SpinQuest/DarkQuest

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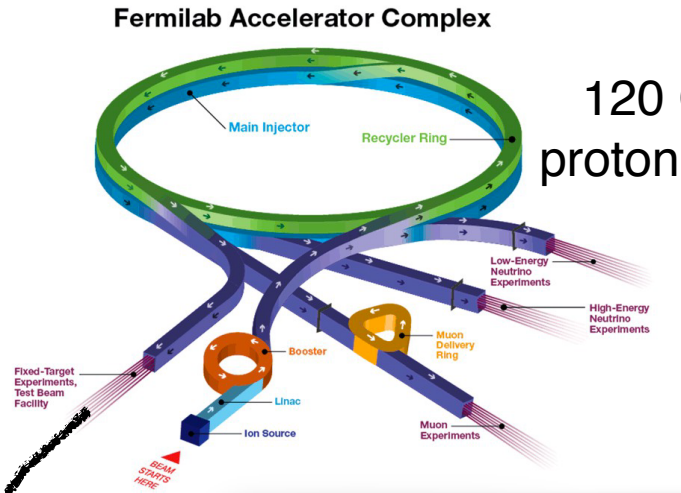
UC Santa Cruz

Hidden Sector Fixed Target Experiments at Fermilab
September 4, 2019

The SeaQuest experiment

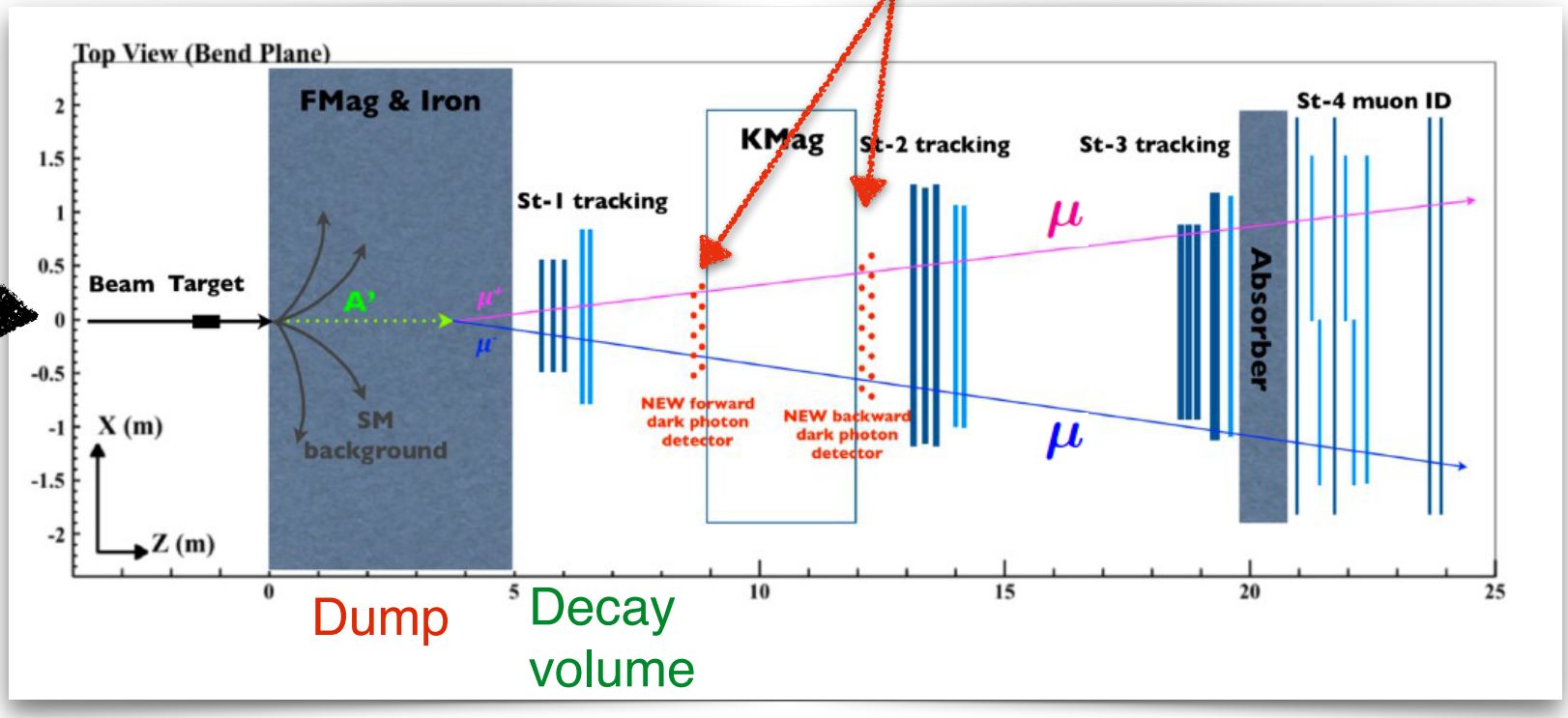


120 GeV
proton beam

5% main
injector
beam

New displaced trigger
installed in 2017

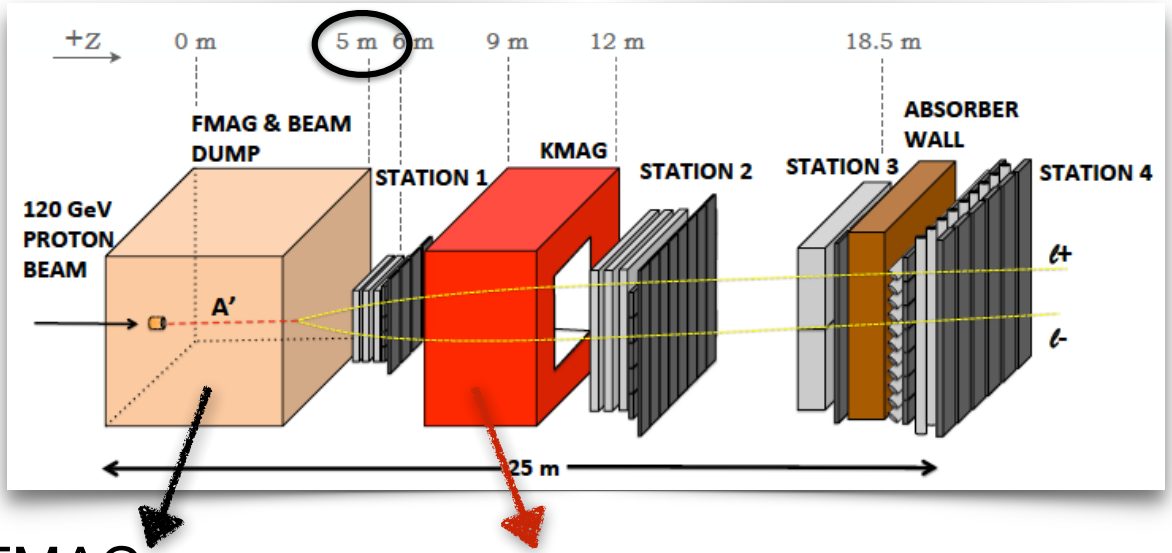
It allows parasitic runs
with E-1039 (SpinQuest)
in 2019-2021



Dump

Decay
volume

SeaQuest in a nutshell



1. Compact geometry

Sensitivity to (slightly) displaced dark particles with **d > 5m**

FMAG sweeps away soft SM radiation ($\Delta p_T \sim 2.9$ GeV)

2. KMAG separating even very forward muons ($\Delta p_T \sim 0.4$ GeV)

Identification of very light dark particles/squeezed spectra

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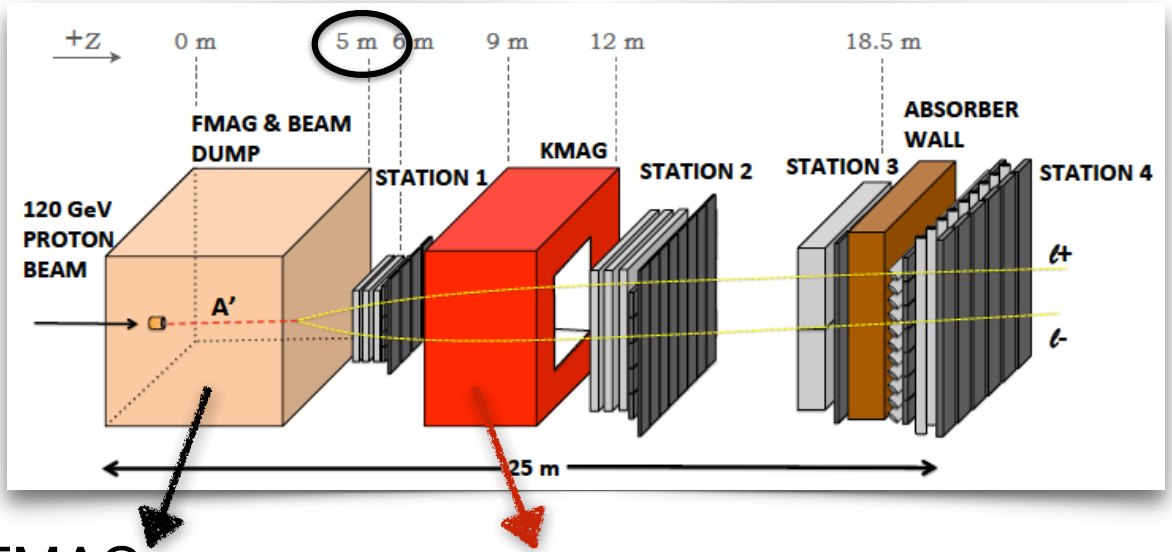

