Dark Matter and Rare Event Searches

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Internship Program 2021

Gravitational Anomalies and Missing Mass

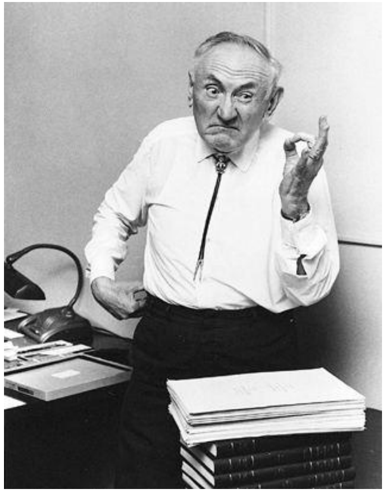
In 1933, **Fritz Zwicky** noticed a large discrepancy in the mass of the **Coma cluster** when calculated using galactic motion or luminosity.

$M_{Virial} = 4.5\times10^{13}\ M_\odot \quad ; \quad M_L \approx 2.6\times10^{11}\ M_\odot$

He proposed that some form of non-luminous matter was responsible for binding the cluster together, calling it "**dark matter**".

This **dark matter** could not emit or absorb radiation, and should be ~200 times more abundant than regular (baryonic) matter.

One year before, **Jan Oort** pointed that additional mass was necessary to explain the motion of stars in our neighbourhood (interstellar gas!).

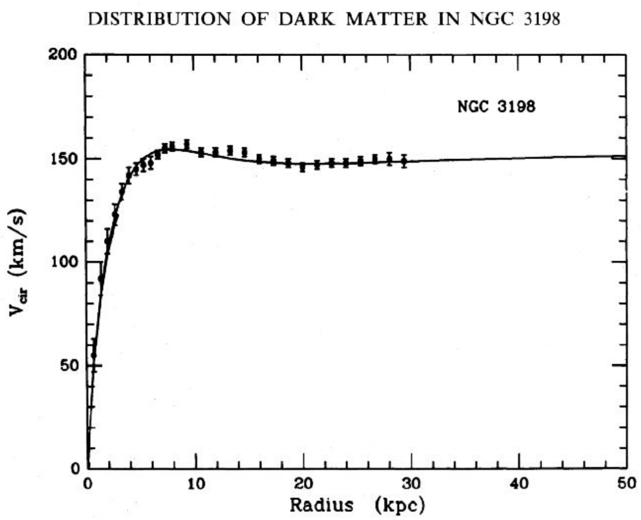


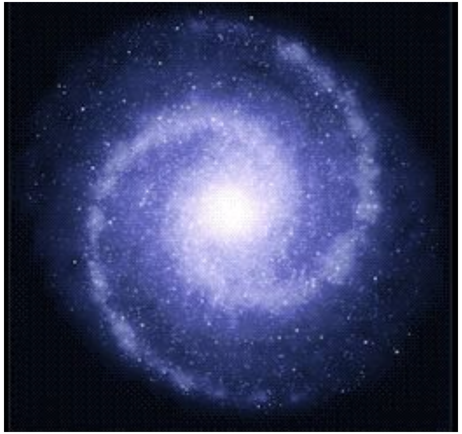
A very upset Fritz Zwicky

Gravitational Anomalies and Missing Mass

The pioneer work of **Vera Rubin** on **galaxy rotation curves** also uncovered a discrepancy between most observations and the expected from Newtonian dynamics:

The velocity of stars remained **approx. constant** at large radii.





Sim. of observed rotation of galaxies, credit: [Ingo Berg]

Vera Rubin

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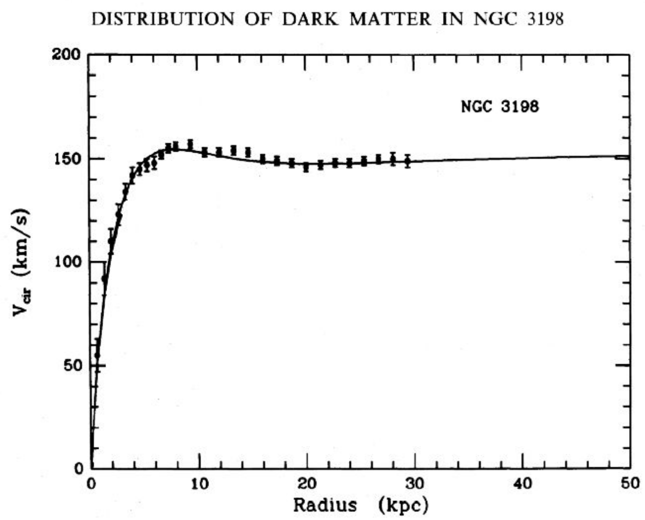

The velocity of stars remained **approx. constant** at large radii.

Two possible explanations:

1. Newtonian dynamics is insufficient
2. **There is missing mass in the system**

Vera Rubin

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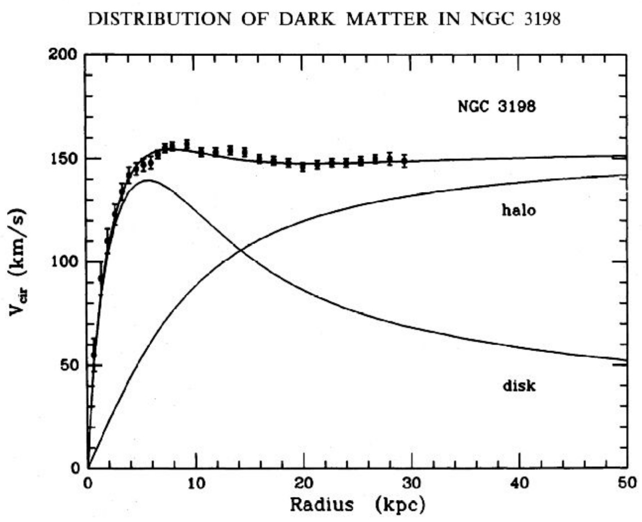

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Missing mass problem

A **dark matter halo** envelops the galaxy and reaches far beyond the galactic disk.

Vera Rubin

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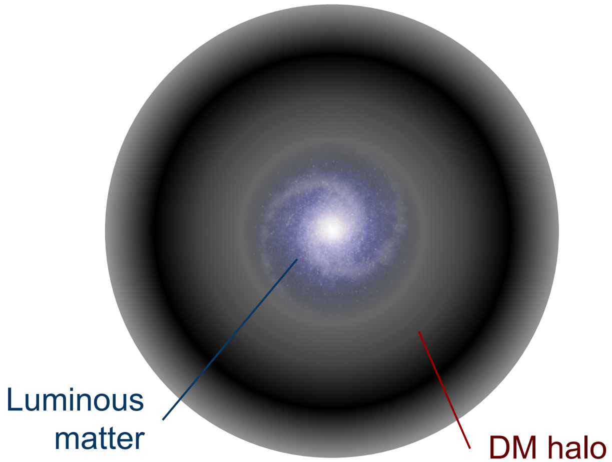


Missing mass problem

A **dark matter halo** envelops the galaxy and reaches far beyond the galactic disk.

Our Milky Way halo is expected to compose ~88.5% of its total mass!

Vera Rubin

Other Gravitational Effects

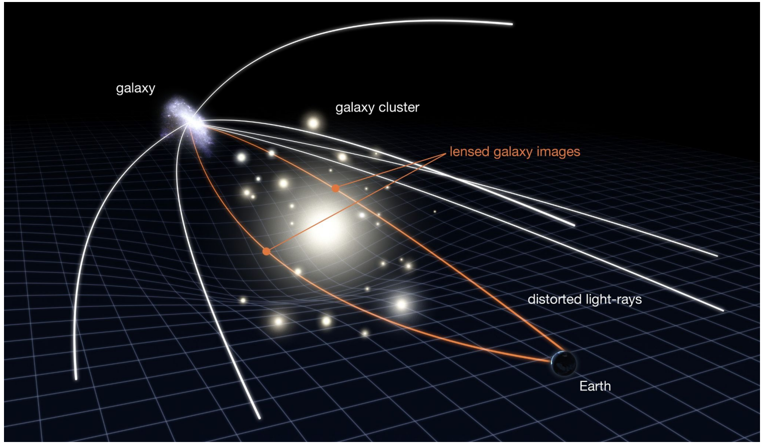
Gravitational Lensing

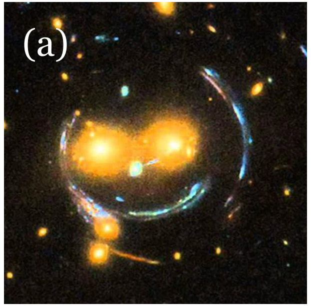
The presence of a massive object generates local distortions of space-time (General Relativity).

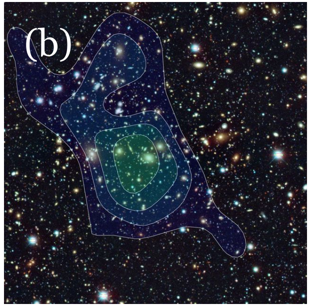
If the massive object is in the optical path of distant light sources, it will distort their image.

1. Strong lensing (a)
2. Weak lensing (b)

The amount of distortion in space-time correlates to the total mass of the object!







Other Gravitational Effects

Gravitational Lensing - Bullet Cluster

Contributions of the intergalactic gas (pink) from its X-rays and the majority of the matter (blue) in the cluster inferred from weak gravitational lensing

The overall mass inferred from lensing cannot be completely justified by luminous (baryonic) matter.

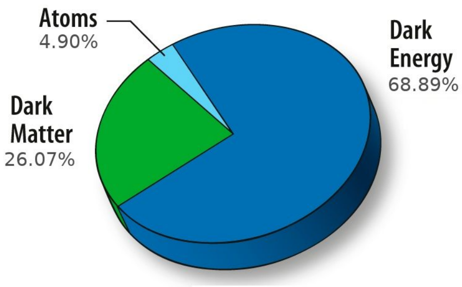
Whatever matter comprises the majority of the mass content of the clusters **does not interact significantly with itself neither with regular matter!**

The Bullet Cluster collision (NASA)

The Cosmic Recipe

Several scientific evidences suggest that **dark matter** and **dark energy** account for roughly 95% of the total mass-energy content of the universe.

Dark matter represents 84% of all matter in the universe!



Λ - Cold Dark Matter (ΛCDM) model of the universe is the Standard Model of Cosmology.

