

# Searches for Dark Sector and New Physics at Fixed Target Experiments

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*Lepton-photon meeting, 2015*



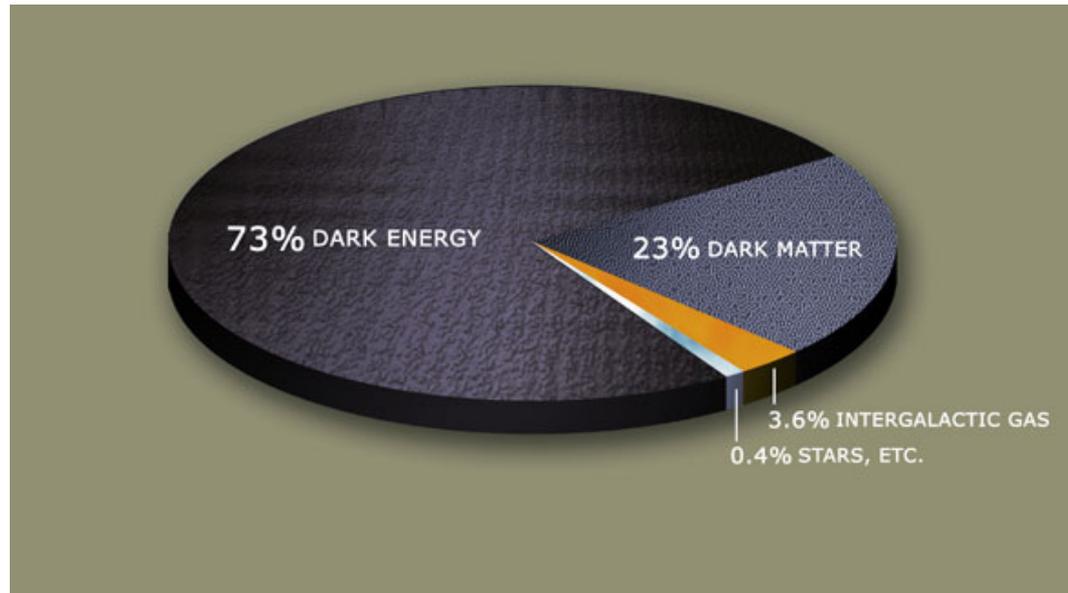
University  
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Canada



# Outline of the talk

1. Introduction. Portals to light new physics.
2. Snapshots of recent activity with fixed target experiments:
  - A. Vector portal,  $g-2$  discrepancy, and the search for dark photon.
  - B. Light dark matter via vector portals.
3. Possible future areas of growth: new fixed target/beam dump experiments and proposals.
4. Ultimate intensity frontier experiment (?)
5. Conclusions

# Big Questions in Physics

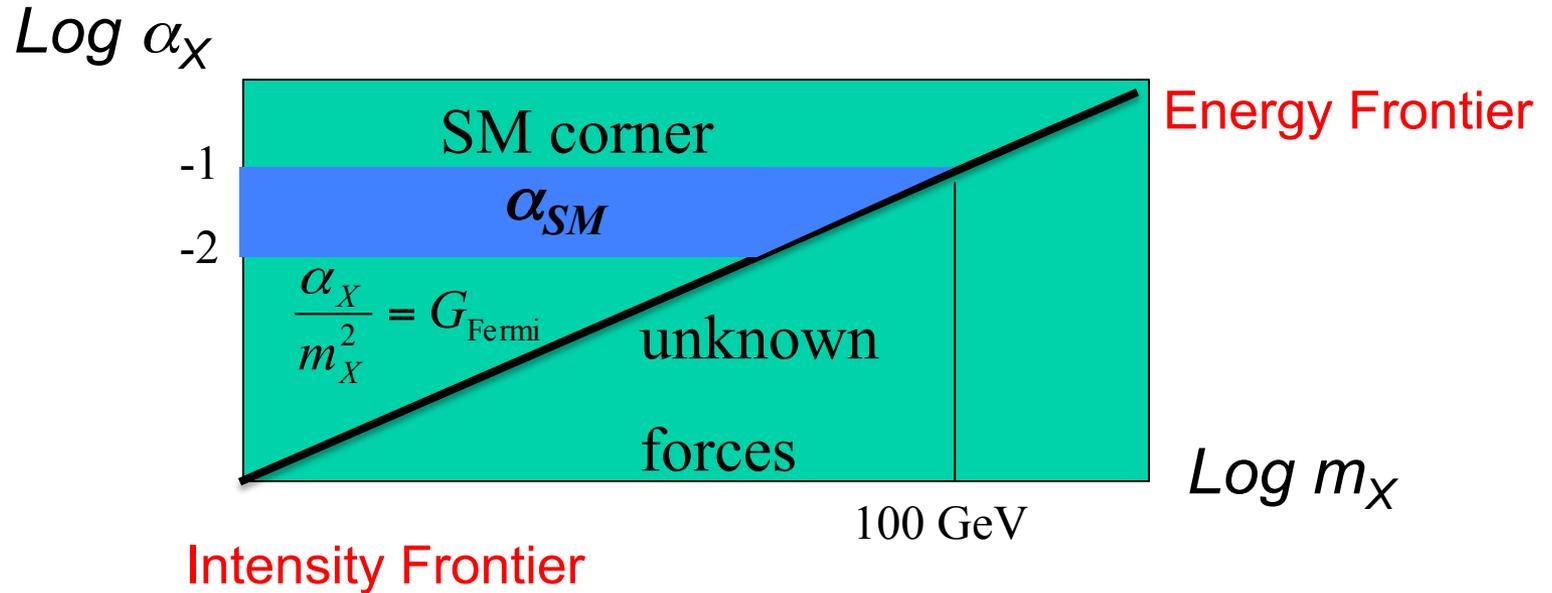


“Missing mass” – what is it?

New particle, new force, ...? *Both?* How to find out?

(History lesson: first “dark matter” problem occurred at the nuclear level, and eventually new particles, neutrons, were identified as a source of a “hidden mass” – and of course immediately with the new force of nature, the strong interaction force.)

# Intensity and Energy Frontiers



$$V(r) = \frac{\alpha_X}{r} \exp(-r / \lambda_X) = \frac{\alpha_X}{r} \exp(-rm_X) \longrightarrow \text{Amplitude} \approx \frac{\alpha_X}{q^2 + m_X^2}$$

**LHC can realistically pick up New Physics with  $\alpha_X \sim \alpha_{SM}$ , and  $m_X \sim 1\text{TeV}$ , but may have little success with  $\alpha_X \sim 10^{-6}$ , and  $m_X \sim \text{GeV}$ . 4**

# Neutral “portals” to the SM

Let us *classify* possible connections between Dark sector and SM

$H^+H$  ( $\lambda S^2 + A S$ ) Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu} V_{\mu\nu}$  “Kinetic mixing” with additional U(1)’ group

(becomes a specific example of  $J_\mu^i A_\mu$  extension)

$LHN$  neutrino Yukawa coupling,  $N$  – RH neutrino

$J_\mu^i A_\mu$  requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that

Nature may have used the  $LHN$  portal...

Dim>4

$J_\mu^A \partial_\mu a / f$  axionic portal

.....

$$\mathcal{L}_{\text{mediation}} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\text{med}}^{(k)} \mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n},$$

# Dark photon

(Holdom 1986; earlier paper by Okun')

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_{\mu}\phi|^2 - V(\phi),$$

This Lagrangian describes an extra U(1)' group (**dark force, hidden photon, secluded gauge boson, shadow boson etc, also known as U-boson, V-boson, A-prime, gamma-prime etc**), attached to the SM via a vector portal (kinetic mixing). Mixing angle  $\kappa$  (also known as  $\varepsilon, \eta$ ) controls the coupling to the SM. New gauge bosons can be light if the mixing angle is small.

In this talk  $\kappa = \varepsilon$

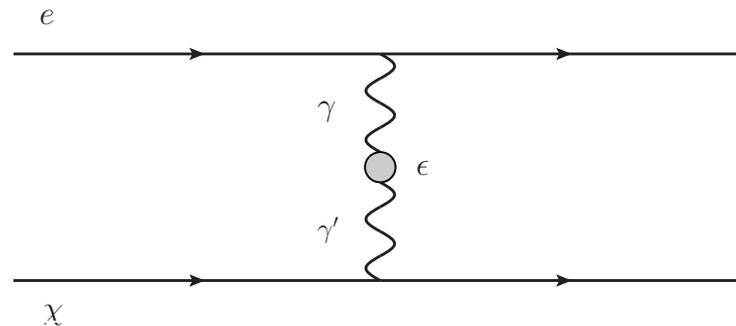
*Low-energy content:* **Additional massive photon-like vector V**, and possibly a new light Higgs h', both with small couplings.

# Model for “mini-charged” particles

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F_{\mu\nu}^2 + \bar{\psi} [\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi] \psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi} [\gamma_\mu (i\partial_\mu - g'A'_\mu) - m_\chi] \chi,$$

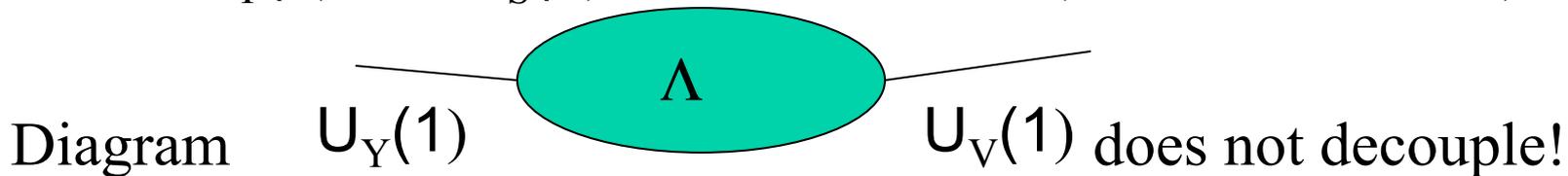


- “Effective” charge of the “dark sector” particle  $\chi$  is  $Q = e \times \epsilon$  (if momentum scale  $q > m_V$ ). At  $q < m_V$  one can say that particle  $\chi$  has a non-vanishing *EM charge radius*,  $r_\chi^2 \simeq 6\epsilon m_V^{-2}$ .
- Dark photon can “communicate” interaction between SM and dark matter. Very light  $\chi$  can be possible.

# “Non-decoupling” of secluded U(1)

## Theoretical expectations for masses and mixing

Suppose that the SM particles are not charged under new  $U_S(1)$ , and communicate with it only via extremely heavy particles of mass scale  $\Lambda$  (however heavy!, e.g. 100000 TeV) charged under the SM  $U_Y(1)$  and  $U_S(1)$  (B. Holdom, 1986)



A mixing term is induced,  $\kappa F_{\mu\nu}^Y F_{\mu\nu}^S$ ,

With  $\kappa$  having only the log dependence on mass scale  $\Lambda$

$$\kappa \sim (\alpha\alpha')^{1/2} (3\pi)^{-1} \log(\Lambda_{UV}/\Lambda) \sim 10^{-3}$$

$$M_V \sim e' \kappa M_{EW} (M_Z \text{ or TeV}) \sim \text{MeV} - \text{GeV}$$

This is very “realistic” in terms of experimental sensitivity range of parameters.

# Higgs Portal Models – attaching a singlet S

Quadratic and linear coupling to Higgs is allowed

$$\mathcal{L}_{\text{int}} = (H^\dagger H)(\lambda S^2 + AS) = hv(\lambda S^2 + AS) + \dots$$

(Linear terms are forbidden if S is charged under dark group)

Integrating out heavy SM Higgs particle, we have

$$\mathcal{L}_{\text{int}} = \mathcal{O}_{\text{SM}}^{(h)} \frac{\lambda S^2 + AS}{m_h^2},$$

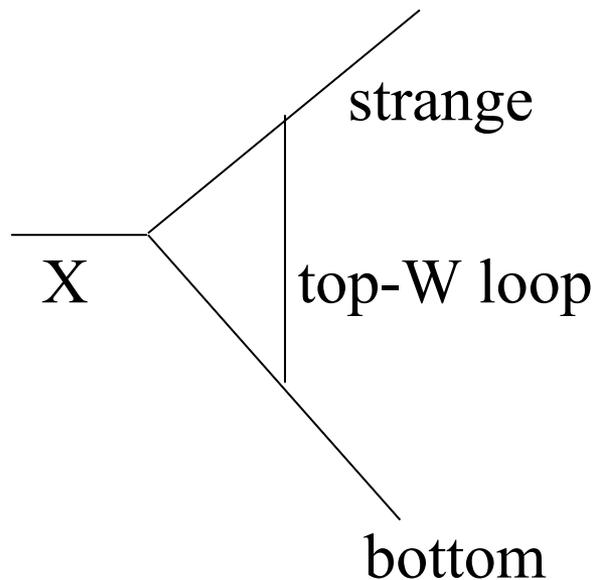
where  $\mathcal{O}_{\text{SM}}^{(h)} = \sum_f m_f \bar{f} f + \dots$

Mass parameter A creates mixing between SM Higgs and S scalar, and the size of the mixing angle  $\kappa' \equiv Av/m_h^2$ : be as large 0.001-0.01 without creating technical naturalness problem.

