Dark matter

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Dark Matter, Phase transitions and Gravitational Waves

Dark Matter

Brief history of the universe

The early years

In the “beginning” the was a hot and dense universe. The interactions between particles were frequent and energetic. Then, the primordial plasma cooled and the light elements were formed (hydrogen, helium and lithium).

With the drop in energy the first stable atoms appeared. This is also the moment when photons started to roam freely.

What we see today is the microwave radiation from this afterglow. The radiation is nearly uniform (about 2.7 K) in all directions.

There are however small variations in the cosmic microwave background in temperature at a level of 1 part in 10 000. These fluctuations reflect tiny variations in the primordial density of matter.

Over time, and under the influence of gravity, these matter fluctuations grew. Dense regions were getting denser. Eventually, galaxies, stars and planets formed.

The early years

However what we “see” today as matter and energy is barely what we have access to in experiments on earth. Most of the universe today consists of forms of strange matter and energy.

Dark matter is required to explain the stability of galaxies and the rate of formation of the large-scale structure of the universe. Dark energy is required to rationalise the striking fact that the expansion of the universe started to accelerate recently (meaning a few billion years ago). What dark matter and dark energy are is still a mystery.

Finally, there is growing evidence that the primordial density perturbations originated from microscopic quantum fluctuations, stretched to cosmic sizes during a period of inflationary expansion. The physical origin of inflation is still a topic of active research.

So what now?

Missing ingredients:

Dark matter - no good dark matter candidates in the SM

Mater-antimatter asymmetry - more CP violation is needed

Neutrino masses…

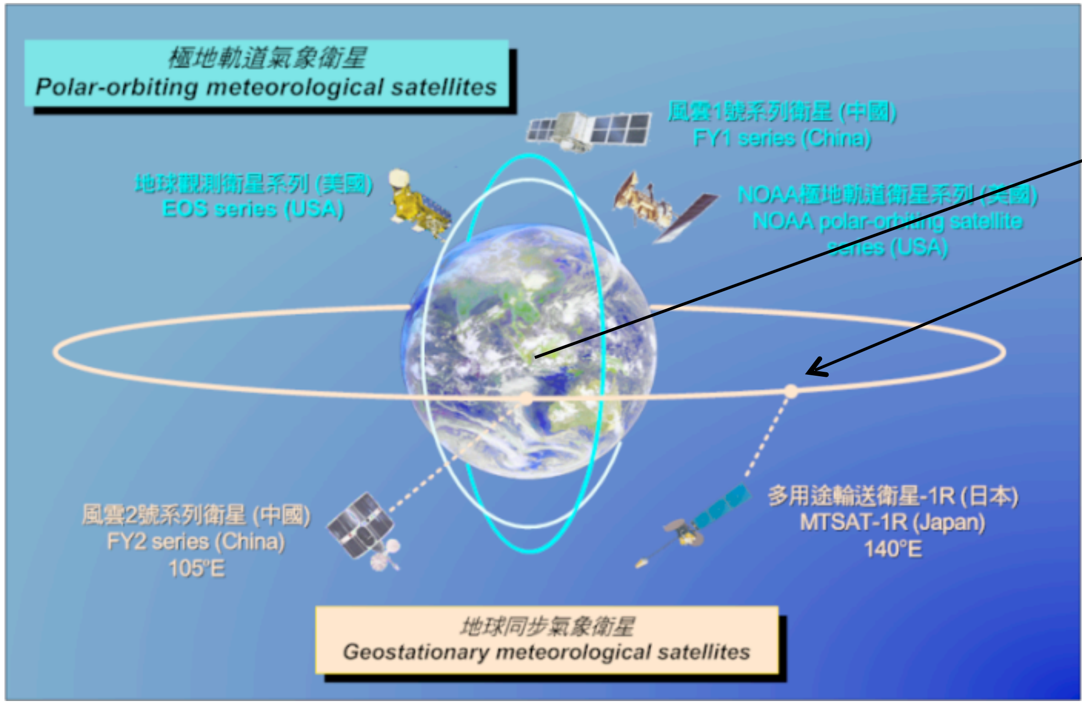
Unexplained experimental results:

Muon magnetic moment… maybe not

There is also gravity and dark energy

Fritz Zwicky (1930) When discussing the discrepancy between the observed and the expected rotation velocity of galaxies.

> "Should this turn out to be true, the surprising result would follow that dark matter is present in a much higher density than radiating matter."



Earth

Satellite

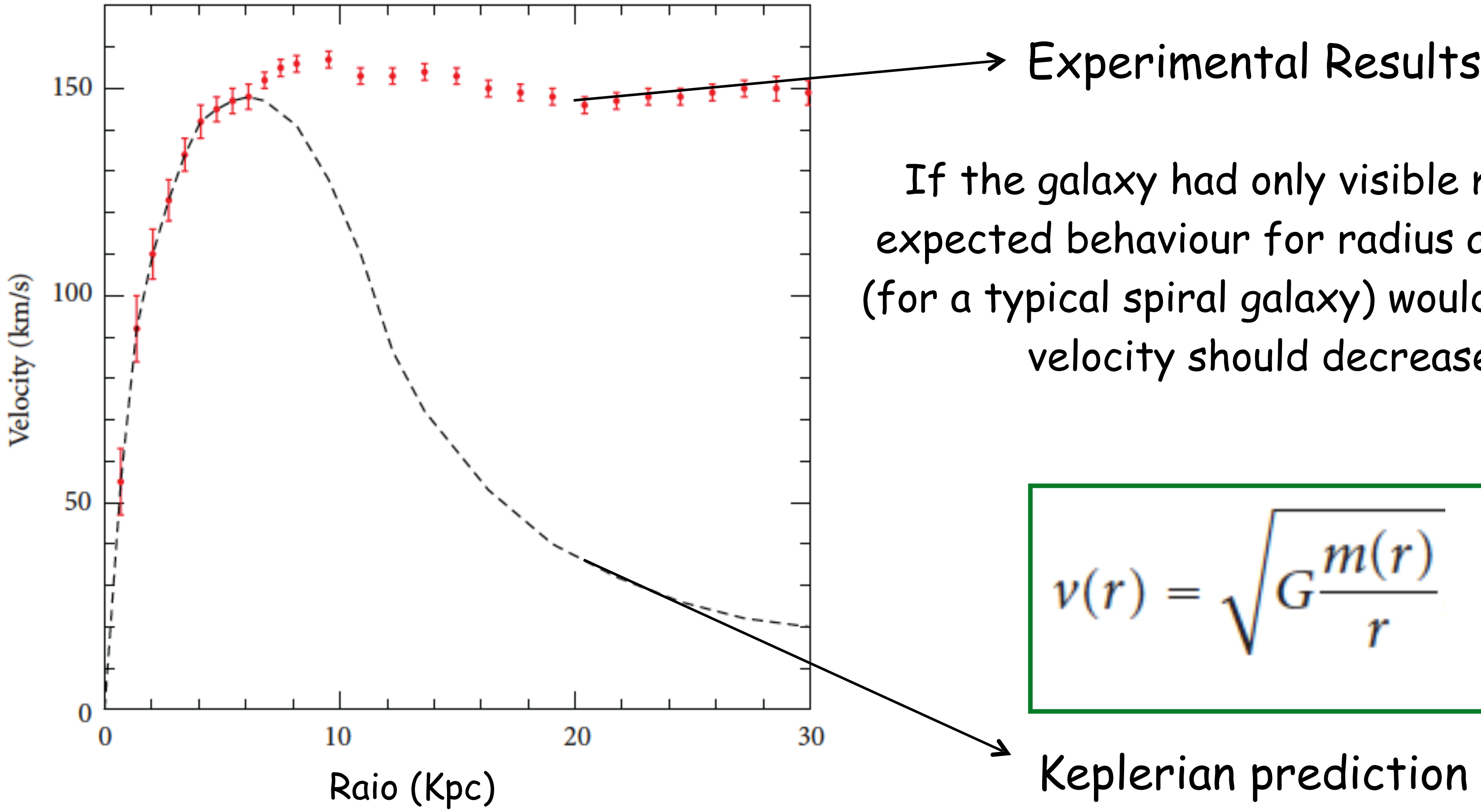
$$\frac{m v^2}{r} = G \frac{m M}{r^2}$$

$$v(r) = \sqrt{G \frac{m(r)}{r}}$$

At a distance of 640 Km, the satellite has a velocity of 27000 Km/h.

Rotation curves of galaxies

K. G. Begeman, "H I rotation curves of spiral galaxies," *Astronomy and Astrophysics*, vol. 223, pp. 47–60, 1989.

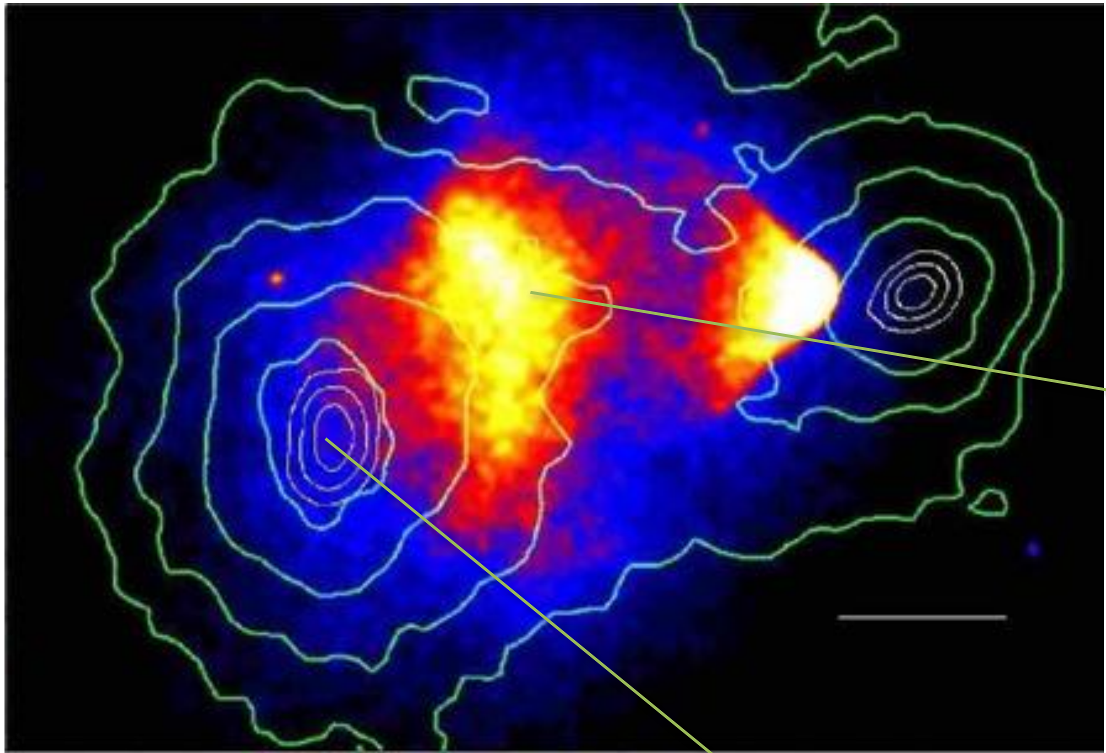


If the galaxy had only visible matter the expected behaviour for radius above 10 Kpc (for a typical spiral galaxy) would be that the velocity should decrease as:

$$v(r) = \sqrt{G\frac{m(r)}{r}}$$

Contrary to luminosity, mass is not concentrated close to centre of spiral galaxies.
The distribution of light does not match the distribution of mass.

The Bullet Cluster



Two galaxies colliding – several sets of observational data superimposed: optical, X-ray, gravitational lensing.

Hot and dense gas. Typical shape of a high speed collision (4000 km/s).

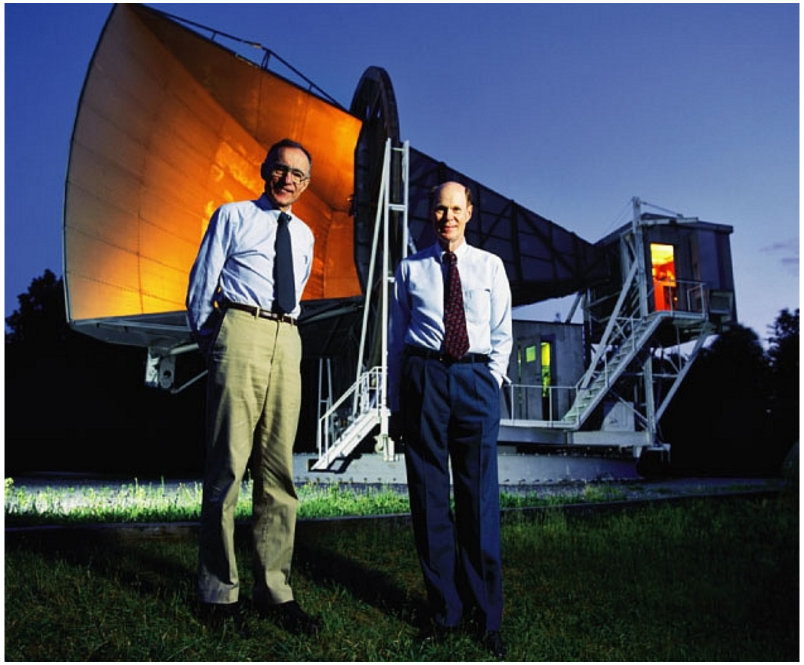
Lines of gravitation potential – from gravitational lensing show that the dark matter is concentrated around the galaxies and that it is not affected by the collisions.

