Dark Matter

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MultiDark
Multimessenger Approach for Dark Matter Detection

XLII International Meeting on Fundamental Physics

Benasque, Jan 26-Feb 01, 2014

OUTLINE

Dark Matter

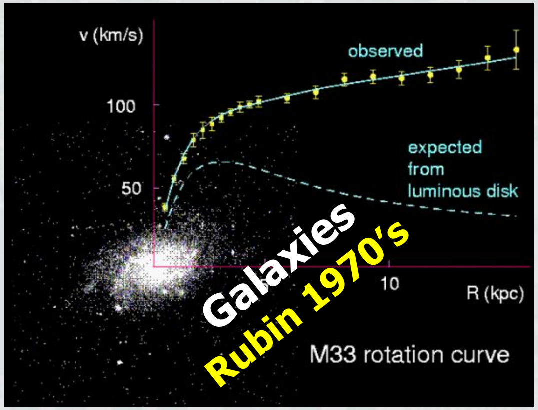
- Evidence for the existence of **DM**
- Particle candidates for **DM**
- Detection of the **DM**:

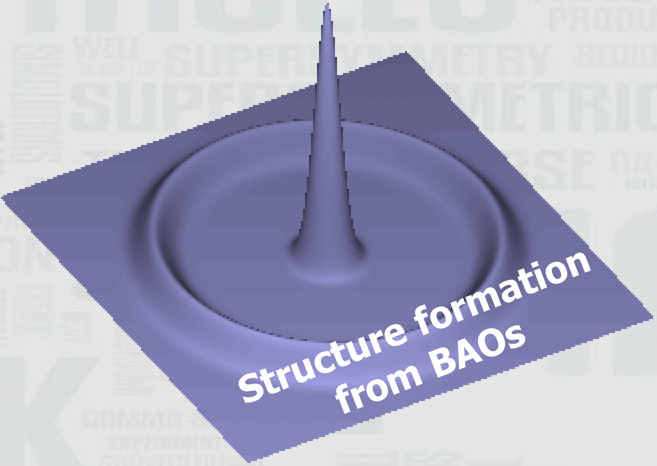
  -Direct Detection

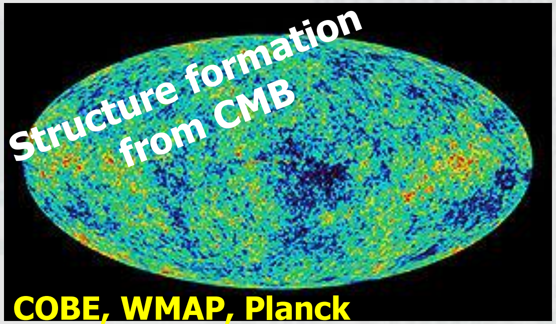
  -Indirect Detection

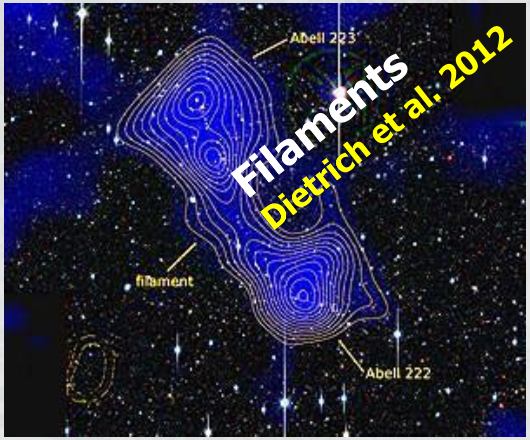
Evidence for DM

- Evidence for DM at very different scales, since 1930's:









Simple gravitational arguments imply that most of the mass in the Universe is some (unknown) non-luminous matter

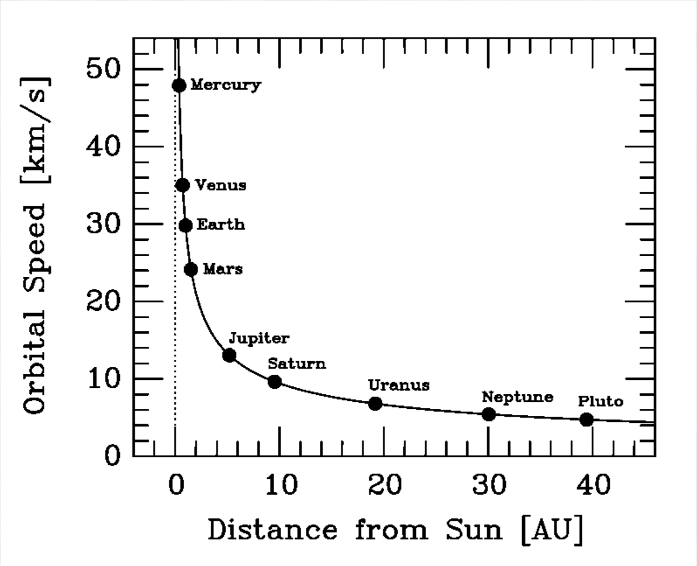
- E.g. one can compute the rotational velocity of a planet around the Sun simply using Newton's law

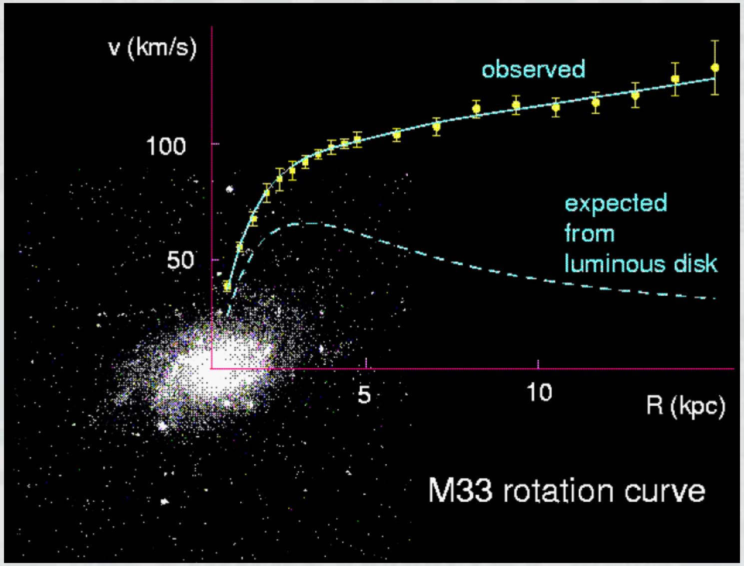
$$\frac{v_{\rm rot}^2}{r} = \frac{G\ M_\odot}{r^2} \quad \Rightarrow \quad v_{\rm rot} = \sqrt{\frac{G\ M_\odot}{r}}$$

- In the same way, one can compute the rotational velocity of isolated stars or hydrogen clouds in the outer parts of Galaxies

$$\Rightarrow \quad v_{\rm rot} = \sqrt{\frac{G\ M_{\rm galaxy}}{r}}$$

- However, by examining the Doppler shifts, the astronomers measure:





1pc=3.26 light-years

This is the so called **PROBLEM OF ROTATION CURVES**

A SOLUTION:

- To assume that there is **non-luminous matter** in and around the Galaxies

Dark Matter

$M(r) \sim r$ → $$v_{\rm rot} = \sqrt{\frac{G\ M(r)}{r}}$$ = constant

A self-gravitating ball of dark matter particles would have this mass profile

Although the nature of the dark matter is still unknown,

its hypothetical existence is not so odd if we remember that the discovery of Neptune in 1846 by Galle was due to the suggestions of Le Verrier and Adams on the basis of the irregular motion of Uranus

The presence of additional mass in the galactic disk was first hypothesized by the astronomer Jan Oort (1900-1992) in 1932 for the case of the Milky Way by examining the Doppler shifts in the spectra of stars

The picture that we have nowadays of the Milky Way (and all galaxies) is the following:

The disk is thought to be flat since luminous matter can radiate photons and therefore gravitationally collapse to a pancake-like structure

In principle, the dark matter halo could be round, elliptical, or even flattened like the disk.

However, it cannot radiate photons, and thus the dark halo should be much more diffuse than the disk.

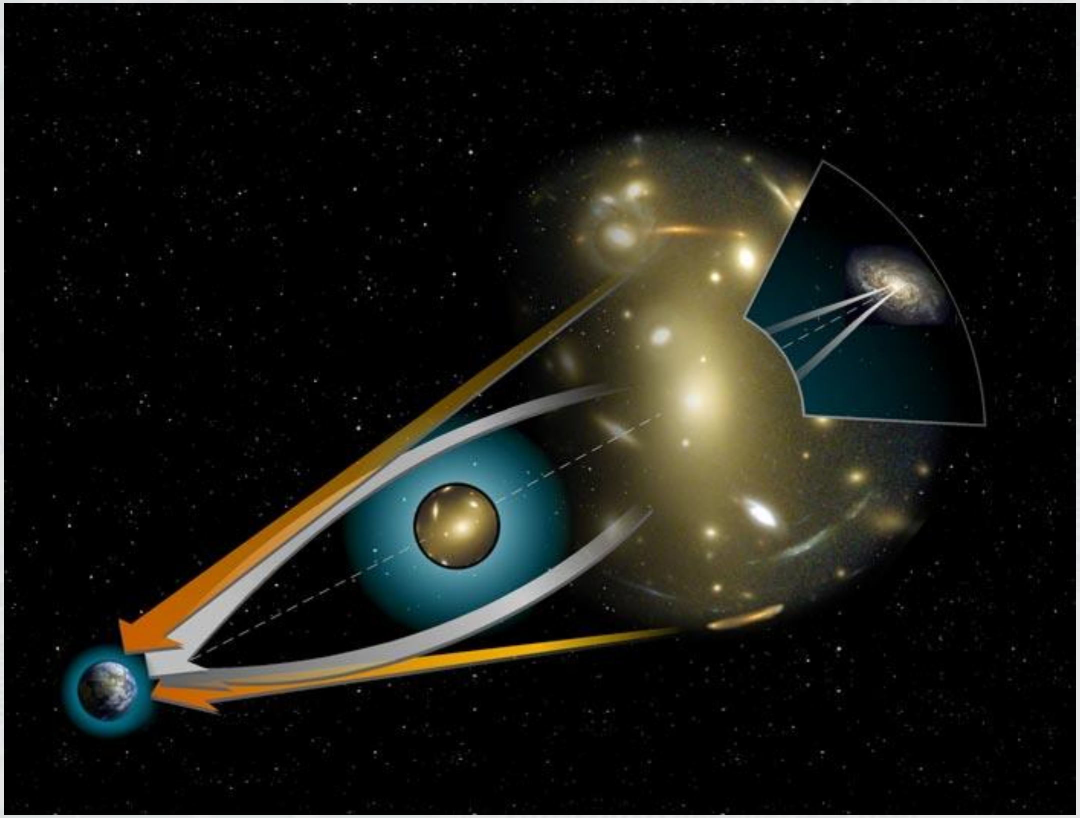
Actually, the term "dark matter" was initially coined by astronomer Fritz Zwicky (1898-1974) in 1933

when he realized that the mass of the luminous matter (stars) in the Coma cluster (measuring 1.5 Mpc across and formed by 1000 galaxies), was much smaller than its total mass implied by the motion of cluster member galaxies.

But, only in the 1970's, with the accurate measurements of galactic rotation curves by Vera Rubin (1928-) and others, the existence of dark matter began to be considered seriously

Nowadays, this phenomenon of anomalous rotation curves has been observed in detail in thousand of galaxies, and in particular also in our galaxy, the Milky Way

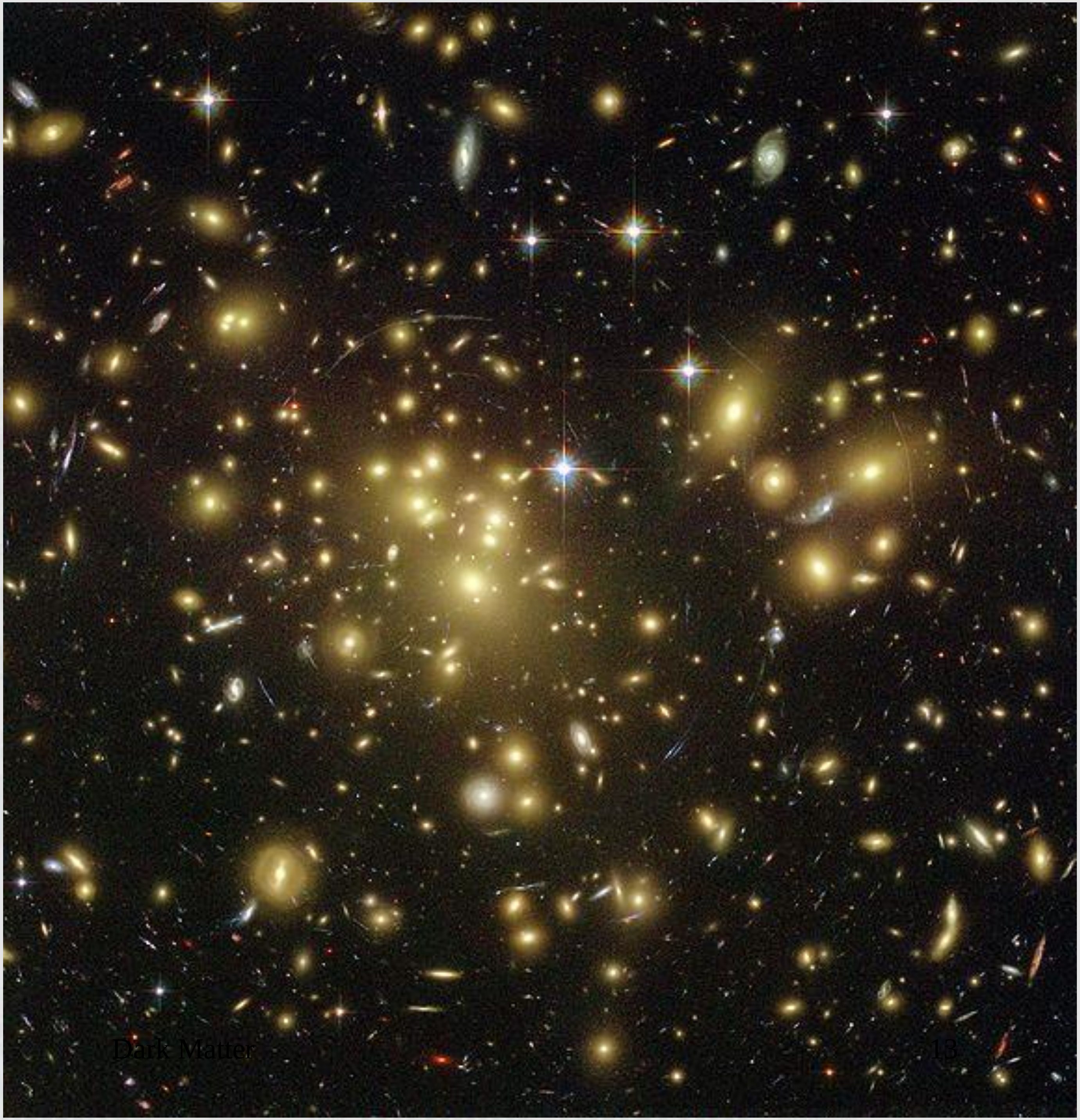
Other techniques have also been used to detect the dark matter in clusters, e.g. gravitational lensing



Bending light around a massive object from a distant source. The orange arrows show the apparent position of the background source. The white arrows show the path of the light from the true position of the source

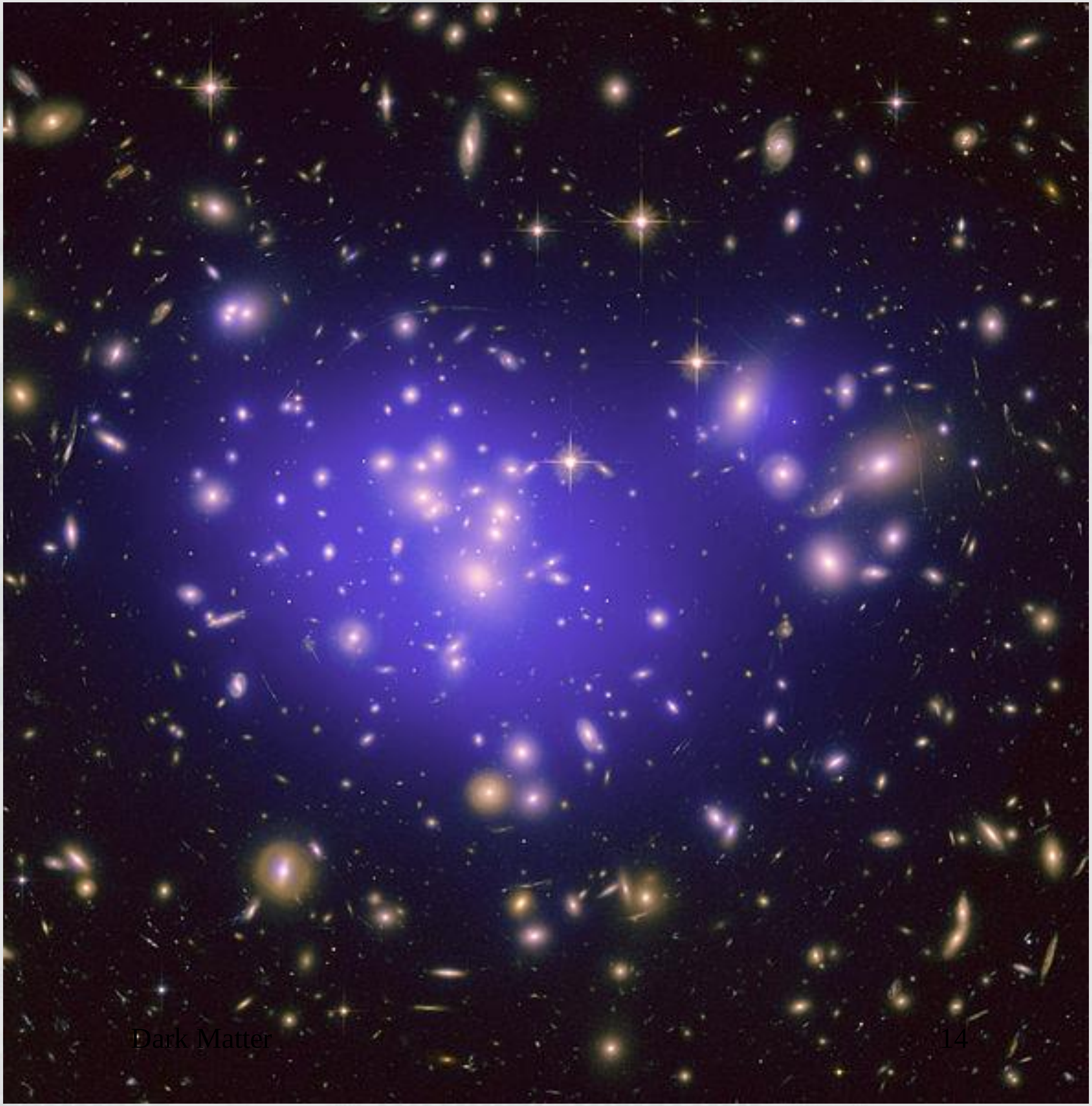
Abell 1689,
754 Mpc distant

The yellow galaxies in this image belong to the cluster itself, however, the red and blue distorted streaks are background galaxies gravitationally lensed by the cluster. Some of the lensed galaxies are over 4000 megaparsec distant. The lensing zone itself is 0.60 megaparsec across.



Abell 1689,
754 Mpc distant

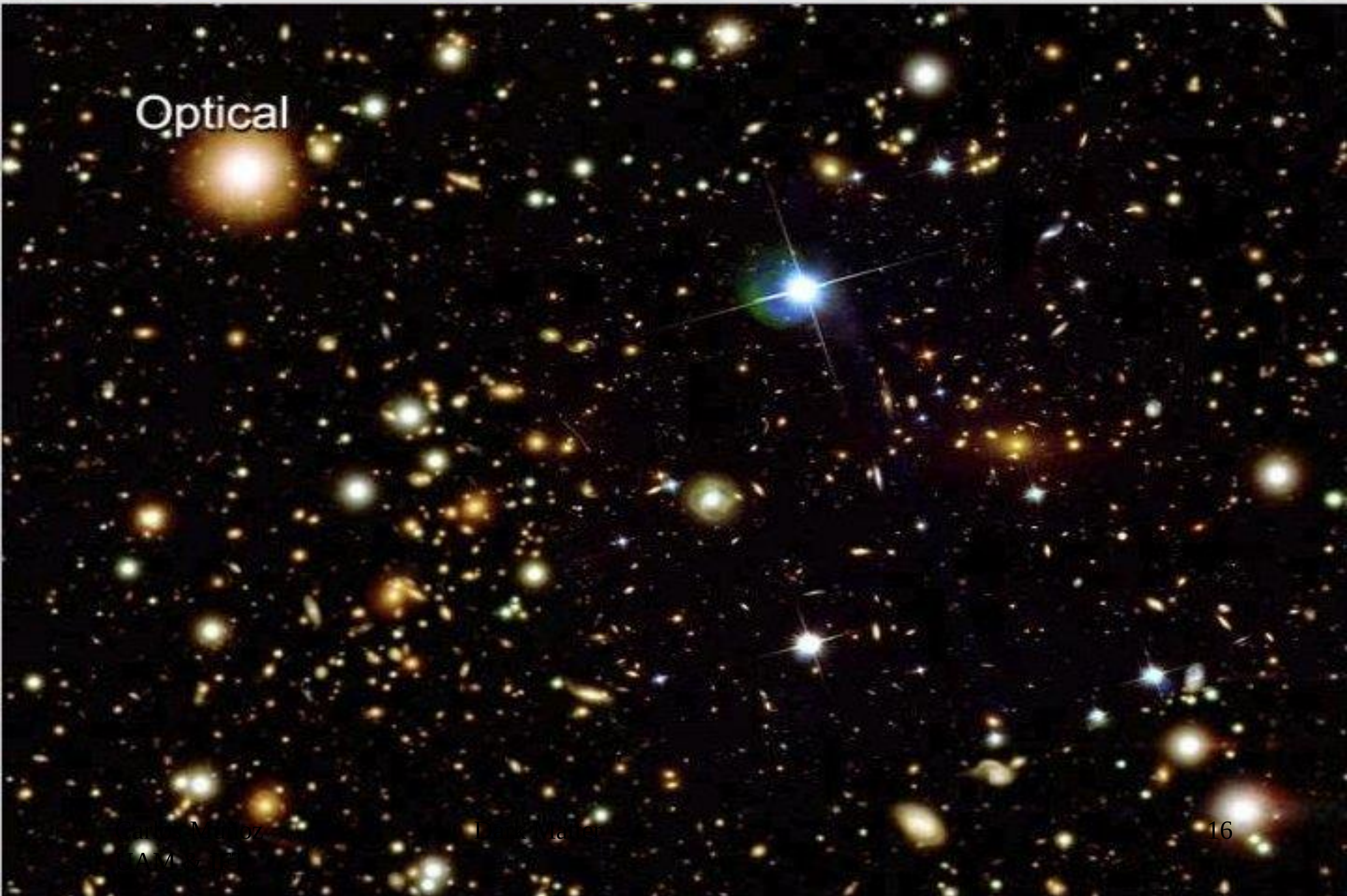
The mass distribution of the dark matter in the gravitational lens overlaid (in purple).



