Title: DAEdALUS and Dark Matter

Date: Dec 03, 2014 11:00 AM

URL: http://pirsa.org/14120021

Abstract: <p>In the search for dark matter, neutrino experiments can play a key role by doubling as dark matter production and detection experiments. I will describe how the proposed DAEdALUS decay-at-rest neutrino experiment can be used to search for MeV-scale dark matter, with particular emphasis on dark matter produced through a dark photon in rare neutral pion decays. The fact that the dark photon need not be on-shell opens up a wide range of new possibilities for the experimental program of searching for dark matter at neutrino experiments.</p>

DAEdALUS and Dark Matter

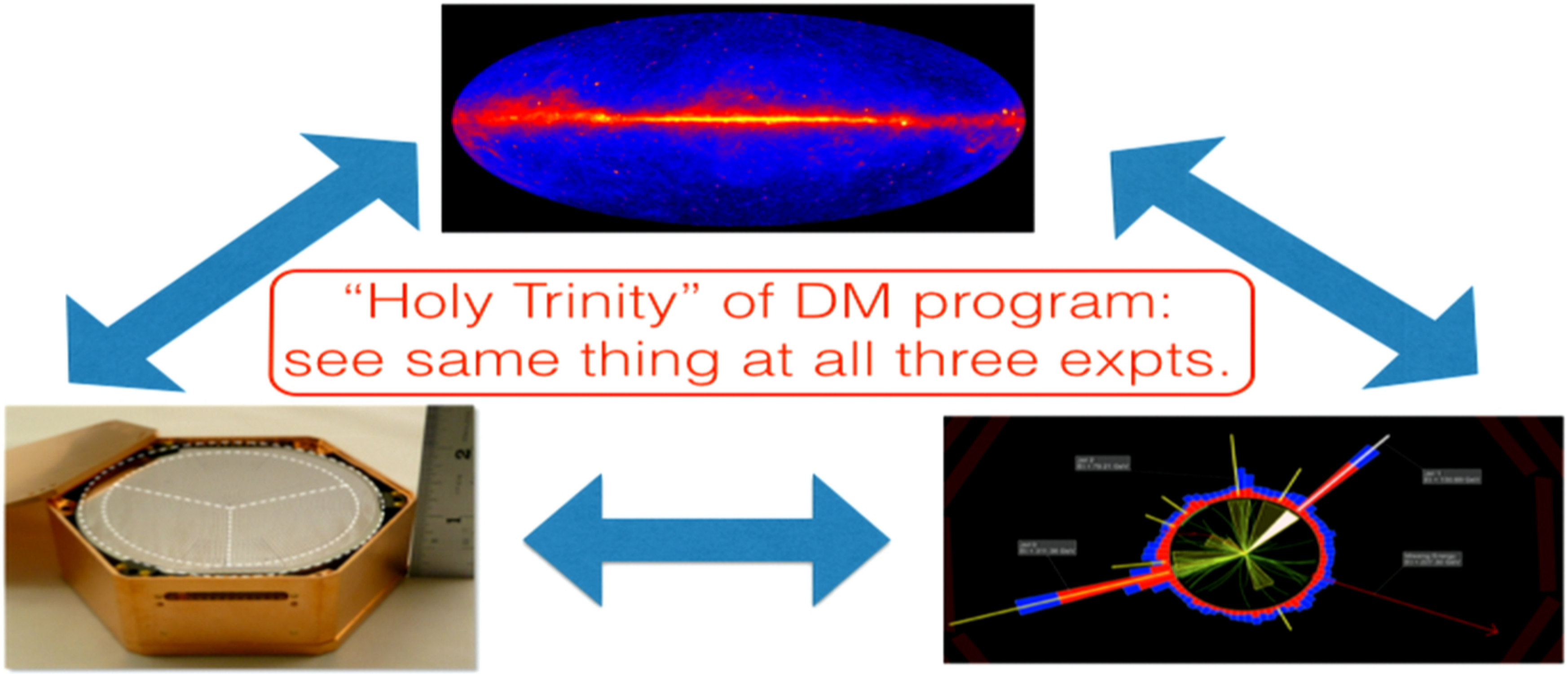
Perimeter Institute, 12/3/14

Yoni Kahn, MIT

with Gordan Krnjaic, Jesse Thaler, and Matthew Toups

1411.1055

Dark matter search strategies



Indirect detection

“Holy Trinity” of DM program:
see same thing at all three expts.

Direct detection

Collider production

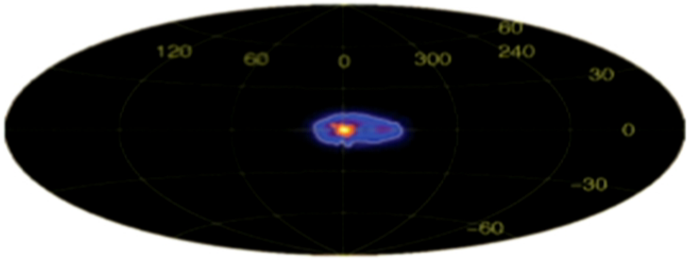
Why an MeV dark sector?

“WIMP” miracle

$$\frac{\Omega_\chi}{\Omega_{DM}} \sim 10^{-3}\left(\frac{\alpha}{\alpha_D}\right)^2\left(\frac{m_\chi}{100\ \mathrm{MeV}}\right)^2$$

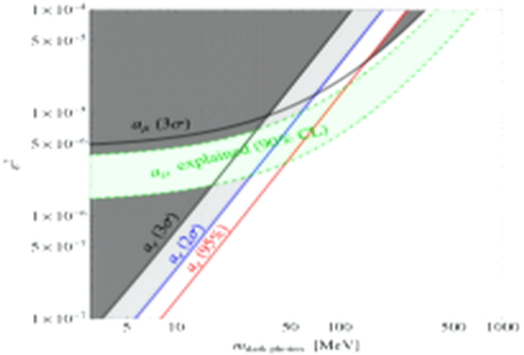
$$(m_\chi > M_{med})$$

Galactic positron excess



[Weidenspointner 2008]

Muon g-2 anomaly



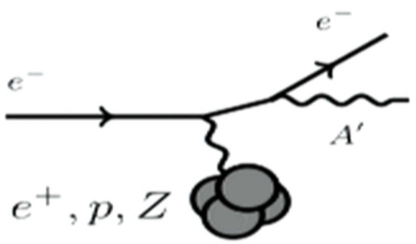
[Pospelov 0811.1030, Lee 1410.8435]

Easily missed in standard WIMP searches!

Too light for colliders, too slow for direct detection, too much background for indirect detection

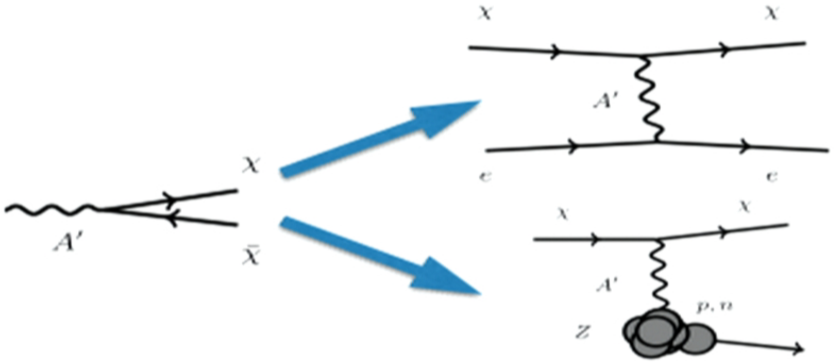
Fixed-target experiments

"Missing-energy" search:



e.g. VEPP-3, DarkLight, new PI proposal
[1207.5089, 1307.4432, 1411.1404]

Production and detection:



e.g. LSND & MiniBooNE, E137, BDX
[0906.5614, 1406.2698, 1406.3028]

Neutrino experiments especially well suited:
neutral-current neutrino scattering looks like DM scattering

Same signals, same detectors!