Dark matter interacts very weakly!

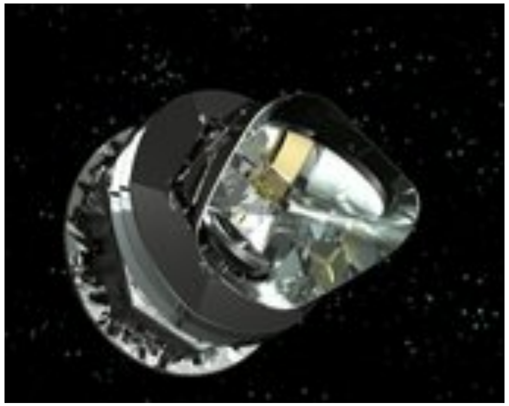
The Cosmic Microwave Background

In the Standard Model of Cosmology, it is assumed that just after the Big Bang the Universe was extremely hot, it then inflated (very rapidly) and cooled down. One effect of the rapid cooling was predicted to be a very low temperature radiation that would populate all space until today.

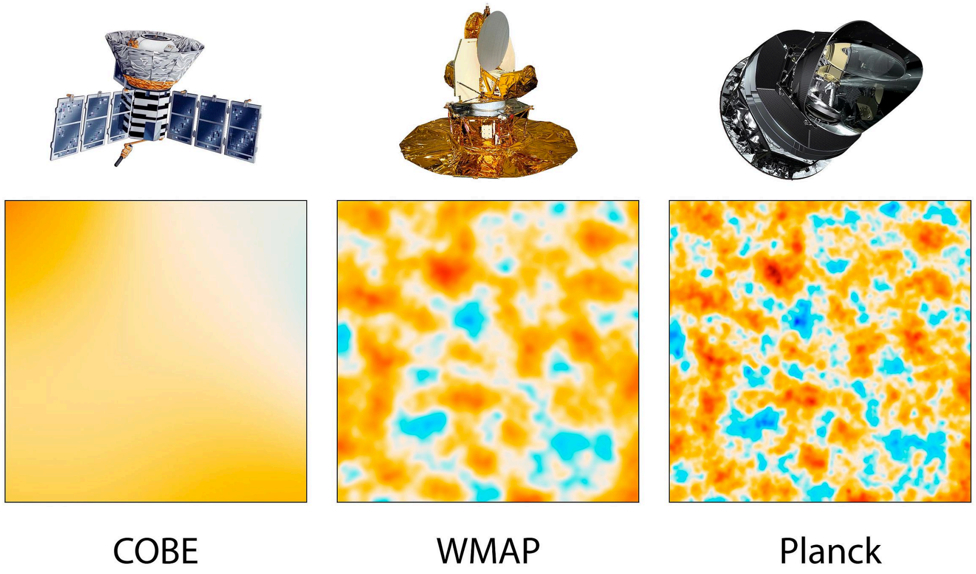
In 1965, astronomers Arno Penzias e Robert Wilson found (by accident – or so they say) an isotropic radiation of 2.725 Kelvin (- 270º C) (Nobel Prize 1978).



What can we learn from the CMB?



Planck



Planck +

cosmological model

Fluctuation in the Cosmic Background Radiation are due to the matter density fluctuations in the early Universe.

Once upon a time all particles were in thermal equilibrium.

As the Universe expanded and cooled, the rate of interactions was not enough to maintain thermal equilibrium (freeze out).

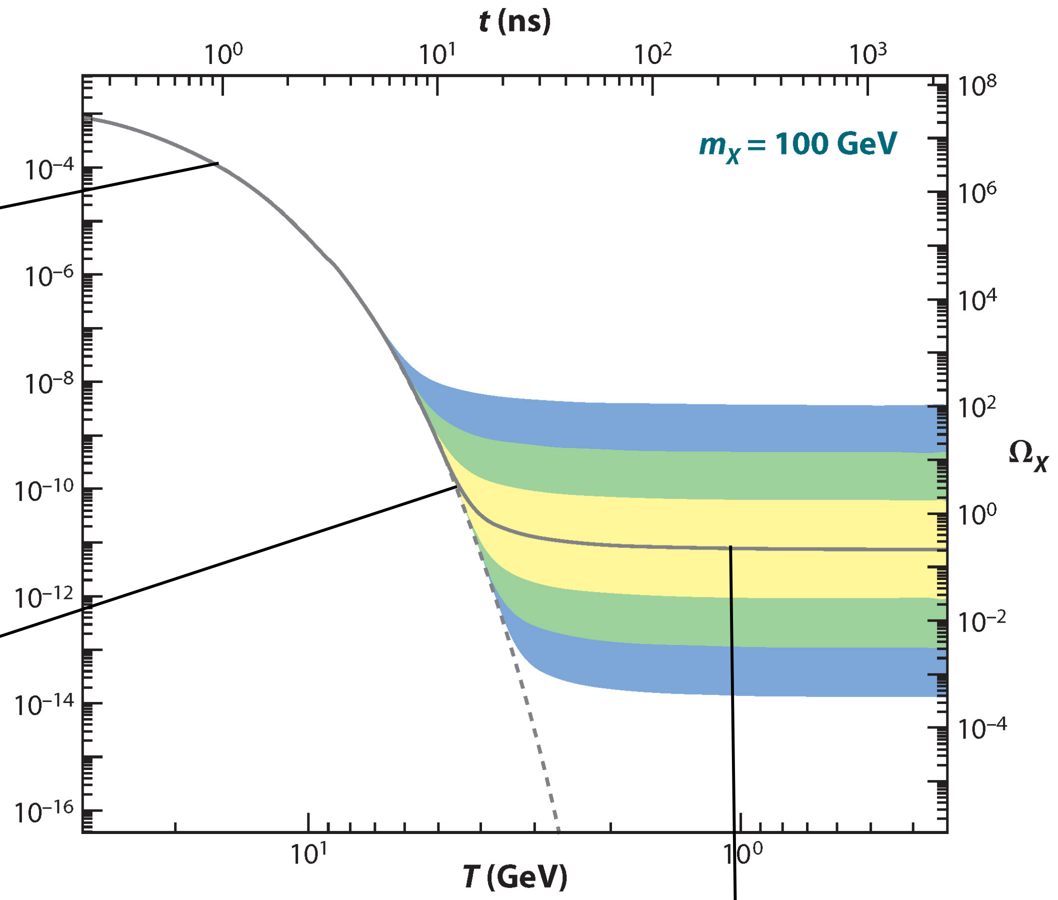
The unstable particles disappeared (decayed); number of stable particles reached a constant (thermal relic density) which has still approximately the same value today.

What happened to dark matter?

Before inflation – thermal equilibrium

Measure of density

Freeze-out



There are other mechanisms like freeze-in!

$$\Omega_{CDM} \approx \frac{6 \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}}{< \sigma v >} \approx 0.23\%$$

Measure of the interaction rate

Why is dark matter so interesting?

- It completely changes our perception of the universe. Just a while ago we thought all matter was made of essentially the same stuff.

- It is the most interdisciplinary (inside physics) subject as it needs general relativity, nuclear physics, particle physics, cosmology, classical physics (thermodynamics and mechanics...)

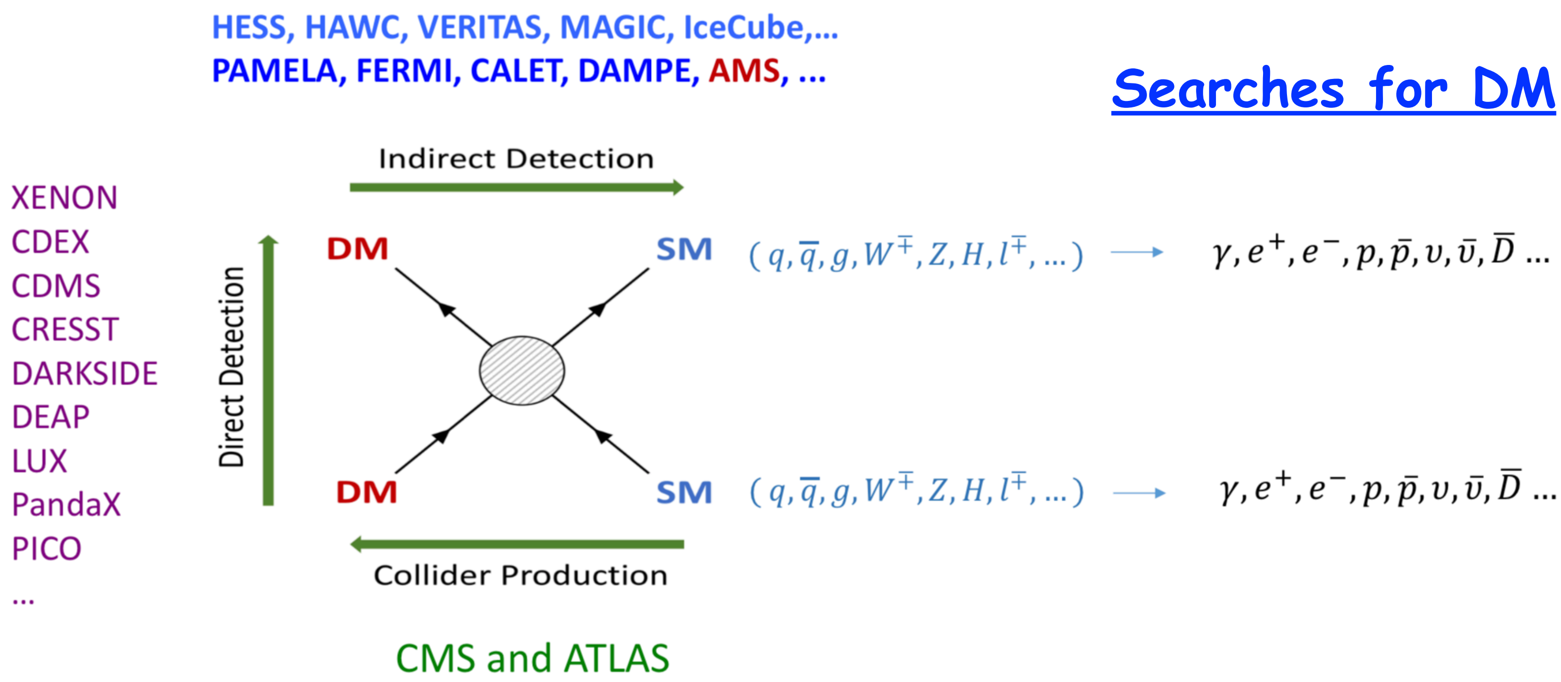
- Mystery – "we know" it exists, "we know where it is", we have some hints on how it behaves but we do not know what it is ...

Why is dark matter so interesting?

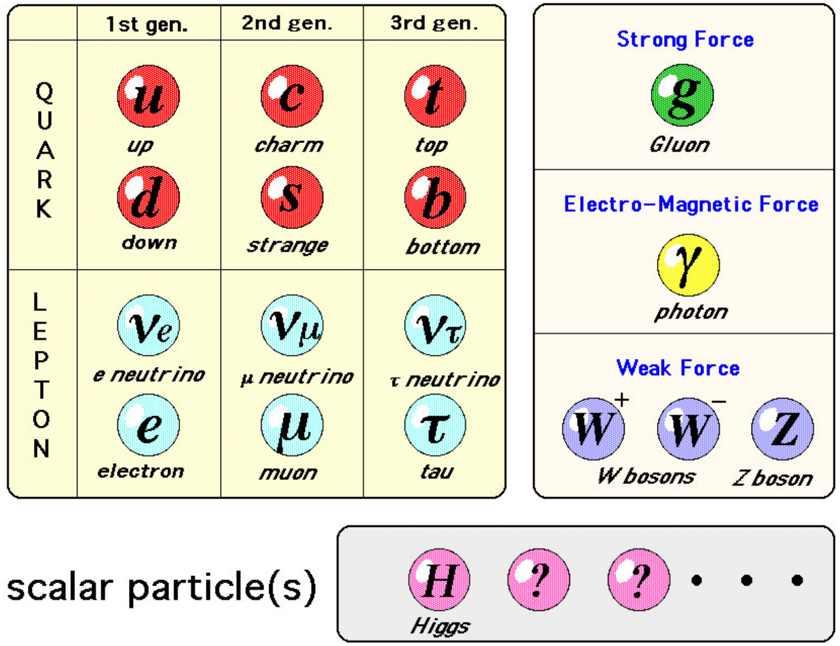
- **Massive, stable, neutral, weak (or none) interaction with SM**

WIMP - weakly interacting massive particles/ Many other possibilities - essentially no mass limits/ all spins possible

