Introduction to dark matter and neutrinos

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Estágios de verão, LIP, 16th of July 2020

OVERVIEW

Dark matter

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

Neutrinos

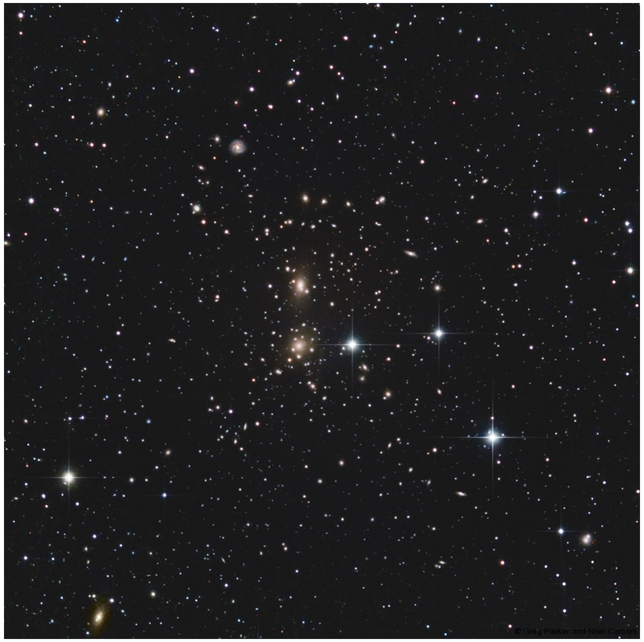
- History of neutrinos
- Open questions in neutrino physics
- Neutrino experiments

Dark matter

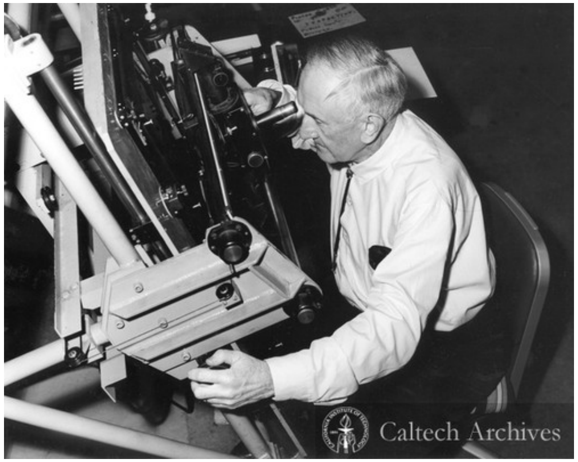
EVIDENCES FOR DARK MATTER

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)

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



Coma cluster



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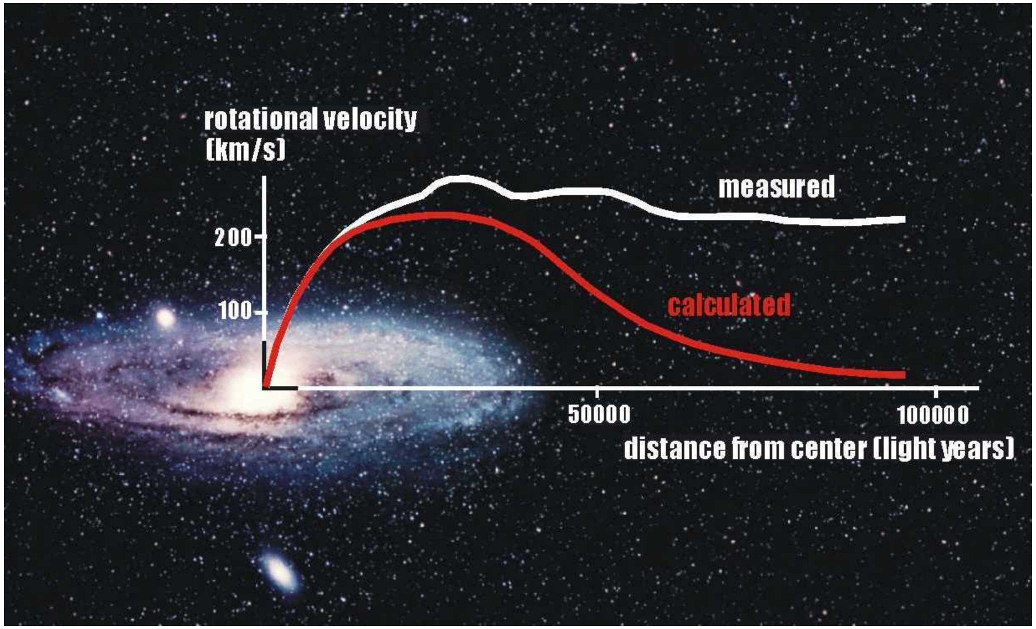
Stars in galaxies (~100 kpc) rotate much faster than expected (Vera Rubin, 1970)



Andromeda galaxy

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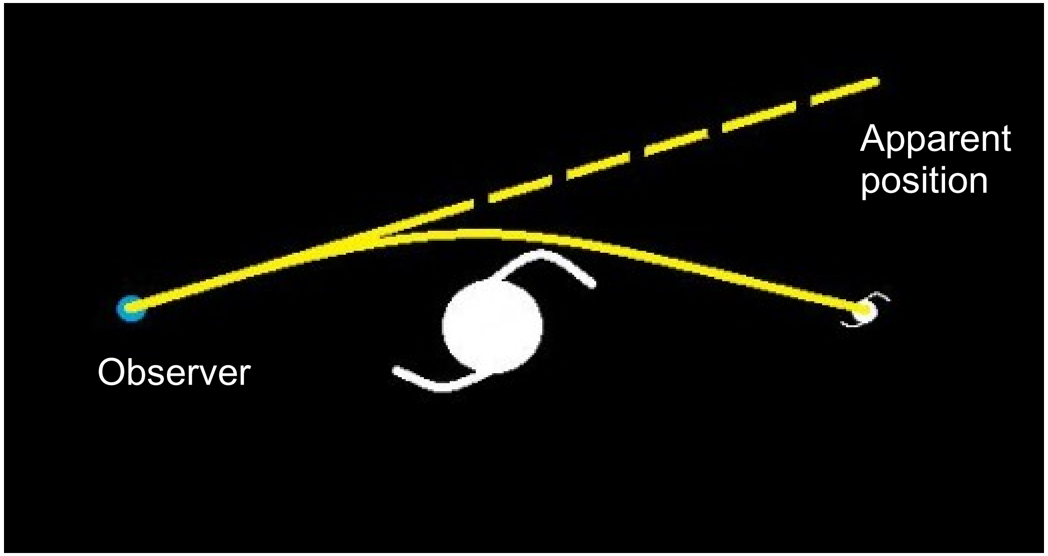
Gravitational lensing, Bullet Cluster, etc



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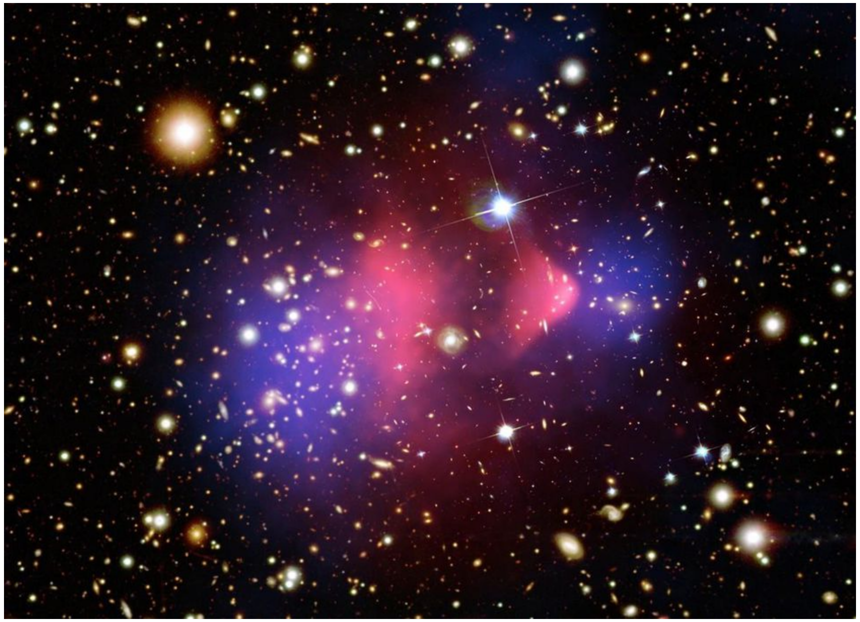

