Light New Physics with underground accelerators

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E. Izaguirre, G. Krnjaic, MP, 2014, to appear in PLB,
Same authors, work in progress

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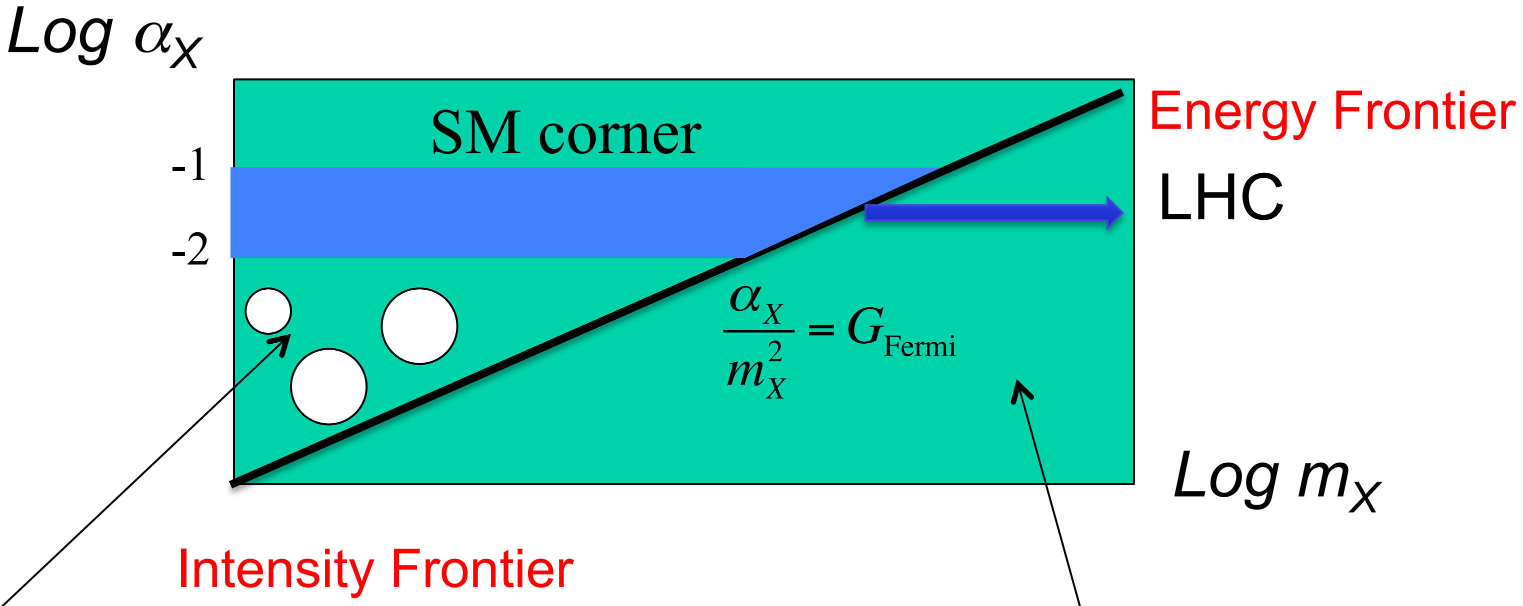
Outline of the talk

1. Introduction. *Pushing boundaries for new physics.*
2. Some motivations for new light states, with DM or without (511 keV line from galactic bulge, DAMA signal from scattering on electrons, muonic H Lamb shift, g-2 etc). Existing searches of MeV dark matter.
4. New opportunity: underground nuclear accelerators and radioactive sources. Constraints on scalar *e-p* scattering force, and a possible search with nuclear underground accelerators.
5. Putting e-linac underground – new possibility to search for light DM.
5. Conclusions

Main idea

- New physics with mass scales of several 100 keV – 100 MeV and very weak couplings to electrons & nucleons can be difficult to search for. Various motivations exist (g-2, “proton charge radius” models, light DM etc.)
- When mass < few MeV (up to 20 MeV), the new states can be accessed via *nuclear reactions*.
- Underground facilities have unique possibilities for producing new states using low-energy proton accelerators, and detecting their decay/scattering with large & clean neutrino detectors (such as Borexino, SuperK, etc.)
- A large progress in covering the parameter space is possible with relatively modest investment.
- Larger investments – e-linac underground – will lead to qualitatively better sensitivity to light New Physics.

“Stronger than weak” New Physics



If you see new effects like e.g. LFV, EDM etc it’ll be here (can be 1000 TeV, difficult to access, and no pressing need for UV completion)

There is a lot of “untouched” territory even for interactions that are “stronger than weak”. Examples: dark photon; baryonic dark vector; gauged flavor symmetries such as L_μ-L_τ

Dark Photons

Consider a new vector particle with the mass, and the coupling to the electromagnetic current, i.e. massive photon (Okun; Holdom…)

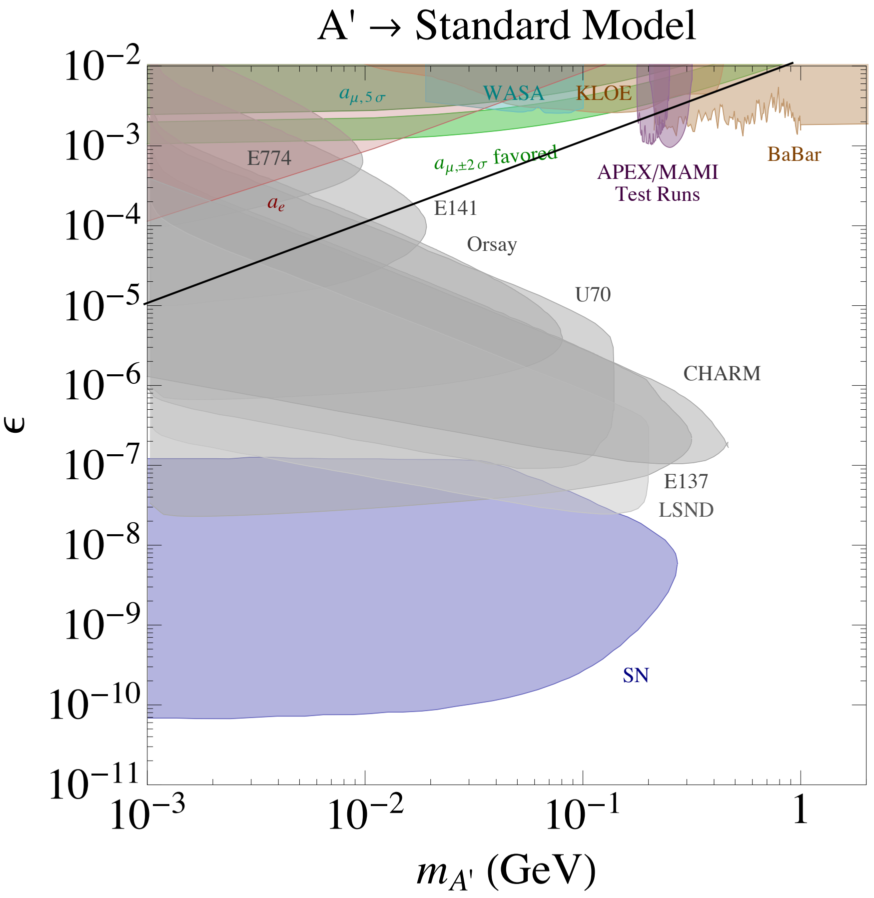
$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi),$$

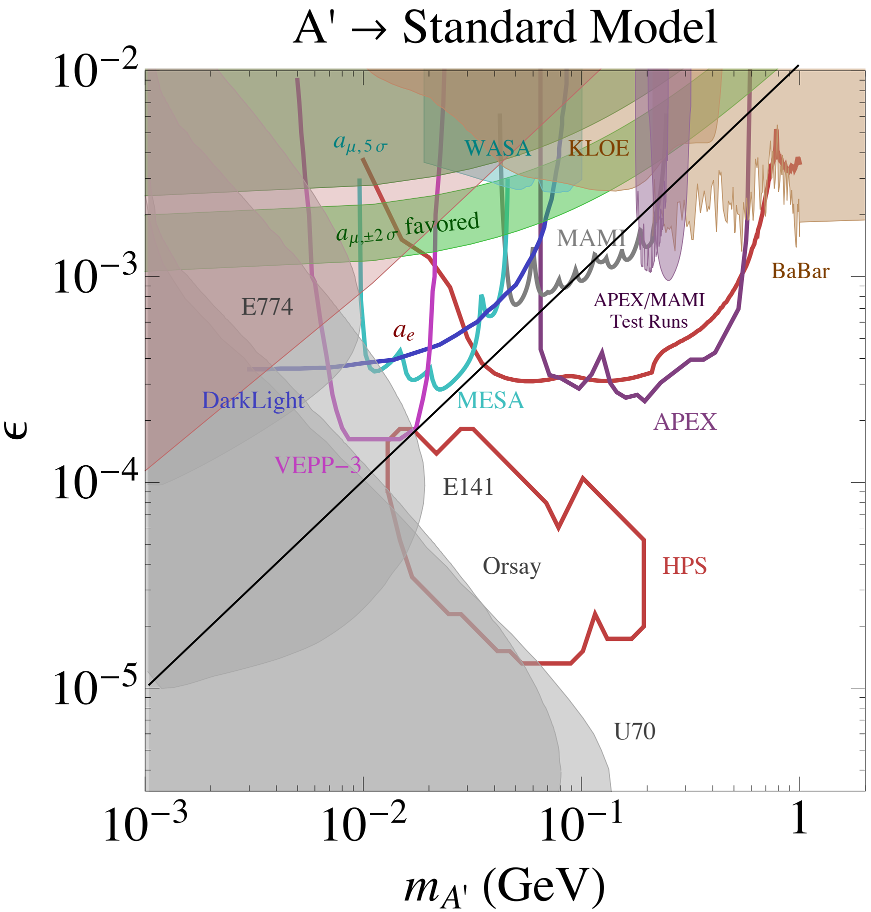
$$\downarrow$$

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa J_\mu^{EM} V_\mu$$

- This is an extremely popular model, subject to a variety of experimental searches in MeV-GeV range with $\kappa \sim 10^{-3}$. Can be used to "regulate" DM abundance or form the super-WIMP DM.

