Identification of Dark Matter Candidates

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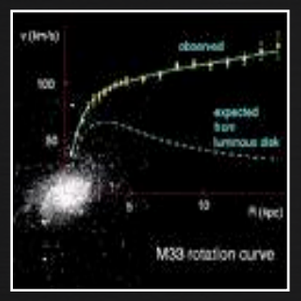
Summary

- Introduction
  - Evidence for DM
  - Properties of the "Good DM Candidate"
- DM searches @ accelerators
  - Principle & Status
  - What can we learn?
- DM Direct Detection
  - Principle & Status
  - What can we learn?
- DM Indirect Detection
  - Strategies
  - Recent data and constraints
- Conclusions

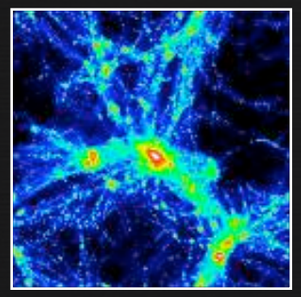
Evidence for Dark Matter

Evidence for the existence of an unseen, "dark", component in the energy density of the Universe comes from several independent observations at different length scales

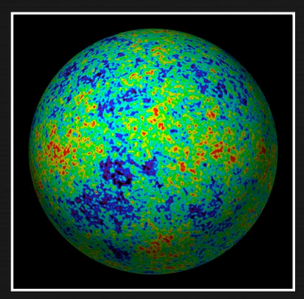
Cosmological observations



• Rotation Curves

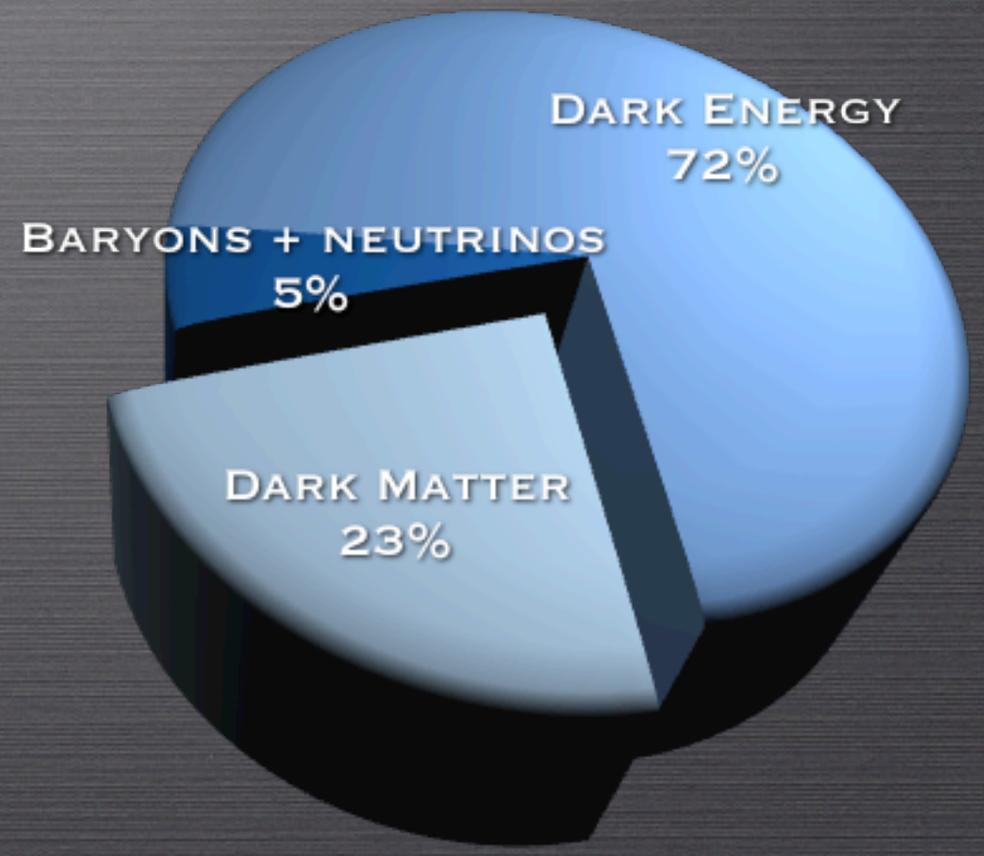


• Clusters of galaxies



•CMB

•Type Ia Supernovae



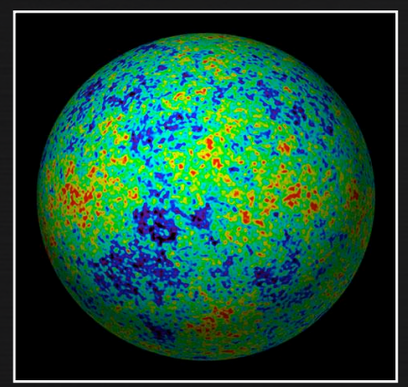
For recent reviews see e.g.:

GB, Hooper & Silk, hep-ph/0404175. Bergstrom, hep-ph/0002126

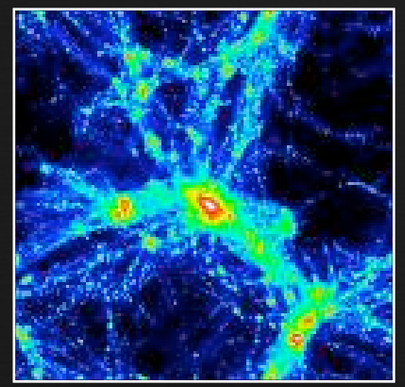
What do we know?

An extraordinarily rich zoo of non-baryonic Dark Matter candidates has been proposed over the last three decades. In order to be considered a viable DM candidate, a new particle has to pass the following 10-point test

1) Ωh^2 OK?

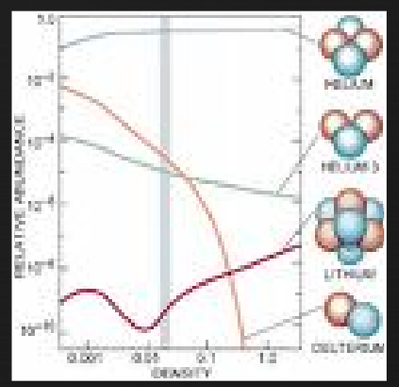


2) Is it cold?

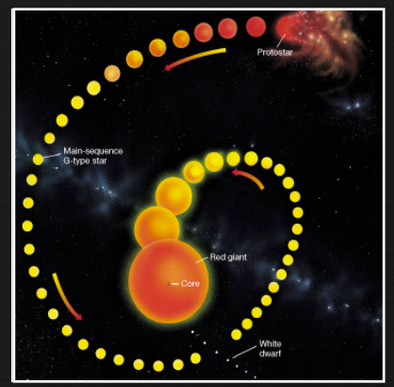


3) Is it neutral?

4) Is BBN ok?

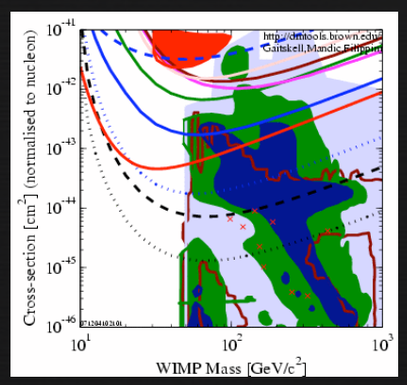


5) Stars OK?

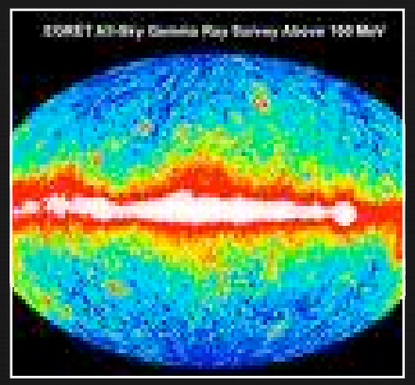


6) Collisionless?

7) Couplings OK?



8) γ-rays OK?



9) Astro bounds?

10) Can probe it?

Taoso, GB & Masiero 2007

The DM candidates Zoo

WIMPs

Natural Candidates
(arising from theories addressing the stability of the electroweak scale etc.)

- **Neutralino, LKP**
- **Also: LZP, LTP, etc.**

Ad-Hoc Candidates
(Postulated to solve the DM Problem)

- Minimal DM
- Inert Doublet Model
- Heavy Neutrinos

Other

- **Axions**
(Postulated to solve the strong CP problem)

- Sterile Neutrinos

- SuperWIMPs
(that inherit the appropriate relic density from the decay of the NTL particle of the new theory)

- WIMPless
(where the appropriate relic density is achieved by a suitable combination of masses and couplings of the DM particle)

- etc. (axino, Q-balls.....)

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10-point test

DM candidate	I Ωh^2	II Cold	III Neutral	IV BBN	V Stars	VI Self	VII Direct	VIII γ-rays	IX Astro	X Probed	Result
SM Neutrinos	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×
Sterile Neutrinos	∼	∼	✓	✓	✓	✓	✓	✓	✓!	✓	∼
Neutralino	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Gravitino	✓	✓	✓	∼	✓	✓	✓	✓	✓	✓	∼
Gravitino (broken R-parity)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sneutrino $\tilde{\nu}_L$	∼	✓	✓	✓	✓	✓	×	✓!	✓!	✓	×
Sneutrino $\tilde{\nu}_R$	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SUSY Q-balls	✓	✓	✓	✓	∼	✓	✓!	✓	✓	✓	∼
B^1 UED	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×[a]
Axion	✓	✓	✓	✓	✓	✓	✓!	✓	✓	✓	✓
Heavy photon (little Higgs)	✓	✓	✓	✓	✓	✓	✓	✓!	✓!	✓	✓
Inert Higgs model	✓	✓	✓	✓	✓	✓	✓	✓!	[b]	✓	✓
CHAMPs	✓	✓	×	✓	×	✓	×	✓	∼	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	∼	∼

[a] It is possible to reconcile a graviton LKP scenario with CMB and diffuse photon background measurements, if the minimal UED model is extended with right-handed neutrinos, [458].
[b] There are not yet studies on neutrino or antimatter signals potentially produced by this dark matter candidate.

TAOSO, GB & MASIERO 2007

Test performance of selected DM candidates. The symbol V is used when the candidates satisfy the corresponding requirement, and it is accompanied by a ! symbol, in the case that present and upcoming experiments will soon probe a significant portion of the candidate's parameter space. If the requirement can be satisfied only in less natural, or non-standard scenarios, or in the case of tension with observational data, the symbol ∼ is used instead. Candidates with a ∼ symbol in the last column, where the final result is shown, should still be considered viable. If one of the requirements is not satisfied, then the symbol °ø is used, and since these requirements are necessary conditions, the presence of a single °ø is sufficient to rule out the particle as a viable DM candidate.

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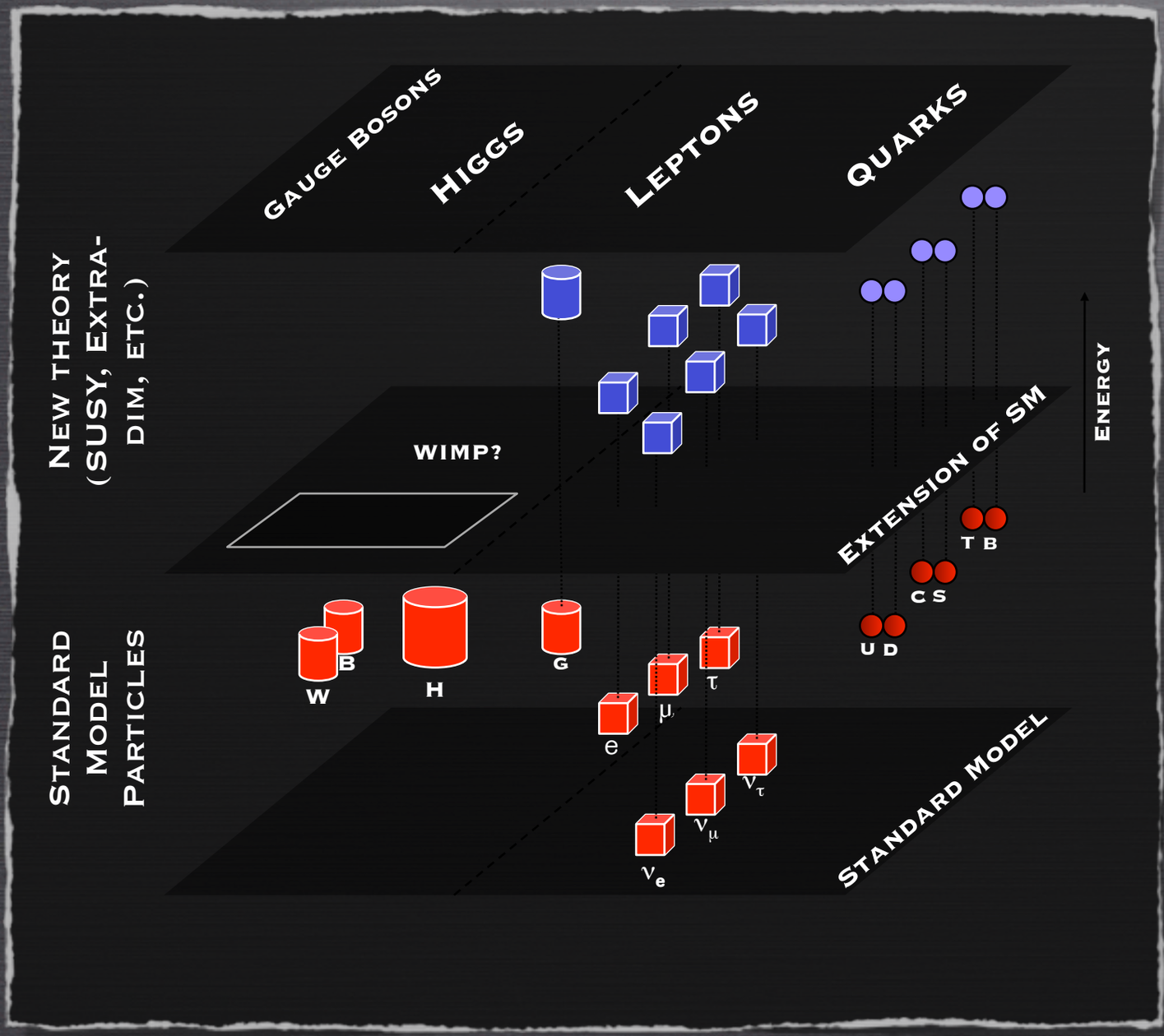
Beyond the Standard Model

The Standard Model provides an accurate description of all known particles and interactions, however there are good reasons to believe that the Standard model is a low-energy limit of a more fundamental theory



To explain the origin of the weak scale, extensions of the Standard model often postulate the existence of new physics at ~100 GeV

On the left, schematic view of the structure of possible extensions of the Standard model

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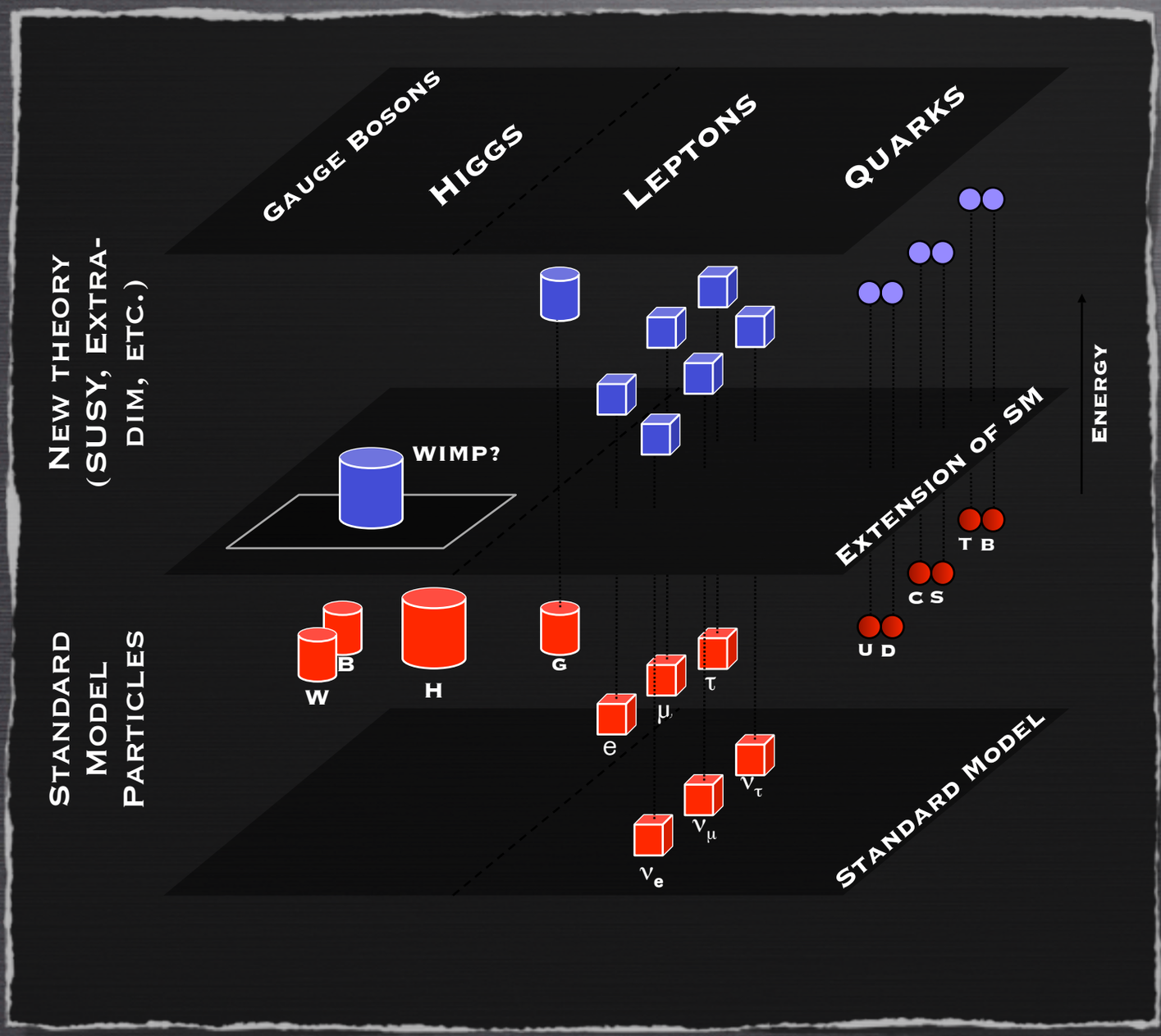

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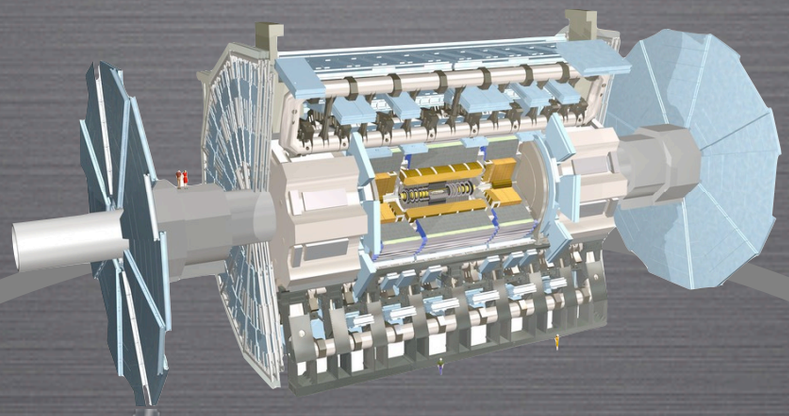
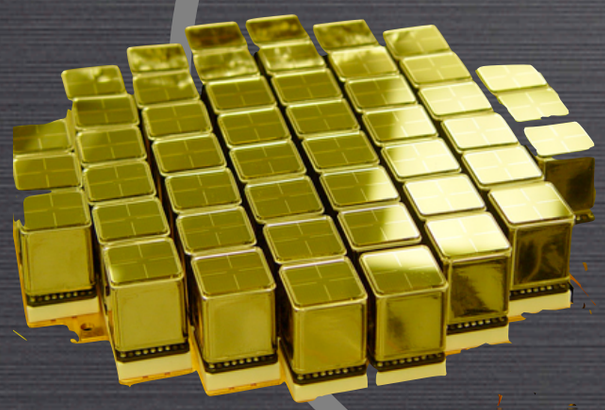
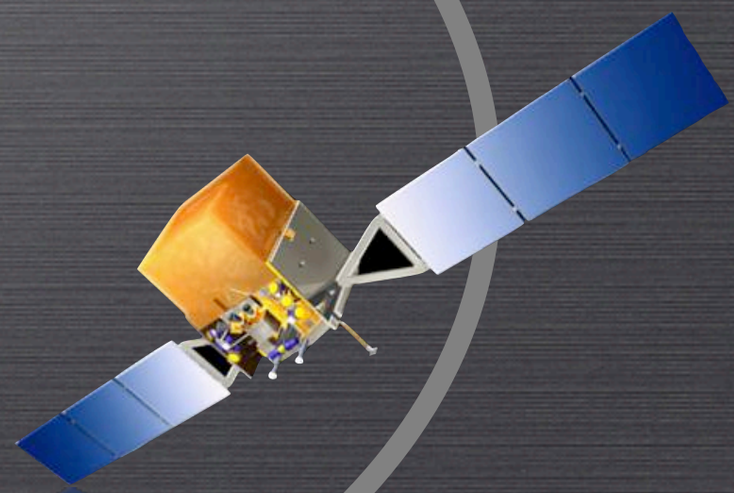
Particle Dark Matter: A multidisciplinary approach



Colliders

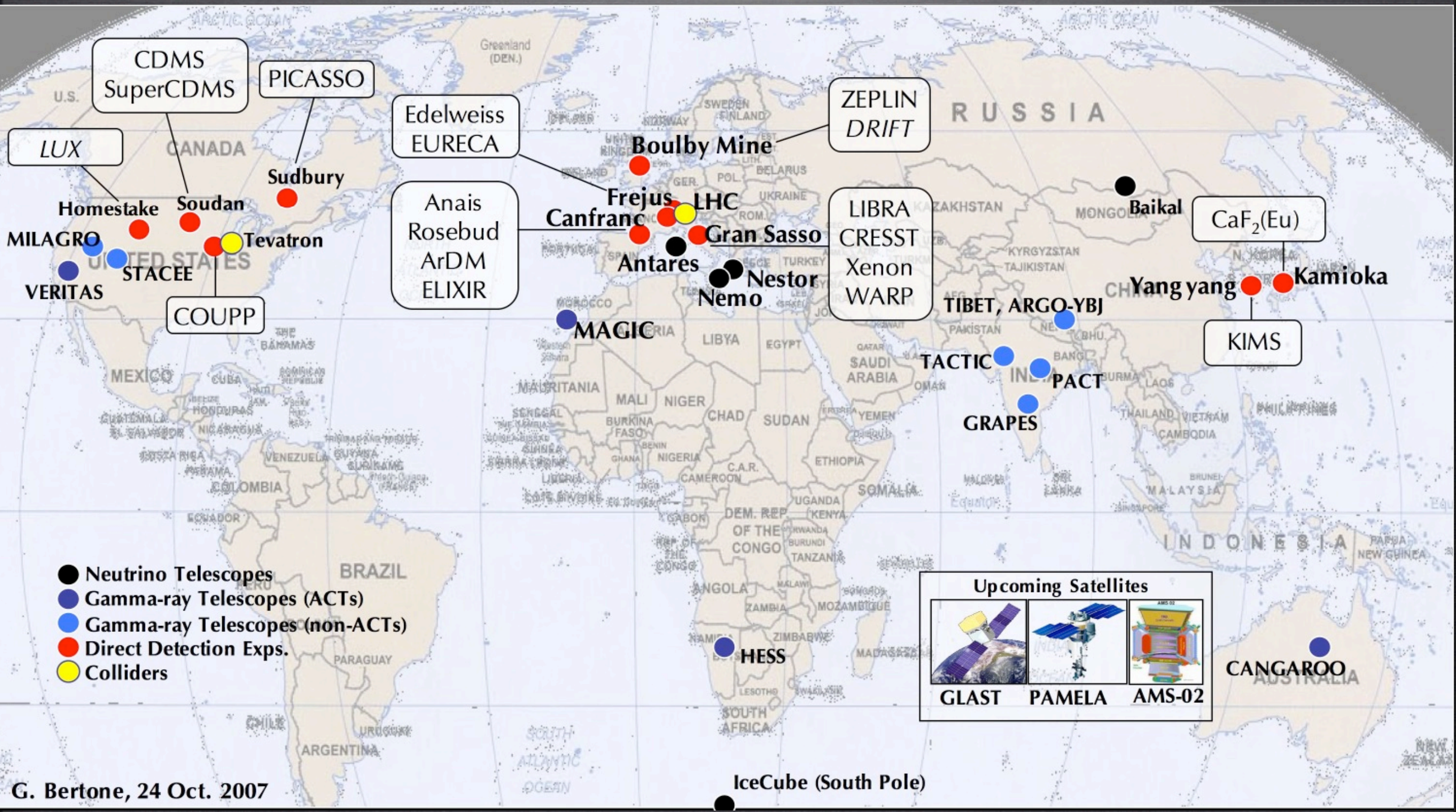


Direct Detection



Indirect Detection

Dark Matter-related Experiments circa 2009



Download: http://www2.iap.fr/users/bertone/

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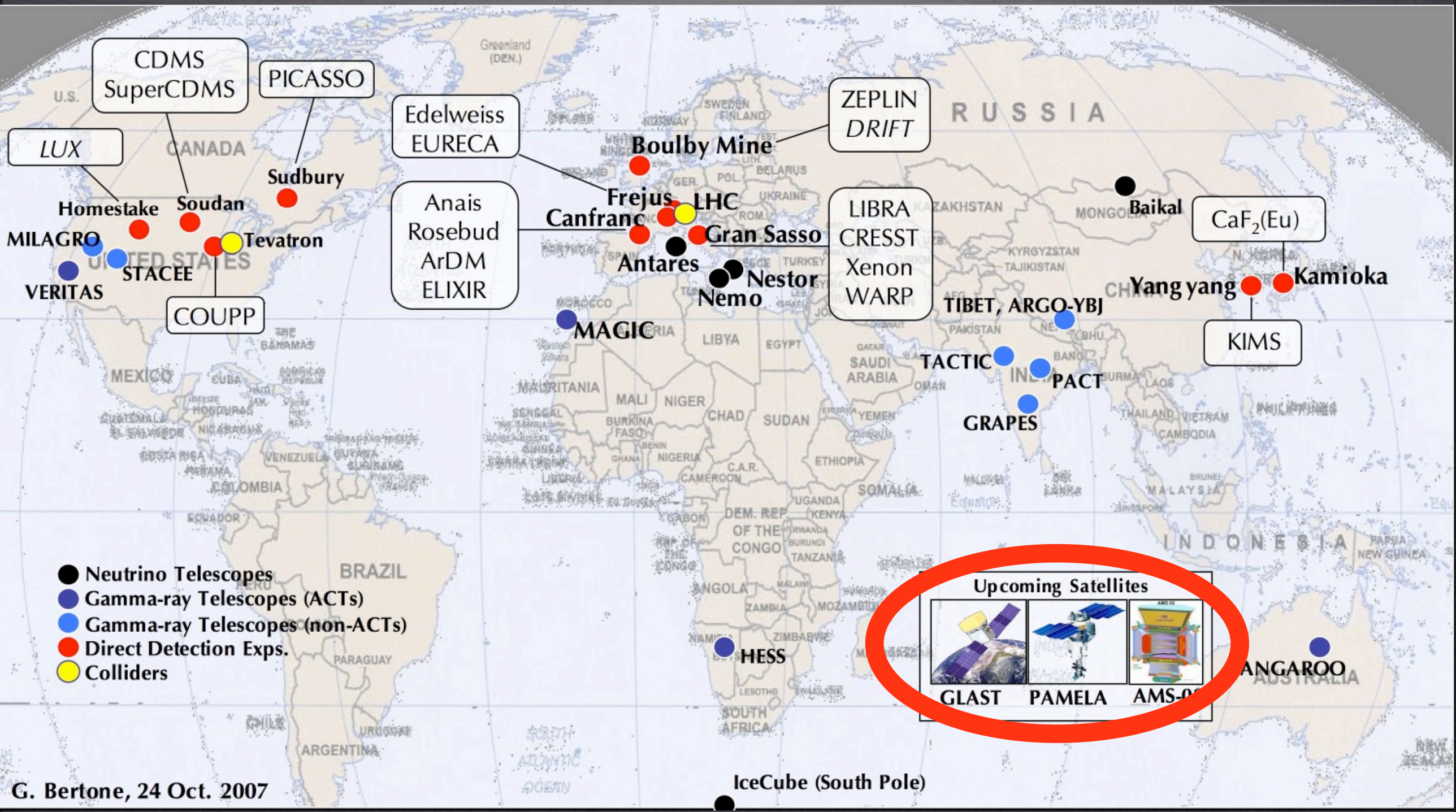

