Direct detection of non-galactic light dark matter

arXiv:2104.04445, recently accepted in PLB

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In the meantime...can we detect non-galactic dark matter?

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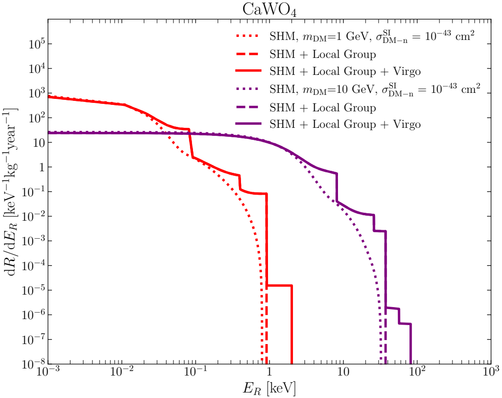
✓ Yes!



And perhaps it is the only **dark matter** that we can detect...

Outline

- **Introduction**: Light dark matter, direct detection.

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- **Standard Halo Model**: Astrophysical uncertainties.

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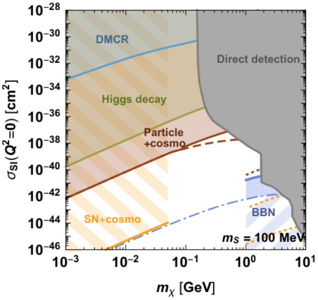
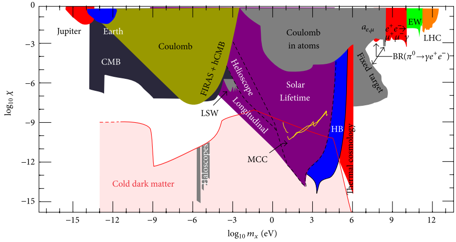
- **Standard Halo Model**: Astrophysical uncertainties.
- **Non-galactic dark matter**: Local Group, Virgo Supercluster.
- **Impact** of non-galactic dark matter in nuclear and electron recoils.

Light dark matter

- Refers to dark matter particles with masses below 1 GeV.
- Phenomenologically viable, although neglected in "traditional" WIMP models.
- It can acquire its relic abundance via freeze-out (freeze-in) for models favouring interactions with nucleons (electrons) with heavy (light) mediators.

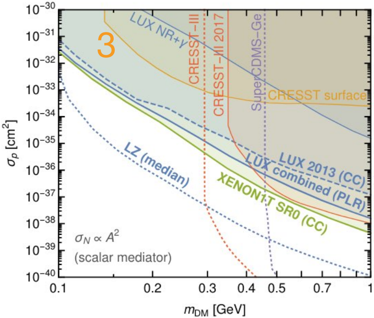


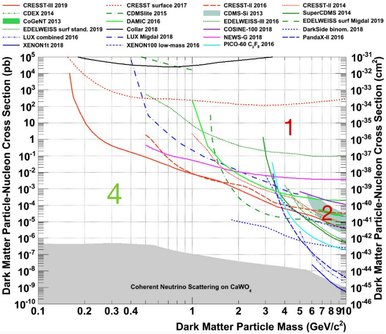
Bondarenko, Boyarsky, Bringmann, Hufnagel, Schmidt, Sokolenko, ’19



Jaeckel ’13

Dolan, Kahlhoefer, McCabe ’17





DD set **strong bounds** in the $\sigma_{\mathrm{DM-nucleon}} - m_{\mathrm{DM}}$ parameter space

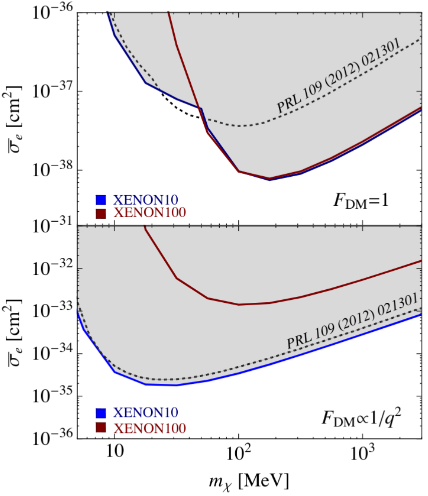
- × 1: Ruled out by several experiments
- × 2: "Islands" not compatible with other experimental results.
- × 3: Ruled out by Migdal (and Bremsstrahlung) effect.
- ✓ 4: Unexplored region!

