Preliminary lecture programme:

1. The particle universe: introduction, cosmological parameters
2. Basic cross sections for neutrinos and gamma-rays; IceCube
3. Density of relic particles from the early Universe
4. Dark matter: Direct and indirect detection methods; the galactic centre & other promising DM sources
5. Neutrinos and antimatter from dark matter, Sommerfeld enhancement.
6. Particular dark matter candidates (WIMPS, Kaluza-Klein particles, sterile neutrinos,...)
7. Supersymmetric dark matter, DarkSUSY.
8. Diffuse extragalactic gamma-rays, Primordial black holes, Hawking radiation
9. Gravitational waves

Good particle physics candidates for Cold Dark Matter:

Independent motivation from particle physics; detectable by other means than through gravity only

- Axions (introduced to solve strong CP problem)
- Weakly Interacting Massive Particles (WIMPs, 3 GeV < m_X < 50 TeV), thermal relics from Big Bang:
  - Supersymmetric neutralino
  - Axino, gravitino
  - Kaluza-Klein states
  - Extended Higgs sector
  - Heavy neutrino-like particles
  - Mirror particles
  - "Little Higgs"
  - plus hundreds more in literature…
- Non-thermal (maybe superheavy) relics, which may decay to give lighter DM candidates
- Of course, we may get surprises (see later)…

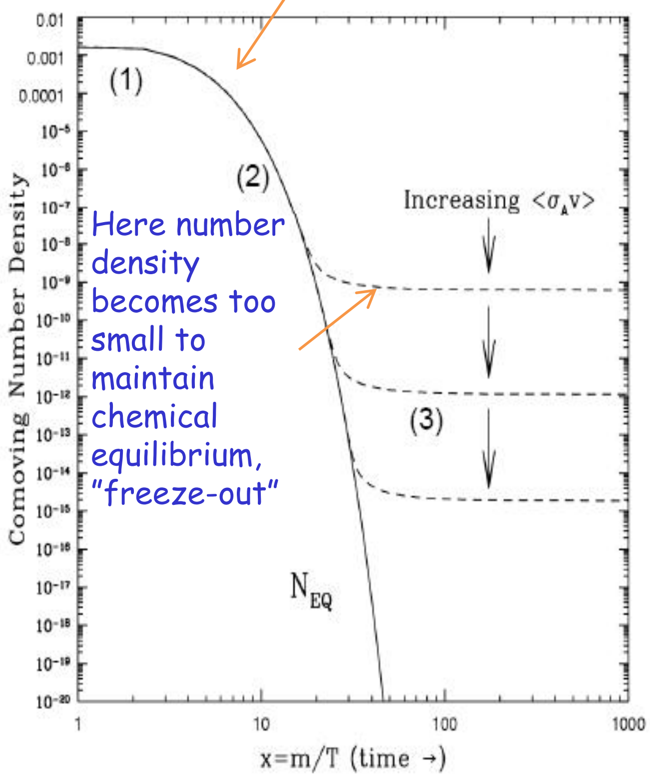
"The WIMP miracle": For typical gauge couplings and masses of order the electroweak scale, $\Omega_{wimp}h^2 \approx 0.1$ (within factor of 10 or so)

$$\Omega_{\mathrm{WIMP}} h^2 \propto \frac{3 \cdot 10^{-27}\ \mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma \cdot \mathrm{v}>}$$

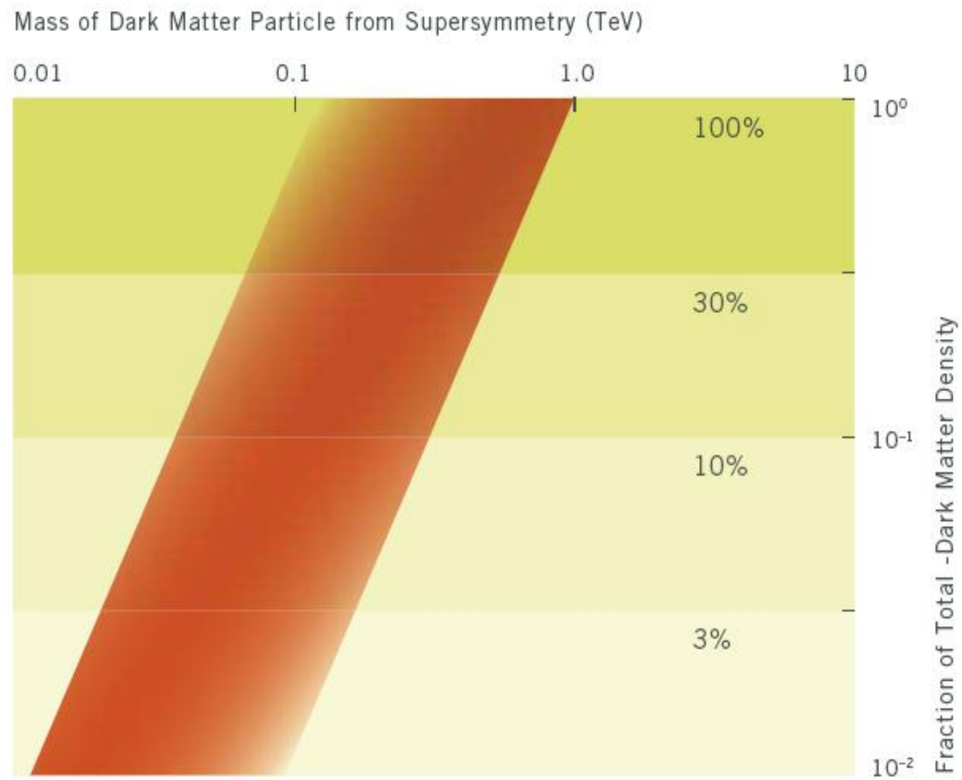
Gives $\langle\sigma v\rangle \sim 3\cdot10^{-26}$ $\mathrm{cm}^3\mathrm{s}^{-1}$ at freezeout

The "WIMP miracle"

Equilibirium curve in early universe



The mass range for SUSY WIMPs is roughly 10 GeV to a few TeV

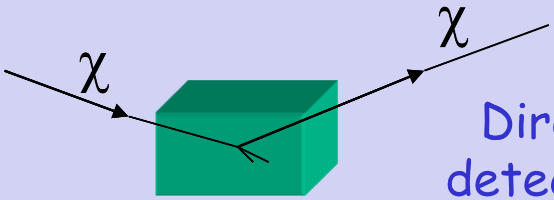


J. Feng & al, ILC report 2005

Methods of WIMP Dark Matter detection:

- Discovery at accelerators (Fermilab, LHC, ILC…).
- Direct detection of halo particles in terrestrial detectors.
- Indirect detection of neutrinos, gamma rays & other e.m. waves, antiprotons, antideuterons, positrons in ground- or space-based experiments.
- For a convincing determination of the identity of dark matter, plausibly need detection by at least two different methods.

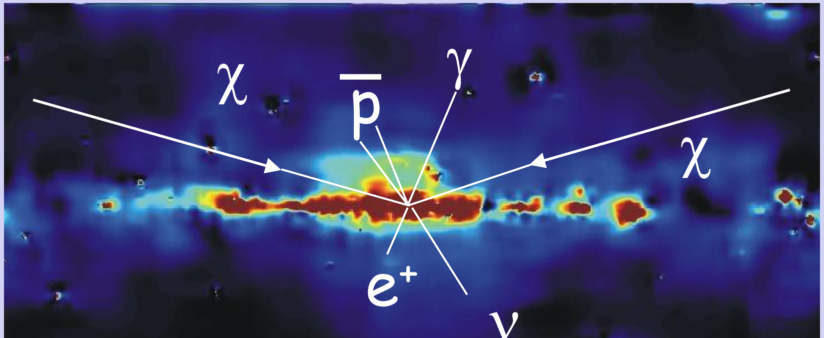
CERN CMS



Direct detection

$$\frac{d\sigma_{si}}{dq} = \frac{1}{\pi v^2}\left(Zf_p + (A-Z)f_n\right)^2 F_A(q) \propto A^2$$

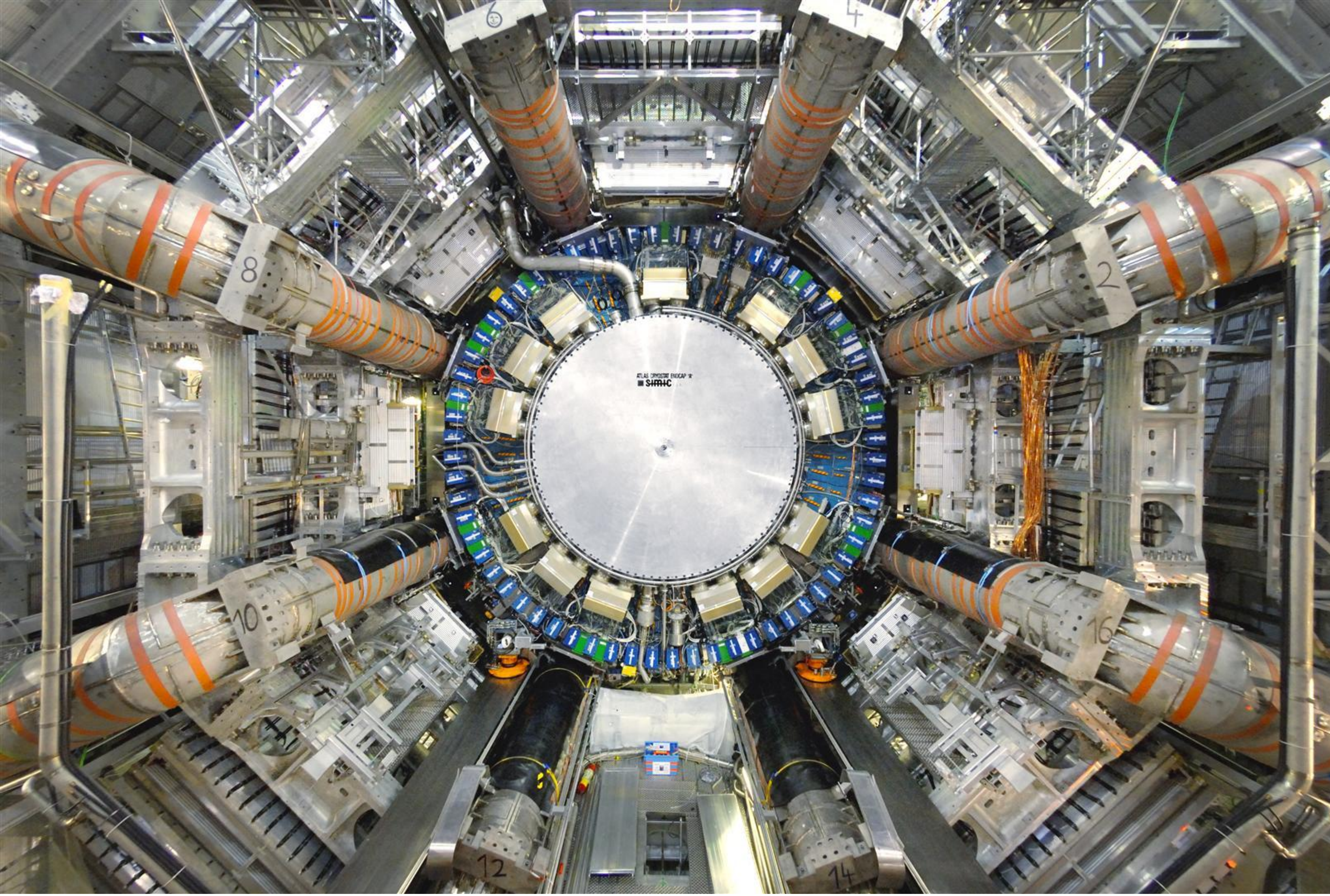
Indirect detection



The Milky Way halo in gamma-rays as measured by EGRET (D.Dixon et al, 1997)

$$\Gamma_{ann} \propto n_\chi^2 \sigma v$$

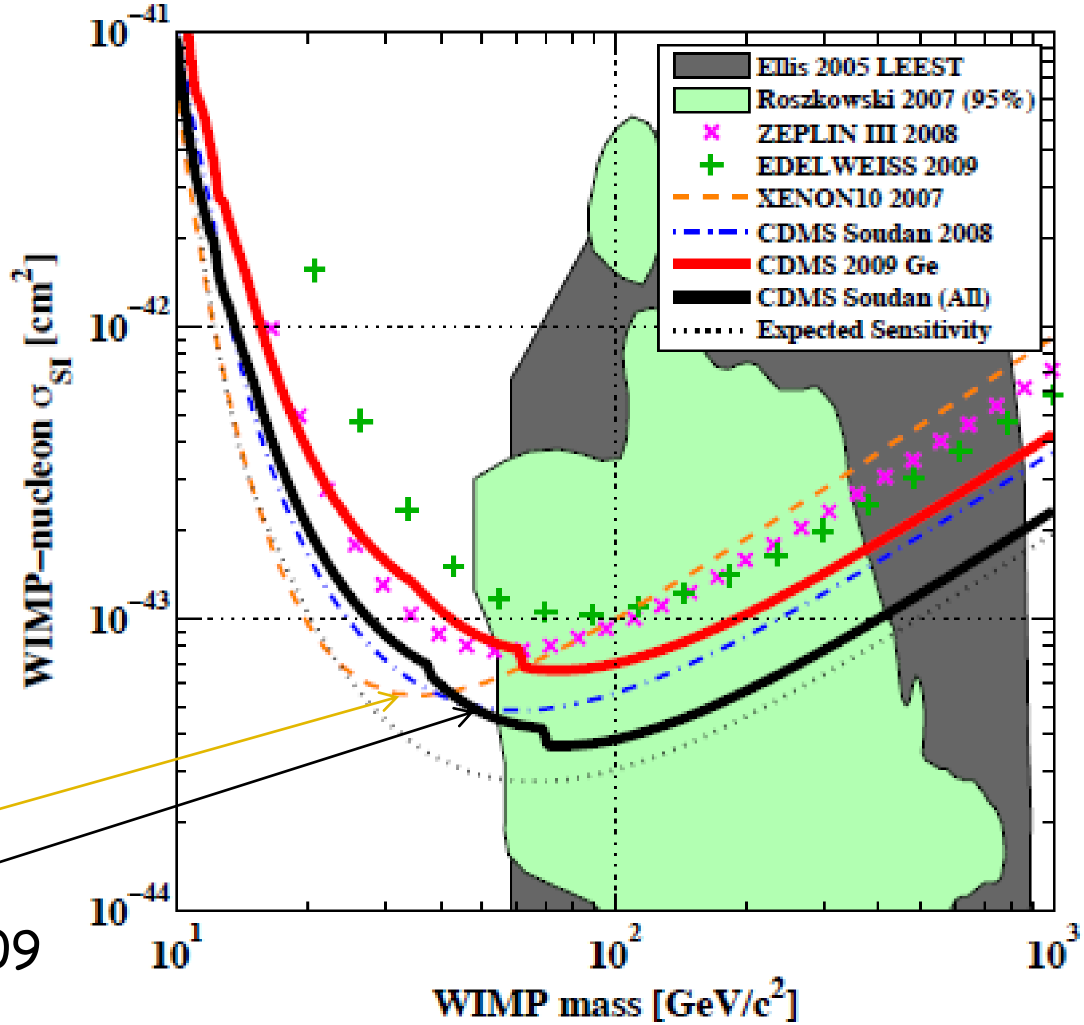
Annihilation rate enhanced for clumpy halo; near galactic centre and in subhalos



CERN's LHC ATLAS detector. LHC has finally turned on (at half the nominal energy) .