Bullet Cluster

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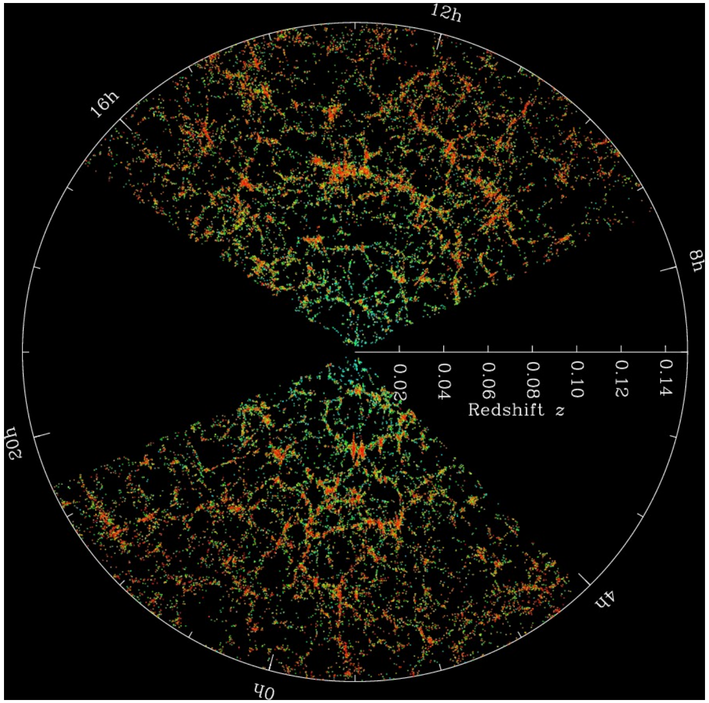
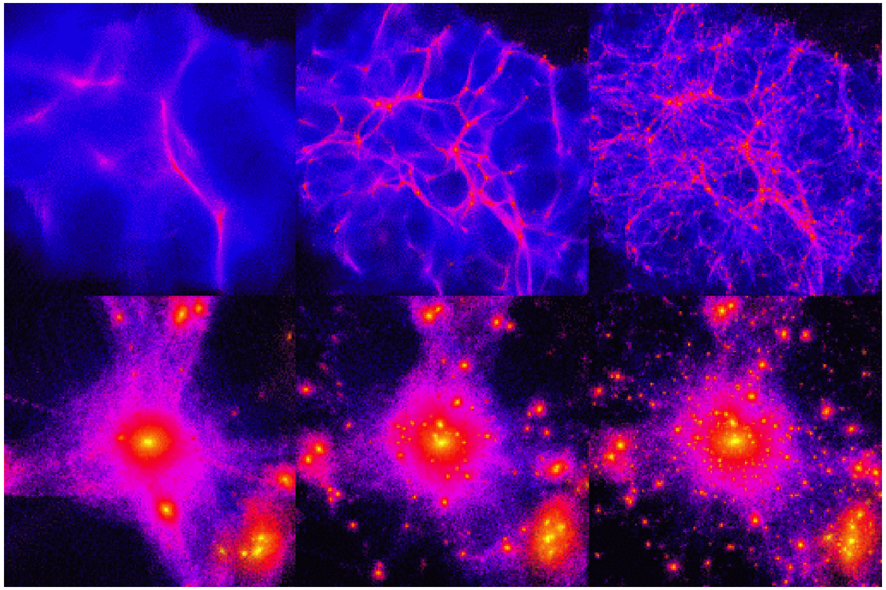
Large-scale structure of the universe (<u>~1 Gpc</u>)





Hot DM | Warm DM | **Cold DM**

EVIDENCES FOR DARK MATTER

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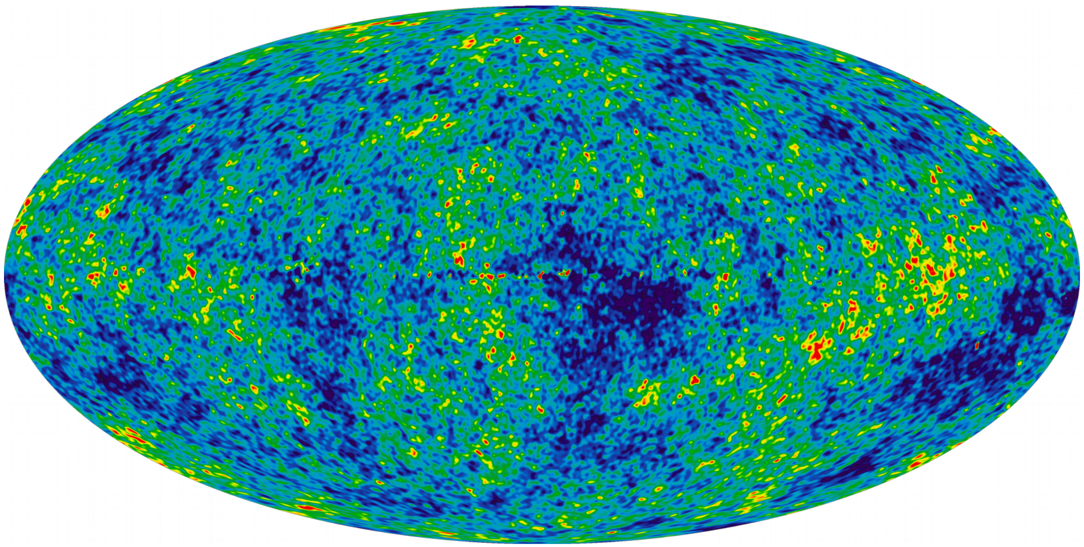
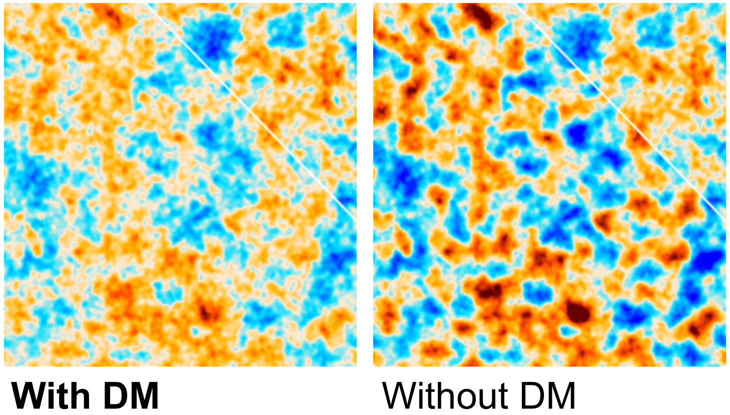
Anisotropies in cosmic microwave background (<u>entire universe</u>)



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



THE DARK MATTER PROBLEM

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

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

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

But what is DM made of?

