Theoretical aspects of Dark Matter search

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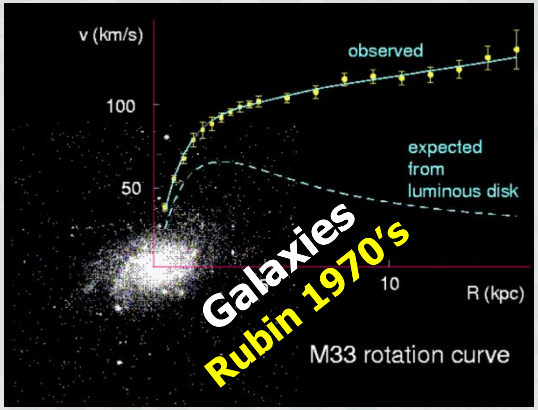
MultiDark
Multimessenger Approach for Dark Matter Detection

RICAP-13, Roma, May 22-24

Evidence for DM

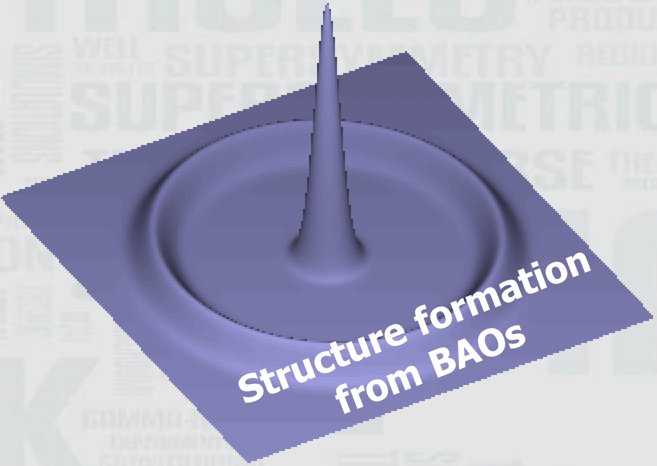
- Evidence for dark matter since 1930's:



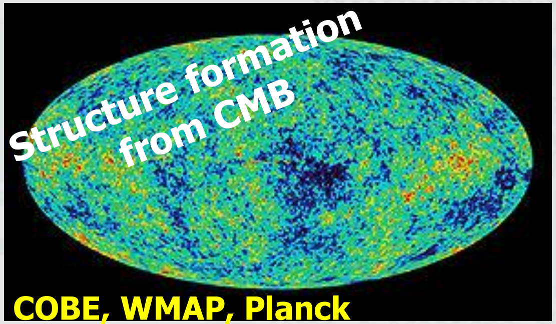
Galaxies
Rubin 1970's

Galaxy Clusters
Zwicky 1933

Bullet Cluster
Clowe et al. 2006

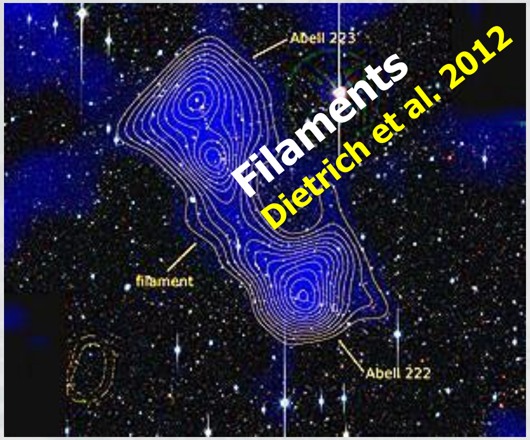


Structure formation from BAOs



Structure formation from CMB

COBE, WMAP, Planck



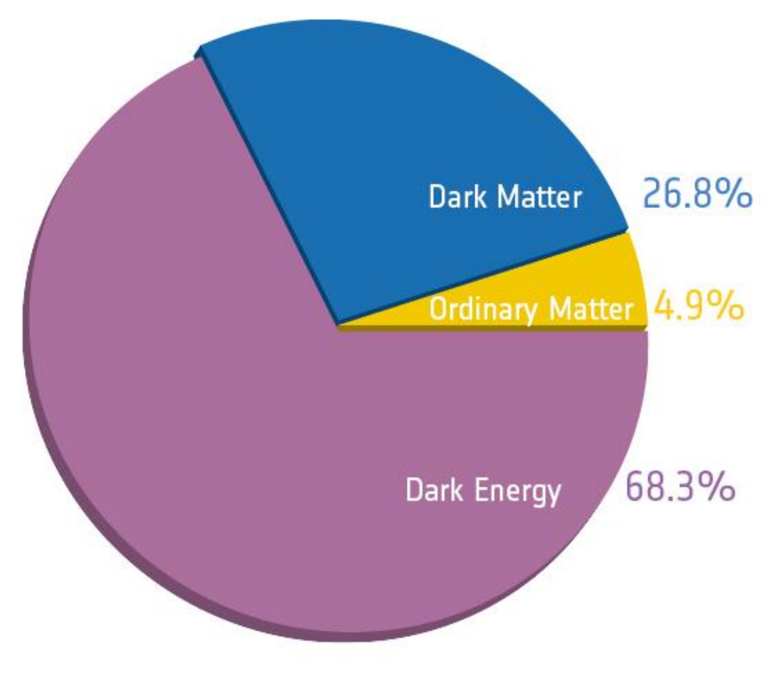
Filaments
Dietrich et al. 2012

- Last results from the Planck satellite,

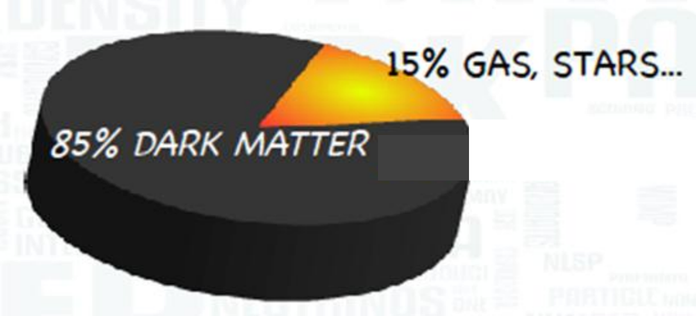
$\Omega_{DM}\, h^2 \approx 0.12$

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

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



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



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 $\Omega_{\mathbf{DM}} h^2 \approx 0.1$
- This kind of (hot) DM cannot reproduce correctly the observed structure in the Universe; galaxies would be too young

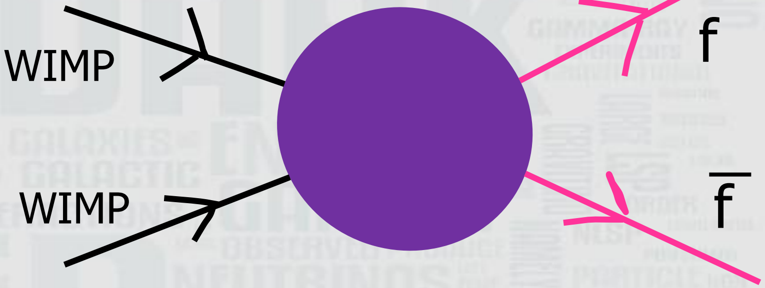
This is a clear indication that we need to go

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

✷ A stable and neutral WIMP is a good candidate for DM, since it 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:

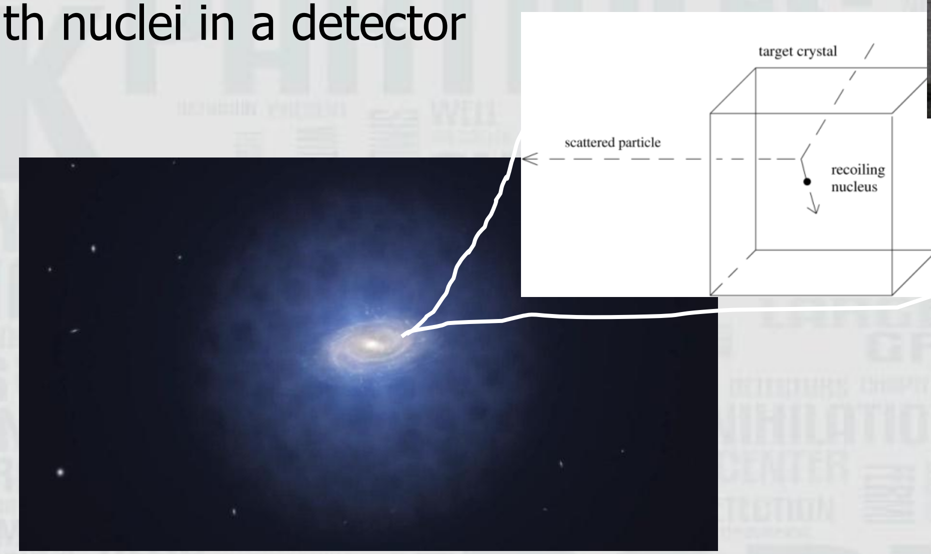
$$\Omega_{\mathrm{WIMP}} h^2 \sim \frac{3 \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\sigma_{\mathrm{ann}} v} \sim 0.1$$

