Dark Matter detection

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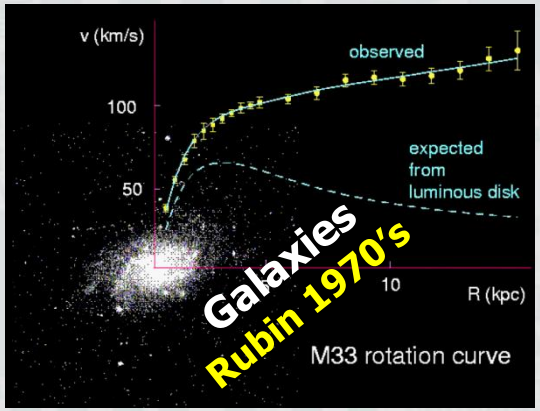
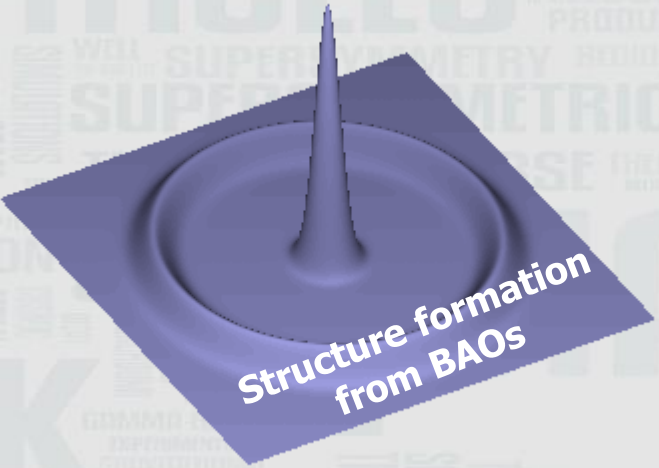
MultiDark
Multimessenger Approach for Dark Matter Detection

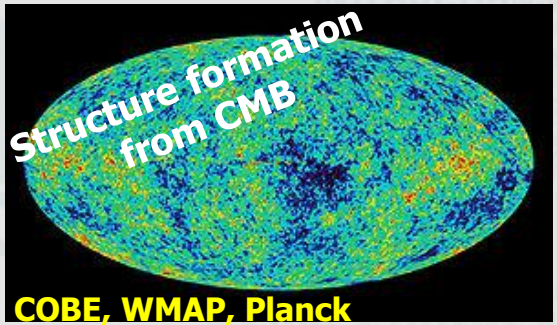
Meeting on Fundamental Cosmology
Santander, 17-19 June 2015

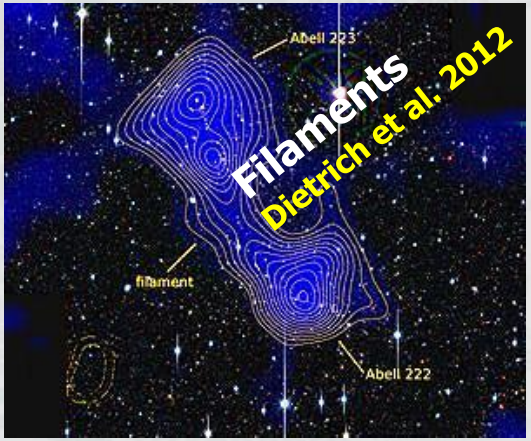
Evidence for DM

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







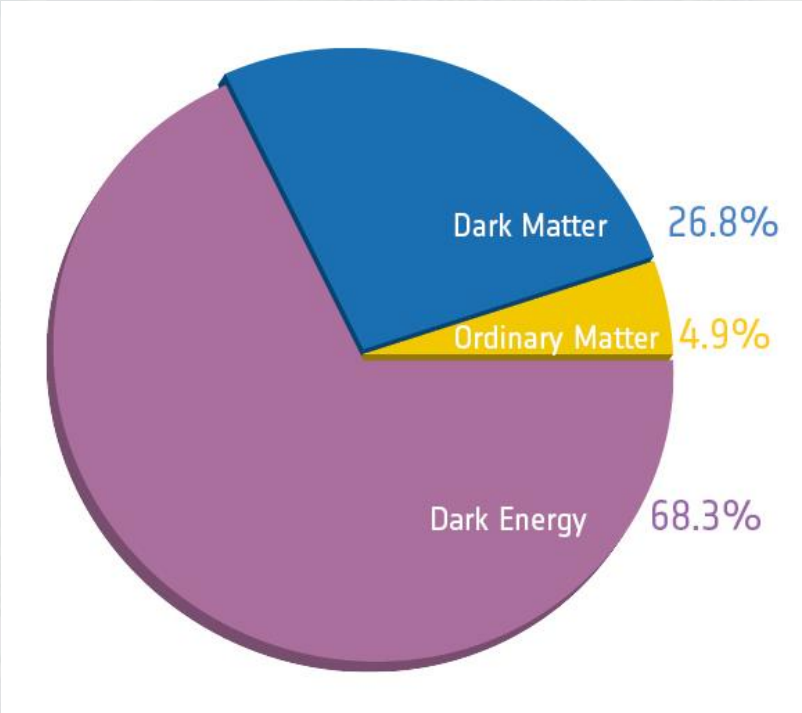


Results from the Planck satellite,

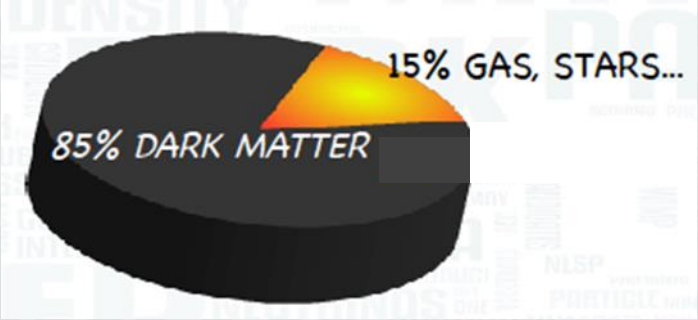
$$\Omega_{DM}\, h^2 \approx 0.12$$

$$\Omega_{b}\, h^2 \approx 0.022$$

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



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



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

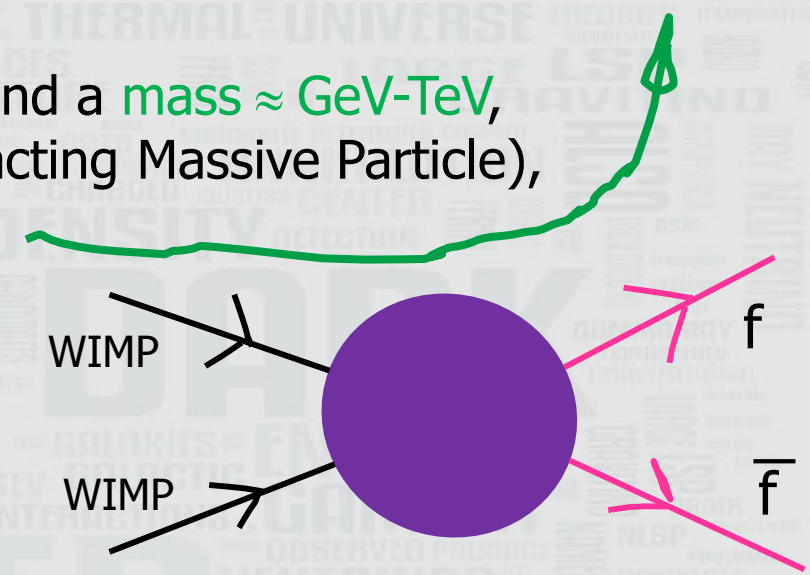
This is a clear indication that we need to go

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

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



In the early Universe, at some temperature the annihilation rate of DM WIMPs dropped below the expansion rate

and their density has been the same since then, with:

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

$\sigma_{ann} = \sigma_{weak}$

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

thermal cross section

DETECTION

The LHC could detect a new kind of particle

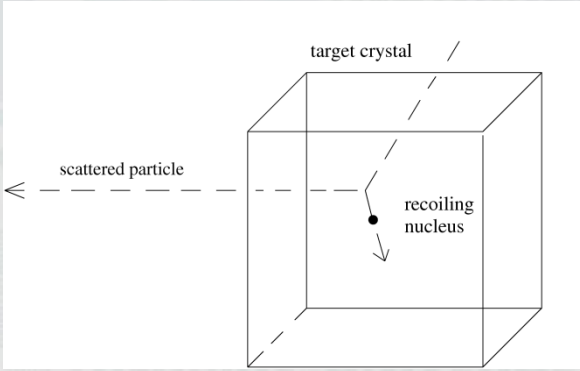
If we are able to measure the mass and interactions of the new particle, checking that $\Omega_{DM} h^2 \approx 0.1$, this would be a great success

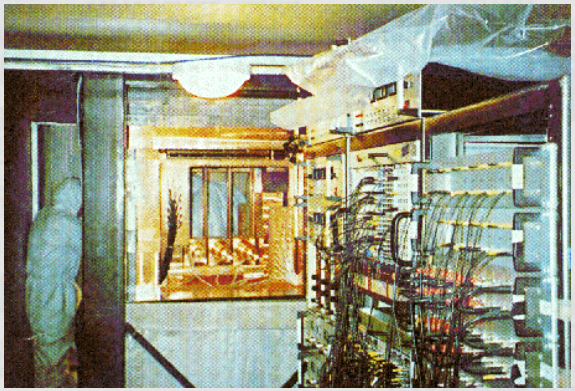
...but how can we be sure it is stable on cosmological scales?

