Dark Matter Searches and Models

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CSIC
Consejo Superior de Investigaciones Científicas

MultiDark
Multimessenger Approach for Dark Matter Detection

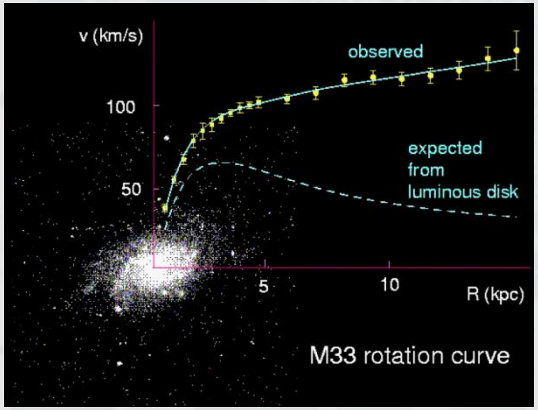
RICAP 2011, Roma, 25-27 May

EVIDENCES

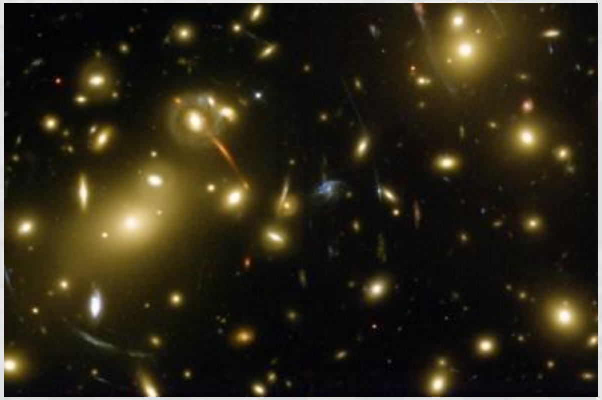
- In 1933, the astronomer Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies:

- Since then, many other evidences:

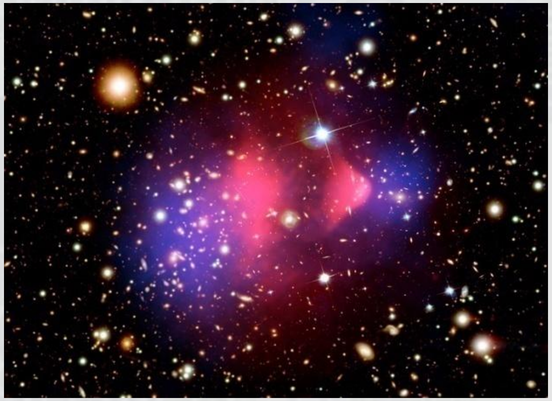
Rotation curves of galaxies



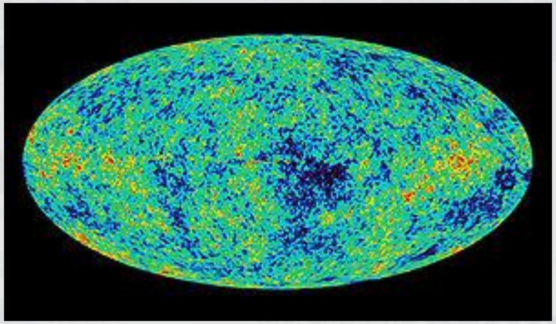
Gravitational lensing



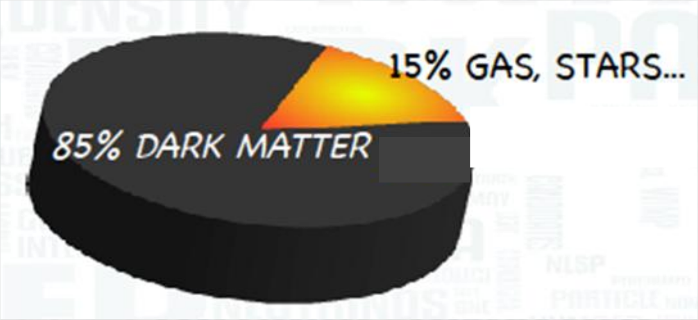
Bullet cluster



Estructure formation as deduced from CMB



Data by WMPA imply:



$\Omega_b h^2 \approx 0.02$

$\Omega_{DM} h^2 \approx 0.1$

PARTICLE CANDIDATES

What particle candidates do we have for dark matter ?

Within the Standard Model of Particle Physics we are only left with the **neutrino** ν

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

In addition, this kind of dark matter cannot reproduce correctly the observed structure in the Universe; galaxies would be too young

Thus the only non-baryonic candidate WHICH IS KNOWN TO EXIST, the neutrino, is excluded

This is a clear indication that we need to go

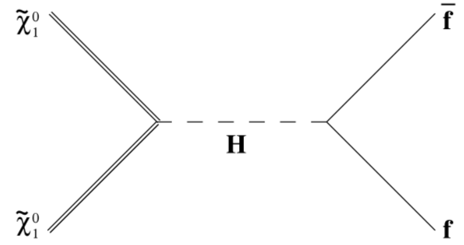
beyond the standard model of particle physics

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 dark matter $\Omega_{DM} h^2 \approx 0.1$

Actually, a particle with weak interactions and a mass ≈ 100 GeV, the so called WIMP (Weakly Interacting Massive Particle), is able to reproduce this number

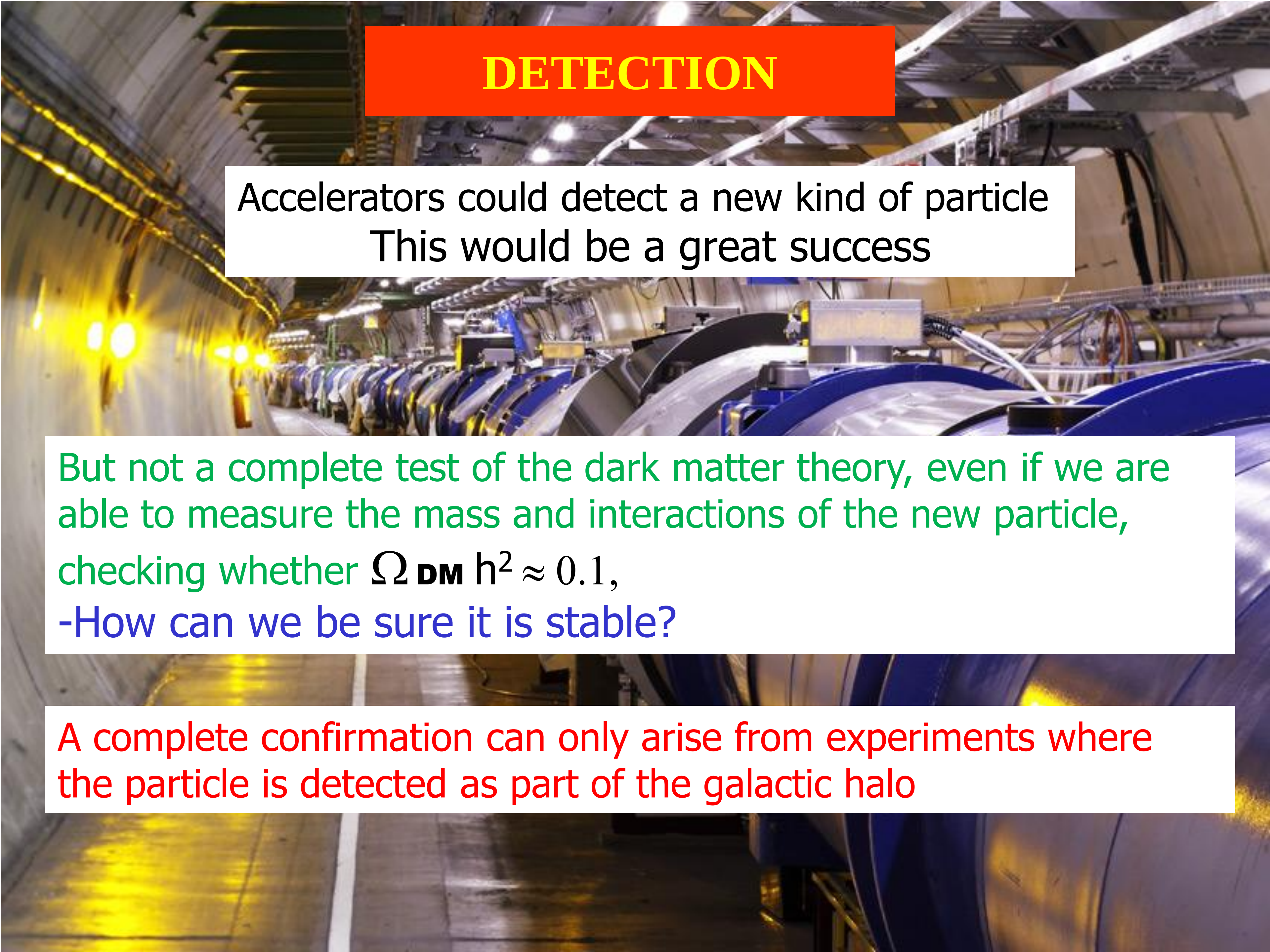
In the early Universe, at some temperature the annihilation rate of dark matter particles dropped below the expansion rate



and their density has been the same since then

$$\Omega_{WIMP} h^2 \propto \frac{1}{\sigma_{annihilation}} \approx 0.1$$

✸ A stable and neutral WIMP is a good candidate for dark matter



DETECTION

Accelerators could detect a new kind of particle
This would be a great success

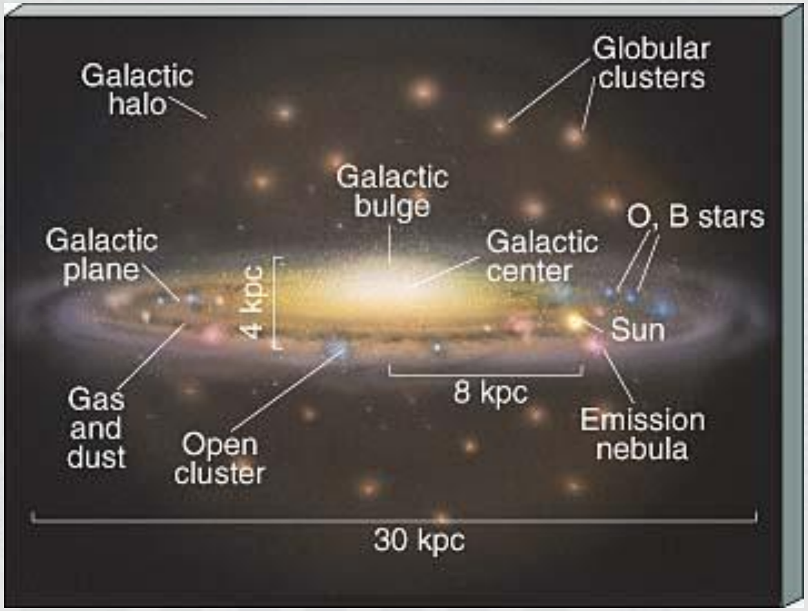
But not a complete test of the dark matter theory, even if we are able to measure the mass and interactions of the new particle, checking whether $\Omega_{DM} h^2 \approx 0.1$,
-How can we be sure it is stable?

