LOOKING FOR DARK MATTER: USUAL AND UNUSUAL WAYS

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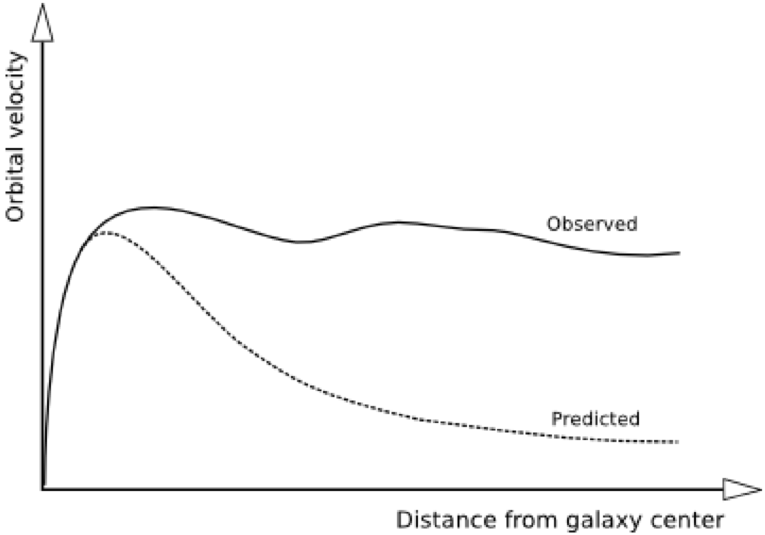
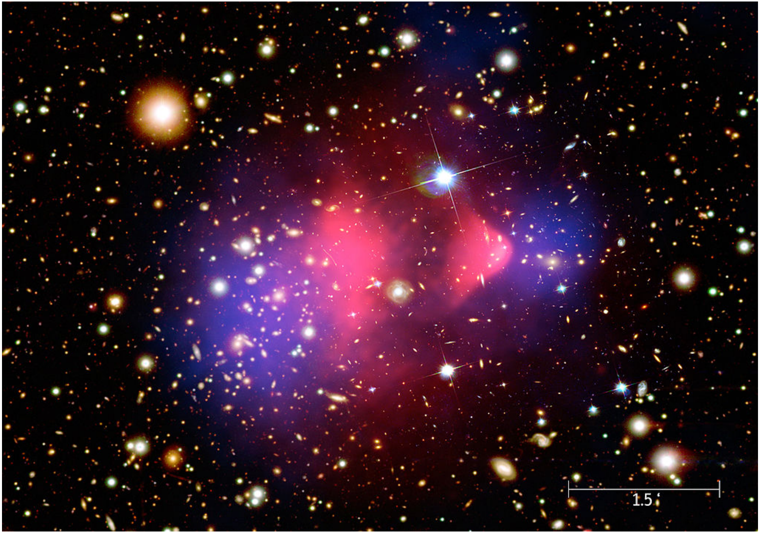
- *Gravitational lensing in bullet clusters etc.....*
- *Observation of photons, excess positrons, excess in galactic antiproton/proton ratio....*

Galactic rotation: the first evidence of dark matter...



$$mv^2/r = GMm/r^2$$

Bullet cluster: hint that dark matter is made of particles...



Proposed particle dark matter scenarios constrained by/expected to be reflected in...

- *Relic density (unaccounted mass)*
  (For thermal DM, Boltzmann transport equation
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- *Various other astro-cosmo data*

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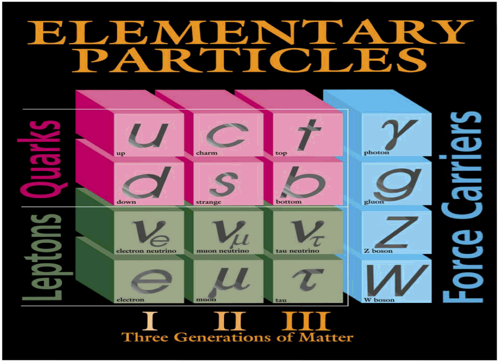
- *Signals at particle colliders*
  as missing energy/momentum if a WIMP-type DM particle is produced
  $\Rightarrow$ *Reconstruction attempts via* $m_{T2}, m_{cT}, \sqrt{\hat{s}}_{min}, \ldots$)

As of now, we have....



Fermilab 95-759

And a spinless particle (the Higgs boson?)

$+$

A theory called the 'standard model' explaining three of the four fundamental forces (electromagnetic, strong, weak)

On the theoretical side....

