Introduction to dark matter

Elías López Asamar

Estágios de verão, LIP Coimbra, 1st of July 2020

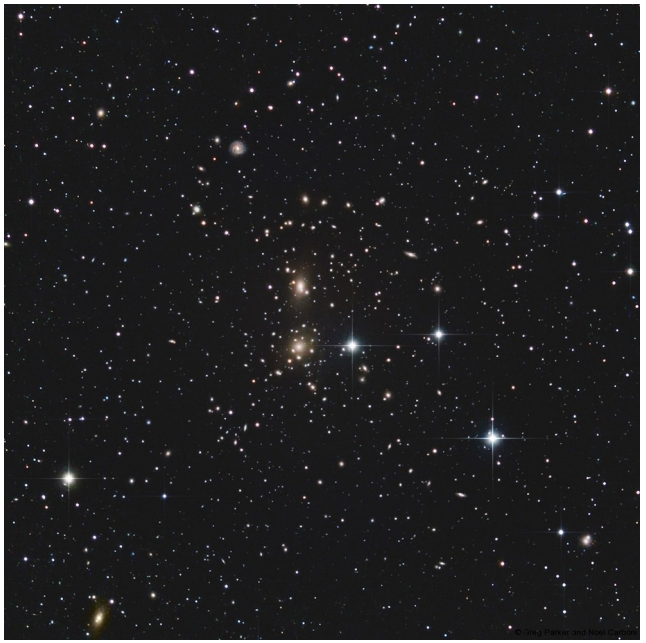
OVERVIEW

- **Evidences for dark matter**
- **The dark matter problem**
- **Dark matter candidates**
- **Search for dark matter particles**
- **Direct detection experiments**

EVIDENCES FOR DARK MATTER

From gravitational effects observed over a wide range of astronomical scales we infer that ~85% of the mass content of the universe does emit or absorb electromagnetic radiation ⇒ Dark matter (DM)

Galaxies in clusters (~10 Mpc) move much faster than expected (Fritz Zwicky, 1933)



Coma cluster

EVIDENCES FOR DARK MATTER

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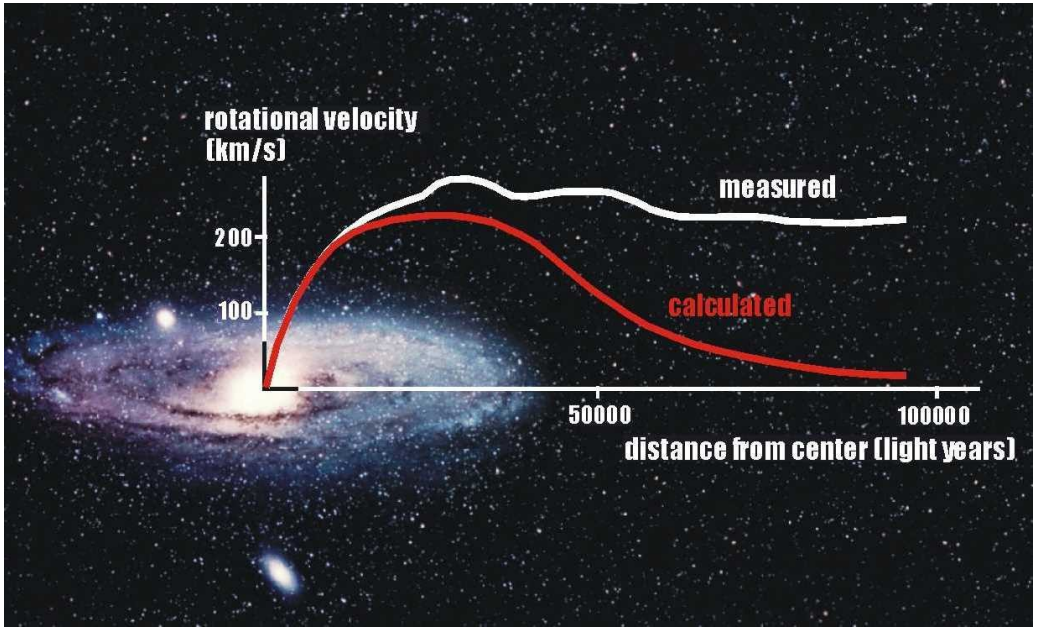
Stars in galaxies (~100 kpc) rotate much faster than expected (Vera Rubin, 1970)

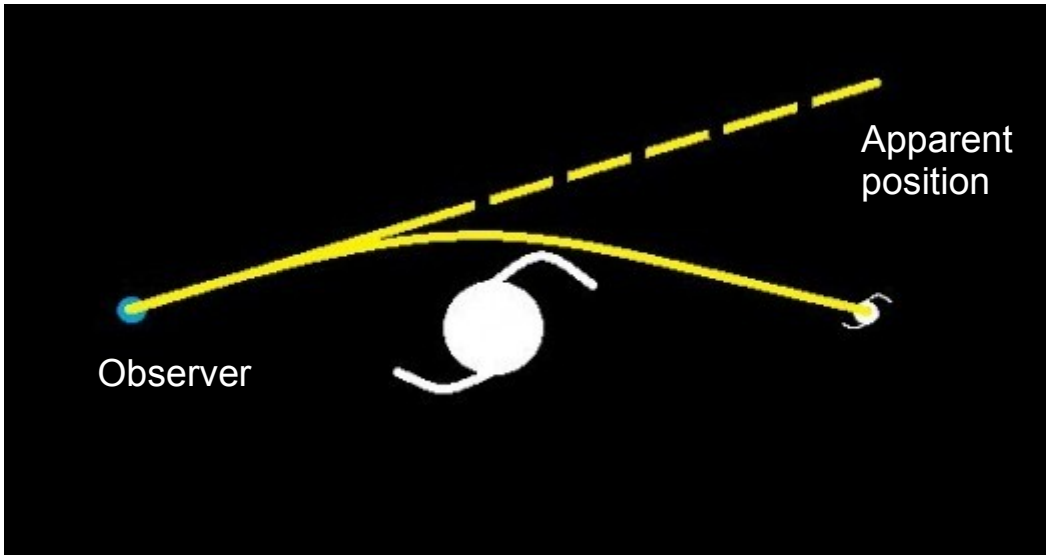


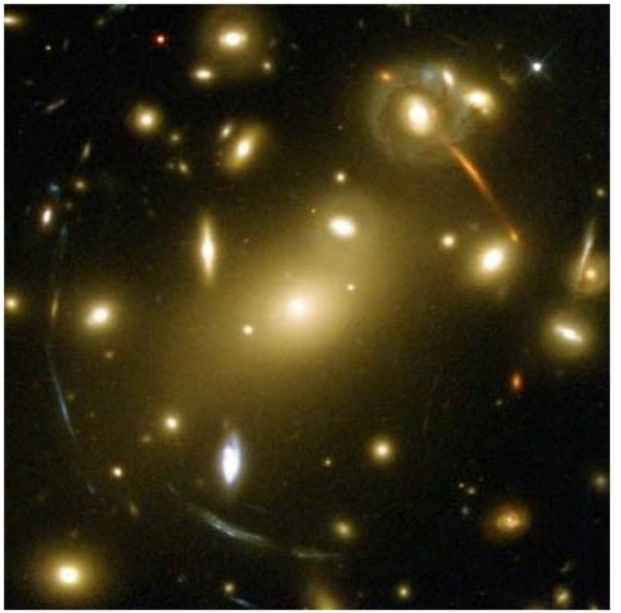
Andromeda galaxy

EVIDENCES FOR DARK MATTER

From <u>gravitational effects</u> observed over a <u>wide range of astronomical scales</u> we infer that ~85% of the mass content of the universe does emit or absorb electromagnetic radiation ⇒ Dark matter (DM)

