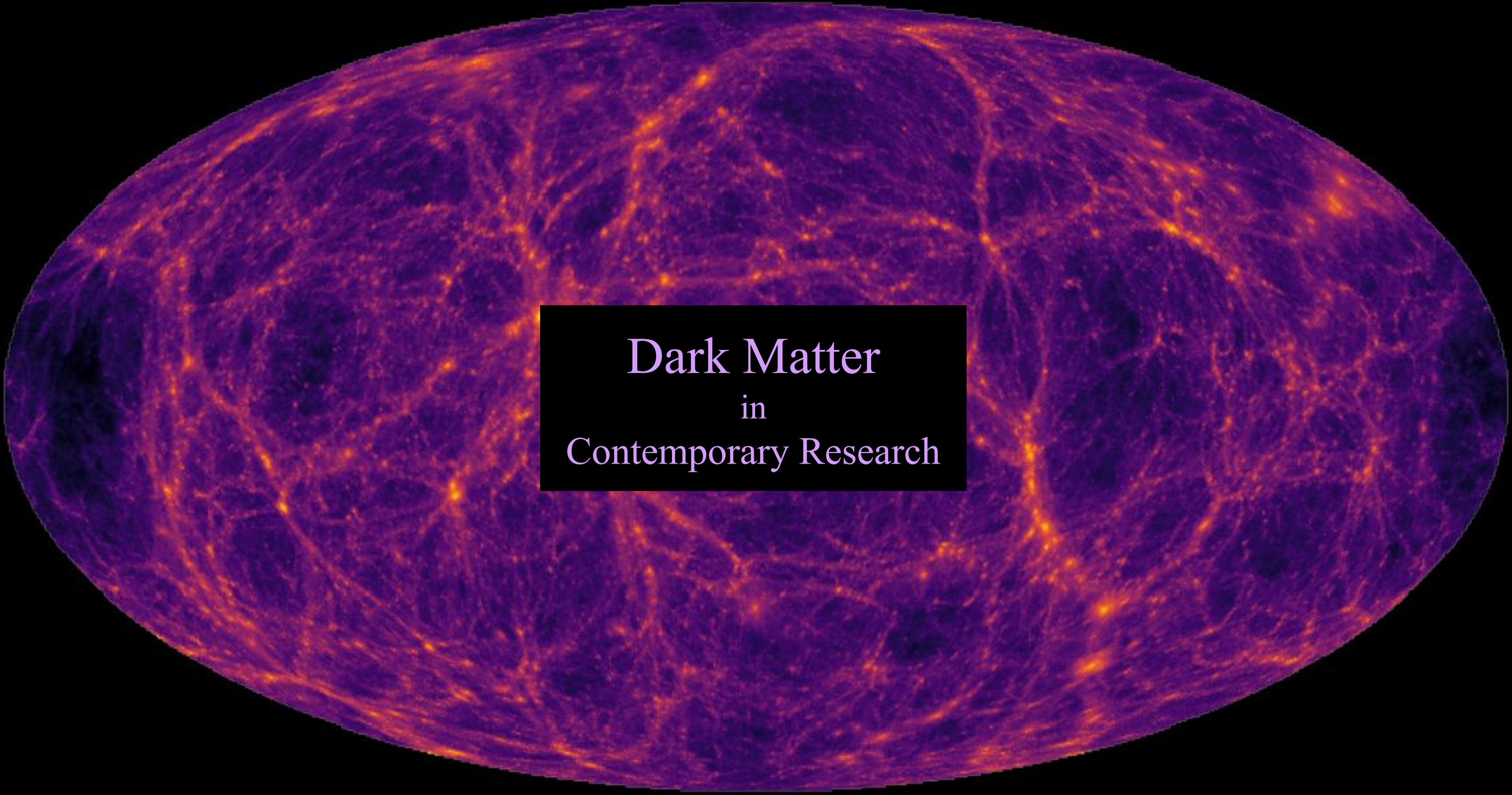
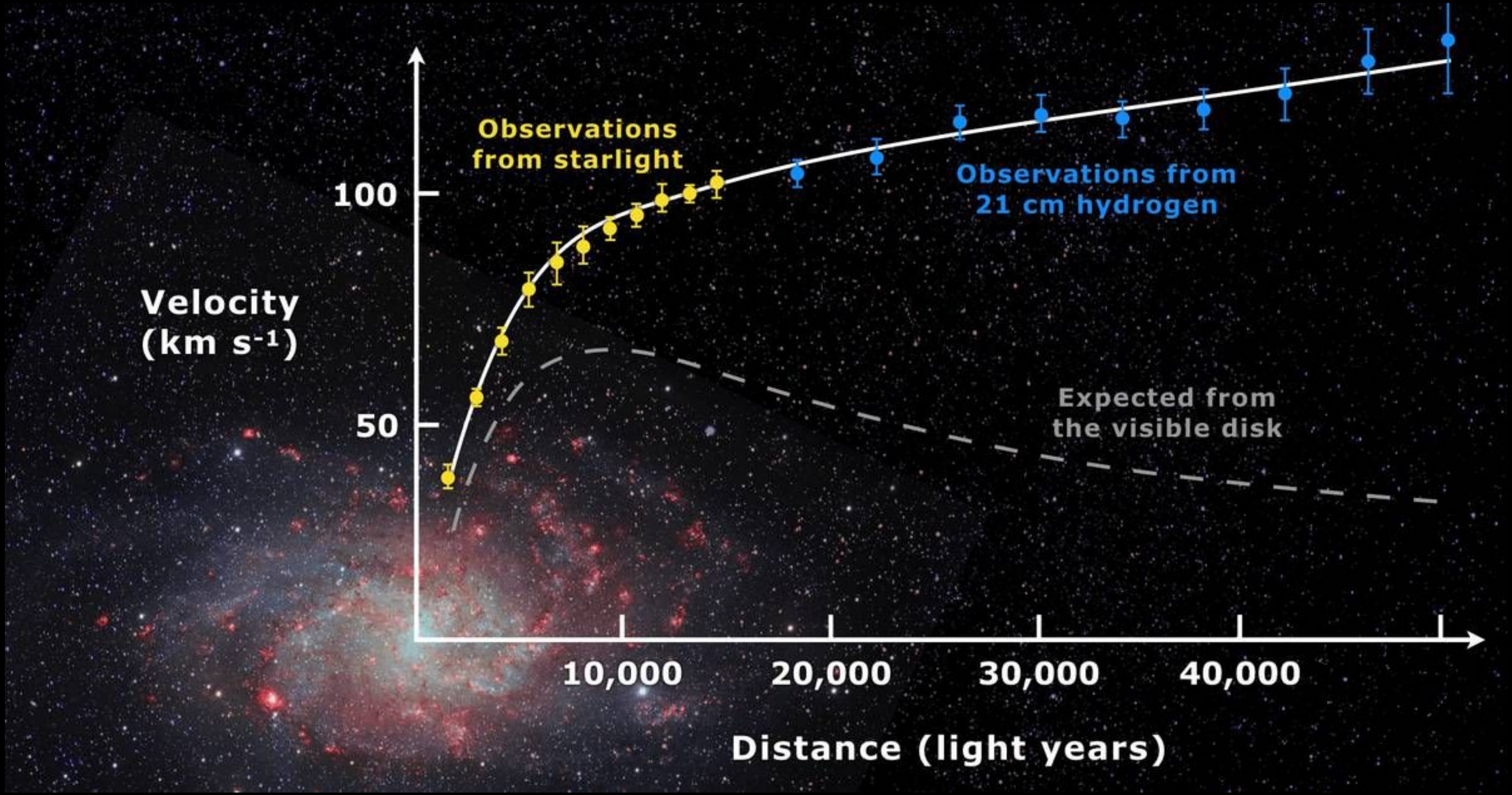
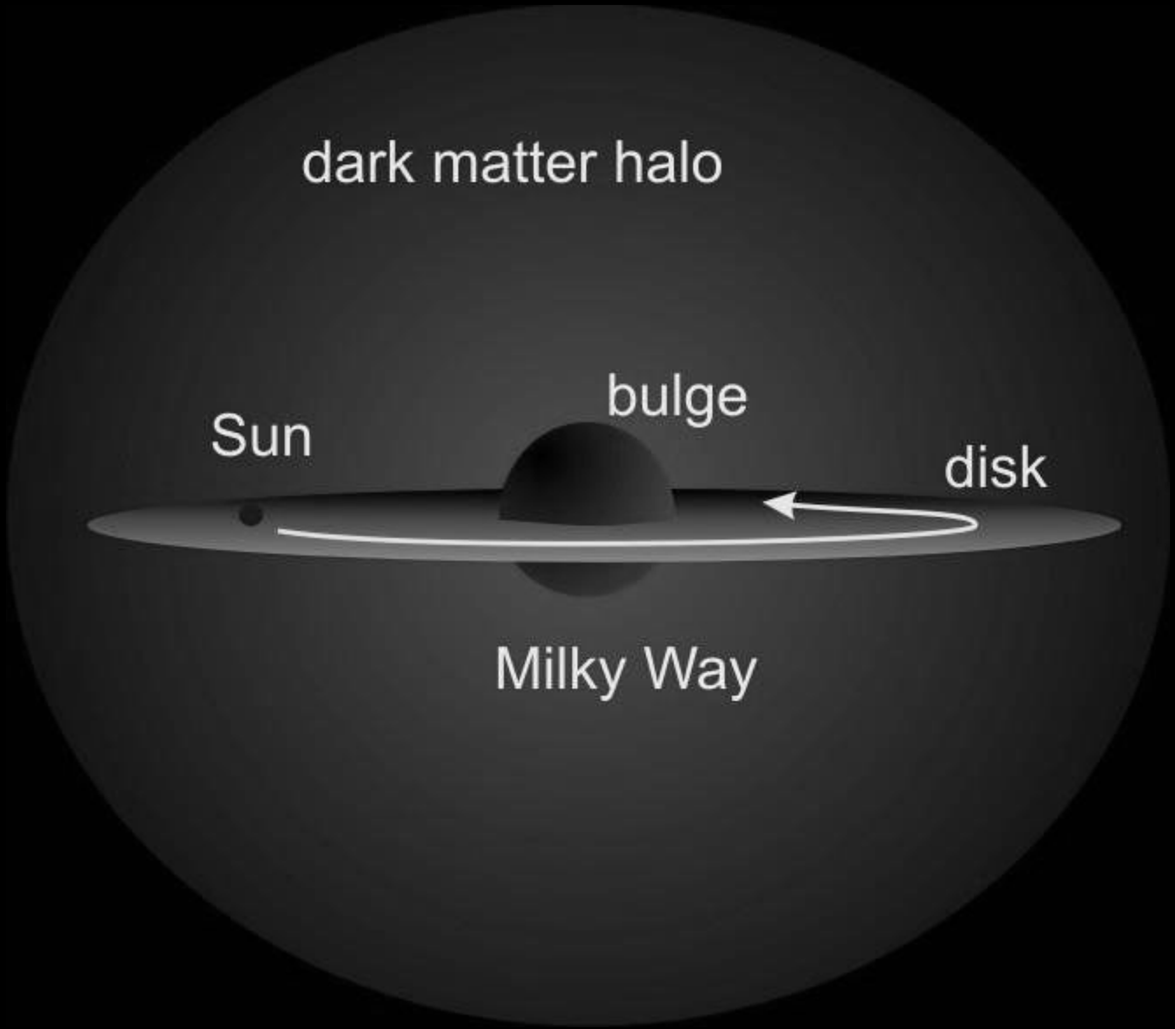
Dark Matter
in
Contemporary Research

