Open questions in particle physics

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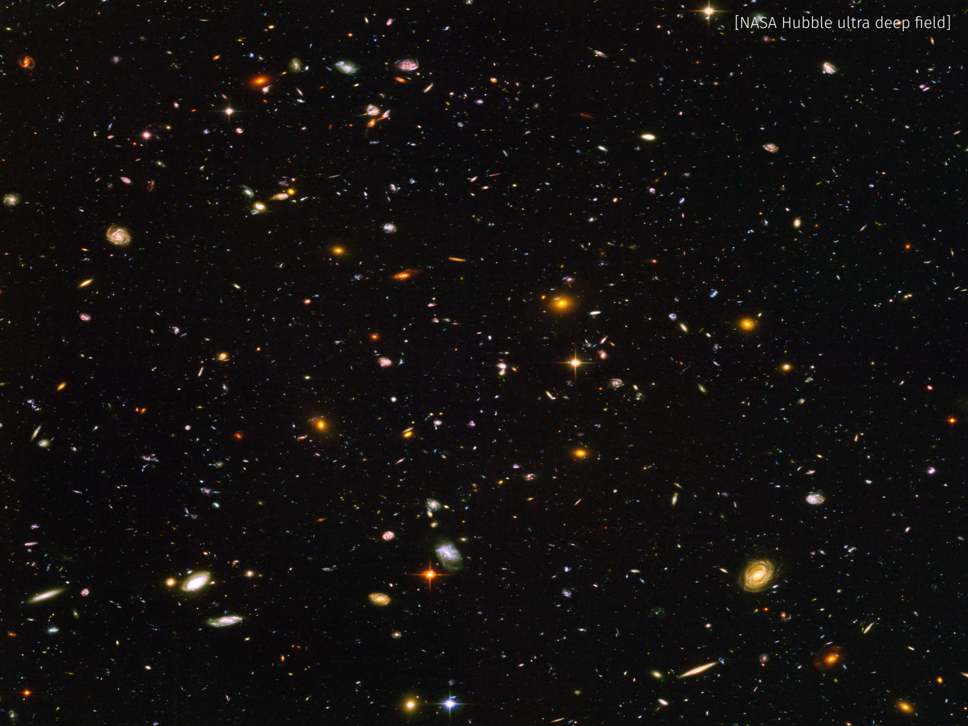
Lecture structure

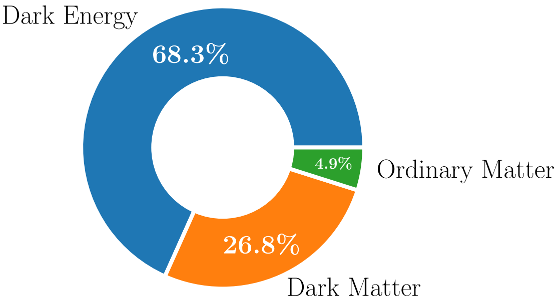
1. Evidence for dark matter
2. Dark matter candidates
3. Indirect detection
4. Direct detection
5. Producing Dark Matter in a collider
6. Outlook

Evidence for dark matter



[NASA Hubble ultra deep field]

A very famous plot

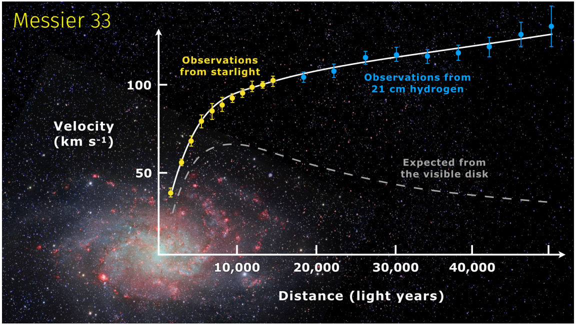


[data from ESA Planck]

What constitutes the universe?

- Content of the universe estimated from cosmological observations
- Ordinary matter account only for $\simeq 5\%$ of the Universe
- Open question: what constitutes the remaining part?

Signs in the sky: galaxy rotation

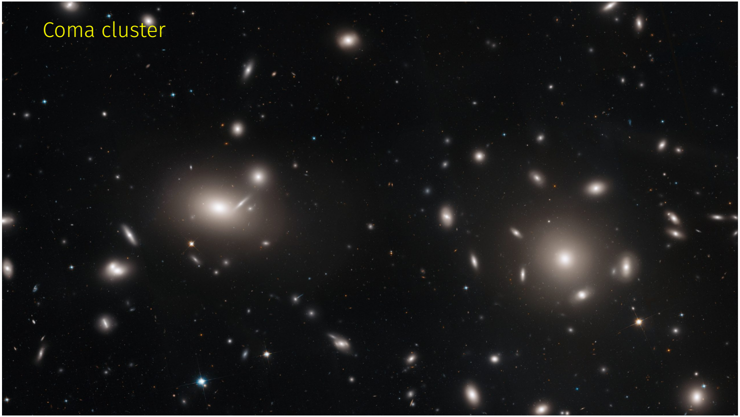


[M. De Leo]

Rotational curves of spiral galaxies

- Plot the orbital velocity of the stars versus their radial distance
- The curve does not follow what is expected from the gravitational potential created by the visible matter [Rubin 70s]

Signs in the sky: galaxy clusters

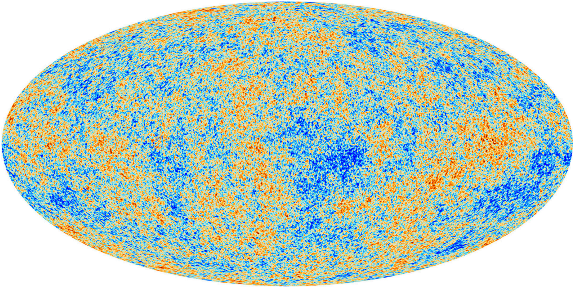


[NASA, ESA]

Galaxy cluster dynamics

- Virial theorem prediction: $E_{\rm kin} = -\frac{1}{2} E_{\rm pot}$
- [Zwicky 1930] finds discrepancy: $E_{\rm kin} \simeq 170 \times -\frac{1}{2} E_{\rm pot}$

Signs in the sky: the cosmic microwave background

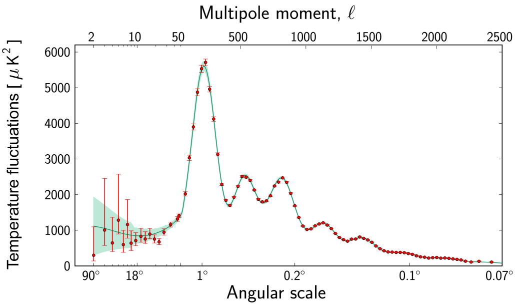


[ESA Planck]

