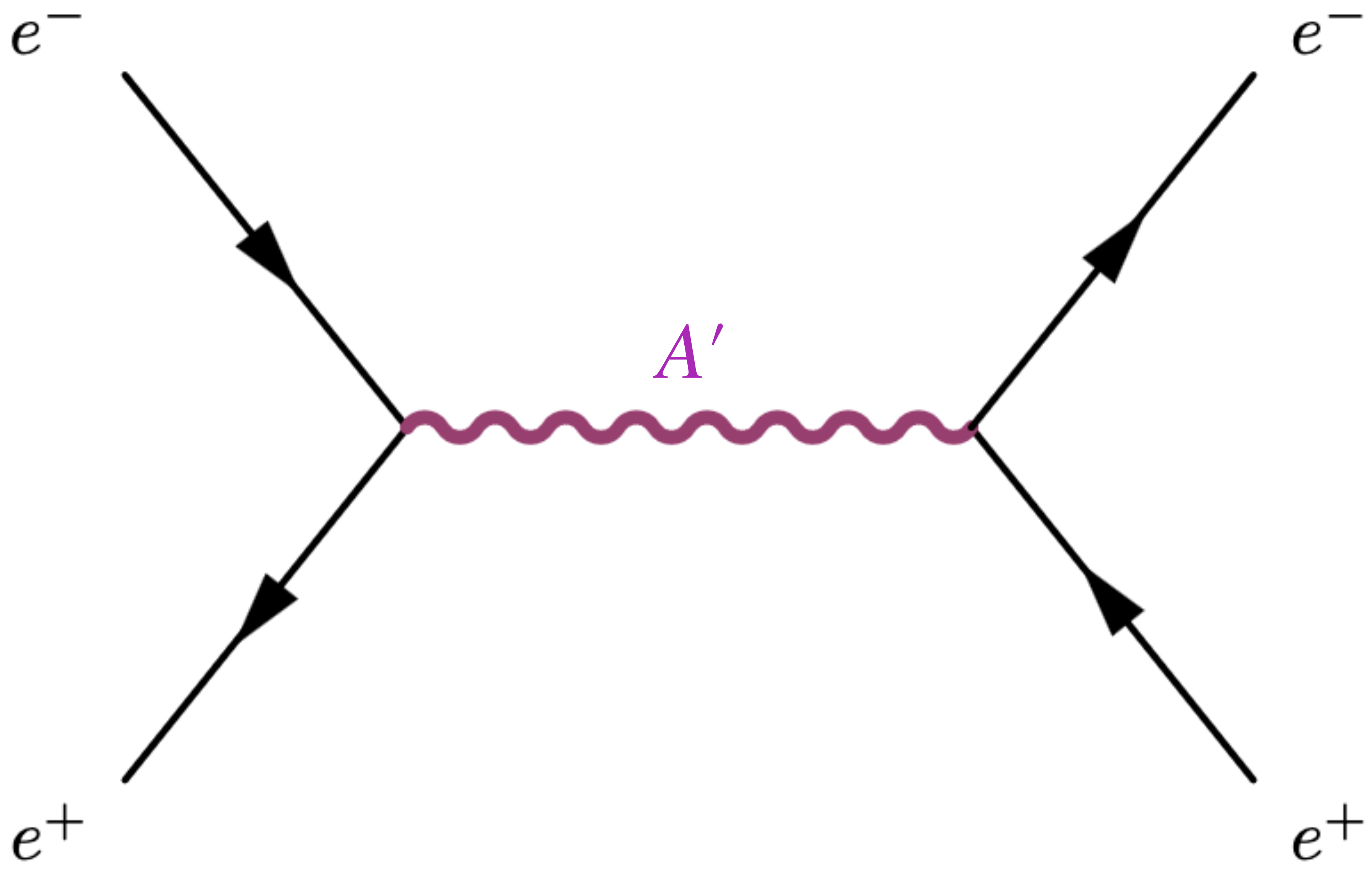

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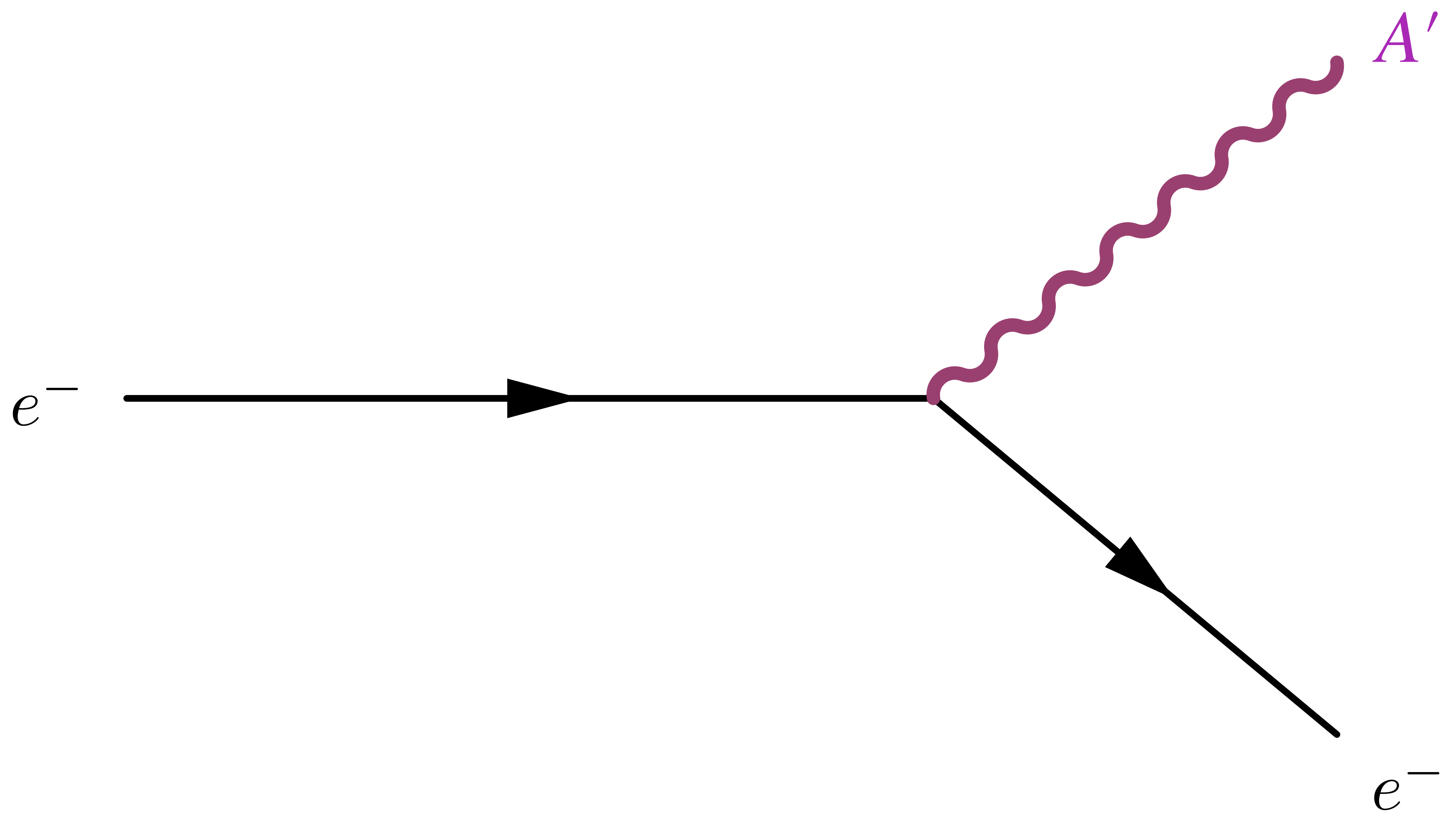

Experimental Anomalies: $g_\mu - 2$

- Anomalous magnetic moment of the muon measured very precisely by the Muon g-2 experiment at FermiLab

Latest result: Phys. Rev. Lett. 131, 161802 (2023)

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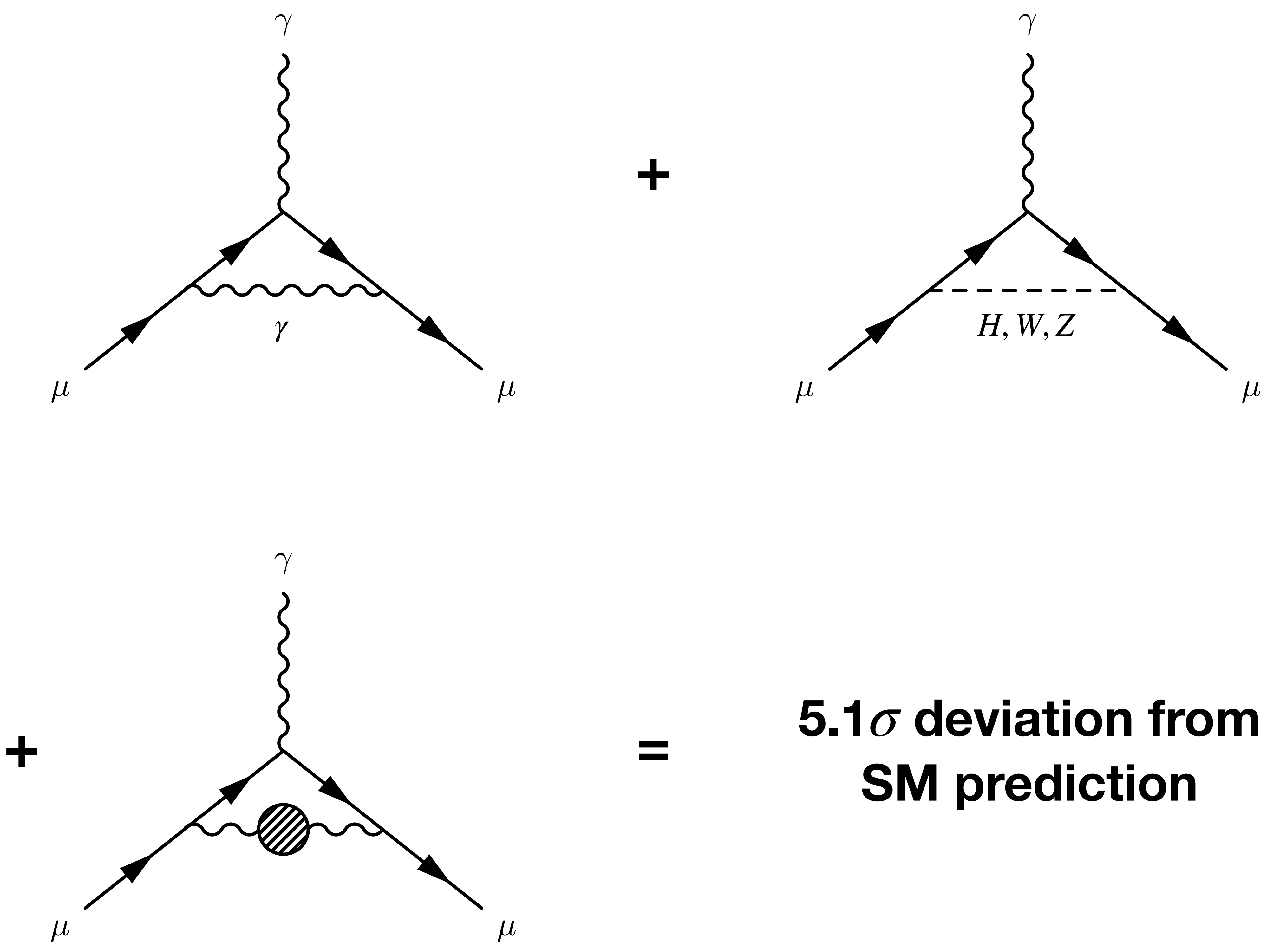
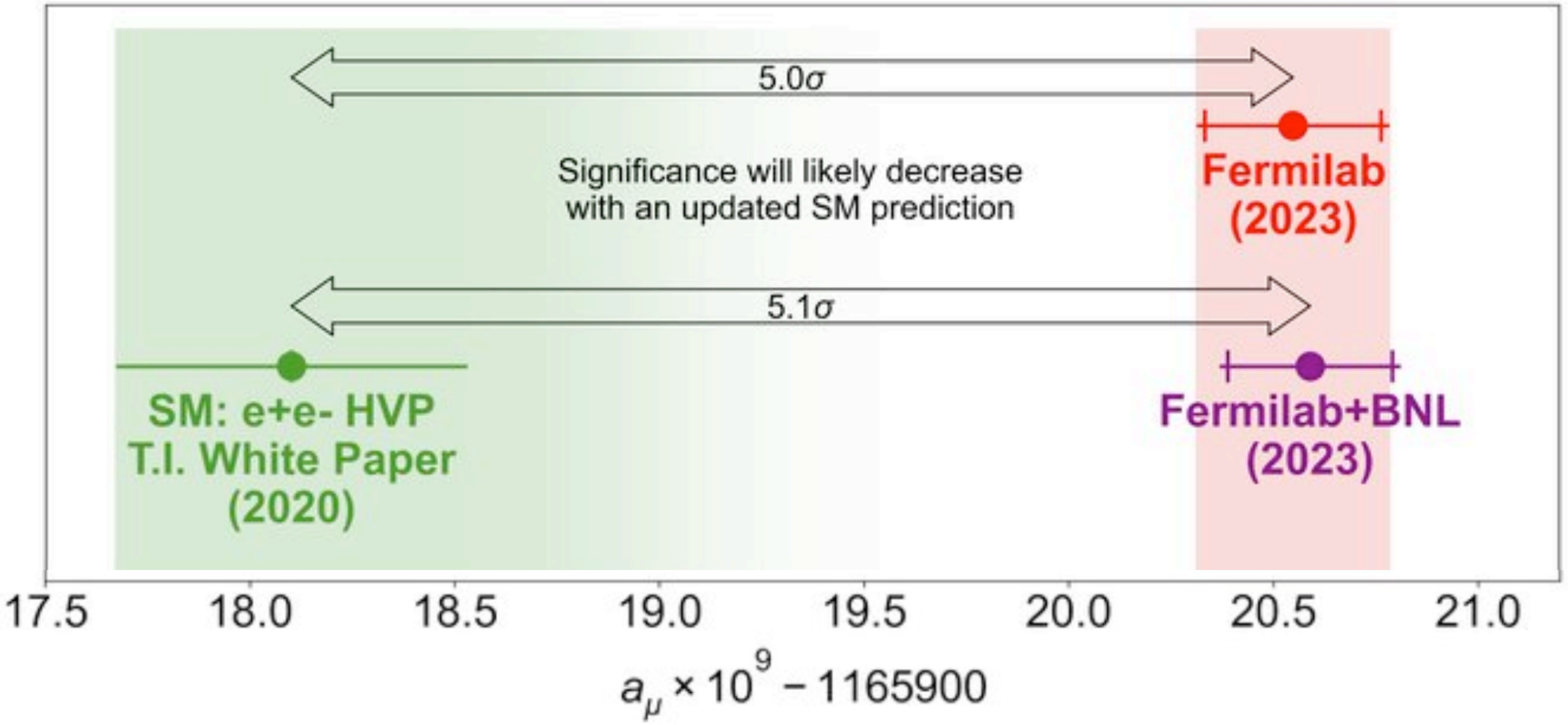


5.1σ deviation from SM prediction



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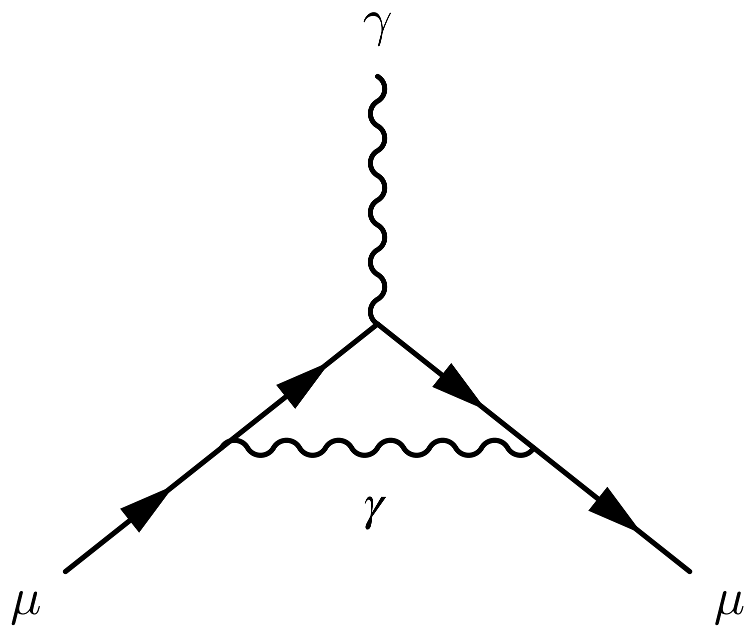

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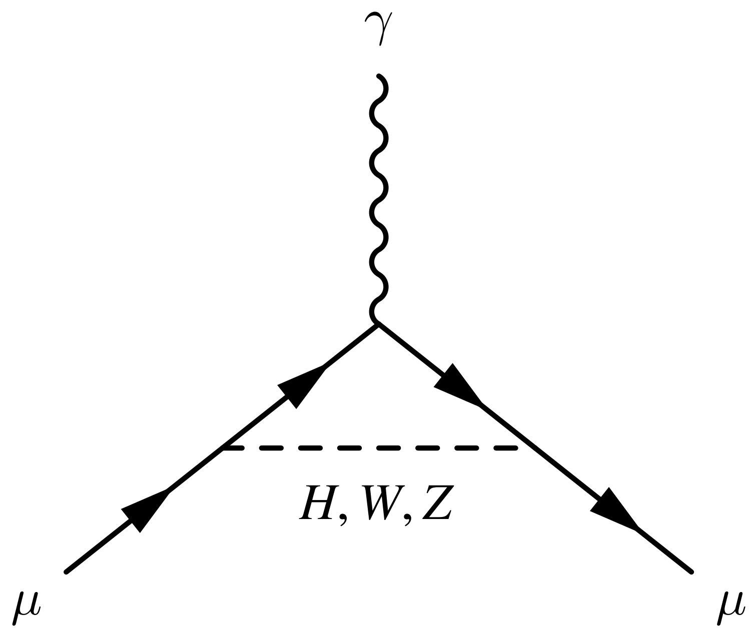

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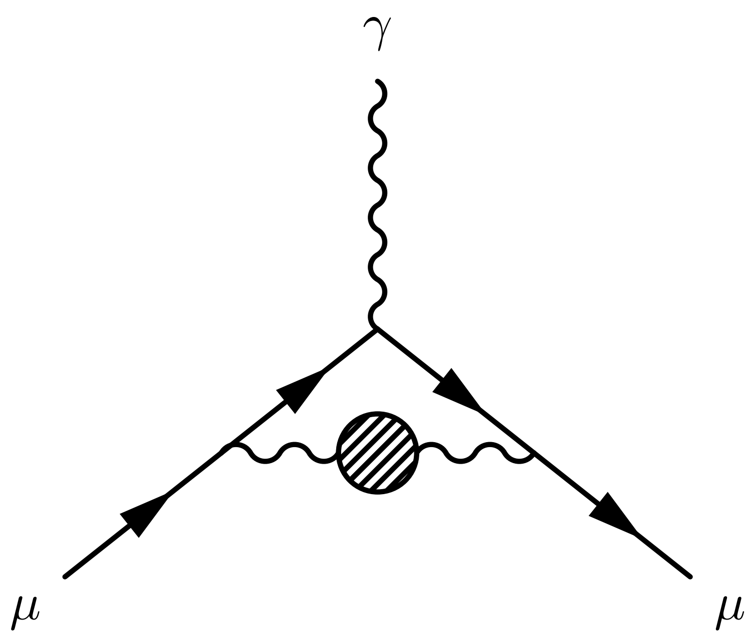

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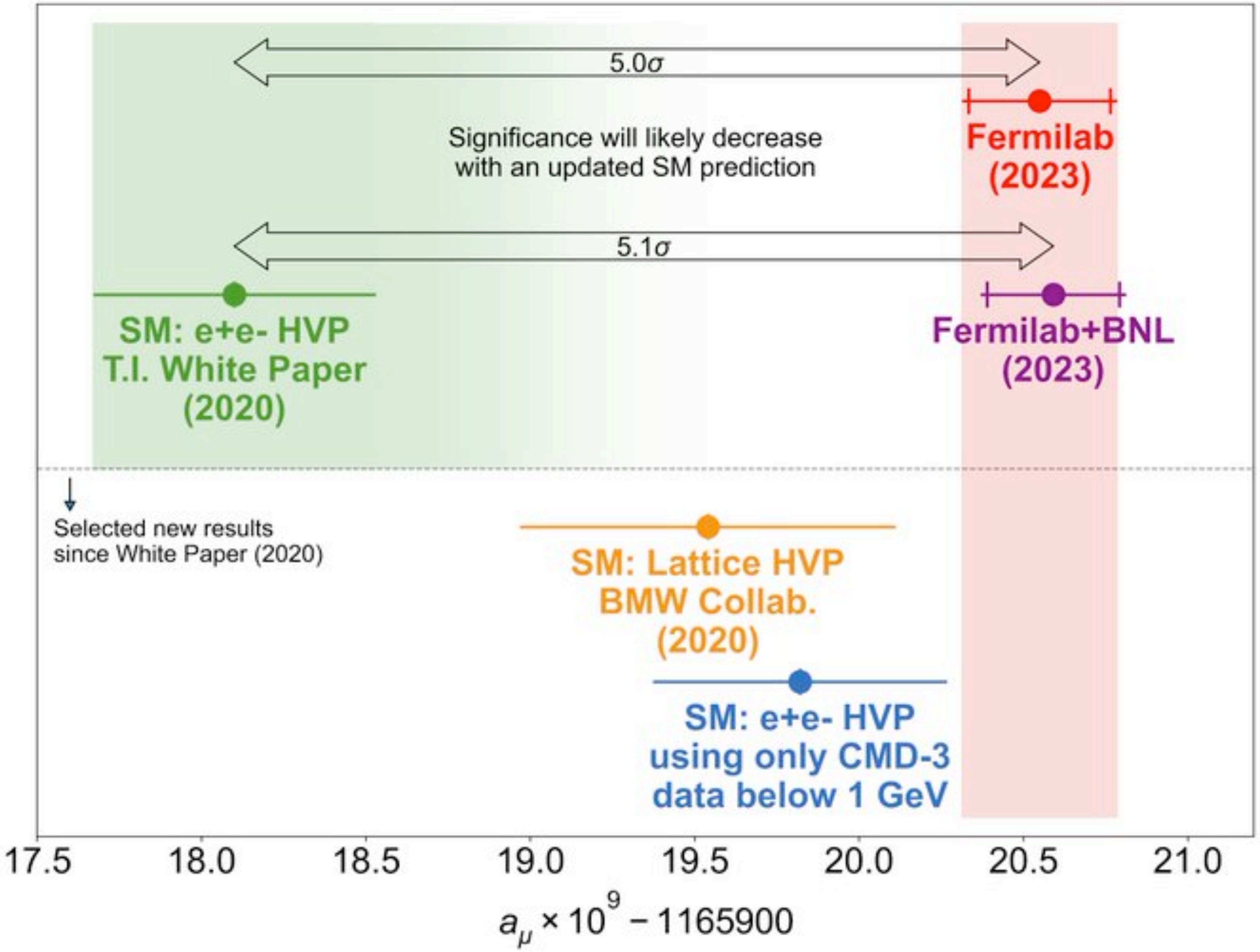

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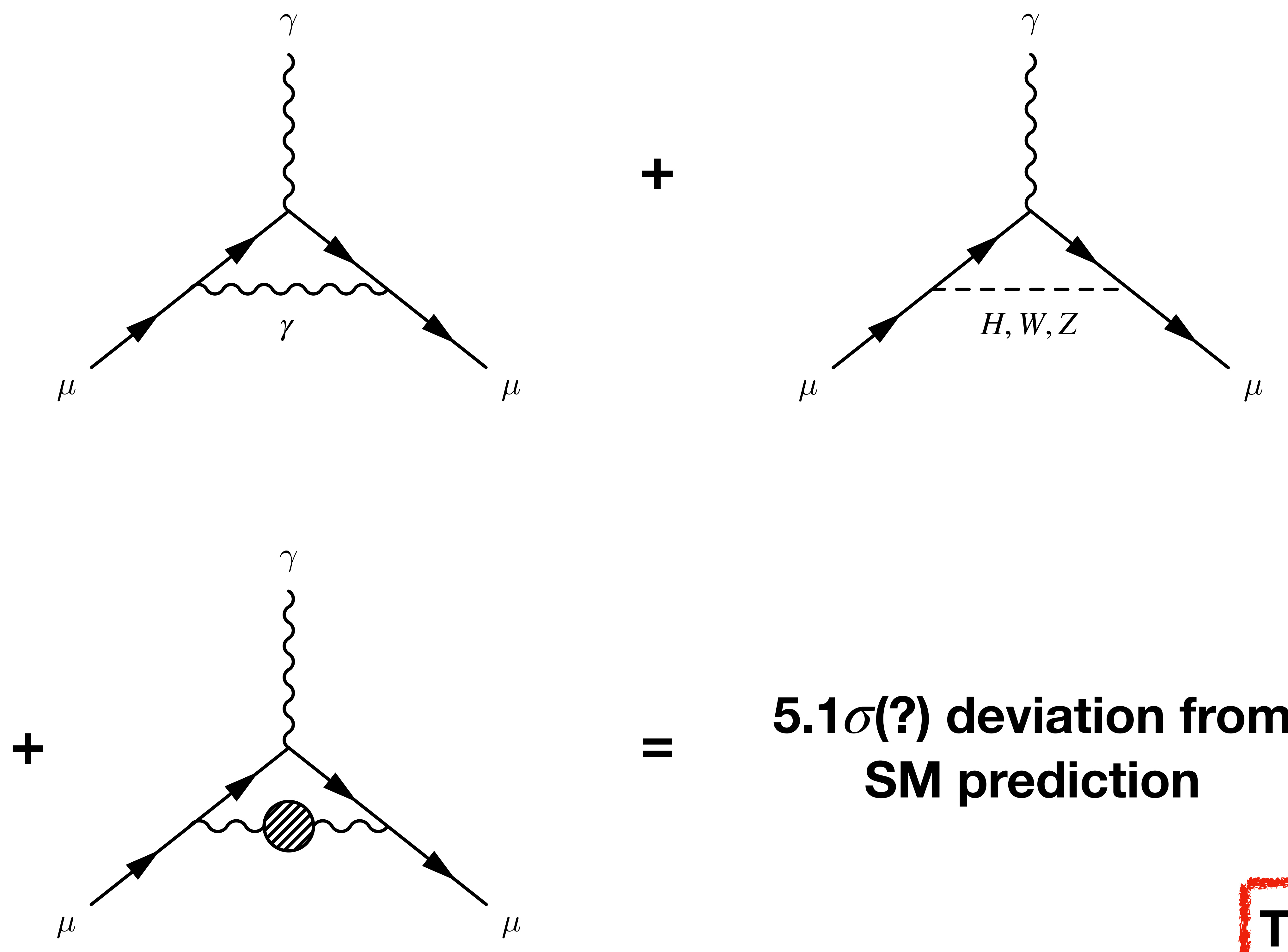

5.1σ(?) deviation from SM prediction

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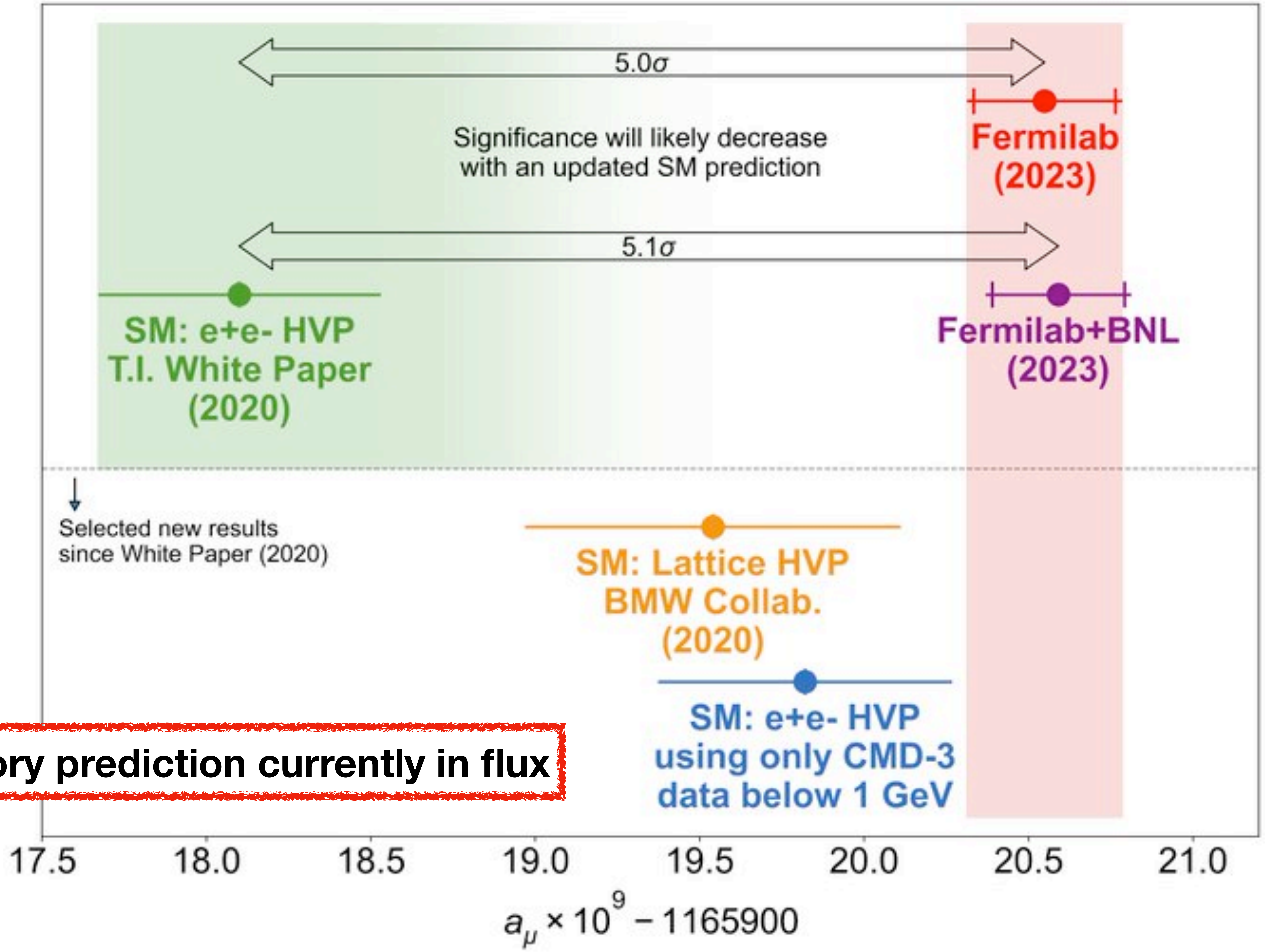

Theory prediction currently in flux

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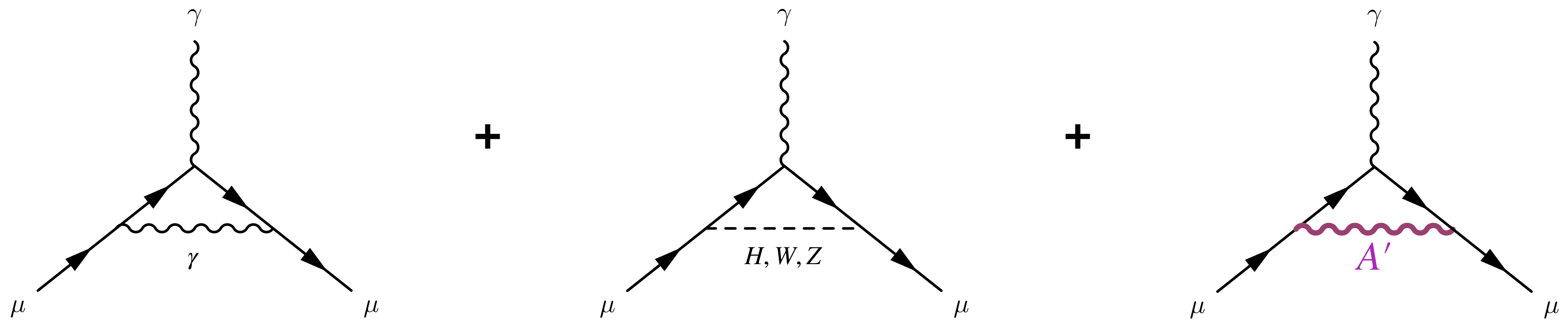
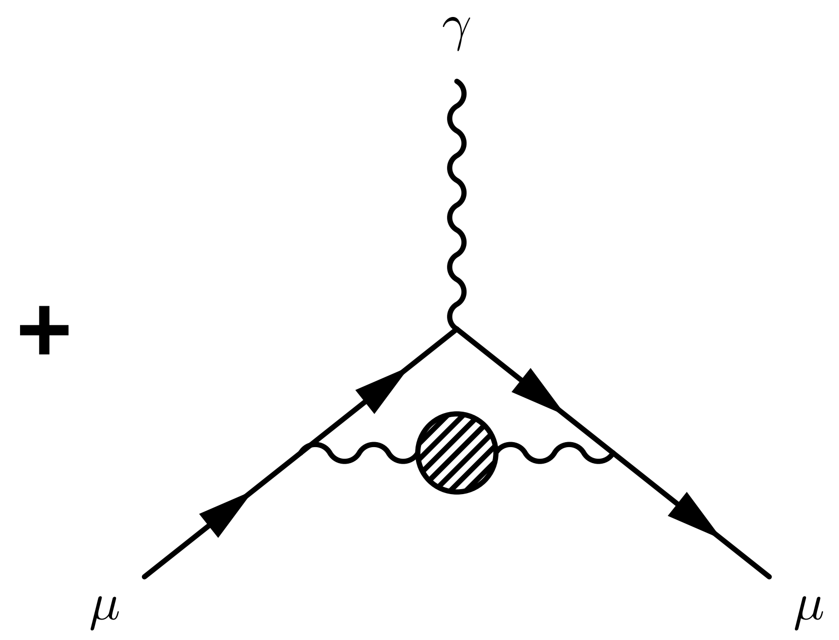