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($\Delta p_T \sim 0.4$ GeV)

Identification of very light dark particles/squeezed spectra

Unique setup

Experiment	Proton energy	POT	Dump	Decay volume	
SeaQuest	120GeV	10^{18}	5 m	10 m	
CHARM	400GeV	2.4×10^{18}	480 m	35 m	Past
LSND	800MeV	10^{22}	30 m	10 m	
NA62	400 GeV	10^{18}	100 m	250 m	Future
SHiP	400 GeV	10^{20}	65 m	125 m	

Status and near term prospects

Nuclear physics program:
Probe sea quarks in the proton

- E906, unpolarized targets (2012–2017)
- E1039, polarized targets (2019–2021)

SpinQuest

The **particle physics program** can run parasitically

- Parasitic searches for dark photons approved 2015 (E1067)
- Spring 2017:
  Displaced dimuon trigger installed
  - Two new fine-grained scintillator hodoscopes measure track
  - 5 days of good data taken with the displaced vertex trigger: ~10^{16} POT

Plan for 10^{18} POT
with & without displaced trigger

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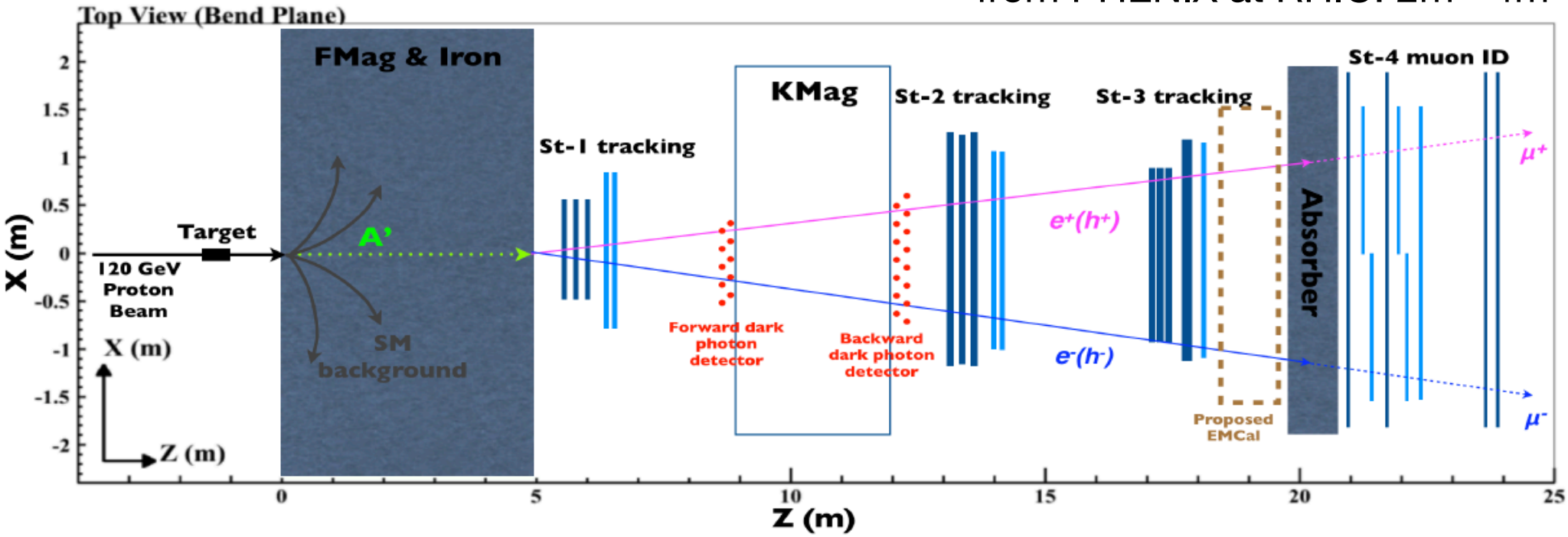
Plan for 10^{18} POT
with & without displaced trigger

Future, after 2021: installation of an EM-Cal? **DarkQuest**
Larger luminosities? How feasible is O(10^{20} POT)?

Near term upgrade plan: DarkQuest

After 2021

An EMCal detector recycled from PHENIX at RHIC: 2m * 4m

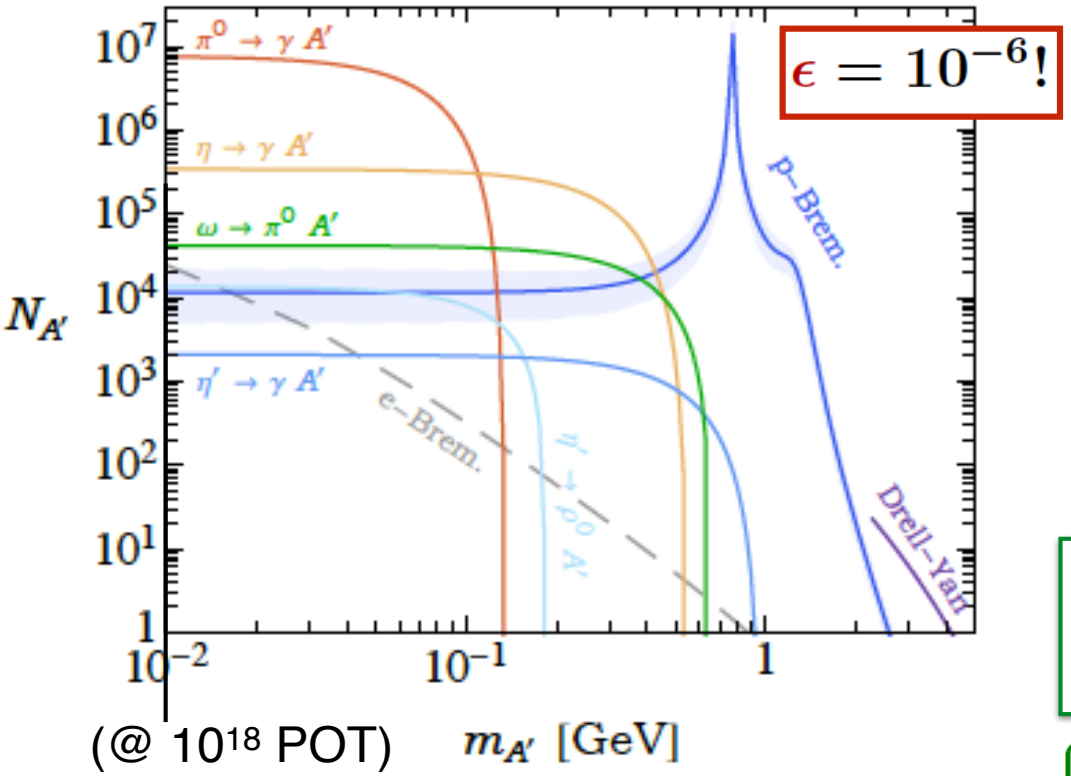


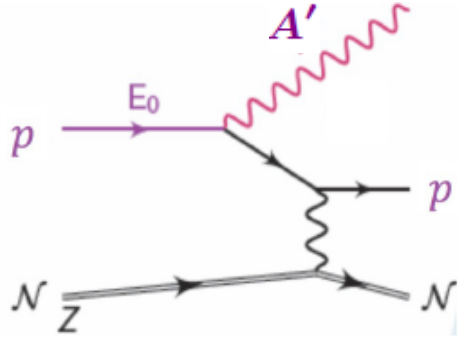
Signal mostly from beam dump.
Electromagnetic objects reconstructed.
Possibility to fully characterize potential signals.

