A Theoretical Perspective on Dark Matter

Maxim Pospelov

University of Victoria, Victoria/Perimeter Institute, Waterloo

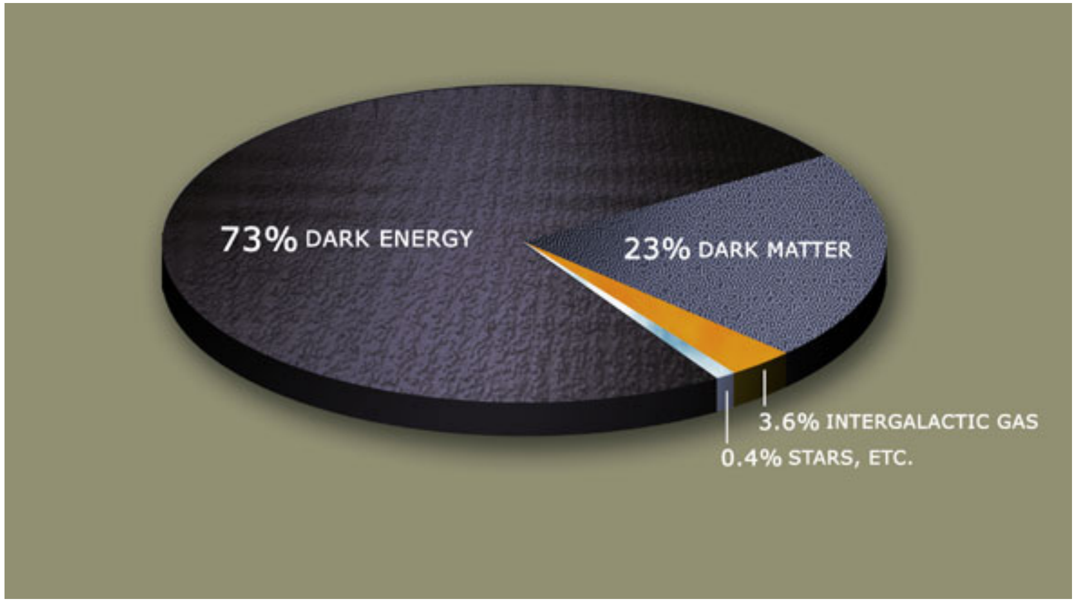
University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. *Introduction. Types of dark matter*
2. Weakly interacting massive particles (WIMPs). Supersymmetry? Higgs portal physics? An impressive record of direct detection experiments.
3. Dark sectors (DM + dark forces). Searches at short baseline neutrino experiments
4. Very light dark matter and macroscopic dark matter – implications from gravitational searches.
5. Conclusions.

Big Questions in Physics

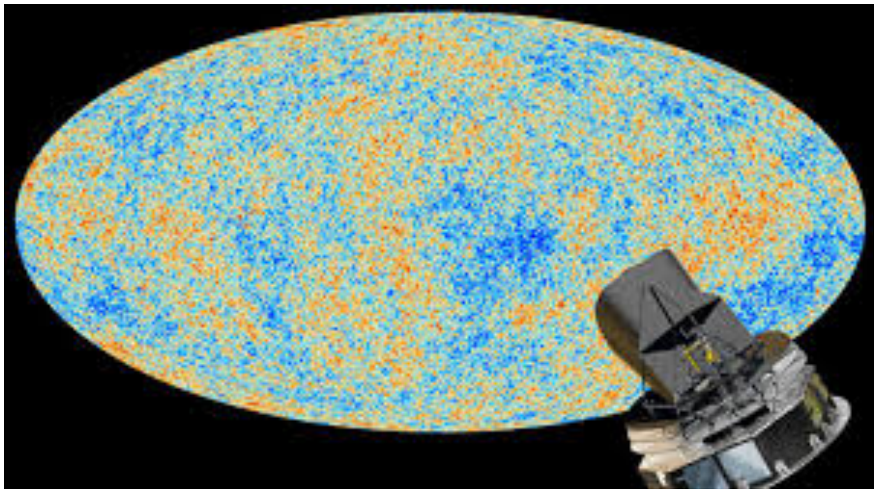


"Missing mass" – what is it?

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.

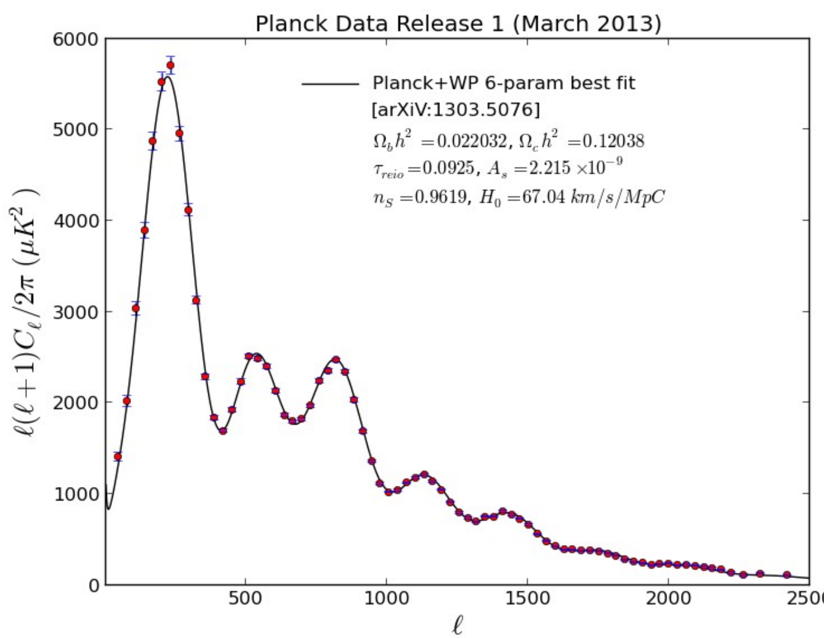
State-of-the-art CMB results



Due to the growth of c/H(t) which determines horizon size, many CMB Universes “fit” into todays sky.

The temperature of these patches is not exactly the same, but differs by $\sim 10^{-5}\, T_{CMB}$ from spot to spot.

Statistics of this fluctuations encodes information about physical conditions during the CMB Universe, and geometrical information about the propagation from the surface of last scattering to us.



Implications of early cosmology

1. Universe was relatively *simple* at T ~ 0.3 eV.

2. The dark matter was already "*in place*" at the time of the matter-radiation equality, when the potential wells created by DM started to grow. We see statistical evidence of H and He falling (and rebounding) into the DM gravitational wells.

3. DM is not "made of ordinary atoms" – and there is 6 times more of it than of ordinary H and He. $\Omega_{\text{dark matter}} / \Omega_{\text{baryons}} = 5.4$

4. What is it? These are *not* known neutrinos : they would have to weigh ~ 50 eV (excluded), and would have a hard time making smaller scale structure (too hot to cluster on small scales).

5. Simplicity of the early Universe, makes many of us suspect that the DM might be in the form of unknown (= e.g. beyond-SM particles).

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**. (asymmetric WIMPs are a variation.)

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**.

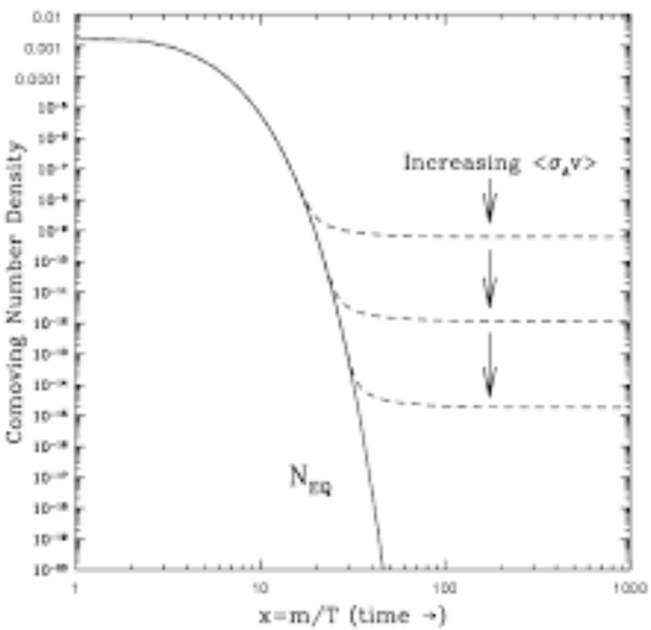
Many reasonable options. *Signatures can be completely different.*

Weakly interacting massive particles

In case of electrons and positrons (when the particle asymmetry = 0), the end point is $n_e/n_{gamma} \sim 10^{-17}$. It is easy to see that this is a consequence of a large annihilation cross section ($\sim \alpha^2/m_e^2$).