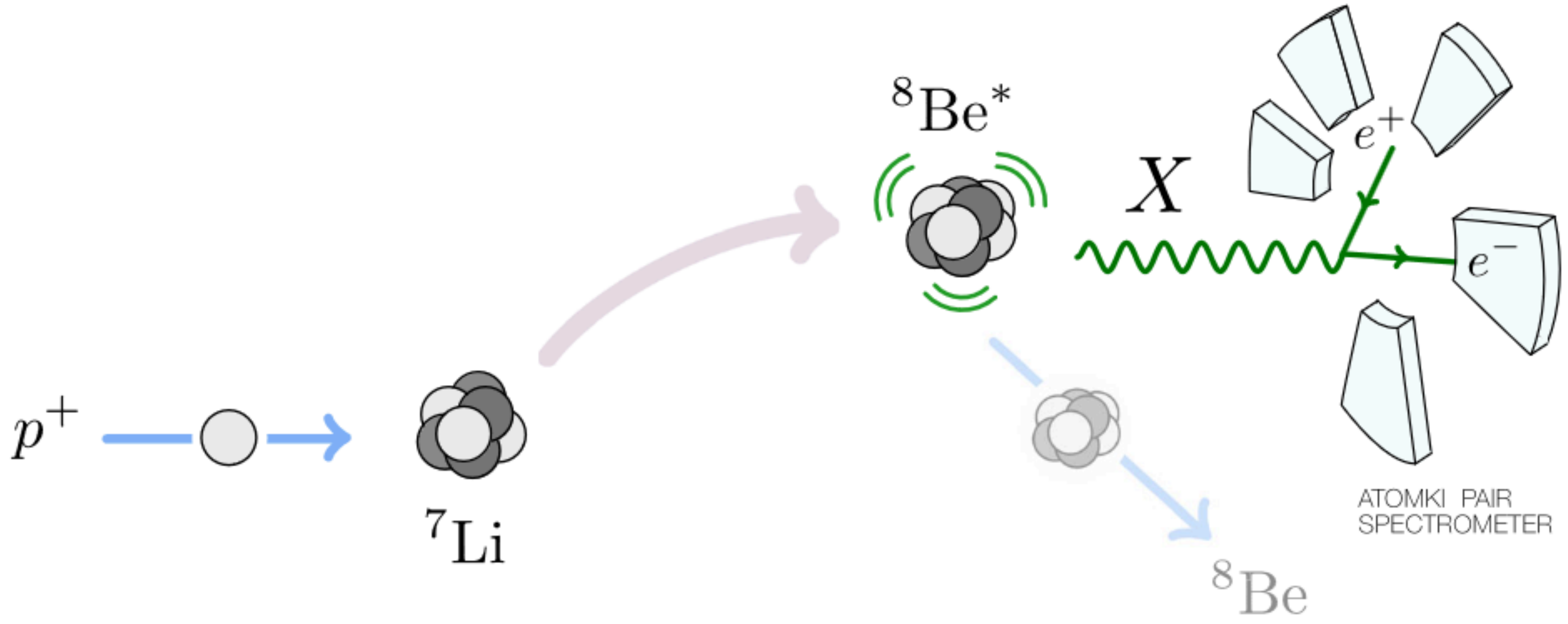


Dark photon could resolve discrepancy

Latest result: Phys. Rev. Lett. 131, 161802 (2023)

Experimental Anomalies: X17

- Originally observed by ATOMKI collaboration in excited state decays of ^{8}Be



Physical Review D 95, 035017 (2017)

See: Phys. Rev. Lett. 116, 042501 (2016), arXiv:1910.10459, Phys. Rev. C 104, 044003 (2021), arXiv:2205.07744, Phys. Rev. C 106, L061601 (2022), arXiv:2308.06473, arXiv:2311.18632, arXiv:2401.11676

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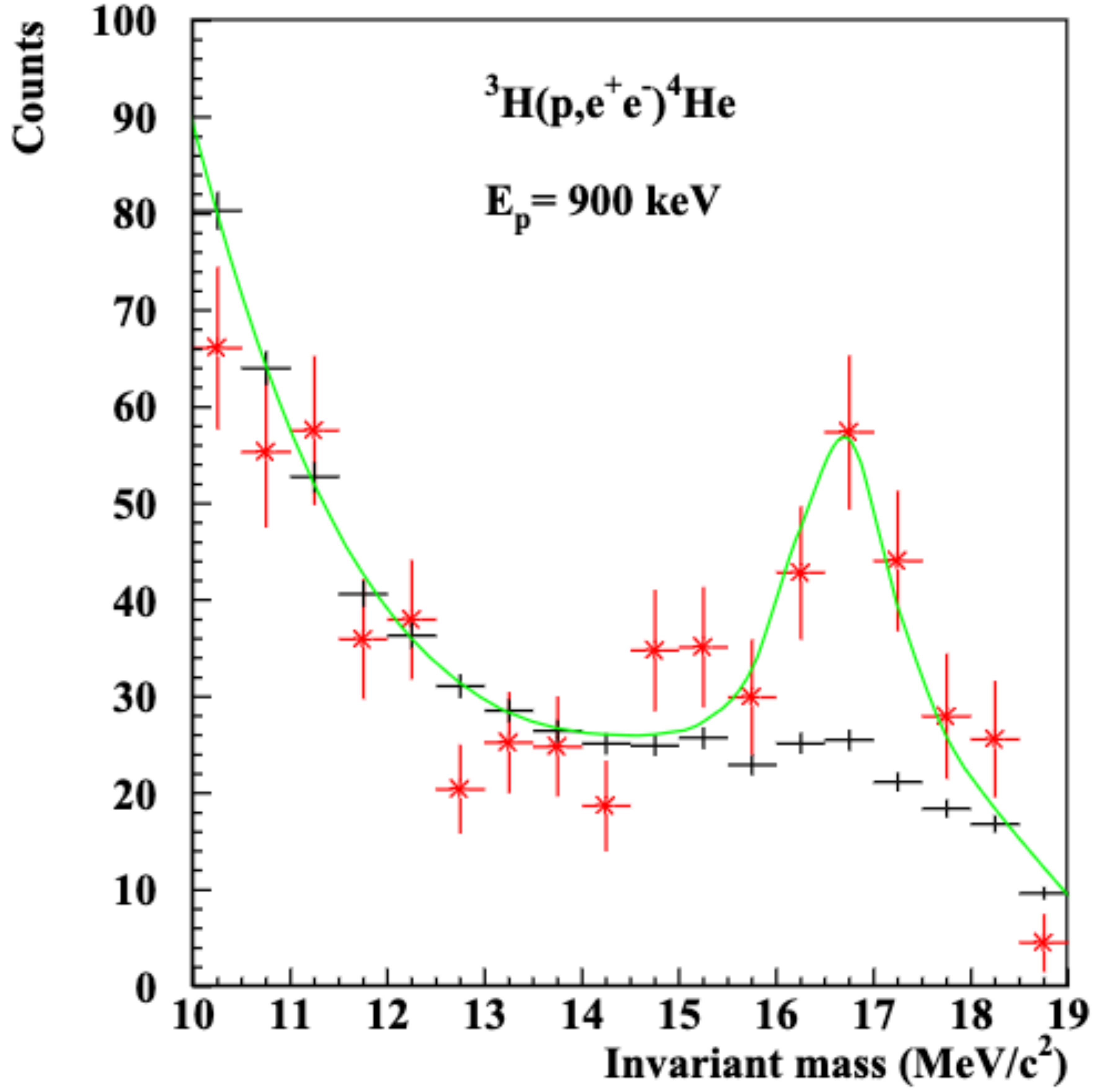


- Excess in e^+e^- invariant mass spectrum possibly indicative of a new boson with mass around 17 MeV

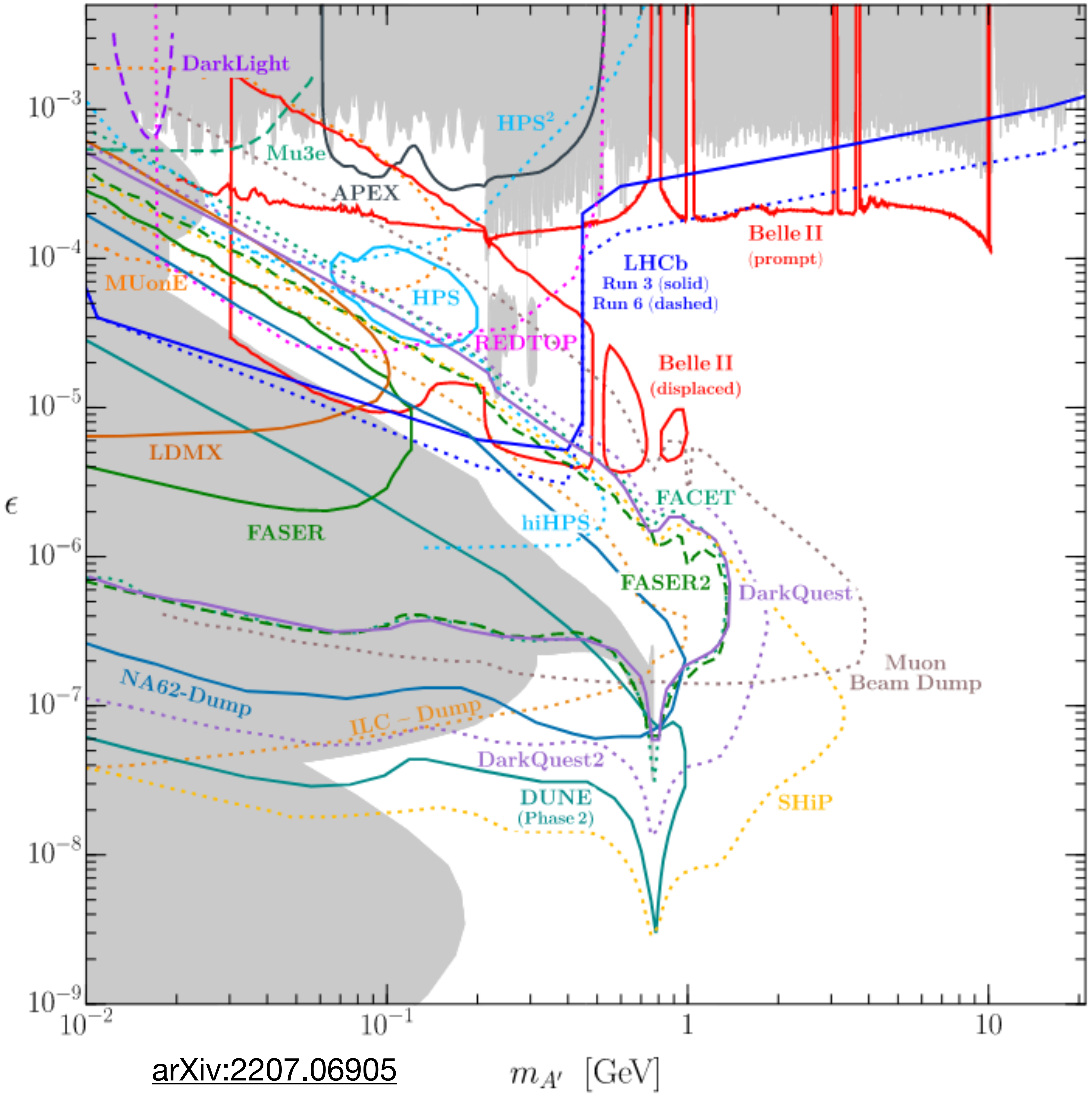
- Similar anomaly observed in ^{4}He, ^{12}C and using an independent apparatus

- Other ongoing efforts to confirm this

See: Phys. Rev. Lett. 116, 042501 (2016), arXiv:1910.10459, Phys. Rev. C 104, 044003 (2021), arXiv:2205.07744, Phys. Rev. C 106, L061601 (2022), arXiv:2308.06473, arXiv:2311.18632, arXiv:2401.11676

Dark Photon: Current Limits

Limits for past (grey) and future dark photon experiments



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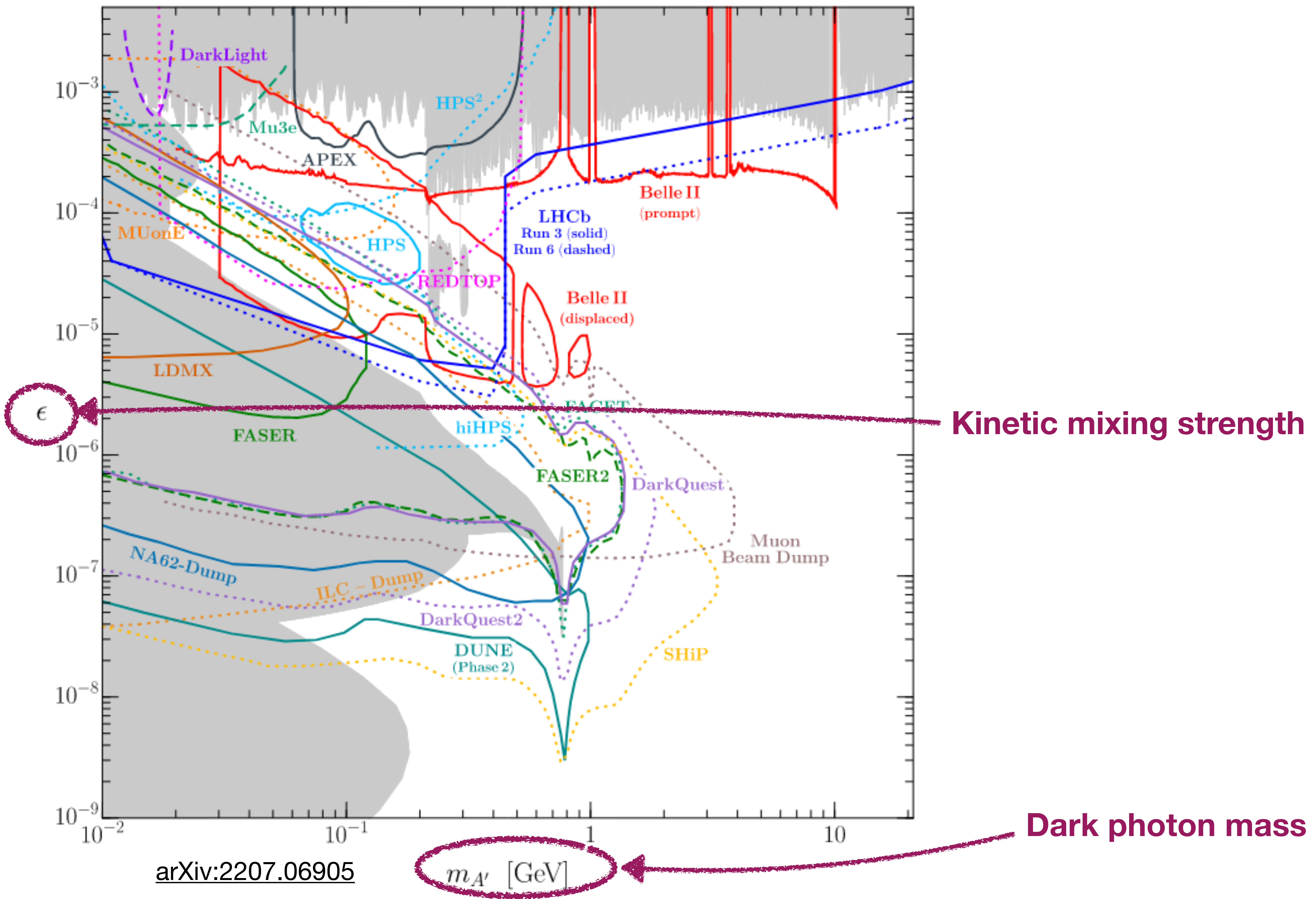

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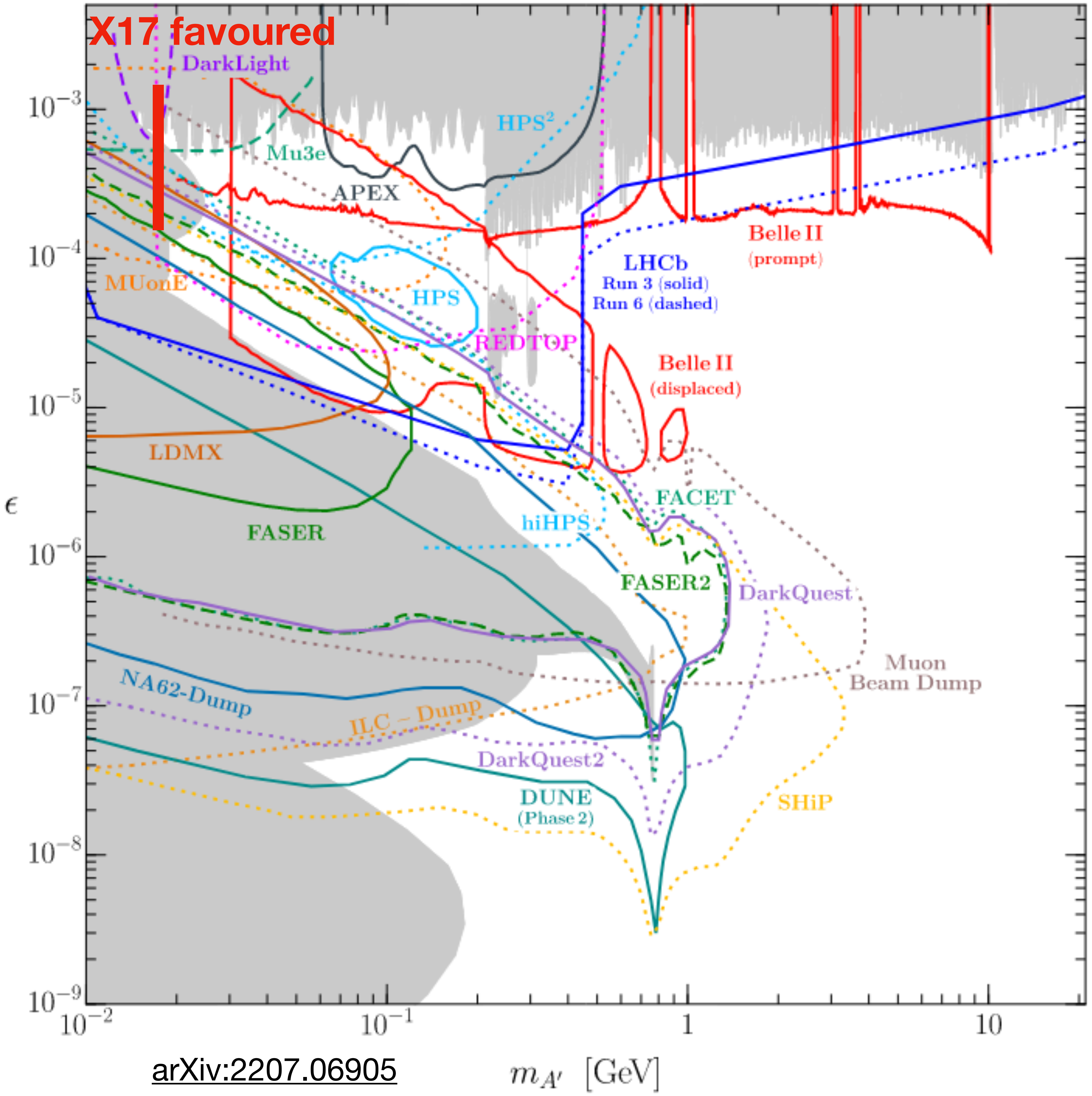

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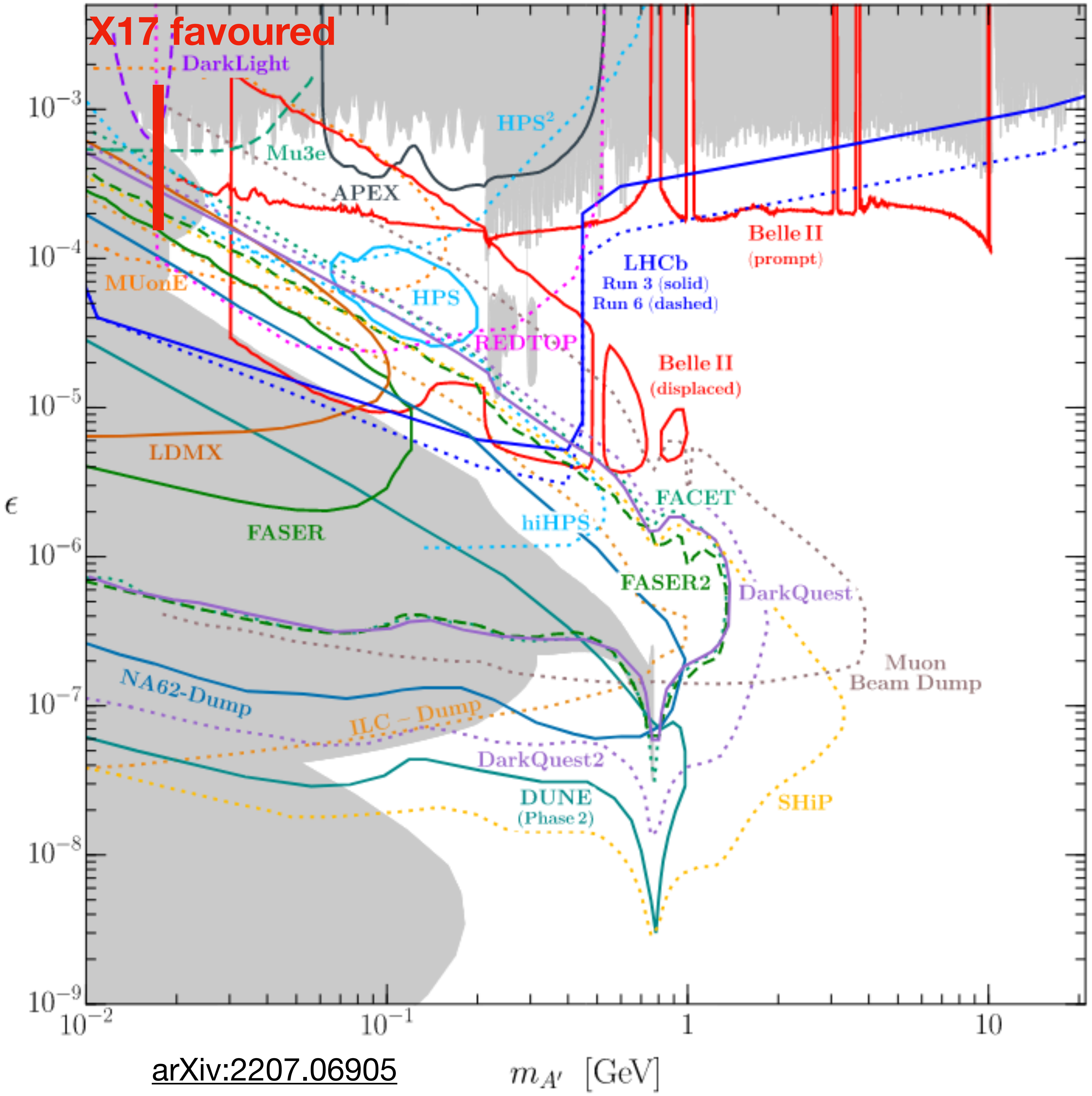

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- Unclear exactly what form the coupling ε takes
- **Protophobic** coupling (reduced coupling to protons) required by the X17
  - Coupling no longer universal to the EM current: $\mathscr{L}_{\text{int}} = e\varepsilon J_\mu A'^\mu$
  - Instead something more complex, but can still display limits in the same parameter space

For more details see: Feng et. al. PRL 117, 071803 (2016), Physical Review D 95, 035017 (2017), Physical Review D 102, 036016 (2020)

Boson
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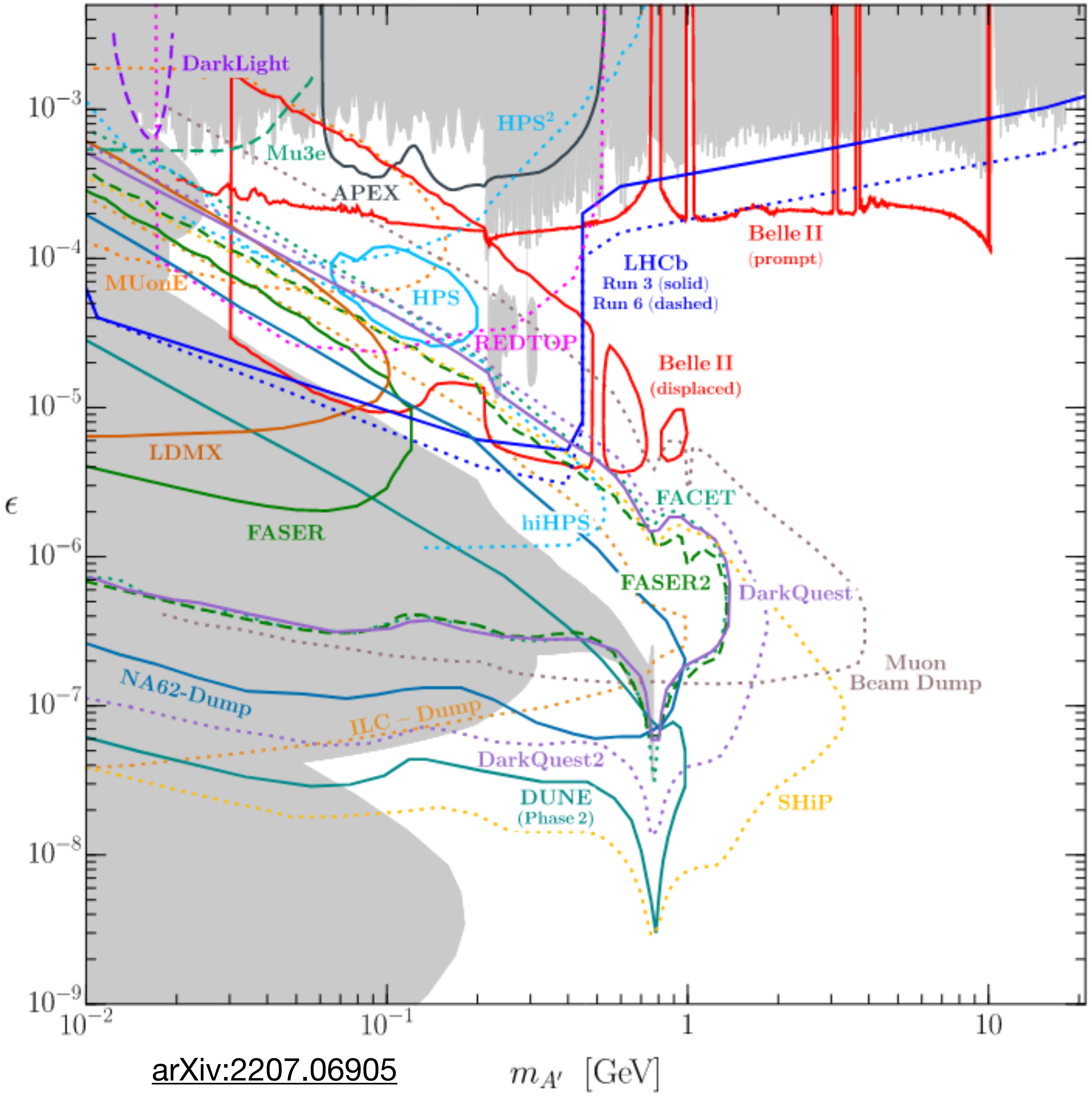

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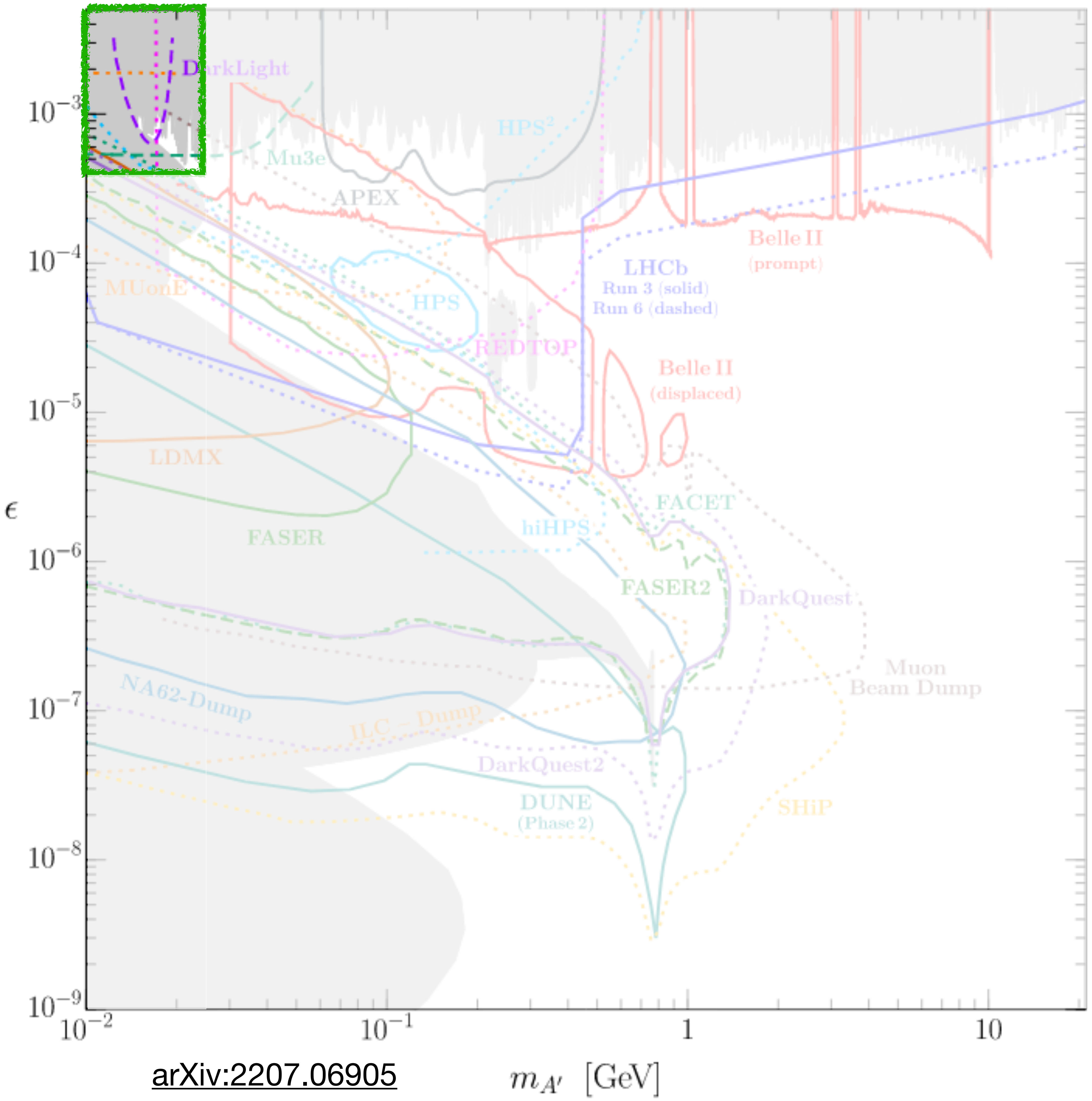

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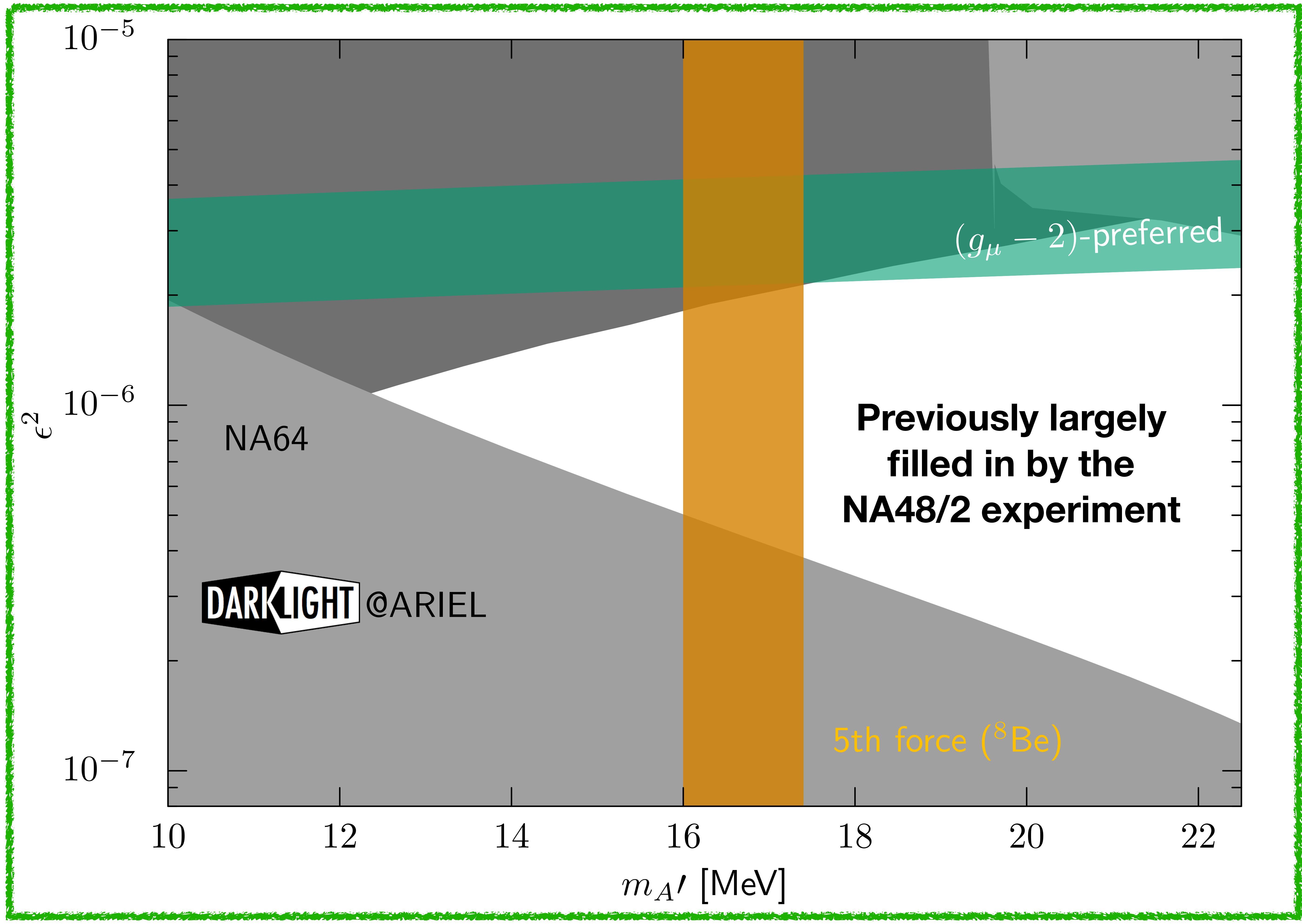

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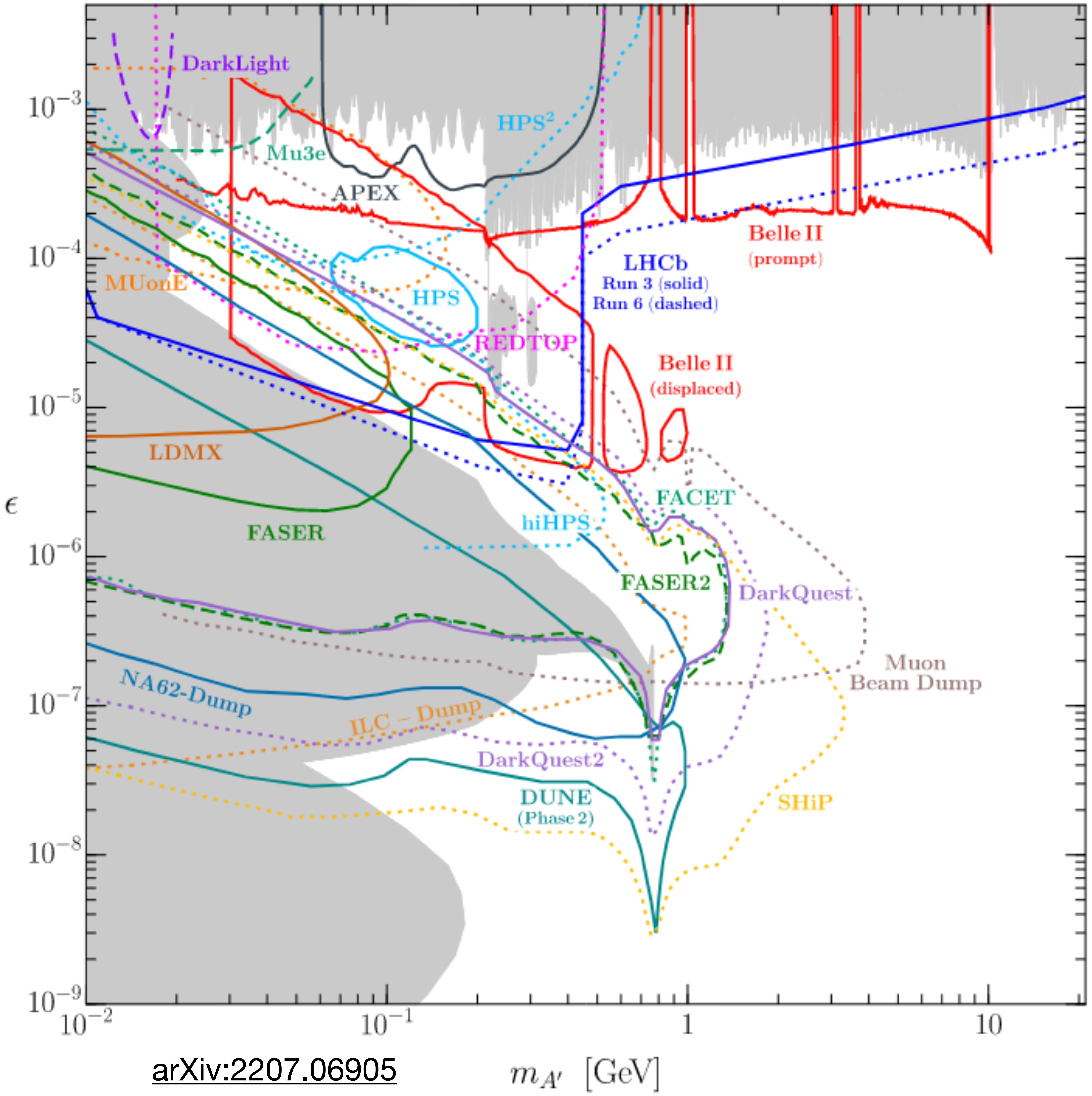

