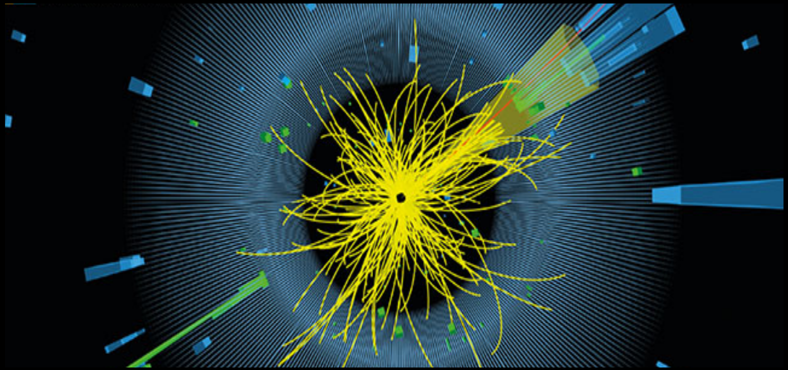
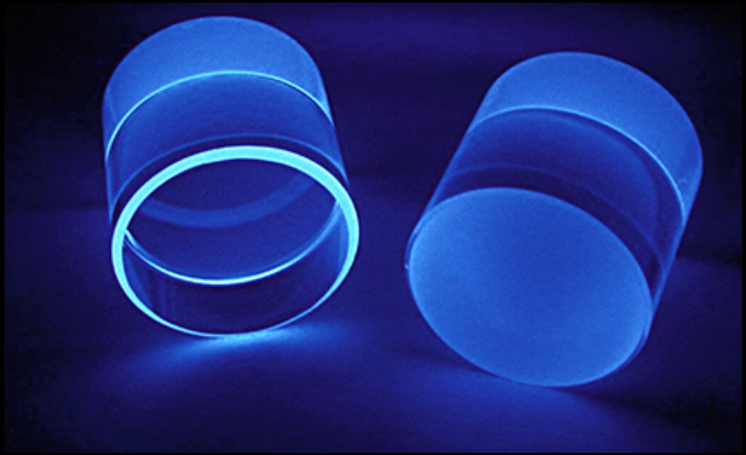


Searches for Dark Matter



Astro Particle Physics

WS 2020/2021 - 7th January 2021

Federico Ambrogi (dep. Meteorology, Univie)

Today, 7th January 2021:

- A brief recap about Dark Matter
- Primordial Nucleosynthesis

- Introduction to Experimental Searches
- What "is" Dark Matter?
- Searches at Colliders (LHC)
- Direct Searches
- Indirect Searches

Next Lecture: 14th January

Gravitational Waves

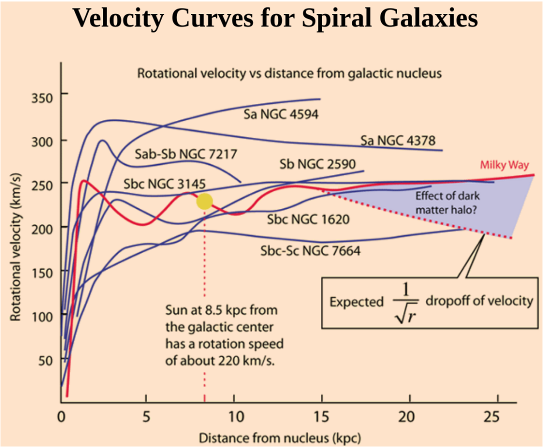
Recap from 1st lecture

- Why do we talk about dark matter i.e. what are the evidences for Dark Matter existence?
- What is the role of Dark Matter in the evolution of the Universe?
- …

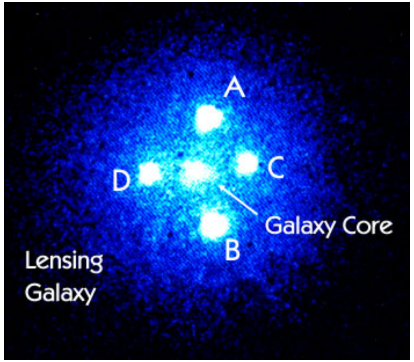
Recap

- Fritz Zwicky (**1933**) -> Anomaly in the velocities of galaxies inside the Coma cluster
  - *He used the viral theorem to estimate the velocities, and found that the observed velocities were almost 1 order of magnitude larger than the calculated values*
  - *"If this would be confirmed, we would get the surprising result that dark matter **(dunkle materie)** is present in much greater amount than luminous matter"*
  - *" [In order to derive the mass of galaxies from their luminosity] we must know how much dark matter is incorporated in nebulae in the form of cool and cold stars, macroscopic and microscopic solid bodies, and gases"*
  - *We introduced the concept of mass-to-light ratio*

- Vera Rubin (**1960s/1970s**) -> Anomaly in the velocities of Hydrogen gas in the edges of spiral galaxies
  - *Rotation curves fit perfectly within the solar system*
  - *Fails for spiral galaxies*
  - *Again, if an extra component in the form of non-visible matter is included, the discrepancy can be explained*

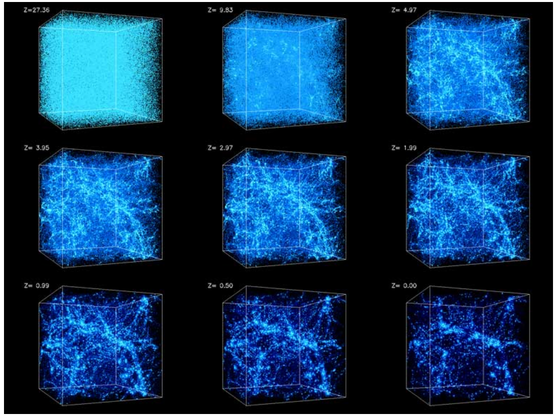


- Gravitational Lensing

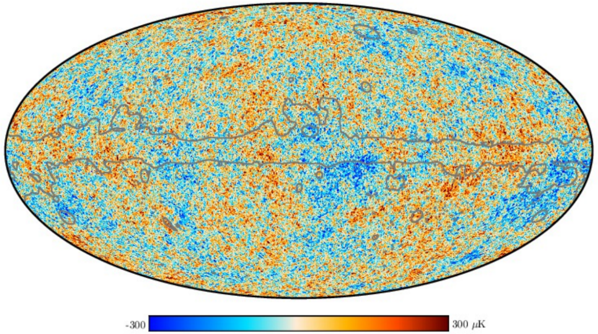


- Bullet Cluster

- Large Scale Structure



- Cosmic Microwave Background

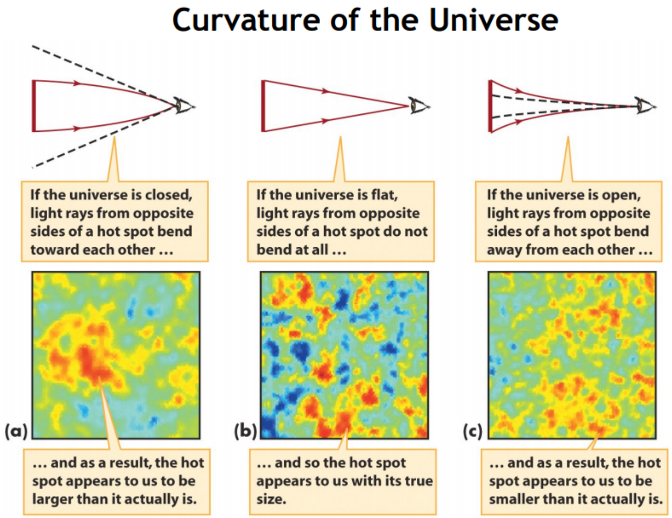


- Building Blocks of Cosmology

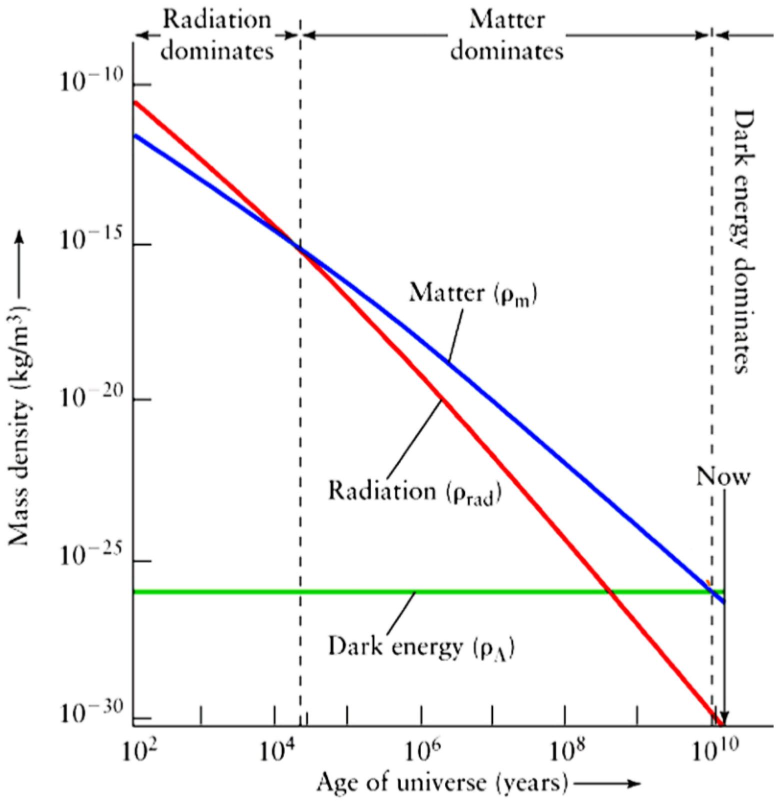
$$R_{ij} - \frac{1}{2}g_{ij}R - \Lambda g_{ij} = \frac{8\pi G}{c^4}T_{ij}$$ -> Einstein's field equation (General Relativity)

- "Cosmological Principle" (CP) : at sufficiently large scales, is homogeneous and isotropic
- Universe as a continuous, homogeneous and isotropic fluid
- Robertson-Friedman-Walker solution
- Three possible geometries of the universe: open, closed, flat
- Hubble's Law and redshift
- Cosmological Constant which acts as "Dark Energy"

$$H^2(z) = H_0^2\,(1+z)^2\left[1 - \sum_w \Omega_{0,w} + \sum_w \Omega_{0,w}\,(1+z)^{1+3w}\right]$$



Recap



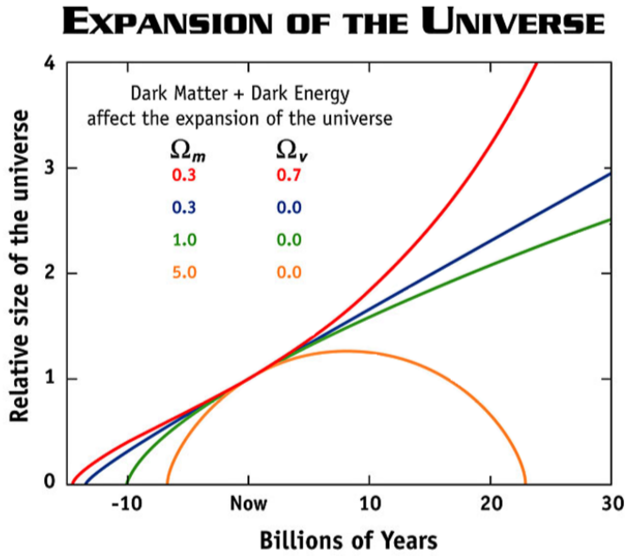
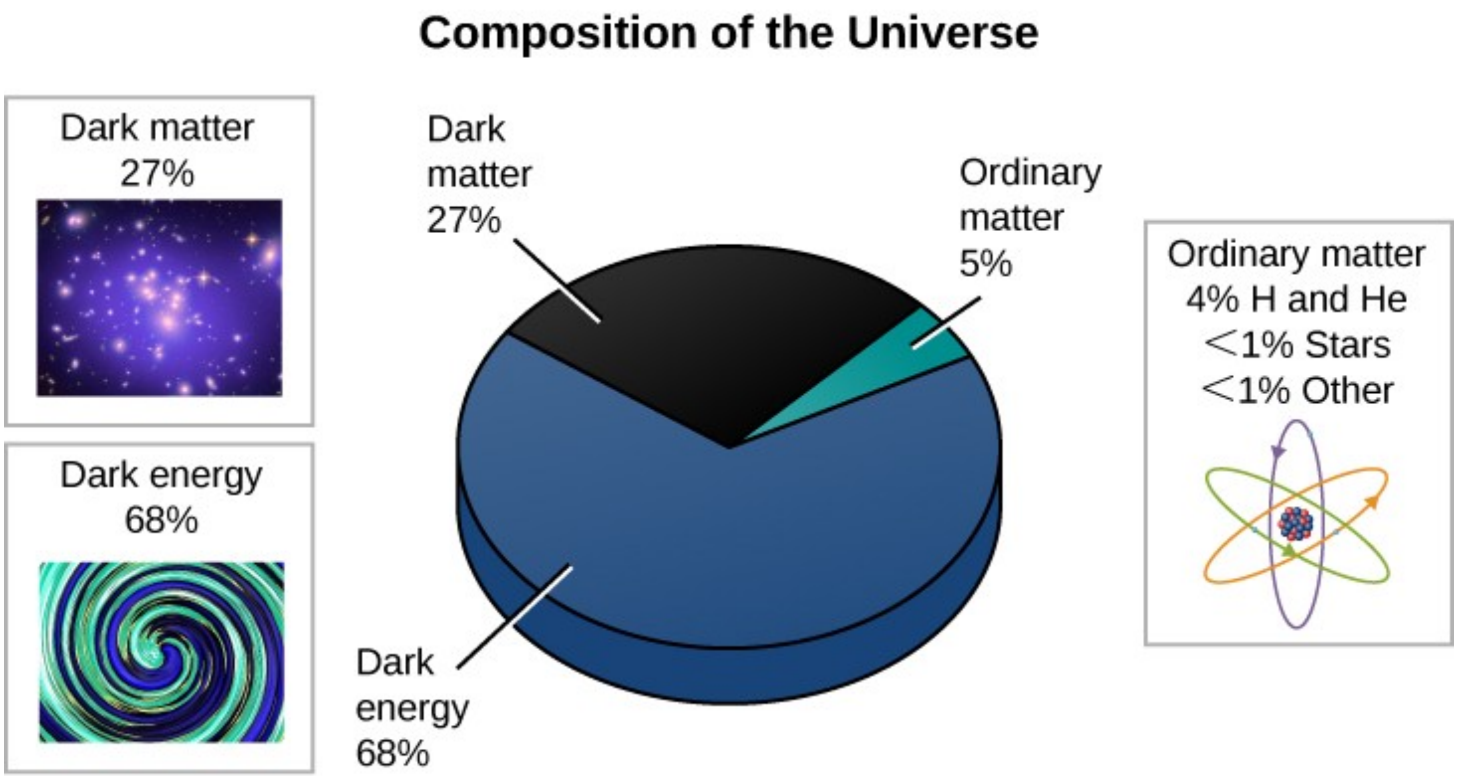
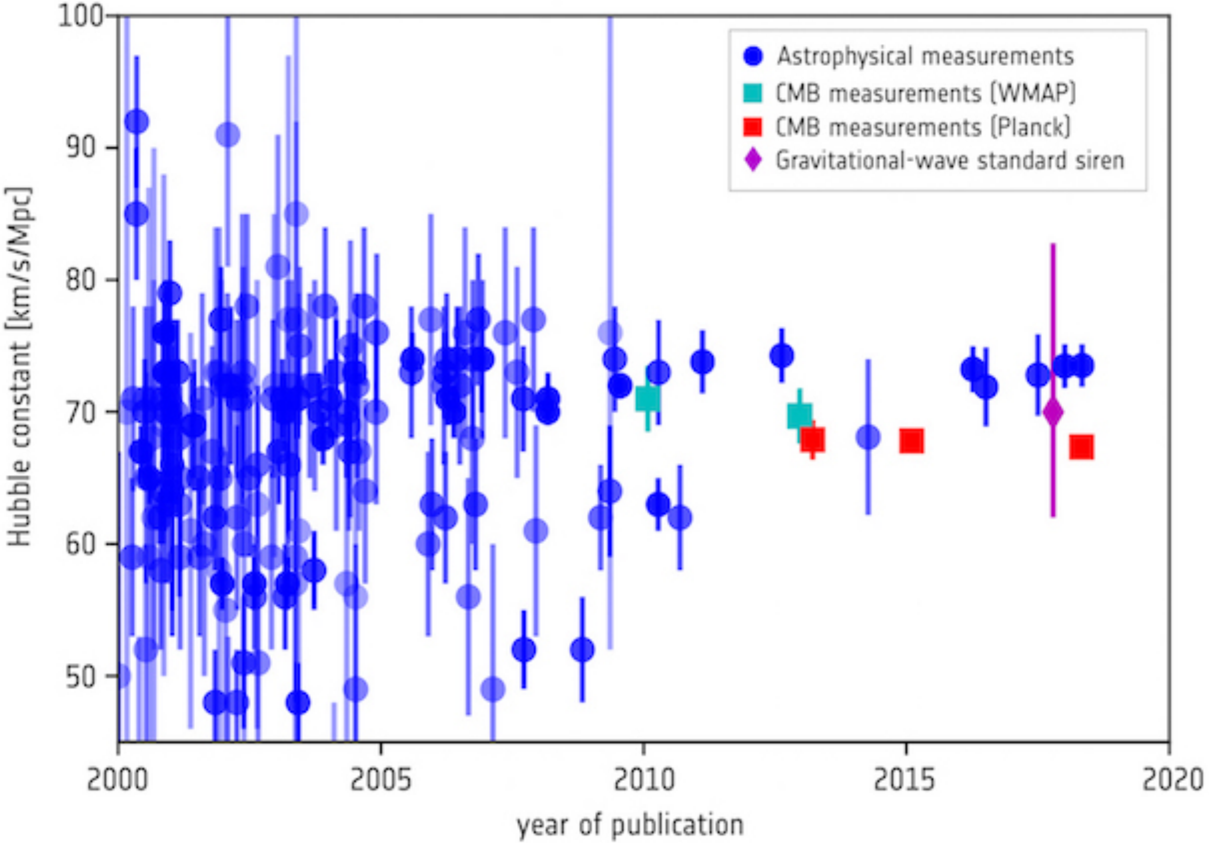
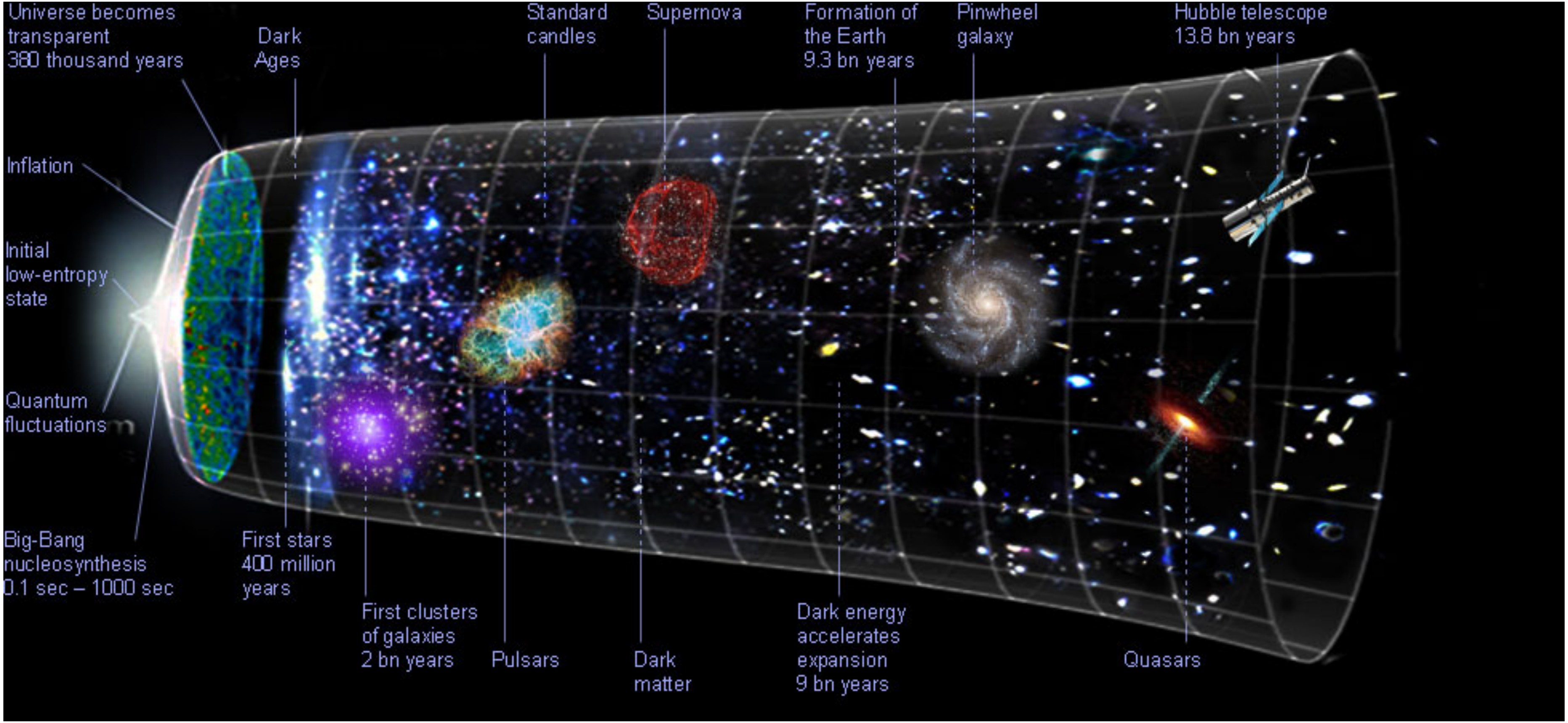


Figure 1.3: Time evolution of the scale parameter, or size of the universe, for different values of the matter and dark energy densities. Times run to the right of the x-axes or analogously, redshift increases to the left of x-axis. The point where the curves cross the time axis (on the left) is known as Big Bang; the time where the closed-model curve intersects the time axis (on the right) is known as Big Crunch. Different models have different ages of the universe, hence different times for the Big Bang. Picture taken from www.nasa.gov .


