Probing light states (including dark matter) with direct detection and cosmology

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Plan

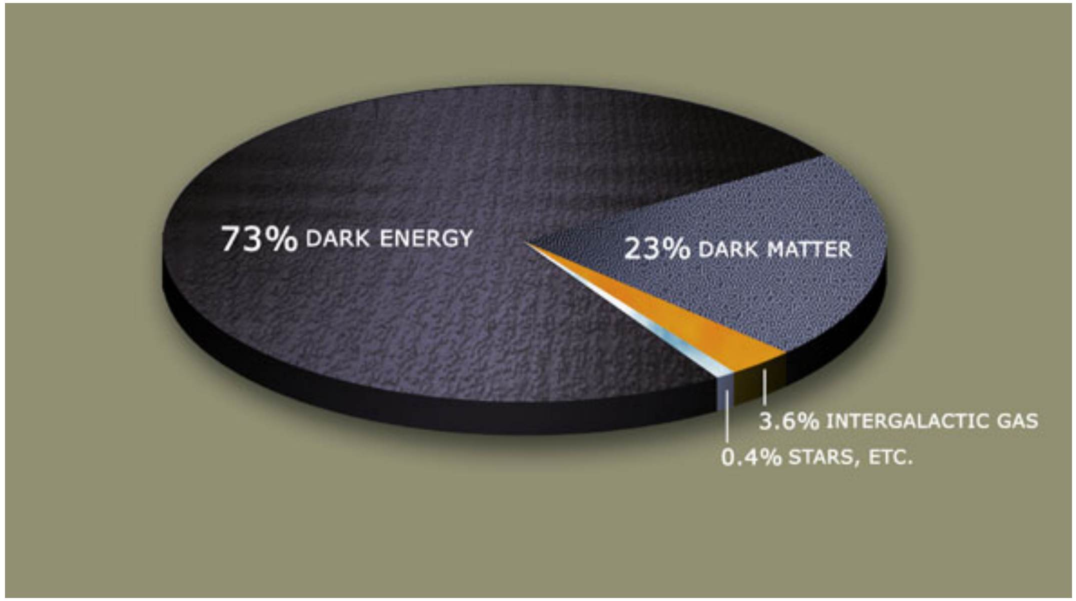
1. Bosonic super-WIMP dark matter, and their absorption signature in "direct detection" experiments. (1412.8378)

2. CMB and BBN limits on MeV-scale dark photons (and dark Higgses). (1407.0993)

3. New idea to use underground accelerators coupled to large detectors to search for light weakly coupled states. (1405.4864)

Conclusions

Big Questions in Physics



"Missing mass" – what is it?

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

Challenges ?? Too many options for DM. *In "direct detection" there is an extrapolations from ~ kpc scale (~ 10^{21} cm) down to 10^2 cm scale*.

Simple classification of particle DM models

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma = 1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**.

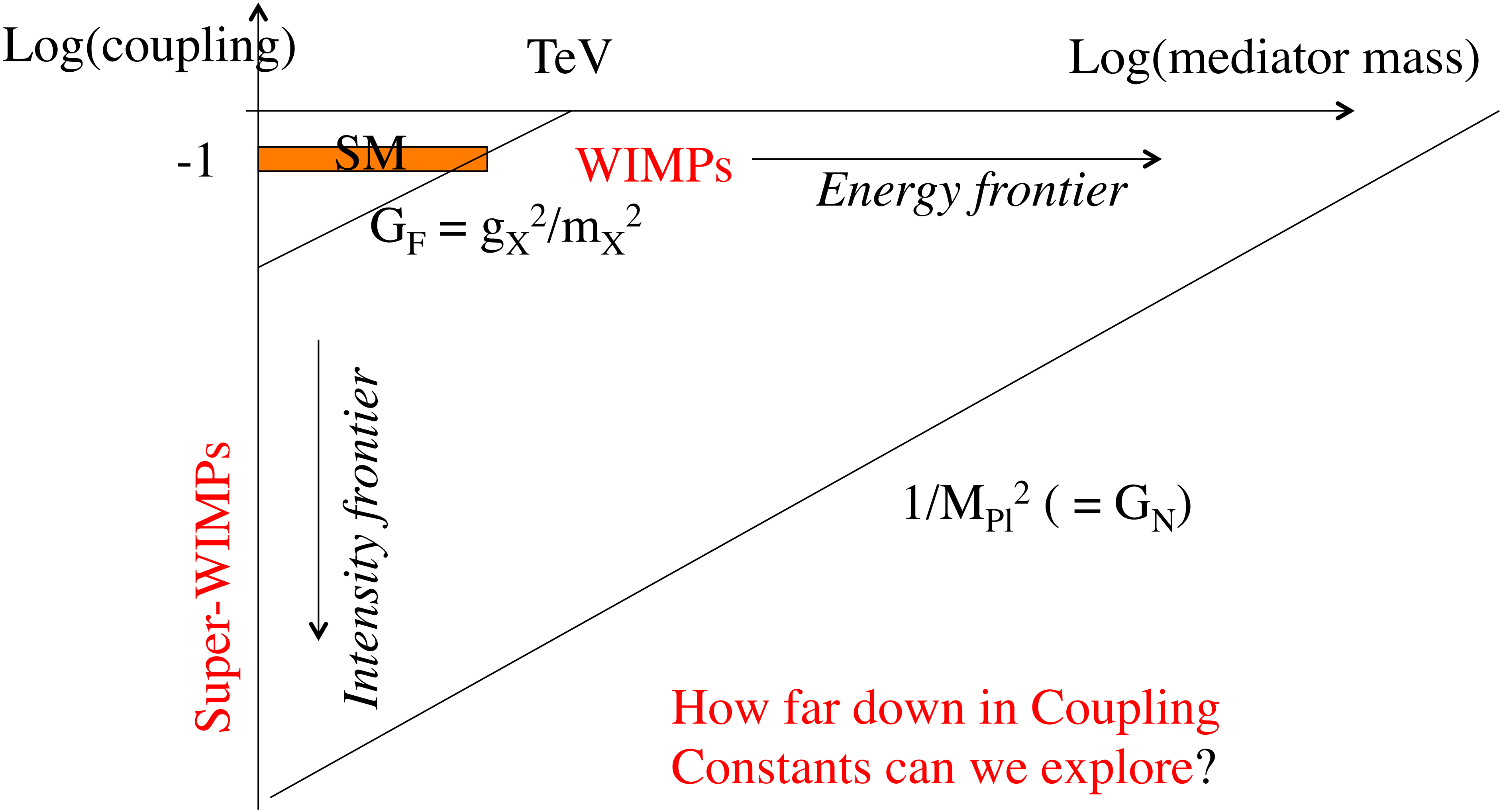
Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **super-WIMPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_\gamma \sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Signatures can be very different; different scales for masses & couplings

Coupling vs mass plot

In 2012-2013 LHC experiments discovered a new particle (Higgs boson) and a new force (Yukawa force). What do we know about forces in nature ?



WIMP “lamp post”

From the Snowmass 2013 summary, 1310.8327

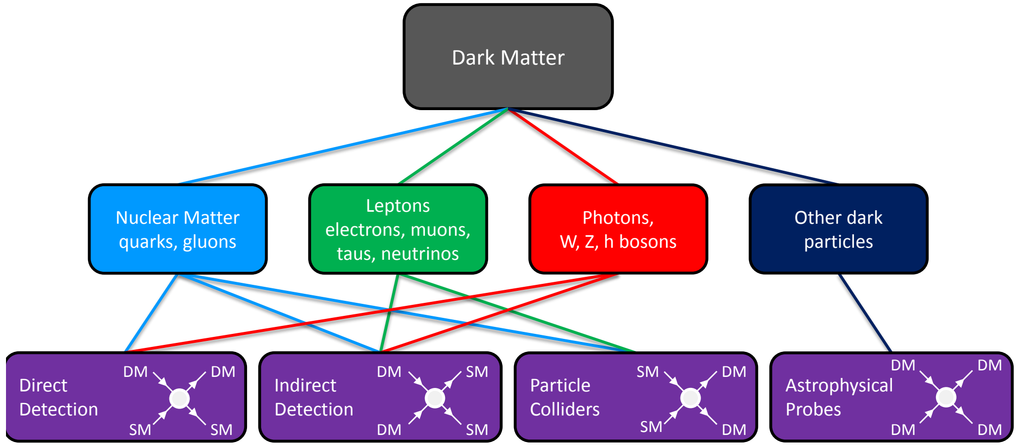
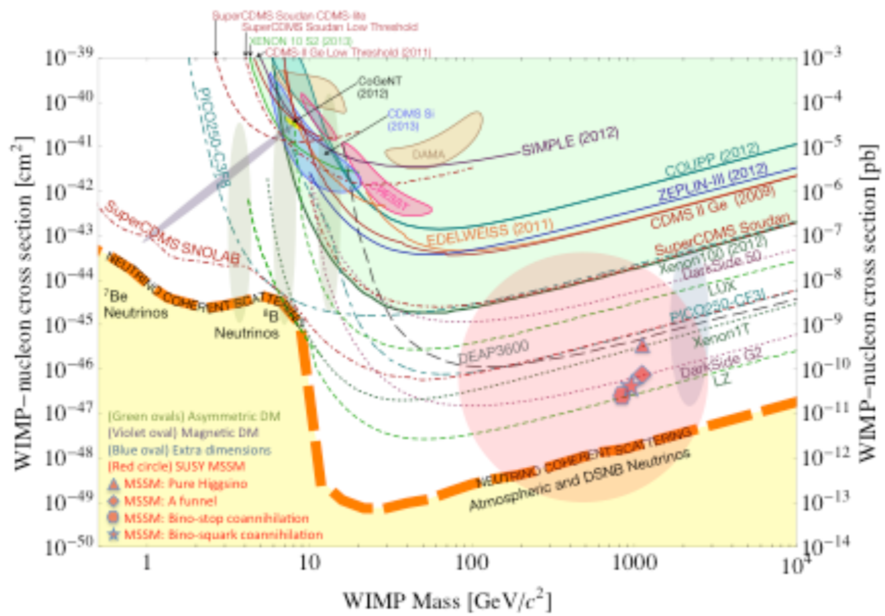


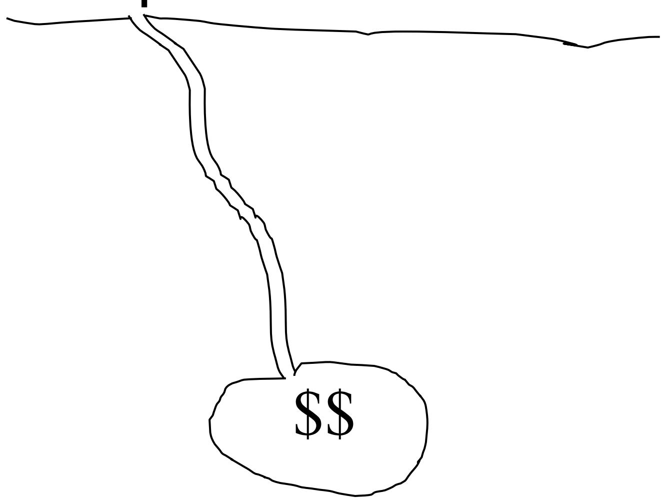
Figure 5. *Dark matter may have non-gravitational interactions with any of the known particles as well as other dark particles, and these interactions can be probed in several different ways.*