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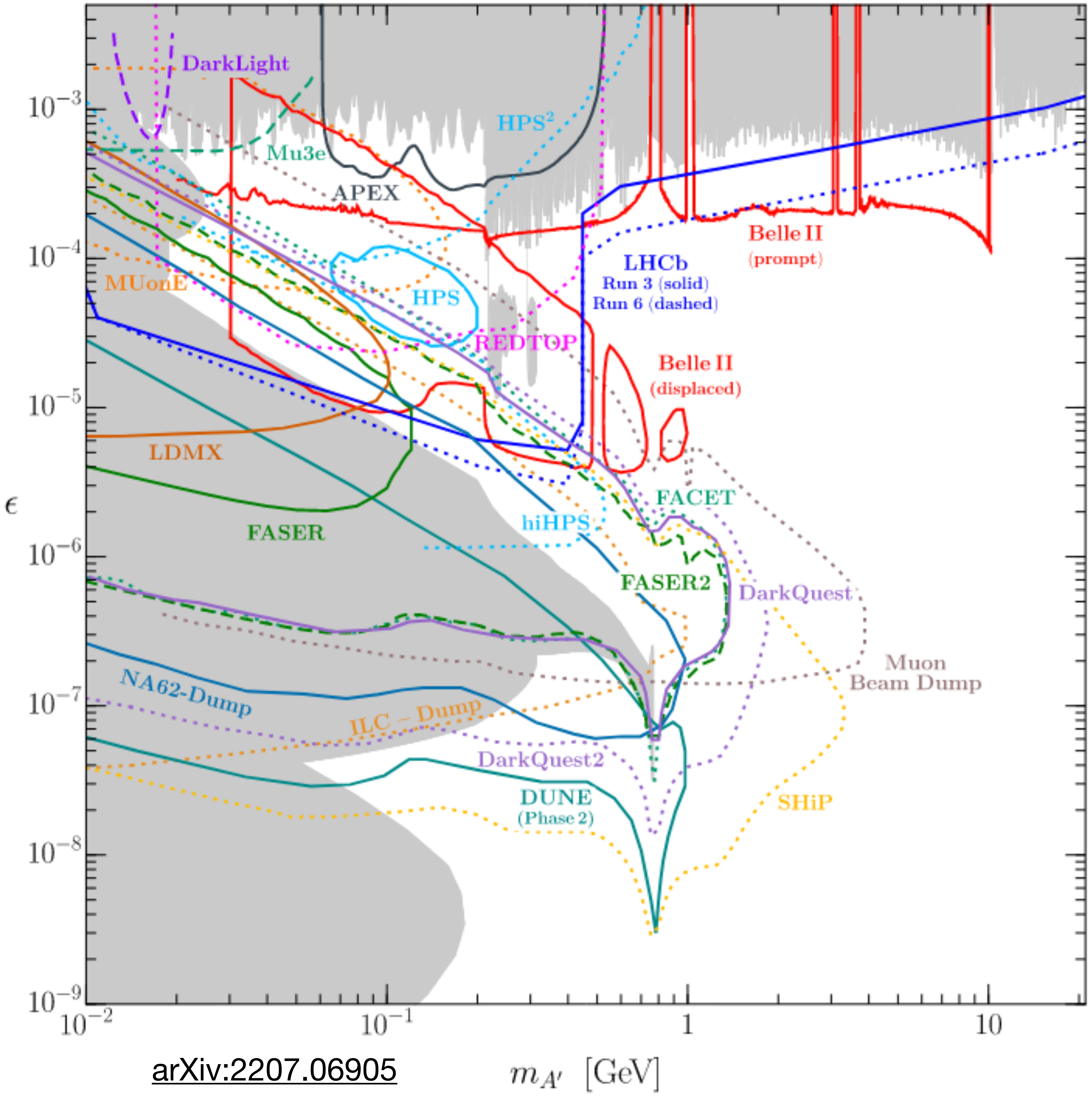

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DARKLIGHT

DarkLight@ARIEL

- Bombard fixed high Z target with low energy high intensity electron beam

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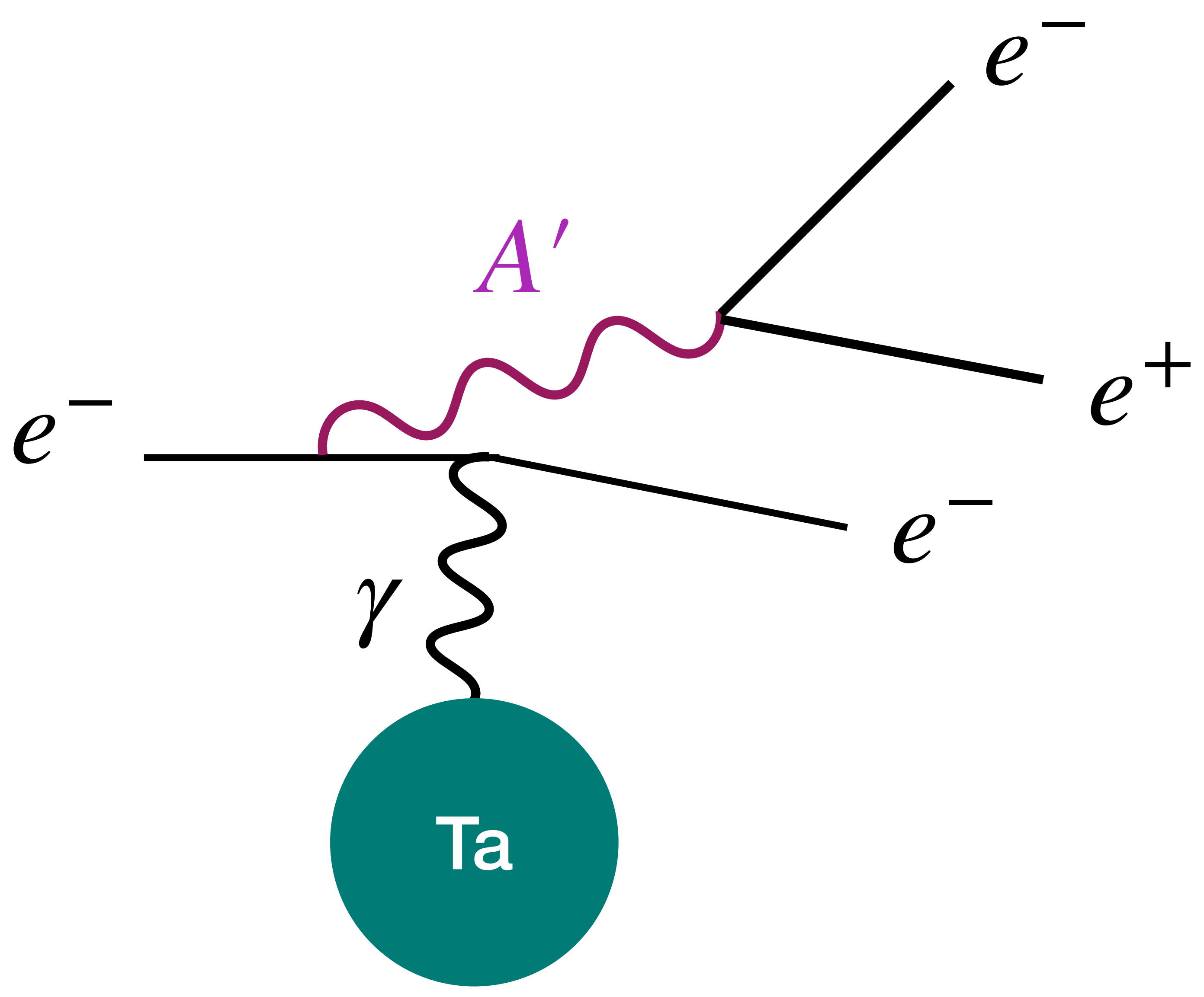

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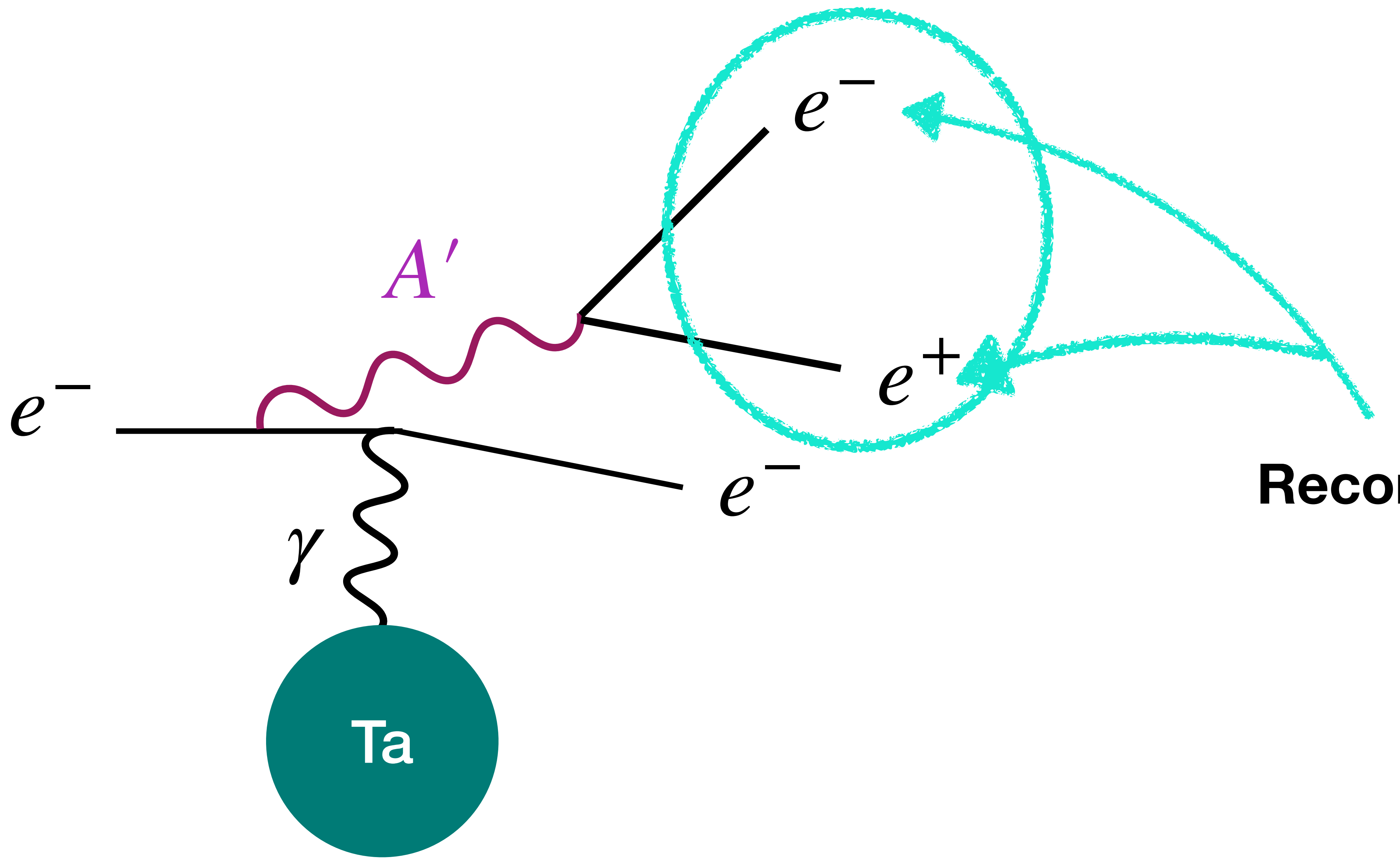

Reconstruct invariant mass of electron-positron system

DarkLight@ARIEL

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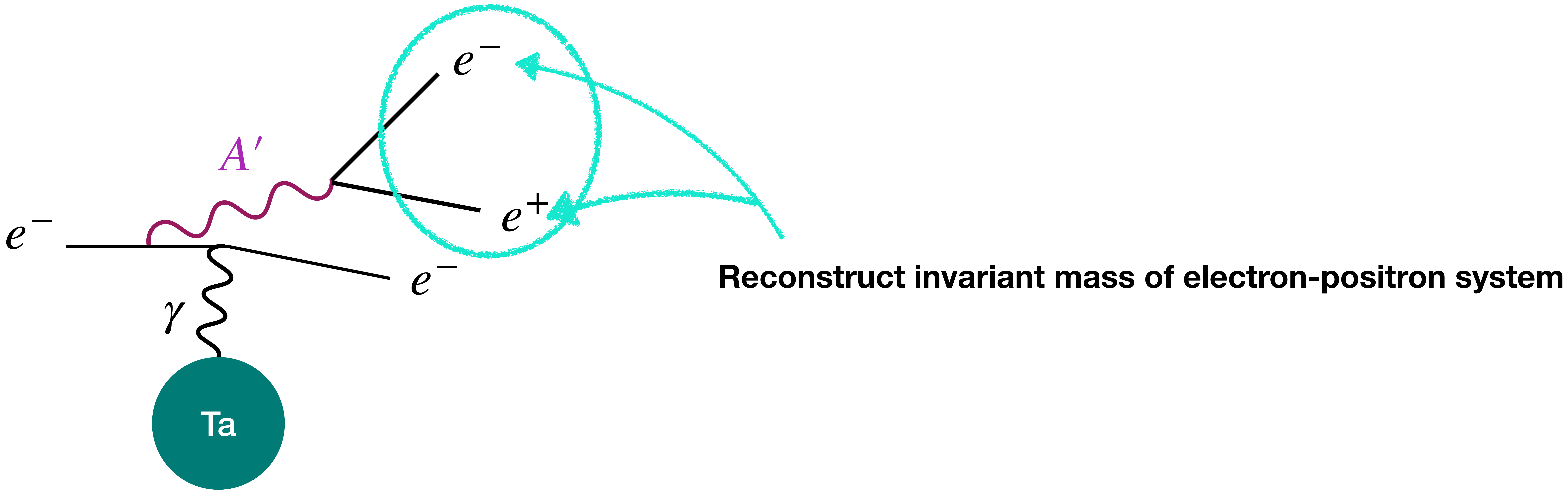
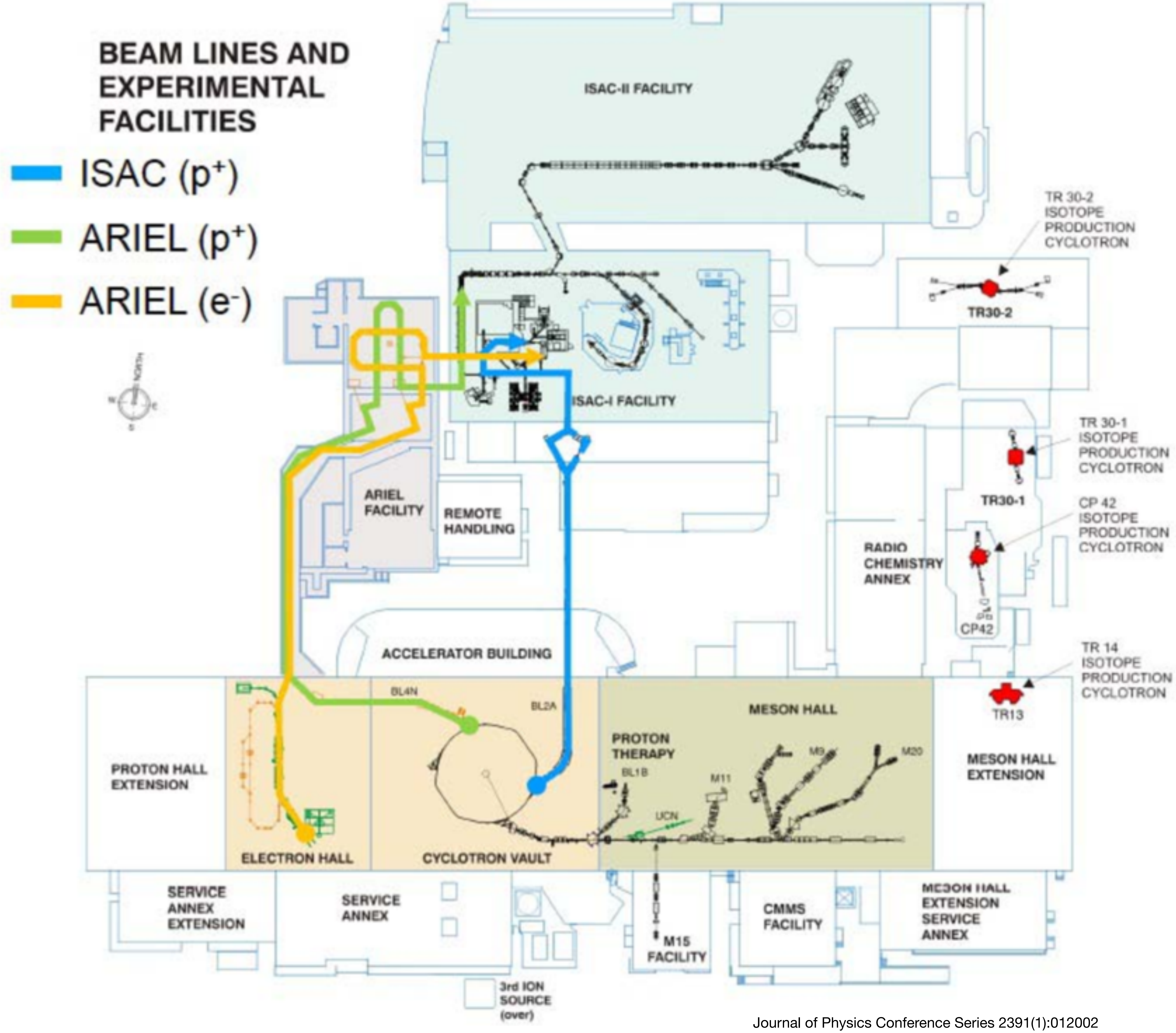


- Low energy allows probe of $g_\mu - 2$ favoured and X17 region, high intensity for lots of statistics

ARIEL



Journal of Physics Conference Series 2391(1):012002

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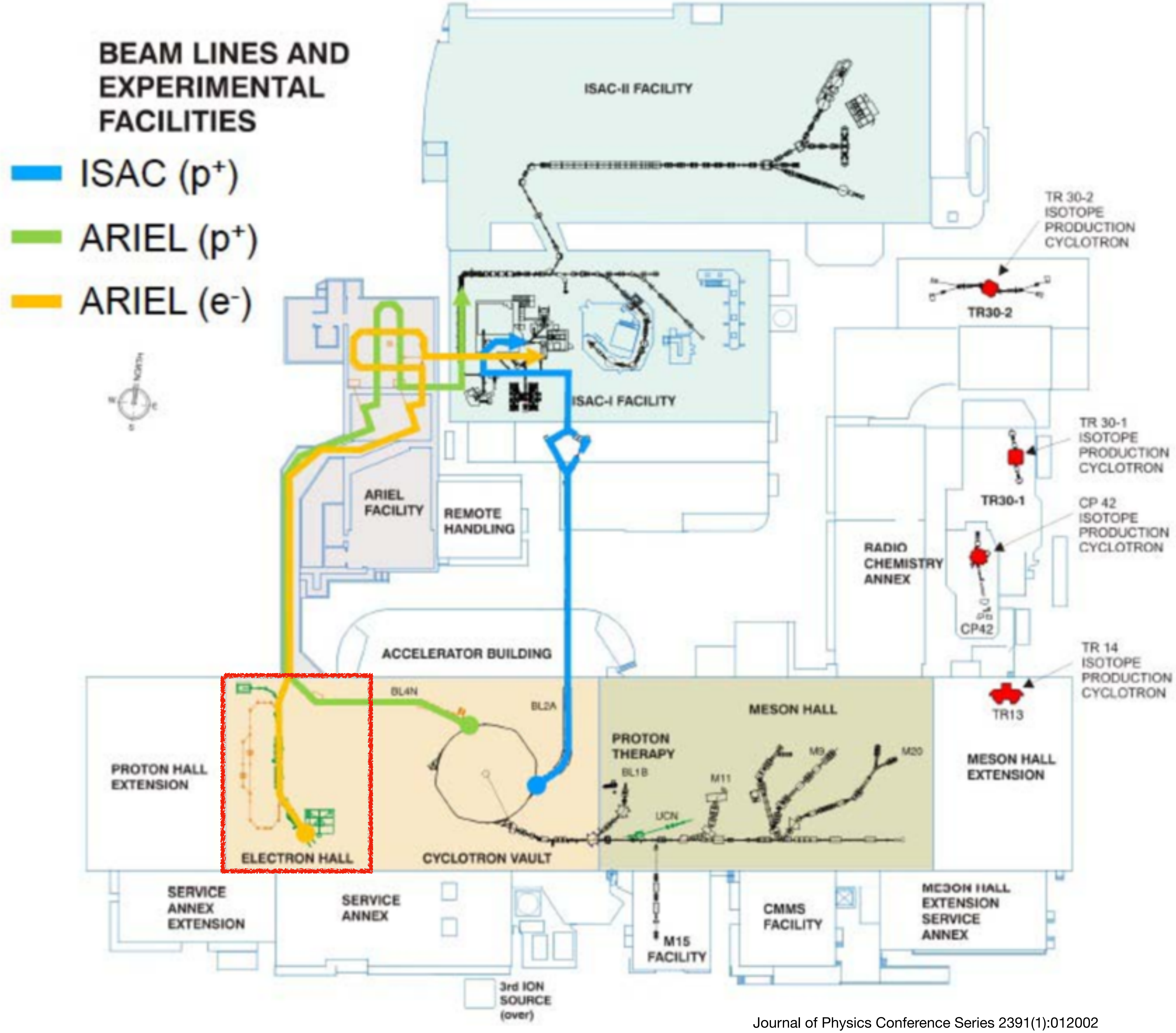

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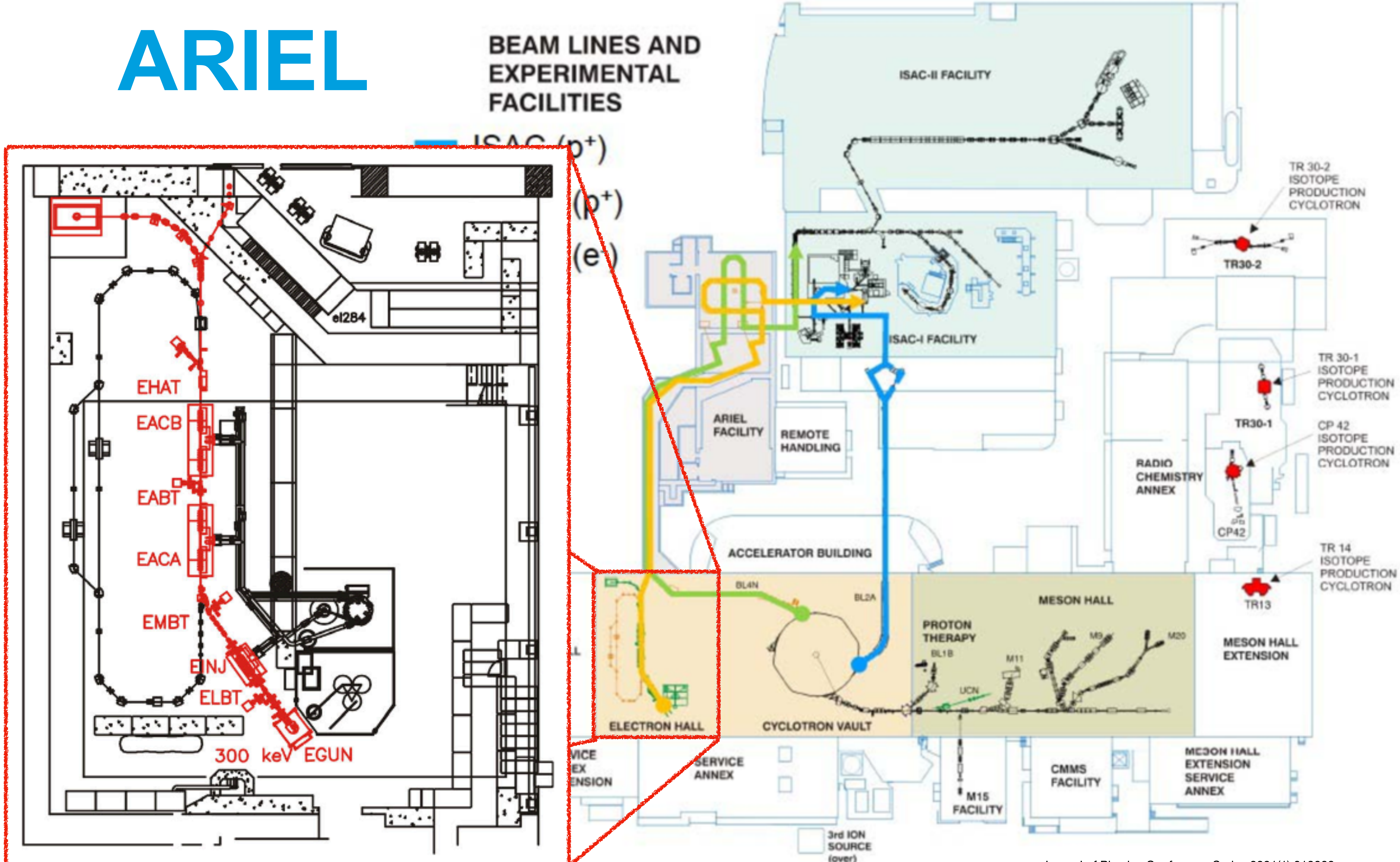

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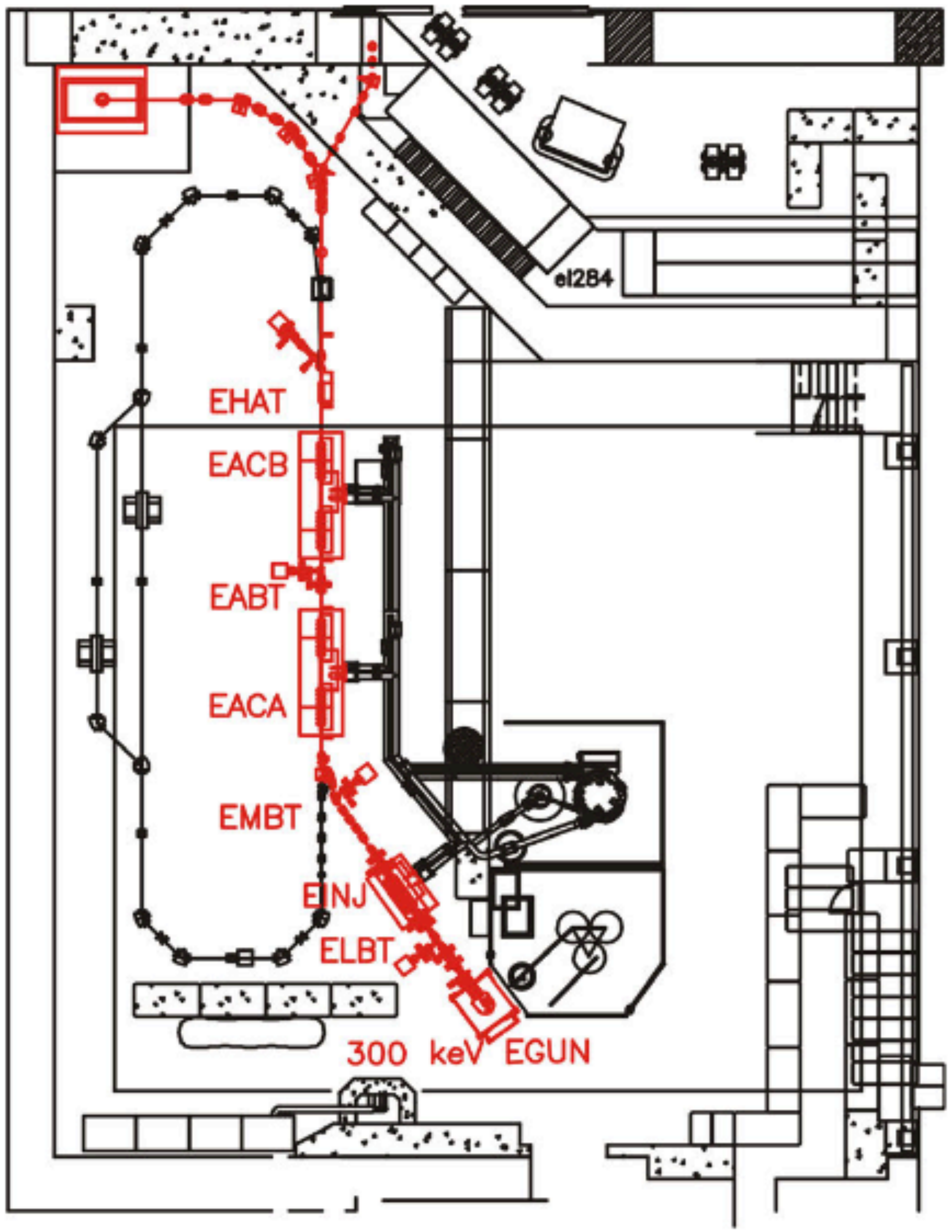
ARIEL e-linac

- 30 MeV electron beam setup



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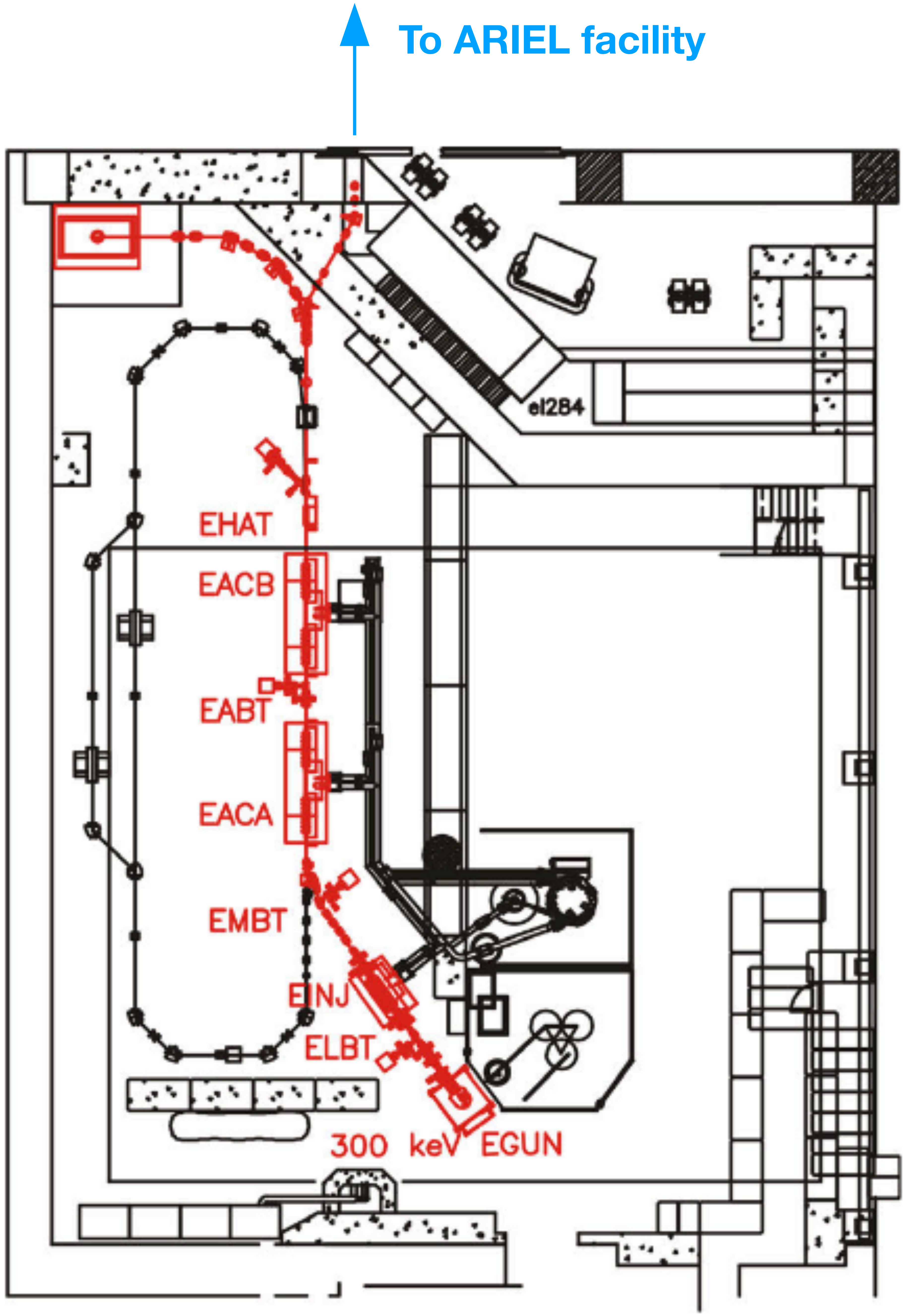