Direct detection (electron) of light(er) dark matter

Bounds in the $\sigma_{\text{DM}-\text{electron}} - m_{\text{DM}}$ parameter space are less constraining

- **Benchmark model**: DM is charged under a hidden $U(1)$ group coupling to electrically charged particles via kinetic mixing with the SM photon

- **Two parametrizations**: A **heavy** mediator ($F_{\text{DM}} = 1$) and an **ultralight** mediator ($F_{\text{DM}} = \alpha^2 m_e^2/q^2$)



Essig, Volansky, Yu, ’17

Nuclear recoils

Differential rate of DM-induced scattering :

$$\frac{dR}{dE_R} \propto \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_{v \geq v_{min}(E_R)} d^3v\, v\, f(\vec{v}+\vec{v}_\odot) \frac{d\sigma}{dE_R}(v, E_R)$$

$$v_{min}(E_R) = \sqrt{\frac{m_A E_R}{2\mu_A^2}}$$

- **Astrophysical uncertainties**
- **Particle/nuclear physics uncertainties**

Electron recoils

Differential rate of DM-induced ionization :

$$\frac{dR^{nl}}{d\ln E_{er}} \propto \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_{v \geq v^{nl}_{\rm min}(E_{er})} \mathrm{d}^3v\, v\, f(\vec{v}+\vec{v}_\odot)\, \frac{\mathrm{d}\sigma^{nl}_{\rm ion}}{d\ln E_{er}}(v, E_{er})$$

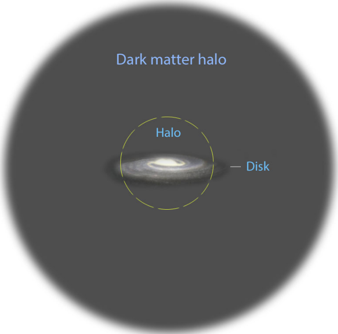
$$v^{nl}_{min}(E_{er}) = \sqrt{\frac{2}{m_{DM}}\left(E_{er} + \left|E^{nl}\right|\right)}$$

$$q^{nl}_{\substack{max\\min}}(E_{er}) = m_{DM}\, v \left[1 \pm \sqrt{1 - \left(\frac{v^{nl}_{min}(E_{er})}{v}\right)^2}\,\right]$$

- **Astrophysical uncertainties**
- **Particle/nuclear physics uncertainties**

The Standard Halo Model : Isothermal Sphere

- The equilibrium distribution of a gas of self-gravitating particles is an **isothermal sphere with density profile** $\rho \propto r^{-2}$
- The velocity distribution $f(\vec{v})$ arises as the solution to the collisionless Boltzmann-equation
- The Maxwell Boltzmann distribution is truncated at the local escape velocity of the Milky Way $v_{esc} \approx 544$ km/s



$$\rho_{\rm SHM}^{loc} = 0.3 \text{ GeV/cm}^3$$

$$f(v) \propto v^2 \exp(-v^2/2\sigma_v^2)$$

$$\sigma_v \approx 156 \text{ km/s}$$

The non-galactic dark matter flux

- The diffuse DM component of the **Local Group** could penetrate in the Milky Way, contributing $\sim$ **12**% to the local DM density
- The **Virgo Supercluster** DM particles are expected to contribute marginally $\sim$ **0.00003**%, but with large velocities

Kahn, Woltjer '59

Makarov, Karachentsev '11

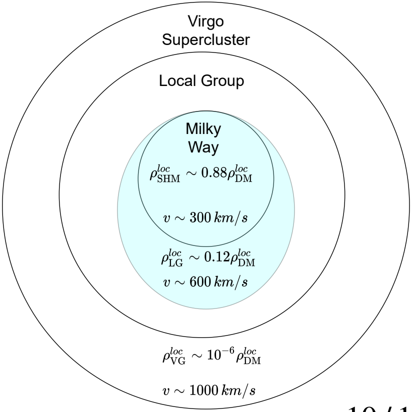
Baushev, '13

$$\mathscr{F}_{\rm SHM}(\vec{v}) = \frac{\rho^{\rm loc}_{\rm SHM}}{m_{\rm DM}} v f_{\rm SHM}(\vec{v})$$