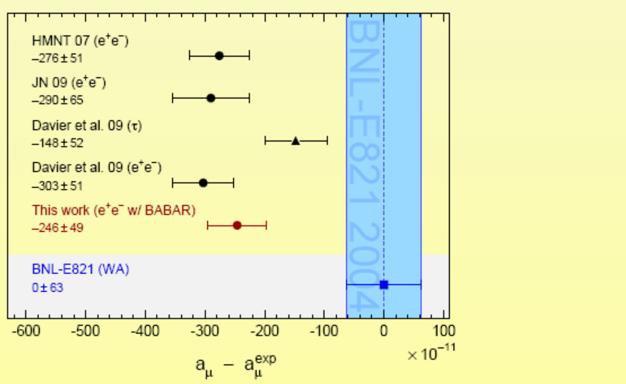
ε (κ, η)-m_V parameter space, Essig et al 2013



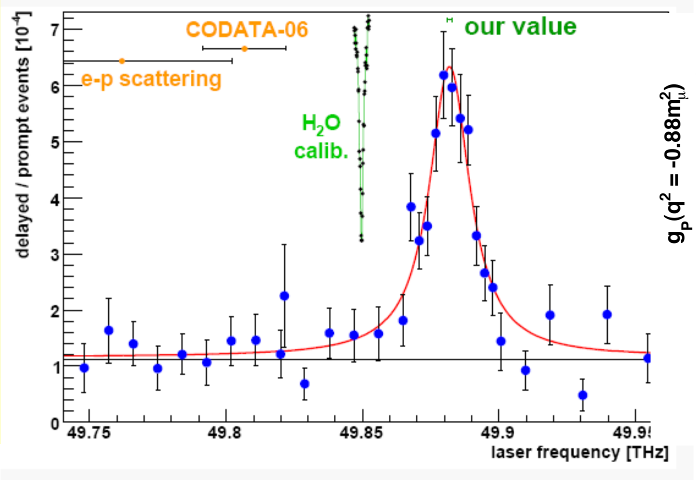


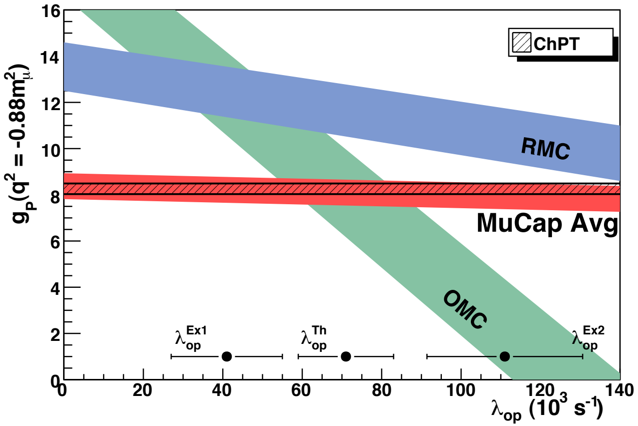
Dark photon models with mass under 1 GeV, and mixing angles ~ 10^{-3} represent a "window of opportunity" for the high-intensity experiments, and soon the g - 2 ROI will be completely covered. *Gradually, all parameter space in the "SM corner" gets probed/excluded.*

[motivation #1] Muon anomalies…



✱ Davier et al. arXiv:0906-5443

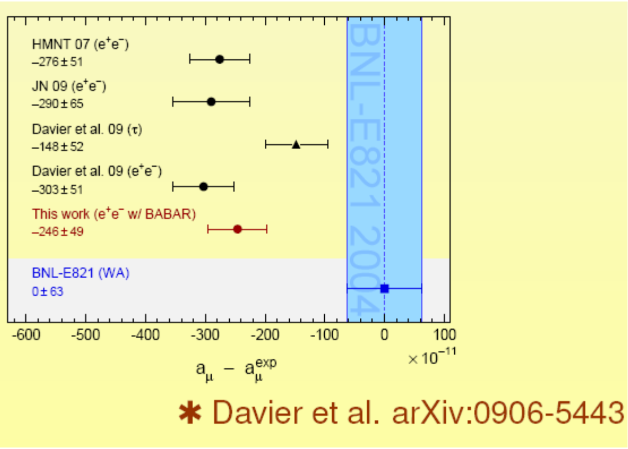




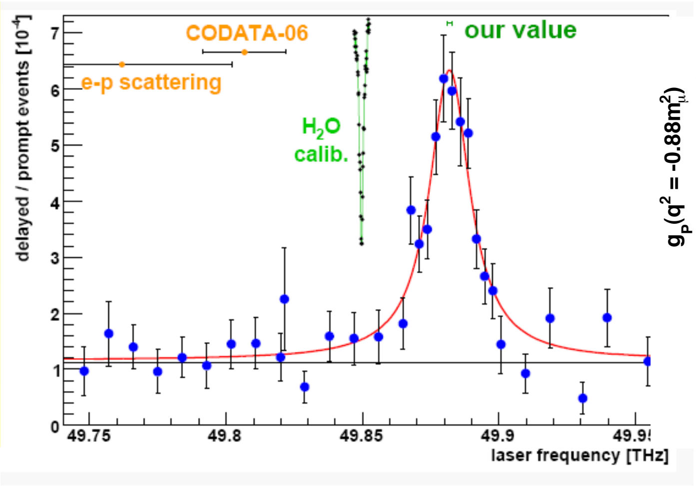
May be something happens with muonic "neutral" channels at low energy. We do not know – therefore it would be quite foolish not to explore additional possibilities of testing "NC-like" signatures in muons at low energy.

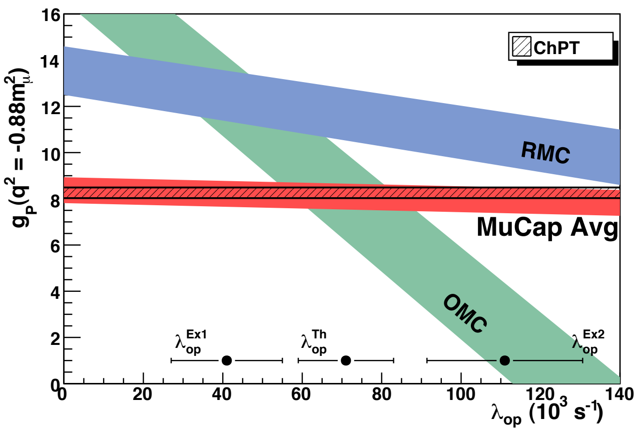
Resolution of current puzzles (r_p, g-2 etc) may come not necessarily from trying to re-measure same quantities again (also important), but from searches *of new phenomena* associated with muons.

Some muon anomalies can be explained by light NP



✱ Davier et al. arXiv:0906-5443





Can result from

New Physics at

100 GeV scale or MeV

scale

IF it is NP, it can only be light, lighter

100 MeV

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + (g_p\bar{p}p + g_e\bar{e}e + g_\mu\bar{\mu}\mu)\phi$$

$m_\phi \sim 1$ MeV, and couplings $g_{p,\mu} \sim 10^{-3}$ can “resolve” g-2 and/or r_p anomalies. [Hard to UV complete in honest way]

