New physics: light and weakly coupled

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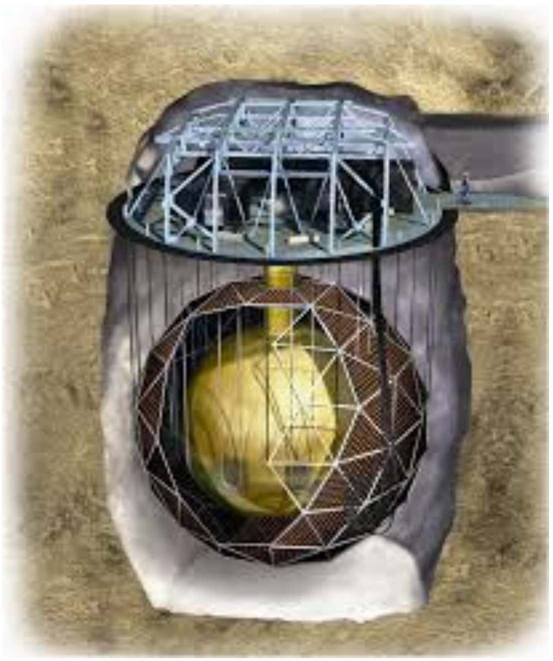
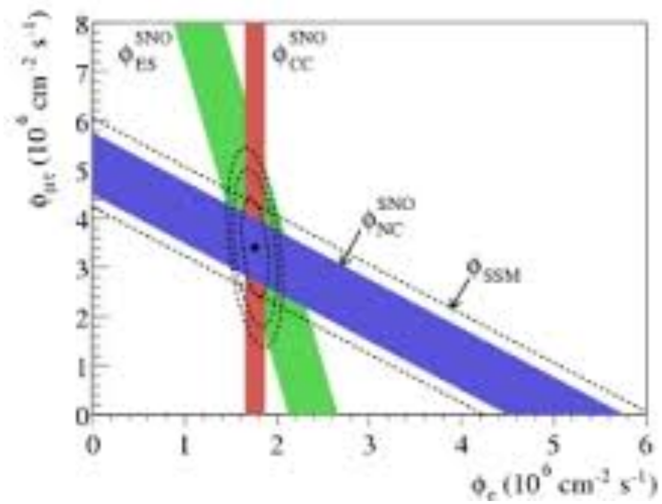
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

NP of 2015 came from solar ν anomaly

Persistence of early brave pioneers (R. Davis Jr., J. Bahcall, others) lead to the establishing the "solar neutrino anomaly", ultimately resulting in discovery of neutrino masses and mixing.



A. McDonald



In finding the correct explanation, as important part of the process, the community had to go through some "conspiratorial" SM explanations based on anomalous reaction rates, resonances etc. But New Physics won in this particular instance!

Outline of the talk

1. Introduction. Portals to light new physics. Generalization: UV physics or IR?
2. Snapshots of recent activity in connection with anomalies

   A. Vector portal, muon g-2 discrepancy, and the search for dark photon. Dark scalars.

   B. New physics for the proton charge radius.

   C. Light dark matter via vector portals. Connection to astrophysical 511 keV anomaly.

   D. Light new physics trying to explain "cosmic lithium problem"
3. Conclusions

Simple messages in today's talk

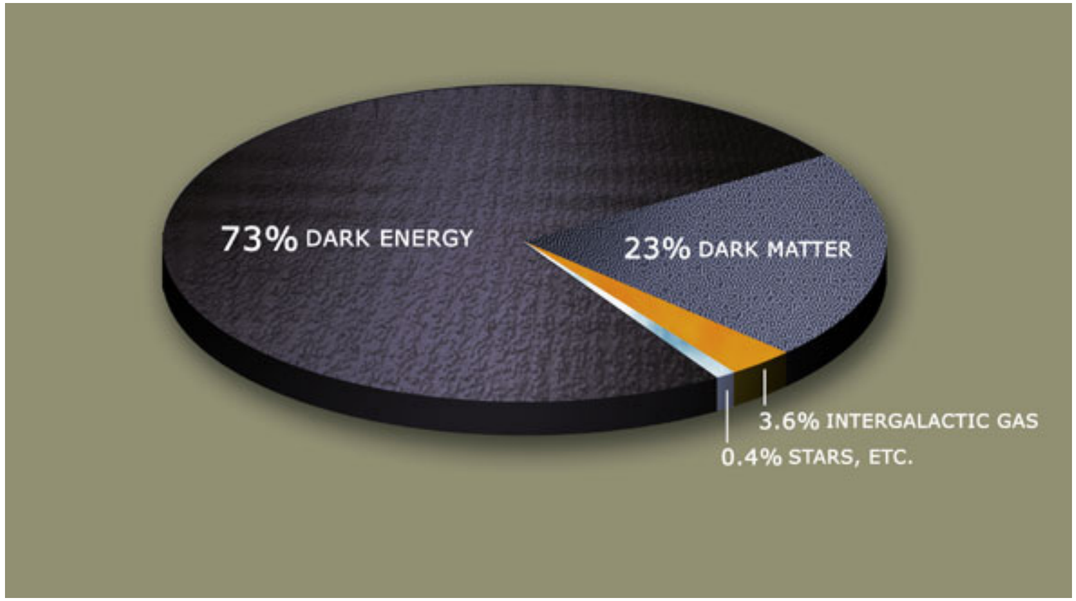
1. *Light weakly coupled new (BSM) physics* is a generic possibility not to be *a priori* discarded.

2. If it does not violate any well-tested symmetry, it can mediate a new interactions that are e.g. *stronger* than some SM interactions.

3. Since 2008, there has been *a revival* of the subject (driven initially by some astrophysics anomalies), with old data being repurposed, new searches added, and new experiments being set up. There is still considerable room for *new ideas*. This subject is here to stay.

4. If light NP is proposed to "explain away" some anomalies (g-2, muon H Lamb shift), it is often the case that NP model can be tested faster than the true origin of given discrepancy is found.

Big Questions in Physics

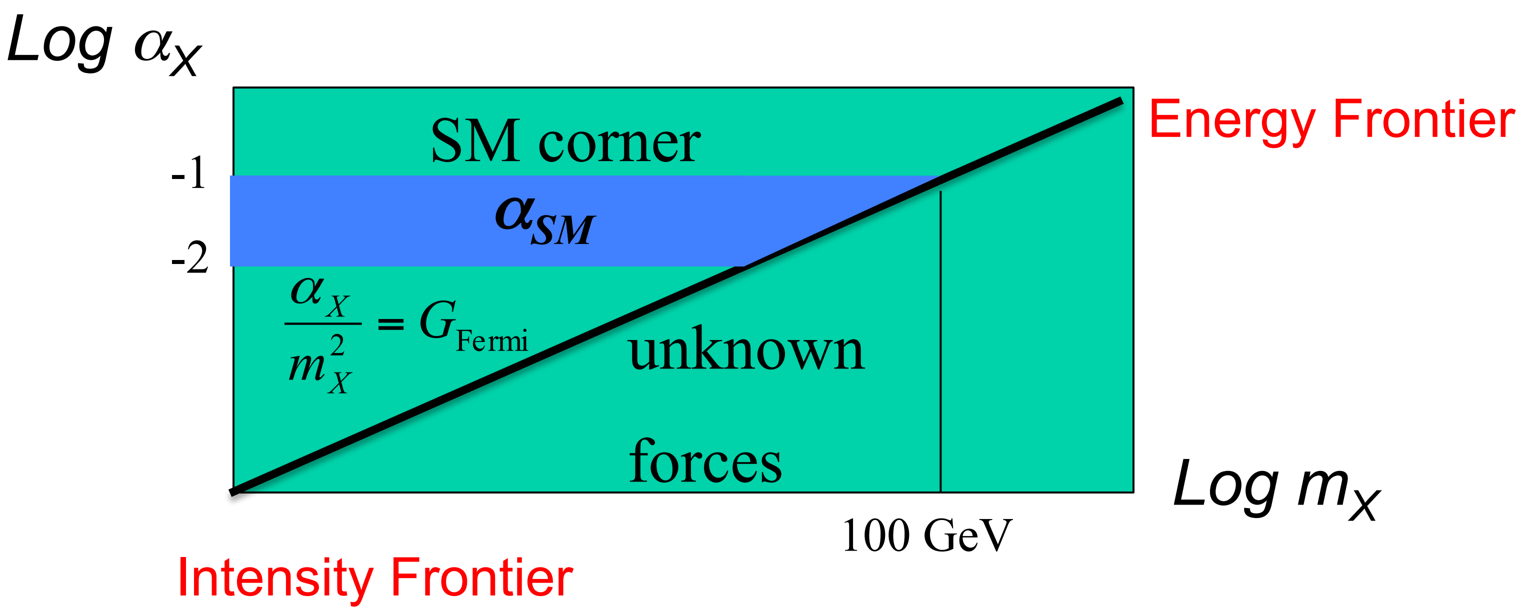


"Missing mass" – what is it?

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.)

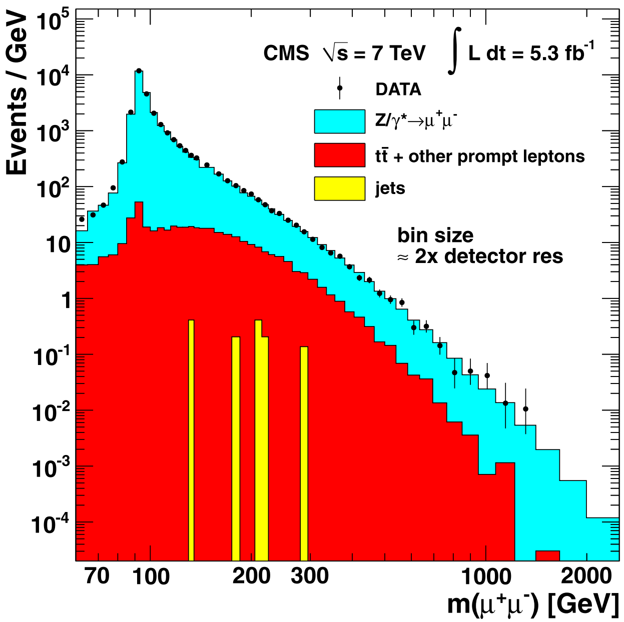
Intensity and Energy Frontiers

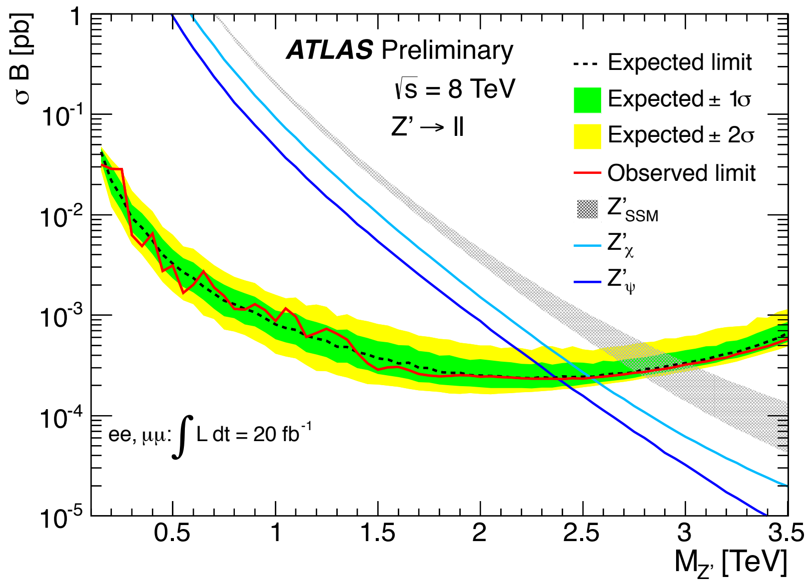


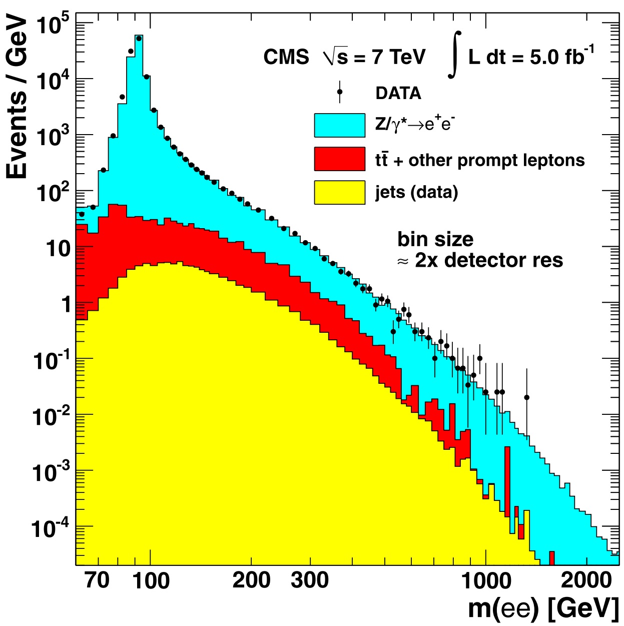
$$V(r) = \frac{\alpha_X}{r}\exp(-r/\lambda_X) = \frac{\alpha_X}{r}\exp(-rm_X) \longrightarrow \text{Amplitude} \approx \frac{\alpha_X}{q^2 + m_X^2}$$

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

No New Physics at high energy thus far (?!)





