Theoretical Advances in Dark Matter

Maxim Pospelov

University of Victoria, Victoria/Perimeter Institute, Waterloo

(*Many thanks to my collaborators*: B Batell, P deNiverville, D McKeen, and A. Ritz)

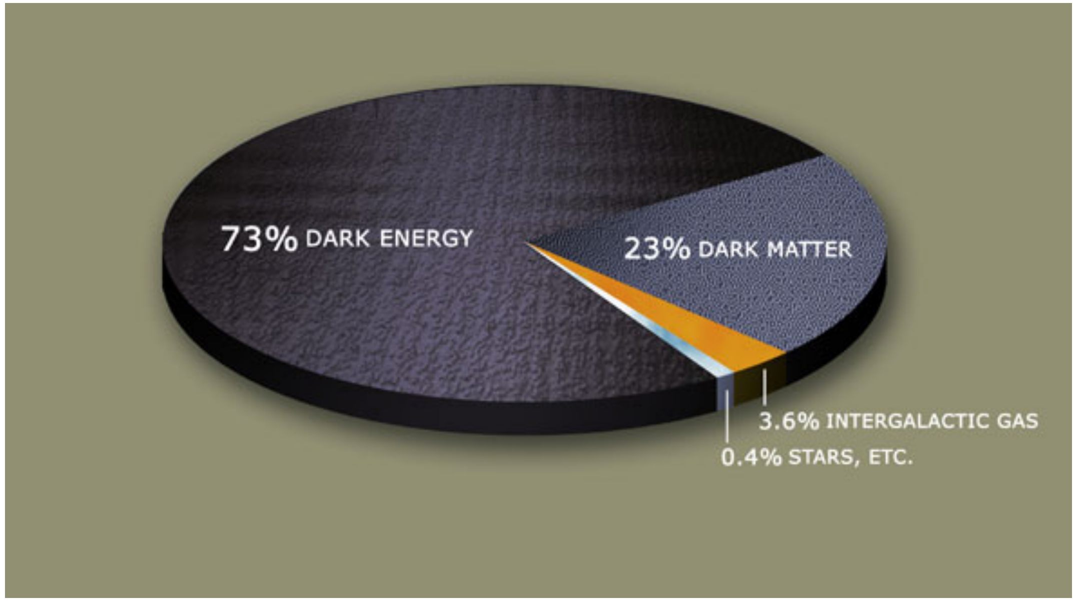
University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. *Introduction. Manchester and "nuclear dark matter".*
2. WIMP dark matter highlights.
3. Super-WIMP dark matter highlights.
4. Bosonic condensate dark matter highlights.
5. Conclusions.

Big Questions in Physics

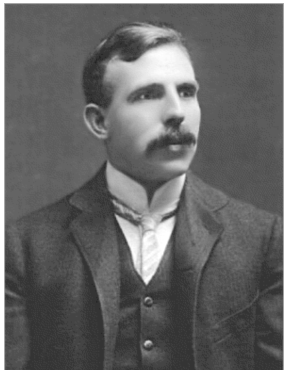


"Missing mass" – what is it?

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.

Manchester and missing mass problem #1




The discovery of atomic nucleus created the

first missing mass problem:

$$A > Z$$

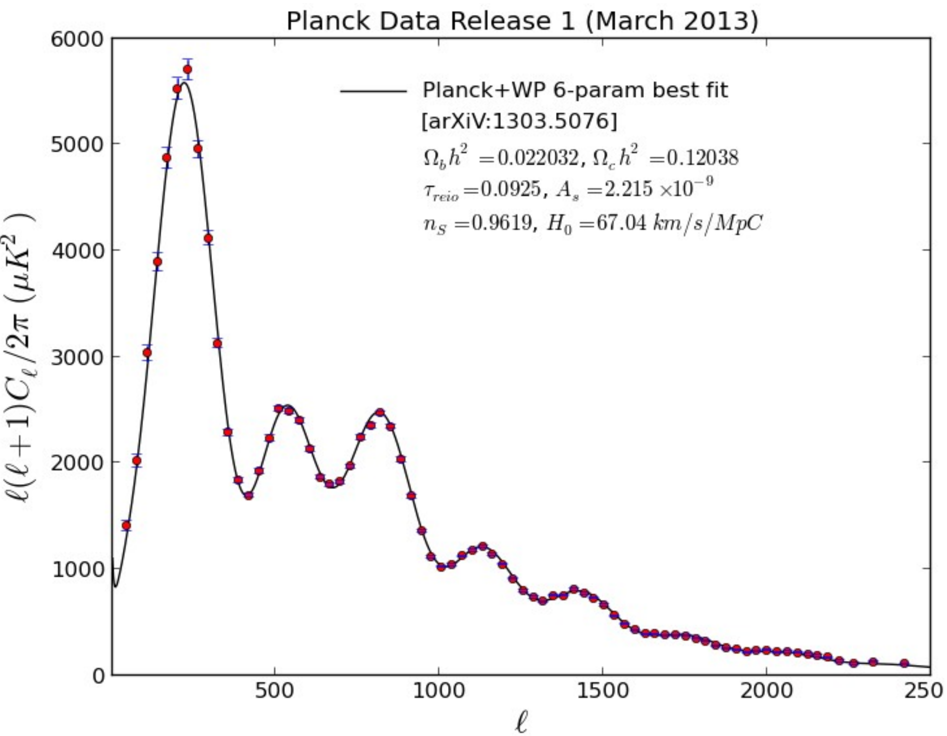
Or why is $M_{nucleus} > Z\, m_{proton}$? And why nuclear mass is $\sim A\, m_{proton}$?

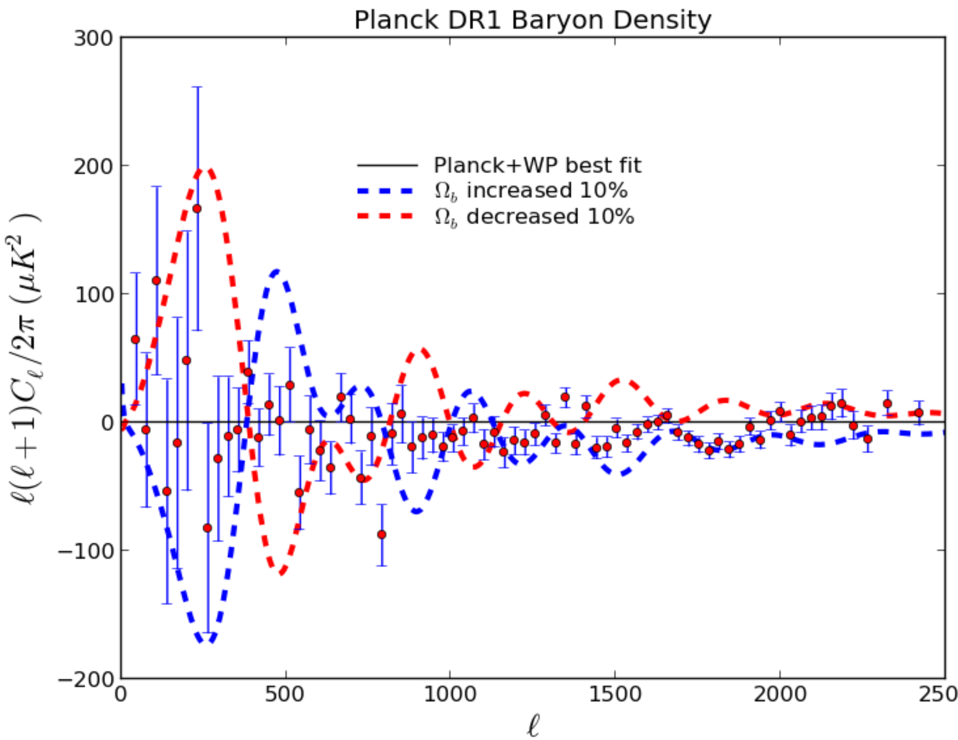
What accounts for 50% or more of the missing mass in a nucleus of an atom?

Rutherford's own suggestion – tightly packed A-Z electrons on top of A protons inside the nucleus – was soon shown to be incorrect via the studies of hyperfine structure of e.g. ^{13}C. A wild theoretical suggestion was floated – a new type of particle, electrically neutral, with spin ½ and strong interaction with protons. New particle + new force ~ 1935 !!!!

Will missing mass problem #2 lead to similar spectacular discoveries ?

Latest Planck data (Figures from Kinney; Natoli talks, KIAS workshop, 2013)





Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026 (is it high?)
$100\theta_*$ (acoustic scale at recombination)	1.04148±0.00062 (~ 500 parts per million accuracy)
τ	0.091±0.014 (WMAP seeded)
$\ln(10^{10}A_s)$	3.090±0.025
n_s	0.9585±0.0070 (<1 at > 5 σ)

Parameter	Value (95%)
Ω_K	-0.0005±0.006
$\Sigma\, m_\nu$ (eV)	<0.23
N_{eff}	3.30±0.54
Y_P	0.267±0.040

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**.

Many reasonable options. *Signatures can be completely different.*

Evolution of theoretical interest to DM

Mid 90's: In the 0^{th} approximation: SUSY neutralino as WIMPs and axion models as "super-cold" DM.

↓

Last ~15 years – O(few 100) or more models of WIMPs (sometimes much simpler than MSSM neutralino), super-WIMPs, and super-cold DM are developed. Some models have a much *broader* observational consequences than "neutralinos and/or axions". Some have no *observable properties* other than gravitational interactions.

↓

Future? Any model of DM that has a chance of satisfying abundance (+may be some theory priors of "technical naturalness") is worth searching for.

Neutral "portals" to the SM – an organizing principle

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)

LHN neutrino Yukawa coupling, N – RH neutrino

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

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

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

……….

