Coherent scattering of “light objects” on nuclei

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Cui, Pospelov, Pradler, 2017, PRD

Bringmann, Pospelov, 2018, subm to PRL

Earlier papers with Deniverville, Batell, Ritz

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Plan

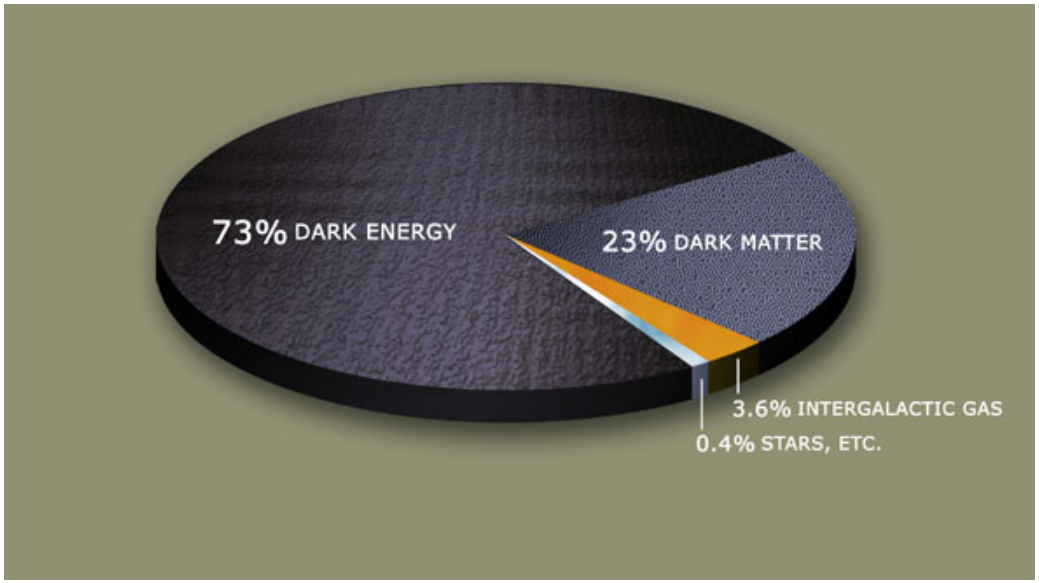
1. *Introduction.* We invest in neutrino and direct detection experiments (including CEνNS) – which are sensitive to variety of New Physics models

2. *Example 1: energetic dark radiation, neutrino or otherwise*

3. *Example 2: light dark matter accelerated to large velocities*

4. Conclusions

Cosmological surprises



Existence of dark matter and dark energy calls into question whether there are other dark components:

Dark Forces? Dark radiation?

Dark Radiation?

- ”Dark radiation” existed in the form of neutrinos. At the time of the matter-radiation equality, about 40% of radiation energy density was encapsulated by neutrinos, and is fully captured by both BBN and CMB.
- New radiation like degrees of freedom ($p_{DR} = 1/3\ \rho_{DR}$) are limited by N_{eff}. SM predicts 3.04. Current limit is 3.04 +/- 0.3. *Strong constraint on fully thermalized species*.
- New DR? If not interacting with the SM – only through N_{eff}. However, if there is interaction, we have additional ways of probing DR.

Two cases for Dark Radiation

- Case 1: numerous soft quanta (interesting for EDGES)

$$\omega_{\rm DR} \ll \omega_{\rm CMB} \ , \quad n_{\rm DR} > n_{\rm RJ} \ , \quad \omega_{\rm DR} n_{\rm DR} \ll \rho_{\rm tot} \ .$$

- Case 2: fewer hard quanta – amenable for detection with DD experiment

$$n_{\rm DR} \ll n_\gamma, \quad E_{\rm DR} \gg E_\gamma, \quad \rho_{\rm DR} (\sim E_{\rm DR} n_{\rm DR}) \leq 0.1 \rho_{\rm DM}$$

Decay of DM to dark radiation

- Scenario: A fraction of DM decays, producing fluxes of relativistic particles. DM → DR + DR, followed by DR + nucleus → recoil

- Daughter particles can be anything: neutrinos and/or other light dark states.