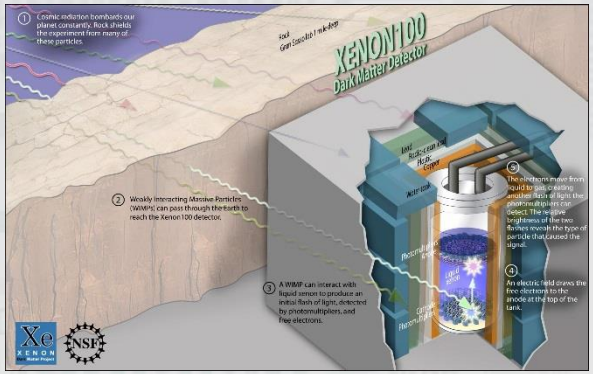
Direct and Indirect Detection

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

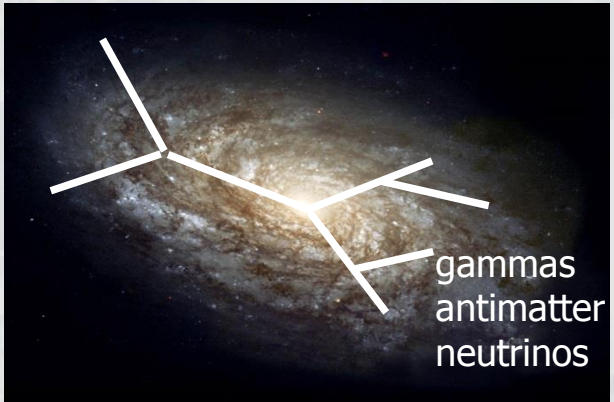
This can come from direct DM searches

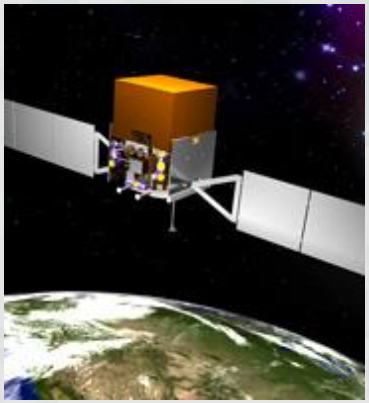


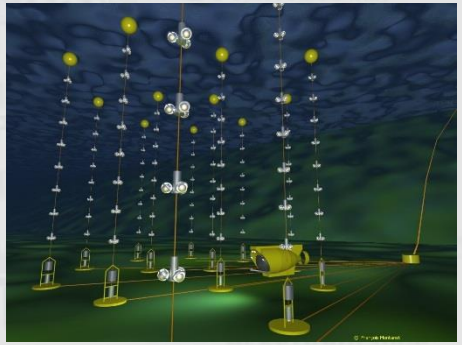




or indirect DM searches

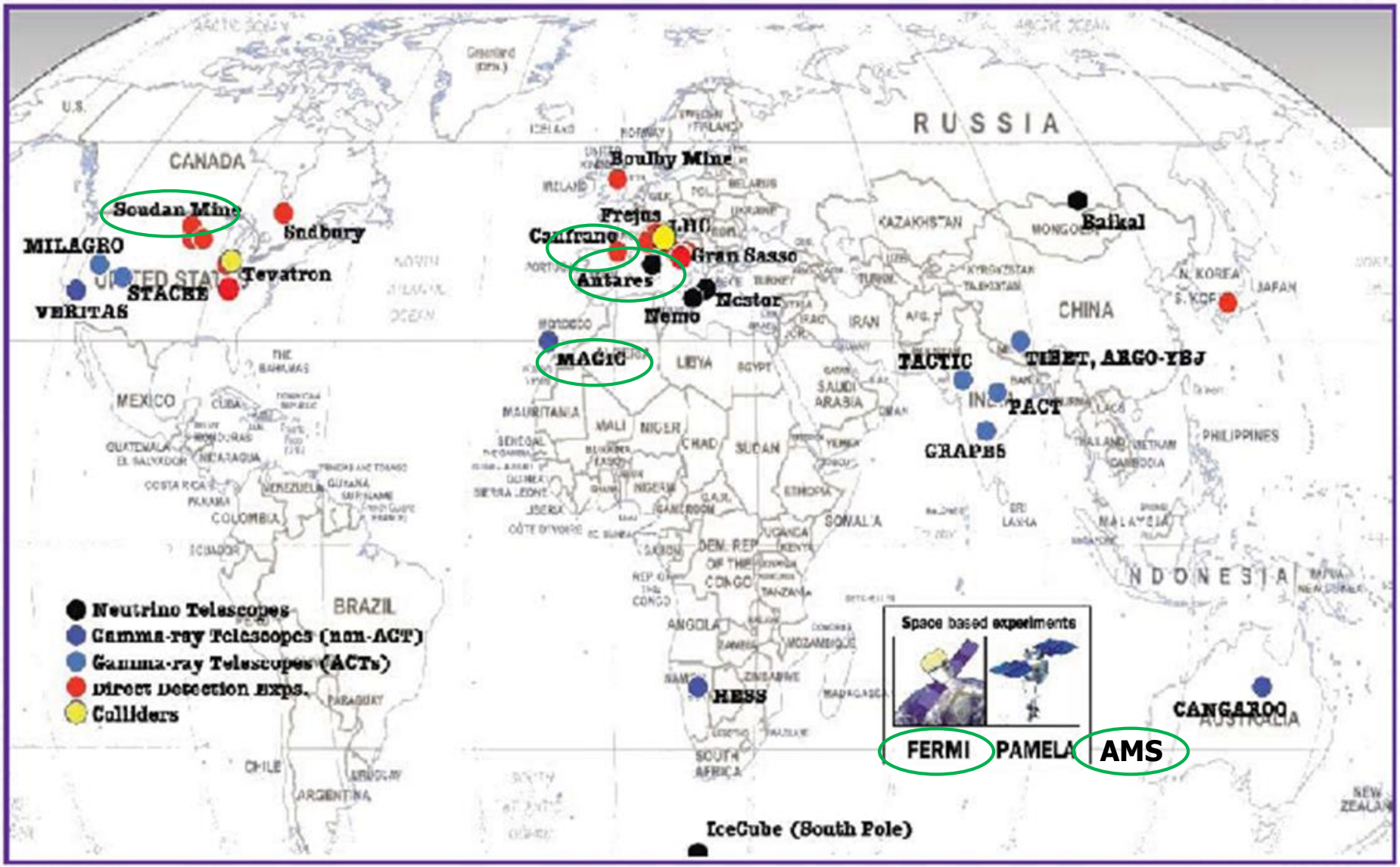






These three detection strategies are ideal because they allow exploring in a complete way many different particle dark matter models