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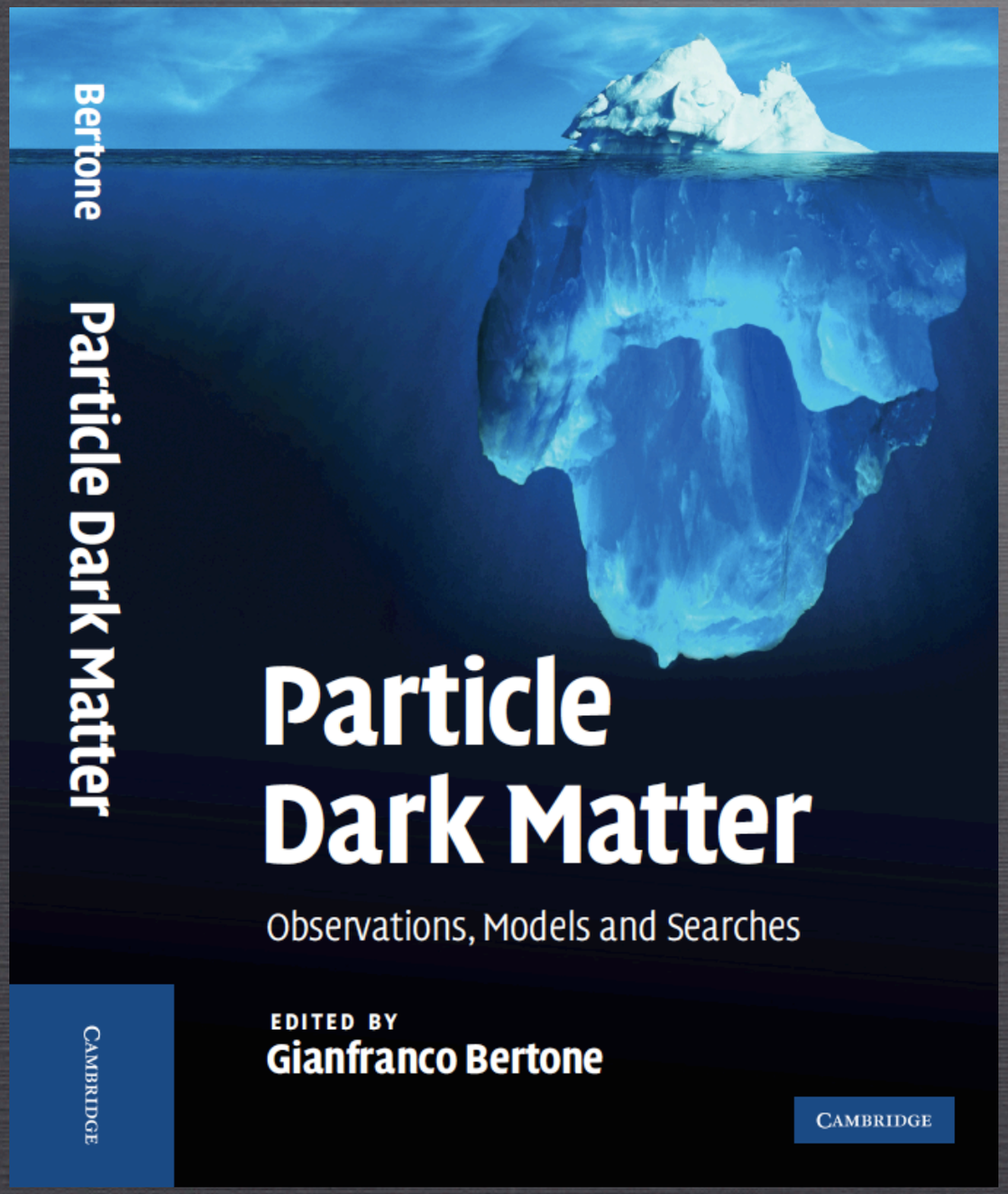
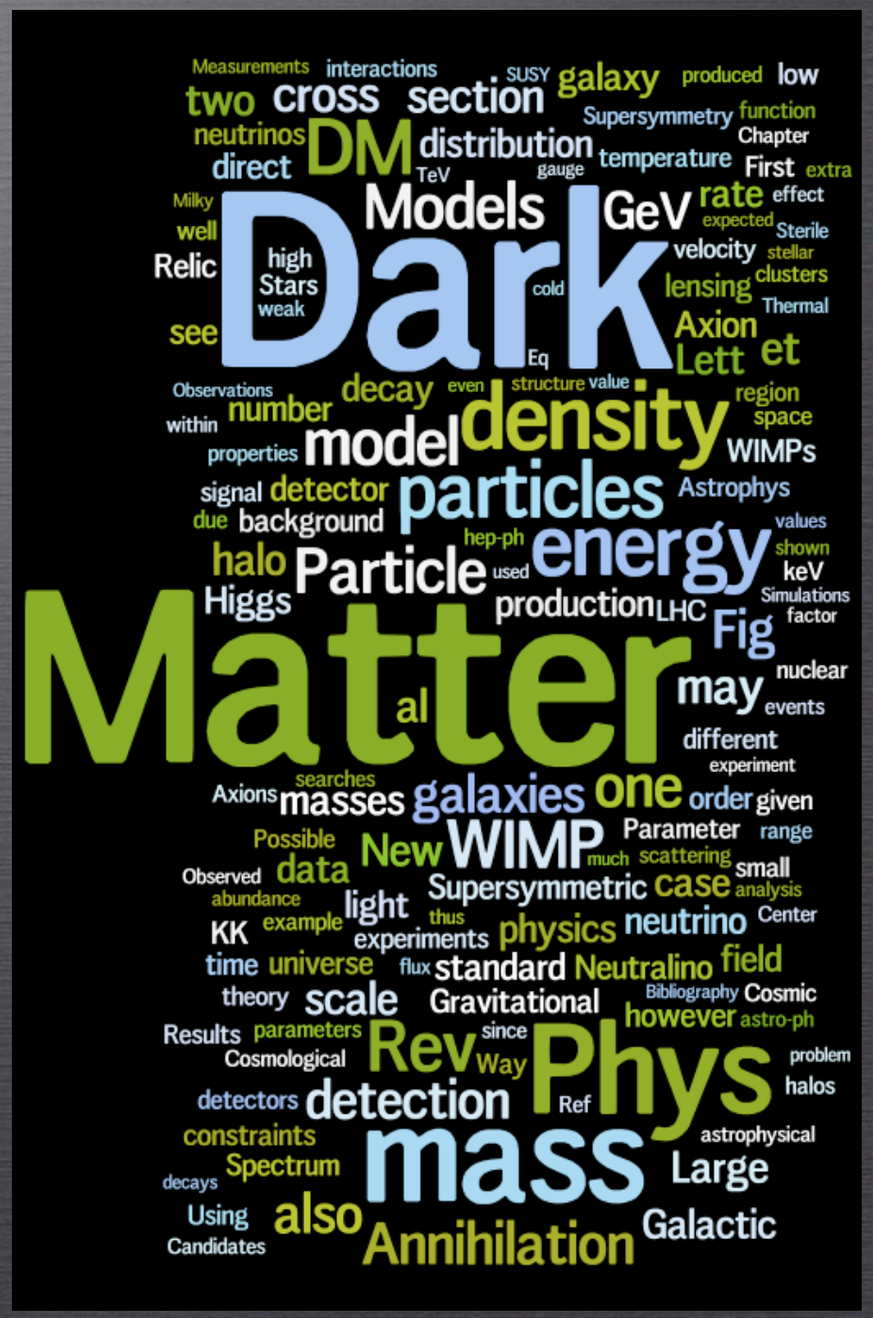
Particle DM

Cambridge U. Press

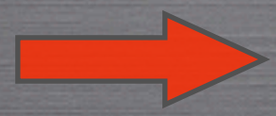


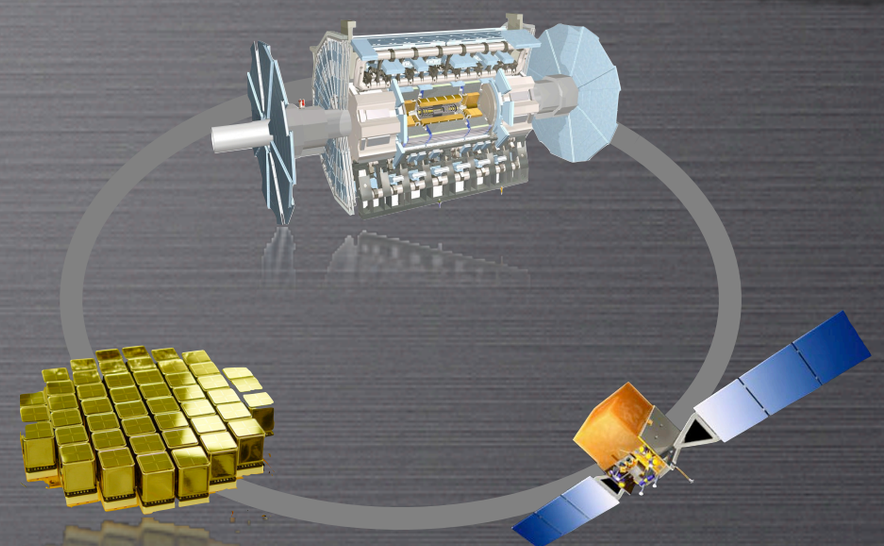


29 Chapters, 45 Authors, Published last month

Where do we stand?

We have built (are building) experiments to search for Dark Matter, and we have been making predictions for decades





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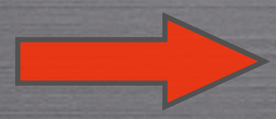
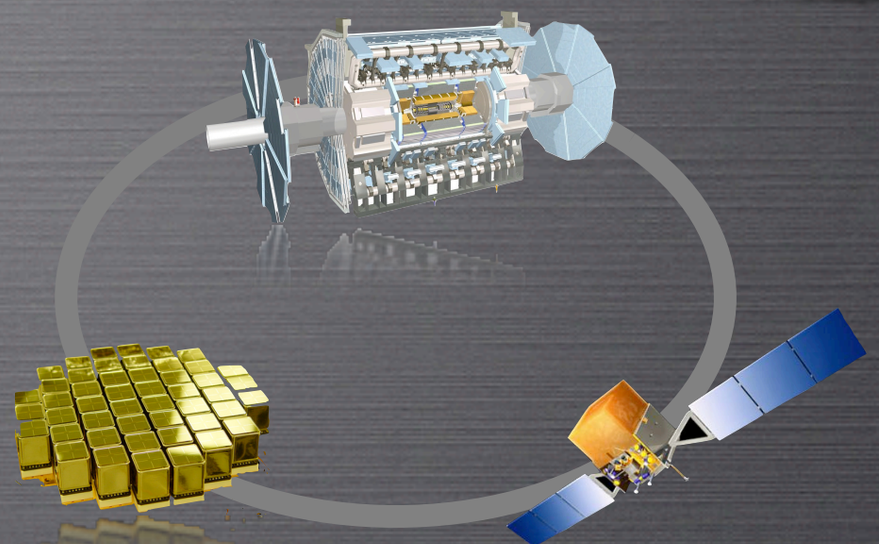
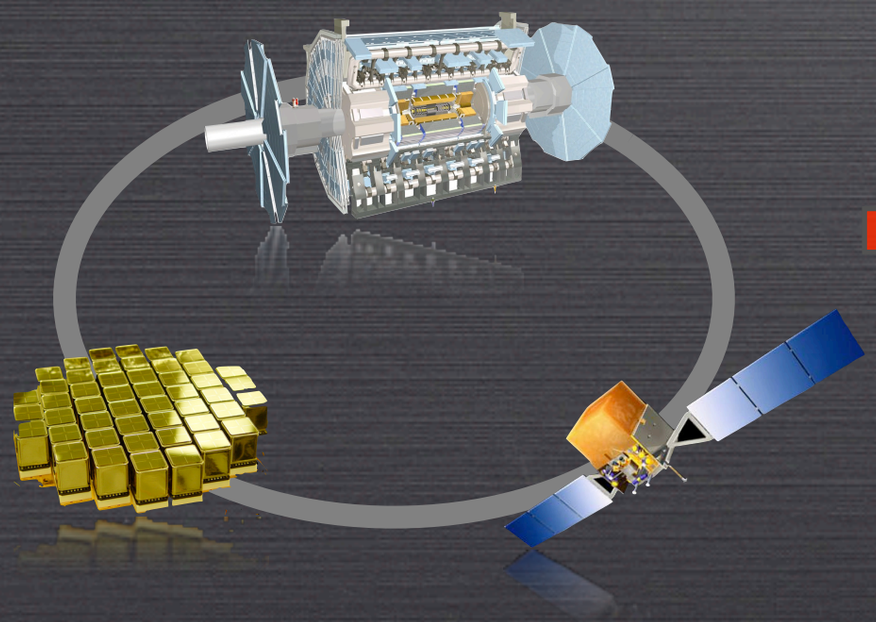




We are getting ready to solve the “inverse Problem” (and hoping that there will be a problem to solve..!)



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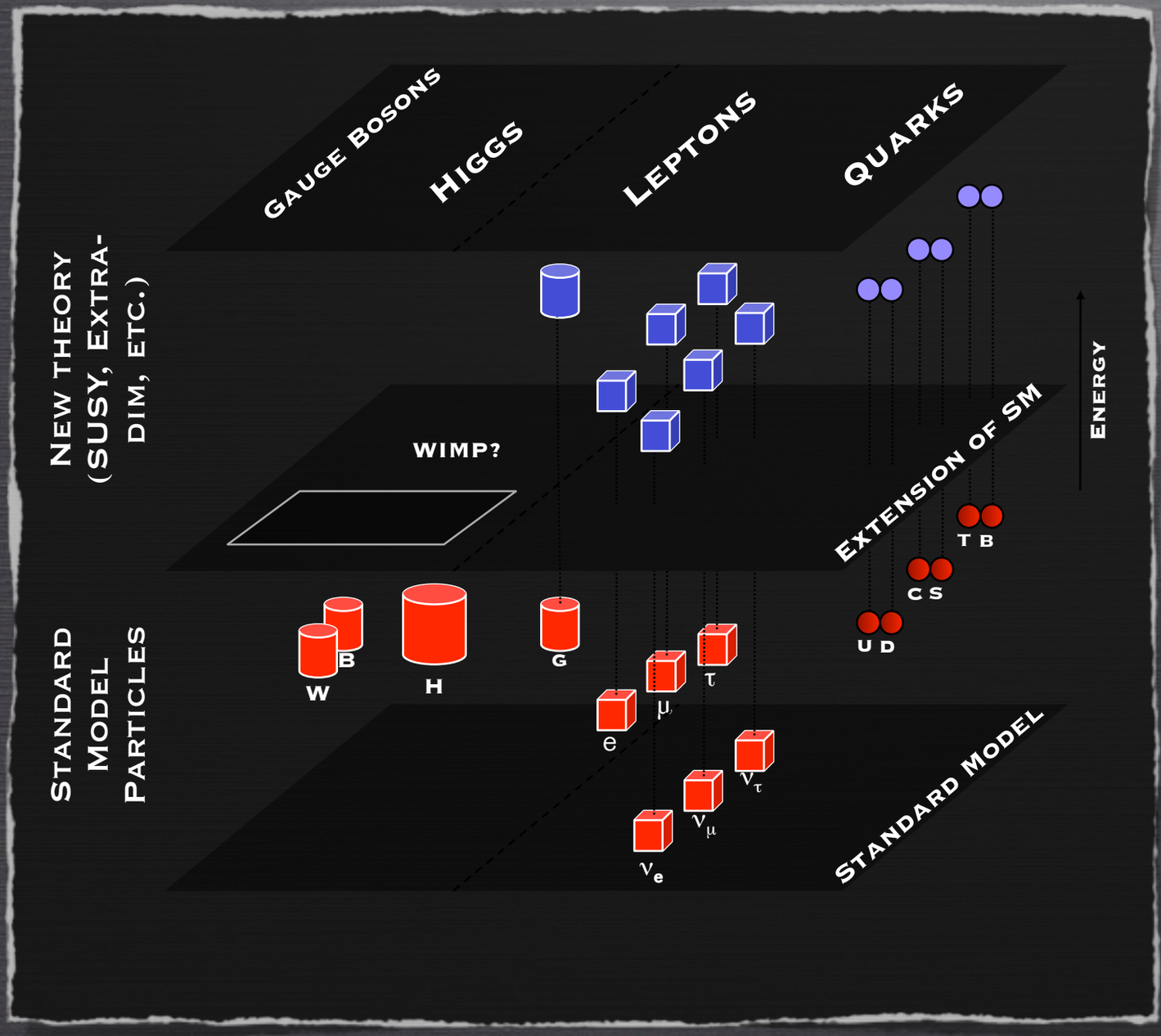
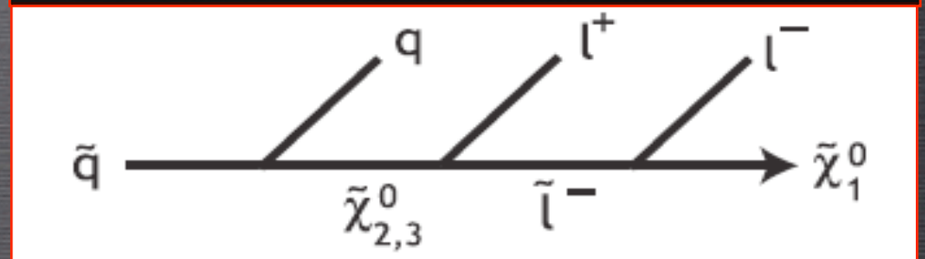


Search at LHC for processes like e.g.



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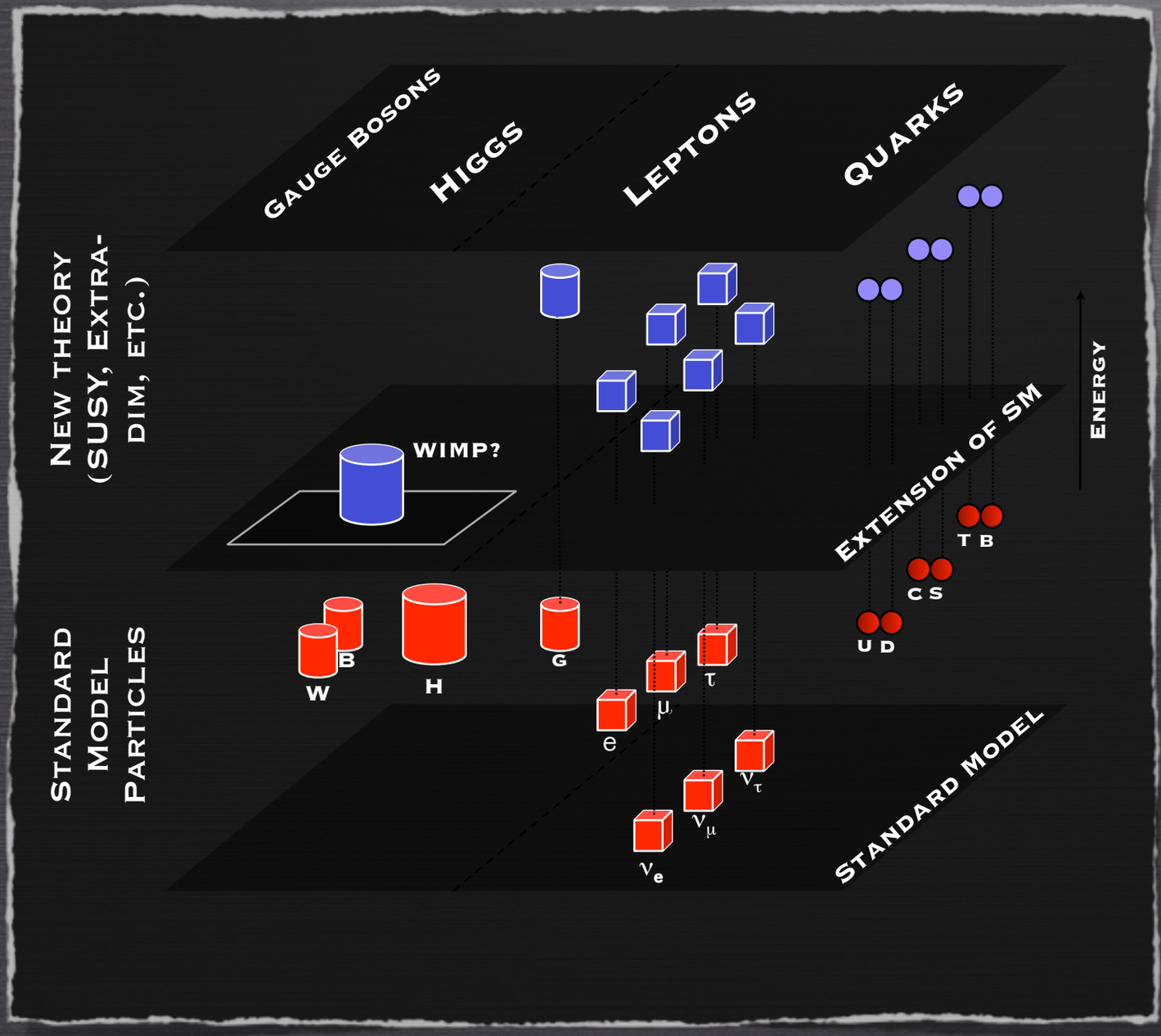