The dream we all hope will come true…

Direct detection limits, steady progress - soon deploy new generation of detectors

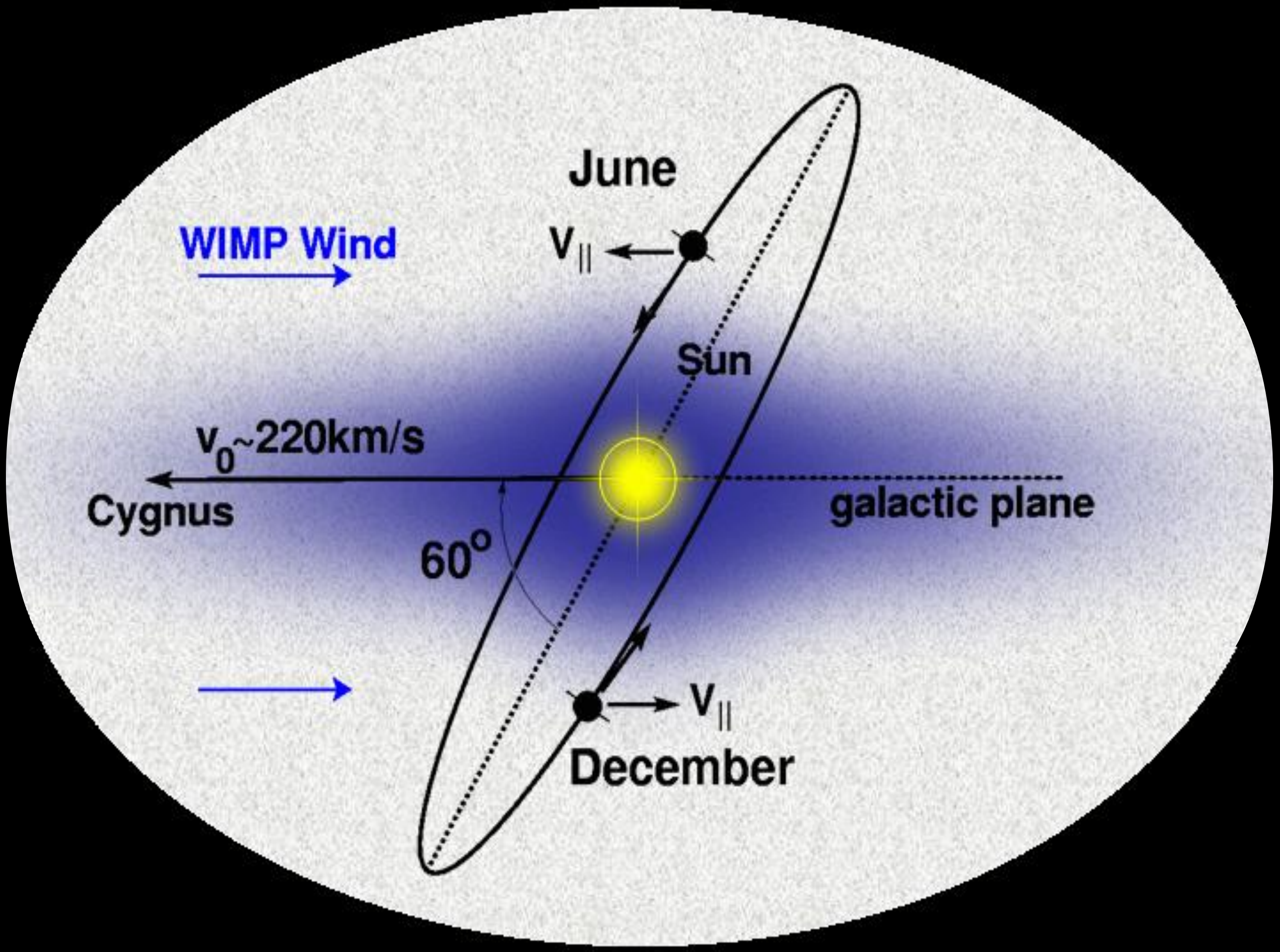


Xenon 10

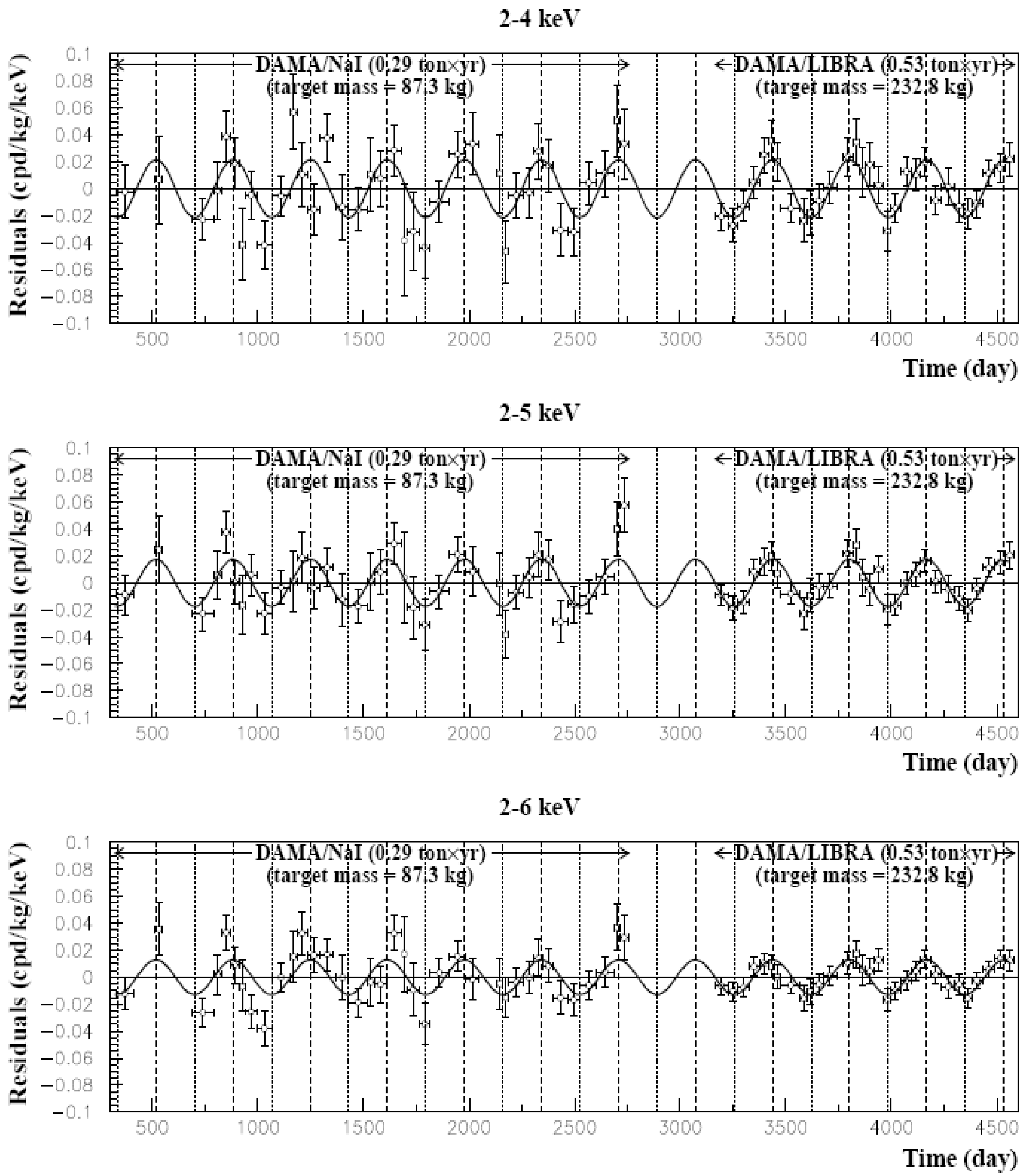
New CDMS result, 2009

(they observe two "unexplained" events...)

Caution: Where does DAMA fit in?



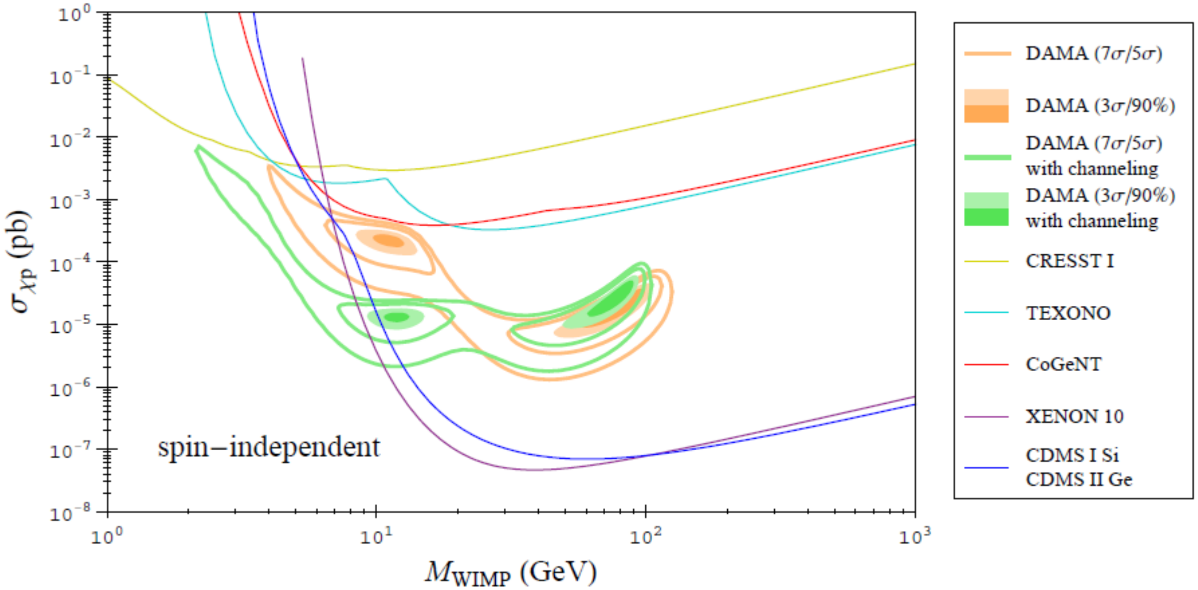
Drukier, Freese, Spergel, 1986



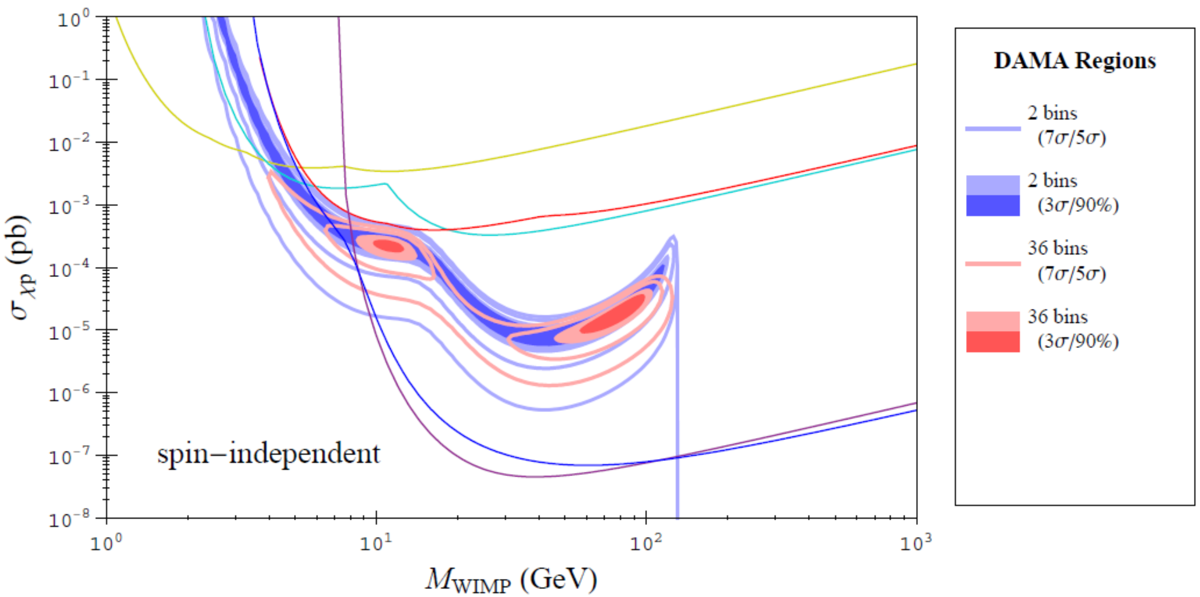
DAMA/LIBRA: Annual modulation of unknown cause. Consistent with dark matter signal (but not confirmed by any other experiment).