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

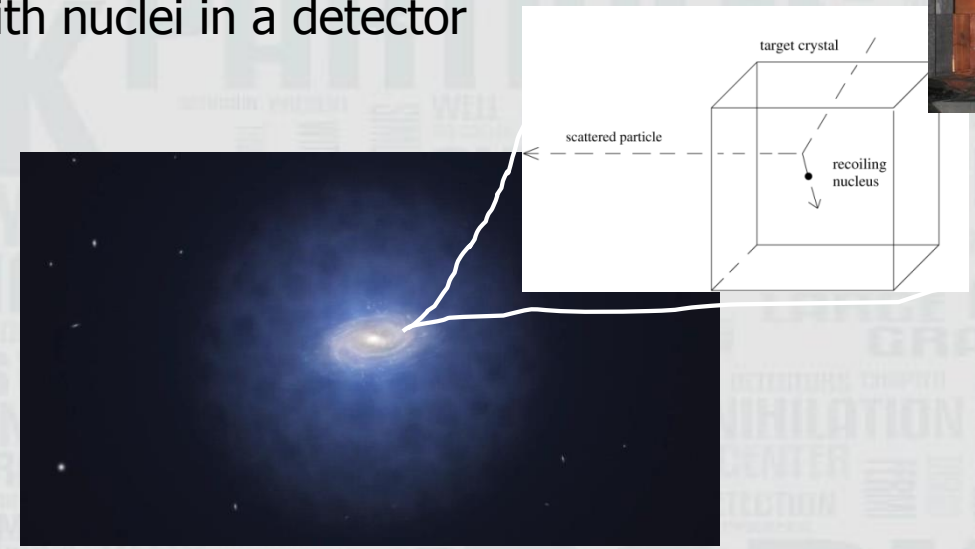


Underground Labs and indirect detection DM experiments around the world

DIRECT DETECTION

through elastic scattering with nuclei in a detector is possible

DAMA/LIBRA photo



- $\rho_0 \sim 0.3\ \mathrm{GeV/cm^3}$
- $v_0 \sim 220\ \mathrm{km/s}$

$J \sim \rho_0 v_0 / m_{WIMP}$
$\sim 10^4$ WIMPs /cm^2 s

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

$R \sim J\, \sigma_{WIMP\text{-}nucleon} / m_N \approx 10^{-2}\text{-}1$ events/kg day → convenient to have as much material as possible

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

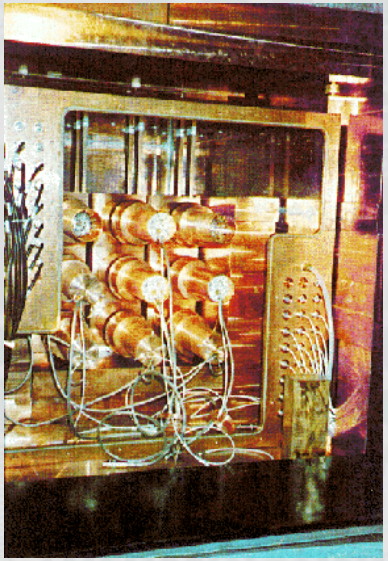
energy produced by the recoiling nucleus can be measured through ionization, scintillation, heat ≈ **few** keV

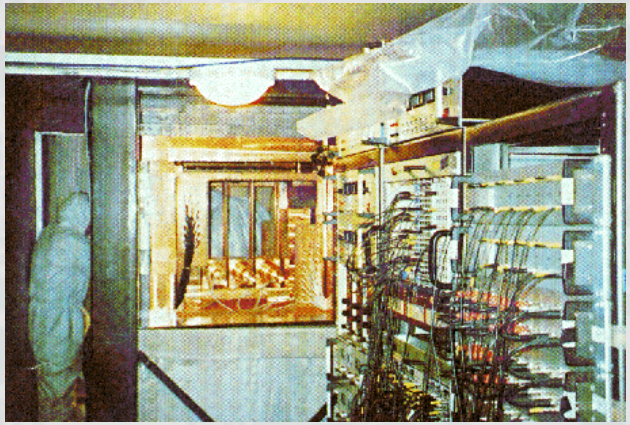
- e.g., DAMA only measures scintillation light → $E_{scintillation} = Q\, E_{recoil}$

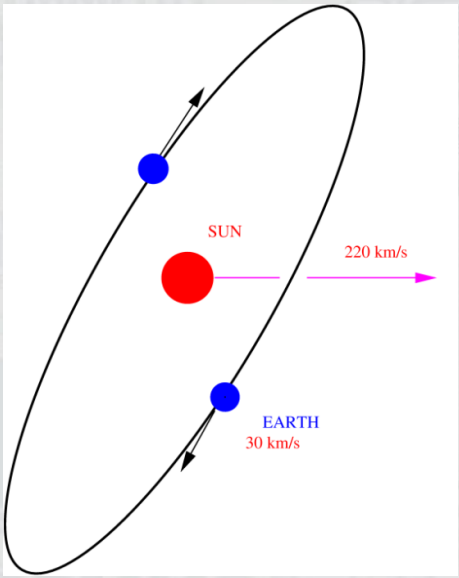
  Q(quenching factor) = 0.3 for Na , 0.09 for I

- DAMA experiment had 100 kg NaI crystals

- Annual modulation

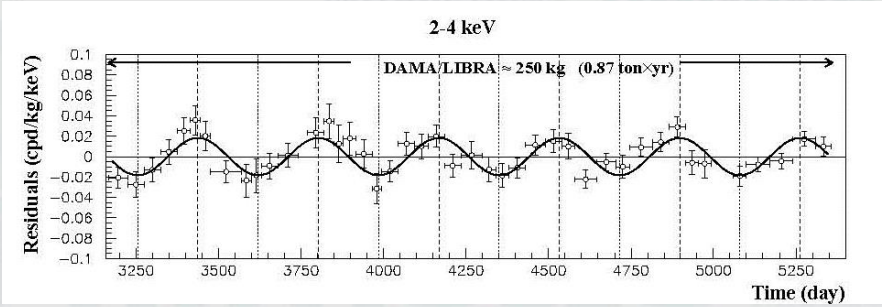






DAMA/LIBRA

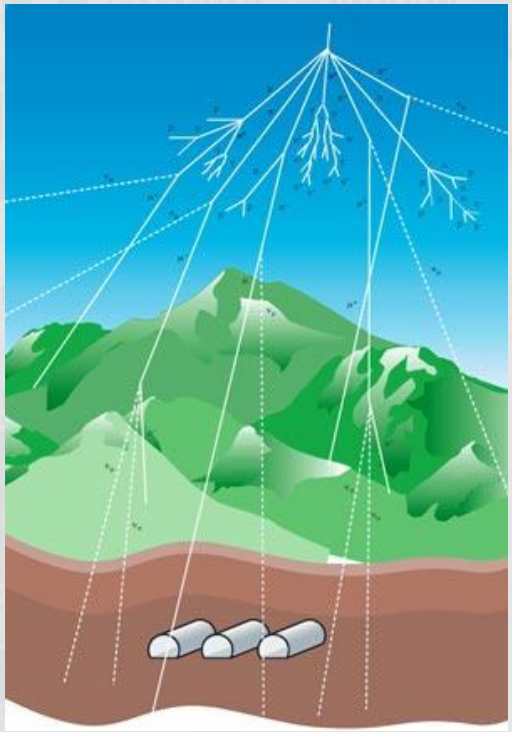
250 kg NaI crystal scintillators at Gran Sasso.