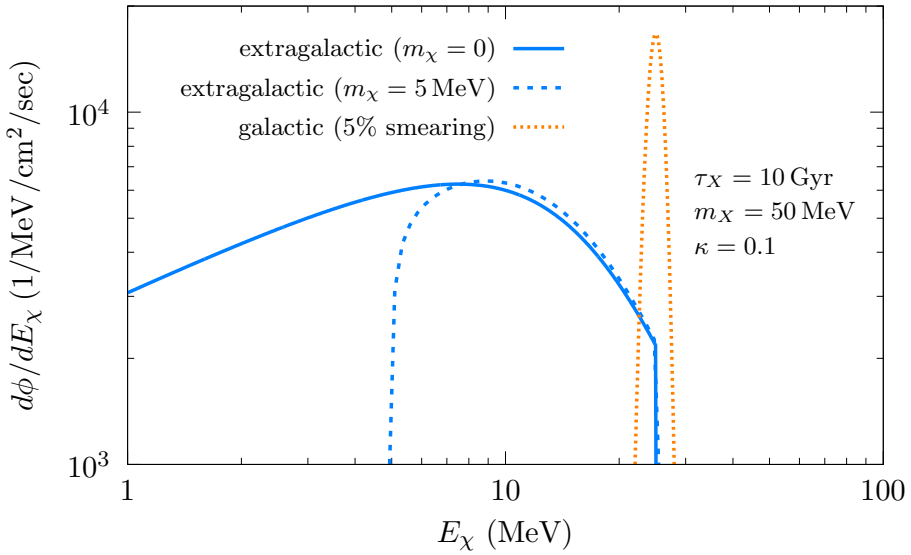
- The parameter space of such models is rather complicated:
  $\{\text{mass}_{\text{DM}}, \text{mass}_{\text{DR}}, \tau_{\text{DM}}, \text{DR interaction strength}\}$

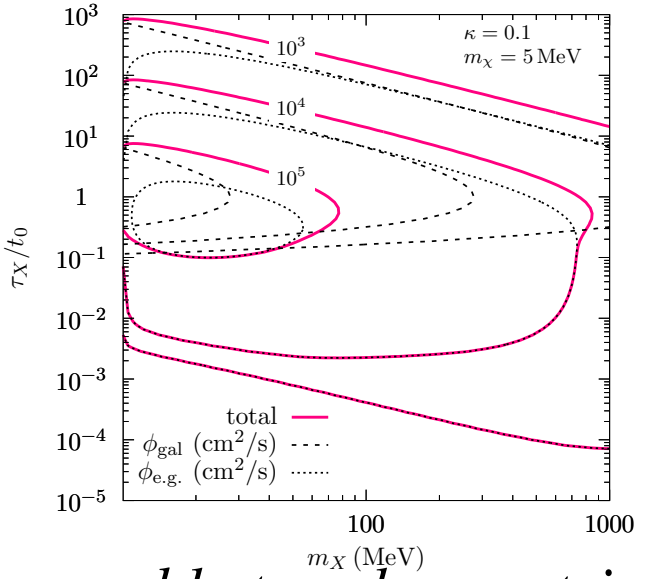
- Region of DM mass of interest for this talk – MeV to GeV

Attainable fluxes of DR.

- Scenario: A fraction of DM decays, producing fluxes of relativistic particles. DM → DR + DR

- Typical spectra has a galactic and extra-galactic component:





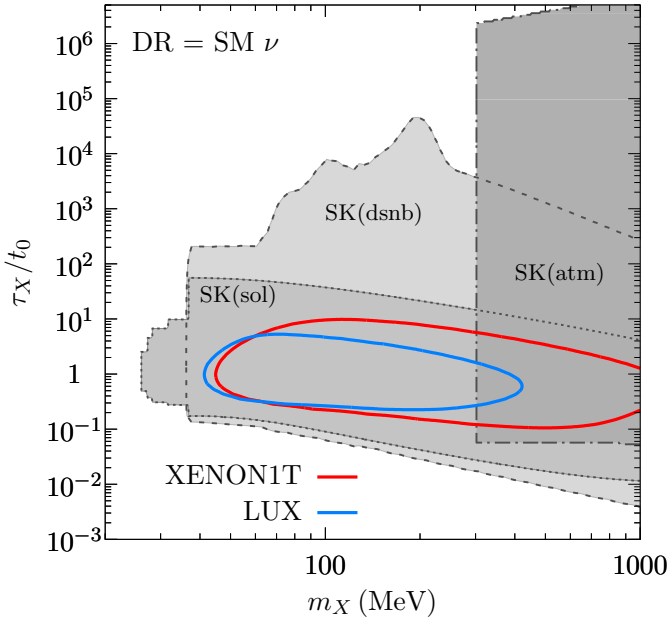
$$\phi_{\mathrm{tot}}^{\mathrm{max}} \sim \frac{10\,\mathrm{MeV}}{m_X} \times 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

- *Could be comparable to solar neutrino fluxes*, but more energetic creating DD sign.