Claimed significance: More than 8σ !

What is it? Does not fit in in standard WIMP scenario…



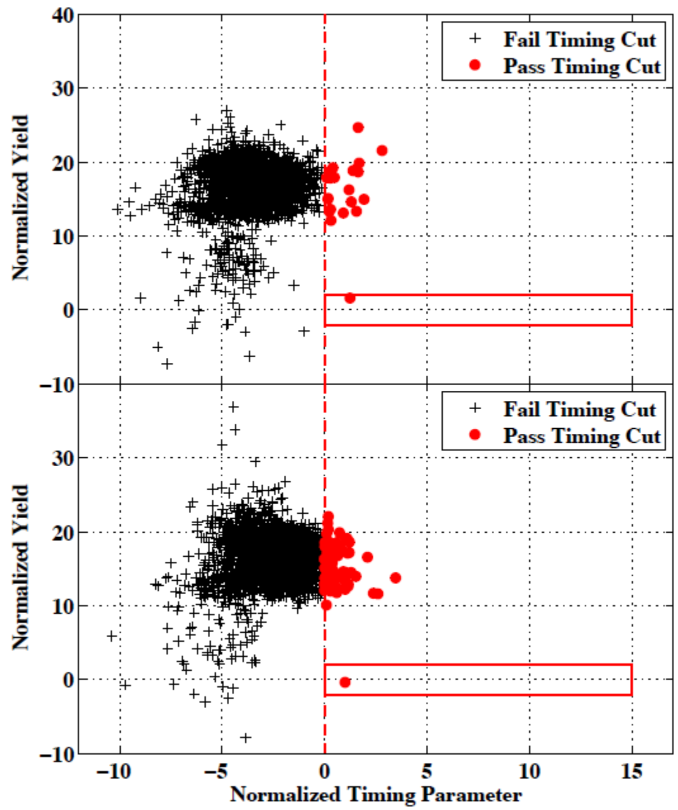
DAMA results are not reproduced by any other experiments



If related to dark matter, something really exotic must be needed…

C. Savage, P. Gondolo, G. Gelmini and K. Freese, arXiv:0808.3607

CDMS II result, December 2009:
what are these 2 events?

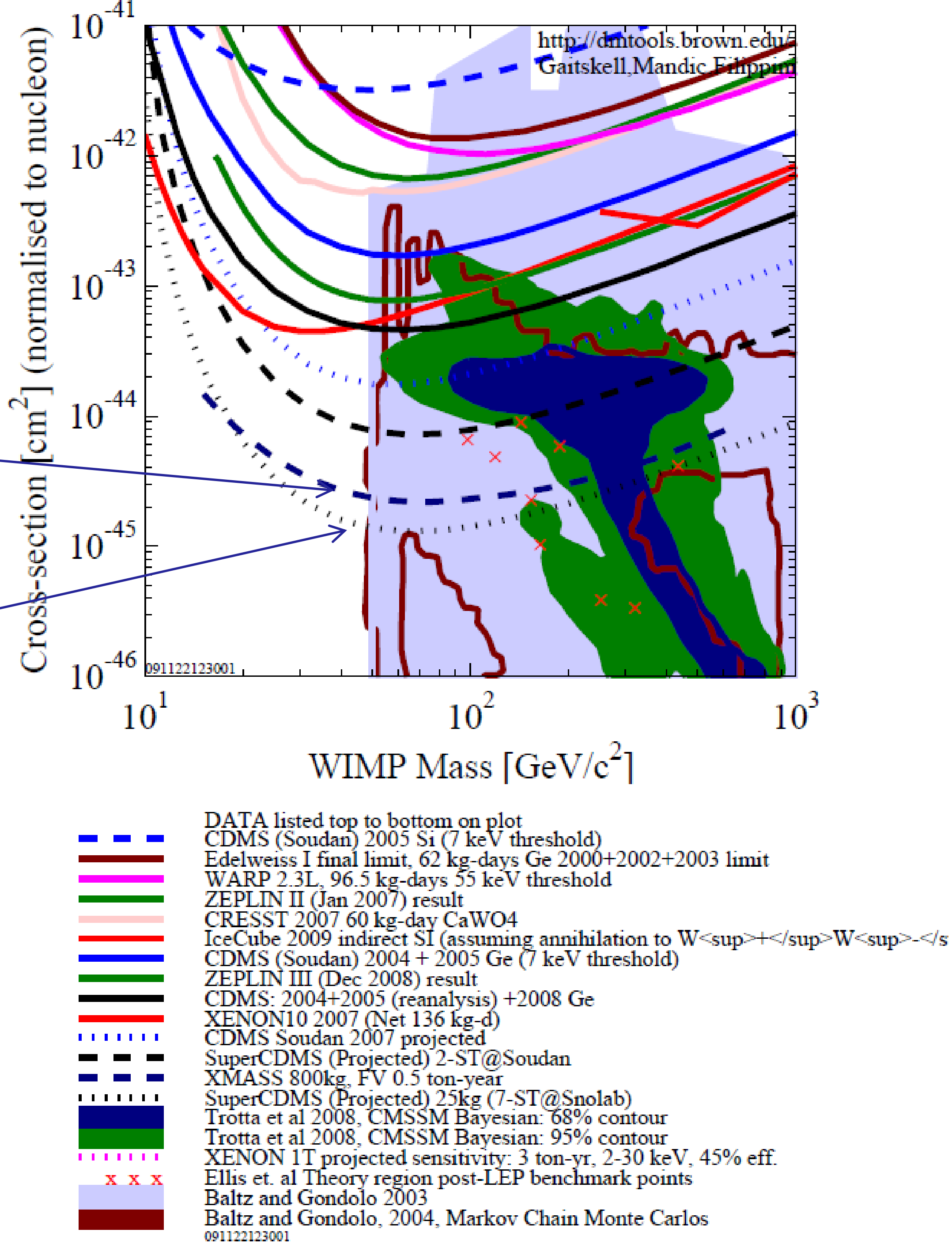


On the other hand, combining 2007 and 2008 data, expect 1.8 background events, see 2 events. Soon (next month?) Xenon100 will provide more data.

Future experiments - impressive development over the last 10 years seems to continue.

XMASS

Super-CDMS

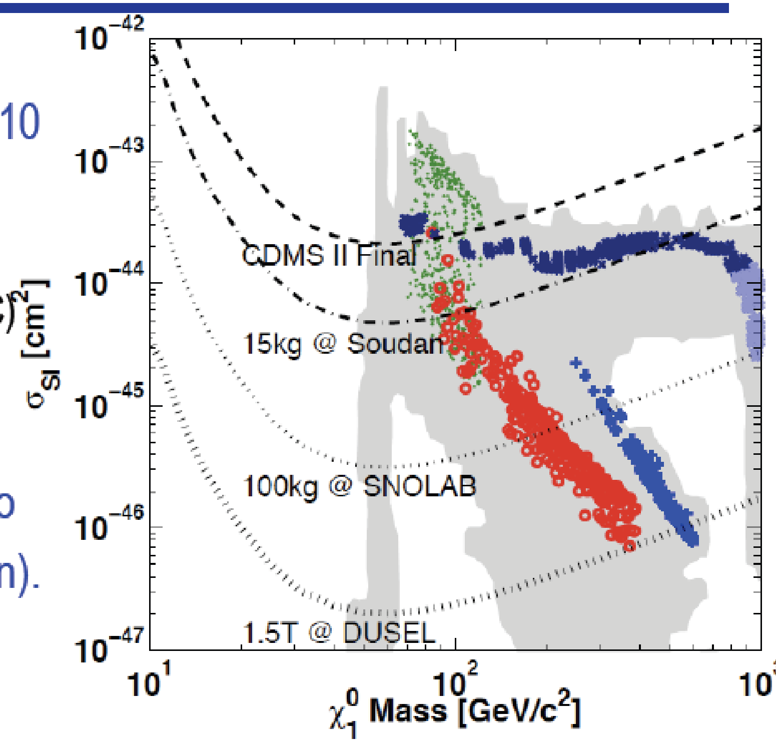


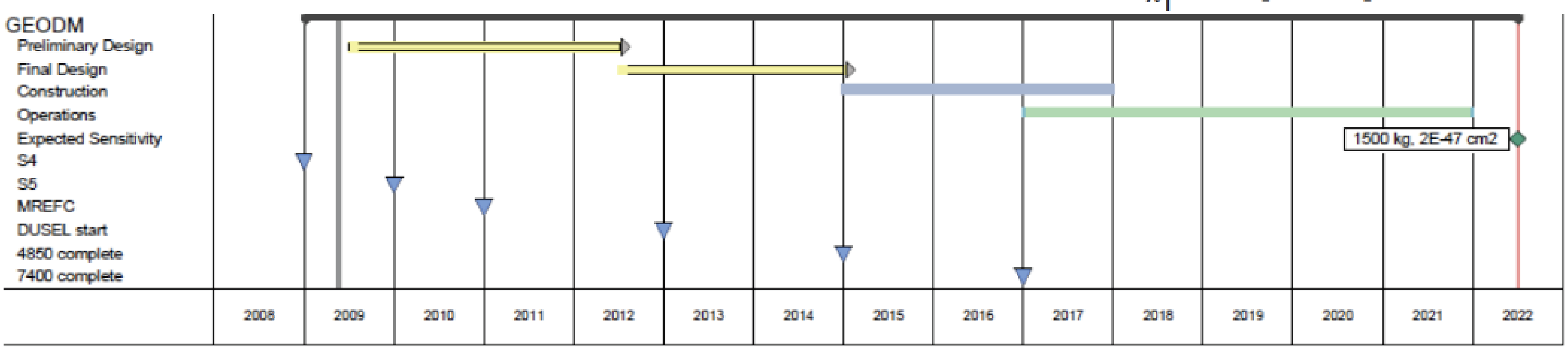
GEODM for 1.5 tonne Ge at DUSEL

DUSEL design study (NSF S4) funded

- Deliver study end of 2012. DUSEL PDR Dec 2010
  - Cryogenic engineering
  - Electrical readout, multiplexing (NIST&MIT)
  - Detector fabrication scalability (TAMU&SLAC)
  - Material screening, background studies.

- Rapid advance on high risk items could feed into earlier programs (eg iZIP for SNOLAB & Soudan).