We need a particle "X" with smaller annihilation cross section,

$X + X \rightarrow$ SM states.

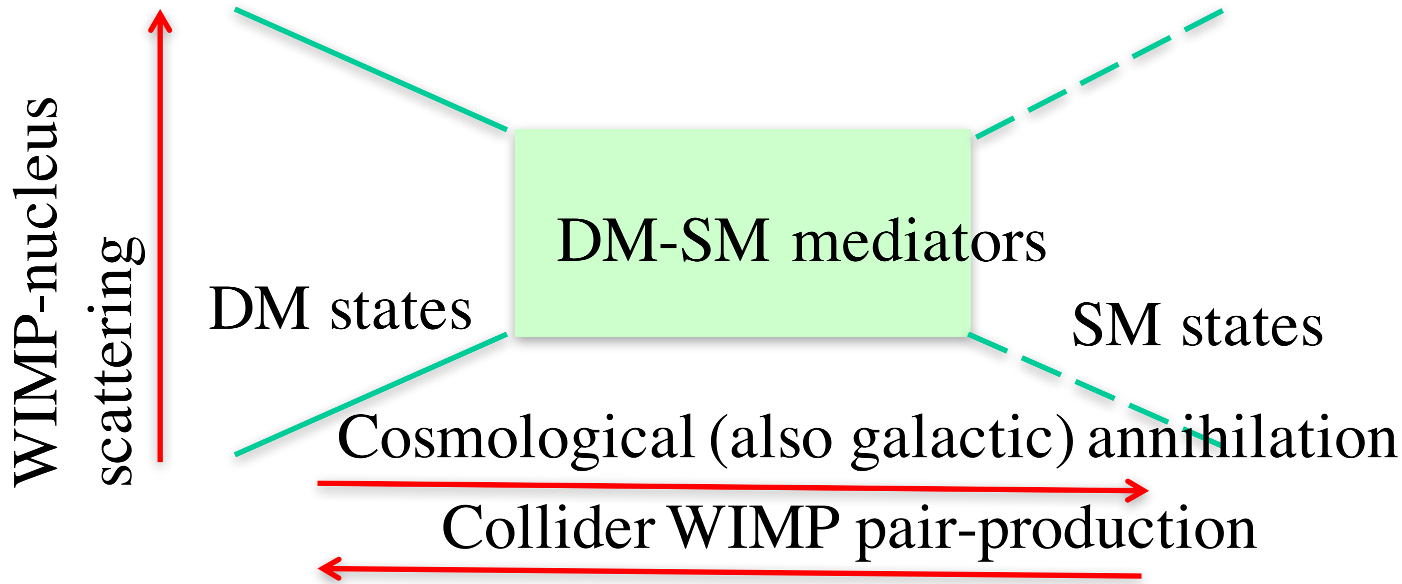


Honest solution of Boltzmann equation gives a remarkably simple result. $\Omega_X = \Omega_{DM}$, observed if the annihilation rate is

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

$10^{-36}\,\text{cm}^2 = \alpha^2/\Lambda^2 \rightarrow \Lambda = 140$ GeV. **$\Lambda \sim$ weak scale!!!** First implementations by (Lee, Weinberg; Dolgov, Zeldovich,….)

WIMP paradigm, some highlights

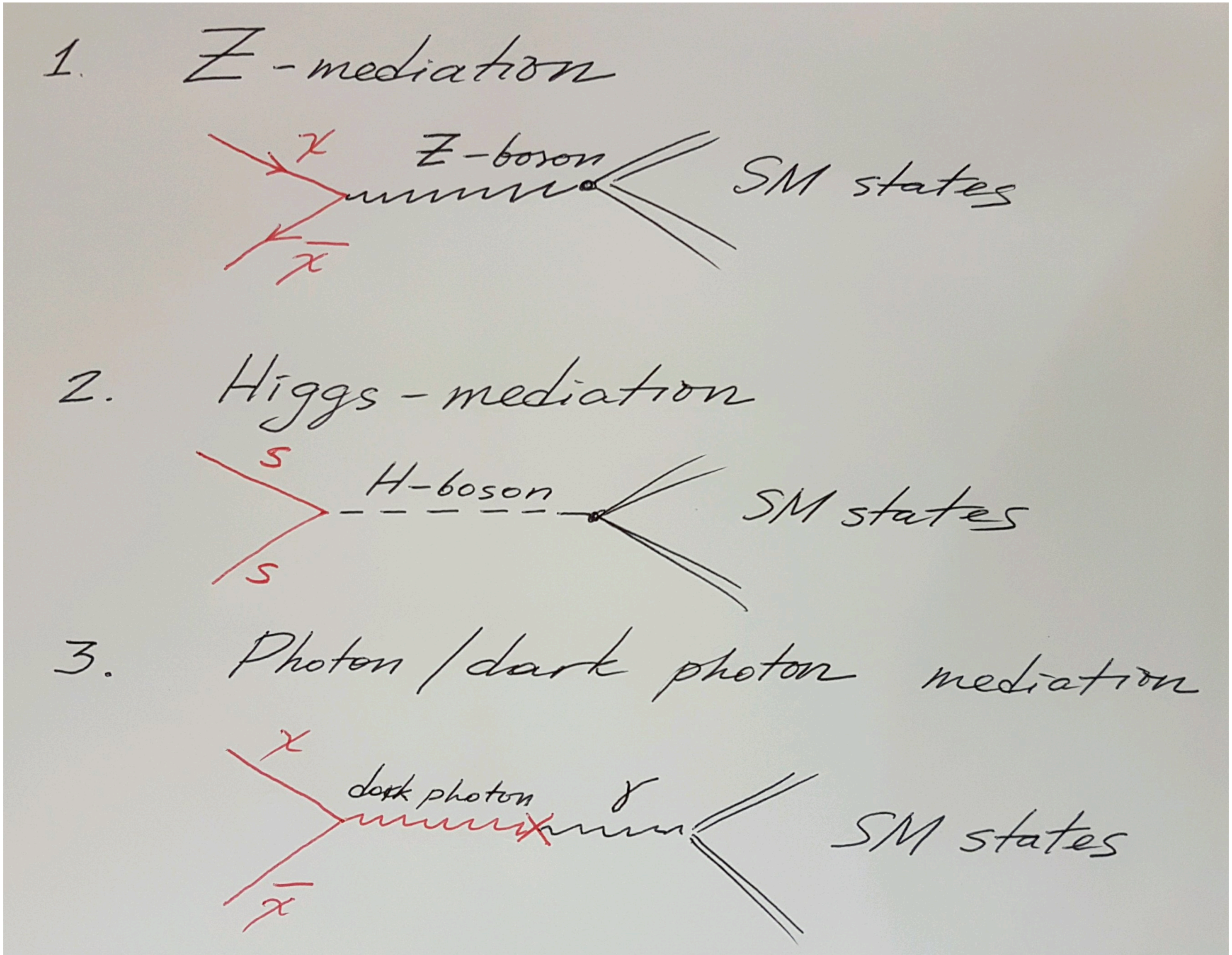


$$\langle \sigma_{ann} v \rangle \approx 1\,\mathrm{pbn} \times c$$

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?