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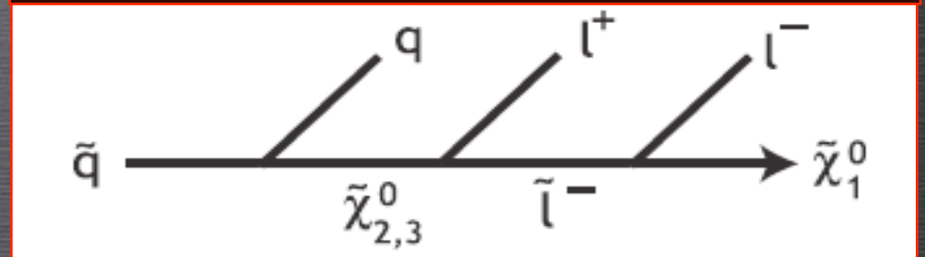
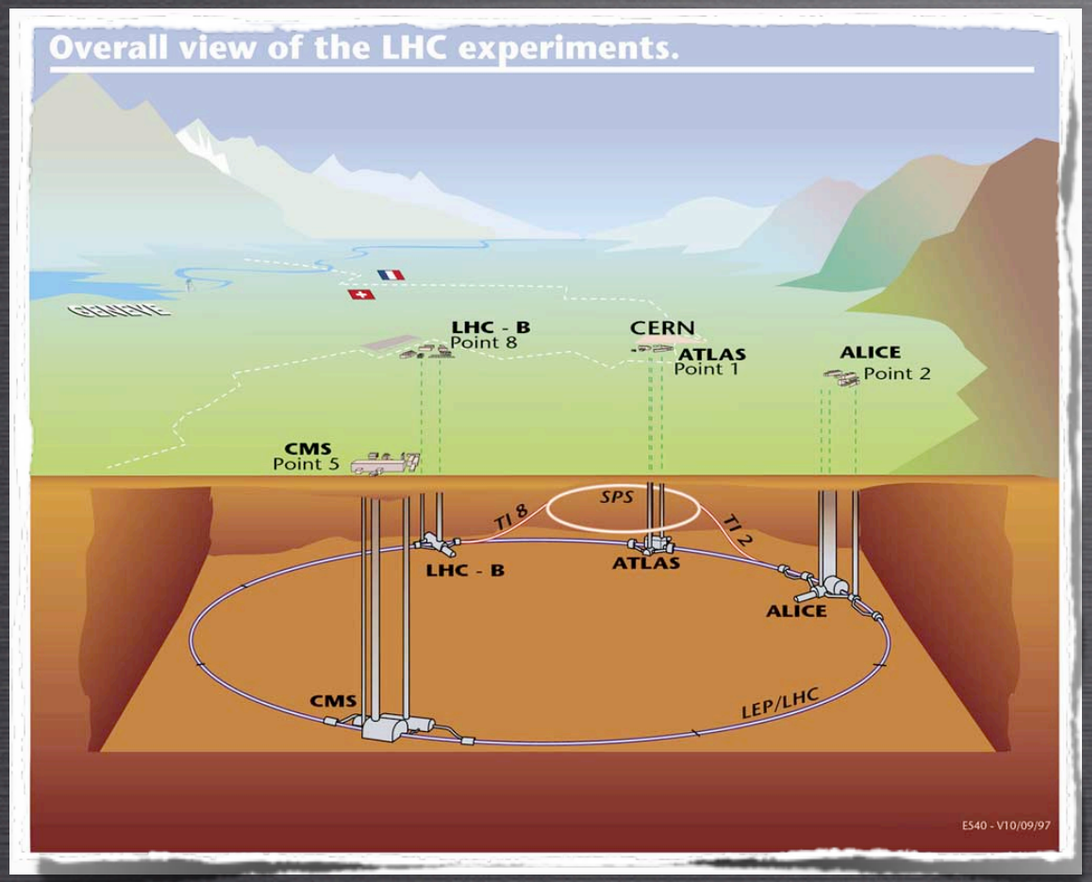
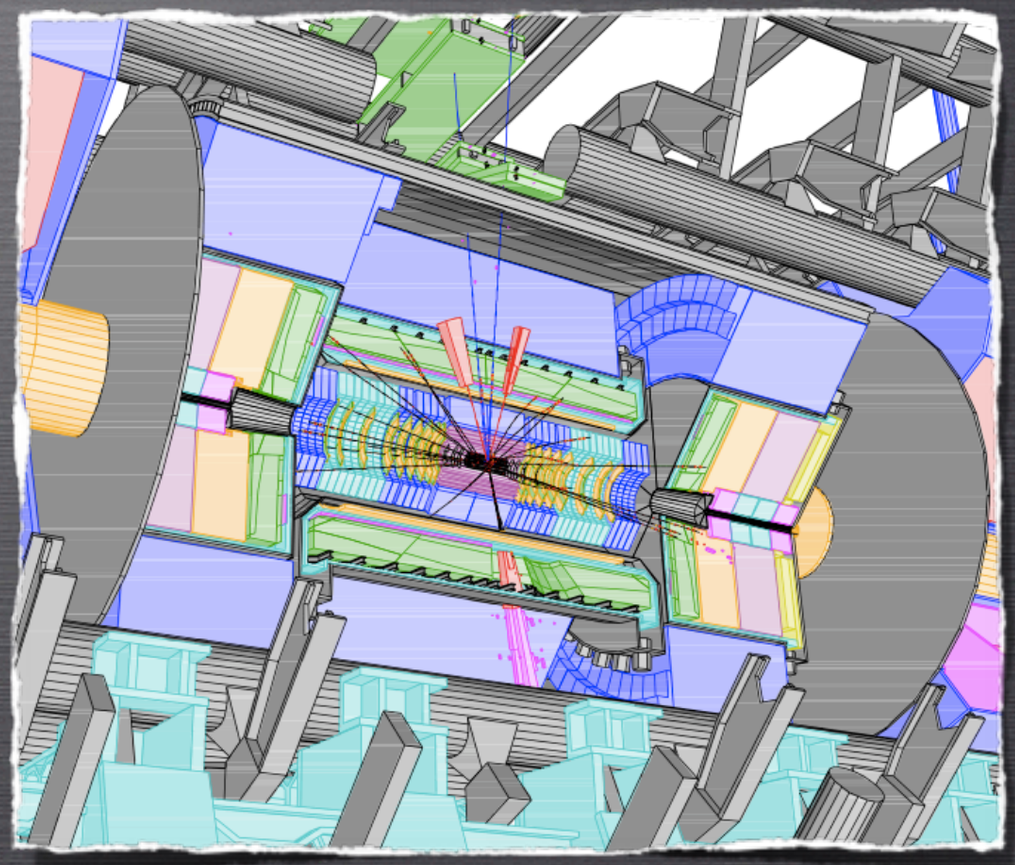


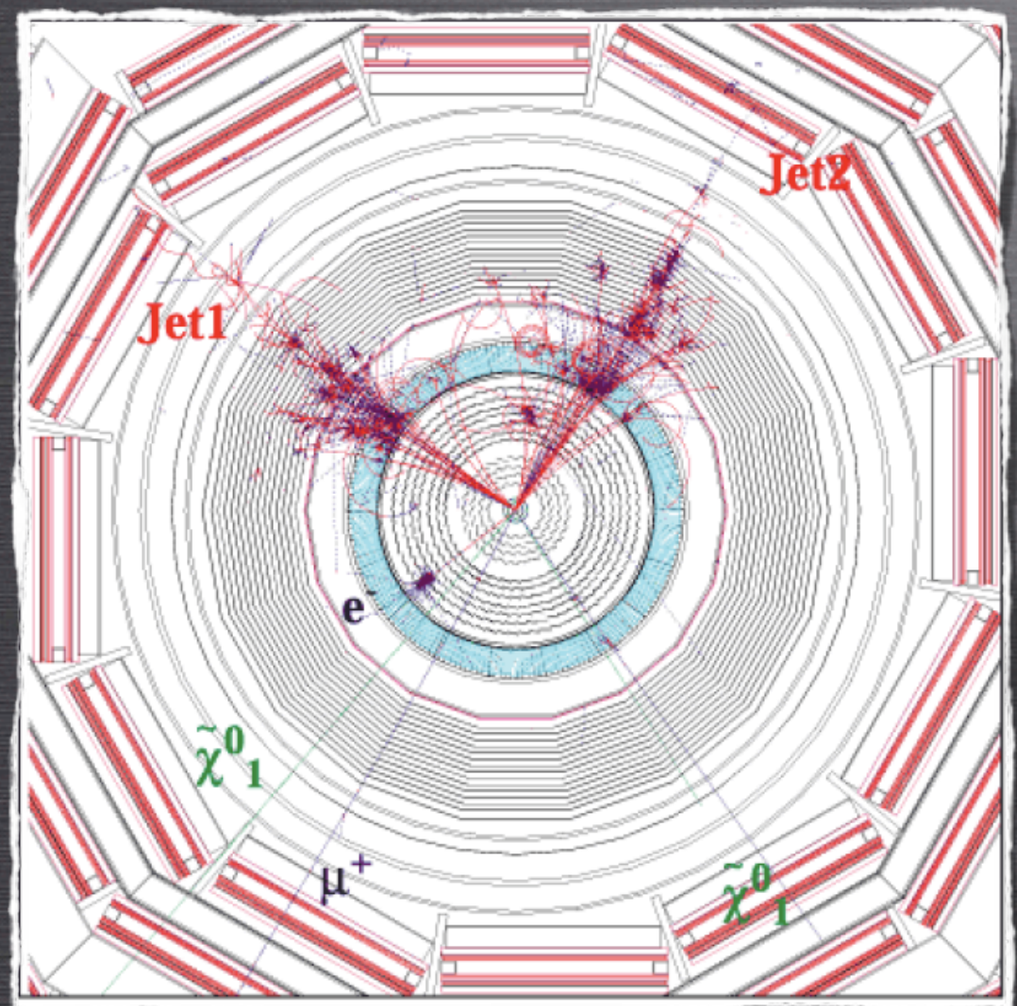
Searching for New Physics at the LHC



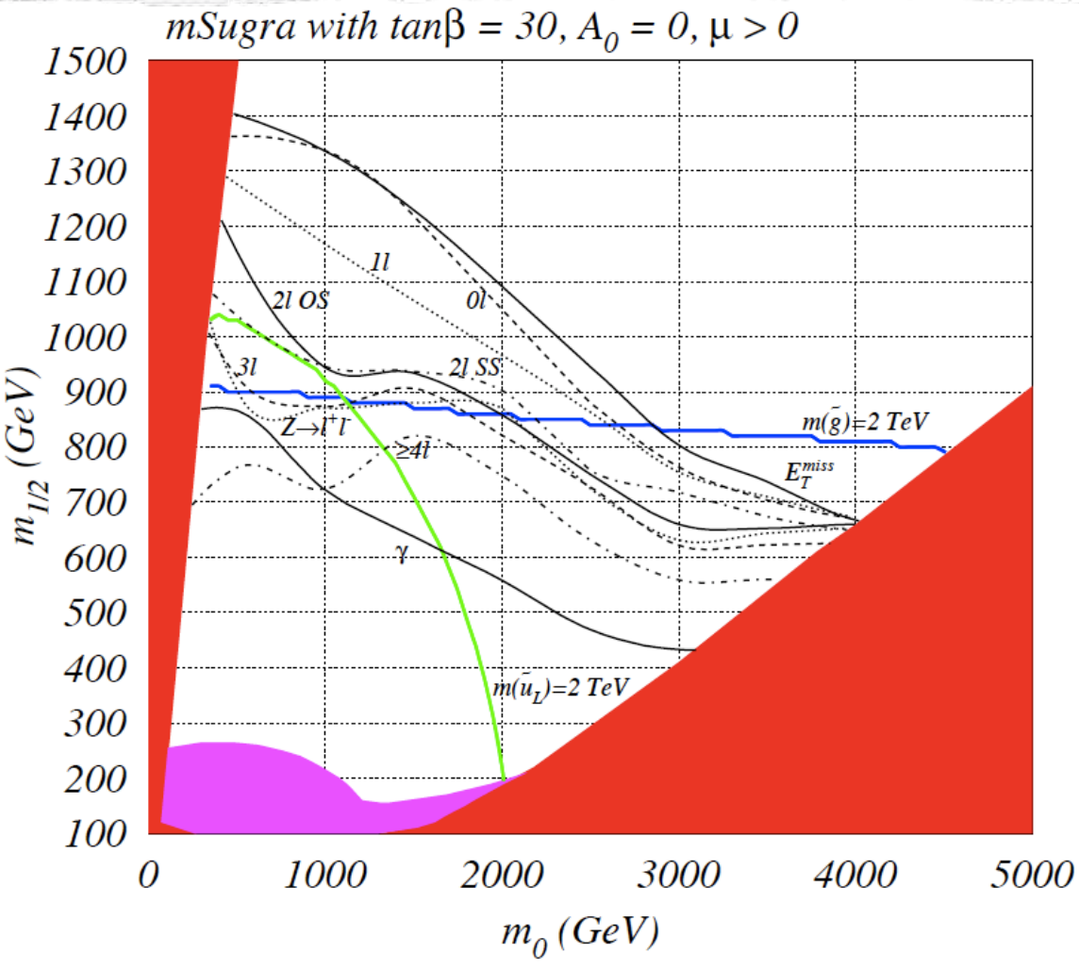


Searching for New Physics at the LHC

Example of analysis in the framework of mSUGRA



Simulation of an event with SUSY particle production in the CMS detector at the LHC



The 100 fb^{-1} reach of LHC for SUSY in the mSUGRA model. For each event topology, the signal is observable below the corresponding contour.

Example of Inverse problem at LHC

Inferring the relic density (thus the DM nature) of newly discovered particles from LHC data... What we would like:

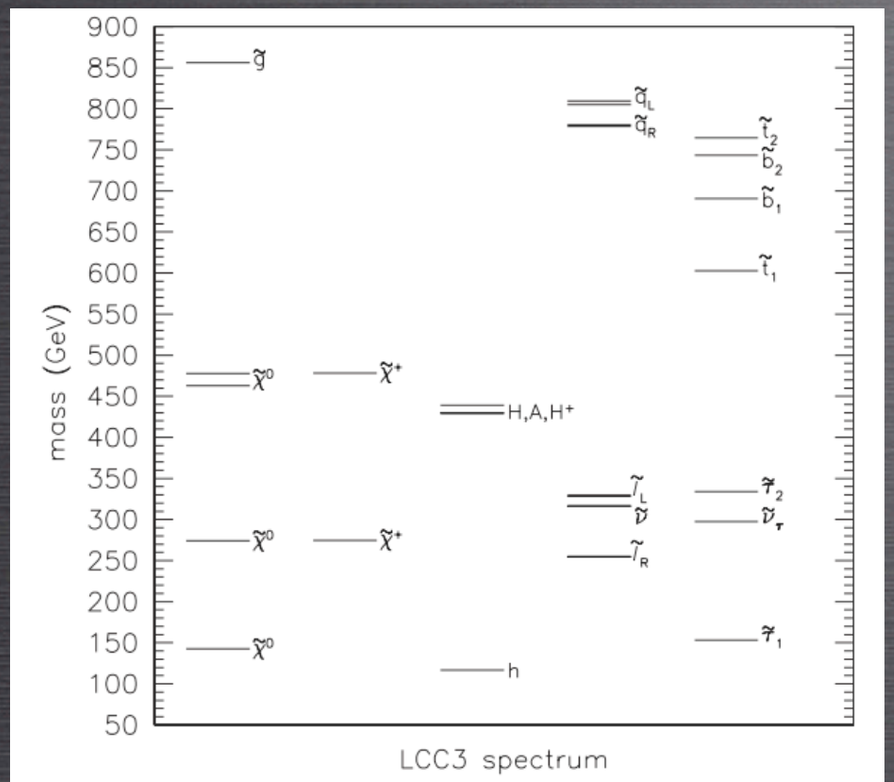
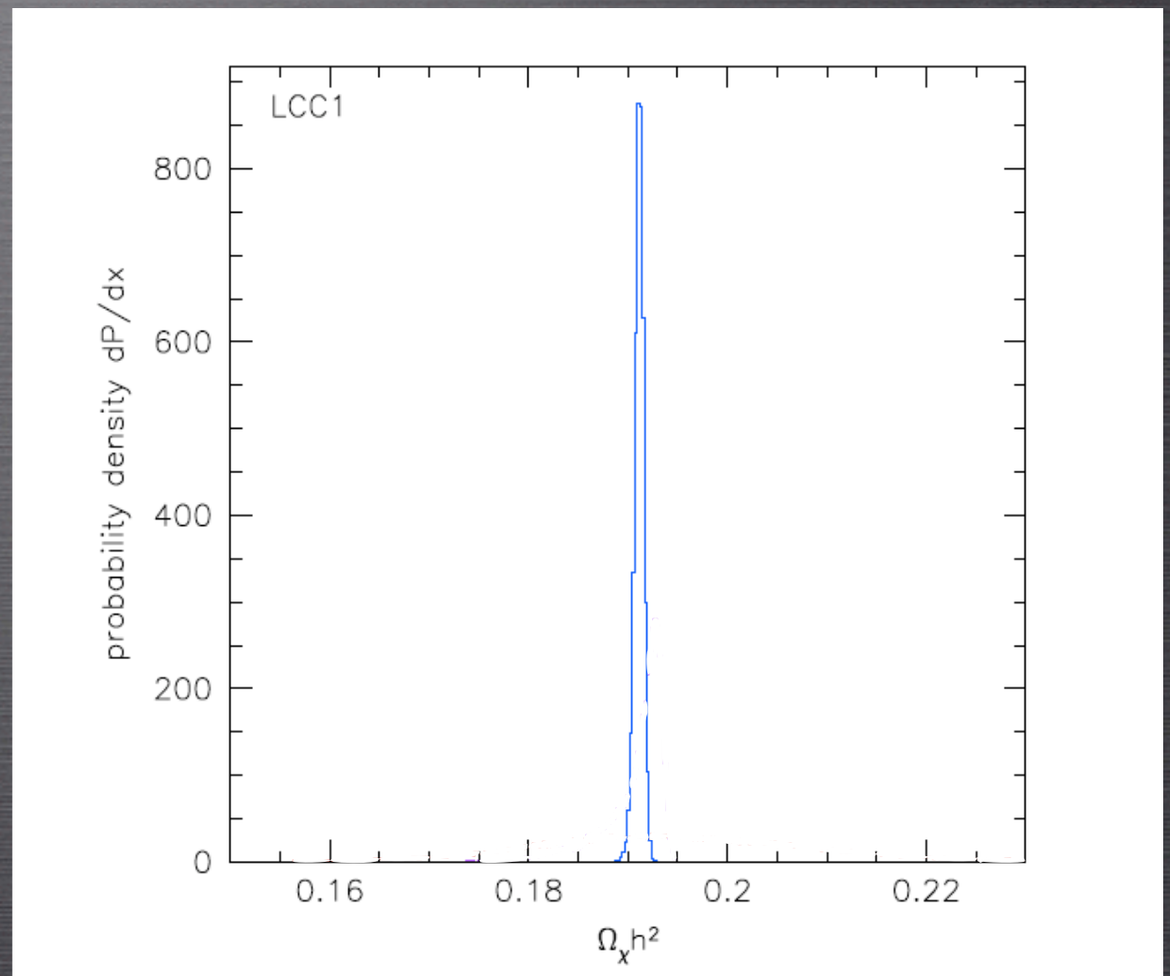
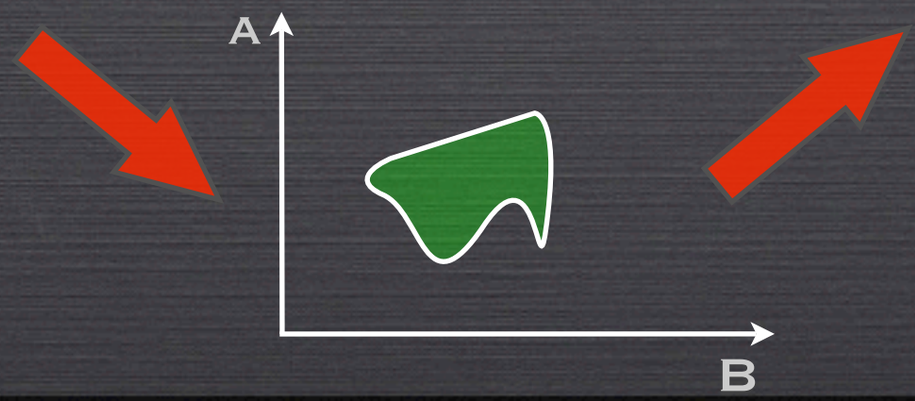


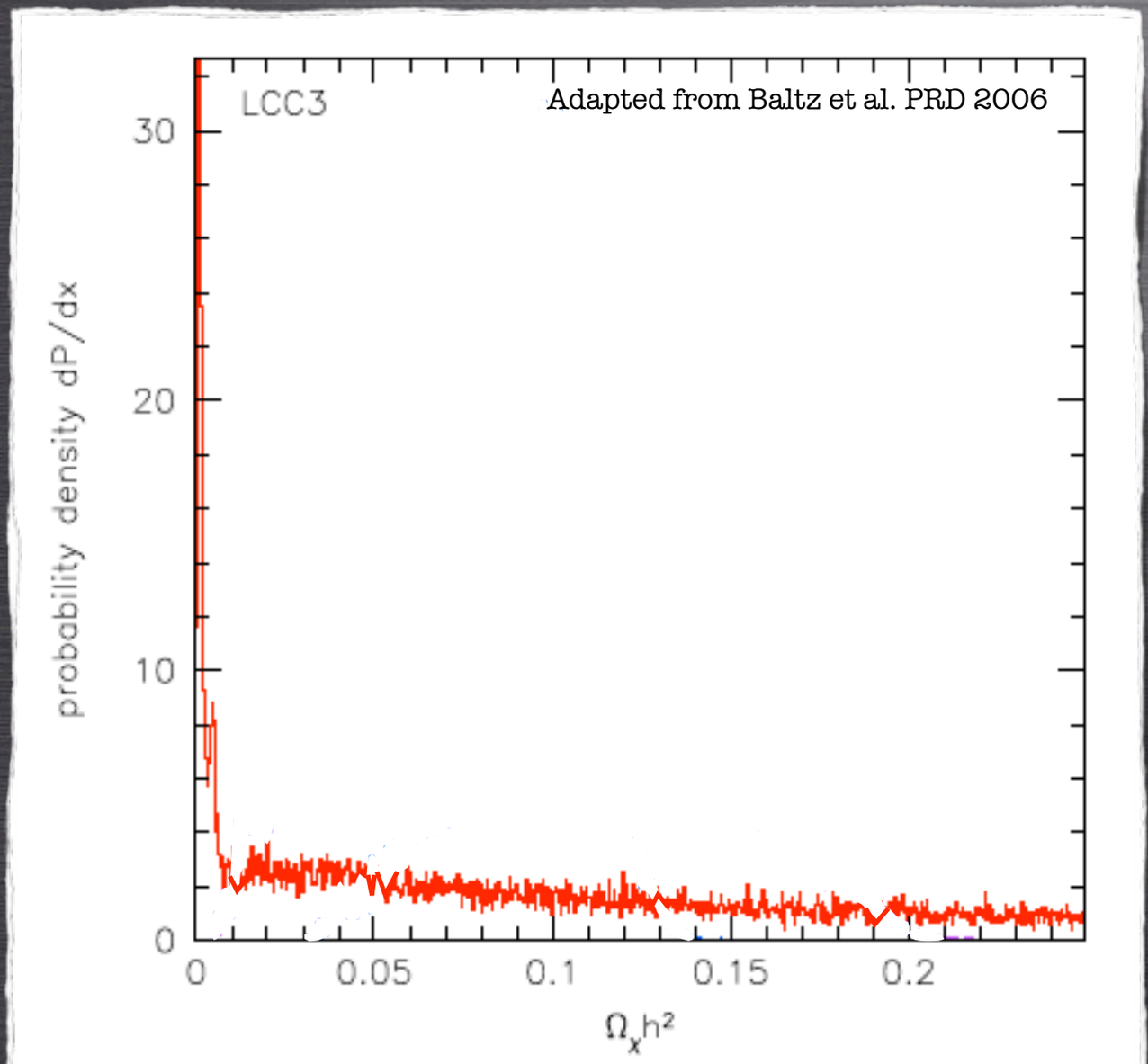
FIG. 34. Particle spectrum for point LCC3. The stau-neutralino mass splitting is 10.8 GeV. The lightest neutralino is predominantly *b*-ino, the second neutralino and light chargino are predominantly *W*-ino, and the heavy neutralinos and chargino are predominantly Higgsino.





Example of Inverse problem at LHC

Inferring the relic density (thus the DM nature) of newly discovered particles from LHC data... what we will most probably get:



Even if SUSY particles are discovered, it will be challenging to determine $\Omega_\chi h^2$ with good accuracy!

	Ωh^2	LHC
LCC1	0.192	7.2%
LCC2	0.109	82.%
LCC3	0.101	167%
LCC4	0.114	405%

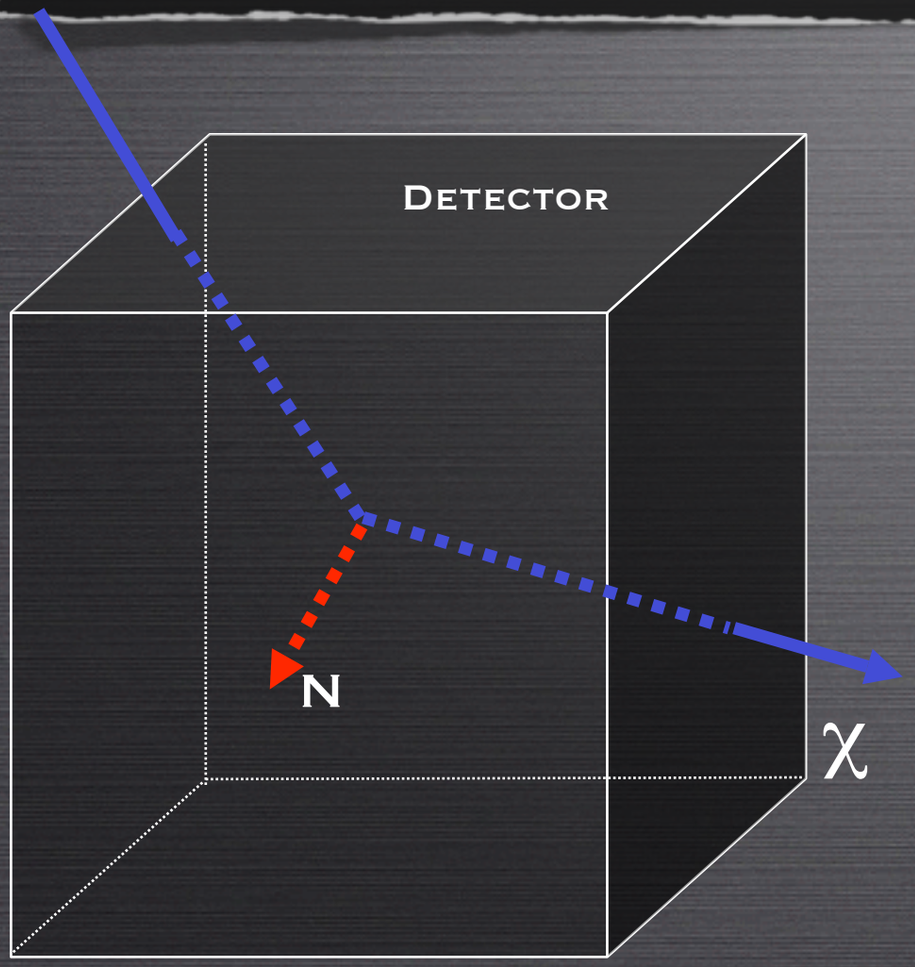
New particles may then turn out to be too abundant (decaying DM?) or not enough (multi-component DM)...