Decay to SM neutrinos

$\{\text{mass}_{\text{DM}}, \cancel{\text{mass}_{\text{DR}}}, \tau_{\text{DM}}, \cancel{\text{DR interaction strength}}\}$

- A new population of SM neutrinos could be created by the DM decay. Constraints on electron antineutrinos by SK are very strong, but for neutrinos with E < 30 MeV the constraints are not that strong, and direct detection will soon become competitive.



- With such exotic ν DR, the "neutrino floor" is closer, at 10^{-47} cm^2.

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

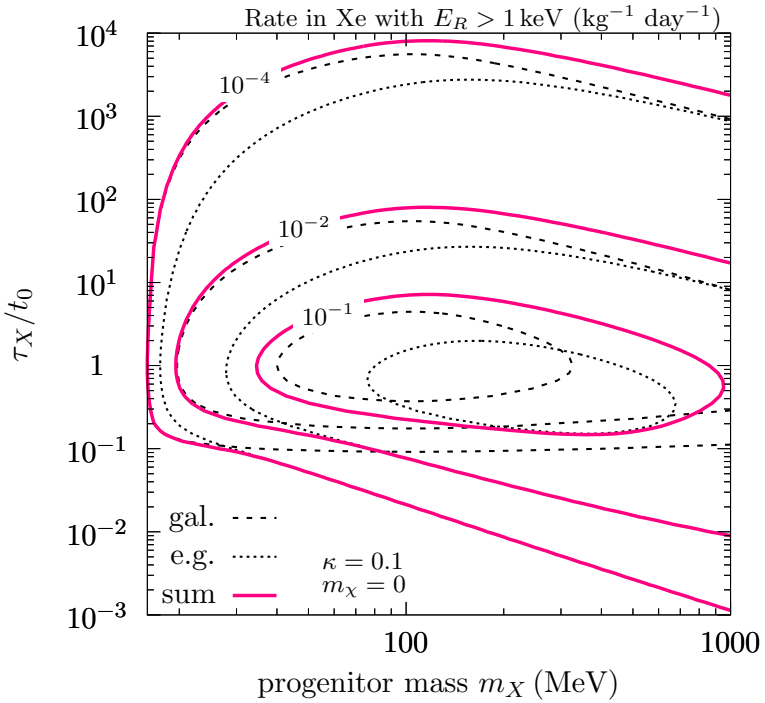
$J_\mu^{\,A}\,\partial_\mu\,a\,/f$ axionic portal

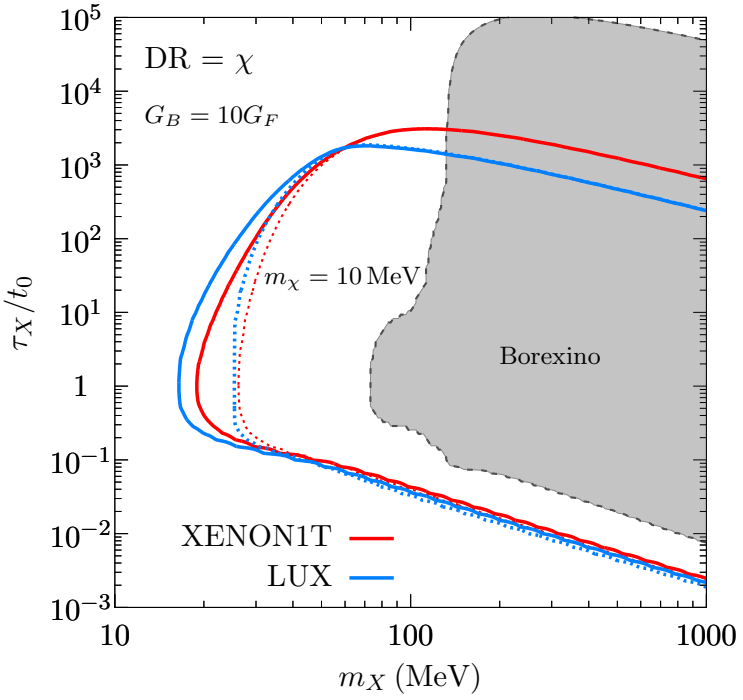
……

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

Decay to DR coupled to baryons

- A new population of fermions that interact with baryonic current could be created by the DM decay. Constraints from SK are not strong, and direct detection is the most sensitive probe:





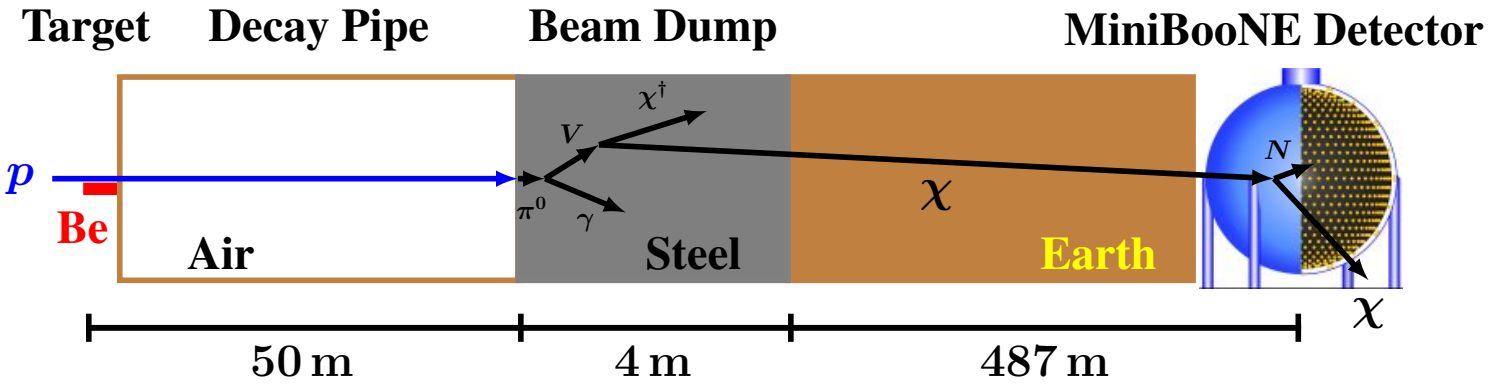
- Direct detection rates put significant constraints on models. Need more than 1 species do differentiate between DR and DM recoil.

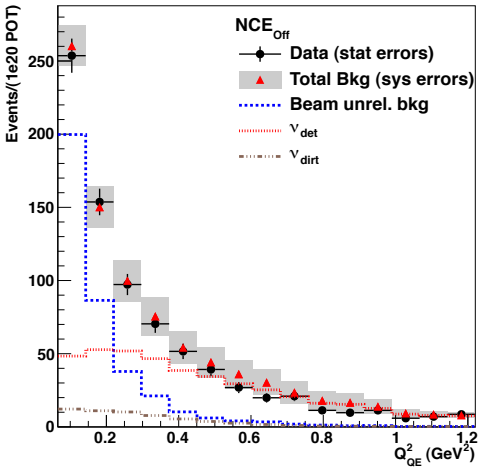
Second topic: light DM

- A limited number of concrete testable models of DM can be constructed in the sub-GeV range. (Battaglieri et al, 2017)
- On can look for it in the neutrino and beam dump experiments (Batell et al, 2009)
- Coherent neutrino scattering is a [future] way of constraining light dark matter created in beam dump (cross section is enhanced)
- There is also some merit in a less model-dependent approach, when you just look for DM within a simplified parameter space: $\{m_\chi, \sigma_\chi\}$