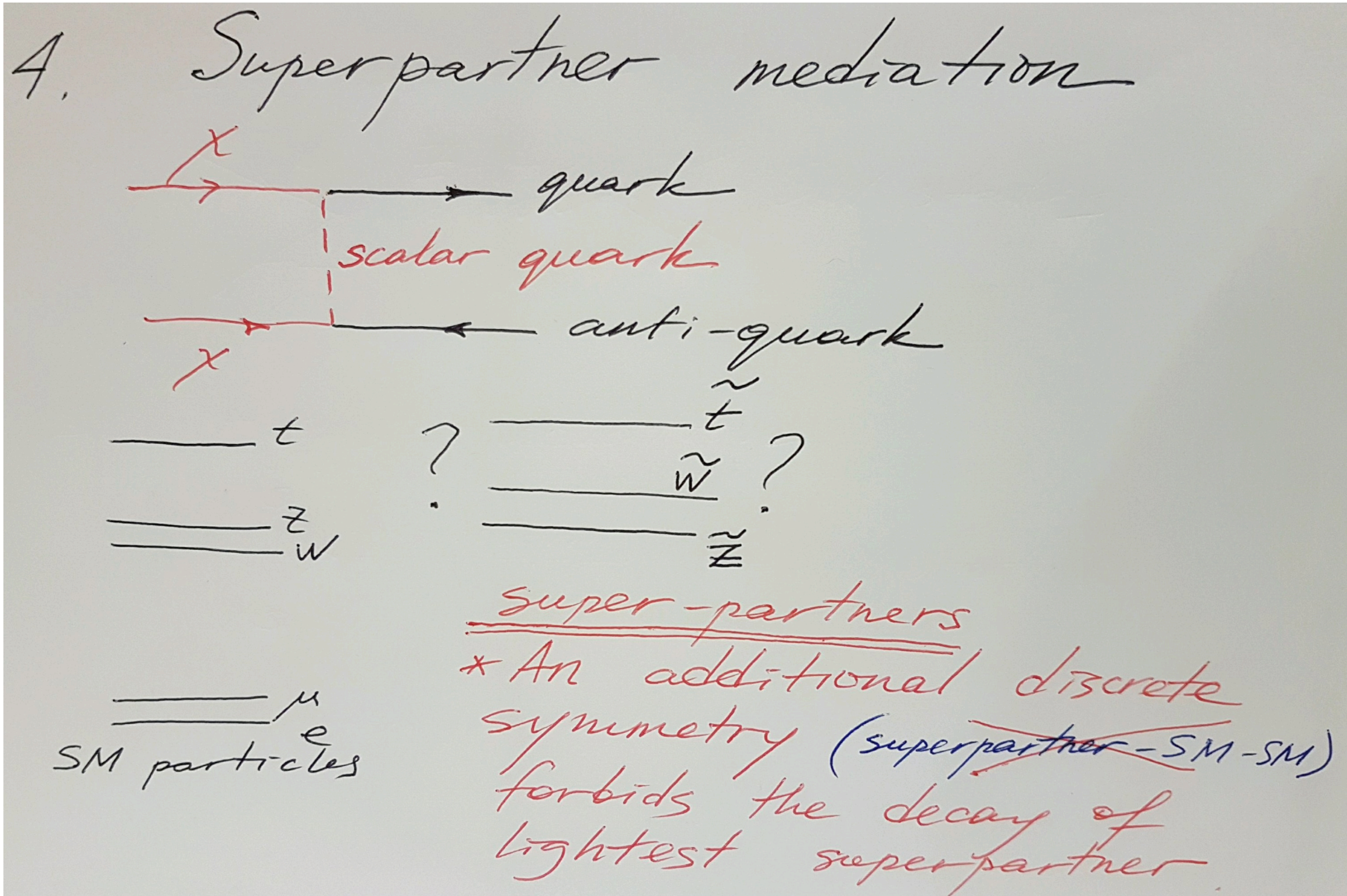
Examples of DM-SM mediation



Very economical extensions of the SM.

DM particles themselves + may be extra mediator force. Can be very predictive.

Supersymmetry may naturally provide a WIMP candidate



The appeal of the model is in linking DM and the issues of stability of EW scale against rad corrections. Many new particles and parameters

WIMP efforts are multi-directional

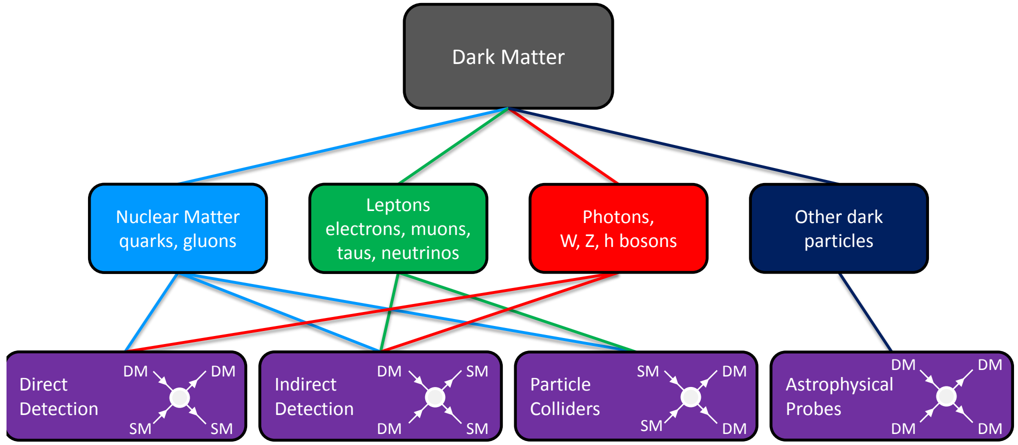
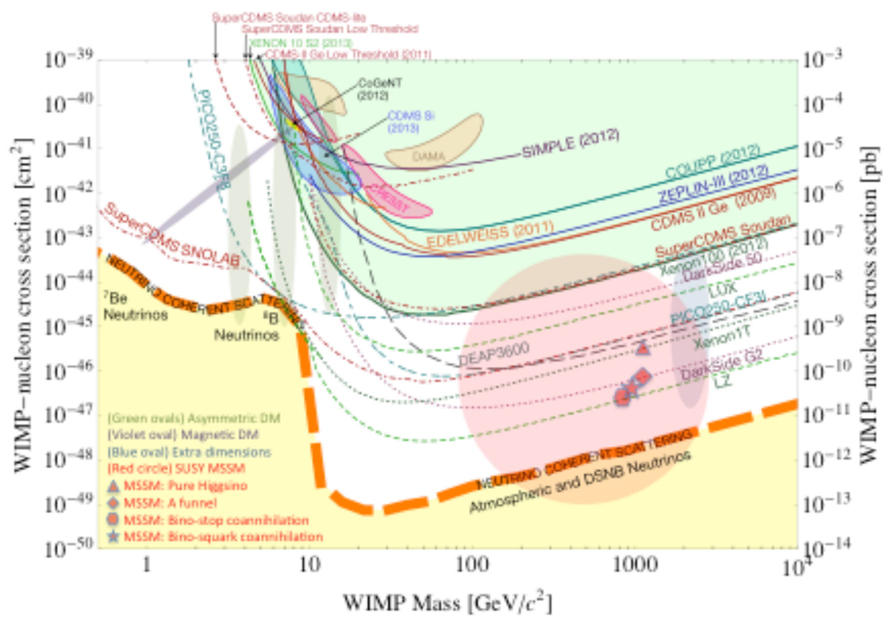


Figure 5. *Dark matter may have non-gravitational interactions with any of the known particles as well as other dark particles, and these interactions can be probed in several different ways.*



From the Snowmass 2013 summary, 1310.8327

Theoretical predictions for $\sigma_{DM\text{-}N}$

- Unlike annihilation of WIMP DM (whose inferred cross section is quite model independent), the scattering cross section $\sigma_{DM\text{-}N}$ does depend on the model.

- Take an "original" WIMP model with a ~ 10 GeV Dirac fermion annihilating into SM particles via an intermediate Z-boson.

$\sigma_{\text{DM-Nucleon}}$ (Z-mediated) ~ $(1/8\pi)\, m_p^{\,2}(G_F)^2 \sim (10^{-39}\text{-}10^{-38})\ \text{cm}^2$ range.

