# *Dark matter: its origin, nature and propects for detection*

## *Summary of the GGI Workshop*
## *Firenze – 26/IV/2010 - 19/VI/2010*

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Diffuse emissions – PCHE @ IAS, Orsay 8-9/VI/2010


**Born in September 2005**
(close to the Observatory):
« The Galileo Galilei Institute for Theoretical Physics (GGI) organizes and hosts small-size advanced workshops in theoretical particle physics in its broadest sense.Each workshop is devoted to a specific topic at the forefront of current research. During its typical duration of 2-3 months it hosts about 10 to 30 participants selected among those most active in the field within the international community. The purpose of each workshop is to foster discussions, confrontation of ideas, and collaborations among participants. »

**Recent workshop (for a taste):**
2009: Searching for new physics at LHC
2009: New perspectives in string theory
2009: New horizons in modern cosmology
2008: Low dimensional QFT and applications
2008: Non-Perturbative methods in strongly coupled gauge theories
Etc.

**This Workshop :**
~ 10-20 participants / week
~ 3 seminars (black board) / week

+++ Conference 17-21/V/2010
The Dark Matter Connection: Theory and Experiment

# *Do we need Dark Matter ?*

• **Strong observational indications based on gravitational effects**
e.g. rotation curves of galaxies, masses of galaxy clusters, CMB

• **Theoretical indications from structure formation**
⇒ despite a few issues, the CDM (or wDM) scenario leads to structures impressively close to what we observe on large scales (the N-body advent)
⇒ though still empirical, including baryons in simulation does not seem to rule out the scenario (debate on small scales: the connection with Dwarph Spheroidals, cusps in galaxy centers)

➡ **From the current understanding, we can fairly answer yes++, while remaining open to other explanations**

# *Some small scale issues for CDM*

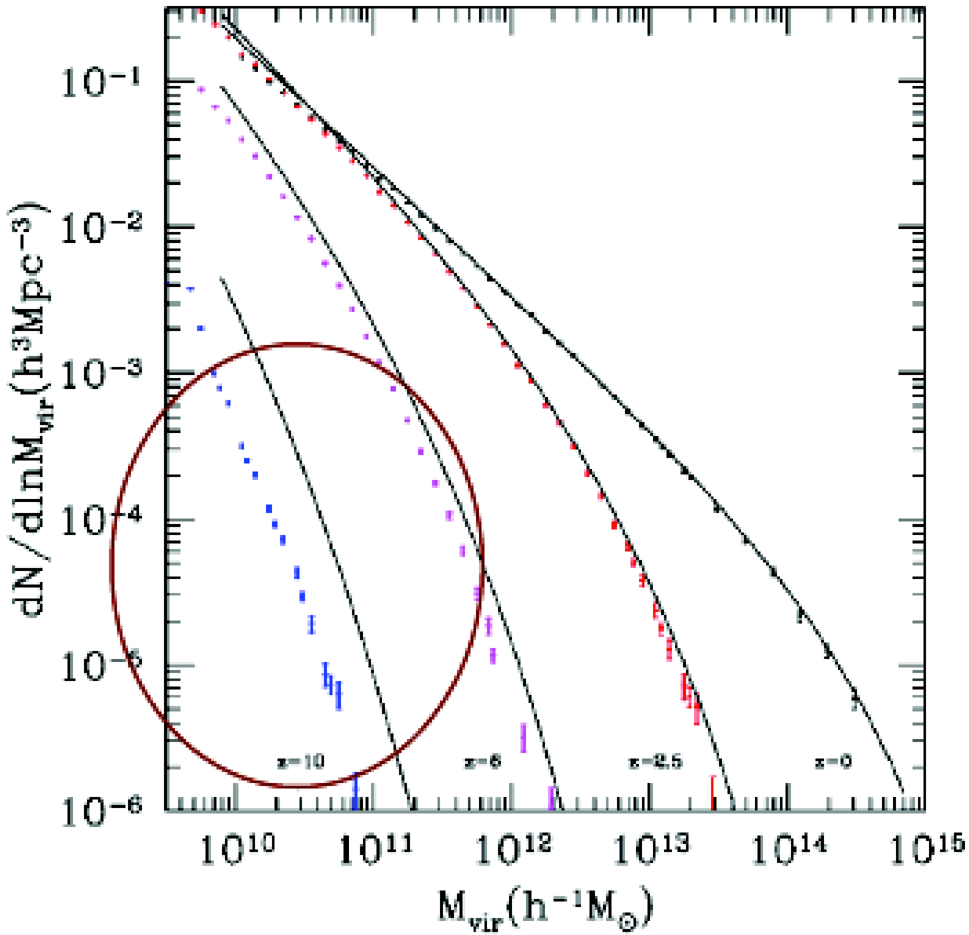
- Over-production of Dwarf Galaxies ($\neq$subhalos !) at z=0

- Under-production of small-scale structures at z > 5
$\Rightarrow$ issue for re-ionization

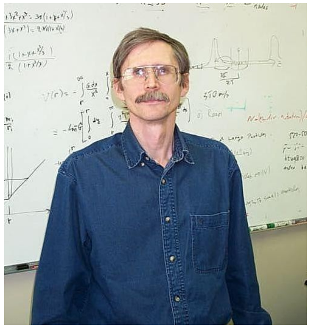
- Baryons: adiabatic compression of the DM density profile in the centers of galaxies
$\Rightarrow$ might be solved with higher resolution and gas density threshold for star formation, though there are still very large theoretical uncertainties