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

DIRECT DETECTION

Can we detect the dark matter 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 our Galaxy:



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

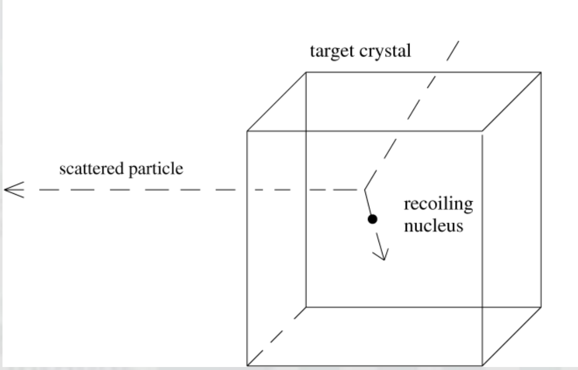
- The velocity dispersion of DM particles is $\mathbf{v_0 \sim 220\ km/s}$

For $\mathbf{m_{DM} \sim 100}$ GeV one obtains

$$J \sim \rho_0 v_0 / m_{DM} \sim 60{,}000 \text{ particles/cm}^2\text{ s}$$

and therefore direct detection through elastic scattering with nuclei in a detector is in principle possible

Goodman, Witten, 85
Wasserman, 86

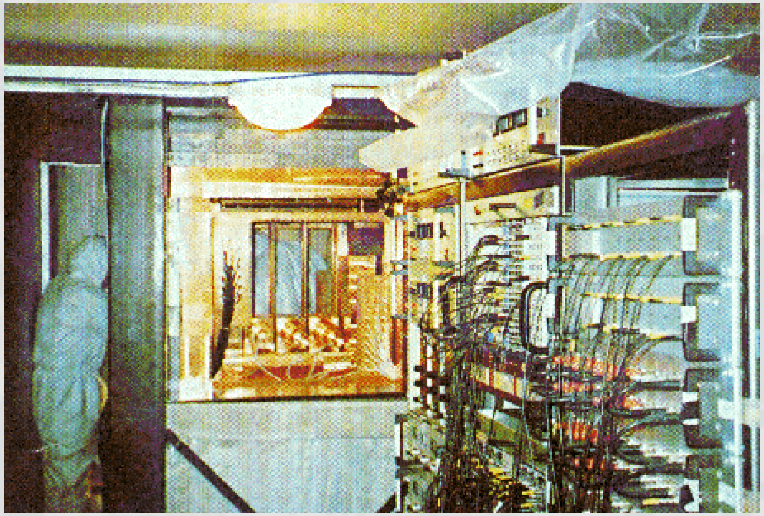


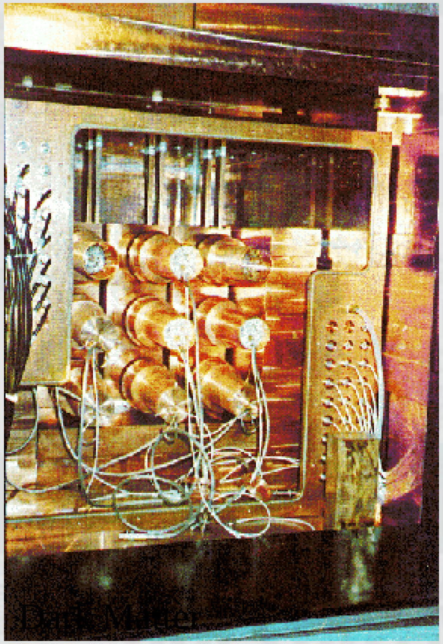
For $\sigma_{\text{WIMP-nucleon}} \approx 10^{-8}$-$10^{-6}$ pb a material with nuclei composed of about 100 nucleons, i.e. $m_N \sim 100$ GeV

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

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

energy produced by the recoiling nucleus can be measured through ionization, scintillation or heat $\approx$ **few** keV



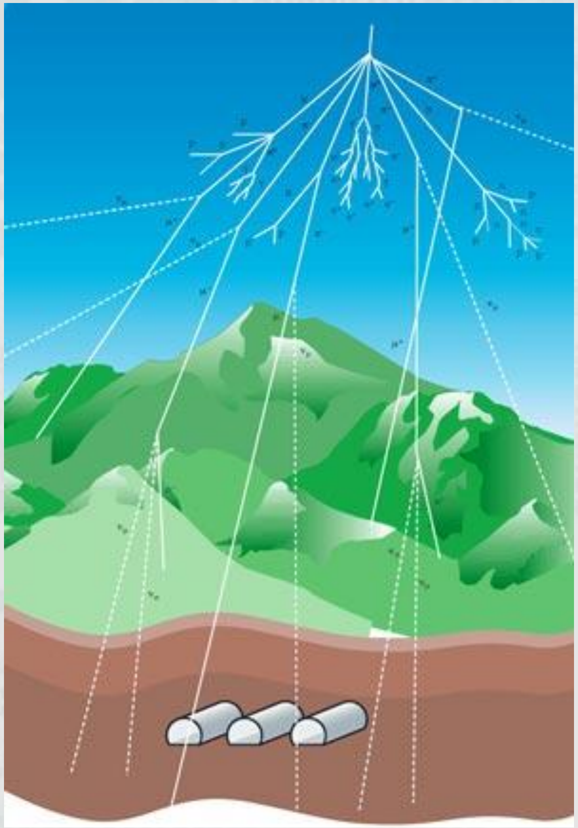


DAMA experiment
100 kg NaI crystal scintillators

The background problem

WIMPs are expected to produce **10^{-2} -1** nuclear recoils/kg day with energies of few keV

But cosmic rays occur at >100 events/kg day with energies ~ keV-MeV and generate 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, the environmental radioactivity generates also neutrons, and photons and electrons, and these produce electron recoils

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

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

In any case, always a small expected rate of misidentified background events remains …everything above background might be a signal

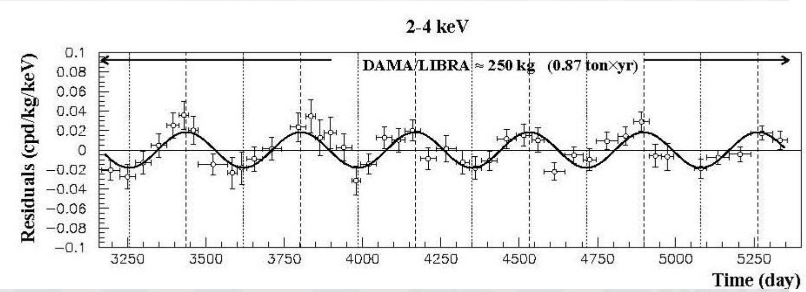
Nowadays there are two types of experiments:

✸ Relying on reduction and interpretation of the background

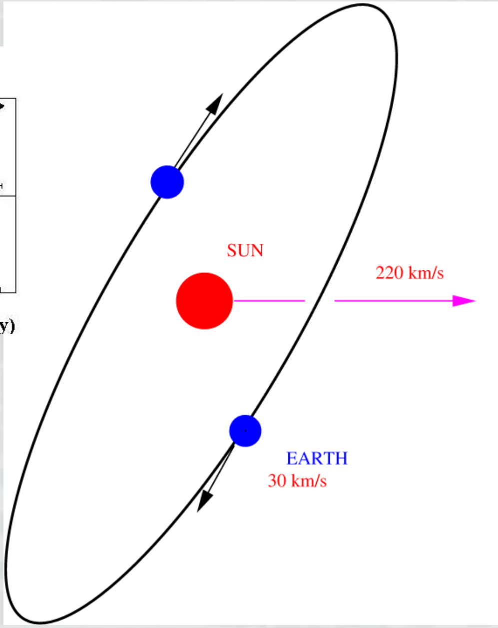
CDMS-II 19 Ge (~ 230 g each) and 11 Si (~ 100 g each) detectors located at Soudan (2090 mwe) measure heat and ionization

XENON 100 62 kg liquid Xenon located at Gran Sasso (~ 3600 mwe) measures scintillation and ionization

EDELWEISS, CoGeNT, ...



✸ Annual modulation



DAMA/LIBRA 250 kg NaI crystal scintillators located at Gran Sasso

do not strongly discriminate between WIMP scatters and background events

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 — exposure 18.48 kg x day
1002.4703 — claims excesses of events over the expected background

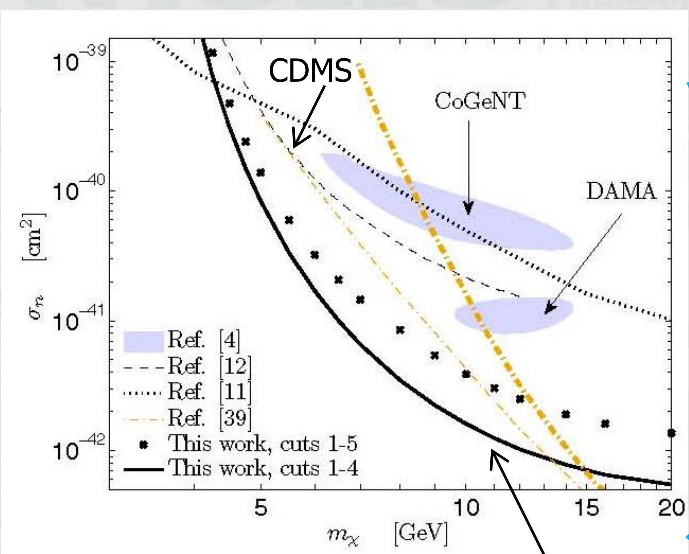
CRESST (?) talk July 2010 " " "

CoGeNT (?) talk April 2011, after 15 months of operations claims a possible modulation