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

WIMP "lamp post"

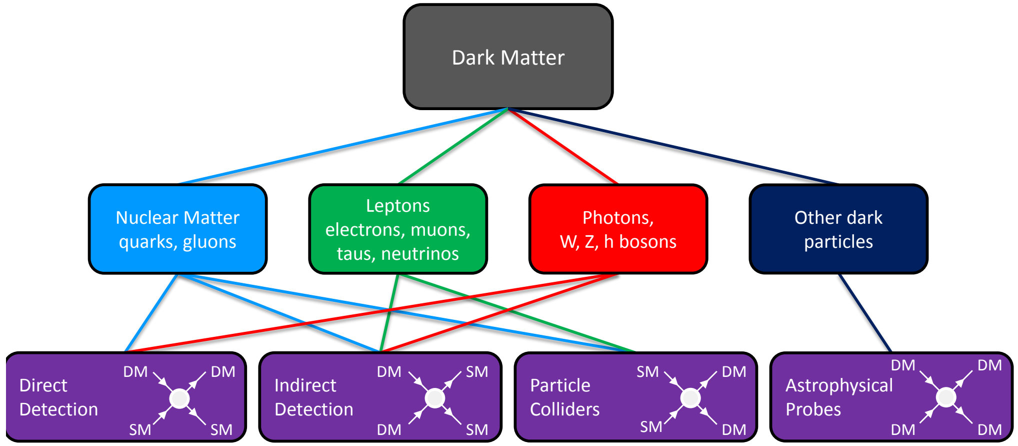
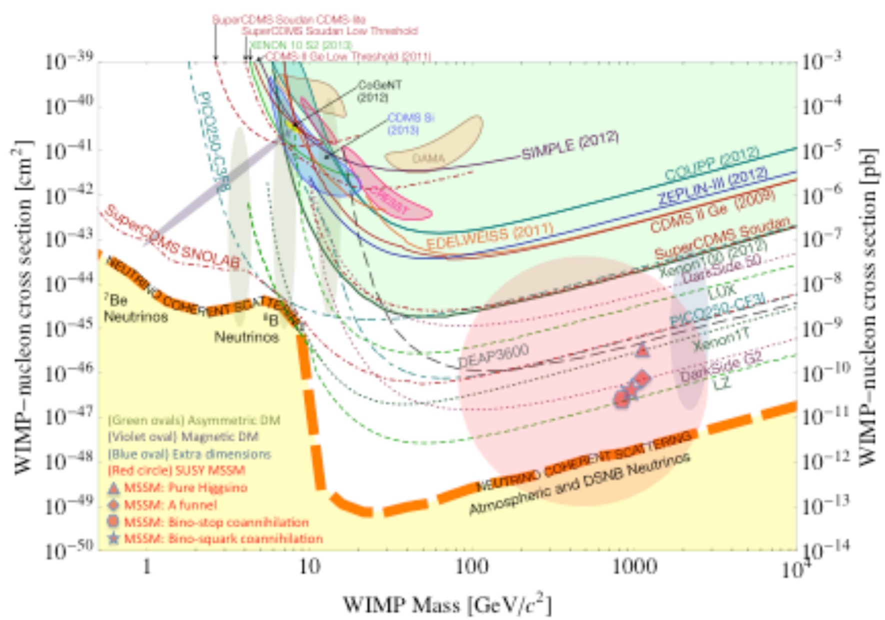
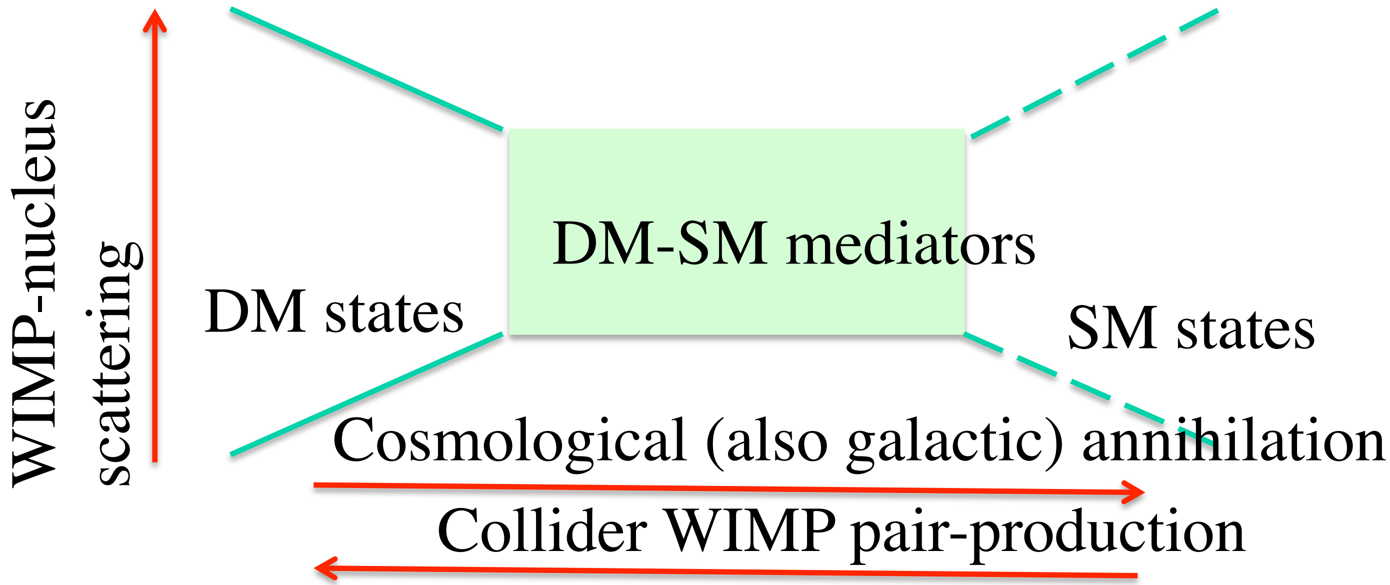


Figure 5. *Dark matter may have non-gravitational interactions with any of the known particles as well as other dark particles, and these interactions can be probed in several different ways.*



From the Snowmass 2013 summary, 1310.8327

WIMP paradigm, some highlights



$$\langle \sigma_{ann} v \rangle \approx 1\text{pbn} \times c$$

1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?

2. Do sizable annihilation cross section always imply sizable scattering rate and collider DM production?

More minimal DM models

Let us get rid of the "dark force" or "extra mediators" concept or may be make them very very heavy.

Then we are down to the SM mediators:

1. Photons: millicharged WIMPs (Hall et al, 1980s) neutral WIMPs with Magnetic Dipole, EDM, charge radius and other EM form factors (MP, ter Veldhuis, 2000).
2. EW boson mediators: Original WIMP heavy ν's (Weinberg, Lee; Russians); [Yet another] minimal WIMP model with Z,W mediation (Cirelli, Fornengo, Strumia, 2005); inert Higgs models etc…
3. SM Higgs-mediated DM (Silveira, Zee; McDonald; Burgess, MP, ter Veldhuis… Also, Yndurain, Veltman).

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis(2000)

DM through the Higgs portal – *minimal model of DM*

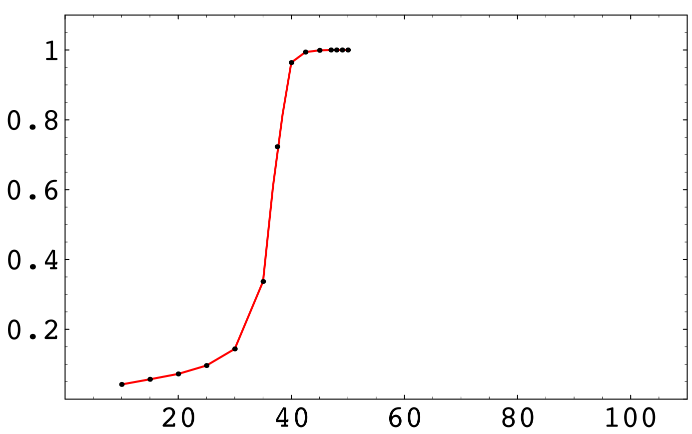
$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$

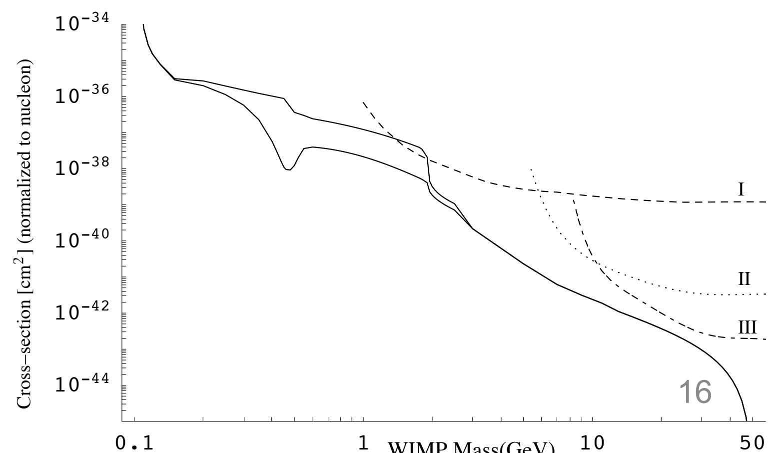
$$= \frac{\lambda_S}{4}S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2}S^2 h^2.$$

125 GeV Higgs is "very fragile" because its with is ~ y_b^2 – very small

$R = \Gamma_{\text{SM modes}}/(\Gamma_{\text{SM modes}}+\Gamma_{\text{DM modes}})$. Light DM can kill Higgs boson easily

(missing Higgs Γ: van der Bij et al., 1990s, Eboli, Zeppenfeld,2000)





Latest LHC results are of great importance for the Higgs- mediated Dark Matter models

- The discovery of the SM(-like) Higgs with mass of ~ 125 GeV has wiped out many DM models with $m_{DM} < 50$ GeV that use Higgs particle for regulating its abundance in a fairly model-independent way.
- Any theorist model-builder who wants to play with sub-50 GeV WIMPs may "run out of SM mediators" and will be then bound to introduce new mediation mechanisms, such as new [scalar] partners of SM fermions, new Higgses and/or new Z'.

Updates on the minimal Higgs-mediated model:

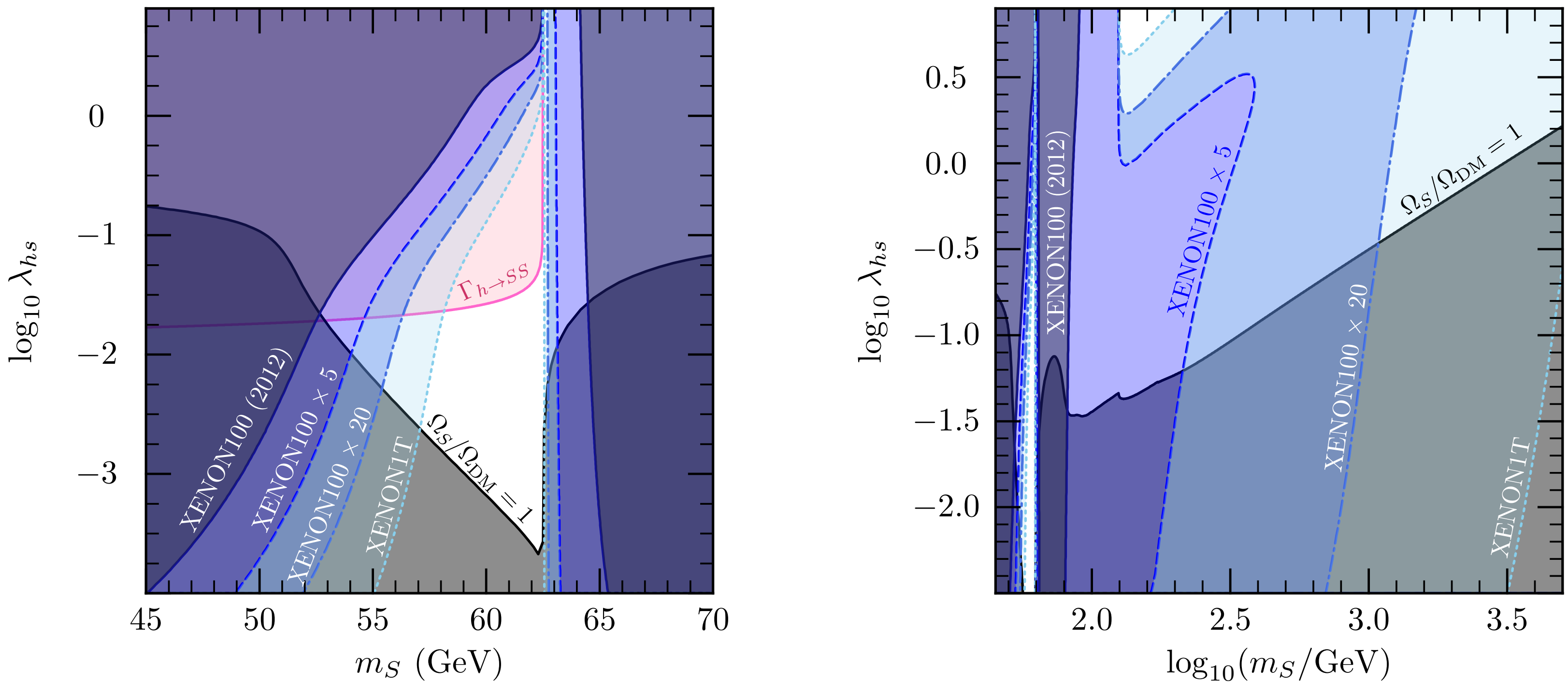


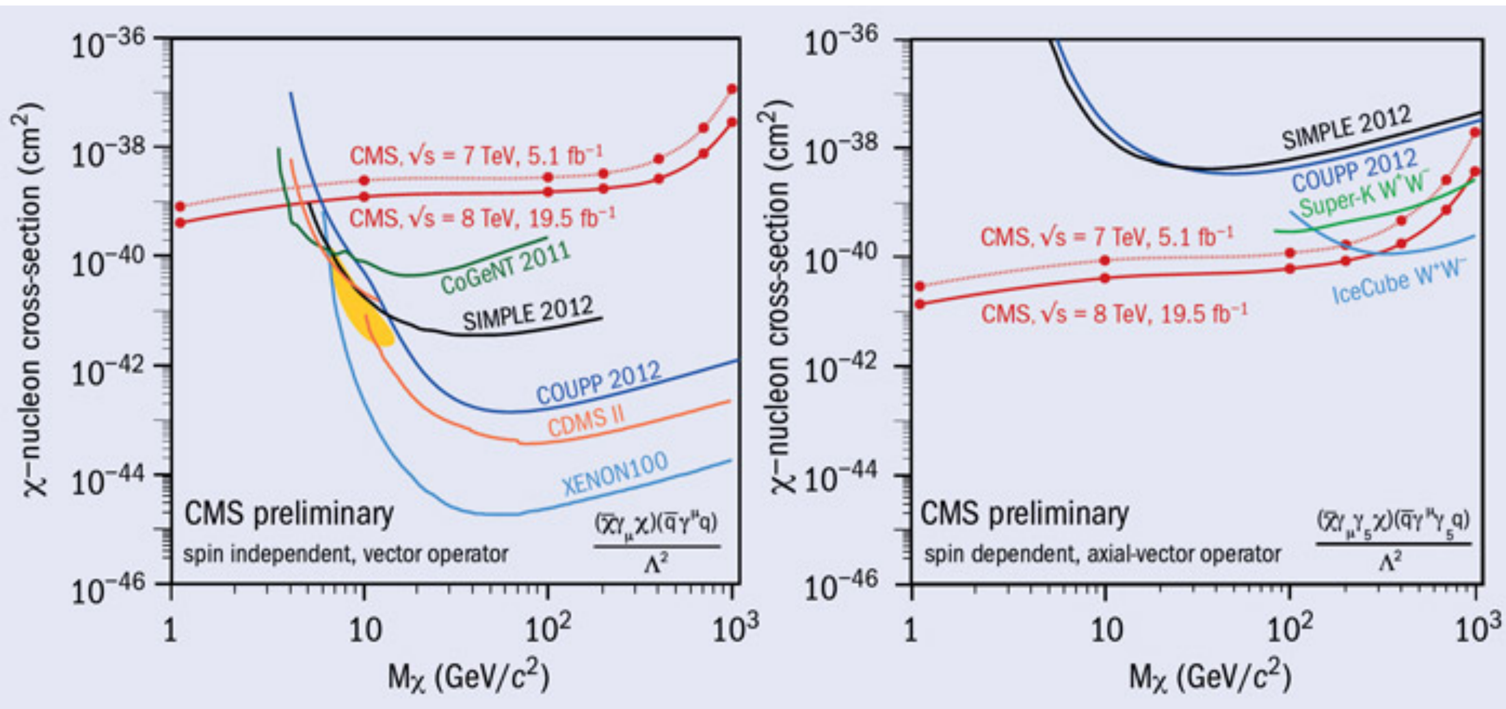
Figure from Cline, Scott, Kainulainen, Weniger, 2013.

Direct detection is competitive with the Higgs constraints.
New generation of direct detection can probe up to TeV scale WIMP masses.

Higgs portal may lead to other forms of dark matter, e.g. based on the non-Abelian "dark group", Hambye, 2008.

LHC constraints on "effective" DM models

- Using the "portal description", ATLAS and CMS set constraints on the parameter space of $\Lambda^{-2}(\eta\, \Gamma_\mu\, \eta)\, (f\, \Gamma_\mu f)$ effective operators. Powerful method, especially for the "spin-dependent" operators. (As suggested by Goodman et al; Bai et al; 2010;…)



It is important to have a search not tied to a particular model!

Secluded WIMPs and Dark Forces

MP, Ritz, Voloshin; Finkbeiner and Weiner, 2007. Original model: Holdom 86

$$\mathcal{L}_{\rm WIMP+mediator} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}B_{\mu\nu} - |D_\mu\phi|^2 - U(\phi\phi^*) + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi.$$

This Lagrangian describes an extra U(1)' group (**dark force**), and some matter charged under it. Mixing angle κ controls the coupling to the SM.

ψ – Dirac type **WIMP**; V_μ – **mediator** particle.

Two kinematic regimes can be readily identified:

- $m_{mediator} > m_{WIMP}$

  ψ + anti-ψ → virtual V^* → SM states

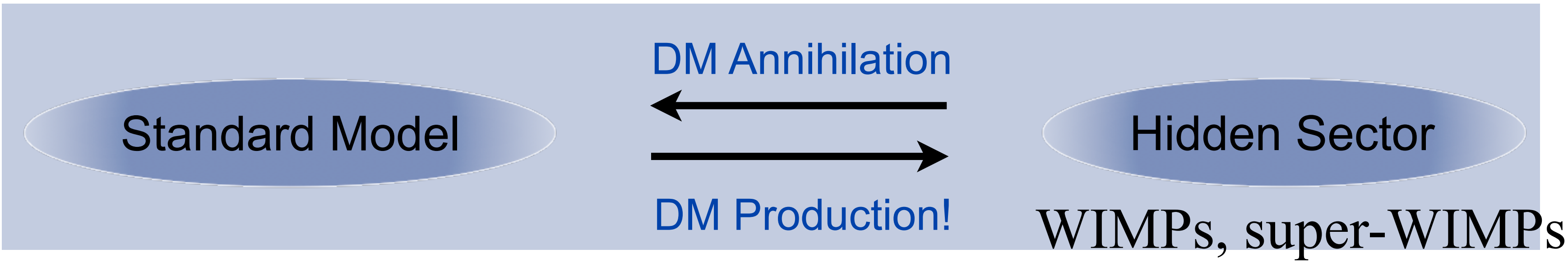
κ has to be sizable to satisfy the constraint on cross section

2. $m_{mediator} < m_{WIMP}$

   ψ + anti-ψ → on-shell V +V, followed by V → SM states

There is almost no constraint on κ other than it has to decay before BBN. $\kappa^2 \sim 10^{-20}$ can do the job.

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

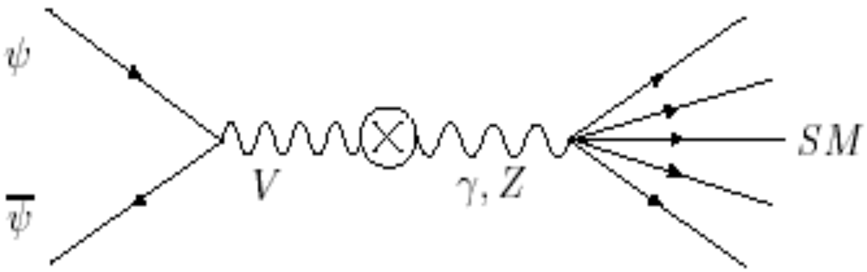
Light WIMPs/heavy mediators: does not work. (Except for super-WIMPs; or non-standard thermal history)

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

Also importantly, direct relation of annihilation/scattering/creation does not hold!

Two types of WIMPs

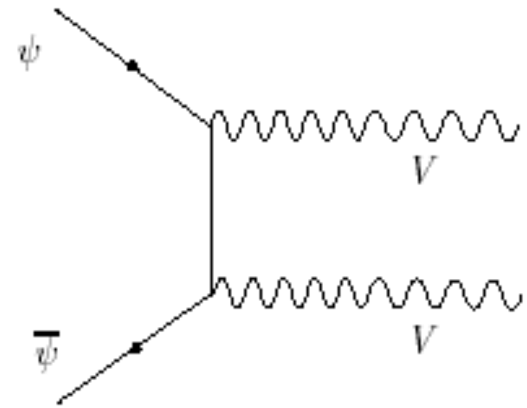
Un-secluded



Ultimately discoverable

Size of mixing*coupling is set by annihilation. Cannot be too small.

Secluded



Potentially well-hidden

Mixing angle can be 10^{-10} or so. It is not fixed by DM annihilation

You think gravitino DM is depressing, but so can be WIMPs

Indirect signatures of secluded WIMPs

Annihilation into a pair of V-bosons, followed by decay create boosted decay products.