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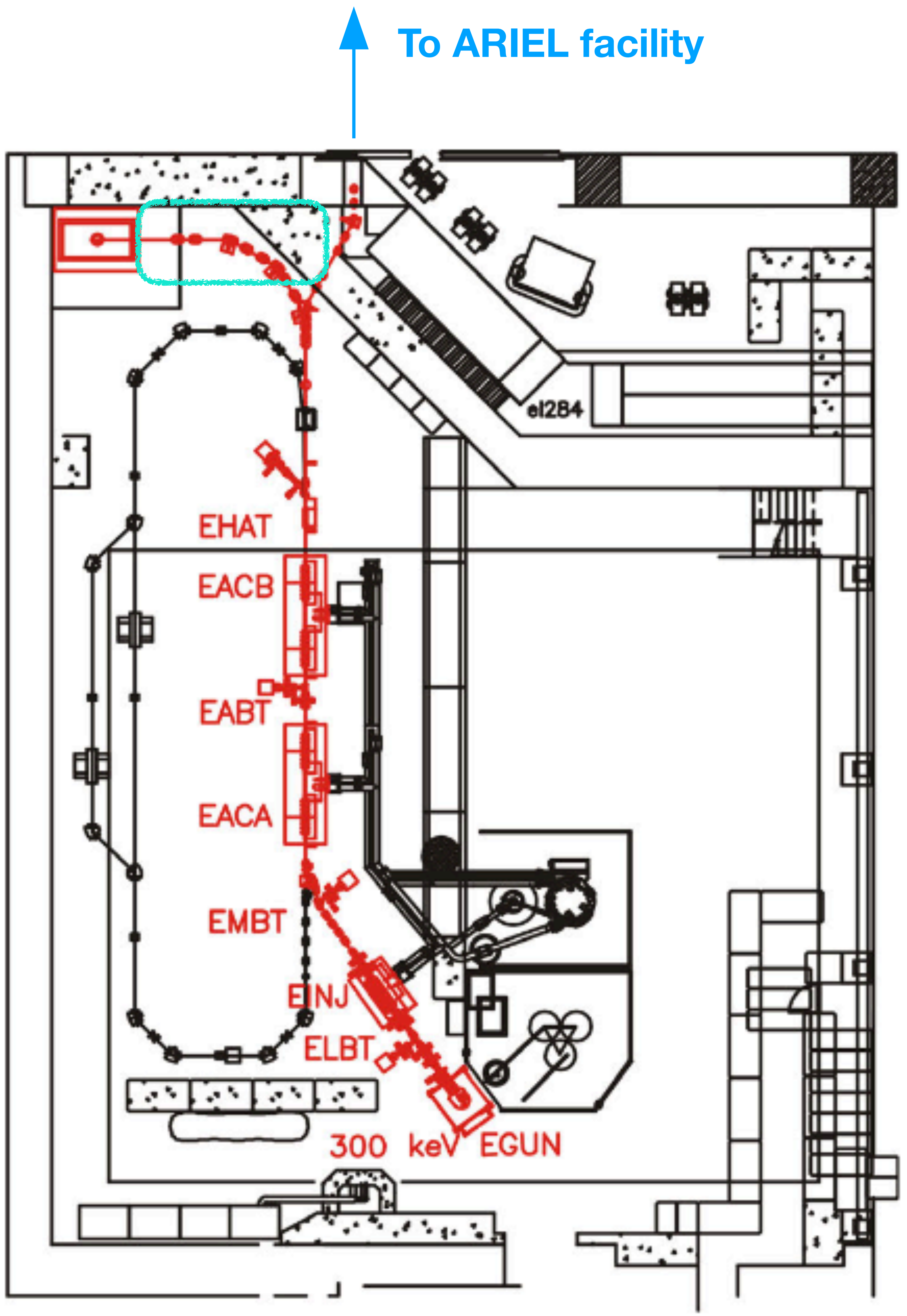
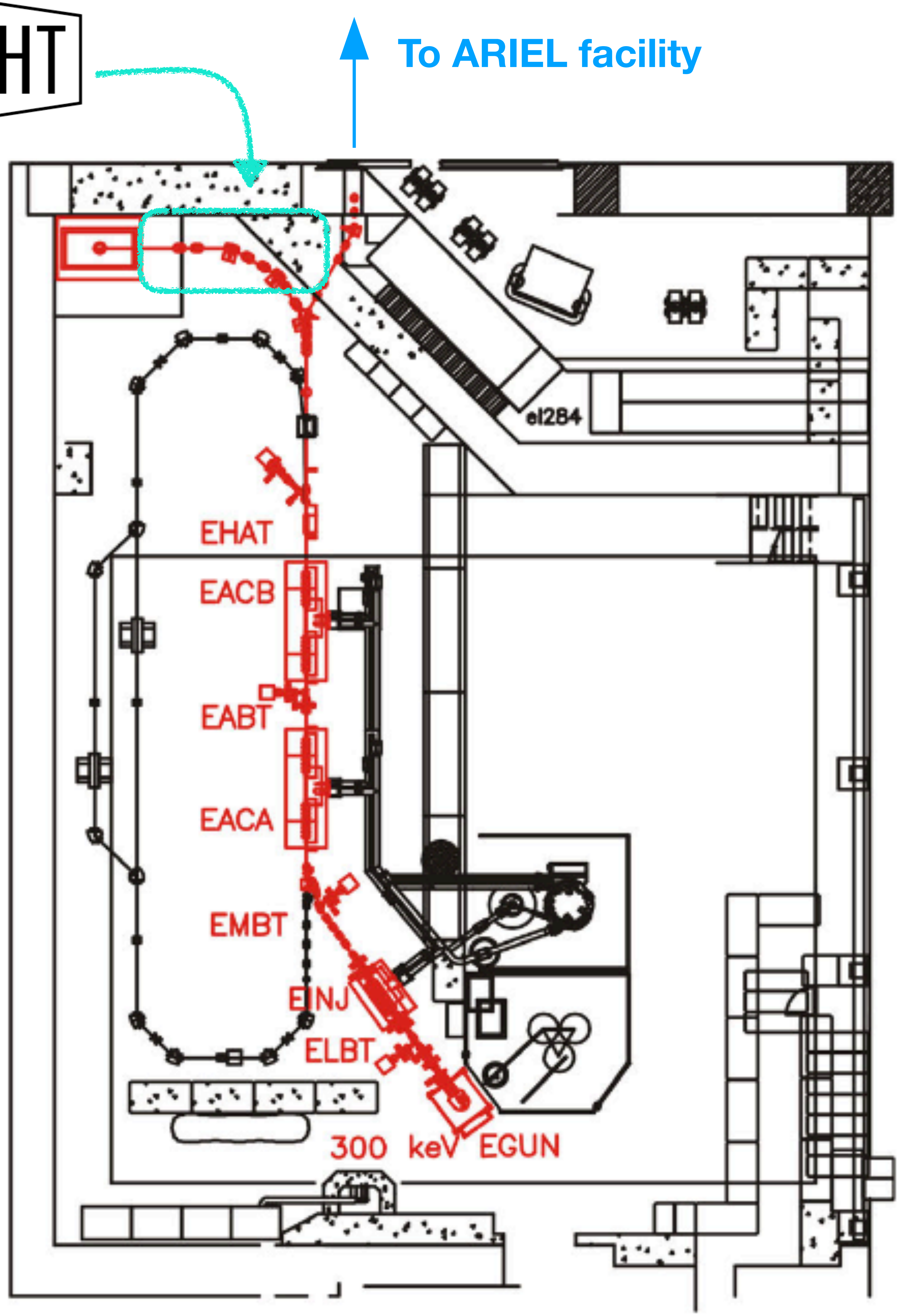


ARIEL e-linac

DARKLIGHT

- 30 MeV electron beam setup
  - Best sensitivity below 17 MeV
  - Excellent for commissioning
- 50 MeV upgrade: new cryomodule
  - Allows probe of X17 favoured region



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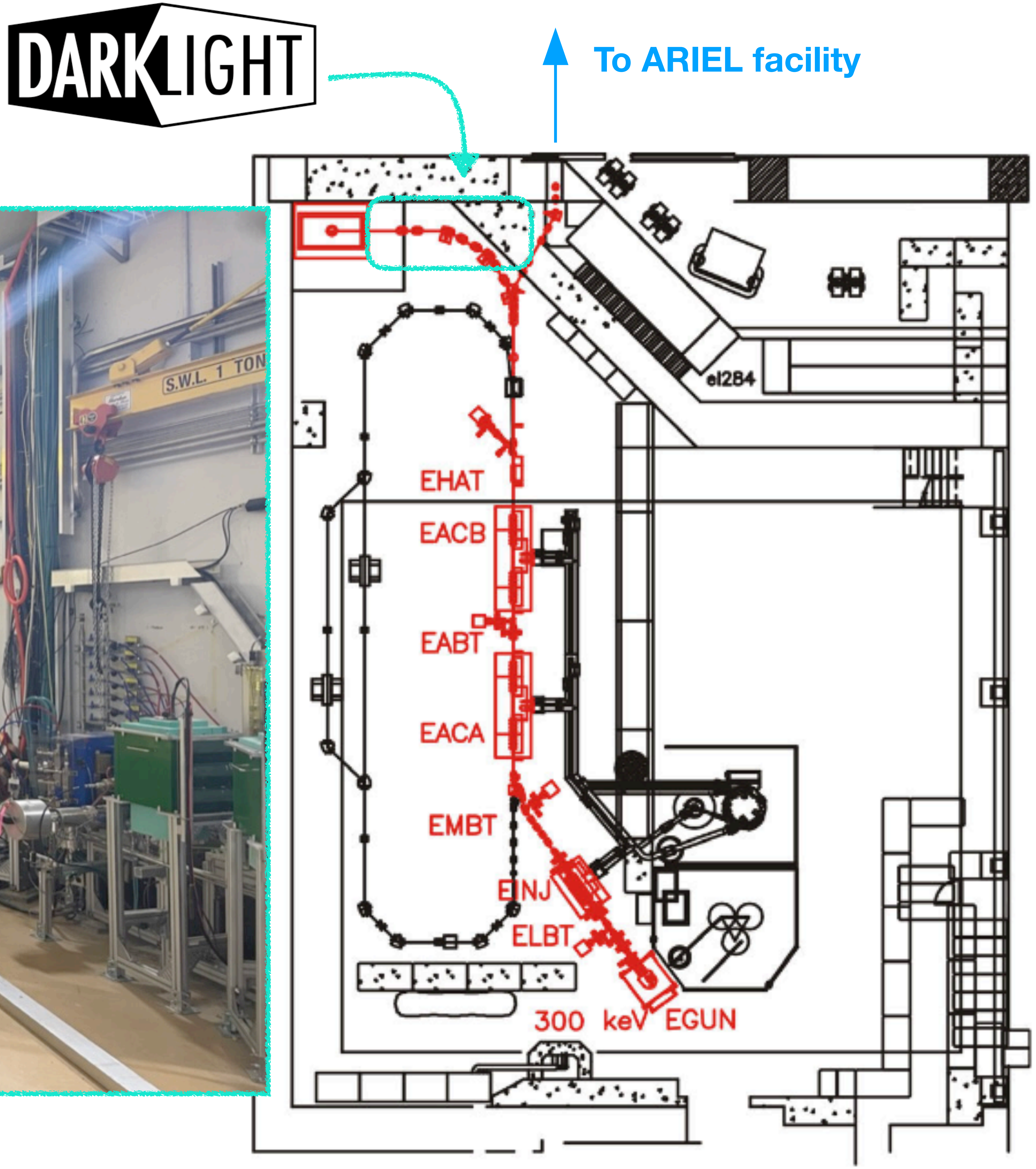

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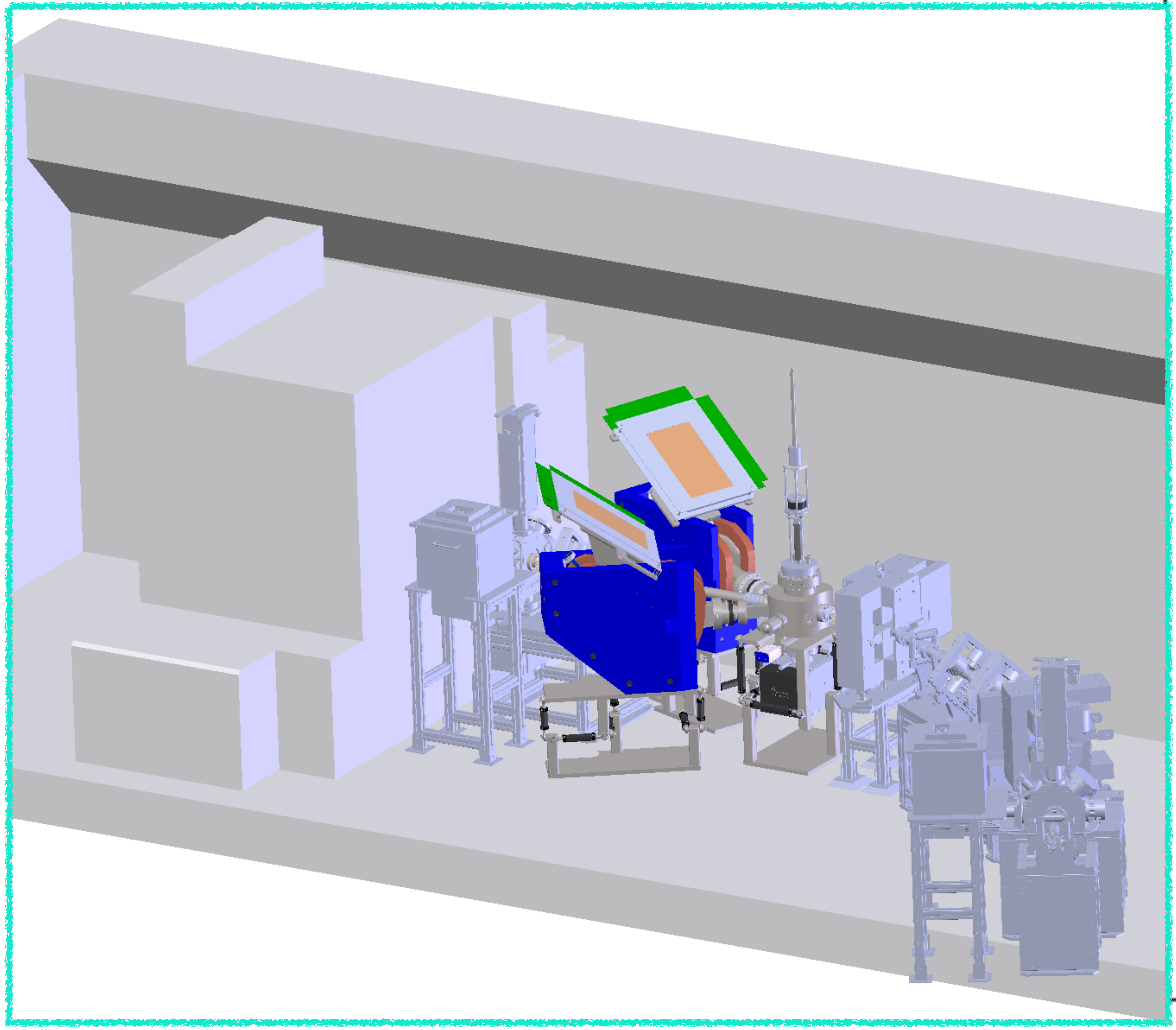
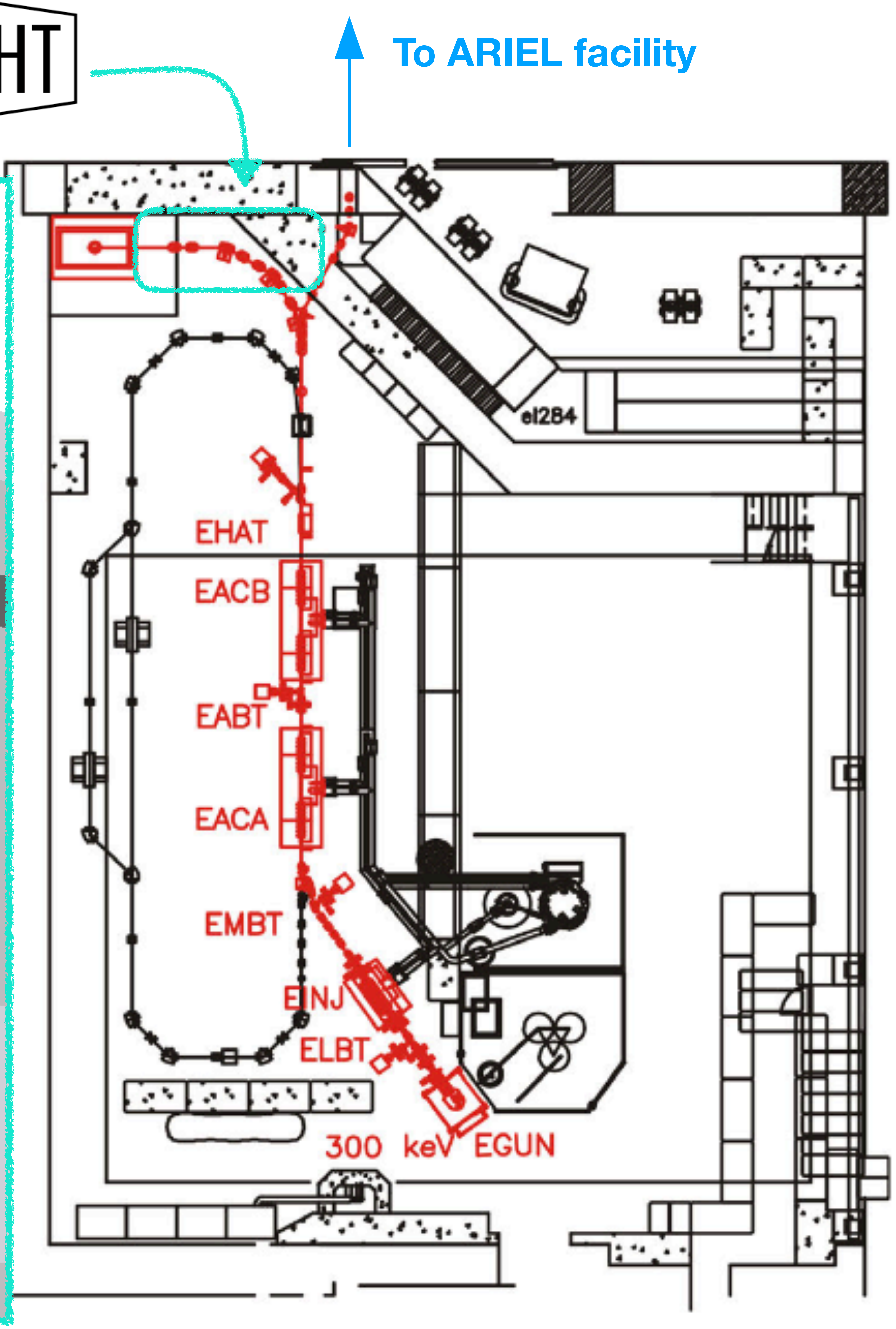
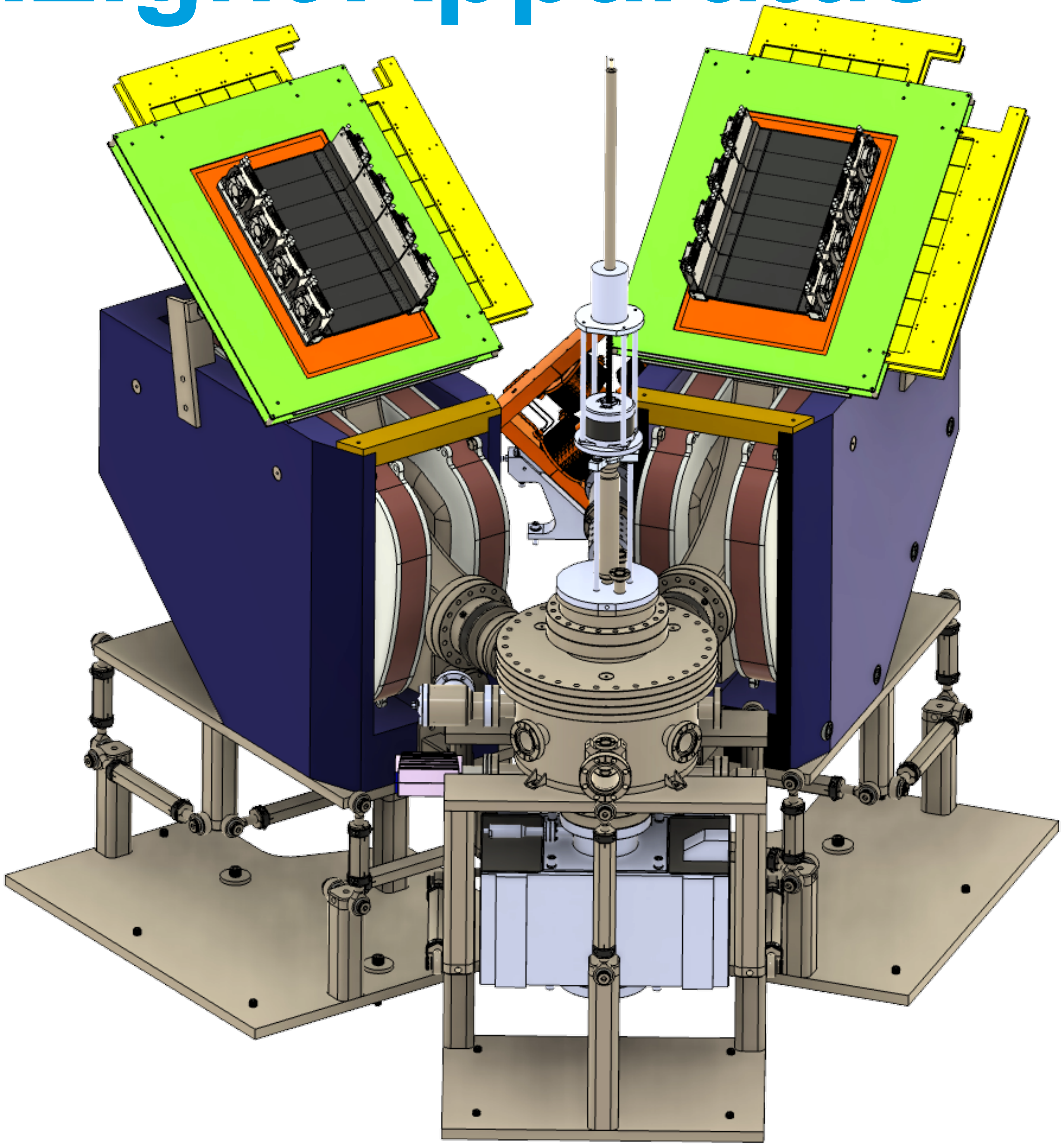




The DarkLight Apparatus



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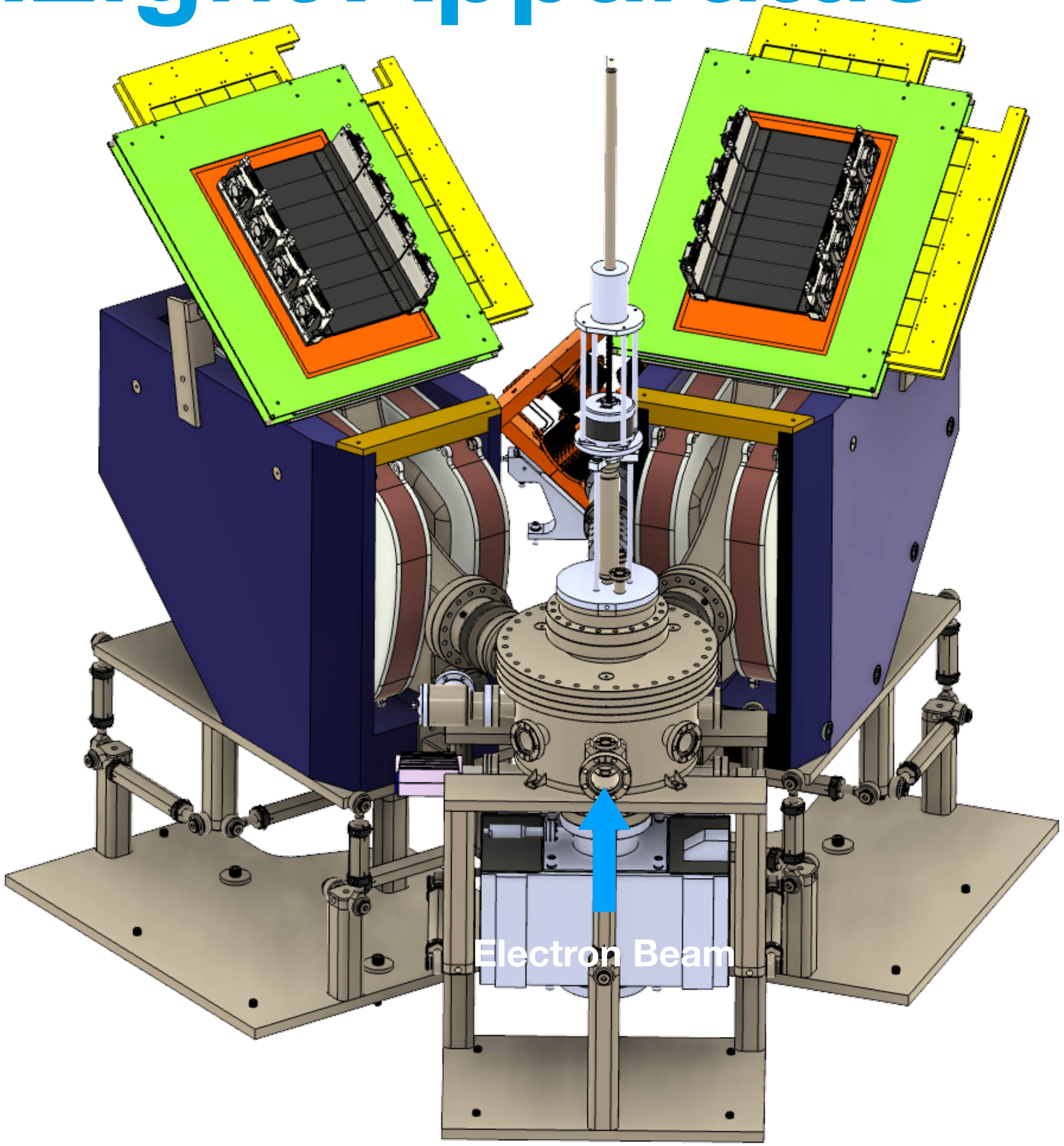

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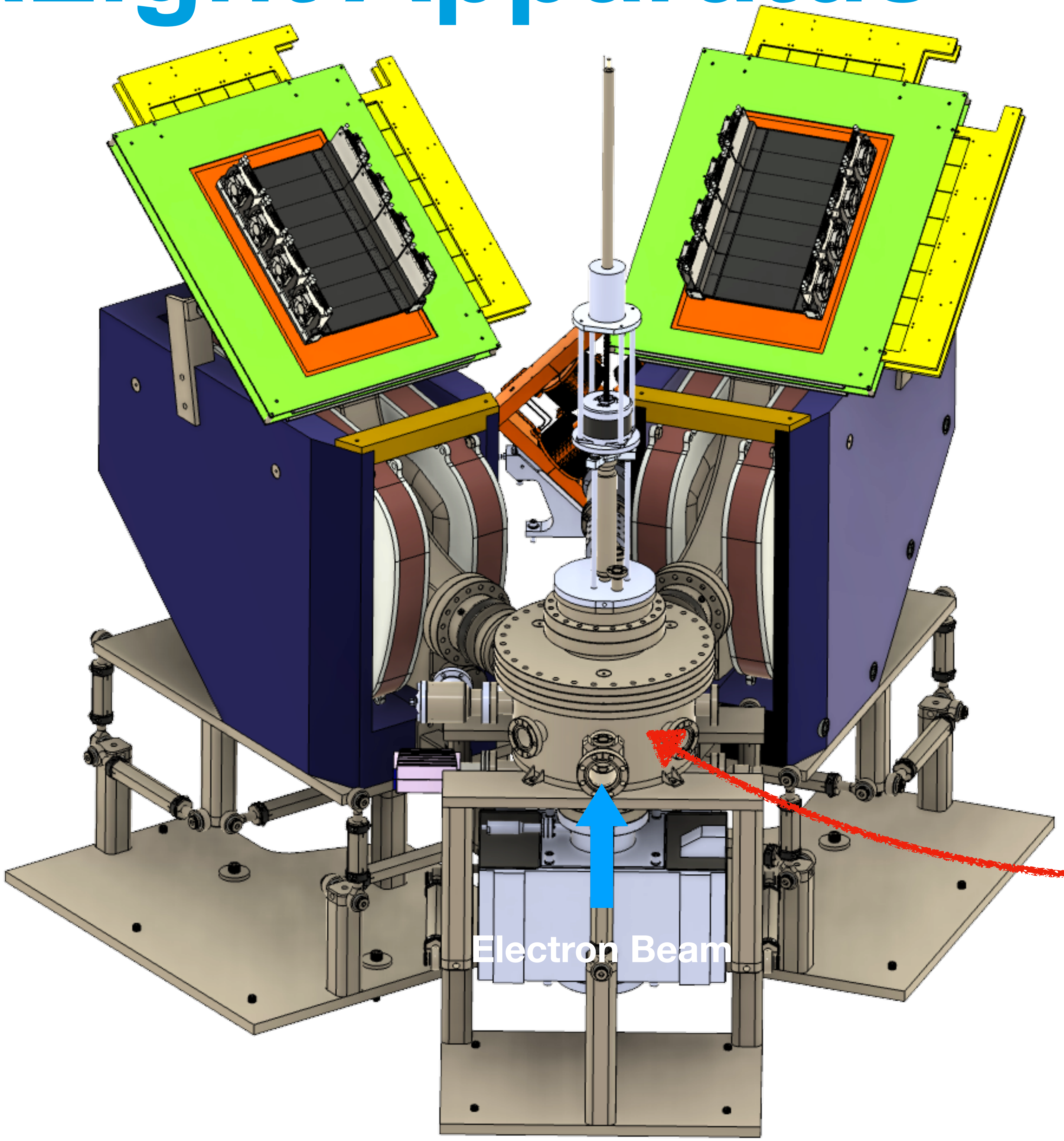

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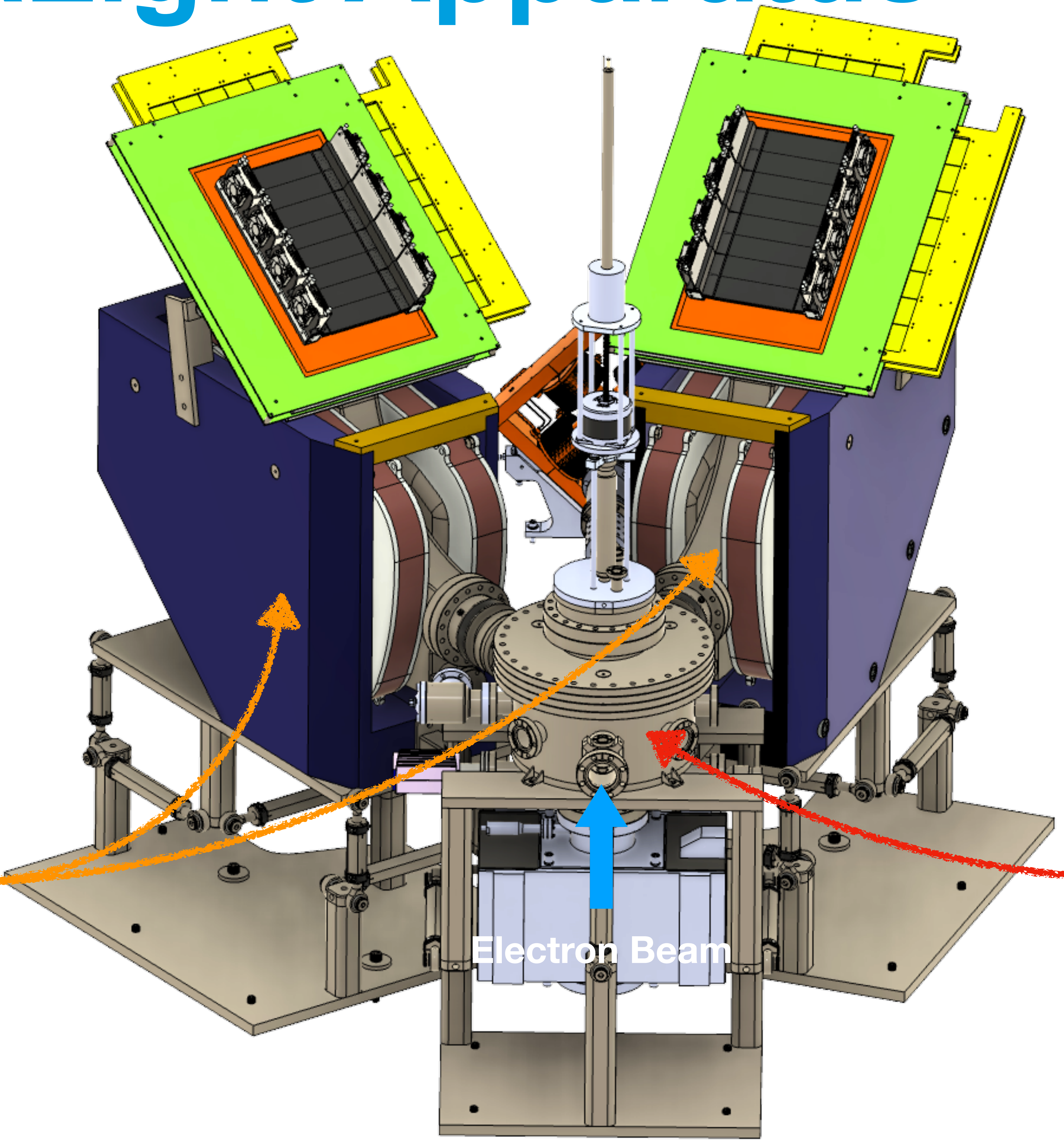
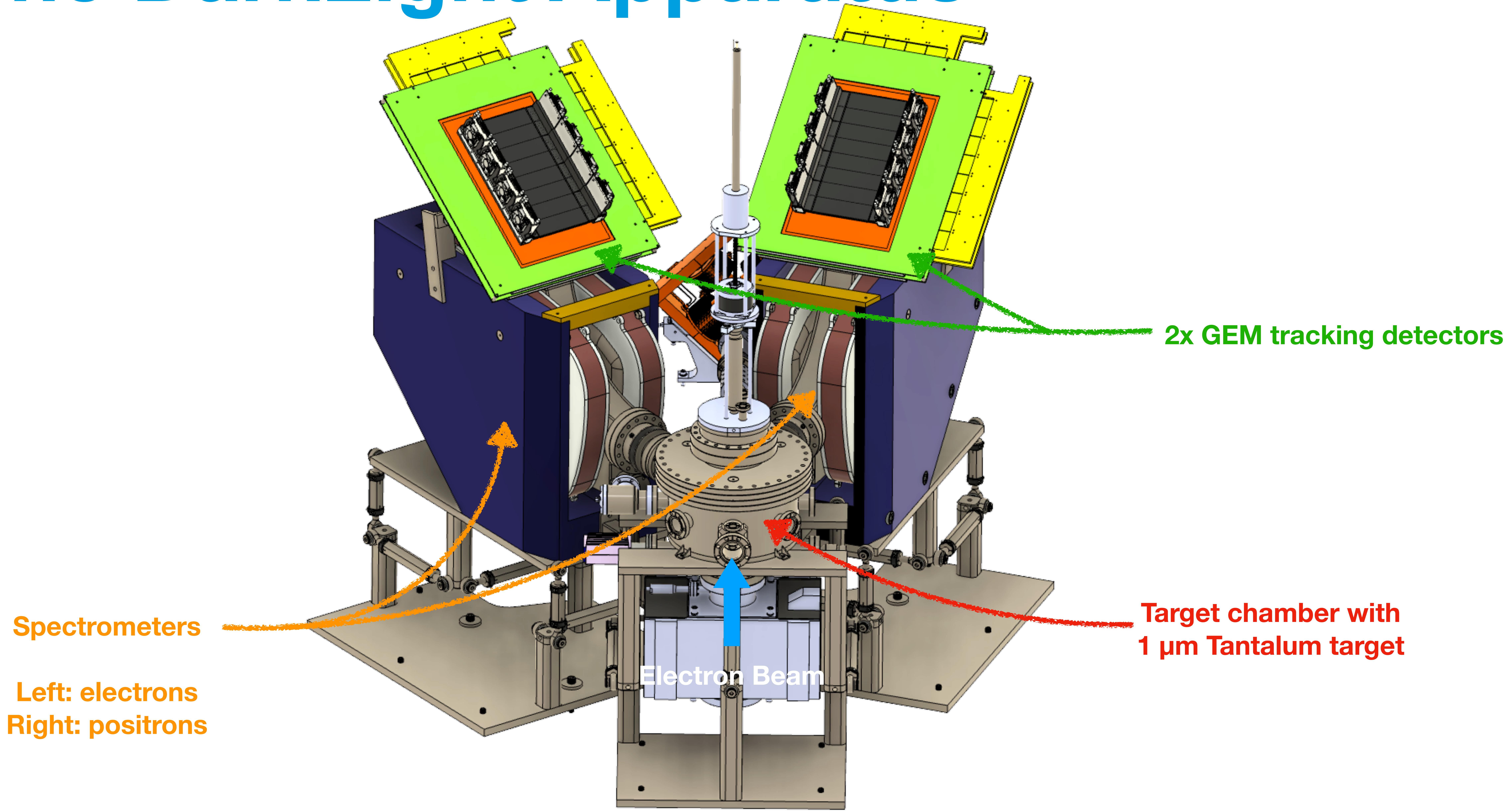


