Searching for dark particles at the SeaQuest experiment

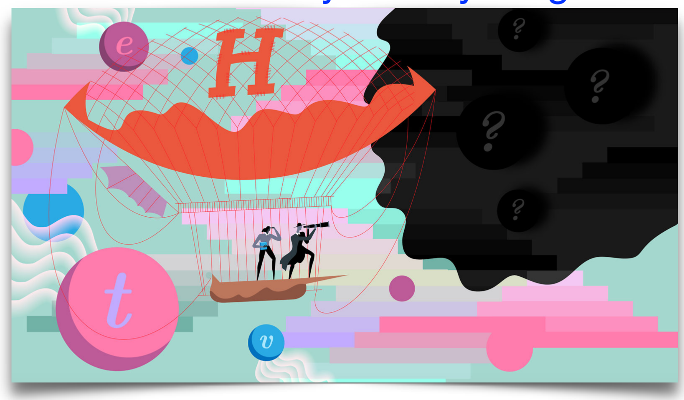
Stefania Gori
UC Santa Cruz

Bay area particle theory seminar (BAPTS)

San Francisco State University
October 12, 2018

Outline

from symmetry magazine



1. Introduction

- Why dark sectors?

2. Fixed target experiments

- The CERN effort (now & future)
- Uniqueness of the SeaQuest experiment at Fermilab

SeaQuest E906

3. Prospects for testing dark sectors at SeaQuest

- Minimal dark photon models
- Inelastic Dark Matter
- Beyond dark photon models

Impact of the SeaQuest **EMCal upgrade** in the search for dark sectors

Dark Matter (DM) is there!

What do we know about it? Not much

Dark Matter (DM) is there!

What do we know about it? Not much

1. It gravitates

1933 Fritz Zwicky

Coma cluster (of galaxies)

1970, Vera Rubin

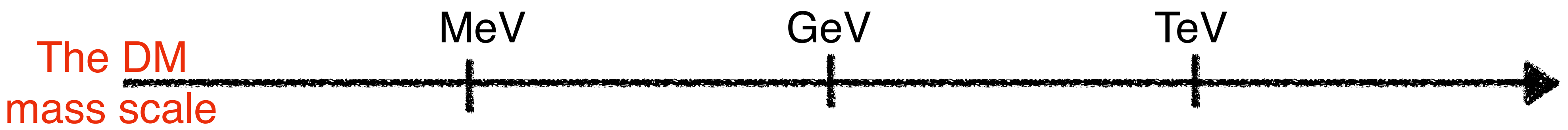
Andromeda Galaxy

2. It is dark (i.e. it does not interact with photons)

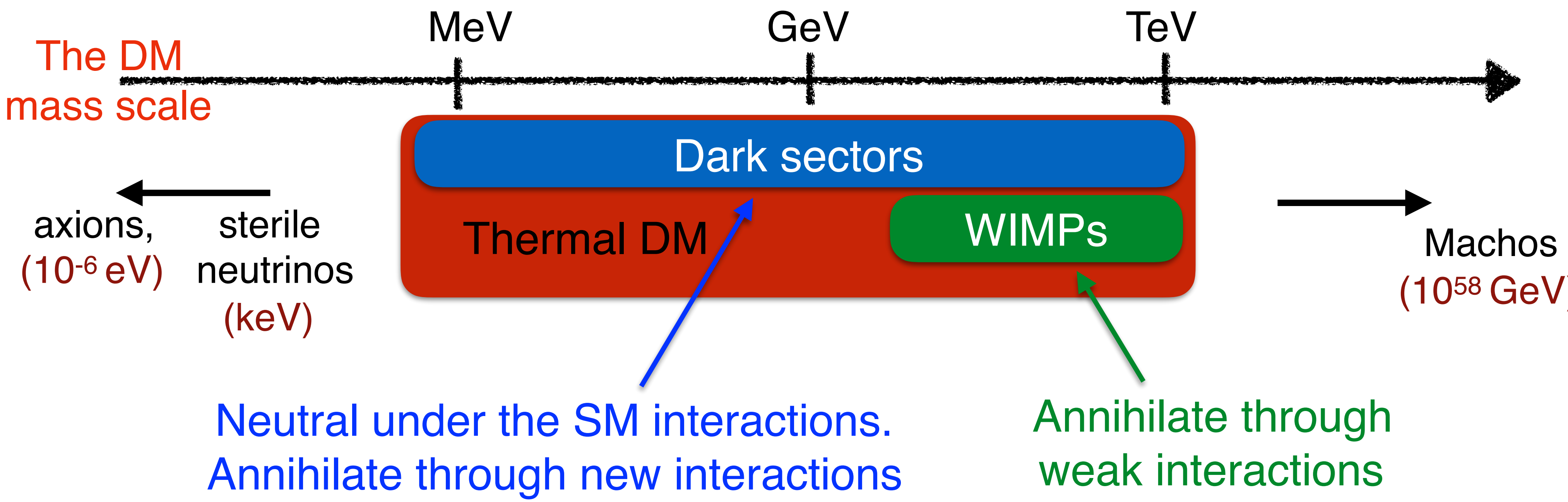
3. It is stable on cosmological scales

Fun fact: There is lots of DM in the Universe, but for DM particles weighing several hundred times the mass of the proton, there should be about one DM particle per coffee-cup-sized volume of space.

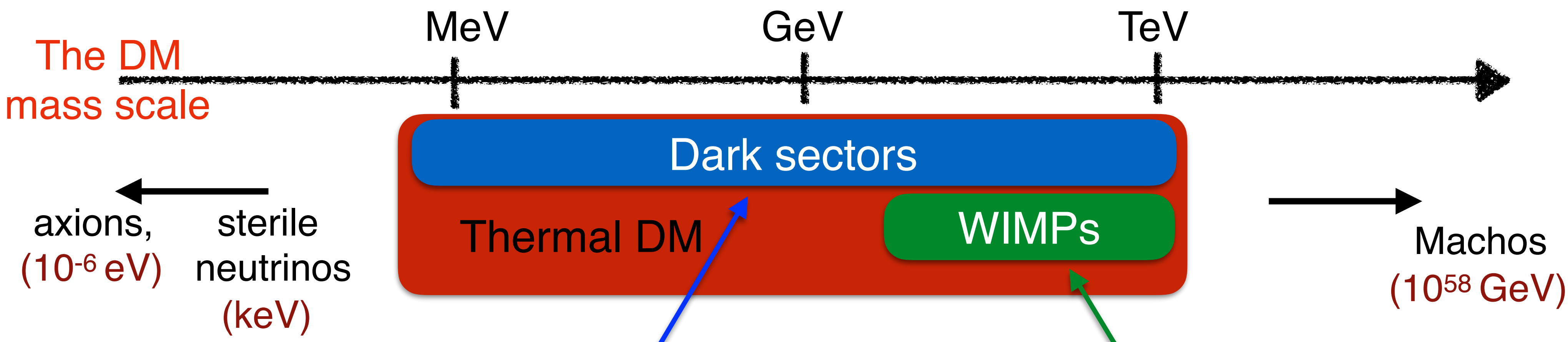
Thermal dark matter



Thermal dark matter

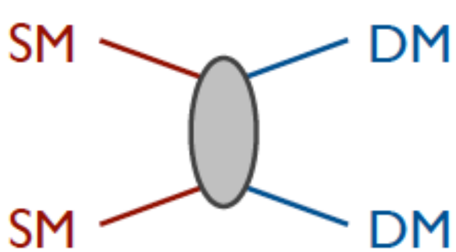


Thermal dark matter



Neutral under the SM interactions.
Annihilate through new interactions

Annihilate through
weak interactions

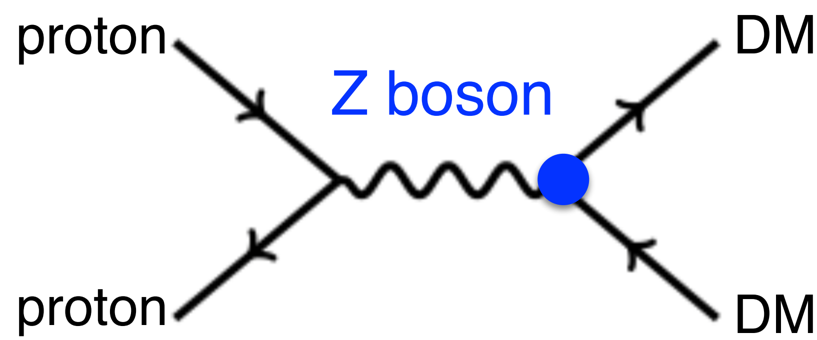


This coupling cannot be too small
for DM to be in thermal equilibrium
with the SM in the early universe

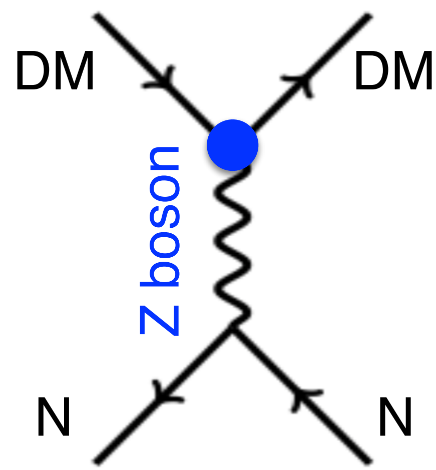
Detectability?

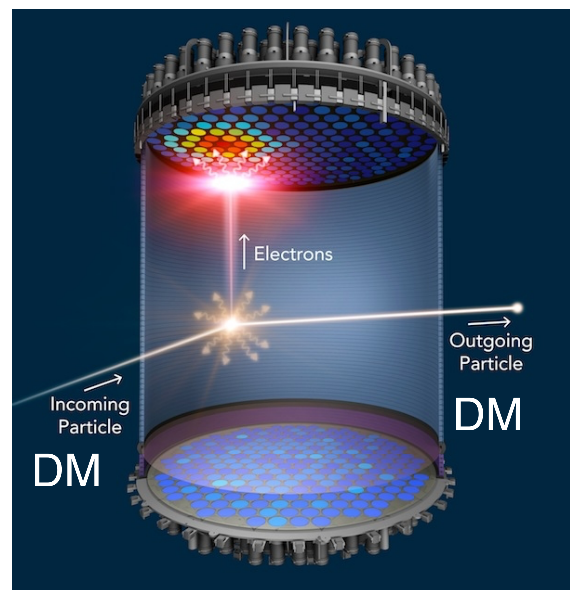
We have learned a lot about WIMPs!