# Some small scale issues for CDM

**Anatoly Klypin @ GGI (from Klypin et al 10)** *Problems*



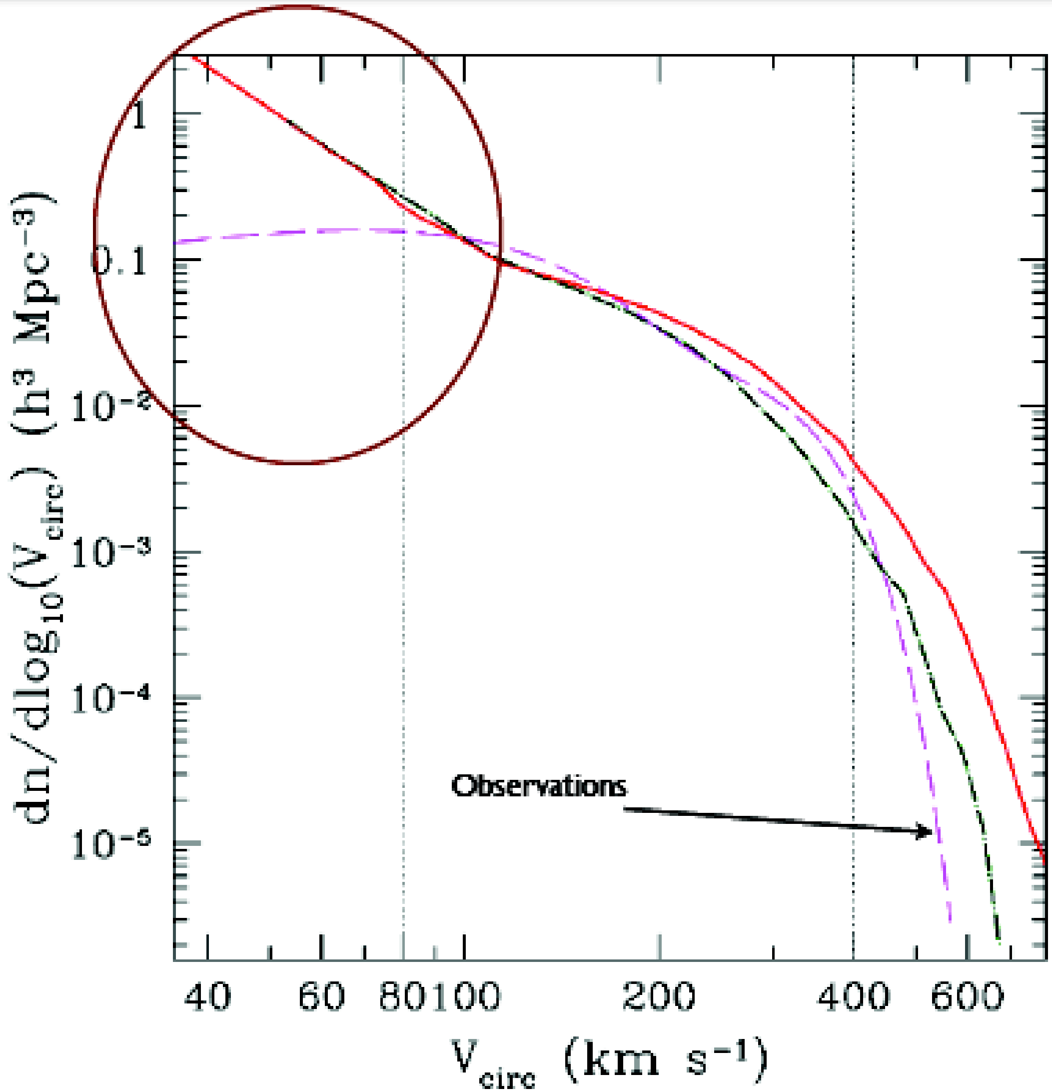

Mass function of halos at z=6-10: too low for models of re-ionization



Full: Sheth&Tormen
Symbols: N-body Bolshoi, Spherical overdensity

# *Some small scale issues for CDM*

## Number of galaxies with Vcirc: observations vs LCDM



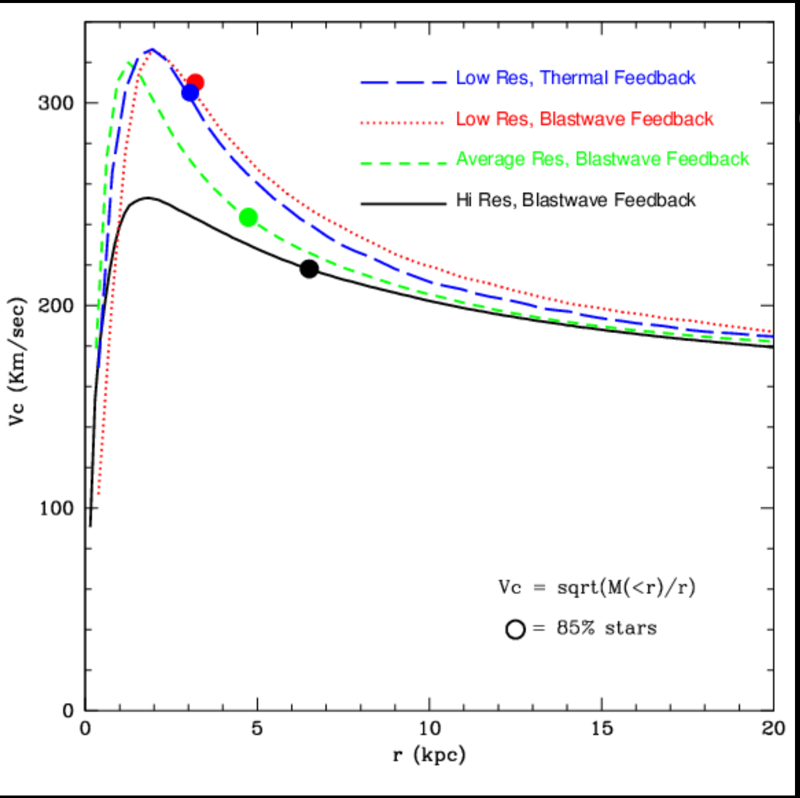

Overabundance of dwarf galaxies with Vcirc =50km/s

**This is a different and much worse problem as compared with the 'satellites' overabundance.**

**Anatoly Klypin @ GGI (from Klypin et al 10)**

# The mass concentration problem in cosmological simulations of galaxy formation

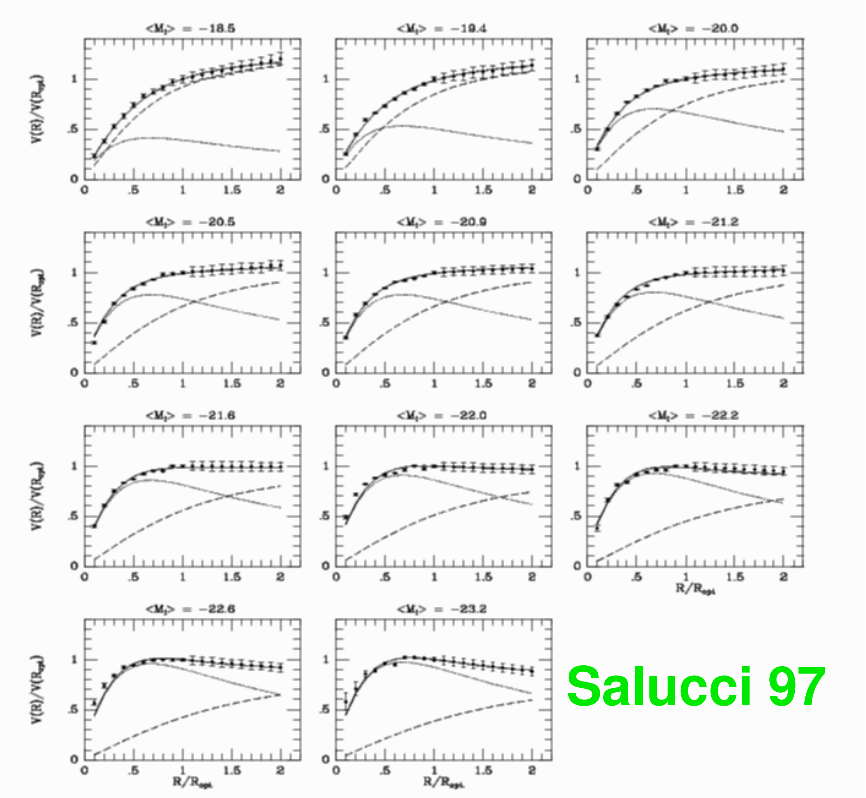
Simulations




Mayer et al. 2008

---→ implied inner slope ~ $r^{-2}$

Observations

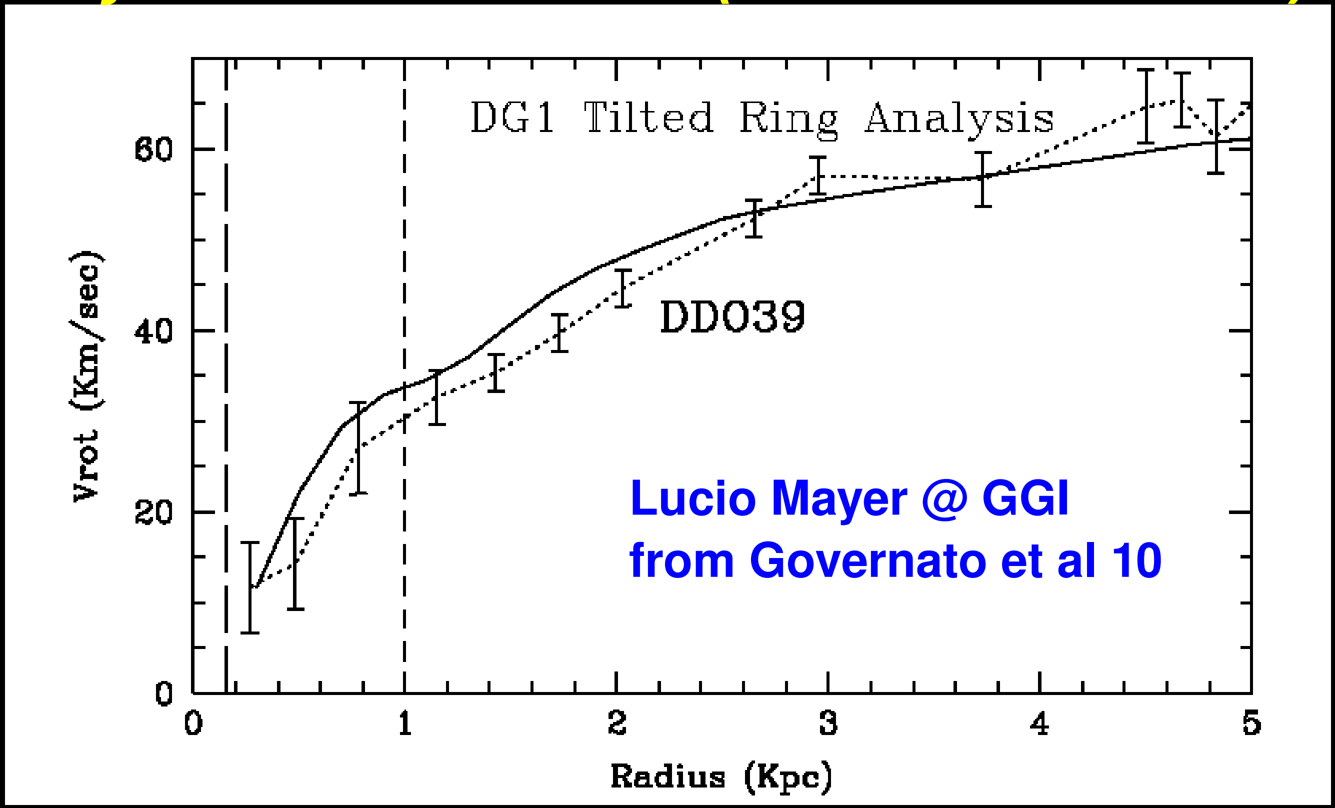



Salucci 97

- Simulations that model collisionless dark matter + dissipational baryonic component with radiative cooling, heating, star formation, feedback processes
- Even more fundamental than the cusp-core problem because it involves the form of the mass distribution at large radii where data more robust

Lucio Mayer @ GGI

