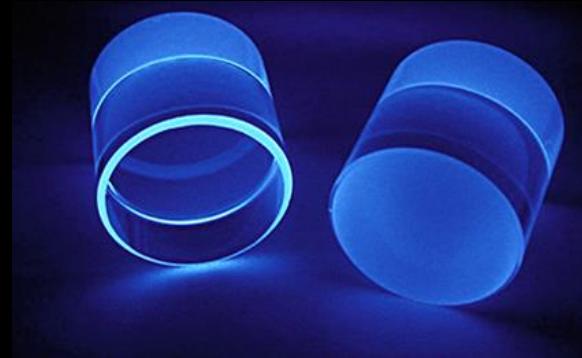
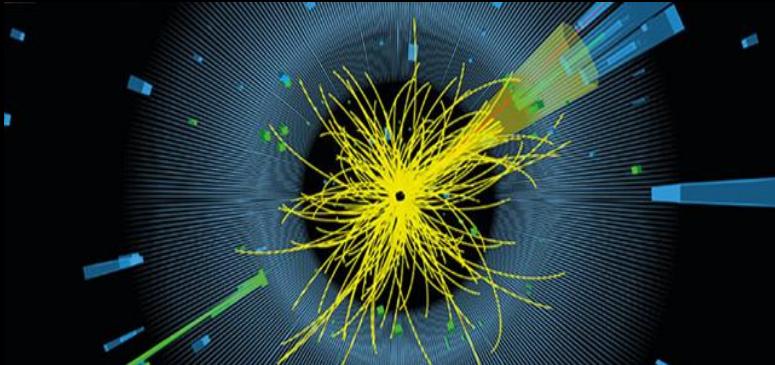


Searches for Dark Matter

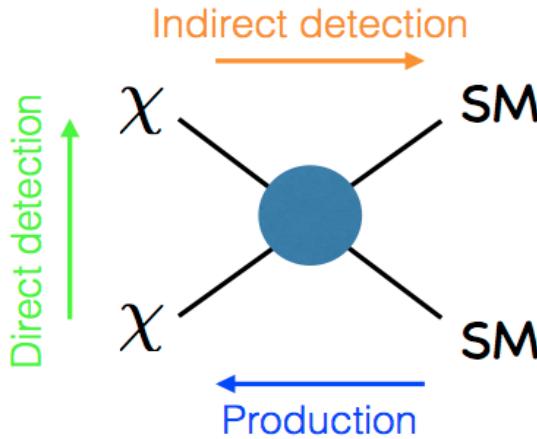


Astroparticle Physics
Part 6 – WS 2019
Federico Ambrogi



If we are finally convinced that Dark Matter exists... how do we search for it?

If we are finally convinced that Dark Matter exists... how do we search for it?



«Make it»

Collide Standard Model (SM) particle, and hope to produce DM

«Shake it»

Hope that DM particles scatter onto some nuclei

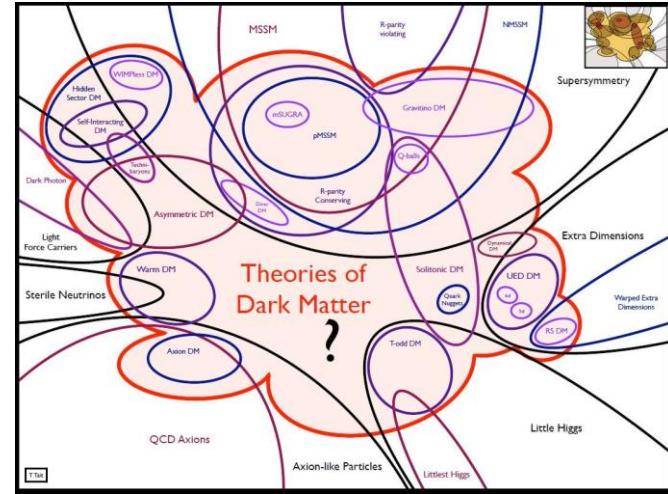
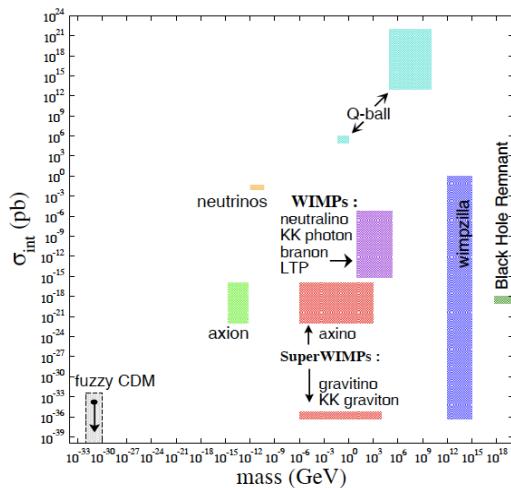
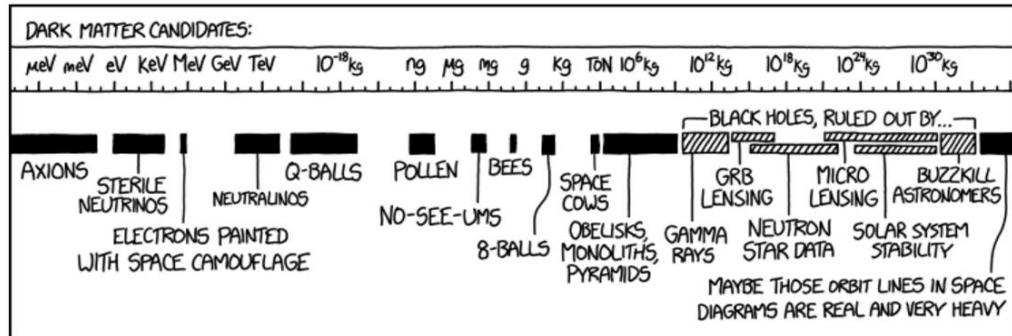
«Break it»

Hope that DM particles interact and annihilate into SM particles

+ « Bake it »

invent nice theories to be tested experimentally

« Bake it »: Build DM Theories



“Bake it”

- Many theories developed by theorists
- Very rich phenomenology! (i.e. can search for DM with many different types of experiments)
- Most of the times, full theories are too complicated to «make sense» easily out of experimental data (→ use simplified models)
- We will take as an example: Supersymmetry

DM Candidates

- Massive Compact Halo Objects (MACHOs): e.g. brown dwarfs, lonely planets, black holes populating the galactic halo. Not a sufficient number was not found e.g. in microlensing surveys
- Primordial black holes (PBHs) produced before big bang nucleosynthesis came again into the focus of interest after the first observations of gravitational waves with unexpected high masses of $20\text{-}30 M_{\odot}$. The total number of detected events is too small and PBHs in this mass range could only constitute $\sim 1\%$
- Baryonic DM can be excluded by measurements of the primordial abundance of light elements produced in the big bang nucleosynthesis (^2H , ^3He , ^4He , ^7Li) and CMB power spectrum $\rightarrow \Omega_b \approx 5\%$
- The free-streaming length of the massive but very light-weight neutrinos would wash out the observed large-scale structure of galaxies in the Universe
- The Standard Model of Particle Physics does not contain a single suitable dark matter candidate it is assumed that dark matter must be made of one (or more?) new particle(s)

Weakly interacting massive particles (WIMPs) e.g.

- the lightest particle in Little Higgs models
- Supersymmetric neutralinos
- lightest Kaluza-Klein particle (LKP, extradimension models)

Others:

Axion-like Particle

Heavy right-handed neutrinos

WIMP Miracle in a Nutshell

Weakly interacting massive particles (WIMPs) are assumed to be thermally produced in the early universe and are now moving with non-relativistic velocities, which makes them the prime candidate for “cold” dark matter

For a WIMP mass at the weak scale, namely for hundreds of GeV, $\langle \sigma_{ann} v \rangle \approx 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. Using an approximation of the relic density :

$$\Omega_{\chi,0} h^2 = \frac{3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{ann} v \rangle}, \quad (2.37)$$

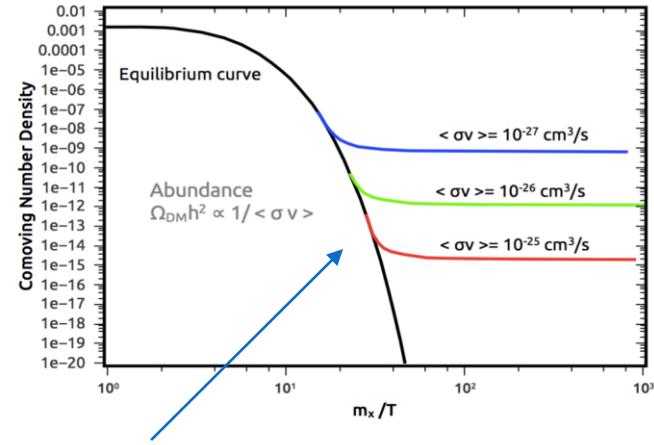
Note that the annihilation cross section fixes the normalisation and absolute value of the relic density, and different DM theoretical models must be able to correctly predict the value of the relic density as constrained by various observations. This is particularly important since it gives a theoretical motivation for searching for DM and in general new physics at the TeV scale, i.e. around or slightly above the electroweak symmetry breaking scale and at energies which are reachable at the LHC. The latest measurement from the Planck Collaboration [13] reports a relic density of

$$\Omega_{DM} h^2 = 0.1197 \pm 0.0022 \quad (7.5)$$

which can be obtained by a cross section of order $\langle \sigma v \rangle \sim 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. When considering a DM mass around the electroweak scale, e.g. $m_\chi = 200 \text{ GeV}$, a typical freeze-out temperature of order $T \sim m_\chi / 20$, and a weak cross section that scales as $\sigma \sim G_F^2 T^2$ (where G_F is the Fermi coupling constant), the predicted relic density approximates the measured value.



DM theories must be compatible with the constraints on the DM relic density

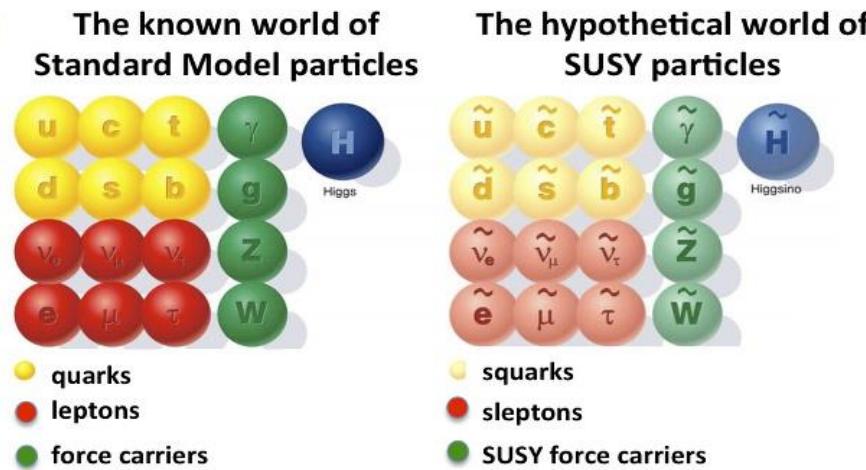


**Density is frozen == relic density
Comoving density becomes constant**

When the temperature becomes negligible comparing to the mass the particle χ , its comobile density decreases (X and \bar{X} cannot anymore annihilate into χ and $\bar{\chi}$: $\langle \sigma_{\chi\bar{\chi}\rightarrow X\bar{X}} v \rangle = \langle \sigma_{ann} v \rangle$) but at a given temperature its interaction rate with the thermal bath drops below the expansion rate of the Universe : χ is decoupled from the thermal bath, it is the *freeze-out* of χ . Its comobile density becomes approximately constant from the decoupling to today an after some assumptions like a constant averaged cross section the current χ yield reads

Example: Supersymmetry

Based on the assumption that there exists a fundamental symmetry that relates Fermionic and Bosonic particles



Name	Sparticle fields	Mass eigenstates
Squarks	$(\tilde{u}_L \tilde{d}_L)$	\tilde{u}_1, \tilde{u}_2
	\tilde{u}_R	\tilde{d}_1, \tilde{d}_2
	\tilde{d}_R	
Sleptons	$(\tilde{\nu}_r \tilde{e}_L)$	$\tilde{\nu}_e$
	\tilde{e}_R	\tilde{e}_1, \tilde{e}_2
Gluino	\tilde{g}	\tilde{g}
Higgsinos	$(\tilde{H}_u^+ \tilde{H}_u^0)$	$\tilde{\chi}_{1,2}^\pm$
	$(\tilde{H}_d^0 \tilde{H}_d^-)$	
Wino	$\tilde{W}^\pm, \tilde{W}^0$	$\tilde{\chi}_{1,2,3,4}^0$
Bino	\tilde{B}^0	

"(Still) our favourite template for a BSM theory:

- Theorists like it for a series of good reasons, and the good reasons tell us that some of the SUSY particles should be in the TeV region
- Experimentalists like it because of rich panoply of signatures, some of them abundantly produced at colliders, and easy to separate from backgrounds"

Possible Supersymmetric DM candidates (LSP, Lightest Supersymmetric Particles):

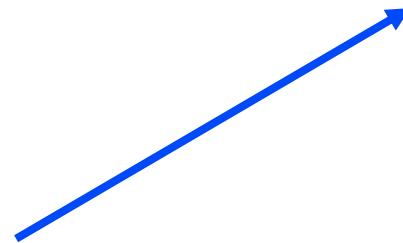
- Lightest
- Gravitinos
- Right-Handed Sneutrinos

Example: Supersymmetry

<https://arxiv.org/pdf/1001.3651.pdf>

1 Motivations

Supersymmetry is one of the best-motivated proposals for physics beyond the Standard Model. There are many idealistic motivations for believing in supersymmetry, such as its intrinsic elegance, its ability to link matter particles and force carriers, its ability to link gravity to the other fundamental interactions, its essential role in string theory, etc. However, none of these aesthetic motivations gives any hint as to the energy scale at which supersymmetry might appear. The following are the principal utilitarian reasons to think that supersymmetry might appear at some energy accessible to forthcoming experiments.



→ depending on the exact mixing or composition of the neutralinos:
different production rates, interactions/couplings to particles, decay modes

The composition of the LSP χ can be expressed as a linear combination of these fields:

$$\chi = \alpha \tilde{B} + \beta \tilde{W}^3 + \gamma \tilde{H}_1 + \delta \tilde{H}_2, \quad (6)$$

whose mass and composition are determined by the $SU(2)_L$ and $U(1)$ gaugino masses, $M_{2,1}$, the Higgs mixing parameter μ , and $\tan\beta$, the ratio of the vacuum expectation values $v_{1,2} \equiv <0|H_{1,2}|0>$ of the two neutral Higgs fields $\tan\beta \equiv v_2/v_1$. The mass of the LSP χ and the mixing coefficients α, β, γ and δ in (6) for the neutralino components that compose the LSP can be found by diagonalizing the mass matrix

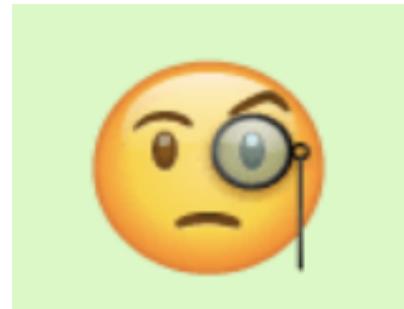
$$(\tilde{W}^3, \tilde{B}, \tilde{H}_1^0, \tilde{H}_2^0) \begin{pmatrix} M_2 & 0 & \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_2 v_2}{\sqrt{2}} \\ 0 & M_1 & \frac{g_1 v_1}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} \\ \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_1 v_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g_2 v_2}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{W}^3 \\ \tilde{B} \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}, \quad (7)$$

In different regions of the supersymmetric parameter space, the LSP may be more bino-like, wino-like, or Higgsino-like, depending on the relative magnitudes of the coefficients α, β, γ and δ .