Dark photon model

[Okun Sov. Phys. 1982, Holdom Phys. Lett. B 1986]

$$\mathcal{L} \supset \frac{\epsilon_Y}{2} F'_{\mu\nu} B^{\mu\nu} + \frac{m_{A'}{}^2}{2} A'_\mu A'^\mu + \bar{\chi}(i\not{\partial} - g_D \not{A}' - m_\chi)\chi$$

kinetic mixing

dark photon mass

dark gauge coupling

DM mass

(consider only fermionic DM for concreteness)

Key feature: kinetic mixing gives universal coupling to EM

$$\mathcal{L} \supset \epsilon A'_\mu J^\mu_{\mathrm{EM}}$$

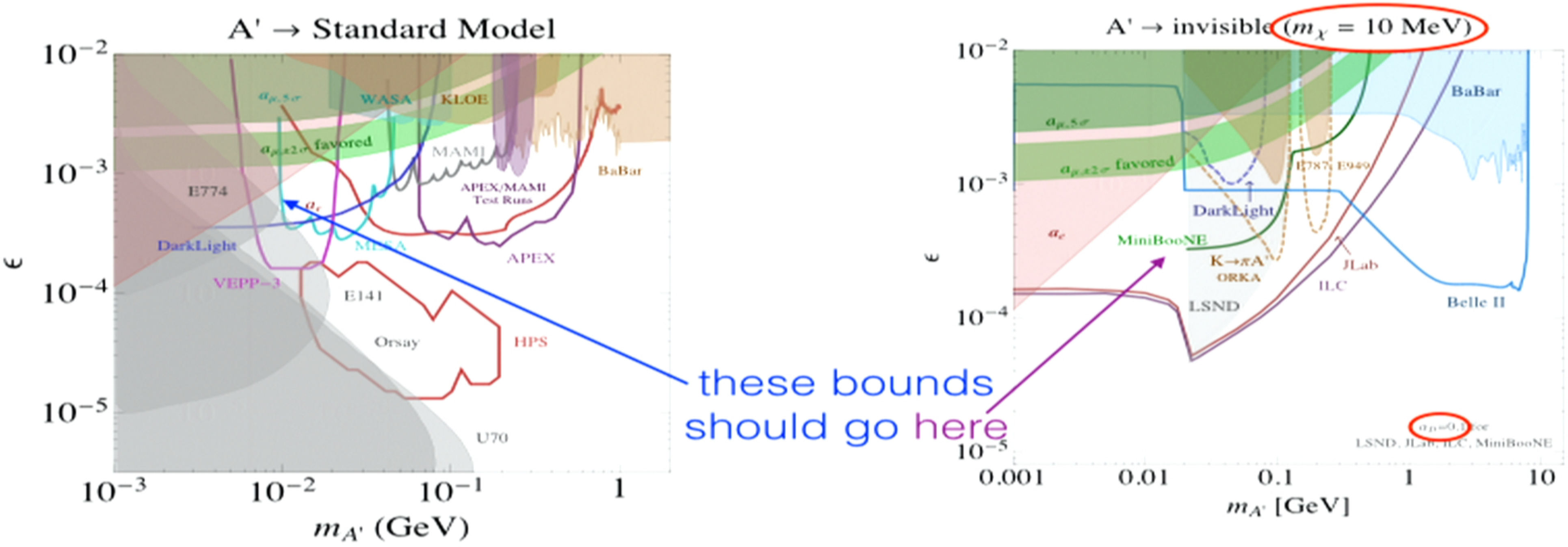
Any source of photons is a source of dark photons (and DM)

$$\alpha \to \epsilon^2 \alpha$$

Full 4-dimensional parameter space is worth exploring!

Parameter space (as of 2013)

[Essig 1311.0029]

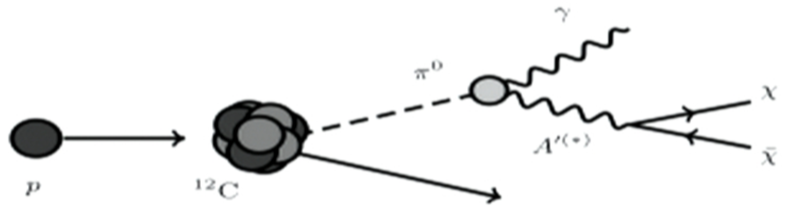


these bounds should go here

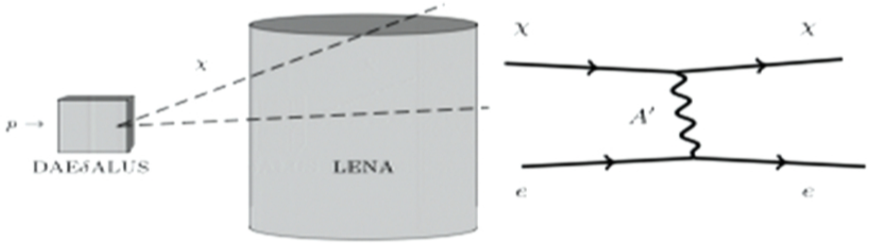
Key takeaway: off-shell dark photons make current results stronger and connect visible/invisible searches

Outline

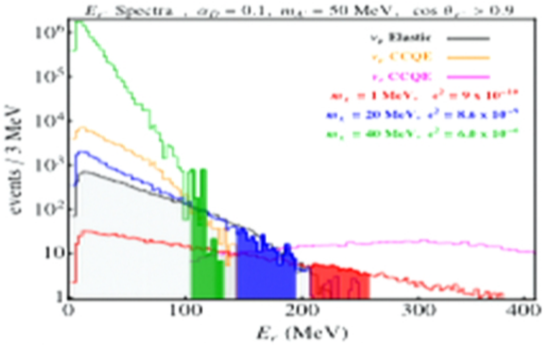
I. MeV DM production at DAEdALUS



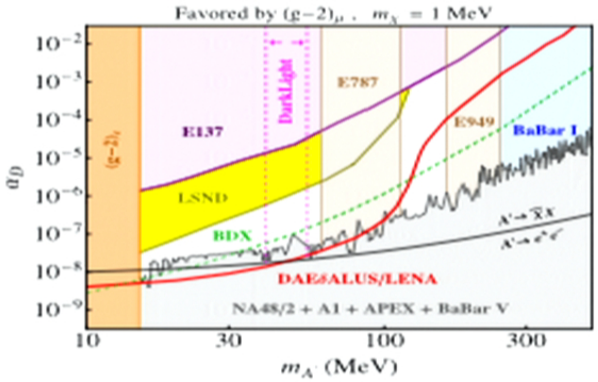
II. DM detection at LENA



III. Backgrounds and analysis strategy



IV. Sensitivities



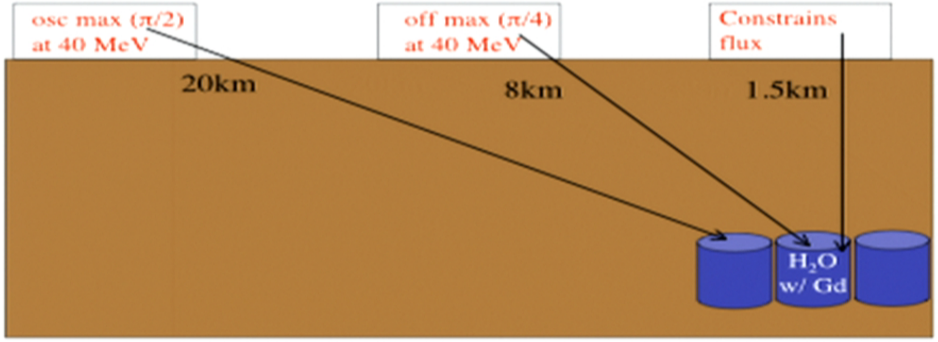
I. MeV DM production at DAEdALUS

DAEdALUS proposal

[Adelmann et al. 1307.6465]

Goal: measure δ_{CP} in neutrino mixing matrix

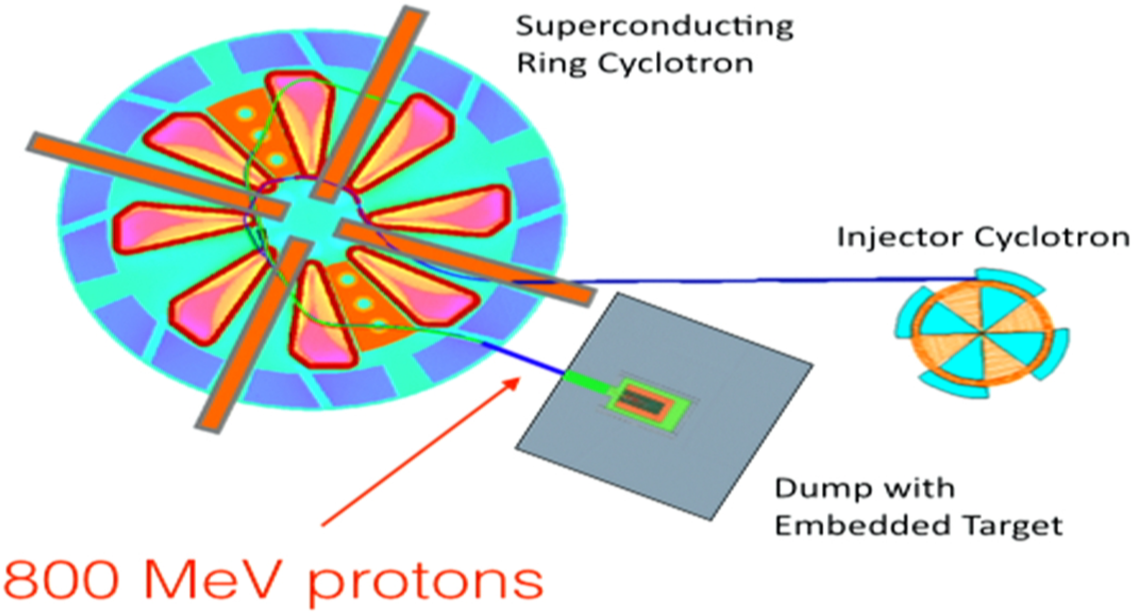
Multi-baseline decay-at-rest $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation experiment



