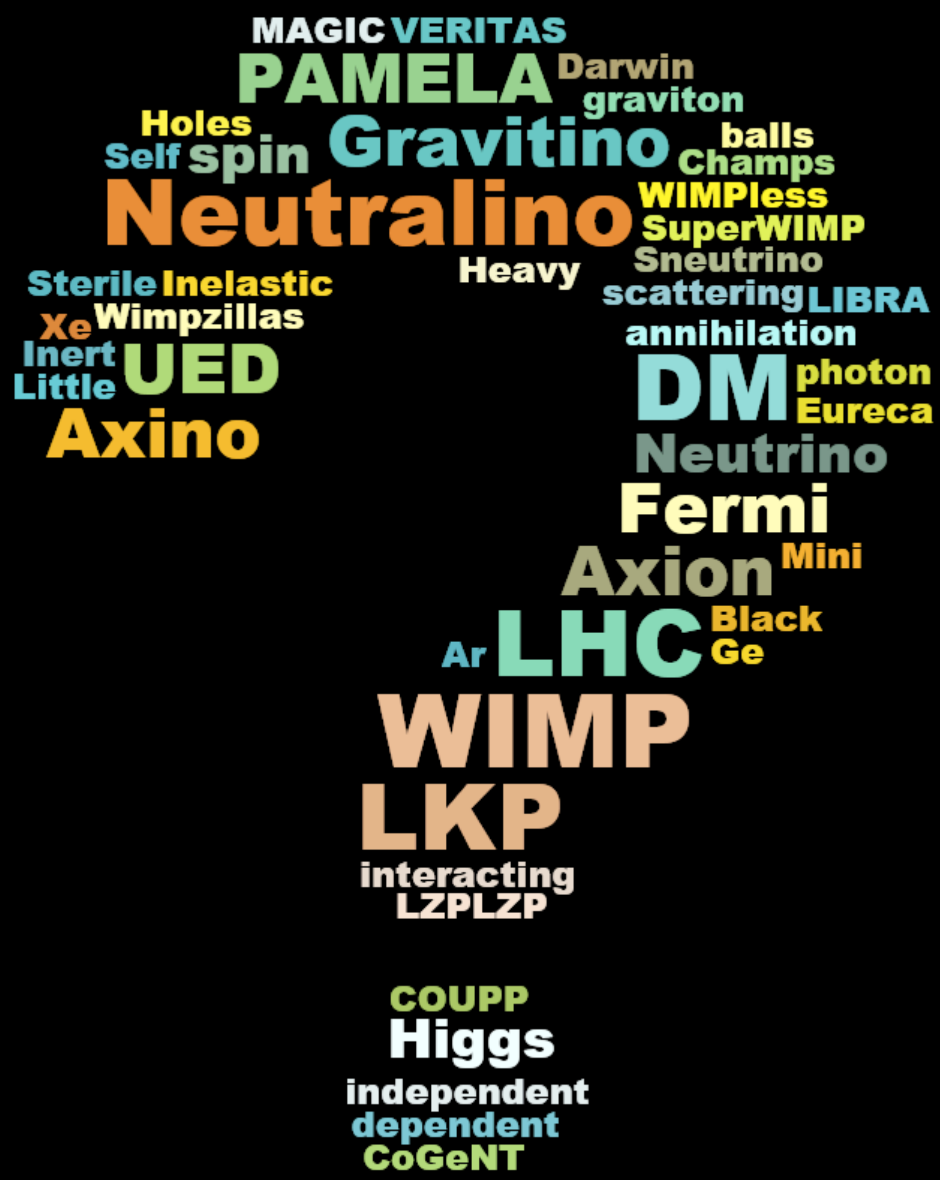
Identifying Dark Matter

Gianfranco Bertone



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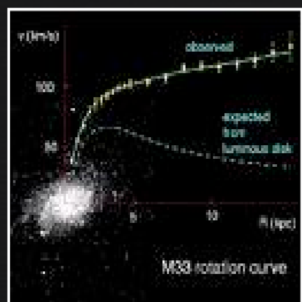
Summary

- 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

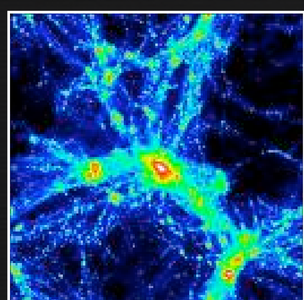
Evidence for Dark Matter

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

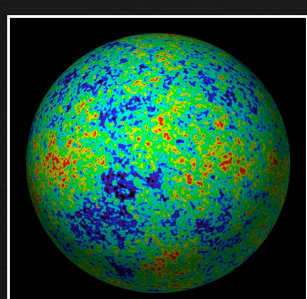
Cosmological observations



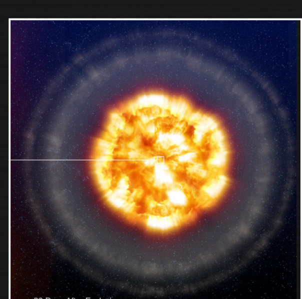
- Rotation Curves



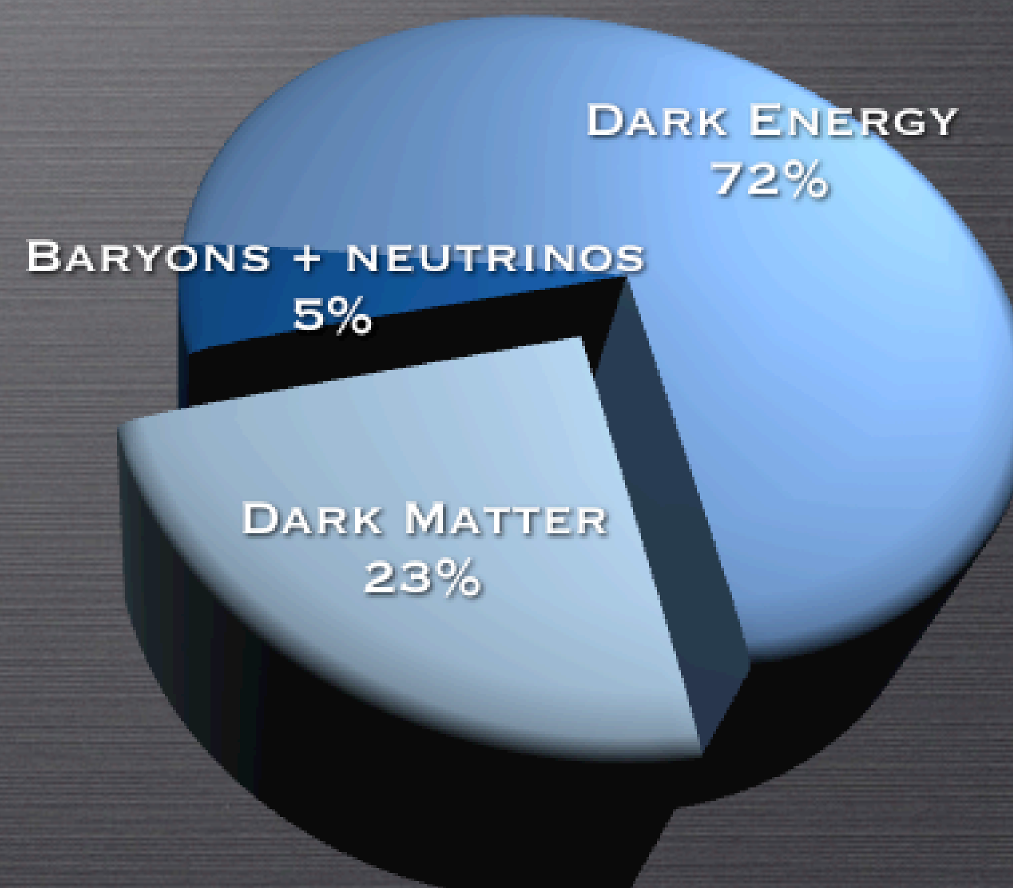
- Clusters of galaxies



- CMB



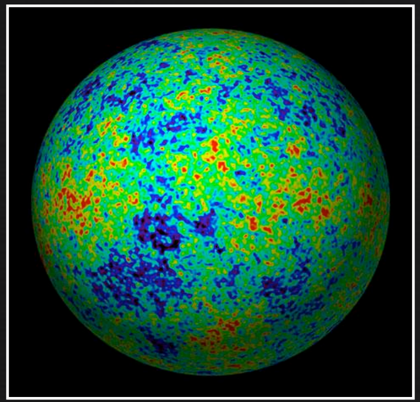
- Type Ia Supernovae



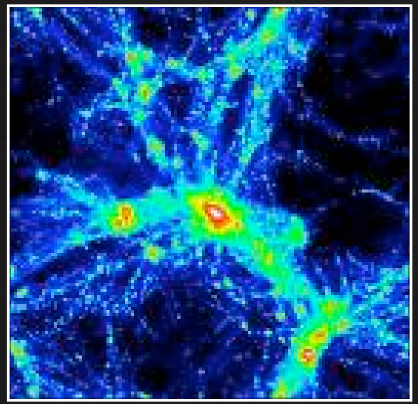
What do we know?

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?

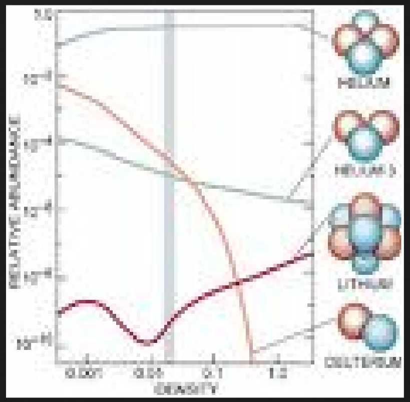


2) Is it cold?

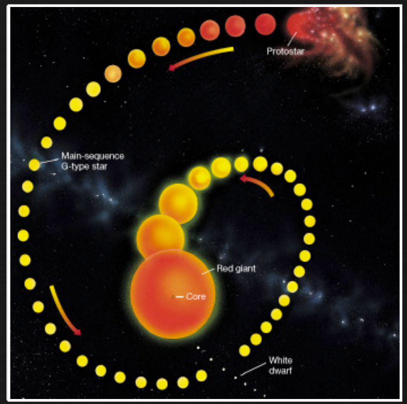


3) Is it neutral?

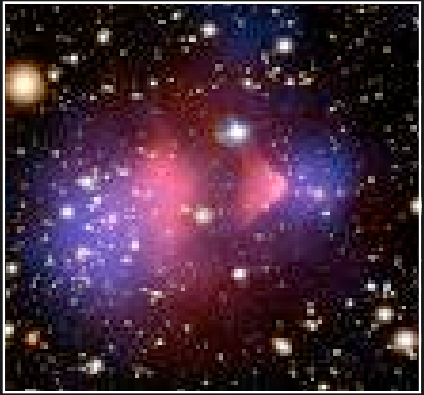
4) Is BBN ok?



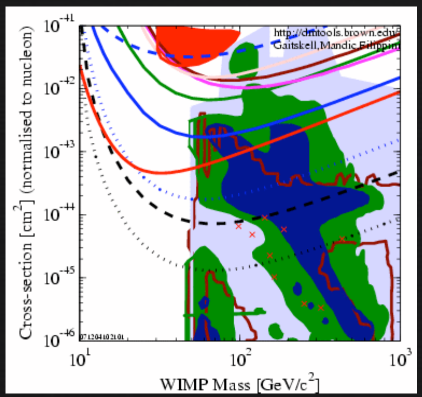
5) Stars OK?



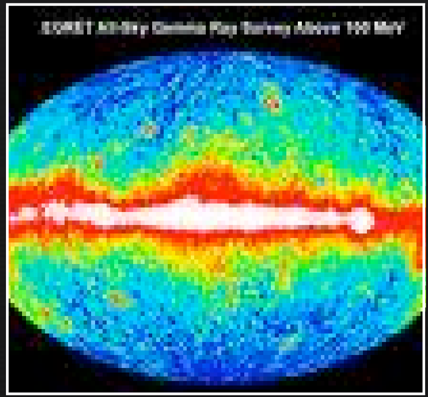
6) Collisionless?



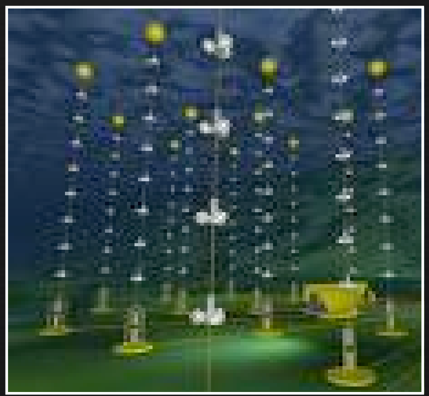
7) Couplings OK?



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

Taoso, GB & Masiero 2007

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.

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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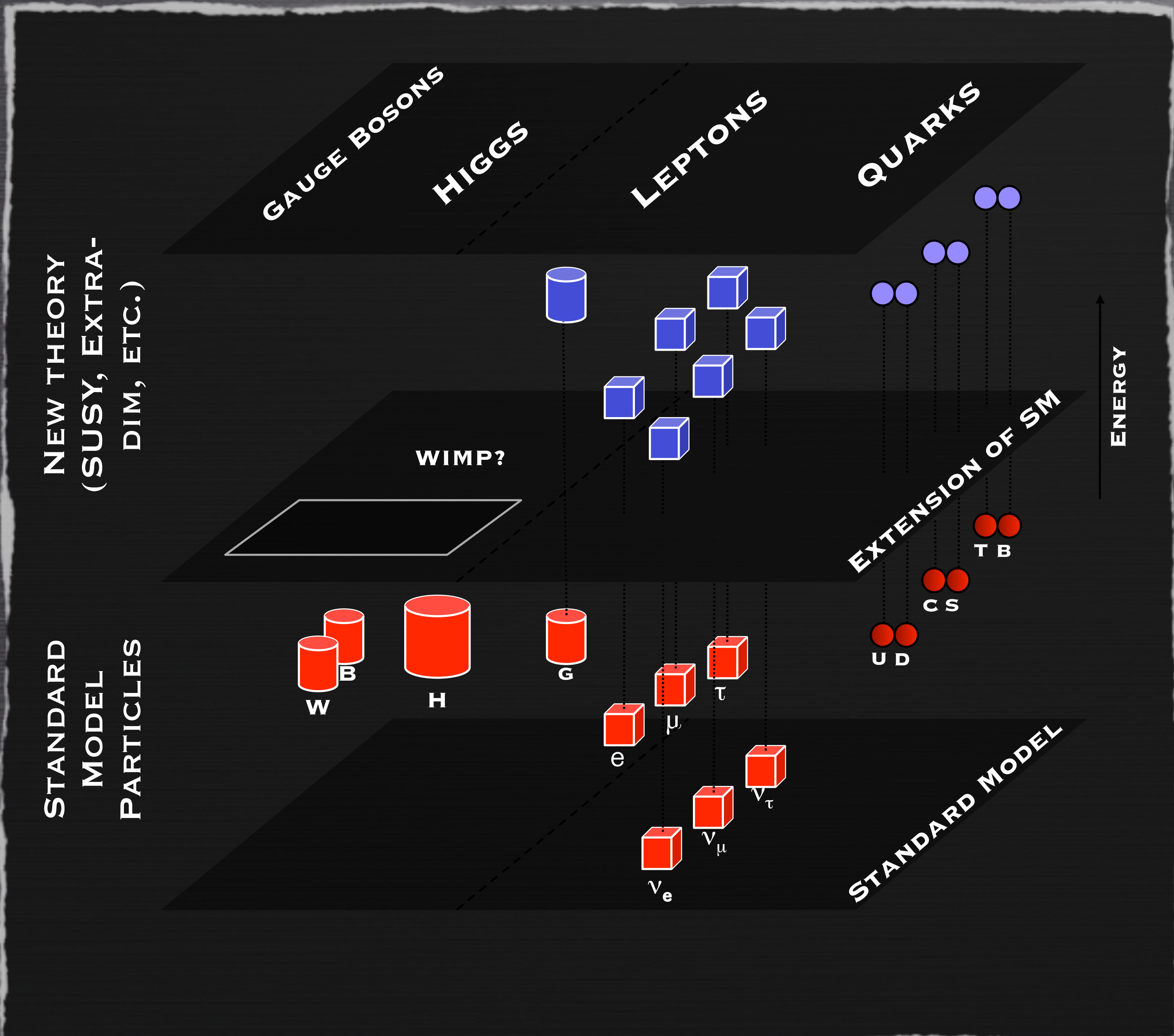
BEYOND THE STANDARD MODEL

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

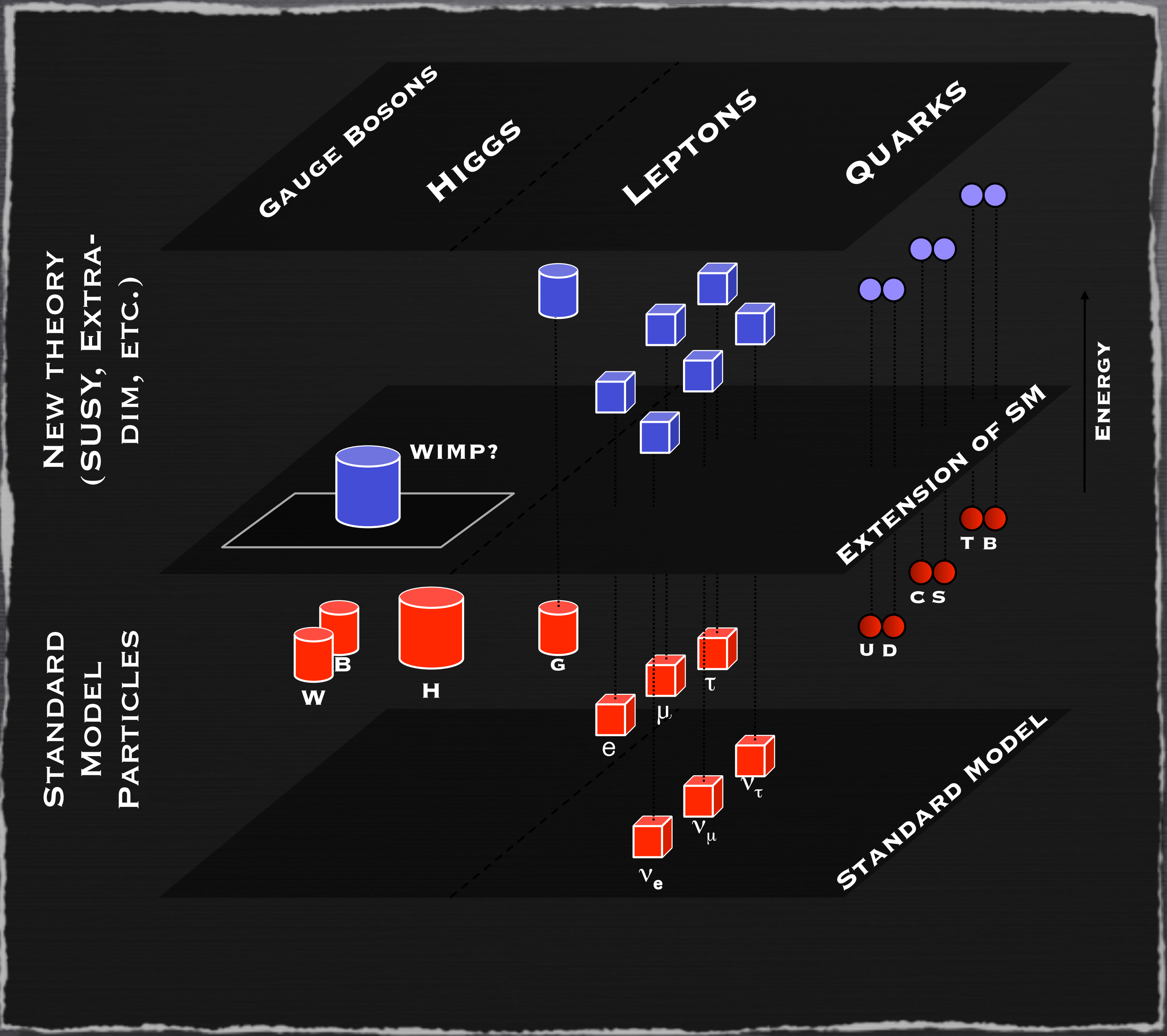


TO EXPLAIN THE ORIGIN OF THE WEAK SCALE, EXTENSIONS OF THE STANDARD MODEL OFTEN POSTULATE THE EXISTENCE OF NEW PHYSICS AT ~100 GEV

ON THE LEFT, SCHEMATIC VIEW OF THE STRUCTURE OF POSSIBLE EXTENSIONS OF THE STANDARD MODEL

Beyond the Standard Model

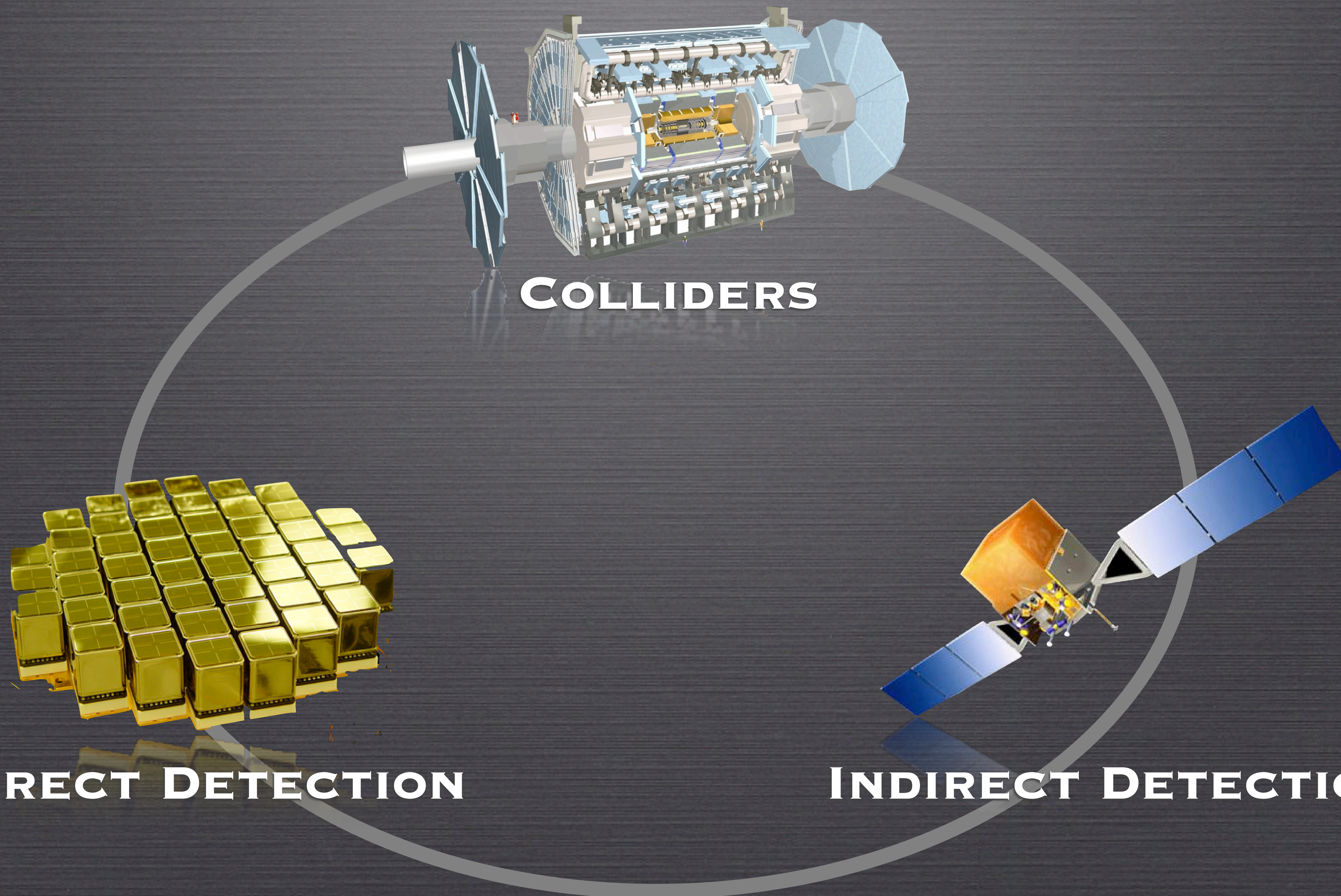
The Standard Model provides an accurate description of all known particles and interactions, however there are good reasons to believe that the Standard model is a low-energy limit of a more fundamental theory



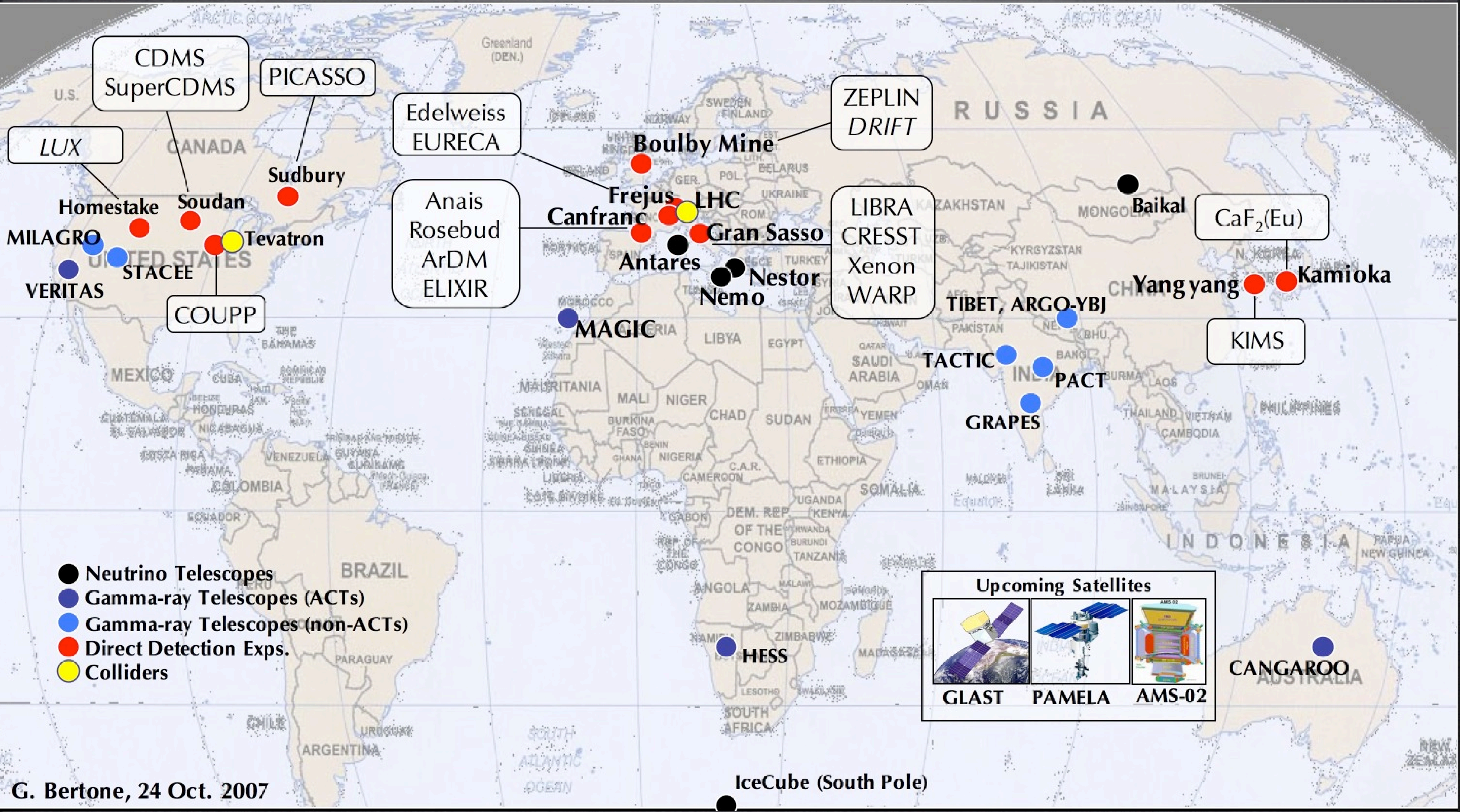
To explain the origin of the weak scale, extensions of the Standard Model often postulate the existence of new physics at ~100 GeV

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 2009



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

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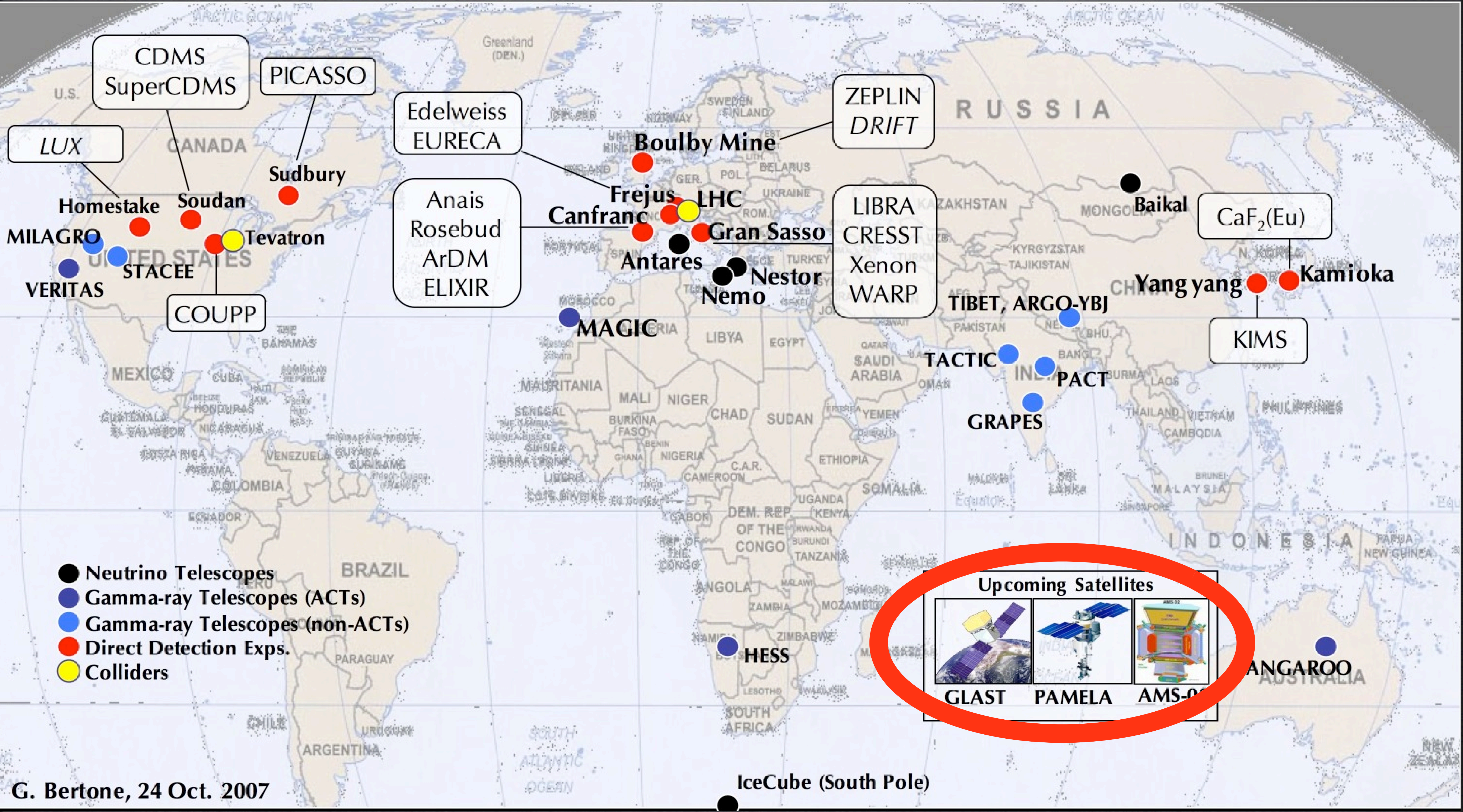

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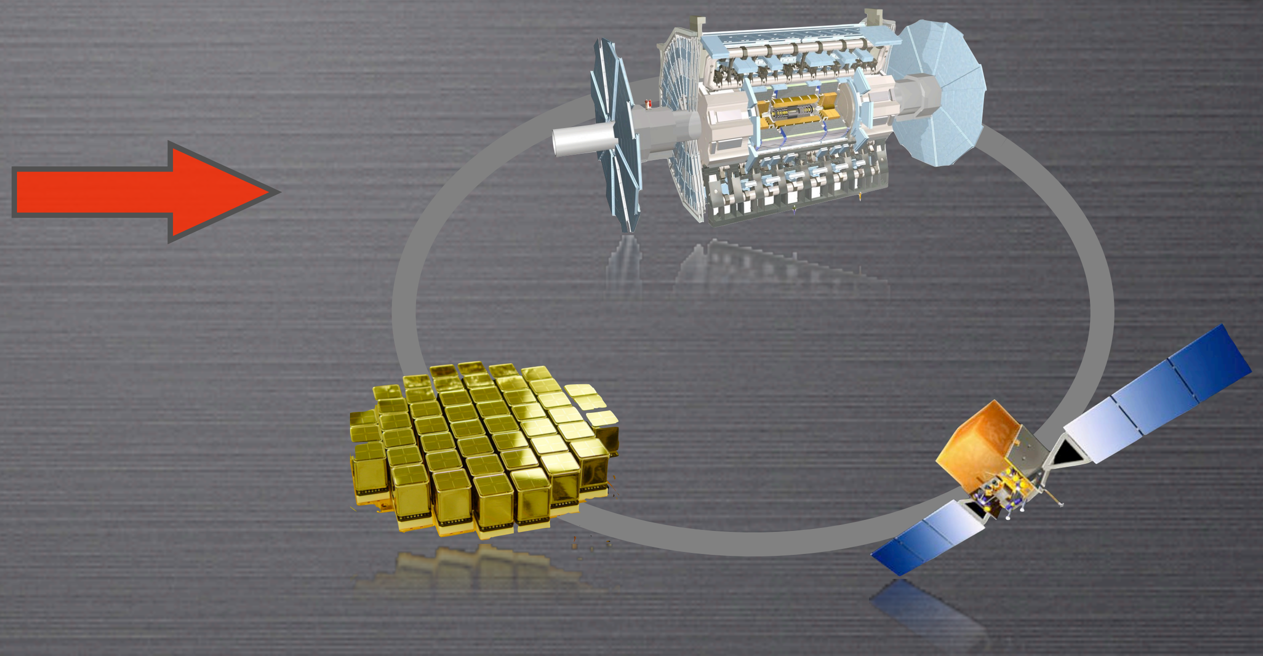
Where do we stand?