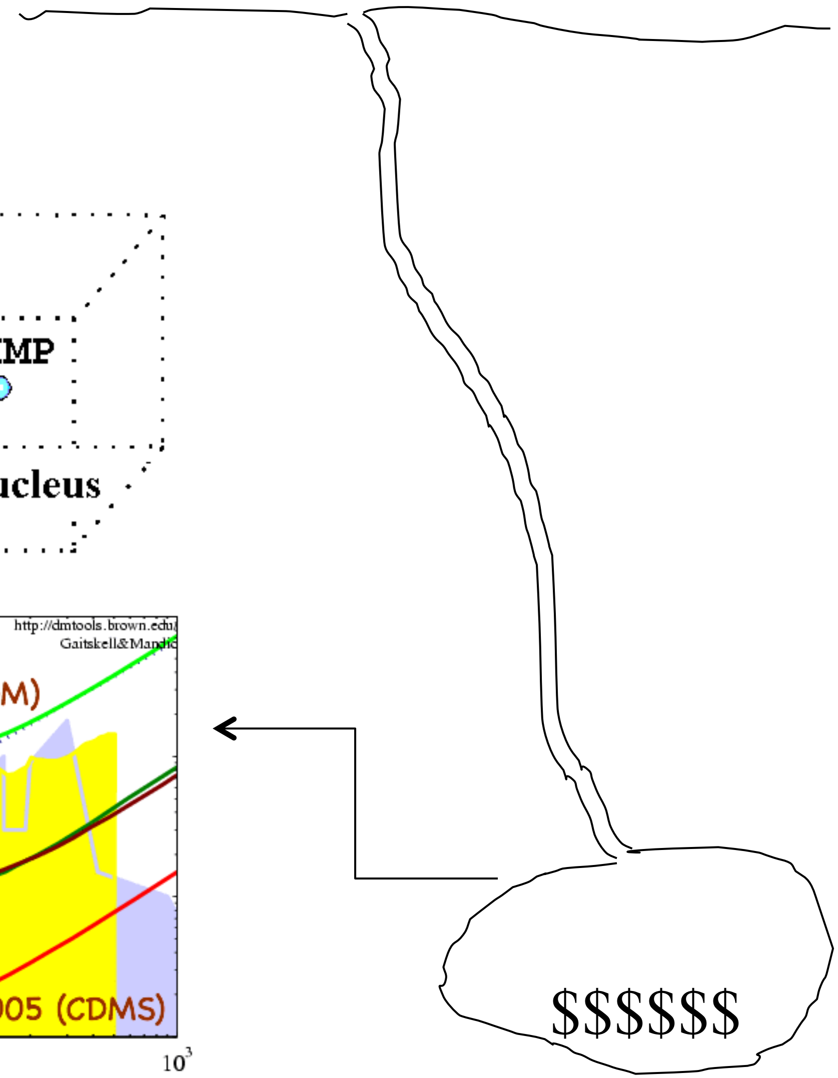
Can we use DM detectors for other type of DM and for non-DM goals?

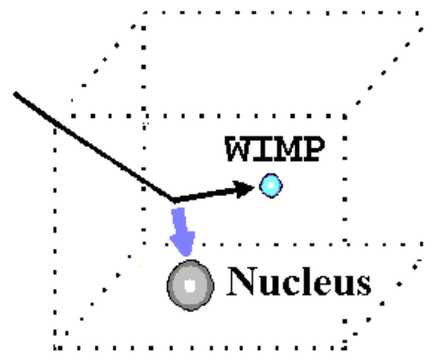
Currently all “direct DM detection” experiments search for the same thing

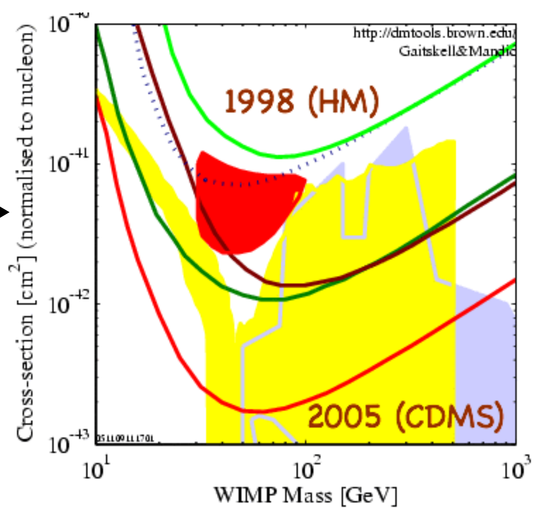
An average Dark Matter experiment



A more expensive DM







Diversifying physics output of direct detection exp’s is needed !!!

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

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

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

$LH\,N$ 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

……….

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

Dark Photons

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

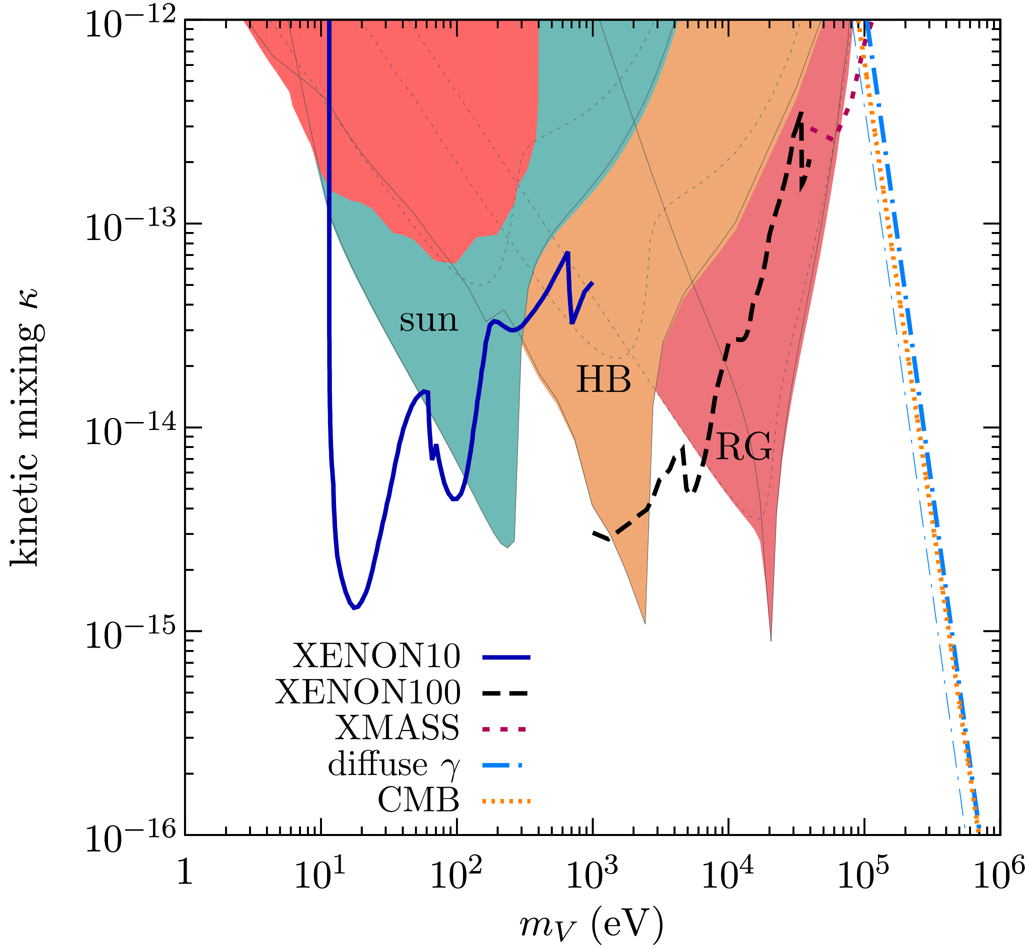
$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi),$$

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

- 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. Mixing angle small than 10^{-10} can easily make it into DM.

Master plot for vector DM absorption signal

An, MP, Pradler, Ritz (Dec. 2014)



Large DM experiments can compete with stellar constraints and have sensitivity to mixing angles down to kappa ~$10^{-15.}$

"Simplified" models of super-WIMPs

- New light bosonic states V, A, S, P, T etc below 1 MeV with small couplings [no worries about stability] can be very long-lived and can constitute the DM.
- The interaction with electrons and photons can be used for their detection

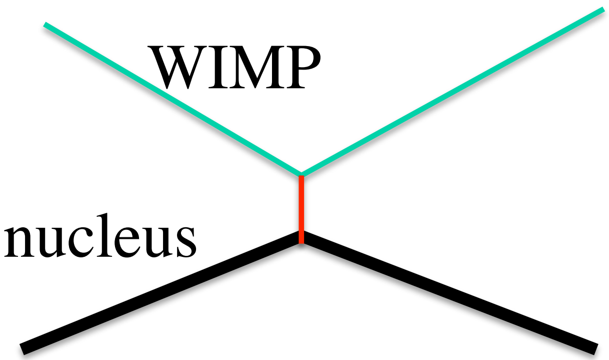
$$\text{(pseudo)scalar} \quad g_S S\bar{\psi}\psi, \quad g_P P\bar{\psi}\gamma_5\psi,$$
$$\text{(pseudo)vector} \quad g_V V_\mu\bar{\psi}\gamma_\mu\psi, \quad g_A \mathcal{A}_\mu\bar{\psi}\gamma_\mu\gamma_5\psi,$$
$$\text{tensor} \quad g_T T_{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi, \quad \cdots$$

- *S* and *P* decays will give 2 photon signature – monochromatic lines – and will in general better constrained by astrophysics. [3.55 keV line can be fit by *S* or *P* without any problems]
- There is no issues with naturalness [conservatively understood]:

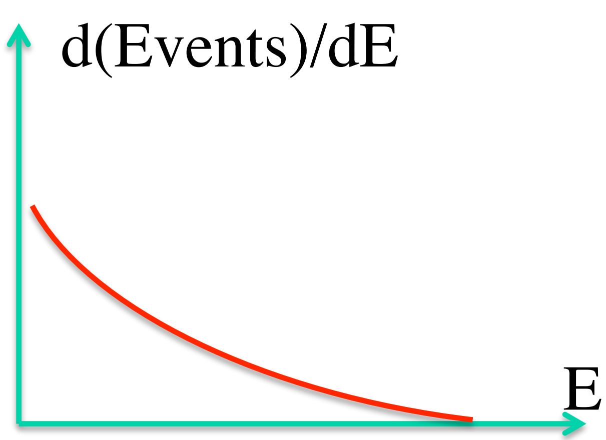
  e.g. $m_S > 10^{-1}\, g_S \times \text{Cutoff} \sim 10^{-11}\, (g_S/10^{-10})$ TeV ~ 10 eV
- Why bosonic? Sterile neutrinos can also do N + e → ν + e, but rates are tiny, and energy deposition is miniscule.

New DM signal: absorption of super-WIMPs

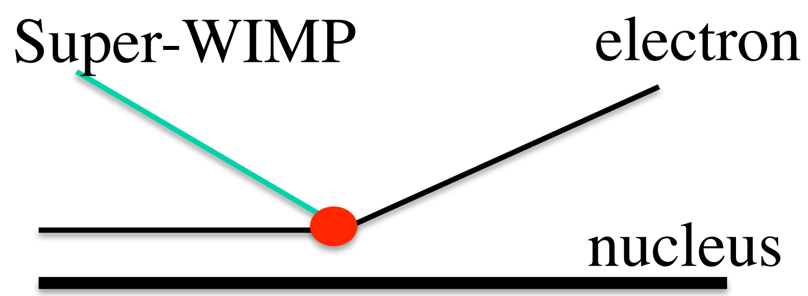
WIMP-nucleus scattering



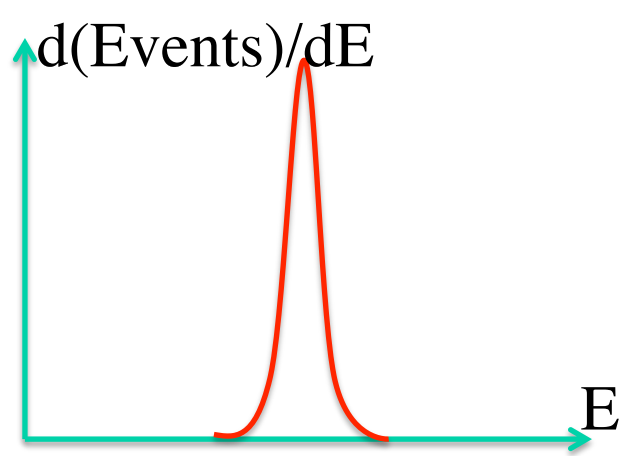
Signal: ionization + phonons/light



Atomic absorption of super-WIMPs



Ionization at $E=m_{superWIMP}$



Brief history of the subject

- *DAMA collaboration* (2008) has claimed that their modulation signal may come from absorption of ~ 3 keV ALPs.
- They made *multiple errors*, including the fatal one: in fact *there is no modulation*. Absorption cross section ~ 1/velocity, σ v = const. Corrected in MP, Ritz, Voloshin (PRV), 2008.
- In keV mass range X-ray limits from decays + stellar energy loss constraints are much more sensitive to ALPs than direct detection (Gondolo, Raffelt, PRV, Postma Redondo, 2008)
- Vector dark matter (where decays to photons is inhibited is a perfect candidate for direct detection search via absorption), PRV.
- Many experiments now (Xenon100, CDMS, Malbec, Xmas, Edelweiss, CoGeNT, and soon LUX) report their sensitivity to the keV-scale ALPs. [Better use vectors, as ALPs are more constrained by astro]
- Below keV only a select few has sensitivity via the signature that T. Volansky discussed in the scattering channel yesterday.