Gravitational lensing, Bullet Cluster, etc





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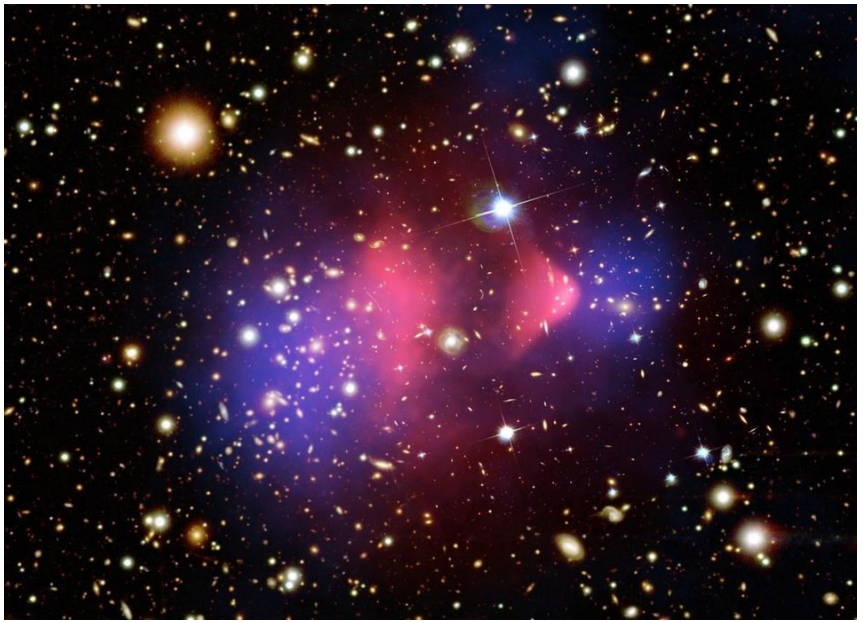
Bullet Cluster, gravitational lensing, etc

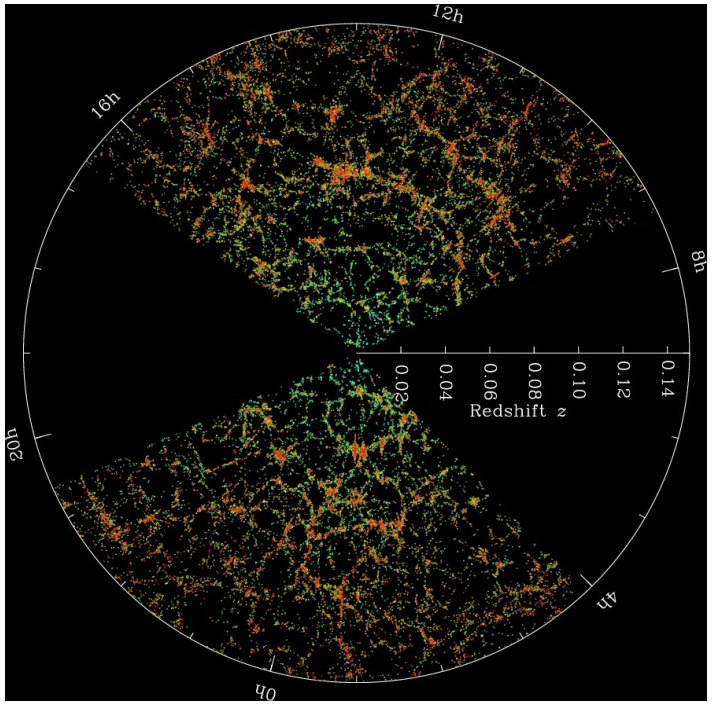


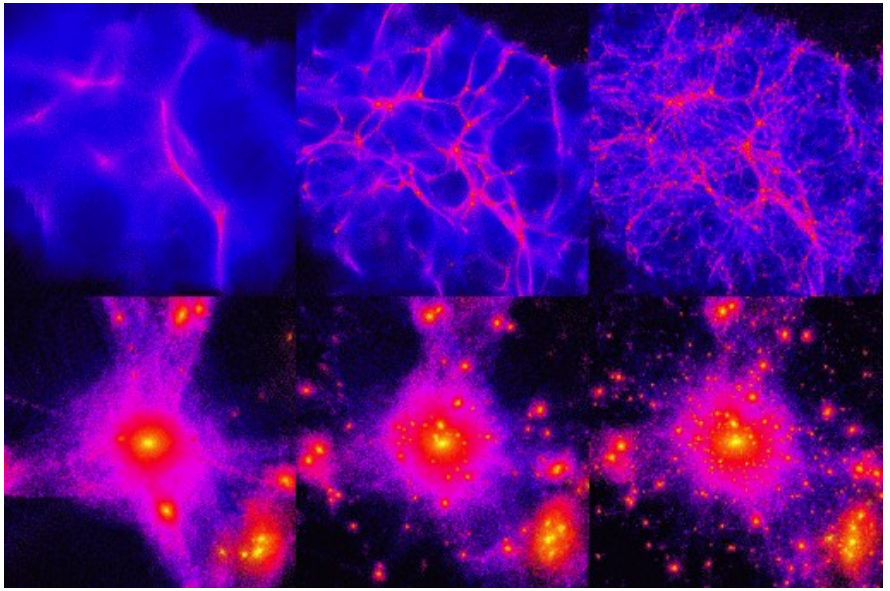
Bullet Cluster

EVIDENCES FOR DARK MATTER

From <u>gravitational effects</u> observed over a <u>wide range of astronomical scales</u> we infer that ~85% of the mass content of the universe does emit or absorb electromagnetic radiation ⇒ Dark matter (DM)

Large-scale structure of the universe (<u>~1 Gpc</u>)



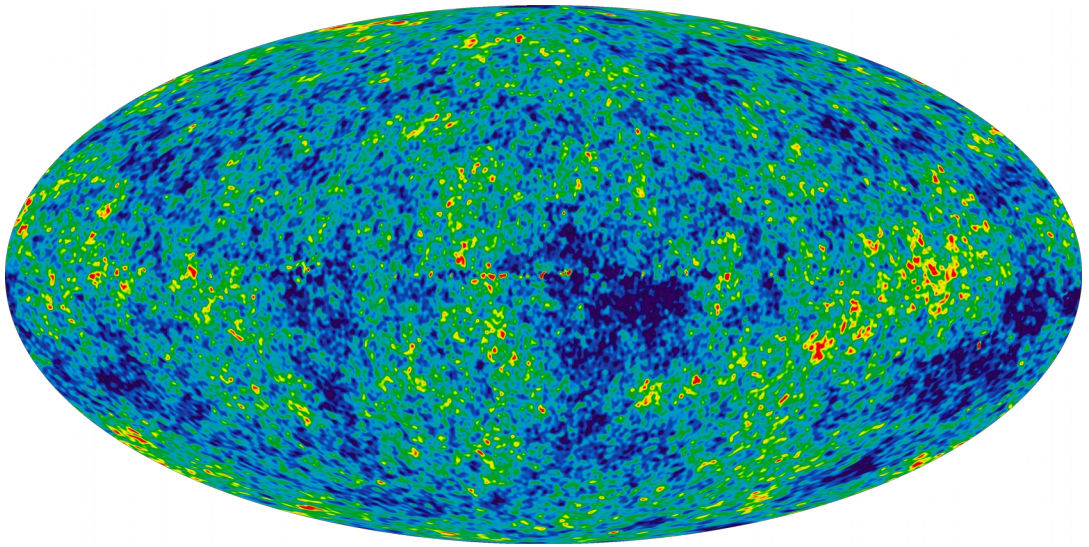


Hot DM Warm DM **Cold DM**

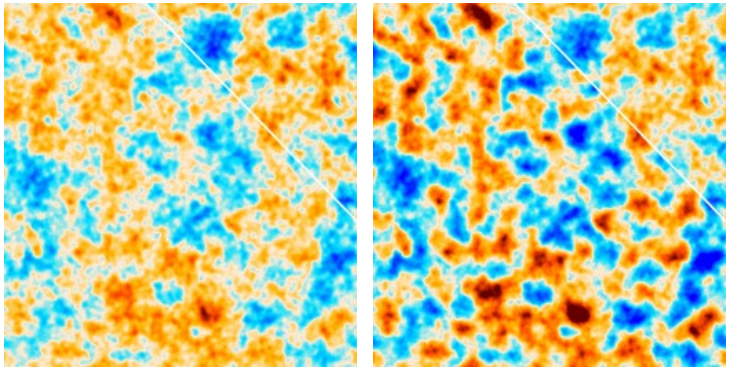
EVIDENCES FOR DARK MATTER

From gravitational effects observed over a wide range of astronomical scales we infer that ~85% of the mass content of the universe does emit or absorb electromagnetic radiation ⇒ Dark matter (DM)

Anisotropies in cosmic microwave background (entire universe)



https://chrisnorth.github.io/planckapps/Simulator/



With DM Without DM

THE DARK MATTER PROBLEM

The evidences for DM are very strong. DM is a necessary component in modern astrophysics and cosmology models (ΛCDM)

From CMB measurements (Planck satellite), our universe is made of:

- **Ordinary matter: (4.8 ± 0.1)%**
- **Cold DM: (25.8 ± 0.5)%**
- **The rest is dark energy**

But what is DM made of?