Temperature fluctuations

- Temperature differences in the CMB as a function of the angular scale in the sky
- The green curve is the best fit of the Λ_{CDM} model (extraction of cosmological parameters)

Signs in the sky: the cosmic microwave background



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Temperature fluctuations

- Temperature differences in the CMB as a function of the angular scale in the sky
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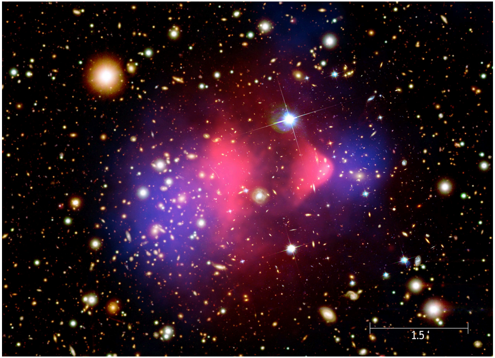
Signs in the sky: gravitational lensing



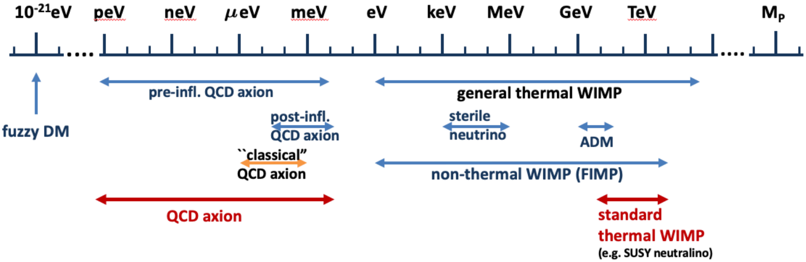
[NASA/Chandra X-ray observatori/STScI/D. Clowe et al.]

Gravitational lensing

- Two colliding galaxy clusters → study of the mass distribution
- In pink X-ray data, in blue the mass distribution inferred from gravitational lensing effect

Dark matter candidates

Weighting Dark Matter

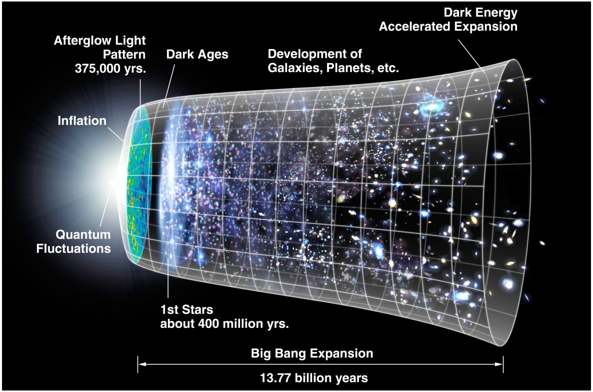


[Direct detection of DM - APPEC committee report, 2104.07634]

Other possibilities: non-particle Dark Matter

- There are also non "fundamental" explanations such as primordial black holes
- Also the possibility of modifying the description of the gravitation interaction on large scale has been studied
- This possibility however encounters difficulties in describing some of the indirect signs of DM

Producing dark matter

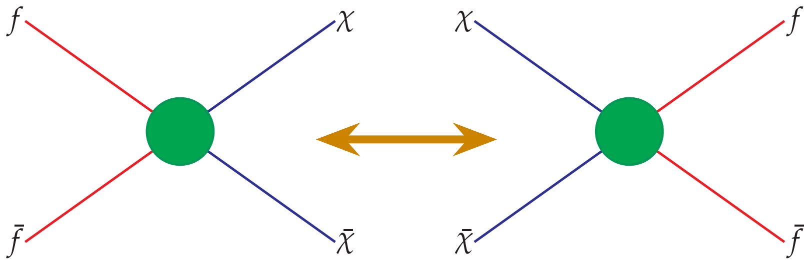


[NASA WMAP]

How do we generate the observed DM content?

- We observe a certain relic density of Dark Matter in the universe
- We assume that it consists possibly of a new particle (or more than one) that interacts in some way with the Standard Model particles
- How can we arrive to have such a relic density?

Dark Matter freeze out



Thermal equilibrium, and then freezeout

- In the early universe the DM is in thermal equilibrium with the SM particles ($\tilde{\chi}\chi \longleftrightarrow \tilde{f}f$)
- The number density of the DM particle is given by $n_{\chi,\mathrm{eq}} = \int \frac{d^3p}{(2\pi)^3} e^{-E_\chi/T}$
- As the temperature drops, the interactions freeze out and we're left with a leftover density of DM particles

Dark Matter freeze out

Thermal equilibrium, and then freezeout

- The dynamics is described by the Boltzmann equation

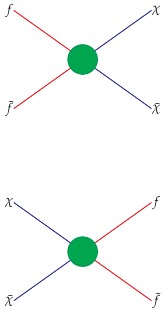
$$\frac{dn_\chi}{dt} + 3n_\chi \frac{\dot{a}}{a} = -\left(n_\chi^2 \langle \sigma\left(\chi\chi \to \bar{\mathrm{f}}\mathrm{f}\right) v_{\mathrm{rel}}\rangle - n_f^2 \langle \sigma\left(\bar{\mathrm{f}}\mathrm{f} \to \chi\chi\right) v_{\mathrm{rel}}\rangle\right)$$

- We then impose the principle of detailed balance

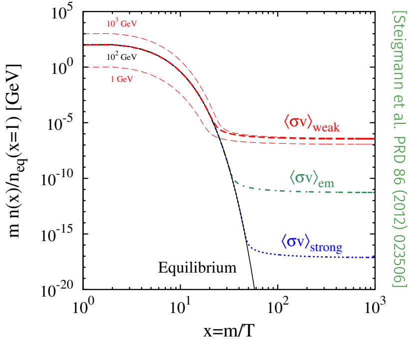
$$n_f^2 \langle \sigma\left(\bar{\mathrm{f}}\mathrm{f} \to \chi\chi\right) v_{\mathrm{rel}}\rangle = n_{\chi,\mathrm{eq}}^2 \langle \sigma\left(\bar{\mathrm{f}}\mathrm{f} \to \chi\chi\right) v_{\mathrm{rel}}\rangle$$

- We are then left with

$$\frac{dn_\chi}{dt} + 3n_\chi \frac{\dot{a}}{a} = -\langle \sigma\left(\chi\chi \to \bar{\mathrm{f}}\mathrm{f}\right) v_{\mathrm{rel}}\rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$$