- The dynamics and evolution of the universe is dominated by dark energy (Λ) and cold dark matter (CDM)

$$\frac{\kappa}{a^2} = H^2 \left(\Omega_r + \Omega_m + \Omega_\Lambda - 1 \right) .$$

Radiation

Matter

Vacuum

$$\Omega_i = \rho_i(t) \frac{8\pi G}{3H^2}$$

$$\Omega_\Lambda = \frac{\Lambda}{3H^2}$$

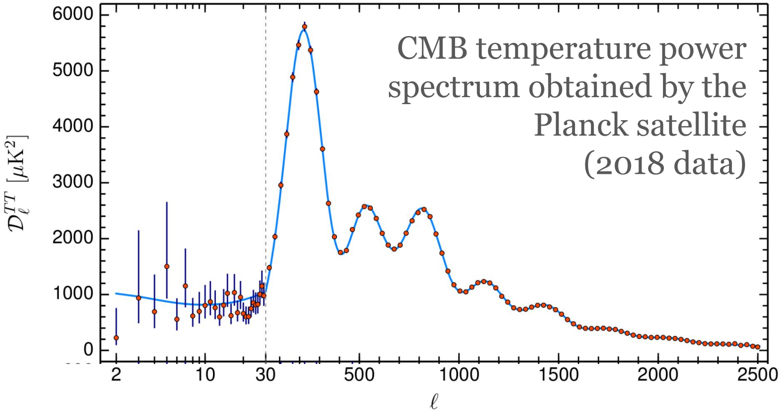
Energy-density parameters

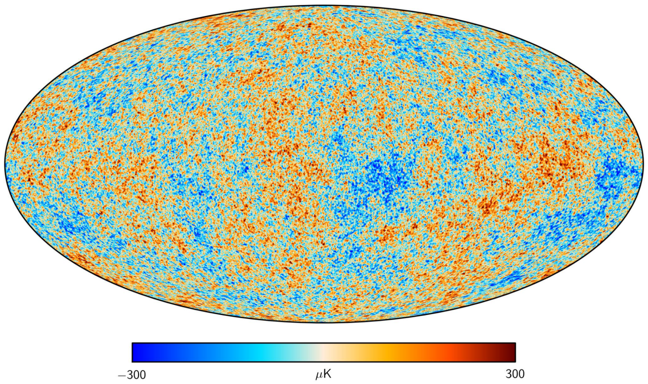
Experimental Evidences of Dark Matter

Cosmic Microwave Background (CMB)

Thermal radiation left over from the **time of last scattering**, ~380 thousand years after the Big Bang

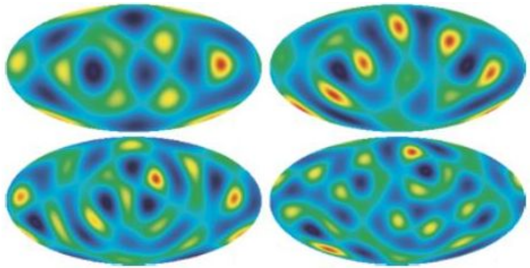
Today it is composed of microwave wavelength photons with a mean temperature of 2.725±0.001 K.





Multipole

analysis

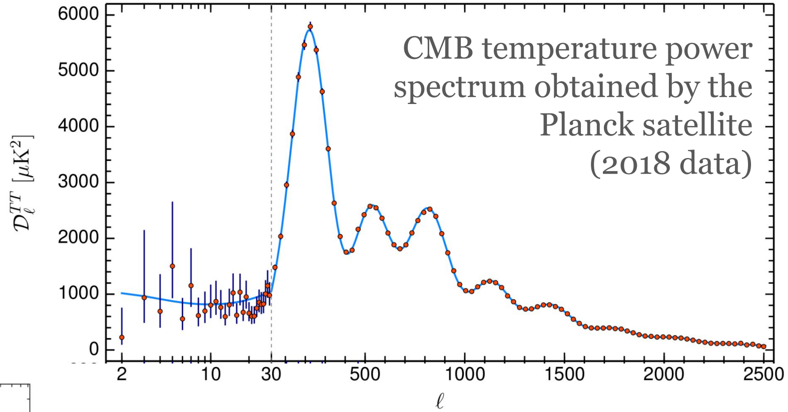


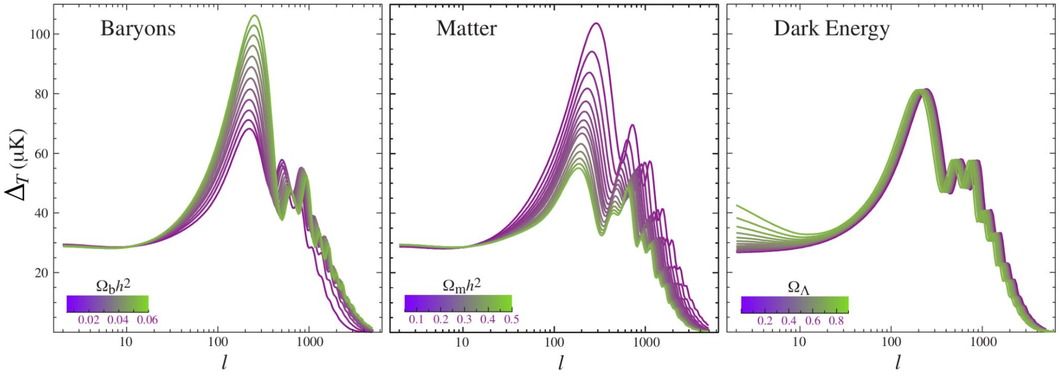
Experimental Evidences of Dark Matter

Cosmic Microwave Background (CMB)

The **fluctuations** in the CMB correspond to density variations in the primordial plasma.

The thermal anisotropies of the CMB encode the values of the **cosmological parameters**!

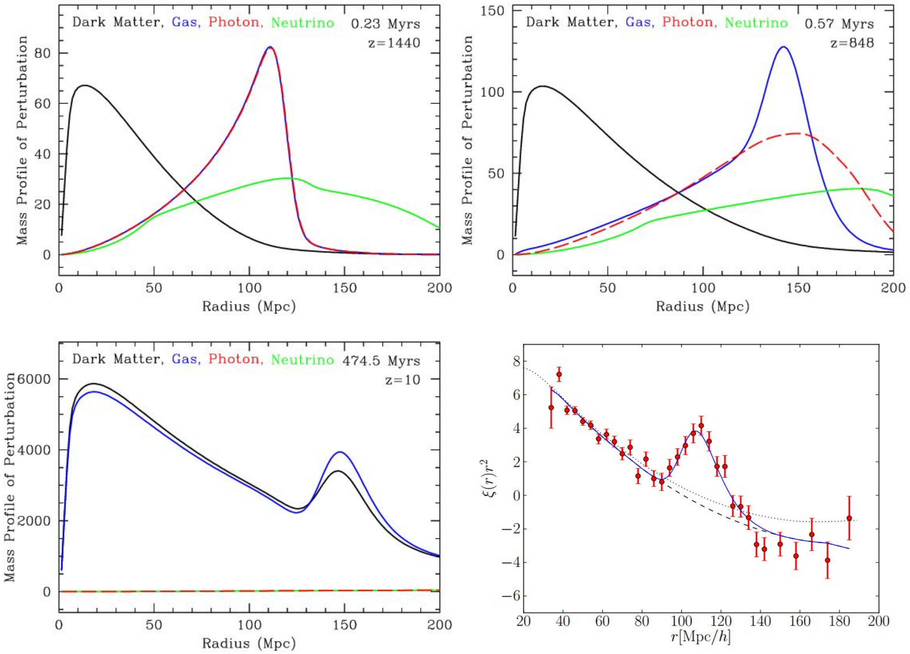




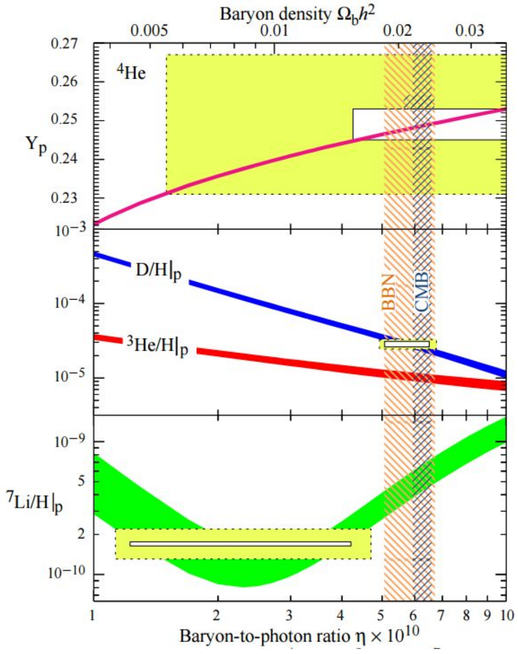
Parameter	Symbol	Value
Hubble constant [km s^{-1} Mpc^{-1}]	H_0	67.66 ± 0.42
Baryon energy density	$\Omega_b h^2$	0.02242 ± 0.00014
Cold Dark Matter energy density	$\Omega_c h^2$	0.11933 ± 0.00091
Total matter energy density	Ω_m	0.3111 ± 0.0056
Dark energy density	Ω_Λ	0.6889 ± 0.0056
Curvature	$\Omega_{\kappa,0}$	0.0007 ± 0.0019
Sum of neutrino masses [eV]	$\sum m_\nu$	< 0.12
Age of the universe [Gy]		13.787 ± 0.020

Experimental Evidences of Dark Matter

Baryon Acoustic Oscillations (BAO)



Big Bang Nucleosynthesis (BBN)



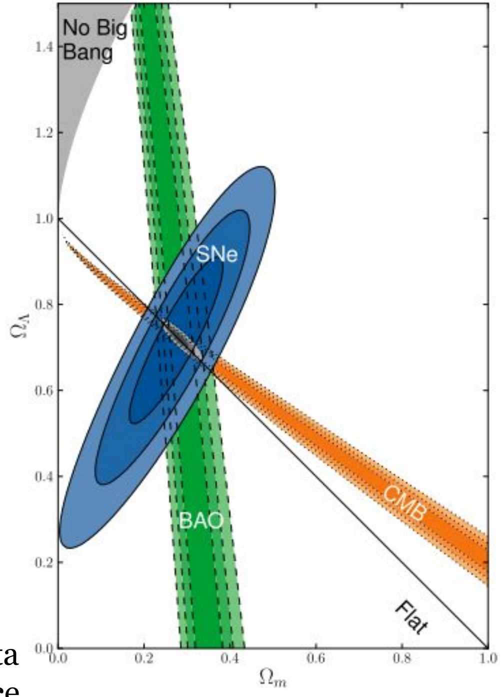
The Agreement of the Different Evidences

So far, all evidences strongly agree with the existence of **dark matter** and support the **ΛCDM** model of the universe.

Figure displays how well the **ΛCDM** fits observations. Supernova (SNe) surveys determine the acceleration history of the universe and indicate that the universe is expanding faster

$$\Omega_\Lambda > 0 \quad \textbf{(dark energy dominated)}$$

Most recent estimates from CMB and Cepheid variables present some tension on the current expansion rate $\mathbf{H_o}$

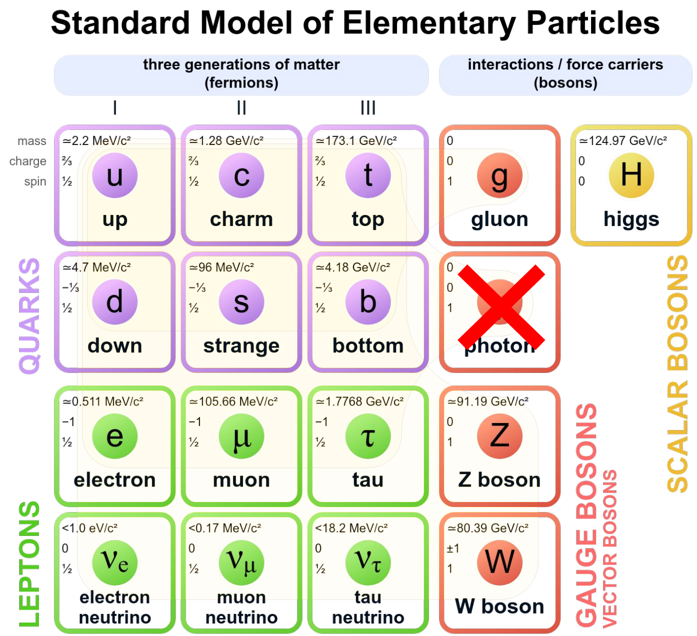


Agreement between data from SNe Ia, CMB and BAO data prior to 2012, over the Ω_m–Ω_Λ phase-space

What is Dark Matter?