Astrophysical motivations (#2): 511 keV line

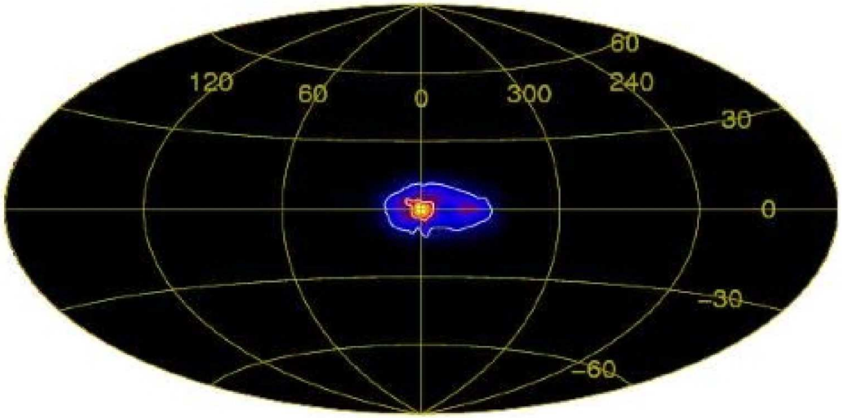


FIG. 4 511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

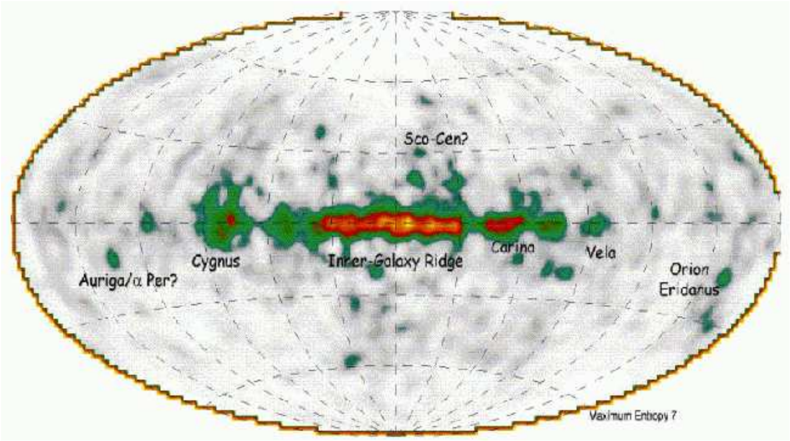
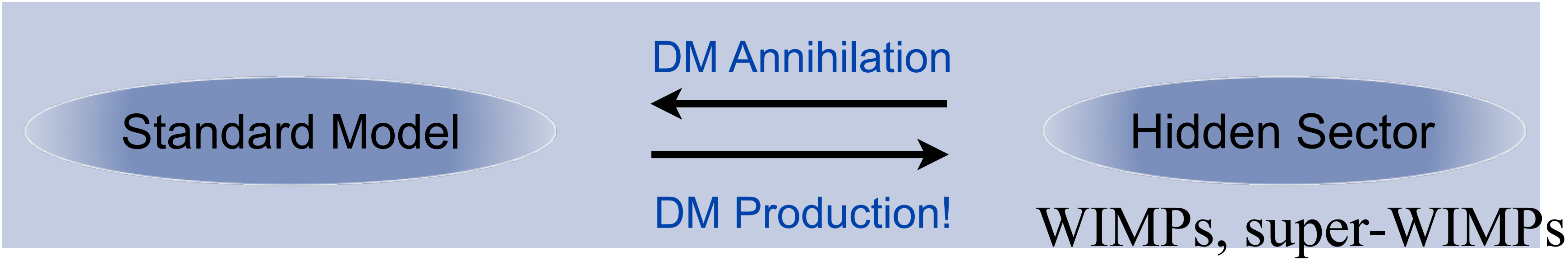


FIG. 7 Map of Galactic ^{26}Al γ-ray emission after 9-year observations with COMPTEL/CGRO (from Plüschke *et al.*, 2001).

There is a lot more positrons coming from the Galactic Center and the bulge that expected. The emission seems to be diffuse.

1. Positrons transported into GC by B-fields?
2. Positrons are created by episodic violent events near central BH?
3. Positrons being produced by DM? Either annihilation or decay?

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 models to explain 511 keV

Basic question – do you need a non-standard component? Reasonable astro people disagree

(Martin, Strong, Jean, Alexis, Diehl, 2012) – extra (nonstandard) component to bulge emission is needed

(Lingenfelter, Higdon, Rothschild, 2009) – there is no need for extra (nonstandard) component to explain bulge emission

If it is annihilation of WIMP DM….

- $m_{DM} < 5$ MeV
- Cross sections for annihilation ~ $O(10^{-4})$ from "standard WIMP" freeze-out cross section in the galactic environment
- Any model of this type will require light mediator (not 100 GeV)
- Must pass CMB constraints – for a "symmetric" WIMP saturating DM abundance, it is almost invariably *p-wave* annihilating DM.

Light DM models to explain 511 keV

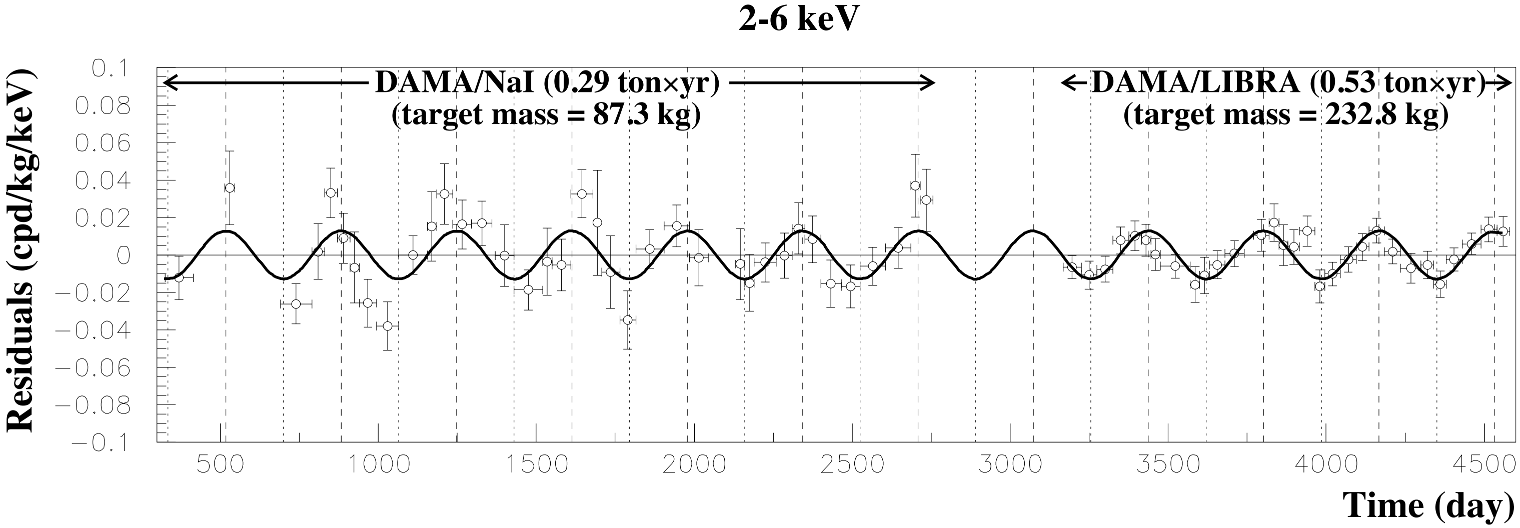
$$\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\kappa}{2}V^{\mu\nu}F_{\mu\nu} + \cdots$$

with

$$\mathcal{L}_\chi = \begin{cases} i\bar{\chi}\,\not{D}\chi - m_\chi\bar{\chi}\chi, & \text{(Dirac fermion DM)} \\ \underline{|D_\mu\chi|^2 - m_\chi^2|\chi|^2}, & \text{(Complex scalar DM)} \end{cases}$$

- Light (5 MeV and lighter) scalar DM can satisfy all criteria (Fayet,…). With mixing angle ~ 10^{-4} and smaller has a chance of evading all the constraints.

Motivation 3: conspiratological DAMA scenarios



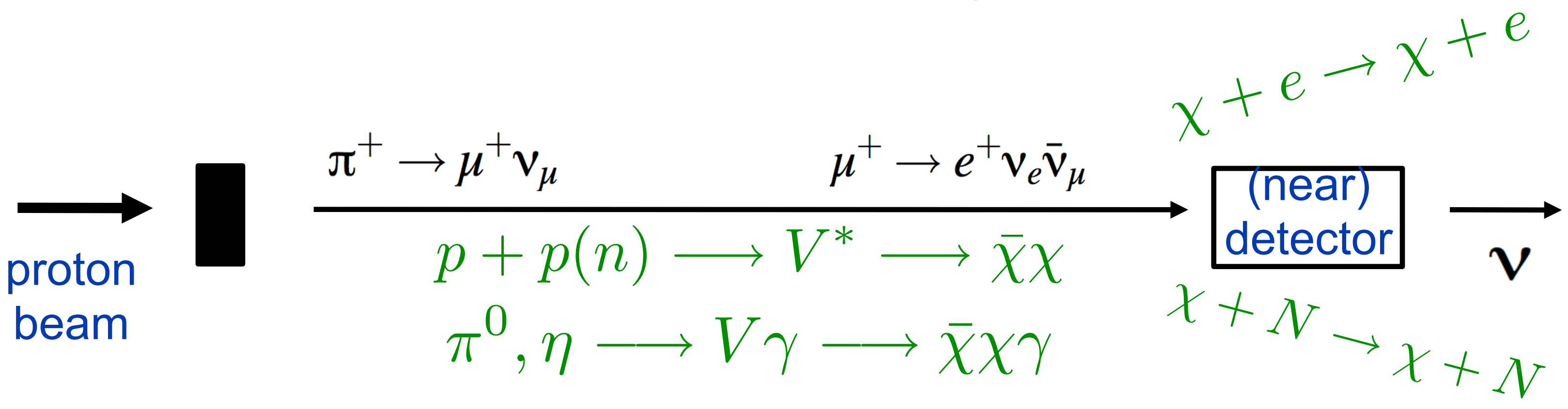
- One possible explanation that is still not completely ruled out is scattering on electrons [not absorption] – leads to ionization of Na and Iodine.
- Requires m_{DM} ~ few GeV and large cross sections – much larger than typical $\sigma \sim G_F^2 * m_e^2$.
- Possible only with *very light mediator* ~ up to few MeV. Kinetic mixing parameter ~ 10^{-4} or so.
- Disclaimer: does not give a good fit to DAMA reported spectrum

How to search for light weakly coupled particles?