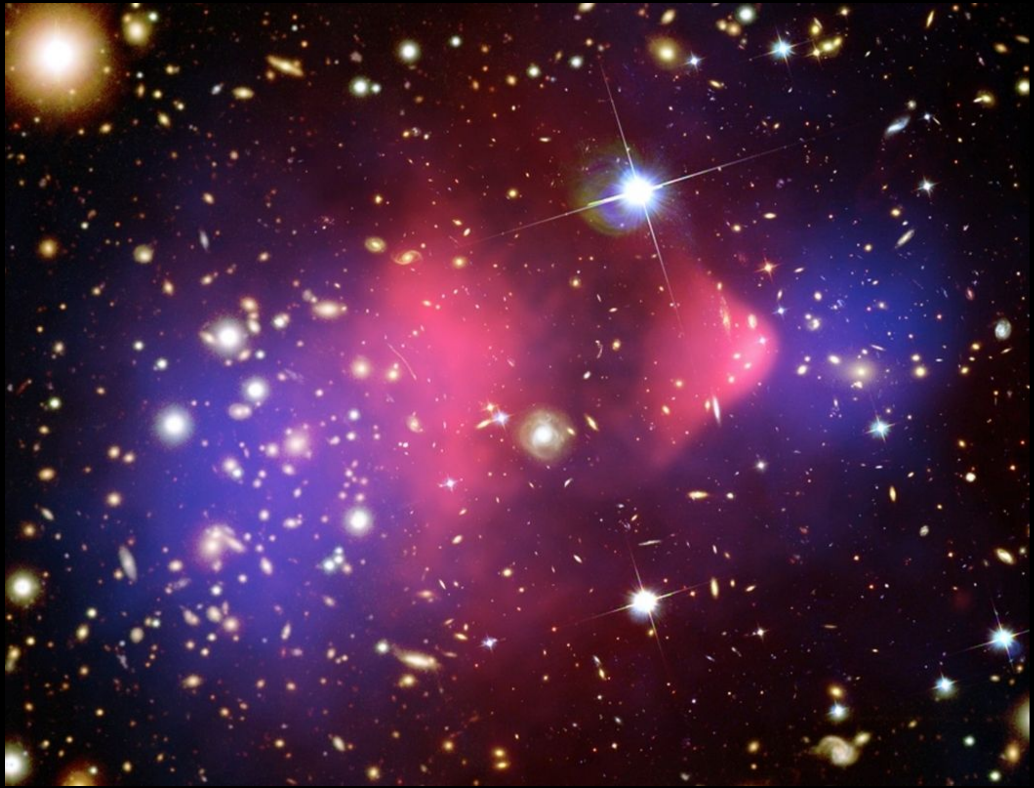


Galaxy Rotation Curves



Jan Oort & Fritz Zwicky (1930s) ; Vera Rubin & Kent Ford (1970s)

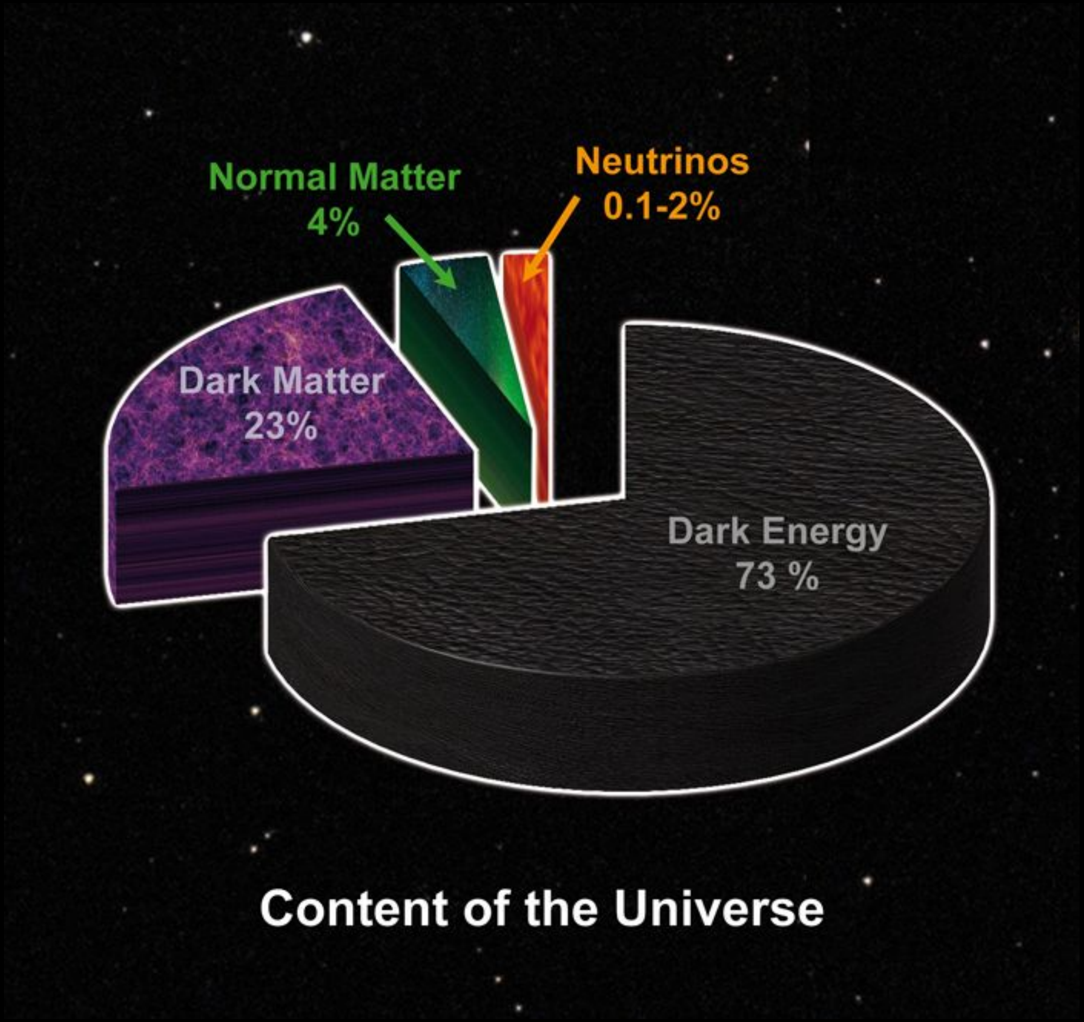

dark matter halo
bulge
Sun
disk
Milky Way



Bullet Cluster (3.72 billion ly away)
Gravitational Lensing (2004)