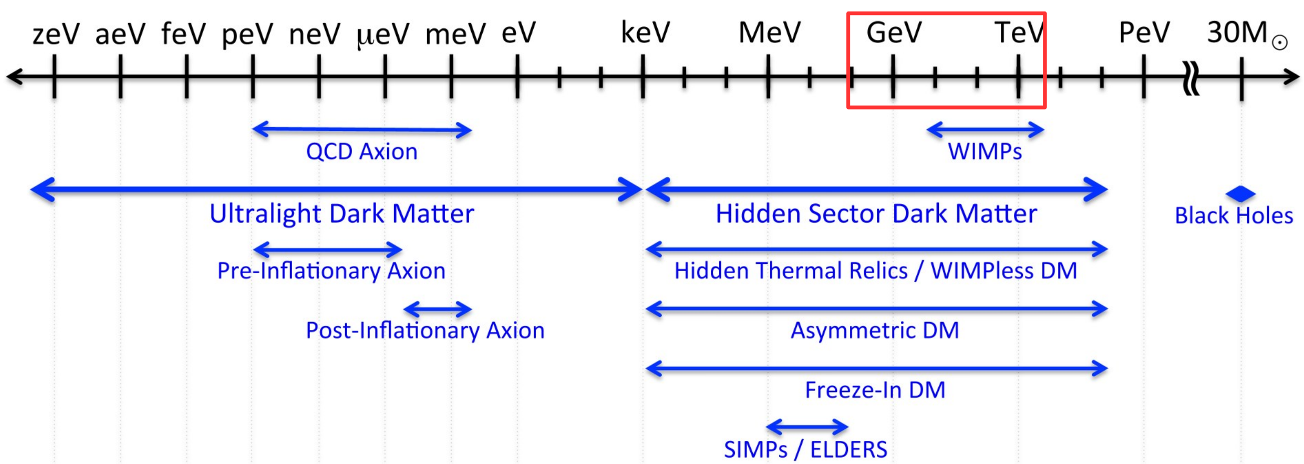
- **Its elementary constituents are <u>neutral</u> (because they do not interact with electromagnetic radiation): excludes quarks and charged leptons**
- **It is <u>cold</u>: excludes neutrinos**

Standard Model (SM) particles cannot account for DM $\Rightarrow$ <u>New elementary particles?</u>

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



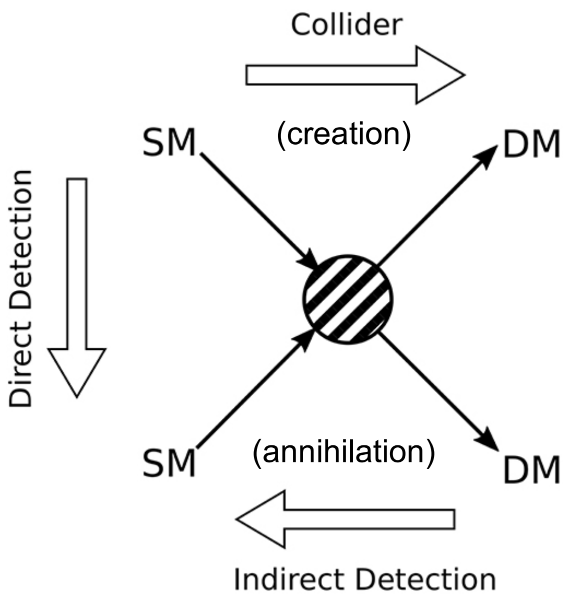
Weakly-interacting massive particles (<u>WIMPs</u>): assume that DM interacts with ordinary matter through the SM weak interaction

WIMPs allow to <u>explain the observed amount of DM in the universe</u>

SEARCH FOR DARK MATTER PARTICLES

Three approaches to search for DM particles:

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



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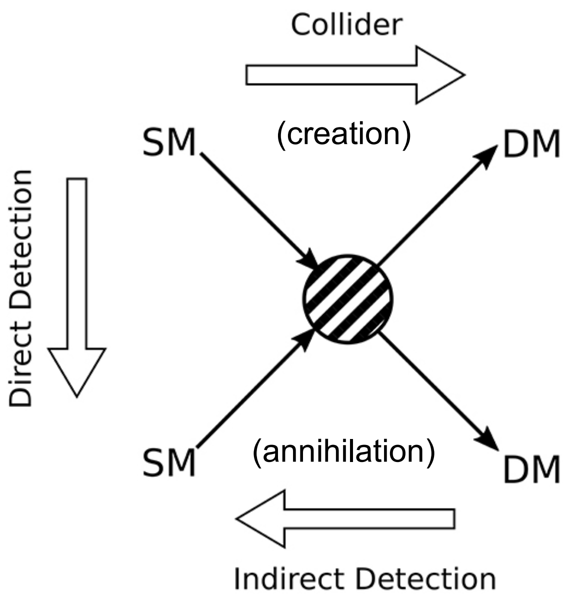

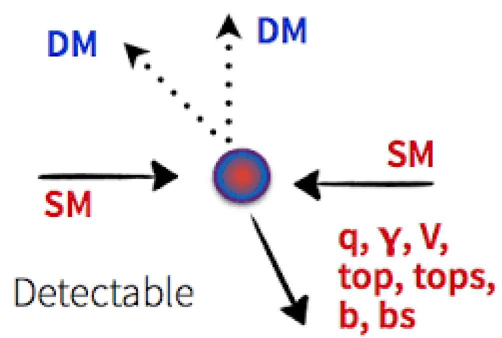

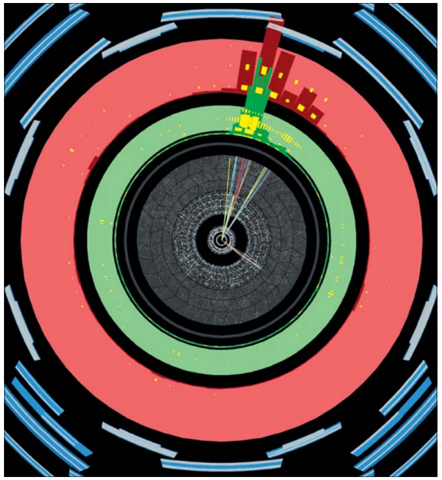

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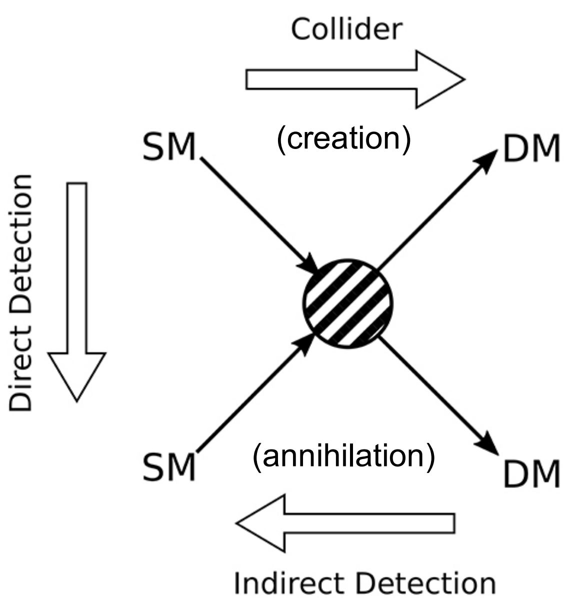