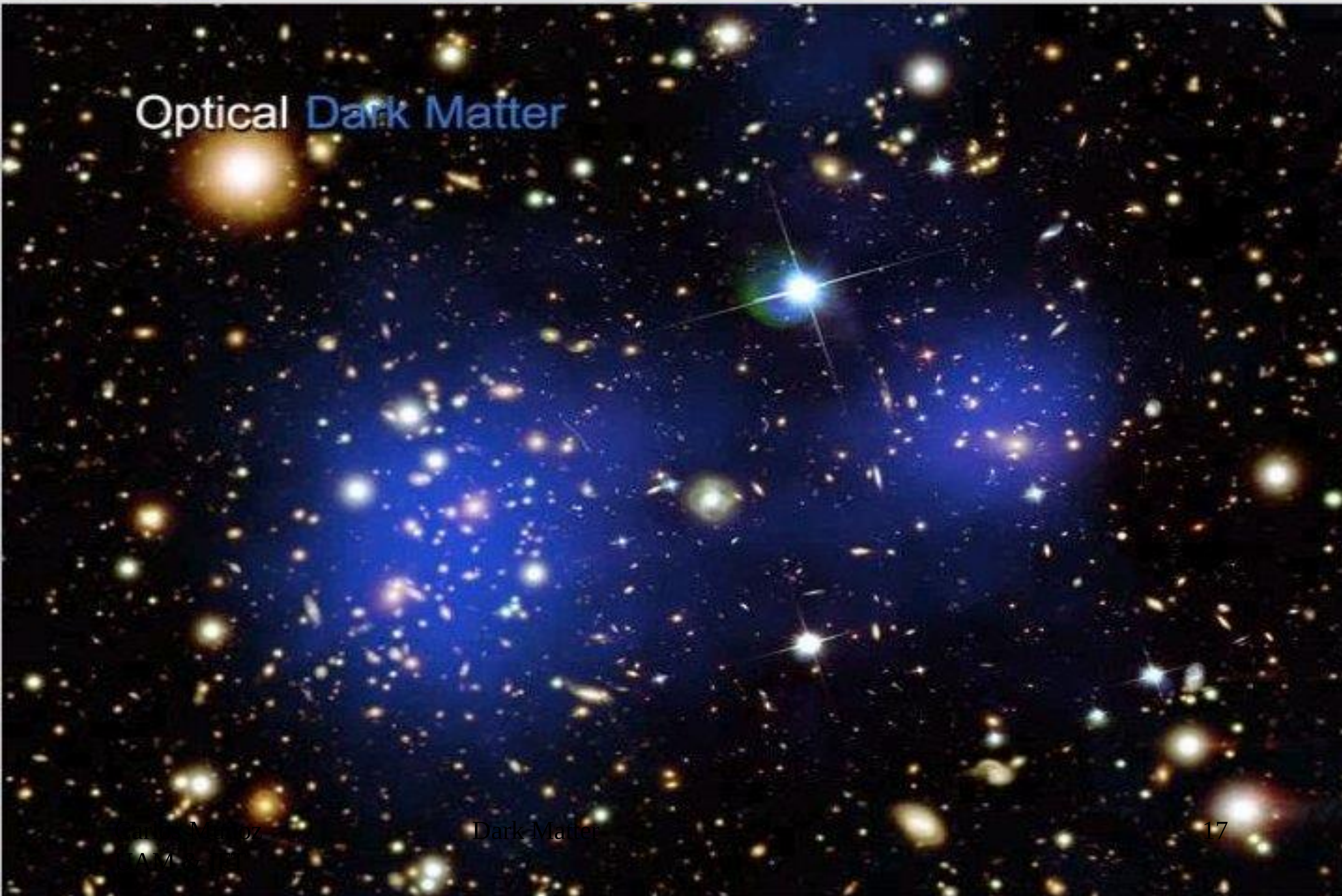

giant galaxy cluster CL0025+1654,
about 1000 Mpc away
The analysis reveals that the cluster's dark matter (shown in blue) is not evenly distributed, but follows the clumps of luminous matter closely

Another evidence: **Bullet Cluster 1E 0657-56**

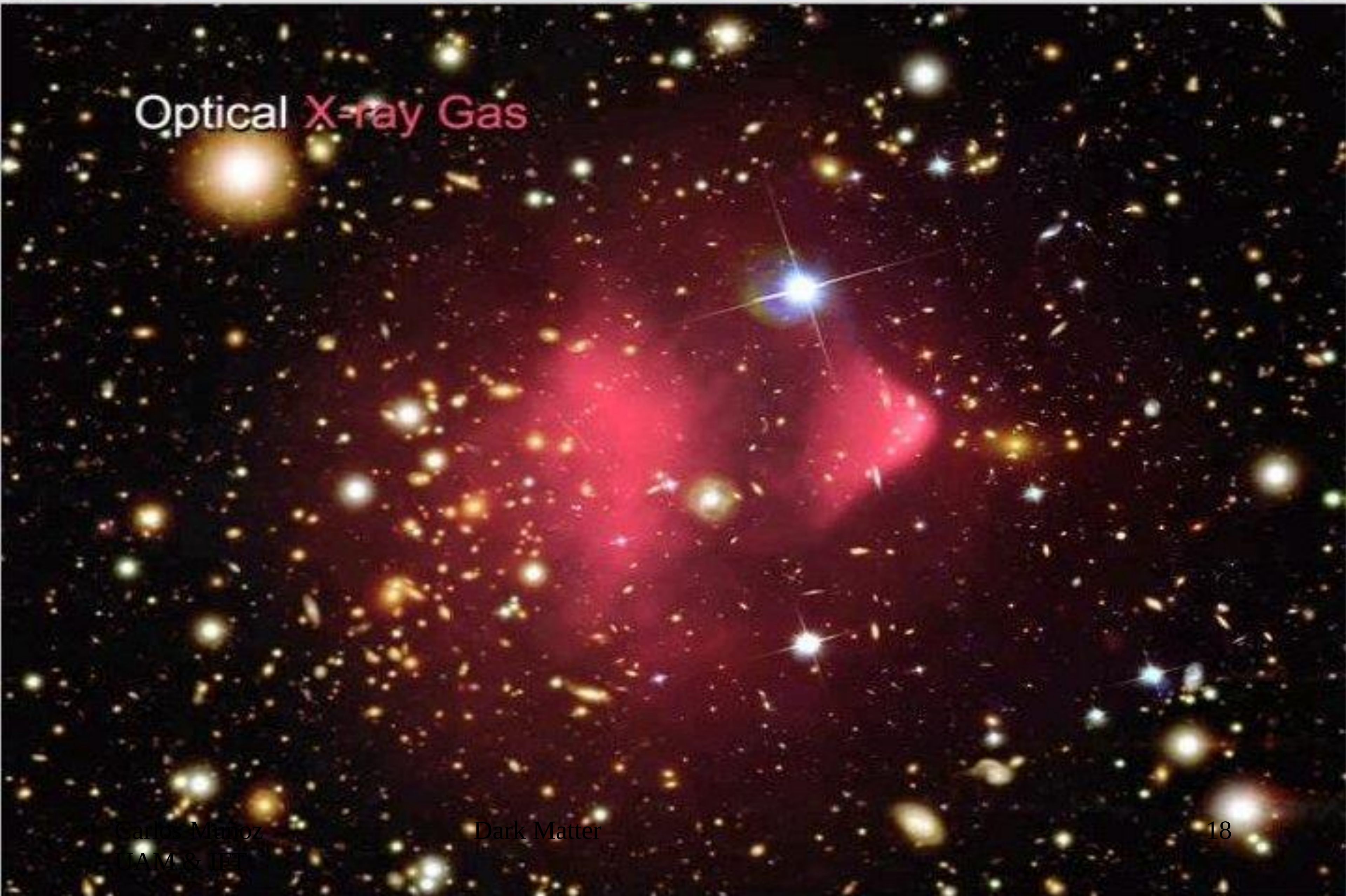
(Two clusters of galaxies that have passed right through each other)



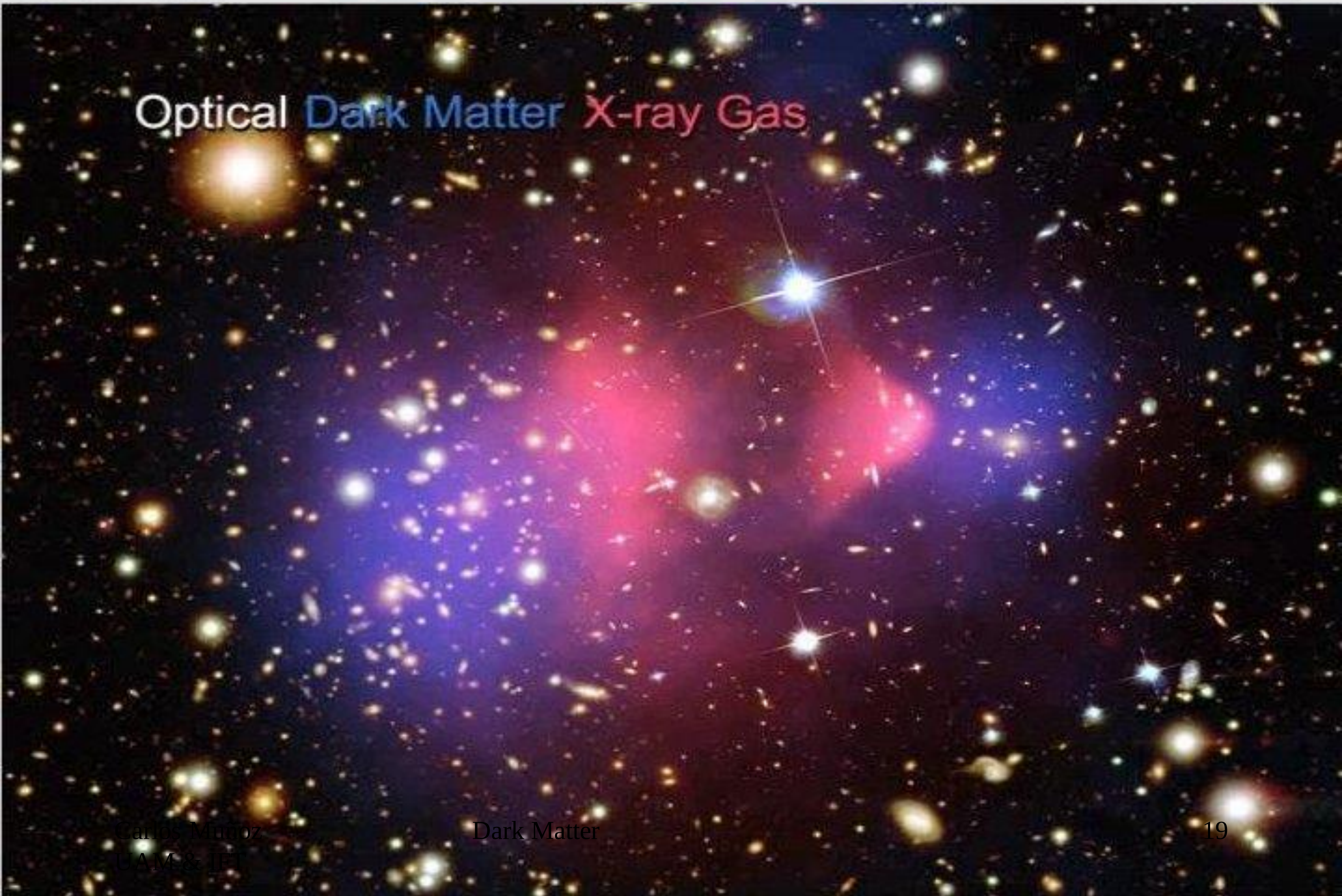
Bullet Cluster: dark matter observed through gravitational lensing



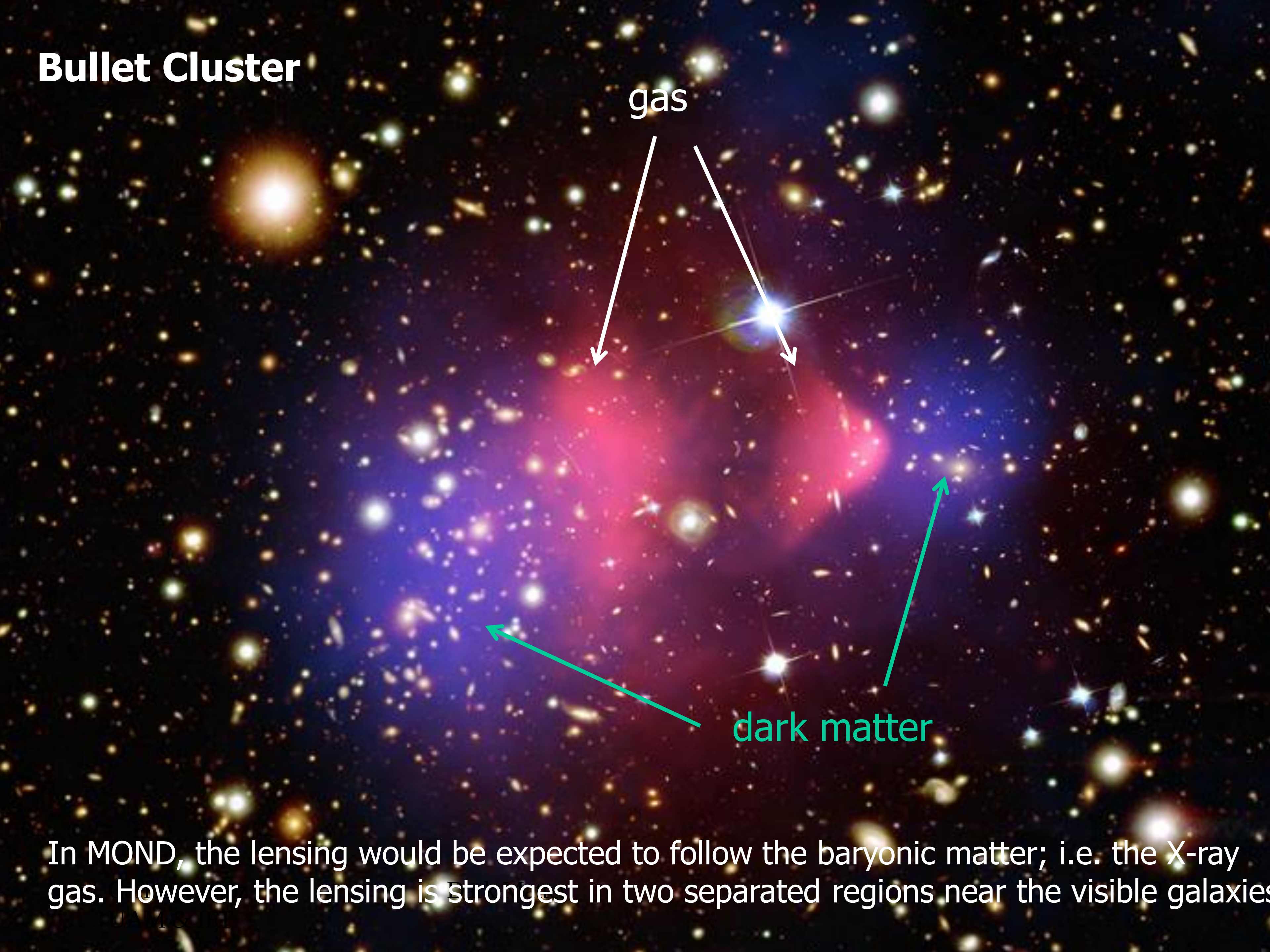
Bullet Cluster: As in all clusters, the large majority of ordinary matter in the bullet is not in the galaxies themselves, but in hot X-ray emitting intergalactic gas



Bullet Cluster: supersimposing the lensing and X-ray maps



Bullet Cluster



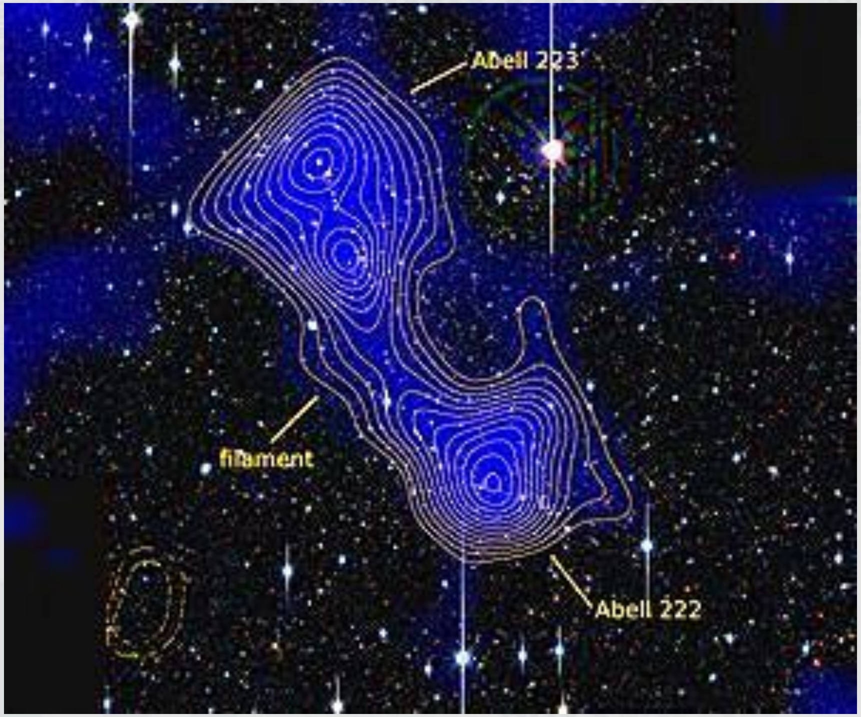
In MOND, the lensing would be expected to follow the baryonic matter; i.e. the X-ray gas. However, the lensing is strongest in two separated regions near the visible galaxies

Very recently, in July 2012, for the first time, a filament of DM between two clusters of galaxies has been discovered, through gravitational lensing

Dietrich et al., 1207.0809 [astro-ph.CO]

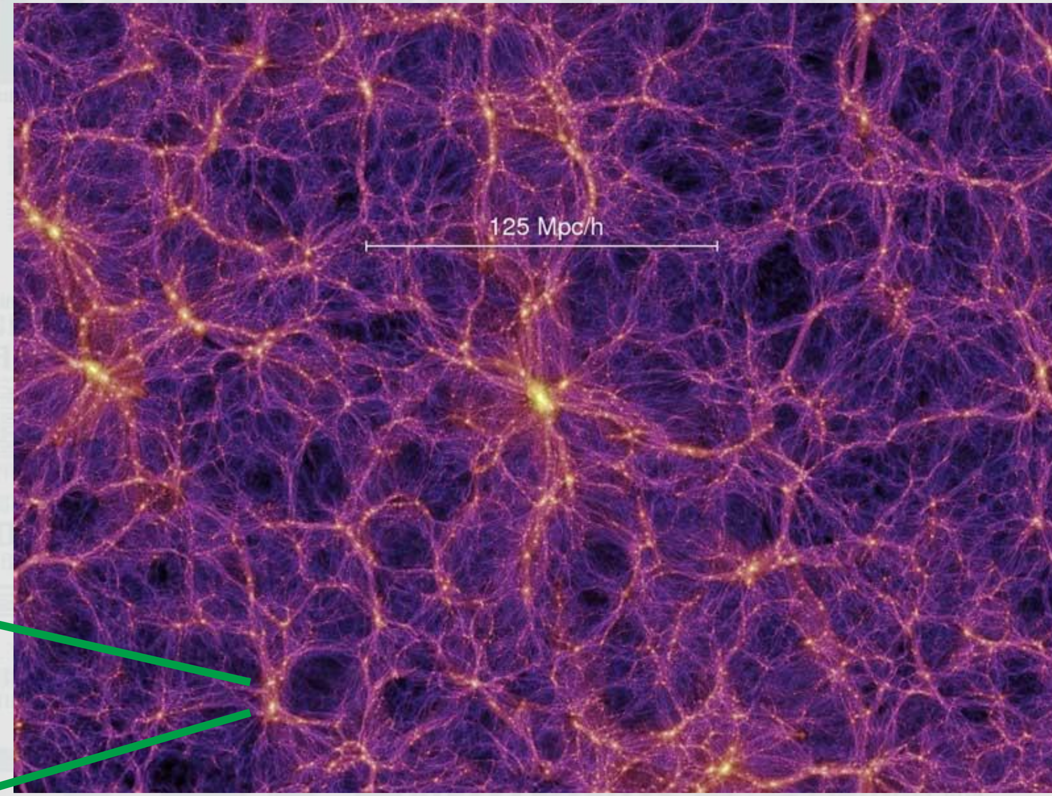
The filament forms a bridge between two huge clusters called Abell 222 and Abell 223

It is about 1Mpc thick and 18 Mpc long

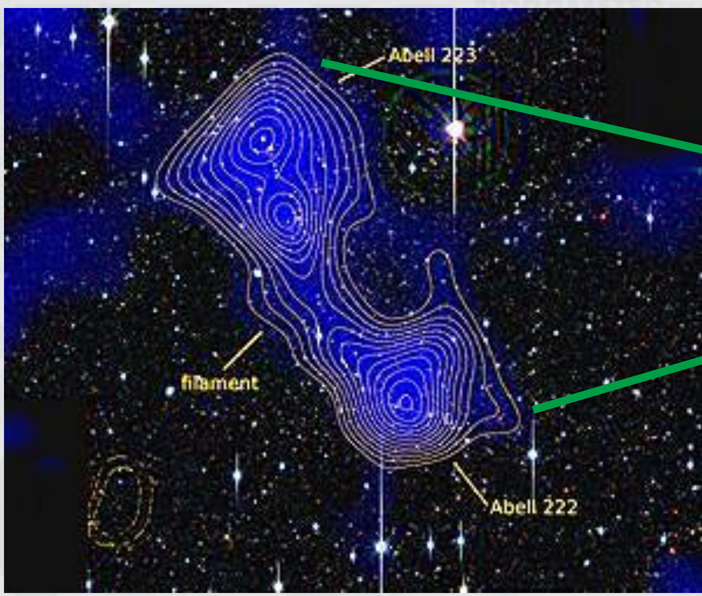


This discovery is consistent with the prediction of computer simulations that galaxy clusters occur at the intersection of large-scale structure filaments

This is due to the way that DM particles swarm together because of their gravitational attraction, combined with the pull of the expanding Universe



Millennium simulation

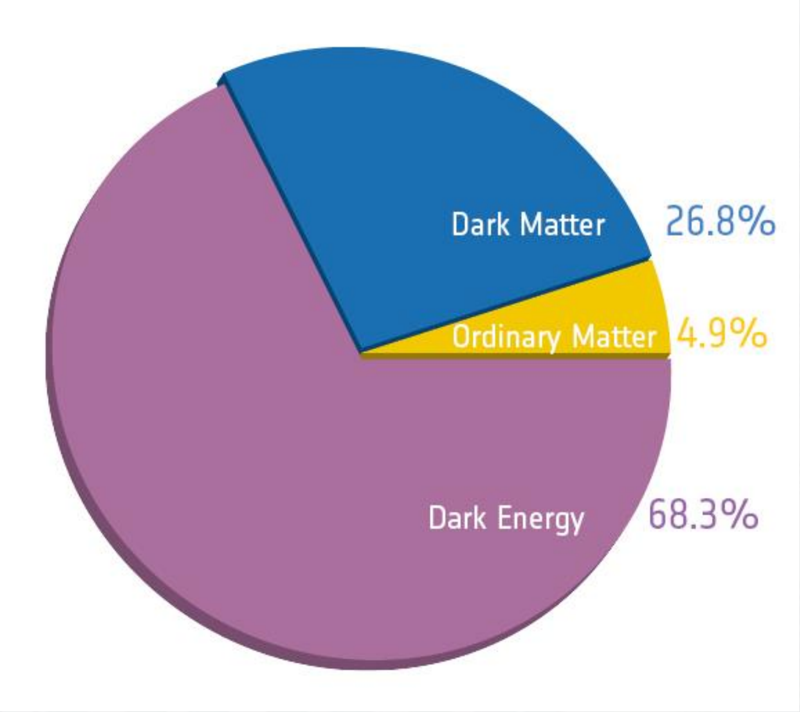


- Last results from the Planck satellite,

$\Omega_{DM} h^2 \approx 0.12$

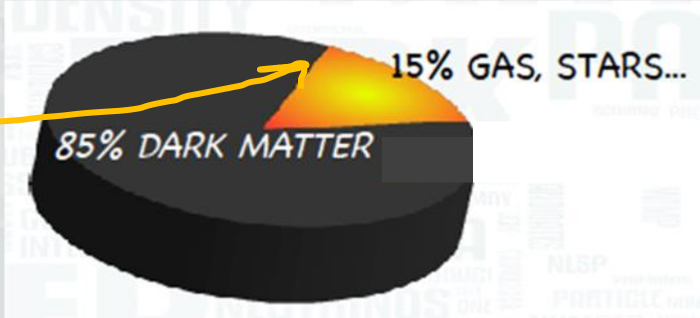
$\Omega_b h^2 \approx 0.022$

$\Omega_{DE} h^2 \approx 0.31$



confirm that about **85% of the matter** in the Universe **is dark**

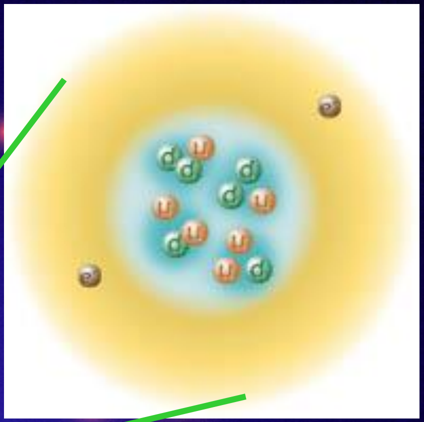
As often remarked, this would lead to another Copernican revolution:



We are not the center of the Universe

+

We are not made of what most of the Universe is made of !



Thus to decipher the nature of the dark matter
is one of the great enigmas still unsolved

PARTICLE CANDIDATES

The only possible candidate for DM within the Standard Model of Particle Physics, the neutrino, is excluded

- Its mass seems to be too small, $m_\nu \sim$ eV to account for $\Omega_{DM} h^2 \approx 0.1$

- This kind of (hot) DM cannot reproduce correctly the observed structure in the Universe; galaxies would be too young

This is a clear indication that we need to go

beyond the standard model of particle physics

We need a new particle with the following properties:

- Stable or long-lived — Produced after the Big Bang and still present today
- Neutral — Otherwise it would bind to nuclei and would be excluded from unsuccessful searches for exotic heavy isotopes
- Reproduce the observed amount of DM $\Omega_{DM} h^2 \approx 0.1$

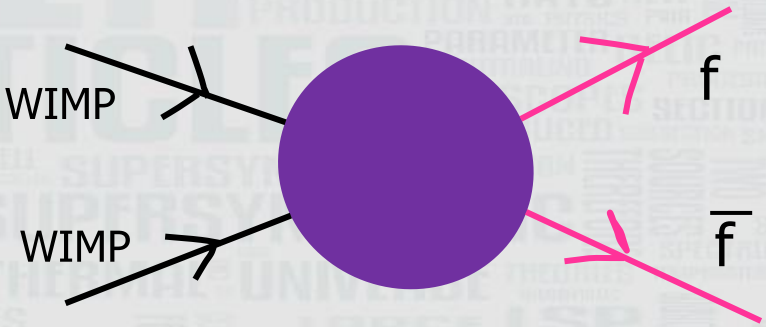
✸ A particle with weak interactions and a mass ≈ GeV-TeV, the so called WIMP (Weakly Interacting Massive Particle), is able to reproduce this number

⬇

A stable and neutral WIMP is a good candidate for DM

Key question: the relic density

In the early Universe, when the temperature was larger than the mass of the DM particle, this was annihilating with its own antiparticle into lighter particles and viceversa.



