Direct detection of non-galactic light dark matter

Gonzalo Herrera
gonzalo.herrera@tum.de

Technische Universität München
Max Planck Institute for Physics

In collaboration with Alejandro Ibarra

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

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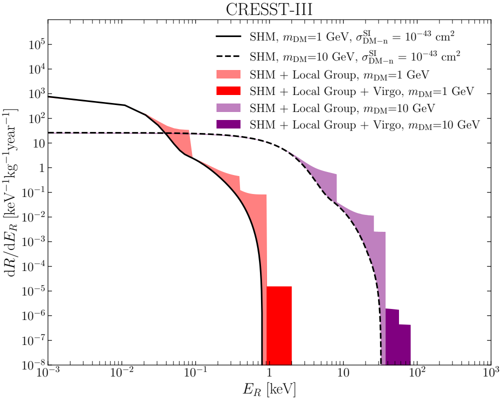
✓ Yes!



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

Outline

- **Introduction**: Evidence for dark matter, direct detection, light dark matter.

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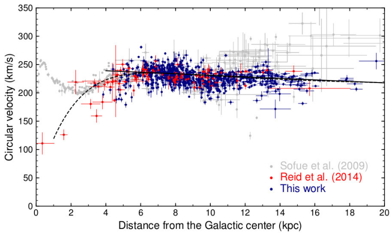
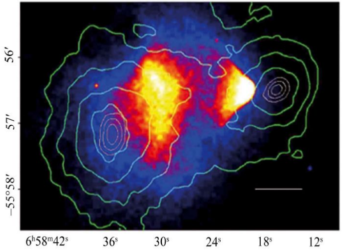
- **Introduction**: Evidence for dark matter, direct detection, light dark matter.
- **Standard Halo Model**: Astrophysical uncertainties.
- **Non-galactic dark matter**: Local Group, Virgo Supercluster.
- **Impact** of non-galactic dark matter in nuclear and electron recoils.

Evidence for dark matter

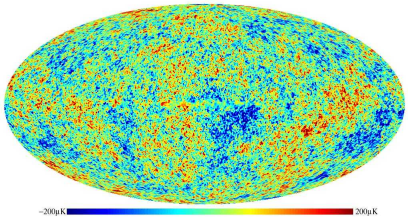
Galaxy rotation curve



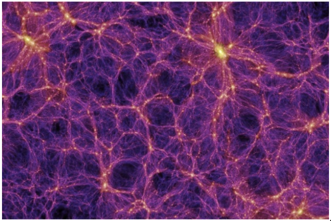
Colliding galaxy clusters



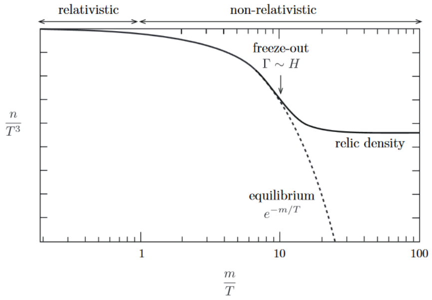
Cosmic Microwave Background

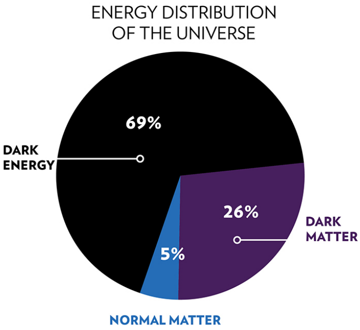


Large-scale structure



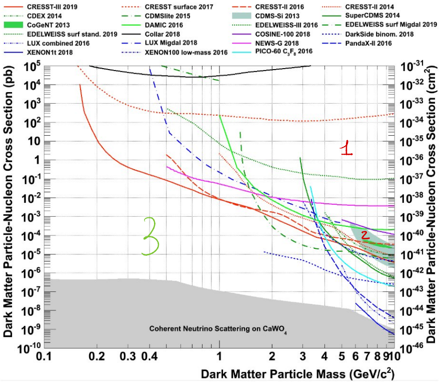
Cold Dark Matter : WIMPS





- **Dark Matter** → **WIMPS (Weakly Interacting Massive Particles)** produced thermally → Relic abundance determined by freeze-out
- **WIMP miracle** → A $\sigma_{\rm DM}$ of the weak interaction range leads to the correct DM relic abundance

Direct detection (Nuclear) : Light dark matter



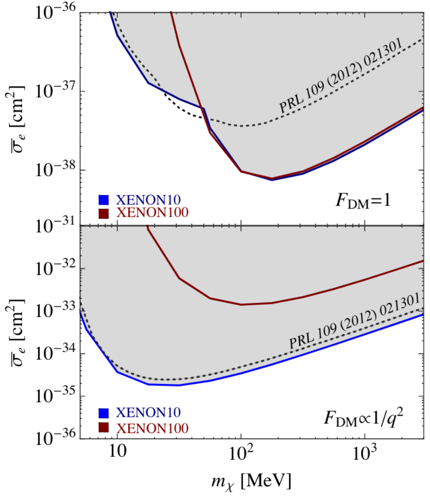
DD set **strong bounds** in the $\sigma_{\mathrm{DM-nucleon}} - m_{\mathrm{DM}}$ parameter space

- × 1: Ruled out by several experiments
- × 2: "Islands" not compatible with other experiments results.
- ✓ 3: Unexplored region, and CRESST is one of the most constraining experiments below 1.6 GeV!