- The LHC is a "WIMP factory":



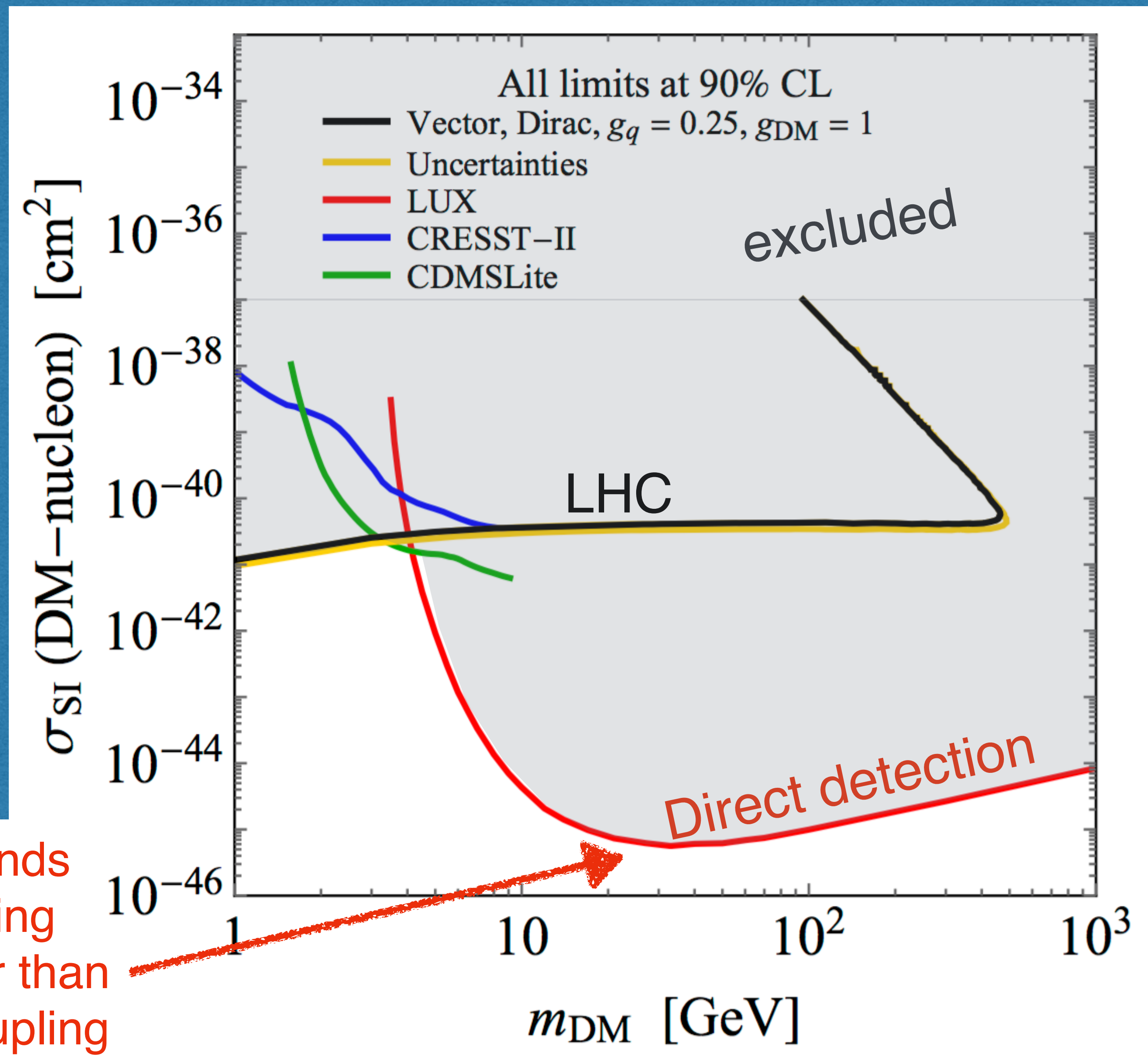
- Additionally,
  direct detection experiments can measure WIMP-nucleus (N) scattering





We have learned a lot about WIMPs!

- The
- Ad dire WIM

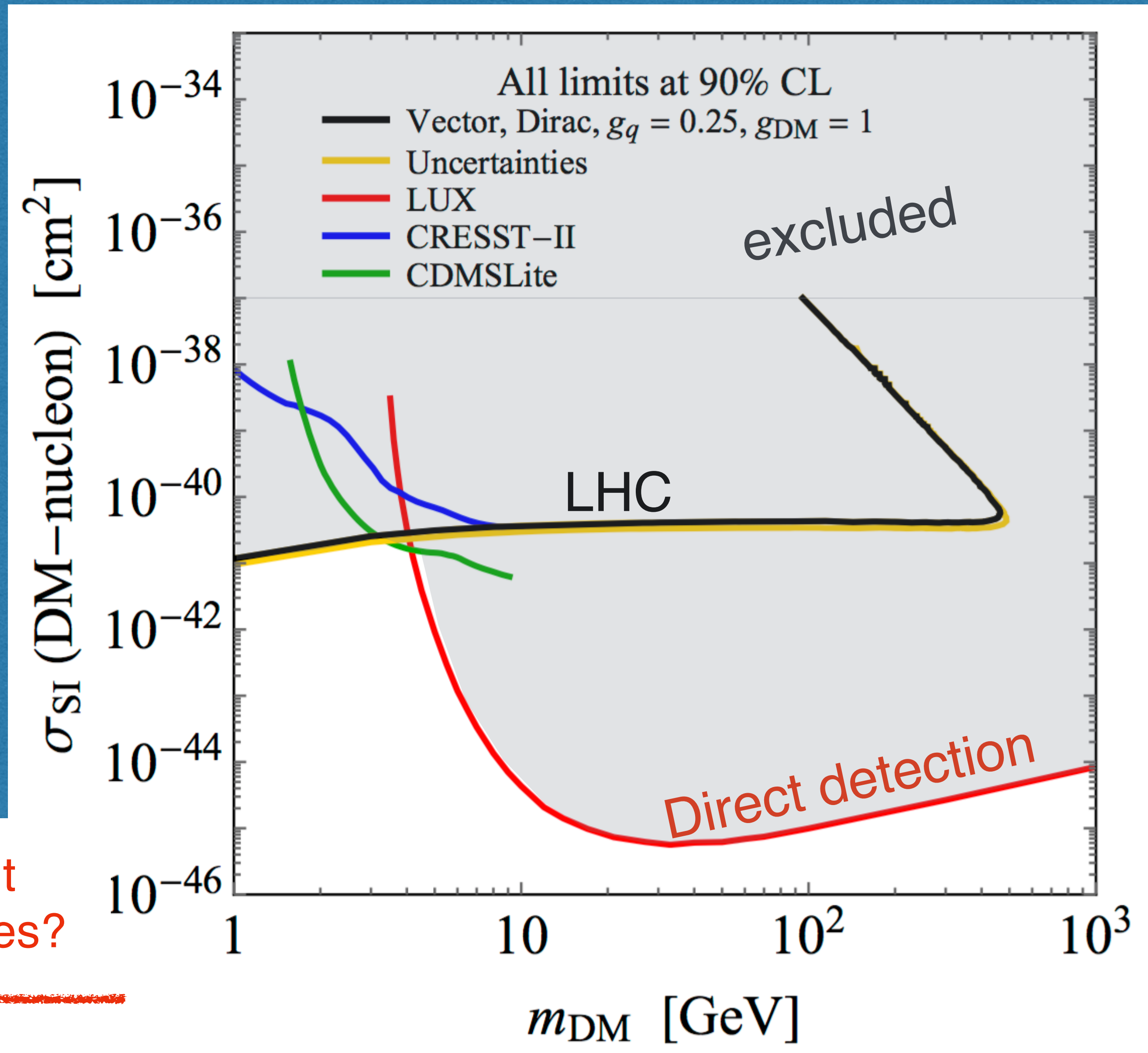


it corresponds to a coupling **~10^{-3}** weaker than the weak coupling

We have learned a lot about WIMPs!

❋ The

❋ Ad
dire
WIM

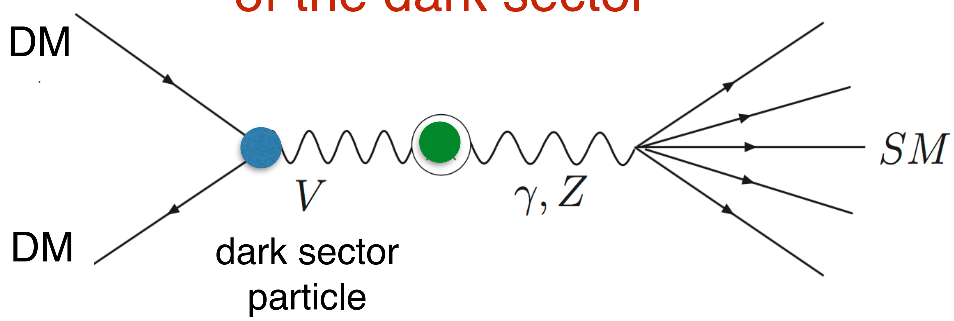


what about lighter masses?

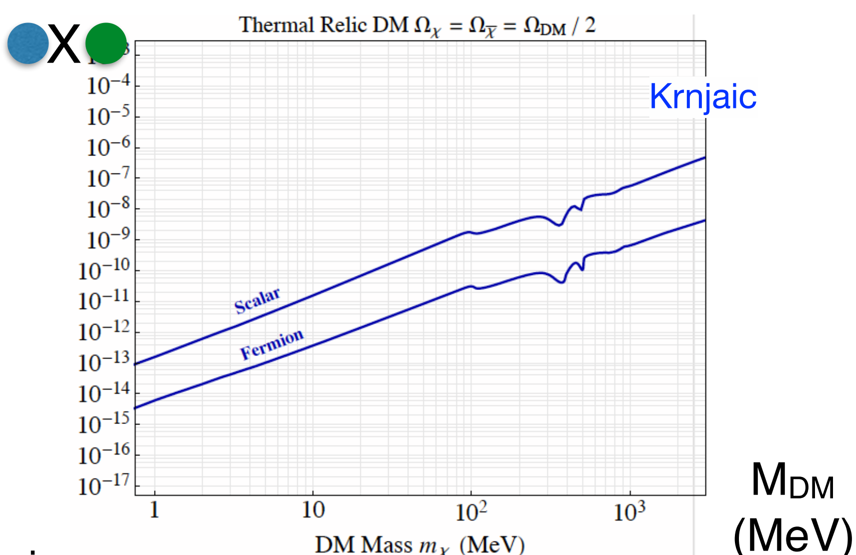
"Thermal goals" for dark sector models

Two general classes of thermal DM:

DM is the lightest state of the dark sector



Relic abundance regulated by ●, ●



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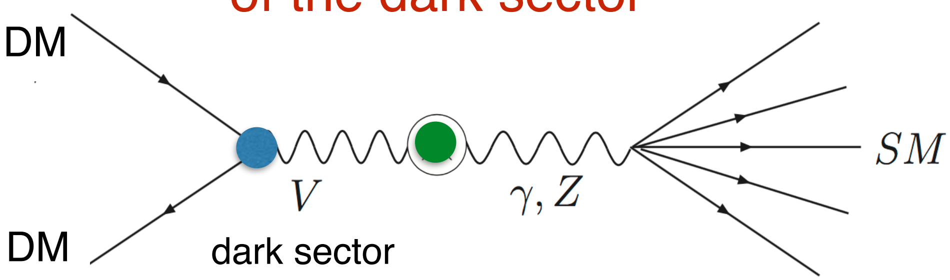

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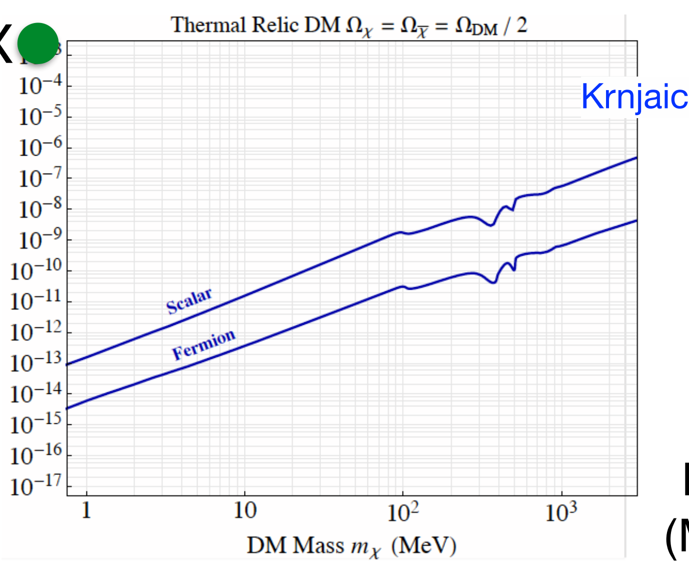
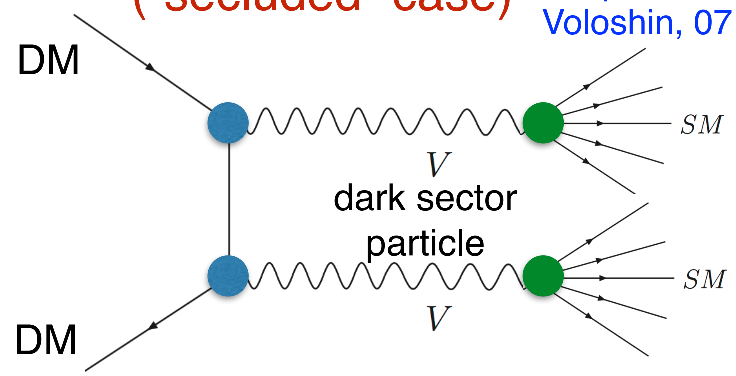
●X●