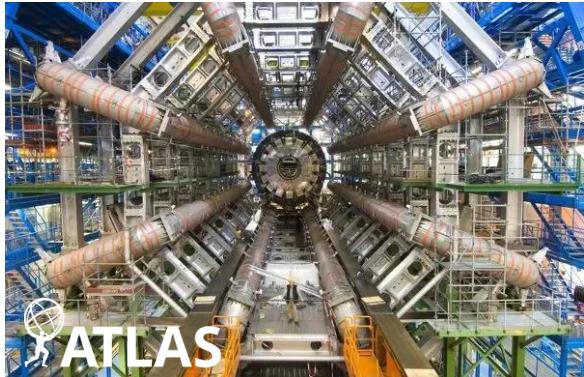
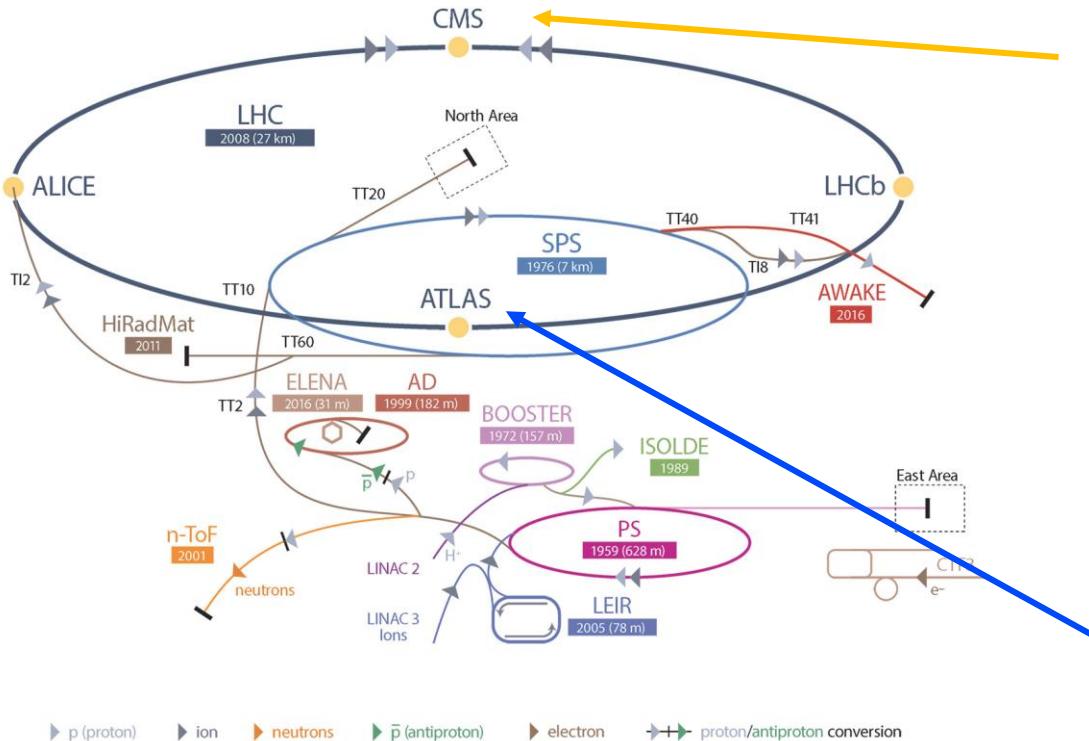




... replace with any other DM candidate

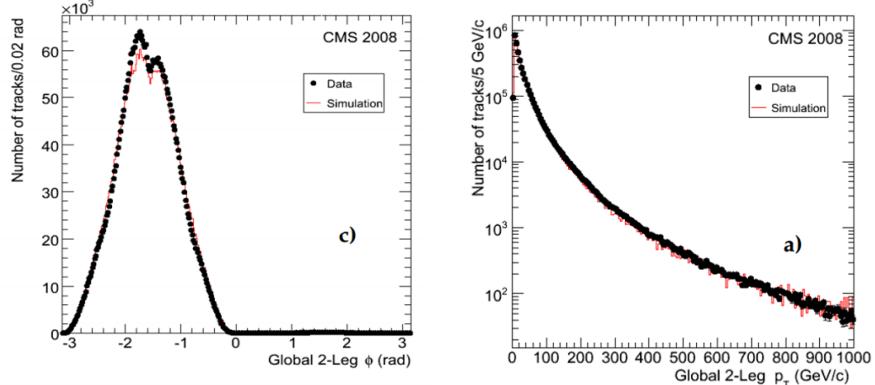


« Make it » : DM Searches at the LHC



Cosmic Muons Studies at ATLAS/CMS

<https://arxiv.org/pdf/0911.4994.pdf>



<https://arxiv.org/pdf/1006.4384.pdf>

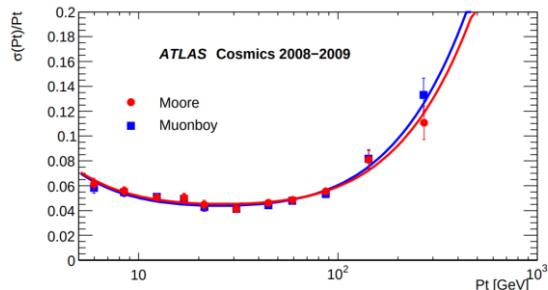
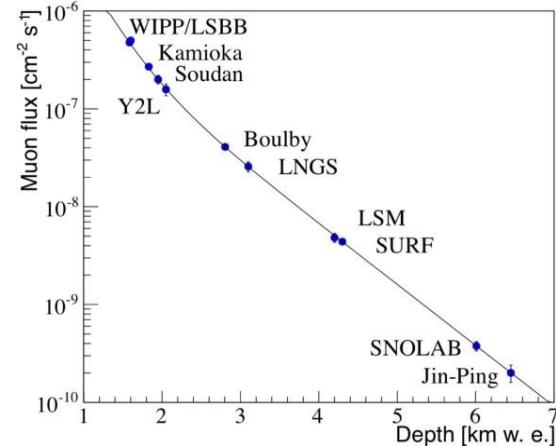


Fig. 35. Transverse momentum resolution evaluated with the top-bottom method explained in the text as a function of p_T , barrel region only ($|\eta| < 1.1$). The fit to the three resolution parameters as described in the text is superimposed.



Muons arrive at **sea level** with an average **flux** of about 1 **muon** per square centimeter per minute

Can use cosmic muons to calibrate the detectors/ make studies

«The ATLAS detector at the Large Hadron Collider has collected several hundred million cosmic ray events during 2008 and 2009. These data were used to commission the Muon Spectrometer and to study the performance of the trigger and tracking chambers, their alignment, the detector control system, the data acquisition and the analysis programs»

LHC Parameters

One of the crucial LHC parameters for physics studies is the total number of proton-proton interactions. The quantity controlling the total number of collision in the unit time is called *luminosity* (\mathcal{L}) and it is defined as:

$$\mathcal{L} = \gamma \frac{n_b N^2 f_{rev}}{4\pi \beta^* \epsilon_n} R \quad (3.1)$$

where γ is the proton beam energy in unit of rest mass, n_b is the number of bunches for each beam (which is 2808 for 25 ns bunch spacing); N is the number of protons in each bunch (1.15×10^{11} at 25 ns); f_{rev} is the revolution frequency (11.2 kHz); β^* is the focal length of the beam (around 0.55 m at the collision point); ϵ_n is the transverse emittance ($3.75 \mu\text{m}$); R is the reduction parameter that accounts for the angular separation of the beam crossings. All the values represent the design nominal values.

The total number of collisions over a time T can be finally calculated by integrating Eq. 3.1:

$$L = \int_T \mathcal{L} dt \quad (3.2)$$

The luminosity enters the calculation of the total rate N for a given physics process of cross section σ , as:

$$N = \sigma \cdot L \quad (3.3)$$

For Run 1, a maximum instantaneous luminosity of $\mathcal{L} = 7.7 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ was achieved, and a total luminosity of around 23 fb^{-1} was delivered to the two general purpose experiments (ATLAS and CMS), at 8 TeV centre-of-mass energy.

The LHC is designed to operate at $\sqrt{s}=14 \text{ TeV}$; the bunch crossing rate will be 40 MHz, at the peak instantaneous luminosity of $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{s}^{-1}$. A total integrated luminosity of 300 fb^{-1} is expected to be collected by the year 2023 (LHC Run 3)[33].

L= (unintegrated) Luminosity

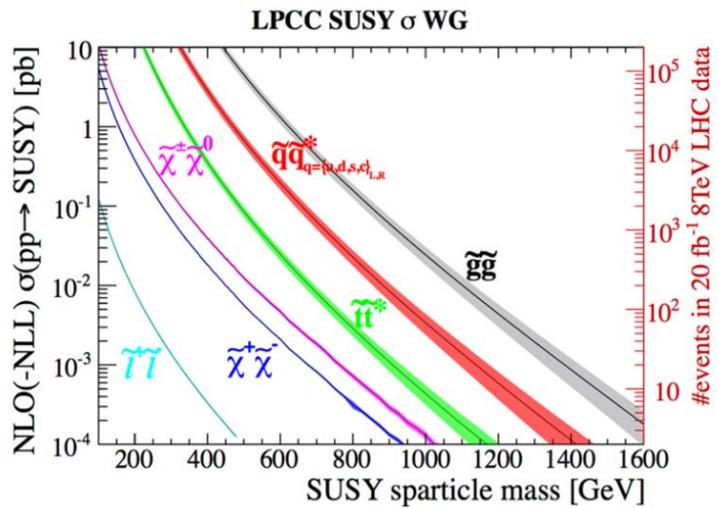
~ total amount of data that we collect at the detectors (which is more than the total amount of data that is really used for the data analyses)

Expected number of events for a given process with a production cross section sigma
-> depends on the particle physics model,
e.g.

SM = Standard Model

BSM = Beyond Standard Model
(e.g. Supersymmetry)

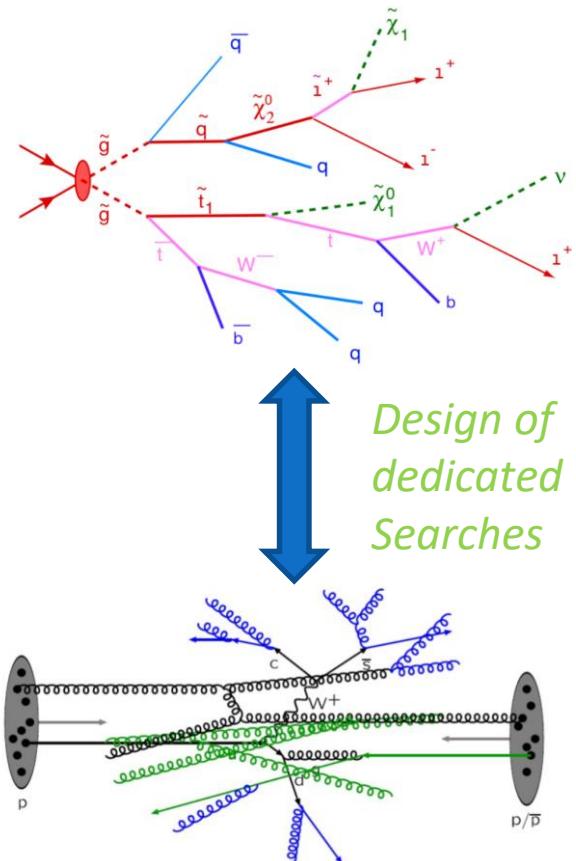
What SUSY theory predicts
for proton-proton (pp) collisions



Production cross section for some SUSY particles pair-production and expected number of events for 8 TeV centre-of-mass energy

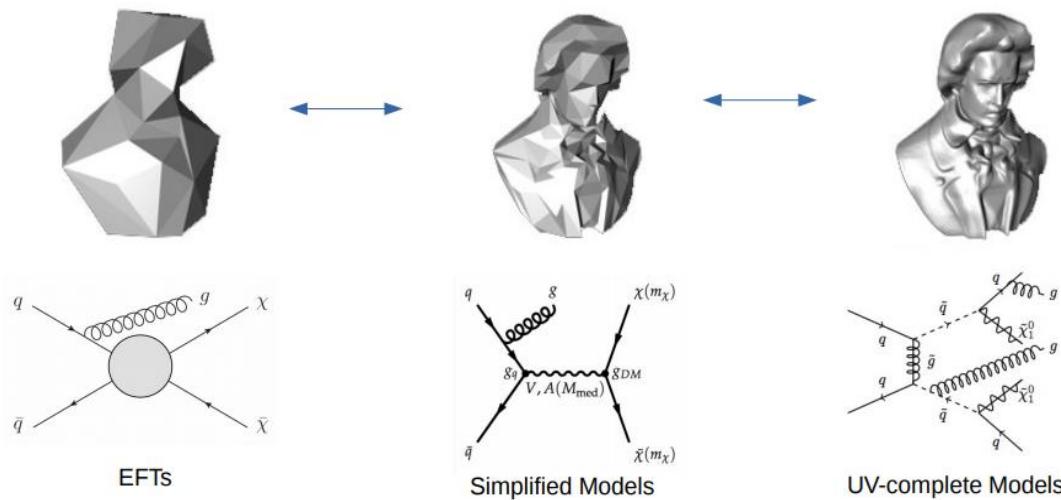
What we would like to see

What really happens...



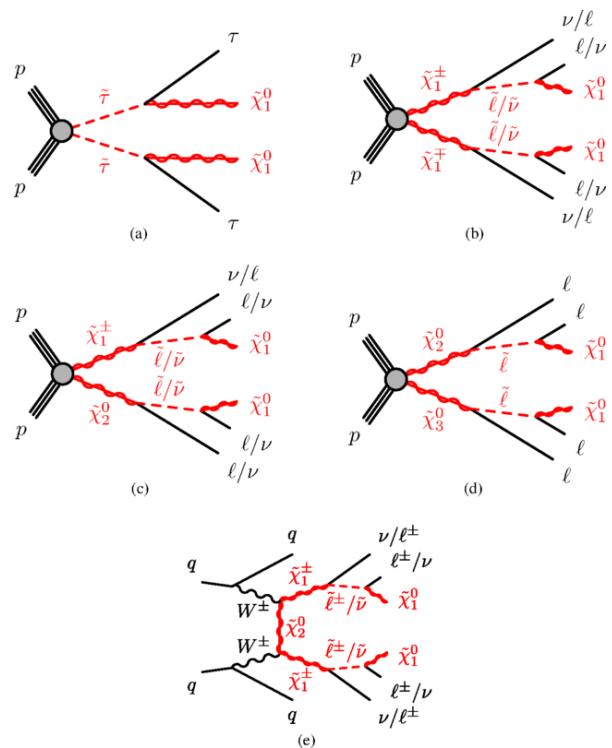
Simplified Models

- Simplified Models are introduced by theorists to simplify the interpretations of the experimental data
- They can only be used efficiently to design new searches (i.e. tune the data analysis to obtain better limits)
- They are NOT realistic models
- The results are valid ONLY under specific assumptions, and the results might hide some interesting underlying features
- Nevertheless: very useful and widely used

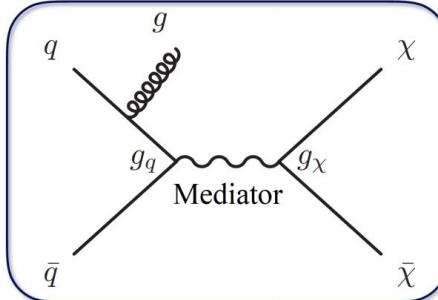


<https://indico.cern.ch/event/606690/contributions/2656661/attachments/1497909/2332228/kristian-hahn-LHCDM-TAUP2017.pdf>

SUSY Simplified Models



DM Simplified Models



→ Relevant parameters :