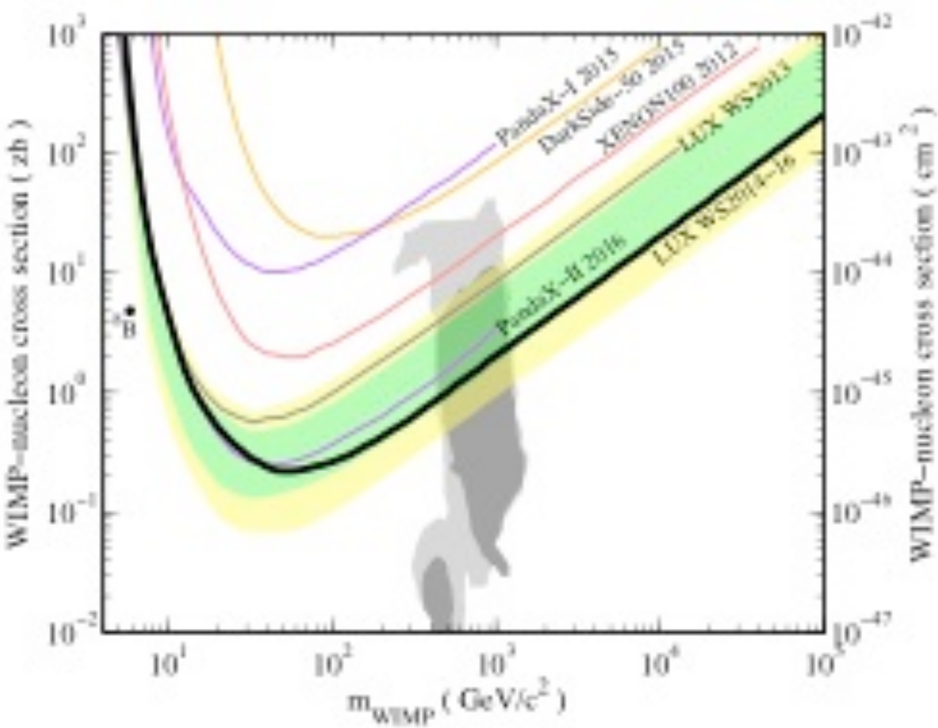
$\sigma_{\text{DM-Nucleon}}$ (Higgs-mediated) ~ $10^{-5} \times \sigma_{\text{DM-Nucleon}}$ (Z-mediated)

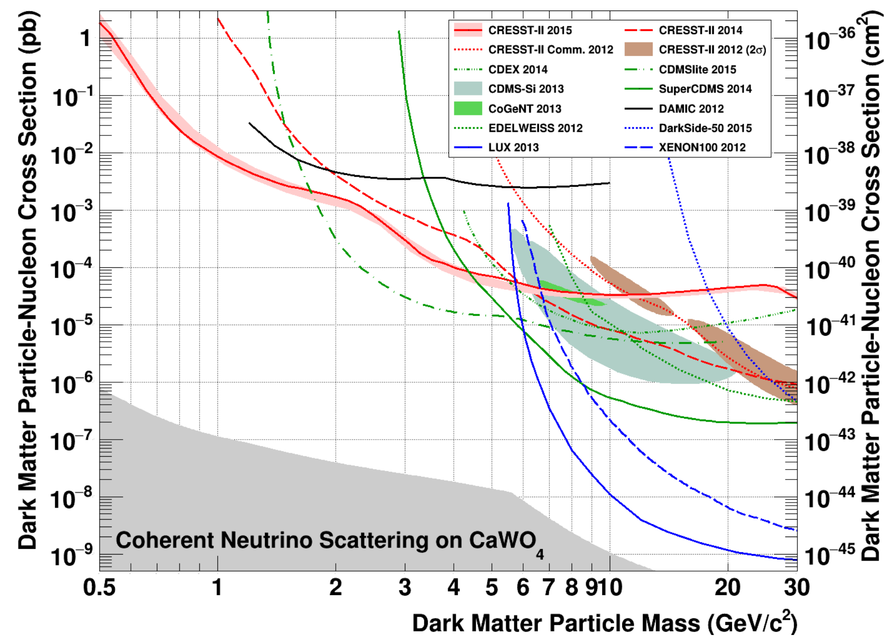
$\sigma_{\text{DM-Nucleon}}$ (EW loop) ~ $10^{-9} \times \sigma_{\text{DM-Nucleon}}$ (Z-mediated)

Looks tiny, but how does it compare with the today's limits?

Progress in direct detection of WIMPs

(latest 2016 LUX and CRESST results)





Spin-independent Z-boson mediated scattering of a Dirac WIMP is excluded from ~ 1 GeV to 100 TeV – i.e. over the entire WIMP mass range. What about the Higgs-mediated models?

Prediction for direct detection

(Higgs-mediated dark matter – Burgess, MP, ter Veldhuis, 2000)
all masses from 100 MeV to 10 TeV were allowed

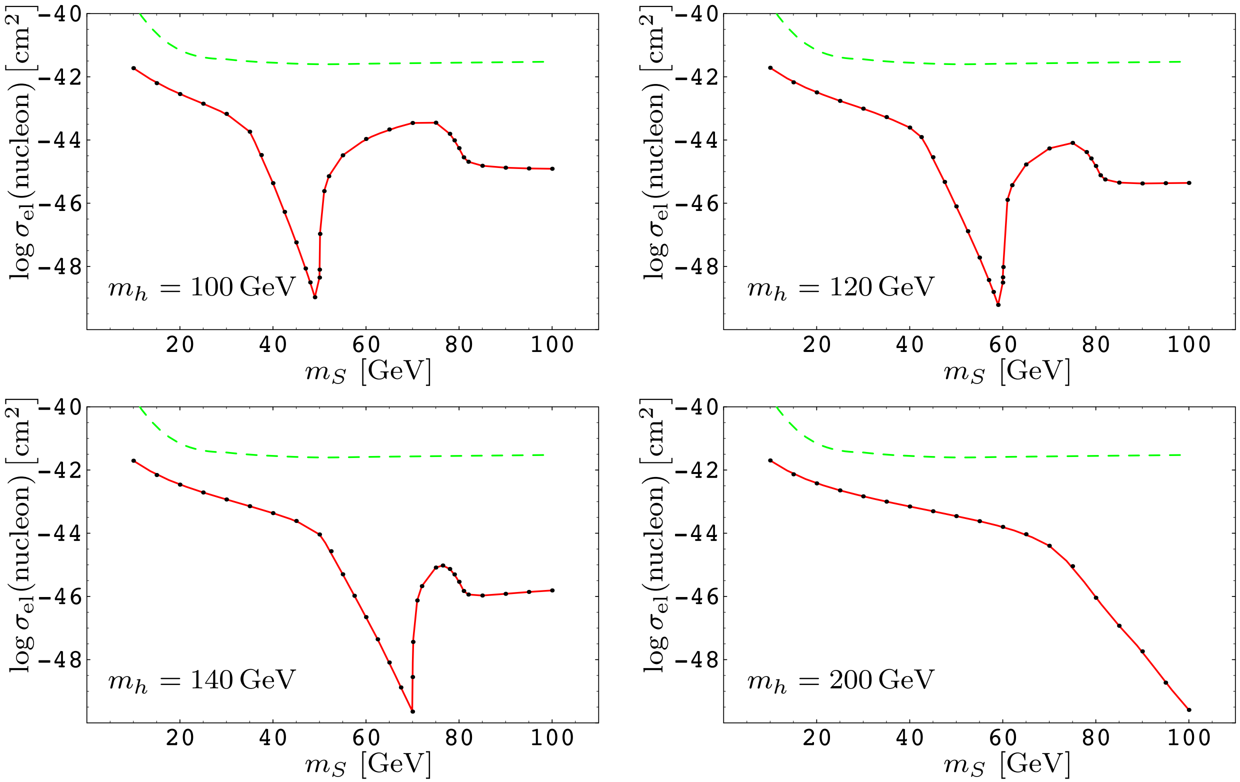
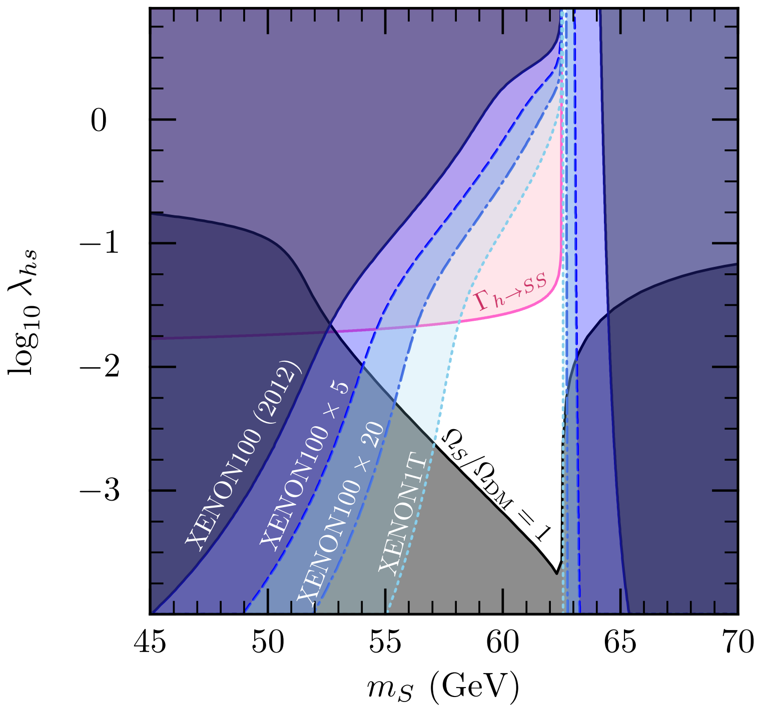
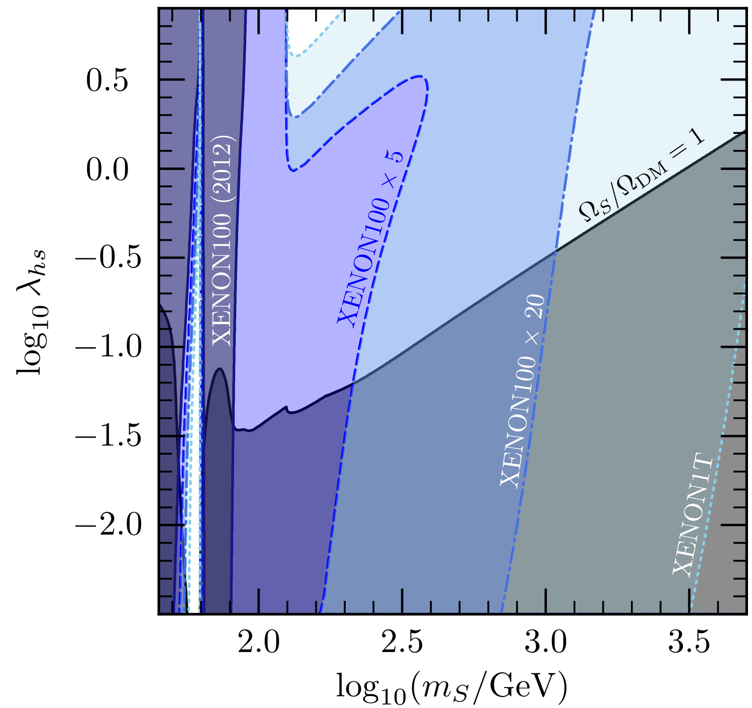