However, after the temperature dropped below the mass of the DM particle, there was no sufficient kinetic energy to create it ($T < m_{WIMP}c^2$).
Thus its number density dropped exponentially

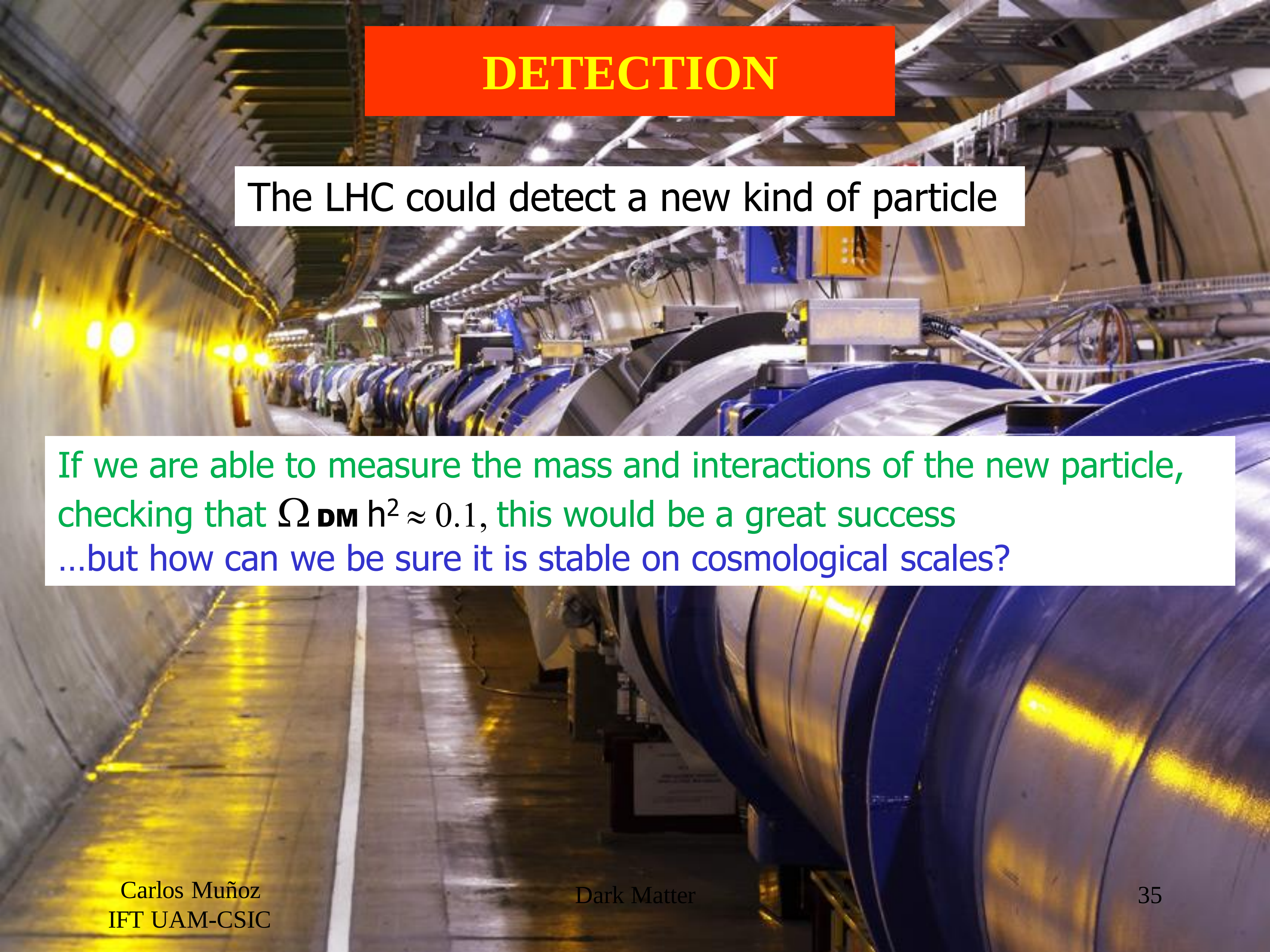
But when the annihilation rate dropped below the expansion rate of the Universe, the DM particles could not annihilate, and their density has been the same since then

Following these arguments, the relic density can be computed with the result

$$\Omega h^2 \sim \frac{3 \times 10^{-27}\ \mathrm{cm^3\ s^{-1}}}{\sigma_{ann} v} \sim 0.1$$

$\sigma_{ann} = \sigma_{WIMP}$

$\sigma_{ann} v \sim 3 \times 10^{-26}\ \mathrm{cm^3\ s^{-1}}$
thermal cross section



DETECTION

The LHC could detect a new kind of particle

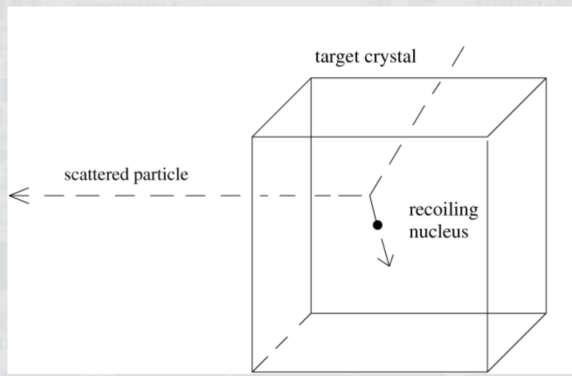
If we are able to measure the mass and interactions of the new particle, checking that $\Omega_{\mathbf{DM}} h^2 \approx 0.1$, this would be a great success

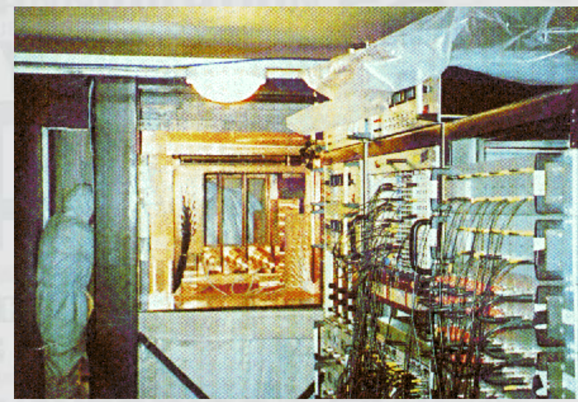
…but how can we be sure it is stable on cosmological scales?

Direct and Indirect Detection

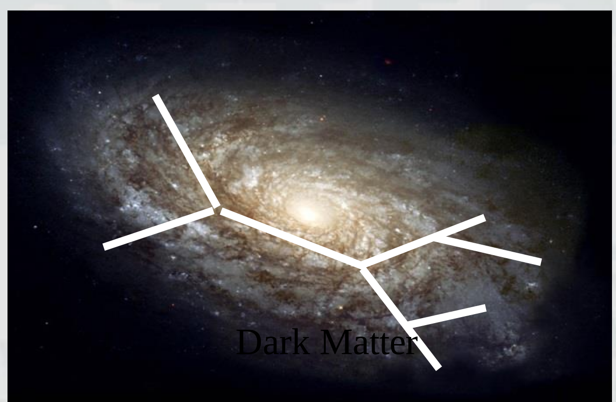
A complete confirmation can only arise from experiments where the particle is detected as part of the galactic halo

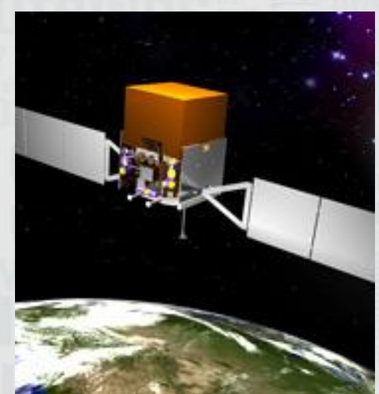
This can only come from direct





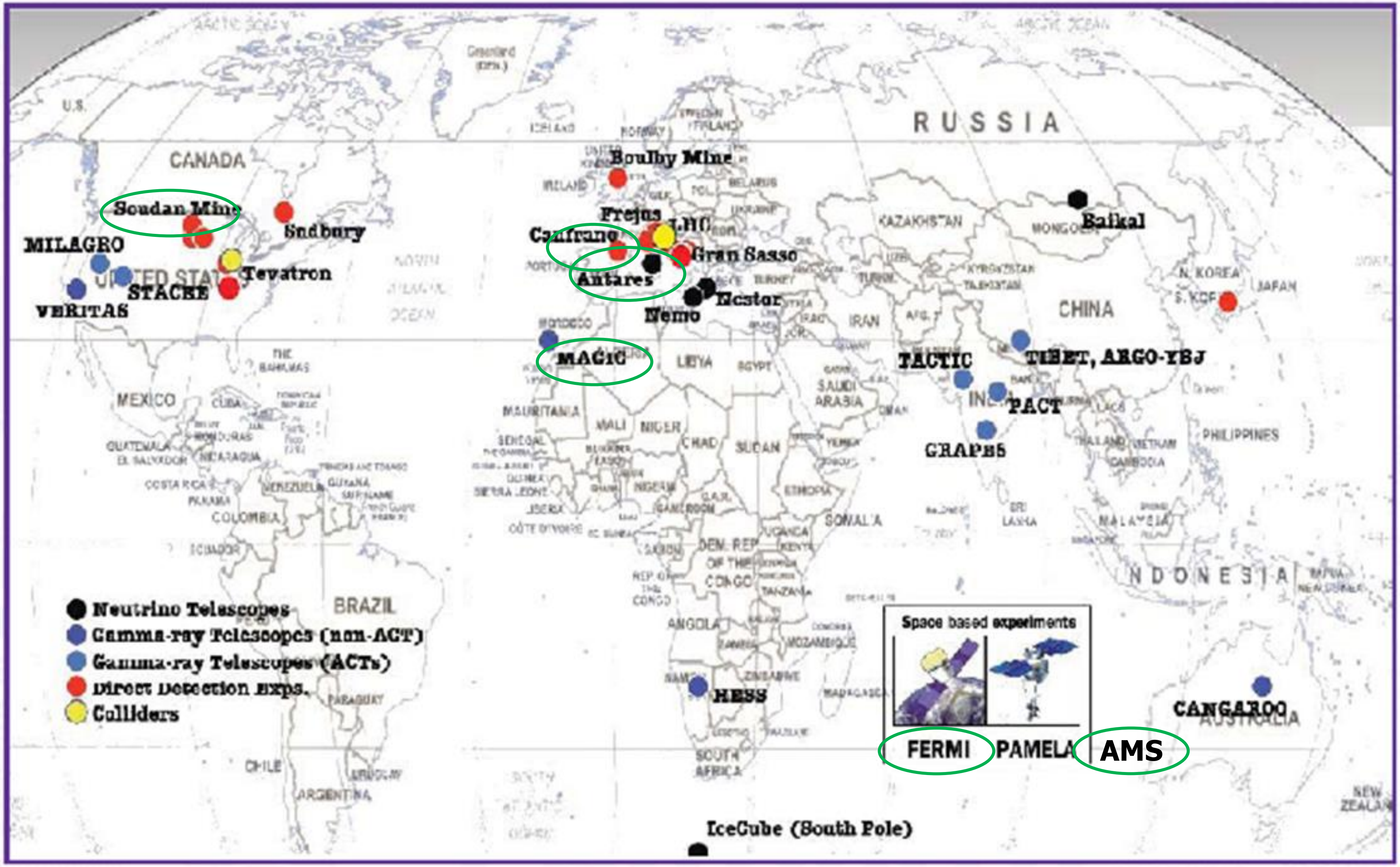
and indirect dark matter searches





These three detection strategies are ideal because they allow exploring in a complete way many different particle dark matter models

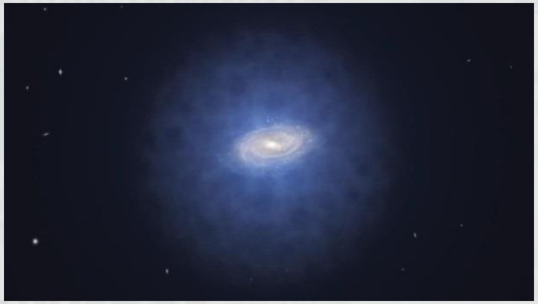
Besides, in the case of a redundant detection
(in two or more different experiments) the combination of their data can provide good insight into the nature of the dark matter

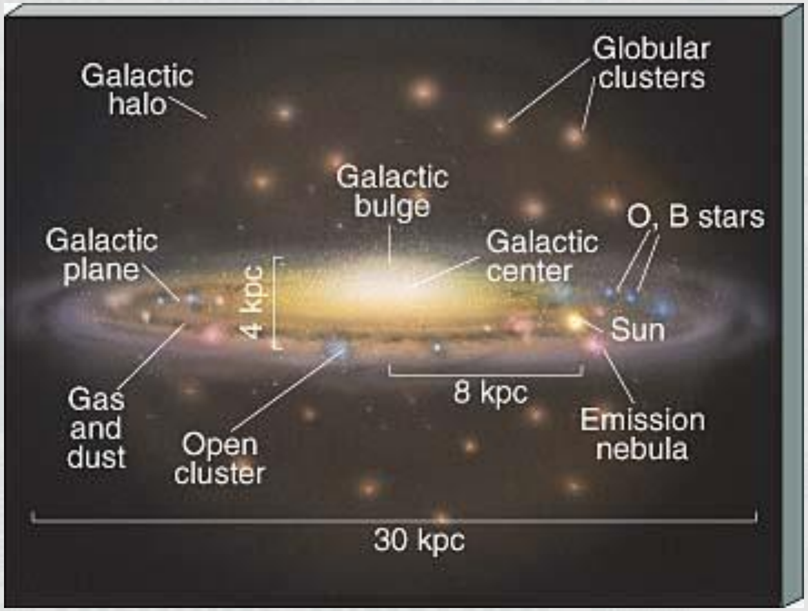


Underground Labs and indirect detection DM experiments around the world

Direct Detection

Can we detect the DM as part of the galactic halo?





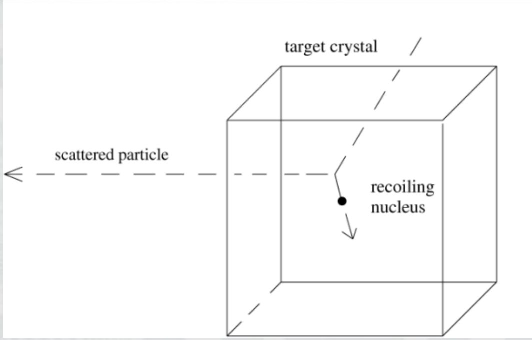
Since the detection will be on the Earth or on satellites, we only need to know the properties of the Galactic halo near the Earth:

- The local mass density necessary to reproduce the rotation curve of our Galaxy is $\rho_0 \sim 0.3\ \mathrm{GeV/cm^3}$

- The velocity dispersion of DM particles is $v_0 \sim 220\ \mathrm{km/s}$

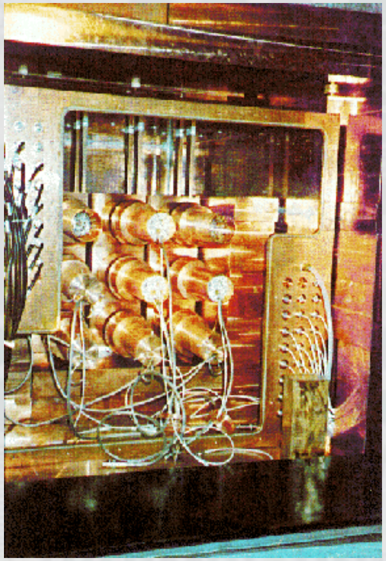
For $m_{DM} \sim 100$ GeV one obtains $J \sim \rho_0\, v_0 / m_{DM} \sim 60{,}000\ \mathrm{particles/cm^2\, s}$, and therefore direct detection through elastic scattering with nuclei in a detector is in principle possible

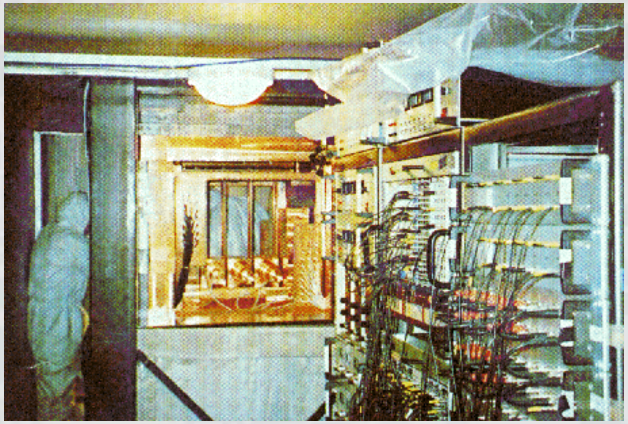
Goodman, Witten, 85
Wasserman, 86



For $\sigma_{\text{WIMP-nucleon}} \approx 10^{-8}$-$10^{-6}$ pb a material with nuclei composed of about 100 nucleons, i.e. $m_N \sim 100$ GeV

✸ $R \sim J\, \sigma_{\text{WIMP-nucleon}} / m_N \approx 10^{-2}$ - 1 events per day per kilogram





It is convenient to have as much material as possible

e.g., DAMA experiment had 100 kg NaI crystals

✸ $E_{DM} \approx 1/2\, (100\ \text{GeV}/c^2)\, (220\ \text{km/s})^2 \approx 25$ keV

the recoiling nucleus loses its energy producing ionization + scintillation + heat

e.g., DAMA only measures scintillation light ⟶ $E_{\text{scintillation}} = Q\, E_{\text{recoil}}$

Q(quenching factor) = 0.3 for Na , 0.09 for I

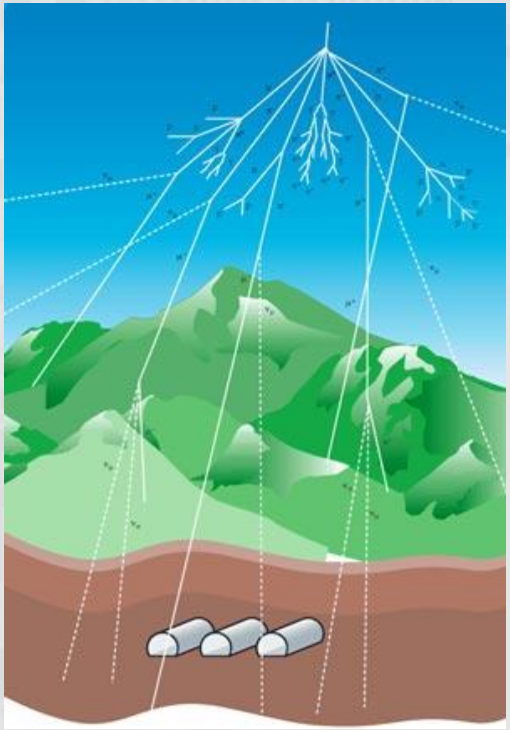
Experiments must be very sensitive being able to measure energies ≈ **few** keV

The background problem

WIMPs are expected to produce less or about **10^{-2}** nuclear recoils/kg day with energies of few keV

- But cosmic rays occur at >100 events/kg day with energies ~ keV-MeV and generate muon-induced neutrons producing nuclear recoils similar to those expected for WIMPs

  Experiments must be located in the deep underground to greatly reduced the rate of these background events



- In addition, neutrons are also generated by the environmental radioactivity, but also γ rays and β particles are generated producing electron recoils

  Detectors must be shielded with layers of lead, polyethylene, several meters of water, etc.

- Still background events remain and the experiments must have a extremely good background discrimination to distinguish nuclear recoils due to WIMPs from neutron-induced nuclear recoils and electron recoils

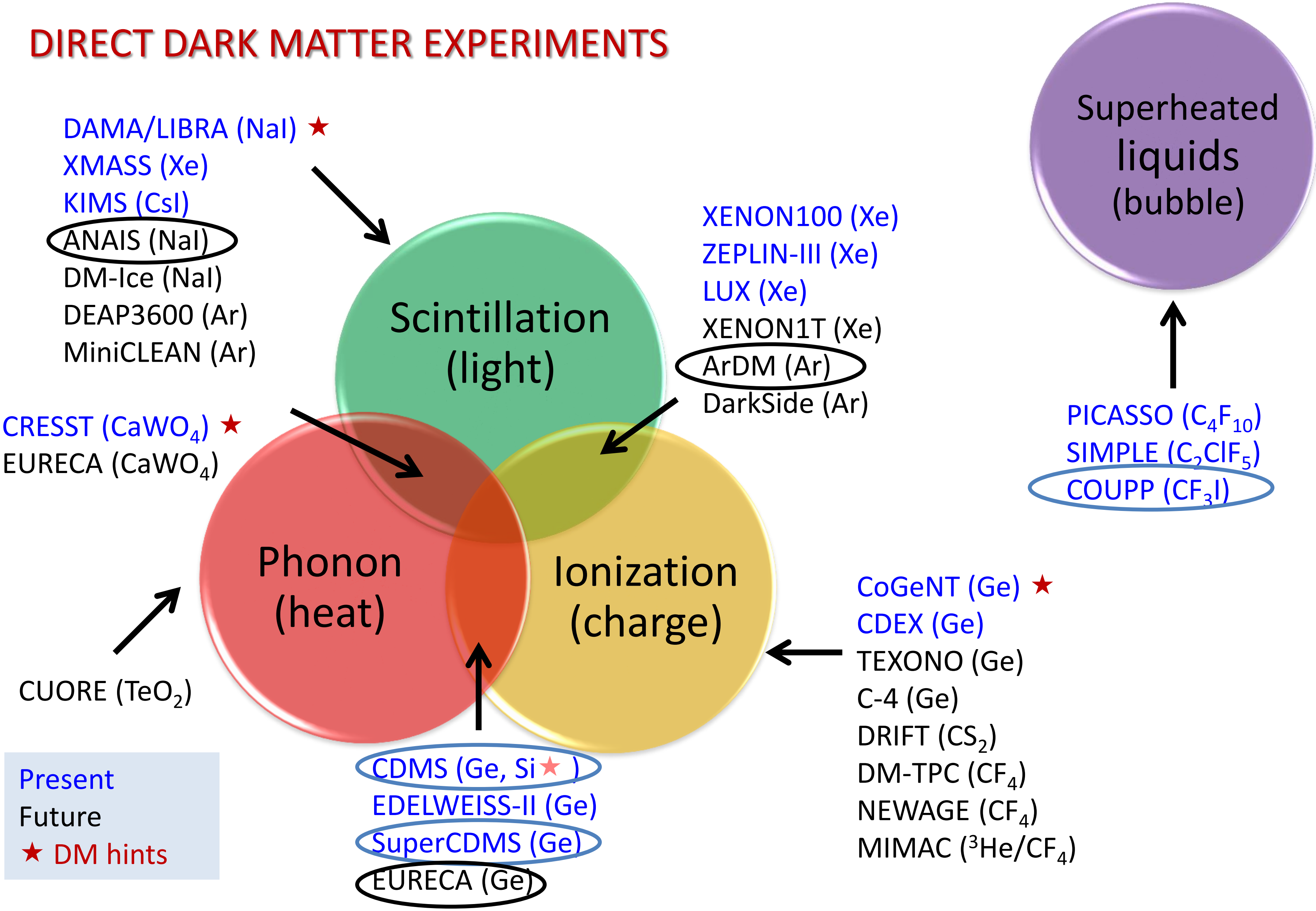
  Unlike WIMPs, neutrons will often produce double-scatter signatures, so the detector must be able to identify (and reject) events with multiple interactions

  Combining two techniques of detection one can discriminate the electron recoils from nuclear recoils:
  heat + ionization , heat + scintillation , scintillation + ionization

- In any case, always a small expected rate of misidentified background events remains

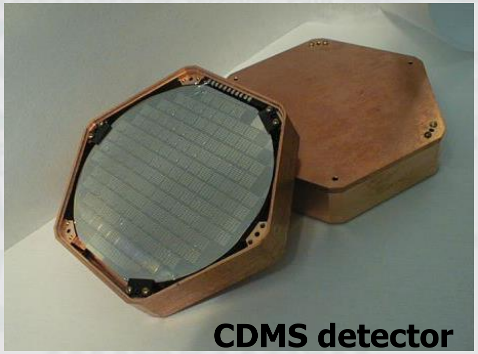
  …everything above background might be a signal

DIRECT DARK MATTER EXPERIMENTS



Type of experiments

✷ Relying on reduction and interpretation of the background



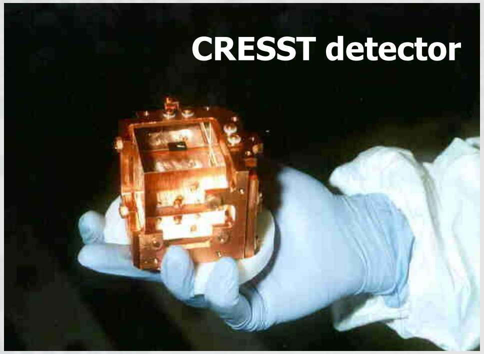
measure heat and ionization:

CDMS-II 19 Ge (~ 230 g each) crystals at Soudan (2100 mwe)

EDELWEISS-II 10 Ge (400 g each) crystals at Modane (4800 mwe)

measure heat and scintillation:

CRESST-II 9 $CaWO_4$ (~ 300 g each) crystals at Gran Sasso (3400 mwe)



measures ionization:

CoGeNT 440 g Ge crystal at Soudan (2100 mwe)

measures scintillation:

KIMS 103.4 kg CsI crystals at YangYang (2000 mwe)

measure scintillation and ionization:

XENON 100 62 kg liquid Xenon at Gran Sasso (3400 mwe)

ZEPLIN-III 12 kg liquid Xenon at Boulby (2850 mwe)

measures bubble nucleation:

SIMPLE 208+215 g superheated liquid C_2ClF_5 droplets at Bas Bruit (1500 mwe)

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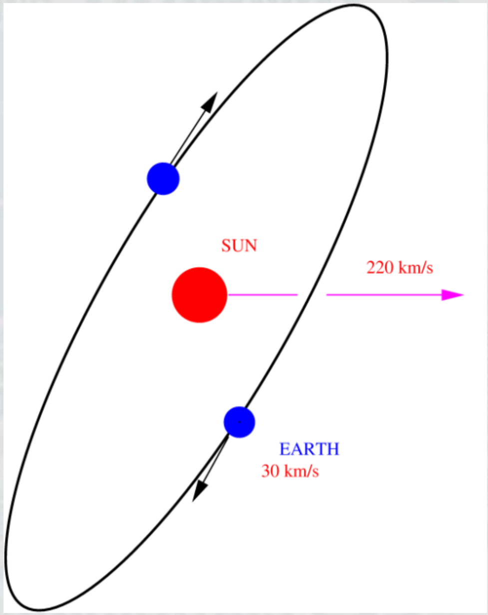
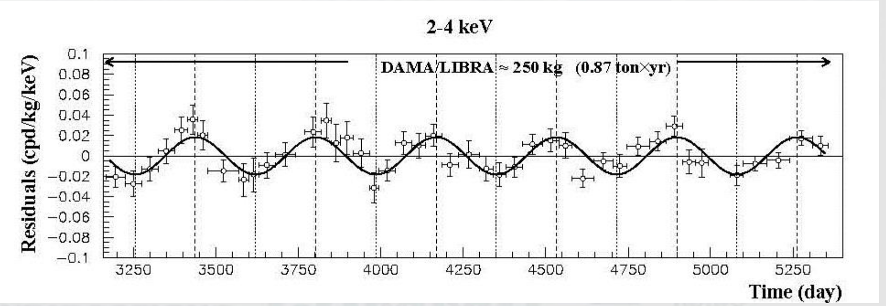
Annual modulation

Drukier, Freese, Spergel, 86
Freese, Frieman, Gould, 88



DAMA/LIBRA
250 kg NaI crystal scintillators at Gran Sasso.
does not strongly discriminate between WIMP scatters and background events



CoGeNT 440 g Ge crystal at Soudan (2100 mwe)

KIMS 103.4 kg CsI crystal scintillators at YangYang (2000 mwe)

ANAIS project 250 kg NaI crystal scintillators at Canfranc (2500 mwe)

DM-Ice project 250 kg NaI crystal scintillators at South Pole (2200 mwe)

...

