2. Dark Matter in Extended Higgs sectors

R. Santos
ISEL & CFTC-UL & LIP

Multi-Higgs day @ LIP

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Dark matter is known for almost 90 years.

Baptized a long time ago

Fritz Zwicky (1930)

Wrote in a paper about the discrepancy about the measured and expected velocity of the rotation of galaxies.

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

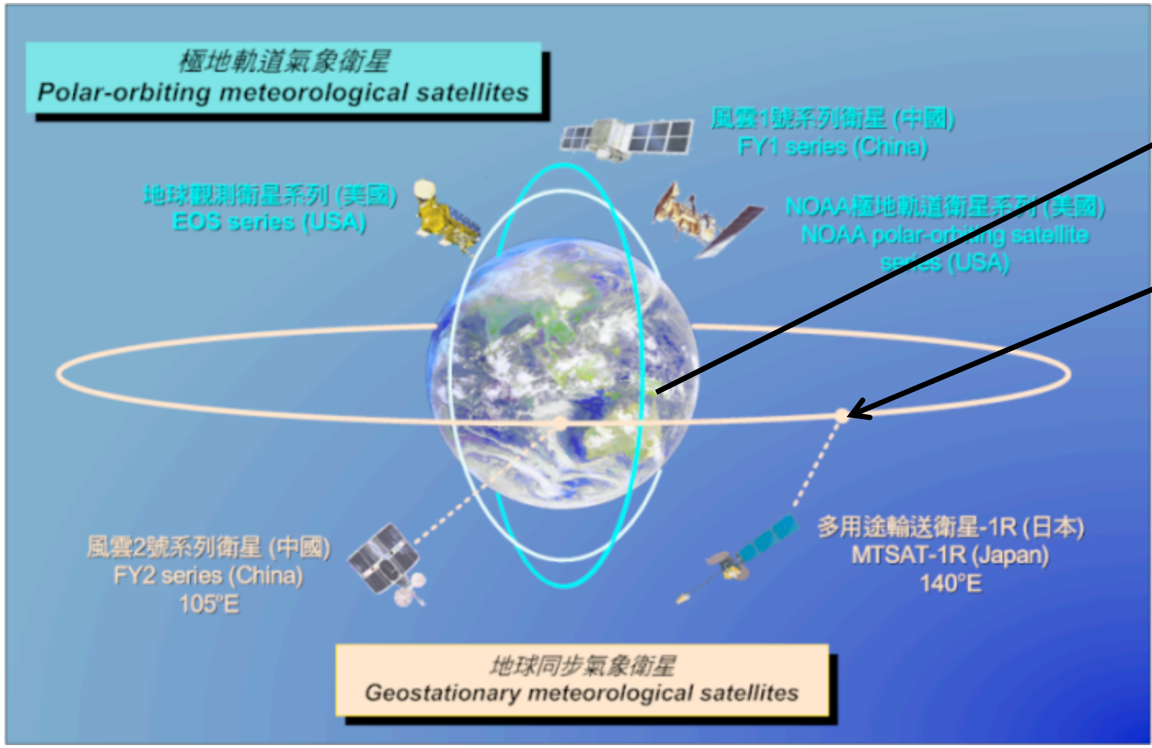
Why is dark matter so interesting?

• 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 uses 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 is it ...

The role of gravity in Earth's rotation



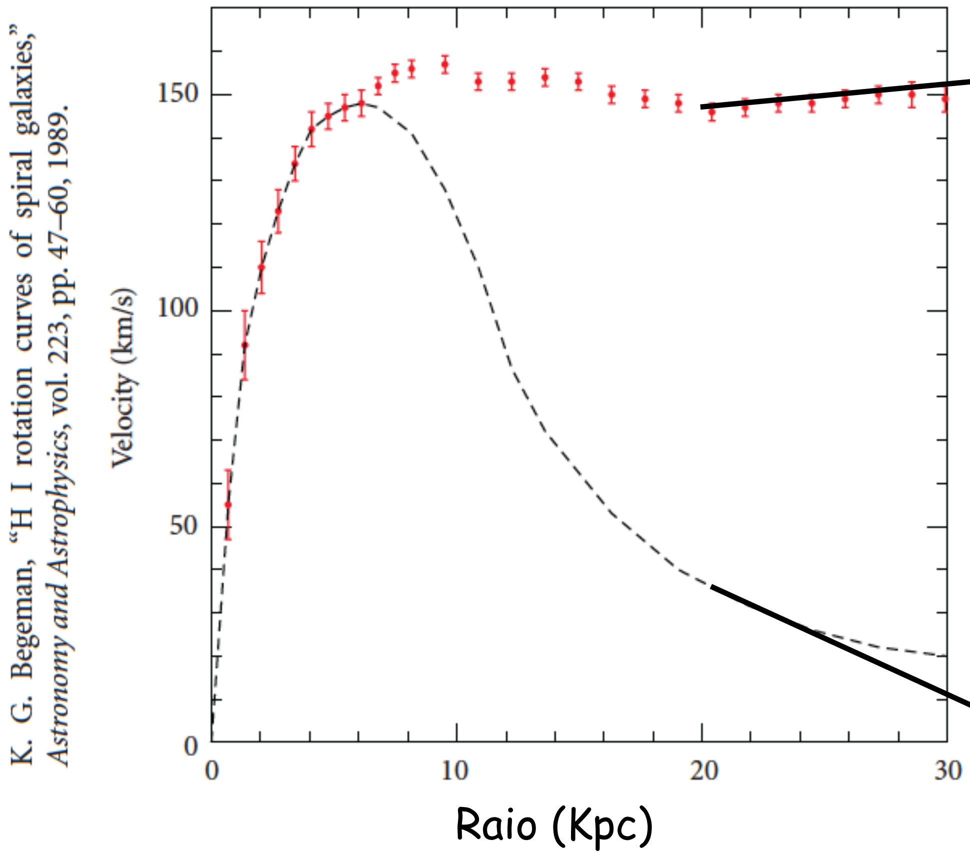
Earth

Satellite

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

For a distance of 640 Km the satellite has a constant speed of 27000 Km/h.

Rotation curves of galaxies



Experimental results

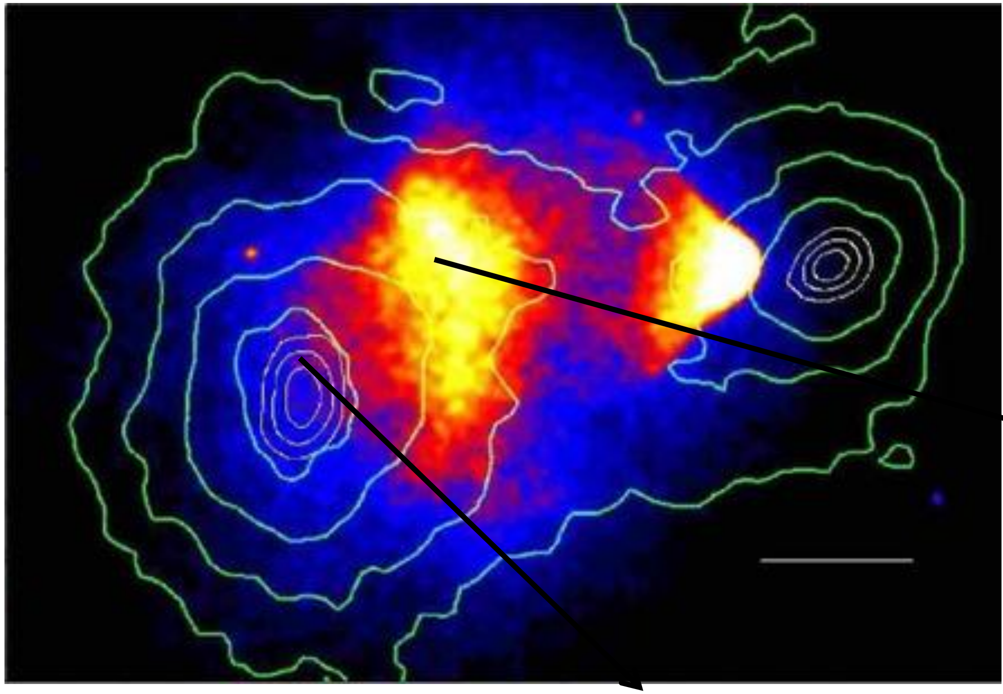
If the galaxy had only visible matter the curve would be given according to:

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

Keplerian expectation

Mass, contrary to luminosity seems to be spread evenly across the entire galaxy. The light distribution is far from representing the mass distribution as we would expect.

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).

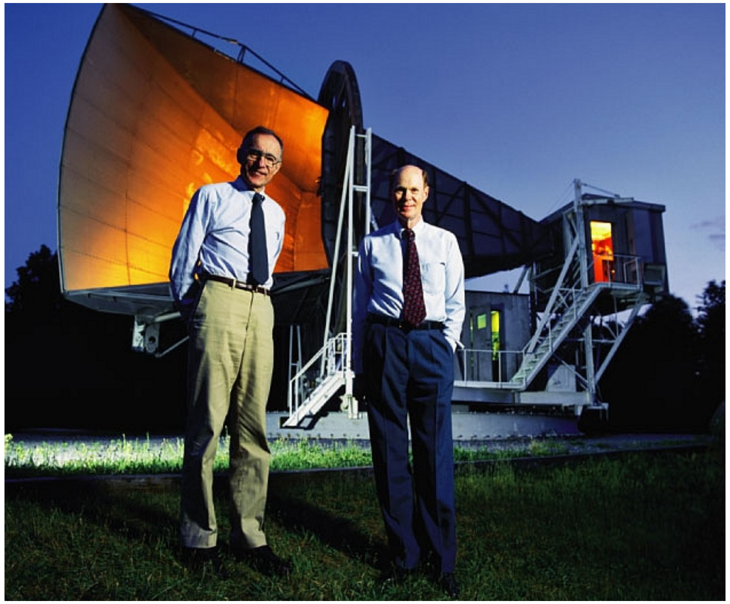
Lines of gravitation potential – from gravitational lensing show that the dark matter is concentrated around the galaxies and that it is not affected by the collisions.

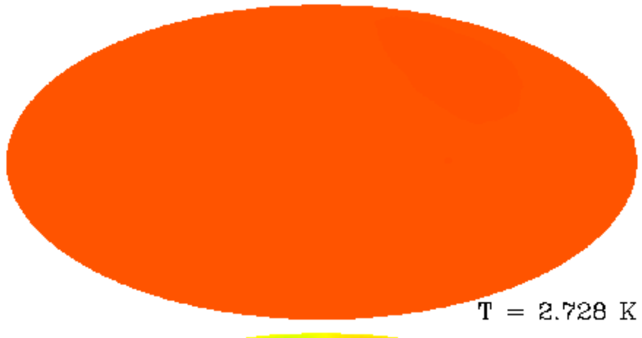
Dark matter interacts very weakly!

Cosmic Microwave background

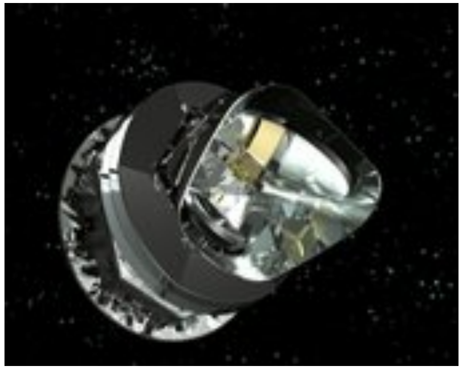
In the Standard Model of Cosmology, it is assumed that just after the Big Bang the Universe was extremely hot, it then inflated (very rapidly) and cooled down. The effect of the rapid cooling was predicted to be a very low temperature radiation that would populate all space until today.

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).





Some lead to constraints (related to dark matter)



Planck + cosmological model

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).

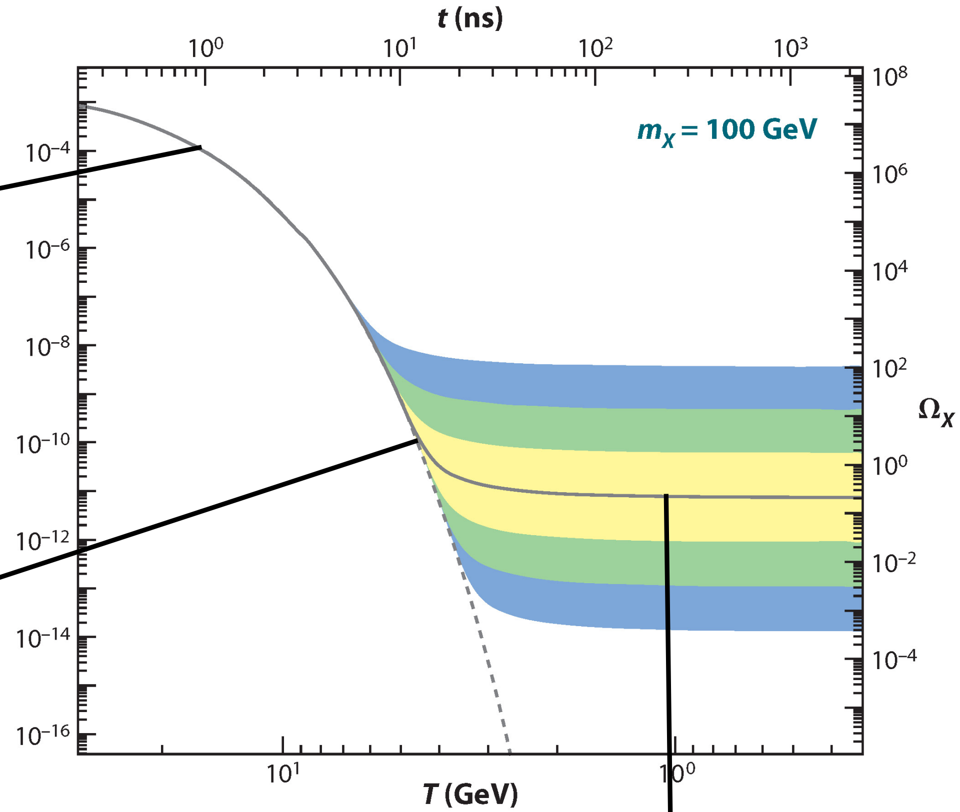
The unstable particles disappeared (decayed); number of stable particles reached a constant (thermal relic density) which has still approximately the same value today.

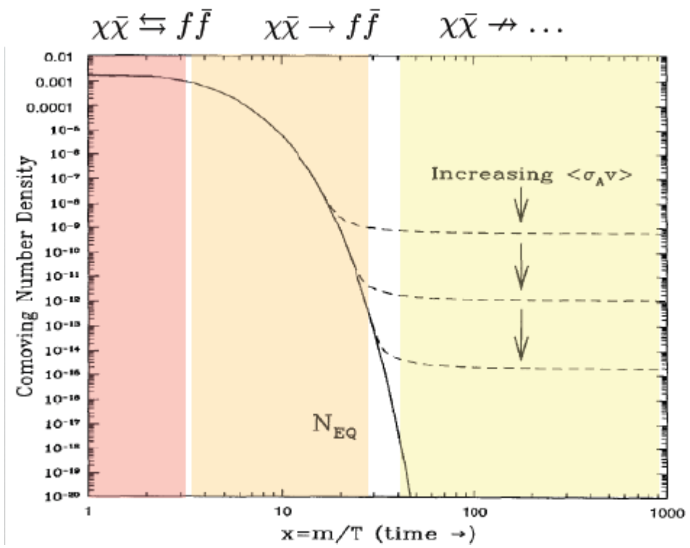
What happened to dark matter?