Figure 4: The predictions for the elastic cross section, $\sigma_{\rm el}$, as a function of m_S, which follows from the $\lambda(m_S)$ dependence dictated by the cosmic abundance. Also shown by a dashed line is the exclusion limit from the CDMS experiment [6] .

Back in ~2000, best experiments were several orders of magnitude away

Updates on the minimal Higgs-mediated model:





Updates on the model from Cline, Scott, Kainulainen, Weniger, 2013.

Direct detection is competitive with the Higgs decay constraints.

New generation of direct detection will probe the entire mass range of the Higgs-mediated models.

Dark Sectors

- On top of WIMP dark matter there could exist a whole dark sector (DM + New gauge interactions, new sets of Higgses etc.)
- One could expect a drastic alteration of phenomenology. Many more things become possible. The range of DM masses can be extended.
- In many cases the connection between σ_{ann} and σ_{scat} may be severed. This occurs specifically in models where DM annihilates to mediators, which further decay to SM particles. Predictivity of simplest models (Higgs-mediated, Z-mediated) is lost.
- Motivates to think of new ways to search for DM.

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

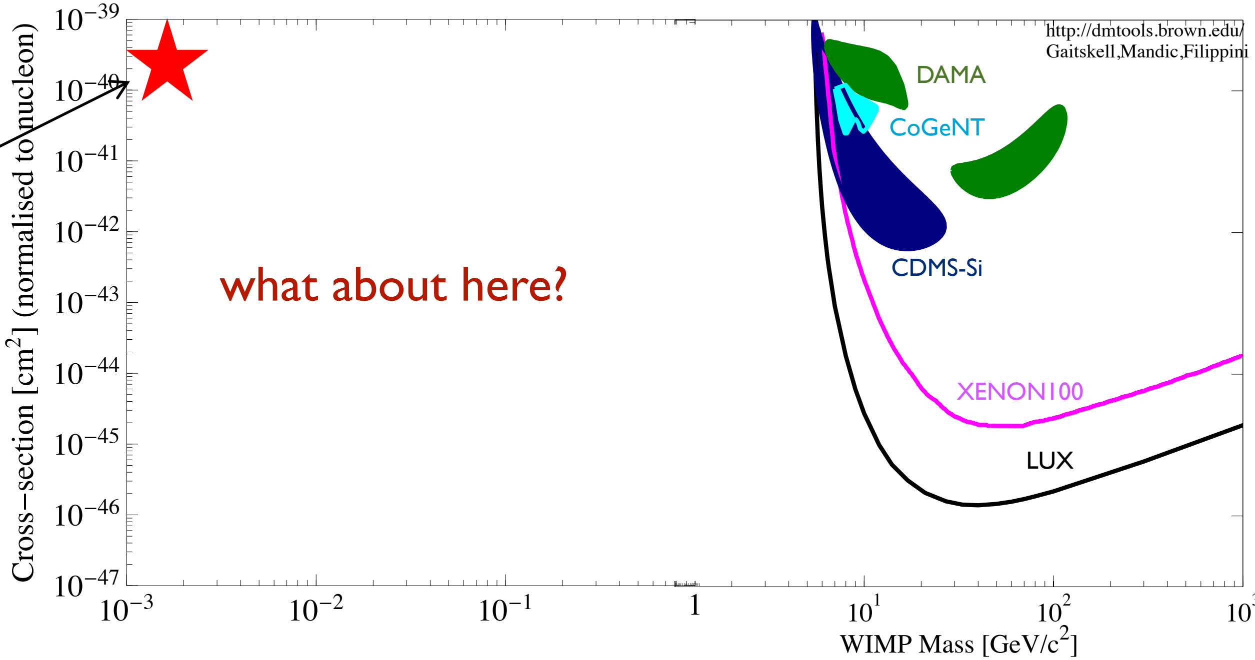
2. $m_{mediator} < m_{WIMP}$

   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.

Light DM – direct production/detection

511 keV motivated

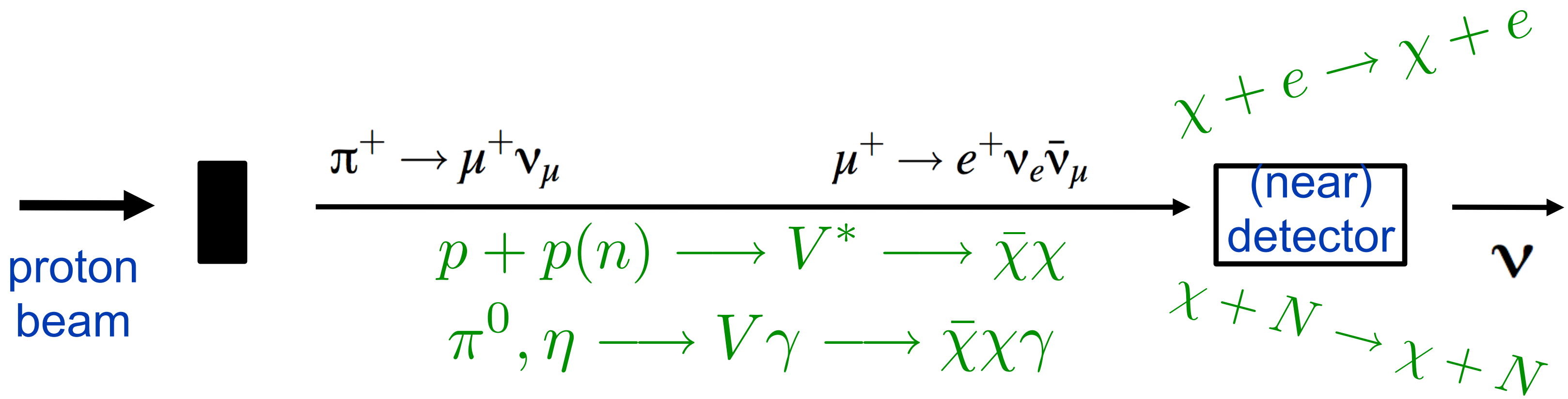


If WIMP dark matter is coupled to light mediators, the WIMP mass can be much lighter than Lee-Weinberg range, (Boehm, Fayet)

