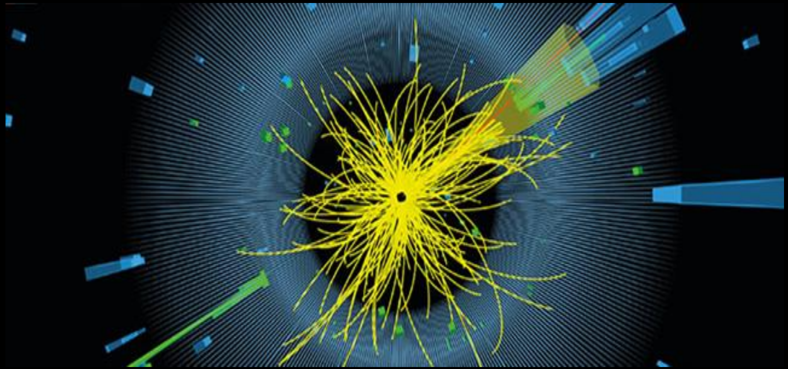
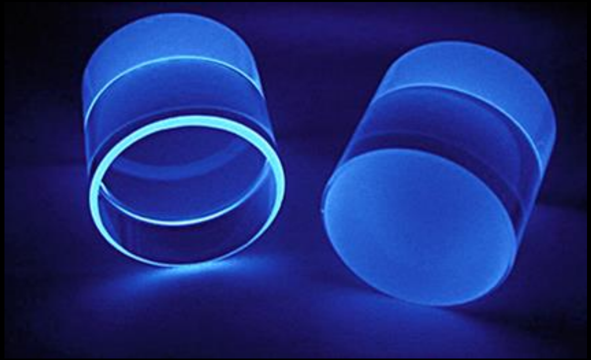
Searches for Dark Matter





Astroparticle Physics
Part 7 – WS 2019
Federico Ambrogi

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

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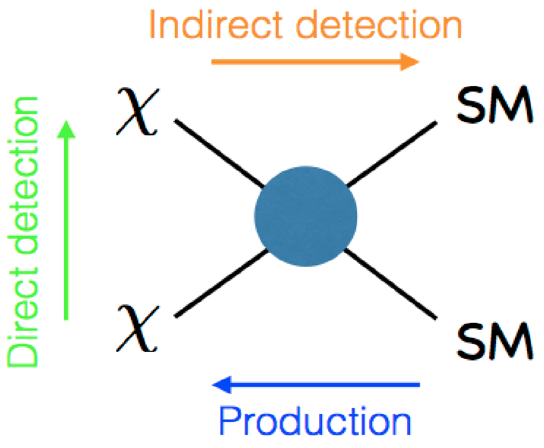


«Make it»

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

«Shake it»

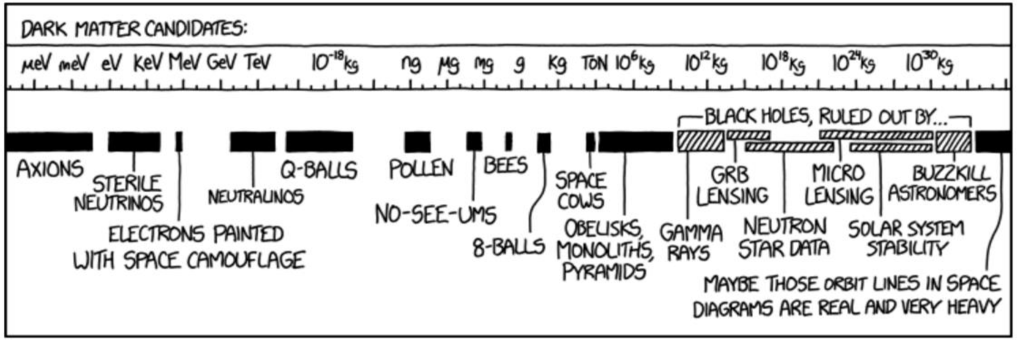
Hope that DM particles scatter onto some nuclei

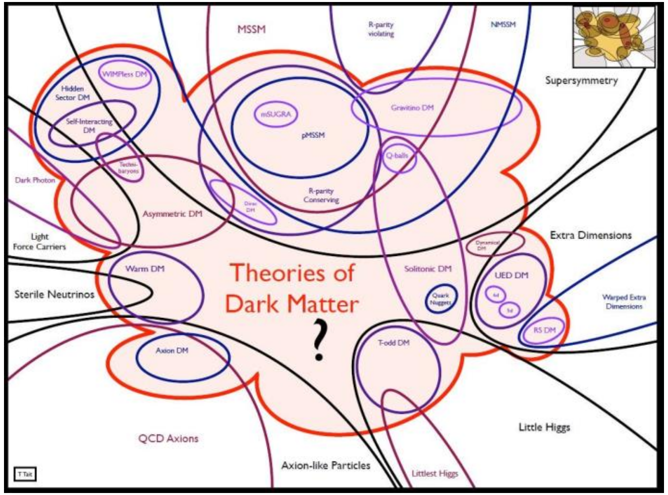
«Break it»

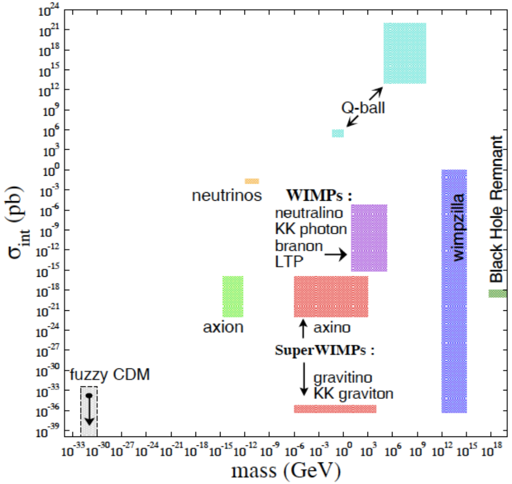
Hope that DM particles interact and annihilate into SM particles

+ « Bake it »

invent nice theories to be tested experimentally







"Bake it"

- 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

- 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 20-30 $M_{\odot}$. The total number of detected events is too small and PBHs in this mass range could only constitute ∼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 → Ωb ≈ 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

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, $\langle \sigma_{ann} v \rangle \approx 10^{-26} \mathrm{cm}^3\,\mathrm{s}^{-1}$. Using an approximation of the relic density :

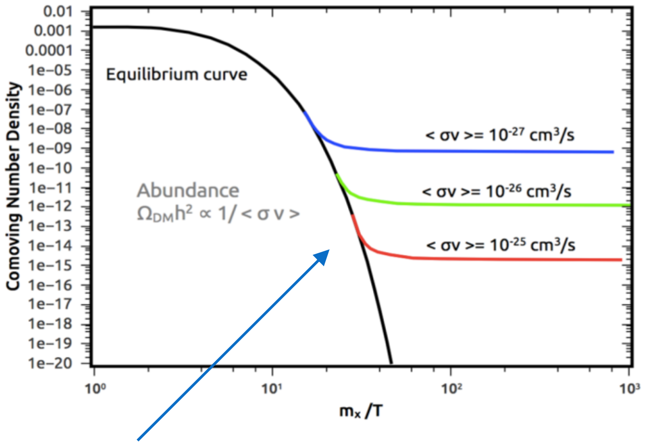
$$\Omega_{\chi,0} h^2 = \frac{3 \times 10^{-27} \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma_{ann} v \rangle}, \quad (2.37)$$

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

$$\Omega_{DM} h^2 = 0.1197 \pm 0.0022 \quad (7.5)$$ [1]

which can be obtained by a cross section of order $\langle \sigma v \rangle \sim 10^{-26}$ cm^3 s^{-1} . When considering a DM mass around the electroweak scale, e.g. $m_\chi = 200$ 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



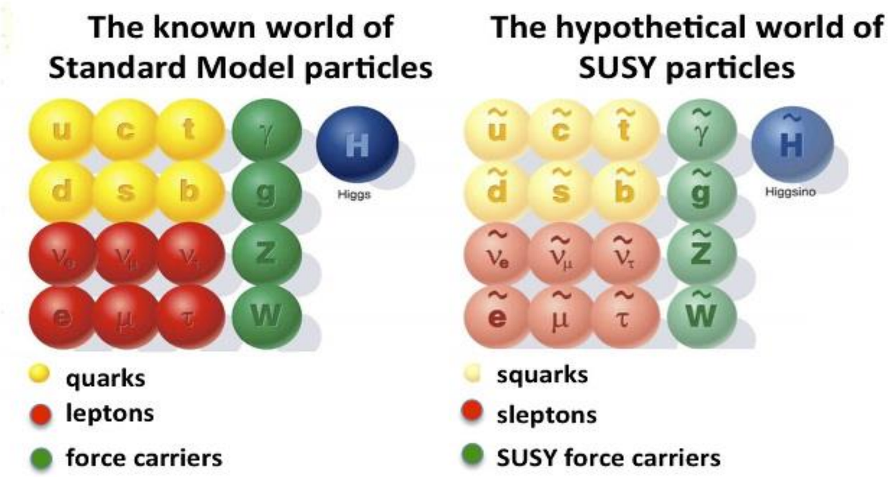
Density is frozen == relic density

→ 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 $\bar{\chi}$: $\langle \sigma_{\chi\bar{\chi} \leftrightarrow X\bar{X}} v \rangle = \langle \sigma_{ann} v \rangle$) 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

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	$(\tilde{H}_u^+\ \tilde{H}_u^0)$	$\tilde{\chi}^{\pm}_{1,2}$
	$(\tilde{H}_d^0\ \tilde{H}_d^-)$	
Wino	$\tilde{W}^{\pm},\ \tilde{W}^0$	$\tilde{\chi}^0_{1,2,3,4}$
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

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.

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

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

whose mass and composition are determined by the $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)$ 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

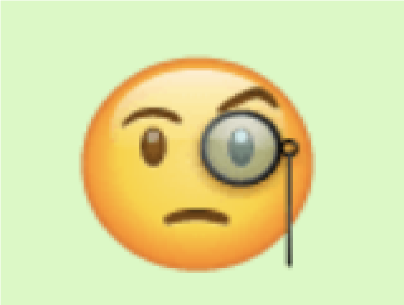
$$(\tilde{W}^3, \tilde{B}, \tilde{H}_1^0, \tilde{H}_2^0) \begin{pmatrix} M_2 & 0 & \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_2 v_2}{\sqrt{2}} \\ 0 & M_1 & \frac{g_1 v_1}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} \\ \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_1 v_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g_2 v_2}{\sqrt{2}} & \frac{-g_1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

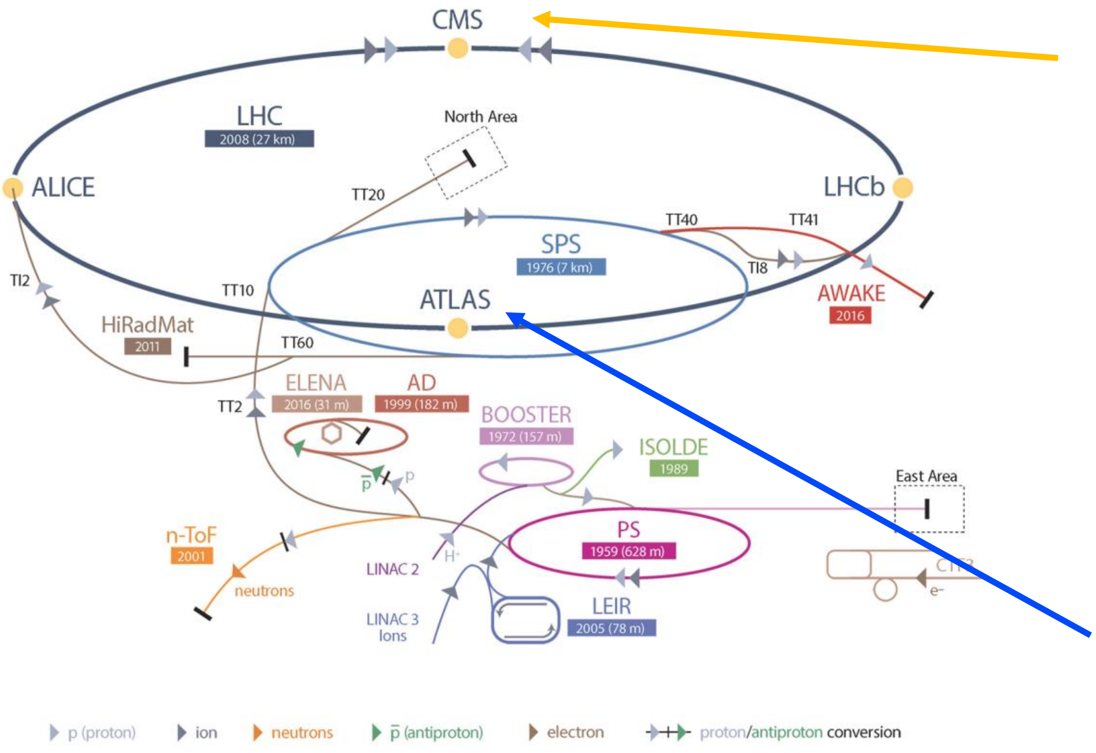
In different regions of the supersymmetric parameter space, the LSP may be more bino-like, wino-like, or Higgsino-like, depending on the relative magnitudes of the coefficients α, β, γ and δ.