<u>Other Evidences:</u>

- *Large-Scale Structure*
- *CMB*


Normal Matter
4%
Neutrinos
0.1-2%
Dark Matter
23%
Dark Energy
73 %
Content of the Universe


BEHOLD, THE UNIVERSE
IN ALL ITS SHINY GLORY
But what's that
shadowy place over there?
THE
DEVIL'S WORK
imgflip.com

Various Dark Matter Models:

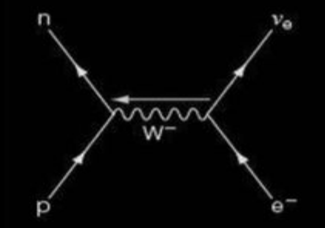
- **What is WDM exactly and how is it different from CDM?**
  - CDM (Cold Dark Matter) is assumed to have been non-relativistic during decoupling and thus would stay relatively stationary in the DM halo.
  - WDM (Warm Dark Matter) is dark matter that is proposed to have been relativistic during decoupling and would thus whiz around the DM halo.

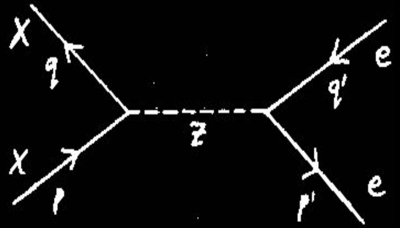
- **What is SIDM exactly and how is it different from CDM?**
  - SIDM (Self-Interacting Dark Matter) may have Yukawa-like strong interactions in addition to only gravity (CDM), and were introduced as a potential solution to the 'Cuspy Halo Problem' - Nearly all CDM simulations form halos with density increasing steeply at small radii, while the observed real rotation curves of most observed dwarf galaxies suggest that they have flat central dark matter density profiles, or "cores".
  - Scattering cross section of ~1 cm^2/g best fits observations.

- **What is FDM exactly and how is it different from CDM?**
  - FDM (Fuzzy Dark Matter) has a rest mass of ~10^(-22)eV and its corresponding de-Broglie wavelength is ~1 kpc. Therefore, the quantum effect of FDM plays an important role in structure formation.
  - For context, the rest mass of electrons is ~0.5MeV (~ 9.1 x 10^(-31) kg).

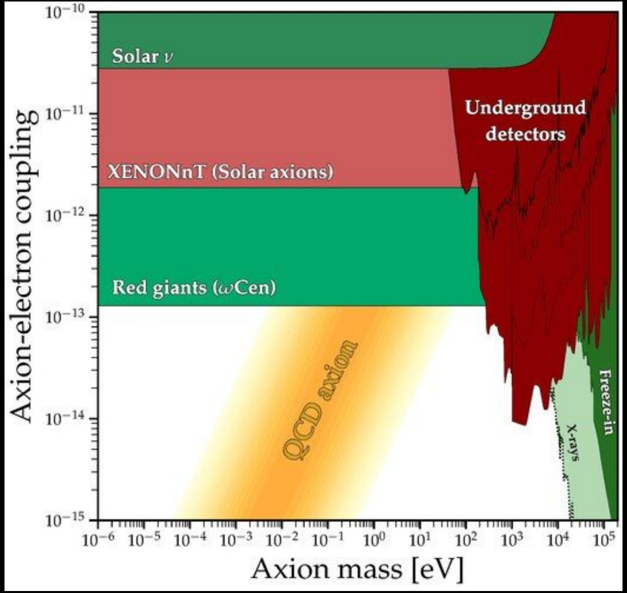
Various Dark Matter Models:

- **What are WIMPs?**
  - Weakly Interacting Massive Particles (WIMPs) are a dark matter candidate similar to SIDM in that they interact with each other and baryonic matter via gravity as well as the weak nuclear force.
  - Neutrinos and neutralinos are candidates for WIMPs.





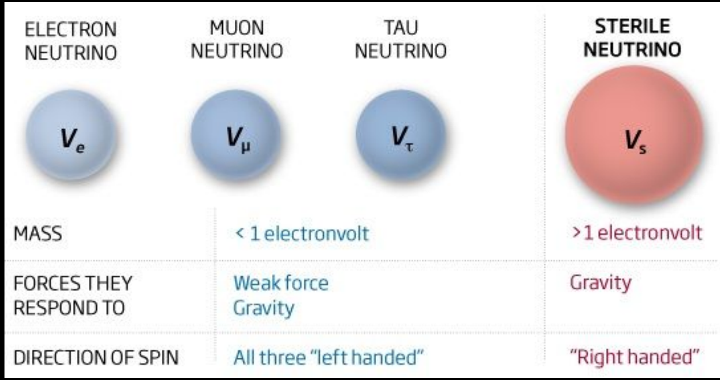
- **What are Axions?**
  - Theoretical DM candidates which interact via EM, strong force and the weak force in addition to gravity. One of the oldest DM candidates with various experimental searches conducted to no fruition.

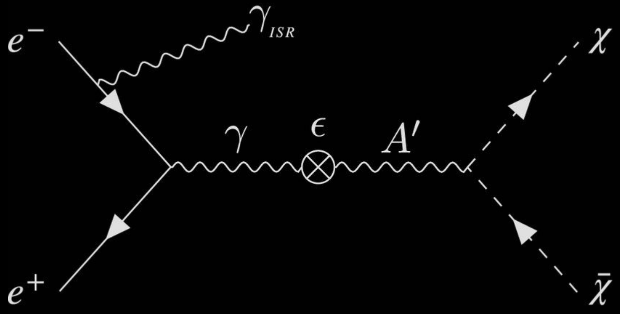


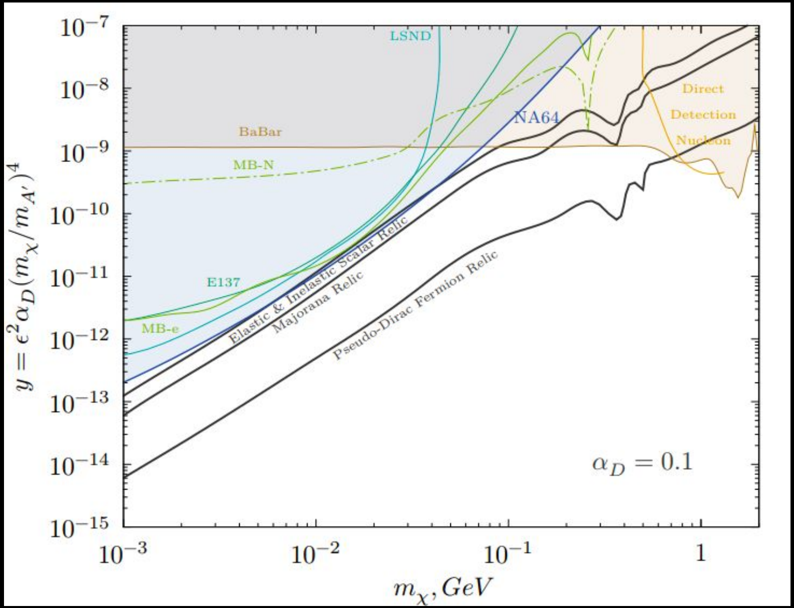
Various Dark Matter Models:

- **What are Sterile Neutrinos?**
  - DM candidates which interact only via gravity.
  - Essentially the CDM story, but narrated by a particle physicist.
  - Gained significant popularity after the discovery of neutrino oscillations.

- **What are the ‘Dark Sectors’ or ‘Hidden Sectors’?**
  - Essentially SIDM on steroids.
  - Whole ‘dark standard model’ hypothesized with ‘dark photons’ and such. Look up ‘mirror matter’.
  - Ongoing Belle II experiment in Japan and the NA64 experiment at CERN one of the premier experiments testing this model.







