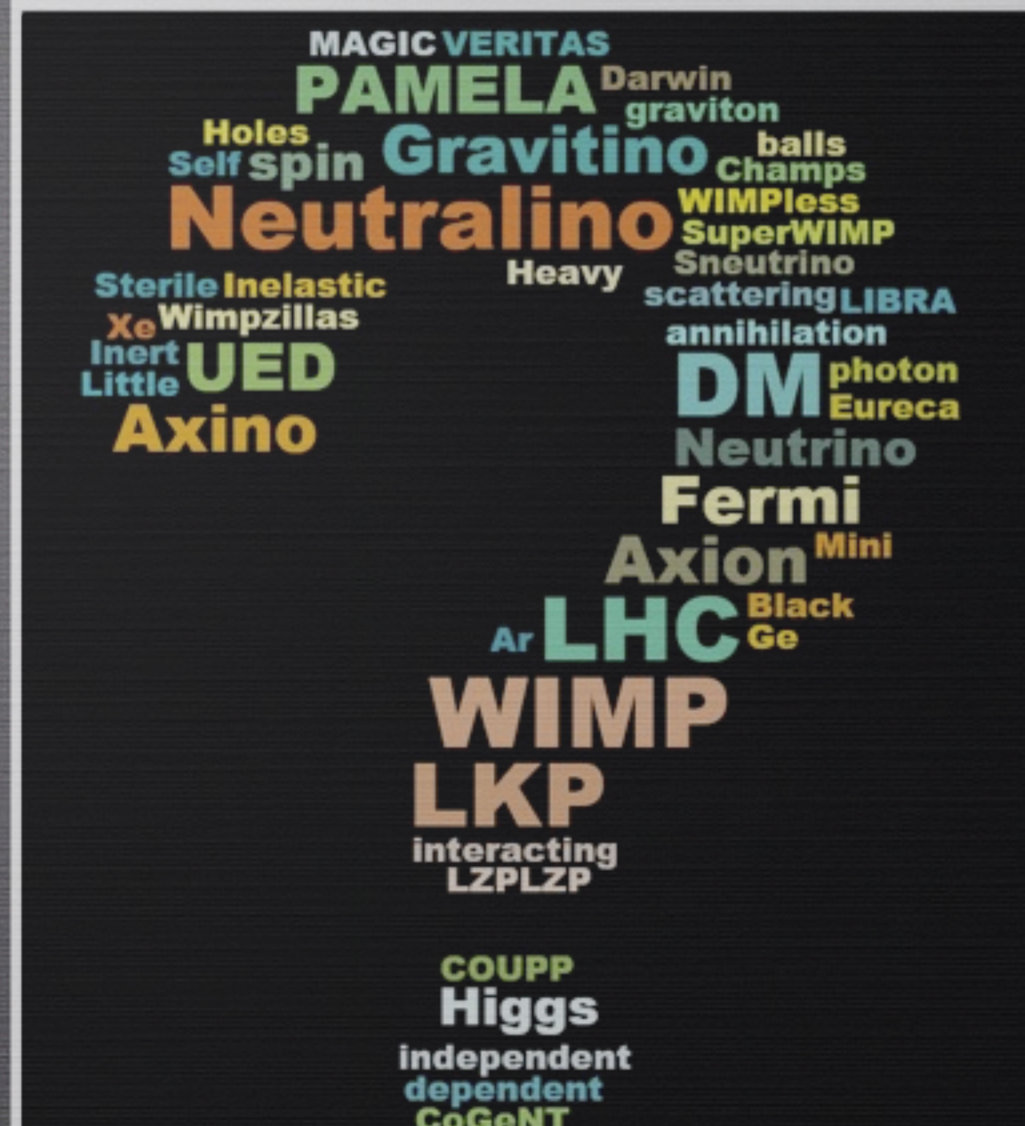
Astrophysical, Cosmological and Particle Physics Aspects of Dark Matter

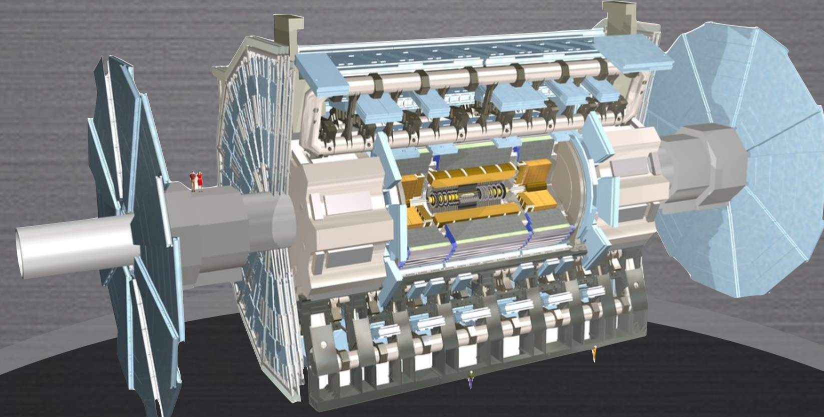
Gianfranco Bertone

Visiting Professor, U. of Zurich
CNRS researcher, IAP Paris

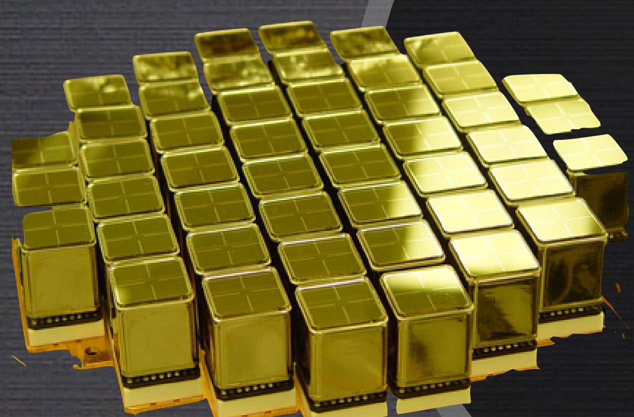
University of Zurich[UZH]



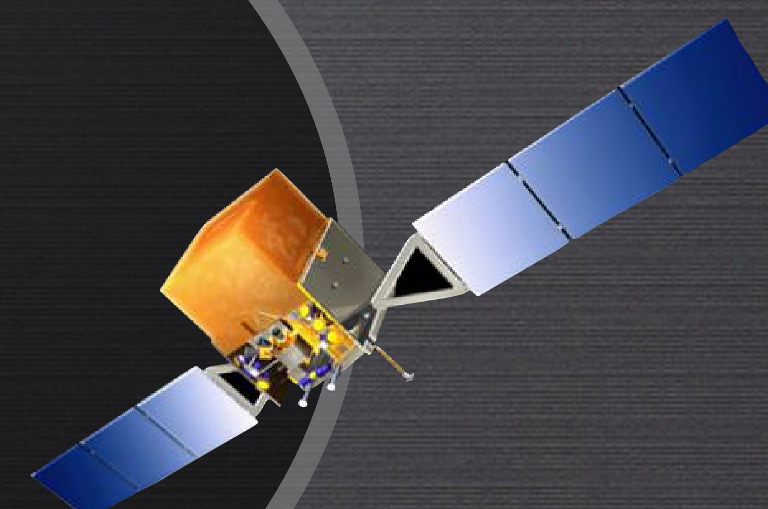
Summary



Colliders

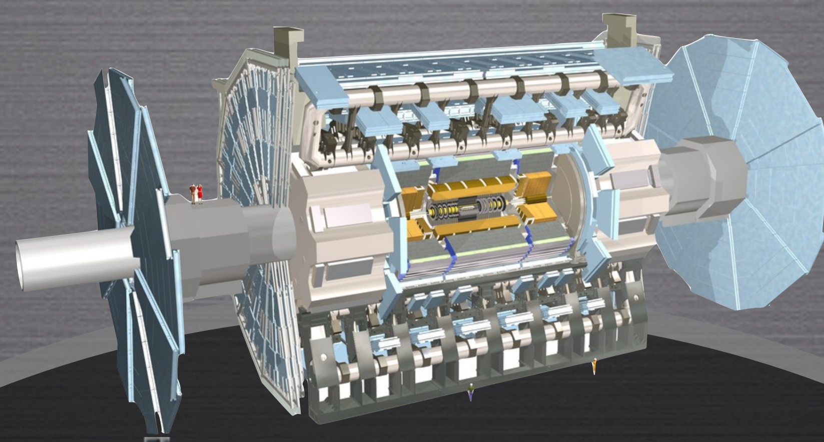


Direct Detection



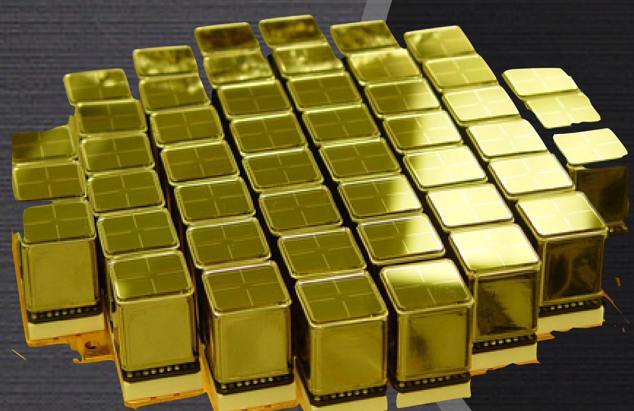
Indirect Detection

Summary

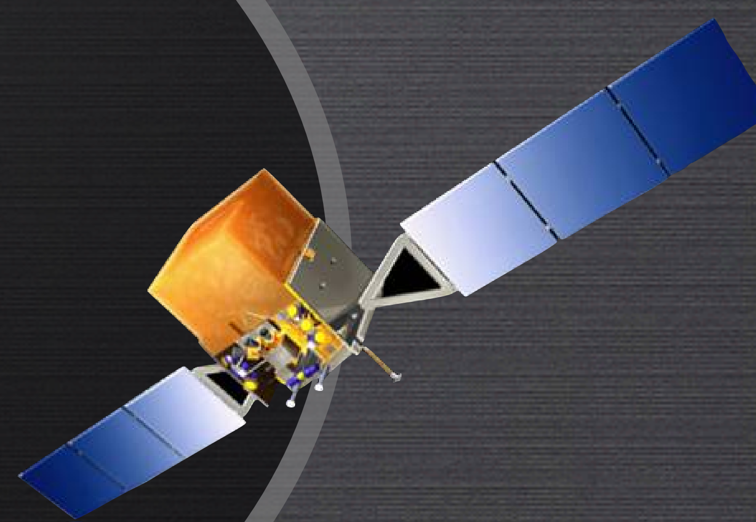


Colliders

1. **Complementarity**
2. **Interplay with Astrophysics**
3. **Identification**



Direct Detection



Indirect Detection

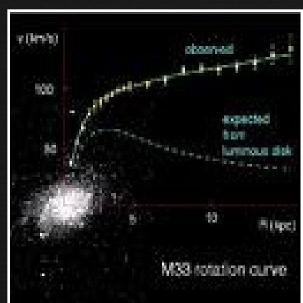
Summary

- 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

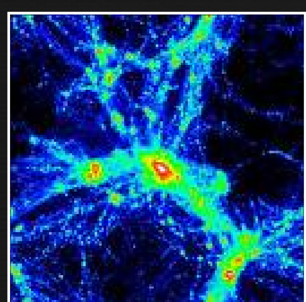
Evidence for Dark Matter

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

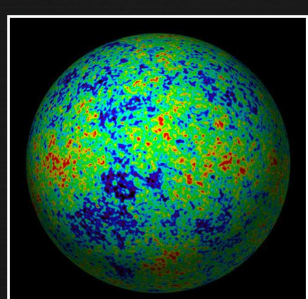
COSMOLOGICAL OBSERVATIONS



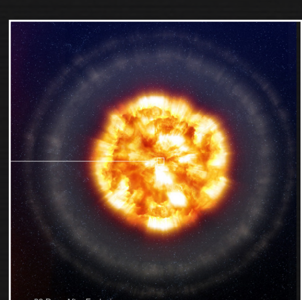
- Rotation Curves



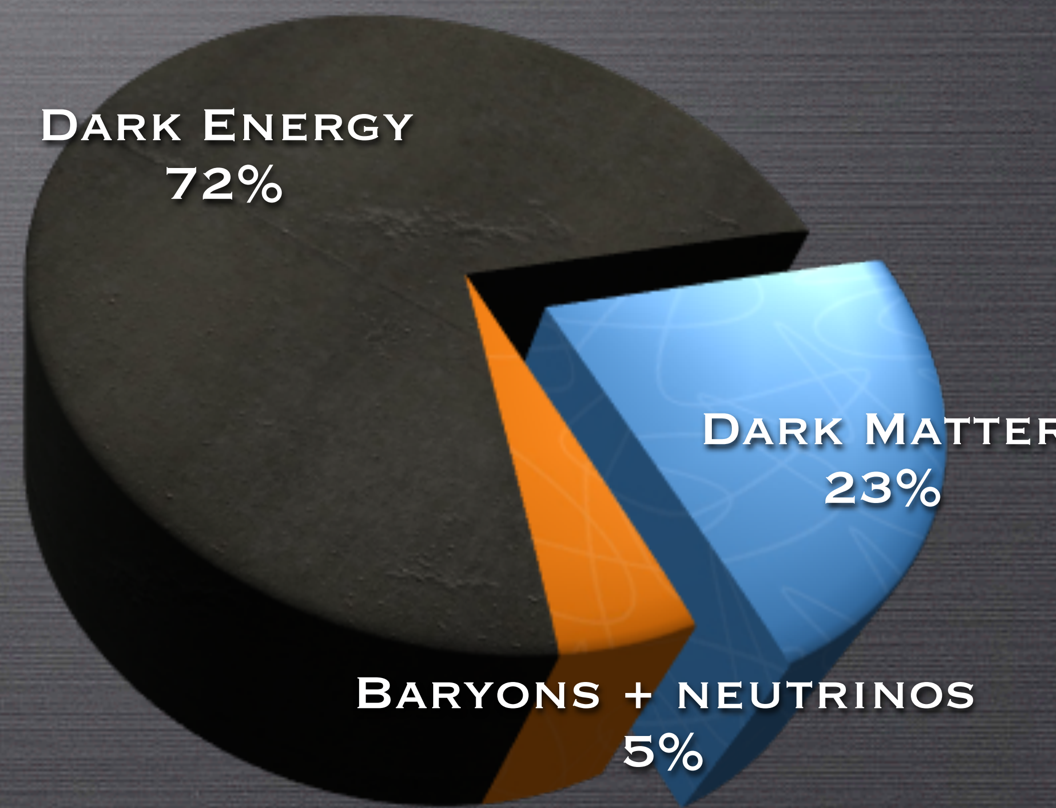
- Clusters of galaxies



- CMB



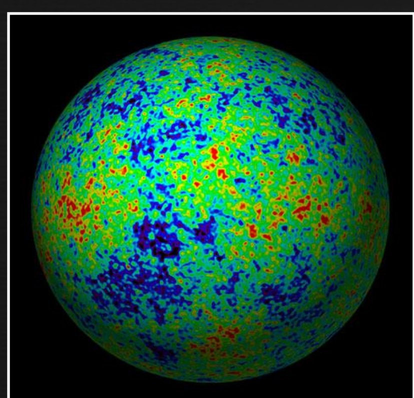
- Type Ia Supernovae



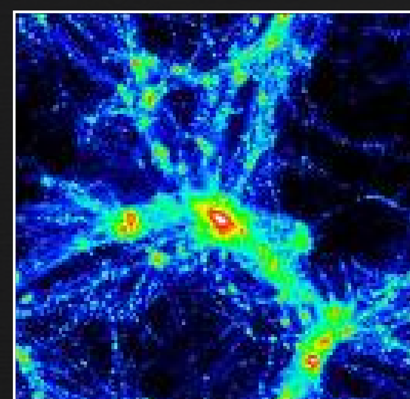
What do we know?

An extraordinarily rich zoo of non-baryonic Dark Matter candidates! In order to be considered a viable DM candidate, a new particle has to pass the following 10-point test

1) Ωh^2 OK?

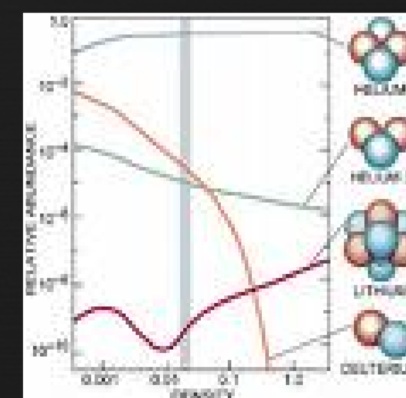


2) Is it cold?

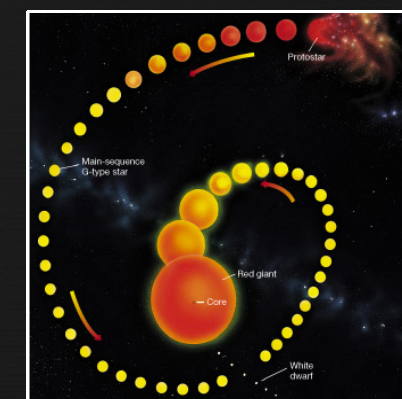


3) Is it neutral?

4) Is BBN ok?

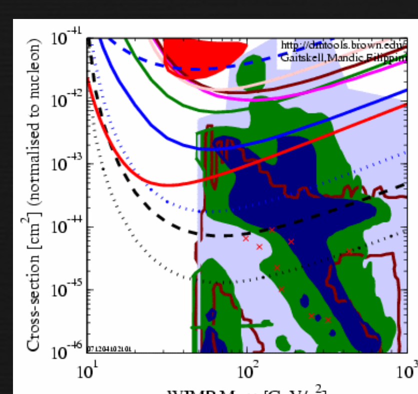


5) Stars OK?

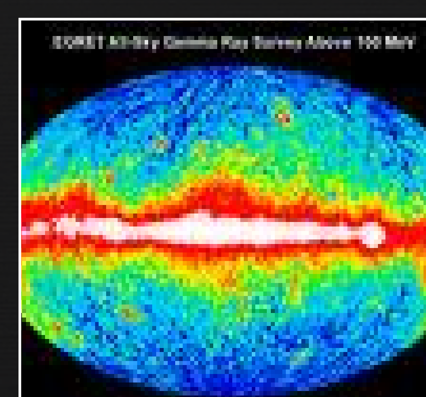


6) Collisionless?

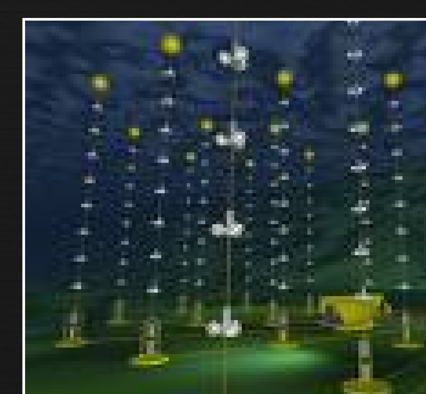
7) Couplings OK?



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.

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

Ad-Hoc Candidates

Postulated to solve the DM Problem

- Minimal DM
- Maverick DM
- etc.

Other

- **Axions**

  Postulated to solve the strong CP problem

- **Sterile Neutrinos**

- **SuperWIMPs**

  Inherit the appropriate relic density from the decay of the NTL particle of the new theory

- **WIMPless**

  Appropriate relic density achieved by a suitable combination of masses and couplings

- Etc. (Axino, Q-balls.....)

The DM candidates Zoo

WIMPs

Natural Candidates

Arising from theories addressing the stability of the electroweak scale etc.

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

Ad-Hoc Candidates

Postulated to solve the DM Problem

- Minimal DM
- Maverick DM
- etc.

Other

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

- **Sterile Neutrinos**

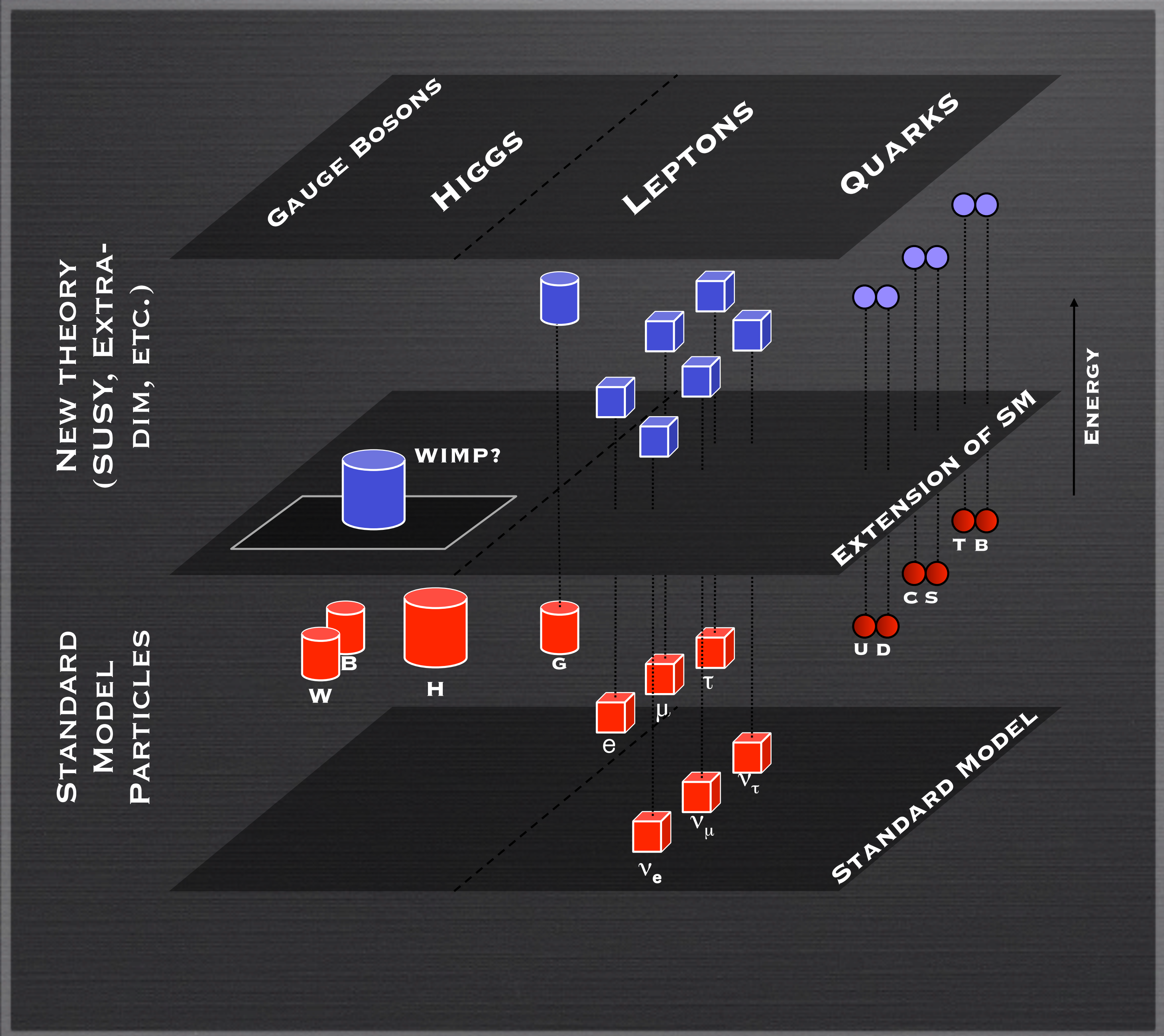
- **SuperWIMPs**
Inherit the appropriate relic density from the decay of the NTL particle of the new theory

- **WIMPless**
Appropriate relic density achieved by a suitable combination of masses and couplings

- Etc. (Axino, Q-balls.....)

Beyond the Standard Model

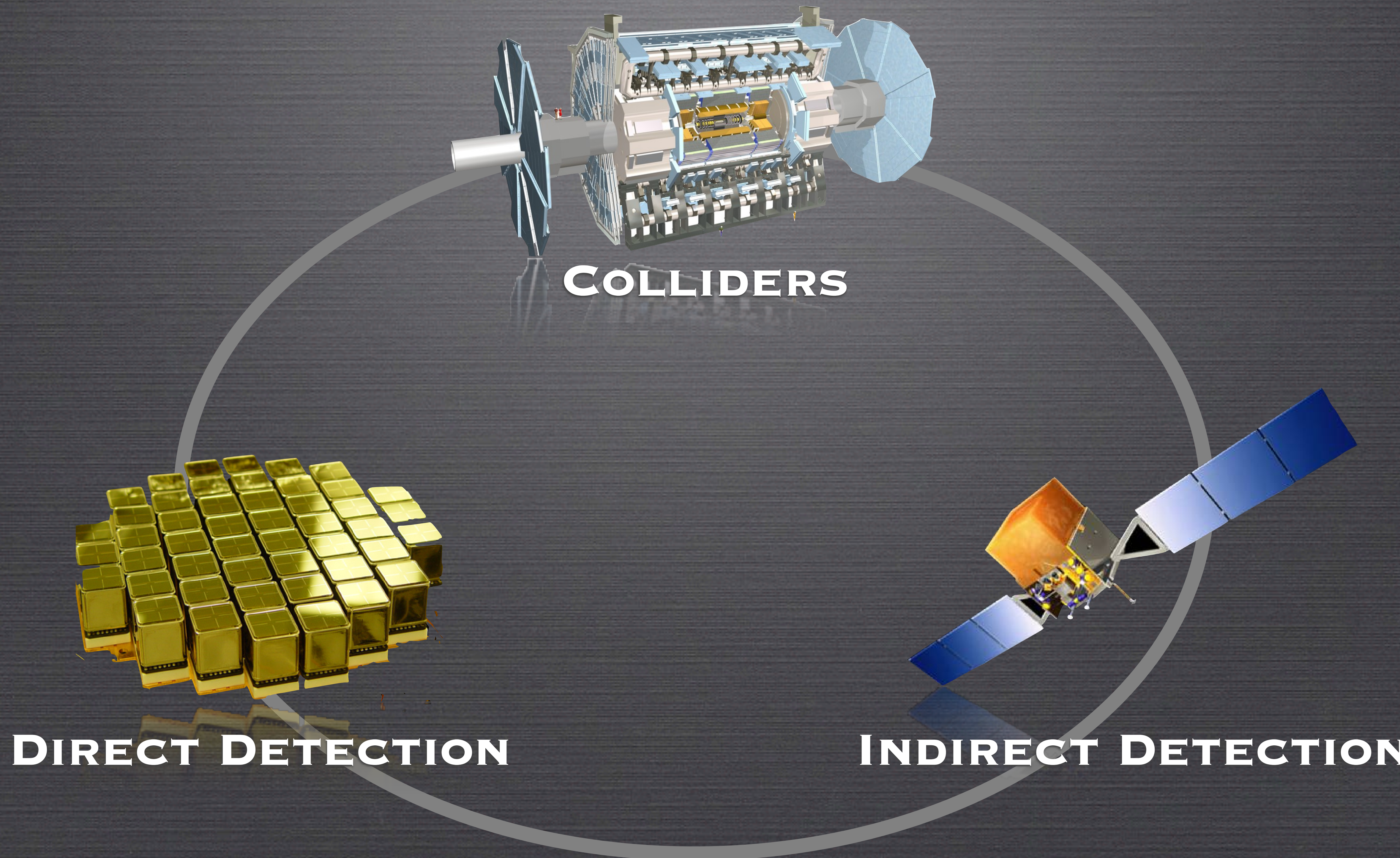
The Standard Model provides an accurate description of all known particles and interactions, however there are good reasons to believe that the Standard model is a low-energy limit of a more fundamental theory



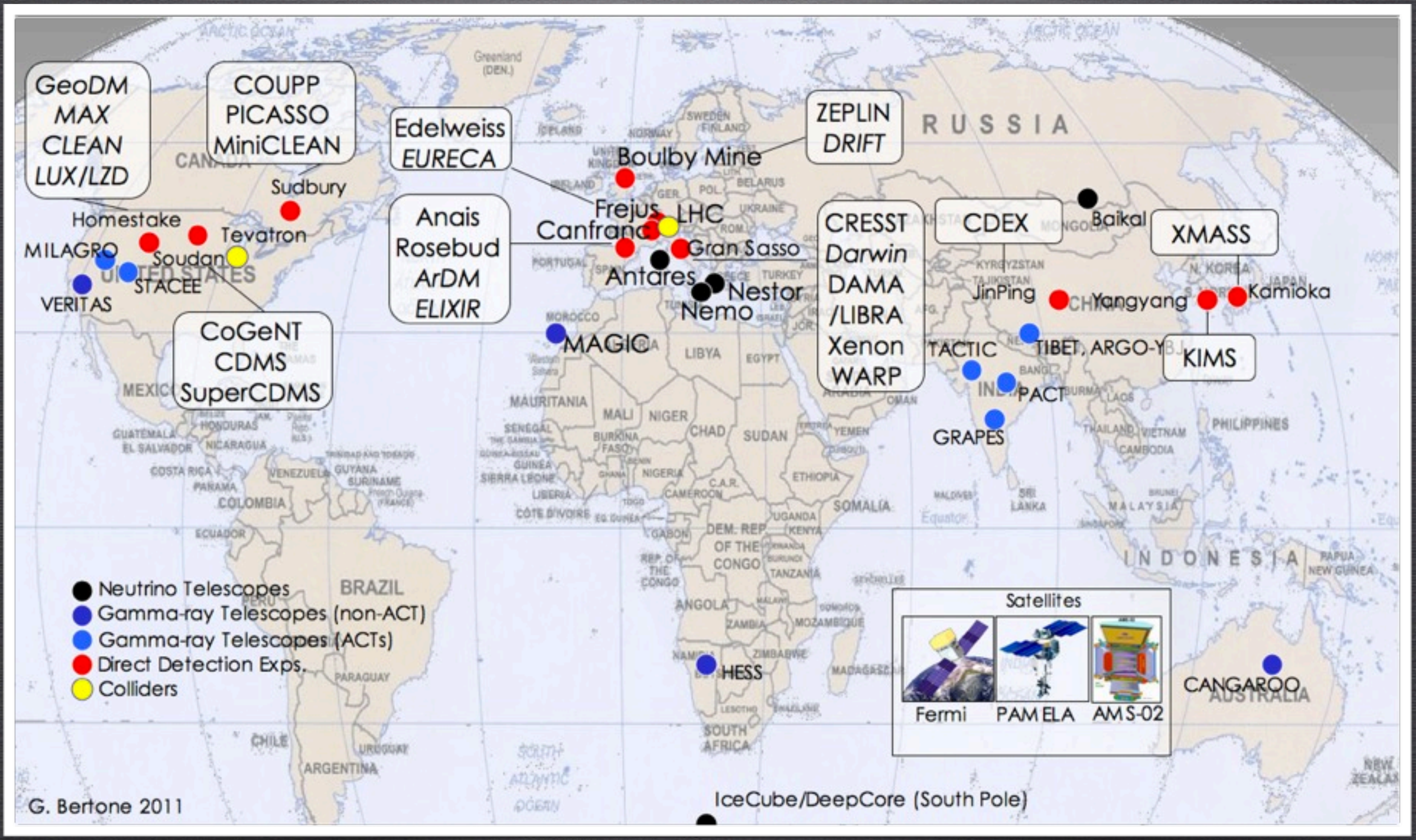
To explain the origin of the weak scale, extensions of the standard model often postulate the existence of new physics at ~100 GeV

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

Particle Dark Matter:
A multidisciplinary approach

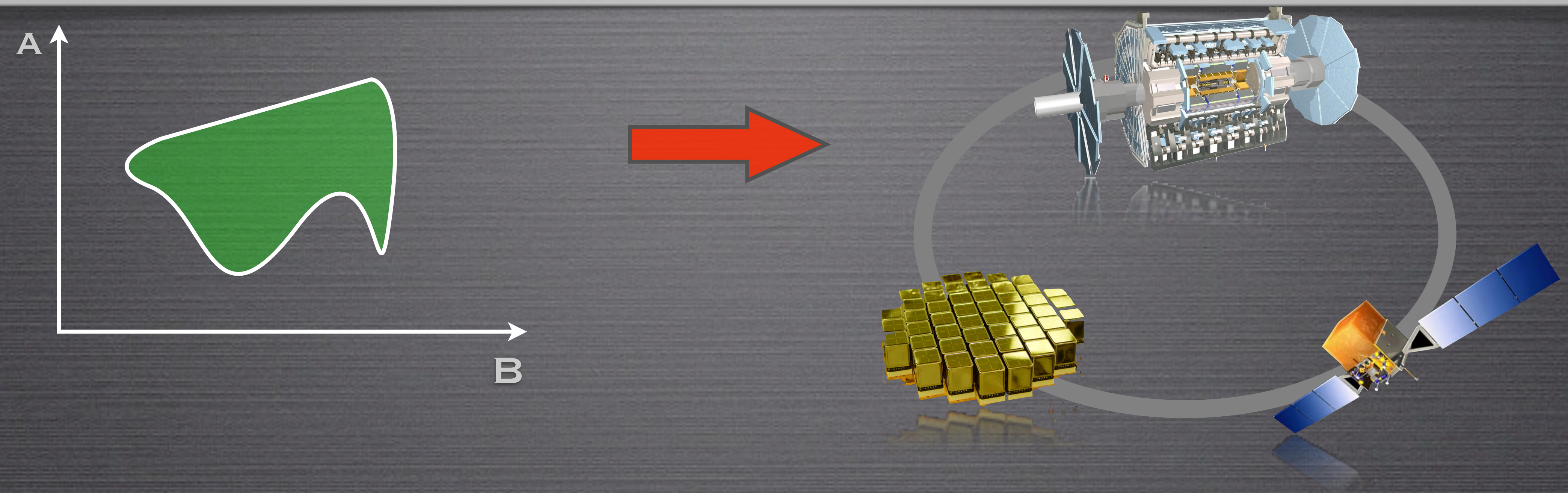


Dark Matter-related Experiments circa 2011



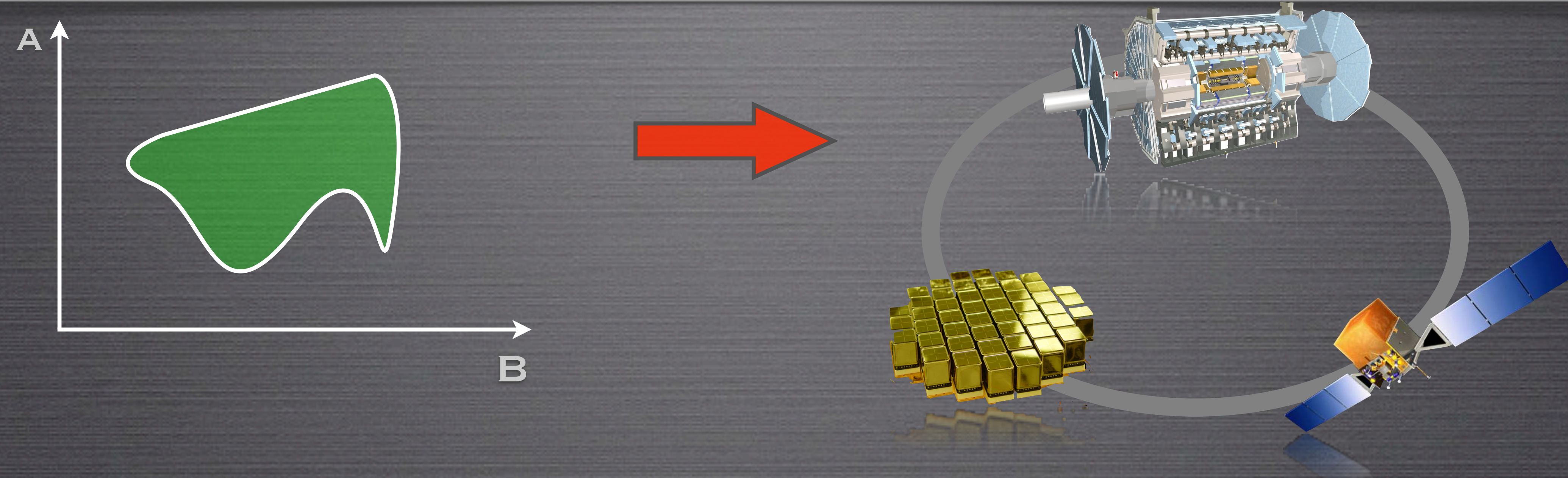
Where do we stand?

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

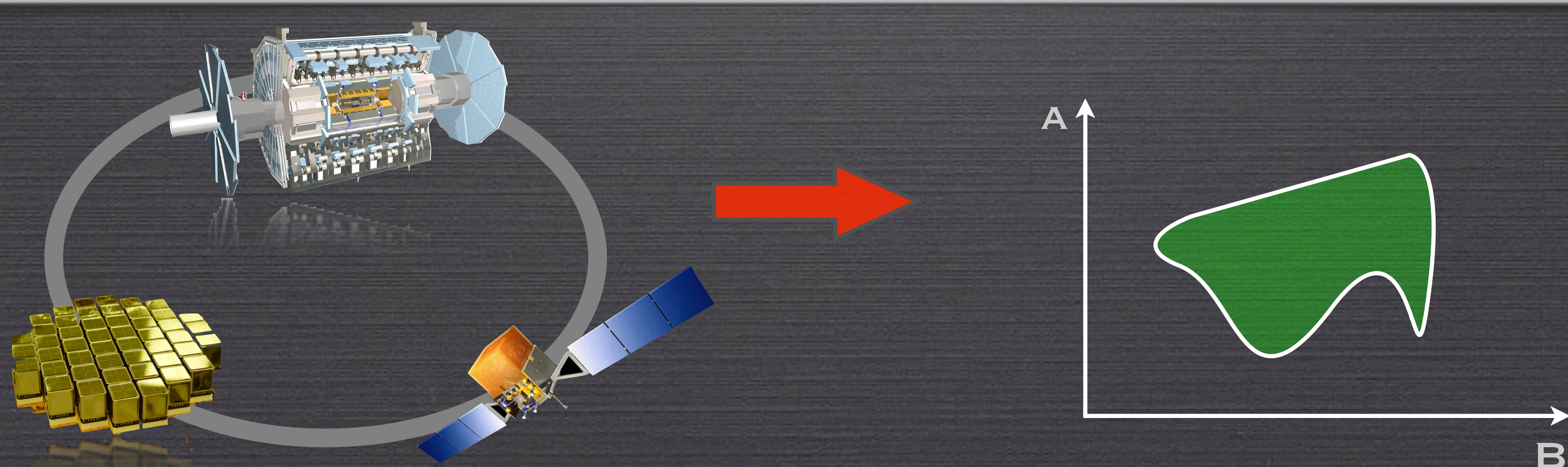


Where do we stand?

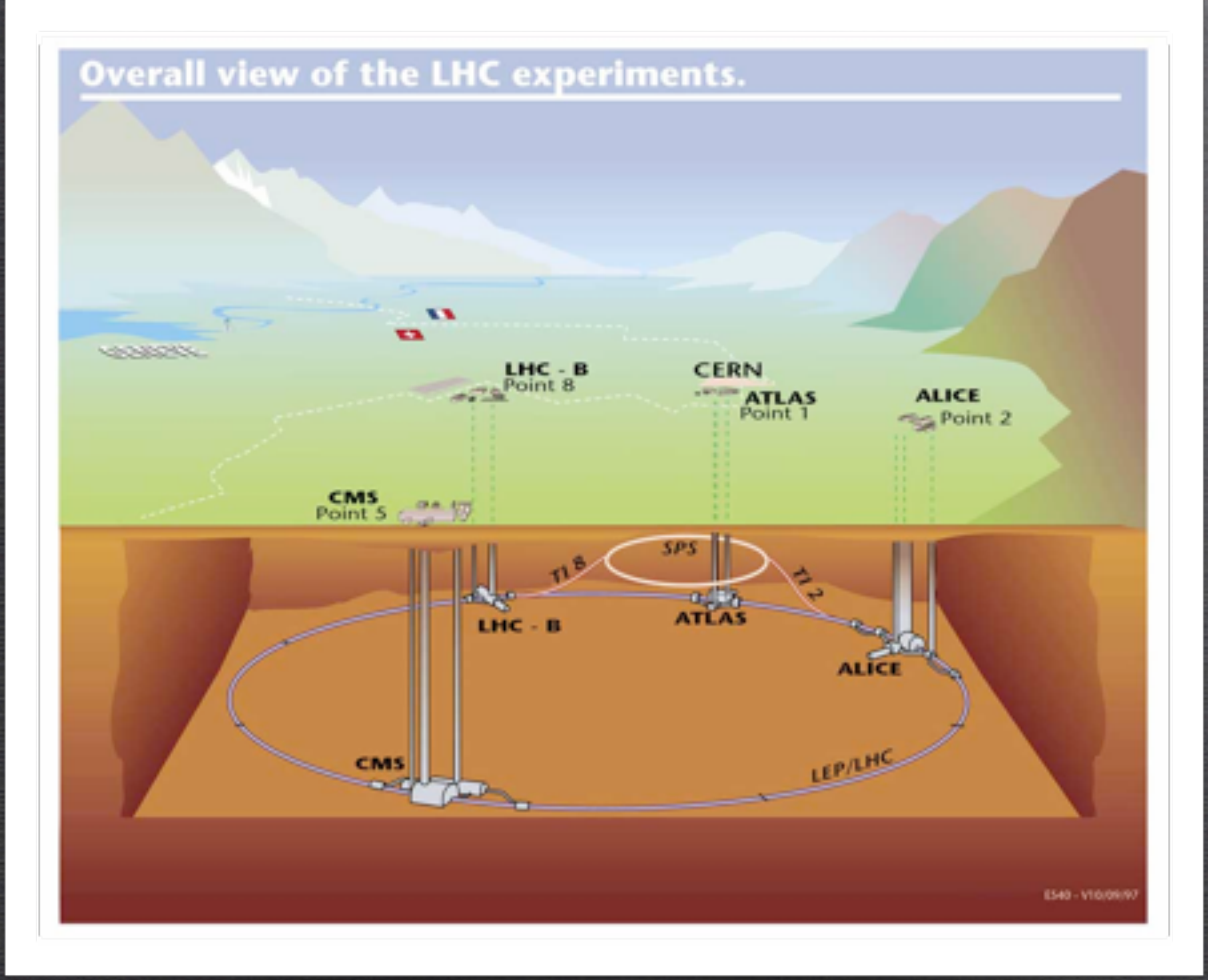
We have built (are building) experiments to search for Dark Matter, and we have been making predictions for decades

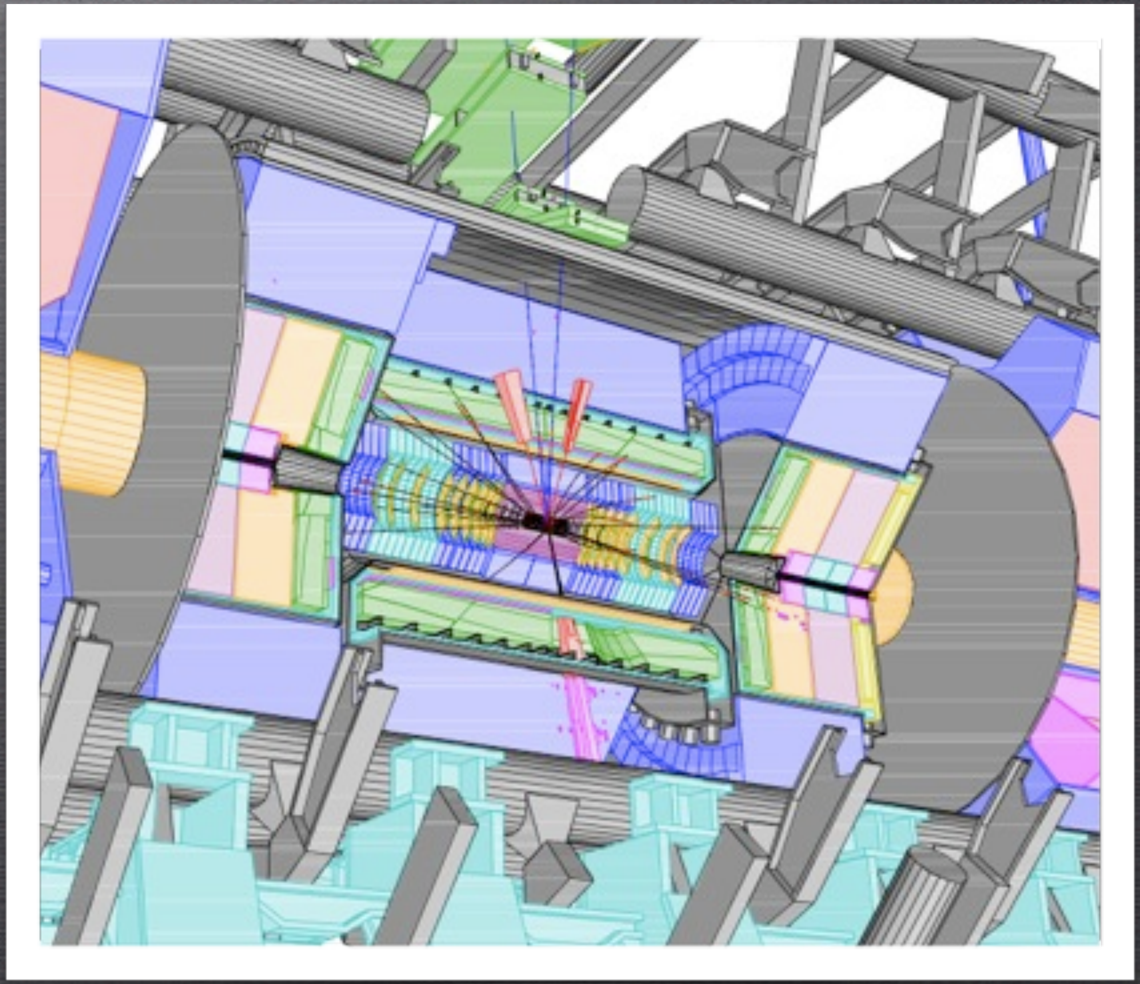


We are getting ready to solve the "inverse Problem" (and hoping that there will be a problem to solve..!)



