Light dark matter

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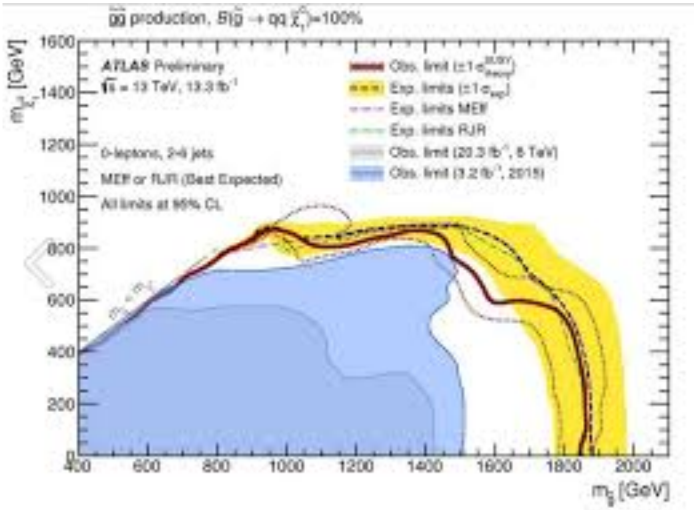
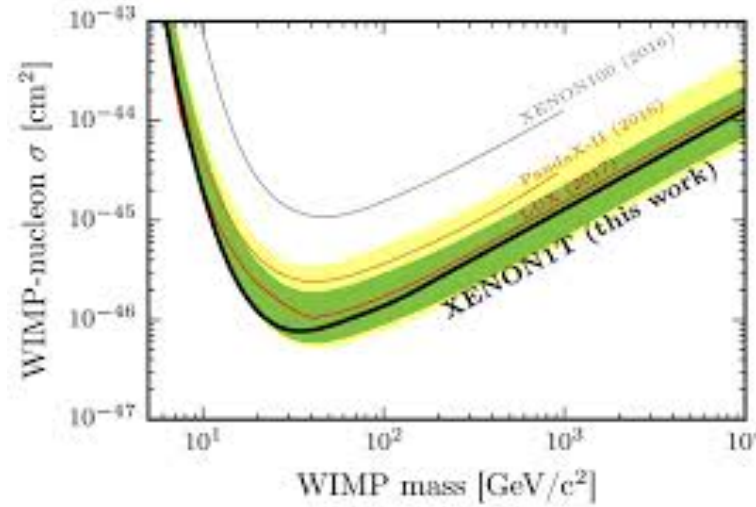
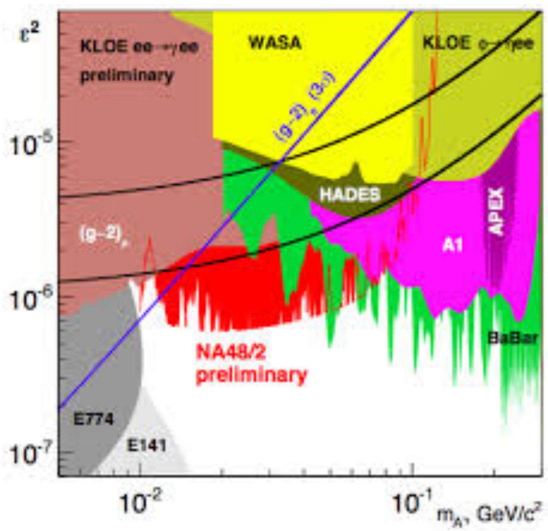
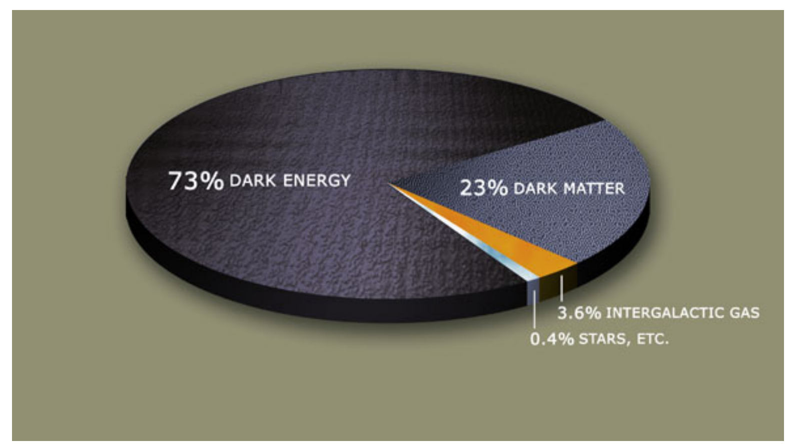
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Lots of efforts – no new physics thus far









The problem of dark matter remains not solved.

Feeling tired?