If m_V is under $m_{DM}\, v_{DM}$ ~ GeV, the following consequences are generic

(Arkani-Hamed, Finkbeiner, Slatyer, Weiner; MP and Ritz, 2008)

1. Annihilation products are dominated by electrons and positrons
2. Antiprotons are absent and monochromatic photon fraction is suppressed
3. The rate of annihilation in the galaxy, $<\sigma_{ann}\, v>$, is enhanced relative to the cosmological $<\sigma_{ann}\, v>$ because of the long-range *attractive* V-mediated force in the DM sector. (Sommerfeld and resonant enhancement)

Fits the PAMELA results. [which can of course be explained by a variety of pure astrophysical mechanisms]

Dark photon model (as possible DM-SM mediator)

(Holdom 1986; earlier paper by Okun')

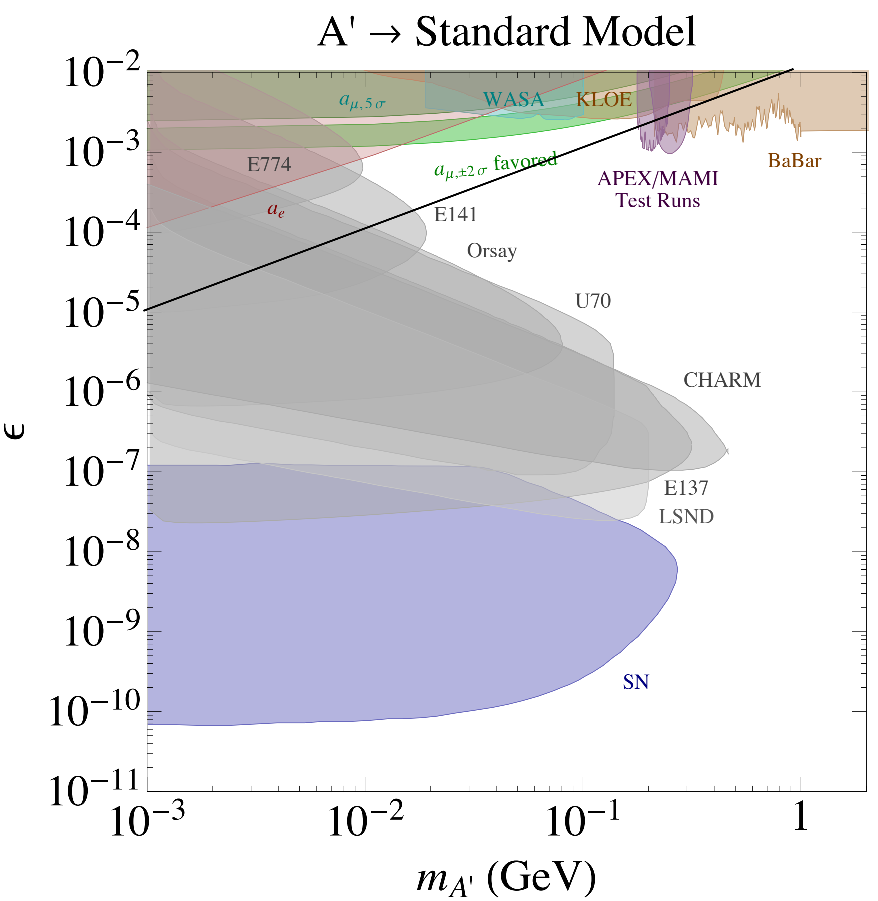
$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi),$$

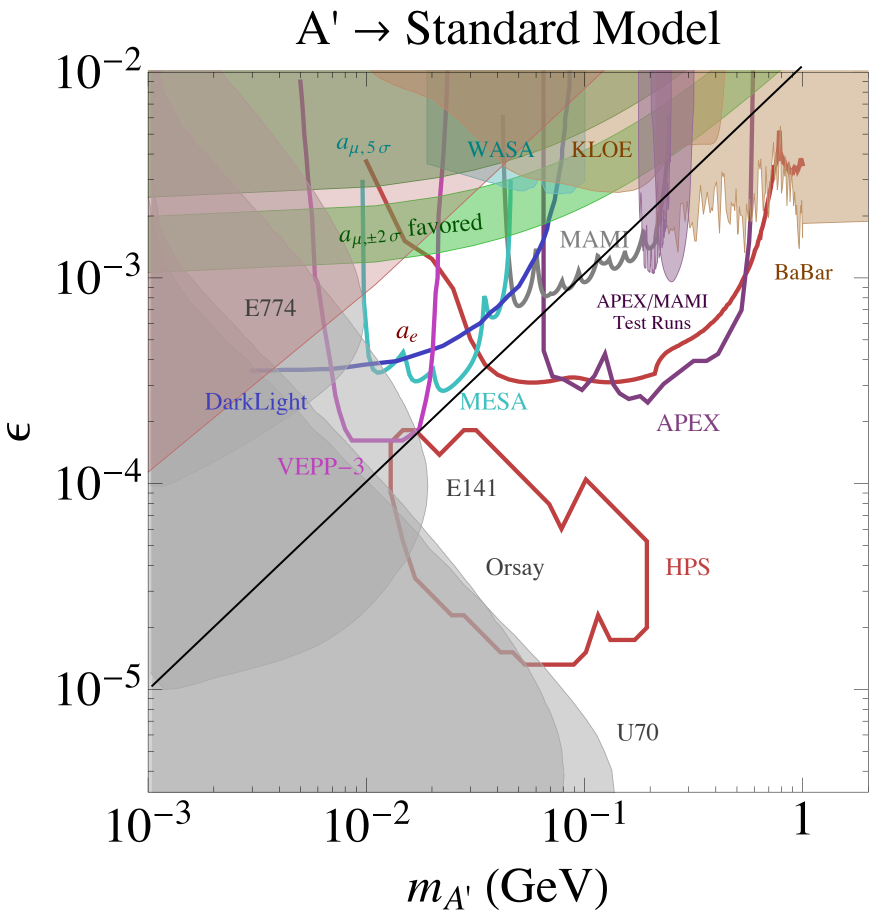
This Lagrangian describes an extra U(1)' group (**dark force, hidden photon, secluded gauge boson, shadow boson etc, also known as U-boson, V-boson, A-prime, gamma-prime etc**), attached to the SM via a vector portal (kinetic mixing). Mixing angle κ (also known as ε, η) controls the coupling to the SM.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

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

Well over several hundred theory papers have been written with the use of this model in some form in the last four years. SUSY generalizations are built in Morrissey et al; Cheung et al, 2009.

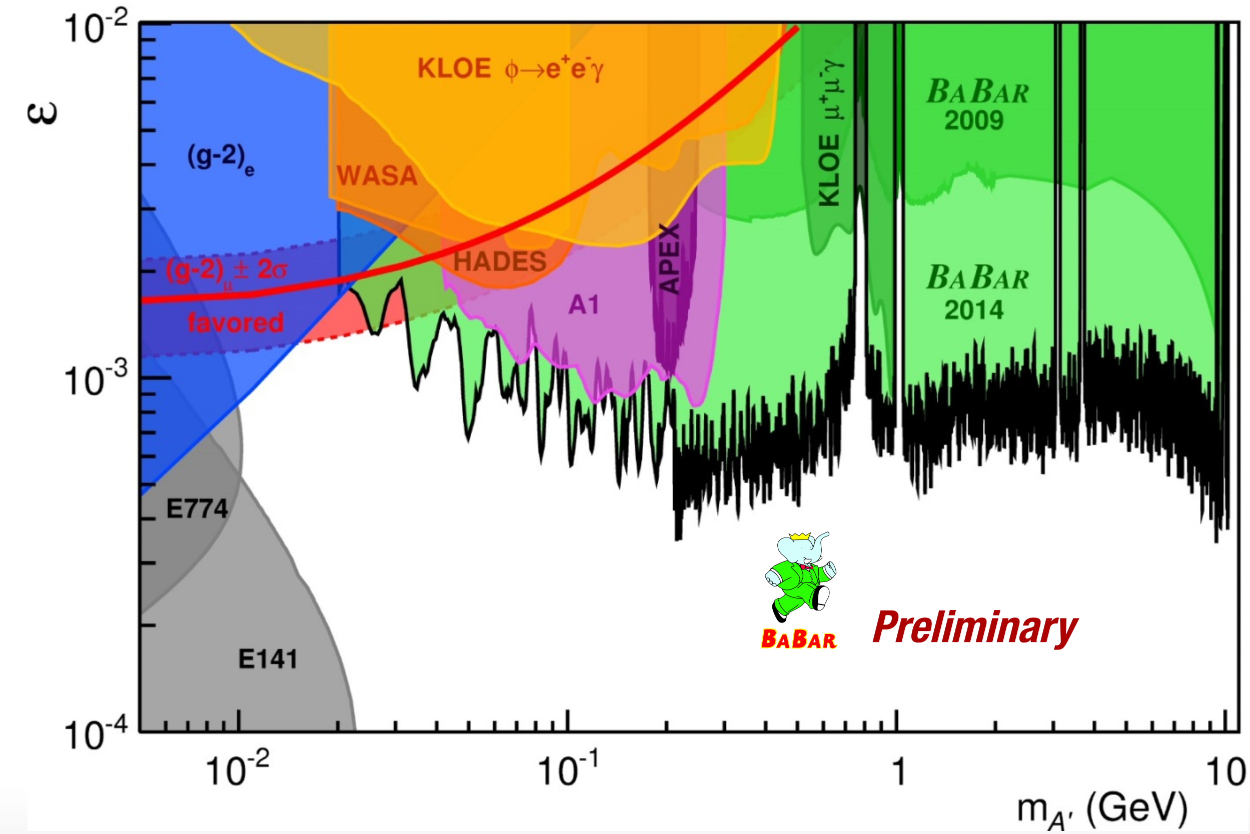
κ-m_V parameter space, Essig et al 2013





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.*

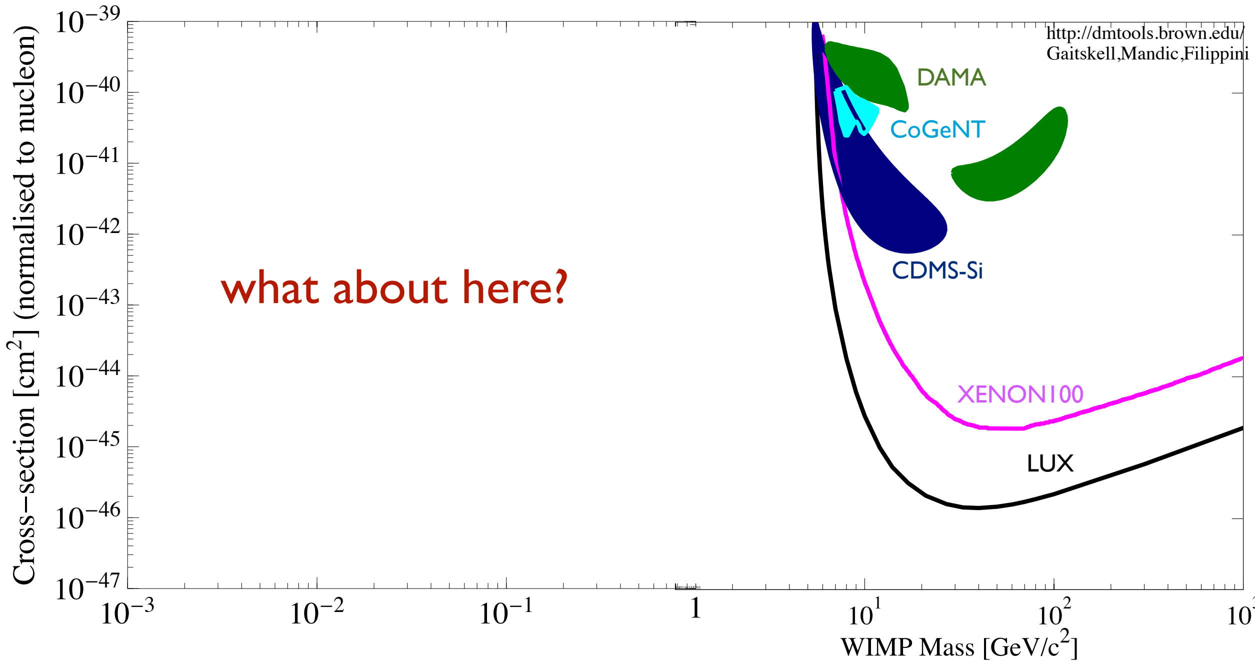
Newest results from Mainz and BaBar



Analysis of full BaBar data set significantly improves the bounds on dark photons.