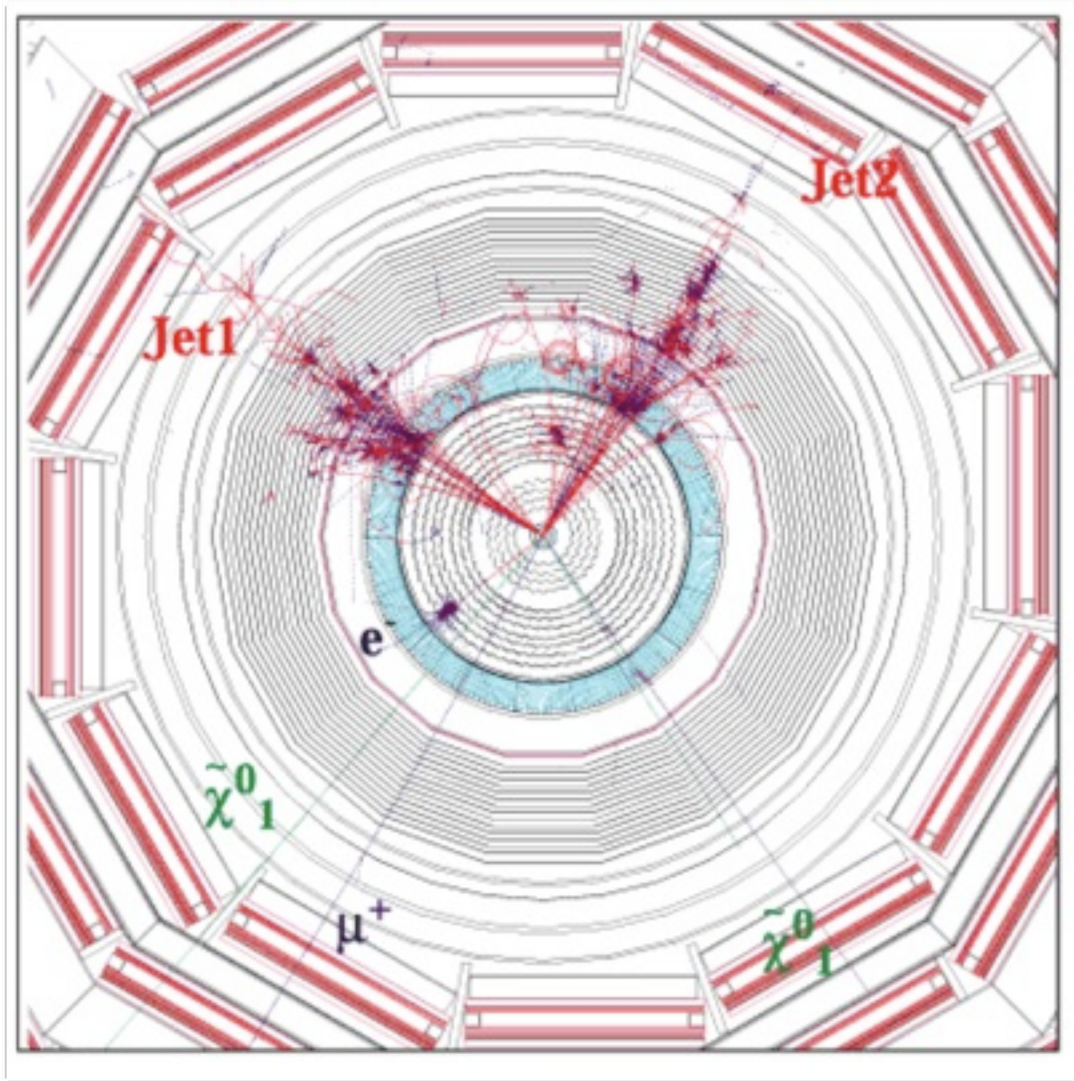
Searching for New Physics at the LHC



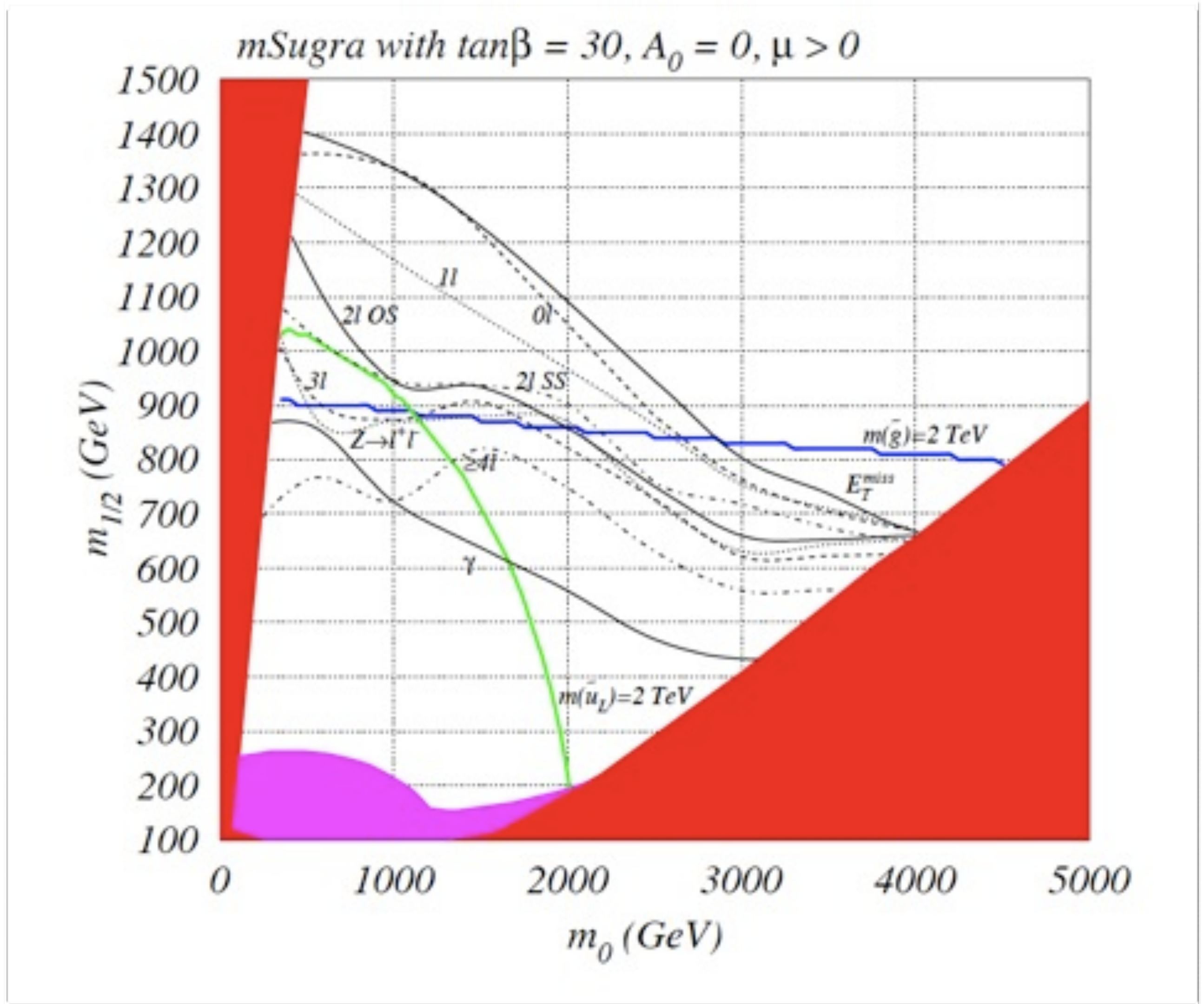


Searching for New Physics at the LHC

Example of analysis in the framework of mSUGRA



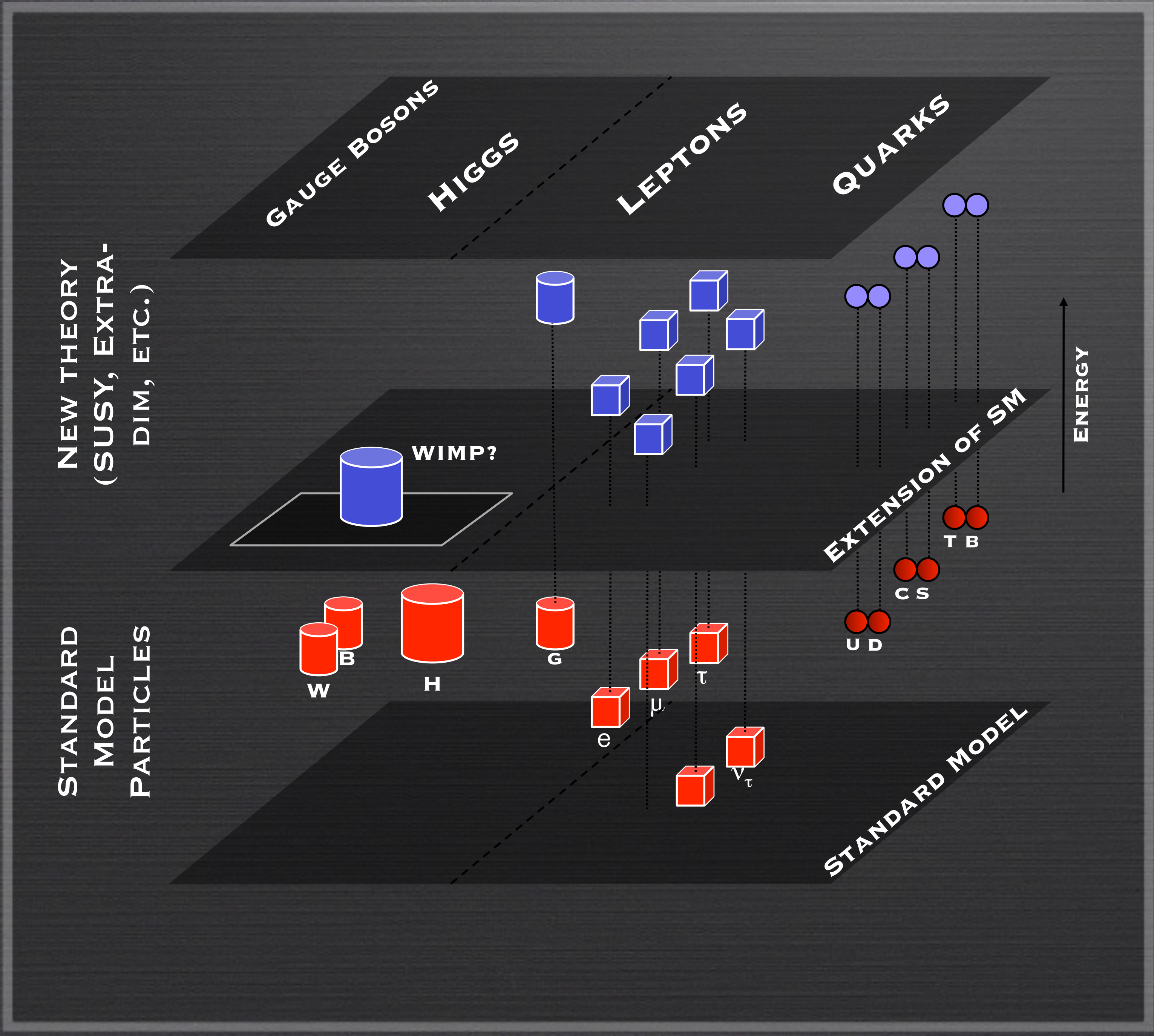
Simulation of an event with SUSY particle production in the CMS detector at the LHC

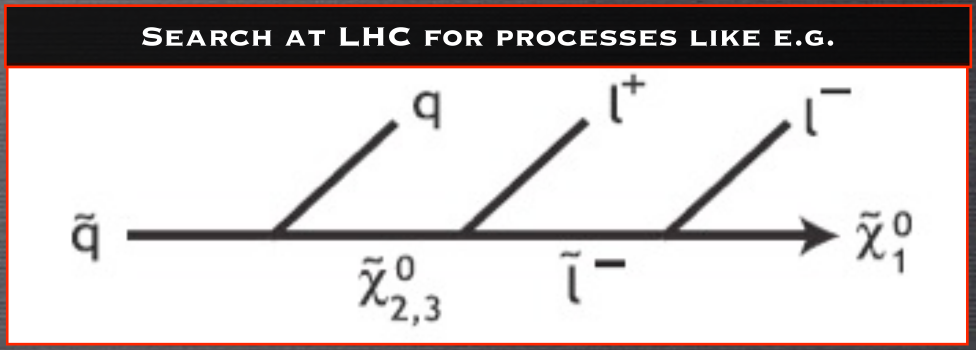


The 100 fb⁻¹ reach of LHC for SUSY in the mSUGRA model. For each event topology, the signal is observable below the corresponding contour.

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





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:

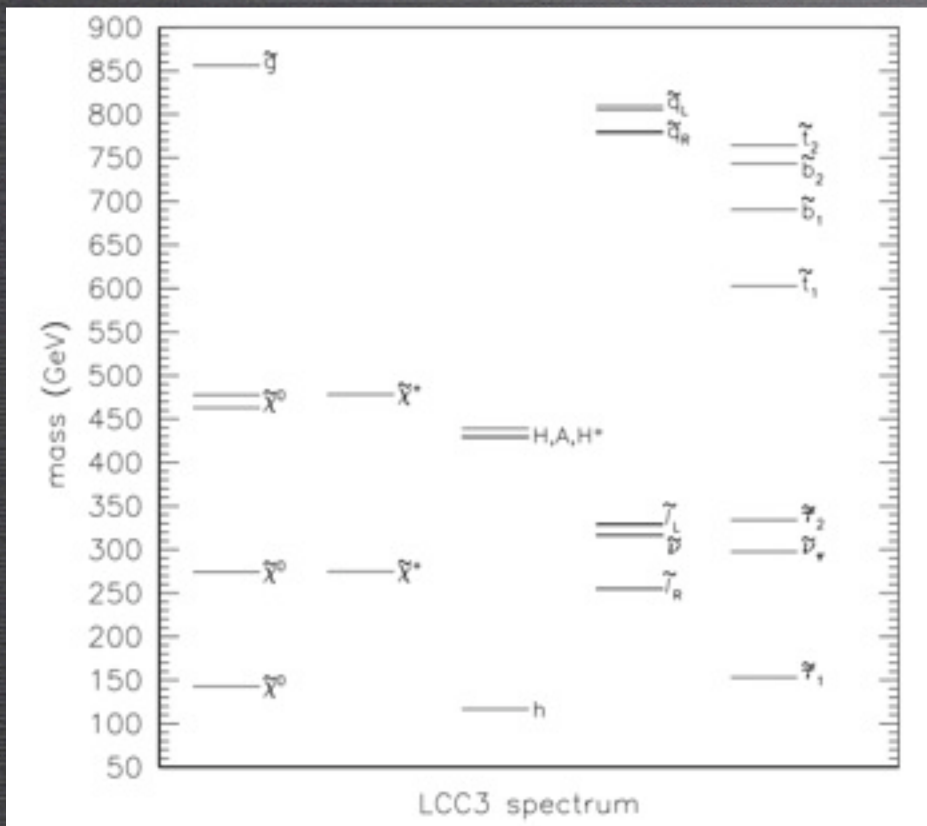
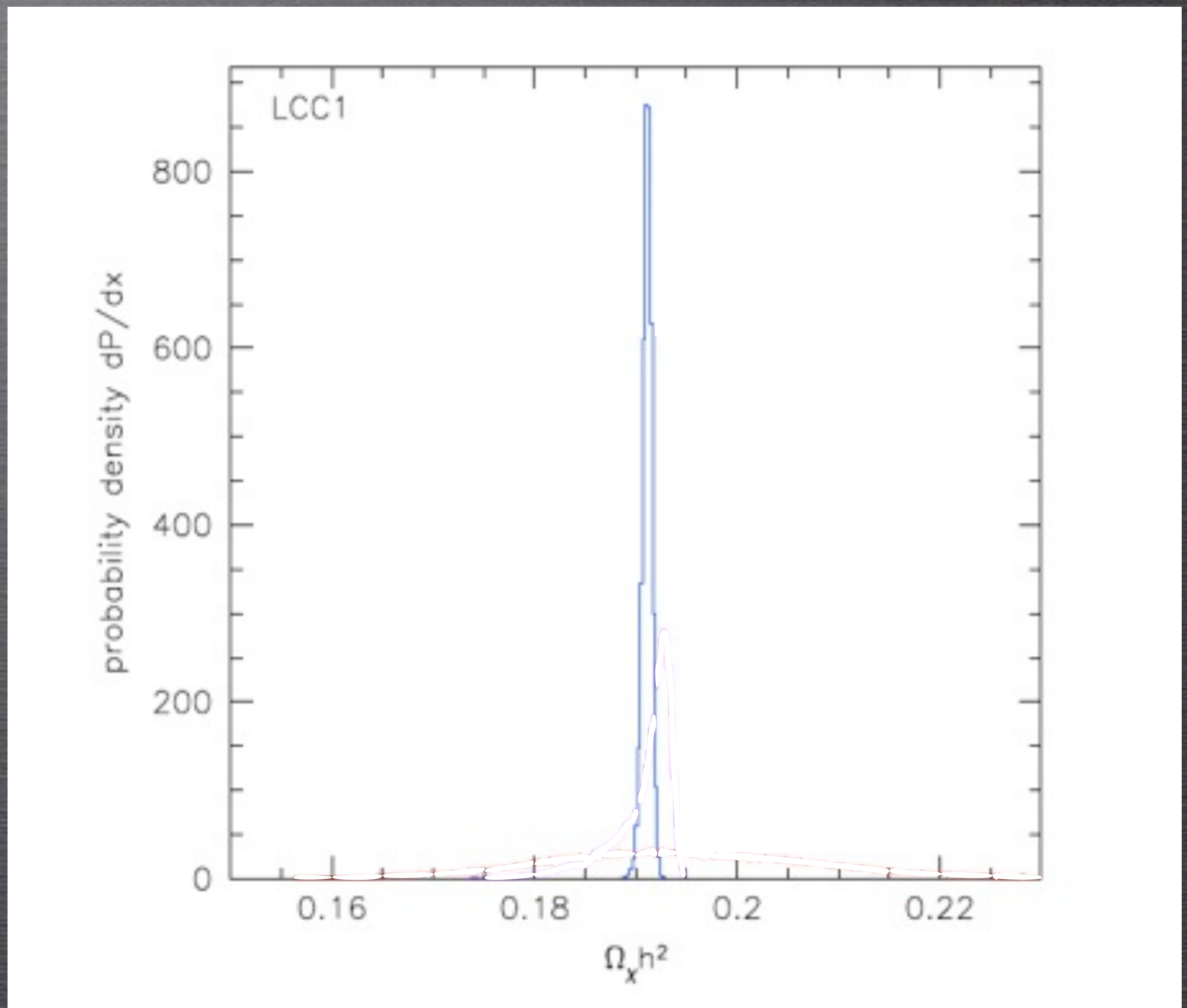
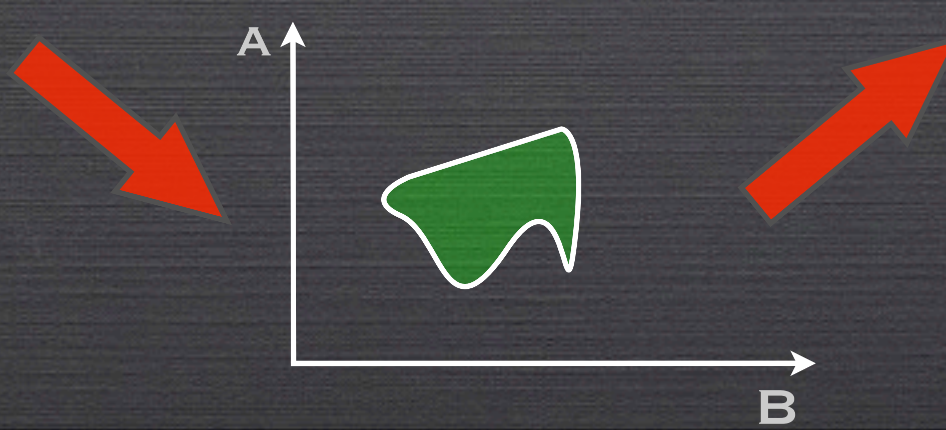


FIG. 34. Particle spectrum for point LCC3. The stau-neutralino mass splitting is 10.8 GeV. The lightest neutralino is predominantly *b*-ino, the second neutralino and light chargino are predominantly *W*-ino, and the heavy neutralinos and chargino are predominantly Higgsino.



Ad. from Baltz, Battaglia, Peskin, Wizansky (2005)



Example of Inverse problem at LHC

(example in the stau coannihilation region, 24 parms pMSSM)

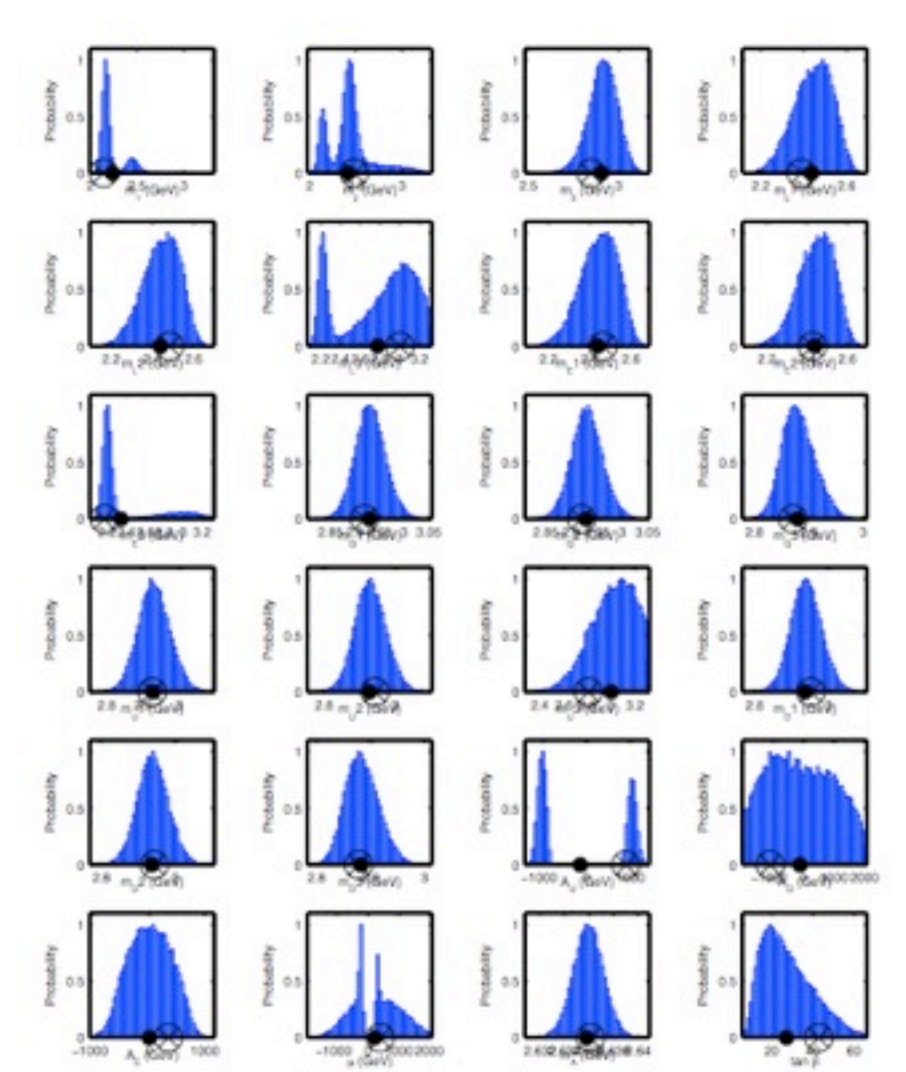
Mass	Benchmark value, μ	LHC error, σ
$m(\tilde{\chi}_1^0)$	139.3	14.0
$m(\tilde{\chi}_2^0)$	269.4	41.0
$m(\tilde{e}_R)$	257.3	50.0
$m(\tilde{\mu}_R)$	257.2	50.0
$m(h)$	118.50	0.25
$m(A)$	432.4	1.5
$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0)$	16.4	2.0
$m(\tilde{u}_R)$	859.4	78.0
$m(\tilde{d}_R)$	882.5	78.0
$m(\tilde{s}_R)$	882.5	78.0
$m(\tilde{c}_R)$	859.4	78.0
$m(\tilde{u}_L)$	876.6	121.0
$m(\tilde{d}_L)$	884.6	121.0
$m(\tilde{s}_L)$	884.6	121.0
$m(\tilde{c}_L)$	876.6	121.0
$m(\tilde{b}_1)$	745.1	35.0
$m(\tilde{b}_2)$	800.7	74.0
$m(\tilde{t}_1)$	624.9	315.0
$m(\tilde{g})$	894.6	171.0
$m(\tilde{e}_L)$	328.9	50.0
$m(\tilde{\mu}_L)$	228.8	50.0

TABLE I: Sparticle spectrum (in GeV) for our benchmark SUSY point and relative estimated measurements errors at the LHC (standard deviation σ).

- Benchmark in the co-annihilation region (similar to LCC3 in Baltz et al.).
- Errors correspond to 300 fb-1.
- Error on mass difference with the stau ~10% for this model can be achieved with 10 fb-1

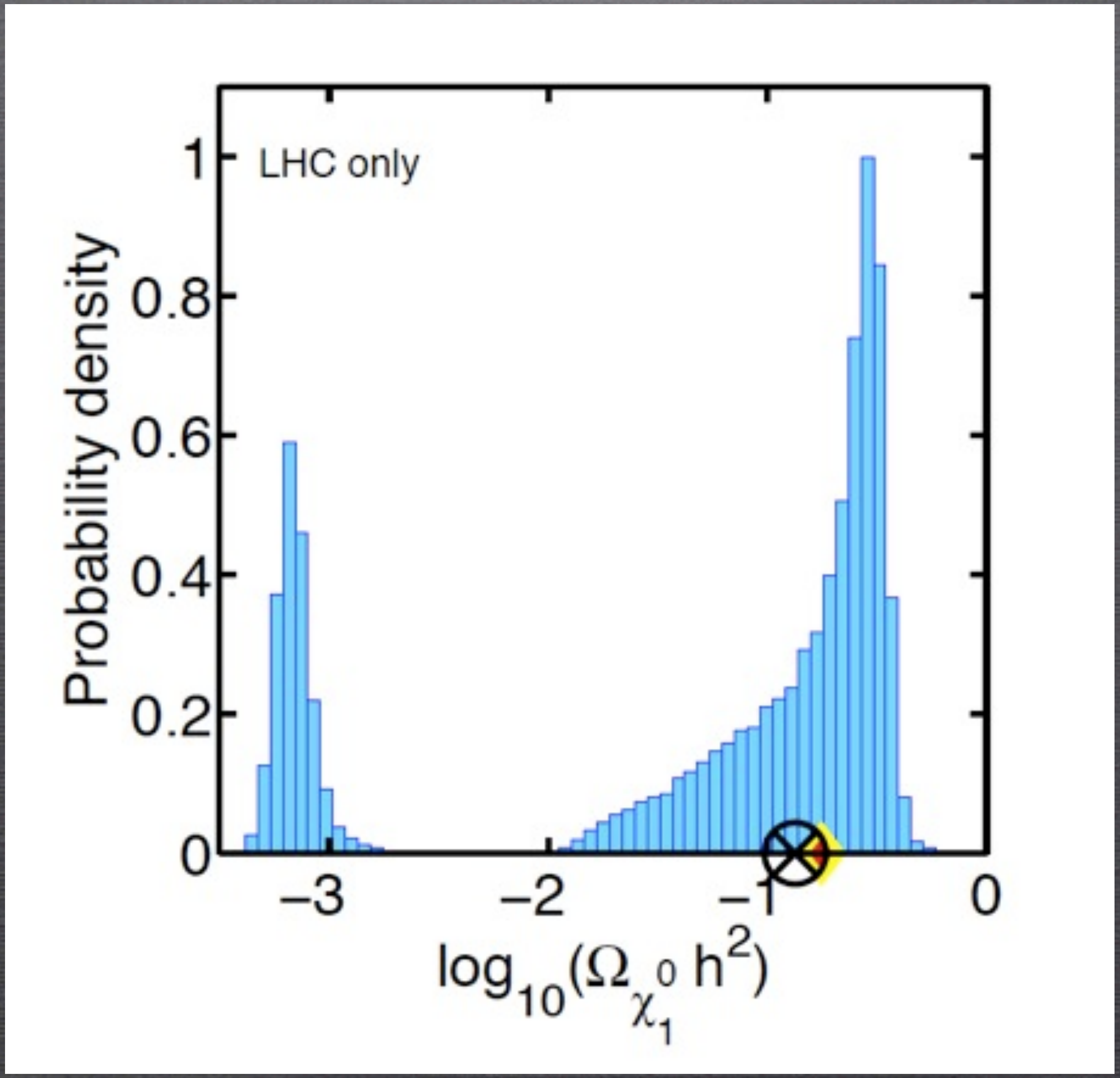
$$p(\mathbf{x}|\mathbf{d}) = \frac{p(\mathbf{d}|\mathbf{x})p(\mathbf{x})}{p(\mathbf{d})},$$

MCMC as implemented in the SuperBayes code



Example of Inverse problem at LHC

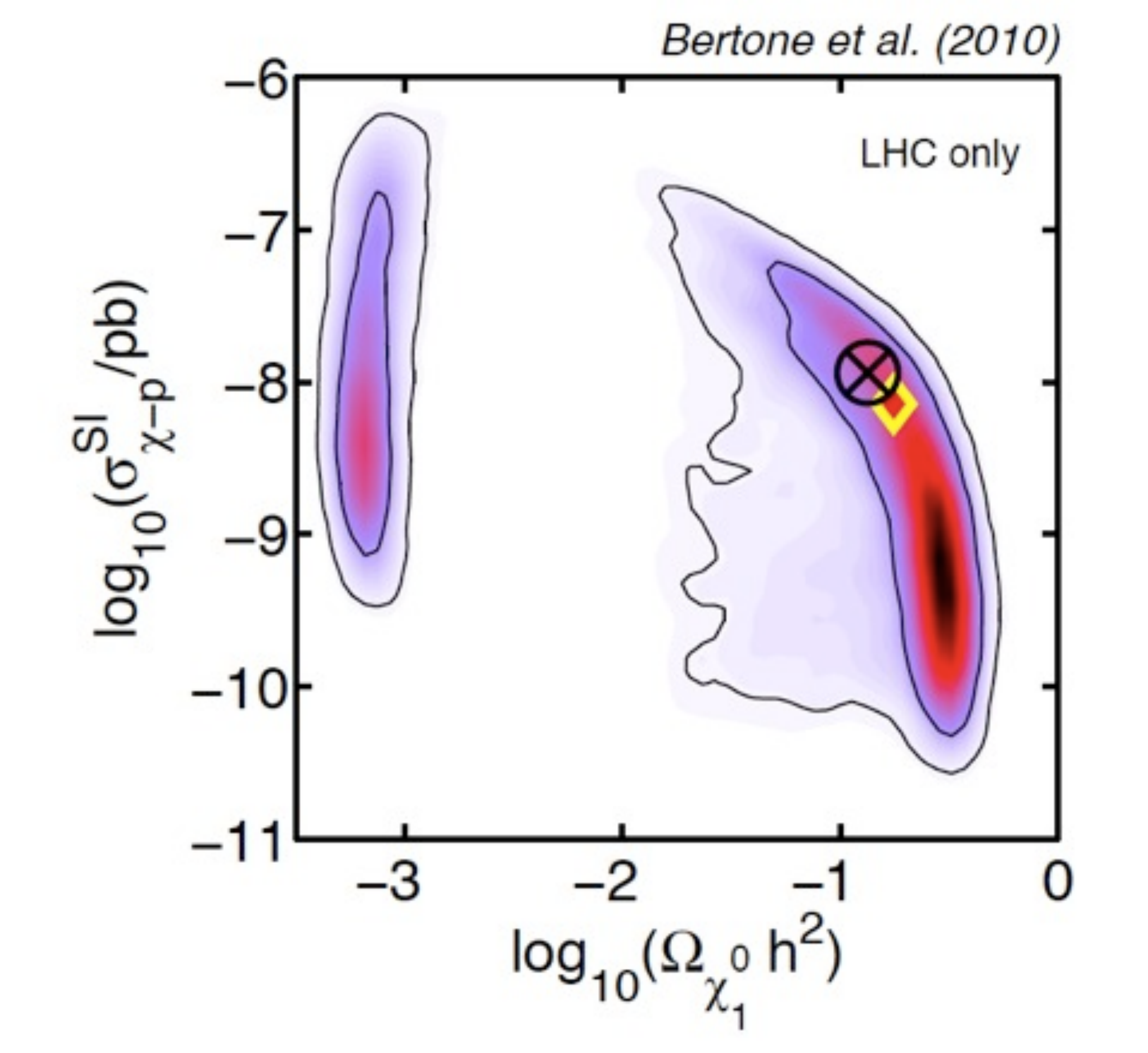
what we will most probably get
(example in the stau coannihilation region, 24 parms MSSM)



GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta, 2010

Example of Inverse problem at LHC

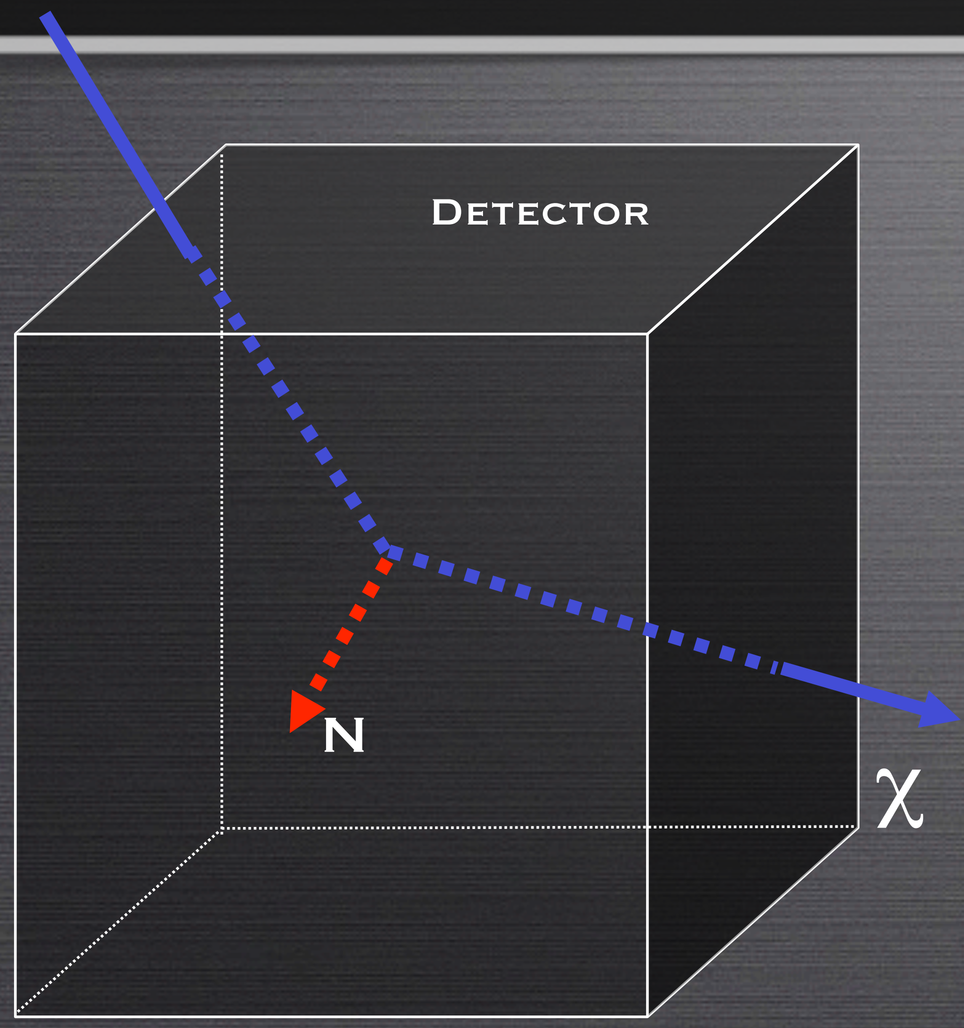
what we will most probably get
(example in the stau coannihilation region, 24 parms MSSM)

