Chasing the phantom: Exploring light dark matter with Forward Physics Facility.

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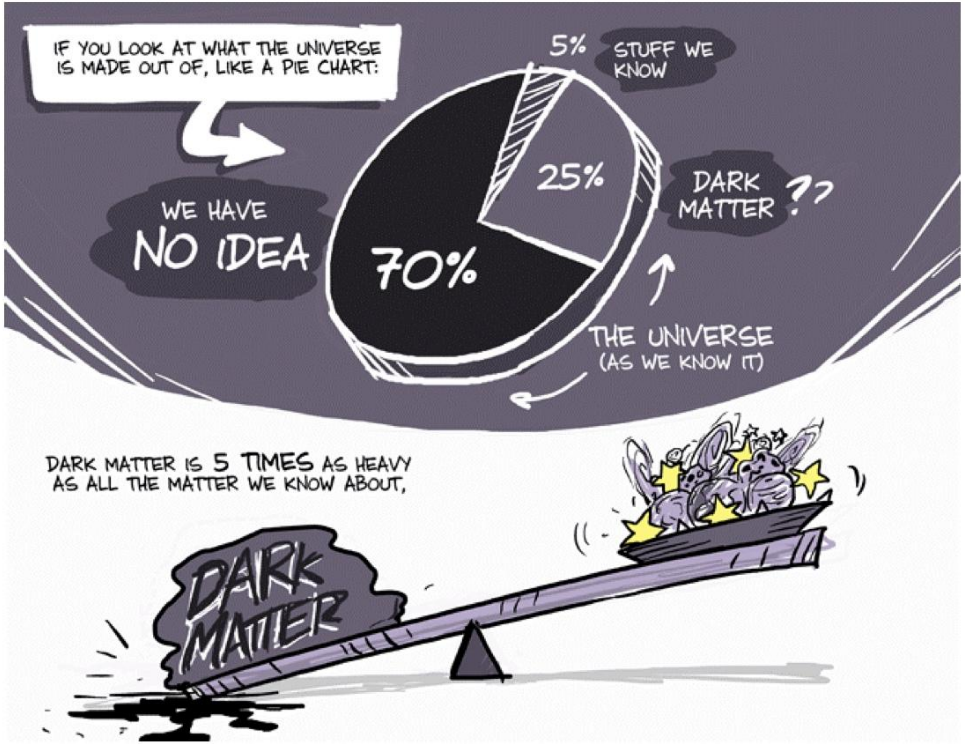
The universe in a pie chart



Credit: Marlene Gotz, Dark matter

This was not the picture earlier.

What has changed since the 1920s??

Evidences of Dark matter

Virial theorem

- For an isolated self gravitating system,

$2T+U = 0$

$$T = \frac{1}{2}M \cdot 3\langle v \rangle^2. \qquad U \sim -G\frac{M^2}{R}.$$

$$M \sim \frac{3R\langle v \rangle^2}{G}.$$

When calculated for the COMA cluster, it has been found that $M \sim 10^{15}\ M_{sun}$.

The Redshift of Extragalactic Nebulae

by F. Zwicky.

(16.II.33.)

Contents. This paper gives a representation of the main characteristics of extragalactic nebulae and of the methods which served their exploration. In particular, the so called redshift of extragalactic nebulae is discussed in detail. Different theories which have been worked out in order to explain this important phenomenon will be discussed briefly. Finally it will be indicated to what degree the redshift promises to be important for the study of penetrating radiation.

From observations it was found that $L \sim 10^{13}\ L_{sun}$

$$\left(\frac{M}{L_{tot}}\right)_{Cluster} \sim 100\frac{M_\odot}{L_\odot}.$$

Structure won't be stable unless there is a larger amount of mass than visible

Evidences of Dark matter

Rotation curves of Galaxies

- ❑ The idea of dark matter once again came into limelight after study of Galactic rotation curves.

$$m\frac{v^2}{R} = \frac{GM(R)m}{R^2}$$

$$v^2 = \frac{GM(R)}{R}$$

The only way to resolve that paradox was to assume that there is a halo of invisible matter surrounding the galaxy

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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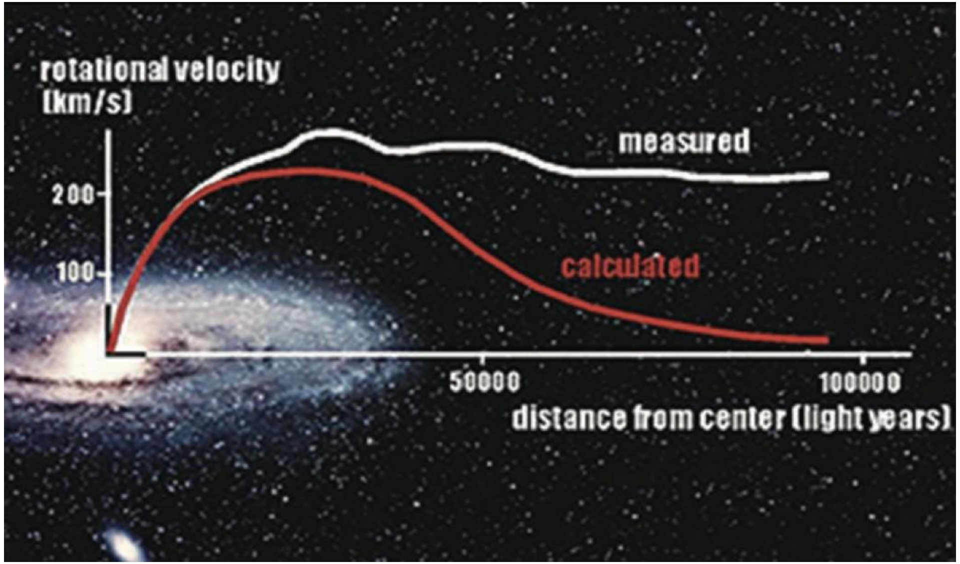


Credit: Paul Gorenstein et. al

Evidences of Dark matter

Bullet cluster

- Analysing the spectral regions shows that the clash caused a strong separation of the individual components of the galaxy clusters.
- The total mass of the cluster was reconstructed by gravitational lensing and it mostly follows the collisionless part of the clusters, not the hot baryonic gas