M_{DM} (MeV)

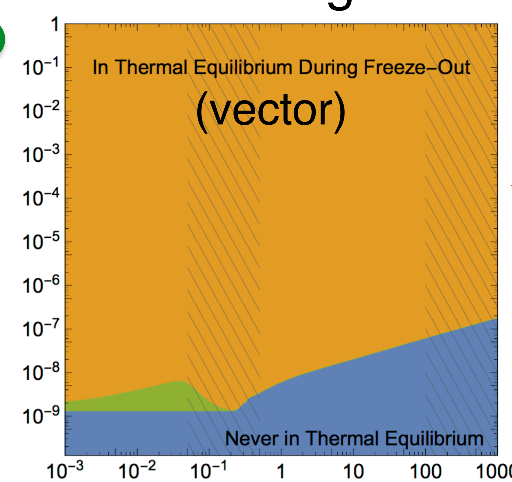
One (or more) particles of the dark sector are lighter than DM

(“secluded” case) Pospelov, Ritz, Voloshin, 0711.4866



Thermalization regulated by ●

●



Lower bound

Evans, SG, Shelton, 1712.03974

“Thermal goals” for dark sector models

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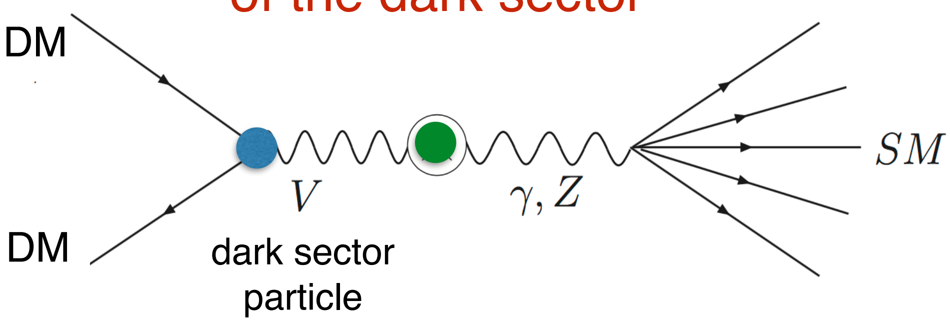
DM is the lightest state
of the dark sector

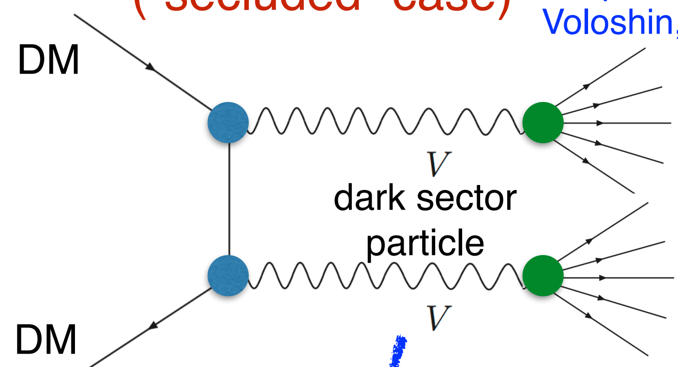


Signatures:

The dark sector particle mainly
decays invisible (to DM)

One (or more) particles of
the dark sector are lighter than DM
(“secluded” case)

Pospelov, Ritz,
Voloshin, 0711.4866



Signatures:

The dark sector particle
decays visible (to SM particles)

Dark sectors in a nutshell

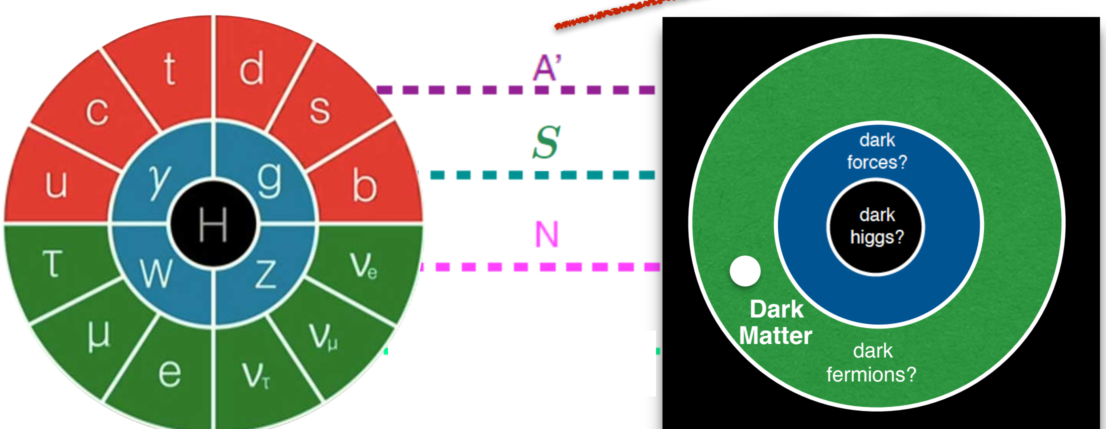
Further motivations?

Several anomalies in data can be addressed by dark sectors (eg. $(g\text{-}2)_\mu$, B-physics anomalies, Dark Matter anomalies, …)

What theories?

DM theories, Supersymmetric theories (NMSSM), neutral naturalness theories, theories for baryogengesis, …

How to test this emerging paradigm?



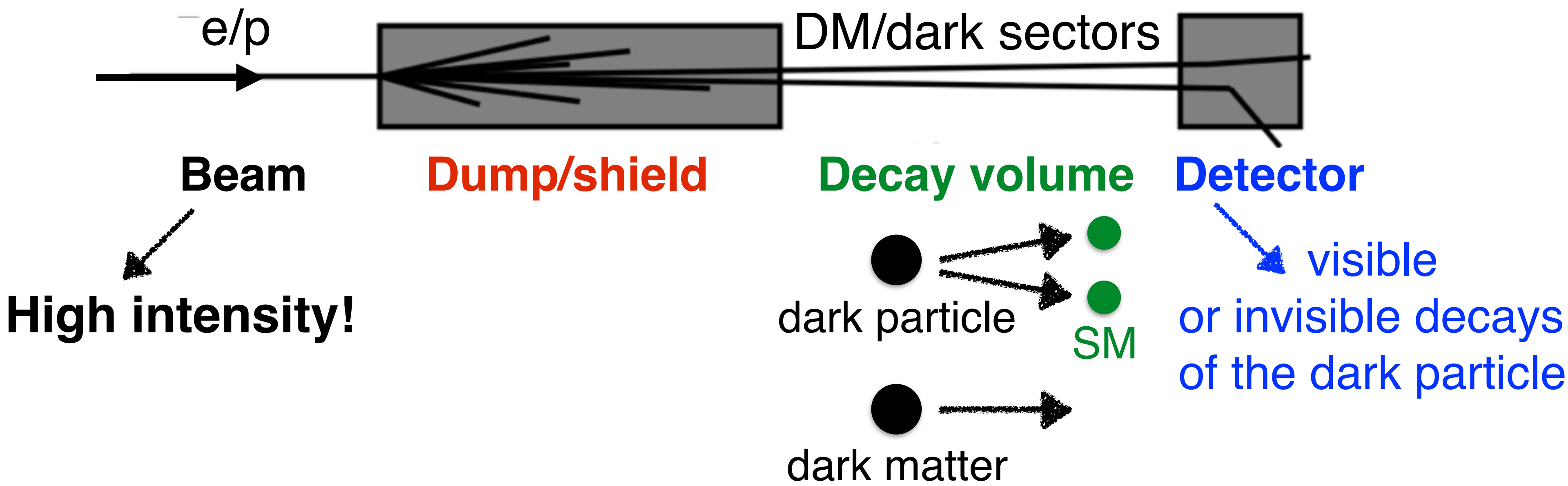
Not charged under the SM gauge symmetries

"Portals":

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H\rvert^2 \lvert S\rvert^2$
Neutrino	$y H L N$

generically small parameters

e/p fixed target experiments



<u>Proton vs. electron fixed target experiments:</u>

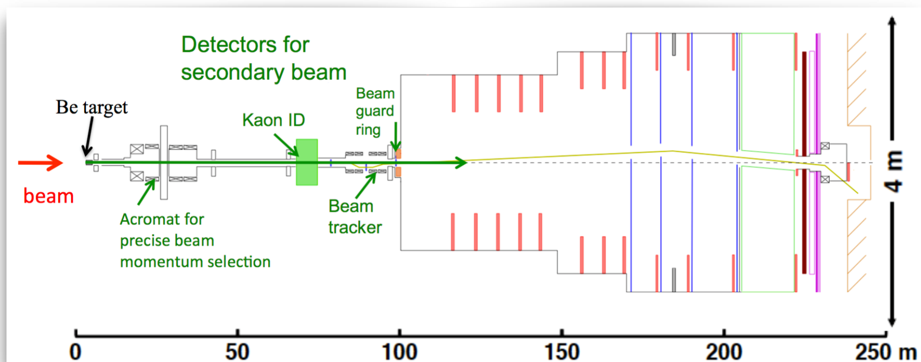
Protons: typically higher energies (➡ reach towards larger dark sector masses)
but larger backgrounds (needs more shielding)

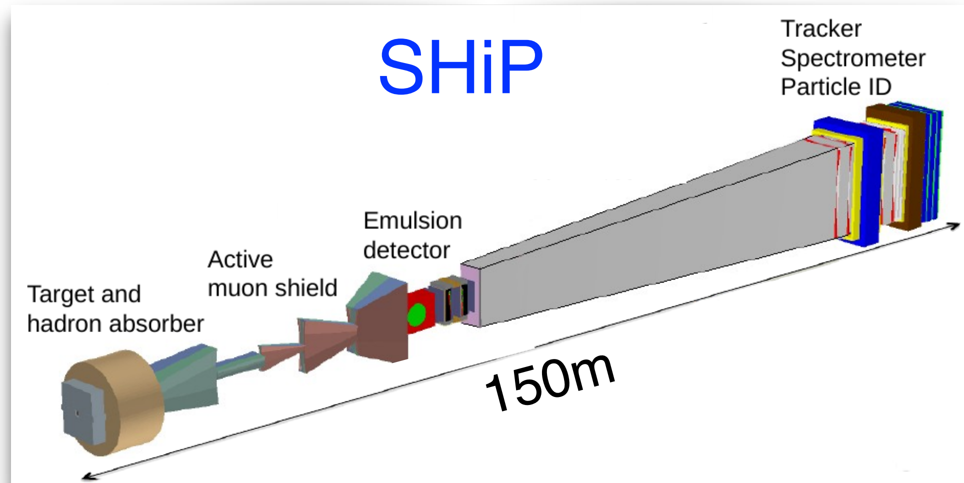
Proton fixed target experiments

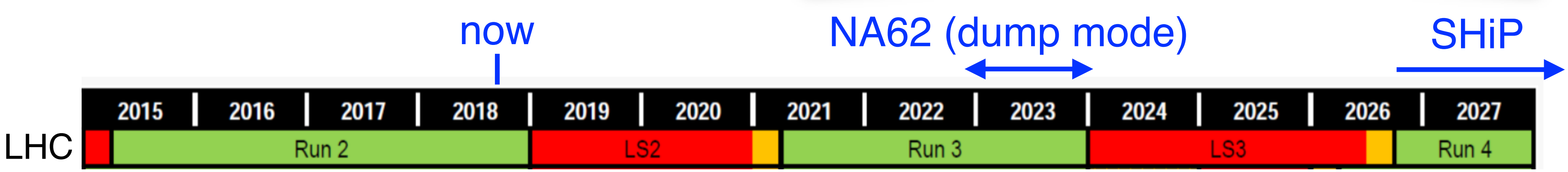
Past experiments: Charm, LSND, …

Present/future experiments: large effort at **CERN** (400 GeV proton beam):