Alternatives to Dark Matter:

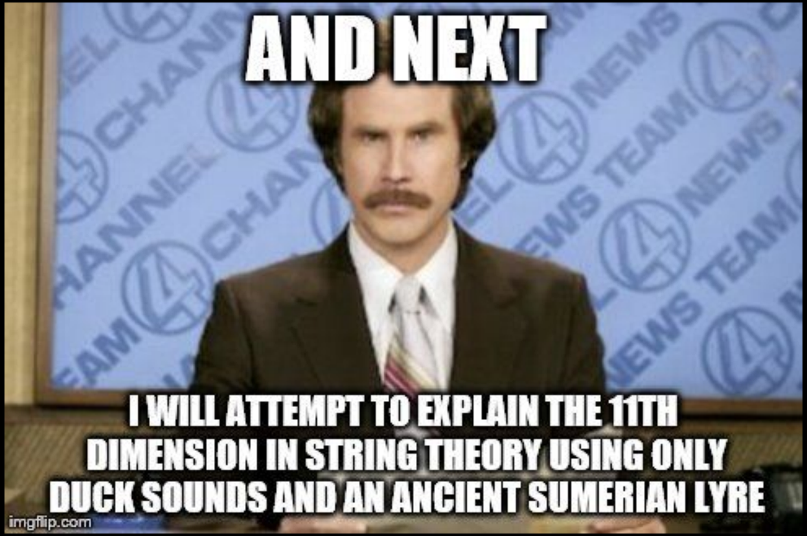
- **Primordial Black Holes**
  - Black holes that formed in the early Universe owing to a young, densely-packed Universe.
  - Gaining traction due to the observation of seemingly impossibly high redshifted galaxies by the JWST.

- **Modified Newtonian Gravity (MOND or Milgromian Dynamics)**
  - Modified theory of Newton’s gravity which explains the galaxy rotation curves.
  - Does not work at large scale.

- **Modified General Relativity**
  - Modified Theory of general relativity.
  - Fails at many points and requires DM in addition to it.

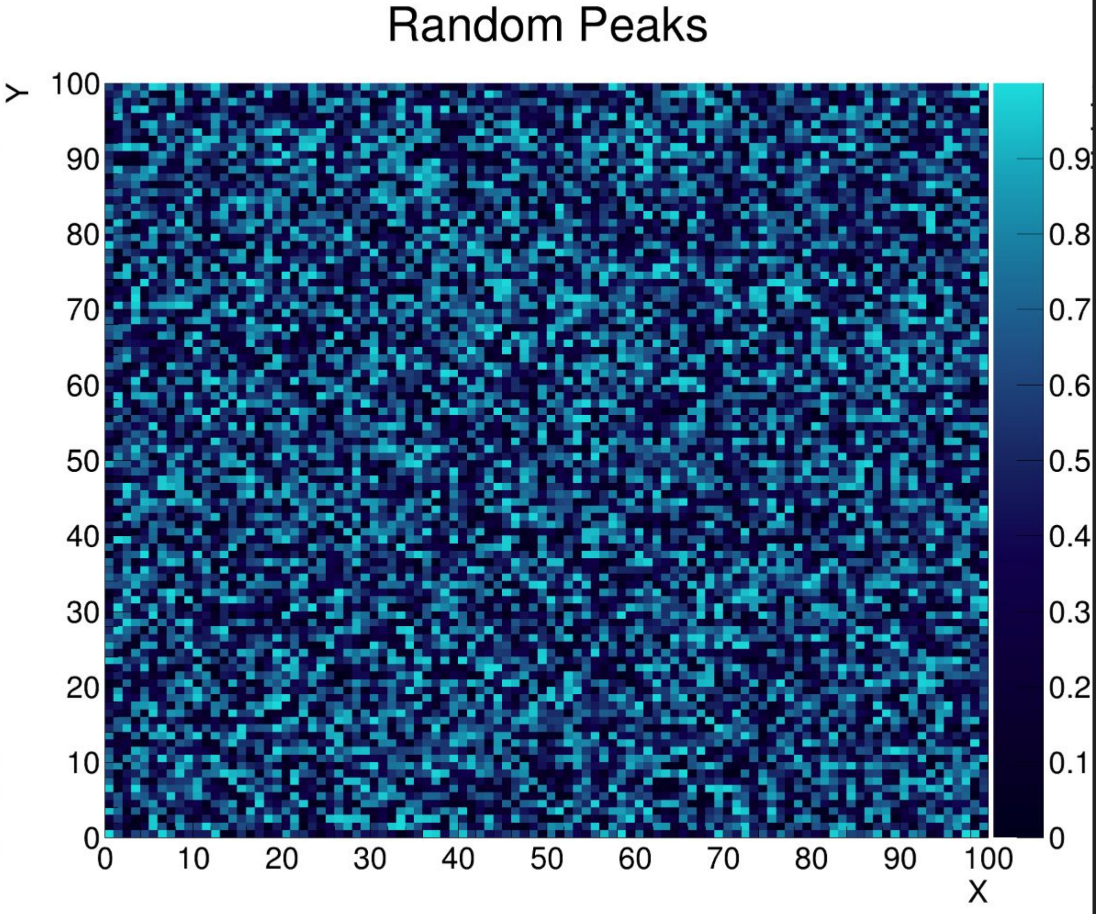
- **Paradigm Shift in Physics**
  - Do it, I dare ya.

- **String Theory**
  - Enough said.