Spectrometers

Left: electrons
Right: positrons

Target chamber with
1 μm Tantalum target

The DarkLight Apparatus



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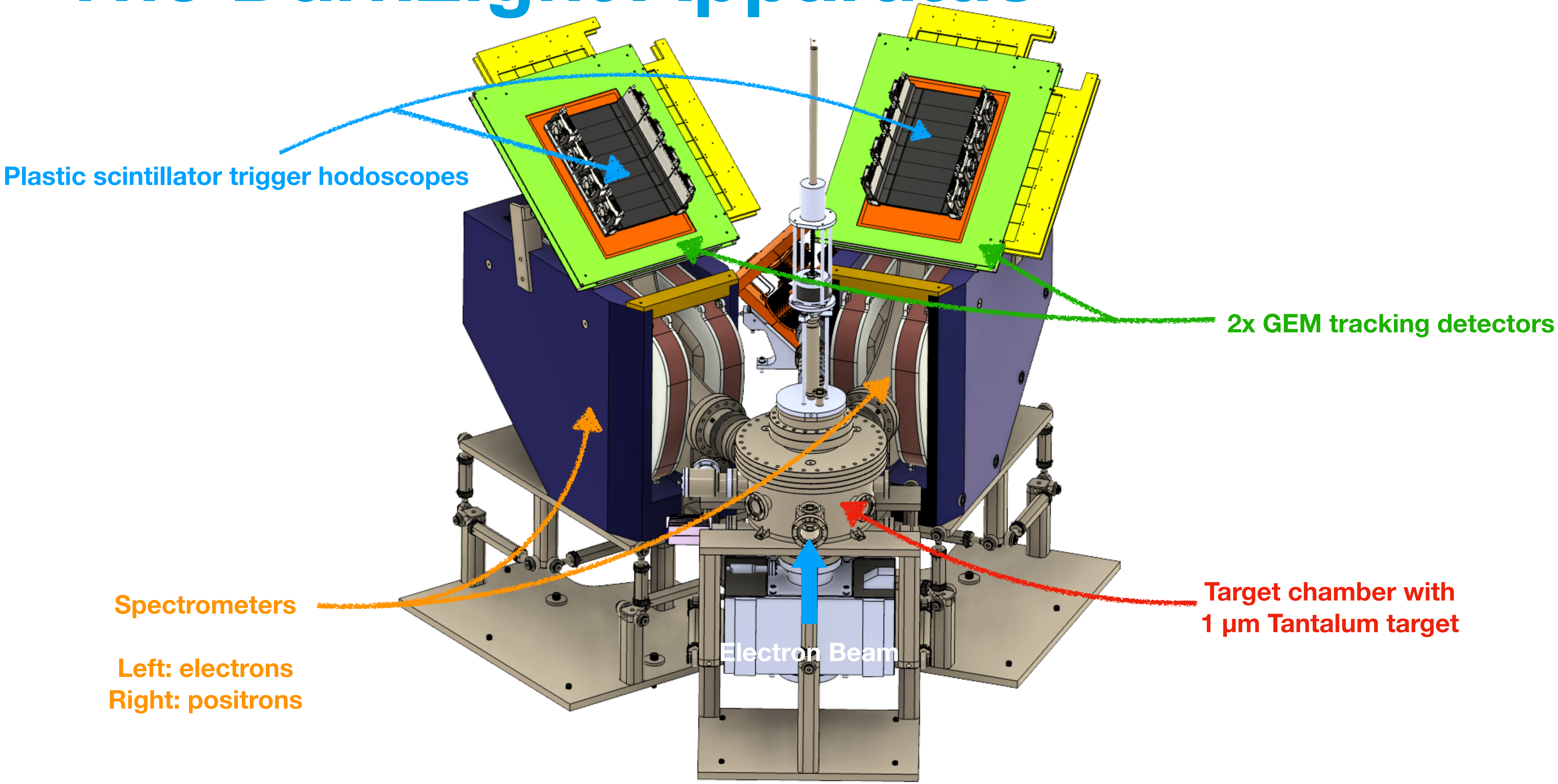
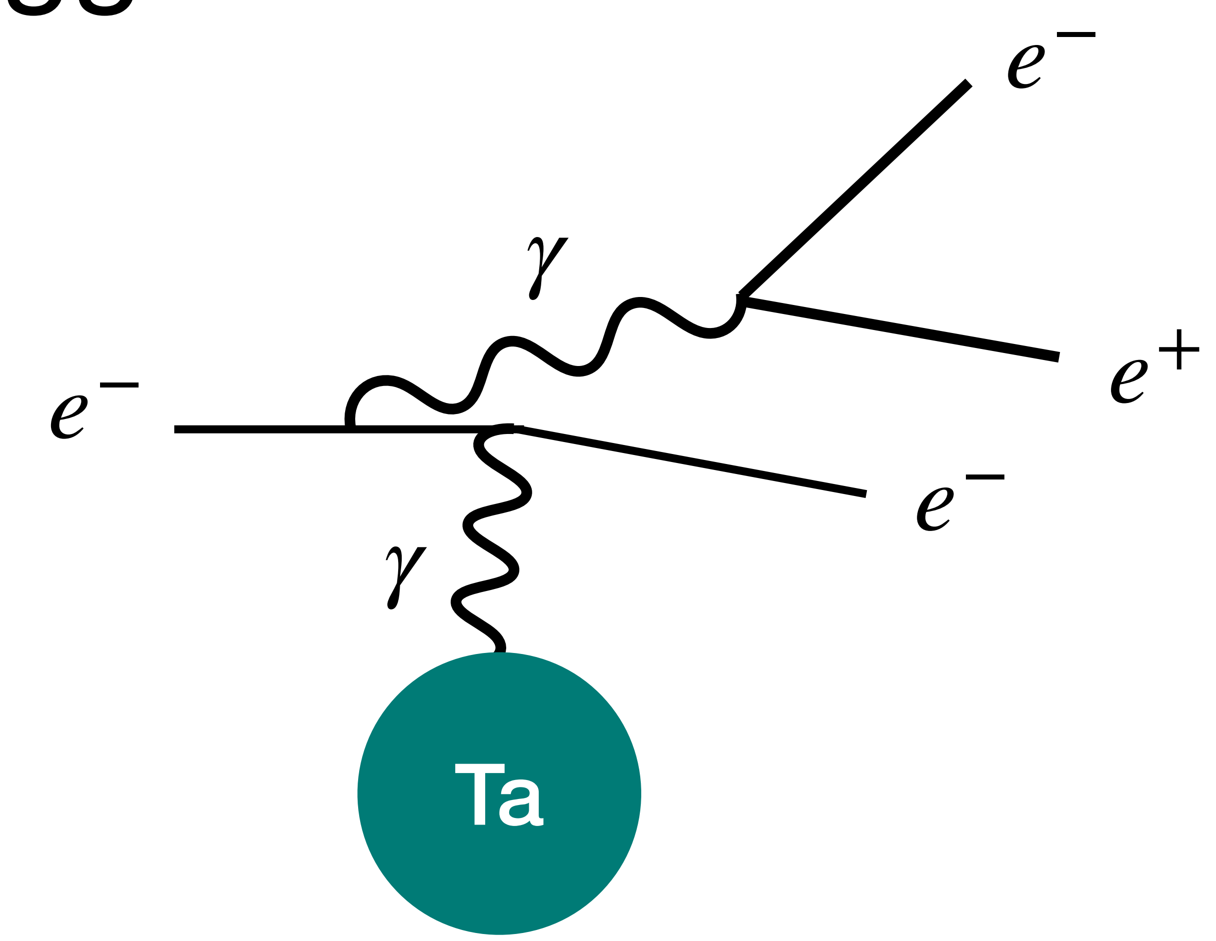


Projected Sensitivities

- Require coincidence in trigger from electron and positron arm to readout GEMs

- Irreducible background:



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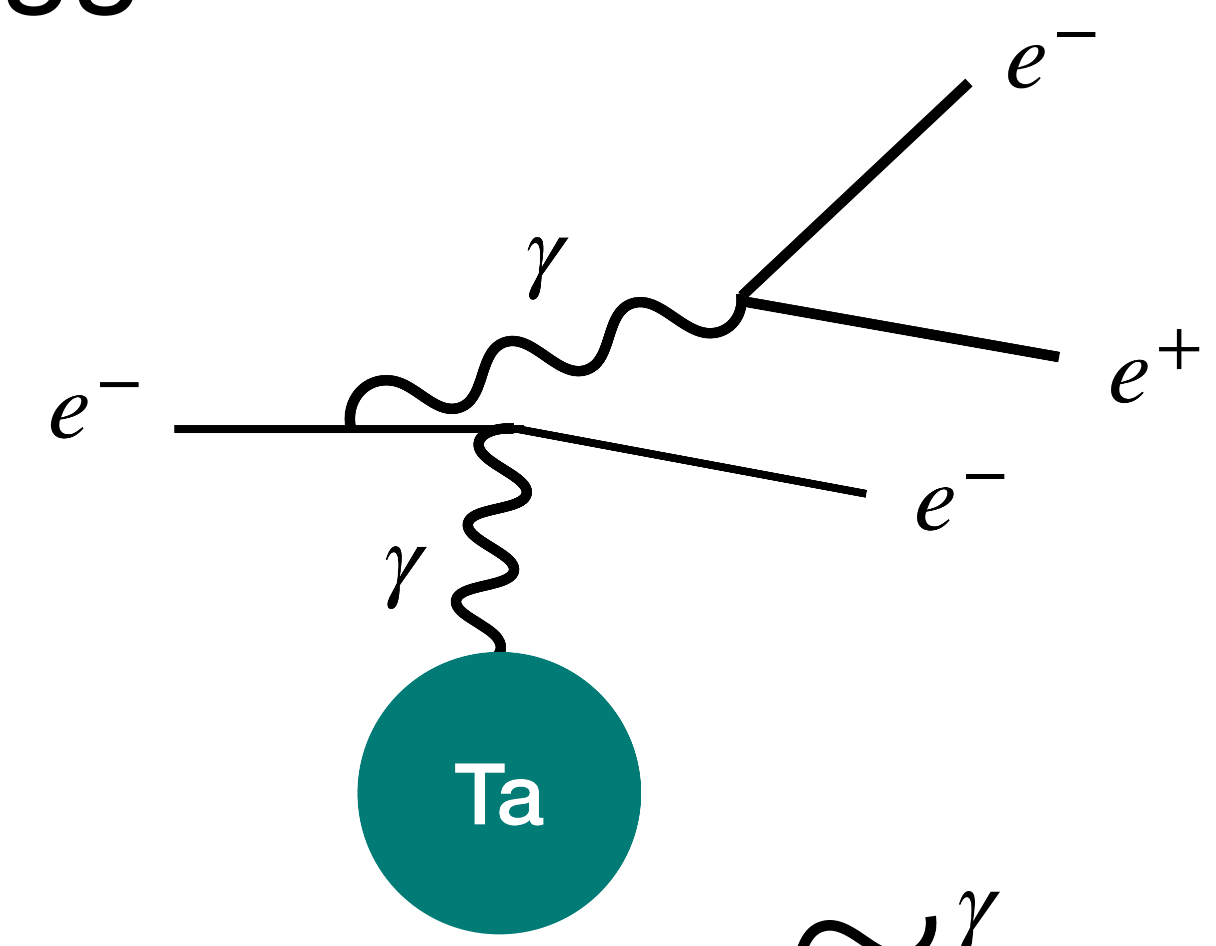
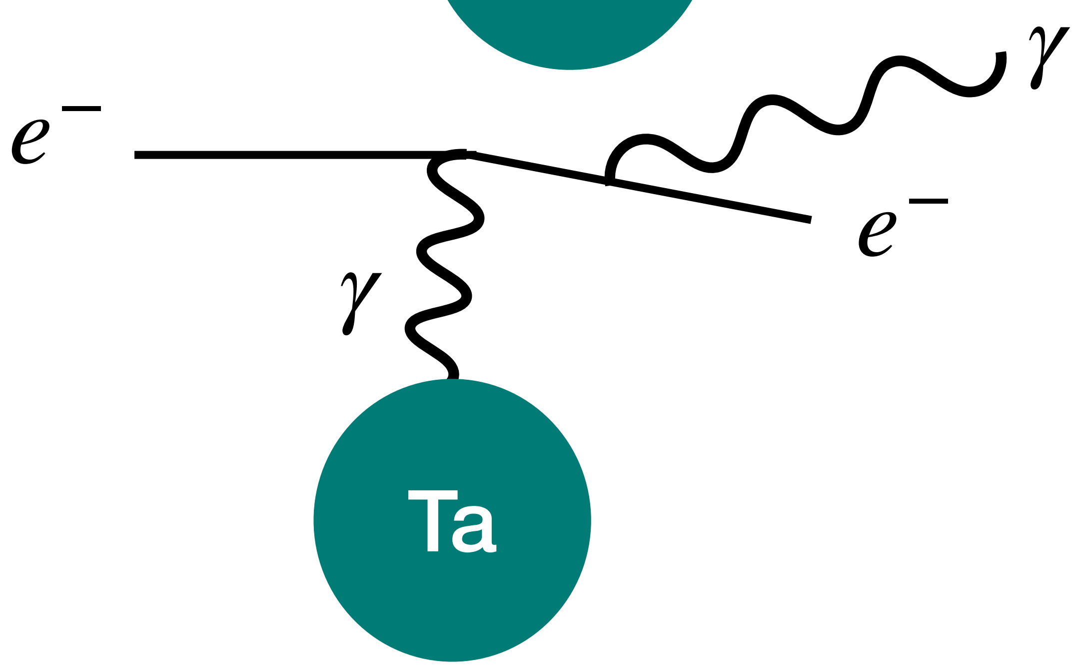


- Reducible background:

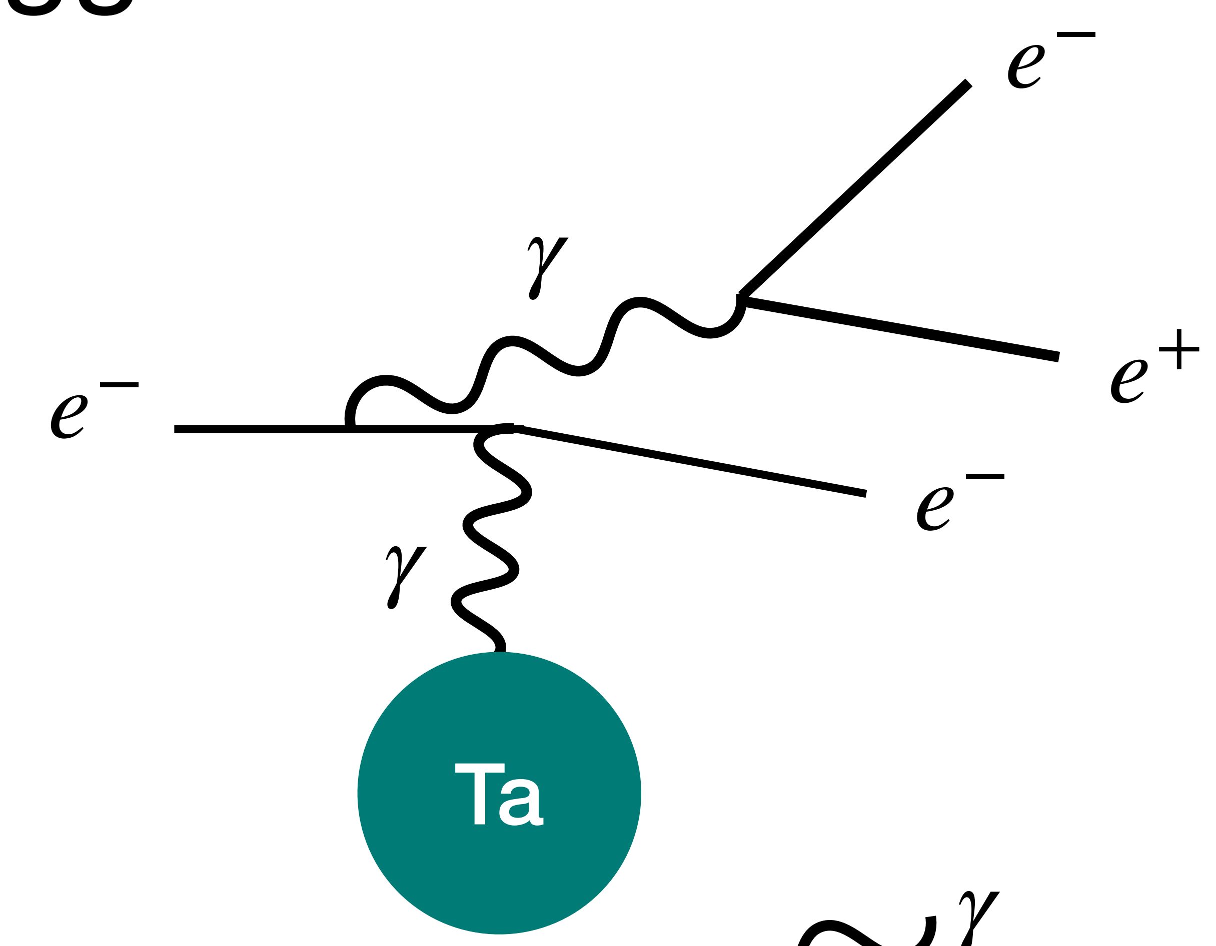


+ any positron

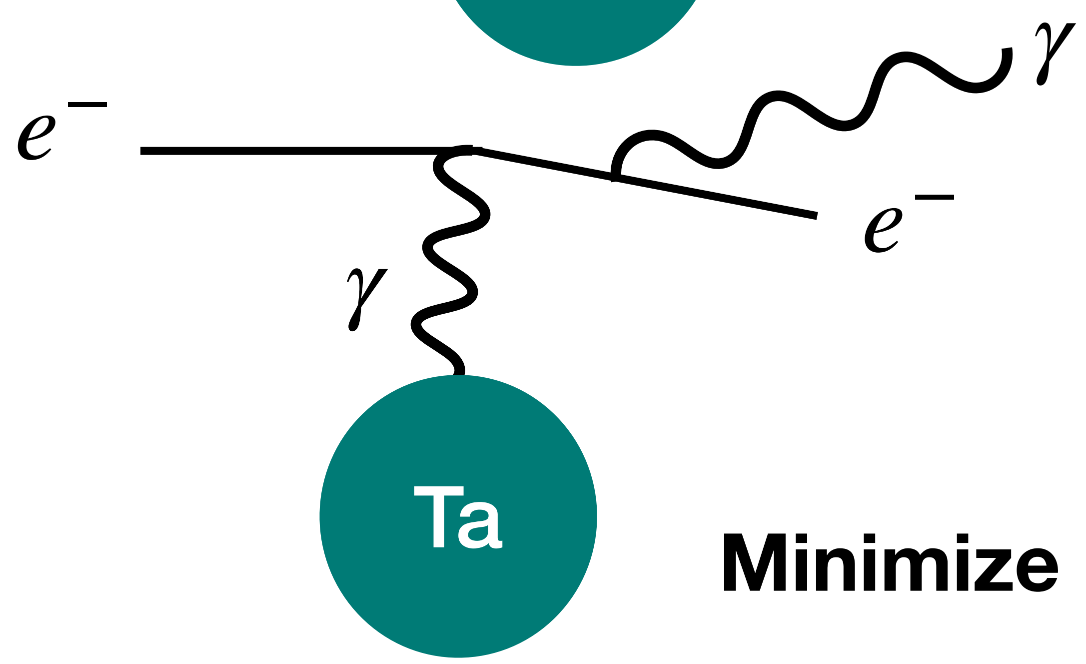
Projected Sensitivities

- Require coincidence in trigger from electron and positron arm to readout GEMs

- Irreducible background:



- Reducible background:

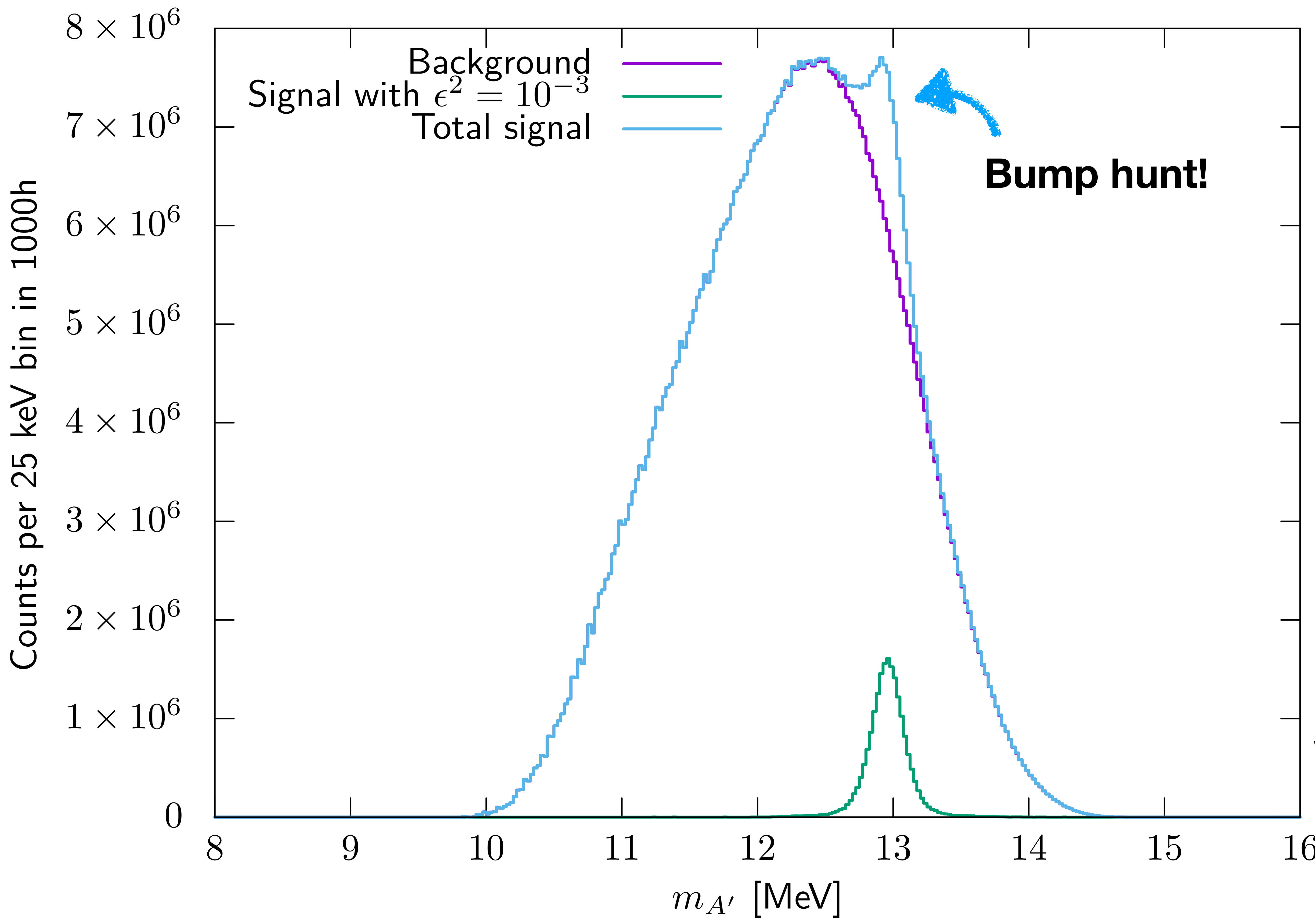


+ any positron

Minimize by carefully selecting spectrometer arm angles
Can be well-modelled

Projected Sensitivities

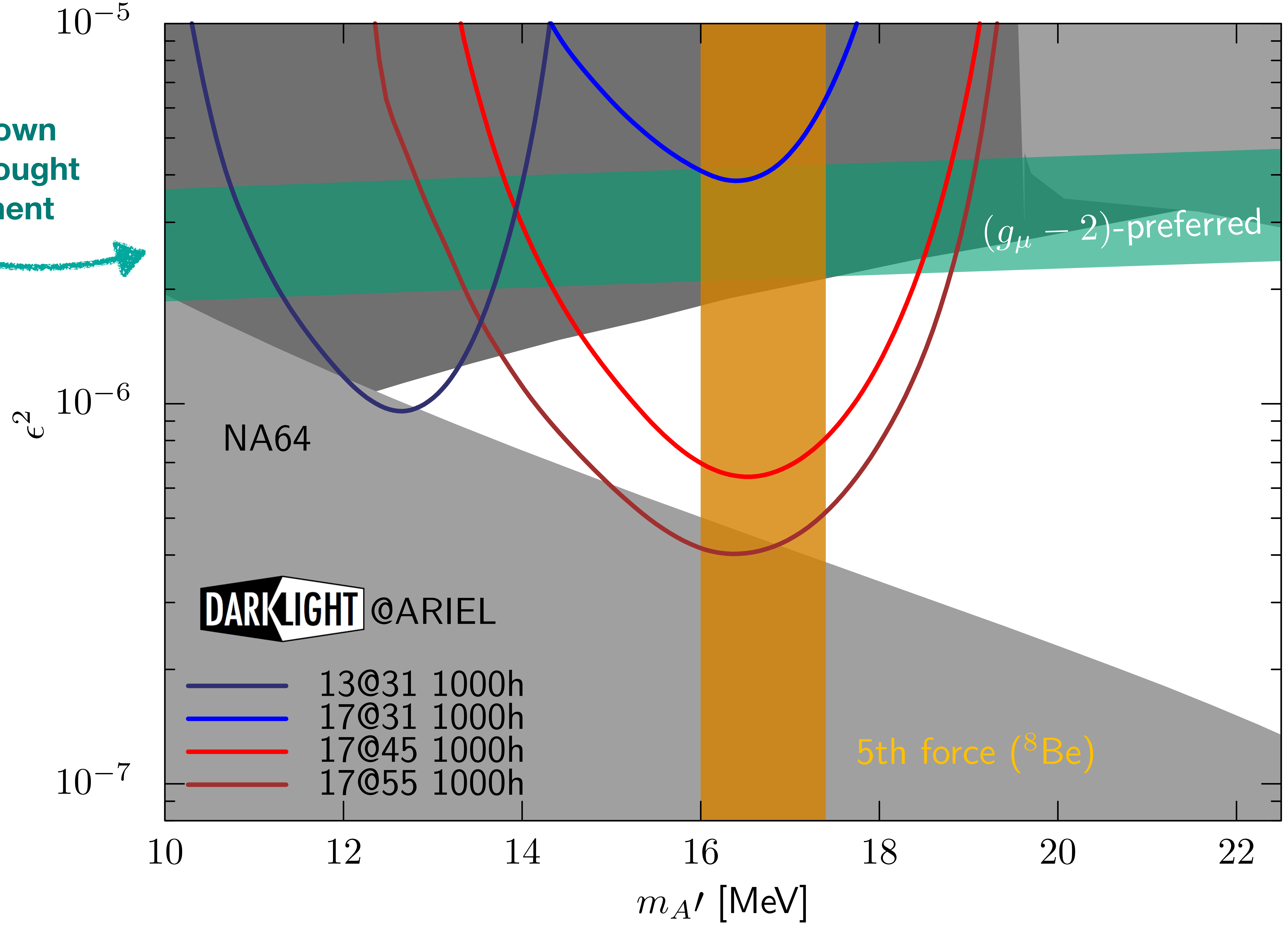
- Require coincidence in trigger from electron and positron arm to readout GEMs