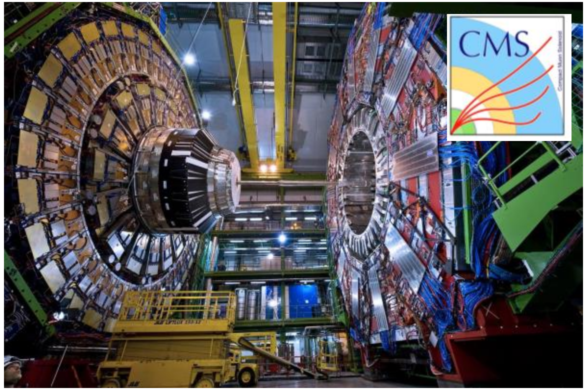
→ *depending on the exact mixing or composition of the neutralinos:*
different production rates, interactions/couplings to particles, decay modes

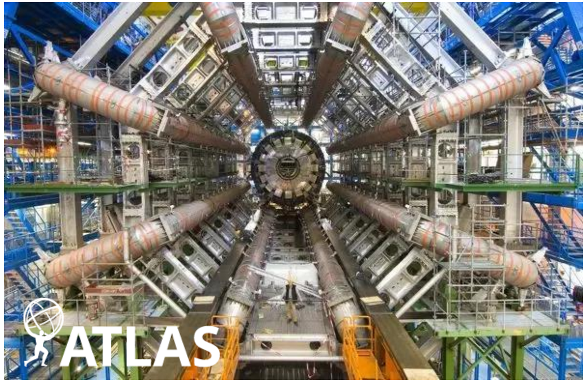

HAVE YOU SEEN ME?
NEUTRALINO
Age: As old as the universe
Weight: Unknown
Size: Tiny
If you have any information on this Neutralino, please contact the nearest scientist.
Dark Matter
100% FAT FREE

... replace with any other DM candidate



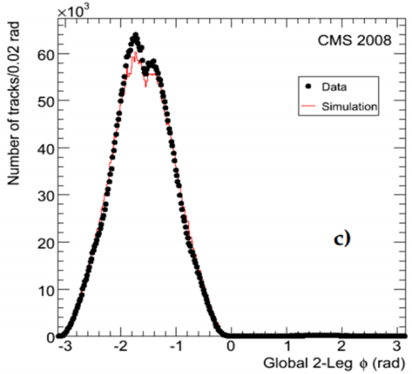

CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
ELENA
2016 (31 m)
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
p̄
p
East Area
n-ToF
2001
PS
1959 (628 m)
H⁺
LINAC 2
neutrons
e–
LINAC 3
Ions
LEIR
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
electron
proton/antiproton conversion

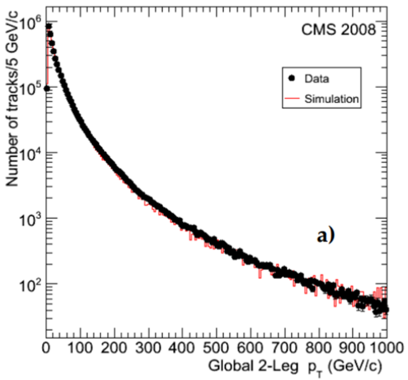

CMS


ATLAS

Cosmic Muons Studies at ATLAS/CMS

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





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

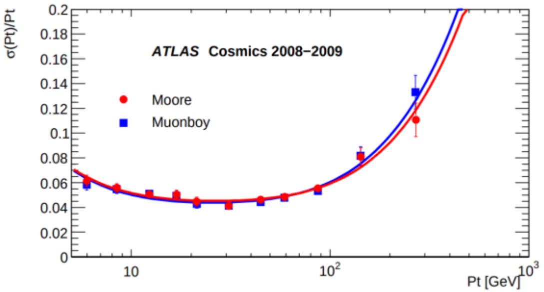
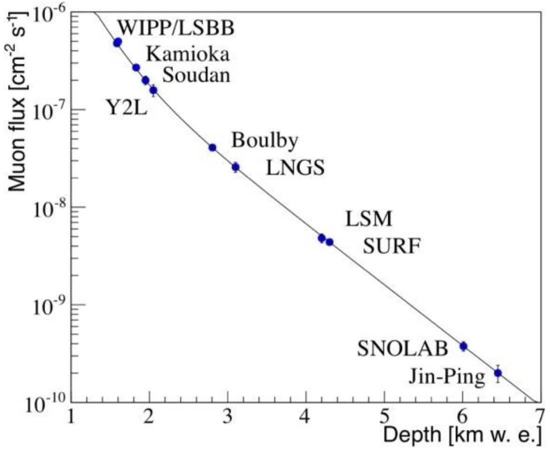


Fig. 35. Transverse momentum resolution evaluated with the top–bottom method explained in the text as a function of p_T, barrel region only ($|\eta| < 1.1$). The fit to the three resolution parameters as described in the text is superimposed.



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»

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:

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

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 μm); 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:

$$L = \int_T \mathcal{L} dt \tag{3.2}$$

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

$$N = \sigma \cdot L \tag{3.3}$$

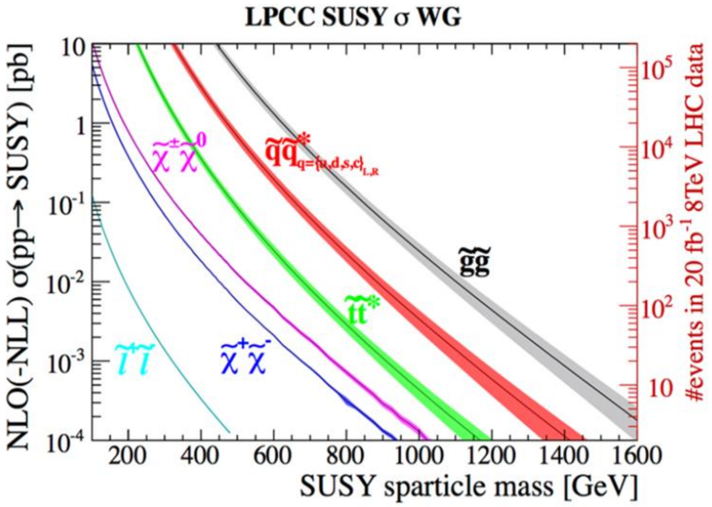
For Run 1, a maximum instantaneous luminosity of $\mathcal{L} = 7.7 \times 10^{33} cm^{-2}s^{-1}$ was achieved, and a total luminosity of around 23 fb^{-1} was delivered to the two general purpose experiments (ATLAS and CMS), at 8 TeV centre-of-mass energy.

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

L= (iuntegrated) 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)

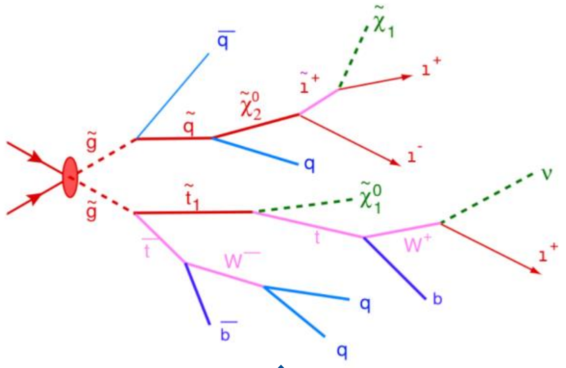
Expected number of events for a given process with a production cross section sigma
-> depends on the particle physics model, e.g.
SM = Standard Model
BSM = Beyond Standard Model (e.g. Supersymmetry)

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

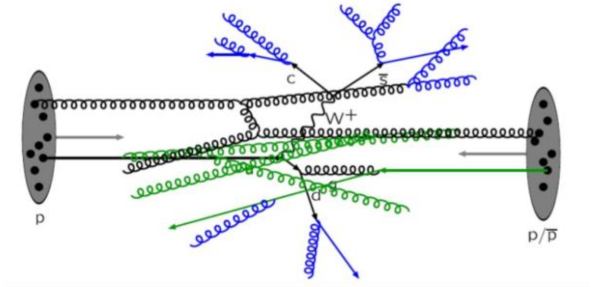


Production cross section for some SUSY particles pair-production and expected number of events for 8 TeV centre-of-mass energy

What we would like to see



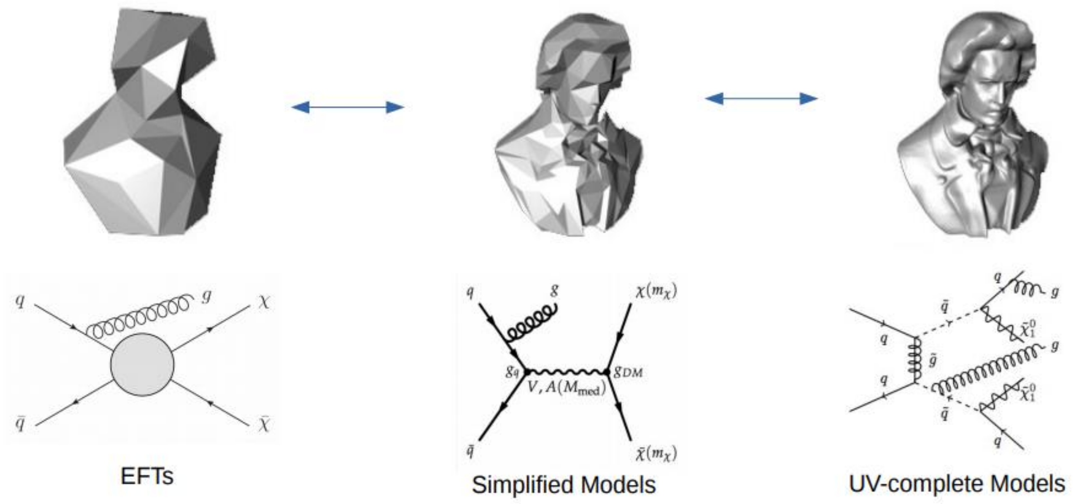
What really happens...



Design of dedicated Searches

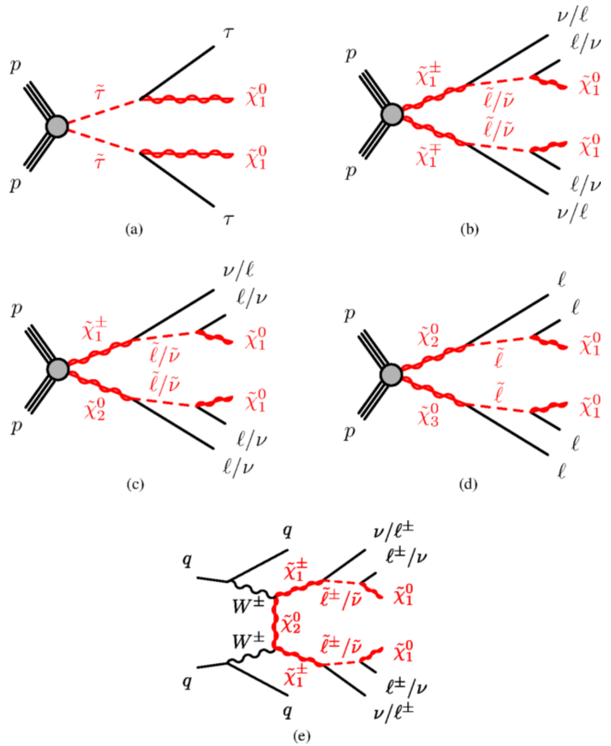
Simplified Models

- 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

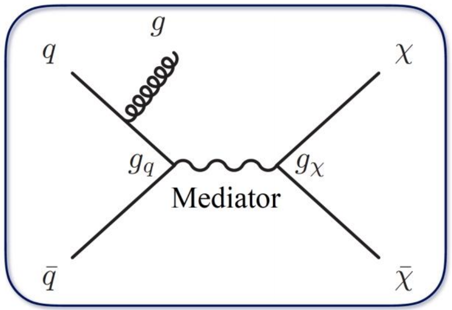


https://indico.cern.ch/event/606690/contributions/2656661/attachments/1497909/2332228/kristian-hahn-LHCDM-TAUP2017.pdf

SUSY Simplified Models



DM Simplified Models



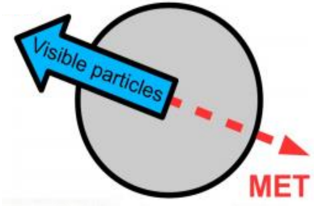
→ **Relevant parameters :**

m_χ, m_{med}, $\mathbf{g_\chi}$ and $\mathbf{g_q}$

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

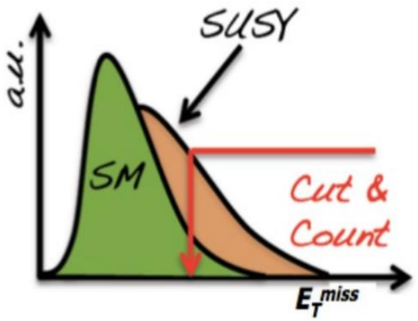
- Assumption: all the SUSY particles will eventually decay to the lightest Neutralino, which is the DM candidate, and it escapes detection since it does not interact with the detector
- This will produce “missing energy” (MET) i.e. an energy imbalance in the event

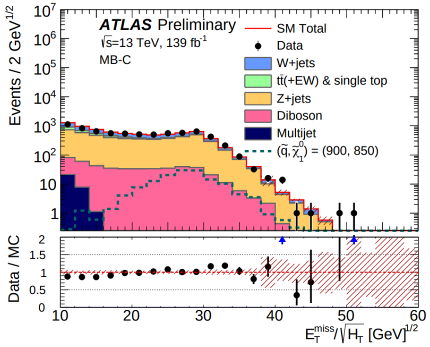
$$E_T^{miss} = |\vec{p}_T^{miss}| = \left|\sum_i \vec{p_T}^i\right|$$



What we “see”

What we do not “see”