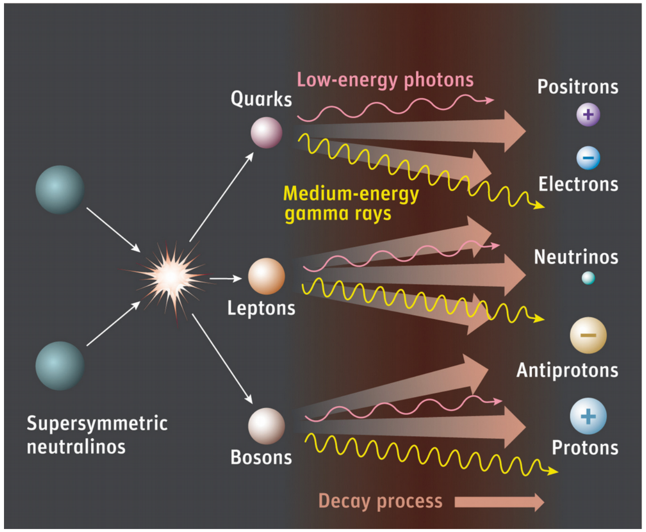

Fermi-LAT

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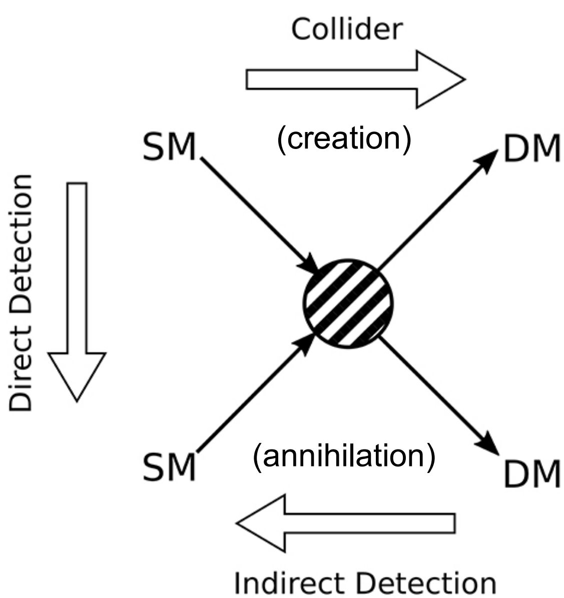
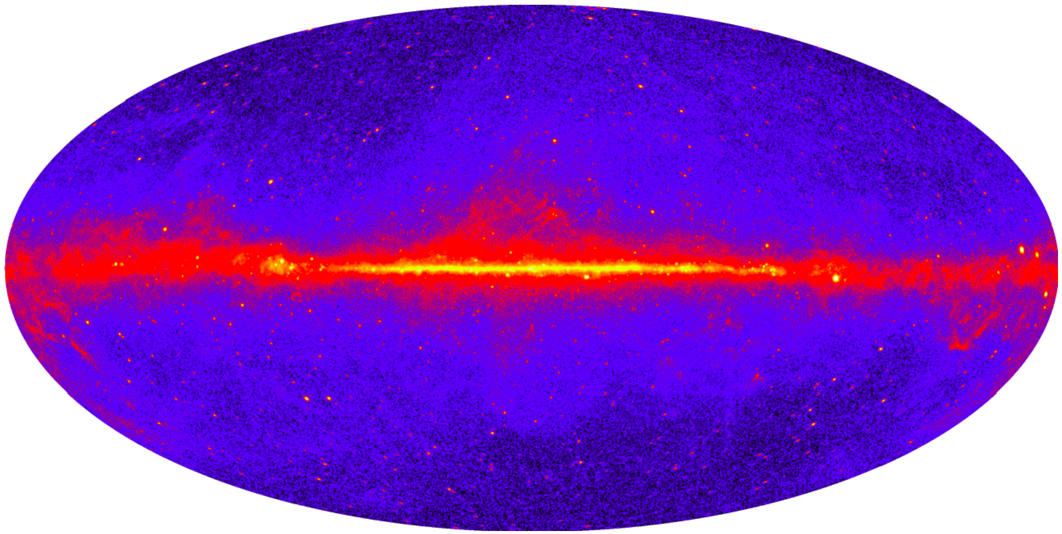




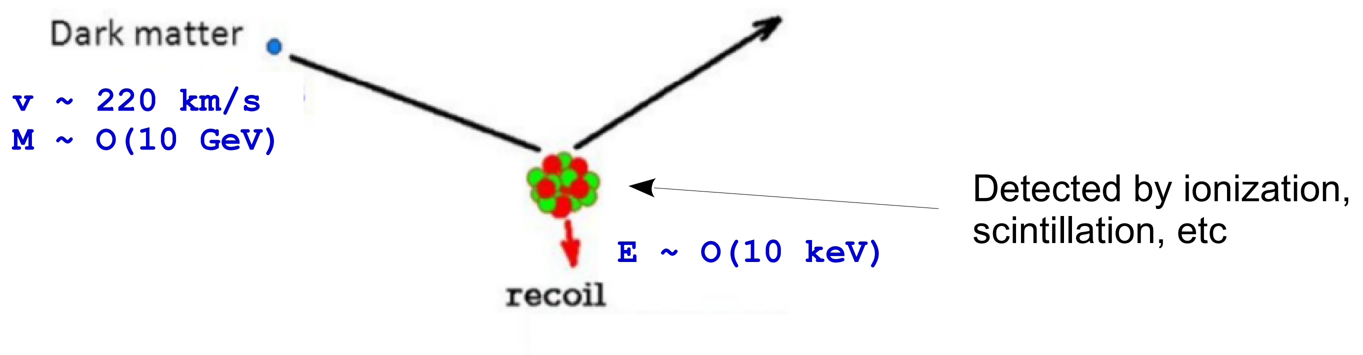
Gamma-ray map from Fermi-LAT

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 experiments: place a detector in a <u>low radiation environment</u> (suppressed radioactivity, etc), and search for an <u>excess of recoiling nuclei or electrons</u>, that could be produced by interactions with DM particles



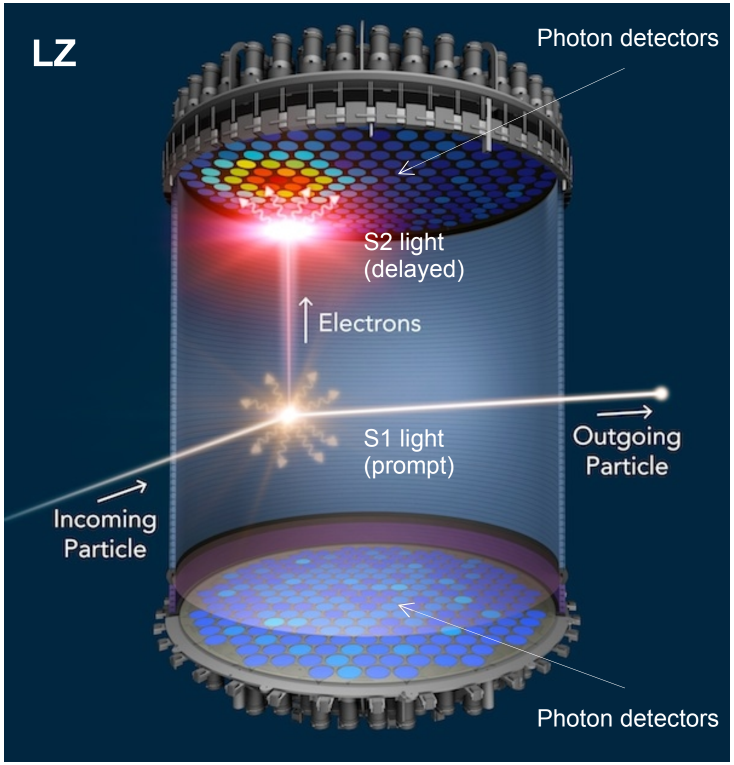
The greatest energy transfer occurs when M(target particle) ~ M(DM), therefore recoiling nuclei are preferred for M(DM) ~ 10 GeV – 100 GeV

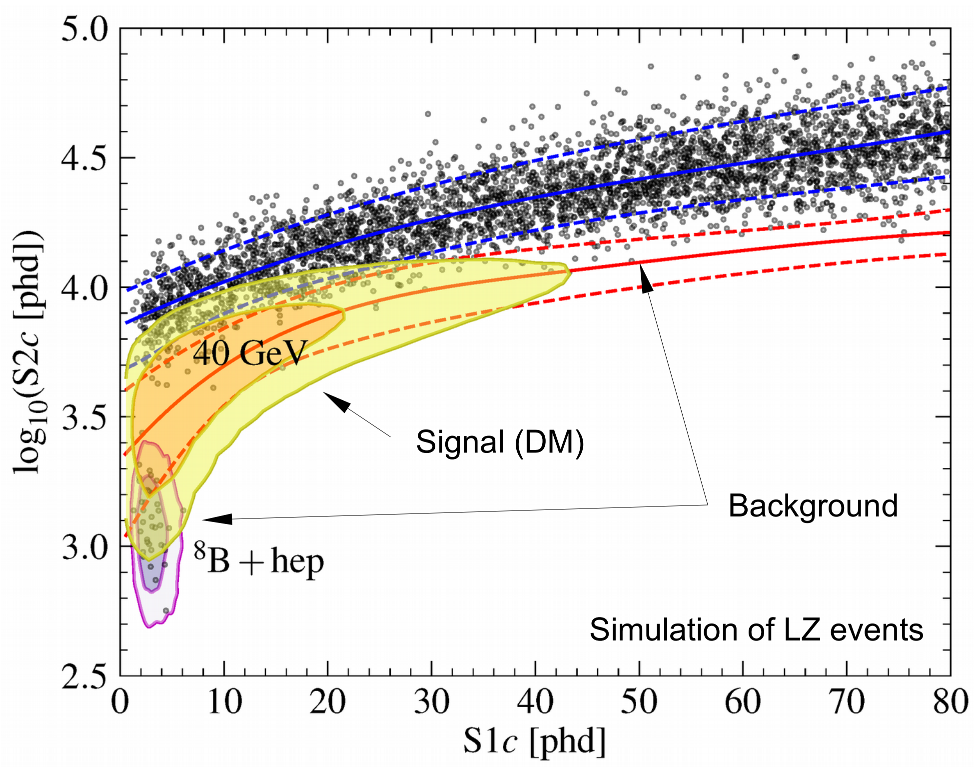
DIRECT SEARCH FOR DARK MATTER

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

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

In addition, need to reject events from known processes (<u>background</u>)