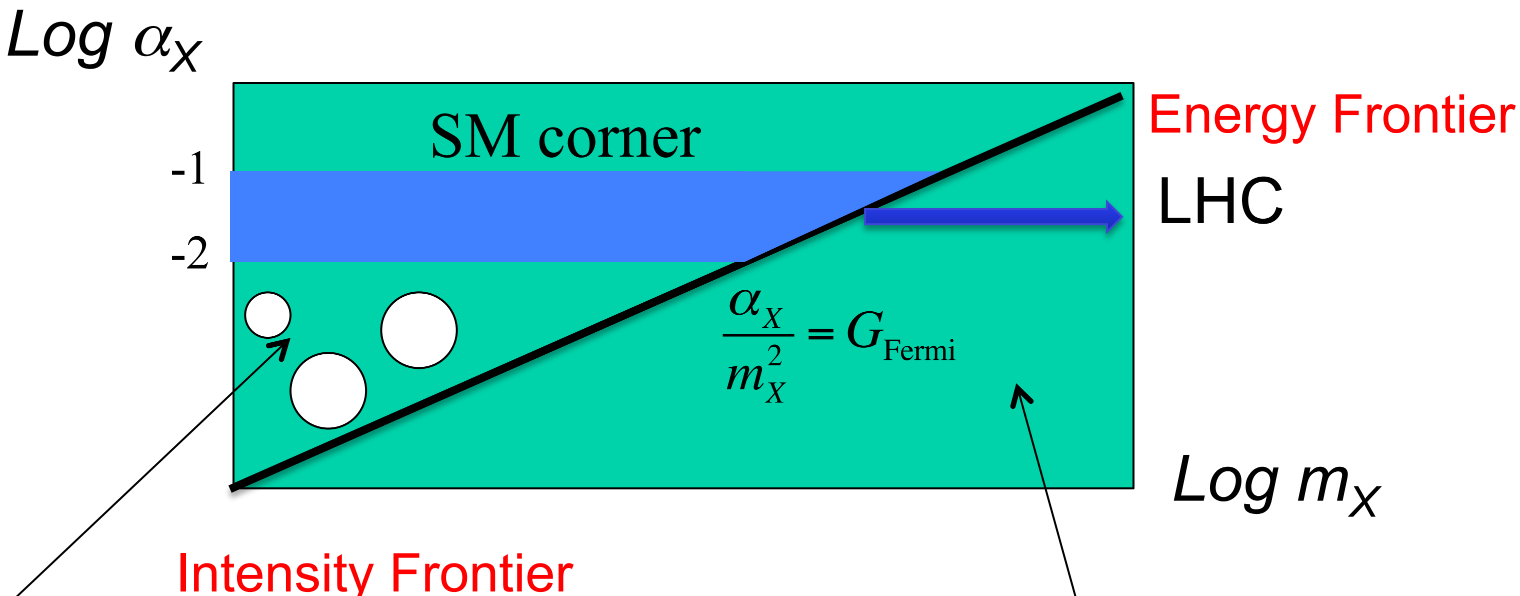


No hints for any kind of new physics. Strong constraints on SUSY, extra dimensions, technicolor resonances.

Constraints on new *Z'* bosons push the mediator mass into multi-TeV territory.

Hint for $m_{\rho'} \sim 2$ TeV ???

"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

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

……….

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

Precision frontier: UV physics or IR?

Typical approach: we measure an observable (e.g. $\mu \to e\,\gamma$, 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, IR pieces or both,

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

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

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

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

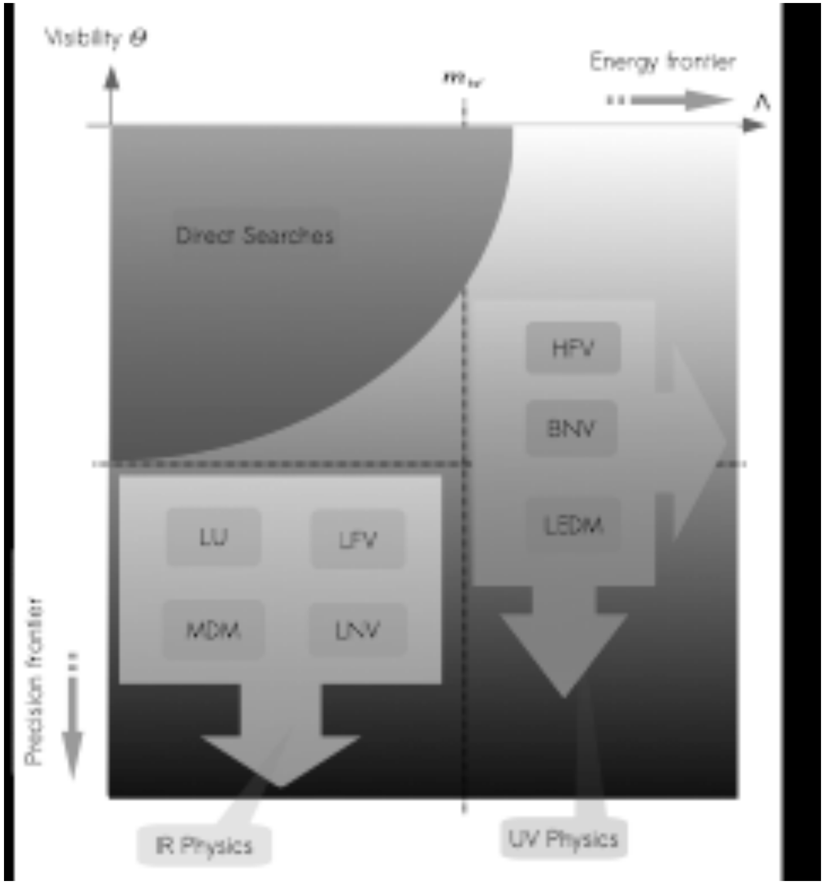
or it is generated by *new IR field*, such as RH component of Dirac neutrinos? *New dedicated experimental efforts are directed in trying to decide between these possibilities.*

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 IR, 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)

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 κ (also known as ε, η) controls the coupling to the SM. New gauge bosons can be light if the mixing angle is small.

In this talk κ = ε

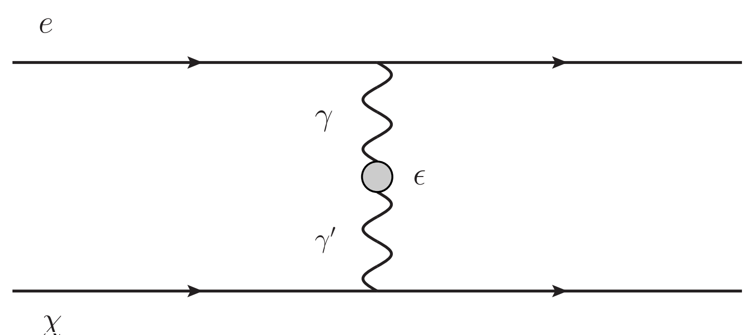
Low-energy content: **Additional massive photon-like vector V**, and possibly a new light Higgs h', both with small couplings.

Model for "mini-charged" particles

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

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

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



- "Effective" charge of the "dark sector" particle χ is Q = e × ε (if momentum scale q > m_V). At q < m_V one can say that particle χ has a non-vanishing *EM charge radius*, $r^2_\chi \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. Very light χ 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 Λ (however heavy!, e.g. 100000 TeV) charged under the SM $U_Y(1)$ and $U_S(1)$ (B. Holdom, 1986)

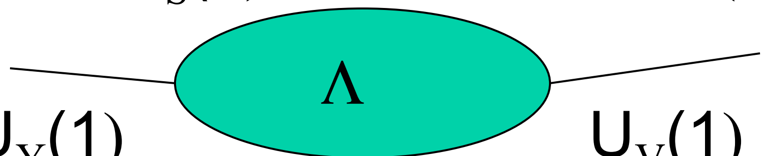


Diagram $U_Y(1)$ $U_V(1)$ does not decouple!

A mixing term is induced, $\kappa F^Y_{\mu\nu} F^S_{\mu\nu}$,

With κ having only the log dependence on mass scale Λ

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

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

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

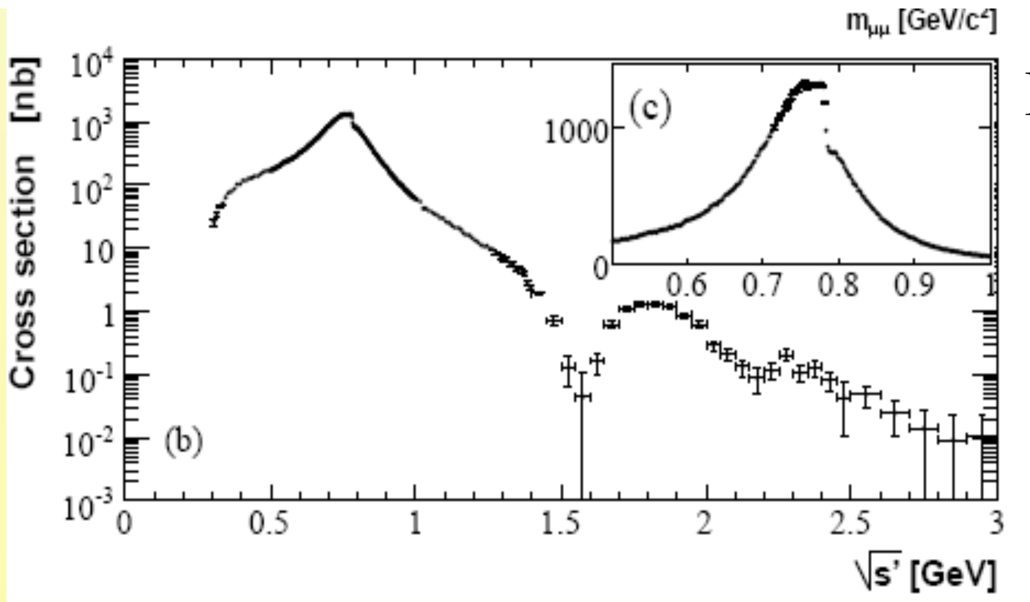
Variations of vector portal: gauged B - L, L_μ - L_τ, baryon number, etc.. symmetries

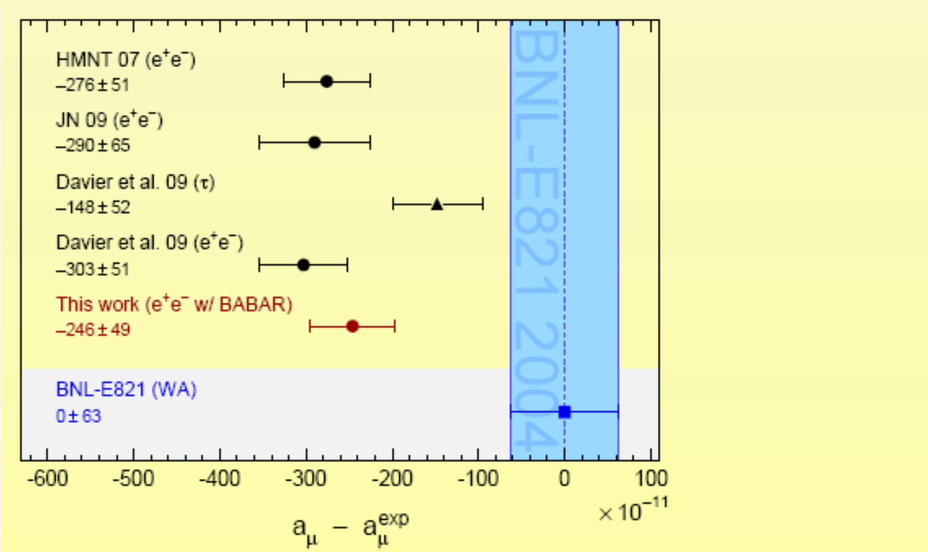
- *Anomaly-free, can be UV complete. (For B, anomaly can be cancelled)*
- A non-zero kinetic mixing will be developed out of RG evolution
- Neutrinos get extra interaction – already constrained!
- L_μ - L_τ is the *least constrained* possibility because neither electrons nor nucleons have extra interactions 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. 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 *without large fine tuning*.

g-2 of muon





✱ Davier et al. arXiv:0906-5443

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.