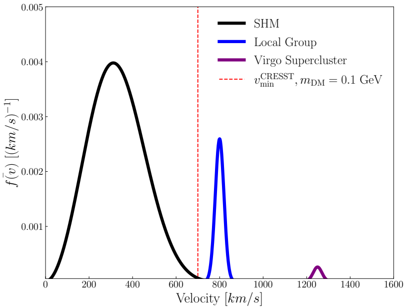
$$\mathscr{F}_{\rm LG}(\vec{v}) = \frac{\rho^{\rm loc}_{\rm LG}}{m_{\rm DM}} v \delta^3(\vec{v} - \vec{v}_{\rm LG})$$

$$\mathscr{F}_{\rm VS}(\vec{v}) = \frac{\rho^{\rm loc}_{\rm VS}}{m_{\rm DM}} v \delta^3(\vec{v} - \vec{v}_{\rm VS})$$

$$\boxed{\mathscr{F}(\vec{v}) = \mathscr{F}_{\rm SHM}(\vec{v}) + \mathscr{F}_{\rm LG}(\vec{v}) + \mathscr{F}_{\rm VS}(\vec{v})}$$

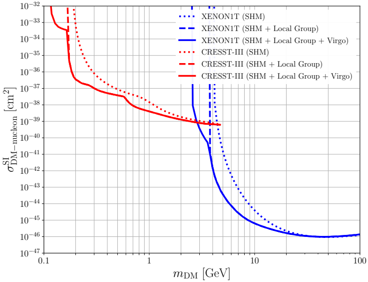


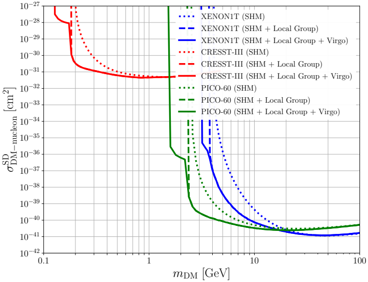
Why is the non-galactic flux important for light dark matter?



- The fraction of the DM flux observed by experiments decreases with $m_{\rm DM}$
- **CRESST-III** could be invisible to galactic DM but not to non-galactic DM !
- The kinematics of DM-electron and DM-nucleon scattering are different → we do not expect the same impact in the rates

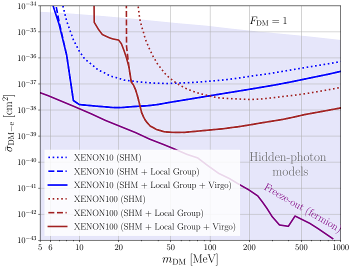
Upper limits: Nuclear recoils

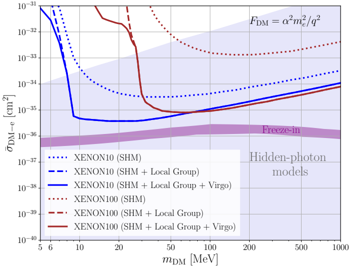




- For $m_{\rm DM}$ below ~ 1 GeV, the Local Group contribution can enhance the sensitivity of **CRESST-III** and **XENON1T** up to 3 orders of magnitude.

- The Virgo Supercluster DM extends the probed $m_{\rm DM}$ range towards lower masses.





- DM from the Local Group can enhance the sensitivity up to 2 orders of magnitude in **XENON10** and 3 in **XENON100**
- The impact is sizable far from the kinematical threshold ($m_{\mathrm{DM}} \gg m_e$)
- The impact of the non-galactic DM flux is stronger for interactions favouring a small momentum transfer ($F \sim 1/q^2$)

Four take-away messages

- Ongoing and future direct detection experiments can constrain the parameter space of light dark matter. There are various types of complementary constraints that need to be considered as well.

- The Solar System could contain dark matter particles not bound to our galaxy, but bound to larger structures wherein the Milky Way is embedded (most notably the Local Group and the Virgo Supercluster).

- The DM flux in a direct detection experiment contains particles with large speeds that can significantly enhance the signal rate, especially for light dark matter.

- A better modeling of the non-galactic components is crucial for a correct theoretical interpretation of direct detection experiments.