Hypothetical “substance” that is **massive, long-lived, chargeless and weakly-interacting** with itself and other matter.

What dark matter is not:



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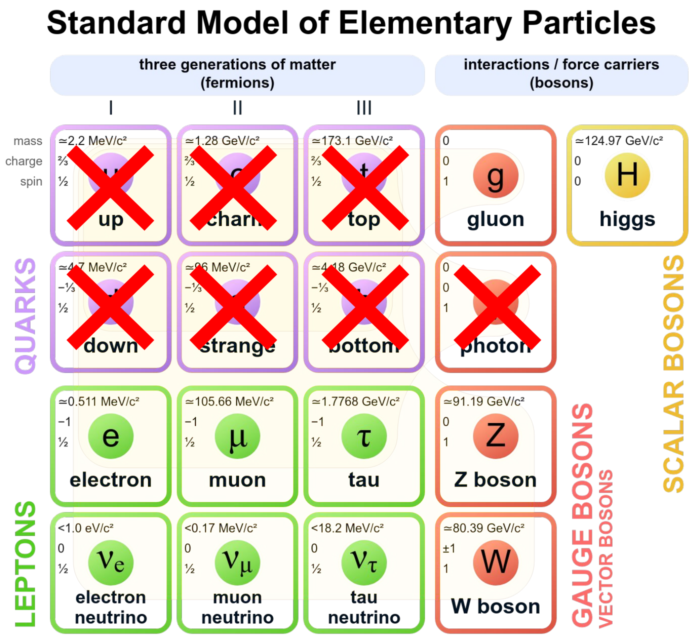

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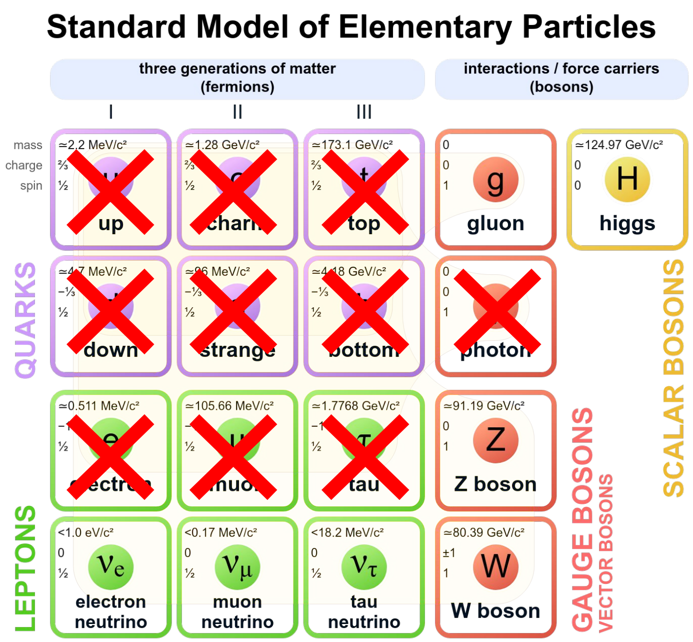

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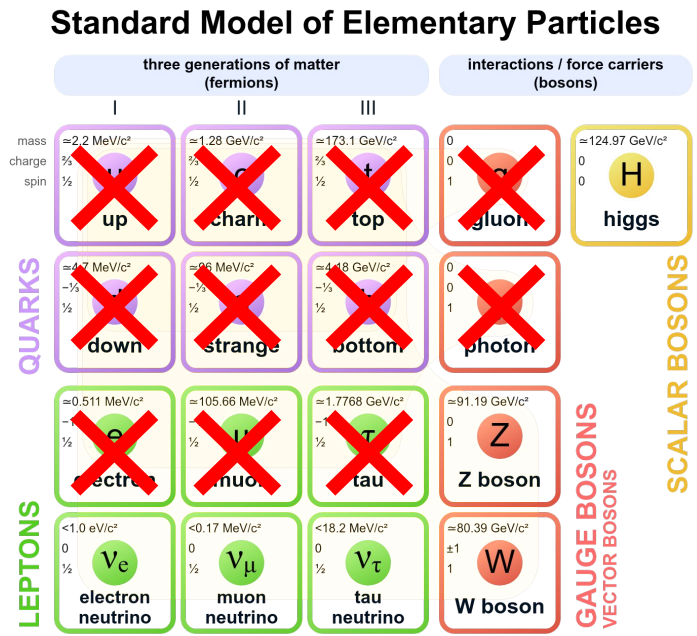
- Gluons



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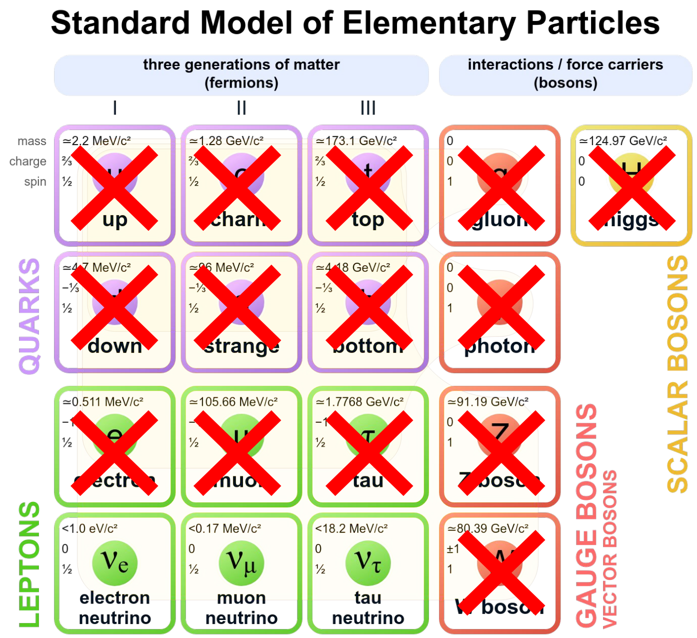

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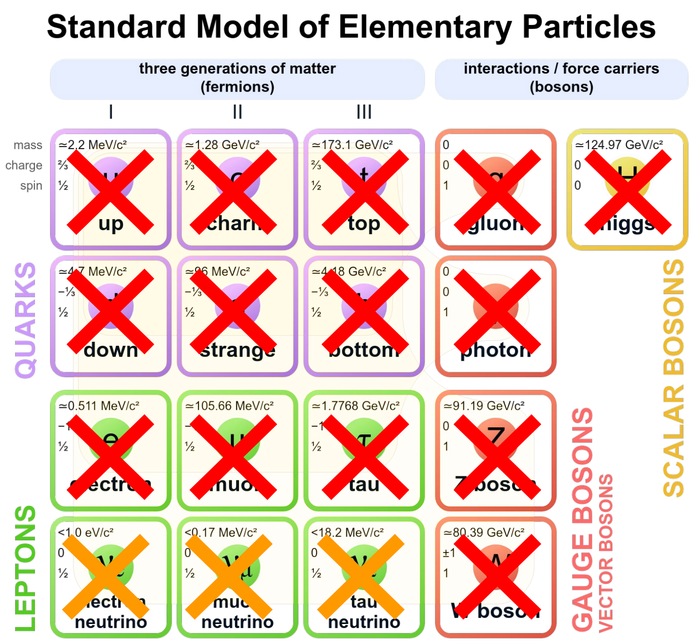
- Heavy bosons
- Neutrinos

SM neutrinos contribute to Hot Dark Matter, but cannot explain all observations.



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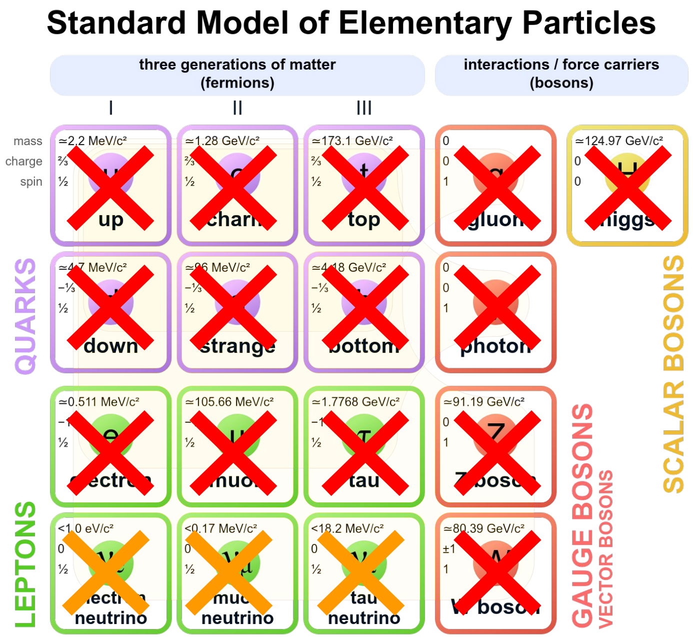
No valid candidate in the Standard Model

Physics BSM!



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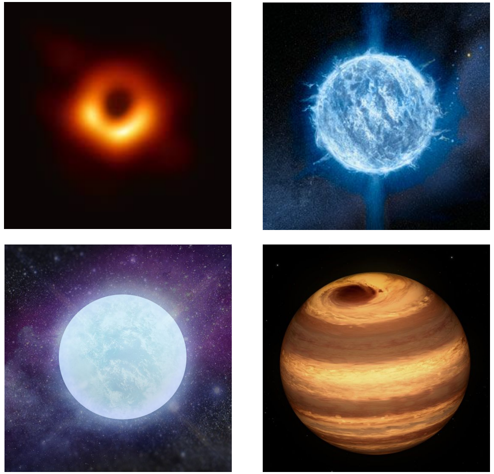
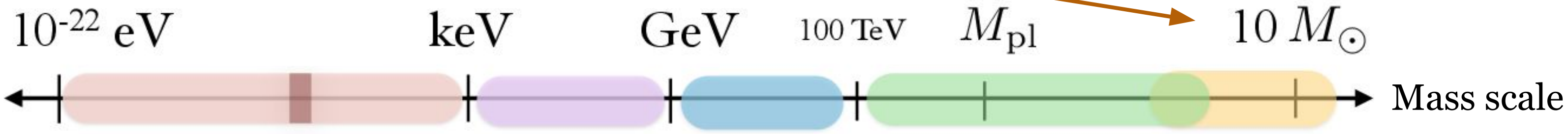
Dark Matter Candidates

MACHOs

Massive Astrophysical Compact Halo Objects, such as neutron stars, white dwarfs, brown dwarfs, Jupiter-like planets, black holes.

Mostly excluded by several evidences and surveys of microlensing and transits.