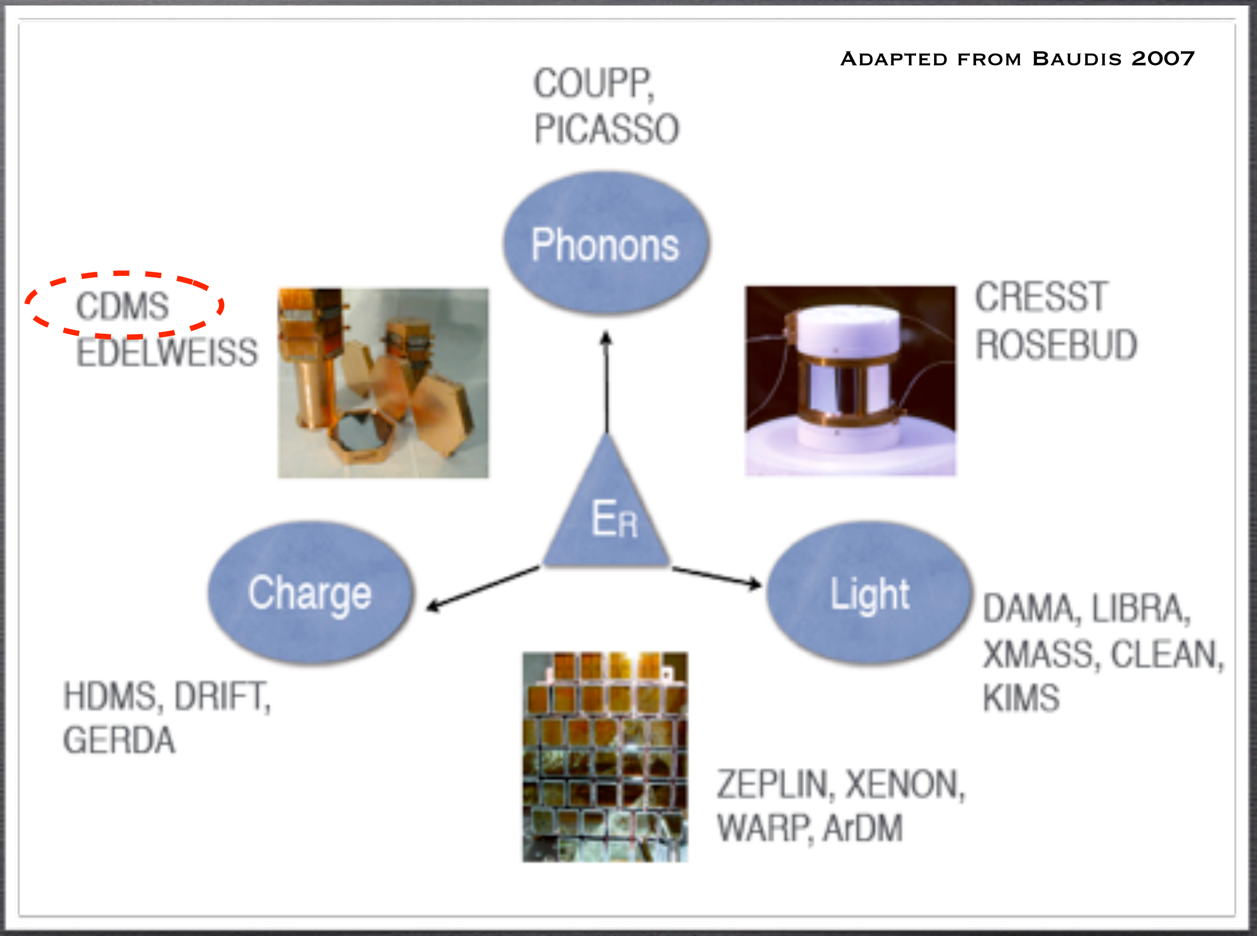


GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta, 2010

Direct Detection

Principle and Detection Techniques





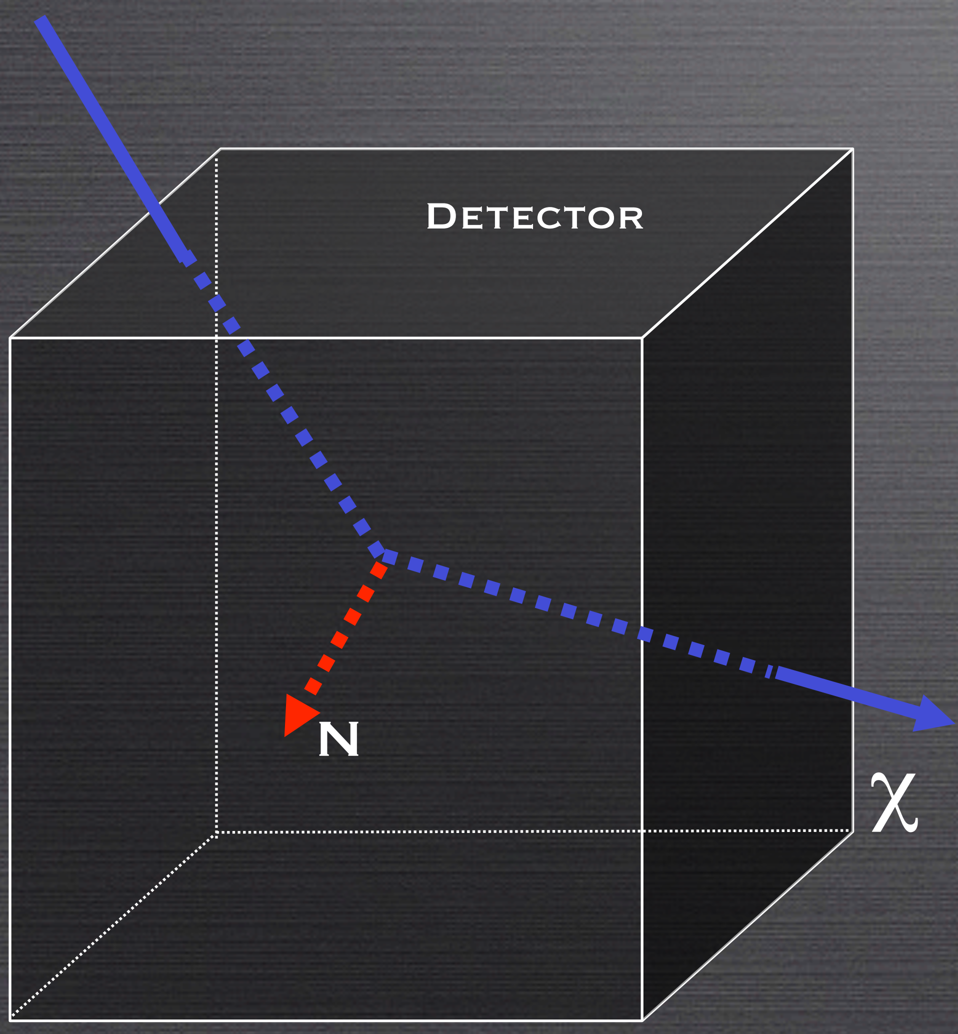
DM scatters off nuclei in the detector

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

Direct Detection

Basics

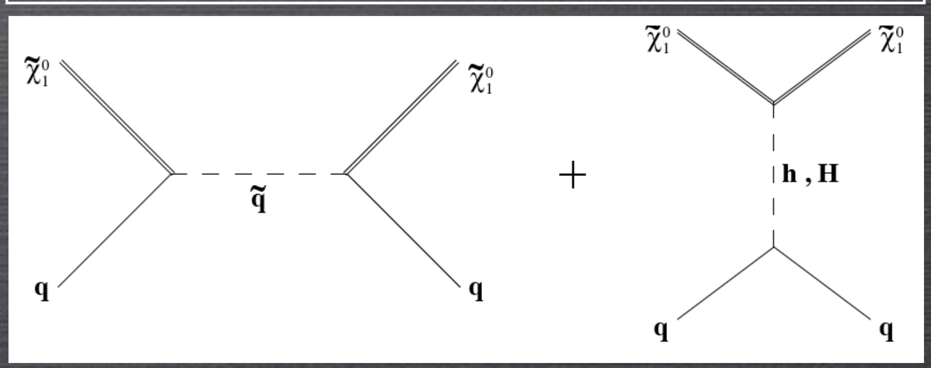
DM Scatters off nuclei in the detector



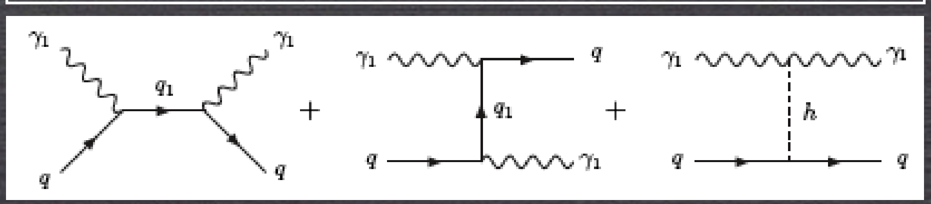
Differential Event Rate

$$\frac{dR}{dE_R}(E_R) = \frac{\rho_0}{m_\chi m_N} \int_{\mathcal{V}} d^3\vec{v}\; v f(\vec{v}+\vec{v_e})\, \frac{d\sigma_{\chi-N}}{dE_R}(v, E_R)$$

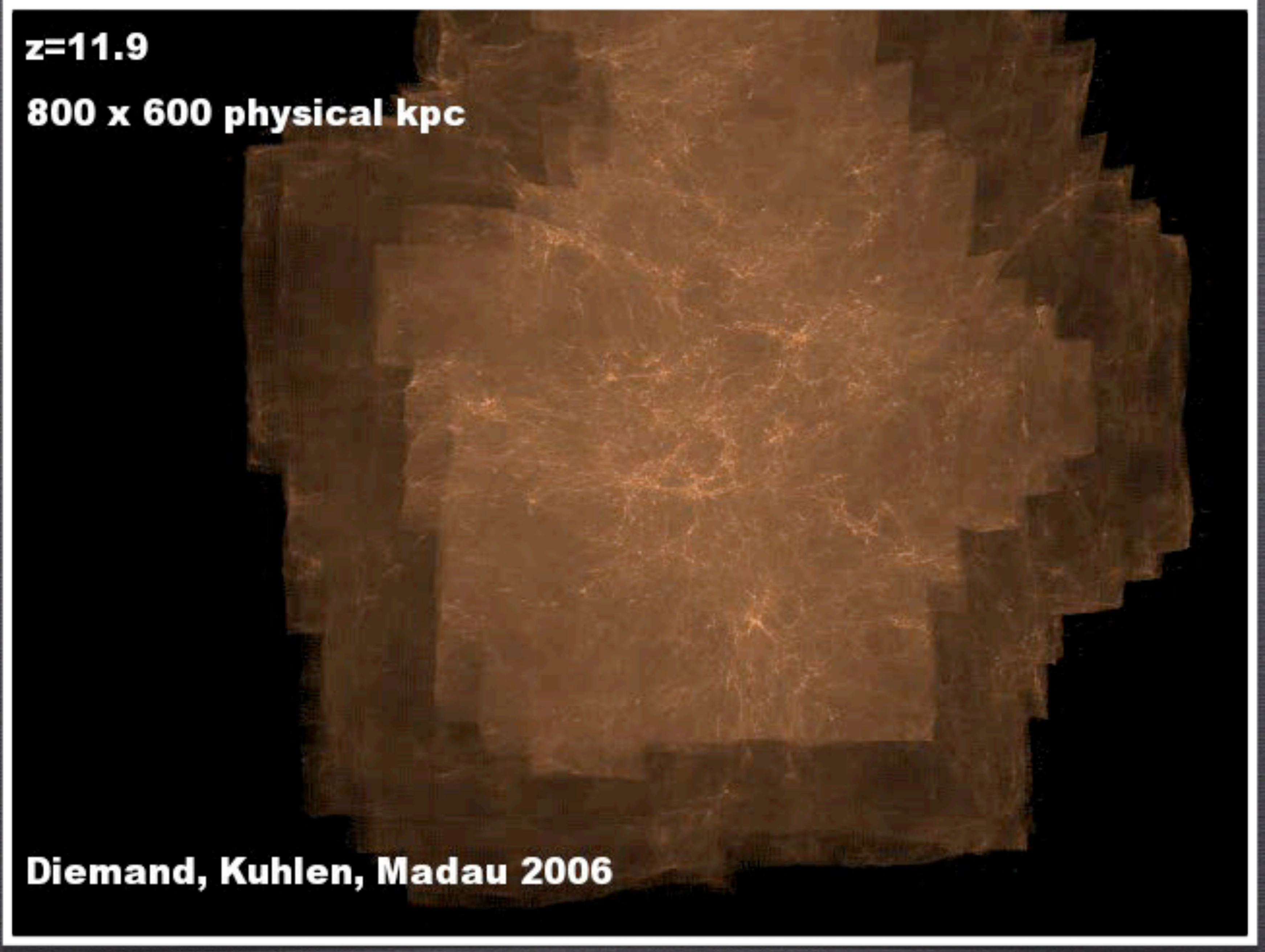
SUSY: squarks and Higgs exchange



UED: 1st level quarks and Higgs exchange



Building up the Milky Way Halo

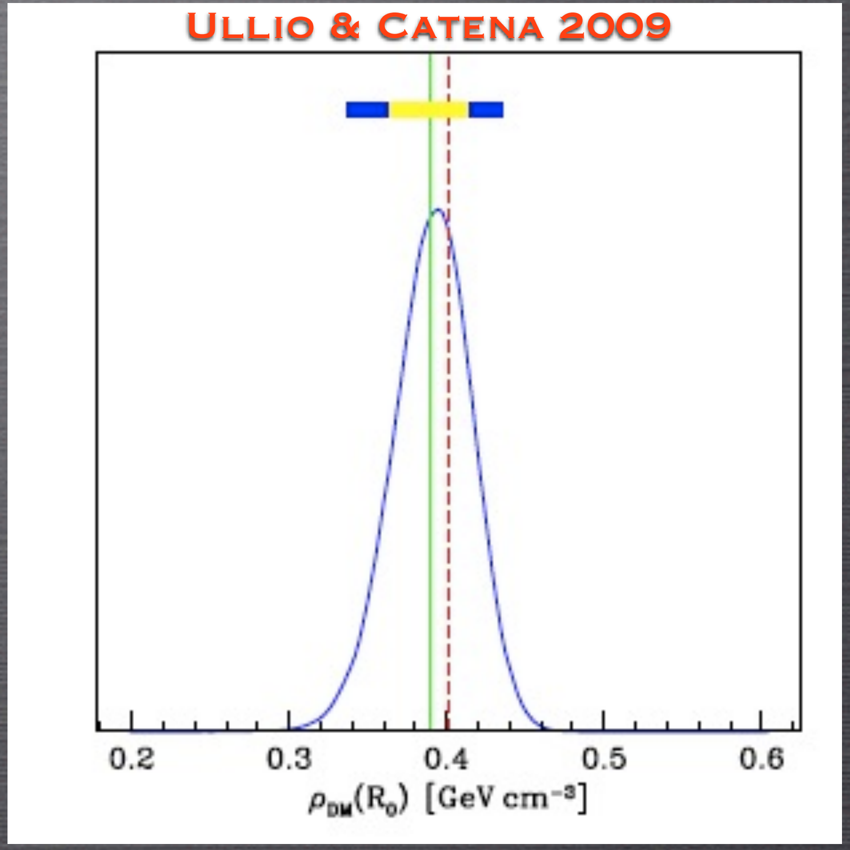


Direct Detection

Local Density

Dynamical Constraints

- Terminal Velocity of Gas Clouds
- Blue Horizontal-Branch (BHB) halo stars from the SDSS
- Estimates of Oort's constants
- Motion of stars perpendicular to the Galactic plane
- Velocity distribution of MW satellites



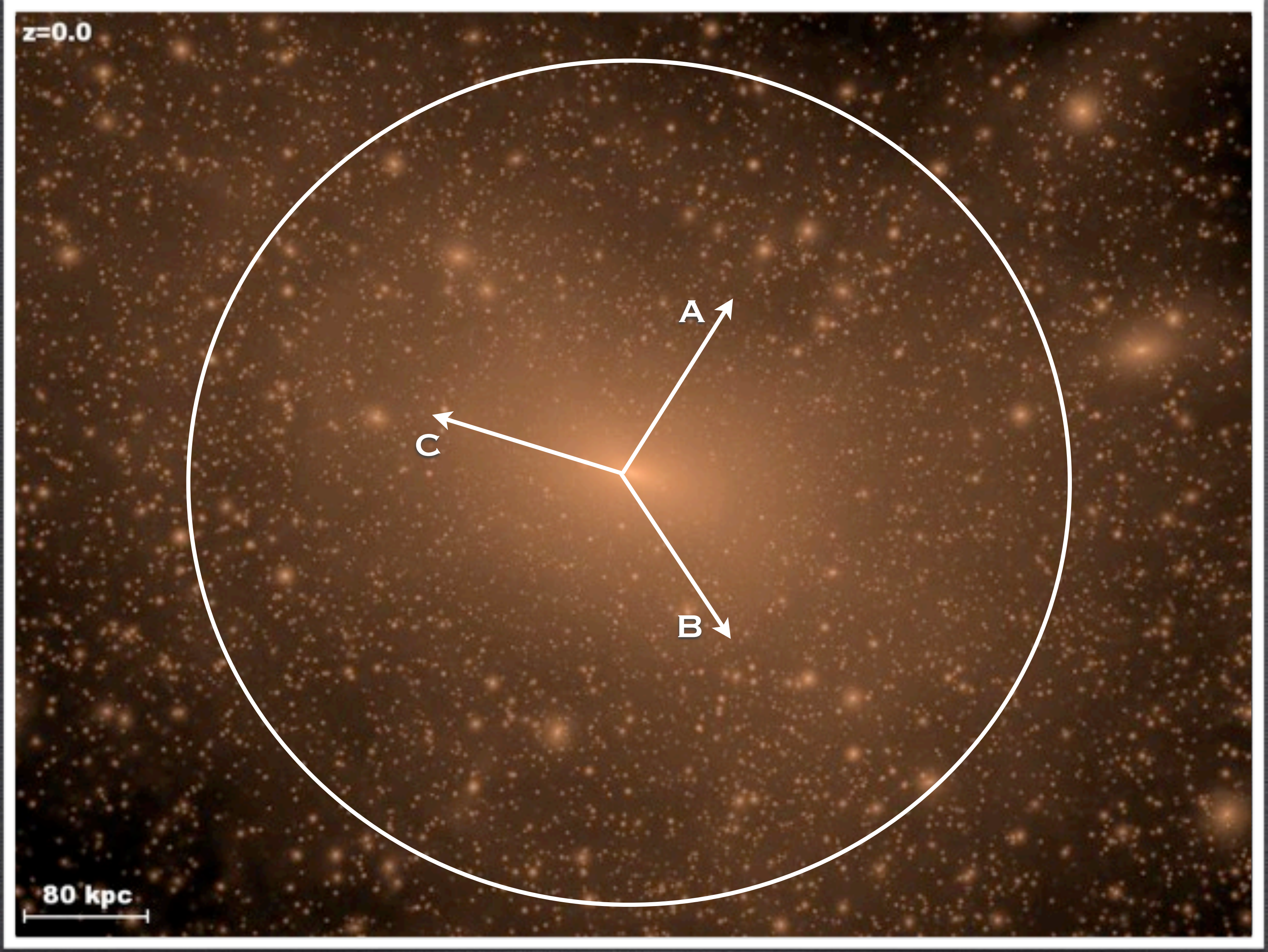
$$\rho_{DM}(R_0) = 0.389 \pm 0.025\,\mathrm{GeV\,cm^{-3}}$$

Constraints on M(<R) -> contraints on ϱ_x

See also Strigari and Trotta 2009; Weber and De Boer 2009; Salucci et al. 2010; Garbari, Lake & Read 2010

Triaxial Halos

Pato, Agertz, GB, Moore, Teyssier, Moore 2010



Moment of Inertia Tensor

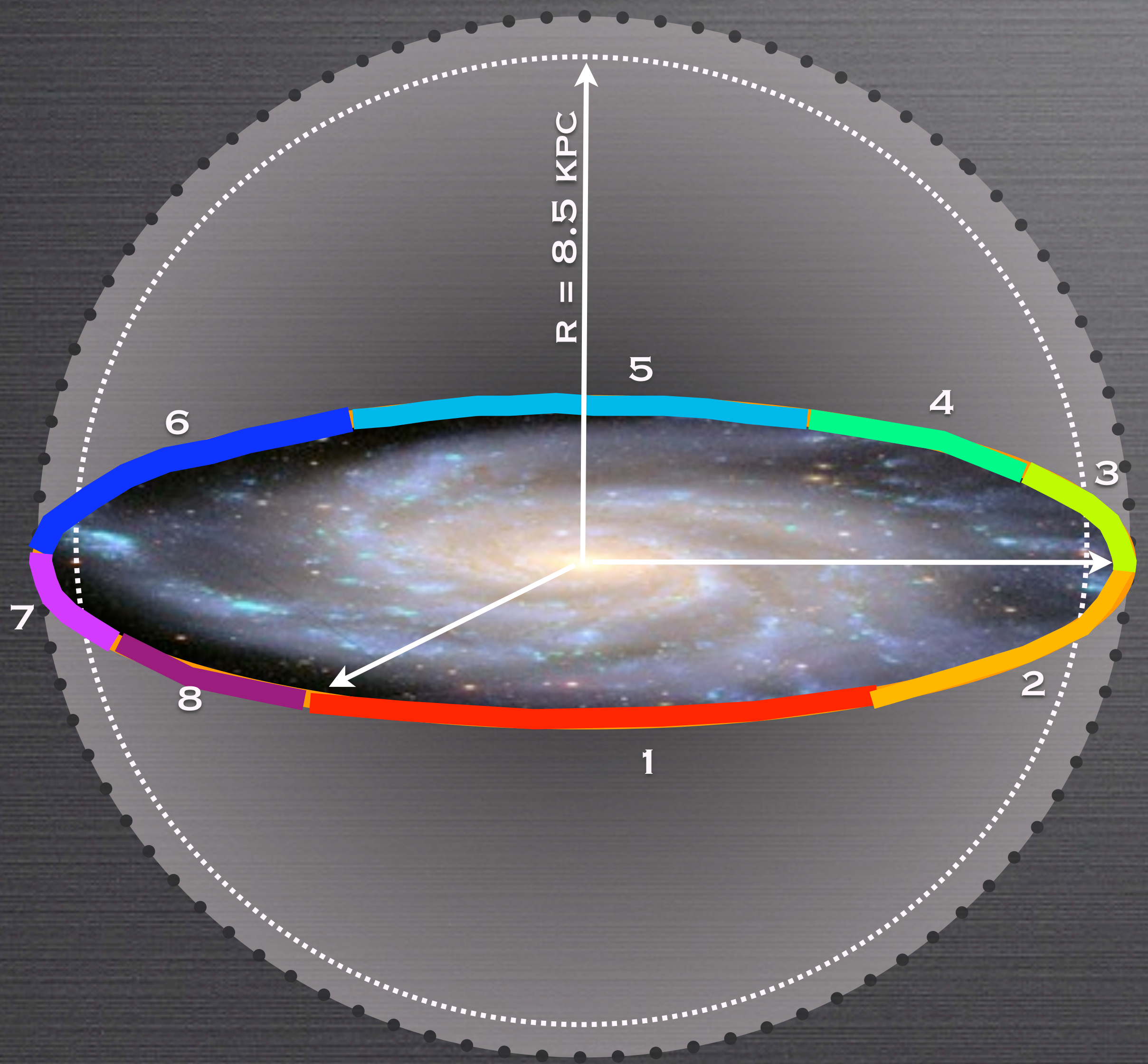
$$I_{ij} = \frac{\sum_{k=1}^{N} m_k r_{i,k} r_{j,k}}{\sum_{k=1}^{N} m_k}.$$

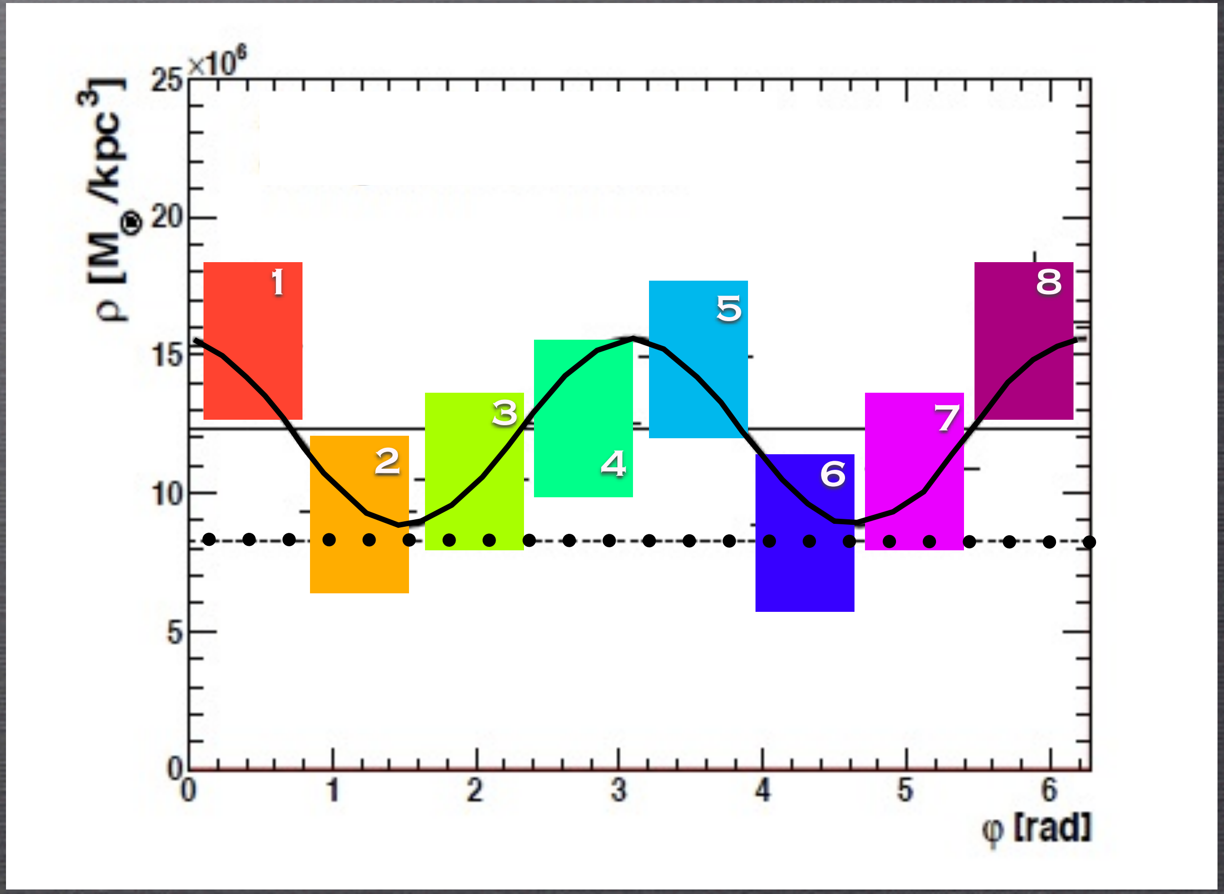
Rotation Axes

(A,B,C)

Modulation of DM density

AT FIXED GC-DISTANCE (PATO, AGERTZ, GB, MOORE, TEYSSIER, MOORE 2010)





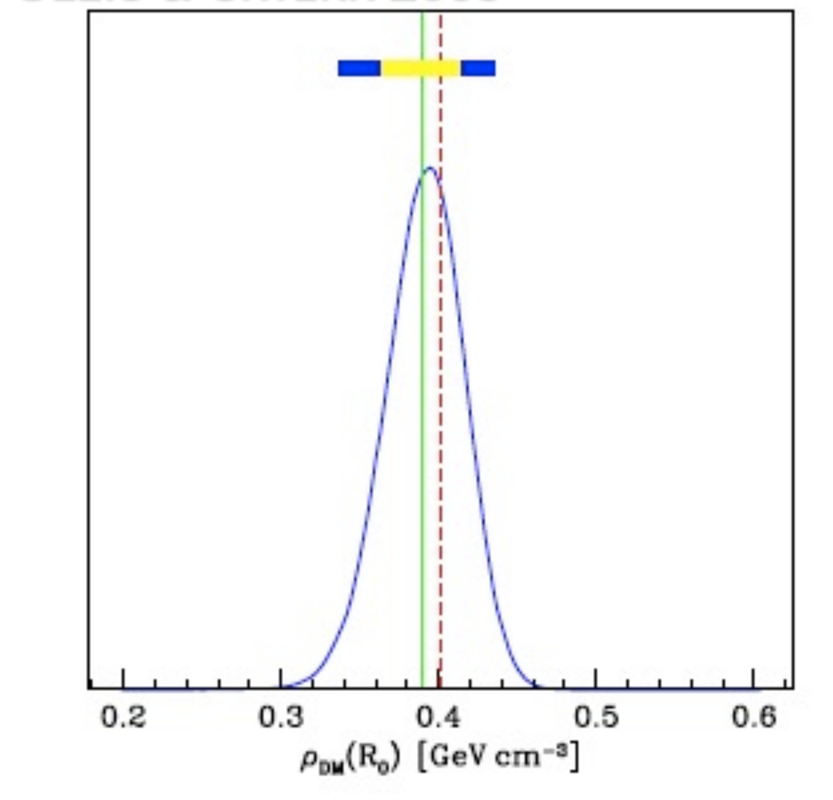
PATO, AGERTZ, GB, MOORE, TEYSSIER, MOORE 2010

Direct Detection

Uncertainties on the Local Density

"Statistical"

Ullio & Catena 2009



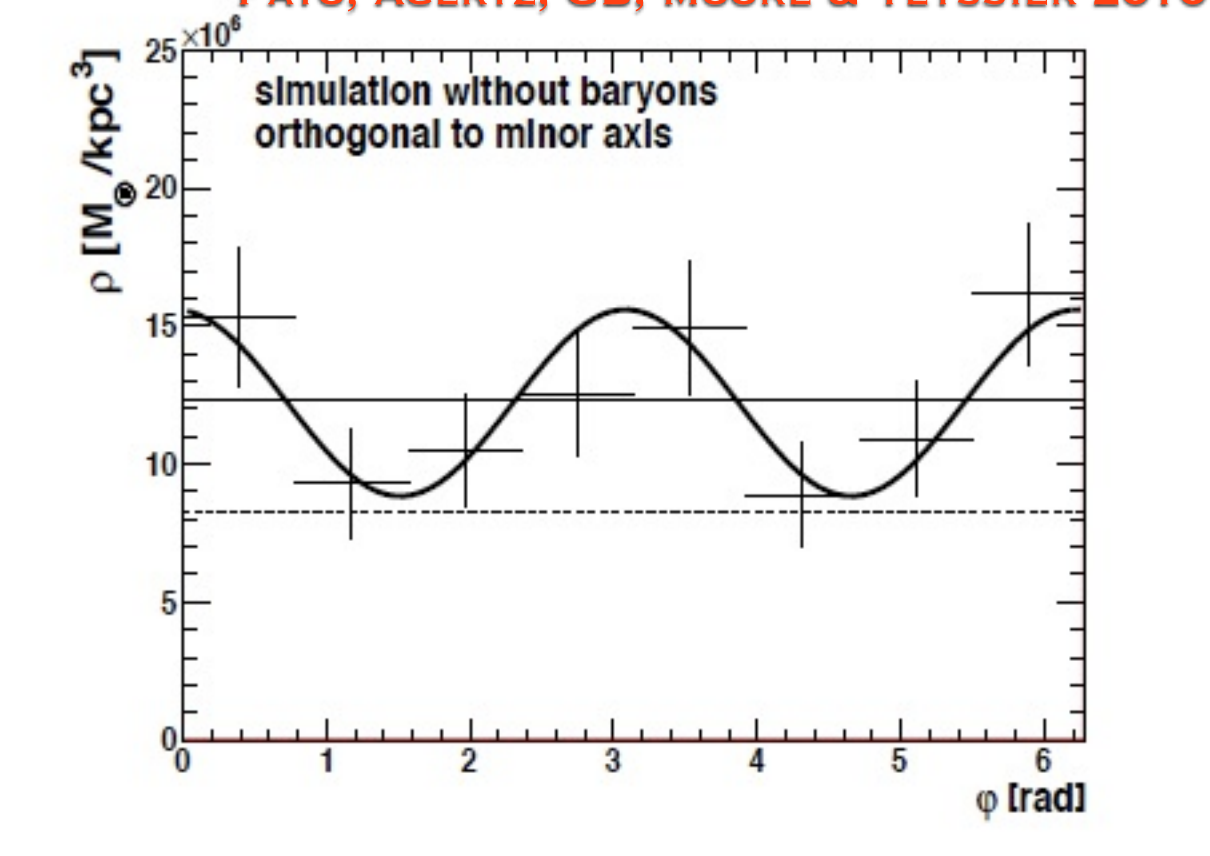
$\rho_{DM}(R_0) = 0.389 \pm 0.025\,\mathrm{GeV\ cm^{-3}}$

From dynamical Observables (see also Strigari & Trotta 2009)

+

"Systematic"

Pato, Agertz, GB, Moore & Teyssier 2010



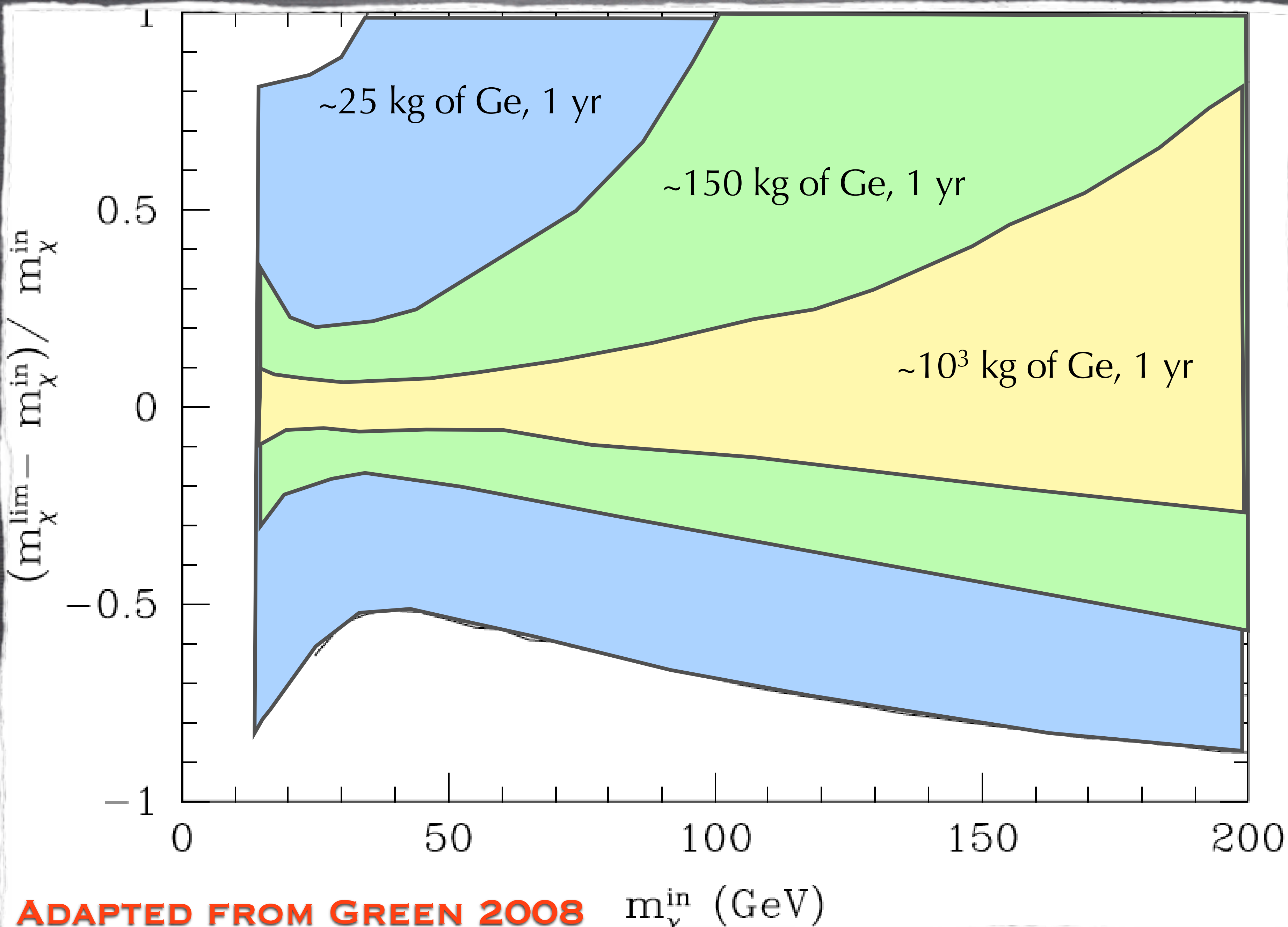
$\rho_0/\bar{\rho}_0 = 1.01 - 1.41$ w/ Baryons

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

$$\rho_0 = 0.466 \pm 0.033(\mathrm{stat}) \pm 0.077(\mathrm{syst})\ \mathrm{GeV\ cm^{-3}}$$

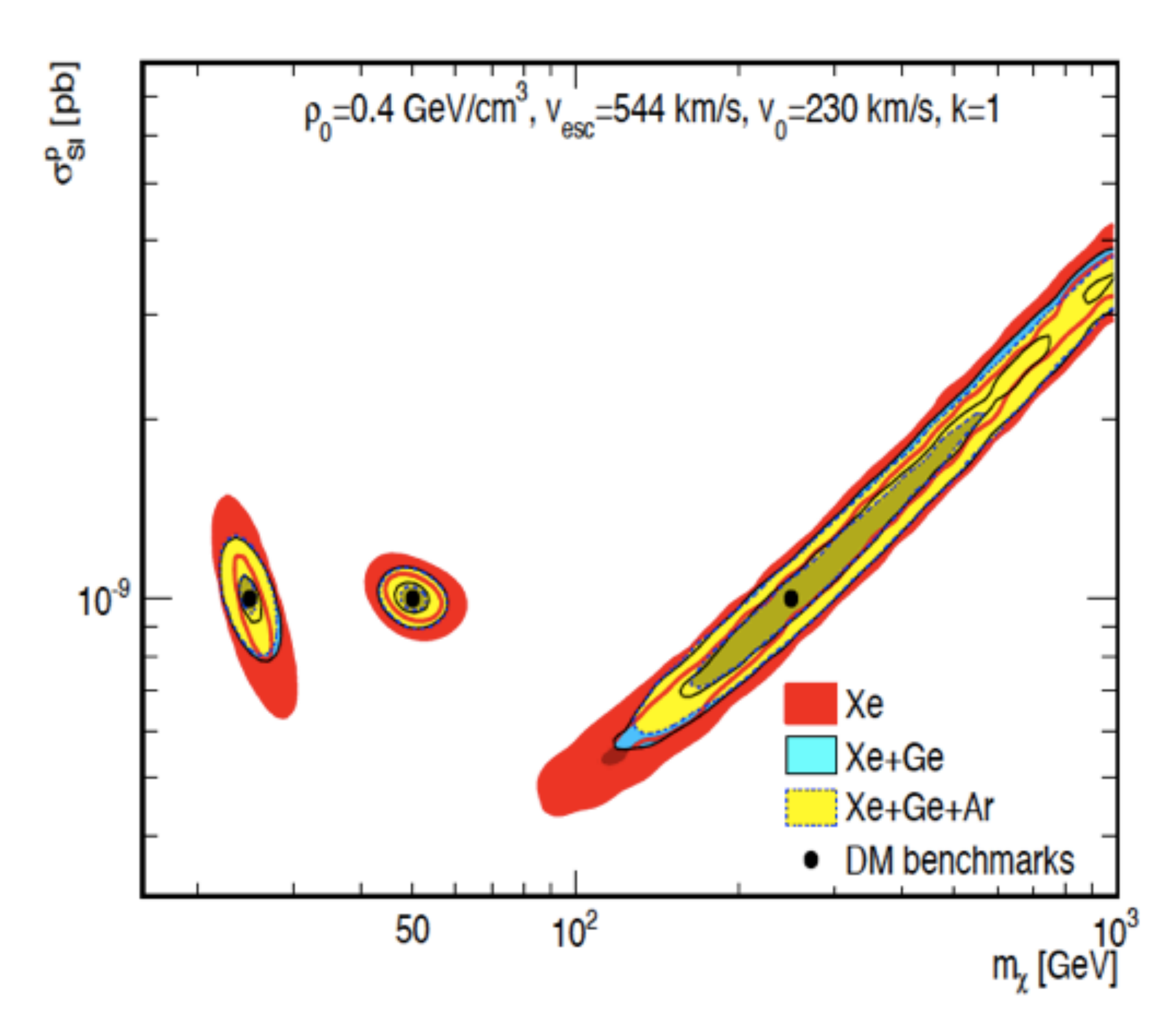
Direct Detection

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



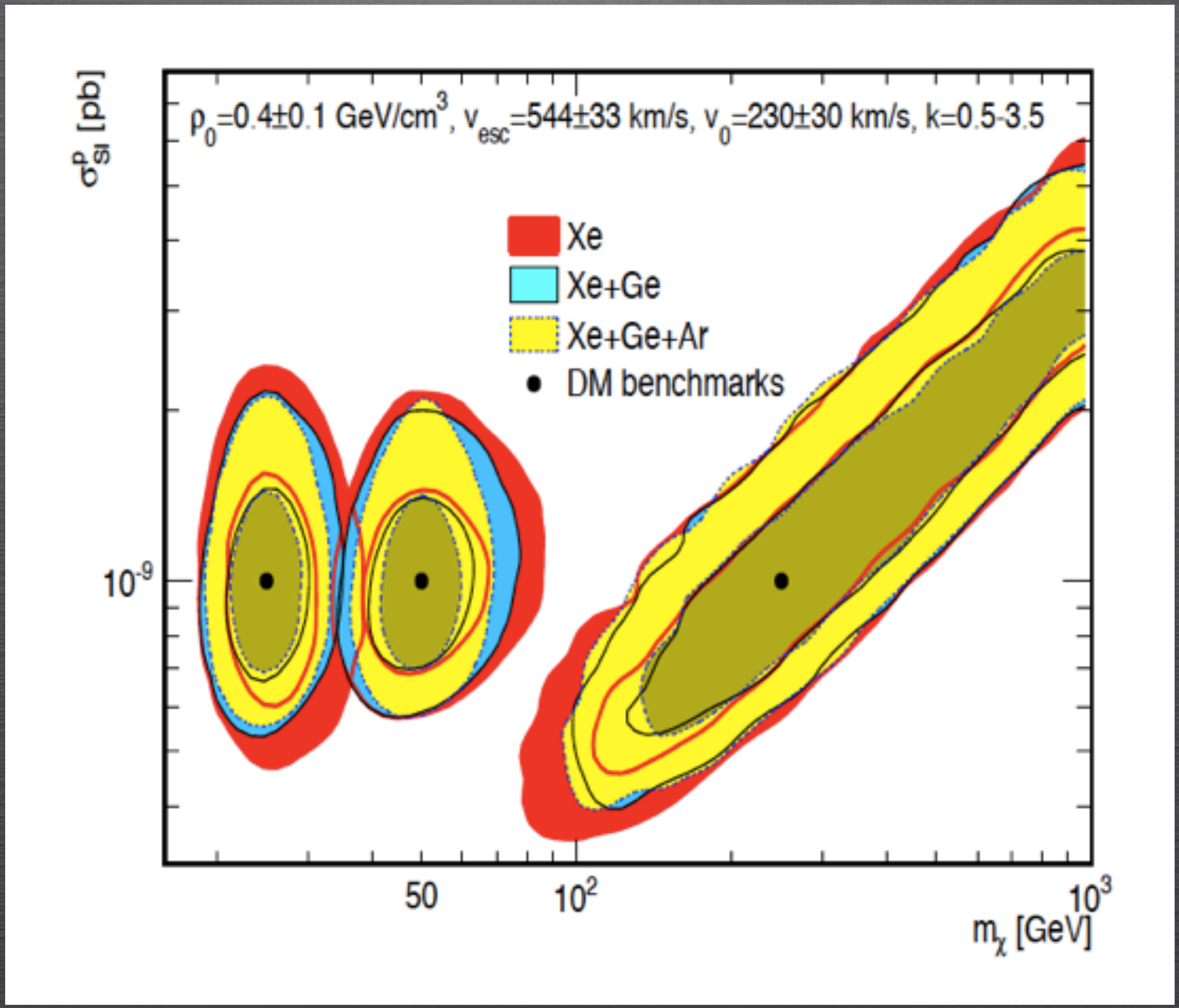
Adapted from Green 2008

Complementarity of DD targets



Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458

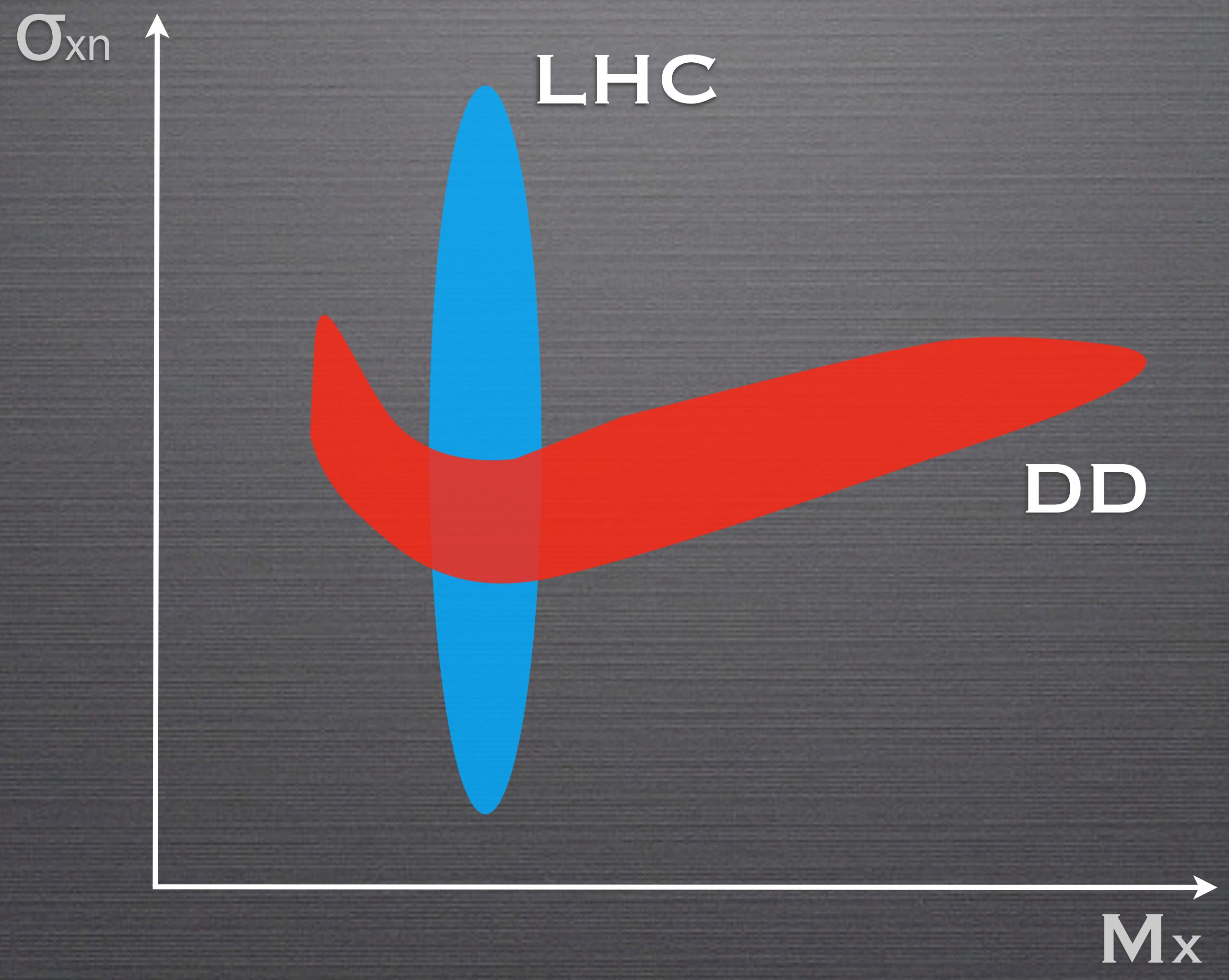
Complementarity of DD targets



Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458
(see also A. Green papers, e.g. arXiv:1009.0916 and refs. therein)