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

DIRECT DETECTION

DAMA/LIBRA photo

through elastic scattering with nuclei in a detector is possible



- $\rho_0 \sim$ **0.3 GeV/cm^3**
- **$v_0 \sim$ 220 km/s**

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

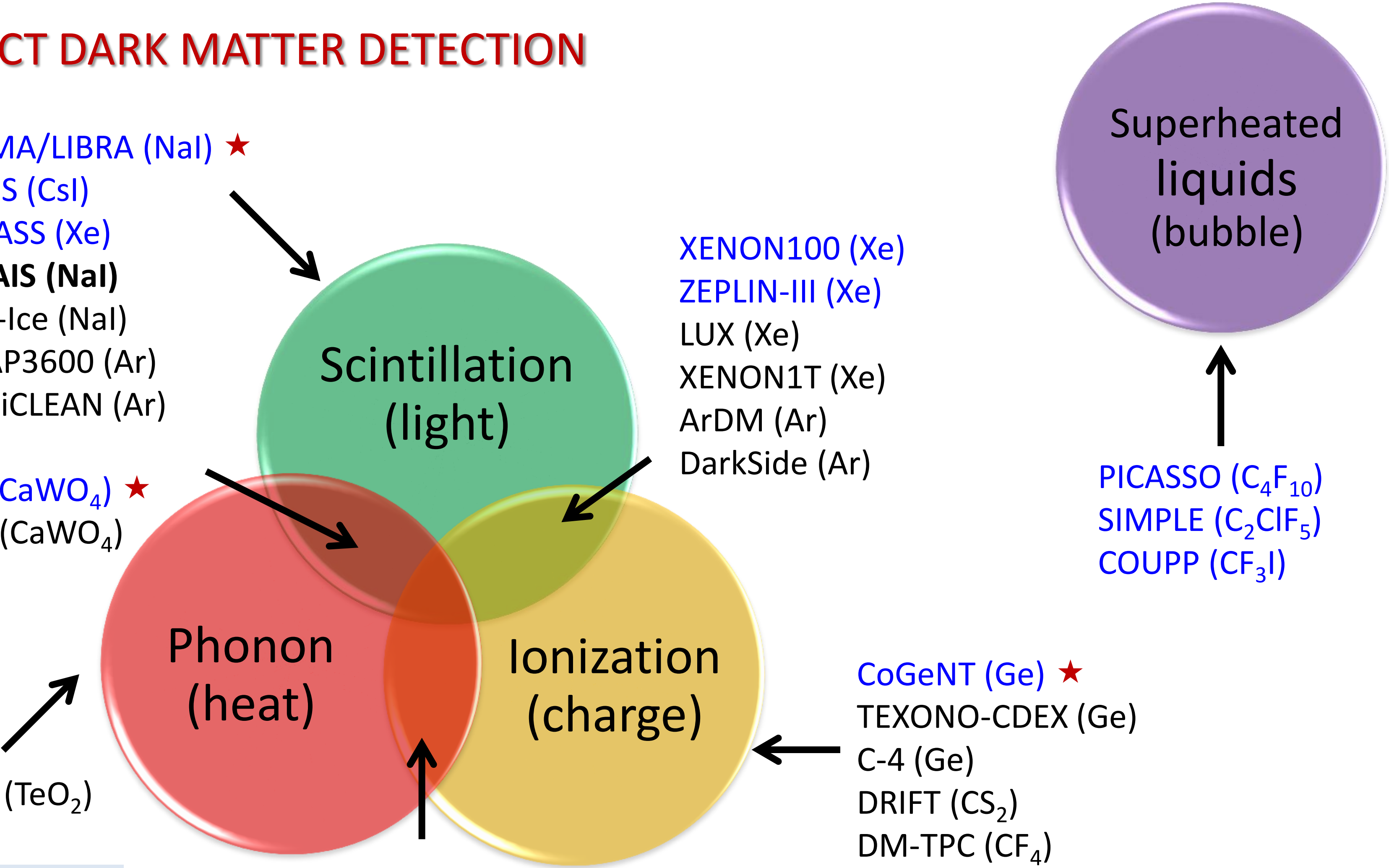
For $\sigma_{\text{WIMP-nucleon}} \approx 10^{-8}$-$10^{-6}$ pb a material with nuclei composed of about 100 nucleons, i.e. $m_N \sim 100$ GeV

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

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

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

DIRECT DARK MATTER DETECTION



DAMA/LIBRA (NaI) ★
KIMS (CsI)
XMASS (Xe)
ANAIS (NaI)
DM-Ice (NaI)
DEAP3600 (Ar)
MiniCLEAN (Ar)

XENON100 (Xe)
ZEPLIN-III (Xe)
LUX (Xe)
XENON1T (Xe)
ArDM (Ar)
DarkSide (Ar)

CRESST ($CaWO_4$) ★
EURECA ($CaWO_4$)

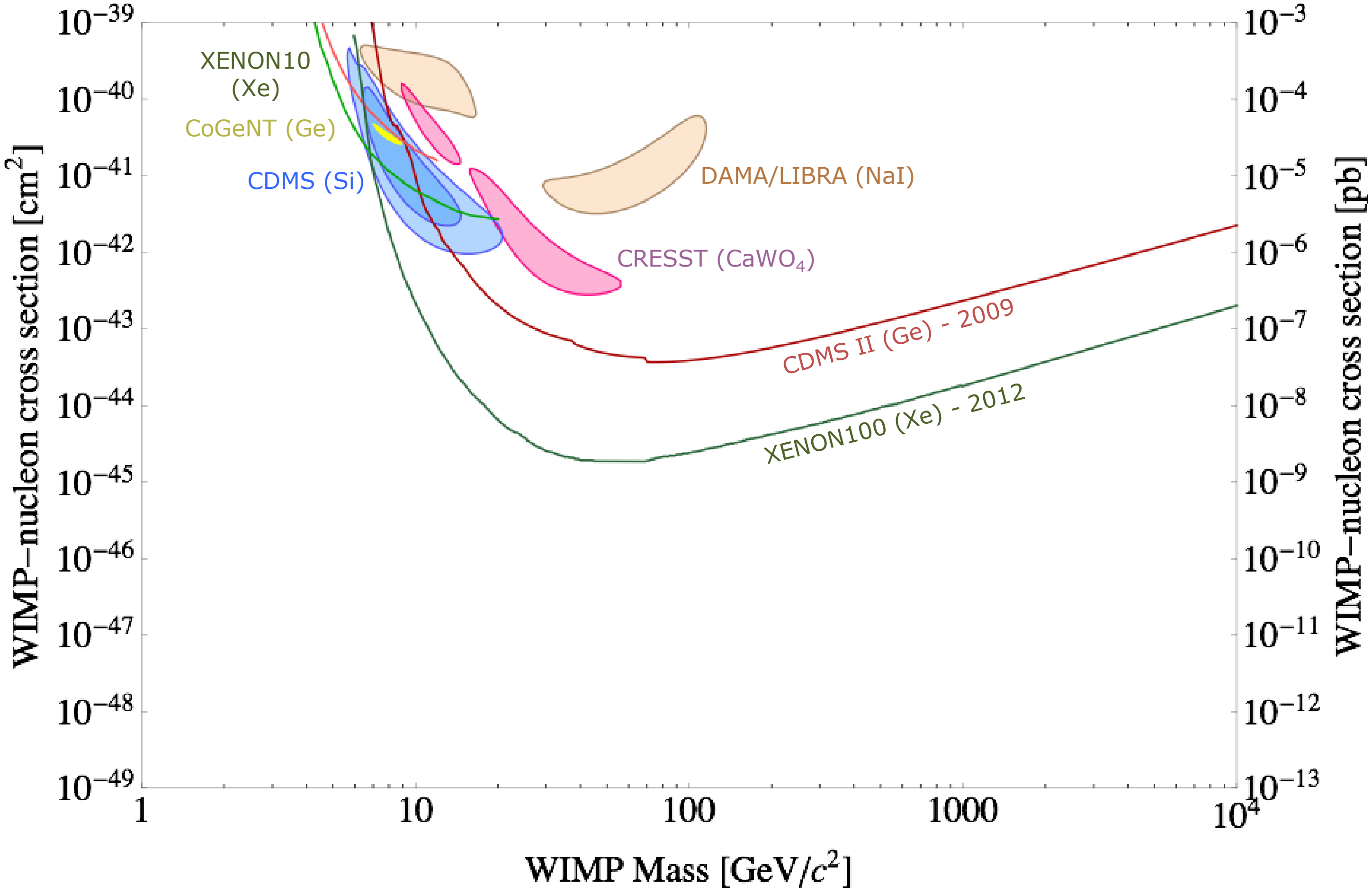
PICASSO (C_4F_{10})
SIMPLE (C_2ClF_5)
COUPP (CF_3I)