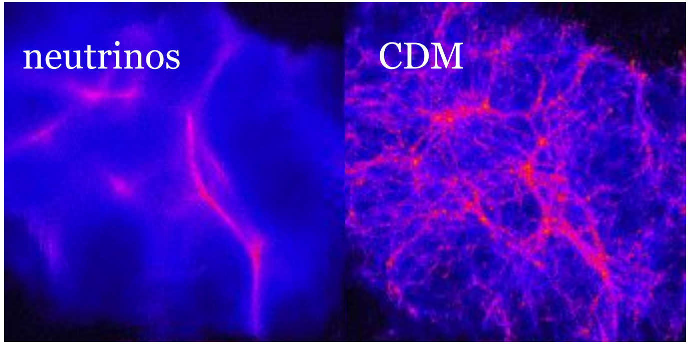


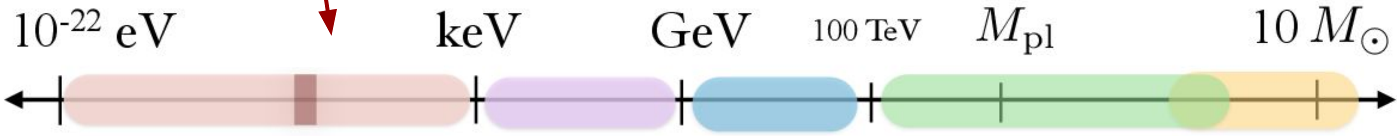
Dark Matter Candidates

Neutrinos

The most abundant particles in the universe aside from photons. Non-zero mass, weakly-interacting.

Warm or Hot Dark Matter candidates - cannot form large scale structures like the ones observed today.





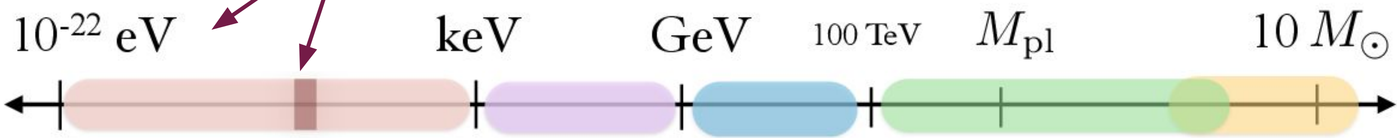
Dark Matter Candidates

Axions and Axion-like Particles (ALPs)

Hypothetical pseudoscalar particles that could justify why CP-violating processes are not observed in strong interactions.

Not produced thermally (contribute to CDM).

Solves two problems with one particle!



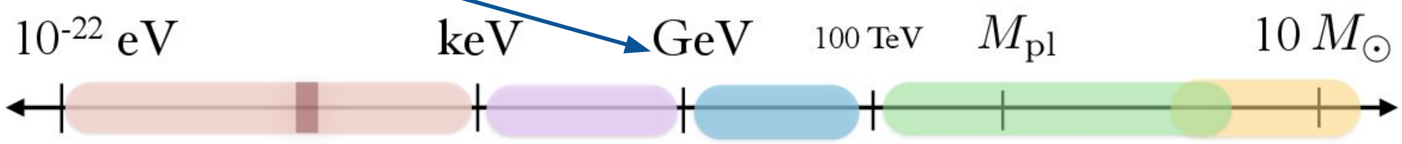
Dark Matter Candidates

WIMPs

Weakly Interacting Massive Particles, generic class of chargeless & heavy particles, produced thermally in the early universe, that provide the inferred amount of non-baryonic dark matter.

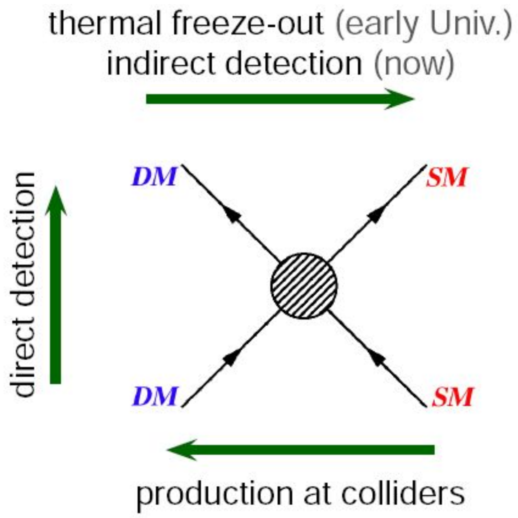
One of the strongest candidates so far!

- May interact with normal matter via weak-like processes
- Consistent with BBN
- **Relic abundance**
- Electroweak symmetry spontaneously broken
- SUSY predicts particles with such characteristics.
  - No evidence for SUSY yet



Dark Matter Detection

1. **Production in Particle Colliders**
   a. Looking for missing momentum in colliders
   b. LHC can already cover most of the mass ranges for main candidates (TeV scale)
2. **Indirect Detection**
   a. Detection of annihilation or decay products
   b. Surveys of dwarf spheroidal galaxies
   c. Axion conversion in strong magnetic fields
3. **Direct Detection**
   a. Searching for dark matter scattering with a target material
   b. Axion conversion in resonance cavities and ASTs

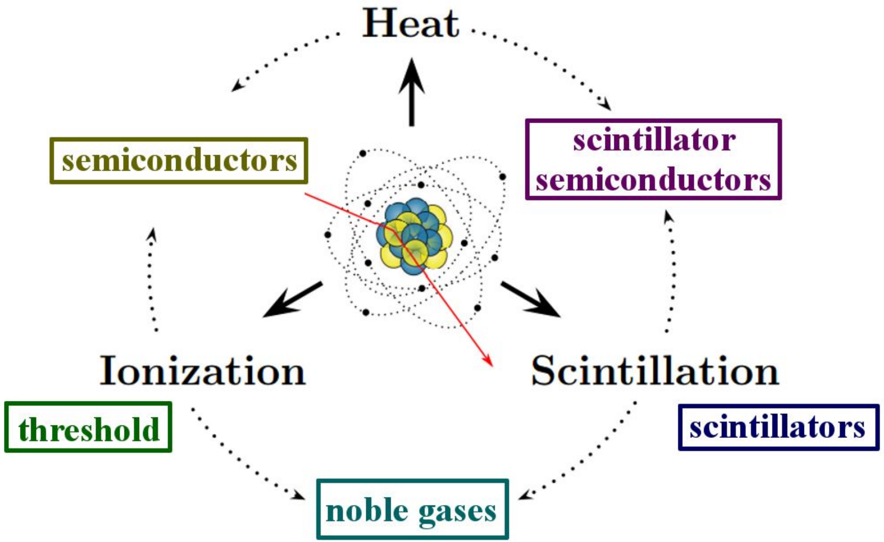


Direct Detection of Dark Matter (WIMPs)

WIMP direct detection experiments aim to measure the rate and energies of nuclear recoils caused by the scattering of dark matter particles with the nuclei in the target material.

Main detector types:

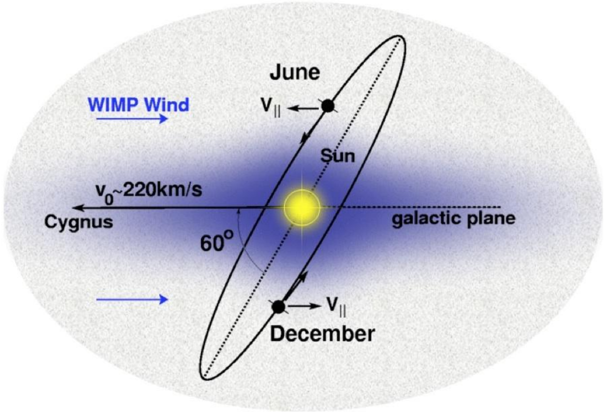
- Dual-phase noble element TPCs
  - LZ, XENON1T, DarkSide, DEAP,...
- Threshold detectors
  - PICO,...
- Crystal scintillation
  - CRESST, COSINE,...
- Cryogenic Semiconductor detectors
  - CUORE, SuperCDMS,...



WIMP Detection Rate

Assuming our WIMP halo is composed of:

- WIMPs with mass, $\mathbf{M_\chi = 100\ GeV}$
- WIMP density, $\boldsymbol{\rho_\chi} \mathbf{= 0.4\ GeV\ cm^{-3}}$
- Earth's velocity in the halo, $\mathbf{v_o = 220\ km\ s^{-1}}$



Using a Xe target (**A=131**) and considering the current best limit on the cross-section WIMP-nucleon, $\boldsymbol{\sigma_{oWn}} \mathbf{=0.9 \times 10^{-46}\ cm^2}$ (XENON1T)

$$R_0 = \frac{2}{\sqrt{\pi}} \frac{N_A}{A} \frac{\rho_{DM}}{M_\chi} \sigma_0 v_0$$

~6 events
per tonne of Xe per month!

E_R=25 keV avg. recoil energy

We're talking about
VERY RARE events...

Rare Event Searches

Experimental searches involving processes that are very unlikely or very heavily shadowed by similar processes (backgrounds).

- ❖ **Detectors designed for rare event searches can often search for more than one signal!**
- ❖ Example: **Dark Matter** detectors are also great at searching for **Rare Decays** of their target's isotopes!
- ❖ These detectors need to **run for several years** in order to collect enough statistics for observation.
    - ➢ E.g., the LZ dark matter detector will run for more than 5 years!

Another Rare Process - Double beta decay

Beta decay with the emission of two electrons and two electron antineutrinos **(2νββ)**

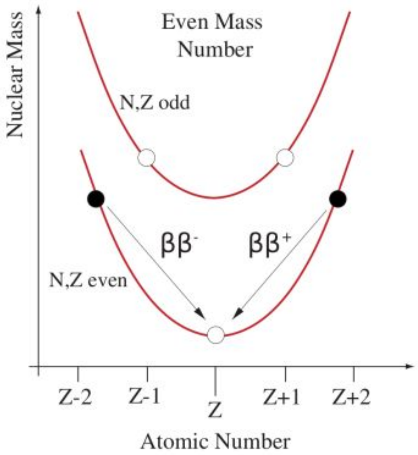
- ★ Only on even nuclei when single beta decay is energetically forbidden.
- ★ There are only 14 confirmed double beta emitters.

The neutrinos avoid detection and only the summed energy of the two electrons is observed.

Other four lepton decays allowed by the Standard Model:

$$
\begin{aligned}
(A,Z) + 2e^- &\longrightarrow (A, Z-2) + 2\nu_e && (2\nu\mathrm{ECEC}),\\
(A,Z) + e^- &\longrightarrow (A, Z-2) + e^+ + 2\nu_e && (2\nu\mathrm{EC}\beta^+),\\
(A,Z) &\longrightarrow (A, Z-2) + 2e^+ + 2\nu_e && (2\nu\beta^+\beta^+),
\end{aligned}
$$

$$(A,Z) \longrightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e. \qquad (2\nu\beta\beta)$$



Half-lives of order of hundreds of trillion (10^{20}) years!

Neutrinoless Double beta decay

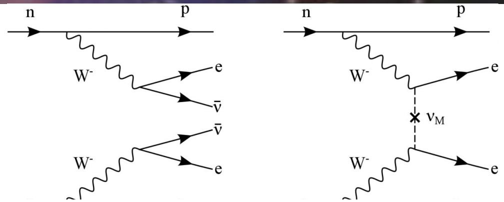
If neutrinos are Majorana particles, a <u>neutrinoless double beta decay</u> (**$0\nu\beta\beta$**) mode is possible

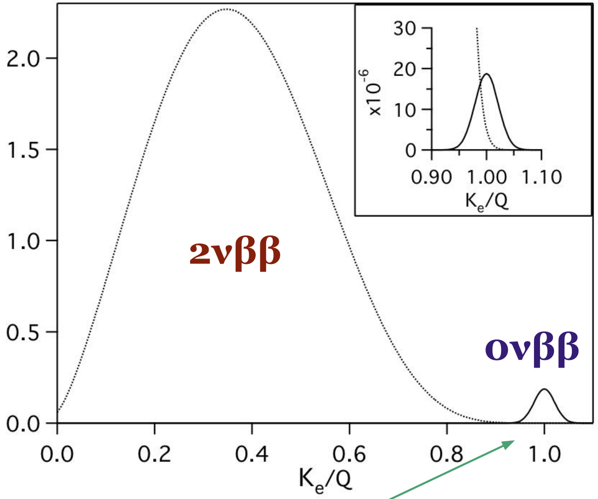
- ★ Not yet observed - very long half-lives
- ★ Electrons carry the total energy of the decay

A detector can look for the **$0\nu\beta\beta$** decay by searching for an <u>excess rate of events</u> at the endpoint energy of the observed **$2\nu\beta\beta$** decay spectrum.