LHC+DD

Combining accelerator and direct searches



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

$f(v)$

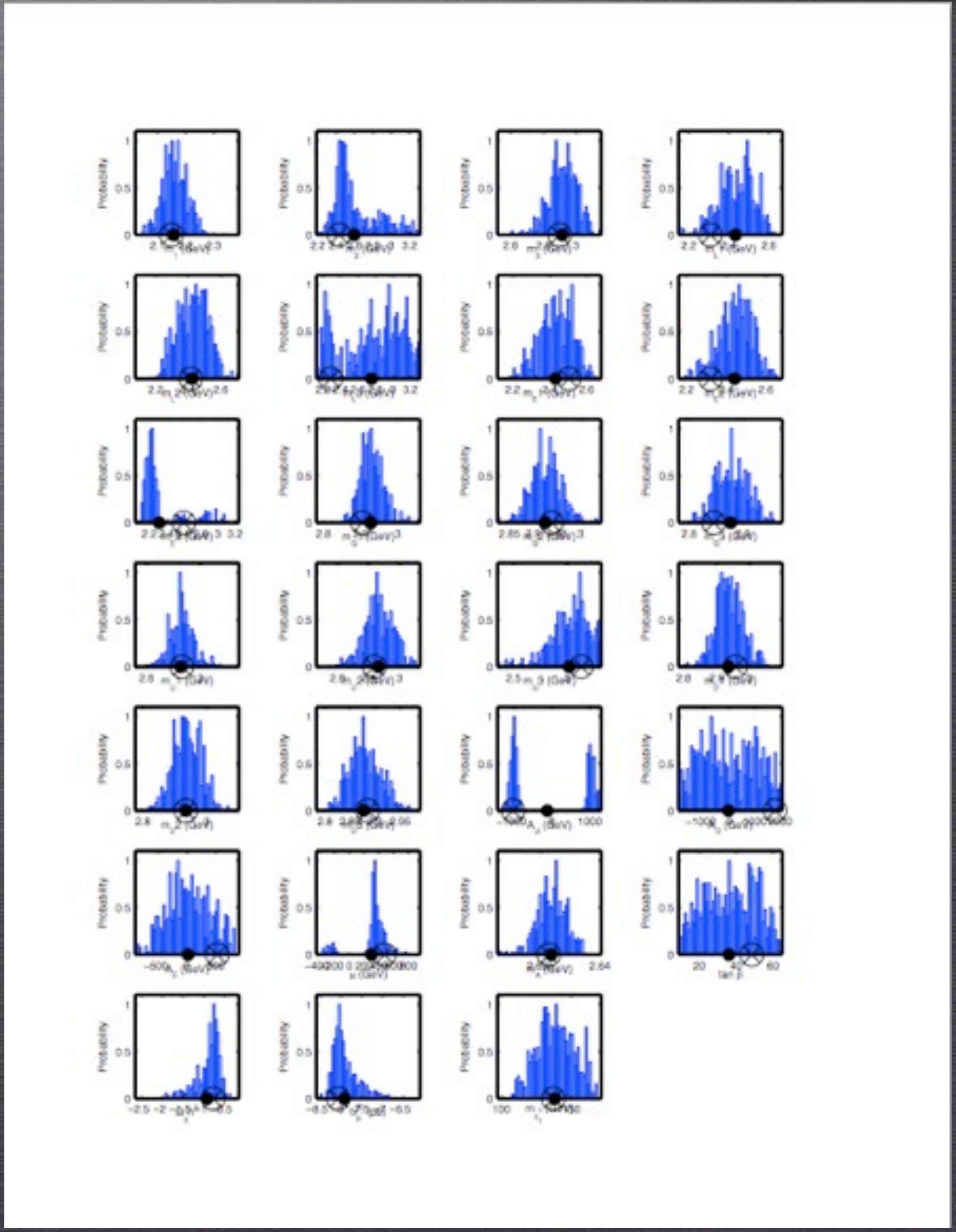
LHC+DD

To combine LHC and DD:

- Specify DM experiment

Target	A	ϵ	$E_{\rm th}$	$E_{\rm max}$	ρ_χ	λ
Ge	73	300 ton day	10 keV	100 keV	0.385 GeV cm^{-3}	638

- add new likelihood built on the number of events
- re-run the chains
- (note that Fixing the number of events = fixing the product of cross section times local density)



GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta (2010)

1st possibility:

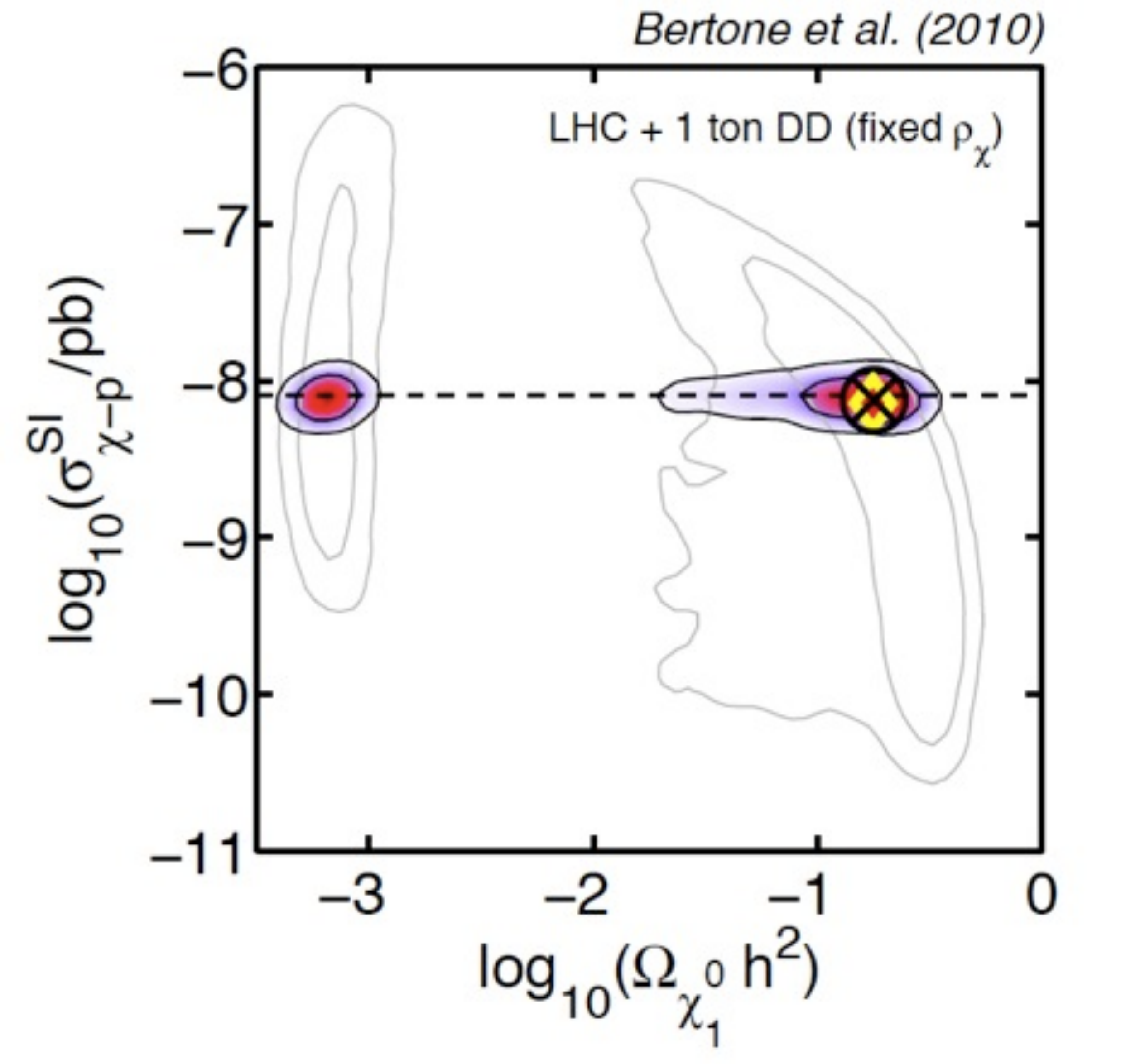
"Consistency check"

$$\rho_\chi = \rho_{\rm DM}$$

OBSERVED n. of events

$$N_{ev} \propto \sigma_{\chi n} \rho_\chi$$

since I'm fixing the local density, the scattering cross section is also fixed.

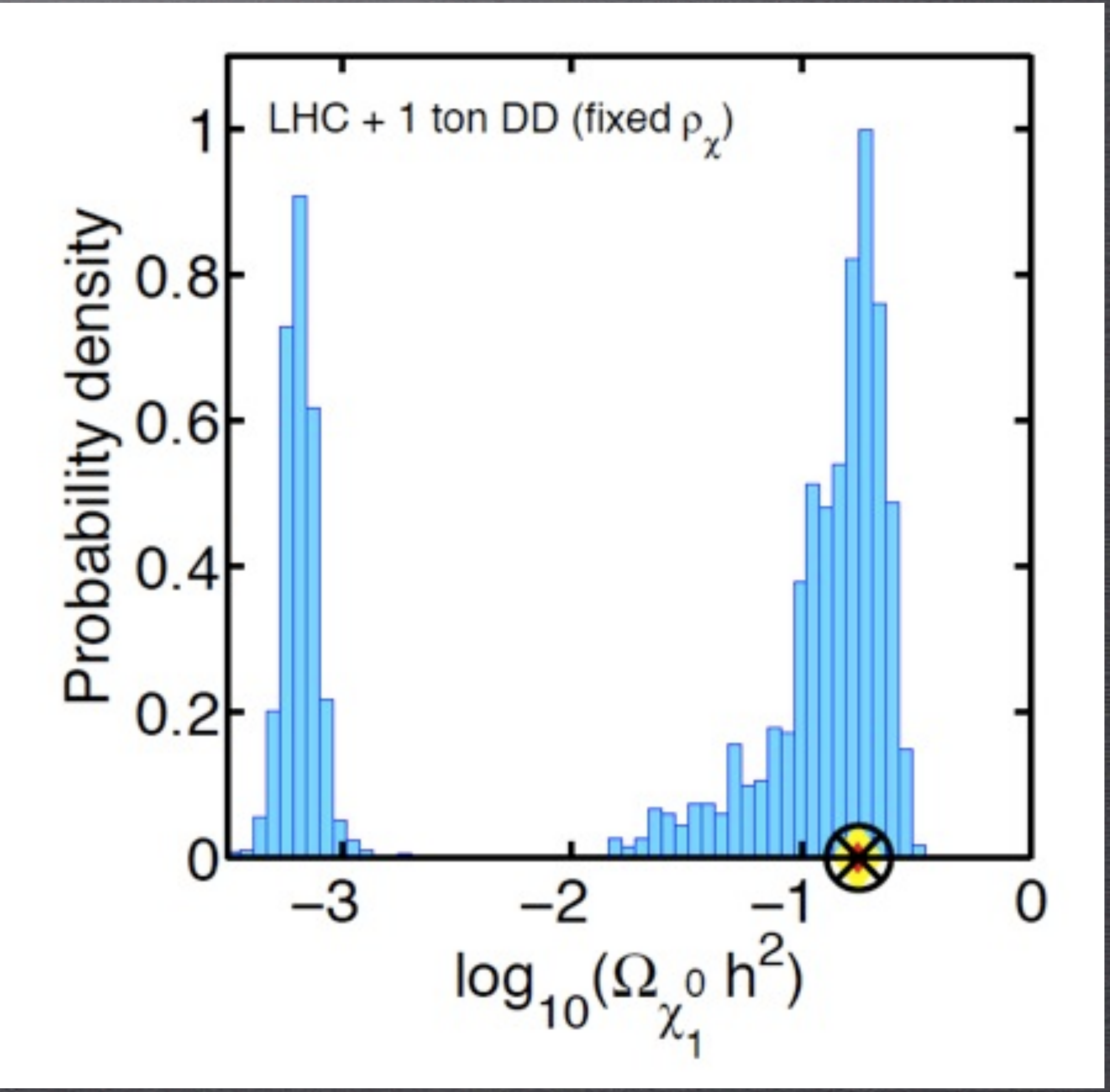


1st possibility:

“Consistency check”

$$\rho_\chi = \rho_{\mathrm{DM}}$$

...even forcing the identification of the neutralino with DM, posterior is multimodal and not very constraining.



2nd (more physical) possibility:

"Scaling" Ansatz

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

OBSERVED n. of events

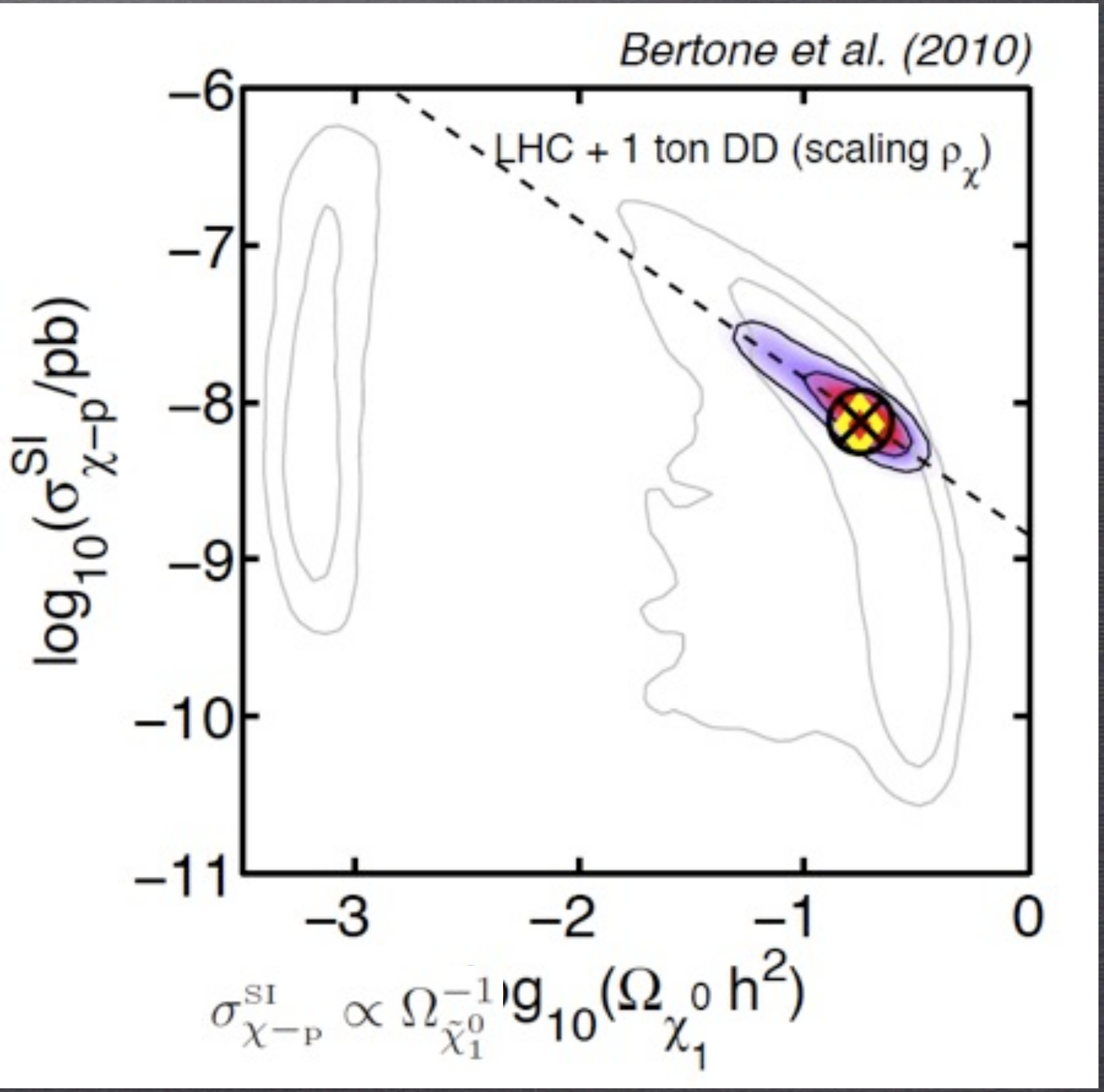
$$N_{ev} \propto \sigma_{\chi n} \rho_\chi$$

but, under the scaling ansatz

$$\rho_\chi = \Omega_\chi \left(\frac{\rho_{dm}}{\Omega_{dm}} \right)$$

therefore

$$\sigma_{\chi n} \propto \left(\frac{N_{ev} \Omega_{dm}}{\rho_{dm}} \right) \Omega_\chi^{-1}$$

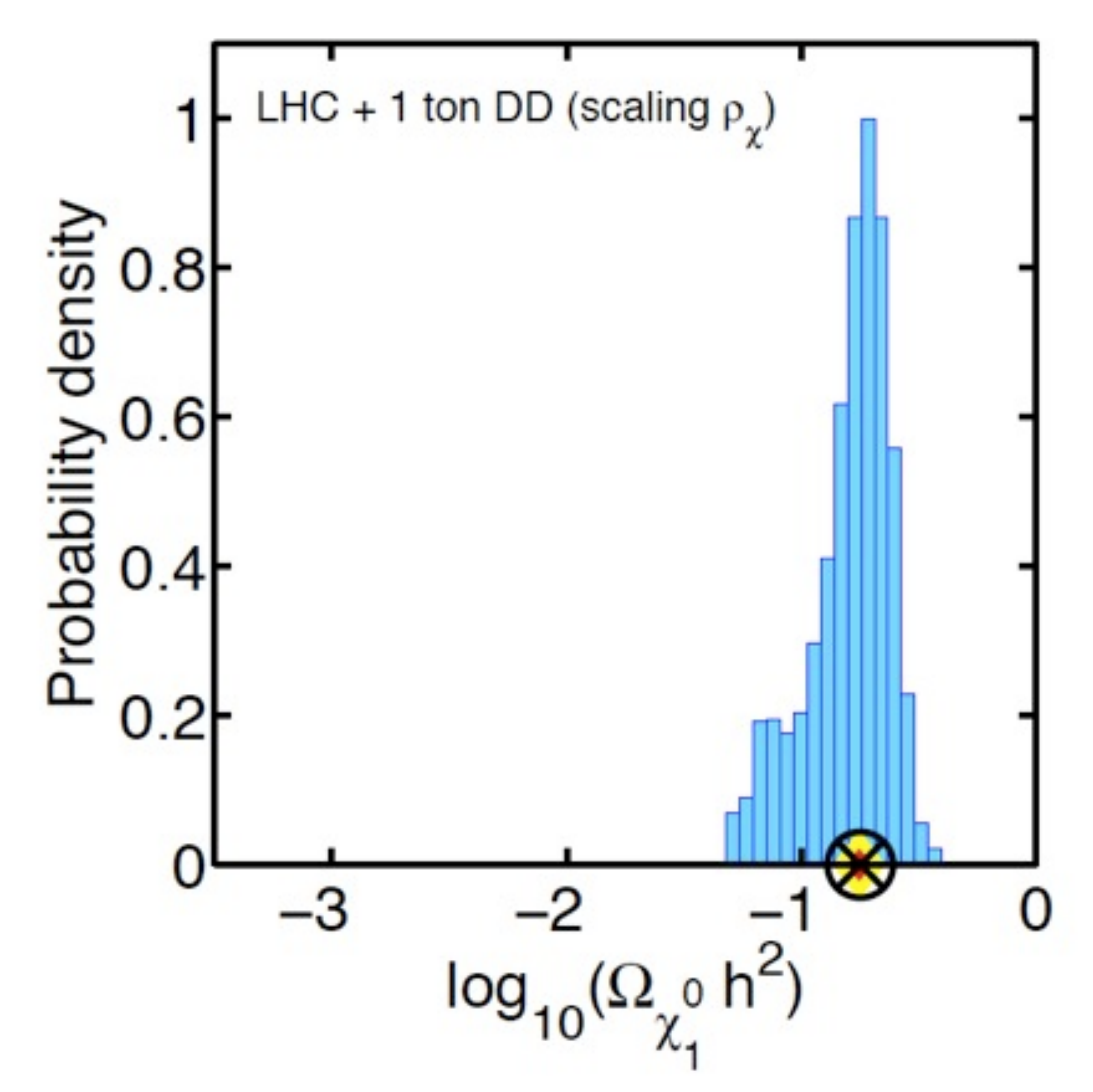


2nd (more physical) possibility:

"Scaling" Ansatz

Omega too large: wrong cosmology

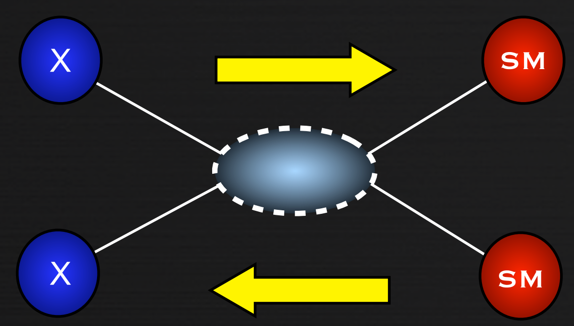
Omega too low: subdominant component OR wrong cosmology



Indirect Detection

X = DARK MATTER SM = STANDARD MODEL PARTICLE

Early Universe



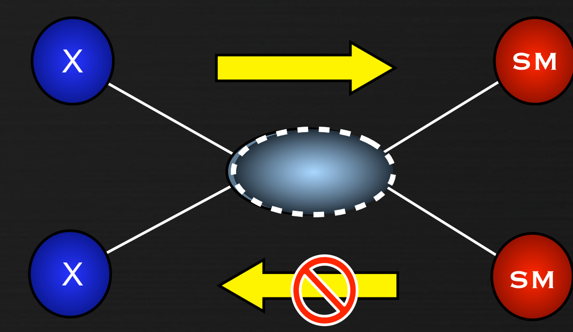
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

Relic density (NR freeze-out)

$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

Electroweak-scale cross sections can reproduce correct relic density.

Today



$$\frac{dn_\chi}{dt} = -(\sigma v)_o n_\chi^2$$

Annihilation Flux

$$\Phi_i(\Omega, E_i) = \frac{dN}{dE_i}\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\int_{los}\rho_\chi^2(\ell, \Omega)d\ell$$

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

Indirect Detection

Why "annihilations"?

X = Dark matter   SM = Standard Model particle

Early Universe   Today

Annihilation Flux

$$\Phi_i(\Omega, E_i) = \frac{dN}{dE_i} \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \int_{los} \rho_\chi^2(\ell, \Omega) d\ell$$

Relic density (NR freeze-out)   Annihilation Flux

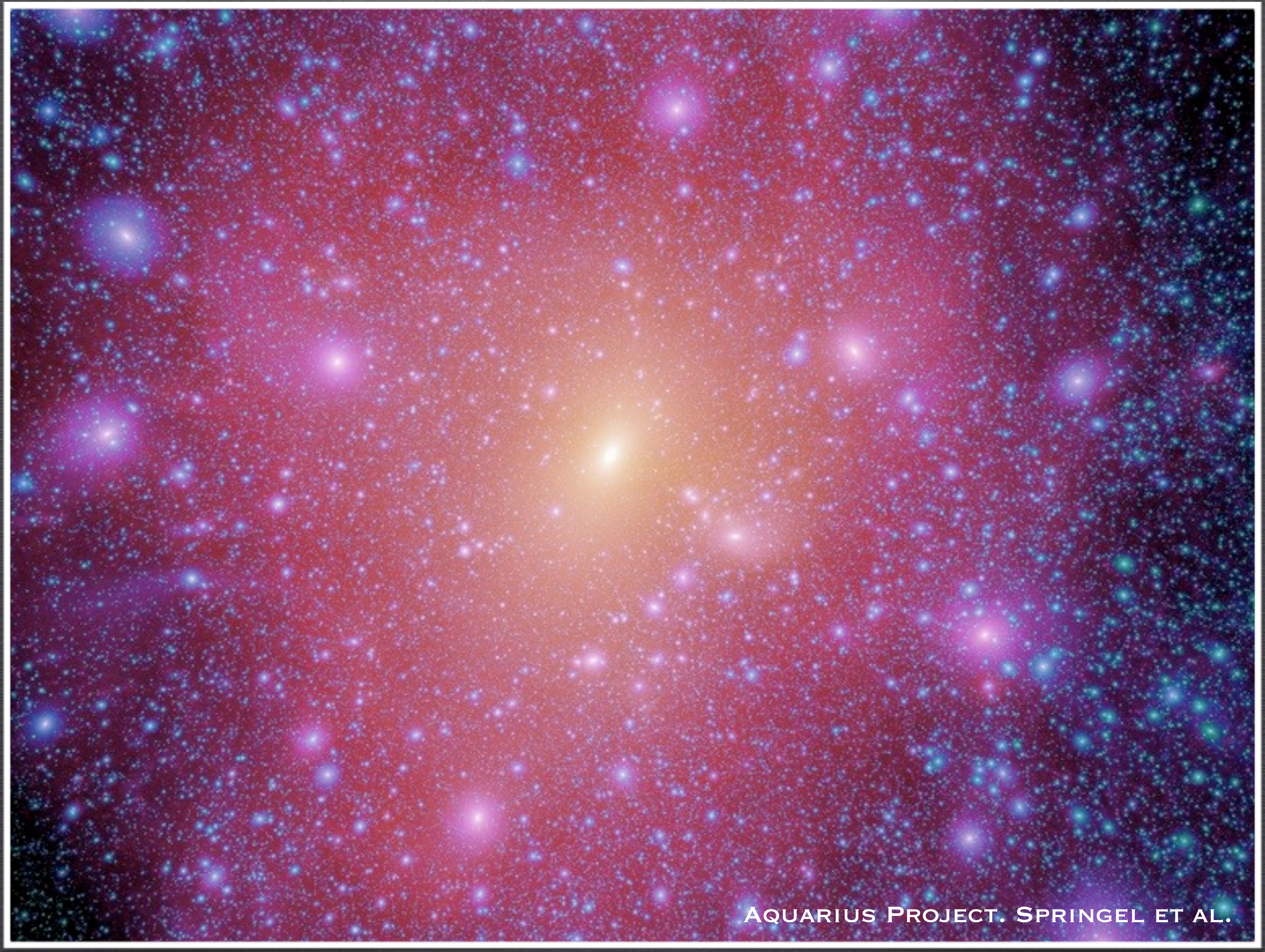
Particle Physics Parameters (underlying theory)

Astrophysics (simulations + Observations)

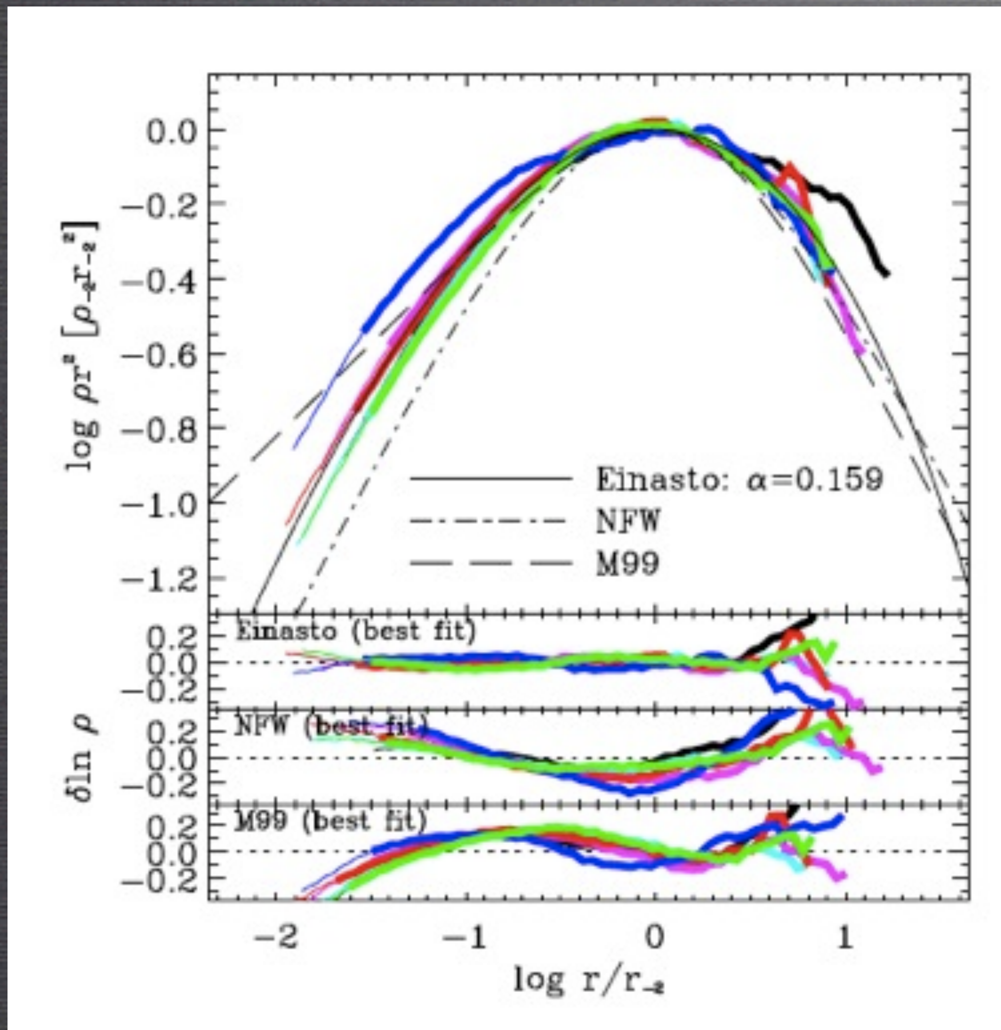
Electroweak-scale cross sections can reproduce correct relic density.

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

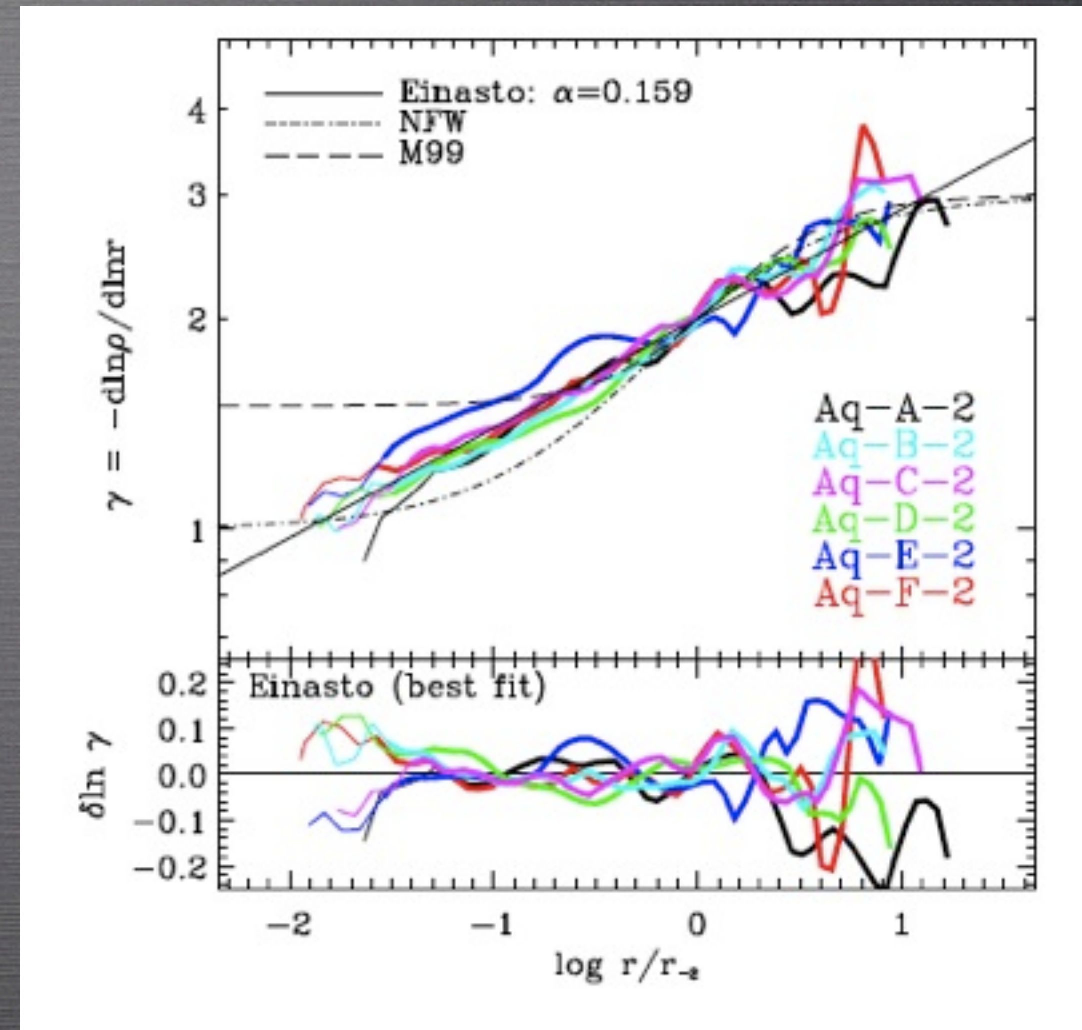
N-body Simulations



Reconstructed density profiles



Navarro et al. 2008



Navarro et al. 2008

Fitting formulae

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2},$$

$$\rho(r) = \frac{\rho_M}{(r/r_M)^{1.5}[1 + (r/r_M)^{1.5}]},$$

$$\ln(\rho(r)/\rho_{-2}) = (-2/\alpha)[(r/r_{-2})^{\alpha} - 1].$$

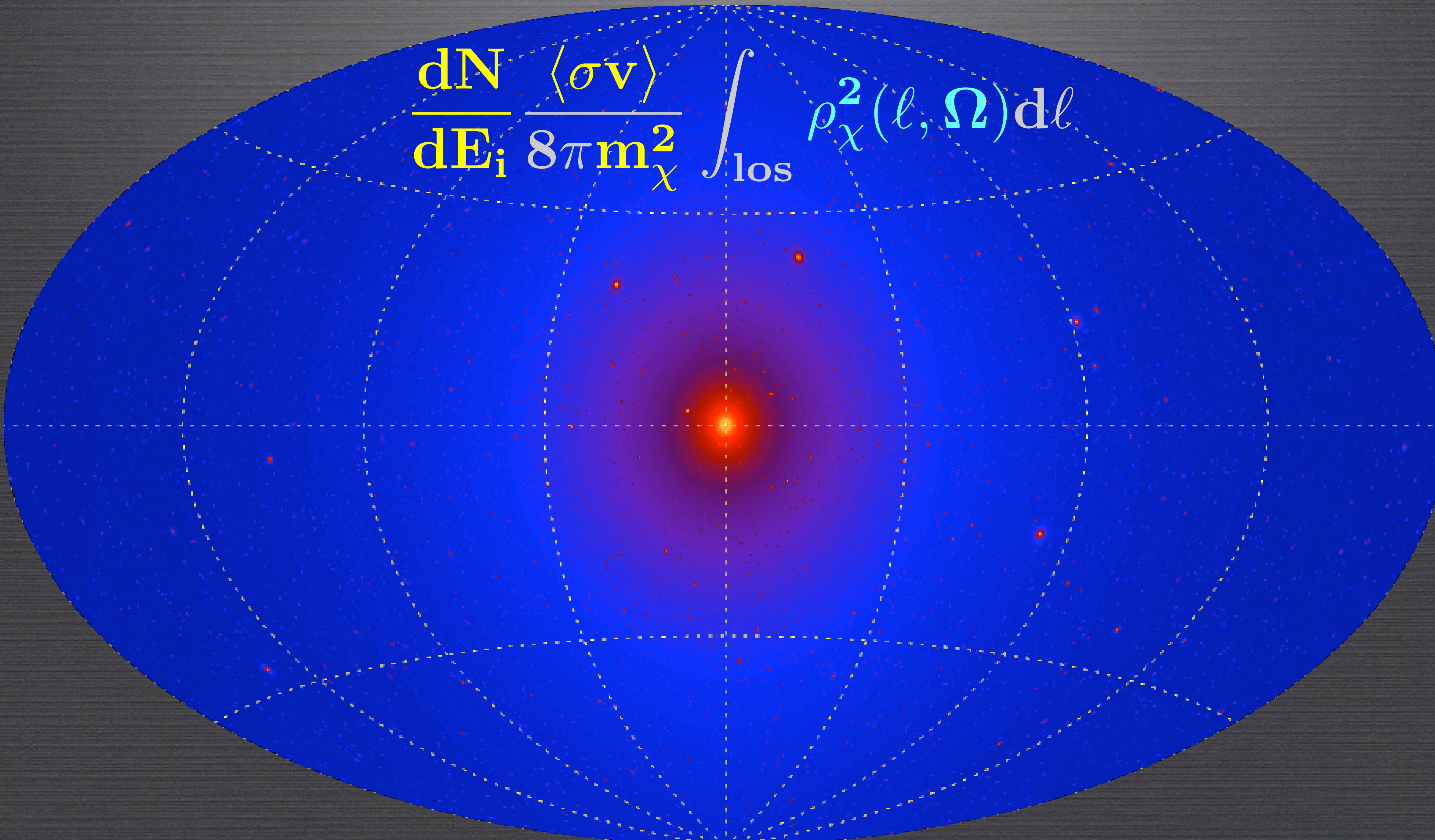
NFW

Moore

Einasto

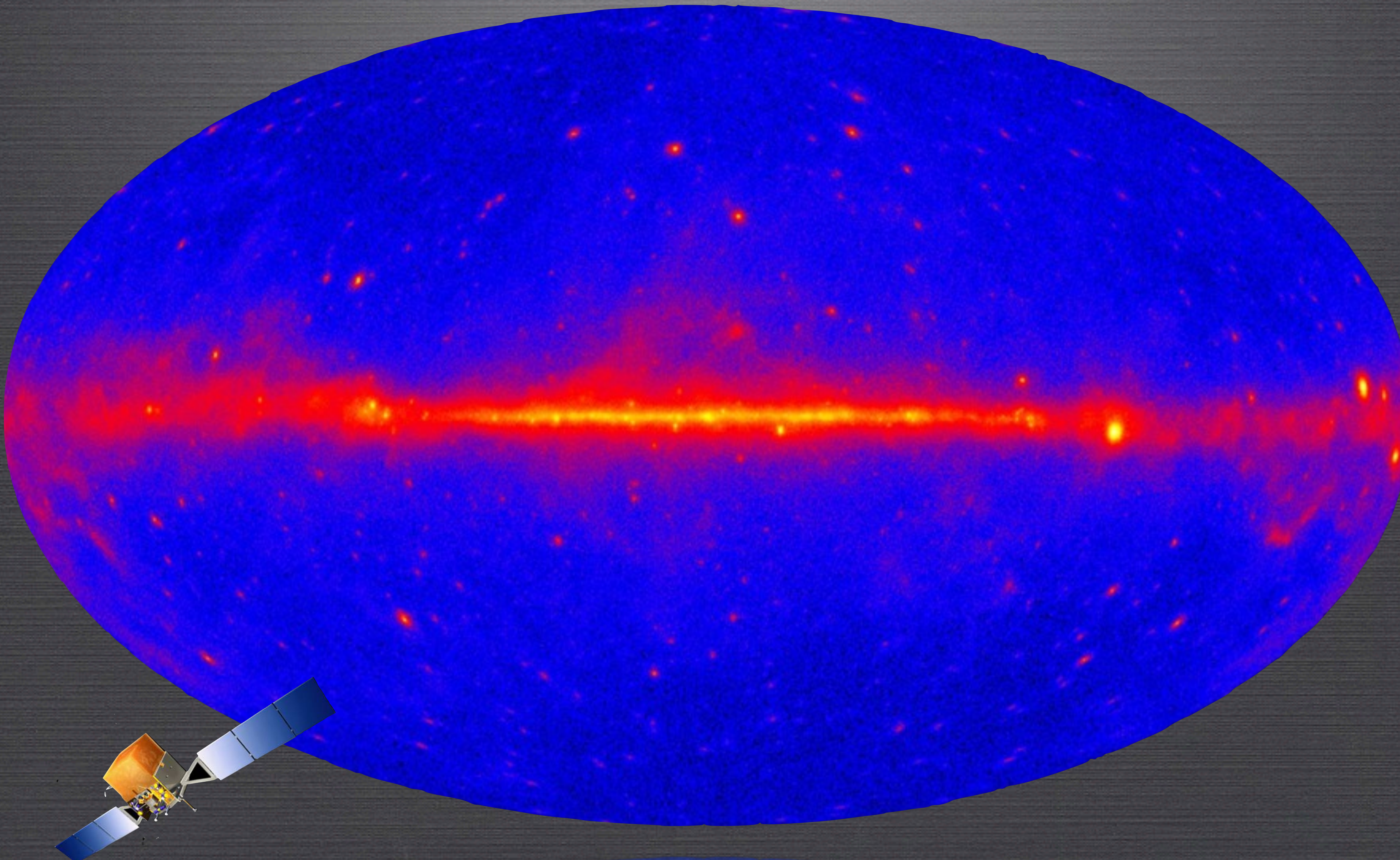
Add Wimp Model → Flux

$$\frac{dN}{dE_i}\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\int_{los}\rho_\chi^2(\ell,\Omega)d\ell$$