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



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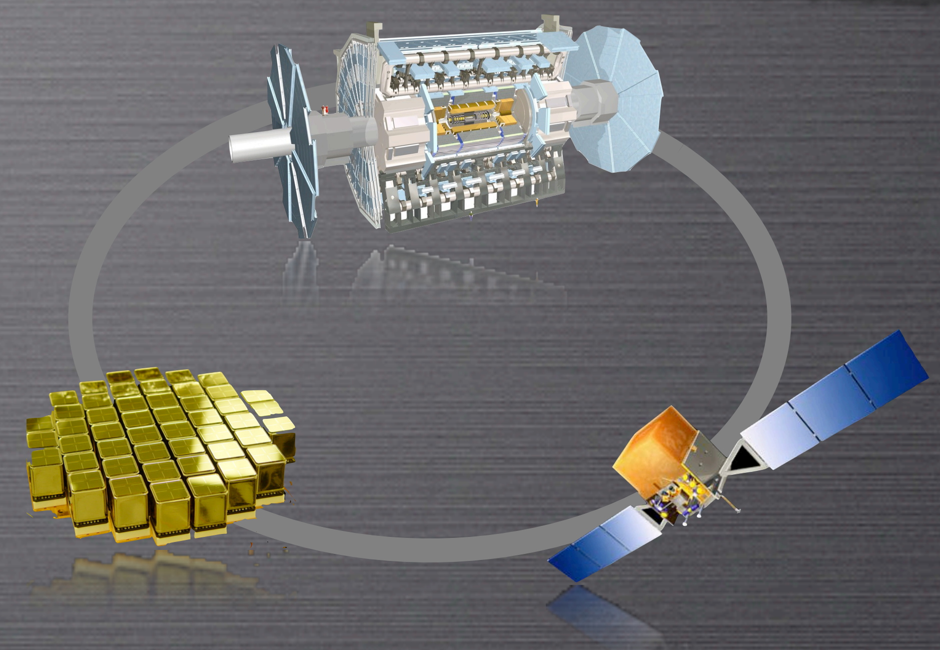
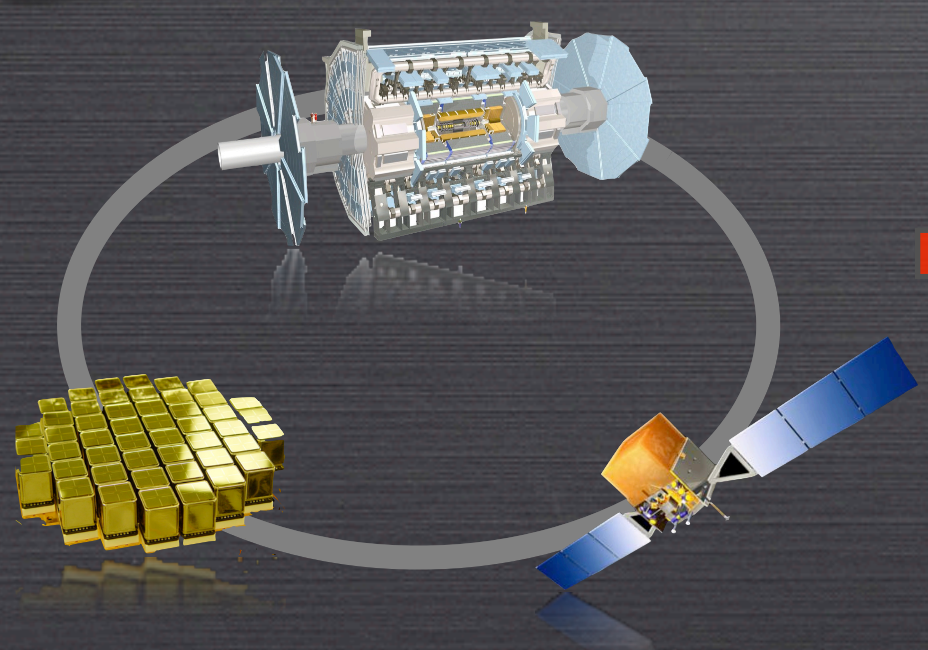


We are getting ready to solve the "inverse Problem" (and hoping that there will be a problem to solve..!)



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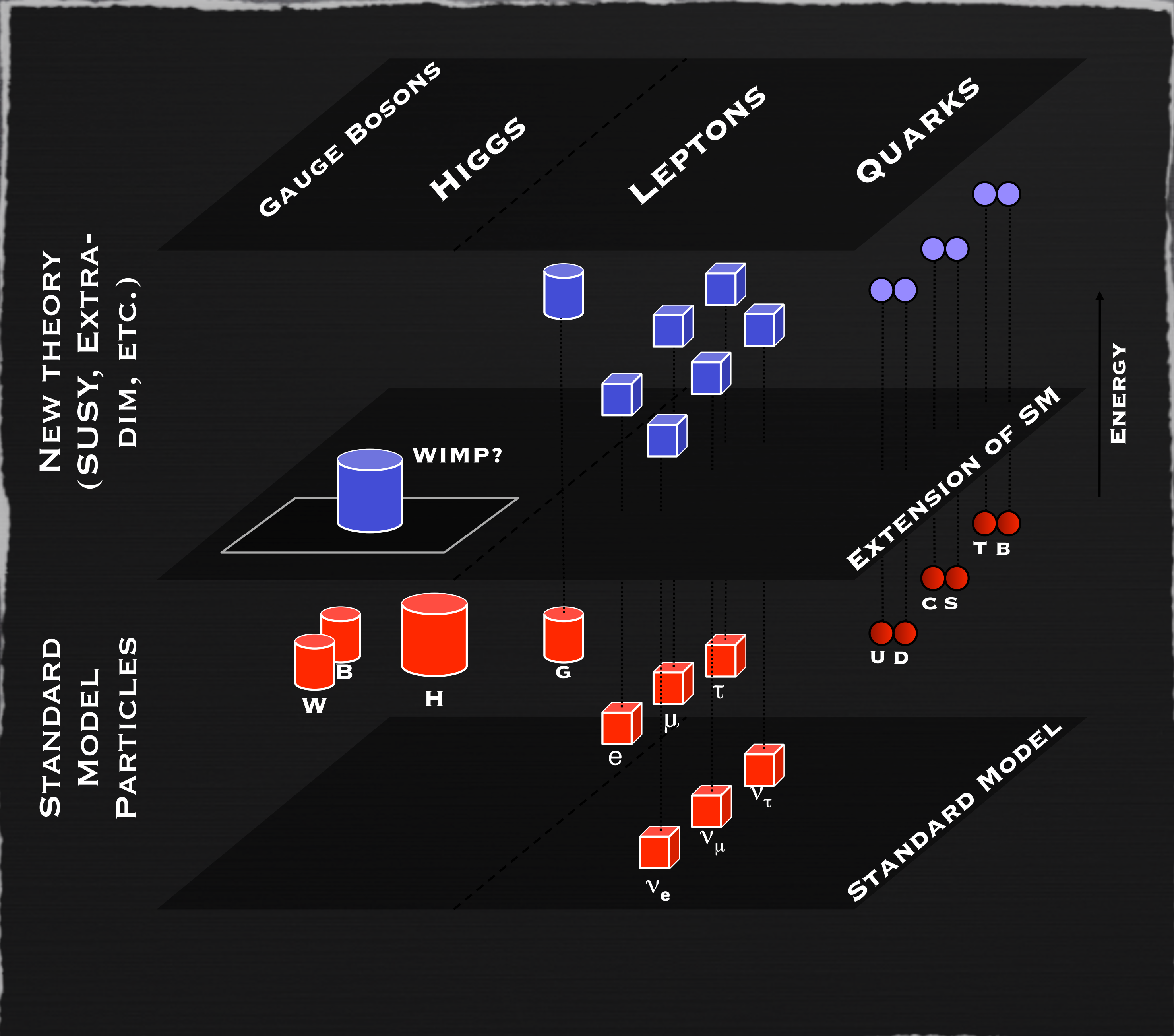
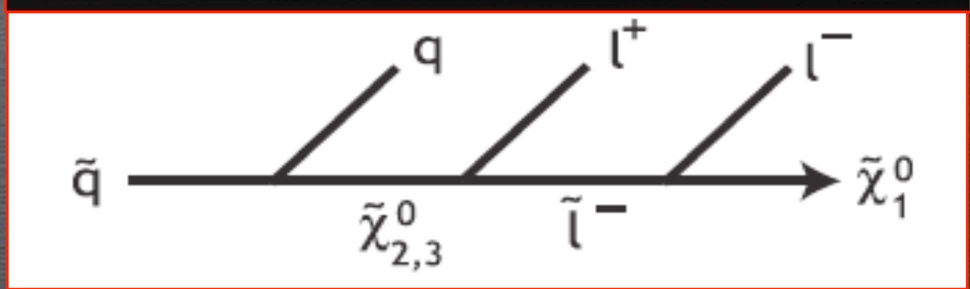
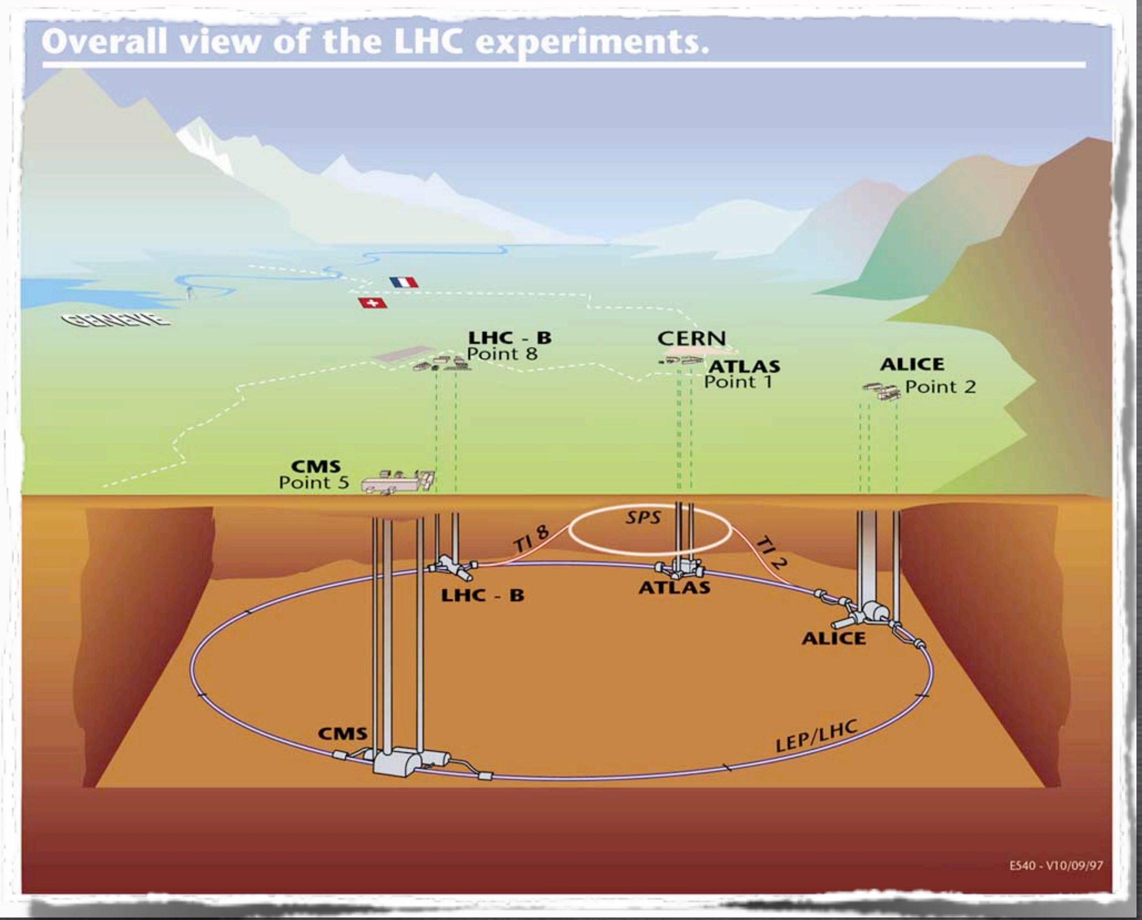
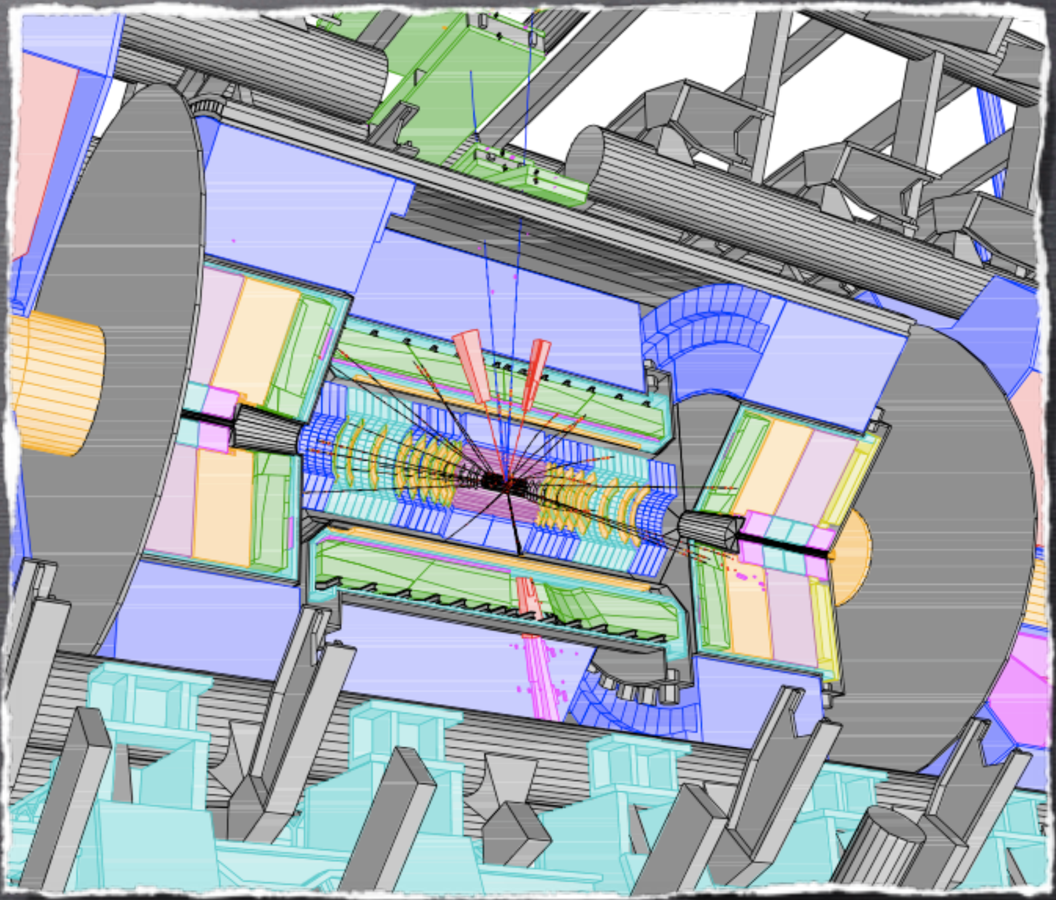


Search at LHC for processes like e.g.



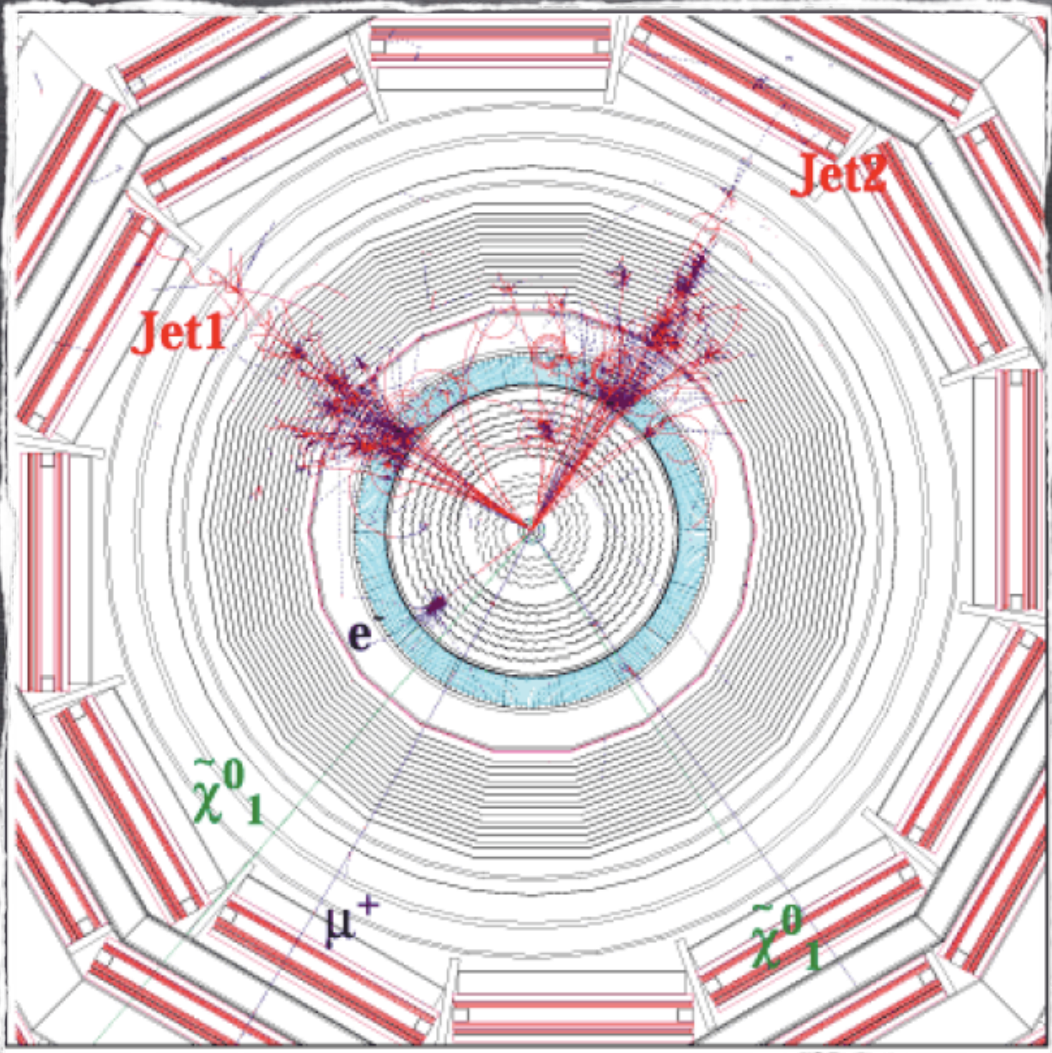
Searching for New Physics at the LHC



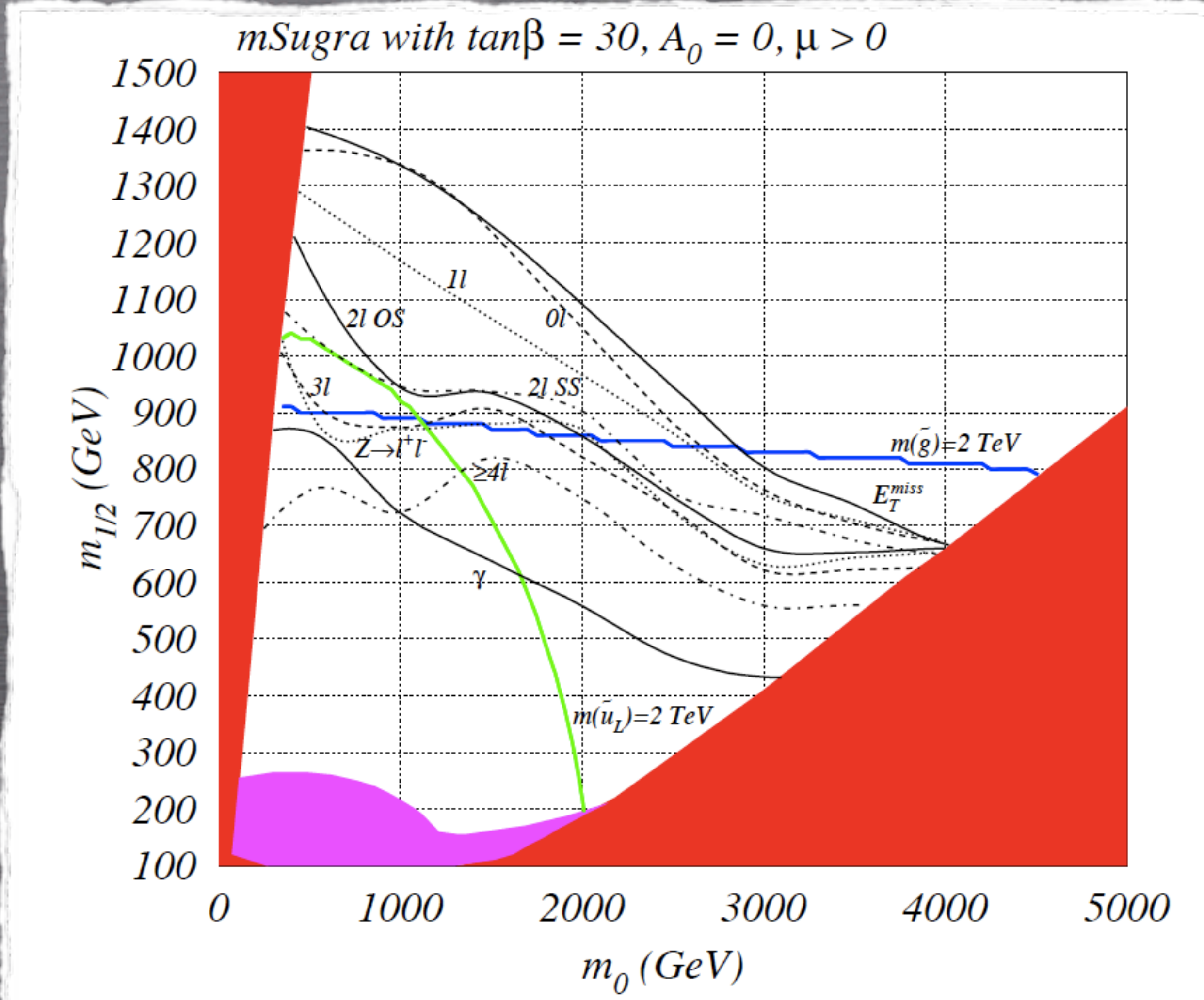


Searching for New Physics at the LHC

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:

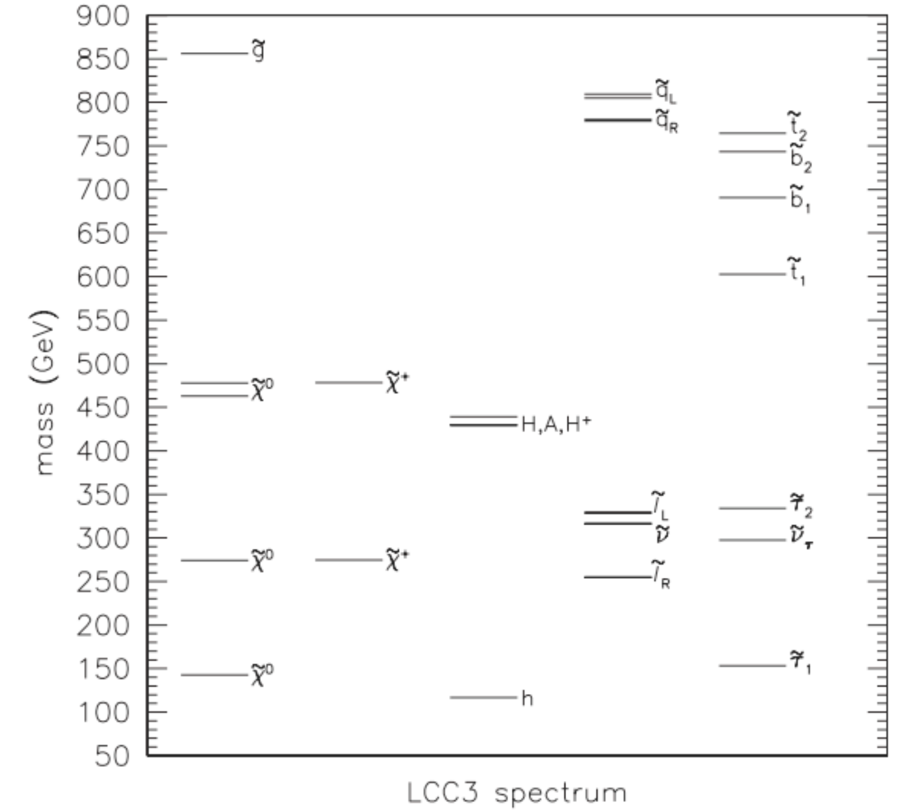
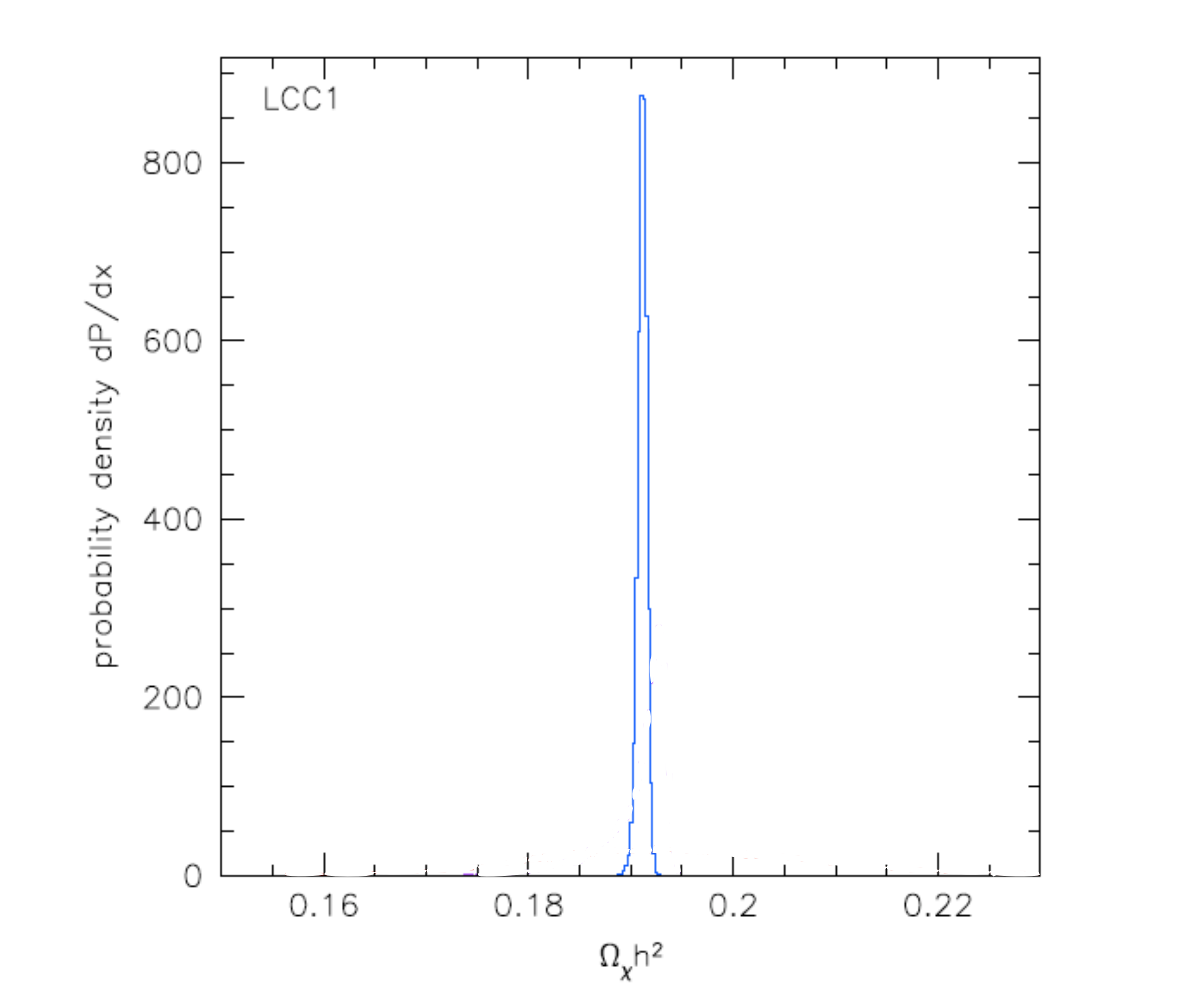
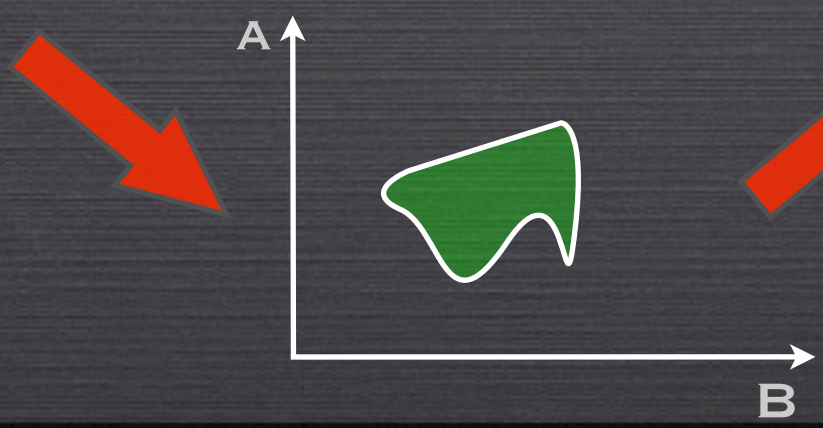


FIG. 34. Particle spectrum for point LCC3. The stau-neutralino mass splitting is 10.8 GeV. The lightest neutralino is predominantly *b*-ino, the second neutralino and light chargino are predominantly *W*-ino, and the heavy neutralinos and chargino are predominantly Higgsino.