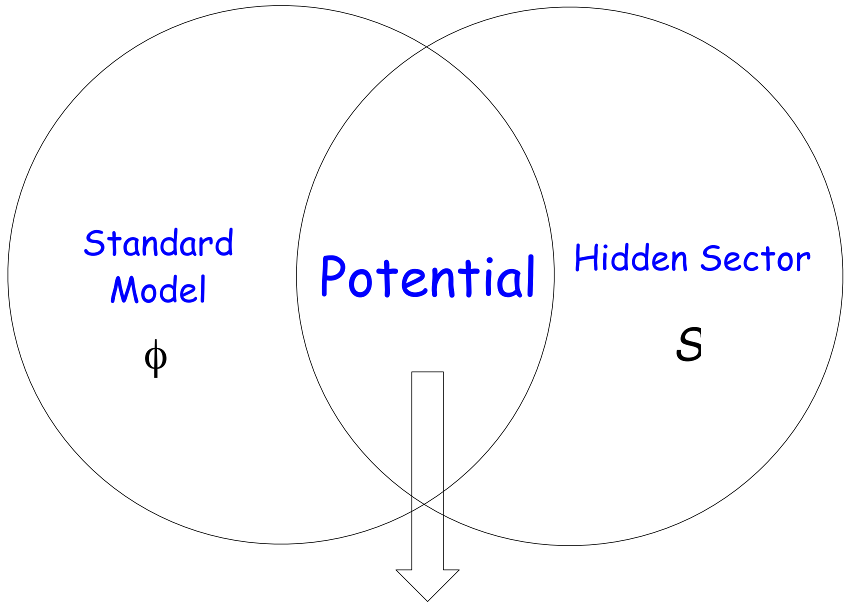
Searches for DM



Extensions of the SM - a new model is needed



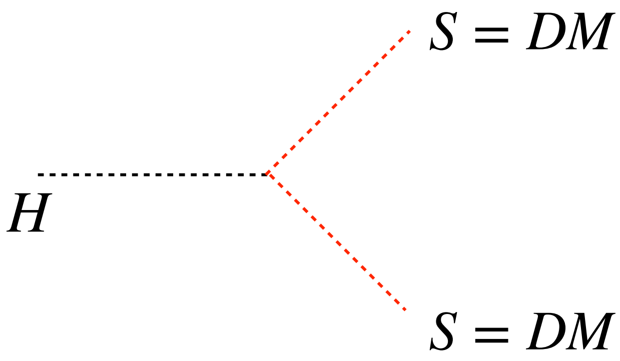
Elements of the Standard Model



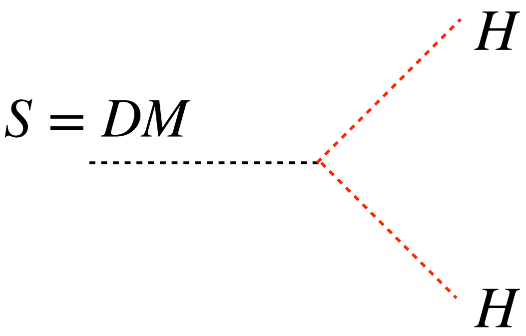
$$V_{\text{int}} = \lambda \phi^{\dagger} \phi S^{2}$$

Lagrangian term that links the SM with the hidden sector. Dark Matter particle has to be stable. Can be done with a new quantum number.

Conserved quantities - darkness



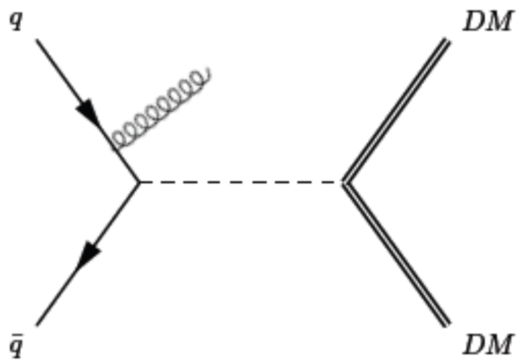
Model should conserve darkness - we need a stable particle. It is like electric charge - darkness number is constant.



Not possible - darkness not conserved.

$$Z(H) = 1;\ Z(DM) = -1$$

Darkness (Z) conserved



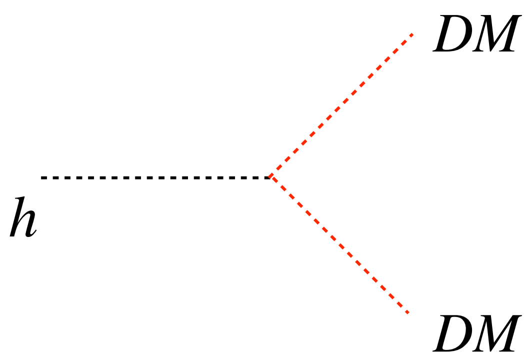
$$q\bar{q} \to g\, DM\, DM$$

$$Z(q\bar{q}) = Z(q)Z(\bar{q}) = 1 \times 1 = 1$$

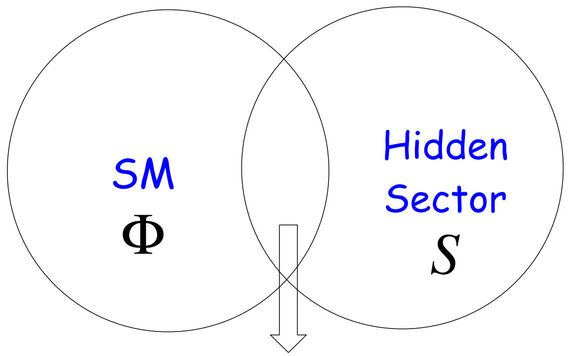
$$Z(q\bar{q}) = Z(g)Z(DM)Z(DM) = 1 \times (-1) \times (-1) = 1$$

All spins allowed

Dark Matter (IDM)

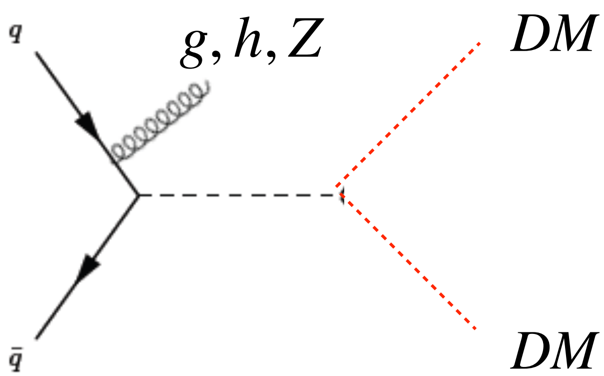


Model should conserve "darkness" - we need a stable particle. The invisible width of the Higgs and the dark matter direct detection experiments set a bound on the so-called portal coupling(s).



$$V_{portal} = \Phi^\dagger \Phi\, S^2$$

Searches need some kind of handle

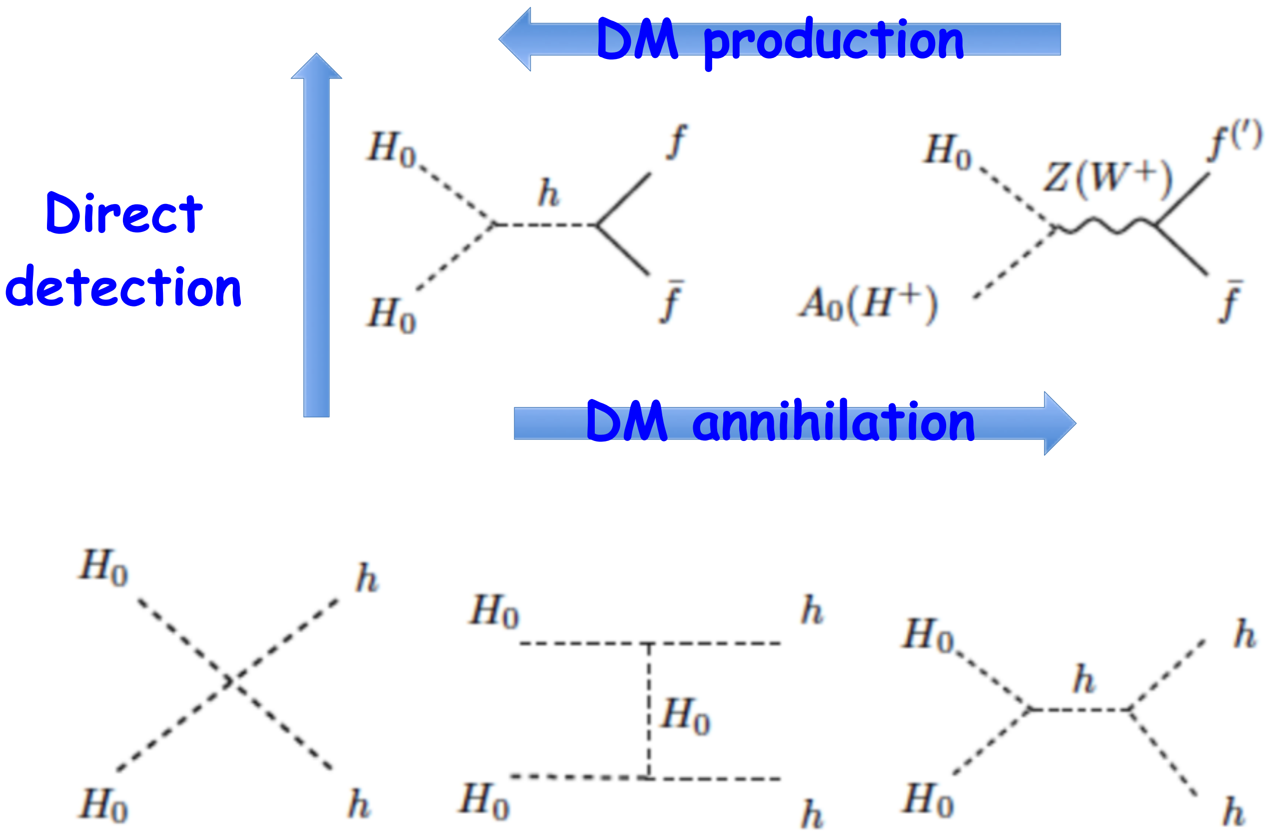


$$q\bar{q} \rightarrow (g, h, Z, \dots)\, DM\, DM$$

$$Z(q\bar{q}) = Z(q)Z(\bar{q}) = 1 \times 1 = 1$$

$$Z(q\bar{q}) = Z(H)Z(DM)Z(DM) = 1 \times (-1) \times (-1) = 1$$

Dark Matter (IDM)

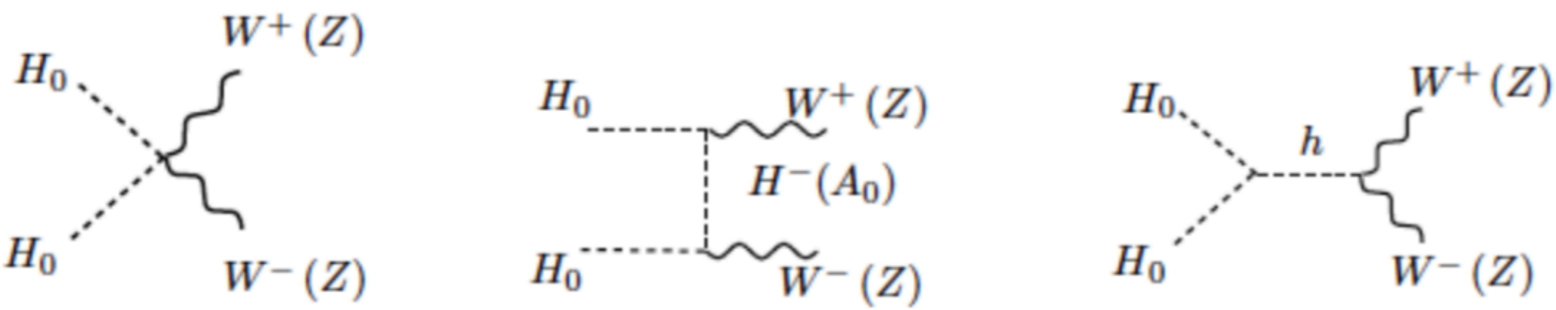


Fermions

WIMPs - Weakly interacting massive particles.

Model constrained mainly by relic density and direct detection.