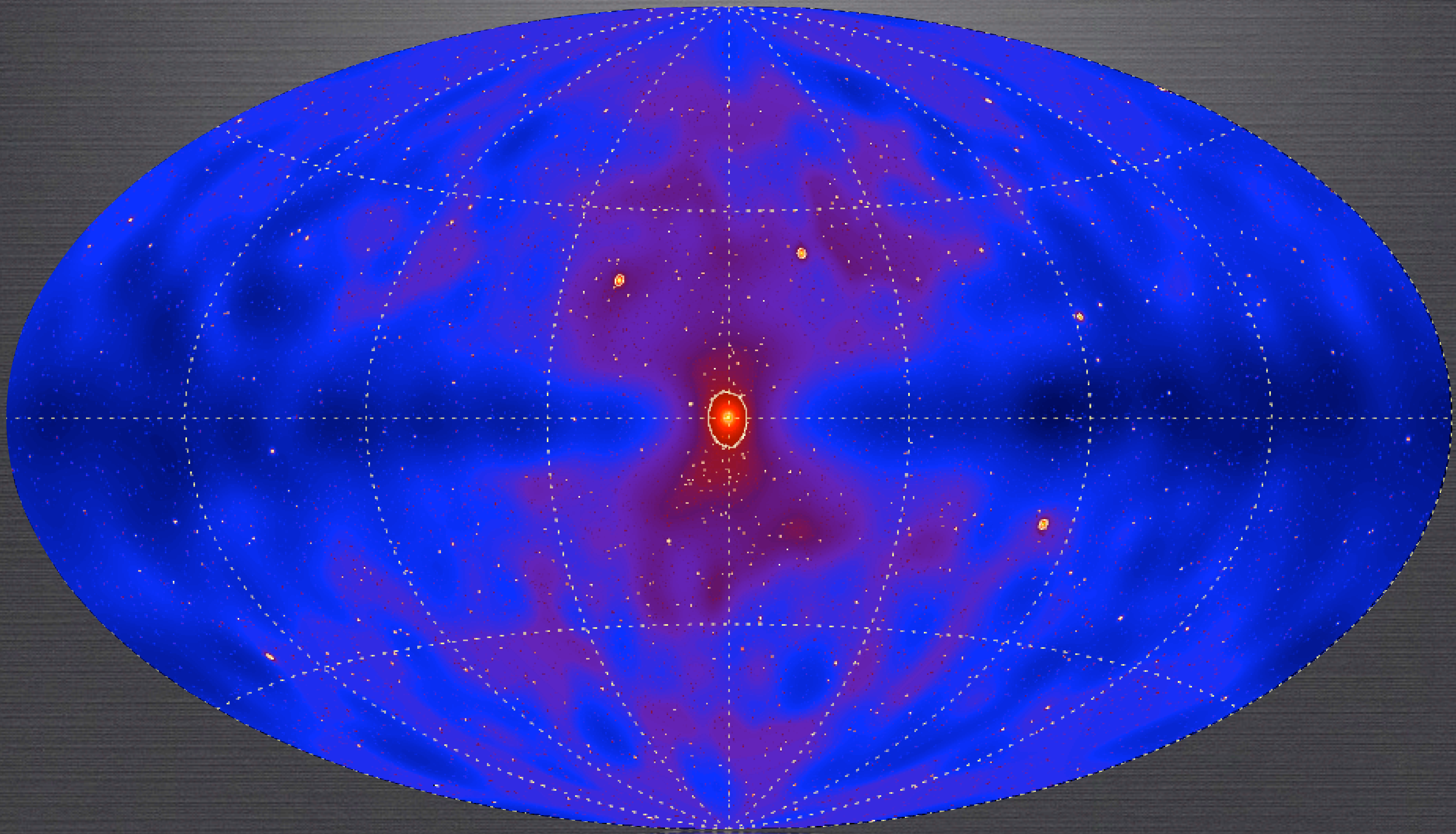
Pieri, GB, Branchini 2009

The FERMI sky



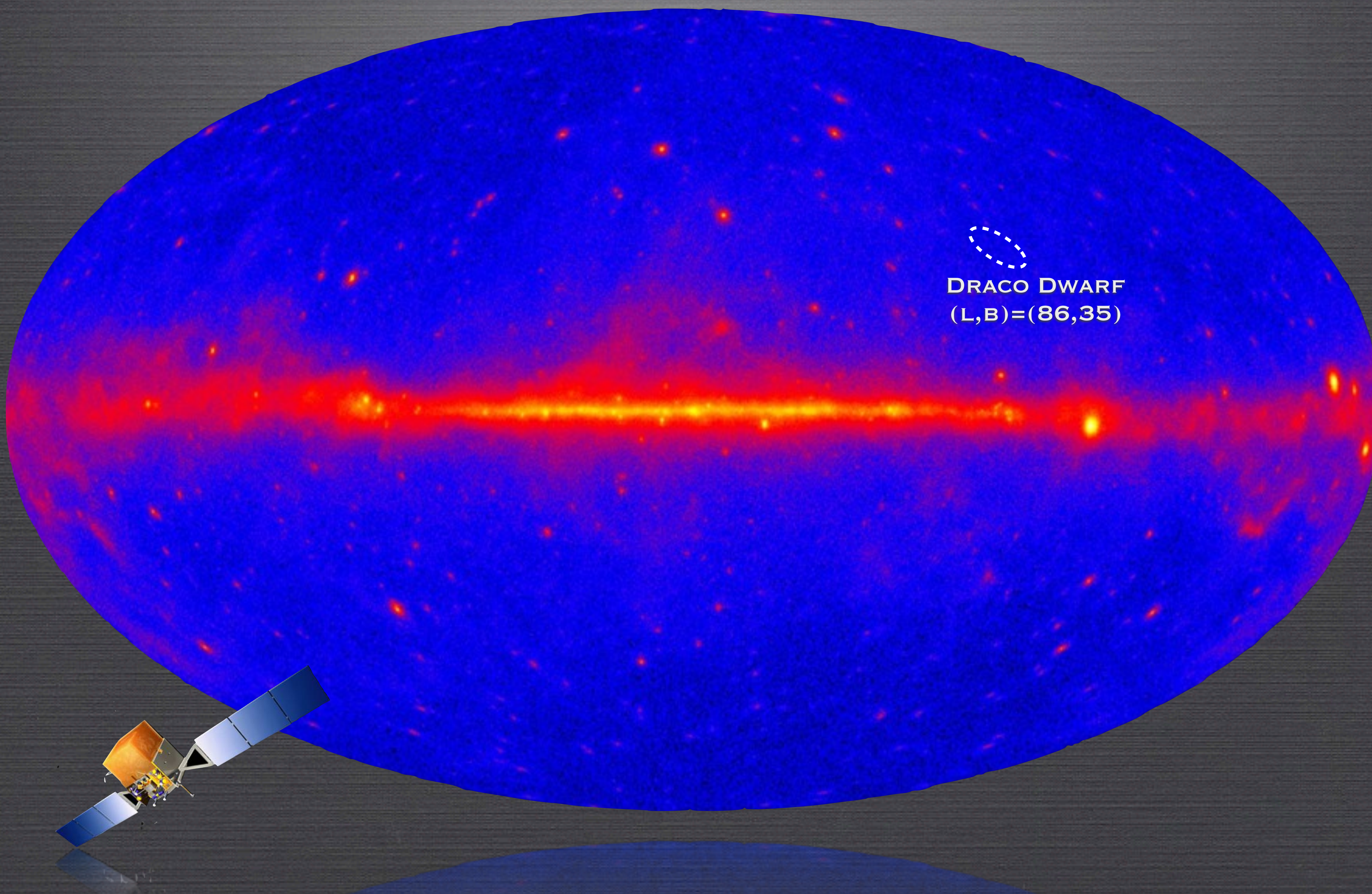
1-year full-sky map. http://fermi.gsfc.nasa.gov

Sensitivity



Pieri, GB, Branchini 2009

The FERMI sky



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

Fermi null searches set an upper limit on the gamma-ray flux from Dwarf Galaxies

Upper limits from Dwarfs

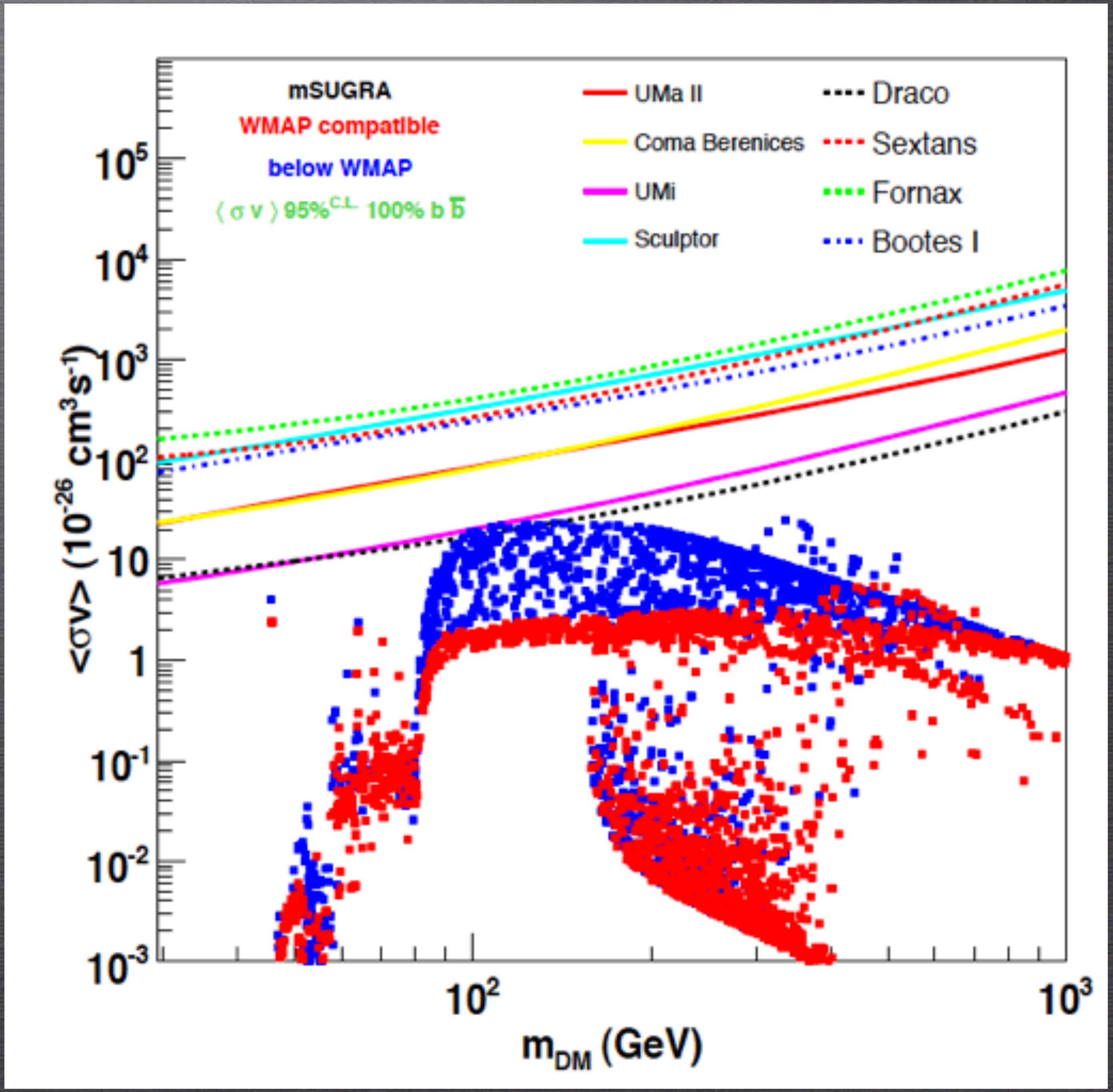
$$\Phi_i(\Omega, E_i) = \frac{dN}{dE_i} \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \int_{los} \rho_\chi^2(\ell, \Omega) d\ell$$

Compare with Fermi upper limit

$\Phi_{max} \sim 10^{-10}$ photons cm^{-2} s^{-1}

(above 1 GeV)

With conservative estimates of the l.o.s. integral



Abdo et al. 2010

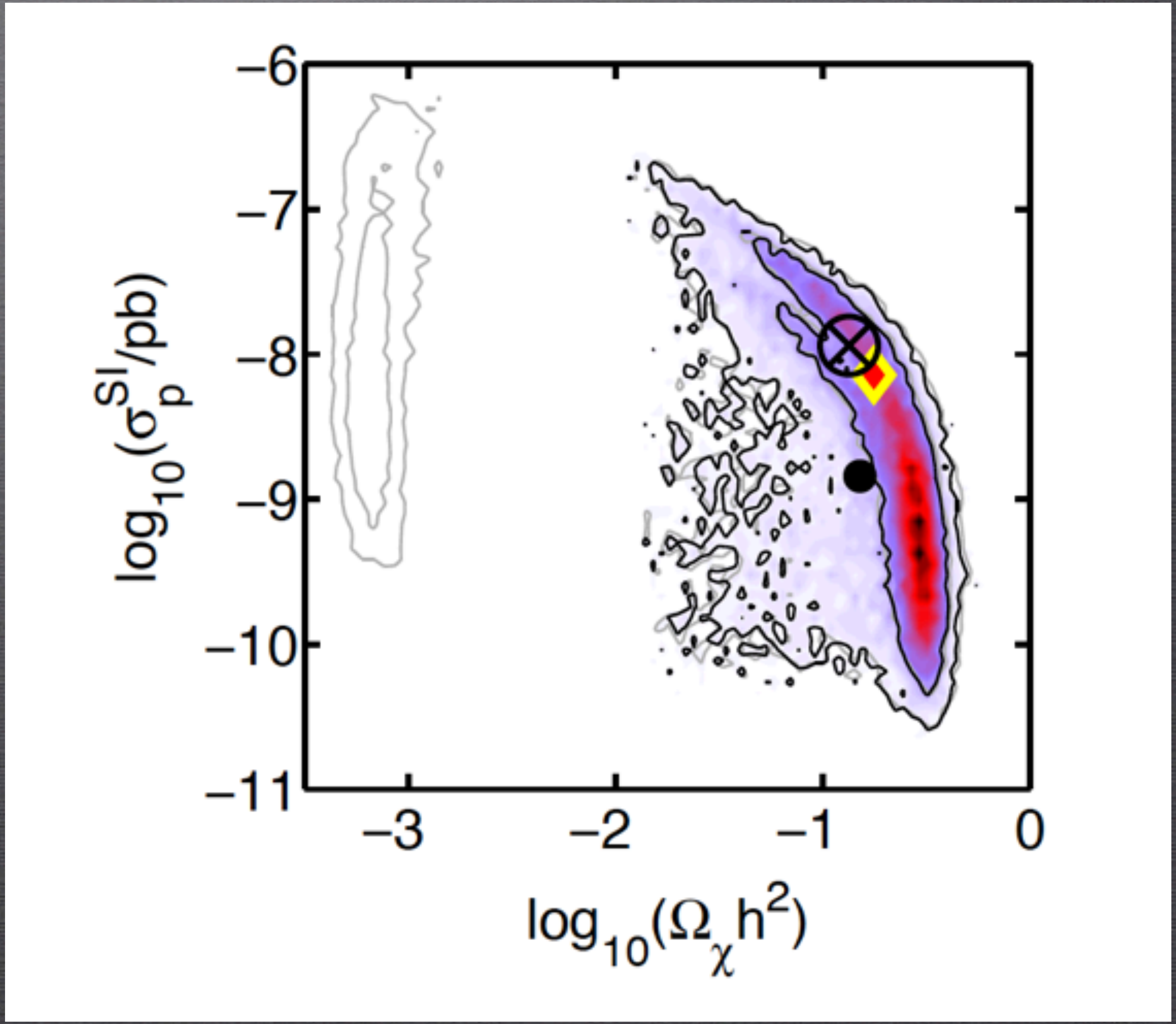
What happens if we add these constraints to the LHC posterior?

LHC + ID

IF we identify neutralino ≡ Dark Matter

(in Draco for Fermi, or in the Universe in the case of CMB)

THEN
we can exclude the spurious solution at low relic density

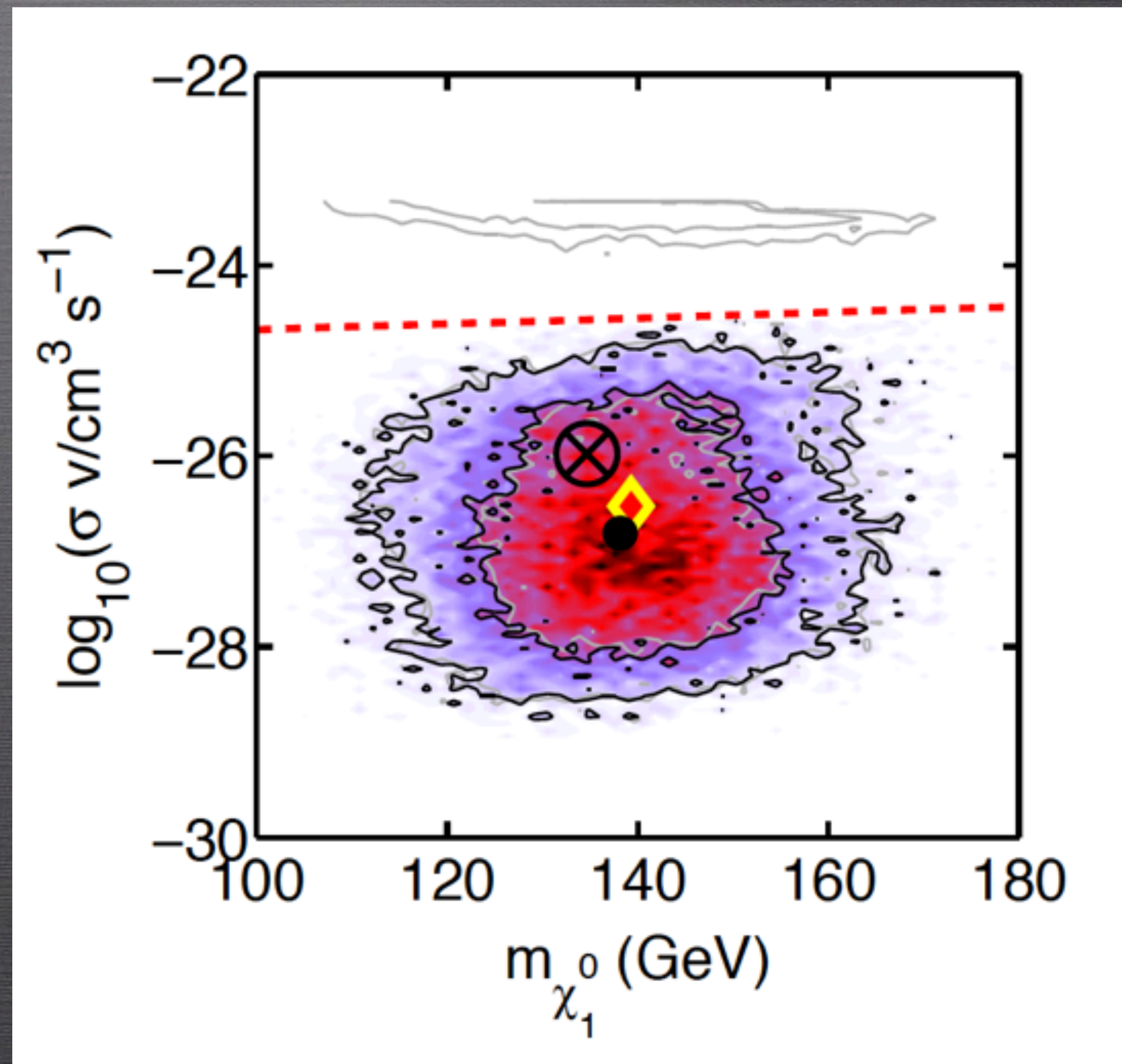


GB, Fornasa, Pieri, Ruiz, Trotta 2011

What happens if we add these constraints to the LHC posterior?

LHC + ID

...since we are basically ruling out the region corresponding to large annihilation cross sections



GB, Fornasa, Pieri, Ruiz, Trotta 2011

… or Constraints from CMB

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

The interaction of secondary particles from DM annihilation with the thermal gas can

1: ionize gas

2: induce Ly–α excitation of H

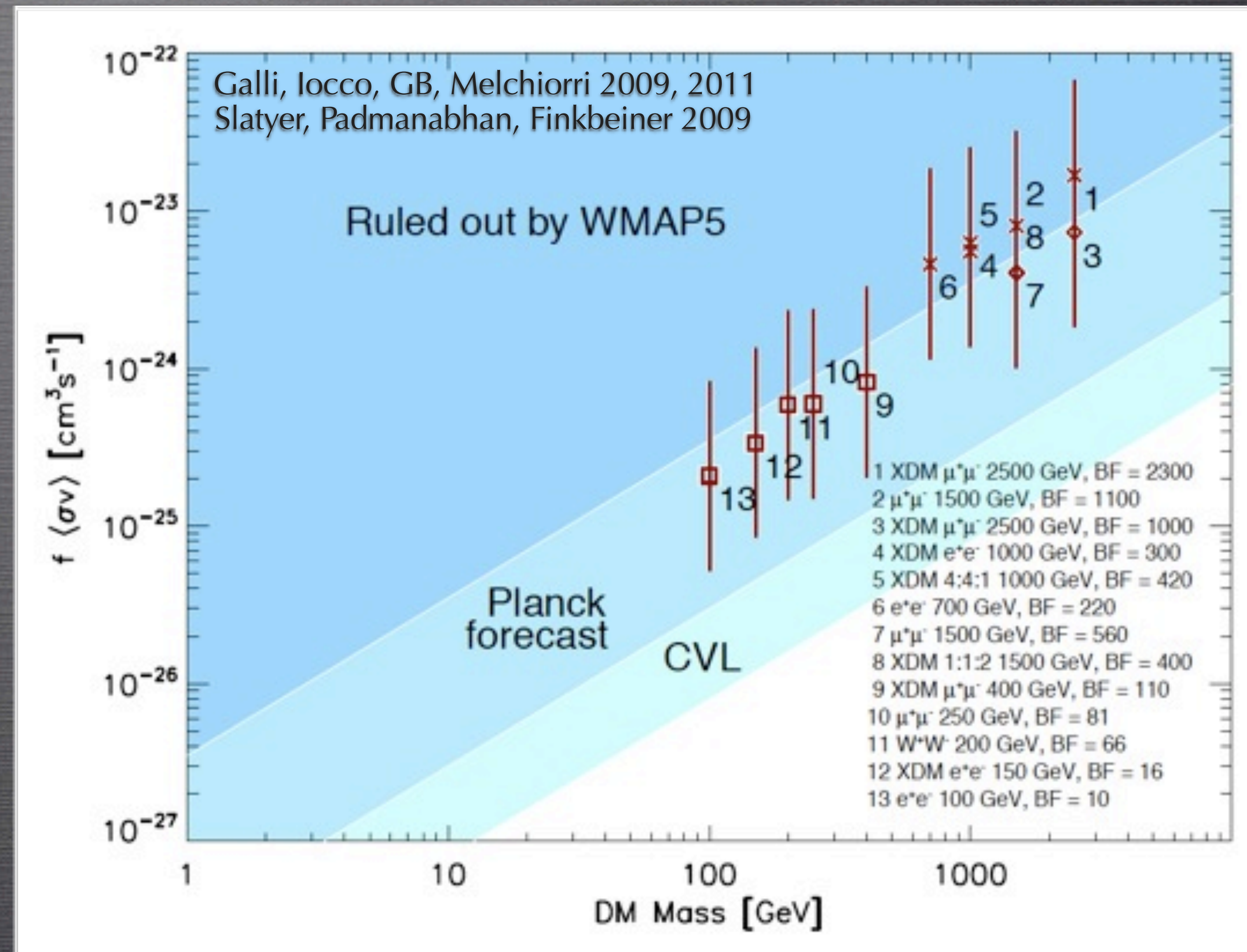
$$\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)}\left[R_s(z) - I_s(z) - I_X(z)\right]$$

3: heat the gas

…extra term in T_B equation

In both cases, effect depends on

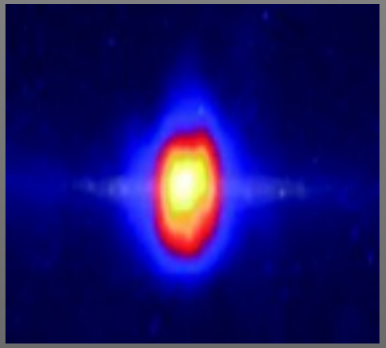
$$\mathbf{p_{ann}} \equiv \frac{\mathbf{f}\langle\sigma\mathbf{v}\rangle}{\mathbf{m}_\chi}$$



Expected constraint with Planck (95% c.l.):

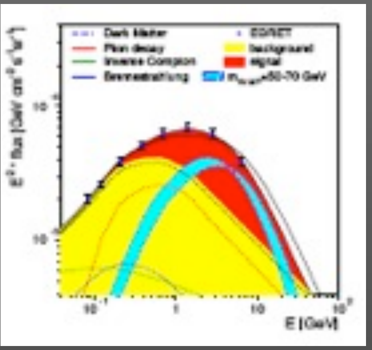
$$p_{ann} < 1.5\ 10^{-7}\ m^3\ s^{-1}\ kg^{-1}$$

Many hints From Indirect searches...



INTEGRAL 511 keV

Evidence for: MeV Dark Matter
Boehm et al (2003,2004), Axino DM (Hooper et al. 2004)

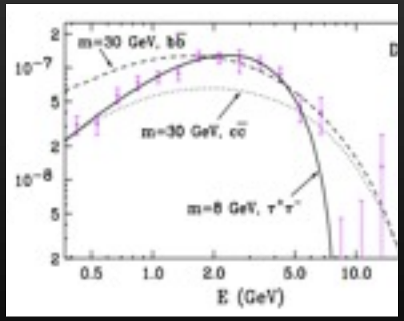


Gamma-rays: EGRET, HESS,

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

WMAP Haze

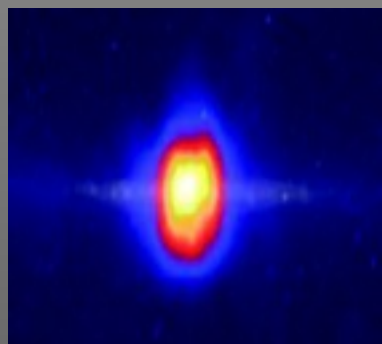
Evidence for: 100 GeV DM
See e.g. Finkbeiner 2004, Hooper, Dobler and Finkbeiner 2007



Gamma-rays: Fermi

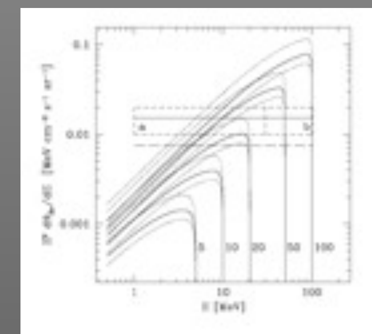
Evidence for: ~10 GeV DM annihilating to taus. Hooper et al. 2010

...BUT NO CONCLUSIVE EVIDENCE!



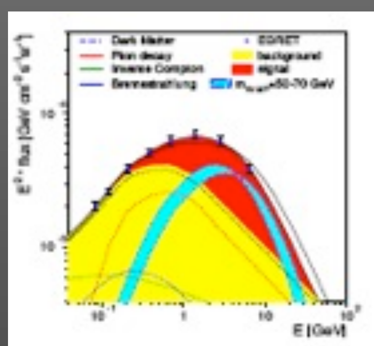
INTEGRAL 511 keV

Evidence for: MeV Dark Matter
Boehm et al (2003,2004), Axino DM (Hooper et al. 2004)



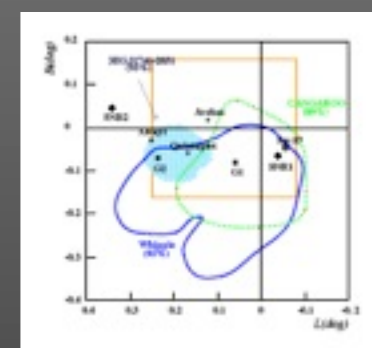
INTEGRAL 511 keV

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



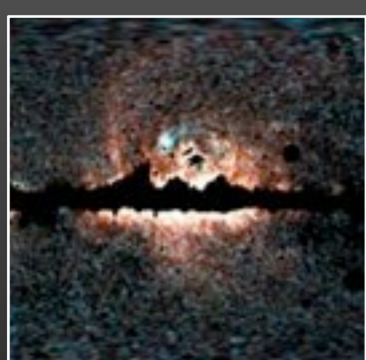
Gamma-rays: EGRET, HESS,

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



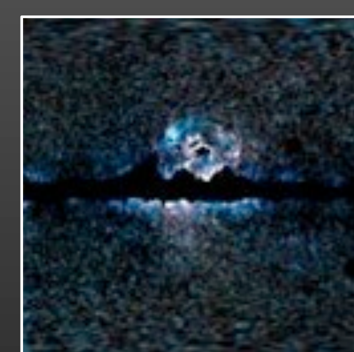
Gamma-rays: EGRET, HESS…

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…*



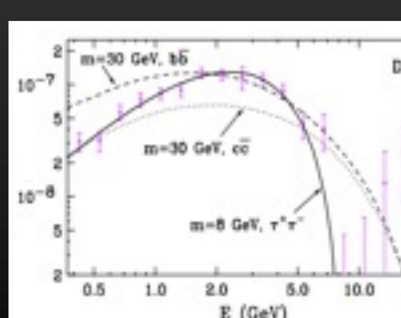
WMAP Haze

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



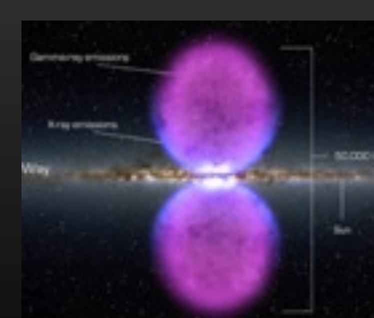
WMAP Haze

No smoking-gun. Cross-check with Fermi?



Gamma-rays: Fermi

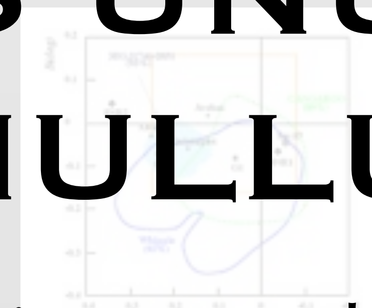
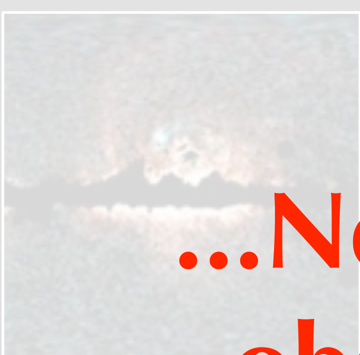
Evidence for: ~10 GeV DM annihilating to taus. Hooper et al. 2010



Gamma-rays: Fermi

Astrophysical background poorly known, featureless spectrum, bizarre DM properties

...BUT NO CONCLUSIVE EVIDENCE!


Most enduring Roman legal adage:

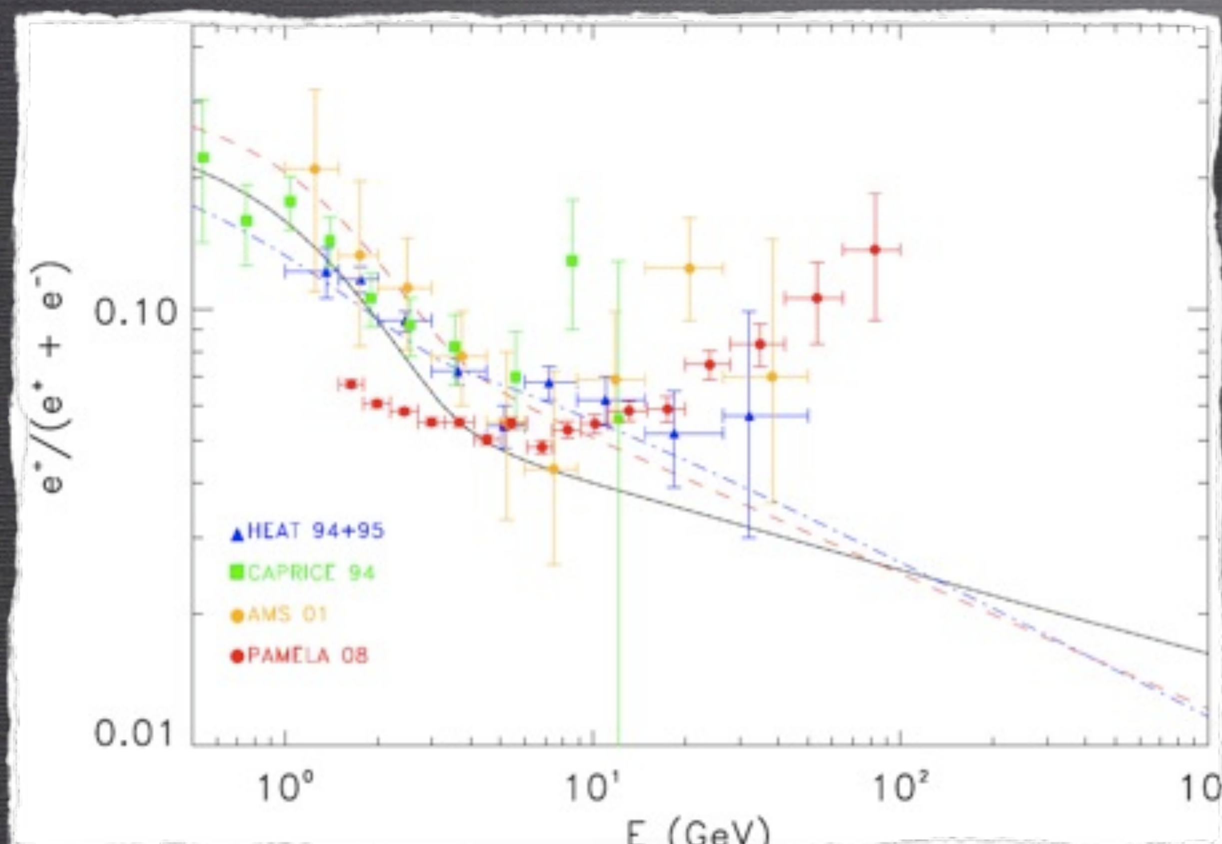
“TESTIS UNUS, TESTIS NULLUS!”

= "A **single** witness is as good as **none**"

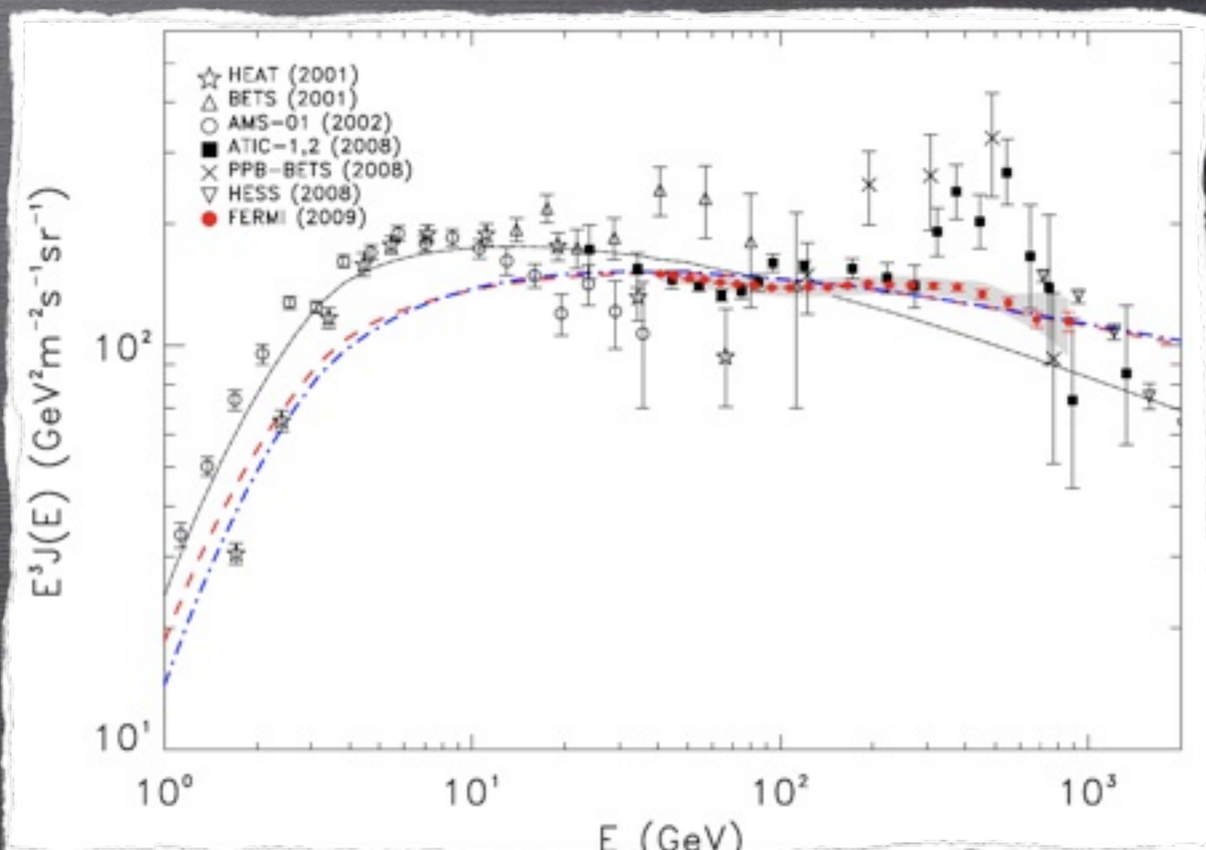
...Need to Cross-check with independent observations before claiming evidence

Cosmic e^+e^-

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

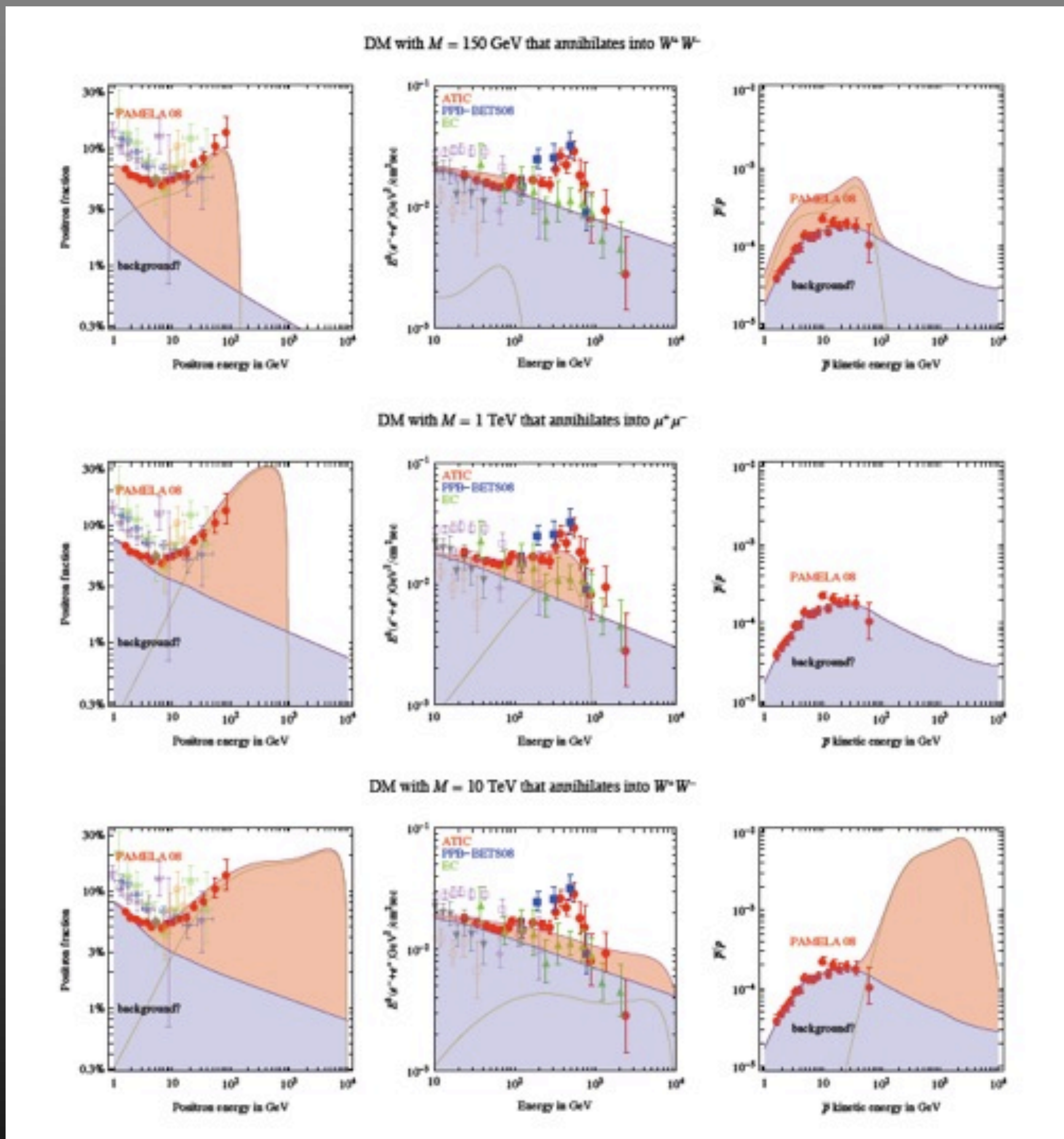


Grasso et al. 2009



Grasso et al. 2009

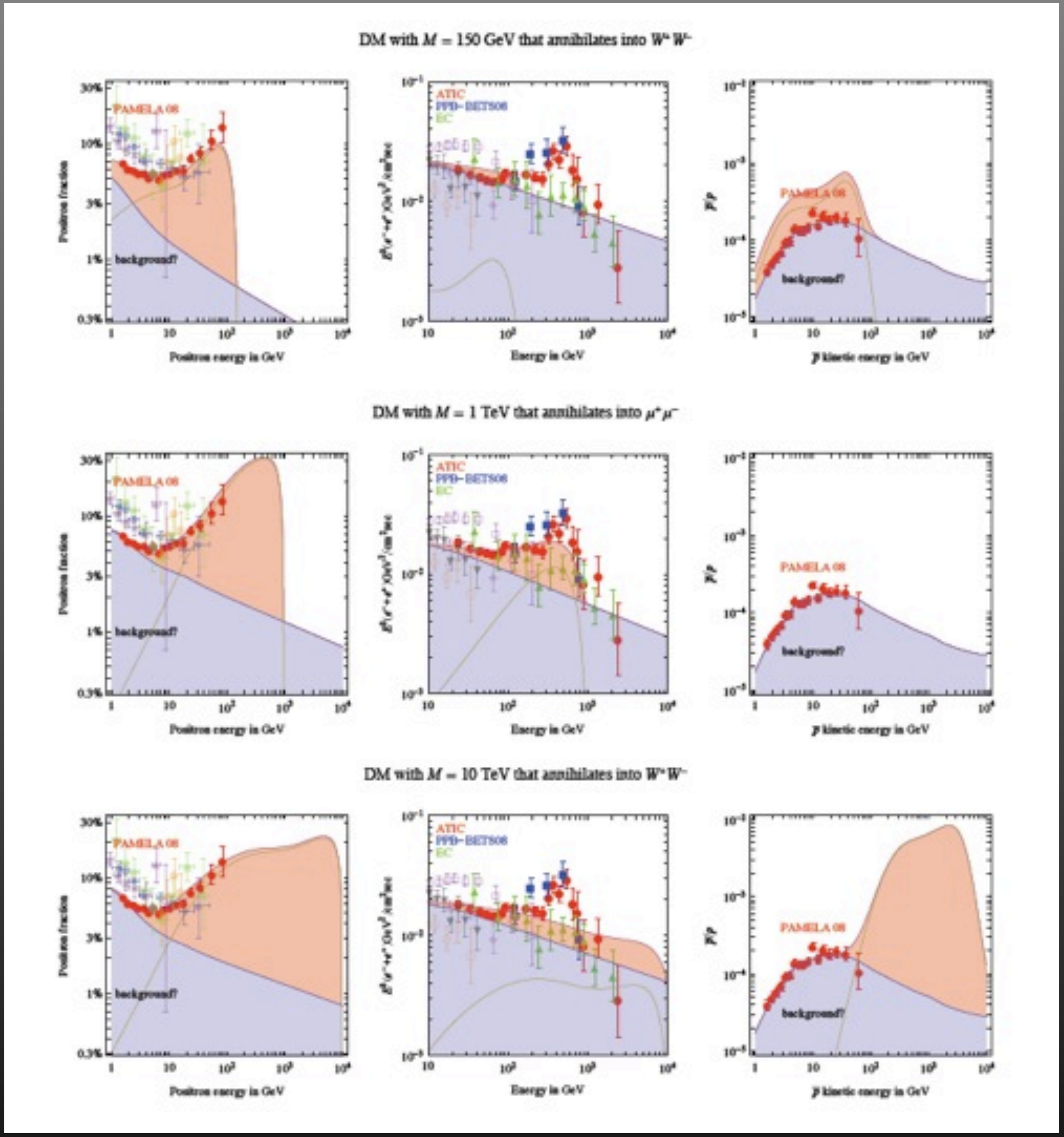
PAMELA / ATIC what do we learn?