One can have a “close relative” of the Higgs, with smaller mass (e.g. GeV) and coupling.

# Scalar currents are very different from conserved vector currents

Conserved vector currents are uniquely positioned to avoid very strong flavor constraints. Axial vector portals, Higgs portals are potentially liable to very strong flavor constraints. Consider generic FCNC penguin-type loop correction.



For a conserved vector current,  $G_F q^2$

For scalar current,  $G_F m_t^2$

There is extremely strong sensitivity to new scalars, pseudoscalars axial-vectors in rare K and B decays.

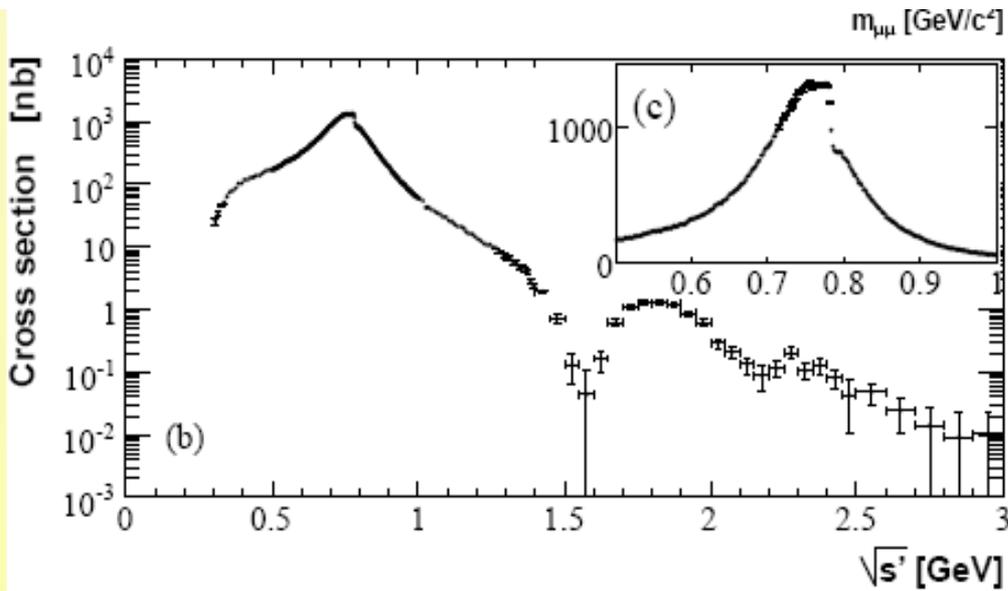
# Variations of vector portal: gauged $B - L$ , $L_\mu - L_\tau$ , ... symmetries

- *Anomaly-free, can be UV complete.*
- A non-zero kinetic mixing will be developed out of RG evolution
- Neutrinos get extra interaction – already constrained!
- $L_\mu - L_\tau$  is the *least constrained* possibility because neither electrons nor nucleons have extra interactions with neutrinos.

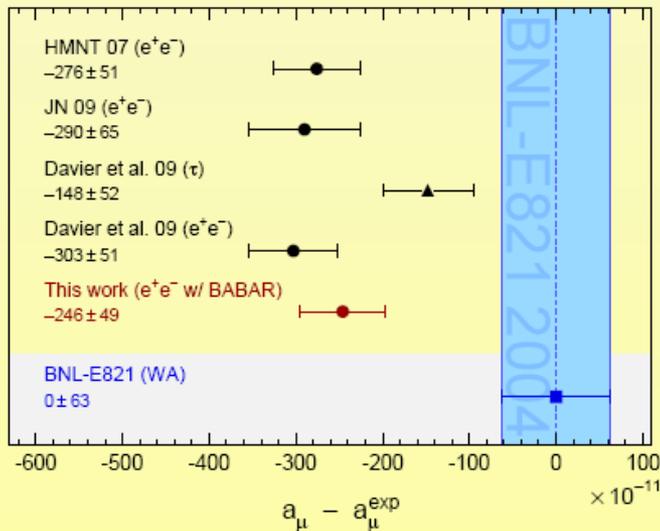
In recent years there has been some increase of experimental activity searching for light particles in MeV-GeV range because of the following speculative motivations.

1. Light New Physics helps to solve some particle physics anomalies (muon  $g-2$ , ...).
2. It helps to tie some astrophysical anomalies (511 keV excess from the bulge, positron excess above 10 GeV etc) with models of dark matter <sup>11</sup> *without large fine tuning.*

# g-2 of muon



More than 3 sigma discrepancy for most of the analyses. Possibly a sign of new physics, but some complicated strong interaction dynamics could still be at play.



Supersymmetric models with large-ish  $\tan\beta$ ; light-ish sleptons, and right sign of  $\mu$  parameter can account for the discrepancy.

Sub-GeV scale vectors/scalars can also be at play.

\* Davier et al. arXiv:0906-5443

# More discrepancies discovered using muons !

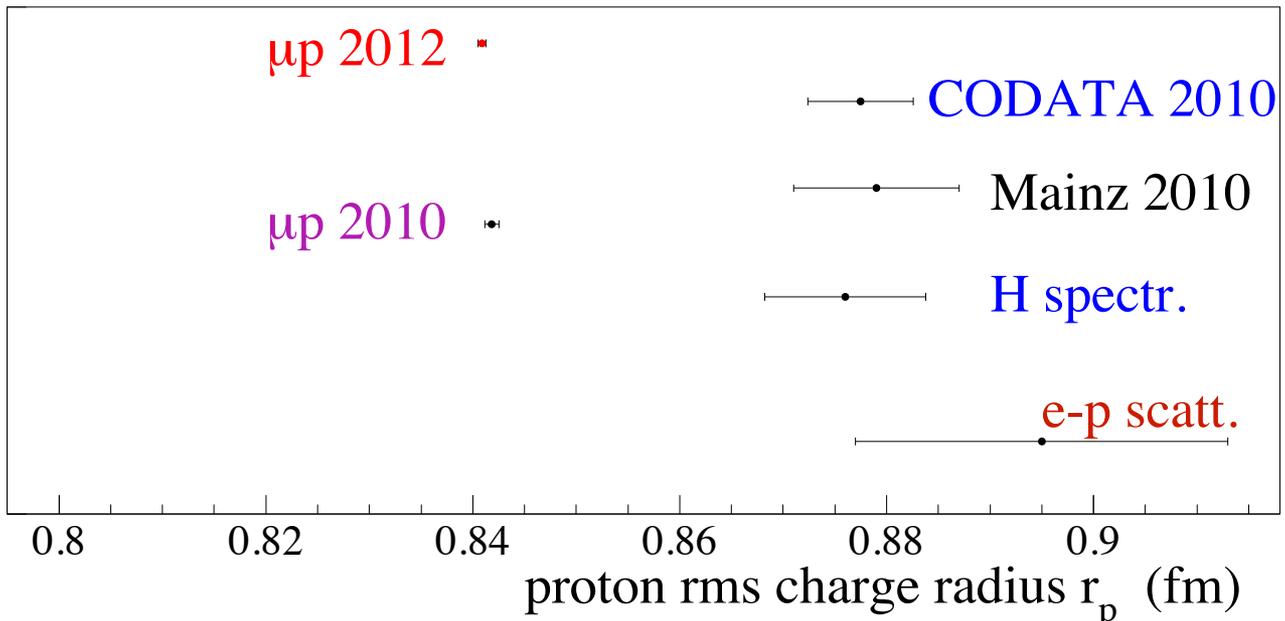
$\nu(2S_{1/2}^{F=1} \rightarrow 2P_{3/2}^{F=2}) = 49881.88(76) \text{ GHz}$  R. Pohl *et al.*, Nature 466, 213 (2010)

$49881.35(64) \text{ GHz}$  preliminary

$\nu(2S_{1/2}^{F=0} \rightarrow 2P_{3/2}^{F=1}) = 54611.16(1.04) \text{ GHz}$  preliminary

Proton charge radius:  $r_p = 0.84089 (26)_{\text{exp}} (29)_{\text{th}} = 0.84089 (39) \text{ fm (prel.)}$

$\mu\text{p}$  theory: A. Antognini *et al.*, arXiv :1208.2637 (atom-ph)

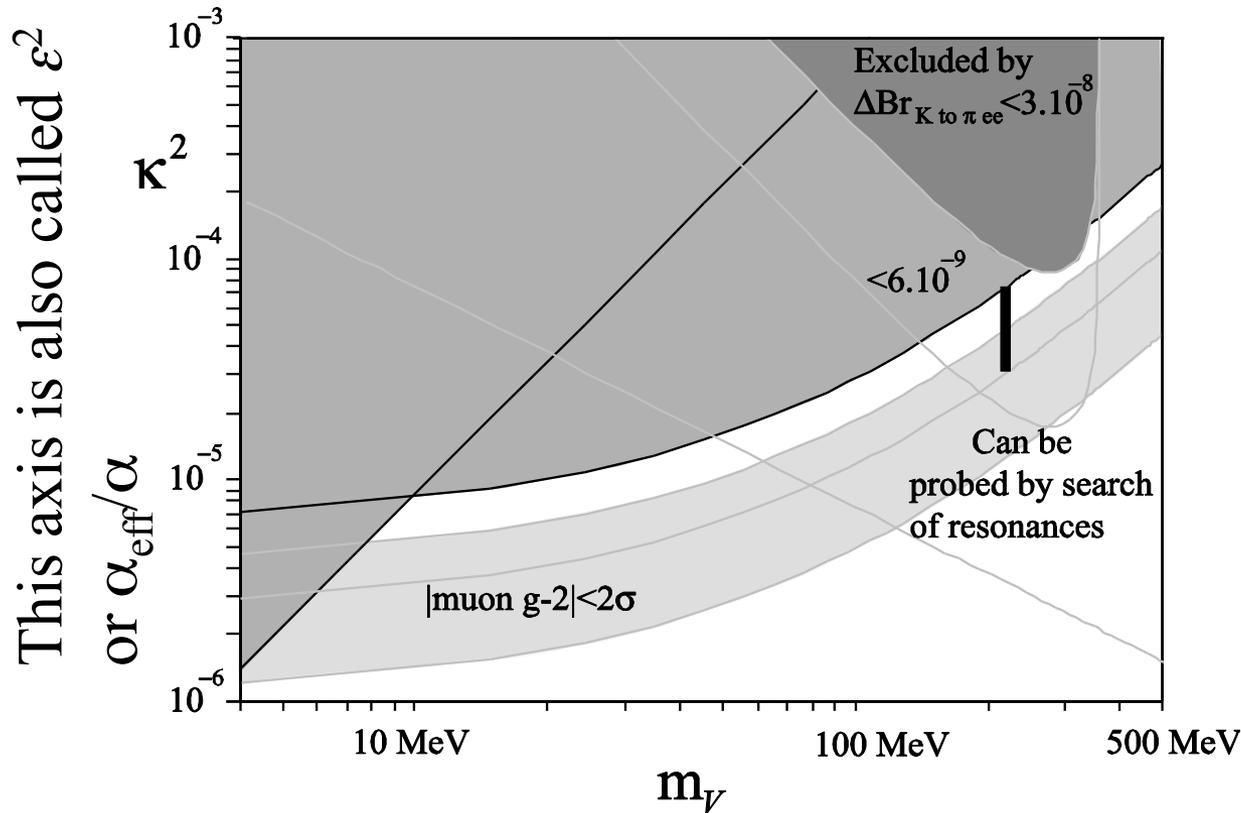


If new physics is responsible for that, it cannot be weak scale, only very light, as  $r_p$  will require  $\sim 10^4 G_F$  effects...