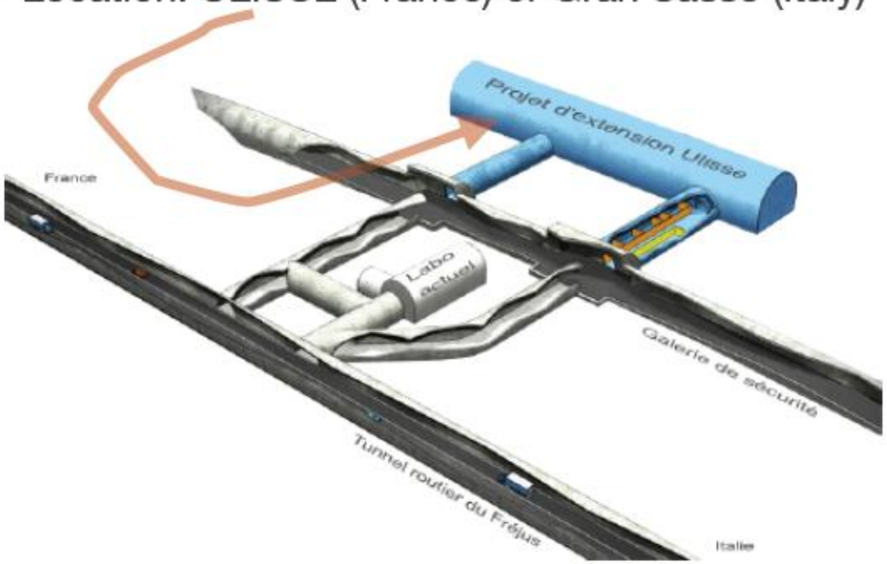


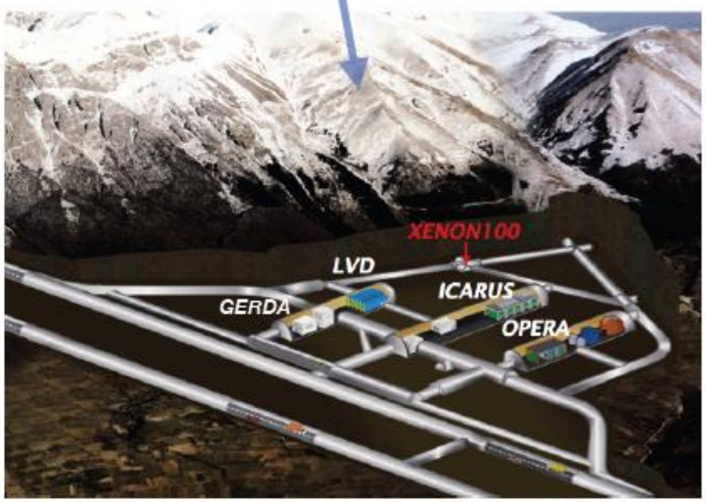


dark matter wimp search in noble liquids
DARWIN

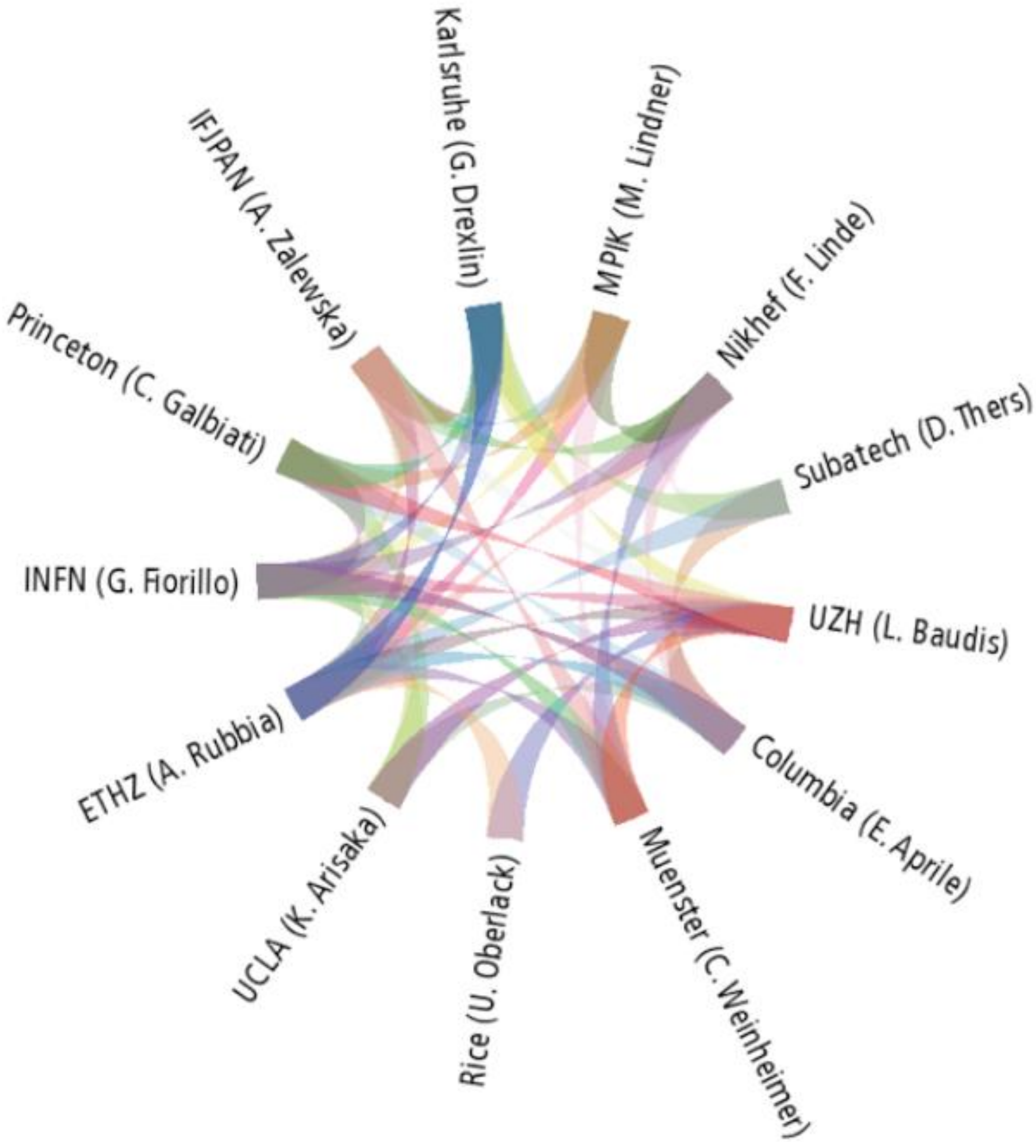
What is DARWIN?

- R&D and design study for a **next-generation noble liquid facility in Europe**
- Approved by ASPERA (AStroParticle ERAnet) in late 2009
- Goal:
  - ➡ study ***liquid xenon AND liquid argon as WIMP targets***
  - ➡ make recommendation for technical design of facility in ***three years from now***
  - ➡ build on the added-value of uniting and coordinating the extensive, existing European expertise in liquid argon, liquid xenon and related technologies for astroparticle physics detectors within a global scenario
- Location: ULISSE (France) or Gran Sasso (Italy)





DARWIN Institutions and Connections



Groups from:

ArDM and WARP for LAr
XENON for LXe

Europe: UZH, INFN, ETHZ, Subatech, MPIK, Münster, Nikhef, KIT, IFJPAN

USA: Columbia, Princeton, Rice, UCLA

Dark Matter
Cryogenic detectors
EURECA experiment
Collaboration
Publications
Internal (restricted)

EURECA

Collaboration

EURECA is a collaboration involving research institutes from across Europe. For more information please co collaboration spokesman, Hans Kraus.

United Kingdom

- University of Oxford

France

CEA - Commissariat à l'Énergie Atomique

- IRFU - Institut de Recherche sur les Lois Fondamentales de l'Univers
- IRAMIS - Institut Rayounement Matière de Saclay

CNRS - Centre National de la Recherche Scientifique

- CSNSM - Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse
- IPNL - Institut de Physique Nucléaire de Lyon
- Institut NÉEL
- IAS - Institut d'Astrophysique Spatiale
- ICMCB - Institut de Chimie de la Matière Condensée de Bordeaux

Germany

- Max-Planck-Institut für Physik München
- Technische Universität München
- Universität Tübingen
- Karlsruhe Institute of Technology

Spain

- Universidad de Zaragoza

Ukraine

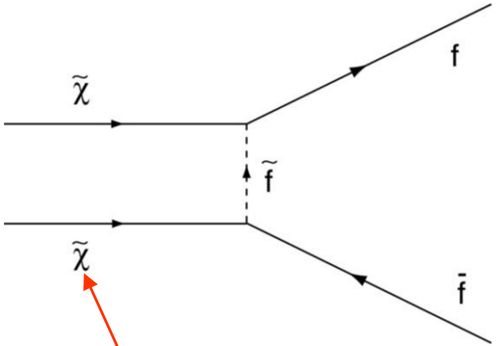
- INR Kiev

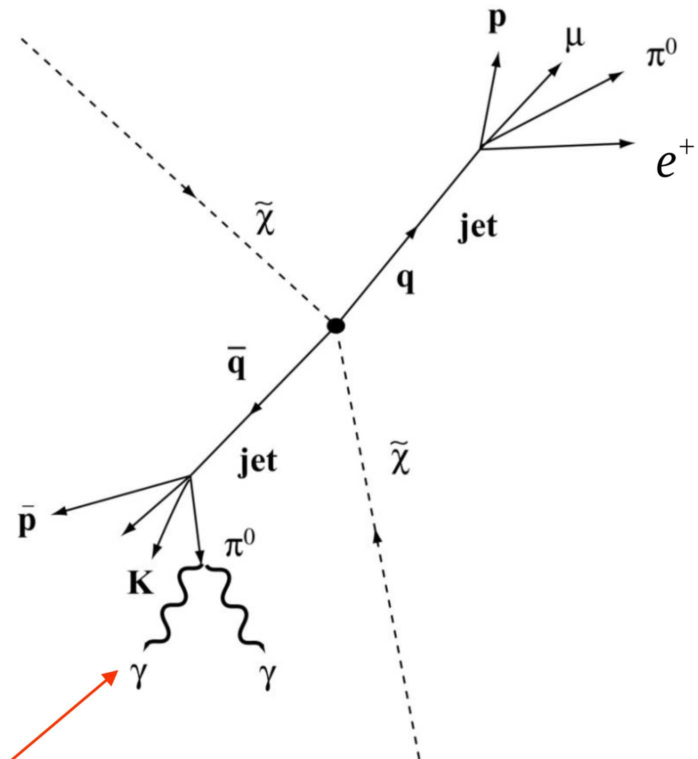
International Organizations

- JINR Dubna
- CERN

Large European solid state DM detector, EURECA - also given support by ASPERA (European Astroparticle community)

Indirect detection, example: WIMP annihilation in the galactic halo



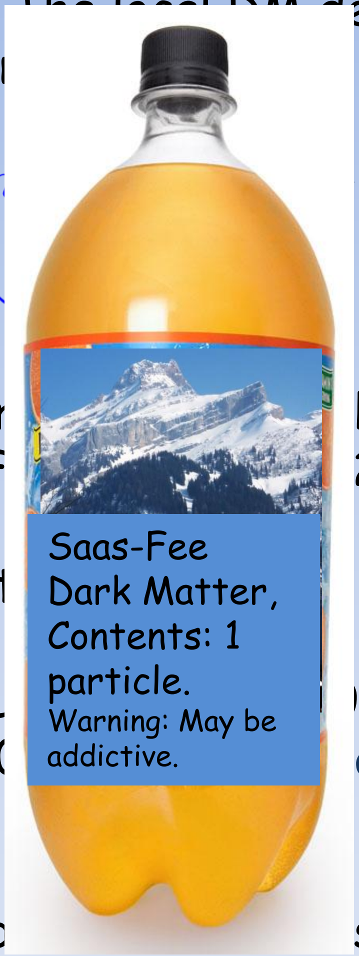


If Majorana particles: helicity factor for fermions $\sigma v \sim m_f^2$

Note: equal amounts of matter and antimatter in annihilations

Decays from neutral pions, kaons etc: DarkSUSY uses PYTHIA.

Investigate the WIMP scenario: Let us invent a dark matter candidate - the Saas-Fee particle! (Or Saas-Fino, if SUSY?) It has mass m_{SF} = 100 GeV, and the annihilation cross section $\sigma v = 3 \times 10^{-26}$ cm^3/s, to get the right relic density (measured by WMAP). The local DM density is $\rho_\odot \approx 0.4\ \mathrm{GeV/cm}^3$ as determined by galactic dyna



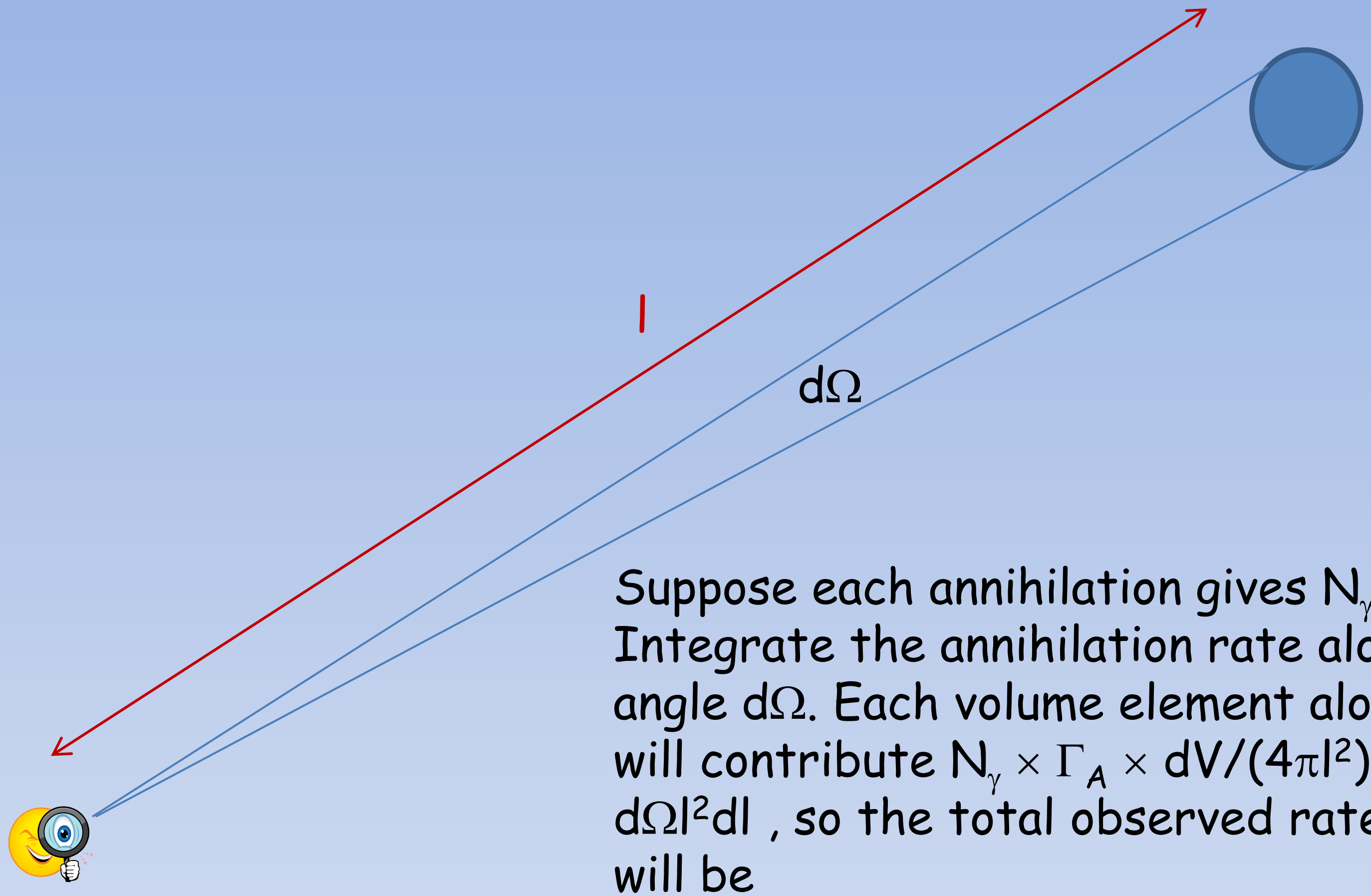
The annihilation rate is $\Gamma_A = n$,

and $n(r) = \rho(r)/m_{SF}$, thus $n_\odot \sim$

So, in this room (and everywher lar neighbourhood) there is about one such 100 GeV Saas-F 2 litres!

On the other hand the annihilat $(4 \times 10^{-3})^2 \times 1.5 \times 10^{-26} = 2.4 \times 10^{-31}$ cm^{-3}s^{-1}.
The volume of this room is arou m^3 = 4×10^9 cm^3 , so the rate of annihilation here is around 1 ability 2×10^{-15} that it happens once during this week.

So, we need a better idea for c se annihilations - look out in the Galaxy!