Dark Matter freeze out



The phases of freezeout

1. Equilibrium, efficient annihilation of DM into SM particles and vice-versa
2. The scattering of SM particles into DM states is less efficient
3. No more equilibrium, freeze-out

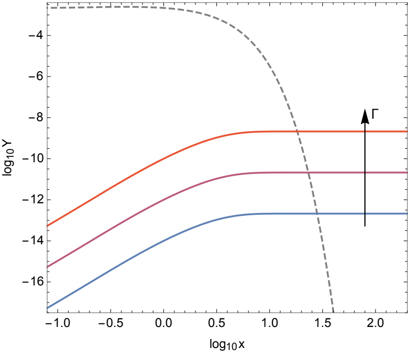
The WIMP miracle

1. We obtain the observed relic density for $\langle \sigma\left(\chi\chi \to \bar{f}f\right) v_{\rm rel}\rangle \simeq 2.2 \times 10^{-26}\mathrm{cm}^3/\mathrm{sec}$
2. SM-like couplings
3. Mass around $\mathcal{O}(100)$ GeV

Annihilation today?

- With such a cross-section it should be possible to observe DM annihilating today in region of high density

Other mechanisms



[Bernal et al. IJMPA 32 (2017) 27, 1730023]

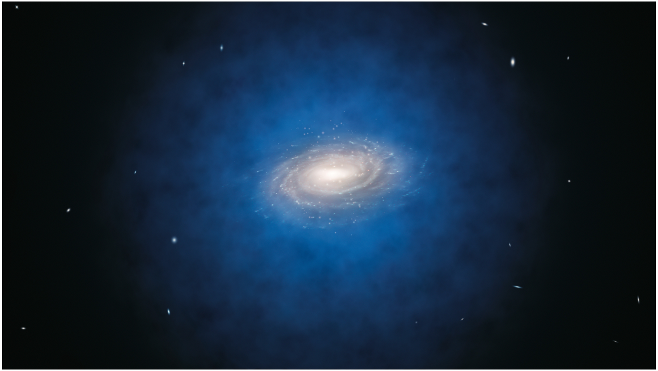
The FIMPS and the freeze-in

- Assume that the particle couples very weakly with the SM states
- The relic density then slow increases up to the currently observed value
- Very small couplings means very difficult/impossible to observe at colliders

Axions

- Field oscillations around the minimum → condenste → Dark Matter
- Low mass axions are good DM candidates ($\mathcal{O}(1-10)\mu eV$)
- Not very well probed at the LHC (LHC most sensitive to ALPs of a few GeVs)

Dark matter halo of the Milky Way



Dark matter in the halo

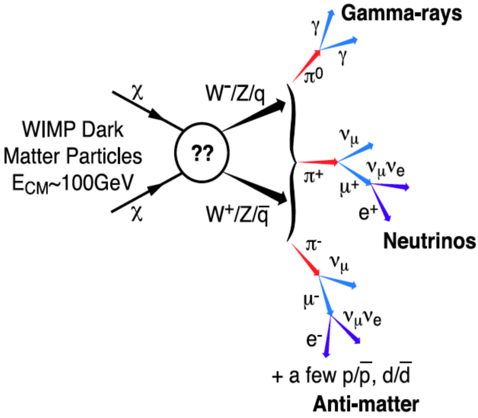
- The sun orbits the center of the Milky Way inside the Dark Matter halo
- Can we detect these particles?

Indirect detection

Can we observe DM annihilation today?

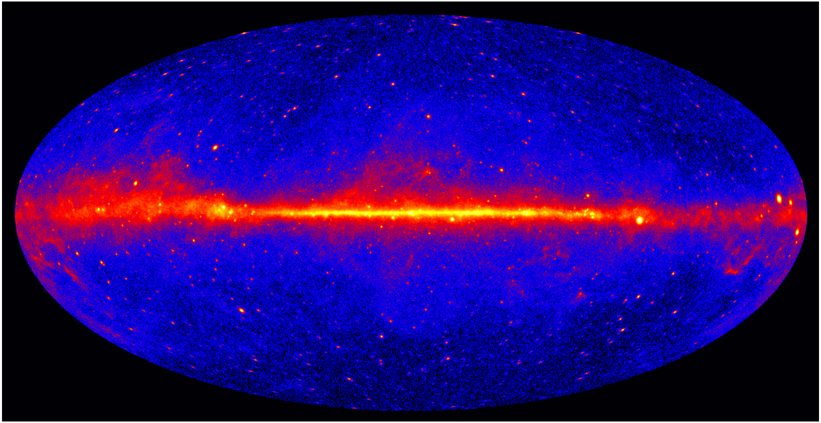
Annihilation today?

- Can we observe the annihilation of DM in space?
- Assuming a WIMP, decay into the SM particles results in mainly a flux of gamma rays, positrons and neutrinos



[Baltz et al. '03]

Where to search for these signals?

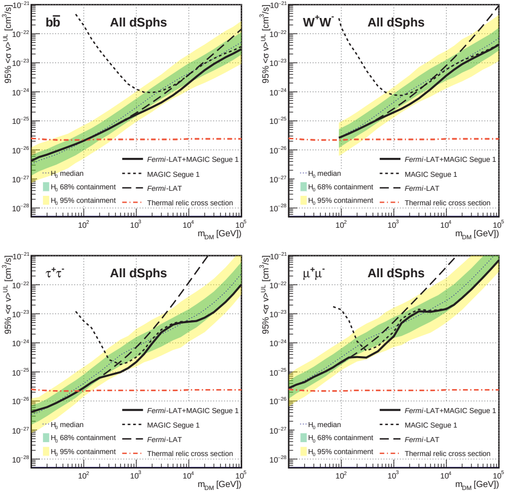


[NASA Fermi]

Detecting annihilation

1. Pros: possibility of probing the distribution of the DM density in the Universe
2. Cons: affected by irreducible astrophysical backgrounds and fake signals
3. Cons: low statistics

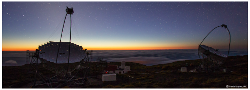
Limits from MAGIC and the Fermi-LAT satellite



[FERMI, MAGIC, JCAP 02 (2016) 039]