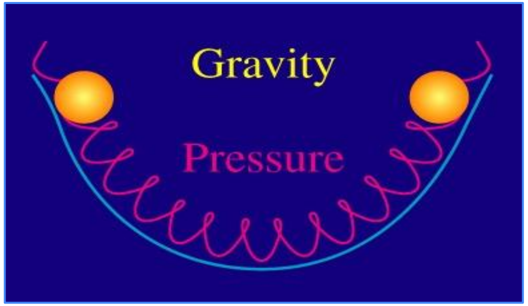
Credit: Paul Gorenstein et. al

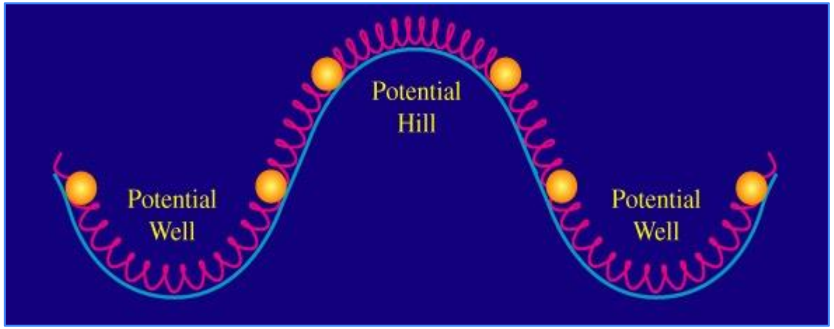
Bullet Cluster, blue: gravitational potential, red: x-ray emitting gas

Therefore there has to be an additional contribution of dark matter.

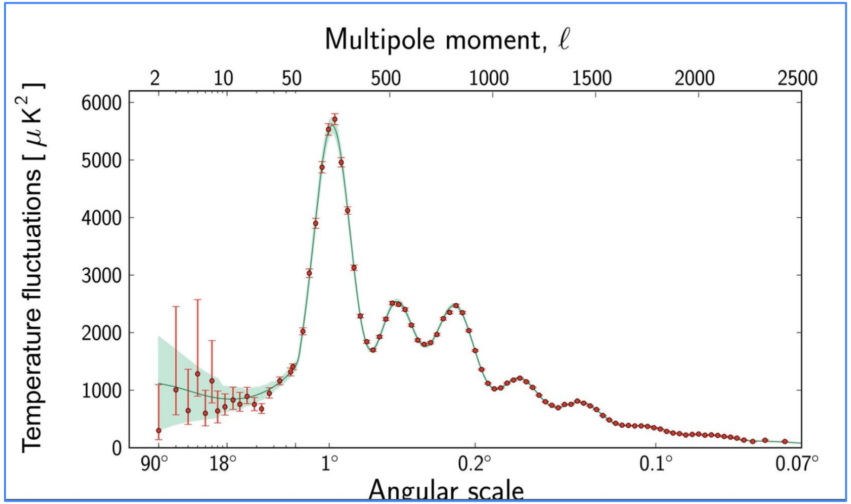
Evidences of Dark matter

Cosmic microwave background





Credit:http://galaxies-cosmology-2015.wikidot.com/baryon-acoustic-oscillations

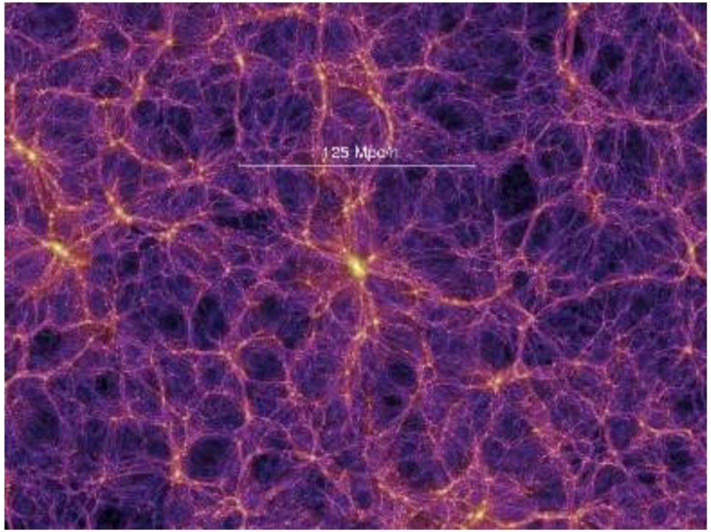


Credit: Paul Gorenstein et. al

Evidences of Dark matter

The evolution of structure

- The amount of mass needed to provide the level of gravitational attraction required for the structure of the universe as it was 4×10^5 years after the Big Bang to evolve into the web-like structure of the galaxies, clusters of galaxies, and the voids we observe today does require a component of dark matter.