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?

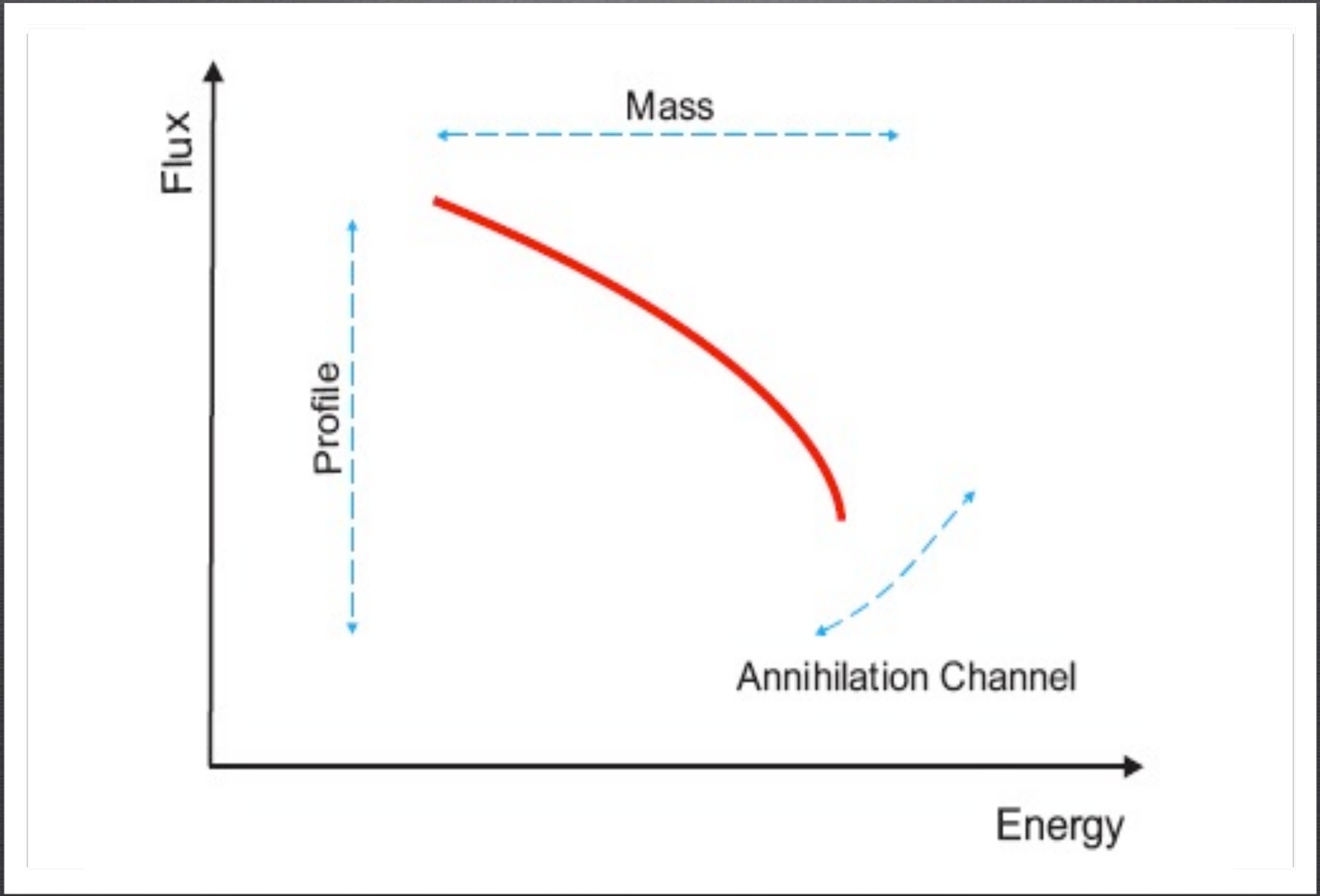


Cirelli, Kadastik, Raidal, Strumia 2008

... 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

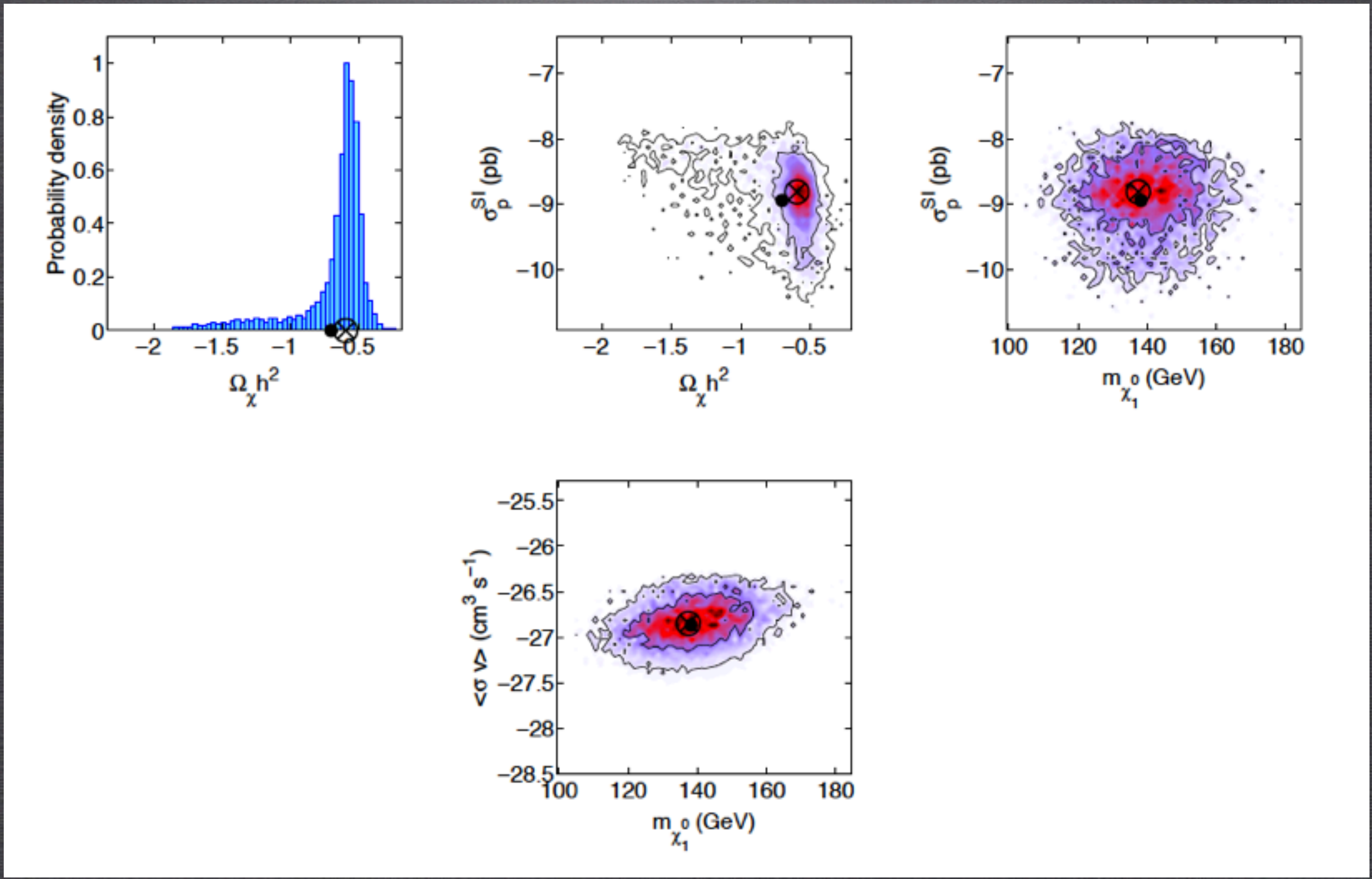


...which means that the "inverse problem" always admits a solution, even when the data have nothing to do with DM!

Beyond upper limits

LHC + ID

GB, Fornasa, Pieri, Ruiz, Trotta 2011



IF a future CTA experiment actually finds a signal
THEN we can set interesting constraints on DM

The quest for the smoking-gun

or

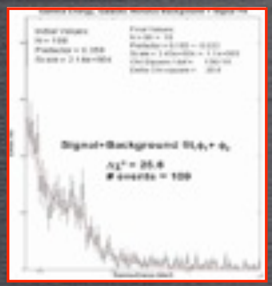
"How to convince a particle physicist?"

The quest for the smoking-gun or "How to convince a particle physicist?"

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"?

The quest for the smoking-gun or "How to convince a particle physicist?"

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"?

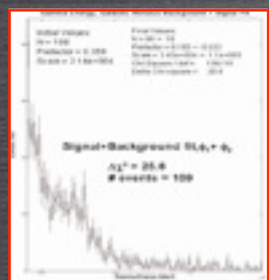


1) Annihilation Lines (or other unmistakable spectral features)

Neutralinos (e.g. Bergstrom and Ullio 1997)
KK Dark Matter in UED (Bringmann et al. 2005)
Inert Higgs DM (Gustafsson et al. 2007)
gravitinos in SUSY with R-parity violation (GB, Buchmueller, Covi & Ibarra 2008)
WIMP FOREST! GB, Jackson, Tait & Vallinotto 2009

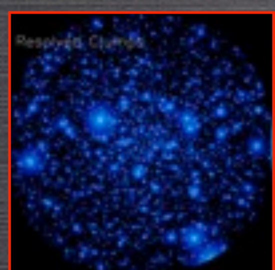
The quest for the smoking-gun or "How to convince a particle physicist?"

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"?



1) Annihilation Lines (or other unmistakable spectral features)

Neutralinos (e.g. Bergstrom and Ullio 1997)
KK Dark Matter in UED (Bringmann et al. 2005)
Inert Higgs DM (Gustafsson et al. 2007)
gravitinos in SUSY with R-parity violation (GB, Buchmueller, Covi & Ibarra 2008)
WIMP FOREST! GB, Jackson, Tait & Vallinotto 2009

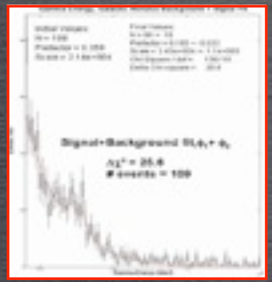


2) Multiple Sources with Identical spectra

e.g. DM clumps or IMBHs

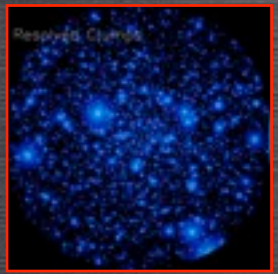
The quest for the smoking-gun
or "How to convince a particle physicist?"

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"?



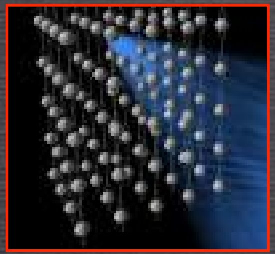
1) Annihilation Lines (or other unmistakable spectral features)

Neutralinos (e.g. Bergstrom and Ullio 1997)
KK Dark Matter in UED (Bringmann et al. 2005)
Inert Higgs DM (Gustafsson et al. 2007)
gravitinos in SUSY with R-parity violation (GB, Buchmueller, Covi & Ibarra 2008)
WIMP FOREST! GB, Jackson, Tait & Vallinotto 2009



2) Multiple Sources with Identical spectra

e.g. DM clumps or IMBHs

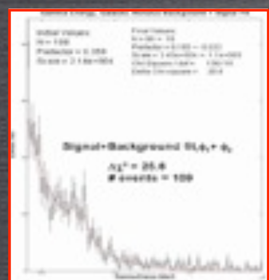


3) High-Energy Neutrinos from the Sun

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

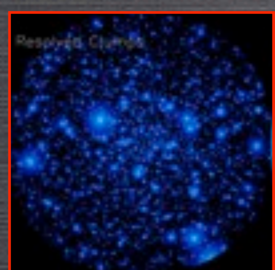
The quest for the smoking-gun or "How to convince a particle physicist?"

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"?



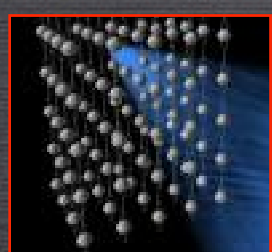
1) Annihilation Lines (or other unmistakable spectral features)

Neutralinos (e.g. Bergstrom and Ullio 1997)
KK Dark Matter in UED (Bringmann et al. 2005)
Inert Higgs DM (Gustafsson et al. 2007)
gravitinos in SUSY with R-parity violation (GB, Buchmueller, Covi & Ibarra 2008)
WIMP FOREST! GB, Jackson, Tait & Vallinotto 2009



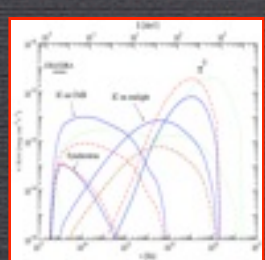
2) Multiple Sources with Identical spectra

e.g. DM clumps or IMBHs



3) High-Energy Neutrinos from the Sun

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

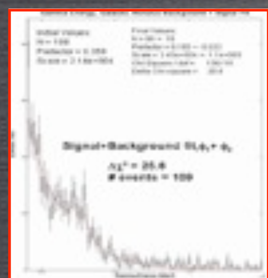


4) Multi-wavelength / multi-messenger approach

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

The quest for the smoking-gun or "How to convince a particle physicist?"

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"?

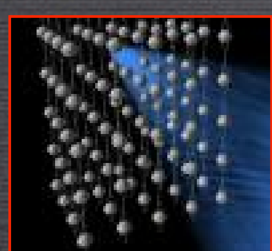


1) Annihilation Lines (or other unmistakable spectral features)

Neutralinos (e.g. Bergstrom and Ullio 1997)
KK Dark Matter in UED (Bringmann et al. 2005)
Inert Higgs DM (Gustafsson et al. 2007)
gravitinos in SUSY with R-parity violation (GB, Buchmueller, Covi & Ibarra 2008)
WIMP FOREST! GB, Jackson, Tait & Vallinotto 2009

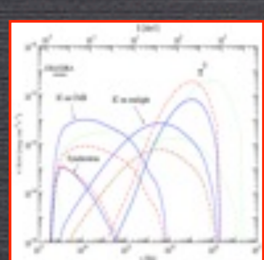
2) Multiple Sources with Identical spectra

e.g. DM clumps or IMBHs



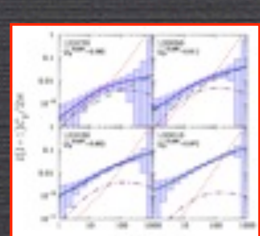
3) High-Energy Neutrinos from the Sun

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



4) Multi-wavelength / multi-messenger approach

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



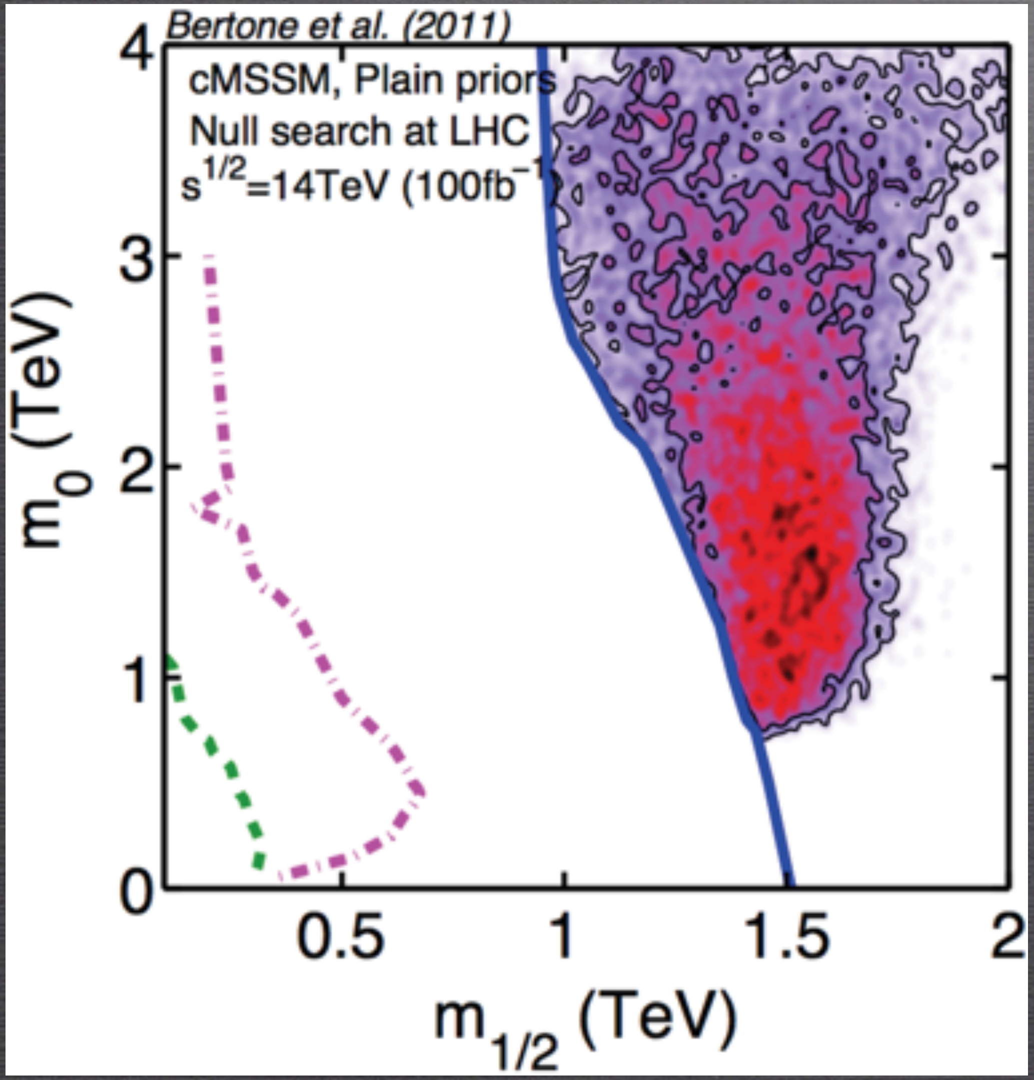
5) Angular power Spectrum of EG Background

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

What if the LHC does NOT find new physics

The Nightmare Scenario

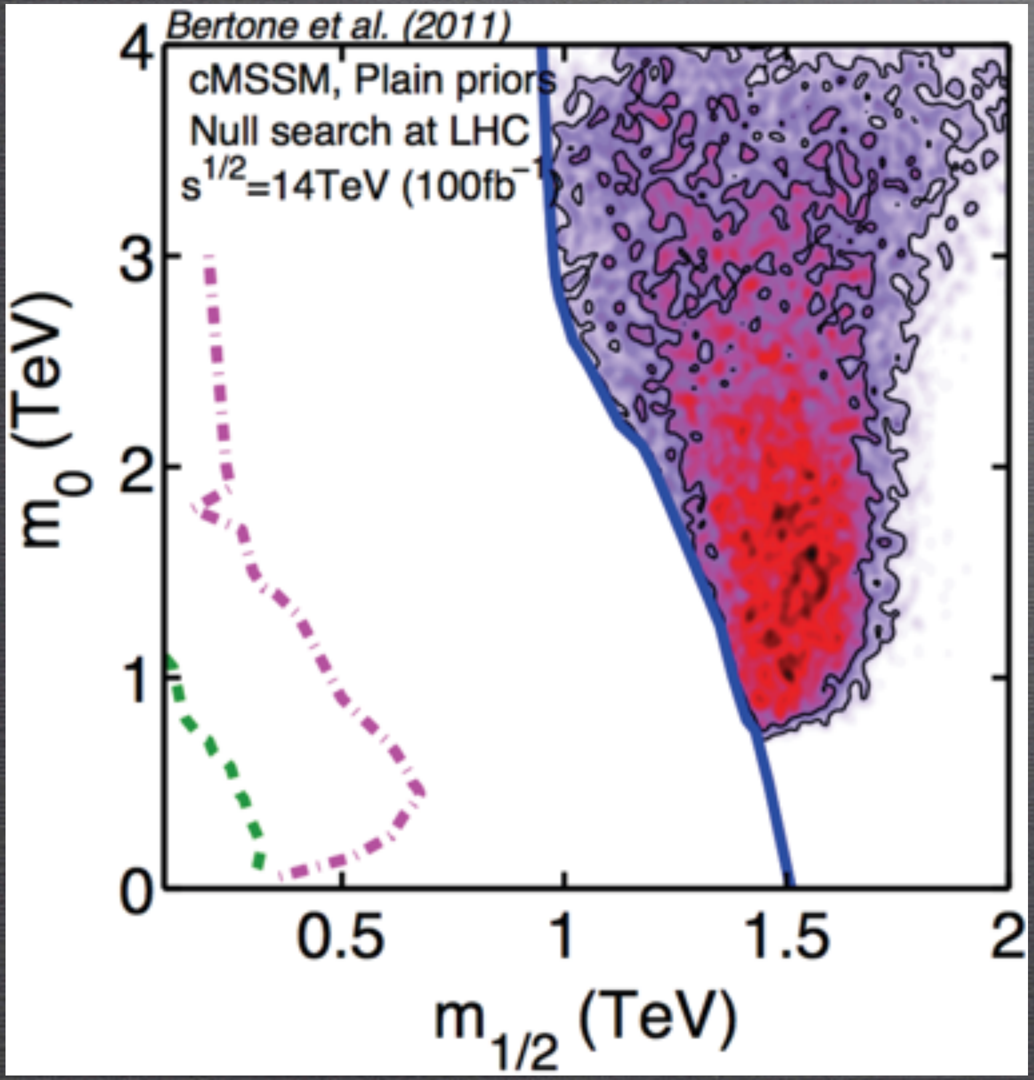
GB, Cumberbatch, Ruiz, Trotta 2011

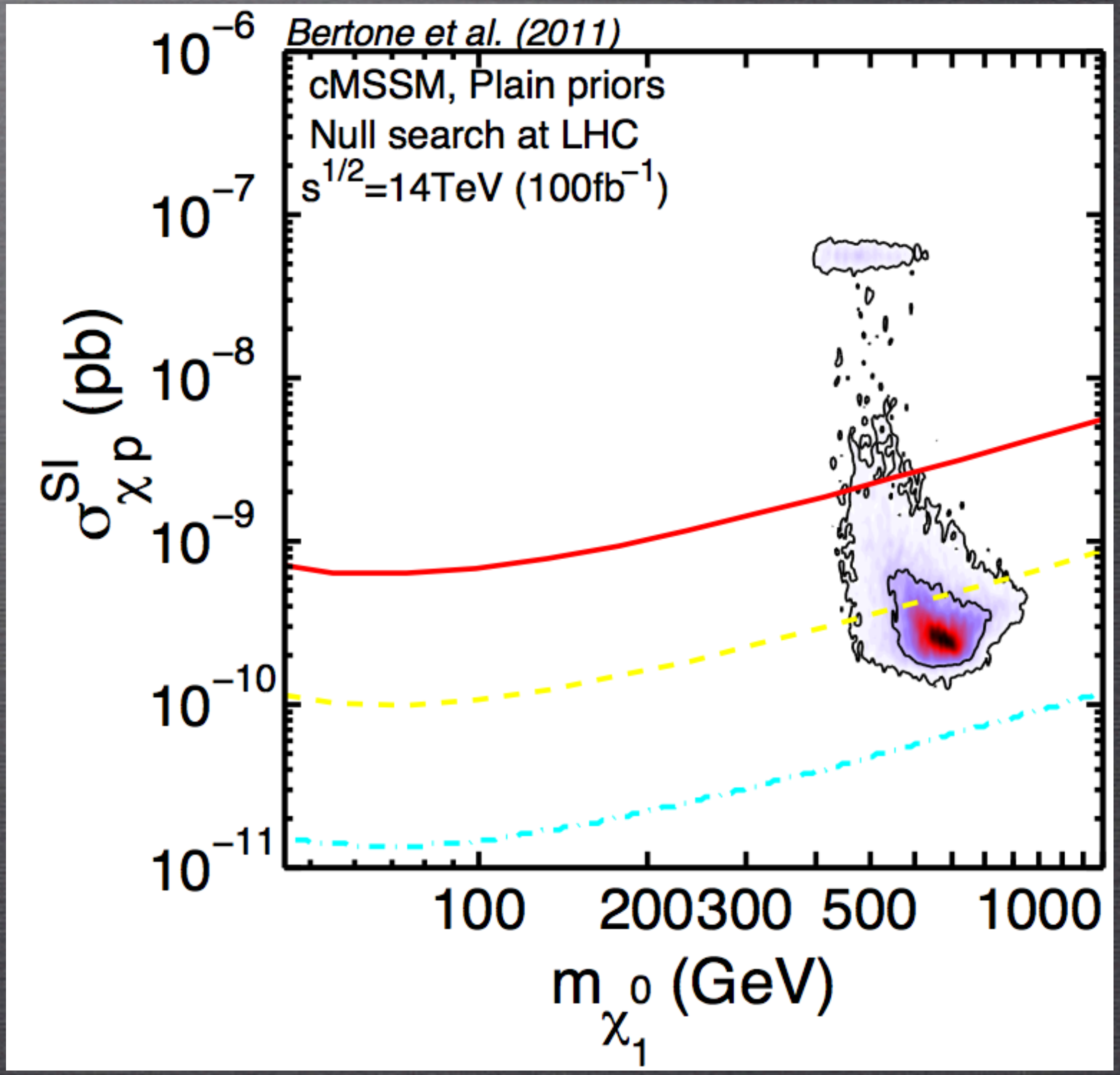


What if the LHC does NOT find new physics

The Nightmare Scenario

GB, Cumberbatch, Ruiz, Trotta 2011





(preliminary!)

Conclusions

- *Huge* Theoretical and experimental effort towards the identification of DM

- LHC is running! Exciting times ahead, but direct and indirect searches likely necessary to <u>identify</u> DM

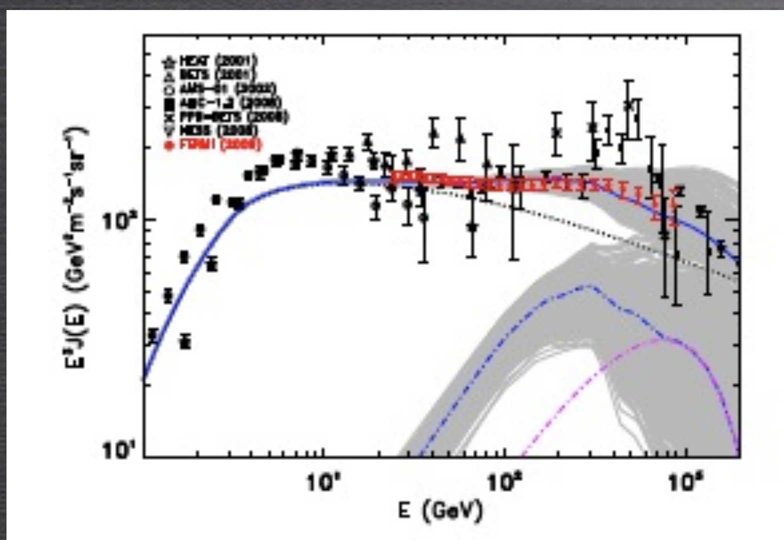
- DM *Direct Detection* looks promising, but info from other exps. is needed to determine DM parameters

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

- A combination of these techniques will allow to identify or to rule out the most promising DM candidates within 5-10 years

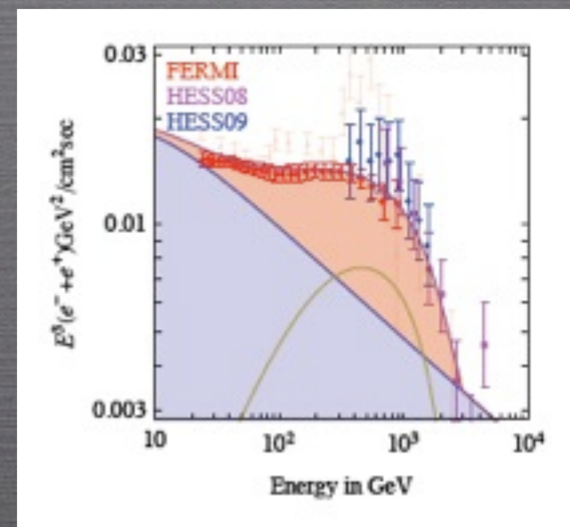
Interpretation

Pulsars



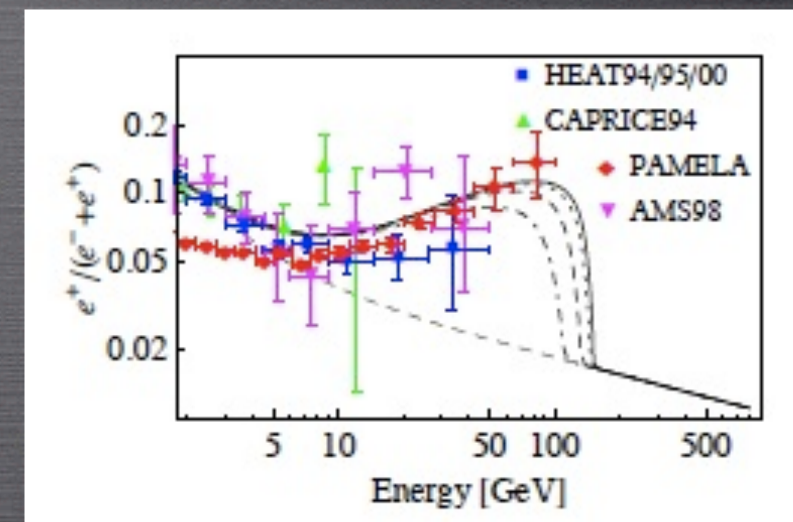
Grasso et al. 2009

DM Annihilation



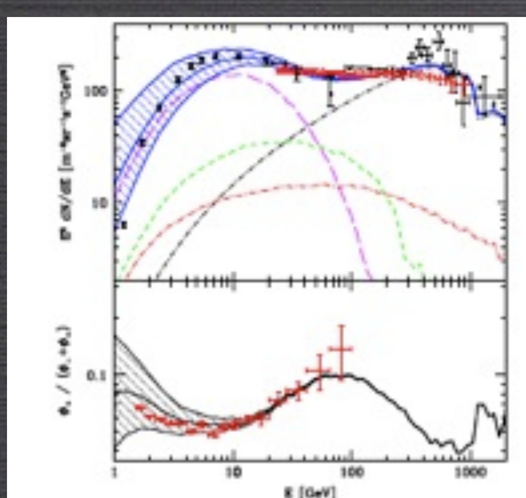
Strumia et al. 2009

DM Decay



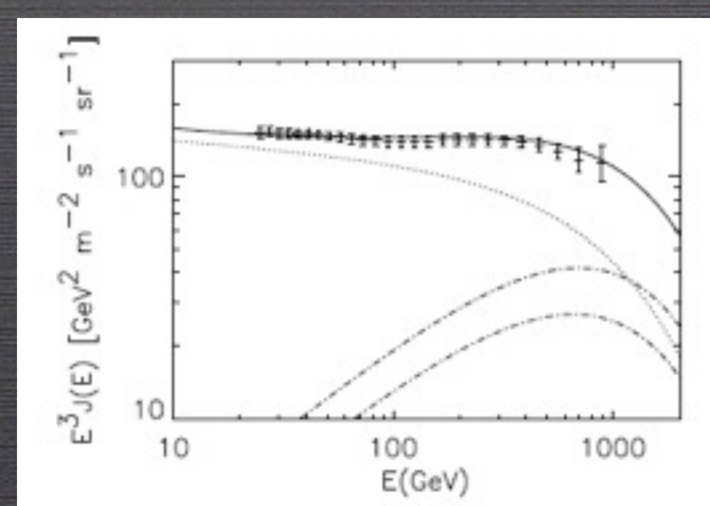
Ibarra et al. 2009

SNRs inhom.



Piran et al. 2009

SNRs 2ndary CR acc.

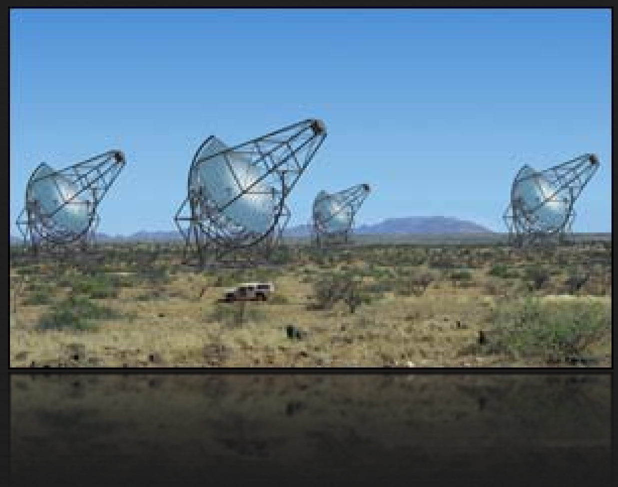


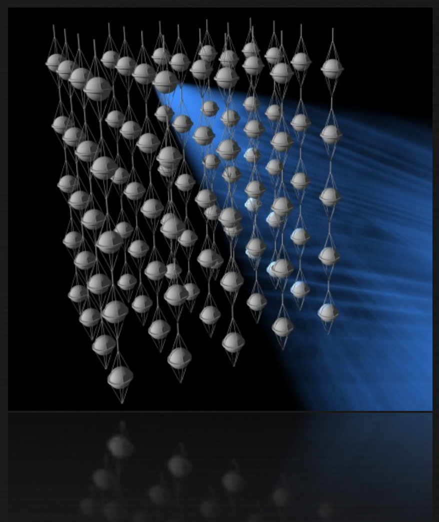
Blasi 2009

... + many MANY other models .

Indirect Detection







Gamma-ray telescopes

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

Neutrino Telescopes

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

Anti-matter Satellites

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

Other

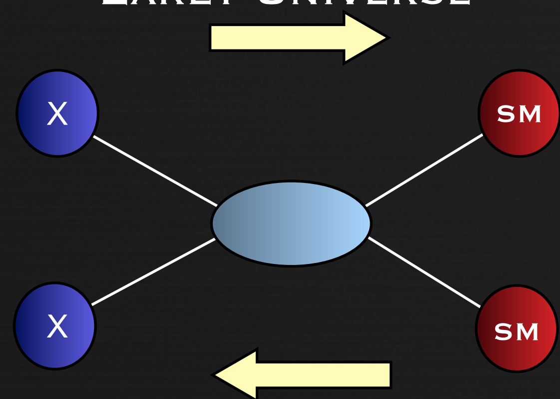
- Synchrotron Emission
- SZ effect
- Effect on Stars

Indirect Detection

Why "annihilations"?

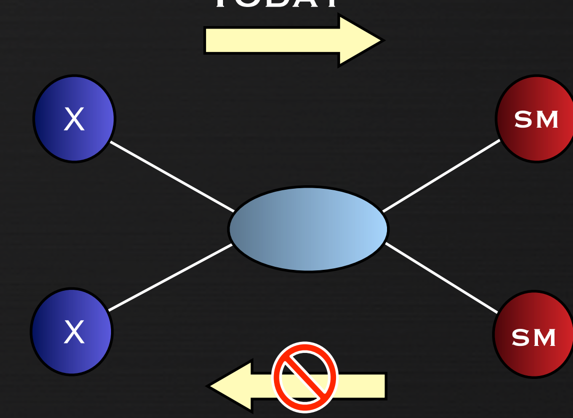
X = dark matter   SM = standard model particle

Early Universe



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

Today



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

Rough estimate of the relic density:

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

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

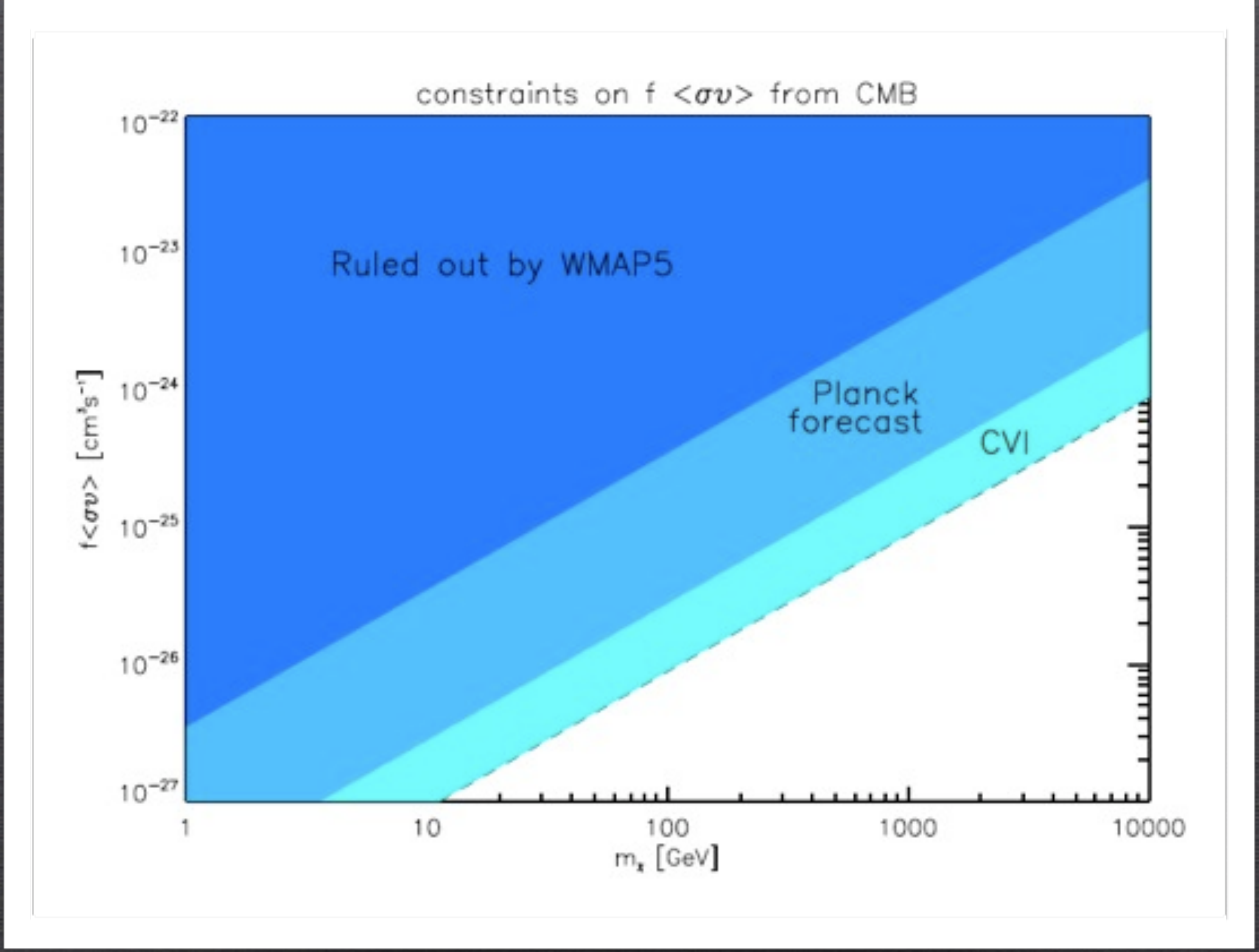
Flux of secondary particles from DM Ann.