It does not strongly discriminate between WIMP scatters and background events

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

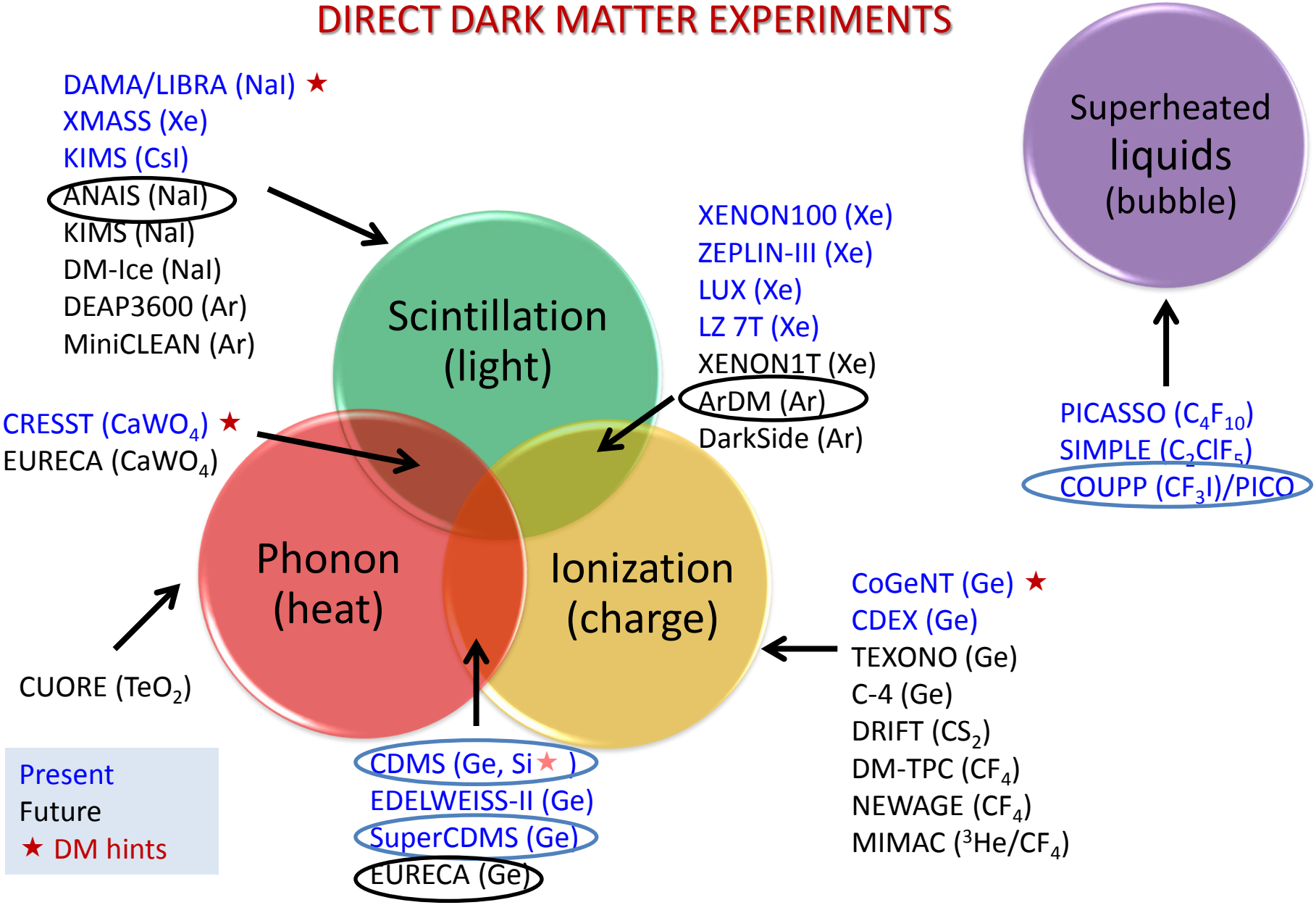
Experiments must be located in the deep underground to greatly reduced the rate of these background events

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

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

…everything above background might be a signal

DIRECT DARK MATTER EXPERIMENTS



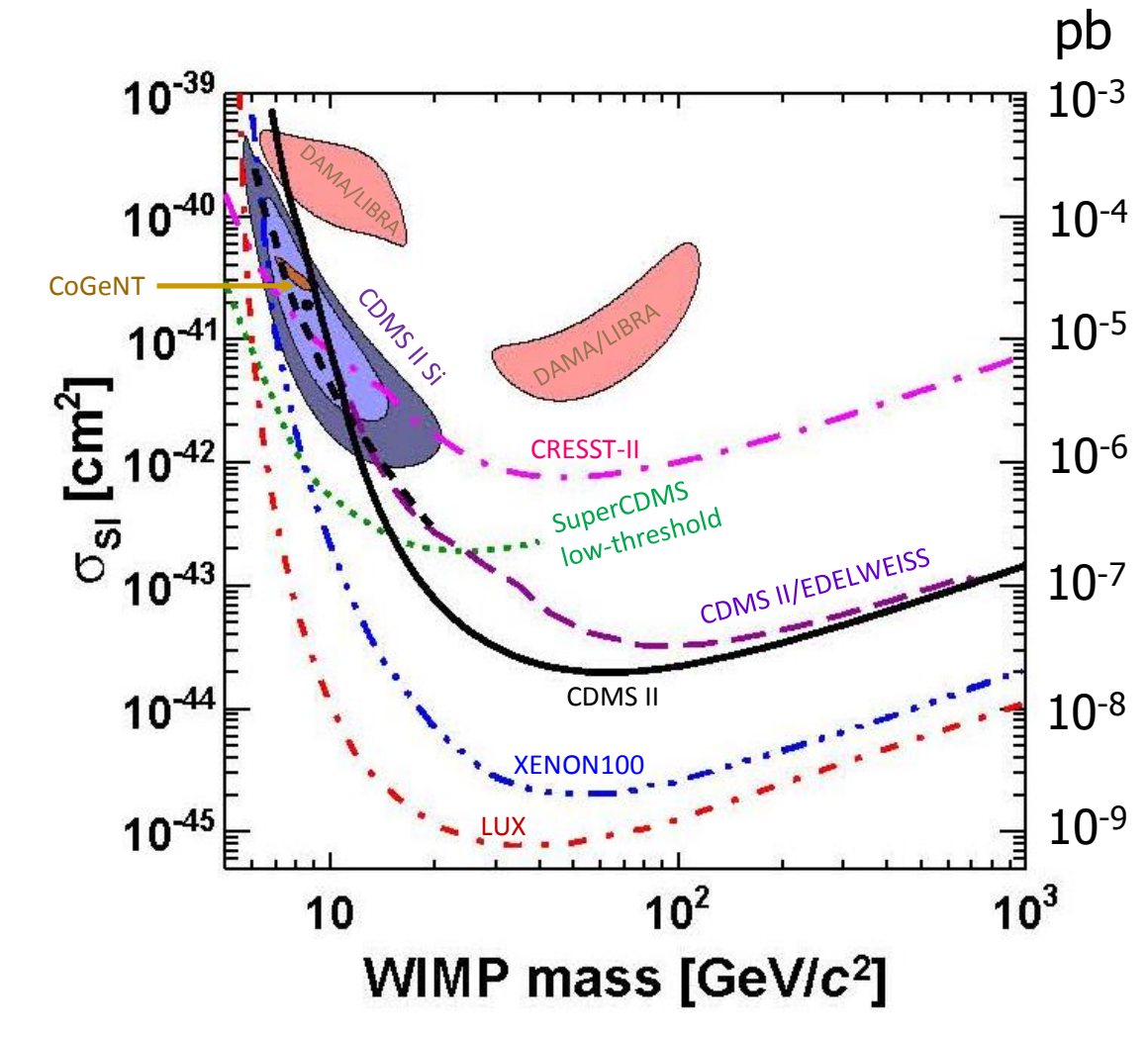


Figure from CDMS collab. 1504.0587

LUX: active 250 kg of liquid Xe
(scintillation + ionization)

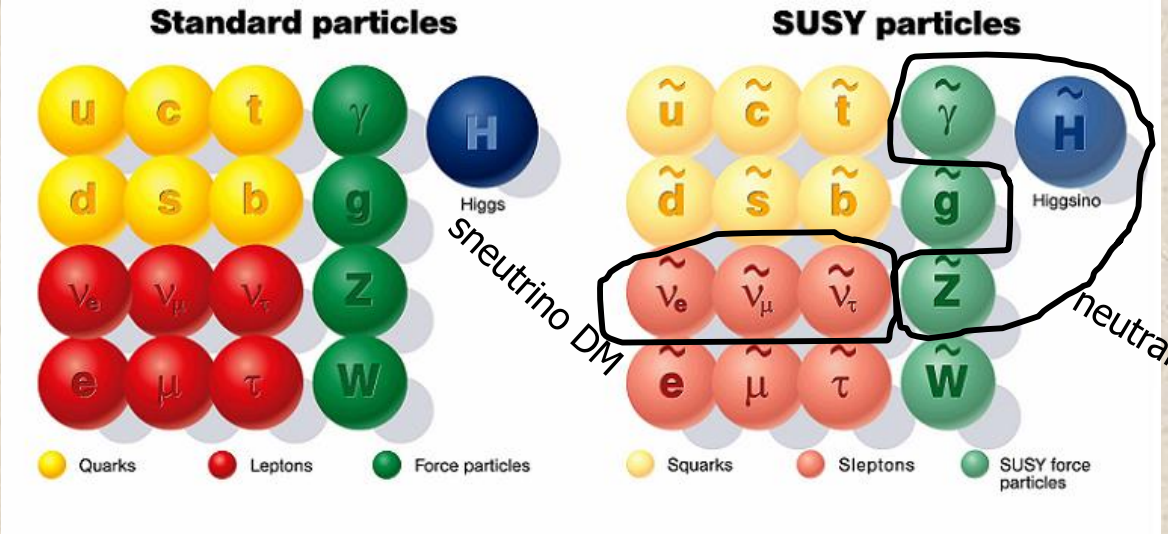
Sanford underground lab. South Dakota

CDMS II: 4.5 kg Ge+1.2 kg Si
(ionization + heat)

Soudan underground lab. Minnesota

But…what these results mean from the theoretical viewpoint?