(After so many campaigns, just before being sent off to Elba)

Plan

1. Classification of light dark matter
2. Viable models of light WIMPs
3. Methods to find them

DM classification

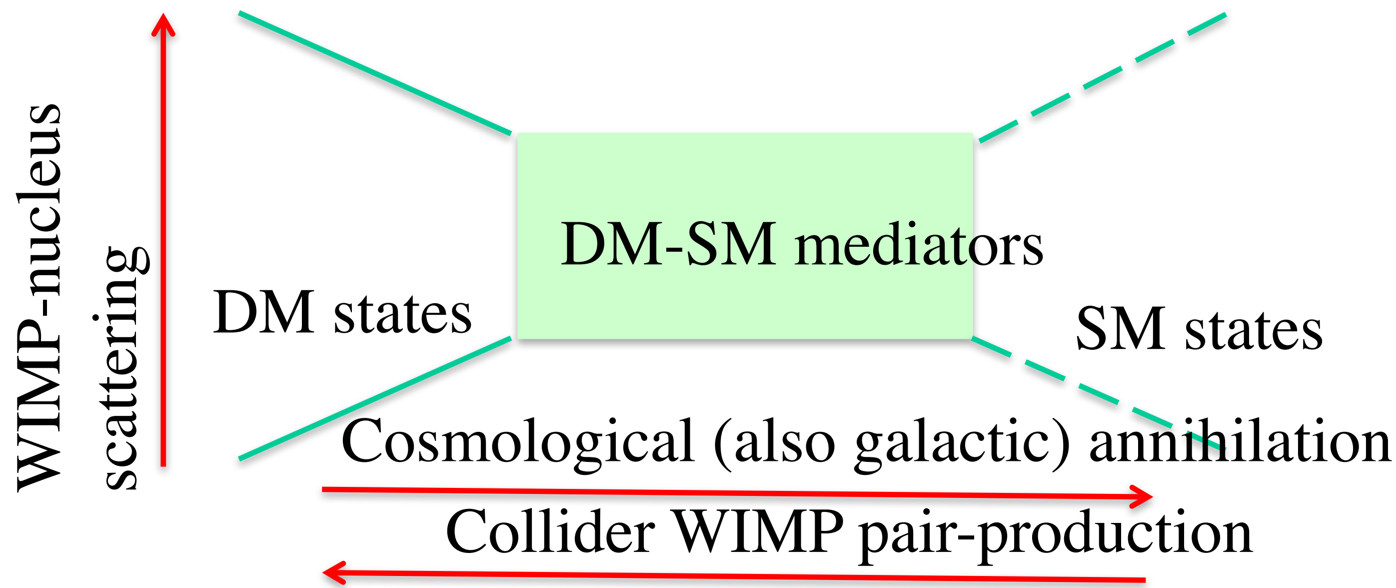
At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

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 DM is also in this category.

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 **superweakly interacting MPs**]

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**.

WIMP paradigm, some highlights



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

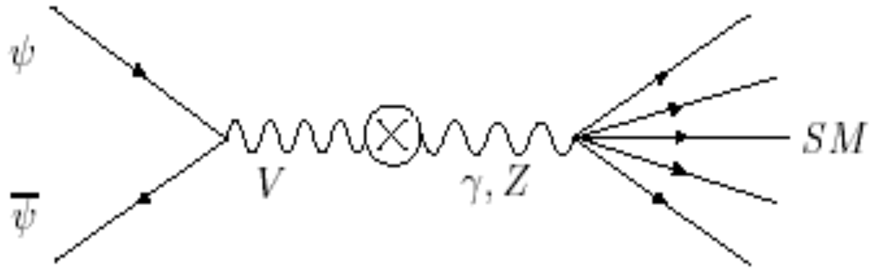
1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?

2. Do sizable annihilation cross section always imply sizable scattering rate and collider DM production? (What is the mass range?)