A huge dark photon production

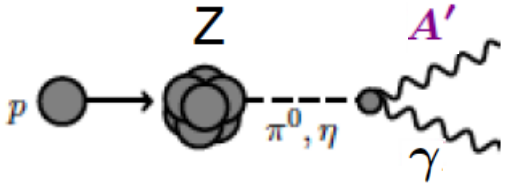
$\epsilon Z^{\mu\nu} A'_{\mu\nu}$

Berlin, SG, Schuster, Toro, 1804.00661





brems-strahlung



meson decay

Generically larger rates than at electron fixed target experiments

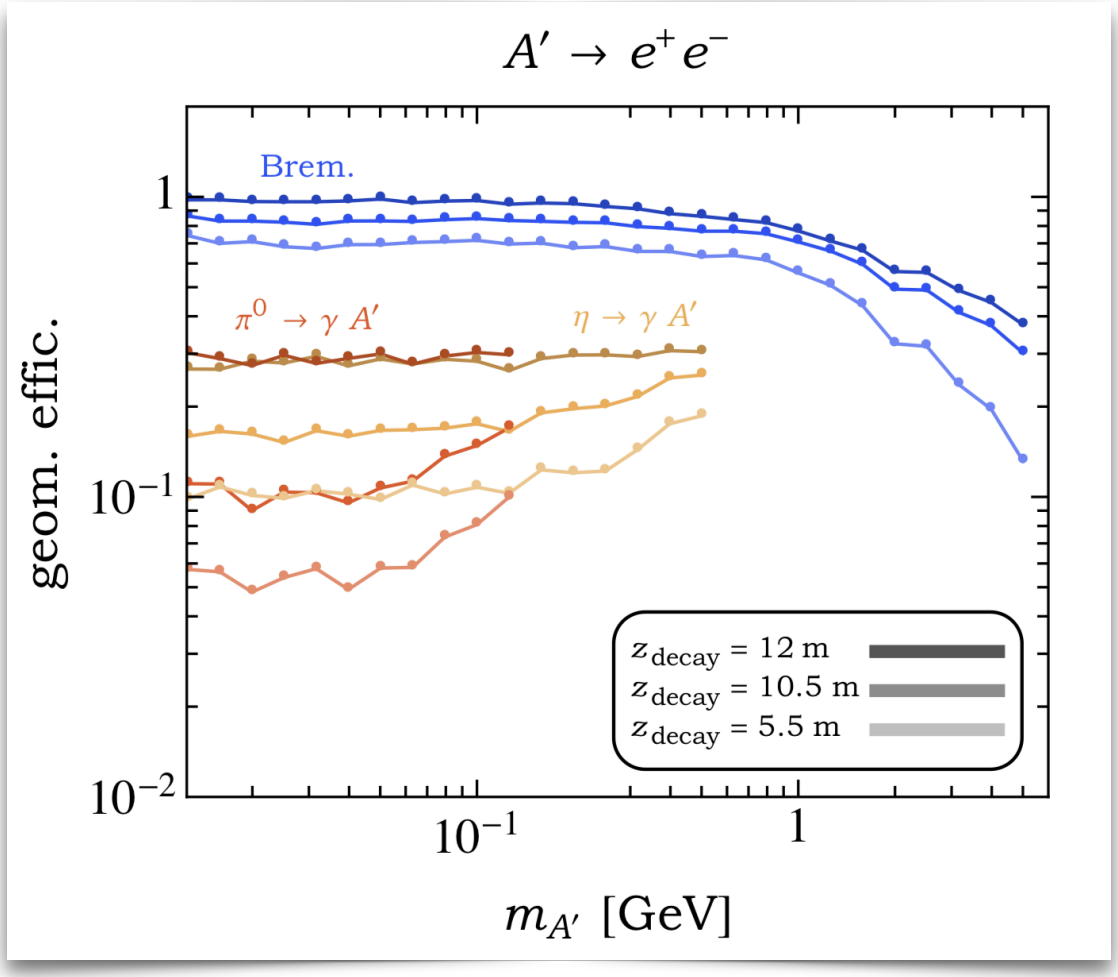
$$N_{A'}(e\ \text{Brem.}) \sim \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{m_{A'}}{\text{GeV}}\right)^{-2} \left(\frac{\text{EOT}}{10^{18}}\right)$$

$$N_{A'}(p\ \text{Brem.}) \sim 10^4 \times \left(\frac{\epsilon}{10^{-6}}\right)^2 \left(\frac{\text{POT}}{10^{18}}\right)$$

Dark photon mediated models

Minimal dark photon model

Very high geometric acceptance due to the compact geometry



Berlin, SG, Schuster, Toro, 1804.00661

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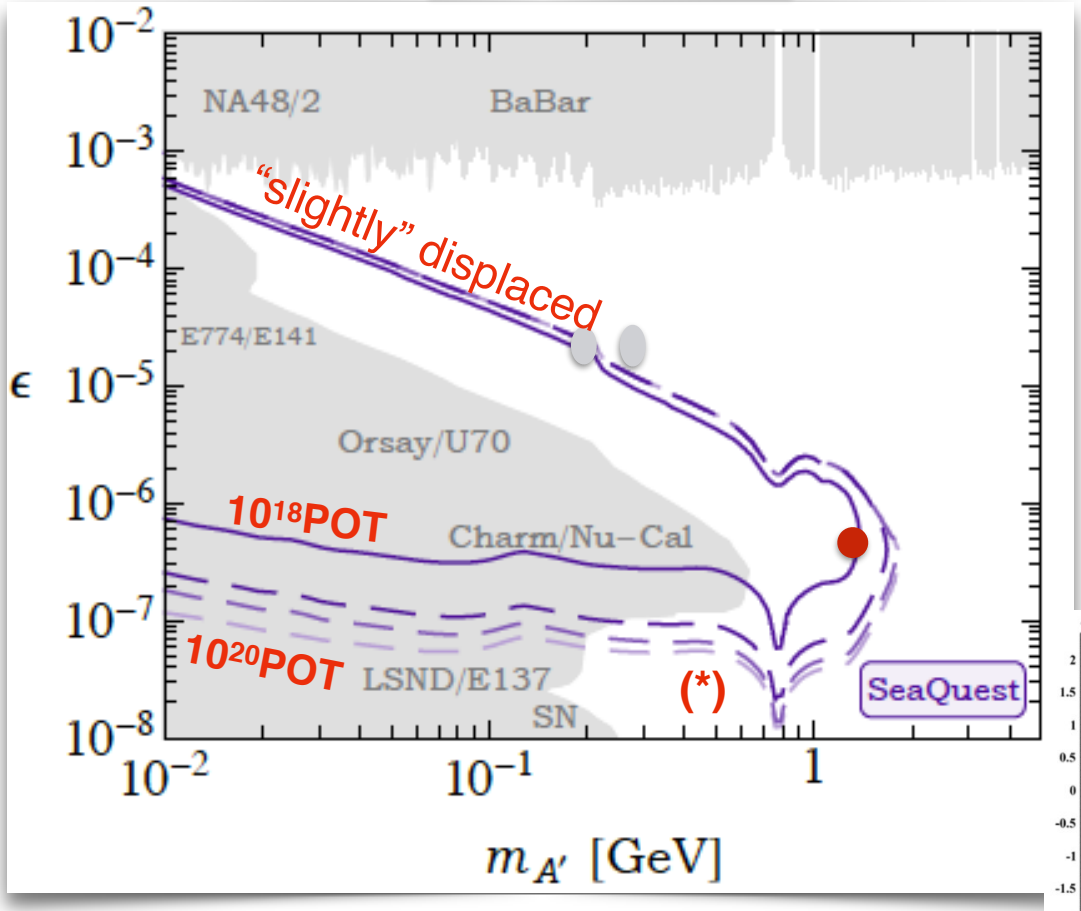
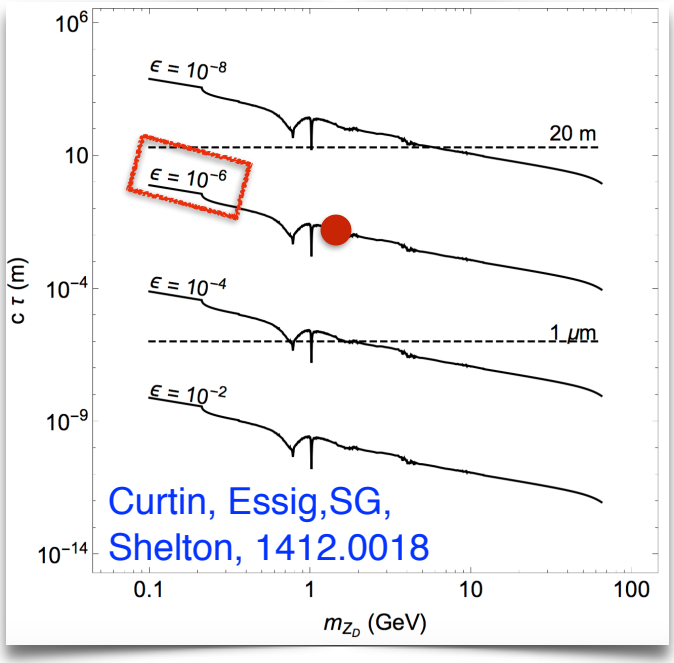
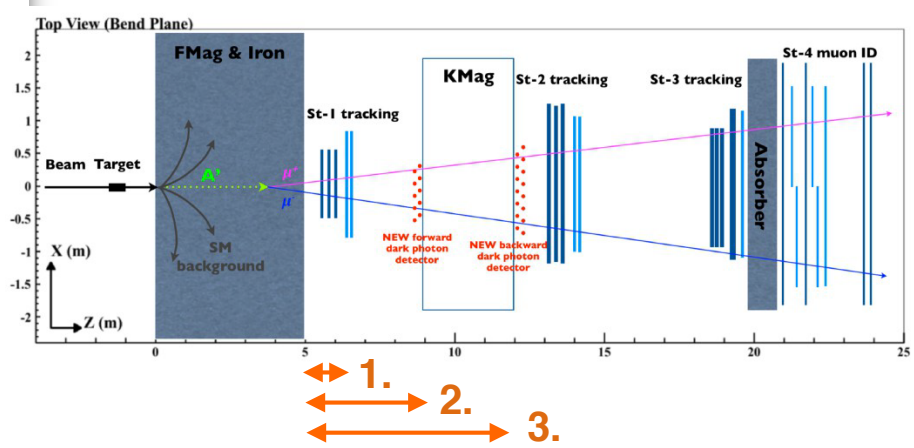
$A' \to e^+ e^-$