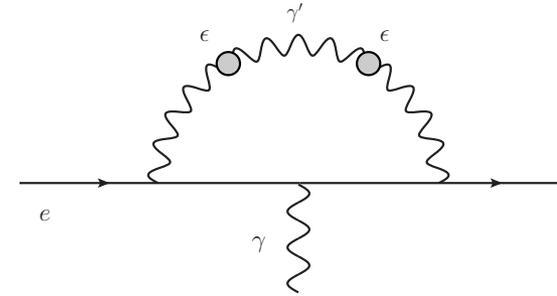
# $K$ - $m_V$ parameter space

If g-2 discrepancy taken seriously, a new vector force can account for deficit. (Krasnikov, Gninenko; Fayet; Pospelov)

E.g. mixing of order few 0.001 and mass  $m_V \sim m_\mu$

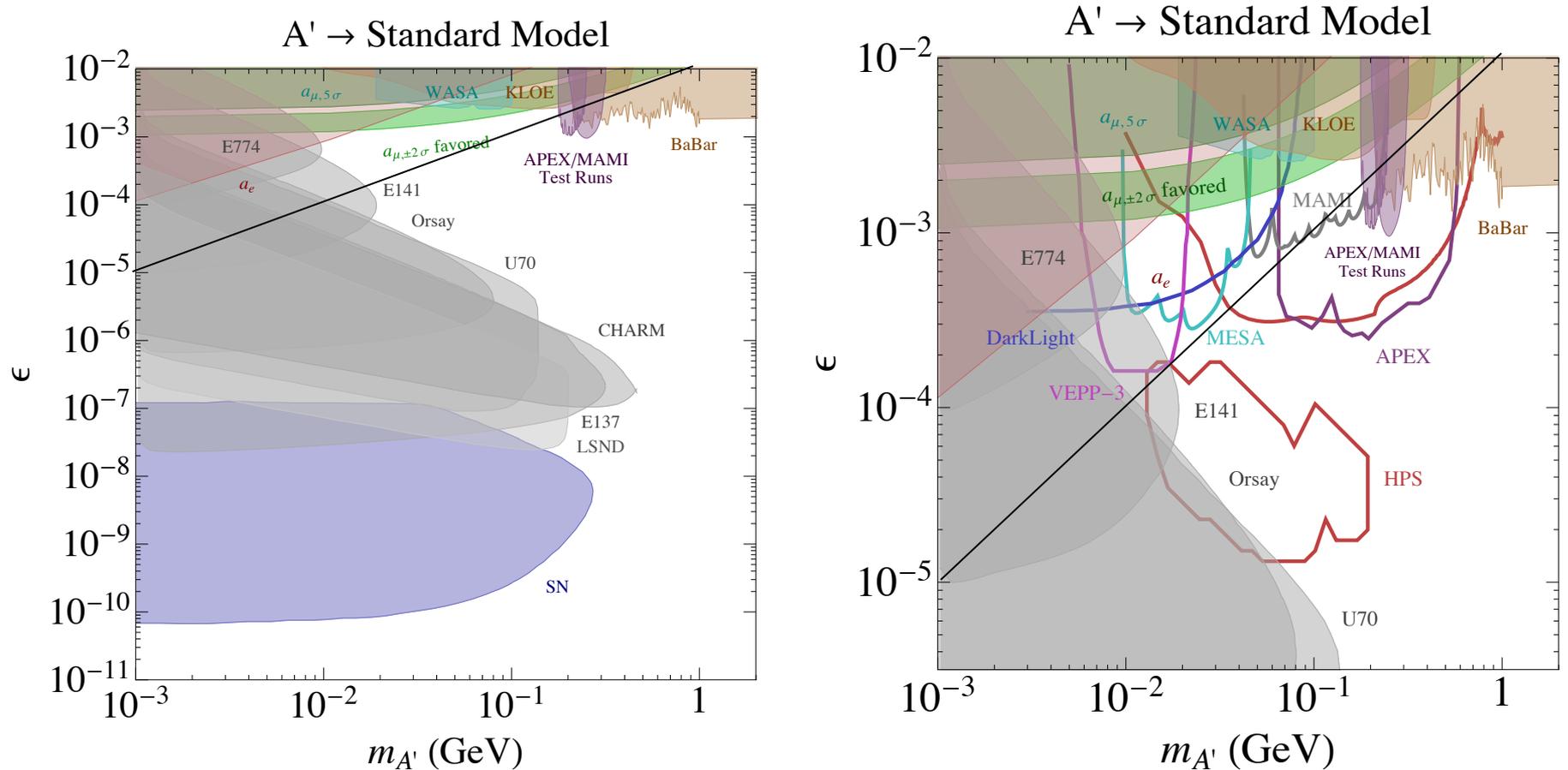


MP, 2008



*Since 2008 a lot more of parameter space got constrained*

# $\epsilon$ - $m_{A'}$ parameter space, Snowmass study, 2013



Dark photon models with mass under 1 GeV, and mixing angles  $\sim 10^{-3}$  represent a “window of opportunity” for the high-intensity experiments, and soon the  $g - 2$  ROI will be completely covered. *Gradually, all parameter space in the “SM corner” gets probed/excluded.*

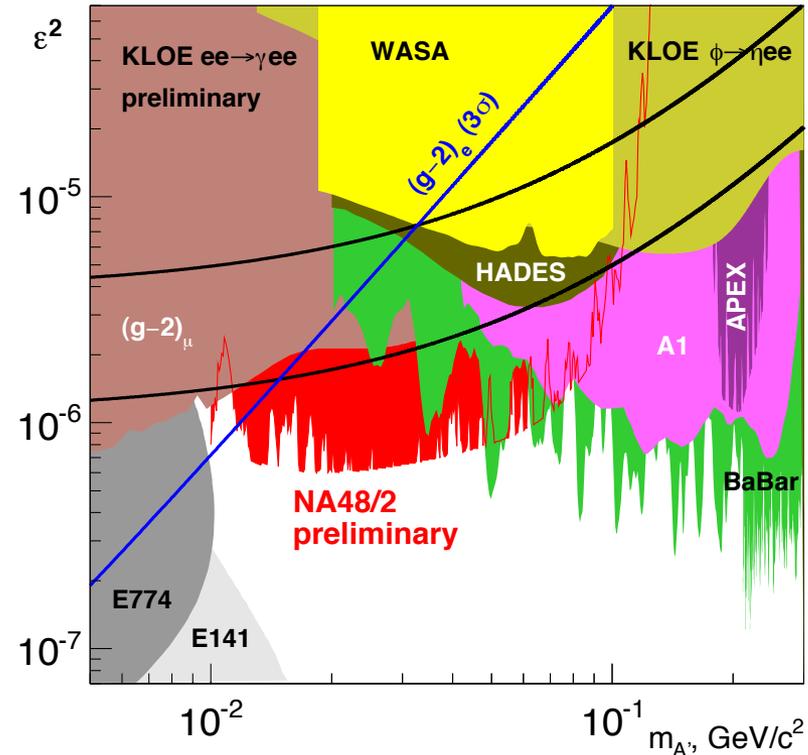
# Latest results: A1, Babar, NA48

Signature: “bump” at invariant mass of  $e^+e^-$  pairs =  $m_A$ ,

**Babar:**  $e^+e^- \rightarrow \gamma V \rightarrow \gamma l^+l^-$

**A1(+ APEX):**  $Z e^- \rightarrow Z e^- V$   
 $\rightarrow Z e^- e^+e^-$

**NA48:**  $\pi^0 \rightarrow \gamma V \rightarrow \gamma e^+e^-$



Latest results by NA48 exclude the remainder of parameter space relevant for  $g-2$  discrepancy.

Only more contrived options for muon  $g-2$  explanation remain, e.g.  $L_\mu - L_\tau$ , or dark photons *decaying* to light dark matter.

# Signatures of $Z'$ of $L_\mu - L_\tau$

## Experimental results on “trident”

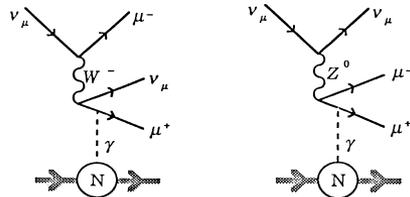


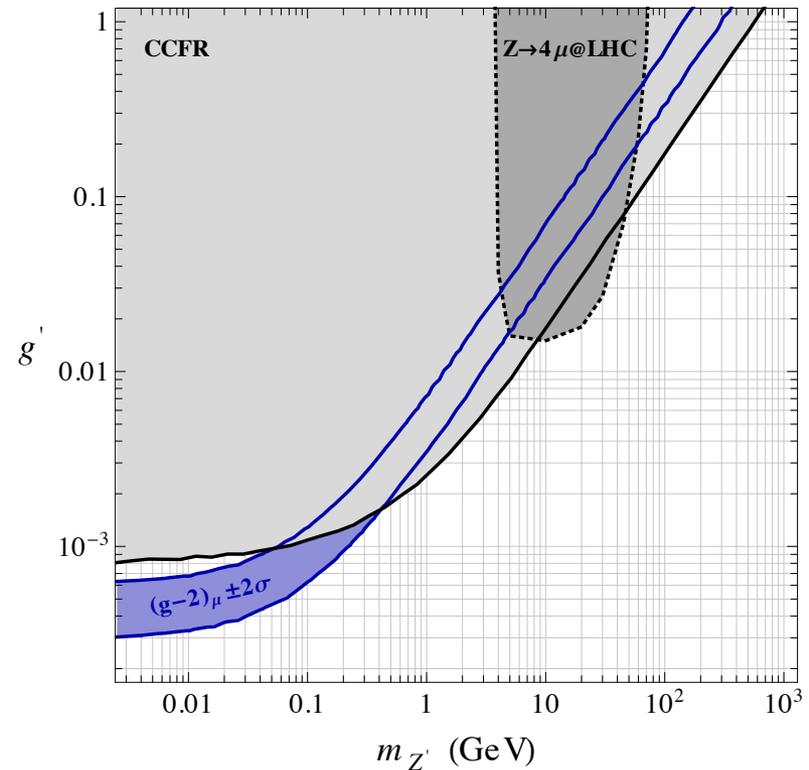
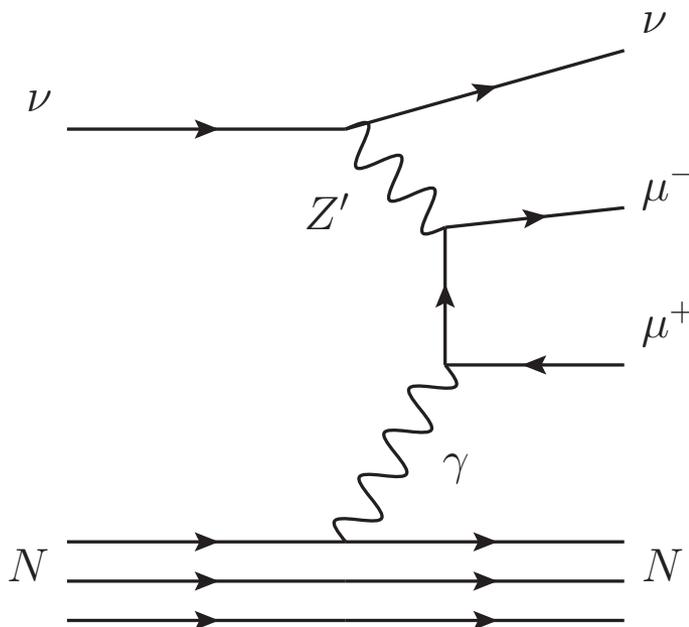
FIG. 1. Feynman diagram showing the neutrino trident production in  $\nu_\mu$ - $A$  scattering via the  $W$  and the  $Z$  channels.

$$\sigma_{\text{CHARM-II}}/\sigma_{\text{SM}} = 1.58 \pm 0.57 ,$$

$$\sigma_{\text{CCFR}}/\sigma_{\text{SM}} = 0.82 \pm 0.28 ,$$

$$\sigma_{\text{NuTeV}}/\sigma_{\text{SM}} = 0.67 \pm 0.27 .$$

Hypothetical  $Z'$  (any  $Z'$  coupled to  $L_\mu$ ) contributes constructively to cross section. (Almannshofer et al., 2014)



# Light WIMPs due to light mediators

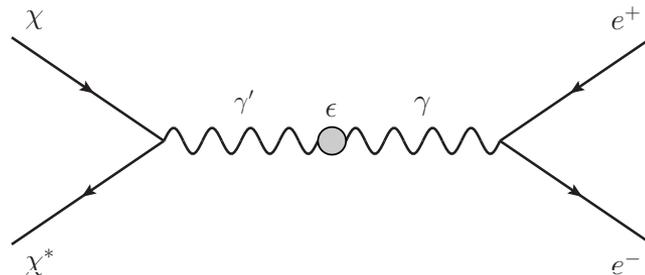
(Boehm, Fayet; MP, Riz, Voloshin ...) Light dark matter is not ruled out if one adds a light mediator.