Thanks for your attention

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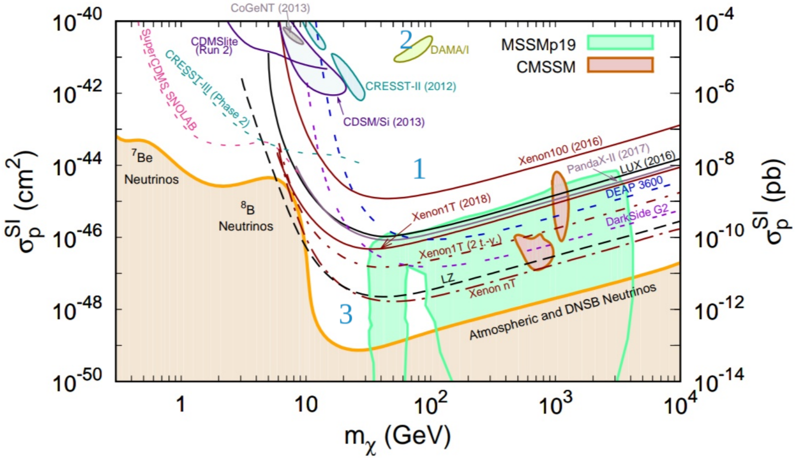
Back-up slides

Direct detection limits: High masses



Astrophysical uncertainties : The local dark matter density

Local measures: Vertical kinematics of stars near the sun (tracers)

- $\rho_{DM} = 0.46 \pm 0.1$ GeV/cm^3, Mon.Not.Roy.Astron.Soc. 478 (2018) 2
- $\rho_{DM} = 0.68 \pm 0.31$ GeV/cm^3, AA 615, A99 (2018)
- $\rho_{DM} = 0.61 \pm 0.38$ GeV/cm^3, JCAP 04 (2019) 026

Global measures : Extrapolate ρ_{DM} from the rotation curve

- $\rho_{DM} \approx 0.2 - 0.4$ GeV/cm^3, J.Phys.G 41 (2014) 063101

DM direct detection (XENON1T, CRESST-III...):

$\rho_{DM} = 0.3$ GeV/cm^3

Sub-GeV DM direct detection (SENSEI, XENON10(100)...):

$\rho_{DM} = 0.4$ GeV/cm^3

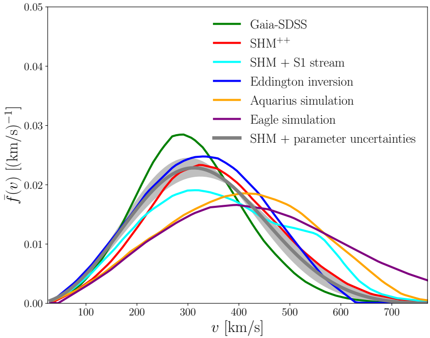
Axion experiments (ADMX, HAYSTAC...):

$\rho_{DM} = 0.45$ GeV/cm^3

This work : $\rho_{DM} = 0.3$ GeV/cm^3

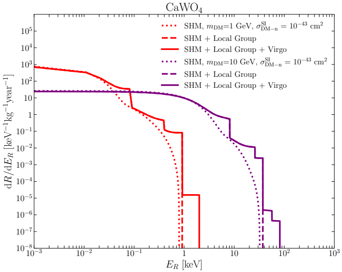
Astrophysical uncertainties: Velocity Distribution Function

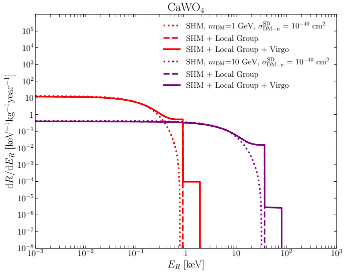
- N-body **simulations** evolve the phase space distribution of a system of DM particles from an initial power spectrum.
- Tracers **observations** infer the dark matter substructure in the Milky Way.

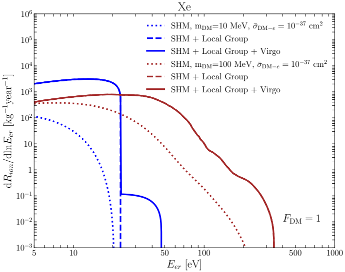


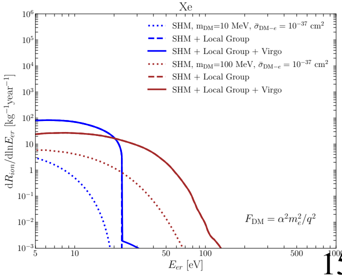
SHM is neither a good fit to **observations** nor to **simulations**