Two types of WIMPs

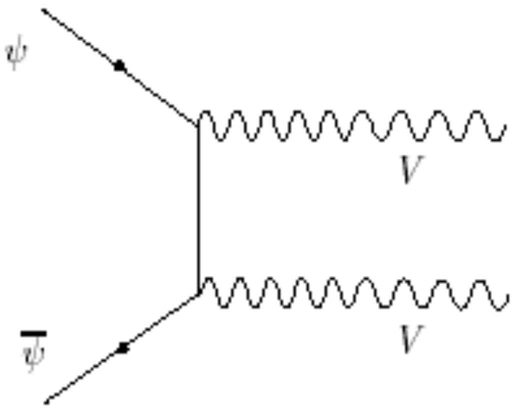
Un-secluded

MP, Ritz, Voloshin



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

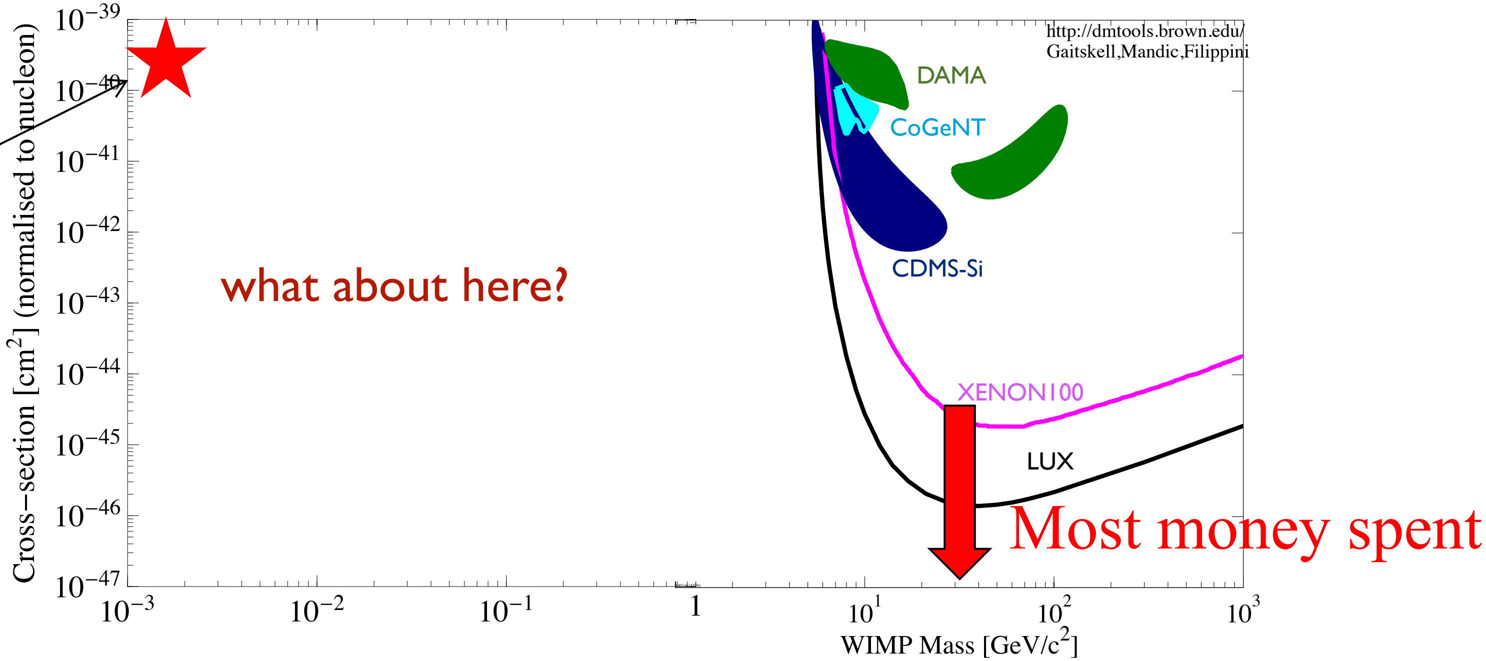
Secluded



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

Light DM – difficult to detect via nuclear recoil

511 keV motivated



- There is a large, potentially interesting part of WIMP DM parameter space that escapes constraints from DM-nuclear scattering, but is potentially within reach of other probes

- Viable models imply *the dark sector*, or accompanying particles facilitating the DM → SM annihilation. Can create additional signatures worth exploring.

Light WIMPs are facilitated by light mediators

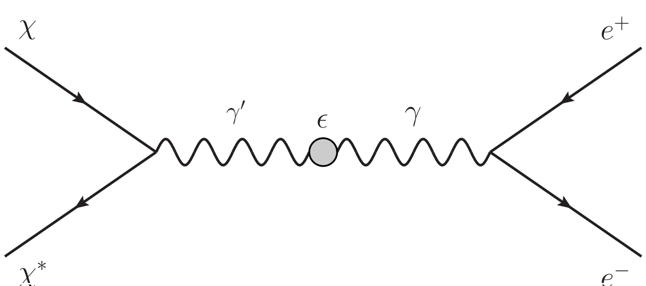
(Boehm, Fayet; MP, Riz, Voloshin …) Light dark matter is not ruled out if one adds a light mediator.

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,

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

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).



$$\sigma_{\rm annih}(v/c) \simeq \frac{8\pi\alpha\alpha_D\epsilon^2(m_\chi^2+2m_e^2)v^2}{3(m_{A'}^2-4m_\chi^2)^2}\sqrt{1-m_e^2/m_\chi^2}.$$

Light WIMP would have to interact stronger than neutrino

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)

$LH\,N$ 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

……….