Before inflation –
thermal equilibrium

Measure of density

Freeze-out





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

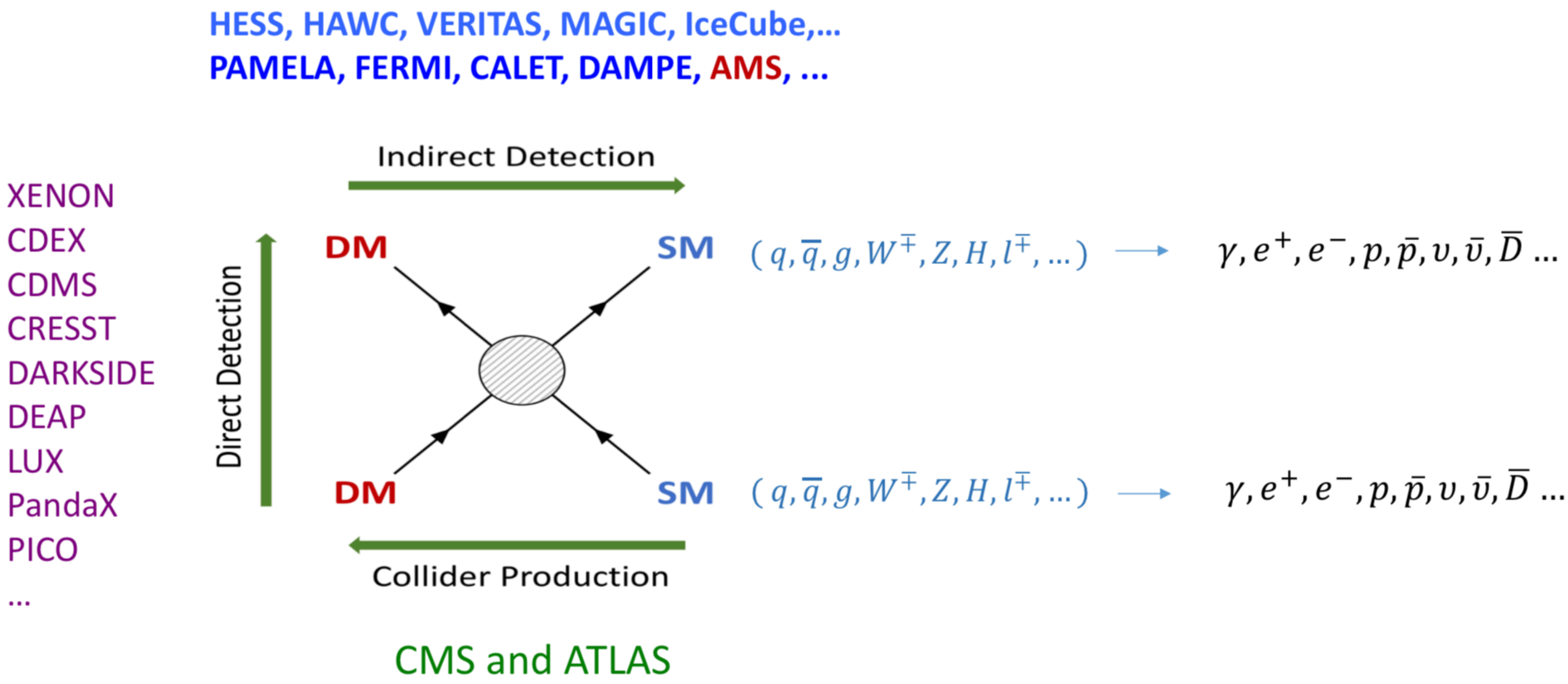
Measure of the interaction rate

Dark matter properties

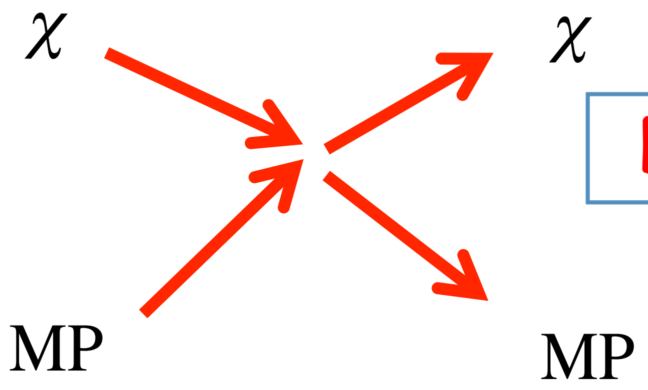
- Massive;
- Stable;
- Neutral;
- Weak (or no) interaction with SM particles.

WIMP - weakly interacting massive particles

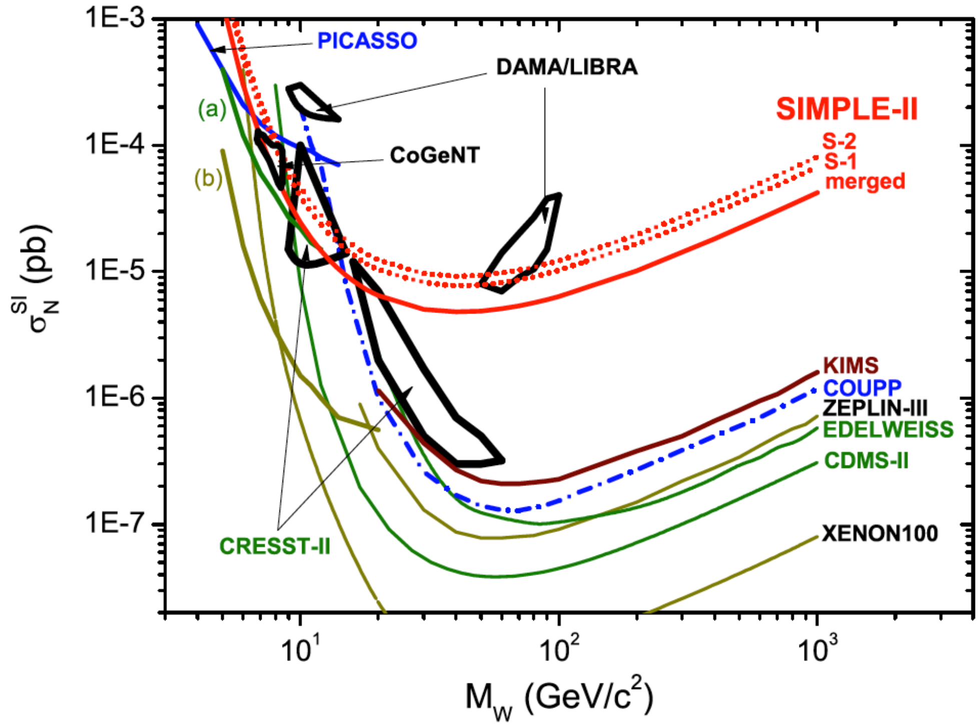
Dark matter searches

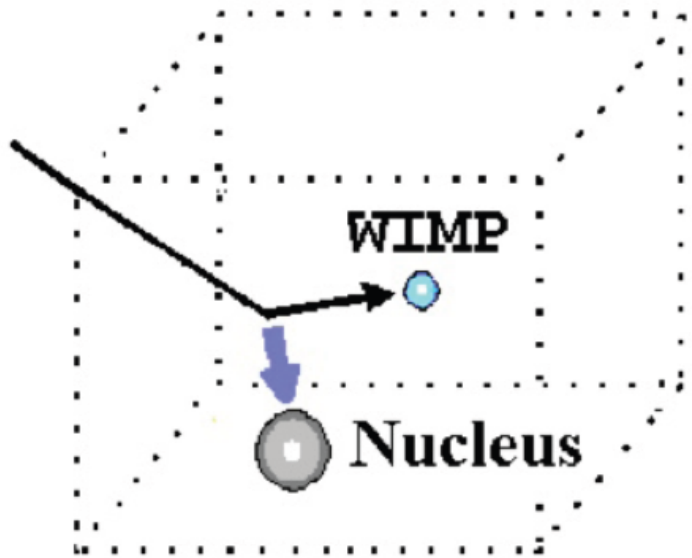


Slide from Suzan Basegmez du Pree talk at ALPS2018.

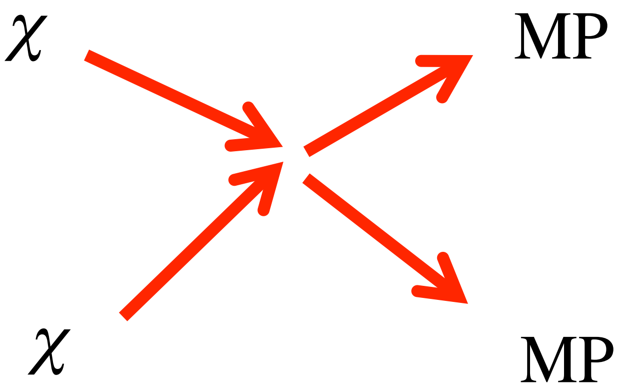


Direct detection

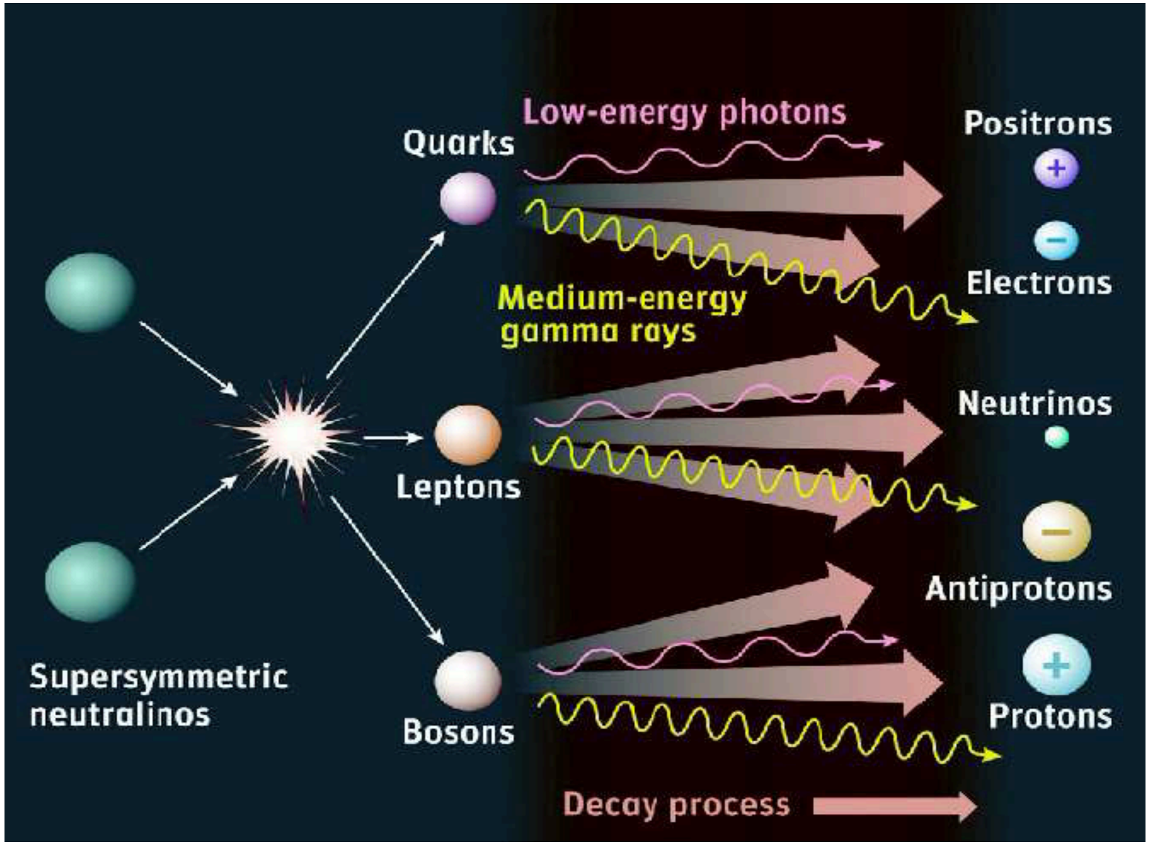




A WIMP may collide elastically with a nucleus – recoil energy is measured.



Indirect detection

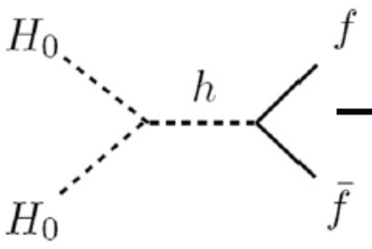


WIMPs may collide and annihilate into photons or particle anti-particle pairs.

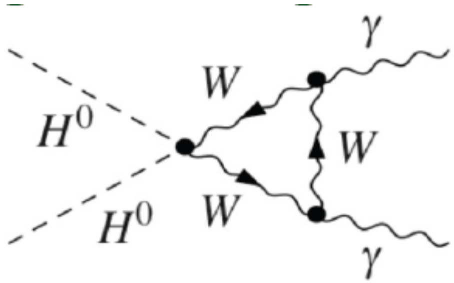
A large number of gamma-rays, anti-protons and positrons could be produced.

Consistency between excesses is a probe for the model

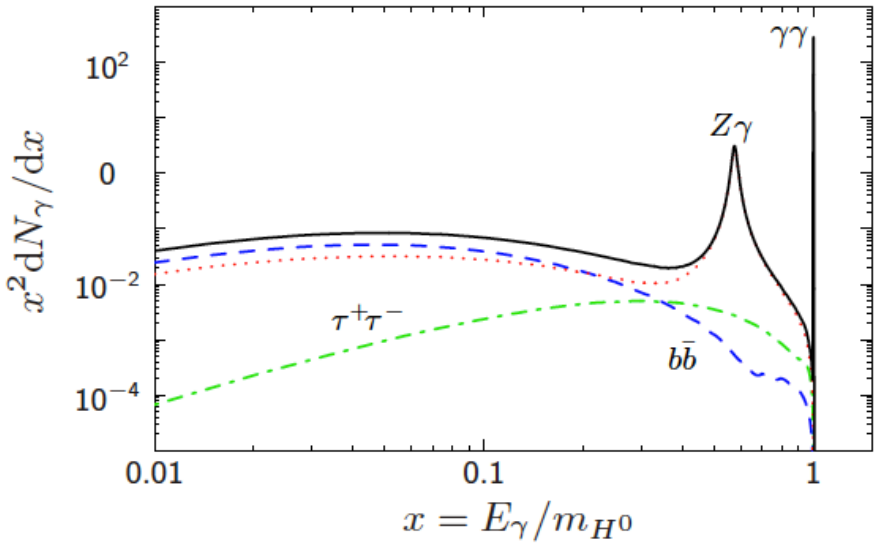
Indirect detection



→ hadronization

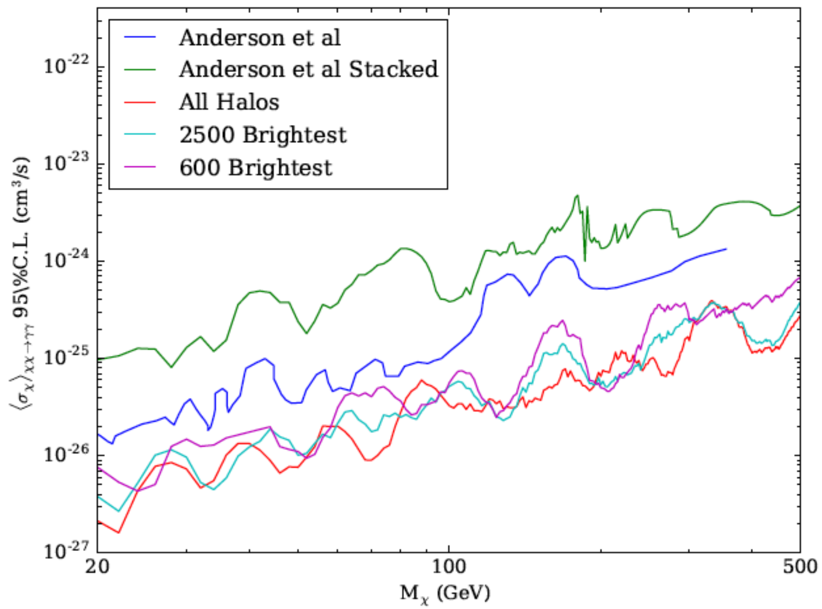


→ γ-rays



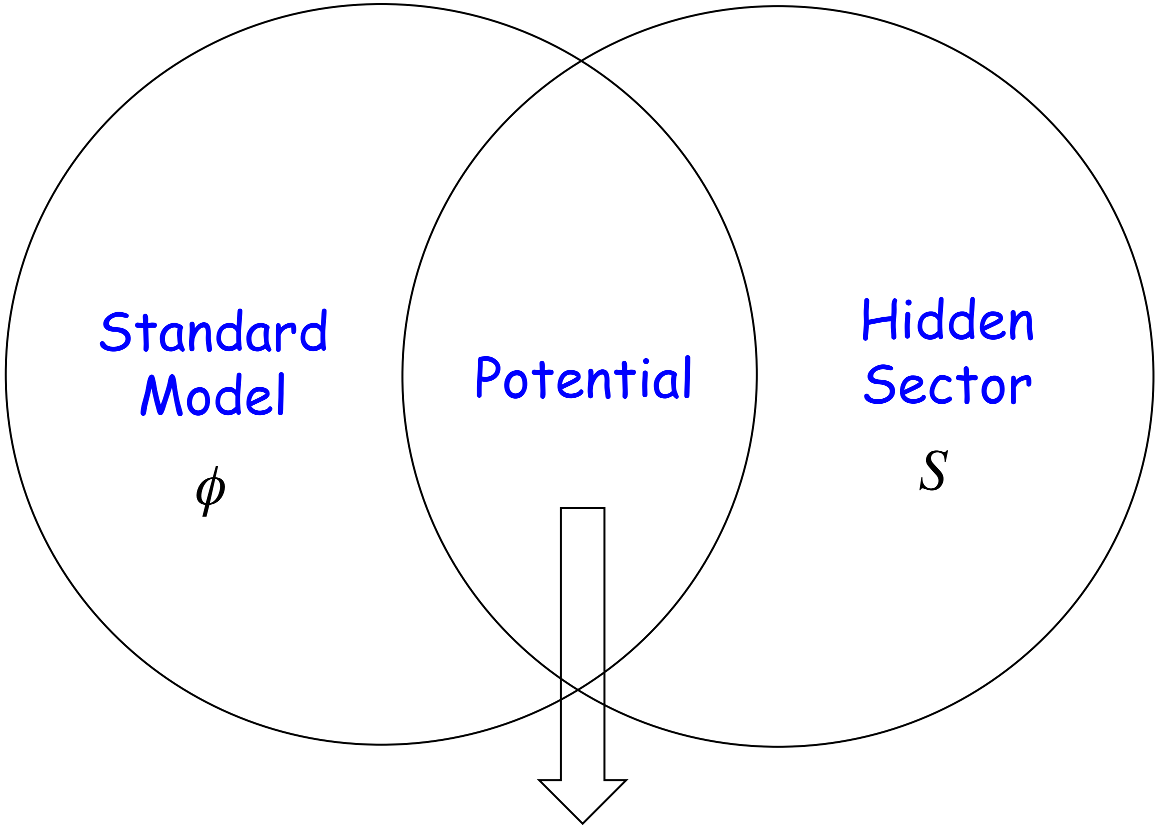
This is the spectrum for a specific model.. Models are tested from searches for dark matter in the galactic centre, halo and clusters of galaxies.