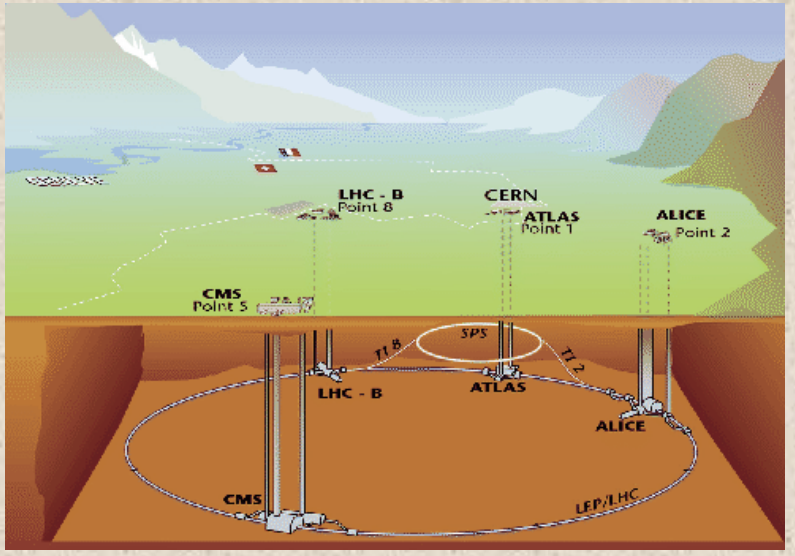
Crucial Moment for Supersymmetry in 2015: LHC Run II 13 TeV

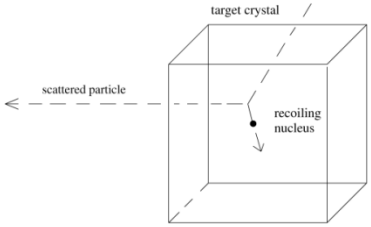


The spectrum of elementary particles is doubled

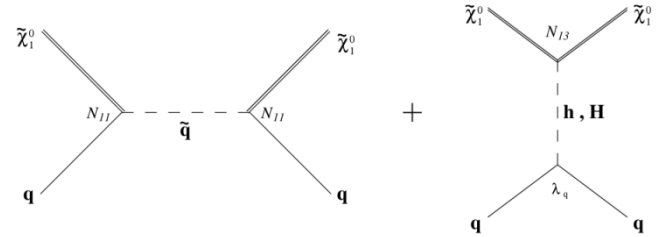
with masses ≈ 1000 GeV

A rich phenomenology





Supersymmetry



Neutralino in the MSSM (with R-parity conservation) is a WIMP

Squark exchange

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

Otherwise unconstrained from LHC

Higgs exchange

Leading contribution (increases with Higgsino component)

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

Also affected by m_H=126 GeV

In view of the LHC constraints on SUSY, Higgs data, flavour physics observables,

in the phenomenological MSSM (pMSSM)

with 19 independent parameters,

M_a, m_α, A_α , tan β , μ,

one obtains

Parameter	Range (in GeV)
$\tan\beta$	[1, 60]
M_A	[50, 2000]
M_1	[-3000, 3000]
M_2	[-3000, 3000]
M_3	[50, 3000]
$A_d = A_s = A_b$	[-10000, 10000]
$A_u = A_c = A_t$	[-10000, 10000]
$A_e = A_\mu = A_\tau$	[-10000, 10000]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 3000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[0, 3000]
$M_{\tilde{\tau}_L}$	[0, 3000]
$M_{\tilde{\tau}_R}$	[0, 3000]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[0, 3000]
$M_{\tilde{q}_{3L}}$	[0, 3000]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[0, 3000]
$M_{\tilde{t}_R}$	[0, 3000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 3000]
$M_{\tilde{b}_R}$	[0, 3000]

Table 1: pMSSM scan ranges.

For the relic density, the upper bound $\Omega_{WIMP} h^2 \sim 0.12$ is applied, allowing for the possibility of multiple DM componentes (neutralinos + axions and/or other candidates)

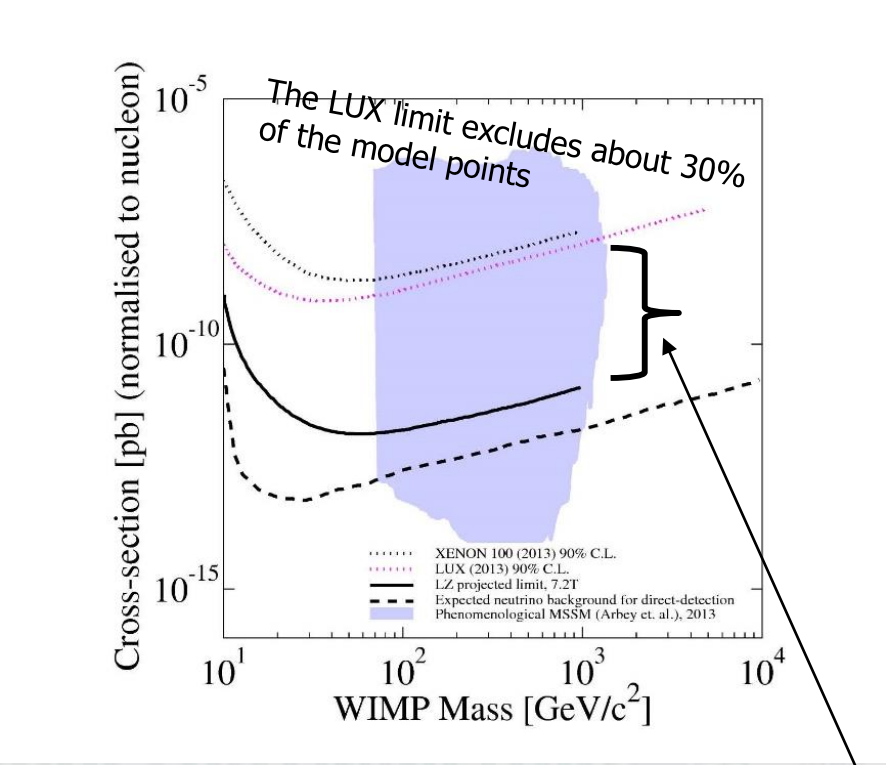


Figure from Mahmoudi, Arbey, 1411.2128

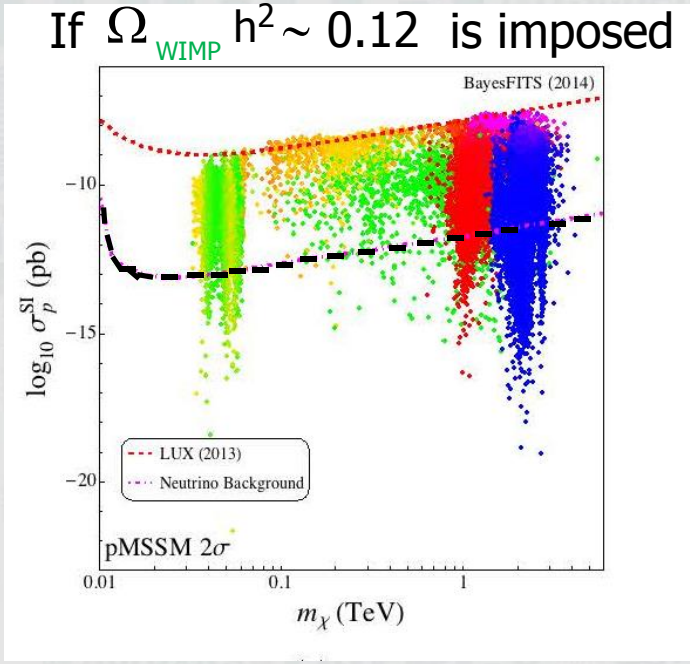
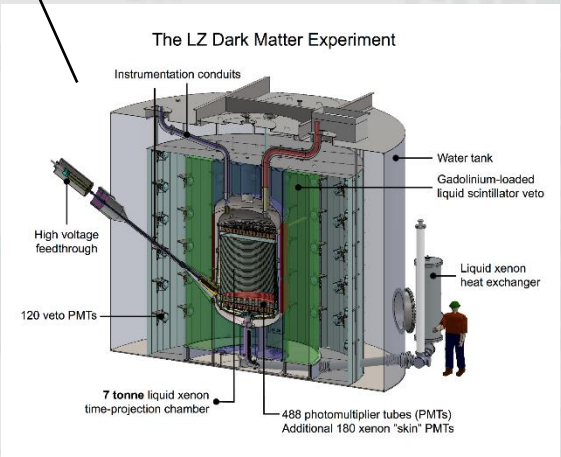
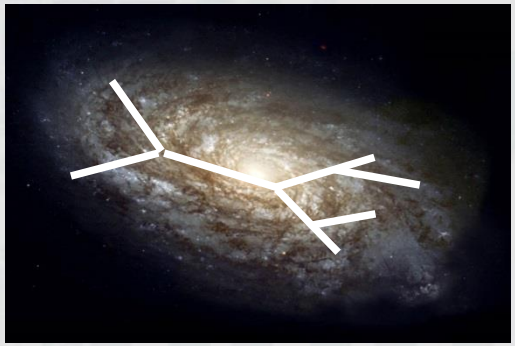