Significant implications for particle physics and cosmology:

- Violation of leptonic number conservation
- B-L symmetry violation
- The first evidence of fundamental Majorana particles
- Leptogenesis





Representation of an excess of events at the endpoint of the $2\nu\beta\beta$ spectrum

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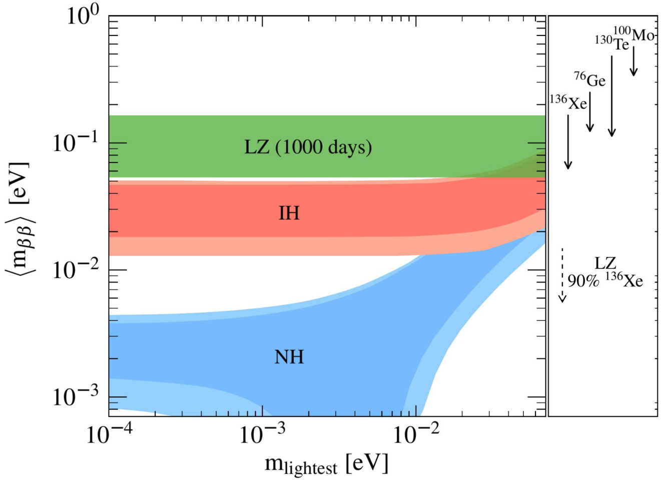
The 0νββ decay is also sensitive to the absolute mass scale and mass hierarchy of the neutrino.



$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\,|\mathcal{M}^{0\nu}|^2\,\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}, \quad \langle m_{\beta\beta}\rangle = \left|\sum_i m_i e^{i\xi_i} U_{ei}^2\right|$$

Neutrinoless Double beta decay

Half-lives > quadrillion (10^{24}) years!

Some current best limits for some isotopes:

- ^{76}Ge $T^{1/2}$ >8.0×10^{25} yr (GERDA, 2018)
- ^{100}Mo $T^{1/2}$ >1.5×10^{24} yr (CUPID-Mo, 2021)
- ^{130}Te $T^{1/2}$ >1.5×10^{25} yr (CUORE, 2018)
- ^{136}Xe $T^{1/2}$ >1.07×10^{26} yr (KamLAND-Zen, 2016)

Dark-Matter Detector Measures Half-Life of Xenon-124 that's Longer than Universe's Age

Apr 26, 2019 by News Staff / Source « Previous | Next »

This headline is for a 2ν2EC decay with $T^{1/2}$~10^{22} yr
(also, talk about selling it short)

Assuming a detector searching for 0νββ decay in ^{136}Xe with:

- 80% signal efficiency
- ±1σ signal acceptance

$$T^{0\nu}_{1/2} = \ln 2 \frac{m_{Xe}\eta_{Xe136}N_A}{M_{Xe136}}\frac{\epsilon}{\mu_s}t,$$

2 decays
per tonne per year!

Rare Event Searches

Experimental searches involving processes that are very unlikely or very heavily shadowed by similar processes (backgrounds).

Two solutions to maximize observation:

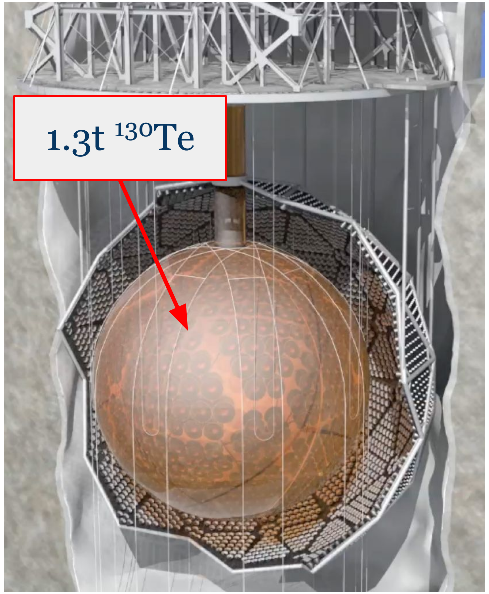
1. Increase the chance of seeing the signal
   a. Large target mass or isotopic abundance
   b. Correct signal energy scale and detector threshold

2. Reduce the backgrounds
   a. Excellent energy and position resolution
   b. Ultra-low background (BG) environment

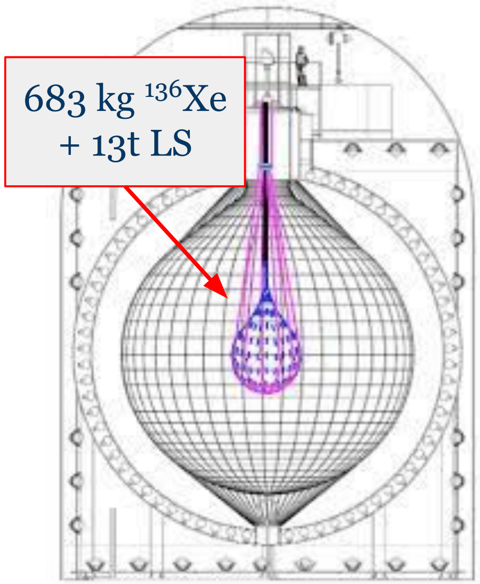
We want to maximize the needles and get rid of the straw!

Detector Requirements for a Rare Event Search

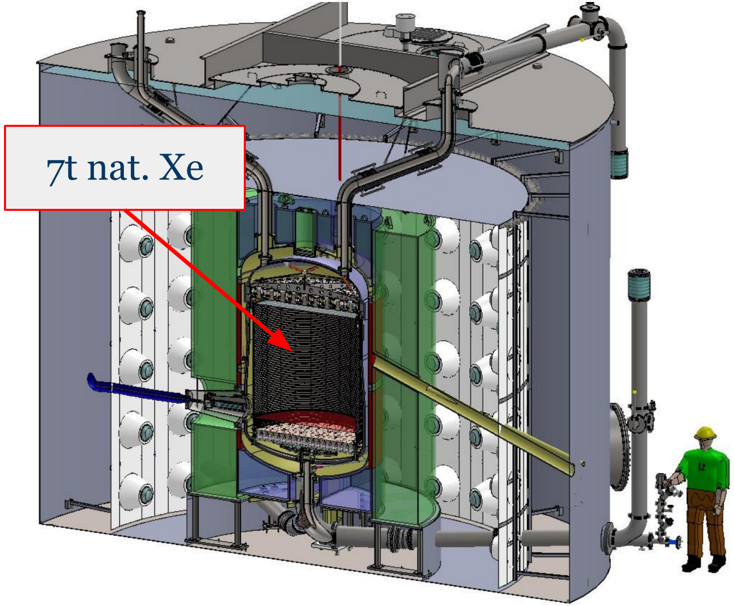
Large target mass or isotopic abundance:



SNO+ (0νββ ^{130}Te)



KanLAND-Zen (0νββ ^{136}Xe)



LZ (dark matter)

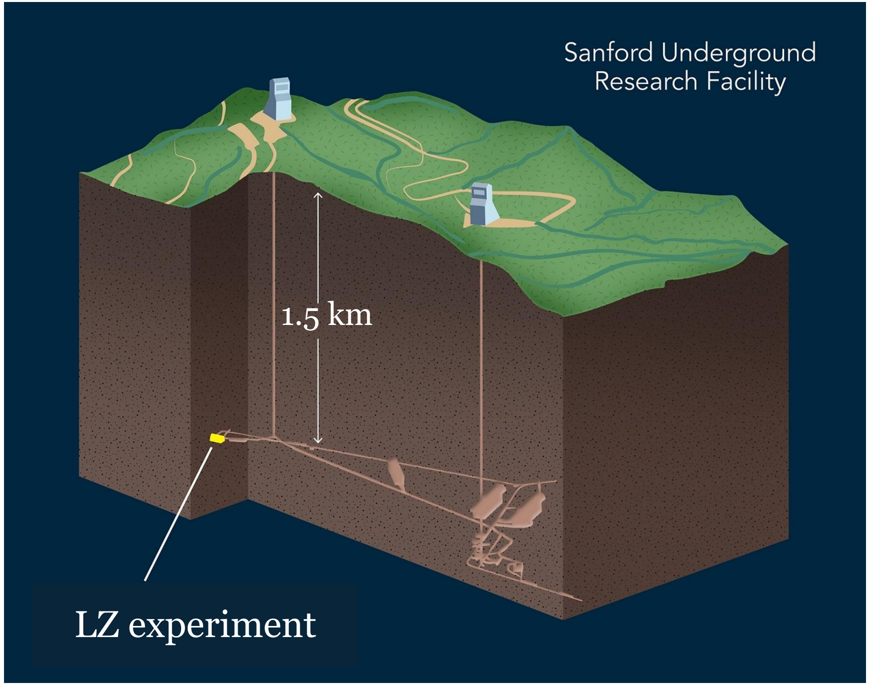
Detector Requirements for a Rare Event Search

Ultra-low background (BG) environment

Reducing radioactive and cosmic radiation is critical in any rare event search!

1. **Move underground!**
    a. Usually over 1 km deep
    b. Using rock overburden to shield from penetrative cosmic ray muons

Decrease of muon and muon-induced BGs by several orders of magnitude!



Detector Requirements for a Rare Event Search

Ultra-low background (BG) environment

Reducing radioactive and cosmic radiation is critical in any rare event search!

1. **Move underground!**
2. **High radiopurity detector materials**
   a. All materials have some natural radioactivity
   b. Prevent BG sources within detector structures - closer to the target!
   c. Also, build the detector in controlled environments to reduce contamination (dust, Radon, neutron activation, etc.)

Detector Requirements for a Rare Event Search

Ultra-low background (BG) environment

Reducing radioactive and cosmic radiation is critical in any rare event search!