Credit: The Millennium Simulation

Now with all the evidences at hand we can ask some questions

1. **What are the possible dark matter candidates??**

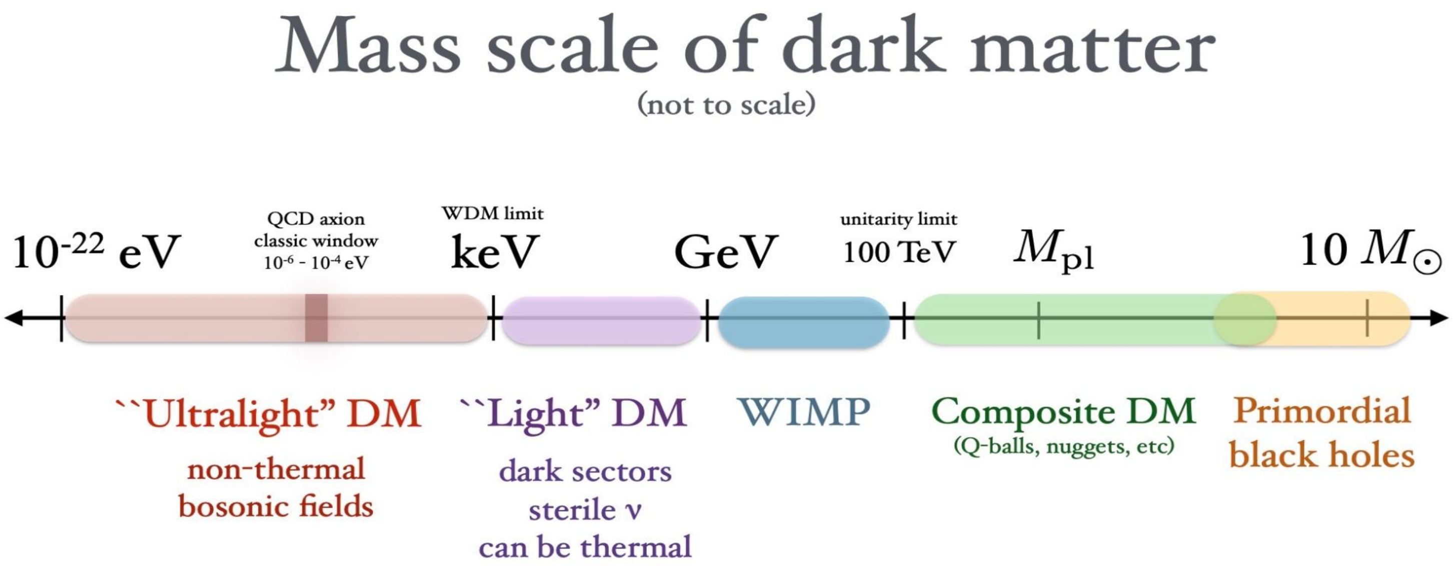
2. **Where did it come from??**

3. **How to detect the particle components of dark matter??**

What can dark matter be and not be

- ❑ Must be non baryonic
- ❑ Stable
- ❑ Electrically neutral
- ❑ Non relativistic
- ❑ Must be produced in sufficient quantity in the early universe

Possible dark matter candidates



Credit:Tongyan Lin,
TASI lectures on DM models and direct detection

The “WIMP miracle”

The freezeout mechanism

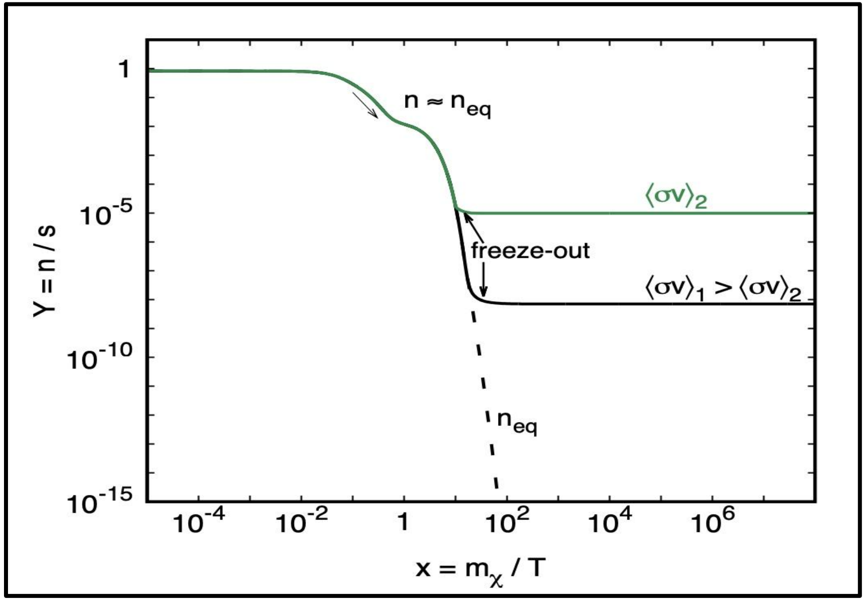
- ❑ During very early and hot Universe SM species and DM were in thermal equilibrium.
- ❑ With expansion of universe, WIMPs froze out of equilibrium with the thermal plasma.

$$\Gamma_{\rm ann} \lesssim H$$

$$\Omega_\chi^0 \approx 0.2 \frac{2.2 \times 10^{-26}\,{\rm cm}^3/s}{\langle \sigma v \rangle}.$$

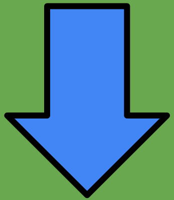
$$\langle \sigma v \rangle \simeq \left(\frac{g}{0.1}\right)^4 \left(\frac{100\,{\rm GeV}}{m_\chi}\right)^2 2.2 \times 10^{-26}\,{\rm cm}^3/s$$

We get a cross section of weak strength for WIMP with mass around the electroweak scale



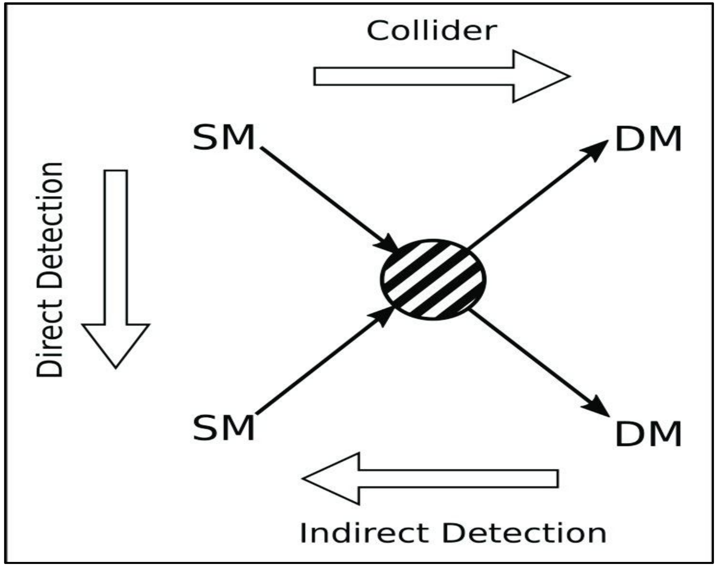
Credit: Roszkowski et. al.

Takeaway message: We've found a mass and coupling range which we can explore for detection of WIMP dark matter.