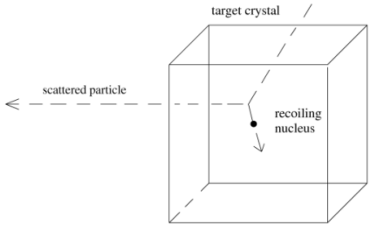
CUORE (TeO_2)

CoGeNT (Ge) ★
TEXONO-CDEX (Ge)
C-4 (Ge)
DRIFT (CS_2)
DM-TPC (CF_4)
NEWAGE (CF_4)
MIMAC ($^3He/CF_4$)
MAJORANA (Ge)
GERDA (Ge)

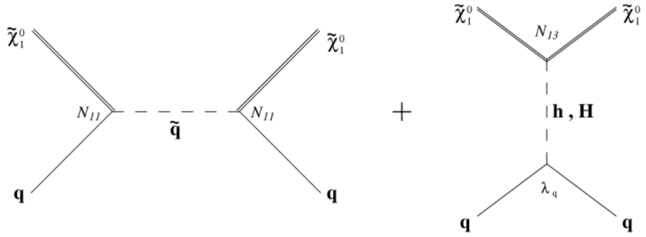
CDMS (Ge, Si★)
EDELWEISS-II (Ge)
SuperCDMS (Ge)
EURECA (Ge)

Present
Future
★ DM hints

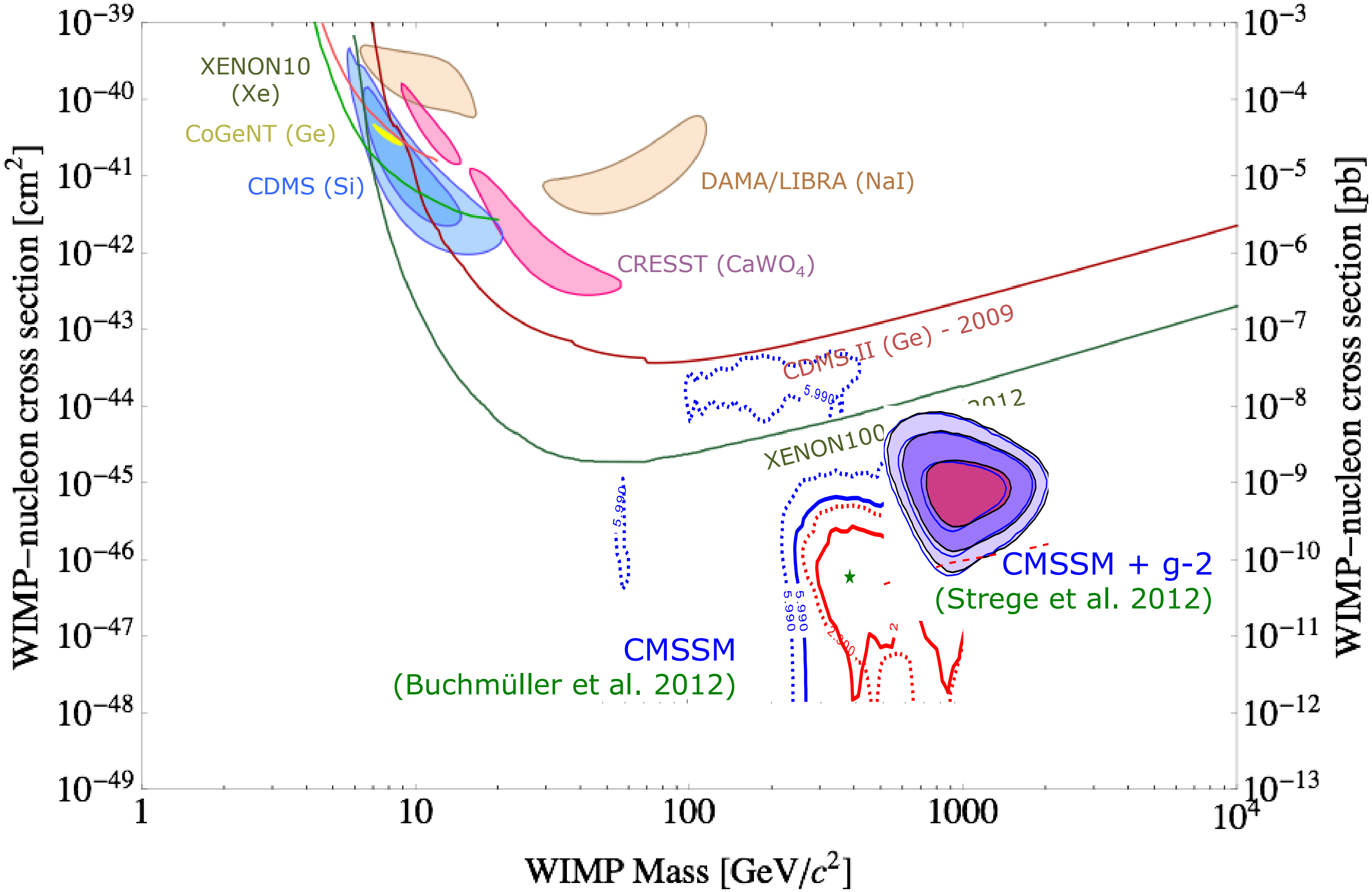

XENON10 (Xe)
CoGeNT (Ge)
CDMS (Si)
DAMA/LIBRA (NaI)
CRESST (CaWO$_4$)
CDMS II (Ge) - 2009
XENON100 (Xe) - 2012
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
1
10
100
1000
10^4