Suppose each annihilation gives N_γ gamma-rays. Integrate the annihilation rate along a cone of solid angle $d\Omega$. Each volume element along the line of sight will contribute $N_\gamma \times \Gamma_A \times dV/(4\pi l^2)$ cm^{-2}sr^{-1}. Here $dV = d\Omega l^2 dl$, so the total observed rate in some direction $\hat{n}$ will be

$$\frac{dI(\hat{n})}{d\Omega} = \frac{1}{4\pi}\int_{\mathrm{line-of-sight}} N_\gamma \Gamma_A(l) dl(\hat{n})$$

Now put in numbers for the Milky Way. The gamma-rays rate from annihilations in the Milky Way halo, as a function of line-of-sight angle Ψ with respect to the Galactic centre is

Typically 10 - 20 for 100 GeV DM

$$\frac{dI}{d\Omega}(\Psi) = 0.94 \cdot 10^{-10} \left(\frac{N_\gamma \sigma v}{10^{-26}\ \mathrm{cm}^3 \mathrm{s}^{-1}} \right) \left(\frac{100\ \mathrm{GeV}}{m_\chi} \right)^2 J(\Psi)\ \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1}$$

Here,

$$J(\Psi) = \frac{1}{8.5\ \mathrm{kpc}} \left(\frac{1}{0.3\ \mathrm{GeV/cm}^3} \right)^2 \int_{\mathrm{line-of-sight}} \rho^2_{DM}(l)\, dl(\Psi)$$

Note! Gives enhancement if there are clumps of DM in the line of sight, or towards the g.c., if spiky.

Here “standard” values of $d_{g.c.}$ = 8.5 kpc (newer estimate: 8.33 ±0.35, Gillessen & al., 2008) and ρ_{DM} = 0.3 GeV/cm^3 (newer estimates: 0.39 ±0.03, Catena & Ullio, 2009; 0.43 ±011 ±0.10, Salucci & al. 2010) have been inserted.

(L.B., P. Ullio & J.H. Buckley, 1998)

One major uncertainty for indirect detection, especially of gamma-rays: The halo dark matter density distribution at small scales is virtually unknown. (Gamma-ray rates towards the Galactic Center may vary by factor of 1000 or more.)

Fits to N-body simulations

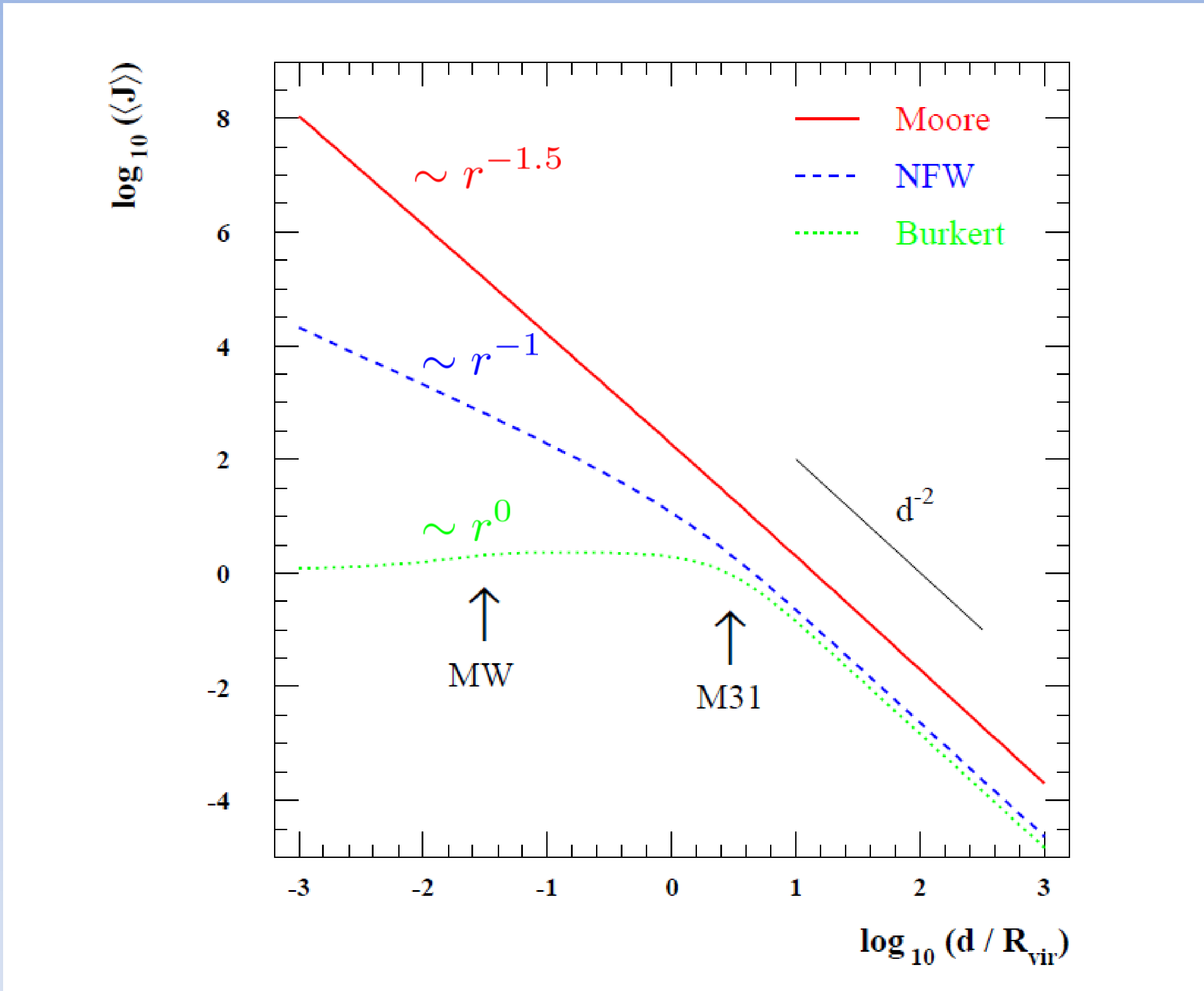
$$\rho_{\mathrm{Einasto}}(r) = \rho_s e^{\left(-\frac{2}{\alpha}\left[\left(\frac{r}{a}\right)^{\alpha}-1\right]\right)}, \ \alpha \approx 0.17$$

$$\rho_{\mathrm{NFW}}(r) = \frac{c}{r(a+r)^2};$$

Fits to rotation curves

$$\rho_{\mathrm{Burkert}}(r) = \frac{c}{(r+a)(a^2+r^2)};$$

$$\rho_{\mathrm{CIS}}(r) = \frac{c}{a^2+r^2};$$



If one is near the centre of a halo (as we are in the Milky Way) the density profile is very important. Our Saas-Fee particle would clearly be seen by FERMI for Moore profile (which does not seem likely today), marginally for NFW, and not at all for Burkert.

For distant halos (like M31, or subhalos in MW) the fluxes are rather similar.

If the Saas-Fee particle annihilates into quark or W pairs, then the gamma distribution follows a simple, empiric form:

$$\frac{dN_\gamma(E)}{dE} = \frac{dN_{\text{cont}}}{dE}(E) + b_{\gamma\gamma}\delta\left(m_\chi - E\right)$$

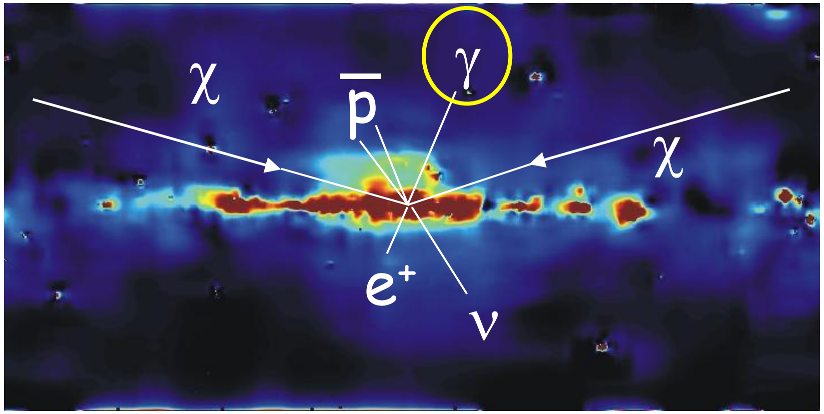
where $b_{\gamma\gamma}$ is typically between 0.1 and a few % (there may also be a $Z\gamma$ piece) , and

Cut-off near m_{SF}

$$\frac{dN_{\text{cont}}}{dE}(E) = \frac{0.42}{m_{SF}} \frac{e^{-8\left(\frac{E}{m_{SF}}\right)}}{\left(\left(\frac{E}{m_{SF}}\right)^{1.5} + 0.00014\right)} \times \theta\left(m_{SF} - E\right)$$

Slope ~ $E^{-1.5}$ at low energies

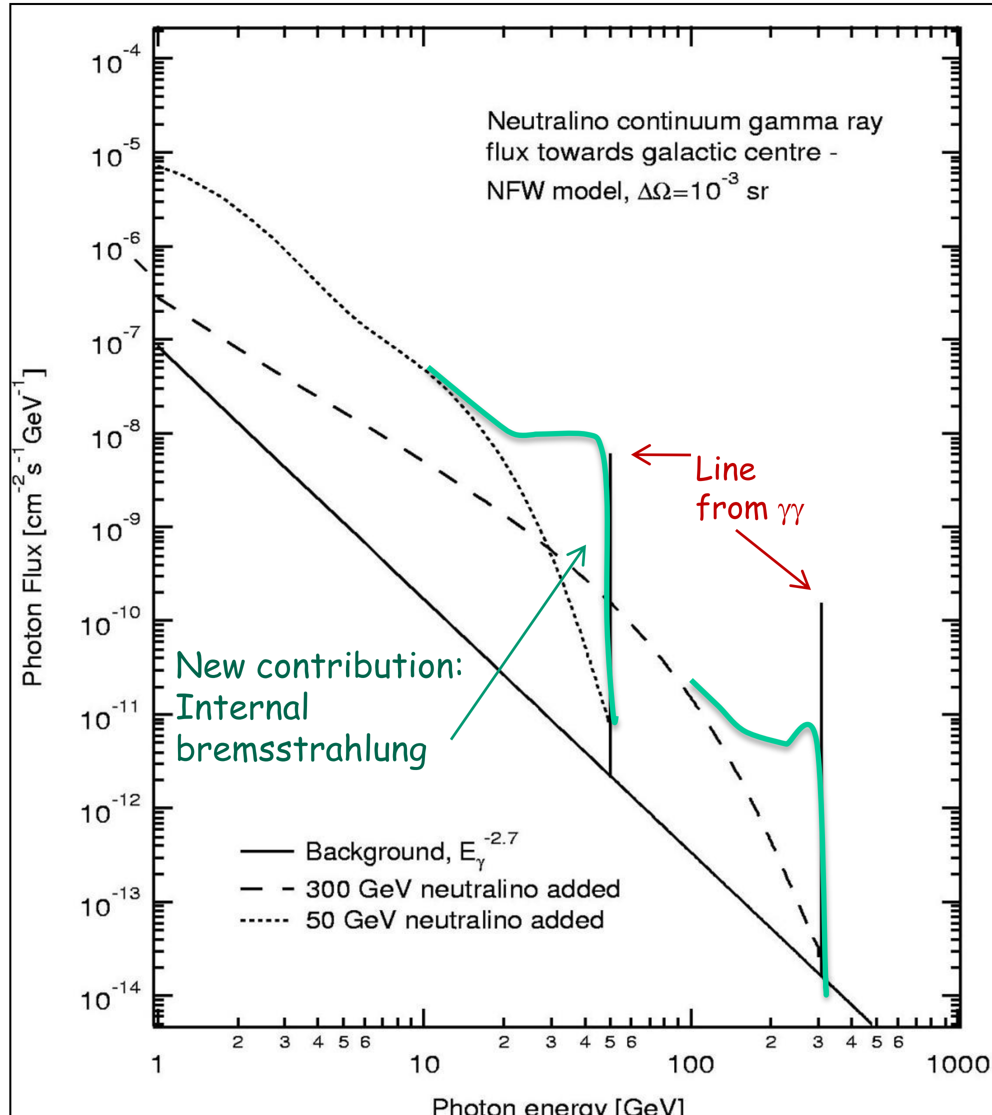
L.B., J. Edsjö & P.Ullio, 2001



Indirect detection through γ-rays.
Three types of signal:

- Continuous from π^0, K^0, … decays
- Monoenergetic line from quantum loop effects, $\chi\chi \rightarrow \gamma\gamma$ and $Z\gamma$
- Internal bremsstrahlung from QED process.

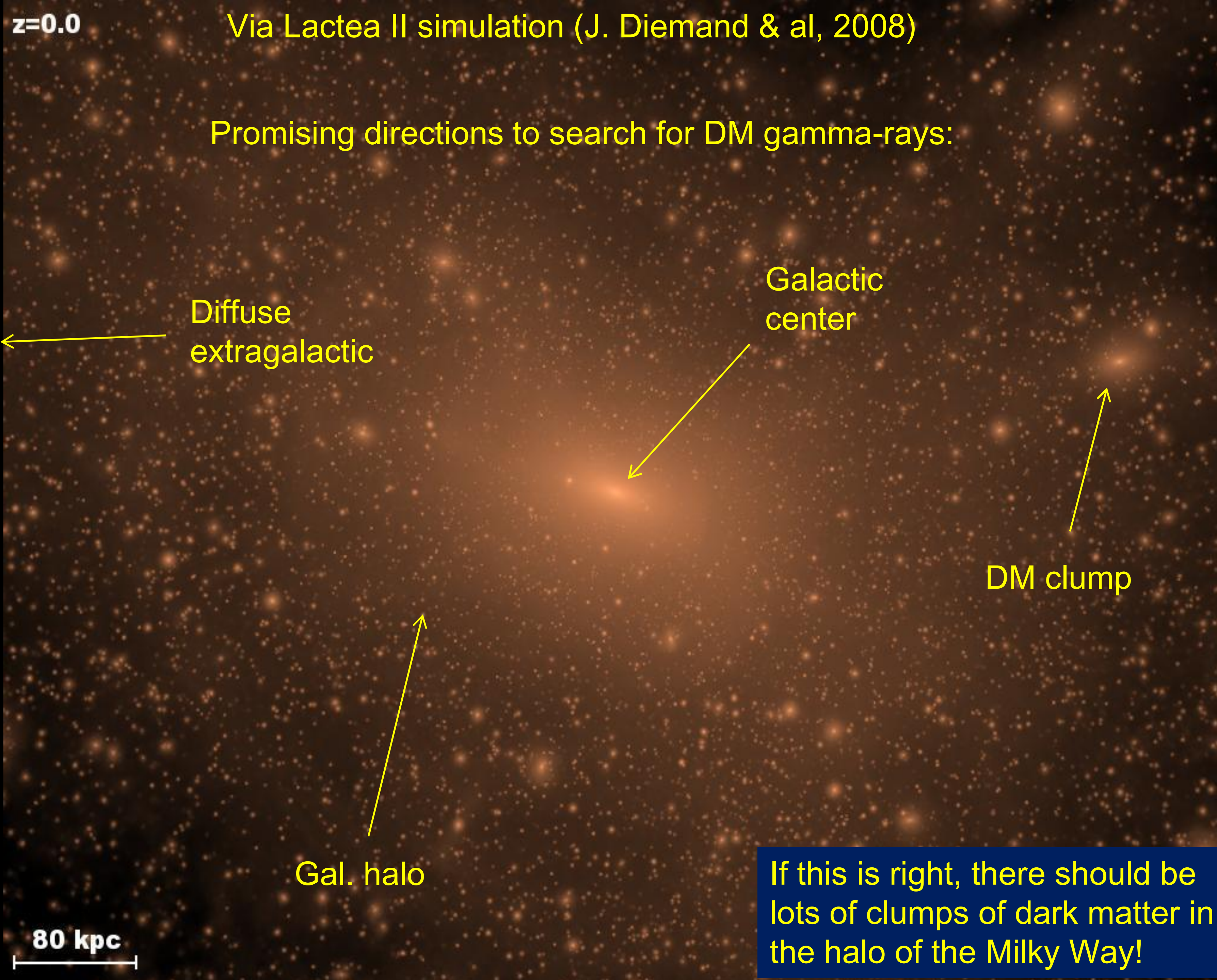
Enhanced flux possible thanks to halo density profile and substructure (as predicted by N-body simulations of CDM).
Good spectral signatures!
Unfortunately, large uncertainties in the predictions of absolute rates.