WIMP paradigm:  $\sigma_{\text{annih}}(v/c) \sim 1 \text{ pbn} \implies \Omega_{\text{DM}} \simeq 0.25,$

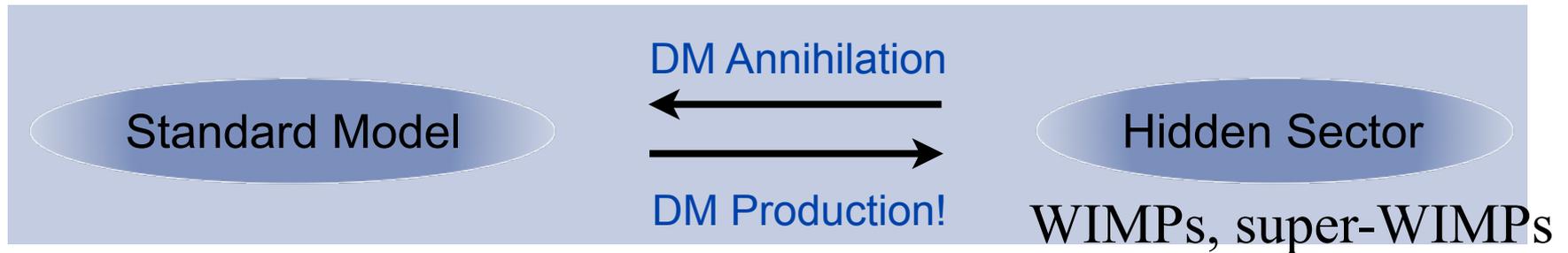
Electroweak mediators lead to the so-called Lee-Weinberg window,

$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for } m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for } m_\chi \gg m_W. \end{cases} \implies \text{few GeV} < m_\chi < \text{few TeV}$$

If instead the annihilation occurs via a force carrier with light mass, DM can be as light as  $\sim \text{MeV}$  (and not ruled out by the CMB if it is a scalar).



# Possible connection to WIMP-y dark matter



## Mediators (SM Z, h etc or dark force)

**Heavy WIMP/heavy mediators:** - “**mainstream**” literature

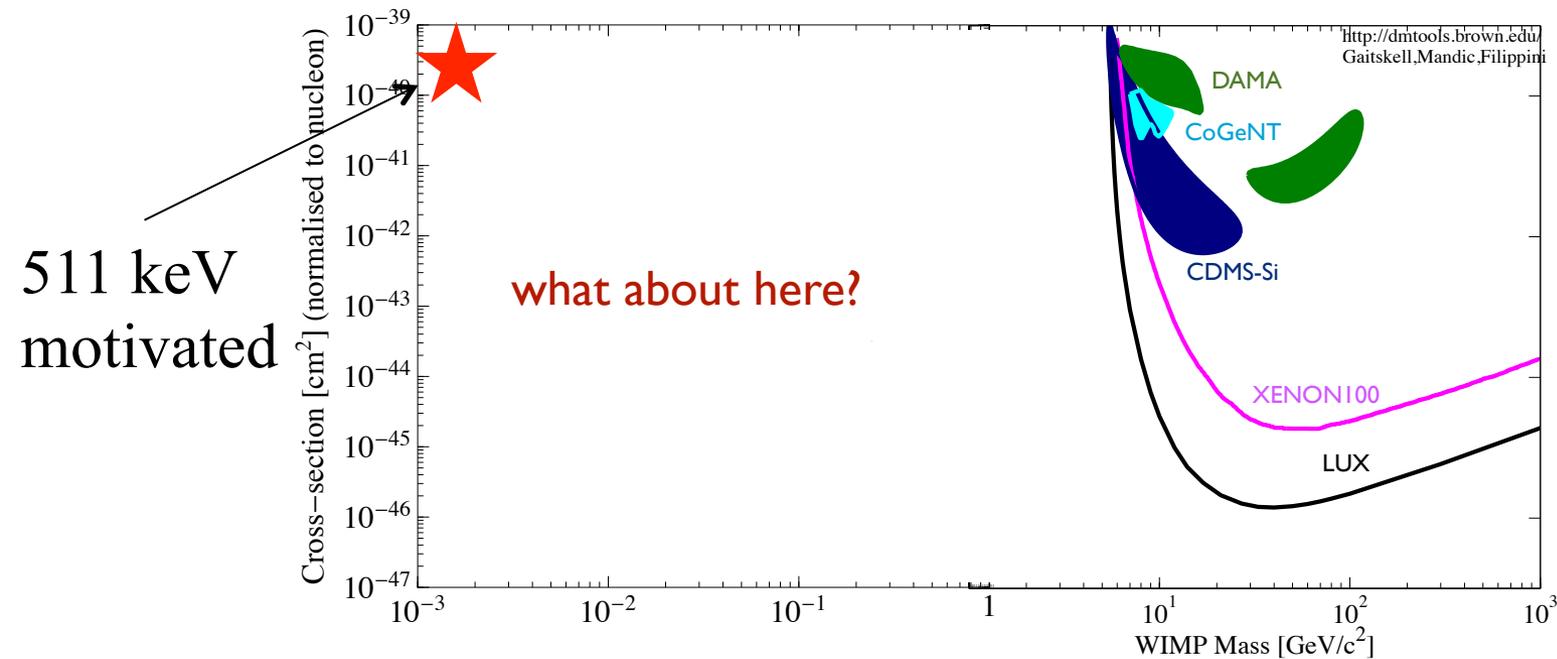
**Light WIMPs/light mediators:** Boehm et al; Fayet; MP, Ritz, Voloshin; Hooper, Zurek; others

**Heavy WIMPs/light mediators:** Finkbeiner, Weiner; Pospelov, Ritz, Voloshin (secluded DM); Arkani-Hamed et al., many others

**Light WIMPs/heavy mediators:** **does not work.** (Except for super-WIMPs; or non-standard thermal history)

Light mediators allow to speculatively tie several anomalies to the possible effects of WIMP dark matter.

# Light DM – direct production/detection



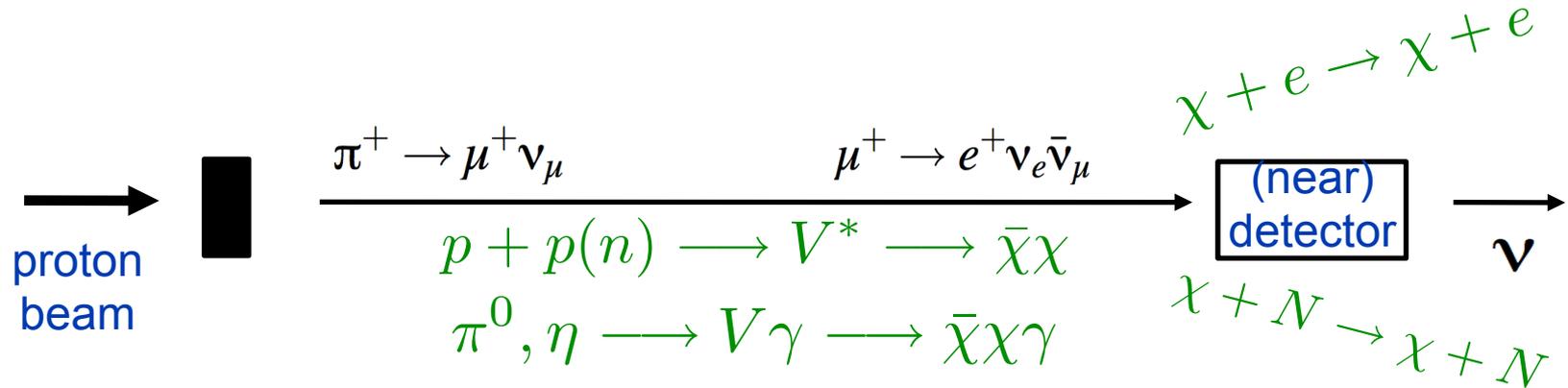
If WIMP dark matter is coupled to light mediators, the WIMP mass scale can be much lighter than nominal Lee-Weinberg bound,

$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} (V_{\mu\nu})^2 + \frac{1}{2} m_V^2 (V_\mu)^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \dots$$

↑ DM
 ↑ mediation

# Fixed target probes - Neutrino Beams

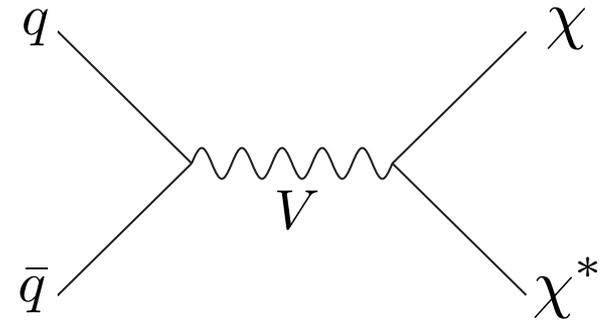
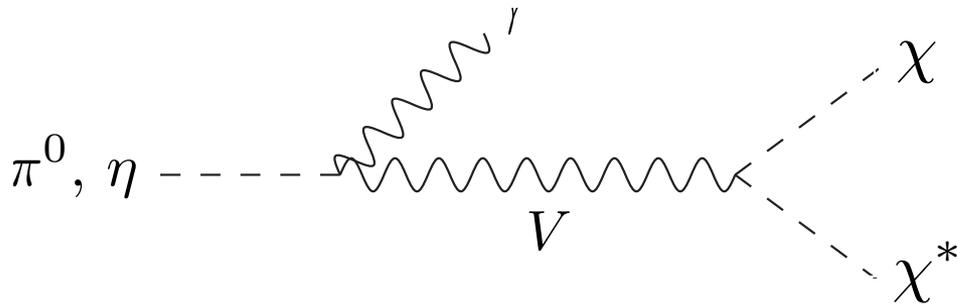
Proposed in **Batell, MP, Ritz**, 2009. Strongest constraints on MeV DM



We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

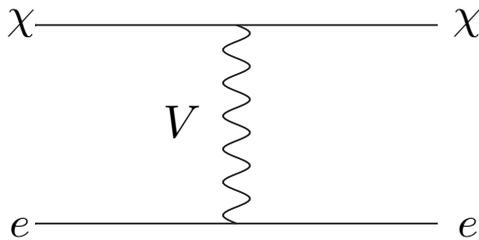
T2K	MINOS	MiniBooNE
30 GeV protons ( $\Rightarrow \sim 5 \times 10^{21}$ POT)	120 GeV protons $10^{21}$ POT	8.9 GeV protons $10^{21}$ POT
280m to on- and off-axis detectors	1km to (~27ton) segmented detector	540m to (~650ton) mineral oil detector

# Light DM - trying to force the issue

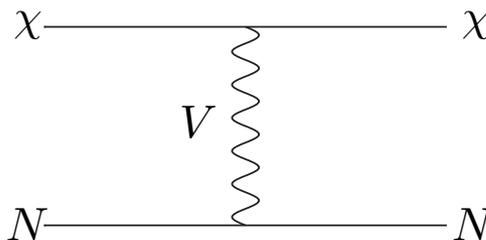


In the detector:

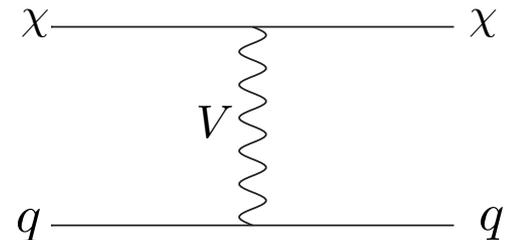
Elastic scattering  
on electrons



Elastic scattering  
on nucleons

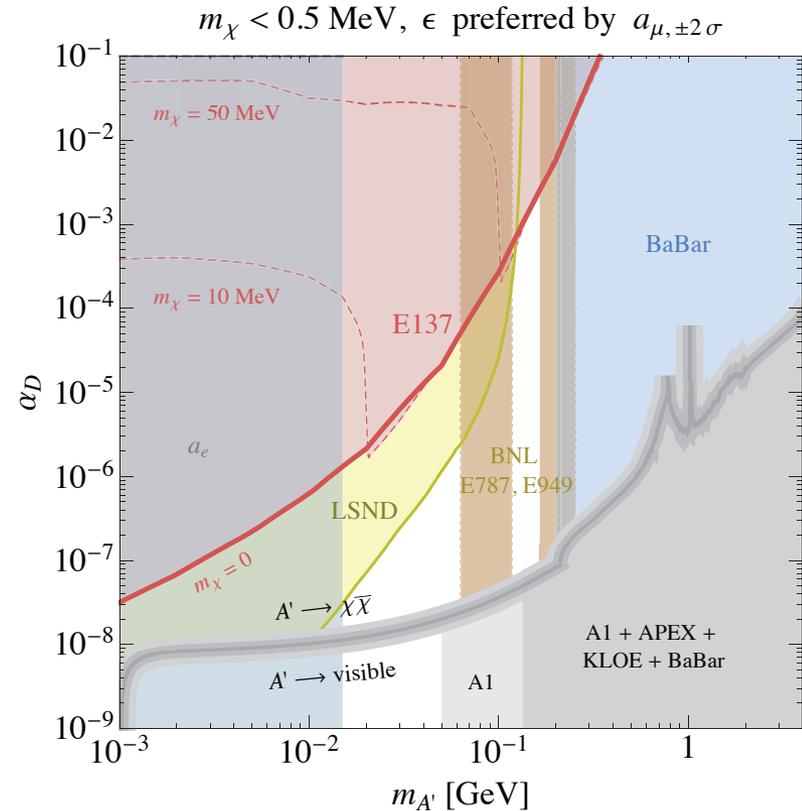
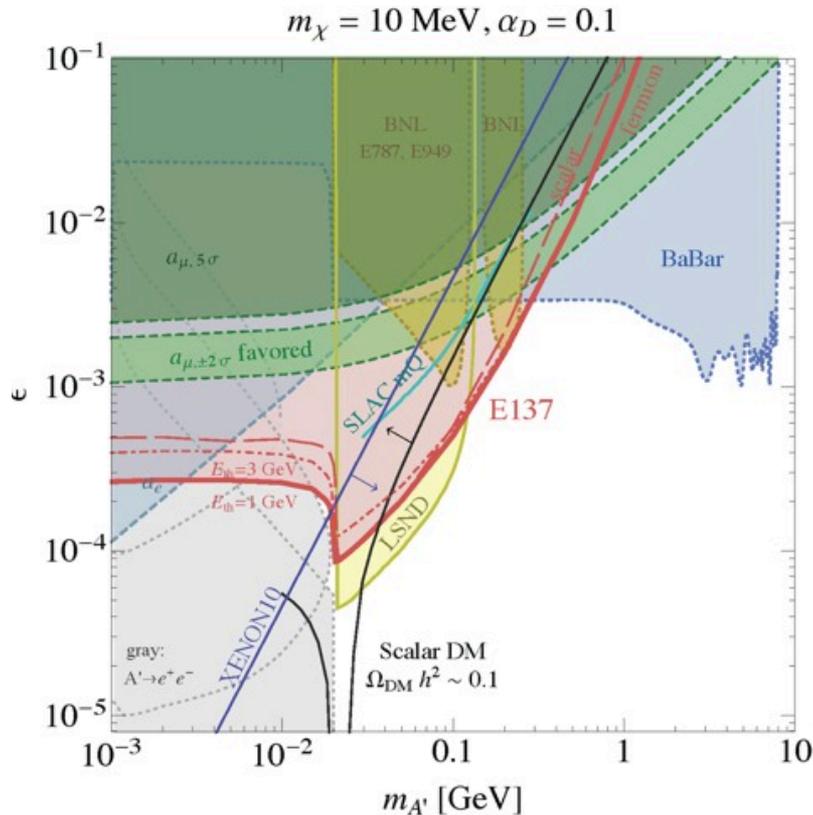