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

UV complete models for light DM

two examples of viable models

- Scalar dark matter talking to the SM via a dark photon (variants: L_{mu}-L_{tau} etc gauge bosons). With $2m_{DM} < m_{mediator}$.

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 - \frac{\epsilon}{2} V_{\mu\nu} F_{\mu\nu}$$

- Fermionic dark matter talking to the SM via a "dark scalar" that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

$$\mathcal{L} = \overline{\chi}(i\partial_\mu \gamma_\mu - m_\chi)\chi + \lambda \overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - AS(H^\dagger H)$$

After EW symmetry breaking *S* mixes with physical *h*, and can be light and weakly coupled provided that coupling A is small.

- Notice how simple/economical these models are!

Two different types of annihilation

- Model 1: one step process:

$$\chi\chi^* \;\rightarrow\; \text{off shell dark photon} \;\rightarrow\; e^+e^-$$

Main signature: mediator [dark photon] can be produced in collisions and it decays to DM

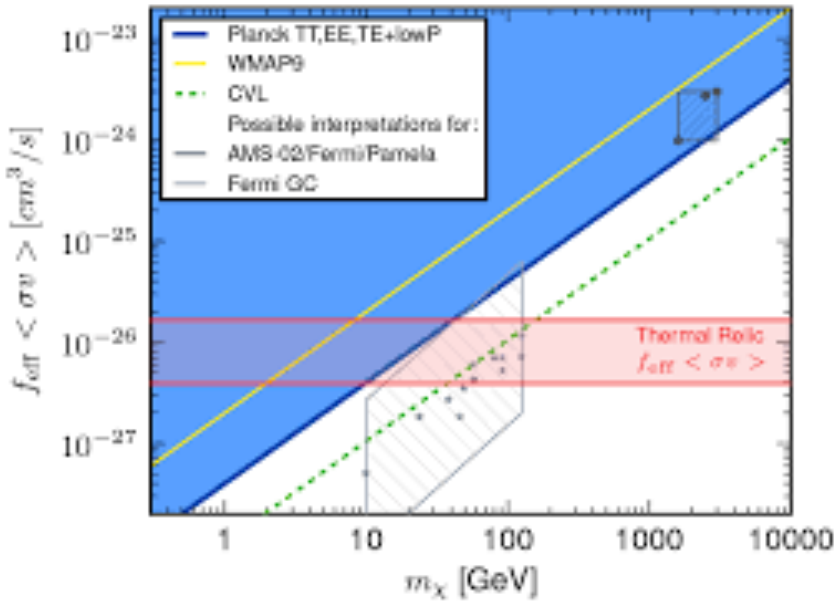
- Model 2: two-step process: annihilation to mediators with subsequent decay

$$\chi\overline{\chi} \;\rightarrow\; S+S \;\rightarrow\; \ldots \;\rightarrow\; (e^+e^-)+(e^+e^-)$$

Main signature: Production of scalar mediator in meson decays (e.g. K or B mesons) with missing energy signal [if long lived], or displaced decays.

Cosmology constraints

In both cases, the annihilation proceed in *p-wave*, and is very suppressed at the recombination time → no CMB constraints.



Thus, (few MeV – to – GeV) range is not excluded by cosmology.

Mass is limited to be > few MeV from the consistency of Big Bang Nucleosynthesis.

Anomalies? A simple concept of dark matter + mediator allows [speculatively] connecting DM to some on-going puzzles

1. Unexpectedly strong and uniform 511 keV emission from galactic bulge could be fit by annihilation of a few MeV galactic WIMPs.
2. If DM is heavy and mediator is light, one can fit its annihilation to the famous positron-to-electron ratio rise (thanks to Sommerfeld enhancement at low velocity, bound states effects, as well as lepto-phylic composition of the final states)
3. Inner density profiles of galaxies can smoothed out by the self-scattering WIMPs with $10^{-24}cm^2/GeV$. For EW scale WIMPs, light mediators can easily provide such cross section.
4. ….

These connections are all rather interesting but not necessarily compelling. We'd like a laboratory probe (Exclusion or confirmation).

How to look for light WIMP DM ?