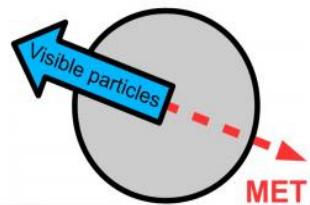
m_χ , m_{med} , \mathbf{g}_χ and \mathbf{g}_q

spin/parity of the mediator : scalar/pseudo-scalar or vector/axial-vector

Example: SUSY at the LHC

- Assumption: all the SUSY particles will eventually decay to the lightest Neutralino, which is the DM candidate, and it escapes detection since it does not interact with the detector
- This will produce “missing energy” (MET) i.e. an energy imbalance in the event

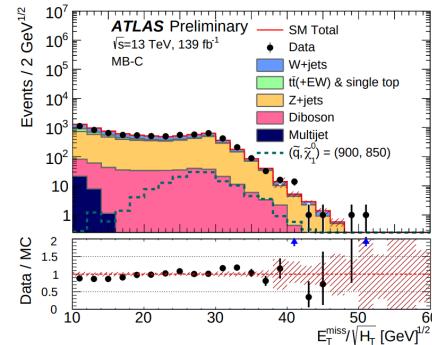
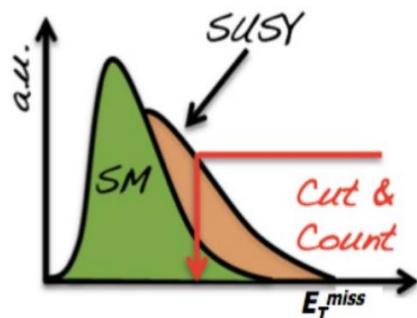
$$E_T^{miss} = |\vec{p}_T^{miss}| = \left| \sum_i p_T^i \right|$$



What we “see”



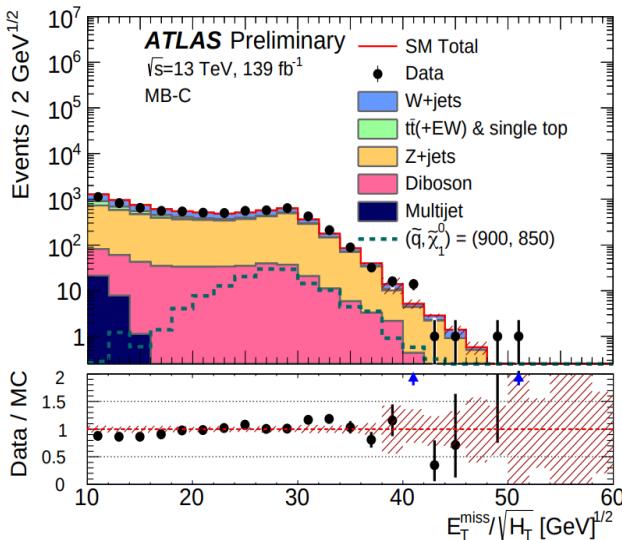
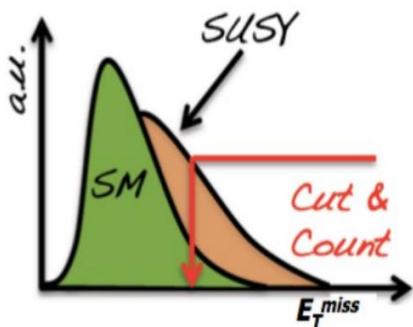
What we do not “see”



Example: SUSY at the LHC

- Assumption: all the SUSY particles will eventually decay to the lightest Neutralino, which is the DM candidate, and it escapes detection since it does not interact with the detector
- This will produce “missing energy” (MET) i.e. an energy imbalance in the event

$$E_T^{\text{miss}} = |\vec{p}_T^{\text{miss}}| = \left| \sum_i \vec{p}_T^i \right|$$



- Evaluate accurately SM background
- Make SUSY signal hypothesis to test with data

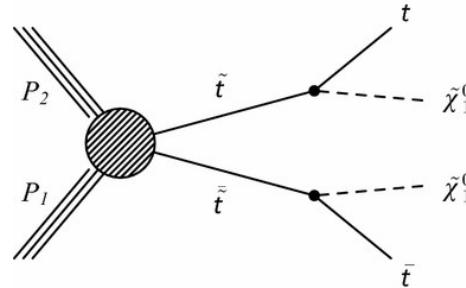
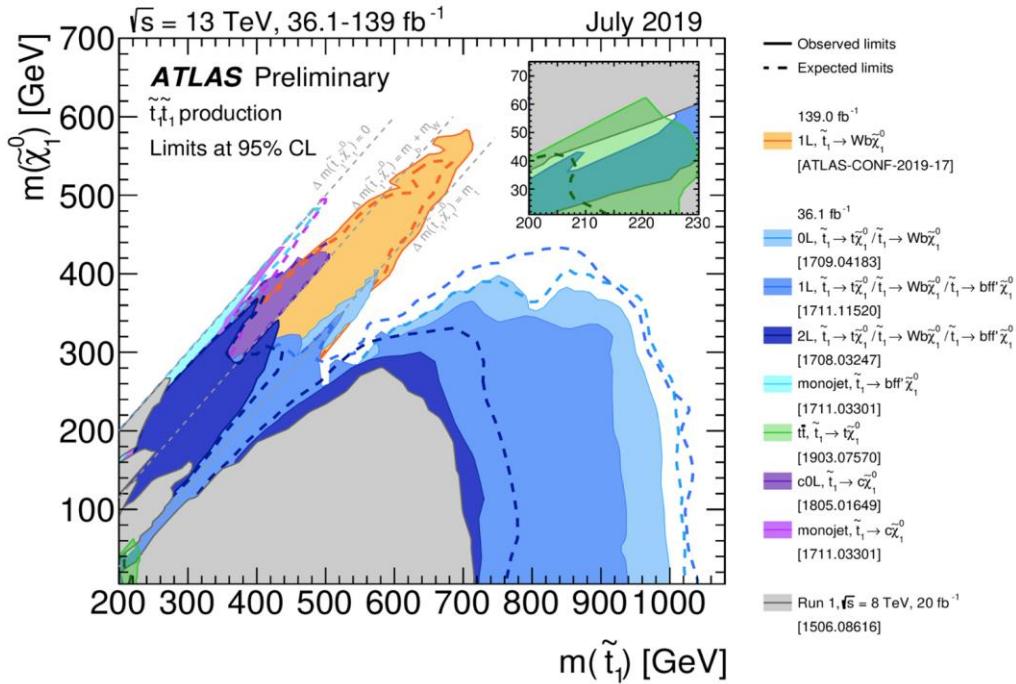
- We expect a lot of missing energy in the events, that cannot be accounted for by SM neutrinos or particles that cannot be revealed by the detectors, systematics, detector acceptance, particle reconstructions efficiency etc.

However:

- “detecting” the presence of such particles does not automatically mean that they are the Cosmological DM candidate

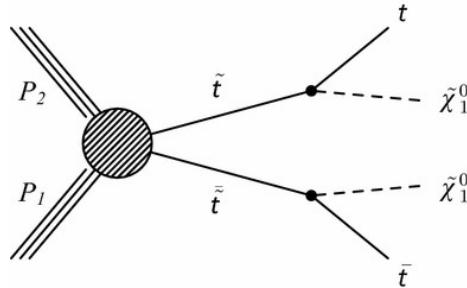
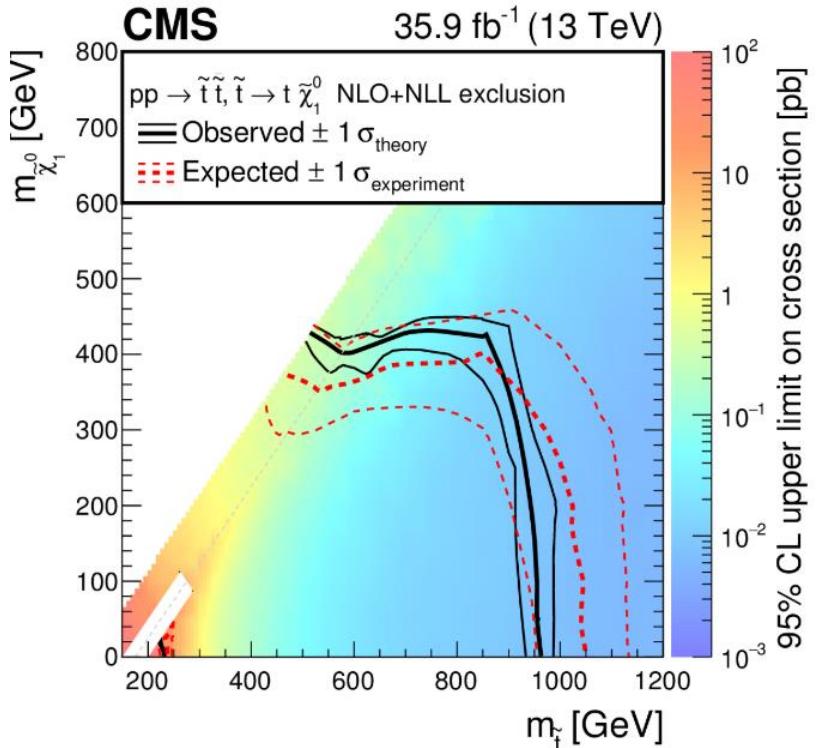
→ Can only state that they are stable while travelling through the detector (this is general of any DM search you perform at the colliders)

Example: SUSY at the LHC



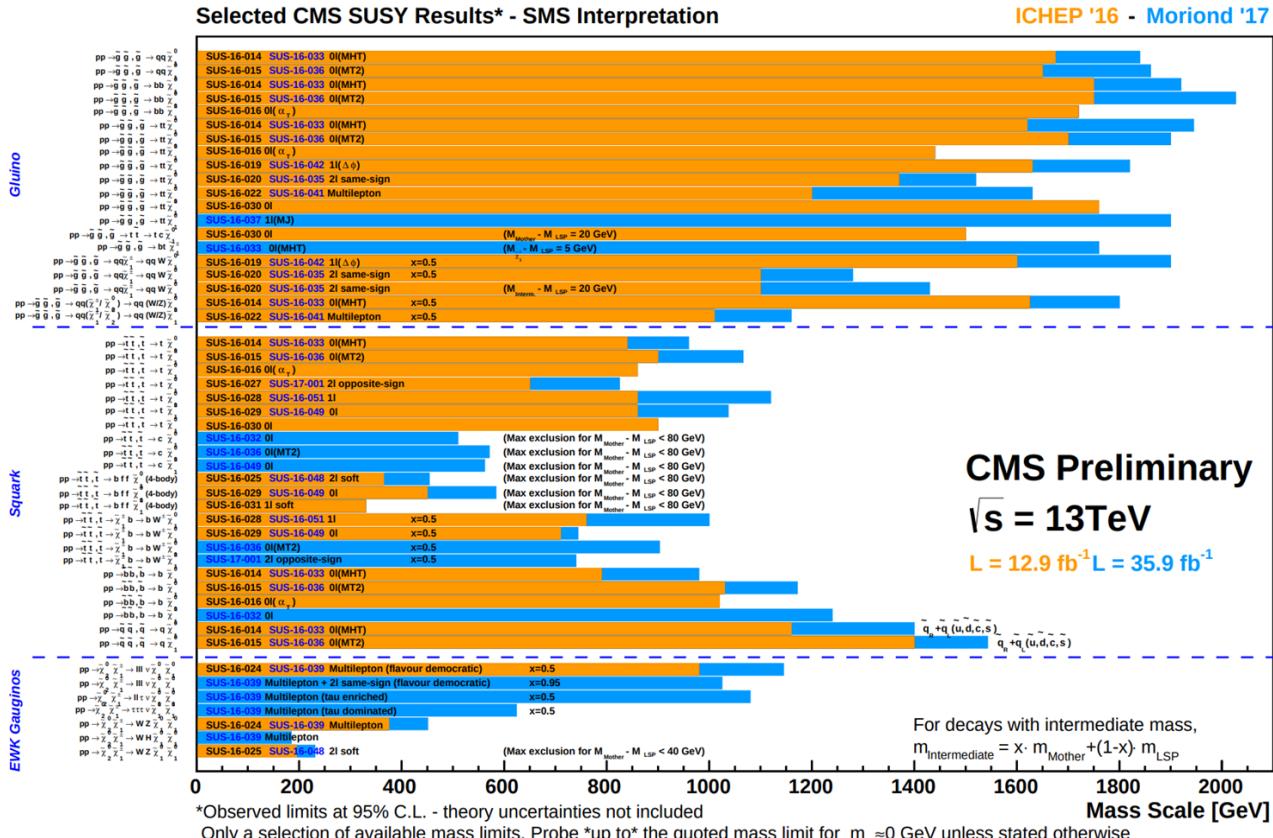
- Several searches targeting the same simplified model
- The coloured regions are excluded by the corresponding search
- i.e. the specific (stop-neutralino) mass parameters can be excluded experimentally by the search
- To each (stop-neutralino) mass parameter you calculate a cross section upper limit for the stop-production (different for each search)

Example: SUSY at the LHC



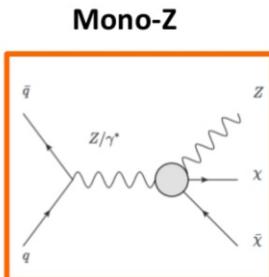
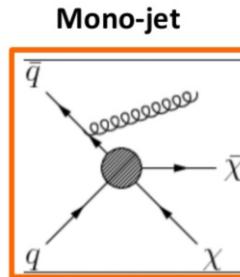
- To each (stop-neutralino) mass parameter you calculate a cross section upper limit for the stop-production (different for each search)

Example: SUSY at the LHC

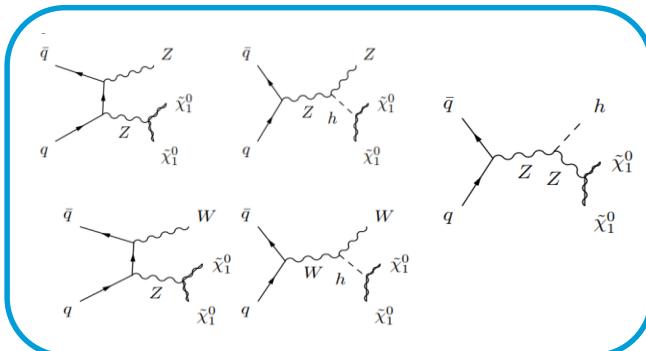


Example: direct DM production and mono-X Searches

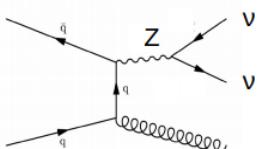
Idea: DM direct production plus “something”



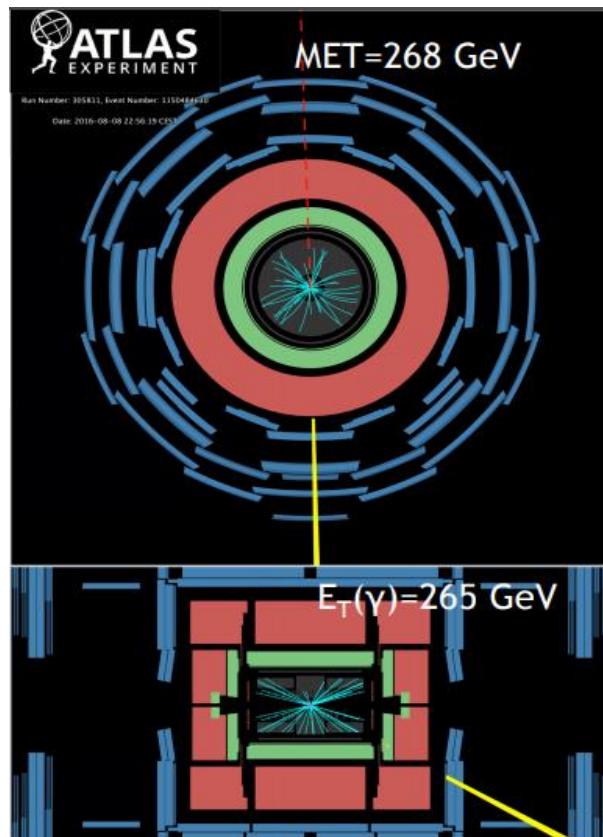
Mono-lepton
Mono-photon
Mono-top
Mono-Higgs
etc ...