NA62







Other proposed experiments at CERN: Codex-b, FASER, …

Proton fixed target experiments

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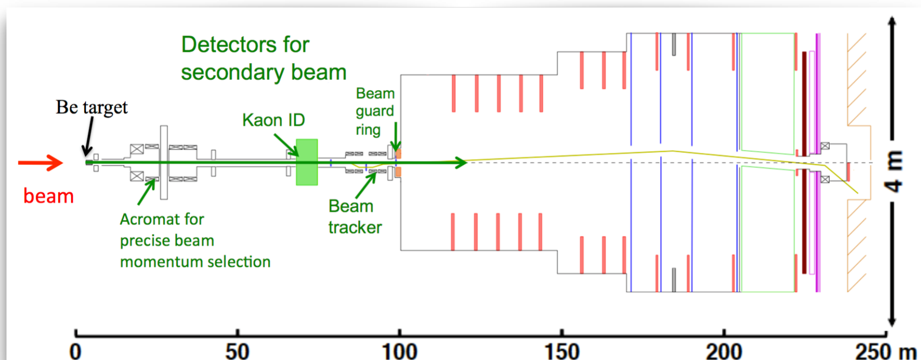
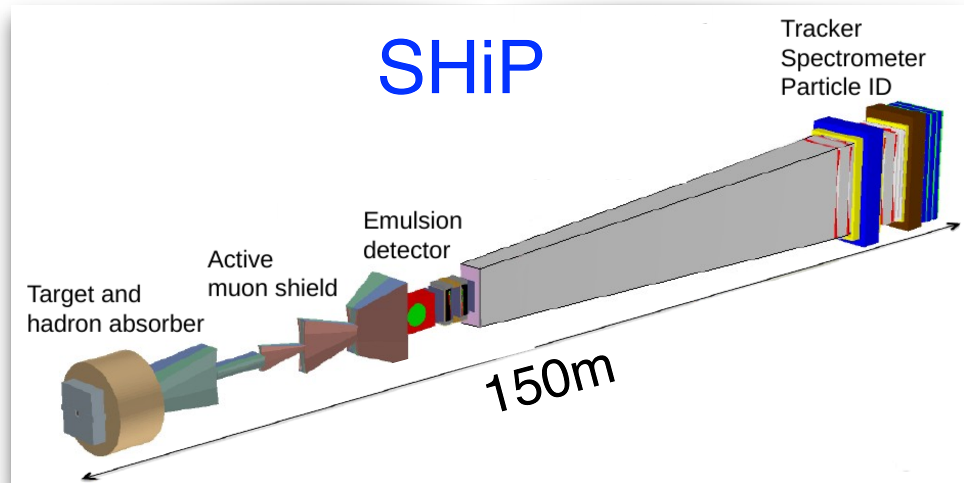
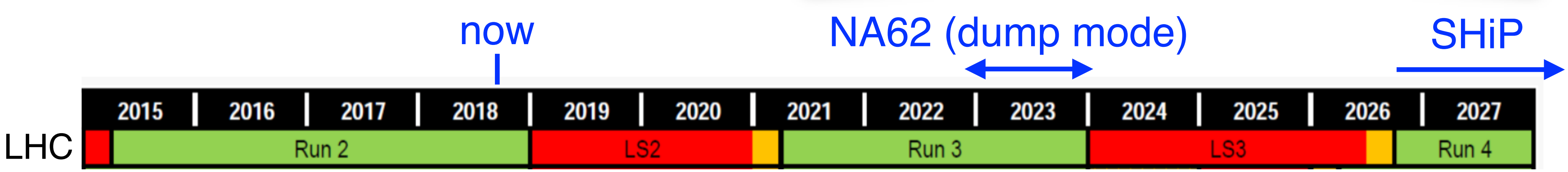


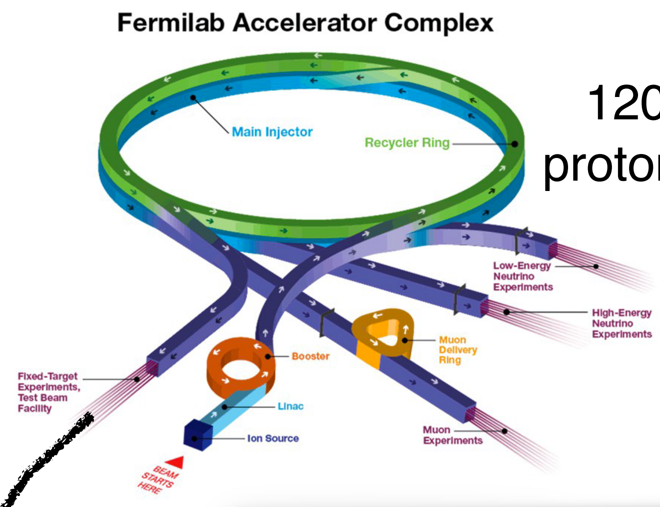




Other proposed experiments at CERN: Codex-b, FASER, …

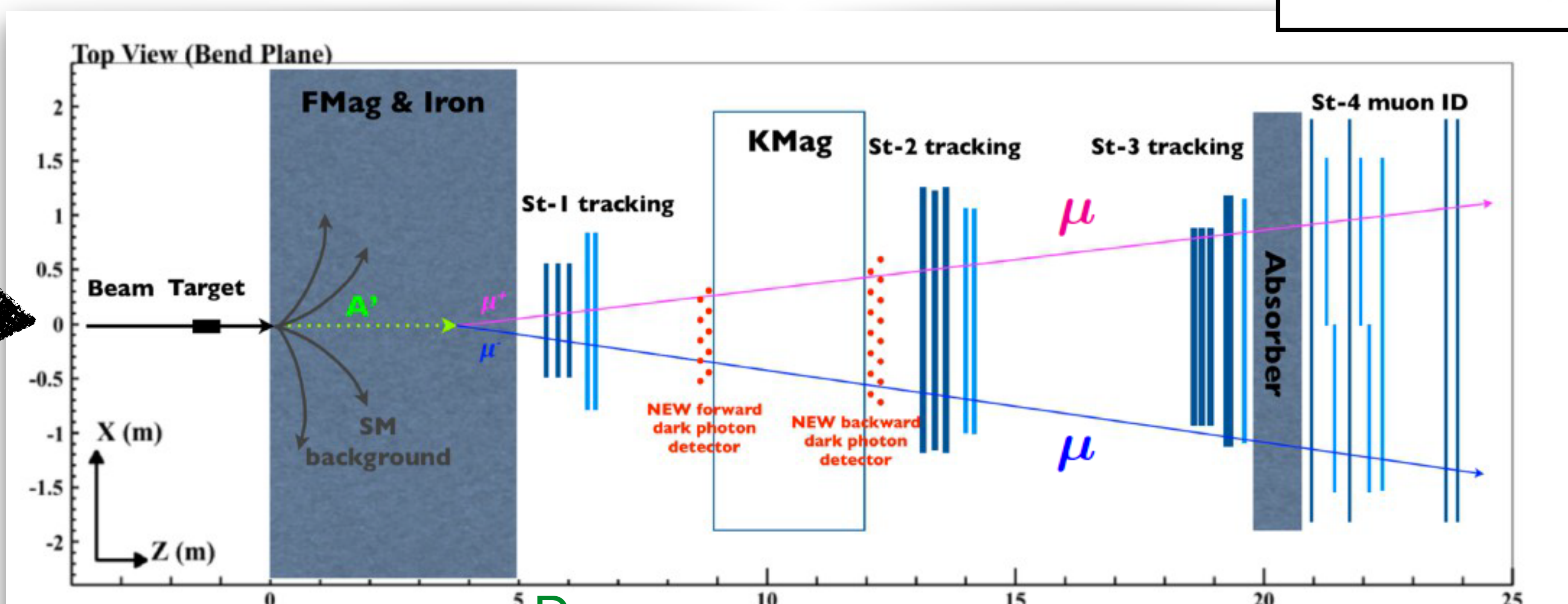
Fermilab has a high intensity/high energy proton beam!

The SeaQuest experiment



120 GeV
proton beam

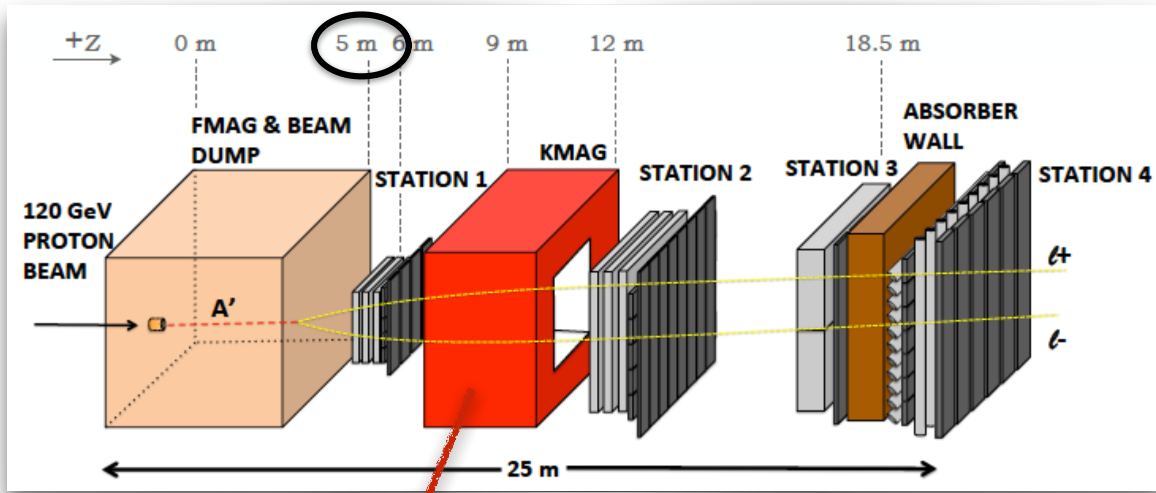
5% main
injector
beam



Dump

Decay
volume

SeaQuest in a nutshell



1. Compact geometry

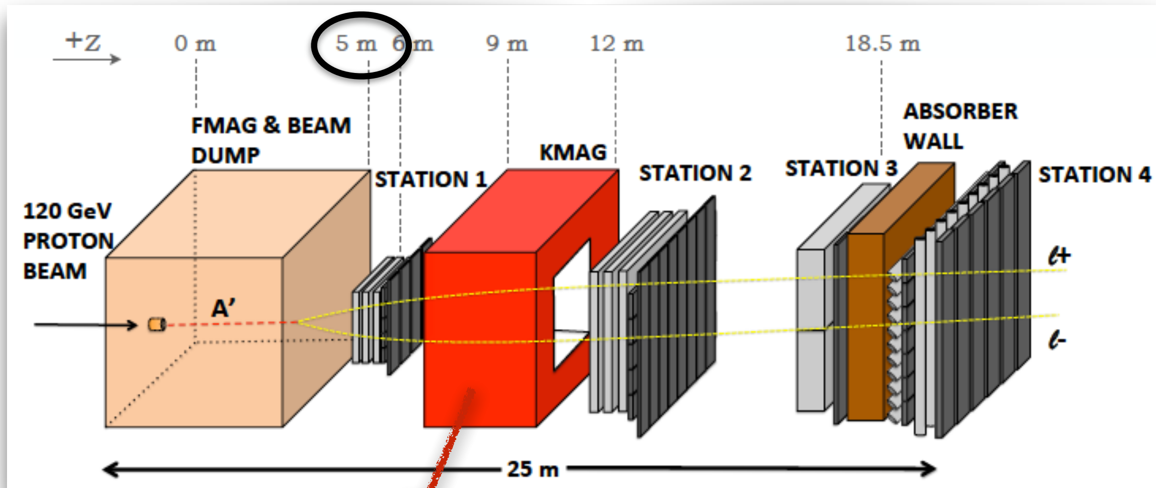
Sensitivity to (slightly) displaced dark particles with **d > 5m**

2. KMAG separating even very forward muons

$(\Delta p_T \sim 0.4\ \text{GeV})$

Identification of very light dark particles/squeezed spectra

SeaQuest in a nutshell



1. Compact geometry

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

2. KMAG separating even very forward muons

($\Delta p_T \sim 0.4$ 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
LSND	800MeV	10^{22}	30 m	10 m
NA62	400 GeV	10^{18}	100 m	250 m
SHiP	400 GeV	10^{20}	65 m	125 m

Past

Future

Status and prospects

Nuclear physics program:
Probe sea quarks in the proton

- E906, unpolarized targets (2012–2017)

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: 8×10^{15} POT

Status and prospects

Nuclear physics program:
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- E1039, polarized targets (2019–2021)

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Plan for 10^{18} POT
with & without displaced trigger **1.**

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

Muon vs. electron signatures

Future: installation of an EM-Cal?