1. Detect missing energy associated with DM produced in collisions of ordinary particles

2. Produce light dark matter in a beam dump experiment, and detect its subsequent scattering in a large [neutrino] detector

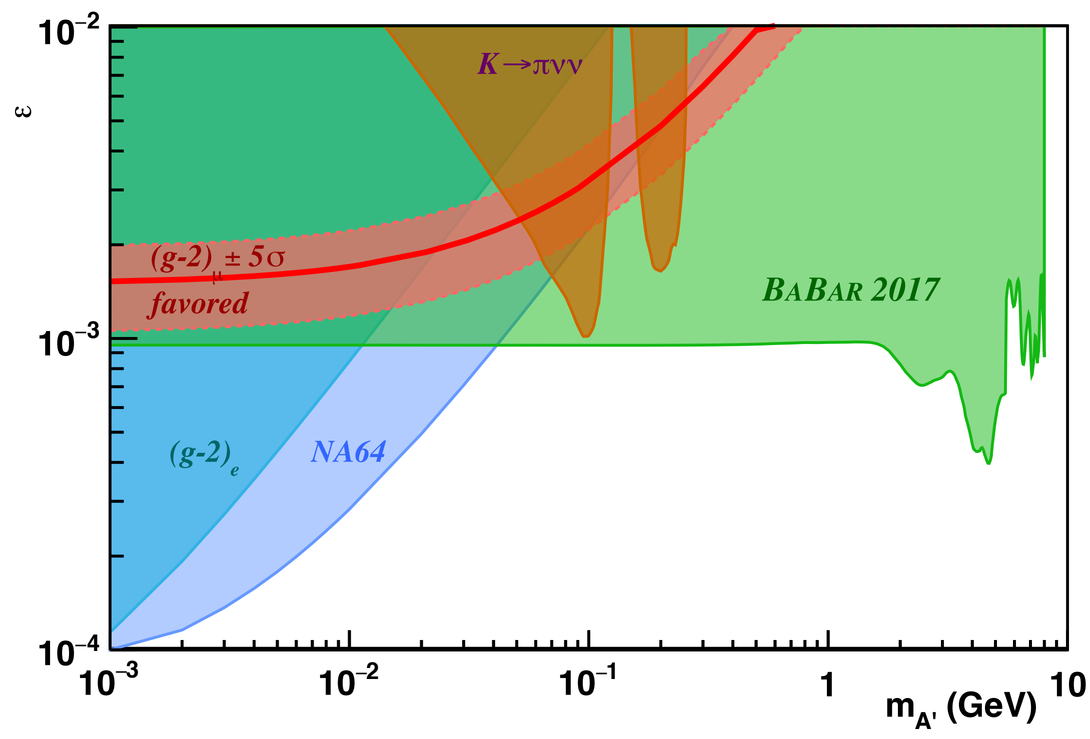
3. Detect scattering of light ambient DM on electrons, and keep lowering the thresholds in energy deposition.

All three strategies are being actively worked on, and pursued by several ongoing and planned experiments.

Missing energy/momentum searches

BaBar and NA64 collaborations has published new results this year.

Search of $e^+e^- \rightarrow \gamma + V \rightarrow \gamma + \chi\chi$

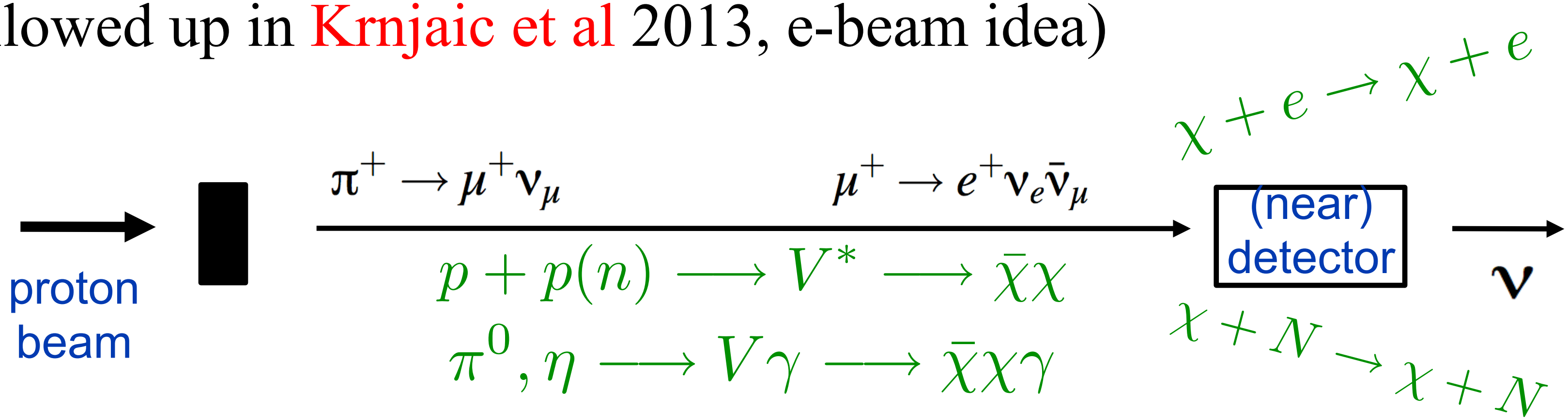


- Covers all of the dark photon parameter space, decaying invisibly, consistent with alleviating the muon g-2 discrepancy