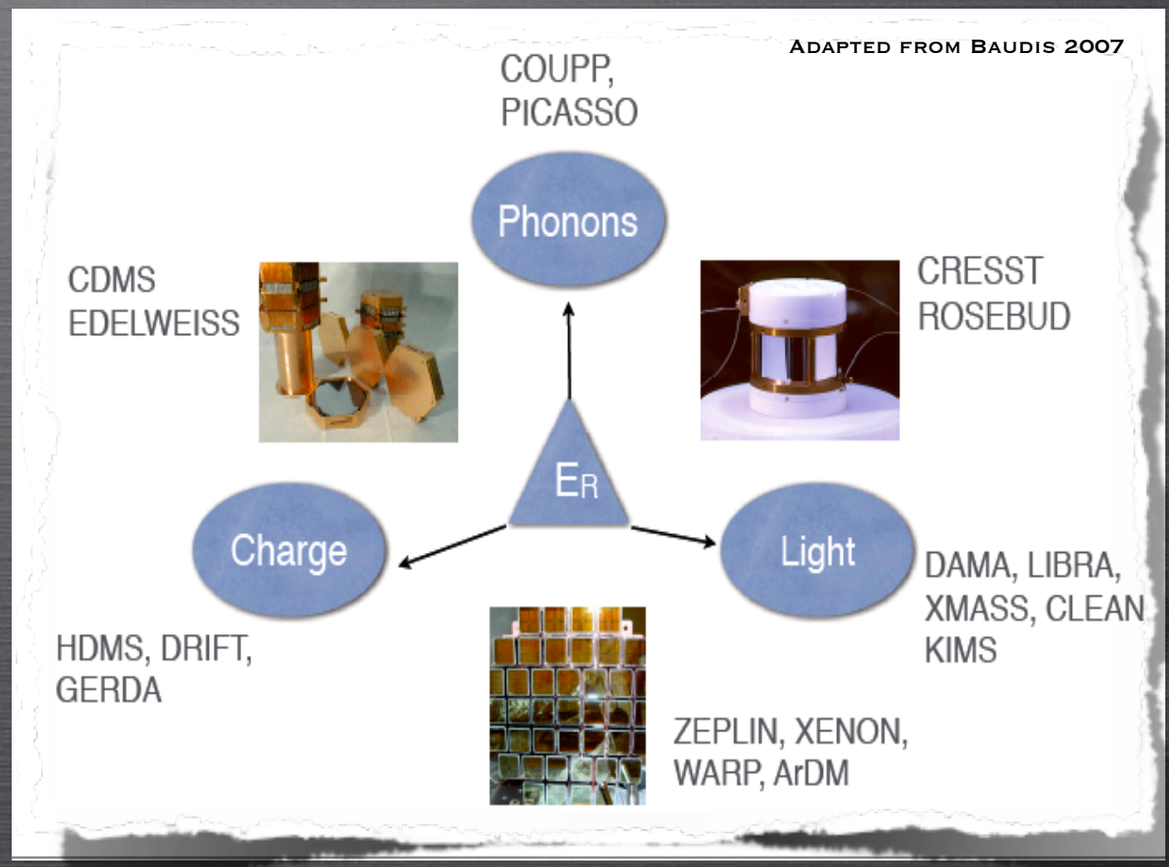
Need particle astrophysics (direct/indirect) experiments to prove that new particles = DM !!

See also B. C. Allanach et al. 2004, M. Nojiri et al. 2006, Roszkowski et al. 2009

Direct Detection

Principle and Detection Techniques

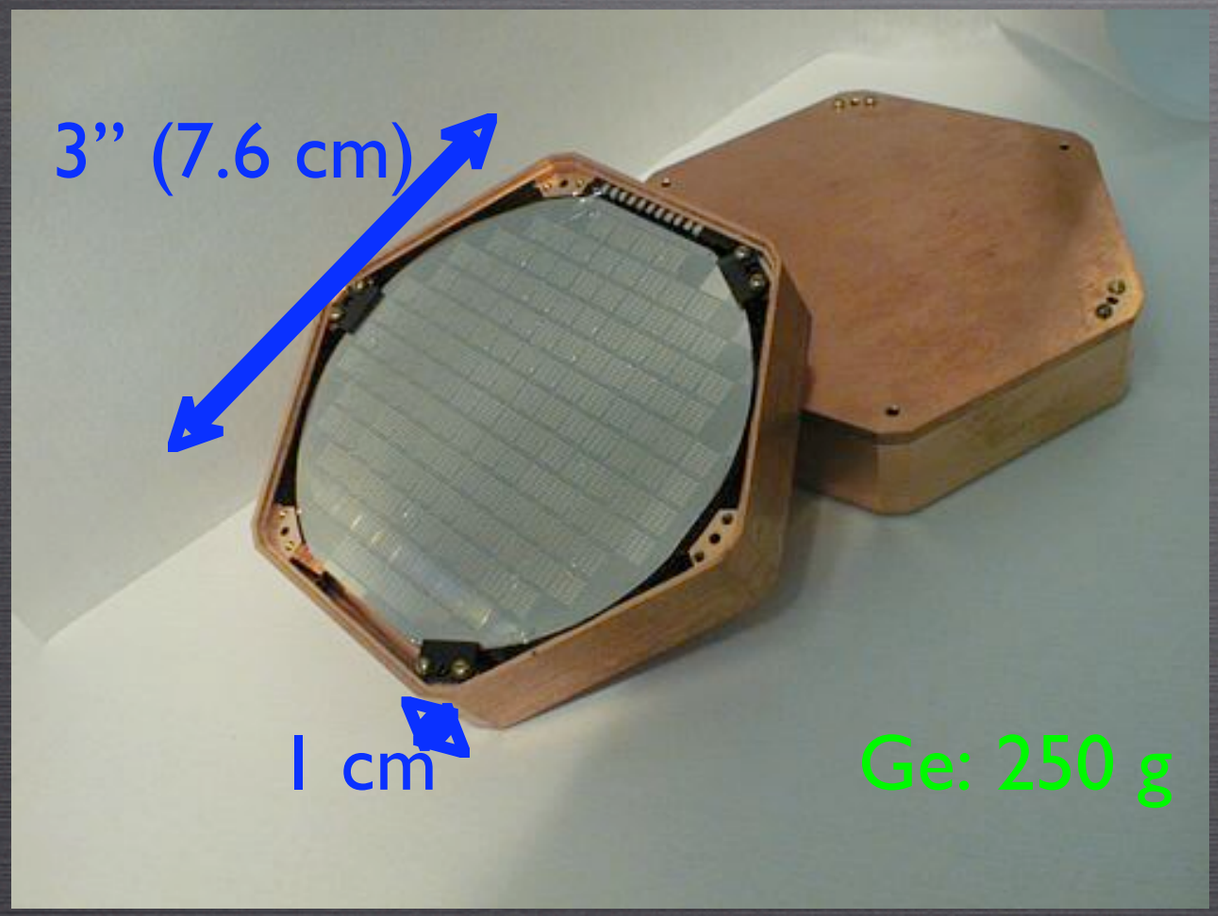




DM Scatters off nuclei in the detector

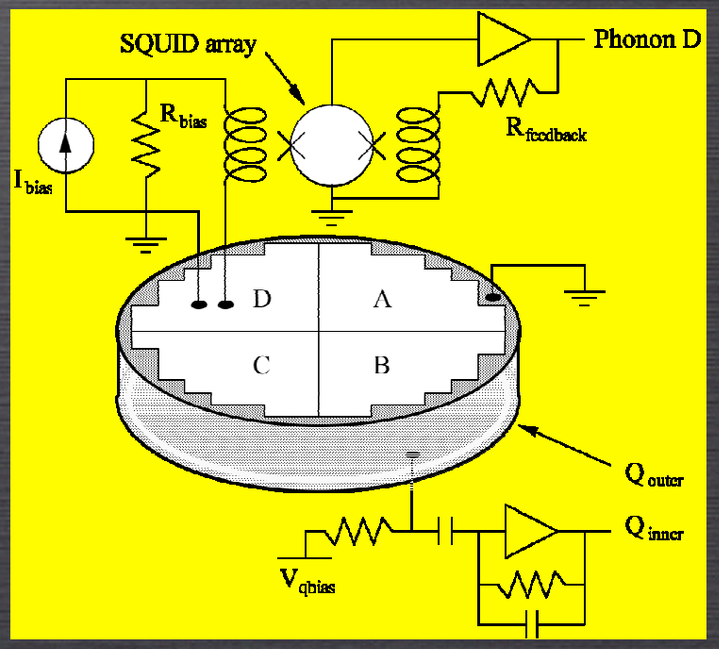
Detection of recoil energy via ionization (charges), scintillation (light) and heat (phonons)

CDMS results, Jan. 2010



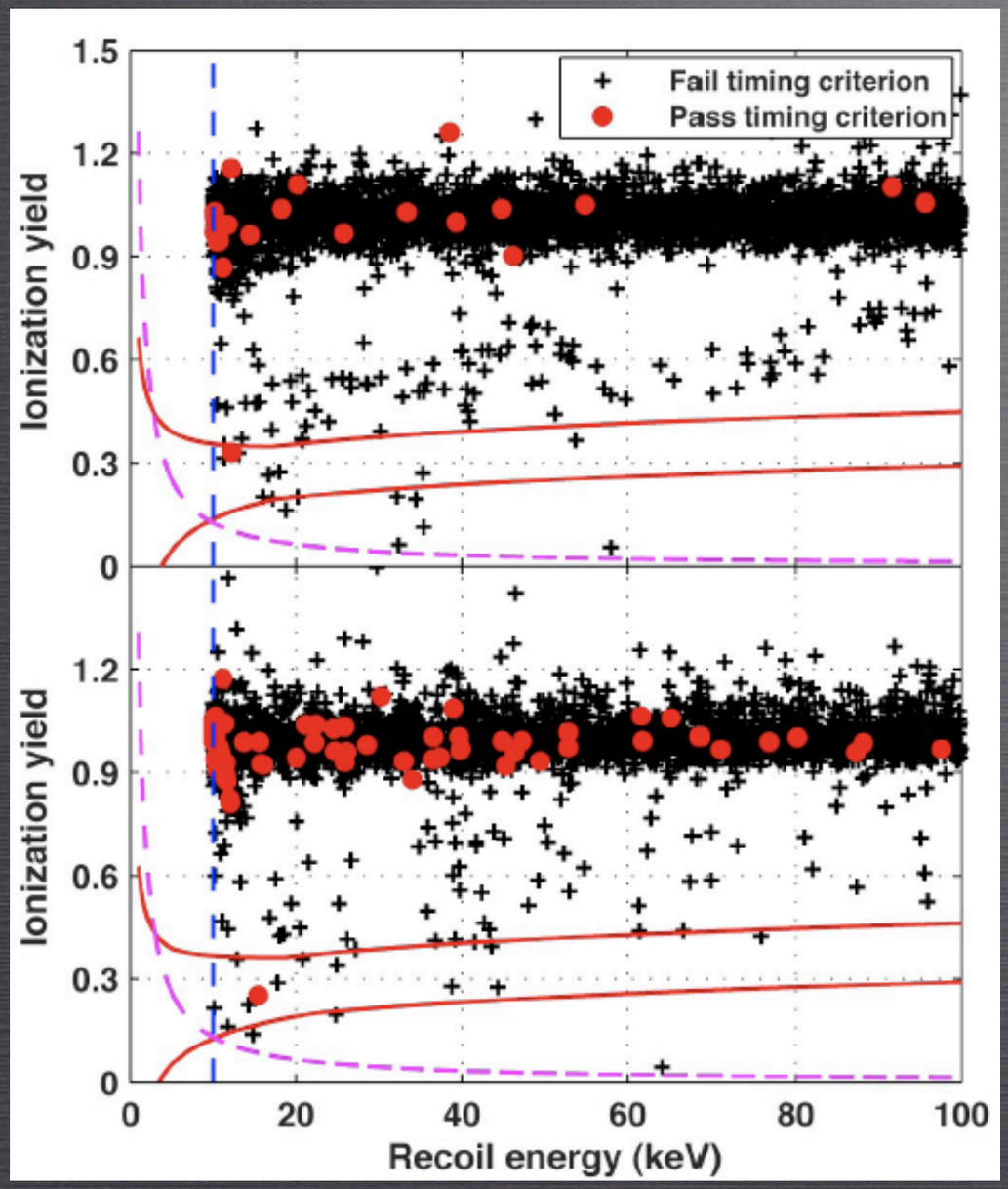
Phonon side: 4 quadrants of athermal phonon sensors
=> ***energy measurement***

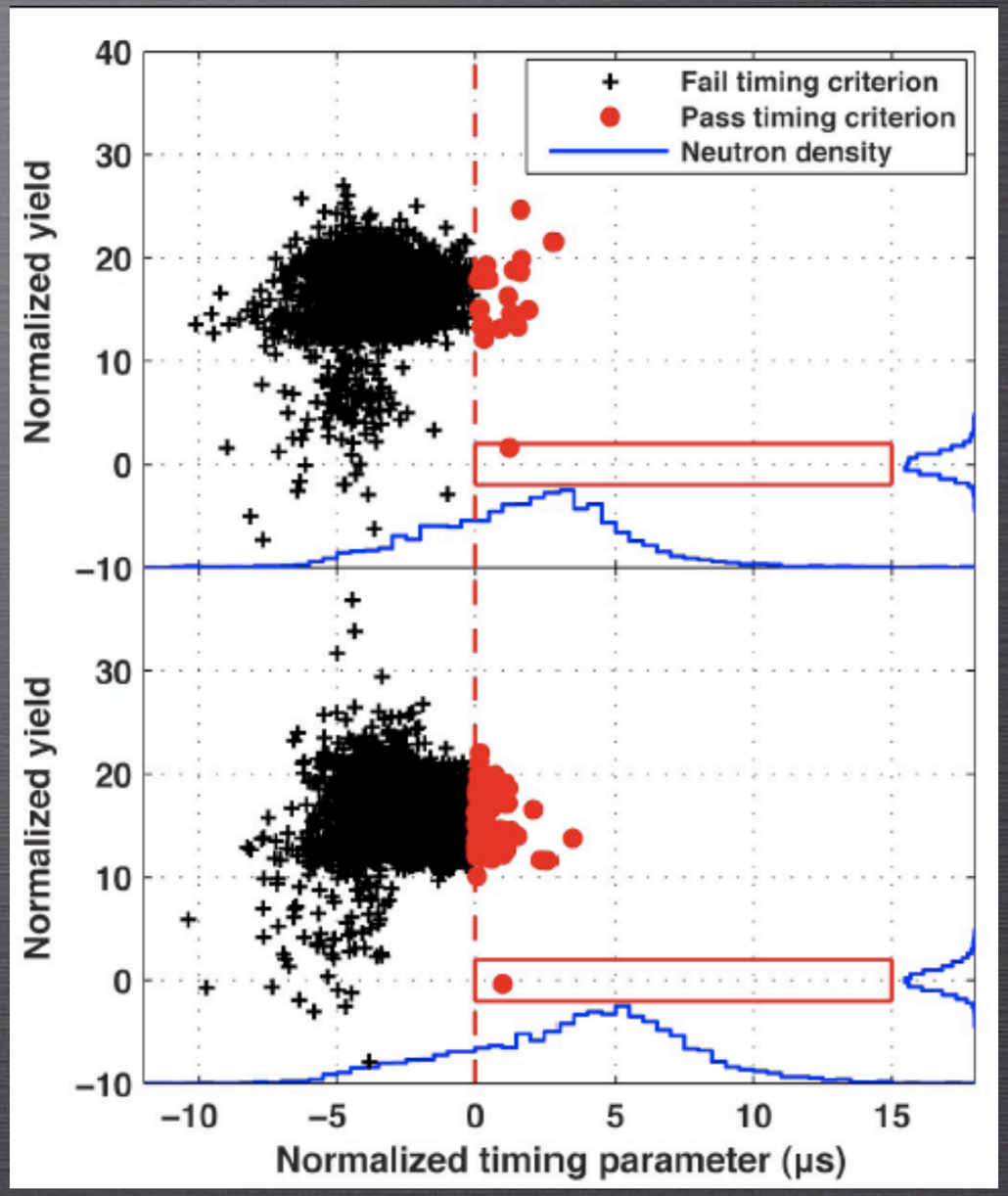
Charge side: 2 concentric electrodes



Operated at **~40 milliKelvin** for good phonon signal-to-noise

CDMS results, Jan. 2010



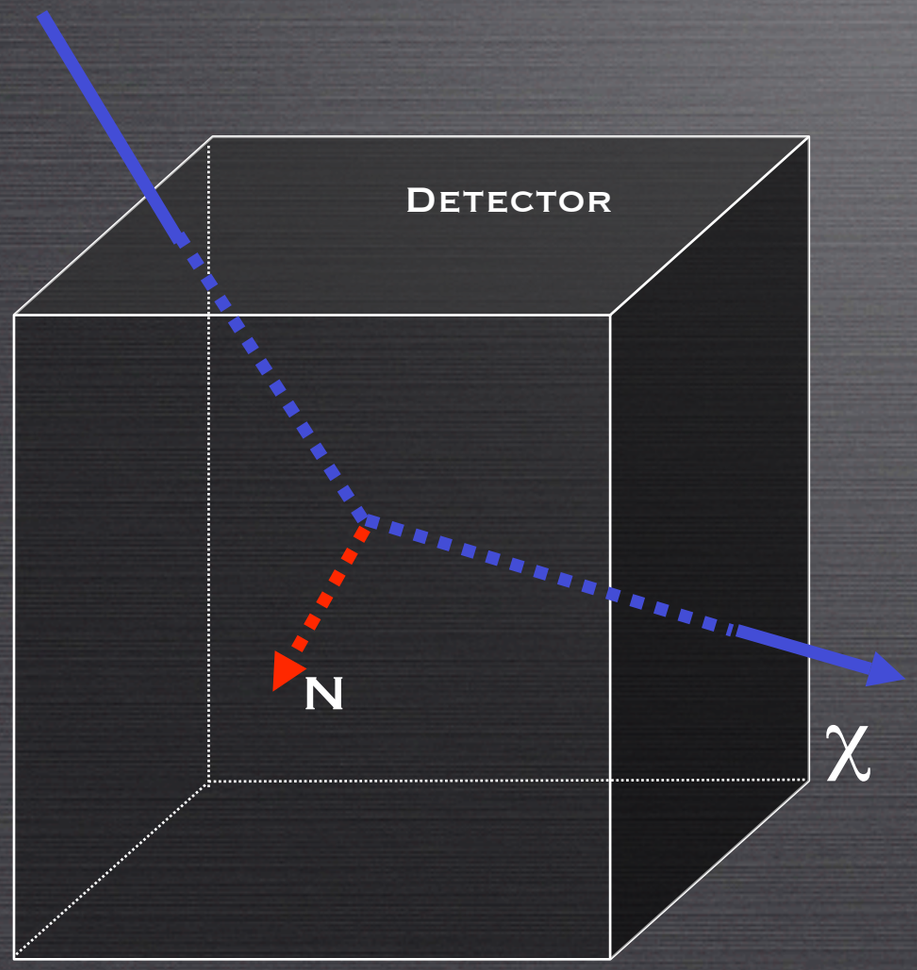


Expected background rate: 0.8. 2 Events observed. Probability of 2 or more events 23%. One event problematic... NOT a detection!

Direct Detection

Principle and Detection Techniques

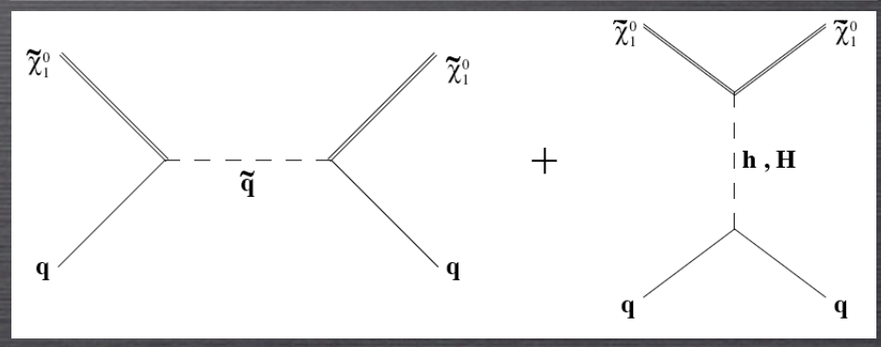
DM Scatters off nuclei in the detector



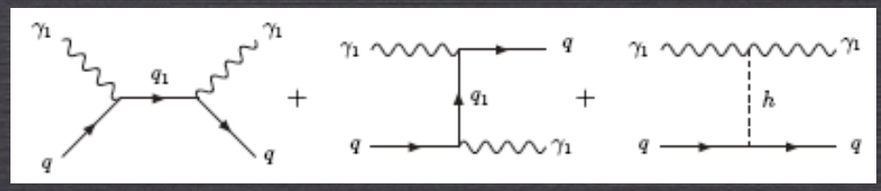
Differential Event Rate

$$\frac{\mathrm{d}R}{\mathrm{d}E}(E) = \frac{\sigma_{\mathrm{p}}\rho_{\chi}}{2\mu_{\mathrm{p}\chi}^2 m_{\chi}} A^2 F^2(E) \langle \int_{v_{\mathrm{min}}}^{\infty} \frac{f^{\mathrm{E}}(v,t)}{v} \mathrm{d}v \rangle$$

SUSY: squarks and Higgs exchange

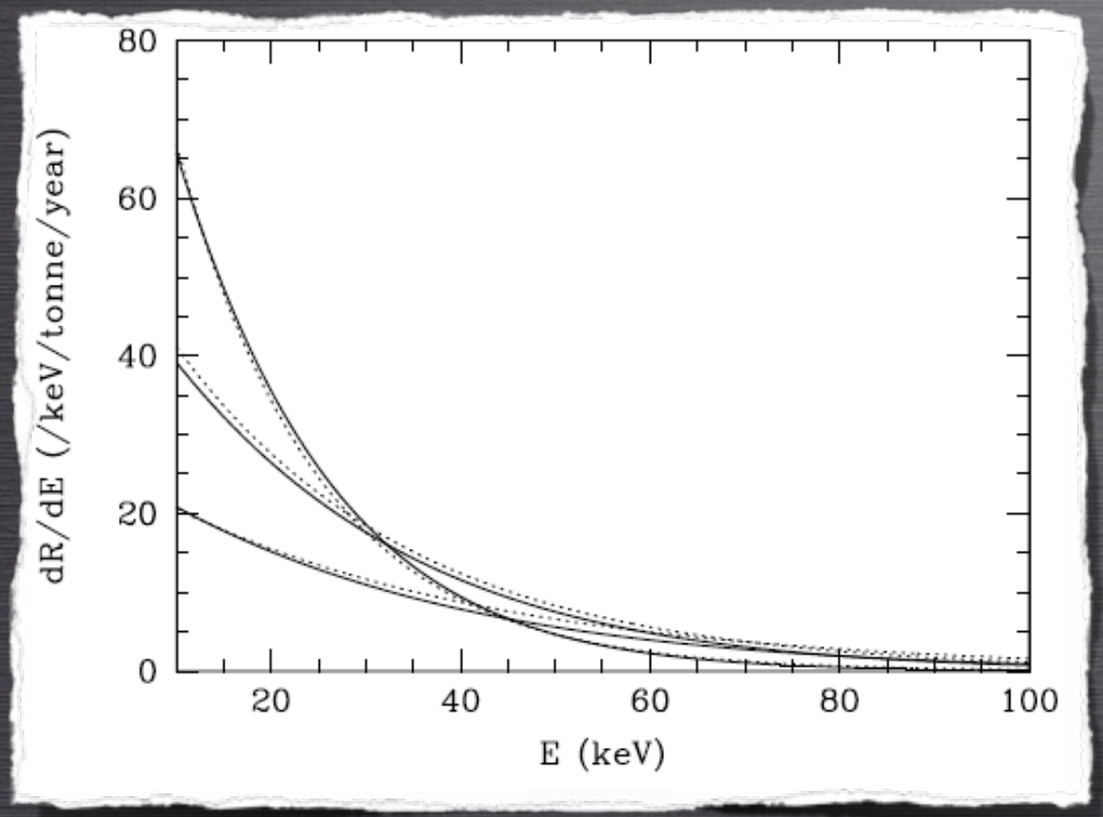


UED: 1st level quarks and Higgs exchange



Direct Detection

Principle and Detection Techniques



Differential Event Rate

$$\frac{\mathrm{d}R}{\mathrm{d}E}(E) = \frac{\sigma_{\mathrm{p}}\rho_{\chi}}{2\mu_{\mathrm{p}\chi}^2 m_{\chi}} A^2 F^2(E) \langle \int_{v_{\mathrm{min}}}^{\infty} \frac{f^{\mathrm{E}}(v,t)}{v} \mathrm{d}v \rangle$$

$$\approx c_1 F^2(E) \left(\frac{\mathrm{d}R}{\mathrm{d}E}\right)_0 \exp\left(-\frac{E}{c_2 E_{\mathrm{R}}}\right)$$