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



Example of Inverse problem at LHC

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

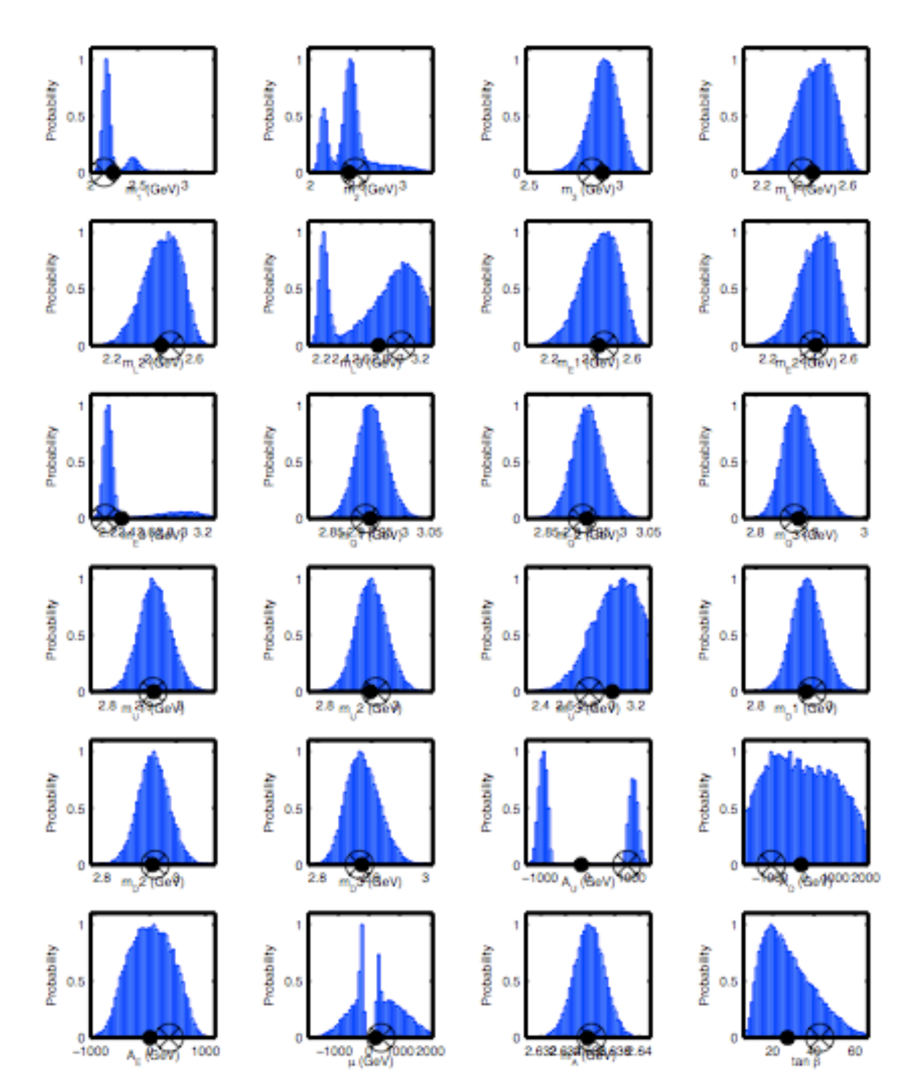
Mass	Benchmark value, μ	LHC error, σ
$m(\tilde{\chi}_1^0)$	139.3	14.0
$m(\tilde{\chi}_2^0)$	269.4	41.0
$m(\tilde{e}_R)$	257.3	50.0
$m(\tilde{\mu}_R)$	257.2	50.0
$m(h)$	118.50	0.25
$m(A)$	432.4	1.5
$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0)$	16.4	2.0
$m(\tilde{u}_R)$	859.4	78.0
$m(\tilde{d}_R)$	882.5	78.0
$m(\tilde{s}_R)$	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-anihilation 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



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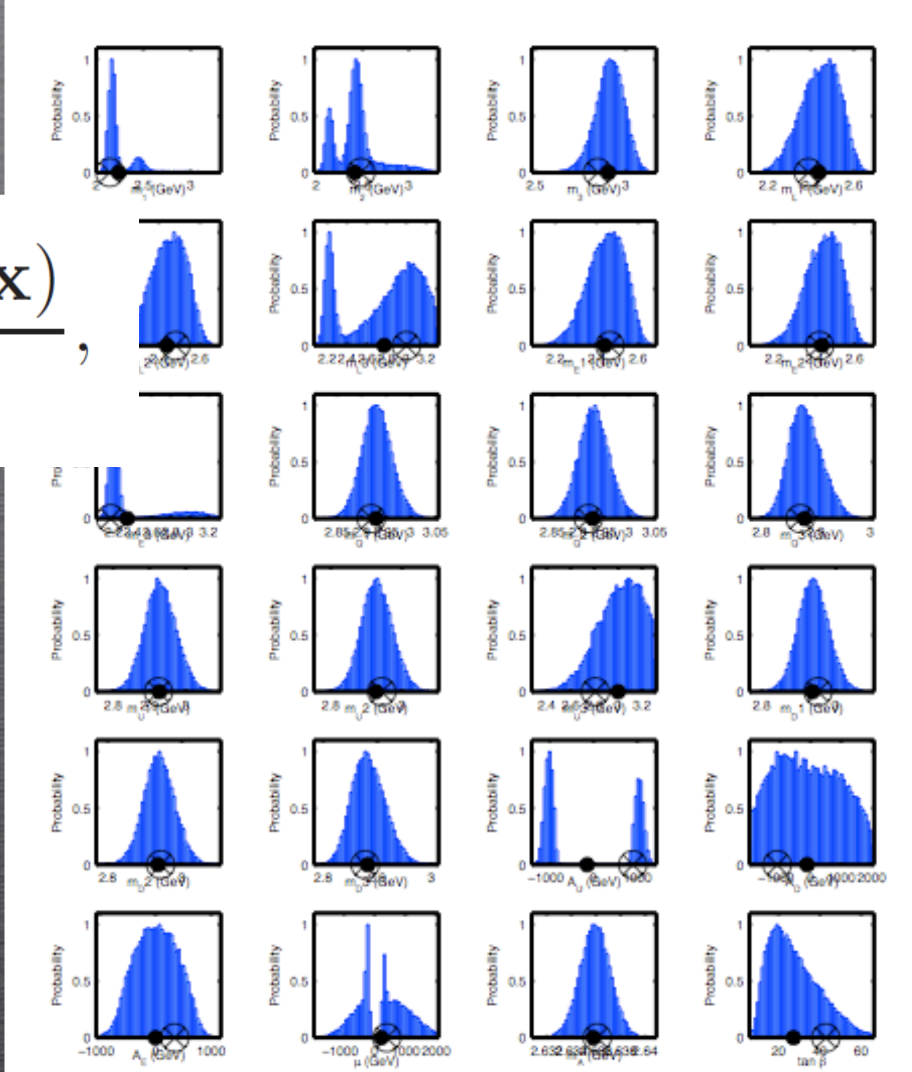

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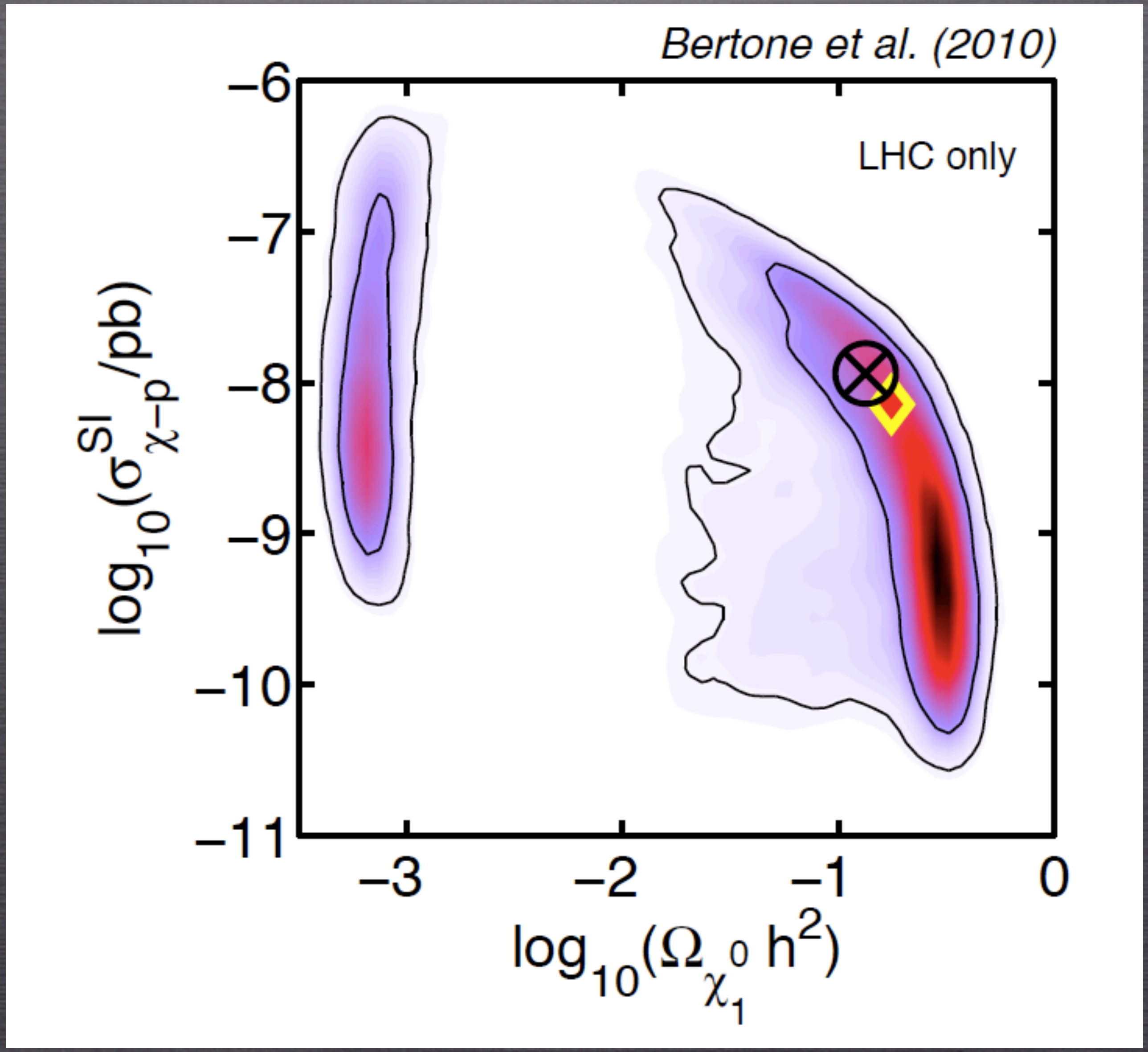
what we will most probably get
(example in the stau coannihilation region, 24 parms MSSM)



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

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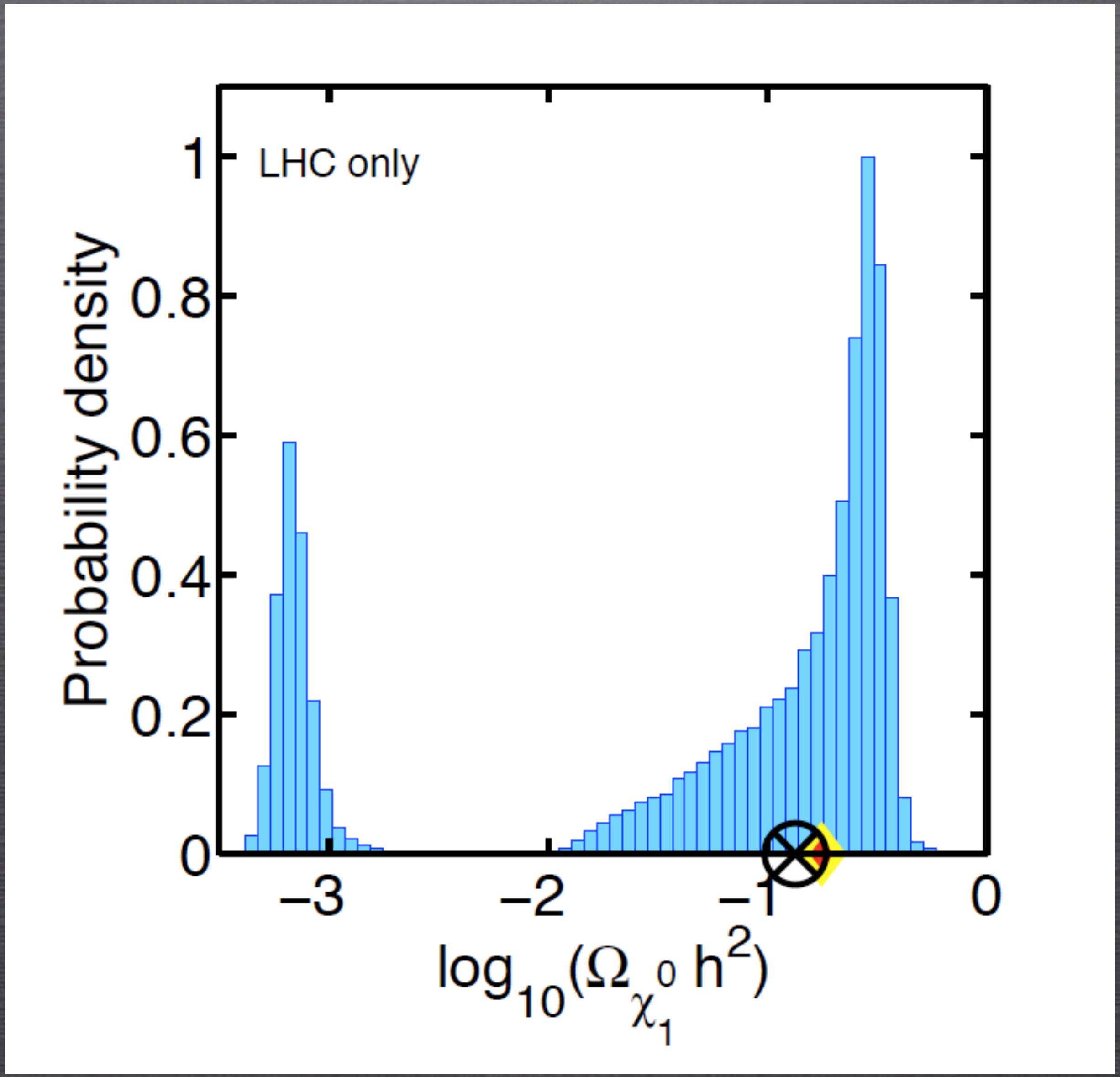
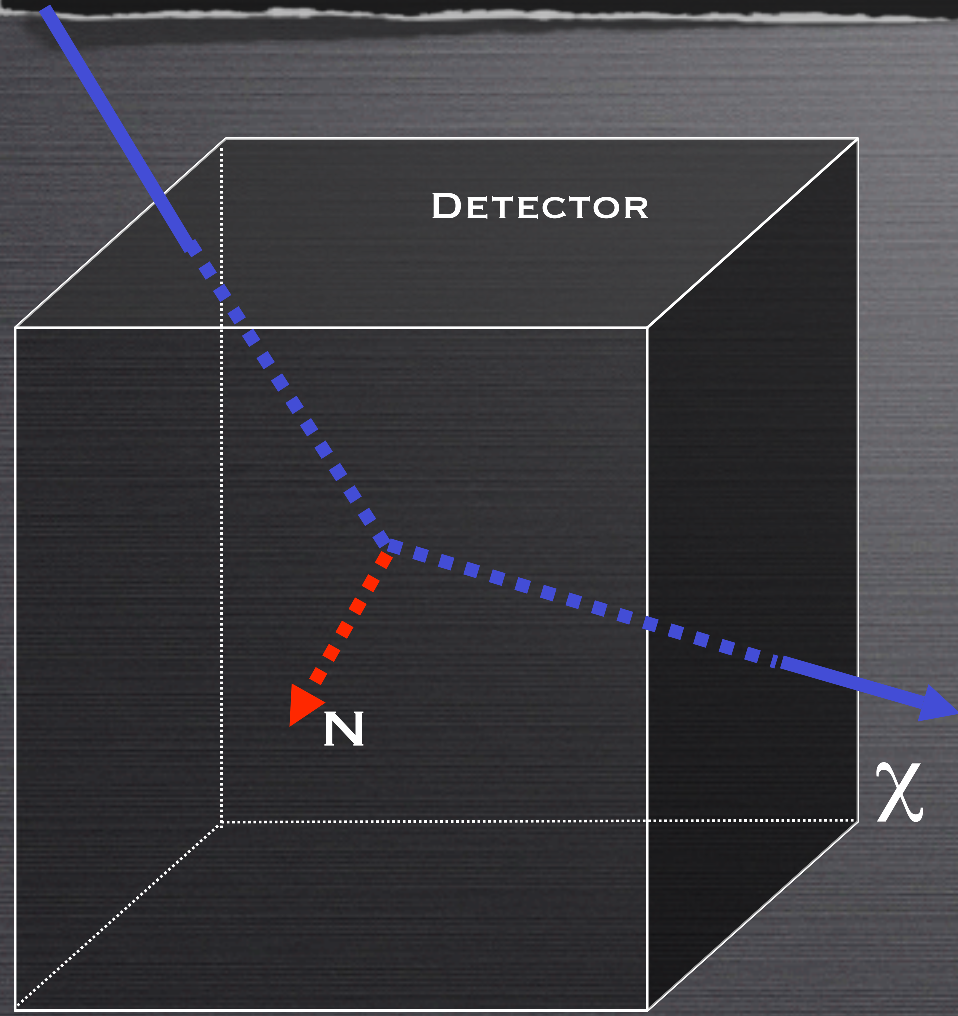
what we will most probably get
(example in the stau coannihilation region, 24 parms MSSM)