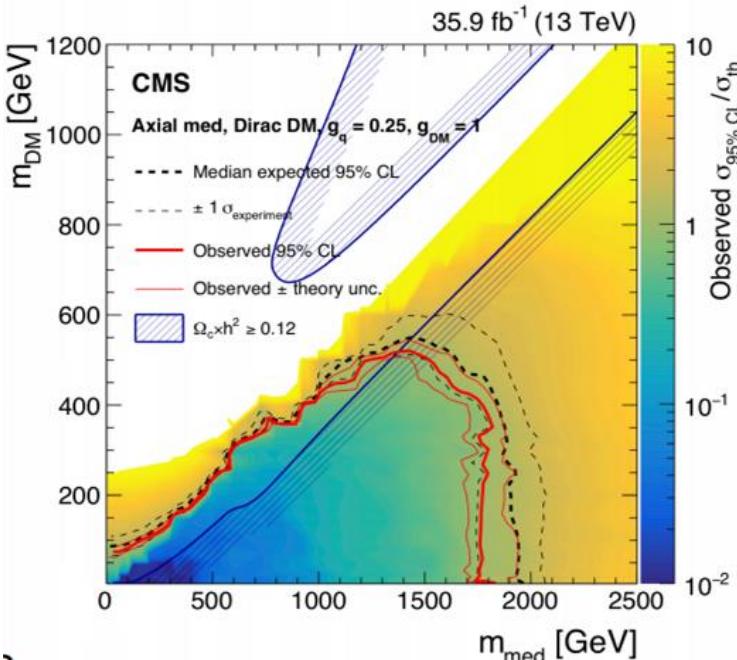
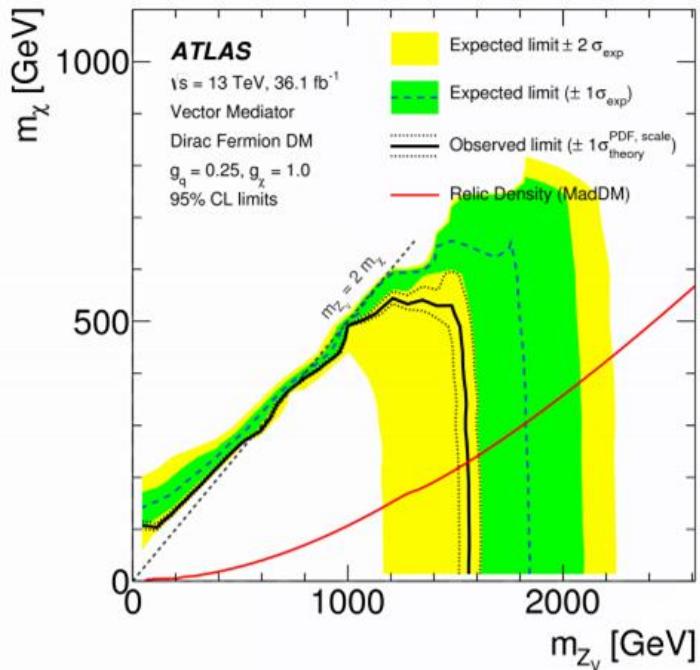
Example for SUSY



Example: Mono-jet SM
irreducible background



Example: direct DM production and mono-X Searches



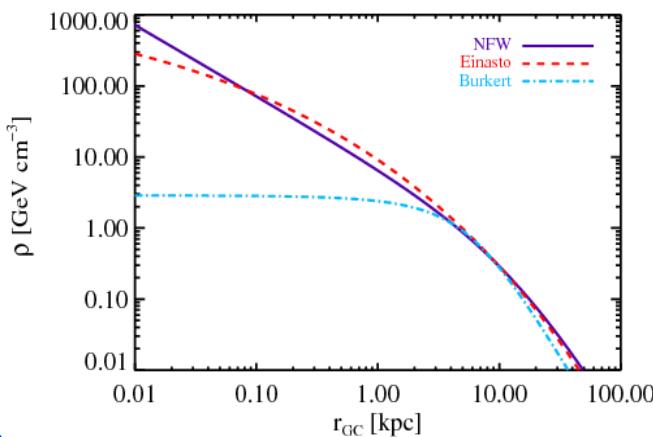
→ Using DM simplified models: put limits on the DM and mediator mass for fixed couplings

« Shake it » : DM Direct Detection

- Idea: the Earth travels through the DM Milky Way's halo, and DM particles might scatter off (heavy) nuclei
- In general, the expected event rate can be expressed as

$$\frac{dR}{dE}(E, t) = \boxed{\frac{\rho_0}{m_\chi m_A}} \int v \cdot f(\mathbf{v}, t) \cdot \frac{\sigma}{dE}(E, v) d^3v$$

Models for the Halo densities



$$\rho(r)_{DM} = \left(\rho_\odot \frac{R_\odot}{R} \right)^\gamma \left(\frac{1 + (R_\odot/a)^\alpha}{1 + (r/a)^\alpha} \right)^{(\beta - \alpha)/\gamma}$$

Profile	α	β	γ
Isothermal	2	2	0
NFW	1	3	1
Moore	1.5	3	1.5

where a is a fit parameters related to the halo scale, $R_\odot = 8.5$ kilo Parsec is the distance of the Sun from the galactic center, and $\rho_\odot \approx 0.3$ [GeV cm⁻³] is the local DM density .

"The precise shape of the density profile for $r \rightarrow 0$ is unknown and different possibilities were derived from N-body simulations. Some solutions exhibit a flat core, others are more cuspy. Recent studies of dwarf galaxies indicate that the "cuspyness" of the density profile depends on the star formation rate which drives fluctuations in the gravitational potential: galaxies with longer lasting star formation have more shallow dark matter cores"

<https://arxiv.org/pdf/1903.03026.pdf>

- Idea: the Earth travels through the DM Milky Way's halo, and DM particles might scatter off (heavy) nuclei
- In general, the expected event rate can be expressed as

$$\frac{dR}{dE}(E, t) = \frac{\rho_0}{m_\chi m_A} \int v \cdot f(\mathbf{v}, t) \cdot \frac{\sigma}{dE}(E, v) d^3v$$

Particle Physics: Scattering Cross Sections

$$\sigma_{SD} = \frac{16}{\pi} \mu_A^2 \cdot \frac{J_A + 1}{J_A} (f'_p + f'_n)^2 \quad \rightarrow \quad \text{Spin dependent cross section (i.e. different for protons and neutrons)}$$

$$\sigma_{SI} = \frac{4}{\pi} \mu_A^2 \cdot [Z \cdot f_p + (A - Z) \cdot f_n]^2 \quad \rightarrow \quad \text{Spin independent cross section (i.e. same for protons and neutrons)}$$

Key points for DM Direct detection:

- DM induced recoils energies are very small (eV ~ keV range)
- Many natural signals can mimic DM scattering e.g. background neutrinos (Sun, radioactive decays...)
- Accurate signal/background discrimination needed
- On the side: they can study DM & other physics at the same time (e.g. neutrino physics, extremely rare radioactive decays)
- Limitation: neutrino floor

Experimental strategies:

- Noble liquid targets
[DARWIN, LUX, Panda-X, XENON, **XENON1T**, XENONnT]
- Cryogenic Crystal Targets
[**CRESST(II,III)** , EDELWEISS, SuperCDMS]
- Others: e.g. bubble chambers, NaI crystals
[ANAIS, **DAMA/LIBRA**, COSINE, PICO...]

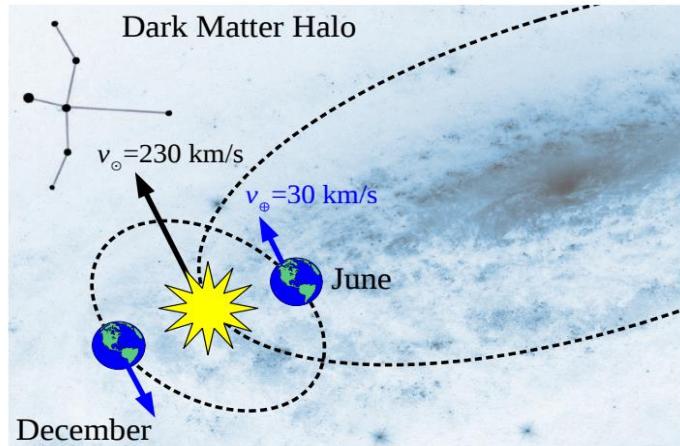
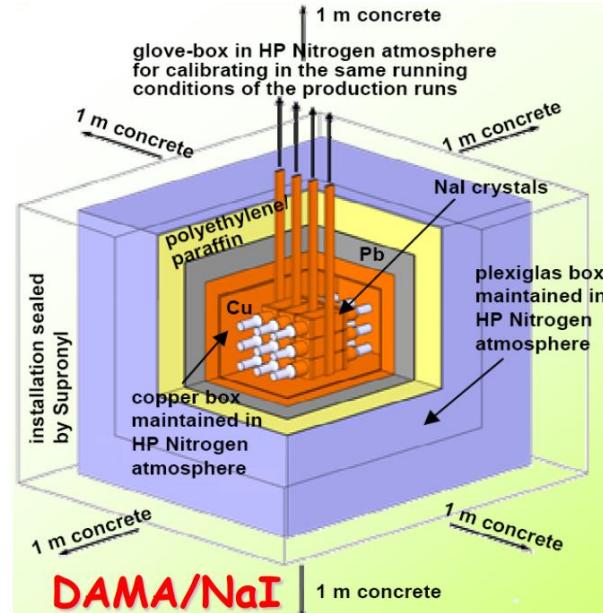
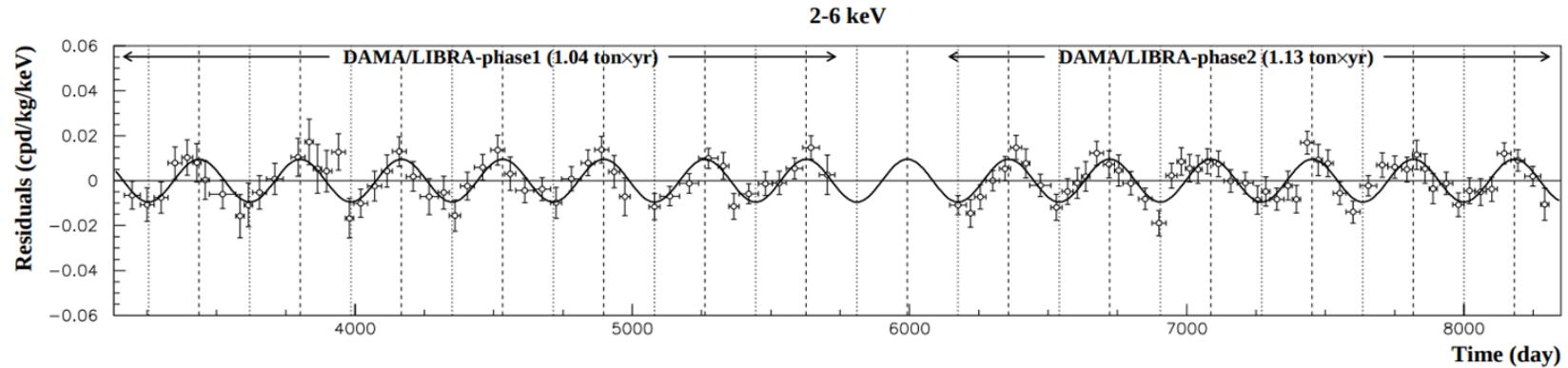


Figure 4. Illustration of the Sun-Earth system moving around the galactic center and through the dark matter halo in the direction of the constellation Cygnus. The varying vector addition of the velocities over the course of a year is expected to induce a modulating dark matter signature.

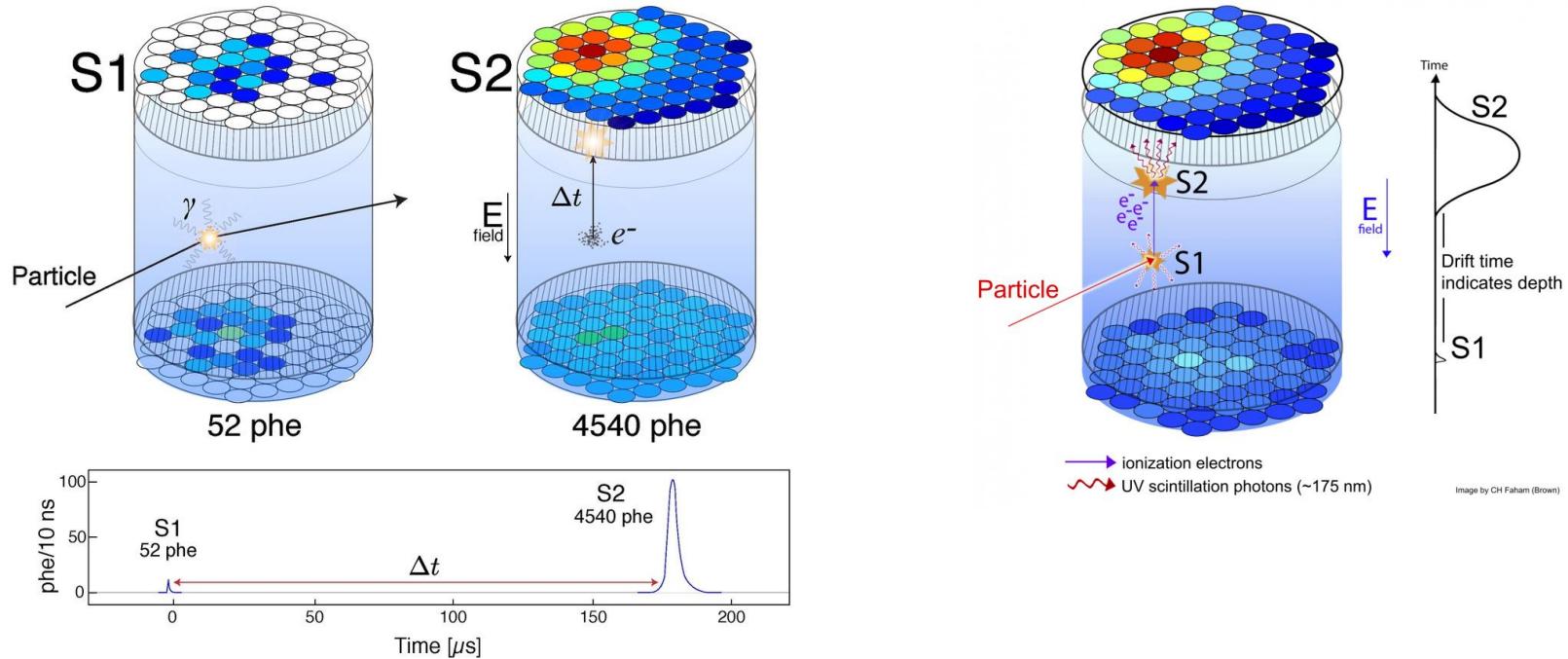


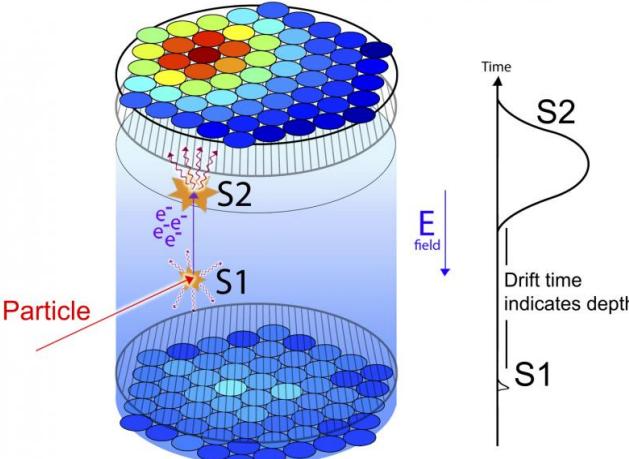


The data of the new DAMA/LIBRA–phase2 confirm a peculiar annual modulation in the (1–6) keV energy region:

- 1) the single-hit events show a clear cosine-like modulation
 - 2) the measured period is equal to (0.999 ± 0.001) yr well compatible with the 1 yr period as expected for the DM signal
 - 3) the measured phase (145 ± 5) days is compatible with the roughly $\simeq 152.5$ days expected for the DM signal
 - 4) the modulation is present only in the low energy (1–6) keV interval and not in other higher energy regions
 - 5) the modulation is present only in the single-hit events, while it is absent in the multiple-hit ones as expected for the DM signal
 - 6) the measured modulation amplitude in NaI(Tl) target of the single-hit scintillation events in the (2–6) keV energy interval, for which data are also available by DAMA/Nal and DAMA/LIBRA–phase1, is: (0.0103 ± 0.0008) cpd/kg/keV (12.9σ C.L.).
- No systematic or side processes able to mimic the signature (...) has been found

Thus, on the basis of the exploited signature, the model independent DAMA results give evidence at **12.9σ C.L.** (over 20 independent annual cycles and in various experimental configurations) for the presence of DM particles in the galactic halo





[For Xenon1T: the electrons are drifted by an electric field to the liquid-gas interface with a speed of about $2 \text{ mm}/\mu\text{s}$.]

