Complementarity of Dark Matter searches

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GRavitation AstroParticle Physics Amsterdam

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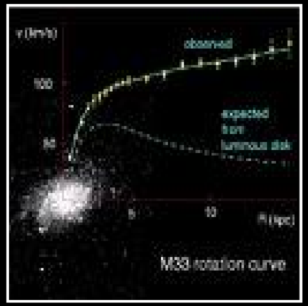
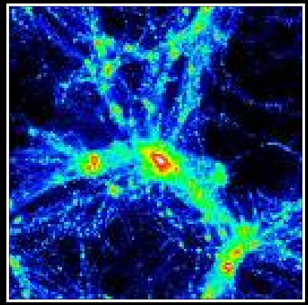
Evidence for Dark Matter

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

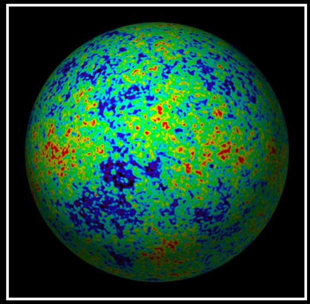
COSMOLOGICAL OBSERVATIONS



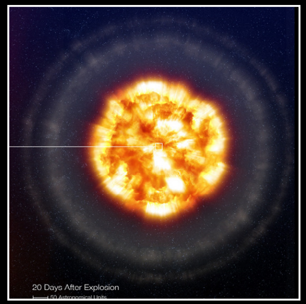
- Rotation Curves



- Clusters of galaxies



- CMB



- Type Ia Supernovae

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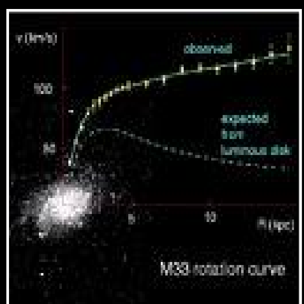

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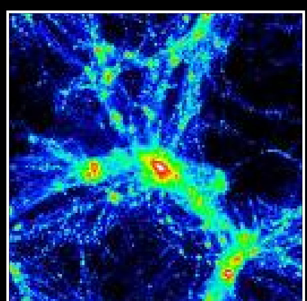

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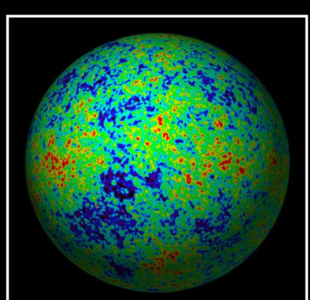