What is the physics case?
Good identification of electrons vs. pions

Access to:
- lighter dark sectors ($A' \to e^+ e^-$)
- squeezed dark sectors ($X_2 \to X_1 e^+ e^-$)
- dark sectors decaying hadronically ($S \to \pi^+ \pi^-$)

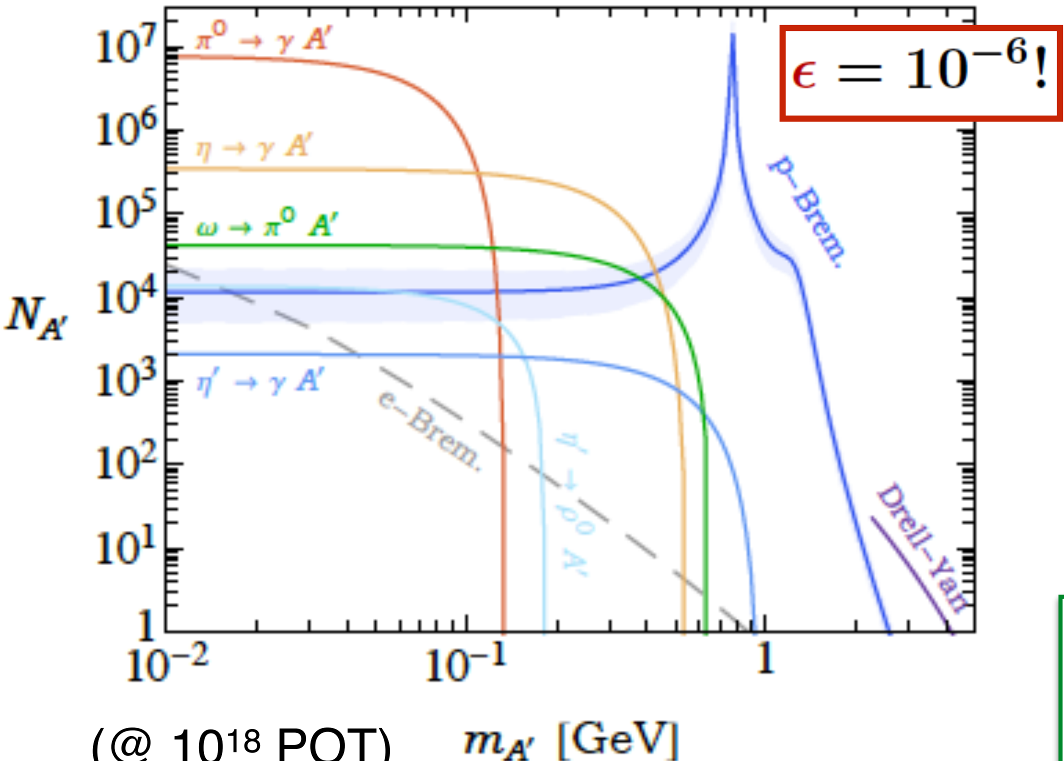
Electron signatures also have smaller backgrounds
(muons are very penetrating particles)

What is the comparison of the physics reach? …

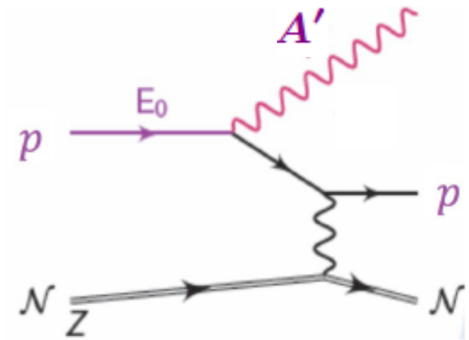
A huge dark photon production

$\boxed{\epsilon B^{\mu\nu} A'_{\mu\nu}}$

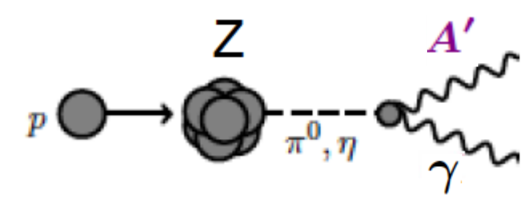
Berlin, SG, Schuster, Toro, 1804.00661



(@ 10^{18} POT)
approved lumi



brems-
strahlung



meson
decay

Generically larger rates than at electron fixed target experiments

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

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

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

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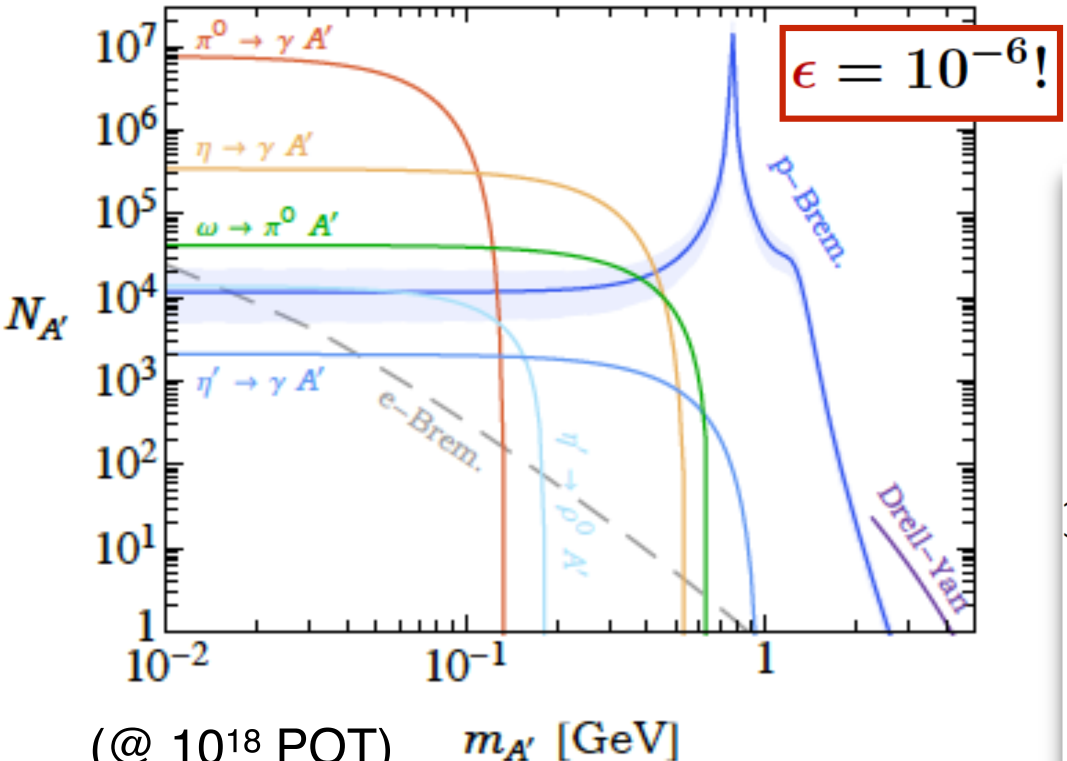

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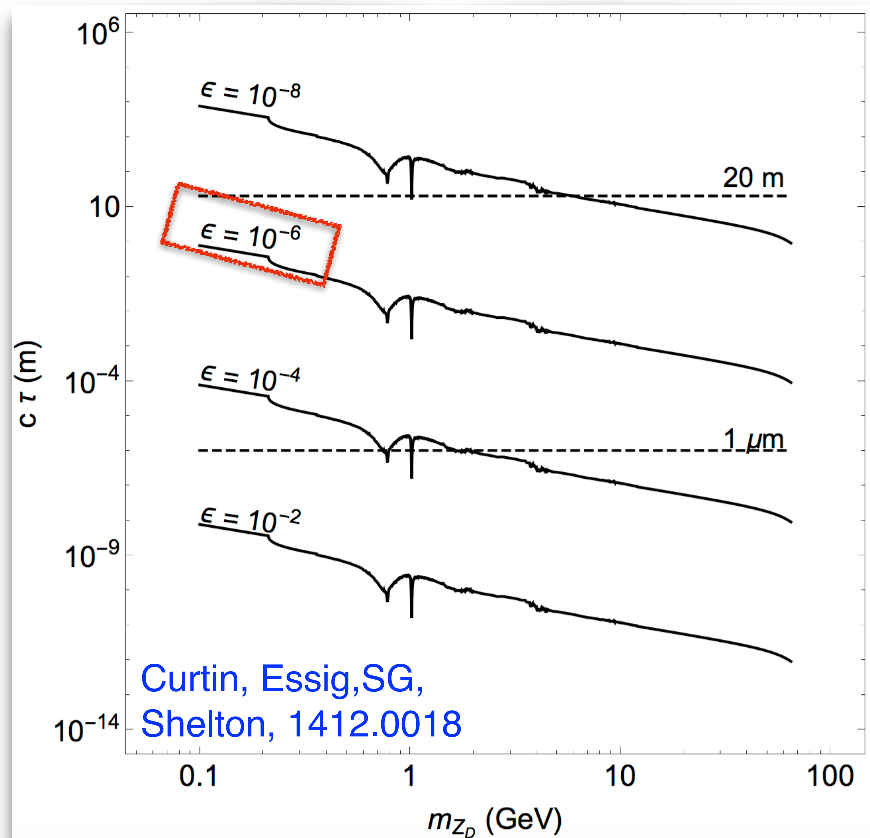