(*) decay regions: (5-6)m, (5-9)m, (5-12)m

1 2 3

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Berlin, SG, Schuster, Toro, 1804.00661

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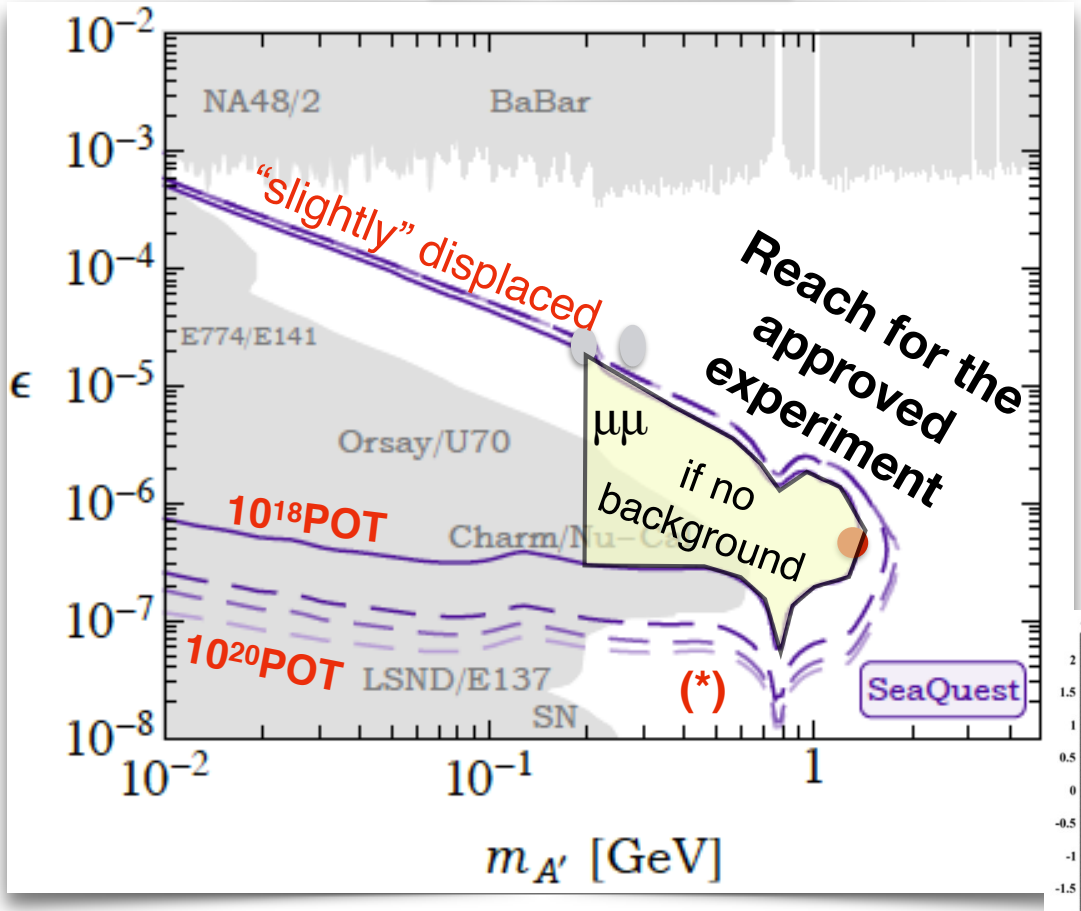

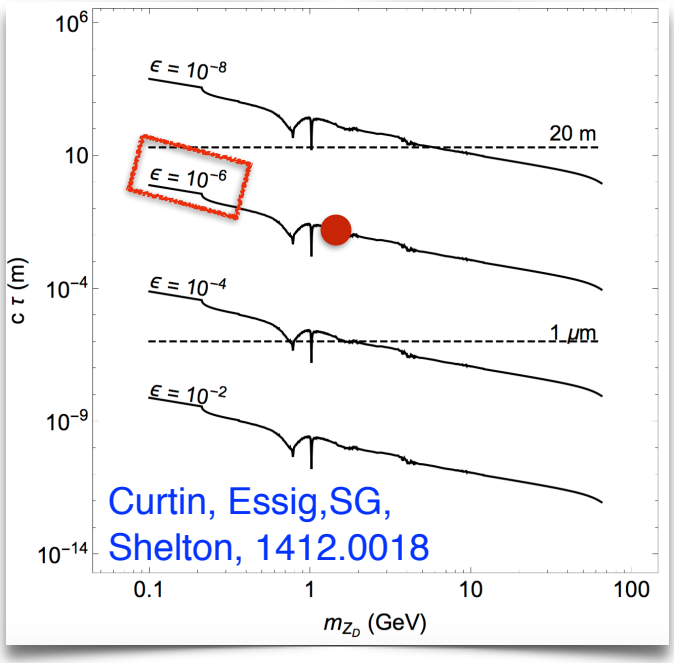

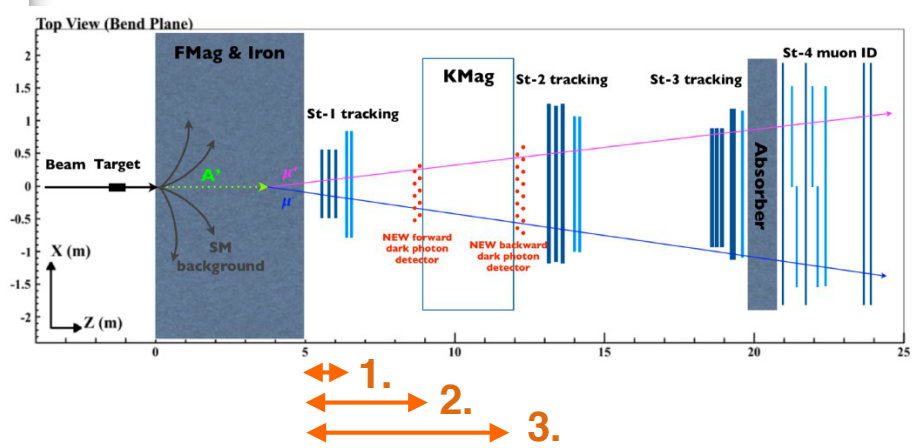

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Dark photon mediated models

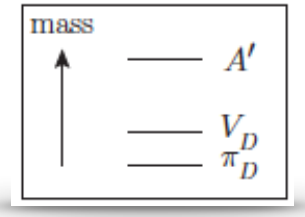
Strongly interacting dark matter models (1)

This is an example of models giving leptons + missing energy signatures (both resonant and non resonant)

DM is the lightest pion in a QCD-like theory SU(N_c) with

$$SU(N_f) \times SU(N_f) \rightarrow SU(N_f)$$

The dark QCD sector can be connected to the SM sector through the dark photon portal.



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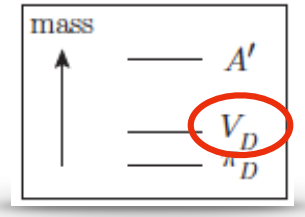

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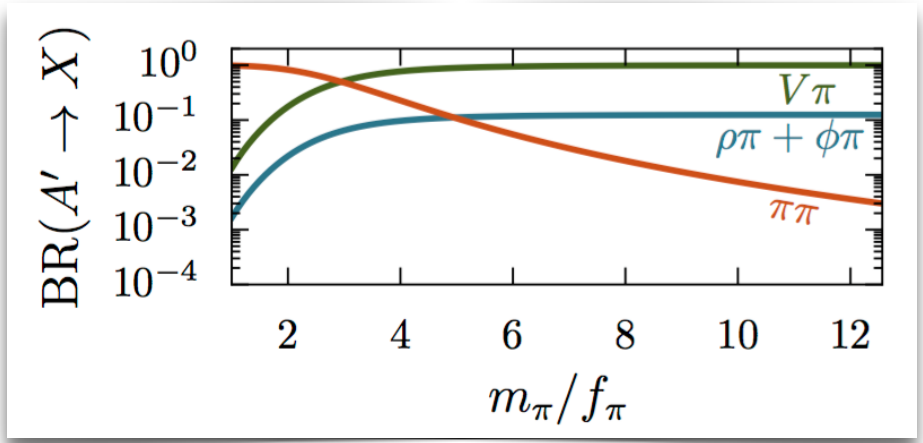
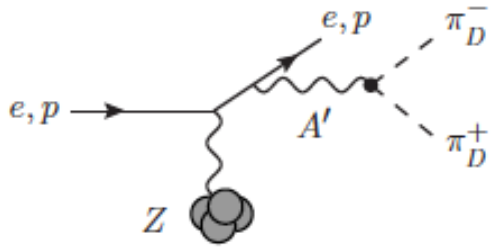
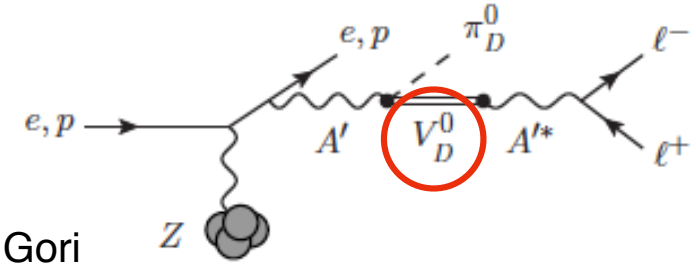
Heavier dark vectors, V_D, lead to a rich phenomenology