“Very Dark Photon” dark matter

- Very weakly coupled dark photons can be dark matter in sub-eV regime due to misalignment mechanism or in the keV regime due to misalignment + thermal emission (MP, Ritz, Voloshin; Postma, Redondo, 2008)

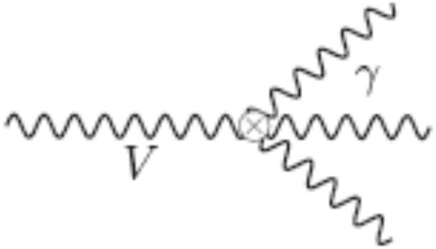
$$\Omega_V h^2 \approx 0.4 \frac{g_*(T_{\rm osc})^{3/4}}{g_{*S}(T_{\rm osc})} \sqrt{\frac{m_V}{1\,{\rm keV}}} \left(\frac{\widetilde{V}_{I,i}}{10^{11}\,{\rm GeV}} \right)^2 .$$

- If $m_V < 2\ m_e$ then only V → 3 γ is possible. It is a delayed decay – larger couplings will be consistent with bounds. No monochromatic photons = weaker limits from x- and gamma-rays.

Superweakly interacting Vector Dark Matter

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F_{\mu\nu} + \mathcal{L}_{h'} + \mathcal{L}_{\dim>4},$$

- Vectors are long-lived if $m_V < 2\, m_e$. V has to decay to 3 photon via the light-by-light loop diagram:



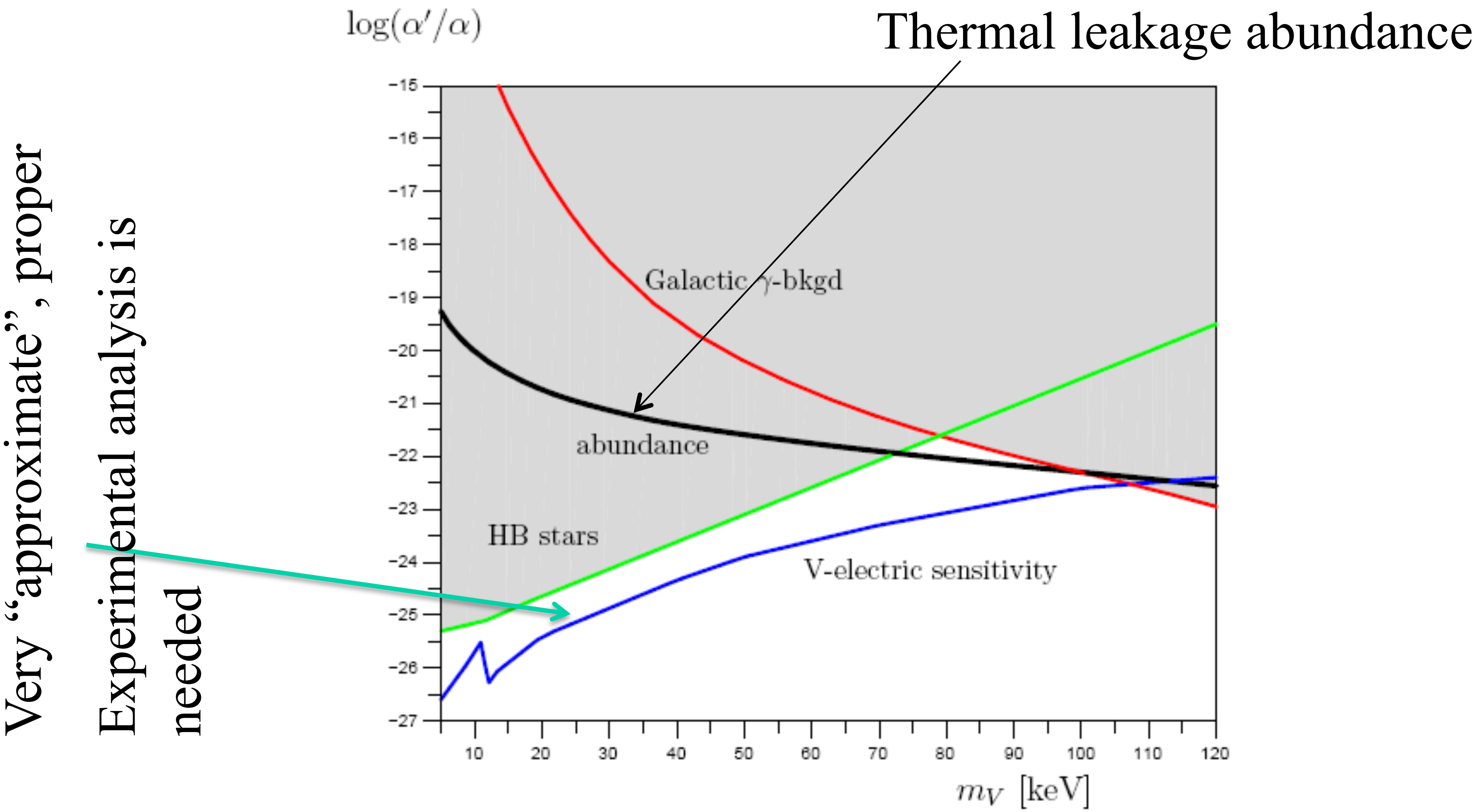
$$\Gamma = \frac{17\,\alpha^3\alpha'}{2^7 3^6 5^3 \pi^3}\,\frac{m_V^9}{m_e^8} \approx \left(4.70\times10^{-8}\right)\,\alpha^3\alpha'\,\frac{m_V^9}{m_e^8}.$$

$$\tau_U \Gamma_{V\to3\gamma} \lesssim 1 \quad\Longrightarrow\quad m_V\,(\alpha')^{1/9} \lesssim 1\,\mathrm{keV}\ .$$

The γ-background constraints are weak. (No monochromatic lines)

Can be viable DM model: MP, Ritz, Voloshin, 2008

Absorbing Dark Photon DM



Direct detection search of Vector super-WIMP should be competitive with other constraints. MP, Ritz, Voloshin, 2008.

Dark photon dark matter can be very long-lived but is subject to stringent *astro constraints*

- Should very light particles other than neutrino exist (axions; sub-keV dark photons etc) they can be produced by the Sun, and searched for with various types of "helioscopes"
- In 2013, (An, Pradler, MP) have re-derived the production of the light dark photons in stars (previous analyses have miscalculated it by several orders of magnitude).
- We have shown that *low-threshold dark matter detectors are world's most sensitive dark photon "helioscopes"*.

In-medium emission of light dark vectors

A "Stuckelberg" mass vector decouples in the limit $m_V \to 0$

$$\mathcal{L}_{\rm int} = -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} + e J^\mu_{\rm em} A_\mu \xrightarrow{\text{on-shell V}} \mathcal{L}_{\rm int} = -\kappa m_V^2 A_\mu V^\mu + e J^\mu_{\rm em} A_\mu .$$

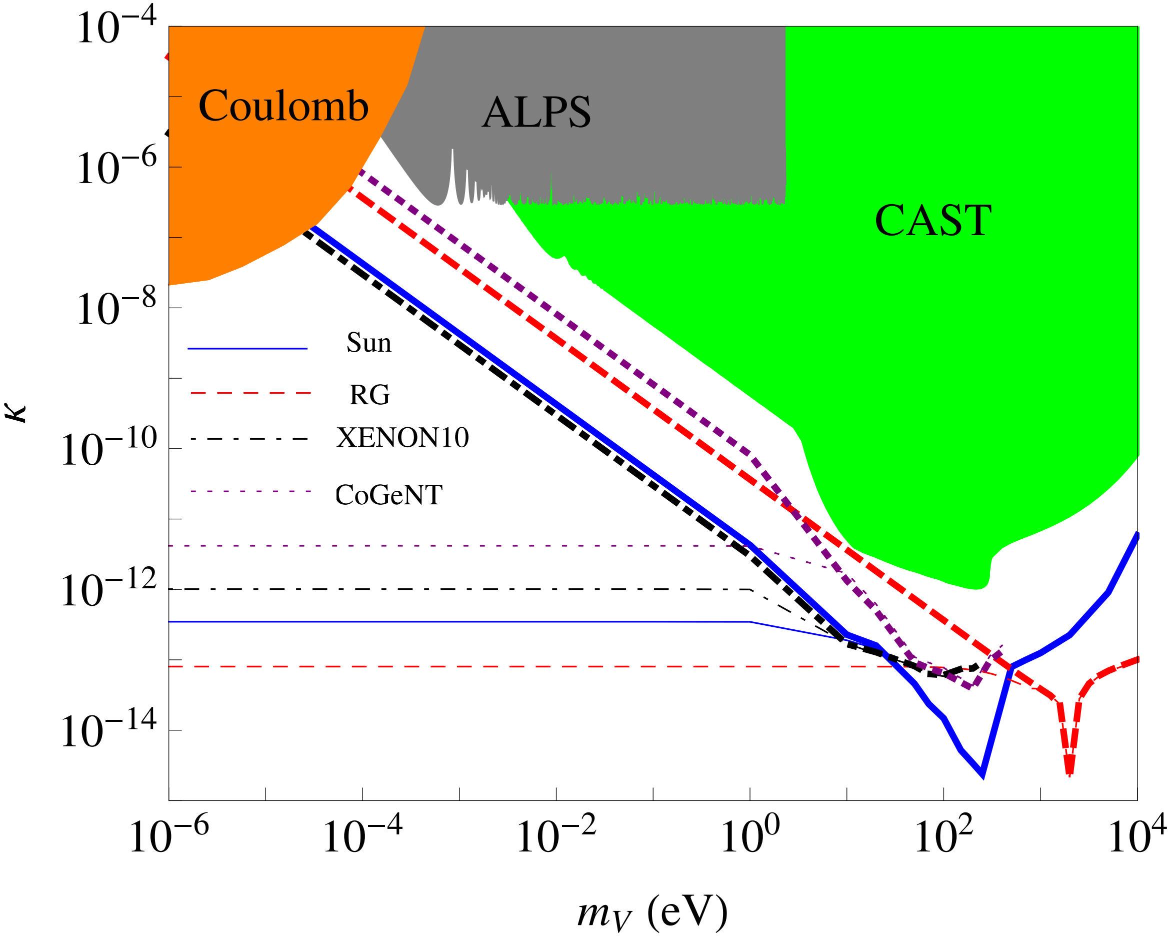
It is clear that the emission will be suppressed if the plasma frequency ω_p is much larger than m_V.

!! The decoupling of longitudinal mode in the rate is always ~ m_V^2 !!