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

Fixed target probes - Neutrino Beams

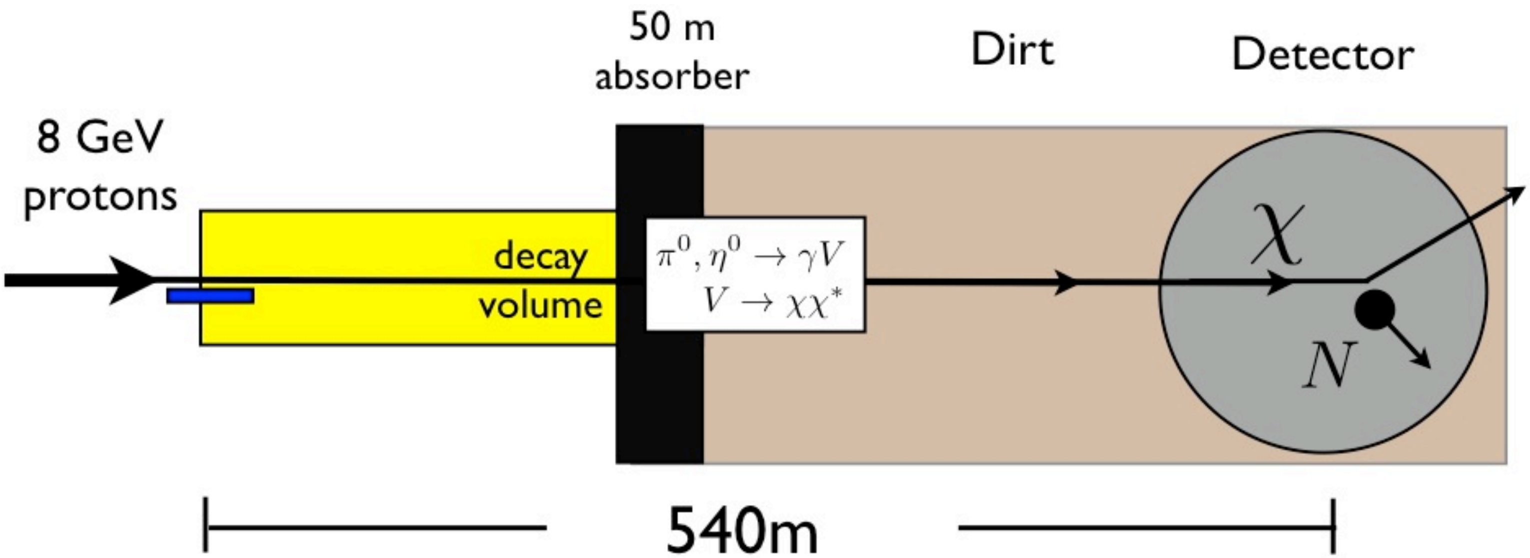
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM



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]

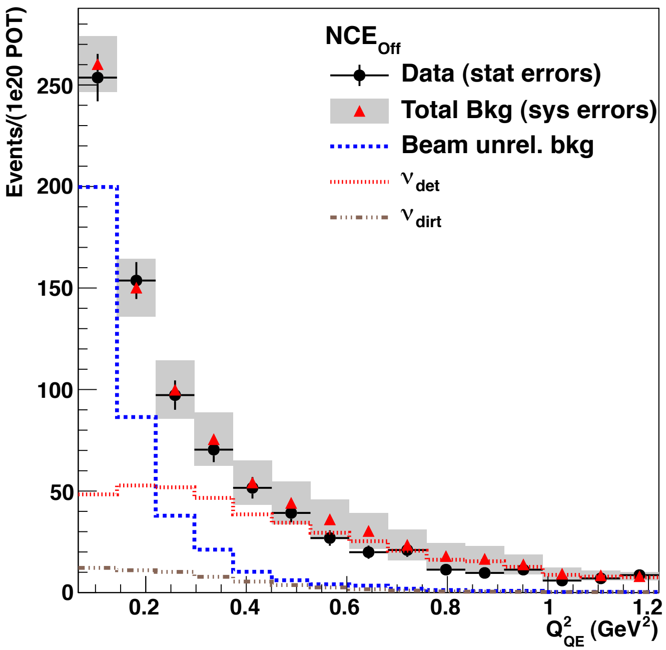
By-passing Be target is crucial for reducing the neutrino background (Richard van de Water et al. …) . Currently, suppression of ν flux ~50.

Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds. First results – this year (2016)

Fermilab W&C talk by R.T. Thornton Sept 2016, new constraints.

On-going and future projects

From the W & C talk by Thornton

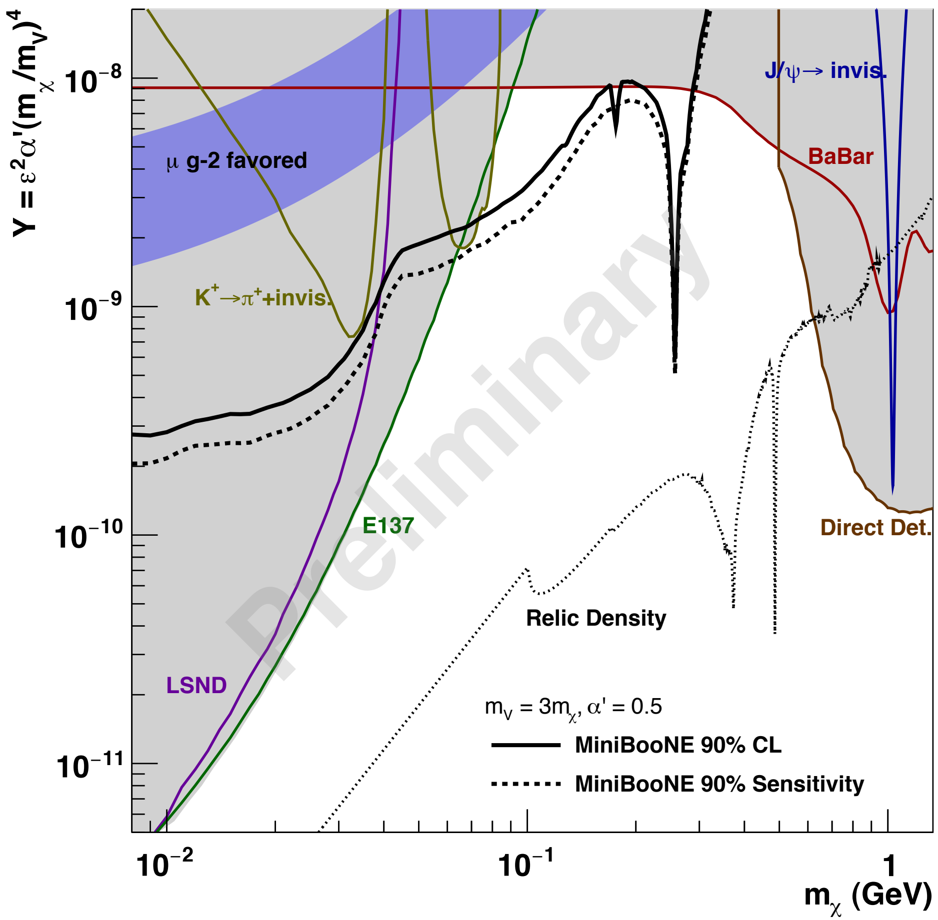


	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)

The off-target run of MiniBoone is a success (despite the absence of DM signal!):

- Neutrino background from the beam is brought down to be comparable from cosmics
- Data are well described by MC

New parts of the parameter space get excluded



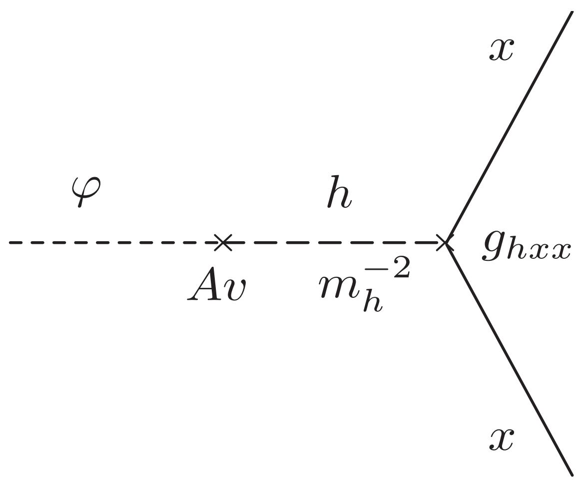
Improves over LSND, SLAC experiments, and Kaon decays in the range of the mediator mass from ~ 100 to few 100 MeV. (My collaborators, B Batell and P deNiverville joined the collaboration to help out!)

Scalar DM through super-renormalizable portal

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

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

- 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.



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

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

- Main consequence of such model is a new scalar force mediated by dark matter.