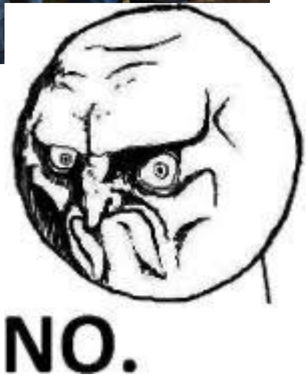
We've established theoretical target for experimental searches

The hunt for dark matter

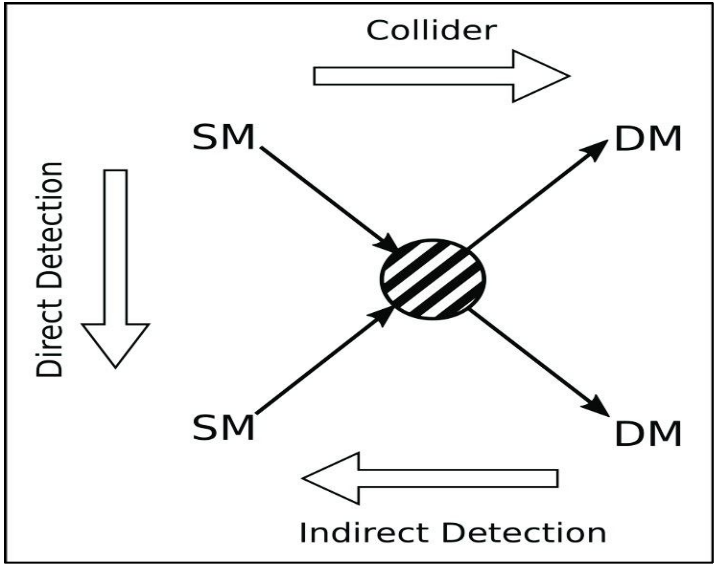


Credit: Stefano Giagu

Hunters

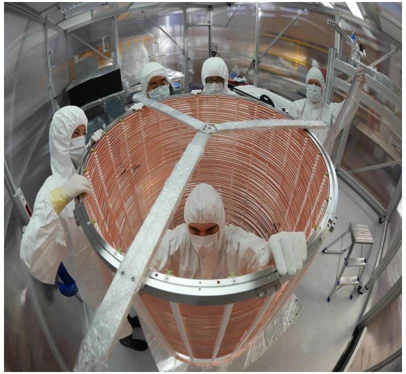


The hunt for dark matter



Credit: Stefano Giagu

Actual Hunters



No signal of WIMPS yet :(

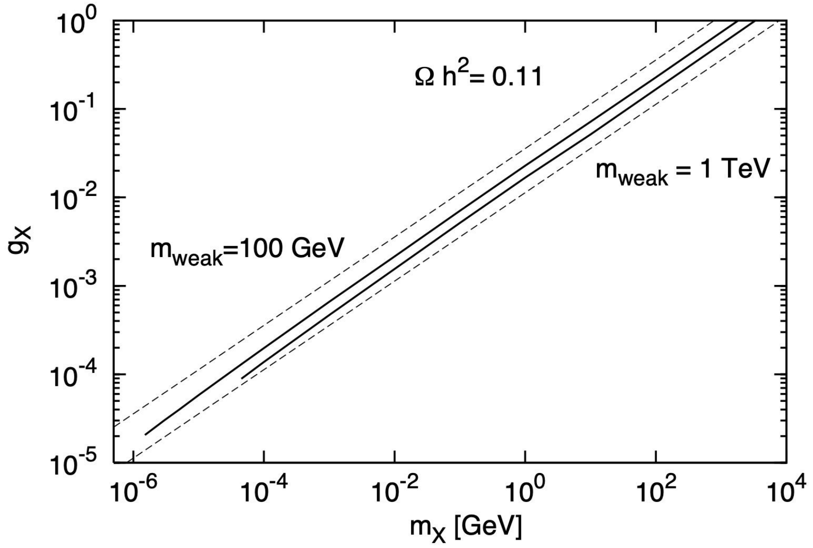
Sad cat noises

Thermal production beyond traditional WIMPs

- Freezeout is still possible without WIMPs.

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- It can be from DM (significantly) heavier than the electroweak scale, up to the unitarity bound ~ 100 TeV
- It can also be from light DM candidates - with mass in the range ~ 10 MeV−10 GeV. where the DM mass m_{DM} is lowered and the coupling g_{DM} is below the weak coupling strength.

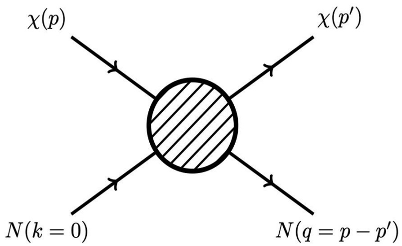


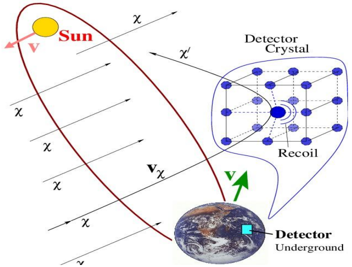
Credit: Jonathan L. Feng et. al

This means we'll have to update our detection techniques for this range of dark matter mass and coupling strength.

Time for the detection techniques !

Direct detection of light dark matter

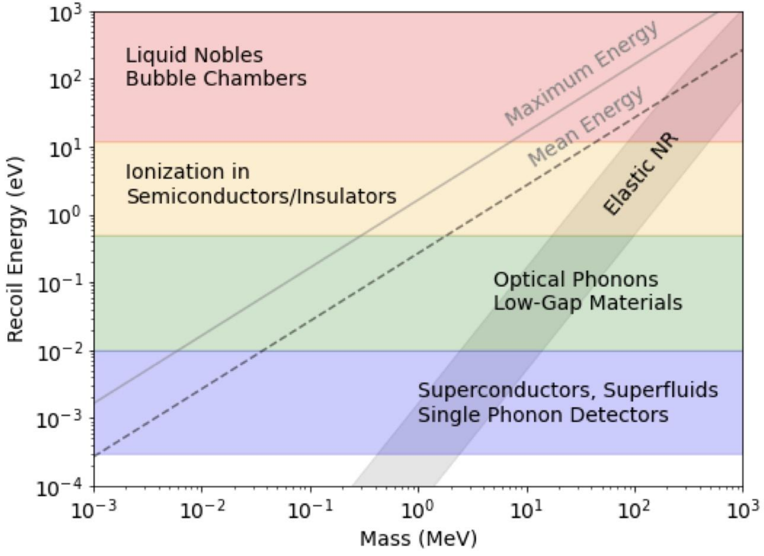




- ❑ The main focus of the direct-detection program in the past few decades has been the search for WIMPS where elastic scattering of DM nucleus has been taken as the basis for observation.
- ❑ But for light dark matter the kinetic energy would decrease and hence the recoil energy of target matter would decrease.