LUX is a dual-phase liquid/gas xenon Time Projection Chamber (TPC). When a WIMP (or other particle) interacts with one of the xenon atoms in the liquid portion of the detector, it causes the xenon nucleus to recoil (**S1** signal).

The recoil leads to a burst of scintillation light and to the ionization of the surrounding xenon atoms, leading to the liberation of “ionization electrons”. They drift to the top of the detector (electric field) where they encounter the gas-liquid interface.

They produce a second burst of light through electroluminescence (**S2**).

The resultant photons from each burst of light are detected by 122 Photomultiplier Tubes (PMTs), split between the top and bottom of the detector.

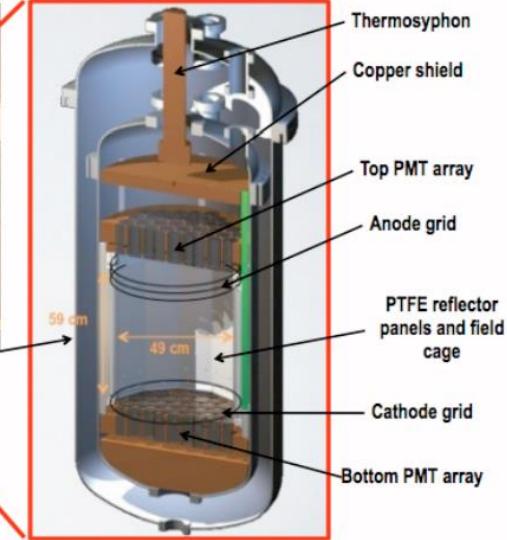
The two signals, S1 and S2, are separated by the drift time of the electrons, from which we can infer the depth of the event.

Combining this information with the geometrical patterns produced by the number of photoelectrons detected by each PMT, the three dimensional position can be reconstructed for each event. This position information is vital for discrimination between signal and background since the xenon self-shielding causes most of the background events to be concentrated near the walls of the detector. Uniform backgrounds such as the decays of radioactive elements contaminating the xenon itself, will produce electron recoils rather than nuclear recoils in the detector.

These events can be distinguished from that of nuclear recoils based on the ratios of their S1 and S2 signals.



370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass





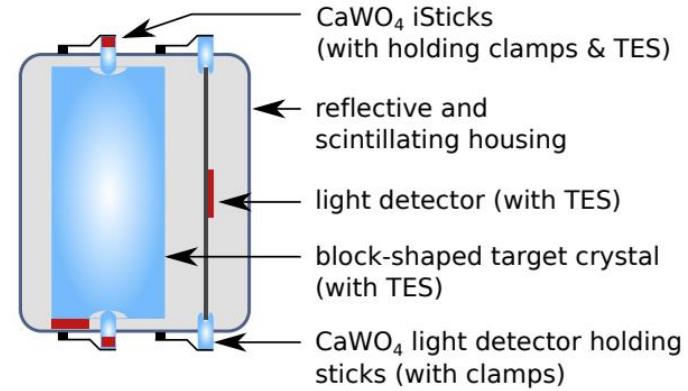
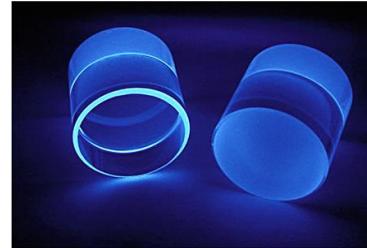
- 3.2 tons of ultra radio-pure liquid Xenon
- Fiducial volume of about 2 tons
- The detector is housed in a 10 m water tank that serves as a muon veto
- The TPC is 1 m in diameter and 1 m in height

“In April 2019, based on measurements performed with the XENON1T detector, the XENON Collaboration reported in [Nature](#) the first direct observation of two-neutrino **double electron capture** in xenon-124 nuclei,

The measured half-life of this process, which is several orders of magnitude larger than the age of the Universe, demonstrates the capabilities of xenon-based detectors to search for rare events and showcases the broad physics reach of even larger next-generation experiments.

This measurement represents a first step in the search for the **neutrinoless double electron capture** process, the detection of which would provide valuable insight into the nature of the **neutrino** and allow to determine its absolute mass”

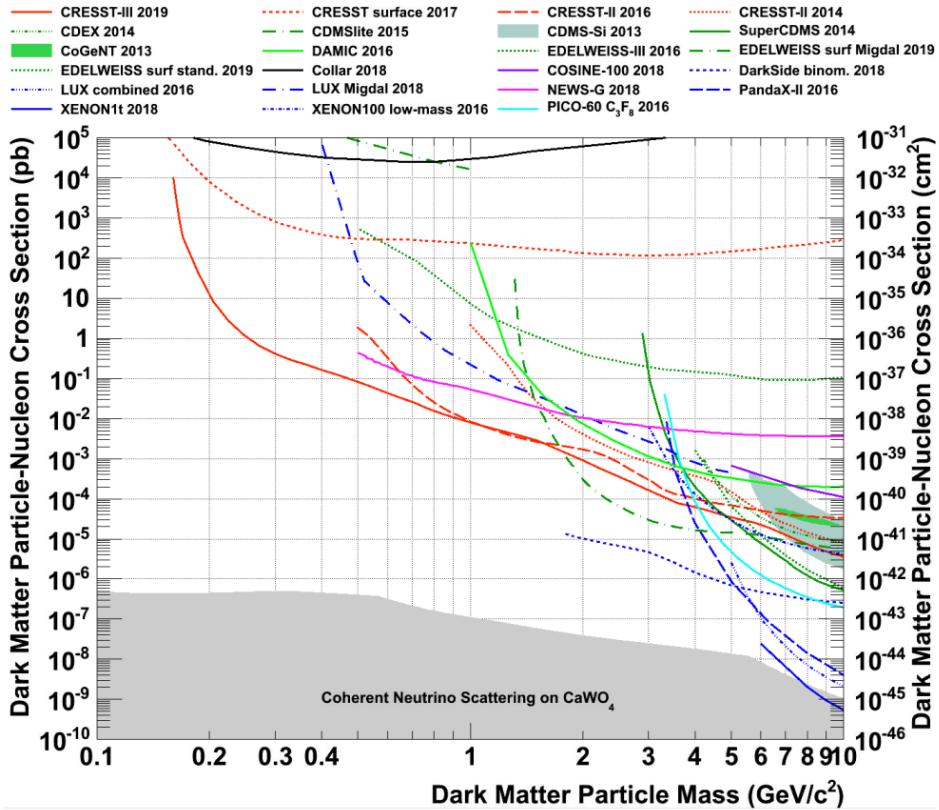
CRESST (Cryogenic Rare Event Search with Superconducting Thermometers)

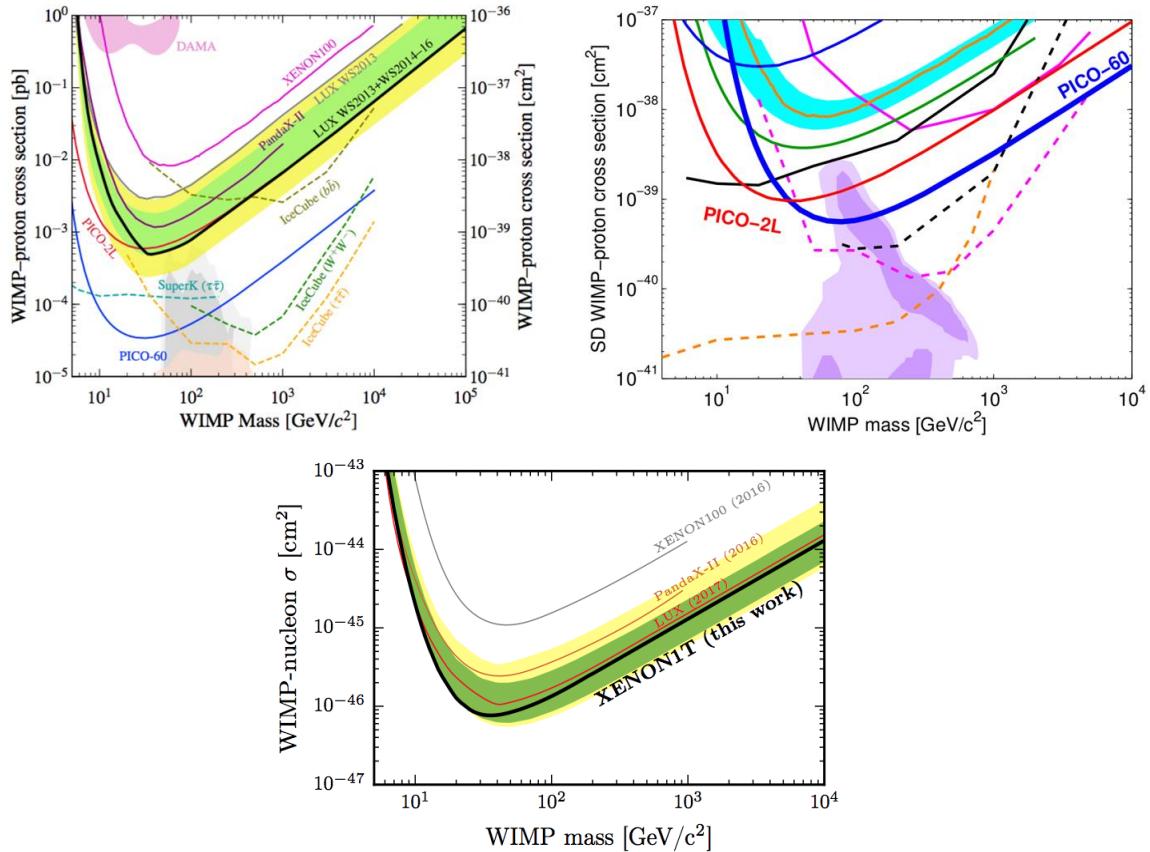


- The CRESST-III experiment operates scintillating CaWO₄ crystals as cryogenic calorimeters, simultaneously measuring a phonon/heat and a scintillation light signal.
- A distinctive feature of the phonon signal is a precise determination of the energy deposited in the crystal, independent from the type of particle interaction.
- This property, in combination with a low energy threshold, makes cryogenic calorimeters particularly suited **for low-mass dark matter detection**.
- Contrary to the phonon signal, the scintillation light strongly depends on the type of particle interaction, yielding event-by-event discrimination between the dominant background (β/γ -interactions) and the sought-for nuclear recoils.

- CRESST is located in the Laboratori Nazionali del Gran Sasso (LNGS) underground laboratory in central Italy which provides an overburden against cosmic radiation with a water equivalent of 3600 m
- Remaining muons are tagged by an active muon veto with 98.7% geometrical coverage
- In addition, the experimental volume is protected by concentric layers of shielding material comprising - from outside to inside - polyethylene, lead and copper.
- The polyethylene shields from environmental neutrons, while lead and copper suppress γ -rays.
- A second layer of polyethylene inside the copper shielding guards against neutrons produced in the lead or the copper shields. A commercial $^3\text{He}/^4\text{He}$ -dilution refrigerator provides the base temperature of about 5 mK. Cryogenic liquids (LN₂ and LHe) are refilled three times a week causing a down-time of about 3 h per refill.

<https://youtube/uz177q5l82Q>





- When a neutrino scatters off a nucleus the interaction depends on the neutrino-nucleon interaction
- for small momentum transfer it does not resolve the internal structure of the nucleus (i.e. does not see nucleons)
- the neutrino scatters off the nucleus as a whole
- give rise to a coherent enhancement of the scattering cross-section
- neutral-current process: experimental signature is nuclear recoils with energies of only few eV to keV.

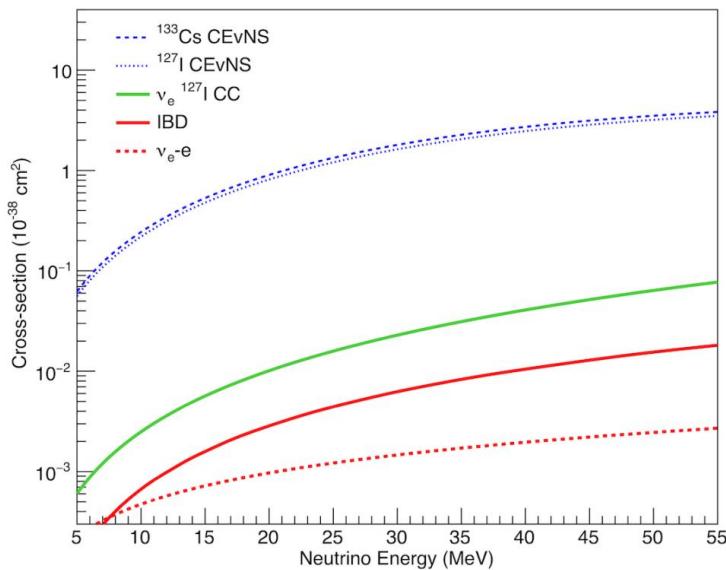
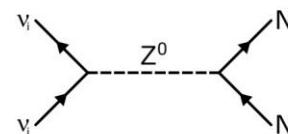
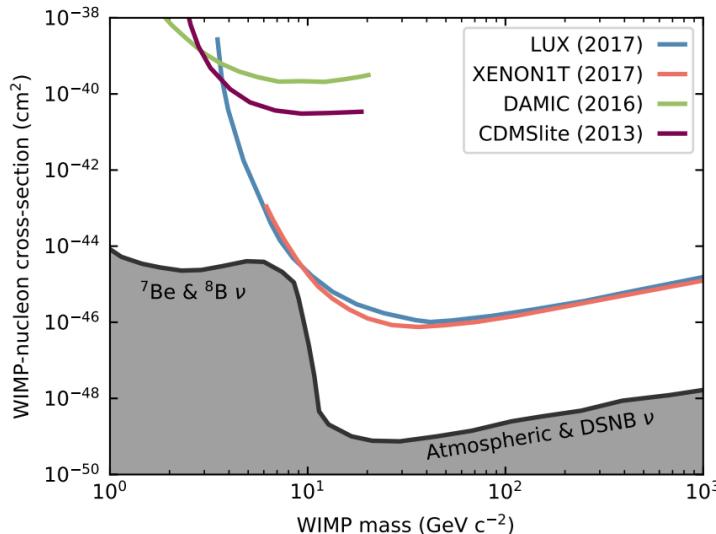


Figure 1.1: Total cross-section for $\text{CE}\nu\text{NS}$ (blue) and other neutrino couplings. Shown are the cross-sections from charged-current (CC) interaction with iodine (green), inverse beta decay (red) and neutrino-electron scattering (dotted red). It is readily visible that $\text{CE}\nu\text{NS}$ provides the largest cross-section, dominating over any charged-current interaction for incoming neutrino energies of less than 55 MeV. Plot adapted from [5].