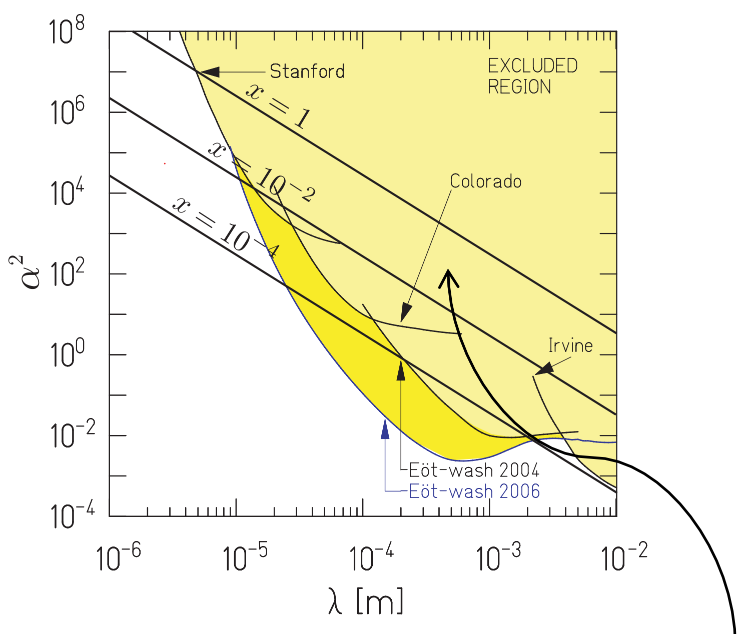
5th force from Dark Matter exchange

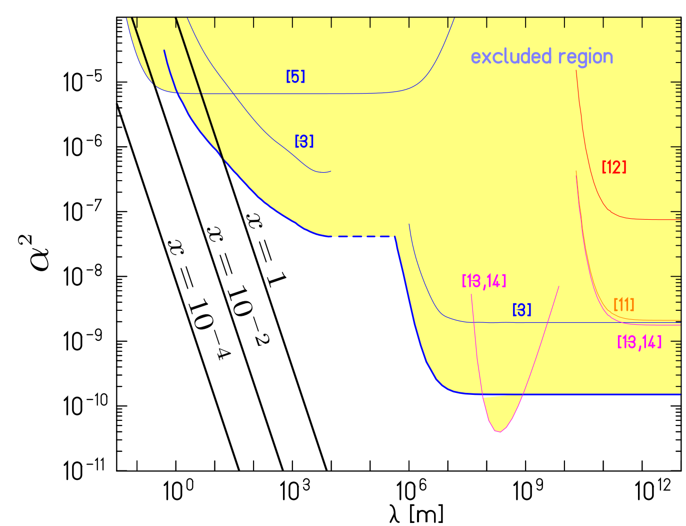
- The main observational consequence of this model: possibility to have an observable 5th force (x= A/mass)
- For the traditional parametrization, $$V(r) = -G\frac{m_A m_B}{r}\left(1+\alpha_A\alpha_B\, e^{-m_\varphi r}\right).$$

we can derive the strength of coupling

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

(! *the second bracket* = 0.83)





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

Anomalous spin precession frequency

Easy to see if e.g. "Lorentz violation" searches are sensitive to ALPs dark matter:

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

Let us saturate ρ_{DM} by oscillating *a(t)*.

Let's take the *maximum allowed* f_a from stellar constraints at 10^9 GeV.

Let us take the range of masses 10^{-17} to 10^{-15} eV where e.g. K-He3 magnetometers designed for LV searches are the most sensitive

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! Reanalysis of "Lorentz Violation" searches can constrain dark matter in this mass range.

Macroscopic size DM *other than primordial black holes*

MP et al, 2012; Derevianko and MP, 2013

Laser Interferometers as Dark Matter Detectors

Evan D. Hall,[1] Thomas Callister,[1] Valery V. Frolov,[2] Holger Müller,[3] Maxim Pospelov,[4,5] and Rana X Adhikari[1]

1606.01103

Extended field configurations of light fields

Take a simple scalar field, give it a self-potential e.g. $V(\phi) = \lambda(\phi^2\text{-}v^2)^2$.

If at x = - infinity, ϕ = -v and at x = +infinity, ϕ = +v, then a stable *domain wall* will form in between, e.g. $\phi = v \tanh(x\, m_\phi)$ with

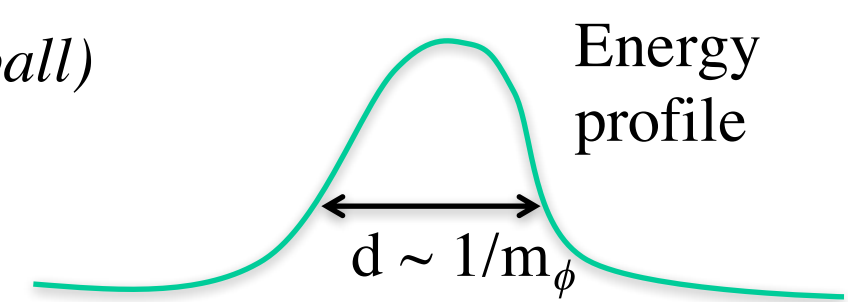
$m_\phi = \lambda^{1/2}\, v$

The characteristic "span" of this object, $d \sim 1/m_\phi$, and it is carrying energy per area $\sim v^2/d \sim v^2\, m_\phi$ Network of such topological *defects* (TD) can give contributions to dark matter/dark energy.

0D object – a *Monopole (also a Q-ball)*

1D object – a *String*

2D object – a *Domain wall*



Transient signals from macroscopic DM

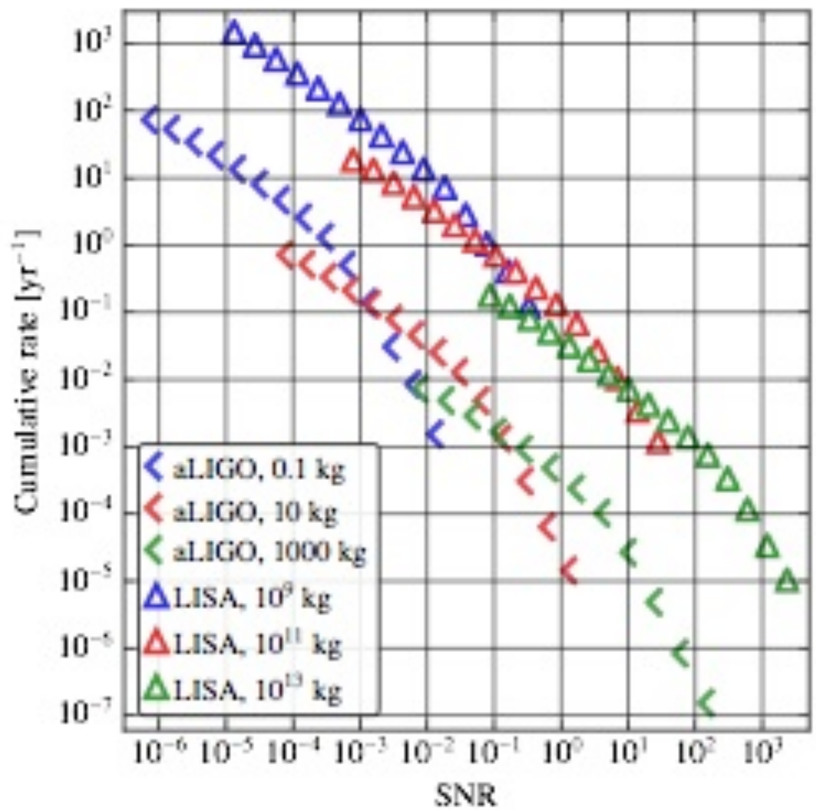
Regardless of precise nature of TD-SM particles interaction it is clear that

1. Unlike the case of WIMPs or axions, most of the time with TD DM there is no DM objects around – and only occasionally they pass through. Therefore the DM signal will [by construction] be *transient* and its duration given by $\sim$ size/velocity.

2. If the S/N is not large, then there can be a benefit from a network of detectors, or co-located detectors searching for a correlated in time signal.

3. There will be a plenty of the constraints on any model of such type with SM-TD interaction, because of additional forces, energy loss mechanisms etc that the additional light fields will provide.

Simulation of sensitivity to grav interaction



A passage of 0-dim objects (e.g. "monopoles") gives a disturbance signal with characteristic $\omega \sim v/L \sim 100$ Hz (a good range for Ligo!). Average energy density is fixed to galactic ρ_{DM}.

A few orders of magnitude short from being able to detect gravitational-size interaction with macroscopic DM.