Recent experimental results

The situation is exciting

Possible hints of light WIMPs (m_{WIMP}~10 GeV)

DAMA (NaI) + DAMA/LIBRA cumulative exposure: 427,000 kg x day (13 annual cycles)
1002.1028 confirms annual modulation effect at 8.9 σ C.L.

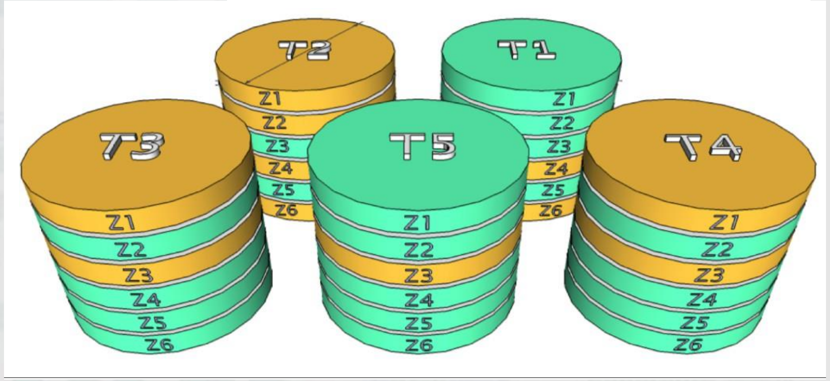
CoGeNT (Ge), 1002.4703, 18.48 kg x day, excesses of events over the expected background
1106.0650, after 15 months, confirms annual modulation effect at 2.8 σ C.L.

CRESST II ($CaWO_4$), 1109.0702, 333 kg x day, 67 events were observed
only ~40 can be explained with the background

CDMS II (Si), 1304.4279, 140.2 kg x day, 3 events
only 0.41 can be explained with the background

Five Towers (30 ZIPS)
Operated 2006-2009

19 Ge detectors (4.5 kg total)
11 Si detectors (1 kg total)



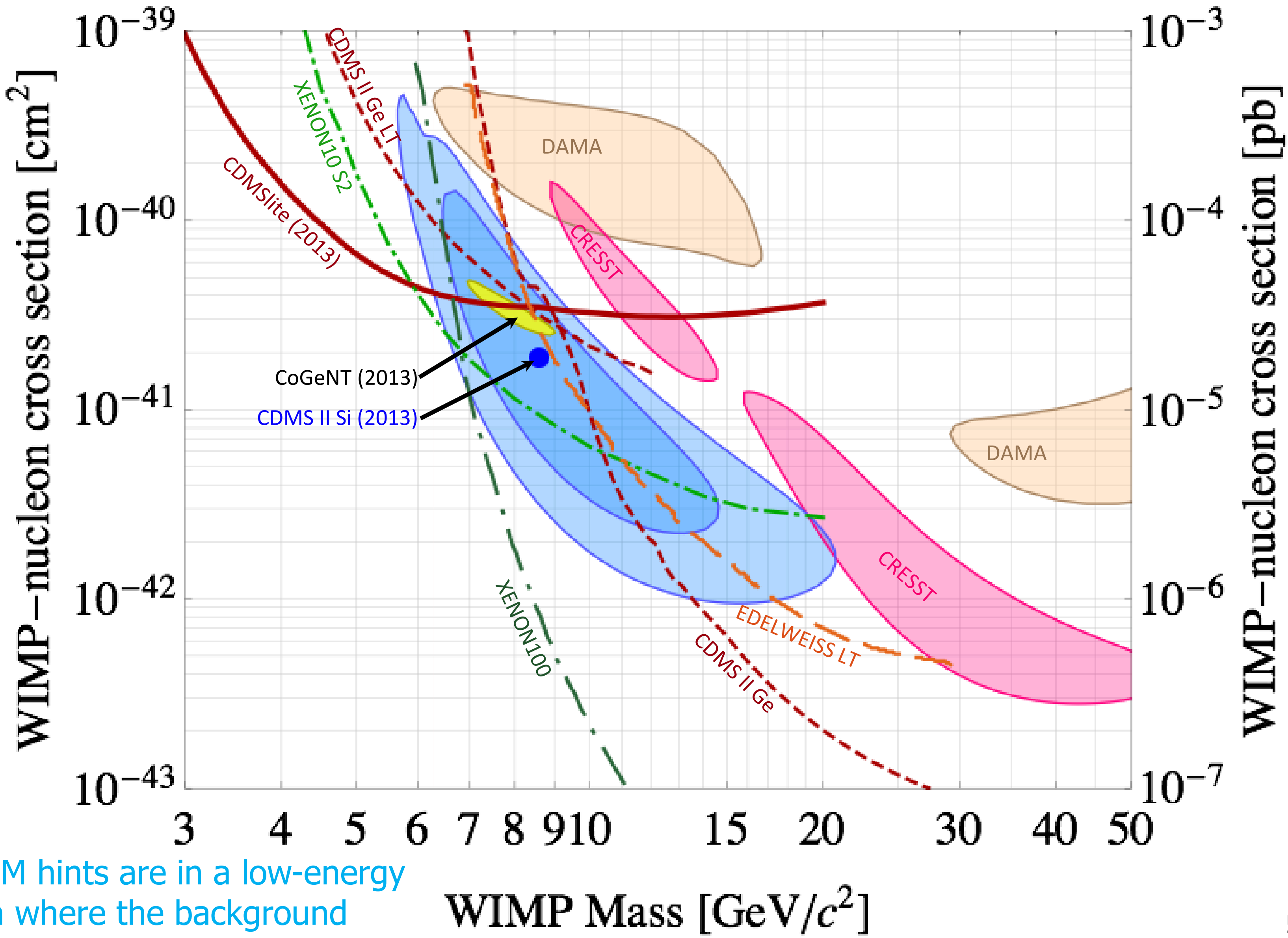
Si (A=28) is more sensitive to light WIMPs than Ge (A=70-76)

The situation is exciting Possible hints of light WIMPs (m_{WIMP}~10 GeV)

...but confusing, since other experiments found no evidence for dark matter

XENON 100	1207.5988	
XENON 100	1104.2549	1471 kg x day
XENON 10	1104.3088	
CDMS II (Ge)	0912.3592	612 kg x day, and energies > 10 keV
	1011.2482	241 kg x day, low-energy reanalysis
CDMSlite (Ge)	1309.3259	6 kg x day
EDELWEISS-II (Ge)	1103.4070	384 kg x day
ZEPLIN-III (Xe)	1110.474769	1344 kg x day

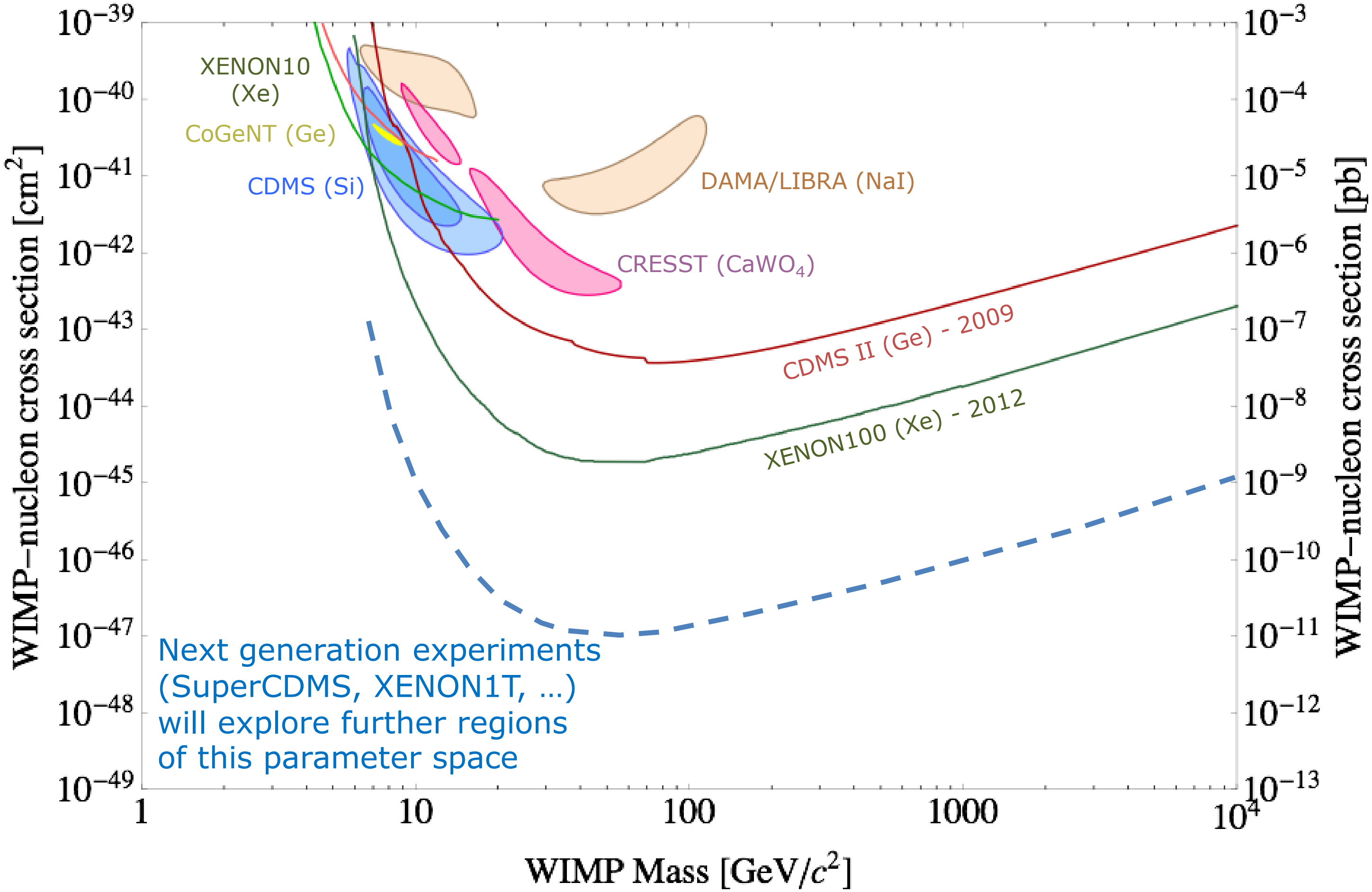
Resulting experimental situation for low-energy WIMPs



The DM hints are in a low-energy region where the background makes analyses very complicated

Non-observation in other experiments sets upper bounds on the cross section

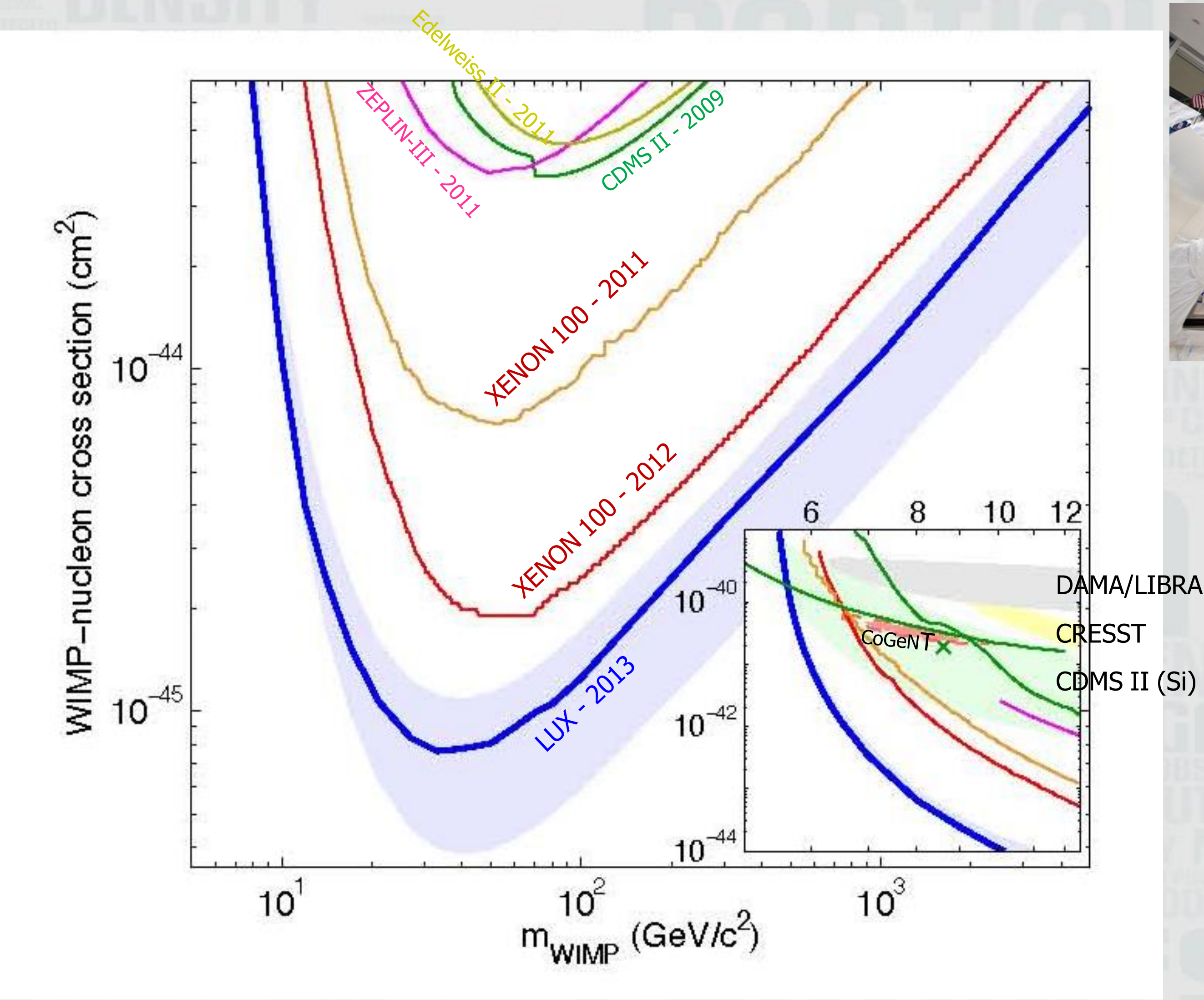
These bounds are in tension with the other observations



Updated after LUX results on liquid Xe

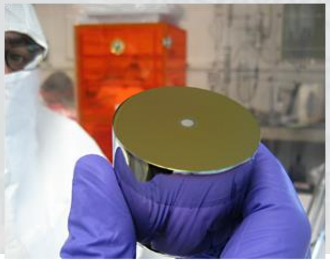
Sanford underground lab.
South Dakota

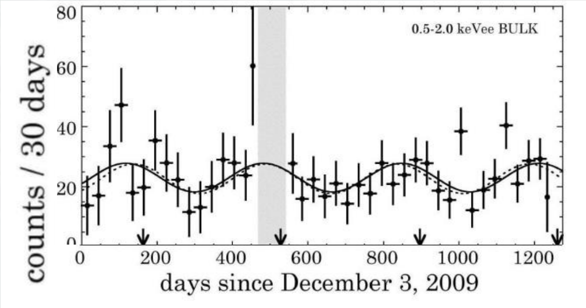
1310.8214, 85.3 live-days of data with a fiducial volumen of 118 kg.



Very recent CoGeNT results on Ge

1401.3295, 1129 live-days of data,
confirms annual modulation effect at 2.2 σ C.L.





But its amplitude is a factor ~4-7 larger than predicted by for a Standard WIMP galactic halo

Assuming that this effect is due to a Non-Maxwellian local halo velocity distribution, the DAMA/LIBRA ROI can be displaced

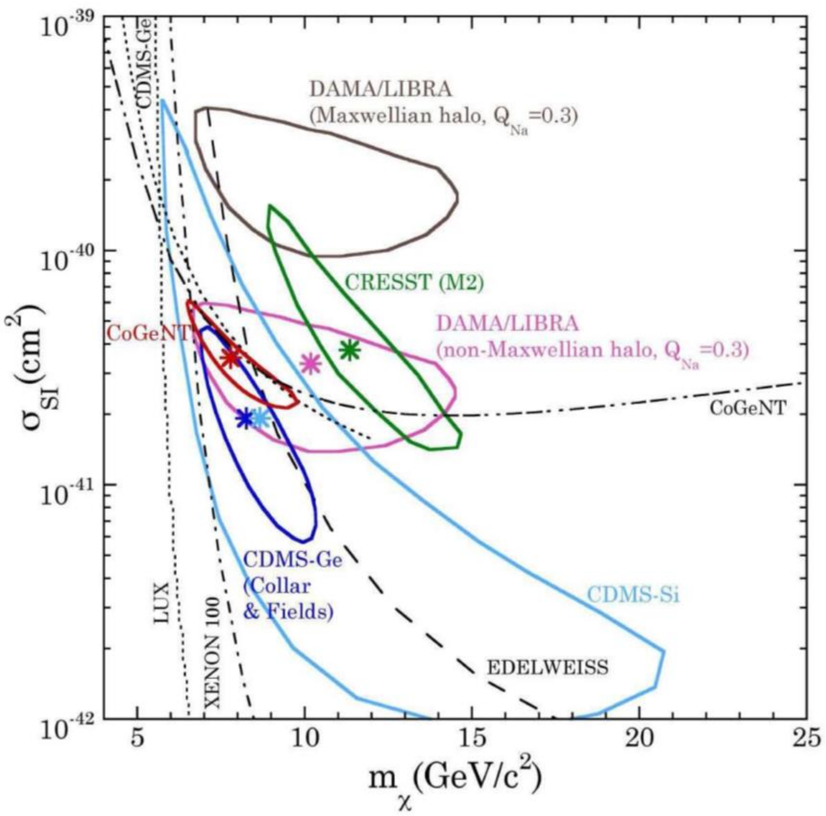
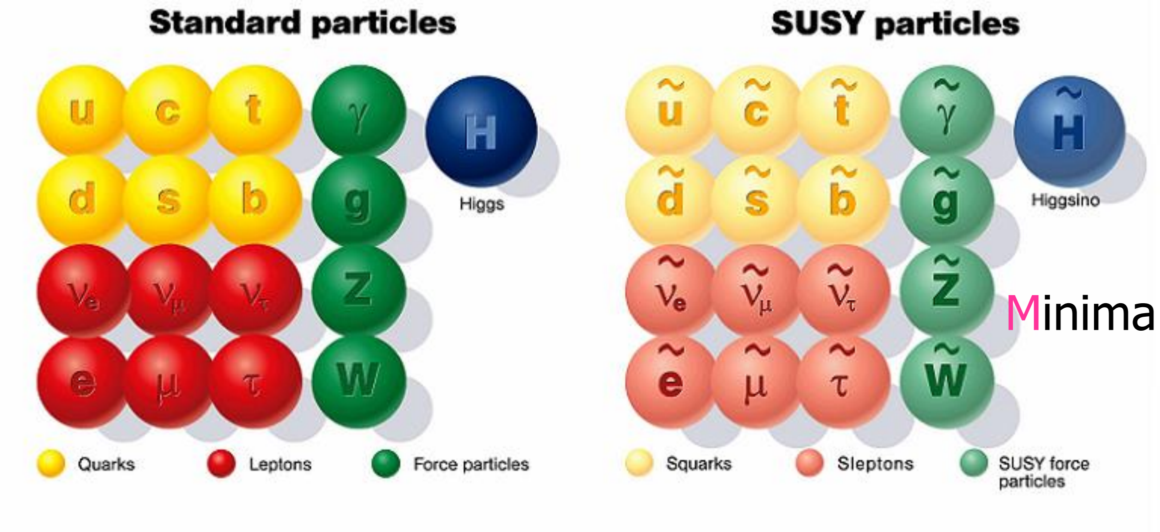


FIG. 8. Displacement towards lower spin-independent scattering cross-section σ_{SI} of the DAMA/LIBRA region of interest (ROI), if a fractional modulation amplitude corresponding to that found for CoGeNT data is assumed.

Crucial Moment for SUSY in 2015:



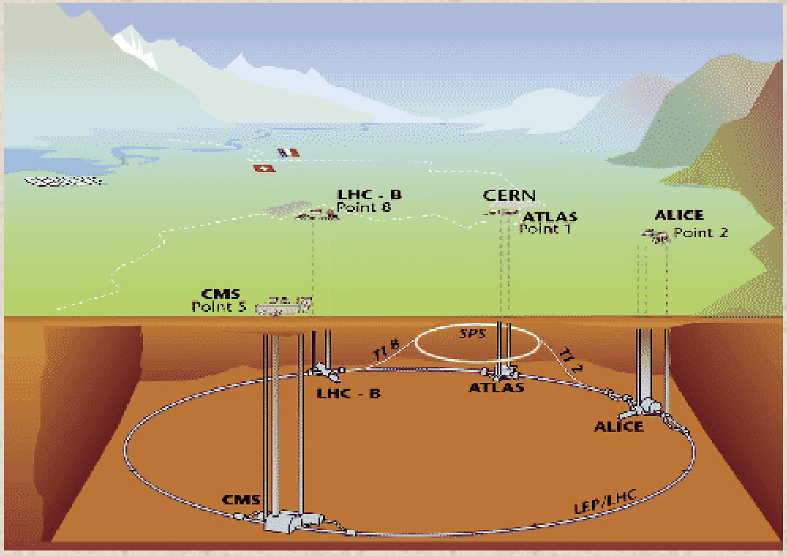
The spectrum of elementary particles is doubled

with masses ≈ 1000 GeV

Minimal Supersymmetric Standard Model

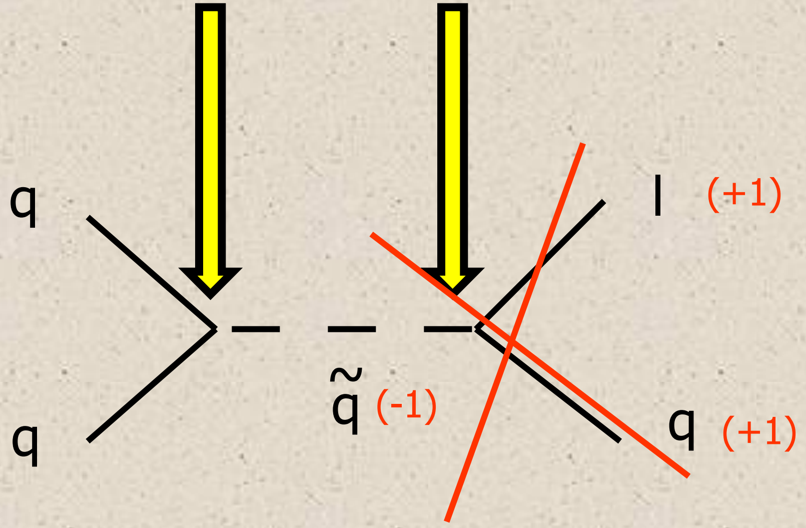
MSSM

A rich phenomenology



- **But, by construction, the MSSM produce too fast proton decay**

Operators like $d^c d^c u^c$, QLd^c , LLe^c , LH_2 are allowed in the superpotential



To preserve B and L conservation one can impose a discrete symmetry (**R parity**)

Particle ⟶ Particle

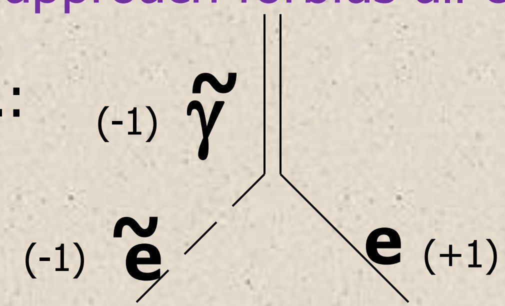
Superpartner ⟶ − Superpartner

i.e. superparticles must appear in pairs

Notice that this (conservative) approach forbids all couplings

In models with R parity the **LSP** is stable since e.g.:

Thus it **is a candidate for dark matter**



So, once eliminated all operators violating baryon and lepton number, we are left with the superpotential of the MSSM:

$$\textbf{MSSM} \quad W = Y_u^{ij}\, \hat{H}_2^b\, \hat{Q}_i^a\, \hat{u}_j^c + Y_d^{ij}\, \hat{H}_1^a\, \hat{Q}_i^b\, \hat{d}_j^c + Y_e^{ij}\, \hat{H}_1^a\, \hat{L}_i^b\, \hat{e}_j^c + \mu\, H_1 H_2$$

where the term $\mu\, H_1 H_2$ is necessary to generate Higgsino masses

Present experimental bounds on chargino masses imply: $\mu \geq 100$ GeV

Here we find another problem of SUSY theories:

μ problem:

*** What is the origin of μ, and why its value is so small?:**

It contributes to the Higgs potential and therefore must be $\mu \sim M_W \ll M_{Planck}$

e.g in Supergravity mediated SUSY breaking

$$V(H_1, H_2) = \underbrace{\frac{1}{8}(g_2^2 + g'^2)\left[|H_1|^2 - |H_2|^2\right]^2}_{\text{D-terms}} + \underbrace{m_1^2 |H_1|^2 + m_2^2 |H_2|^2}_{\text{soft terms}} + \underbrace{(m_3)^2}_{\equiv\, B\mu} H_1 H_2$$

The **MSSM** does not solve the μ problem.