Fixed target probes - Neutrino Beams

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

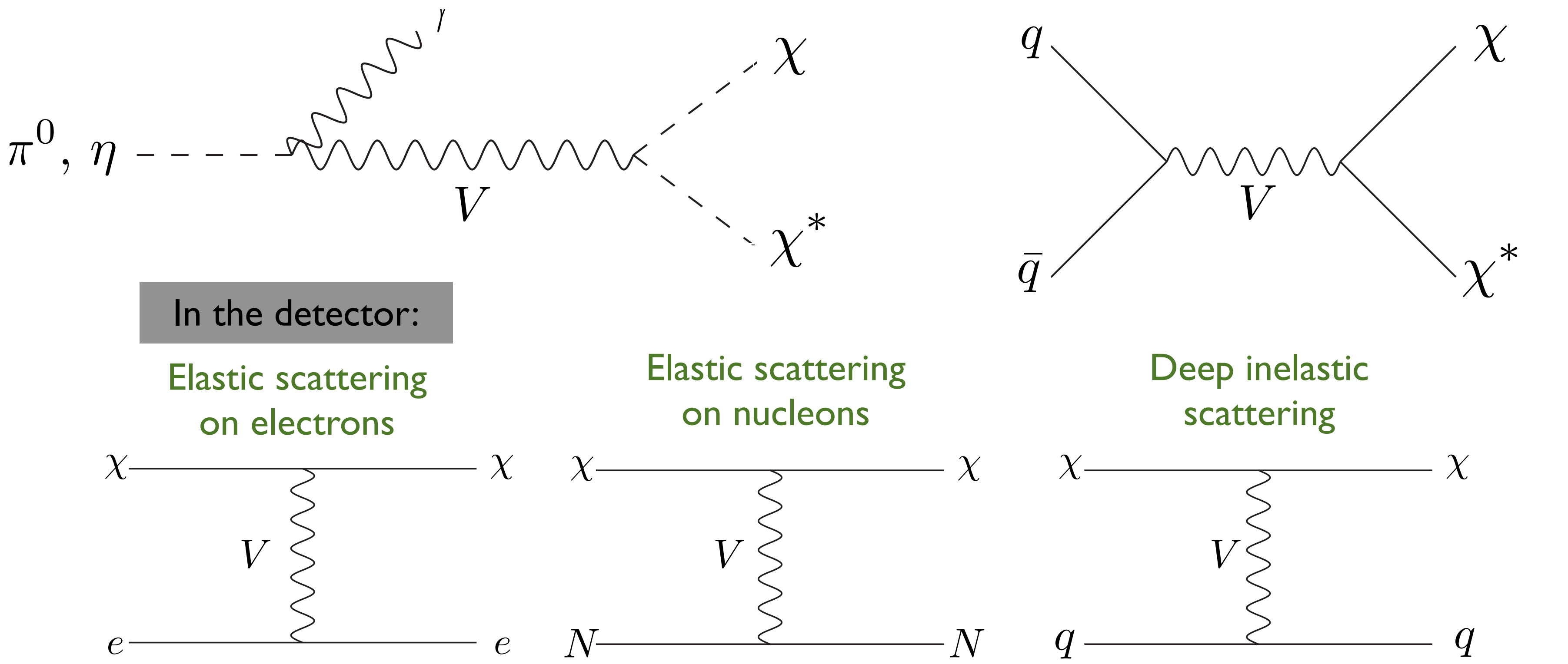
(followed up in Krnjaic et al 2013, e-beam idea)



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

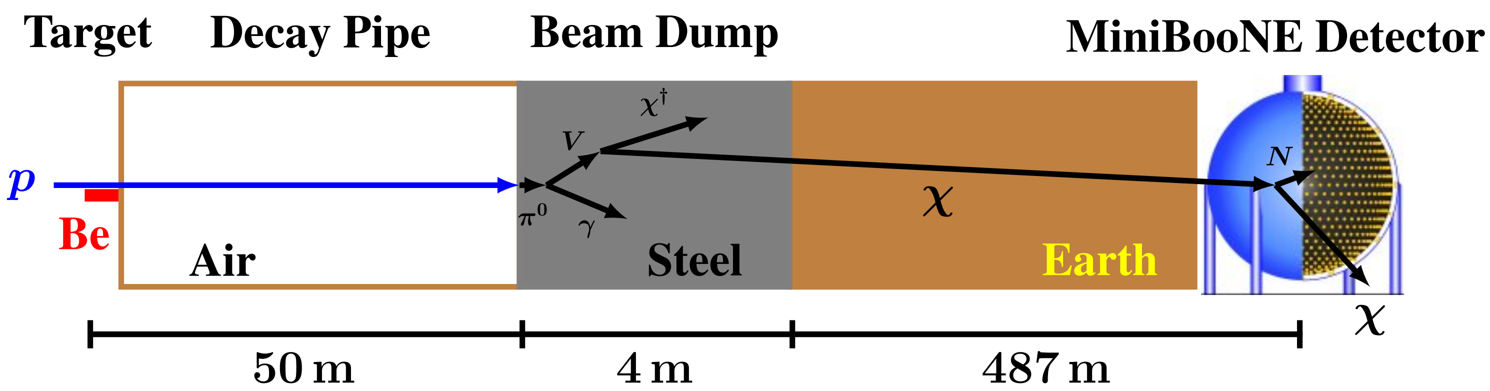
Light DM - trying to see production + scattering