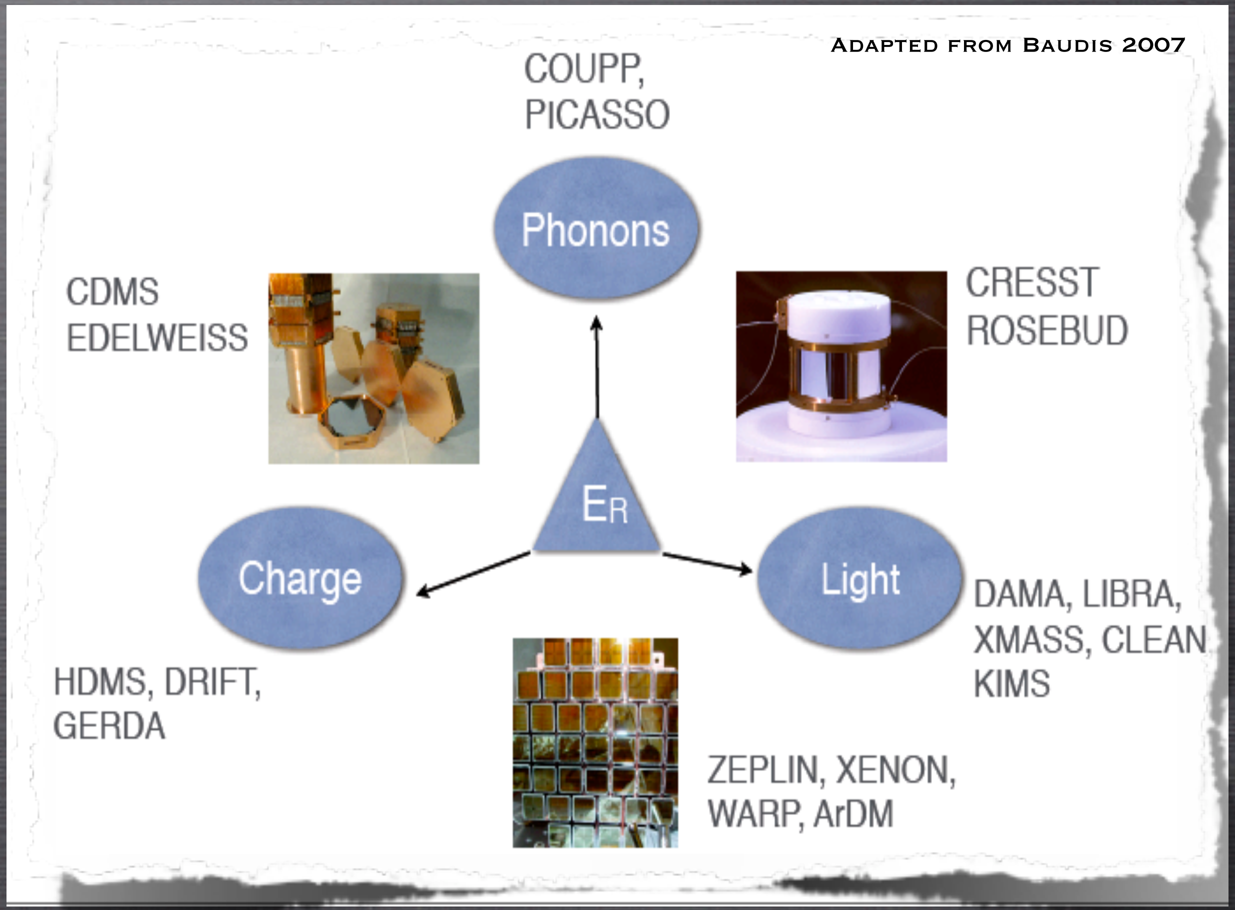


GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta, 2010

Direct Detection

Principle and Detection Techniques



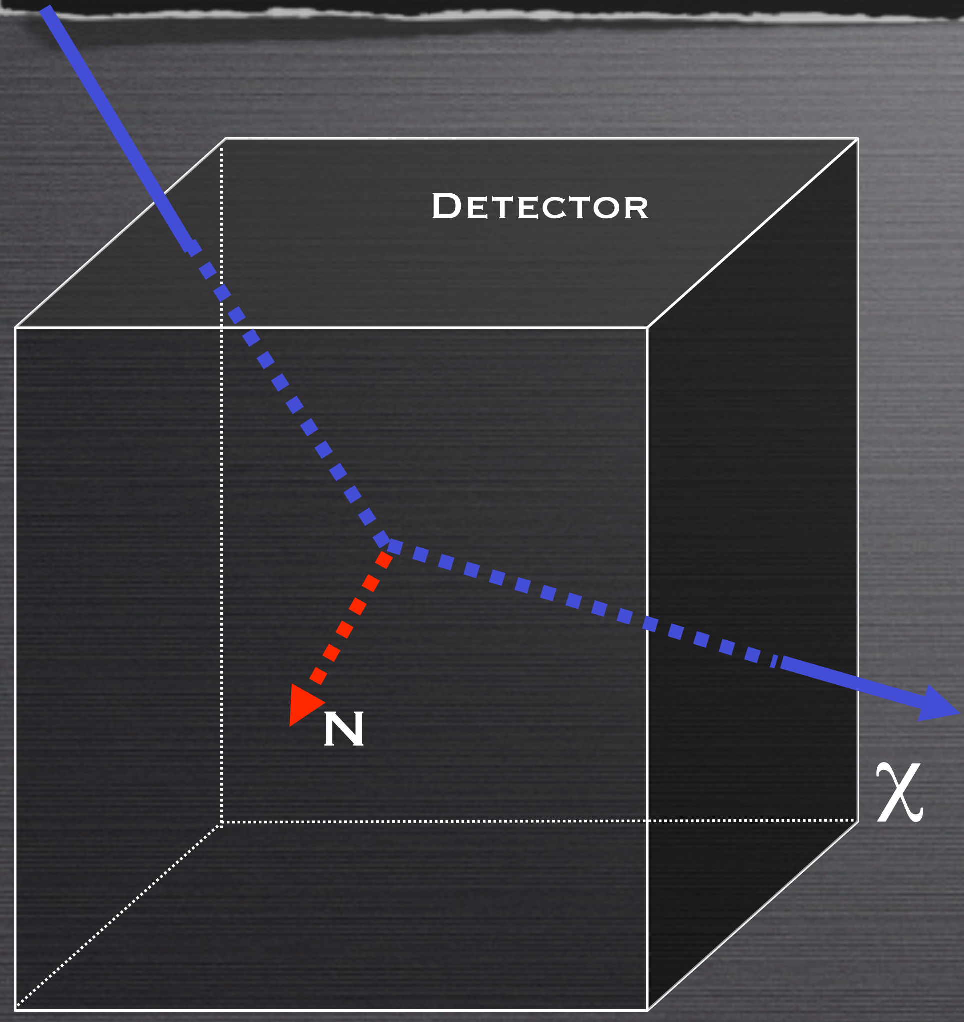


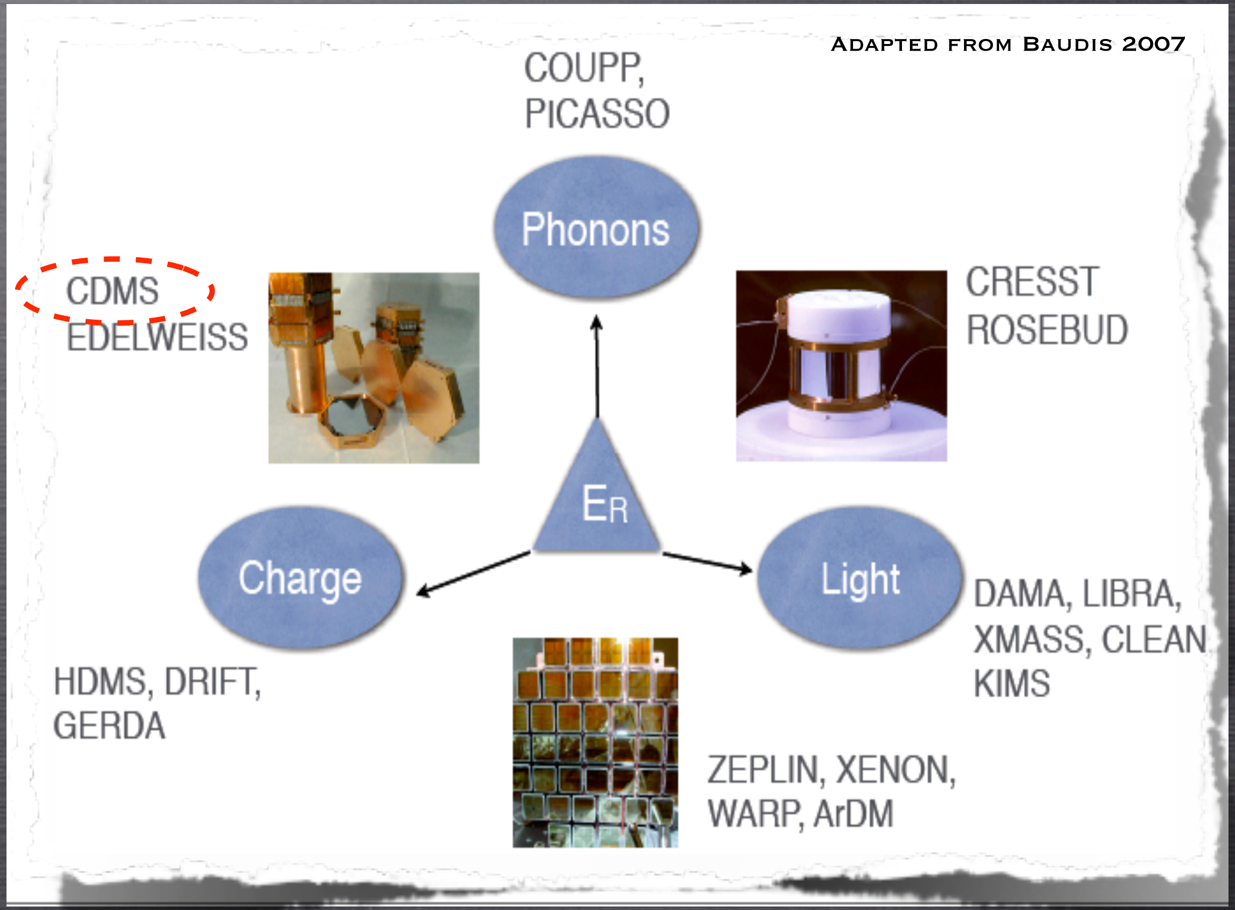
DM scatters off nuclei in the detector

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

Direct Detection

Principle and Detection Techniques





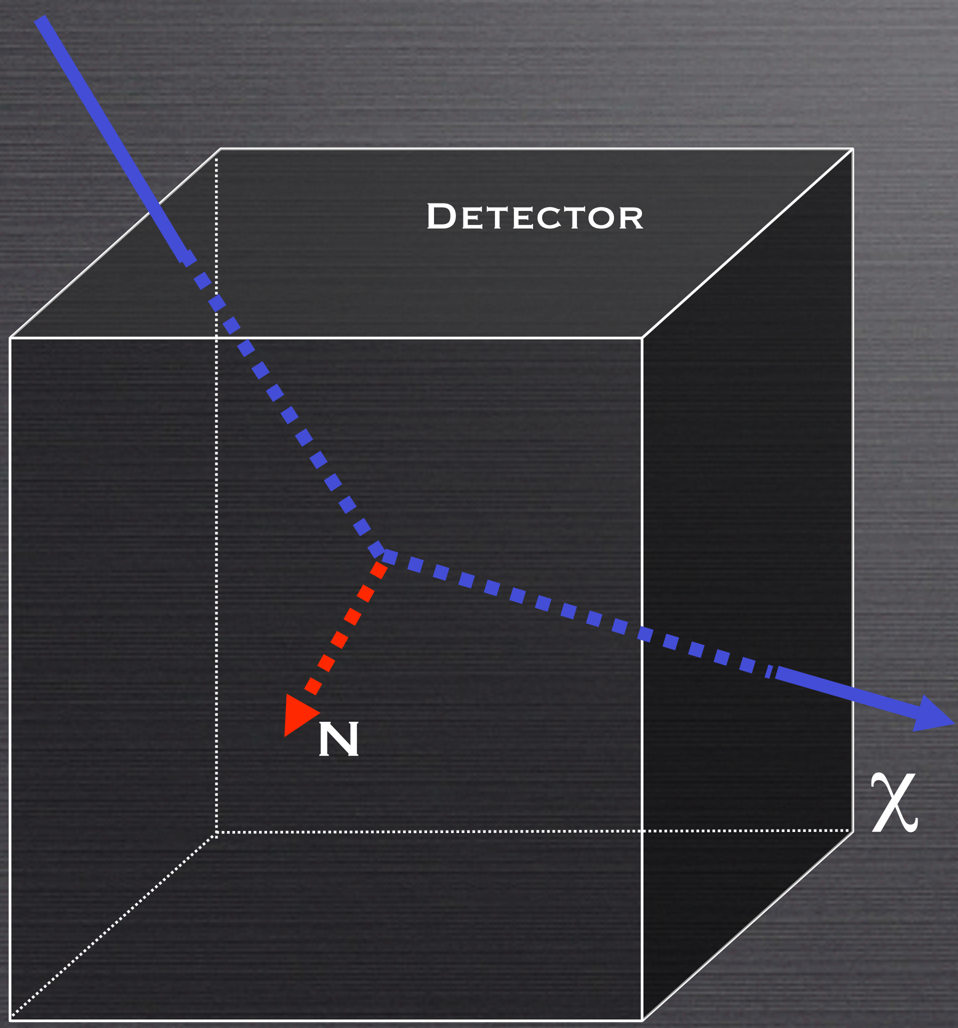
DM scatters off nuclei in the detector

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

Direct Detection

Basics

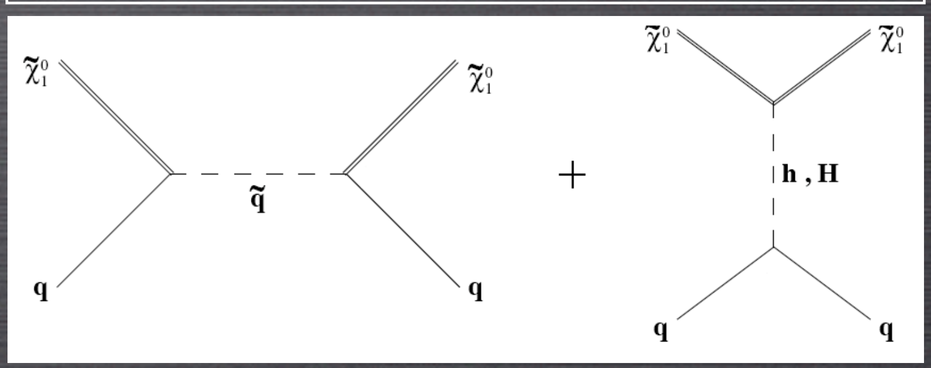
DM Scatters off nuclei in the detector



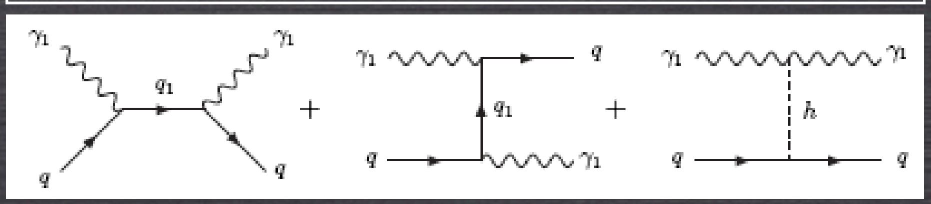
Differential Event Rate

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

SUSY: squarks and Higgs exchange



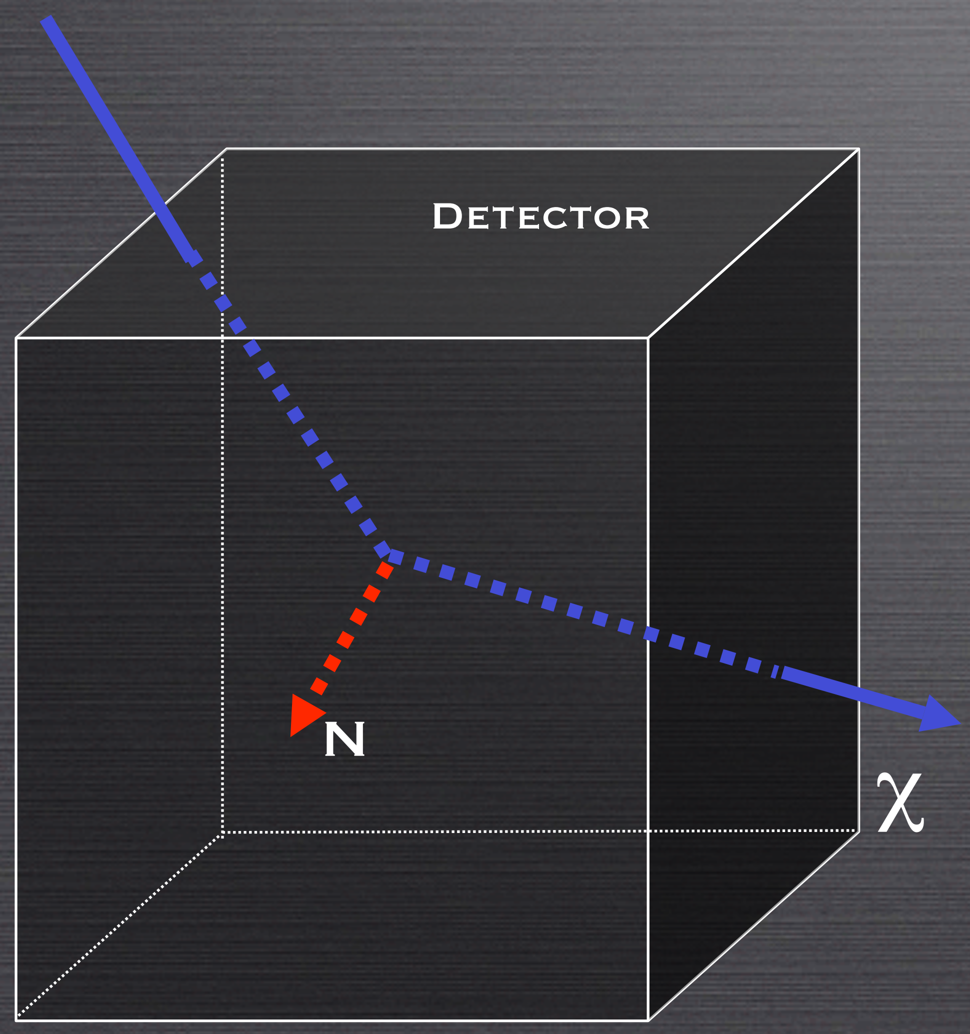
UED: 1st level quarks and Higgs exchange



Direct Detection

Basics

DM Scatters off nuclei in the detector



Differential Event Rate

$$\frac{dR}{dE}(E) = \frac{\sigma_p \rho_\chi}{2\mu_{p\chi}^2 m_\chi} A^2 F^2(E) \langle \int_{v_{min}}^{\infty} \frac{f^E(v,t)}{v} dv \rangle$$

Theoretical Uncertainties

Ellis, Olive & Savage 2008; Bottino et al. 2000; etc.

Uncertainties on f(v)

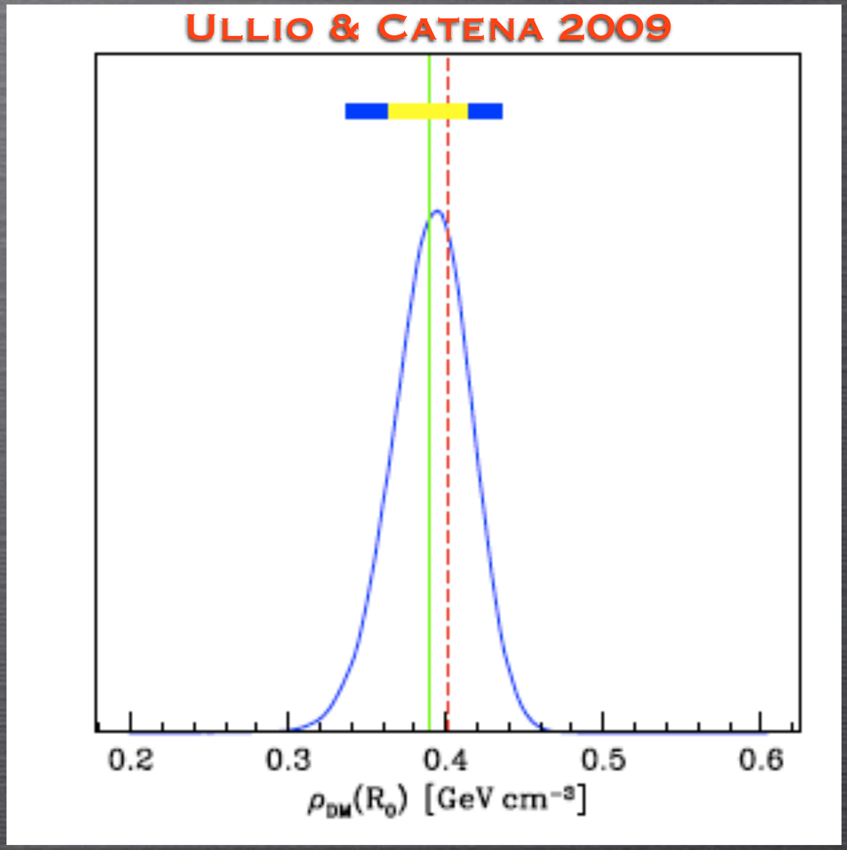
Ling et al. 2009; Widrow et al. 2000; Helmi et al 2002

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



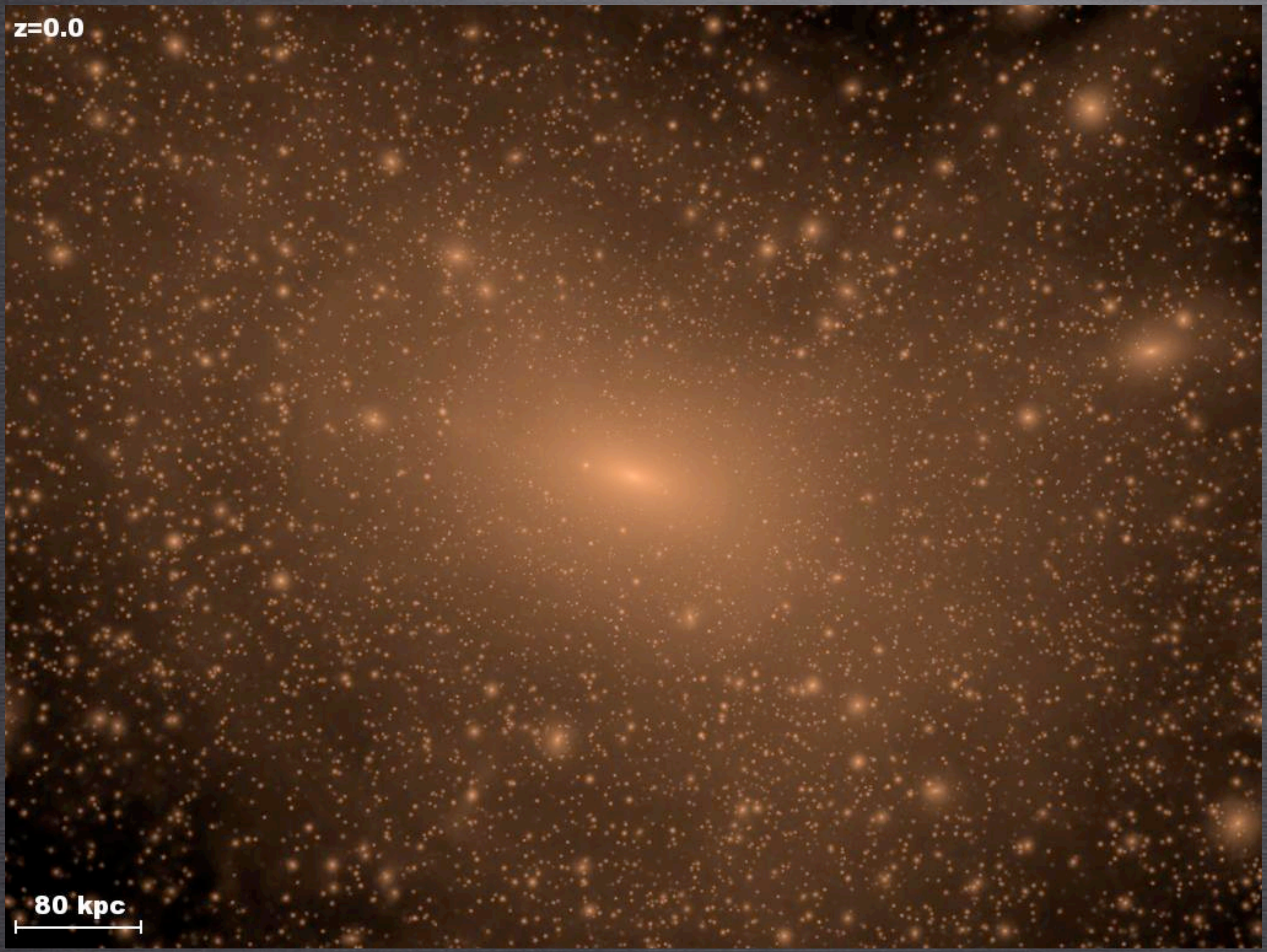
$$\rho_{DM}(R_0) = 0.389 \pm 0.025 \,\text{GeV cm}^{-3}$$

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

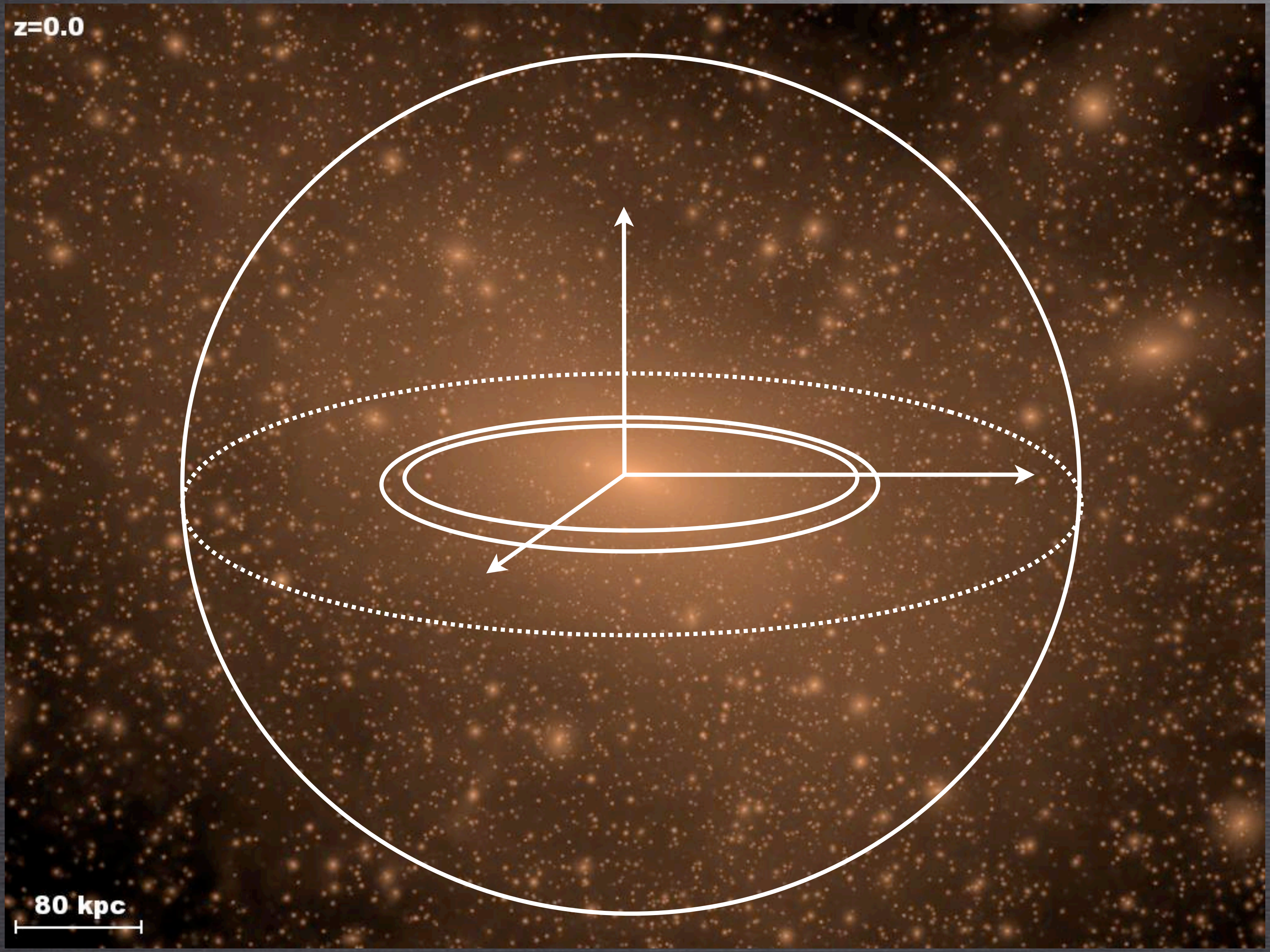
Pato, Agertz, GB, Moore, Teyssier, Moore 2010



http://www.ucolick.org/~diemand/vl/images.html

Triaxial Halos

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



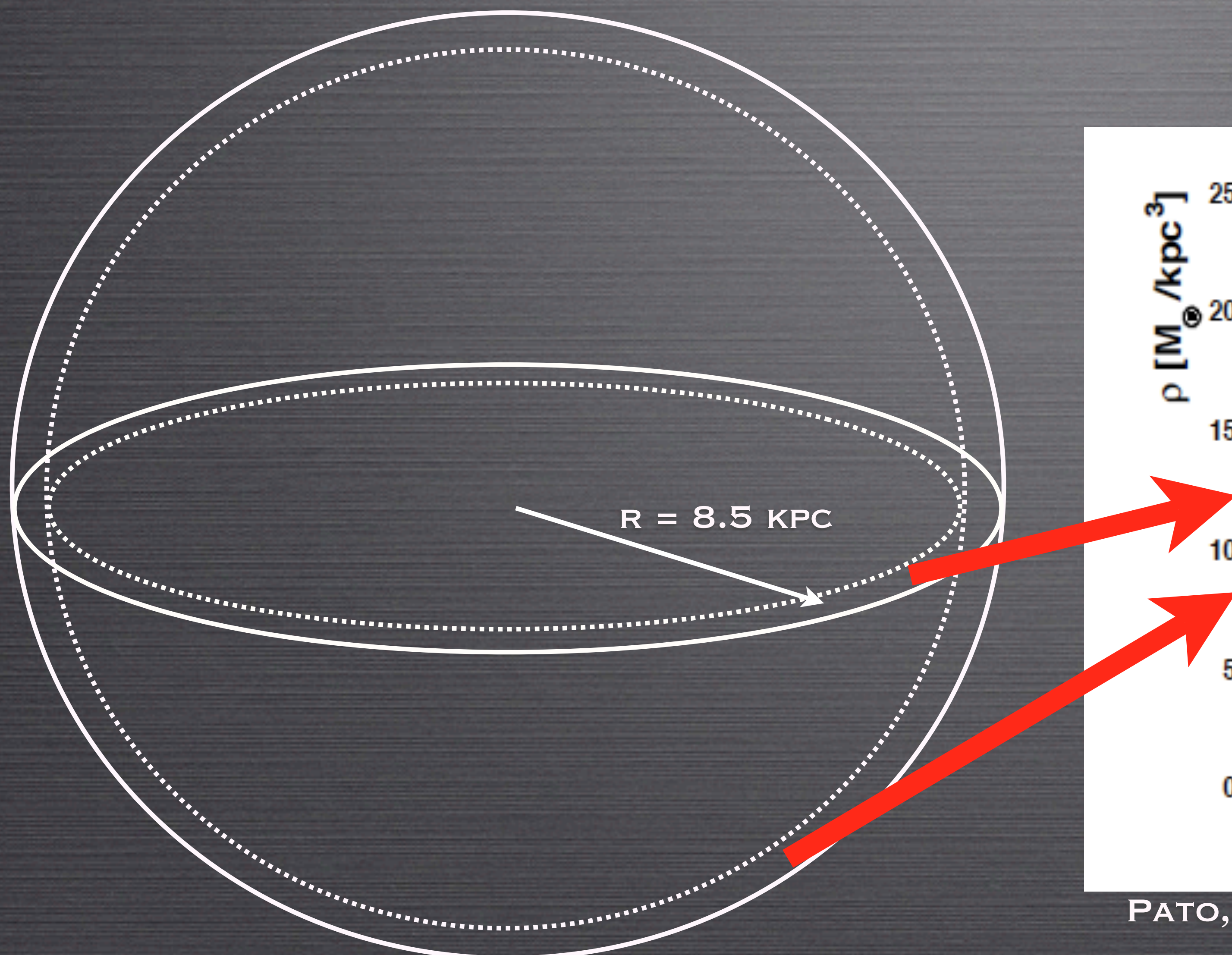
Moment of Inertia Tensor

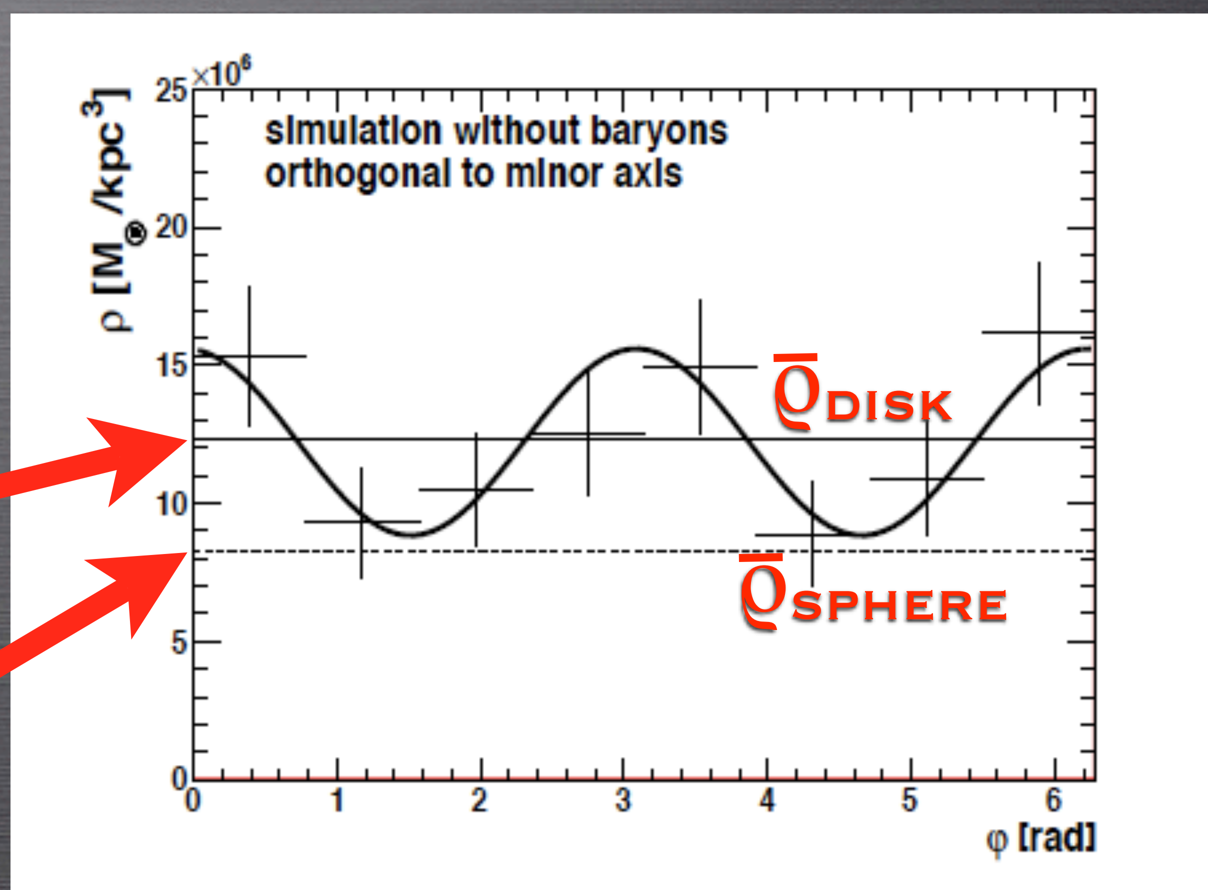
$$I_{ij} = \frac{\sum_{k=1}^{N} m_k r_{i,k} r_{j,k}}{\sum_{k=1}^{N} m_k}.$$

Rotation Axes
(A,B,C)

Modulation of DM density

at fixed GC-distance





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

Modulation of DM density

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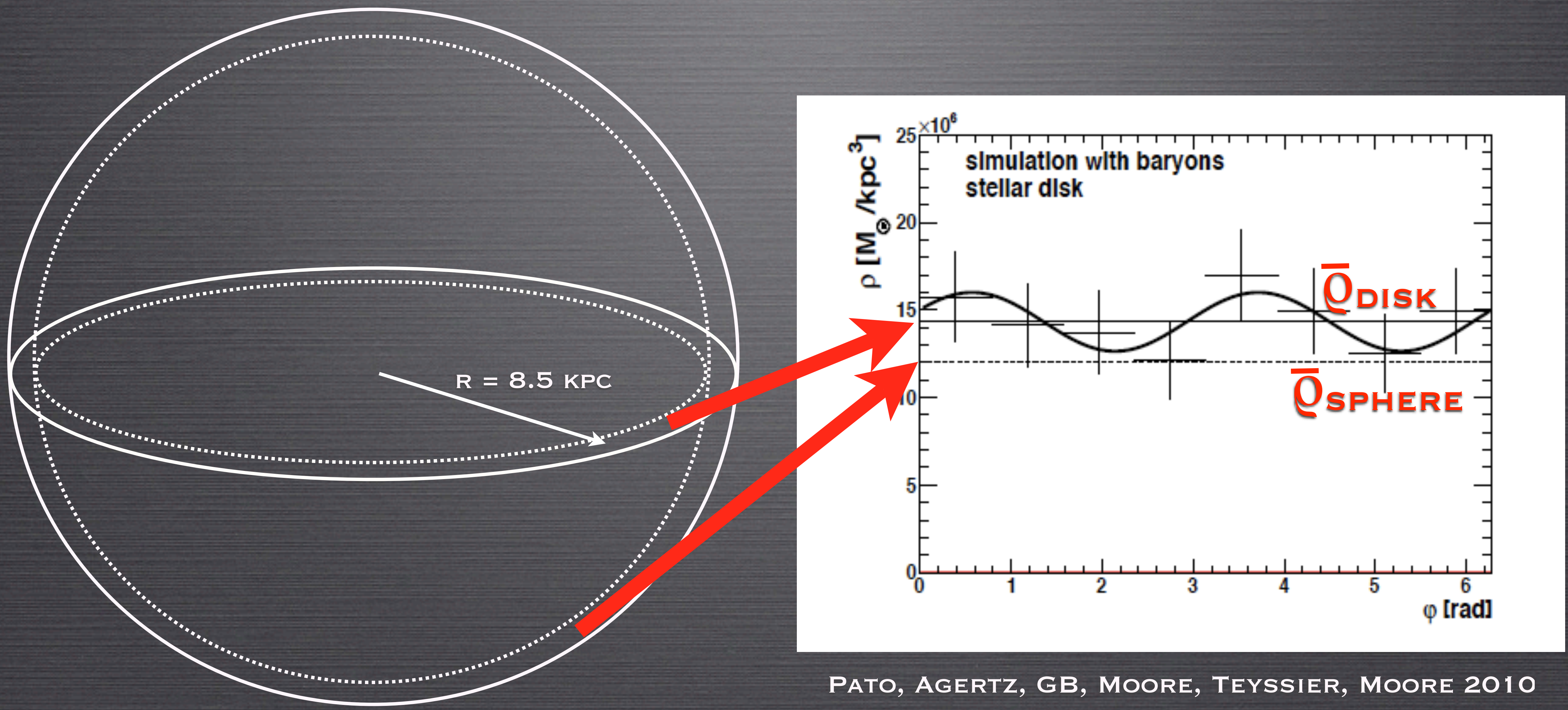
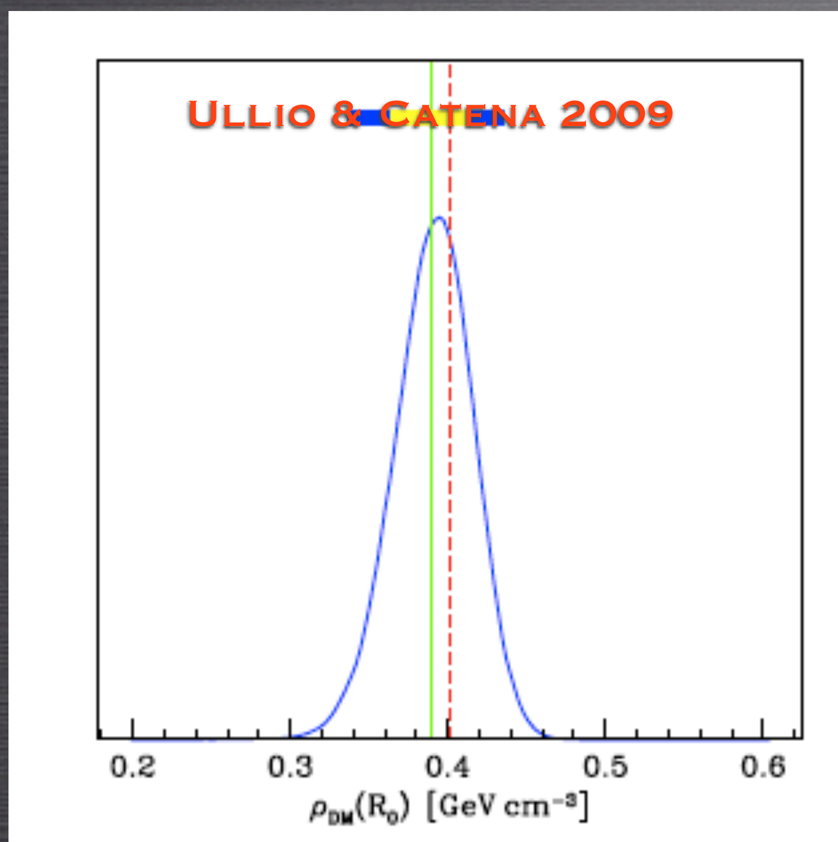