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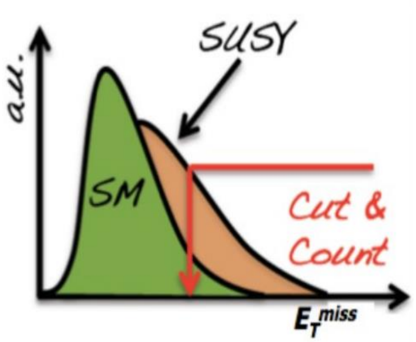
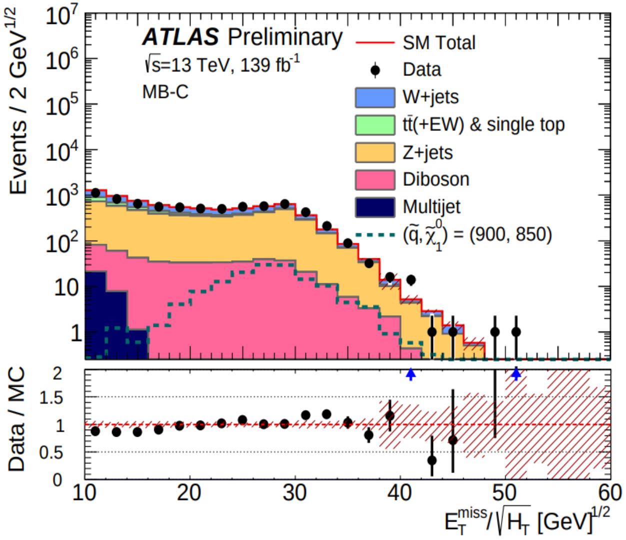




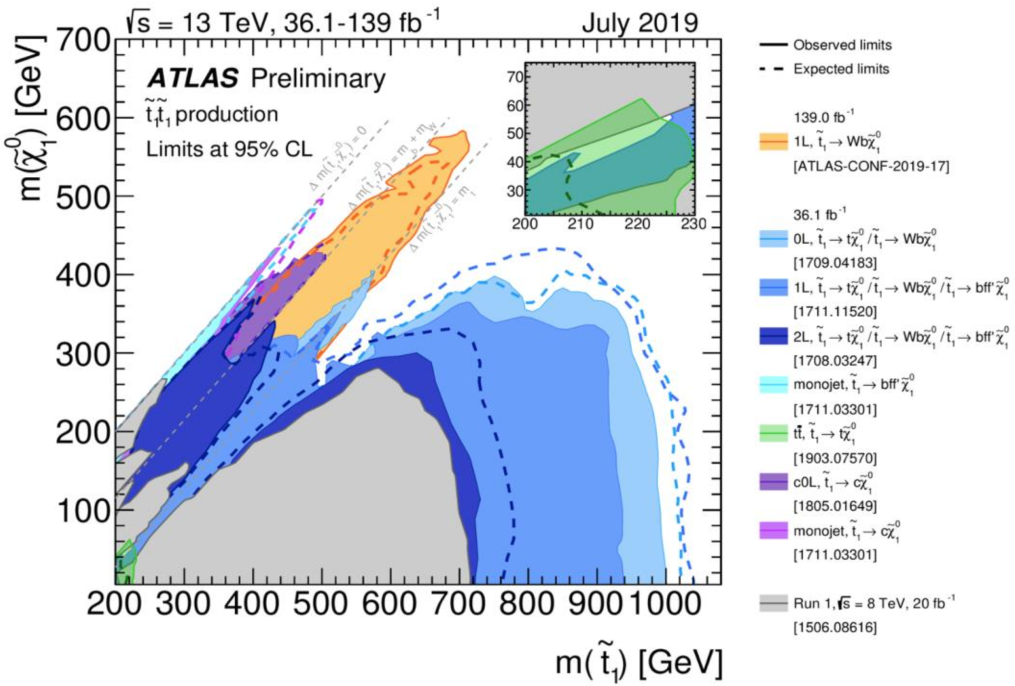
- We expect a lot of missing energy in the events, that cannot be accounted for by SM neutrinos or particles that cannot be revealed by the detectors, systematics, detector acceptance, particle reconstructions efficiency etc.

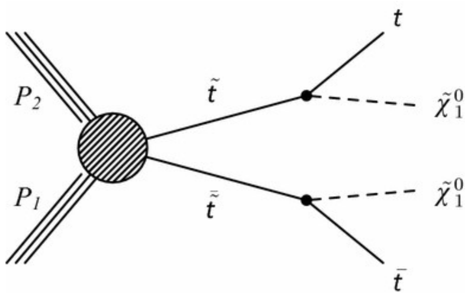
However:

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

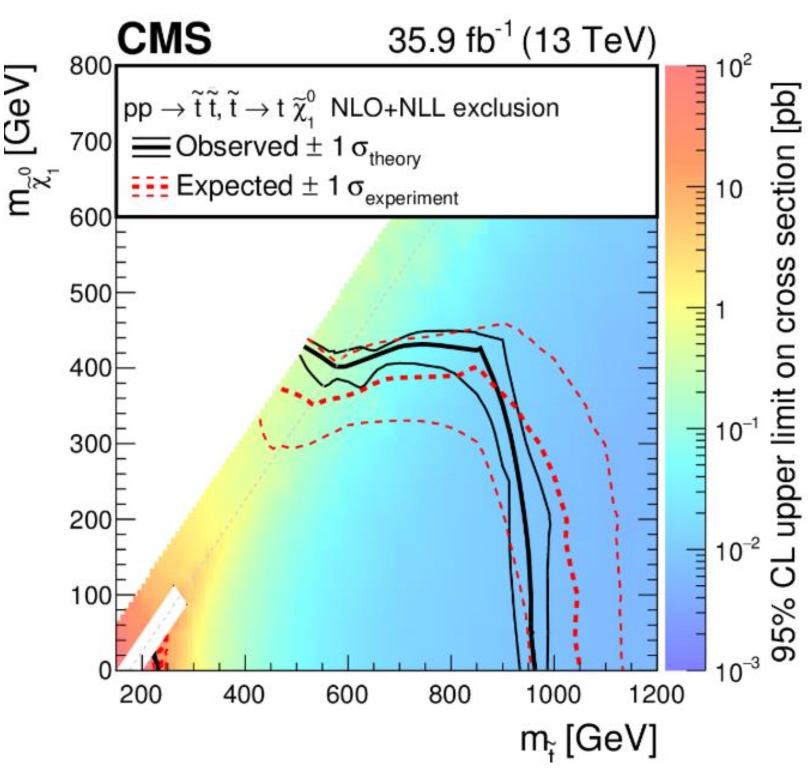
→ Can only state that they are stable while travelling through the detector (this is general of any DM search you perform at the colliders)

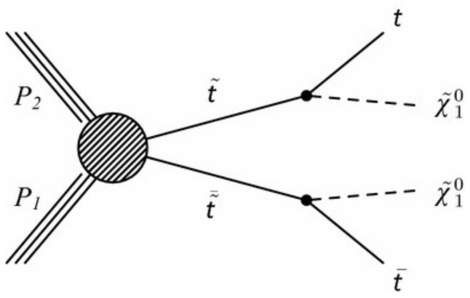
- Evaluate accurately SM background
- Make SUSY signal hypothesys to test with data





- 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)





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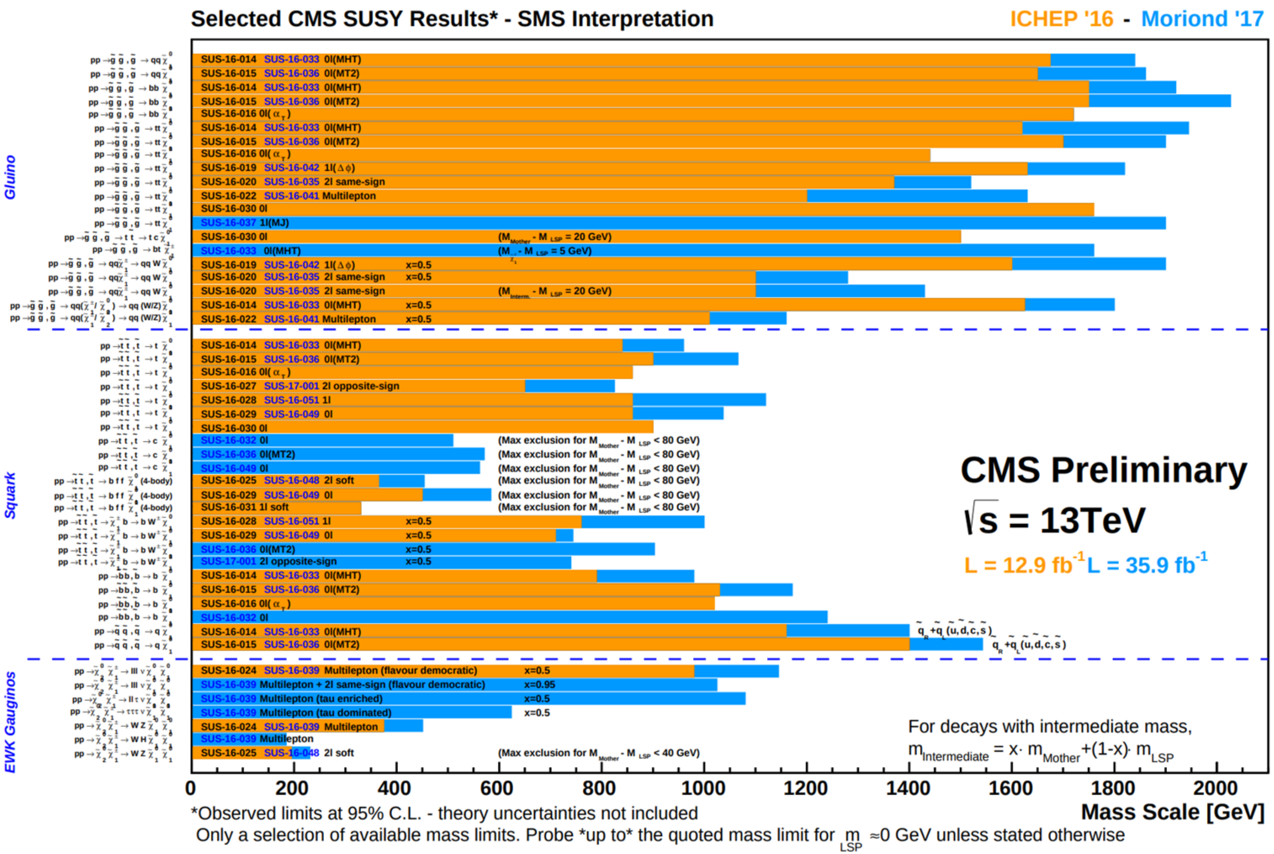
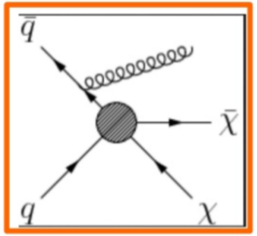
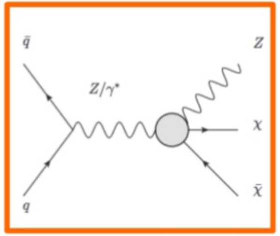

Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-016 0l(αT)
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-016 0l(αT)
SUS-16-019 SUS-16-042 1l(Δφ)
SUS-16-020 SUS-16-035 2l same-sign
SUS-16-022 SUS-16-041 Multilepton
SUS-16-030 0l
SUS-16-037 1l(MJ)
SUS-16-030 0l
SUS-16-033 0l(MHT)
SUS-16-019 SUS-16-042 1l(Δφ) x=0.5
SUS-16-020 SUS-16-035 2l same-sign x=0.5
SUS-16-020 SUS-16-035 2l same-sign
SUS-16-014 SUS-16-033 0l(MHT) x=0.5
SUS-16-022 SUS-16-041 Multilepton x=0.5
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-016 0l(αT)
SUS-16-027 SUS-17-001 2l opposite-sign
SUS-16-028 SUS-16-051 1l
SUS-16-029 SUS-16-049 0l
SUS-16-030 0l
SUS-16-032 0l
SUS-16-036 0l(MT2)
SUS-16-049 0l
SUS-16-025 SUS-16-048 2l soft
SUS-16-029 SUS-16-049 0l
SUS-16-031 1l soft
(Max exclusion for M Mother - M LSP < 80 GeV)
SUS-16-028 SUS-16-051 1l x=0.5
SUS-16-029 SUS-16-049 0l x=0.5
SUS-16-036 0l(MT2) x=0.5
SUS-17-001 2l opposite-sign x=0.5
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-016 0l(αT)
SUS-16-032 0l
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-024 SUS-16-039 Multilepton (flavour democratic) x=0.5
SUS-16-039 Multilepton + 2l same-sign (flavour democratic) x=0.95
SUS-16-039 Multilepton (tau enriched) x=0.5
SUS-16-039 Multilepton (tau dominated) x=0.5
SUS-16-024 SUS-16-039 Multilepton
SUS-16-039 Multilepton
SUS-16-025 SUS-16-048 2l soft
(Max exclusion for M Mother - M LSP < 40 GeV)
CMS Preliminary
√s = 13TeV
L = 12.9 fb-1 L = 35.9 fb-1
For decays with intermediate mass,
m Intermediate = x· m Mother +(1-x)· m LSP
0 200 400 600 800 1000 1200 1400 1600 1800 2000
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m LSP ≈0 GeV unless stated otherwise

Idea: DM direct production plus “something”