1. **Move underground!**
2. **High radiopurity detector materials**
3. **Passive shielding**
    a. Surround the detector with materials with high stopping power.
    b. E.g., ancient lead or metals for <u>γ-rays</u>, HDPE or water for <u>neutrons</u>.
    c. Use dense and massive target materials (fiducialization)

Lead and copper shielding of the MAJORANA DEMONSTRATOR

Detector Requirements for a Rare Event Search

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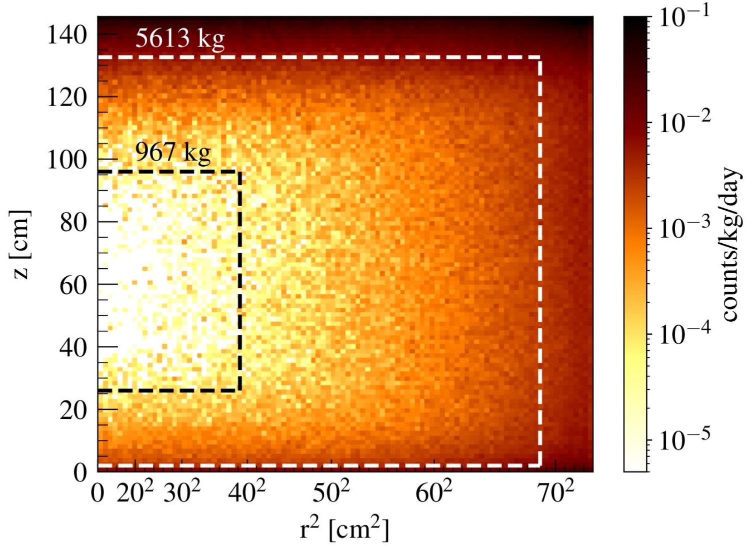


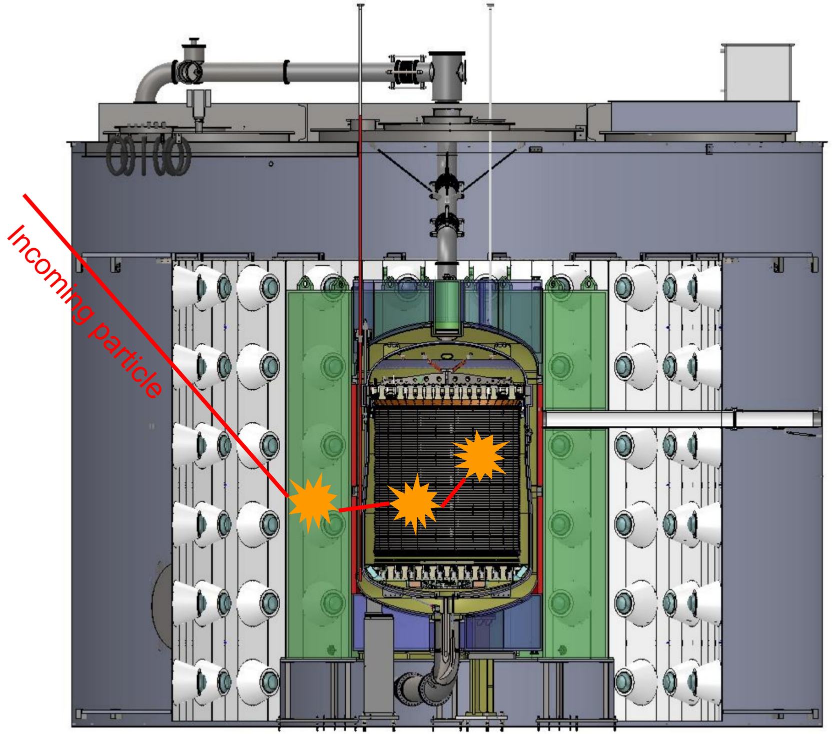
The strong attenuation of high-E γ-rays in liquid Xenon

Detector Requirements for a Rare Event Search

Ultra-low background (BG) environment

Reducing radioactive and cosmic radiation is critical in any rare event search!

1. **Move underground!**
2. **High radiopurity detector materials**
3. **Passive shielding**
4. **Active shielding**
   a. Good position resolution allows single vs multiple scatter discrimination.
   b. Deploy coincidence detectors (vetoes) that surround the main detector.

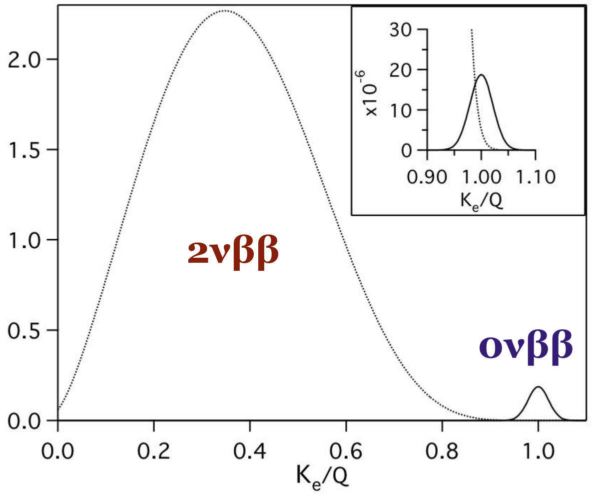


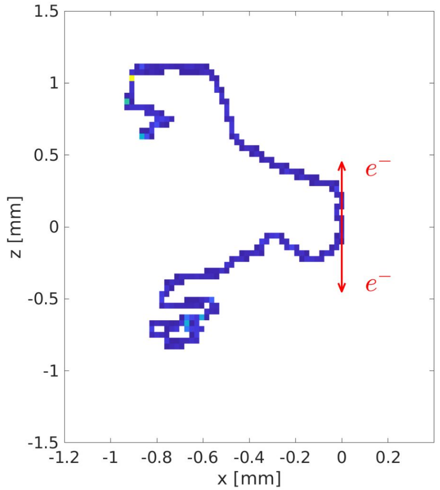
Detector Requirements for a Rare Event Search

Energy and position resolution

The 0νββ decay signal is only distinguishable from the 2νββ decay BG by energy resolution.

A good position resolution might help to identify the type of interaction, e.g., distinguish the individual tracks from both β in the decay.

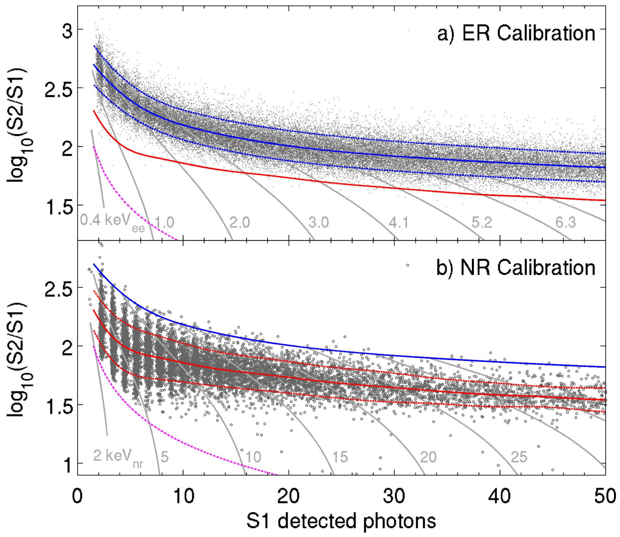




Background Discrimination

Some detectors allow clever background discrimination techniques during data analysis, e.g. electron vs nuclear recoil in WIMP dark matter detectors:

- Dark matter is more likely to interact with the nucleus of an atom of the target.
- Backgrounds from γ-rays and β particles are more likely to interact with atomic electrons .
- However, neutrons will mimic WIMP signals by scattering off nuclei.



Some other detectors can use pulse-shape discrimination for the same effect.

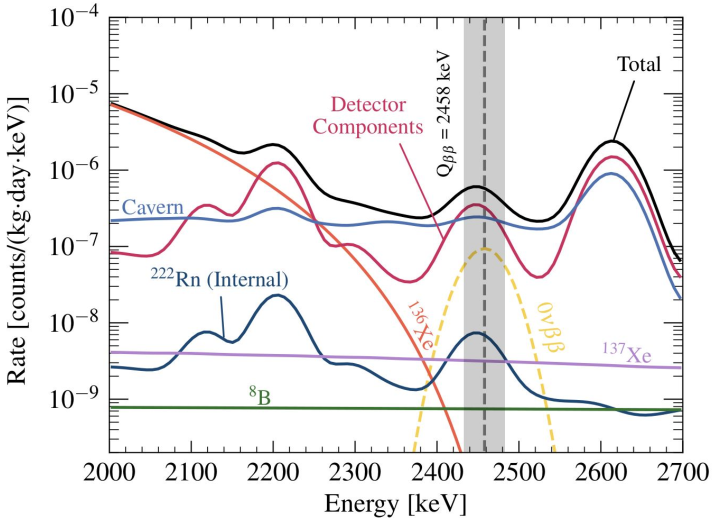
Simulation and Background Modelling

Fundamental in experimental physics!

Predict and model the BGs in the detector with detailed Monte Carlo simulations aided by:

- Detailed models of physics processes.
- Radioactive assays of detector materials.
- Measurements of environmental BGs in the lab.
- Modelling of environmental and cosmogenic BGs.
- Detailed detector geometry models, material properties and detector response.

These detailed models will then be used to constrain the observed BGs and place limits on the signal.



Expected background rates for LZ around the ^{136}Xe $0\nu\beta\beta$ decay energy region

Thank you!

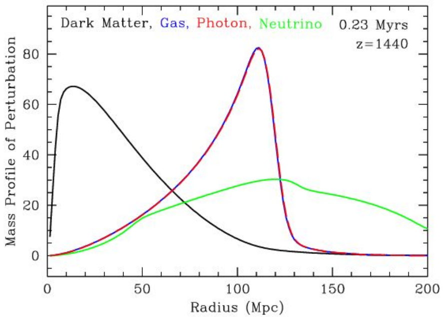
BACKUPS

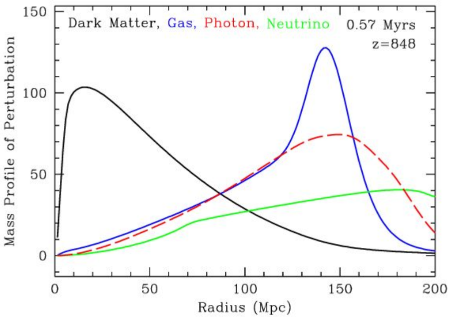
Experimental Evidences of Dark Matter

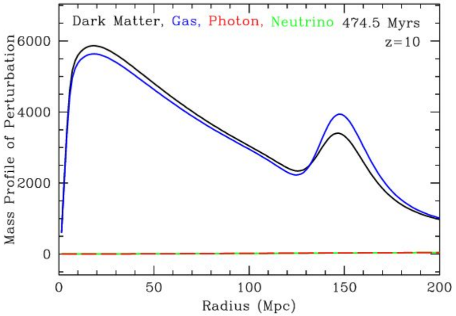
Baryon Acoustic Oscillations (BAO)

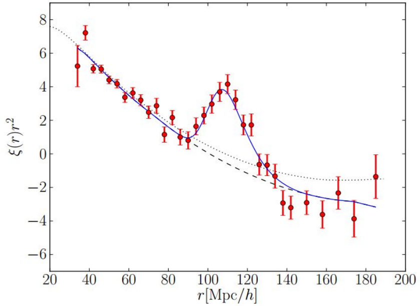
Pressure waves in the primordial plasma that seeded the formation of cosmological structures.

1. A photon-baryon plasma pressure wave travels outwards.
2. When photons and baryons decouple the pressure is relieved and the baryons stall.
3. Over time, dark matter and baryonic matter coalesce, leaving a peak at the sound horizon.
4. Measurement of matter distribution (galaxies and intergalactic gas) reveal the BAO peak.