Resonant production of vector modes from solar plasma

$$\frac{d\Gamma^{\rm prod}}{d\omega} \simeq \left(\frac{2r^2}{e^{\omega/T(r)} - 1} \frac{\sqrt{\omega^2 - m_V^2}}{|\partial \omega_P^2(r)/\partial r|} \right)_{r=r_{\rm res}} \times \begin{cases} \kappa^2 m_V^2 \omega^2 & \text{longitudinal,} \\ \kappa^2 m_V^4 & \text{transverse,} \end{cases}$$

Limits on Dark Photons



Constraint from the ionization at Xenon10 surpasses even very strong constraints from stellar cooling (also derived by our group)

An, MP, Pradler, PRL 201. *Xenon100 analysis is coming up?*

More on DM composed from light vector fields

- Abundance is created via thermal mechanism, which for most parts turns out to be insufficient.

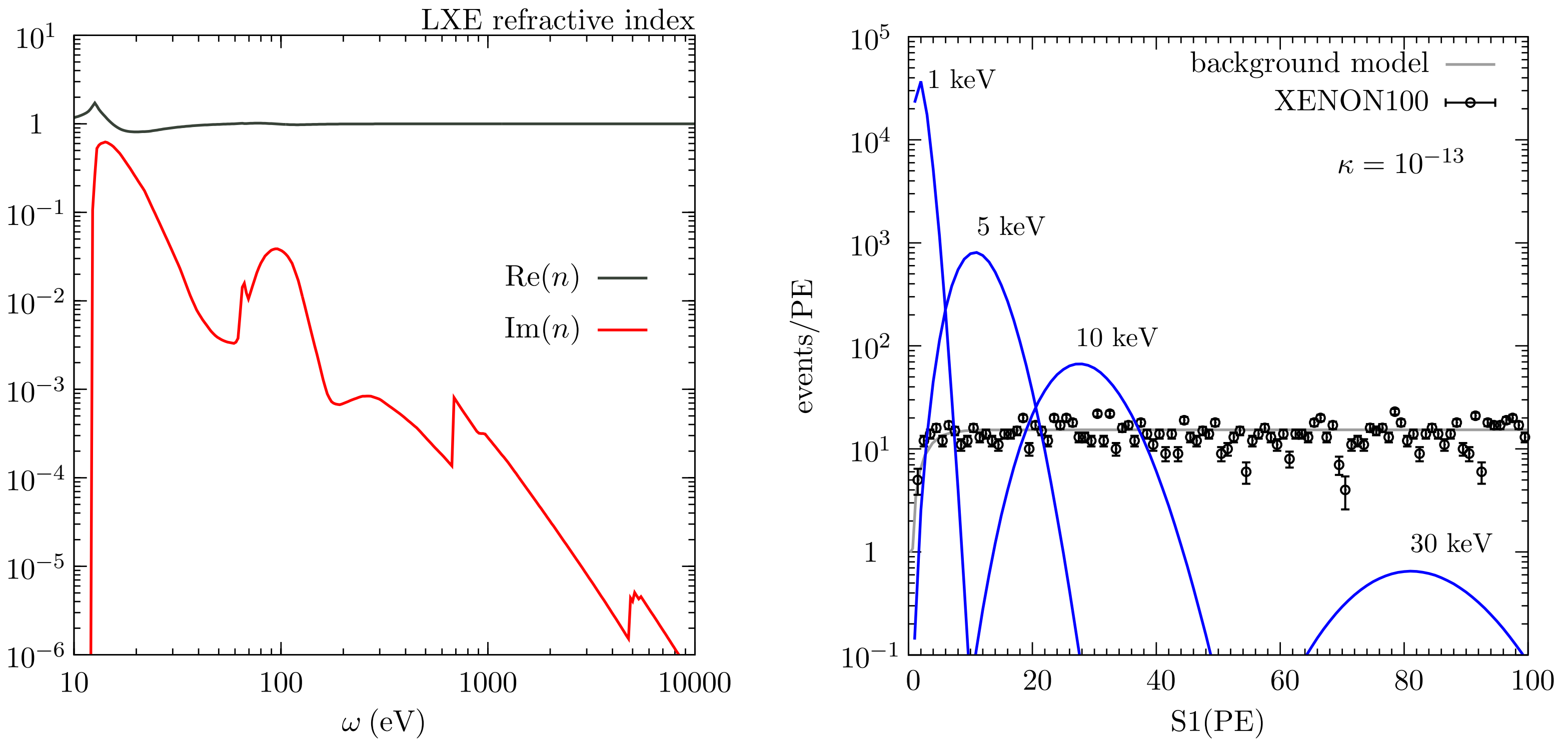
- Non-thermal mechanism for populating dark photons is required. The simplest model uses initial displacement from equilibrium, (similar to axion idea).

- The correct abundance is achieved if initial amplitude is rather large (and possibly related to inflationary scale)

$$\Omega_V h^2 \approx 0.4 \frac{g_*(T_{\rm osc})^{3/4}}{g_{*S}(T_{\rm osc})} \sqrt{\frac{m_V}{1\,{\rm keV}}} \left(\frac{\widetilde{V}_{I,i}}{10^{11}\,{\rm GeV}} \right)^2 .$$

- DM abundance can be easily saturated by O(10 eV) bosonic particles.

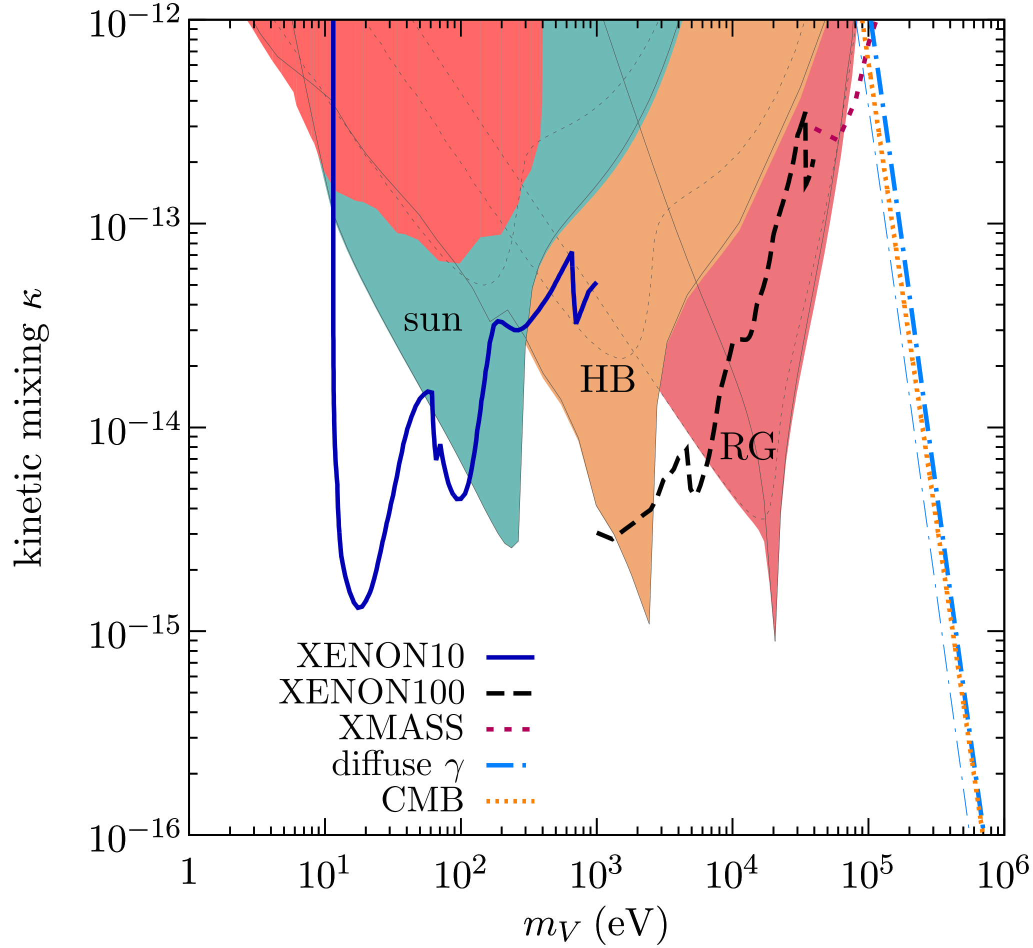
Absorption of [dark] photons in Xe



- The absorption cross section is strongly enhanced for small values of m_V.

Master plot for DM absorption signal

An, MP, Pradler, Ritz



Large DM experiments can compete with stellar constraints and have sensitivity to mixing angles down to kappa ~10^{-15} … *New analysis by XENON 100 collaboration is expected*. New ideas for detecting dark vector DM in the sub-eV range are given in Redondo et al, Graham et al

Topic #2: cosmo constraints on very dark photons in the MeV range

Let us study ~ a few MeV mass Vector with coupling $\kappa \sim 10^{-18}$ so that

$$\alpha_{\rm eff} \sim \alpha\, \kappa^2 \sim 10^{-38} \;!!!!$$

NB: $m_p^2/M_{Pl}^2 \sim 10^{-38}$

Production cross section for the $e^+e^- \to V\gamma$ process is

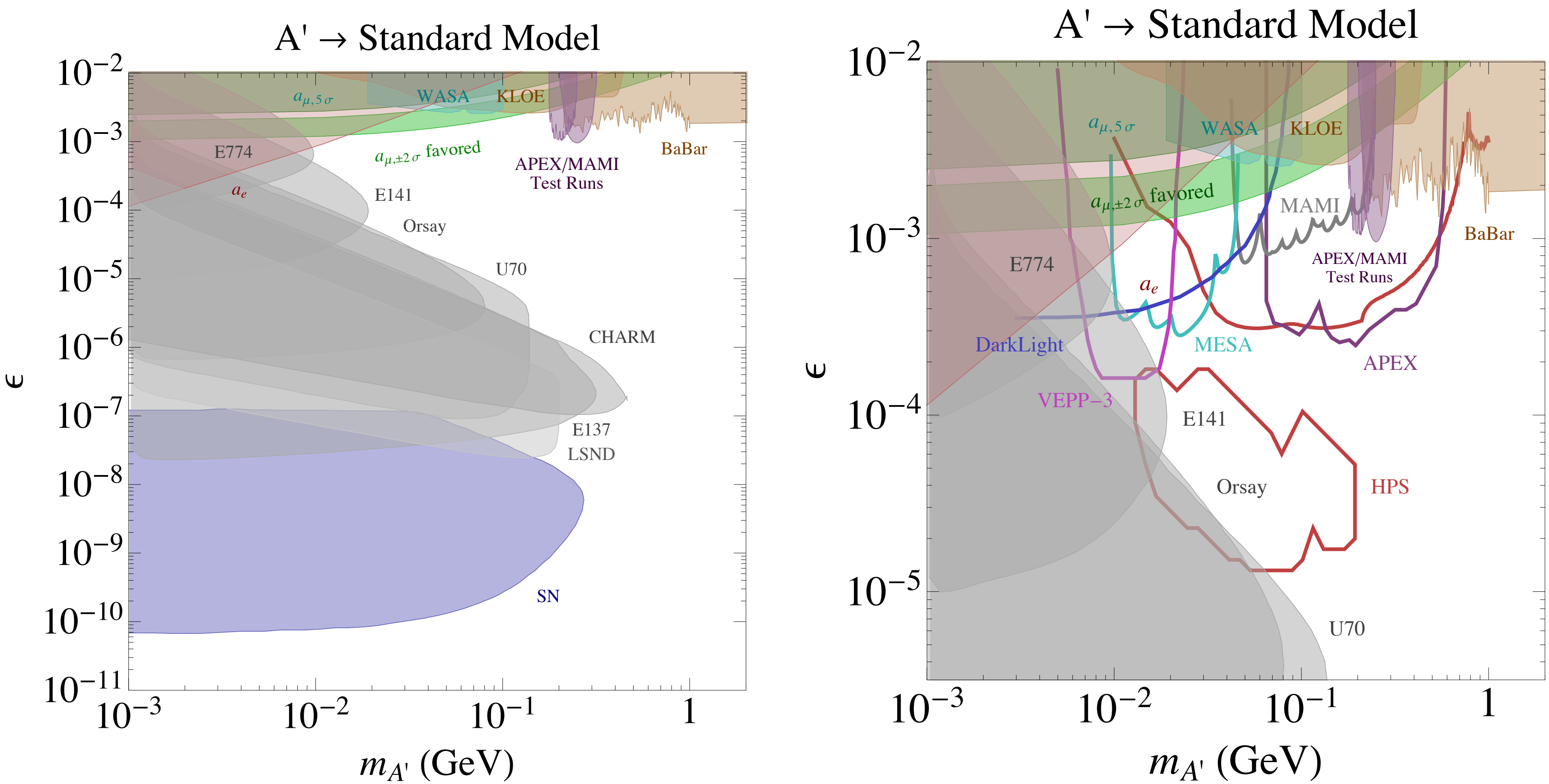
……………

$$\sigma_{\rm prod} \sim \frac{\pi \alpha \alpha_{\rm eff}}{E^2_{\rm c.m.}} \sim 10^{-66} \quad {\rm cm}^2$$

HEP experimentalist's reaction: ????