L.B., P.Ullio & J. Buckley 1998; T. Bringmann, L.B., J. Edsjö, 2007

Via Lactea II simulation (J. Diemand & al, 2008)

Promising directions to search for DM gamma-rays:



If this is right, there should be lots of clumps of dark matter in the halo of the Milky Way!

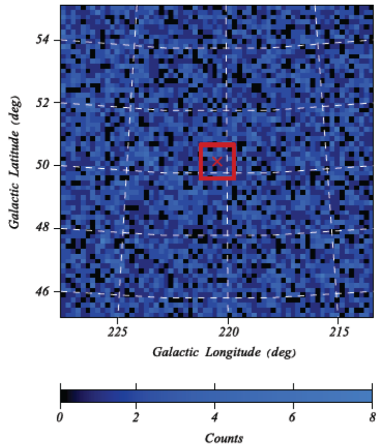
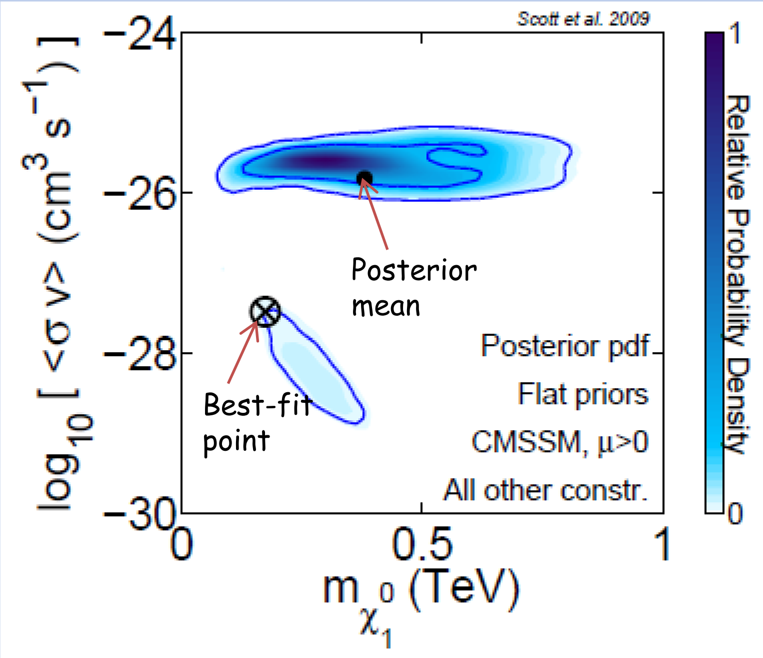


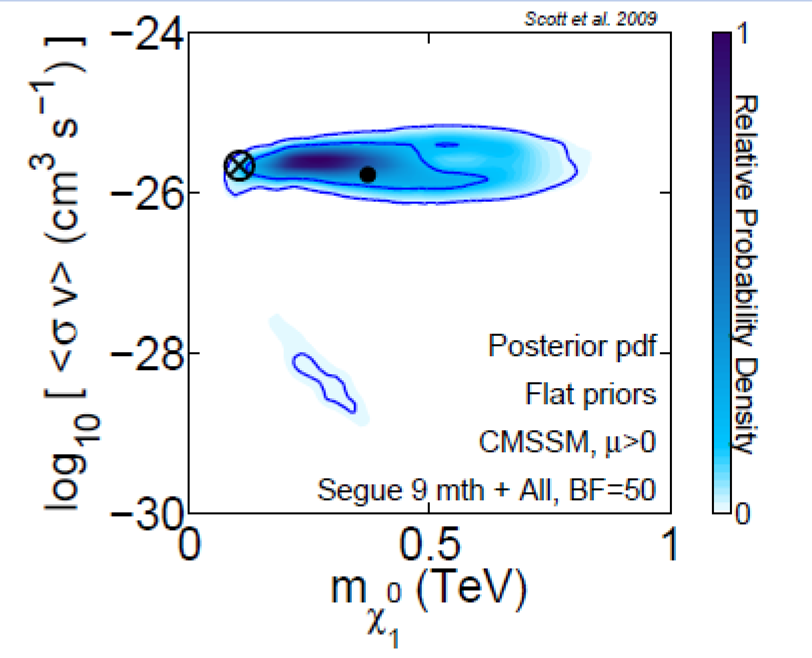
Figure 1: Photon counts observed by *Fermi* in the region around Segue 1 during the first 9 months of LAT operation in all-sky survey mode.

P. Scott, J. Conrad, J. Edsjö, L.B., C. Farnier, Y. Akrami, arXiv:0909.3300, Direct Constraints on Minimal Supersymmetry from Fermi-LAT Observations of the Dwarf Galaxy Segue 1