Composition of the Universe
Dark matter
27%
Dark energy
68%
Dark
matter
27%
Ordinary
matter
5%
Dark
energy
68%
Ordinary matter
4% H and He
<1% Stars
<1% Other


Astrophysical measurements
CMB measurements (WMAP)
CMB measurements (Planck)
Gravitational-wave standard siren
Hubble constant [km/s/Mpc]
100
90
80
70
60
50
2000
2005
2010
2015
2020
year of publication

The History of the Universe



Big-Bang or Primordial Nucleosynthesis

- Nuchleosynthesis is the fundamental process through which elemens were created right the Big-bang
- It explains the very homogeneous distribution of ~light elements (H, He, Li) found in the universe
- "Metals" in Astronomy : elements other than H and He
- The element which is typically tracked is Iron (Fe), since it is assumed that the relative abundance of the other elements (e.g. C, N, Ca…) is proportional
- Metallicity = [Fe/H] : how many Fe atoms are present per H atoms

$$\boxed{[Fe/H] = \log \frac{(Fe/H)}{(Fe/H)_{Sun}} = \log(Fe/H) - \log(Fe/H)_{Sun}}$$

Examples:
[Fe/H] = -1 ➔ 10% of solar metallicity
[Fe/H] = 0 ➔ solar metallicity

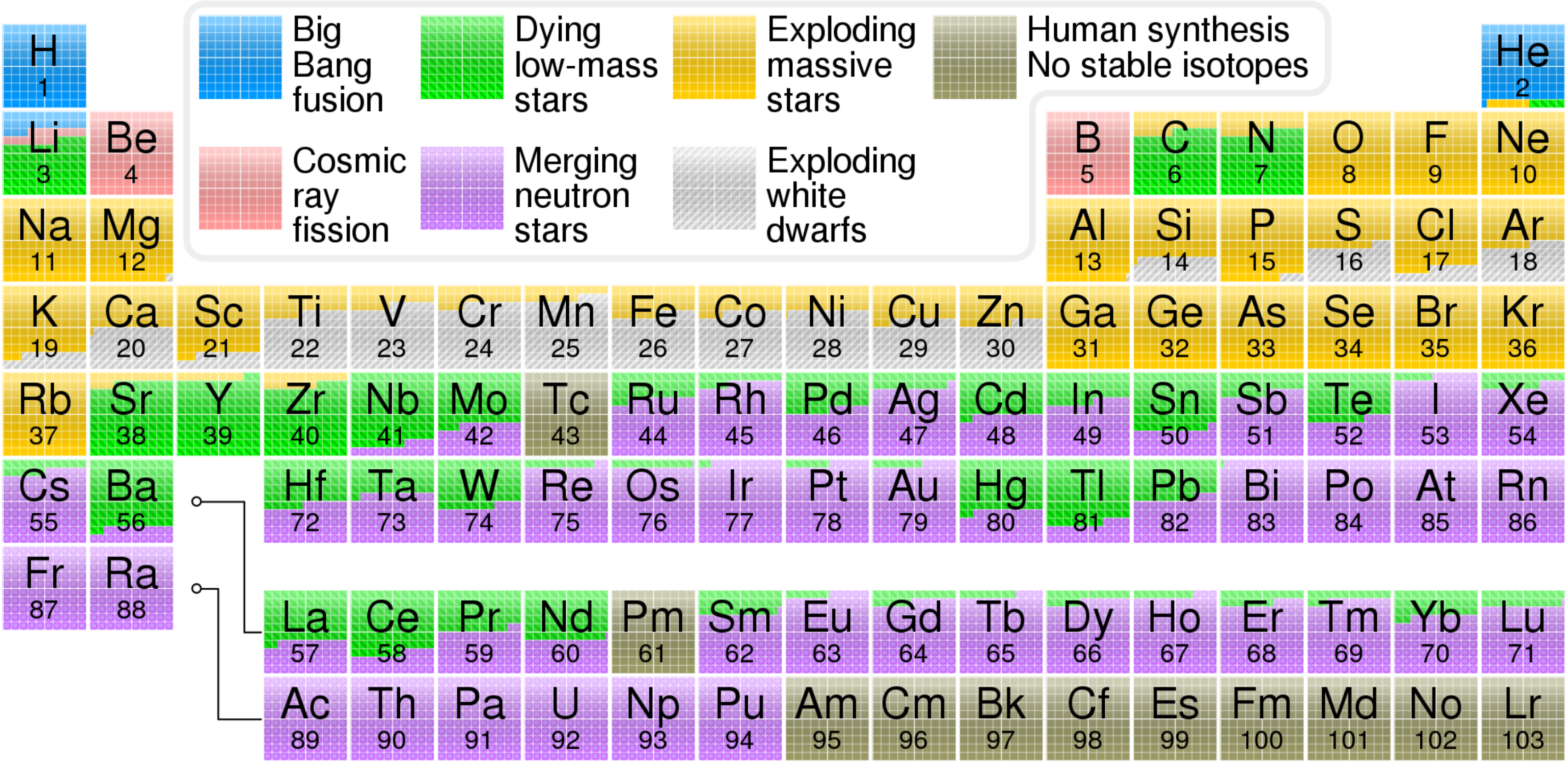
Range in our Galaxy: -5 < [Fe/H] < +1

Convenient to describe the chemical content of a star by **fractional mass** in different elements w.r.t. total mass:

X = H
Y = He
Z = all the rest

X+Y+Z = 1

$X_\odot \sim 0.7$
$Y_\odot \sim 0.28$ Solar values
$Z_\odot \sim 0.02$



see also “cosmic rays spallation"

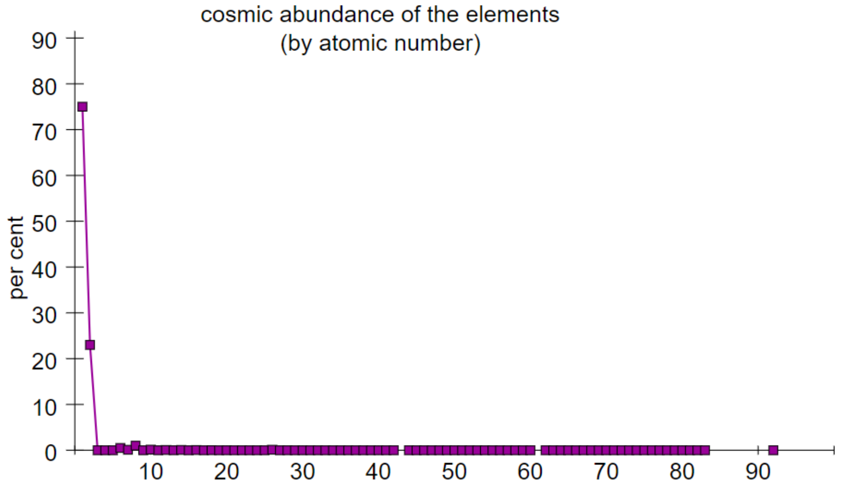
Big-Bang Nucleosynthesis

"By the first millisecond, the universe had cooled to a few trillion kelvins (10^{12} K) and quarks finally had the opportunity to bind together into free protons and neutrons. Free neutrons are unstable with a half-life of about ten minutes (614.8 s) and formed in much smaller numbers. The abundance ratio was about seven protons for every neutron. Before one neutron half-life passed nearly every neutron had paired up with a proton, and nearly every one of these pairs had paired up to form helium. By this time the universe had cooled to a few billion kelvins (10^9 K) and the rate of nucleosynthesis had slowed down significantly.

By the time the universe was three minutes old the process had basically stopped and the relative abundances of the elements was fixed at ratios that didn't change for a very long time: **75% hydrogen**, **25% helium**, with trace amounts of deuterium (hydrogen-2), helium-3, and lithium-7.

Big Bang nucleosynthesis produced no elements heavier than lithium. To do that you need stars, which means waiting around for at least 200 billion years"

https://physics.info/nucleosynthesis/



The hypotheses usually made to explain the cosmological origin of the light elements are as follows.

1. The Universe has passed through a hot phase with $T \geqslant 10^{12}$ K, during which its components were in thermal equilibrium.
2. General Relativity and known laws of particle physics apply at this time.
3. The Universe is homogeneous and isotropic at the time of nucleosynthesis.
4. The number of neutrino types is not high (in fact we shall assume $N_\nu \simeq 3$).
5. The neutrinos have a negligible degeneracy parameter.
6. The Universe is not composed in such a way that some regions contain matter and others antimatter.
7. There is no appreciable magnetic field at the epoch of nucleosynthesis.
8. The density of any exotic particles (photinos, gravitinos, etc.) at T_e is negligible compared with the density of the photons.

Weak interaction: maintain the thermal equilibrium between neutrons and protons (Boltzman distribution)

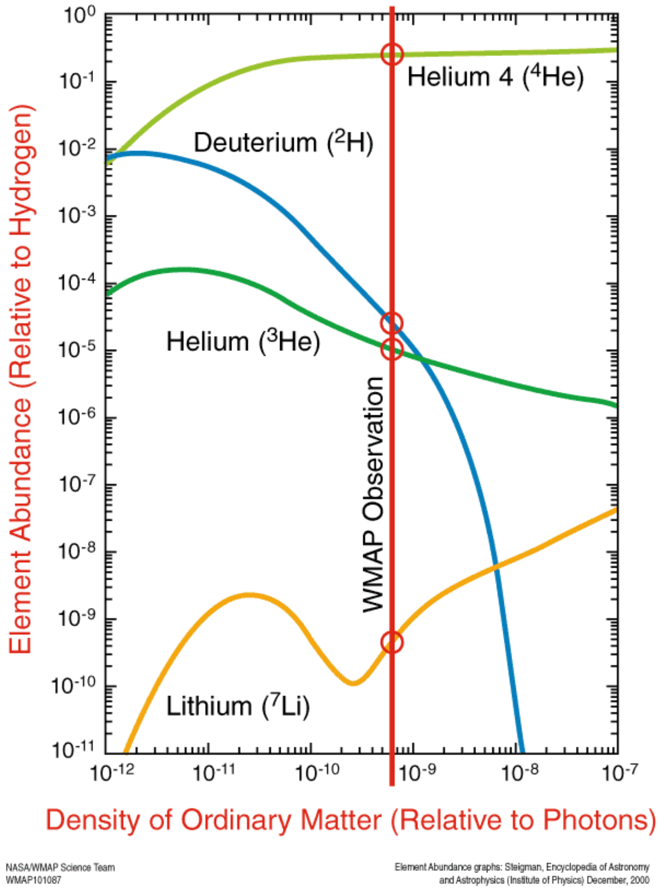
$$\mathrm{n} + \nu_\mathrm{e} \rightleftharpoons \mathrm{p} + \mathrm{e}^-, \qquad \mathrm{n} + \mathrm{e}^+ \rightleftharpoons \mathrm{p} + \bar{\nu}_\mathrm{e}, \quad \Rightarrow \quad \frac{n_\mathrm{n}}{n_\mathrm{p}} \simeq \exp\left(-\frac{Q}{k_\mathrm{B}T}\right) = \exp\left(-\frac{1.5\times 10^{10}\,\mathrm{K}}{T}\right)$$

$$Q = (m_\mathrm{n} - m_\mathrm{p})c^2 \simeq 1.3\ \mathrm{MeV}$$

is the difference in rest-mass energy between ‘n’ and ‘p’, corresponding to a temperature $T_\mathrm{pn} \equiv Q/k_\mathrm{B} \simeq 1.5\times 10^{10}$ K. For $T \gg T_\mathrm{pn}$, the number of protons is virtually identical to the number of neutrons.

(…calculations…)

- It can be shown that the predicted fraction of Helium produced is Y ~ 0.25
- All the other isotopes and elements are below %



Solar values

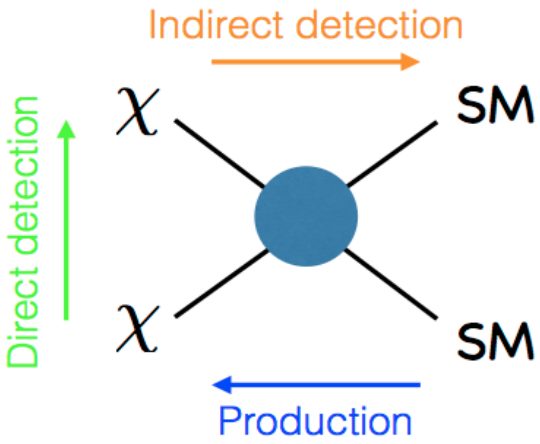
$X_\odot \sim 0.7$

$Y_\odot \sim 0.28$

$Z_\odot \sim 0.02$

Experimental Searches

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



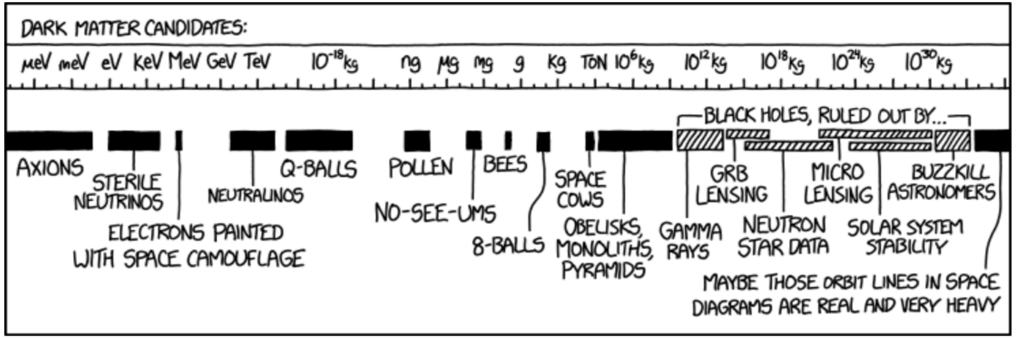
«Make it»
Standard Model (SM) particles collisions might produce DM

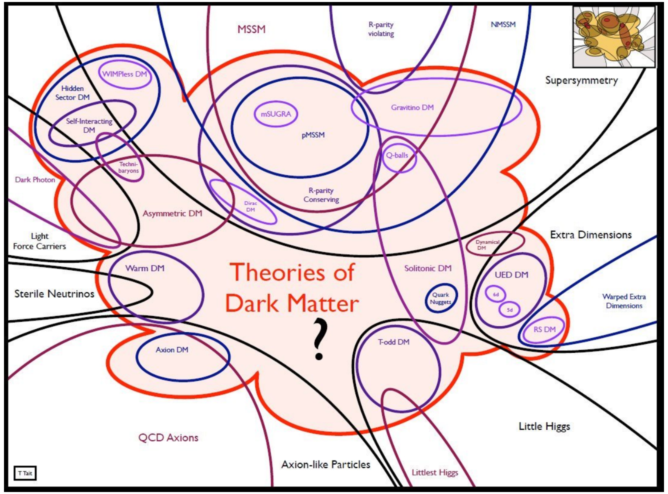
«Shake it»
DM particles might scatter onto some nuclei

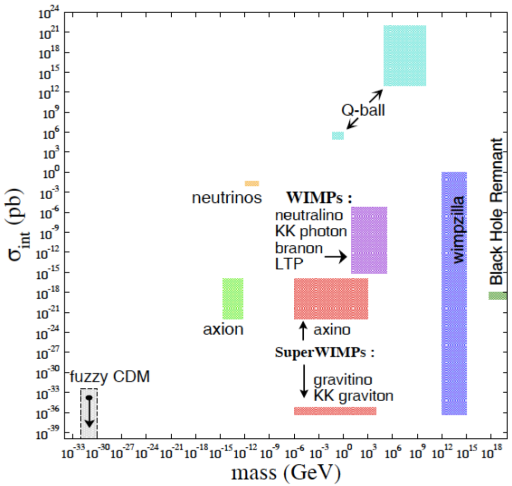
«Break it»
DM particles might interact and annihilate into SM particles

+ « Bake it » invent nice theories to be tested experimentally

“Bake” DM Candidates







“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 micro-lensing 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 → $\Omega b \approx 4\%$
- 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 (e.g. extradimension models)

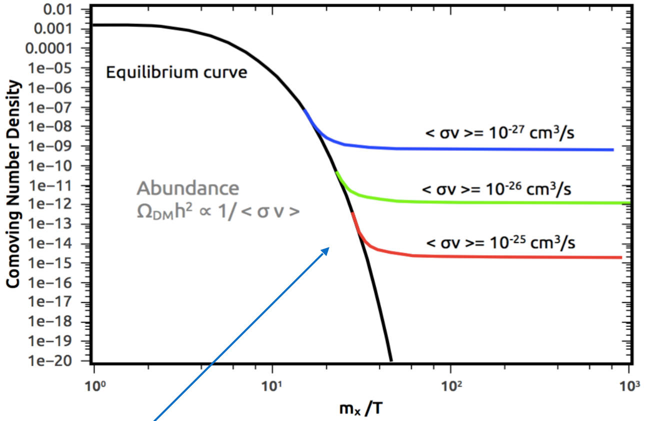
Others:
Axion-like Particle
Heavy right-handed neutrinos

DM as WIMPS

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 :

$$\Omega_{\chi,0}h^2 = \frac{3\times10^{-27}\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma_{ann}v\rangle}, \tag{2.37}$$



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

$$\Omega_{DM}h^2 = 0.1197 \pm 0.0022^1 \tag{7.5}$$

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.