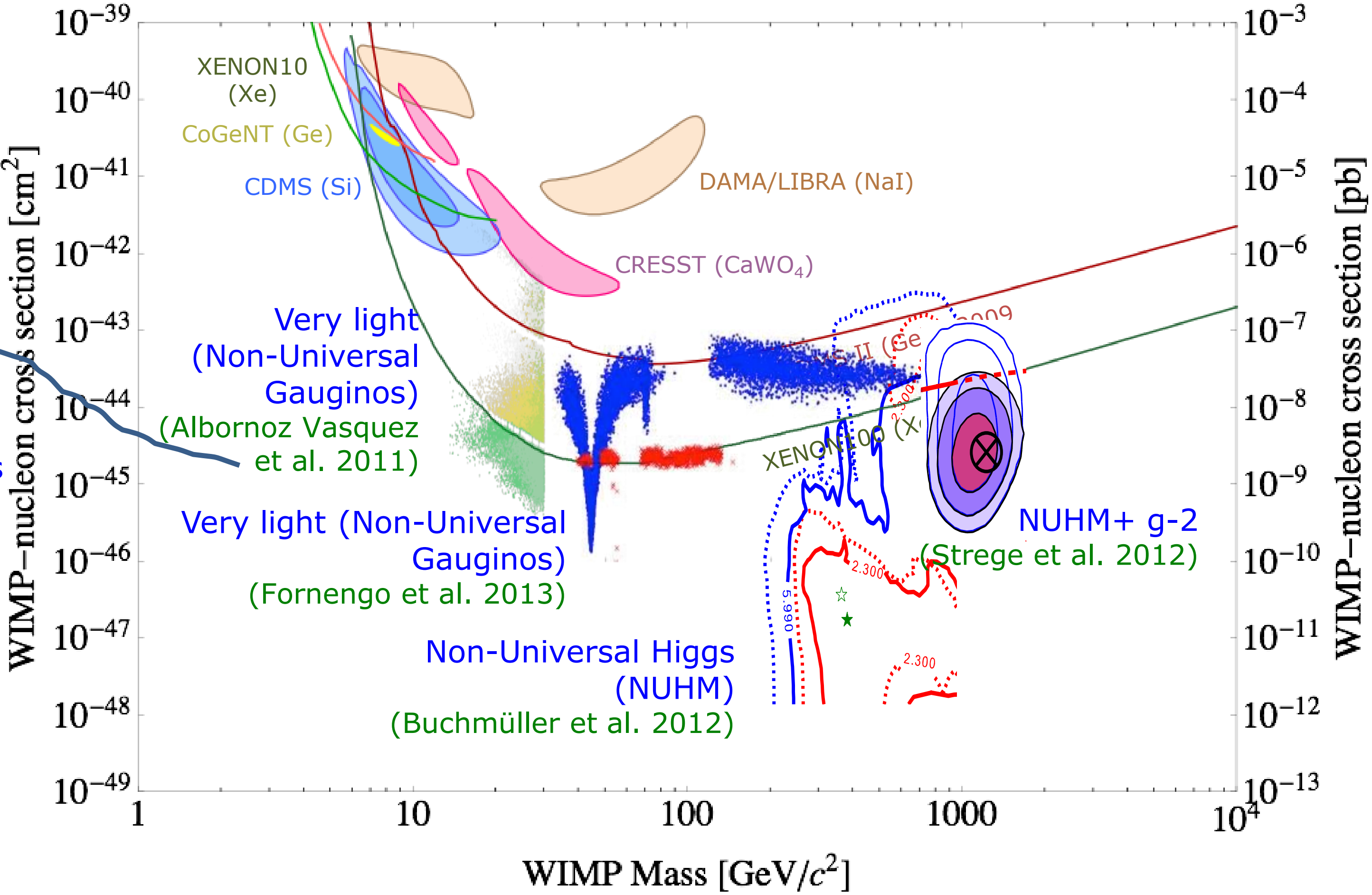
Supersymmetry



Neutralino in the (Constrained) MSSM



Neutralino in the MSSM – Unconstrained scenarios



without the recent constrains on the Higgs sector,
like the 125 GeV Mass, and the invisible Higgs decay

Neutralino in the Next-to-MSSM (NMSSM)

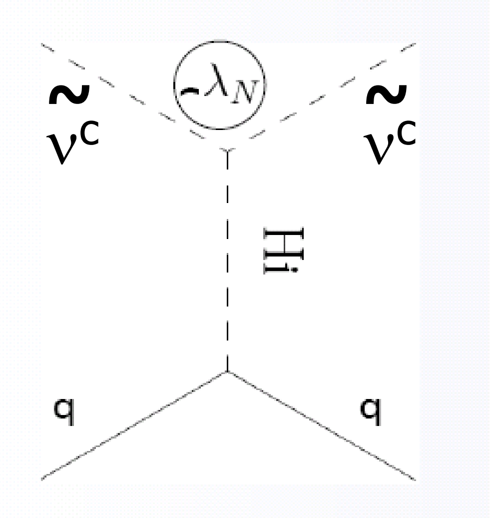
$$W=\mu H_1 H_2 \longrightarrow \lambda N H_1 H_2$$

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

Light **Bino-singlino** neutralinos are possible

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 RH sneutrino implies scattering cross section too small, relic density too large, here the N provides efficient interactions of sneutrino too

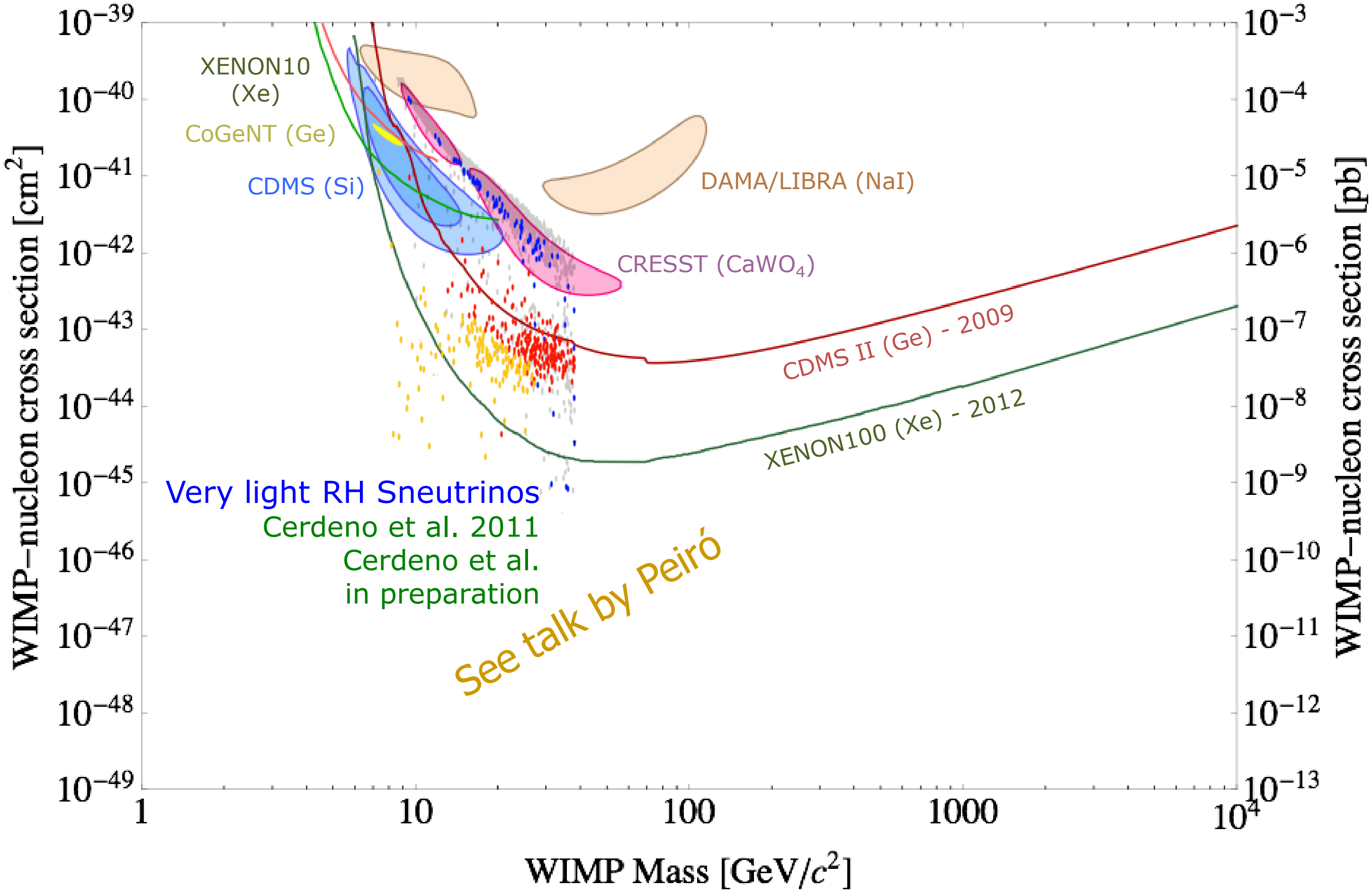
- ○ Viable, accessible and not yet excluded

  (Cerdeño, C.M., Seto '08)

- ○ Light sneutrinos are viable and distinct from MSSM neutralinos

  (Cerdeño, Seto '09)

Right-handed sneutrino in the Next-to-MSSM

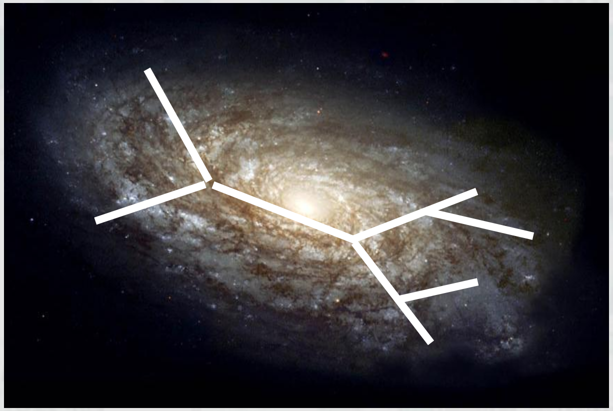


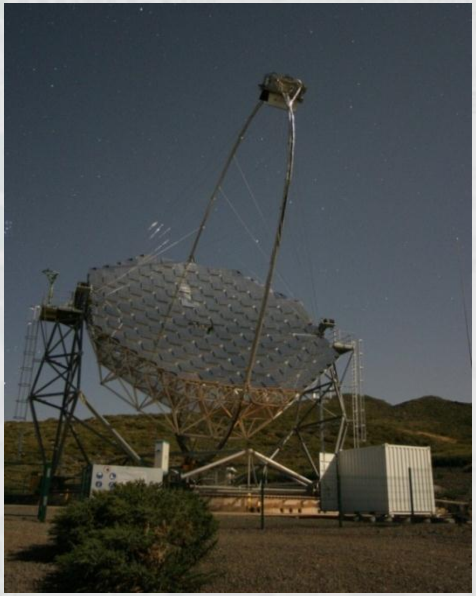
Very light RH Sneutrinos
Cerdeno et al. 2011
Cerdeno et al.
in preparation