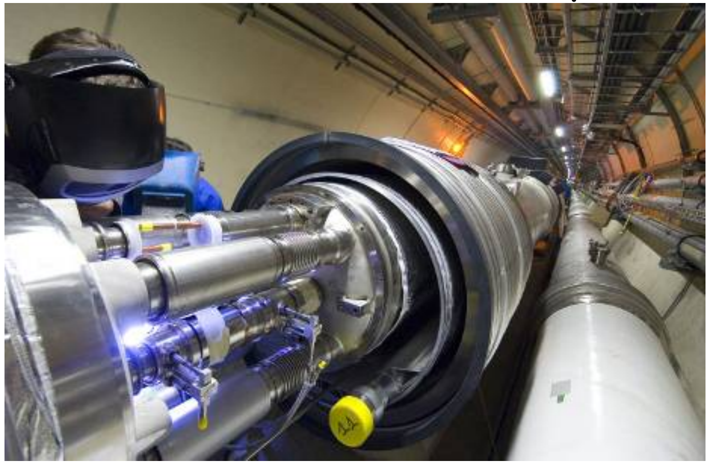
Higgs



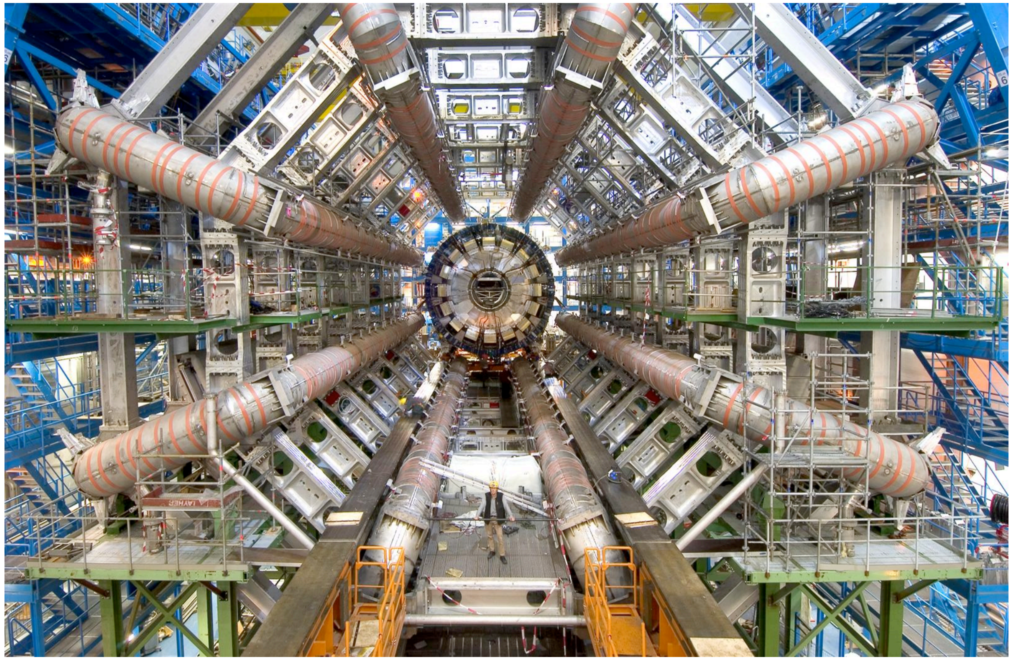
Gauge bosons

A collider is useful

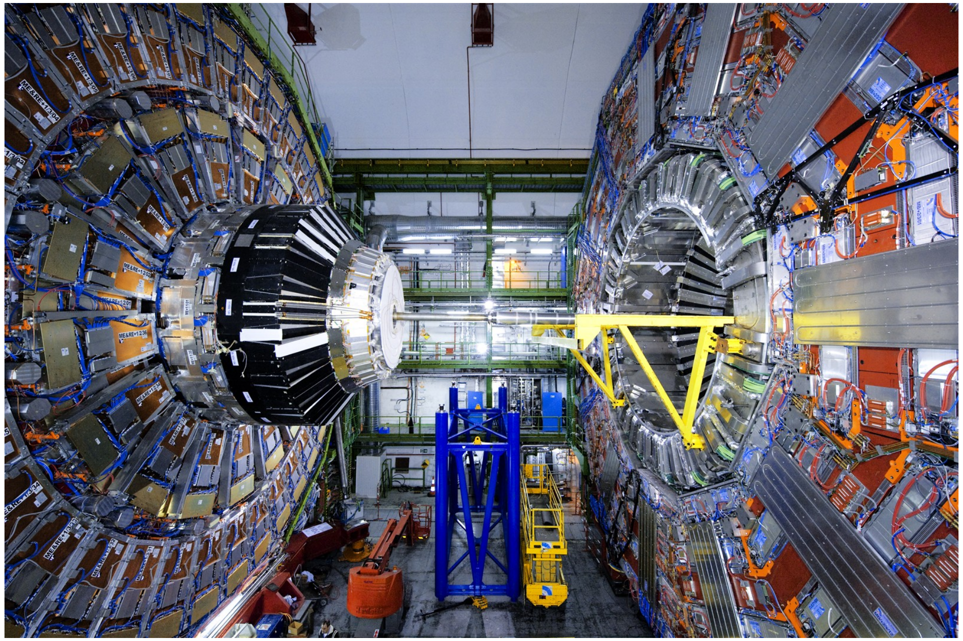
Where the protons travel



People

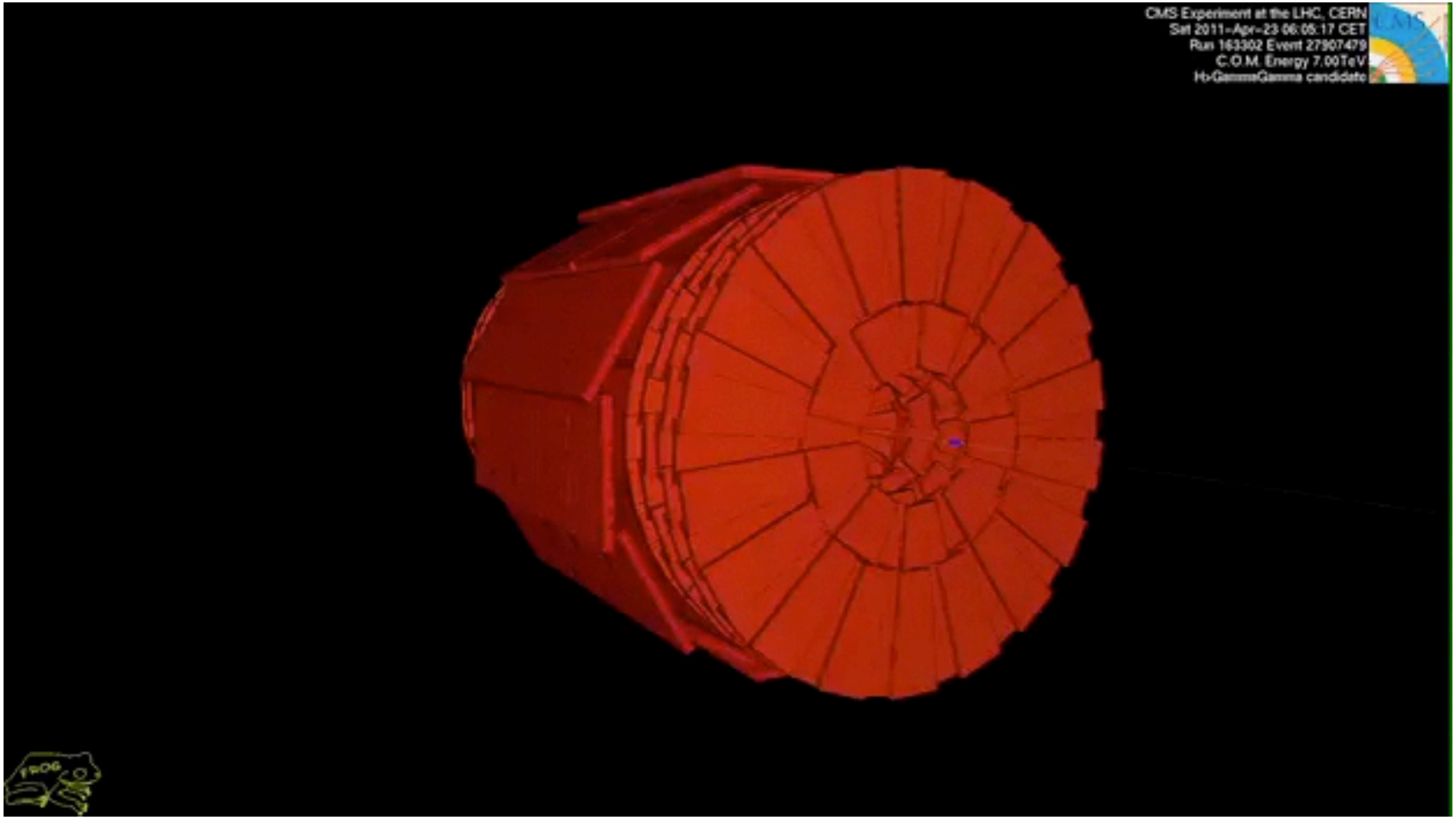


ATLAS

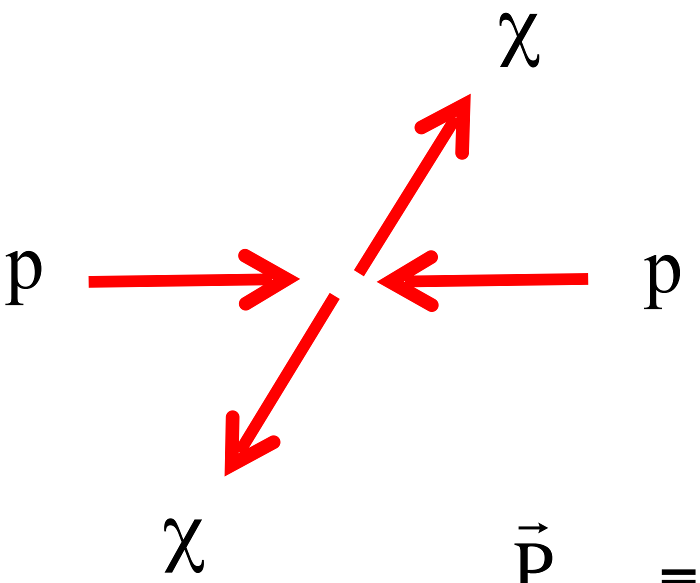


CMS

Particles collide…



Back to the LHC - Dark matter production



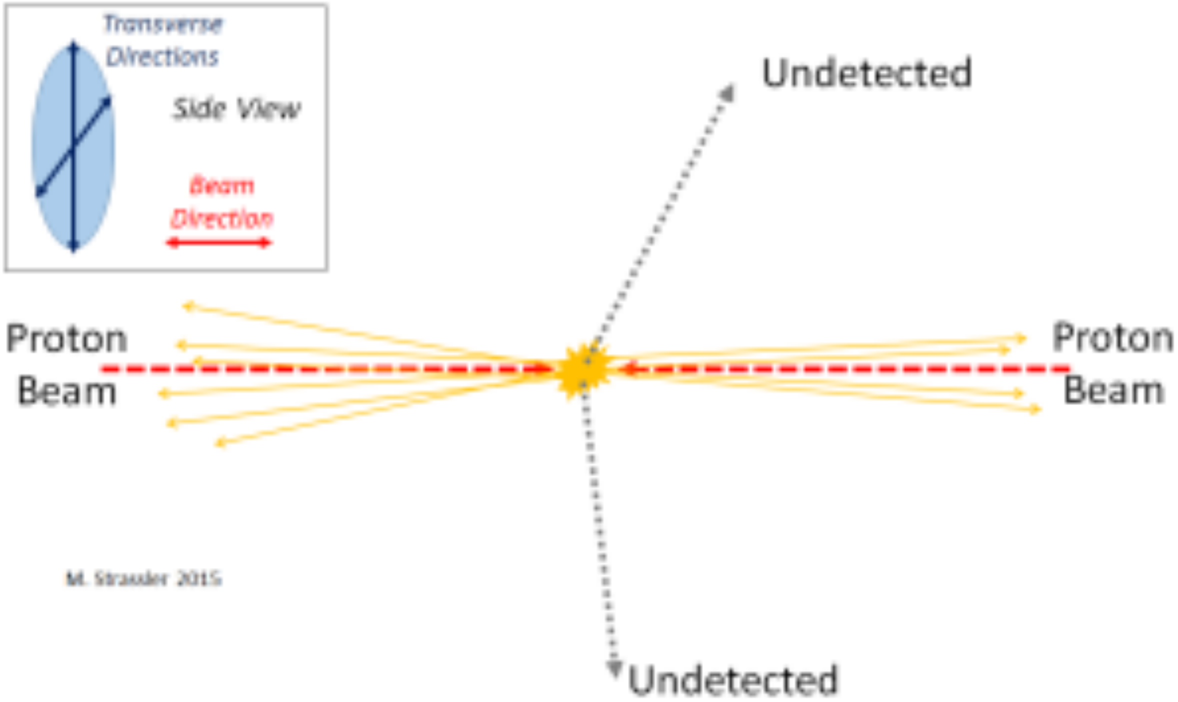
Darkness quantum number is conserved and therefore dark particles are produced in pairs

$$\vec{P}_{Total} = 0 \quad \xrightarrow{\text{LHC}} \quad P^{T}_{Total} = 0$$

But dark matter does not interact (or it does but very weakly) with the SM particles. We see nothing!

There will be MET – but still we see nothing!