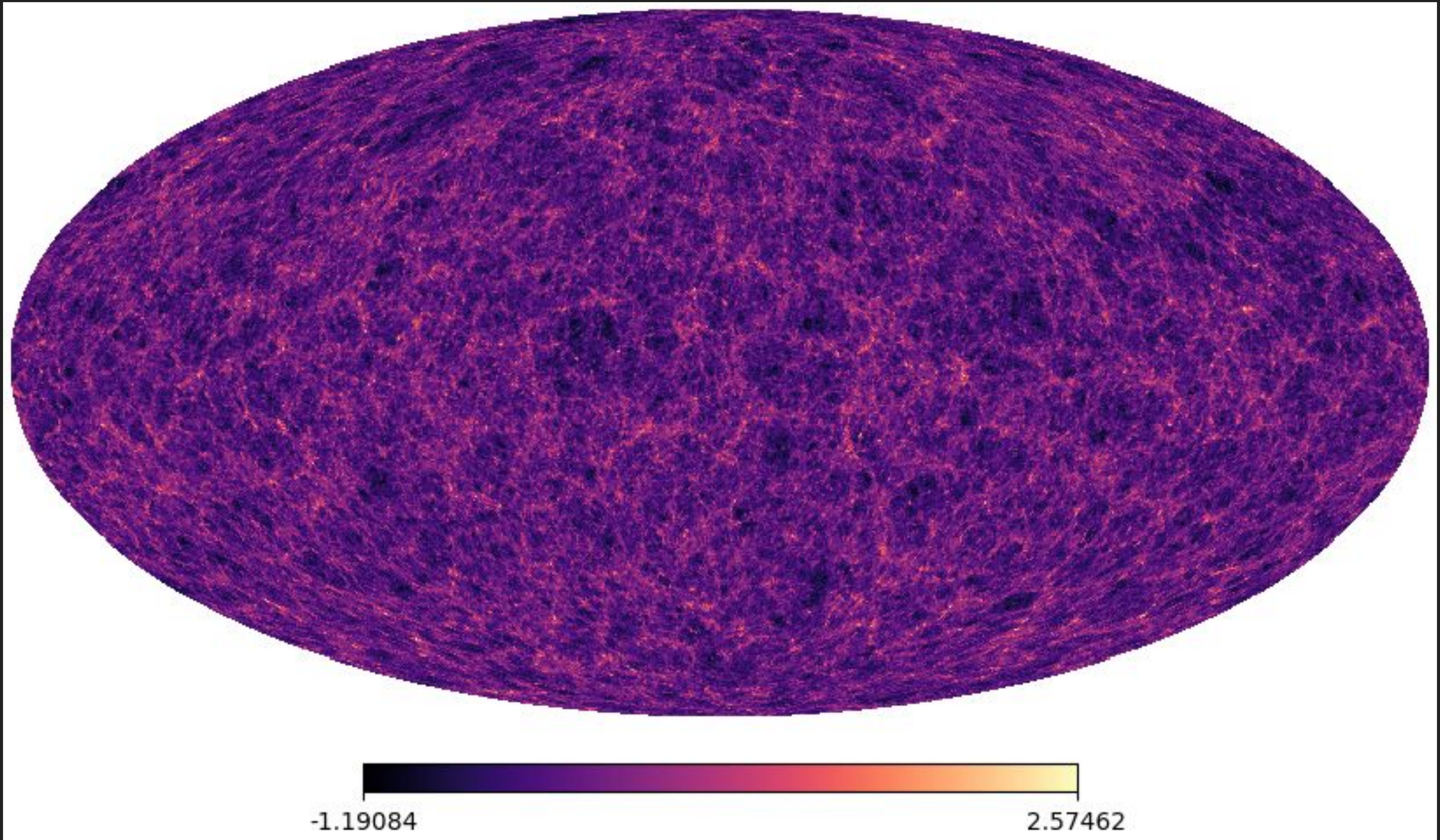
Dark Matter Research in Cosmology

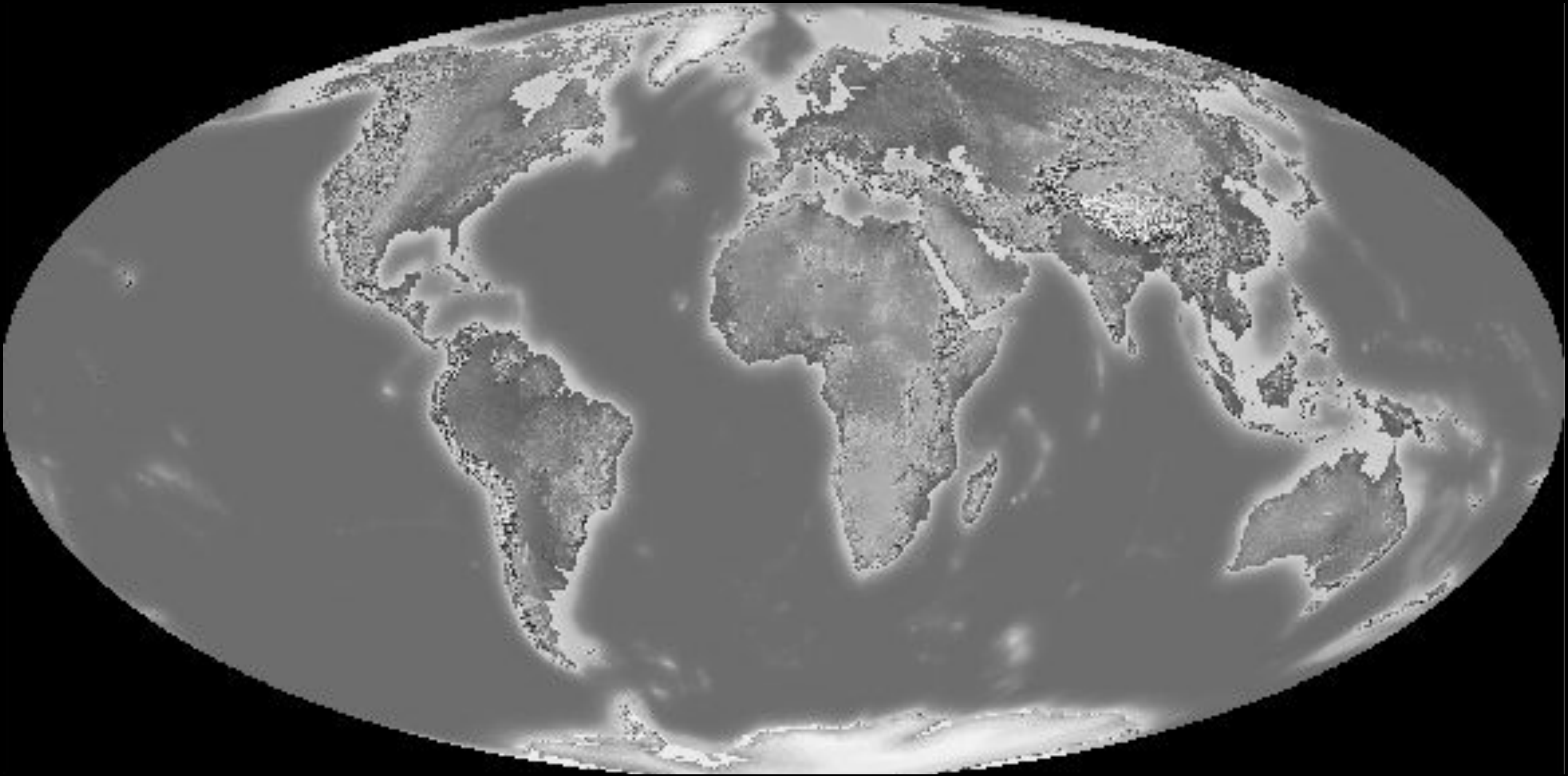
Peak Statistics

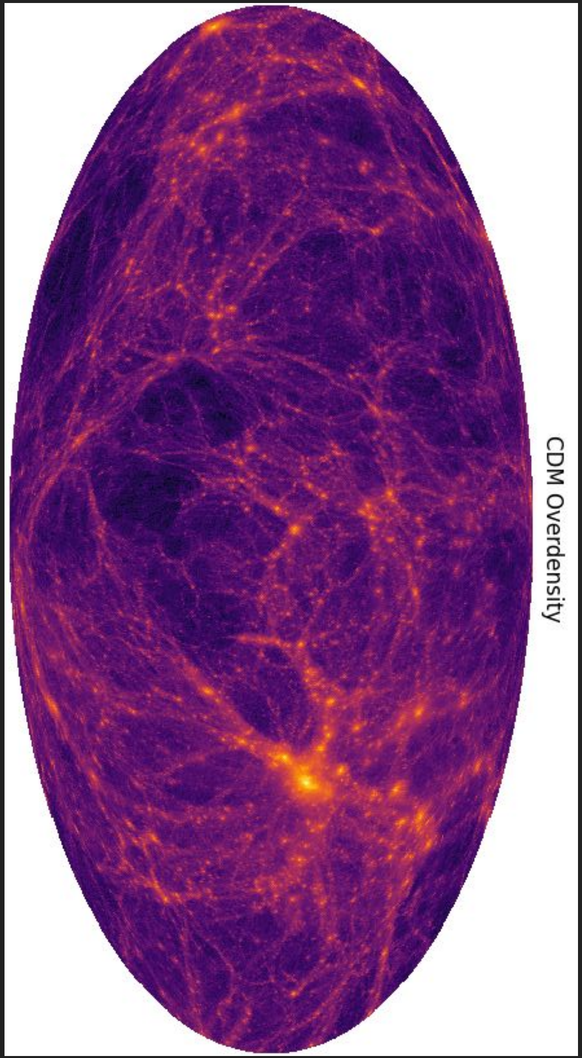


For a threshold of 0.5, the number of peaks is: 1142.

Cold Dark Matter Density Map

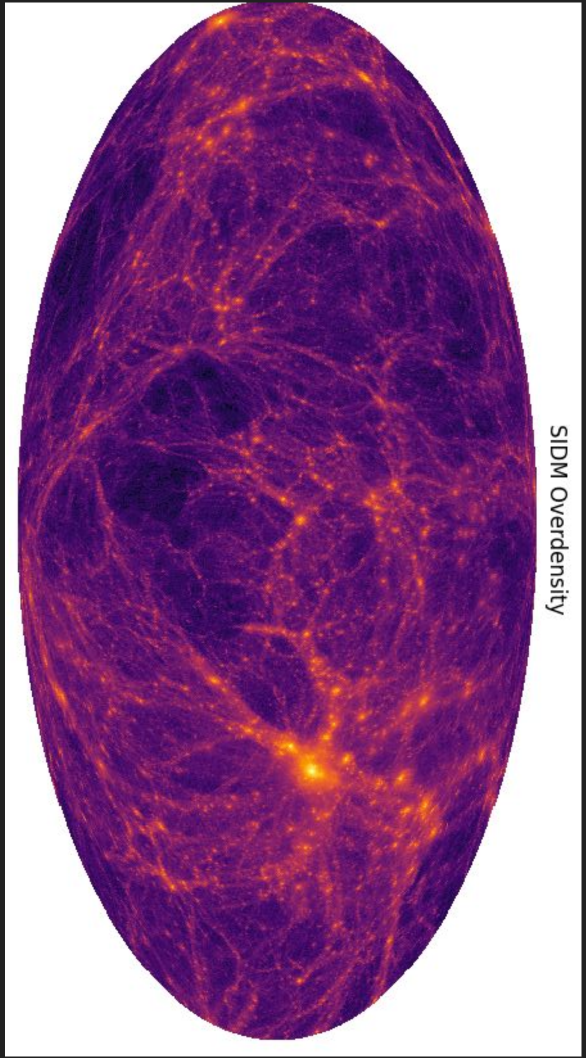






CDM
vs
SIDM

z = 0.00
L = 40 Mpc



Fuzzy Dark Matter:

Zhang, J., Liu, H., & Chu, M. C. (2019). *Cosmological simulation for fuzzy dark matter model. Frontiers in Astronomy and Space Sciences*, 5, 48:

"Fuzzy Dark Matter (FDM), motivated by string theory, has recently become a hot candidate for dark matter. The rest mass of FDM is believed to be ~10^(-22)eV and the corresponding de-Broglie wavelength is ~1 kpc. Therefore, the quantum effect of FDM plays an important role in structure formation. .... The "small-scale crisis" in CDM might be solved in the FDM model, but more studies are needed to confirm this suggestion."