Fermi Large Area Telescope



Simple models with dark matter

Very simple extensions of the SM can generate dark matter



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

Lagrangian term that links the SM and the hidden sector

The simplest model – just add a singlet

SM plus $\mathbb{S} = (S + iA)/\sqrt{2}$,

Changes in the potential

$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1 \mathbb{S} + c.c.\right)$$

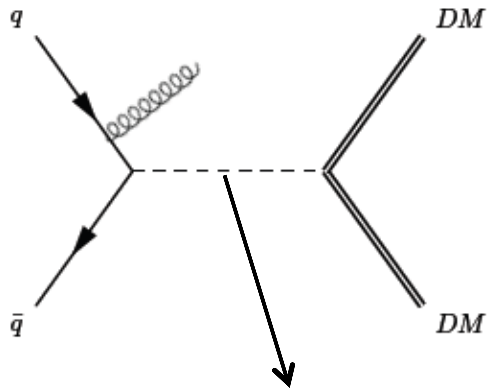
Model	Phase	VEVs at global minimum
$\mathbb{U}(1)$	Higgs+2 degenerate dark	$\langle \mathbb{S} \rangle = 0$
	2 mixed + 1 Goldstone	$\langle A \rangle = 0$ ($\cancel{\mathbb{U}}(1) \to \mathbb{Z}_2'$)
$\mathbb{Z}_2 \times \mathbb{Z}_2'$	Higgs + 2 dark	$\langle \mathbb{S} \rangle = 0$
	2 mixed + 1 dark	$\langle A \rangle = 0$ ($\cancel{\mathbb{Z}_2} \times \mathbb{Z}_2' \to \mathbb{Z}_2'$)
$\mathbb{Z}_2'$	2 mixed + 1 dark	$\langle A \rangle = 0$
	3 mixed	$\langle \mathbb{S} \rangle \neq 0$ ($\cancel{\mathbb{Z}_2'}$)

The simplest model – just add a singlet

- $\mathbb{Z}_2$ phase ($v_S \neq 0, v_A = 0$): 2 Higgs mix + 1 dark

$$\begin{pmatrix} h_1 \\ h_2 \\ h_{DM} \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ s \\ A \end{pmatrix}$$

- No couplings to fermions
- No couplings to gauge bosons
- Couples only to scalars

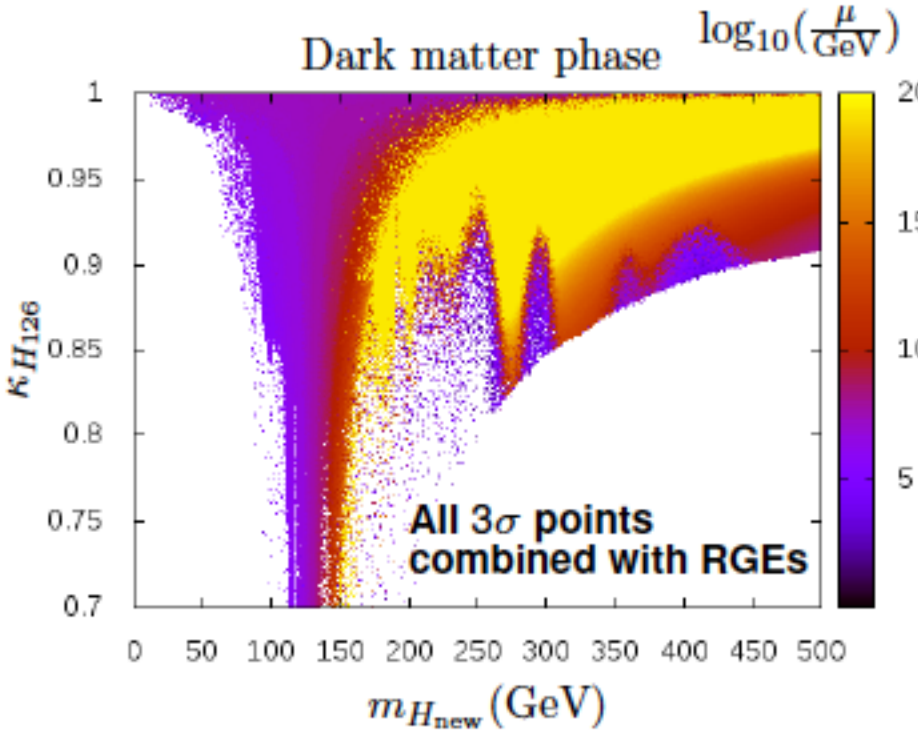


Mediator: h_1 or h_2

$$h\chi\,\chi \longrightarrow Z(h) = 1;\; Z(\chi) = -1$$

Darkness is conserved in the interaction

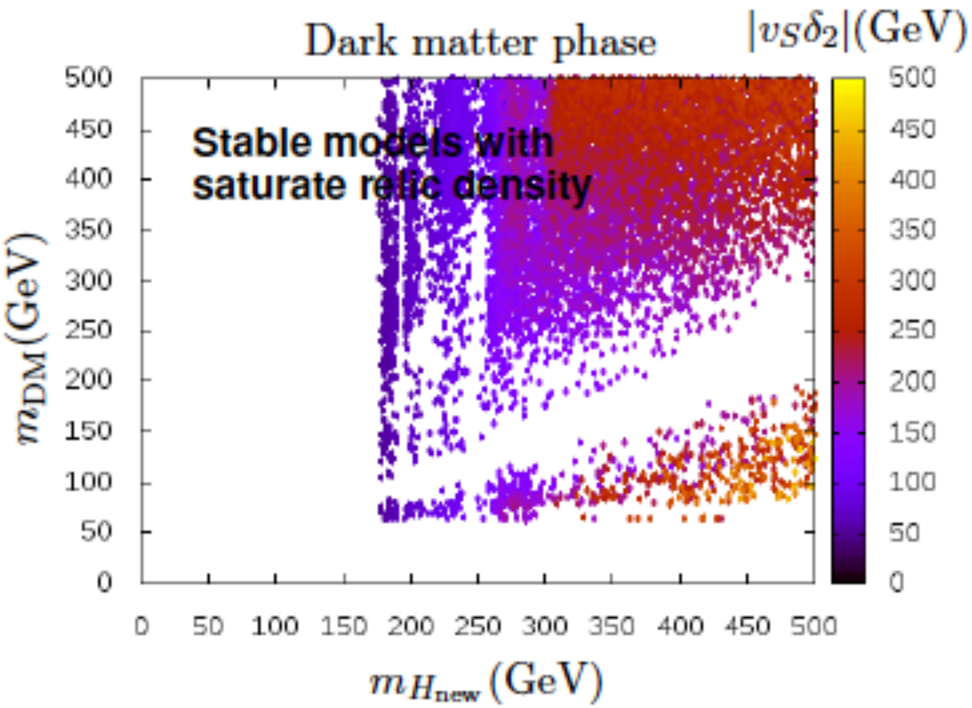
Stability + constraints + pheno



Three interesting limits:

m_{Hnew} > 170 GeV from the combination of all theoretical and experimental constraints.

m_{DM} > $\frac{1}{2}$ m_{125} due to the constraints on the invisible decay width bound.



m_{DM} > $\frac{1}{2}$ m_{Hnew} corresponds to regions where the dark matter anihilation channels DM DM → Hi (visible Higgs bosons) are very efficient in reducing the relic desity and therefore it becomes hard to saturate Ωc.

The Inert Model (2HDM)

SM

$$V = \boxed{\mu_1^2|H_1|^2} + \mu_2^2|H_2|^2 + \boxed{\lambda_1|H_1|^4} + \lambda_2|H_2|^4$$
$$+ \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \lambda_5 Re\left[(H_1^\dagger H_2)^2\right]$$

VEV

Higgs boson

$$H_1 = \begin{pmatrix} 0 \\ v + h/\sqrt{2} \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H^\pm \\ (H^0 + iA^0)/\sqrt{2} \end{pmatrix}$$

Inert doublet

Inert scalars

There is an exact discrete symmetry that forces the second doublet to have only stable particles.

$$H_2 \xrightarrow{Z_2} -H_2$$

This is the discrete symmetry we call darkness.

The Inert Model (2HDM)

VEV   Higgs boson

$$H_1 = \begin{pmatrix} 0 \\ v + h/\sqrt{2} \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H^{\pm} \\ (H^0 + iA^0)/\sqrt{2} \end{pmatrix}$$

Inert doublet   Inert scalars

Mass eigenstates

$$m_h^2 = \mu_1^2 + 3\lambda_1 v^2$$
$$m_{H^0}^2 = \mu_2^2 + \lambda_L v^2$$
$$m_{A^0}^2 = \mu_2^2 + \lambda_S v^2$$
$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$

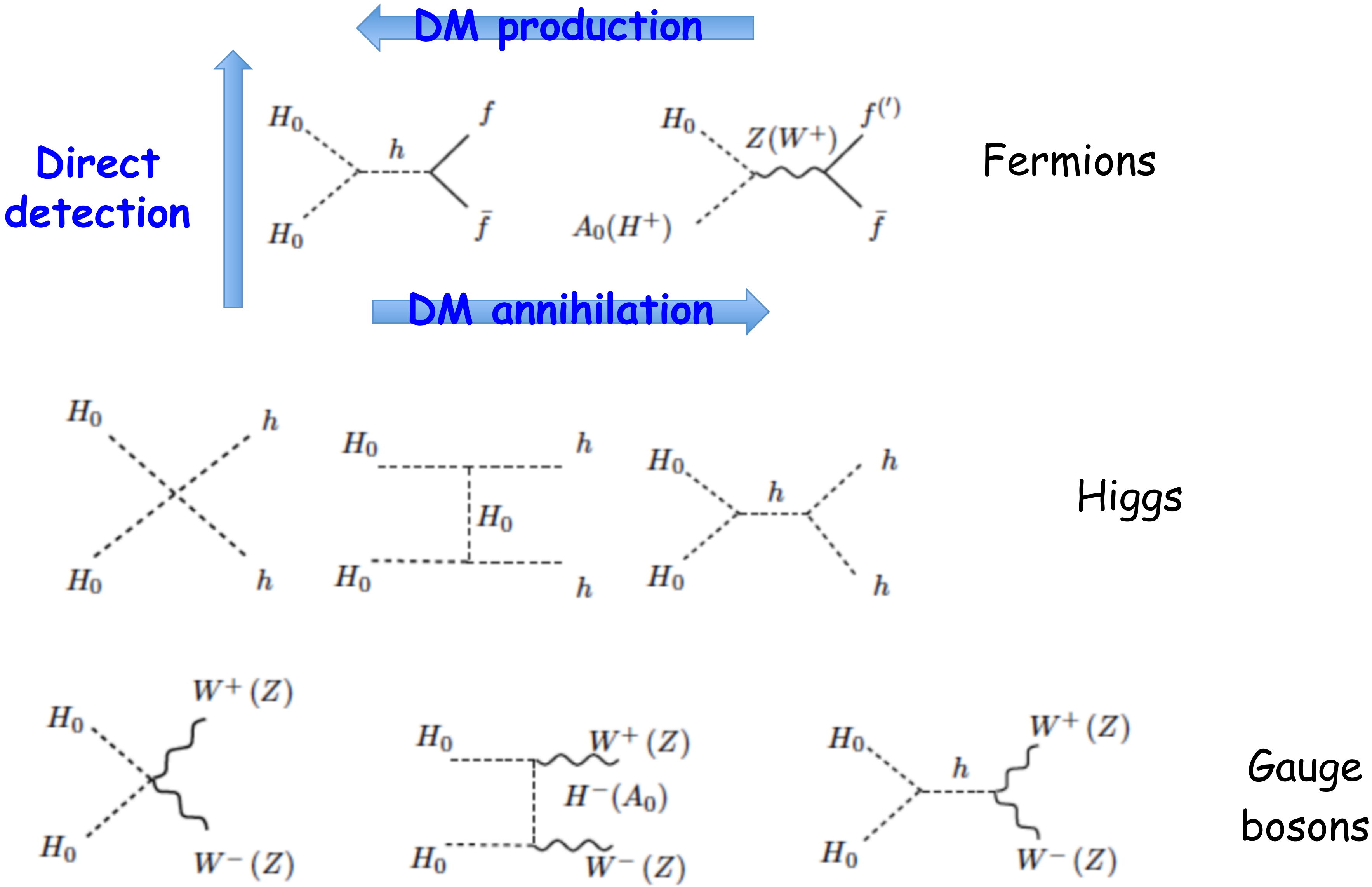
$$\lambda_{L,S} = \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5)$$

All constraints are then imposed as in the usual 2HDM + dark matter constraints

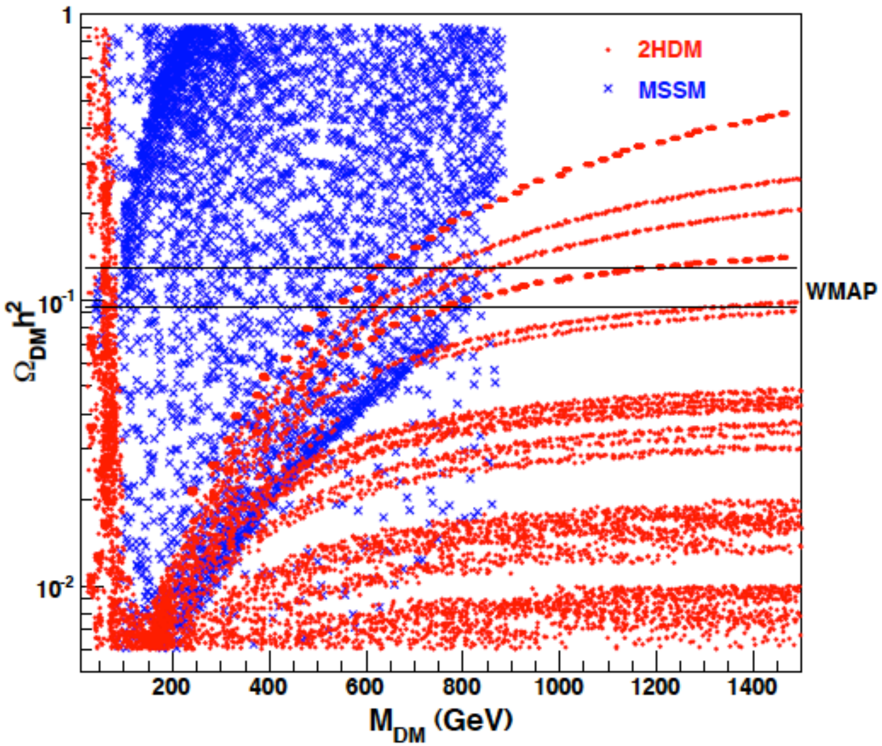
It is usually assumed that $m_{H^0} < m_{A^0},\ m_{H^\pm}$

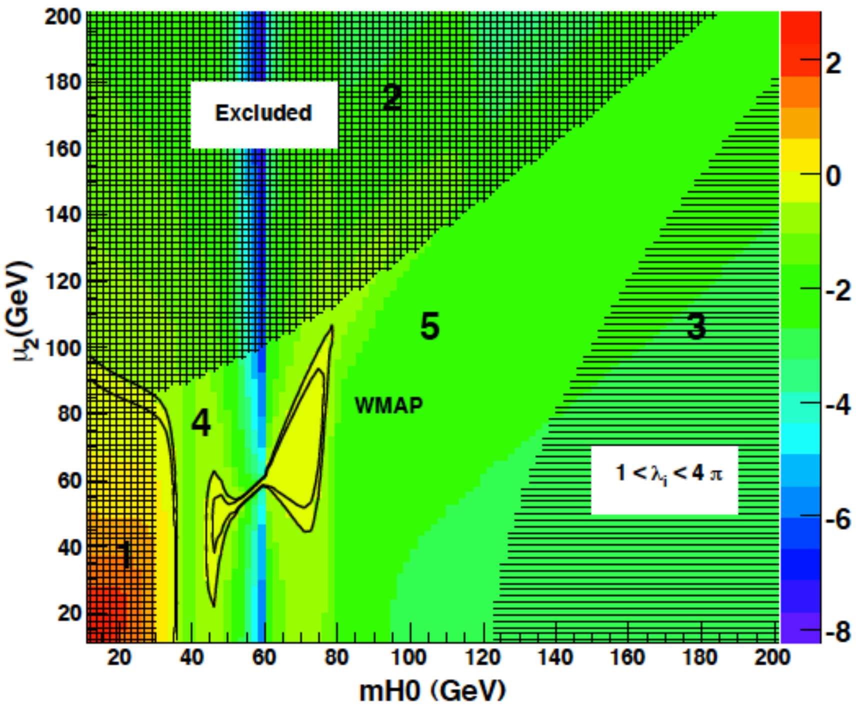
The Inert Model (2HDM)

In the doublet case DM couples to gauge bosons - isospin



Constraints on (dark matter) in the Inert Model





Some old plots showing the relic density bounds.