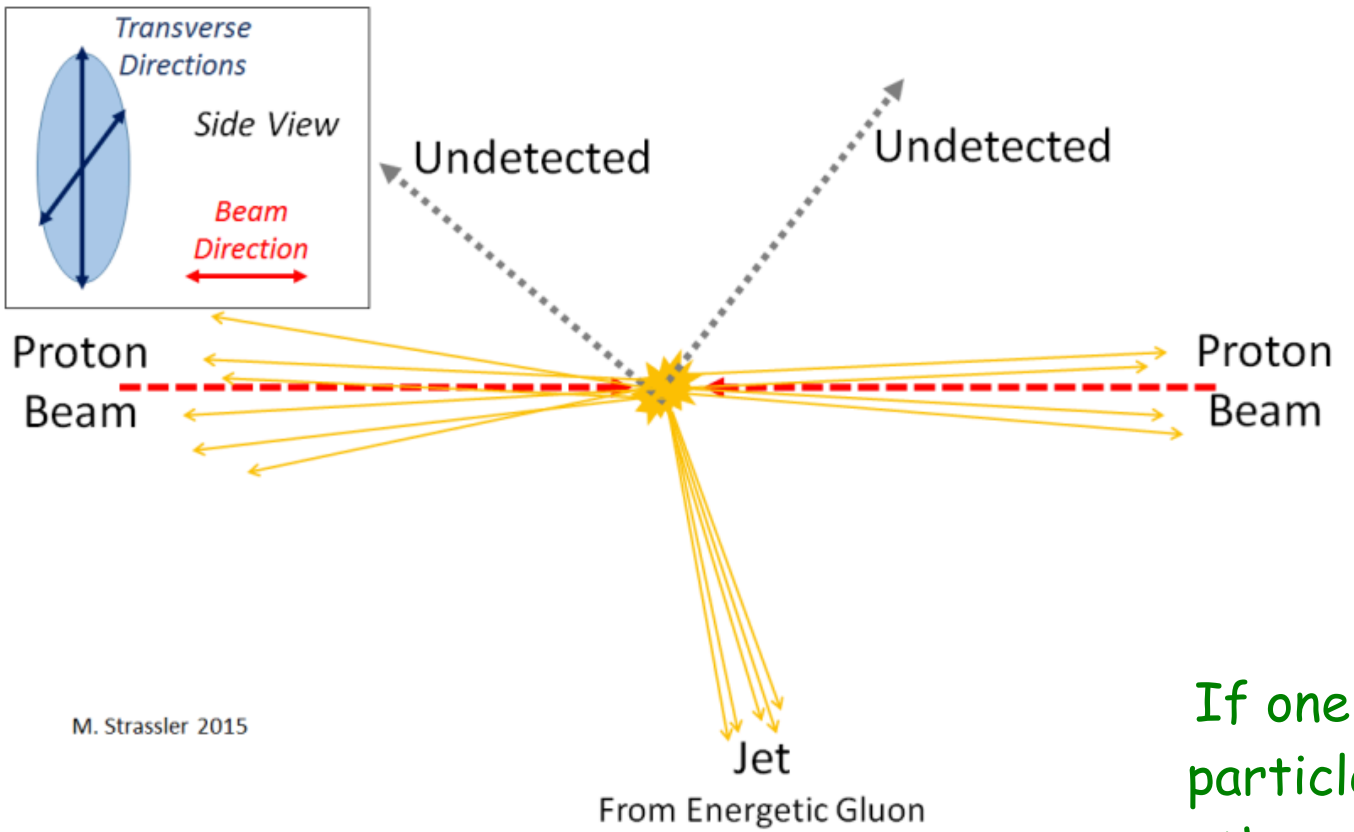
Back to the LHC - Dark matter production

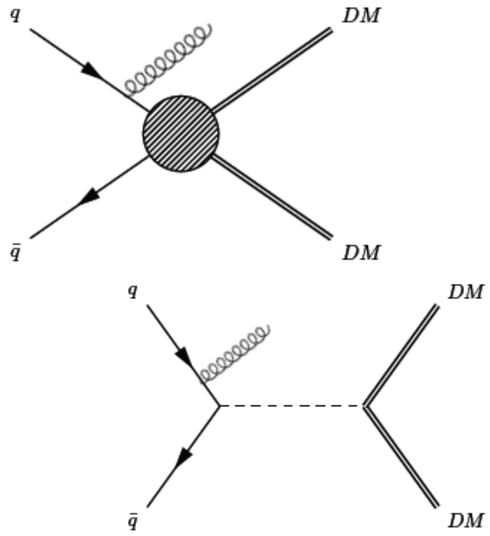


$$P^{T}_{Total} = 0$$

So the scenario where only dark matter is produced cannot simply be probed at any level.

Mono-X (X = Z, jet, Higgs…)

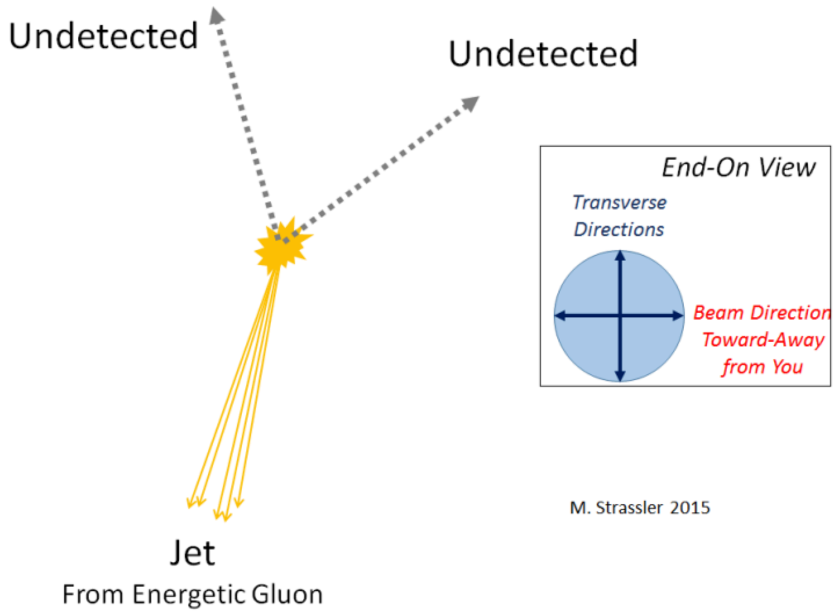




If one or more (high-energy) particles are also produced in the process then we have a mono-X (multi-X – still called mono-X) event! The X (for instance a jet) has a very large pT.

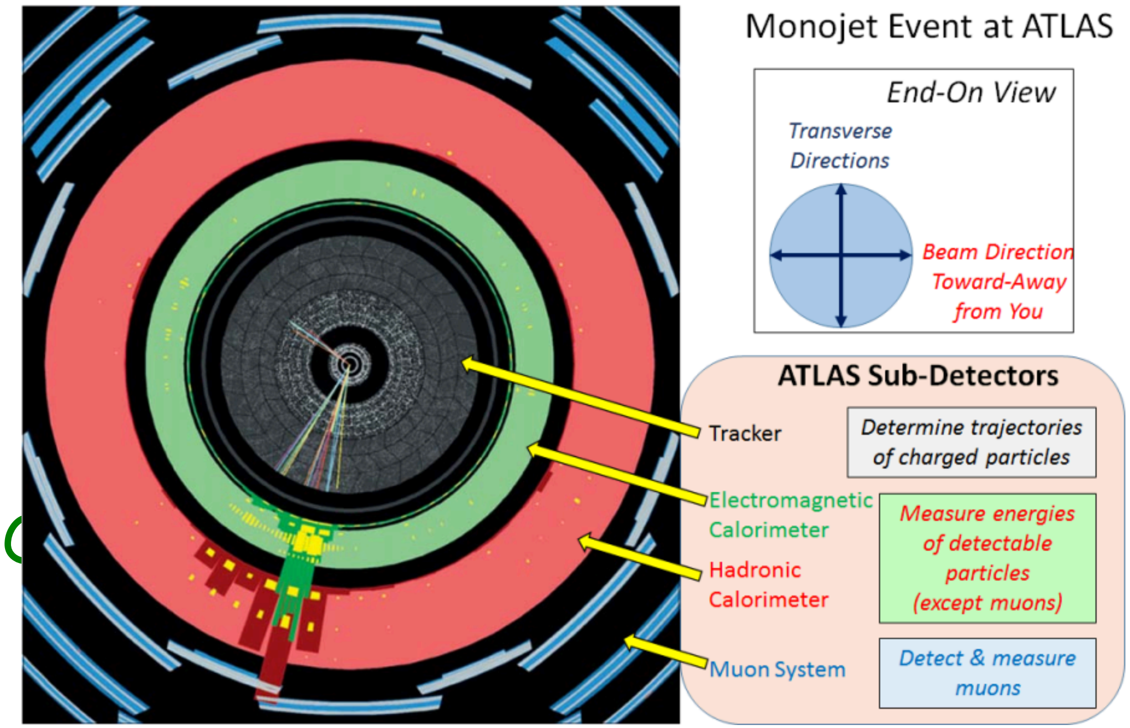
However, this can also be MET from neutrinos.

A monojet in ATLAS

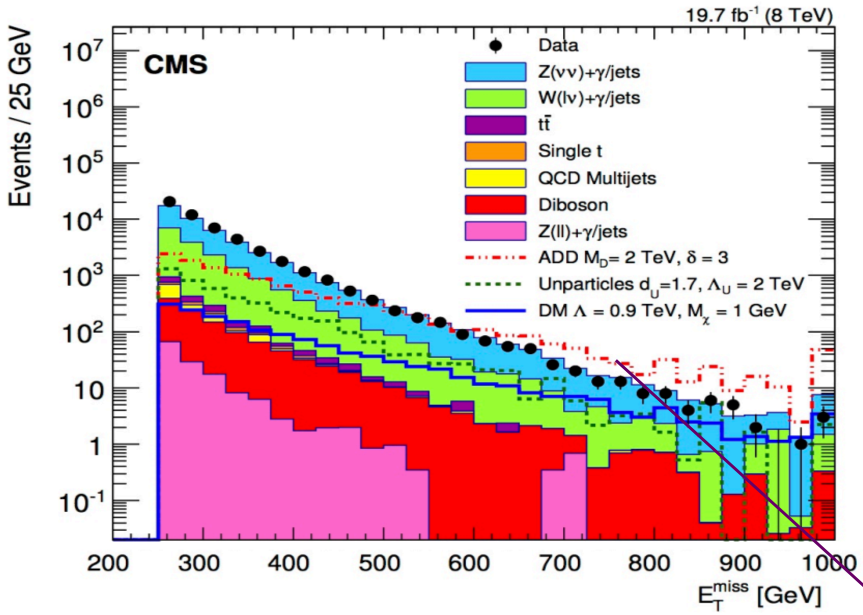


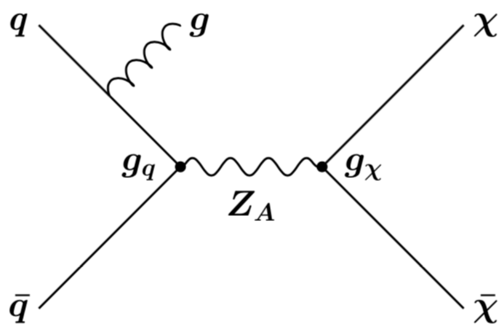
In the transverse plane.

Monojet event in the ATLAS detector.