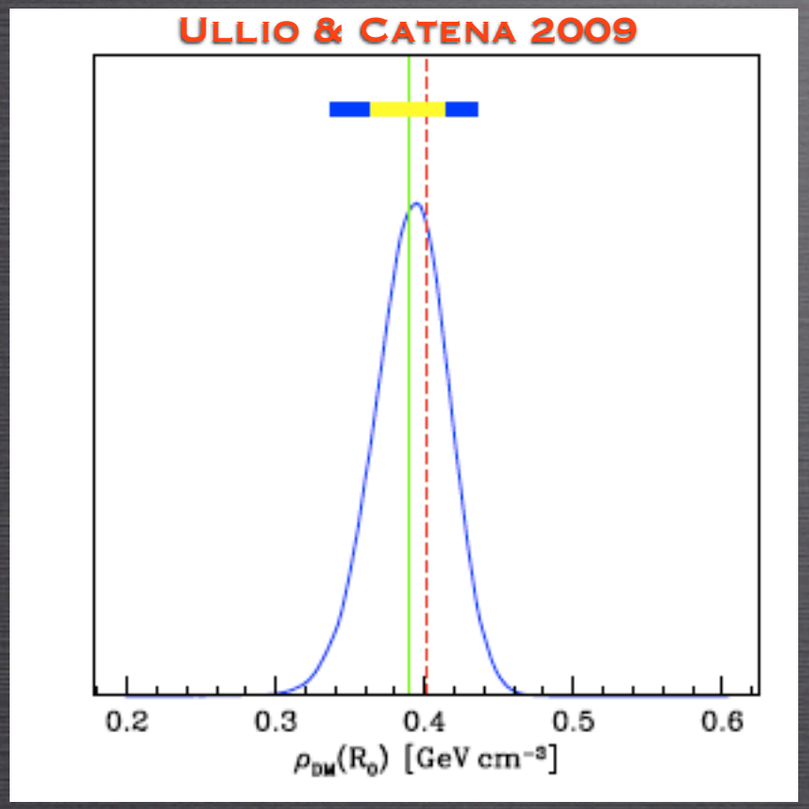
$$E_{\mathrm{R}} = \frac{2 m_{\mathrm{A}} m_{\chi}^2 v_{\mathrm{c}}^2}{(m_{\chi} + m_{\mathrm{A}})^2}$$

Differential energy spectra (from top to bottom at E = 0 keV) for WIMPs with m = 50, 100 and 200GeV. Green 2008

Direct Detection

Uncertainties on the Local Density

"Statistical"

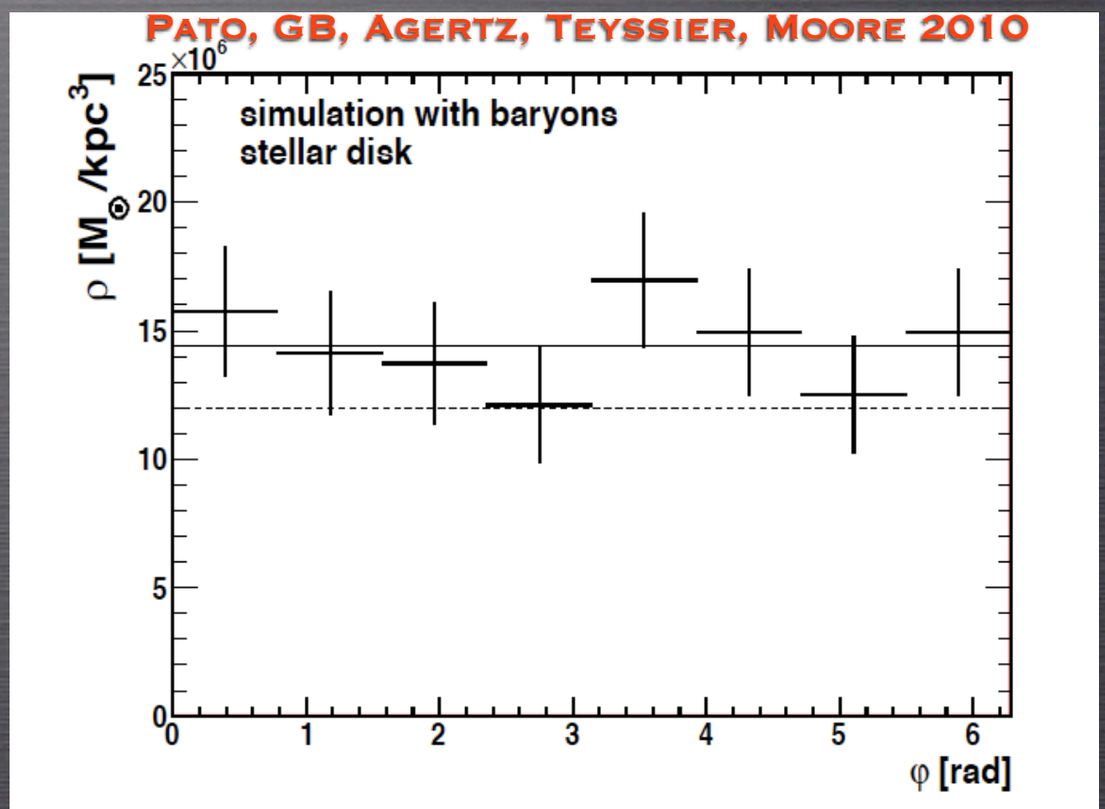


$$\rho_{DM}(R_0) = 0.389 \pm 0.025\,\mathrm{GeV\ cm^{-3}}$$

From dyanamical Observables

+

"Systematic"



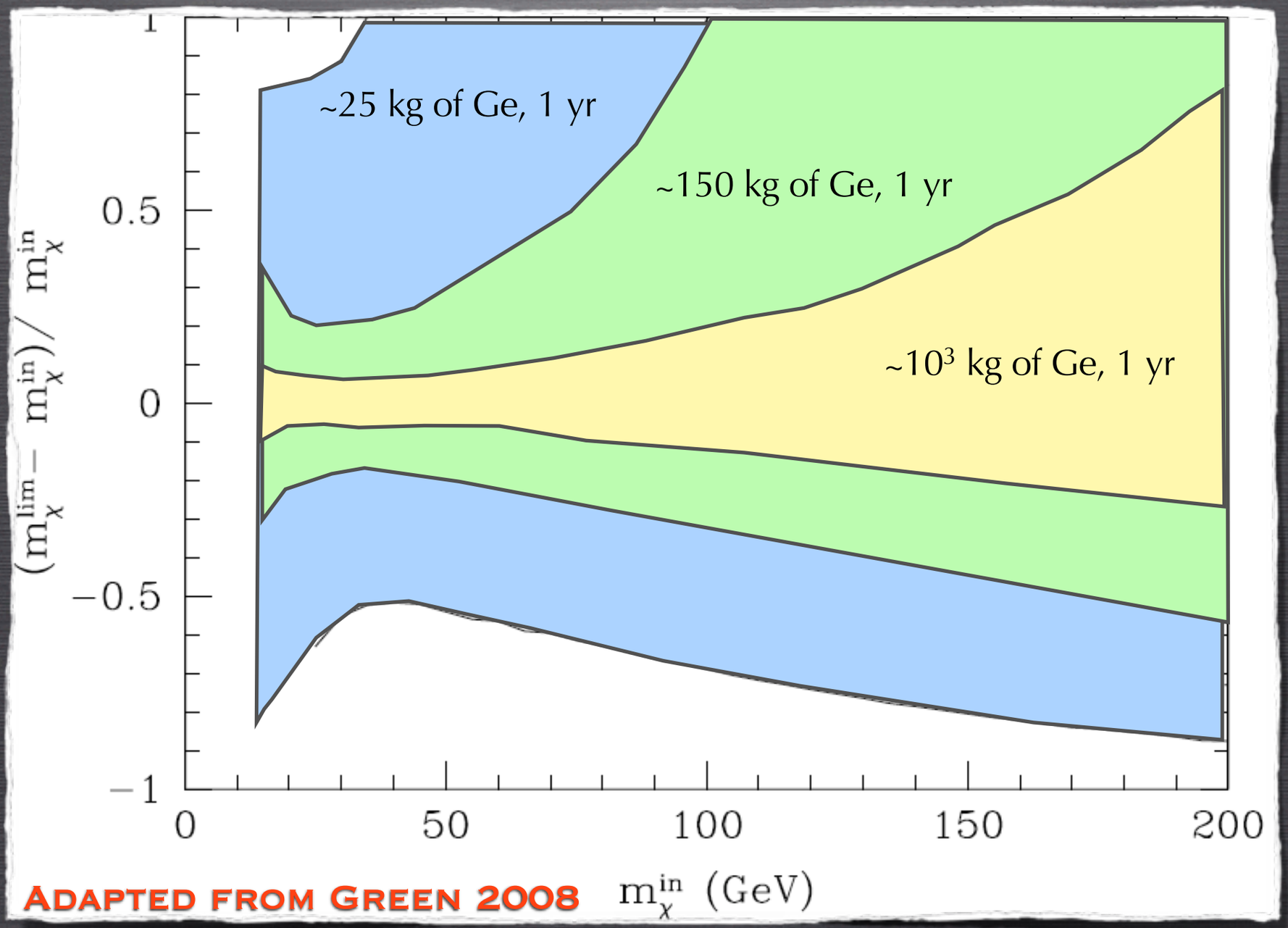
$$\rho_0/\bar{\rho}_0 = 1.01 - 1.41$$ w/ Baryons

$$\rho_0/\bar{\rho}_0 = 0.39 - 1.94$$ DM only

Triaxiality, Baryons, etc.

Direct Detection

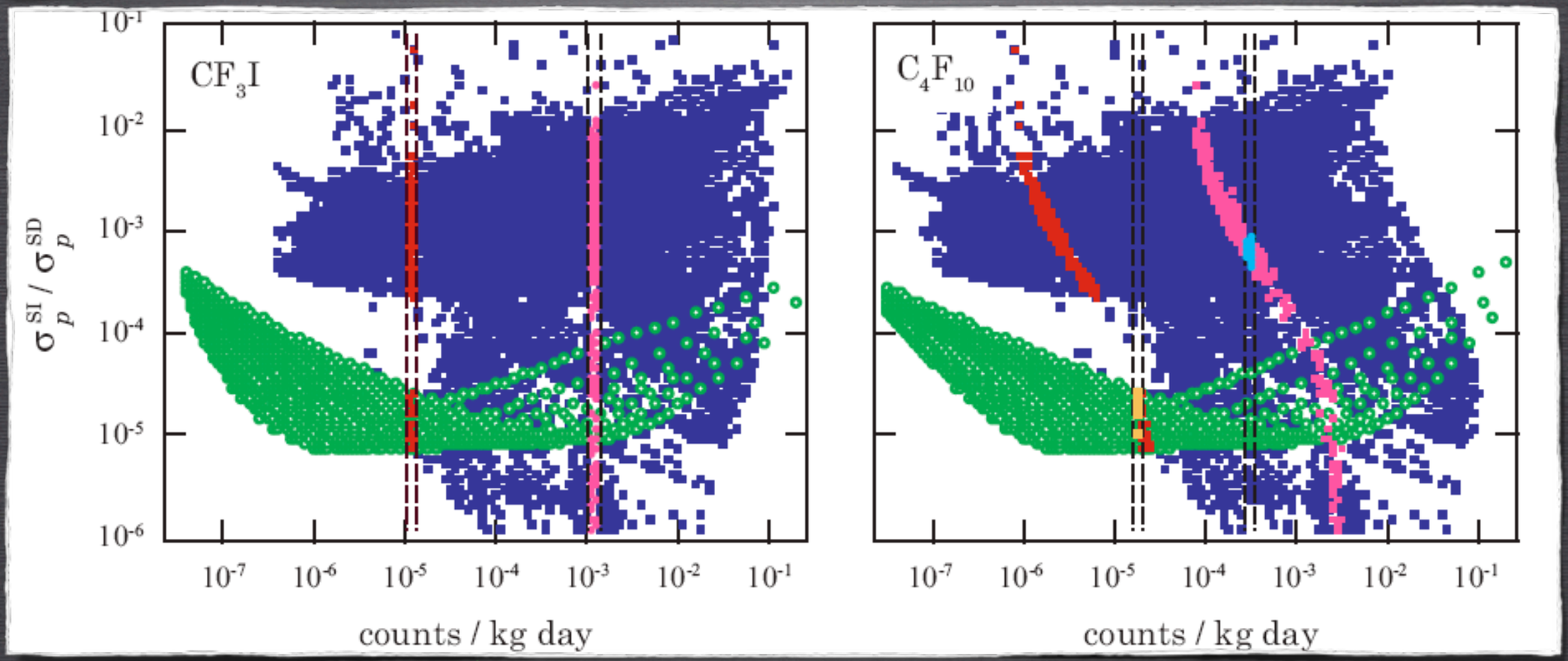
95% C.L. constraint on the reconstructed DM mass



Adapted from Green 2008

Direct Detection

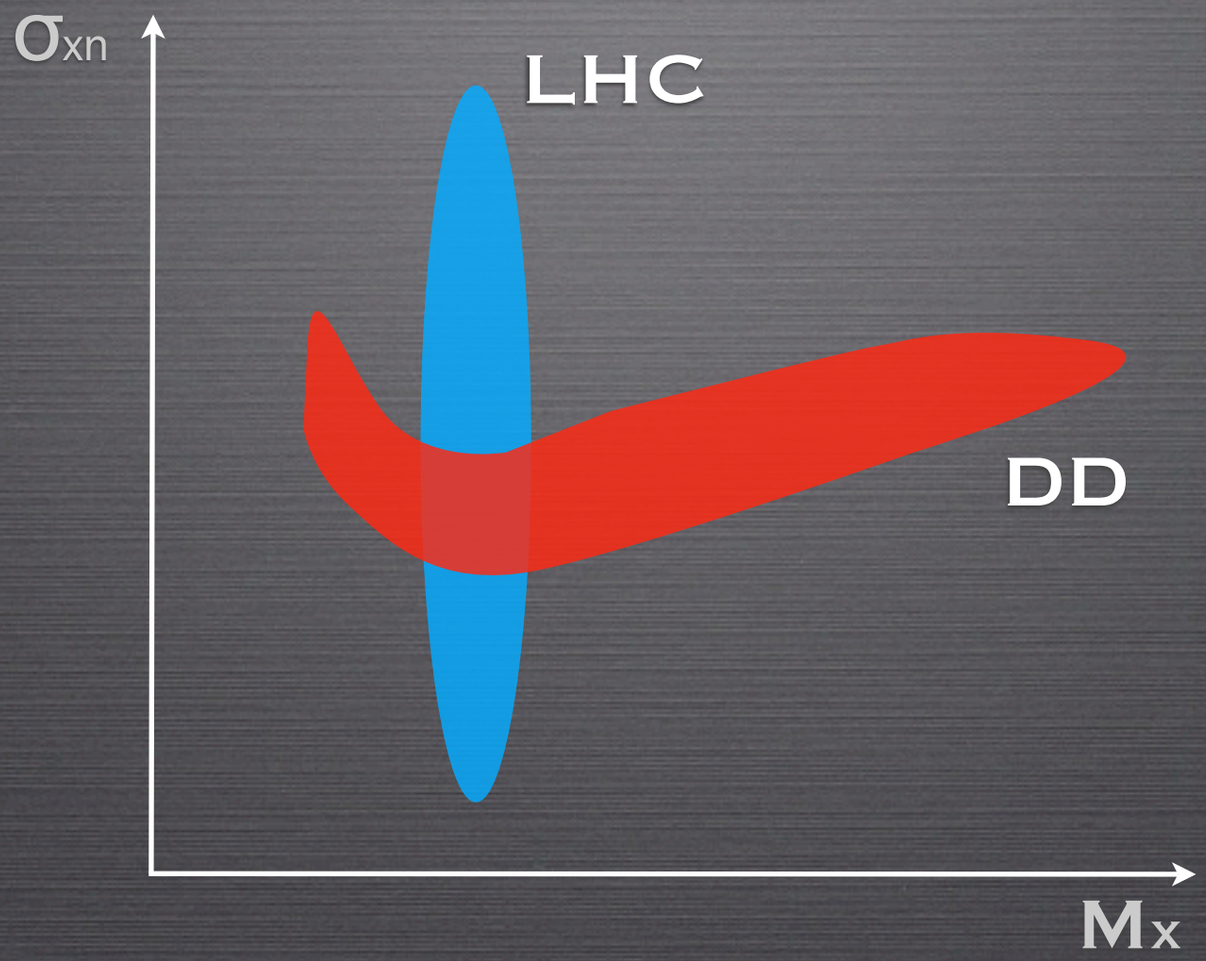
Better constraints combining results from different targets



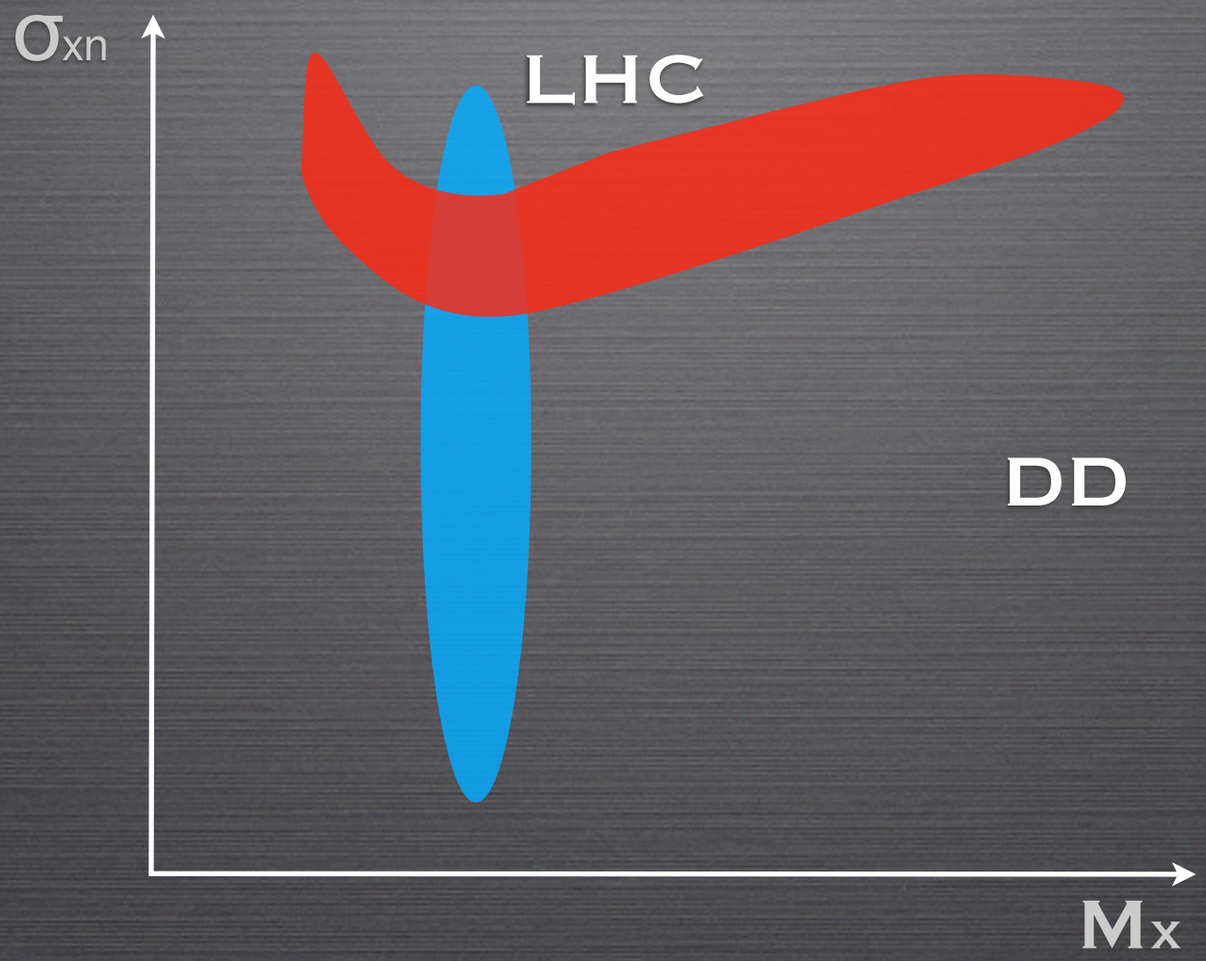
The case of COUPP. GB, Cerdeno, Collar & Odom 2007

Or combine with information from Accelerators...