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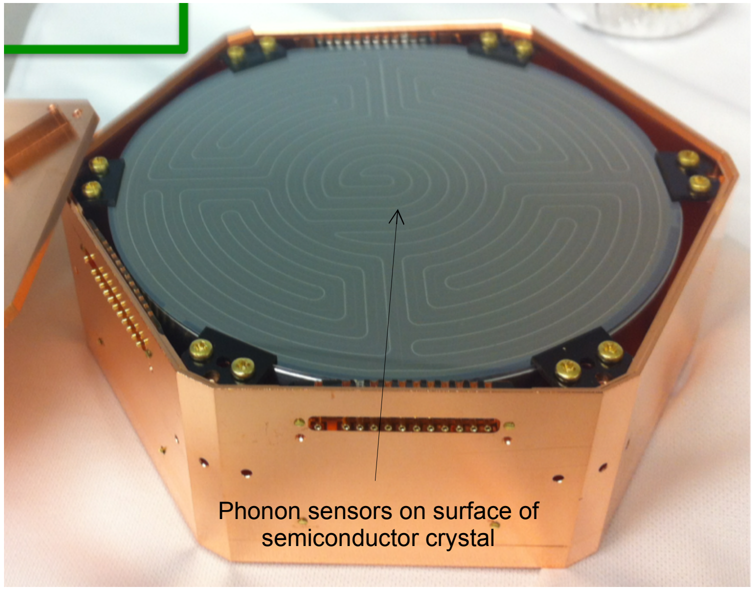
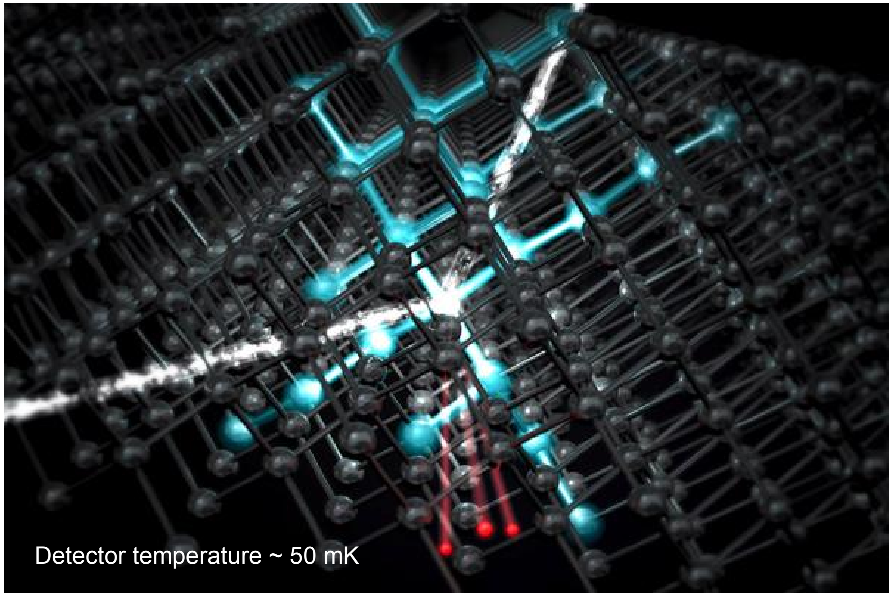
- **Phonons+ionization: SuperCDMS (Ge, Si), EDELWEISS (Ge)**

In addition, need to reject events from known processes (<u>background</u>)



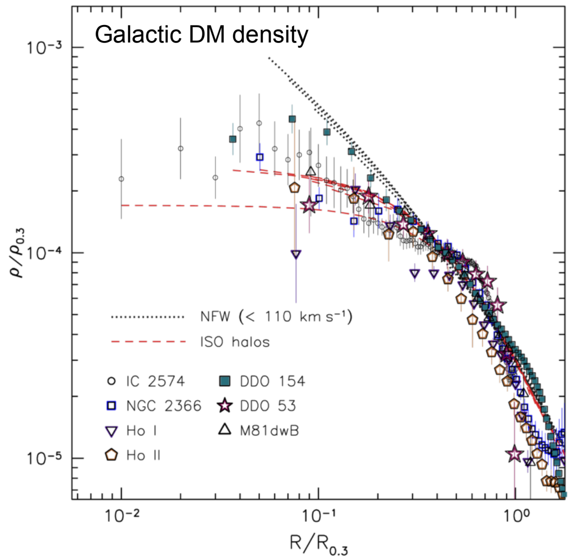
SuperCDMS detector unit



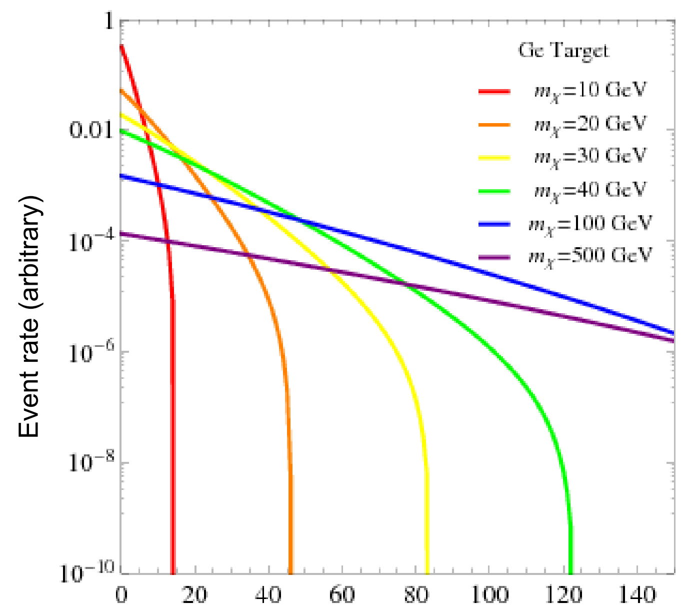
DIRECT SEARCH FOR DARK MATTER

Assuming that we know the <u>density</u> and <u>velocity distribution</u> of DM particles in the Solar System:

- **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> ($\sigma_{\chi N}$)**



DM velocity distribution: regular gas (Maxwell-Boltzmann distribution)



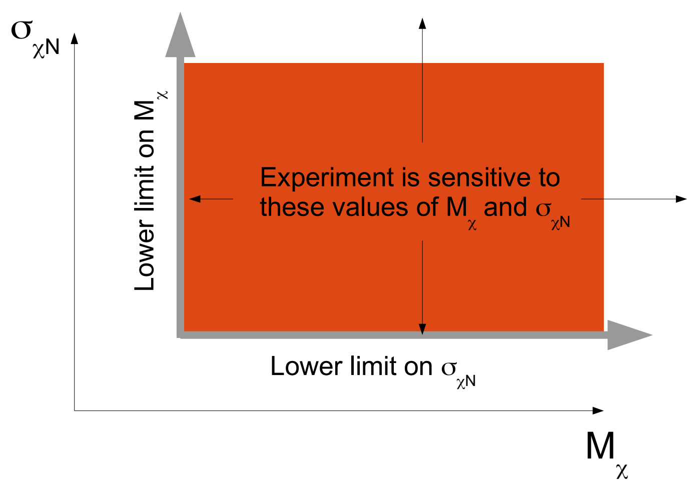
DIRECT SEARCH FOR DARK MATTER

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 M_χ that can be attained is determined by the minimum energy that can be measured by the detector