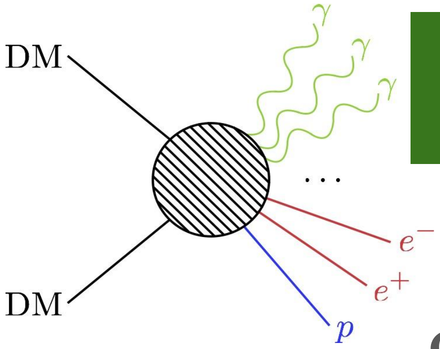
So, need to explore other scattering channels:

- DM scattering with bound electrons.
- DM scattering with nuclei through the Migdal effect or accompanied by a photon from bremsstrahlung.
- DM-target scattering that produces a collective excitation.



Credit: Rouven Essig et. al.

Indirect detection of sub GeV dark matter



Light DM annihilations generate signals in the sub-GeV range, and the relevant indirect detection searches need to be sensitive to this.

Cosmic probes

- ❑ The energy injected from Dark matter annihilation and decay could potentially ionize the neutral hydrogen gas. Can modify the measured anisotropies of the CMB.

Telescopes in space

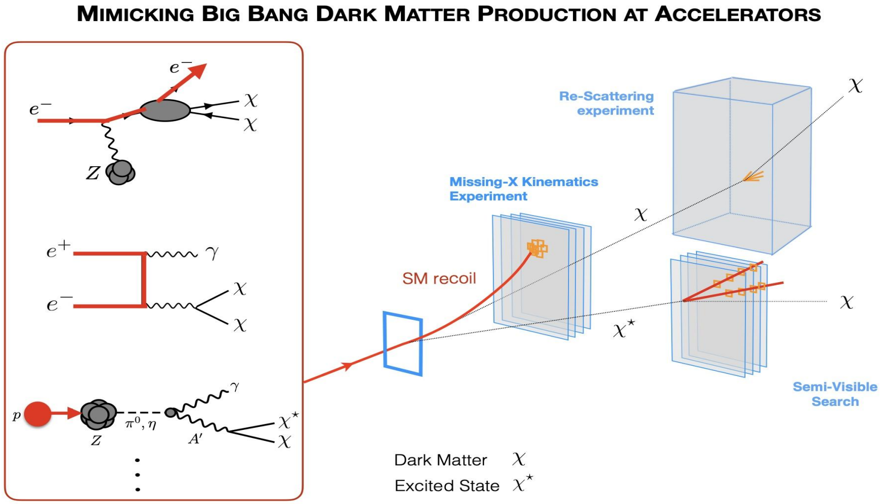
- ❑ Fermi LAT observations of Dwarf Spheroidal galaxies.
- ❑ Observation of Galactic centre by Fermi LAT

Planck data currently exclude light dark matter with the cross section up to 2 orders of magnitude below the thermal target, but the bounds change if the cross-section is velocity-suppressed.

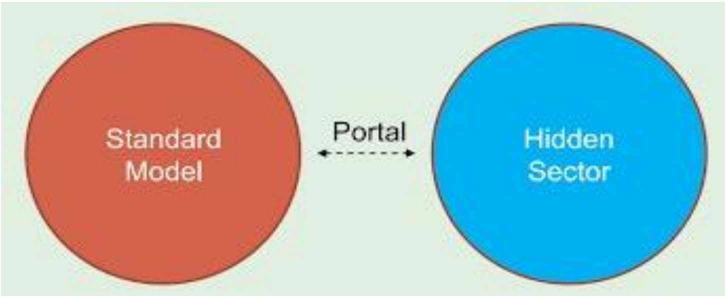
Accelerator search

Why accelerators?

- ❑ In contrast to heavy dark matter, light dark matter can be produced abundantly in accelerators.
- ❑ Therefore we can probe the interactions.
- ❑ Probe it in relativistic regime.
- ❑ Can also probe mediator particles.



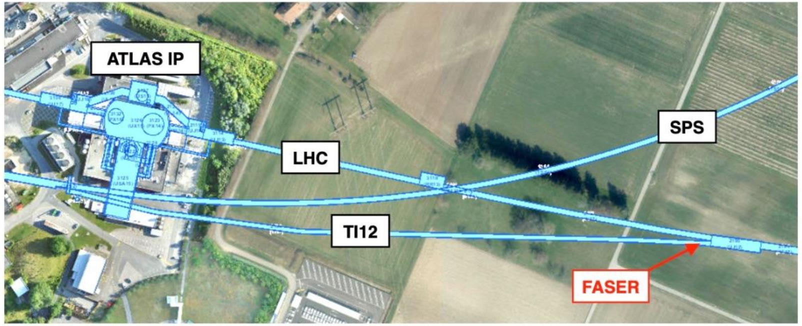
Credit: A. Berlin et. al

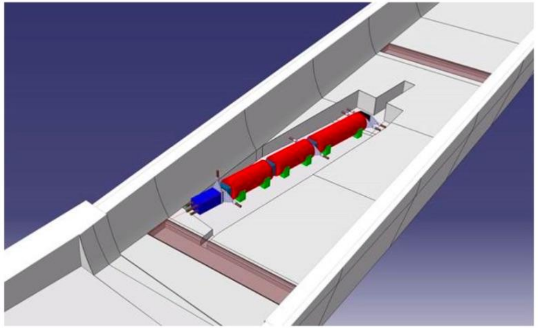


Credit: K. Jodłowski, PhD thesis

Forward LHC search and FASER

FASER: ForwArd Search ExpeRiment





Credit: FASER collaboration

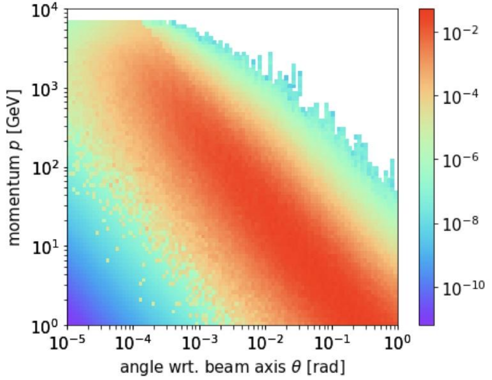
In the high pT region, the production cross section of light dark matter particles and mediator particles is low as compared to low pT region. Hence, the idea of putting forward a detector in the forward region of LHC.

How do we get to know what to expect in the FASER detector?