But ….. *Not only such a model can be tested – as it turns out it is excluded by the data* !!!

κ-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.*

New constraints on *very dark photons*

- The production cross section is ridiculously small, but in the early Universe at T > m_V , in fact, *every colliding pair of particles can produce such Vectors*, and there is a lot of time available for this.
- Once produced such particles *live for a very long time*, and decay in the "quiet" Universe, depositing non-thermal amounts of energy and changing physics of primordial matter after recombination.
- Precision determination of optical depth during the CMB, position of Doppler peaks and the slope of the Silk diffusion tale provide tight restrictions on the amount of energy injected.
- Due to BBN we also have a pretty good evidence that the Universe in fact once was at least T ~ a few MeV hot…..
- Fradette, Pradler, MP, Ritz, arxiv:1407.0993

VDP live very long time and can store a lot of energy

- Lifetime against the decay to electron-positron pairs

$$\tau_V \simeq \frac{3}{\alpha_{\rm eff} m_V} = 0.6 \text{ mln yr} \times \frac{10\,\text{MeV}}{m_V} \times \frac{10^{-35}}{\alpha_{\rm eff}}$$

- $e^+e^- \rightarrow V$ in the early Universe leads to the energy stored per baryon

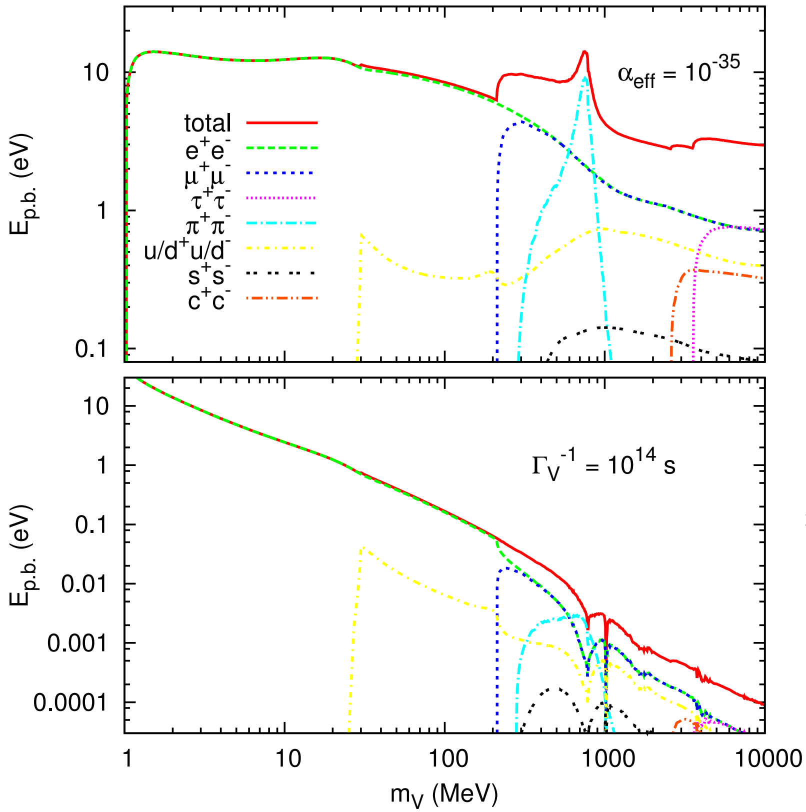
$$E_{\rm p.b.} \sim \frac{m_V \Gamma_{\rm prod} H^{-1}_{T=m_V}}{n_{b,T=m_V}} \sim \frac{0.1\alpha_{\rm eff} M_{\rm Pl}}{\eta_b} \sim \alpha_{\rm eff} \times 10^{36}\,\text{eV}$$

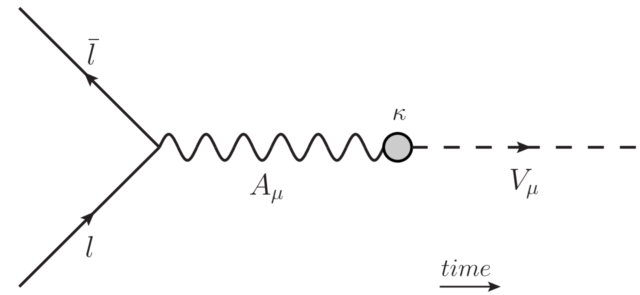
$$\text{for} \quad \Gamma_V^{-1} = 10^{14}\text{s.}$$

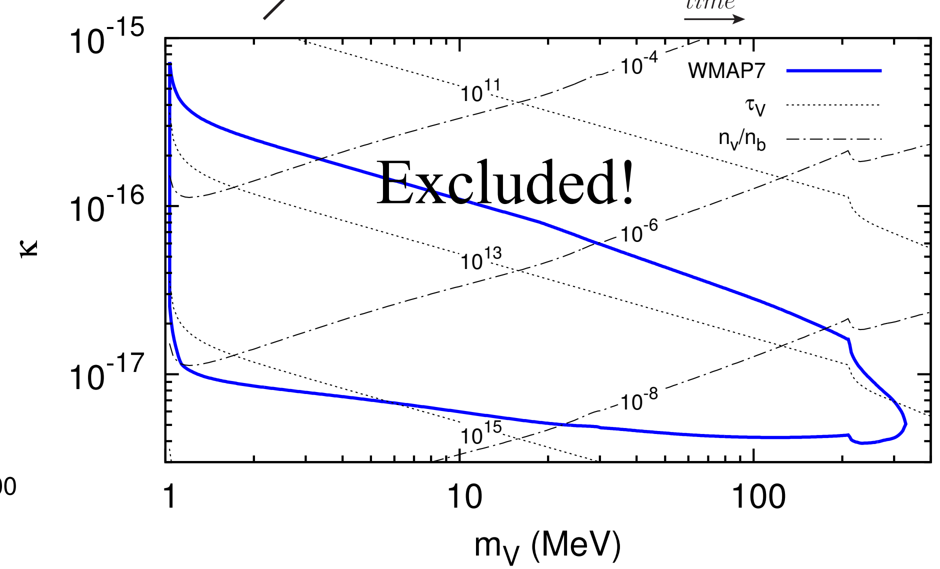
(Previously calculated in Postma, Redondo, 2008 – we improve over it by including hadronic channels and resonant production.)

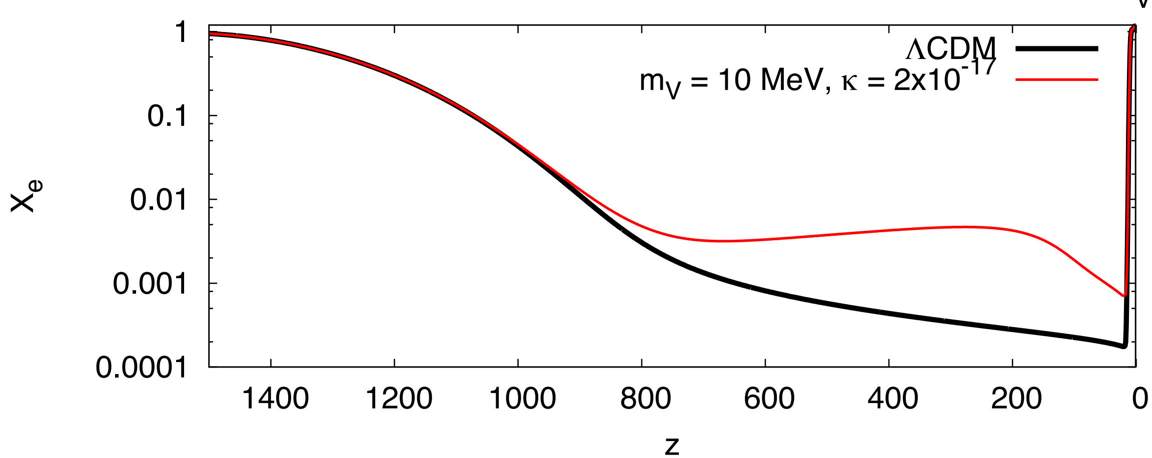
- Once injected back to the medium via $V \rightarrow e^+e^-$ $\sim 1/3$ of the stored energy leads to ionization. E.g. 1 eV p.b. recreates $X_e \sim$ few 10^{-2}.

VDP change ionization history

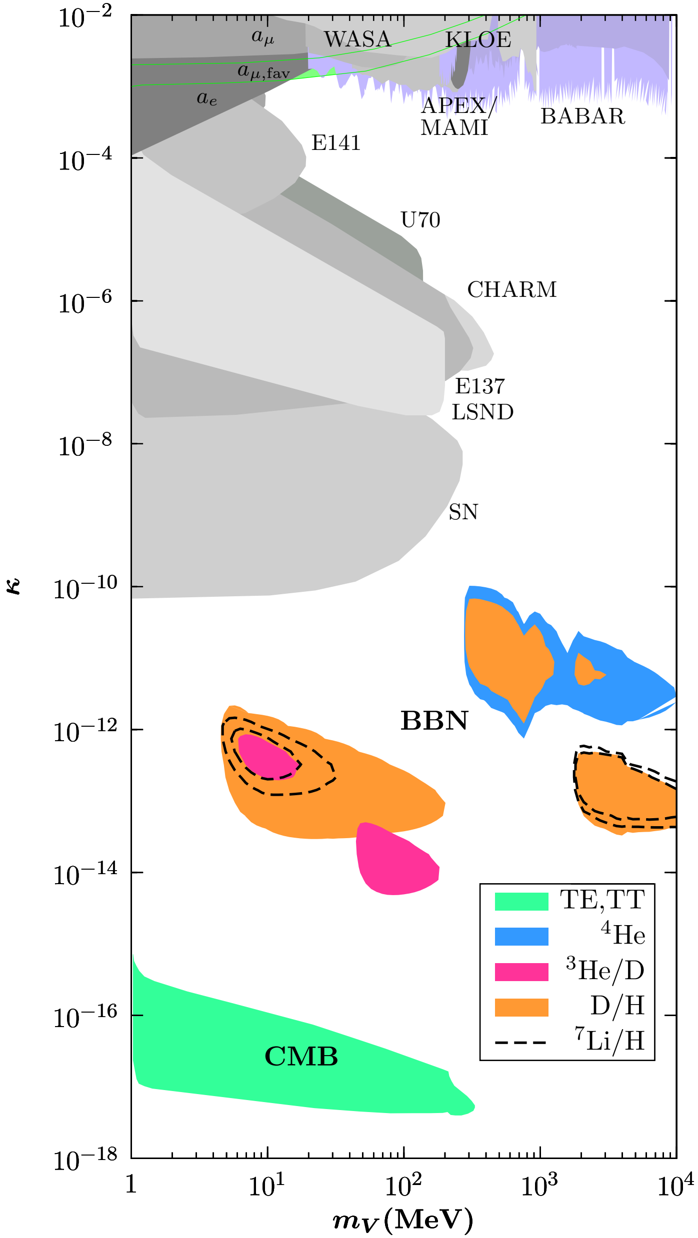








Master plot



- We rule out significant fraction of dark photon parameter space.
- These new limits are inevitable: only rely on thermal production and require that the Universe was T~ 0.3 m_V hot.
- Non-thermal component of $< V_\mu >$ (so-called "vacuum misalignment") will only make limits stronger. Existence of "dark Higgs" can only make limits stronger.
- Limits/sensitivity can be further improved with Planck polarization data. Independent assessment of D/H is needed.
- Next: $V = -\frac{m_h^2}{2} H^\dagger H + \lambda (H^\dagger H)^2 + A H^\dagger H \phi + \frac{m_\varphi^2}{2} \phi^2.$