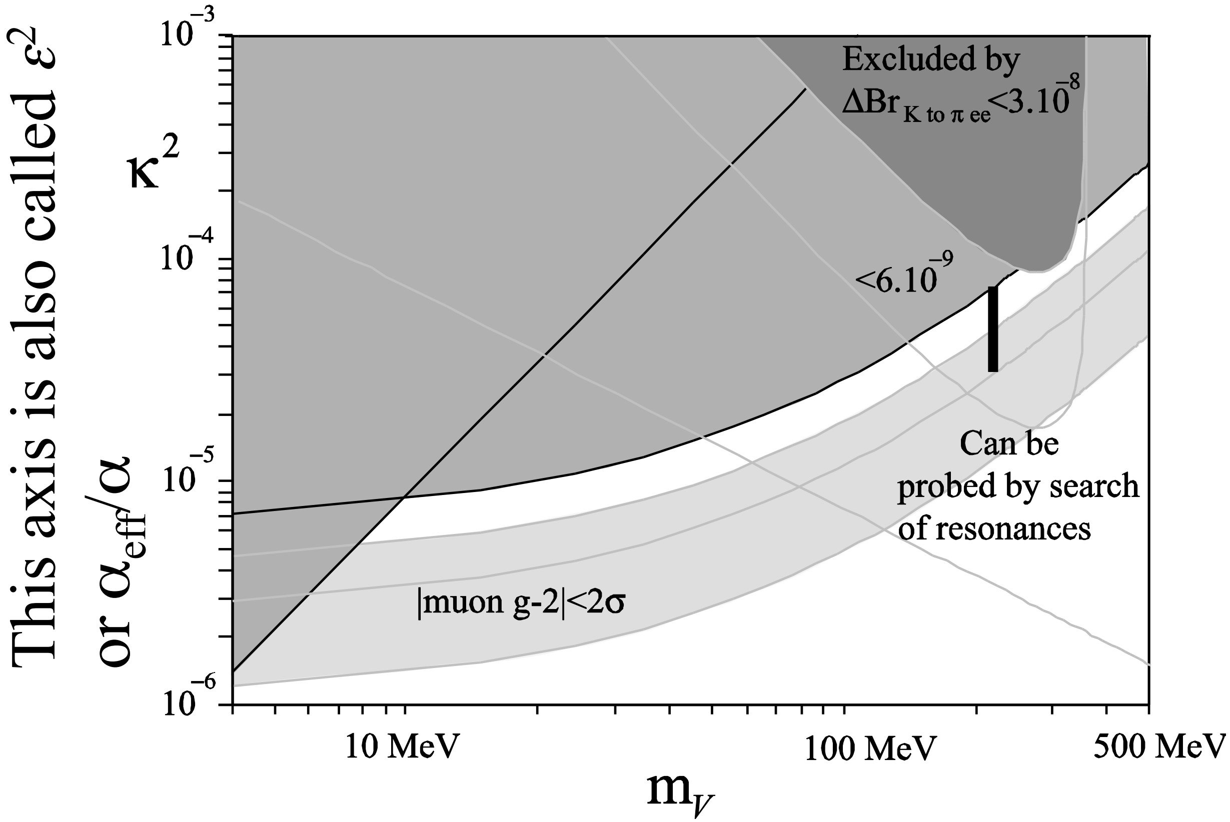
Supersymmetric models with large-ish *tanβ*; light-ish sleptons, and right sign of μ parameter can account for the discrepancy.

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

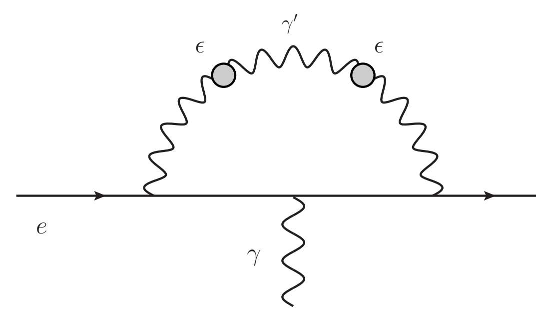
g-2 signature of light particles

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 $m_V \sim m_\mu$

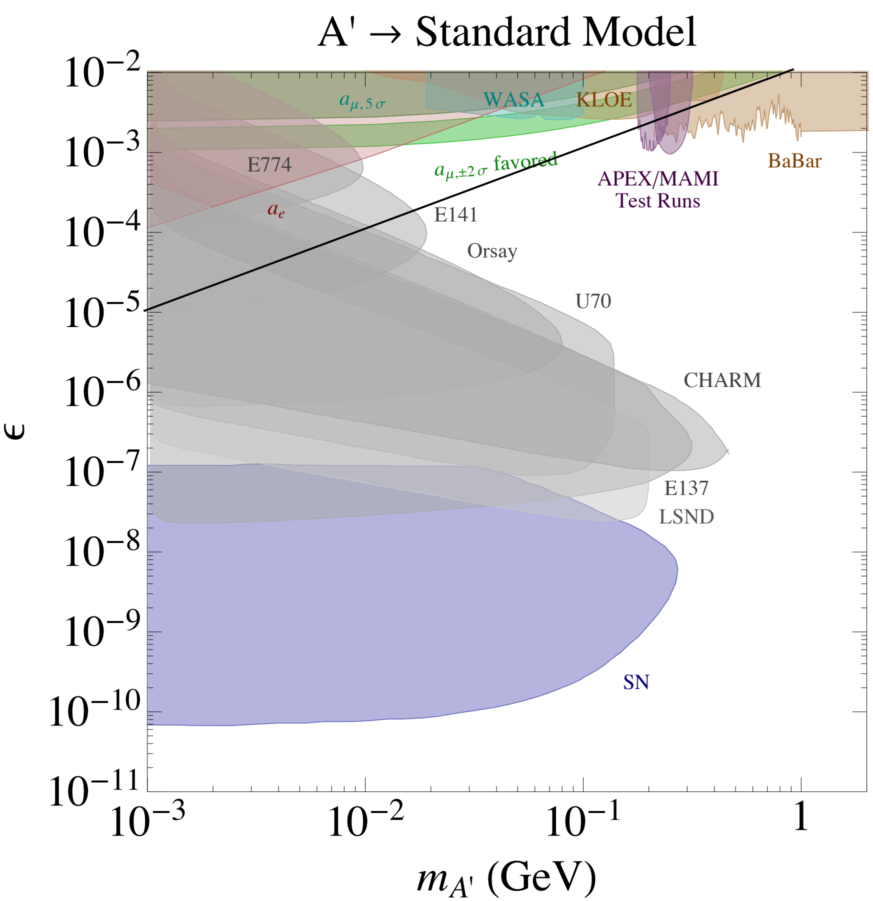


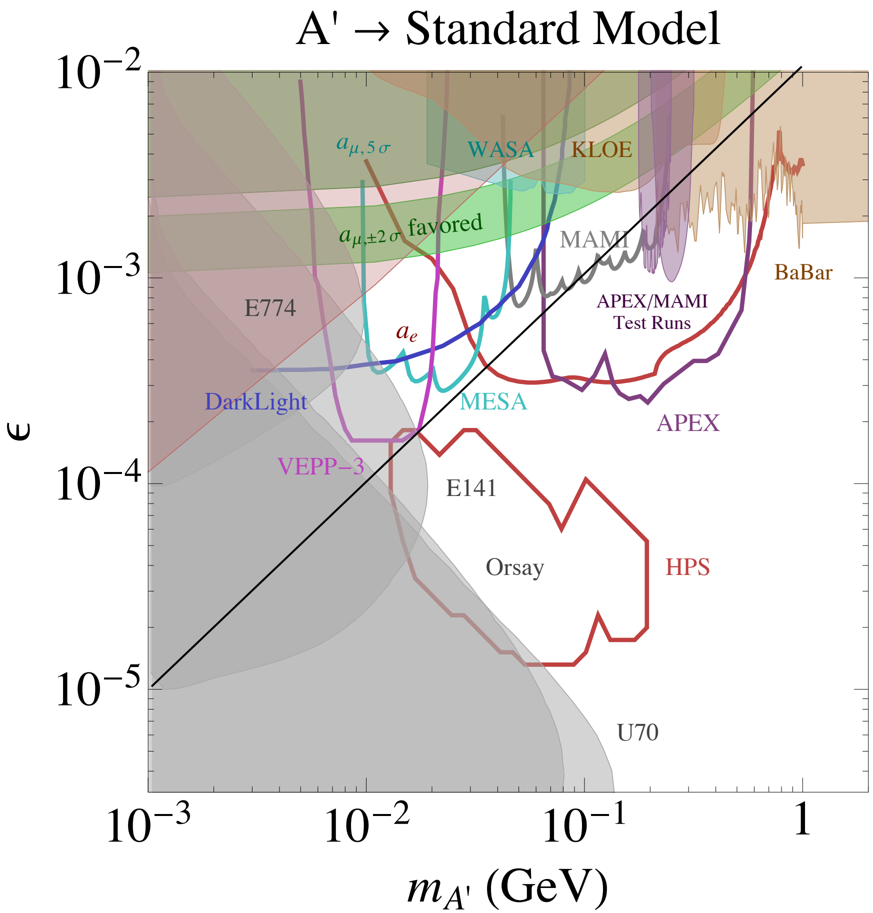
MP, 2008



Since 2008 a lot more of parameter space got constrained

ε-m_V parameter space, Snowmass study, 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.*

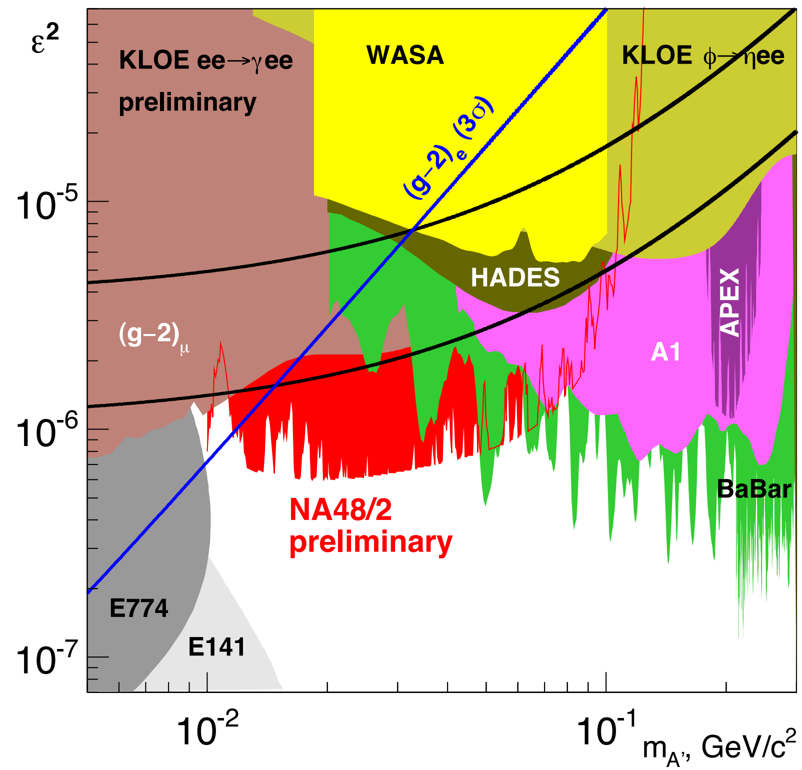
Latest results: A1, Babar, NA48

Signature: "bump" at invariant mass of e^+e^- pairs = $m_{A'}$

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

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

NA48/2: $\pi^0 \rightarrow \gamma V \rightarrow \gamma e^+e^-$
Latest results by NA48 exclude the remainder of parameter space relevant for g-2 discrepancy.