FORESEE

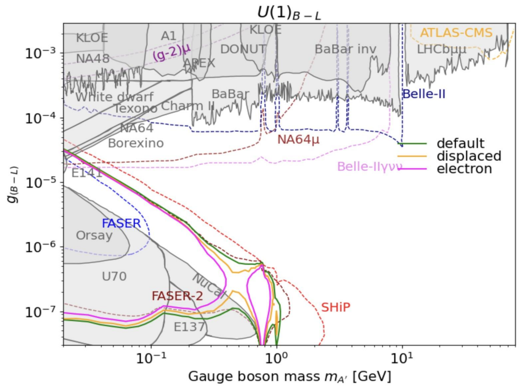
What is FORESEE: python based simulation tool for long lived particle searches at FASER

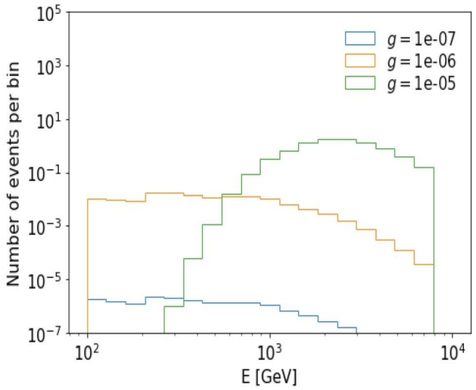
available on github: https://github.com/KlingFelix/FORESEE



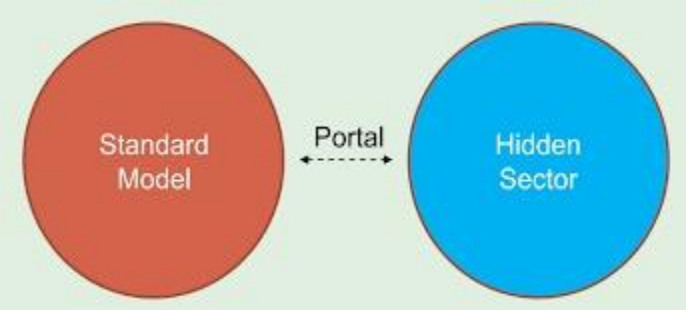
How does it work:

1. Define the model with production, lifetime and decay modes.
2. Obtain the long lived particle spectrum.
3. Define detector specifics (can be FASER but can be others too)
4. Obtain the number of event expected in the detector.
5. Obtain parameter space available for exploring the model in specific detector.





Models



Vector portal models:
- Dark photon
- $U(1)_{B-L}$
- $U(1)_{B}$

Axion-like particles:
- ALP-Photon
- ALP-W

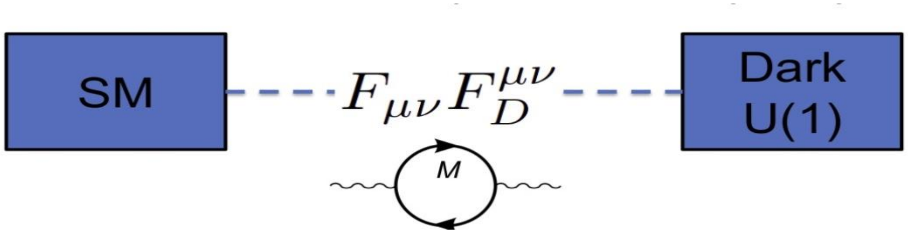
Dark scalar portal
- Dark Higgs

- ❑ Complex Scalar dark matter
- ❑ Inelastic dark matter model

Dark photon model

New light (~sub-GeV) vector secluded from the SM, coupled via kinetic mixing

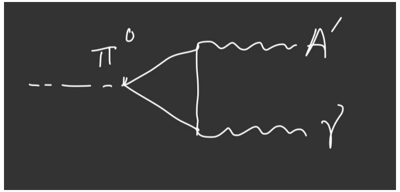
(can be induced by heavy new fields at the loop level charged under both U(1) and U(1)D)

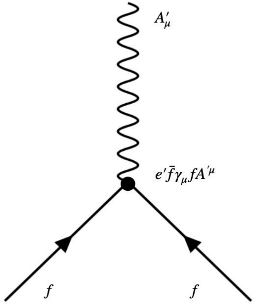


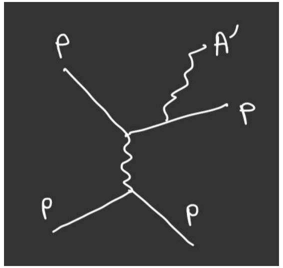
$$\mathcal{L} = \frac{1}{2} {m_{A'}}^2 A'^2 - \epsilon e \sum \bar{f}\gamma^\mu f A'_\mu$$

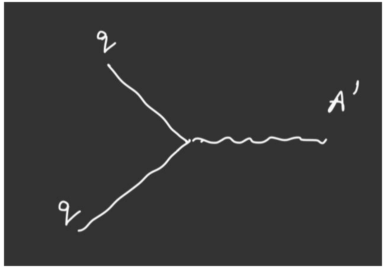
Dark photon model

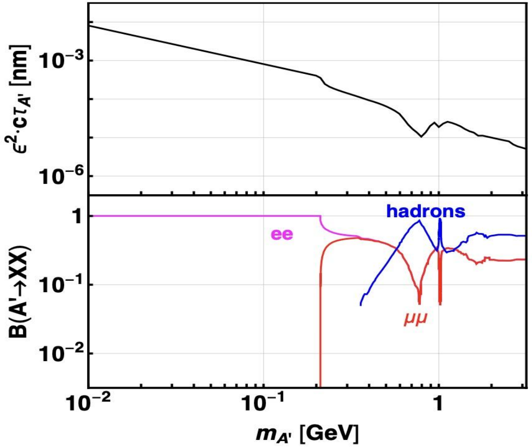
$$\mathcal{L} = \frac{1}{2} m_{A'}{}^2 A'^2 - \epsilon e \sum \bar{f} \gamma^\mu f A'_\mu$$