Curtin, Essig,SG,
Shelton, 1412.0018

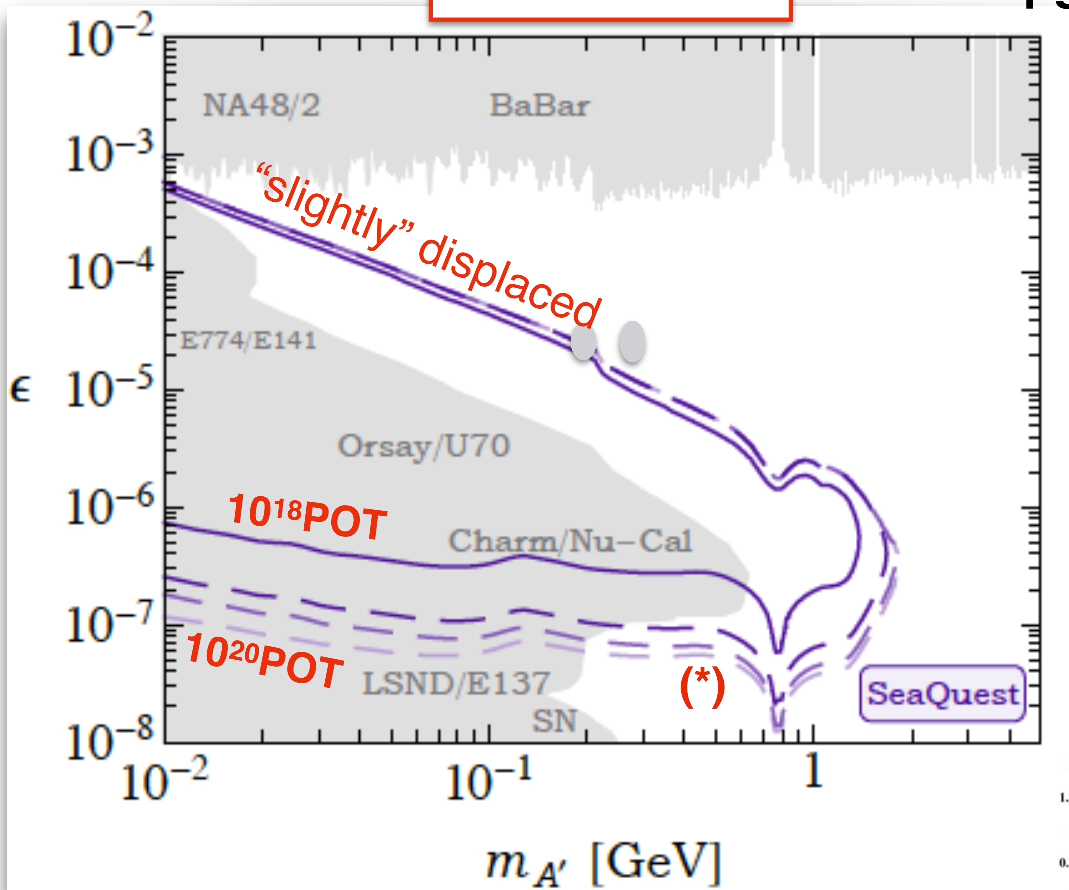
The reach for the minimal A' model

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

$\boxed{A' \to e^+ e^-}$

Reach for EMCal upgrade 2.

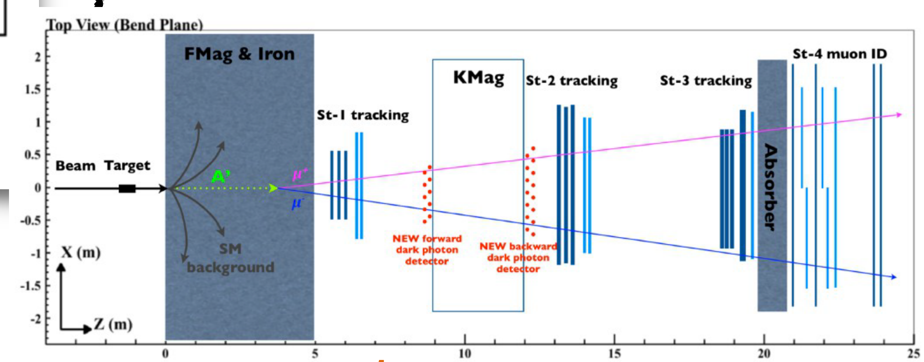
Berlin, SG, Schuster, Toro, 1804.00661



(*) decay regions: (5-6)m, (5-9)m, (5-12)m
1 2 3

Very large production & acceptance for dark photons at SeaQuest

The entire parameter space is motivated by thermal DM!
(our goal)



1.
2.
3.

The reach for the minimal A' model

Berlin, SG, Schuster, Toro, 1804.00661

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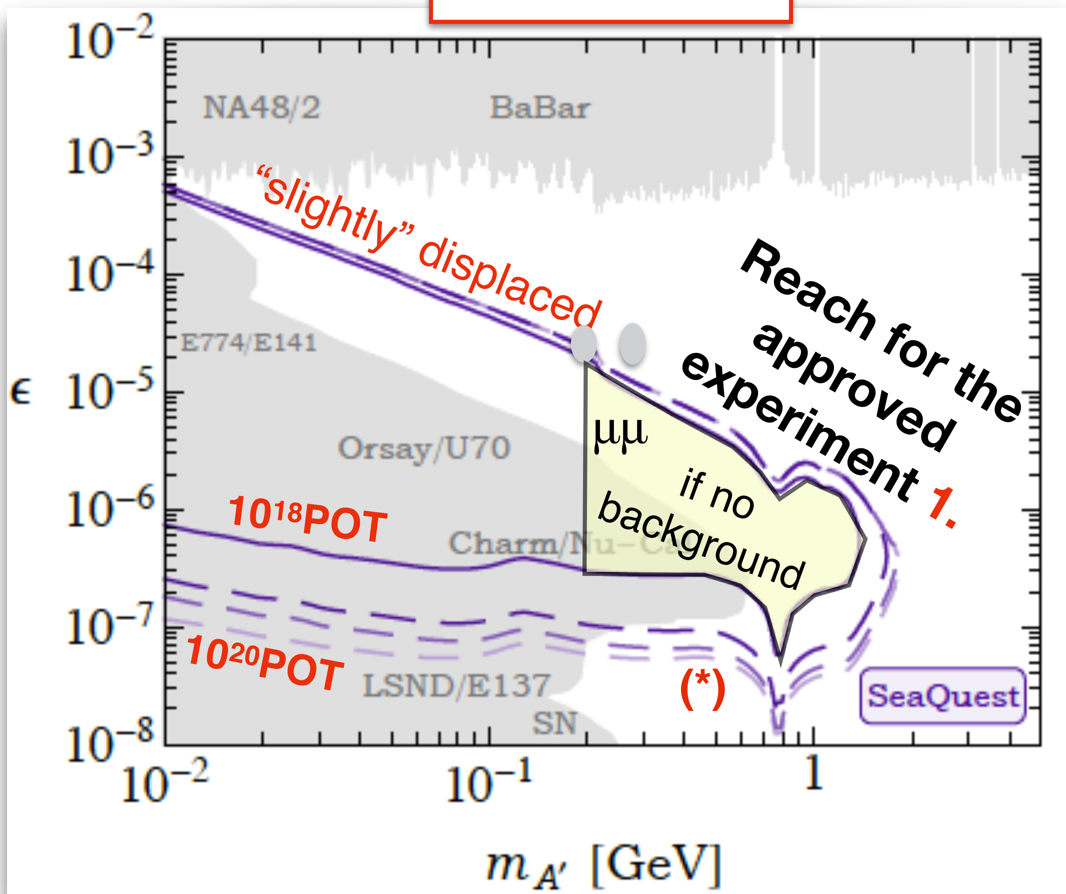

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1 2 3

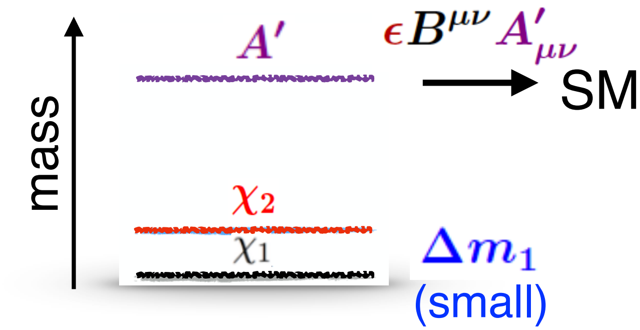
Backgrounds for muon signatures under investigation by the collaboration, using the ~10^{16} POT data set

This search can be done already now!

See Gardner, Holt, Tadepalli, 1509.00050 for the muon reach as well

Inelastic DM & displaced decays

Spectrum of Inelastic DM (IDM) models:
χ_1 (DM), χ_2 (DM excited state), A' (mediator)



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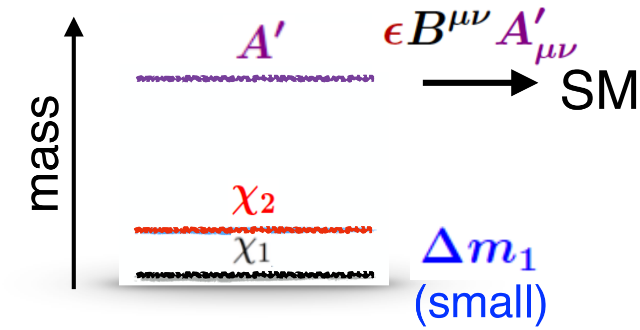
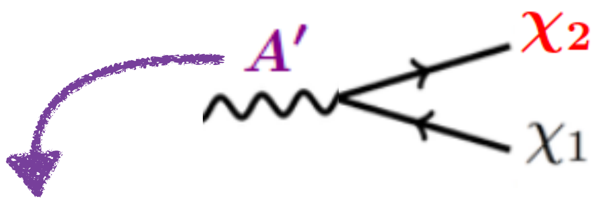
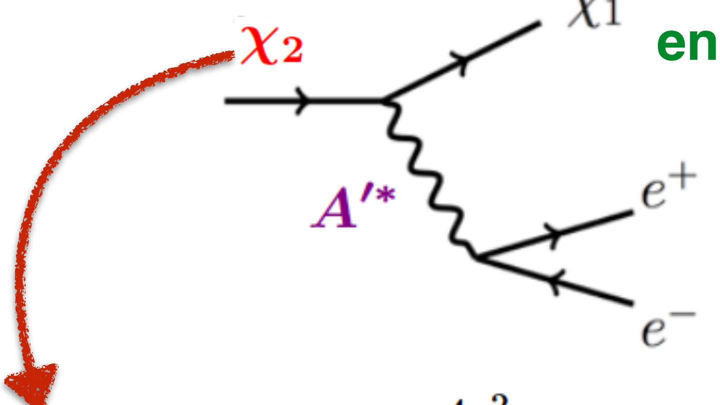




Copiously produced at fixed target experiments

with



Missing energy

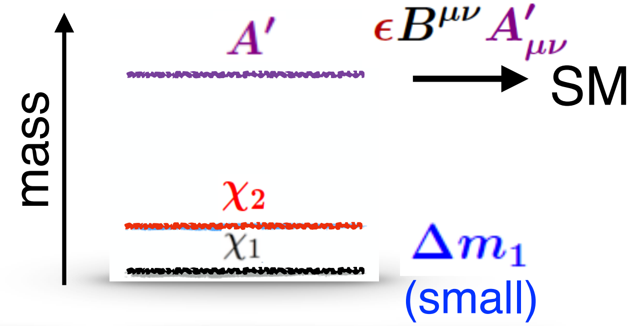
$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq \frac{4\epsilon^2\, \alpha_{\rm em}\, \alpha_D\, \Delta^5 m_1^5}{15\pi m_{A'}^4}$$

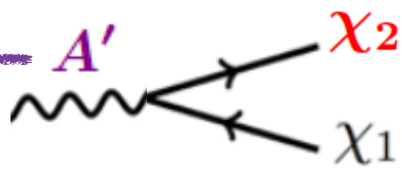
Non-resonant decays

Similar signatures for SIMP models
Berlin, Blinov, SG, Schuster, Toro, 1801.05805

Inelastic DM & displaced decays

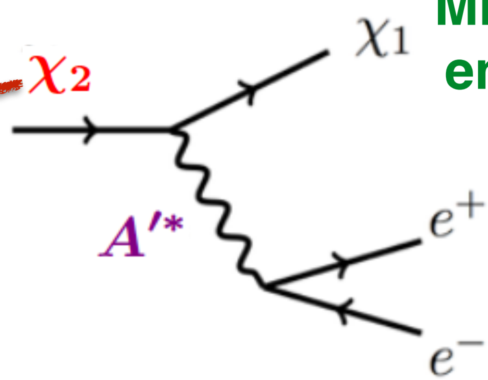
Spectrum of Inelastic DM (IDM) models:
χ_1 (DM), χ_2 (DM excited state), A' (mediator)