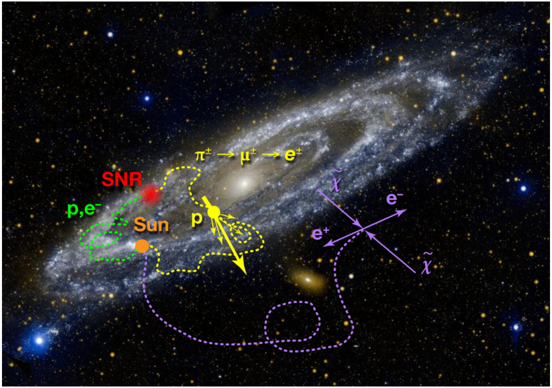
$$\frac{d\Phi}{dE}(\Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle J(\Delta\Omega)}{2m_\chi^2}\frac{dN}{dE}$$

[FERMI]



[MAGIC]

Cosmic rays

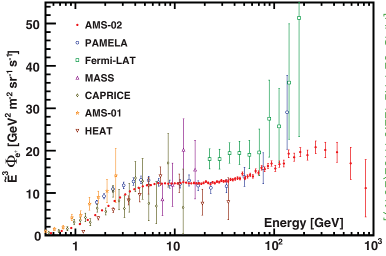


[GALEX, JPL-Caltech, NASA; APS]

Cosmic rays detection

- Detecting particles such as positron or proton/anitproton is a more complex endeavour
- These particles travel across the galaxy and are affected by it
- Non-trivial to estimate backgrounds from astrophysical systems (e.g pulsars)

Positron excess



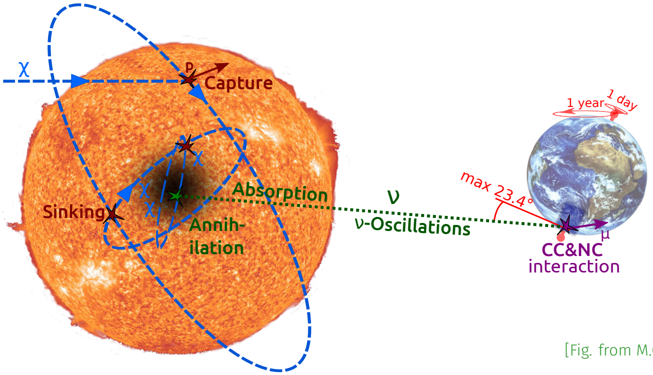
[AMS-02 PRL 122.041102(2019)]

[AMS-02]

A possible sign of Dark Matter ... or not

- Several experiments detect an excess in the positron flux
- Most precise measurements from the Alpha Magnetic Spectrometer (AMS-02) on board the International Space Station
- Open question whether this is a Dark Matter signal or an astrophysical background

Neutrinos from the Sun

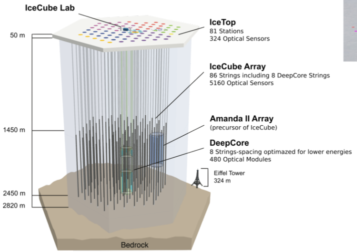


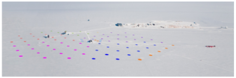
[Fig. from M.C.R. Zoll, PhD thesis]

Detecting annihilation in the Sun

- Another possibility is that the DM is captured by the sun and it annihilates in its center
- We can detect these processes by looking at neutrinos coming from the sun

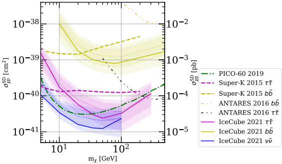
Neutrino detection





IceCube Aerial View

Digital Optical Module (DOM)



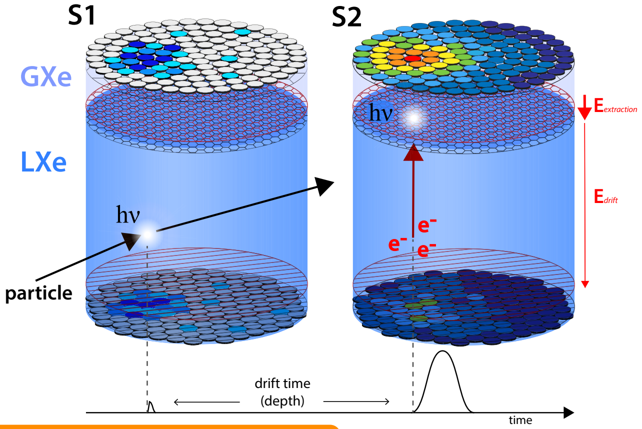
[IceCube, 2111.09970]

Icecube

- Neutrino telescope located at the South Pole
- Look at the interactions of high-energy neutrinos in the ice
- Observations interpreted in terms of limits to the cross-section of the dark matter with ordinary matter

Direct detection

Principles of WIMP direct detection



[Di Gangi et al, XENON coll., Universe 2021, 7, 313]

Dual-phase liquid Xenon detector design

- Different design for these experiments possible
- Most sensitive ones for searches in the WIMP range are based on concept of the dual-phase Time Projection Chamber design

Dark matter experiments

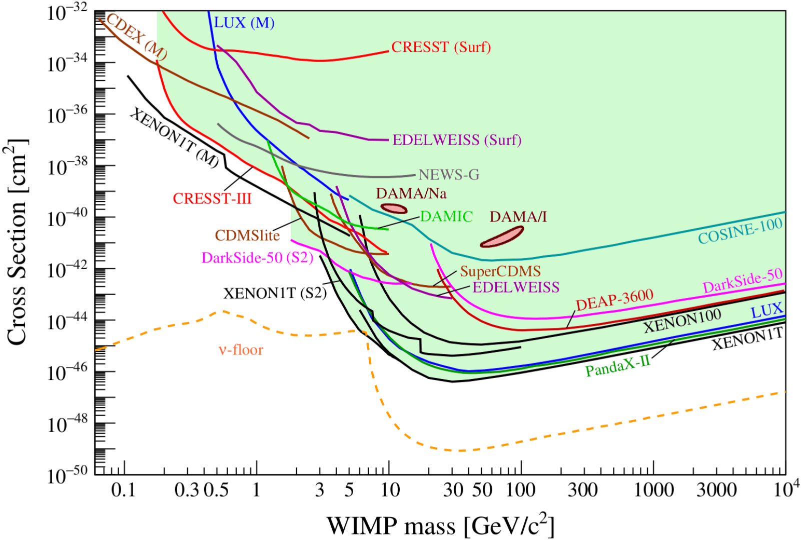
[XENON1T]

[LUX]