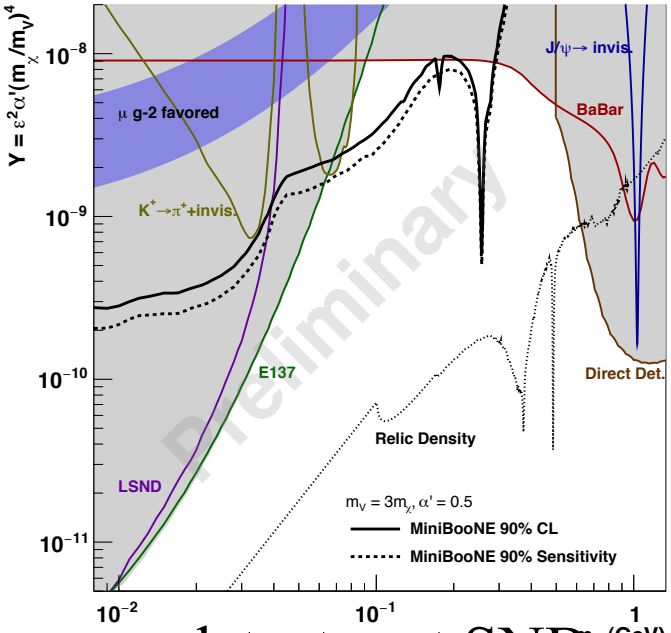
MiniBooNE search for light DM

arXiv:1702.02688, PRL 2017





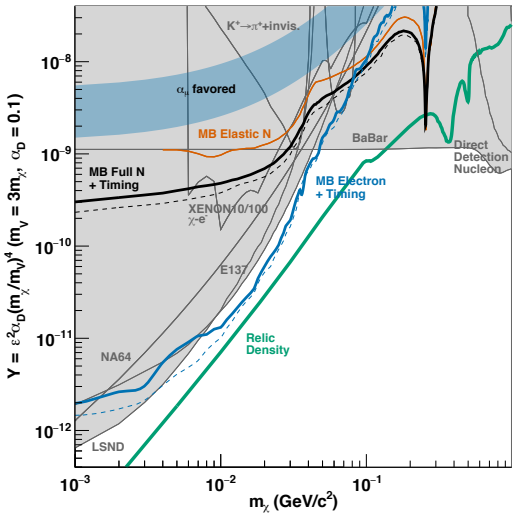
	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)



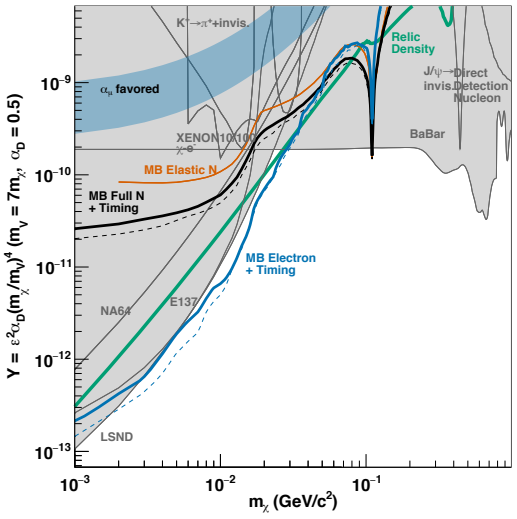
Subject to future improvement with much closer new detector at SNB

Recent results and new proposals

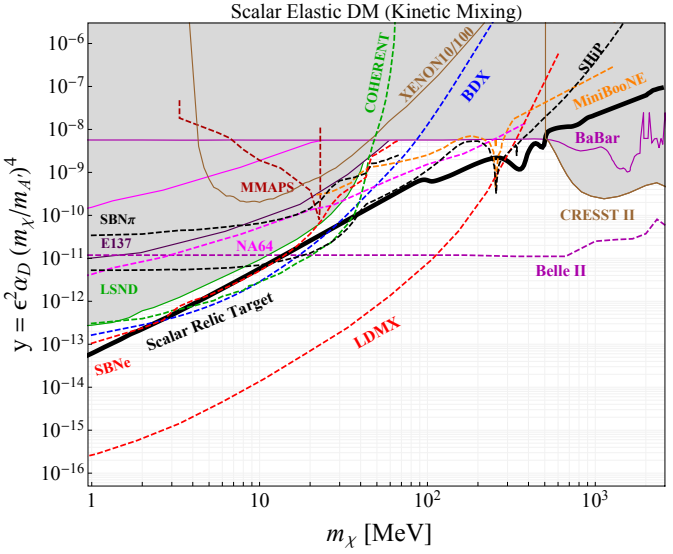
- Example from this year: MiniBoNE result of light DM search (1807.06137):
- Very expensive and versatile experiments in particle physics have already been built, or will be built (LHC, Belle-II, DUNE, Hyper-K)
- Dark sector research will be important direction for many.



(a) vector portal ($\alpha_D = 0.1, m_V = 3m_\chi$)