LHC+DD

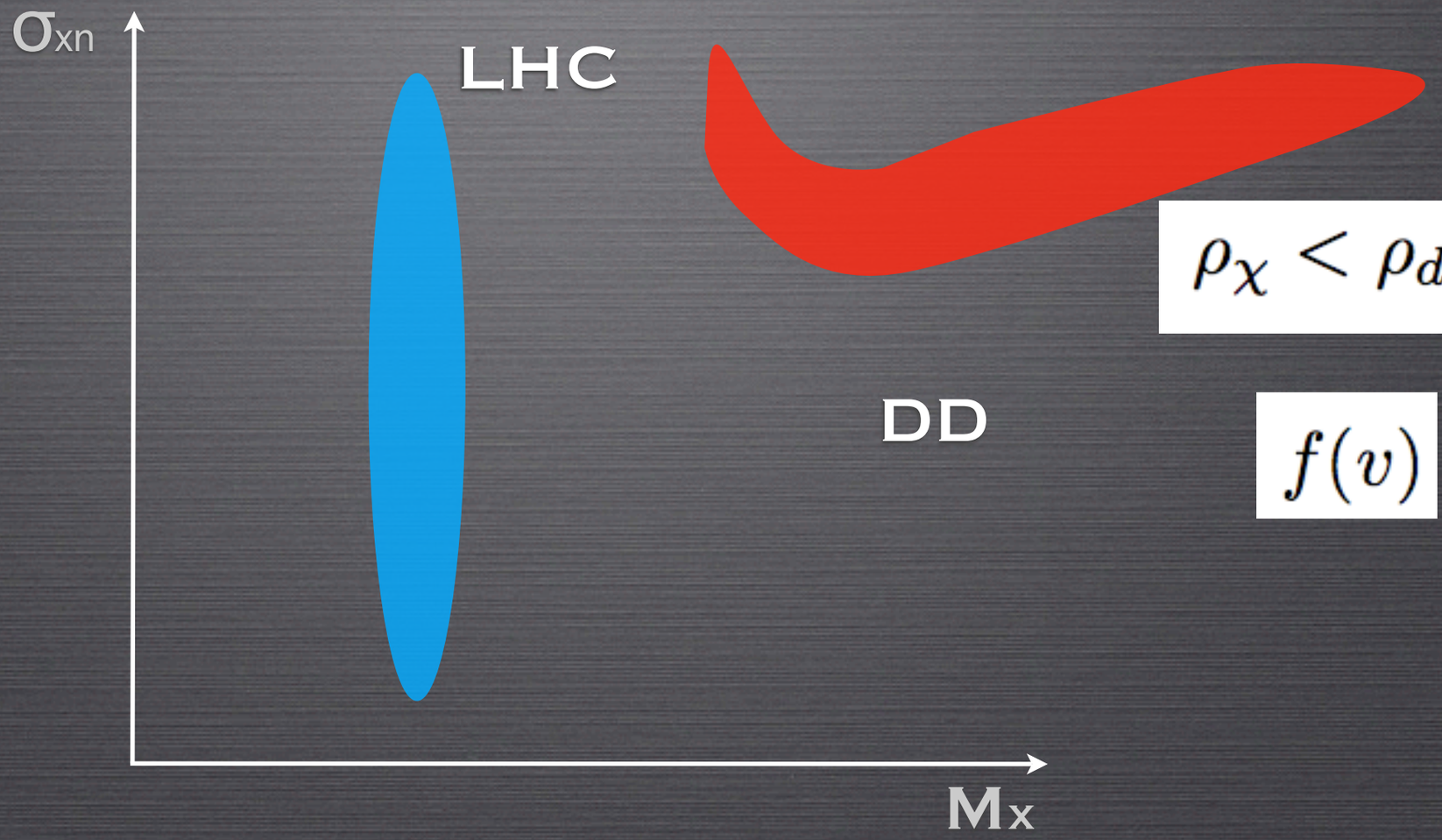


LHC+DD

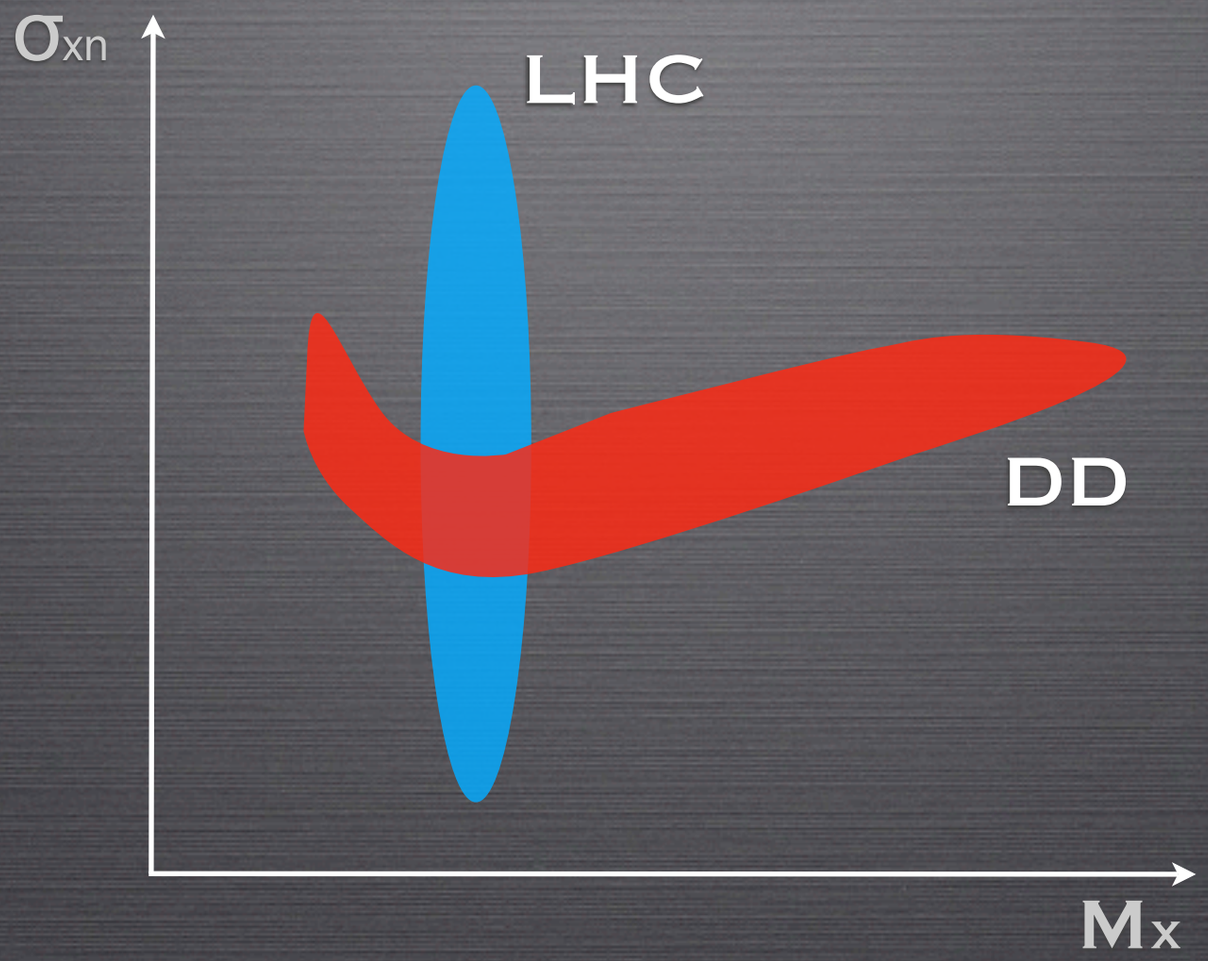


$$\rho_\chi < \rho_{dm}$$

LHC+DD



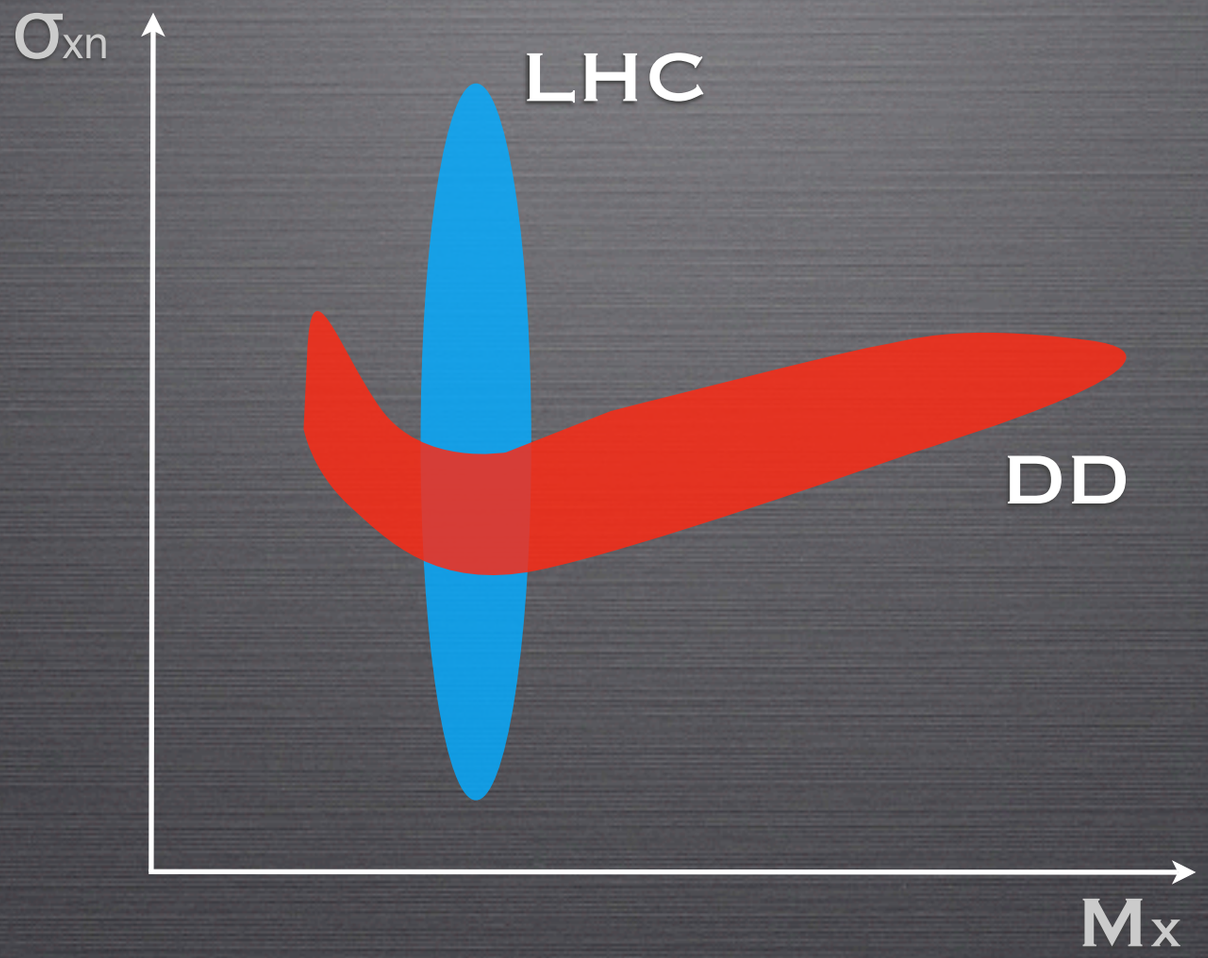
LHC+DD



$$\rho_\chi < \rho_{dm}$$

$$f(v)$$

LHC+DD



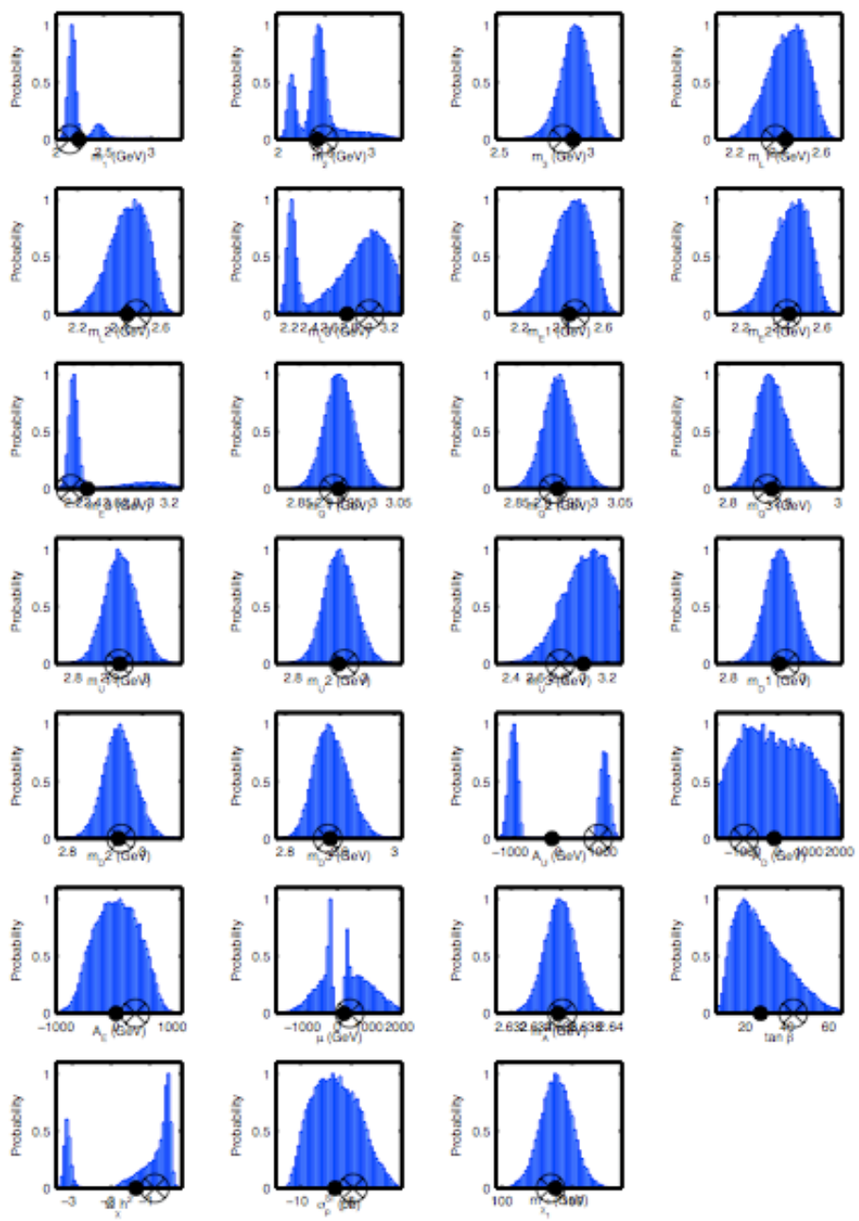
$$\rho_\chi < \rho_{dm}$$

$$f(v)$$

Ansatz:

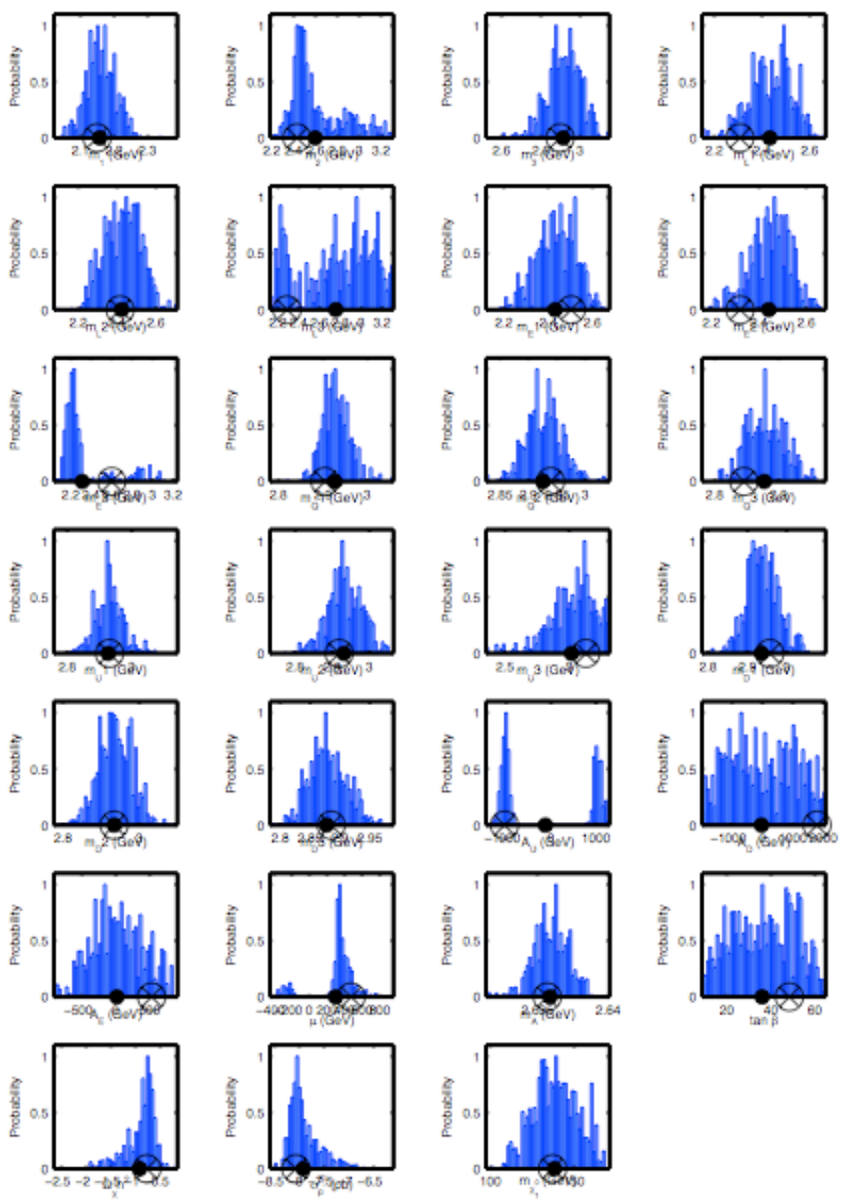
$$\frac{\rho_\chi}{\rho_{dm}} = \frac{\Omega_\chi}{\Omega_{dm}}$$

LHC+DD



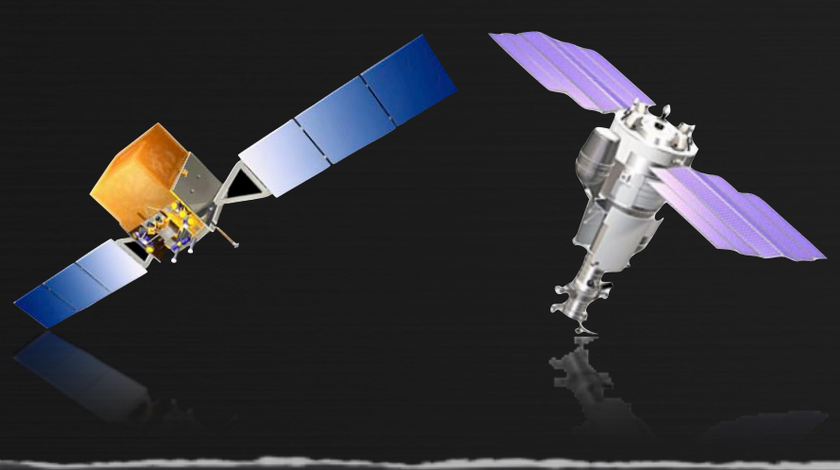
GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta (in preparation)

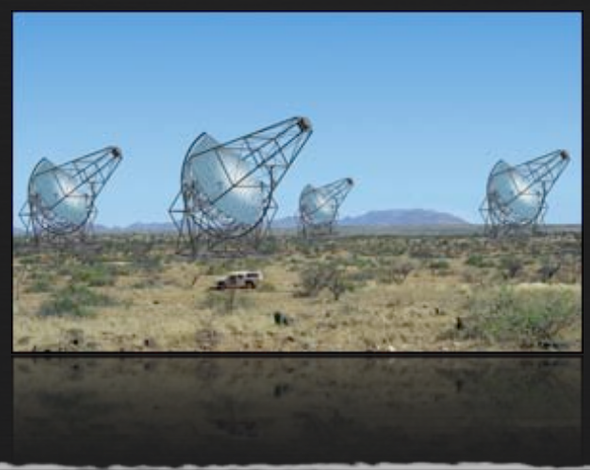
LHC+DD

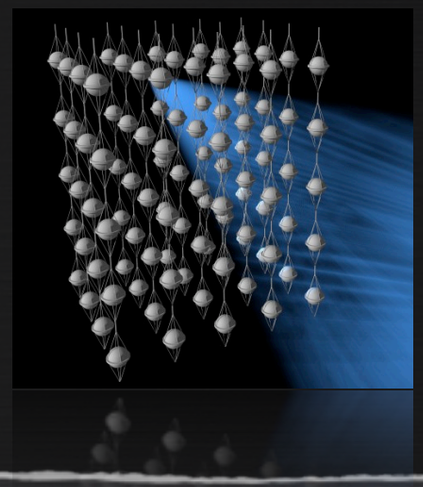


GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta (in preparation)

Indirect Detection







Gamma-ray telescopes

- Ground Based (CANGAROO, HESS, MAGIC, MILAGRO, VERITAS)
- Space satellite FERMI
- Plans for a future Cherenkov Telescope Array

Neutrino Telescopes

- Amanda, IceCube
- Antares, Nemo, Nestor
- Km3

Anti-matter Satellites

- PAMELA
- ATIC,PPB-BETS
- AMS-02

Other

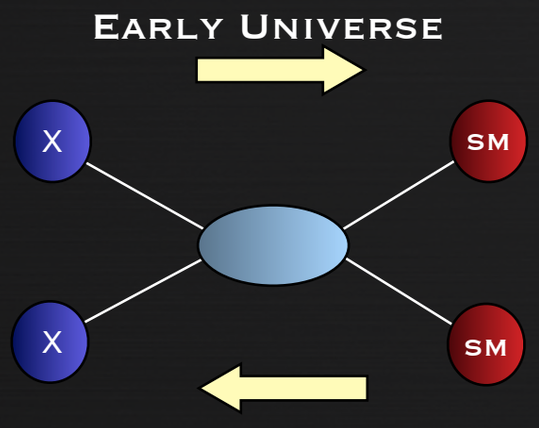
- Synchrotron Emission
- SZ effect
- Effect on Stars

Indirect Detection

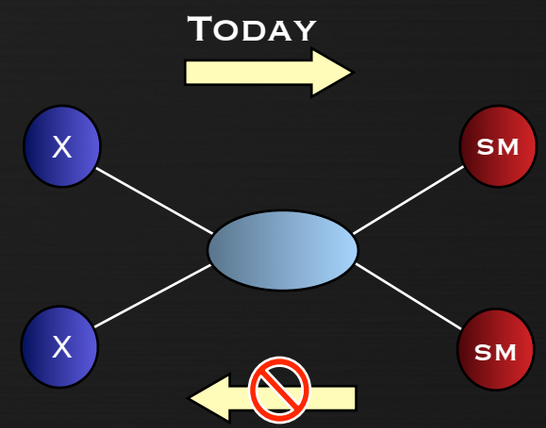
Why "annihilations"?

X = Dark Matter

SM = Standard Model particle



$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle[n_\chi^2 - (n_\chi^{\rm eq})^2]$$



$$\dot{n}_\chi(r,t) = -\sigma v\, n_\chi^2$$

Rough estimate of the relic density:

$$\Omega_X h^2 \approx \frac{3\times 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle\sigma v\rangle}$$

Electroweak-scale cross sections can reproduce correct relic density. LSP in SUSY scenarios KK DM in UED scenarios are OK!!

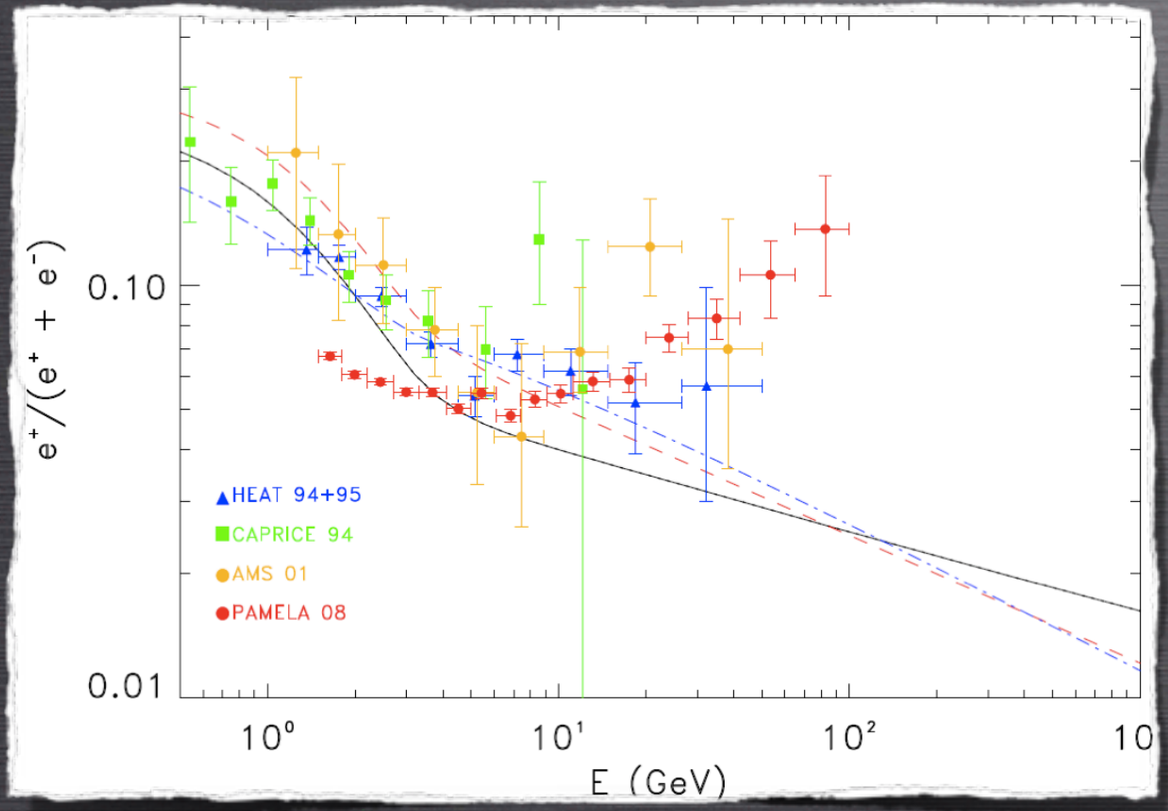
Flux of secondary particles from DM Ann.

$$\Phi(\Delta\Omega, E) = \Delta\Omega \frac{dN}{dE}\frac{\langle\sigma v\rangle}{4\pi m^2}\overline{J}_{\Delta\Omega}$$

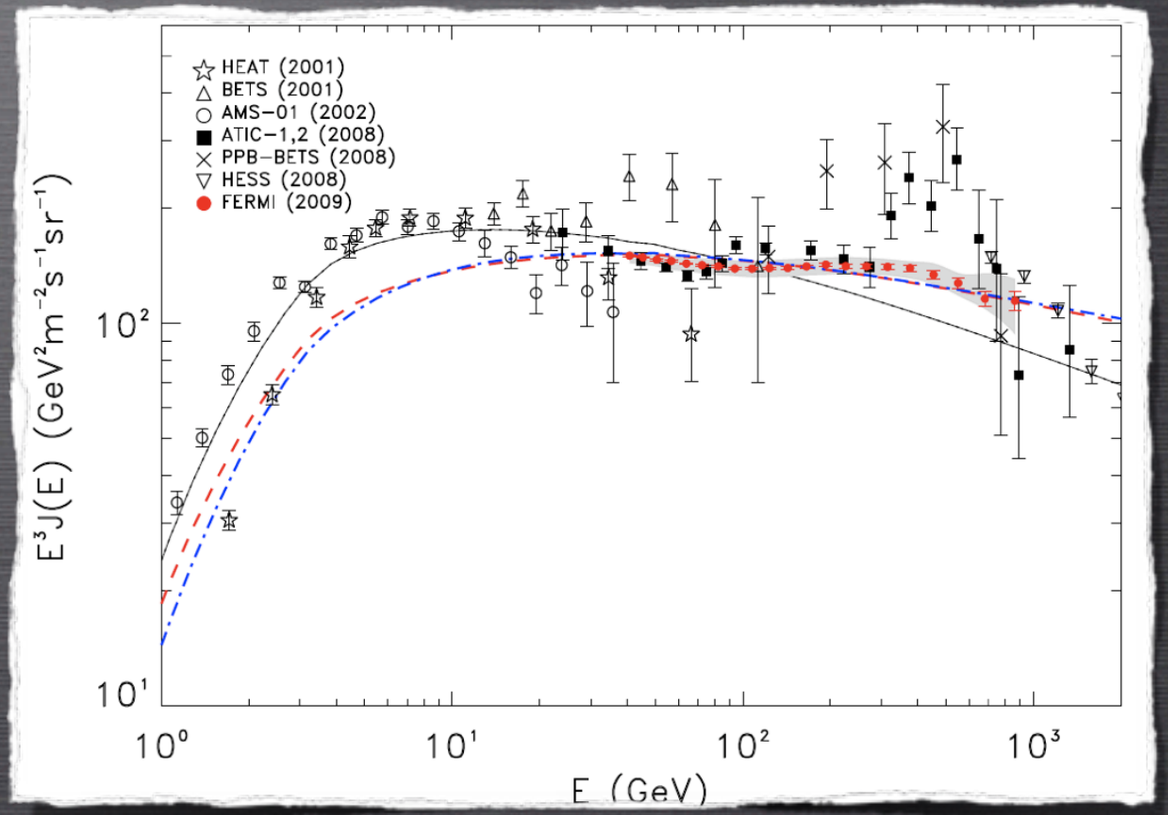
Particle physics input from extensions of the Standard Model. Need to specify distribution of DM along the line of sight

Cosmic e^+e^-

PAMELA, HESS, Fermi, ATIC, PPB-BETS, HEAT, AMS, Caprice...