# *A slowly rising rotation curve produced: high density threshold for SF (> 100 atoms/cm3) – needs hi-res*




**How?**

**(1) Removal of baryons (baryonic disk mass fraction ~ 0.04 at z=0, so 4 times lower than cosmic fb) + (2) flattening of dark matter profile**

**-- During strongest outflows (at z > 1) inner dark matter mass expands as a result of impulsive removal of mass + transient gas clumps transfer energy due to dynamical friction**

***(confirms earlier models of e.g. Navarro et al. 1996; Read et al. 2003; Maschchenko et al. 2008 – see also Ceverino & Klypin 2009)***

***Dark matter density decreases by a factor of ~ 2 at r < 1 kpc and density profile becomes shallower ~ $r^{-0.5}$ rather than ~ $r^{-1.3}$***

# CDM: connection with BSM Particle Physics

**Present "Observational" Evidence for New Physics**

- NEUTRINO MASSES ☆☆☆
- DARK MATTER ☆☆☆
- MATTER-ANTIMATTER ASYMMETRY ☆☆
- INFLATION ☆

**THEORETICAL REASONS TO GO BEYOND THE SM**

- *FLAVOR PUZZLE* → RATIONALE FOR FERMION MASSES AND MIXINGS
- *UNIFICATION PROBLEM* → NO REAL UNIF. OF ELW.+STRONG INTERACTIONS +GRAVITY LEFT OUT OF THE GAME
- *HIERARCHY PROBLEM(S)* →
- ULTRAVIOLET COMPLETION OF THE SM TO (NATURALLY) STABILIZE THE ELW. BREAKING SCALE
- TUNING OF THE COSMOLOGICAL CONSTANT
- STRONG CP PROBLEM ( TUNING OF THE QCD θ ANGLE)

+ strong CP pb : axions required !