Check the famous WIMP miracle (weak cross sections with masses around the electroweak scale).

The Inert Model (2HDM)

dominant production modes: through Z; Z, γ, h for AH; $H^+ H^-$

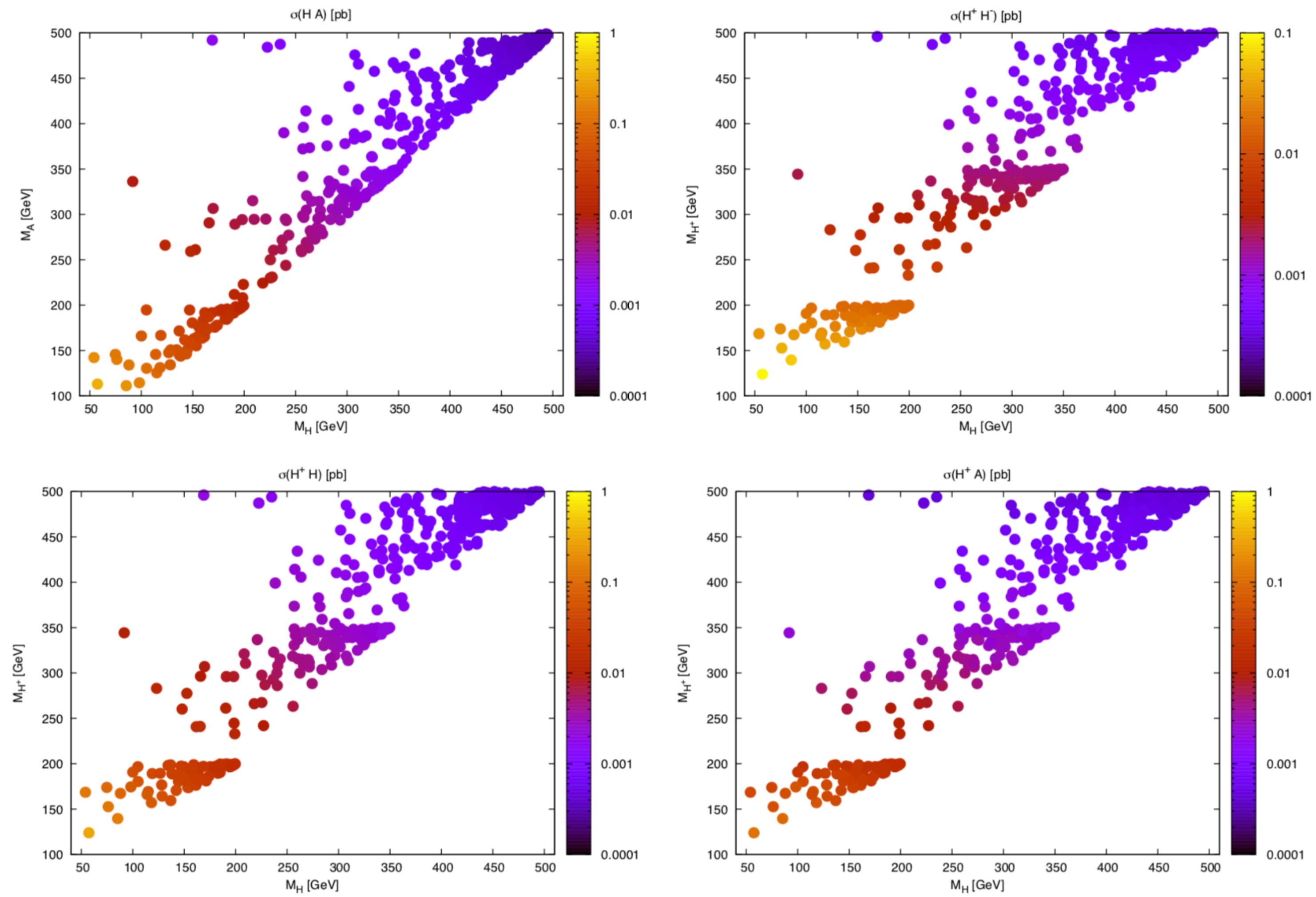
important couplings:

- $Z\,H\,A$: $\sim\ \frac{e}{s_W\,c_W}$
- $Z\,H^+\,H^-$: $\sim\ e\ \coth\,(2\,\theta_w)$
- $\gamma\,H^+\,H^-$: $\sim\ e$
- $h\,H^+\,H^-$: $\lambda_3\,v$
- $H^+\,W^+\,H$: $\sim\ \frac{e}{s_W}$
- $H^+\,W^+\,A$: $\sim\ \frac{e}{s_W}$

!! mainly determined by electroweak SM parameters !!

Slide from Tania Robens - talk at Scalars2015.

The Inert Model (2HDM)



$$p\,p \rightarrow H\,A$$

$$p\,p \rightarrow H^{\pm}\,H$$

$$p\,p \rightarrow H^{\pm}\,A$$

$$p\,p \rightarrow H^{+}\,H^{-}$$

Figure : Production cross sections in pb at a 13 TeV LHC

Slide from Tania Robens - talk at Scalars2015.

Massive vector dark matter

A renormalizable model where a new gauge boson is introduced. The symmetry is broken via a VEV on the scalar that gives mass do the dark matter vector

$$\mathcal{L}_{\rm d} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu S)^\dagger D^\mu S + \mu_S^2 |S|^2 - \lambda_S |S|^4 - \kappa |S|^2 |H|^2$$

with symmetries

$$X_\mu \to -X_\mu \,, \quad S \to S^*$$

$$M_W = \frac{1}{2} g v, \qquad M_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v \quad \text{and} \quad M_{Z'} = g_x v_x,$$

singlet VEV

The scalar singlet mixes with the SM – in that respect the model is exactly the same as singlet extension of the SM with no dark matter candidate.

Fermionic dark matter

Particle	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$	Coupling
Dark Matter, χ	1/2	1	1	0	-1	
Baryonic Scalar	0	3	2	1/6	-1	$\bar{q}_L \chi_R S_b$
mediator, S_b	0	3	1	$2/3, -1/3$	-1	$\bar{u}_R \chi_L S_b$, $\bar{d}_R \chi_L S_b$
Leptonic Scalar	0	1	2	$-1/2$	-1	$\bar{l}_L \chi_R S_l$
mediator, S_l	0	1	1	-1	-1	$\bar{e}_R \chi_L S_l$
Baryonic Vector	1	3	2	1/6	-1	$\bar{q}_L \gamma_\mu \chi_L V_b^\mu$
mediator, V_b^μ	1	3	1	$2/3, -1/3$	-1	$\bar{u}_R \gamma_\mu \chi_R V_b^\mu$, $\bar{d}_R \gamma_\mu \chi_R V_b^\mu$
Leptonic Vector	1	1	2	$-1/2$	-1	$\bar{l}_L \gamma_\mu \chi_L V_l^\mu$
mediator, V_l^μ	1	1	1	-1	-1	$\bar{e}_R \gamma_\mu \chi_R V_l^\mu$

Table 1. Particle content with corresponding quantum numbers and interactions in a t-channel model by considering fermionic dark matter candidate χ interacting with the SM fermions through scalar and vector mediators.

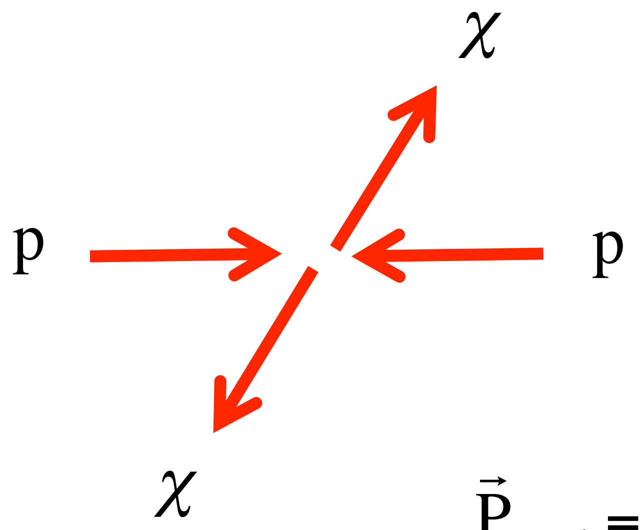
Written in terms of effective operators of different dimension.

(a)Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	7	SI
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	SD
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI

Searches at the LHC

Dark matter production



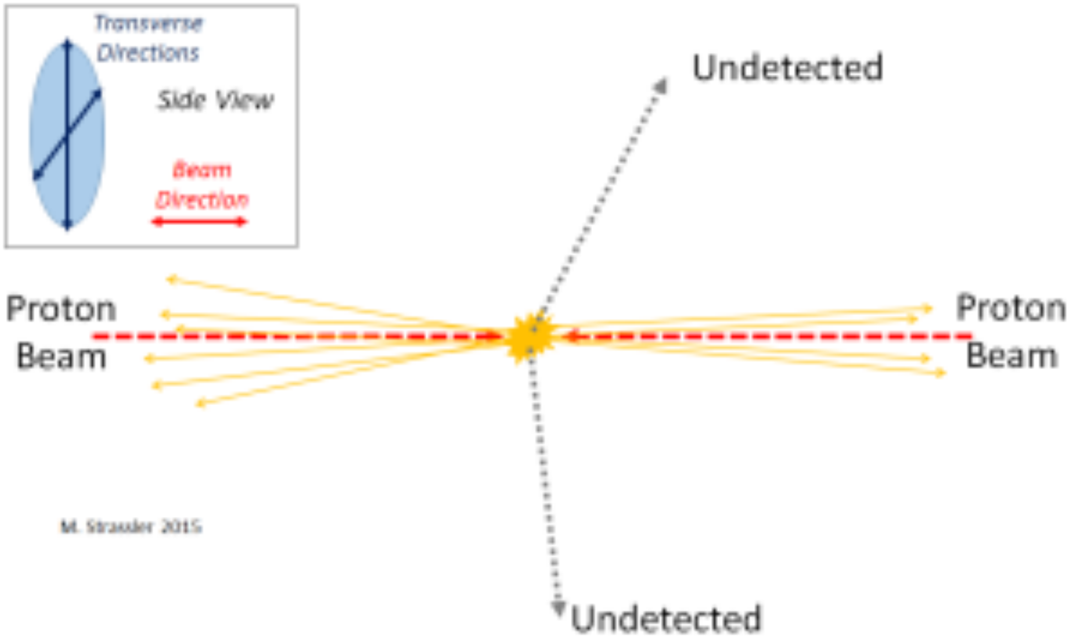
Darkness is conserved and therefore dark particles are produced in pairs

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

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!

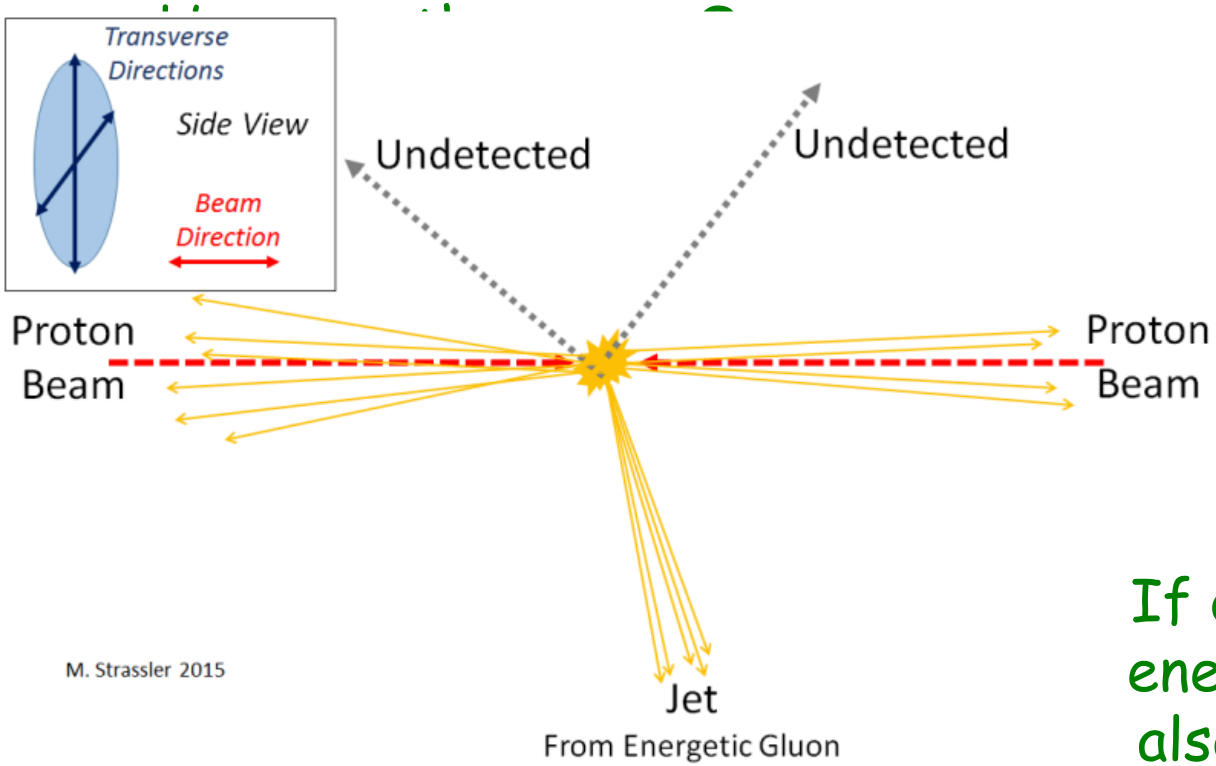
Dark matter production

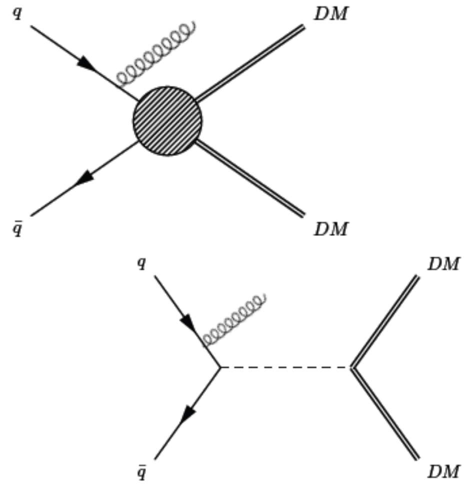


$$P^{T}_{Total} = 0$$

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

Mono-X

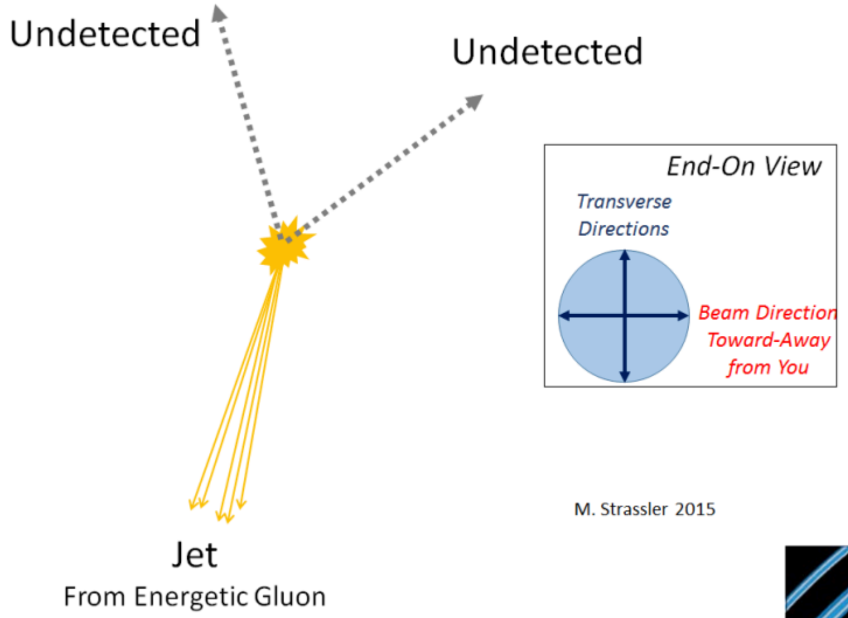




If one or more (high-energy) particles are also produced in the process then we have a mono-X (multi-X – still called mono-X) event! The X (for instance a jet) has a very large pT.