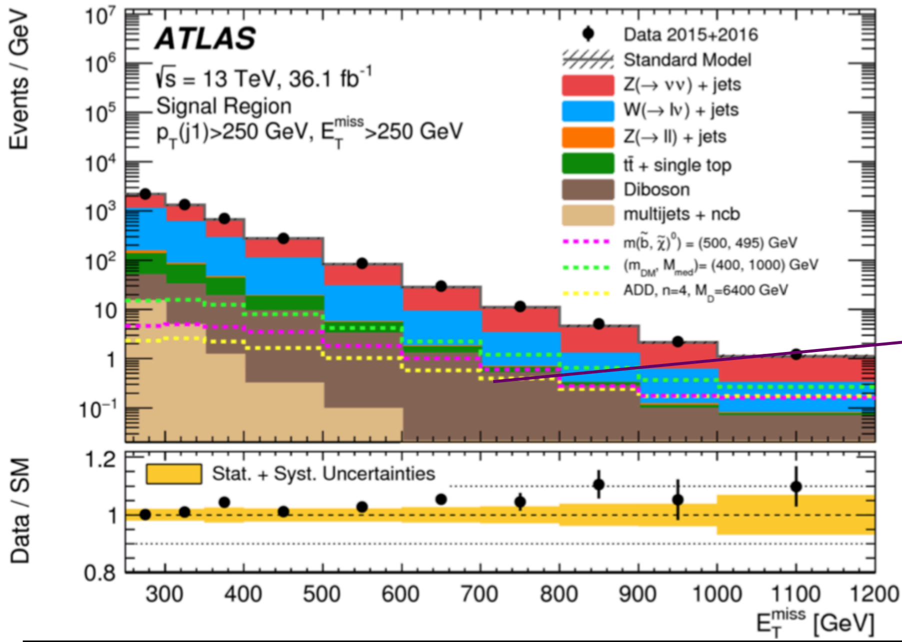


Mono-jet model interpretation in CMS



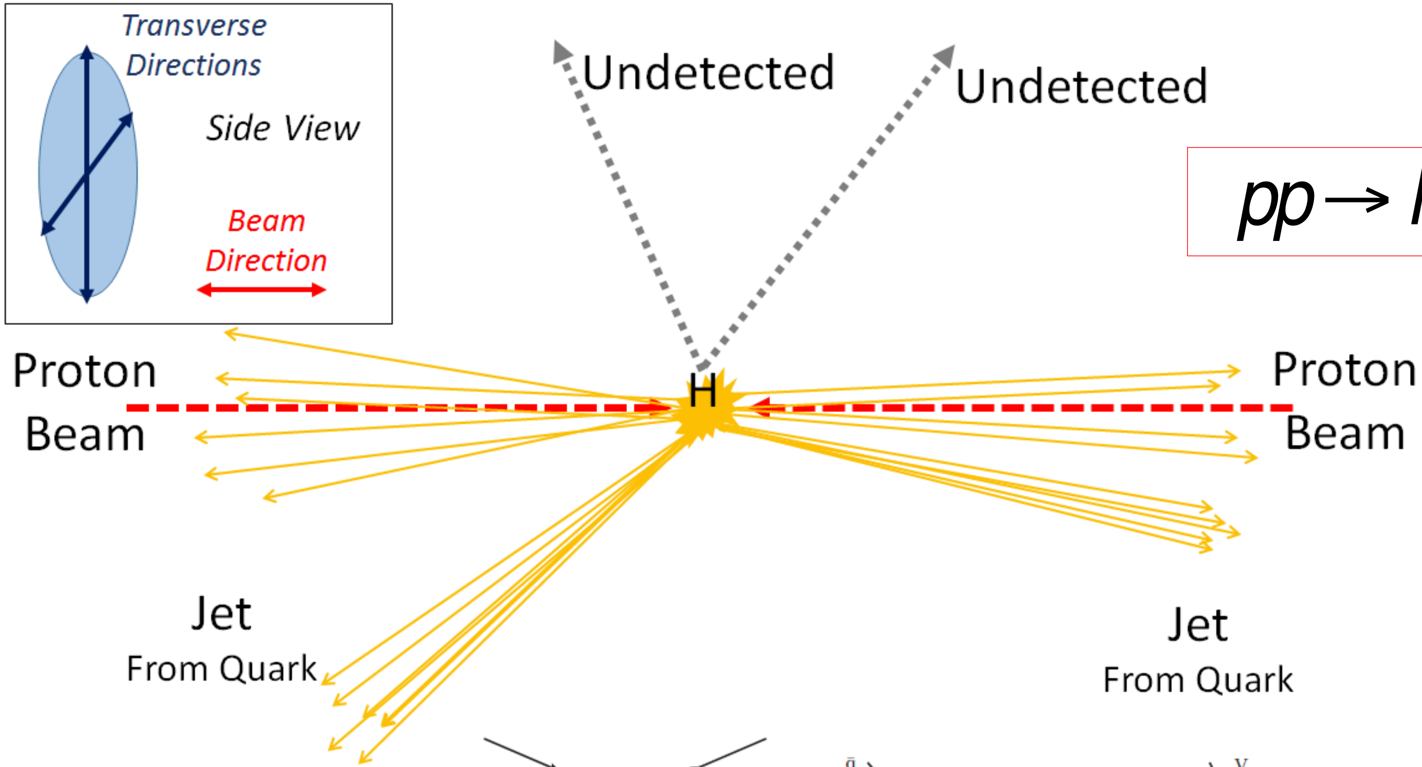


We know the SM background. This particular case is for an effective vertex with gluons.

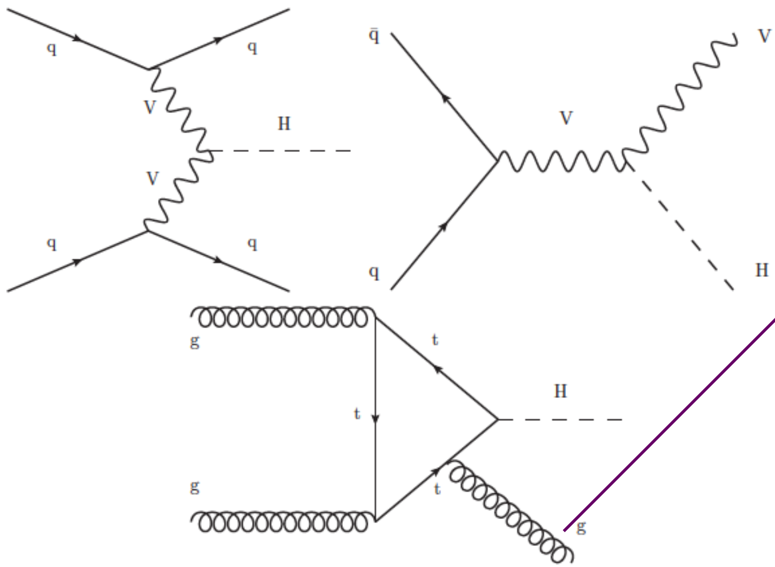


Dark matter line for a given cross section and mass of dark matter.

Another possibility

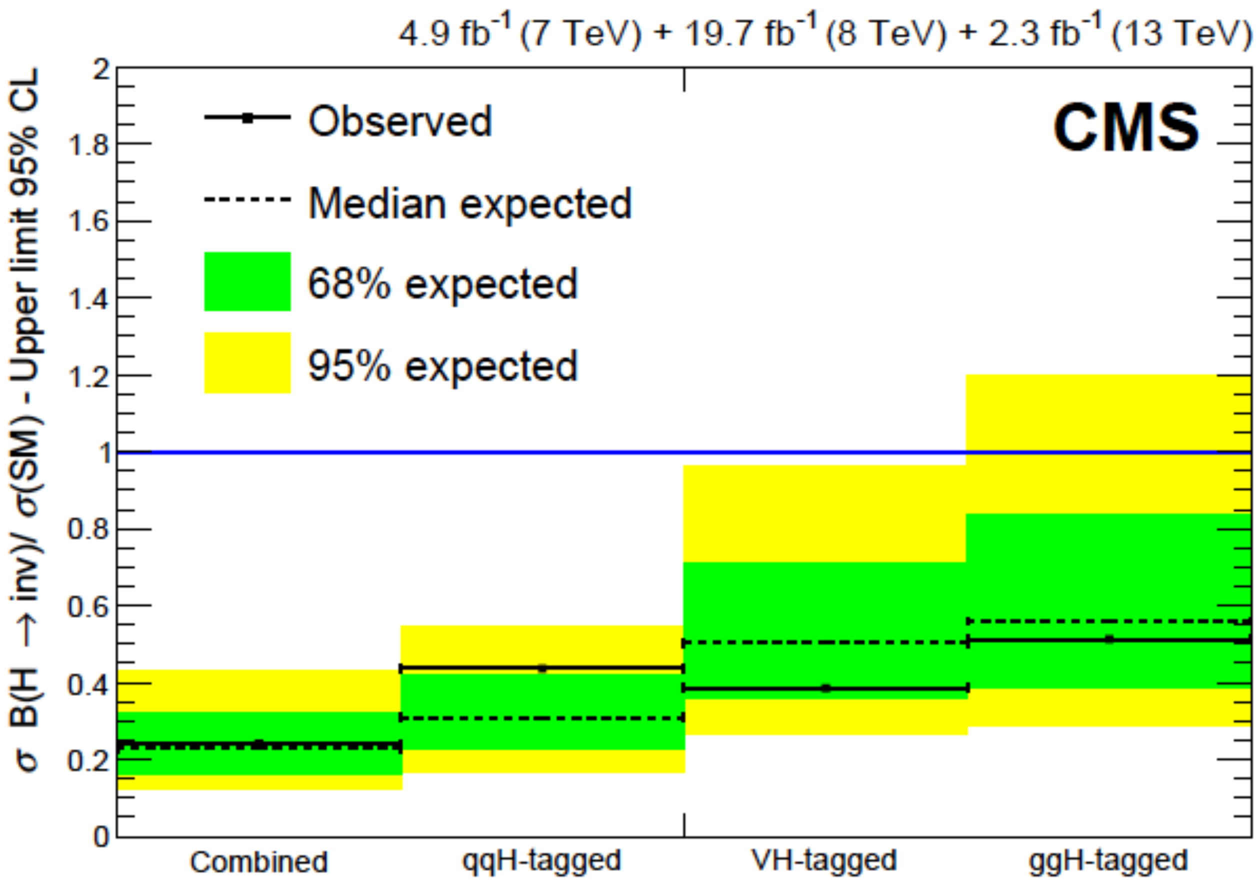


$$pp \to hjj \to \chi\chi\, jj \to METjj$$



This is just one of the several possible channels.

Invisible decays

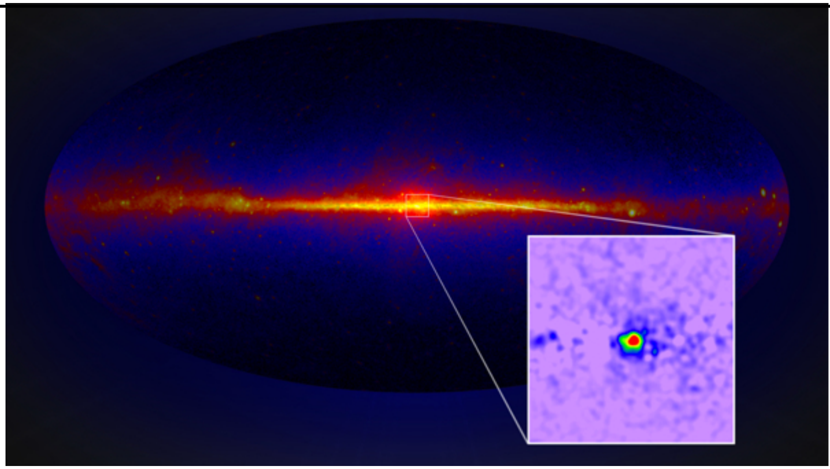


CMS results for the exclusion in the different channels

Assuming a SM production cross section for the Higgs boson, CMS obtains a limit

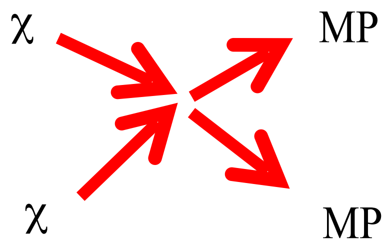
$$\mathcal{B}(\mathrm{H} \to \mathrm{inv}) < 0.24\ (0.23)\ \text{at the } 95\%\ \mathrm{CL}$$

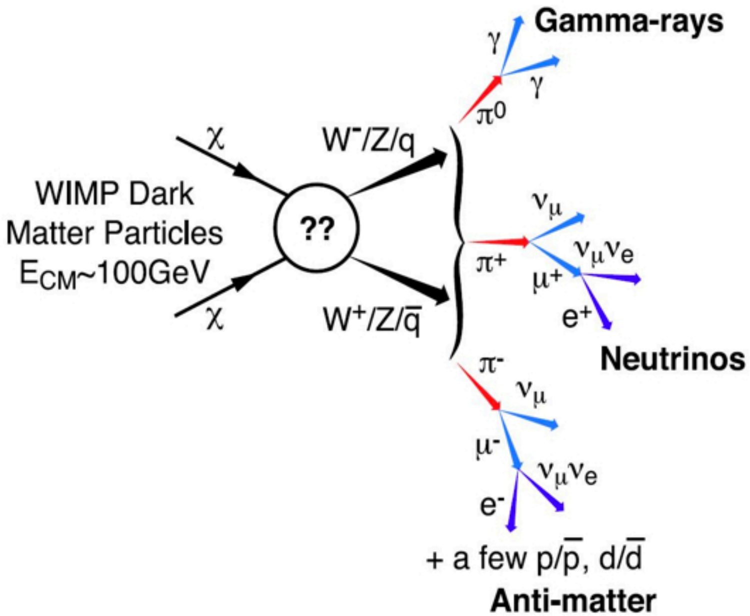
Indirect detection

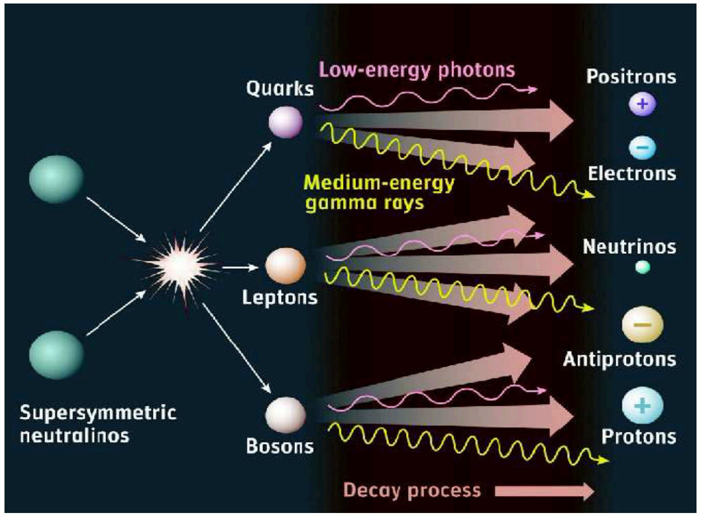


The Fermi Large Area Telescope (LAT) detects gamma radiation with energies between 0.3 and 300 GeV. It also detects electrons and positrons.