In that sense it is a kind of effective theory

In the MSSM $W = \epsilon_{ab} \left(Y_u^{ij} \hat{H}_2^b \hat{Q}_i^a \hat{u}_j^c + Y_d^{ij} \hat{H}_1^a \hat{Q}_i^b \hat{d}_j^c + Y_e^{ij} \hat{H}_1^a \hat{L}_i^b \hat{e}_j^c \right)$ $+ \mu H_1 H_2$

there is a mixing of neutral gauginos and Higgsinos:

$$(\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0) \longrightarrow \mathcal{M} = \begin{pmatrix} M_1 & 0 & -\frac{g'\nu_1}{\sqrt{2}} & \frac{g'\nu_2}{\sqrt{2}} \\ 0 & M_2 & \frac{g\nu_1}{\sqrt{2}} & -\frac{g\nu_2}{\sqrt{2}} \\ -\frac{g'\nu_1}{\sqrt{2}} & \frac{g\nu_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g'\nu_2}{\sqrt{2}} & -\frac{g\nu_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix}$$

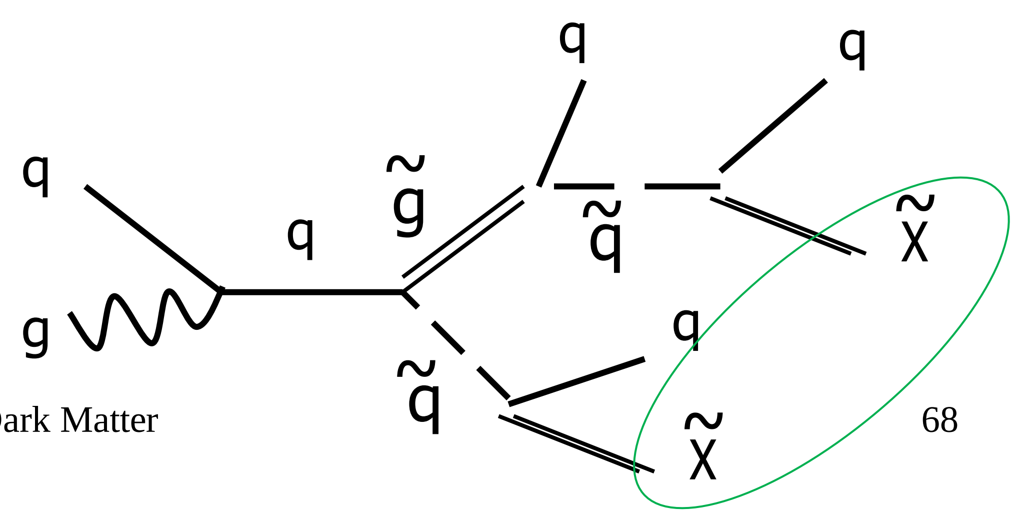
$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

Thus the lightest mass eigenstate (lightest neutralino) with a typical mass ~ GeV-TeV

- is a neutral particle

- if it is the LSP, because of R-parity conservation it can be stable

★ can be detected at the LHC through the usual missing energy signatures



In the MSSM $W = \epsilon_{ab} \left(Y_u^{ij} \hat{H}_2^b \hat{Q}_i^a \hat{u}_j^c + Y_d^{ij} \hat{H}_1^a \hat{Q}_i^b \hat{d}_j^c + Y_e^{ij} \hat{H}_1^a \hat{L}_i^b \hat{e}_j^c \right)$ + μ H_1 H_2

there is a mixing of neutral gauginos and Higgsinos:

$$(\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0) \longrightarrow \mathcal{M} = \begin{pmatrix} M_1 & 0 & -\frac{g'\nu_1}{\sqrt{2}} & \frac{g'\nu_2}{\sqrt{2}} \\ 0 & M_2 & \frac{g\nu_1}{\sqrt{2}} & -\frac{g\nu_2}{\sqrt{2}} \\ -\frac{g'\nu_1}{\sqrt{2}} & \frac{g\nu_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g'\nu_2}{\sqrt{2}} & -\frac{g\nu_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix}$$

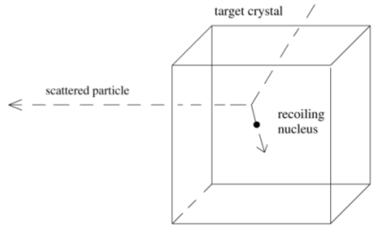
$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

Thus the lightest mass eigenstate (lightest neutralino) with a typical mass ~ GeV-TeV

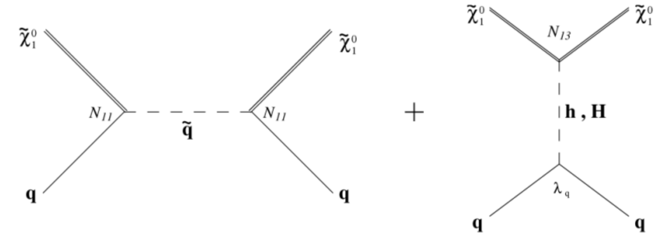
- is a neutral particle
- if it is the LSP, because of R-parity conservation it can be stable
- is a **WIMP**

And therefore a good candidate for DM

Goldberg, 83;
Ellis, Hagelin, Nanopoulos, Olive,Srednicki , 83
Krauss, 83
Ellis, Hagelin, Nanopoulos, Olive,Srednicki, 84



Supersymmetry



Neutralino in the MSSM

Squark exchange

Generally small (1^{st}, 2^{nd} gen. squarks are heavy)

Otherwise unconstrained from LHC

Higgs exchange

Leading contribution (increases with the Higgsino component)

Constrained by the results on $BR(h^0_{SM} \to inv)$

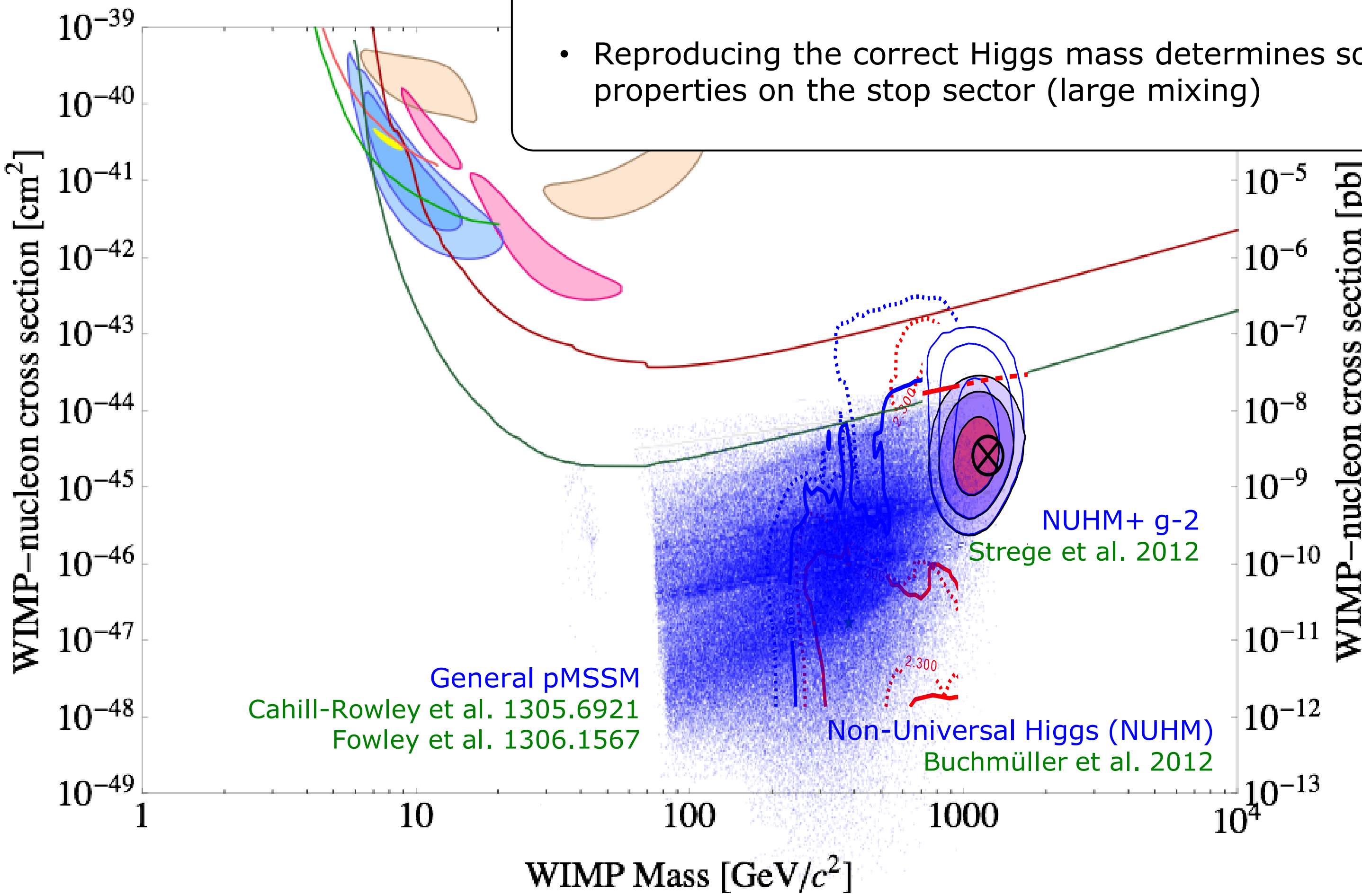
Also affected by m_H=126 GeV

In the general MSSM parameter space, $\mathbf{M_a}$, $\mathbf{m_\alpha}$, $\mathbf{A_\alpha}$, $\mathbf{\tan\beta}$, $\mathbf{\mu}$ one obtains:

Neutralino in the MSSM

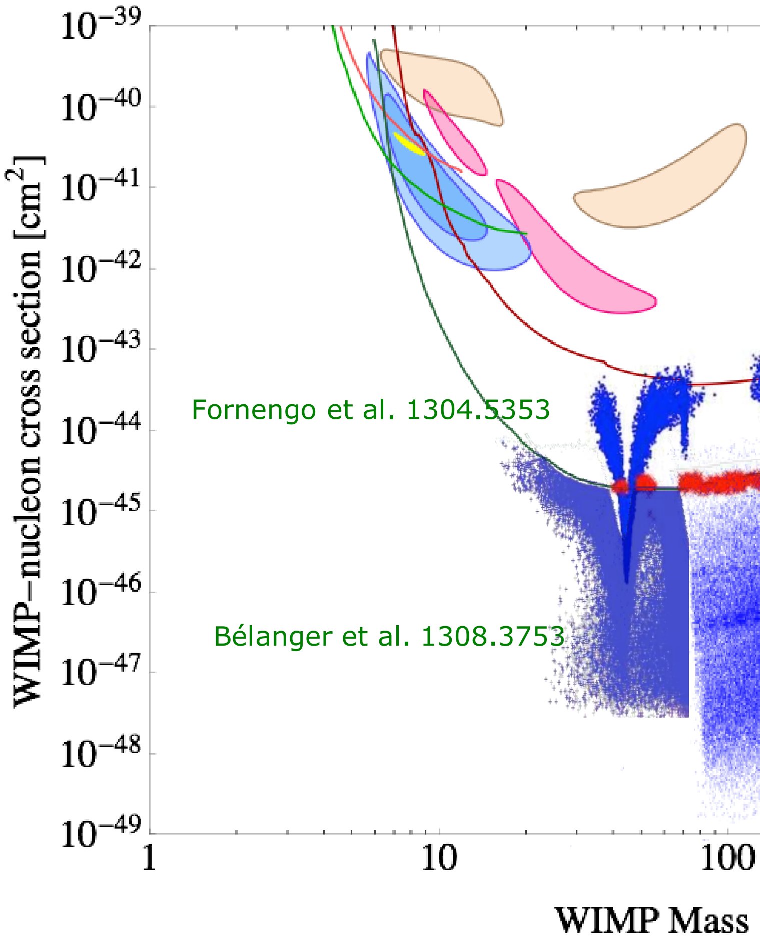
A wide region of the neutralino parameter space is valid

- Large masses appear naturally $m_{X} > 100$ GeV
- Reproducing the correct Higgs mass determines some properties on the stop sector (large mixing)



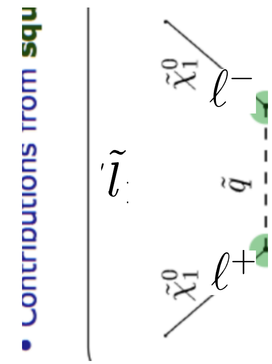
The predictions for its scattering cross section still span many orders of magnitude (excellent motivation for more sensitive detectors)

Neutralino in the MSSM



Very light neutralinos are viable in corners of the parameter space

- Light sleptons are needed to reproduce the correct relic abundance

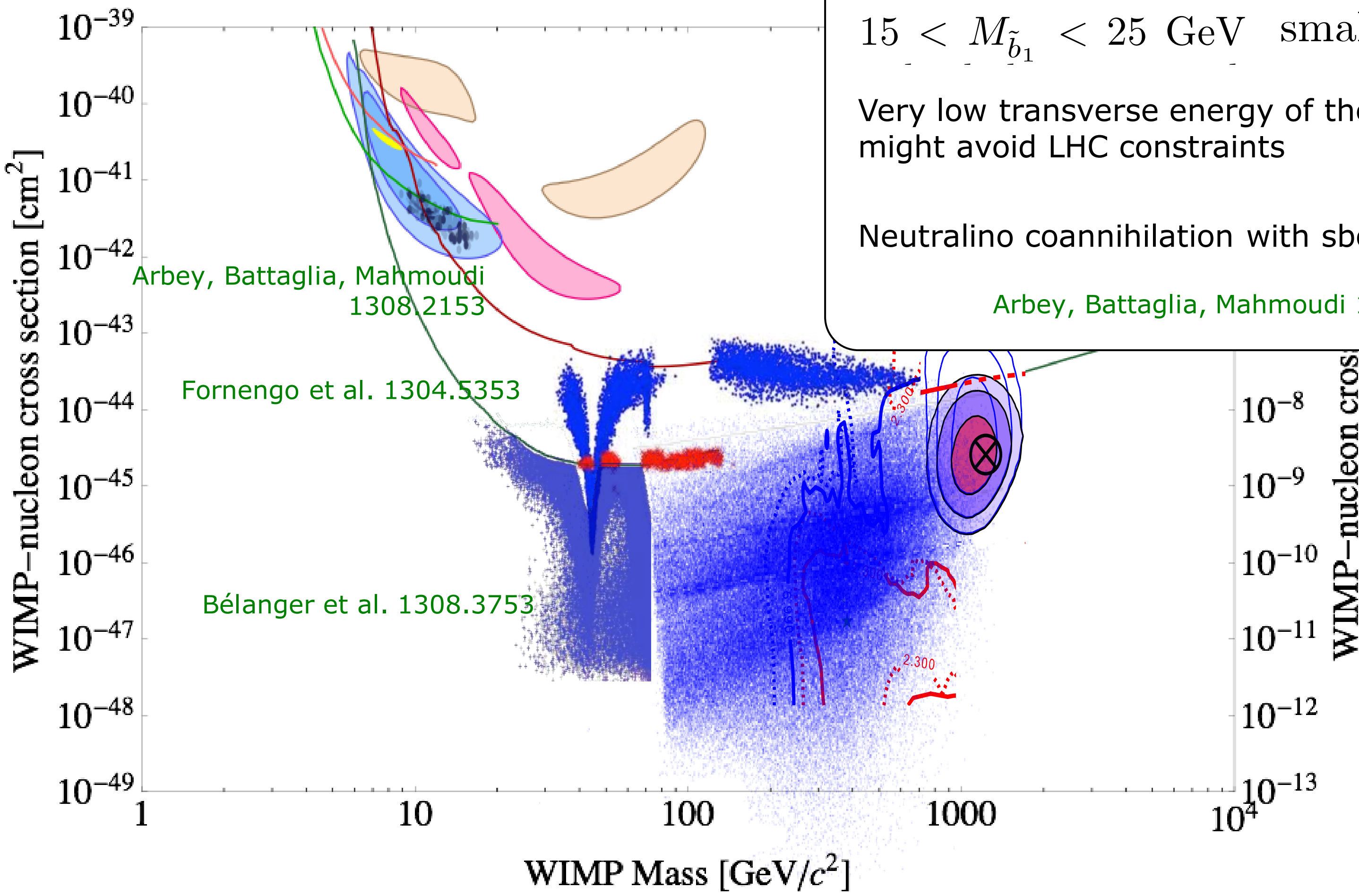


Uncorrelated to direct detection diagrams (smaller σ^{SI})

- The scattering cross section is not within the CoGeNT (Ge) – CDMS II (Si) area

The predictions for its scattering cross section still span many orders of magnitude (excellent motivation for more sensitive detectors)

Neutralino in the MSSM



Extremely light sbottom

$$15 < M_{\tilde{b}_1} < 25 \text{ GeV} \quad \text{small } \cos\theta_b$$

Very low transverse energy of the jets might avoid LHC constraints

Neutralino coannihilation with sbottom

Arbey, Battaglia, Mahmoudi 1308.2153

Very light neutralinos are viable (though quite fine-tuned) in the Minimal Supersymmetric Standard Model.

NMSSM

- Going beyond the MSSM: adding singlet superfield S – the NMSSM

  ↳ Elegant solution to the μ-problem of the MSSM

  $\mu H_1 H_2 \longrightarrow \lambda S H_1 H_2 \Rightarrow \mu_{eff} = \lambda \langle S \rangle$

  $$W = Y_u H_2 Q u + Y_d H_1 Q d + Y_e H_1 L e - \lambda S H_1 H_2 + \frac{1}{3}\kappa S^3$$

- NMSSM has a richer and more complex collider & DM phenomenology:

  2 extra Higgses (CP-even, CP-odd)
  1 additional neutralino $\tilde{S}$

  ↳ A light Higgs is experimentally viable: Implications for $\sigma_{\chi-n}$

- Parameter space of the NMSSM:

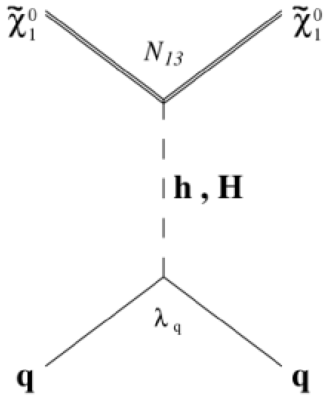
$$\lambda\,, \quad \kappa\,, \quad \mu(=\lambda s)\,, \quad \tan\beta\,, \quad A_\lambda\,, \quad A_\kappa\,, \quad M_1\,, \quad M_2$$

Neutralino in the NMSSM

- Different predictions from the MSSM

The detection cross section can be larger (through the exchange of light Higgses)

(Cerdeño, Gabrielli, López-Fogliani, Teixeira, C.M. ´07)



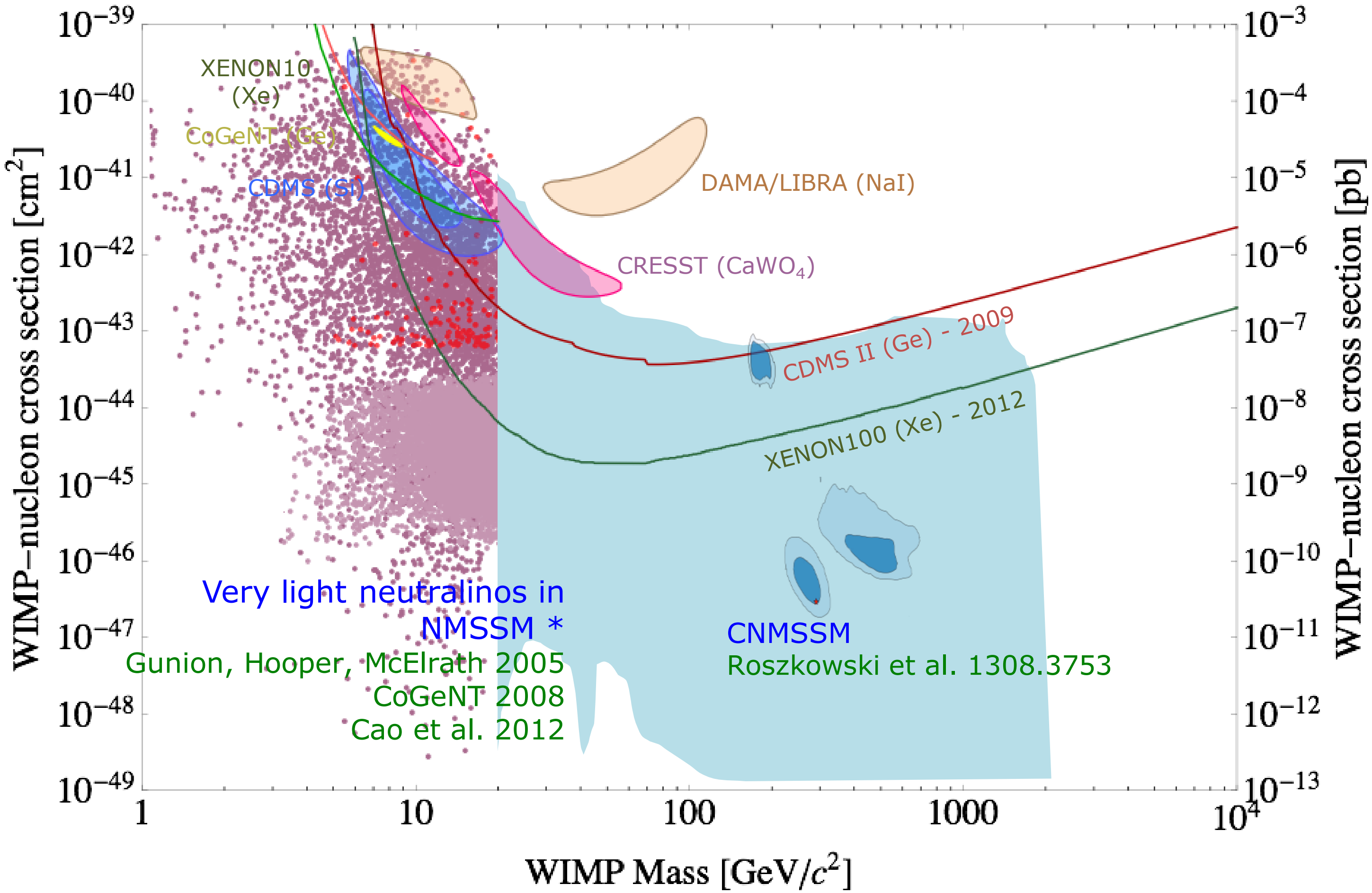
A very light (singlet-like) pseudoscalar can help getting the correct relic abundance for m_X<45 GeV

Gunion, Hooper, McElrath, hep-ph/0509024

Very light **Bino-singlino** neutralinos are possible

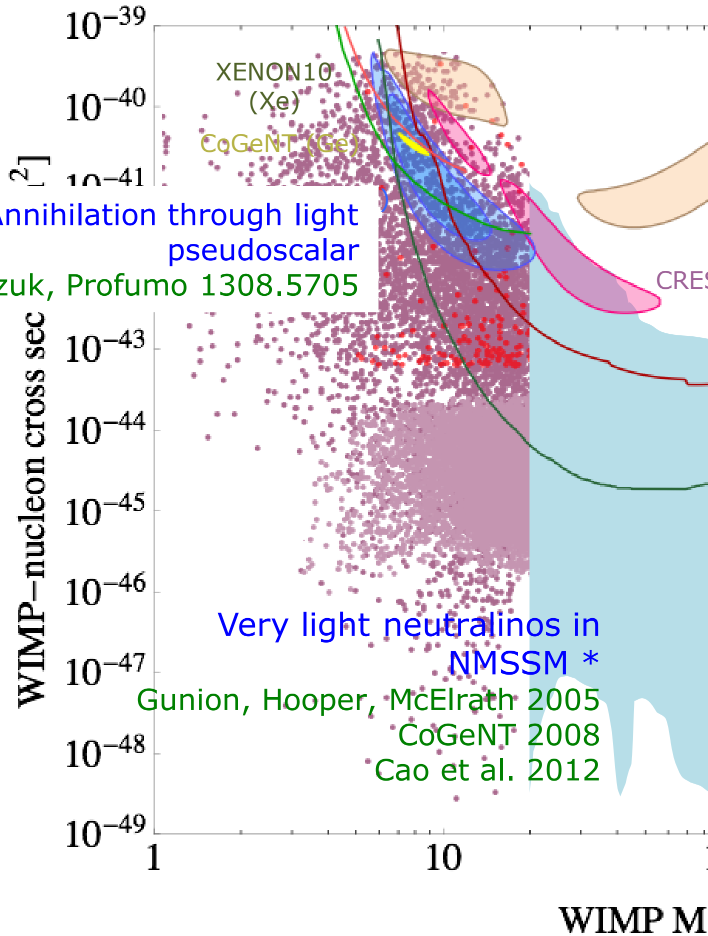
Neutralinos in the NMSSM

Predictions more flexible than in the MSSM



* without constrains on the Higgs sector

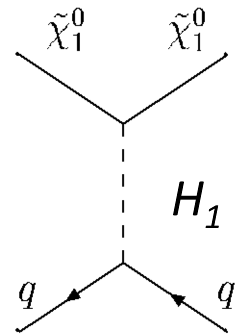
Neutralinos in the NMSSM



Annihilation through light pseudoscalar
Kozaczuk, Profumo 1308.5705

Very light neutralinos in NMSSM *
Gunion, Hooper, McElrath 2005
CoGeNT 2008
Cao et al. 2012

Very light neutralinos are also possible



Annihilation and scattering can take place through the lighter Higgs

Thus avoiding constraints on the invisible decay width of H_{SM}.