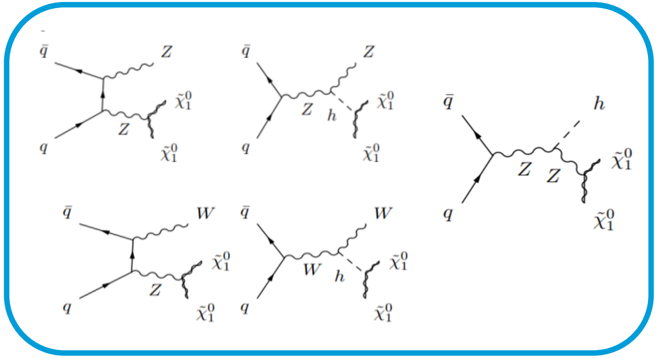
Mono-jet



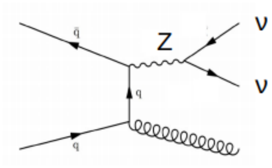
Mono-Z



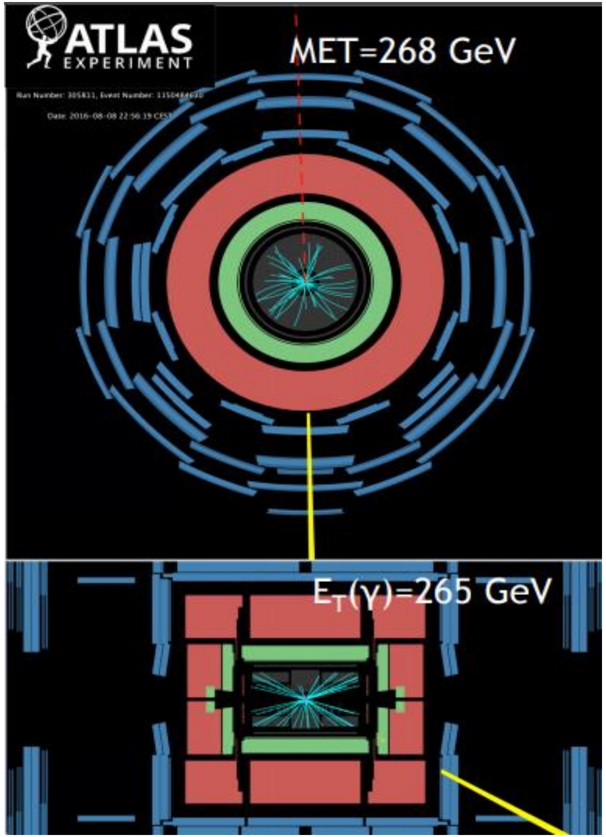
Mono-lepton
Mono-photon
Mono-top
Mono-Higgs
etc …

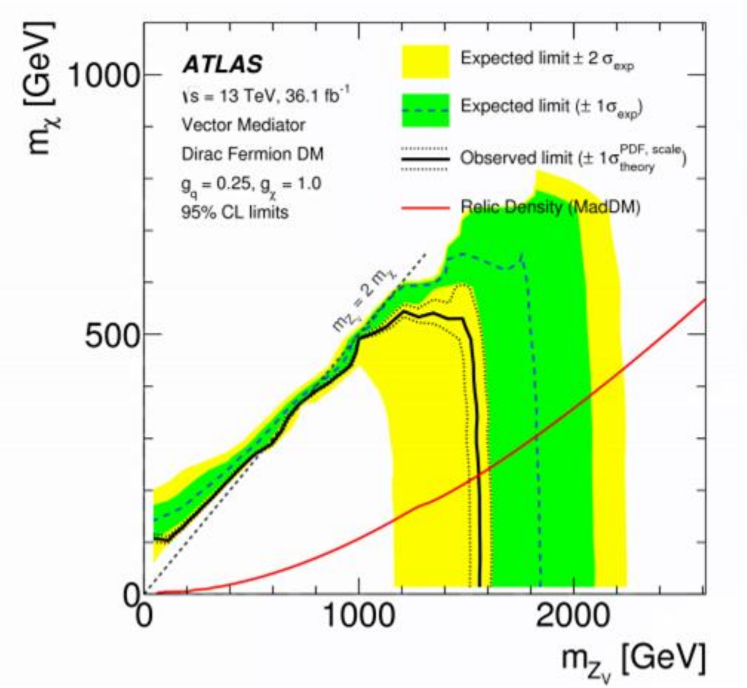


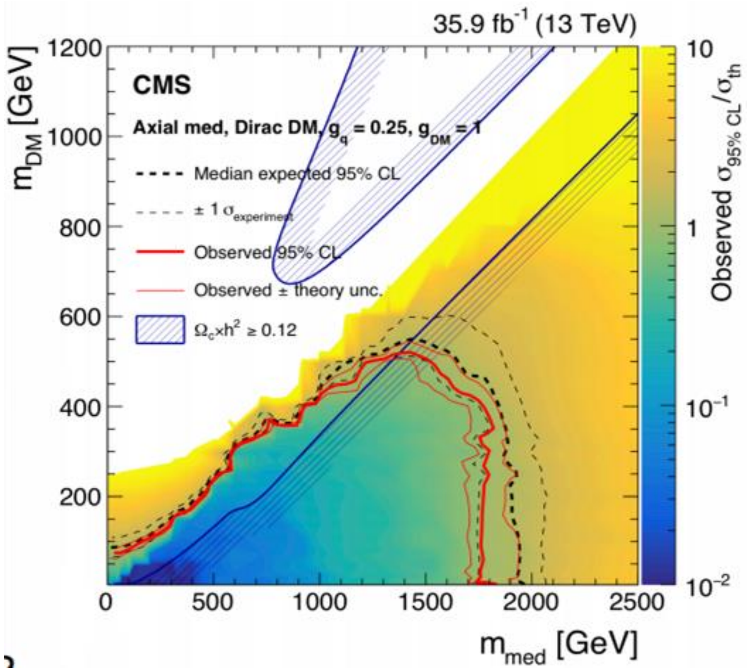
Example for SUSY



Example: Mono-jet SM irreducible background





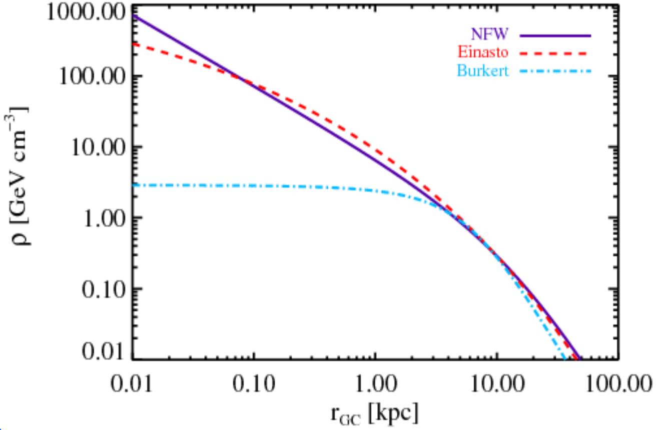


→ Using DM simplified models: put limits on the DM and mediator mass for fixed couplings

- 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 → 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

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

Particle Physics: Scattering Cross Sections

$$\sigma_{SD} = \frac{16}{\pi}\mu_A^2 \cdot \frac{J_A+1}{J_A}(f'_p + f'_n)^2$$

$\Rightarrow$ Spin dependent cross section (i.e. different for protons and neutrons)

$$\sigma_{SI} = \frac{4}{\pi}\mu_A^2 \cdot [Z \cdot f_p + (A-Z) \cdot f_n]^2$$

$\Rightarrow$ 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…]

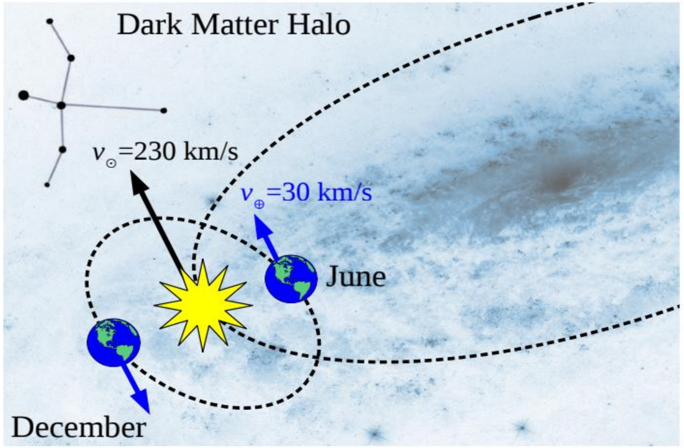
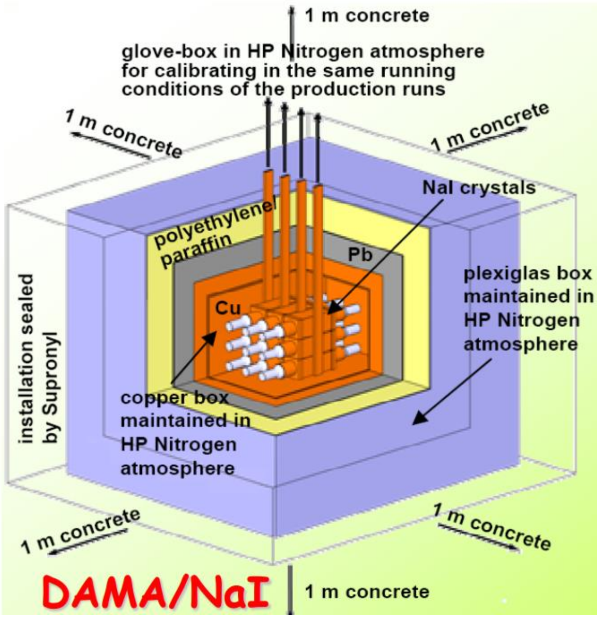
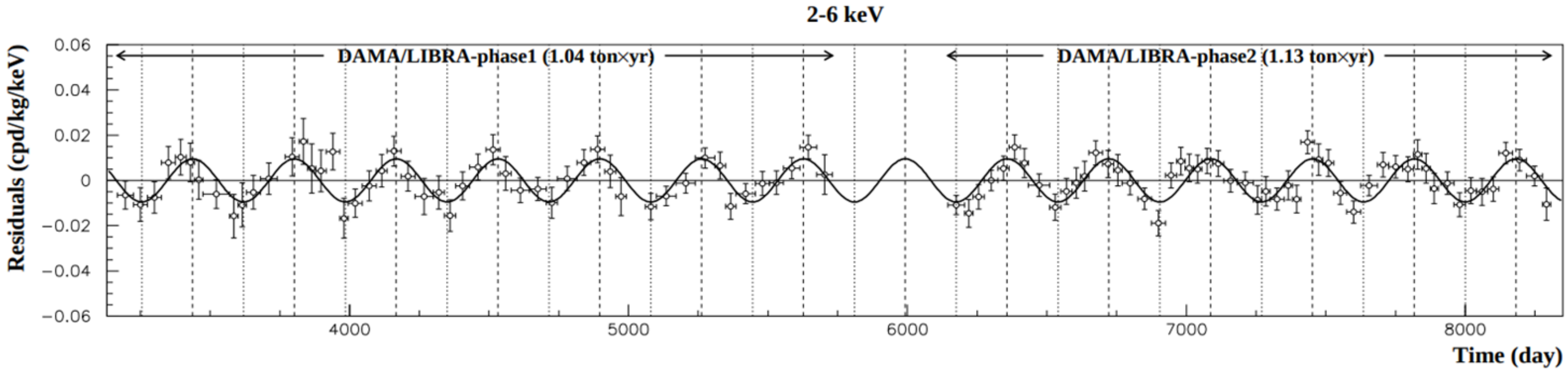


Figure 4. Illustration of the Sun-Earth system moving around the galactic center and through the dark matter halo in the direction of the constellation Cygnus. The varying vector addition of the velocities over the course of a year is expected to induce a modulating dark matter signature.

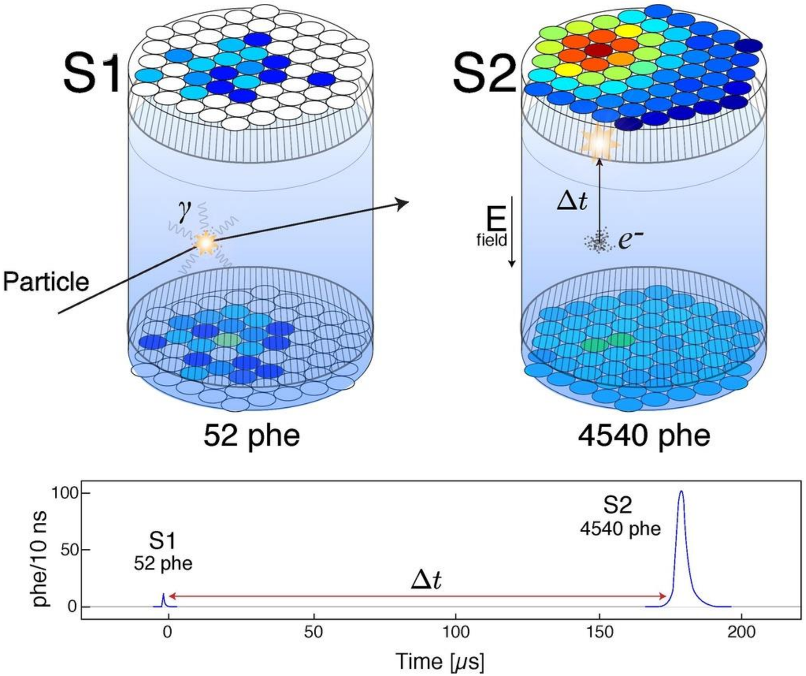


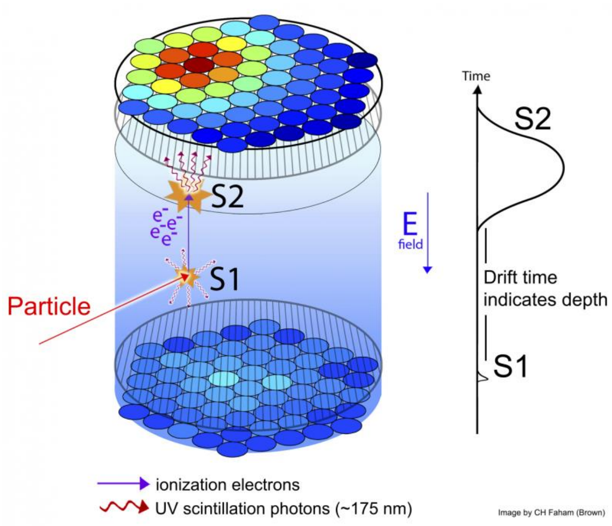


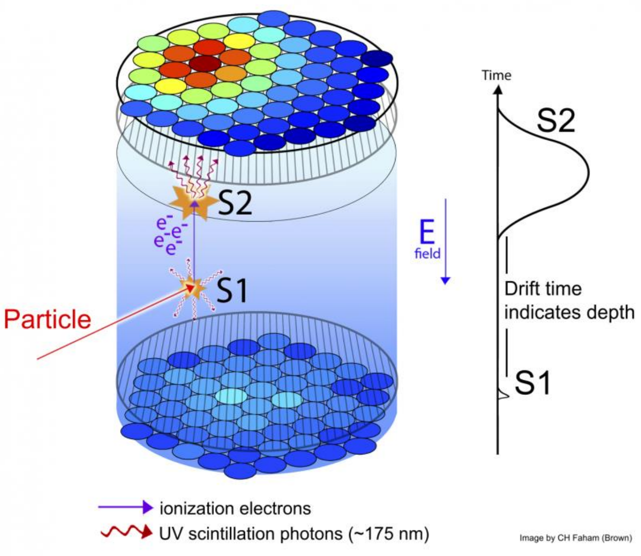
The data of the new DAMA/LIBRA–phase2 confirm a peculiar annual modulation in the (1–6) keV energy region:
1) the single-hit events show a clear cosine-like modulation
2) the measured period is equal to (0.999± 0.001) yr well compatible with the 1 yr period as expected for the DM signal
3) the measured phase (145 ± 5) days is compatible with the roughly ≃ 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/NaI and DAMA/LIBRA–phase1, is: (0.0103 ± 0.0008) cpd/kg/keV (12.9 σ 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

LUX


S1
S2
γ
Particle
E
field
Δt
e⁻
52 phe
4540 phe
100
50
0
phe/10 ns
S1
52 phe
S2
4540 phe
Δt
0
50
100
150
200
Time [μs]


Time
S2
S2
e⁻e⁻e⁻e⁻
S1
Particle
E
field
Drift time
indicates depth
S1
ionization electrons
UV scintillation photons (~175 nm)
Image by CH Faham (Brown)



[For Xenon1T: the electrons are drifted by an electric field to the liquid-gas interface with a speed of about 2 mm/μs.]