Deep inelastic  
scattering



Same force that is responsible for depletion of  $\chi$  to acceptable levels in the early Universe will be responsible for its production at the collision point and subsequent scattering in the detector.

# Compilation of current constraints on dark photons decaying to light DM



The sensitivity of electron beam dump experiments to light DM is investigated in [Izaguirre et al, 2013](#); [Batell, Essig, Surujon, 2014](#).

# On-going and future projects

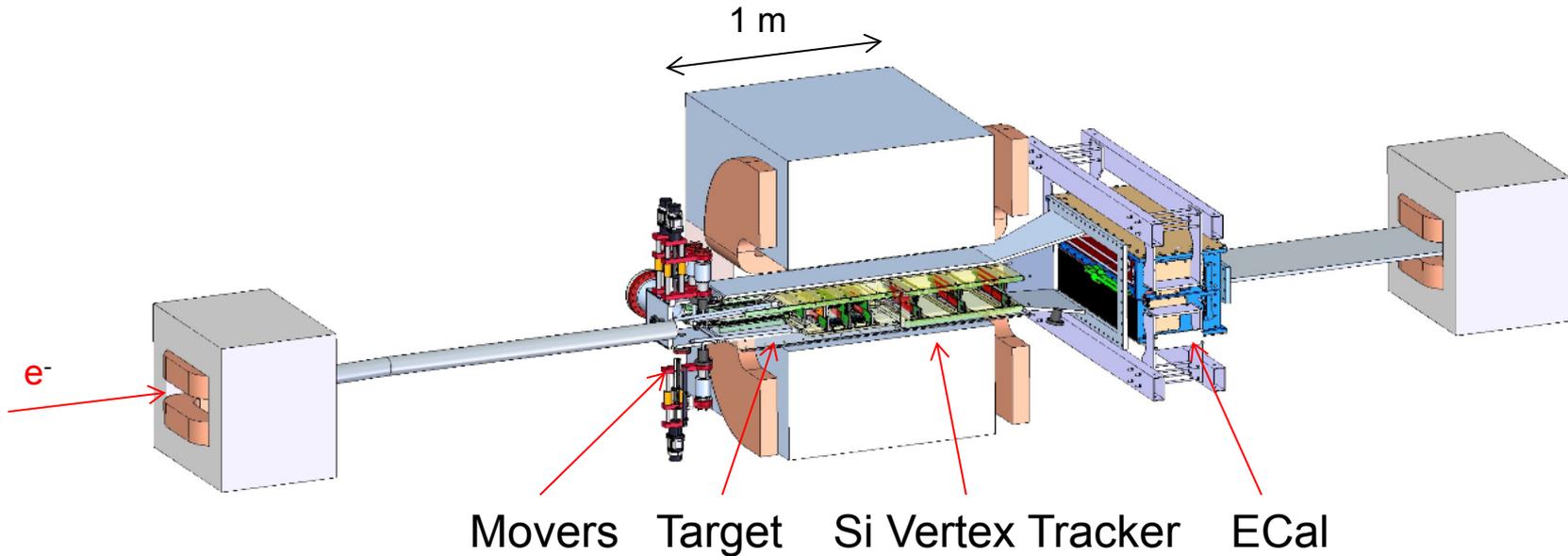
Fixed Target/beam dump experiments sensitive to

- Dark Photons: [HPS](#), [DarkLight](#), [APEX](#), [Mainz](#), [SHiP](#)...
- Light dark matter production + scattering: [MiniBoNE](#), [BDX](#), [SHiP](#)...
- Right-handed neutrinos: [SHiP](#)
- Missing energy via DM production: [NA62](#) ( $K \rightarrow \pi \nu \nu$  mode), [positron beam dumps](#)...
- Extra  $Z'$  in neutrino scattering: [DUNE near detector](#) (?)

# HPS experiment at JLab

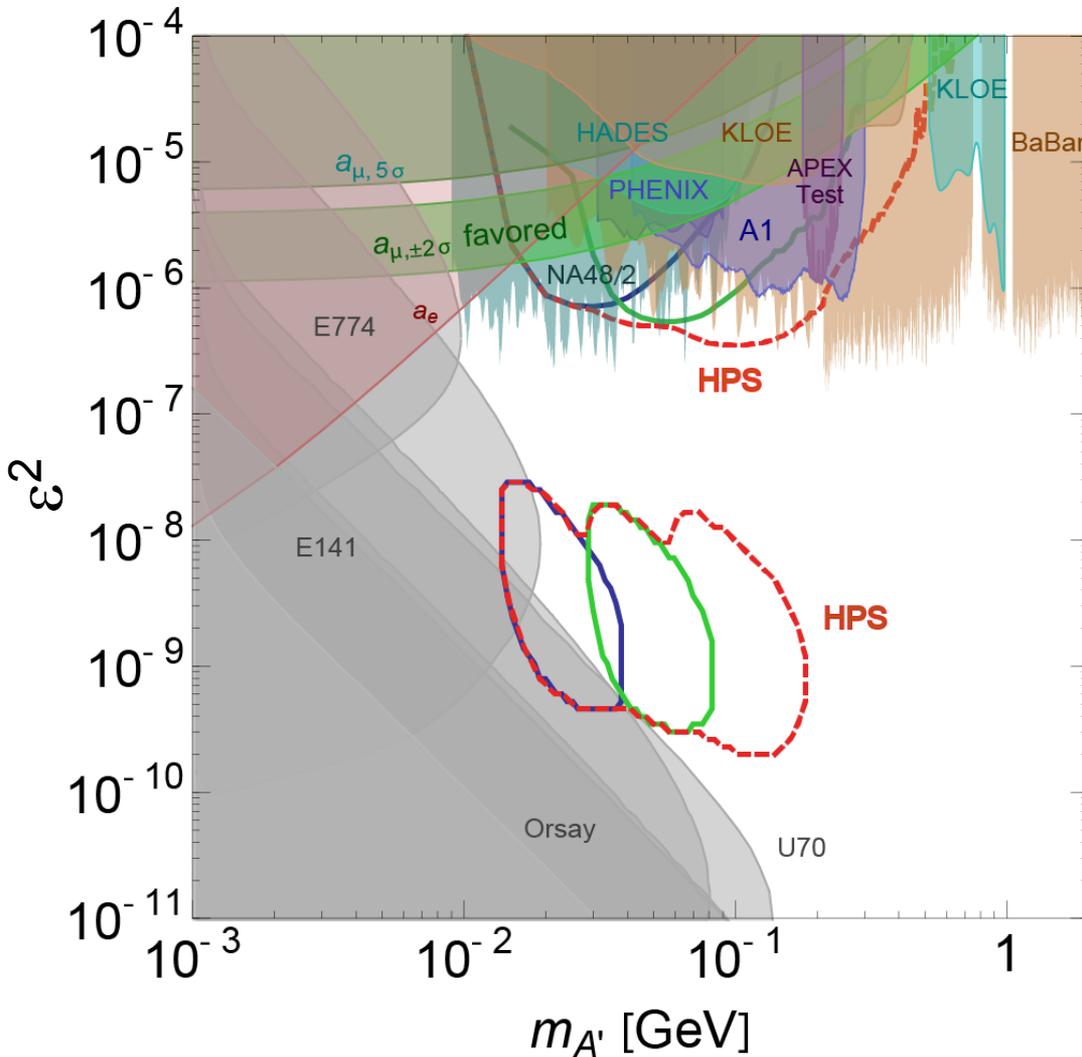
Sensitivity via:

1. invariant mass reconstruction
2. displaced decays



- The experiment has finished the engineering run.

# Expected HPS Reach



One week, 50nA @ 1.1 GeV

One week, 200nA @ 2.2 GeV

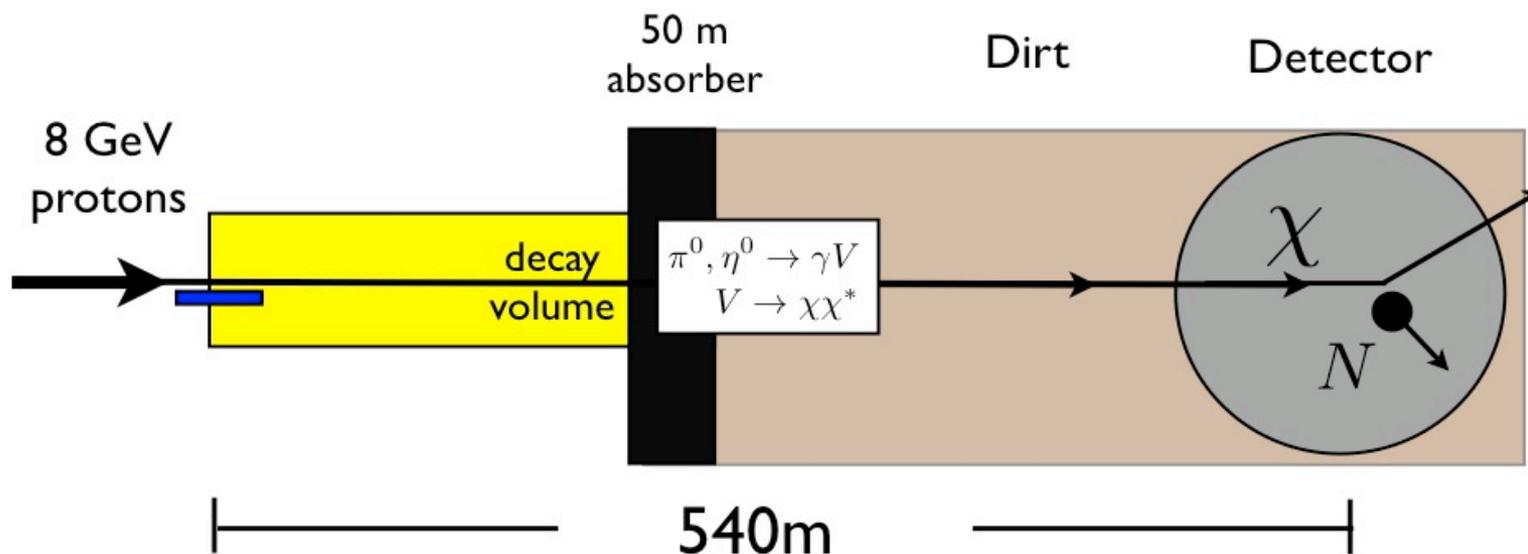
Four week total reach = above  
+  
Two weeks, 300nA @ 4.4 GeV

Times are PAC times  
(Clock time/2)