... Essentially the same happens
in the case of WIMPS !

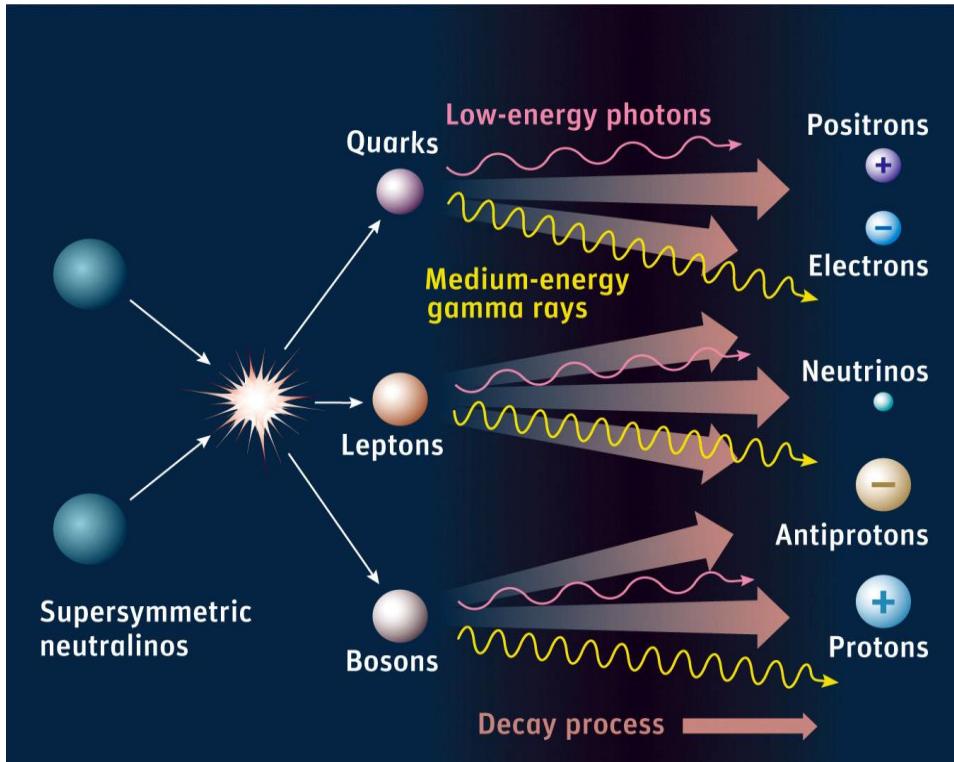
<https://arxiv.org/pdf/1904.01155.pdf>



- For a vanishing momentum transfer between the incoming WIMP and the target nucleus an analogous coherent enhancement of the scattering cross-section is expected.
- the CEvNS cross-section scales with the total neutron number N^2
- the assumed dark matter coupling to both protons and neutrons is non-negligible and approximately equal
- the cross-section for WIMP-nucleus scattering scales with the square of the total nucleon number A^2 instead

<https://arxiv.org/pdf/1904.01155.pdf>

- Dark matter searches will run into an irreducible CEvNS background (“neutrino floor”)
- This background is induced by neutrinos from astrophysical sources, such as the sun, or the diffuse supernova neutrino background (DSNB)
- Since the sole detectable signal for both CEvNS and WIMP scattering is a low energy nuclear recoil it is impossible to distinguish the two



- Idea: DM particles can interact and produce visible SM particle
- Ideal environments: regions with large expected DM density
 - Galactic centre
 - **Dwarf Spheroidal Galaxies**

Dwarf Spheroidal Galaxies (Milky Way Satellites)

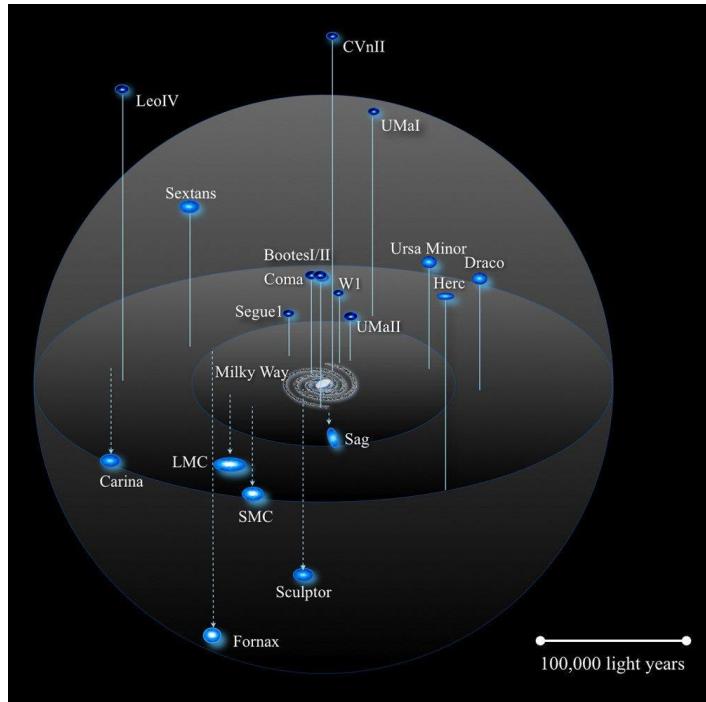
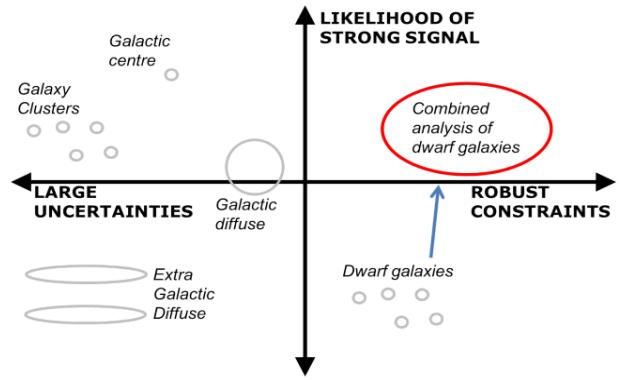
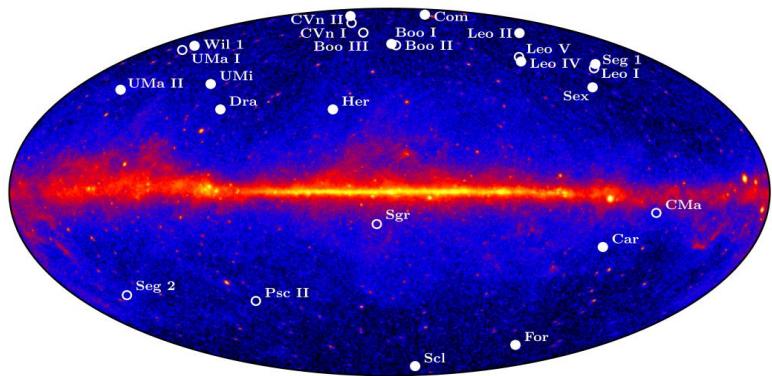
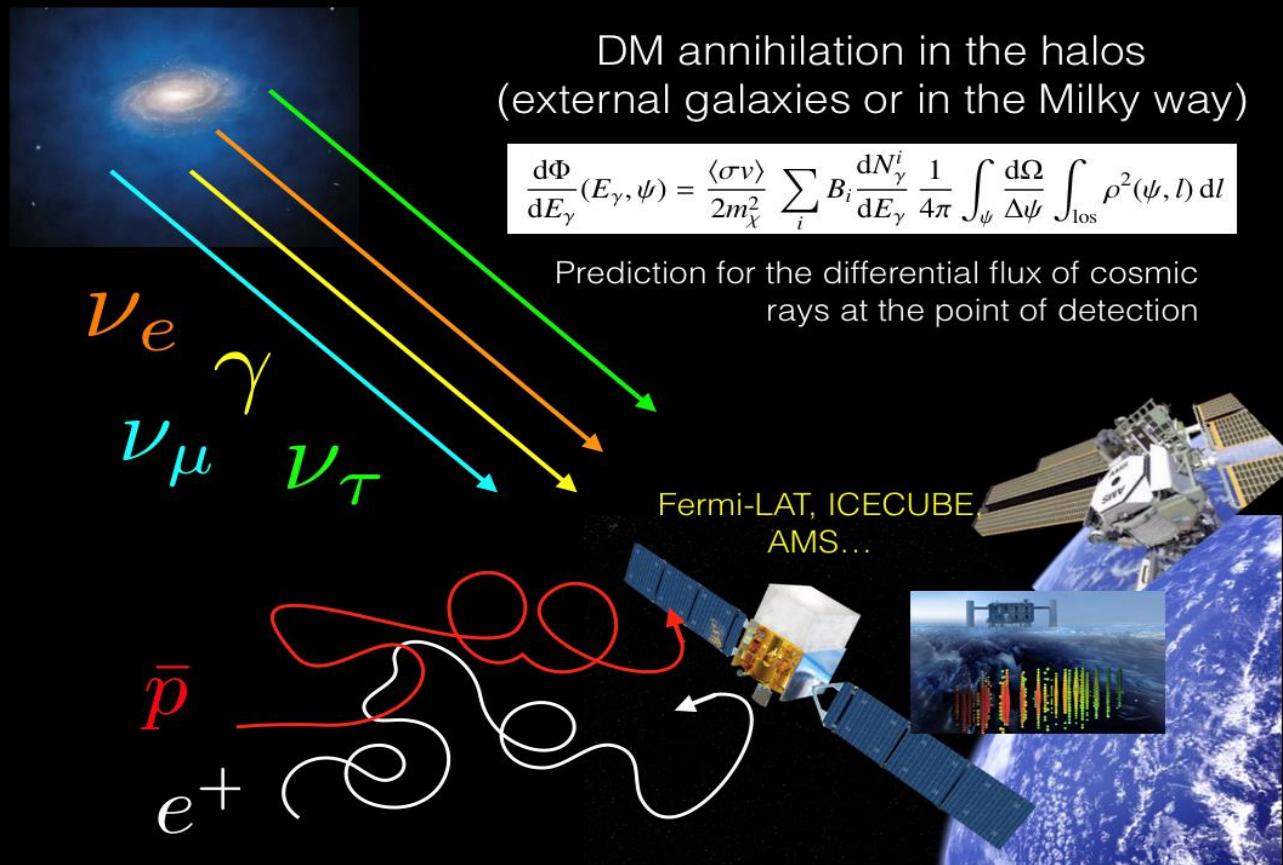
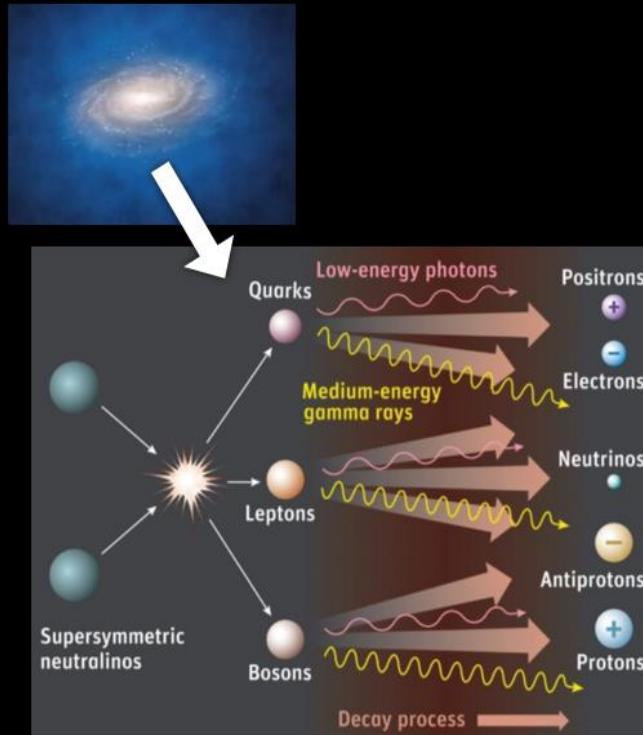


Figure 1: An attempt to visualize the usefulness of different targets for gamma-ray (and neutrino) detection of WIMPs. A plane is defined of likelihood of strong signal versus robustness of constraints. Circles illustrate region of interest for analyses.

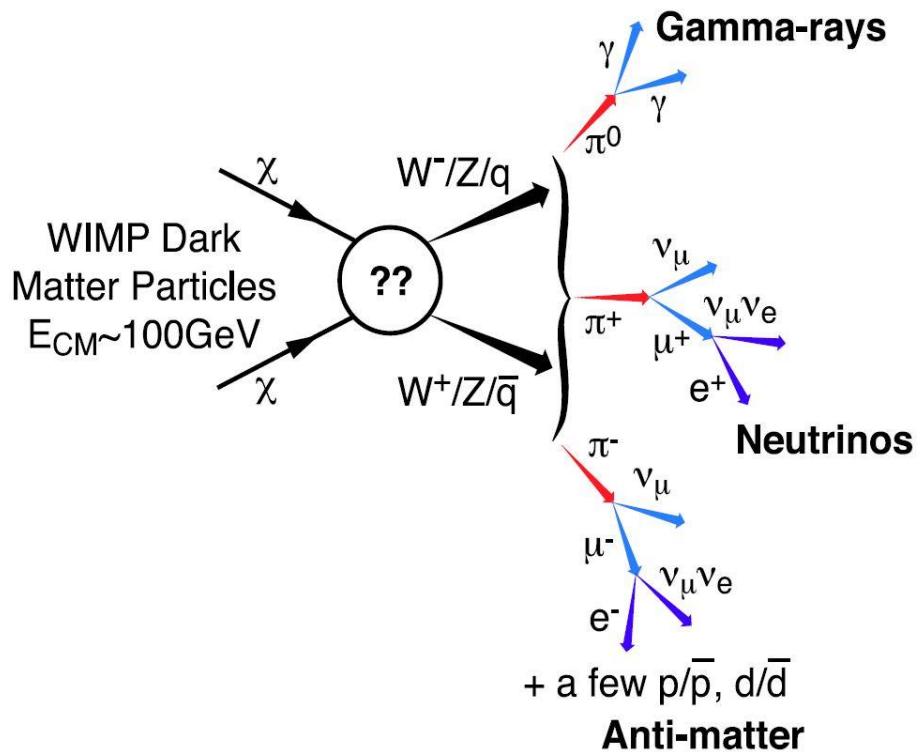




- DM annihilates inside galactic halos
- Typically 2-to-2 processes are considered i.e. $\chi \chi \rightarrow \text{SM SM}$ (called Simplified Models)
- From SM to Cosmic Rays (CR):

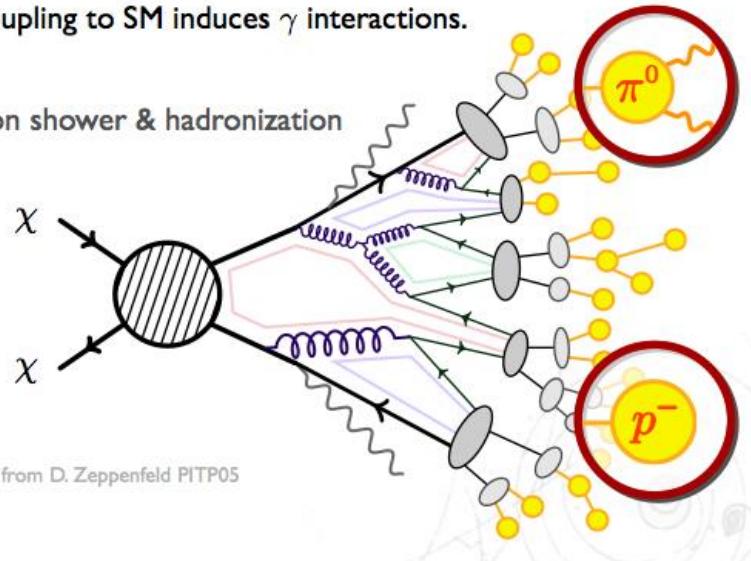
$$\gamma, \nu_e, \nu_\mu, \nu_\tau, e^+, \bar{p}$$
- CRs are detected at Earth (orbit)
e.g. Ice-cube, AMS, **Fermi-LAT**, ...
- Key observable: CRs **Differential energy spectrum**

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi)$$



DM coupling to SM induces γ interactions.