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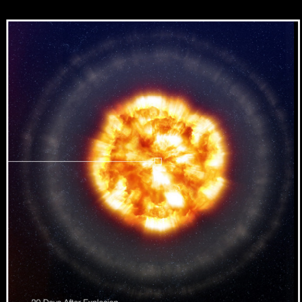
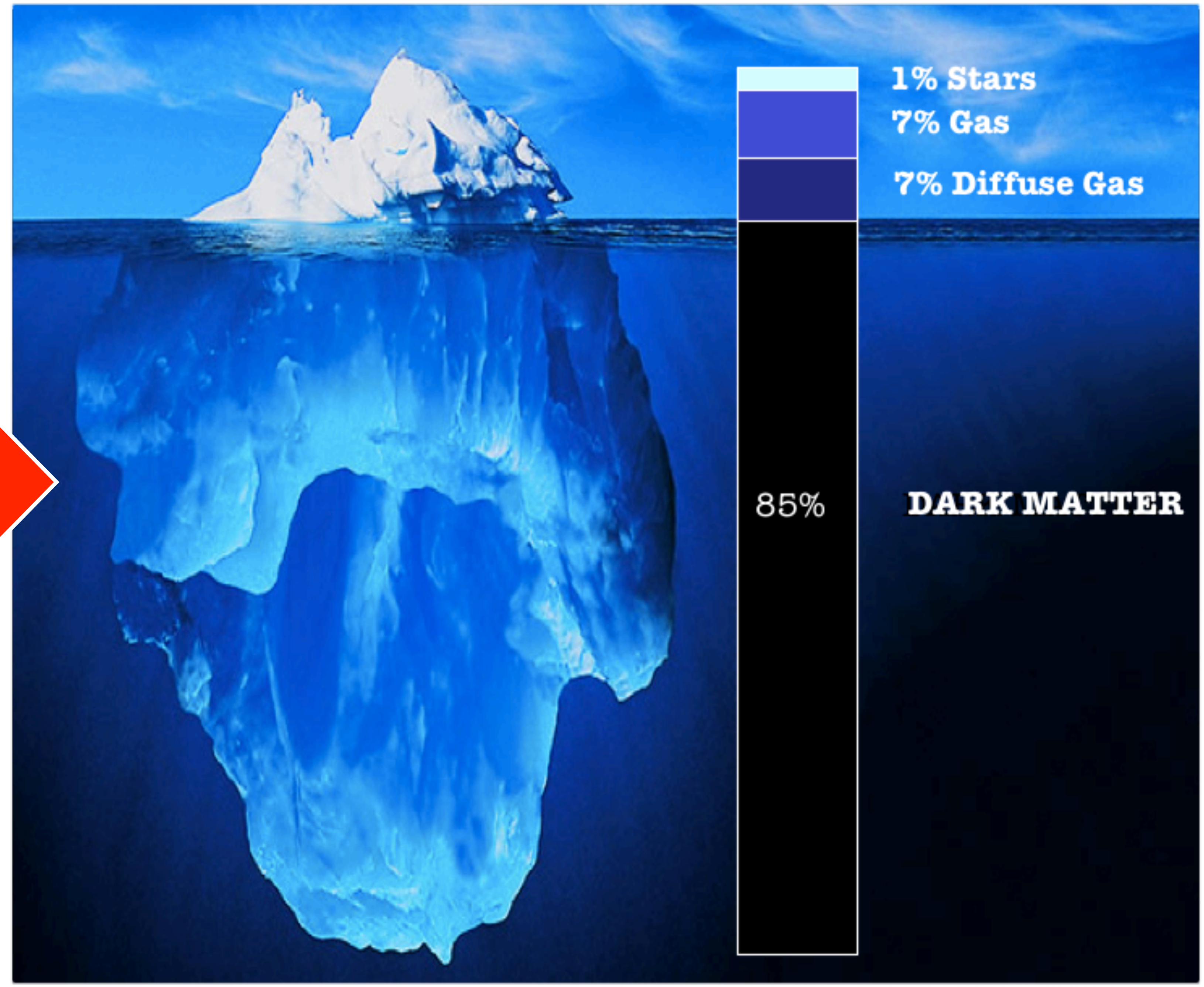


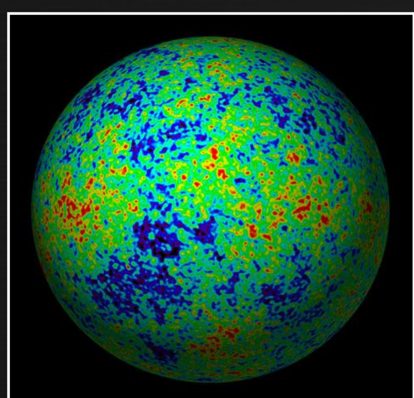
- Type Ia Supernovae



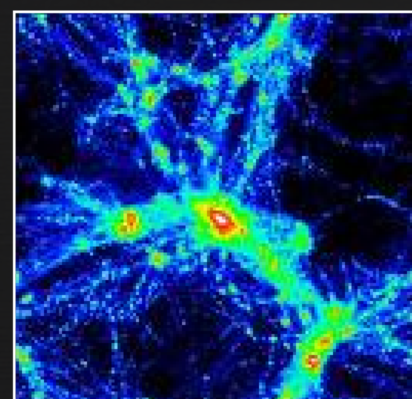
What do we know?

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

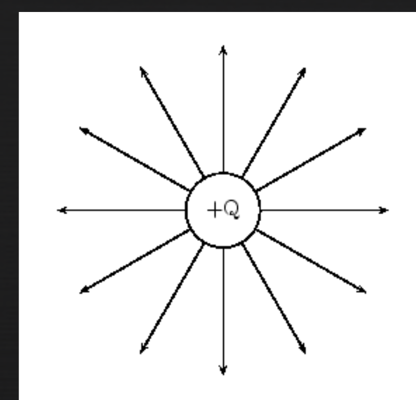
1) Ωh^2 OK?