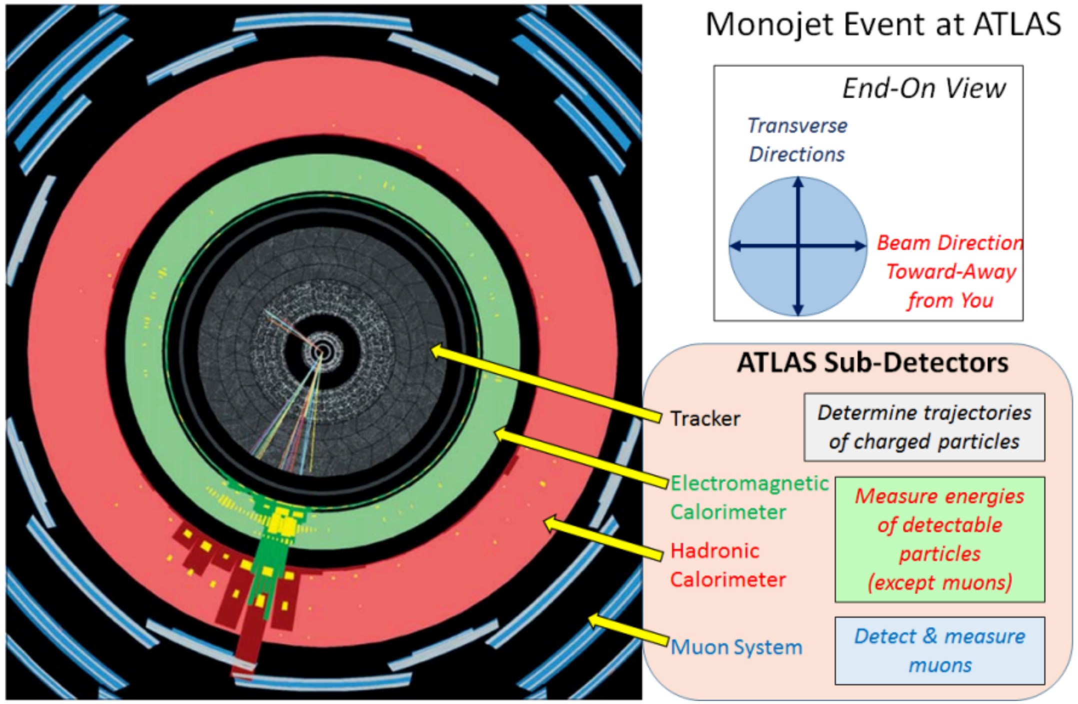
However, this can also be MET from neutrinos.

A monojet in ATLAS

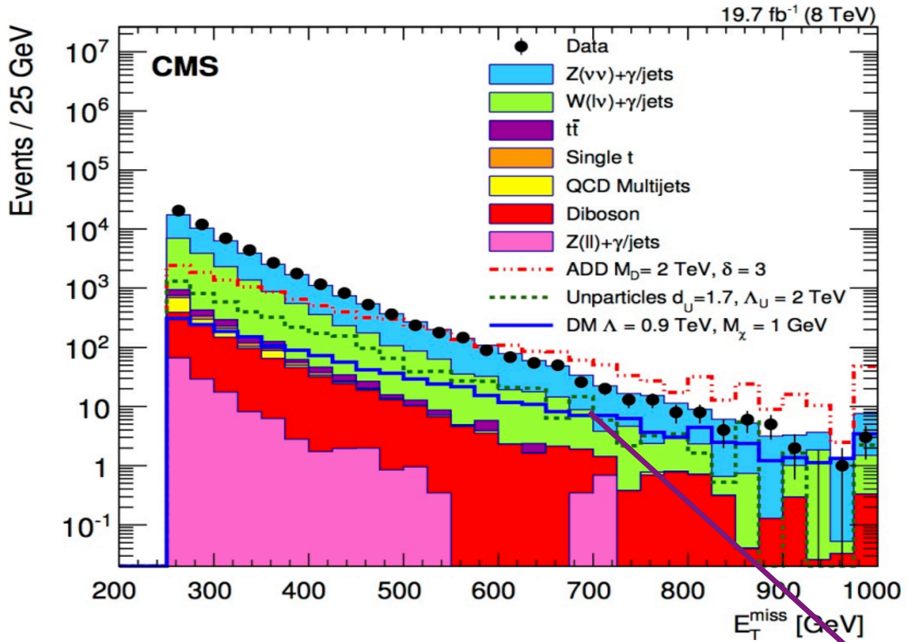


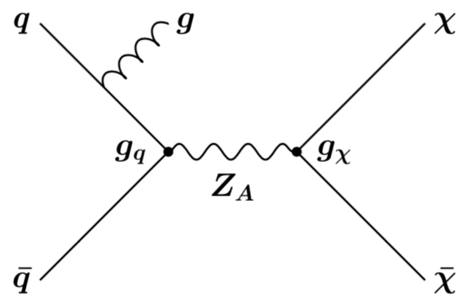
In the transverse plane.

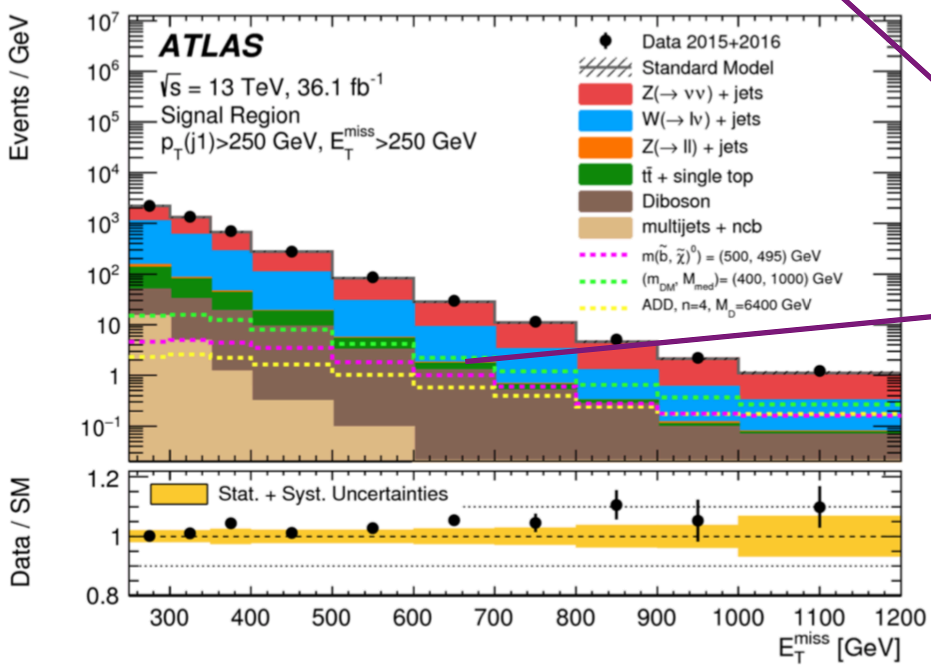
Monojet event in the ATLAS detector.



Mono-jet model interpretation in CMS





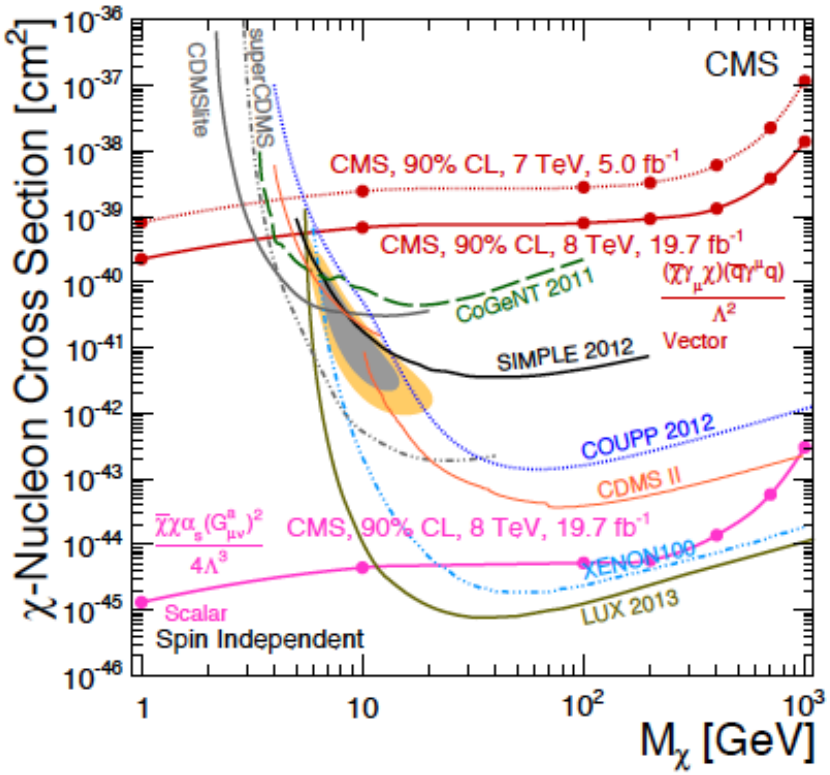


We know the SM background. This particular case is for an effective vertex with gluons.

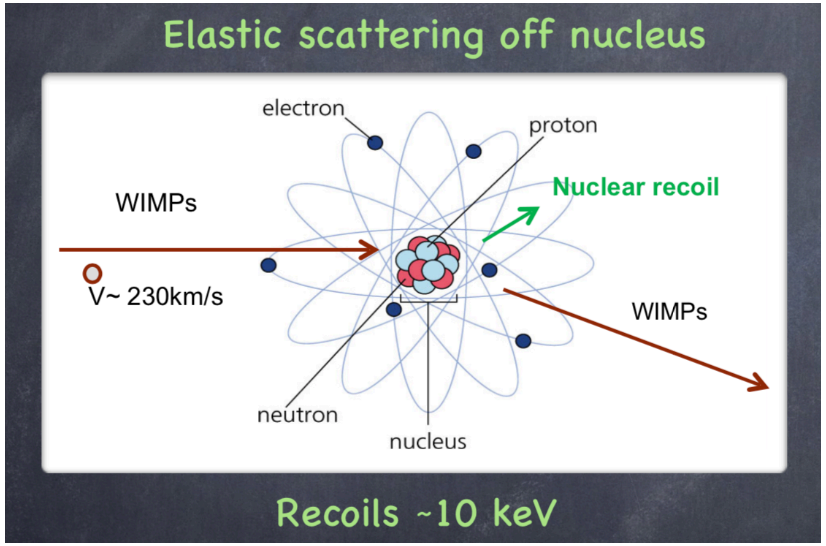
Dark matter line for a given cross section and mass of dark matter.

Comparison with direct detection limits

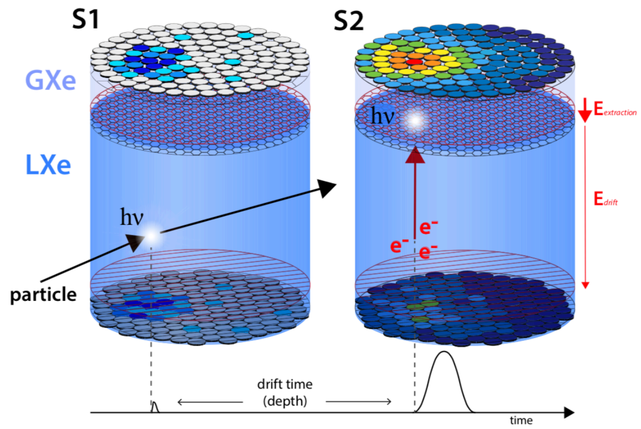
Direct detection vs. LHC.



The attained limit is about 1 TeV.



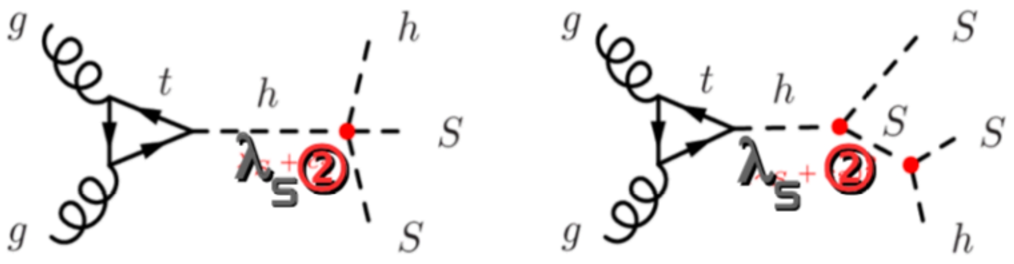
$$\chi N \to \chi N$$

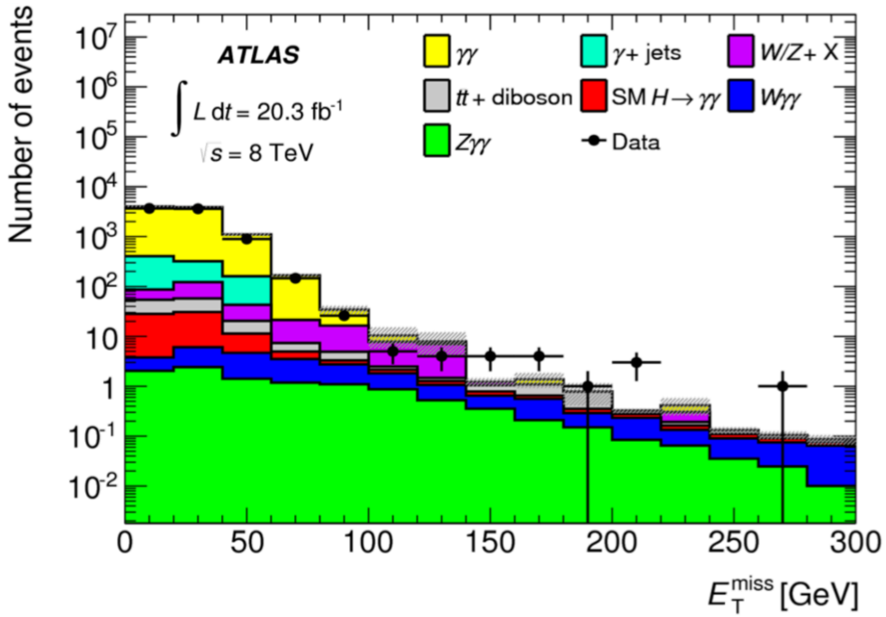


Xenon

The Inert Model (2HDM)

Mono-Higgs:





Promising in

$$\not{E}_T + h \quad (h \to b\bar{b})$$

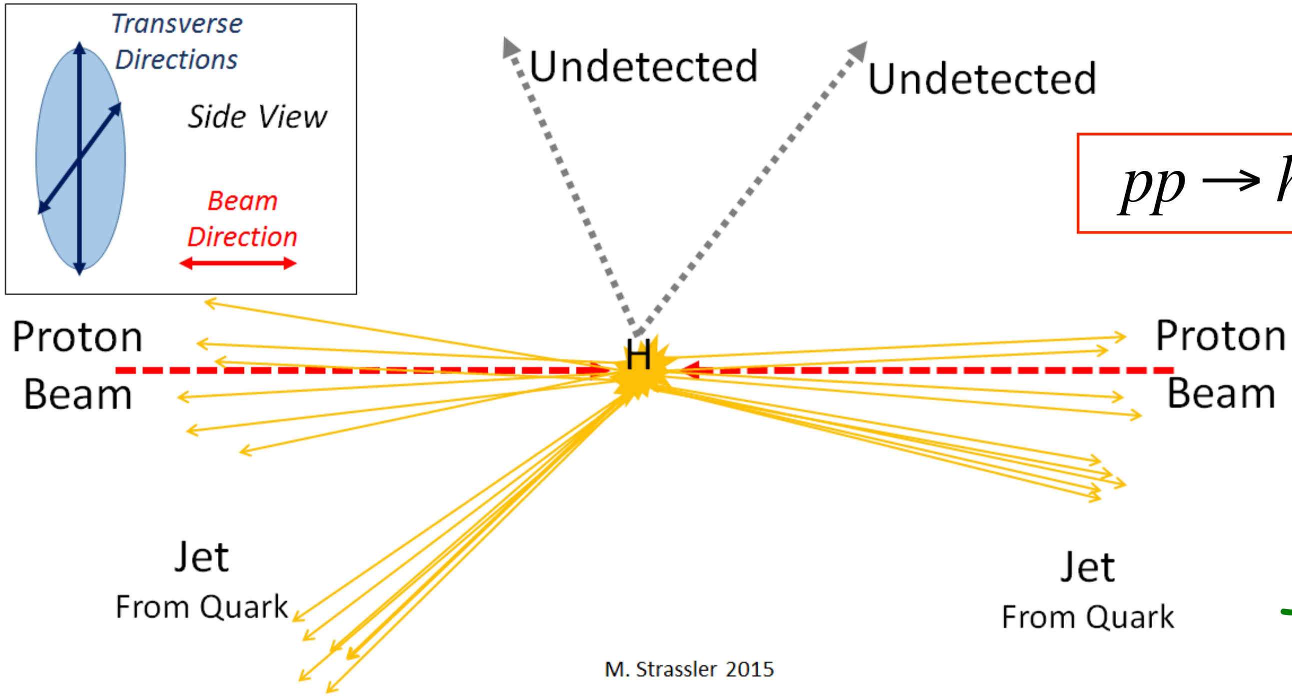
ATLAS Collaboration, 1510.06218

$$\not{E}_T + h \quad (h \to \gamma\gamma)$$

ATLAS Collaboration, 1506.01081 (Phys. Rev. Lett. 115 (2015) 131801)

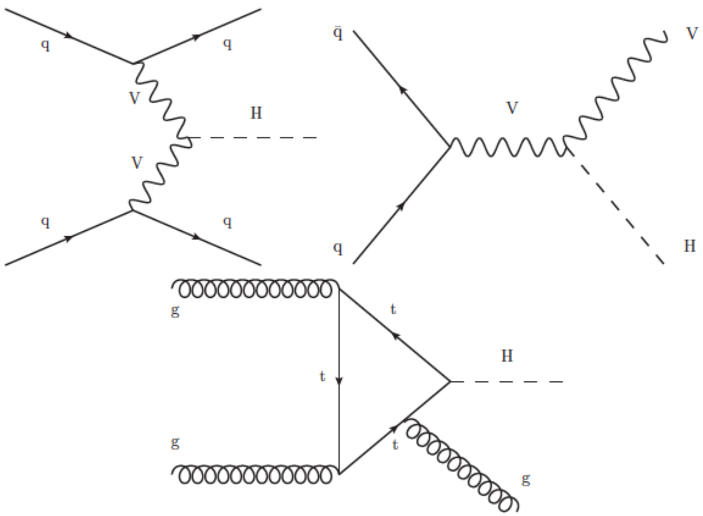
Slide from Jose Miguel No - talk at Scalars2015.