- Large intensities, low backgrounds are required
- For detection of light DM, large detectors can be a big plus
- Larg(est) energies are not necessarily a decisive factor

Fixed target probes - Neutrino Beams

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



$\chi + e \to \chi + e$

$\pi^+ \to \mu^+ \nu_\mu$ $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

proton beam

$p + p(n) \longrightarrow V^* \longrightarrow \bar{\chi}\chi$

$\pi^0, \eta \longrightarrow V\gamma \longrightarrow \bar{\chi}\chi\gamma$

(near) detector

ν

$\chi + N \to \chi + N$

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	120 GeV protons	8.9 GeV protons
(➠ ~5x10^{21} POT)	10^{21} POT	10^{21} POT
280m to on- and off-axis detectors	1km to (~27ton) segmented detector	540m to (~650ton) mineral oil detector

Comparison of Neutrino and light DM

Neutrinos:

Production:

Strong scale $\sigma \sim 100$ mbn

Detection:

Weak scale $\sigma \sim G_F^2 E_{cm}^2$

Light WIMPs:

Production:

$\sigma \sim \sigma_{\mathrm{strong}} \times \varepsilon^2$

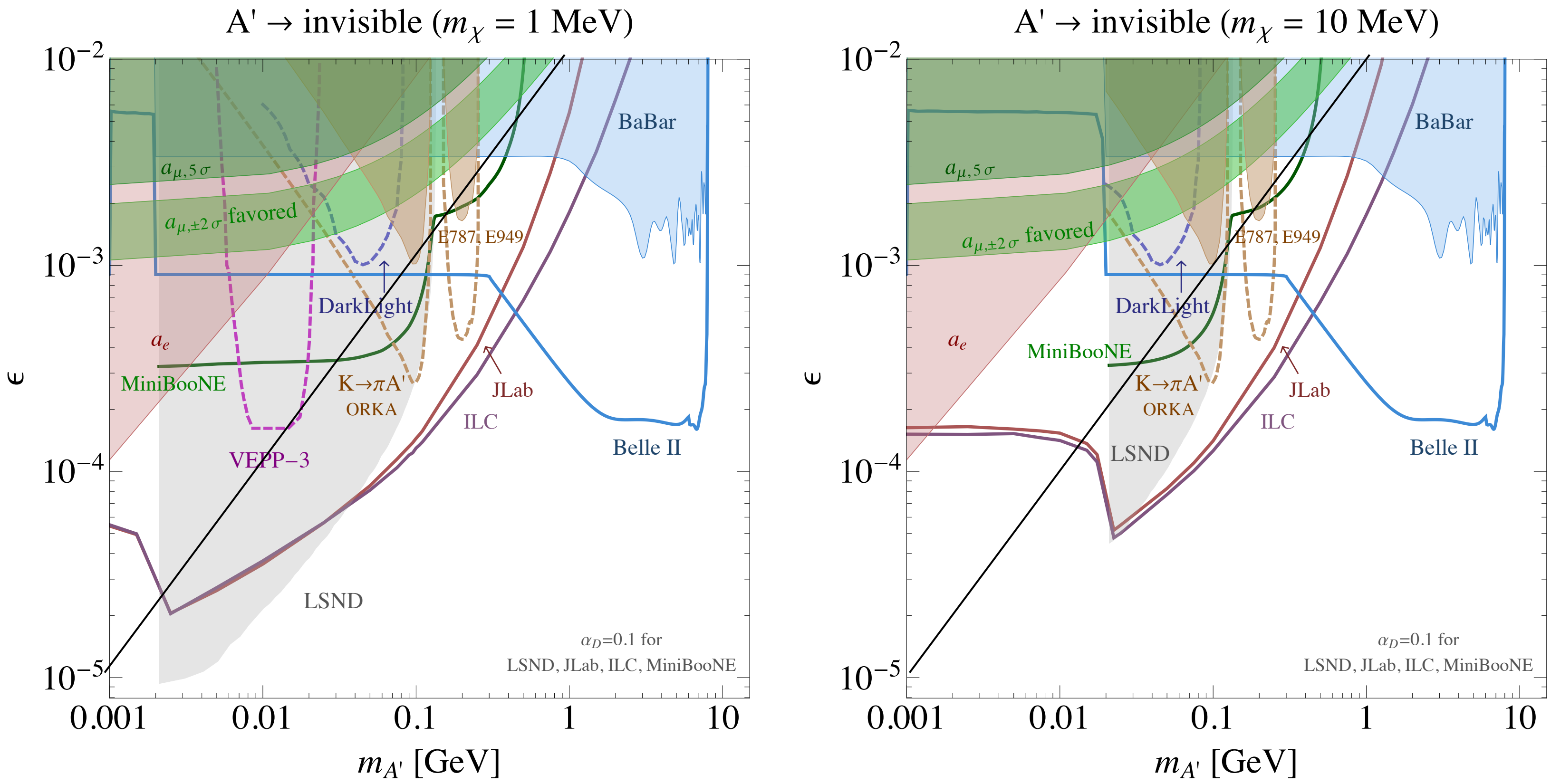
Detection:

Larger than weak scale!

Signals $\sim \sigma_{\mathrm{production}} \times \sigma_{\mathrm{detection}}$ can be of comparable strength

The reason for "stronger-than-weak" force for light dark matter comes from the Lee-Weinberg argument. (The weak-scale force will be *insufficient* in depleting WIMP DM abundance to observable levels if $m_{DM}<$ few GeV. Therefore, stronger-than-weak force and therefore relatively light mediator is needed for sub-GeV WIMP dark matter).

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, Krnjaic, Schuster, Toro 2013; Surujon et al.

How to search for new sub-MeV scalar?

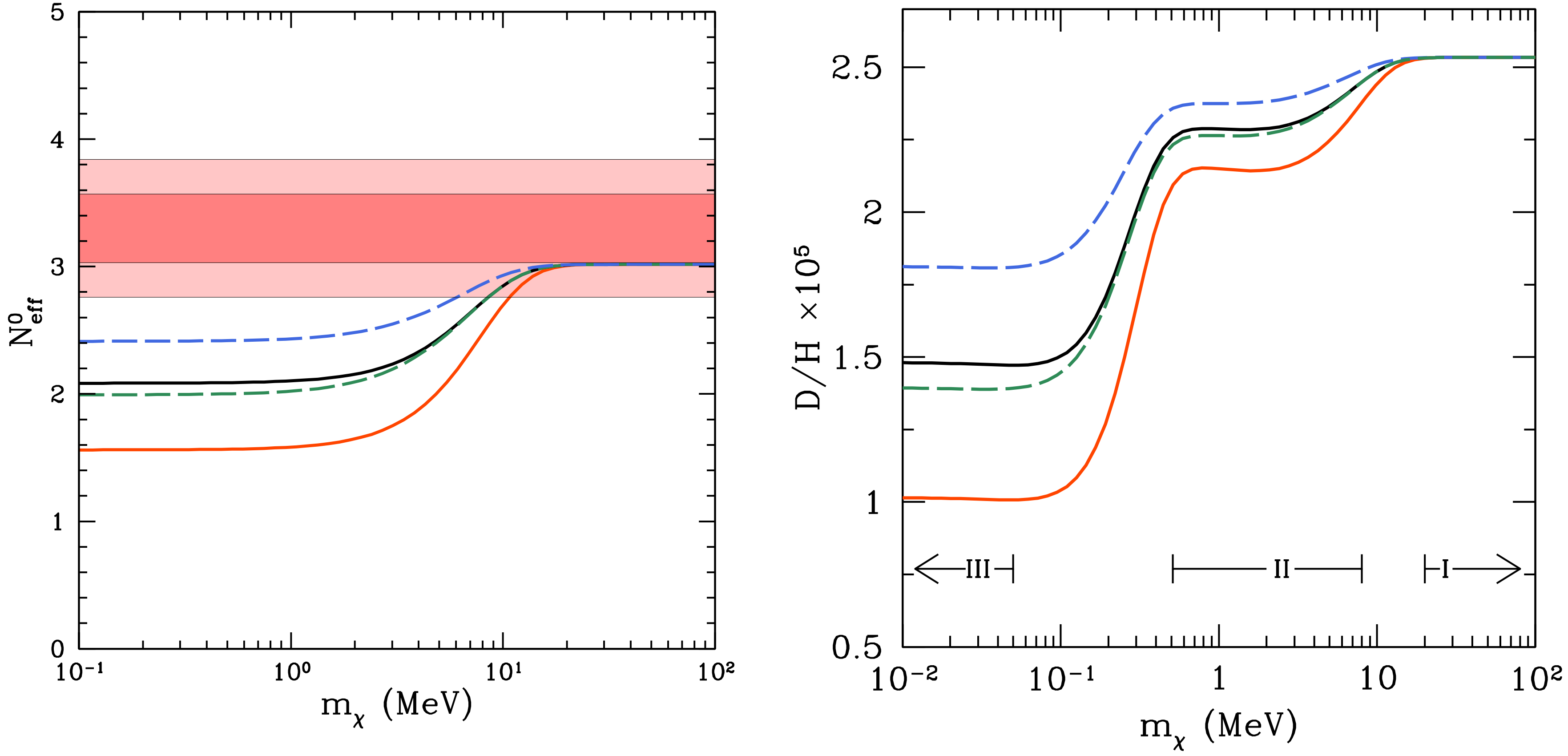
Project with Eder Izaguirre and Gordan Krnjaic, 2014