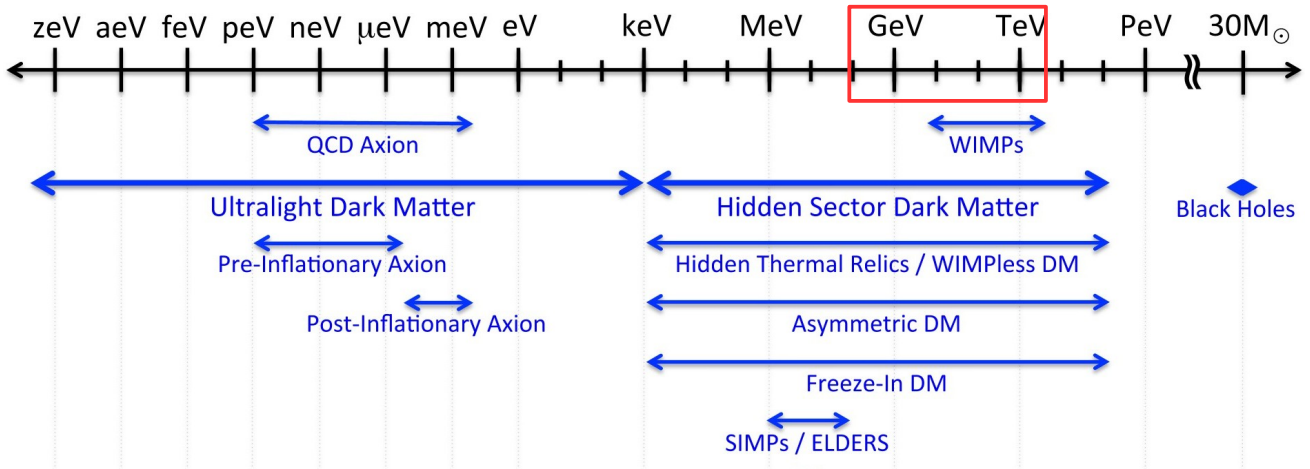
- **Its elementary constituents are neutral (because they do not interact with electromagnetic radiation): excludes quarks and charged leptons**
- **It is cold: excludes neutrinos**

Standard Model (SM) particles cannot account for DM ⇒ New elementary particles?

DARK MATTER CANDIDATES

DM is a problem that extends from astrophysics and cosmology to <u>particle physics</u>

Astronomical observations do not provide any information on the mass of DM particles ⇒ The mass of DM particles is largely unconstrained

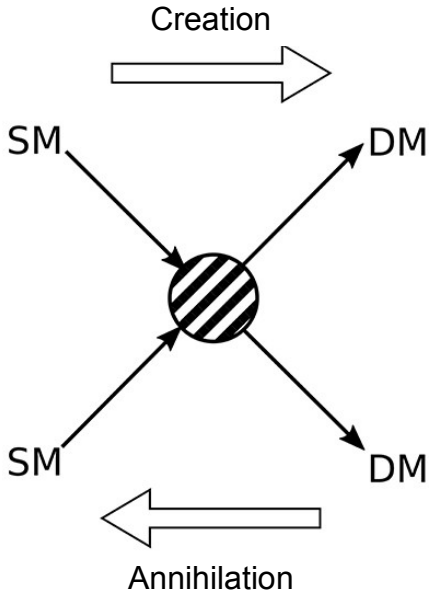


DARK MATTER CANDIDATES

DM is a problem that extends from astrophysics and cosmology to particle physics

It is assumed that DM has some type of interaction with ordinary matter besides gravity ⇒ Possible processes are:

- **Creation of DM from SM particles**
- **Annihilation of DM into SM particles**



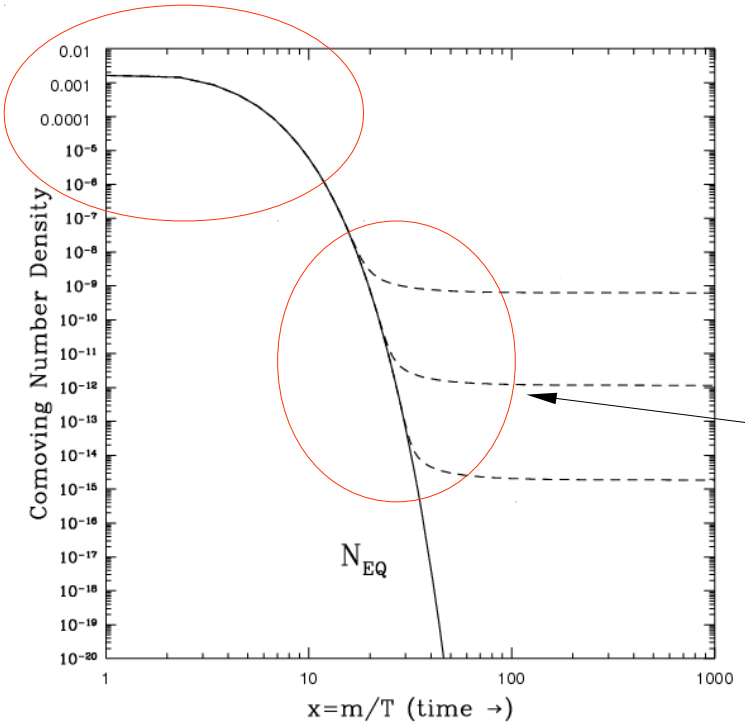
DARK MATTER CANDIDATES

Weakly-interacting massive particles (WIMPs): assume that DM interacts with ordinary matter through the SM weak interaction

This hypothesis directly explains the observed amount of DM in the universe through the freeze-out mechanism ("WIMP miracle")

High particle density: DM in equilibrium with ordinary matter and radiation

Creation of DM (SM → DM) is balanced with annihilation of DM (DM → SM)



Lower particle density: Unable to sustain creation or annihilation of DM

Number of DM particles remains constant

N(DM) = N(anti-DM)

DARK MATTER CANDIDATES

<u>Hidden sector DM</u>: theories based also on the freeze-out mechanism, that use new interactions to couple DM to ordinary matter

Dark photons, Higgs portals, etc

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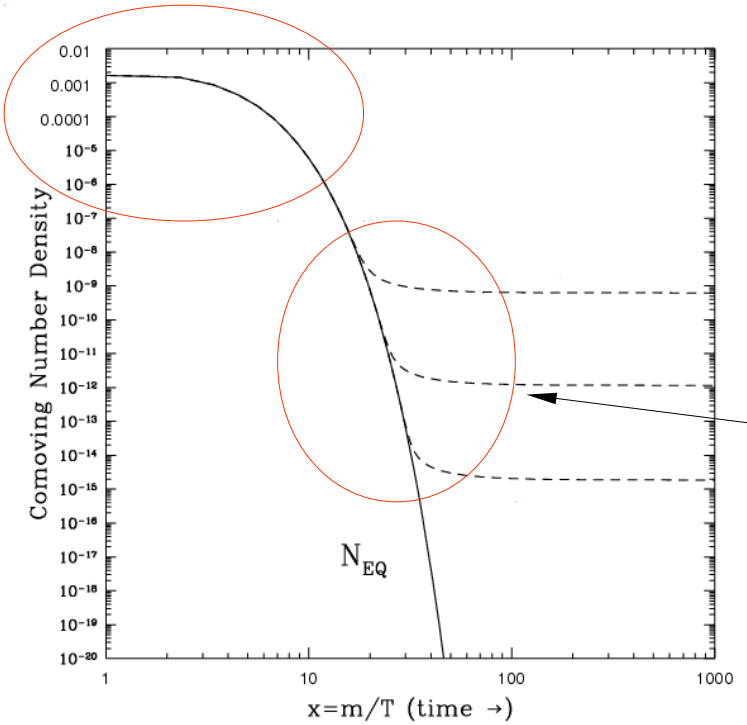