Only *less minimal* options for muon g-2 explanation remain:
A. $L_\mu - L_\tau$, B. Dark photons *decaying* to dark state (light dark matter), C. dark scalar (W. Marciano talk)

Signatures of Z' of L_μ - L_τ

Experimental results on "trident"

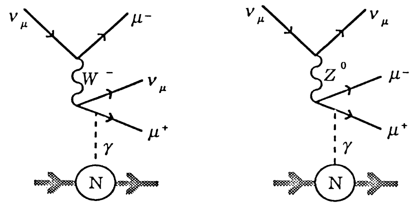
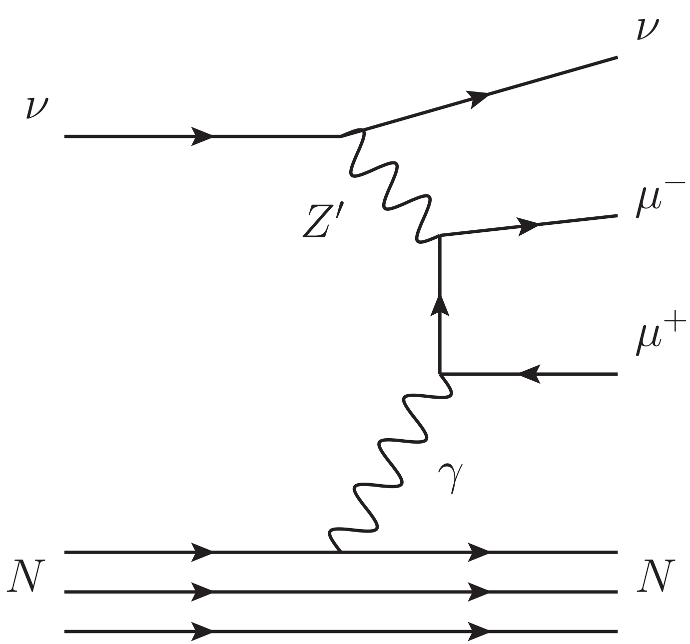
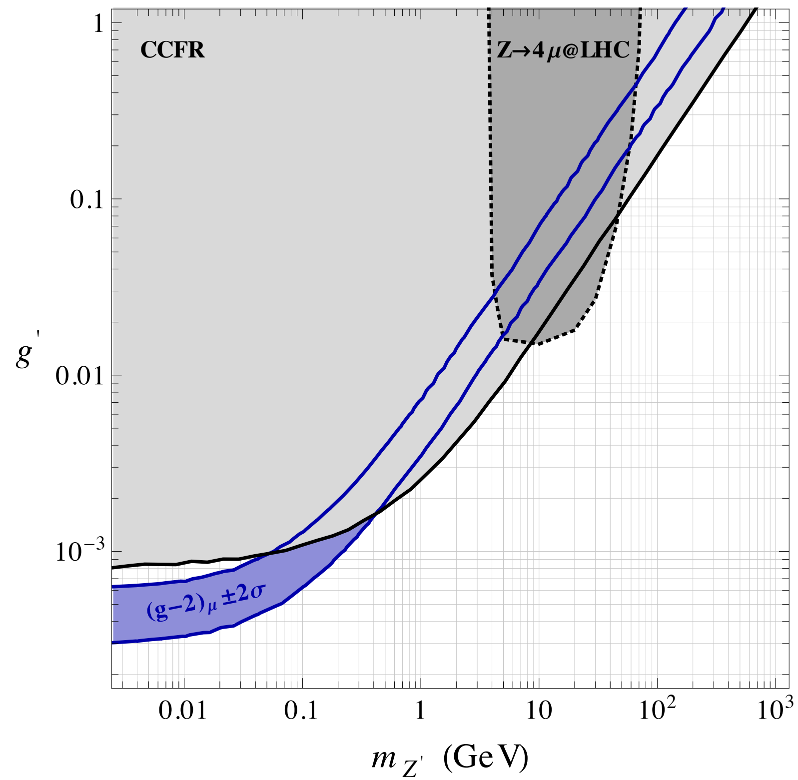


FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

$$\sigma_{\rm CHARM-II}/\sigma_{\rm SM} = 1.58 \pm 0.57 \,,$$
$$\sigma_{\rm CCFR}/\sigma_{\rm SM} = 0.82 \pm 0.28 \,,$$
$$\sigma_{\rm NuTeV}/\sigma_{\rm SM} = 0.67 \pm 0.27 \,.$$

Hypothetical Z' (any Z' coupled to L_μ) contributes constructively to cross section. (Almannshofer et al., 2014)





Leptonic 2HDM + singlet scalar

Consider 2HDM where one of the Higgses (Φ_1) will mostly couple to leptons, and also mixes with a singlet that is "light" relative to EW scale.

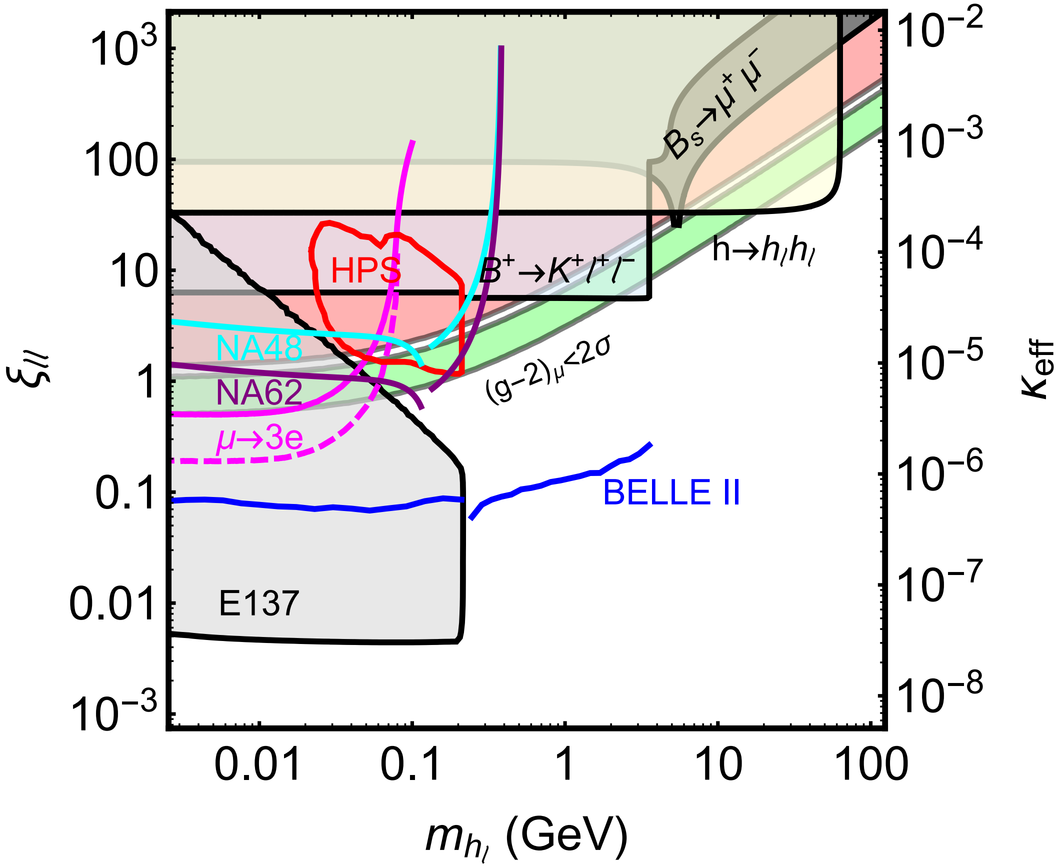
$$
\begin{aligned}
V &= V_{\text{2HDM}} + V_S + V_{\text{portal}} \\
V_{\text{2HDM}} &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 \\
&\quad + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_2\right)^2\right] \\
V_S &= BS + \frac{1}{2} m_0^2 S^2 + \frac{A_S}{2} S^3 + \frac{\lambda_S}{4} S^4 \\
V_{\text{portal}} &= S\left[A_{11}\Phi_1^\dagger \Phi_1 + A_{22}\Phi_2^\dagger \Phi_2 + A_{12}\left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right)\right]
\end{aligned}
$$

Calling the the lightest scalar particle "h_l", one takes a large tan beta regime, and considers an effective Yukawa interaction,

$$
\begin{aligned}
\mathcal{L}_{\text{Yuk}} &= \frac{m_\ell}{v c_\beta}\rho_1 \bar{\ell}\ell + \frac{m_q}{v s_\beta}\rho_2 \bar{q} q \\
&\equiv \frac{m_\ell}{v}\left(\xi_{h\ell\ell} h + \xi_{H\ell\ell} H + \xi_{\ell\ell} h_\ell\right)\bar{\ell}\ell + \frac{m_q}{v}\left(\xi_{hqq} h + \xi_{Hqq} H + \xi_{qq} h_\ell\right)\bar{q} q
\end{aligned}
$$

where it is important that 1. h_l is light, 2. couples mostly to leptons, proportionally to their masses. This leads to an effective "reweighting" of the traditional e-mV parameter space for all effect involving muons.

Constraints on the parameter space



"Effective" mixing angle for electrons

$$\kappa_{\mathrm{eff}} \equiv m_e \xi_{\ell\ell}/ev$$

Batell, Lange, McKeen, Pospelov, Ritz, *to appear [eventually]*.

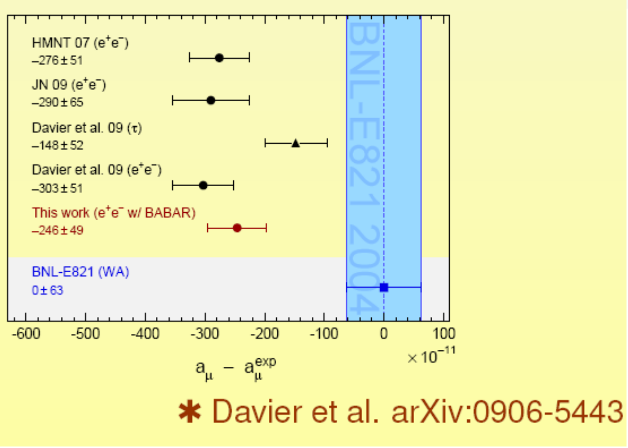
Muon, Kaon decays will bring progress; B-factory signal from the associated ττ + Scalar → ττμμ production will resolutely test the model below ~ 6 GeV.

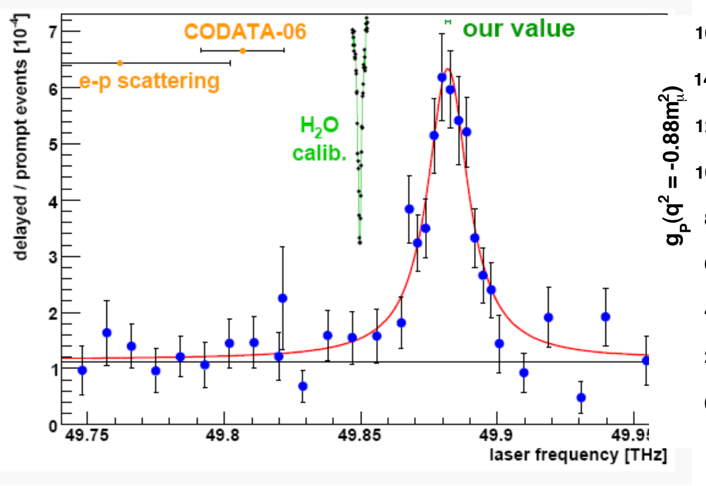
"The hardest thing of all is to find a black cat in a dark room, especially if there is no cat." — Confucius

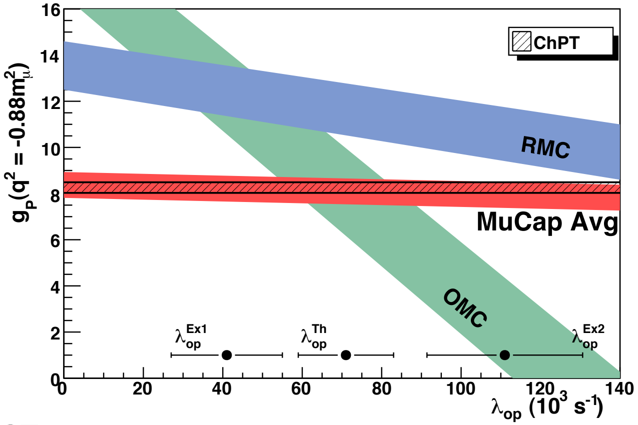
- With the g-2 explanations by light weakly coupled particles, we have passed the stage of "black cat".
- We've learned that the "room must be dark" as well.