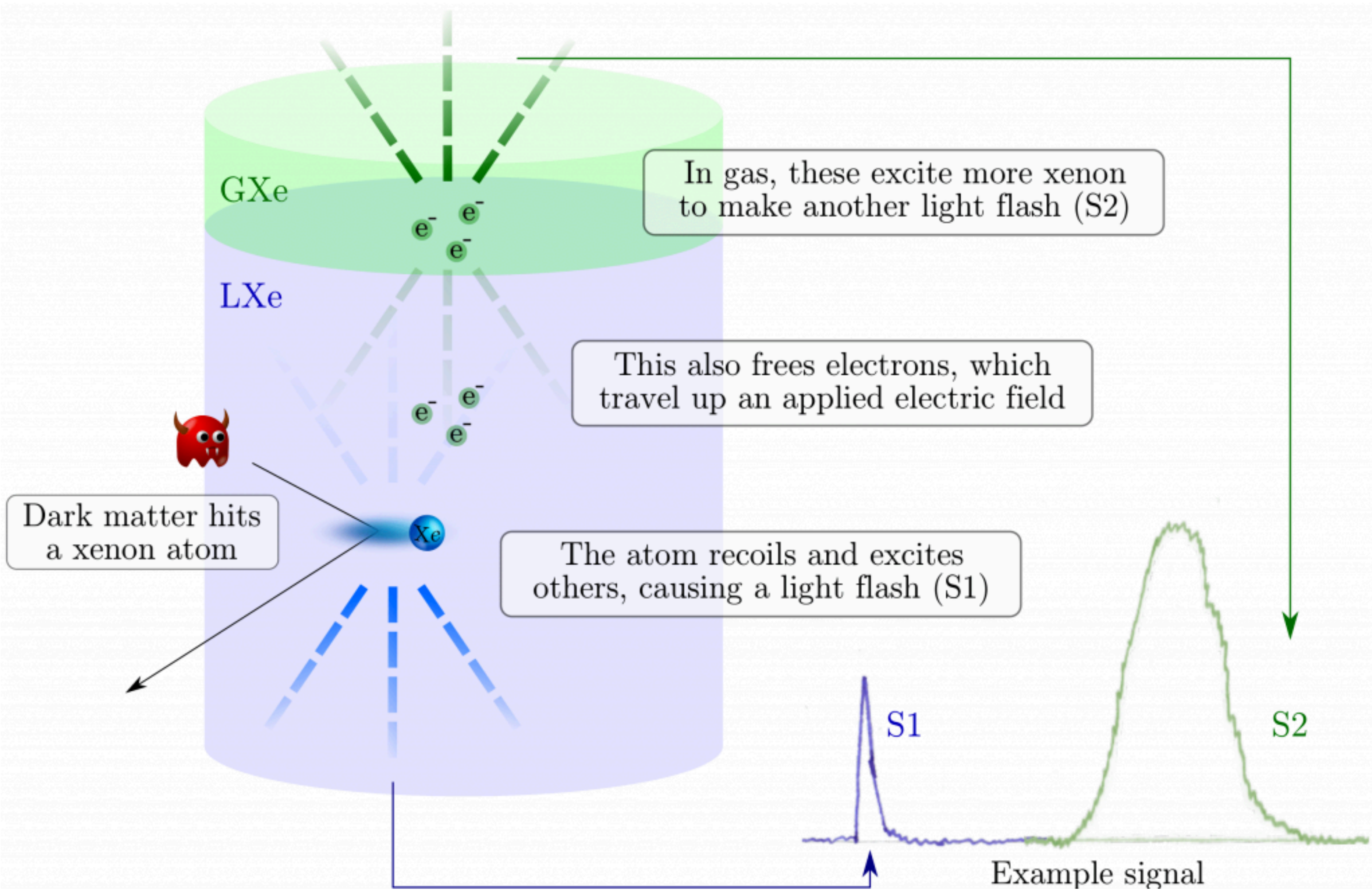
WIMPs collide producing either photons or particle anti-particle pairs.

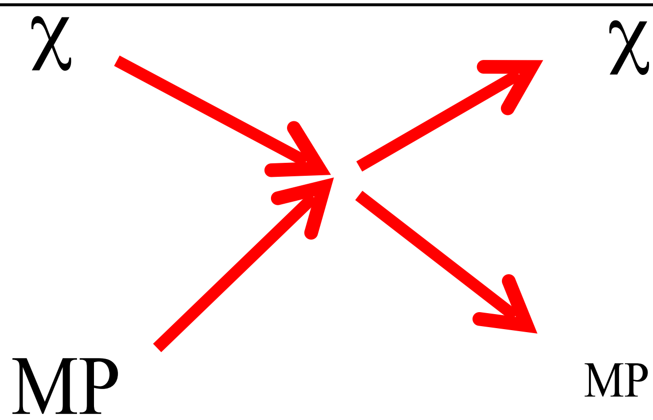


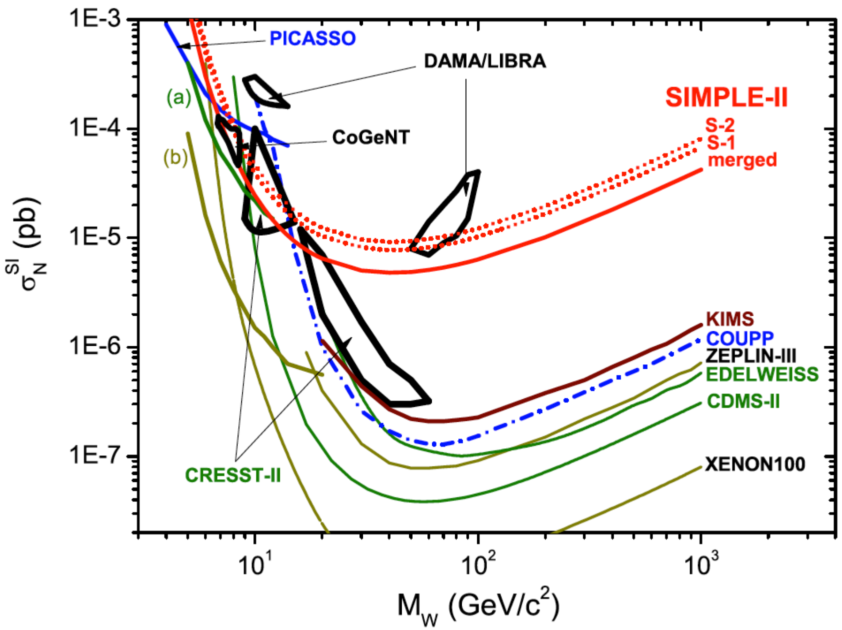


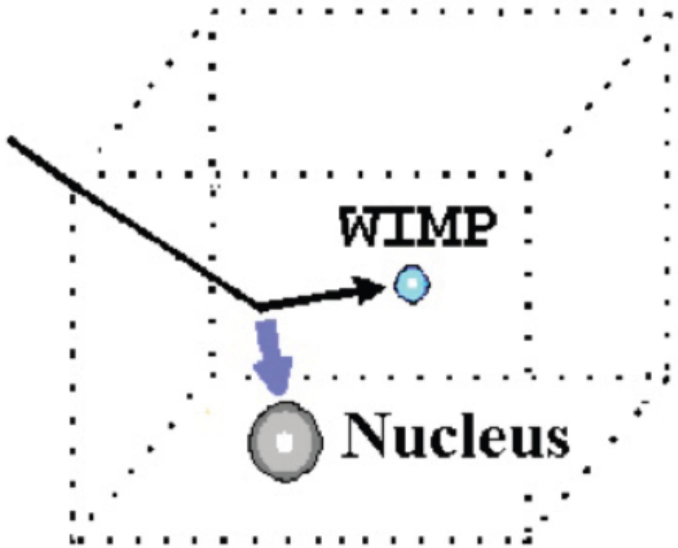


Direct detection



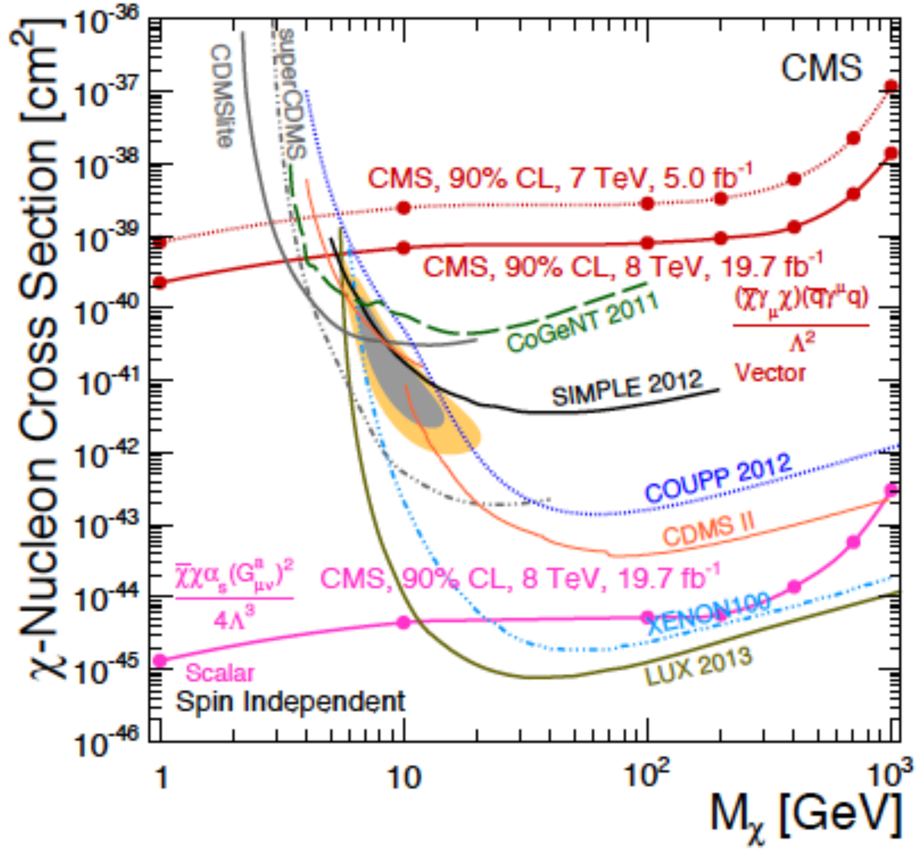


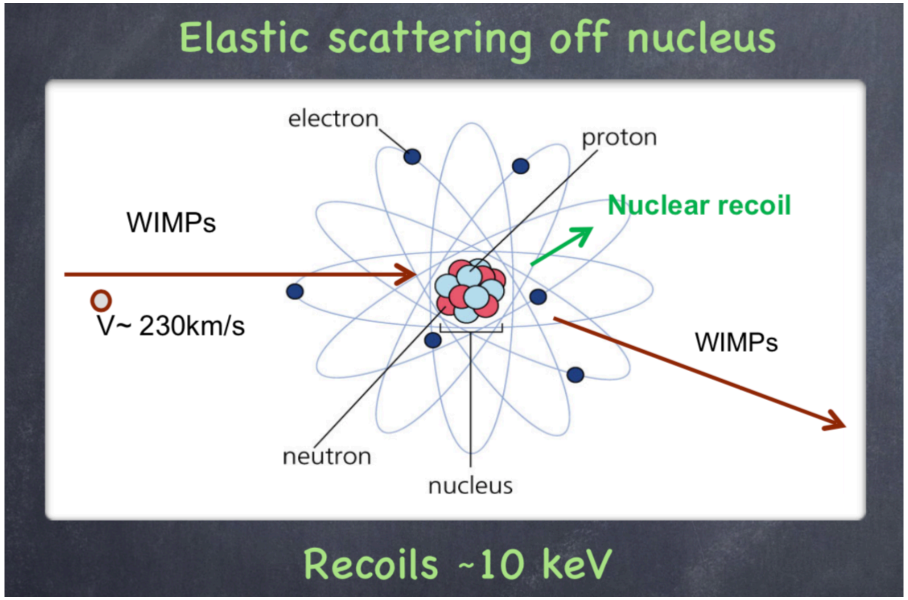




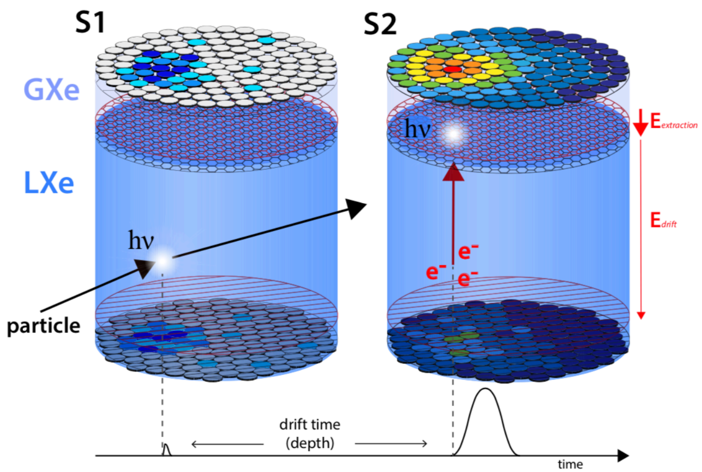
WIMP collides with nucleus - recoil energy can be measured.