What if dark photon decay to light dark matter ?

Light DM – direct production/detection



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

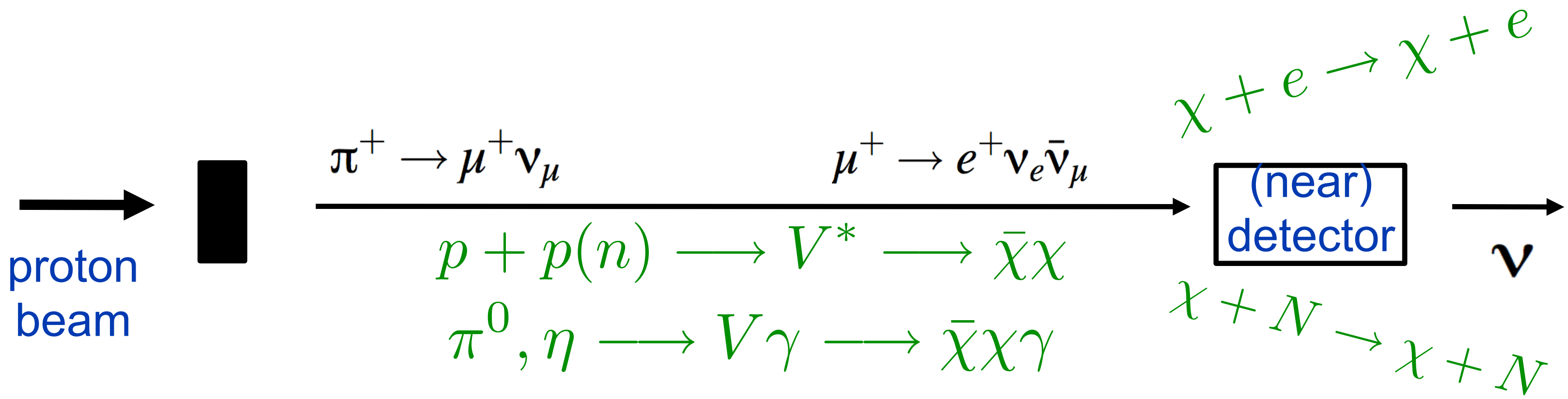
$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(V_{\mu\nu})^2 + +\frac{1}{2} m_V^2 (V_\mu)^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \dots$$

$\uparrow$ DM

$\uparrow$ mediation

Fixed target probes - Neutrino Beams

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



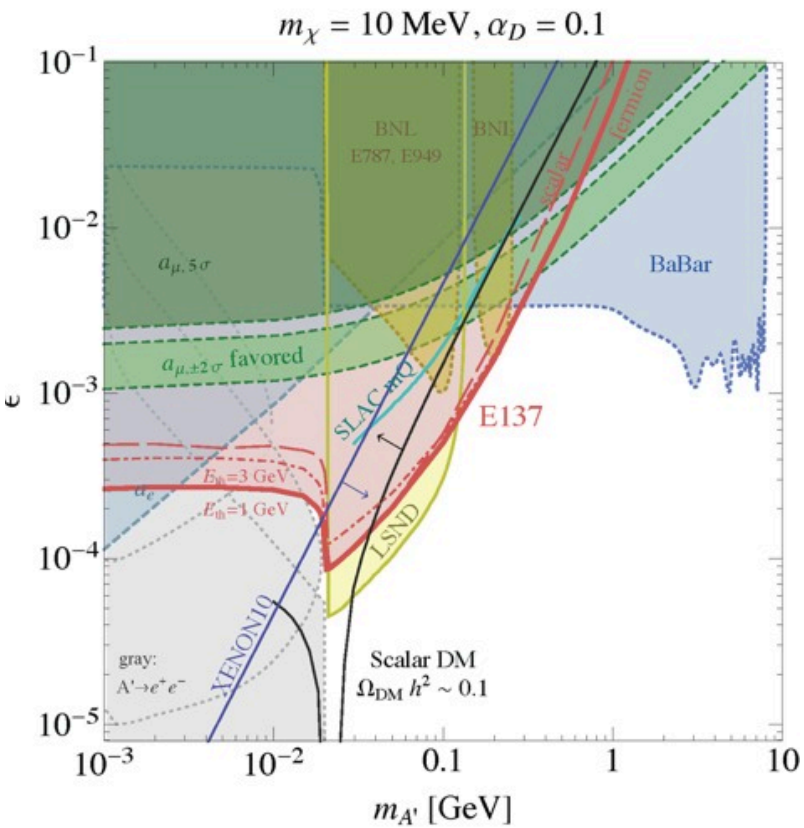
We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

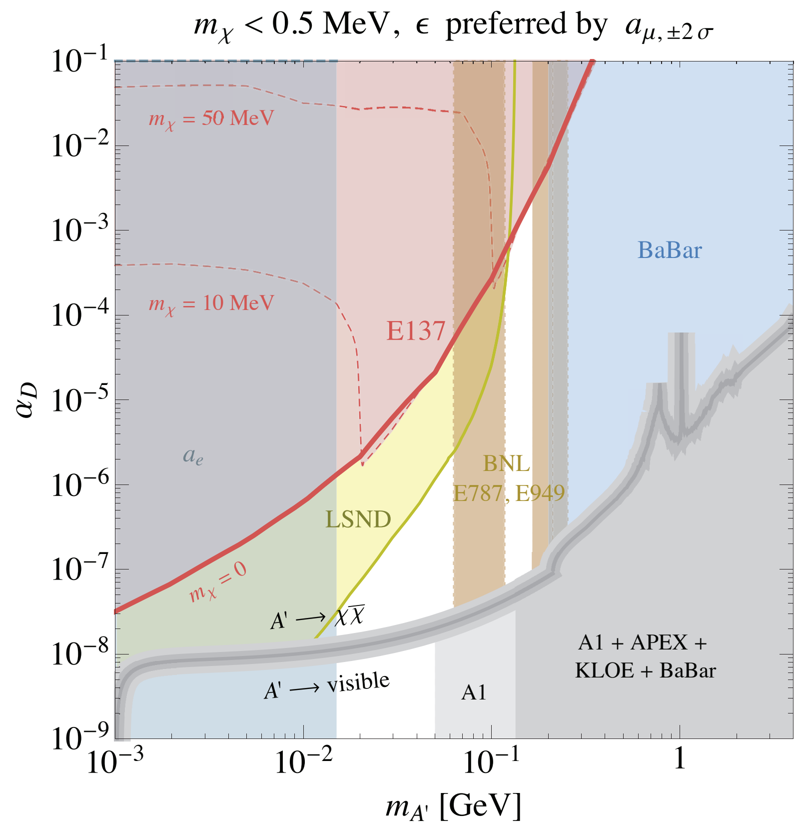
T2K
30 GeV protons
(➠ ~5x10^{21} POT)
280m to on- and off-axis detectors

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

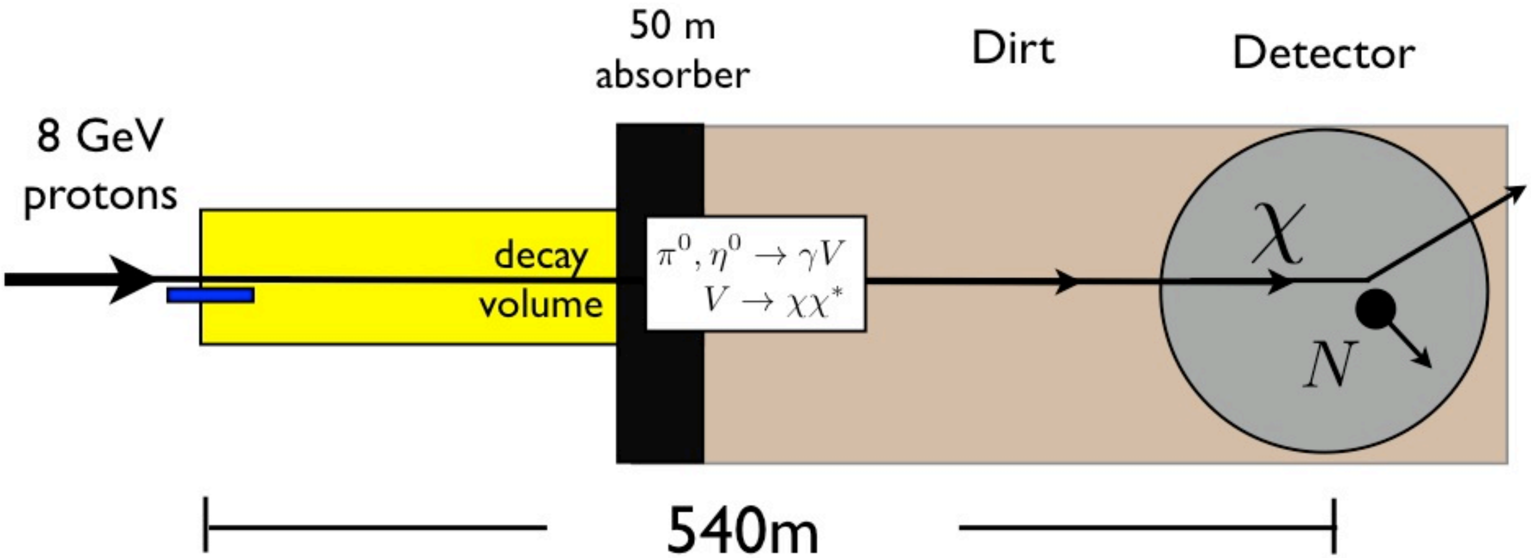
Combination of current constraints for models with dark photon as mediator





Latest constraints can be found in Batell, Essig, Surujon, 2014.