2015 Spring Engineering run  
accumulated 1/3 PAC week  
at 1.056GeV

N. Graf presentation, Camogli workshop on light dark matter, 2015

# MiniBooNE search for light DM

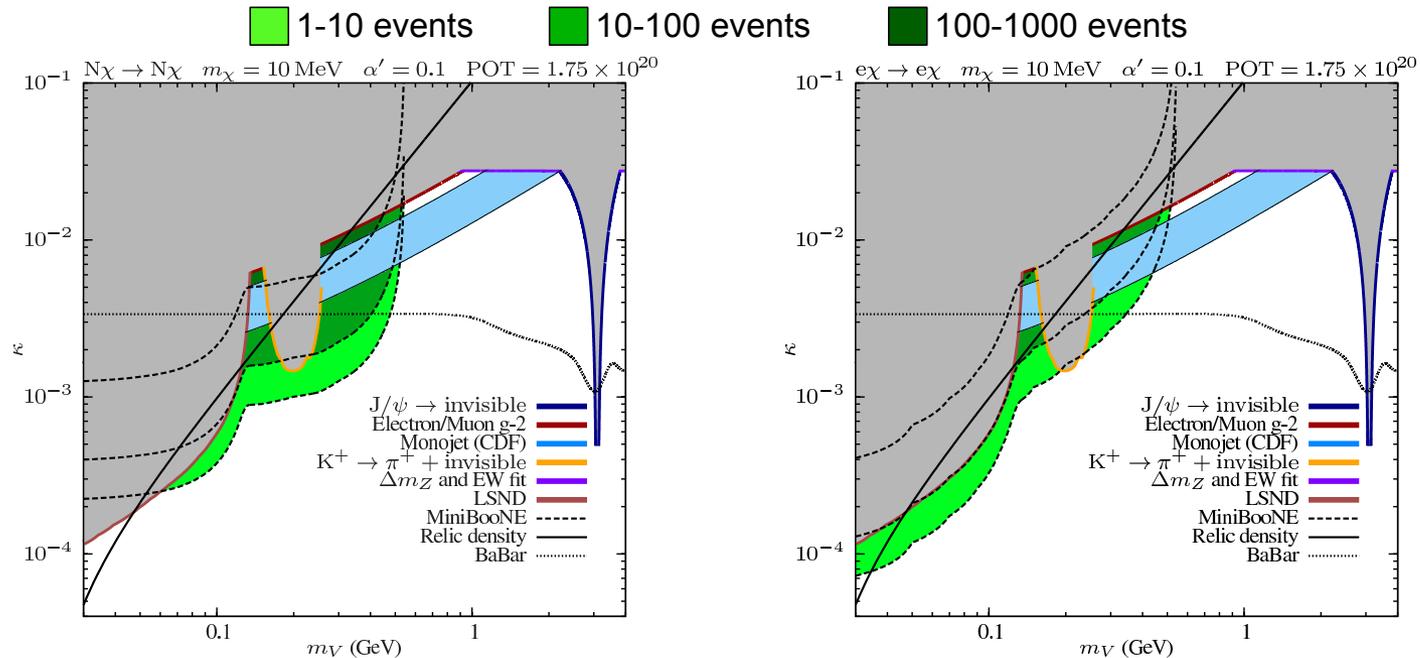


MiniBoone has completed a long run in the beam dump mode, as suggested in [\[arXiv:1211.2258\]](#)

By-passing Be target is crucial for reducing the neutrino background (R. van de Water et al. ...). Currently, suppression of  $\nu$  flux  $\sim 50$ .

Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds. **First results – this year (2015)**

# MiBooNE search for DM



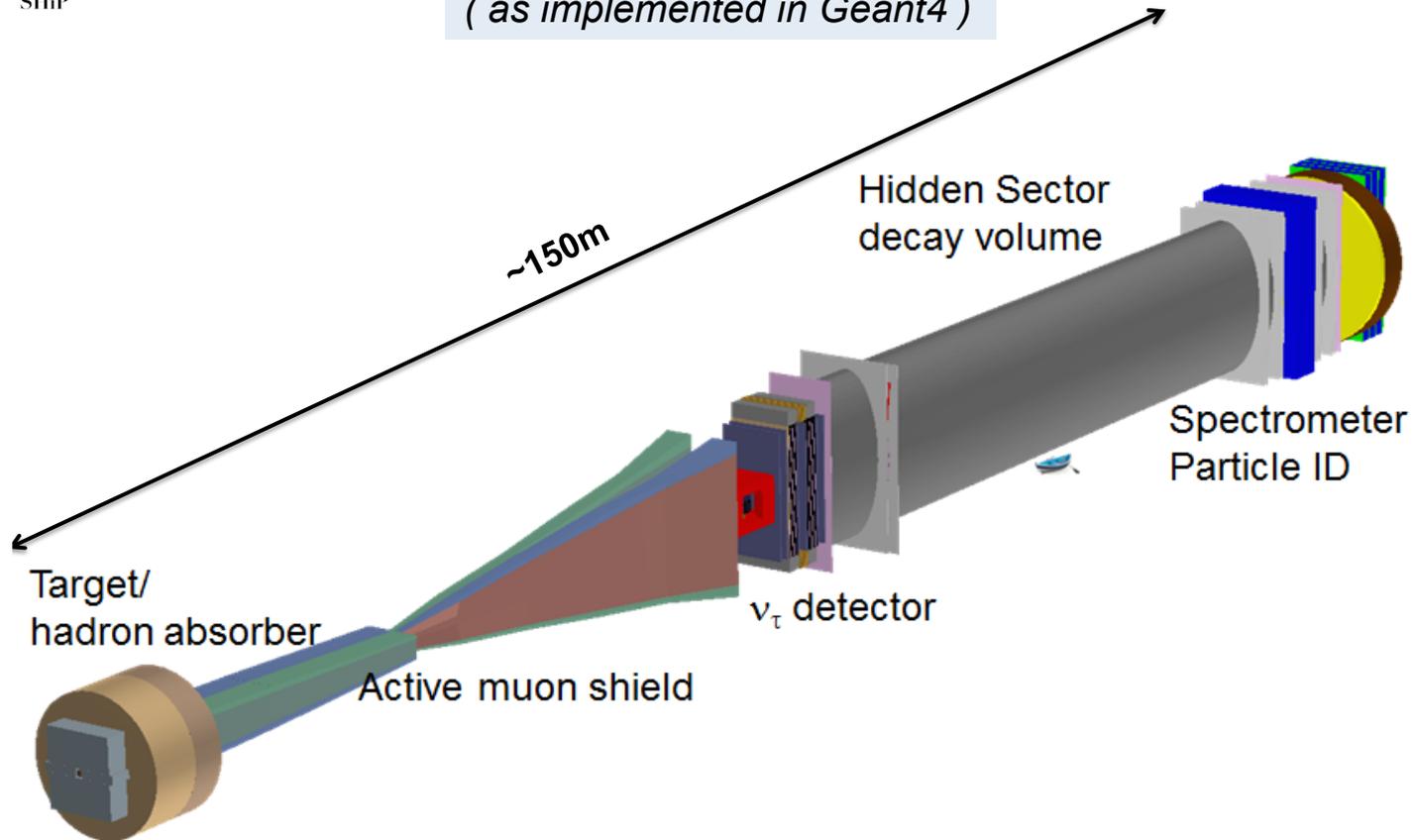
R. Cooper presentation, Camogli workshop on light dark matter, 2015

- MiniBooNE has collected  $1.86 \times 10^{20}$  POT in beam-off-target configuration to search for sub-GeV dark matter
- Beam-off-target suppresses neutrino backgrounds  
 → beam uncorrelated backgrounds dominant

# Future: SHiP project at CERN



*The SHiP experiment*  
( as implemented in Geant4 )

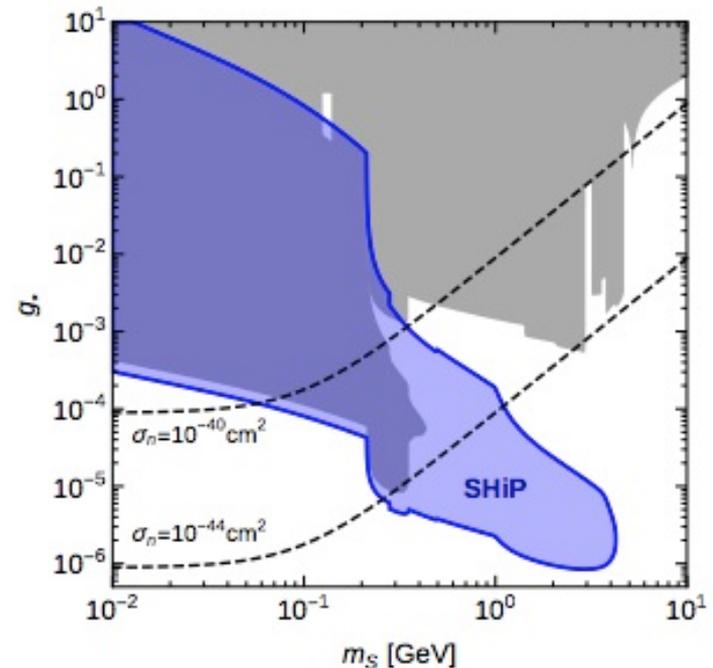
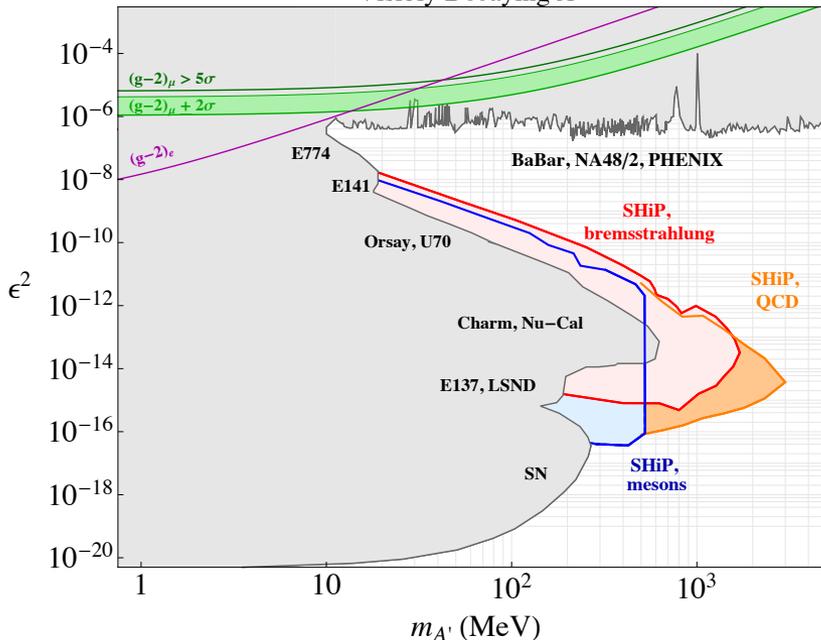


See e.g. [A. Golutvin](#) presentation, CERN SHiP symposium, 2015

# SHiP sensitivity to vector and scalar portals

- SHiP will collect  $2 \times 10^{20}$  protons of 400 GeV dumped on target
- Sensitivity to dark vectors is via the unflavored meson decays, and through direct production,  $pp \rightarrow \dots V \rightarrow \dots l^+l^-$
- Sensitivity to light scalar mixed with Higgs is via B-meson decays,  $b \rightarrow s + \text{Scalar} \rightarrow \dots \mu^+\mu^-$

Visibly Decaying  $A'$



Details can be found in the white paper, 1505.01865, [Alekhin et al.](#)

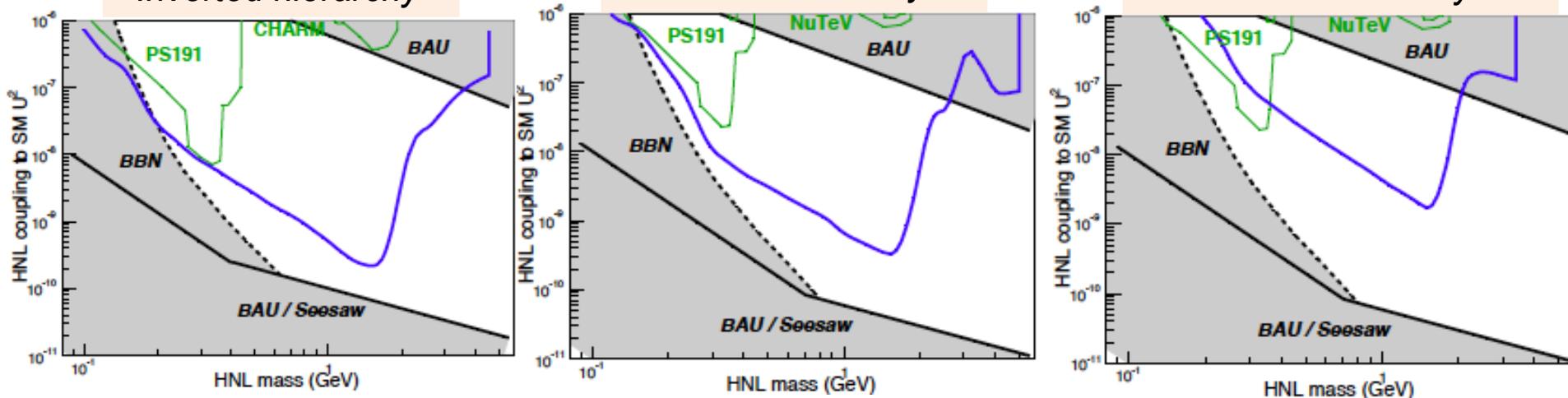
# SHiP has unique sensitivity to RH neutrinos

- Production channel is through charm  $pp \rightarrow c \text{ cbar} \rightarrow N_R$ . ( $N_R$  are often called Heavy Neutral Leptons, or HNL)
- Detection is through their occasional decay via small mixing angle  $U$ , with charged states in the final state, e.g.  $\pi^+\mu^-$ ,  $\pi^-\mu^+$ , etc.
- Decays are slow, so that the sensitivity is proportional to  
(Mixing angle)<sup>4</sup>.