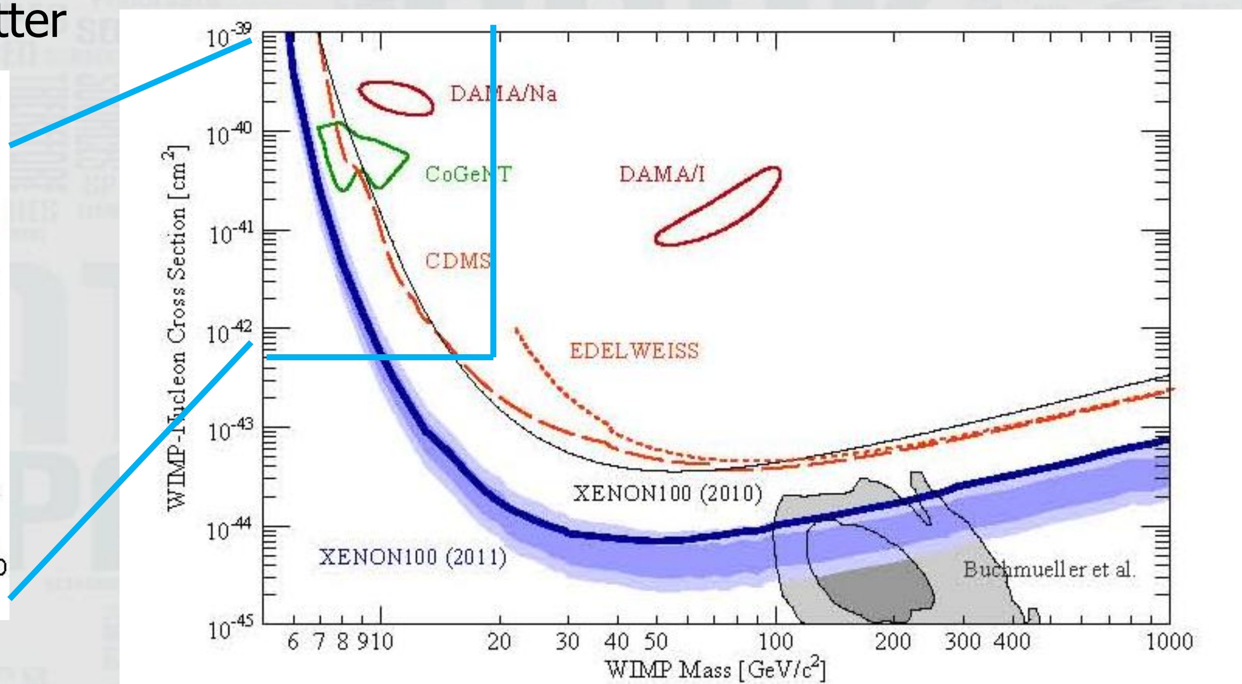
On the contrary, CDMS II 0912.3592 612 kg x day, and energies > 10 keV
1011.2482 241 kg x day, low-energy reanalysis

XENON 100 1104.2549 1471 kg x day

found no evidence for dark matter

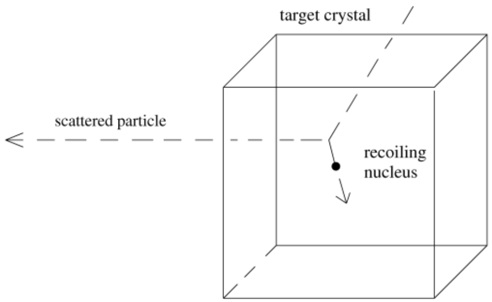


XENON 10 1104.3088

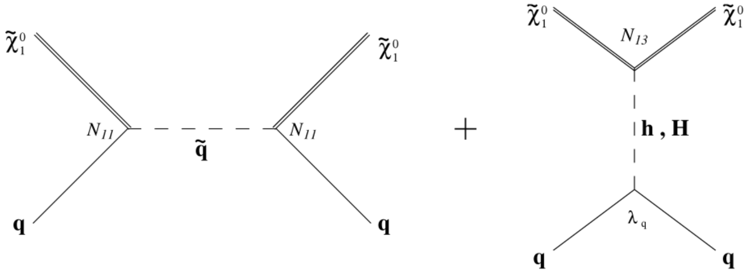


Neutralino is a WIMP and a good candidate for dark matter

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

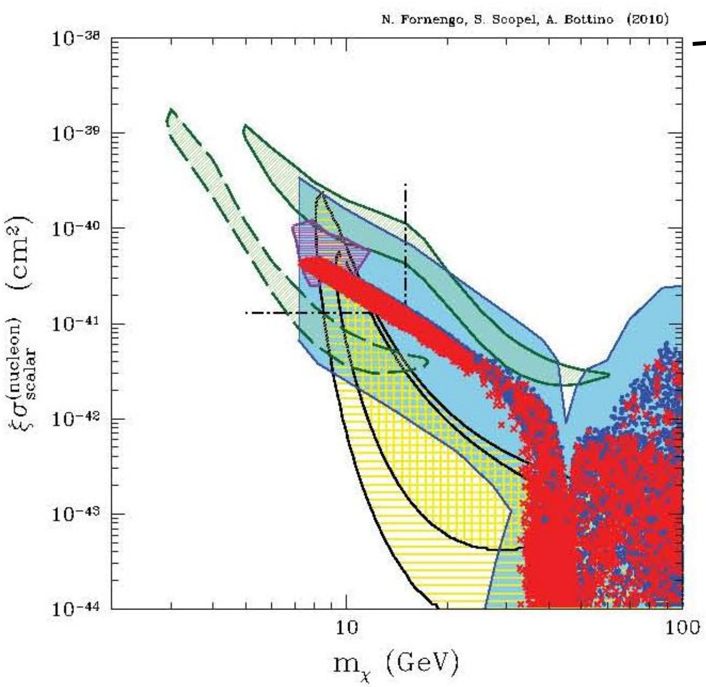


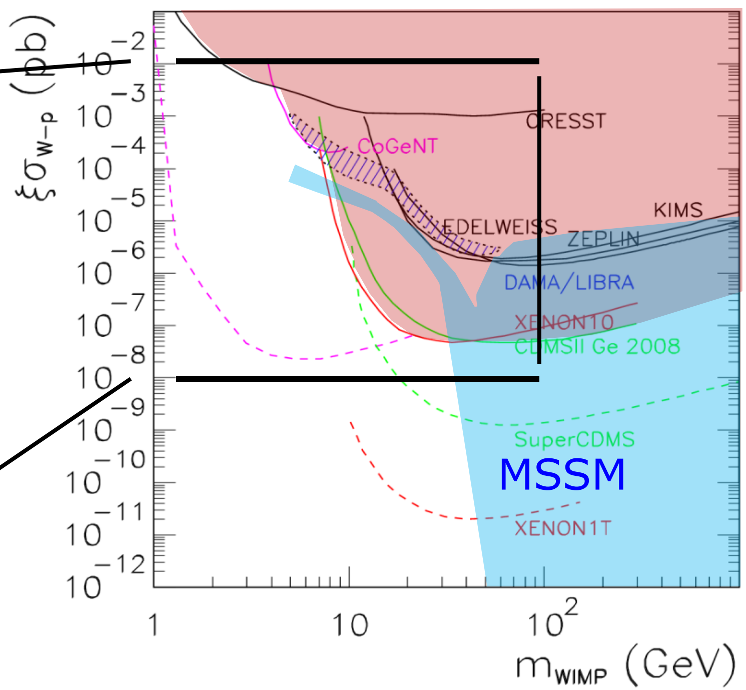
Supersymmetry



In the general SUSY parameter space (effMSSM), M_a , m_α , A_α , $\tan\beta$, one obtains:

Large cross section with correct relic density for a wide range of masses





Very light **Bino-like** neutralinos with masses ~10 GeV

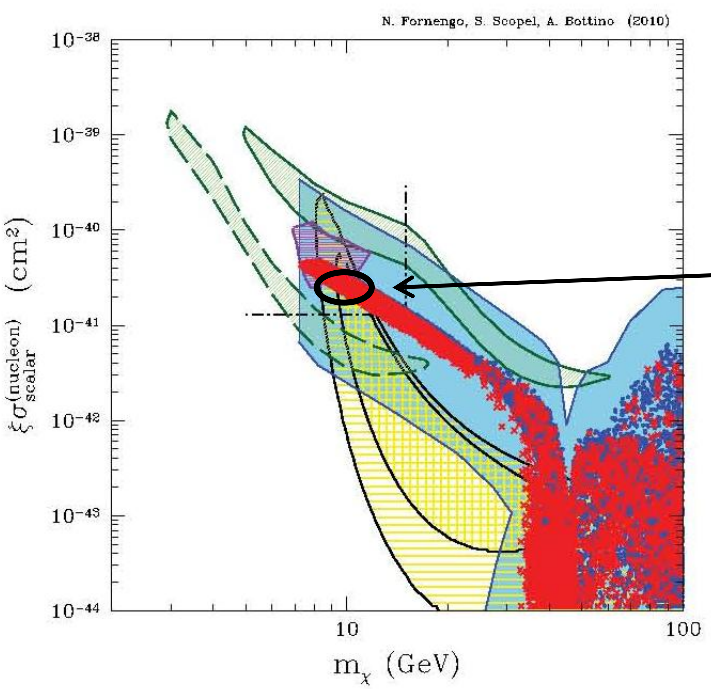
(Bottino, Donato, Fornengo, Scopel '02-'08)

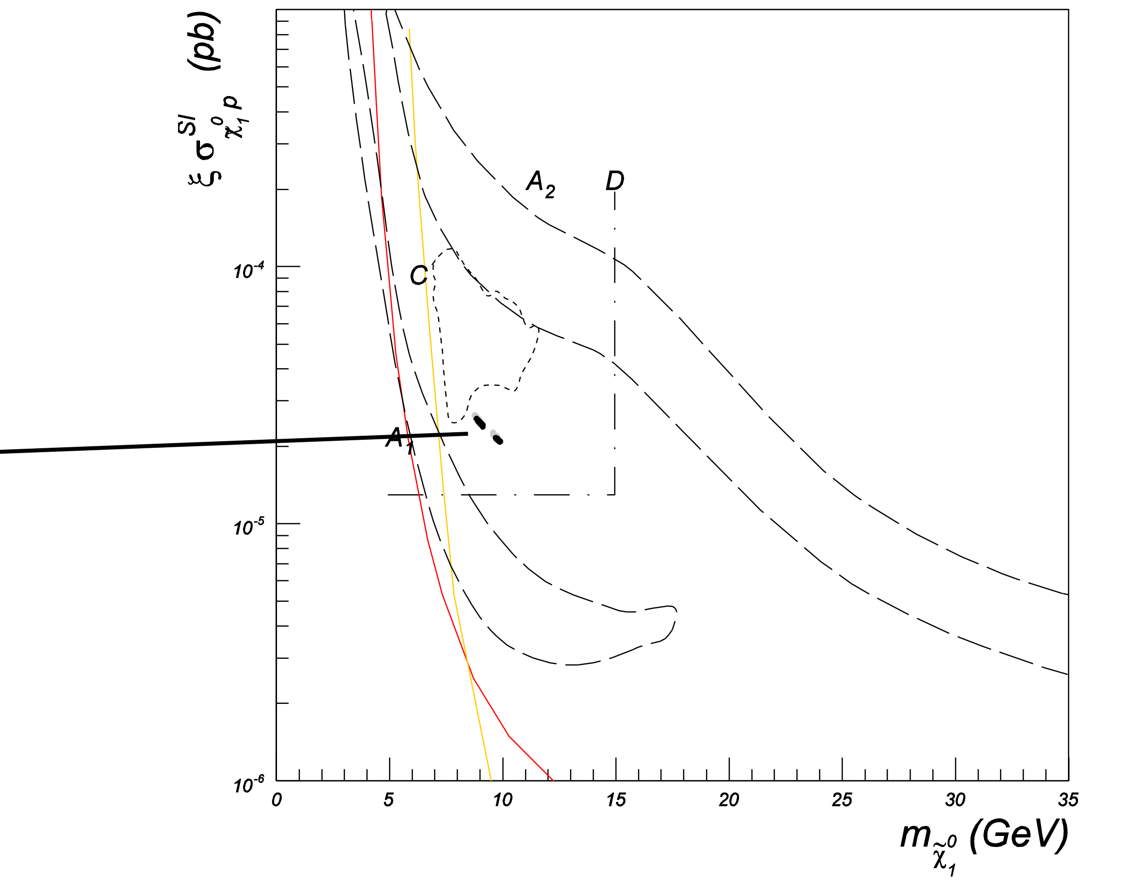
Very light neutralino dark matter in supergravity scenarios for the MSSM