Topic #3: search for light dark matter and light mediators using underground accelerators

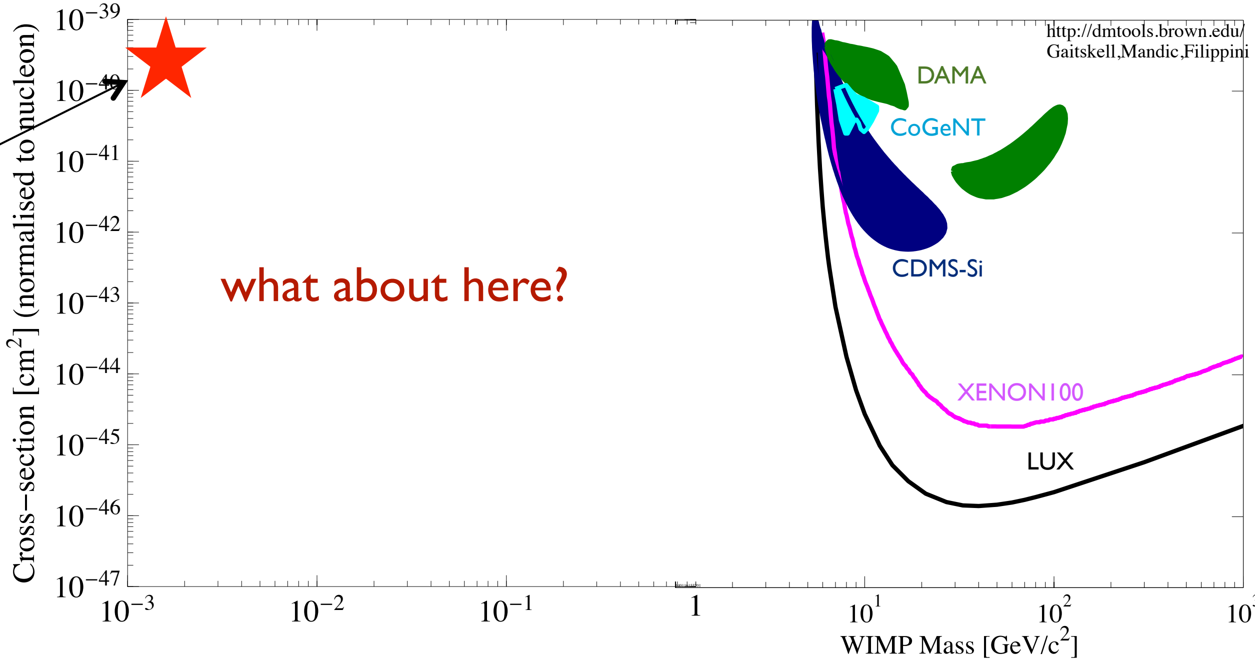
- Tying many astrophysical anomalies to WIMPs often requires light mediator particles (attempts to explain PAMELA signal.)
- Light (5 MeV and lighter) scalar WIMP DM can be used as an explanation of 511 keV excess (Fayet,…). With mixing angle ~ 10^{-4} and smaller has a chance of evading all the constraints.
- Light WIMP dark matter (~ MeV) is way outside the range of existing "direct detection" experiments.
- Can be searched for in the scattering signal analogous to neutrino neutral current.
- *For certain domains of parameter space, the most efficient searches can be done using underground accelerators.*

How to search for light weakly coupled particles in direct experiments?

- 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

Light DM – direct production/detection

511 keV motivated



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

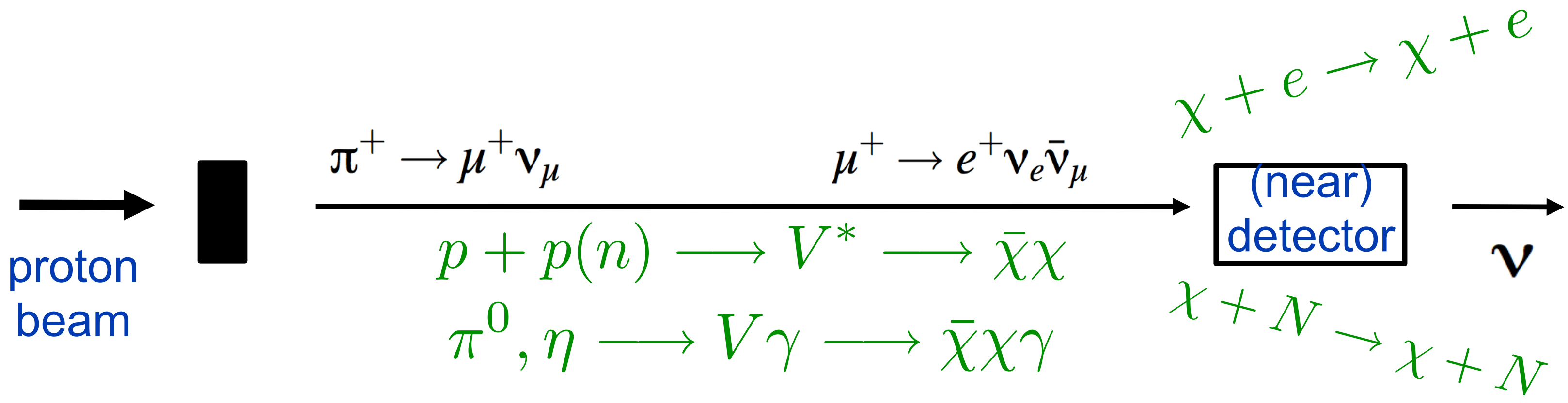
$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(V_{\mu\nu})^2 + + \frac{1}{2} m_V^2 (V_\mu)^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \ldots$$

↑ DM

↑ mediation

Fixed target probes - Neutrino Beams

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



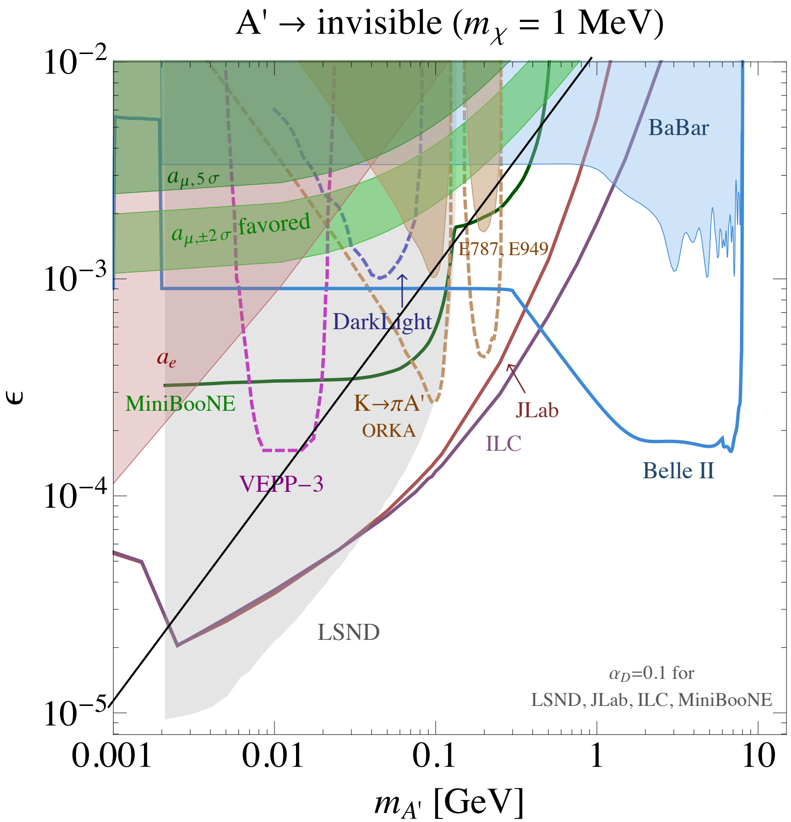
We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

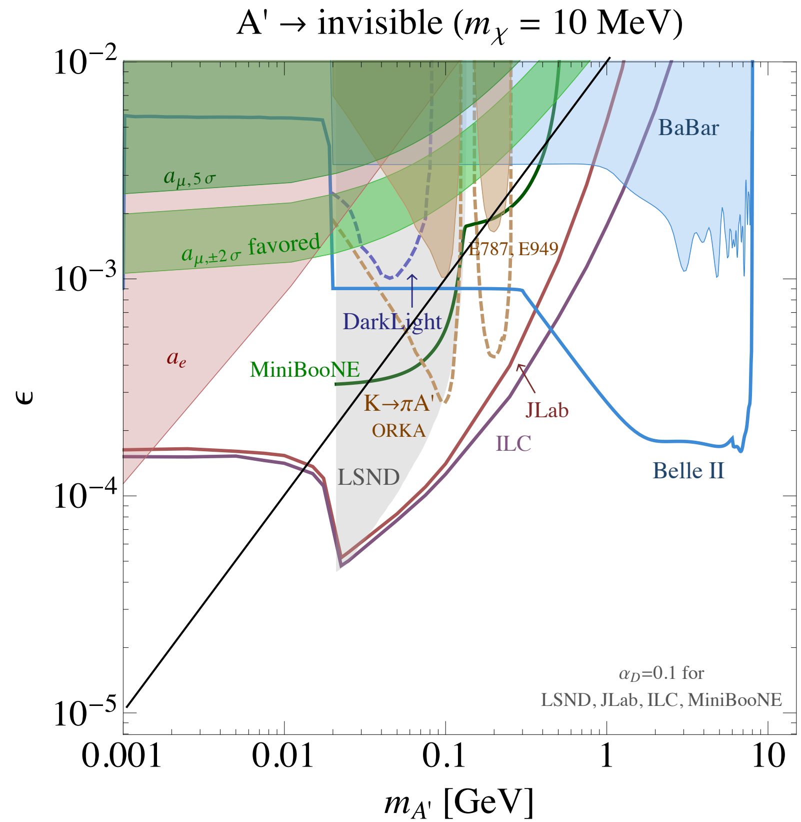
T2K
30 GeV protons
(➠ ~5x10^{21} POT)
280m to on- and off-axis detectors

MINOS
120 GeV protons
10^{21} POT
1km to (~27ton) segmented detector

MiniBooNE
8.9 GeV protons
10^{21} POT
540m to (~650ton) mineral oil 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, Krnjaic, Schuster, Toro 2013; Surujon et al.