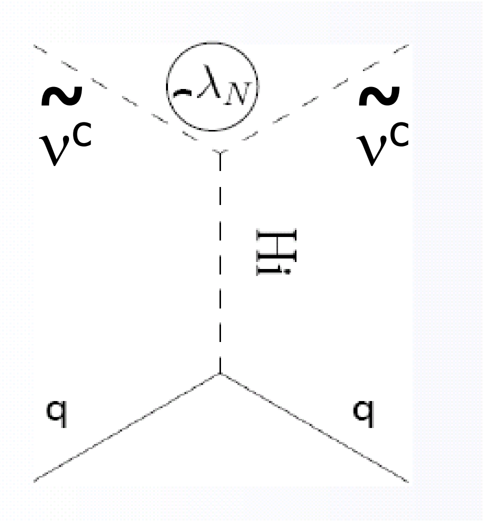
This is also generic of other two-Higgs scenarios for DM

* without constrains on the Higgs sector

The light WIMP region becomes more populated: an excellent motivation for low-threshold experiments.

Right-handed sneutrinos can also be the dark matter in extensions of the NMSSM

$$\lambda\ S\ H_1\ H_2 + \lambda_S\ S\ \nu^c\ \nu^c$$



Whereas in the MSSM a LSP purely RH sneutrino implies scattering cross section too small, relic density too large, here the S provides efficient interactions of sneutrino too

- Viable, accessible and not yet excluded

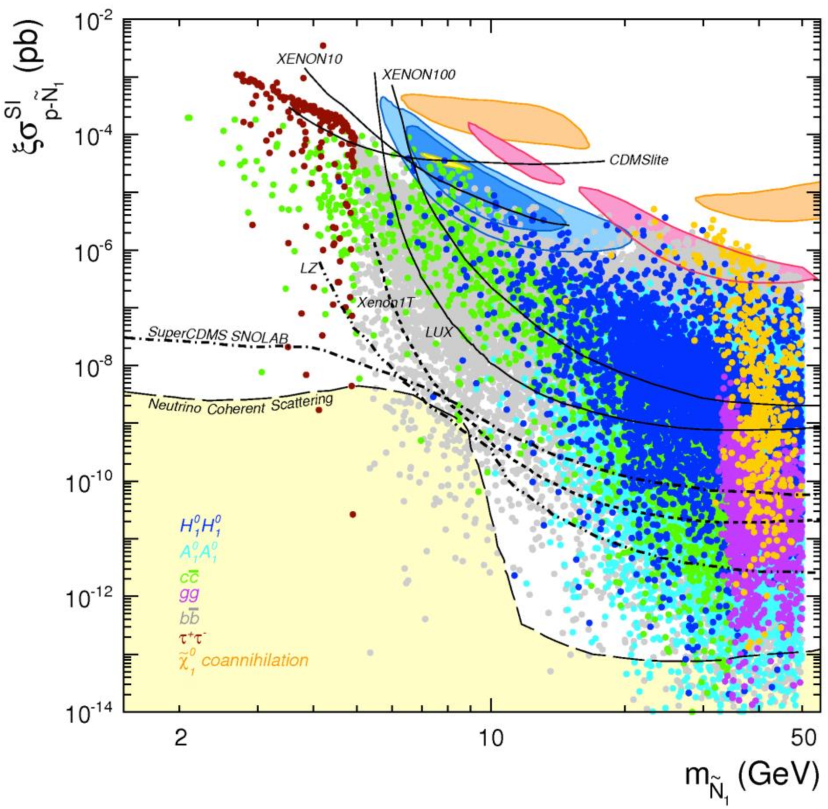
  (Cerdeño, C.M., Seto '08)

  - The correct relic density can be obtained for $\lambda_N \sim 0.1$ (it is a WIMP) and a wide range of sneutrino masses

- Light sneutrinos are viable and distinct from MSSM neutralinos

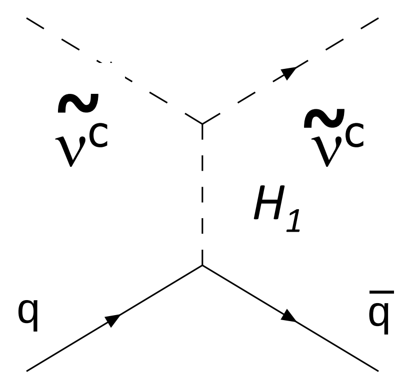
  (Cerdeño, Seto '09)

Very light Right-handed sneutrino in the extension of the NMSSM



DGC Peiro Robles in preparation

Light sneutrinos are viable if the sneutrino couples to a singlet-like Higgs



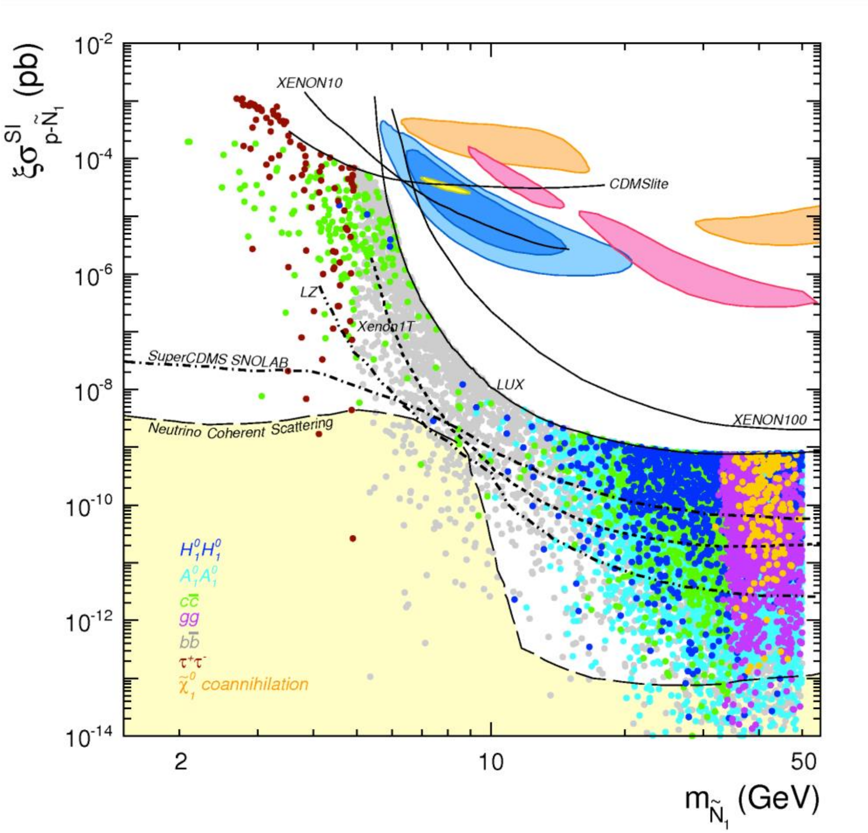
Main annihilation channels:

$\tilde{\nu}^c\tilde{\nu}^c \rightarrow a_1 a_1,\ h_1 h_1$

$\tilde{\nu}^c\tilde{\nu}^c \rightarrow bb,\ cc,\ \tau\tau,\ gg$

Sneutrinos as light as m_N=6 GeV can be obtained in agreement with LHC data and featuring a LARGE scattering cross section.

Very light Right-handed sneutrino in the extension of the NMSSM



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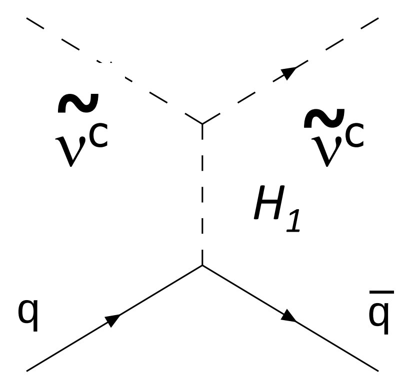

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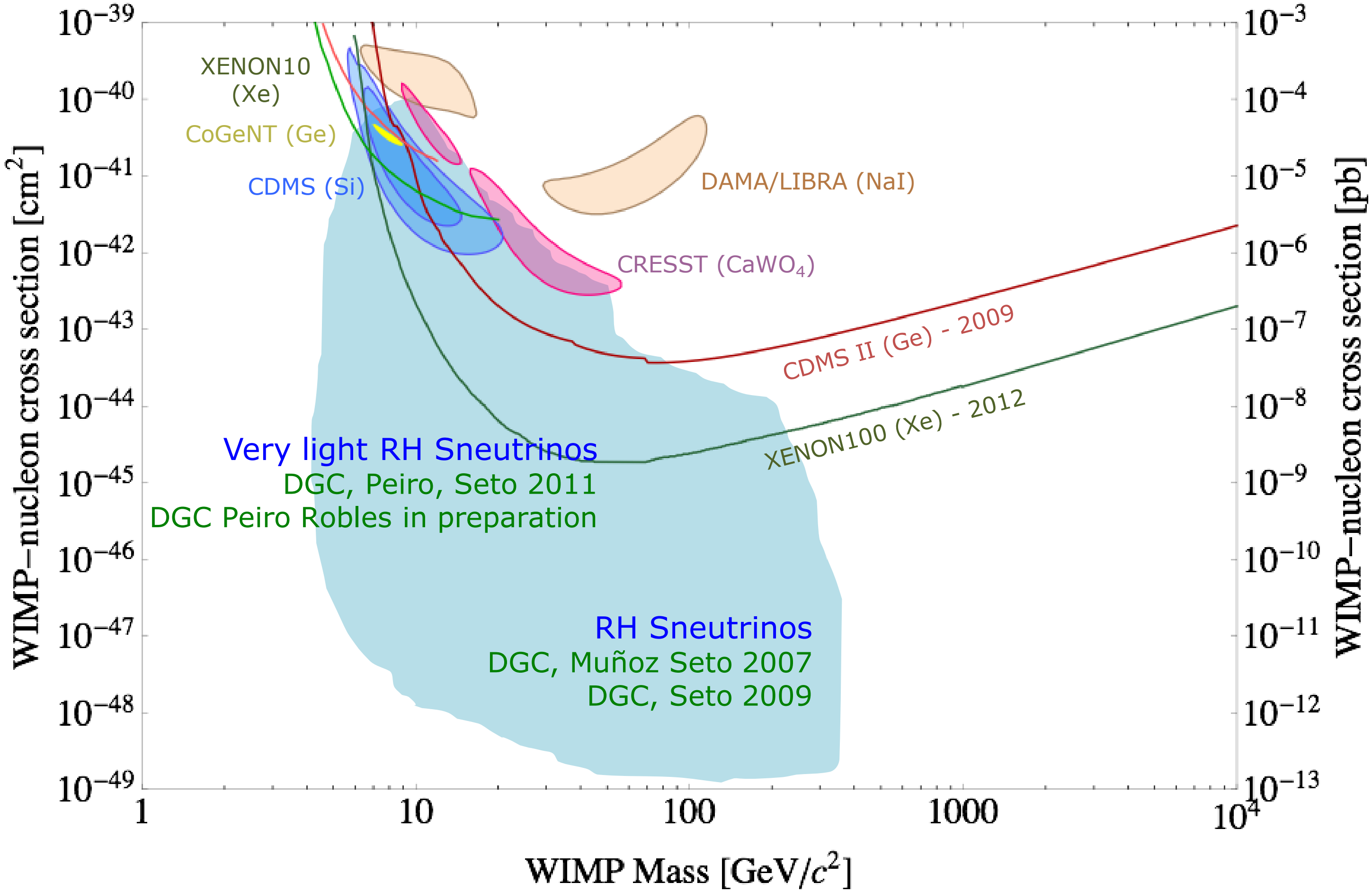
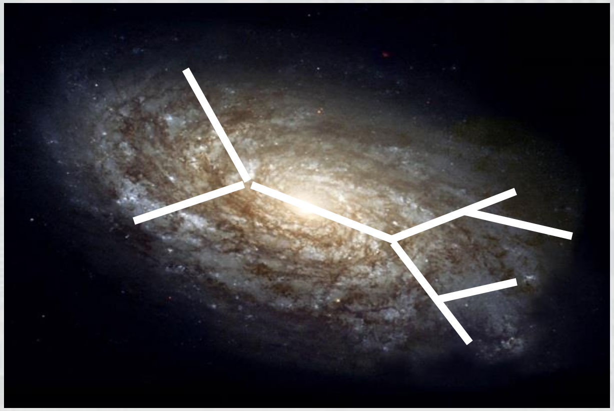
Sneutrinos as light as m_N=6 GeV can be obtained in agreement with LHC data and featuring a LARGE scattering cross section.

Right-handed sneutrino in the Next-to-MSSM

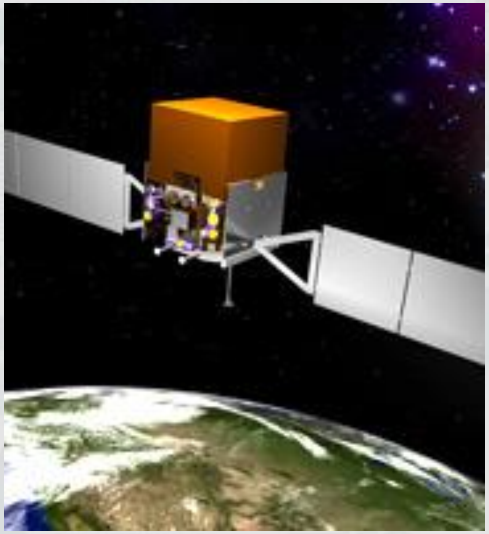


INDIRECT DETECTION

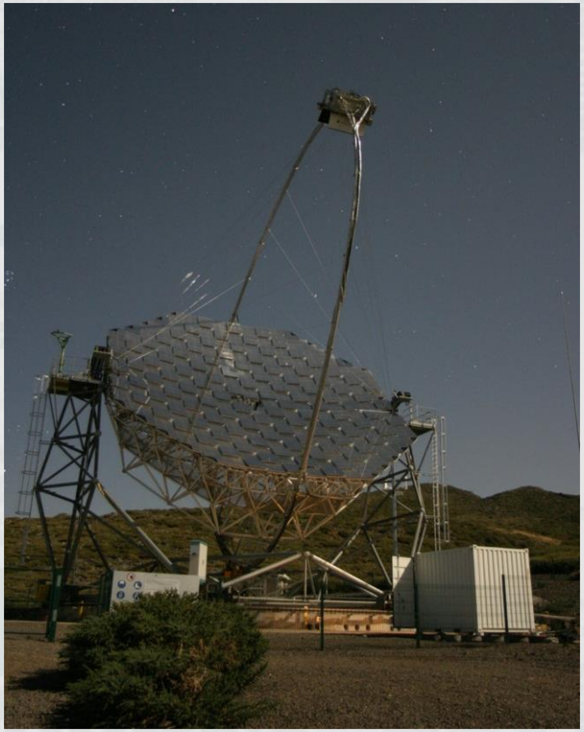


- Annihilation of dark matter particles in the galactic halo will produce gamma rays, antimatter, neutrinos

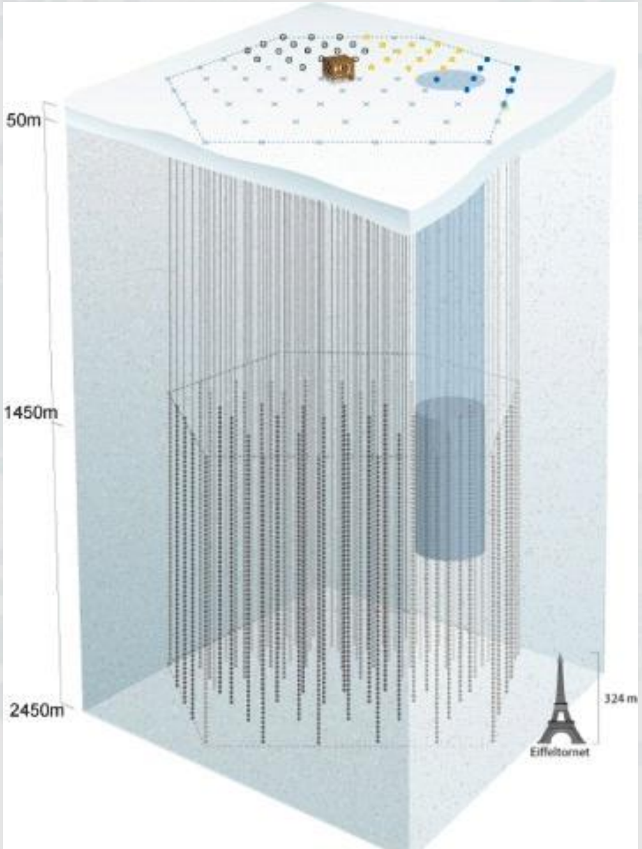
  and these can be measured in space–based detectors: *Fermi* (gammas), PAMELA, AMS (antimatter)



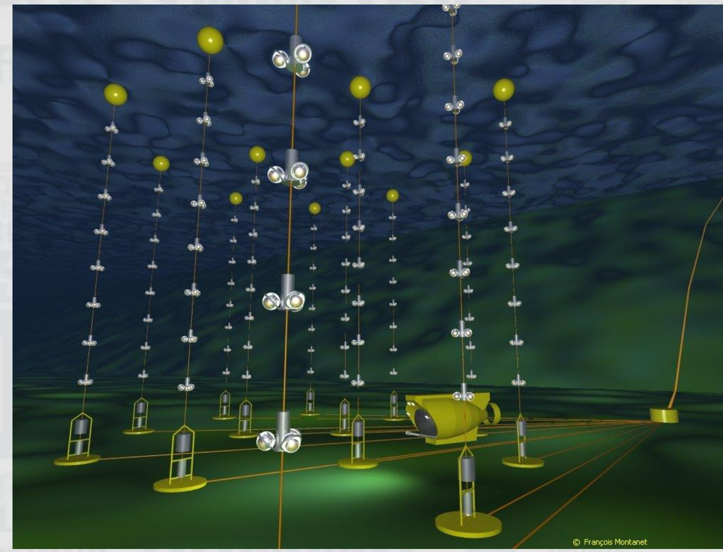
or Cherenkov telescopes MAGIC, HESS, VERITAS, CANGAROO (gammas)



❖Dark matter can accumulate in the Sun or the Earth. Its annihilation will produce neutrinos which can be detected in neutrino telescopes, specially through the muons produced by their interactions in the rock

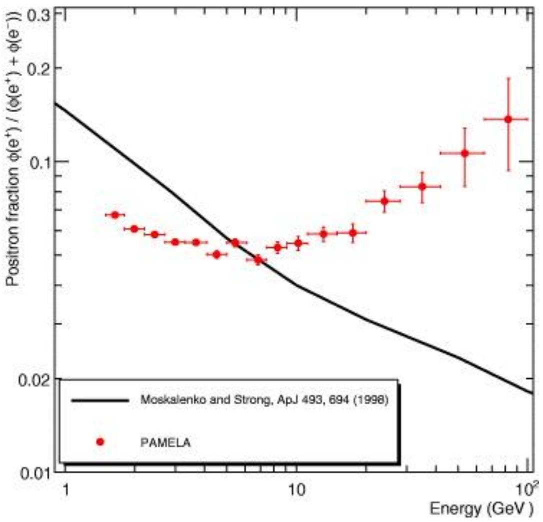


Under-ice experiments (IceCube with a size 10^6 m^2)

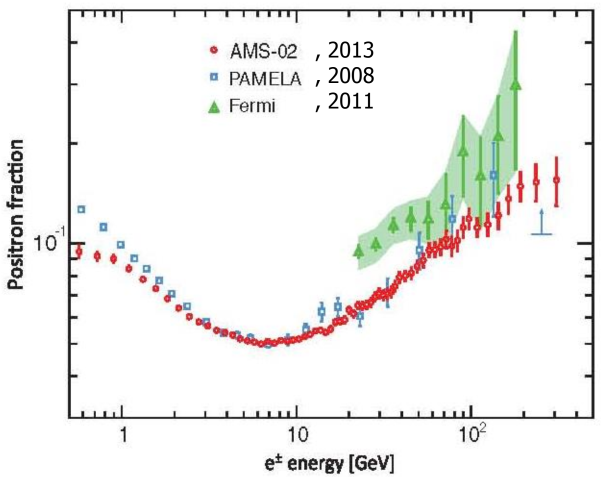


Underwater experiments (ANTARES with a size of 10^4 m^2. In the future KM3NeT with a size of 10^6 m^2)

e.g. an excess of **antiparticles** could be a signature of DM annihilations



e.g. an excess of **antiparticles** could be a signature of DM annihilations



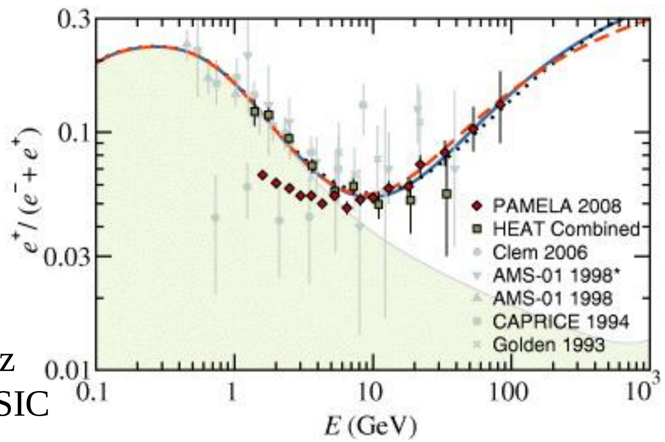
problems with the DM explanation:

- No antiproton excess is observed
- Data implies $\sigma_{ann}v \sim 10^{-23}$ cm^3 s^{-1} , but this would produce

$$\Omega h^2 \sim \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma v>} << 0.1$$

- Otherwise we would have to require boost factors ranging between 10^2 and 10^4 provided by clumpiness in the dark matter distribution

but the high energy positrons mainly come from a region within few kpc from the Sun (those far away lose their energies during the propagation), where boost factors > 10 are not expected



Possible astrophysical explanation:

Contributions of e^- and e^+ from Geminga pulsar assuming different distance, age and energetic of the pulsar.

an excess of gamma rays could be a signature of DM annihilations

An interesting possibility could be to search for **DM around the Galactic Center** where the density is very large

Fermi-LAT:
Morselli, Cañadas, Vitale, 2010
analized the inner galaxy region

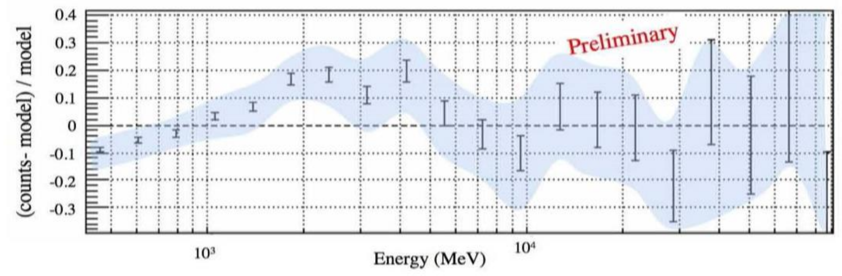


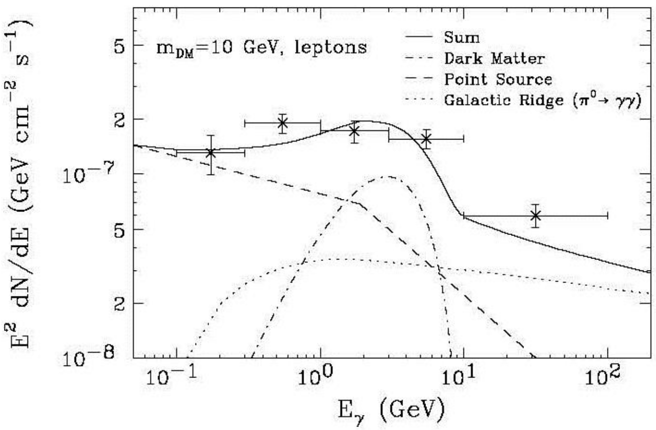
Fig. 4. – Residuals ((exp.data - model)/model) of the above likelihood analysis. The blue area shows the systematic errors on the effective area.

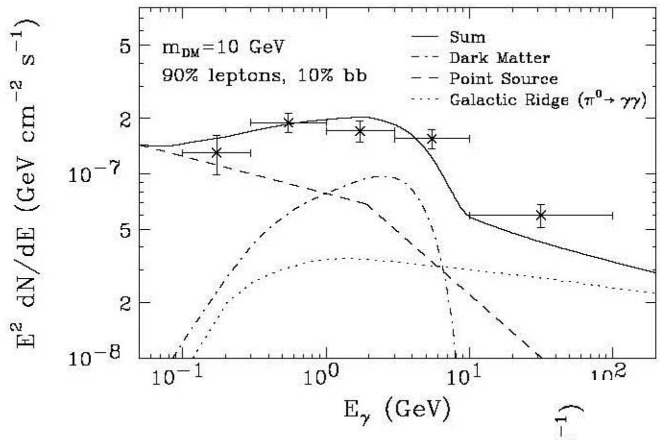
But conventional astrophysics in the galactic center is not well understood. An excess might be due to the modeling of the diffuse emission, unresolved sources, etc.