TPC experiments

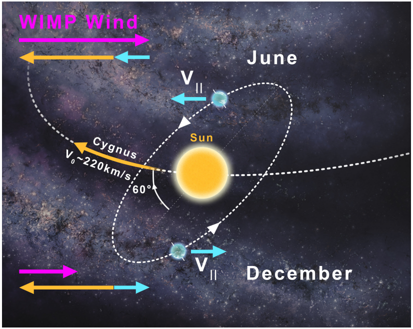
- The largest experimenrts are the ones of the XENON1T, LUX and PandaX II collaborations
- Successor experiments are in the process of being design and built (e.g. comissioning of XENONnT is currently ongoing)

Results



[Direct detection of DM - APPEC committee report, 2104.07634]

The DAMA excess

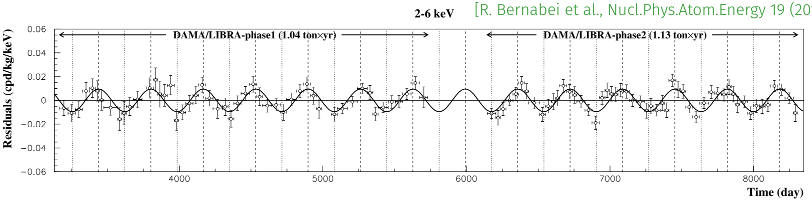


[F. Froborg, A.R.Duffy, J.Phys.G 47 (2020) 9, 094002]

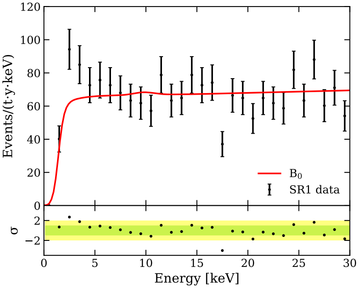
A controversial result

- DAMA sees an annual modulation in the scattering rates detected by their experiment
- In conflict with the results of other experiments, but different technology
- Other experiments are now trying to reproduce the result (COSINE, ANAIS), for the moment no signal detected

[R. Bernabei et al., Nucl.Phys.Atom.Energy 19 (2018)4]

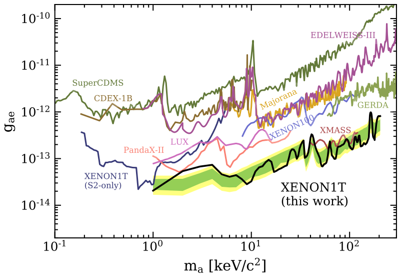


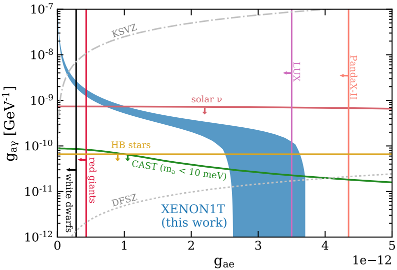
XENON1T low mass excess



Another hint, this time at low-masses

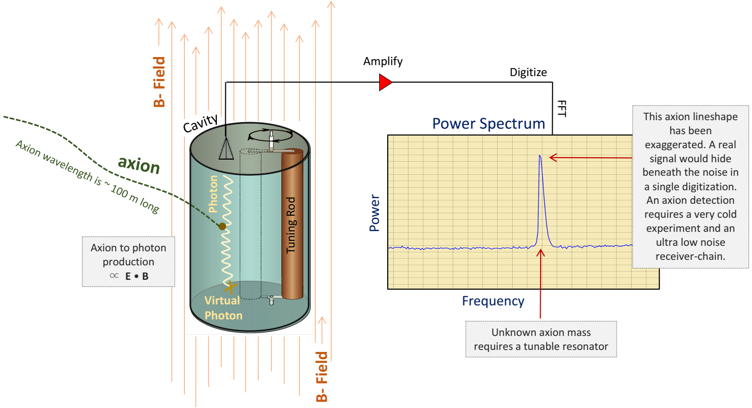
- Excess in electron-recoil signals
- Could be explained by light particles such as solar axions
- Could be also background from tritium
- Will be clarified quickly by the XENONnT experiment





[XENON Coll., PRD 102 (2020) 7, 072004]

Detecting axion in the halo of the galaxy

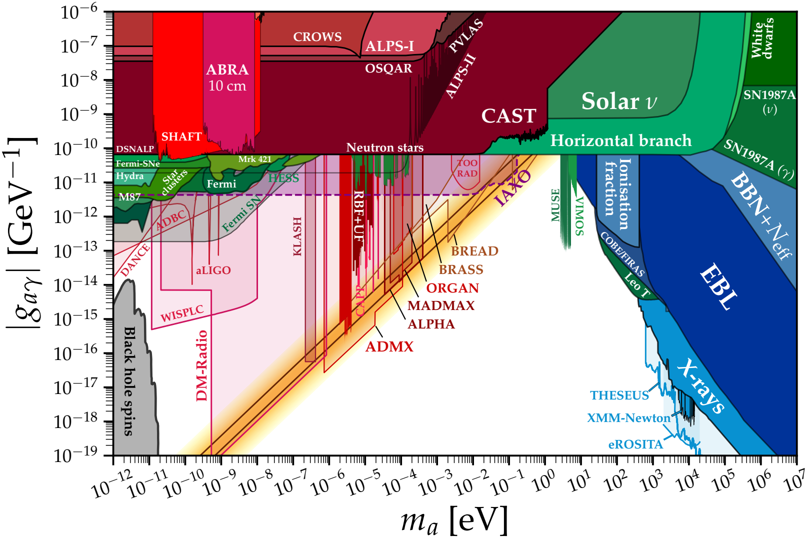


[ADMX, C. Boutan]

The haloscope concept

- Based on the reverse Primakov effect [Sikivie PRL 51, 1415; PRD 32, 2988]
- In a static magnetic field oscillations of the axion field induce oscillations in the electric field with a frequency corresponding to the axion mass
- Detect the axion in the milky way halo

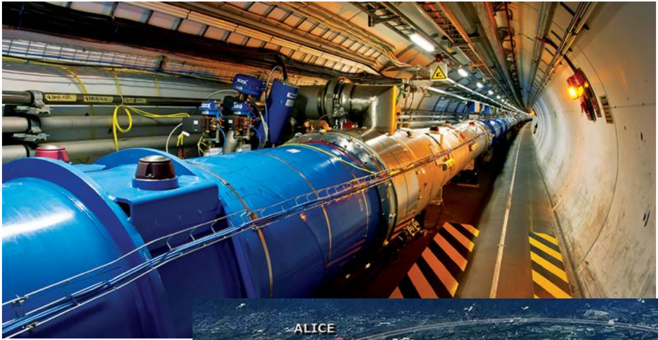
Limits on ALPs



[C. A. J. O'Hare AxionLimits webpage]