In some sense, one can say similar things about SUSY explanations: the simplest (circa 2001 Snowmass) SUSY models are dead.

More anomalies with muons







Can result from

New Physics at

100 GeV-TeV scale or sub-GeV

scale

IF it is NP, it can only be light

More discrepancies discovered using muons !

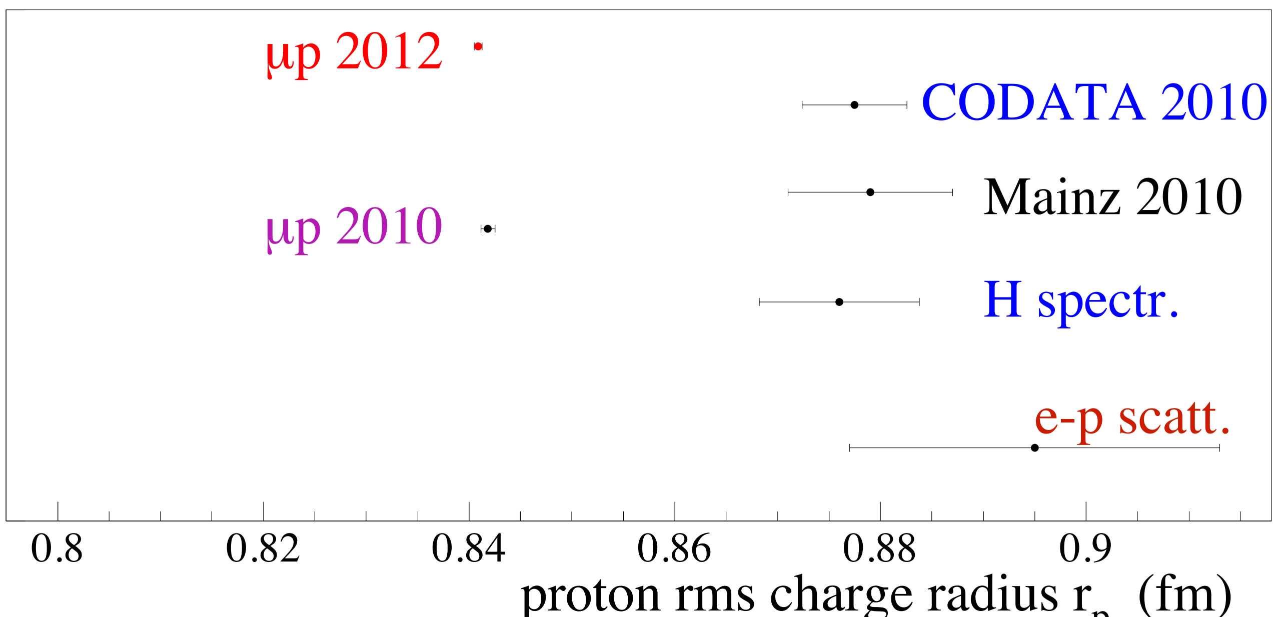
$\nu(2S_{1/2}^{F=1} \to 2P_{3/2}^{F=2})$ = 49881.88(76) GHz R. Pohl *et al.*, Nature 466, 213 (2010)

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_p = 0.84089 $(26)_\mathrm{exp}$ $(29)_\mathrm{th}$ = 0.84089 (39) fm (prel.)

μp theory: A. Antogini *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 ~ 10^4 G_F effects…

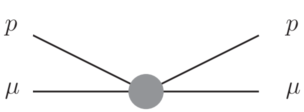
Why should we care about r_p problem?

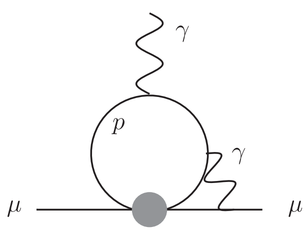
G-2 experiment "migrated" from BNL to Fermilab.

r_p problem is a huge challenge: if by any chance the muon-proton interaction is "large": either the two-photon strong interaction diagram or "light new physics", then g-2 is not really calculable with required precision!

$$\Delta\mathcal{L} \simeq C(\bar{\psi}_\mu \psi_\mu)(\bar{\psi}_p \psi_p),$$

$$C \text{ needs to be } \sim (4\pi\alpha) \times 0.01 \text{ fm}^2$$





$$\Delta(a_\mu) \sim -C \times \frac{\alpha m_\mu m_p}{8\pi^3} \times \begin{cases} 1.7; & \Lambda_{\rm had} \sim m_p \\ 0.08; & \Lambda_{\rm had} \sim m_\pi \end{cases}$$

$$5 \times 10^{-9} \lesssim |\Delta(a_\mu)| \lesssim 10^{-7}.$$

Shift is much larger than hadronic LBL error! Larger than discrepancy…

New U(1) forces for right-handed muons

Batell, McKeen, MP, PRL 2011 – Imbeds a new force into SM

Despite considerable theoretical difficulties to build a consistent model of "muonic forces" relevant for r_p discrepancy, gauged RH muon number could be still alive:

$$\mathcal{L} = -\frac{1}{4}V_{\alpha\beta}^2 + |D_\alpha\phi|^2 + \bar{\mu}_R i\not{D}\mu_R - \frac{\kappa}{2}V_{\alpha\beta}F^{\alpha\beta} - \mathcal{L}_m$$

Main logical chain leading to this:

Vector force has to NOT couple to left-handed leptons – otherwise huge new effects for neutrinos. Then has to couple to RH muons,

$$V_\alpha \bar{l}\gamma_\alpha l \subset V_\alpha(c_1\bar{L}\gamma_\alpha L + c_2\bar{R}\gamma_\alpha R),\ c_1 \neq -c_2.$$

* This "model" needs to fine tune $(g\text{-}2)_\mu$, Parity violation in Cs (generated at two loops), and tolerate the anomaly. *Solution could be worse than initial problem.*

Other possibilities??

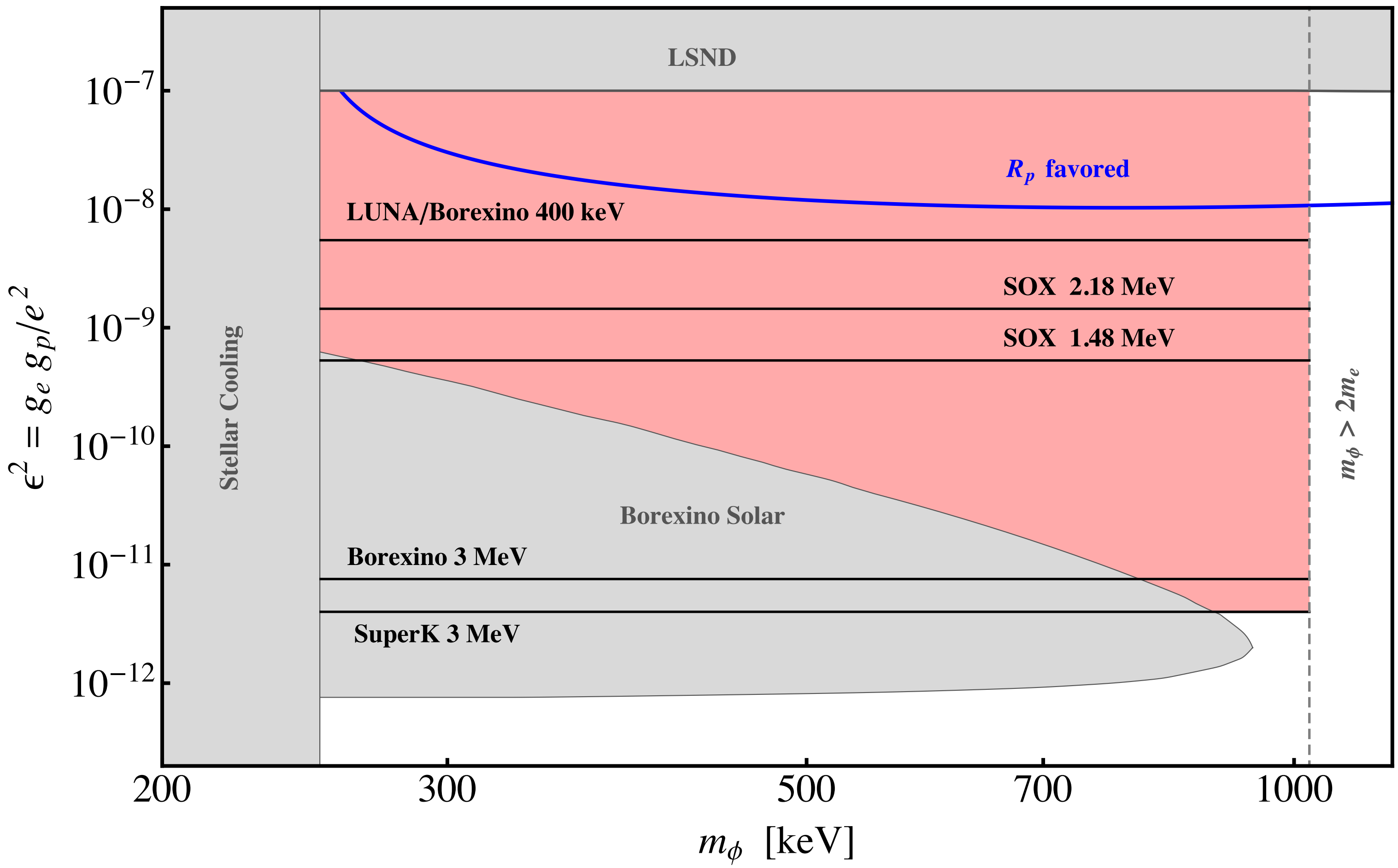
- How about the scalar force – call it *S* – that provides e-p repulsion and fixes r_p discrepancies at least between normal H and μH (Tucker-Smith, Yavin proposal)?

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

- Couplings will be very small, and the mass will be small, O(200 keV- 1MeV), $y_e y_p / e^2 \sim - 10^{-8}$.
- This turns out to be somewhat of a blind spot in terms of astro and cosmo constraints. *Issues with UV completion, n scattering*
- Izaguirre, Krnjaic, MP: 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 $^{19}F + p \rightarrow {}^{16}O(*) + {}^{4}He$ reaction

Sensitivity to scalar mediator

- ^{16}O de-excitation of 6.05 MeV as a source of scalars
- *r_p relevant region can be fully covered.*



Light WIMPs due to light mediators

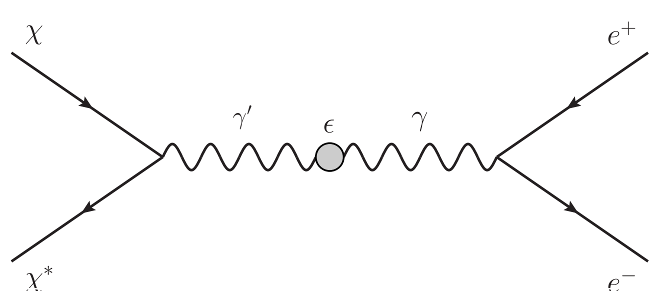
(Boehm, Fayet; MP, Riz, Voloshin …) Light dark matter is not ruled out if one adds a light mediator.