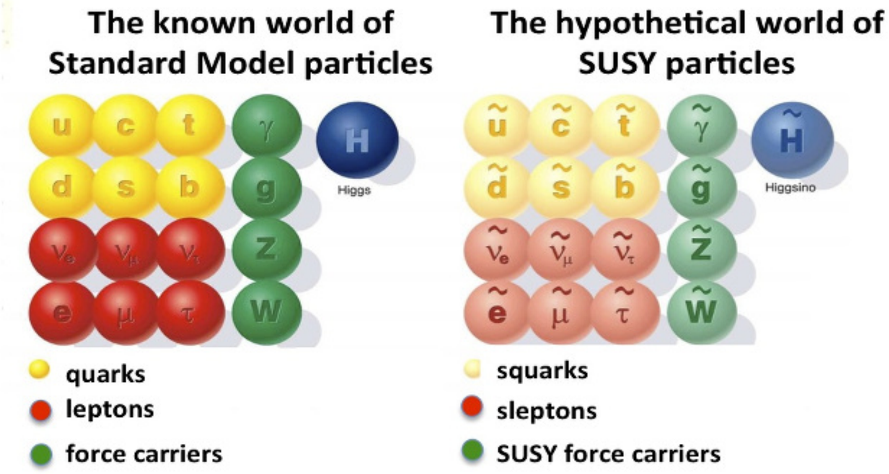
Density is frozen == relic density
→ Comoving density becomes constant

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

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

DM as Supersymmetric Particles

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, e.g. some of the SUSY particles should have a mass 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 Neutralino**
- Gravitinos
- Right-Handed Sneutrinos

DM as Supersymmetric Particles

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 $SU(2)_L$ 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

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

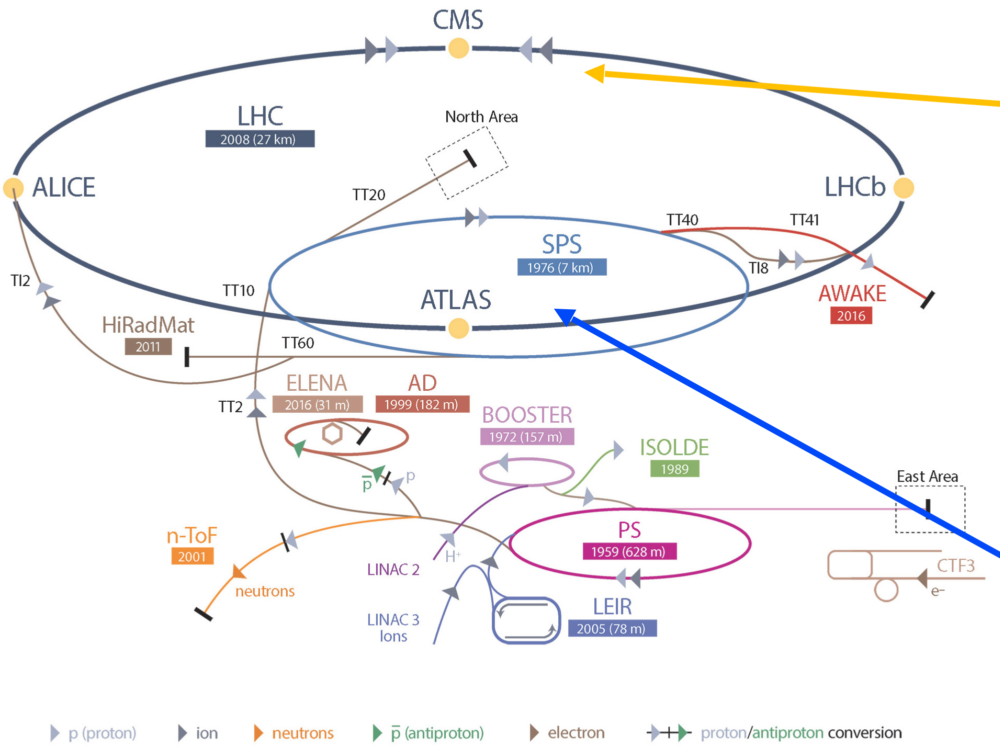
In different regions of the supersymmetric parameter space, the LSP may be more bino-like, wino-like, or Higgsino-like, depending on the relative magnitudes of the coefficients α, β, γ and δ.

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

To remember: *the masses of SUSY particles are free parameters of the SUSY theory*
i.e. they can only be measured experimentally


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

Searches at the LHC


CMS
LHC
2008 (27 km)
North Area
ALICE
TT20
LHCb
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
CTF3
e–
neutrons
LINAC 3
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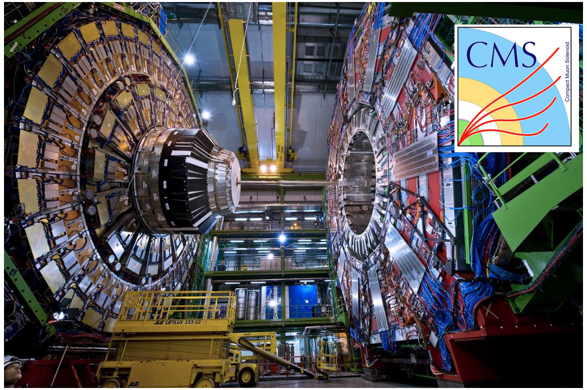
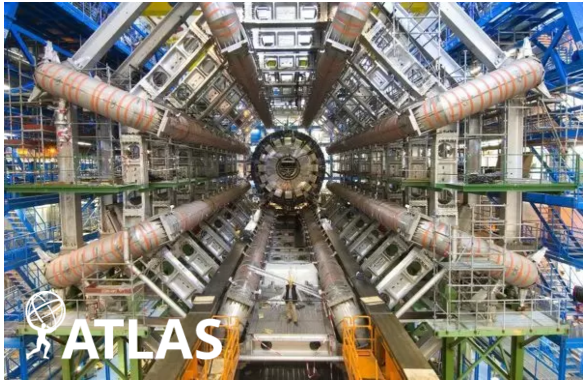
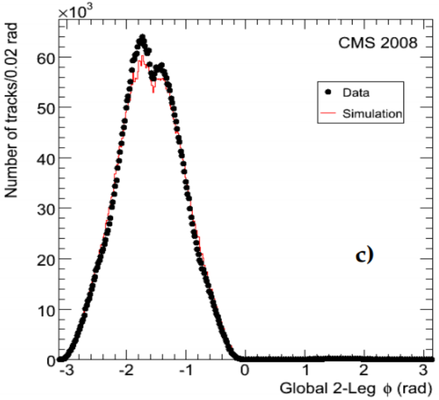
electron
proton/antiproton conversion

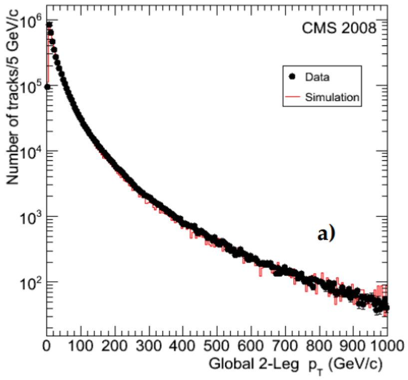

CMS


ATLAS

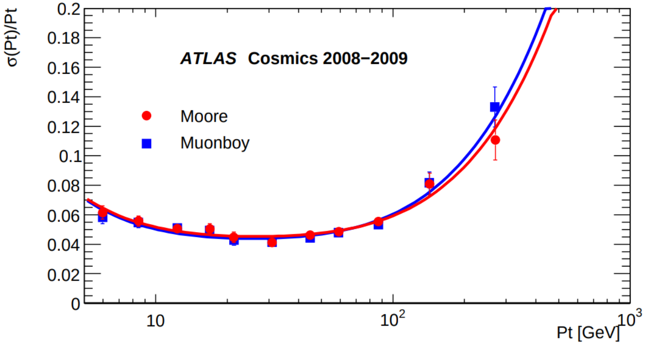
Cosmic Muons Studies at ATLAS/CMS

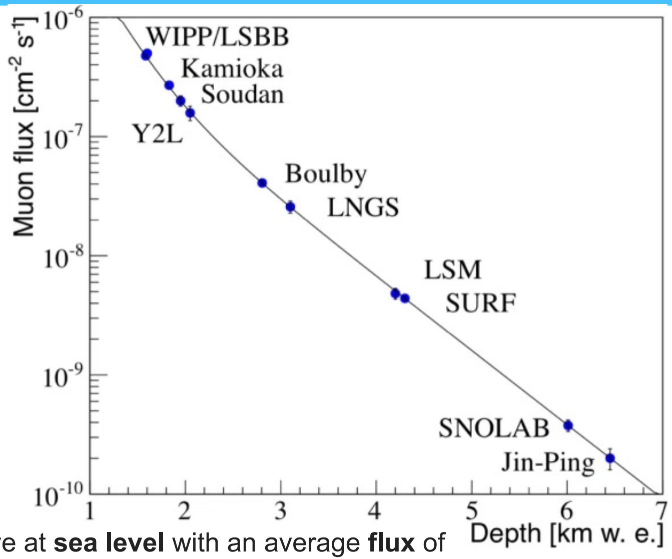
https://arxiv.org/pdf/0911.4994.pdf





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



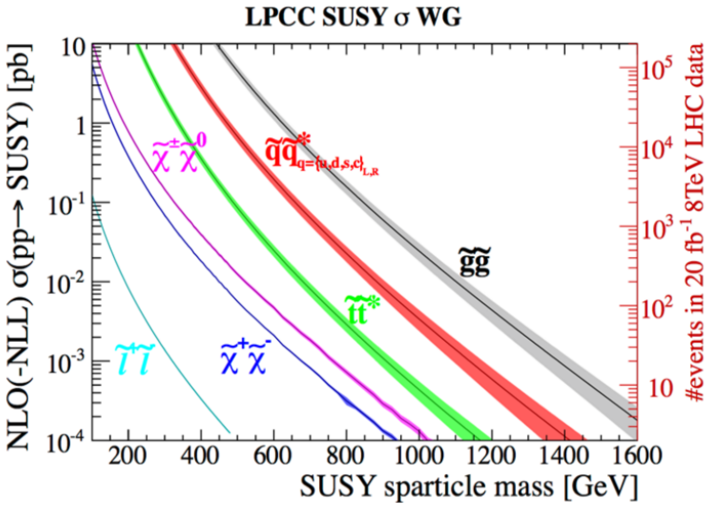


Muons arrive at **sea level** with an average **flux** of about 1 **muon** per square centimetre per minute

Can use cosmic muons to calibrate the detectors/ make studies

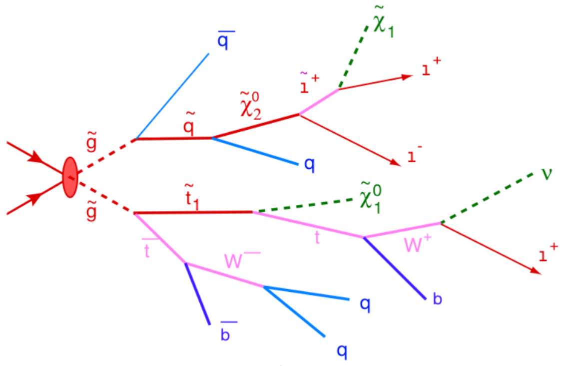
«The ATLAS detector at the Large Hadron Collider has collected several hundred million cosmic ray events during 2008 and 2009. These data were used to commission the Muon Spectrometer and to study the performance of the trigger and tracking chambers, their alignment, the detector control system, the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

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



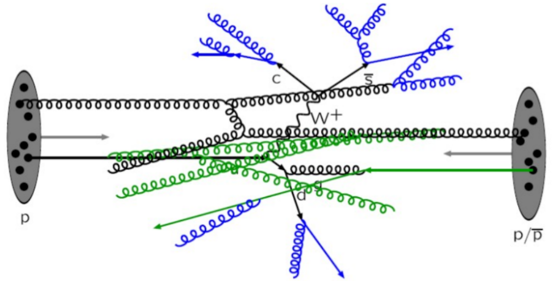
Production cross section for some SUSY particles pair-production and expected number of events for 8 TeV centre-of-mass energy

What we would
like to see

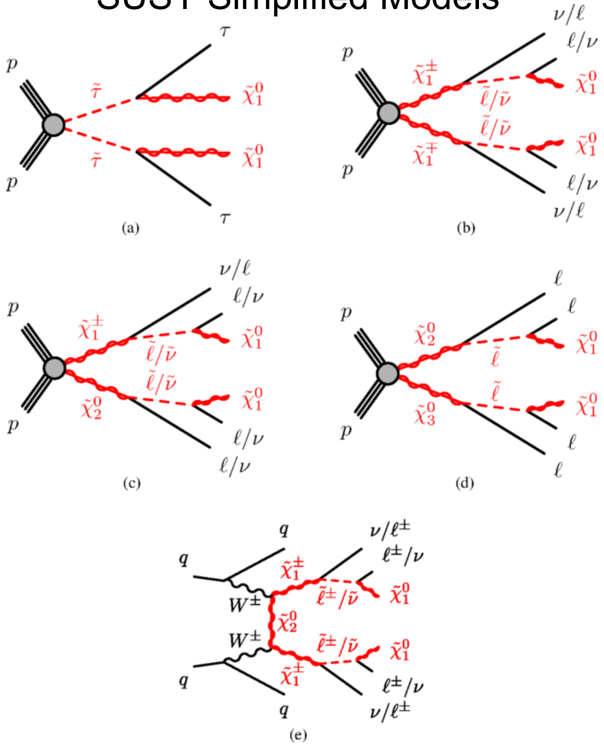


What really
happens…

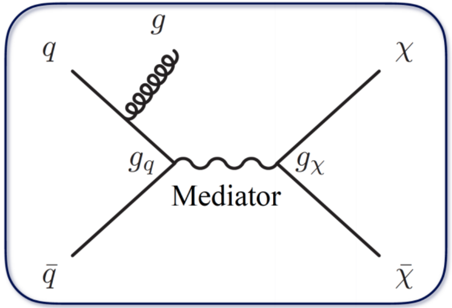
Design of dedicated Searches



SUSY Simplified Models



DM Simplified Models



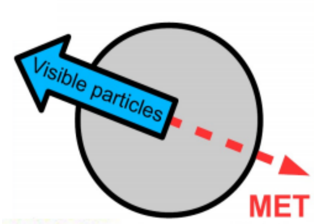
→ **Relevant parameters :**
m_{χ}, m_{med}, $\mathbf{g_{\chi}}$ and $\mathbf{g_{q}}$
spin/parity of the mediator : scalar/pseudo-scalar or vector/axial-vector

- Simplified Models: introduce only a small set of new particles
- They are much easier to understand than “full” models
- They are in general difficult to generalise

Example: SUSY at the LHC

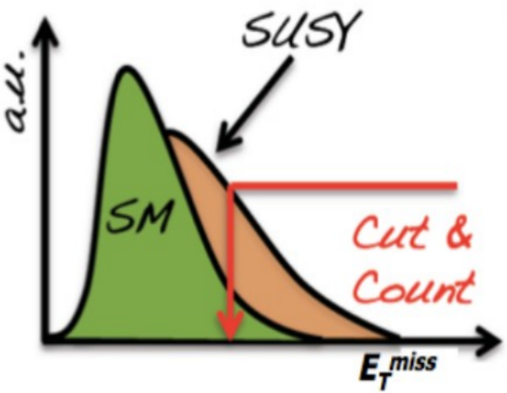
- Assumption: all the SUSY particles will eventually decay to the lightest Neutralino, which is the DM candidate here considered, and it *escapes detection* since *it does not interact with the detector*
- This will produce “missing energy” (MET) i.e. an energy imbalance in the event

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



What we “see”

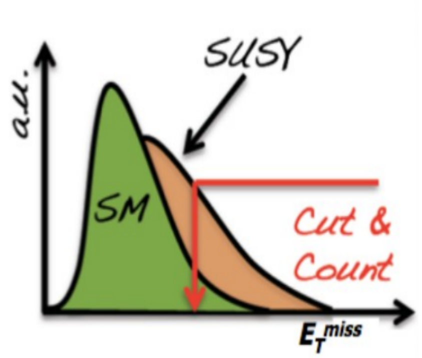
What we do not “see”

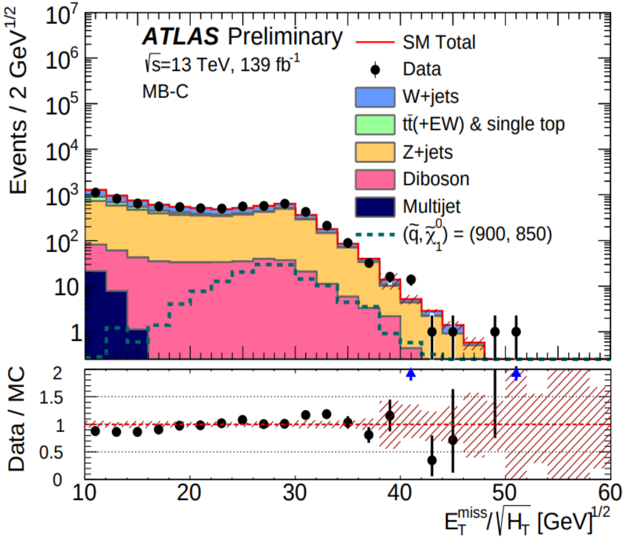


-> The presence of a DM candidate in the events (i.e. each interaction recorded at the detector), will produce an imbalance in the total energy/momentum of the visible particles

- Assumption: all the SUSY particles will eventually decay to the lightest Neutralino, which is the DM candidate here considered, 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

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





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

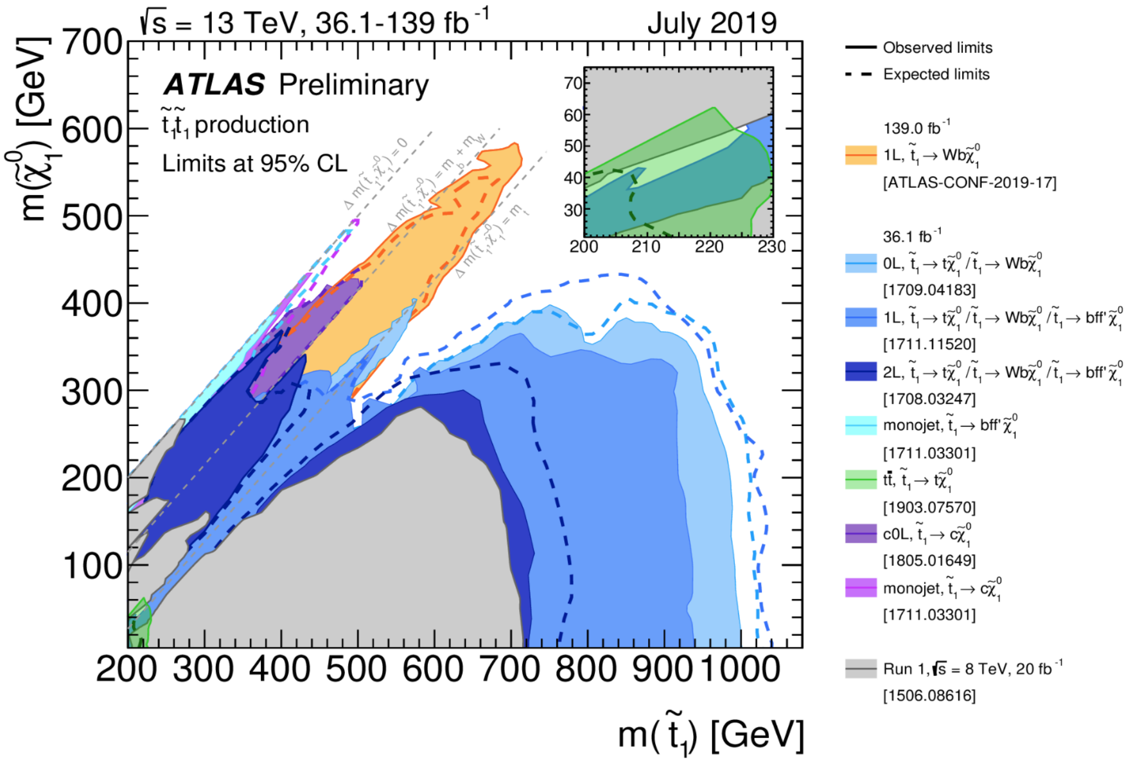
- We expect a lot of missing energy in the events, that cannot be accounted for by SM neutrinos or particles that cannot be revealed by the detectors, systematic errors, detector acceptance, particle reconstructions efficiency etc.