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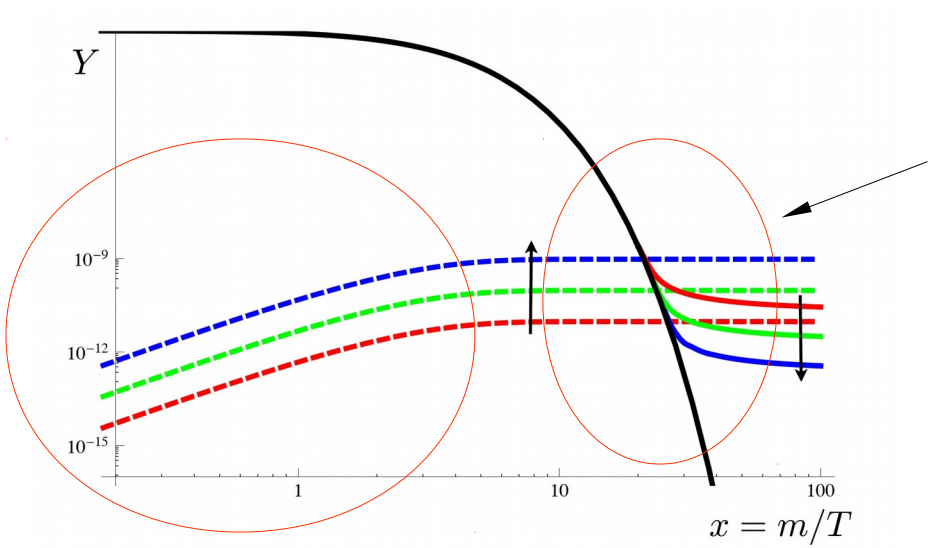
DARK MATTER CANDIDATES

<u>Freeze-in DM</u>: explains the observed amount of DM in the universe by assuming 1) very small interaction with ordinary matter, and 2) no DM in early universe

As in freeze-out mechanism, the amount of DM does not depend on details of the early universe



Lower particle density: Unable to sustain creation of DM

Number of DM particles remains constant

N(DM) = N(anti-DM)

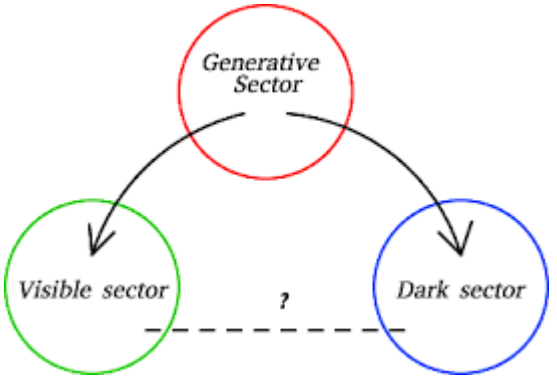
High particle density: allows creation of DM from SM particles

DARK MATTER CANDIDATES

<u>Asymmetric DM</u>: assumes that the process that caused baryon asymmetry also generated DM ⇒ Asymmetry between DM and anti-DM

Directly explains why the amounts of DM and ordinary matter are nearly of the same order of magnitude

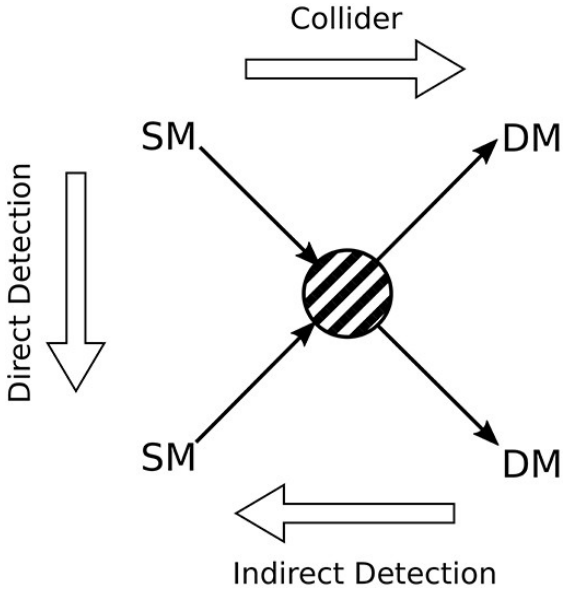
If N(DM) = N(protons, neutrons), then M(DM) ≈ 5×M(proton) ≈ 5 GeV



SEARCH FOR DARK MATTER PARTICLES

Three approaches to search for DM particles:

- **<u>Collider production</u>: search for excess of events with missing transverse energy due to new undetected particles (although not necessarily DM!)**
- **<u>Indirect detection</u>: search for excess of cosmic rays due to DM annihilation occurring in galaxy centers, etc**
- **<u>Direct detection</u> (more details later)**



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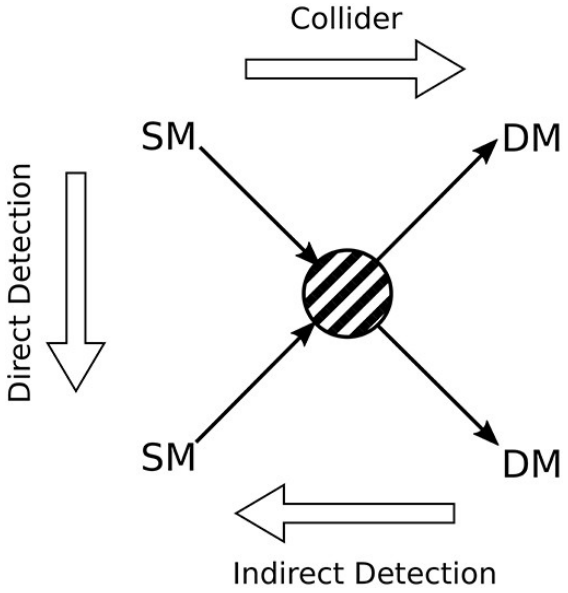

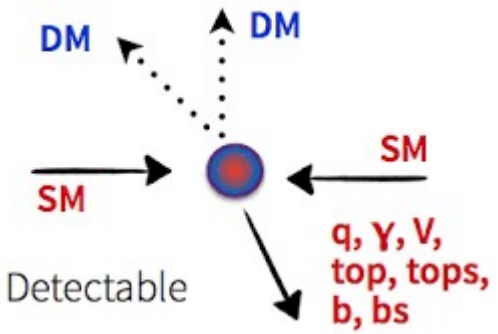

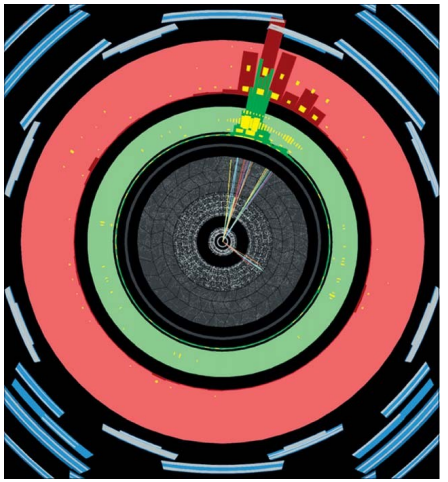

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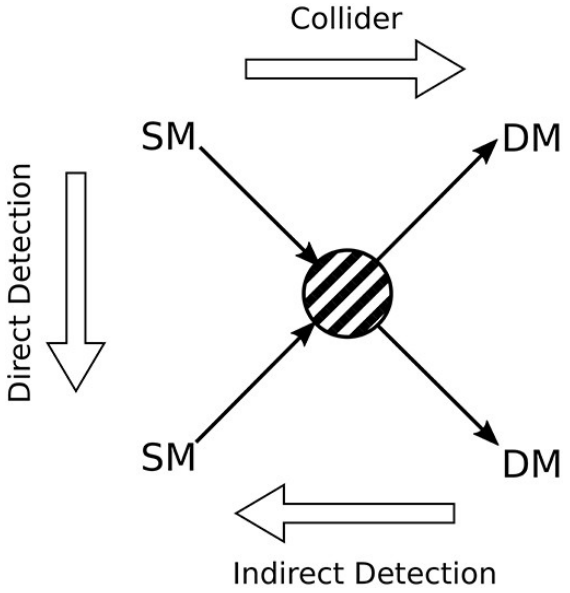