Direct detection (Electron) : Light(er) dark matter

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

- DM in the **MeV** range challenges the standard WIMP
- **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 a **light** mediator ($F_{\text{DM}} = \alpha^2 m_e^2/q^2$)



Essig, Volansky, Yu, '17

Nuclear recoils

Differential rate of DM-induced scattering :

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

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

Electron recoils

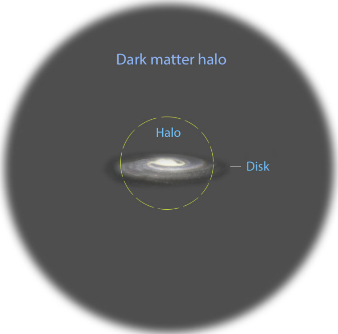
Differential rate of DM-induced ionization :

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

- **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



$$\rho^{loc}_{\text{SHM}} = 0.3 \text{ GeV/cm}^3$$

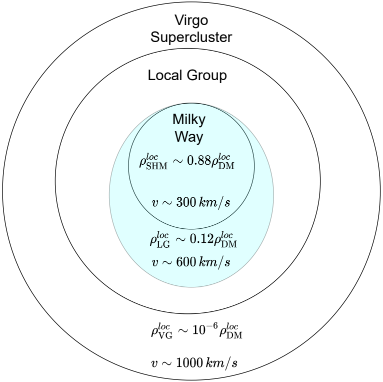
$$f(v) \propto v^2 \exp(-v^2/2\sigma_v^2)$$

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

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

Baushev, ’13



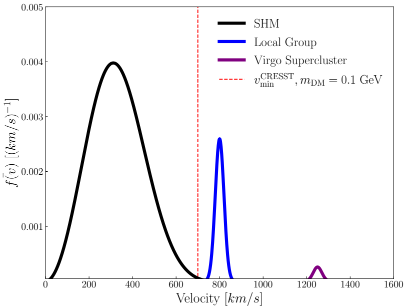
$$\mathcal{F}_{\rm SHM}(\vec{v}) = \frac{\rho^{\rm loc}_{\rm SHM}}{m_{\rm DM}} v\, f_{\rm SHM}(\vec{v})$$

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

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

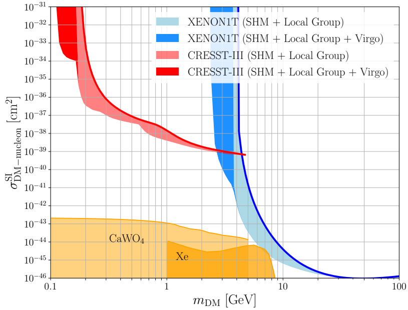
$$\boxed{\mathcal{F}(\vec{v}) = \mathcal{F}_{\rm SHM}(\vec{v}) + \mathcal{F}_{\rm LG}(\vec{v}) + \mathcal{F}_{\rm VS}(\vec{v})}$$

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



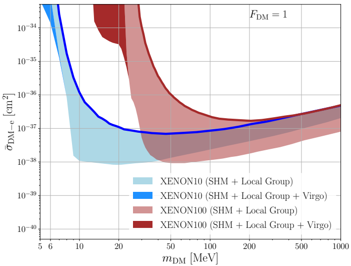
- The fraction of the DM flux observed by experiments decreases with $m_{\rm DM}$
- **CRESST-III** could be invisible to galactic DM but not to non-galactic DM !
- The kinematics of DM-electron and DM-nucleon scattering are different $\rightarrow$ we do not expect the same impact in the rates

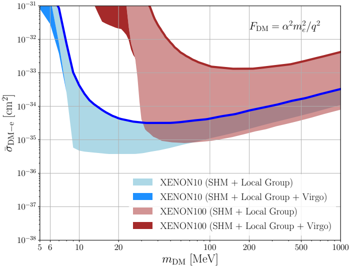
Upper limits: Nuclear recoils



- For m_{DM} below $\sim$ 10 GeV, the Local Group contribution can enhance the sensitivity of **XENON1T** up to 4 orders of magnitude, even grazing the neutrino floor
- For **CRESST-III**, the enhancement is similar near the kinematical threshold $m_{DM} \sim 0.2$ GeV
- The Virgo Supercluster DM extends the probed m_{DM} range