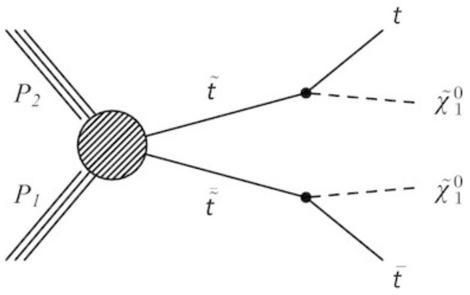
However:

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

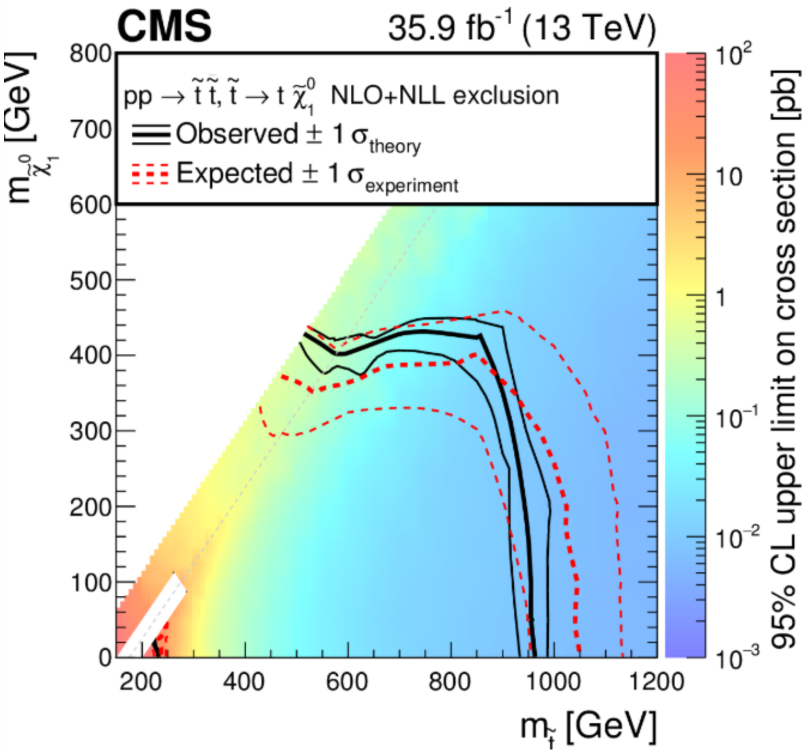
→ Can only state that they are stable while travelling through the detector (this is general of any DM search you perform at the colliders)

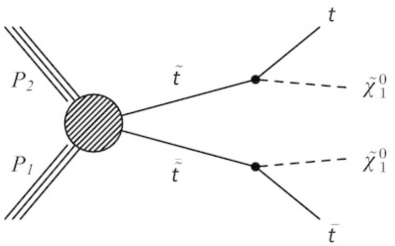
Example: SUSY at the LHC





- 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)





- The 95% CL upper limit on the cross section for the stop-production (different for each search) is measured
- The upper limit (given by the color code) has to be compared with the theoretical cross section
- If the theory calculation is > experimental limit: the mass point (stop-neutralino) point can be excluded i.e. your theoretical model is excluded by the experimental results

Example: SUSY at the LHC

- The 95% CL upper limit on the cross section for the stop-production (different for each search) is measured
- The upper limit (given by the color code) has to be compared with the theoretical cross section
- If the theory calculation is > experimental limit: the mass point (stop-neutralino) point can be excluded i.e. your theoretical model is excluded by the experimental results

$\sigma_{theo} > \sigma_{exp}$

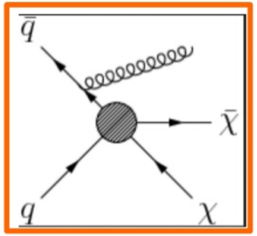
The theory prediction exceeds the experimental upper limit, so the point is excluded.
This means that, according to your theoretical cross section, you should have produced enough “stop” pairs to be able to find a SUSY signature in your data (which unfortunately you have not found)

$\sigma_{theo} < \sigma_{exp}$

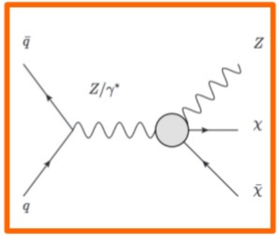
It is not possible to rule out the presence of SUSY particles in the collected data,
i.e. the additional signal coming from SUSY particles is still compatible with what is seen in the data

Idea: DM direct production plus “something”

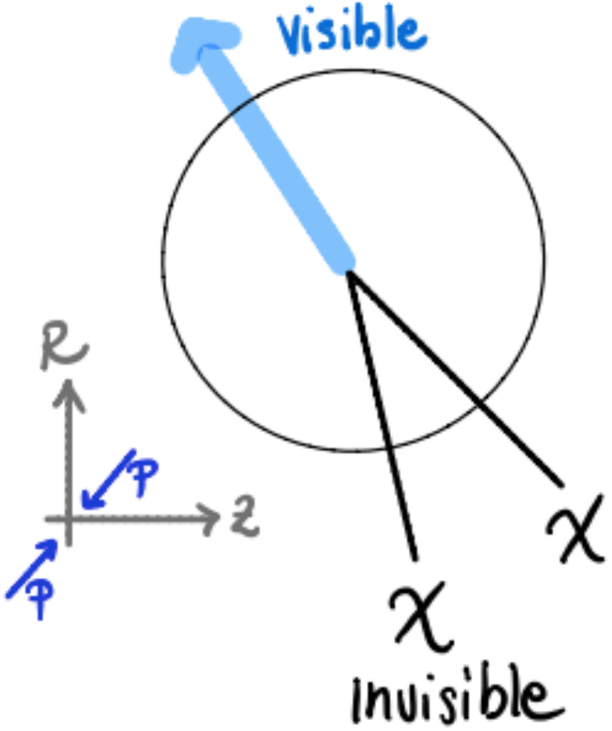
Mono-jet

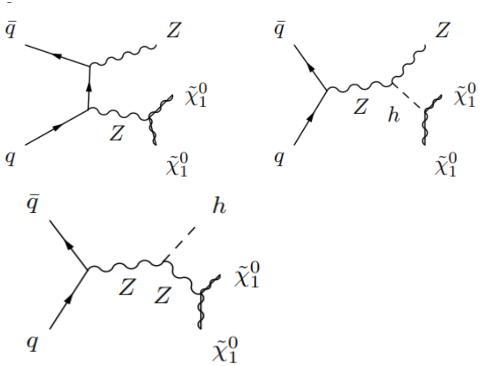


Mono-Z

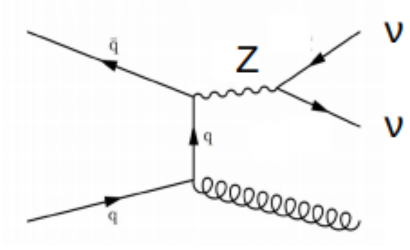


Mono-lepton
Mono-photon
Mono-top
Mono-Higgs
etc …





Example for SUSY

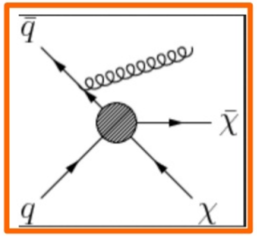


Example: Mono-jet SM irreducible background

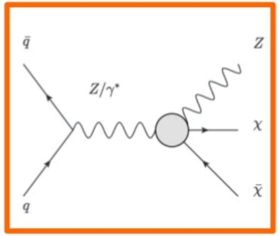
Example: direct DM production and mono-X Searches

Idea: DM direct production plus “something”

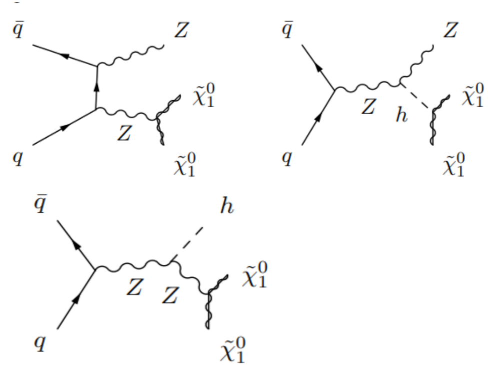
Mono-jet



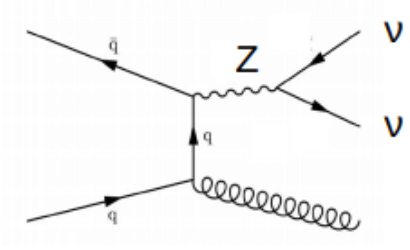
Mono-Z



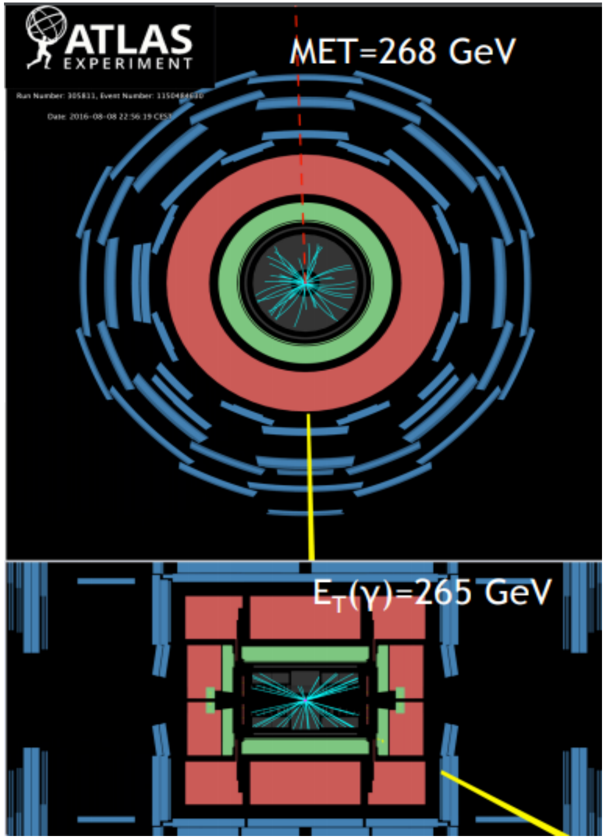
Mono-lepton
Mono-photon
Mono-top
Mono-Higgs
etc ...

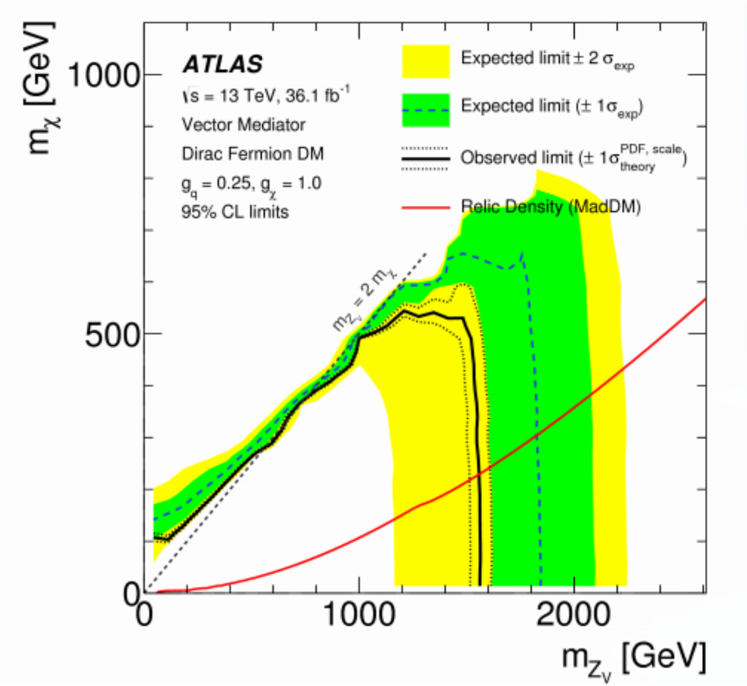


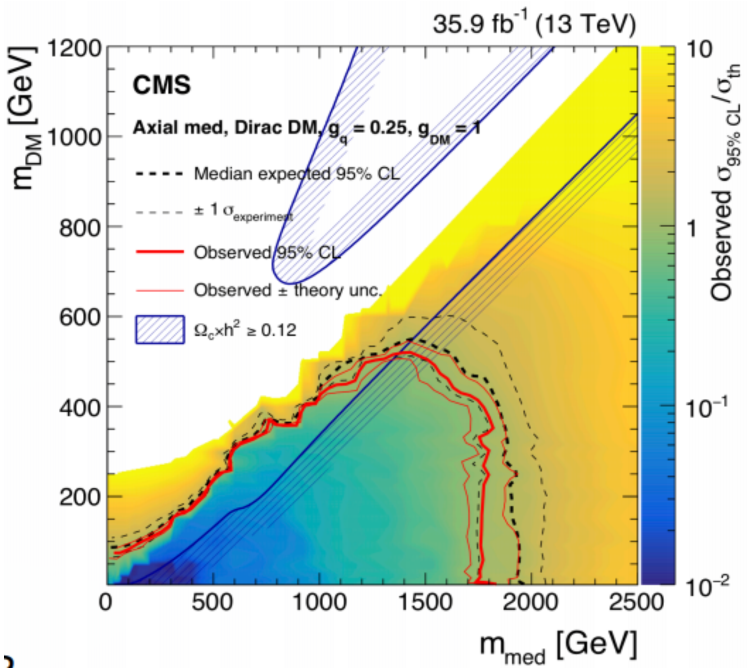
Example for SUSY



Example: Mono-jet SM irreducible background



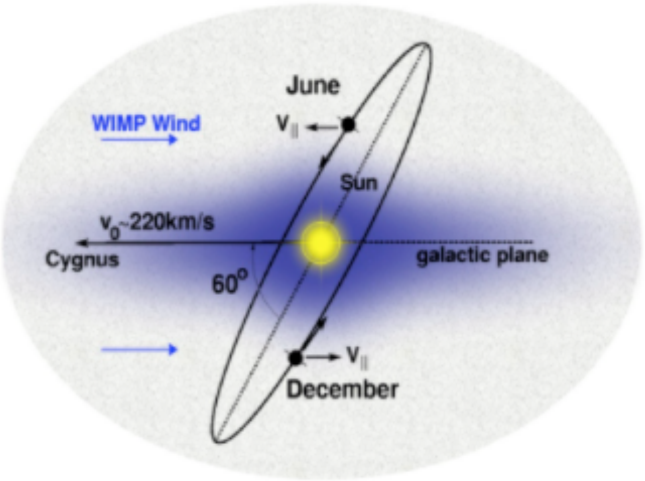


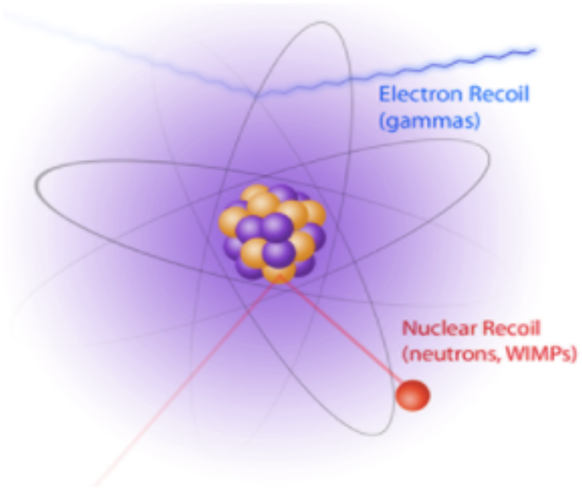


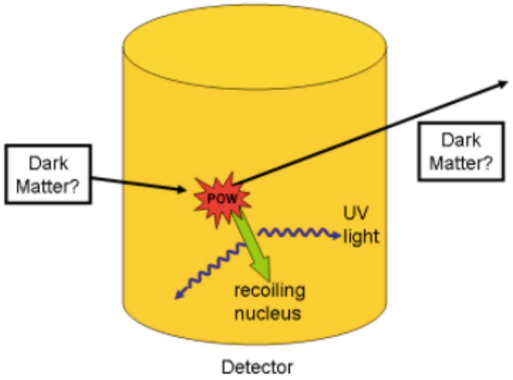
→ Using DM simplified models: put limits on the DM and mediator mass for fixed couplings

Direct Detection

- Idea: the Earth travels through the DM Milky Way's halo, and DM particles might scatter off (heavy) nuclei



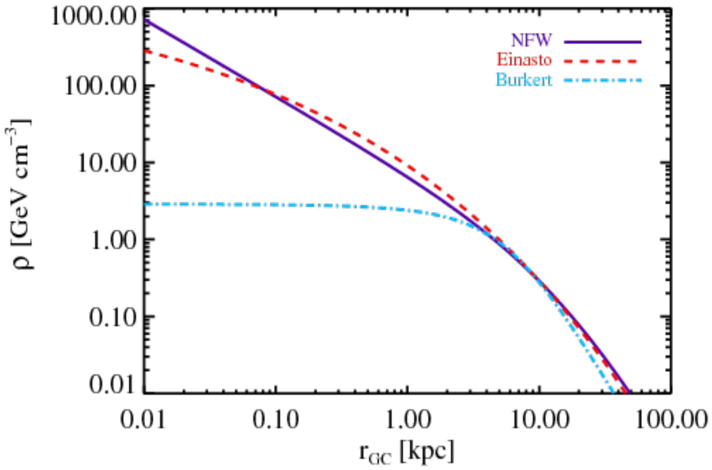




- Idea: the Earth travels through the DM Milky Way's halo, and DM particles might scatter off (heavy) nuclei
- In general, the expected event rate can be expressed as

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

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

« 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

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

Particle Physics: Scattering Cross Sections

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

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

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

Spin independent cross section (i.e. same for protons and neutrons)

DM Direct Detection

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(sodium-iodine crystals)**, COSINE, PICO…]