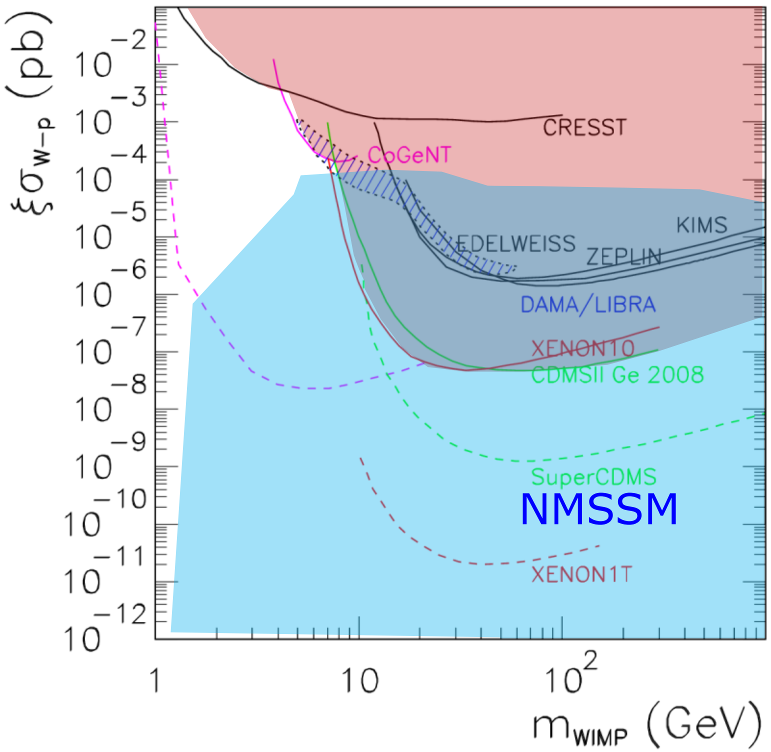
Cerdeño, Fornengo, C.M., Peiró, Scopel, in preparation

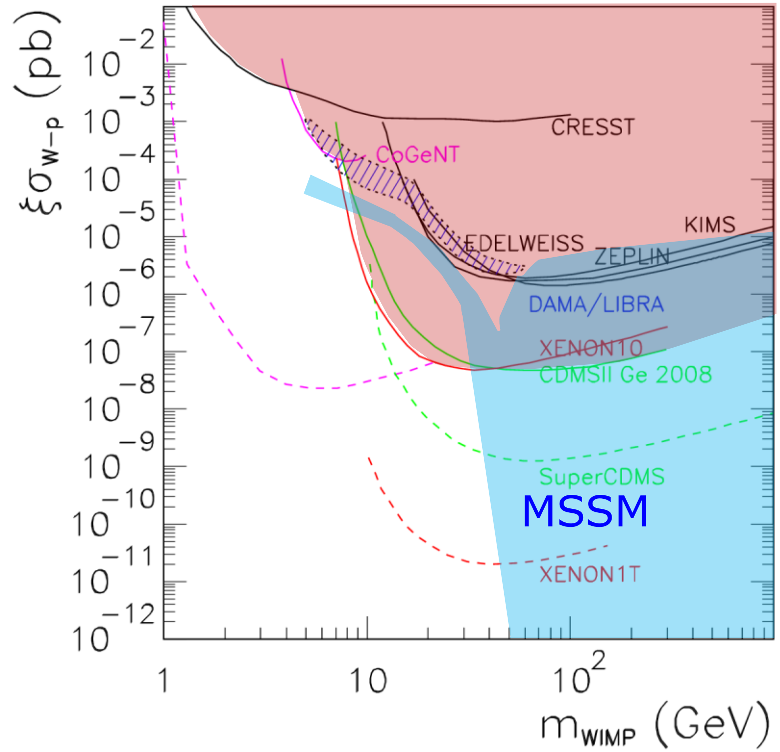
Imposing:
- Parameters defined at the GUT scale
- RGEs equations
- fulfil all experimental constraints

With non-universal soft terms, $M_1 < M_{2,3}/10$, … it is possible to get masses around 8-10 GeV









$\mu H_1 H_2 \rightarrow \lambda N H_1 H_2$

The detection cross section can be larger (through the exchange of light Higgses) (Cerdeño, Gabrielli, López-Fogliani, C.M. Teixeira, ´07)

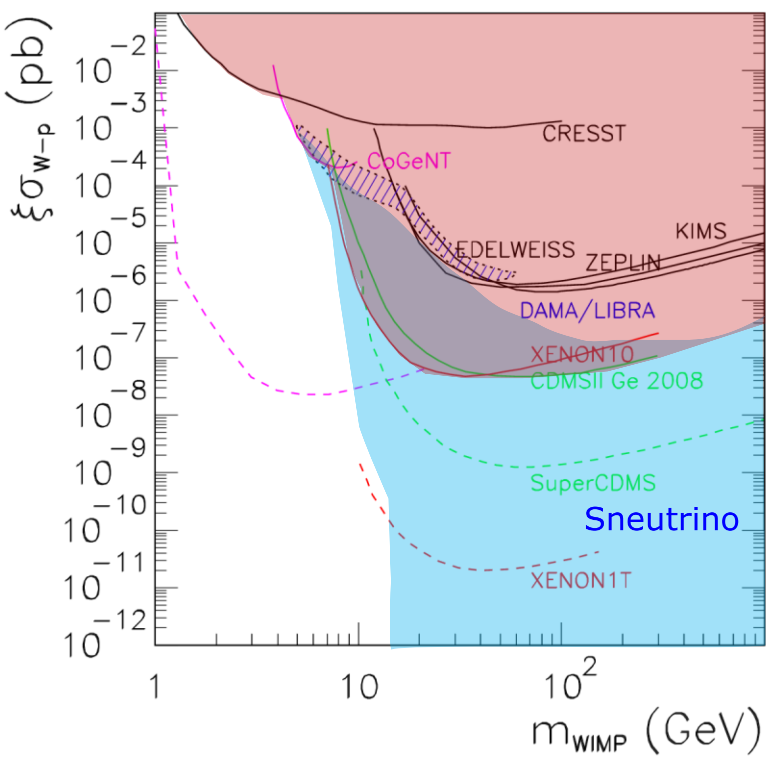
Very light **Bino-singlino** neutralinos are possible (Gunion, Hooper, McElrath '05)

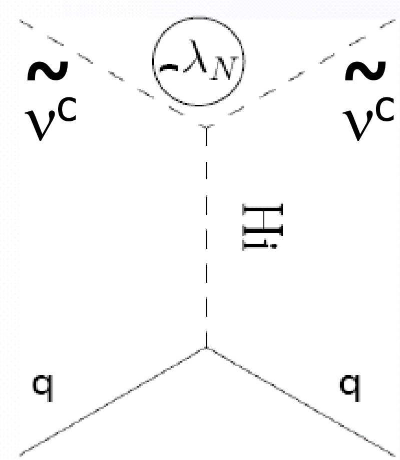
And their detection cross section significantly differs from that in the MSSM (CoGeNT '08)

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

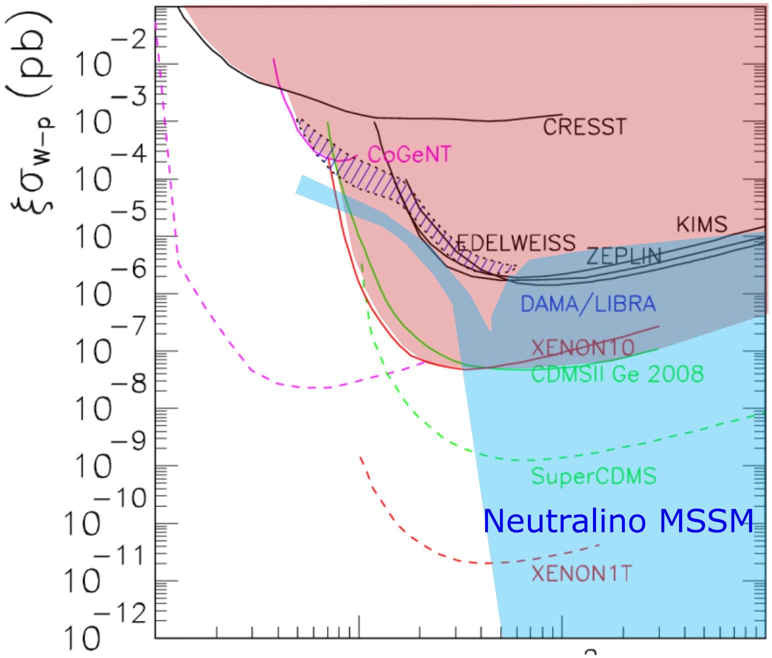
$$\lambda\ N\ H_1\ H_2 + \lambda_N\ N\ \nu^c\ \nu^c$$

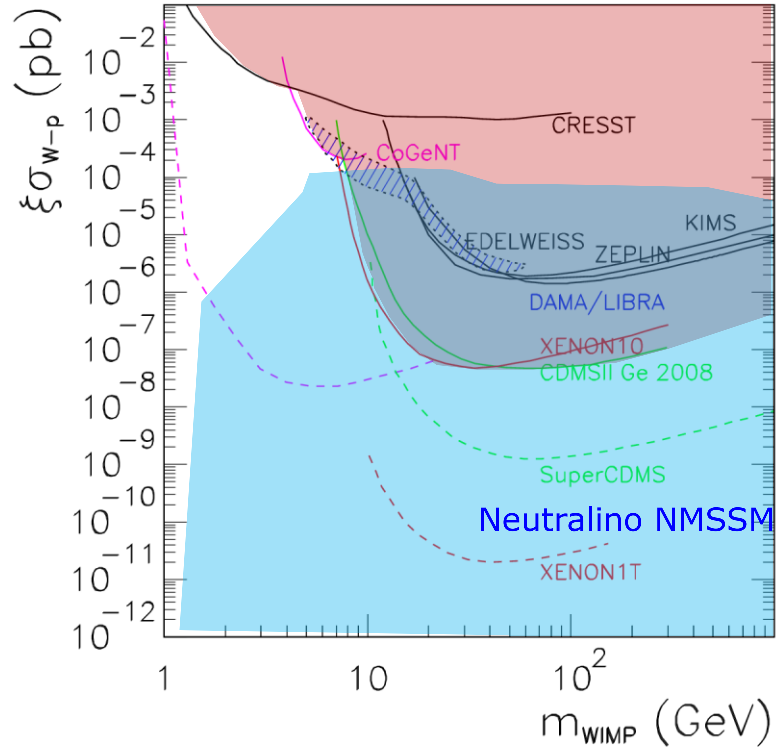
Whereas in the MSSM a LSP purely right-handed sneutrino implies scattering cross section too small, relic density too large, here the N provides efficient interactions of sneutrino too