Signal exaggerated for illustration

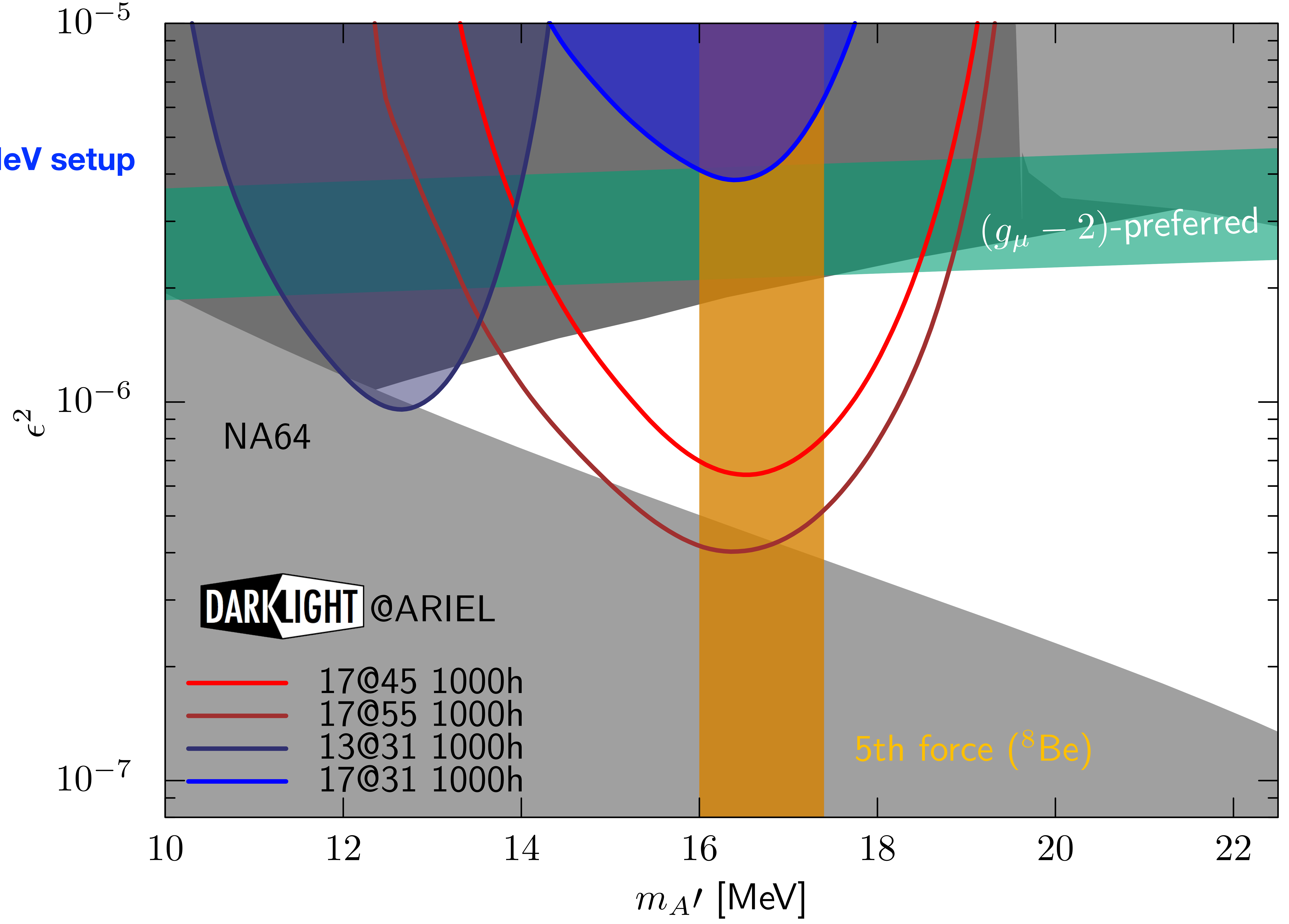
Projected Sensitivities

Will move slightly down if SM prediction is brought closer to measurement

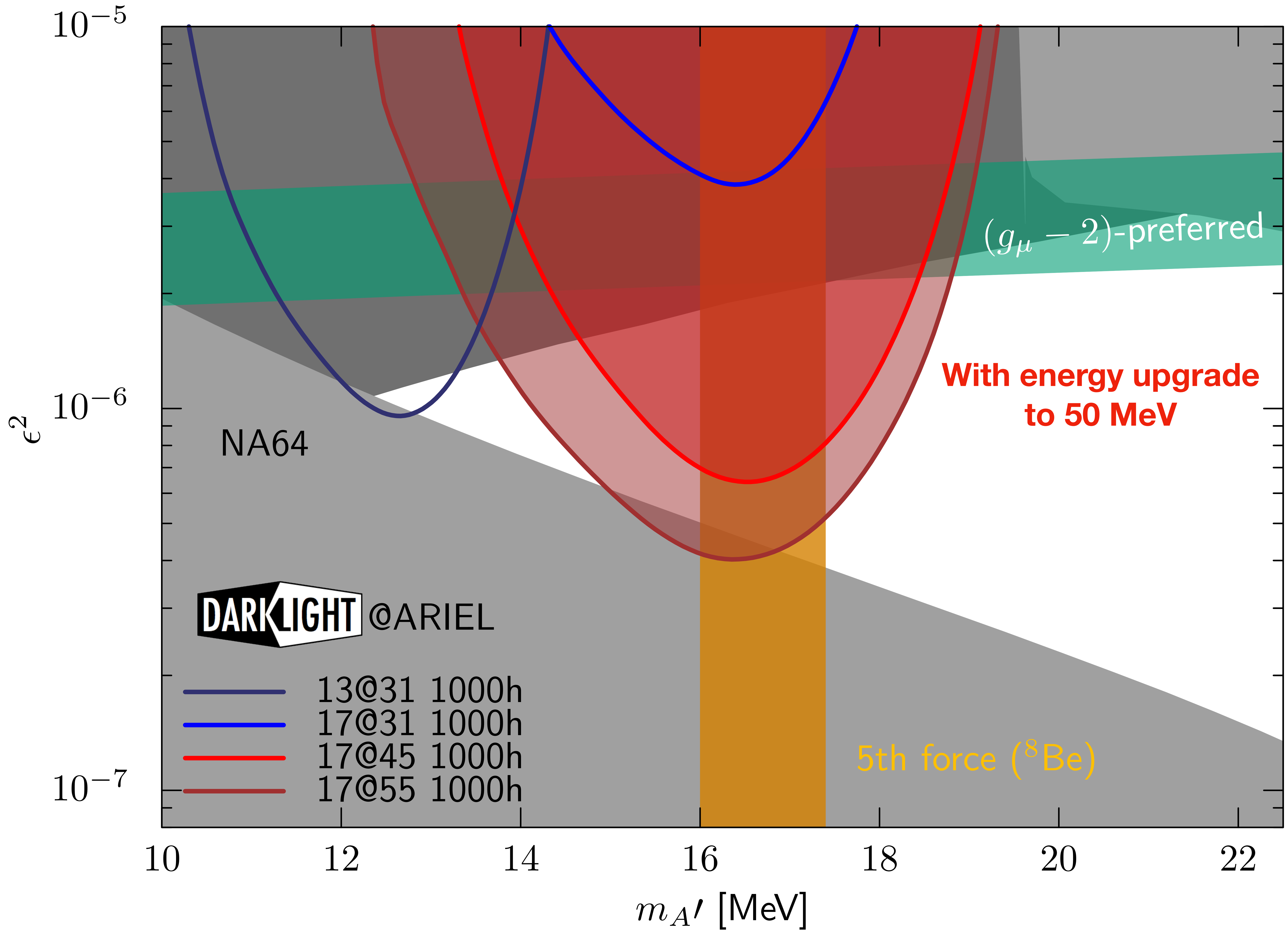


Projected Sensitivities

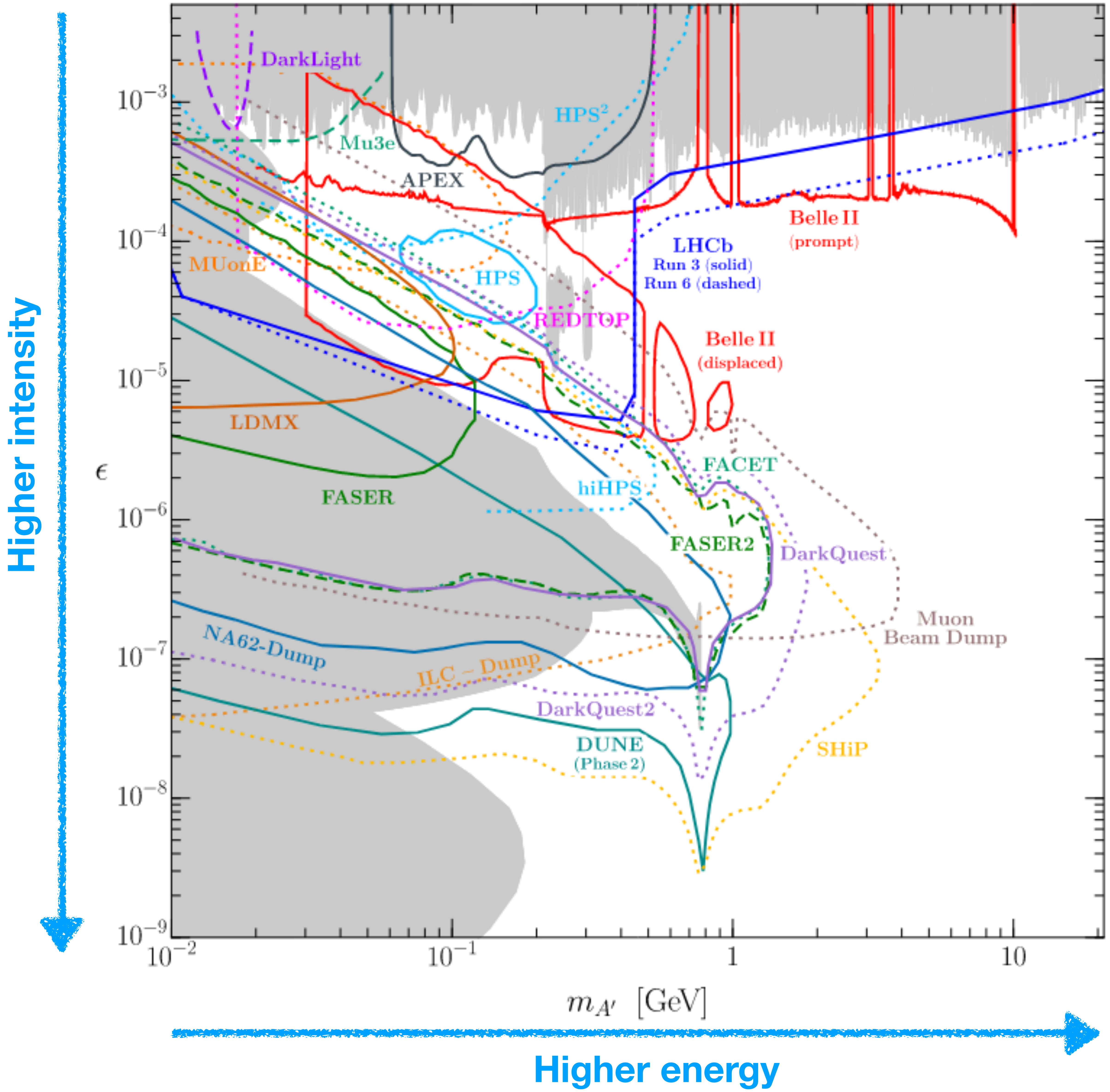
With current 30 MeV setup



Projected Sensitivities



Small(ish) Dark Photon Experiments



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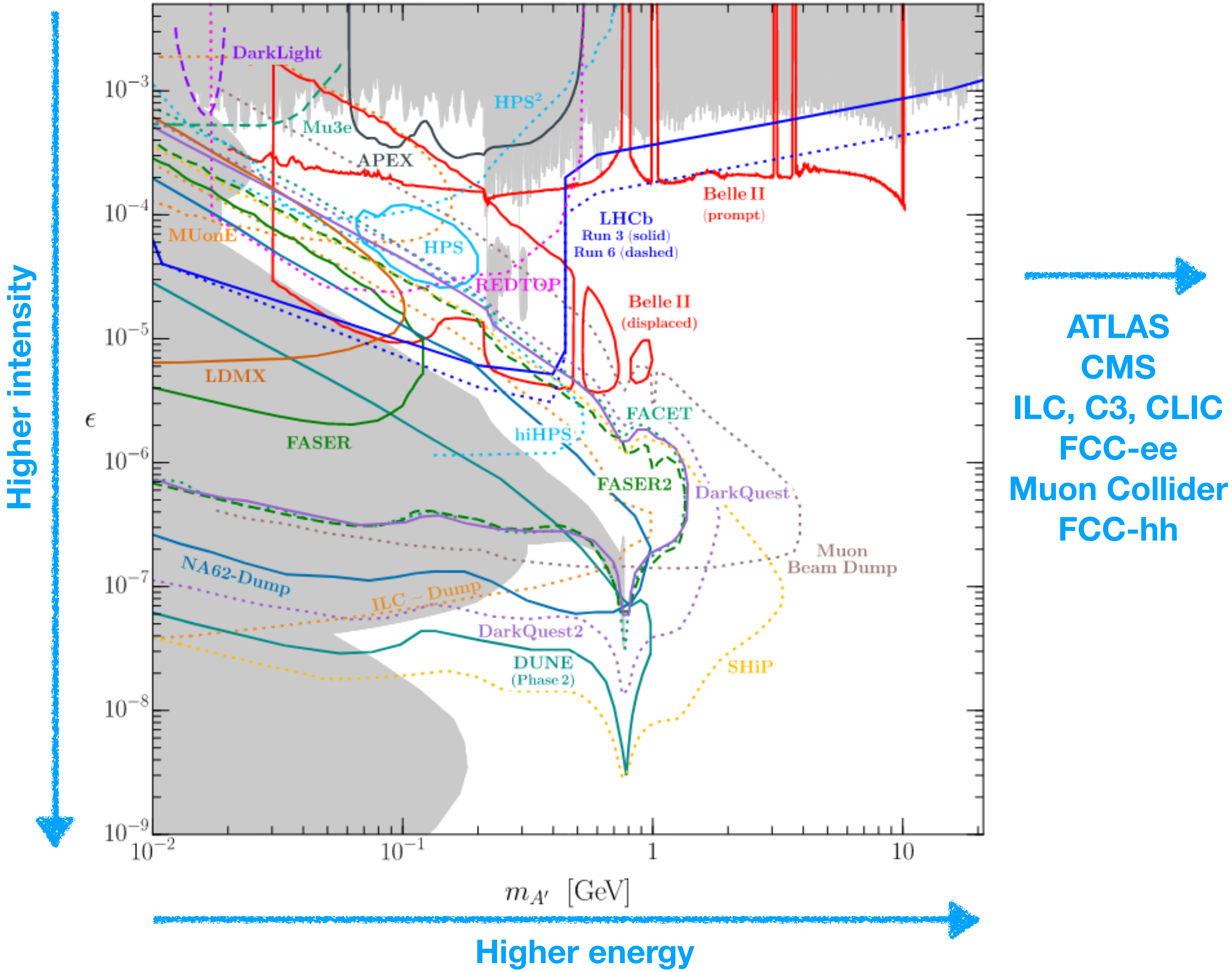
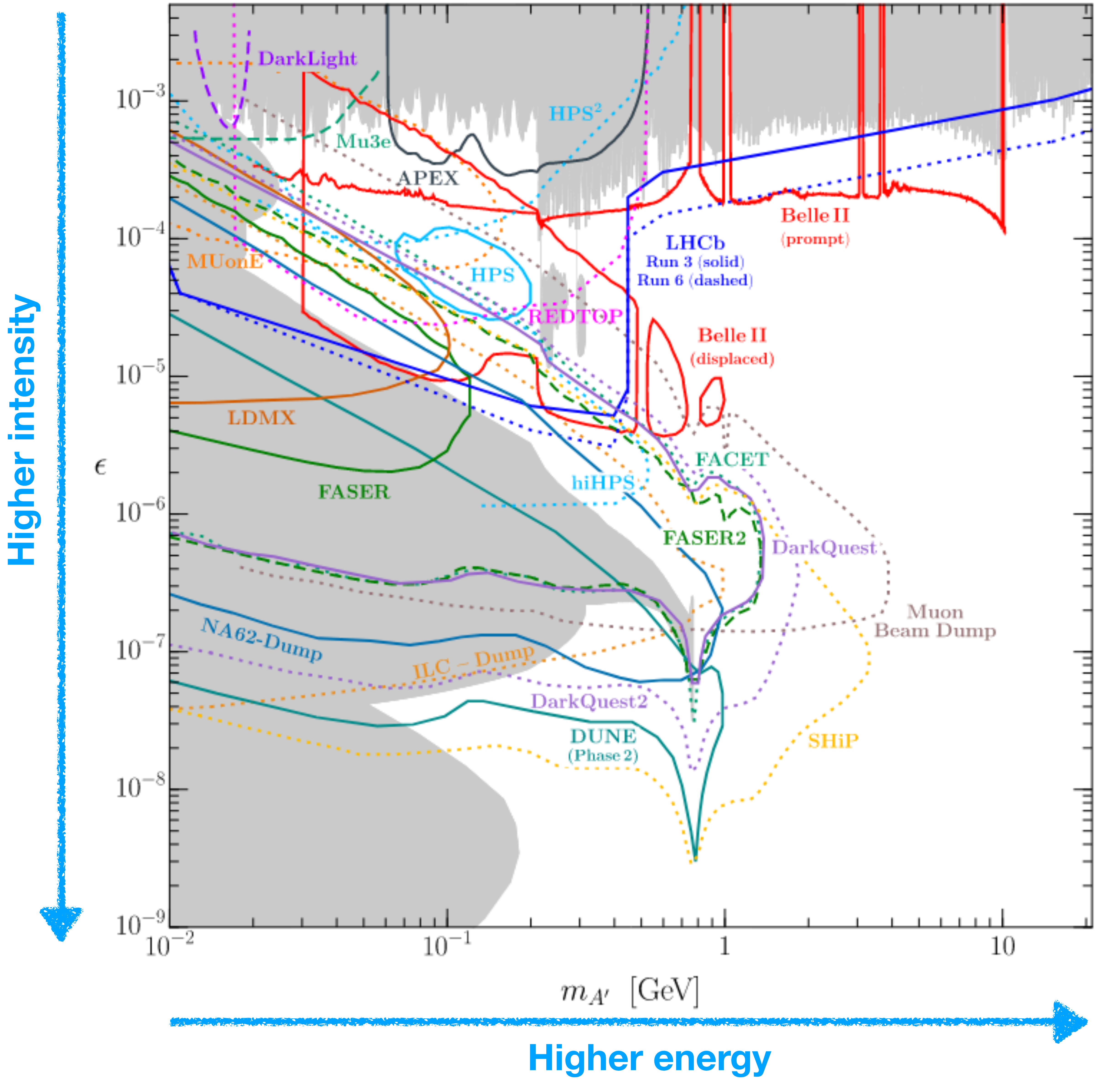


ATLAS
CMS
ILC, C3, CLIC
FCC-ee
Muon Collider
FCC-hh

Small(ish) Dark Photon Experiments

- Need smaller experiments to probe full parameter space

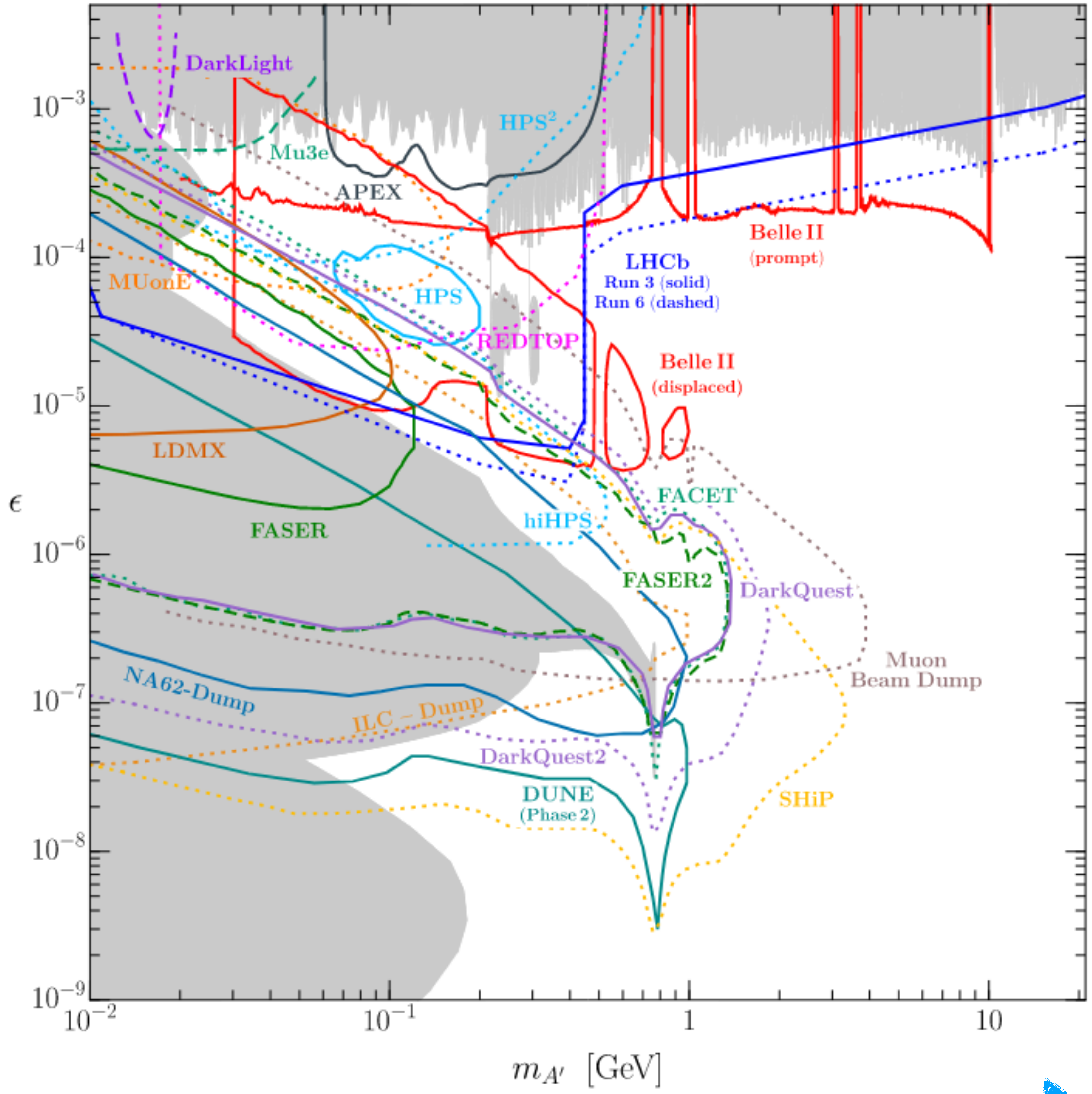


ATLAS
CMS
ILC, C3, CLIC
FCC-ee
Muon Collider
FCC-hh

Small(ish) Dark Photon Experiments

- Need smaller experiments to probe full parameter space
- Complementary to main experiments
- Cost effective: generally built off of existing (or proposed) infrastructure
- For those built off future collider infrastructure: would elevate physics case

Higher intensity



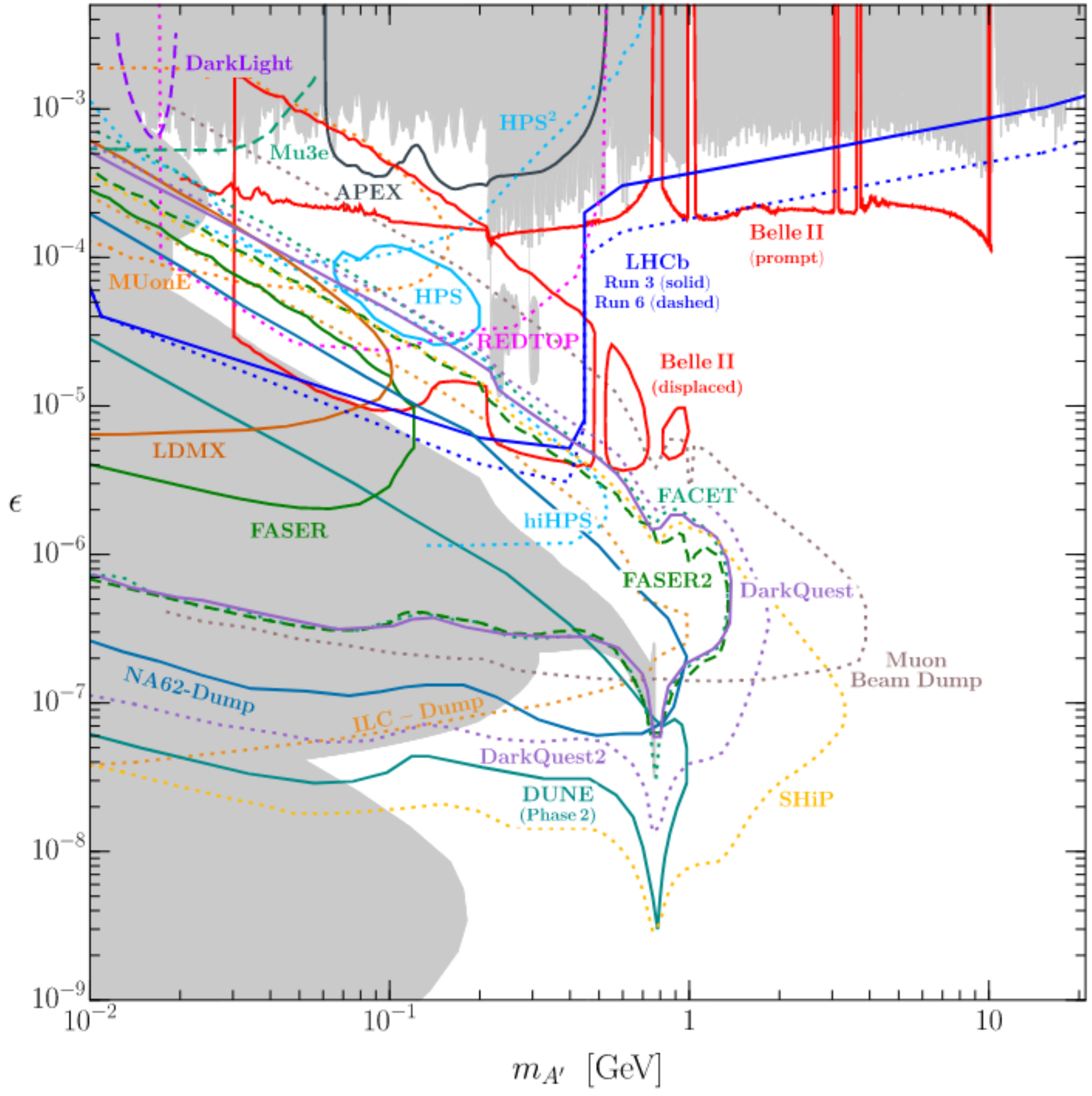
Higher energy

ATLAS
CMS
ILC, C3, CLIC
FCC-ee
Muon Collider
FCC-hh

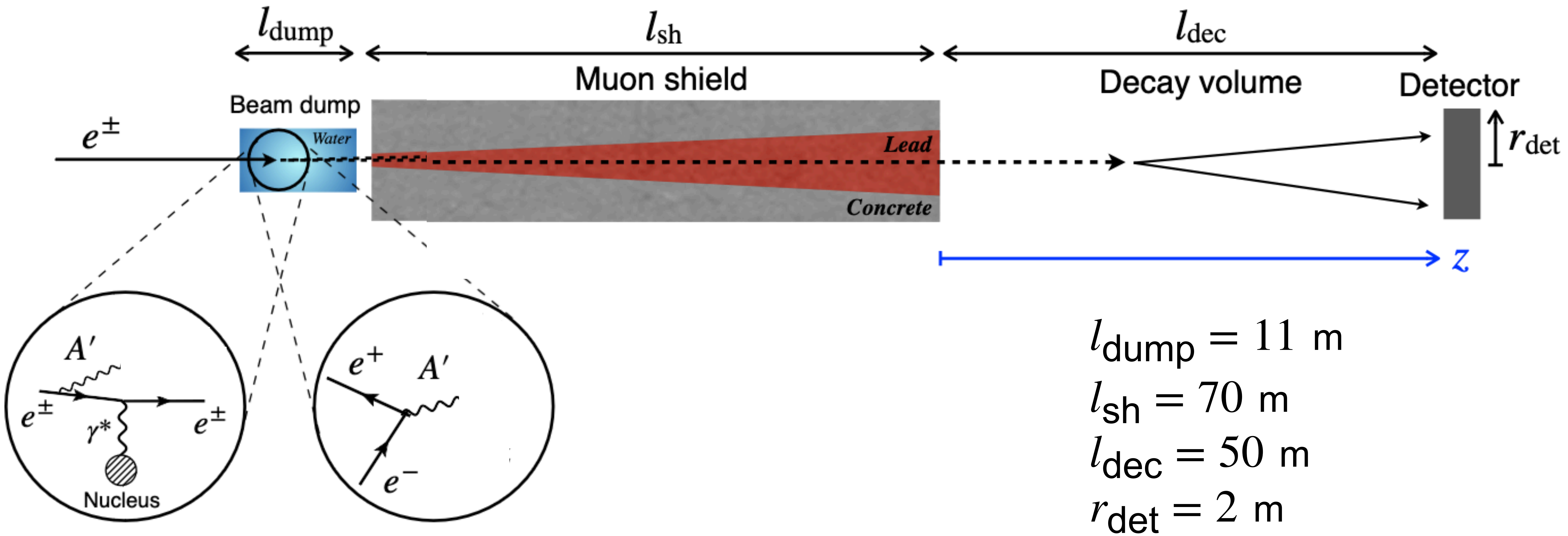
Small(ish) Dark Photon Experiments

- (Very) Rough timeline:

Complete, analyzing/ taking data or commissioning	**FASER** **HPS** **NA62-Dump** **APEX** **MUonE**
Installing, active R&D	**DarkLight** **DarkQuest** **Mu3e** **LDMX**
HL-LHC era	**SHiP** **FASER2** **DarkQuest2** **FACET** **REDTOP**
Future collider era	**ILC beam dump** **Muon beam dump**



ILC Beam Dump

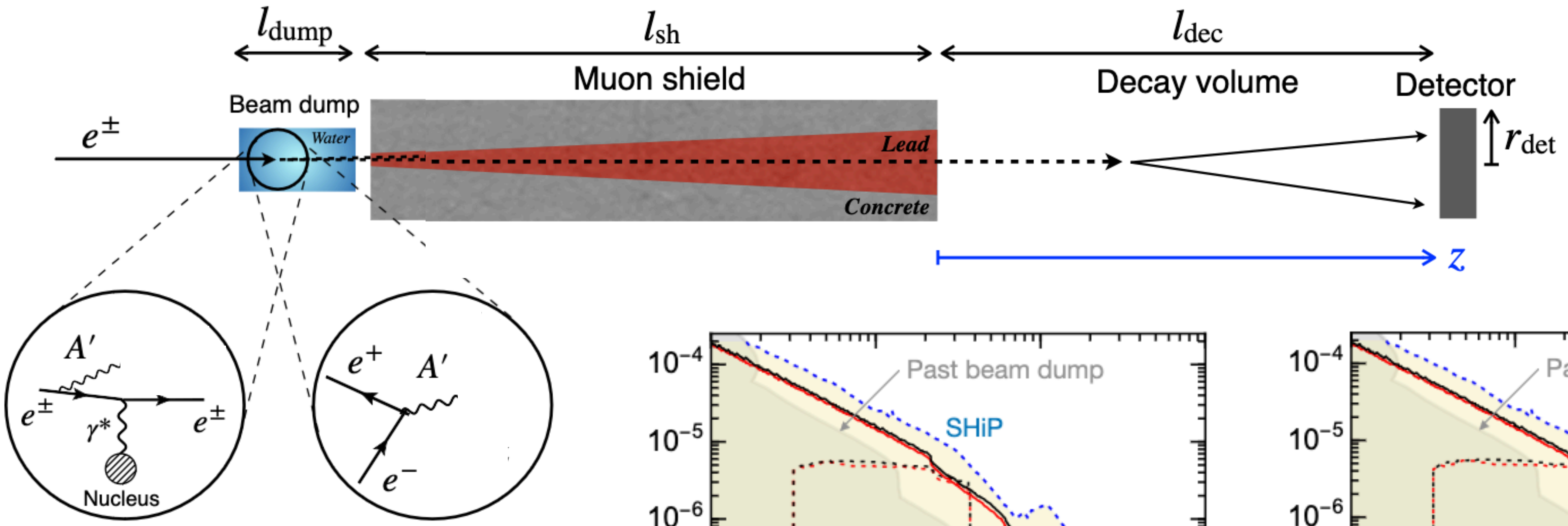


Annihilation or Bremsstrahlung production of A'

$l_{\text{dump}} = 11$ m
$l_{\text{sh}} = 70$ m
$l_{\text{dec}} = 50$ m
$r_{\text{det}} = 2$ m

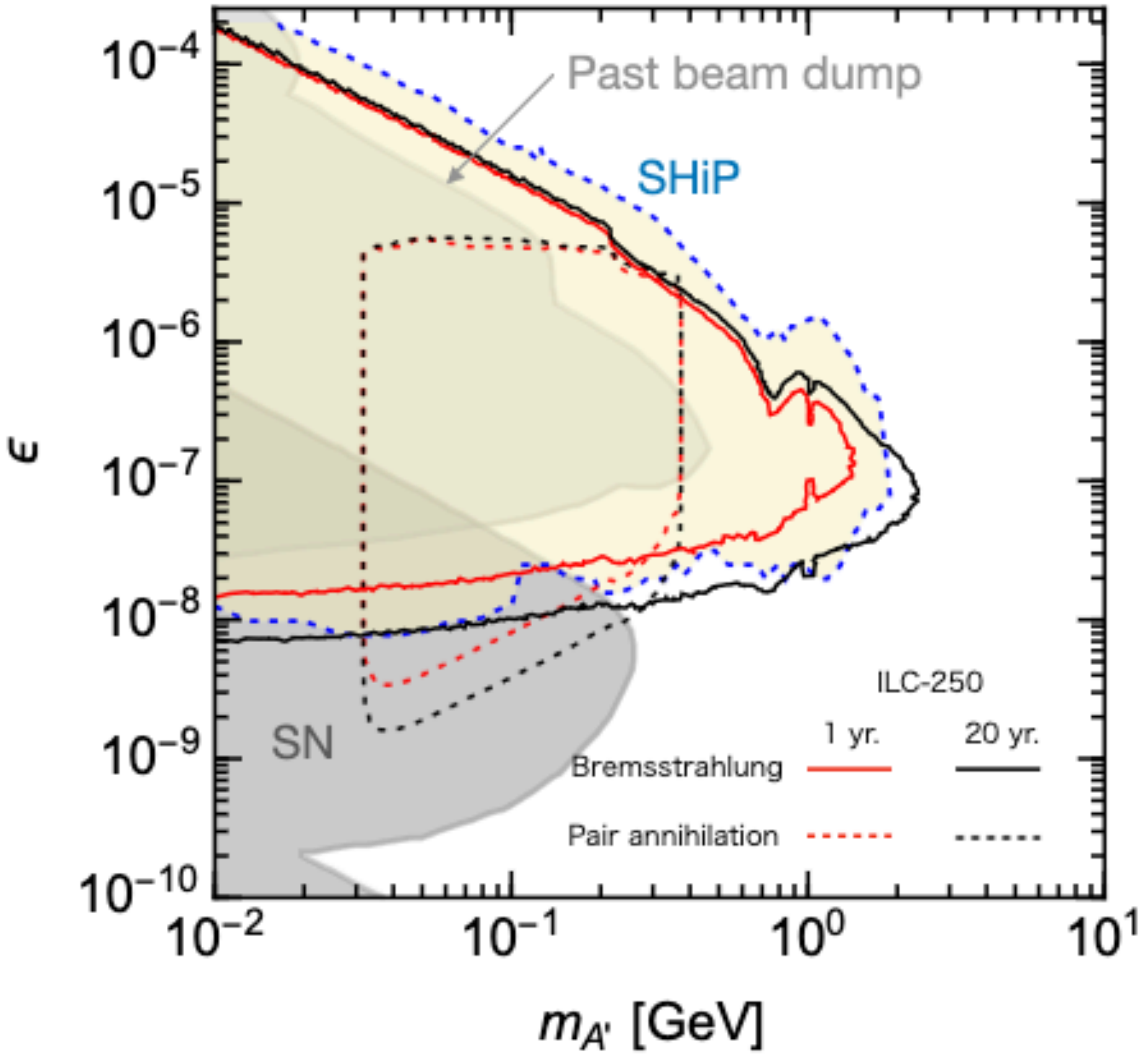
- Preliminary study focused around ILC-250 design proposal
  - $E_{\text{beam}} = 125$ GeV, $N_{e^{\pm}} = 4 \times 10^{21}$/year