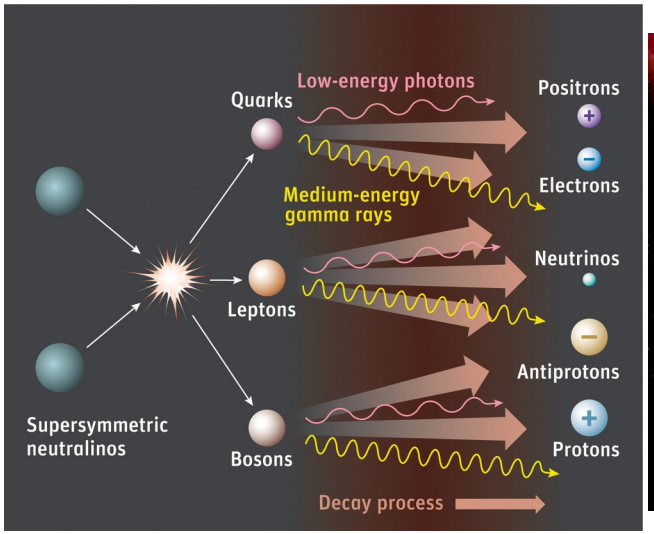

Fermi-LAT

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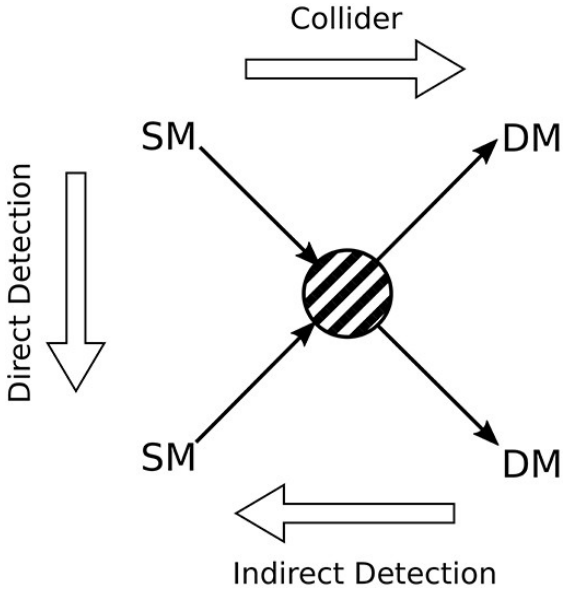
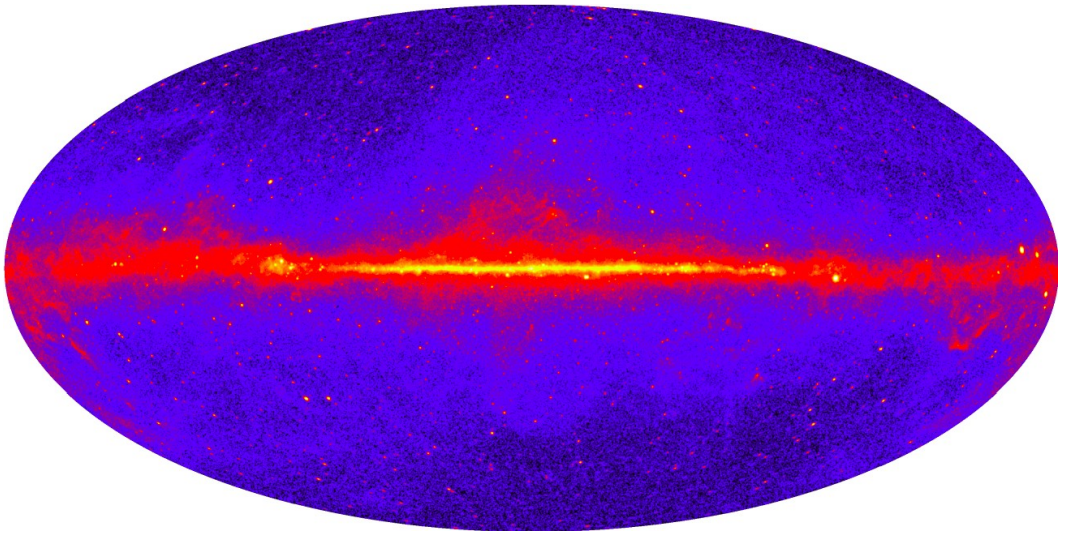




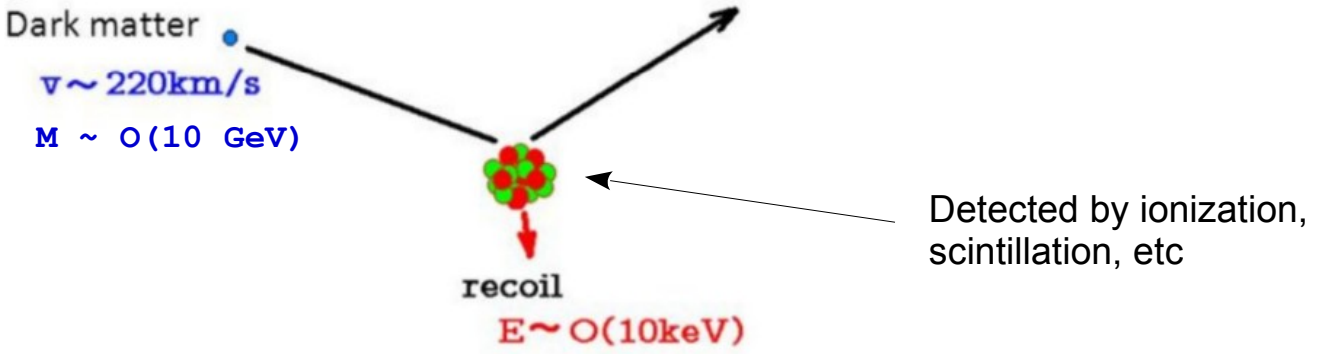
Gamma-ray map from Fermi-LAT

DIRECT DETECTION EXPERIMENTS

DM is expected to be distributed all over our galaxy, including our Solar System

Then, if DM has some coupling to SM particles, we expect it to interact with ordinary matter on Earth

Direct DM search: signal is a recoiling nucleus/electron, produced by the interaction with a DM particle



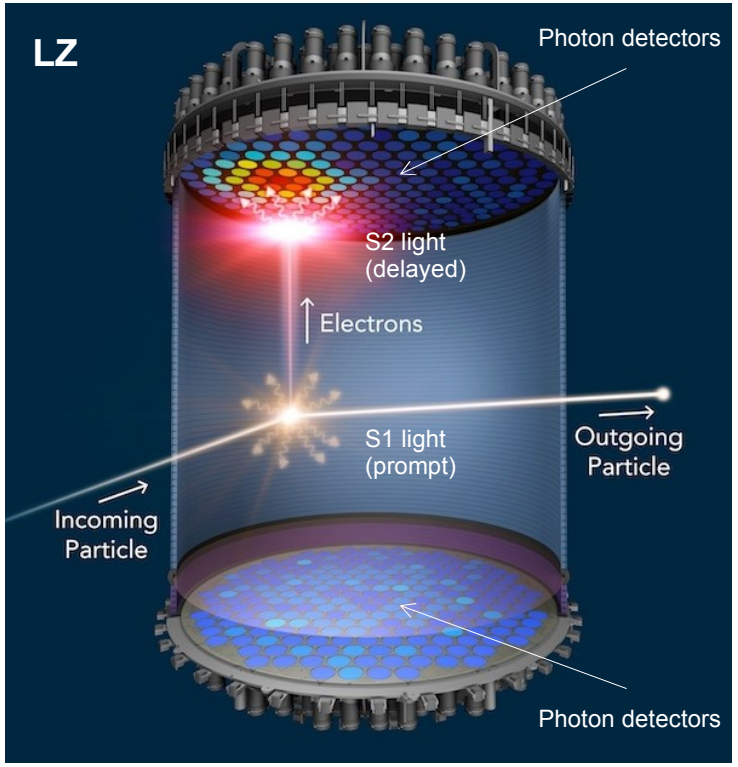
The greatest energy transfer occurs when M(target particle) ~ M(DM), therefore recoiling nuclei are preferred for M(DM) ~ 10 GeV – 100 GeV