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

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

Constraints from CMB

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

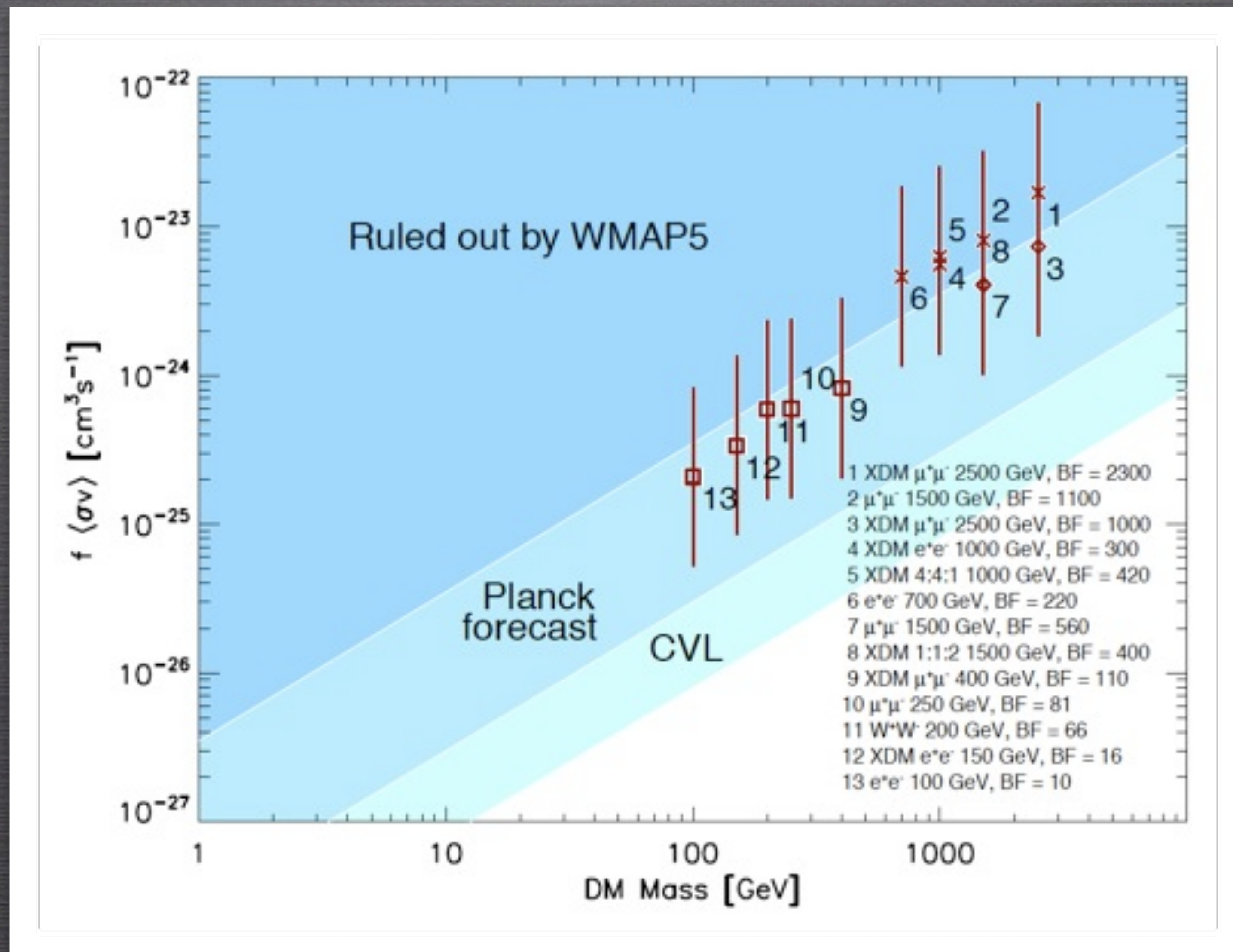


Galli, Iocco, GB, Melchiorri 2009

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.

Constraints from CMB

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



Slatyer, Padmanabhan, Finkbeiner 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.

Conclusions

- Huge Theoretical and experimental effort towards the identification of DM

- LHC is running! Exciting times ahead, but direct and indirect searches likely necessary to identify DM

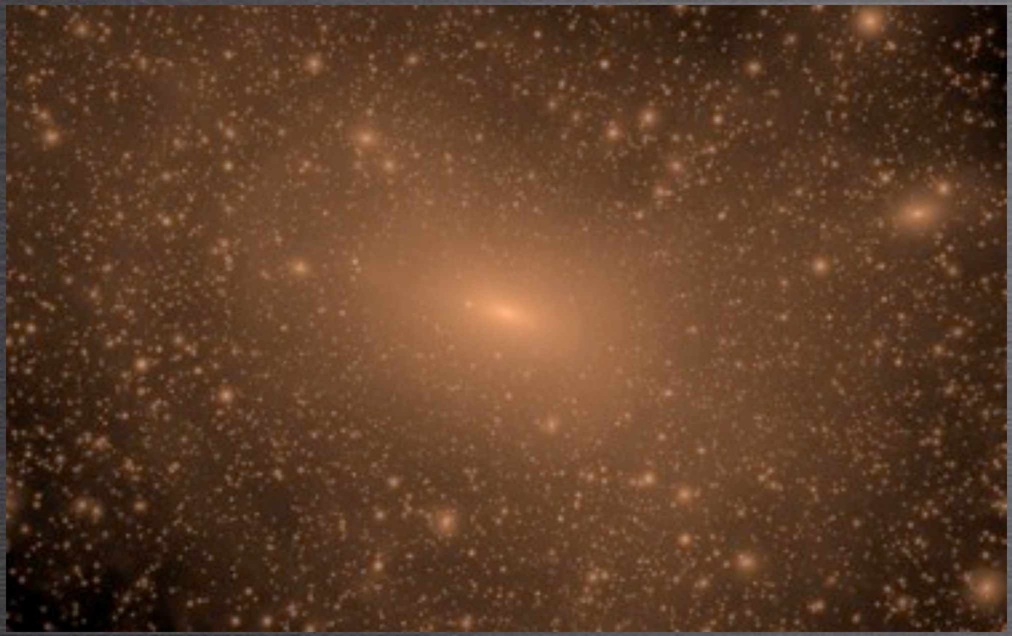
- DM Direct Detection looks promising, but info from other exps. is needed to determine DM parameters

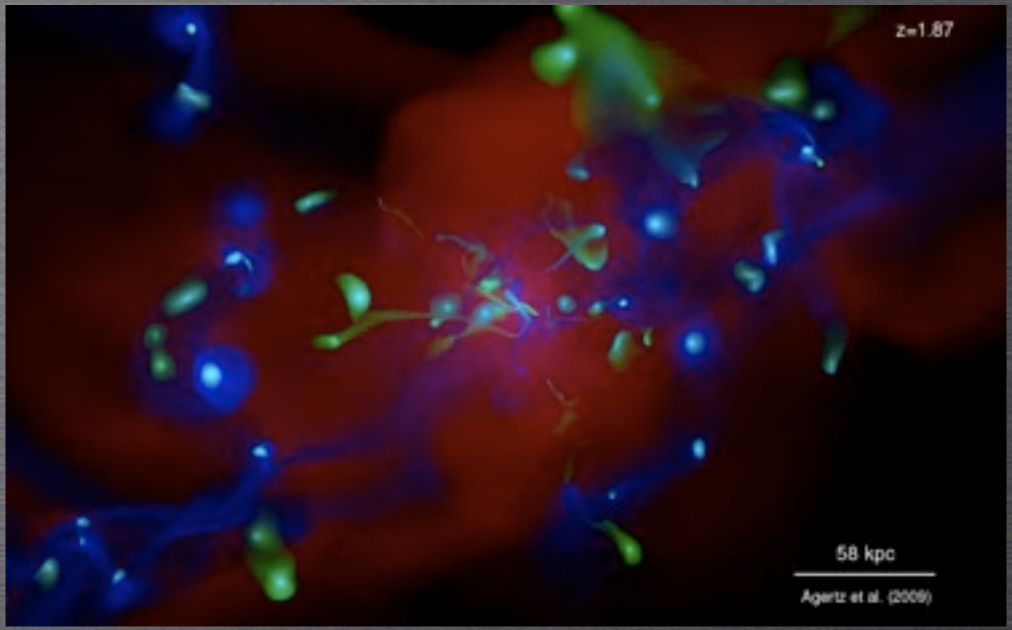
- DM Indirect Detection more and more constrained, but detection still possible

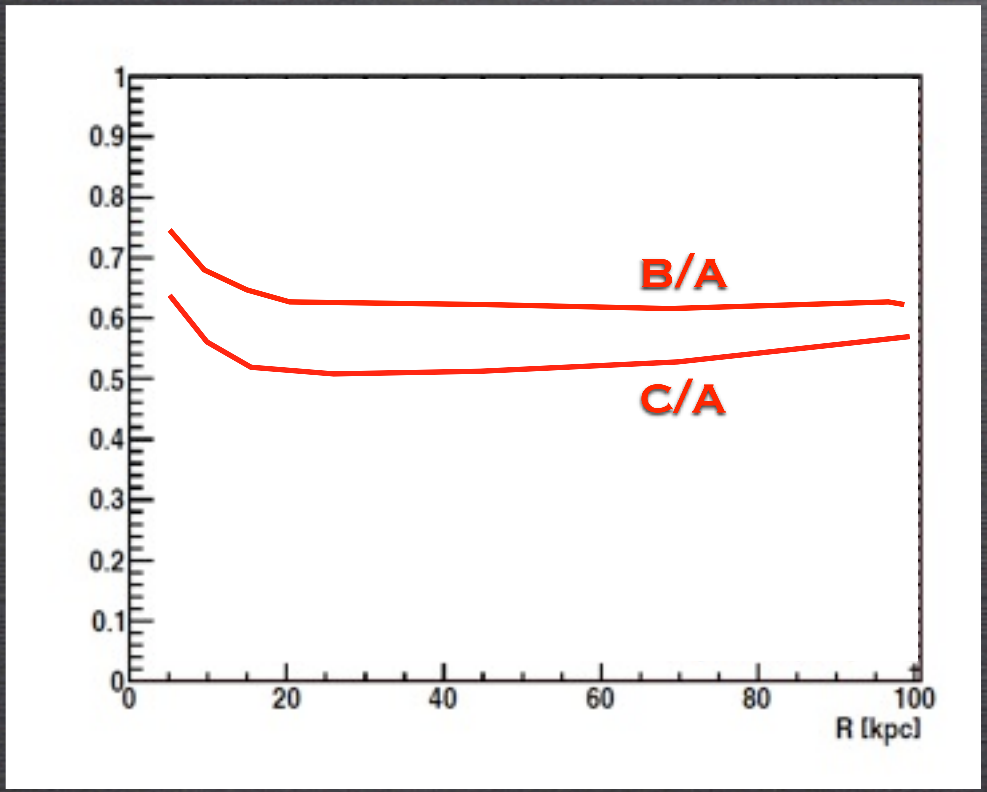
- We Need Data! In ~10 Yrs. discovery of Wimps or Paradigm shift..

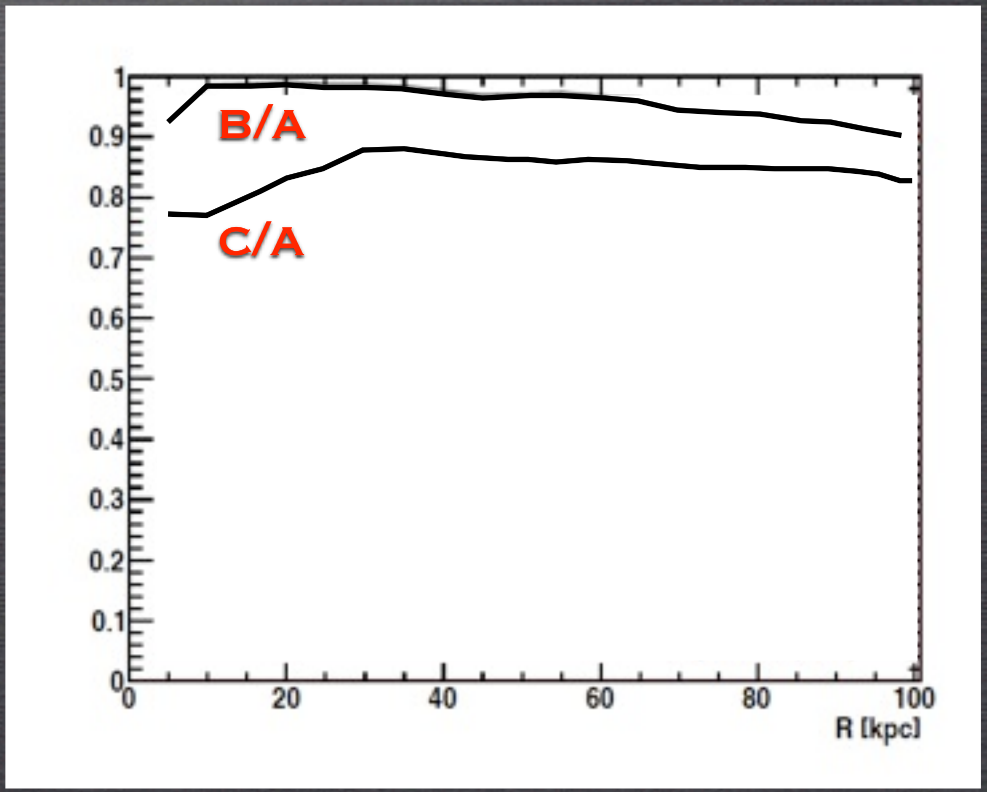
Triaxial Halos

Pato, Agertz, GB, Moore, Teyssier, Moore 2010



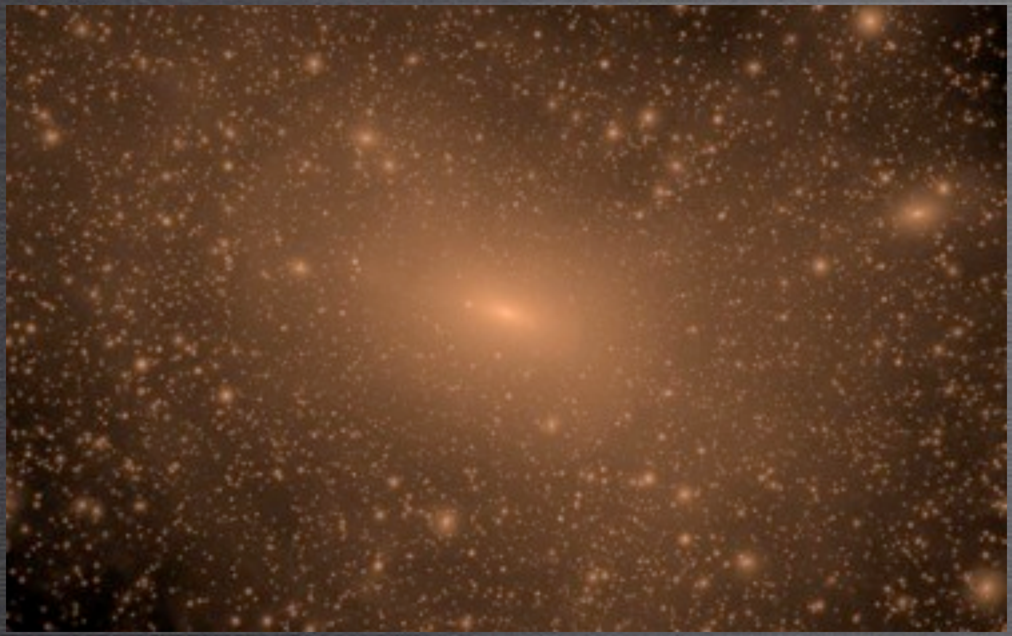


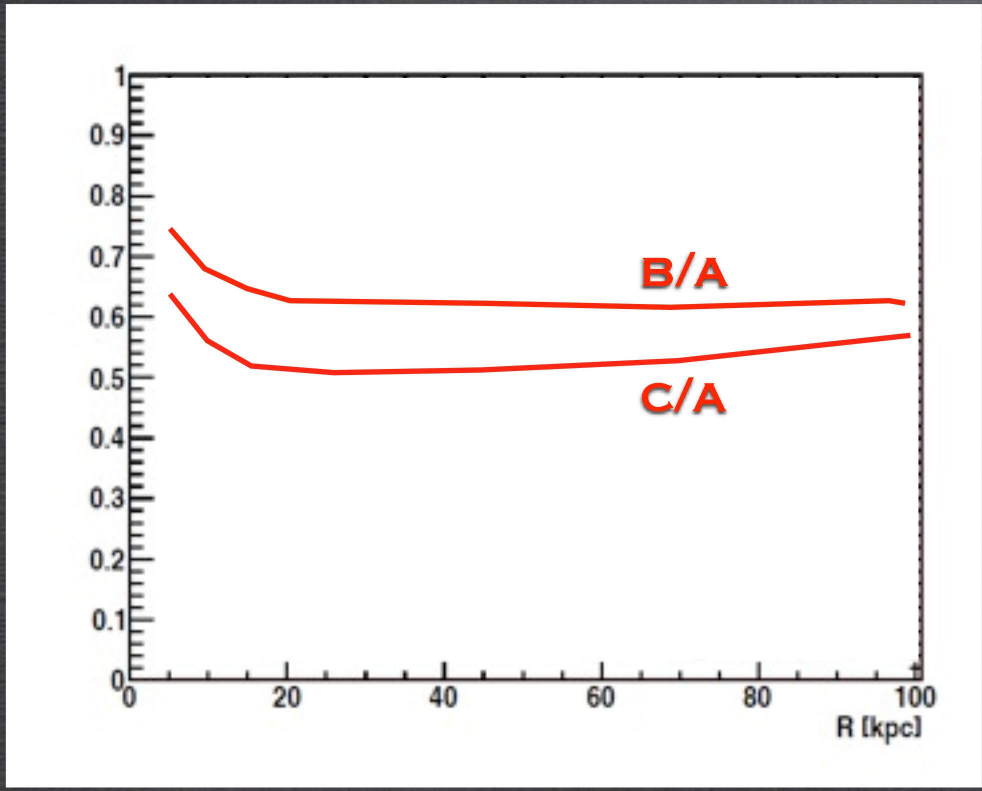




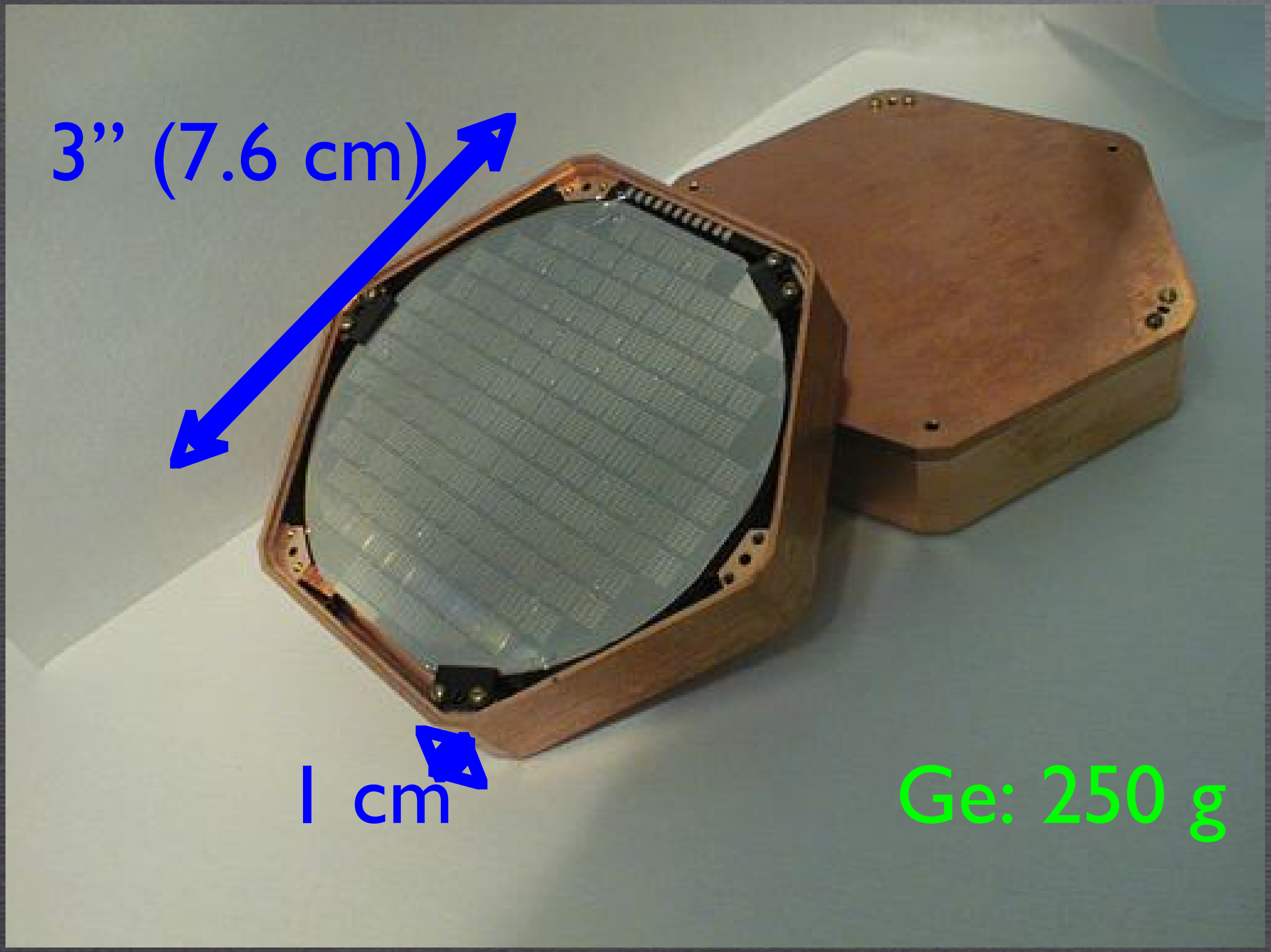
Triaxial Halos

Pato, Agertz, GB, Moore, Teyssier, Moore 2010



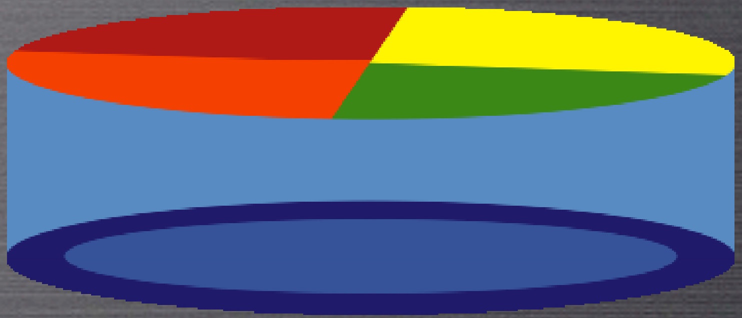


CDMS results, Dec. 2010

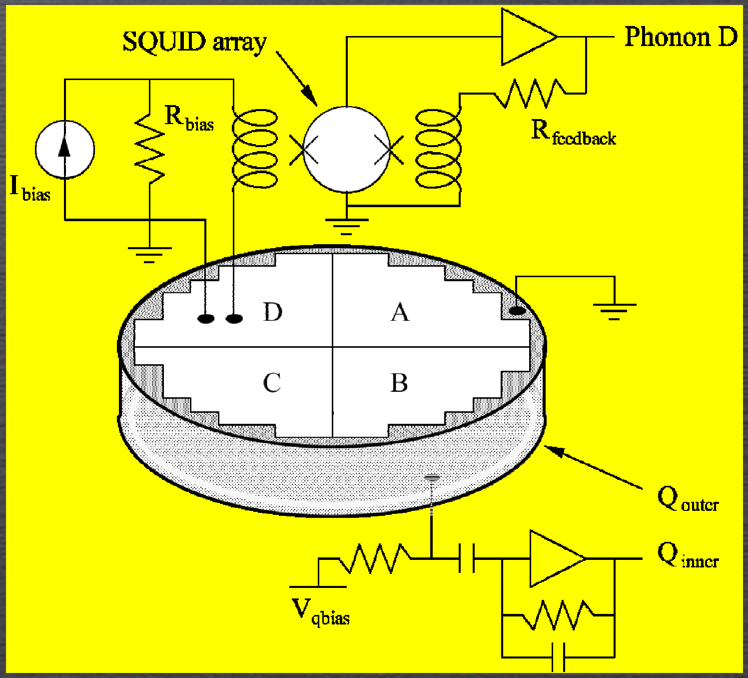


Operated at **~40 milliKelvin** for good phonon signal-to-noise

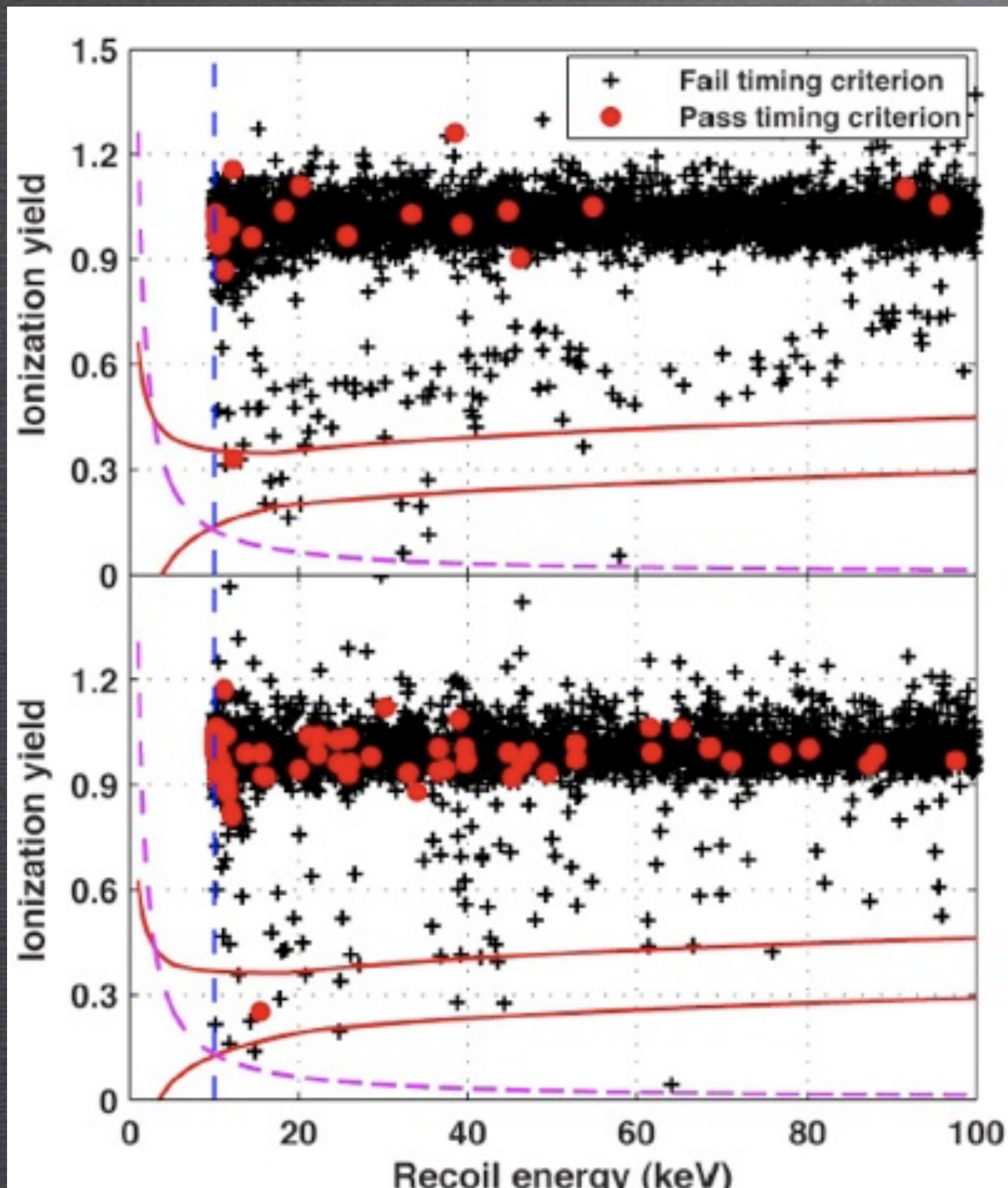
Phonon side: 4 quadrants of athermal phonon sensors => ***energy measurement***

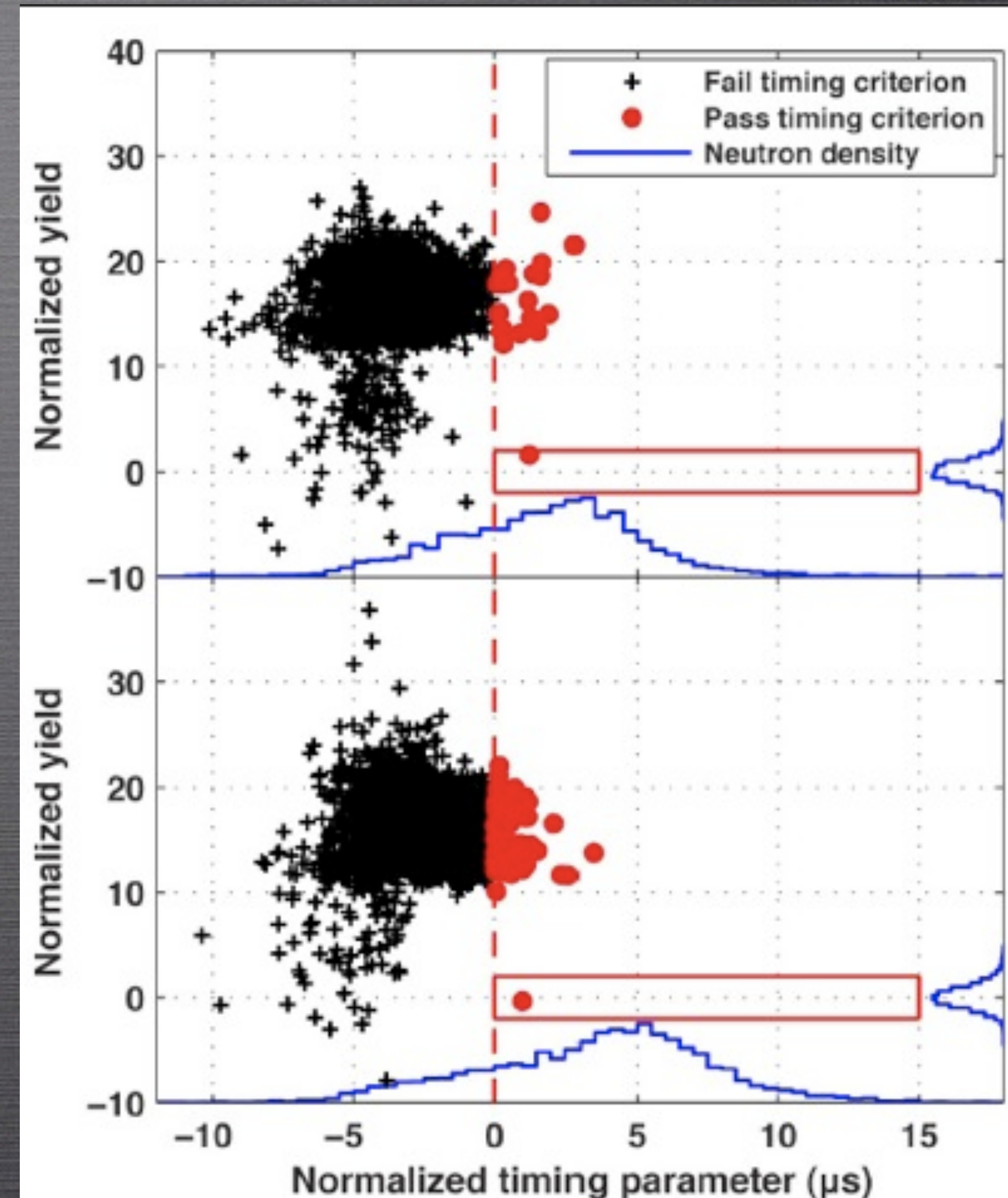


Charge side: 2 concentric electrodes



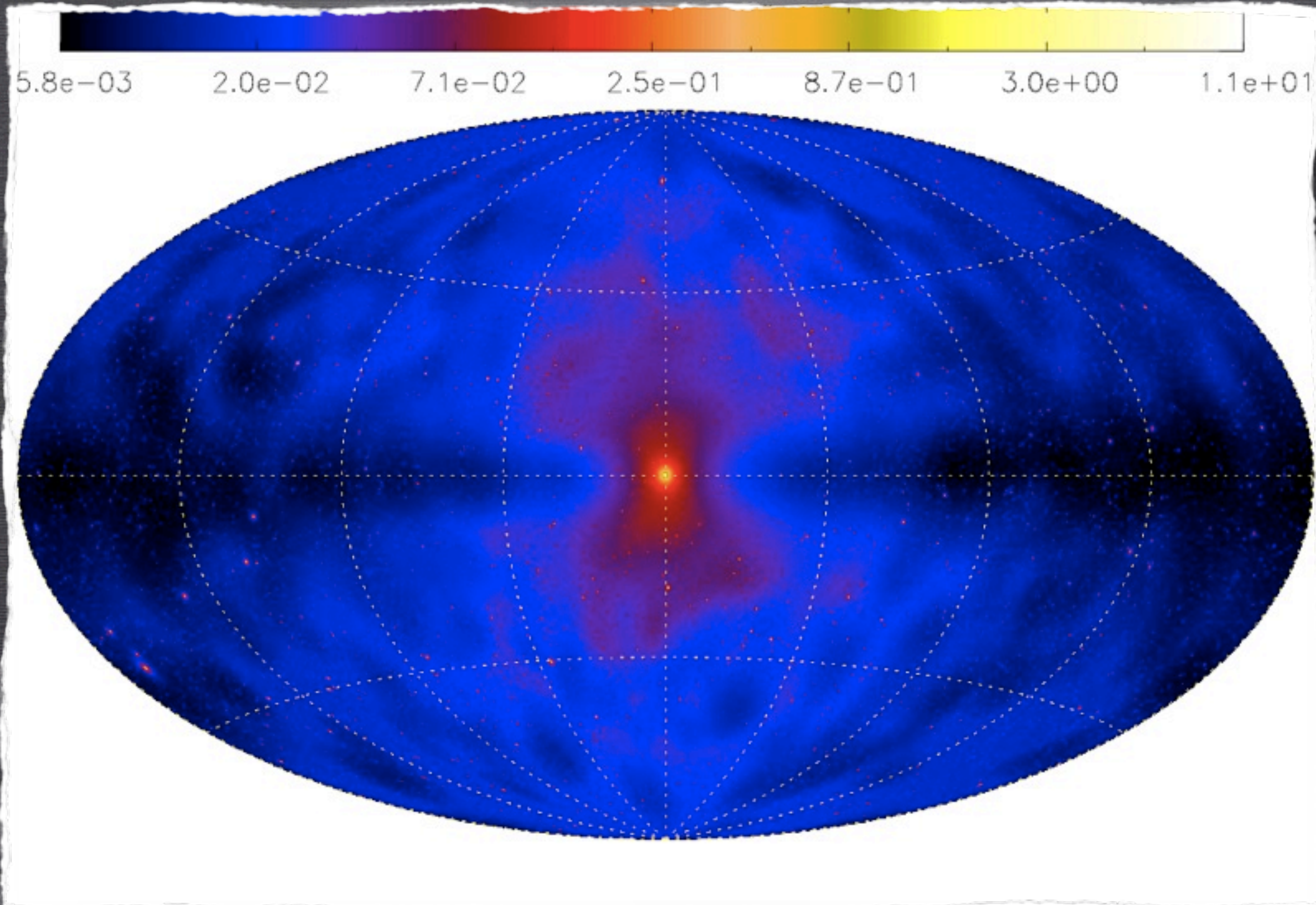
CDMS results, Dec. 2010





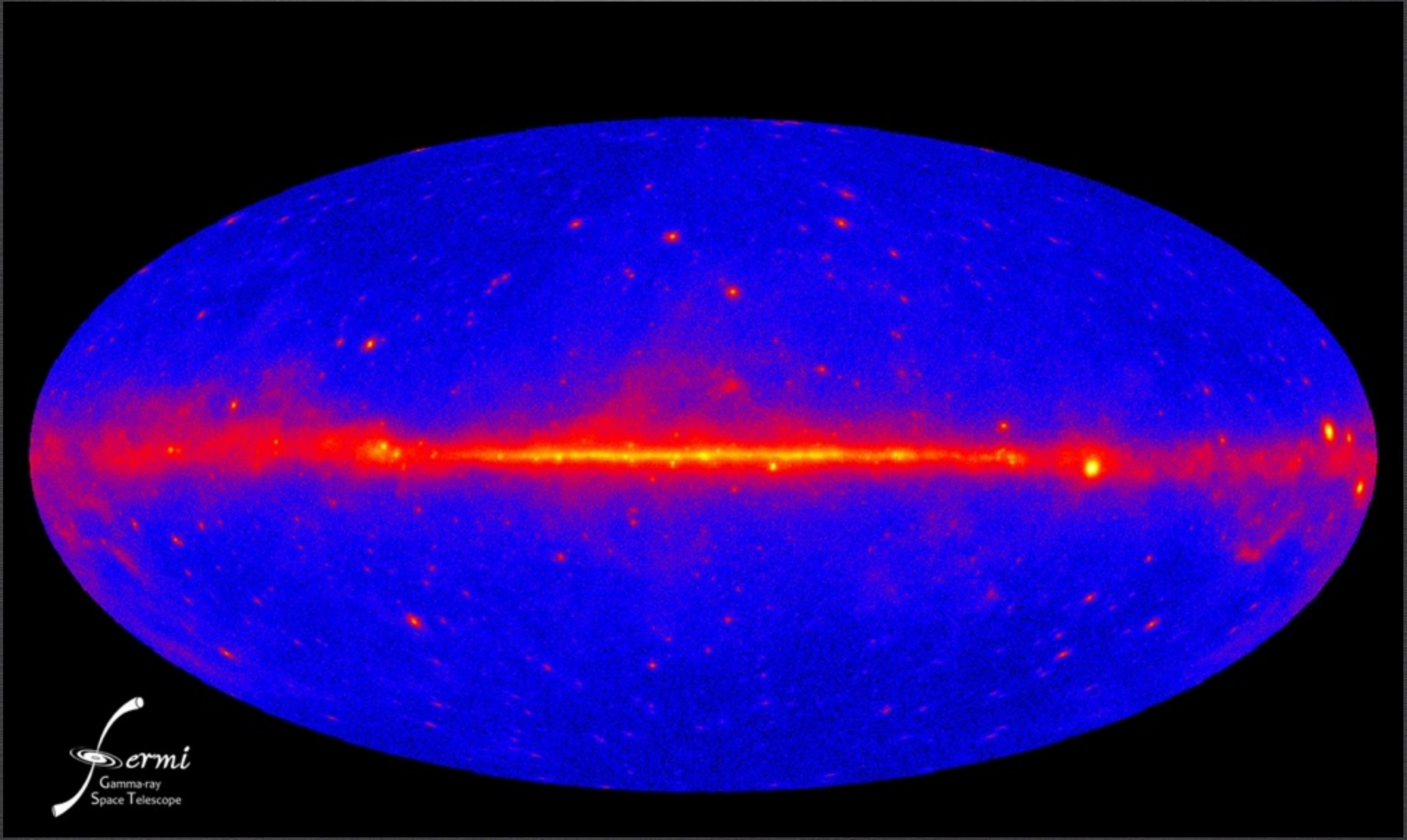
Expected background rate: 0.8. 2 Events observed. Probability of 2 or more events 23%. One event problematic... NOT A DETECTION!

Sensitivity



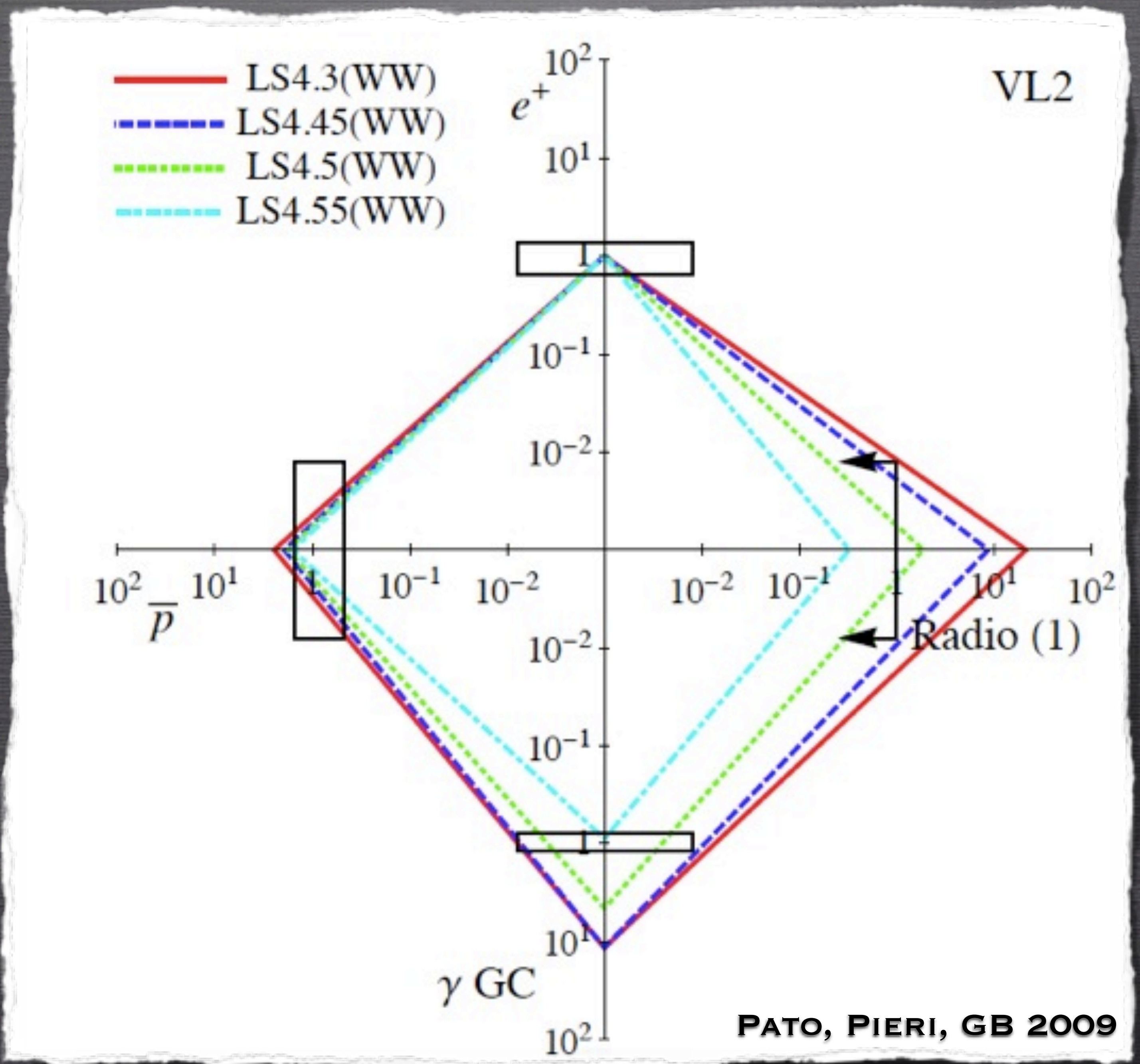
Pieri, GB, Branchini 2009

The FERMI sky

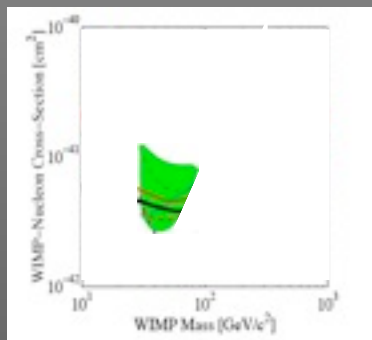


1-year full-sky map. http://fermi.gsfc.nasa.gov

DM interpretation
Increasingly Constrained

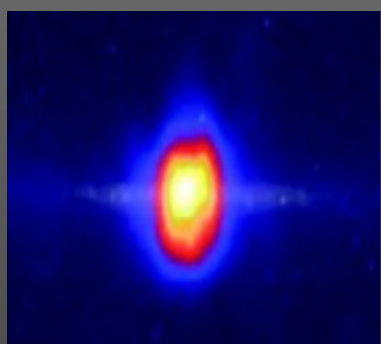


We have already many Hints of 'detection'!