Copiously produced at fixed target experiments

with



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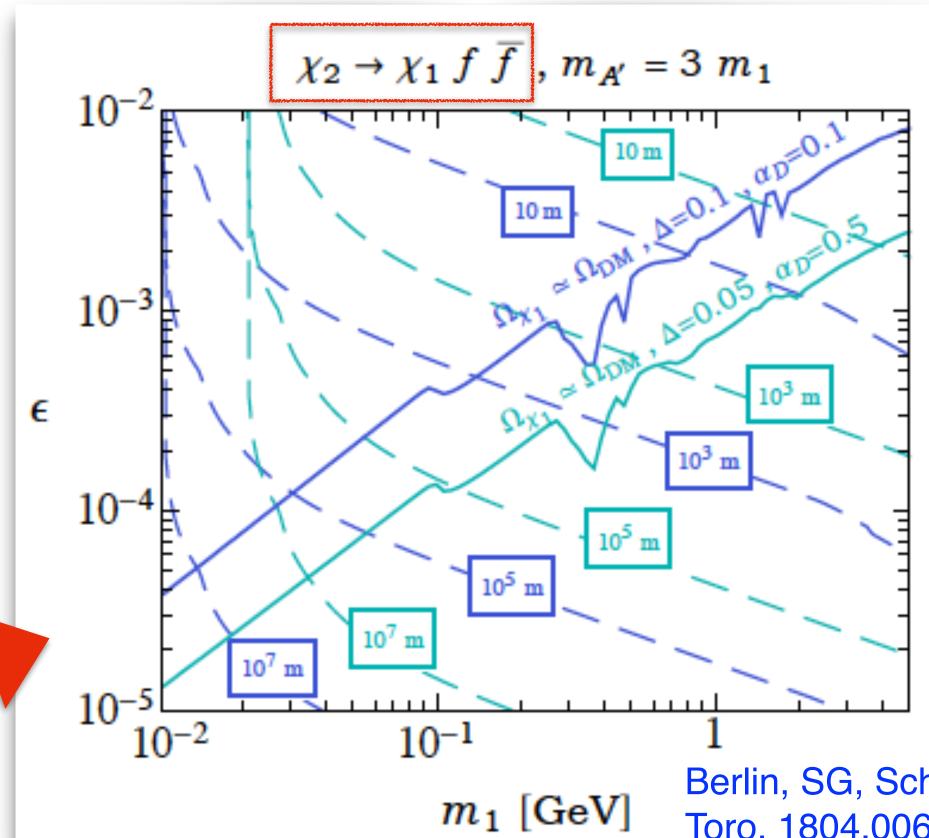
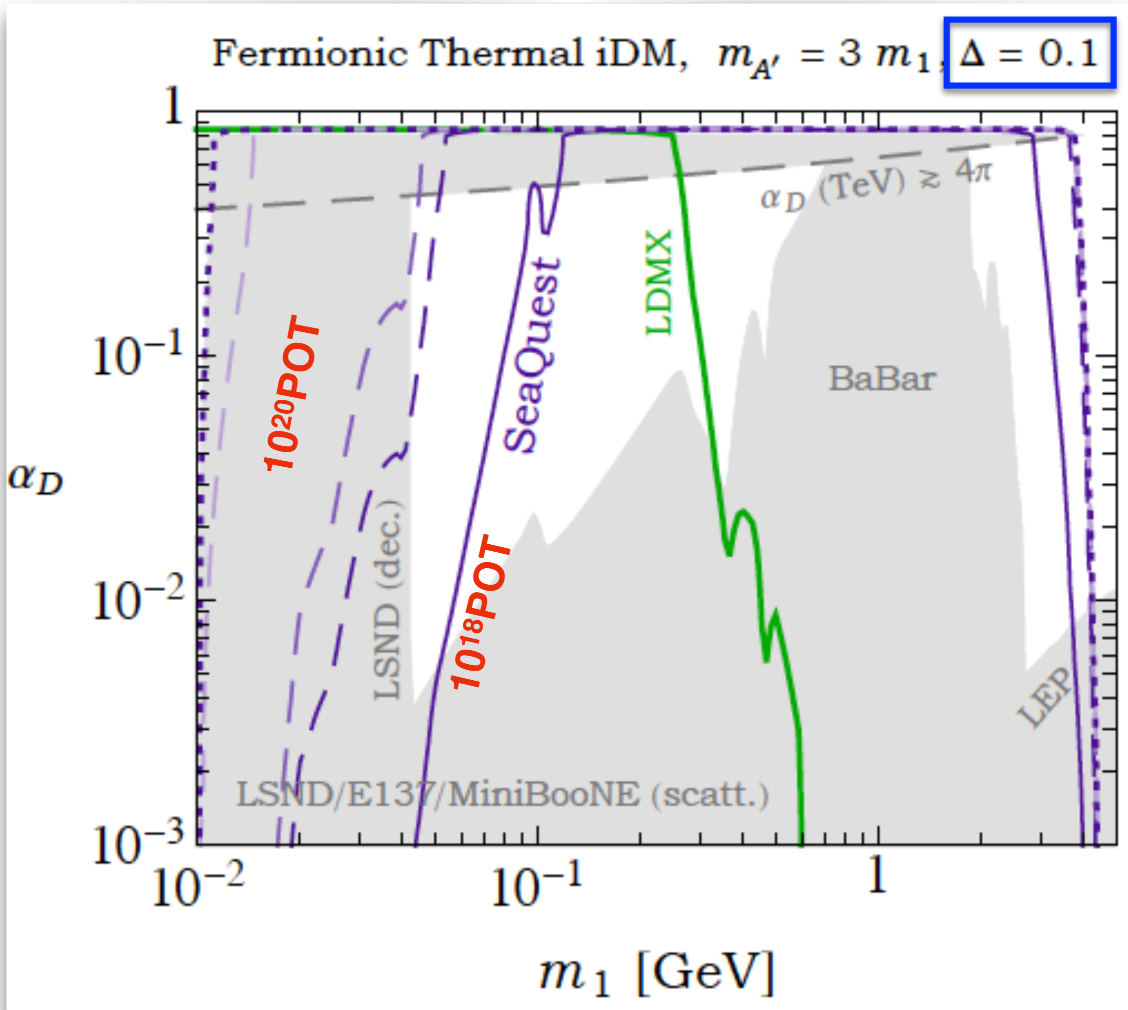


Berlin, SG, Schuster, Toro, 1804.00661

Displaced decays

The reach for IDM

Berlin, SG, Schuster, Toro, 1804.00661



10^{18} POT

10^{20} POT

(5-6)m
(5-9)m
(5-12)m

From darker to lighter

10^{20} POT

(5-6)m, no KMAG

Reach for EMCal upgrade 2.

see also Izaguirre, Krnjaic, Shuve, 1508.03050

SeaQuest has a good reach also to smaller mass splittings (up to Δ ~ a few %)

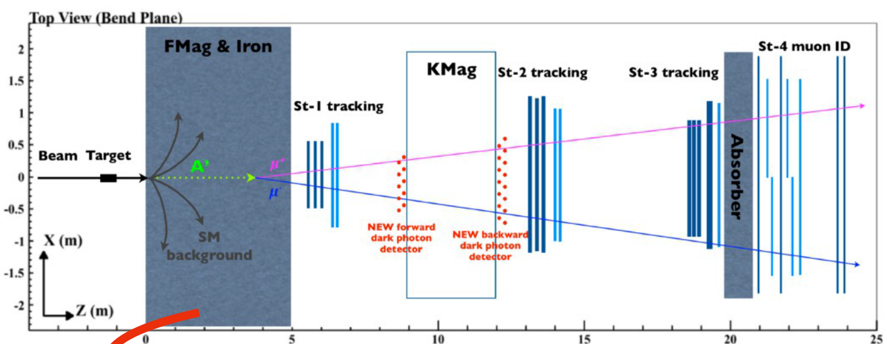
Beyond dark photon models…

Leptophilic scalars

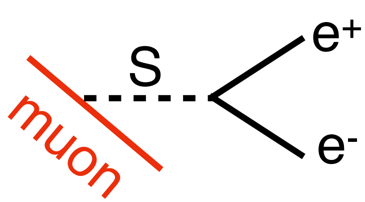
1.

$$-\mathcal{L} \supset \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{\Lambda} S\,\bar{\ell}\,\ell \;\Rightarrow\; -\mathcal{L} \supset g_\mu \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{m_\mu} S\,\bar{\ell}\ell$$

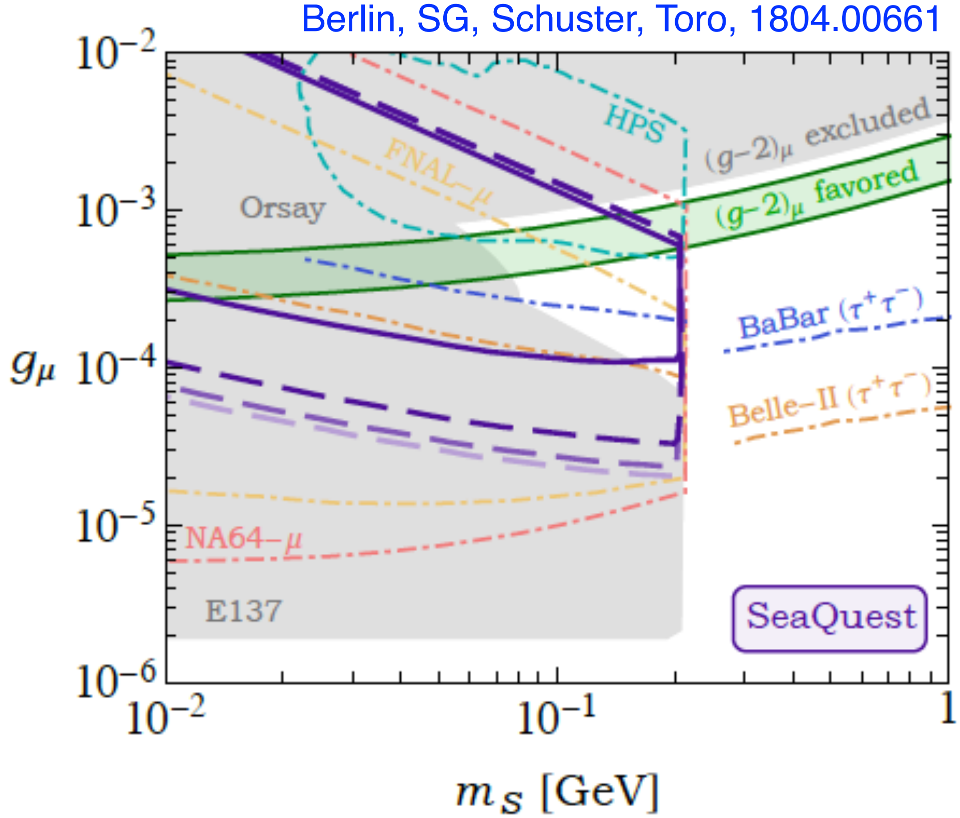
These scalars are **not copiously** produced from "standard" mechanisms **BUT**