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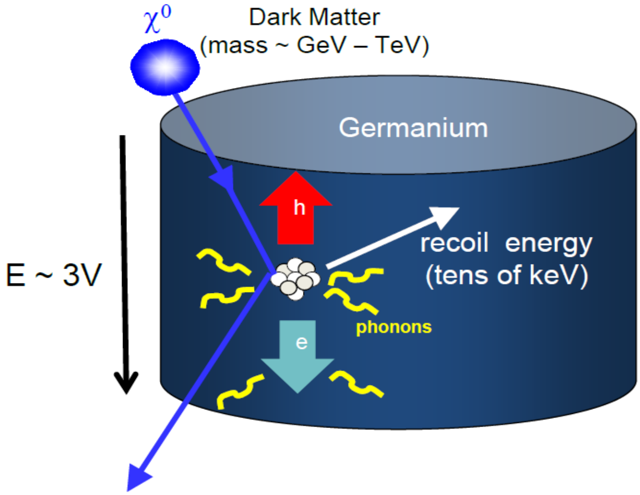
- *Something that does not decay into lighter particles.*

- *Some unknown symmetry, resulting in a conserved quantum number, dictating*
  - *The nature of scattering in direct detection experiments*
  - *Pair-production of DM particles at colliders (if they are produced at all !)*

Weakly interacting dark matter: a typical direct search set-up...



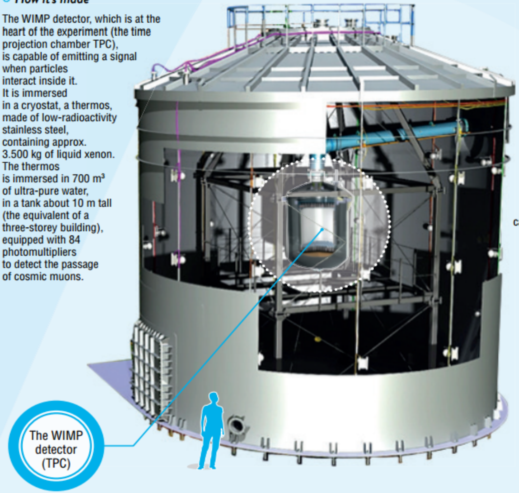
The most recent searches done with this detector...

The Experiment

Dark matter interacts with standard matter, albeit rarely. XENON1T, like an extremely sensitive recorder immersed in the cosmic silence of the Gran Sasso underground laboratory, is searching for these rare interactions.

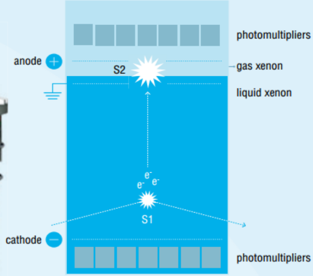
How it's made

The WIMP detector, which is at the heart of the experiment (the time projection chamber TPC), is capable of emitting a signal when particles interact inside it. It is immersed in a cryostat, a thermos, made of low-radioactivity stainless steel, containing approx. 3.500 kg of liquid xenon. The thermos is immersed in 700 m³ of ultra-pure water, in a tank about 10 m tall (the equivalent of a three-storey building), equipped with 84 photomultipliers to detect the passage of cosmic muons.



How it works

When a WIMP interacts with the xenon it creates a weak burst of light. To capture these interactions, XENON1T is fitted with about 248 photomultiplier tubes; sophisticated eyes that convert light signals into electronic signals.

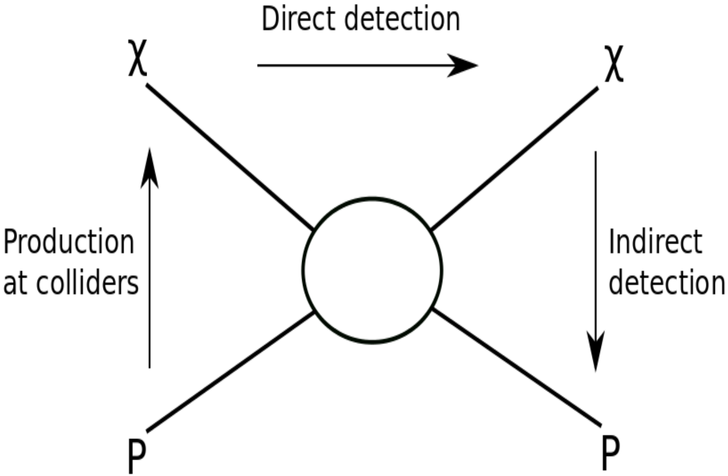


Whenever a particle interacts with the liquid xenon it creates two signals, a primary flash of light (S1) and a charge signal that will generate a delayed light signal (S2).
Together, the two signals permit the measurement of the energy and position of the interaction, and the nature of the particle.