Pato, Agertz, GB, Moore, Teyssier, Moore 2010

Direct Detection

Uncertainties on the Local Density

"Statistical"

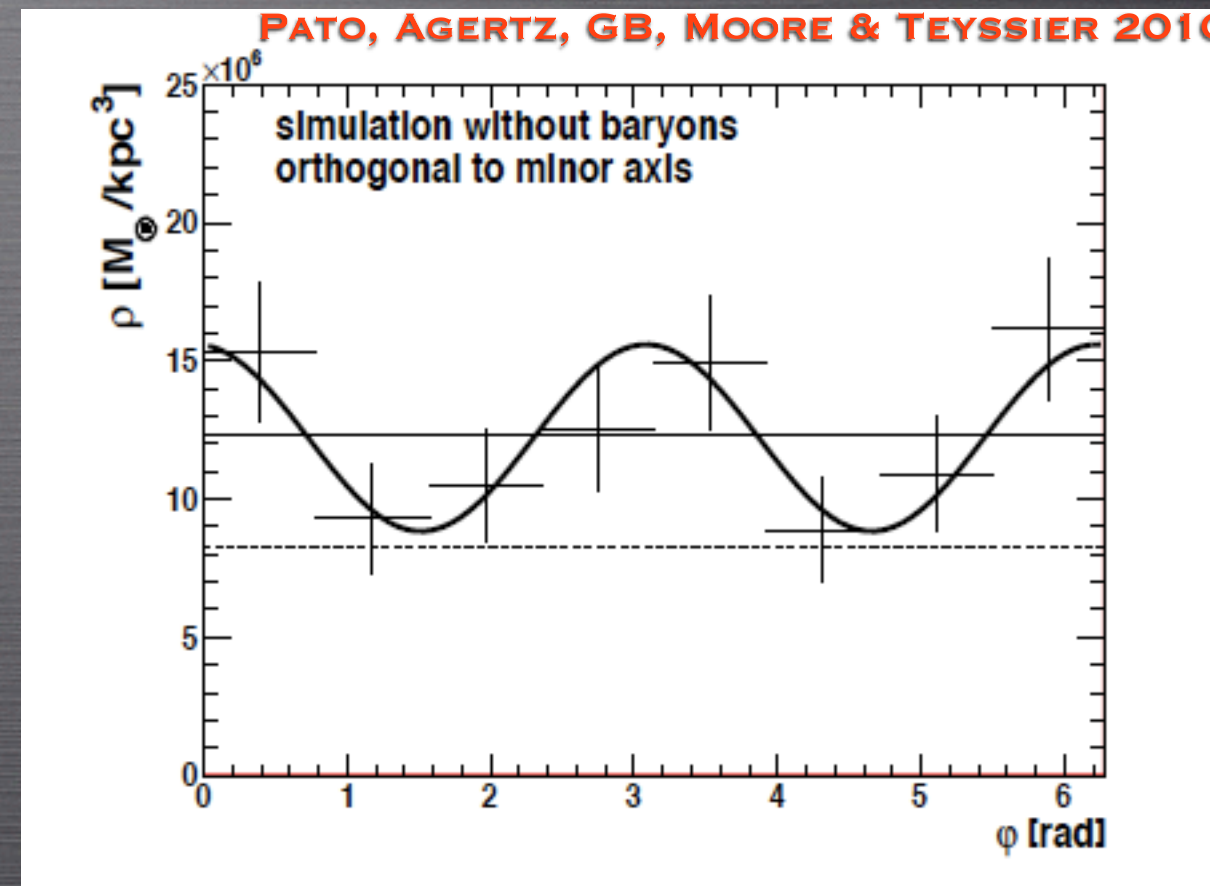


$$\rho_{DM}(R_0) = 0.389 \pm 0.025\,\text{GeV cm}^{-3}$$

From dynamical Observables (see also Strigari & Trotta 2009)

+

"Systematic"



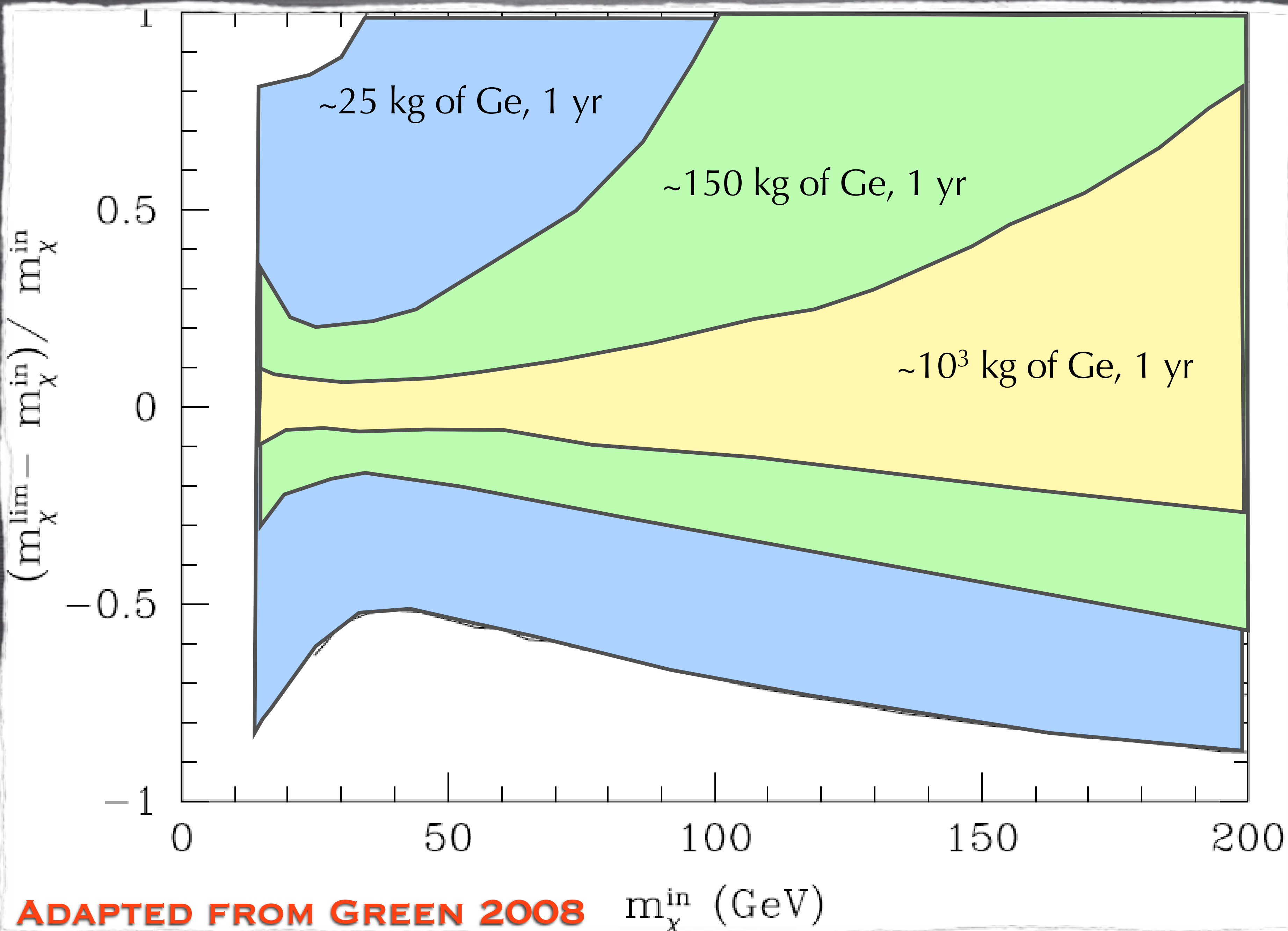
$$\rho_0/\bar{\rho}_0 = 1.01 - 1.41$$ w/ Baryons

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

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

Direct Detection

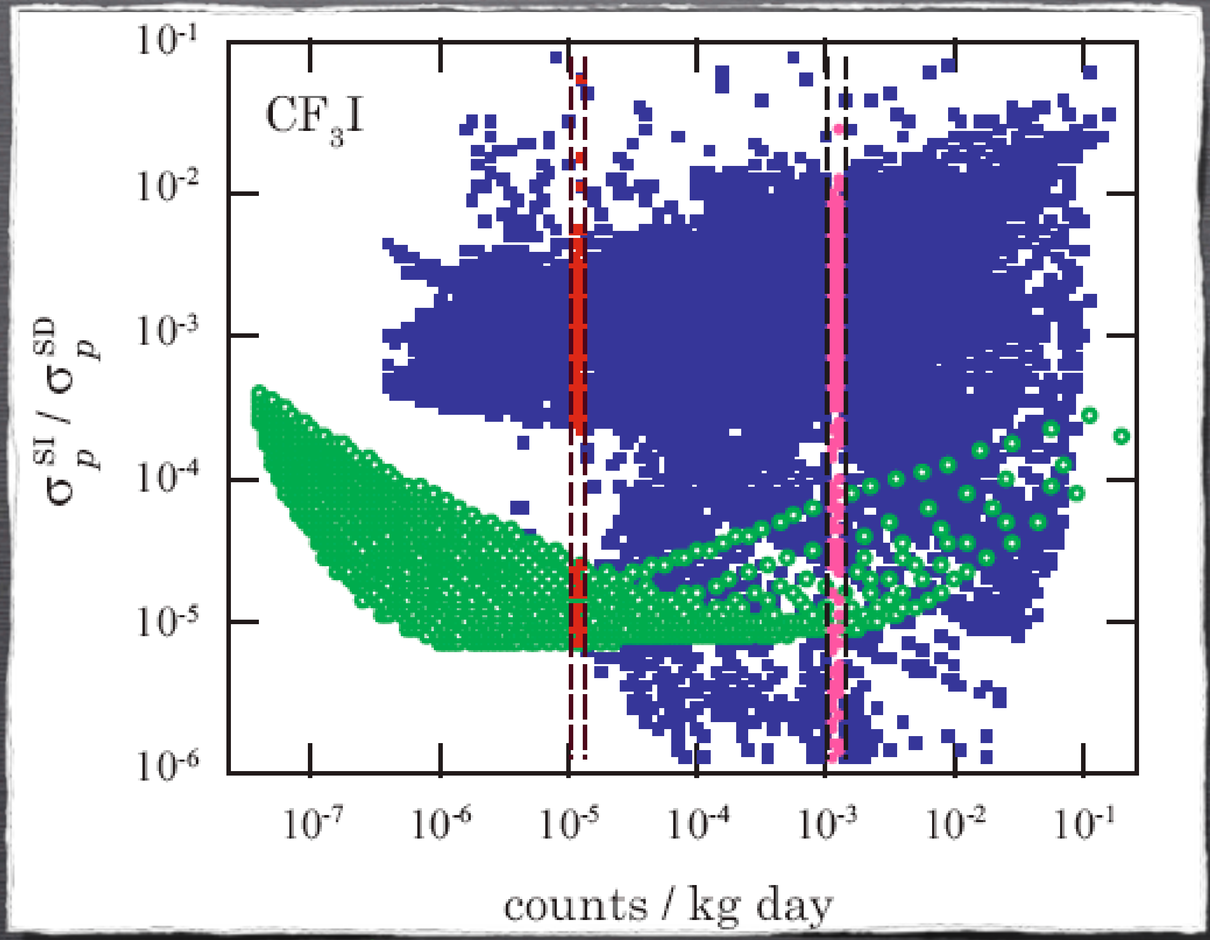
95% C.L. constraint on the reconstructed DM mass



Adapted from Green 2008

Direct Detection

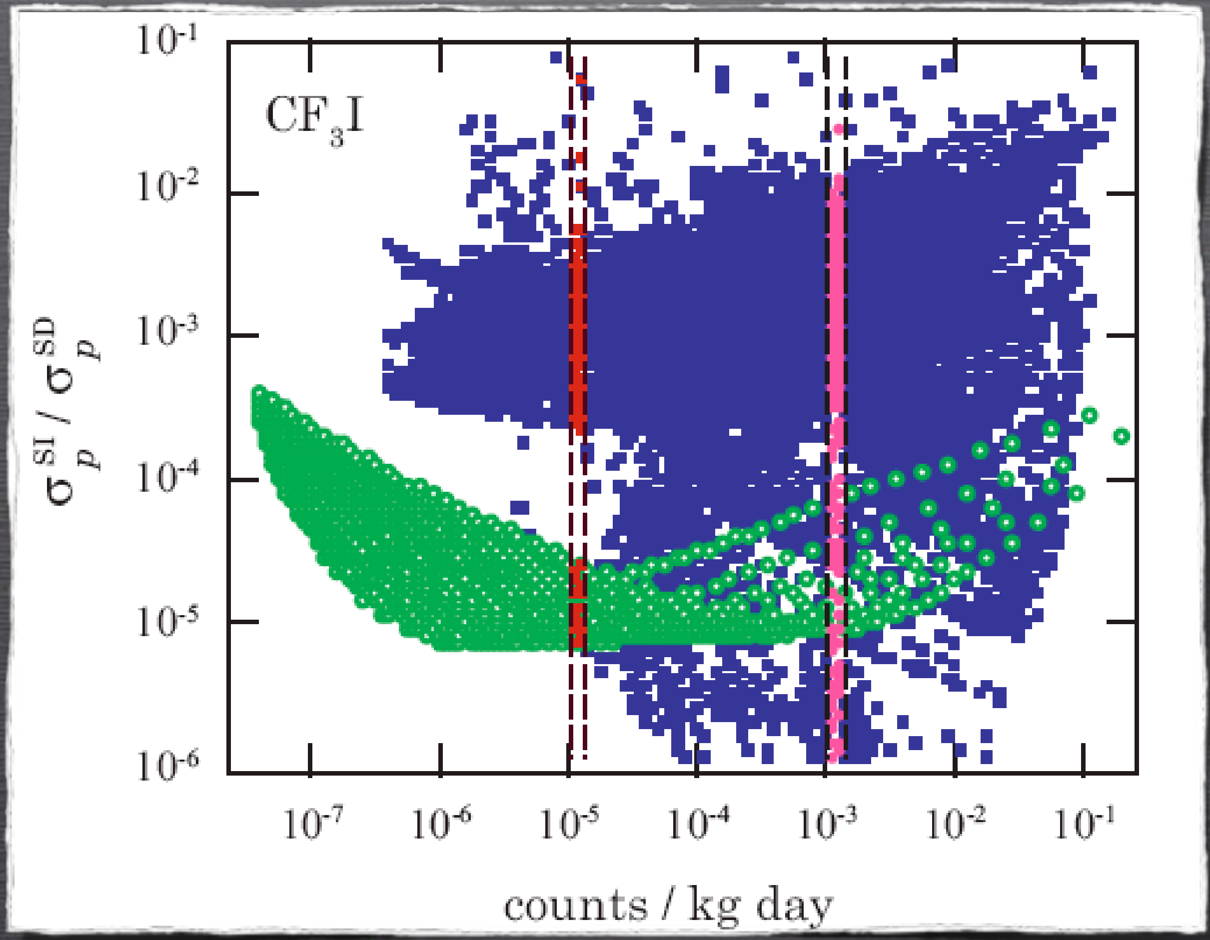
Better constraints combining results from different targets



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

Direct Detection

Better constraints combining results from different targets



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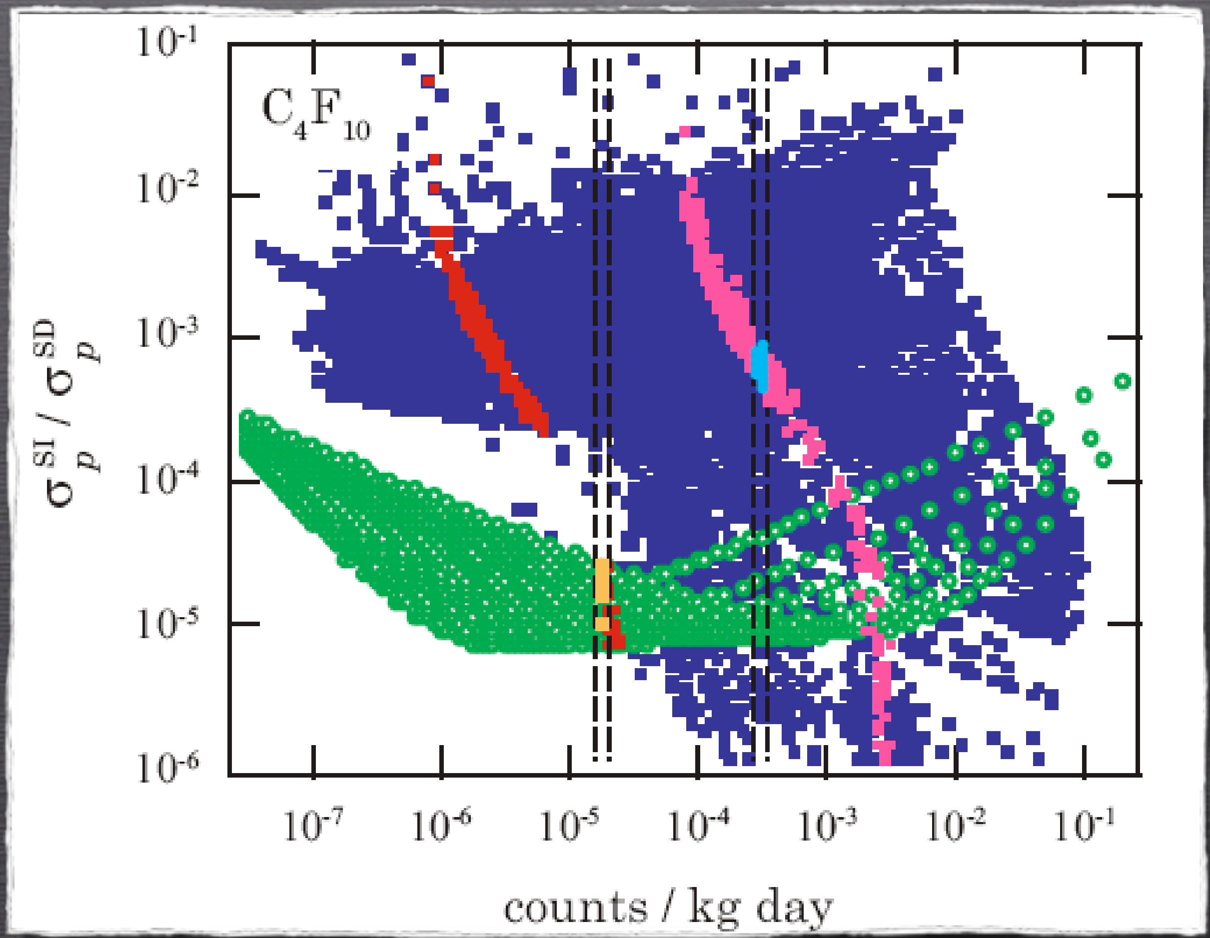

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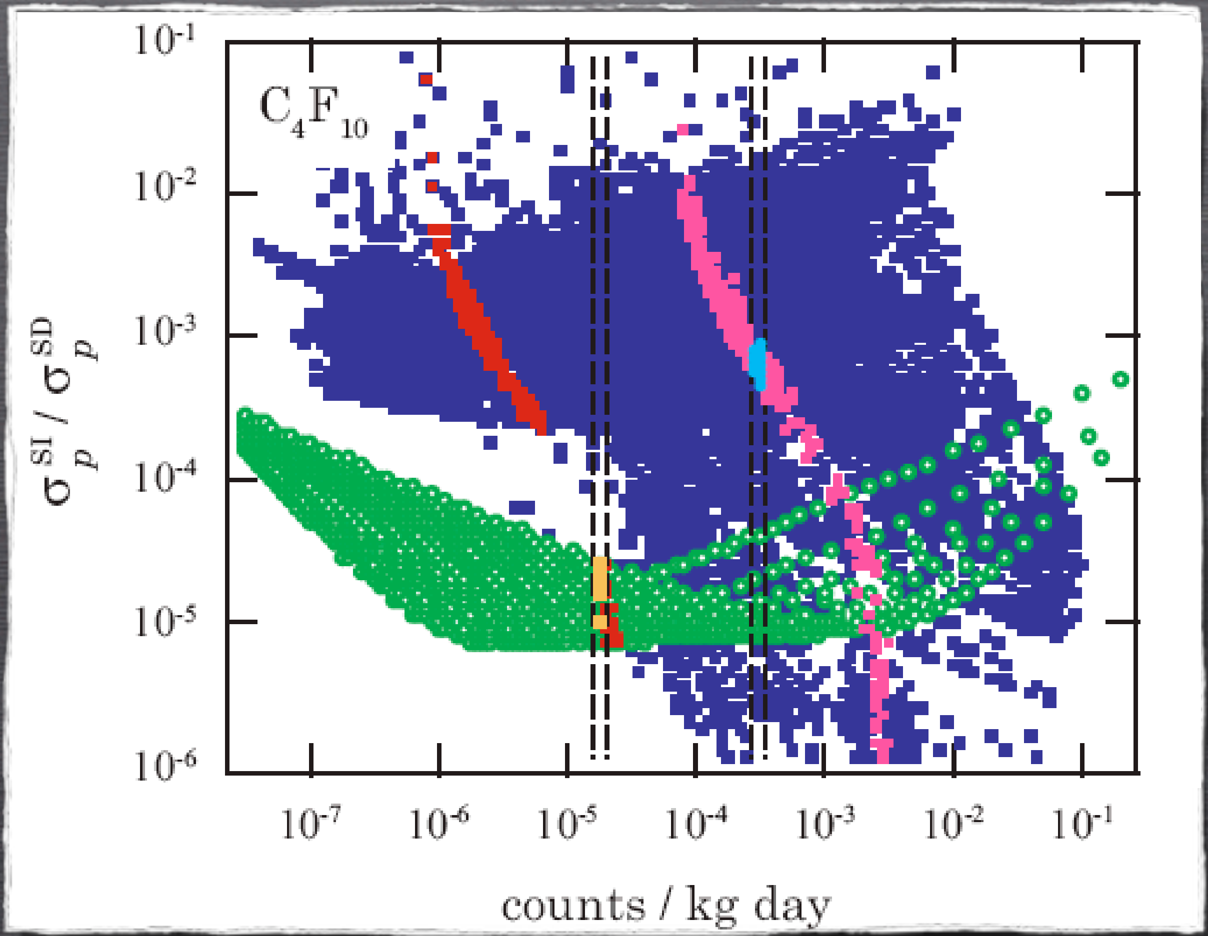
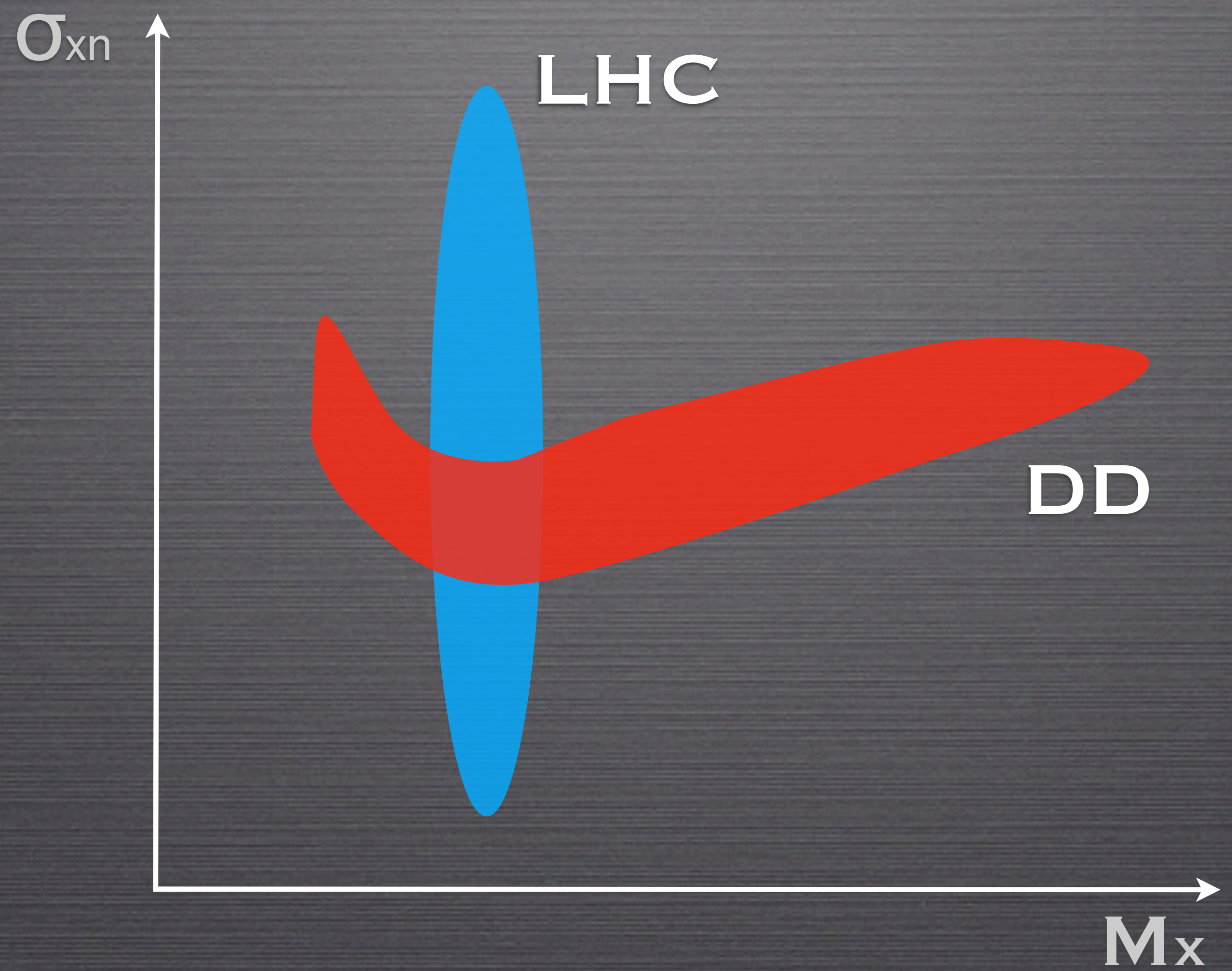


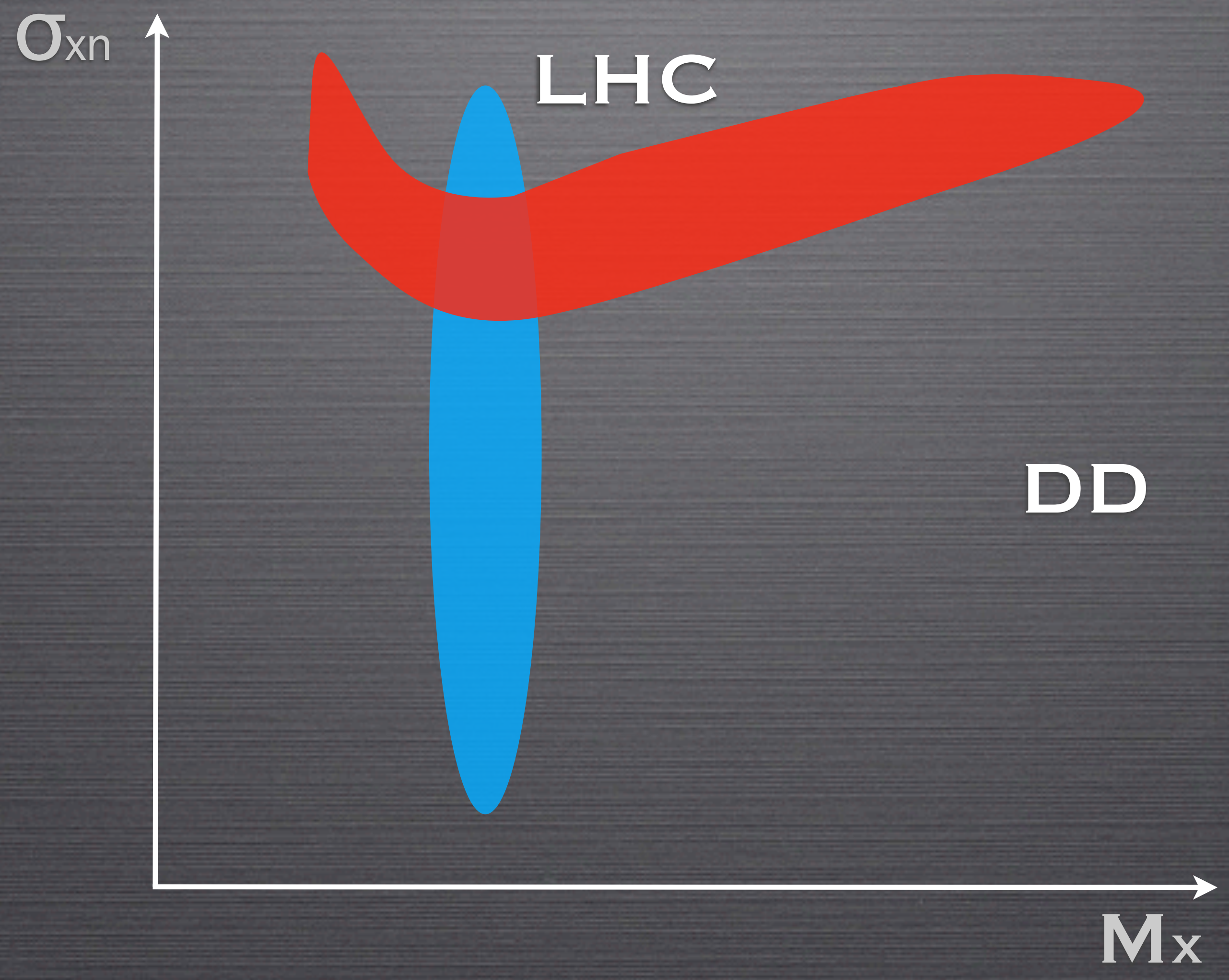
The case of COUPP. GB, Cerdeno, Collar & Odom 2007

Or combine with information from Accelerators...