Assuming an excess, and that the DM density in the inner galaxy is $\rho(r) \sim \rho_0/r^\gamma$, one can deduce possible DM examples reproducing the observations

$$\Phi_\gamma(E_\gamma,\psi) = \frac{1}{2}\frac{\langle\sigma_{ann}\, v\rangle}{4\pi m_{\rm DM}^2}\sum_i \frac{dN_\gamma^i}{dE_\gamma}B_i \int_{l.o.s.} \rho^2\, dl\ ,$$

particle physics | astrophysics

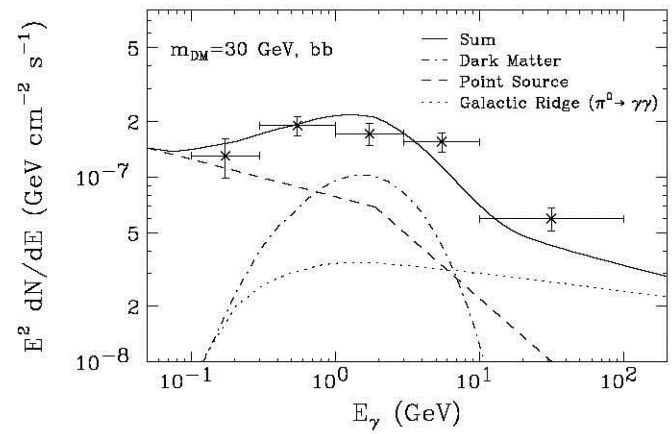




Hooper, Goodenough, 1010.2751
Hooper, Linden, 1110.0006

$\gamma \sim 1.3$

$\sigma_{ann}v \sim 7 \times 10^{-27}$ cm^3 s^{-1}



But there are other possible explanations:

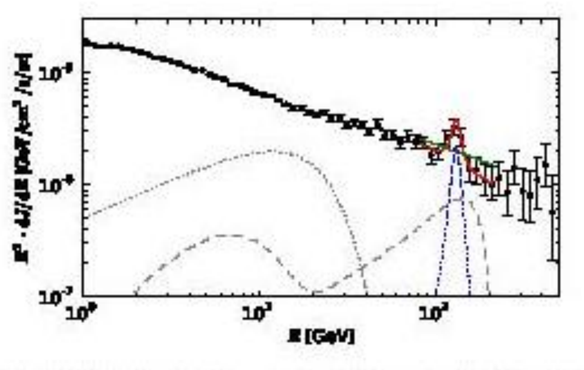
-Consistency of the excess with a millisecond pulsar population, Abazajian 1011.4275

-Cosmic-ray effects, Chernyakova 1009.2630

-Different spectrum of the point source at the galactic center, Boyarsky, Malyshev, Ruchayskiy, 1012.5839

Gamma-ray lines are traditional smoking gun signatures for DM annihilation

Weniger, 1204.2797 presented a search for lines in the Fermi-LAT 43 month of data concentrating on energies between 20 - 300 GeV.

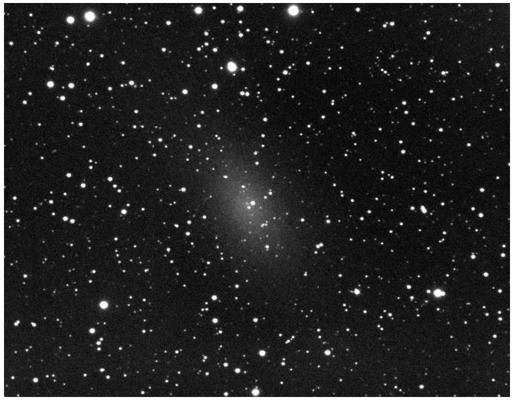


In regions close to the Galactic Center he found an indication for a gamma-ray line at an energy ~ 130 GeV

(see also the previous work by Bringmann, Huang, Ibarra, Vogl, Weniger, 1203.1312)

If interpreted in terms of DM particles annihilating to a photon pair, the observations would imply $m_{DM} \sim 130$ GeV, $\sigma_{ann} v \sim 10^{-27}$ cm^3 s^{-1} when using Einasto profile

Local Group **dwarf spheroidal galaxies** (dSph) are attractive targets because:



-they are nearby
-largely dark matter dominated systems
-relatively free from gamma-ray emission from other astrophysical sources

But 24-month measurements of 10 dSph reported by Fermi-LAT show no excess

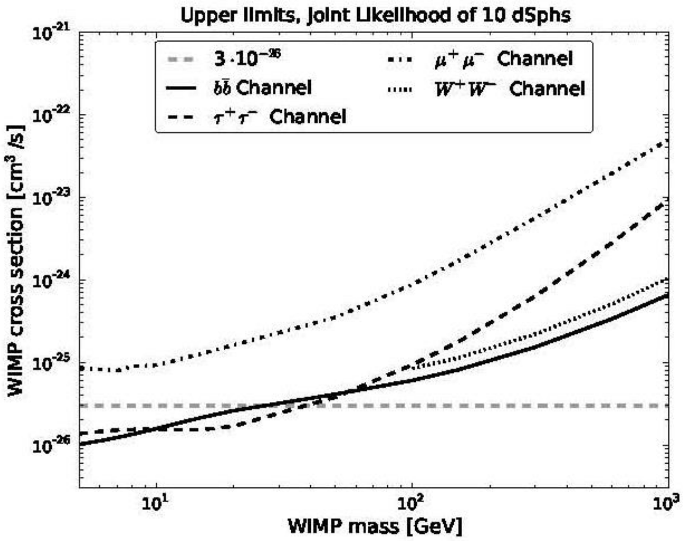
1108.3546

one can constrain DM particle properties:

WIMPs are ruled out to a mass of about

27 GeV for the bb channel

37 GeV for the $\tau^+\tau^-$ channel



$\sigma_{ann}v \sim 3 \times 10^{-26}\ cm^3\ s^{-1}$ thermal cross section

FIG. 2. Derived 95% C.L. upper limits on a WIMP annihilation cross section for the $b\bar{b}$ channel, the $\tau^+\tau^-$ channel, the $\mu^+\mu^-$ channel, and the W^+W^- channel. The most generic cross section ($\sim 3 \cdot 10^{-26}\ cm^3 s^{-1}$ for a purely s-wave cross section) is plotted as a reference. Uncertainties in the J factor are included.

Similar results using Fermi-LAT Galactic halo observations, 1205.6474

No excess has been observed from dSphs in Cherenkov telescopes:

Sagittarius by HESS
Draco and Ursa Minor by Whipple and Veritas
Draco, Willman 1, Segue 1 by MAGIC

Implying limits on the annihilation cross seccion between $\sigma_{ann} v \sim 10^{-23}$ to 10^{-22} cm^3 s^{-1} for a 1 TeV mass neutralino, assuming a NFW dwarf density profile

Nearby clusters of galaxies are also attractive targets

-they are more distant, but more massive than dSphs
-very dark matter dominated like dSphs
-typically lie at high galactic latitudes where the contamination from galactic gamma-ray background emission is low

3-year Fermi-LAT data show no excess Han et al., 1207.6749:
(also the observations of Coma by HESS and Perseus by MAGIC)

Geringer-Sameth, Koushiappas, 1108.2914

Fermi-LAT, 1002.2239

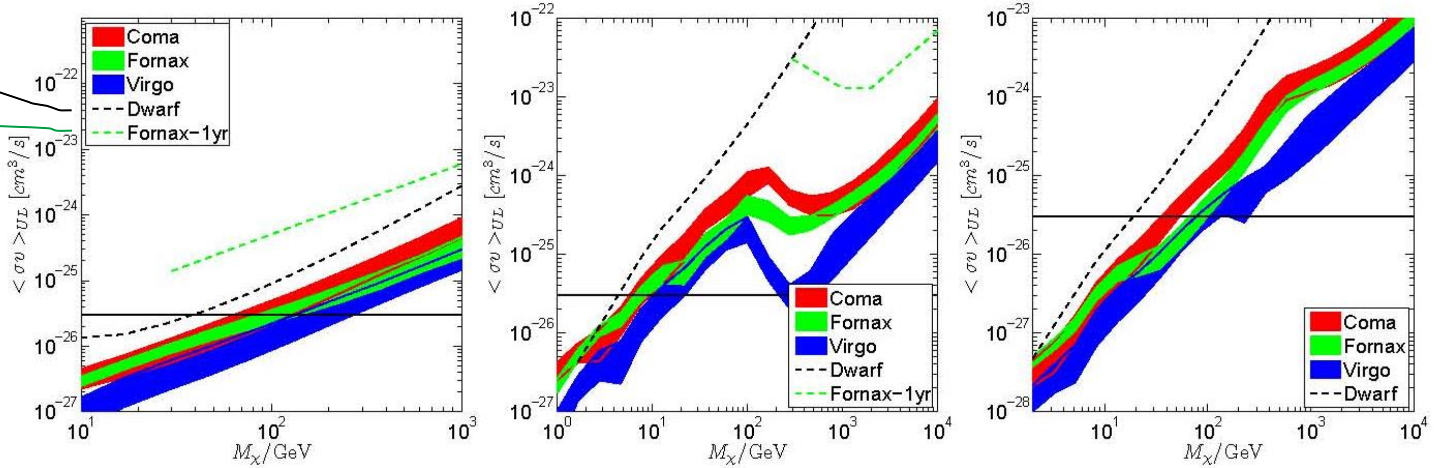
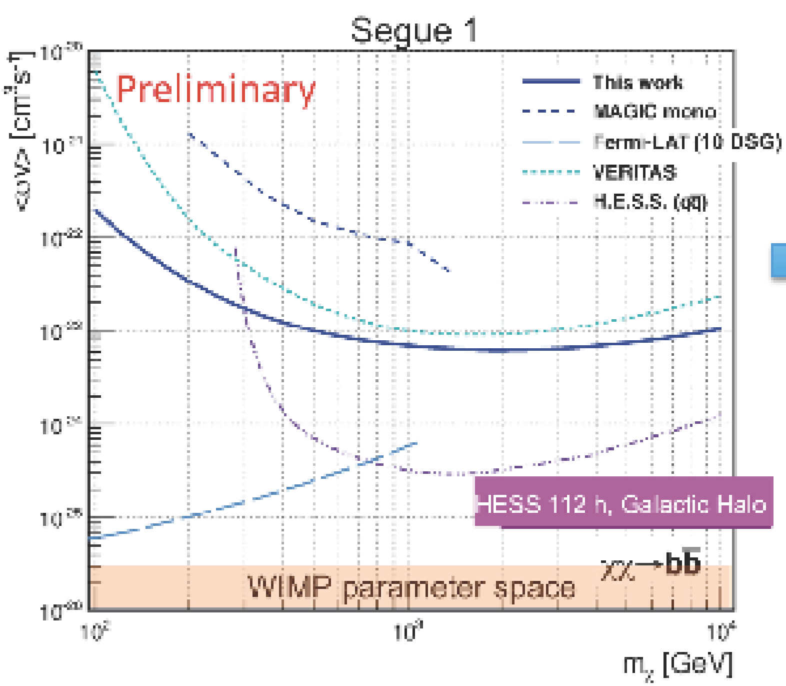


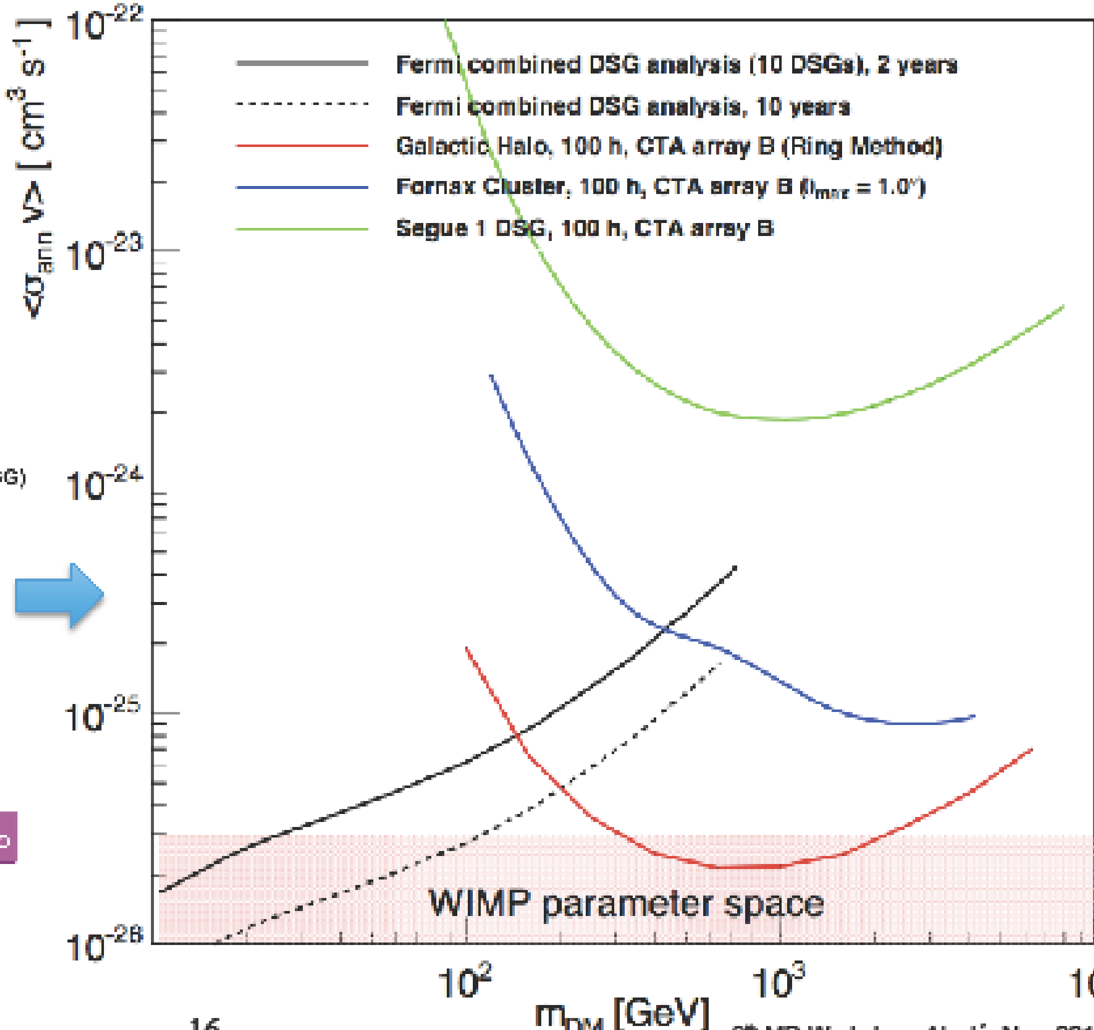
Figure 10. Upper limits for the DM annihilation cross-section in the $b\bar{b}$ (left), $\mu^+\mu^-$ (middle), and $\tau^+\tau^-$ (right) channels, after including the effect of undetected point sources. Line styles are as in Fig. 6, but only the EXT results are shown. Note that the lower bounds of each band are still determined by the results without including undetected point sources in the analysis.

Adopting a boost factor of ~ 10^3 from subhalos, WIMPs are ruled out to a mass of about 100 GeV for the bb and $\tau^+\tau^-$ channels, and 10 GeV for the $\mu^+\mu^-$ channel

CTA prospect summary

- DM CTA prospects:
  - At least factor 10 improvement wrt current IACTs
  - Halo of GC reaching WIMP parameter space
  - CTA & Fermi sinergy





Let us come back to the region around the Galactic Center,

Is it possible to derive (even more) stringent constraints on parameters of generic DM candidates?

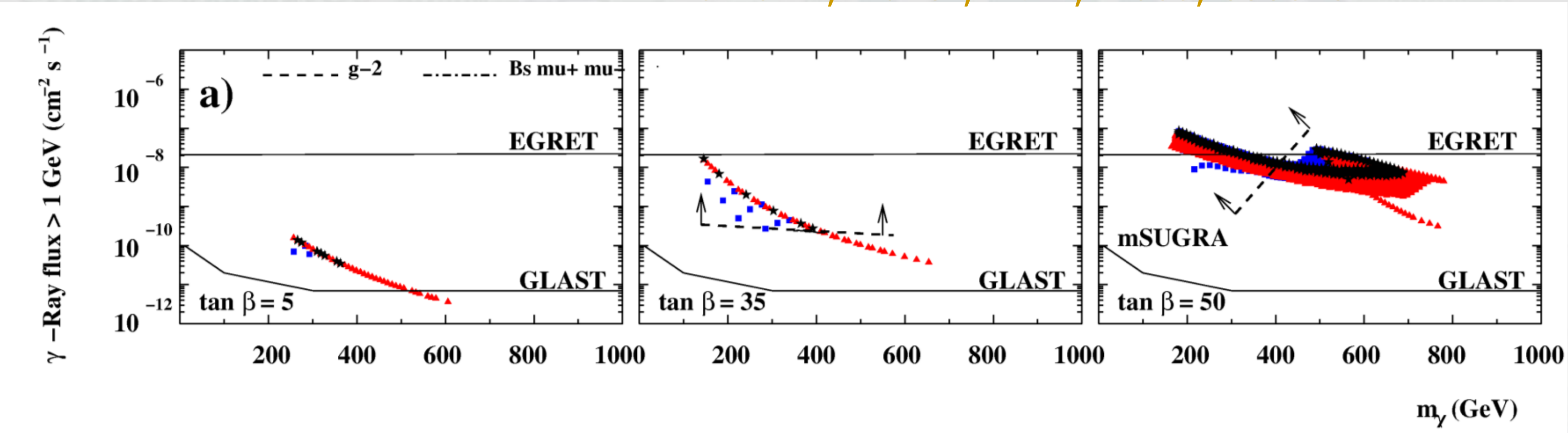
YES in the likely case that the collapse of baryons to the Galactic Center is accompanied by the contraction of the DM

Prada, Klypin, Flix Molina, Martinez, Simonneau, 0401512
Mambrini, Munoz, Nezri, Prada, 0506204

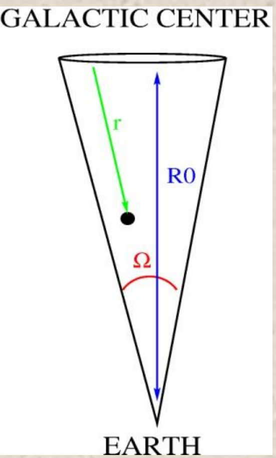
The behavior of NFW might be modified $\rho \longrightarrow 1/r$ making it steeper: $1/r^{\gamma}$

Constraining e.g. the SUSY parameter, as discussed in this old work:

Mambrini, Munoz, Nezri, Prada, 0506204



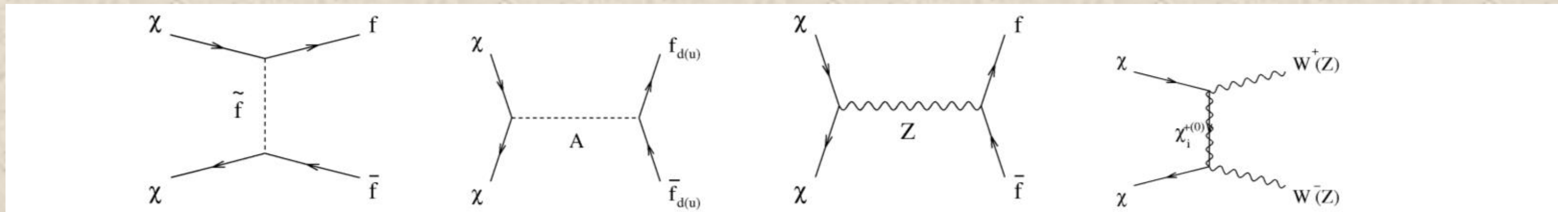
Theoretical Predictions



$$\phi \sim \left(\int_{\text{line of sight}} \rho^2 \, dr\right) \sigma_{ann} v / m^2$$

Astrophysics

Particle physics



Particle physics: $\propto \frac{m_\chi m_f}{m_{\tilde{f}}^2} Z_{11}^2$ $\quad \propto \frac{m_\chi^2}{m_A^2} \frac{Z_{11}Z_{13,14}}{m_W} m_{f_d} \tan\beta (\frac{m_{f_u}}{\tan\beta})$ $\quad \propto \frac{m_f m_\chi}{m_Z^2} Z_{13,14}^2$ $\quad \propto \frac{[-Z_{14}V_{21}^* + \sqrt{2}Z_{12}V_{11}^*]^2(-Z_{13}N_{31}^* + Z_{14}N_{41}^*)^2}{1+m^2_{\chi_i^{+(0)}}/m_\chi^2 - m^2_{W(Z)}/m_\chi^2}$

Astrophysics: e.g. a **NFW profile** for our galaxy, has for small distances from the galactic center $\rho(r) \sim \rho_0 / r$

Because these are DM-only simulations, but central regions of galaxies like the Milky Way are dominated by baryons

They might modify e.g. the behaviour of NFW $\rho \longrightarrow 1/r$ making it steeper

The baryons lose energy through radiative processes and fall into the central regions of a forming galaxy. Thus the resulting gravitational potential is deeper, and the DM must move closer to the center increasing its density

Zeldovich, Klypin, Khlopov, Chechetkin, 1980
Blumenthal, Faber, Flores, Primack, 1986
Gnedin, Kravtsov, Klypin, Nagai, 0406247

The effect seems to be confirmed by high-resolution hydrodynamic simulations that self-consistently include complex baryonic physics such as gas dissipation, star formation and supernova feedback

Gustafsson, Fairbairn, Sommmer-Larsen, 0608634
Colín, Valenzuela, Klypin, 0506627
Tissera, White, Pedrosa, Scannapieco, 0911.2316
O.Y. Gnedin, Ceverino, N.Y. Gnedin, Klypin, Kravtsov, Levine, Nagai, Yepes, 1108.5736

Cerdeño, Huh, Klypin, Mambrini, C.M., Peiró, Prada, Gómez-Vargas, Morselli, Sánchez-Conde
arXiv:1308.3515

MultiDark + Fermi-LAT

From observational data of the Milky Way, the parameters of the DM profiles have been constrained. Fitting the data

- in the inner region $\rho \rightarrow 1/r$ ⟶ in the inner region $\rho \rightarrow 1/r^{1.37}$

Caution:

Astrophysicists identified another process, which tends to decrease the DM density and flatten the DM cusp

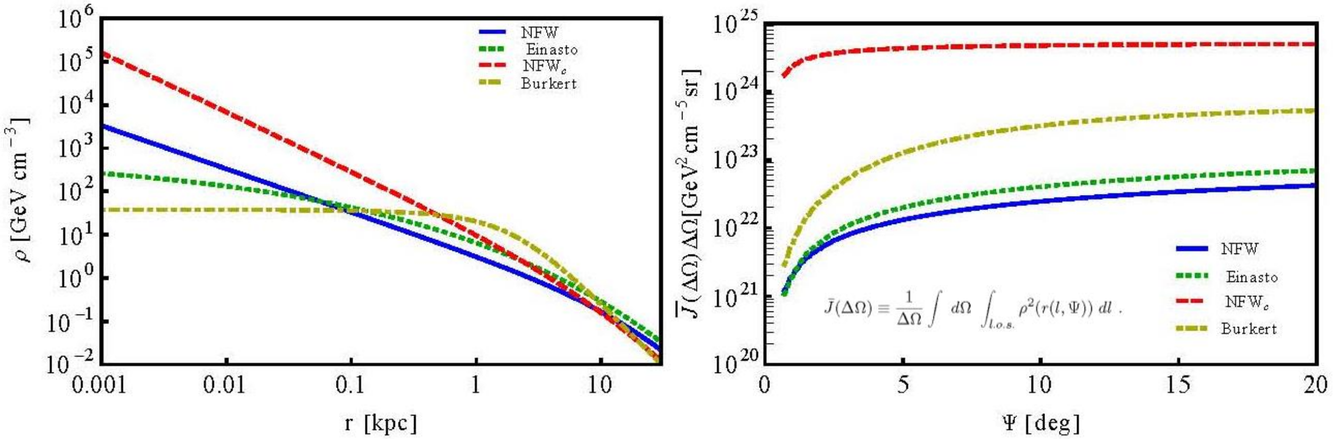
Mashchenko, Couchman, Wadsley, 0605672, 0711.4803
Pontzen, Governato, Blumenthal, 1106.0499

The mechanism relies on numerous episodes of baryon infall followed by a strong burst of star formation, which expels the baryons producing at the end a significant decline of the DM density.

Cosmological simulations which implement this process show this result

Governato et al., 0911.2237
Maccio et al, 1111.5620

Whether the process happened in reality in the Milky Way is still unclear…



The theory

$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{prompt} = \sum_i \frac{dN_\gamma^i}{dE_\gamma} \frac{\langle\sigma_i v\rangle}{8\pi m_{DM}^2} \bar{J}(\Delta\Omega)\Delta\Omega \ ,$$

to be compared with the observations

Figure 1: Left panel: DM density profiles used in this work, with the parameters given in Table 1. Right panel: The $\bar{J}(\Delta\Omega)\Delta\Omega$ quantity integrated on a ring with inner radius of 0.5 deg (~ 0.07 kpc) and external radius of Ψ ($R_\odot \tan\Psi$) for the DM density profiles given in Table 1. Blue (solid),

To set constraints we request that the expected DM signal does not exceed the observed flux (due to DM + astrophysical background)

No subtraction of any astrophysical background is made.

Very conservative analysis!

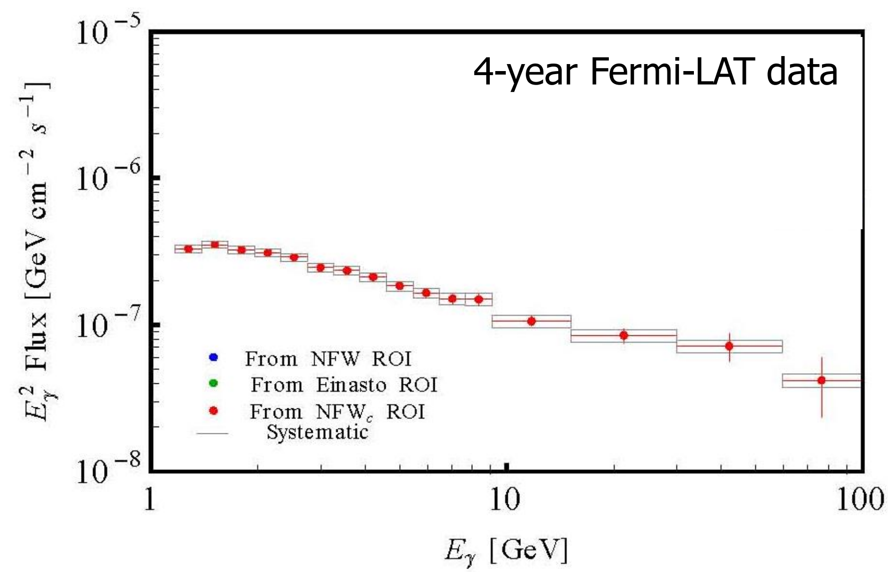


Figure 4: Energy spectrum extracted from Fermi-LAT data for the optimized regions that are shown in Figure 3. Data are shown as points and the vertical error bars represent the statistical errors. The latter are in many cases smaller than the point size. The boxes represent the systematic error in the Fermi-LAT effective area.