See talk by Peiró

INDIRECT DETECTION

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





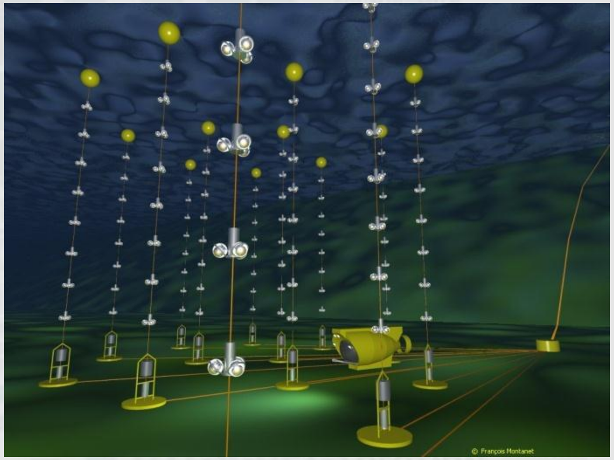
and these can be measured
in space–based detectors:
Fermi (gammas),
PAMELA, AMS (antimatter)

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

See talk by Doro

- Also neutrino telescopes like ANTARES or ICECUBE can be used for detecting DM annihilation from the Sun, Earth or galactic center

See talks by Zornoza & Taboada

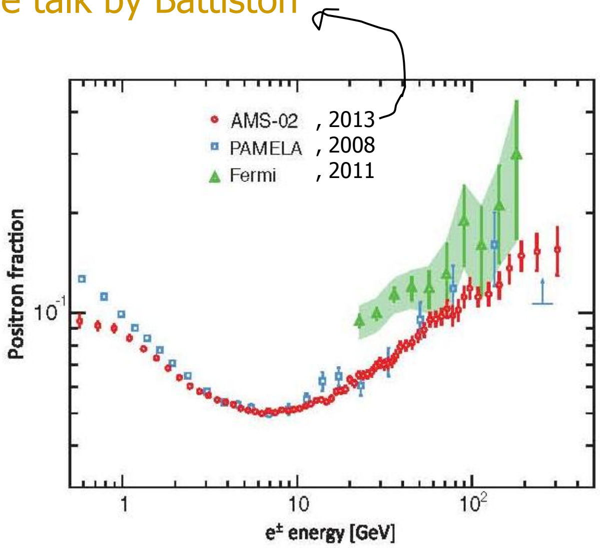


Synchrotron emission from electrons and positrons generated by DM annihilation in the galactic halo, when interacting with the galactic magnetic field, can be measured in radio surveys

See talk by Lineros

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

See talk by Battiston



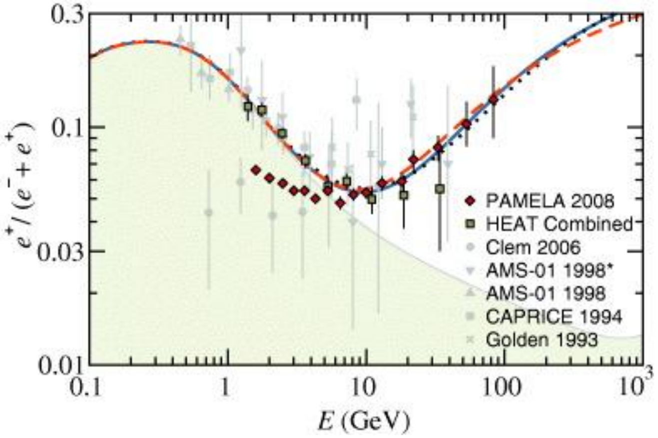
problems with the DM explanation:

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

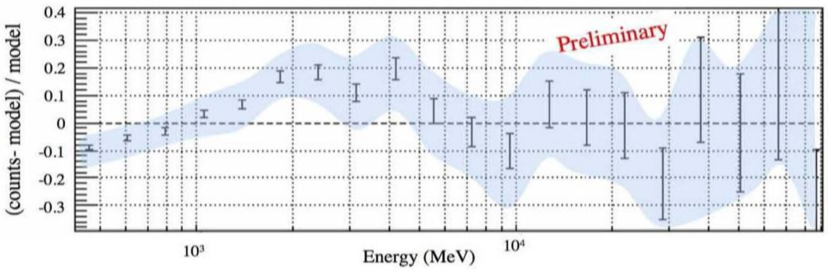


Fig. 4. – Residuals ((exp.data - model)/model) of the above likelihood analysis. The blue area shows the systematic errors on the effective area.

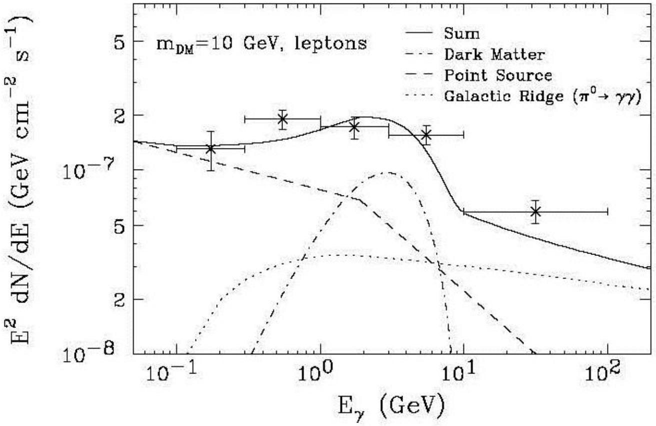
But conventional astrophysics in the galactic center is not well understood. An excess might be due to the modeling of the diffuse emission, unresolved sources, etc.

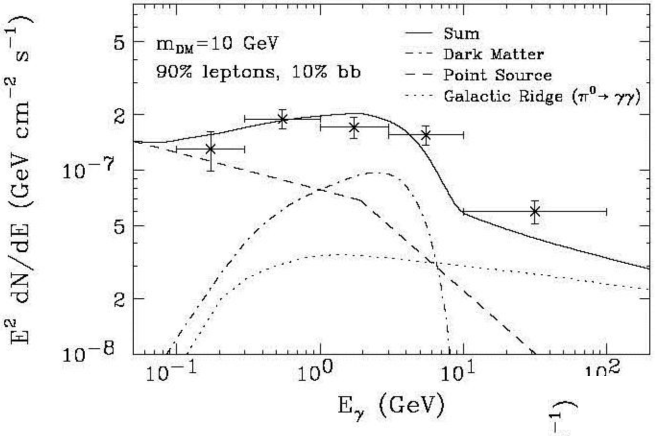
Assuming an excess, and that the DM density in the inner galaxy is $\rho(r) \sim \rho_0/r^{\gamma}$, one can deduce possible DM examples reproducing the observations

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

particle physics

astrophysics

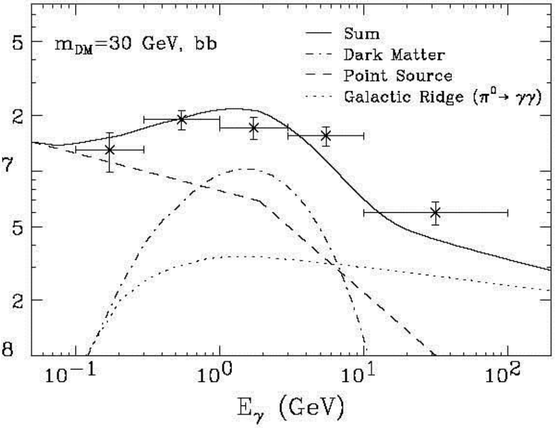




Hooper, Goodenough, 1010.2751
Hooper, Linden, 1110.0006

$\gamma \sim 1.3$

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



But there are other possible explanations:

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

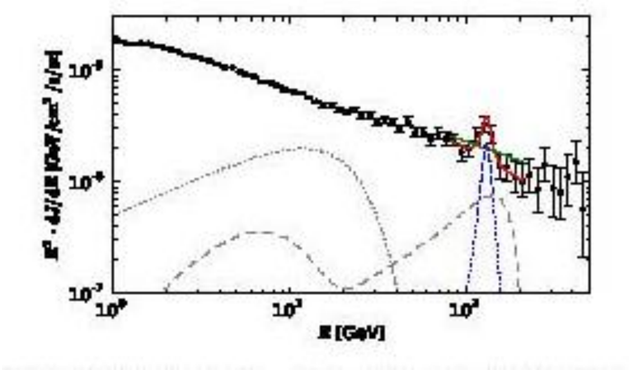
-Cosmic-ray effects, Chernyakova 1009.2630

-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.