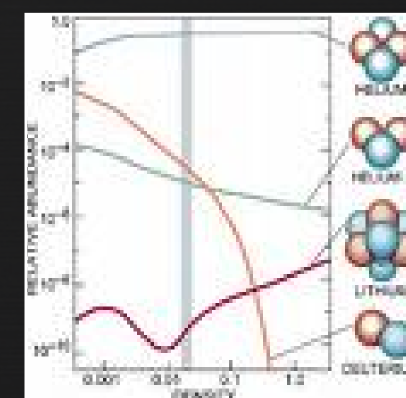
2) Is it cold?



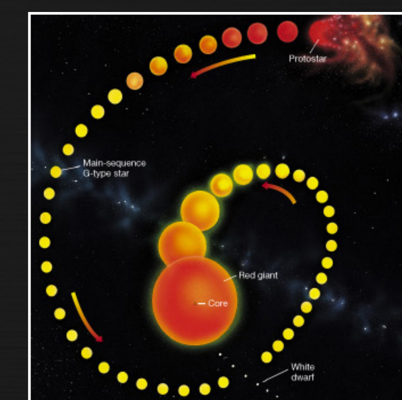
3) Is it neutral?



4) Is BBN ok?

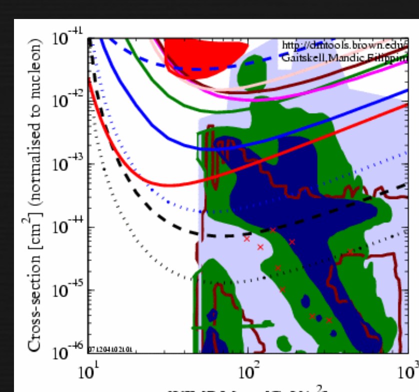


5) Stars OK?

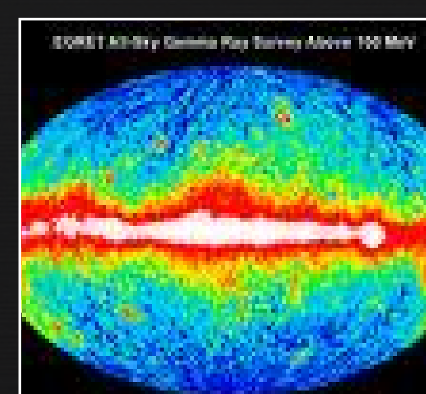


6) Collisionless?

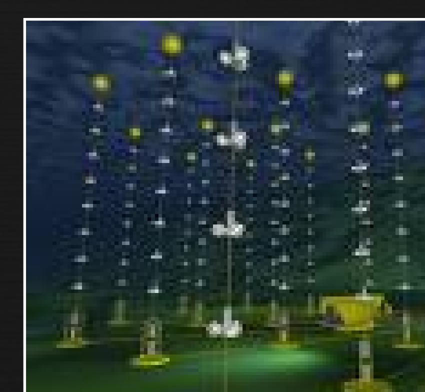
7) Couplings OK?



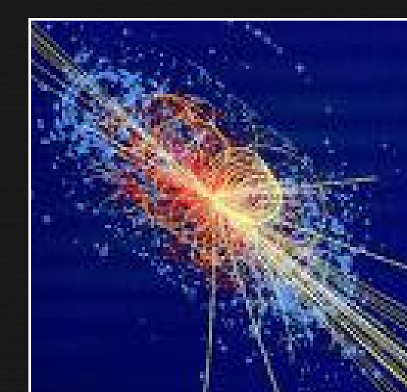
8) γ-rays OK?



9) Astro bounds?



10) Can probe it?



Taoso, GB & Masiero 2007

Dark Matter candidates

- Neutralino?