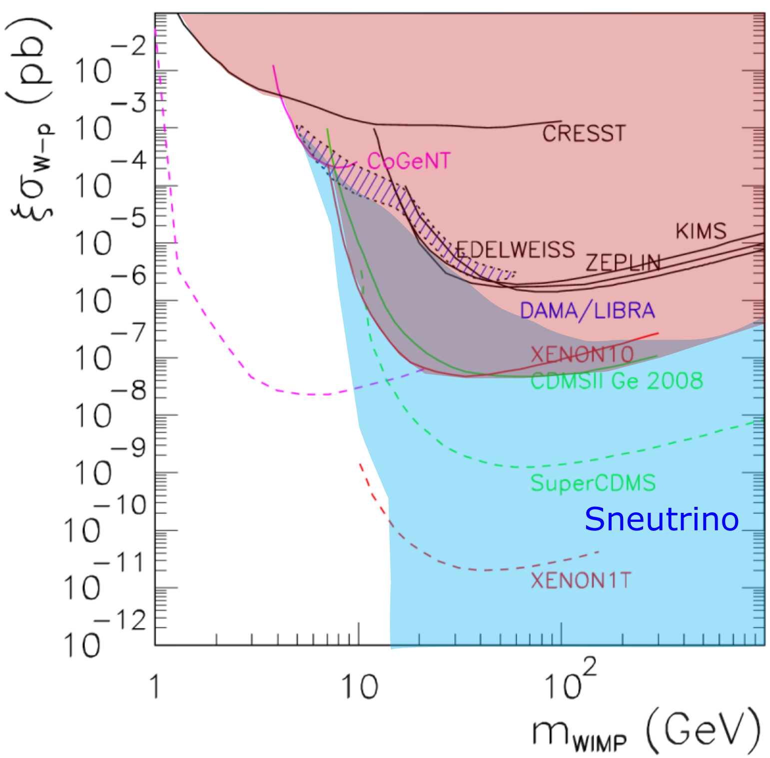




- Viable, accessible and not yet excluded (Cerdeño, C.M., Seto '08)
- Light sneutrinos are viable and distinct from MSSM neutralinos (Cerdeño, Seto '09)

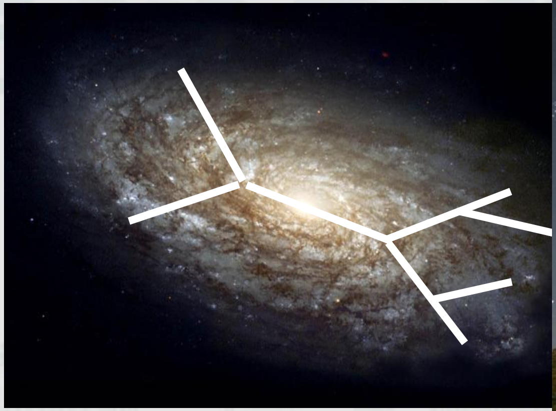

$\xi\sigma_{W-p}$ (pb)
CRESST
CoGeNT
EDELWEISS
KIMS
ZEPLIN
DAMA/LIBRA
XENON10
CDMSII Ge 2008
SuperCDMS
Neutralino MSSM
XENON1T

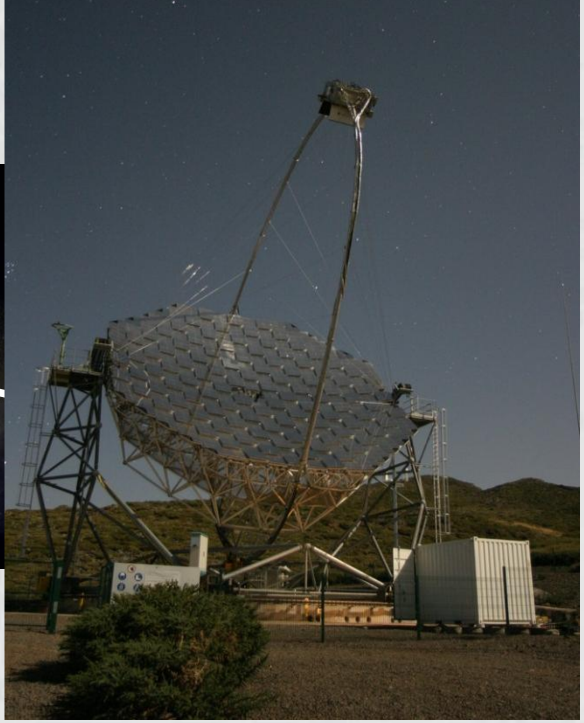

$\xi\sigma_{W-p}$ (pb)
CRESST
CoGeNT
EDELWEISS
KIMS
ZEPLIN
DAMA/LIBRA
XENON10
CDMSII Ge 2008
SuperCDMS
Neutralino NMSSM
XENON1T
m_{WIMP} (GeV)


$\xi\sigma_{W-p}$ (pb)
CRESST
CoGeNT
EDELWEISS
KIMS
ZEPLIN
DAMA/LIBRA
XENON10
CDMSII Ge 2008
SuperCDMS
Sneutrino
XENON1T
m_{WIMP} (GeV)

INDIRECT DETECTION

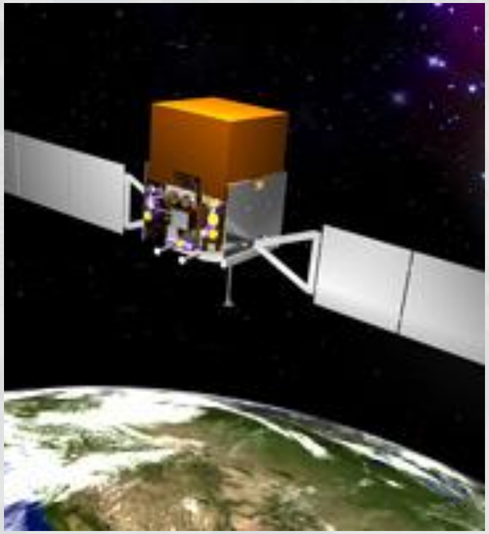
- Annihilation of dark matter particles in the galactic halo will produce gamma rays, antimatter



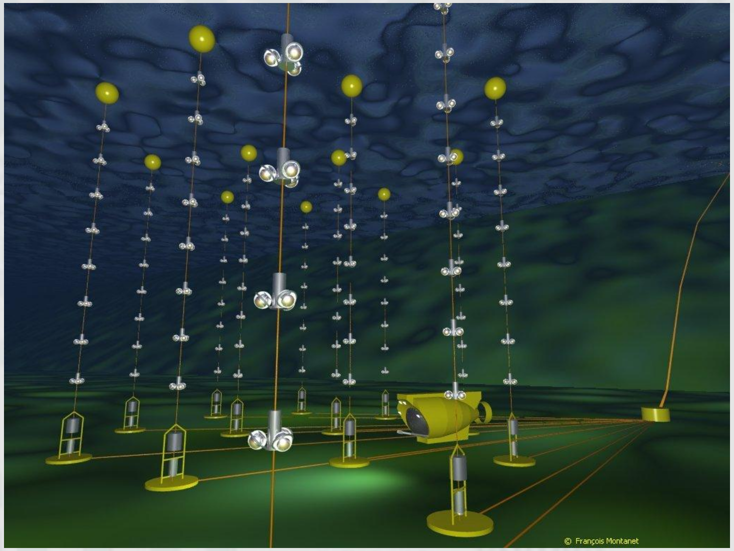


and these can be measured in space–based detectors:
Fermi (gammas),
PAMELA, AMS (antimatter)

or in atmospheric telescopes:
MAGIC, HESS, VERITAS,
CANGAROO (gammas)

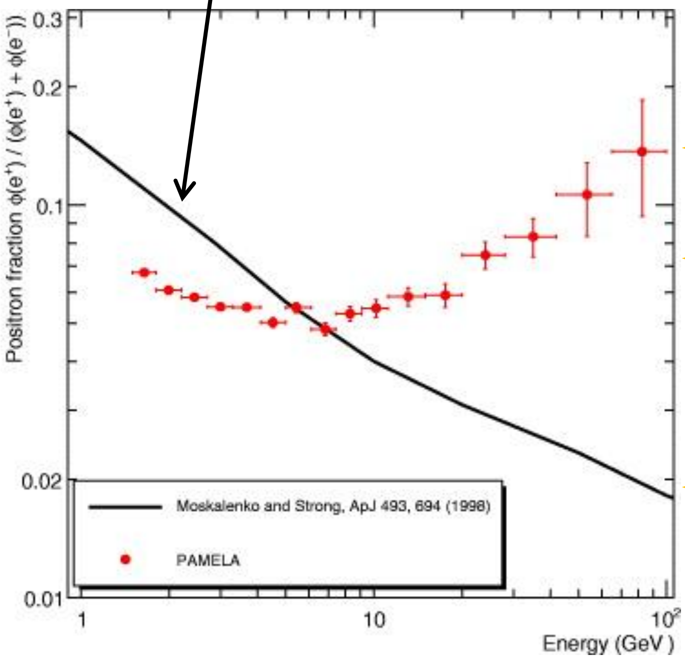


- Also neutrino telescopes like ANTARES or ICECUBE can be used for DM detection



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

background model of secondary particles produced by the interaction of CR with the ISM



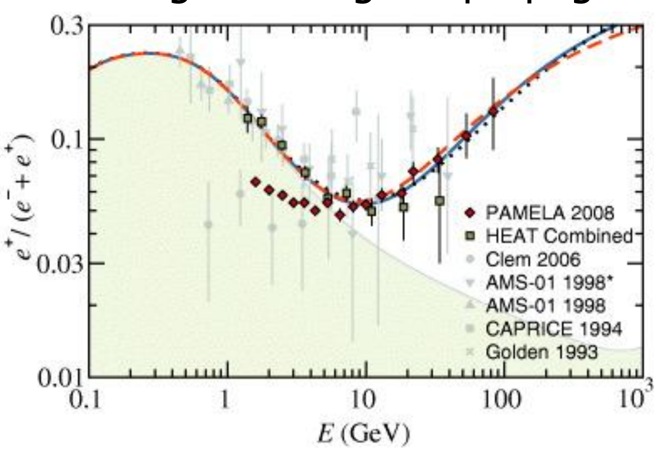
problems with the dark matter explanation:

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

$$\Omega h^2 \sim \frac{3\times10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma v>} << 0.1$$