**The Energy Scale from the "Observational" New Physics**

neutrino masses, dark matter, baryogenesis, inflation → NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE

**The Energy Scale from the "Theoretical" New Physics**

☆☆☆ Stabilization of the electroweak symmetry breaking at $M_W$ calls for an *ULTRAVIOLET COMPLETION of the SM already at the TeV scale* +

☆ *CORRECT GRAND UNIFICATION "CALLS" FOR NEW PARTICLES AT THE ELW. SCALE*

**Antonio Masiero @ GGI**

# *Dark Matter Candidates ?*

# *Dark Matter Candidates ?*

## *(a bit more seriously)*

A reason for an astrophysicist to feel more comfortable with the particle origin of DM ?

⇒ Most of candidates did not arise to solve the DM issue

(... this is a very recent bias ... sometimes fair ... but often outrageous ...)

Generic feature in BSM theories (SUSY, extra-dim):

- Extend the particle content to solve hierarchy pbs
- Stability of the proton ⇒ discrete symmetry ⇒ stability of the LEP (lightest exotic particle = LSP, LKP, LWYWP, etc.)

Serious candidates (subjective choice)

- Axions (strong CP pb in standard model)
- Sterile neutrinos (neutrino mass)
- SUSY: neutralinos, sneutrinos, gravitinos
- Extra-dim
- Scalar particles somehow connected with neutrino mass

**Detection strategies:** colliders, energy deposite, annihilation or decay products

# DM searches at colliders

## SUSY at the LHC

Final states → Model Parameters

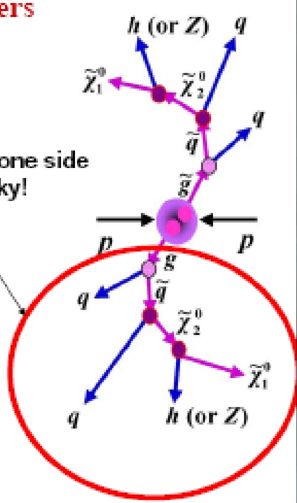
Reconstruct sparticle masses, e.g.,

$$\tilde{Q} \rightarrow q + l + \tilde{\chi}_1^0$$

$$\tilde{L} \rightarrow l + \tilde{\chi}_1^0$$

$$\tilde{\chi}_{2,3,4}^0 \rightarrow Z, h, \bar{l}l + \tilde{\chi}_1^0 \quad \text{etc.}$$

Identifying one side is very tricky!




We may not be able to solve for masses all the sparticles from a model

Solving for the MSSM : Very difficult

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## DM Relic Density in mSUGRA

| | | |
|---|---|---|
| $M_{\tilde{g}}$ | = | 831 GeV |
| $M_{\tilde{\chi}_2^0}$ | = | 260 GeV |
| $M_{\tilde{\tau}}$ | = | 151.3 GeV |
| $M_{\tilde{\chi}_1^0}$ | = | 140.7 GeV |

[1] Established the CA region by detecting low energy $\tau$'s ($p_T^{vis} > 20$ GeV)

[2] Measured 5 SUSY masses ($\Delta M$, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{q}$, $\tilde{g}$ )
gaugino Universality at ~15% (10 fb$^{-1}$)

| | | |
|---|---|---|
| $m_0$ | = | |
| $m_{1/2}$ | = | |
| $\tan\beta$ | = | |
| $A_0$ | = | |
| $sgn(\mu)$ | > | 0 |

[3] Determine the dark matter relic density by determining $m_0$, $m_{1/2}$, $\tan\beta$, and $A_0$

So far using: a) $E_T^{miss}$+ 4$j$
b) $E_T^{miss}$+ 2$j$+2$\tau$

$$\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_0, m_{1/2} \tan\beta, A_0)$$

$$M_{j\tau\tau}^{peak} = X_1(m_{1/2}, m_0)$$
$$M_{\tau\tau}^{peak} = X_2(m_{1/2}, m_0, \tan\beta, A_0)$$
$$M_{eff}^{peak} = X_3(m_{1/2}, m_0)$$
$$? = X_4(m_{1/2}, m_0, \tan\beta, A_0)$$

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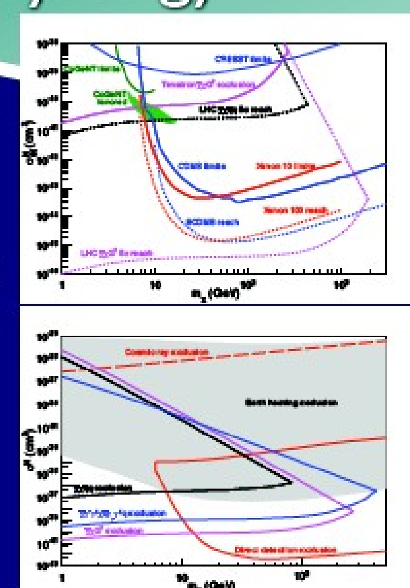
**Bashkar Dutta @ GGI**

**Typical SUSY signatures:**
**jets + n leptons + missing energy**
**Parameter reconstruction only in mSUGRA (fewer parameters)**

## Collider/Direct Synergy

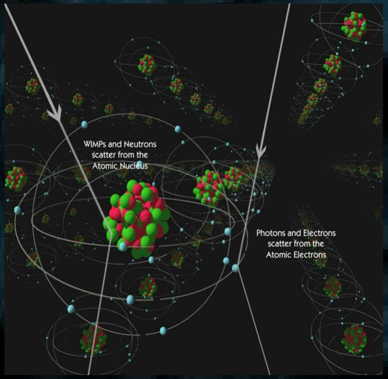
- Spin-independent scattering, colliders and direct searches show a lot of complementarity.
  - Colliders win at low WIMP masses and for gluon interactions.
  - Direct detection can reach much lower cross sections for quark-scattering at ~100 GeV masses.
  - Tevatron already says something about the DAMA/CoGeNT low mass region; LHC will say a lot.
  - Also note: Xenon100 low mass analysis. (which I guess Elena will show us tomorrow).