Invisible decays



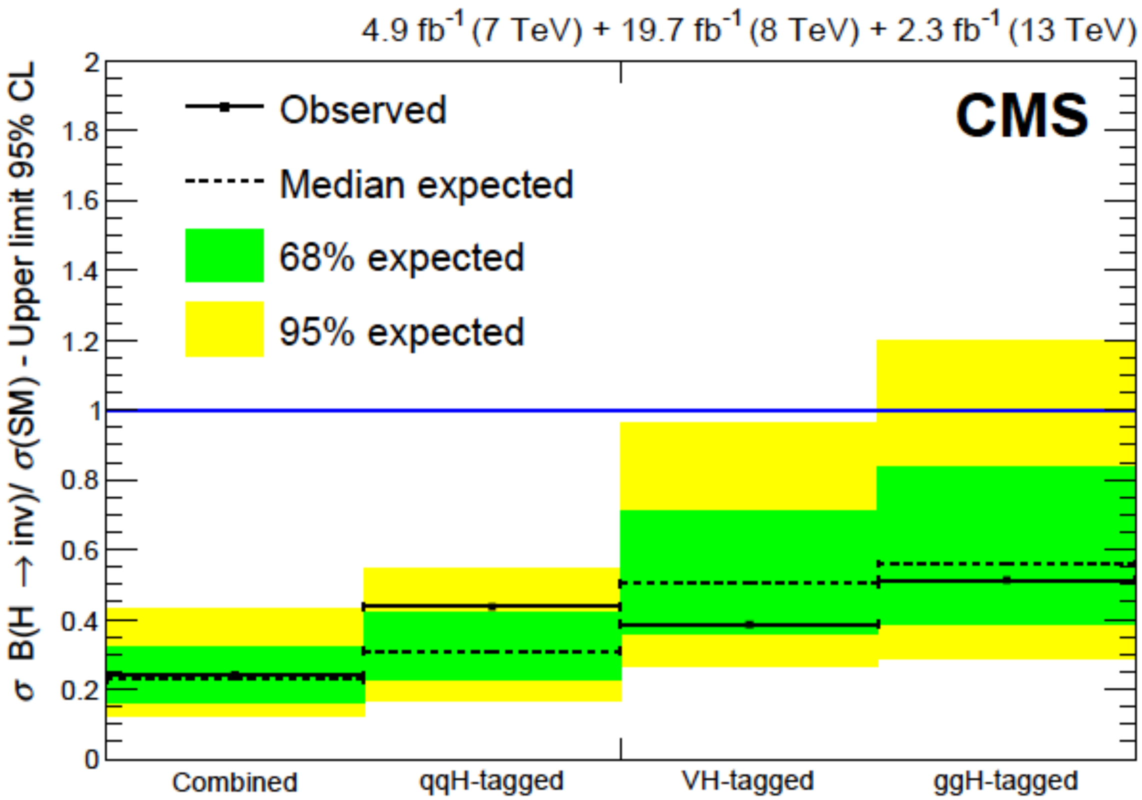
$$pp \to hjj \to \chi\chi\, jj \to METjj$$

This is the VBF case but it is possible to combine many channels



Three channels

Invisible decays



CMS results for 3 channels and combination.

Using the SM decay ratios it is possible to obtain a limit

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

Limits for the different types of dark matter

The cross section limits together with invisible widths can be translated for the different models.

$$\text{scalar } S: \Gamma^{\text{inv}}(h \to SS) = \lambda_{hSS}^2 \frac{v^2 \beta_S}{128\pi m_h}$$

$$\text{fermion } f: \Gamma^{\text{inv}}(h \to ff) = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{v^2 \beta_f^3 m_h}{64\pi}$$

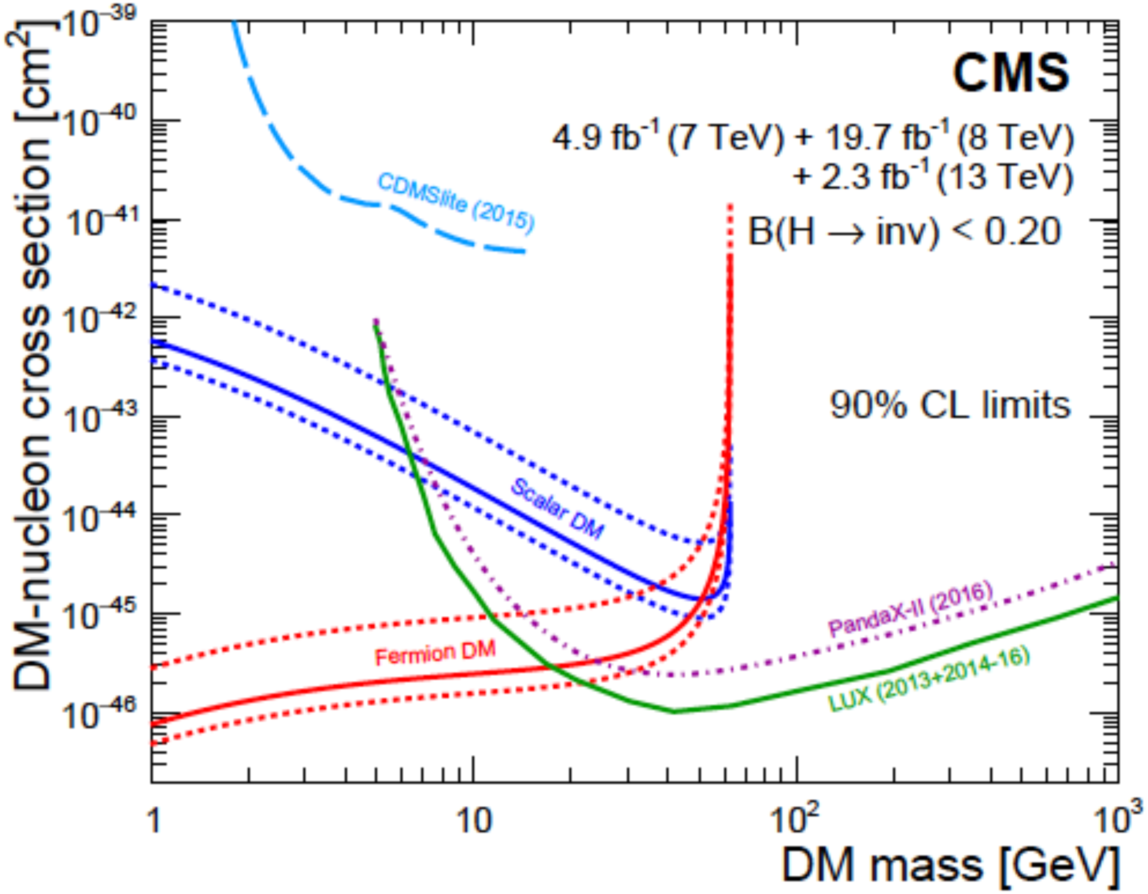
$$\text{vector } V: \Gamma^{\text{inv}}(h \to VV) = \lambda_{hVV}^2 \frac{v^2 \beta_V m_h^3}{512\pi m_V^4} \times \left(1 - 4\frac{m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)$$

Limits can be plotted along side with the ones from <u>direct detection</u>.

$$\text{scalar } S: \quad \sigma_{S-N} = \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_S + m_N)^2}$$

$$\text{fermion } f: \quad \sigma_{f-N} = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4\pi m_h^4 (m_f + m_N)^2}$$

$$\text{vector } V: \quad \sigma_{V-N} = \lambda_{hVV}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_V + m_N)^2}$$

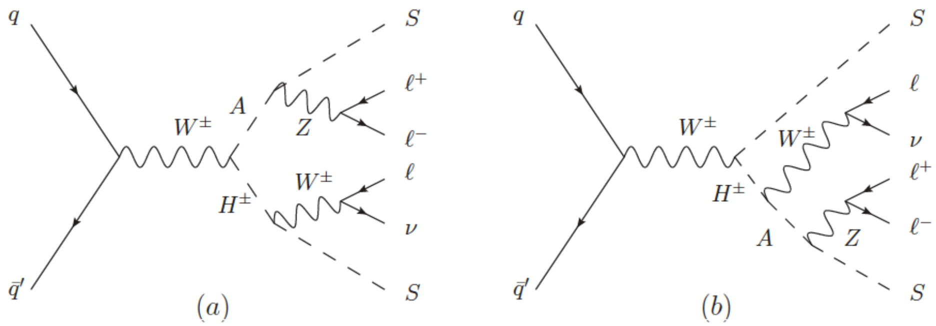


<u>Maximum limit (colliders) for half the Higgs mass.</u>

$$\boxed{h_{125} \to \chi\chi}$$

The Inert Model (2HDM)

Cascade decays



Final state: 3l + missing energy

Benchmark	m_h (GeV)	m_S (GeV)	δ_1 (GeV)	δ_2 (GeV)	λ_L
LH1	150	40	100	100	−0.275
LH2	120	40	70	70	−0.15
LH3	120	82	50	50	−0.20
LH6	130	40	100	70	−0.18
LH7	117	37	70	100	−0.14
LH8	120	78	70	35	−0.18

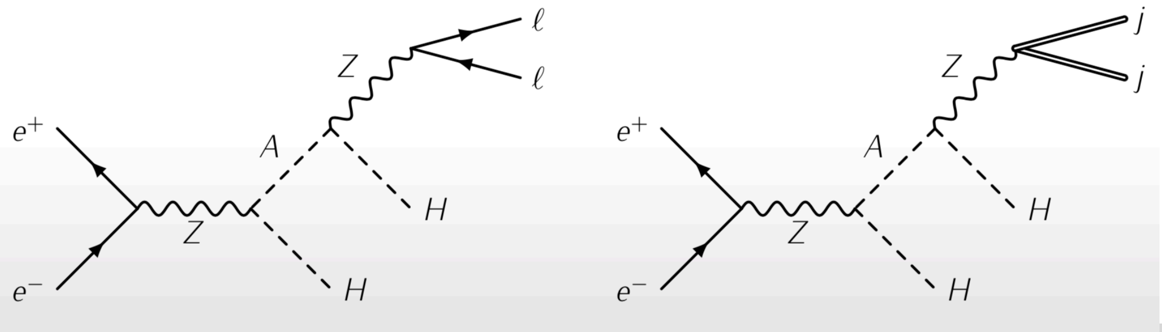
By the end of Run2?

Miau, Su, Thomas 2010.

Benchmark	Level III Cuts						
	$\sigma_{H^\pm A}$ (fb)	σ_{WZ/γ^*} (fb)	$\sigma_{t\bar{t}(j)}$ (fb)	$\sigma_{Wt(j)}$ (fb)	$\sigma_{\rm BG}^{\rm comb}$ (fb)	S/B	$S/\sqrt{B}$ (300 $\rm fb^{-1}$)
LH1	0.038	0.159	0.020	0.011	0.191	0.20	2.15
LH2	0.078	0.073	0.019	0.021	0.114	0.68	5.64
LH3	0.035	0.093	0.023	0.014	0.131	0.27	2.36
LH6	0.101	0.185	0.030	0.007	0.221	0.46	5.27
LH7	0.270	7.137	0.084	0.038	7.259	0.04	2.45
LH8	0.031	0.385	0.144	0.061	0.591	0.05	1.00

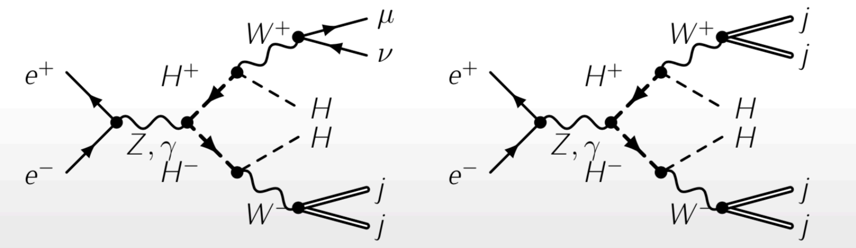
The Inert Model (2HDM)

More Cascade decays



leptonic final state

HA analysis, leptonic final state selection		
Selection cut	$\sqrt{s} = 0.5$ TeV	$\sqrt{s} = 1$ TeV
2 leptons	$E_T > 1$ GeV	$E_T > 5$ GeV
E_T^{miss}	$10 < E_T^{\text{miss}} < 120$ GeV	$10 < E_T^{\text{miss}} < 250$ GeV
$m_{\ell 1,\ell 2}$	$\lvert m_{\ell 1,\ell 2} - m_Z \rvert > 20$ GeV	$\lvert m_{\ell 1,\ell 2} - m_Z \rvert > 20$ GeV



Hashemi, Krawczyk, Zarnecki 2015.

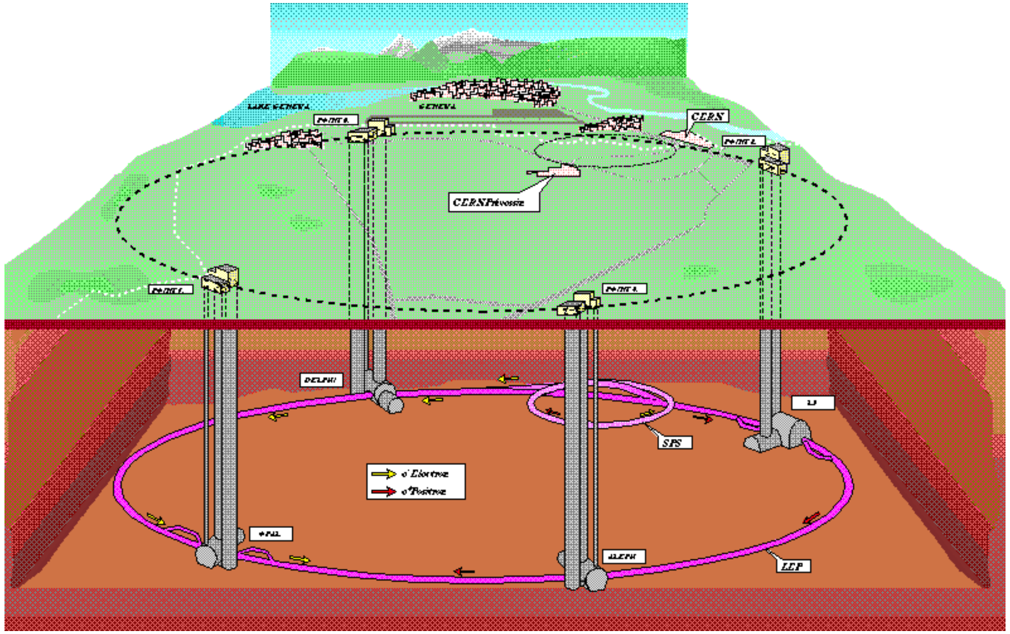
What if we find something at the LHC?