$U_e^2 : U_{\mu}^2 : U_{\tau}^2 \sim 52:1:1$   
Inverted hierarchy

$U_e^2 : U_{\mu}^2 : U_{\tau}^2 \sim 1:16:3.8$   
Normal hierarchy

$U_e^2 : U_{\mu}^2 : U_{\tau}^2 \sim 0.061:1:4.3$   
Normal hierarchy



HNL production can be enhanced in non-minimal models, [Batell et al.](#)<sup>31</sup>

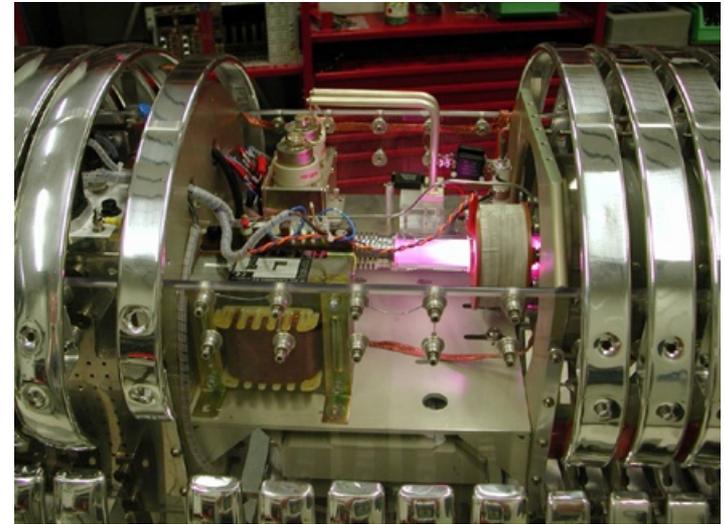
# Additional physics at SHiP

- Over  $10^3$  tau neutrino events in the tau neutrino detector
- New measurements of intrinsic strangeness
- Possibly, new constraints on non-standard neutrino properties (magnetic moment); sensitivity to trident production (may be).
- The sensitivity of SHiP tau neutrino detector to scattering of light dark matter through *light mediators* can be improved, around  $m_{\text{mediator}} \sim 300 \text{ MeV} - 1 \text{ GeV}$ .

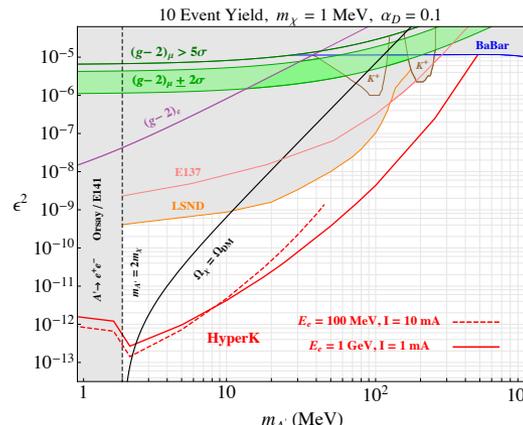
Details can be found in the white paper, 1505.01865, [Alekhin et al.](#)

# More coverage of dark sector using underground accelerators and neutrino detectors

with Eder Izaguirre and Gordan Krnjaic, 2015



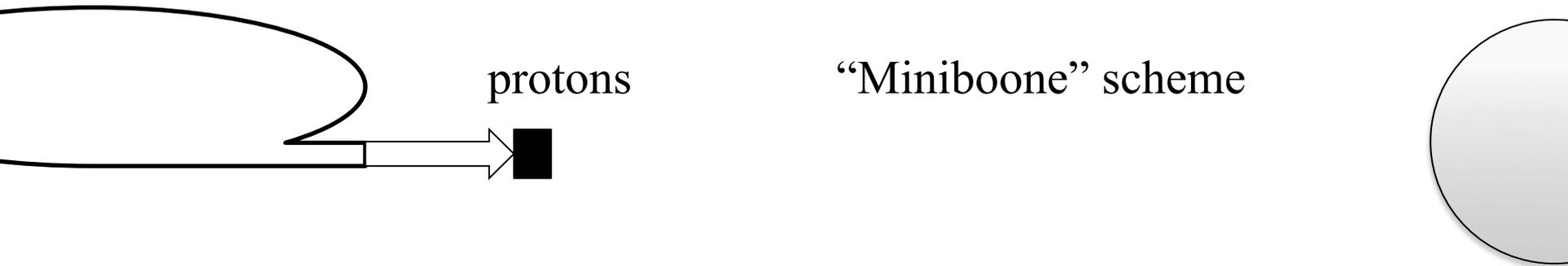
Borexino, Kamland,  
SNO+, SuperK, JUNO,  
Hyper-K (?) ...



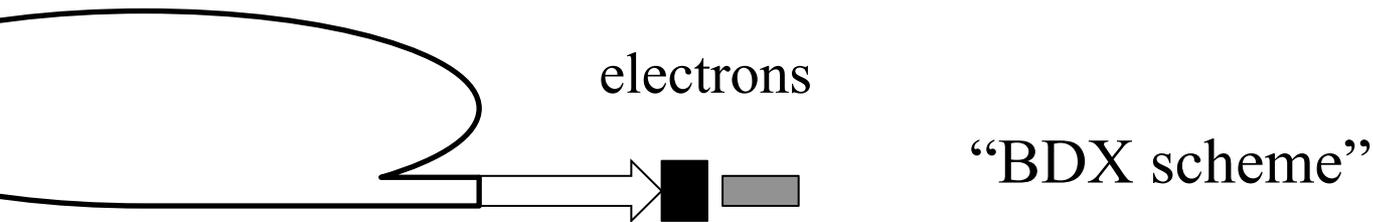
LUNA, DIANA, ...,  
1 e-linac for calibration

# Three schemes to search for light DM

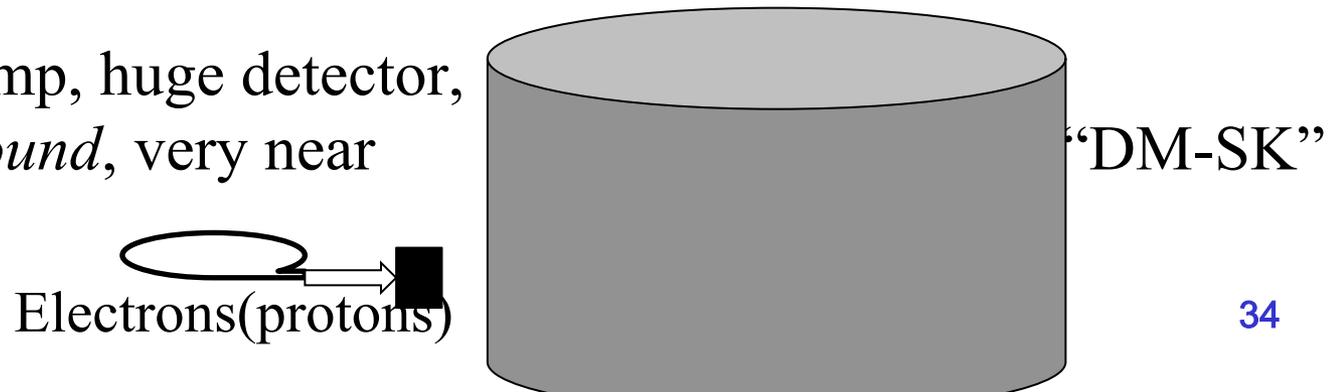
1. Proton beam dump, large neutrino detector, near surface, 0.5 km



2. Electron beam dump, small-ish detector, very near beam dump



3. Electron beam dump, huge detector, *deep underground*, very near beam dump



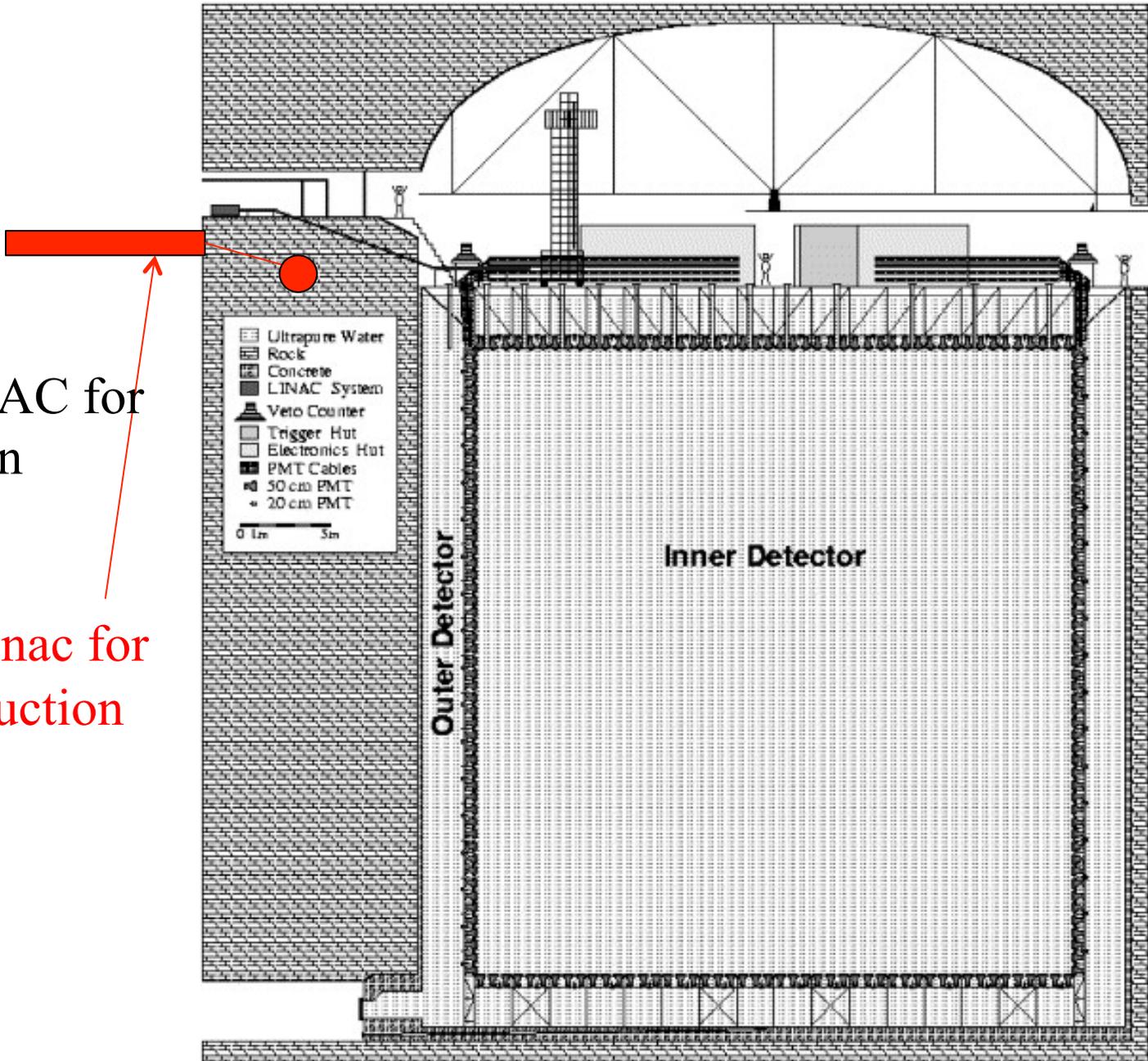
# Largest underground detectors

- **SNO** (*settled solar neutrino problem*), decommissioned.
- **Borexino** (8.5m inner volume diameter; discovered several components of solar flux, pp, pep, Be7, checked LMA solution).  
Future – sensitivity to sterile neutrinos via radioactive sources
- **Super-K** (50-ktons of water; discovered neutrino oscillations, best limits on p-decay, ...) Future: loading with Gd?
- **Kamland** (13m; saw reactor neutrino oscillations, measured  $m_{12}$ ...) Central region loaded with  $^{136}\text{Xe}$ , and used as neutrinoless double-beta decay experiment
- **SNO+** (12m), will be loaded with  $^{130}\text{Te}$ .
- **JUNO** (35 m) – construction began...
- **Hyper-K** ????. Cannot go bigger than that.
- Also, Xenon1T, LUX, LZ – smaller, but high Z.
- **For many experiments the original goals are fulfilled – new applications of these detectors? *Light new particles and light DM***<sup>5!</sup>