Sensitivity to new Yukawa interaction

- A non-gravitational interaction between DM and SM could be parametrized by a Yukawa force,

- $V_{\text{atom1-atom2}} = - G_N m_1 m_2 /r \ (1 + \delta_{SM}^2 \, \text{Exp}[-r/\lambda])$
- $V_{\text{atom-DM}} = - G_N m_{\text{atom}} m_{DM} /r \ (1 + \delta_{SM}\delta_{DM} \, \text{Exp}[-r/\lambda])$

- From the 5th force measurements we will know that the extra SM couplings are small, $\delta_{SM}^2 < 10^{-5}$. In contrast, the coupling to the dark sector can be large, $\delta_{DM} >> 1$ if the range of the force is much smaller than the galactic size (e.g. $\lambda \sim$ few km).

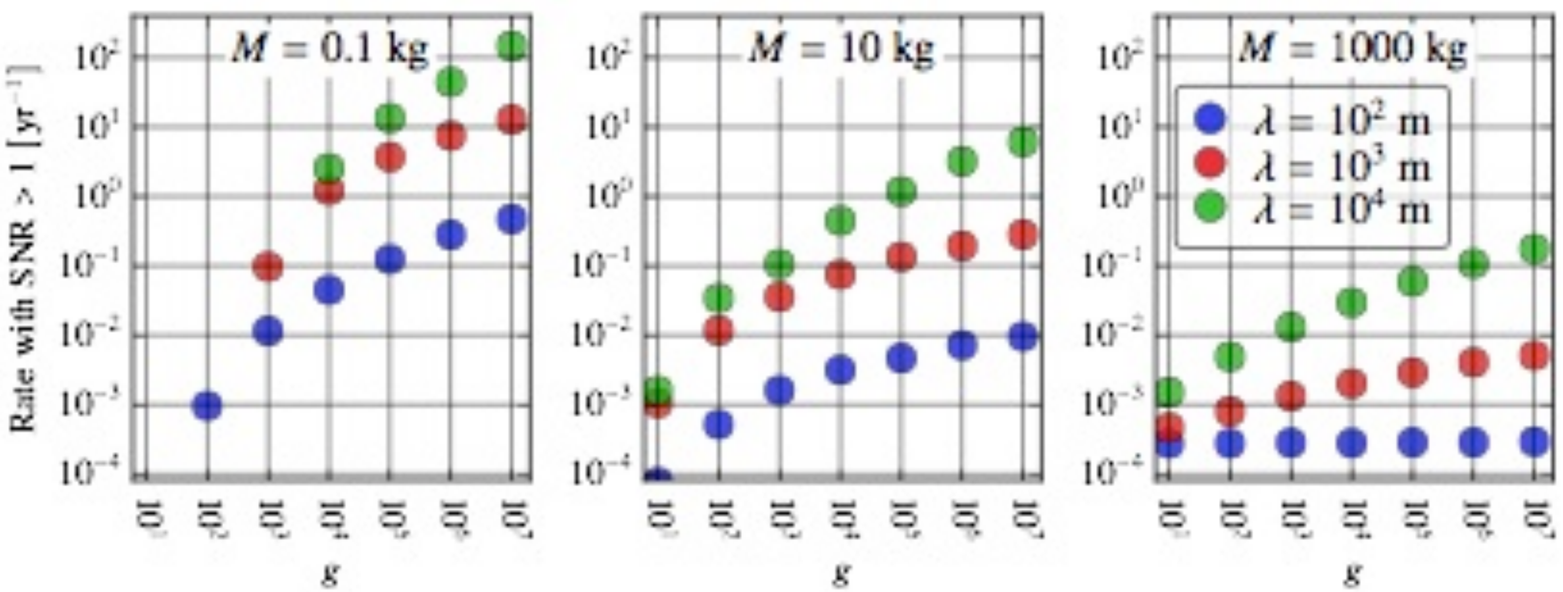
$$\sigma_{\text{DM-DM}} = 16\pi \times \frac{G_N^2 M_{\text{DM}}^2 \delta_{\text{DM}}^4}{v_{\text{DM}}^4} \times \log\left[\frac{\lambda}{r_{\text{DM}}}\right].$$

$$|\delta_{\text{DM}}| \lesssim 5 \times 10^9 \times \left(\frac{1\ \text{kg}}{M_{\text{DM}}}\right)^{1/4}.$$

Sensitivity to new Yukawa interaction

- $g=\delta_{SM}\delta_{DM.}$ (maximum value of g can be 10^7)

aLIGO

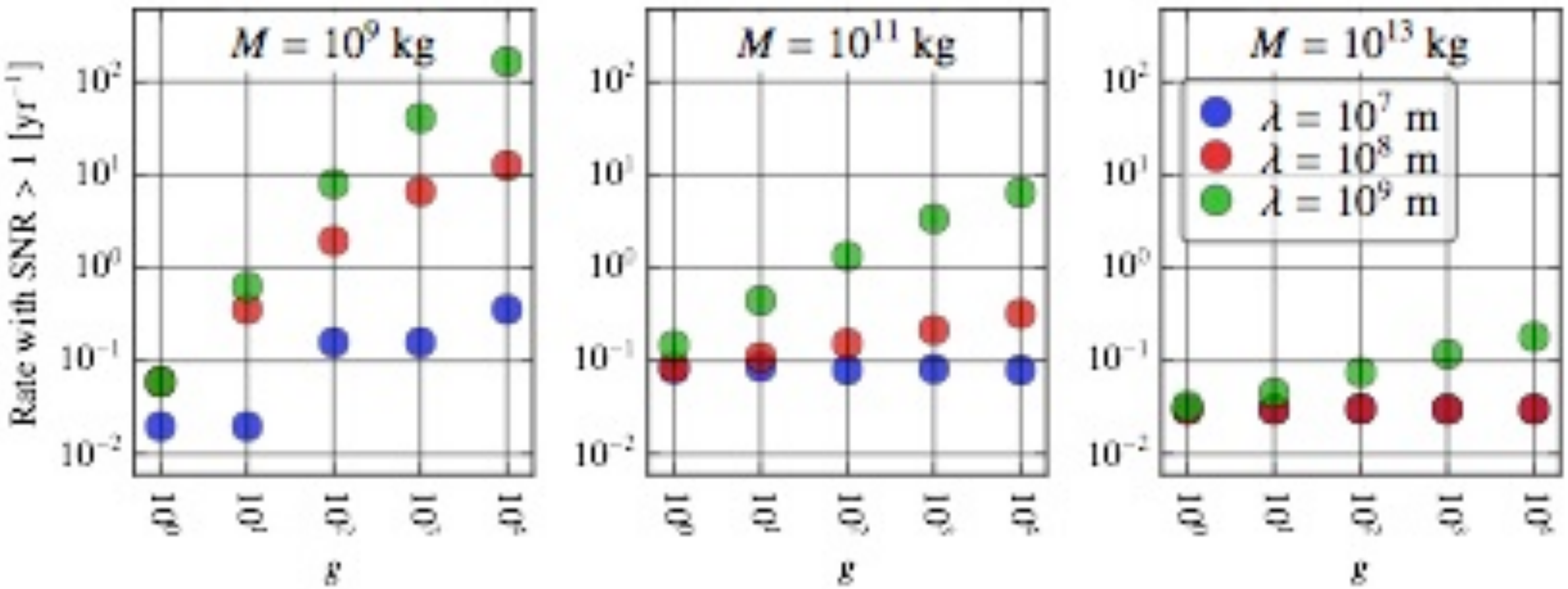


Maximal g of 10^7 can result in O(100) signal events at aLIGO.

Sensitivity to new Yukawa interaction

- $g=\delta_{SM}\delta_{DM}$

LISA



LISA event rate could be huge!

Conclusions

1. Dark matter takes 25% of the Universe's energy budget. Its identity is not known. Many theoretical possibilities for the CDM exist: WIMPs, super-WIMPs, super-cold DM, may be smth more exotic.
2. **It is important to cast as wide an experimental net as possible*, as we continue our investments in WIMP searches*
3. Progress in search of WIMPs has been remarkable, constraining or ruling out variety of models.
4. New signals of MeV dark matter can be investigated in the beam dump experiments from production and scattering.
5. Analysis of precision physics data ("Lorentz violation" searches, 5^{th} force searches) may reveal the presence of new states.
6. *Altogether different possibility*: macroscopic dark matter inducing transient signal. Advanced Ligo will have strong sensitivity.