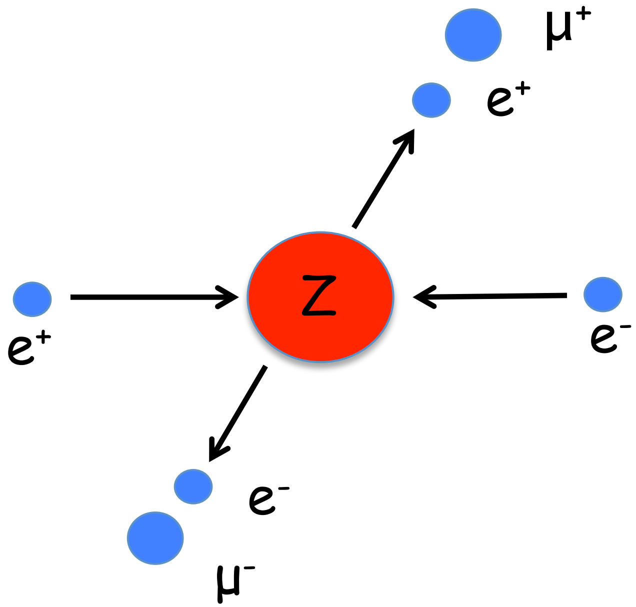
- The LHC cannot confirm the existence of dark matter
- Confirmation from direct detection needed
- And it can be just part of the total dark matter
- And it can be just a long lived particle escaping the detector
- Maybe indirection detection can also help

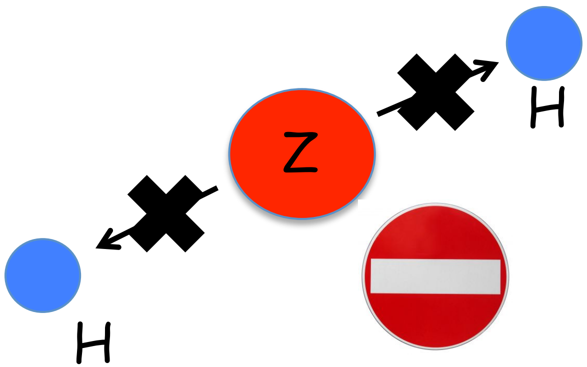
Complementary searches at colliders

LEP

LEP II (Z bosons factory)





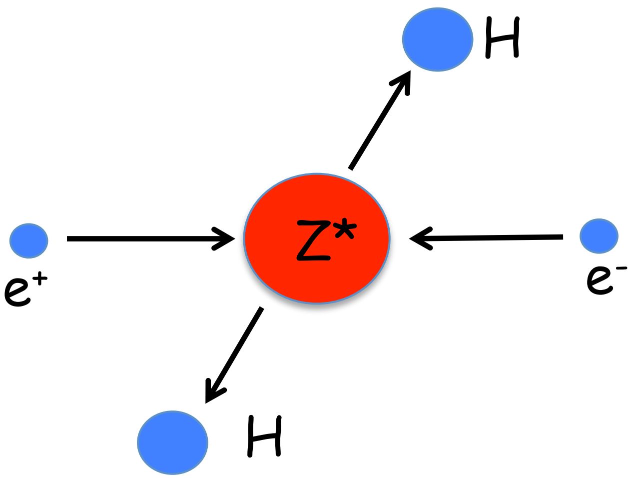


Great precision in width measurement – there is no more Z!

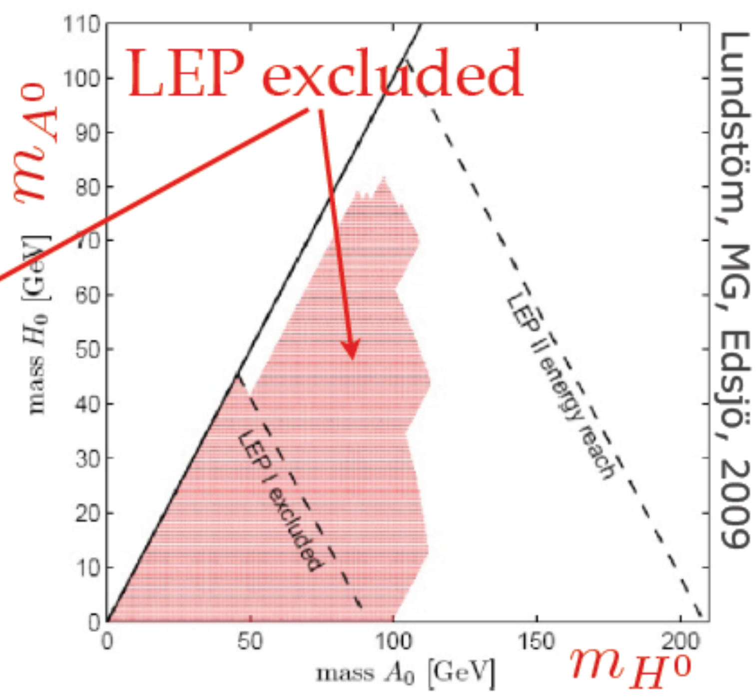
LEP

W e Z

$$\cancel{\begin{pmatrix} W \to H^{\pm}H^{0}, H^{\pm}A^{0} \\ Z \to H^{0}A^{0}, H^{\pm}H^{\mp} \end{pmatrix}} \left\{ \begin{array}{l} m_{H^{\pm}} + m_{H^{0},A^{0}} \gtrsim m_W \\ m_{H^0} + m_{A^0}, 2m_{H^{\pm}} \gtrsim m_Z \end{array} \right.$$



Even with a virtual Z no new particles were found.



Excludes the mass region

$$m_{H^0} \lesssim 80\,\mathrm{GeV},\ m_{A^0} \lesssim 100\,\mathrm{GeV}$$
$$\text{and} \quad \Delta m_{A^0-H^0} \gtrsim 8\,\mathrm{GeV}$$

Conclusions

None!

BUP slides

Case against neutrinos

Gunn-Tremaine bound imposes lower bound required for dark matter particle that decoupled when relativistic, $m_{DM} \gtrsim 100\text{eV}$

Momentum distribution in Galactic halo Maxwell-Boltzmann, $\Delta p \sim m_{DM}\langle v\rangle \sim 300\text{km/sec}$

Mean spacing $\Delta x \sim n_{DM}^{-1/3} \sim (\rho_{DM}/m_{DM})^{-1/3}$

$\Delta x \Delta p \gtrsim \hbar \Rightarrow m_{DM} \gtrsim 50\text{eV}$

Much too massive for SM neutrinos

Total relic density from neutrinos is:

$$\Omega_\nu h^2 = \sum_{i=1}^{3} \frac{m_i}{93\text{eV}}$$

Upper bound of neutrino masses from β-decay experiments: $m_\nu < 2.05\text{eV}$

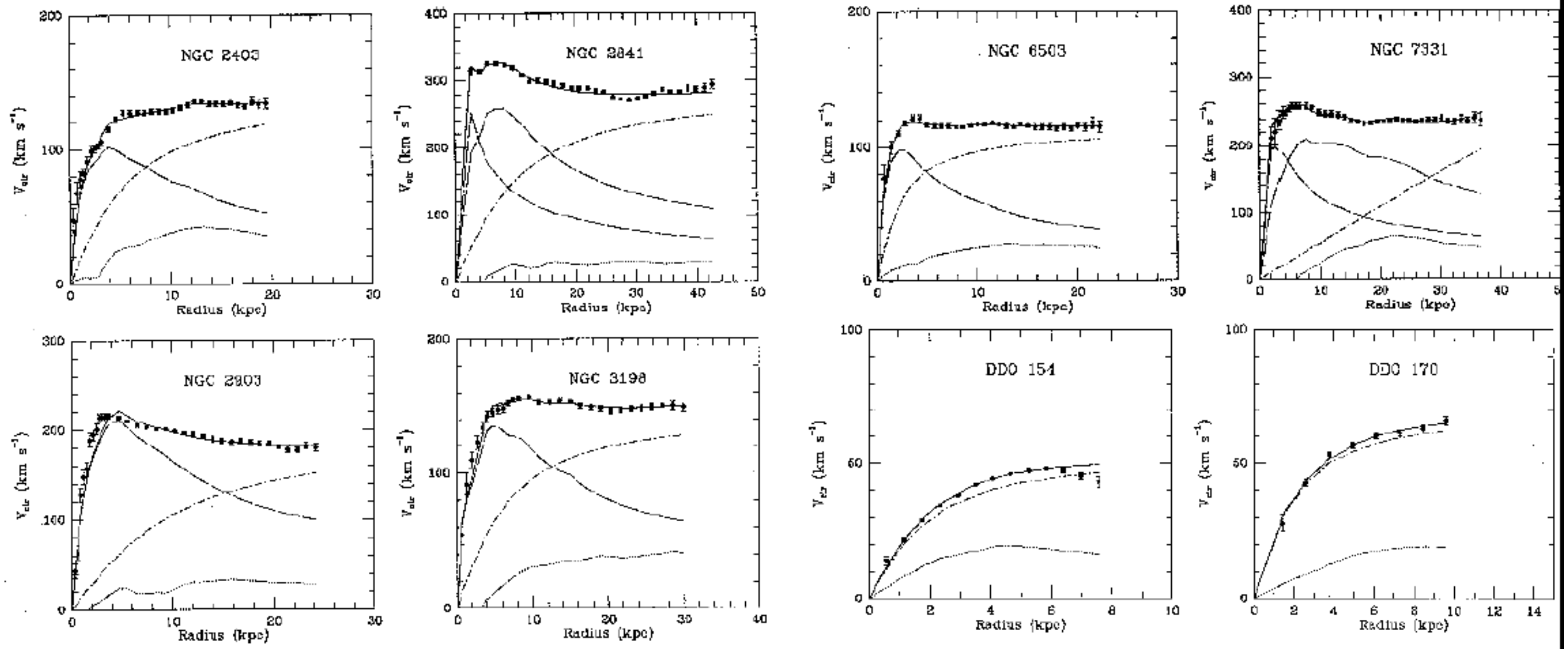
$$\Rightarrow \Omega_\nu h^2 \lesssim 0.07$$

Neutrinos not abundant enough to dominate dark matter.

CMB + LSS constraints even more stringent, giving $\Omega_\nu h^2 \lesssim 0.0067$

Measured rotation curves

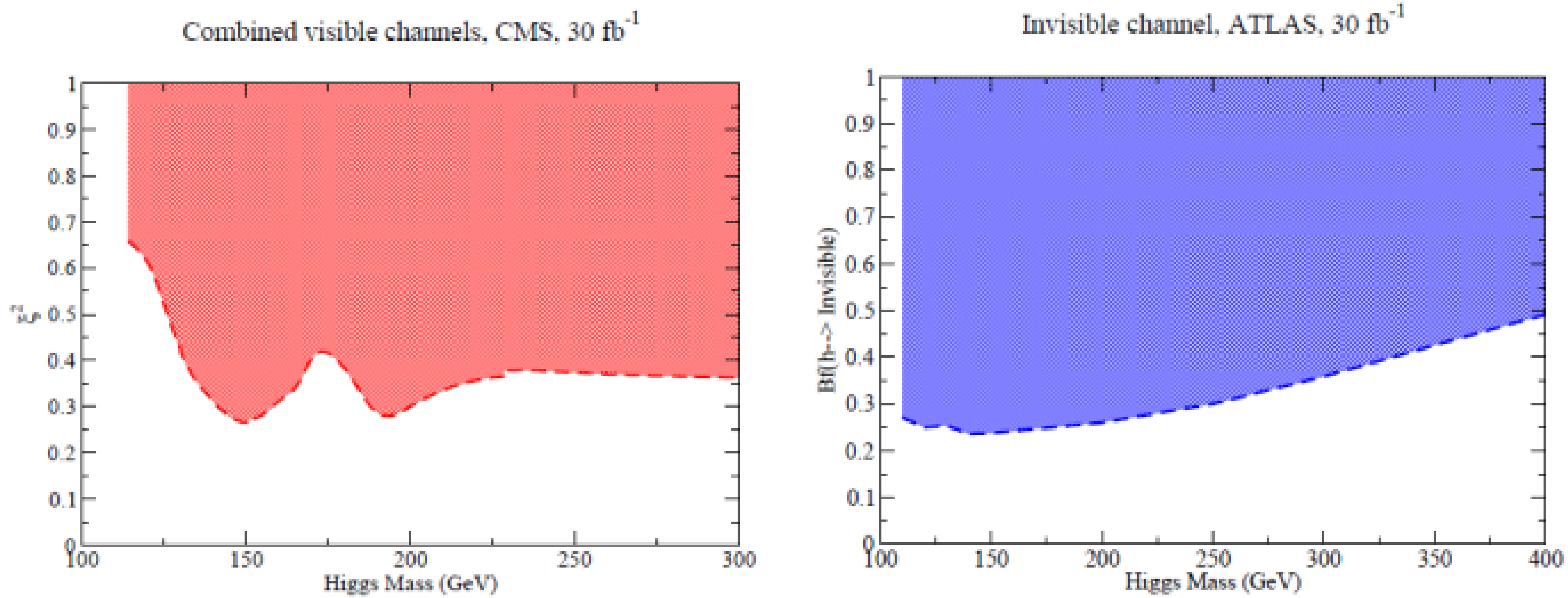
Three parameter fits (solid) to measured rotation curves, with individual components, visible component (dashed), gas (dotted), and dark halo (dash-dot)



Begeman *et al.* 1991

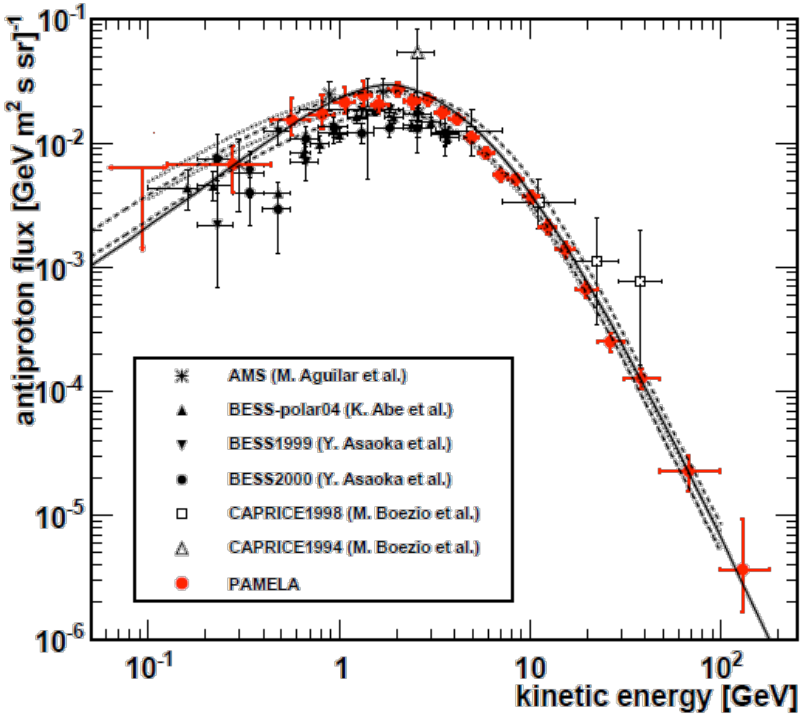
SM + complex singlet

$$\xi_i^2 = R_{i1}^2 \times \mathrm{BF}(H_i \to X_{\mathrm{SM}}) \qquad R_{i1} = \begin{cases} \cos\phi & i=1 \\ \sin\phi & i=2 \end{cases}$$



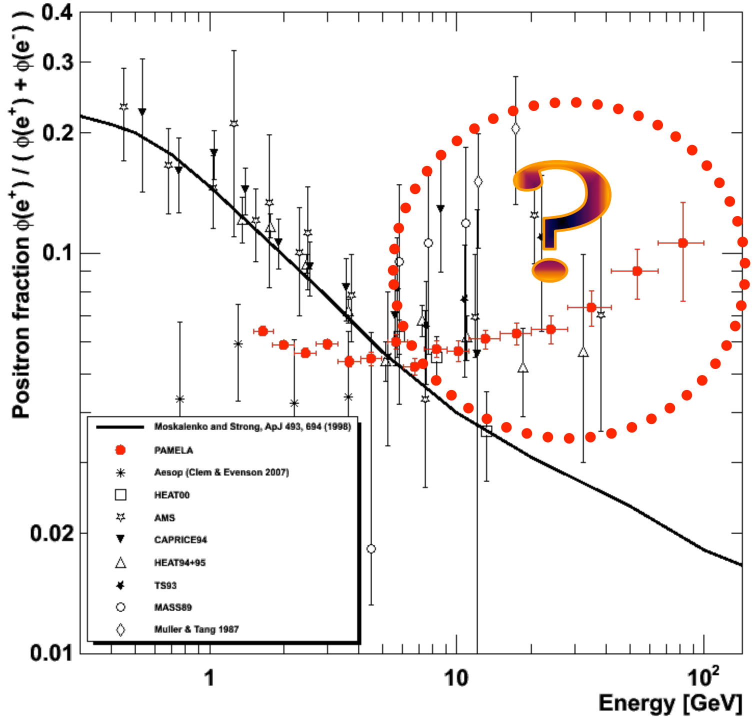
PaMeLa
a Payload for Antimatter Matter Exploration and Light–nuclei Astrophysics