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

- **The number of target nuclei (amount of target material) and exposure time**
- **The background levels (events from known processes)**

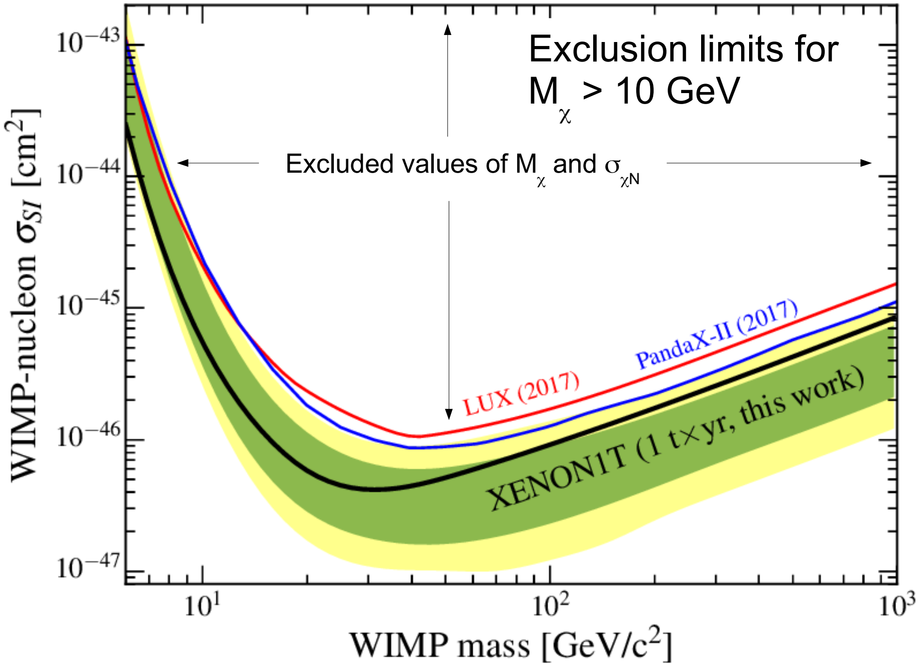


DIRECT SEARCH FOR DARK MATTER

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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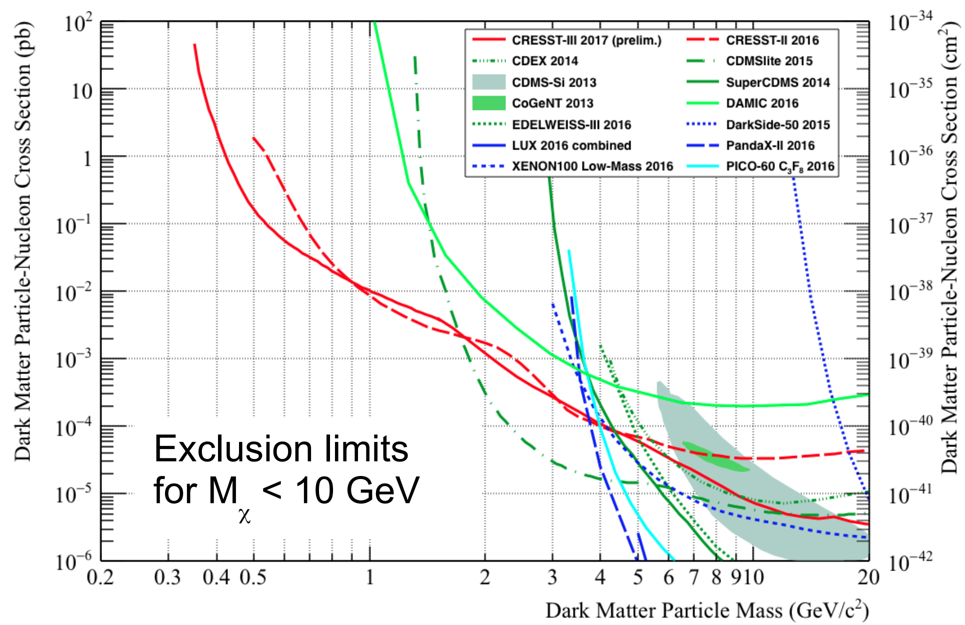


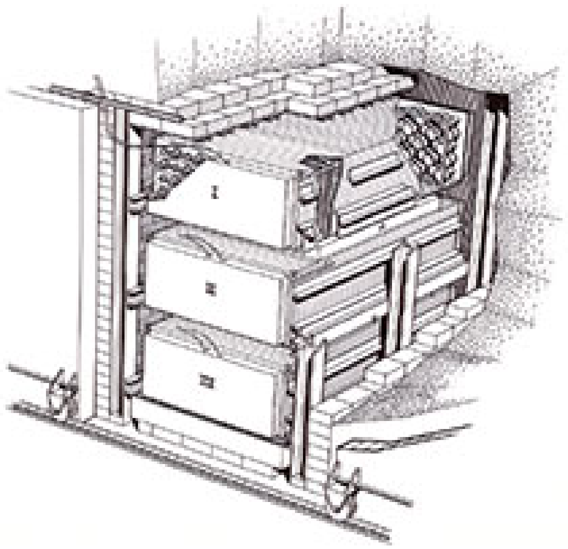
(*) DarkSide-50 results (2018) not included

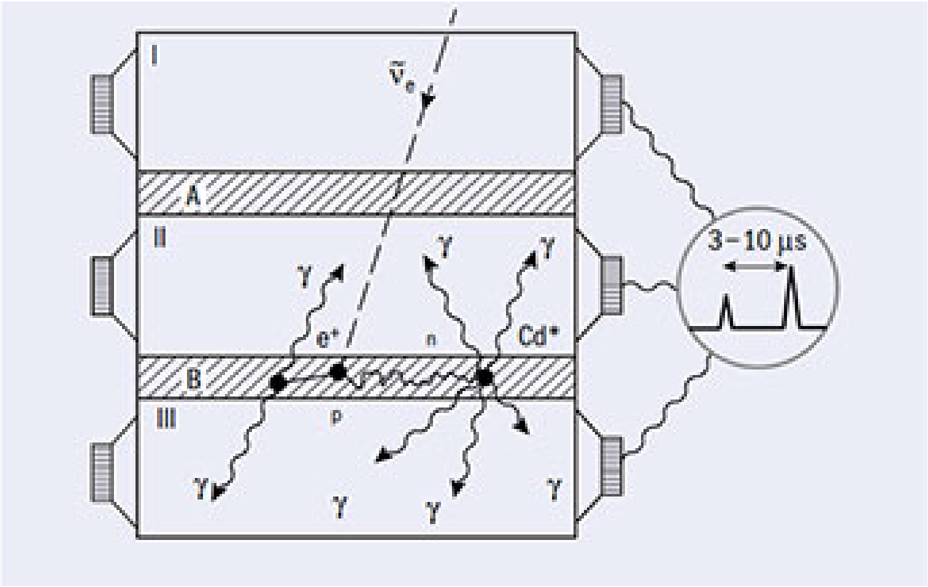
Neutrinos

HISTORY OF NEUTRINOS

Neutrino was introduced to enforce energy and momentum conservation in beta decay (Pauli, 1931)

Discovered by detecting reactor neutrinos via $\nu + p \rightarrow n + e^{+}$ (Cowan and Reines, 1956)