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

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

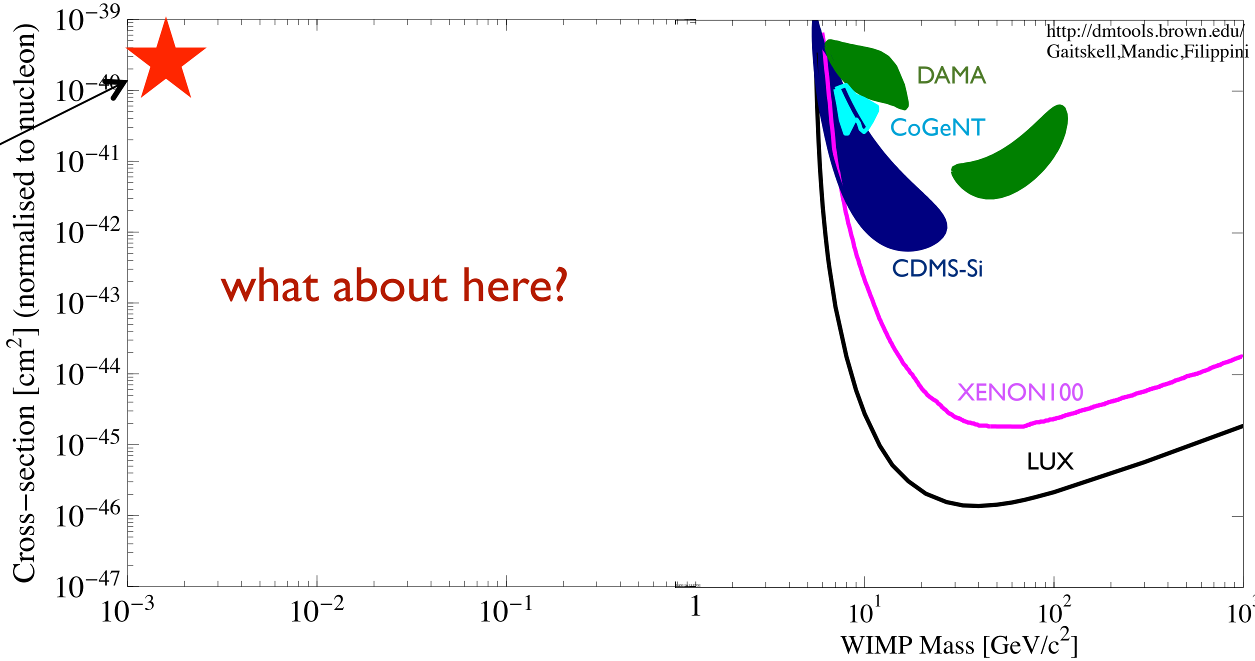
$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for} \quad m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for} \quad m_\chi \gg m_W. \end{cases} \quad \implies \quad \text{few GeV} < m_\chi < \text{few TeV}$$

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



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

Astrophysical motivations: 511 keV line

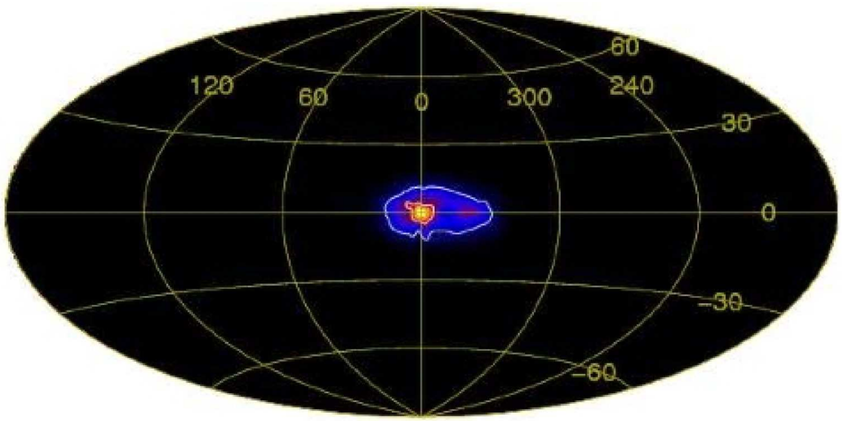


FIG. 4 511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

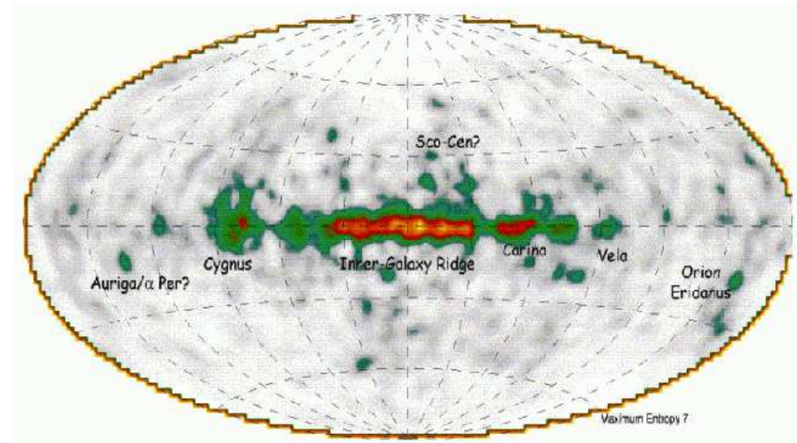


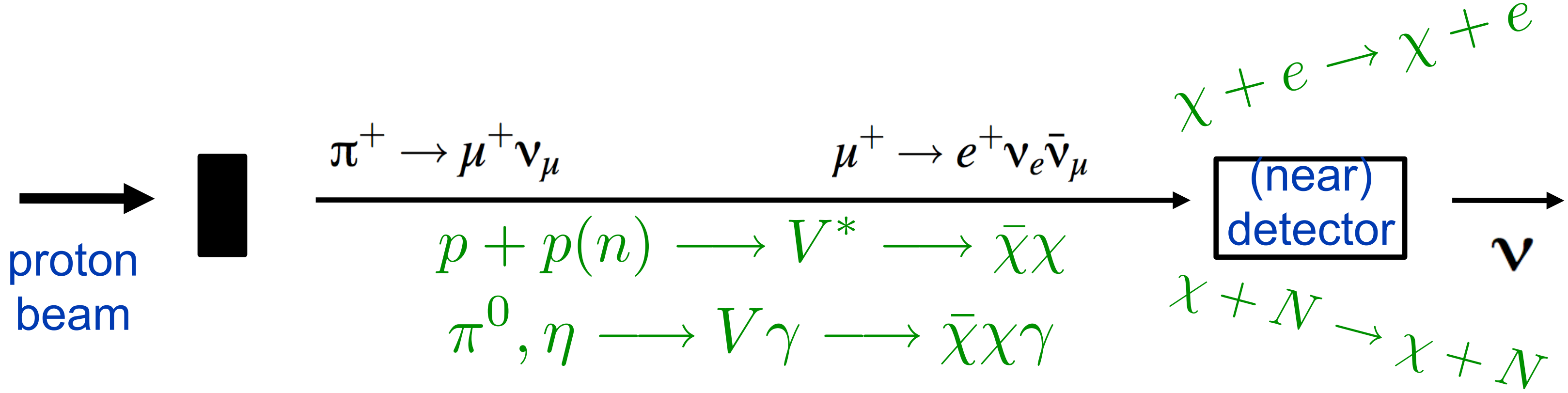
FIG. 7 Map of Galactic ^{26}Al γ-ray emission after 9-year observations with COMPTEL/CGRO (from Plüschke *et al.*, 2001).

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?

Fixed target probes - Neutrino Beams

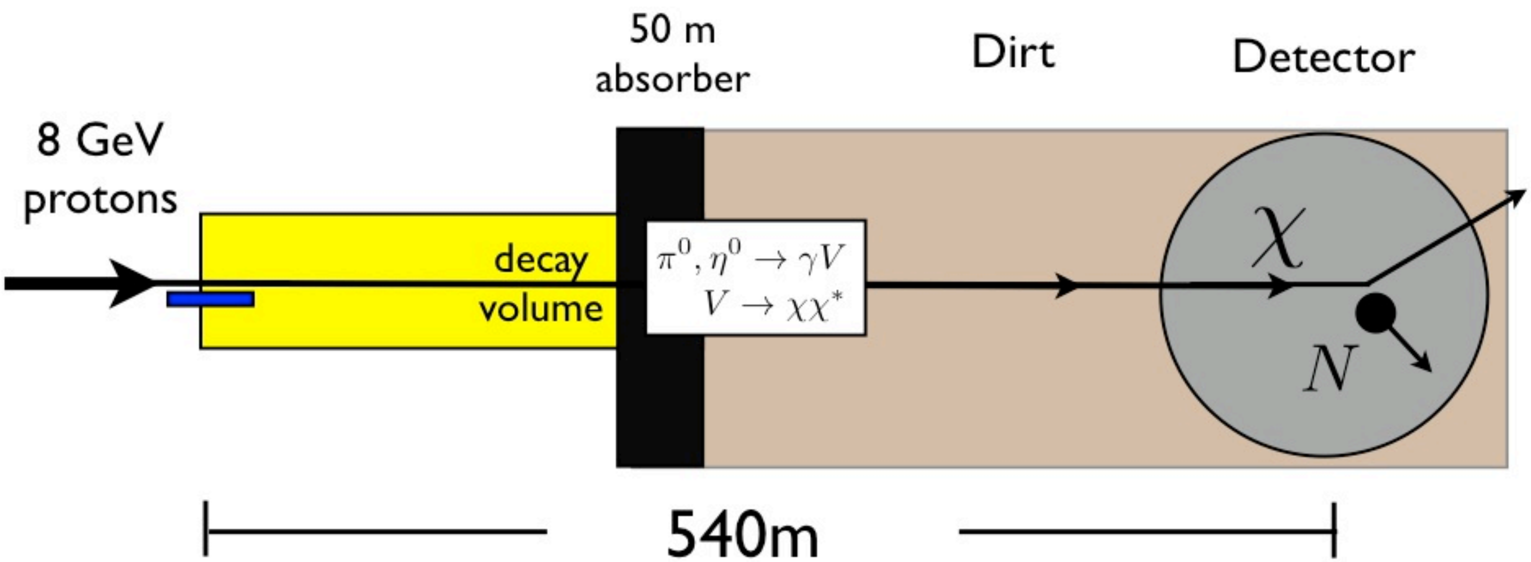
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM



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	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

MiniBooNE search for light DM

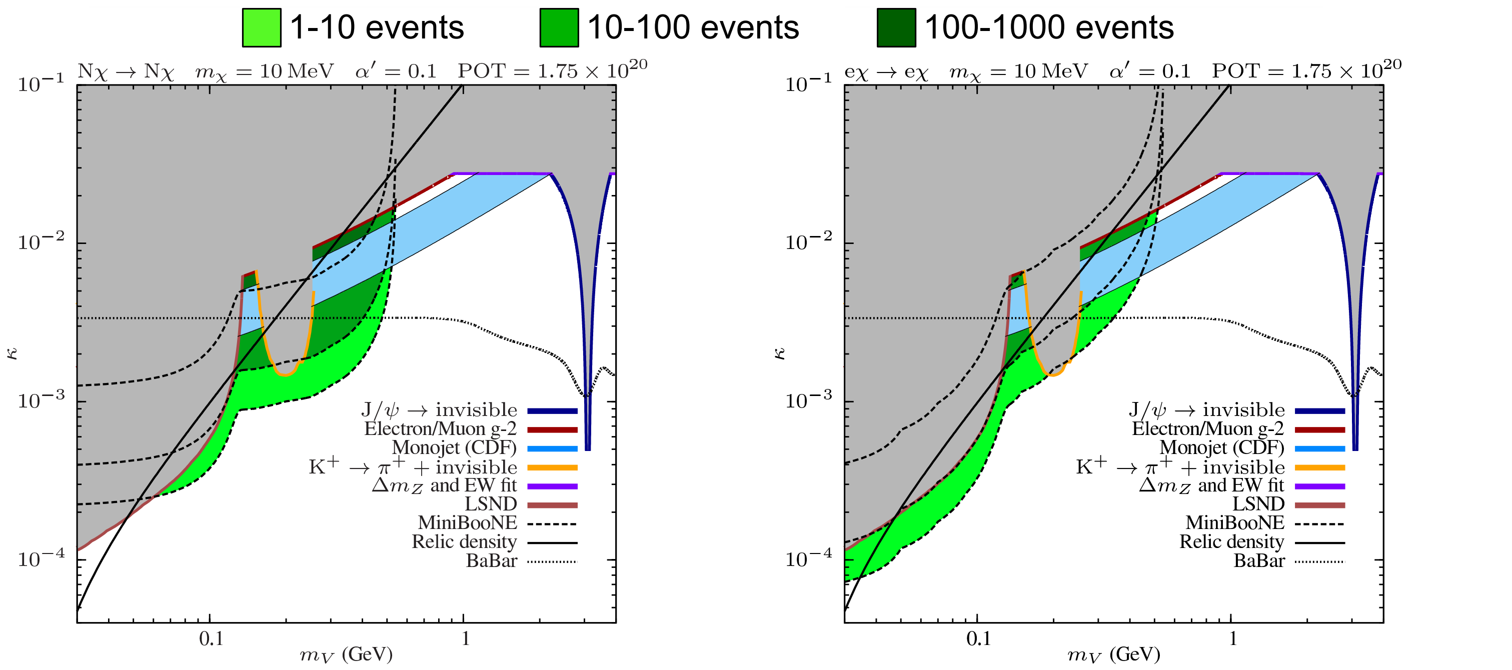


MiniBoone has completed a long run in the beam dump mode, as suggested in [arXiv:1211.2258]