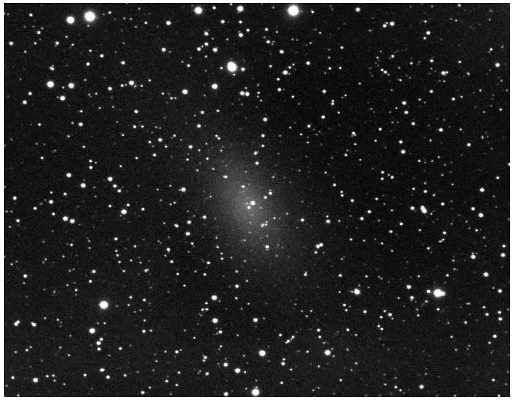
In regions close to the Galactic Center he found an indication for a gamma-ray line at an energy ~ 130 GeV



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

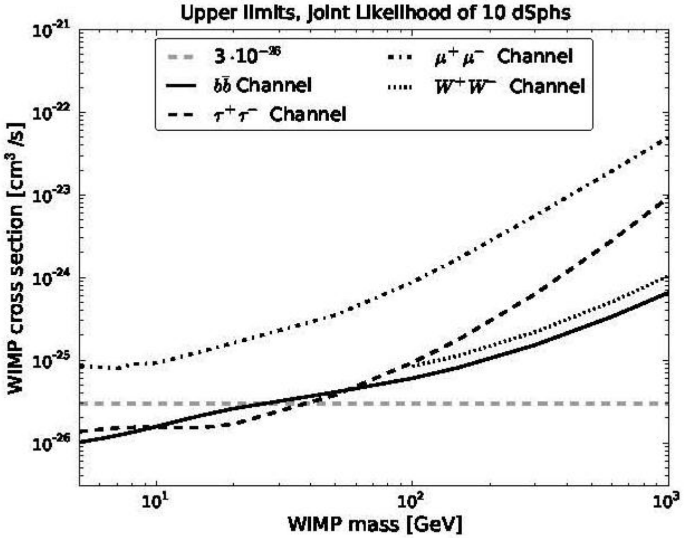
one can constrain DM particle properties:

WIMPs are ruled out to a mass of about

27 GeV for the bb channel

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

See the talk by Cuoco for similar results using Fermi-LAT Galactic halo observations, 1205.6474



$\sigma_{ann}v \sim 3 \times 10^{-26}$ 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 ($\sim 3\cdot 10^{-26}\,\mathrm{cm^3 s^{-1}}$ for a purely s-wave cross section) is plotted as a reference. Uncertainties in the J factor are included.

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:

Geringer-Sameth,
Koushiappas, 1108.2914

Fermi-LAT, 1002.2239

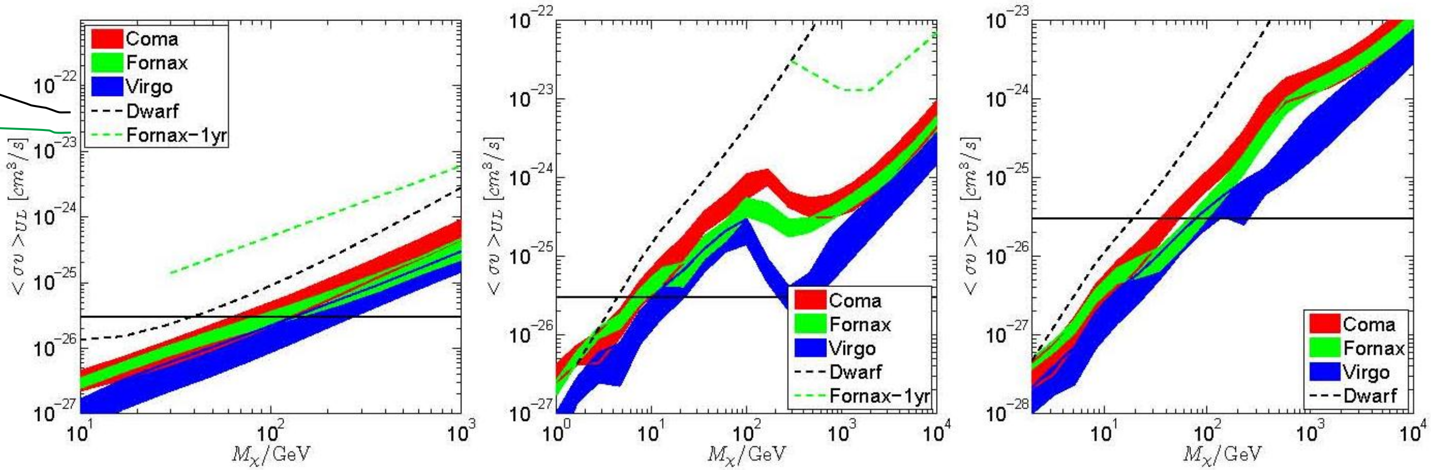


Figure 10. Upper limits for the DM annihilation cross-section in the $b\bar{b}$ (left), $\mu^+\mu^-$ (middle), and $\tau^+\tau^-$ (right) channels, after including the effect of undetected point sources. Line styles are as in Fig. 6, but only the EXT results are shown. Note that the lower bounds of each 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

Fermi-LAT measurements of anisotropies in the diffuse gamma-ray background can also have implications for dark matter constraints

See talk by Gómez-Vargas

Let us analyze **again** 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 behaviour of NFW might be modified $\rho \longrightarrow 1/r$ making steeper: $1/r^{\gamma}$

Cerdeño, Huh, Klypin, Mambrini, C.M., Peiró, Prada,
Gómez-Vargas, Morselli, Sánchez-Conde
Preliminary results

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 $\rho \rightarrow 1/r^{1.37}$

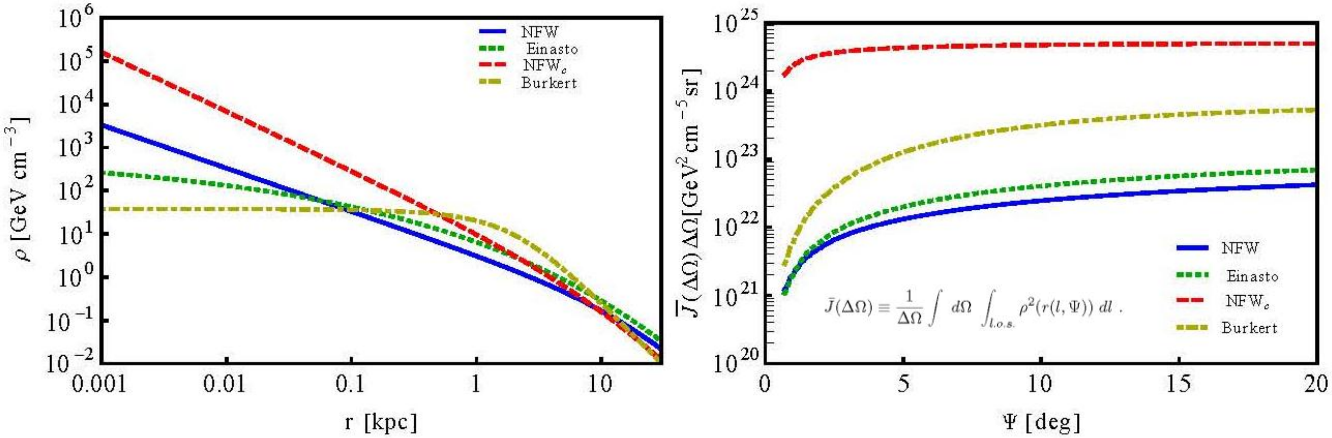


Figure 1: Left panel: DM density profiles used in this work, with the parameters given in Table 1. Right panel: The $\bar{J}(\Delta\Omega)\Delta\Omega$ quantity integrated on a ring with inner radius of 0.5 deg (~ 0.07 kpc) and external radius of Ψ ($R_\odot \tan\Psi$) for the DM density profiles given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

The theory

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

to be compared
with the observations

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!