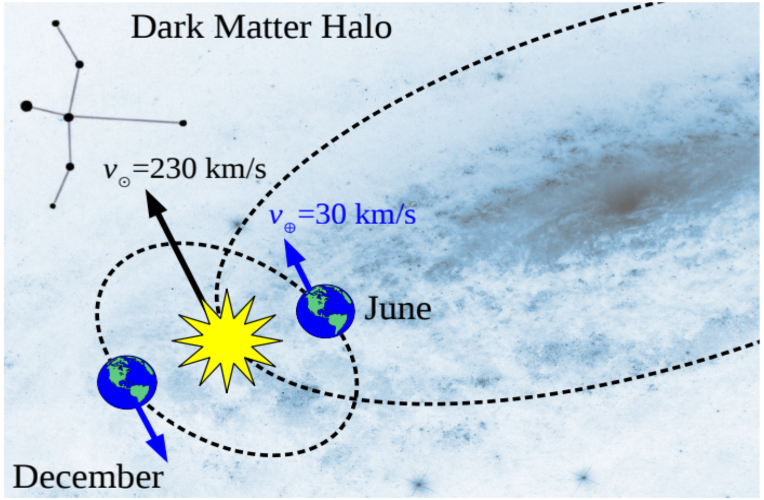
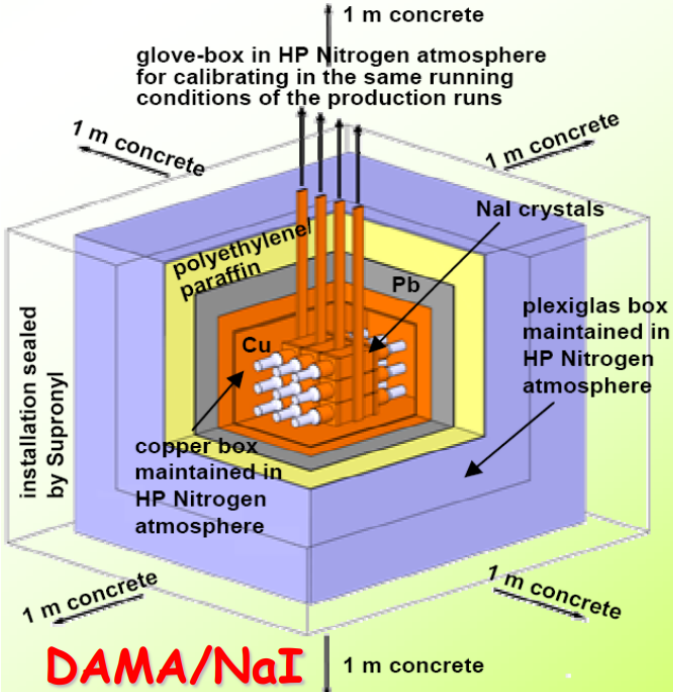
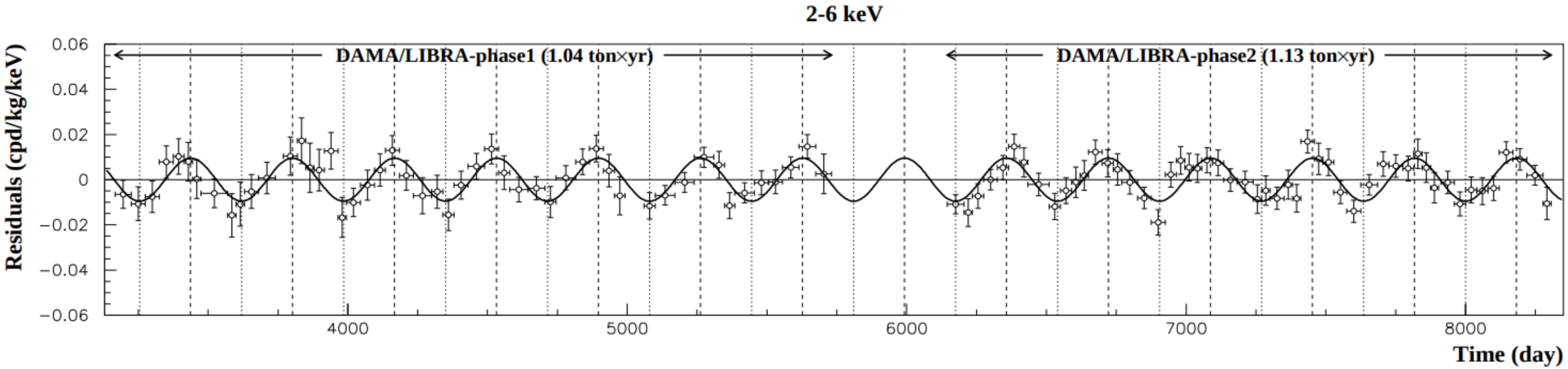


Figure 4. Illustration of the Sun-Earth system moving around the galactic center and through the dark matter halo in the direction of the constellation Cygnus. The varying vector addition of the velocities over the course of a year is expected to induce a modulating dark matter signature.



DAMA/LIBRA and the Annual Modulation

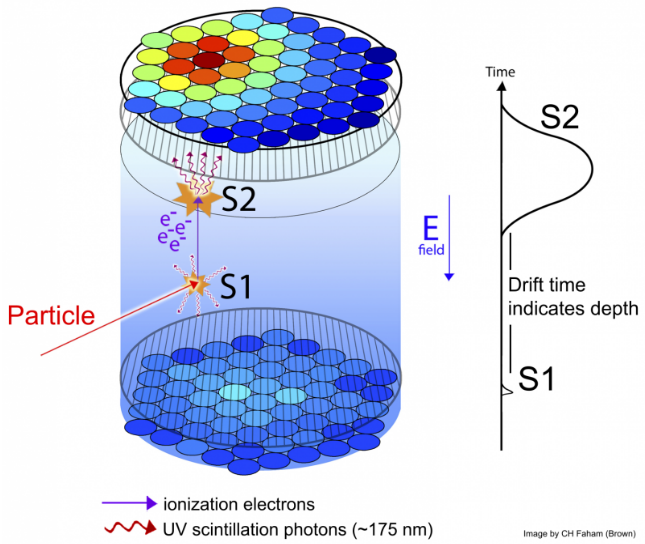


The data of the new DAMA/LIBRA–phase2 confirm a peculiar annual modulation in the (1–6) keV energy region:

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



https://www.hep.ucl.ac.uk/darkMatter/

[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) [South Dakota]
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).

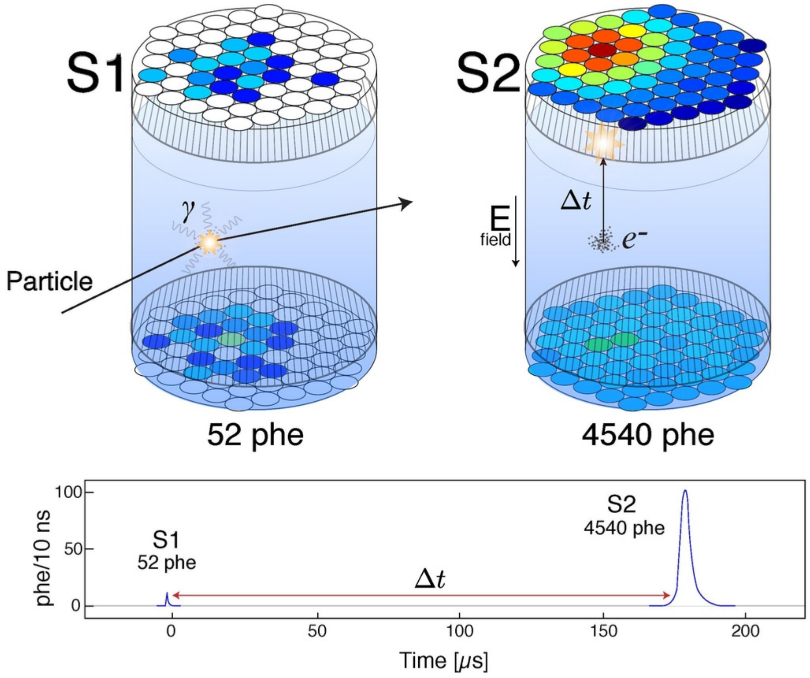
The recoil leads to a burst of scintillation light and to the ionization of the surrounding xenon atoms, leading to the liberation of “ionization electrons.
They drift to the top of the detector (electric field) where they encounter the gas-liquid interface.

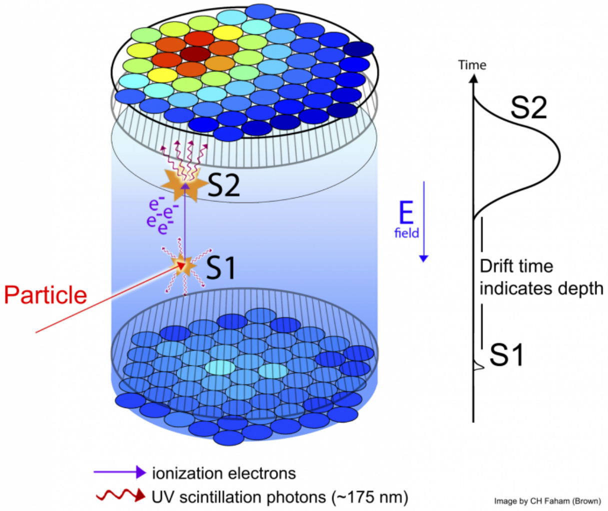
They produce a second burst of light through electroluminescence (**S2**).

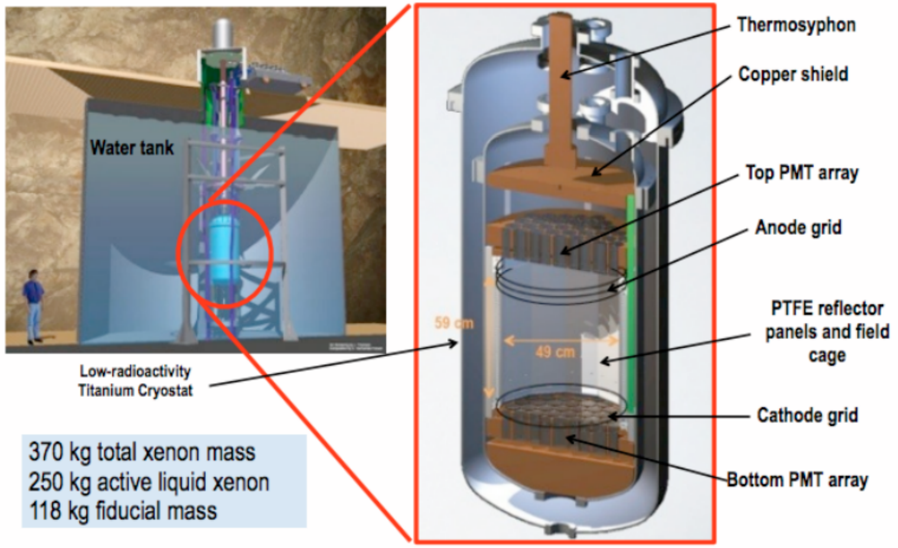
The resultant photons from each burst of light are detected by 122 Photomultiplier Tubes (PMTs), split between the top and bottom of the detector.

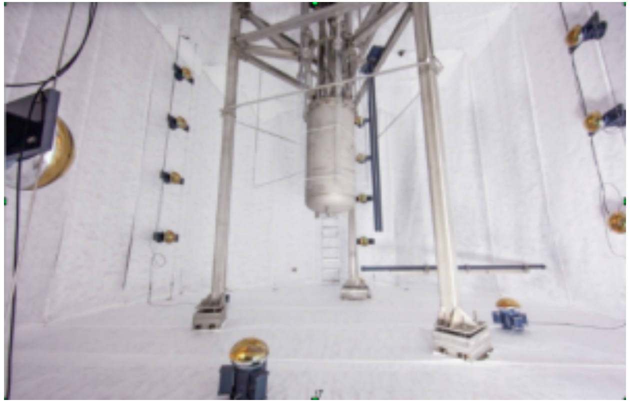
The two signals, S1 and S2, are separated by the drift time of the electrons, from which we can infer the depth of the event.

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.

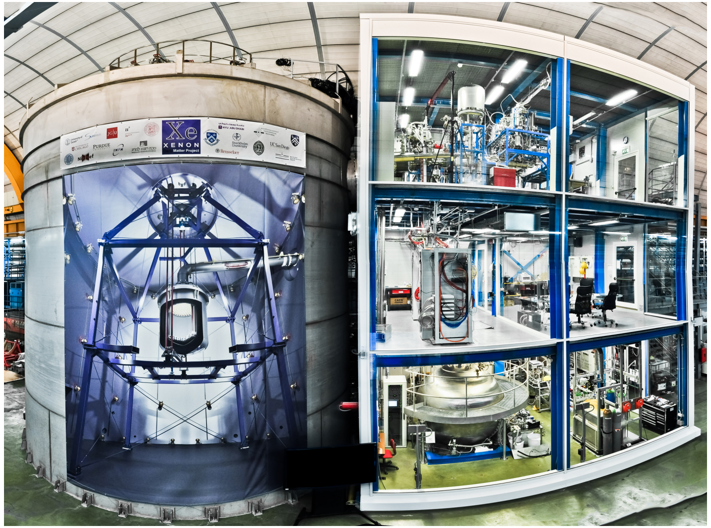

S1
S2
γ
Particle
E
field
Δt
e^-
52 phe
4540 phe
S1
52 phe
S2
4540 phe
Δt
phe/10 ns
Time [μs]


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


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



XENON 1T



- 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,

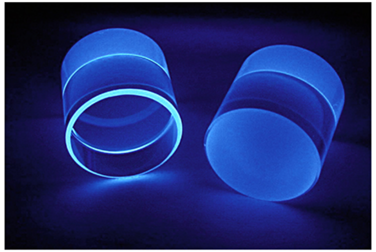
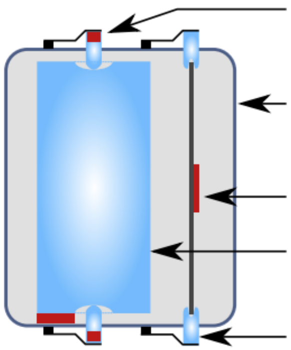
The measured half-life of this process, which is several orders of magnitude larger than the age of the Universe, demonstrates the capabilities of xenon-based detectors to search for rare events and showcases the broad physics reach of even larger next-generation experiments.

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

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



- The CRESST-III experiment operates scintillating CaWO4 (calcium-tungstate) 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

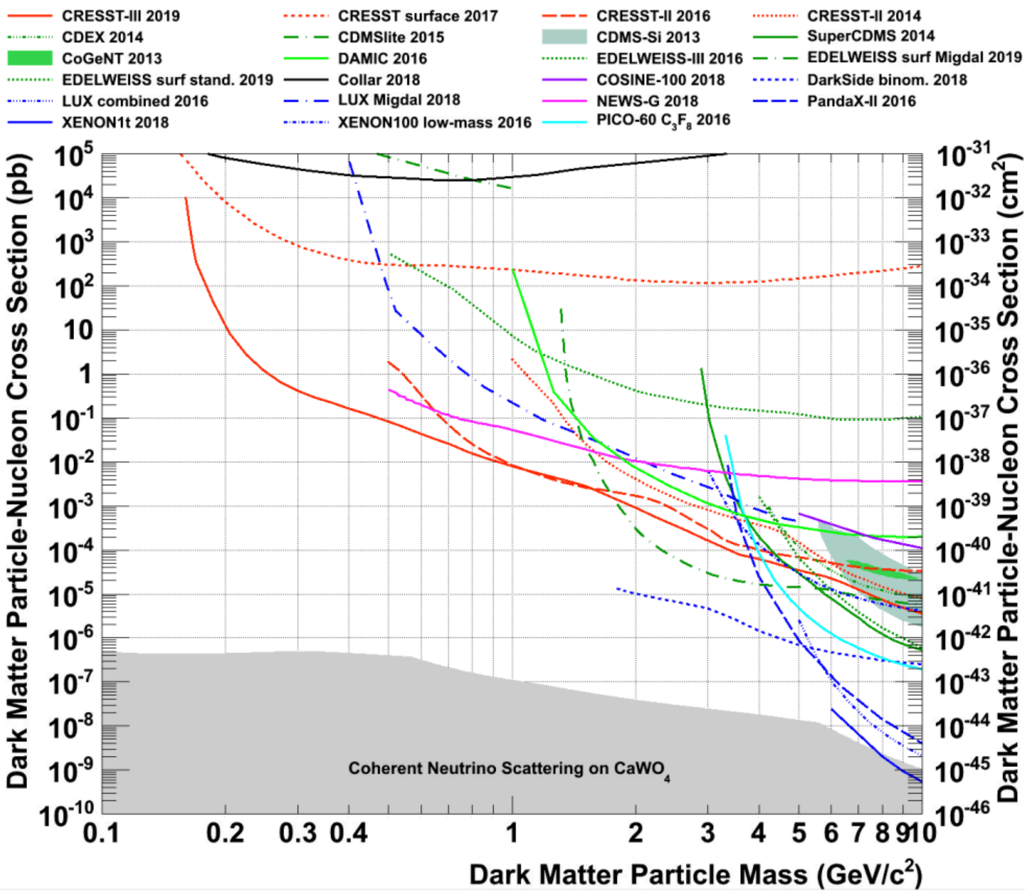
- In addition, the experimental volume is protected by concentric layers of shielding material comprising - from outside to inside - polyethylene, lead and copper.

- 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 (LN_2 and LHe) are refilled three times a week causing a down-time of about 3 h per refill.