By-passing Be target is crucial for reducing the neutrino background (Richard van de Water et al. …) . Currently, suppression of ν flux ~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

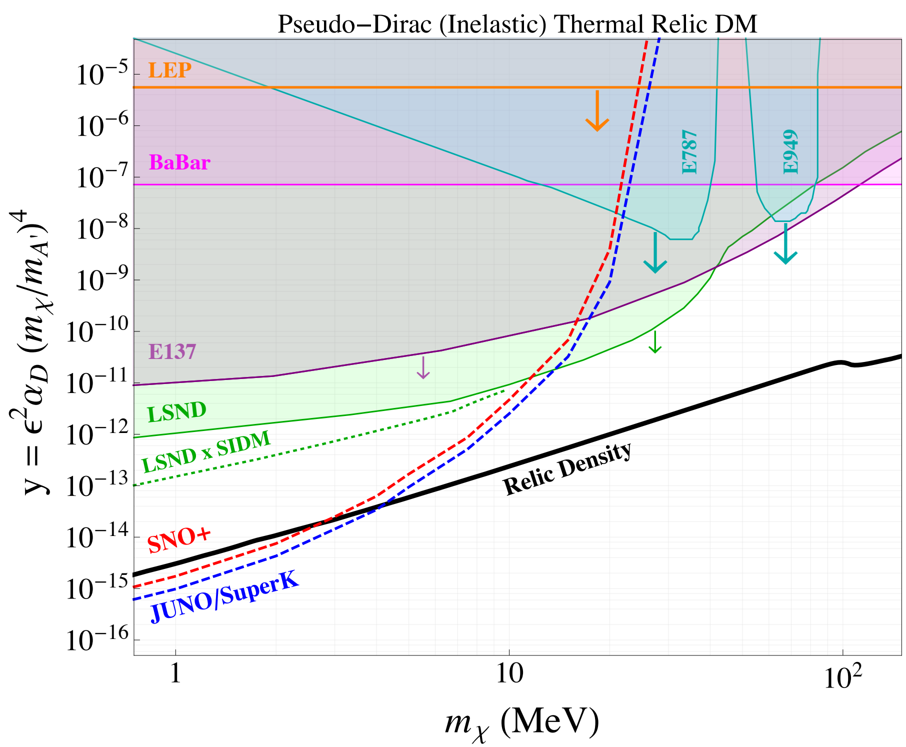


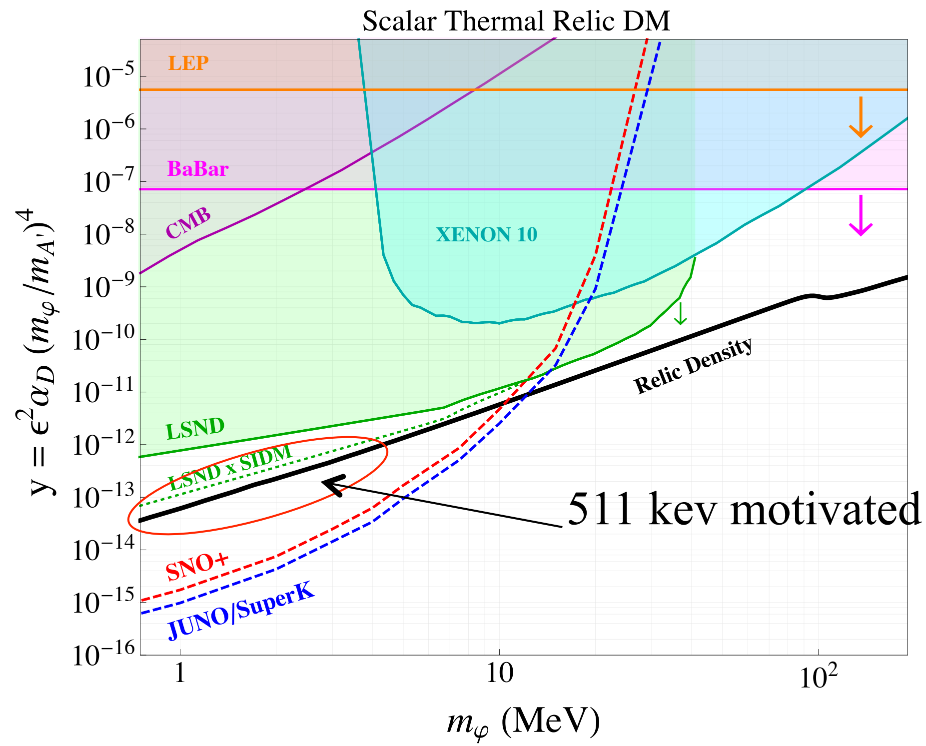
R. Cooper presentation, Camogli workshop on light dark matter, 2015

- MiniBooNE has collected 1.86×10^{20} POT in beam-off-target configuration to search for sub-GeV dark matter

- Beam-off-target suppresses neutrino backgrounds
  → beam uncorrelated backgrounds dominant

Sensitivity to light DM in a setup involving 100 MeV electron beam dump next to a large neutrino detector

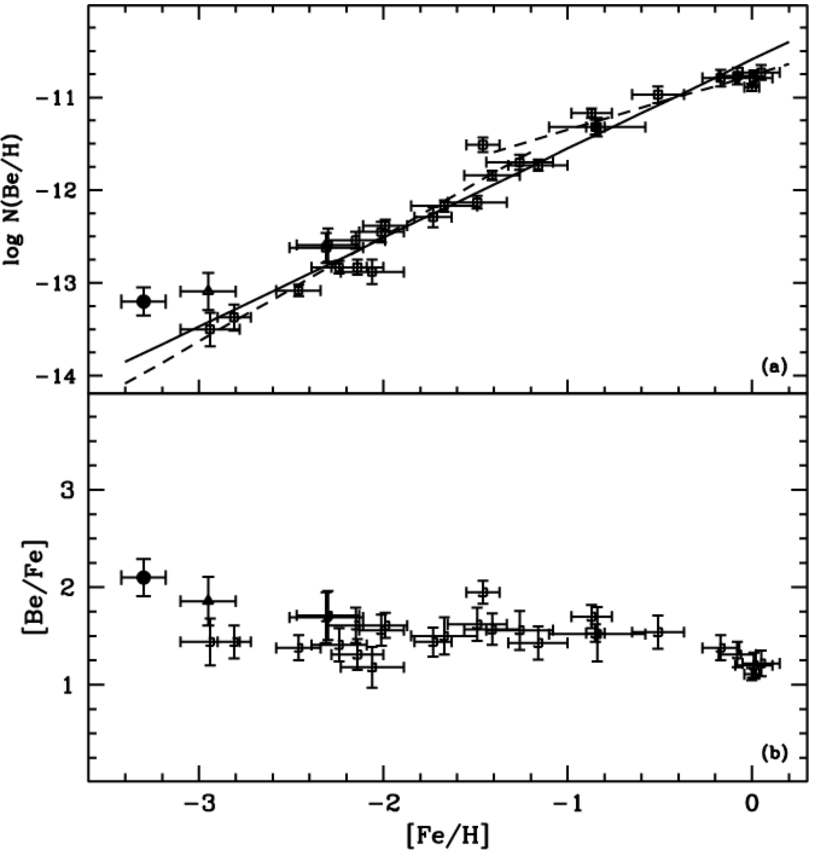


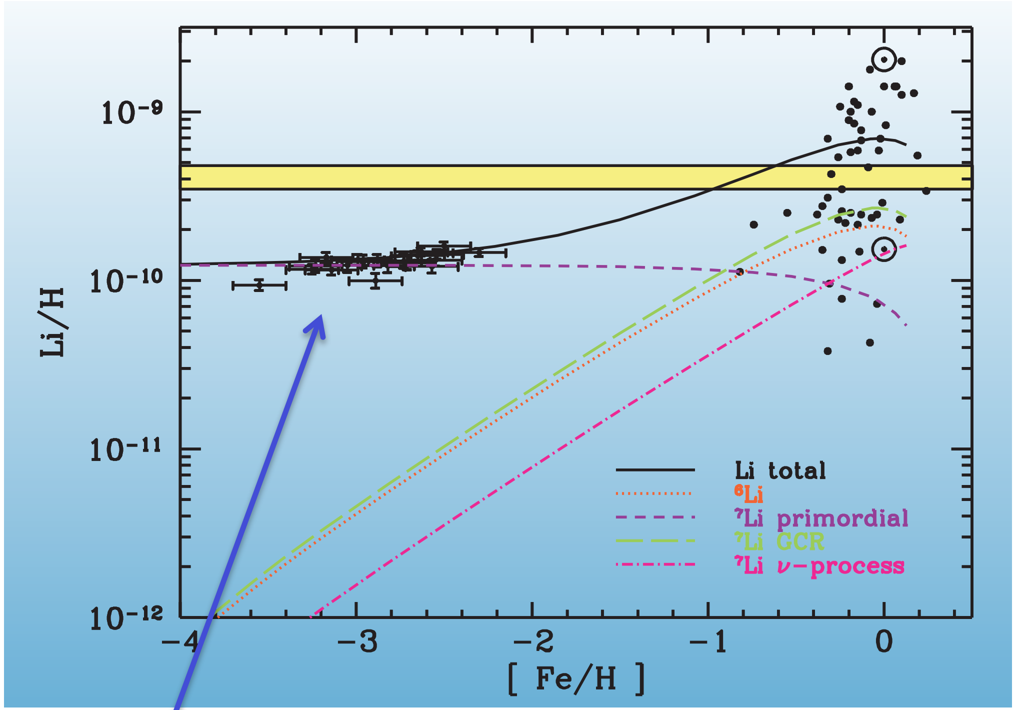


One will significantly advance sensitivity to light DM in the sub-100 MeV mass range. Assuming 10^{24} 100 MeV electrons on target

Izaguirre, Krnjaic, MP, 1507.0268, to appear in the PRD.

Cosmic lithium problem





Spite plateau (Ryan et al)

^{7}Li exhibits a "plateau" with low dispersion – indicator or BBN value

$$\text{Spite plateau value :} \quad \frac{^7\text{Li}}{\text{H}} = 1.23^{+0.34}_{-0.16} \times 10^{-10}$$

$$\text{BBN theory :} \quad \frac{^7\text{Li}}{\text{H}} = 5.24^{+0.71}_{-0.67} \times 10^{-10}$$

There is no practical implication if we find missing Li

Why should anyone care?

1. Li problem may hold clues to non-standard physics that existed at BBN time (e.g. 10 minutes after the Big Bang)
2. Li problem may be trying to tell us something profound about the evolution of the oldest [surviving] stars in the Universe that formed at z ~ 15.

1991 review

PRIMORDIAL NUCLEOSYNTHESIS REDUX

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ABSTRACT

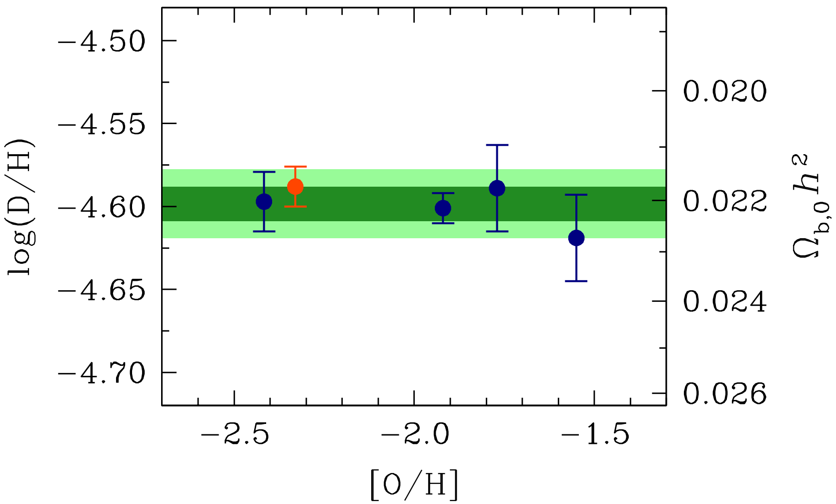
The latest nuclear reaction cross sections (including the most recent determinations of the neutron lifetime) are used to recalculate the abundances of deuterium, ^{3}He, ^{4}He, and ^{7}Li within the framework of primordial nucleosynthesis in the standard (homogeneous and isotropic) hot, big bang model. The observational data leading to estimates of (or bounds to) the primordial abundances of the light elements is reviewed with an emphasis on ^{7}Li and ^{4}He. A comparison between theory and observation reveals the consistency of the predictions of the standard model and leads to bounds to the nucleon-to-photon ratio, $2.8 \leq \eta_{10} \leq 4.0$ ($\eta_{10} \equiv 10^{10} n_B/n_\gamma$), which constrains the baryon density parameter, $\Omega_B h_{50}^2 = 0.05 \pm 0.01$ (the Hubble parameter is $H_0 = 50 h_{50}$ km s^{-1} Mpc^{-1}). These bounds imply that the bulk of the baryons in the universe are *dark* if $\Omega_{TOT} = 1$ and would require that the universe be dominated by nonbaryonic matter. An upper bound to the primordial mass fraction of ^{4}He, $Y_p \leq 0.240$, constrains the number of light (equivalent) neutrinos to $N_\nu \leq 3.3$, in excellent agreement with the LEP and SLC collider results. Alternatively, for $N_\nu = 3$, we bound the predicted primordial abundance of ^{4}He: $0.236 \leq Y_p \leq 0.243$ (for $882 \leq \tau_n \leq 896$ s).