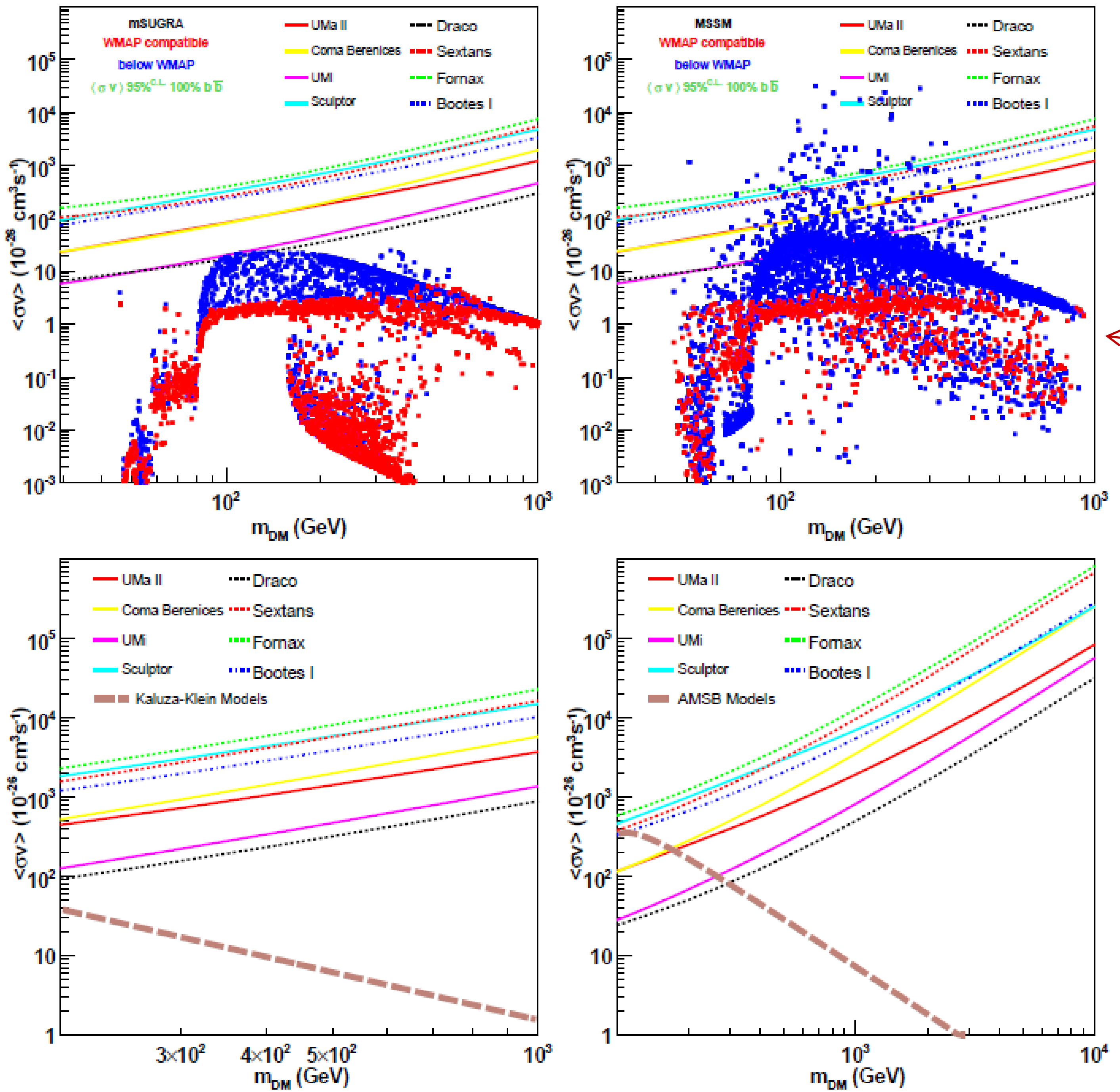
Without Fermi data



With 9 months of Fermi data

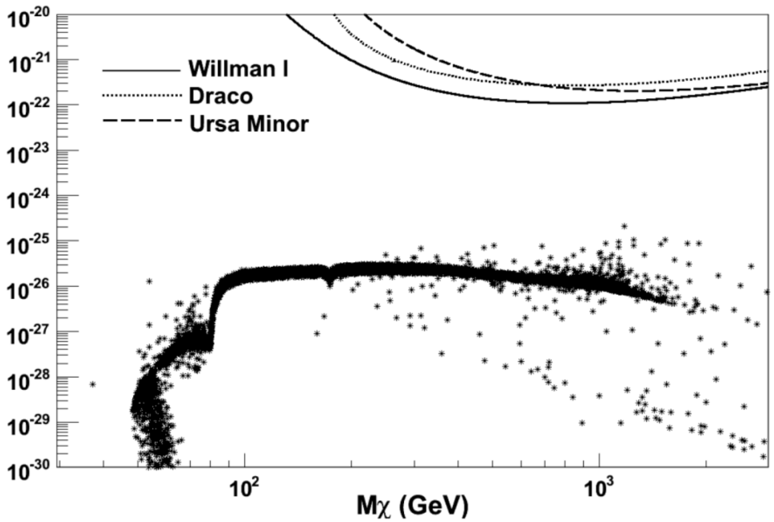


Too early to draw any strong conclusions…

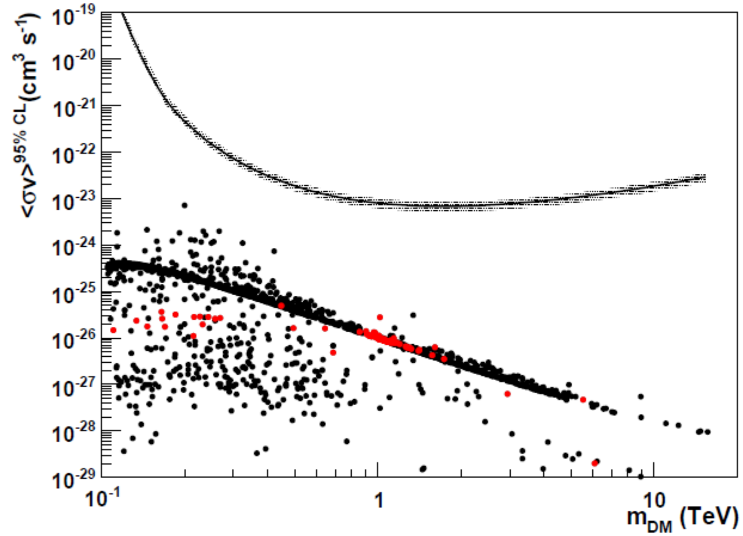


Red points have correct relic density

Fermi Collaboration, 2010

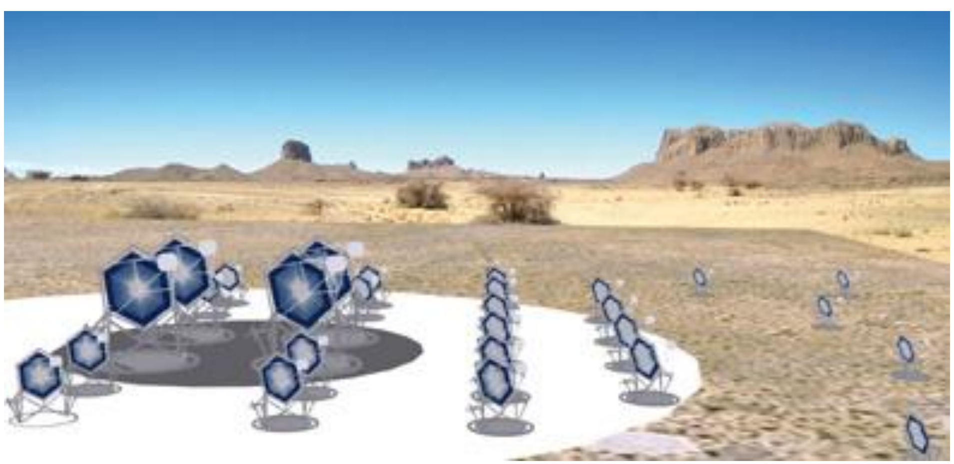


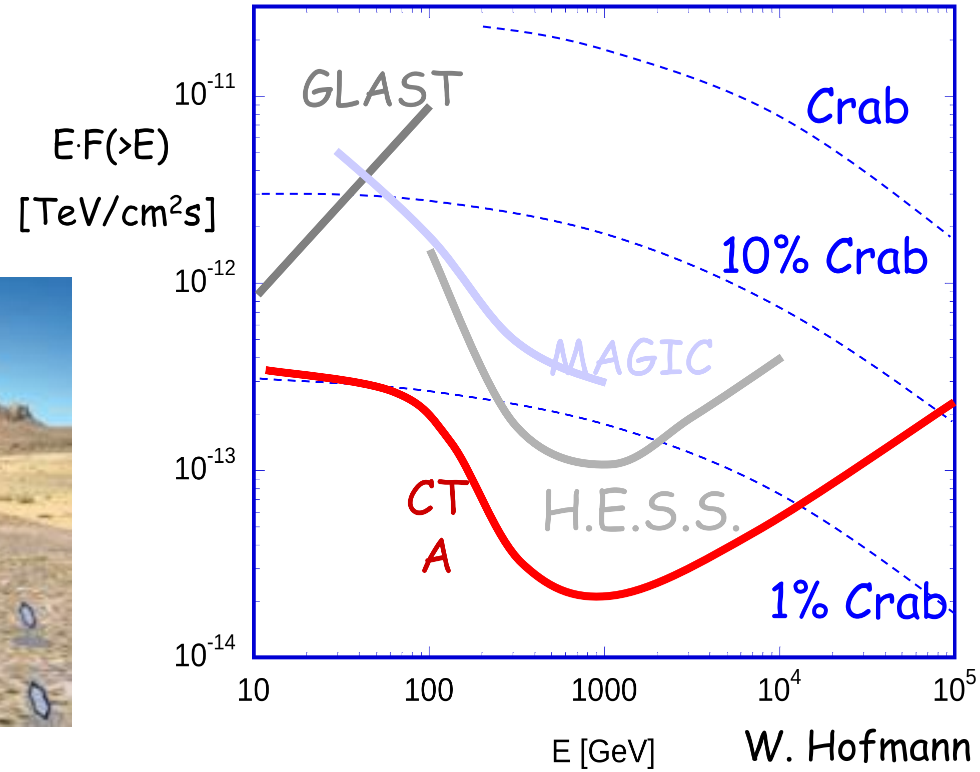
Present bounds from VERITAS (R.A. Ong, M. Wood & al, 2009)



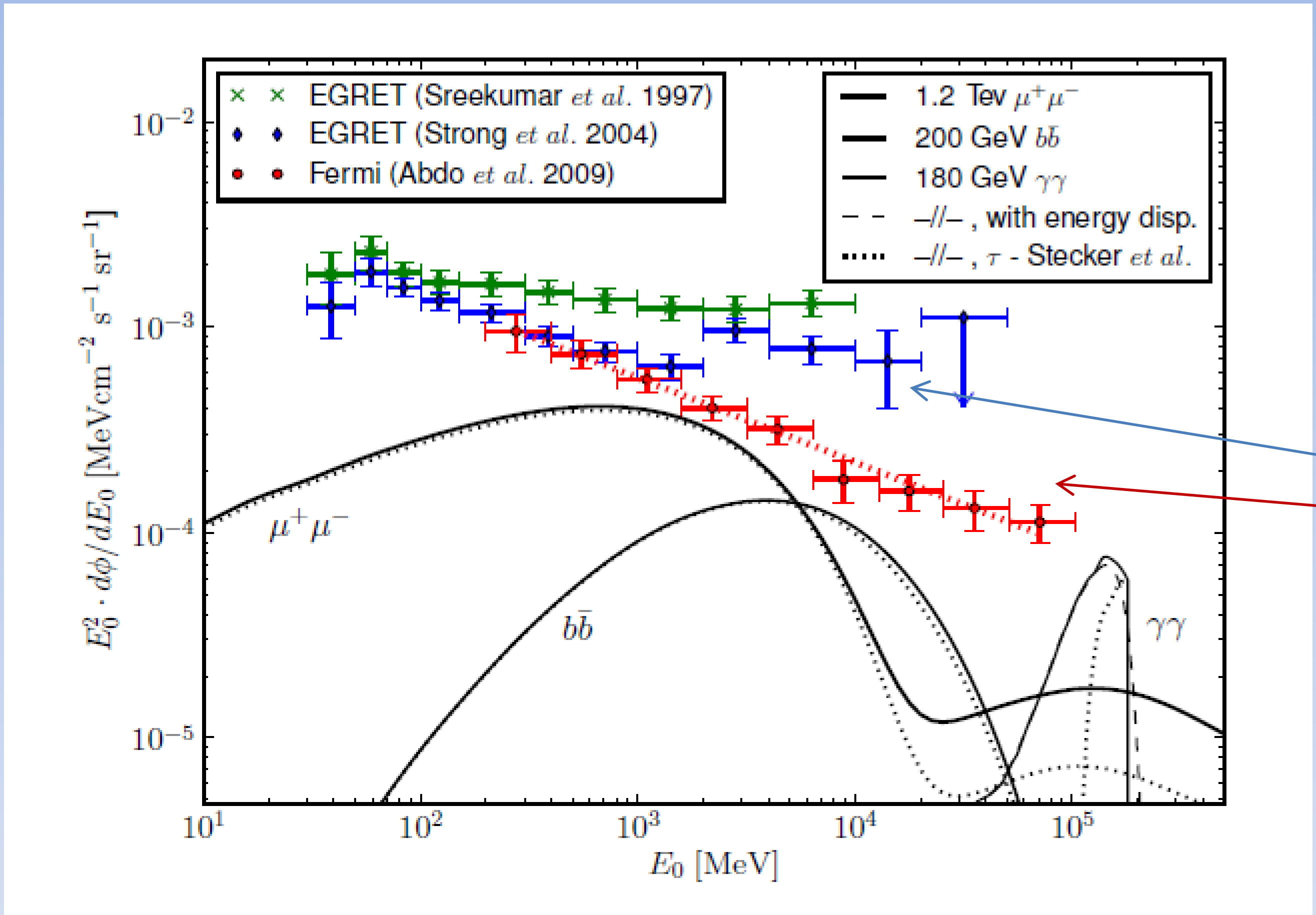
Present bounds (Canis Major) from HESS (F. Aharonian & al., 2008)

The future? Possible Cherenkov Telescope Array (CTA) in Europe (Also AGIS in the US)



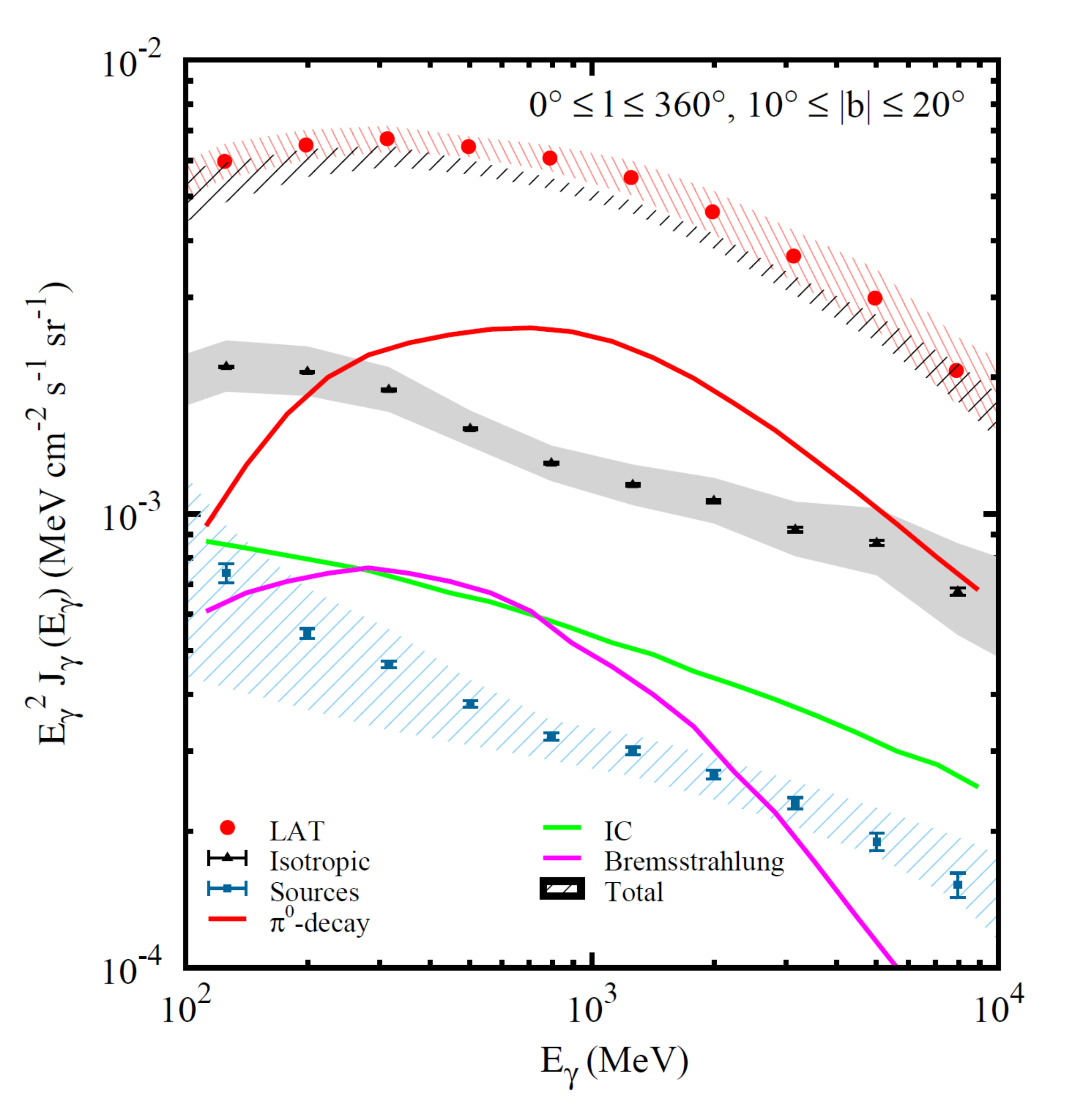


W. Hofmann



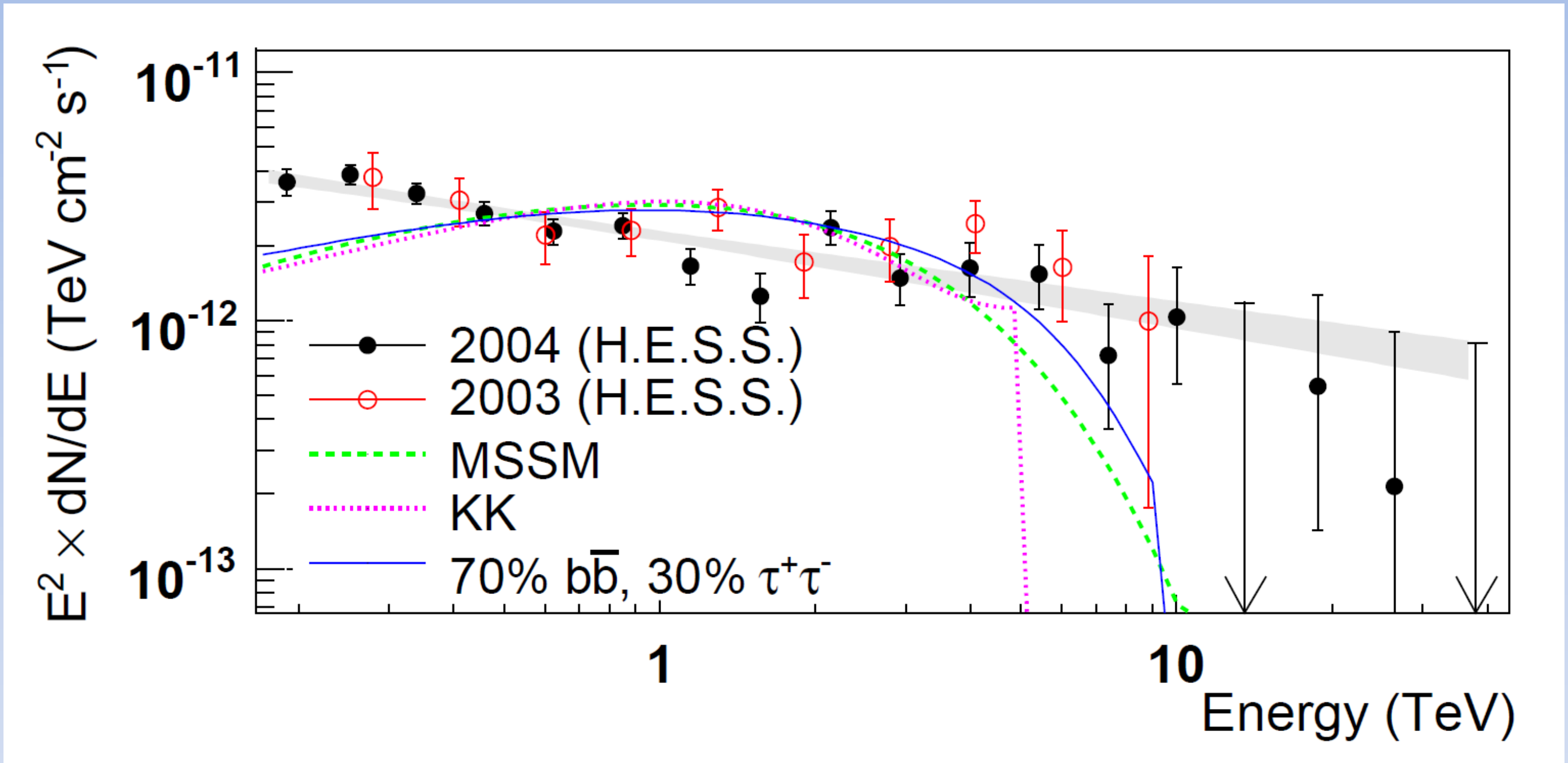
EGRET "GeV excess" seems now gone

Fermi diffuse exatragalactic data, 2010



Diffuse Galactic, FERMI, 2009

Galactic Center, HESS data (F.Aharonian & al., 2006)



Dark matter fit seems to have wrong shape. Also, the source is consistent with being point-like, not expected from DM.