Anti-protons - consistent



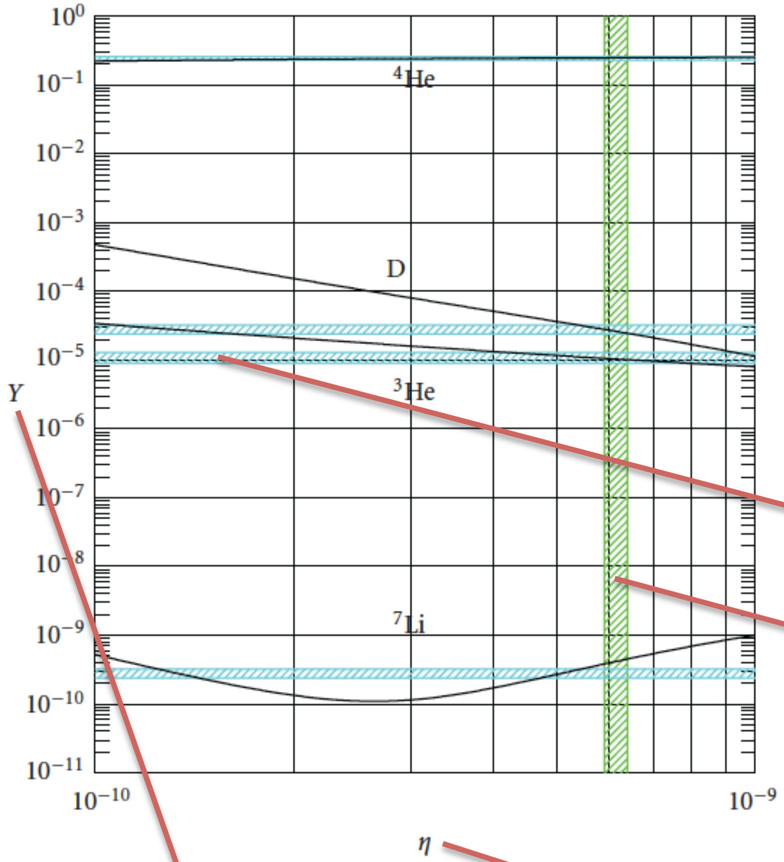
Adriani et al. –PRL 105 (2010) 121101

Positrons – excess for high energies



Adriani et al. –AP 34 (2010) 1

Nucleosíntese Primordial



Procurar lugares no universo onde a abundância de elementos leves não foi alterada por reacções estelares.

Medir abundâncias e compará-las com o modelo BBN e neste caso também com o resultados de WMAP.

Abundâncias medidas.

WMAP

Abundância (relativa a H)

Razão entre número de fotões e número de bariões.

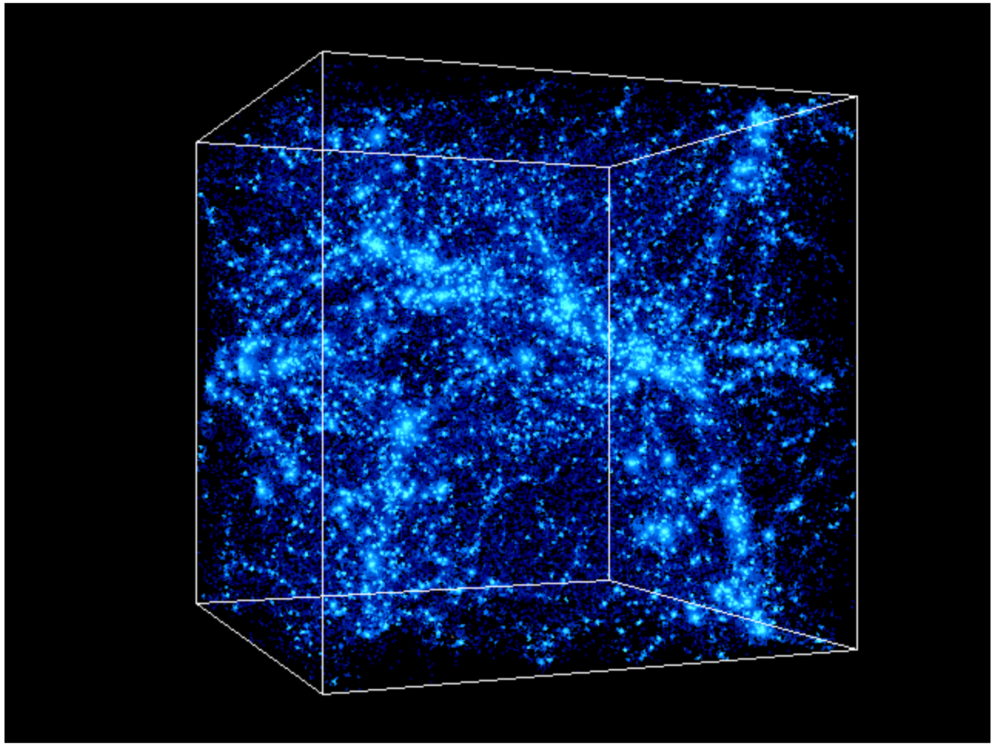
Formação de estruturas e o neutrino como matéria escura

A formação de estruturas tem 3 ingredientes fundamentais

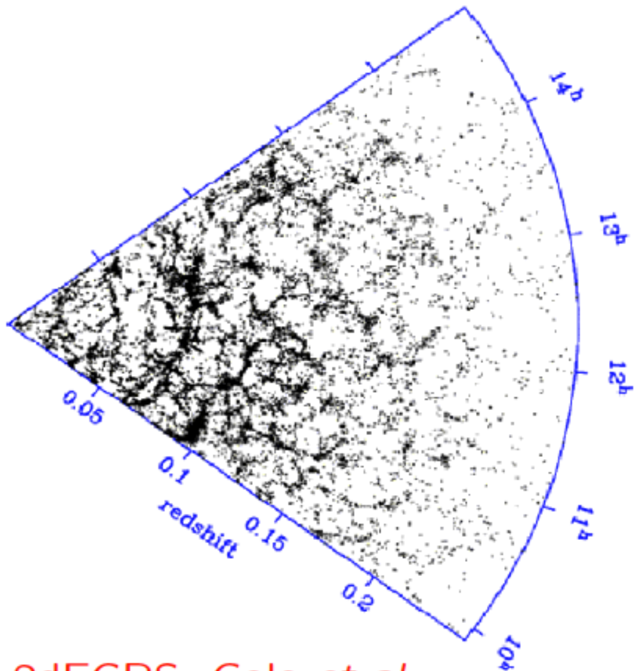
1. Fundo cosmológico – considera-se que em larga escala o universo é homogéneo e isotrópico
2. Flutuações – o único modelo viável para introduzir flutuações é a inflação: houve um período na história do universo em que as flutuações do vácuo foram amplificadas por uma expansão acelerada.
3. Tipos de matéria escura – a forma como as estruturas crescem depende do tipo de matéria escura incluída: para o modelo ser viável é preciso que a maior parte da matéria escura seja fria (não relativista) – pode haver alguma matéria escura relativista mas não "muita".

A única partícula do Modelo Padrão, candidata a matéria escura não passa o teste.

Formação de estruturas e o neutrino como matéria escura



A cosmologia computacional encontrou valores compatíveis com os valores medidos tendo em conta os três pontos apresentados antes.



2dFGRS, Cole *et al.*

Mas apenas se:

a) for introduzida matéria escura

b) a maior parte for não relativista.

Teorias Alternativas?

MOND – MOdified Newton Dynamics (Milgrom 1983)

$$\vec{F} = m\mu\left(\frac{a}{a_0}\right)\vec{a}, \qquad a_0 \approx 2 \times 10^{-8}\,\mathrm{cm\,s^{-2}}$$

$$\mu(x \gg 1) \approx 1, \quad \mu(x \ll 1) \approx x,$$

Regime Newtoniano.

Órbitas de objectos muito afastados do centro galáctico.

$$a = \frac{\sqrt{GMa_0}}{r} = \frac{v^2}{r} \Rightarrow \boxed{v = \sqrt[4]{GMa_0}}$$

Curvas de rotação das galáxias.

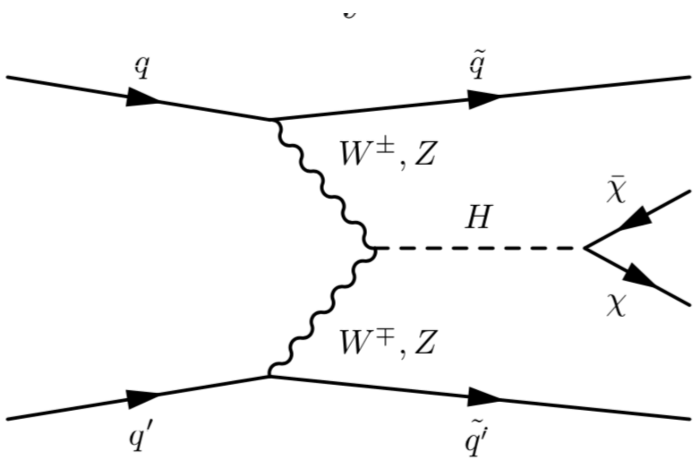
Candidatos a CDM

Matéria escura fria (CDM) – matéria não-relativista na época de formação de estruturas – será a maior parte da matéria escura;

- WIMP – weakly interacting massive particles – partículas pesadas (com massa algumas dezenas de vezes superior à do protão)

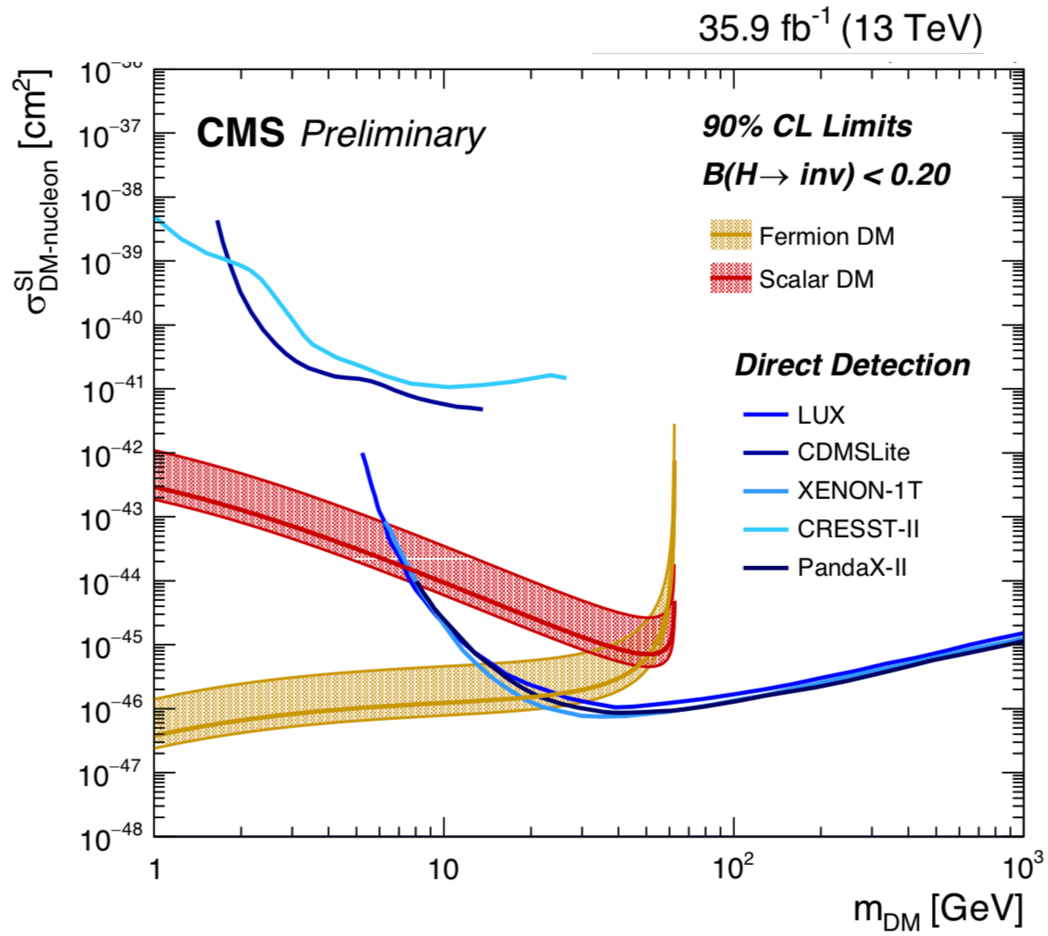
- MACHOs – massive compact halo objects – compostos por matéria bariónica ordinária em estruturas como buracos negros, estrelas de neutrões, anãs brancas e planetas. *Microlensing* sugere que possam ser 20 % da via láctea.

Invisible decays



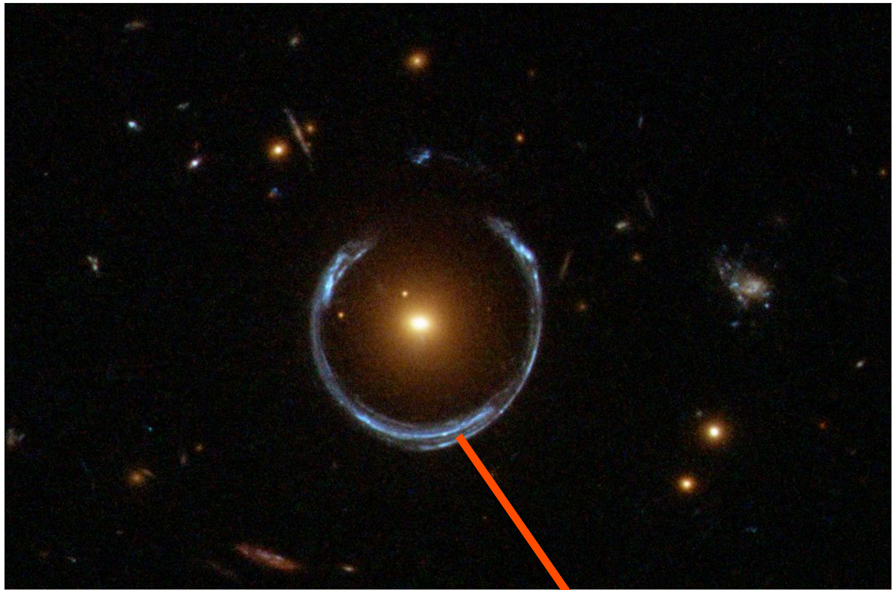
$\mathcal{B}$(H$\rightarrow$inv) < 0.2 at 90% CL interpreted in context of Higgs-portal DM model.

Strongest limits for fermion (scalar) χ for $m_\chi < 20$ (7) GeV.

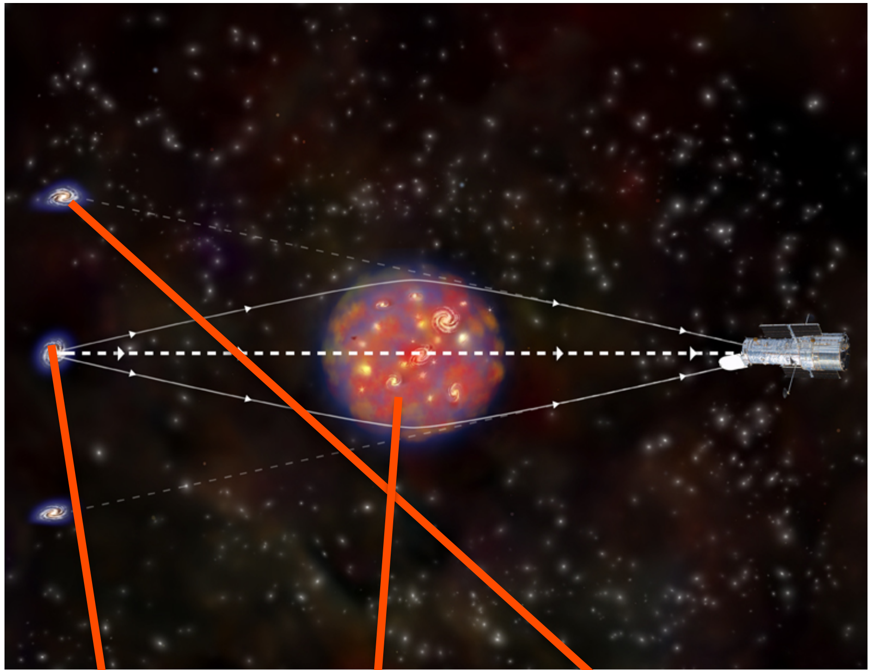


CMS-PAS-HIG-17-023 (14 March 2018)

Gravitational lenses



Einstein Ring



Source Lens Image

$$\boxed{\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_{LS}}{d_L d_S}},}$$

Conclusion: the lens' mass is much larger than its visible mass.