- *What if some scalar force* – call it ϕ – fixes r_p discrepancies at least between normal H and μH?
- Couplings will be very small, and the mass will be small, O(500 keV), $y_e y_p / e^2 \sim 10^{-8}$.
- This turns out to be somewhat of a blind spot in terms of constraints
- Our proposal: use small *underground accelerators* coupled with large scale detectors such as *Borexino, Super-K* etc… Up to ~ 20 MeV kinematic reach is available due to nuclear binding.
- Use of nuclear reactions and scintillator or water Cerenkov detectors provide direct sensitivity to the product $y_e y_p$

O(0.5 MeV) scalars with O(10^{-4}) couplings – an unexpected blind spot

1. No tree level FCNC, and too weakly coupled to be killed by loop effects in flavor. Too weakly coupled to be excluded by e.g. LSND
2. Too heavy to be produced in regular stars thermally – no strong energy loss constraints.
3. Too strongly coupled to matter and *not* coupled to neutrinos – thermalized during the SN explosions. No energy loss, no effect on neutrino spectra.
4. Being produced inside the Sun in the pp chain, particles can get absorbed/decay before exiting the Sun.
5. In cosmology, such particles give *negative* shift to N_{eff} , and are "gone" before the main sequence of BBN reactions begins.

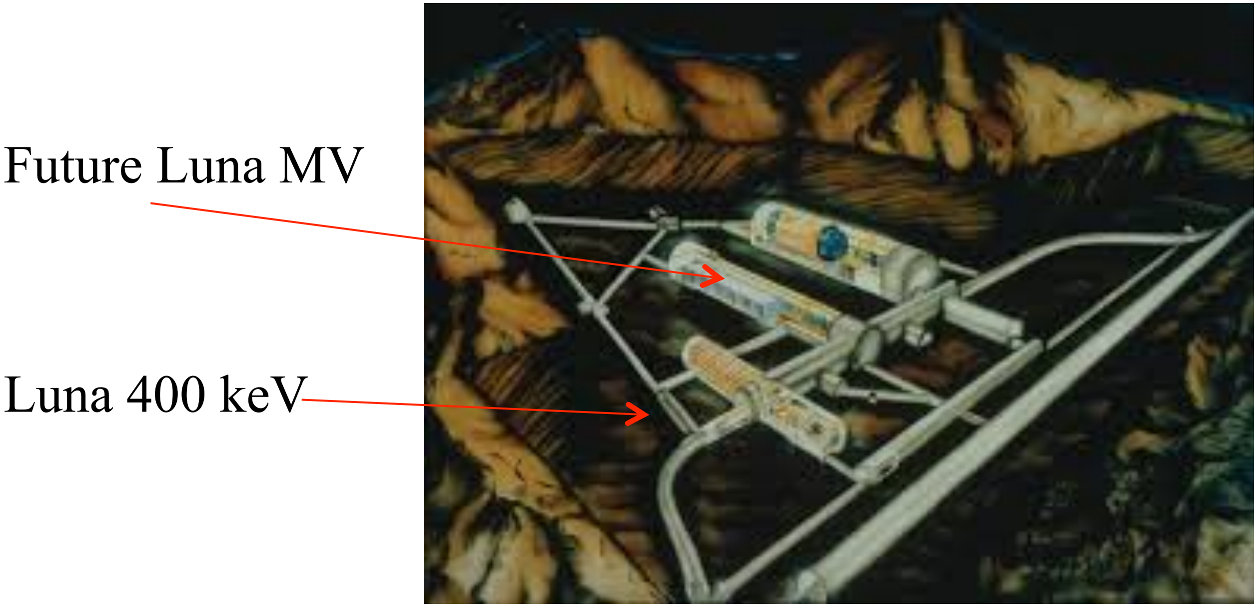
Cosmological "effective" N_{eff}



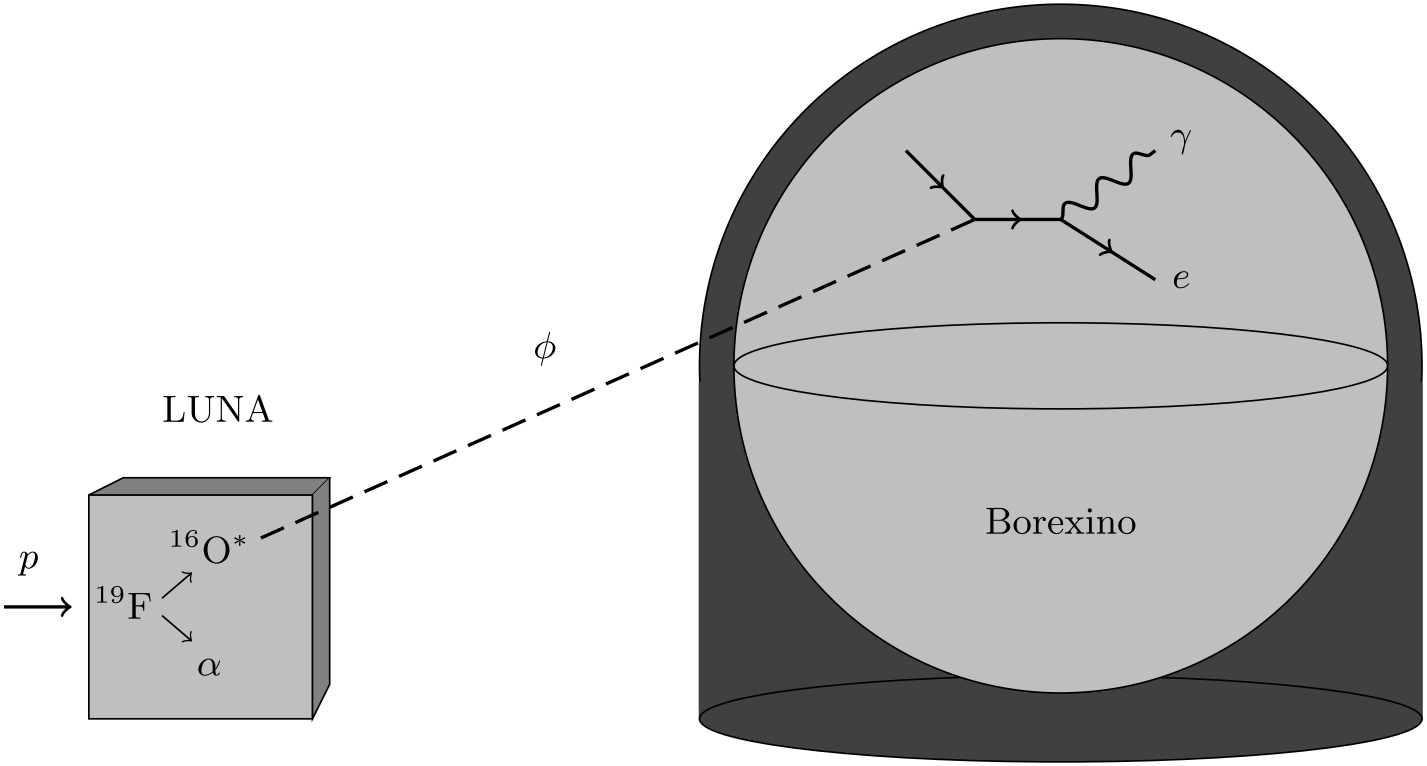
From Nollett, Steigman 2013; scalar - blue curve. N_{eff} of 2.5 is probably still OK, and if not it is easy to arrange a positive contribution to N_{eff} (e.g. new neutrinos.)

What are underground accelerators ???

- Built for the needs of measuring rare reactions in nuclear physics. Relatively cheap. Example: LUNA at LNGS.
- Using proton of ^{3}He on targets with energy < 0.5 MeV, and in the future up to 3 MeV.
- Located in the cleanest possible environments.
- Other projects in the works (DIANA) at Sanford Lab.



Main idea schematically



Potential problem: nuclear reactions can liberate some neutrons (e.g. via ^{19}F $+\alpha \rightarrow$ ^{22}Na +n), and there are stringent requirements on not increasing *n* background at the location of DM experiments.

Production stage; candidate reactions

- $T + p \rightarrow {}^{4}\mathrm{He} + \gamma$;

Up to 20 MeV mass can be explored, production x-section: ~10μbn.

- ${}^{15}\mathrm{N} + p \rightarrow {}^{16}\mathrm{O} + \gamma$ $({}^{7}\mathrm{Li} + p \rightarrow {}^{8}\mathrm{Be} + \gamma; {}^{11}\mathrm{B} + p \rightarrow {}^{12}\mathrm{C} + \gamma\ldots)$

Very similar; was studied by LUNA before.

- Photon-less reactions leading to excited nuclear states. Whenever you can emit gamma, you can emit scalar particle.