Upper limits: Electron recoils





- 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 ($m_{\rm DM} \gg m_e$)
- The impact of the non-galactic DM flux is stronger for interactions favouring a small momentum transfer ($F \sim 1/q^2$)

Three take-away messages

- 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

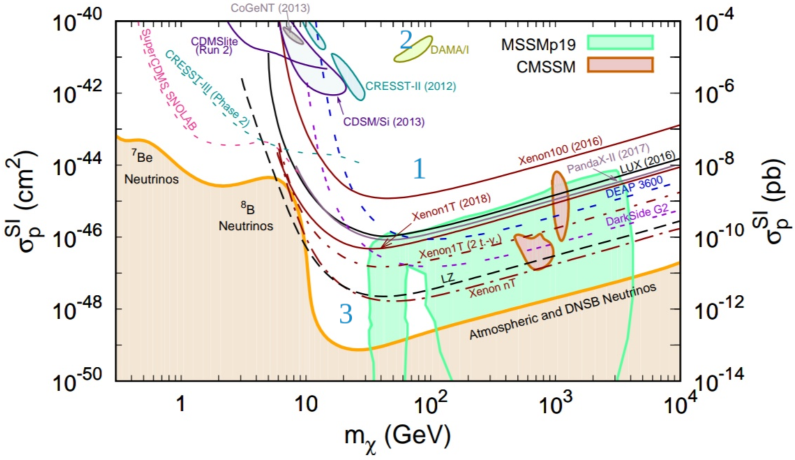
- A better modeling of the non-galactic components is crucial for a correct theoretical interpretation of direct detection experiments.

Thanks for your attention

gonzalo.herrera@tum.de

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)

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

Global measures : Extrapolate $\rho_{\rm DM}$ from the rotation curve

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

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

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

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

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

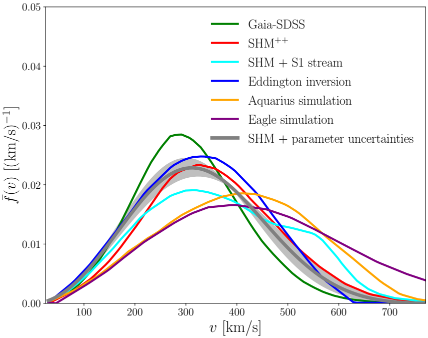
Axion experiments (ADMX, HAYSTAC...):

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

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

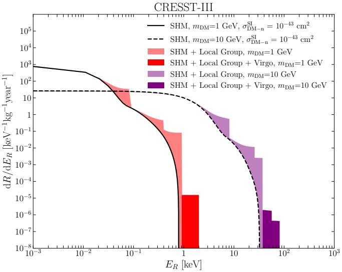
Astrophysical uncertainties: Velocity Distribution Function

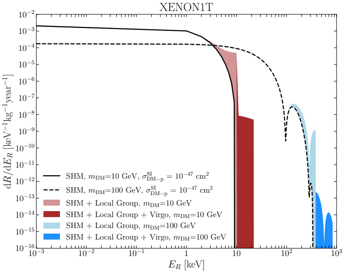
- N-body **simulations** evolve the phase space distribution of a system of DM particles from an initial power spectrum.
- Tracers **observations** infer the dark matter substructure in the Milky Way.

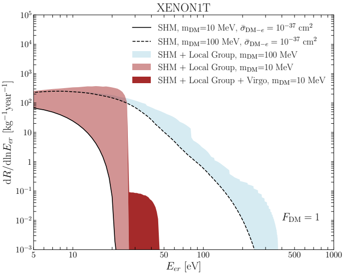


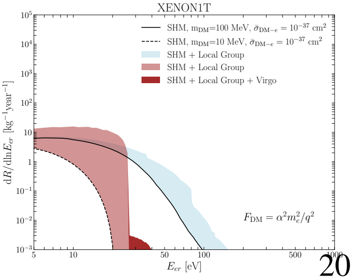
SHM is neither a good fit to **observations** nor to **simulations**