Experimental Evidences of Dark Matter

Big Bang Nucleosynthesis (BBN)

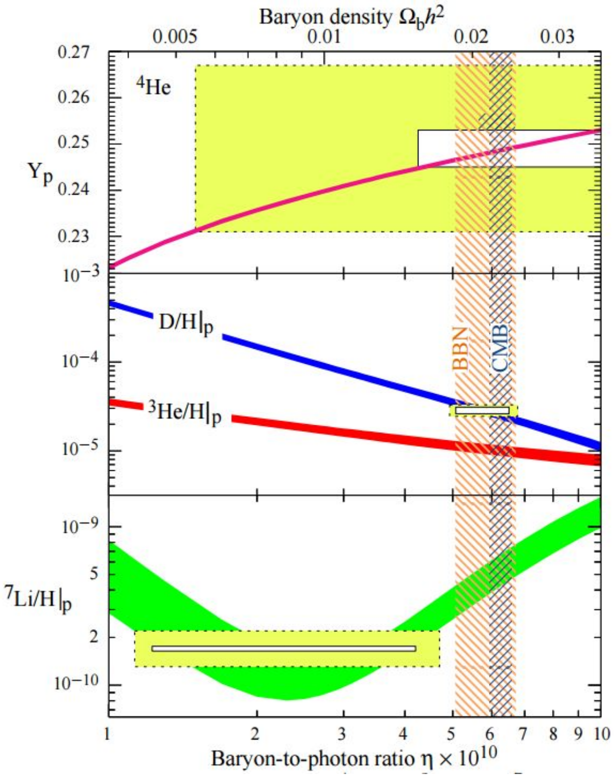
The production of light elements seconds after the Big Bang through a chain of reactions.

Sensitive to the baryon-to-photon ratio, η, that in turn informs about the total baryon density Ω_b.

$\boldsymbol{\Omega_m \approx 0.3}$ from CMB data

$\boldsymbol{\Omega_b \approx 0.048}$ from BBN data

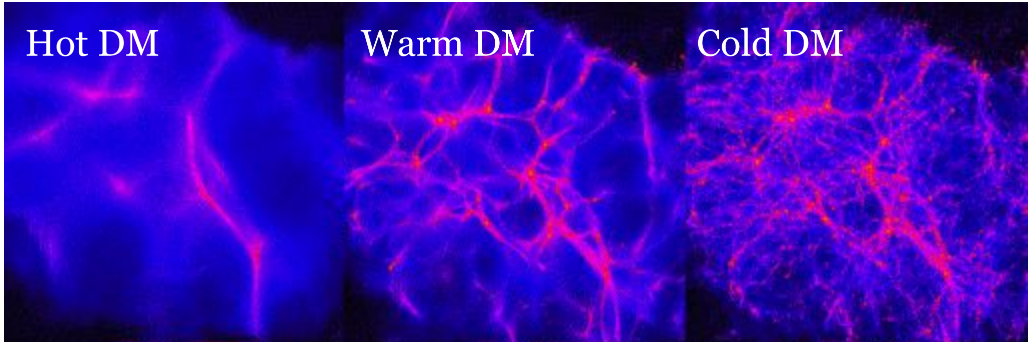
This means that the vast majority of the matter in the universe **is non-baryonic in nature!**

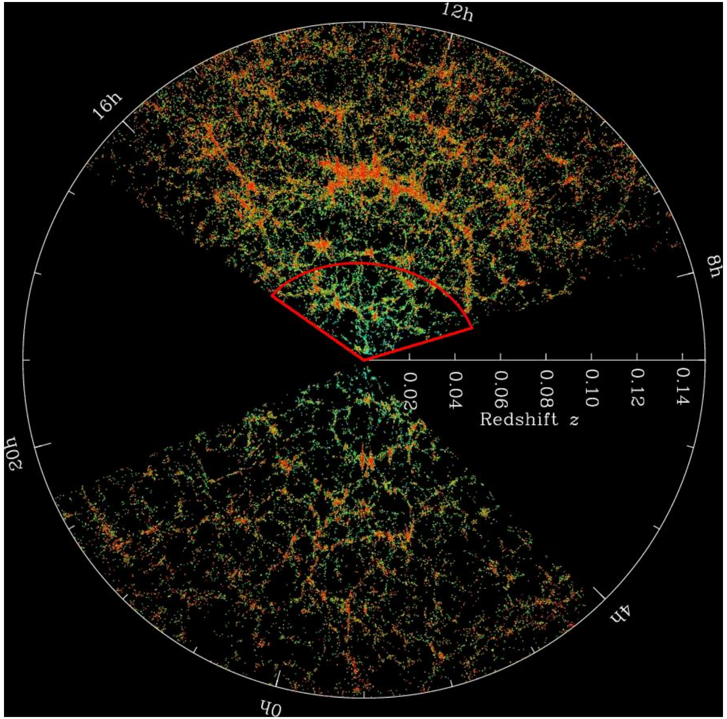


Large Scale Structures

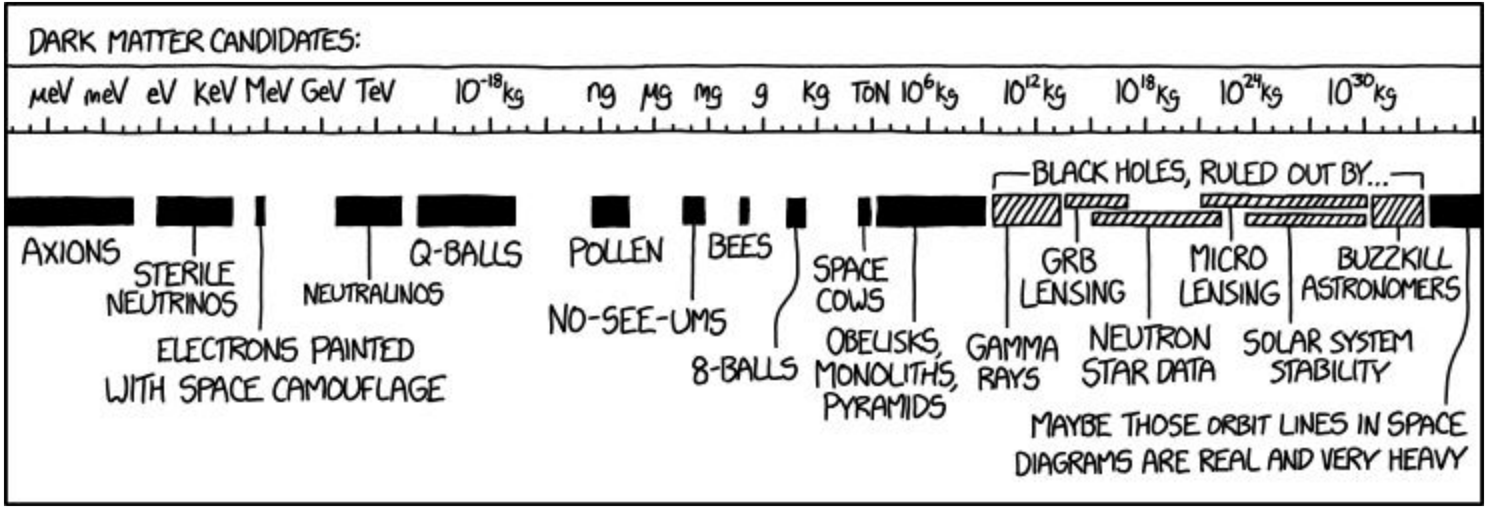
Simulation models of structure formation are used to determine the conditions and cosmological parameters needed to reproduce the observed large scale structure of the universe.

Agreement with a dominating **weakly-interacting Cold Dark Matter (CDM)** component.





Large-scale structures of galaxies from the Sloan Digital Sky Survey


DARK MATTER CANDIDATES:
μeV meV eV KeV MeV GeV TeV 10^-18 kg ng μg mg g Kg TON 10^6 kg 10^12 kg 10^18 kg 10^24 kg 10^30 kg
BLACK HOLES, RULED OUT BY...
AXIONS
STERILE NEUTRINOS
ELECTRONS PAINTED WITH SPACE CAMOUFLAGE
NEUTRALINOS
Q-BALLS
POLLEN
NO-SEE-UMS
BEES
8-BALLS
SPACE COWS
OBELISKS, MONOLITHS, PYRAMIDS
GAMMA RAYS
GRB LENSING
NEUTRON STAR DATA
MICRO LENSING
SOLAR SYSTEM STABILITY
BUZZKILL ASTRONOMERS
MAYBE THOSE ORBIT LINES IN SPACE DIAGRAMS ARE REAL AND VERY HEAVY

Dual Phase Noble Element TPCs

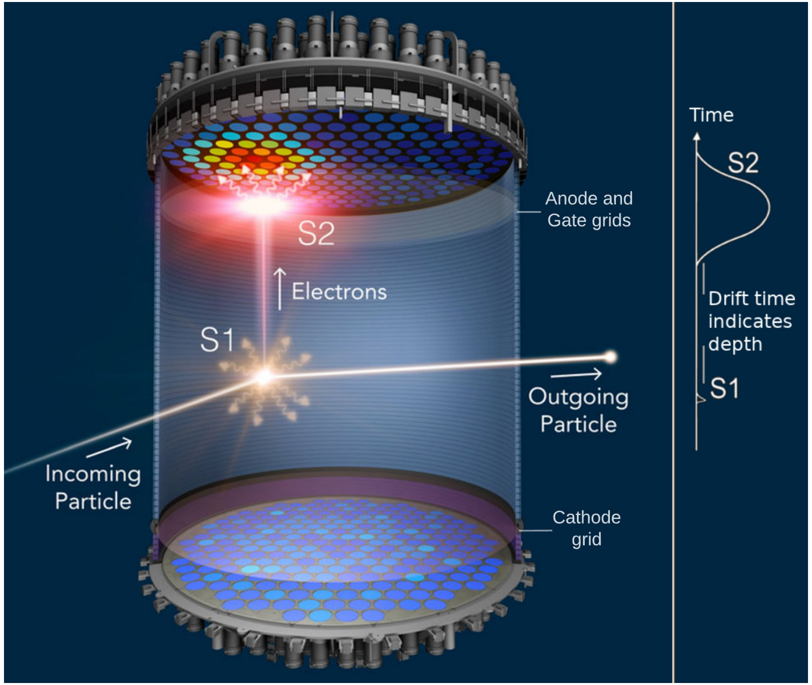
Ultra-low background rare event observatories using **Xenon** or **Argon** as targets.

- ❖ Xenon is very dense (2.9 g/cm^3)
  - ➢ Self-shielding and active vetoing
- ❖ High Atomic mass enhances WIMP cross-section

Record **scintillation** and **ionization** from interactions with the target.

- ❖ Discrimination of particle recoiling with the electrons (ER) or **nuclei (NR)** of the target.

Low energy threshold (~keV) and excellent energy and position resolution.

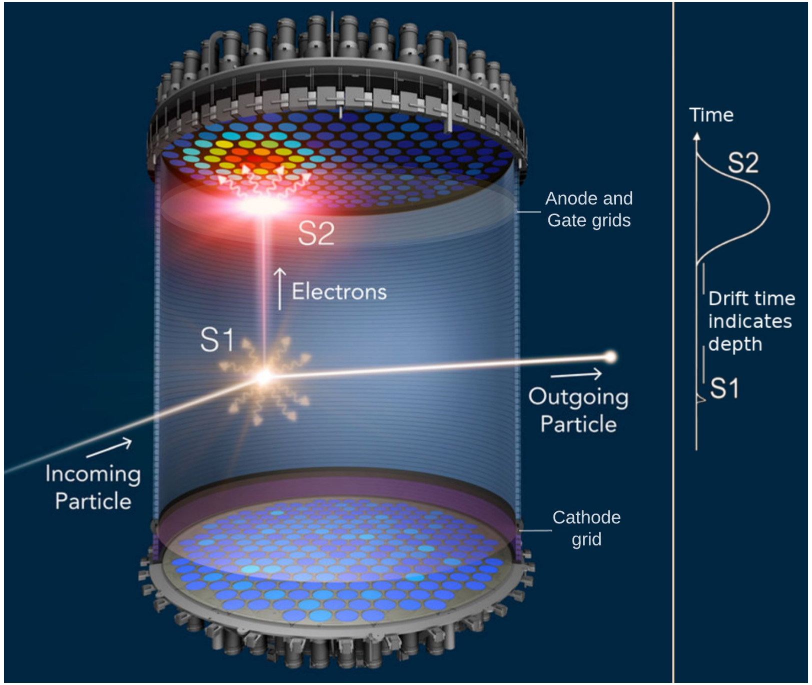


Dual Phase Noble Element TPCs

Working principle:

1. Particle interaction excites and ionizes target material.
2. Scintillation is promptly detected (S1).
3. Ionization drift towards the gas by electric field.
4. Stronger field extracts electrons to produce electroluminescence (S2).