${}^{6}\mathrm{Li} + {}^{3}\mathrm{He} \rightarrow {}^{8}\mathrm{Be}^{*} + \mathrm{p}$

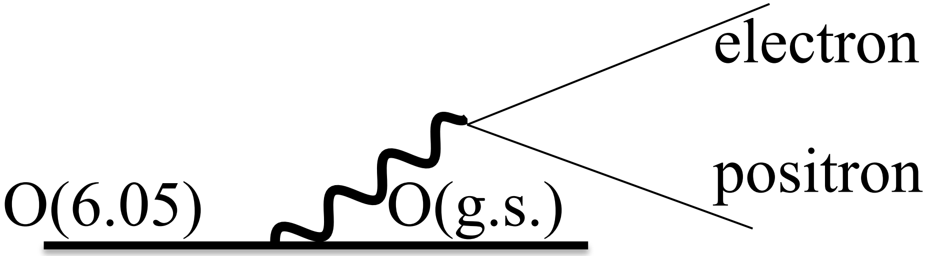
${}^{19}\mathrm{F} + p \rightarrow {}^{16}\mathrm{O}^{*} + {}^{4}\mathrm{He}, \ldots$

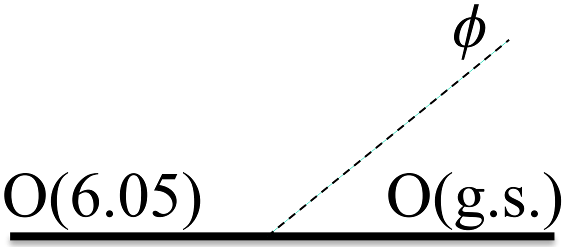
- Reaction cross sections in 10's of milli-barn.

$^{19}F + p \rightarrow {}^{16}O^* + {}^{4}He$ is the best candidate!

- $^{19}F + p \rightarrow {}^{16}O + {}^{4}He$ populates the first excited 6.05 MeV state of oxygen. Cross sections are in ~ 20 mbn range [i.e. *not small*].
- Normal decay of O(6.05 MeV) is due to $0^+ \rightarrow 0^+$ transition with the emission of electron-positron pair. Very suppressed.
- *The enhancement of the branching is*

$$Br[O(6.05) \rightarrow O(g.s.) + \phi] = 3600 * (y_p^2/e^2)$$





6.05 MeV is in the "cleanest" region of Borexino – no ^{208}Tl background.

Calculation of the production rate

- At E ~ MeV, nuclear reactions are improbable as Coulomb stopping is more efficient. Probability is given by

$$P(E_0) = \int_0^{E_0} dE \, \frac{\sigma_{\text{nucl}}(E) n_{\text{target}}}{|dE/dx|}$$

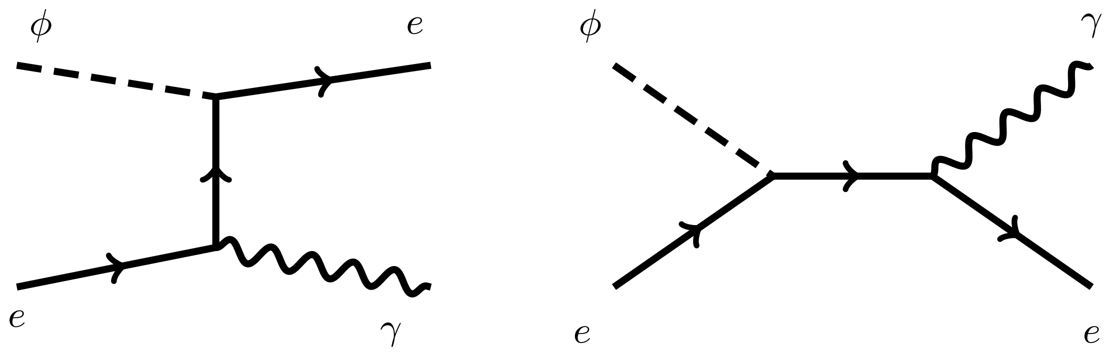
- For p on ^{19}F reaction, we calculate the probability of exciting 6.05 MeV oxygen state as P(3 MeV) = 6 × 10^{-6}.

- With achievable currents on the order of ~ 10 mAmp,

the Production Rate = $(y_p/e)^2 \times 10^{15}$ Hz.

- *Alternatively, one can also use SOX set-up: radioactive beta sources with ~PBq activity that can produce "dark scalars", "dark photons" etc if they are < MeV in mass.*

Scattering rate



- Scattering rate is readily computable, with cross sections

$$\sigma(e+\phi \rightarrow e+\gamma) \sim (\mathrm{y_e}/\mathrm{e})^2 \times \sigma_{\mathrm{Compton}}$$

In Borexino [that has good energy resolution] all events are recorded and will appear at 6 MeV. In Super-K, only the most energetic electrons > 4-5 MeV can be detected.

Advantage of being clean…

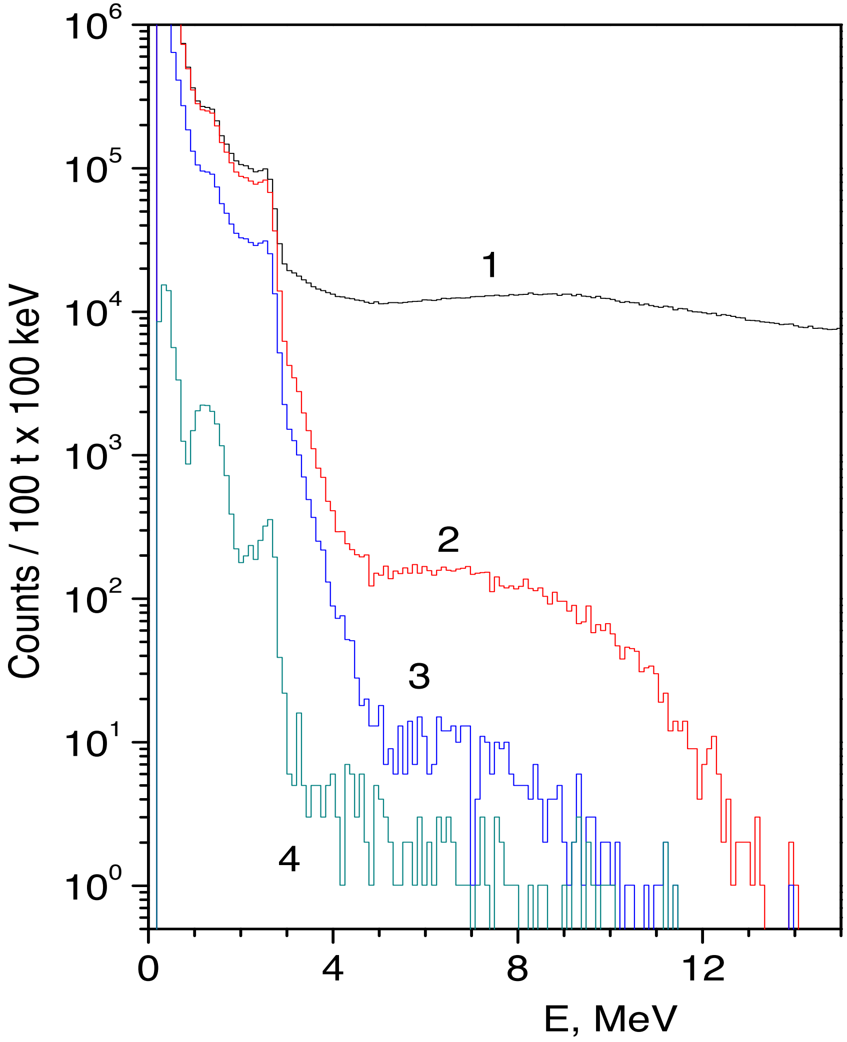
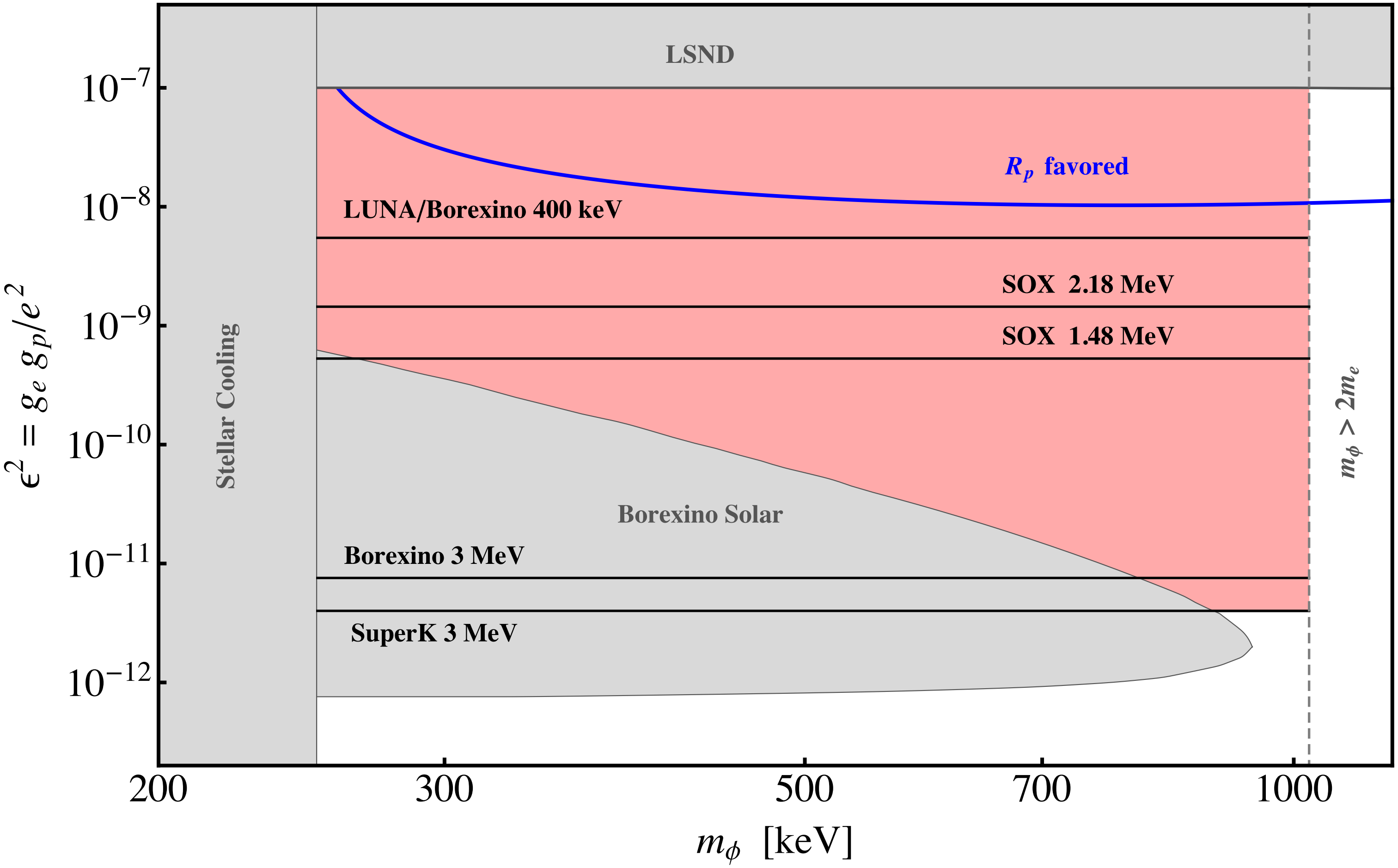