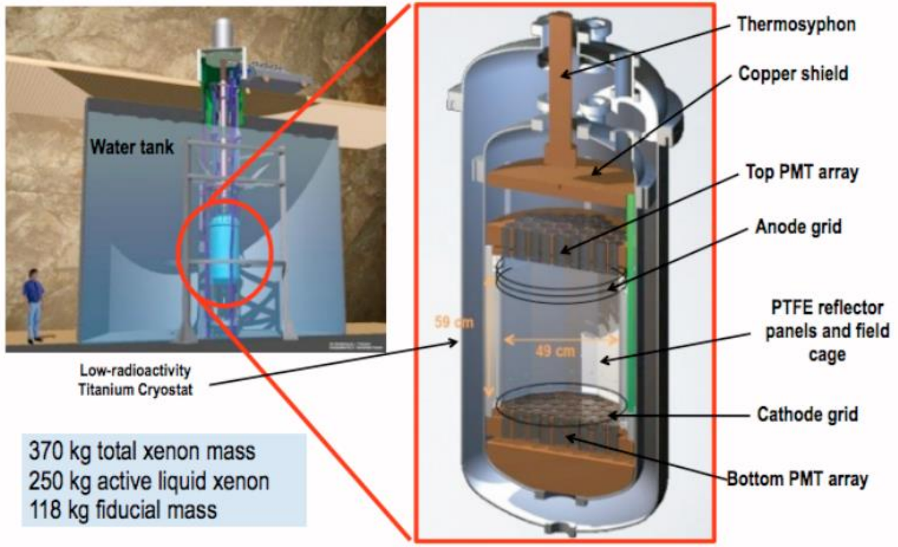
LUX is a dual-phase liquid/gas xenon Time Projection Chamber (TPC)
When a WIMP (or other particle) interacts with one of the xenon atoms in the liquid portion of the detector, it causes the xenon nucleus to recoil (**S1** signal).

The recoil leads to a burst of scintillation light and to the ionization of the surrounding xenon atoms, leading to the liberation of “ionization electronsThey 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.



Water tank
Low-radioactivity Titanium Cryostat
370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass
59 cm
49 cm
Thermosyphon
Copper shield
Top PMT array
Anode grid
PTFE reflector panels and field cage
Cathode grid
Bottom PMT array

XENON1T

- 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

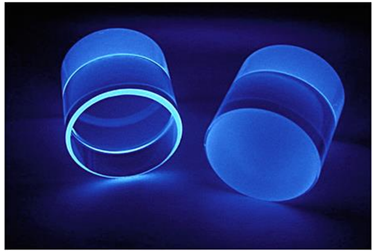
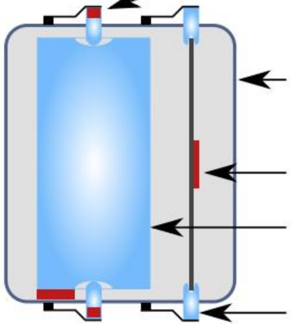
“In April 2019, based on measurements performed with the XENON1T detector, the XENON Collaboration reported in Nature the first direct observation of two-neutrino double electron capture in xenon-124 nuclei,

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 (**C**ryogenic **R**are **E**vent **S**earch with **S**uperconducting **T**hermometers)



- 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

- 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

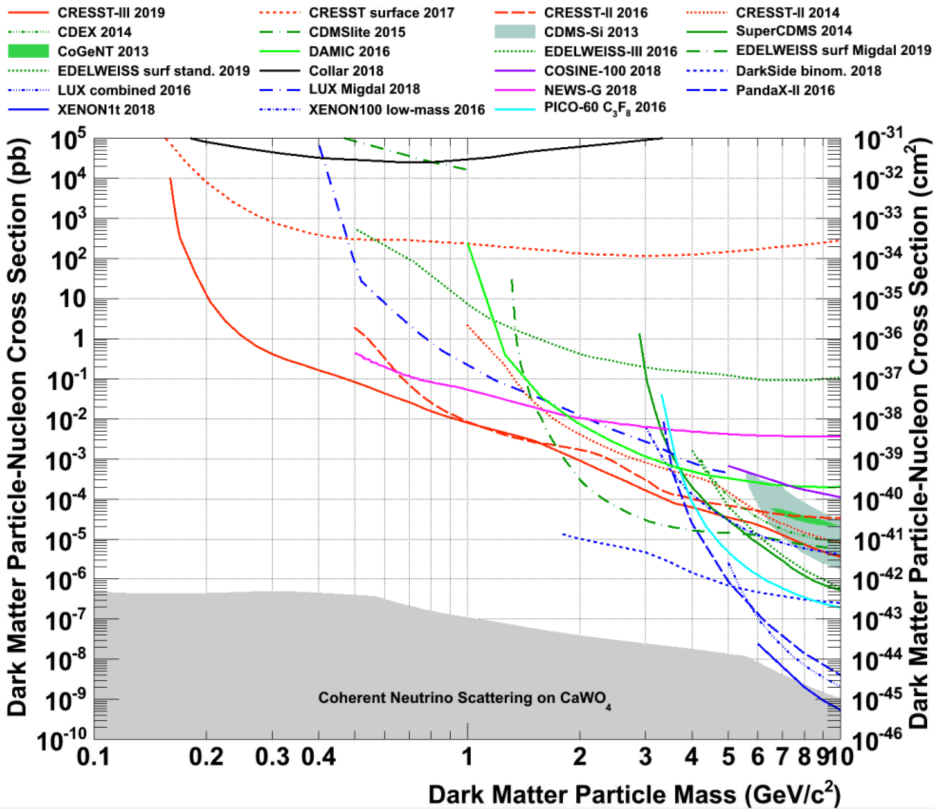
- Remaining muons are tagged by an active muon veto with 98.7% geometrical coverage

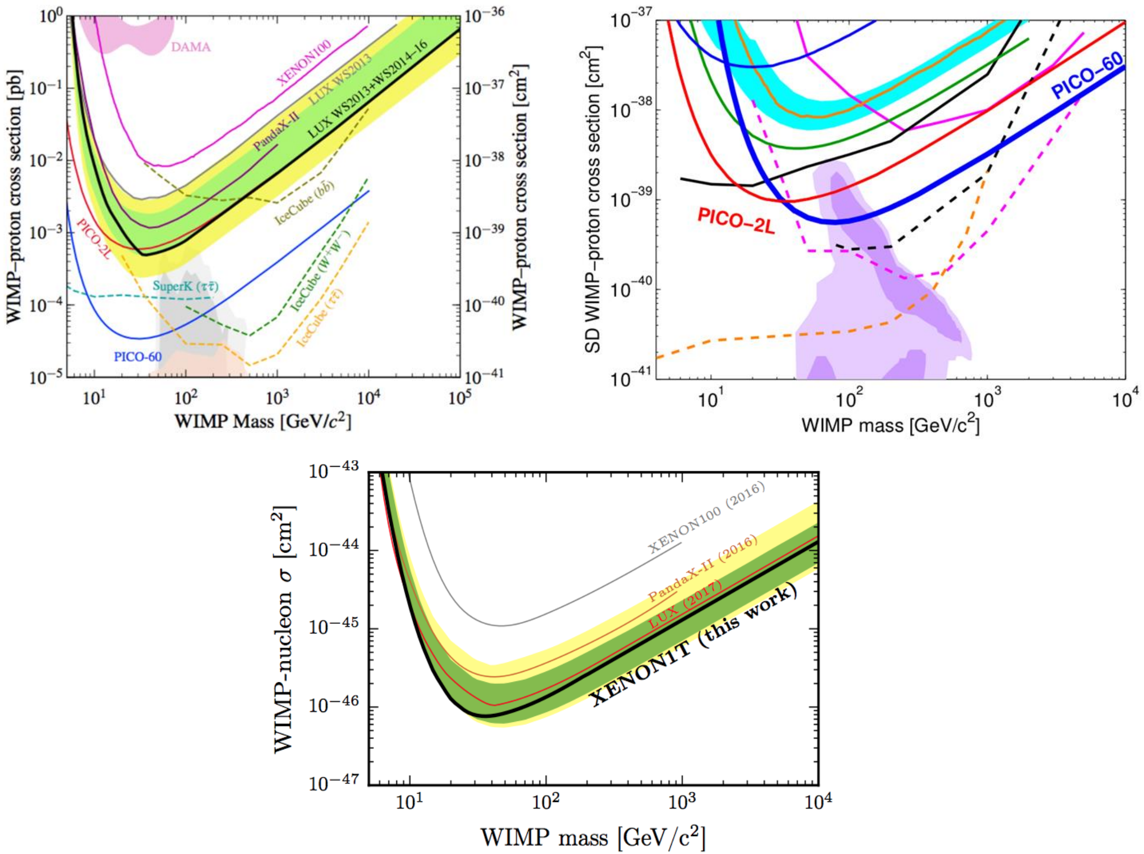
- In addition, the experimental volume is protected by concentric layers of shielding material comprising - from outside to inside - polyethylene, lead and copper.

- The polyethylene shields from environmental neutrons, while lead and copper suppress γ-rays.

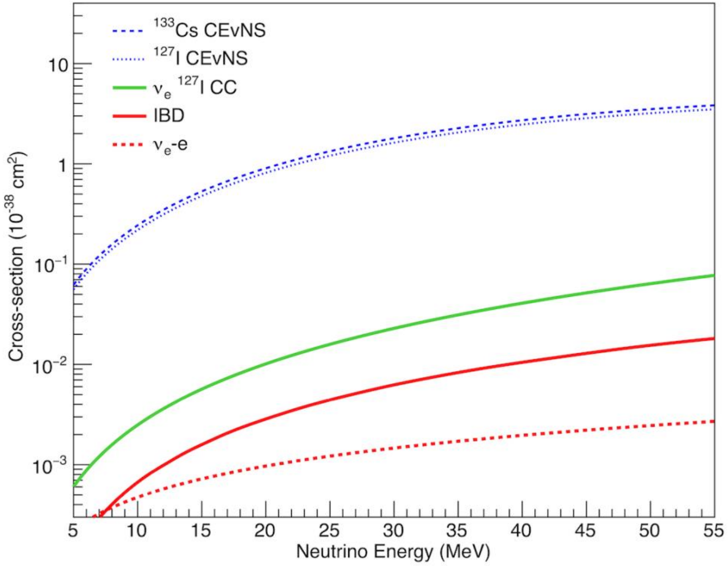
- A second layer of polyethylene inside the copper shielding guards against neutrons produced in the lead or the copper shields. A commercial 3He/4He-dilution refrigerator provides the base temperature of about 5 mK. Cryogenic liquids (LN2 and LHe) are refilled three times a week causing a down-time of about 3 h per refill.

https://youtube/uz177q5l82Q


CRESST-III 2019
CRESST surface 2017
CRESST-II 2016
CRESST-II 2014
CDEX 2014
CDMSlite 2015
CDMS-Si 2013
SuperCDMS 2014
CoGeNT 2013
DAMIC 2016
EDELWEISS-III 2016
EDELWEISS surf Migdal 2019
EDELWEISS surf stand. 2019
Collar 2018
COSINE-100 2018
DarkSide binom. 2018
LUX combined 2016
LUX Migdal 2018
NEWS-G 2018
PandaX-II 2016
XENON1t 2018
XENON100 low-mass 2016
PICO-60 C3F8 2016
Dark Matter Particle-Nucleon Cross Section (pb)
Dark Matter Particle-Nucleon Cross Section (cm2)
Coherent Neutrino Scattering on CaWO4
Dark Matter Particle Mass (GeV/c2)


DAMA
XENON100
LUX WS2013
LUX WS2013+WS2014-16
PandaX-II
IceCube ($b\bar{b}$)
PICO-2L
SuperK ($\tau\bar{\tau}$)
IceCube (W^+W^-)
IceCube ($\tau\bar{\tau}$)
PICO-60
WIMP-proton cross section [pb]
WIMP-proton cross section [cm^2]
WIMP Mass [GeV/c^2]
PICO-60
PICO-2L
SD WIMP-proton cross section [cm^2]
WIMP mass [GeV/c^2]
XENON100 (2016)
PandaX-II (2016)
LUX (2017)
XENON1T (this work)
WIMP-nucleon σ [cm^2]
WIMP mass [GeV/c^2]

- 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.