More coverage of parameter space using underground accelerators and neutrino detectors

with Eder Izaguirre and Gordan Krnjaic, 2014

Borexino, Kamland, SNO+, SuperK, …

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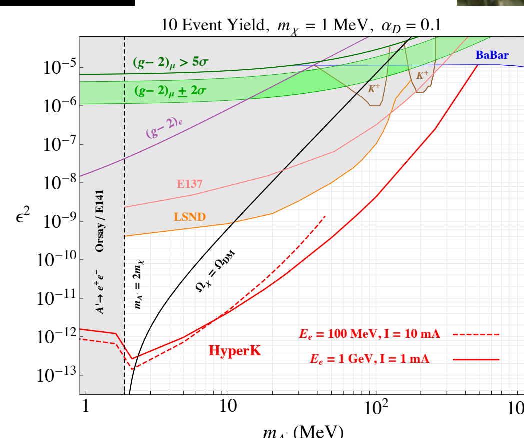
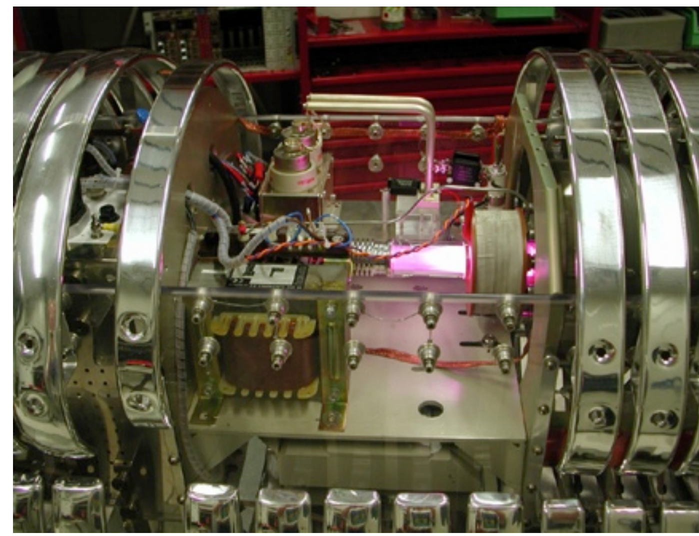
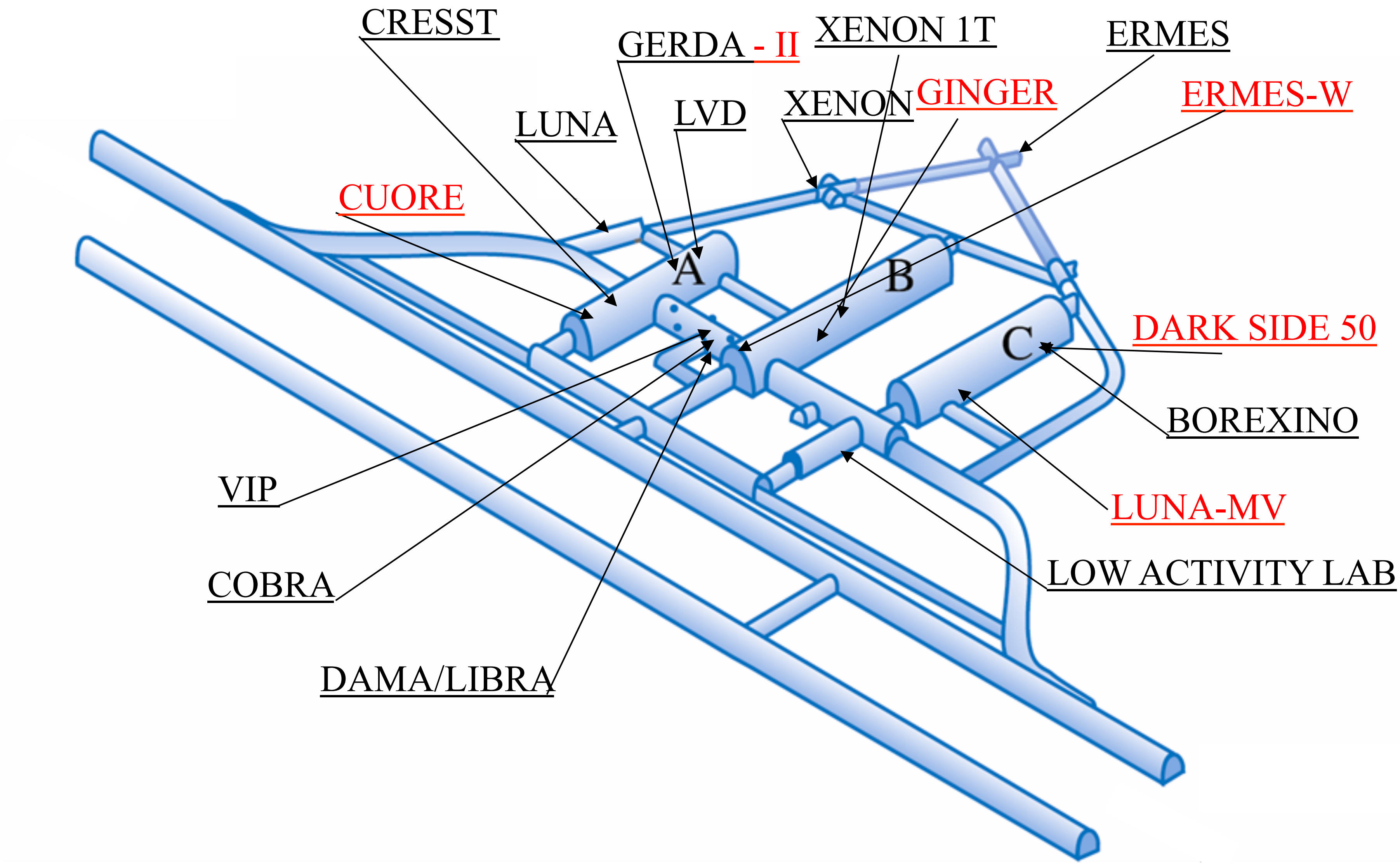


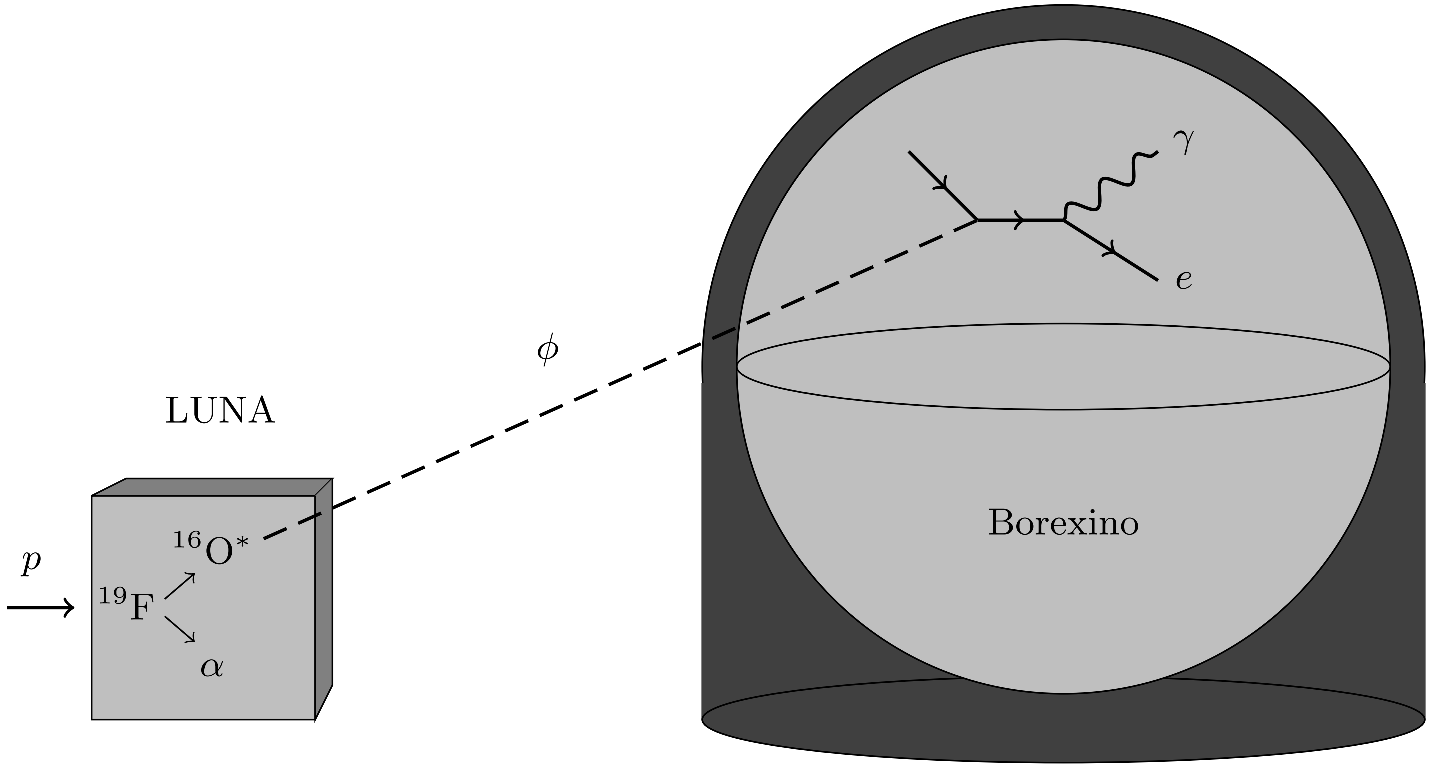


LUNA, DIANA,…



Planned location of LUNA-MV is in direct proximity of Borexino

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.

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

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.

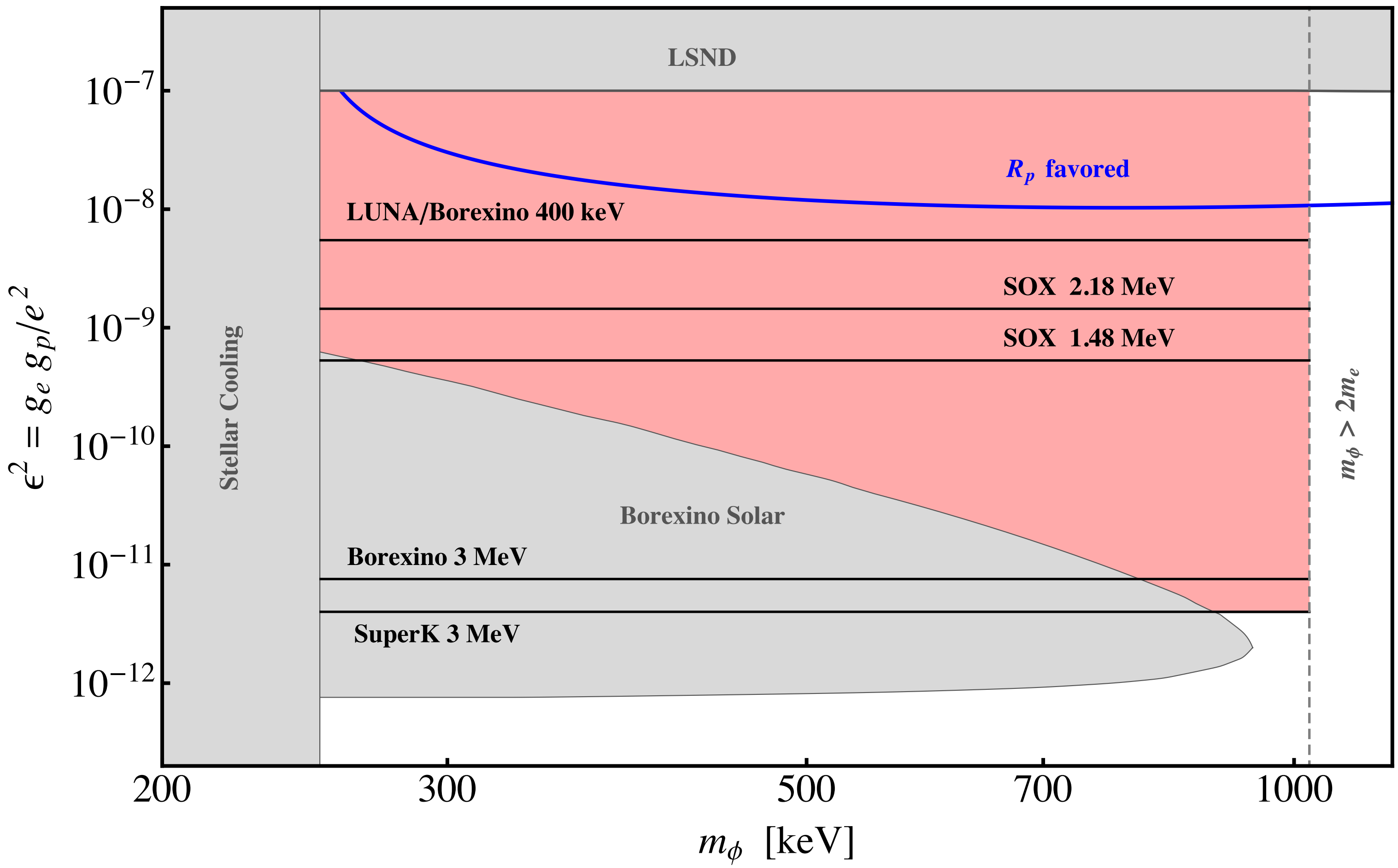
${}^{6}\mathrm{Li} + {}^{3}\mathrm{He} \rightarrow {}^{8}\mathrm{Be}^* + \mathrm{p}$