Prospects in improving sensitivity: protons

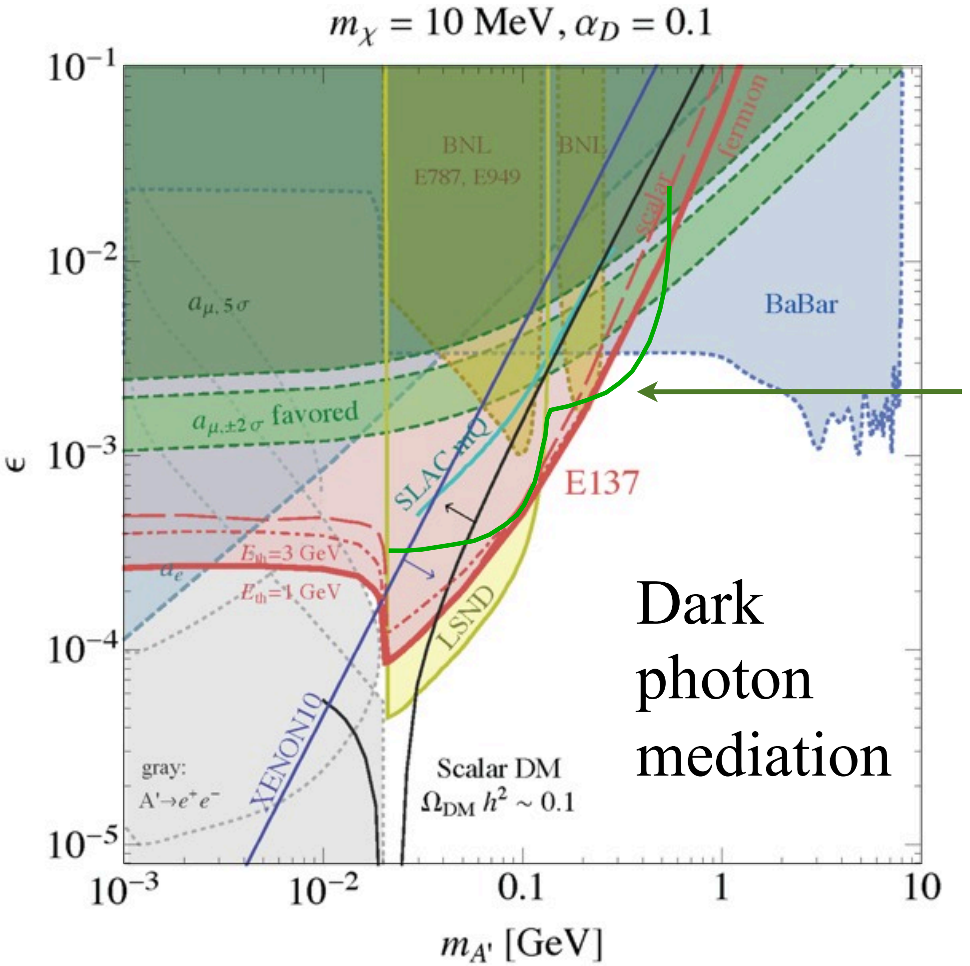


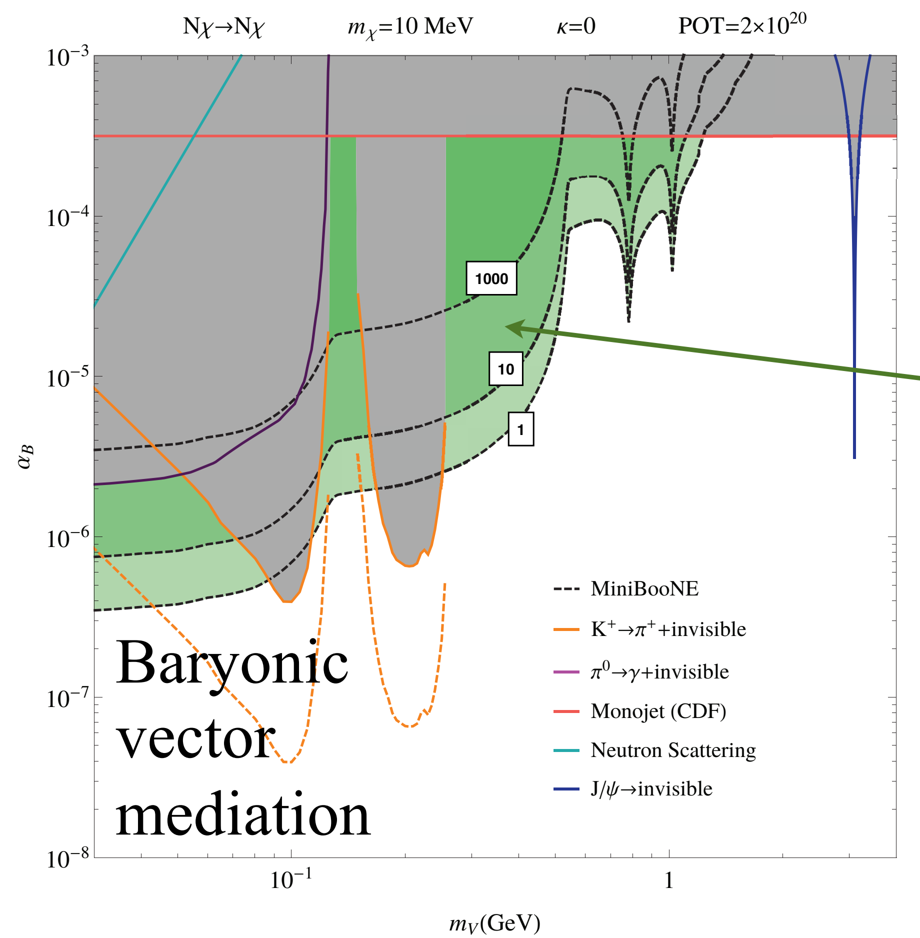
MiniBoone is *currently running* in the beam dump mode, as suggested in [arXiv:1211.2258]

By-passing Be target is crucial for reducing the background (R. van de Water +…)

Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds

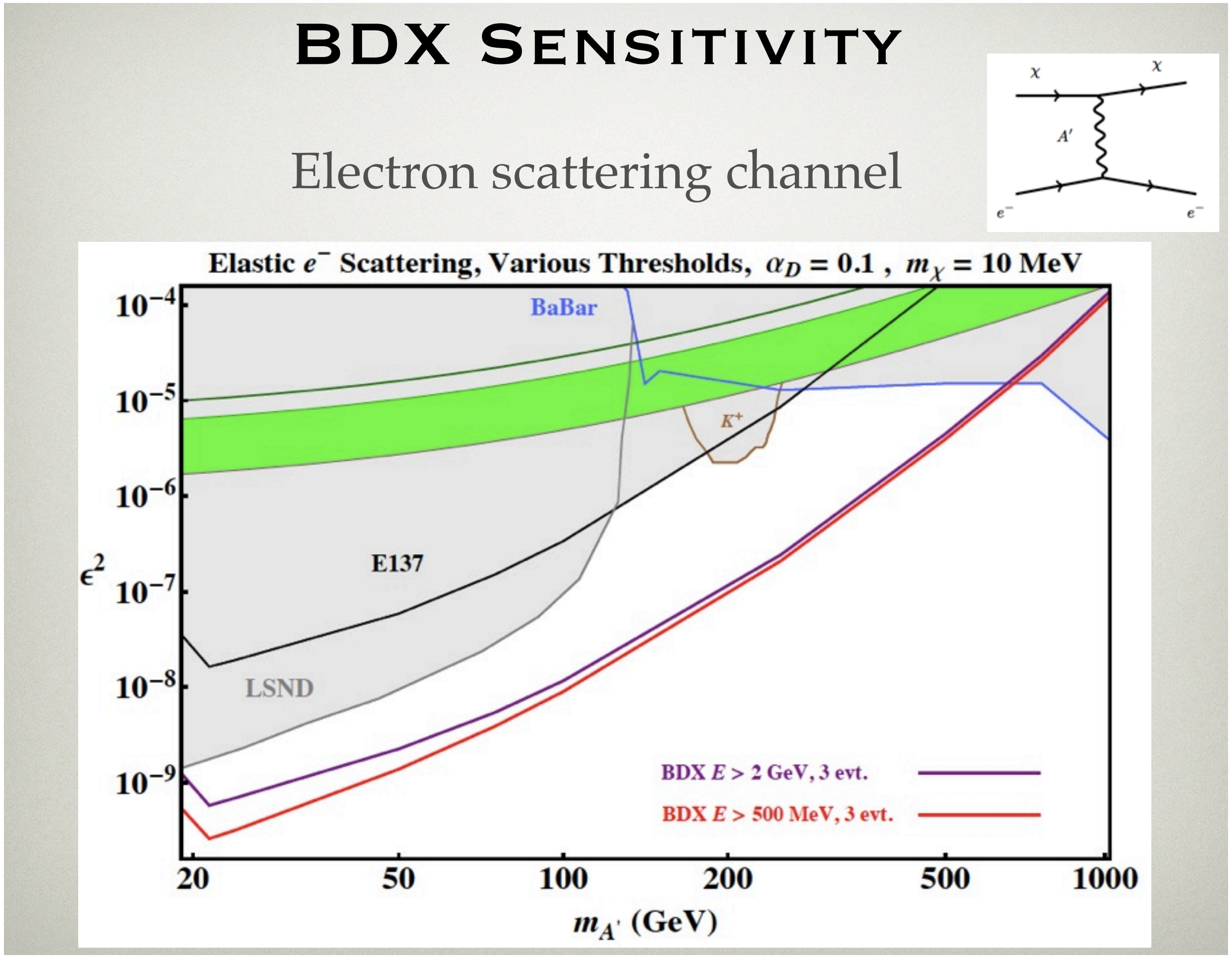
MiniBooNE sensitivity





MiniBooNE can significantly improve sensitivity to light dark matter, especially in models where mediation mechanism is via gauged baryon number – see Batell et al, arXiv:1405.7049, for details.