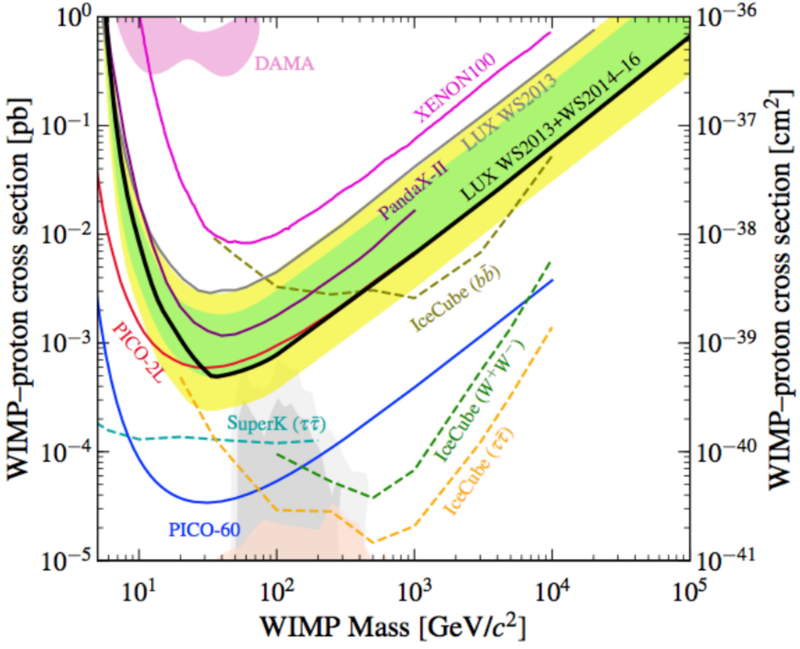
https://youtube/uz177q5l82Q

Results

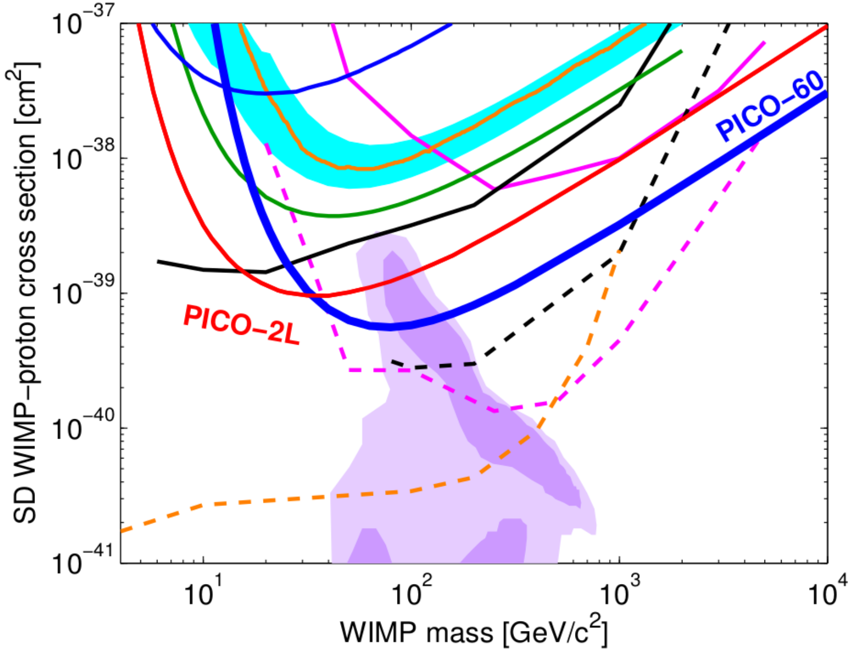


CRESST-III 2019
CRESST surface 2017
CRESST-II 2016
CRESST-II 2014
CDEX 2014
CDMSlite 2015
CDMS-Si 2013
SuperCDMS 2014
CoGeNT 2013
DAMIC 2016
EDELWEISS-III 2016
EDELWEISS surf Migdal 2019
EDELWEISS surf stand. 2019
Collar 2018
COSINE-100 2018
DarkSide binom. 2018
LUX combined 2016
LUX Migdal 2018
NEWS-G 2018
PandaX-II 2016
XENON1t 2018
XENON100 low-mass 2016
PICO-60 C_3F_8 2016
Dark Matter Particle-Nucleon Cross Section (pb)
Dark Matter Particle-Nucleon Cross Section (cm^2)
Dark Matter Particle Mass (GeV/c^2)
Coherent Neutrino Scattering on $CaWO_4$

Results

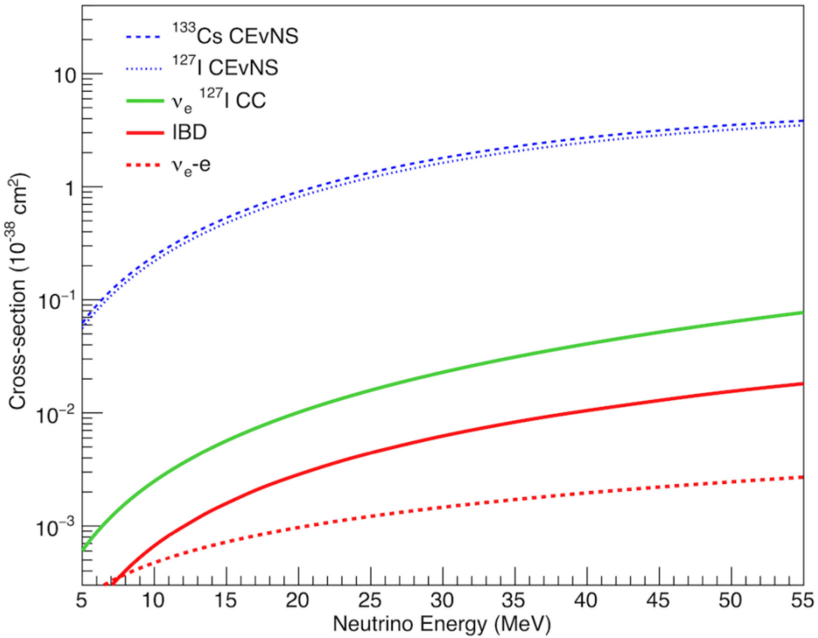


DAMA
XENON100
LUX WS2013
PandaX-II
LUX WS2013+WS2014-16
IceCube ($b\bar{b}$)
PICO-2L
SuperK ($\tau\bar{\tau}$)
IceCube (W^+W^-)
IceCube ($\tau\bar{\tau}$)
PICO-60
WIMP–proton cross section [pb]
WIMP–proton cross section [cm^2]
WIMP Mass [GeV/c^2]



PICO–2L
PICO–60
SD WIMP–proton cross section [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.



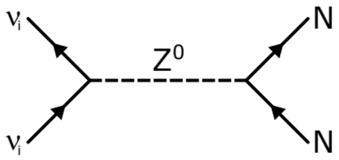
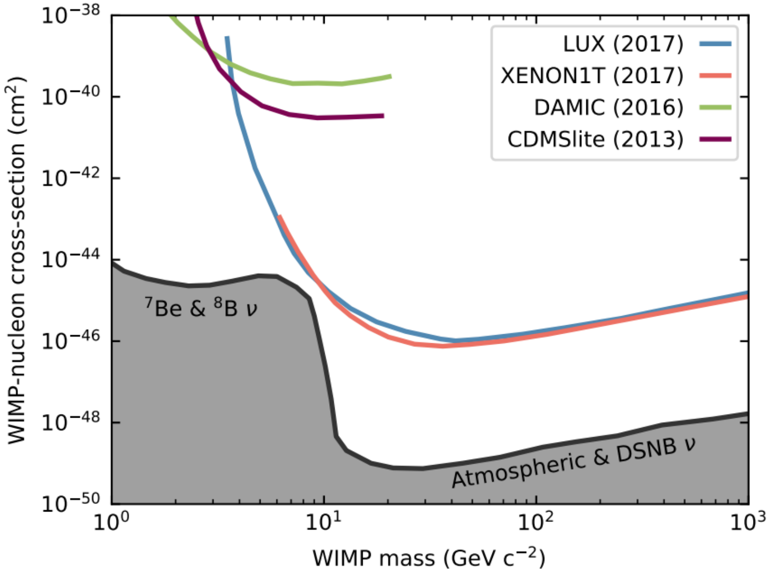


Figure 2.1: Feynman diagram for CEνNS. Here ν_i describes both neutrinos and anti-neutrinos of any flavor and N denotes any nucleus.

… 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

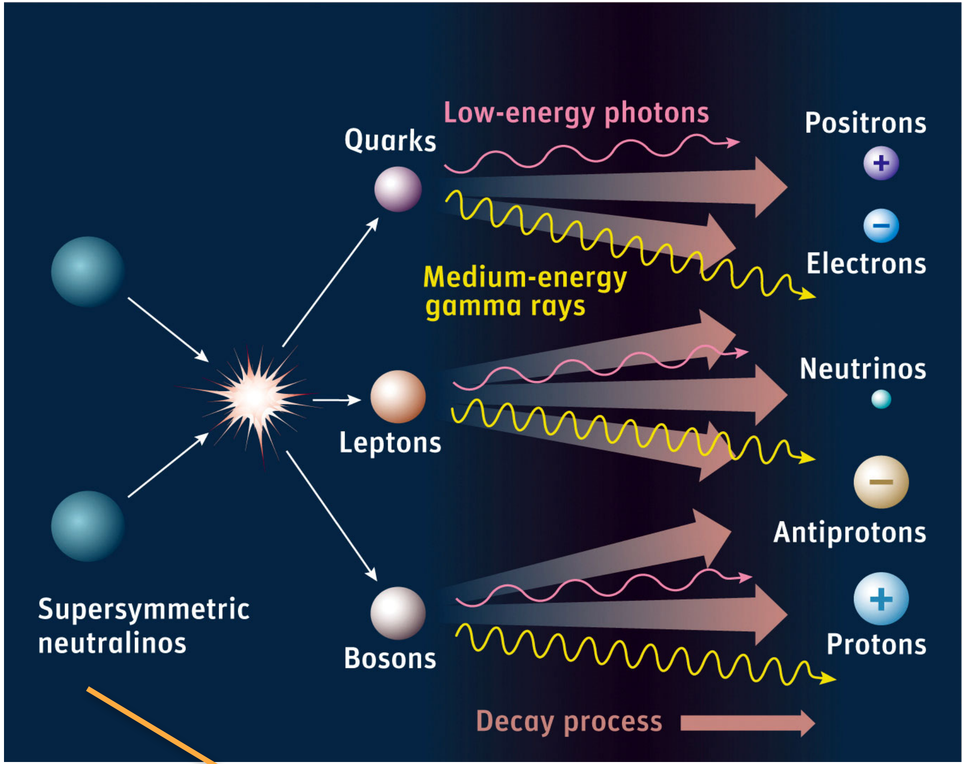


- For a vanishing momentum transfer between the incoming WIMP and the target nucleus an analogous coherent enhancement of the scattering cross-section is expected.
- the CEvNS cross-section scales with the total neutron number
- the assumed dark matter coupling to both protons and neutrons is non-negligible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

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

Direct Detection



Or any other DM candidate

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

- Galactic centre
- **Dwarph Spheroidal Galaxies**

Dwarf Spheroidal Galaxies (Milky Way Satellites)

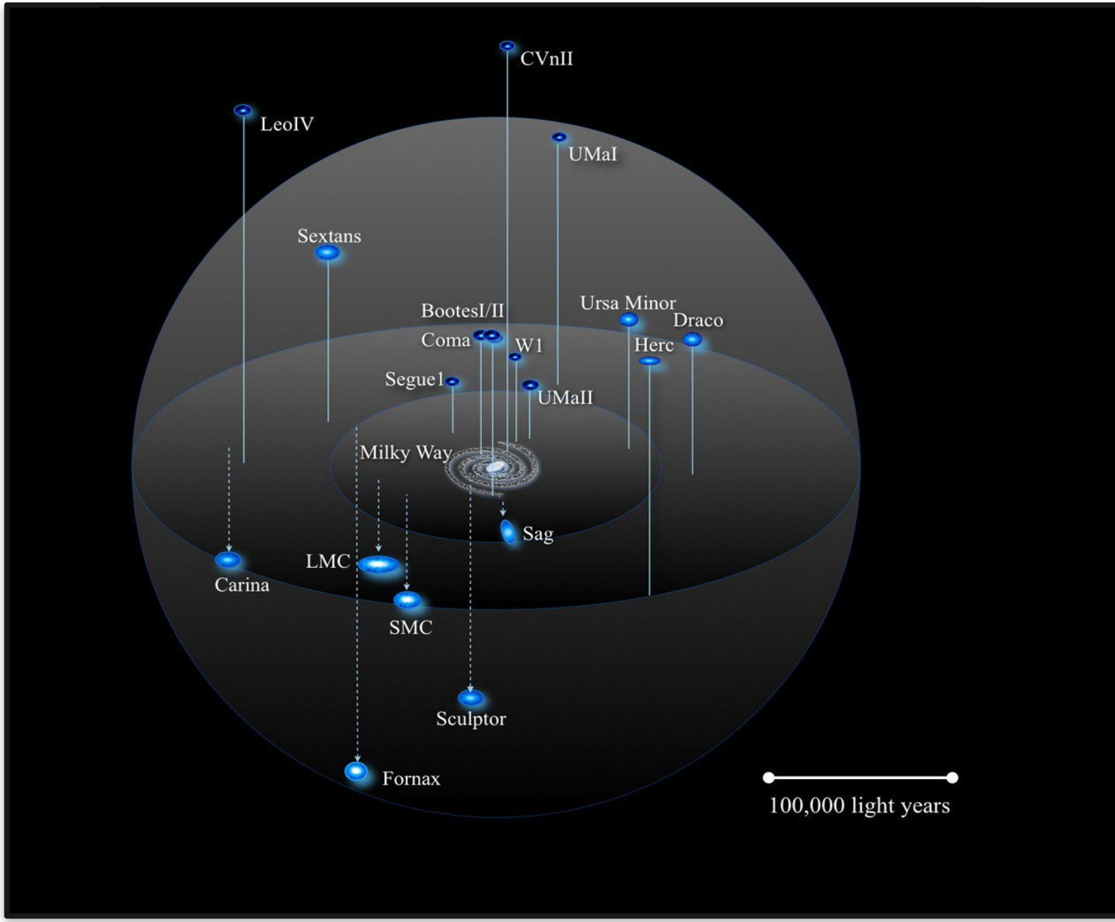
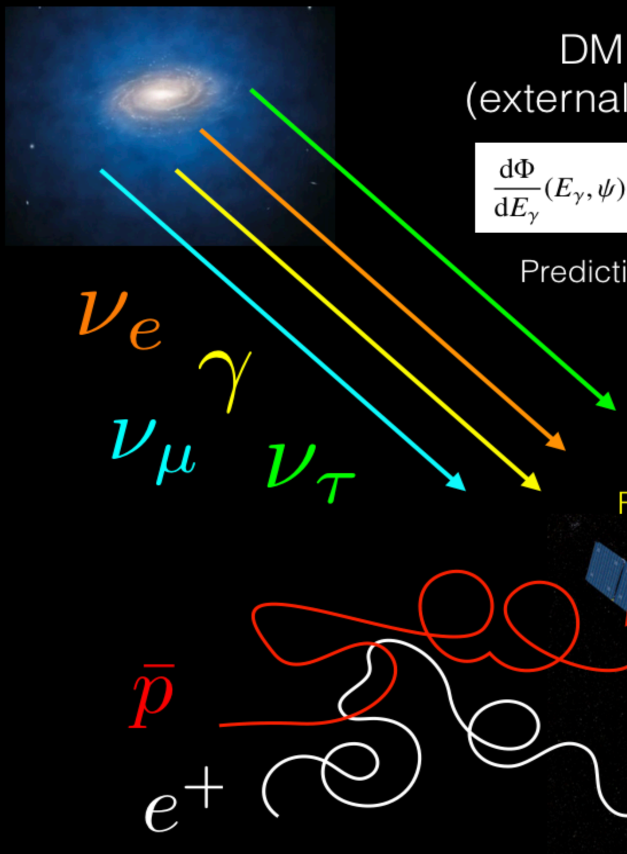


TABLE I. Properties of Milky Way dSphs.

Name	ℓ^{a} (deg)	b^{a} (deg)	Distance (kpc)	$\log_{10}(J_{\rm obs})^{b}$ ($\log_{10}[\mathrm{GeV}^2\,\mathrm{cm}^{-5}]$)	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]

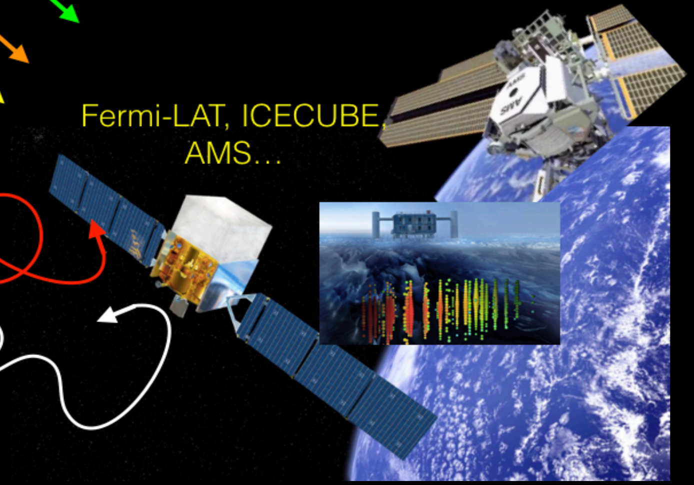
[a] Galactic longitude and latitude.
[b] J-factors are calculated assuming an NFW density profile and integrated over a circular region with a solid angle of $\Delta\Omega \sim 2.4 \times 10^{-4}$ sr (angular radius of 0.5°).

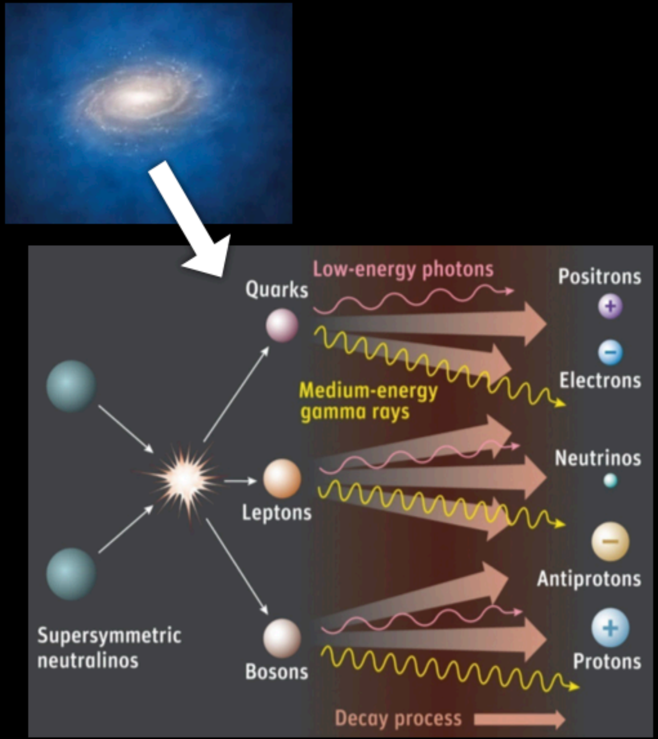


DM annihilation in the halos
(external galaxies or in the Milky way)

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

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





$\chi\,\chi$ —> SM SM —> Cosmic Rays

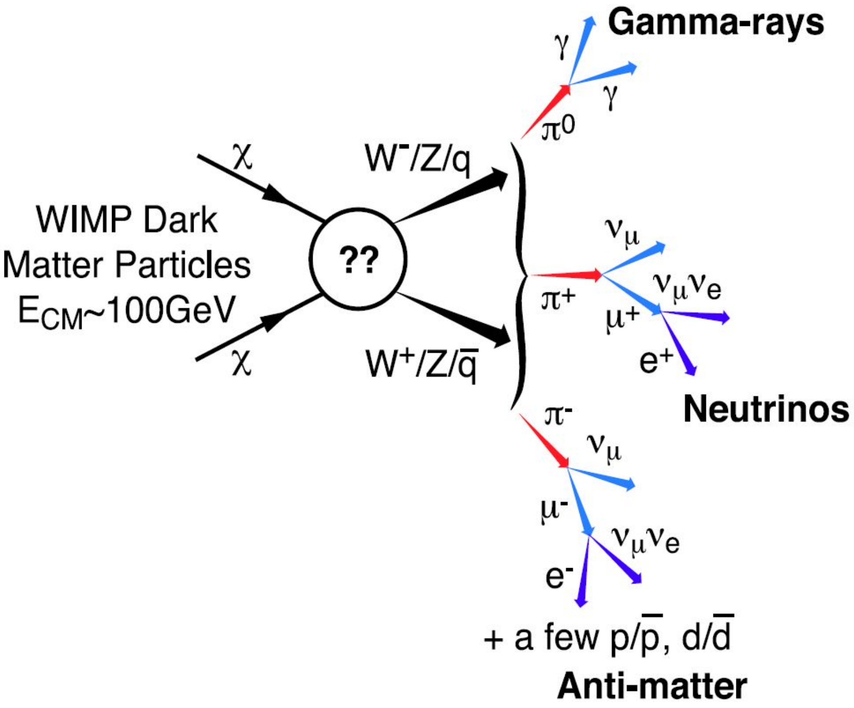
- DM annihilates inside galactic halos
- Typically 2-to-2 processes are considered i.e. $\chi\,\chi$ —> SM SM (called Simplified Models)
- From SM to Cosmic Rays (CR):