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

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

Sensitivity plot

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



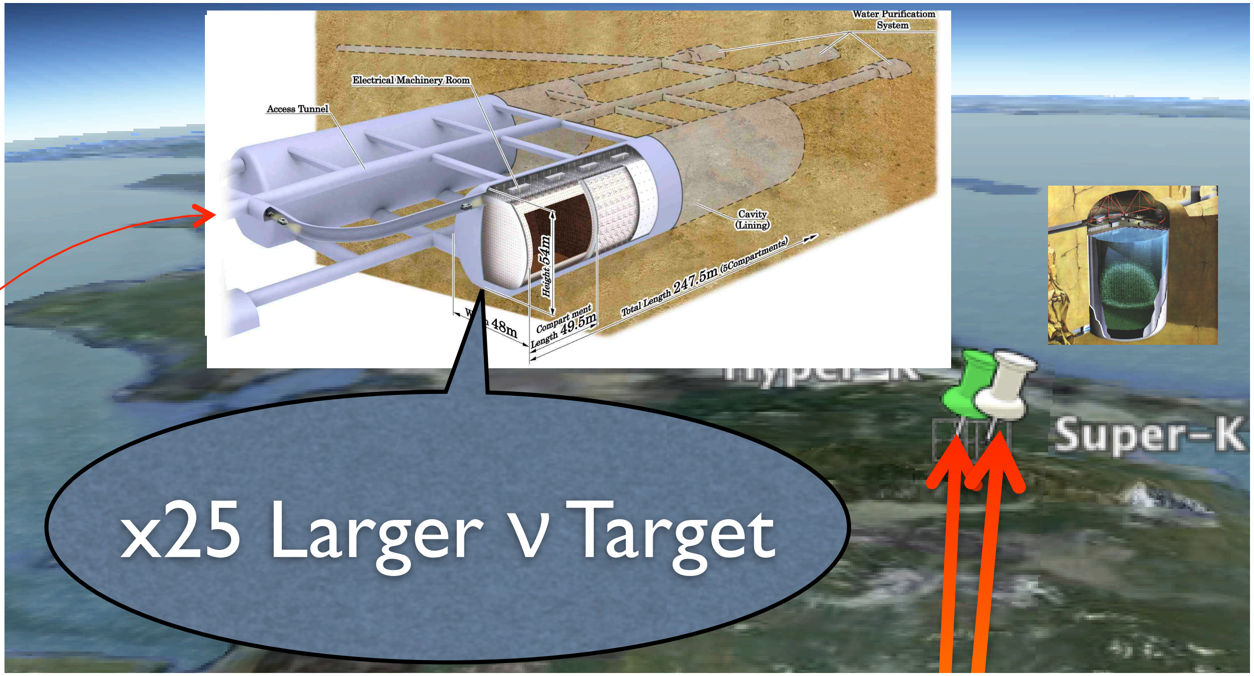
Ultimate intensity frontier experiment?

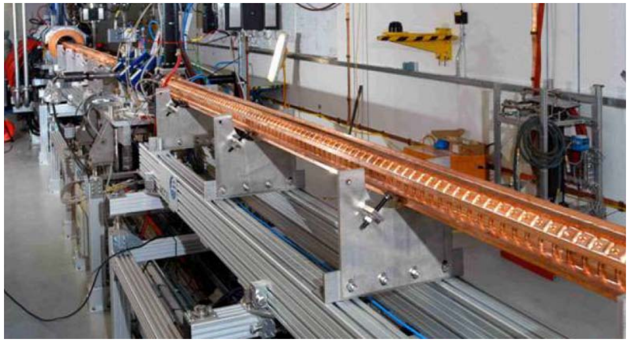
Project with Eder Izaguirre and Gordan Krnjaic, *ongoing*

- 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*



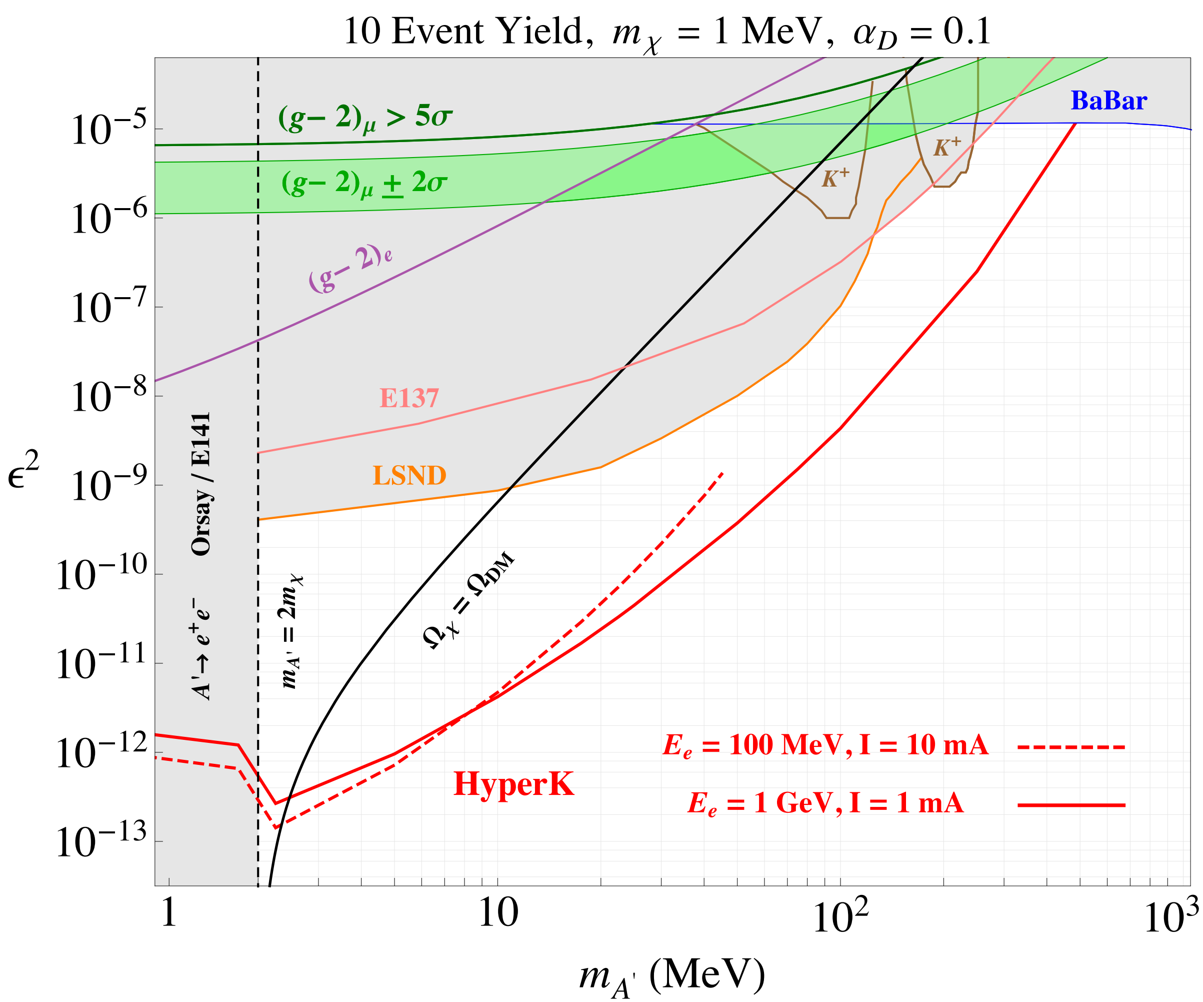


Electron linear accelerator

Construction cost estimation

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

Sensitivity to light DM



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

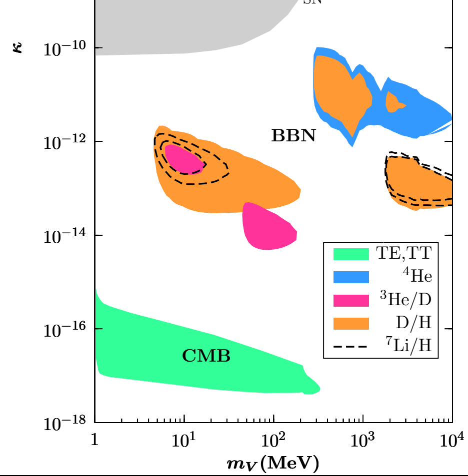
with

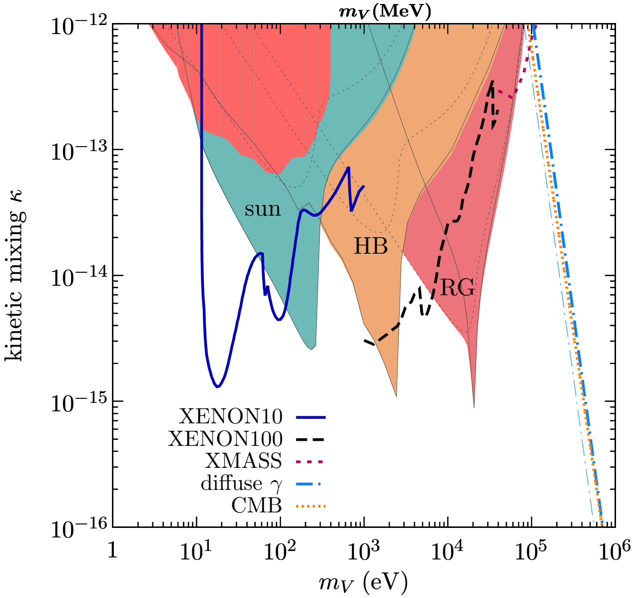
$$\mathcal{L}_\chi = \begin{cases} i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi, & \text{(Dirac fermion DM)} \\ |D_\mu\chi|^2 - m_\chi^2|\chi|^2, & \text{(Complex scalar DM)} \end{cases}$$

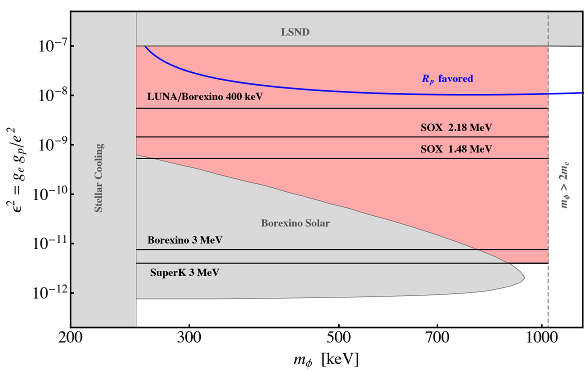
One can have a chance on improving sensitivity to very light DM, and e.g. decisively test models that aim at explaining 511 keV bulge excess via DM annihilation.

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

Conclusions







- *New constraints on very dark photons derived in MeV -100 MeV range.*
- *Light vector dark matter (10 eV – 100 keV) can be searched for with dark matter experiments looking for ionization signal. Current sensitivity to light dark photon dark matter reaches (mixing angle)~ 10^{-15}.*
- *Direct sensitivity to very weakly coupled light weakly coupled particles in 100 keV- 100 MeV range can be improved with the use of underground accelerators*

http://ictp_dm/off_the_bitten_track/totally_exotic/completely_sick/in_denial/pospelov.ppt