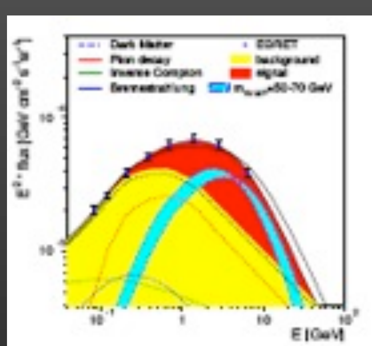
DAMA Direct Detection

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)



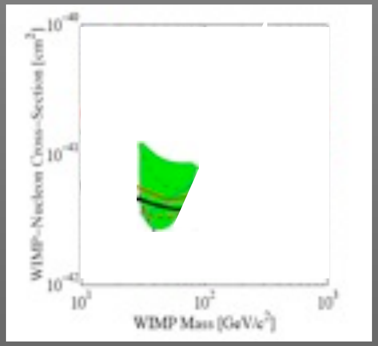
Gamma-rays: EGRET, HESS,

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

WMAP & Fermi Haze

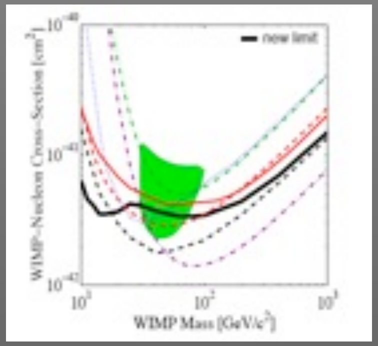
Evidence for: 100 GeV DM
See e.g. Finkbeiner 2004, Hooper, Dobler and Finkbeiner 2007; Dobler et al. 2009

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



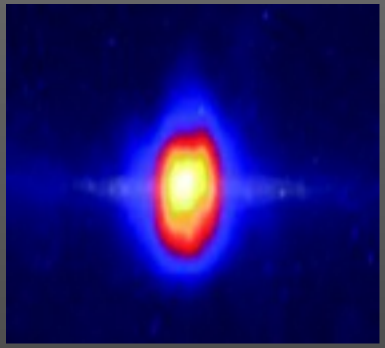
DAMA Direct Detection

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



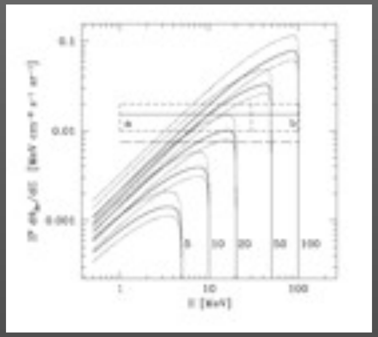
DAMA Direct Detection

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



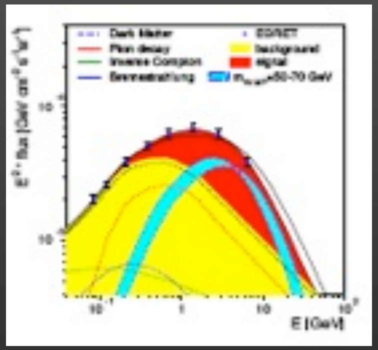
INTEGRAL 511 keV

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



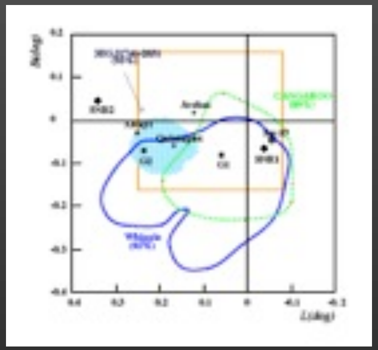
INTEGRAL 511 keV

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,

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



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..

Spectrum

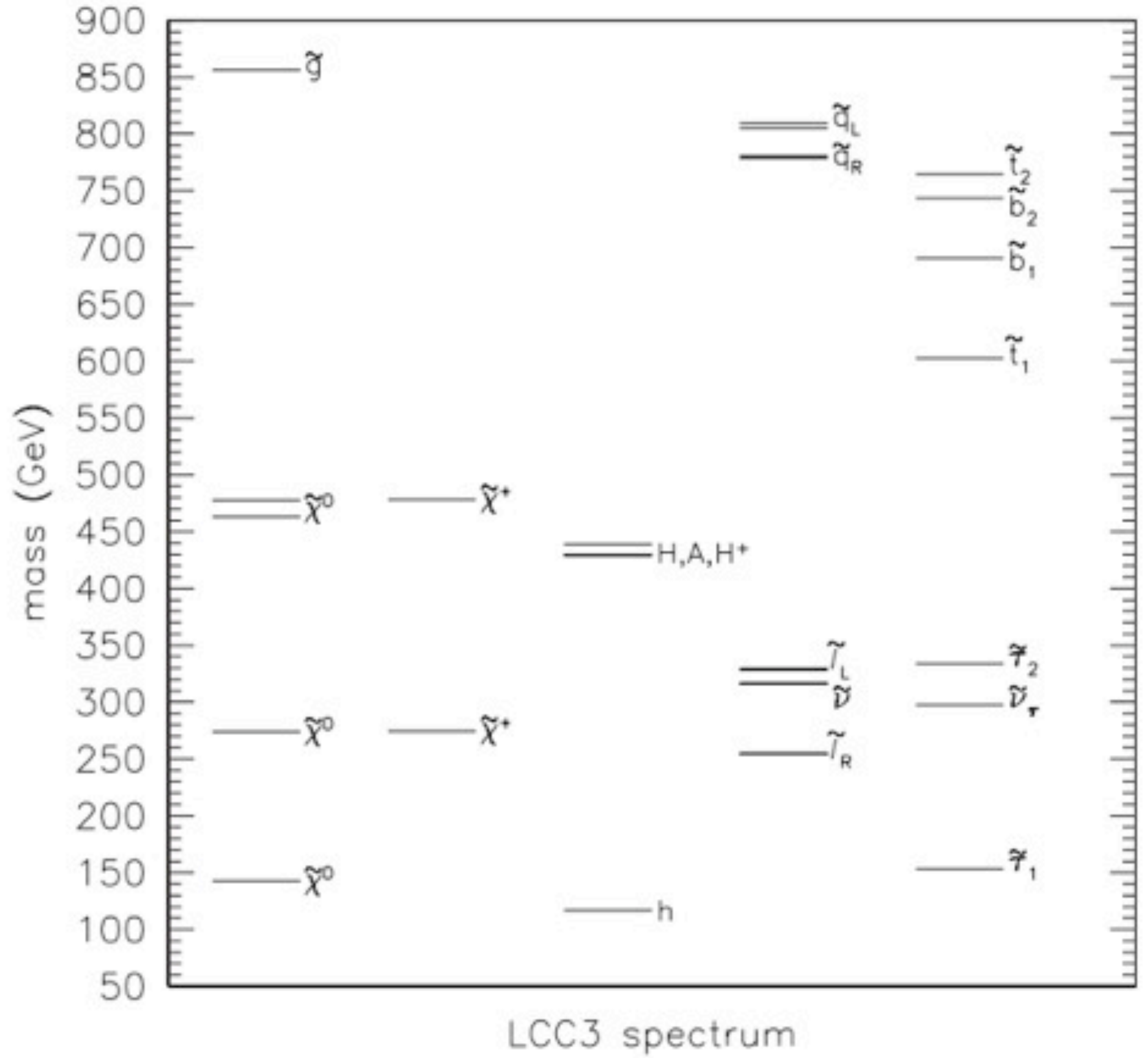
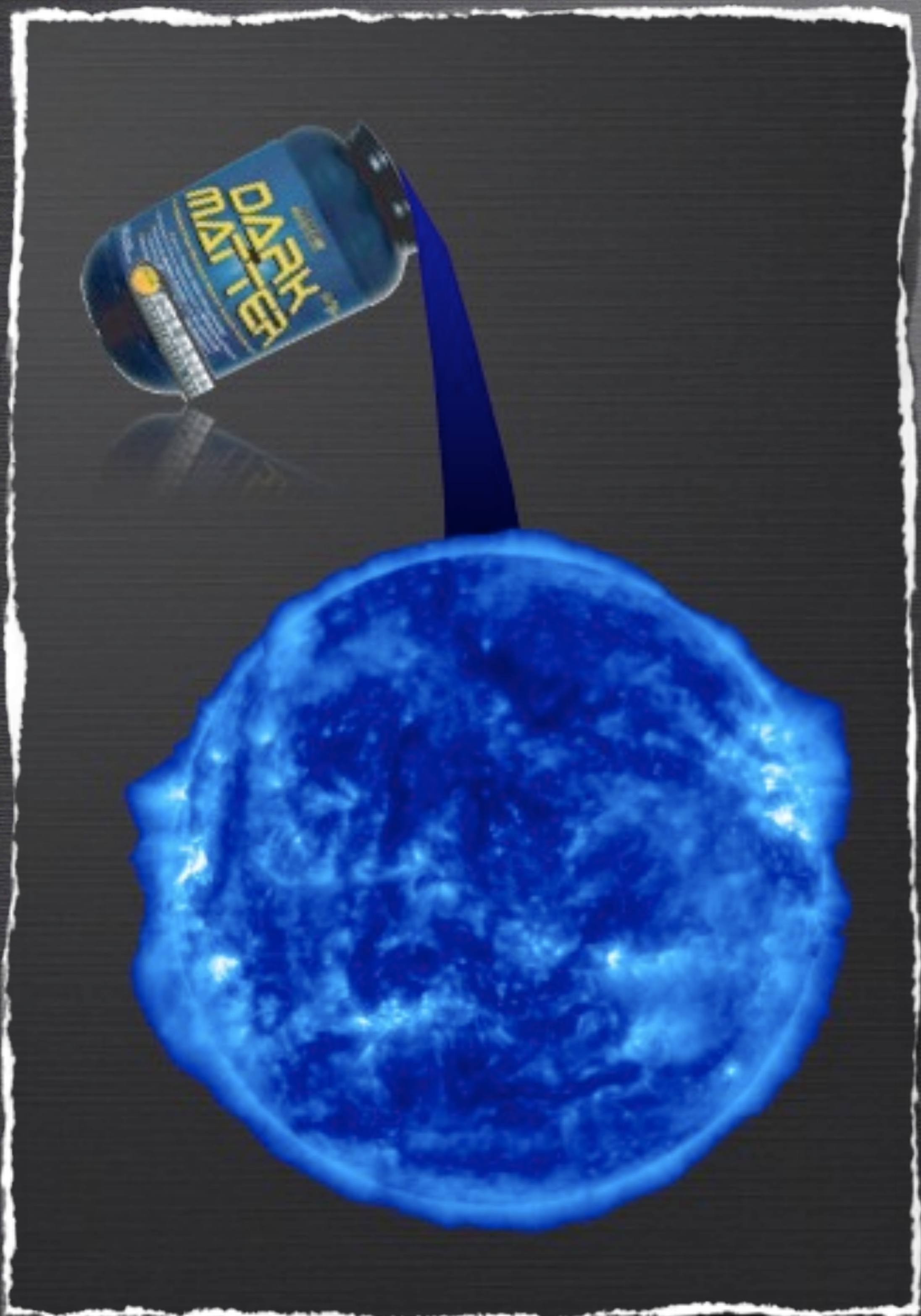
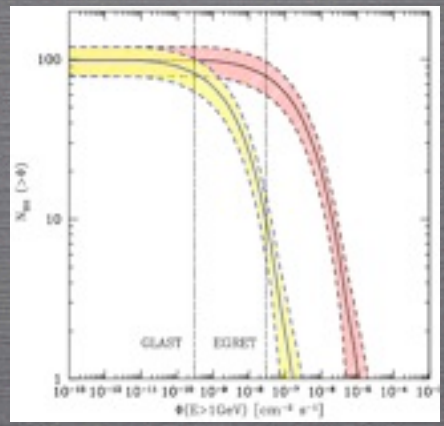


FIG. 34. Particle spectrum for point LCC3. The stau-neutralino mass splitting is 10.8 GeV. The lightest neutralino is predominantly *b*-ino, the second neutralino and light chargino are predominantly *W*-ino, and the heavy neutralinos and chargino are predominantly Higgsino.

Particle Spectrum, from Baltz et al. 2005

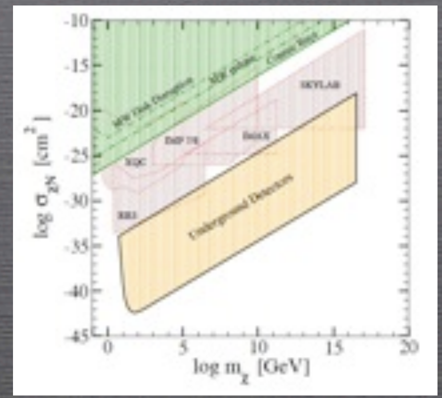
DM and Stars





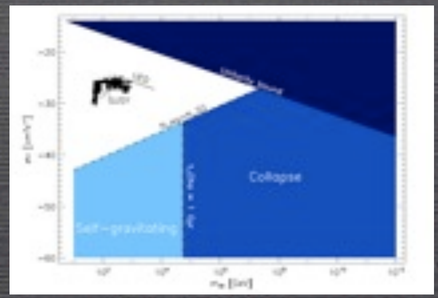
Effect on Supermassive and Intermediate Mass Black Holes

GB, Sigl and Silk 2002; GB and Merritt 2005, 2006; Ahn et al. 2006; GB, Zentner & Silk 2005; Taoso et al 2008; Fornasa and GB 2008; GB et al. 2009



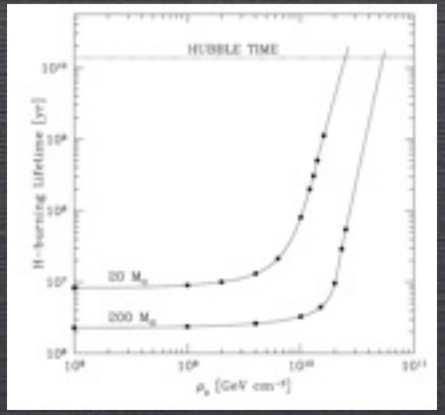
Effect on the Earth

Mack, Beacom and GB 2007



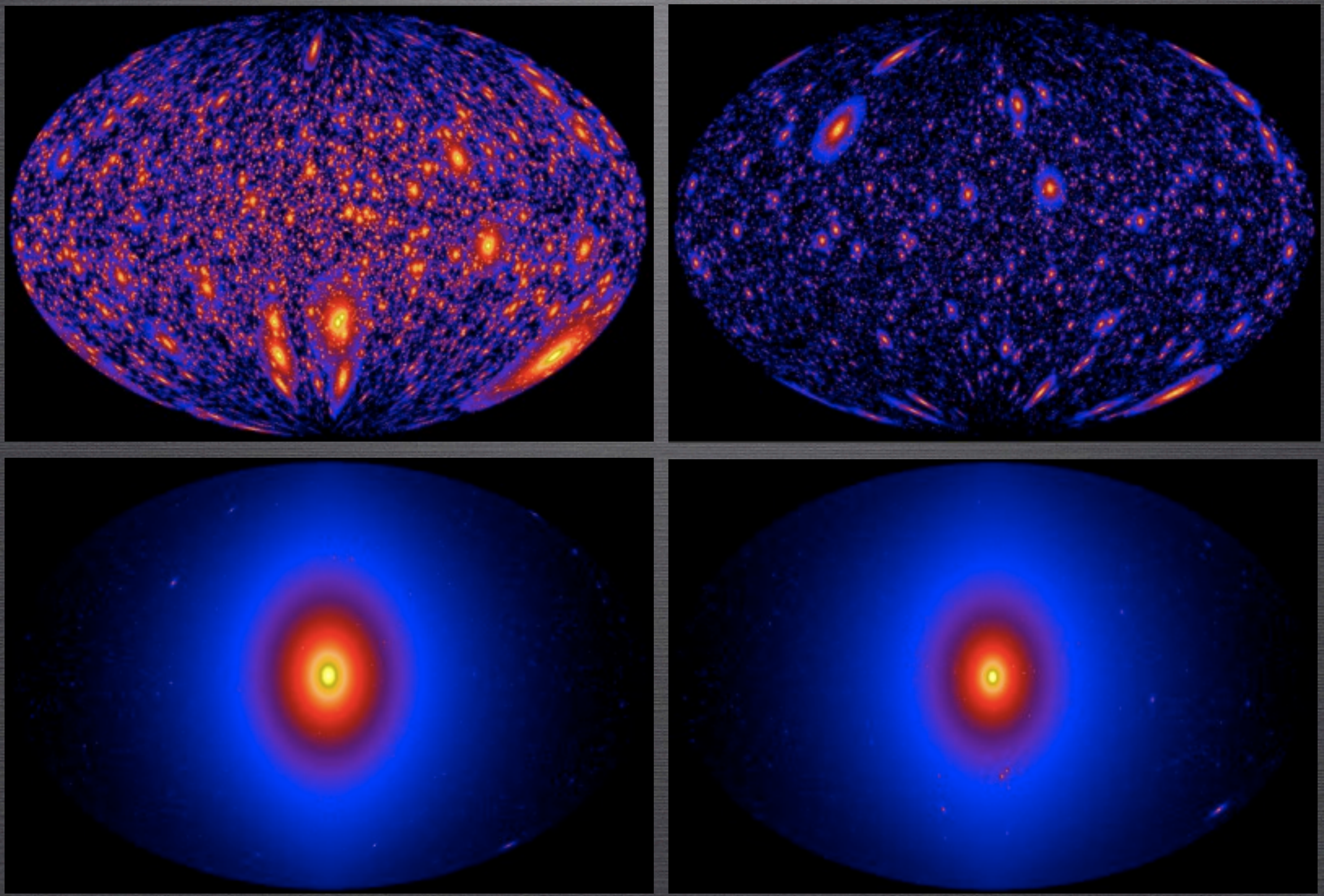
Effect on Compact Objects

GB and Fairbairn 2008



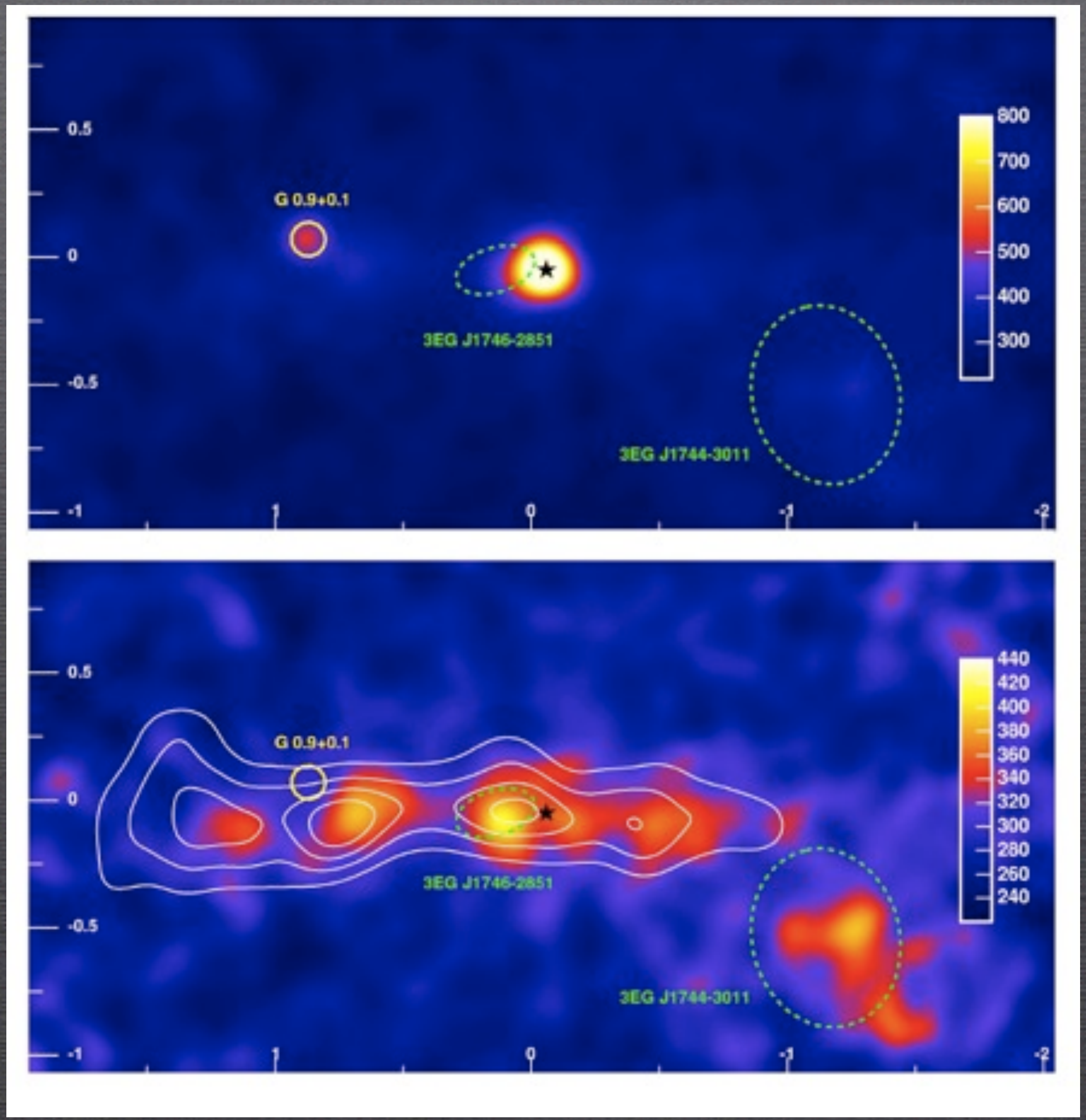
Effect on Stars (Pop III & Sun)

GB, Lopes & Silk 2002; GB, Taoso and Meynet 2007; GB, Iocco, Taoso and Meynet 2009



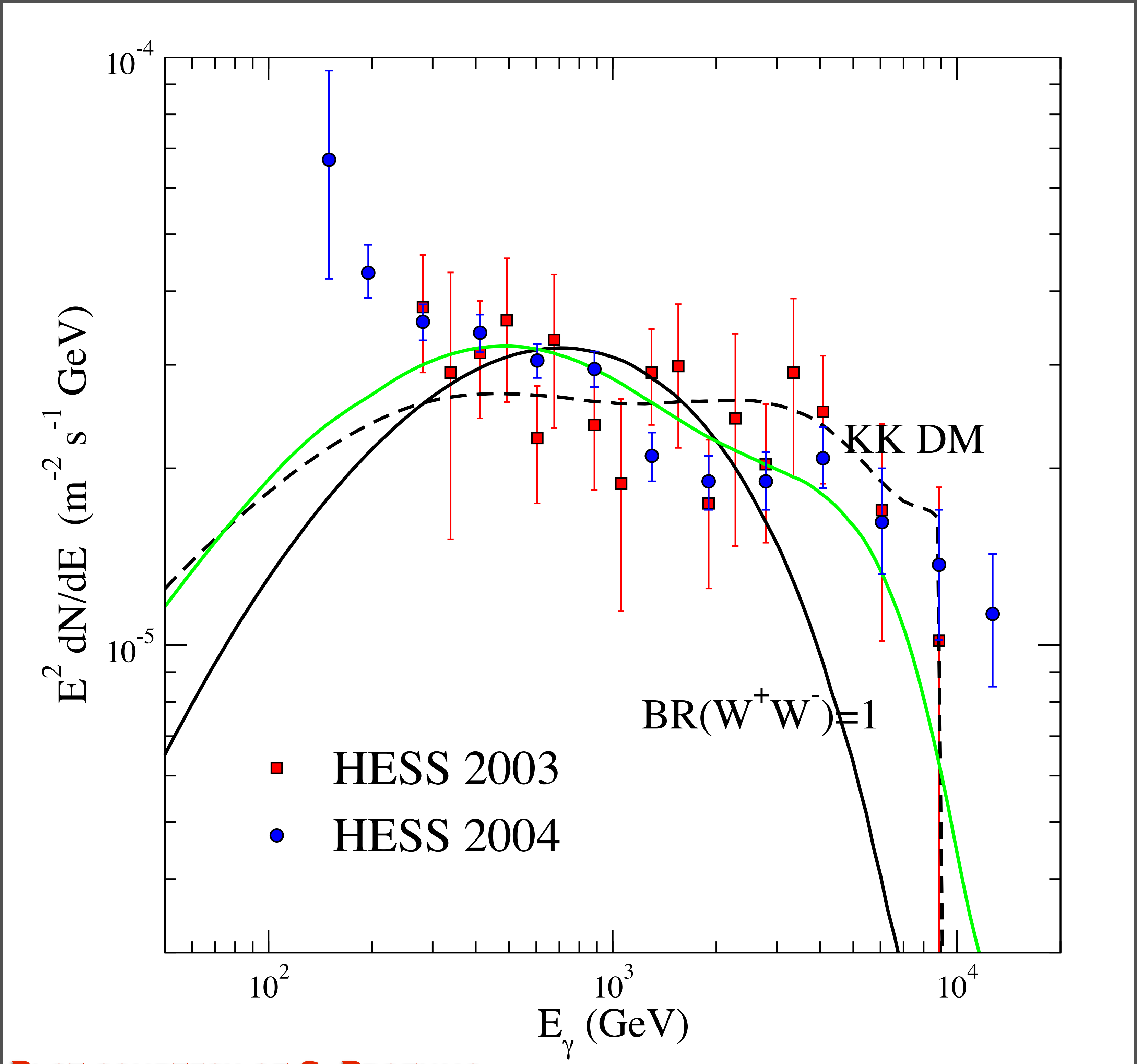
…and the Galactic Ridge

VHE Gamma-ray images of the GC region



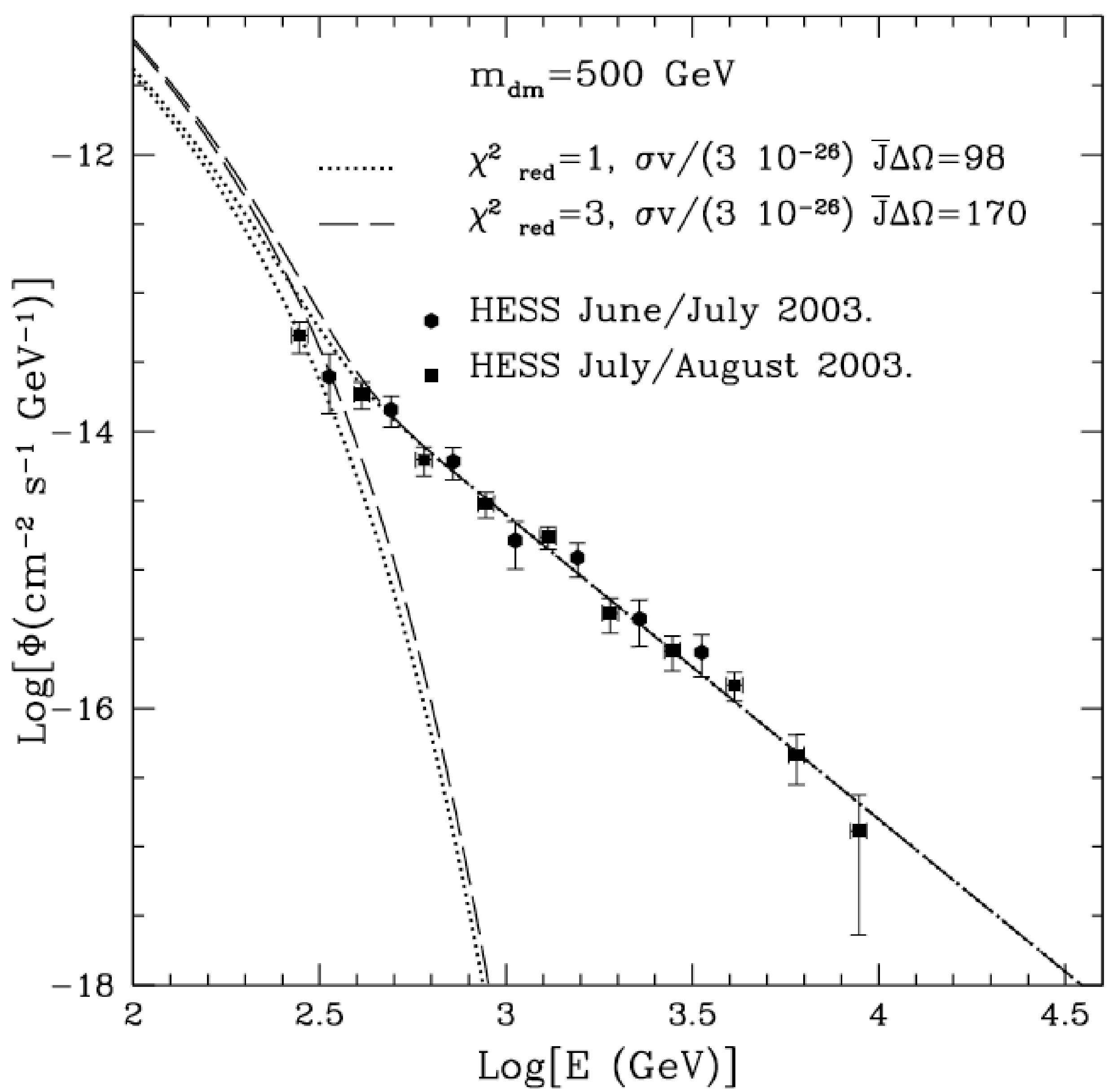
Aharonian et al. 2006

DM annihilations?



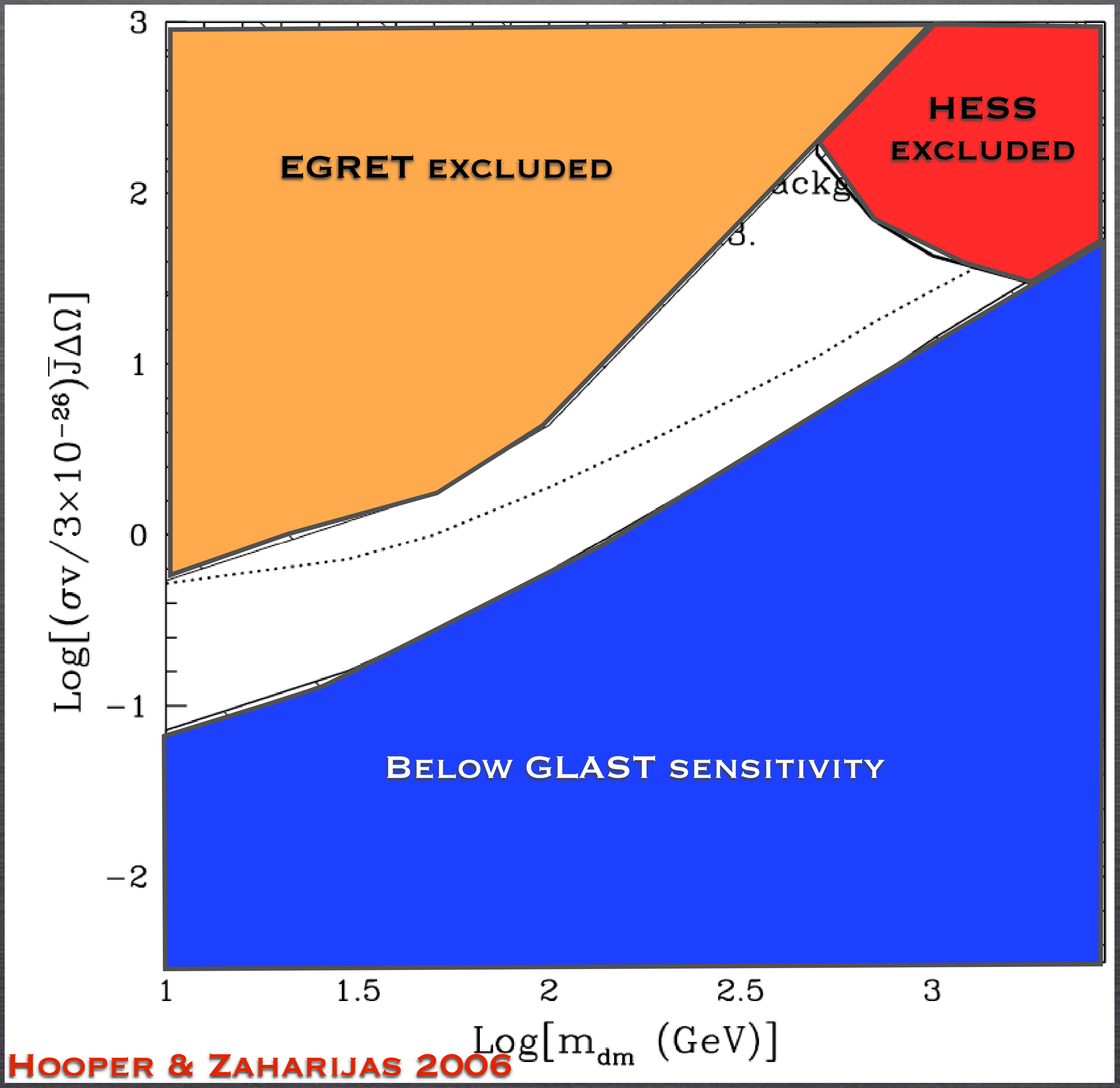
Plot courtesy of S. Profumo

Prospects for GLAST in light of the HESS (and MAGIC) results



Hooper & Zaharijas 2006

Prospects for GLAST in light of the HESS (and MAGIC) results



Hooper & Zaharijas 2006

The WIMP Forest

GB, Jackson, Shaughnessy, Tait, Vallinotto 2009

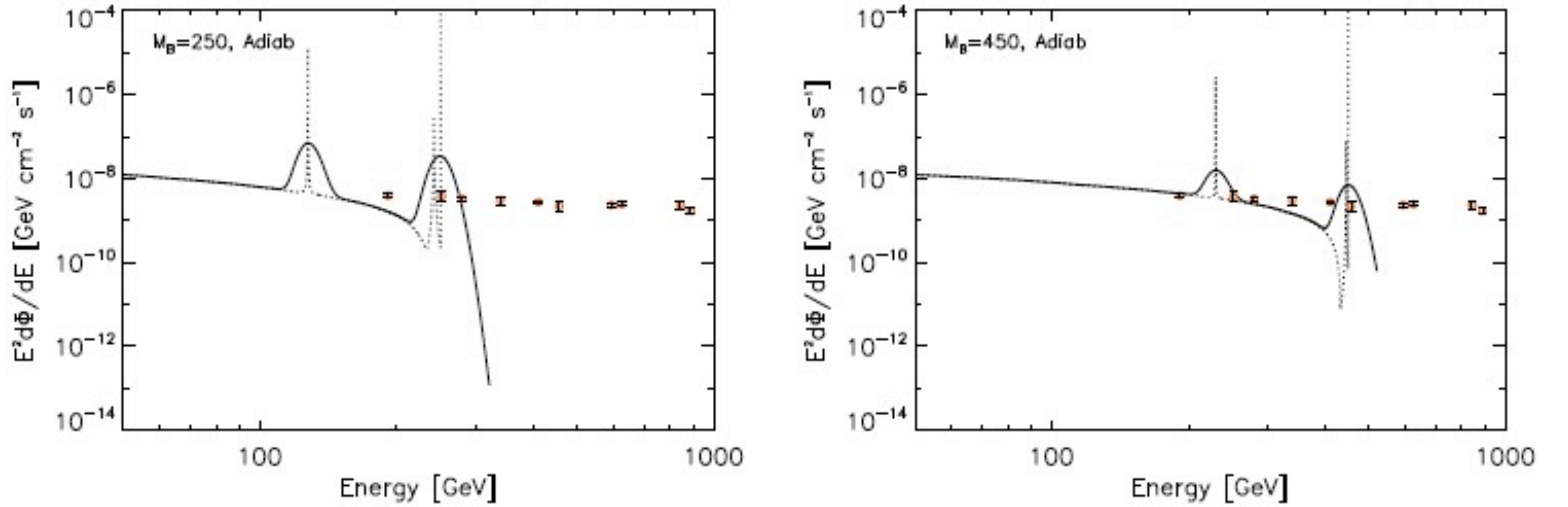
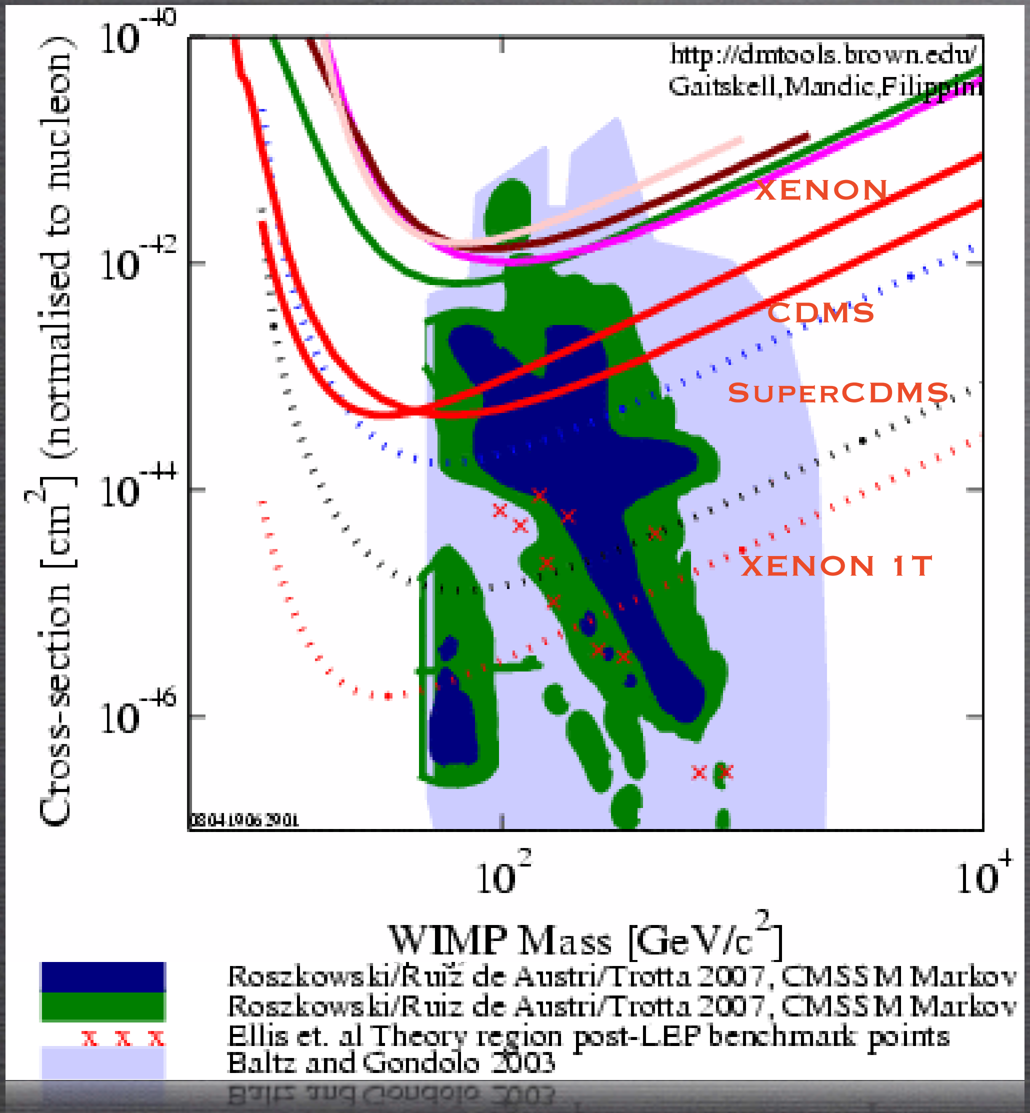


FIG. 4: Predicted fluxes, from a solid angle $\Delta\Omega = 10^{-5}$ towards the GC, for the chiral square model with $M_{B_H} = 250$ GeV (left column) and $M_{B_H} = 450$ GeV (right). We show both the actual spectrum (dotted lines) and the spectrum as it would be observed by an experiment with a 10% energy resolution (solid) like Fermi LAT. An NFW (adiabatically compressed) profile has been adopted for the lower (upper) panels. We show for reference the HESS data relative to the gamma-ray source detected at the Galactic center.

$$E_\gamma = m_{DM}\left(1 - \frac{M_X^2}{4m_{DM}^2}\right)$$

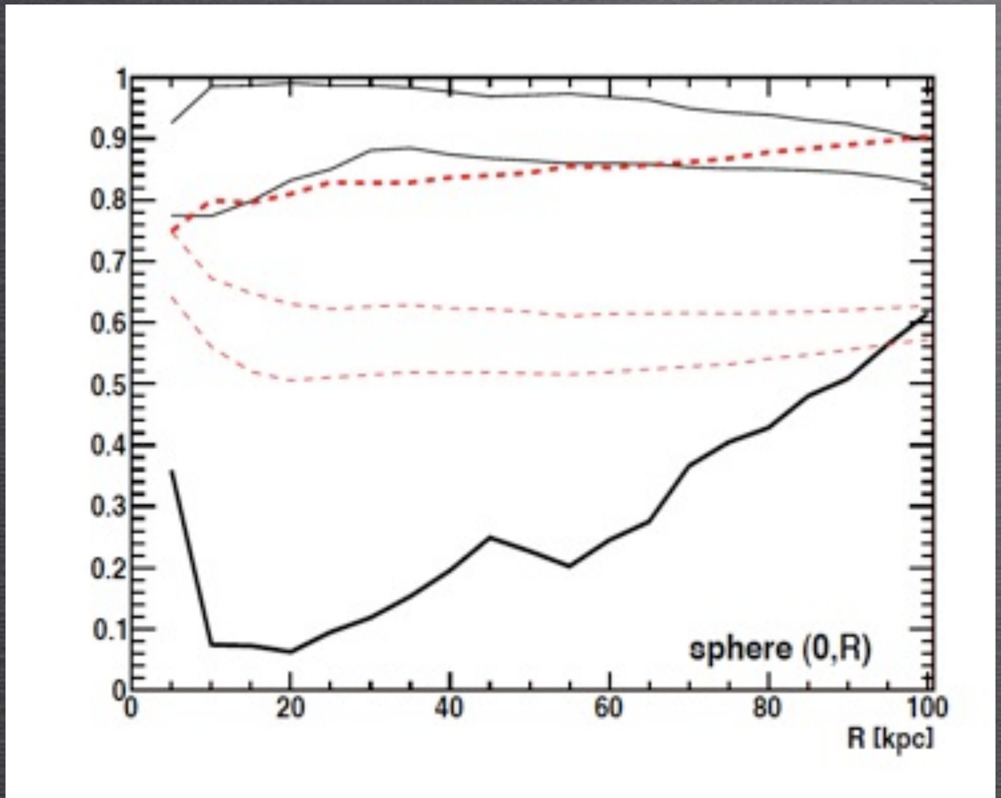
Direct Detection

status



- Xenon and CDMS are the current leaders on spin-independent cross-sections
- Future reach should cover large portion (but not all) of the SUSY parameter space

Triaxial Halos



Pato, GB, Agertz, Teyssier, Moore 2010