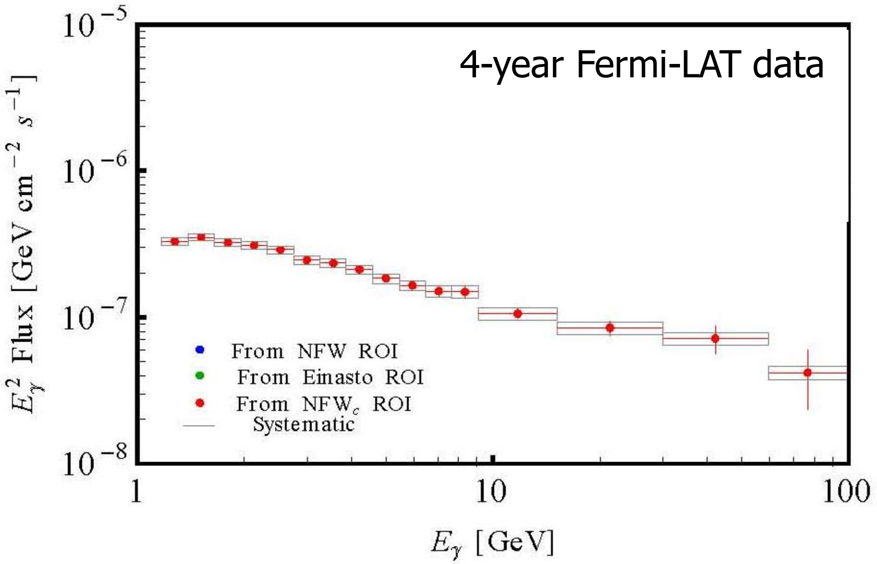
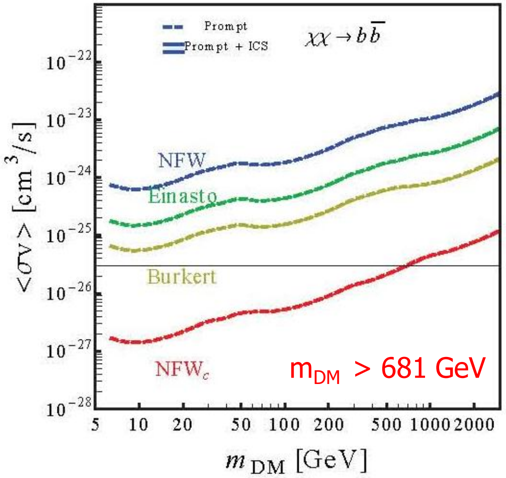
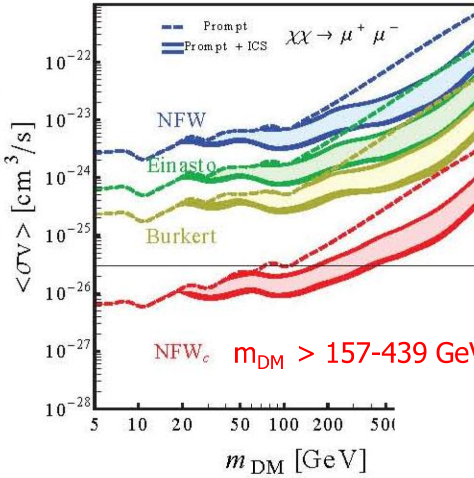


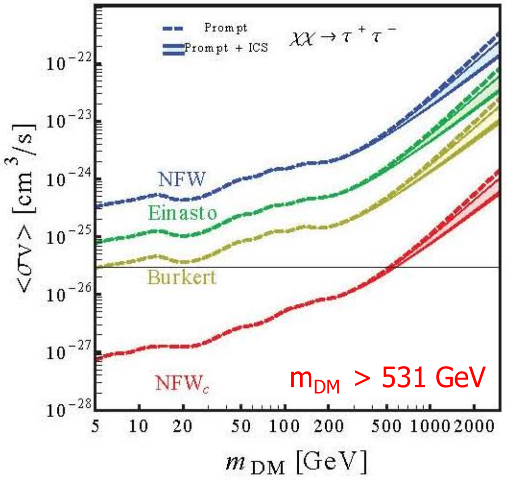
Figure 4: Energy spectrum extracted from Fermi-LAT data for the optimized regions that are shown in Figure 3. Data are shown as points and the vertical error bars represent the statistical errors. The latter are in many cases smaller than the point size. The boxes represent the systematic error in the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



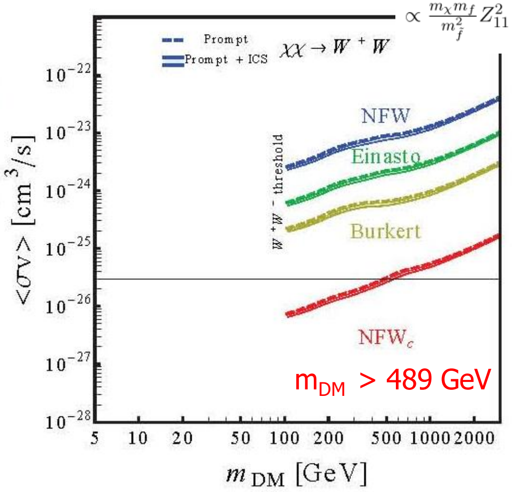
m$_{DM}$ > 681 GeV



m$_{DM}$ > 157-439 GeV



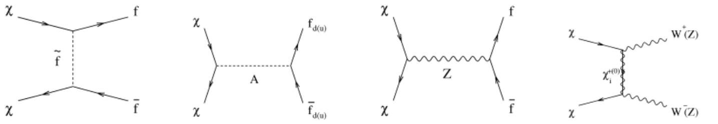
m$_{DM}$ > 531 GeV



m$_{DM}$ > 489 GeV

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% ττ for a Bino DM, and 100% W$^+$W$^-$ for a Wino DM



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

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:

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

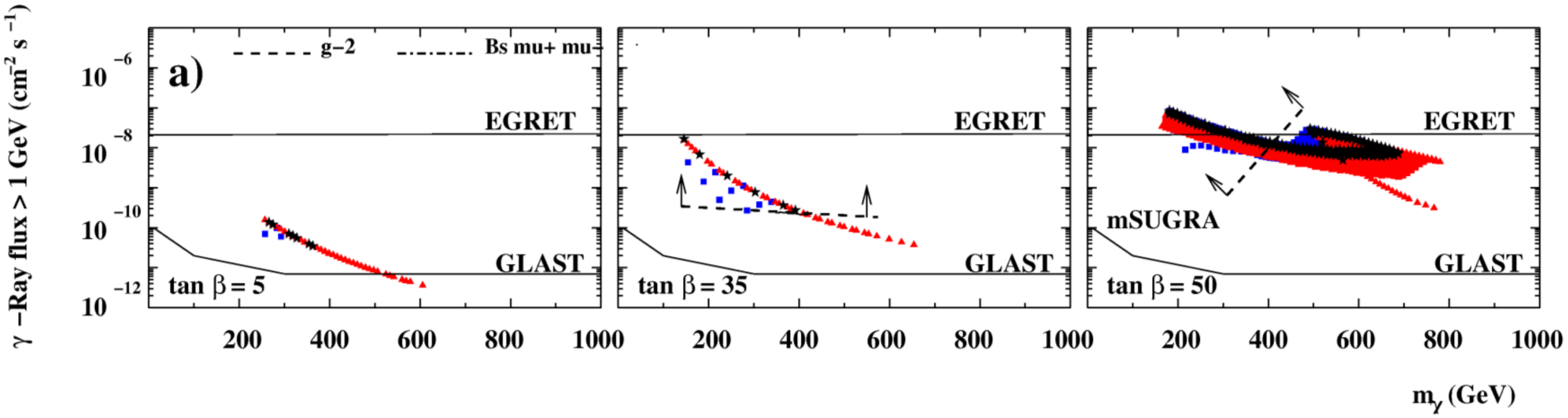
In this sense, the results derived for pure annihilation channels can be interpreted as limiting cases which give an idea of what can happen in realistic scenarios

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, Huh, Klypin, Mambrini, Morselli, C.M., Peiró, Prada, Sánchez-Conde in preparation

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

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

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)