- 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

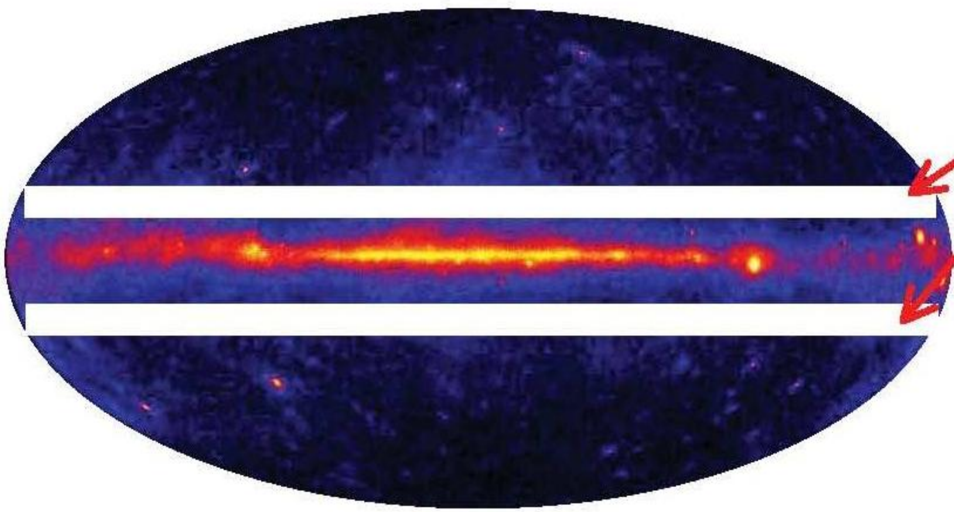


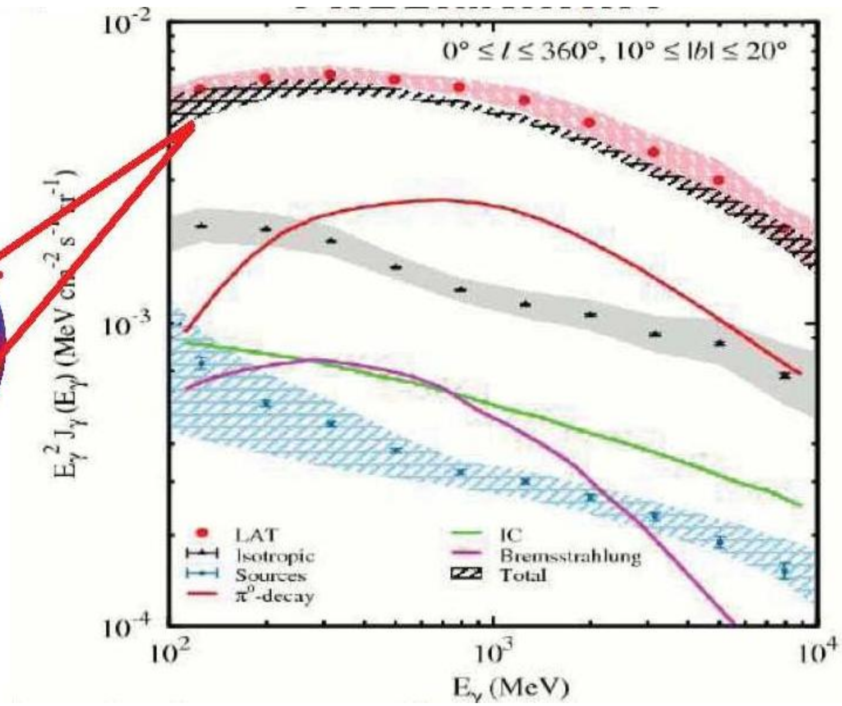
Possible astrophysical explanation:

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 dark matter annihilations

But 5-month measurements reported by Fermi-LAT 0912.0973
show no GeV excess **at mid-latitude**





An interesting possibility could be to search for **DM in the Galactic Center**

e.g. **NFW** has for small distances from the galactic center $\rho(r) \sim \rho_0/r$

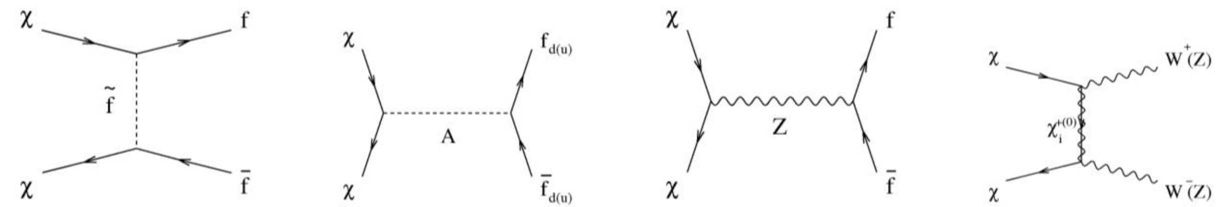
$$\phi \sim \left(\int_{\text{line of sight}} \rho^2\, dr\right) \sigma_{\text{ann}} v\, / m^2$$

Astrophysics

Particle physics

Particle physics is well under control

e.g. in the MSSM



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

However, there are important astrophysical uncertainties

NFW including baryons has $\rho(r) \sim \rho_0/r^{1.45}$, producing ϕ **x 100**

Prada, Klypin, Flix, Martinez, Simonneau, 04

Mambrini, C.M., Nezri, Prada, 05

No Fermi publication about the Galactic Center yet However…

Hooper, Goodenough, Dark matter annihilation in the galactic center as seen by the Fermi gamma ray space telescope, 1010.2752

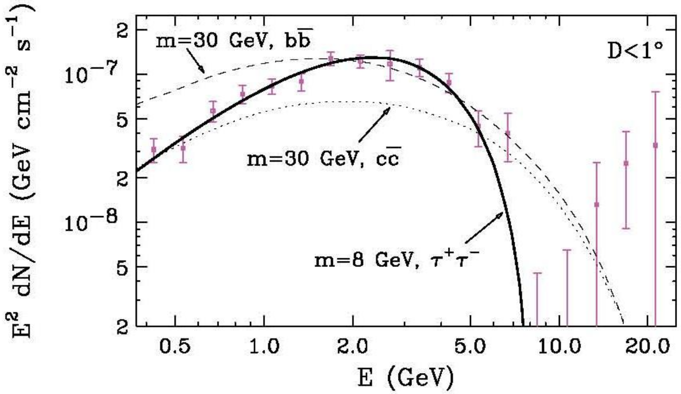


FIG. 15: The spectrum of the excess emission in the region within 1° of the Galaxy's dynamical center (by excess, we mean that emission not associated with the disk, bulge, or resolved point sources). The spectrum shown has been corrected to account for the finite point spread function of FGST. We also compare the observed spectrum with that predicted from annihilating dark matter (solid, dashed and dotted lines). The case of an approximately 8 GeV particle annihilating to tau leptons provides a particularly good fit to the data.

Buckley, Hooper, Tait, Particle physics implications for CoGeNT, DAMA, and Fermi, 1011.1499

The problem with this kind of claims is that the conventional astrophysics in the galactic center is not well understood. Perhaps an excess may be due to the modeling of the diffuse emission, unresolved sources, etc.

e.g.: Abazajian, Consistency with a millisecond pulsar population in the central stellar cluster, 1011.4275

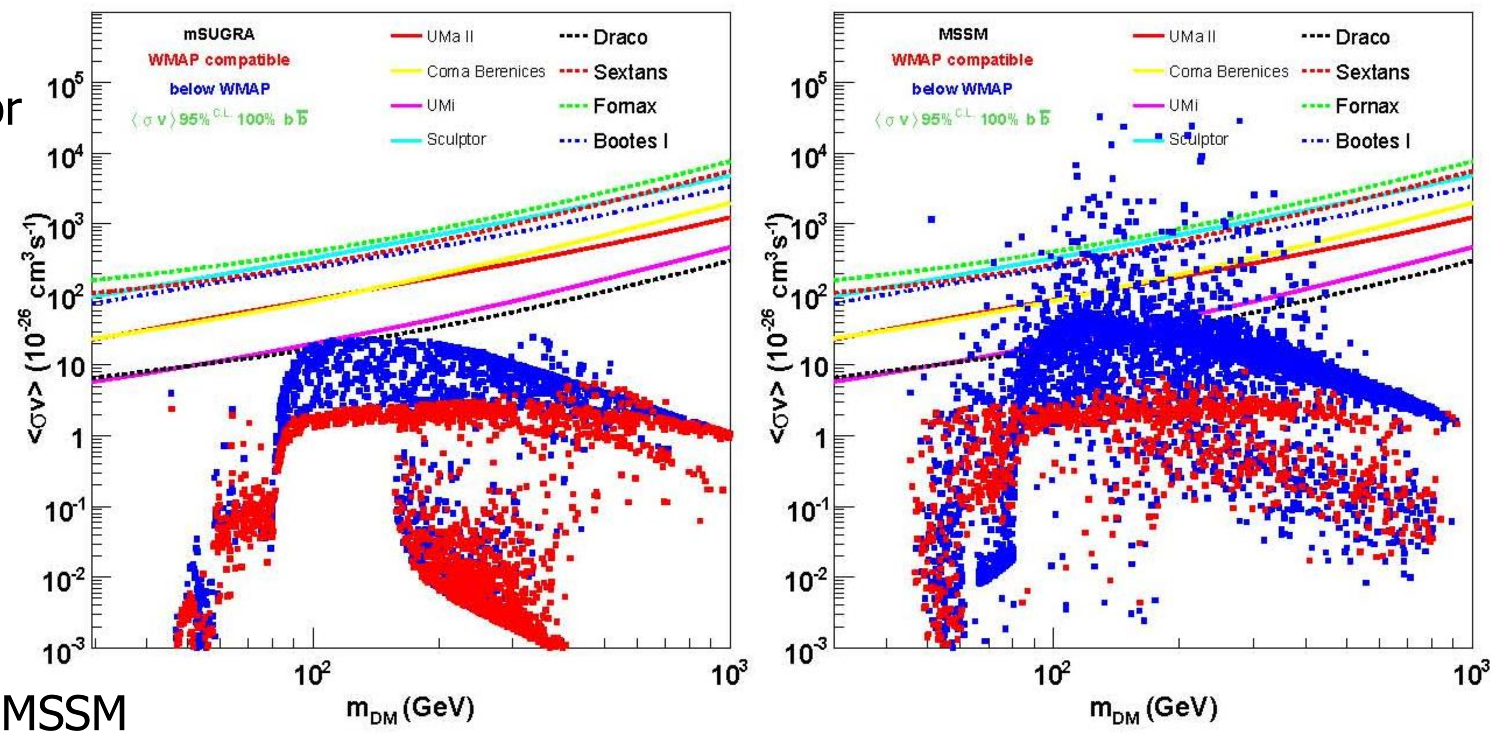
Local Group **dwarf spheroidal galaxies** (dSph) are attractive targets because:

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

But 11-month measurements of 14 dSphs reported by Fermi-LAT show no excess above 100 MeV 1001.4531

Using a NFW density profile for each galaxy

one can constrain dark matter particle properties



Neutralino in mSUGRA and MSSM

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

$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \rho^2(l)\mathrm{d}l(\psi).$$

$$J \simeq \frac{1}{D^2}\int_{\mathrm{Vol}} r^2\rho^2(r)\mathrm{d}r$$

But 11-month measurements of
AWM 7, Fornax, M49, NGC 4636, Centaurus, and Coma Clusters
reported by Fermi-LAT show no excess 1002.2239