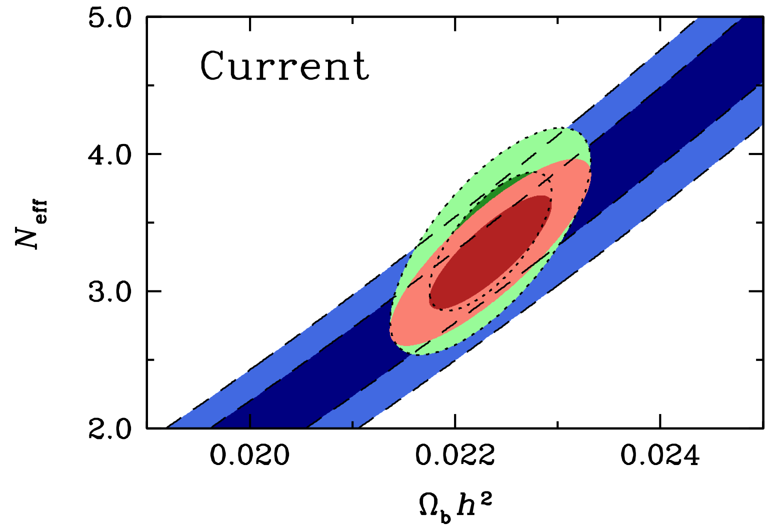
Subject headings: abundances — early universe — elementary particles — nucleosynthesis

Current value $\eta_{10} = 6.1$ is well outside the "BBN range of 1991" 2.8-4.0. *At that time particle physicists did take ^{7}Li seriously.*

Latest developments

- Planck re-measures most of the cosmological parameters, but there is no drastic change in η compared to WMAP/SPT/ACT.
- Planck determines helium abundance Y_p. Accuracy approaches 10%.
- Cooke et al (2013) claim better accuracy and less scatter for the re-evaluated observational abundance of D/H. Perfect agreement, it seems!





- With latest results, no evidence of ^{6}Li in the stellar atmospheres.
- Only ^{7}Li remains a problem.

Extra neutrons from particle physics reduce ^{7}Be

^{3}He+α → ^{7}Be + γ - IN.

^{7}Be +n → p +^{7}Li – OUT, (followed by ^{7}Li+p → 2α)

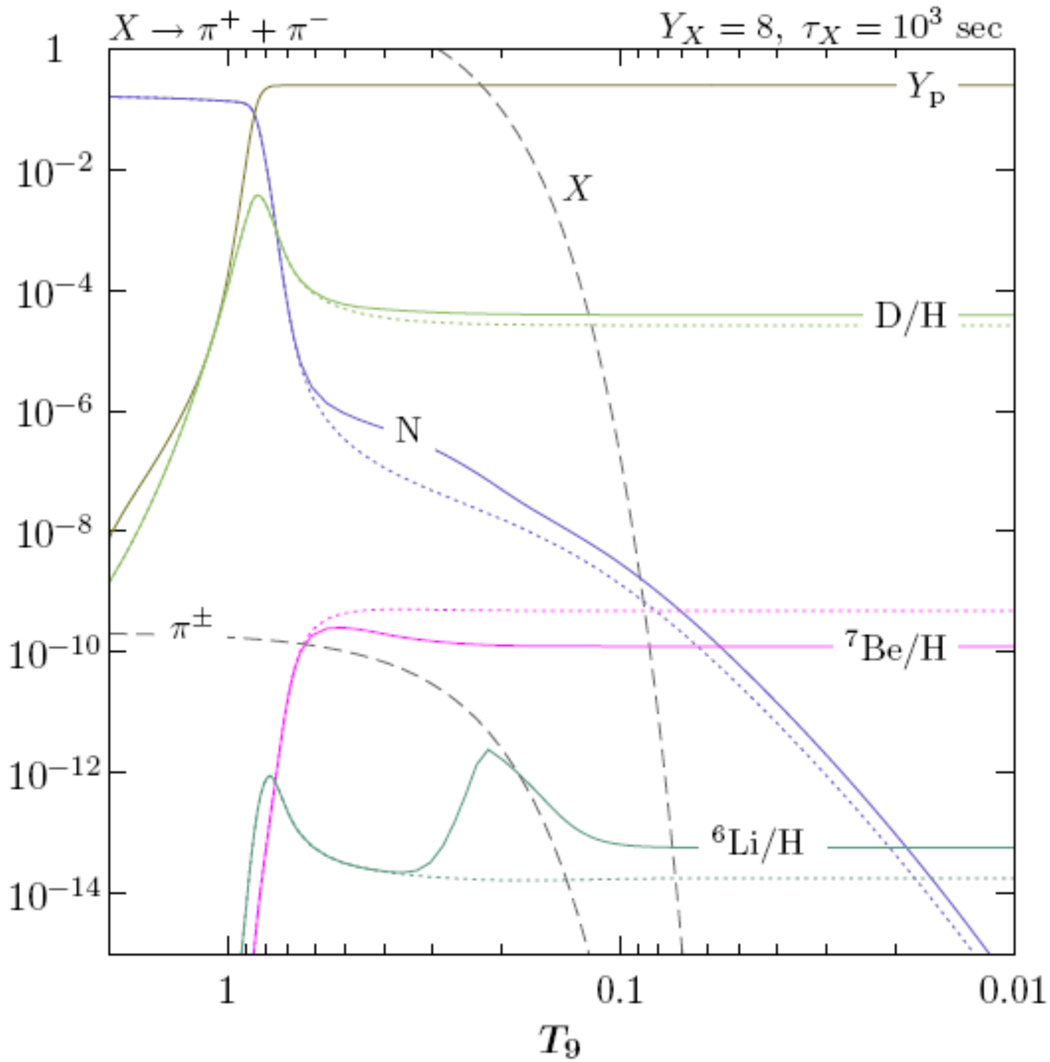
Also leads to p + n → D + γ

nBBN scenario

Addition of O(10^{-5}) neutrons per proton at T~40 keV accelerates burning of ^{7}Be. It does not matter how you generate extra neutrons (particle decays, annihilation etc). (Reno, Seckel; Jedamzik; Kohri et al.). This mechanism is sensitive to hadronic fraction of decays/annihilation.

Candidates: scalar lepton NLSP → gravitino LSP decays (many studies); gravitino decays; R-parity violating decays; super-WIMP decays… You can have arbitrarily many models that do that. They *may or may not* have associated collider signatures.

Time evolution of abundances in nBBN



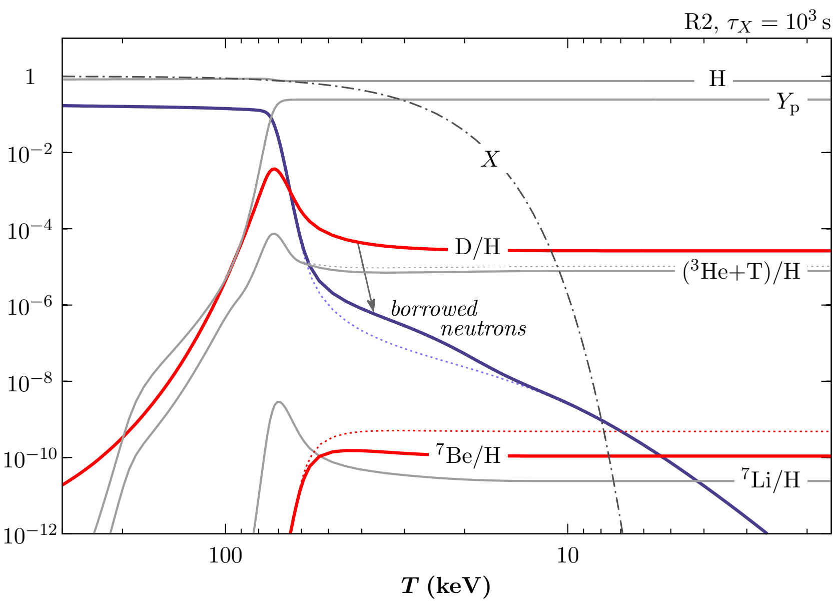
All models of neutron injection are disfavored because of elevated D/H. (Coc, MP, Vagioni, Uzan, 2014). Plot from MP, Pradler, 2010

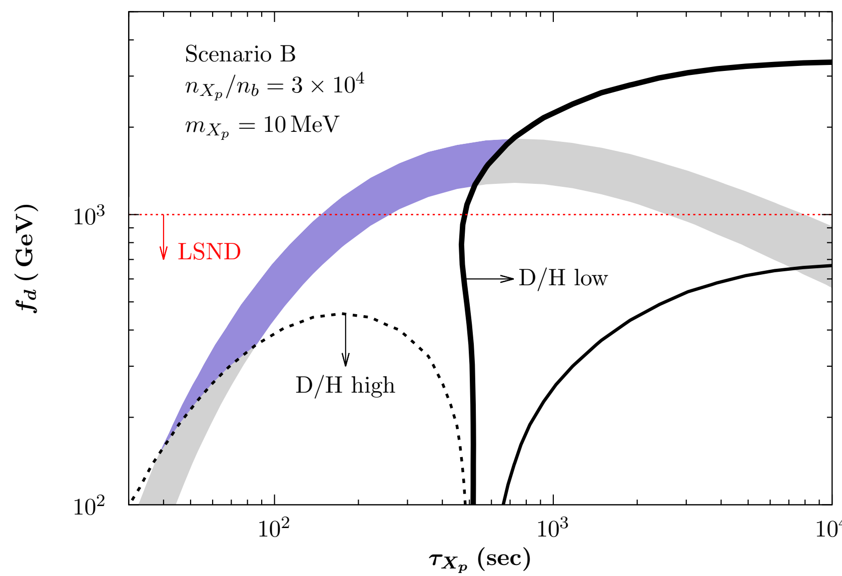
X-BBN scenario

Light New Physics – e.g. new light axion-like particles – can "kill" ^{7}Be, if their abundances are large, and couplings are small. Goudelis, MP, Pradler, Oct 2015.

$$\mathrm{R1}: \; {}^7\mathrm{Be}(X,\alpha)^3\mathrm{He}; \quad \mathrm{R2}: \; \mathrm{D}(X,p)n$$

$$(n_X/n_b) \times \sigma_{\mathrm{Be}} v \simeq (1-2) \times 10^{-31}\ \mathrm{cm}^2,$$
$$(n_X/n_b) \times \sigma_{\mathrm{D}} v \simeq (3-7) \times 10^{-31}\ \mathrm{cm}^2.$$





- Deuterium is unaffected because neutrons are not "extra" but "borrowed"
- 1/TeV hadronic ALPs can be searched with proton beam dump experiments

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 is being searched for at MiniBoone. HPS is taking data.
4. There is a big potential for increasing sensitivity by placing medium energy linacs next to large underground ν detectors, including ruling out the remainder of models designed to explain r_p anomaly
5. Lithium problem is still interesting. If it is new physics affecting BBN, it is *not* weak scale, as D/H comes out too high. Light particles can differentially affect Li, keeping the rest unchanged