Parton shower & hadronization



Adapted from D. Zeppenfeld PITP05

Flux at detection and DM Annihilation Simplified Channels

[particles/(GeV sr cm² s)]

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} \int_\psi \frac{d\Omega}{\Delta\psi} \int_{\text{los}} \rho^2(\psi, l) dl$$

Velocity averaged
annihilation cross section

Energy spectra
(summing over all the ‘i’
simplified channels)

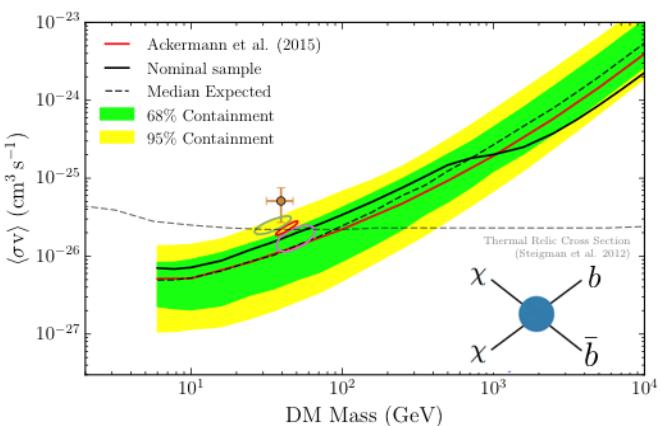
J-factor from
astrophysical observation

$\chi\chi \rightarrow gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$

$\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$

$\chi\chi \rightarrow gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$

$\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$



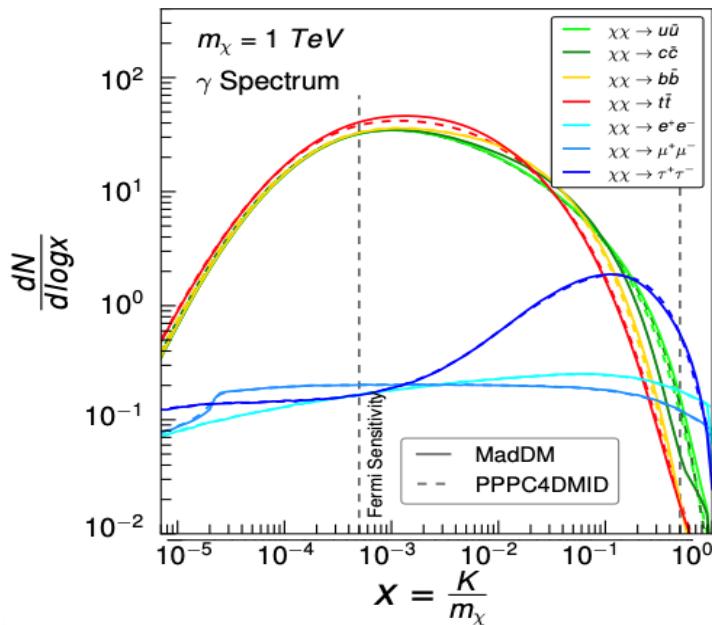
- Limits on the annihilation cross section from gamma rays fluxes
- Fermi-LAT results available only for the $\chi\chi \rightarrow bb$ and $\chi\chi \rightarrow \tau\tau$ channels
Simplified Models for DM annihilation
- Experimental data & recipes to calculate upper limits for arbitrary channels provided by Fermi-LAT

Flux at detection and DM Annihilation Simplified Channels

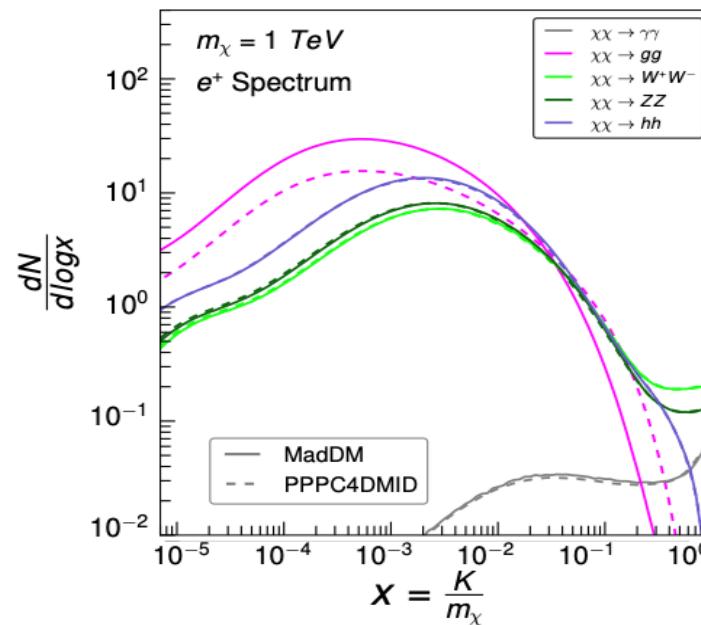
$$\chi\chi \rightarrow gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^- \\ \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$$

2-to-2- processes of DM annihilation
into all SM Fermions and Bosons

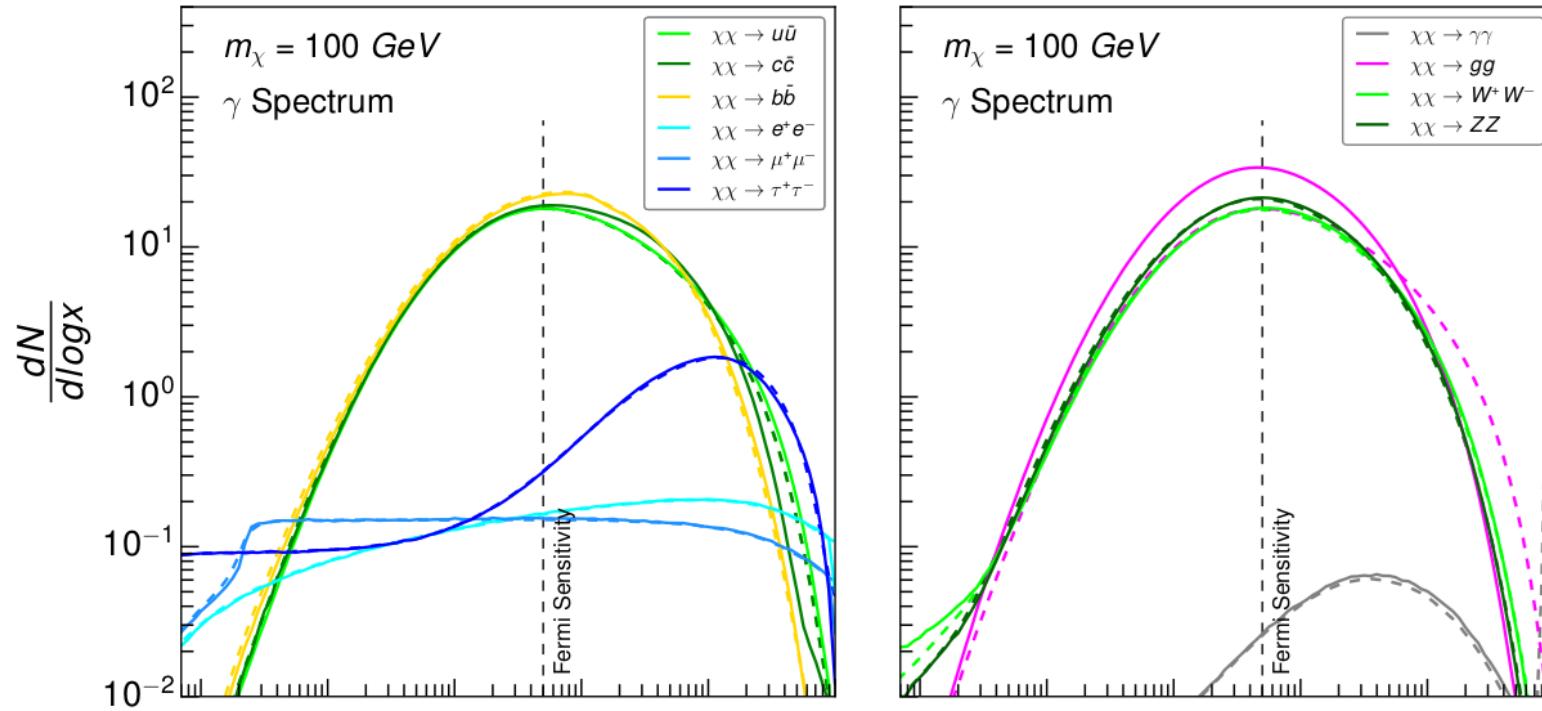
Gamma Rays spectra for Fermions

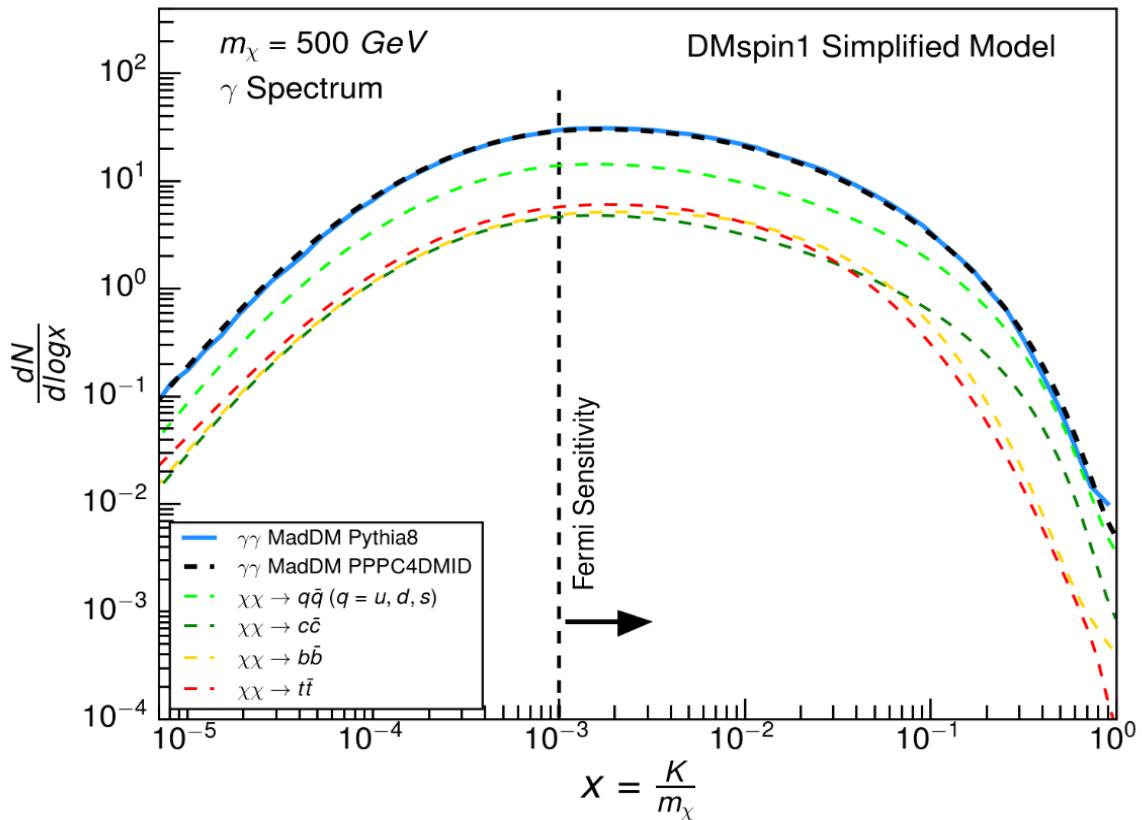


Positrons spectra for Bosons



Fermi-LAT sensitive to γ in the energy range $\sim [0.5 - 500 \text{ GeV}]$





Spectra are assumed to be largely independent of the specific (simplified model) chosen

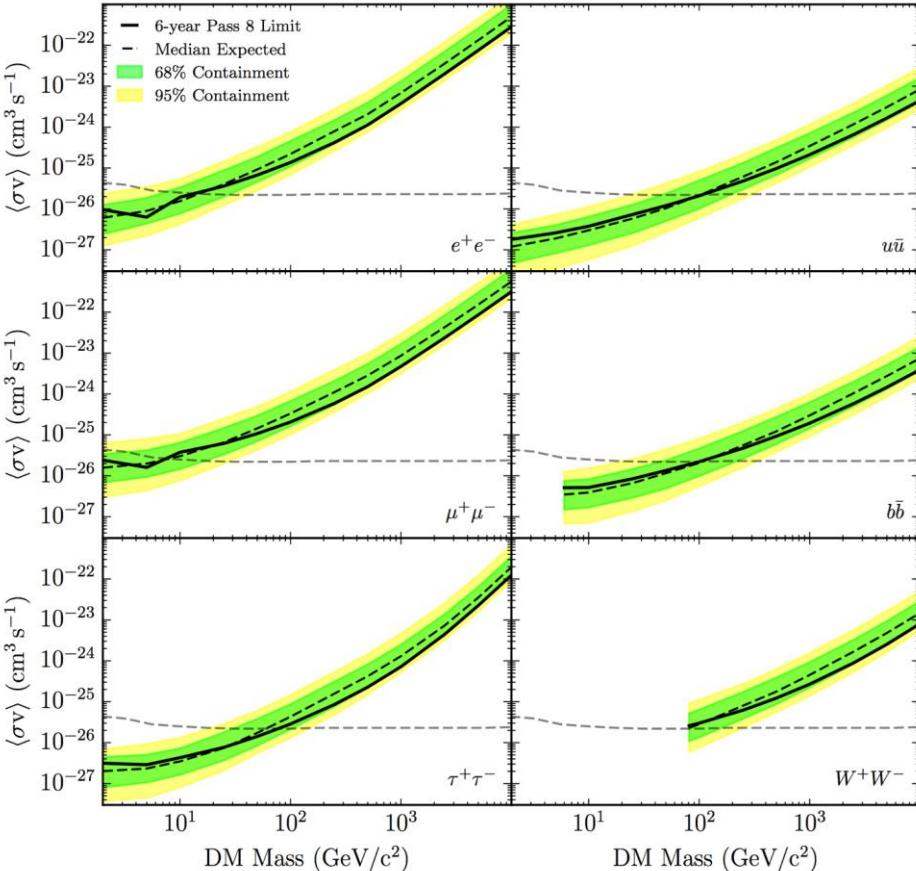
TABLE I. Properties of Milky Way dSphs.