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

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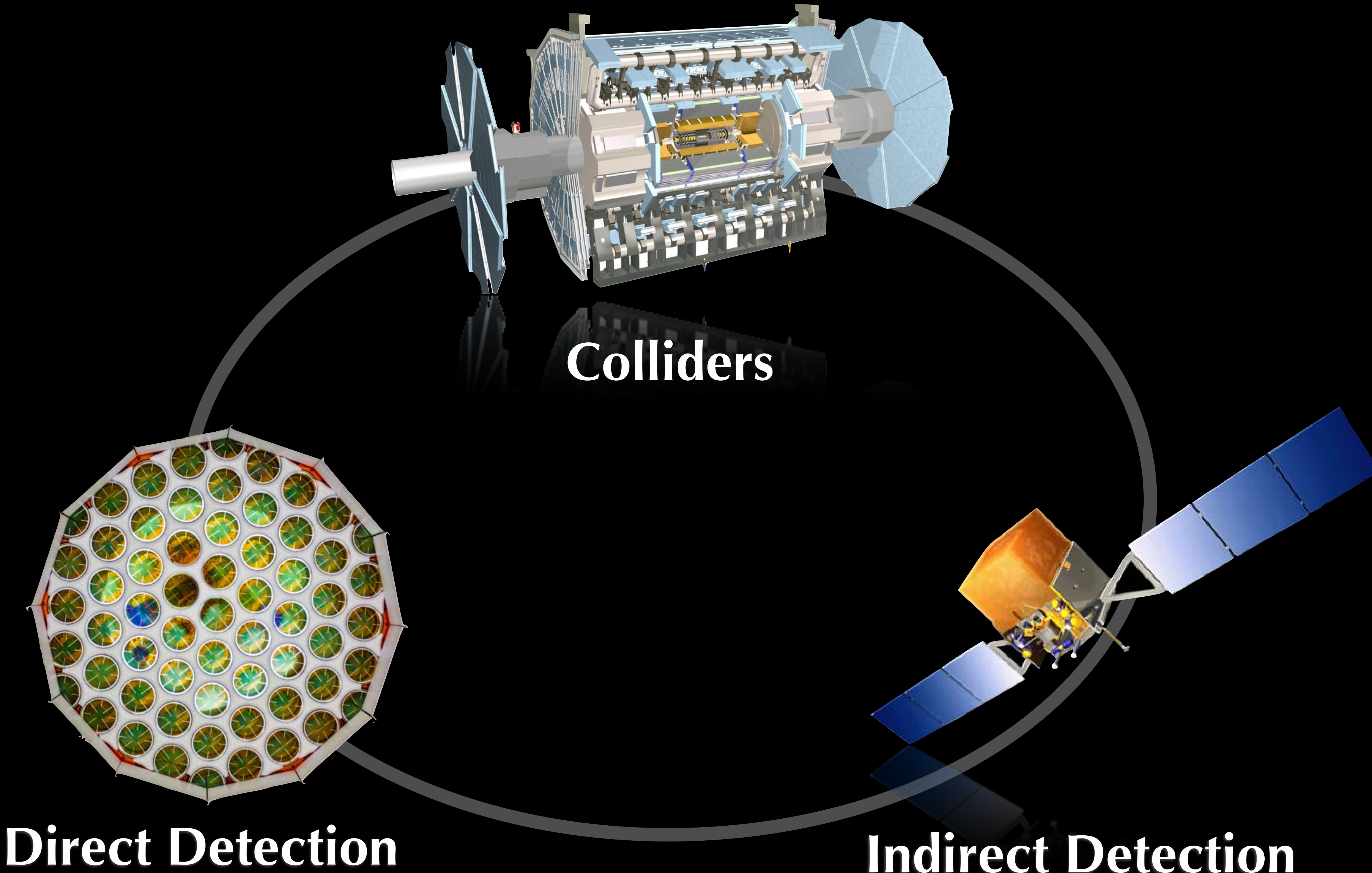
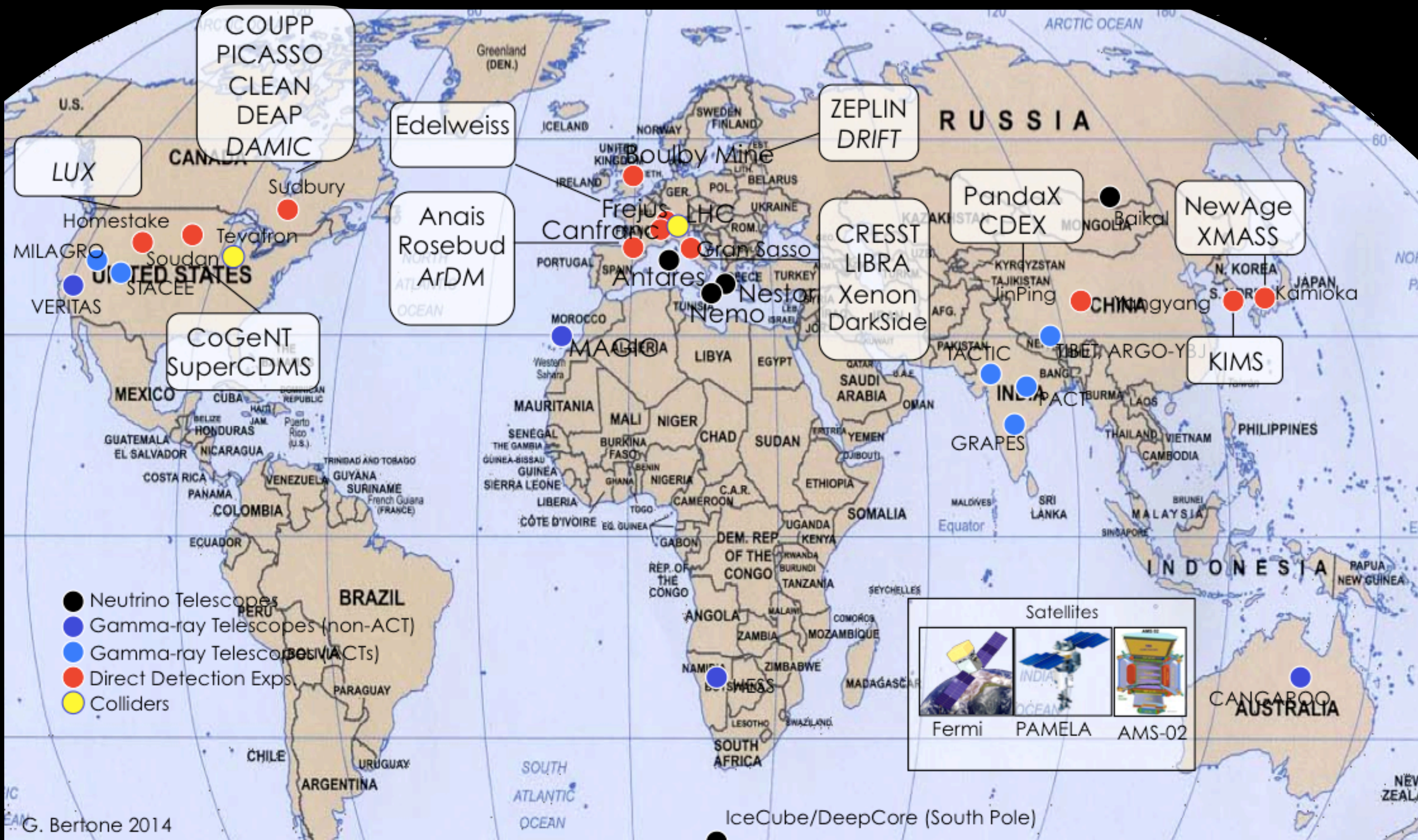
The quest for Dark Matter