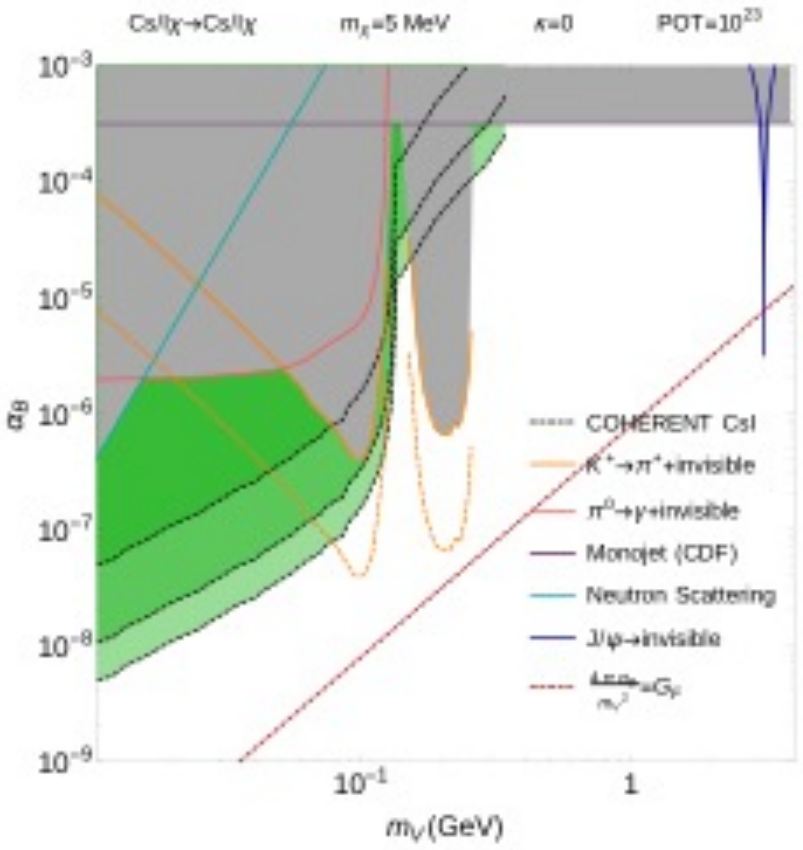
(b) vector portal ($\alpha_D = 0.5, m_V = 7m_\chi$)



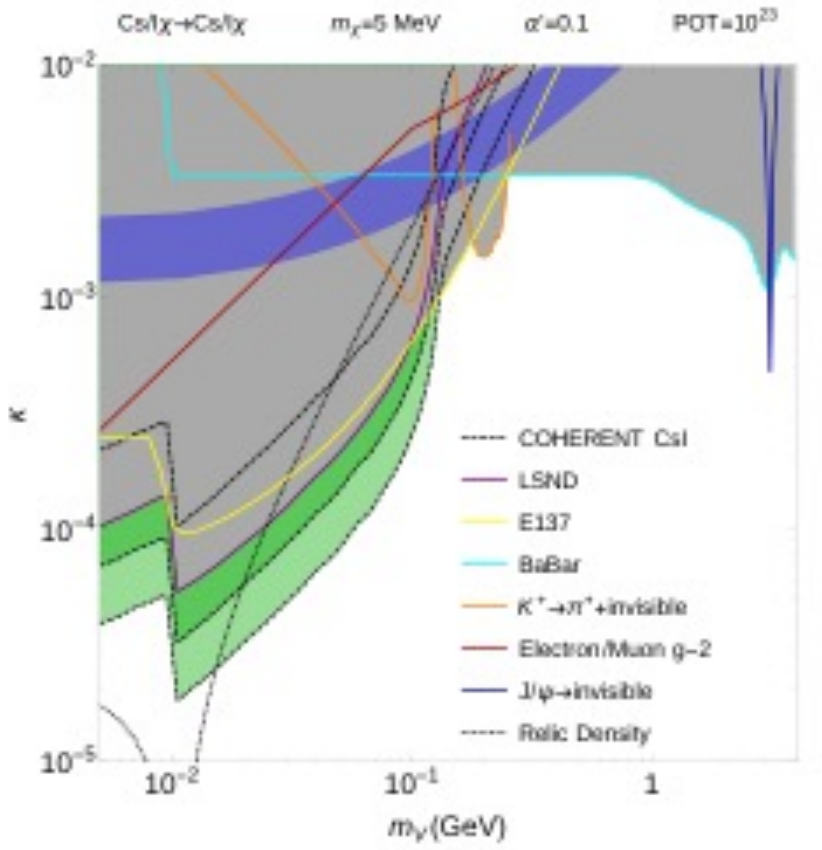
- Future LDMX-type experiments will add larger capabilities