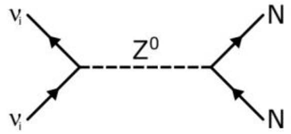
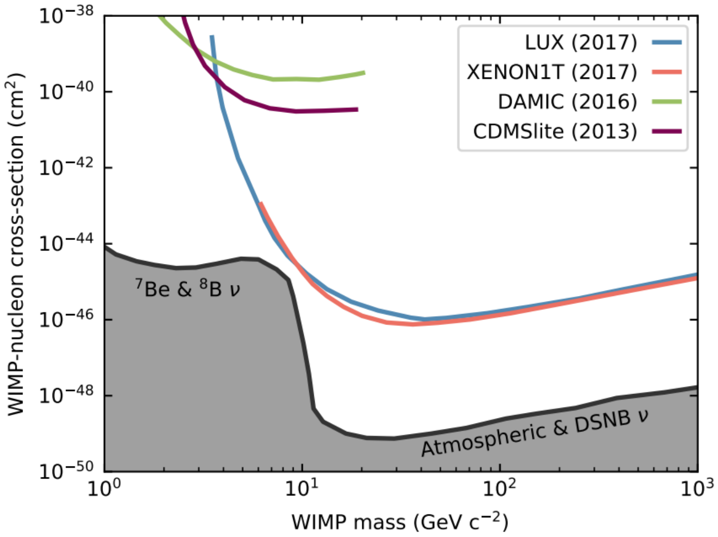


Figure 2.1: Feynman diagram for CEνNS. Here ν_i describes both neutrinos and anti-neutrinos of any flavor and N denotes any nucleus.

… Essentially the same happens in the case of WIMPS !

Figure 1.1: Total cross-section for CEνNS (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 CEνNS provides the largest cross-section, dominating over any charged-current interaction for incoming neutrino energies of less than 55 MeV. Plot adapted from [5].

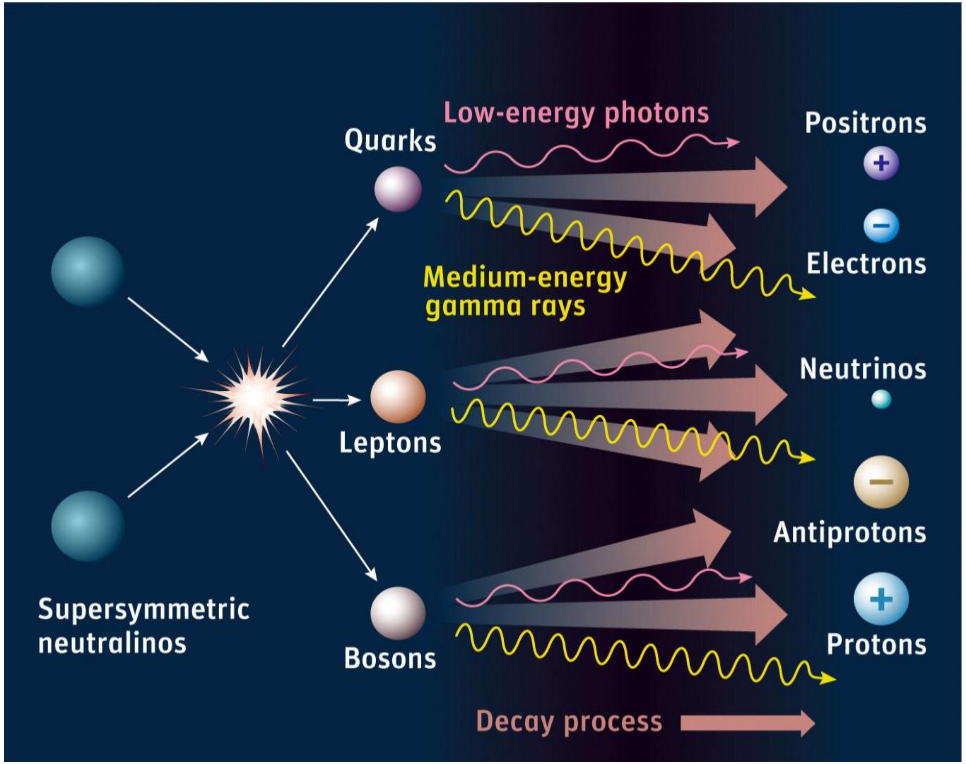
https://arxiv.org/pdf/1904.01155.pdf



- 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 N2
- 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 A2 instead

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

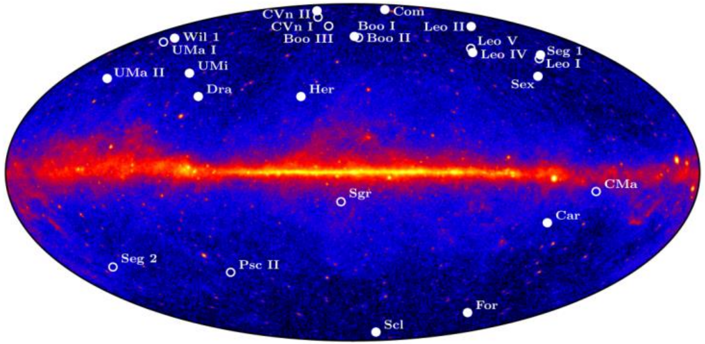
- Dark matter searches will run into an irreducible CEvNS background (“neutrino floor”)
- This background is induced by neutrinos from astrophysical sources, such as the sun, or the diffuse supernova neutrino background (DSNB)
- Since the sole detectable signal for both CEvNS and WIMP scattering is a 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
- **Dwarph Spheroidal Galaxies**

(very large mass-to-light ratio or J-factor)

Dwarf Spheroidal Galaxies (Milky Way Satellites)



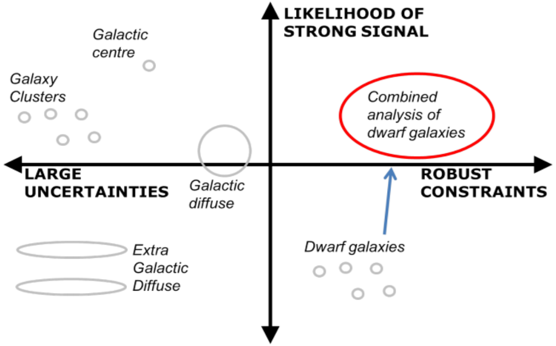
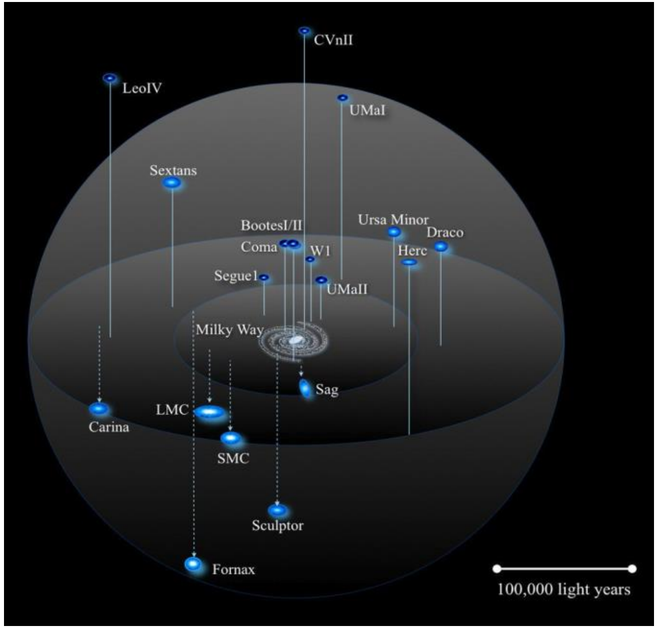


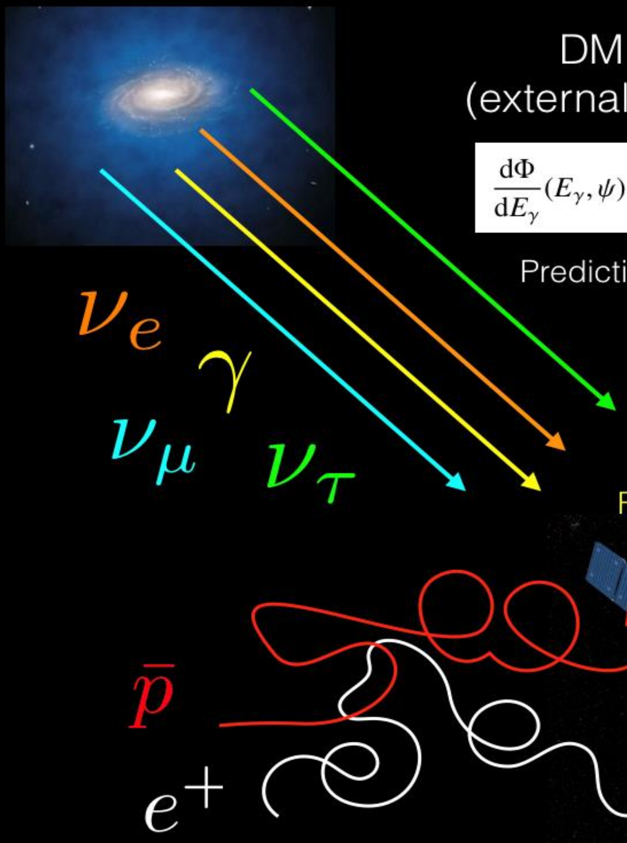
Figure 1: An attempt to visualize the usefulness of different targets for gamma-ray (and neutrino) detection of WIMPs. A plane is defined of likelihood of strong signal versus robustness of constraints. Circles illustrate region of interest for analyses.

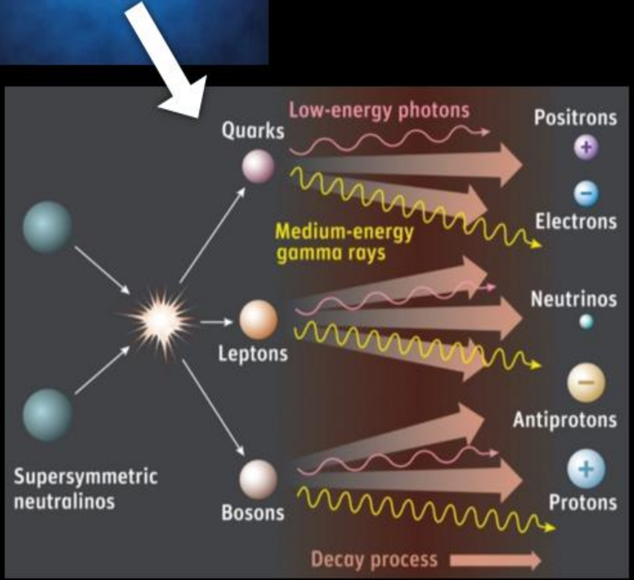


DM annihilation in the halos
(external galaxies or in the Milky way)

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

Prediction for the differential flux of cosmic rays at the point of detection





$\chi\,\chi$ —> SM SM —> Cosmic Rays

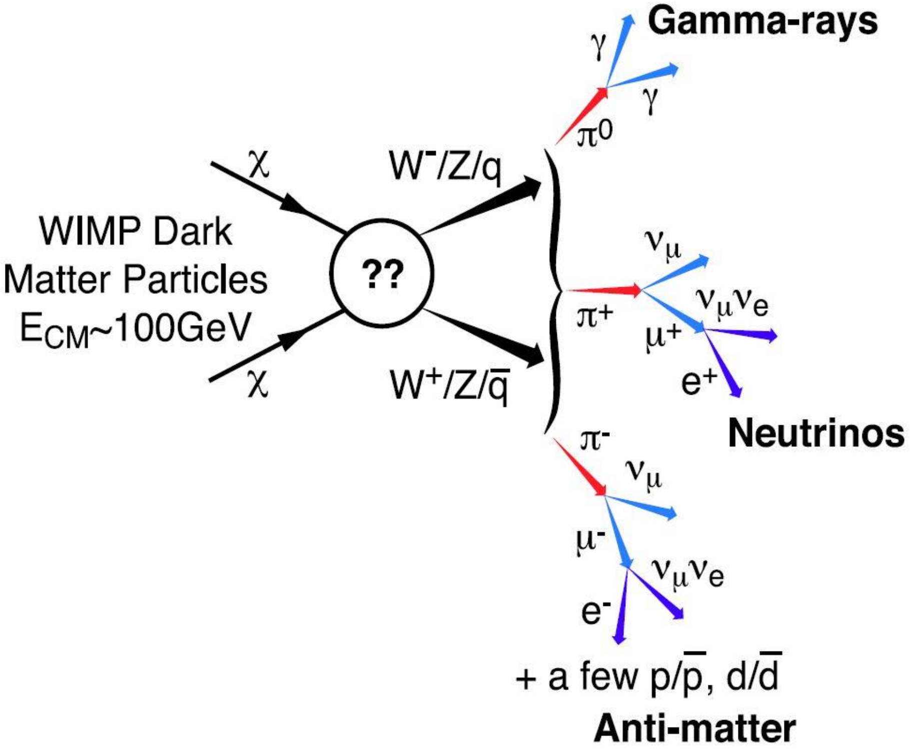
- DM annihilates inside galactic halos
- Typically 2-to-2 processes are considered i.e. $\chi\,\chi$ —> SM SM (called Simplified Models)
- From SM to Cosmic Rays (CR):