**Tim Tait @ GGI**

**Constraints on effective model (light Majorana WIMP):**
**Competitive and complementary to direct searches**
**(gluon vs quark operators)**

# *Direct searches*

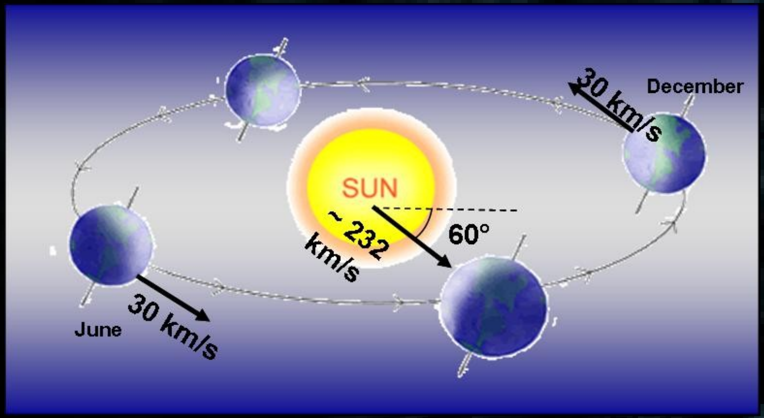



Principle:

• Elastic collision between WIMPs and target atoms: measure the recoil energy

• Cryogenic detectors (NaI, Ge), or 2-phase noble gas detectors (Xe)

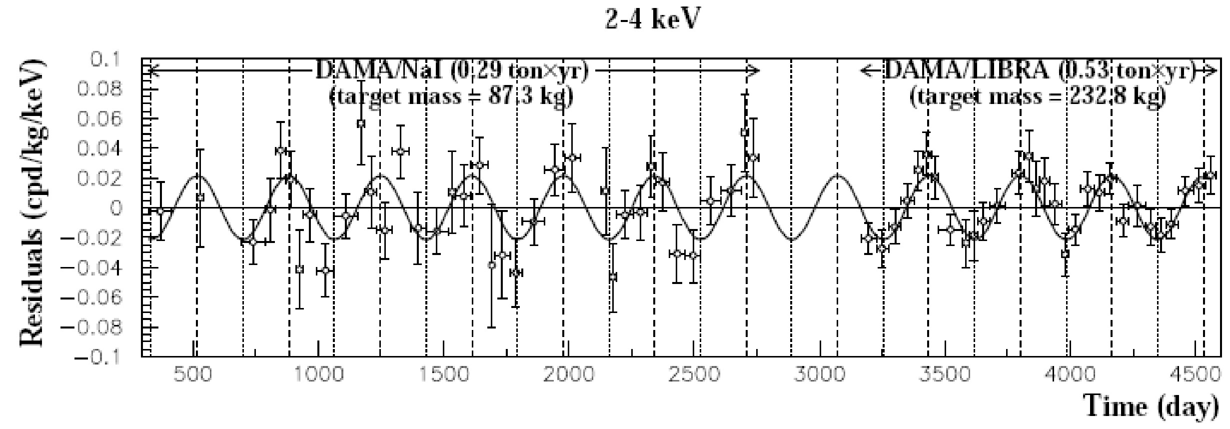
Shield the experiments againts cosmic rays and natural radioactivity: pure material + deep underground




Predicted feature on top of signal: Annual modulation of the amplitude (a few % of the expected DM signal).