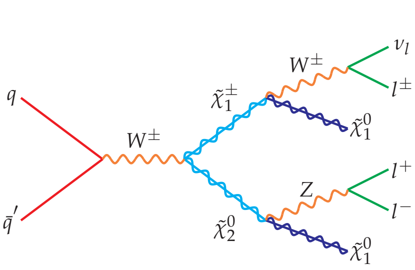
Producing Dark Matter in a collider

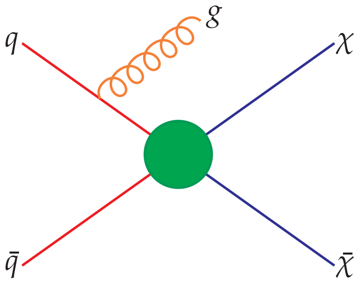
The Large Hadron Collider



[CERN]

Searching for DM at the LHC





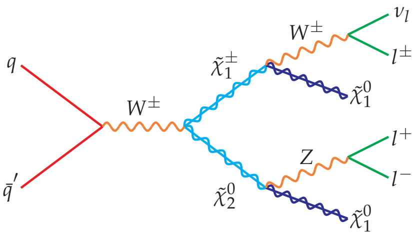
Explicit SM extensions

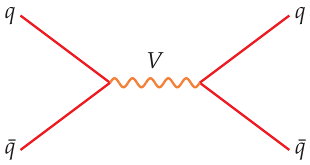
- One can consider a well-defined extension of the Standard Model
- The couplings between the Dark Matter and the Standard Model state are well defined and will produce a specific pattern of final state particles

Model-independent approaches

- Look at signatures where one produced two dark matter particles in association with a single SM signature (one jet, one photon etc.)
- Generically earch for mediators in decay channels to SM particles (dijet, dilepton final states)

Searching for DM at the LHC





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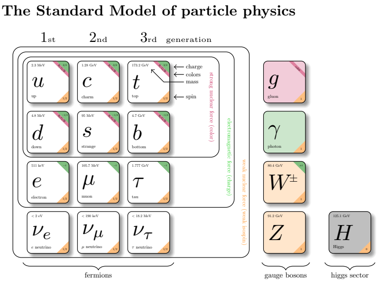
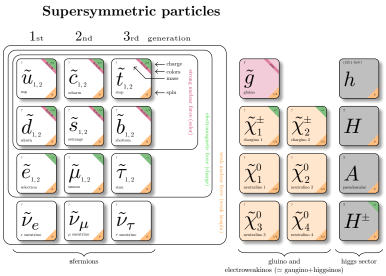
Minimal Supersymmetric Standard Model extension

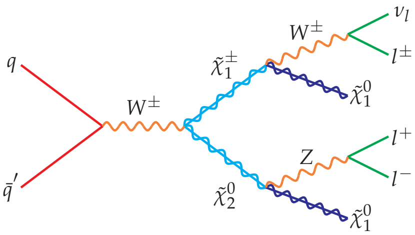


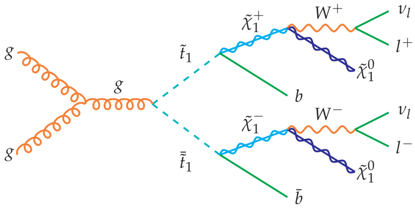


The MSSM

- One of the most widely studied extension of the Standard Model
- It features a state called the neutralino which is the archetype WIMP Dark Matter (if it is the lightest state of the model)
- Widely investigated at the LHC and at direct detection experiments – no detection so far
- We do not have a clear prediction for the masses of the new states

Searching for the neutralino





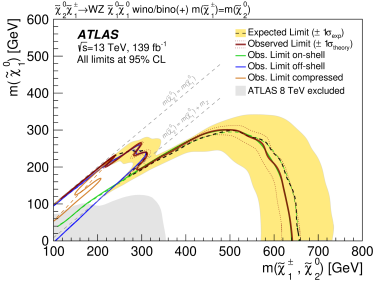
Electroweak production

- Neutralinos can be produced via a Z (or W) boson in association with another neutralino (chargino)
- Smaller cross-sections with respect to the production via decay of colored states but could be cleaner

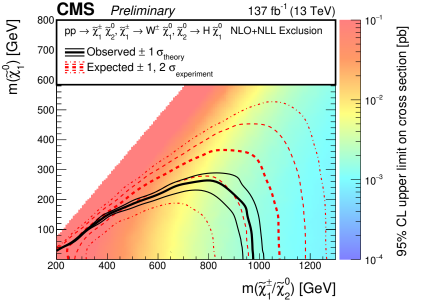
From the decays of colored/Higgs states

- Being the lightest MSSM state, other the decay chains of the other SUSY states always end with one neutralino
- In specific scenarios can be also produced as the decay of the Higgs bosons of the MSSM

Results from the LHC



[ATLAS EPJC (2021) 81:1118]

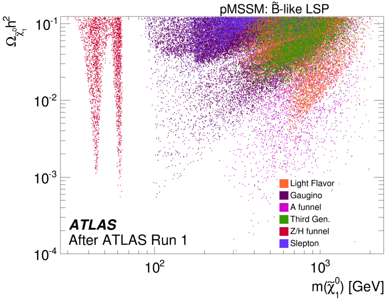


[CMS SUS-21-002-PAS]

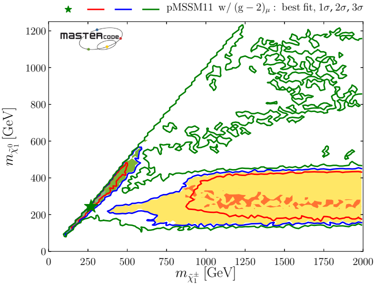
From the experiment to the theory

- Experimental collaborations presnts the results of their analysis in terms of limits of SUSY simplified models
- Useful to understand the progress of the analyses
- Can be used for recasting by theorists for phenomenological studies

The neutralino as Dark Matter



[ATLAS JHEP 10 (2015) 134]

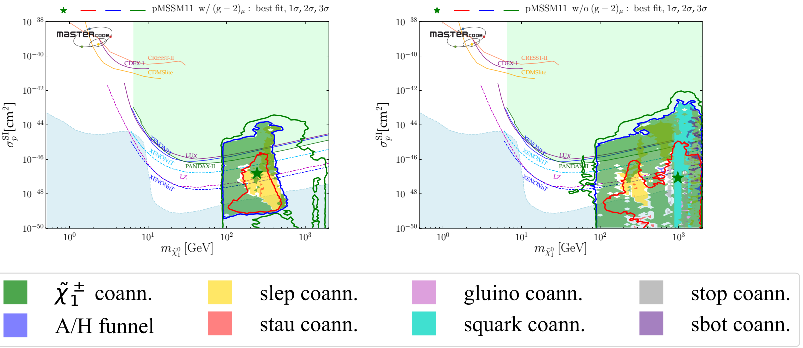


[Bagnaschi et al. EPJC 78 (2018) 3, 256]