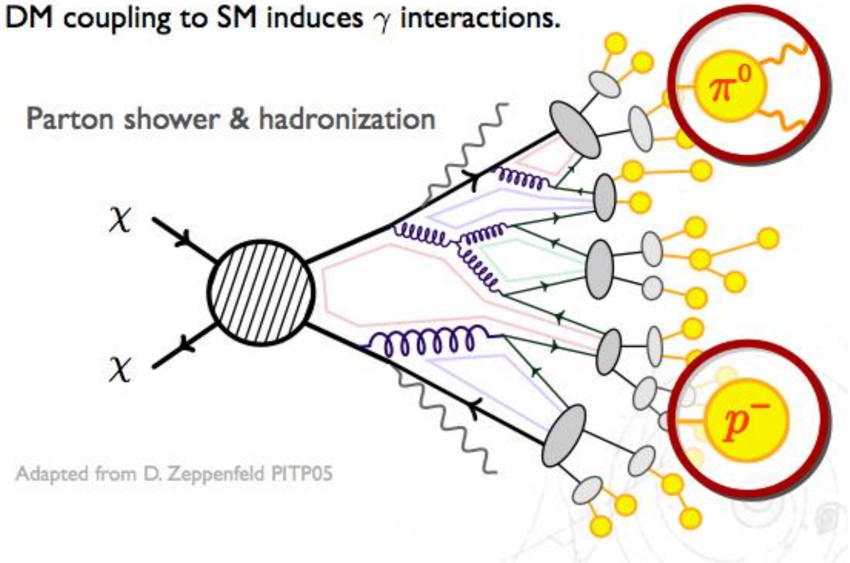
$$\gamma, \nu_e, \nu_\mu, \nu_\tau, e^+, \bar{p}$$

What is typically detected and analyzed

- CRs are detected at Earth (orbit) e.g. Ice-cube, AMS, **Fermi-LAT**, …
- Key observable: CRs **Differential energy spectrum**

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


Gamma-rays
γ
γ
π0
χ
W-/Z/q
WIMP Dark
Matter Particles
ECM~100GeV
??
χ
W+/Z/q̄
νμ
π+
νμνe
μ+
e+
Neutrinos
π-
νμ
μ-
νμνe
e-
+ a few p/p̄, d/d̄
Anti-matter


DM coupling to SM induces γ interactions.
Parton shower & hadronization
χ
χ
π0
p−
Adapted from D. Zeppenfeld PITP05

[particles/(GeV sr cm^2 s]

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

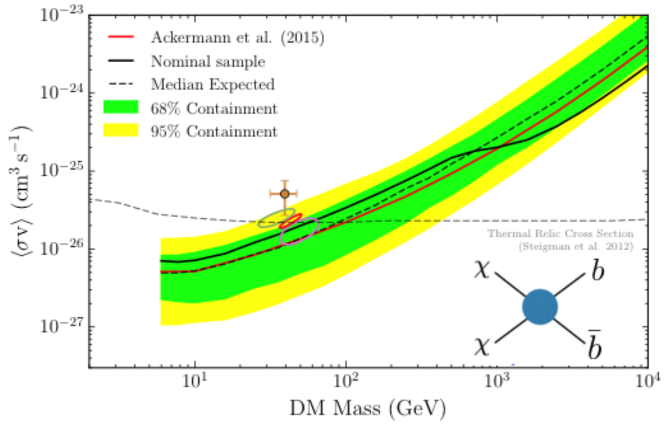
$$\chi\chi \rightarrow gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$$
$$\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$$

Velocity averaged annihilation cross section

Energy spectra (summing over all the 'i' simplified channels)

J-factor from astrophysical observation

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

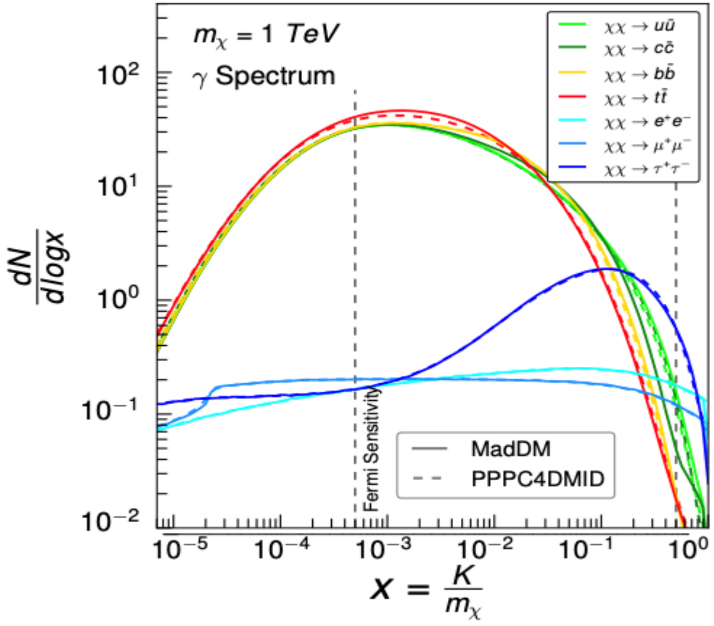


- Limits on the annihilation cross section from gamma rays fluxes
- Fermi-LAT results available only for the $\chi\chi$—>bb and $\chi\chi$—>$\tau\tau$ channels
  Simplified Models for DM annihilation
- Experimental data & recipes to calculate upper limits for arbitrary channels provided by Fermi-LAT

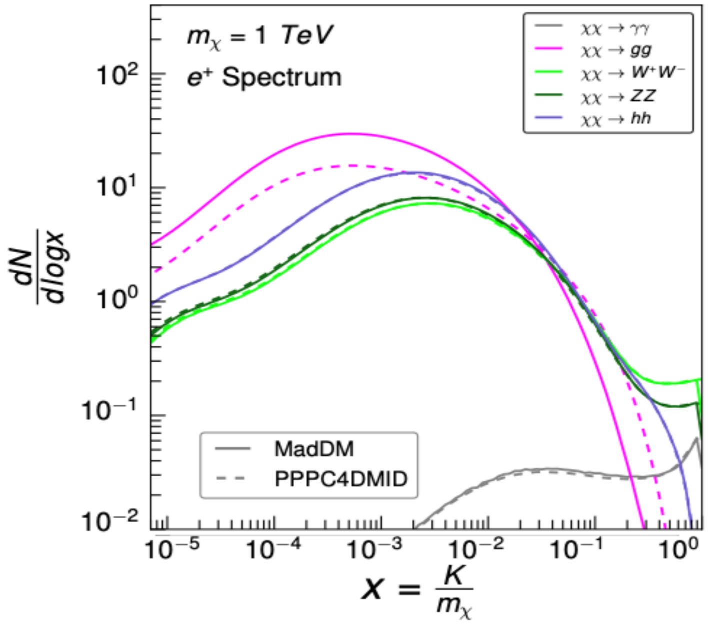
$$\chi\chi \rightarrow gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^- \\ \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$$

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

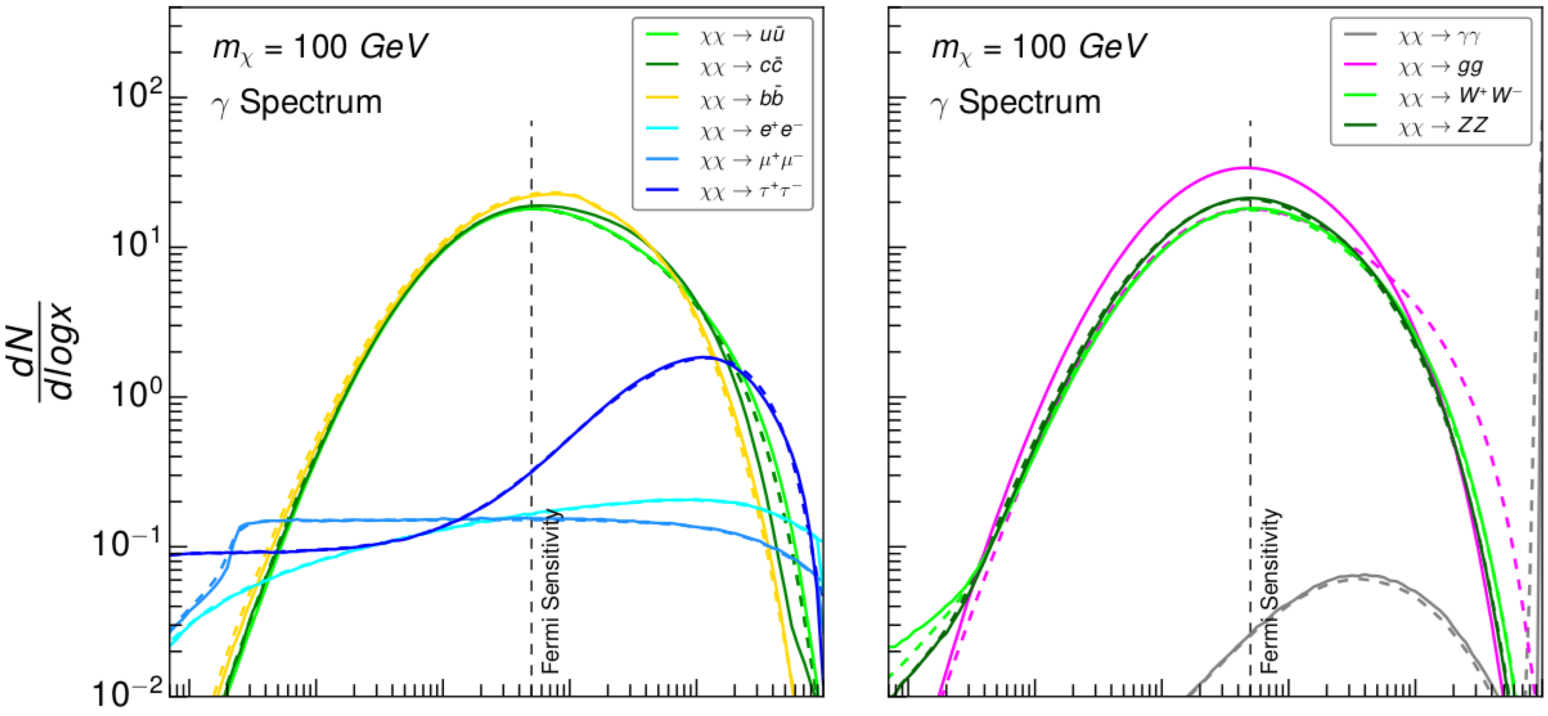
Gamma Rays spectra for Fermions

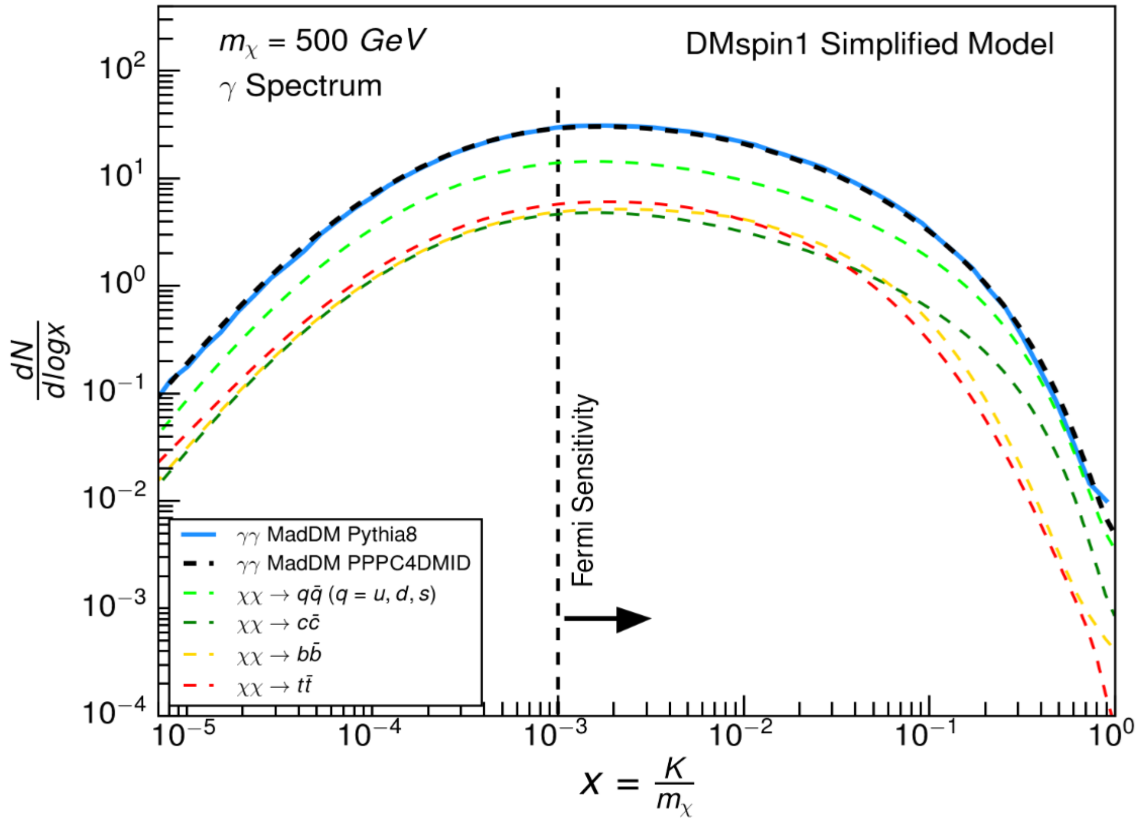


Positrons spectra for Bosons



Fermi-LAT sensitive to γ in the energy range ~ [0.5 - 500 GeV]


m_χ = 100 GeV
γ Spectrum
$\chi\chi \to u\bar{u}$
$\chi\chi \to c\bar{c}$
$\chi\chi \to b\bar{b}$
$\chi\chi \to e^+e^-$
$\chi\chi \to \mu^+\mu^-$
$\chi\chi \to \tau^+\tau^-$
$\frac{dN}{dlogx}$
10^2
10^1
10^0
10^{-1}
10^{-2}
Fermi Sensitivity
m_χ = 100 GeV
γ Spectrum
$\chi\chi \to \gamma\gamma$
$\chi\chi \to gg$
$\chi\chi \to W^+W^-$
$\chi\chi \to ZZ$
Fermi Sensitivity