FIG. 2. Energy spectra of the events surviving incremental selection cuts. From top to bottom: (1) raw spectrum; (2) 2 ms post-muon veto cut; (3) 20 s after muons crossing the SSS cut; (4) FV cut. See text for details.

- If new particle is stable on the scale of underground Lab, it will fly into e.g. Borexino etc causing $e + \phi \rightarrow e + \gamma$, and releasing O (6-20) MeV energy depending on the reaction.
- In the cleanest experiments, e.g. Borexino, above 5 MeV there is no ^{208}Tl events, and the background for this search are only ^{8}B neutrinos.

Sensitivity plot

- 6.05 MeV is in the “cleanest” region of Borexino.
- *r_p relevant region can be fully covered.*



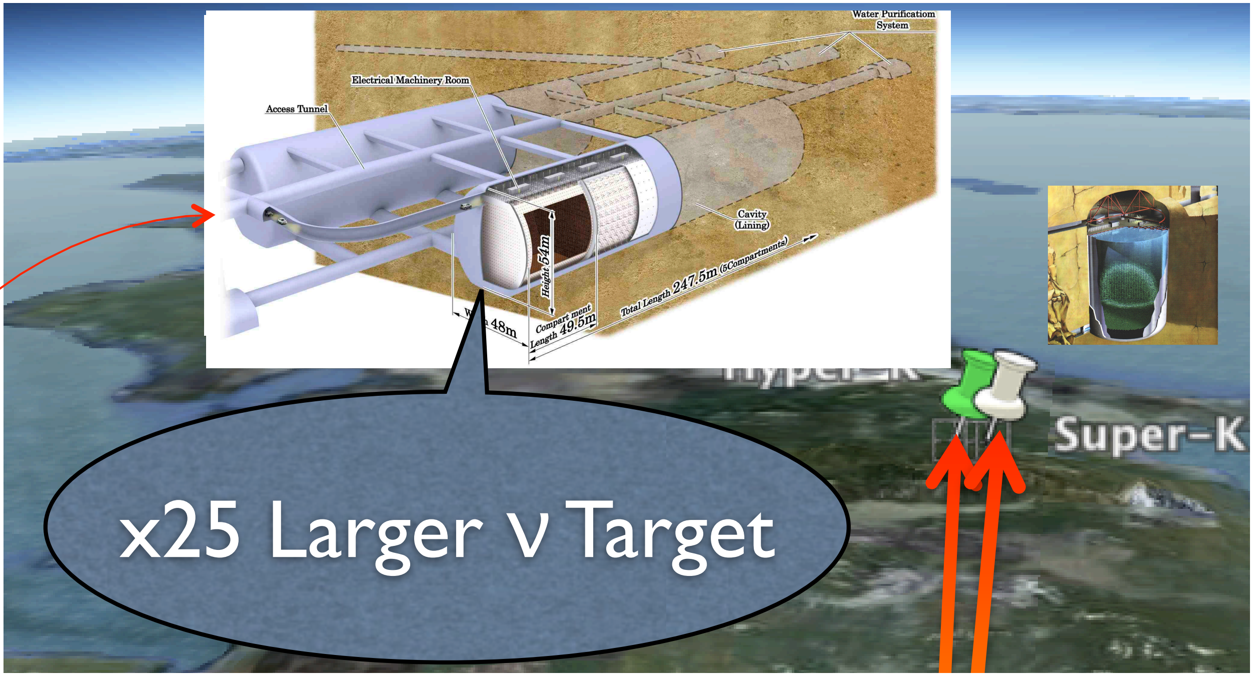
Ultimate intensity frontier experiment?

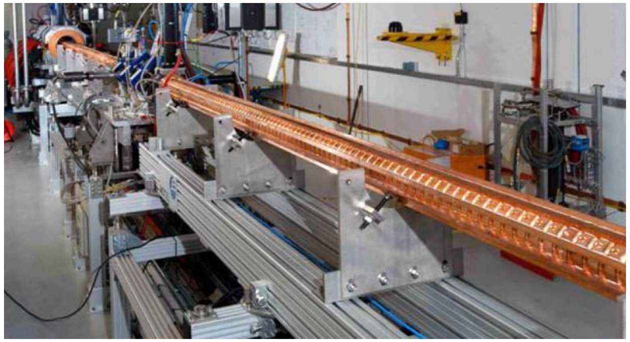
Project with Eder Izaguirre and Gordan Krnjaic, *ongoing*

- Biggest possible detector with low-ish threshold: e.g. *Hyper-K*
- *Powerful electron accelerator* underground, close to Hyper-K
- No neutrino backgrounds (c.f. with Y. Kahn et al, 2014 proposal to use cyclotrons underground). High efficiency of producing light particles compared to nuclear accelerators.
- As a result, best sensitivity to light DM, to O(MeV) scale metastable particles, to anything at all that can be kinematically produced, and then scatters/decays in Hyper-K volume.
- If the cost of Hyper-K project can indeed be 10^9\$, a 20 mln accelerator nearby can be a small perturbation.

Ultimate intensity frontier experiment?