Why xenon

Its characteristics make it perfect for hunting dark matter.
It is very **dense**: with its self-shielding properties, it prevents any external signals not captured by the rock shielding from passing through it.
It has almost **no radioactive isotopes**, whose signals could interfere with the instrument.
Lastly, it is highly **sensitive**: even a weak interaction with dark matter will cause it to emit a flash of light.

Various ways of looking for dark matter...



Particle physics scenarios: conventional and unconventional...

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- *A possible consequence: accelerator signals not as missing energy/momentum*

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- *The DM candidate has very feeble interaction with the rest of the spectrum, so that*
  - *It does not thermalise*
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  - *The signal is NOT missing energy/momentum at collider experiments, but something new*

Example: The minimal SUSY standard model with $\tilde{\nu}_R$

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- *The $\tilde{\nu}_R$ never thermalises, but is produced from the frozen-out NLSP, and also from freeze-in*

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- *Relaxed constraints on mSUGRA-type SUSY S. Banerjee, G. Belanger, BM, P. Serpico (2016)*

Non-SUSY scenarios with similar phenomenology....

General accompanying features:

- *A Z_2 symmetry (say), the DM particle as the lightest Z_2-odd one, and*
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- *Compatibility with direct search constraints*

An example....

A. Ghosh, T. Mondal, BM, JHEP (2017)

Type-3 seesaw mechanism requires at least two fermion triplets ($Y = 0$)

Suppose there is a third triplet , odd under a Z_2 ($\Sigma^+, \Sigma^0, \Sigma^-$)

Σ^0 can be a DM candidate, but only with trans-TeV mass
E. Ma and D. Suematsu (2009)

Mixture with an RH singlet ν_s generates DM at low masses as well
M. Hirsch et al. (2013), A. Chaudhuri, S. Rakshit, BM (2015)

A tiny Σ^0 component $\Rightarrow$ a singlet-dominated DM
$\Rightarrow$ The DM can be non-thermal

- *The triplet-singlet mixing may be driven by dim-5 terms like*

$$\mathcal{L}_5 = \frac{\alpha_{\Sigma\nu_s}}{\Lambda}\Phi^\dagger\bar{\Sigma}_{3R}\Phi\nu_{sR}^c + \frac{\alpha_{\Sigma\nu_s}}{\Lambda}\Phi^\dagger\bar{\Sigma}_{3R}^c\Phi\nu_{sR} + \frac{\alpha_{\nu_s}}{\Lambda}\Phi^\dagger\Phi\bar{\nu}_{sR}\nu_{sR}^c + \frac{\alpha_\Sigma}{\Lambda}\Phi^\dagger\bar{\Sigma}_{3R}\Sigma_{3R}^c\Phi + h.c.$$

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- *If DM candidate* $= \chi = (.)\Sigma^0 + (.)\nu_s,$
  Decays like $\eta^+ \to \chi_1$ *is very slow for*
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  $(\eta^+ = \Sigma^+ + \Sigma^{-c})$
- Consequences:
  (a) No direct search constraint
  (b) η^+ NLOP $\Rightarrow$ long-lived massive charged track signals

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- *Consequence: Constraints in the plane Λ - $M_{\eta^+} - M_\chi$*

Freeze-in:

$$\frac{dY_{NLOP}}{dx} = -\sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2}M_\Sigma}{x^2}\langle\sigma v_{Mol}\rangle$$

$$(Y_{NLOP}^2 - Y_{NLOP}^{eq2}) - \sqrt{\frac{45}{\pi^3 G}}\frac{x}{2\sqrt{g_{eff}}M_\Sigma^2}\langle\Gamma\rangle Y_{NLOP}$$

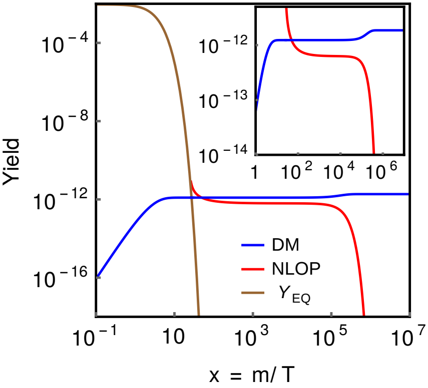
$$\frac{dY_\chi}{dx} = \sqrt{\frac{45}{\pi^3 G}}\frac{x}{2\sqrt{g_{eff}}M_\Sigma^2}\langle\,\Gamma\,\rangle Y_{NLOP}$$