LHC+DD

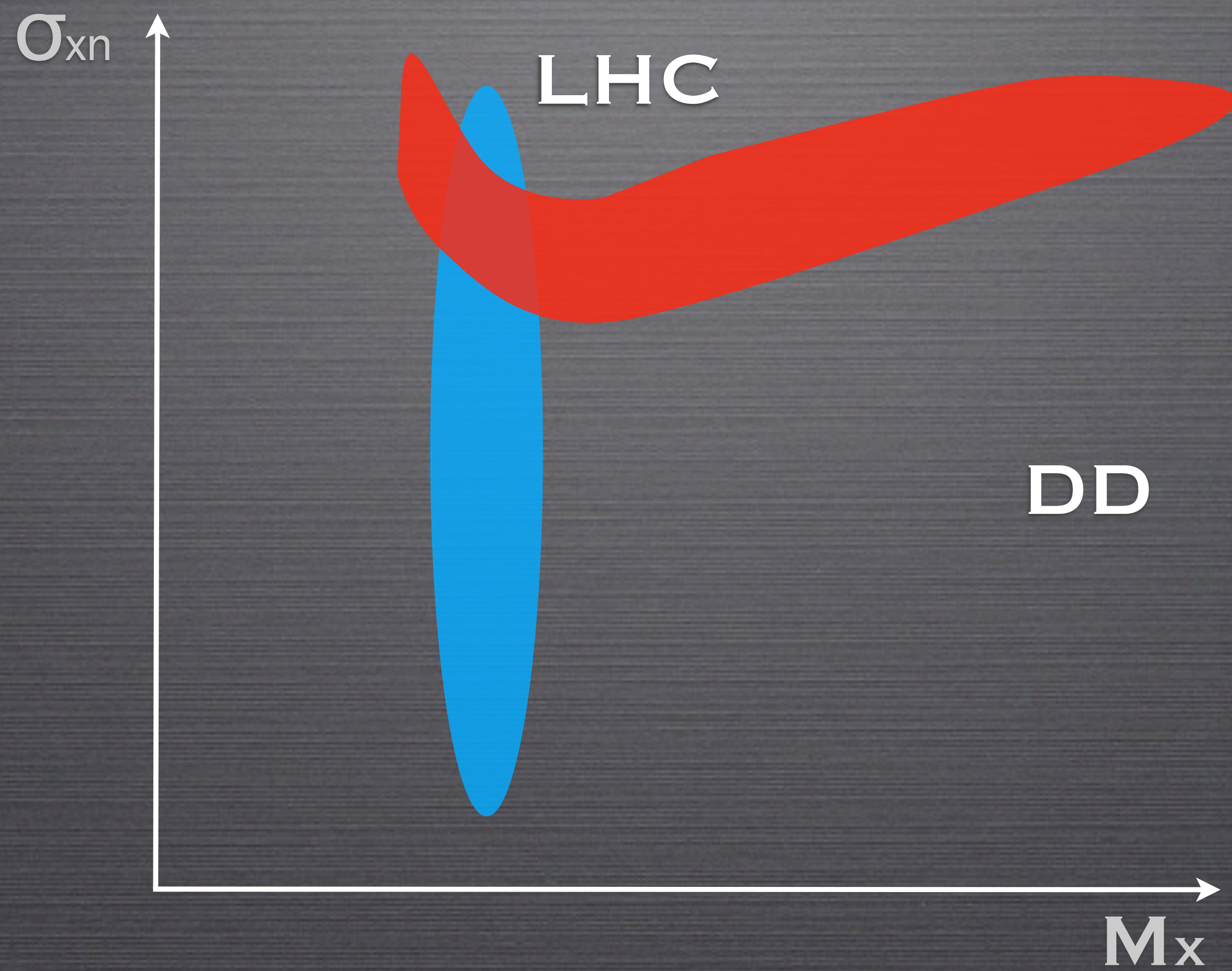


LHC+DD



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

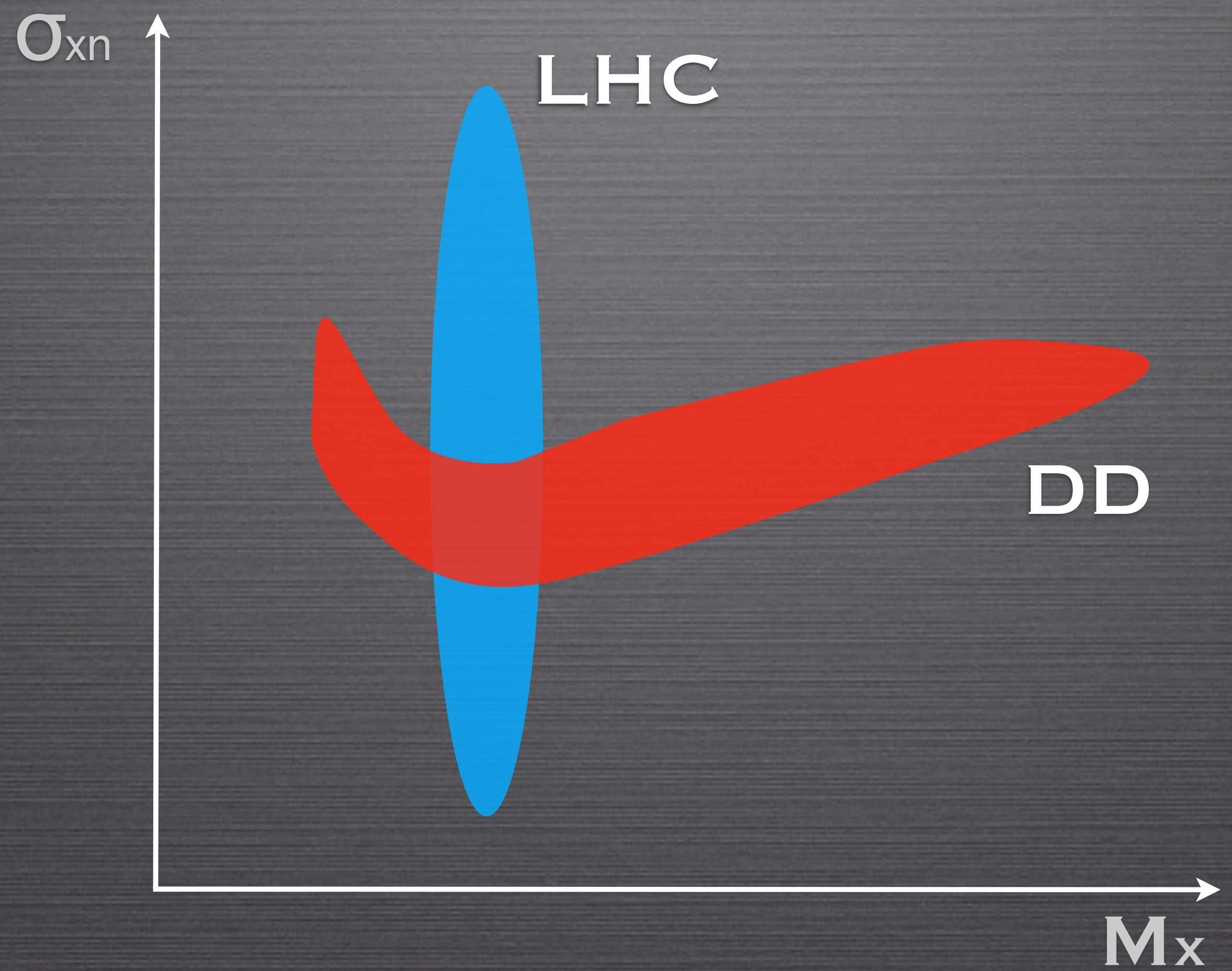
LHC+DD



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

$f(v)$

LHC+DD



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

$$f(v)$$

LHC+DD

To combine LHC and DD:

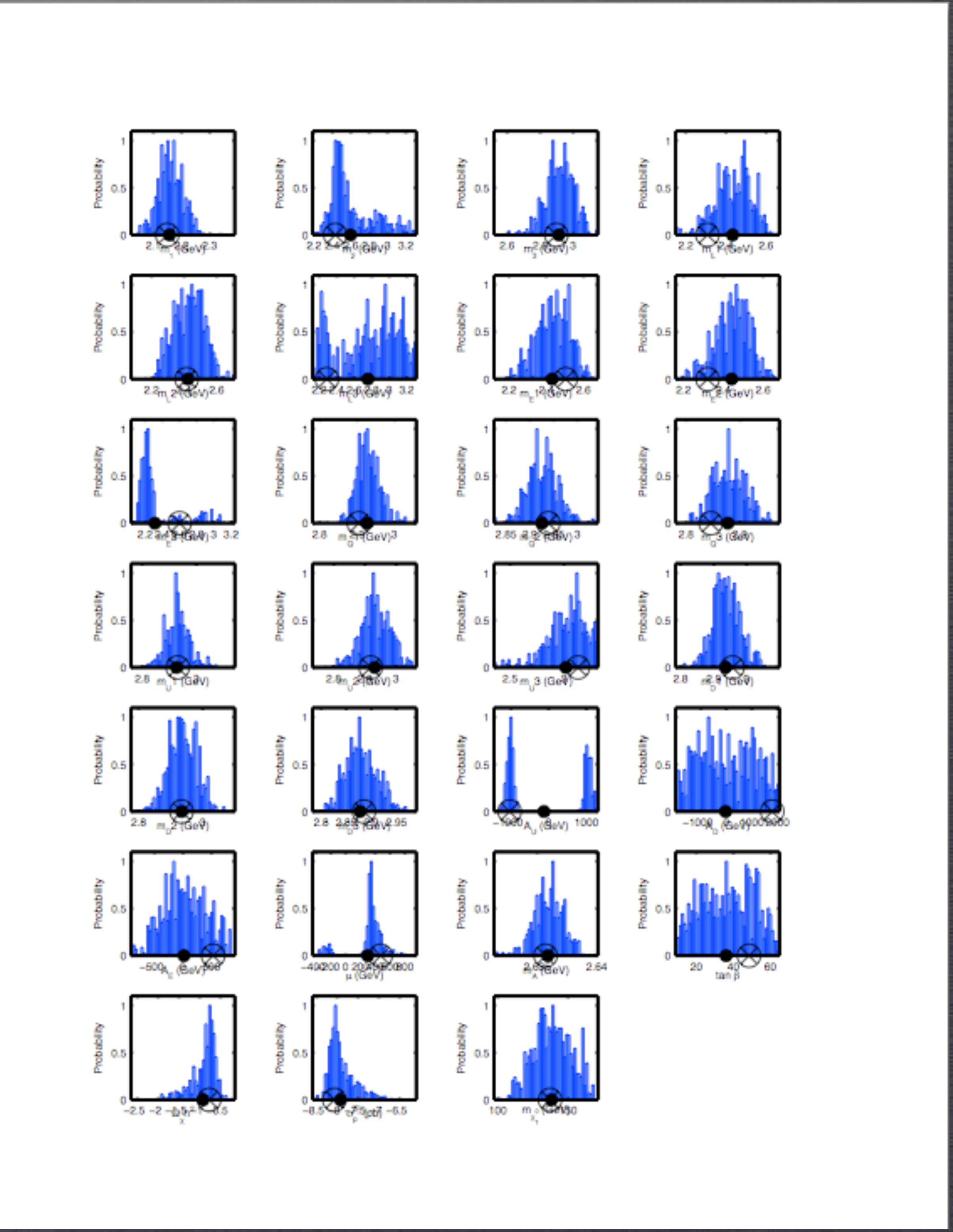
- Specify DM experiment

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

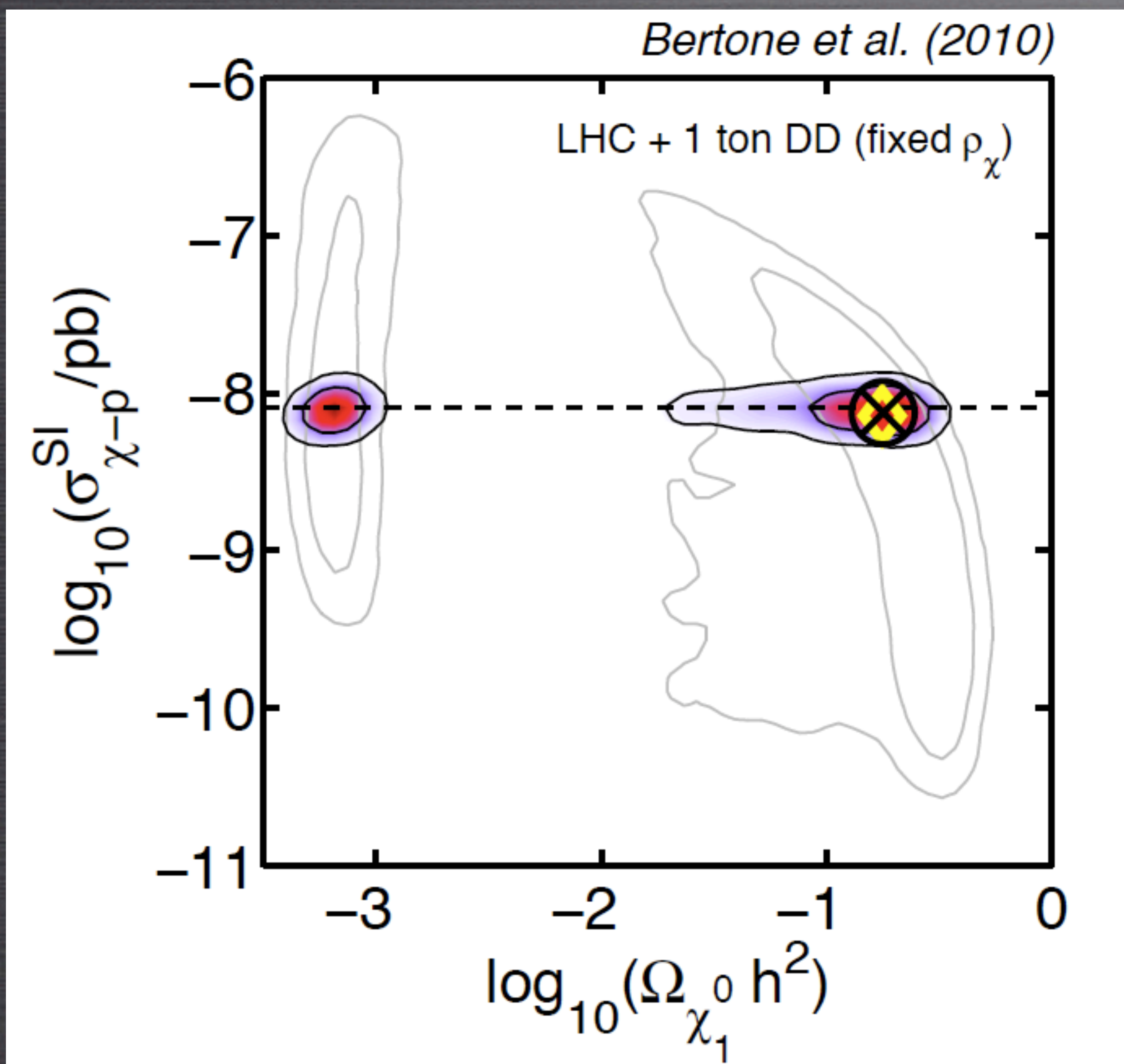
- (note that Fixing the number of events = fixing the product of cross section times local density)

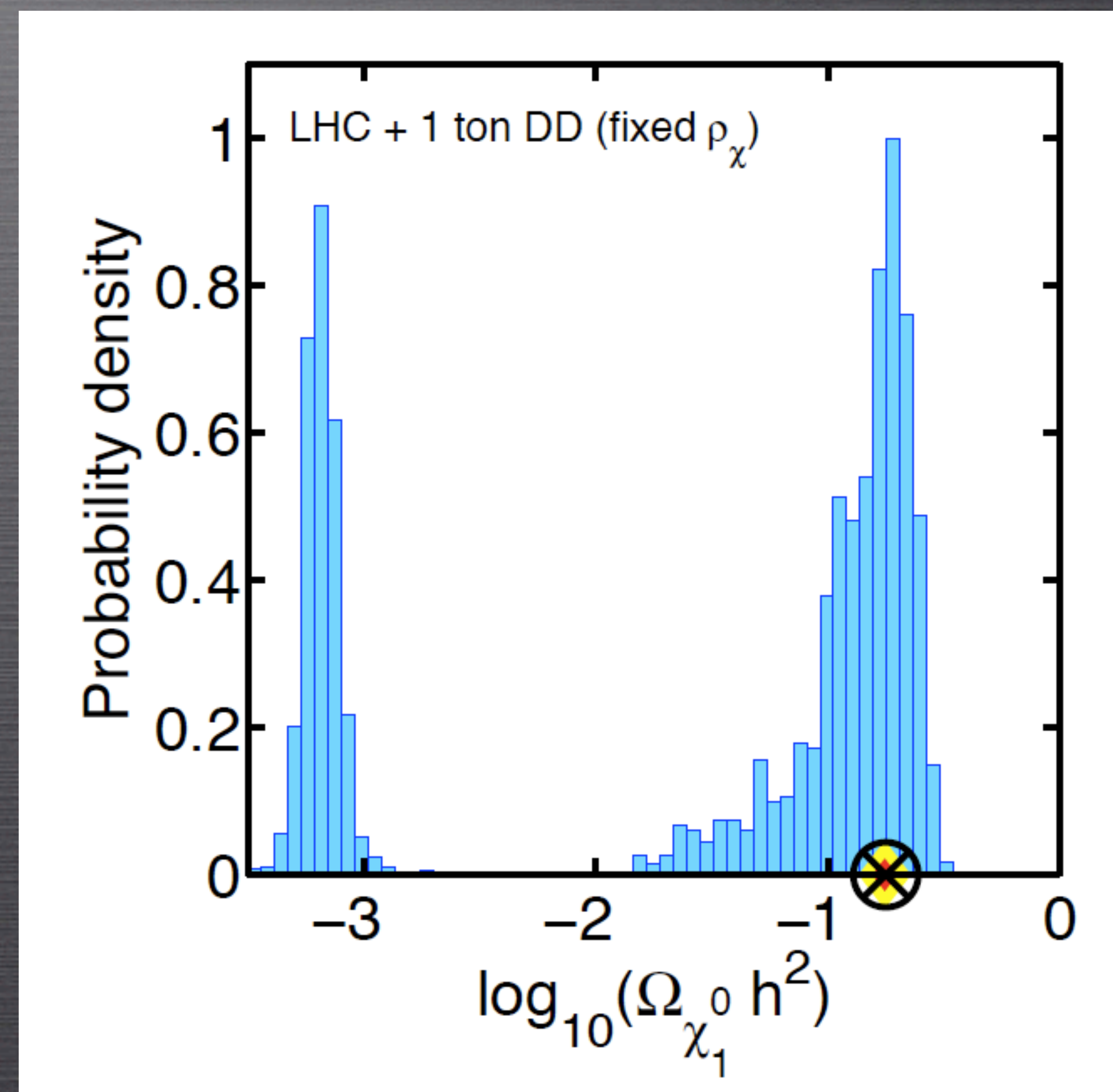


GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta (2010)

1st possibility: "consistency check"

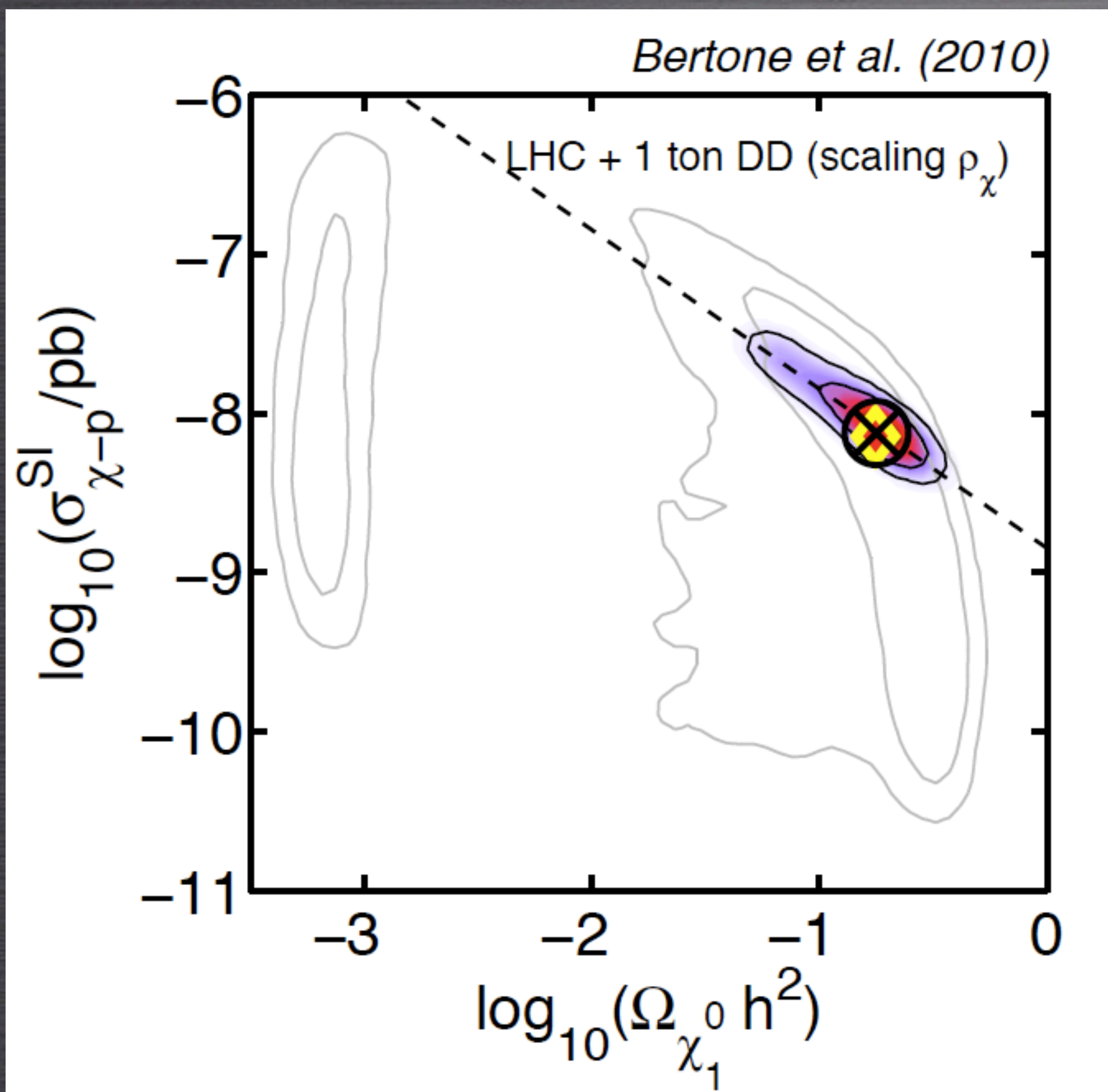
$$\rho_\chi = \rho_{\mathrm{DM}}$$

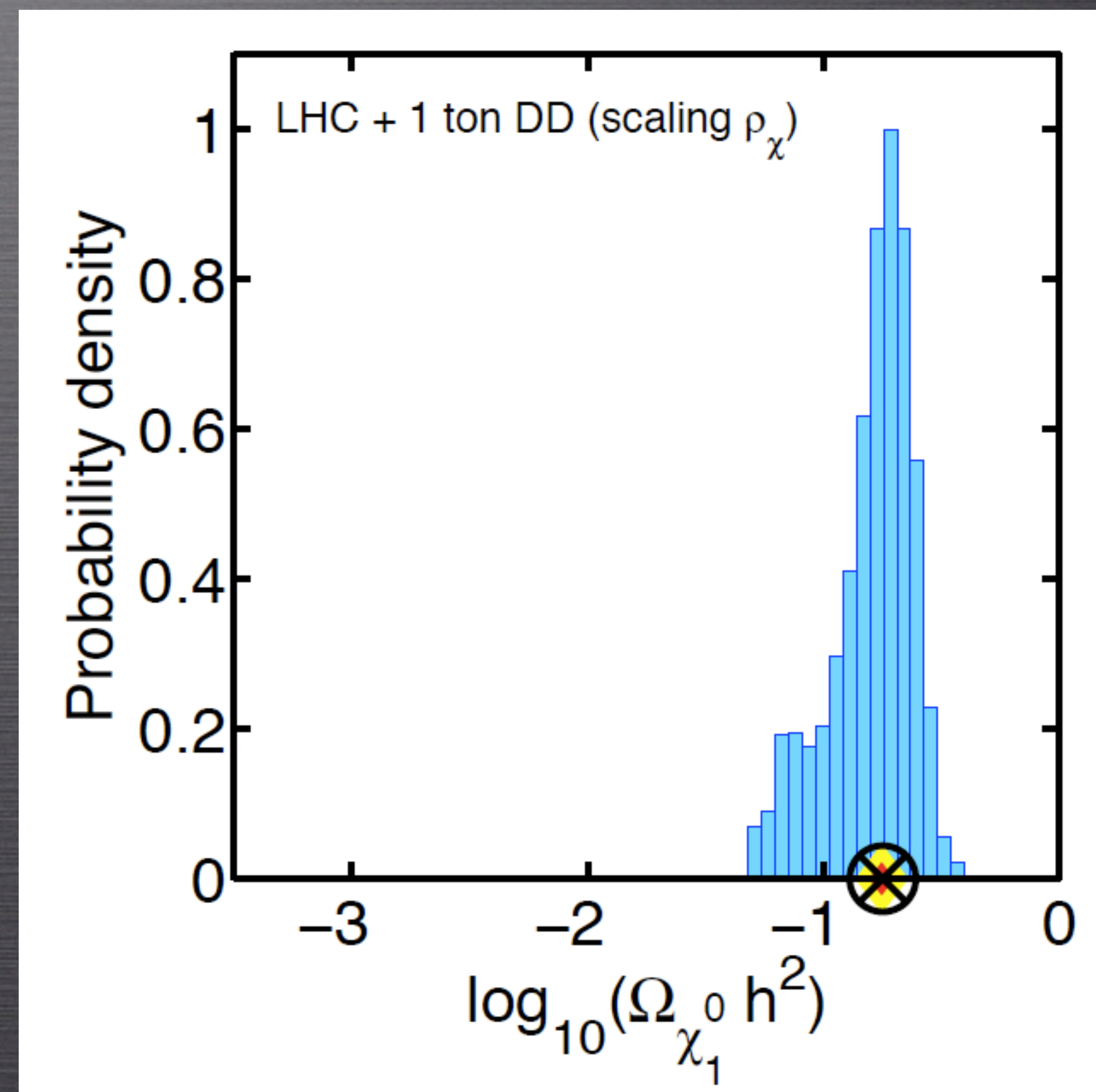




2nd (more physical) possibility: "Scaling" Ansatz

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

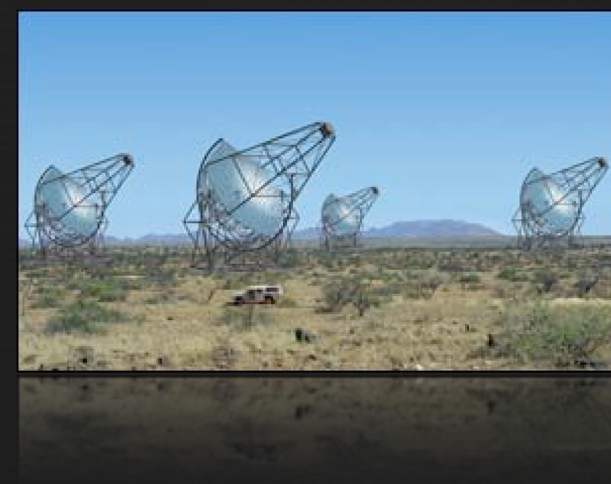
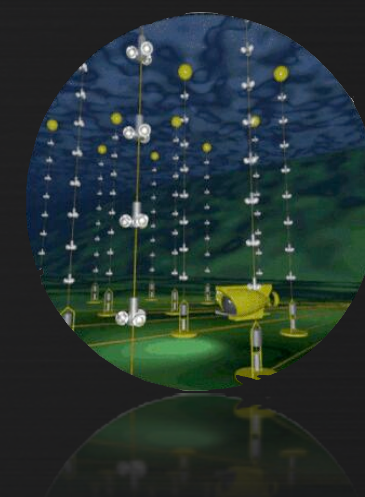
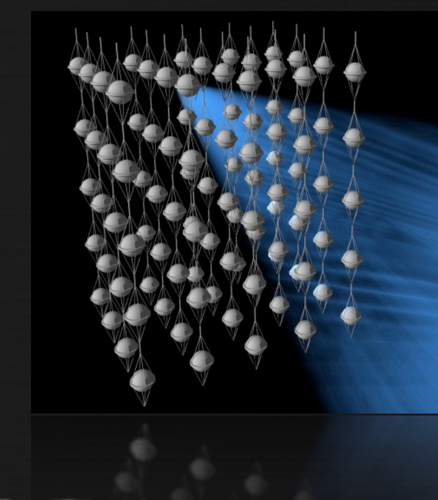




$$\sigma^{\rm SI}_{\chi-\rm p} \propto \Omega^{-1}_{\tilde{\chi}^0_1}$$

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

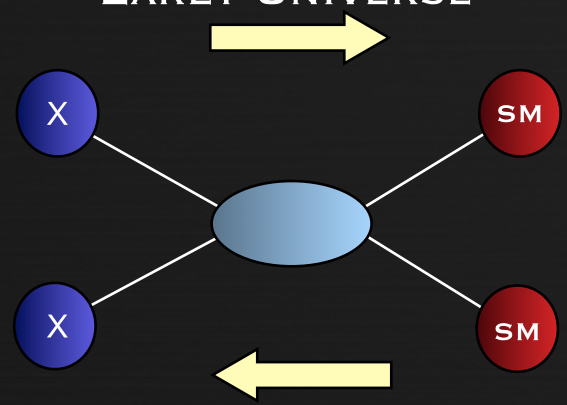
- Synchrotron Emission
- SZ effect
- Effect on Stars

Indirect Detection

Why "annihilations"?

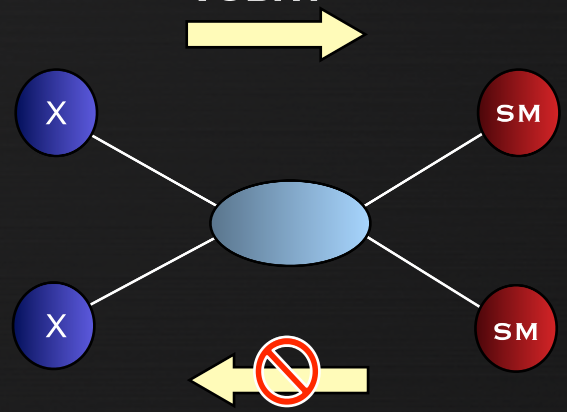
X = dark matter   SM = standard model particle

Early Universe



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

Today



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

Rough estimate of the relic density:

$$\Omega_X h^2 \approx \frac{3\times10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle\sigma v\rangle}$$

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.