Figure from Roszkowski, Sessolo, Williams, 1411.5214

Similar results for neutralinos or sneutrinos in the NMSSM are expected

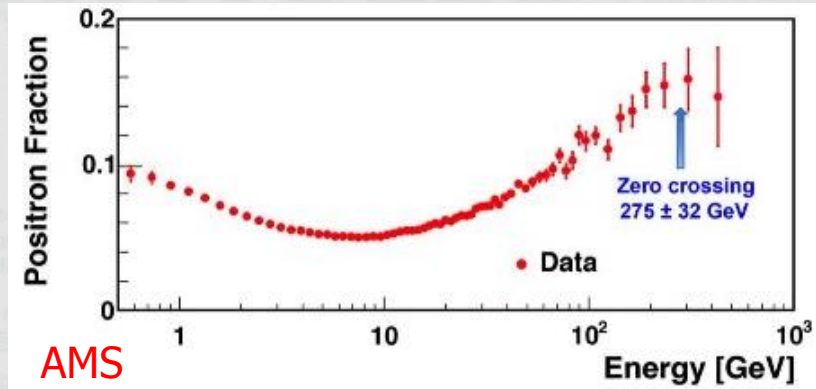


Future experiments will explore large regions of the parameter space



INDIRECT DETECTION

An excess of **positrons** for energies larger than 10 GeV has been detected by PAMELA (2008), Fermi-LAT (2010) and AMS (2013)



problems with the WIMP (~1 TeV) explanation:

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

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

- Otherwise boost factors, ranging 10^2 - 10^4, provided by clumpiness in the DM distribution, are needed

Possible astrophysical explanations:

- Contributions of e^- and e^+ from Monogem or Geminga pulsar or a sum of Milky Way pulsar population, assuming different distance, age and energetic of the pulsars.
- Super Nova Remnants

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

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

on behalf of the Fermi-LAT:
Morselli, Vitale, 0912.3828
Morselli, Cañadas, Vitale 1012.2292
analized the inner galaxy region

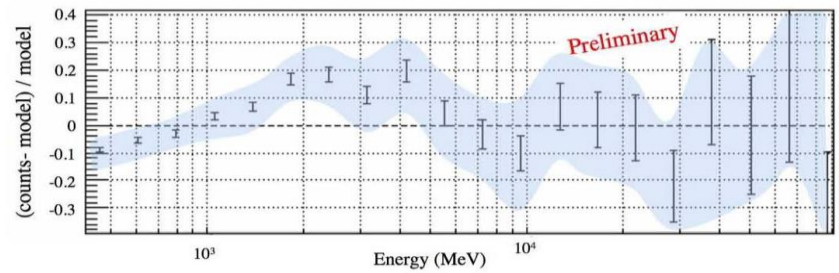
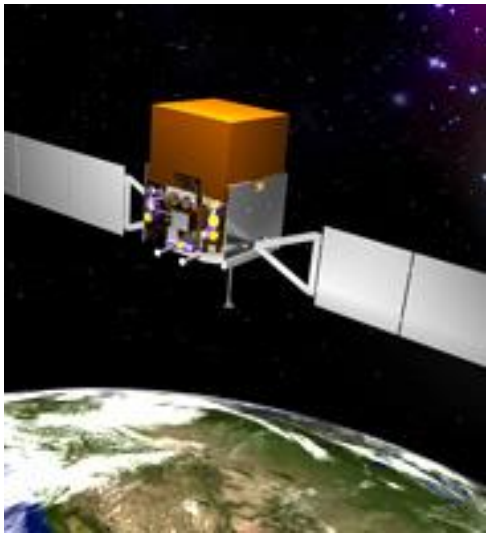


Fig. 4. – Residuals ((exp.data - model)/model) of the above likelihood analysis. The blue area shows the systematic errors on the effective area.



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

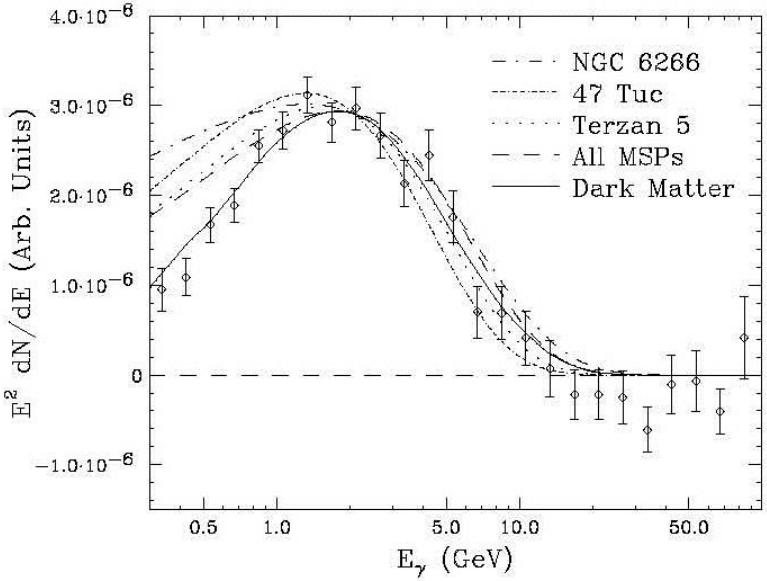


FIG. 17: A comparison of the spectral shape of the gamma-ray excess described in this paper (error bars) to that measured from a number of high-significance globular clusters (NGC 6266, 47 Tuc, and Terzan 5), and from the sum of all millisecond pulsars detected as individual point sources by *Fermi*. The gamma-ray spectrum measured from millisecond pulsars and from globular clusters (whose emission is believed to be dominated by millisecond pulsars) is consistently softer than that of the observed excess at energies below ~1 GeV.

Hooper, Goodenough, 1010.2751
Hooper, Linden, 1110.0006
Abazajian, Canac, Horiuchi, Kaplinghat, 1402.4090
Daylan, Finkbeiner, Hooper, Linden et al., 1402.6703
Calore, Cholis, Weniger, 1409.0042

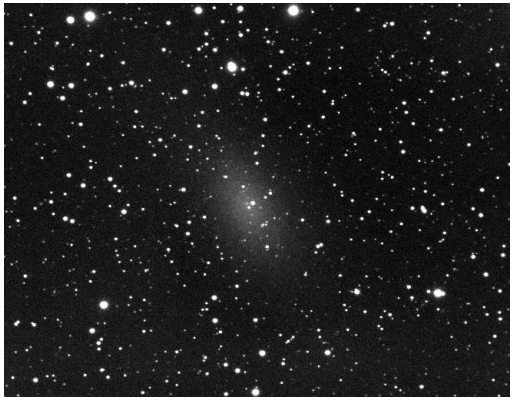
The spectrum of the excess peaks at 1-3 GeV, and is well fit by 31-40 GeV DM particle annihilating to $b\bar{b}$