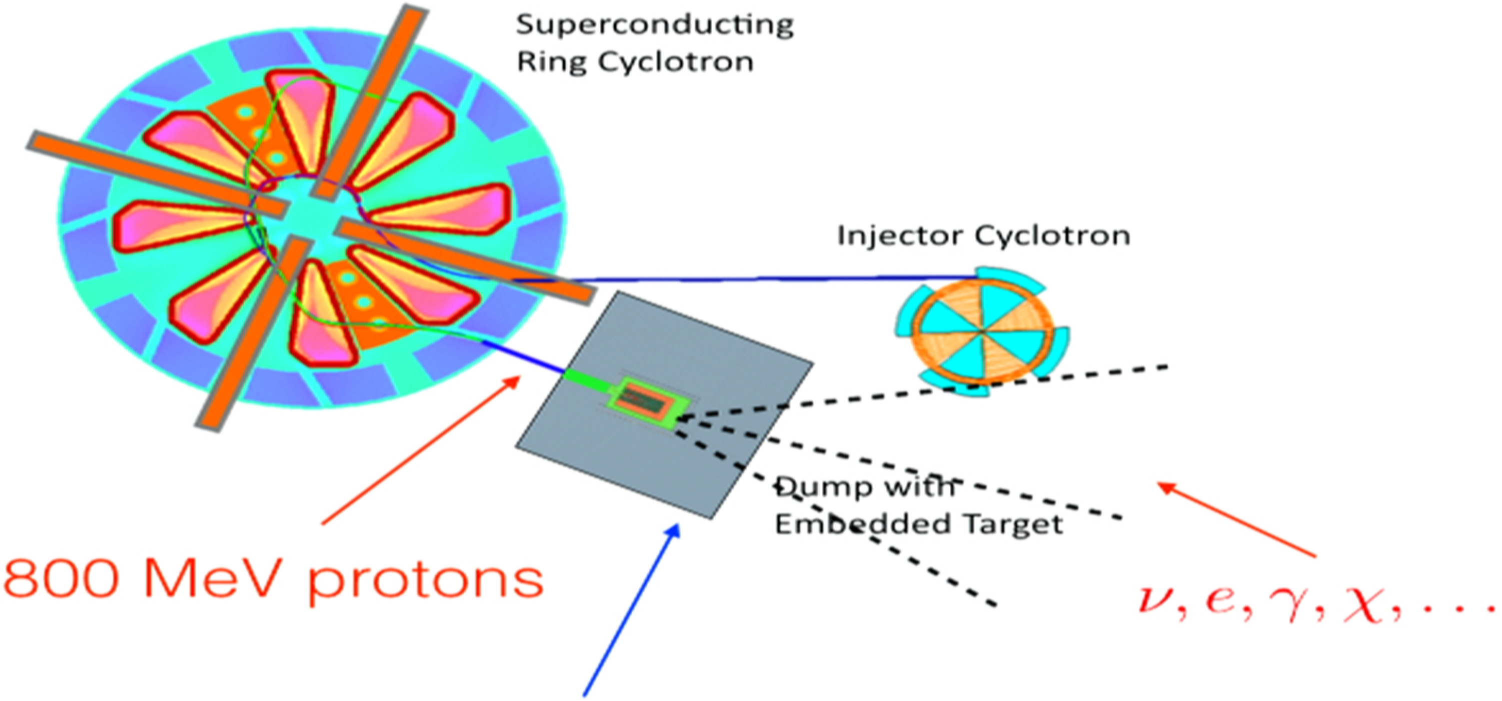
Three cyclotron sources are expensive...

However, exciting physics opportunities with only one source!

DAEdALUS source



DAEdALUS source



800 MeV protons

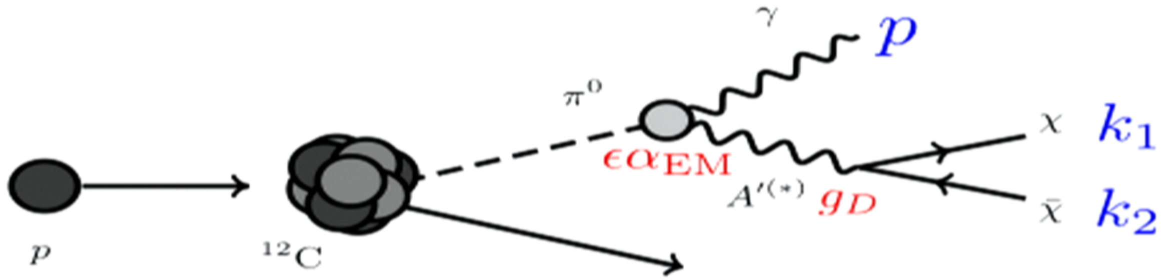
$\nu, e, \gamma, \chi, \ldots$

Thick specialized target stops most charged pions and muons, neutrinos primarily produced from decays at rest

DM production from pions

Neutrino source is also a DM source!

π^0 are main source of energetic photons at 800 MeV
(Δ, bremsstrahlung subdominant)

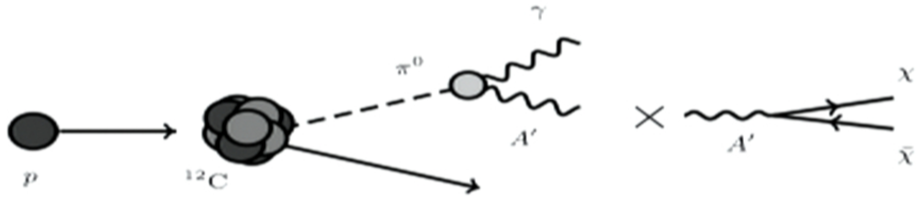


$$\langle|\mathcal{A}_{\pi^0\to\gamma\chi\bar{\chi}}|^2\rangle = \frac{4\epsilon^2\alpha_D\alpha_{\rm EM}^2}{\pi f_\pi^2[(s-m_{A'}^2)^2+m_{A'}^2\Gamma_{A'}^2]}\left[(s+2m_\chi^2)\left(m_{\pi^0}^2-s\right)^2-8s(p\cdot k_1)(p\cdot k_2)\right]$$

Nice feature: neutral pions decay fast, retain boost!

On-shell vs. off-shell

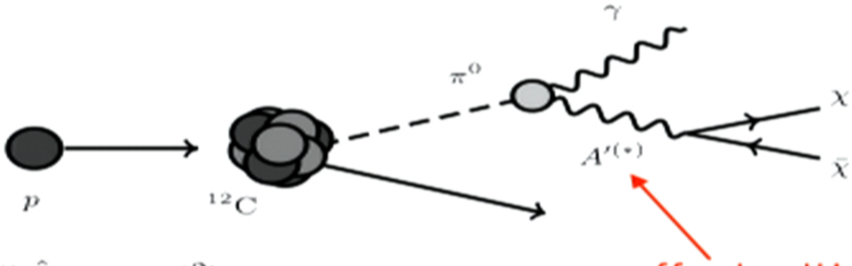
$2m_\chi < m_{A'} < m_{\pi^0}$:



narrow width approx. $\mathrm{Br}(\pi^0 \to \gamma\chi\overline{\chi}) = \mathrm{Br}(\pi^0 \to \gamma\gamma) \times 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \times \mathrm{Br}(A' \to \chi\overline{\chi})$

factor of α_D in A' width cancels with amplitude

$m_{A'} < 2m_\chi$ or $m_{A'} > m_{\pi^0}$:



off-shell!

$$\mathrm{Br}(\pi^0 \to \gamma\chi\overline{\chi}) = \frac{1}{\Gamma_{\pi^0}} \times \frac{\epsilon^2\alpha_D}{2m_{\pi^0}} \int d\Phi_{\pi^0\to\gamma A'}\, d\Phi_{A'\to\chi\overline{\chi}}\, \frac{ds}{2\pi} \langle|\hat{\mathcal{A}}_{\pi^0\to\gamma\chi\overline{\chi}}|^2\rangle$$

No sharp kinematic cutoffs!