# *Direct searches*

The DAMA puzzle: claim for DM detection since 1998

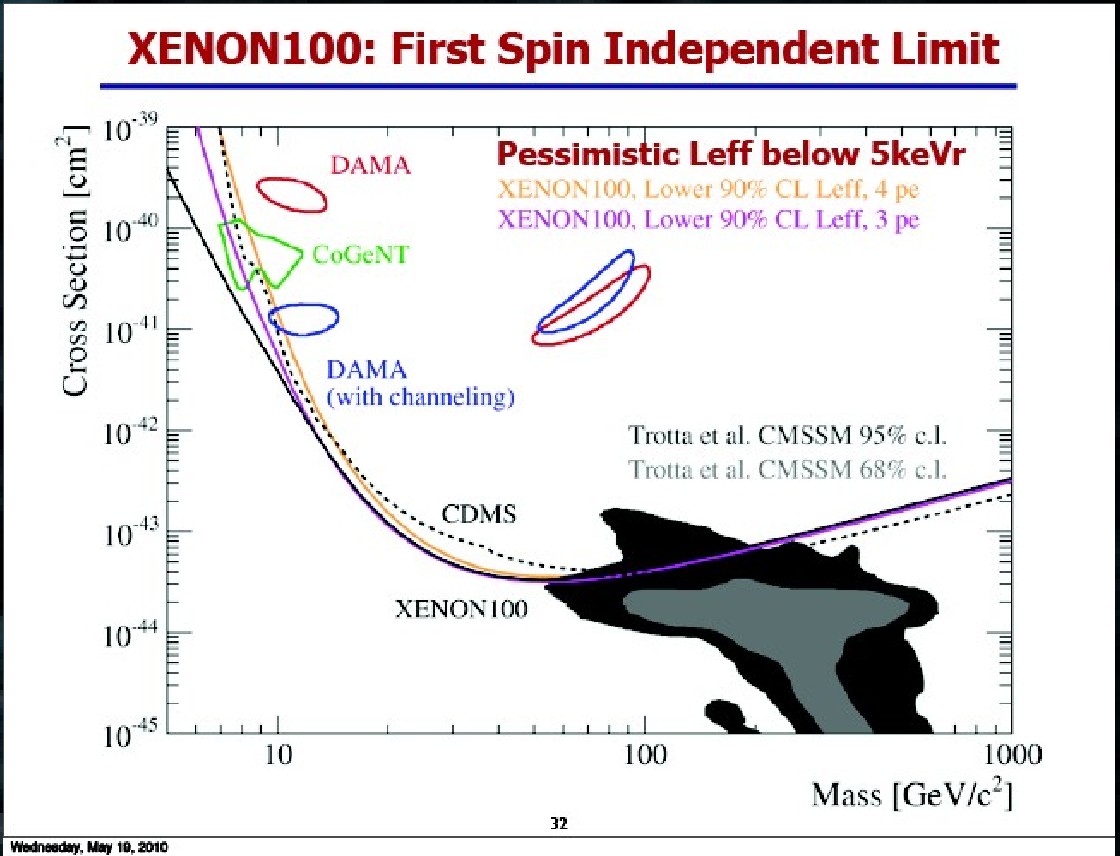



1-year period, peak around June 2nd (day 152.5)
Bernabei et al 08

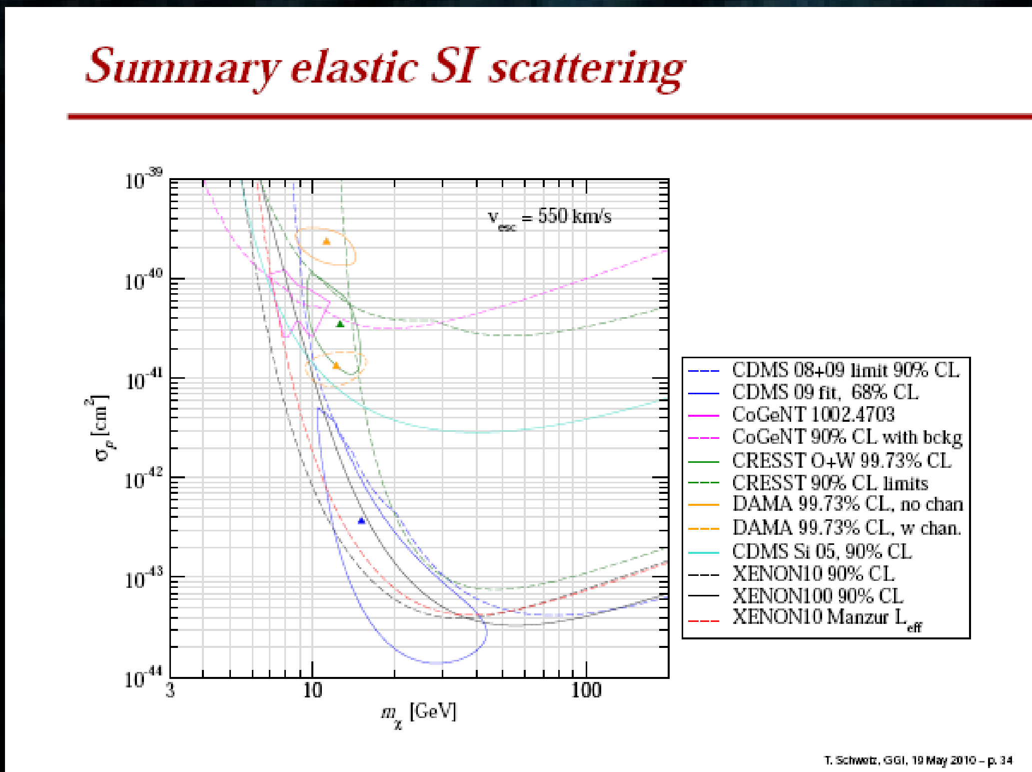
**Pierluigi Belli @ GGI**

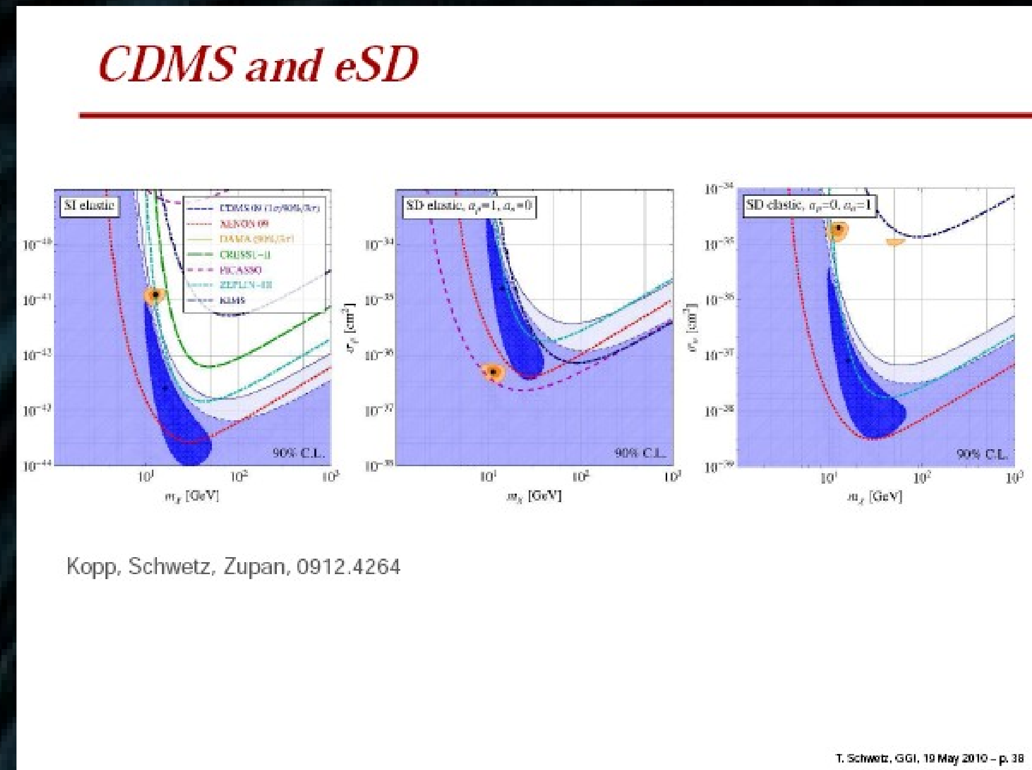
Xenon 100
Located at Gran Sasso (same as DAMA)
Nothing found.

**Elena Aprile @ GGI**



# Direct searches : summary




**Thomas Schwetz @ GGI**

Dark Matter interpretation of experimental results:

- DAMA regions excluded (then what do they see ?)
- Cogent region excluded
- Small window left for CDMS

(but 2 events with 23% background prob)

- DD has still an important discovery potential

# *Theoretical uncertainties for direct searches: The local DM phase-space (density, velocity)*

**From Catena & Ullio 09**

- Numerically we find:

$$\rho_{DM}(R_0) = (0.385 \pm 0.027)\,\mathrm{GeV\,cm^{-3}} \qquad \text{(Einasto)}$$