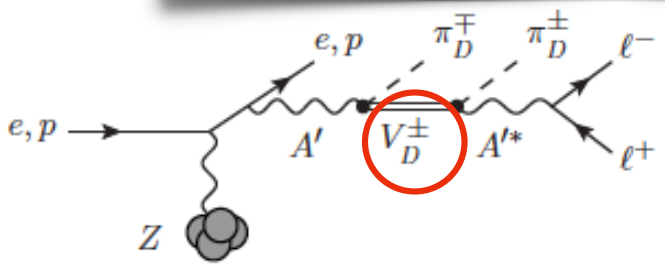
Berlin, Blinov, SG, Schuster, Toro, 1801.05805





Invisible
A' decay



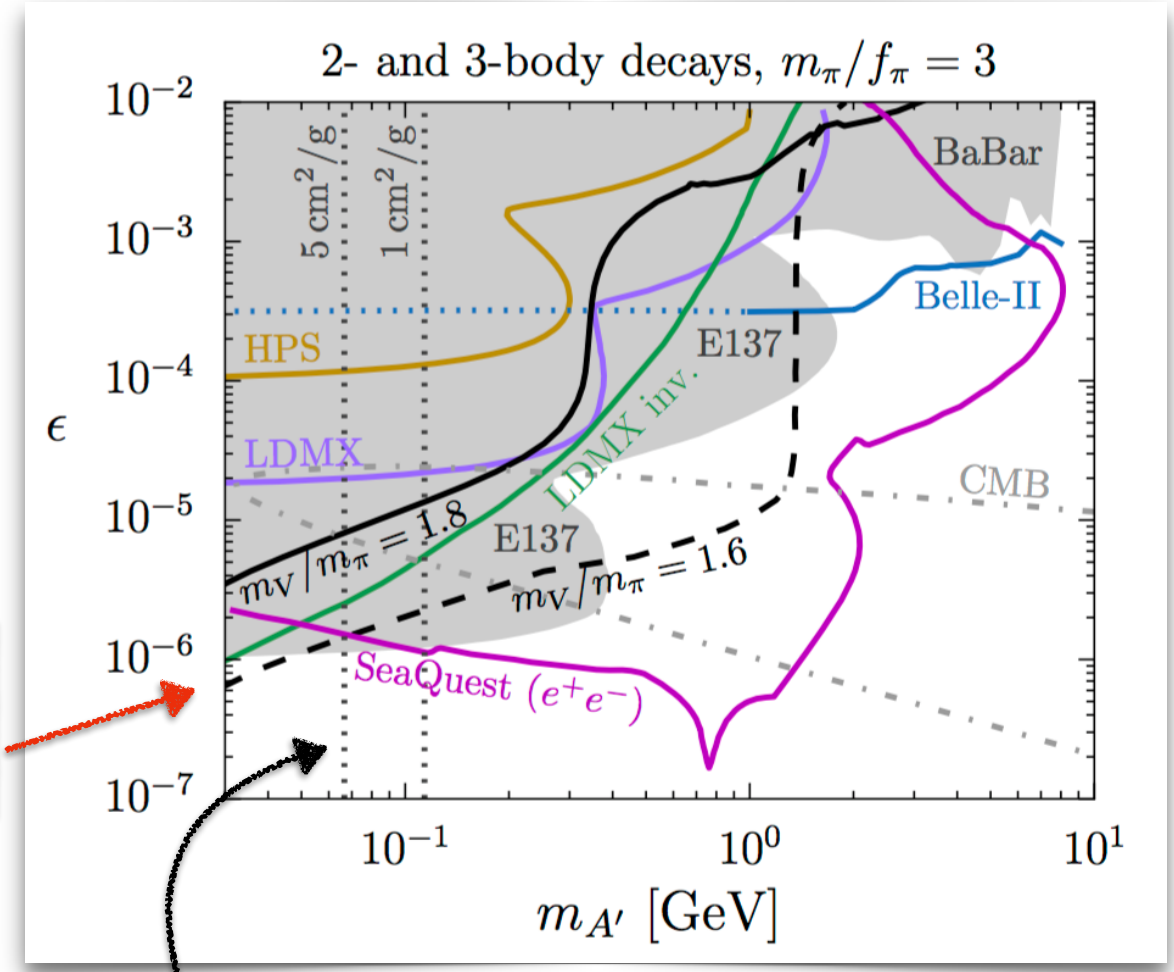


Visible
A' decay

Dark photon mediated models

Strongly interacting dark matter models (2)

Reach of DarkQuest



Relic line (our goal)

Bound from DM self-interaction

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

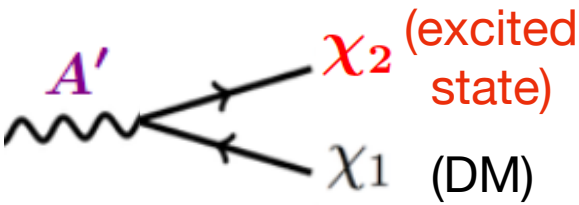
3-body decay $V_D^\pm \to \pi_D^\pm \ell^+\ell^-$

2-body decay $V_D^0 \to \ell^+\ell^-$

Dark vectors are generically long-lived

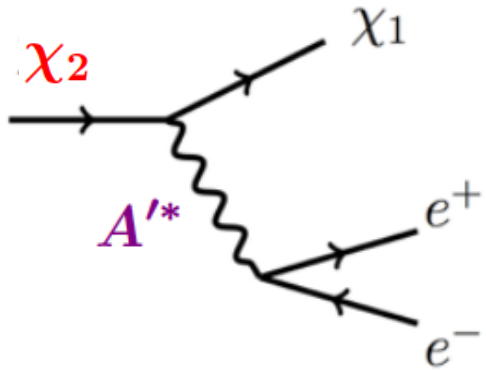
Dark photon mediated models

Inelastic Dark Matter models



Similar signature but more squeezed phase space.

Interestingly, the geometric acceptance is still relatively good



$$\Delta \equiv \frac{m_2 - m_1}{m_1} \ll 1$$

Dark photon mediated models

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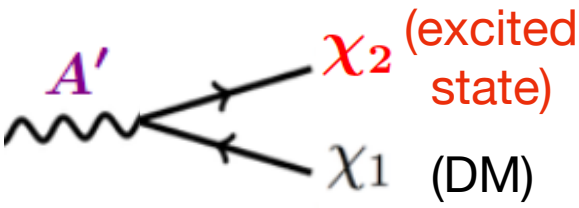