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

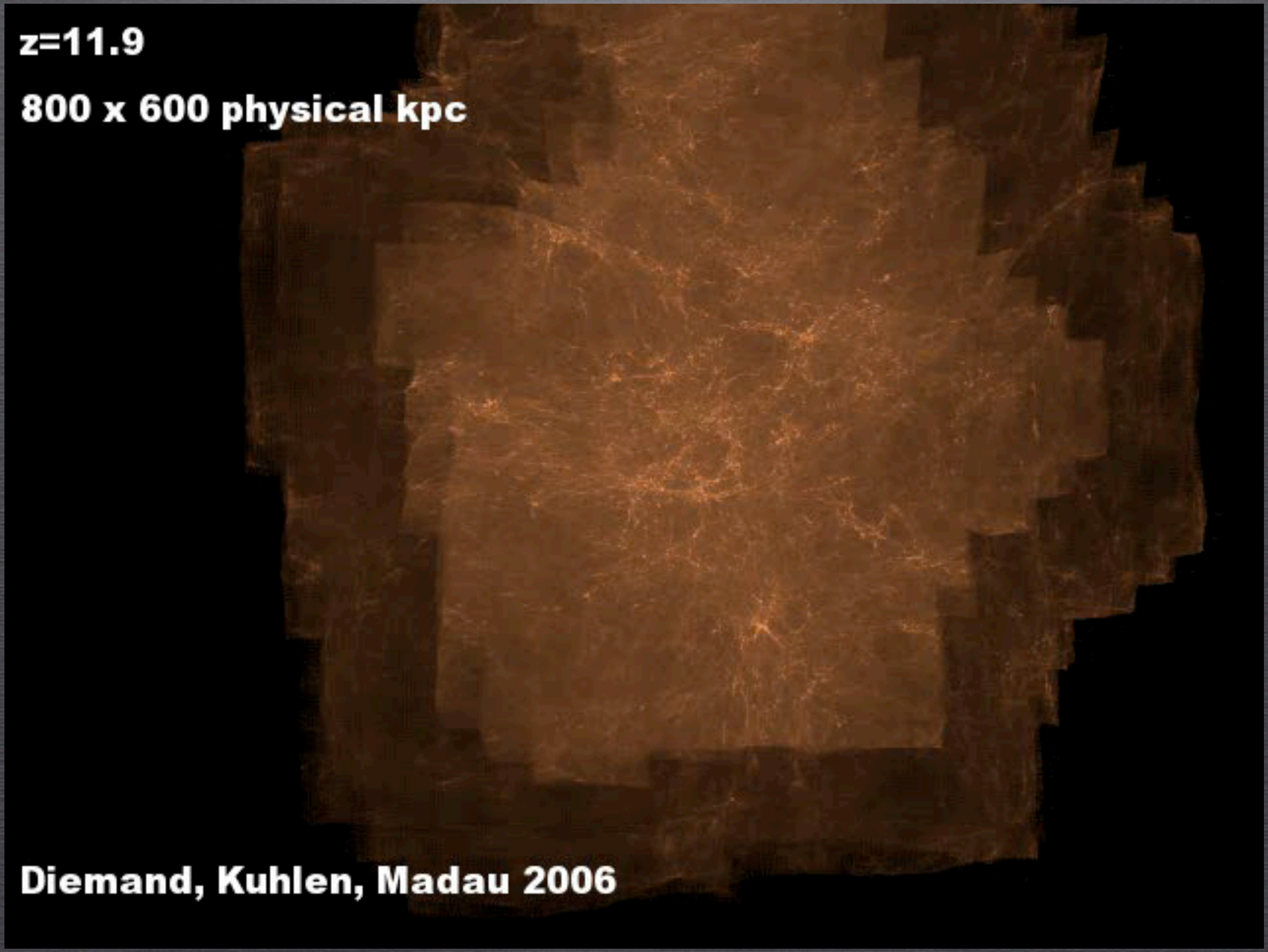
Particle physics input from extensions of the Standard Model. Need to specify distribution of DM along the line of sight

Deriving Exclusion Plots

I. Take a numerical simulation

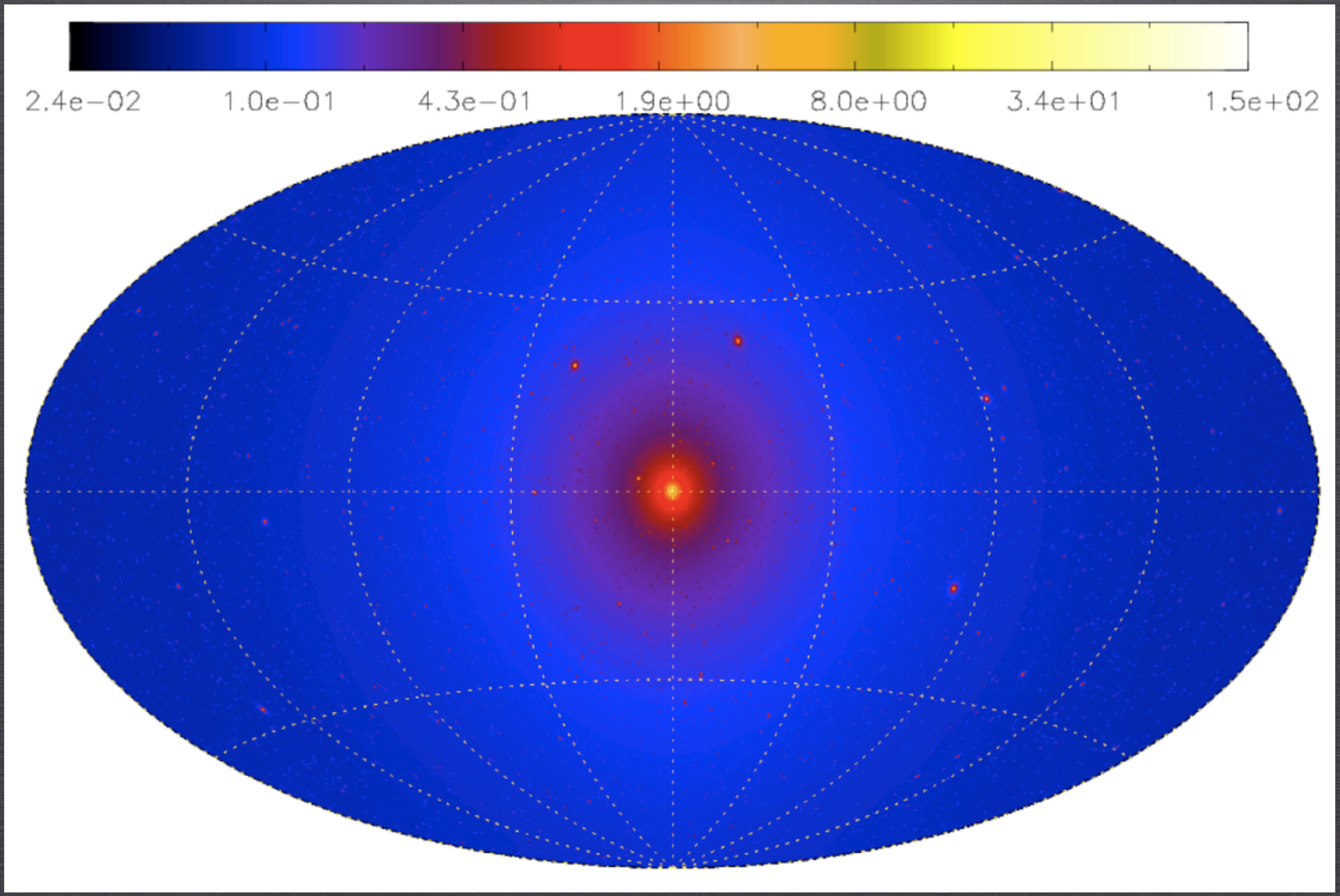
Deriving Exclusion Plots

I. Take a numerical simulation



Deriving Exclusion Plots

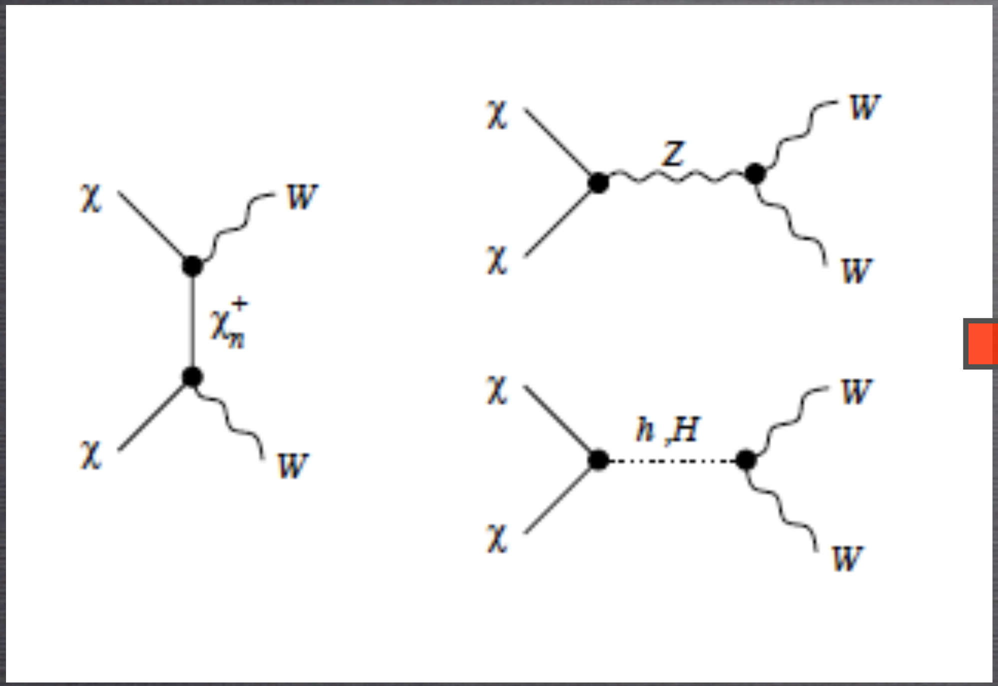
II. Calculate annihilation maps (integral of ϱ² along l.o.s.)



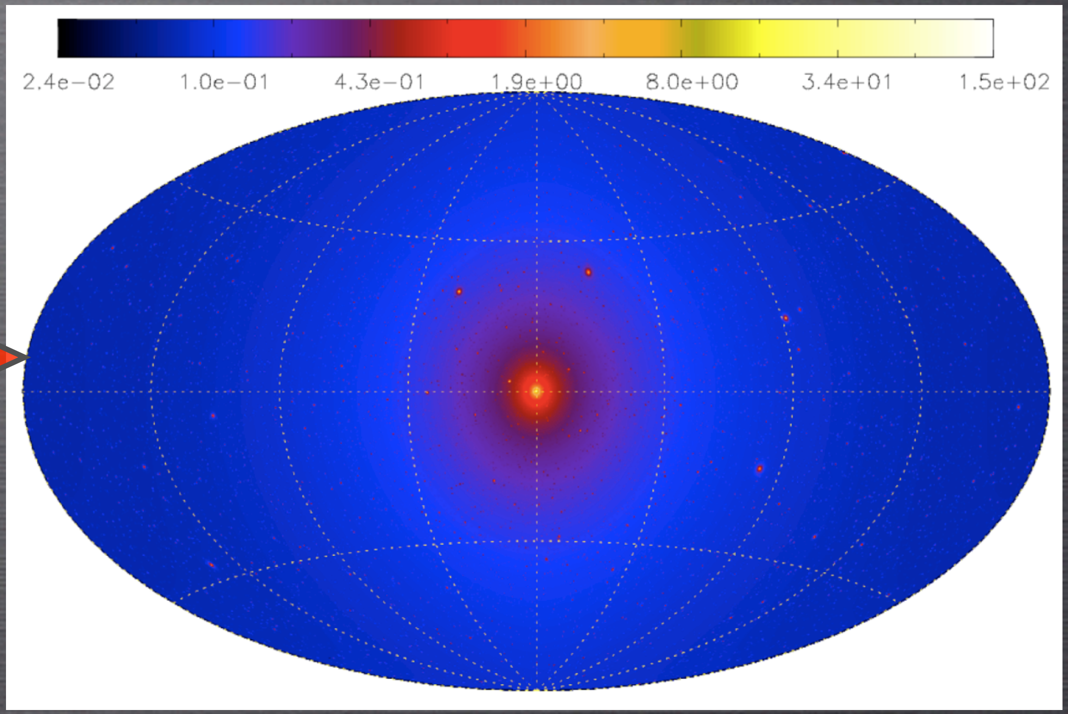
Pieri, Lavalle, GB, Branchini 2009

How to obtain robust results

III. Add particle physics input



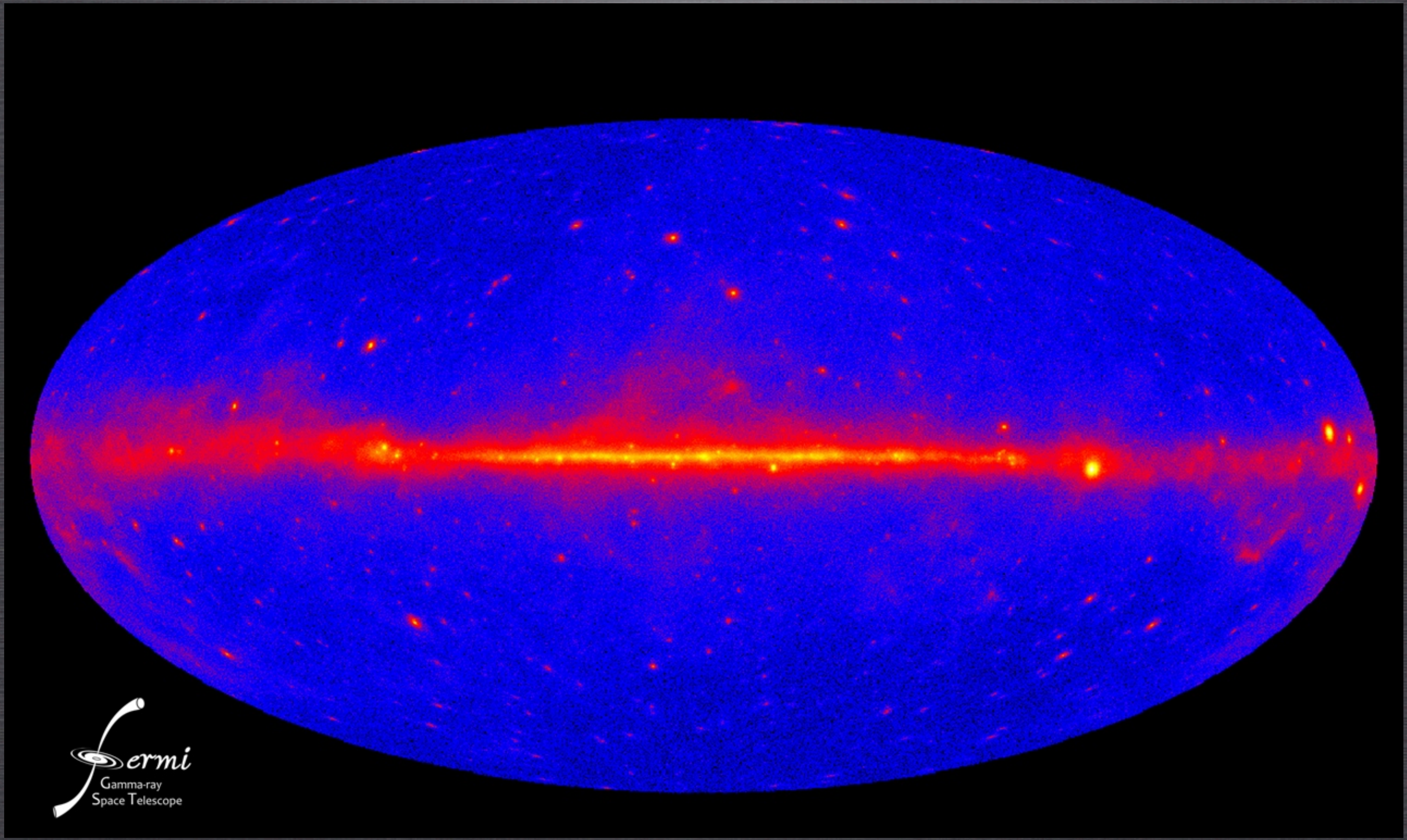
Specify mass, σv, branching ratios, and calculate gamma-ray spectrum per annihilation (e.g. for SUSY models, or other BSM theories)



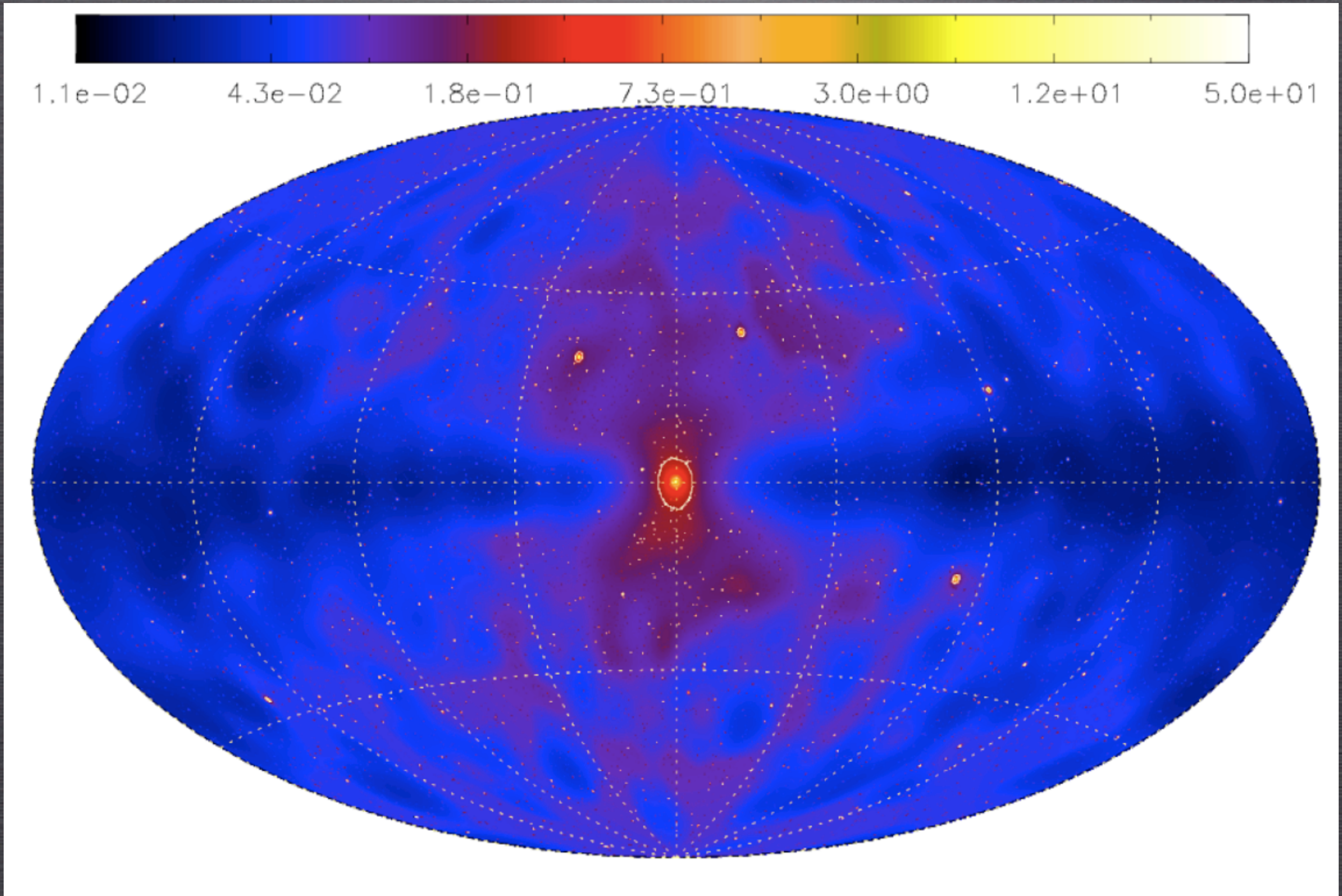
Obtain mock maps (photons per pixel) to be compared with observations.

Deriving Exclusion Plots

IV. Compare with observations



Regions with maximum S/N

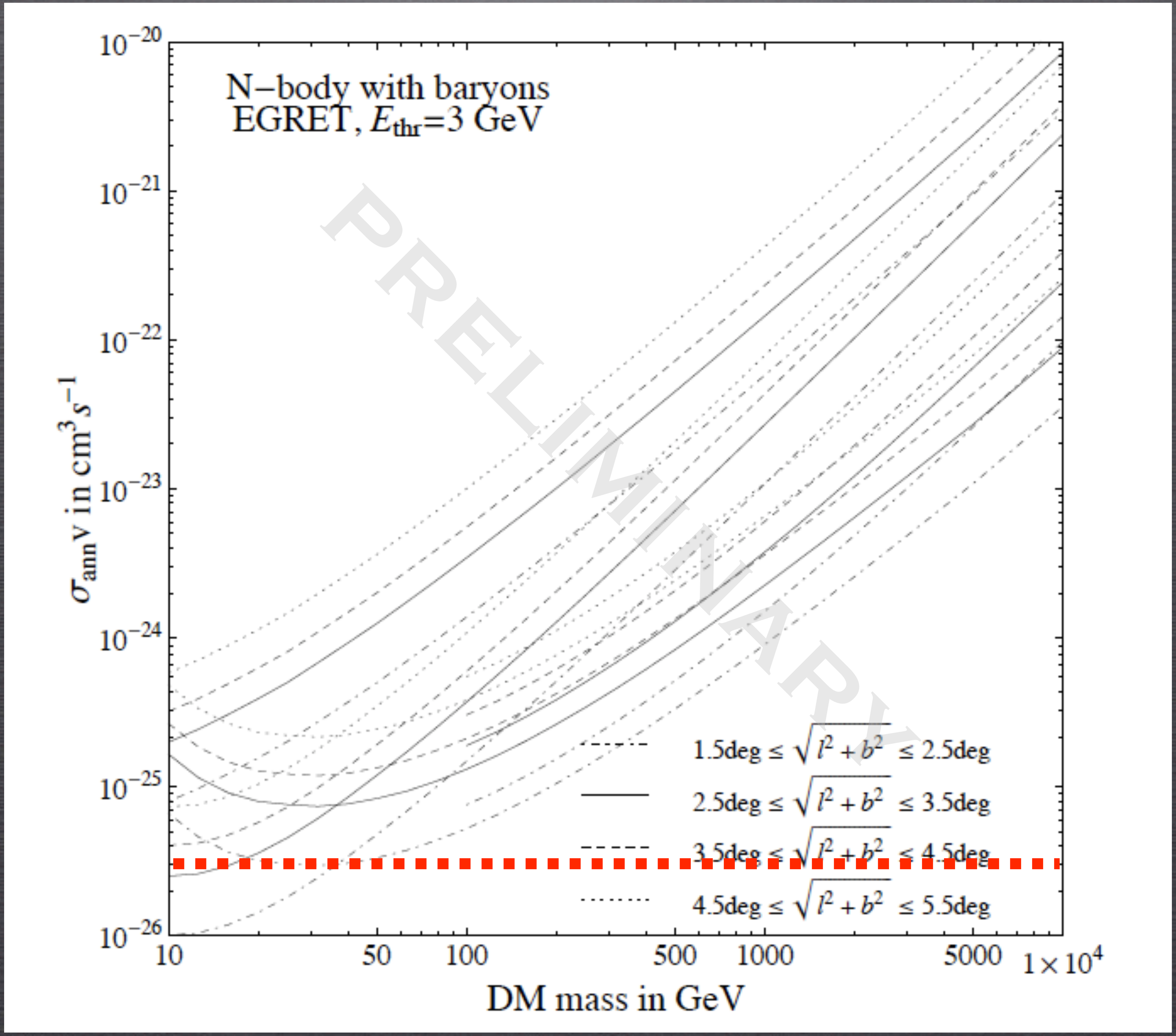


Pieri, Lavalle, GB, Branchini 2009

How to obtain robust results

Deriving upper Limits

5. Calculate exclusion plots. Pato, Agertz, Pieri, GB, Moore, Teyssier (2010)



How to obtain robust results

Deriving upper Limits

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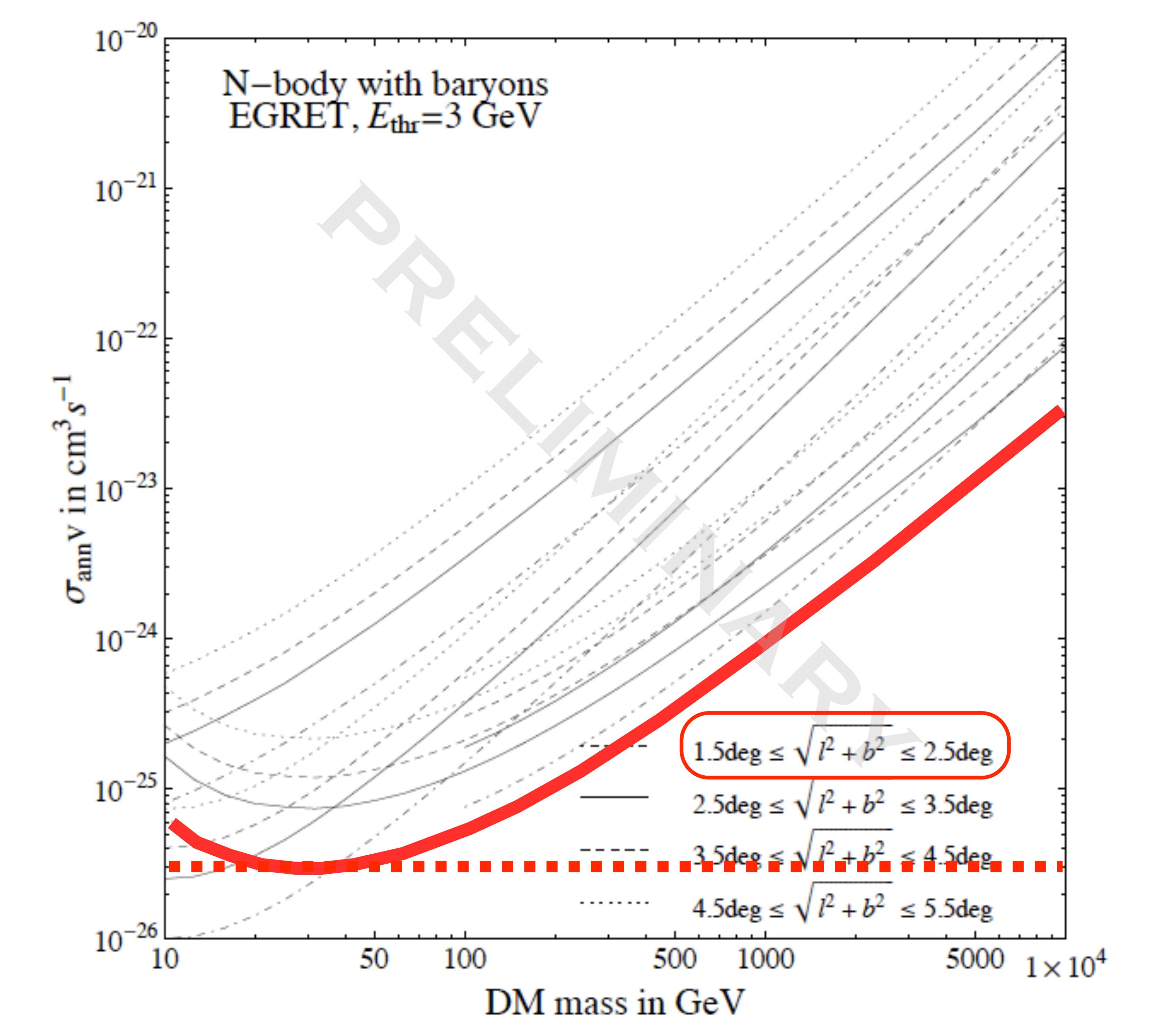
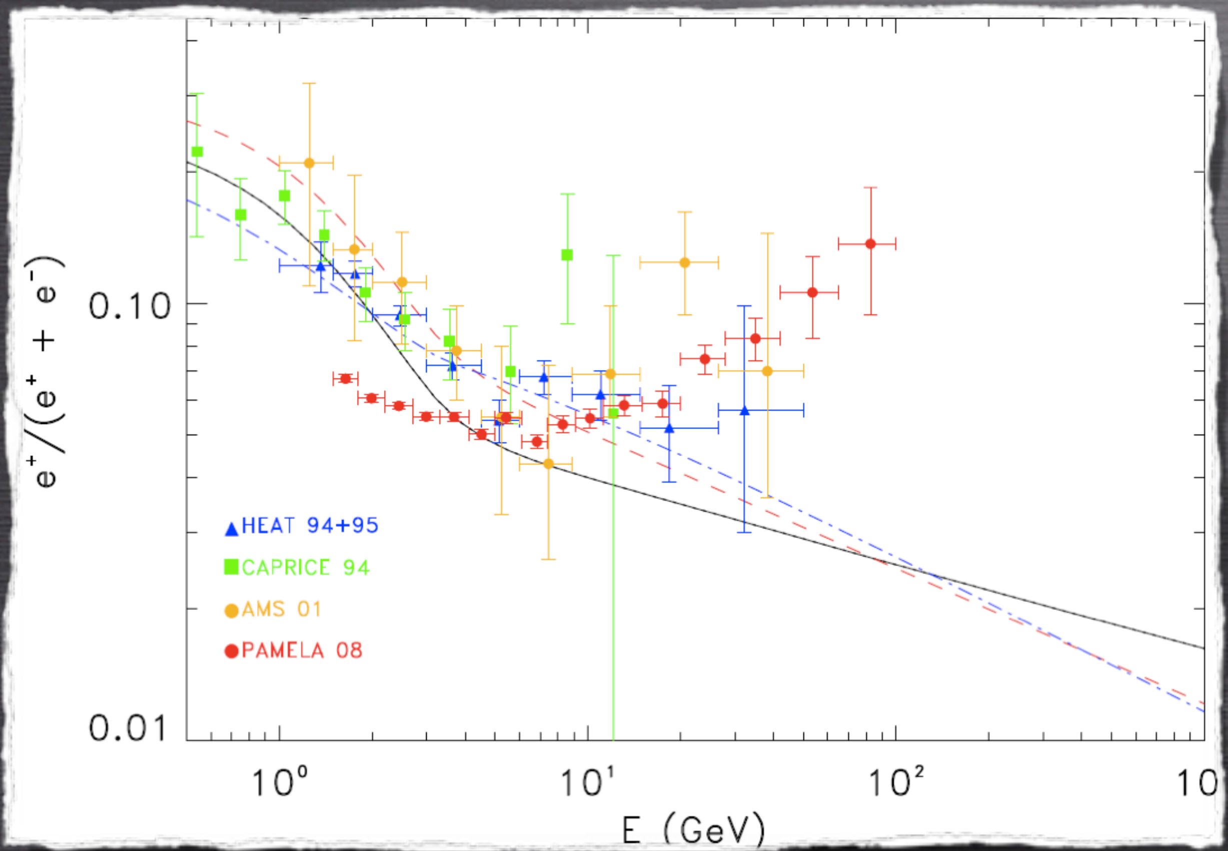
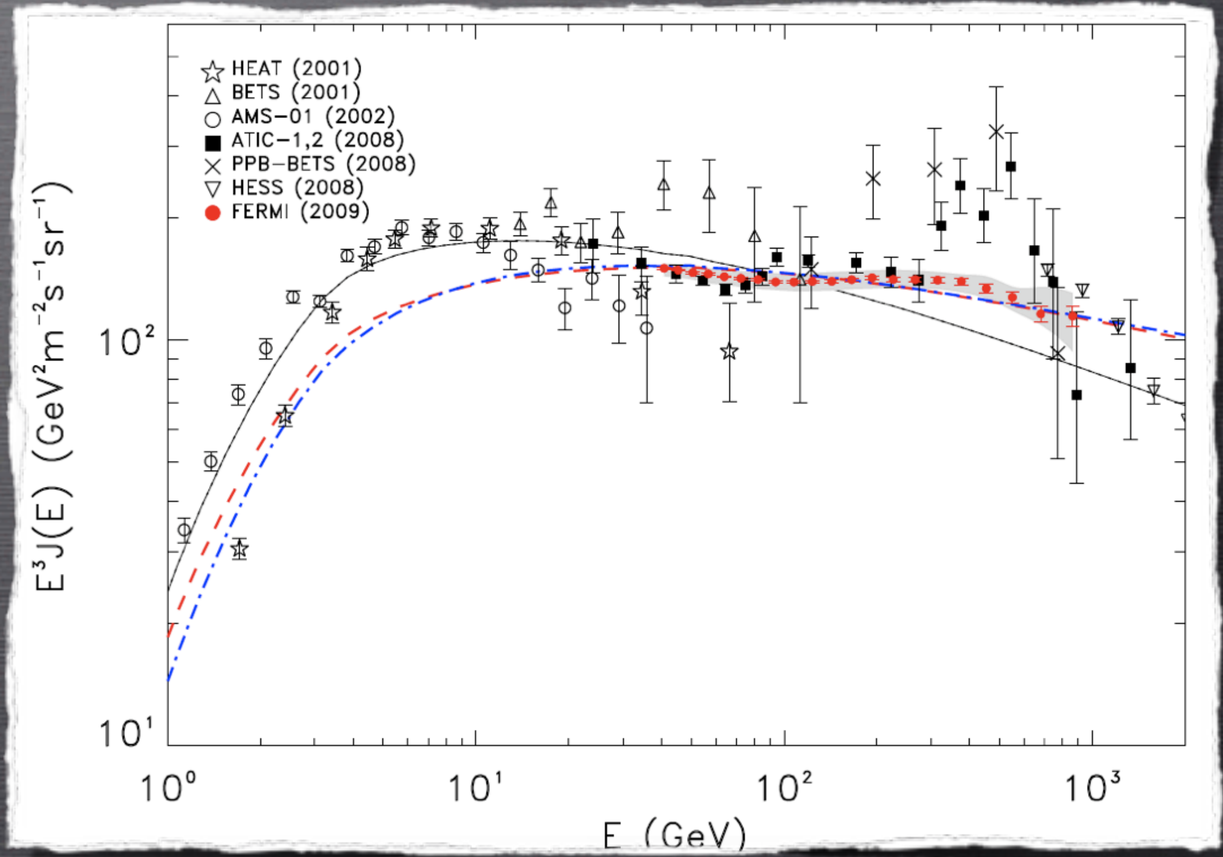