- Rest Mass of Electrons ~0.5MeV (~ 9.1 x 10^(-31) kg)

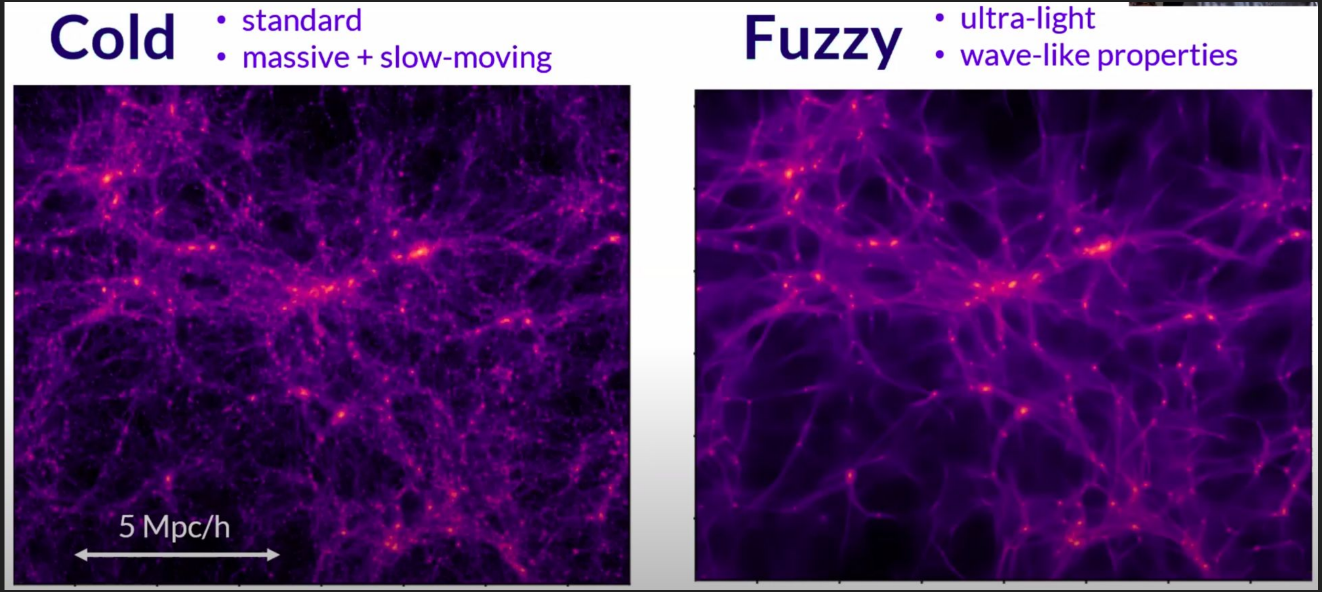


IMAGE CREDITS:

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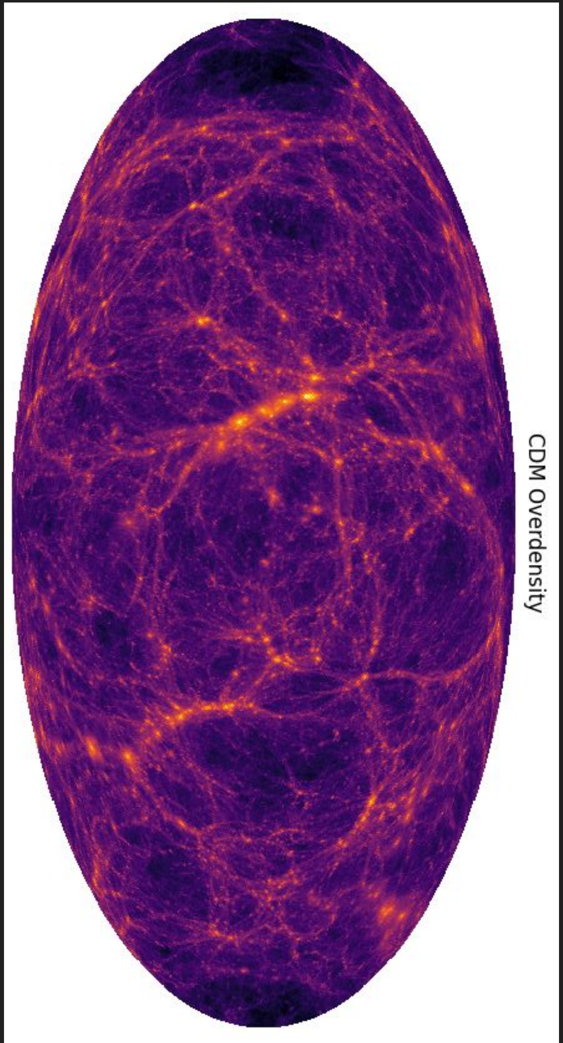
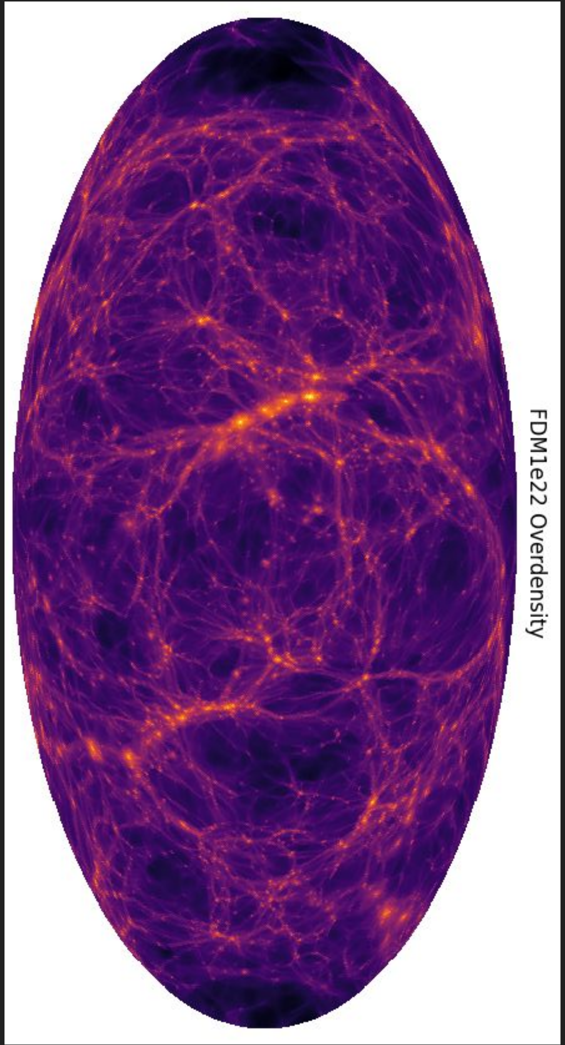
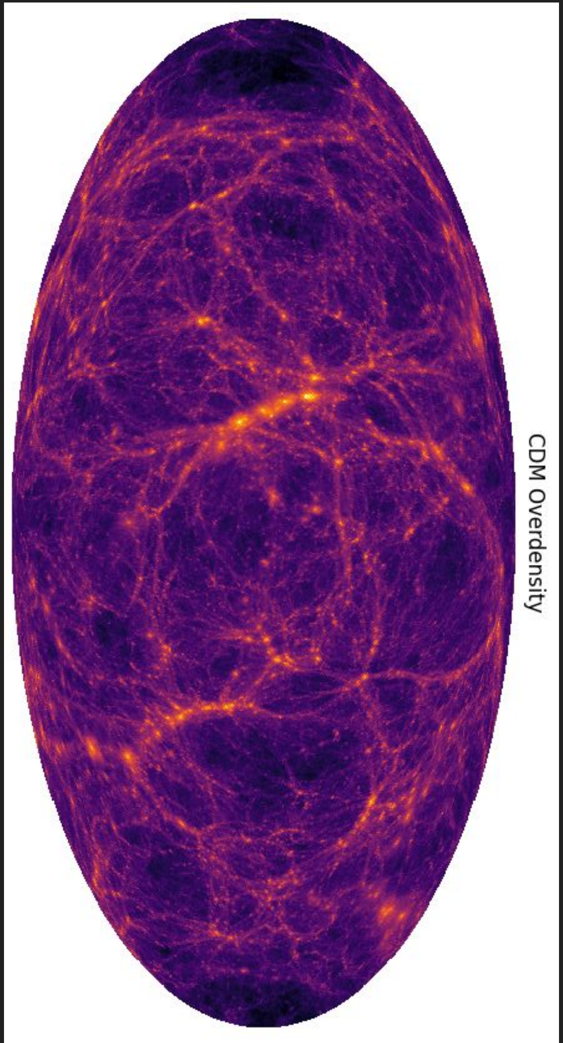
CASSI 2021 Talk