Project with Eder Izaguirre and Gordan Krnjaic, *ongoing*



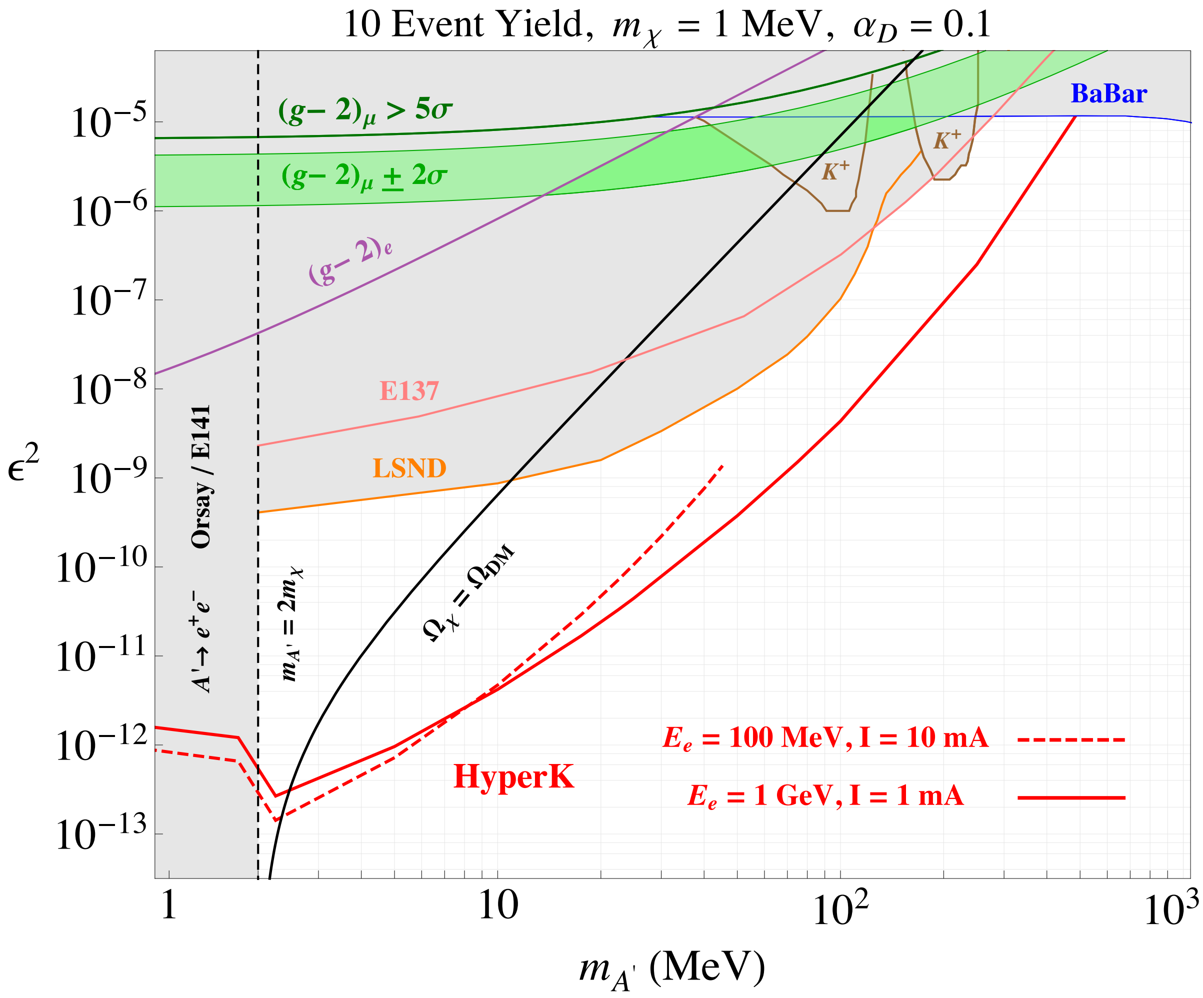


Electron linear accelerator

Construction cost estimation

Total	~80Billion JPY	
Excavation	30Billion JPY	
Tank	30Billion JPY	
Photo-detectors	20Billion JPY	High QE HPD

Sensitivity to light DM



$$\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\kappa}{2}V^{\mu\nu}F_{\mu\nu} + \cdots$$

with

$$\mathcal{L}_\chi = \begin{cases} i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi, & \text{(Dirac fermion DM)} \\ |D_\mu\chi|^2 - m_\chi^2|\chi|^2, & \text{(Complex scalar DM)} \end{cases}$$

One can have a chance on improving sensitivity to very light DM, and e.g. decisively test models that aim at explaining 511 keV bulge excess via DM annihilation.

One will advance sensitivity to ALPs in 200 keV < m_a <100 MeV range

Conclusions

- Light new particles (e.g. ~ MeV) with 10-3 and smaller couplings are difficult to rule out in general. Can be invoked for explanations of various particle and astro anomalies.
- Very light scalar particle (~ 0.2-0.5 MeV), providing additional repulsion between protons and electrons is one of the logical possibilities that could help reconciling eH and μH results. Can be very efficiently searched for in underground accelerators as source of exotic particles and large clean detectors (Borexino, Super-K, …). It looks as reasonably cost-effective search.
- Ultimate searches for light particles can be done using e-linacs in the underground labs. Sensitivity to broad classes of light new physics (including MeV-scale WIMP dark matter, ALPs in O(10 MeV) range etc) can be improved quite decisively.

Current status

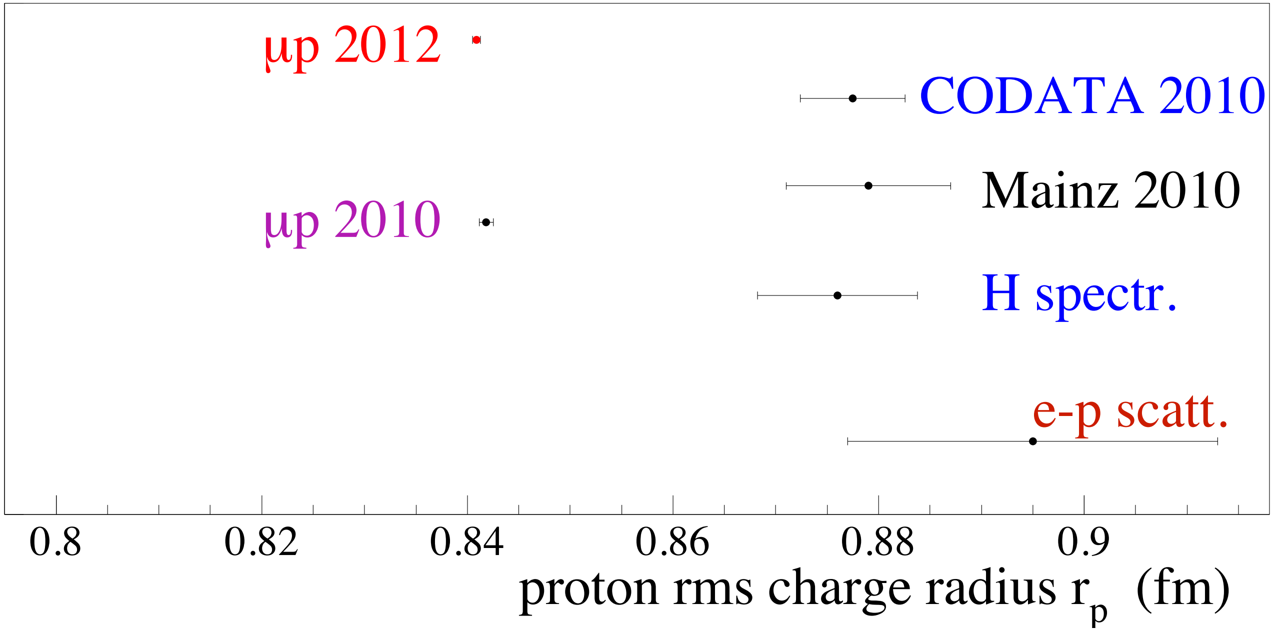
$\nu(2S_{1/2}^{F=1} \to 2P_{3/2}^{F=2})$ = 49881.88(76) GHz R. Pohl *et al.*, Nature 466, 213 (2010)

49881.35(64) GHz preliminary

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

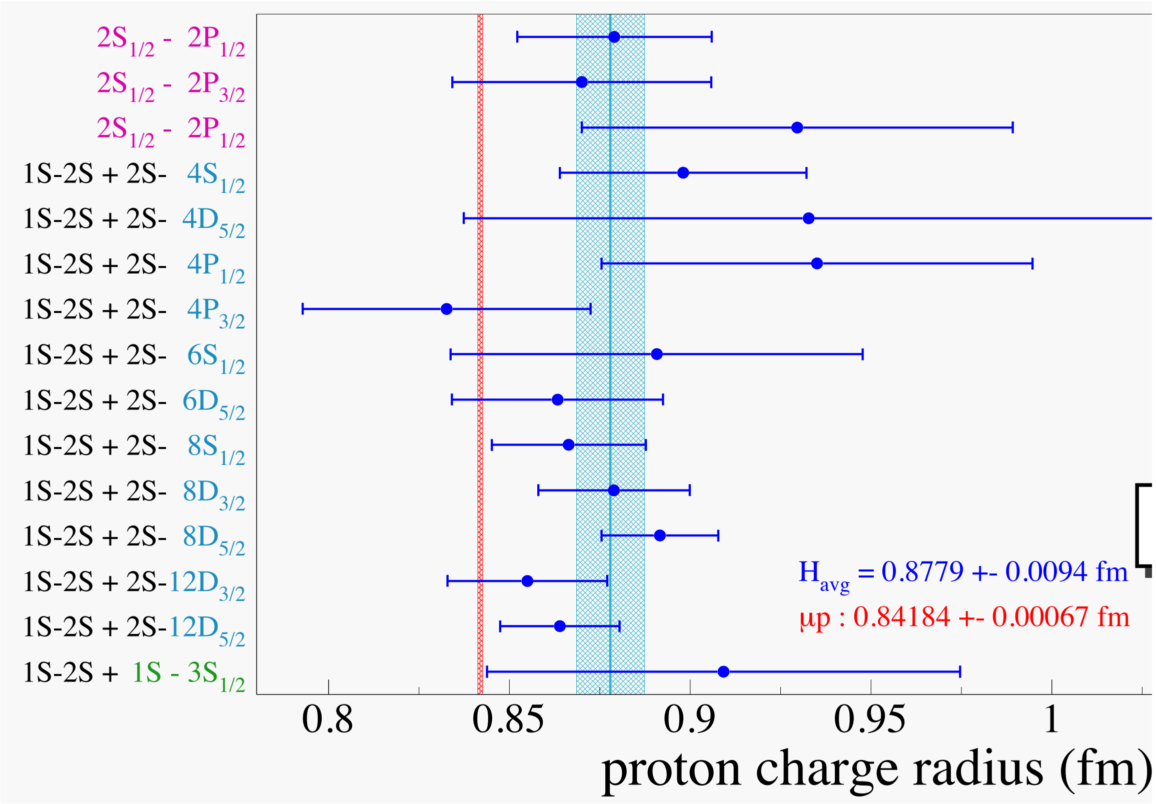
Proton charge radius: $r_\mathrm{p} = 0.84089\ (26)_\mathrm{exp}\ (29)_\mathrm{th} = 0.84089\ (39)$ fm (prel.)

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



Importantly, *Zeemach radius* extracted from 2 lines is perfectly consistent with previous (normal hydrogen) determinations

r_p from Normal Hydrogen



Red line – muonic hydrogen result

Blue band – fitted value of r_p from precision spectroscopy of normal hydrogen.

It is a serious 5σ discrepancy (but only when one takes into account many transitions!)