The constraints on particle models are generally weaker
than those found for nearby dSphs

Although they improve significantly those constraints obtained
also from observations of clusters by IACTs:
-Coma by HESS
-Perseus by MAGIC

Gravitino as decaying dark matter

neutralino, sneutrino, …, but also the gravitino might be a good candidate and detectable

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

Nevertheless, **the gravitino** (superWIMP) can be a good candidate

Takayama, Yamaguchi, 2000

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

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)

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

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

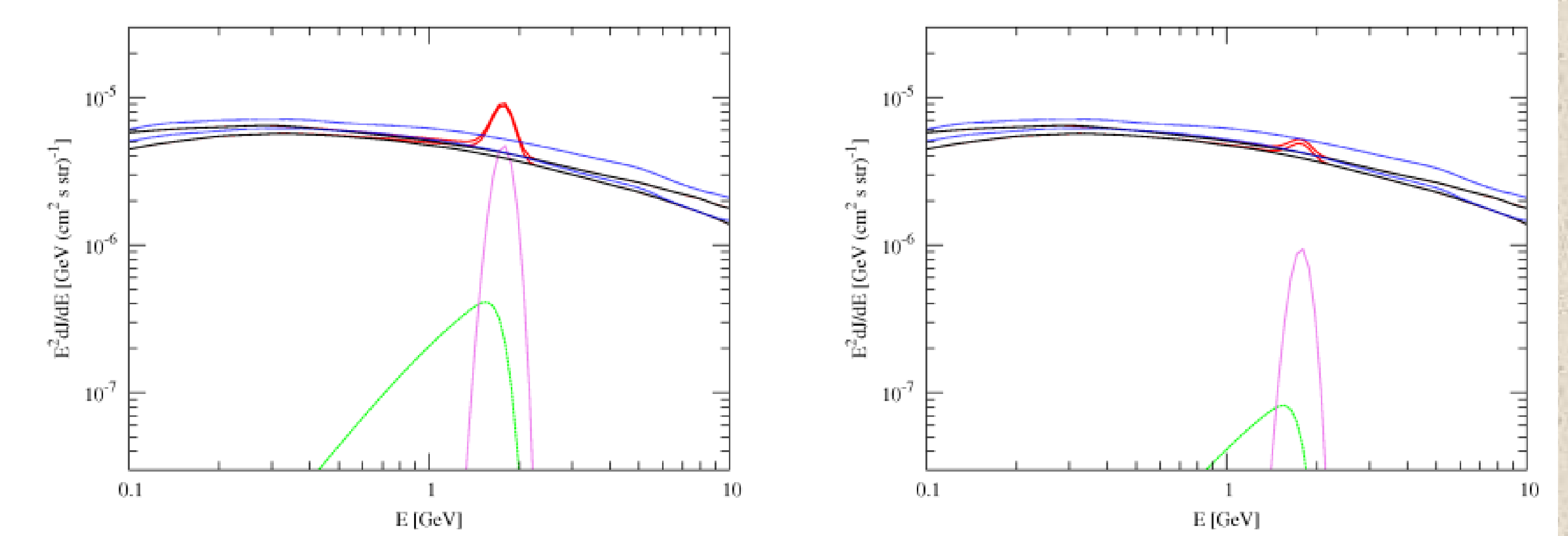
μνSSM

López-Fogliani, C.M, 05

$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat H_2^b\,\hat Q_i^a\,\hat u_j^c + Y_d^{ij}\,\hat H_1^a\,\hat Q_i^b\,\hat d_j^c + Y_e^{ij}\,\hat H_1^a\,\hat L_i^b\,\hat e_j^c + Y_\nu^{ij}\,\hat H_2^b\,\hat L_i^a\,\hat \nu_j^c\right) - \epsilon_{ab}\lambda^i\,\hat\nu_i^c\,\hat H_1^a \hat H_2^b + \frac{1}{3}\kappa^{ijk}\hat\nu_i^c\hat\nu_j^c\hat\nu_k^c\,,$$

Choi, López-Fogliani, C. M., Ruiz de Austri, 09

Constraints from mid-latitude

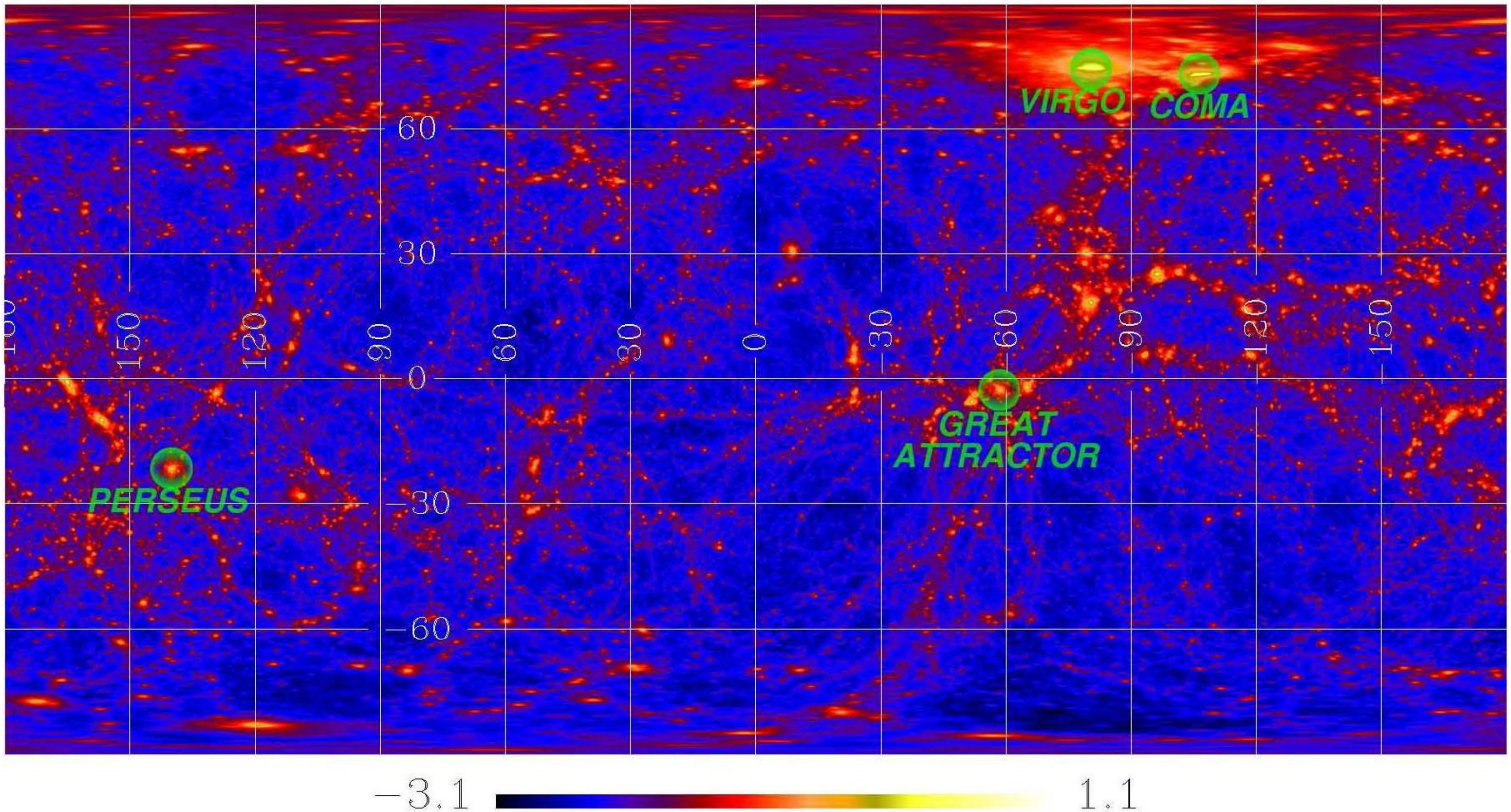


Values of the gravitino mass larger than 10 GeV are disfavoured,
as well as lifetimes smaller than about (3-5) x 10^{27} s.

Gravitino dark matter detection in **nearby extragalactic structures**

Strategy: 1-obtain the dark matter distribution from a constrained N-body simulation from the CLUES project

CLUES
Constrained Local UniversE Simulations



Cuesta et al., 2010

2-obtain the flux multiplying the values in the map by the particle physics factor, and use this as an input for the Fermi-LAT observation simulations