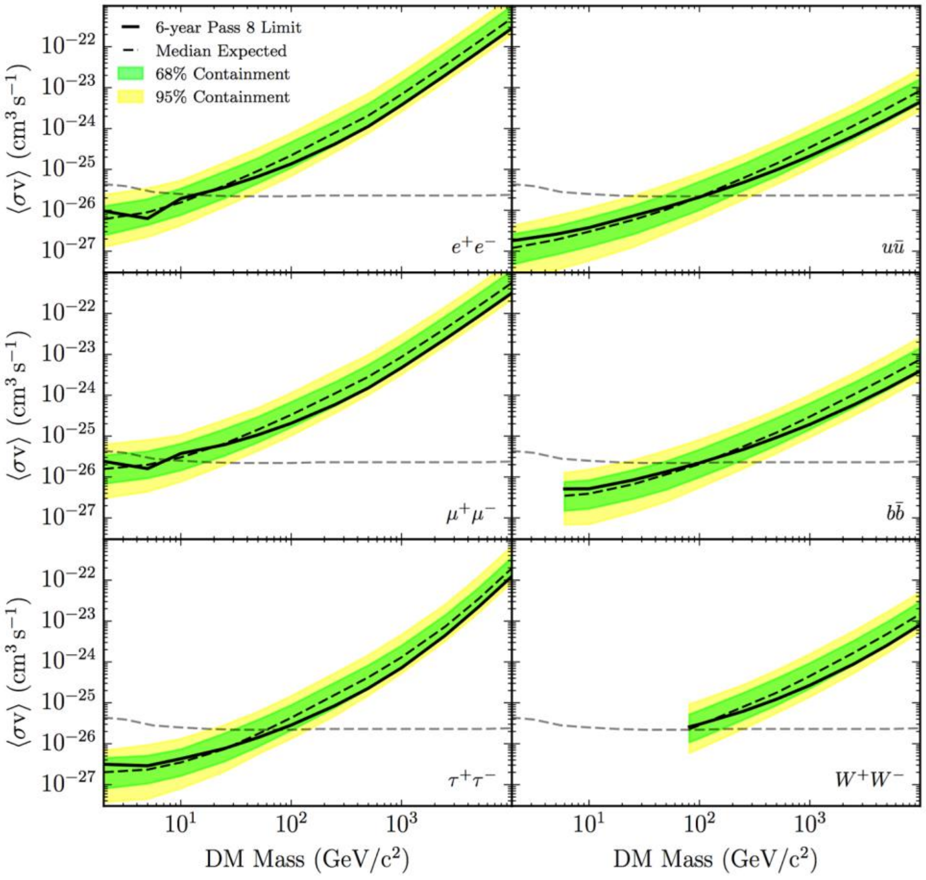


Spectra are assumed to be largely independent of the specific (simplified model) chosen

TABLE I. Properties of Milky Way dSphs.

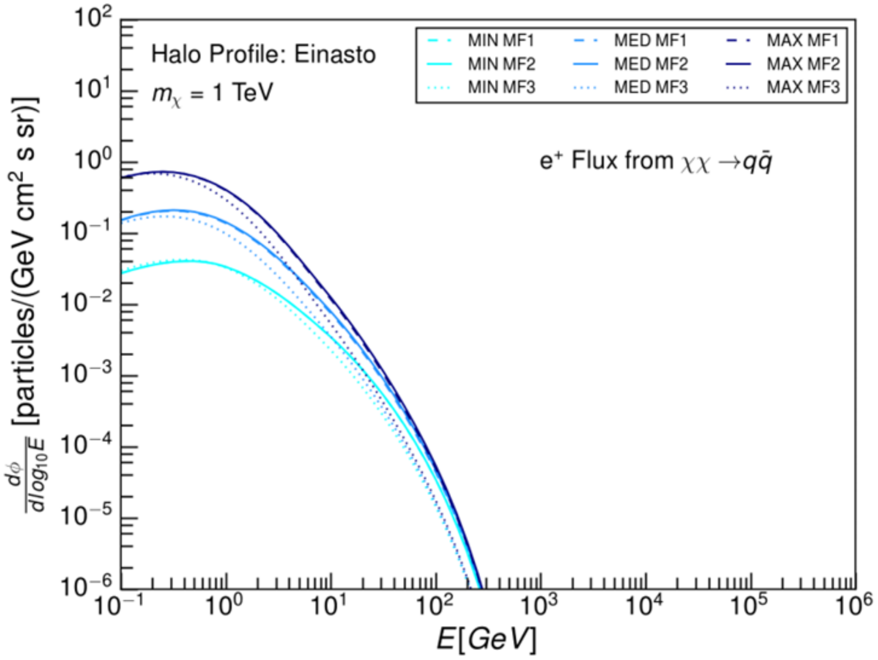
Name	ℓ^a (deg)	b^a (deg)	Distance (kpc)	$\log_{10}(J_{obs})^b$ ($\log_{10}[\mathrm{GeV}^2\,\mathrm{cm}^{-5}]$)	Ref.
Bootes I	358.1	69.6	66	18.8 ± 0.22	[41]
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25	[42]
Carina	260.1	−22.2	105	18.1 ± 0.23	[43]
Coma Berenices	241.9	83.6	44	19.0 ± 0.25	[42]
Draco	86.4	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]

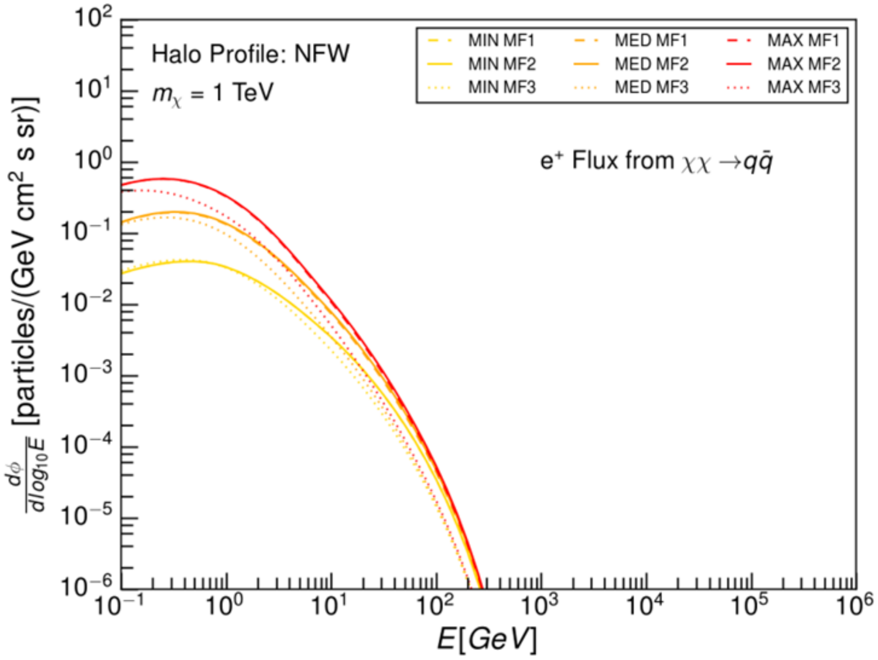
[a] Galactic longitude and latitude.
[b] J-factors are calculated assuming an NFW density profile and integrated over a circular region with a solid angle of $\Delta\Omega \sim 2.4 \times 10^{-4}$ sr (angular radius of 0.5°).
[c] dSphs below the horizontal line are not included in the combined analysis.



Charged CR Propagation Effects

- 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





How to Put Everything *(as much as we can)* Together

- 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

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```
***** 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: xxdxxdb_ccx        Thermal = 2.05e-39     ALLOWED      All DM = 7.89e-38     ALLOWED      Fermi ul         = 4.54e-26
INFO: xxdxxdb_ddx        Thermal = 3.22e-44     ALLOWED      All DM = 1.24e-42     ALLOWED      Fermi ul         = 4.67e-26
INFO: xxdxxdb_uux        Thermal = 8.26e-45     ALLOWED      All DM = 3.18e-43     ALLOWED      Fermi ul         = 4.67e-26
INFO: xxdxxdb_bbx        Thermal = 2.80e-38     ALLOWED      All DM = 1.08e-36     ALLOWED      Fermi ul         = 5.00e-26
INFO: xxdxxdb_ssx        Thermal = 1.30e-41     ALLOWED      All DM = 4.99e-40     ALLOWED      Fermi ul         = 4.67e-26
INFO: xxdxxdb_ttx        Thermal = 4.94e-36     ALLOWED      All DM = 1.90e-34     ALLOWED      Fermi ul         = 6.08e-26
INFO: xxdxxdb_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: xxcxxcb, xxrxxr
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
```

http://pdg.lbl.gov/2019/reviews/rpp2018-rev-astrophysical-constants.pdf

Solar angular velocity around the Galactic center	Θ_0/R_0	30.3 ± 0.9 km s^{-1} kpc^{-1}	[17]
Solar distance from Galactic center	R_0	8.4(6) kpc	[17,18]
circular velocity at R_0	v_0 or Θ_0	254(16) km s^{-1}	[17]
local disk density	ρ_{disk}	3–12 $\times 10^{-24}$ g cm^{-3} $\approx$ 2–7 GeV/c^2 cm^{-3}	[19]
local dark matter density	ρ_χ	canonical value 0.3 GeV/c^2 cm^{-3} within factor 2–3	[20]
escape velocity from Galaxy	v_{esc}	498 km/s $< v_{\text{esc}} <$ 608 km/s	[21]
present day CMB temperature	T_0	2.7255(6) K	[22,23]
present day CMB dipole amplitude		3.355(8) mK	[22,24]
Solar velocity with respect to CMB		369(1) 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) km/s towards $(\ell, b) = (276(3)^\circ, 30(3)^\circ)$	[22,24]
entropy density/Boltzmann constant	s/k	$2\,891.2\ (T/2.7255)^3$ cm^{-3}	[25]
number density of CMB photons	n_γ	$410.7(T/2.7255)^3$ cm^{-3}	[25]
baryon-to-photon ratio	$\eta = n_{\text{b}}/n_\gamma$	$6.05(7) \times 10^{-10}$ (CMB)	[26]
		$5.7 \times 10^{-10} \leq \eta \leq 6.7 \times 10^{-10}$ (95% CL)	[26]
present day Hubble expansion rate	H_0	100 h km s^{-1} Mpc^{-1} = $h \times (9.777\,752$ Gyr$)^{-1}$	[29]
scale factor for Hubble expansion rate	h	0.673(12)	[2,3]
Hubble length	c/H_0	$0.925\,0629 \times 10^{26}\ h^{-1}$ m $= 1.37(2) \times 10^{26}$ m	
scale factor for cosmological constant	$c^2/3H_0^2$	$2.85247 \times 10^{51}\ h^{-2}$ m^2 $= 6.3(2) \times 10^{51}$ m^2	
critical density of the Universe	$\rho_{\text{crit}} = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\ h^2\ M_\odot$Mpc^{-3}	
		$= 1.878\,47(23) \times 10^{-29}\ h^2$ g cm^{-3}	
		$= 1.053\,75(13) \times 10^{-5}\ h^2$ (GeV/c^2) cm^{-3}	
number density of baryons	n_{b}	$2.482(32) \times 10^{-7}$ cm^{-3}	[2,3,27,28]
		$(2.1 \times 10^{-7} < n_{\text{b}} < 2.7 \times 10^{-7})$ cm^{-3} (95% CL)	$\eta \times n_\gamma$
baryon density of the Universe	$\Omega_{\text{b}} = \rho_{\text{b}}/\rho_{\text{crit}}$	$^\ddagger 0.02207(27)\ h^{-2} = {}^\dagger 0.0499(22)$	[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	$^\ddagger 0.091^{+0.013}_{-0.014}$	[2,3]
scalar spectral index	n_{s}	$^\ddagger 0.958(7)$	[2,3]
ln pwr primordial curvature pert. (k_0=0.05 Mpc^{-1})	$\ln(10^{10}\Delta^2_{\mathcal{R}})$	$^\ddagger 3.090(25)$	[2,3]

Quantity	Symbol, equation	Value	Reference, footnote
dark energy density of the ΛCDM Universe	Ω_Λ	$0.685^{+0.017}_{-0.016}$	[2,3]
pressureless matter density of the Universe	$\Omega_{\rm m} = \Omega_{\rm cdm} + \Omega_{\rm b}$	$0.315^{+0.016}_{-0.017}$ (From Ω_Λ and flatness constraint)	[2,3]
dark energy equation of state parameter	w	♯ $-1.10^{+0.08}_{-0.07}$ (*Planck*+WMAP+BAO+SN)	[32]
CMB radiation density of the Universe	$\Omega_\gamma = \rho_\gamma/\rho_{\rm c}$	$2.473 \times 10^{-5} (T/2.7255)^4\, h^{-2} = 5.46(19) \times 10^{-5}$	[25]
effective number of neutrinos	$N_{\rm eff}$	† 3.36 ± 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	$\Omega_{\rm tot} = \Omega_{\rm m} + \ldots + \Omega_\Lambda$	♯ $0.96^{+0.4}_{-0.5}$ (95%CL)	[2]
		♯ 1.000(7) (95% CL; CMB+BAO)	[2]
fluctuation amplitude at $8\, h^{-1}$ Mpc scale	σ_8	† 0.828 ± 0.012	[2,3]
running spectral index slope, $k_0 = 0.002$ Mpc^{-1}	$dn_{\rm s}/d\ln k$	♯ $-0.015(9)$	[2]
tensor-to-scalar field perturbations ratio, k_0=0.002 Mpc^{-1}	$r = T/S$	♯ < 0.11 at 95% CL; no running	[2,3]
redshift at decoupling	$z_{\rm dec}$	† 1090.2 ± 0.7	[2]
age at decoupling	t_*	† 3.72×10^5 yr	
sound horizon at decoupling	$r_s(z_*)$	† 147.5 ± 0.6 Mpc (*Planck* CMB)	[32]
redshift of matter-radiation equality	$z_{\rm eq}$	† 3360 ± 70	[2]
redshift at half reionization	$z_{\rm reion}$	† 11.1 ± 1.1	[2]
age at half reionization	$t_{\rm reion}$	† 462 Myr	
age of the Universe	t_0	† 13.81 ± 0.05 Gyr	[2]