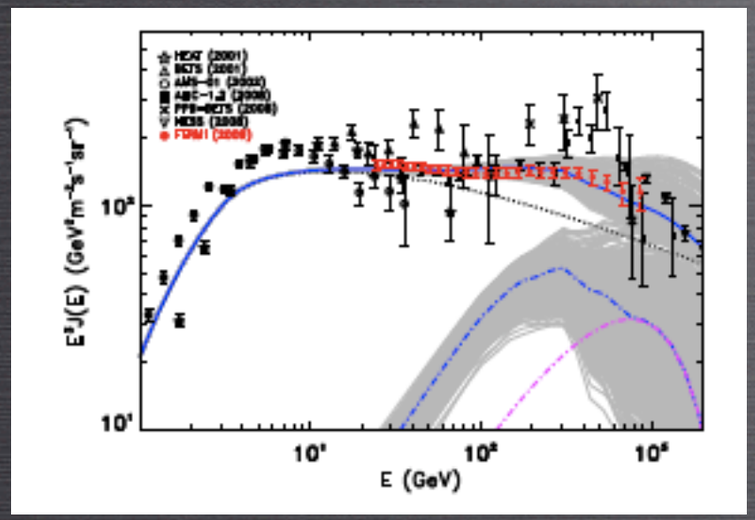
Grasso et al. 2009



Grasso et al. 2009

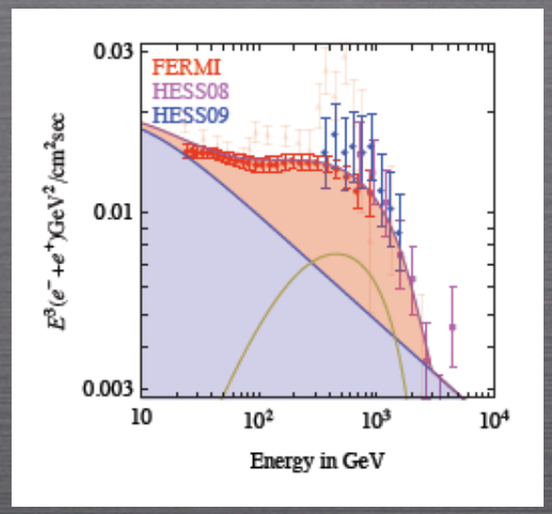
Interpretation

Pulsars



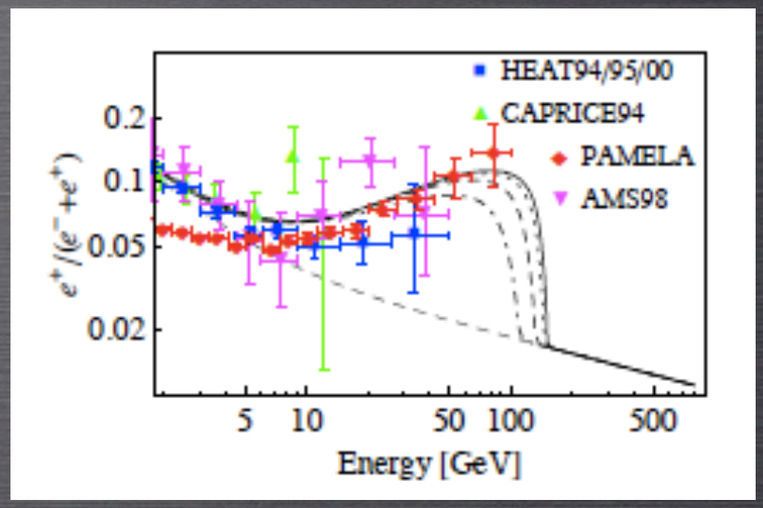
Grasso et al. 2009

DM Annihilation



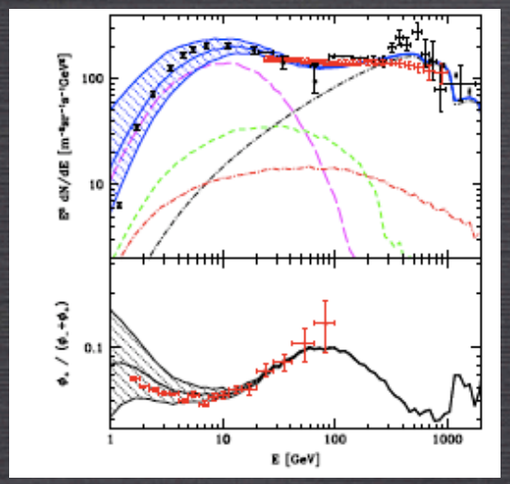
Strumia et al. 2009

DM Decay



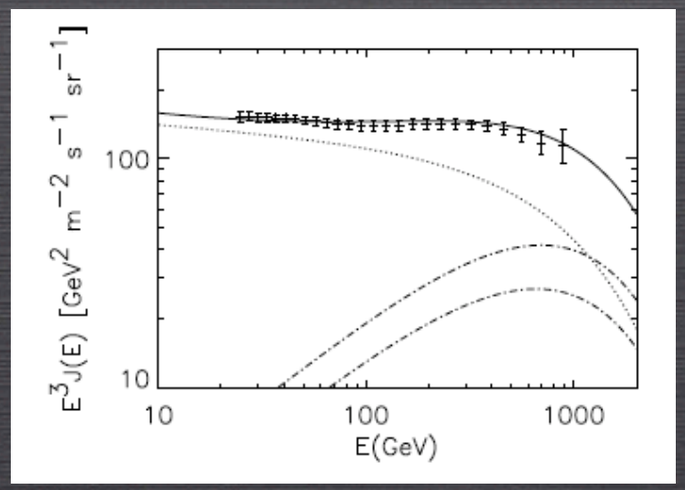
Ibarra et al. 2009

SNRs inhom.



Piran et al. 2009

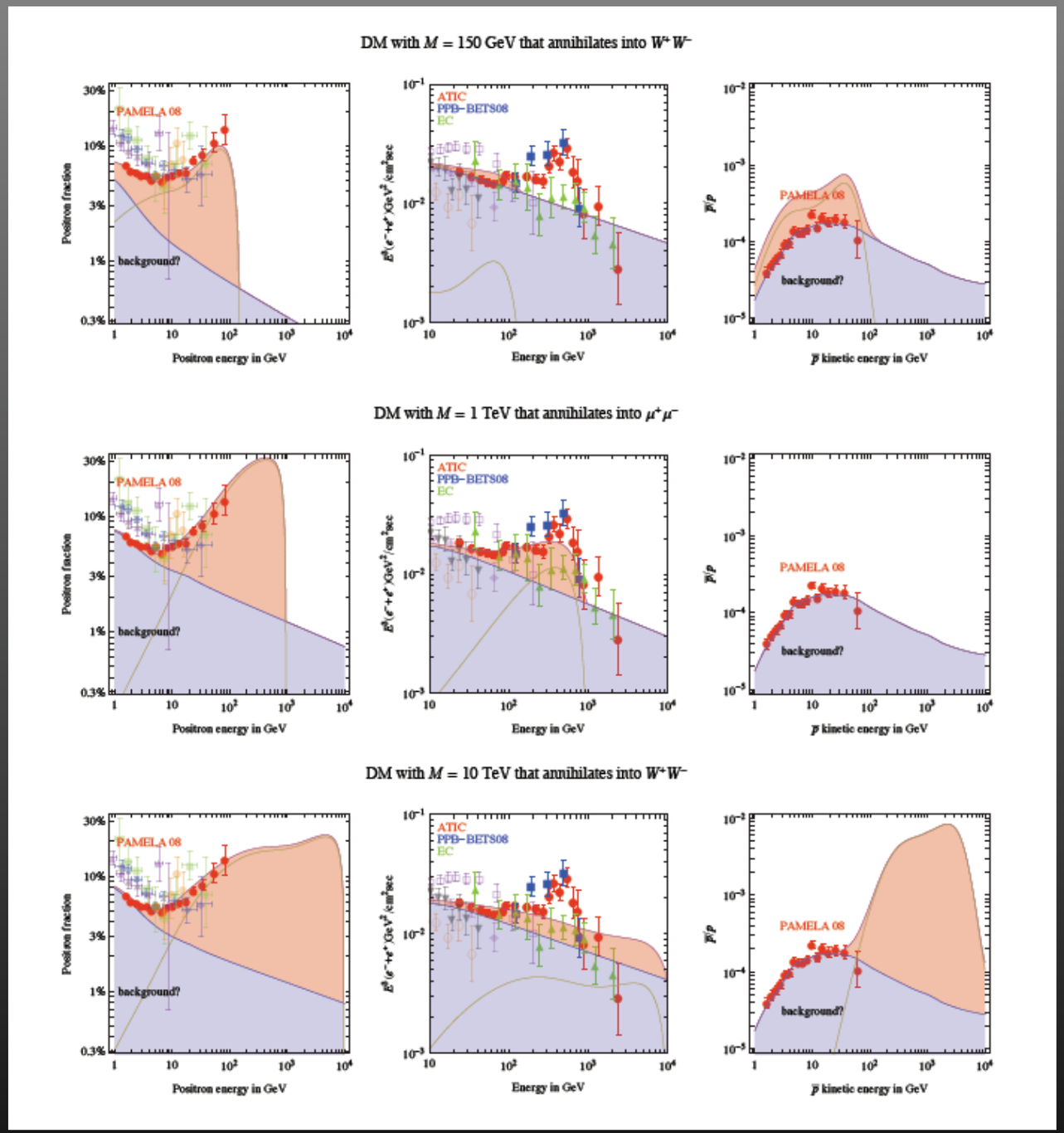
SNRs 2ndary CR acc.



Blasi 2009

... + many MANY other models .

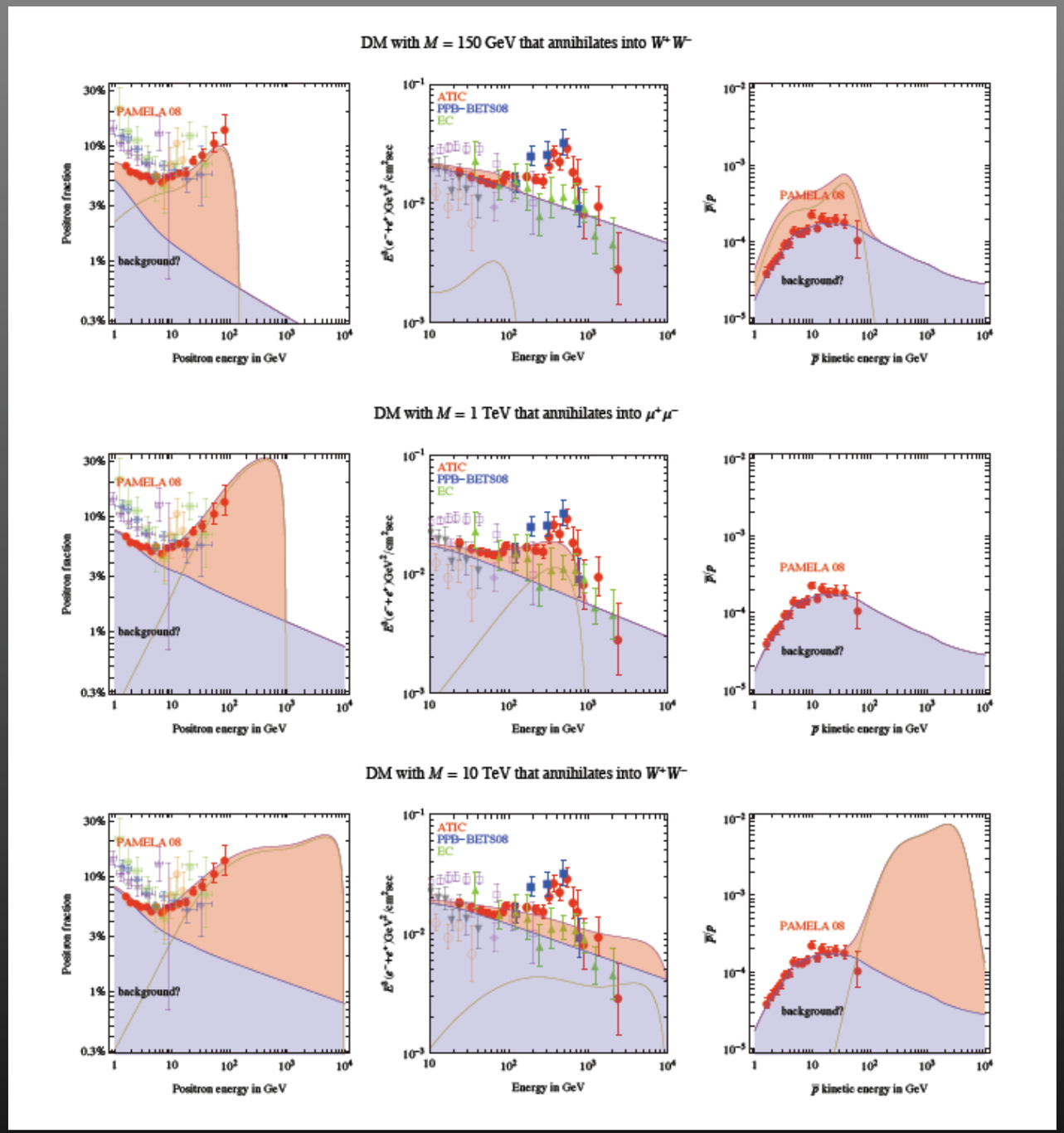
PAMELA / ATIC WHAT DO WE LEARN?



Cirelli, Kadastik, Raidal, Strumia 2008

... some DM candidates, with peculiar particle physics and astrophysical parameters, can fit the PAMELA and/or ATIC excesses...

PAMELA / ATIC WHAT DO WE LEARN?

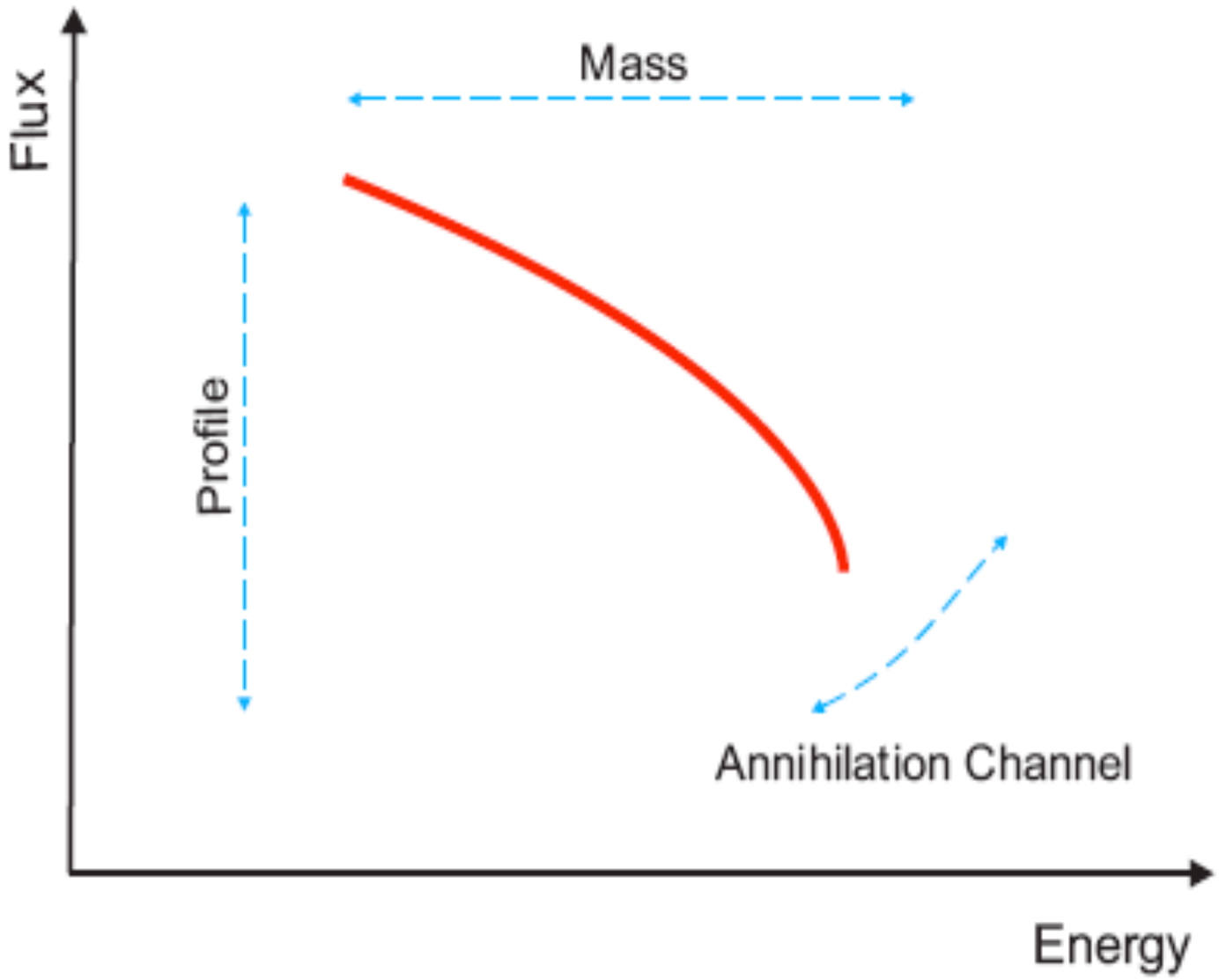


Cirelli, Kadastik, Raidal, Strumia 2008

... some DM candidates, with peculiar particle physics and astrophysical parameters, can fit the PAMELA and/or ATIC excesses...

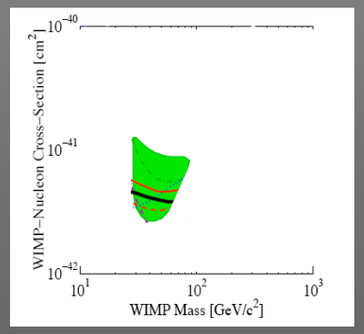
So what ??

The trouble with indirect searches



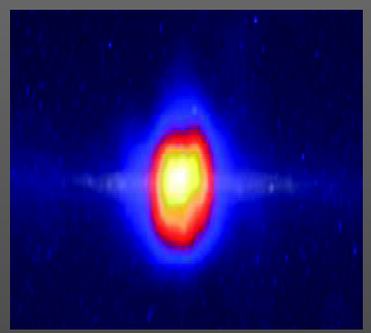
...which means that the "inverse problem" always admits a solution, even when the data have nothing to do with DM!

We have already many Hints of 'detection'!



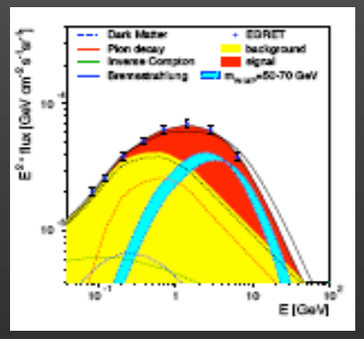
DAMA Direct Detection

Evidence for: annual modulation.
Interpretation unclear.
Bernabei et al (1996,2000,2005,...)



INTEGRAL 511 keV

Evidence for: MeV Dark Matter
Boehm et al (2003,2004)



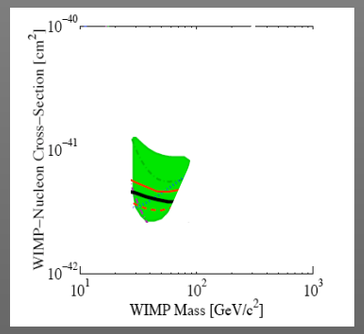
Gamma-rays: EGRET, HESS,

Evidence for: GeV / multi-TEV DM
E.g.: Cesarini et al. 2005, *De Boer (2005,...), Hooper et al. 2006, ...*

WMAP & Fermi Haze

Evidence for: 100 GeV DM
See e.g. Finkbeiner 2004, Hooper, Dobler and Finkbeiner 2007; Dobler et al. 2009

...BUT MOSTLY INCOMPATIBLE WITH EACH OTHER, IS DM BEHIND ANY OF THEM?



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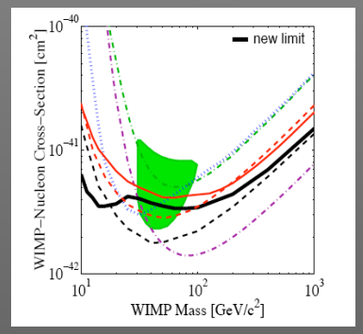
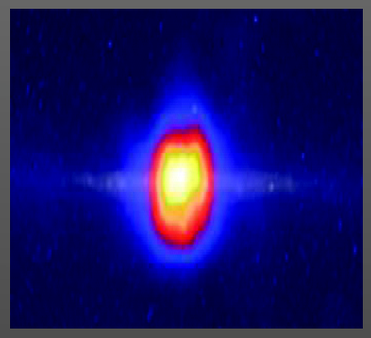


DAMA Direct Detection

Does not fit with the most nave explanations. New candidates? New "new physics"?



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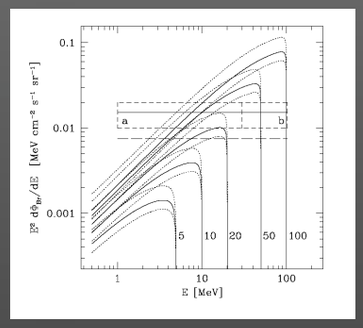
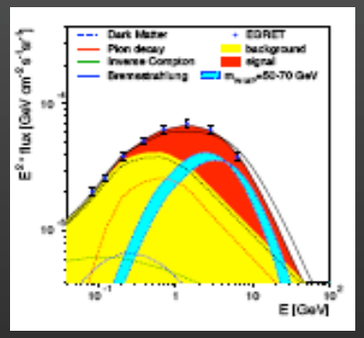


INTEGRAL 511 keV

Scenario is severely constrained: Beacom, Bell & Bertone 2003, Beacom and Yuksel 2004, Hooper, Sigl and Fayet 2006. Emission appears now lopsided, LMXBs?



Gamma-rays: EGRET, HESS,

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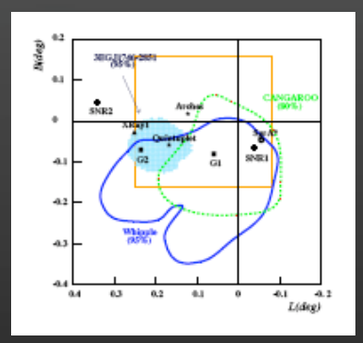
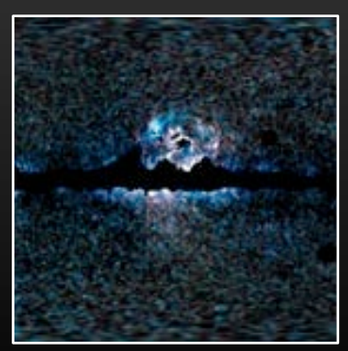


Gamma-rays: EGRET, HESS…

EGRET not confirmed by Fermi. Anti-proton flux in conflict with De Boer et al. HESS: Mass scale "not natural", astrophys. source? See papers by: *Bergstrom, Bertone, Hooper, Profumo, Ullio…*

WMAP & Fermi Haze

Evidence for: 100 GeV DM
See e.g. Finkbeiner 2004, Hooper, Dobler and Finkbeiner 2007; Dobler et al. 2009

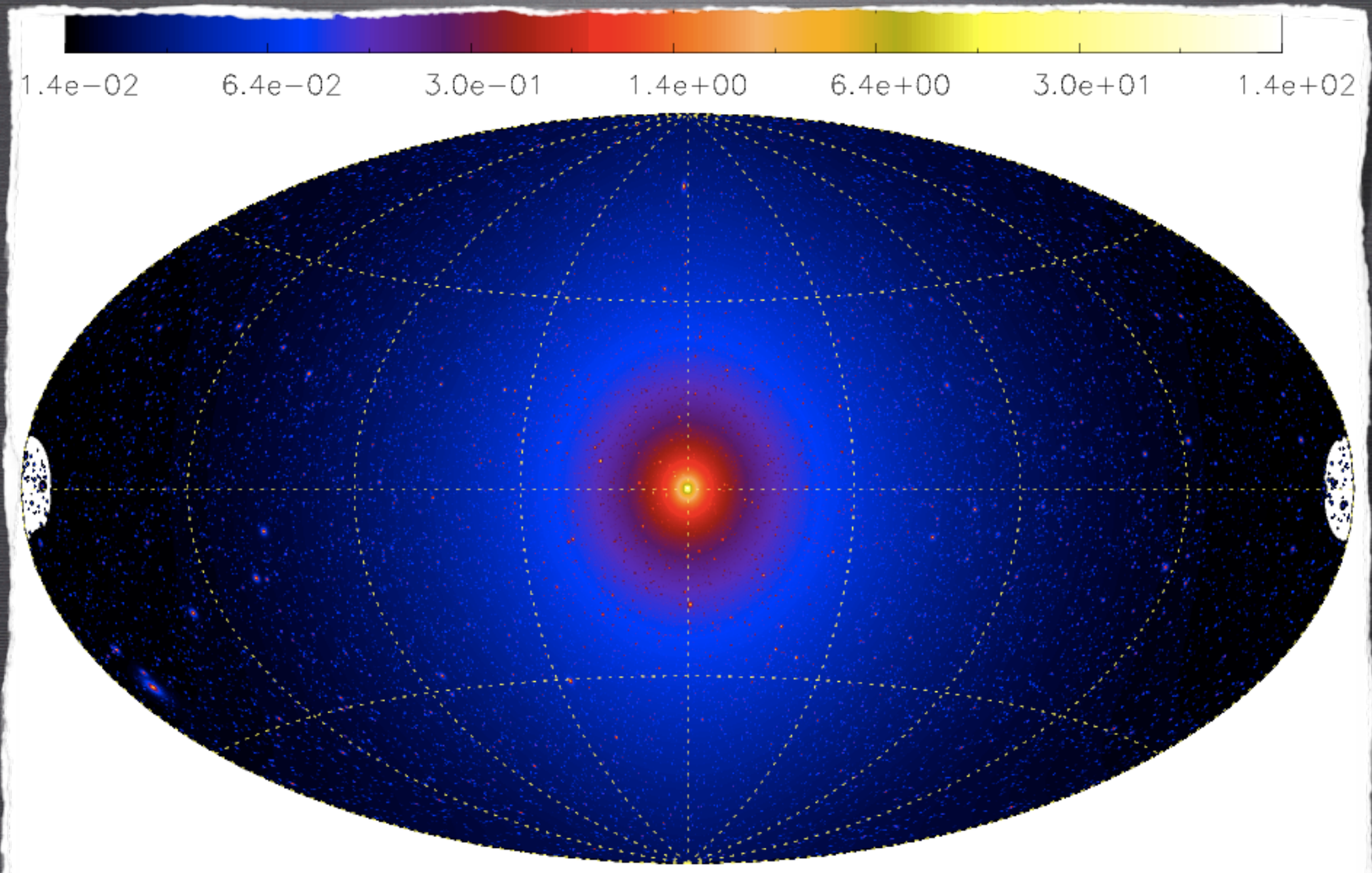


WMAP & Fermi Haze

No smoking-gun. Very complicated astrophysical backgrounds..