The case of gravitino dark matter in the $\mu\nu$SSM is under study

Gomez Vargas, Fornasa, Zandanel, Cuesta, C.M., Prada, Yepes, in preparation

see Gomez Vargas talk

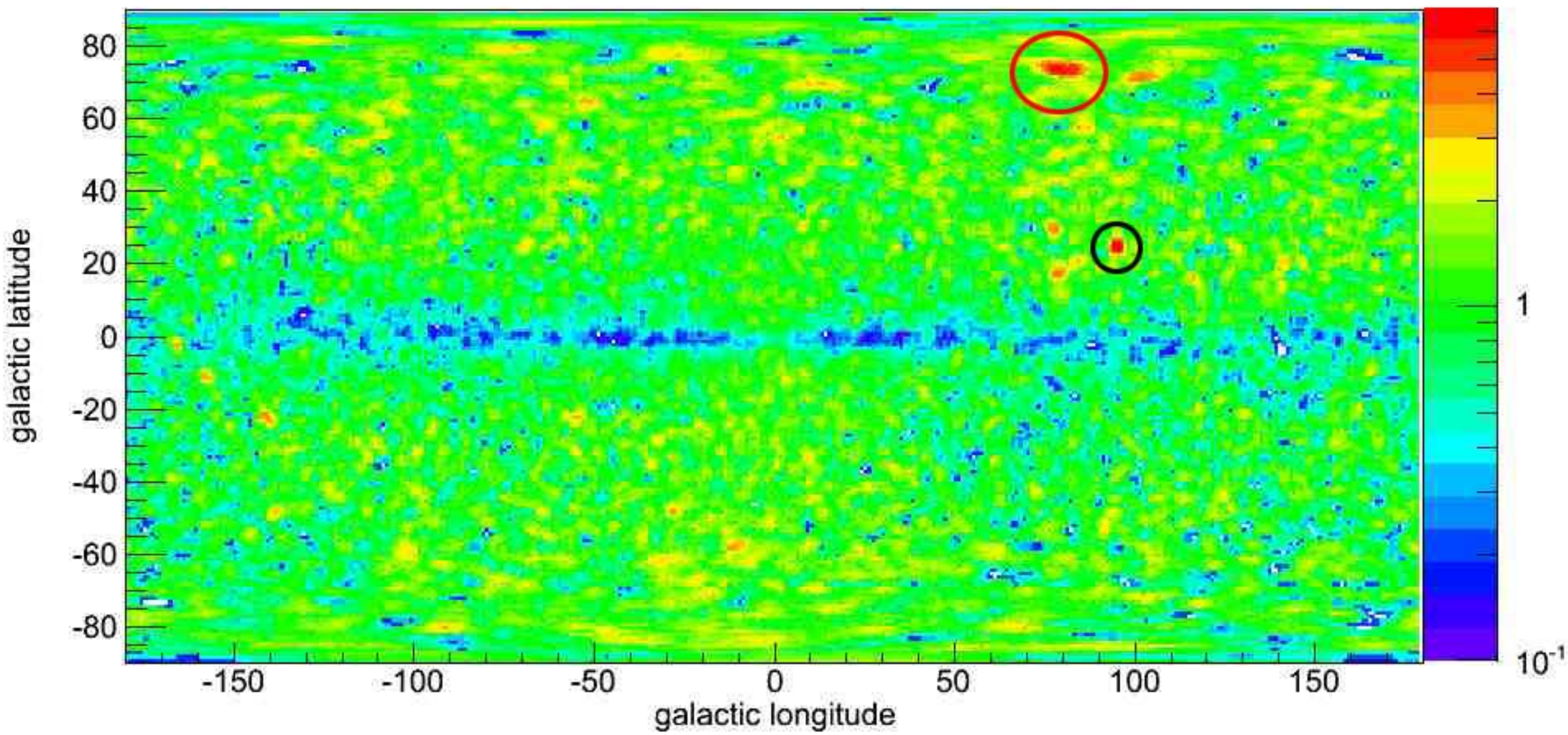


FIG. 1: S/N all-sky map of gamma-ray emission from gravitino DM decay simulated using the Fermi Science Tools. DM events are generated assuming the decay of a $\mu\nu$SSM gravitino with $m_{3/2} = 8$ GeV and $\tau_{3/2} = 5 \times 10^{27}$ s. The black circle indicates the DM clump associated with the Great Attractor and the red circle indicates the position of the Virgo cluster. Pixels in the map have an angular dimension of 1×1 degrees.

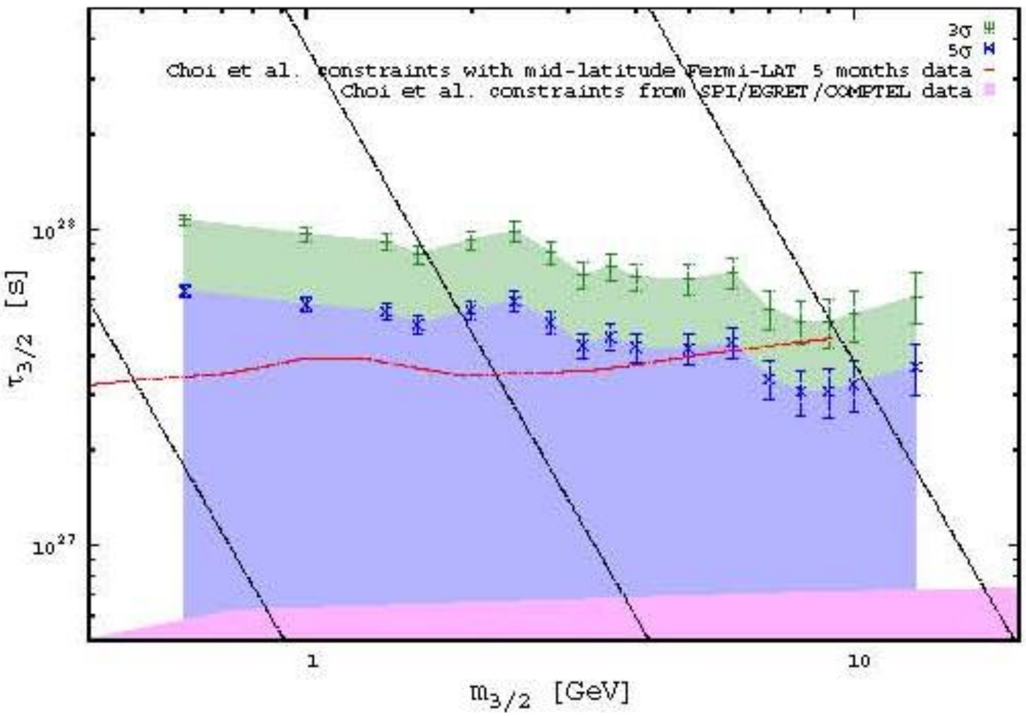


FIG. 2: Constraints on lifetime versus mass for gravitino DM in the $\mu\nu$SSM. Blue (green) points indicate values of $\tau_{3/2}$ and $m_{3/2}$ of the $\mu\nu$SSM gravitino corresponding to a detection of gamma-rays with a S/N of 5σ (3σ) in the 5×5 degree region centered on the position of the Virgo cluster, for a 5 years simulation using the Fermi Science Tools. The blue (green) region indicates points with S/N larger than 5σ (3σ). The red dot-dashed line indicates the lower limit on $\tau_{3/2}$ obtained from the Fermi-LAT measurements of the mid-latitude gamma-ray diffuse emission after 5 months [5]. The black dashed lines correspond to the predictions of the $\mu\nu$SSM [5] (see discussion in Eq. (1)) for several representative values $|U_{\tilde{\gamma}\nu}|^2 = 10^{-16}$ (right), 10^{-14} (center), 10^{-12} (left). The magenta shaded region is excluded by gamma-ray observations such as SPI, COMPTEL and EGRET [28].

Summarizing, we find that a gravitino DM with a mass range of about 0.6–10 GeV, and with a lifetime of about 5×10^{27} s (10^{28} s) would be detectable by the Fermi-LAT with a signal-to-noise ratio of 5σ (3σ). Obviously, if no gamma-ray lines are detected in 5 years, these regions of the parameter space of the $\mu\nu$SSM with gravitino DM would be excluded.

Conclusions

- There are impressive experimental efforts by many groups around the world to detect the dark matter:

  DAMA, CoGeNT, CRESST, CDMS, XENON,…, Fermi, PAMELA, etc.

Thus the present experimental situation is very exciting.

And, besides, the LHC is working

So, stay tuned !

What is MultiDark ?

MultiDark is a Spanish Project supported by the Ministry of Science and Innovation's Consolider-Ingenio 2010 Programme.
It started in 2010, and will last 5 years

- Prompted by a call by the Spanish Ministry of Science and Innovation (MICINN) for funding excellence projects grouping together many researchers, most of the Spanish community involved in the field of Dark Matter decided to apply for a common research project.

In 2009 the MICINN selected 13 out of a total of 101 proposals in all branches of science and humanities.

MultiDark was one of these 13

MultiDark is formed by 19 theoretical, experimental and astrophysics groups belonging to Spanish universities and research institutes, and includes also 14 foreign members. In total the project involves more than 100 researches, as well as more than 20 hired members

G. Bertone	IAP-France
A. Morselli	INFN/Roma Tor Vergata
V. Vitale	“
M. Casolino	“
K. Choi	KAIST-Korea
J. Collar	Univ. Chicago
N. Fornengo	Univ. Torino/INFN
S. Gottlober	AIP-Germany
S. Nuza	“
A. Partl	“
K. Riebe	“
Y. Mambrini	LPT/Orsay-France
M. Ricci	LNF-Frascati/INFN
J.D. Vergados	Univ. Ioannina

Summary of Activities during 2010

- Publications
- Collaborations
- Calls – Postdoctoral (I) January 2010
- Calls – Postdoctoral (II) December 2010
- Calls – Predoctorals September 2010
- Calls – Summer Students Summer 2010
- Workshops
- Training
- Seminars
- Sponsorship
- In the media

MultiDark
Multimessenger Approach for Dark Matter Detection

Calls – Hired ITALIAN members

- Currently working for the project:

Postdocs 2010-2012

- Mattia Fornasa, 2 years, IAA
- Mirco Cannoni, 2 years, UHU
- Marco Taoso, 1 year, IFIC-AHEP

- Roberto Lineros, 1 year, IFIC-AHEP
- Julien Lavalle, 2 years, **MultiDark**

MultiDark
Multimessenger Approach for Dark Matter Detection

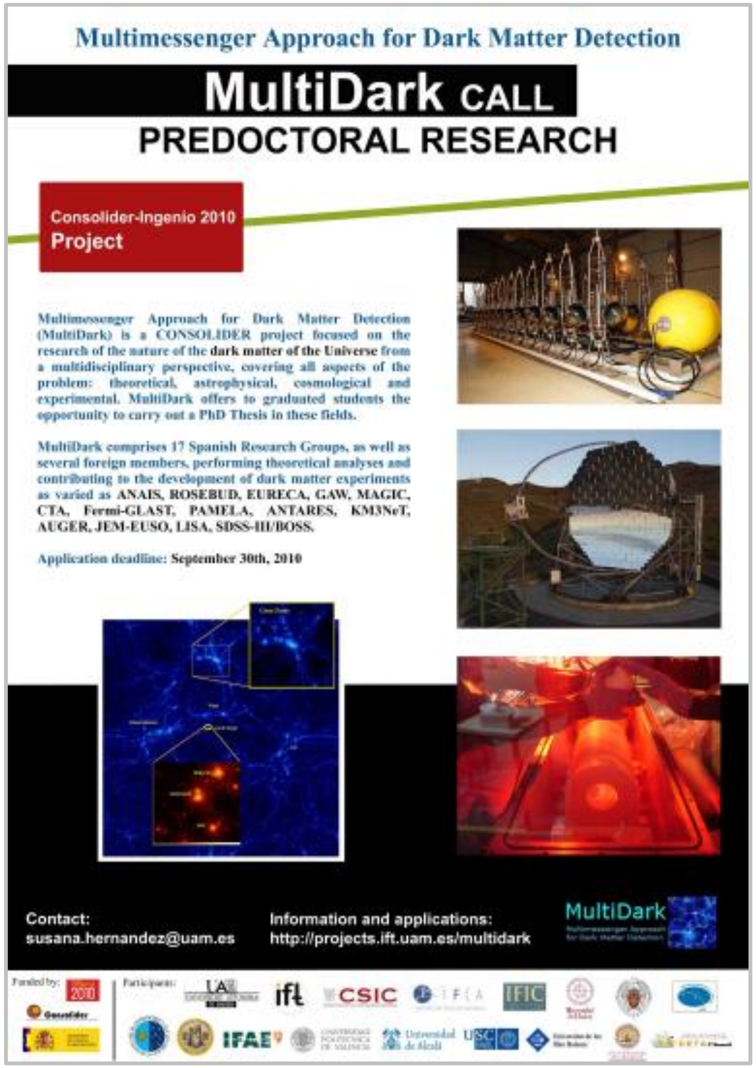
Calls – ITALIAN Predoctorals

Currently working for the project:

Predocs 2010-2014

Ginevra Favole, IAA

Viviana Gammaldi, UCM-Th



MultiDark
Multimessenger Approach for Dark Matter Detection

MultiDark members talking in RICAP:

Migue Ángel Sánchez-Conde, IAC
Mattia Fornasa, IAA
Germán A. Gómez Vargas, UAM/IFT & Roma tor Vergata
Juan de Dios Zornoza, IFIC-Exp.


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