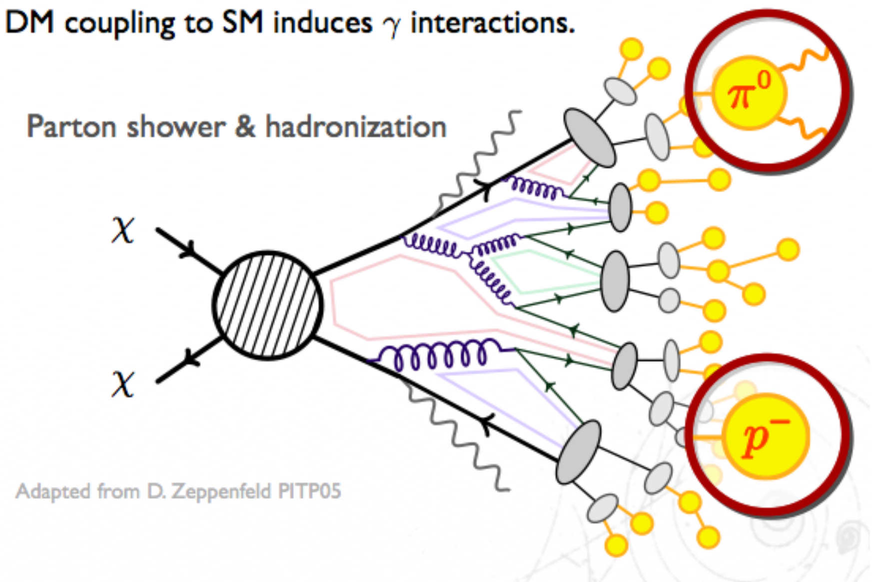
$$\gamma, \nu_e, \nu_\mu, \nu_\tau, e^+, \bar{p}$$

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
π^0
χ
$W^-/Z/q$
WIMP Dark
Matter Particles
E_{CM}~100GeV
??
χ
$W^+/Z/\bar{q}$
ν_μ
π^+
$\nu_\mu\nu_e$
μ^+
e^+
Neutrinos
π^-
ν_μ
μ^-
$\nu_\mu\nu_e$
e^-
+ a few $p/\bar{p}$, $d/\bar{d}$
Anti-matter


DM coupling to SM induces γ interactions.
Parton shower & hadronization
χ
χ
π^0
p^-
Adapted from D. Zeppenfeld PITP05

[particles/(GeV sr cm^2 s]

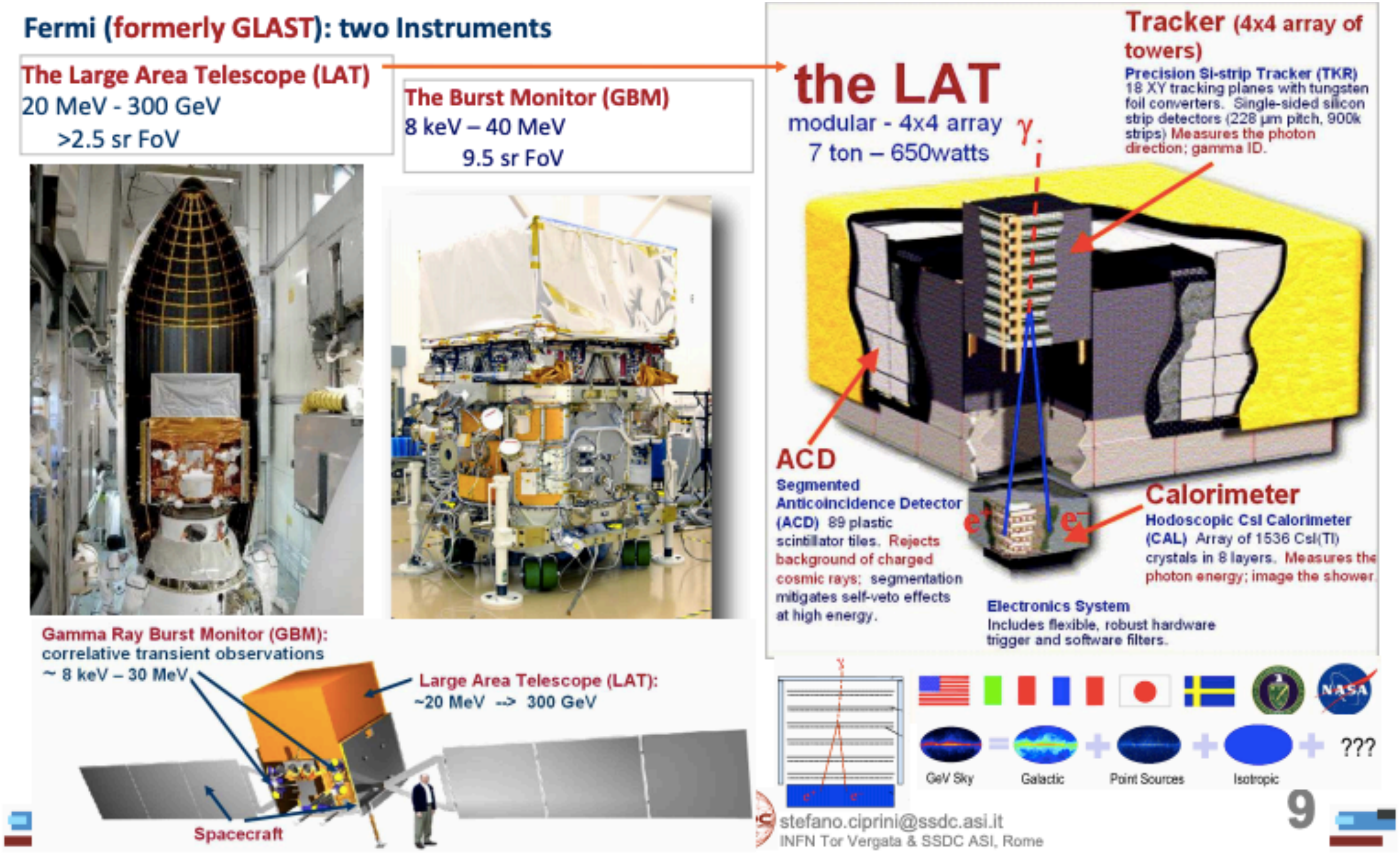
$$\frac{d\Phi}{dE_\gamma}(E_\gamma,\psi) = \frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_i B_i \frac{dN_\gamma^i}{dE_\gamma}\frac{1}{4\pi}\int_\psi \frac{d\Omega}{\Delta\psi}\int_{\text{los}} \rho^2(\psi,l)\, dl$$

Velocity averaged
annihilation cross section

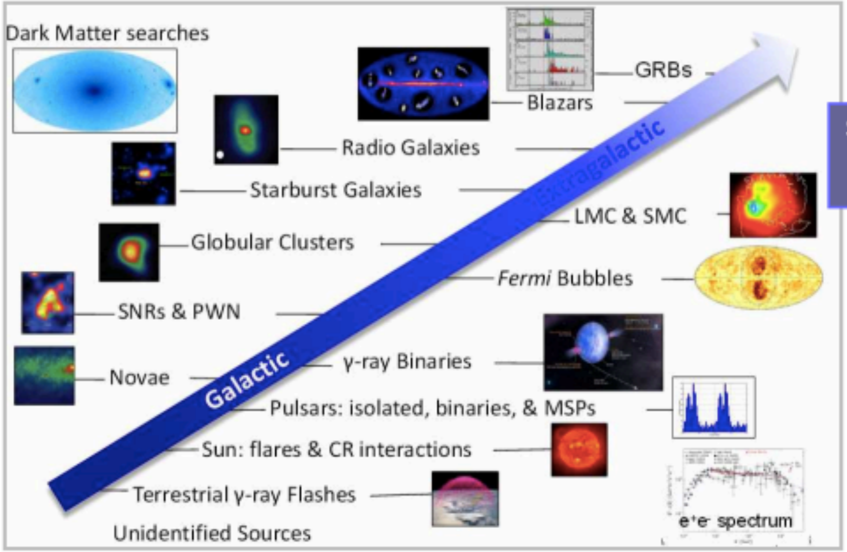
Energy spectra
(summing over all the ‘i’
simplified channels)

J-factor from
astrophysical observation

Fermi-LAT Large Array Telescope: focus on gamma rays (photons)

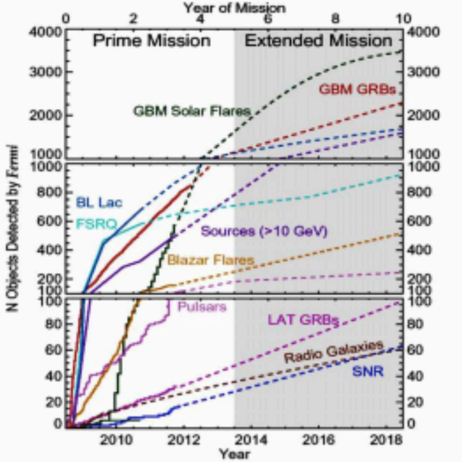

Fermi (formerly GLAST): two Instruments
The Large Area Telescope (LAT)
20 MeV - 300 GeV
>2.5 sr FoV
The Burst Monitor (GBM)
8 keV – 40 MeV
9.5 sr FoV
the LAT
modular - 4x4 array
7 ton – 650watts
γ
Tracker (4x4 array of towers)
Precision Si-strip Tracker (TKR)
18 XY tracking planes with tungsten foil converters. Single-sided silicon strip detectors (228 μm pitch, 900k strips) Measures the photon direction; gamma ID.
ACD
Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles. Rejects background of charged cosmic rays; segmentation mitigates self-veto effects at high energy.
e+
e−
Calorimeter
Hodoscopic CsI Calorimeter (CAL) Array of 1536 CsI(Tl) crystals in 8 layers. Measures the photon energy; image the shower.
Electronics System
Includes flexible, robust hardware trigger and software filters.
Gamma Ray Burst Monitor (GBM):
correlative transient observations
~ 8 keV – 30 MeV
Large Area Telescope (LAT):
~20 MeV --> 300 GeV
Spacecraft
GeV Sky
Galactic
Point Sources
Isotropic
???
9
stefano.ciprini@ssdc.asi.it
INFN Tor Vergata & SSDC ASI, Rome

Fermi Science Menu



ALL-SKY + ALL-TIMES (i.e. spatial SURVEY + TIME-DOMAIN monitor) mission for the HE g-ray Universe.

SURVEY → uniformity, serendipity, variability, transients, cross-corr, cross-match, time domain monitor.



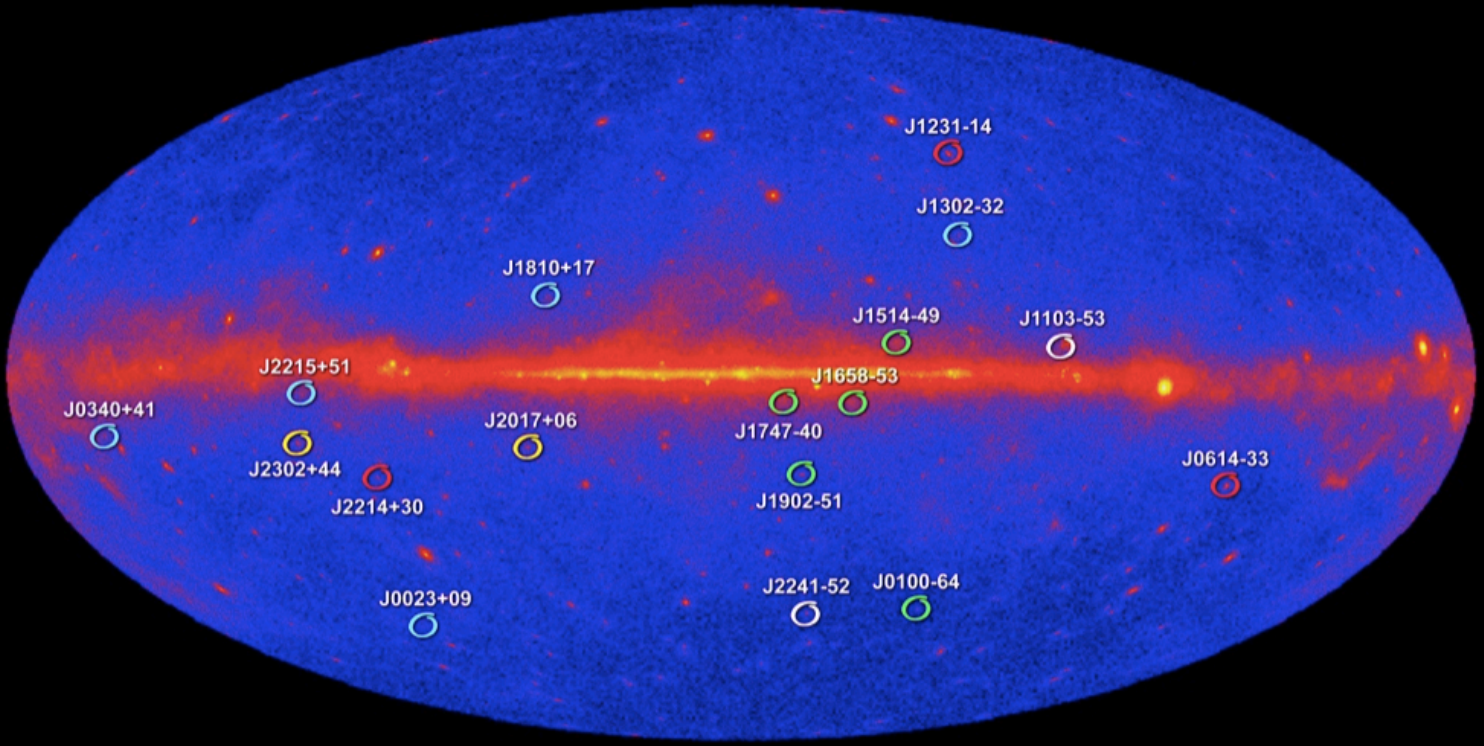
Fermi increased the number of known gamma-ray emitting objects by nearly one order of magnitude compared to previous experiments, and has added several new source classes not previously known in this energy range.

Fermi mission operations: 1) primary mode (sky survey): scan entire sky every 3 hours. 2) Autonomous Repoint Request (ARR) for GRB/transient on-board sw triggers. 3) Target of Opportunity (ToO) following GI proposals/notes. 4) Modified survey profile (e.g. Galactic center biased in Dec.2013-Dec.2014).

Fermi: a tool to study cosmic accelerators
in energy, time, sky position/distribution, cosmic distance

stefano.ciprini@ssdc.asi.it 11

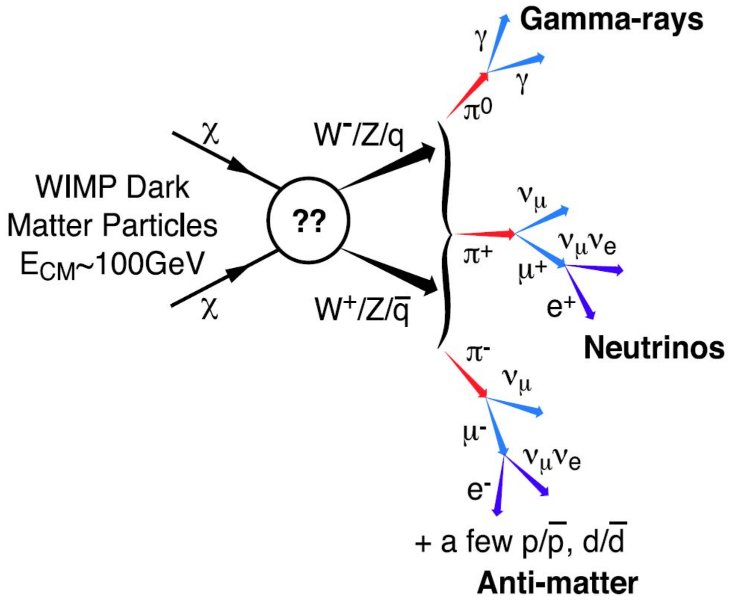
New Millisecond Radio Pulsars Found in Fermi LAT Unidentified Sources

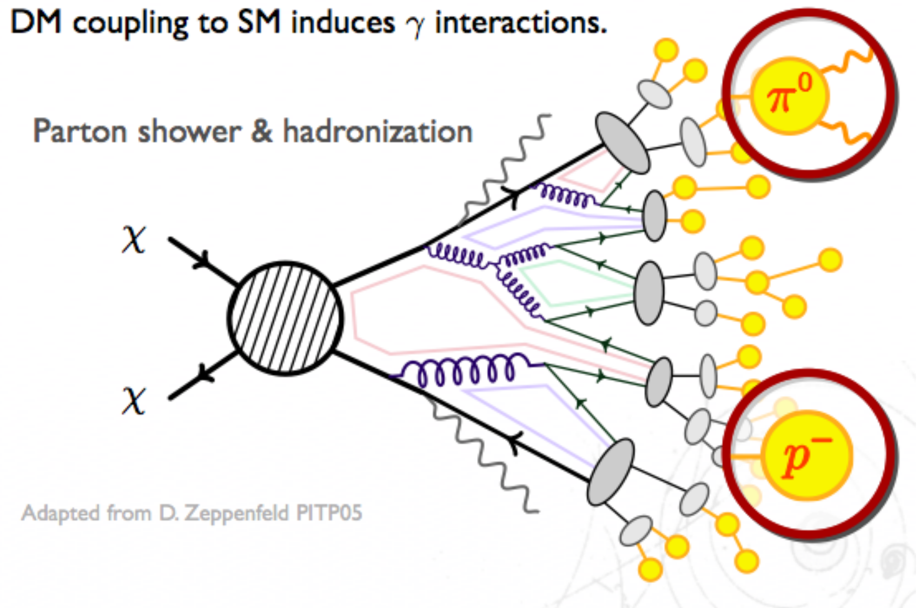


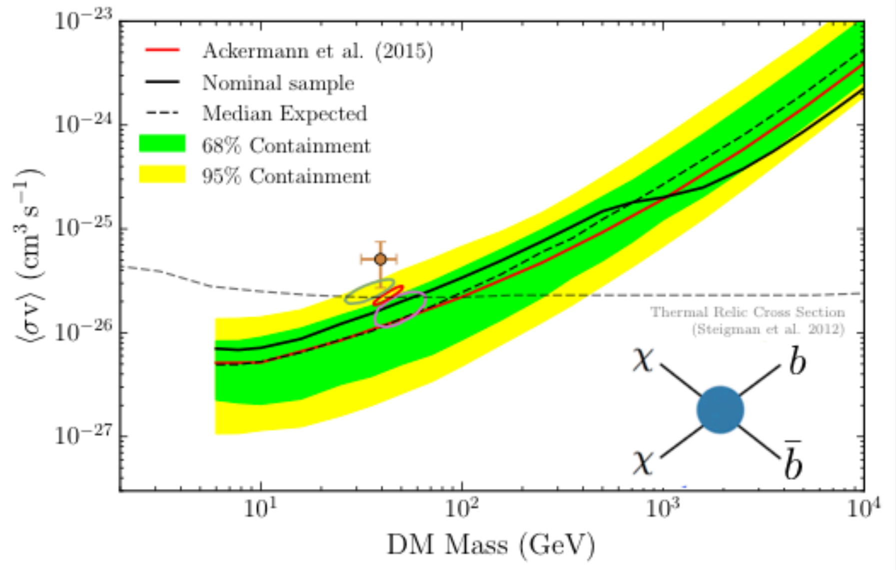
- Led by Fernando Camilo (Columbia Univ.) using Australia's CSIRO Parkes Observatory
- Led by Mallory Roberts (Eureka Scientific/GMU/NRL) using the NRAO's Green Bank Telescope
- Led by Scott Ransom (NRAO) using the Green Bank Telescope
- Led by Ismael Cognard (CNRS) using France's Nançay Radio Telescope
- Led by Mike Keith (ATNF) using Parkes Observatory