Light DM can be searched with coherent scattering on nuclei

- Assuming 1 ton experiment, Deniverville, Pospelov, Ritz, 2015



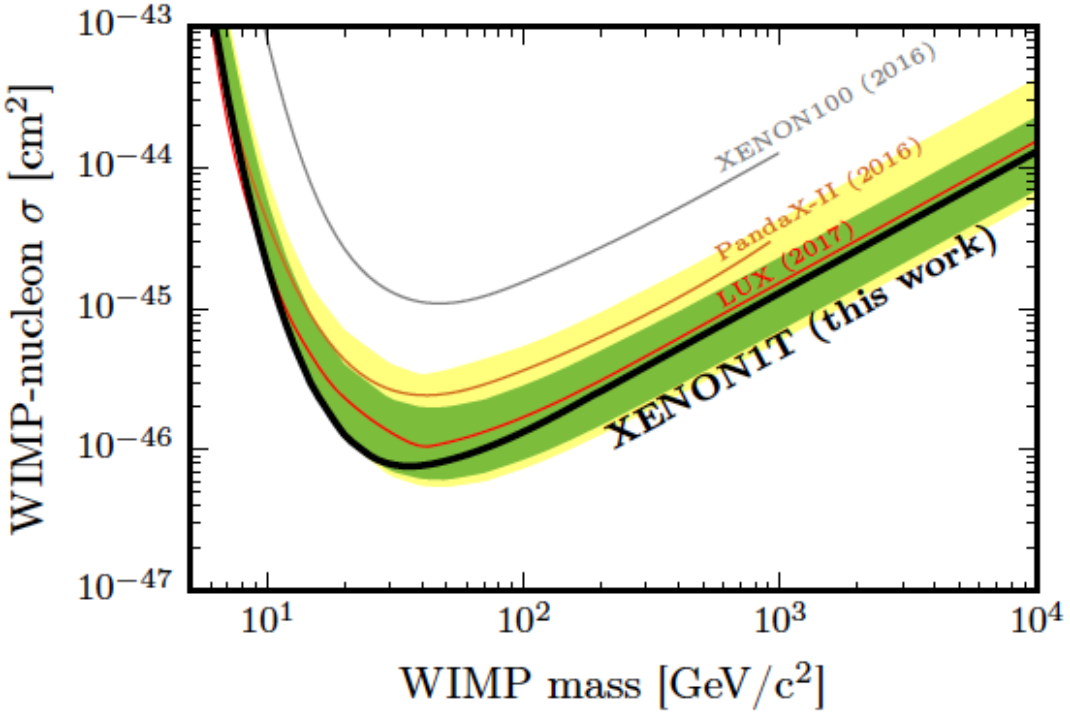
baryonic force



dark photon force

Search for WIMP-nucleus scattering
(latest LUX, XENON 1T and PANDA-X results)

What about MeV mass range ?



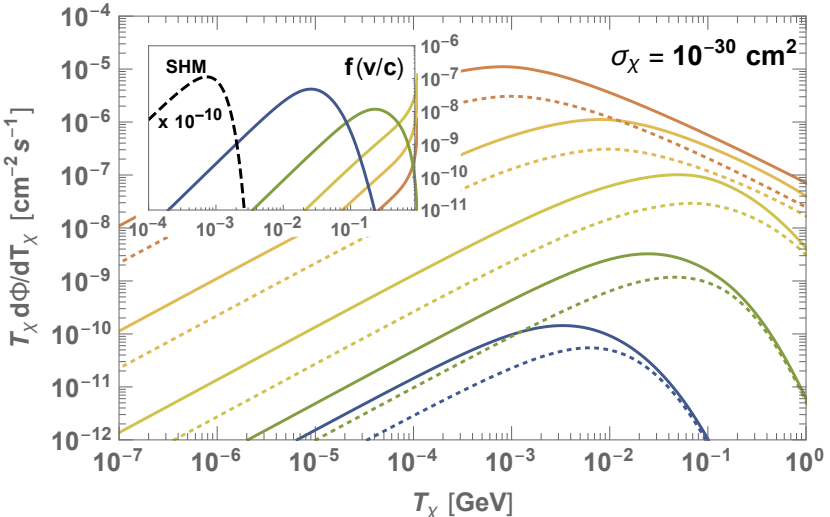
- Optimum sensitivity, $m_{WIMP} \sim m_{Nucleus}$ (a little lighter because of nuclear form factor).
- No sensitivity below m_{WIMP} ~ few GeV, due to exceedingly small recoil that does not give much light or scintillation.