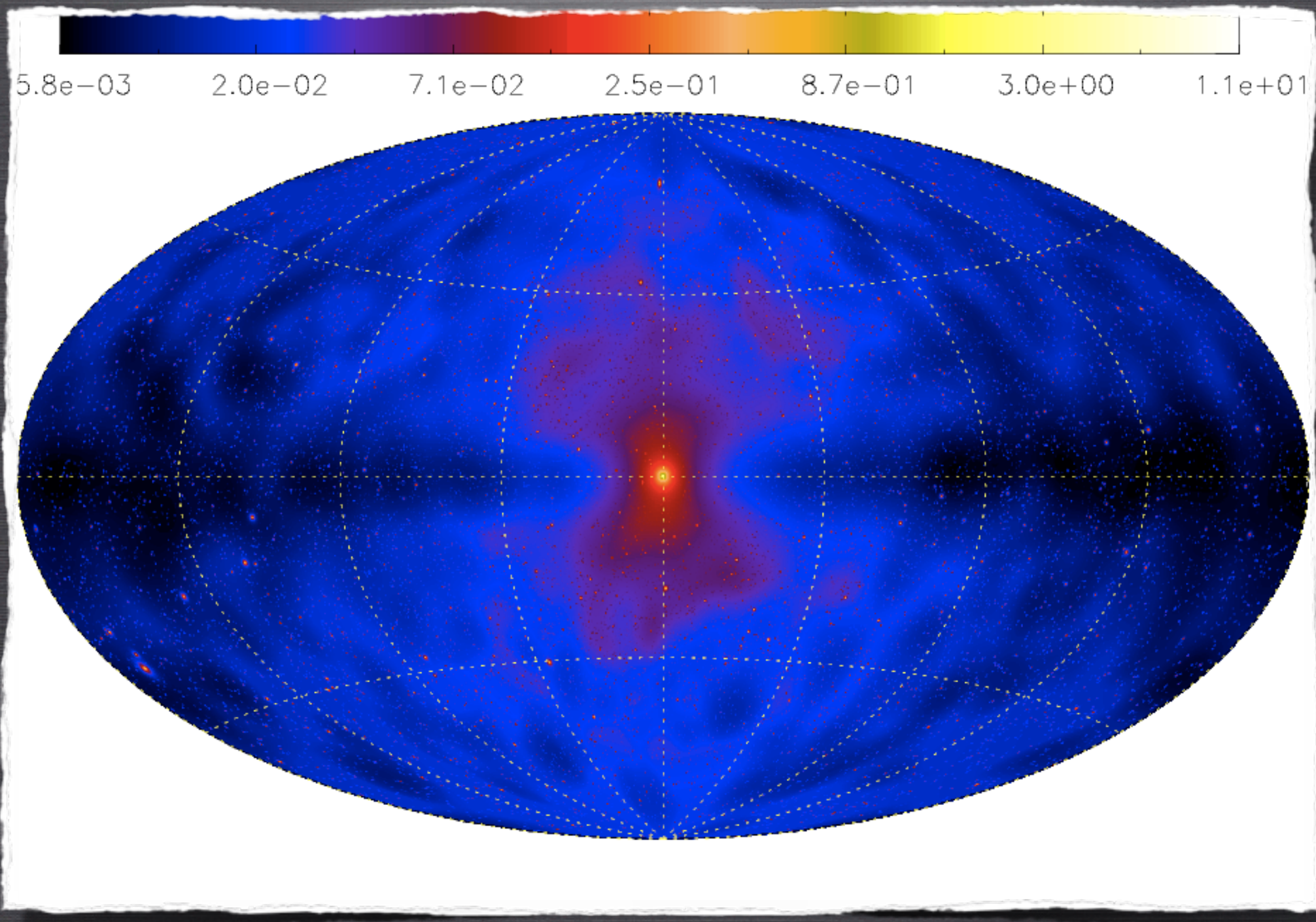
DM annihilation Signal

(Res+Unres+Smooth+Extragal.)



Pieri, GB, Branchini 2009

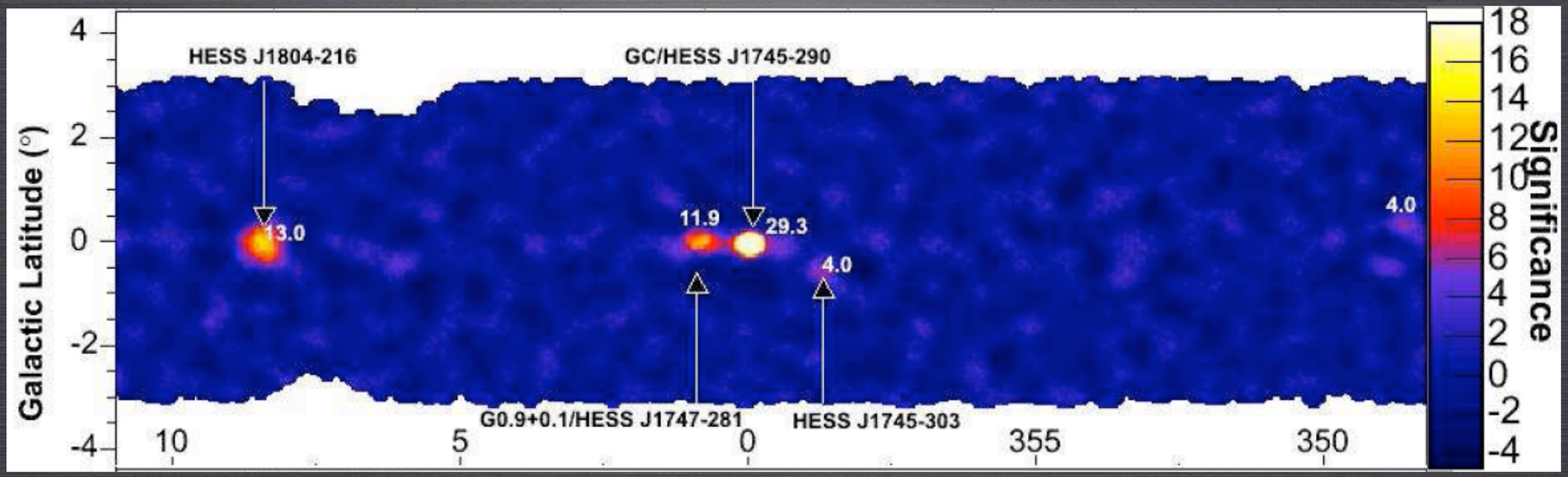
Sensitivity



Pieri, GB, Branchini 2009

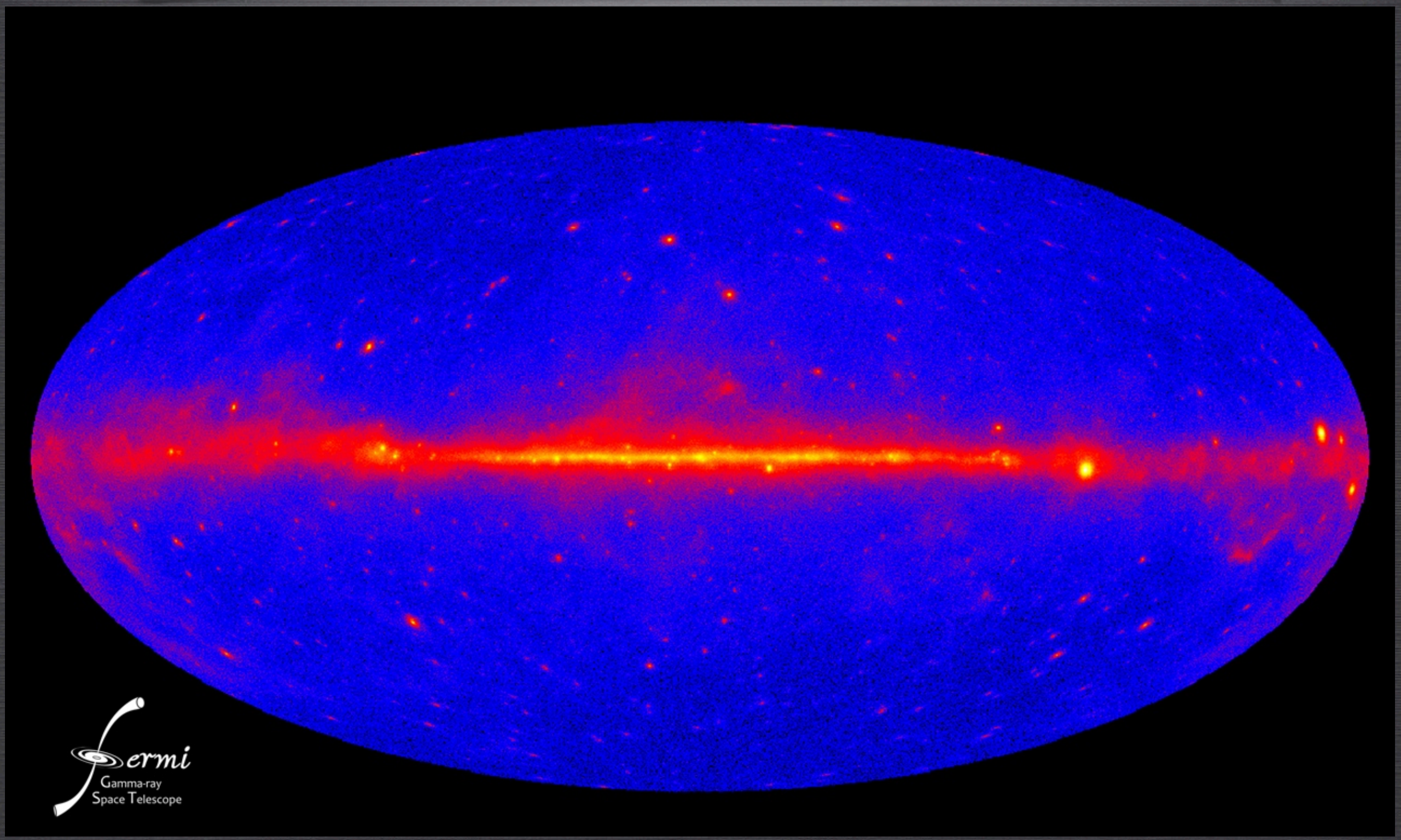
The Galactic center

bright gamma-ray source detected by HESS, MAGIC and now Fermi



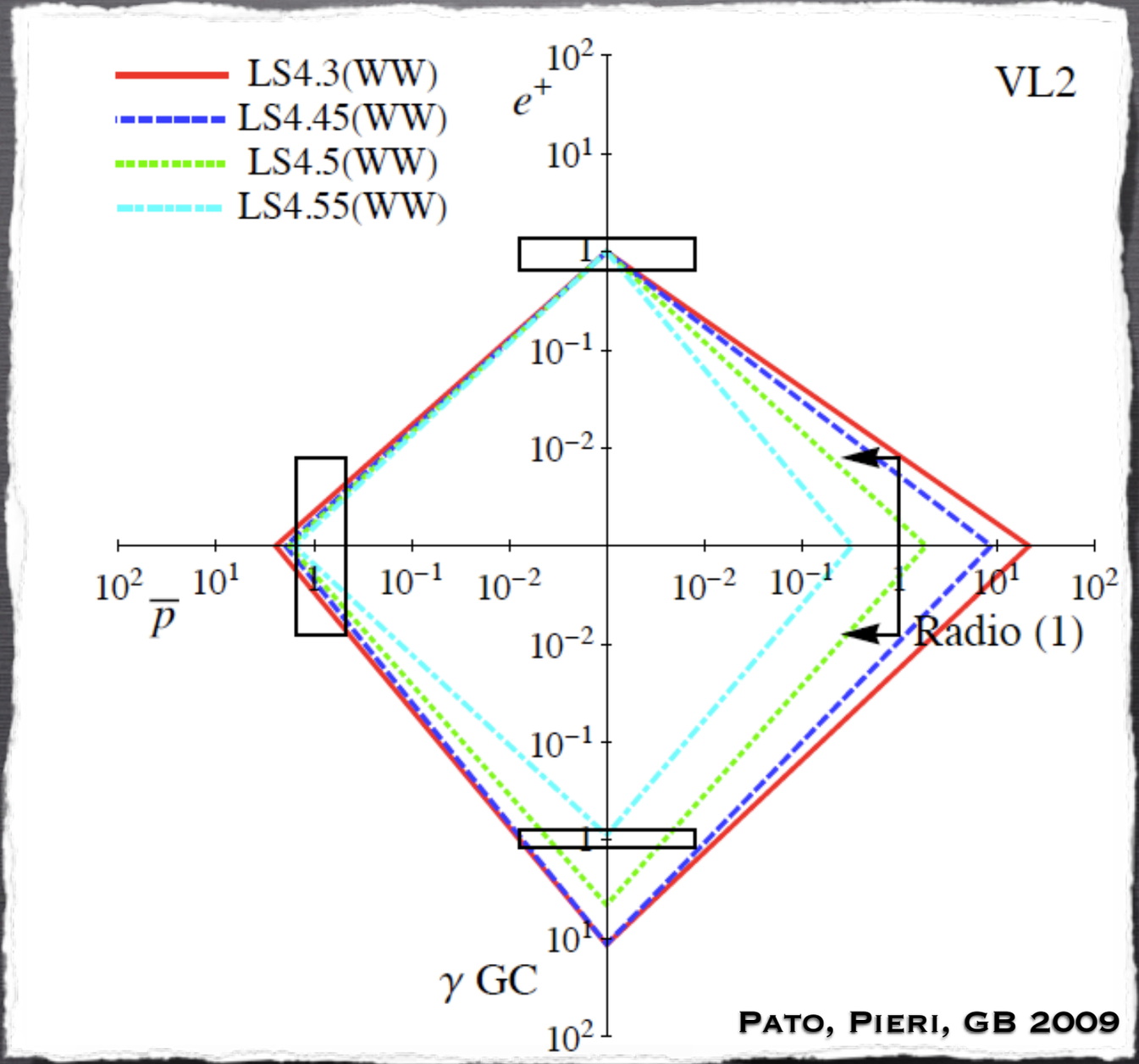
Aharonian et al. 2007

The FERMI sky



1-year full-sky map. http://fermi.gsfc.nasa.gov

DM interpretation
Increasingly Constrained

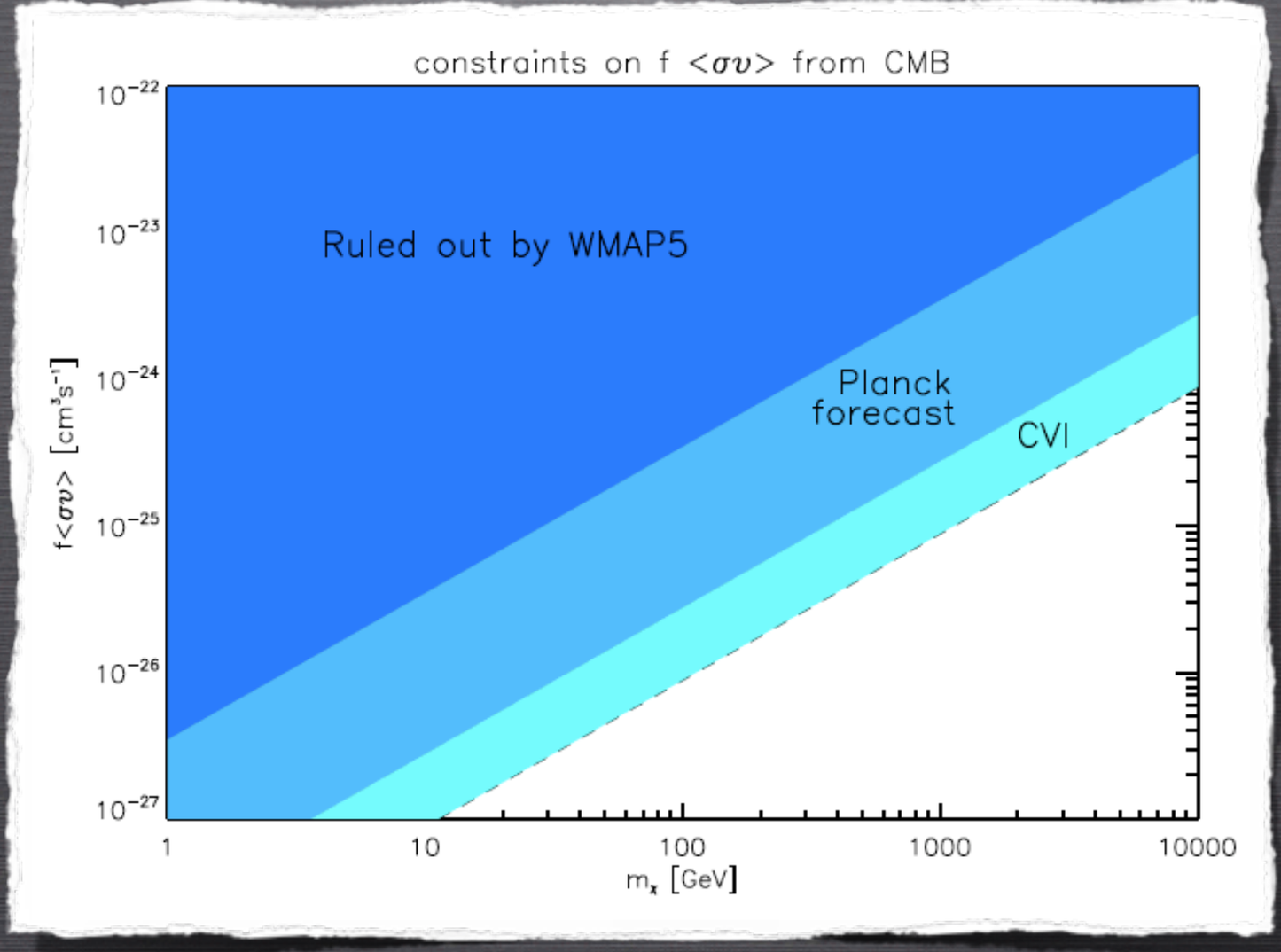


Pato, Pieri, GB 2009

Constraints from CMB

on the ann. cross section at recombination, i.e. v/c~10^{-8}

(cfr. Talks by Iocco and Hector on Monday)



Galli, Iocco, GB, Melchiorri 2009

The interaction of secondary particle from DM annihilation with the thermal gas can 1: ionize it, 2: induce Ly–α excitation of the hydrogen and 3: heat the plasma. The first two modify the evolution of the free electron fraction xe, the third affects the temperature of baryons.

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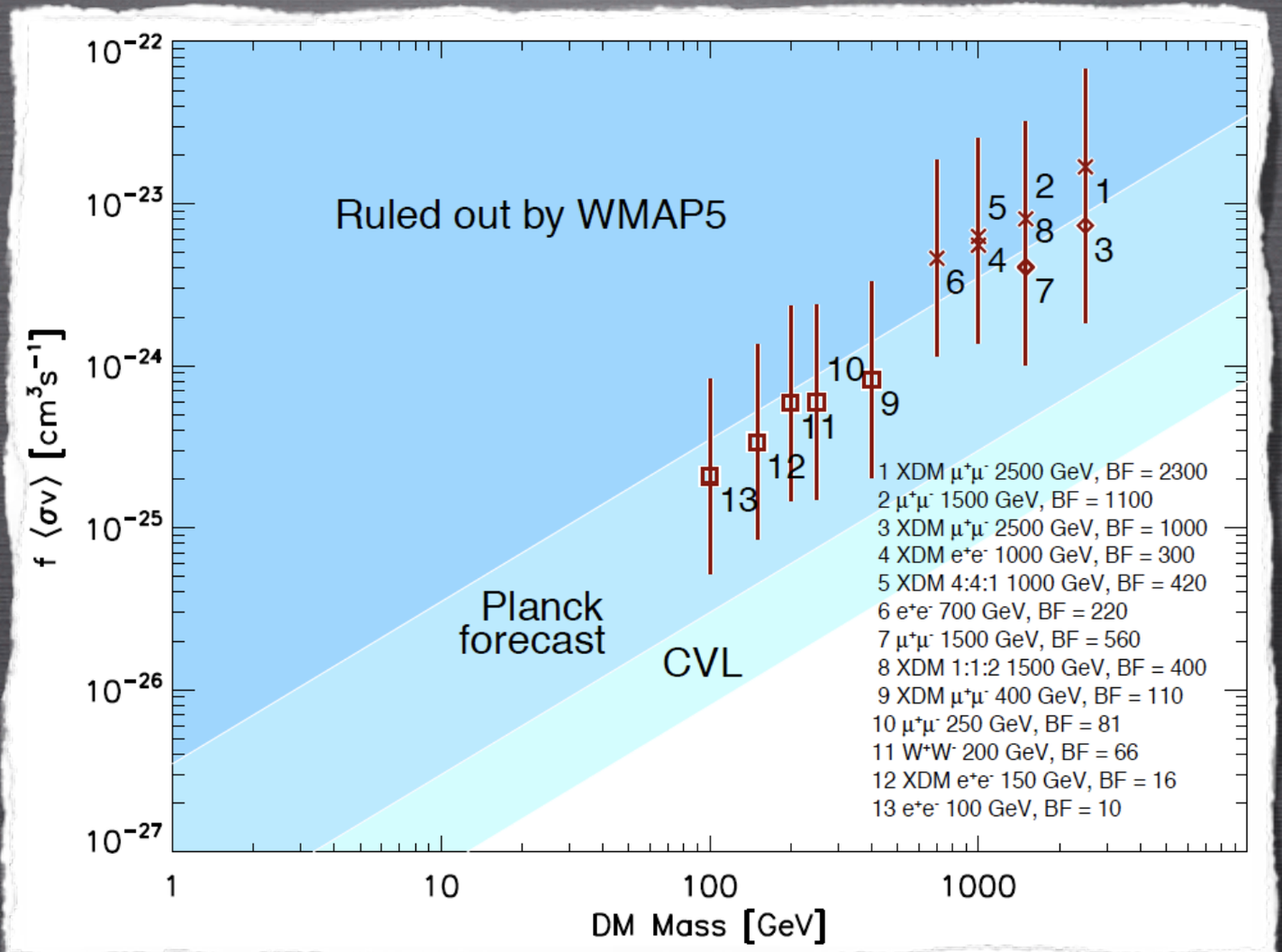

Slatyer, Padmanabhan, Finkbeiner 2009

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The quest for the smoking-gun
or
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Claims of discovery have been made over the years (EGRET source, HEAT excess, INTEGRAL 511 keV line, WMAP Haze). The footprint of DM could be anywhere, but how do we go from "hints" to "discovery"?

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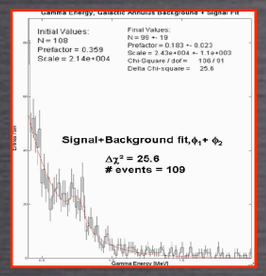

1) Annihilation Lines (or other unmistakable spectral features)

Neutralinos (e.g. Bergstrom and Ullio 1997)
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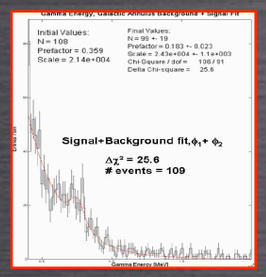

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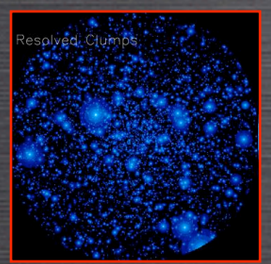

2) Multiple Sources with Identical spectra

e.g. DM clumps or IMBHs

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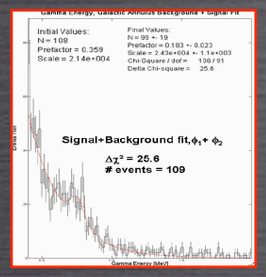

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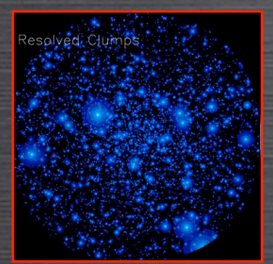

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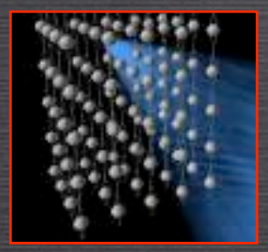

3) High-Energy Neutrinos from the Sun

Icecube, Antares, km3
Fluxes proportional to SCATTERING not annihilation cross section

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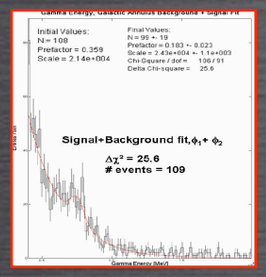

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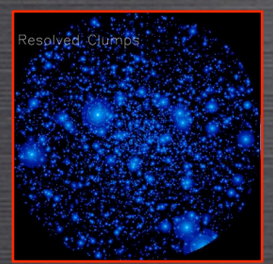

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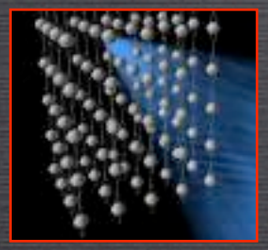

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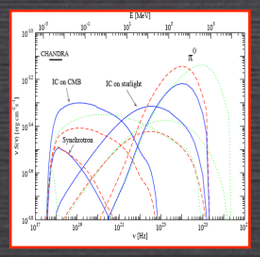

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Bertone, Sigl & Silk 2001; Aloisio, Blasi & Olinto 2004; Colafrancesco, Profumo & Ullio 2005; Regis & Ullio 2007, Jeltema and Profumo 2008 etc.

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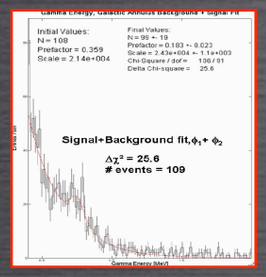

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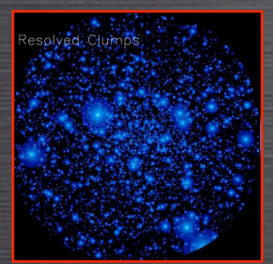

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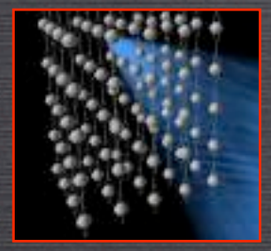

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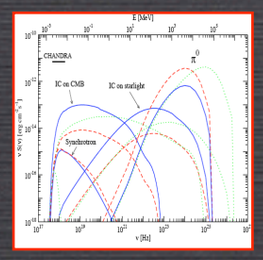

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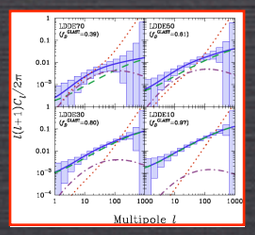

5) Angular power Spectrum of EG Background

Ando & Komatsu 2006, Ando et al. 2007; Siegal-Gaskins 2008; Fornasa, GB et al. 2008
Fermi Guest Investigator Grant!

Conclusions

- Huge Theoretical and experimental effort towards the identification of DM

- LHC is about to start. Exciting times ahead, but direct and indirect searches likely necessary to identify DM

- DM Direct Detection looks promising, but info from other exps. is needed to determine DM parameters

- DM Indirect Detection more and more constrained, but detection still possible

- We Need Data! In ~5 Yrs. discovery of Wimps or Paradigm shift..