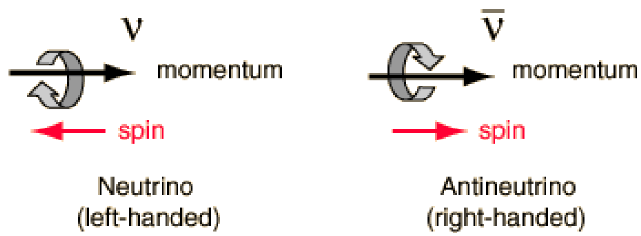


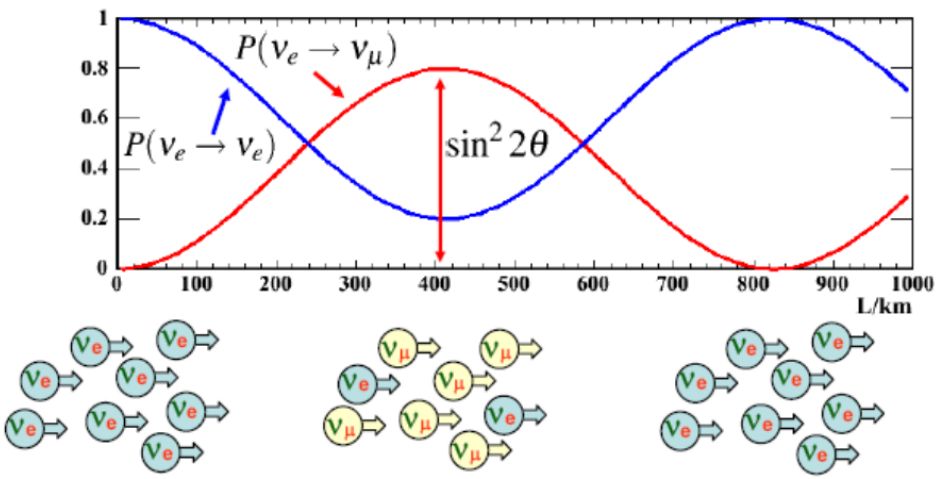


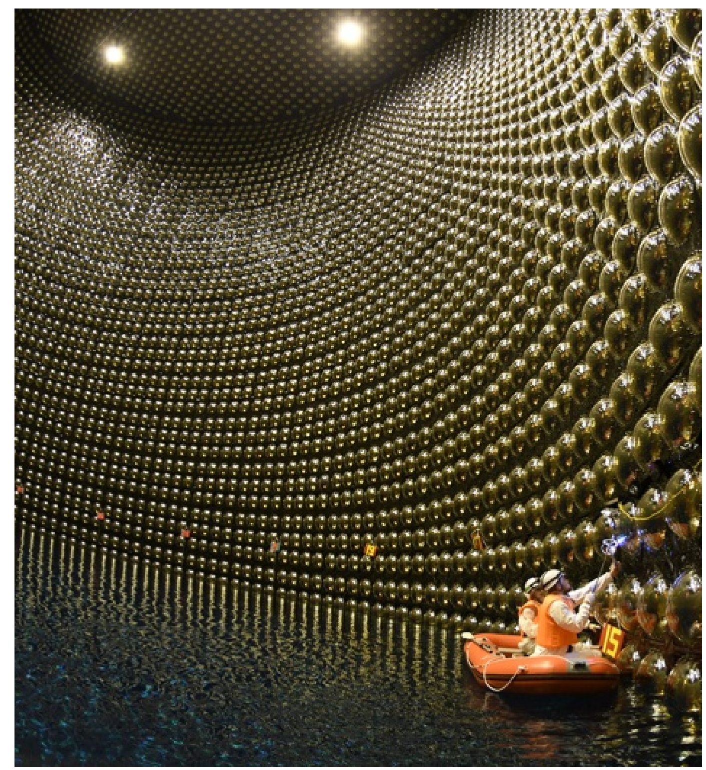
HISTORY OF NEUTRINOS

From reaction $^{152m}Eu + e^- \rightarrow \nu + {}^{152}Sm^* \rightarrow \nu + {}^{152}Sm + \gamma$ **it was established that <u>only left-handed neutrinos exist</u> (Goldhaber, 1957)**

The observation of neutrino flavour oscillation established that <u>neutrinos have non-zero mass</u> (SuperKamiokande Collaboration, 1998)







OPEN QUESTIONS IN NEUTRINO PHYSICS

<u>The neutrino masses have not been determined yet</u>, but from experiments we know that they must be below 1.1 eV

Particles that couple to Higgs boson change their chirality (left-handed to right-handed, or *vice versa*) ⇒ Only left-handed neutrinos exist, therefore they can not couple to Higgs boson

Higgs mechanism is not valid to explain neutrino masses ⇒ <u>New physics</u>

One proposed solution: neutrino might be a <u>Majorana fermion</u>

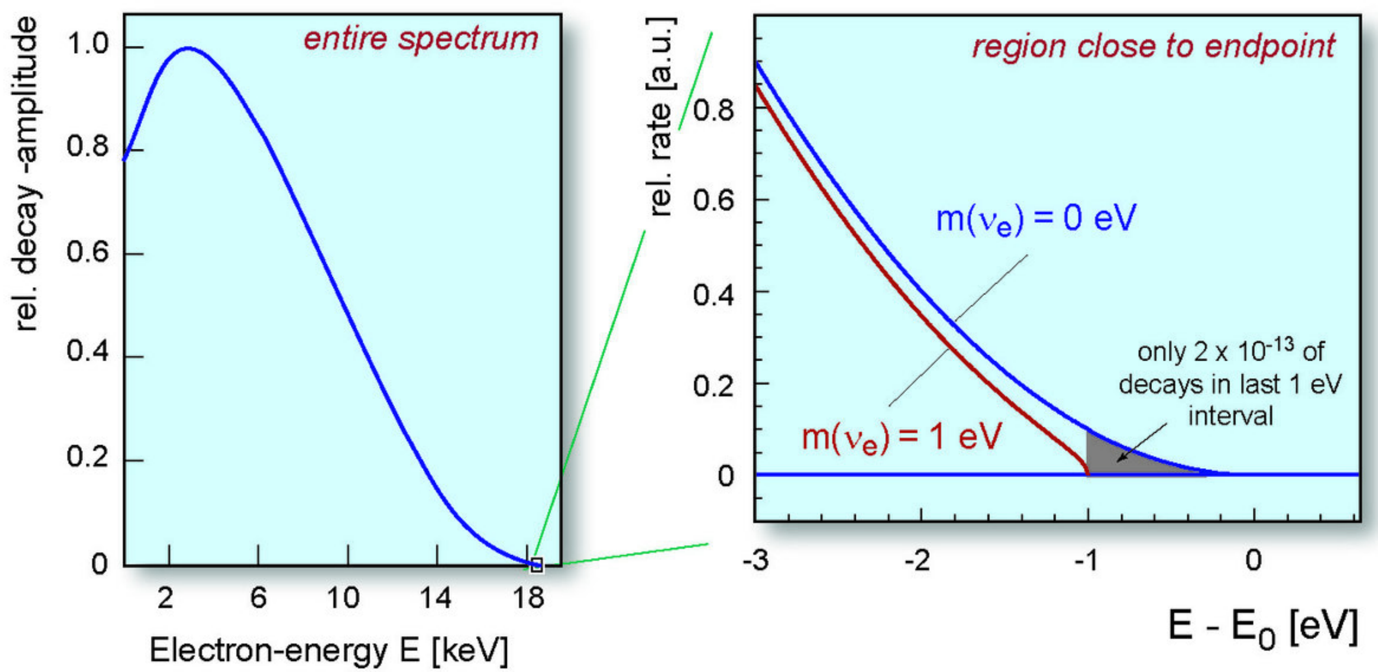
- **Dirac fermion: particle and antiparticle are different fermions. Quarks and leptons are Dirac fermions**
- **Majorana fermions: particle and antiparticle are the same fermion (in different states)**

Besides, <u>CP violation</u> might be present in neutrino flavour oscillations, as observed in quark flavour mixing

NEUTRINO EXPERIMENTS

Several neutrino experiments aim to address these open questions:

- **<u>Neutrino mass</u>: study of end-point of tritium (^3H) beta decay spectrum**
- **<u>Majorana neutrinos</u>: search for neutrinoless double-beta (0ν2β) decay**
- **<u>CP violation</u>: study of differences between neutrino and antineutrino oscillations**



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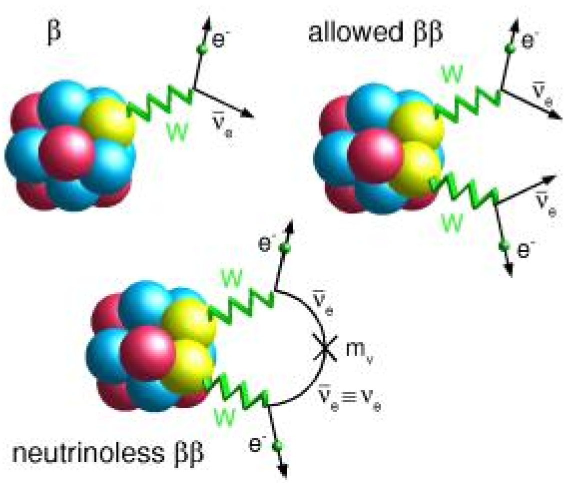