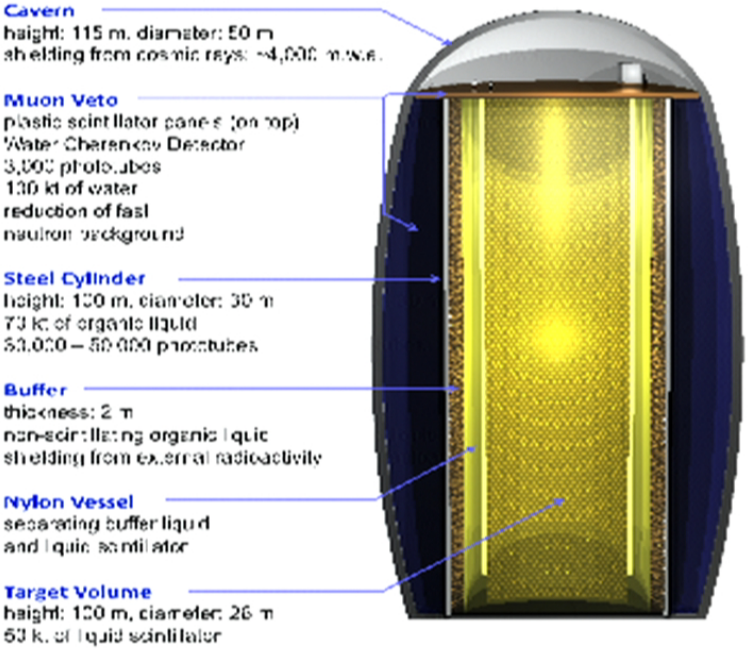
Will find sensitivity to $m_{A'}$ well above pion mass

II. DM detection at LENA

The LENA detector

[Wurm et al. 1104.5620]

(a.k.a. an underground football field filled with laundry detergent)



Cavern
height: 115 m, diameter: 50 m
shielding from cosmic rays: ~4,000 m.w.e.

Muon Veto
plastic scintillator panels (on top)
Water Cherenkov Detector
3,000 phototubes
100 kt of water
reduction of fast
neutron background

Steel Cylinder
height: 100 m, diameter: 30 m
70 kt of organic liquid
30,000 – 50,000 phototubes

Buffer
thickness: 2 m
non-scintillating organic liquid
shielding from external radioactivity

Nylon Vessel
separating buffer liquid
and liquid scintillator

Target Volume
height: 100 m, diameter: 26 m
50 kt of liquid scintillator

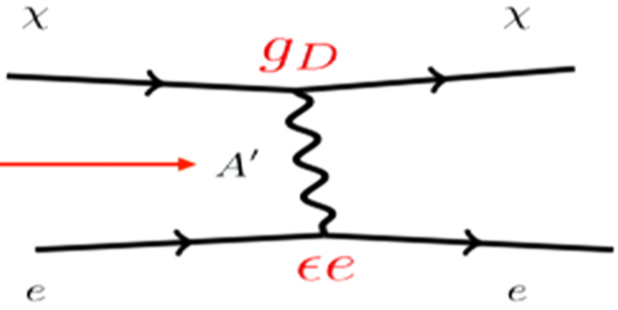
(Anything underground works: JUNO, Hyper-K, ...)

Electron scattering

Form factor suppression at MeV momentum transfers:

nuclear scattering highly suppressed

production
and detection
through same
mediator



$\propto \epsilon^2 \alpha_D$

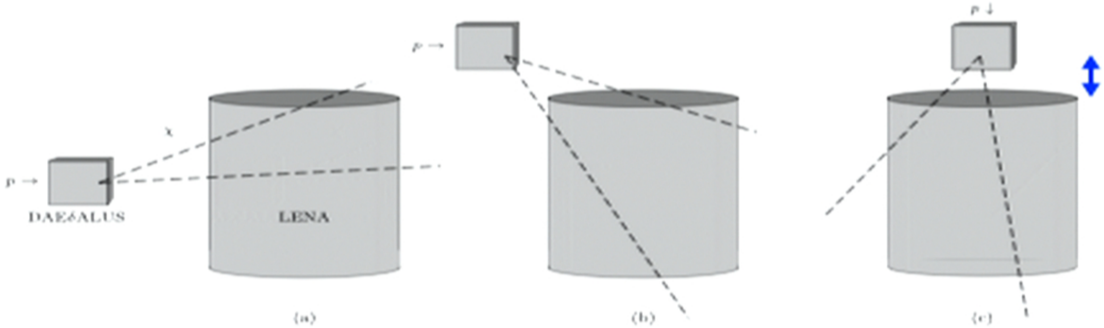
$$N_{\rm sig} = n_e \int_{E_e^{\rm low}(m_\chi)}^{E_e^{\rm high}(m_\chi)} dE_e \int_{E_\chi^{\rm min}(E_e)} dE_\chi \int_{\rm LENA} d\Omega\, \ell(\Omega) \frac{d^2 N_\chi}{d\Omega\, dE_\chi} \frac{d\sigma}{dE_e}$$

energy cuts

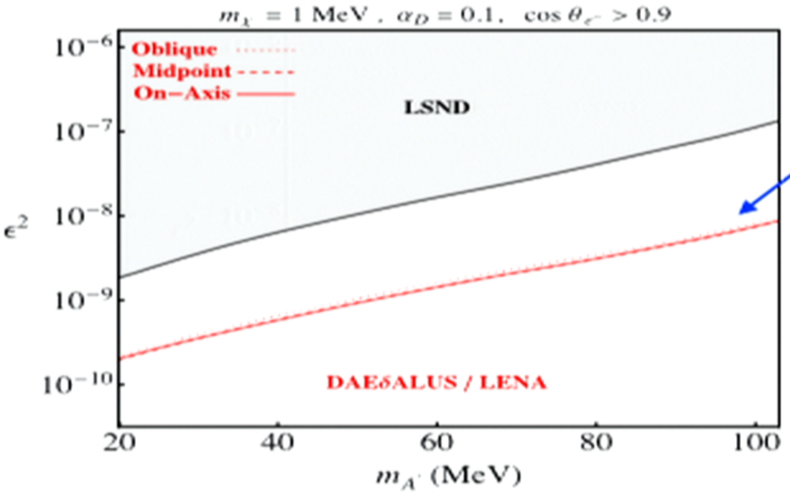
geometry

$$E_\chi^{\rm min}(E_e) = \frac{T_e}{2}\left[1 + \sqrt{\left(1 + \frac{2m_e}{T_e}\right)\left(1 + \frac{2m_\chi^2}{m_e T_e}\right)}\right], \qquad T_e \equiv E_e - m_e$$

Geometries



↕ 20 m



sig/BG distributions very similar, geometry doesn't appreciably affect reach

Can piggyback on existing neutrino expt. setups!

III. Backgrounds and analysis strategy

Elastic and CCQE scattering

Any event which gives a single energetic charged lepton (plus any other soft junk) is a potential background

Two main types of BG:

Elastic scattering (irreducible)

$$\nu e \rightarrow \nu e$$

- Same final state as signal
- Identical kinematics to signal

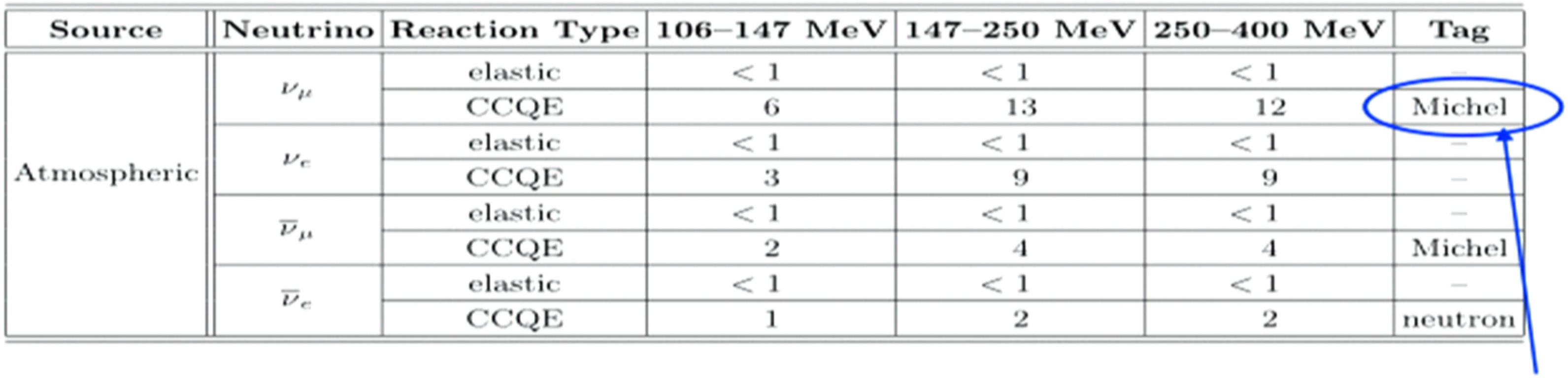
Charged-current quasi-elastic (partially reducible)

$$\nu_\ell \, n \rightarrow \ell^- \, p, \;\; \overline{\nu}_\ell \, p \rightarrow \ell^+ \, n$$

- Nuclear activity indistinguishable from lepton
- Muons can fake electrons
- Recoil spectrum has sharp cutoffs and distinctive kinematics