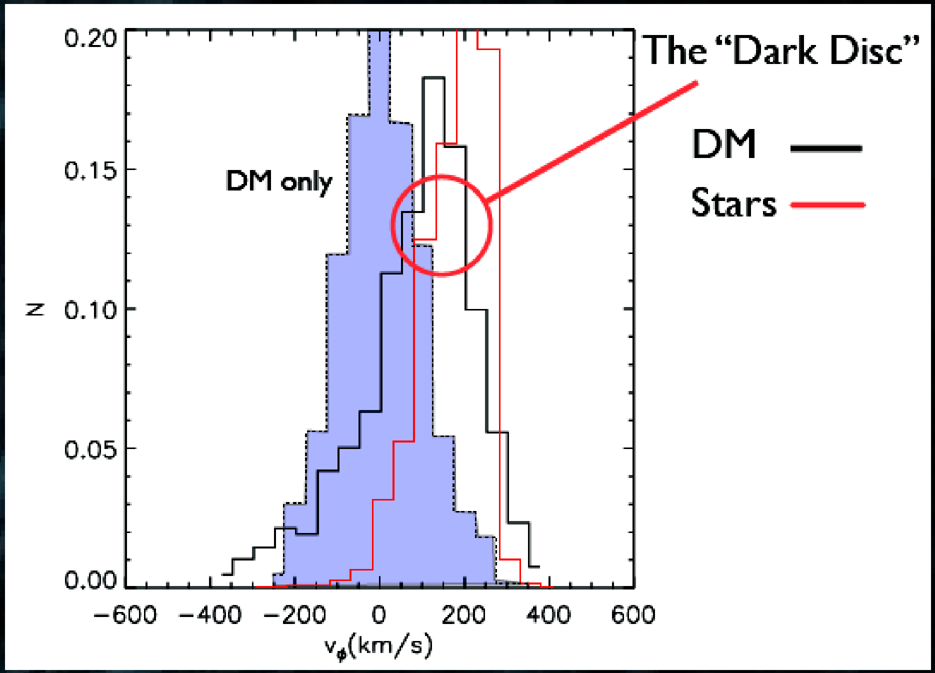
$$\rho_{DM}(R_0) = (0.389 \pm 0.025)\,\mathrm{GeV\,cm^{-3}} \qquad \text{(NFW)}$$

$$\rho_{DM}(R_0) = (0.409 \pm 0.029)\,\mathrm{GeV\,cm^{-3}} \qquad \text{(Burkert)}$$

- No strong dependences from the assumed halo profile.

**Riccardo Catena @ GGI**

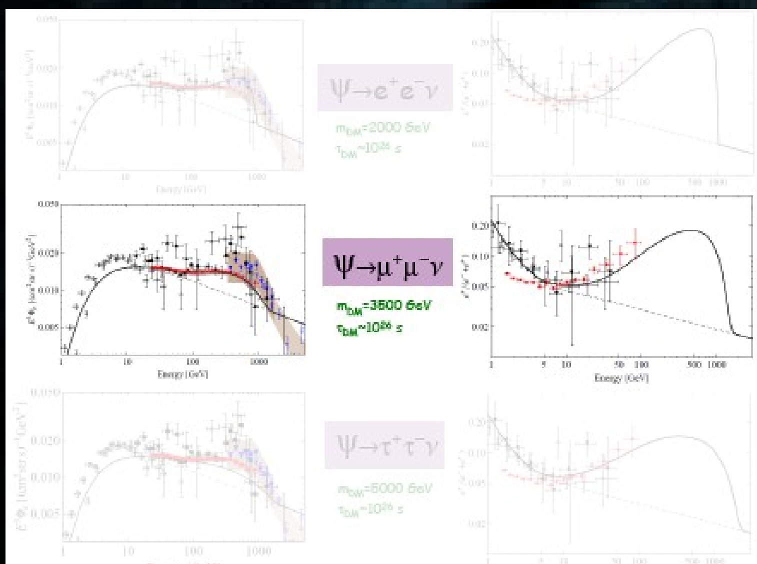
**From Read et al 08**

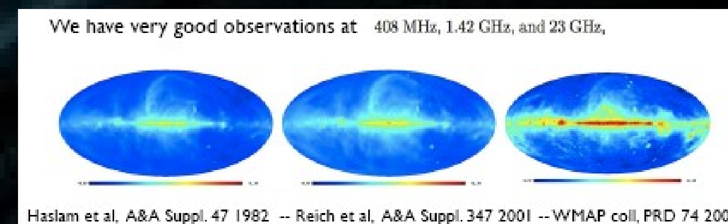


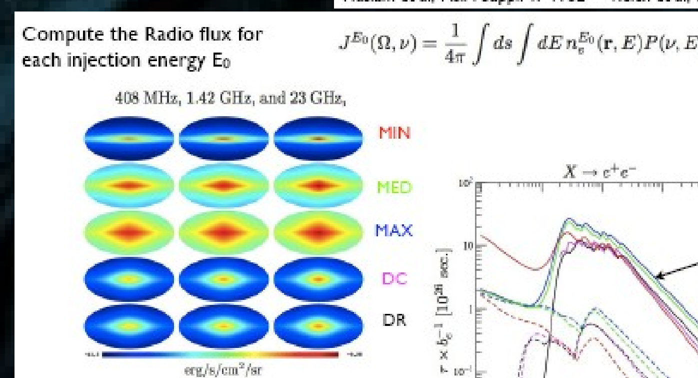

**Justin Read @ GGI**

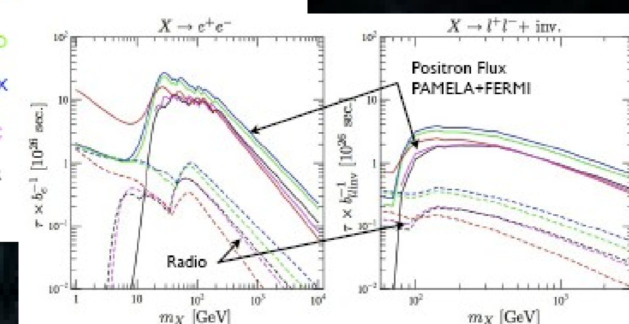
# *Indirect searches: annihilation or decay products in high energy radiations or cosmic rays ?*