Patterns of the MSSM

- To be compatible with the observed relic density in the universe, specific mass-relationships between the particles states are required
- Clear prediction of the spectra, but due to the current exp. constraints only very specific regions with " degenerate" spectra or the so-called "funnel" regions are possible

Spin-independent scattering cross-section

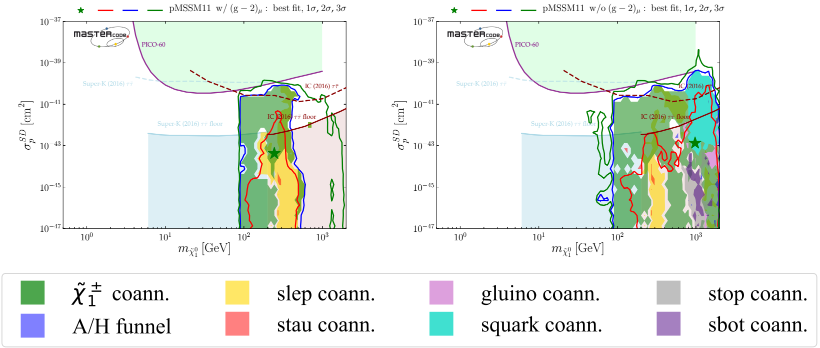


[Bagnaschi et al. EPJC 78 (2018) 3, 256]

Correlating collider and non-collider constraints

- Complementarity of collider searches vs direct-detection searches.
- Relieving $(g-2)_\mu$ allows for light higgs funnel/Z funnel/t-channel-stau regions to appear at the 2σ and 3σ level.

Spin-dependent scattering cross-section

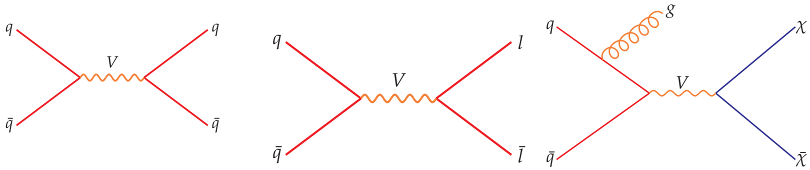


[Bagnaschi et al. EPJC 78 (2018) 3, 256]

Correlating collider and non-collider constraints

- PICO-60 results touch the 3σ contours.
- We cross-checked for a selection of points that IC constraints are relevant only for a minority of points in our sample.

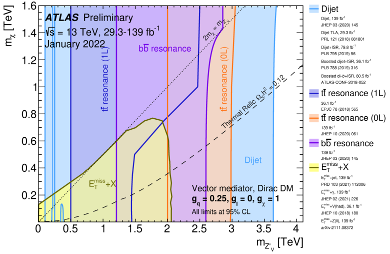
Dark Matter Simplified Models

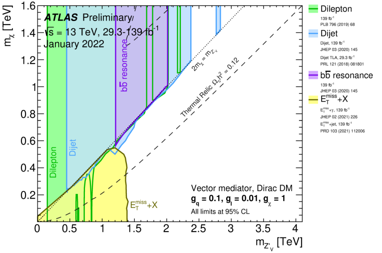


Simplified descriptions

- Capture the “essence” of dark matter physics in a simplified model
- In their simples incarnations, we add one state that is our Dark Matter particle and another state that is the mediator between the Standard Model and the DM
- We can then search for both the production of the DM and of the mediator at the LHC

LHC Results

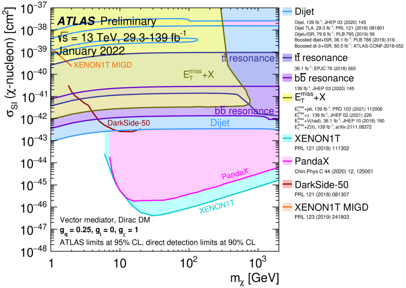


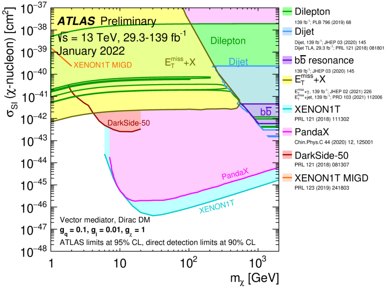


[ATLAS ATL-PHYS-PUB-2021-045]

Collider probes

- Different searches effective for different mass combinations
- Strong sensitivity to the values of the couplings





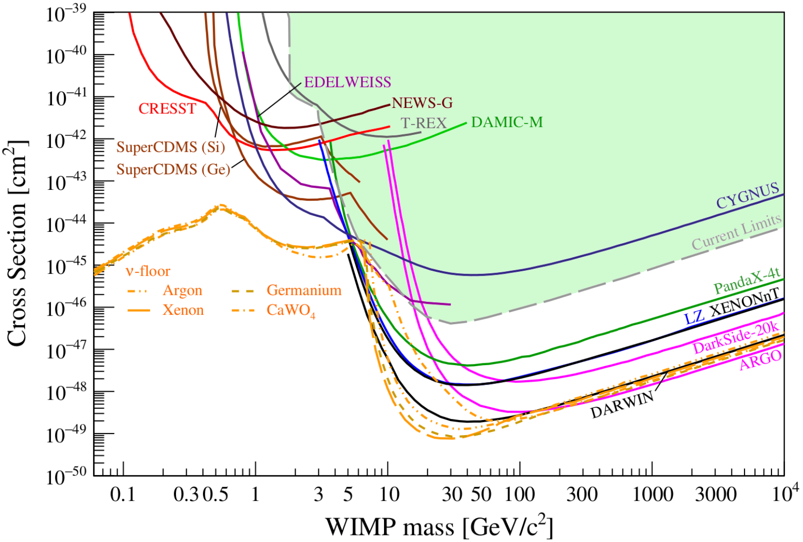
[ATLAS ATL-PHYS-PUB-2021-045]

Collider vs direct detection

- Complementarity between LHC and direct detection experiments
- LHC covers more efficiently the mass range, direct detection experiments gets to lower cross-sections