Beam-off backgrounds

Underground detector renders everything
but atmospherics negligible

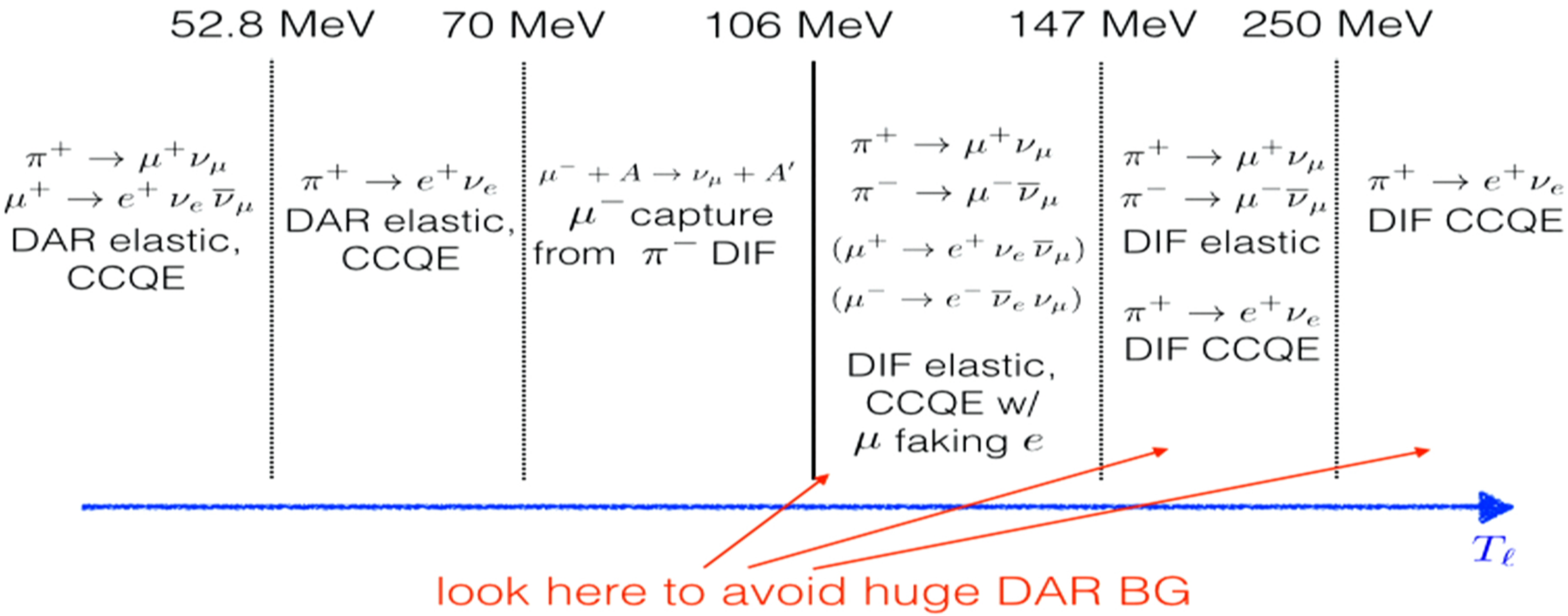


Source	Neutrino	Reaction Type	106–147 MeV	147–250 MeV	250–400 MeV	Tag
Atmospheric	ν_μ	elastic	< 1	< 1	< 1	–
		CCQE	6	13	12	Michel
	ν_e	elastic	< 1	< 1	< 1	–
		CCQE	3	9	9	–
	$\overline{\nu}_\mu$	elastic	< 1	< 1	< 1	–
		CCQE	2	4	4	Michel
	$\overline{\nu}_e$	elastic	< 1	< 1	< 1	–
		CCQE	1	2	2	neutron

can tag muon
decay 70%

Small, manageable rates,
can measure during 75% beam-off time

Beam-on BG: processes



52.8 MeV

70 MeV

106 MeV

147 MeV

250 MeV

$\pi^+ \to \mu^+ \nu_\mu$
$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$
DAR elastic, CCQE

$\pi^+ \to e^+ \nu_e$
DAR elastic, CCQE

$\mu^- + A \to \nu_\mu + A'$
μ^- capture from π^- DIF

$\pi^+ \to \mu^+ \nu_\mu$
$\pi^- \to \mu^- \overline{\nu}_\mu$
$(\mu^+ \to e^+ \nu_e \overline{\nu}_\mu)$
$(\mu^- \to e^- \overline{\nu}_e \nu_\mu)$
DIF elastic, CCQE w/ μ faking e

$\pi^+ \to \mu^+ \nu_\mu$
$\pi^- \to \mu^- \overline{\nu}_\mu$
DIF elastic

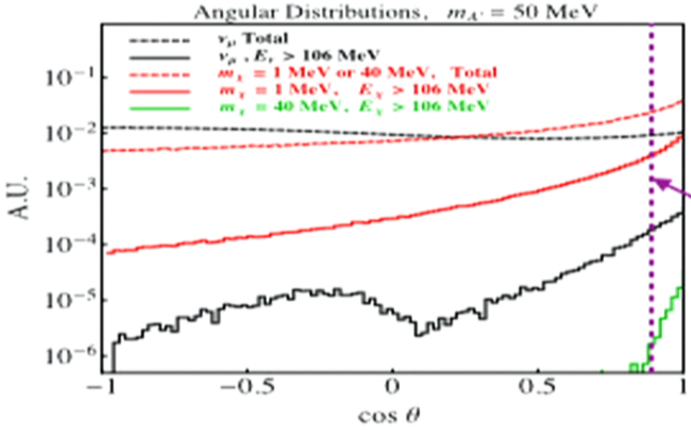
$\pi^+ \to e^+ \nu_e$
DIF CCQE

$\pi^+ \to e^+ \nu_e$
DIF CCQE

T_ℓ

look here to avoid huge DAR BG

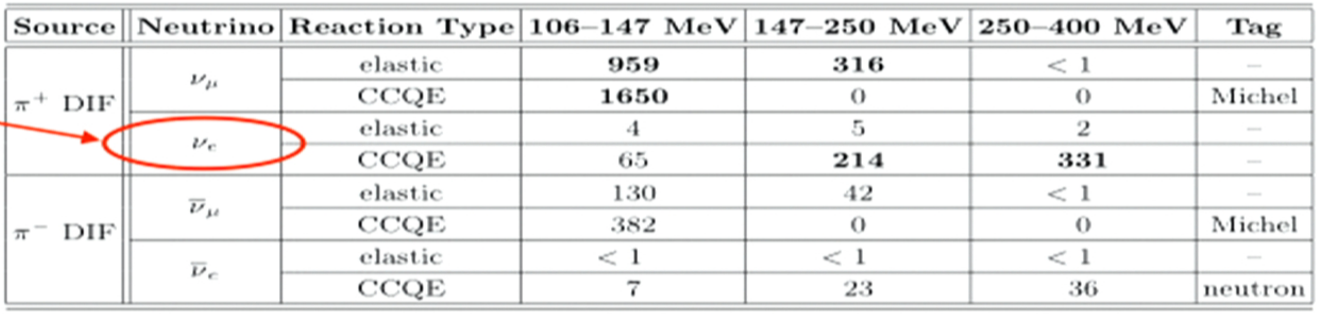
Beam-on BG: rates



keeps most signal,
cuts down elastic
(and isotropic CCQE)

Even after exploiting angular kinematics…

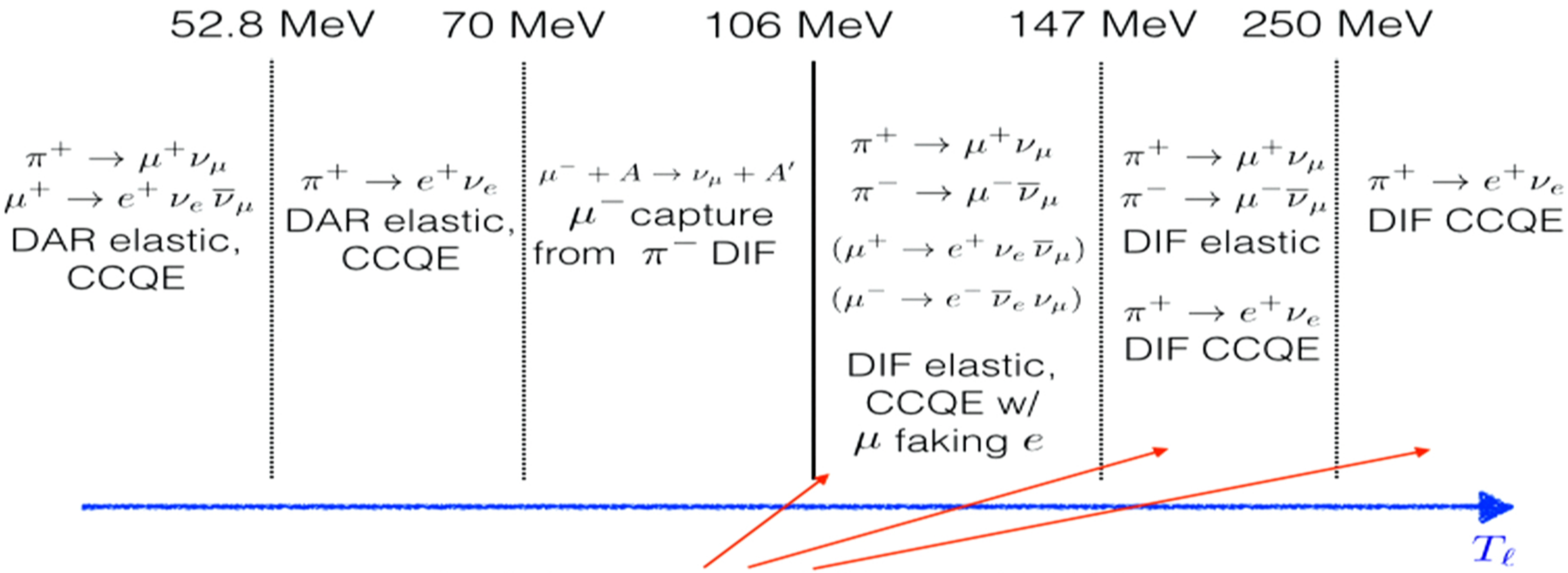
from
$\pi^+ \to e^+\nu_e$
with
10^{-4} BR!