Name	ℓ^a (deg)	b^a (deg)	Distance (kpc)	$\log_{10}(J_{\text{obs}})^b$ ($\log_{10}[\text{GeV}^2 \text{cm}^{-5}]$)	Ref.
Bootes I	358.1	69.6	66	18.8 ± 0.22	[41]
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25	[42]
Carina	260.1	-22.2	105	18.1 ± 0.23	[43]
Coma Berenices	241.9	83.6	44	19.0 ± 0.25	[42]
Draco	86.4	34.7	76	18.8 ± 0.16	[44]
Fornax	237.1	-65.7	147	18.2 ± 0.21	[43]
Hercules	28.7	36.9	132	18.1 ± 0.25	[42]
Leo II	220.2	67.2	233	17.6 ± 0.18	[45]
Leo IV	265.4	56.5	154	17.9 ± 0.28	[42]
Sculptor	287.5	-83.2	86	18.6 ± 0.18	[43]
Segue 1	220.5	50.4	23	19.5 ± 0.29	[46]
Sextans	243.5	42.3	86	18.4 ± 0.27	[43]
Ursa Major II	152.5	37.4	32	19.3 ± 0.28	[42]
Ursa Minor	105.0	44.8	76	18.8 ± 0.19	[44]
Willman 1	158.6	56.8	38	19.1 ± 0.31	[47]
Bootes II ^c	353.7	68.9	42	—	—
Bootes III	35.4	75.4	47	—	—
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26	[42]
Canis Major	240.0	-8.0	7	—	—
Leo I	226.0	49.1	254	17.7 ± 0.18	[48]
Leo V	261.9	58.5	178	—	—
Pisces II	79.2	-47.1	182	—	—
Sagittarius	5.6	-14.2	26	—	—
Segue 2	149.4	-38.1	35	—	—
Ursa Major I	159.4	54.4	97	18.3 ± 0.24	[42]

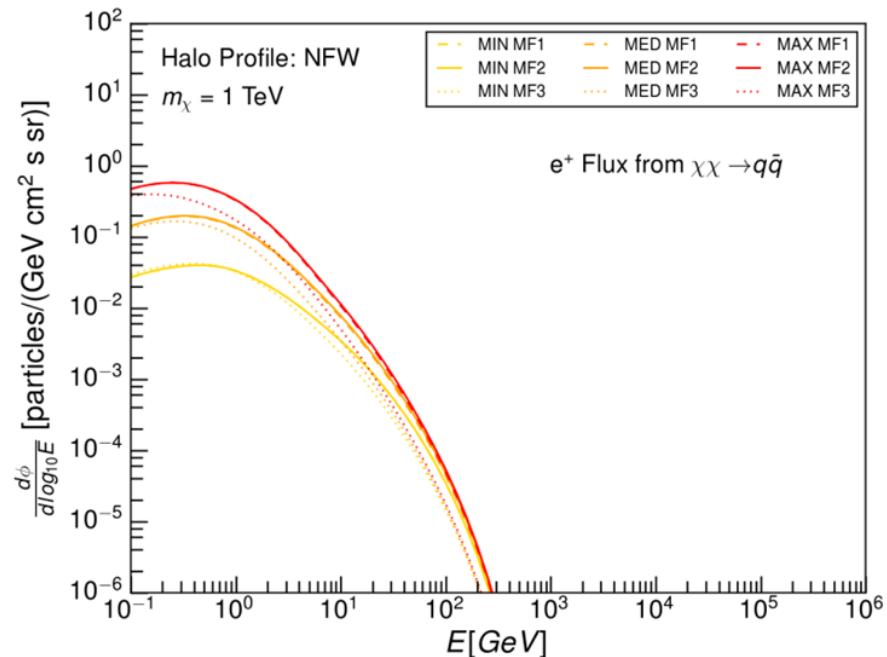
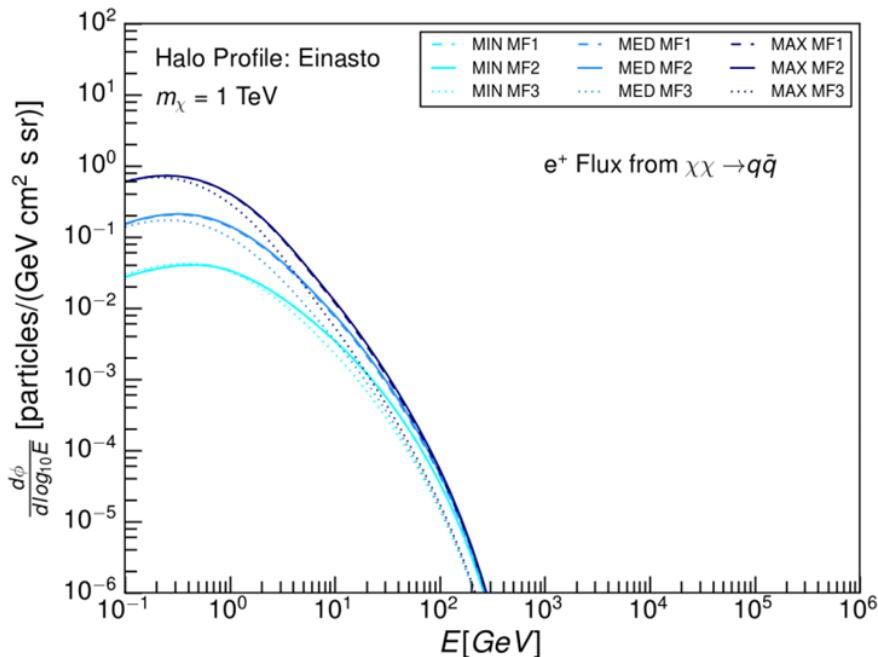
^a Galactic longitude and latitude.

^b J-factors are calculated assuming an NFW density profile and integrated over a circular region with a solid angle of $\Delta\Omega \sim 2.4 \times 10^{-4}$ sr (angular radius of 0.5°).

^c dSphs below the horizontal line are not included in the combined analysis.



- The propagation of charged CR in the galaxies depends strongly on the parametrization of the galaxy
- In particular, the modelization of source points e.g. Pulsars seems very important, as well as the dense region in the inner part
- the predicted flux at Earth



- Theorists develop tools that allow to calculate accurate theory predictions (e.g. Annihilation cross sections, detection rates, fluxes, relic densities) that can be compared with the latest experimental results



MadDM

- Theorists develop tool that allow to calculate accurate theory predictions (e.g. Annihilation cross sections, detection rates, fluxes, relic densities) that can be compared with the latest experimental results

***** Relic Density
 INFO: Relic Density = 1.93e-02
 INFO: x_f = 2.40e+01
 INFO: sigmav(xf) = 1.17e-08
 INFO: xsi = 1.61e-01

***** Direct detection [cm^2]:
 INFO: SigmaN_SI_p Thermal = 2.05e-43 EXCLUDED All DM = 1.27e-42 EXCLUDED Xenon1ton ul = 2.60e-46
 INFO: SigmaN_SI_n Thermal = 2.08e-43 EXCLUDED All DM = 1.29e-42 EXCLUDED Xenon1ton ul = 2.60e-46
 INFO: SigmaN_SD_p Thermal = 0.00e+00 ALLOWED All DM = 0.00e+00 ALLOWED Pico60 ul = 9.13e-41
 INFO: SigmaN_SD_n Thermal = 0.00e+00 ALLOWED All DM = 0.00e+00 ALLOWED Lux2017 ul = 5.24e-41

***** Indirect detection [cm^3/s]:
 INFO: <sigma v> method: reshuffling
 INFO: DM particle halo velocity: 2e-05/c
 INFO: xxddxxdb_ccx Thermal = 2.05e-39 ALLOWED All DM = 7.89e-38 ALLOWED Fermi ul = 4.54e-26
 INFO: xxddxxdb_ddx Thermal = 3.22e-44 ALLOWED All DM = 1.24e-42 ALLOWED Fermi ul = 4.67e-26
 INFO: xxddxxdb_uux Thermal = 8.26e-45 ALLOWED All DM = 3.18e-43 ALLOWED Fermi ul = 4.67e-26
 INFO: xxddxxdb_bbx Thermal = 2.80e-38 ALLOWED All DM = 1.08e-36 ALLOWED Fermi ul = 5.00e-26
 INFO: xxddxxdb_ssx Thermal = 1.30e-41 ALLOWED All DM = 4.99e-40 ALLOWED Fermi ul = 4.67e-26
 INFO: xxddxxdb_ttx Thermal = 4.94e-36 ALLOWED All DM = 1.90e-34 ALLOWED Fermi ul = 6.08e-26
 INFO: xxddxxdb_y0y0 Thermal = 7.91e-35 NO LIMIT All DM = 3.05e-33 NO LIMIT Fermi ul = -1.00e+00
 INFO: Skipping zero cross section processes for: xxccxcb, xxrrxxr
 INFO: Using generic Fermi limits for light quarks (u,d,s)
 INFO: Total limits calculated with Fermi likelihood:
 INFO: DM DM > all Thermal = 8.41e-35 ALLOWED All DM = 3.24e-33 ALLOWED Fermi ul = 9.98e-26
 INFO:
 INFO: *** Fluxes at earth [particle/(cm^2 sr)]:
 INFO: gammas Flux = 7.74e-18
 INFO: neutrinos_e Flux = 1.15e-19
 INFO: neutrinos_mu Flux = 1.25e-19
 INFO: neutrinos_tau Flux = 1.13e-19

Example: GAMBIT

- the DM relic density measurement $\Omega_c h^2 = 0.1188 \pm 0.0010$ from *Planck* [182] (implemented as an upper limit, so as to permit an additional non-neutralino DM component)
- *Fermi-LAT* Pass 8 dwarf limits on DM annihilation [183],
- IceCube 79-string limits on DM annihilation in the Sun [47, 184],
- direct DM searches by LUX [185–187], Panda-X [188], PICO [189, 190], XENON100 [191], Super-CDMS [192] and SIMPLE [193],
- the anomalous magnetic moment of the muon [194, 195],
- MSSM contributions to the mass of the W boson,
- 59 different flavour observables measured by LHCb, Babar and Belle,
- 13 different ATLAS and CMS analyses from Run I and Run II (as in the companion paper [166], we apply the Run II searches as a postprocessing step),
- Higgs limits, mass measurements and signal strengths from LEP and the LHC, and
- limits from LEP on sparticle production and decay in 18 different channels.
- nuisance likelihoods associated the local density of DM [178], the quark contents of the nucleon [178], the top mass [196] and the strong coupling [196].

Solar angular velocity around the Galactic center	Θ_0/R_0	$30.3 \pm 0.9 \text{ km s}^{-1} \text{ kpc}^{-1}$	[17]
Solar distance from Galactic center	R_0	$8.4(6) \text{ kpc}$	[17,18]
circular velocity at R_0	v_0 or Θ_0	$254(16) \text{ km s}^{-1}$	[17]
local disk density	ρ_{disk}	$3-12 \times 10^{-24} \text{ g cm}^{-3} \approx 2-7 \text{ GeV}/c^2 \text{ cm}^{-3}$	[19]
local dark matter density	ρ_χ	canonical value $0.3 \text{ GeV}/c^2 \text{ cm}^{-3}$ within factor 2-3	[20]
escape velocity from Galaxy	v_{esc}	$498 \text{ km/s} < v_{\text{esc}} < 608 \text{ km/s}$	[21]
present day CMB temperature	T_0	$2.7255(6) \text{ K}$	[22,23]
present day CMB dipole amplitude		$3.355(8) \text{ mK}$	[22,24]
Solar velocity with respect to CMB		$369(1) \text{ km/s towards } (\ell, b) = (263.99(14)^\circ, 48.26(3)^\circ)$	[22,24]
Local Group velocity with respect to CMB	v_{LG}	$627(22) \text{ km/s towards } (\ell, b) = (276(3)^\circ, 30(3)^\circ)$	[22,24]
entropy density/Boltzmann constant	s/k	$2.891.2 (T/2.7255)^3 \text{ cm}^{-3}$	[25]
number density of CMB photons	n_γ	$410.7 (T/2.7255)^3 \text{ cm}^{-3}$	[25]
baryon-to-photon ratio	$\eta = n_b/n_\gamma$	$6.05(7) \times 10^{-10} \text{ (CMB)}$ $5.7 \times 10^{-10} \leq \eta \leq 6.7 \times 10^{-10} \text{ (95% CL)}$	[26]
present day Hubble expansion rate	H_0	$100 h \text{ km s}^{-1} \text{ Mpc}^{-1} = h \times (9.777\,752 \text{ Gyr})^{-1}$	[29]
scale factor for Hubble expansion rate	h	$0.673(12)$	[2,3]
Hubble length	c/H_0	$0.925\,0629 \times 10^{26} h^{-1} \text{ m} = 1.37(2) \times 10^{26} \text{ m}$	
scale factor for cosmological constant	$c^2/3H_0^2$	$2.85247 \times 10^{51} h^{-2} \text{ m}^2 = 6.3(2) \times 10^{51} \text{ m}^2$	
critical density of the Universe	$\rho_{\text{crit}} = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11} h^2 M_\odot \text{Mpc}^{-3}$ $= 1.878\,47(23) \times 10^{-29} h^2 \text{ g cm}^{-3}$ $= 1.053\,75(13) \times 10^{-5} h^2 (\text{GeV}/c^2) \text{ cm}^{-3}$	
number density of baryons	n_b	$2.482(32) \times 10^{-7} \text{ cm}^{-3}$ $(2.1 \times 10^{-7} < n_b < 2.7 \times 10^{-7}) \text{ cm}^{-3} \text{ (95% CL)}$	[2,3,27,28] $\eta \times n_\gamma$
baryon density of the Universe	$\Omega_b = \rho_b/\rho_{\text{crit}}$	$\ddagger 0.02207(27) h^{-2} = \dagger 0.0499(22)$	[2,3]
cold dark matter density of the universe	$\Omega_{\text{cdm}} = \rho_{\text{cdm}}/\rho_{\text{crit}}$	$\ddagger 0.1198(26) h^{-2} = \dagger 0.265(11)$	[2,3]
$100 \times$ approx to r_*/D_A	$100 \times \theta_{\text{MC}}$	$\ddagger 1.0413(6)$	[2,3]
reionization optical depth	τ	$\ddagger 0.091_{-0.014}^{+0.013}$	[2,3]
scalar spectral index	n_s	$\ddagger 0.958(7)$	[2,3]
ln pwr primordial curvature pert. ($k_0=0.05 \text{ Mpc}^{-1}$)	$\ln(10^{10} \Delta_{\mathcal{R}}^2)$	$\ddagger 3.090(25)$	[2,3]

Quantity	Symbol, equation	Value	Reference, footnote
dark energy density of the Λ CDM Universe	Ω_Λ	$0.685^{+0.017}_{-0.016}$	[2,3]
pressureless matter density of the Universe	$\Omega_m = \Omega_{cdm} + \Omega_b$	$0.315^{+0.016}_{-0.017}$ (From Ω_Λ and flatness constraint)	[2,3]
dark energy equation of state parameter	w	$\# -1.10^{+0.08}_{-0.07}$ (<i>Planck</i> +WMAP+BAO+SN)	[32]
CMB radiation density of the Universe	$\Omega_\gamma = \rho_\gamma / \rho_c$	$2.473 \times 10^{-5} (T/2.7255)^4 h^{-2} = 5.46(19) \times 10^{-5}$	[25]
effective number of neutrinos	N_{eff}	$\dagger 3.36 \pm 0.34$	[2]
sum of neutrino masses	$\sum m_\nu$	< 0.23 eV (95% CL; CMB+BAO) $\Rightarrow \Omega_\nu h^2 < 0.0025$	[2,30,31]
neutrino density of the Universe	Ω_ν	$< 0.0025 h^{-2} \Rightarrow < 0.0055$ (95% CL; CMB+BAO)	[2,30,31]
curvature	$\Omega_{\text{tot}} = \Omega_m + \dots + \Omega_\Lambda$	$\# 0.96^{+0.4}_{-0.5}$ (95%CL)	[2]
fluctuation amplitude at $8 h^{-1}$ Mpc scale	σ_8	$\# 1.000(7)$ (95% CL; CMB+BAO)	[2]
running spectral index slope, $k_0 = 0.002$ Mpc $^{-1}$	$dn_s/d\ln k$	$\dagger 0.828 \pm 0.012$	[2,3]
tensor-to-scalar field perturbations ratio, $k_0 = 0.002$ Mpc $^{-1}$	$r = T/S$	$\# -0.015(9)$	[2]
redshift at decoupling	z_{dec}	$\# < 0.11$ at 95% CL; no running	[2,3]
age at decoupling	t_*	$\dagger 1090.2 \pm 0.7$	[2]
sound horizon at decoupling	$r_s(z_*)$	$\dagger 3.72 \times 10^5$ yr	[32]
redshift of matter-radiation equality	z_{eq}	$\dagger 147.5 \pm 0.6$ Mpc (Planck CMB)	[2]
redshift at half reionization	z_{reion}	$\dagger 3360 \pm 70$	[2]
age at half reionization	t_{reion}	$\dagger 11.1 \pm 1.1$	[2]
age of the Universe	t_0	$\dagger 462$ Myr	[2]
		$\dagger 13.81 \pm 0.05$ Gyr	[2]

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