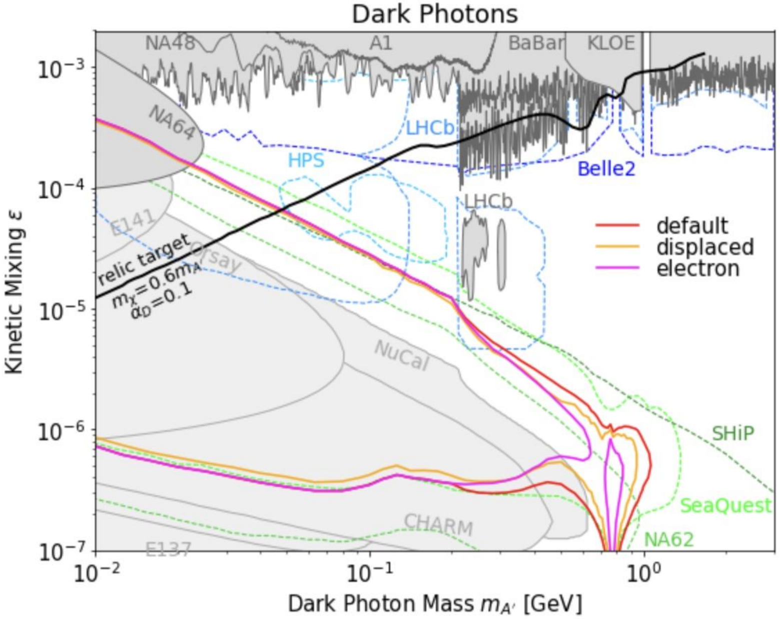








Credit: FASER collaboration

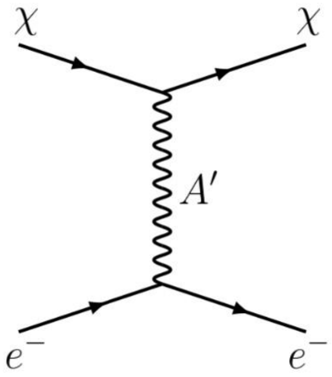


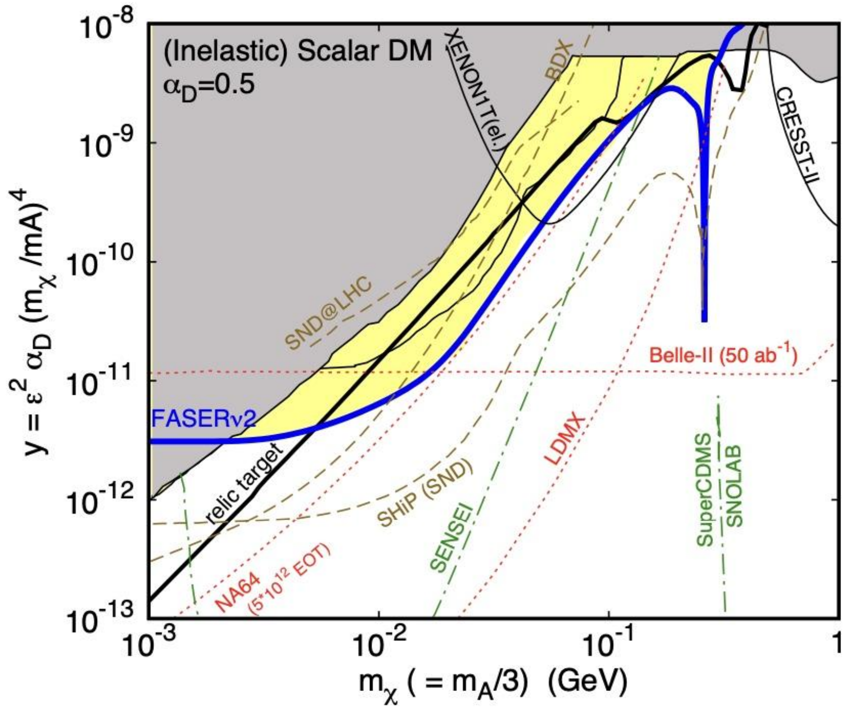
Credit FASER collaboration

Complex scalar dark matter

$$\mathcal{L} = |\partial_\mu \chi|^2 - m_\chi^2 |\chi|^2 + \frac{1}{2} m_{A'} A'^2 + A'_\mu (e\epsilon J^\mu_{EM} + g_D J^\mu_D)$$

Signature:Scattering



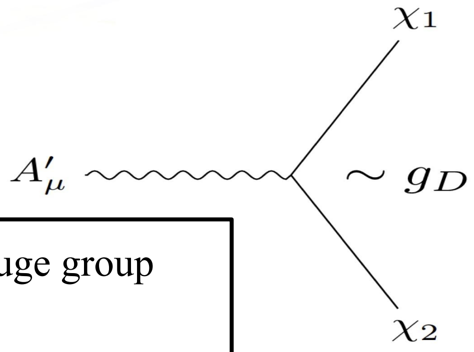


Credit: Brian Batell et. al.


JUST. ONE.
MORE. EPISODE.
Model!

Inelastic Dark matter

- This model contains two particles almost identical in mass, the lightest one being the Dark matter candidate.
- Interaction with the standard model is via Dark photon



Theory of iDM

We consider two Weyl fermions ψ_1 and ψ_2 with charges +1 and -1 under the gauge group U(1)'.

$$\mathcal{L} = -g_d\, A'_\mu \left(\psi_1^\dagger \bar{\sigma}^\mu \psi_1 - \psi_2^\dagger \bar{\sigma}^\mu \psi_2\right) - \left(m_D \psi_1 \psi_2 + \frac{\delta m_1}{2}\psi_1\psi_1 + \frac{\delta m_2}{2}\psi_2\psi_2 + h.c\right),$$

$$m_{1,2} = m_D \mp \frac{\delta m_1 + \delta m_2}{2}$$

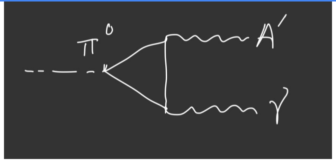
$$\delta m_{1,2} \ll m_D$$

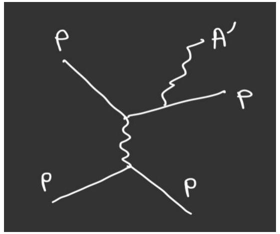
$$\mathcal{L}_{\text{int}}^{\chi} = i g_d\, \bar{\chi}_2 \gamma^\mu \chi_1 A'_\mu + \mathcal{O}\left(\frac{\delta m_1 - \delta m_2}{m_D}\right)$$

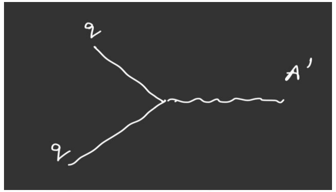
$$\Delta_\chi = \frac{m_{\chi_2} - m_{\chi_1}}{m_{\chi_1}}$$