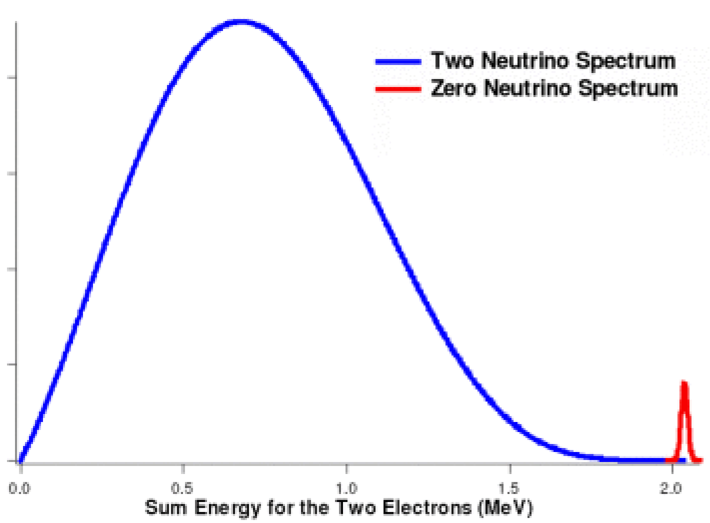

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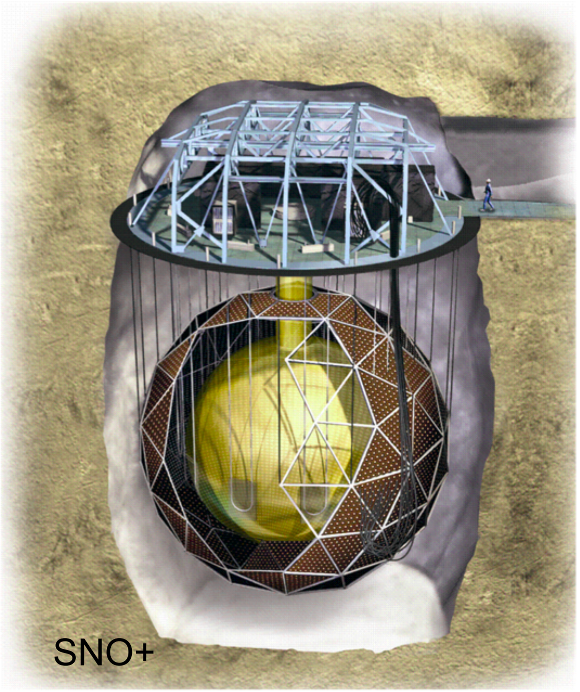

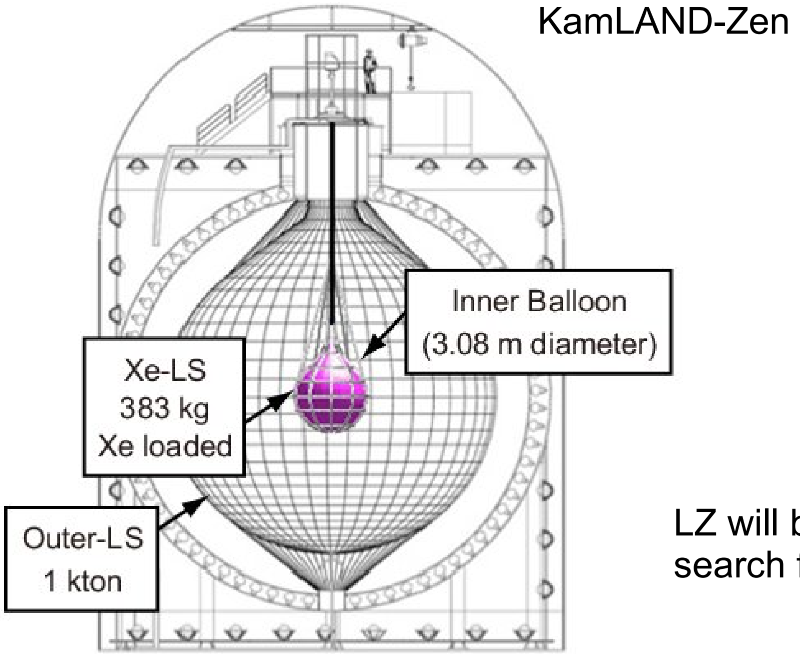

LZ will be also competitive to search for 0ν2β decay in Xe

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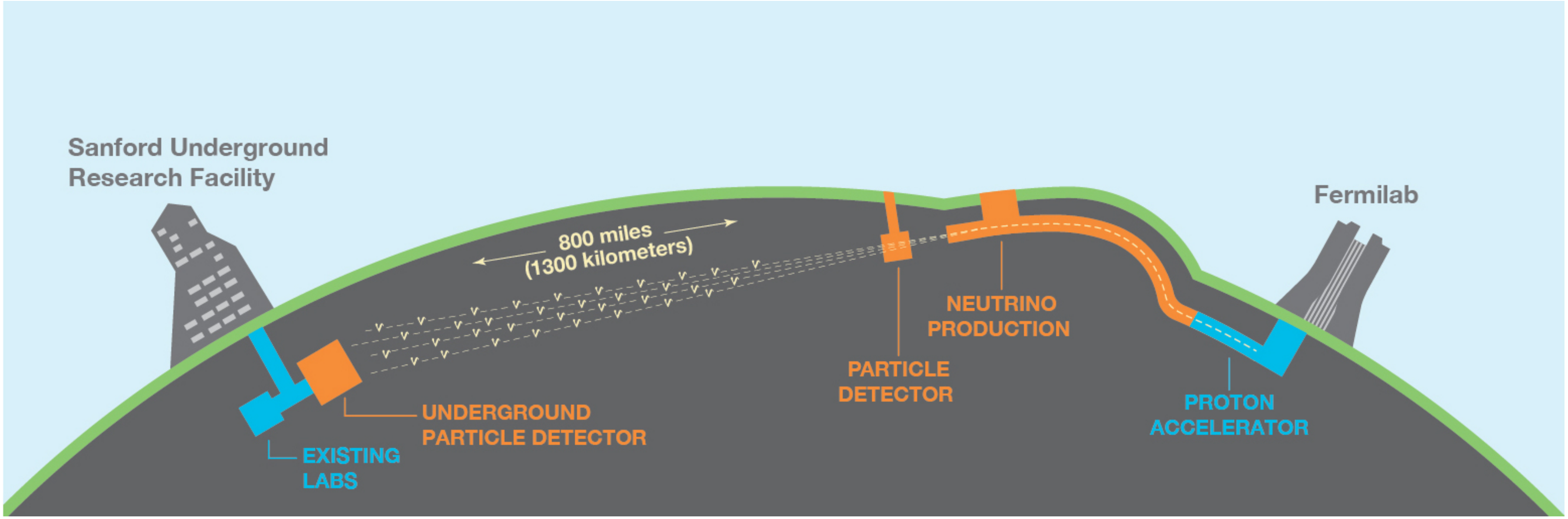

DUNE

CONCLUSIONS

- **The existence of DM is based on very strong evidences, but we do not know what it is made of yet (⇒ <u>new physics</u>)**
- **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**
- **Direct detection experiments have not provided a conclusive signal yet, but constrain the properties of DM particles**
- **Neutrinos have non-zero masses, but Higgs mechanism can not generate them (⇒ <u>new physics</u>)**
- **One proposed solution is to assume that neutrinos are Majorana fermions, that can be tested by searching for neutrinoless double beta decay**
- **CP violation might be present in neutrino flavour oscillations**

In the near future several experiments will look for answers to the open questions in dark matter and neutrino physics: STAY TUNED!

THANK YOU FOR YOUR ATTENTION…