Finally: light DM accelerated due to its interaction

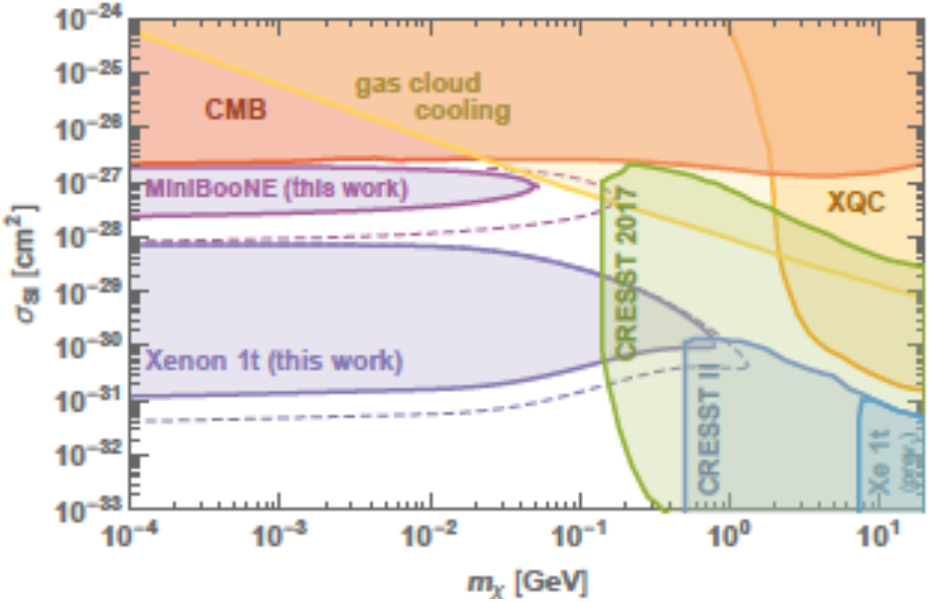
- There is always a small energetic component to DM flux (Bringmann, Pospelov, 2018). There is also some merit in a less model-dependent approach, when you just look for DM within a simplified parameter space: $\{m_\chi, \sigma_\chi\}$. Typically: MeV DM mass → keV kinetic energy → sub-eV nuclear recoils. No limits for $\sigma_{\text{nucleon-DM}}$ for DM in the MeV range.

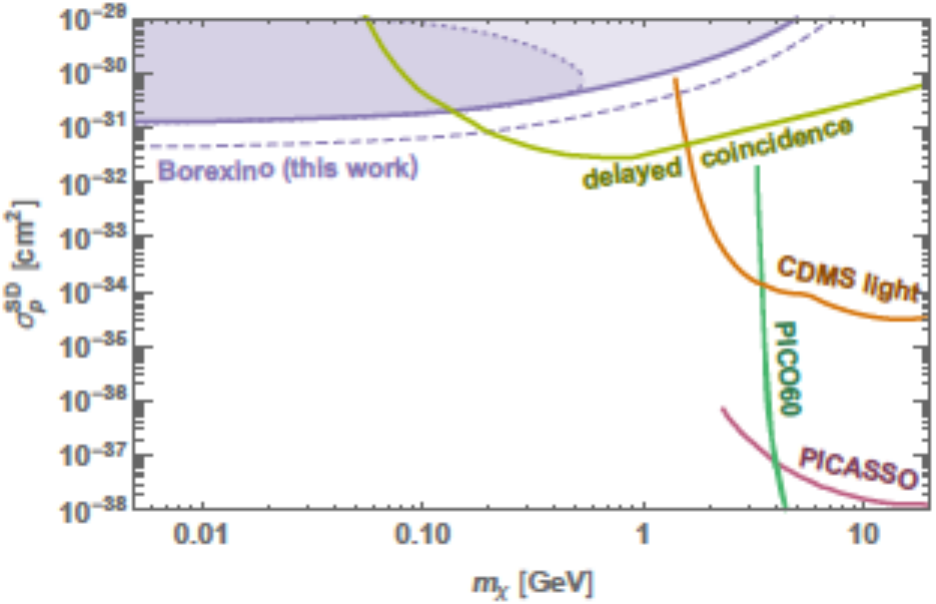
- This is not quite true because there is always an energetic component for DM, not bound to the galaxy. Generated through the very same interaction cross section: σ_χ

Main idea: Collisions of DM with cosmic rays generate sub-dominant DM flux with ~ 100 MeV momentum – perfect for direct detection type recoil.



Resulting limits





- Spin-independent limits. [Notice the constraint from Miniboone, from measurements of NC nu-p scattering]. Exclusion of $\sigma = 10^{-29}$-10^{-31}cm^2 !

- Scattering on free protons in e.g. Borexino is also very constraining for the spin-dependent scattering.

Conclusions

1. Interacting DR can be searched for in direct detection [of DM] experiments. The *maximum* strength signal from DR neutrinos will be reached relatively soon.

2. Future 1 ton experiments ~~looking for~~ measuring (!) CEνNS, can also be used for constraining very light DM created in beam dumps.

3. New limits are derived on $\{m_\chi, \sigma_\chi\}$ parameter space using subdominant energetic fraction of DM created by collisions with cosmic rays – with subsequent scattering in DM and neutrino experiments.