$\gamma \sim 1.1 - 1.3$

$\sigma_{ann} v \sim 1.4 - 2.0 \times 10^{-26}\ cm^3\ s^{-1}$

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



6-years of Fermi-LAT data. No excess from a combined analysis of 15 dSph

1503.02641

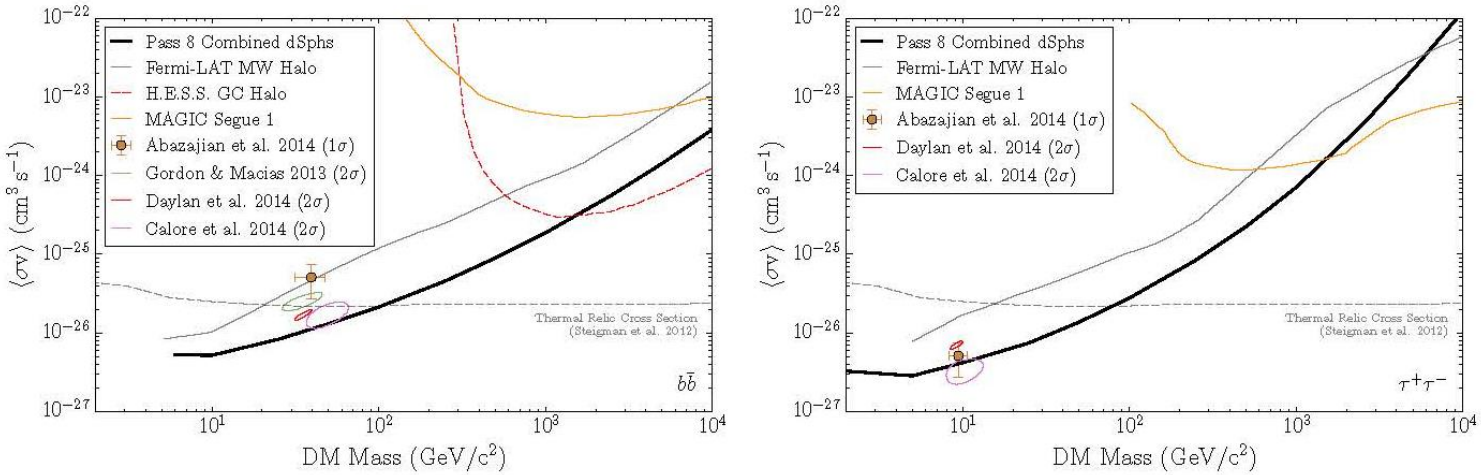
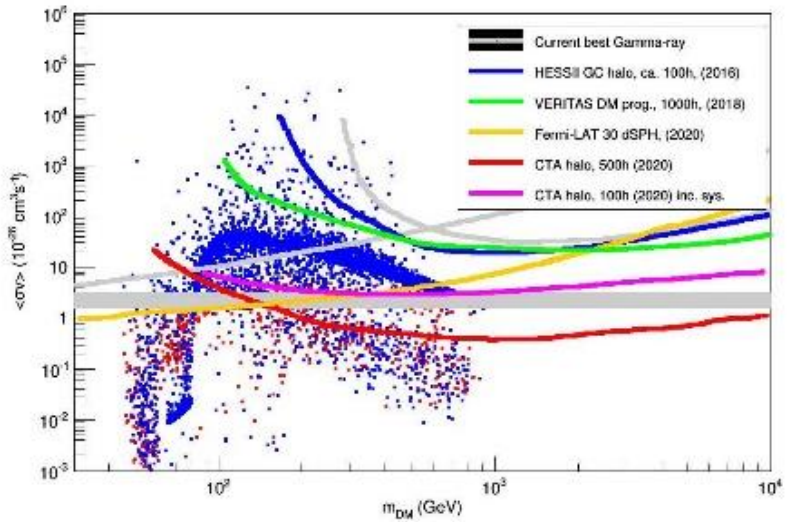


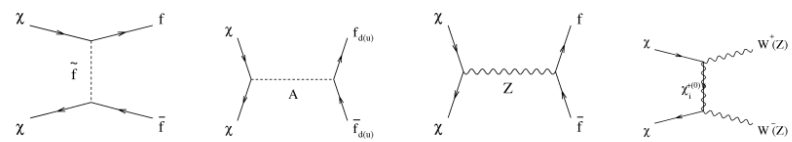
FIG. 2. Comparison of constraints on the DM annihilation cross section for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels from this work with previously published constraints from LAT analysis of the Milky Way halo (3σ limit) [33], 112 hours of observations of the Galactic Center with H.E.S.S. [34], and 157.9 hours of observations of Segue 1 with MAGIC [35]. Closed contours and the marker with error bars show the best-fit cross section and mass from several interpretations of the Galactic center excess [16–19].

Constraints lie below the canonical termal relic cross section for DM of mass $\lesssim$ 100 GeV annihilating via $b\bar{b}$ channel and $\tau^+\tau^-$ channel



In general the final state will be a combination of the final states shown 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



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

Quark channels Constraints in the next decade:
VERITAS 1000h DM programme [32], HESSII (my guess), Fermi-LAT dwarf and CTA [35] and CTA including systematic uncertainties [36]. Model points, taken from Fermi 1001.4531 represent MSSM-7 with red colour: consistent with cosmological dark matter density, blue colour: allowed to be smaller.

Figure from Conrad, 1411.1925

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

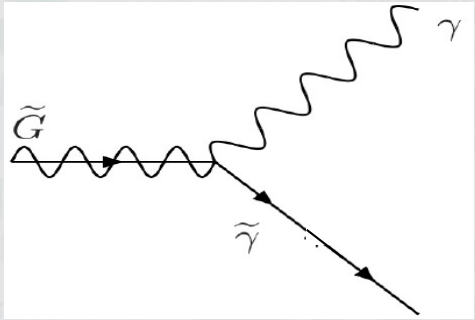
Gravitino as decaying dark matter

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

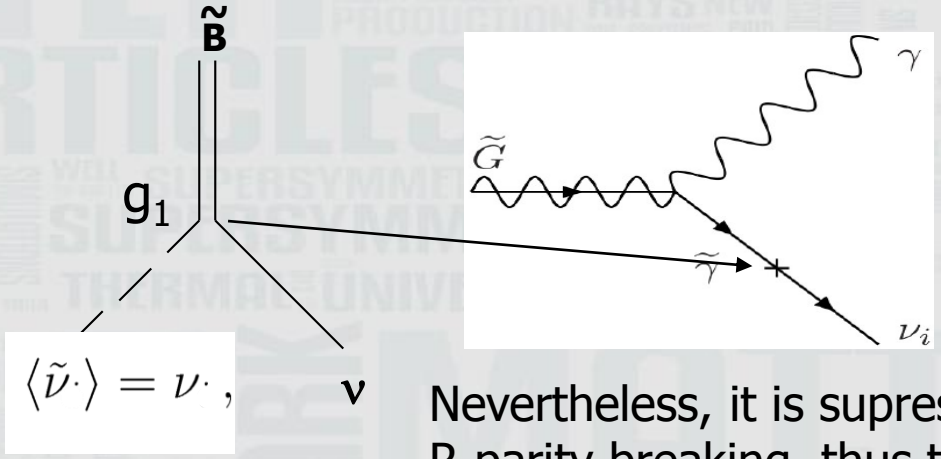
The gravitino LSP also decays through the interaction gravitino-photon-photino (λ)

Takayama, Yamaguchi, 2000

$$L_{int} = -\frac{i}{8M_{pl}}\bar{\psi}_\mu[\gamma^\nu, \gamma^\rho]\gamma^\mu \lambda F_{\nu\rho},$$



due to the photino-neutrino mixing after sneutrinos develop VEVs , opening the channel



$$\langle \tilde{\nu}\cdot \rangle = \nu\cdot ,$$

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

Nevertheless, it 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)

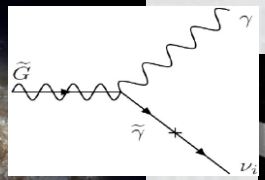
$$\tau_{3/2} = \Gamma^{-1}(\tilde{G} \to \gamma\nu) \simeq 8.3 \times 10^{26}\,\text{sec} \times \left(\frac{m_{3/2}}{1\text{GeV}}\right)^{-3} \left(\frac{|U_{\gamma\nu}|^2}{7 \times 10^{-13}}\right)^{-1} .$$

Thus, the gravitino (**superWIMP**) can be a good (decaying) DM candidate

Since the gravitino decays into a photon and neutrino, the former produces a gamma-ray line at energies equal to $\mathbf{m_{3/2}/2}$

FERMI might in principle detect these gamma rays

$$\left[E^2 \frac{dJ}{dE}\right]_{\rm halo} = \frac{2E^2}{m_{3/2}} \frac{dN_\gamma}{dE} \frac{1}{8\pi\tau_{3/2}} \int_{\rm los} \rho_{\rm halo}(\vec{l}) d\vec{l}\,,$$



μνSSM

Lopez-Fogliani, C. M., PRL 97 (2006) 041801

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

Neutrino content of the photino.