The worldwide race



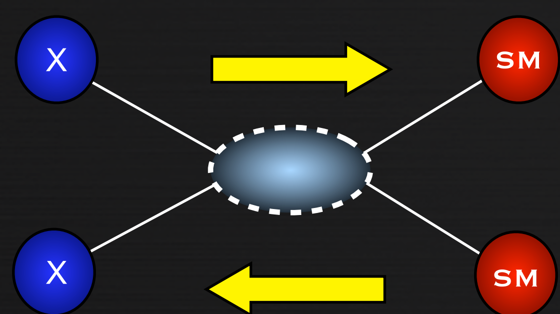
Indirect Detection

Why "annihilations"?

X = DARK MATTER

SM = STANDARD MODEL PARTICLE

Early Universe



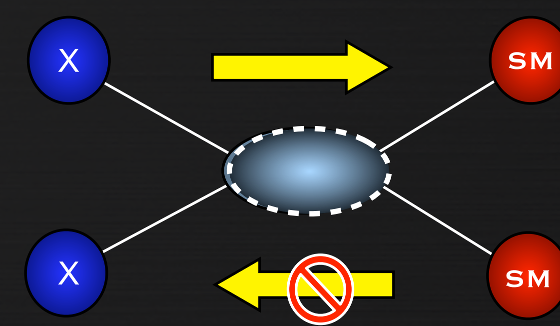
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