Slide from D. Hooper, UCLA DM Symposium Feb. 2010:

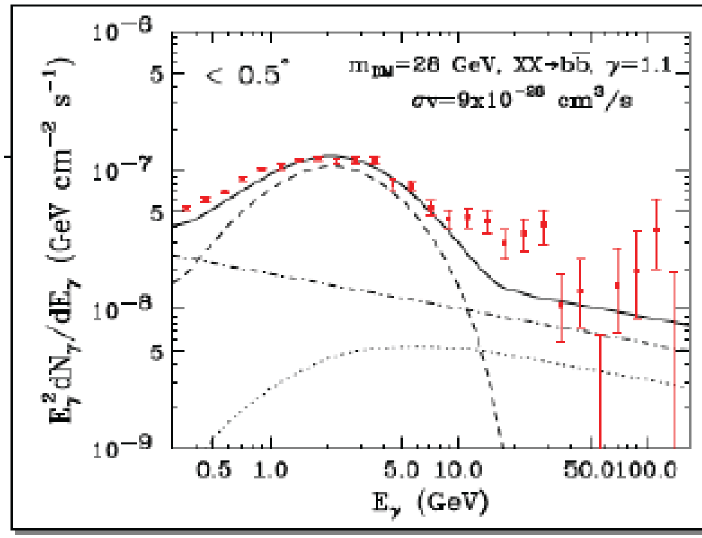
The Galactic Center Region As Seen By FGST

A conservative tact on studies of the galactic center…

- A common criticism of galactic center matter studies (including ours) is that astrophysical backgrounds are not well a large extent this is true

- This does NOT, however, mean that progress cannot be made

- Even without any foreknowledge of the backgrounds, one can look at the galactic and quickly derive limits comparable to those from the more useful dwarf galaxies

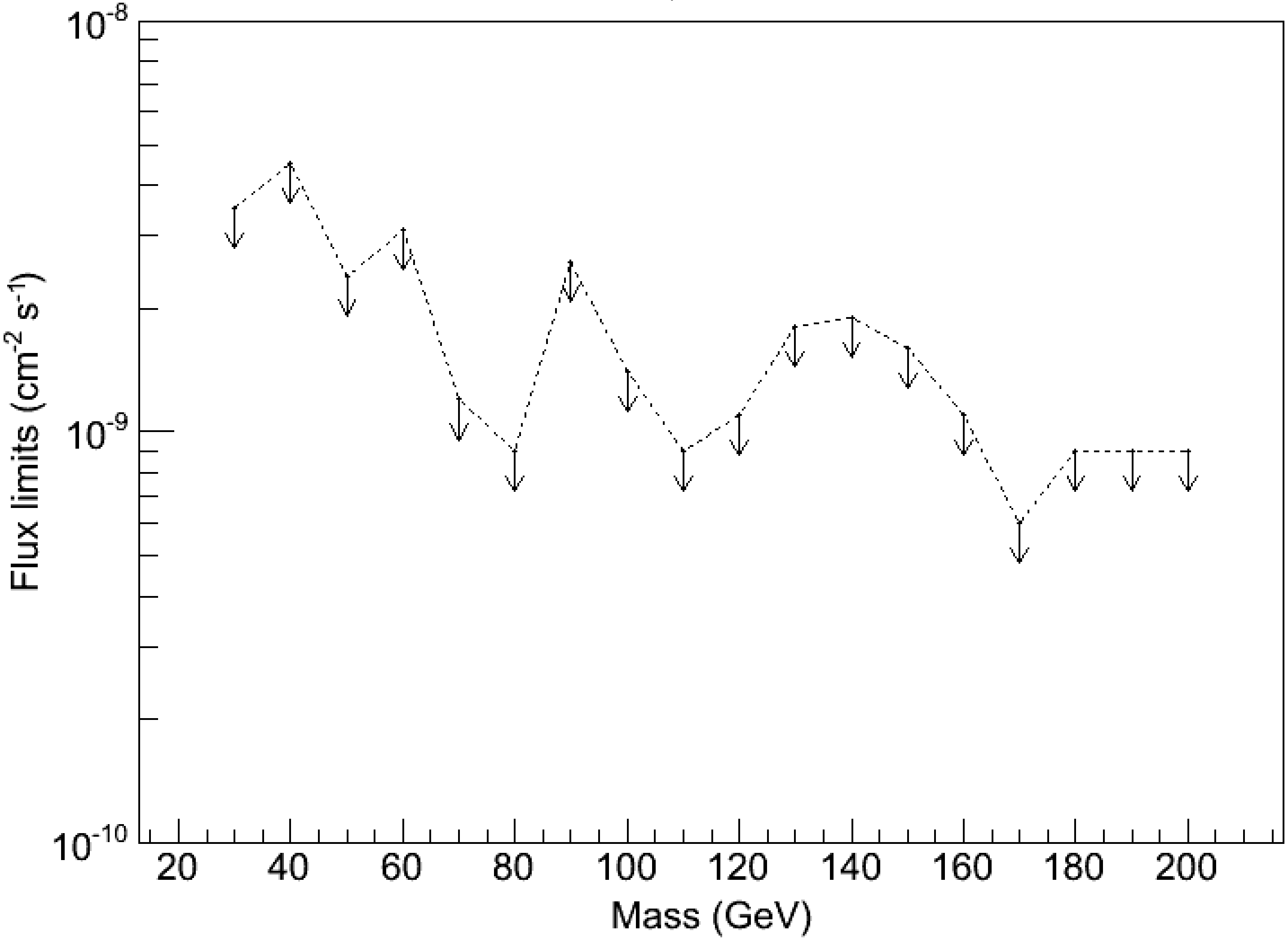


L. Goodenough and D. Hooper, 2009

- If even very modest assumptions are made about the nature of these backgrounds, considerably stronger limits are possible

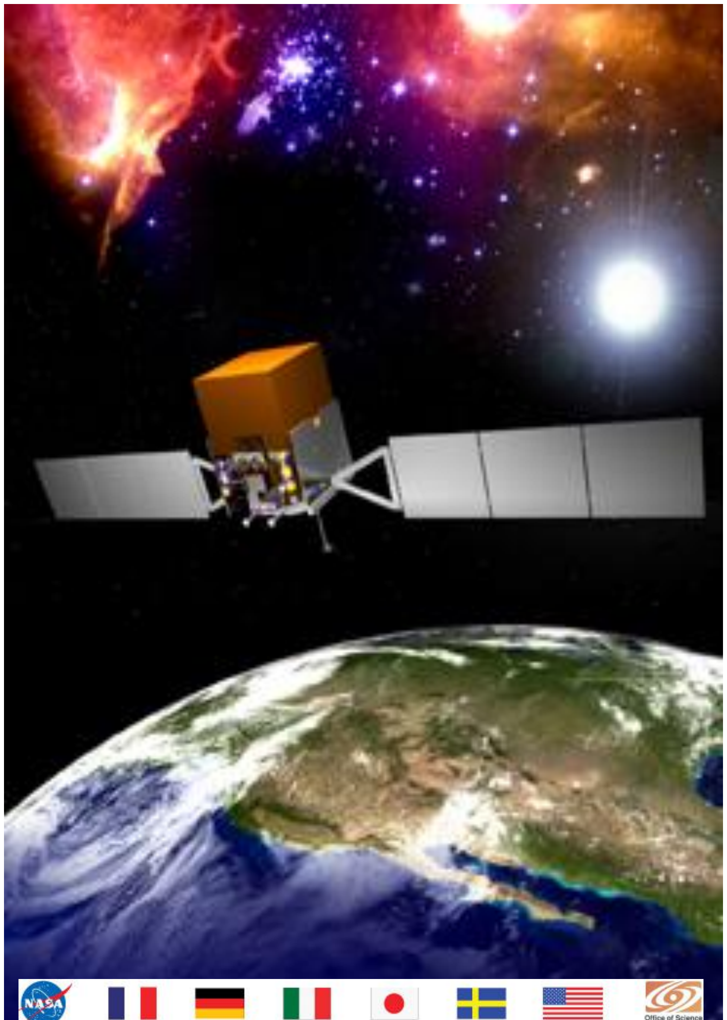
The Fermi Collaboration do not agree that this is a detected signal from dark matter. Backgrounds are not properly treated? Stay tuned…

Fermi line search, 11 months of data

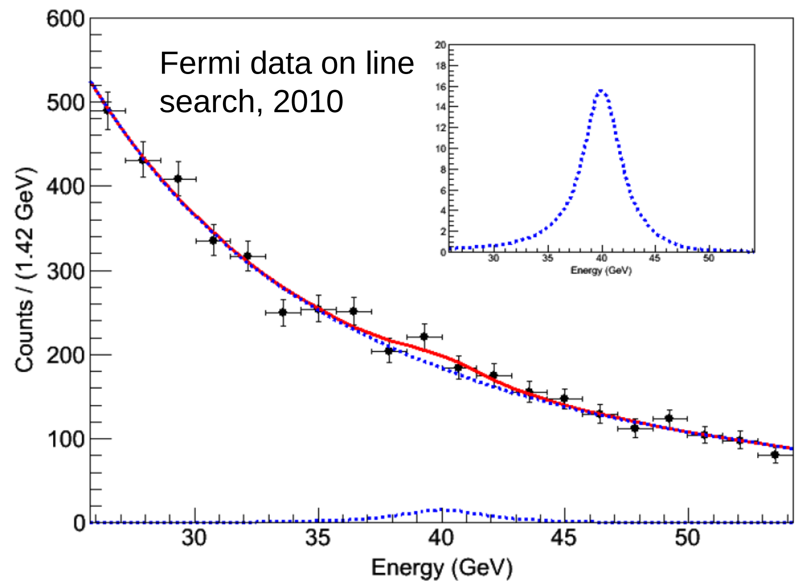


Fermi Collaboration, T. Ylinen & al. 2010

Gamma-rays:

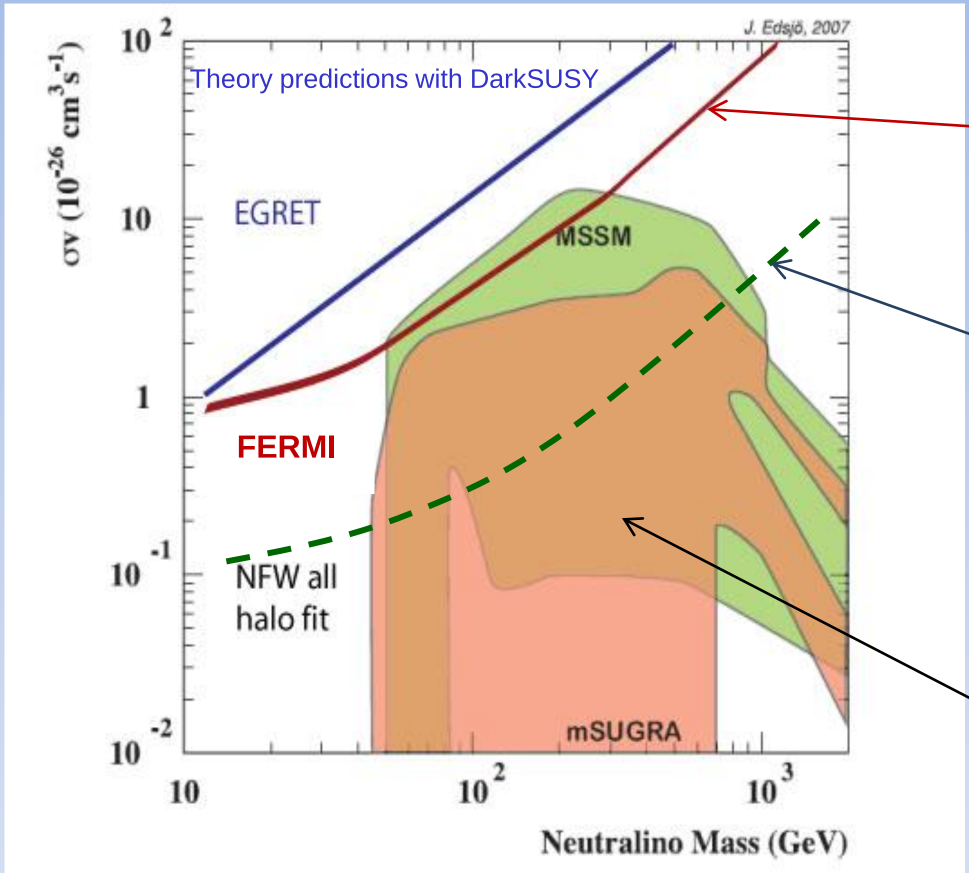


USA-France-Italy-Sweden-Japan – Germany collaboration, launched June 2008



Fermi can search for dark matter signals in gamma-rays up to 300 GeV – no unambiguous signal found so far (but still not probing much of SUSY parameter space, for example).

Gamma-rays, 3σ exclusion limit, 1 year of Fermi data, pre-launch predictions



"Conservative" approach, g.c.,

NFW halo profile assumed, no substructure.

Including all halo, with substructure

Will not be probed by Fermi, but by next generation of (ground-based) gamma-ray instruments, like CTA or AGIS

Fermi/GLAST working group on Dark Matter and New Physics, E.A. Baltz & al., JCAP, 2008.