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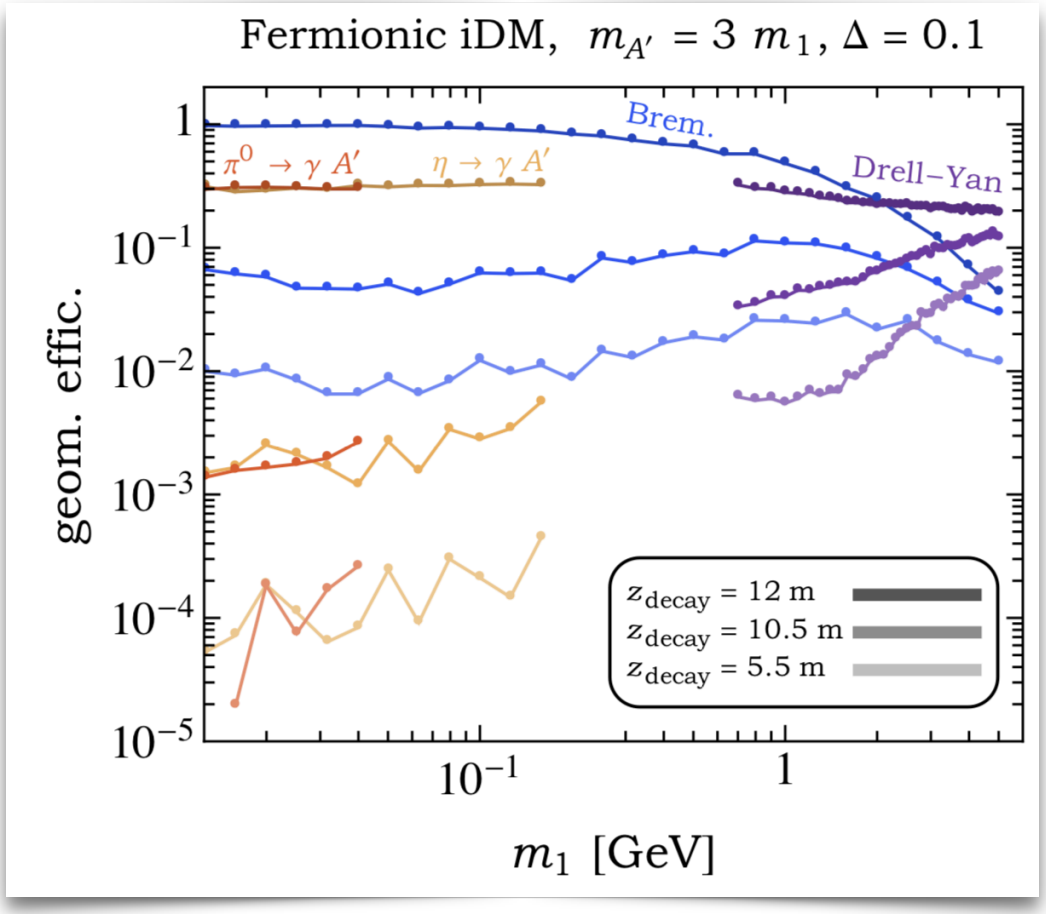
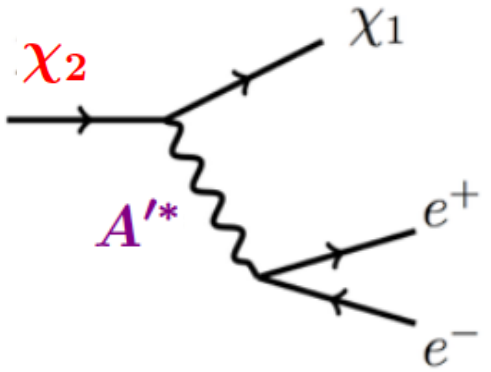


Berlin, SG, Schuster, Toro, 1804.00661



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see also Izaguirre, Krnjaic, Shuve, 1508.03050

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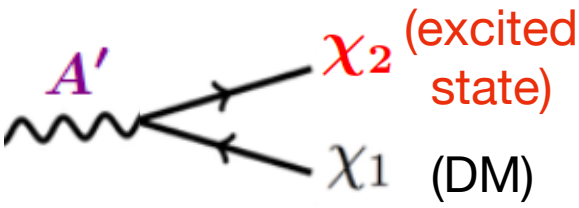

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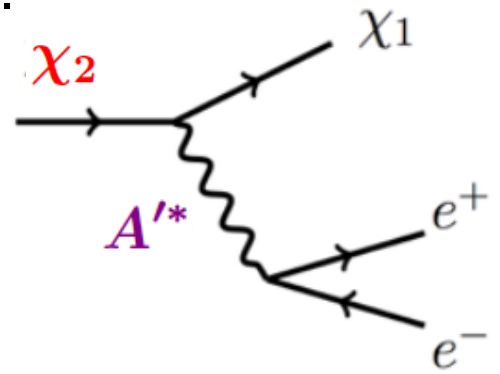

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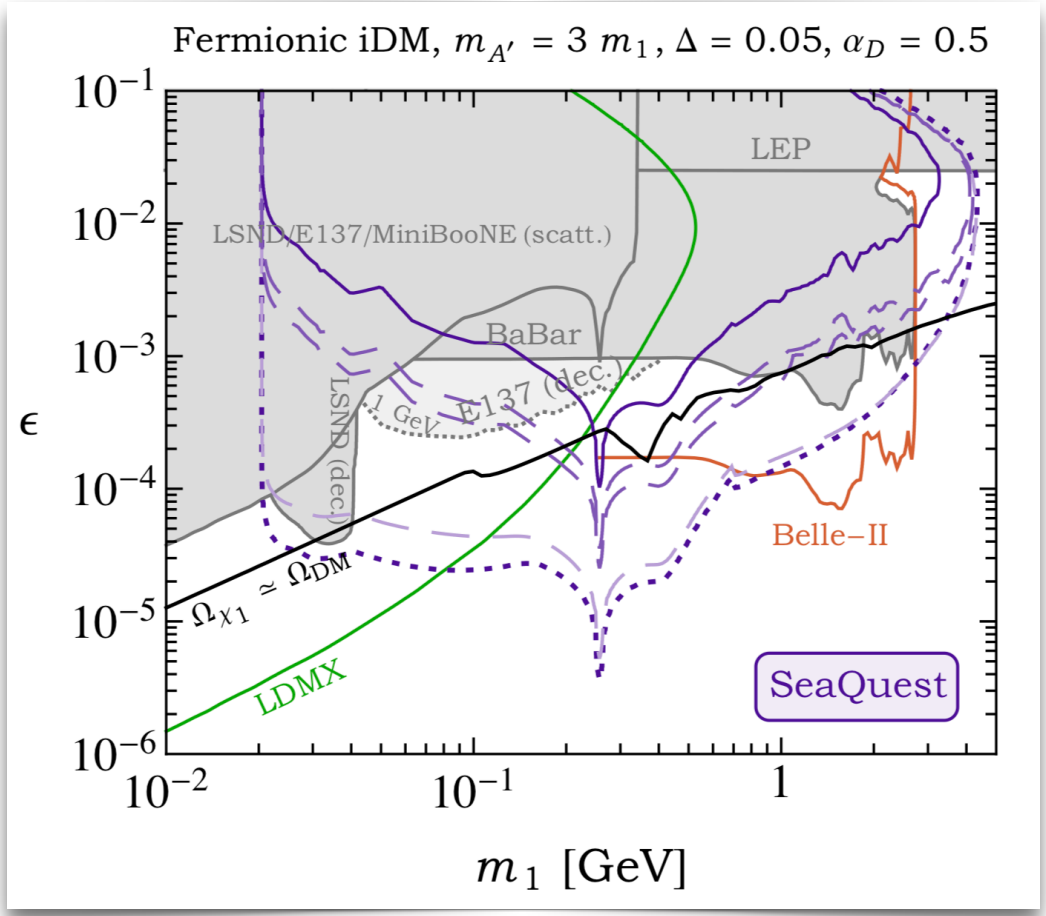

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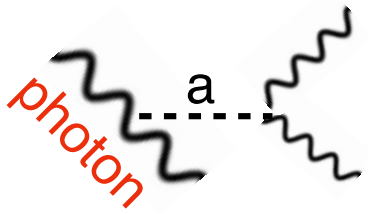
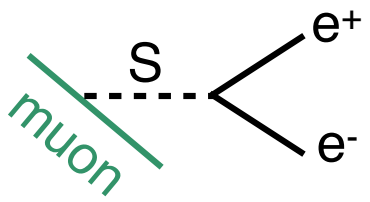
Beyond dark photon models

SeaQuest/DarkQuest produces a huge number of (relatively energetic) photons and muons ⇨ Possibility to radiate dark particles

Axion-like particles



Dark scalars



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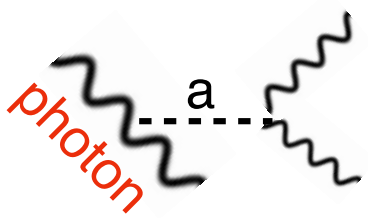