Event rate at CRESST-III and XENON1T

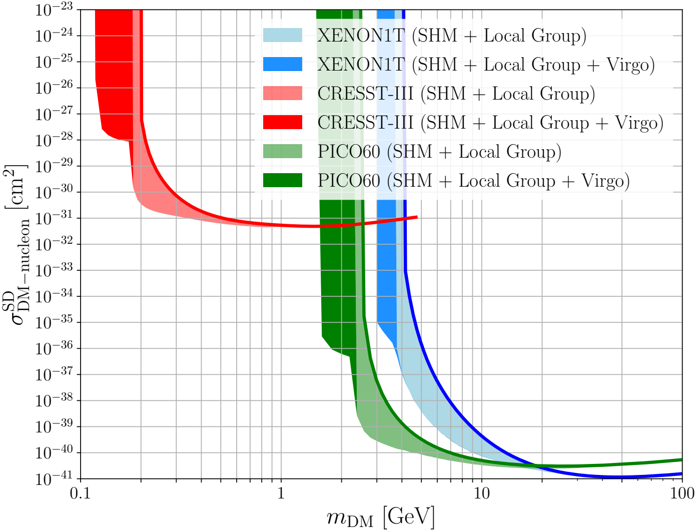








Upper limits: Nuclear recoils (SD)



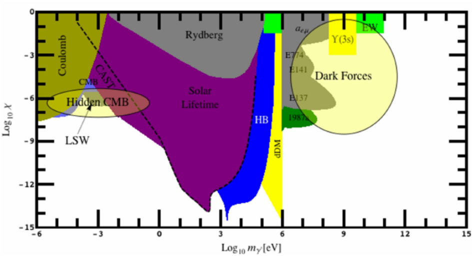
- We are setting bounds on $\bar{\sigma}_e$, the non-relativistic DM-electron elastic scattering cross section at fixed momentum transfer $q = \alpha m_e$:

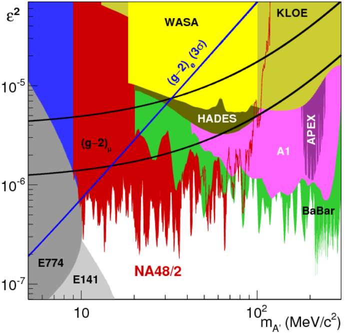
$$\bar{\sigma}_e = \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2} \left|\mathcal{M}_{\chi e}(q)^2\right|_{q^2=\alpha^2 m_e^2}$$

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

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

Dark 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 Milky Way envelope modeling

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

$$\text{dm=f(r}_0\text{)}\frac{2\mu}{\alpha^2}e^{\frac{-\mu^2}{\alpha^2}}d\mu dr_0$$

- 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:

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

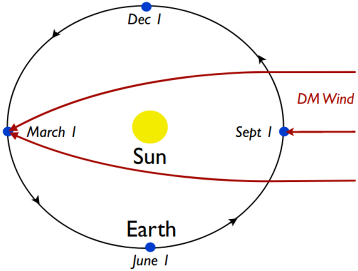
- **Velocity dispersion**:

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

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.

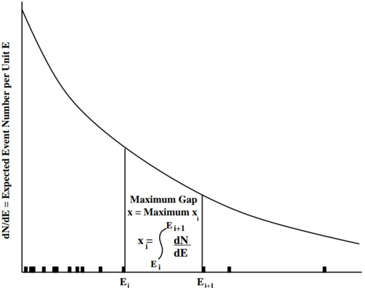
The enhancement is $\sim 1 + \frac{v_{esc}^2}{v_{VS}^2}$



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

CRESST Limits: The Yellin Methods

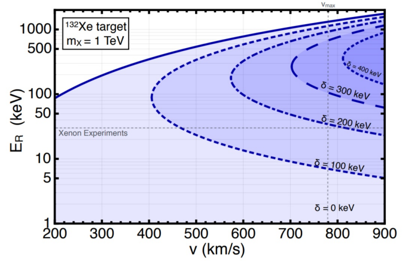
- **Backgrounds are not known a priori**
- **Maximum gap**: A cross section σ is excluded as being too high if most random experiments would give smaller maximum gaps $\rightarrow$ Function $C_0(x, \mu)$ that equals the desired **confidence**
- Extension to **Optimum interval** method $\rightarrow$ consider all integrals with 1,2,..n_{obs} events, new $C_n(x_n, \mu)$ obtained via Monte Carlo
- **Frequentist method !**

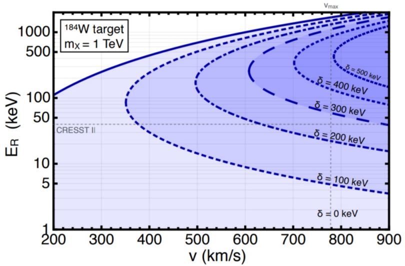


Different kinematics : Inelastic DM

- In some models Dark Matter can interact inelastically with nucleai accesing an excited state with mass splitting δ
- Minimal velocity to induce a recoil: $v_{min} = \sqrt{\frac{2\delta}{\mu}}$

(arXiv:1608.02662)





$v_{min,Xe}(E_R) = 392 km/s$

$v_{min,W}(E_R) = 340 km/s$

Experiments are only sensitive to the high velocity tail for IDM