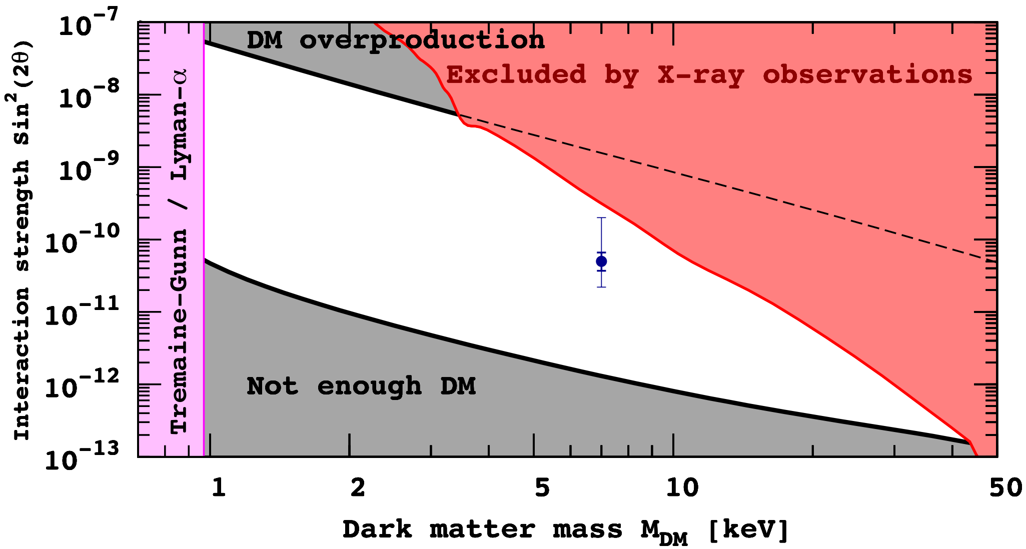
Prospects in improving sensitivity: electrons



New proposal at Jlab – beam dump experiment with small baseline – can significantly improve sensitivity to light dark matter via kinetically mixed portal (G Krnjaic, E Izaguirre, P Schuster, N Toro +experimental collaborators)

Super-WIMP dark matter

- Many examples have been investigated, especially *gravitino dark matter, and sterile neutrino dark matter.*
- Abundance achieved via "freeze-in" mechanism.
- Main constraints are from astrophysics, cosmology



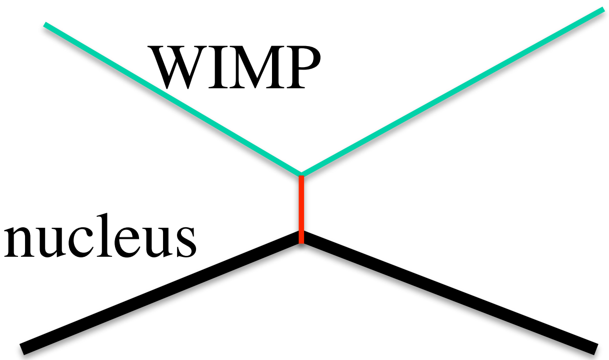
- Tantalizing excess around 3.5 keV
- New proposal to probe MeV-GeV scale sterile neutrinos at CERN fixed target experiment, SHIP, W. Bonivento et al (2013).

Bosonic super-WIMP dark matter

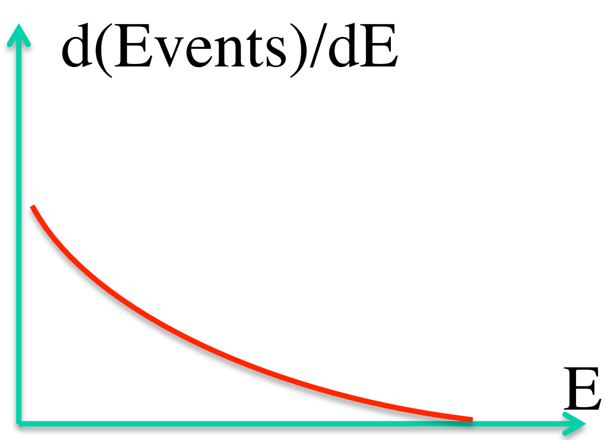
- *Very weakly coupled dark photons* can be dark matter in sub-eV regime due to misalignment mechanism (see J Mardon's talk) or in the keV regime due to thermal emission (MP, Ritz, Voloshin; Postma, Redondo, 2008)
- If $m_V < 2\ m_e$ then only $V \rightarrow 3\ \gamma$ is possible. It is a delayed decay – larger couplings will be consistent with bounds. No monochromatic photons = weaker limits from x- and gamma-rays.
- Direct coupling to electrons = mono-energetic electron recoil in direct dark matter detection.
- First searches of spikes in electronic recoil have been performed by several dark matter detection collaborations.

New signal: absorption of super-WIMPs

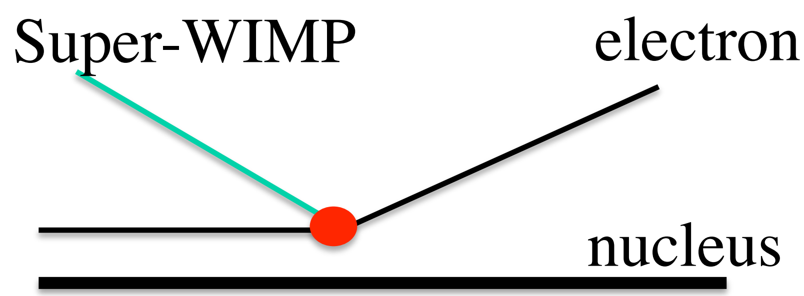
WIMP-nucleus scattering



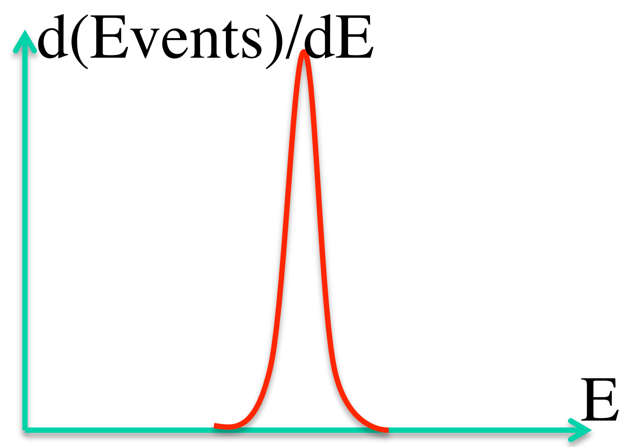
Signal: ionization + phonons/light



Atomic absorption of super-WIMPs



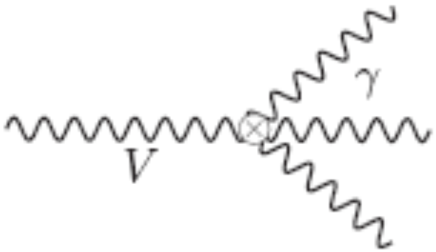
Ionization at $E=m_{superWIMP}$



Superweakly interacting Vector Dark Matter

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

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



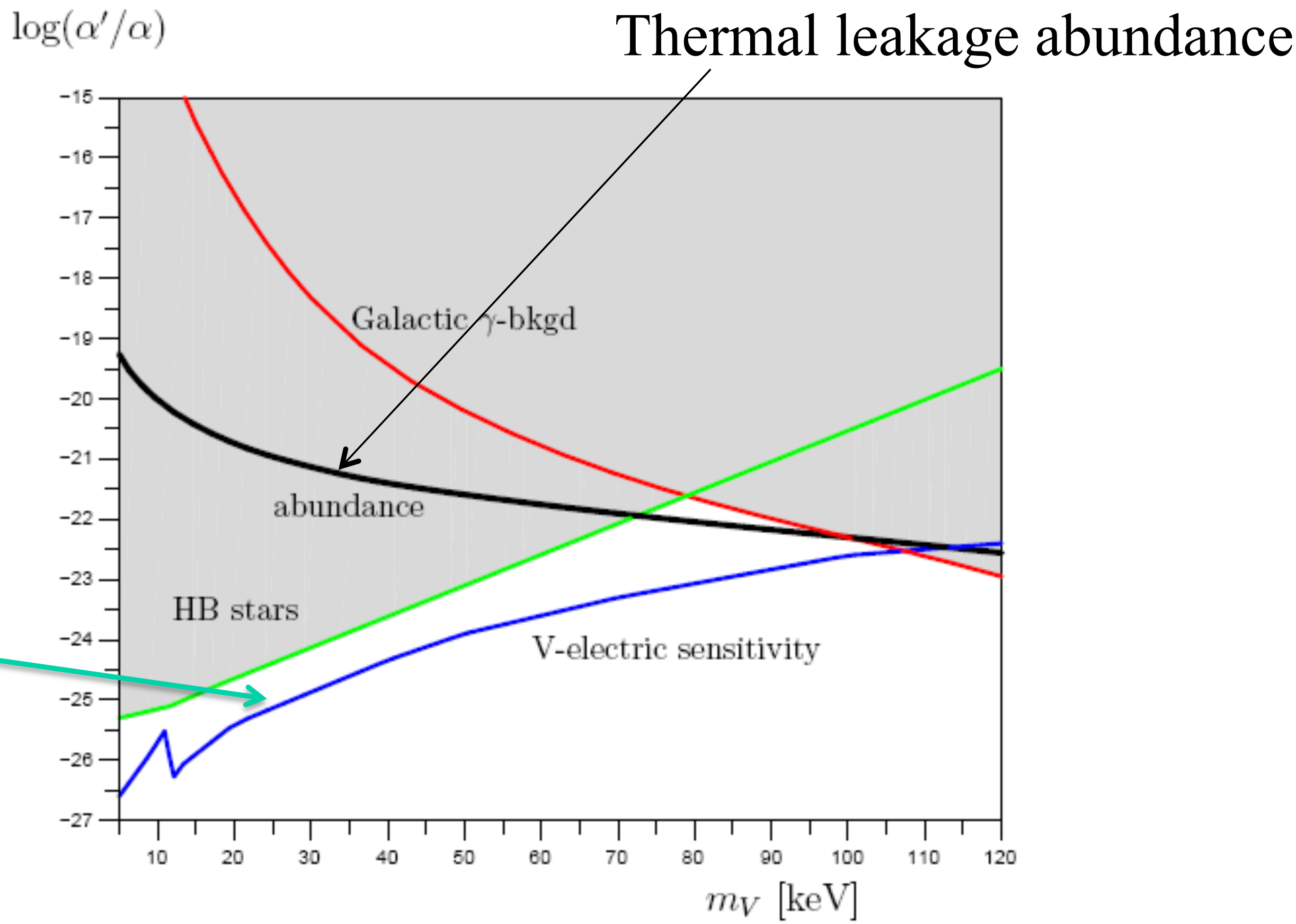
$$\Gamma = \frac{17\,\alpha^3\alpha'}{2^7 3^6 5^3 \pi^3}\,\frac{m_V^9}{m_e^8} \approx \left(4.70\times 10^{-8}\right)\,\alpha^3\alpha'\,\frac{m_V^9}{m_e^8}.$$

$$\tau_{\mathrm{U}}\Gamma_{V\to 3\gamma} \lesssim 1 \quad\Longrightarrow\quad m_V\,(\alpha')^{1/9} \lesssim 1\,\mathrm{keV}\ .$$