Same force that is responsible for depletion of χ to acceptable levels in the early Universe will be responsible for it production at the collision point and subsequent scattering in the detector.

Signal scales as (mixing angle)^4.

MiniBooNE search for light DM



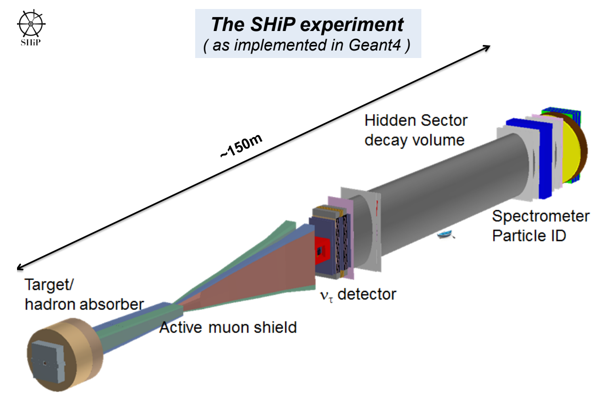
MiniBoone has completed a long run in the beam dump mode, as suggested in [arXiv:1211.2258]

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

Future directions

To improve on sensitivity to light dark matter in beam dump/fixed target experiments:

- **SHiP**



- NA64-like with more intensity (LDMX)
- More experiments at short neutrino baseline program and DUNE near detector.
- Electron beam dump + scattering (BDX)
- Ultimate beam dump experiment looking for light DM in scattering = powerful accelerator next to large neutrino detectors deep underground for least background.
- New important results in K and B decays (NA62, LHCb, BelleII)

Pushing down the sensitivity to energy deposition in direct detection

- In the last few years there has been a push to extend the sensitivity of direct detection to very light dark matter, and go below the 1 keV energy deposition scale

Ionization,
E_{th} > few eV,
10^2/kg/day/keV

Large direct detection experiments

E_{th} >1keV counting rates ~ 10^{-2}/kg/day/keV for E ~ few keV

Large neutrino experiments E_{th} >200 keV counting rates at ~ 10^{-2}/ton/day/MeV for E ~ few MeV

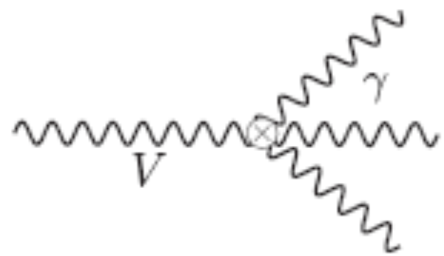
Active field of exploration, starting from

Essig, Mardon, Sorensen, Volansky …

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:



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

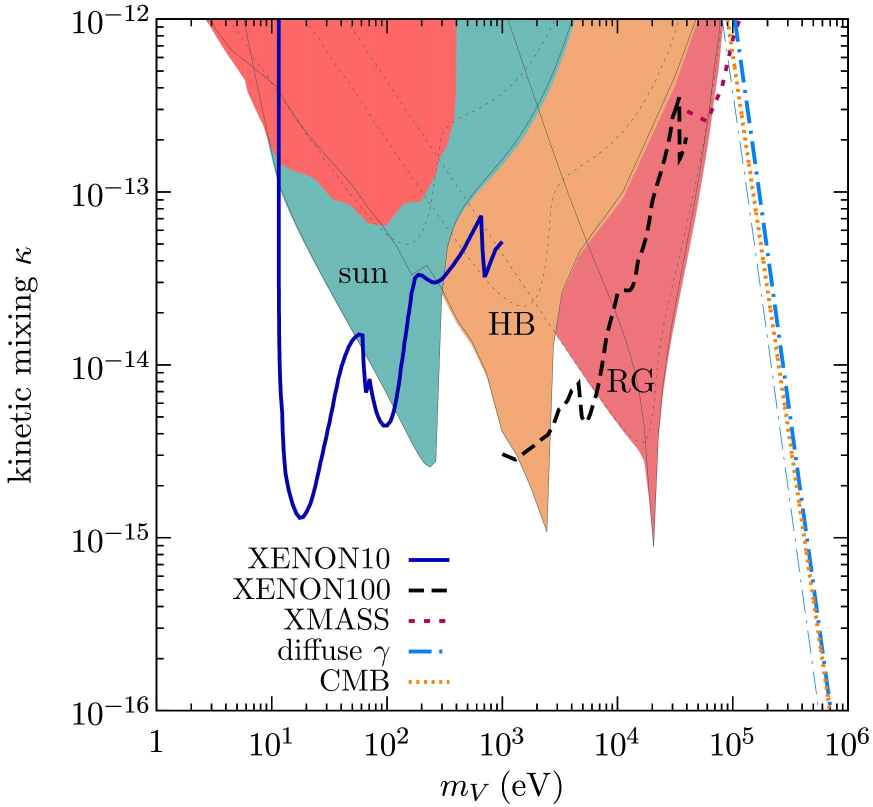
$$\tau_U \Gamma_{V\to3\gamma} \lesssim 1 \quad\Longrightarrow\quad m_V\,(\alpha')^{1/9} \lesssim 1\,\mathrm{keV}\ .$$