Direct detection vs. LHC



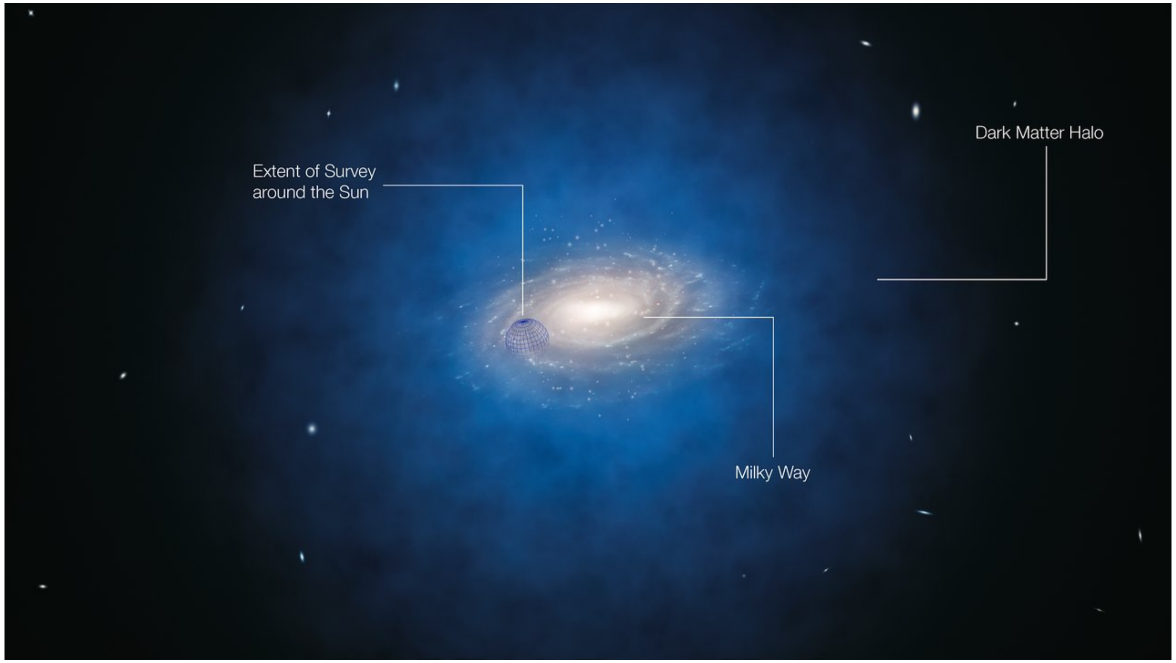


$$\chi N \rightarrow \chi N$$



Xenon

Halos



The visible disk of the Milky Way Galaxy is thought to be embedded in a much larger, roughly spherical halo of dark matter. The dark matter density drops off with distance from the galactic center.

It is now believed that about 95% of the galaxy is composed of dark matter. The luminous matter makes up approximately $9{\times}10^{10}$ solar masses. The dark matter halo is likely to include around $6{\times}10^{11}$ to $3{\times}10^{12}$ solar masses of dark matter. A 2014 analysis of stellar motions calculated the dark matter density (at the sun's distance from the galactic centre) = 0.0088 (+0.0024 −0.0018) solar masses/parsec^3.

The radial velocity dispersion shows an almost constant value of 120 km/s out to 30 kpc and then continuously declines down to 50 km/s at about 120 kpc. This fall-off puts important constraints on the density profile and total mass of the dark matter halo of the Milky Way.

The simplest DM models

Scalar DM Model

The spin 0 extension - real

The SM is extended by an extra real scalar singlet S. The most general Lagrangian we can write is

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - aS - bS^2 - cS^3 - dS^4 - \kappa_1 S^2 H^\dagger H - \kappa_2 S H^\dagger H$$

with (in the unitary gauge)

$$H = \begin{pmatrix} 0 \\ h \end{pmatrix}$$

If we include the Z_2 symmetry $S \to -S$, the potential reduces to

$$V_N = bS^2 + dS^4 + \kappa_1 S^2 H^\dagger H + \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

The minimum conditions for the potential are

$$\begin{cases} \dfrac{\partial V}{\partial S} = 2bS + 4dS^3 + 2\kappa_1 S h^2 = 0 \\ \dfrac{\partial V}{\partial h} = 2h\mu^2 + 4\lambda h^3 + 2\kappa_1 S^2 h = 0 \end{cases}$$

The spin 0 extension - real

This set equation has four solutions

$$1)\, S=0;\; h=0; \quad 2)\, S=-b/(2d);\; h=0; \quad 3)\, S=0;\; h^2=-\mu^2/(2\lambda); \quad 4)\, S\neq 0; h\neq 0$$

The first is the symmetric solution. So SSB does not occur. This is also true for solution 2. Solution 3 is the DM + SM one. In solution 4 the dark symmetry is broken by the vacuum.

P: Show that solution 3) has a DM candidate

P: Why doesn't SSB occur is scenario 2)?

P: Find solution 4) explicitly; find the mass eigenstates in this scenario; is there a DM candidate?

The spin 0 extension - complex

Let us now consider the extension by a complex singlet $\mathbb{S}$. The most general Lagrangian we can write is

$$\mathscr{L} = \mathscr{L}_{SM} + (D_\mu \mathbb{S})^\dagger (D^\mu \mathbb{S}) + \mu_S^2 \left|\mathbb{S}\right|^2 - \lambda_S \left|\mathbb{S}\right|^4 - \kappa \left|\mathbb{S}\right|^2 H^\dagger H + \mu^2(\mathbb{S}^2 + \mathbb{S}^{*2}) \qquad \mathbb{S} = \frac{1}{\sqrt{2}}(S + iA)$$

Model	Phase	VEVs at global minimum
$\mathbb{U}(1)$	Higgs+2 degenerate dark	$\langle \mathbb{S} \rangle = 0$
	2 mixed + 1 Goldstone	$\langle A \rangle = 0$ ($\not{\mathbb{U}}(1) \to \mathbb{Z}_2'$)
$\mathbb{Z}_2 \times \mathbb{Z}_2'$	Higgs + 2 dark	$\langle \mathbb{S} \rangle = 0$
	2 mixed + 1 dark	$\langle A \rangle = 0$ ($\not{\mathbb{Z}}_2 \times \mathbb{Z}_2' \to \mathbb{Z}_2'$)
$\mathbb{Z}_2'$	2 mixed + 1 dark	$\langle A \rangle = 0$
	3 mixed	$\langle \mathbb{S} \rangle \neq 0$ ($\not{\mathbb{Z}}_2'$)

The spin 0 extension - complex

One particular case: black Lagrangian is U(1) symmetric. Black plus red

$$\mathscr{L} = \mathscr{L}_{SM} + (D_\mu \mathbb{S})^\dagger (D^\mu \mathbb{S}) + \mu_S^2 \left|\mathbb{S}\right|^2 - \lambda_S \left|\mathbb{S}\right|^4 - \kappa \left|\mathbb{S}\right|^2 H^\dagger H + \mu^2(\mathbb{S}^2 + \mathbb{S}^{*2}) \qquad \mathbb{S} \to \mathbb{S}^*$$

SM + dark matter candidate A + a new scalar that mixes with the CP-even field in the doublet such that

$$m_\pm = \lambda_H v_H^2 + \lambda_S v_S^2 \pm \sqrt{\lambda_H^2 v_H^4 + \lambda_S^2 v_S^4 + \kappa v_H^2 v_S^2 - 2\lambda_H \lambda_S v_H^2 v_S^2}$$

The mass eigenstates fields h_1 and h_2 are obtained from h and S via

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

The conditions for the potential to be bounded from below are the same for the two models

$$\lambda_H > 0, \qquad \lambda_S > 0, \qquad \kappa > -2\sqrt{\lambda_H \lambda_S}.$$

The scalar mass matrix is

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_H v^2 & \kappa v v_S & 0 \\ \kappa v v_S & 2\lambda_S v_S^2 & 0 \\ 0 & 0 & -4\mu^2 \end{pmatrix}$$

$$m_{DM} = -4\mu^2$$

SM+2RSS model with $\mathcal{Z}_2^{(1)} \times \mathcal{Z}_2^{(2)}$ symmetry

- $\mathcal{Z}_2^{(1)} \times \mathcal{Z}_2^{(2)}$ symmetry ➡
$$\begin{cases} \mathcal{Z}_2^{(1)} : S_1 \to -S_1,\ S_2 \to +S_2,\ \mathrm{SM} \to +\mathrm{SM} \\ \mathcal{Z}_2^{(2)} : S_1 \to +S_1,\ S_2 \to -S_2,\ \mathrm{SM} \to +\mathrm{SM} \end{cases}$$

- Most general renormalizable and $\mathcal{G}_{\mathrm{SM}} \times \mathcal{Z}_2^{(1)} \times \mathcal{Z}_2^{(2)}$ invariant Lagrangian:

$$\mathcal{L}_{\mathrm{SM+2RSS}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}(\partial_\mu S_1)\partial^\mu S_1 + \frac{1}{2}(\partial_\mu S_2)\partial^\mu S_2 - \frac{1}{2}\mu_1^2 S_1^2 - \frac{1}{2}\mu_2^2 S_2^2 - \frac{\lambda_1}{4!}S_1^4 - \frac{\lambda_2}{4!}S_2^4$$
$$\underbrace{-\frac{\kappa_{H1}}{2}S_1^2\Phi^\dagger\Phi}_{=\mathcal{L}_{\mathrm{portal}(1)}} \underbrace{-\frac{\kappa_{H2}}{2}S_2^2\Phi^\dagger\Phi}_{=\mathcal{L}_{\mathrm{portal}(2)}} \underbrace{-\frac{\lambda_{12}}{4}S_1^2 S_2^2}_{=\mathcal{L}_{\mathrm{int}(1,2)}}$$

- From 8 possible $\mathcal{G}_{\mathrm{SM}} \times \mathcal{Z}_2^{(1)} \times \mathcal{Z}_2^{(2)}$ invariant solution sets, we consider the vacuum configuration:

$$\langle\Phi\rangle_0^\dagger \langle\Phi\rangle_0 = -\frac{\mu_H^2}{2\lambda_H} \equiv \frac{v^2}{2} \quad \bigwedge_{r=1}^{2} \quad \langle S_r\rangle_0 = 0$$

➡ $SU(2)_L \times U(1)_Y \to \mathrm{U}(1)_Q$ SSB and $\mathcal{Z}_2^{(1)} \times \mathcal{Z}_2^{(2)}$ unbroken ➡ 0 extra Higgs-like + 2 DM candidates

The spin 0 extension - 2 singlets - one symmetry

- Most general renormalizable and $\mathcal{G}_{\rm SM}\times\mathcal{Z}_2^{(1)}\times\mathcal{Z}_2^{(2)}$ invariant Lagrangian:

$$\mathcal{L}_{\rm SM+2RSS} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S_1)\partial^\mu S_1 + \frac{1}{2}(\partial_\mu S_2)\partial^\mu S_2 - \frac{1}{2}\mu_1^2 S_1^2 - \frac{1}{2}\mu_2^2 S_2^2 - \frac{\lambda_1}{4!}S_1^4 - \frac{\lambda_2}{4!}S_2^4$$
$$\underbrace{-\frac{\kappa_{H1}}{2}S_1^2\Phi^\dagger\Phi}_{=\mathcal{L}_{\rm portal(1)}}\underbrace{-\frac{\kappa_{H2}}{2}S_2^2\Phi^\dagger\Phi}_{=\mathcal{L}_{\rm portal(2)}}\underbrace{-\frac{\lambda_{12}}{4}S_1^2S_2^2}_{=\mathcal{L}_{\rm int(1,2)}}$$

P: What changes?

The spin 0 extension - 3 singlets

The $\mathcal{Z}_2^{(r)}$ ($r = 1, 2, 3$) charges can be interpreted as three independent *dark* (intrinsic) parity quantum numbers. Therefore, the most general renormalizable Lagrangian density invariant under $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathcal{Z}_2^{(1)} \times \mathcal{Z}_2^{(2)} \times \mathcal{Z}_2^{(3)}$ transformations is given by

$$\mathcal{L}_{\text{SM+3RSS}} = \mathcal{L}_{\text{SM}} + \sum_{r=1}^{3} \left[\frac{1}{2}(\partial_\mu S_r)\partial^\mu S_r - \frac{1}{2}\mu_r^2 S_r^2 - \frac{\lambda_r}{4!} S_r^4 \underbrace{- \frac{\kappa_{Hr}}{2} S_r^2 \Phi^\dagger \Phi}_{= \mathcal{L}_{\text{portal}(r)}} \right]$$
$$\underbrace{- \frac{\lambda_{12}}{4} S_1^2 S_2^2}_{= \mathcal{L}_{\text{int}(1,2)}} \underbrace{- \frac{\lambda_{23}}{4} S_2^2 S_3^2}_{= \mathcal{L}_{\text{int}(2,3)}} \underbrace{- \frac{\lambda_{31}}{4} S_3^2 S_1^2}_{= \mathcal{L}_{\text{int}(3,1)}} \supset -V(|\Phi|, S_1, S_2, S_3)\,, \tag{5.4}$$

where $\Phi(x) = \begin{pmatrix} G^+(x) & \phi^0(x) \end{pmatrix}^\top \sim (\mathbf{1}, \mathbf{2}, +1/2)$ is the Higgs doublet, and the scalar potential is now given by

$$V(|\Phi|, S_1, S_2, S_3) = \mu_H^2 \Phi^\dagger \Phi + \lambda_H (\Phi^\dagger \Phi)^2 + \sum_{r=1}^{3} \left[\frac{1}{2}\mu_r^2 S_r^2 + \frac{\lambda_r}{4!} S_r^4 + \frac{\kappa_{Hr}}{2} S_r^2 \Phi^\dagger \Phi \right]$$
$$+ \frac{\lambda_{12}}{4} S_1^2 S_2^2 + \frac{\lambda_{23}}{4} S_2^2 S_3^2 + \frac{\lambda_{31}}{4} S_3^2 S_1^2\,. \tag{5.5}$$