**The « PAMELA Show »**



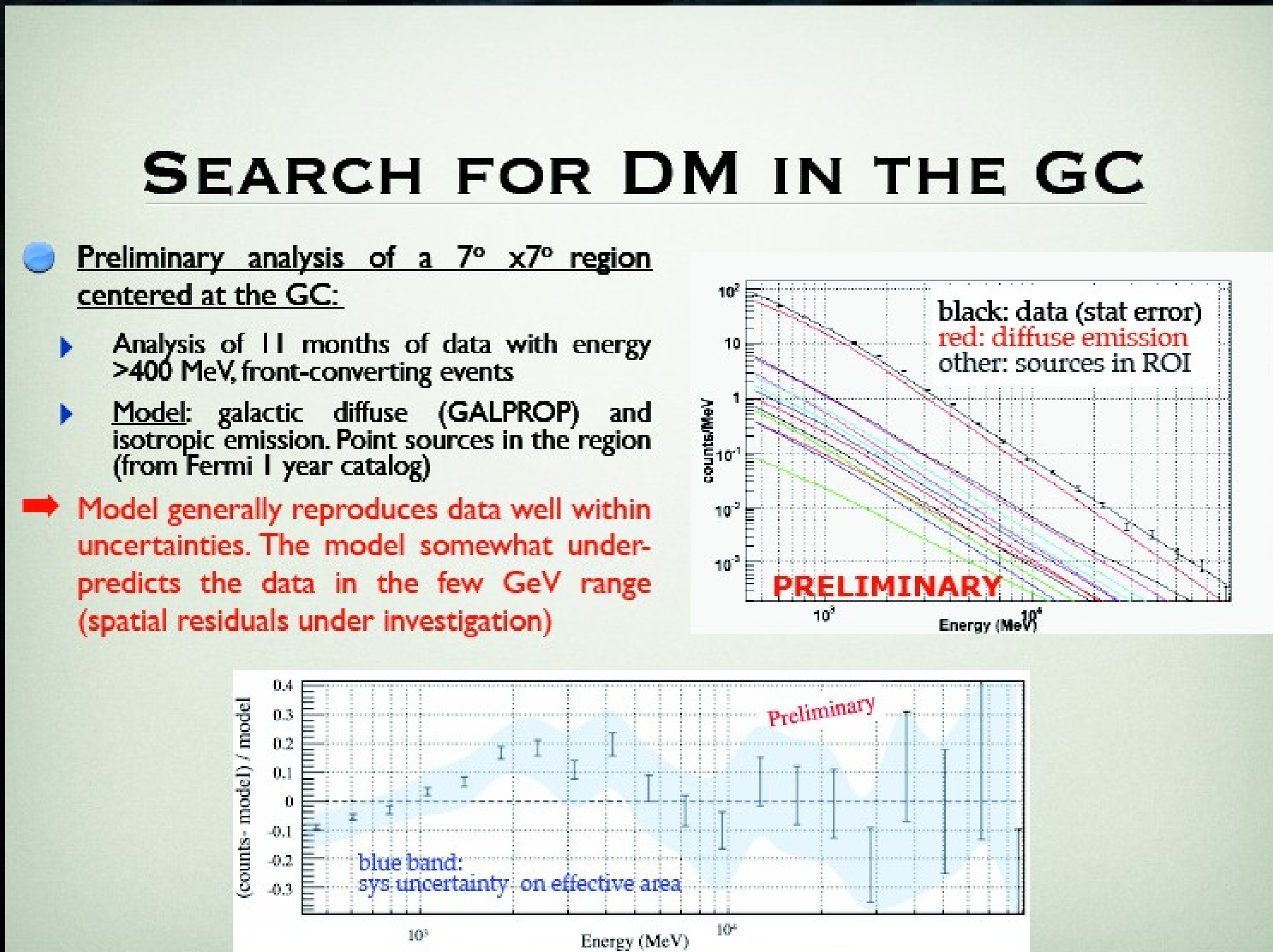

**Alejandro Ibarra @ GGI**

Although astrophysical explanations exist (e.g. pulsars), many have seen DM annihilation or decay in e+e- measurements (PAMELA, Fermi) – O(100) papers in the arXiv.

Excluded from gamma and radio constraints

**Javier Redondo @ GGI**

# *Indirect searches: Fermi results (Abdo et al)*




**Observed targets :**

**GC:** large theoretical errors from background estimate

**Dwarf spheroidals :** (bkgd ok) no signal

**Galaxy clusters :** (bkgd ok) no signal

**Subhalos :** (blind) no signal

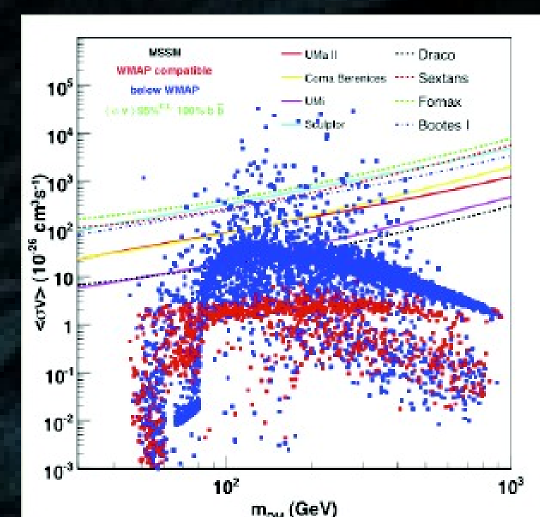
**Diffuse G:** constraints, no signal

**EG :** constraints, no signal

**Simona Murgia @ GGI**

Main issues for searches: astro bkgd + point-source contamination

Best targets: Dsph (DM dominated and almost bkg free)



# *Indirect searches : Summary*

**Reminder of the requirements:**
(i) signal/bkgd ok, (ii) control of bkgd, (iii) spectral feature wrt bkgd.

**Important remark :** most of WIMP candidates not predicted to be observable so far !

**Local antimatter cosmic rays:**
PAMELA and Fermi « excesses » compatible with standard astrophysical expectations.
No antiproton excess so far. Antideuterons ??? (GAPS coming)
AMS is coming, but 10 yr of data will be necessary (back to old magnet)
Understand the bkgd !!!!

**Gamma-rays:**
No signal so far, Dsph promising but with a much longer exposure: CTA will be determining +++ line searches (but weak)
Understand the bkgd !!!!

**Radio emission:**
Planck measurements: understand the bgkd !!!!

**Others:** CMB (constraints), solar neutrinos (unambiguous, compl. with DD), X-rays (sterile neutrinos), BBN, etc.

# *Conclusions*

**LHC + direct detection (Xenon, CDMS, Edelweiss, etc.)**
**++ Fermi + Planck + HESS (and avatars) + CTA + PAMELA (maybe AMS), etc.**

**... Many experiments = increased discovery/exclusion potential ...**
**... + a lot work – especially on backgrounds !!!**
**... multi*(experiment+scale+messenger+wavelength)**

**... Maybe an answer soon (1-10 yr timescale), discovery or not ...**

**... a single new particle discovered at LHC**
**would confort the particle hypothesis for DM ...**

**............... Stay tuned !!!!**

Thanks !