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

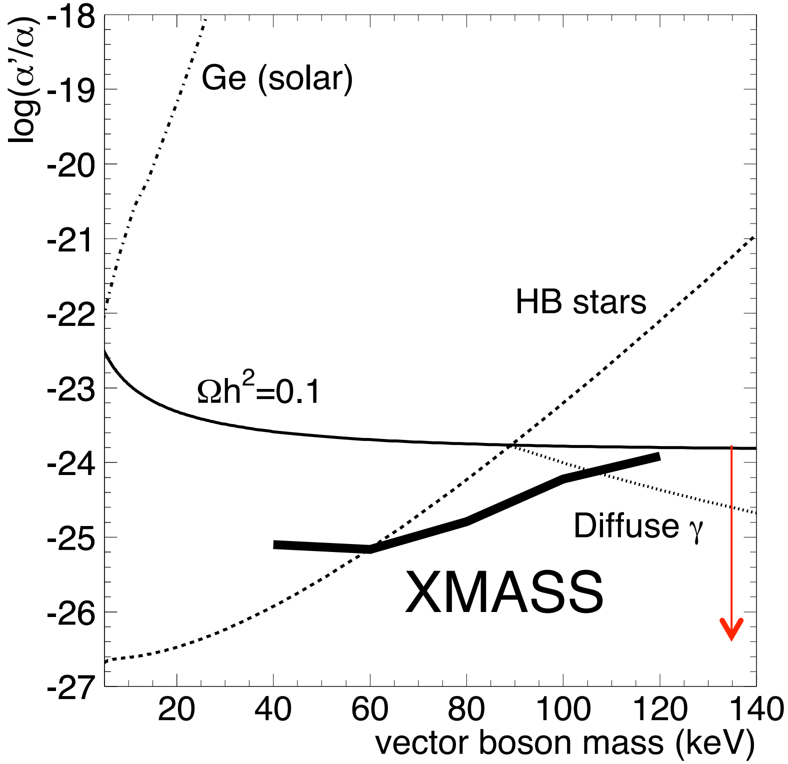
Absorbing Dark Photon DM

Very "approximate", proper Experimental analysis is needed



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

- Searches for "odd lines" in electron recoil was performed by e.g. CDMS, EDELWEISS, CoGeNT (but only in the limited range of energies up to ~ 10 keV). *Region around ~60-120 keV is least constrained by astrophysics.*
- Xenon100 analysis extends it to 30 keV.
- X-mass group publishes new constraint, arXiv:1406.0502



- Red arrow indicates where the abundance curve will move if there is some non-thermal component to the DM abundance
- Current constraints already require extra contributions to abundance (non-thermal component or additional couplings giving more of thermal production)
- These searches can be extended to similar types of vector dark matter and other portals (baryonic etc).

Super-cool Dark Matter from misalignment

Sub-eV mass ranges – has to be non-thermal.

- QCD axion (1981- onwards).

…

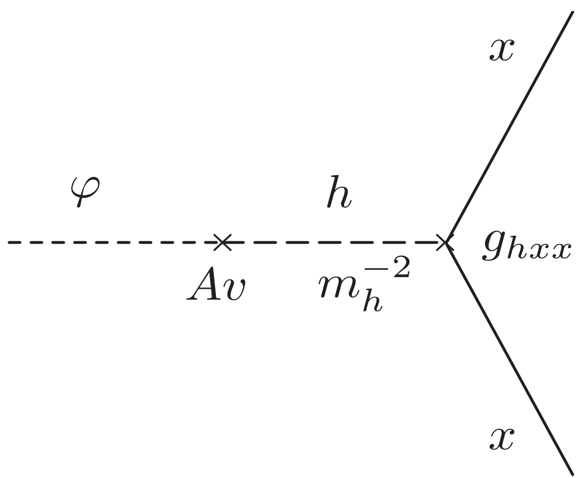
- Scalar DM through the super-renormalizable Higgs portal (Piazza, MP, 2010) Pointed out Dark Photon DM possibility.
- Nelson, Scholtz (2011); Arias et al (2012); Jaeckel, Redondo, (2013); … J Mardon et al, (2014).
- Most models are subject to uncertainty related to the "initial displacement" of the field from minimum (and possible isocurvature perturbation constraints.)

Scalar DM through super-renormalizable portal

- Piazza, MP, 2010: *There is a unique portal in the SM*

$$V = -\frac{m_h^2}{2} H^\dagger H + \lambda (H^\dagger H)^2 + A H^\dagger H \phi + \frac{m_\varphi^2}{2}\phi^2 \,.$$

- There is no runaway direction if $A^2/m_\varphi^2 < 2\lambda$
- After integrating out the Higgs, the theory becomes very similar to Brans-Dicke – but *better* because of UV completeness our theory.



$$g_{\varphi xx} = \frac{Av}{m_h^2} g_{hxx}$$

$$g_{hNN} \simeq \frac{200 - 500\,\mathrm{MeV}}{v} \sim O(10^{-3})$$

- Parameter "A" is of positive mass dimension. Loop corrections to mass^2 of scalar field scale as $\sim A^2\,\mathrm{Log}(\Lambda)$. *Under control* !

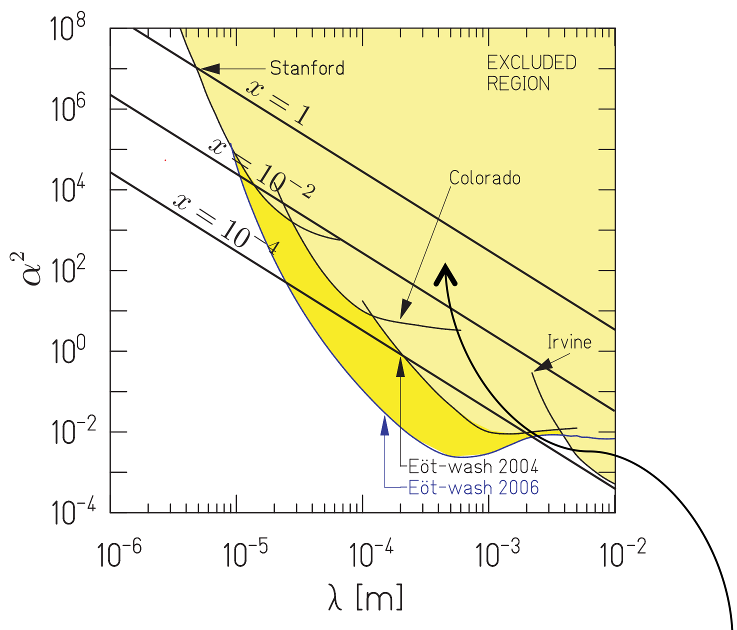
5th force from Dark Matter exchange

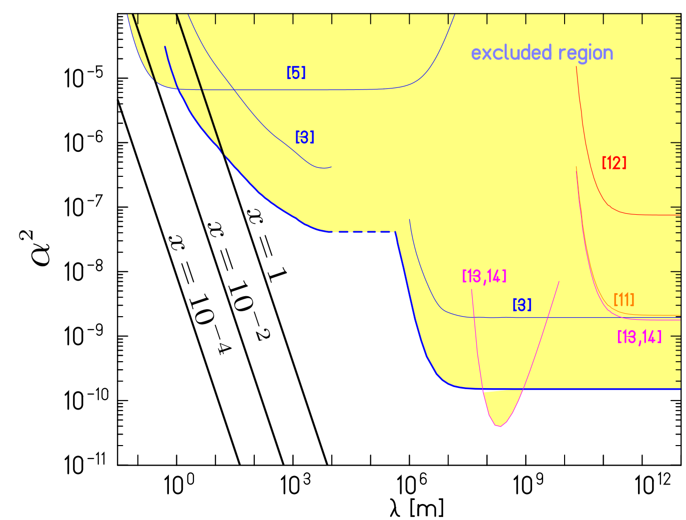
- The main observational consequence of this model: possibility to have an observable 5th force (x= A/mass)
- For the traditional parametrization, $V(r) = -G\frac{m_A m_B}{r}\left(1 + \alpha_A \alpha_B\, e^{-m_\varphi r}\right).$

we can derive the strength of coupling

$$\alpha = g_{hNN}\frac{\sqrt{2}M_P}{m_{\rm nuc}}\frac{Av}{m_h^2} \simeq 10^{-3}\left(\frac{m_h}{115\,{\rm GeV}}\right)^{-2}\frac{A}{10^{-8}{\rm eV}}.$$

(! *the second bracket* = 0.83)





One can expect a “natural” 5th force from DM in 10 micron – 100 m range

Oscillating force on He3 spin

Recent suggestions to search for ALP dark matter by Graham, Rajendran

Easy to see if e.g. M. Romalis' "Lorentz violation" search is sensitive to ALPs dark matter:

$$\mathcal{L} = \frac{\partial_\mu a}{f_a} \overline{n} \gamma_\mu \gamma_5 n$$

As everyone else in this game, I will saturate ρ_{DM} by oscillating a(t).

If I take the *maximum allowed* f_a from stellar constraints, the range of masses 10^{-17} to 10^{-15} eV where the K-He3 magnetometer is the most sensitive and can probe ALP dark matter.

The energy shift due to DM:

$$\Delta E = \frac{m_a a}{f_a} \frac{v}{c} = \frac{\sqrt{\rho_{DM}}}{f_a} \frac{v}{c}$$

$$= 1.5 \times 10^{-33} \mathrm{GeV} \times \frac{10^9 \ \mathrm{GeV}}{f_a} \times \left(\frac{\rho_{DM}}{0.3 \mathrm{GeVcm}^{-3}} \right)^{1/2} \times \frac{v/c}{10^{-3}}$$

Right at the edge of current sensitivity!!

Conclusions

1. Dark matter takes 25% of the Universe's energy budget. It's identity is not known. Many theoretical possibilities for the CDM exist: WIMPs, super-WIMPs, super-cold DM – *many within SUSY context*. **It is important to cast as wide an experimental net as possible**

2. In WIMP physics, the recent discovery of the Higgs significantly restricts the possibility of any sub-50-GeV WIMP dark matter coupled via the Higgs portal. New forces in the DM sector may significantly alter the expectations from simplest 2←→2 WIMP-SM scattering/annihilation paradigm. MeV range of WIMP dark matter is being searched for in e/p-on-fixed-target experiments.

3. Super-weakly interacting massive particles (again, many examples!) can be amenable to direct detection via a photo-electric like effect, especially for vector DM. New target for direct detection searches.

4. Super-cold DM (oscillations of very light fields) can be generalized beyond axions (scalars, vectors): new possibilities for direct searches.