CDM
vs
FDM1e22

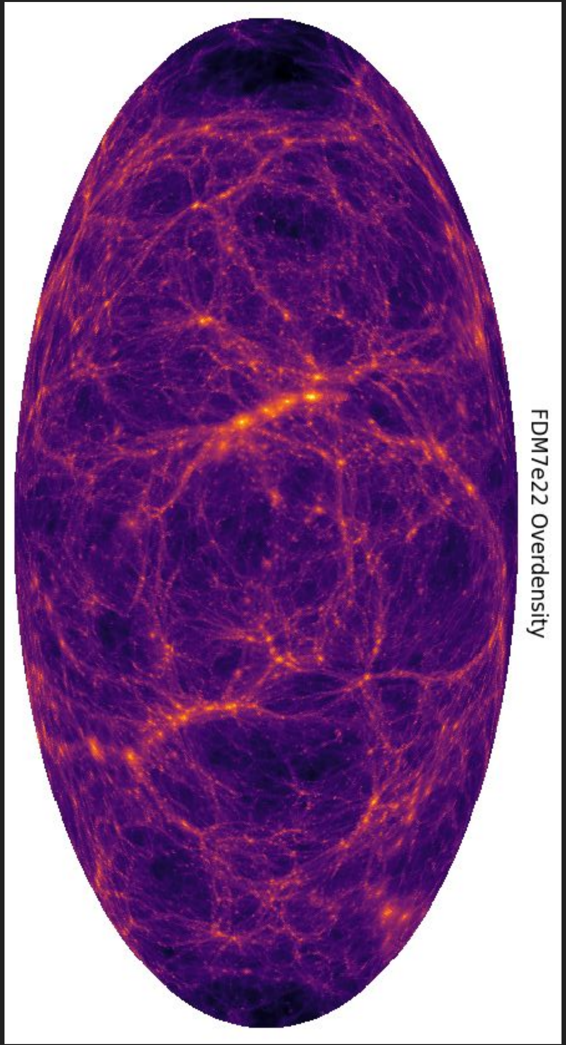
z = 0.99729
L = 40 Mpc

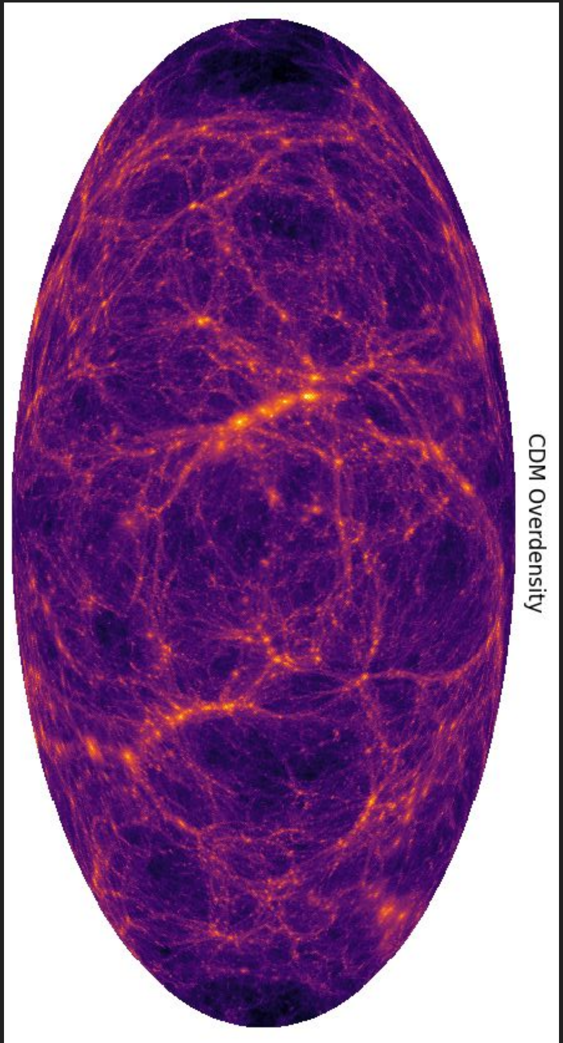




CDM
vs
FDM7e22

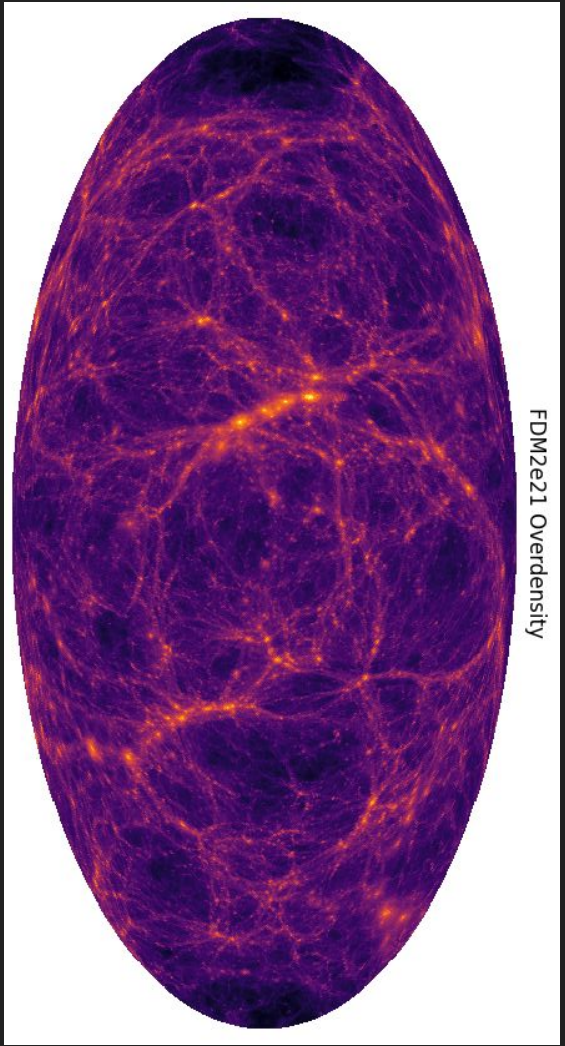
z = 0.99729
L = 40 Mpc





CDM
vs
FDM2e21

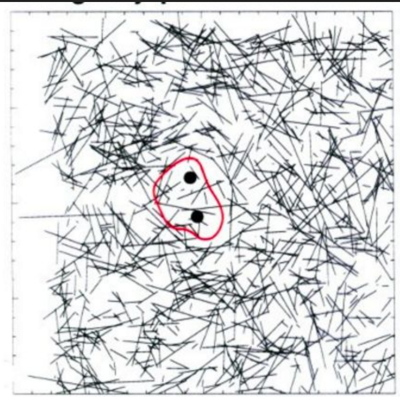
z = 0.99729
L = 40 Mpc

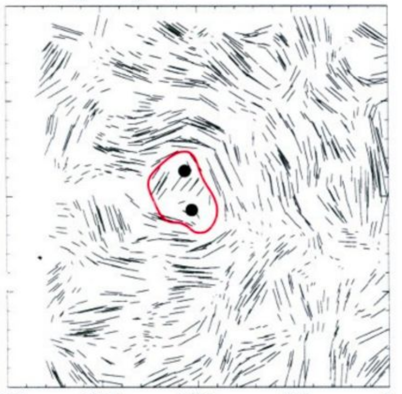


Weak Lensing Pipeline:

- Astronomical data is first collected in the form of the ellipticities of galaxies. From these galaxy ellipticity maps, it is possible to extract the shear maps by establishing a mean shape of spiral and elliptical galaxies and measuring the deviations from said shapes owing to weak lensing. Then, convergence maps can be extracted from the shear maps using algorithms (such as the 'Kaiser-Squires' algorithm), which can be used directly or in the form of overdensity maps after scaling the map by the critical density.

Ellipticity Map → Shear Field Map → Convergence Map





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Overdensity Map
(Projected Surface Mass Density Map)

- **Hence, weak lensing allows us to directly probe the mass distribution of the universe which can be predicted much more easily than the distribution of visible matter, and thus also makes it a fantastic tool to study dark matter.**

Dark Matter Research in Particle Physics

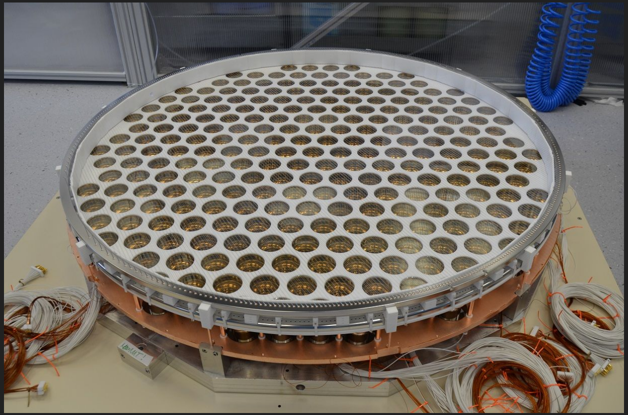
XLZD Collaboration, NA64, etc.