- Time between S1 and S2 indicates **depth**
- Light map of S2 indicates **XY position**
- S1 and S2 size used to reconstruct **Energy**



The LUX-ZEPLIN Detector

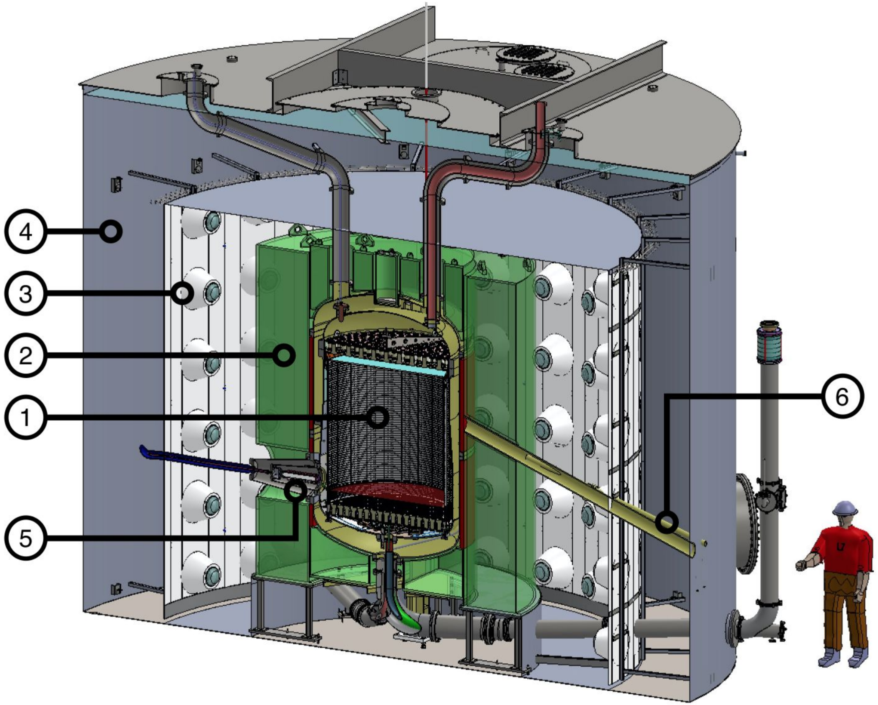
A 10 tonne liquid Xe ultra-low background dark matter detector. Rare event observatory: dark matter, 0νββ decay, neutrinos, axions, etc.

Composed of 3 distinct detectors:

1. 7 tonne liquid Xe TPC with 494 PMTs **(1)**
2. ~3 tonne Xe “skin” detector around TPC
3. 17.3 tonne Gd-loaded liquid scintillator Outer Detector with 120 PMTs **(2)**

228 tonne water shield and muon veto **(4)**

1478 m underground in a gold mine in the USA.



Modified Gravity?

Modification of the way gravity behaves at large scales to reproduce the observations without including unseen mass in the system.

- ❖ Accurate description of several galactic phenomena
- ❖ Doesn't exclude non-baryonic matter
- ❖ Clusters show a residual mass discrepancy
- ❖ Can't explain gravitational lensing observations

Modifications that describe one system well seem to fail to explain other systems completely.

Proposed a new unseen planet beyond Uranus that could explain its orbital discrepancies.

➔ **Later Neptune was discovered!**

Urbain le Verrier

Also proposed a new planet beyond Mercury to explain the precession of its perihelion.

➔ **Solved by Einstein, that successfully modified Newton's gravity and introduced GR!**

Dark Matter Candidates

MACHOs

Massive Astrophysical Compact Halo Objects, such as neutron stars, white dwarfs, brown dwarfs, Jupiter-like planets, black holes. Mostly excluded by several evidences and observation.

Axions

Hypothetical pseudoscalar particle that could justify why CP-violating processes are not observed in strong interactions. Not produced thermally (cold). Also Axion-like Particles (ALPs).

Neutrinos

The most abundant particles in the universe aside from photons. Non-zero mass, weakly-interacting. Warm or Hot Dark Matter candidates - cannot form large scale structures like the ones observed.

WIMPs

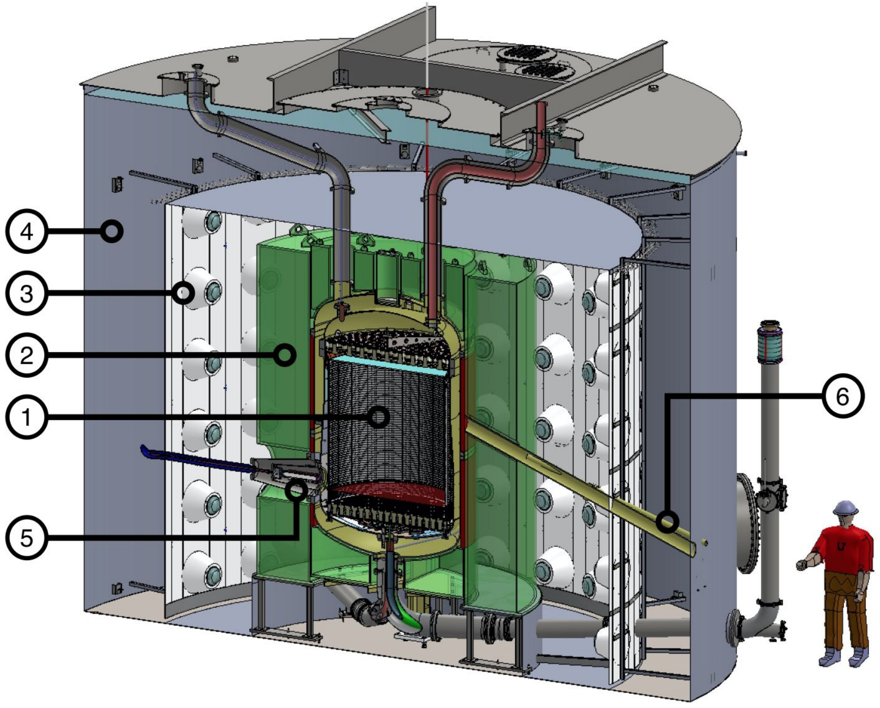
Weakly Interacting Massive Particles, generic class of chargeless & heavy particles, produced thermally in the early Universe, that provide the inferred amount of non-baryonic dark matter.

The LUX-ZEPLIN Detector

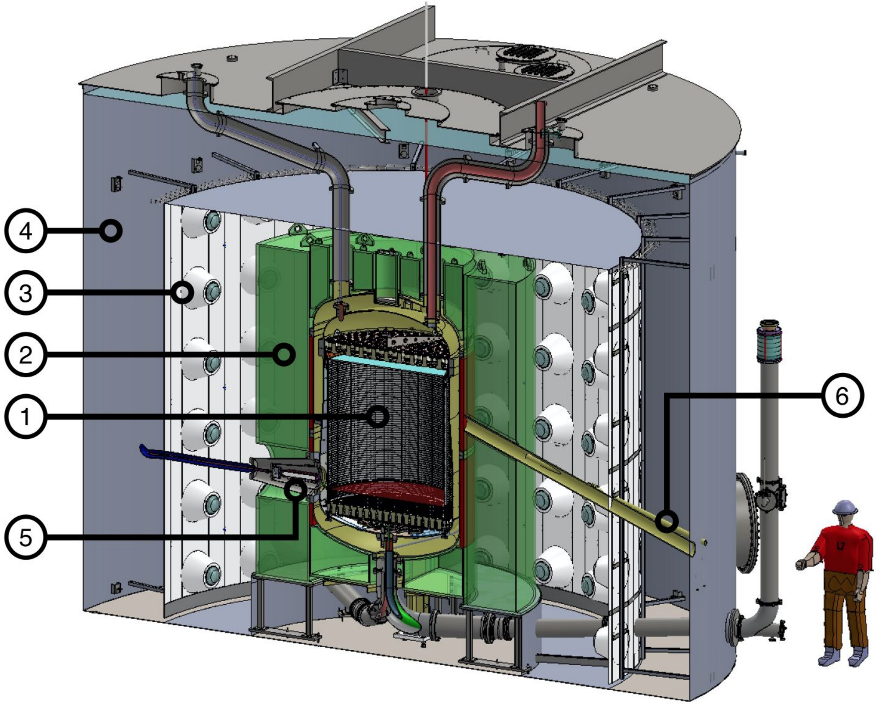
A 10 tonne liquid Xe ultra-low background dark matter detector.

<u>Rare event observatory</u>: dark matter, 0νββ decay, neutrinos, axions, etc.

1. TPC with 1.5 × 1.5 m and **7 tonnes** of liquid Xe, observed by **494** 3-inch PMTs
2. Outer detector (Gd-loaded liquid scintillator)
3. Array of **120** 8-inch PMTs
4. Water tank (228 tonnes)
5. High-voltage umbilical
6. Neutron source tube
7. Xe conduit



The LUX-ZEPLIN Detector



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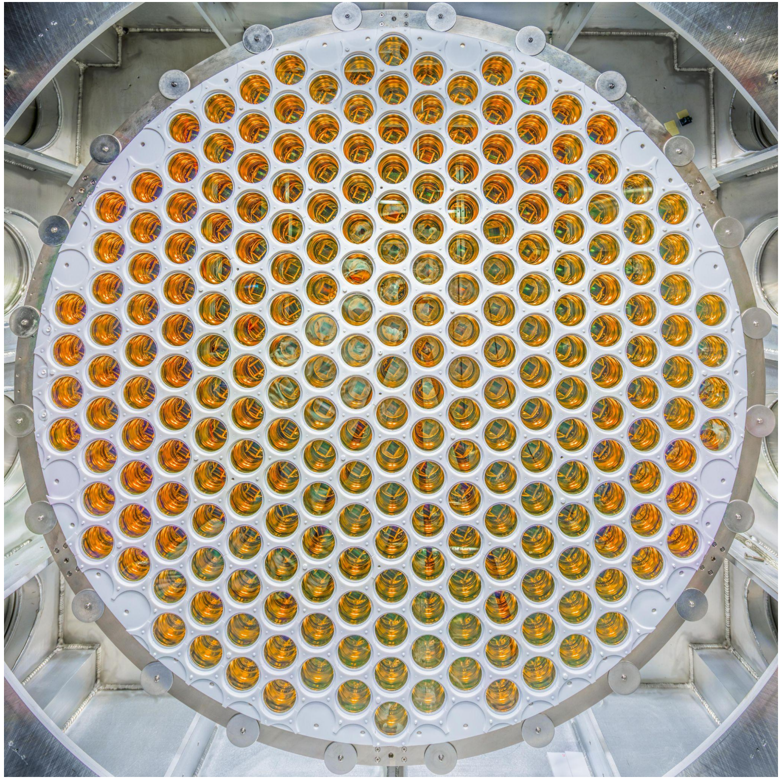

The LUX-ZEPLIN Detector

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