Source	Neutrino	Reaction Type	106–147 MeV	147–250 MeV	250–400 MeV	Tag
π^+ DIF	ν_μ	elastic	**959**	**316**	< 1	–
		CCQE	**1650**	0	0	Michel
	ν_e	elastic	4	5	2	–
		CCQE	65	**214**	**331**	–
π^- DIF	$\overline{\nu}_\mu$	elastic	130	42	< 1	–
		CCQE	382	0	0	Michel
	$\overline{\nu}_e$	elastic	< 1	< 1	< 1	–
		CCQE	7	23	36	neutron

CCQE dominant at low and high energies

Beam-on BG: processes



52.8 MeV

70 MeV

106 MeV

147 MeV

250 MeV

$\pi^+ \to \mu^+ \nu_\mu$
$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$
DAR elastic,
CCQE

$\pi^+ \to e^+ \nu_e$
DAR elastic,
CCQE

$\mu^- + A \to \nu_\mu + A'$
μ^- capture
from π^- DIF

$\pi^+ \to \mu^+ \nu_\mu$
$\pi^- \to \mu^- \overline{\nu}_\mu$
$(\mu^+ \to e^+ \nu_e \overline{\nu}_\mu)$
$(\mu^- \to e^- \overline{\nu}_e \nu_\mu)$
DIF elastic,
CCQE w/
μ faking e

$\pi^+ \to \mu^+ \nu_\mu$
$\pi^- \to \mu^- \overline{\nu}_\mu$
DIF elastic

$\pi^+ \to e^+ \nu_e$
DIF CCQE

$\pi^+ \to e^+ \nu_e$
DIF CCQE

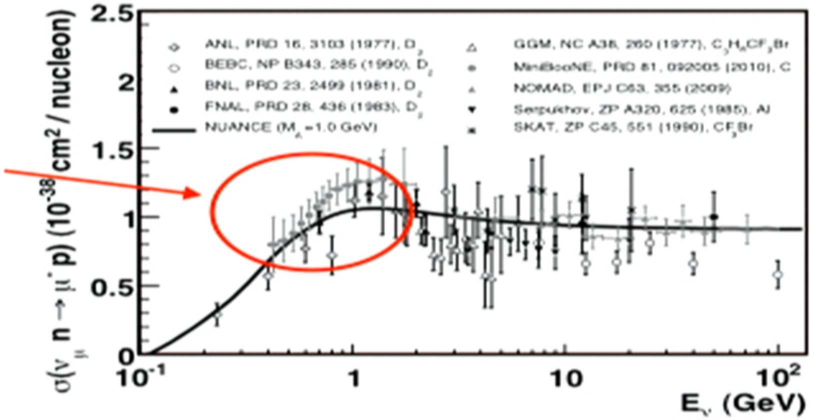
T_ℓ

look here to avoid huge DAR BG

Background uncertainties

Persistent issue at neutrino experiments is flux calibration

Need some process other than electron scattering to calibrate…but nuclear processes have large systematic uncertainties!



??

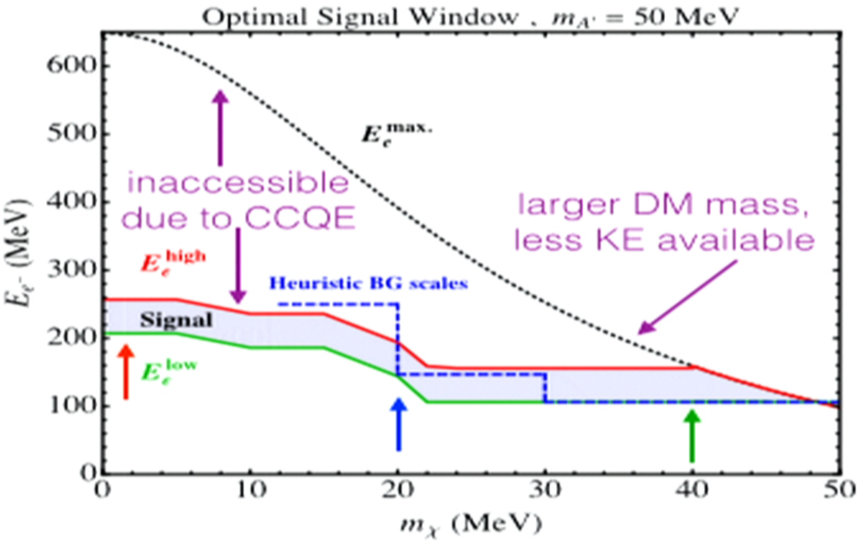
[Formaggio and Zeller, 1305.7513]

Beam-off rate low enough to be stats-dominated, but beam-on rate is systematics-dominated

Take $\delta B = 0.2B$ to be conservative

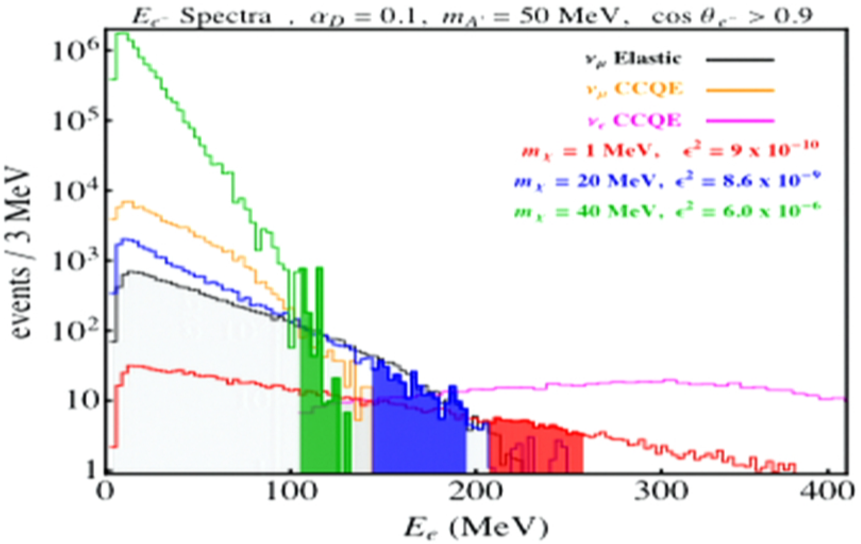
Optimal recoil cuts

Optimize S/B for all points in parameter space:



inaccessible due to CCQE

larger DM mass, less KE available



CCQE is main BG almost everywhere, need narrow signal window!

DAEdALUS/LENA vs. LSND

- **Higher energy range for electron recoils**

  LSND: Cerenkov with 18-52 MeV analysis window
  LENA: Scintillator with poor resolution at low energies, can work above DAR threshold (> 106 MeV)

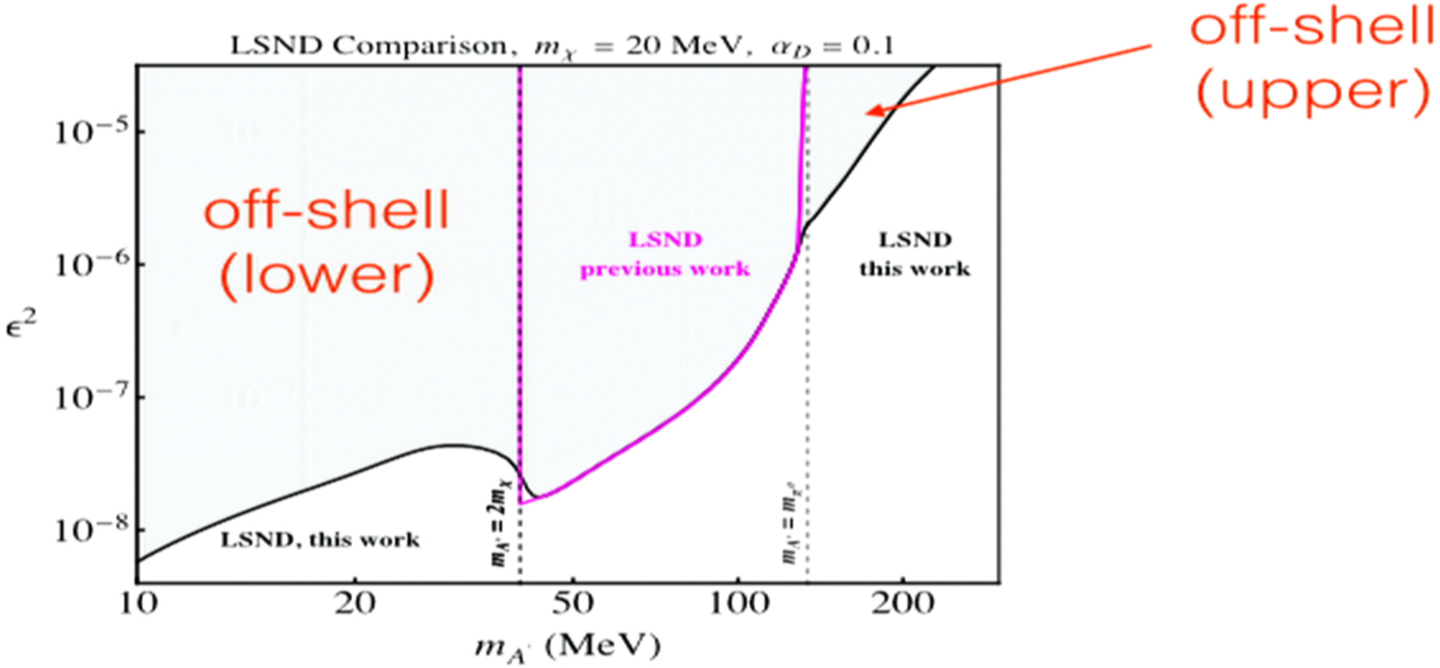
- *Higher luminosity: DAEdALUS delivers 10x more POT in 1 year than whole life of LSND experiment