Event rate at CRESST-III and XENON1T









Hidden photons: DM cross section and form factor

- We are setting bounds on $\bar{\sigma}_e$, the non-relativistic DM-electron elastic scattering cross section at fixed momentum transfer $q = \alpha m_e$:

$$\bar{\sigma}_e = \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2} \left|\mathcal{M}_{\chi e}(q)^2\right|_{q^2=\alpha^2 m_e^2}$$

$$\left|\mathcal{M}_{\chi e}(q)^2\right| = \left|\mathcal{M}_{\chi e}(q)^2\right|_{q^2=\alpha^2 m_e^2} \times |F_{DM}(q)|^2$$

$$F_{DM}(q) = \frac{m_{A'}^2+\alpha^2 m_e^2}{m_{A'}^2+q^2}$$

How to probe light dark matter? An incomplete list...

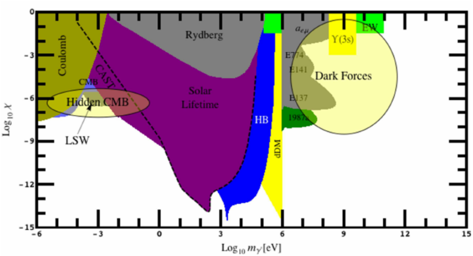
Direct detection:

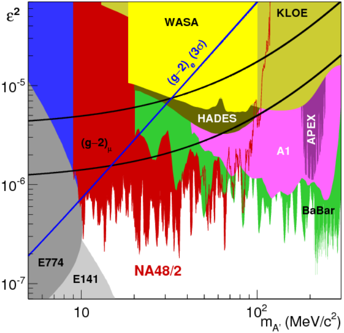
- **Nuclear recoils**
  (CRESST, CDMSlite...)
- **Electron recoils**
  (Essig, Volansky, Yu '17)
- Bremsstrahlung
  (Kouvaris, Pradler '17)
- The Migdal effect
  (Ibe, Nakano, Shoji, Suzuki '18)
- Cosmic ray dark matter
  (Bringmann, Pospelov '19)
- **Non-galactic dark matter**
  (Herrera, Ibarra '21)

Cosmology/Astrophysics/Other:

- **Dark matter relic density**
  (Lee, Weinberg '76)
- Energy losses in stars
  (Raffelt '96)
- Dark matter self interactions
  (Spergel, Steindhart '99)
- Big Bang Nucleosynthesis
  (Serpico, Raffelt '04)
- Dark matter-proton CMB
  (Gluscevic, K. Boddy '18)
- Colliders, beam dump
  (LHCb, CHARM, E949...)

Hidden photon constraints





- $m_{A'} < 1$ MeV $\rightarrow$ Astrophysical/cosmological constraints
- $m_{A'} > 1$ MeV $\rightarrow$ beam-dump, fixed-target experiments and e^+e^- colliders

The Local group envelope

- Mass of DM particles in an interval of **maximum radius** they can move (r_0) and **angular momentum** (μ):

$$\mathrm{dm{=}f(r_0)}\frac{2\mu}{\alpha^2}e^{\frac{-\mu^2}{\alpha^2}}\,d\mu dr_0$$

- The density of DM from the LG is: $\rho \propto \frac{M_{env}v_{esc}}{<\alpha>^2<T>}$

$$\alpha(r_0) = \alpha(r_{out})(\frac{r_0}{r_{out}})^i$$
$$T(r_0) = T(r_{in})(\frac{r_0}{r_{in}})^{1-\frac{j}{2}}$$

- **Velocity** of DM particles:

$$\mathrm{v}_{LG} \sim \sqrt{2(\phi(r_0) - \phi(l_\odot))}$$

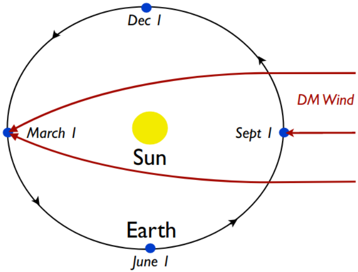
- **Velocity dispersion**:

$$\Delta v_{LG} \sim \sqrt{v_{LG}^2 + 2(\phi(r_{out}) - \phi(r_{in}))} - v_{LG}$$

Gravitational focusing

The Milky Way potential deflects the incoming DM particles from the Virgo Supercluster, increasing their density as they pass by the solar system.

The enhancement is $\sim 1 + \frac{v_{esc}^2}{v_{VS}^2}$



→ example of the gravitational focusing of the sun in annual modulation effects