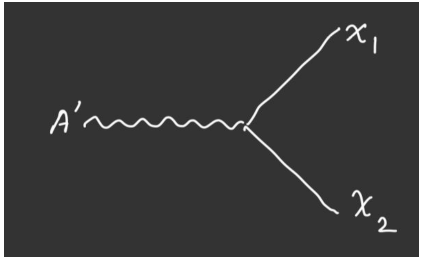
Inelastic Dark matter

Production

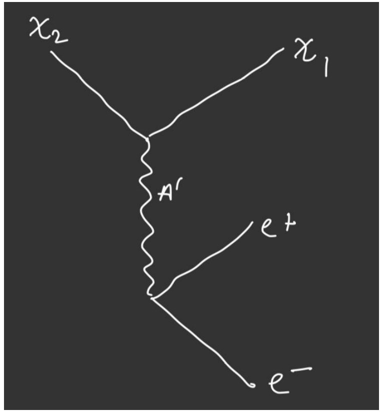




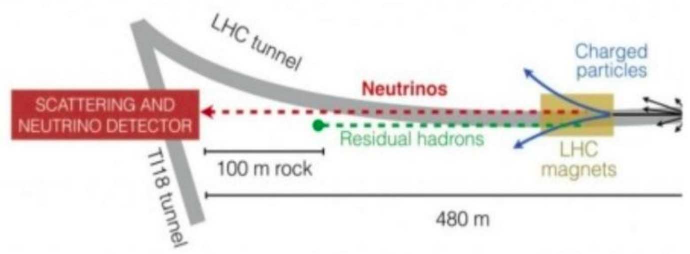


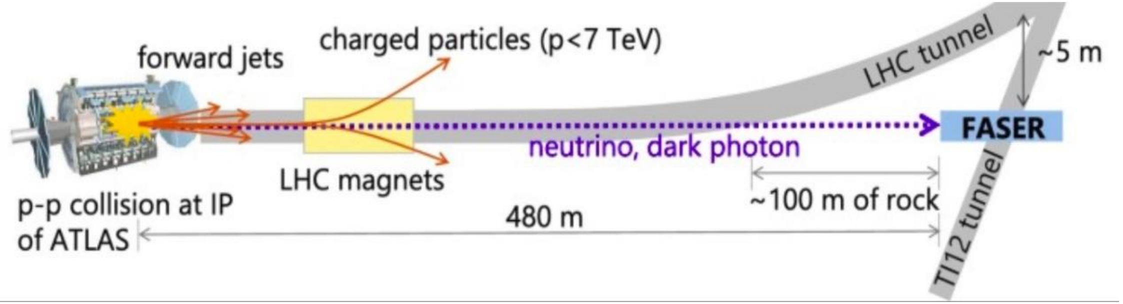


Decay



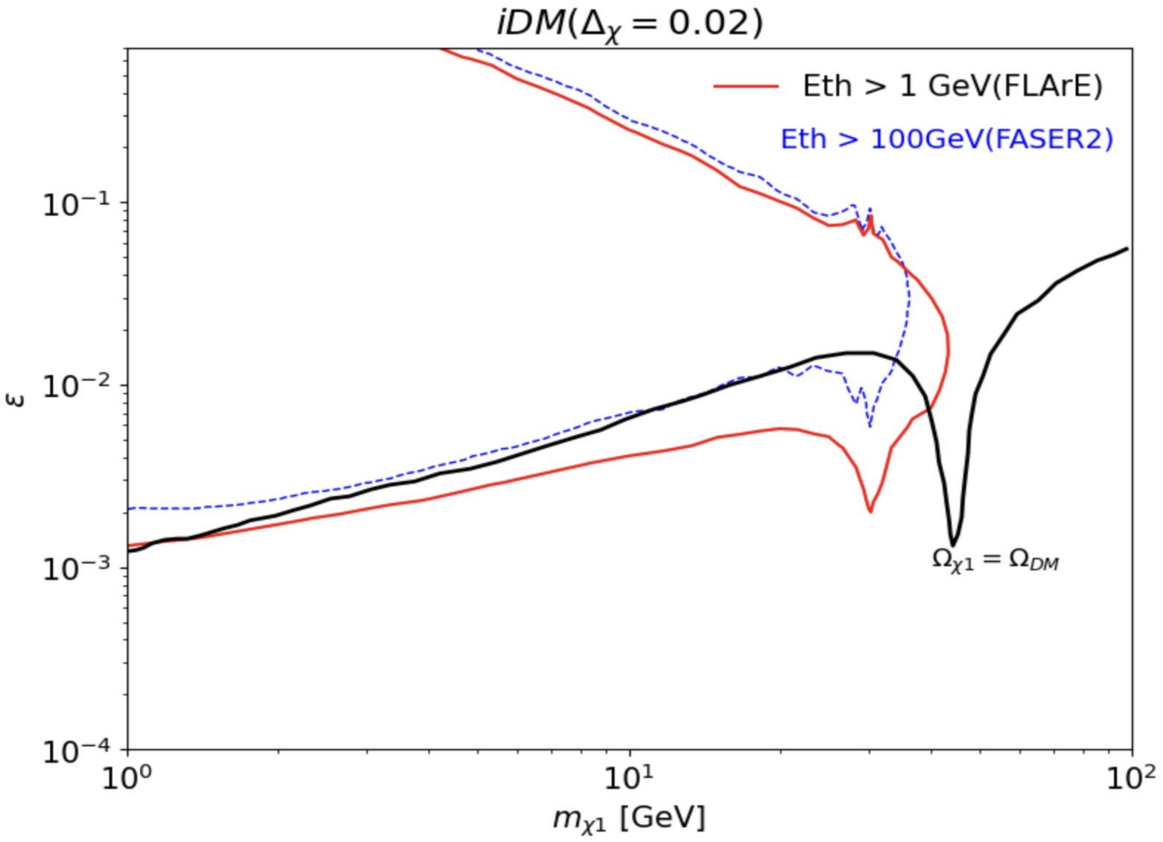
Detection in FASER





Inelastic Dark matter

Result



By reducing the threshold, we find it that it would be helpful to probe the relic target line!!

Future plans

- ❑ Release the updated FORESEE with the new models.
- ❑ Probe dark matter models in the relativistic regime where non relativistic interactions are suppressed so that it evades direct and indirect detection and can be probed in high energy collider experiments.


THANK YOU FOR YOUR ATTENTION
ANY QUESTIONS?