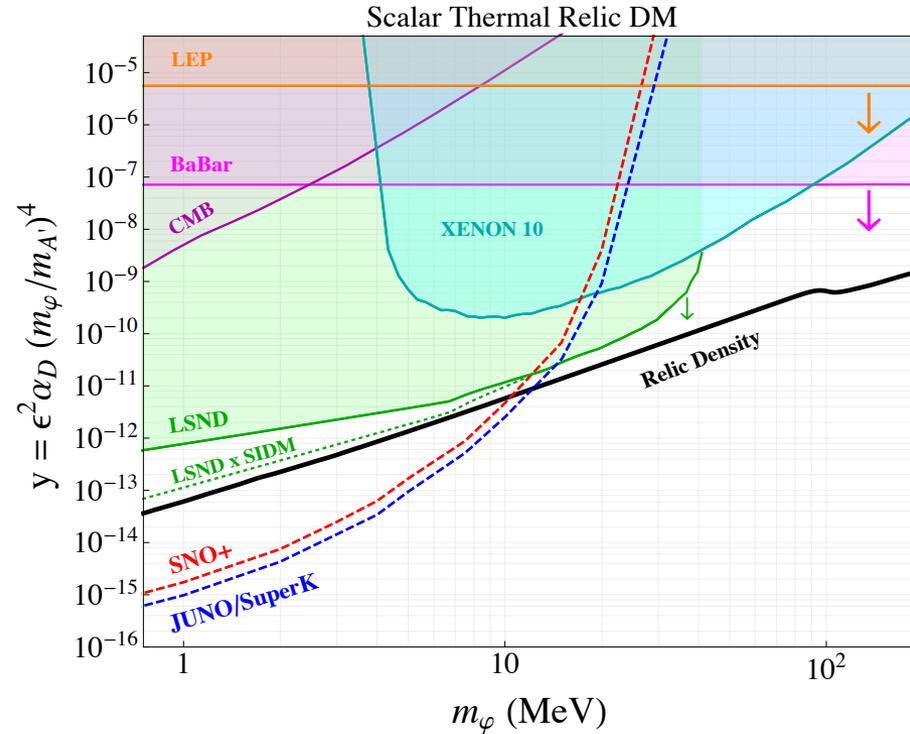
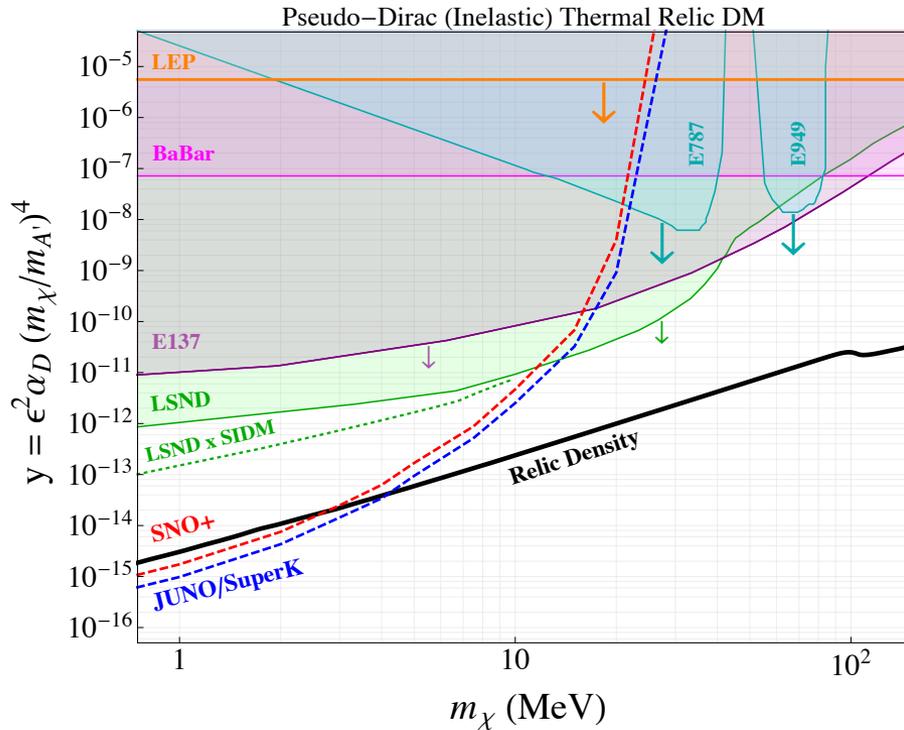
Tiny LINAC for calibration

+

Bigger Linac for DM production



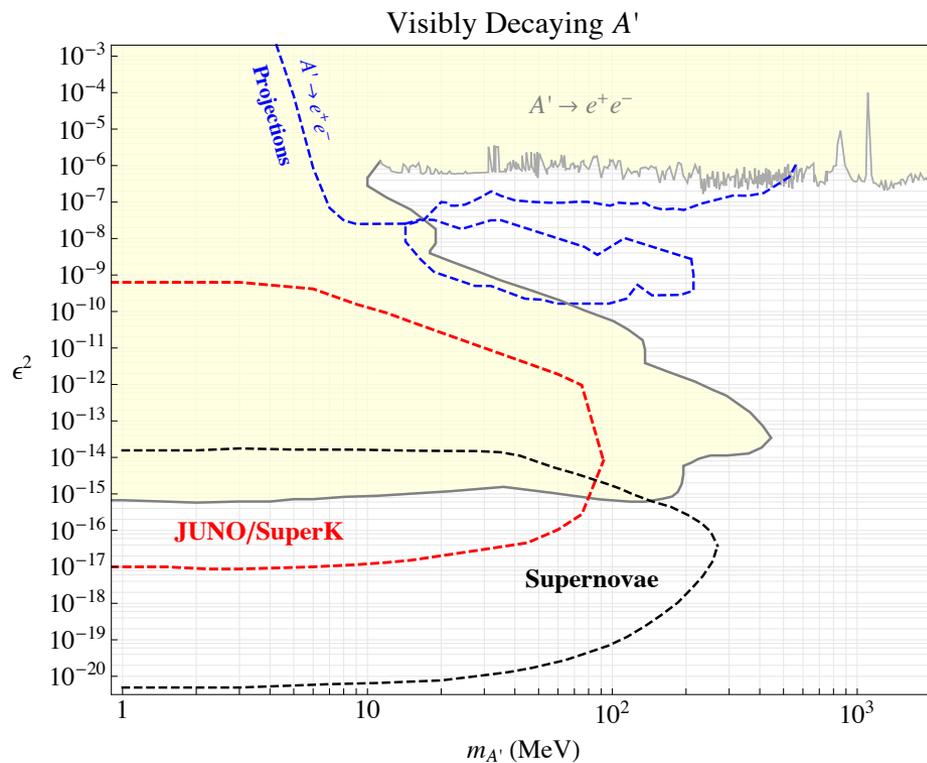
# Sensitivity to light DM



One will significantly advance sensitivity to light DM in the sub-100 MeV mass range. Assuming  $10^{24}$  100 MeV electrons on target

Izaguirre, Krnjaic, MP, 1507.02681

# Visible dark photon decay



Sensitivity to dark photon is better than any terrestrial experiments, comparable with SN constraints.

# Conclusions

1. Light New Physics (not-so-large masses, tiny couplings) is a generic possibility. Some models (dark photon, scalar coupled Higgs portal) are quite natural, and can be searched for in fixed target experiments.
2. Concerted effort in “dark photon” case rules out minimal model as a cause of  $g-2$  discrepancy. Other possibilities remain.
3. Currently, light dark matter via production & scattering can be searched for at MiniBoone. HPS is taking data.
4. Future: more experimental possibilities. Watch out for the SHiP project (the only one where all types of portals will be probed)! There is a big potential for increasing sensitivity by placing medium energy linacs next to large underground  $\nu$  detectors

# Precision frontier: UV physics or IR?

**Typical approach:** we measure an observable (e.g.  $\mu \rightarrow e \gamma$ , EDM, rare meson decays etc), we perform calculation of the same quantity in the SM, take a difference, and whatever is left is interpreted in terms of physics at a TeV, 10 TeV, XXX TeV scales – *all of them being UV scales.*

**More correct approach:** Assume that New Physics consist of UV pieces, Assume IR pieces or both,

$$\mathcal{L}_{\text{NP}} = \mathcal{L}_{\text{UV}} + \mathcal{L}_{\text{IR}}.$$

$$\mathcal{L}_{\text{UV}} = \sum_{d \geq 5} \frac{1}{\Lambda_{\text{UV}}^{d-4}} \mathcal{O}_d. \quad \mathcal{L}_{\text{IR}} = \kappa B^{\mu\nu} V_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N L H N + \mathcal{L}_{\text{hid}}$$

If result for NP is consistent with 0, we can set constraints on both. If it is non-zero: then *more work is required in deciding IR or UV*

# UV physics or IR: examples of NP that we know

**Neutrino oscillations:** We know that new phenomenon exists, and if interpreted as neutrino masses and mixing, is it coming from deep UV, via e. .g Weinberg's operator

$$\mathcal{L}_{\text{NP}} \propto (HL)(HL)/\Lambda_{\text{UV}} \text{ with } \Lambda_{\text{UV}} \gg \langle H \rangle$$

or it is generated by *new IR field*, such as RH component of Dirac neutrinos? *New dedicated experimental efforts are directed in trying to decide between these possibilities.*

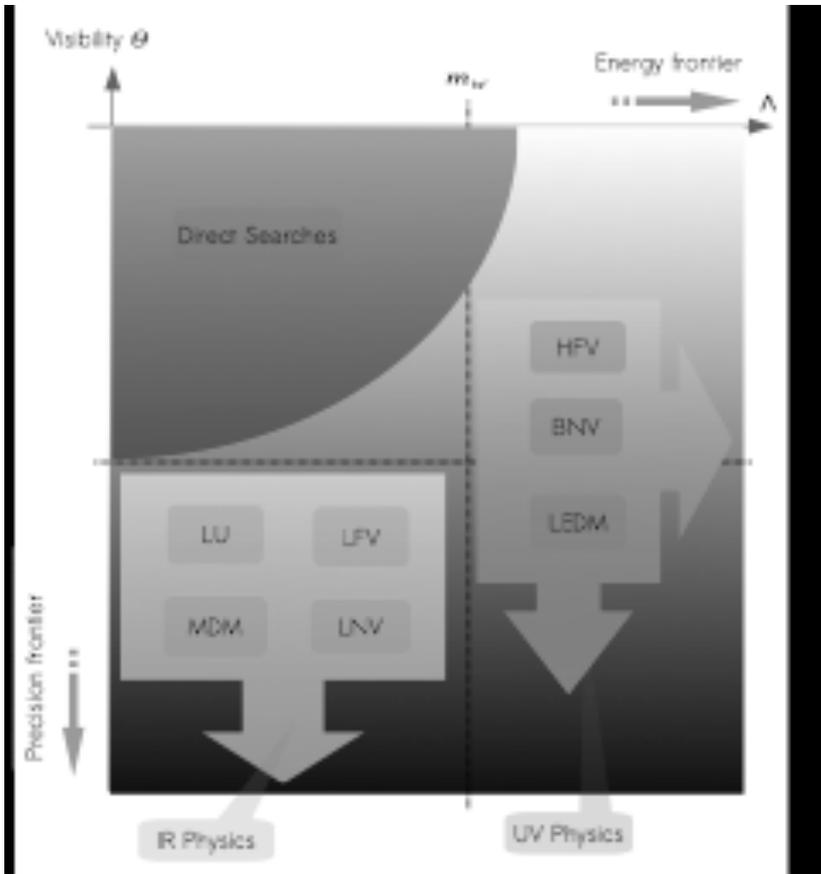
**Dark matter:** 25% of Universe's energy balance is in dark matter: we can set constraints on both. If it is embedded in particle physics, then e.g. neutralinos or axions imply new UV scales.

However, *there are models of DM where NP is completely localized in the UV, and no new scales are necessary.*

New efforts underway both in the UV and IR category.

# Mini-analysis

Le Dall, MP, Ritz, 2015



Observable	(A,B) Portals	(C,D) UV-incomplete
LFV	✓	✓
LU	✓	✓
$(g - 2)_l$	✓	✓
LNV	✓	✓
LEDMs		✓
HFV		✓
BNV		✓

At current level of experimental accuracy many lepton observables ( $g-2$ , LFV, LU) but EDM can be induced by IR physics (e.g. new massive sterile neutrinos below the weak scale).

Quark sector observables would typically require NP at UV scale (except neutron EDM)