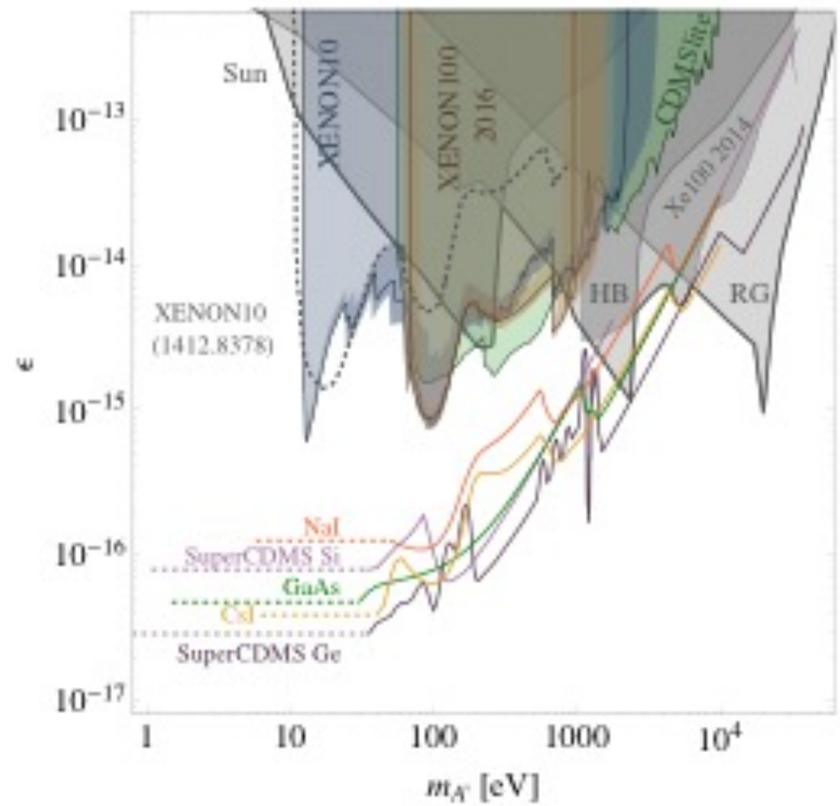
The γ-background constraints are weak. (No monochromatic lines)

Can be viable DM model: MP, Ritz, Voloshin; Redondo, Postma

“Super-WIMP” DM absorption signal

An, MP,Pradler, Ritz, PRD 2014, Bloch et al (Tian-Tian Yu)





Large DM experiments can compete with stellar constraints and have sensitivity to mixing angles down to $\varepsilon \sim 10^{-15}$. (unfortunately, $\varepsilon = 0$ is also ok)

New physics: UV or IR? (let's say IR/UV boundary ~ EW scale)

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?

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 lives completely in the IR, and no new scales are necessary*.

Both options deserve a close look. In particular, *light and very weakly coupled states are often overlooked, but deserve attention*.

Conclusions

1. Light New Physics (not-so-large masses, tiny couplings) is a generic possibility. Some models (e.g. dark photon or dark Higgs-mediated models) are quite minimal yet UV complete, and have diverse DM phenomenology.
2. Sub-GeV WIMP dark matter can be searched for via production & scattering or missing energy. New results from NA64, BaBar, MiniBoone are all less than few months/weeks old. *No signal, improved constraints*. SHiP will improve on that.
3. Search for mediators (diversifying away from dark photon) benefit significantly from flavor searches.
4. Taking direct detection below keV energy thresholds seriously allows probing sub-GeV masses of WIMPs *and* break into the super-weakly interacting DM territory probing freeze-in dark matter, absorption of DM particles etc.