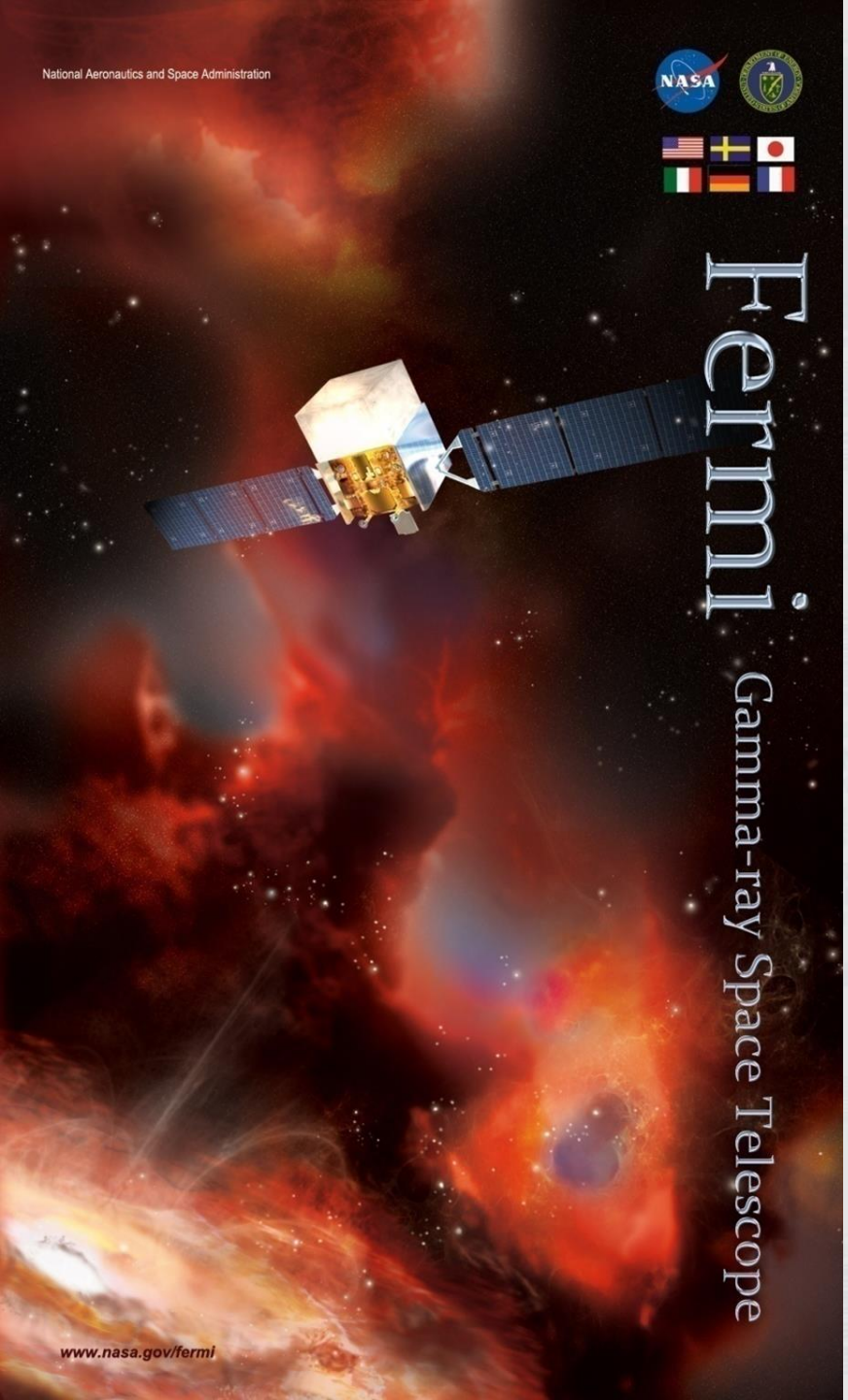
$$\tau_{3/2} \simeq 3.8\times 10^{27}\,{\rm s}\left(\frac{|U_{\tilde{\gamma}\nu}|^2}{10^{-16}}\right)^{-1}\left(\frac{m_{3/2}}{10\,{\rm GeV}}\right)^{-3}.$$

In the $\mu\nu$SSM in order to reproduce neutrino data:

$$10^{-15} \lesssim |U_{\tilde{\gamma}\nu}|^2 \lesssim 5\times 10^{-14}$$

As a consequence, values of the gravitino mass larger than about **10 GeV** are disfavoured by *Fermi* LAT data

Choi, López-Fogliani, C.M., Ruiz de Austri, 0906.3681



More recently,
together with Fermi-LAT collaborators
we performed the following search:

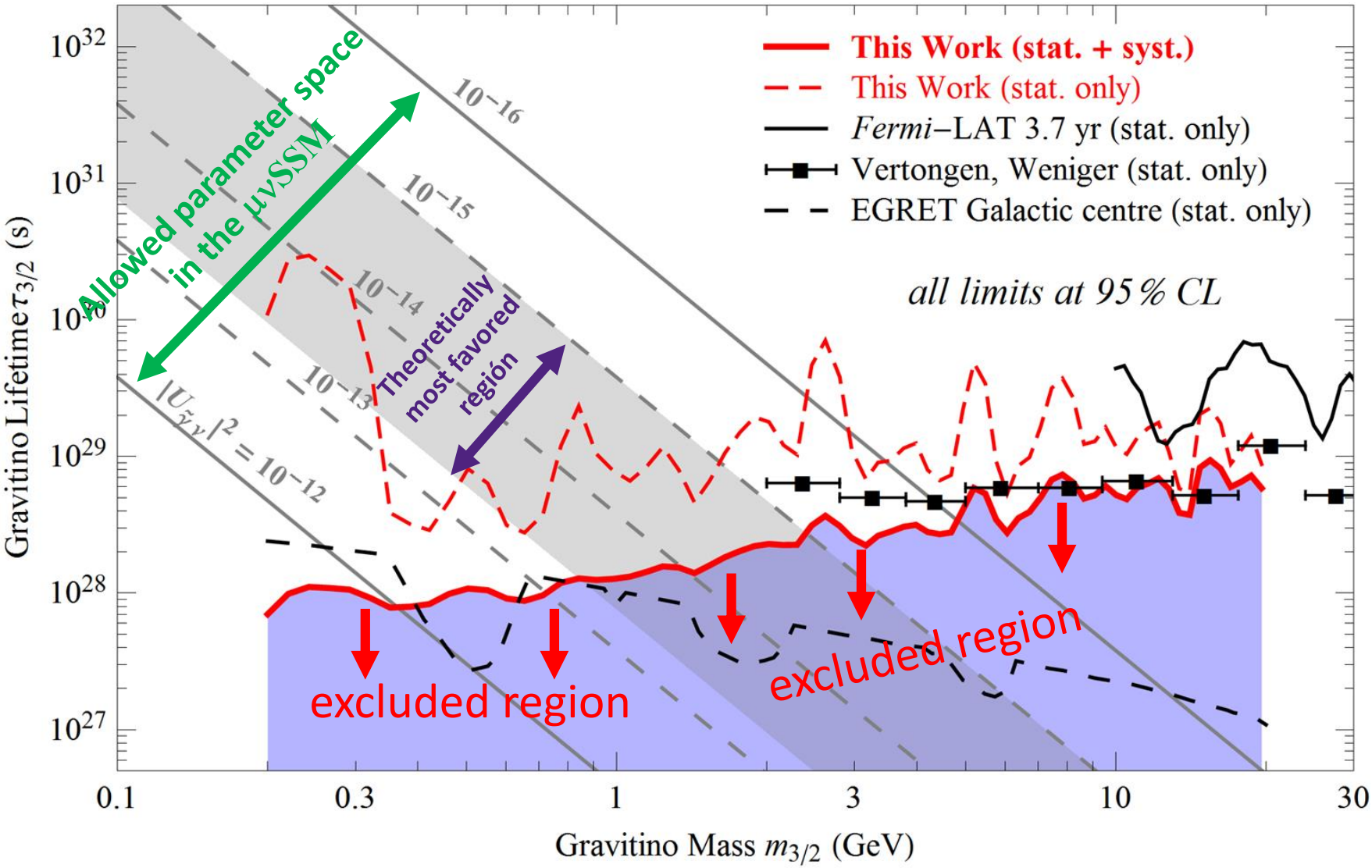
Search for 100 MeV to 10 GeV γ-ray lines in the *Fermi*-LAT data and implications for gravitino dark matter in the μνSSM

arXiv:1406.3430 [astro-ph.HE], *JCAP 10 (2014) 023*

Category II paper:
-*Fermi*-LAT Collaboration: Albert, Bloom, Charles, Gómez-Vargas, Mazziotta, Morselli
External authors: C. M., Grefe, Weniger

Applying these bounds to our model:

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



μνSSM gravitinos with masses larger than **4.8 (2.4)** GeV
or lifetimes smaller than **7.9 x 10^{27} (1.3 x 10^{28})** s are excluded as DM candidates

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

- Particle candidates for Dark Matter

-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 collaborations around the world:

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

Thus the present experimental situation is very exciting

And, besides, the LHC is back

So, stay tuned !

DM
experiments
also
groups
detection
project
collaboration
FERMI
Spanish
energy
searches
group
different
indirect
MULTIDARK
data
new
MAGIC
mass
candidates
models
analysis
telescopes
matter
detector
Milestone
WIMPs
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THE END