Cosmic e^+e^-

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



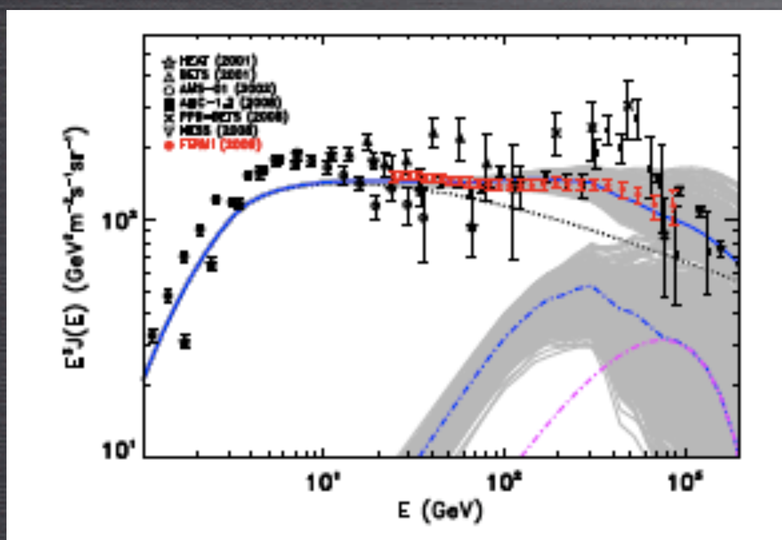
Grasso et al. 2009



Grasso et al. 2009

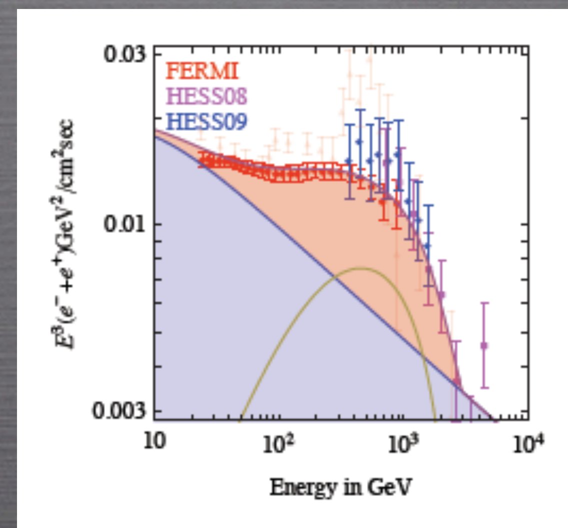
Interpretation

Pulsars



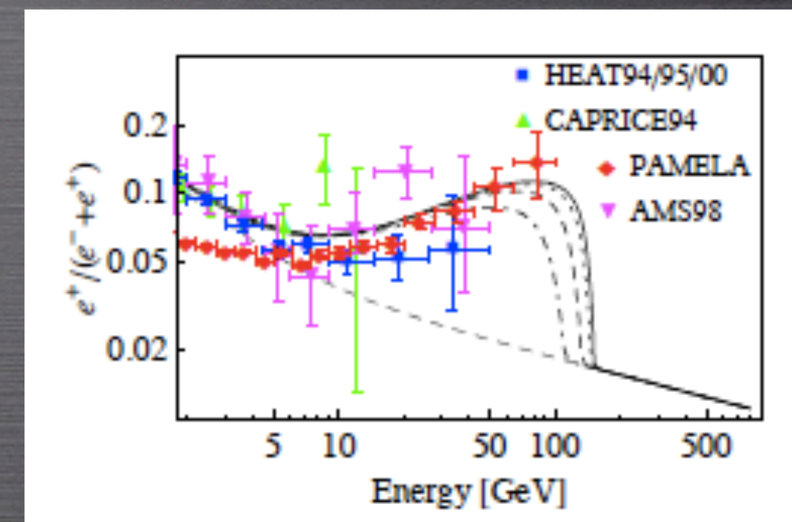
Grasso et al. 2009

DM Annihilation



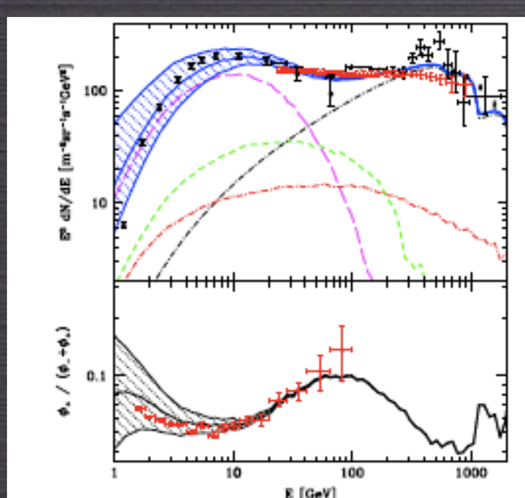
Strumia et al. 2009

DM Decay



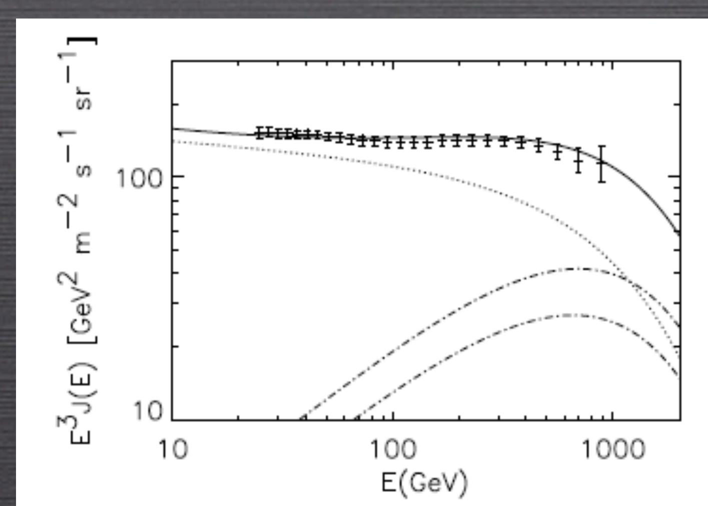
Ibarra et al. 2009

SNRs inhom.



Piran et al. 2009

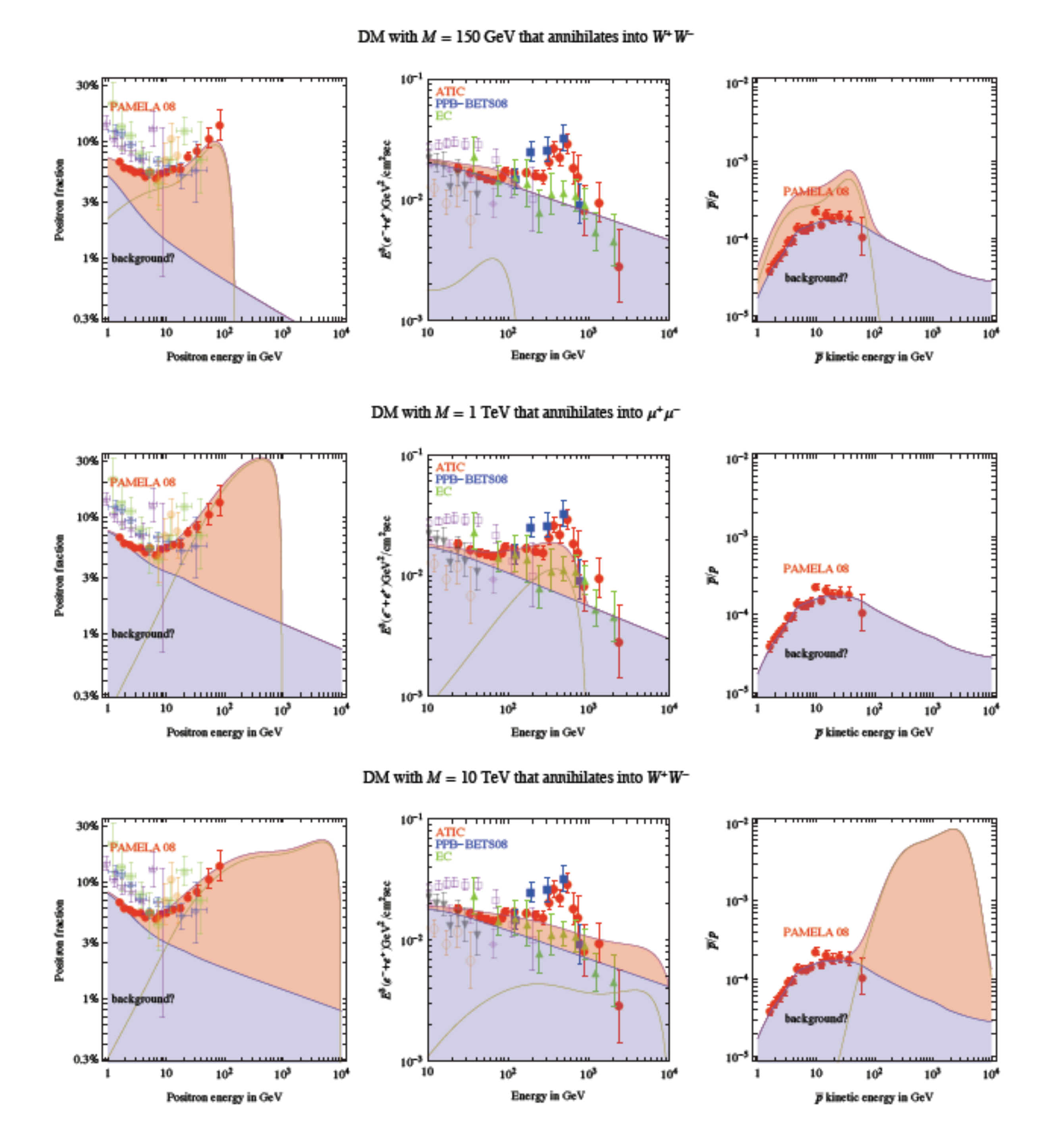
SNRs 2ndary CR acc.



Blasi 2009

... + many MANY other models .

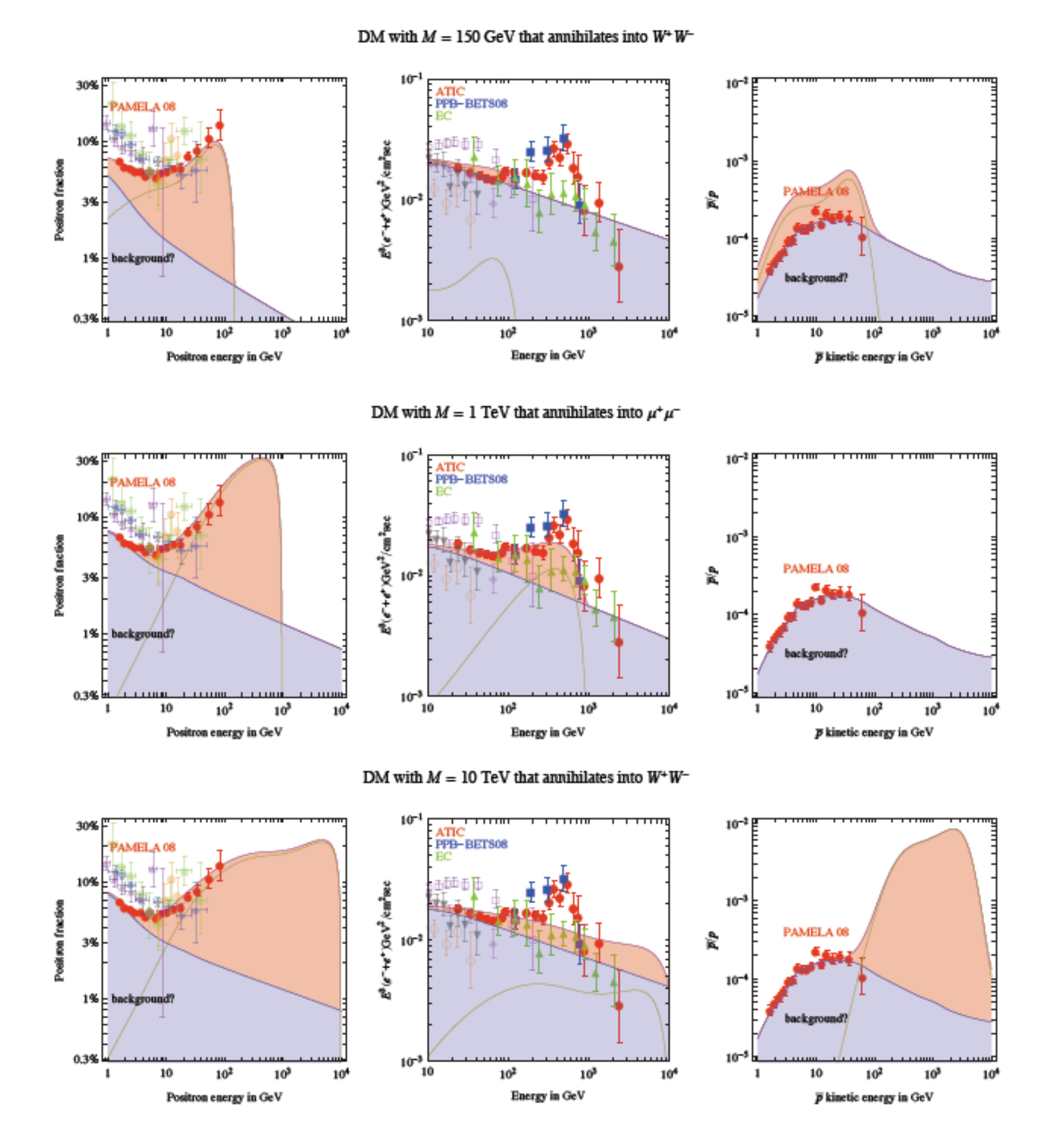
PAMELA / ATIC what do we learn?



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?

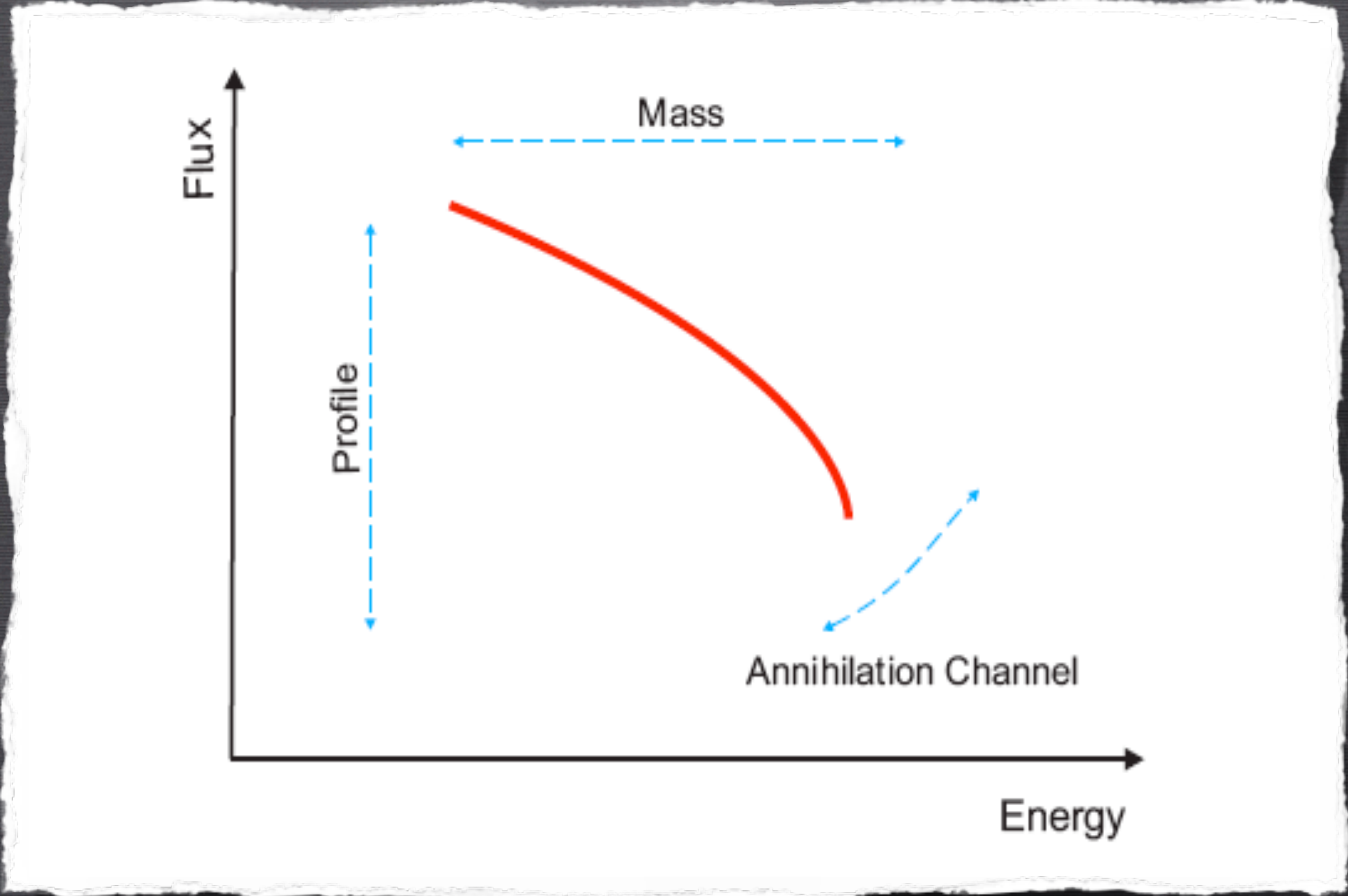


CIRELLI, KADASTIK, RAIDAL, STRUMIA 2008

... 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!

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?"

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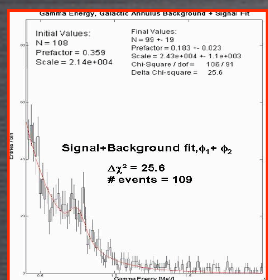

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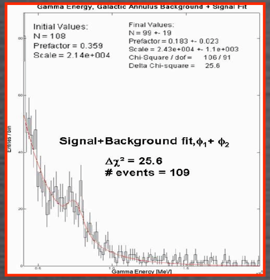

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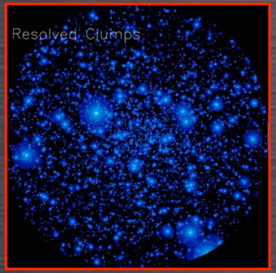

2) Multiple Sources with Identical spectra

e.g. DM clumps or IMBHs

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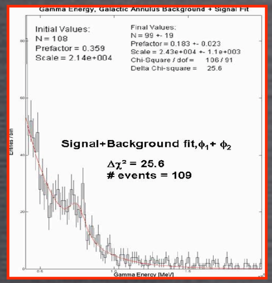

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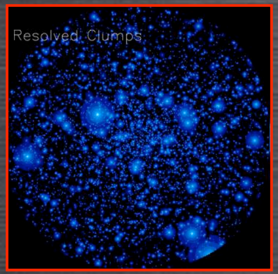

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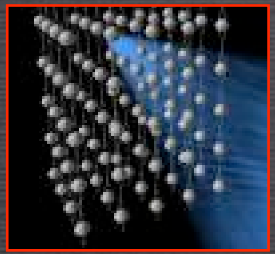

3) High-Energy Neutrinos from the Sun

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

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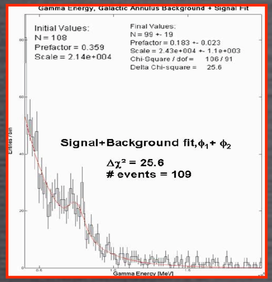

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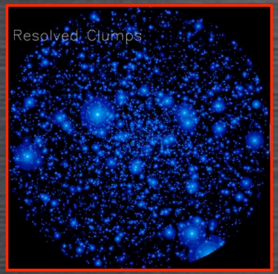

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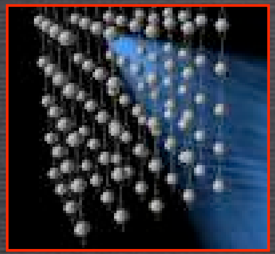

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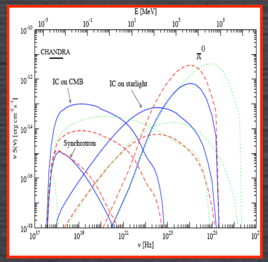

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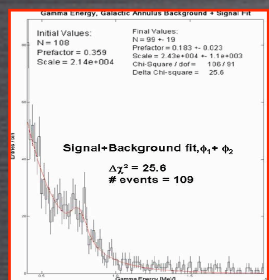

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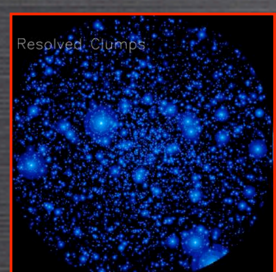

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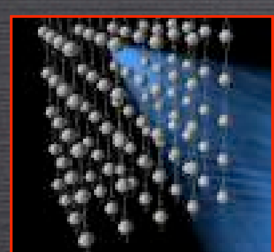

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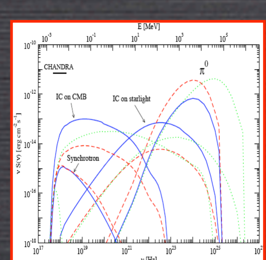

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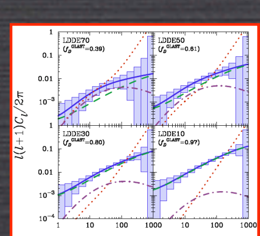


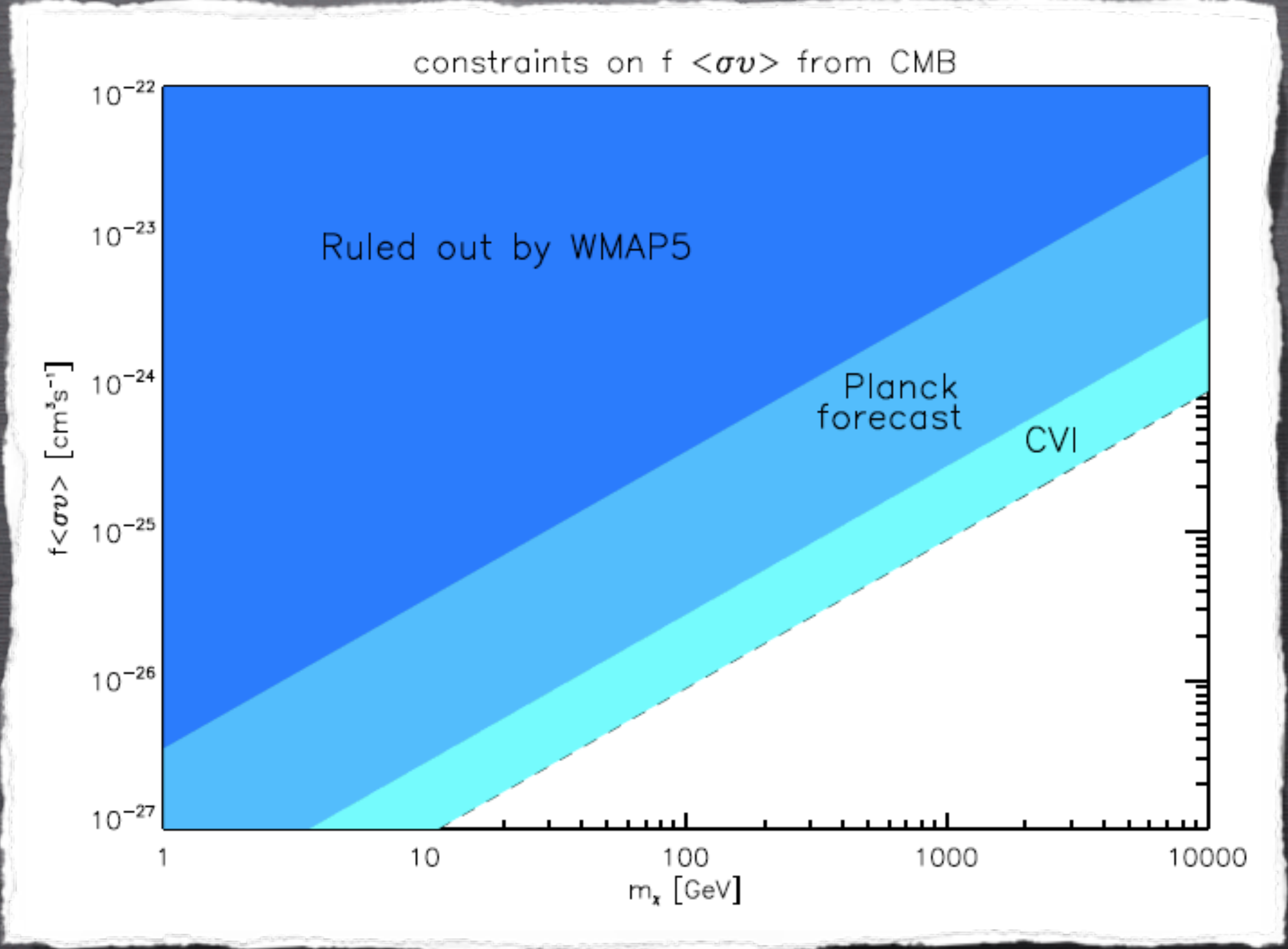
5) Angular power Spectrum of EG Background

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

Constraints from CMB

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

(cfr. Talks by Iocco and Hector on Monday)



Galli, Iocco, GB, Melchiorri 2009

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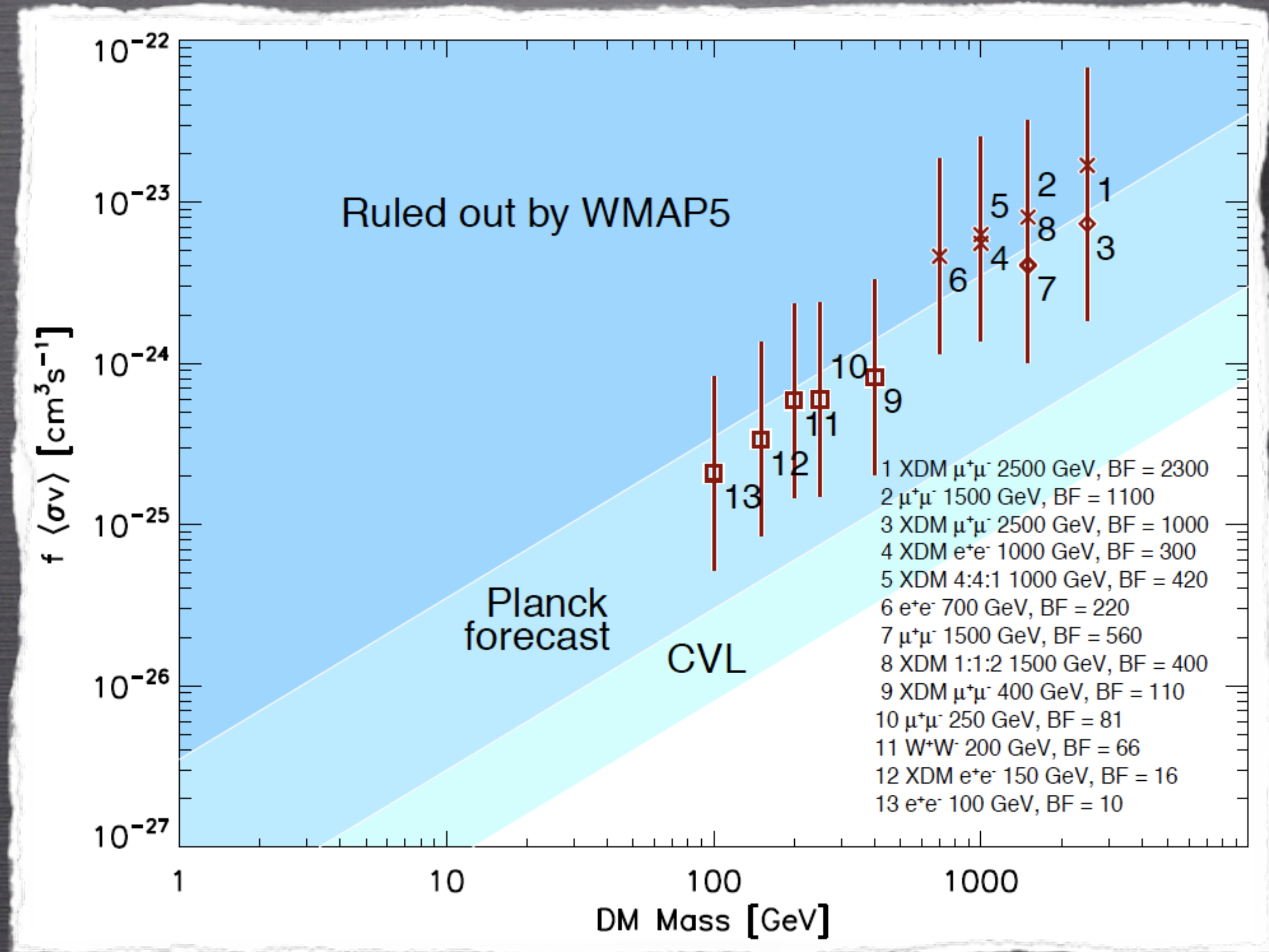

Slatyer, Padmanabhan, Finkbeiner 2009

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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 ~5 Yrs. discovery of Wimps or Paradigm shift..