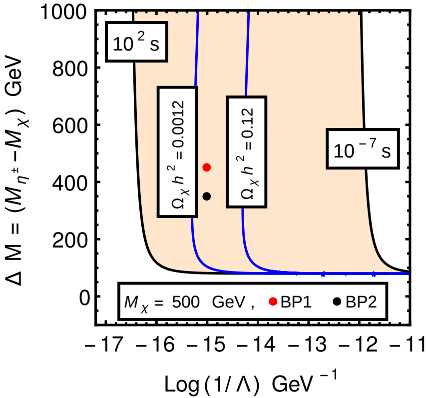
$$Y_\chi = \frac{45}{(4\pi^4)1.66}\frac{g_\Sigma\ M_{Pl}\ \Gamma}{M_\Sigma^2\ \ h_{eff}\sqrt{g_{eff}}}\int_{x=0}^{x_f}K_1(x)x^3dx$$

$$x = \frac{M_\chi}{T}$$

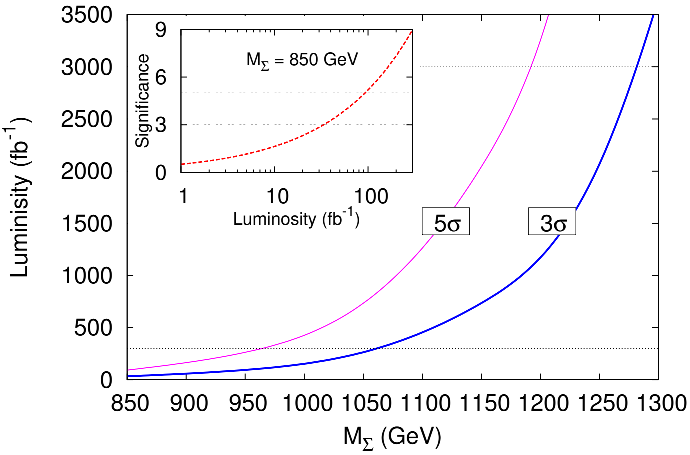
$$\Omega_\chi h^2 \simeq 2.8\times 10^8\times\left(\frac{M_{\nu_s}}{GeV}\right)Y_\chi(x\to\infty)$$

The effects of freeze-in constraints....





LHC reach....



Both single-and double-track events expected:
(via both $pp \to W^* \to \Sigma^\pm\Sigma^0$ and $pp \to Z^* \to \Sigma^+\Sigma^-$)

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- *Such models often have at least one electroweak singlet (scalar/fermion), and some new particles with gauge charges, to ensure a production mechanism for DM*

  Small Yukawas ⇒ The DM particle decays very slowly

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- *DM decay product flux consistent with data*

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- *Useful sources: dwarf spheroidal galaxies (dSph)*

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- *Signals for $m_{DM} \simeq 5 - 8$ TeV can be seen in SKA - 1*
  (A. Kar, S. Mitra, BM, T. Roy Choudhury, 2018)

From A. Kar *et al.*, arXiv:1808.05793, PRD Rap. Com.

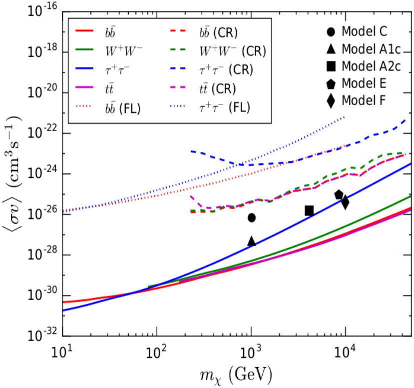

Figure 1: Lower limits (solid lines) of observability of radio flux from Draco dSph in the $\langle \sigma v \rangle - m_\chi$ ($m_{\chi_1^0}$ in MSSM) plane at SKA1 with 100 hours, for various DM annihilation channels with conservative choices of astrophysical parameters. Dashed and dotted lines denote the corresponding 95% C.L. upper limits from cosmic-ray (CR) antiproton observation and 6 years of Fermi LAT (FL) data respectively. The black points represent various high mass MSSM benchmark points.

Conclusion: None!!!

THANK YOU