- *Larger acceptance: can put DAEdALUS closer to LENA, detector is 100 m long compared to 8 m for LSND

  *can be important if stats-limited, rather than sys-limited

IV. Sensitivities

Updated LSND bounds

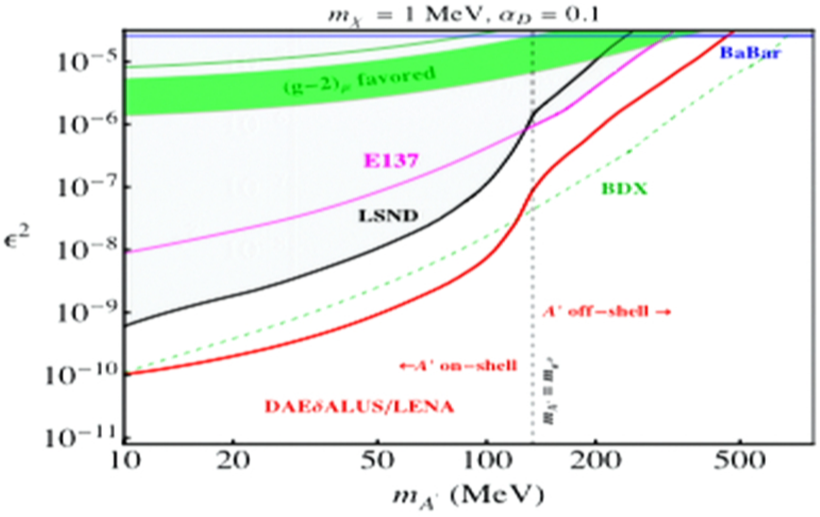


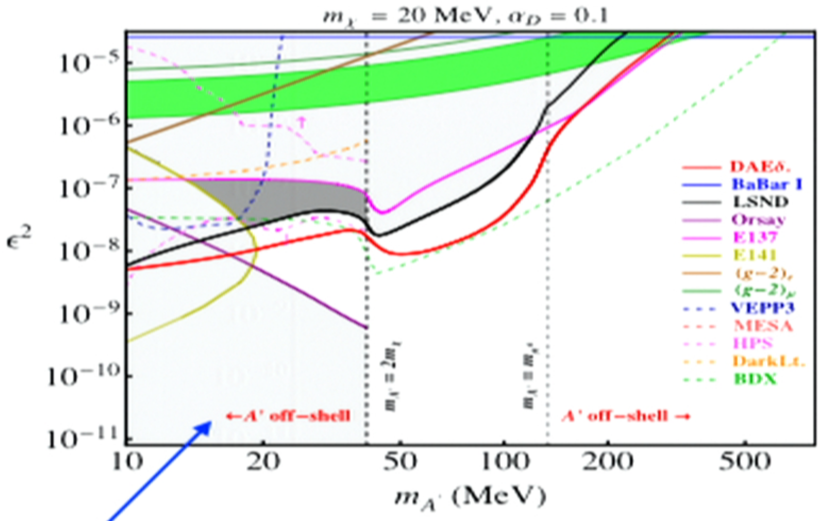
off-shell (upper)

off-shell (lower)

Huge region of parameter space excluded for free!
Potential to run same analysis with higher-energy LSND window [LSND collab. nucl-ex/9706006]

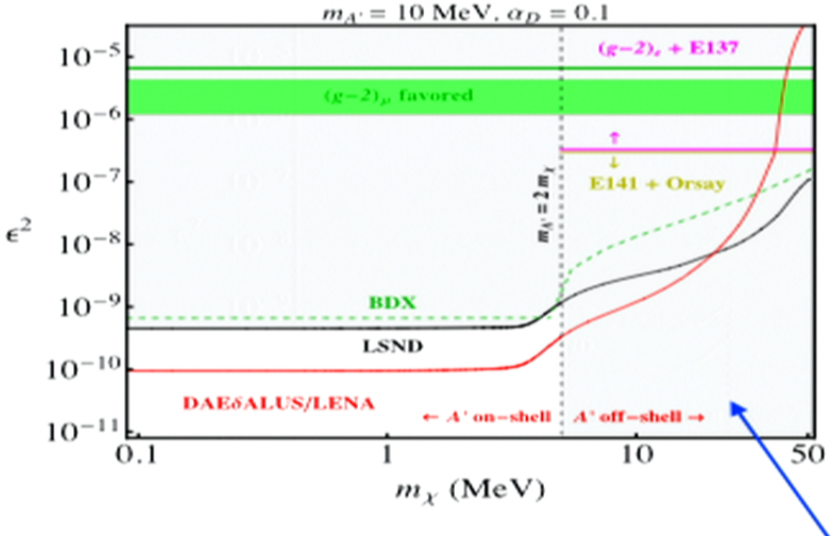
Fixed DM mass

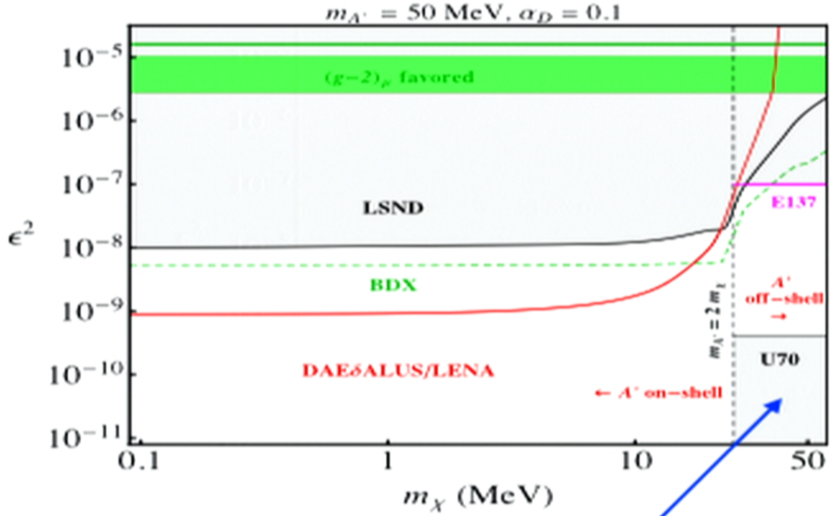




Lower off-shell regime probes same parameter space as visible searches!