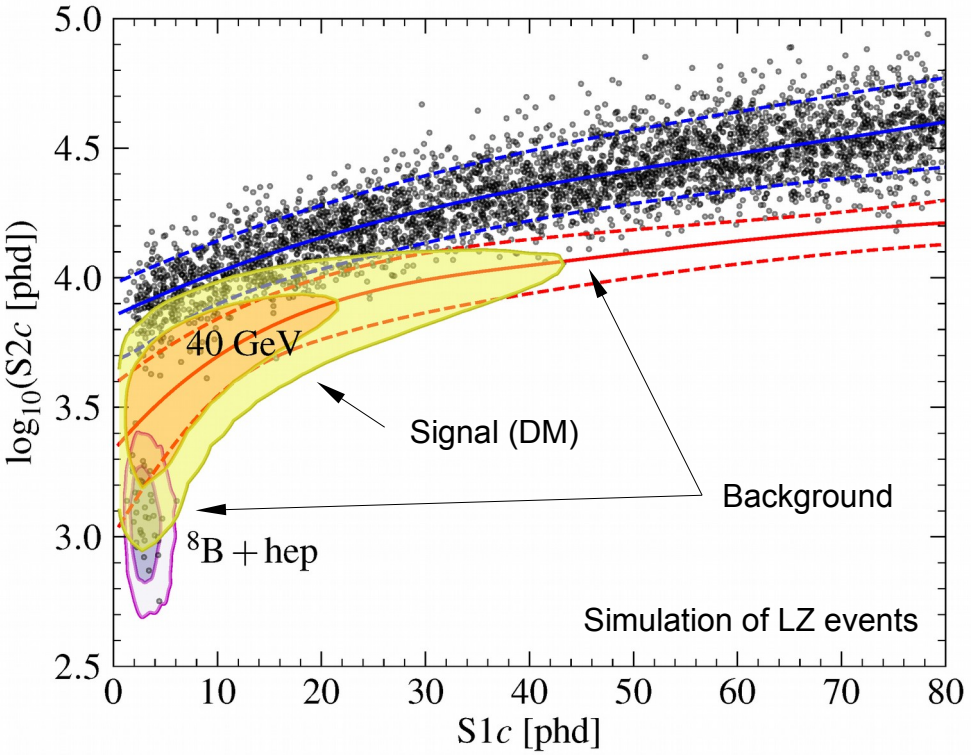
DIRECT SEARCH FOR DARK MATTER

Direct detection (DD) experiments consist of a specific target material that has also the ability to detect recoiling particles

Experiments usually combine signals to identify recoiling nuclei:

- **Ionization+scintillation: LZ, XENON (Xe), DarkSide (Ar)**





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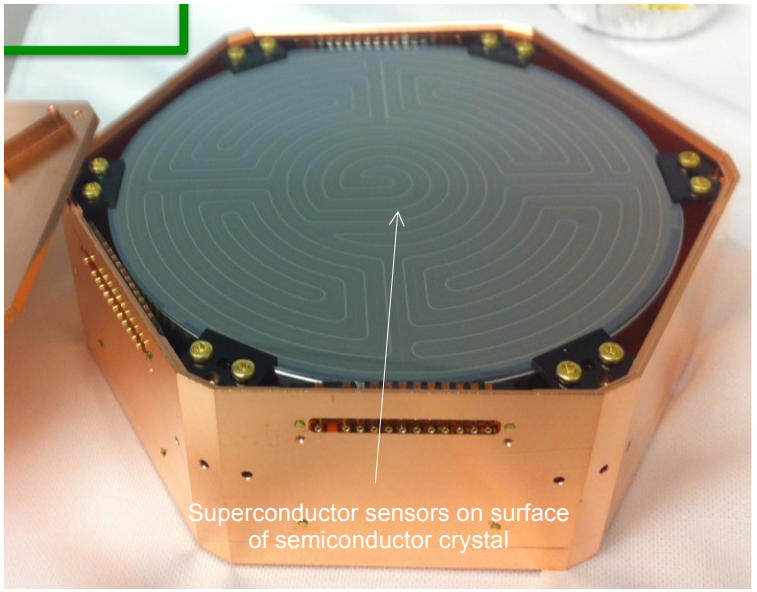

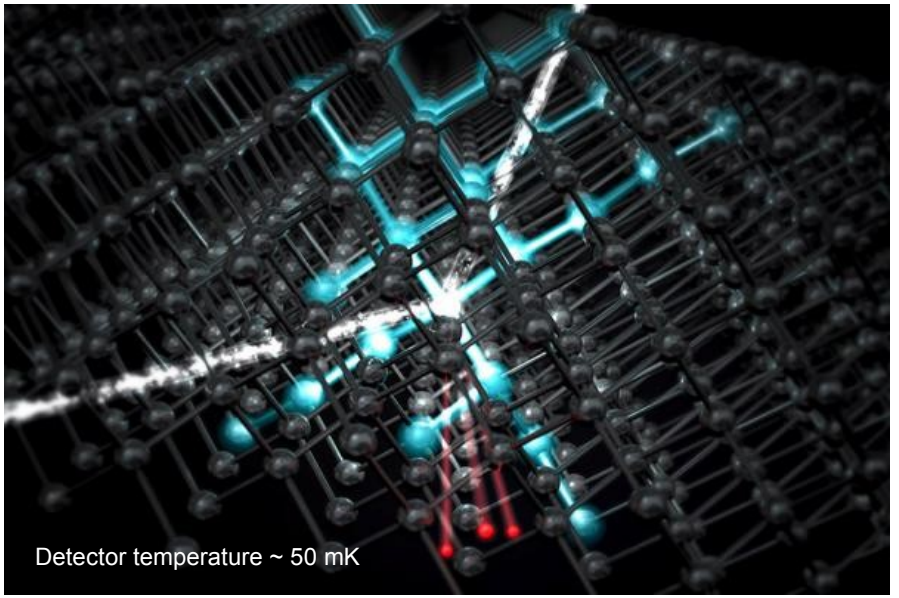

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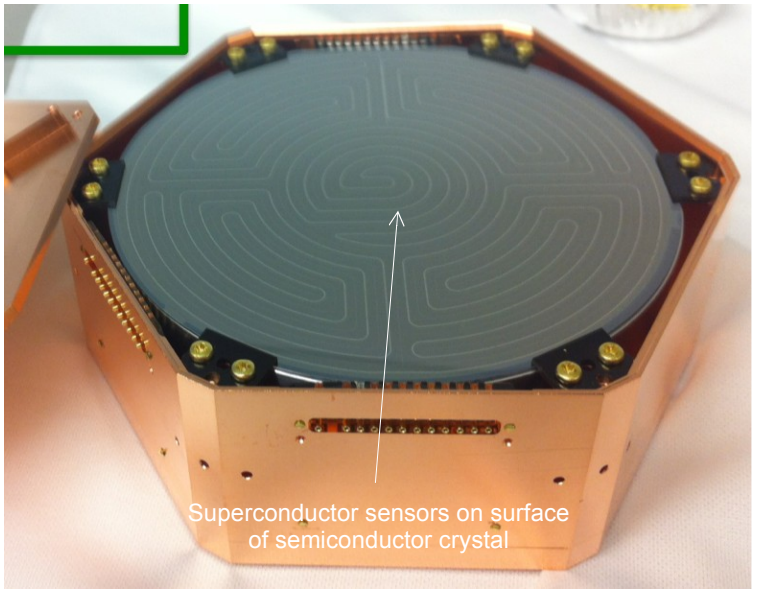
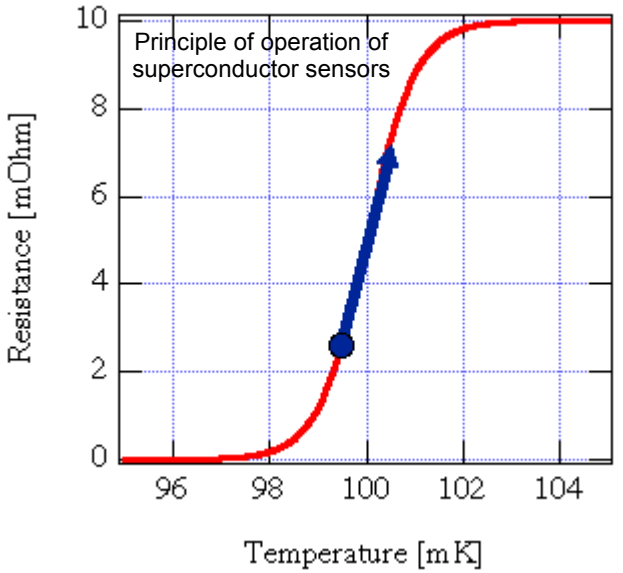




DIRECT SEARCH FOR DARK MATTER

Direct detection (DD) experiments consist of a specific <u>target</u> material that has also the ability to <u>detect recoiling particles</u>