ILC Beam Dump

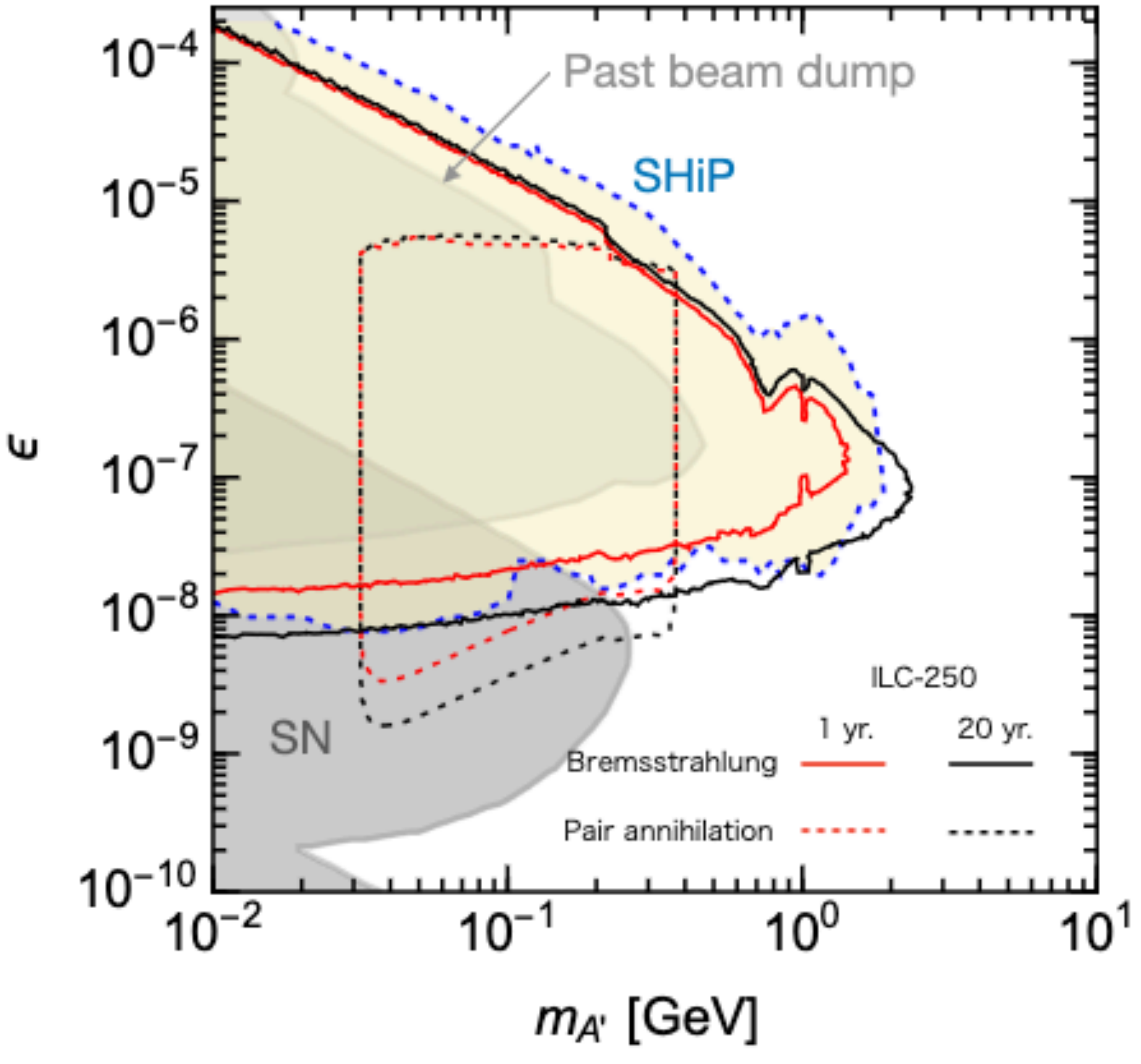


- Exclusion curves dependent on which particle is going into the dump

- Positron beam dump has better sensitivity at lower ε

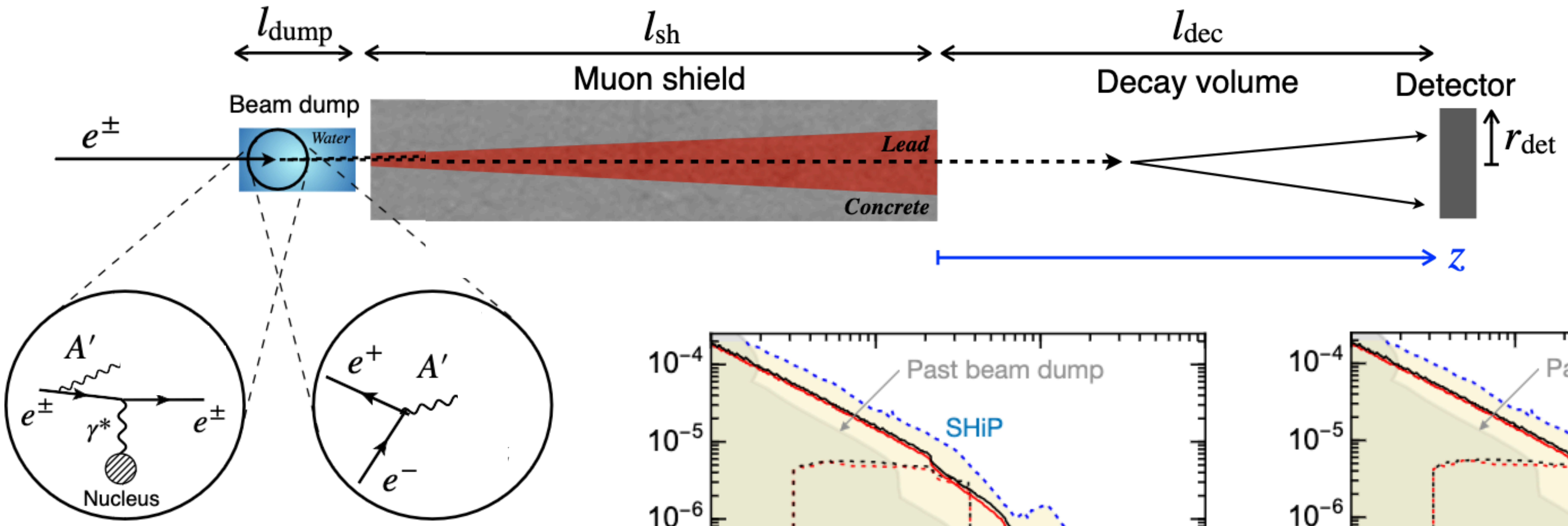


(a) electron beam dump

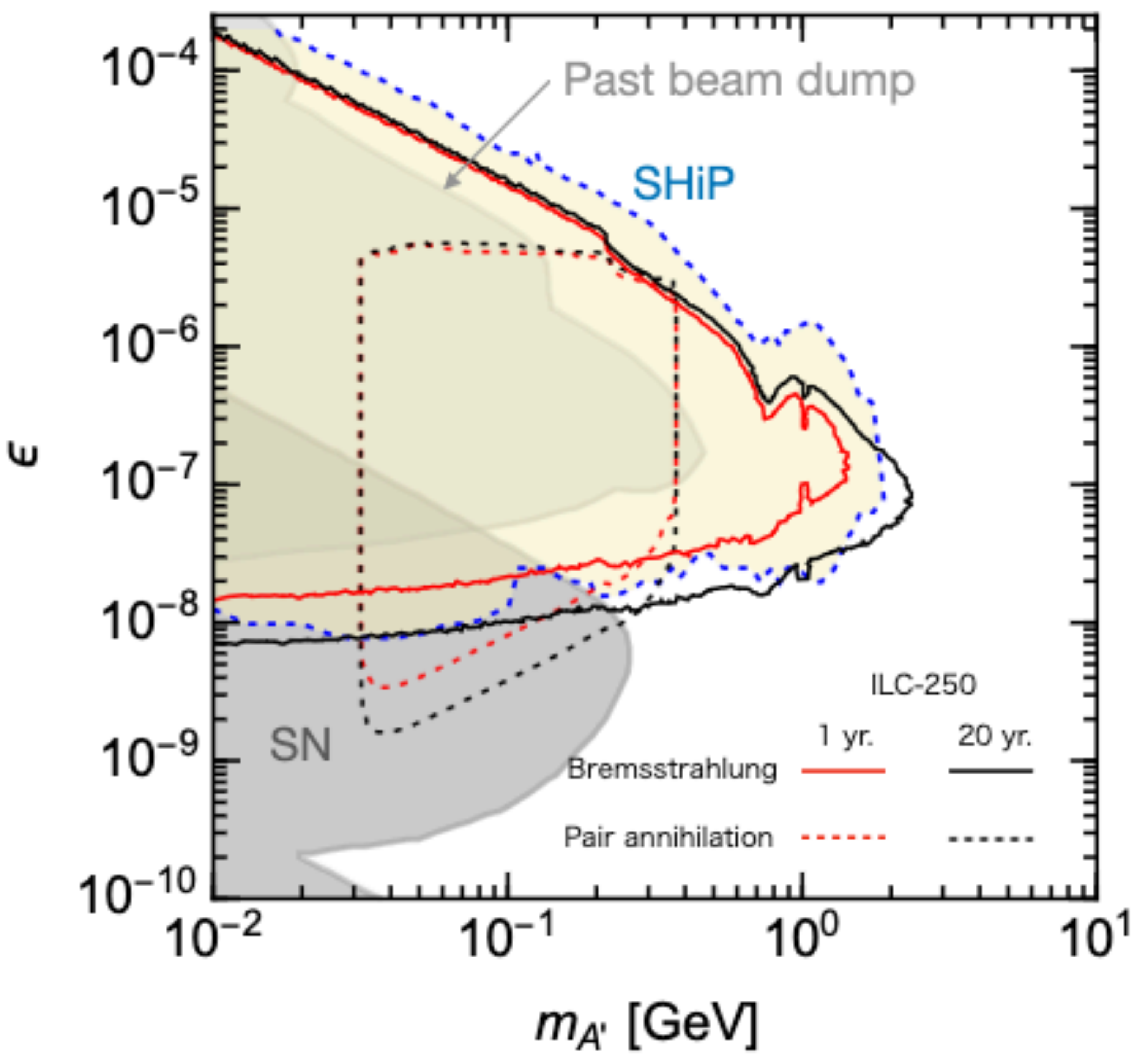


(b) positron beam dump

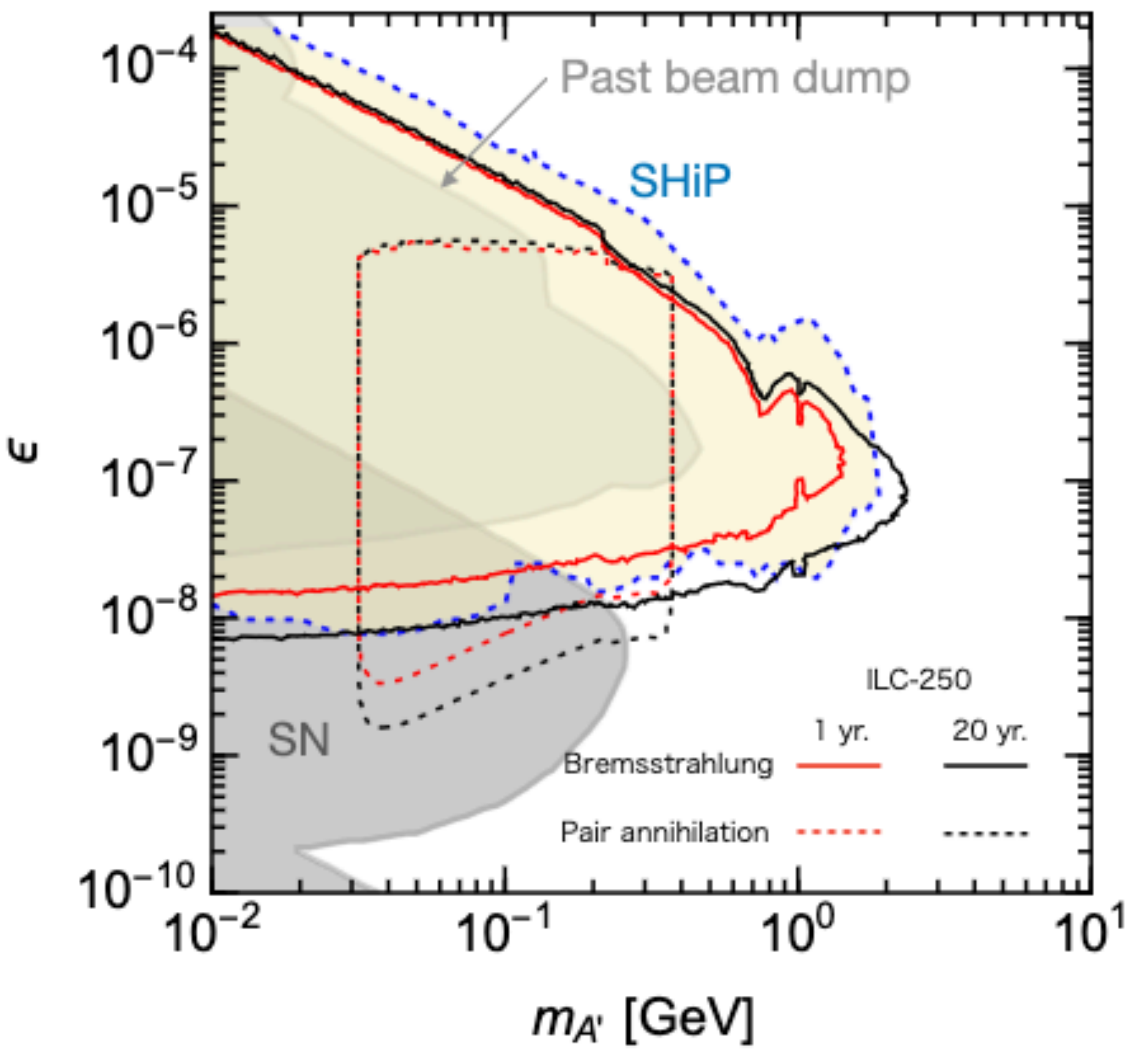
ILC Beam Dump



- More detailed MC studies needed to fully quantify acceptance effects
- Effect of polarized beams?
- Detector?
- Study neglects muon production modes

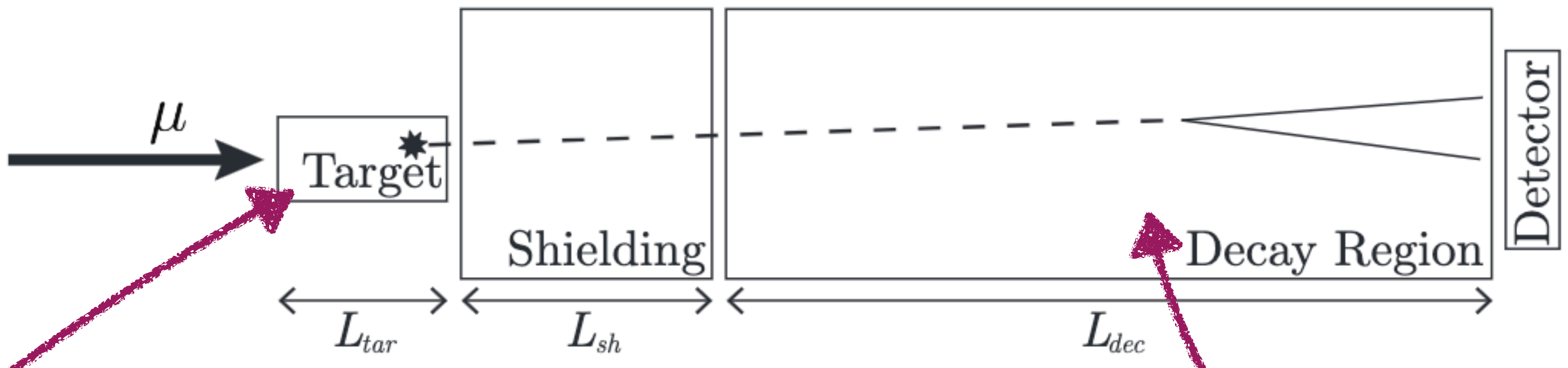


(a) electron beam dump



(b) positron beam dump

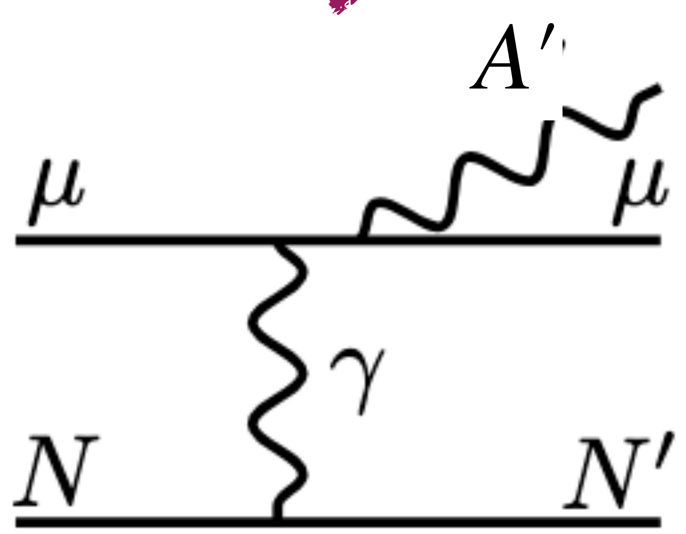
Muon Beam Dump



Tracker or calorimeter

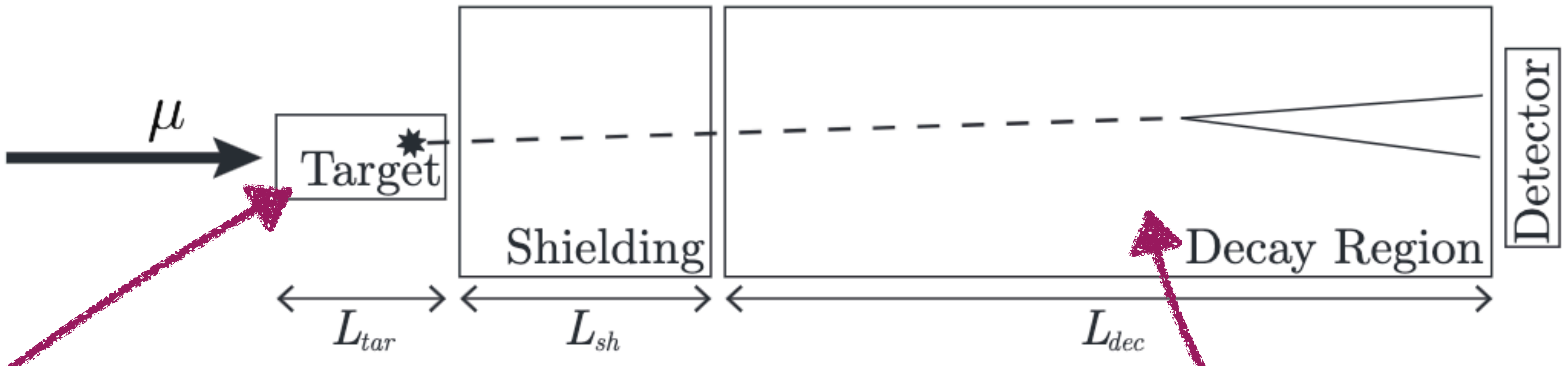
Shielding material to stop light particles + magnetic field to remove remaining beam particles

Decay region, gives time for new particles to decay back to SM

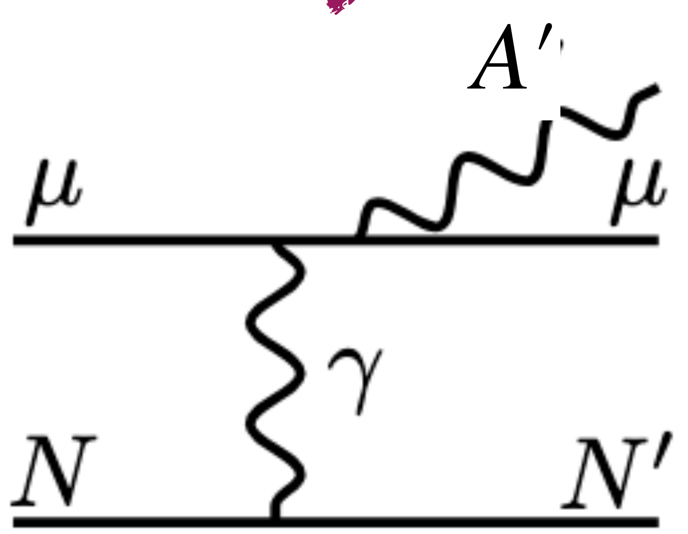


Bremsstrahlung production of A' in lead or water target

Muon Beam Dump



Tracker or calorimeter



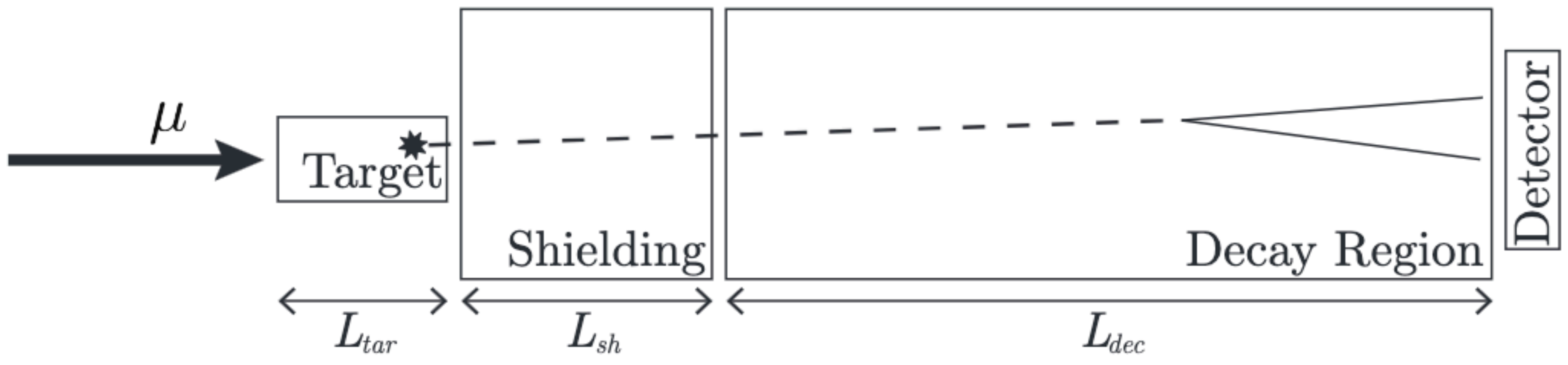
Bremsstrahlung production of A' in lead or water target

Shielding material to stop light particles + magnetic field to remove remaining beam particles

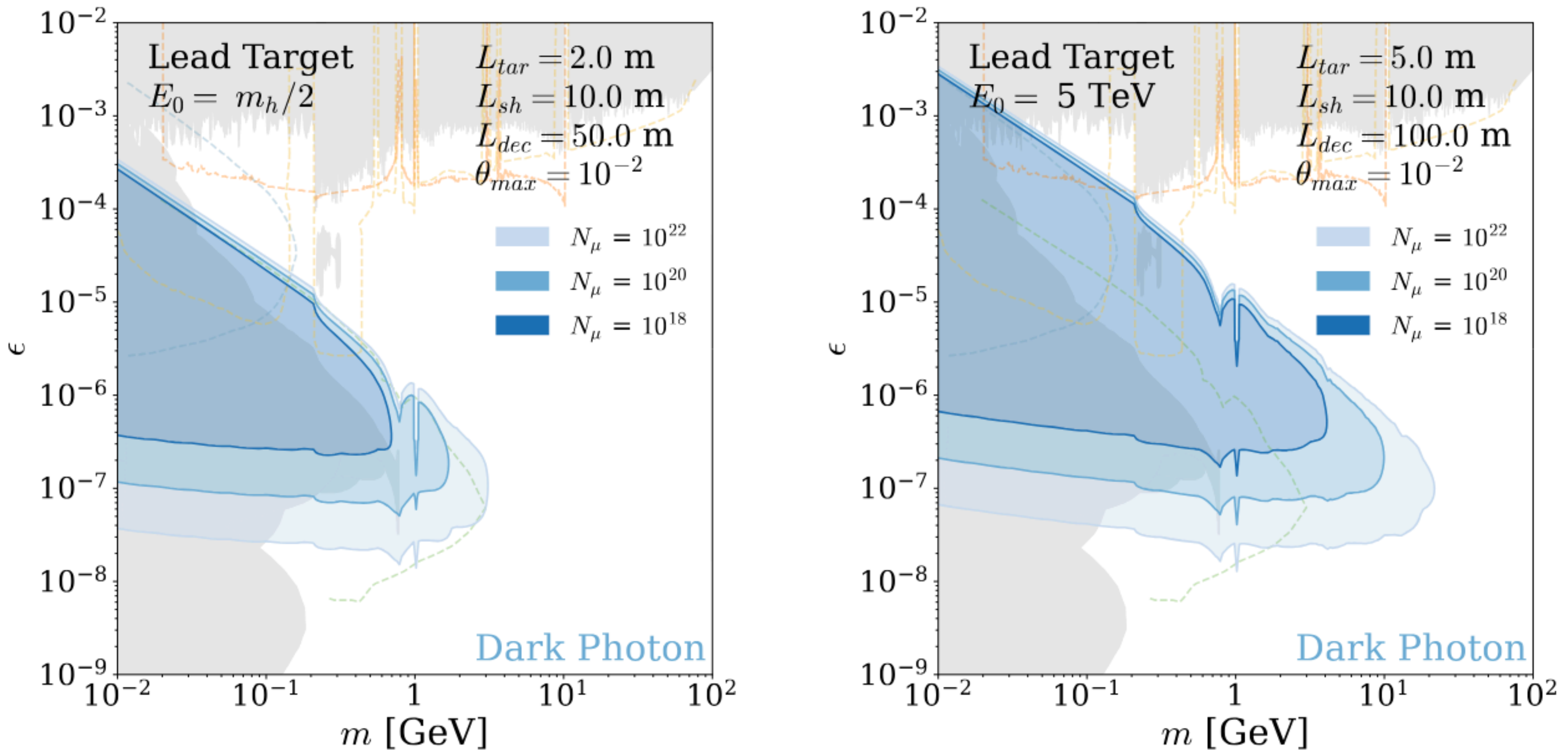
Decay region, gives time for new particles to decay back to SM

- Proposal examines visible final states with muon beam energies from order 10 GeV to 5 TeV, with various numbers of muons on target

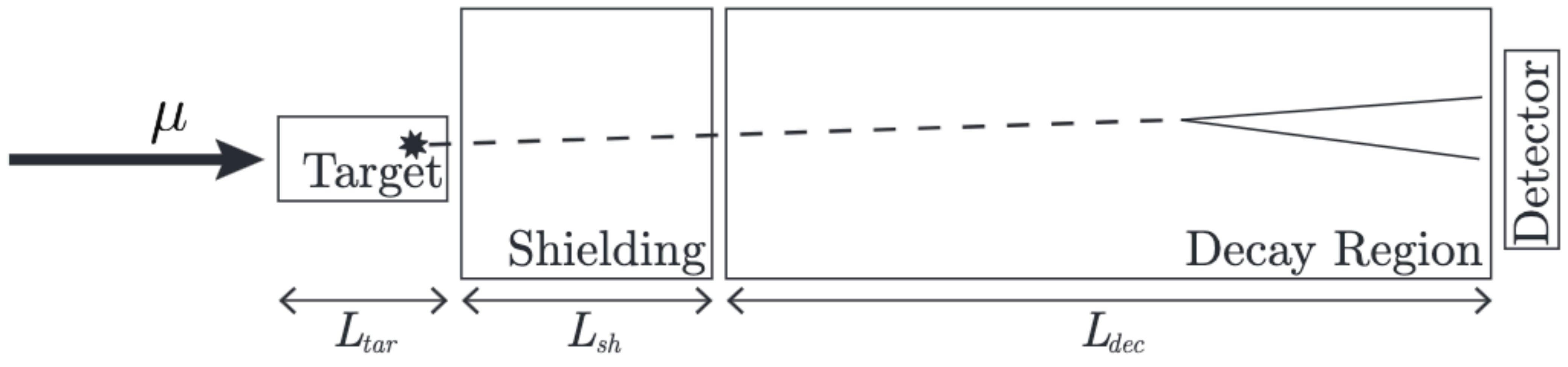
Muon Beam Dump

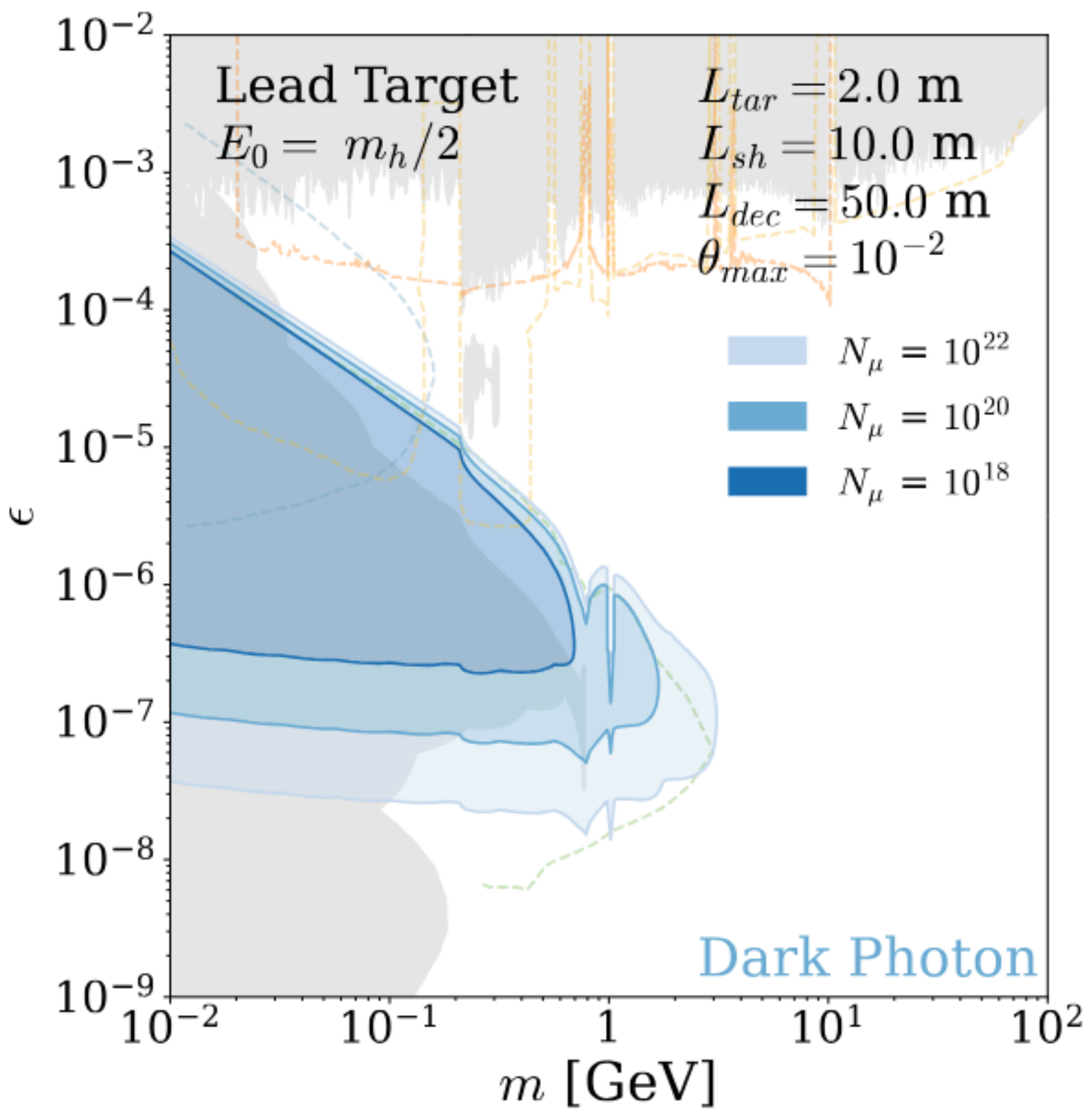


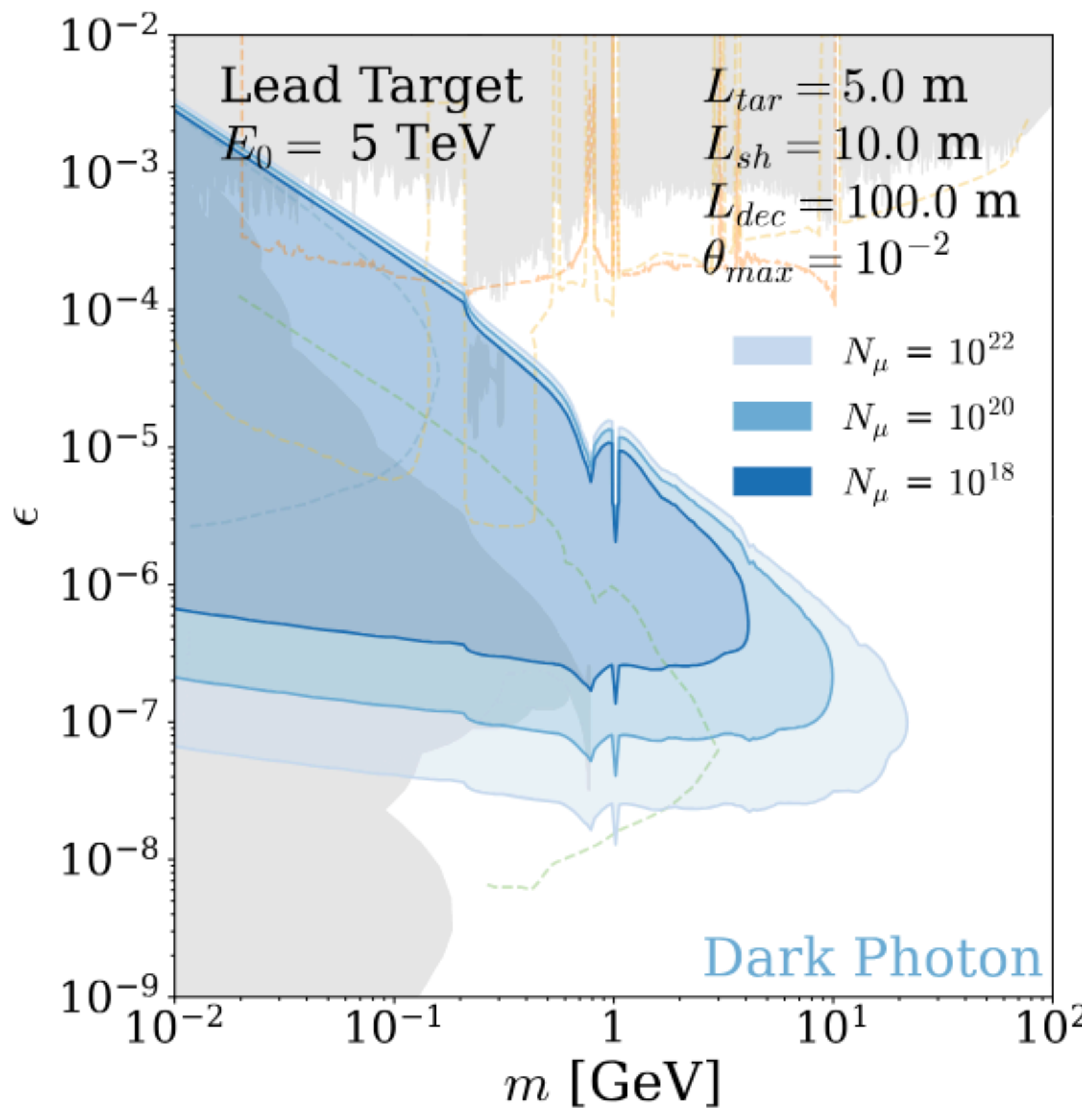
- Good reach even at more modest energies