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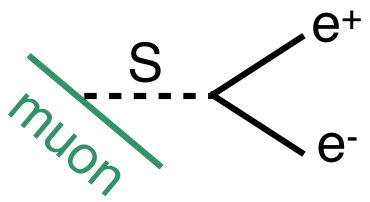
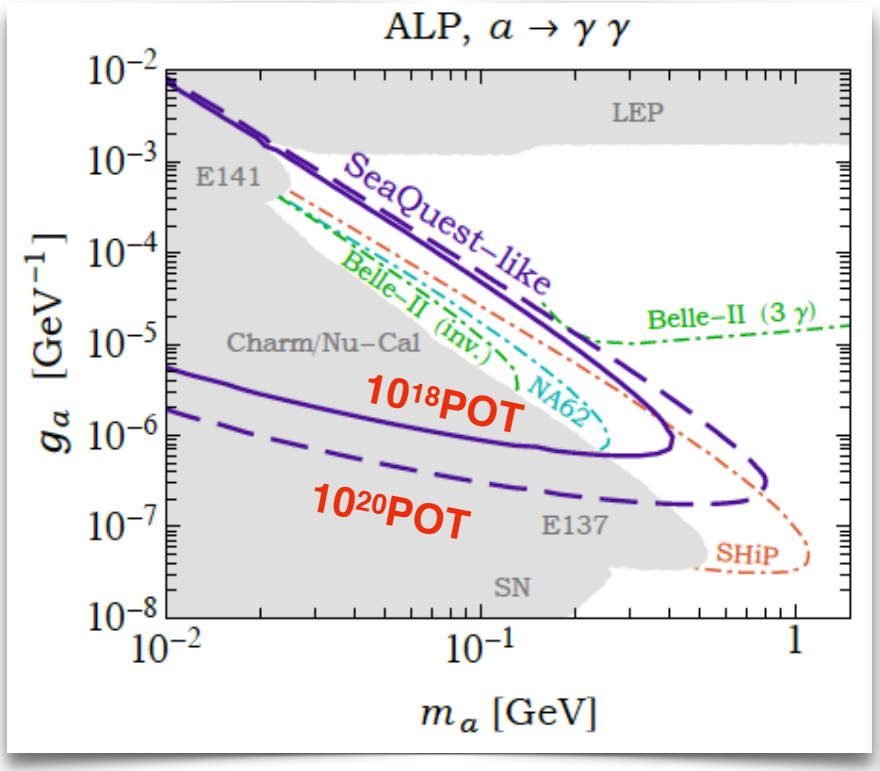
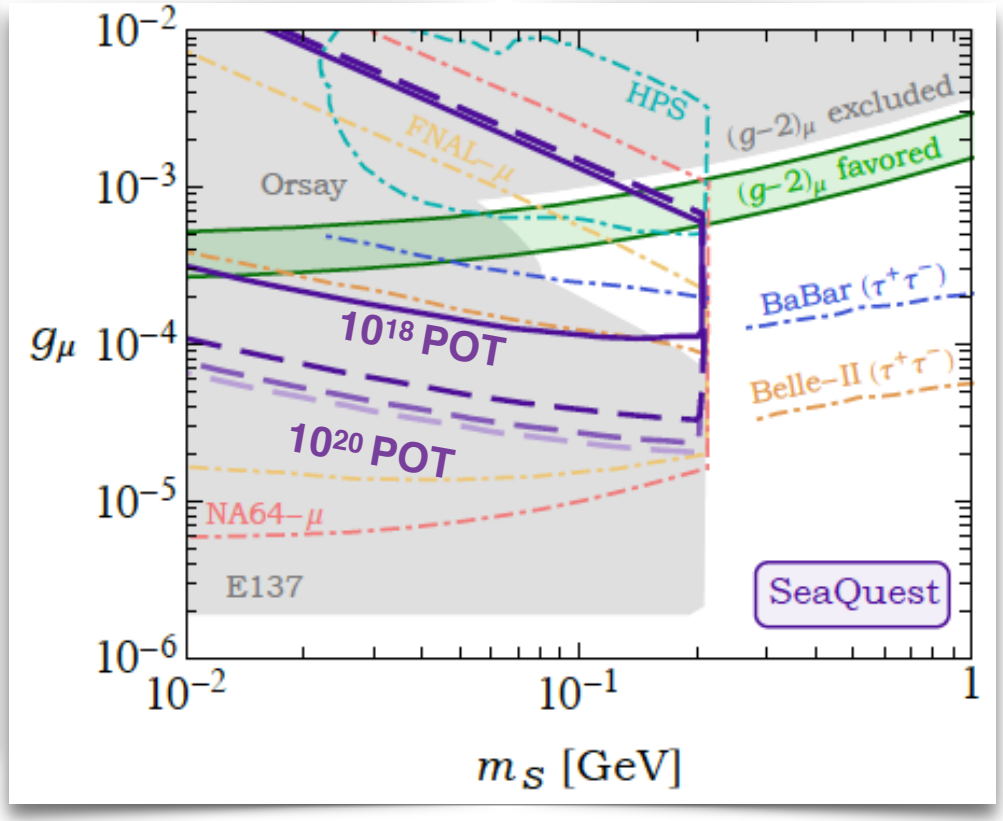






Few more meters of iron to shield from $K_L \to \gamma\gamma$?

Additional opportunities

Right-handed neutrinos produced from heavy meson decays

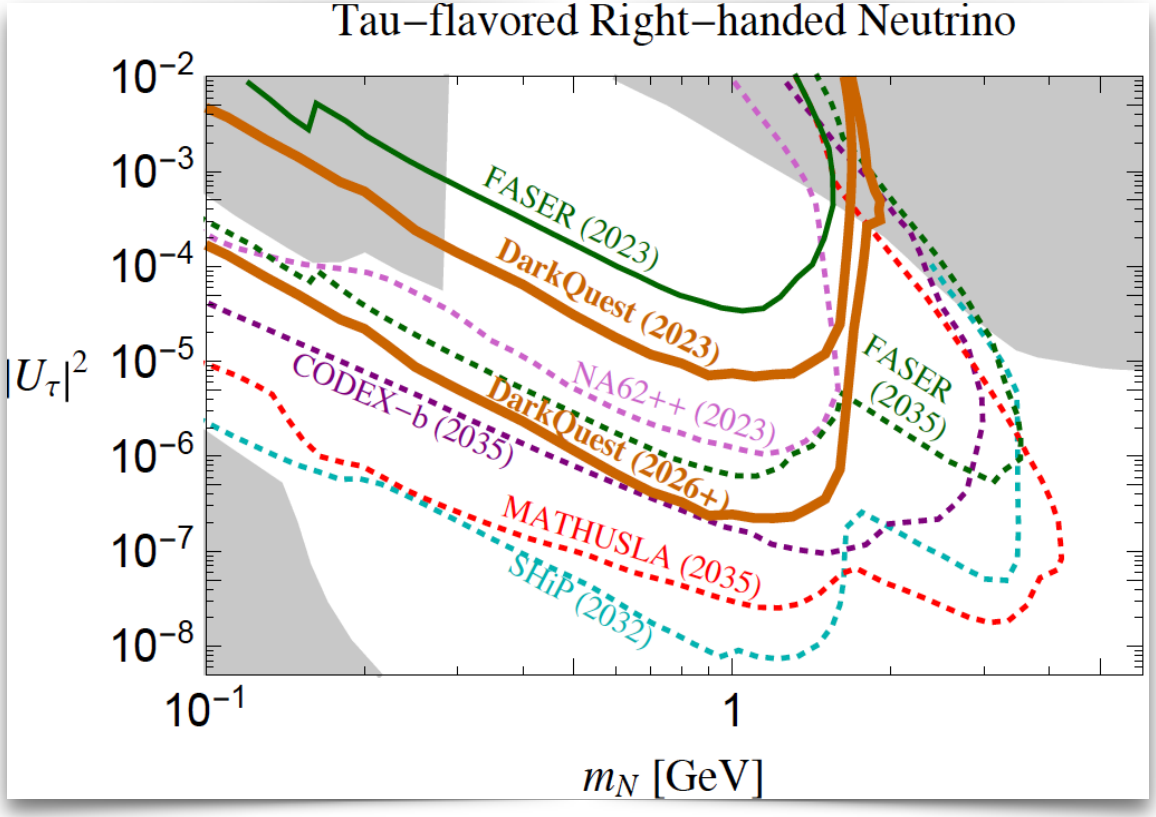
1. Mesons and taus will decay to sterile neutrinos, N.

A few examples:

$$B \to D\ell N$$
$$B \to \ell N$$
$$D \to K\ell N$$
$$D \to \ell N$$
$$\tau \to \ell N$$

2. Sterile neutrinos, N, will decay:

$$N \to \pi^{\pm}\ell^{\mp},\ N \to \ell^{+}\ell^{-}\nu, \ldots$$

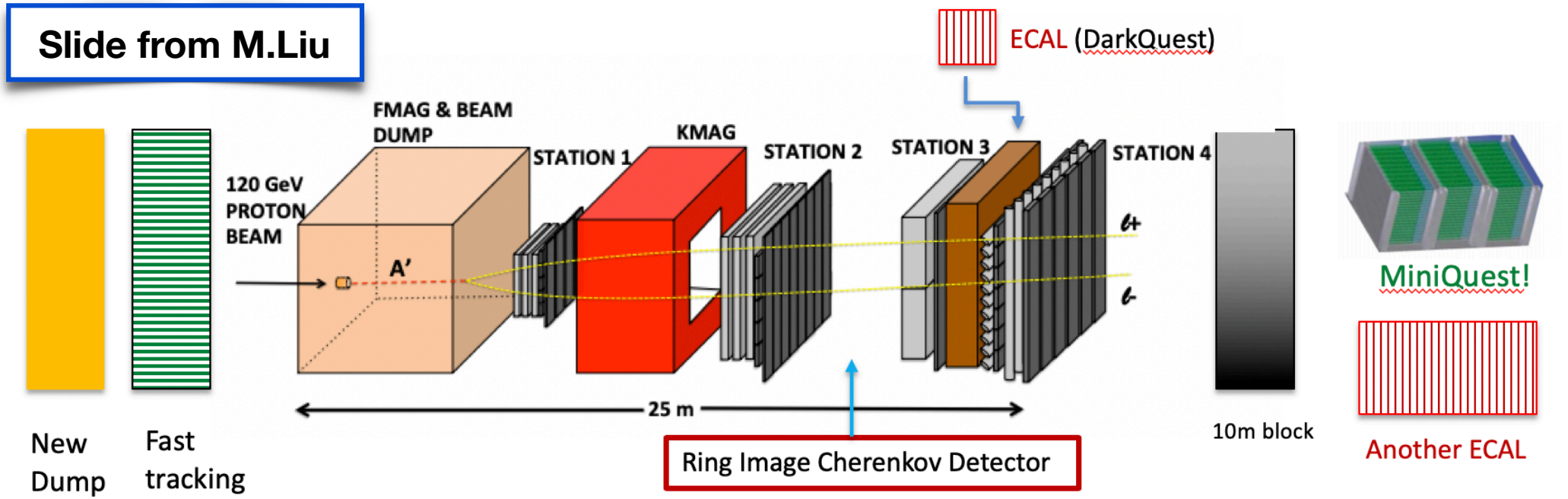


Batell, Evans, SG, in preparation

LongQuest: Three Stage Retool of SpinQuest, as Dedicated Long-Lived Particle Experiment