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

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

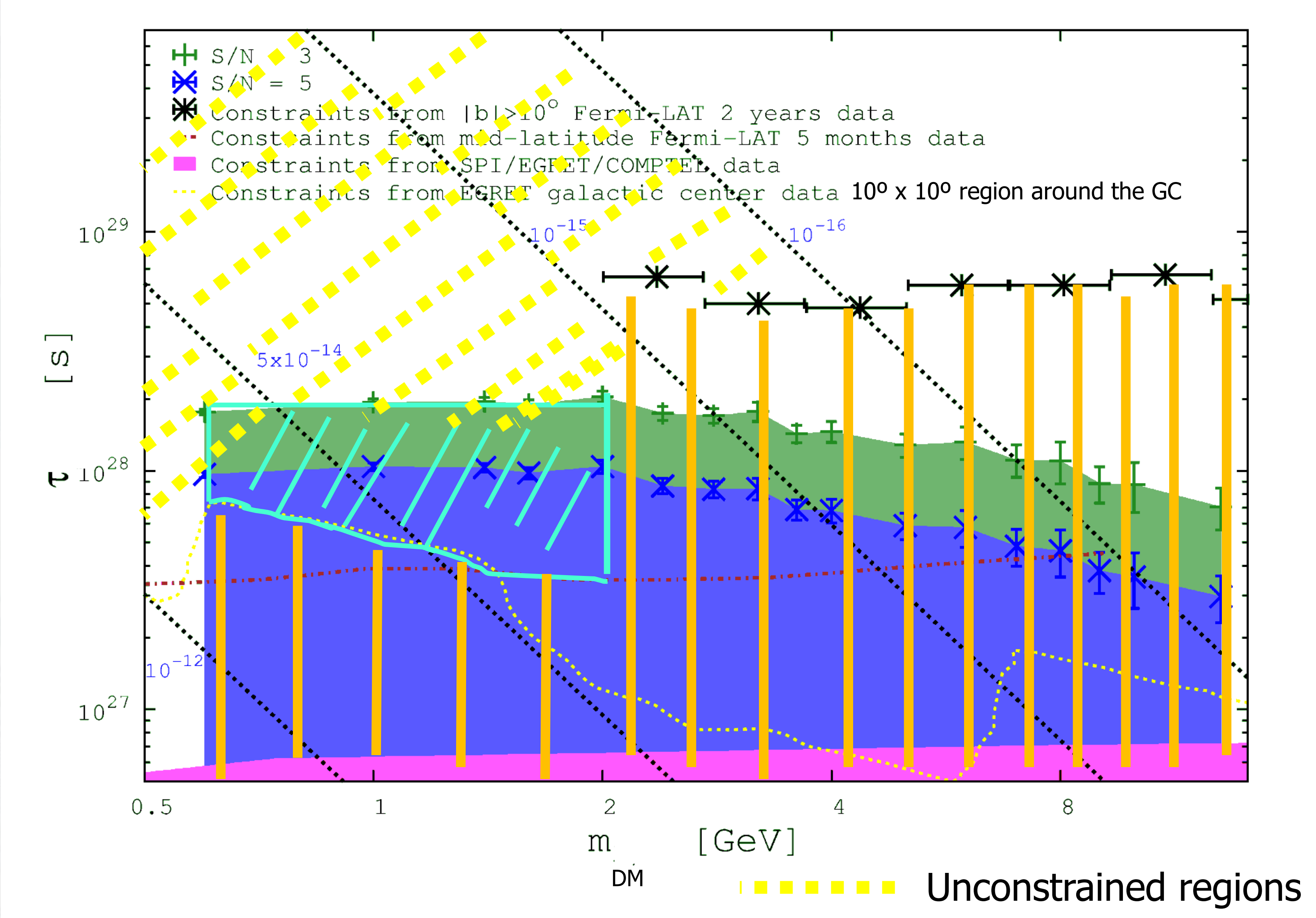
$$W = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_2^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_1^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_1^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\underline{\hat{H}_2^b\,\hat{L}_i^a\,\hat{\nu}_j^c}\right) - \underline{\epsilon_{ab}\lambda^i\,\hat{\nu}_i^c\,\hat{H}_1^a\hat{H}_2^b}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

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

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

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, as well as lifetimes smaller than about 3×10^{27} s.

Conclusions

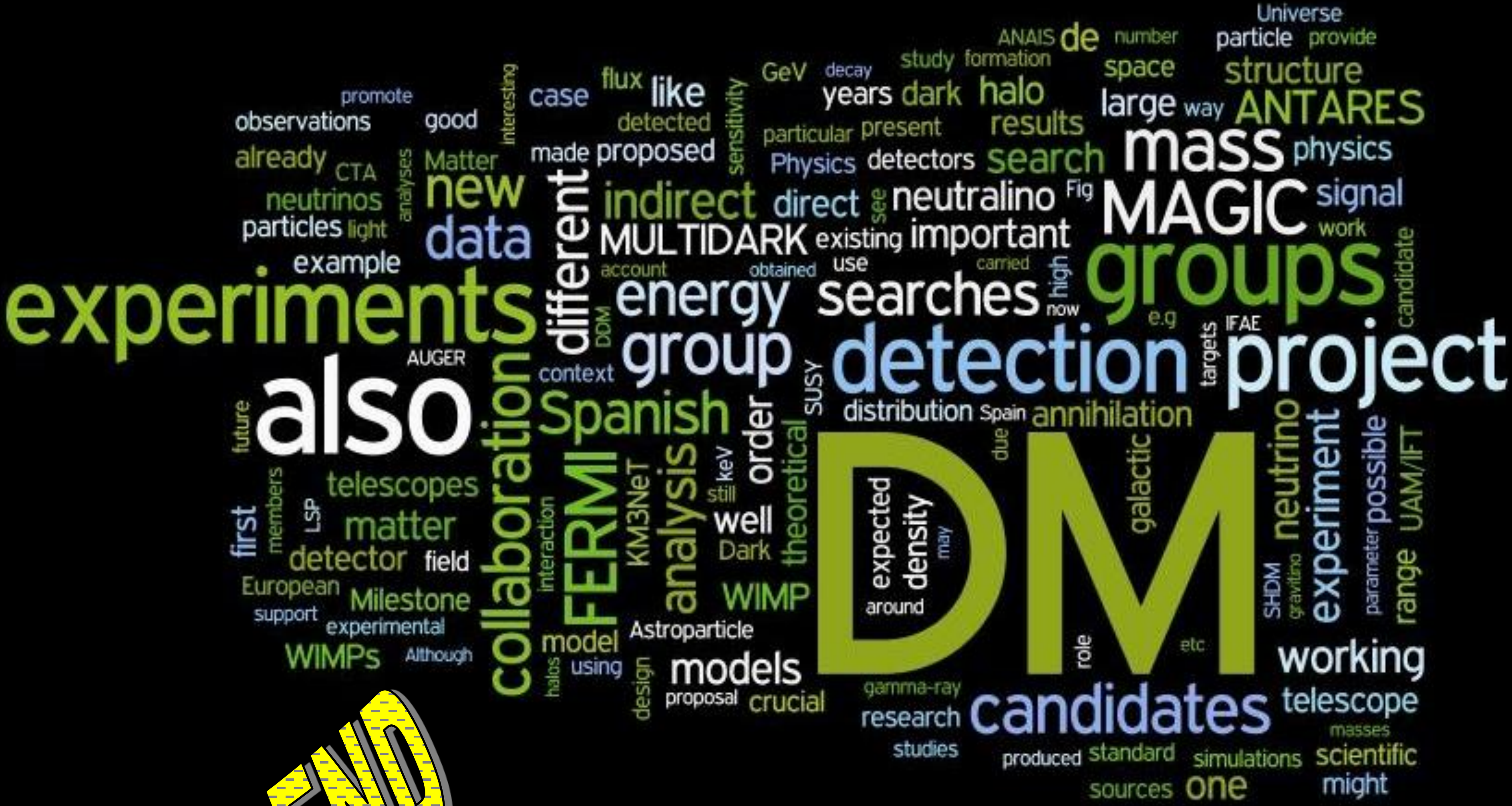
- There are impressive experimental efforts by many groups around the world to detect the dark matter:

DAMA/LIBRA, CoGeNT, CRESST, CDMS, XENON,…, Fermi, PAMELA, AMS, etc.

Thus the present experimental situation is very exciting.

And, besides, the LHC is working

So, stay tuned !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THE END

BACK UP SLICES

But these are DM-only simulations, and 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

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…