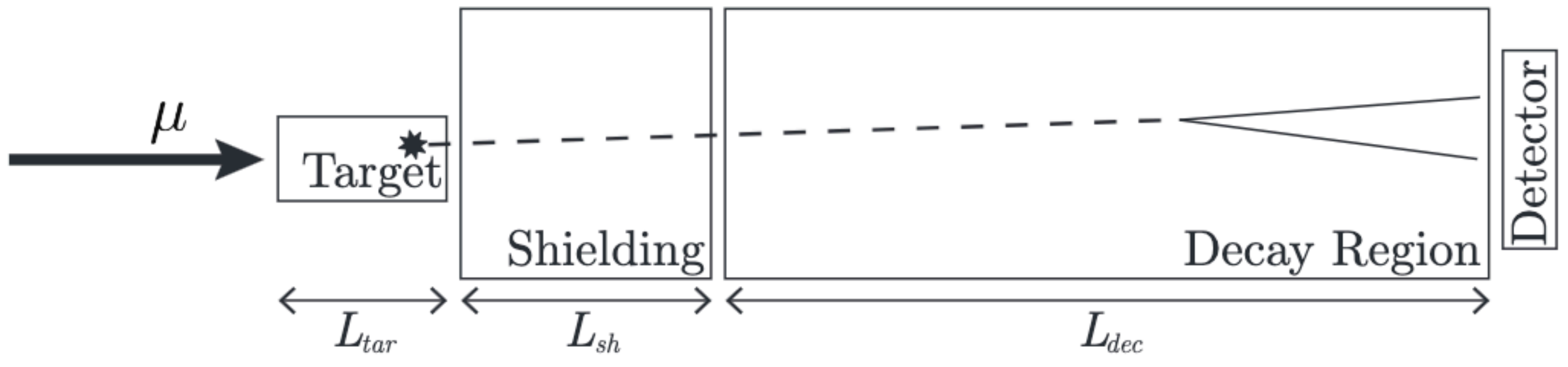
Muon Beam Dump



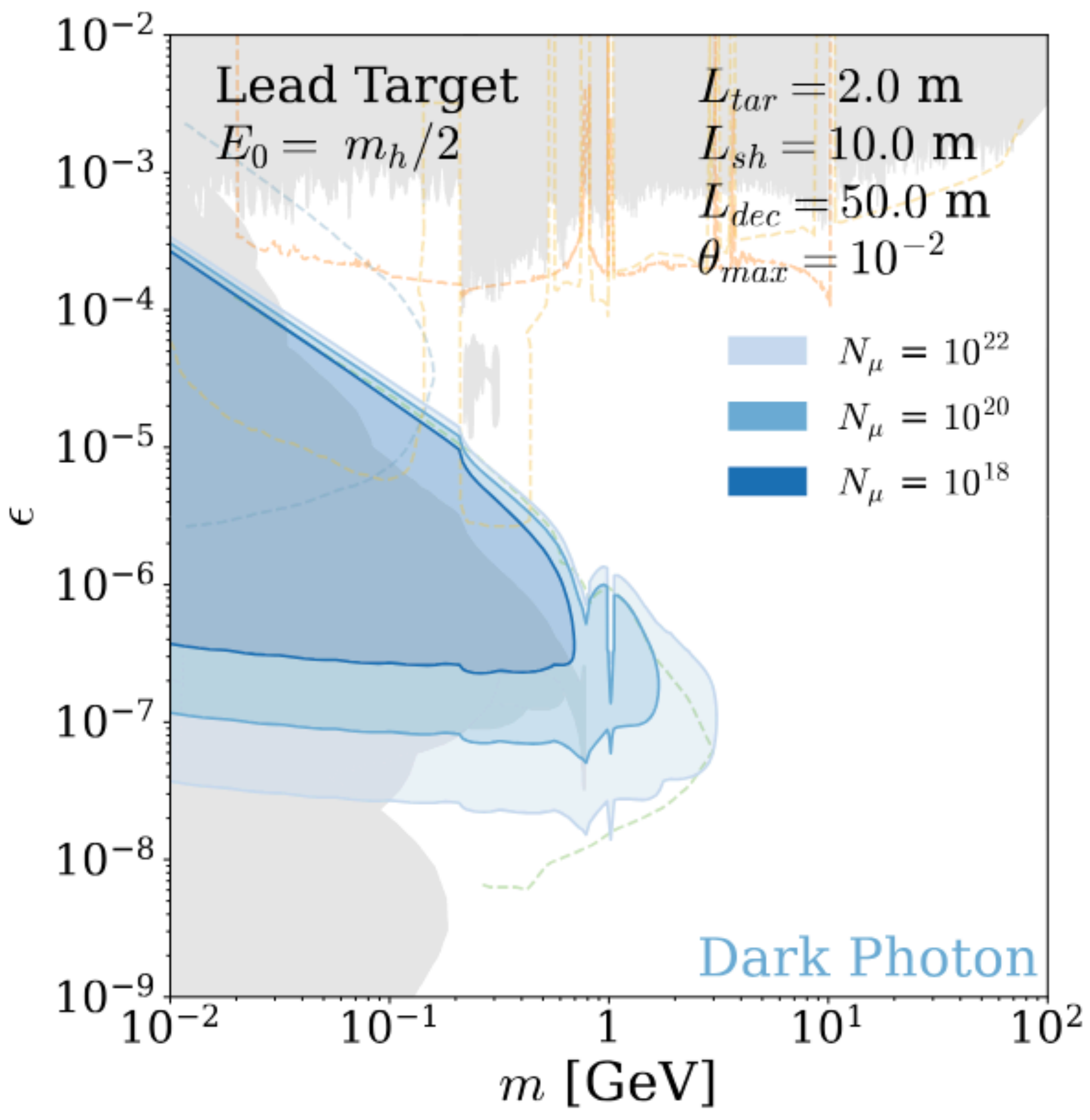


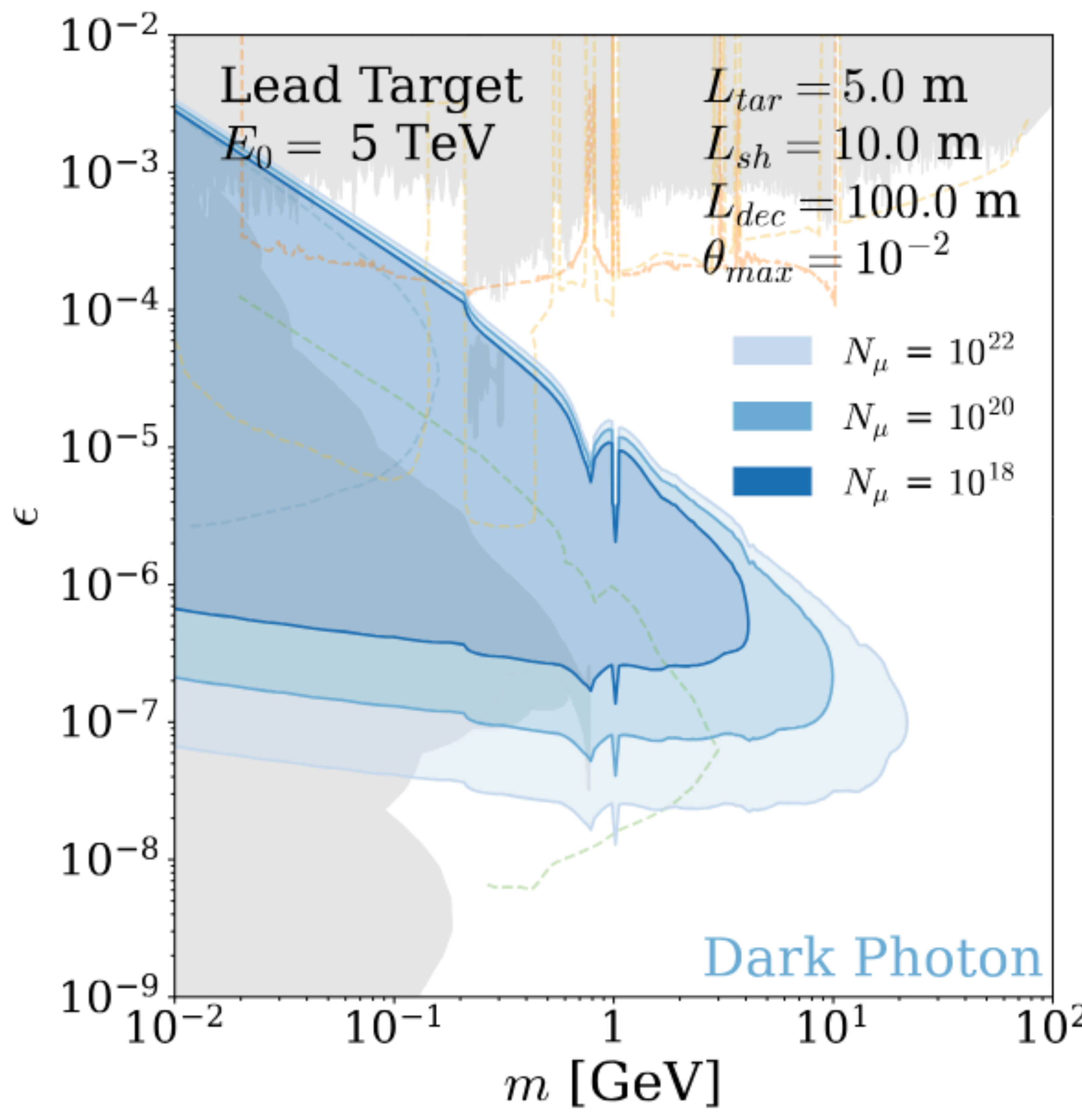


Muon Beam Dump

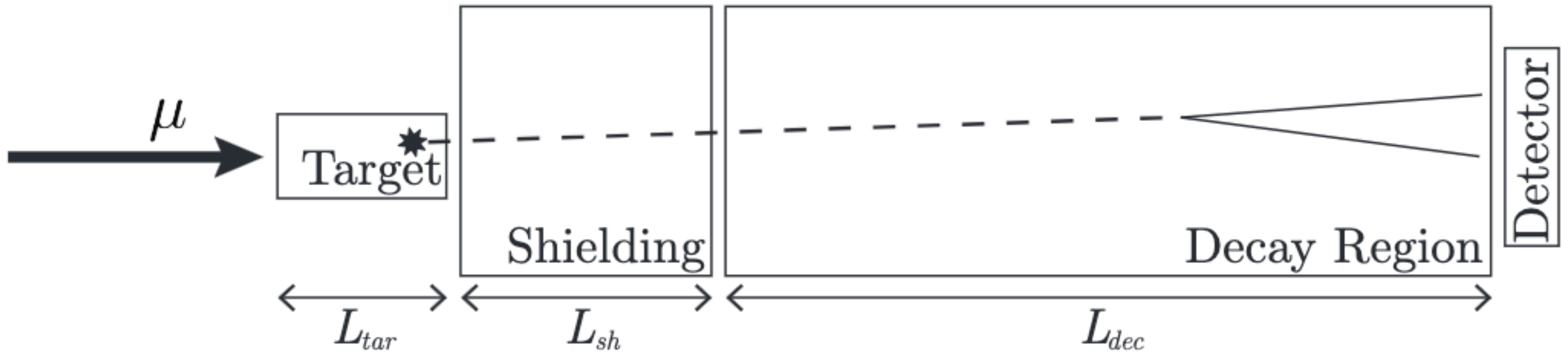


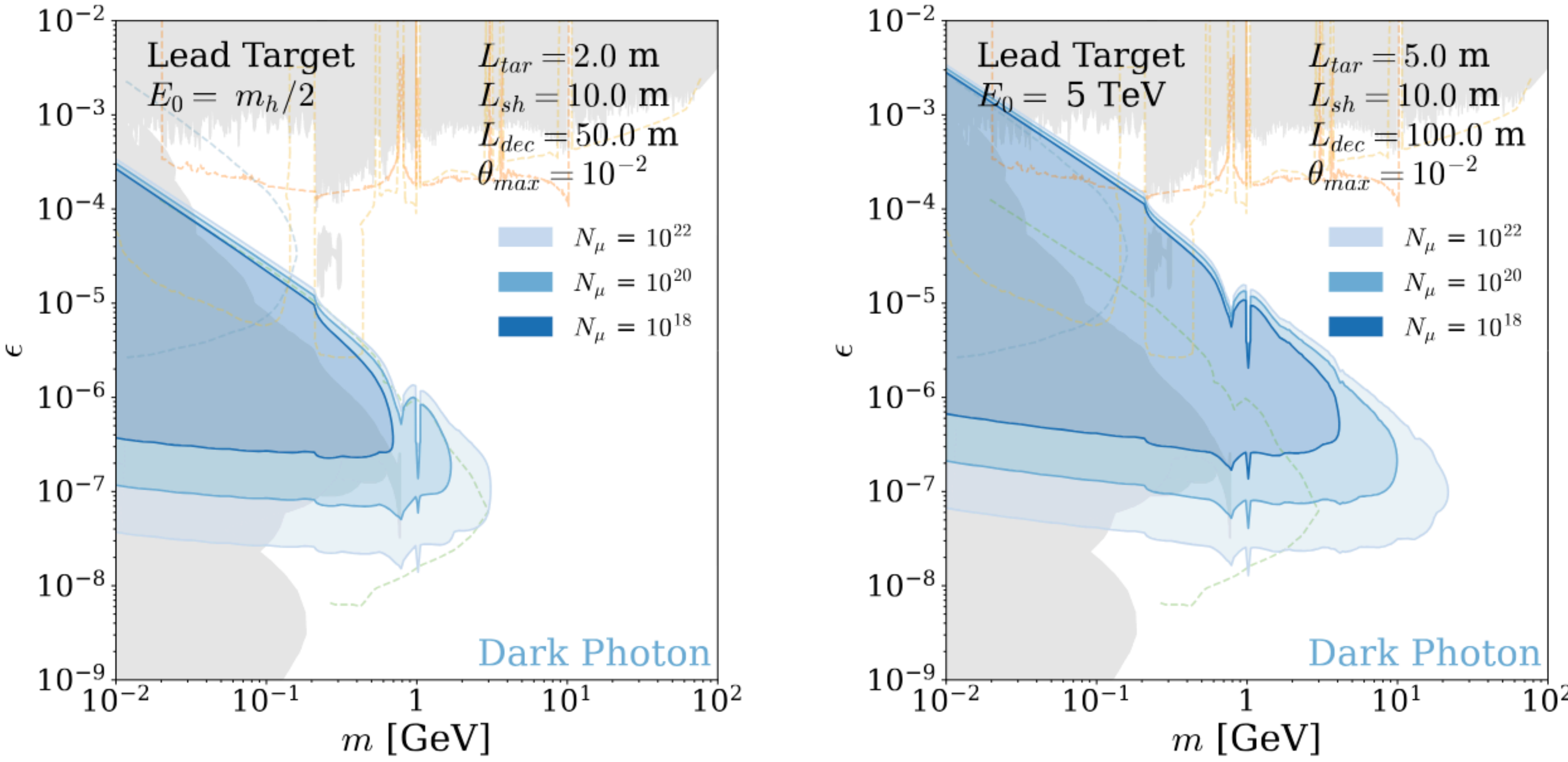
What's next?





Muon Beam Dump

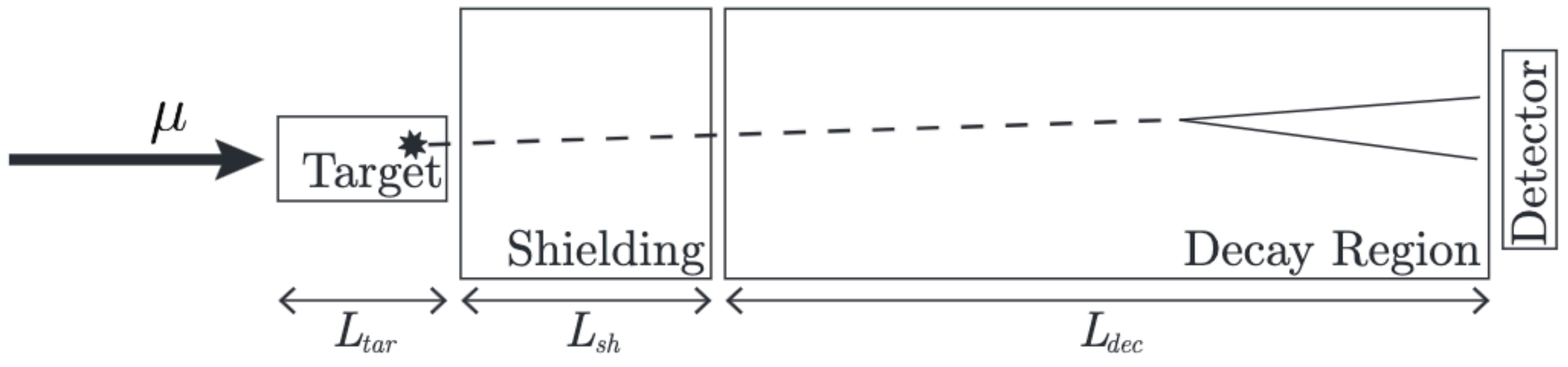


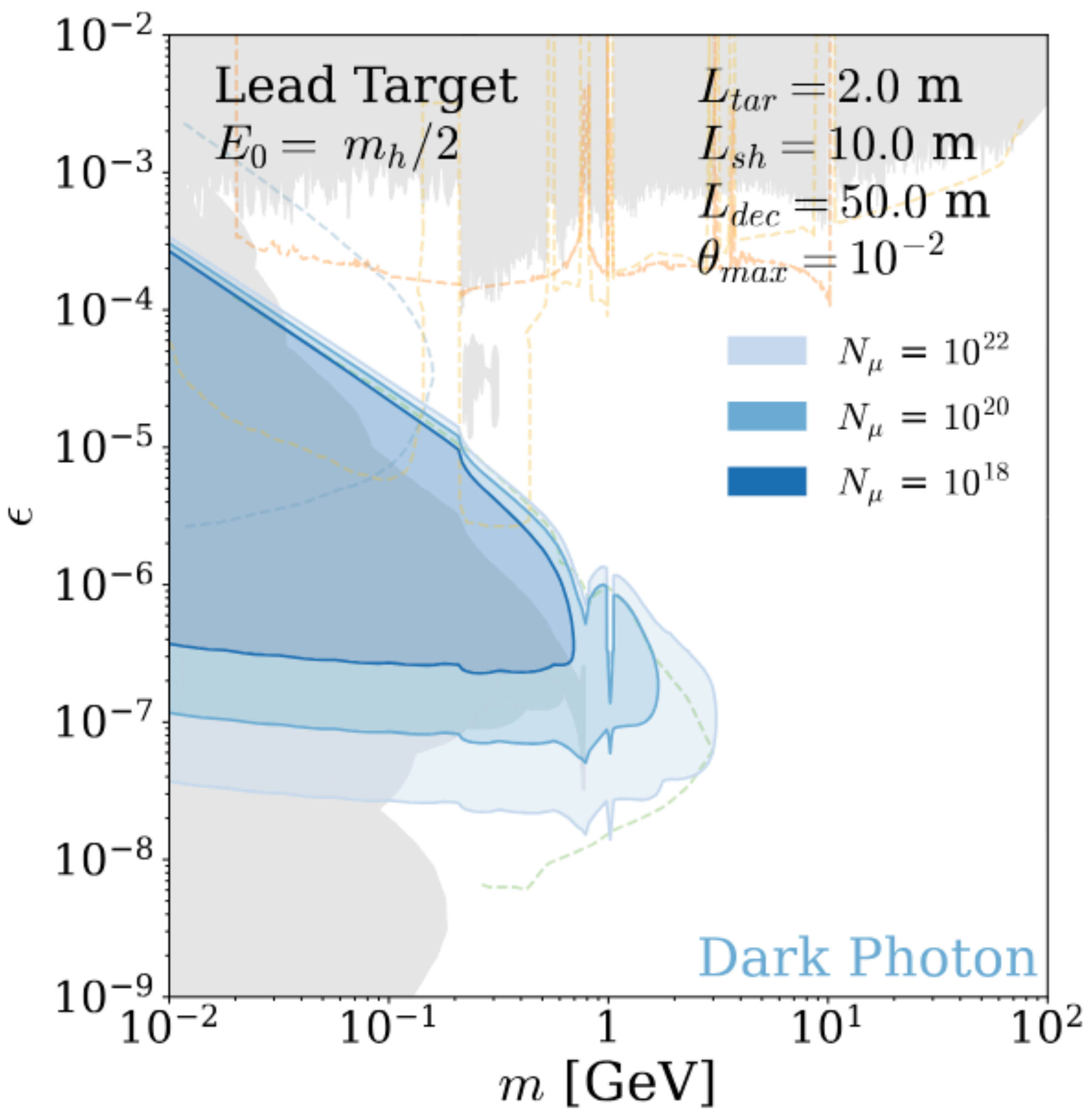


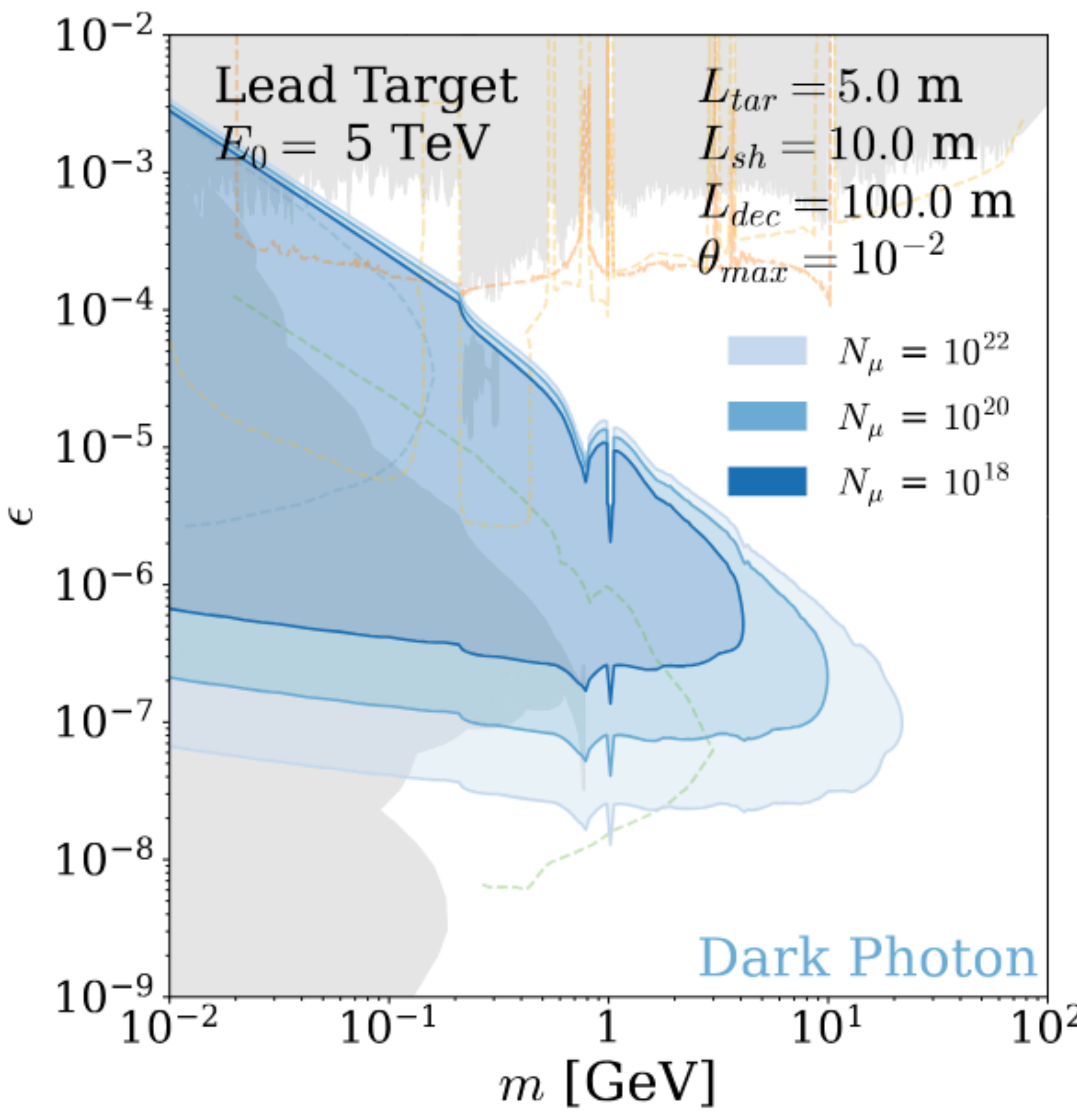
What's next?

- Detailed signal and background studies
- Target feasibility studies
- Additional final states? Only e^+e^- and $\mu^+\mu^-$ examined here
- What kind of detector?
- Efficiency studies

Muon Beam Dump







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+ other muon collider related challenges to overcome

Notes and next steps

Both MuC and e^+e^-

- Both proposals look at several other new physics models, not just dark photons

Notes and next steps

See also Douglas' talk tomorrow

Both MuC and e^+e^-

- Both proposals look at several other new physics models, not just dark photons
  - E.g. Long lived particles, light scalar bosons, ALPs, leptophilic gauge bosons…

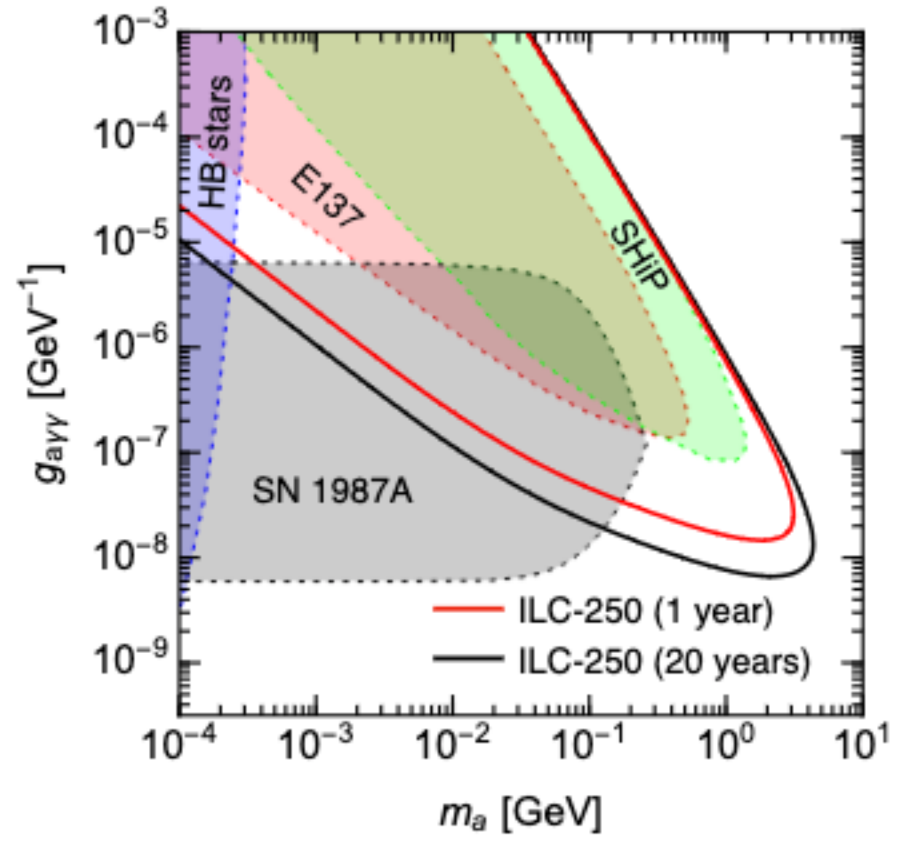
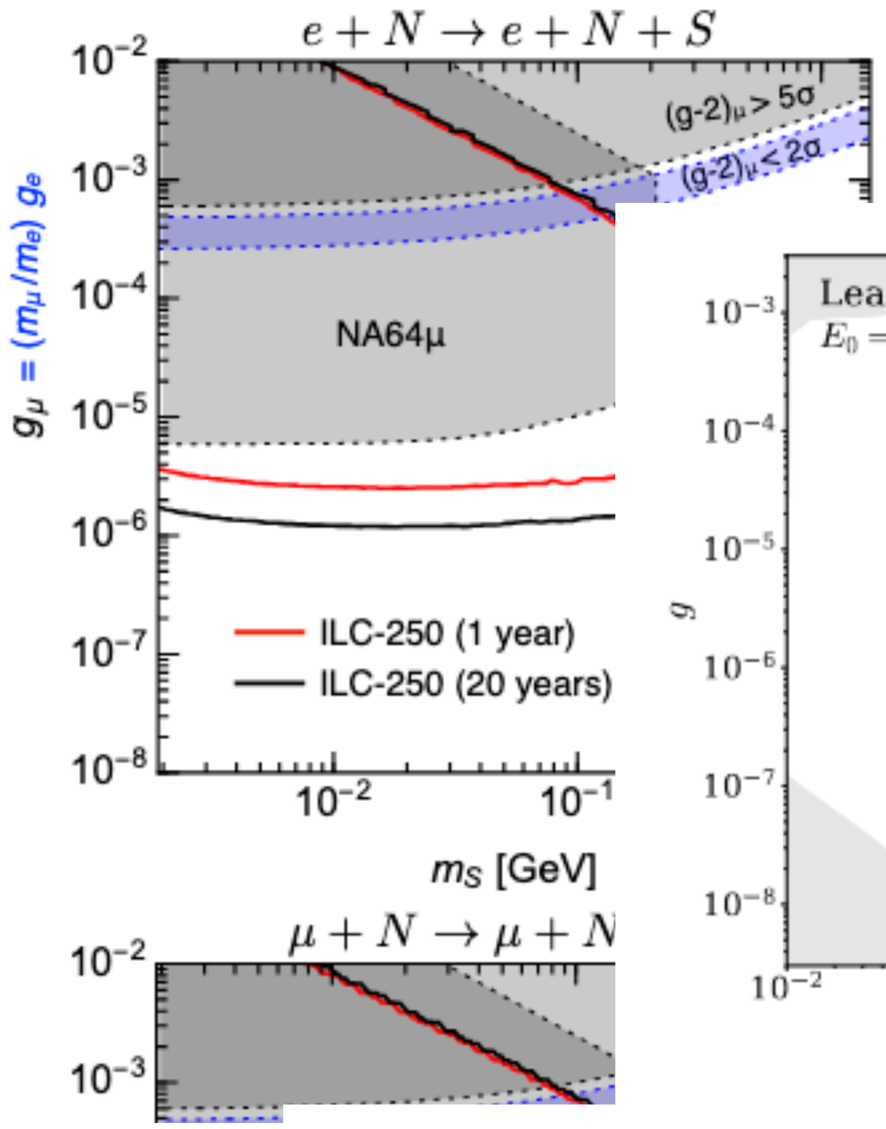
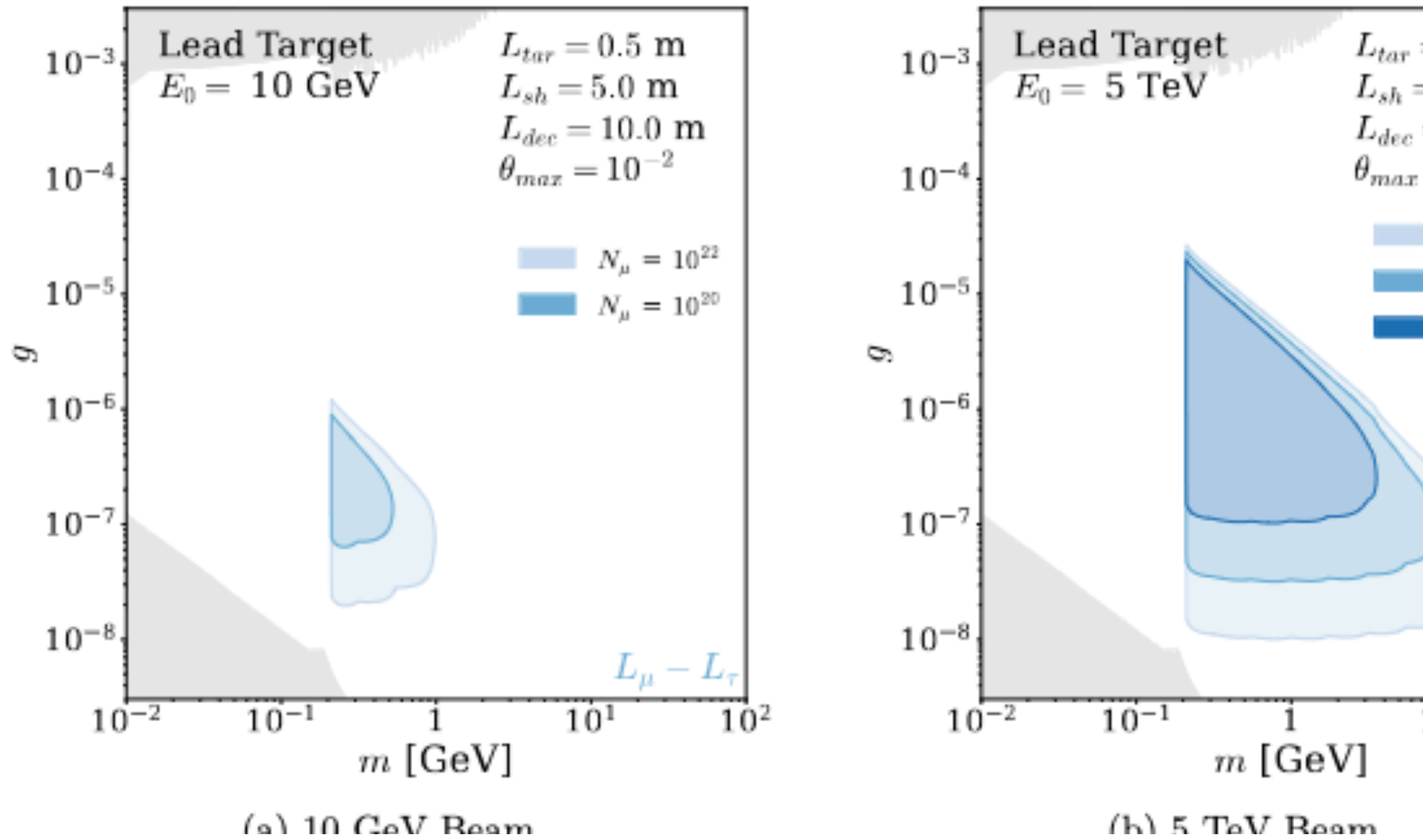


FIG. 2. The red and black curves show the bounds of se sitivity for ILC-250 GeV at 95% C.L. with 1- and 20-ye statistics. The shaded regions are constraints for E137 frc [25], SN 1987A from [25, 26], HB stars from [27], and SH from [18, 25, 29].





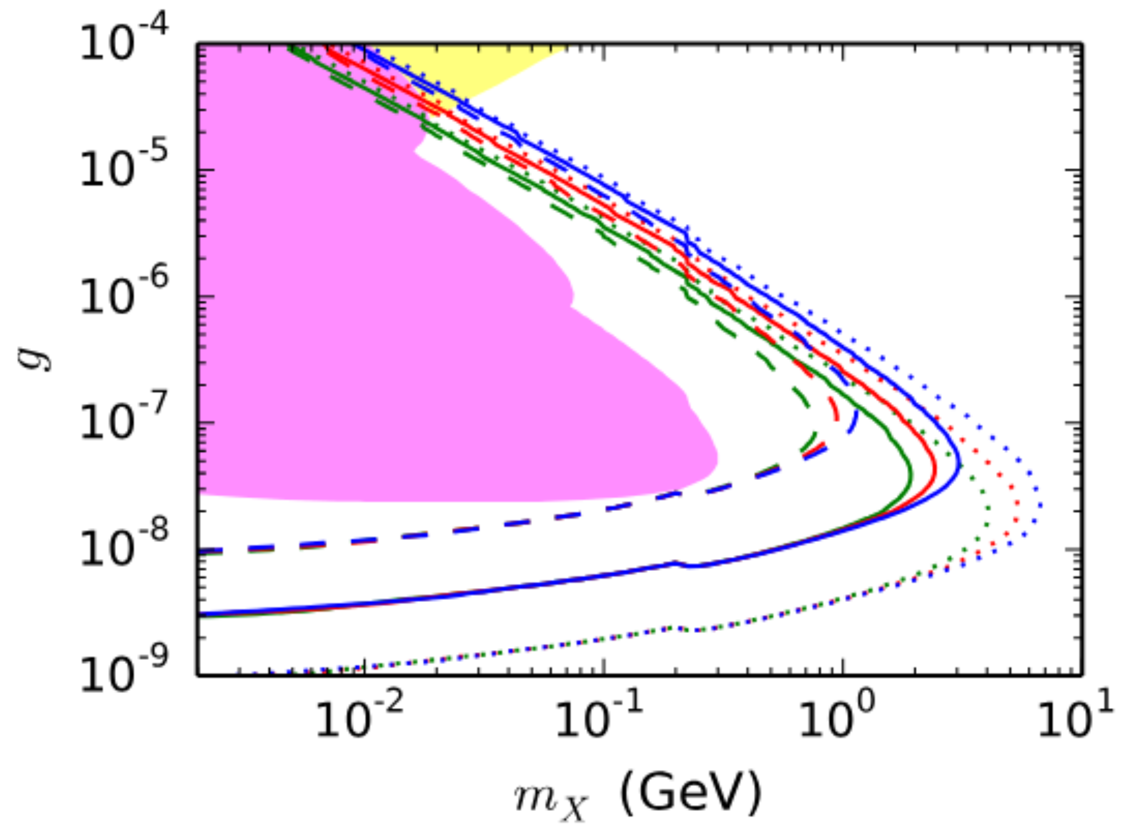
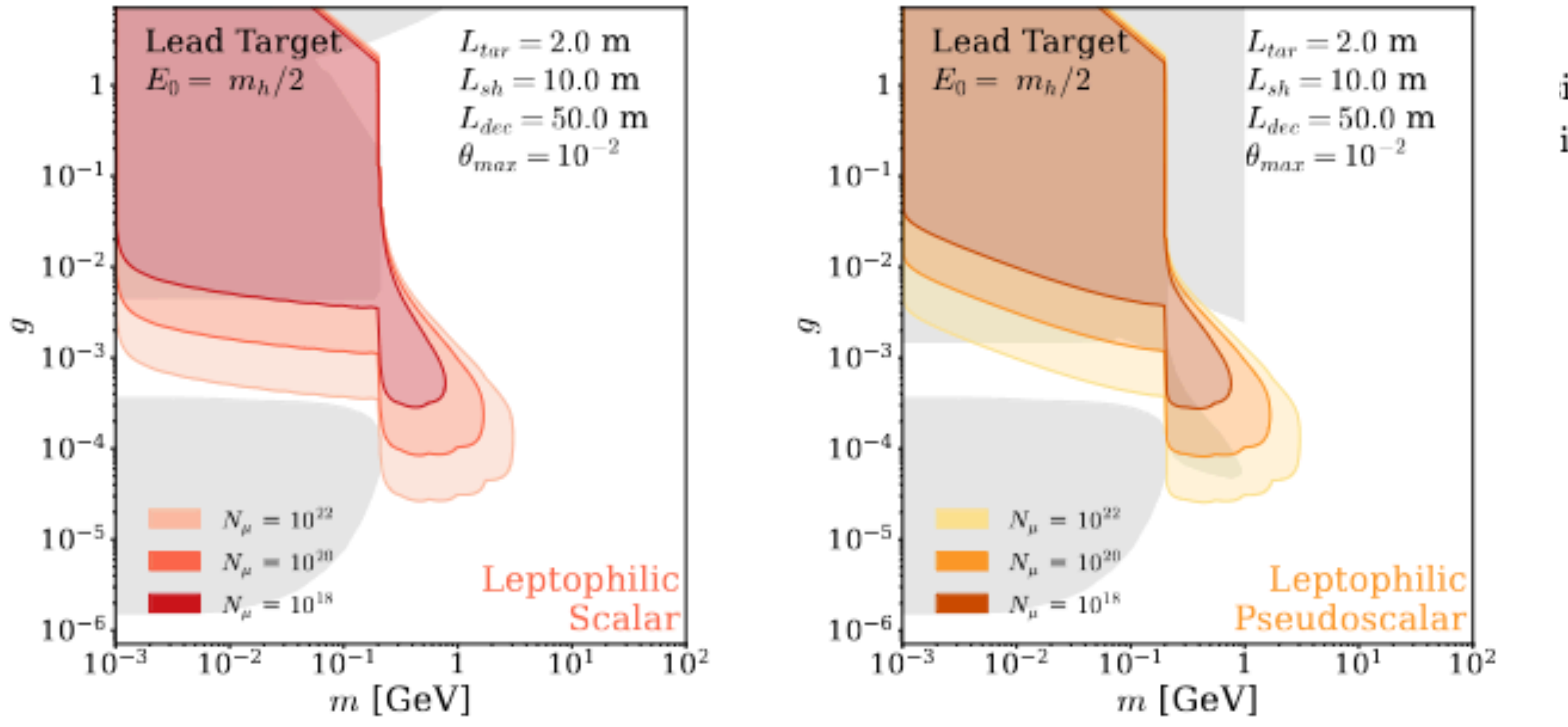


Figure 1: Contours of expected number of signal events for the $U(1)_{e-\mu}$ model. energy is taken to be $E_{\text{beam}} = 125$ (green), 250 (red), and 500 GeV (blue). The dc and dashed lines are for $N_{\text{sig}} = 10^{-2}$, 1, and 10^2, respectively, taking $N_e = 4\times$ mixing parameter is taken to be $\kappa_\epsilon = 1$. The pink and yellow shaded regions ai by beam dump and neutrino-electron scattering experiments, respectively.



(a) Scalar Production

(b) Pseudoscalar Production

Figure 7: The reach plots for a 63 GeV muon beam ($m_h/2$) on a lead target for the various particles species with a leptophilic coupling as defined in Eq. (4.2). We consider only the scalar and pseudoscalars out of theoretical motivation. The 10 GeV scenario is not shown as it does not cover new parameter space.

Notes and next steps

Both MuC and e^+e^-

- Both proposals look at several other new physics models, not just dark photons
  - E.g. Long lived particles, light scalar bosons, ALPs, leptophilic gauge bosons…
- Length parameters and target materials will need to be optimized for overall best case scenario for new physics
  - Better Monte Carlo, proposed detectors?
- Only one proposal each so far

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e^+e^- Collider

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  - No dedicated proposals for other potential e^+e^- colliders, or higher energy ILC
  - Will have two beam dumps, can accommodate more than one experiment
- Shorter time scale

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Muon Collider

- Much more R&D to take place on muon collider technology in coming years
  - Opportunities for additional smaller experiments during this R&D phase, with some dedicated proposals already in place (e.g. neutrino measurements)
- Beam dump experiments would also lend well to precision SM measurements

Conclusion

- DarkLight:
  - With the current 30 MeV setup: installation by end of year, commissioning to follow
  - Future 50 MeV upgrade to allow us to probe X17 favoured region
- Future collider outlook: lots of interesting physics can be probed with beam dump experiments at future colliders
  - Lots of cool work to be done determining best experimental approaches