XENONnT

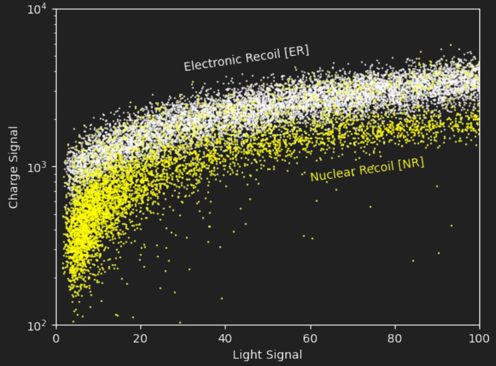
- The TPC filled with liquid xenon to a certain level, with a gaseous xenon layer above. Xenon has excellent stopping power for low-energy gammas and is a natural scintillator.

- Gamma and Beta particles scatter off the electronic shell of the xenon atom, referred to as electronic recoil (ER) interactions.

- Heavier particles such as WIMPs or neutrons can interact with the nucleus itself, referred to as nuclear recoil (NR) interactions. Neutrons can then be differentiated from WIMPs by comparing signatures.



Time Projection Chamber

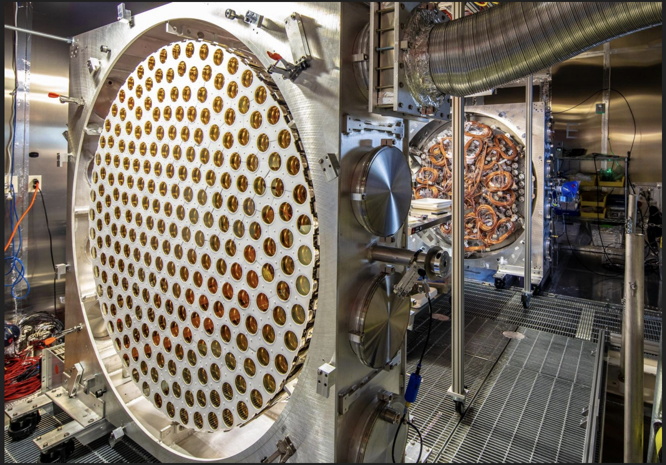


LUX-ZEPLIN

- Also looking for WIMPs like XENONnT and shares the use of xenon and a TPC with XENONnT as its main detector, however differs in technical details.

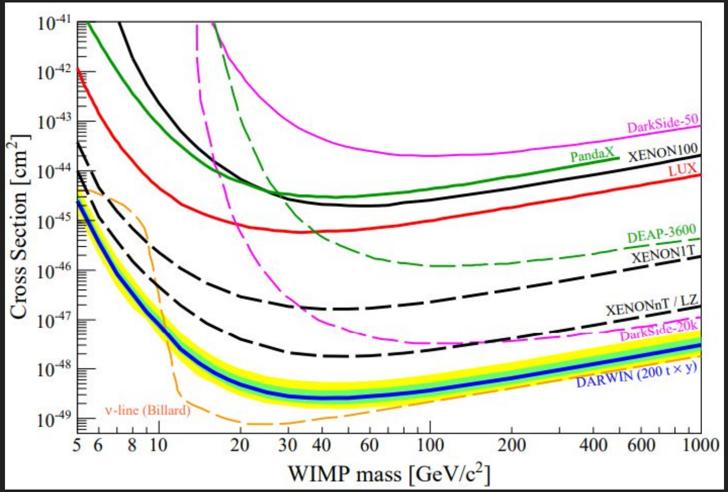
- Goal of XENONnT is to look for WIMPs and solar axions, while LZ aims to look for WIMPs and rare decays that may indicate the existence of dark sectors in the Universe.

- The experiments also differ in their detector setup and particle signatures. This is of utmost importance to confirm the existence of WIMPs, if found, with different methods.



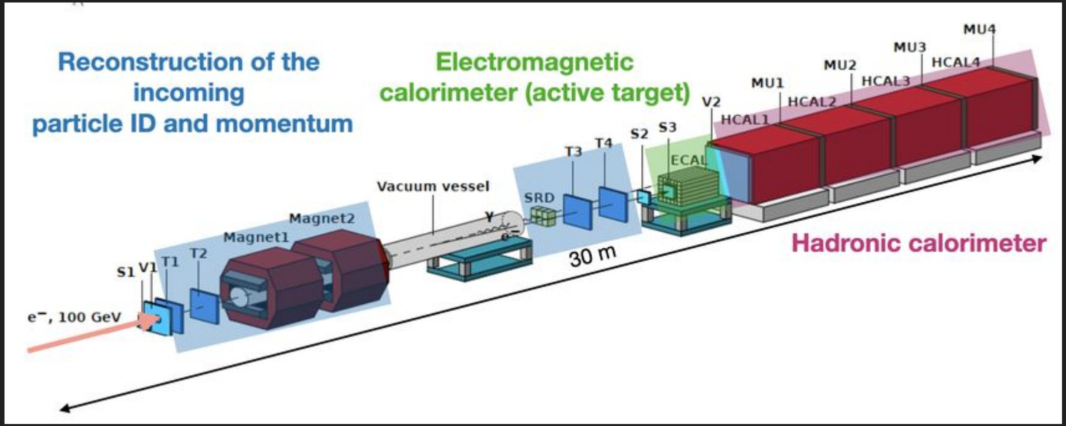
DARWIN

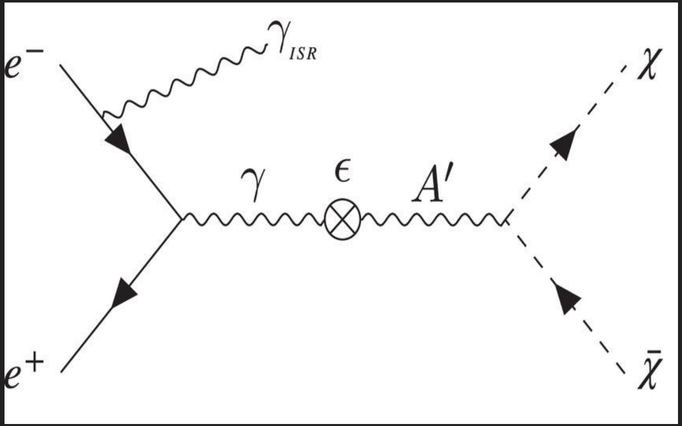
- DARWIN aims to search for WIMPs over a wide range of mass - 5 GeV/c^2 to >10 TeV/c^2, via various possible couplings (spin-independent, spin-dependent, inelastic). Aims to begin data taking in 2030.
- Low backgrounds will also allow searches of rare events such as solar neutrinos, neutrinoless double beta-decay of 136Xe, axions and axion-like particles, neutrinos from supernovae and various rare nuclear processes.
- 50 tonnes of liquid xenon will be used compared to ~10 tonnes used by LZ and XENONnT which will allow for an increased sensitivity as well as searches for rare decays and neutrino flavour physics as mentioned above.
- Will showcase extremely low backgrounds (enough to remove neutrino background) and a much more sophisticated particle signature. DARWIN aims to do to LZ and XENONnT what the JWST did to the Hubble Telescope.



NA64 (CERN)

- NA64 is a fixed target experiment at CERN that is aimed primarily at searching for dark sector physics, e.g. dark photons (known as U or A’ boson) and their interactions with baryonic matter.
- It was also used to study rare processes such as the lepton flavor violation and to test lepton universality.
- 100 MeV electrons or 160 MeV muons are directed onto a electromagnetic calorimeter target (ECAL, which is a target and a detector) which is theorized to possibly produce dark photons which can then be detected either directly (if they interact with baryonic matter) by the ECAL, indirectly (if they decay to give baryonic products) by the hadronic calorimeters (HCALs) placed behind the ECAL.
- Limits were set for the photon-dark photon coupling to [1 MeV < m(A′) < 1 GeV].





Many more dark matter detection experiments have been conducted and are being conducted currently, however none have yielded any positive results thus far. Notable ongoing experiments using various methods have been listed below:

- Noble Liquid Experiments
    - XLZD and PandaX-4T (Xenon) ; DarkSide-20k and ARGO (Argon)
- Cryogenic Solid State Experiments
    - CRESST-III, EDELWEISS-III
- Indirect Detection Experiments
    - AMS (AntiMatter in Space) ; IceCube, KM3NeT, ANTARES (Neutrinos) ; Cherenkov Telescope Array, Fermi-LAT, HAWC (Gamma Rays)
- Collider and Fixed Target Experiments
    - SHiP, FASER, CMS, ATLAS (Collider) ; NA64, LDMX, SeaQuest / FerMINI (Target)

So… will they find anything?

FIN