Fermi Gamma-ray Space Telescope

« Break it » : DM Indirect Detection

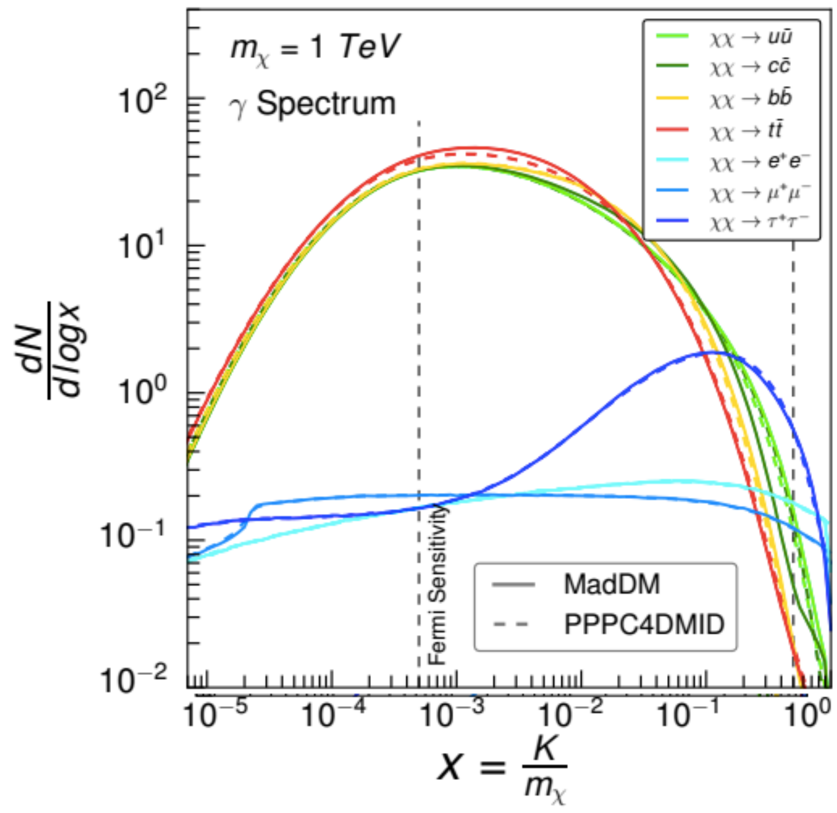


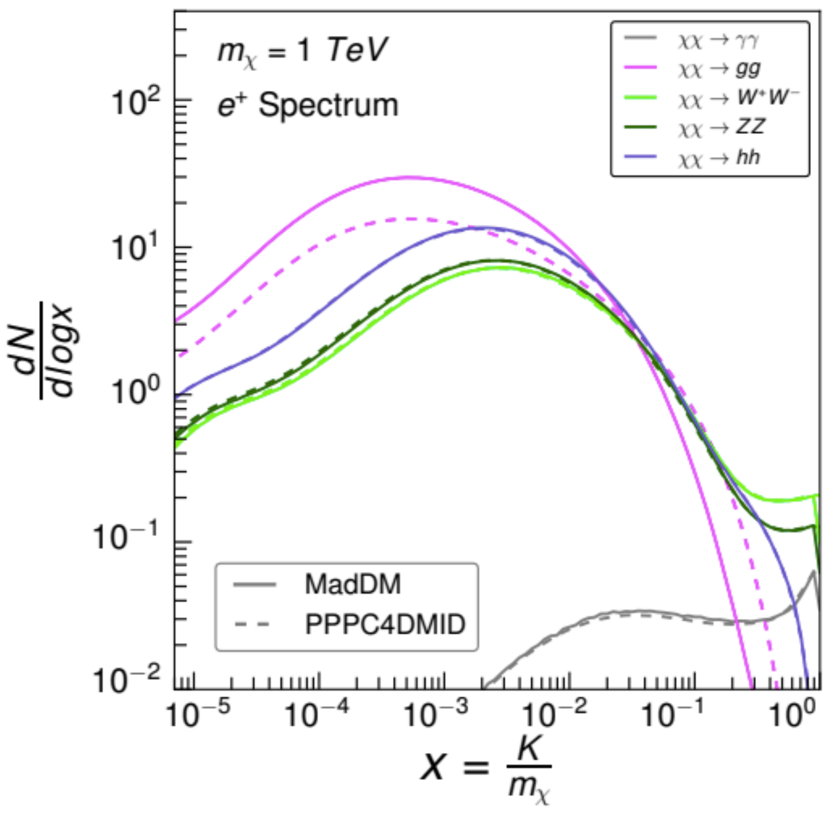




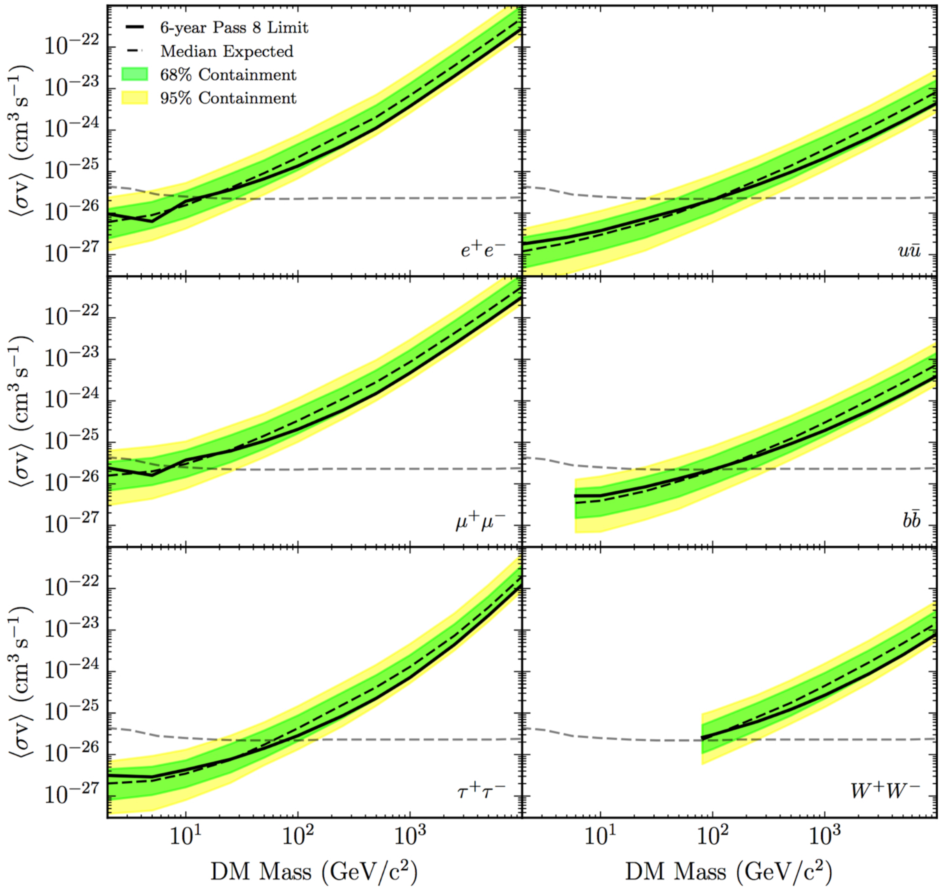
- Limits on the annihilation cross section from gamma rays fluxes
- Fermi-LAT results available only for the $\chi\chi$—>bb and $\chi\chi$—>$\tau\tau$ channels
  Simplified Models for DM annihilation
- Experimental data & recipes to calculate upper limits for arbitrary channels provided by Fermi-LAT

Example: gammas and positron spectra (at source)





Fermi-LAT Results

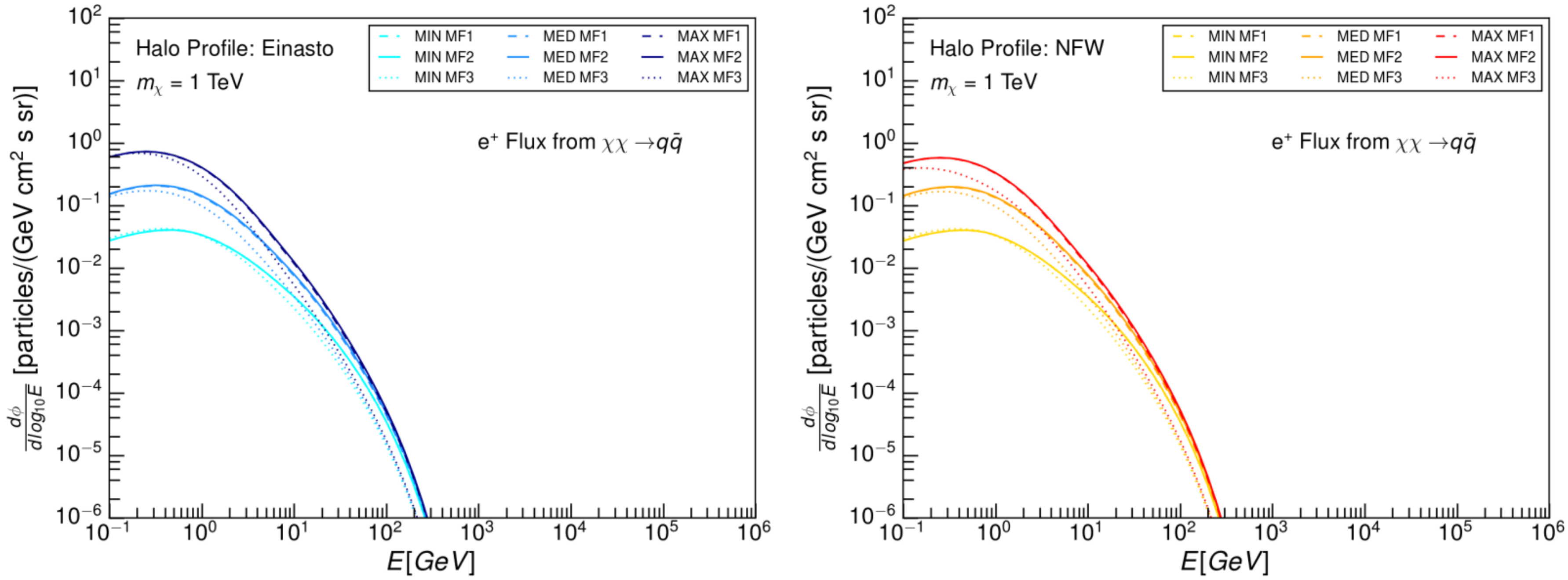


$$\chi\chi \rightarrow gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$$
$$\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$$

Fermi-LAT upper limits on the velocity-averaged cross section for DM annihilations into several SM channels (simplified models)

derived using gamma-rays observations from dwarf spheroidal galaxies

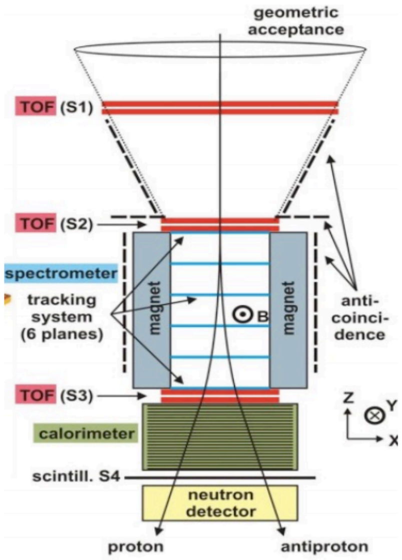
- The propagation of charged CR in the galaxies depends strongly on the parametrization of the galaxy
- In particular, the modelling of source points e.g. Pulsars seems very important, as well as the dense region in the inner part

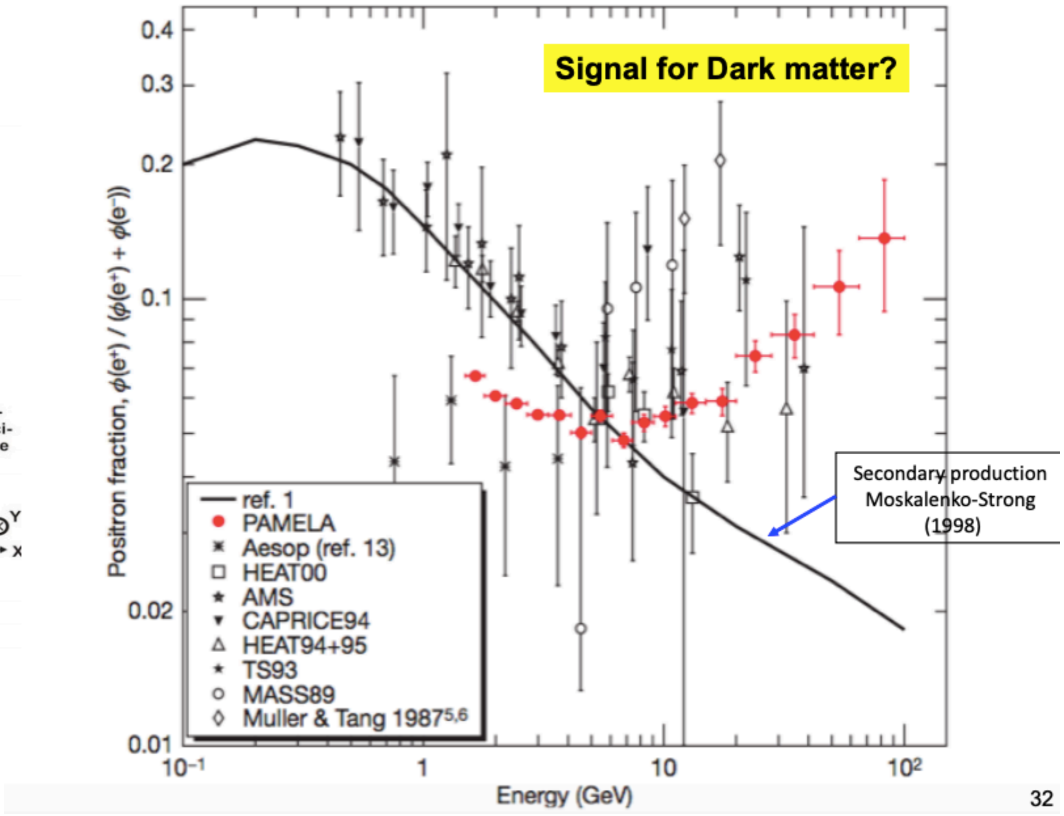


Reminder: from Prof. Jeitler's lecture

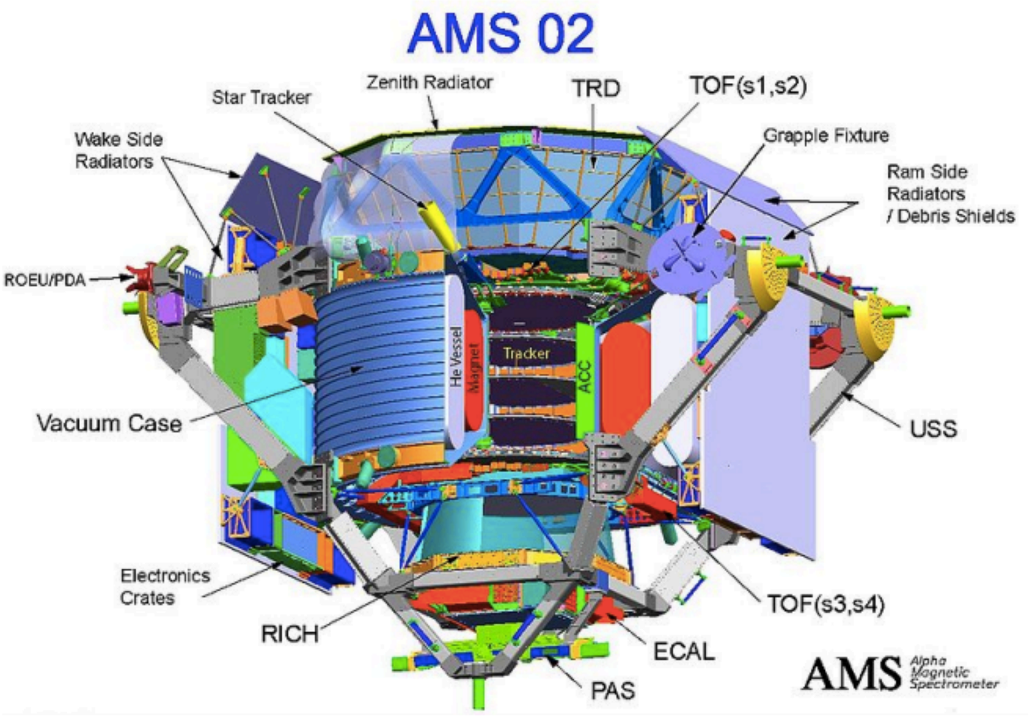
PAMELA Instrument

- Satellite-borne instrument.
  - size: 1.02 m (ϕ) x 1.3 m (H)
  - weight: 470 kg
  - power: 355 W
- Time of flight
  - Mass identification up to 1 GeV
- Magnetic spectrometer
  - 0.43 T permanent magnet
  - Silicon strip detector
  - Charge sign and momentum
- Electromagnetic Calorimeter
  - W/Si sampling: $16.3X_0$, $0.6\lambda_I$
  - Electron/positron ID.
  - Energy measurement.





AMS: The Alpha Magnetic Spectrometer



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]
		$5.7 \times 10^{-10} \le \eta \le 6.7 \times 10^{-10}$ (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	$^\sharp -1.10^{+0.08}_{-0.07}$ (*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	$N_{\rm eff}$	$^\dagger 3.36 \pm 0.34$	[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	$\Omega_{\rm tot} = \Omega_{\rm m} + \ldots + \Omega_\Lambda$	$^\sharp 0.96^{+0.4}_{-0.5}$ (95%CL)	[2]
		$^\sharp 1.000(7)$ (95% CL; CMB+BAO)	[2]
fluctuation amplitude at $8\,h^{-1}$ Mpc scale	σ_8	$^\dagger 0.828 \pm 0.012$	[2,3]
running spectral index slope, $k_0 = 0.002$ Mpc^{-1}	$dn_{\rm s}/d\ln k$	$^\sharp -0.015(9)$	[2]
tensor-to-scalar field perturbations ratio, k_0=0.002 Mpc^{-1}	$r = T/S$	$^\sharp < 0.11$ at 95% CL; no running	[2,3]
redshift at decoupling	$z_{\rm dec}$	$^\dagger 1090.2 \pm 0.7$	[2]
age at decoupling	t_*	$^\dagger 3.72 \times 10^5$ yr	
sound horizon at decoupling	$r_s(z_*)$	$^\dagger 147.5 \pm 0.6$ Mpc (*Planck* CMB)	[32]
redshift of matter-radiation equality	$z_{\rm eq}$	$^\dagger 3360 \pm 70$	[2]
redshift at half reionization	$z_{\rm reion}$	$^\dagger 11.1 \pm 1.1$	[2]
age at half reionization	$t_{\rm reion}$	$^\dagger 462$ Myr	
age of the Universe	t_0	$^\dagger 13.81 \pm 0.05$ Gyr	[2]