huge production of (relatively energetic) muons



Berlin, SG, Schuster, Toro, 1804.00661

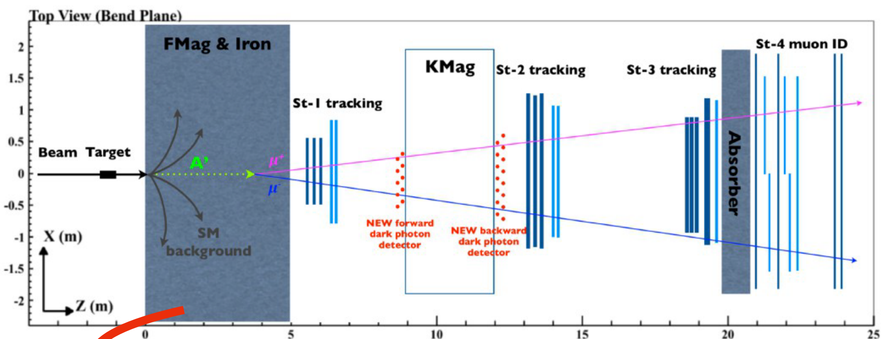


Beyond dark photon models…

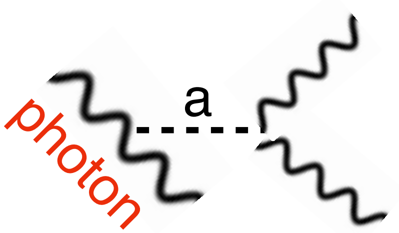
Axion-like particles

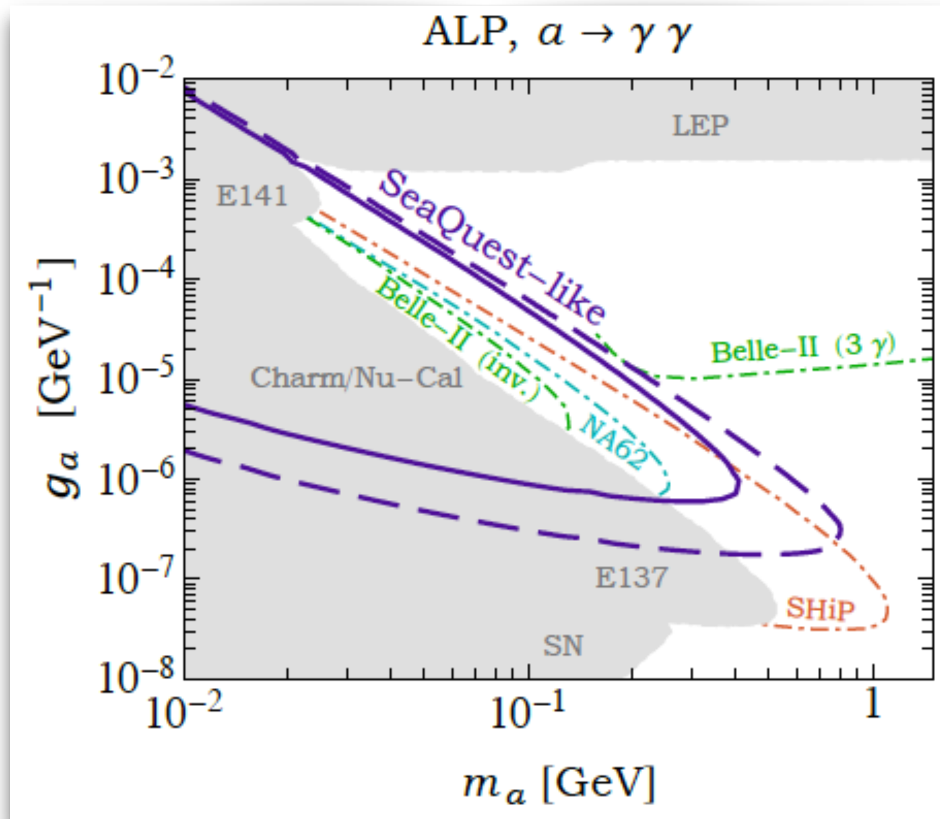
2.

$$\mathcal{L} \supset g_a \, a \, F_{\mu\nu} \, \tilde{F}^{\mu\nu} \quad \Rightarrow \quad \Gamma(a \to \gamma\gamma) = \frac{g_a^2 \, m_a^3}{4\pi}$$



huge production of (relatively energetic) photons





Backgrounds for photon signatures?

$K_L \to \gamma\gamma$ few more meters of iron?

Berlin, SG, Schuster, Toro, 1804.00661

Many new signatures to explore

A (very incomplete) list:

in progress
Altmannshofer, Batell, SG

Signature	Dark particle
$\pi^-\mu^+$	Heavy neutral lepton
$K^-\mu^+$	Heavy neutral lepton
$\mu^+\mu^- + \mathrm{MET}$	Inelastic Dark Matter
$e^+e^- + \mathrm{MET}$	Inelastic Dark Matter
$\mu^+\mu^-$	Dark photon & dark scalar
e^+e^-	Dark photon & dark scalar
$\gamma\gamma$	Axion like particle
K^+K^-, $\pi^+\pi^-$	Dark scalar
$\gamma\gamma + \mathrm{MET}$	Hidden neutral SUSY
$\mu^+\mu^-\mu^+\mu^-$	Dark scalar/dark photon model
$\mu^+\mu^-e^+e^-$	Dark scalar/dark photon model
$e^+e^-e^+e^-$	Dark scalar/dark photon model

New ideas?

Only with EMCal upgrade

This talk

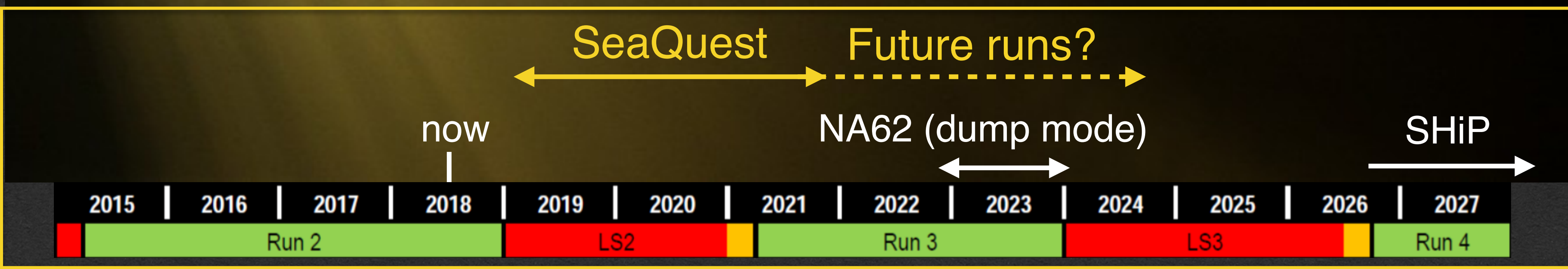
Conclusions & Outlook

Fermilab can cover a **crucial role** in the search for dark sectors: the SeaQuest experiment

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

Minimal dark photon & dark scalar;
Inelastic DM; axions; strongly-interacting DM
models can be broadly explored

Additional models that SeaQuest can explore?
Particle physics case?
Larger luminosities? Upgrades (EMCal upgrade)?

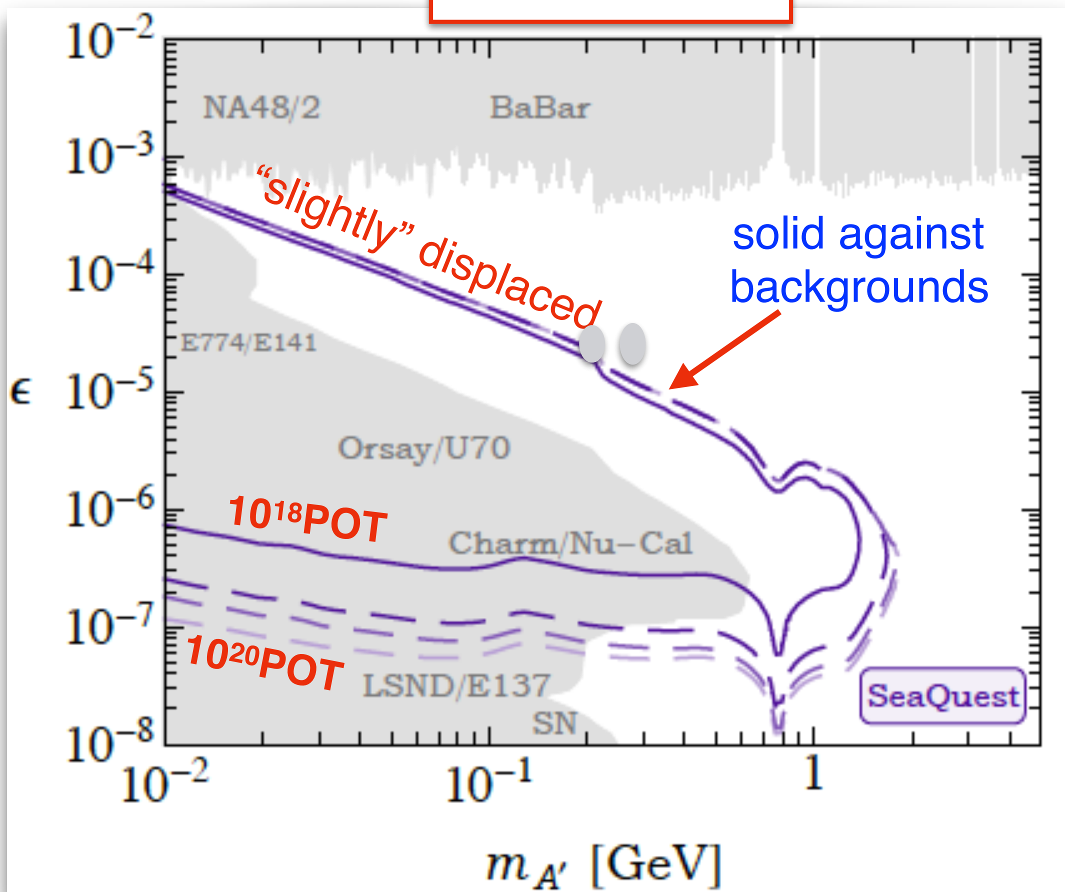


1. The reach for the minimal A' model

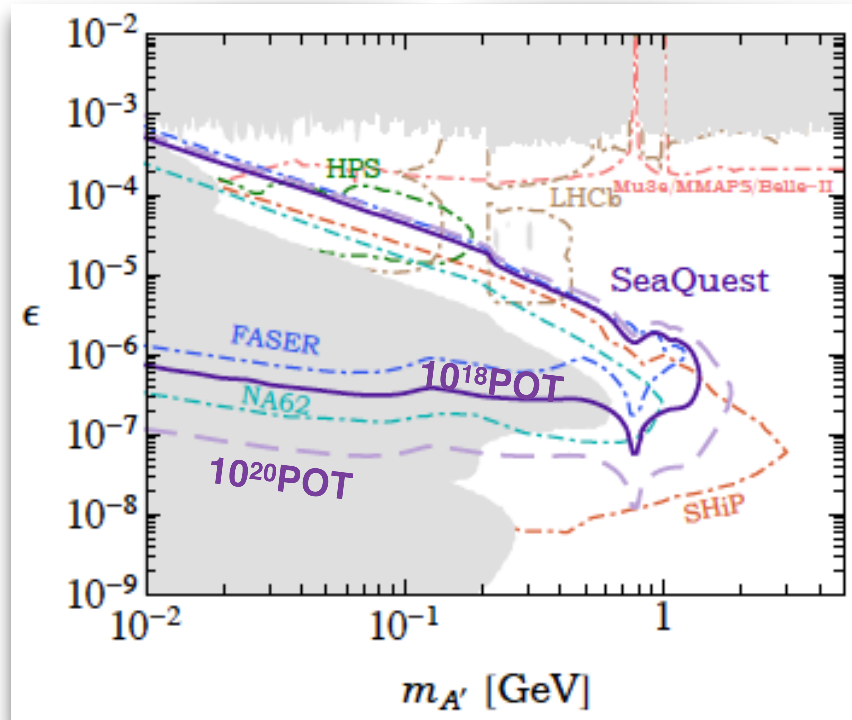
$\epsilon Z^{\mu\nu} A'_{\mu\nu}$

$\boxed{A' \to e^+ e^-}$

(Reach for EMCal upgrade)



(*) decay regions: (5-6)m, (5-9)m, (5-12)m
1 2 3



FASER:
Feng et al.,
1708.09389

NA62:
Lanfranchi
@ CERN-EPFL-Korean
theory institute

~2023

SHiP:
Alekhin et al.,
1504.04855

~2027