Outlook

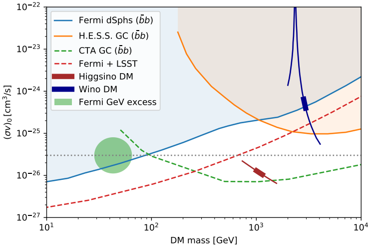
Future direct detection experiments



[Direct detection of DM - APPEC committee report, 2104.07634]

Future indirect detection experiments

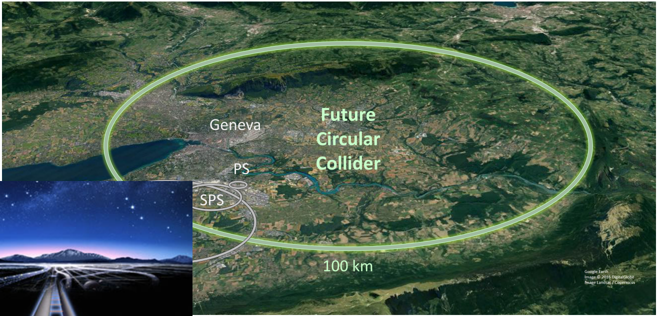
[Direct detection of DM - APPEC committee report, 2104.07634]



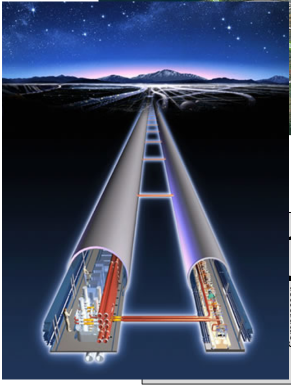
CTA

- The Cherenkov Telescope Array (CTA) will be the next large experiments for indirect DM detection
- Two arrays of Cherenkov telescopes, one (north site) in La Palma, in Spain, and one (south site) in Paranal, Chile.

Future colliders

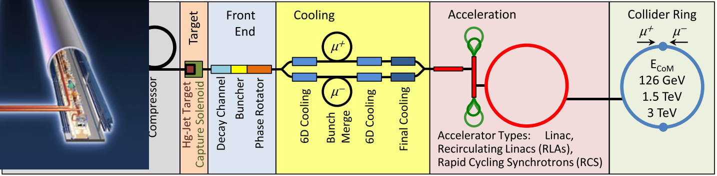


[CERN]

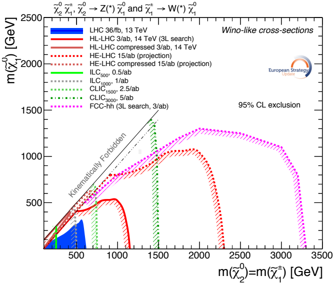


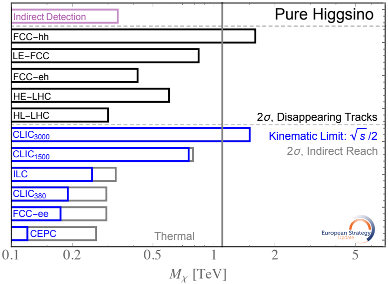
[ILC]

[Amapane et al. Nuovo Cim.C 42 (2020) 6, 259]



[Physics Briefing book of the ESPP update 2020, 1910.11775]

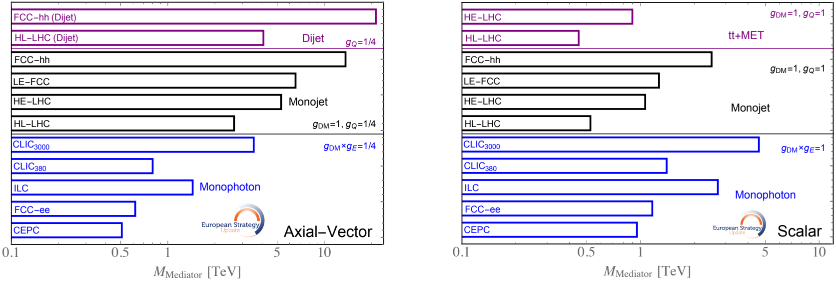




Supersymmetry reach

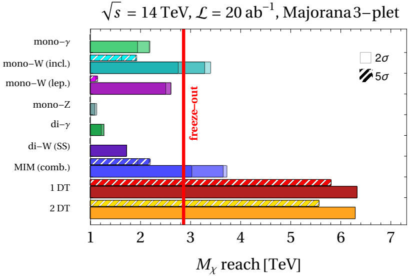
- Future colliders will continue in their search for supersymmetry
- Linear colliders more efficient in the compressed region
- Hadron collider reach larger masses due to their higher center of mass energy

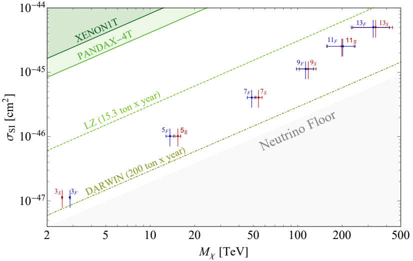
[Physics Briefing book of the ESPP update 2020, 1910.11775]



DMSMs reach

- Dark Matter Simplified Models are a good benchmark to understand the capability of the machines
- However no prediction for the mass



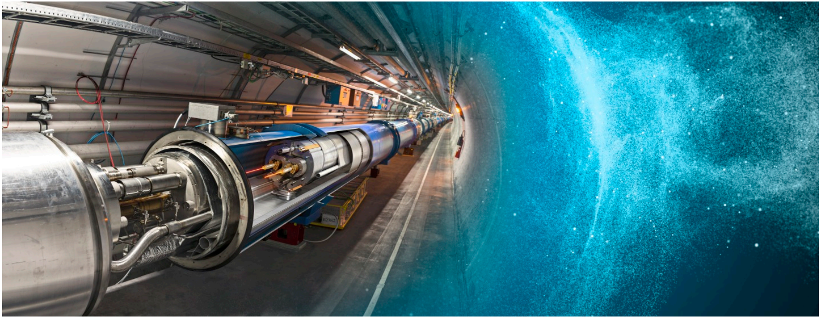


[Bottaro et al., EPJC 82 (2022) 1, 31]

Muon collider reach

- The muon collider is a more experimental concept
- However it would be able to probe more efficiently various DM candidates

Summary



Summary

- Understanding the nature of Dark Matter remains one of the most important open task of particle physics
- To properly address this challenge we need a coordinated approach across domains, raning from astro-particle to collider/lab experiments
- Many possibilities are still open and they will be explored by the current and future generations of experiments