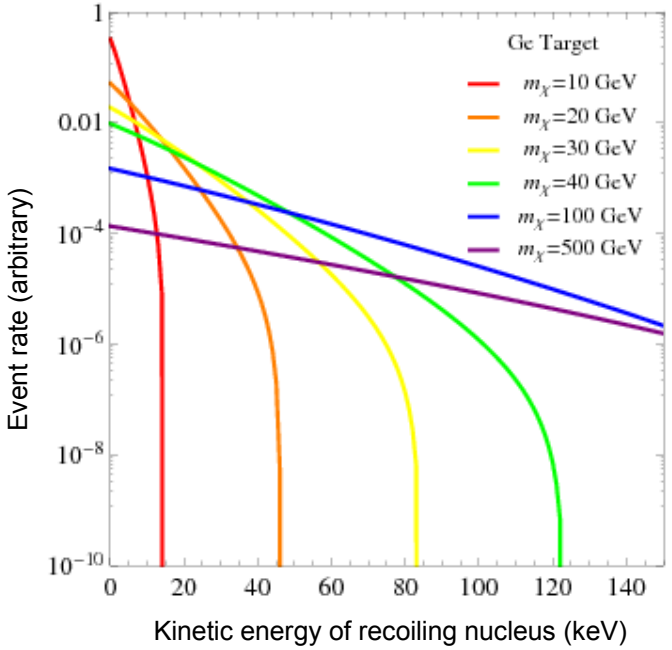
Experiments usually combine signals to identify recoiling nuclei:

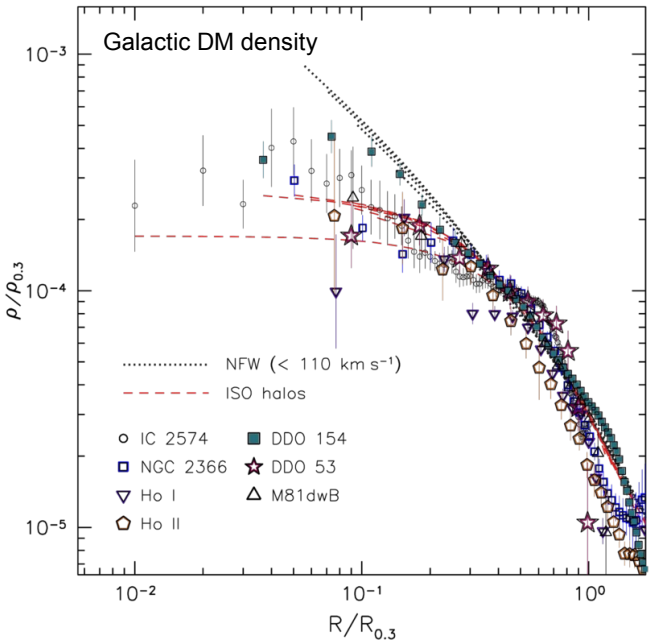
- **Phonons+scintillation: CRESST ($CaWO_4$)**

DIRECT SEARCH FOR DARK MATTER

- **Energy spectrum of recoiling nuclei depends on <u>mass of DM particles</u> (M_χ)**
- **Number of recoiling nuclei depends on <u>strength of DM-nucleon interaction</u> ($\sigma_{\chi N}$)**

The <u>density</u> and <u>velocity distribution</u> of DM particles are assumed to be known





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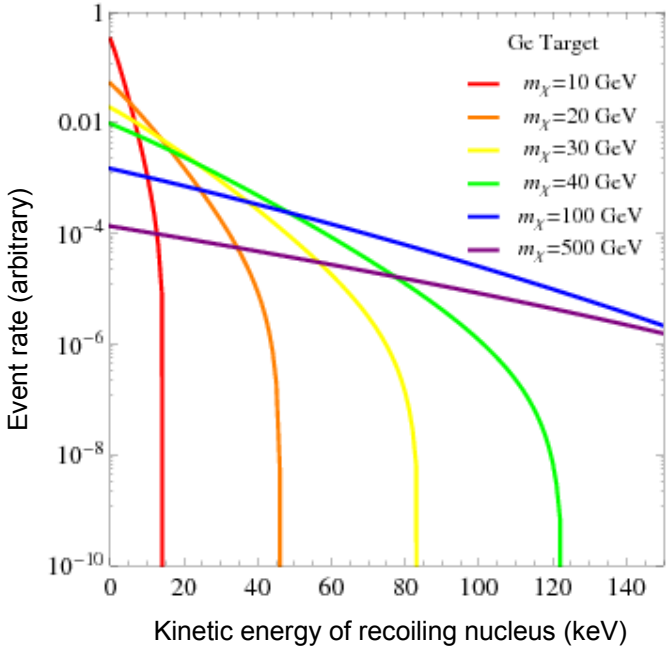
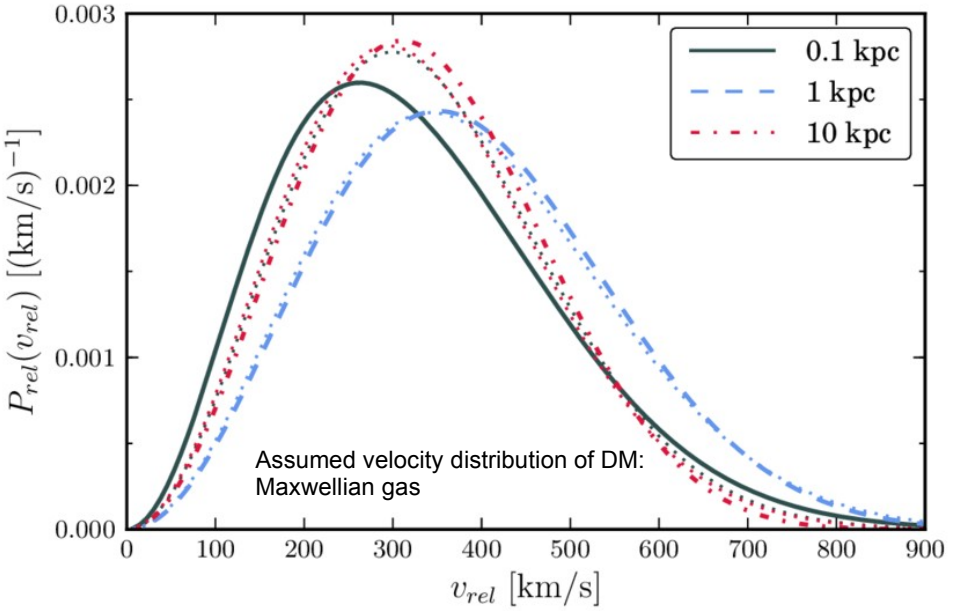


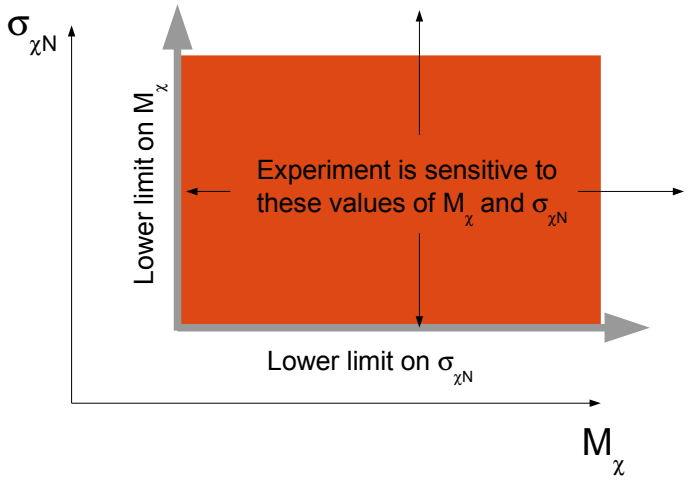


DIRECT SEARCH FOR DARK MATTER

Therefore, the result of a DD experiment provides information about the existence of DM particles with specific values of M_χ and $\sigma_{\chi N}$

The minimum value of $\sigma_{\chi N}$ that can be attained depends on:

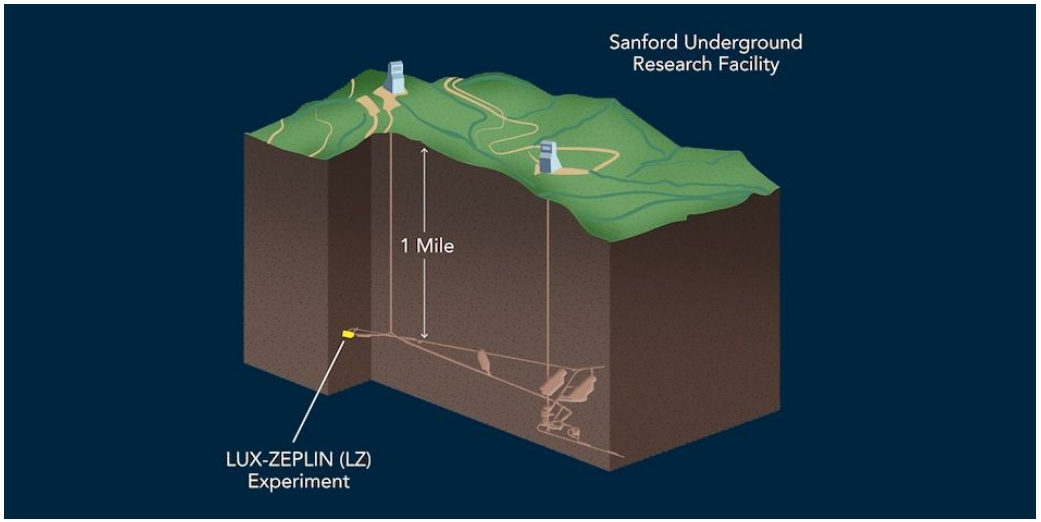
- **The number of target nuclei (i. e. the amount of target material)**
- **The exposure time**
- **The occurrence of events other than recoiling nuclei caused by DM: <u>Background</u>**

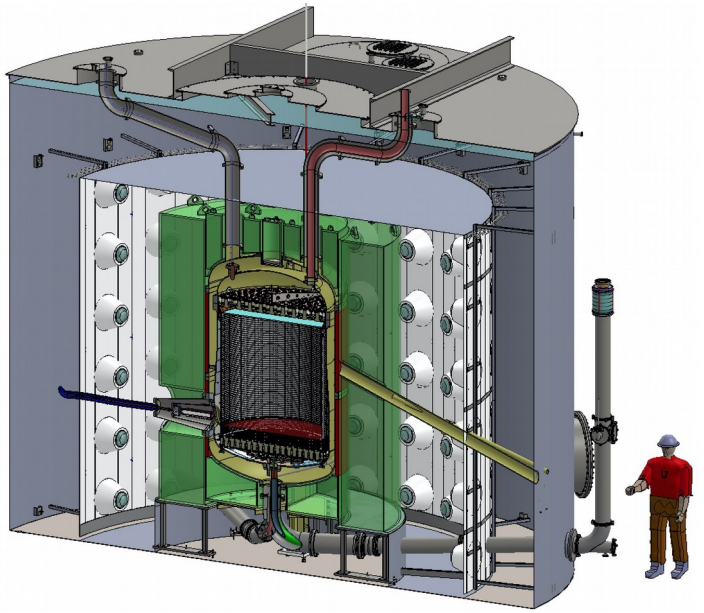


DIRECT SEARCH FOR DARK MATTER

Background sources:

- **Cosmic radiation reaching Earth surface (muons) ⇒ Underground laboratories**
- **External radioactivity (gammas, neutrons) ⇒ Shielding+radiopure materials**
- **Internal radioactivity (betas) ⇒ Purification of target material**





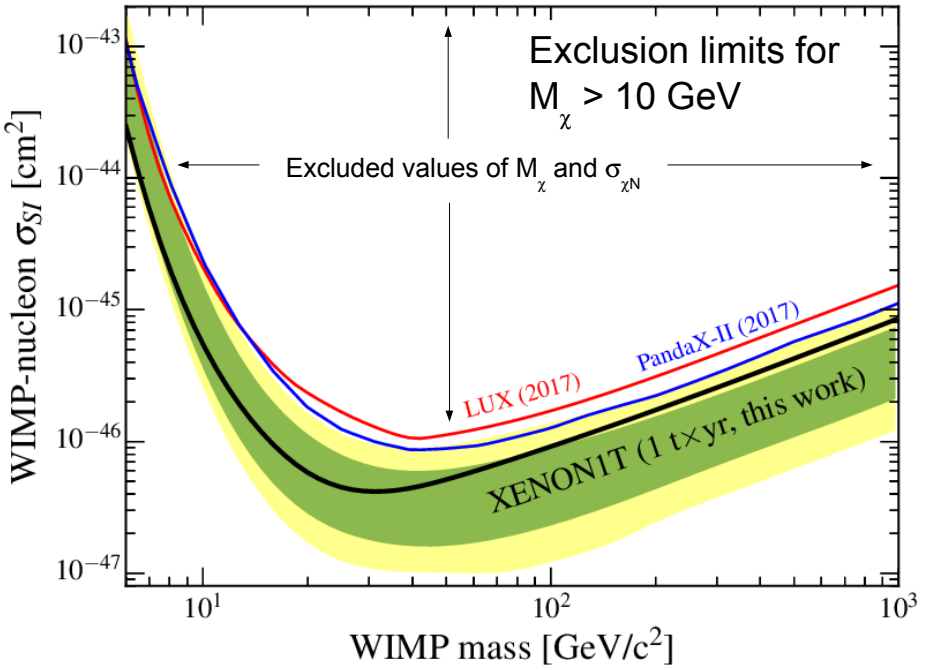
LZ shielding+cryostat+TPC

DIRECT SEARCH FOR DARK MATTER

Traditionally, DD experiments have searched for DM particles with mass ~10 GeV – 100 GeV (WIMPs)

But: So far, these experiments have not found a conclusive DM signal yet

The null results obtained so far constrain the value of m_χ and $\sigma_{\chi N}$



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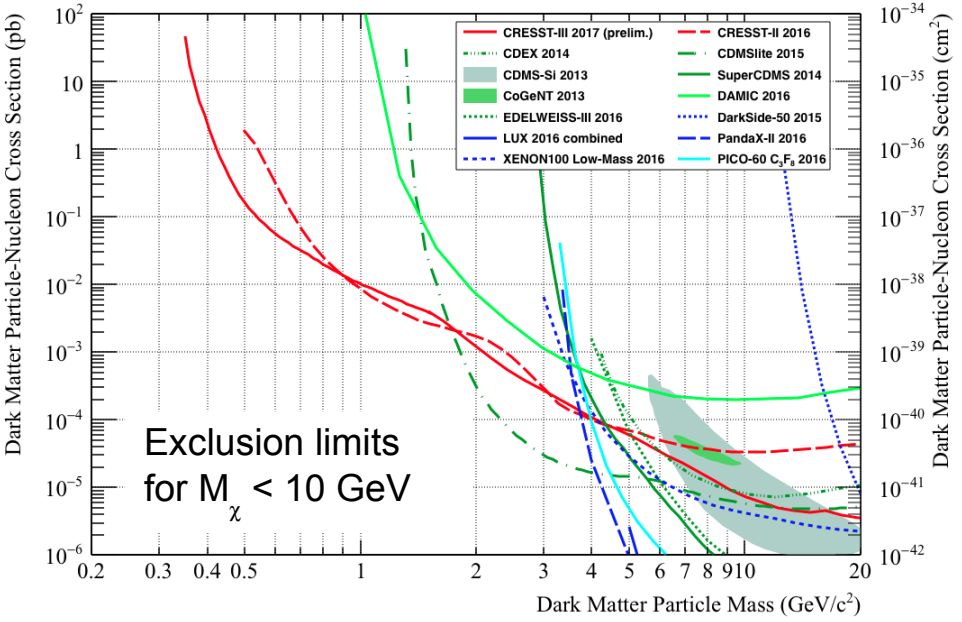

(*) DarkSide-50 results (2018) not included

CONCLUSIONS

- **The existence of DM is based on very strong evidences, but we do not know what it is made of yet ($\Rightarrow$ new physics)**
- **There are many theories to explain DM, that predict particle candidates that extend over a wide range of masses**
- **Determining the elementary constituents of DM is one of the most pressing objectives of modern science**
- **There are three approaches to search for DM particles: collider production, indirect detection and direct detection**
- **Direct searches aim to detect atomic constituents (nuclei or electrons) that recoil due to interactions with DM particles**
- **So far direct detection experiments have not provided a conclusive signal, therefore motivating further research in this area**

THANK YOU FOR YOUR ATTENTION...