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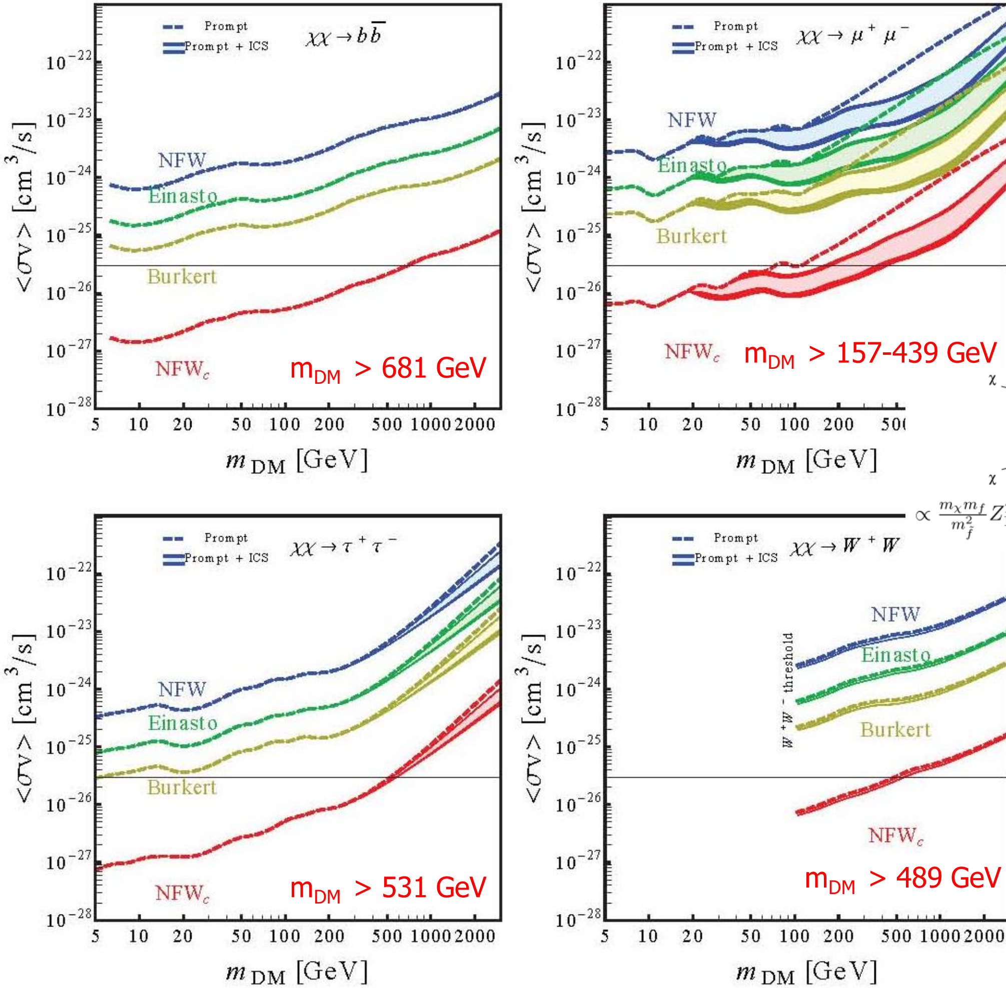
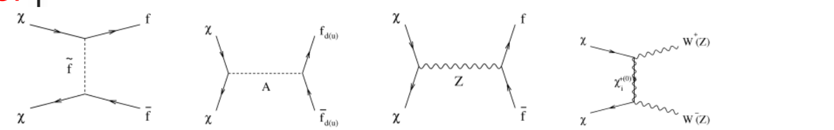
IFT UAM-CSIC

In general the final state will be a combination of the final states presented here

e.g., in SUSY, the neutralino annihilation modes are 70% bb - 30% $\tau\tau$ for a Bino DM, and 100% W^+W^- for a Wino DM





$\propto \frac{m_\chi m_f}{m_{\tilde{f}}^2} Z_{11}^2 \quad \propto \frac{m_\chi^2}{m_A^2} \frac{Z_{11} Z_{13,14}}{m_W} m_{f_d} \tan\beta (\frac{m_{f_u}}{\tan\beta}) \quad \propto \frac{m_f m_\chi}{m_Z^2} Z_{13,14}^2 \quad \propto \frac{[-Z_{14} V_{21}^* + \sqrt{2} Z_{12} V_{11}^*]^2 (-Z_{13} N_{31}^* + Z_{14} N_{41}^*)^2}{1 + m^2_{\chi_i^{+(0)}}/m_\chi^2 - m_{W(Z)}^2/m_\chi^2}$

Also, the value of σv in the Galactic halo might be smaller than 3 x10^{-26} cm^3 s^{-1}

- e.g., in SUSY, in the early Universe coannihilation channels can also contribute to σv

- Also, DM particles whose annihilation in the Early Universe is dominated by velocity dependent contributions would have a smaller value of σv in the Galactic halo, where the DM velocity is much smaller, and can escape this constraint:

$$\Omega h^2 \approx 3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1} \langle \sigma v \rangle^{-1} \approx 0.1$$

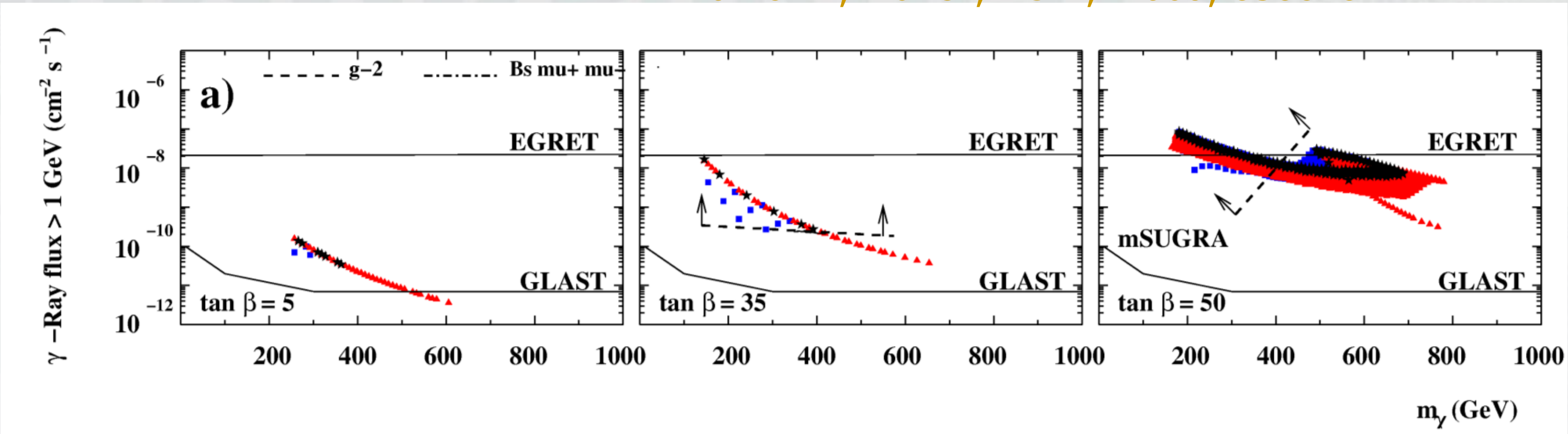
In this sense, the results derived for pure annihilation channels can be interpreted as limiting cases which give an idea of what can happen in realistic scenarios

But still Fermi-LAT data imply that large regions of parameters of DM candidates are not compatible with compressed DM density profiles

Work in progress,

Constraining the SUSY parameter space inspired by an old study of the MSSM:

Mambrini, Munoz, Nezri, Prada, 0506204



So we are now updating the neutralino MSSM case and studying the NMSSM, and the sneutrino in the extension of the NMSSM, ...

Cerdeño, Gómez-Vargas, C.M., Peiró *et al.* in preparation

Decaying Dark Matter

Let us discuss an example of **decaying DM**

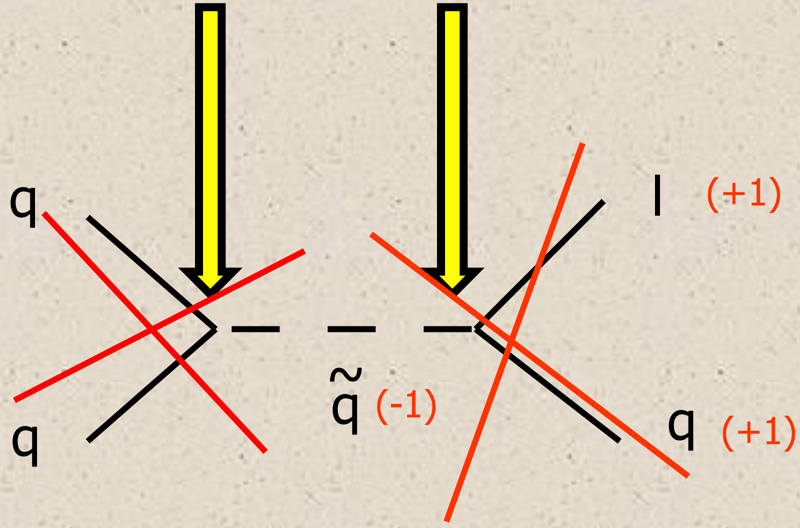
In supersymmetric models where R-parity is broken, the **neutralino** with very short lifetime **cannot be used as candidate for dark matter**

Nevertheless, **the gravitino** (*superWIMP*), with a lifetime longer than the age of the Universe, can be a good candidate

Searches through gamma-ray lines using Fermi-LAT ?

- **By construction, the MSSM produce too fast proton decay**

Operators like $d^c d^c u^c$, QLd^c , LLe^c , LH_2 are allowed in the superpotential

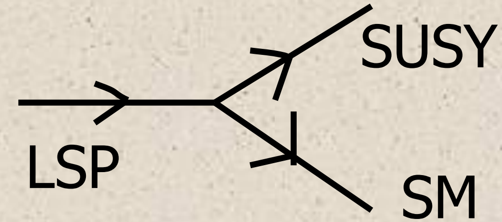


To preserve B and L conservation one can impose a discrete symmetry (**R parity**)

Particle $\longrightarrow$ Particle
Superpartner $\longrightarrow$ – Superpartner

i.e. superparticles must appear in pairs

Thus the **LSP** is stable since this process is forbidden:



The LSP is a candidate for dark matter

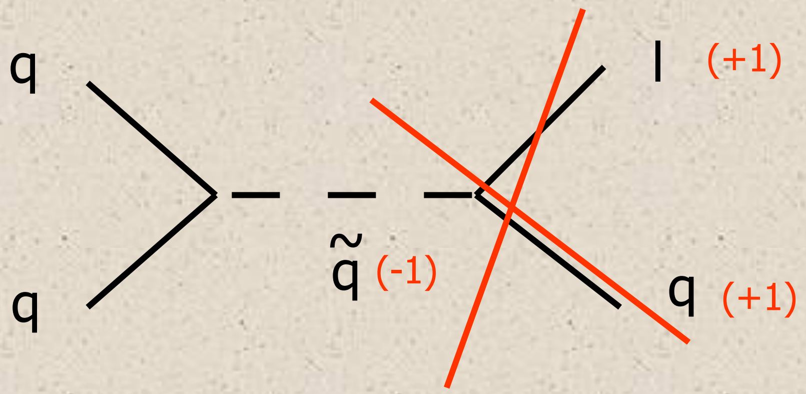
But this is a very conservative approach since it forbids all couplings

But the choice of R-parity is *ad hoc.* There are other symmetries that forbid some of the operators, but others are allowed.

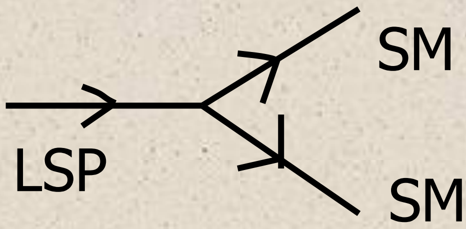
A*lso stringy selection rules: particles are attached to different sectors in the compact space, or they have extra U(1) charges*

We might forbid only some of the couplings,
if this is sufficient to avoid proton decay

e.g. $d^c d^c u^c$, QLd^c , LLe^c , LH_2



Thus R-parity is broken
and the **LSP** is not stable since processes of the type:
are allowed



But the LSP can still be a candidate for dark matter

if its lifetime is longer than the age of the Universe

Why can a model breaking R-parity be interesting?

It might be helpful to solve several problems of supersymmetric models

- The μ problem
- The generation of neutrino masses

An R-parity breaking model trying to solve both problems: $\mu\nu$SSM

In addition to the MSSM Yukawas for quarks and charged leptons, the $\mu\nu$SSM superpotential contains Yukawas for neutrinos, and two additional type of terms

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c\right) - \epsilon_{ab}\lambda^i\,\hat{\nu}_i^c\,\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c\,,$$

López-Fogliani, C.M., PRL 2006

However, when the scalar components of the superfields $\hat{\nu}_i^c$, denoted by $\tilde{\nu}_i^c$, acquire VEVs of order the electroweak scale, an effective interaction $\mu\hat{H}_1\hat{H}_2$ is generated through the fifth term in (1), with $\mu \equiv \lambda^i\langle\tilde{\nu}_i^c\rangle$.

a "μ from ν" Supersymmetric Standard Model ($\mu\nu$SSM)

The last type of terms in (1) is allowed by all symmetries, and avoids the presence of a Goldstone boson associated to a global U(1) symmetry.

In addition, it generates effective Majorana masses for neutrinos at the EW scale. : EW seesaw

No ad-hoc scales

Thus neutrino masses are obtained at tree level

$m_\nu \sim m_D^2/M_M = (Y_\nu H_2)^2/(k\,\nu_R) \sim (10^{-6}\,10^2)^2/10^3 = 10^{-11}$ GeV $= 10^{-2}$ eV

Gravitino as decaying dark matter

In models where R-parity is broken, the neutralino or the sneutrino with very short lifetimes **cannot be used as candidates for (annihilating) DM**

Nevertheless, the gravitino (**superWIMP**) can be a good (decaying) DM candidate and detectable

Although the gravitino also decays through the interaction gravitino-photon-photino due to the photino-neutrino mixing

$$\Gamma(\psi_{3/2} \to \gamma\nu) = \frac{1}{32\pi} |U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{M_{\rm P}{}^2} \,.$$

Takayama, Yamaguchi, 2000

its decay is supressed both by the Planck mass and the small R-parity breaking, thus the lifetime of the gravitino can be longer than the age of the Universe (~10^{17} s)

$$\tau_{3/2} = \Gamma^{-1}(\tilde{G} \to \gamma\nu) \simeq 8.3 \times 10^{26} \sec \times \left(\frac{m_{3/2}}{1\mathrm{GeV}}\right)^{-3} \left(\frac{|U_{\gamma\nu}|^2}{7 \times 10^{-13}}\right)^{-1} .$$

Since the gravitino decays into a photon and neutrino, the former produces a monochromatic line at energies equal to **$m_{3/2}/2$**

FERMI might in principle detect these gamma rays

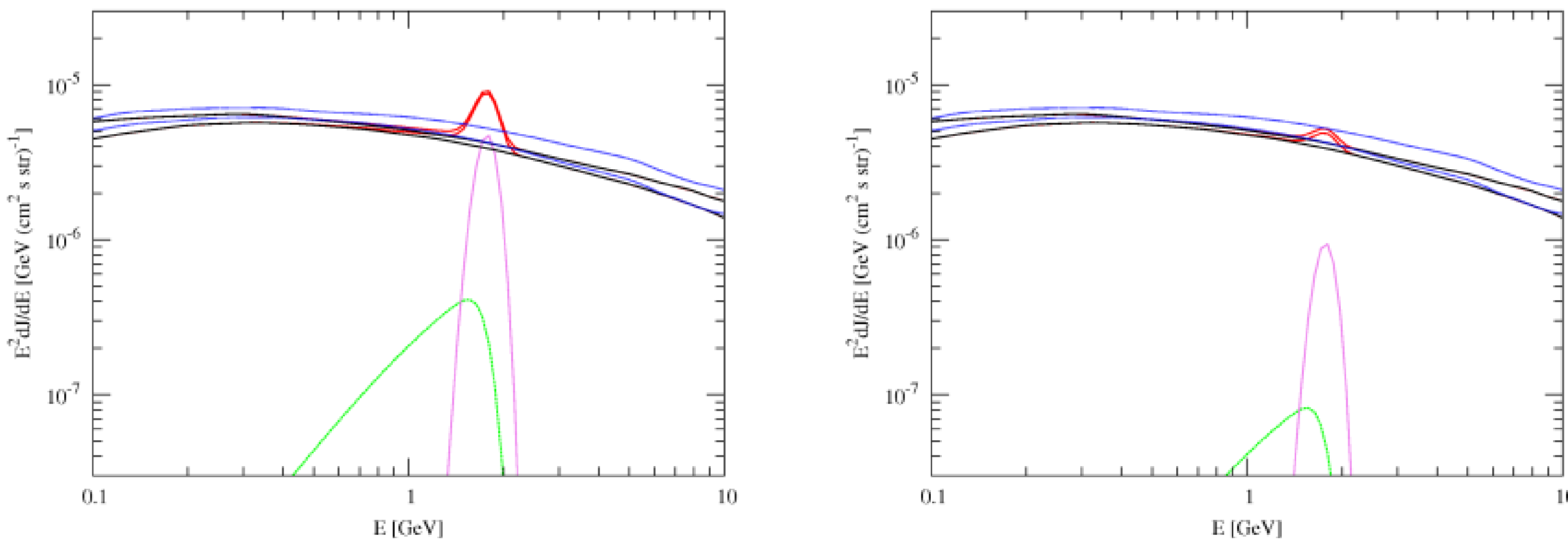
Buchmuller, Covi, Hamaguchi, Ibarra, Yanagida, 07
Bertone, Buchmuller, Covi, Ibarra, 07
Ibarra, Tran, 08
Ishiwata, Matsumoto, Moroi, 08

μνSSM

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c\right) - \epsilon_{ab}\lambda^i\,\hat{\nu}_i^c\,\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c\,,$$

Constraints on μνSSM gravitino DM analyzed in

Choi, López-Fogliani, C.M., Ruiz de Austri, 0906.3681
Gómez-Vargas, Fornasa, Zandanel, Cuesta, C.M., Prada, Yepes, 1110.3305

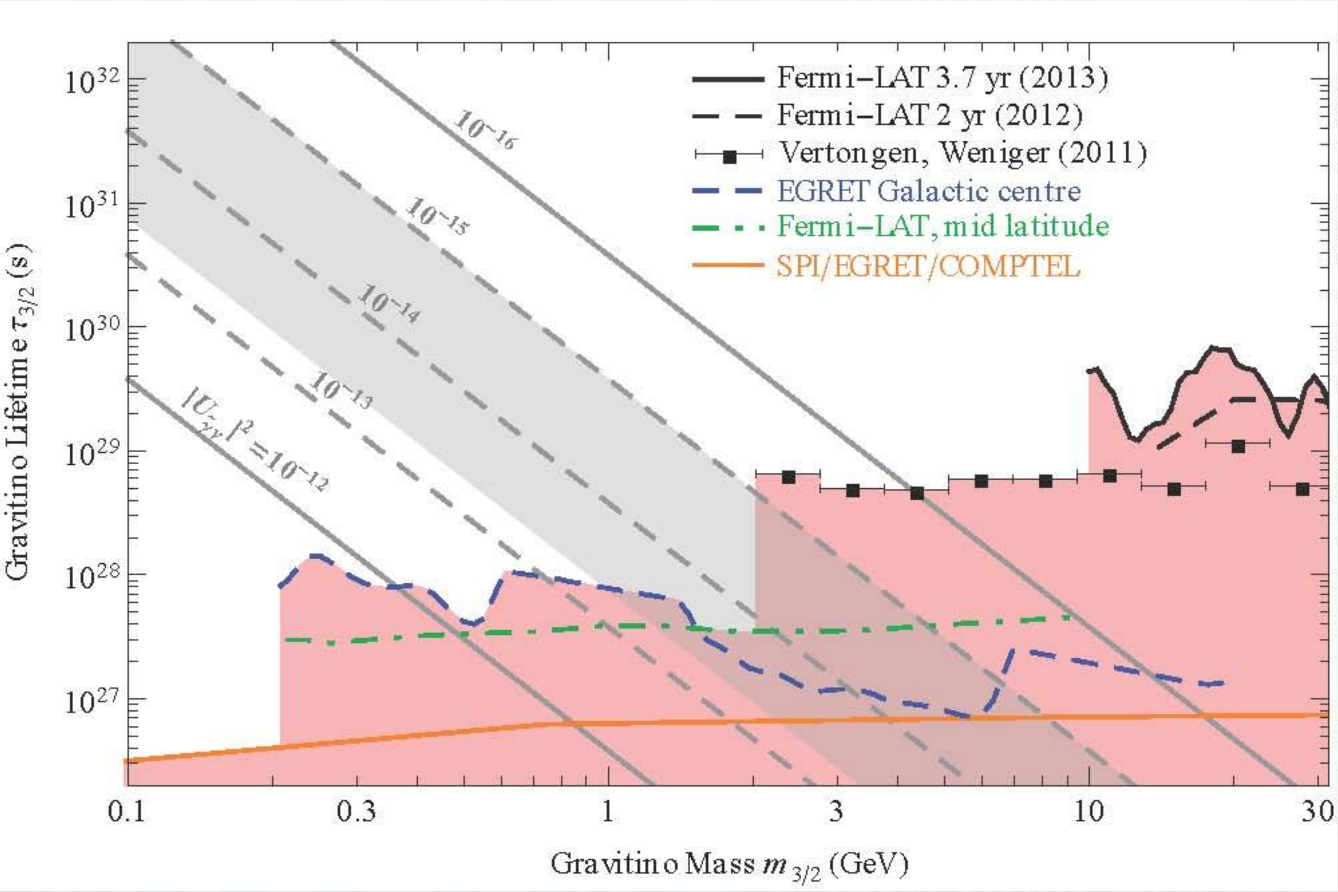


(a) (b)

Figure 3: Expected gamma-ray spectrum for an example of gravitino dark matter decay in the mid-latitude range ($10^\circ \le |b| \le 20^\circ$) in the $\mu\nu$SSM with $m_{3/2} = 3.5\,\text{GeV}$ and (a) $|U_{\tilde{\gamma}\nu}|^2 = 8.8 \times 10^{-15}$ corresponding to $\tau_{3/2} = 10^{27}$ s, (b) $|U_{\tilde{\gamma}\nu}|^2 = 1.7 \times 10^{-15}$ corresponding to $\tau_{3/2} = 5 \times 10^{27}$ s. The green dashed, magenta solid, and black solid lines correspond to the diffuse extragalactic gamma ray flux, the gamma-ray flux from the halo, and to the conventional background, respectively. The total gamma-ray flux is shown with red solid lines. The blue solid lines are explained in the note added in Sect. 6.

$$\tau_{3/2} \simeq 3.8 \times 10^{27}\ \mathrm{s} \left(\frac{|U_{\tilde{\gamma}\nu}|^2}{10^{-16}}\right)^{-1} \left(\frac{m_{3/2}}{10\,\mathrm{GeV}}\right)^{-3}$$

In the μνSSM: $U \sim g_1\ \nu/M_1 \sim 10^{-6} - 10^{-8}$



Values of the gravitino mass larger than 4 GeV are disfavoured by Fermi-LAT

Grefe, C.M., Weniger +
Gómez-Vargas, Albert, Bloom, Charles, Morselli, Mazziotta,… Fermi-LAT
in preparation an analysis for lower energies

CONCLUSIONS

- Evidence for the existence of Dark Matter

-is overwhelming: galaxies, clusters, filaments, CMB, structure formation, …

-about 85% of the matter of the Universe is dark

-is distributed with a universal profile (NFW), although the fine details are still under investigation: compression, substructures, …

- Particle candidates for Dark Matter

There are very interesting models of new physics:

MSSM, NMSSM, BRpV, $\mu\nu$SSM,...

-stable WIMPs like neutralino, sneutrino or *Kaluza-Klein*, *scalar DM, fermion DM*
decaying superWIMPs like gravitino or *axion*, ...

▪ Detection of the Dark Matter

-There are impressive experimental efforts by many groups around the world:

DAMA/LIBRA, CoGeNT, CRESST, CDMS, XENON,…
Fermi, PAMELA, AMS, …
IceCube, ANTARES,…

Thus the present experimental situation is very exciting

And, besides, the LHC is back soon

So, stay tuned !

THE END
DM
experiments
also
detection
project
groups
mass
MAGIC
candidates
group
searches
energy
collaboration
Spanish
FERMI
analysis
MULTIDARK
indirect
direct
neutralino
important
data
new
different
models
telescopes
matter
detector
Milestone
WIMPs
WIMP
European
experimental
support
Although
field
first
members
LSP
future
AUGER
example
particles
light
neutrinos
already
CTA
Matter
observations
promote
good
interesting
analyses
case
flux
like
made
proposed
detected
sensitivity
GeV
decay
Physics
particular
present
years
dark
halo
study
formation
ANAIS
de
number
Universe
particle
provide
space
structure
large
way
ANTARES
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search
physics
detectors
signal
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work
see
existing
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high
now
e.g
IFAE
candidate
context
DDM
SUSY
targets
distribution
Spain
annihilation
order
theoretical
keV
still
well
Dark
KM3NeT
interaction
model
using
halos
design
proposal
Astroparticle
crucial
expected
density
may
around
due
galactic
role
etc
neutrino
experiment
possible
UAM/IFT
parameter
gravitino
SHDM
range
working
telescope
masses
scientific
might
simulations
one
standard
sources
produced
research
studies
gamma-ray