arXiv:1908.07525, Tsai, DeNiverville, Liu '19

Slide from M.Liu



LongQuest III

Front dump and fast tracking

LongQuest I

Add RICH or HBD for main detector

LongQuest II

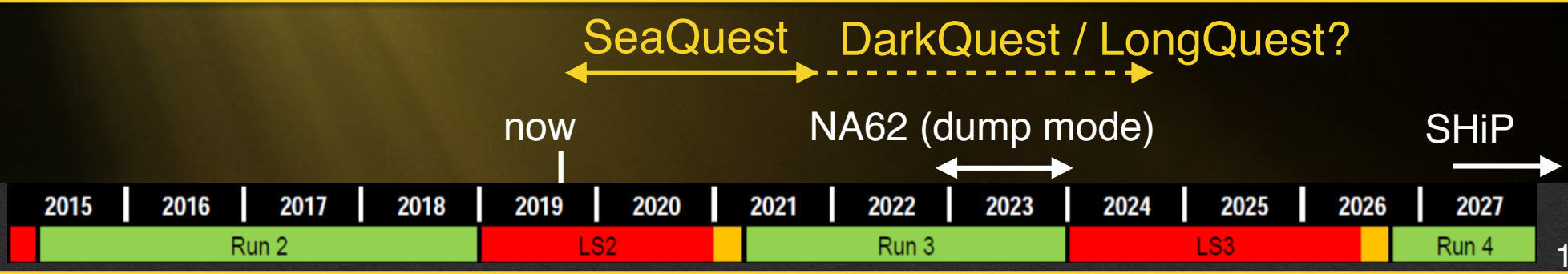
Add Far Detectors!

Conclusions & Outlook

The SeaQuest experiment and its upgrades,
the DarkQuest and LongQuest experiments,
can play a crucial role in the search for dark particles.

Unique features (compared to other beam dump fixed target experiments):
compact geometry; sensitivity to soft signatures

Interesting Dark Matter models can be broadly explored:
Inelastic DM and strongly-interacting DM
Many signatures can be looked for



Many new signatures to explore

Signature	Model
e^+e^-	dark photon dark Higgs leptophilic scalar*
$e^+e^-e^+e^-$	Higgsed dark photon
$e^\pm\pi^\mp, e^\pm K^\mp, \cdots$	sterile neutrino
$e^+e^- + \text{MET}$	inelastic dark matter strongly interacting dark matter hidden valleys
$\pi^+\pi^-, K^+K^-, \cdots$	dark Higgs*
$\gamma\gamma$	axion-like particle*

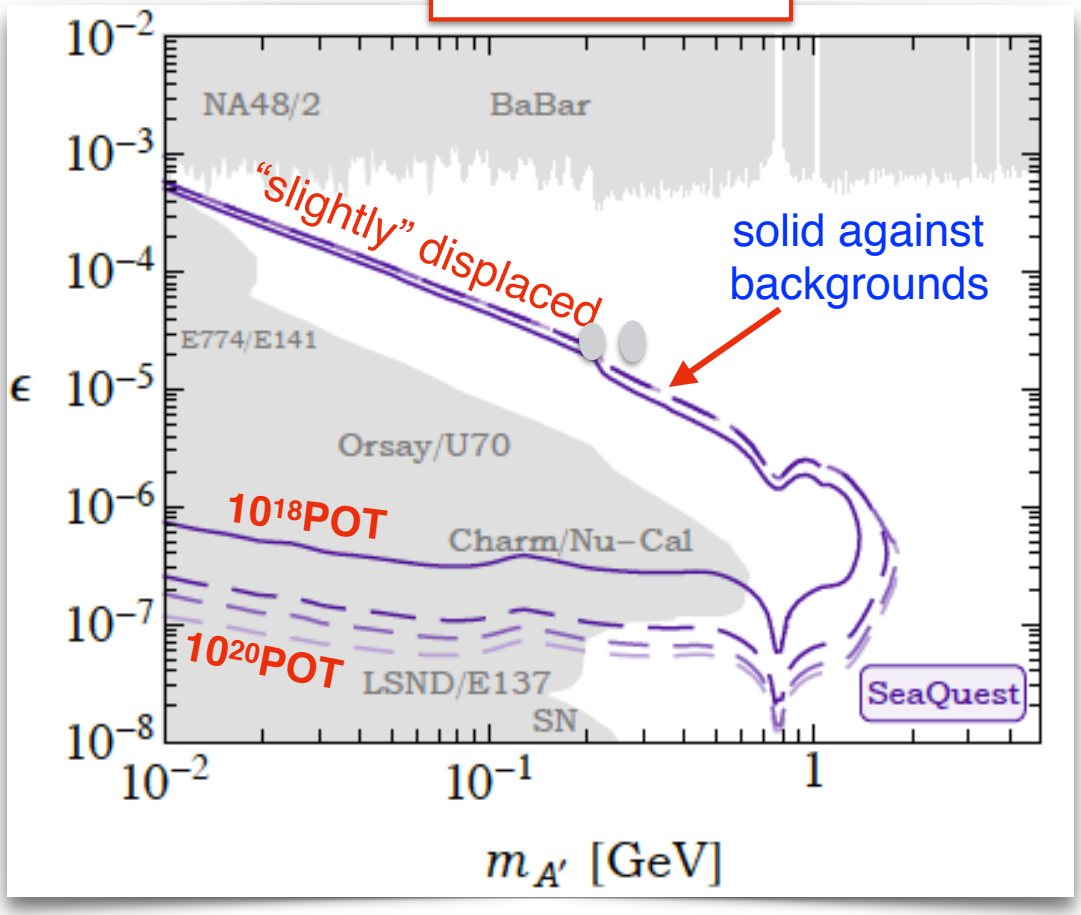
From the DOE proposal
"Search for Dark Sectors with the DarkQuest Experiment at Fermilab"

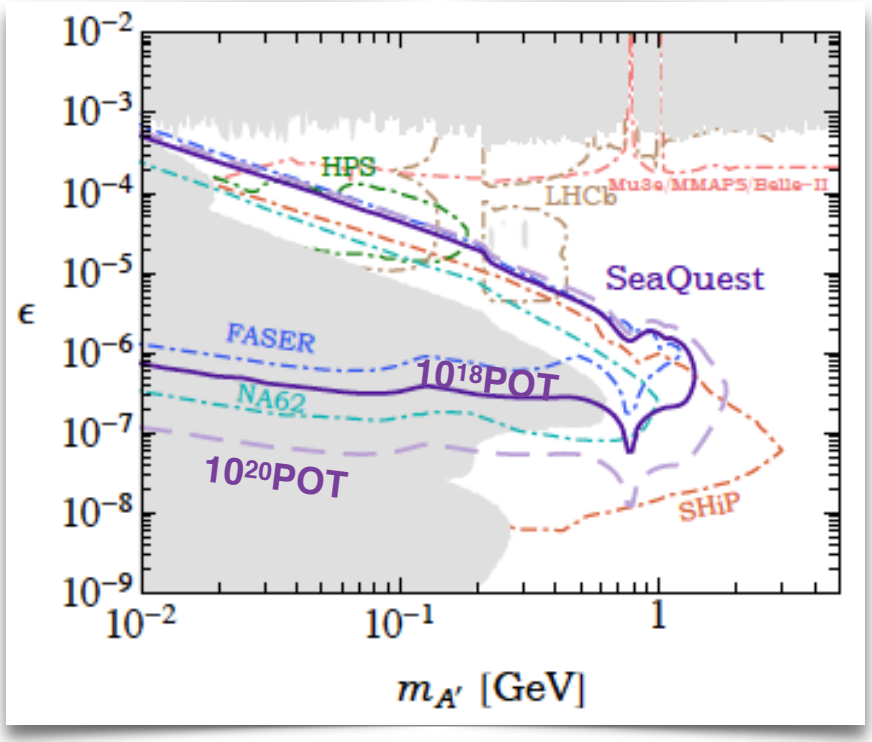
1. The reach for the minimal A' model

(Reach for EMCal upgrade)

$\epsilon Z^{\mu\nu} A'_{\mu\nu}$

$A' \to e^+ e^-$





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1 2 3

FASER: Feng et al., 1708.09389

NA62: Lanfranchi @ CERN-EPFL-Korean theory institute

~2023

SHiP: Alekhin et al., 1504.04855

~2027