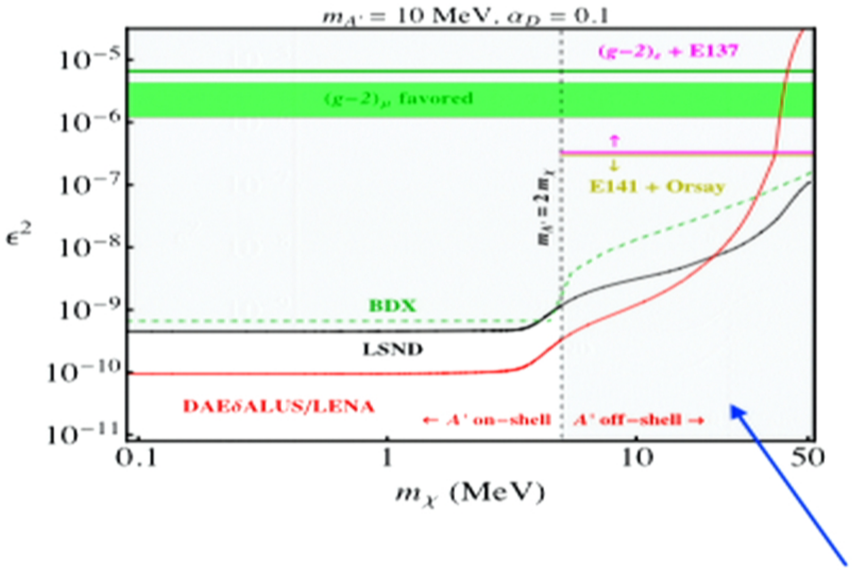
Fixed dark photon mass

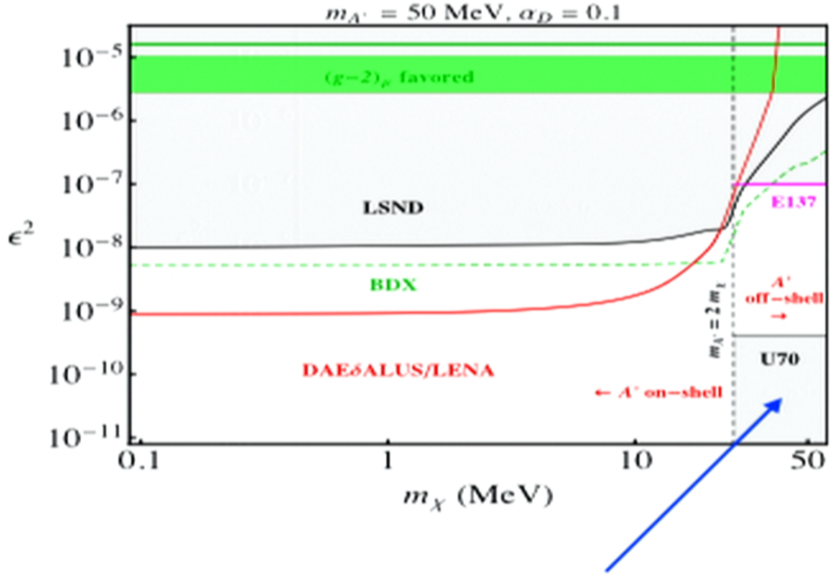




Lower off-shell regime probes same parameter space as visible searches!

Fixed dark photon mass

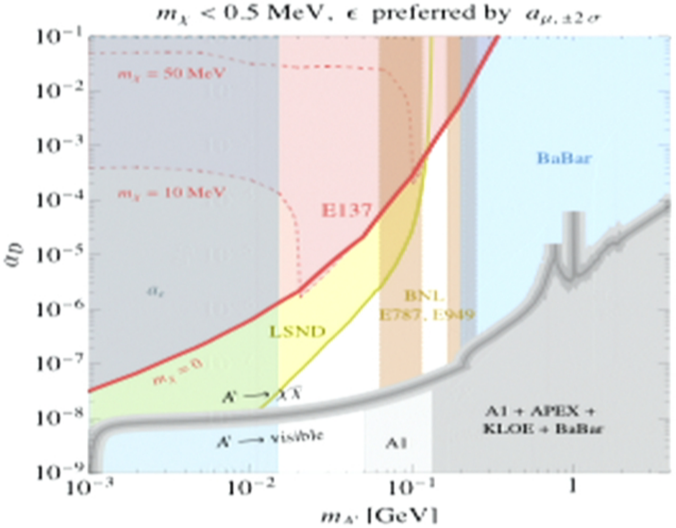




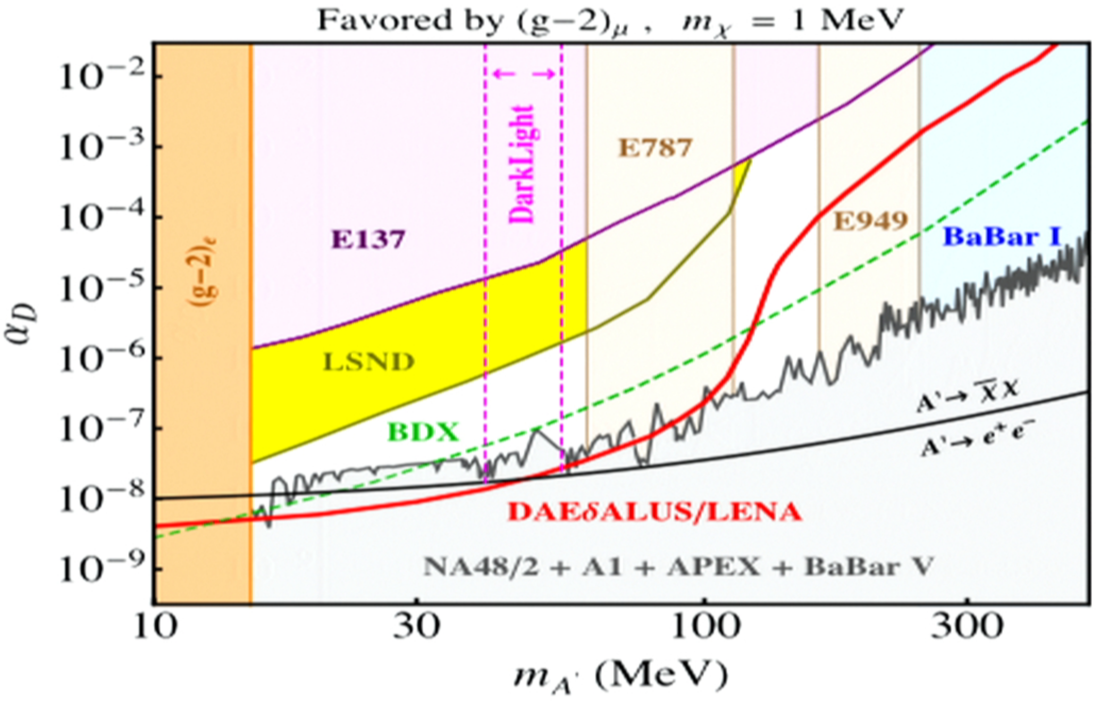
Lower off-shell regime probes same parameter space as visible searches!

Fixed kinetic mixing

old



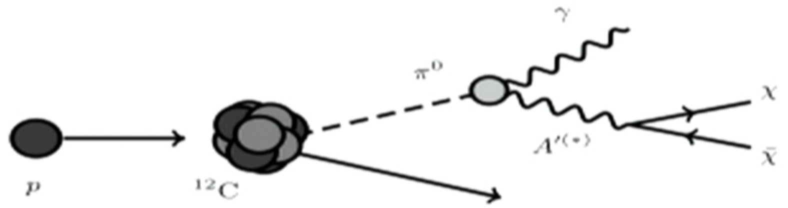
new



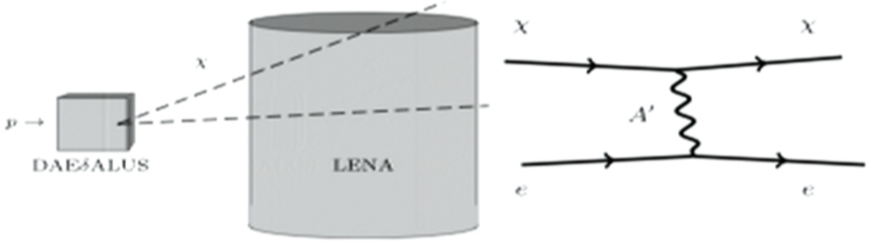
The g-2 window is closing! But not dead yet…

Summary

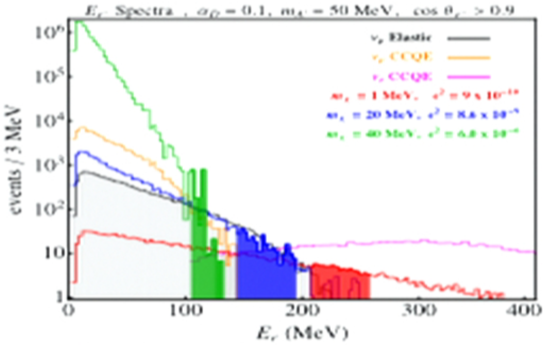
I. MeV DM produced through rare 3-body pion decay



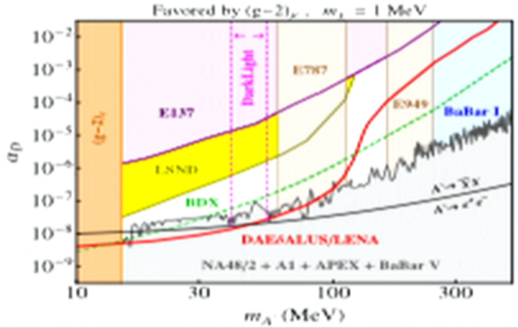
II. DM detected via electron scattering



III. CCQE backgrounds from rare decays are main BG



IV. DAEdALUS/LENA stronger than LSND by an order of mag.



Conclusions

- DAEdALUS with a suitable detector like LENA can improve LSND by an order of magnitude after 1 year
- Off-shell reach is surprisingly strong, important for whole program of dark photon searches from meson decay (e.g. MiniBooNE)
- Exciting symbiosis between neutrino and DM communities in the coming years!