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

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

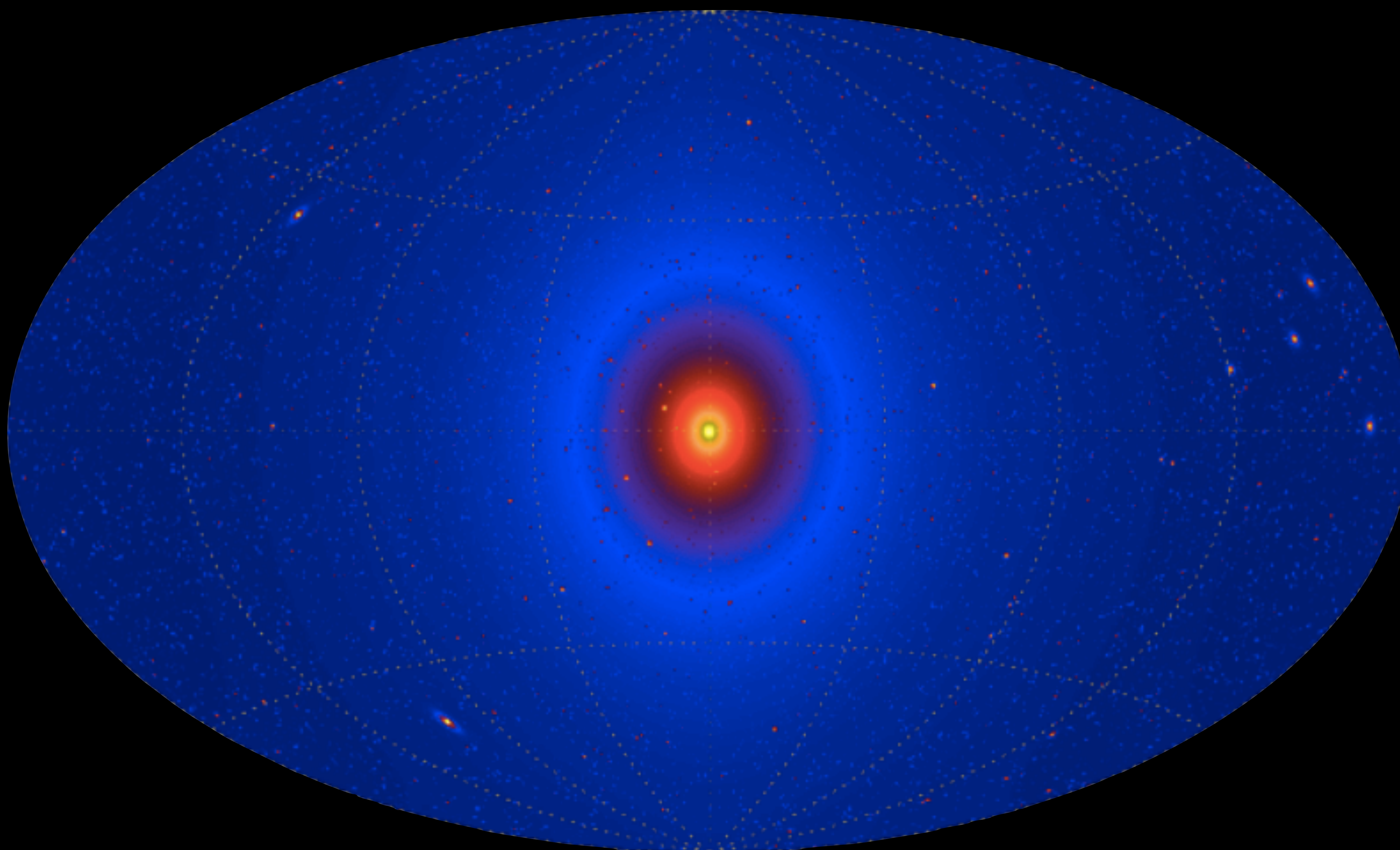
Particle physics input from extensions of the Standard Model. Need to specify distribution of DM along the line of sight.

Simulating Galaxy Formation

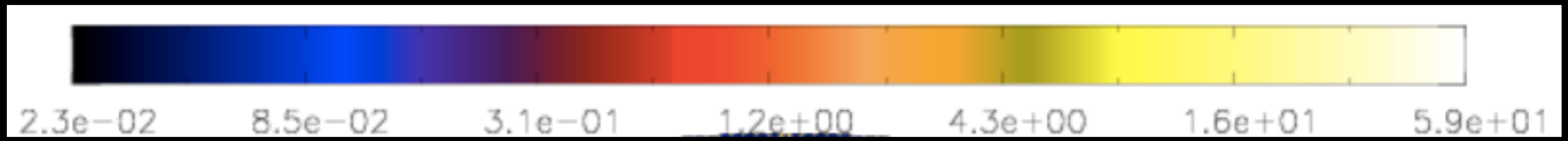
http://www.illustris-project.org/media/

Predicted Annihilation Flux

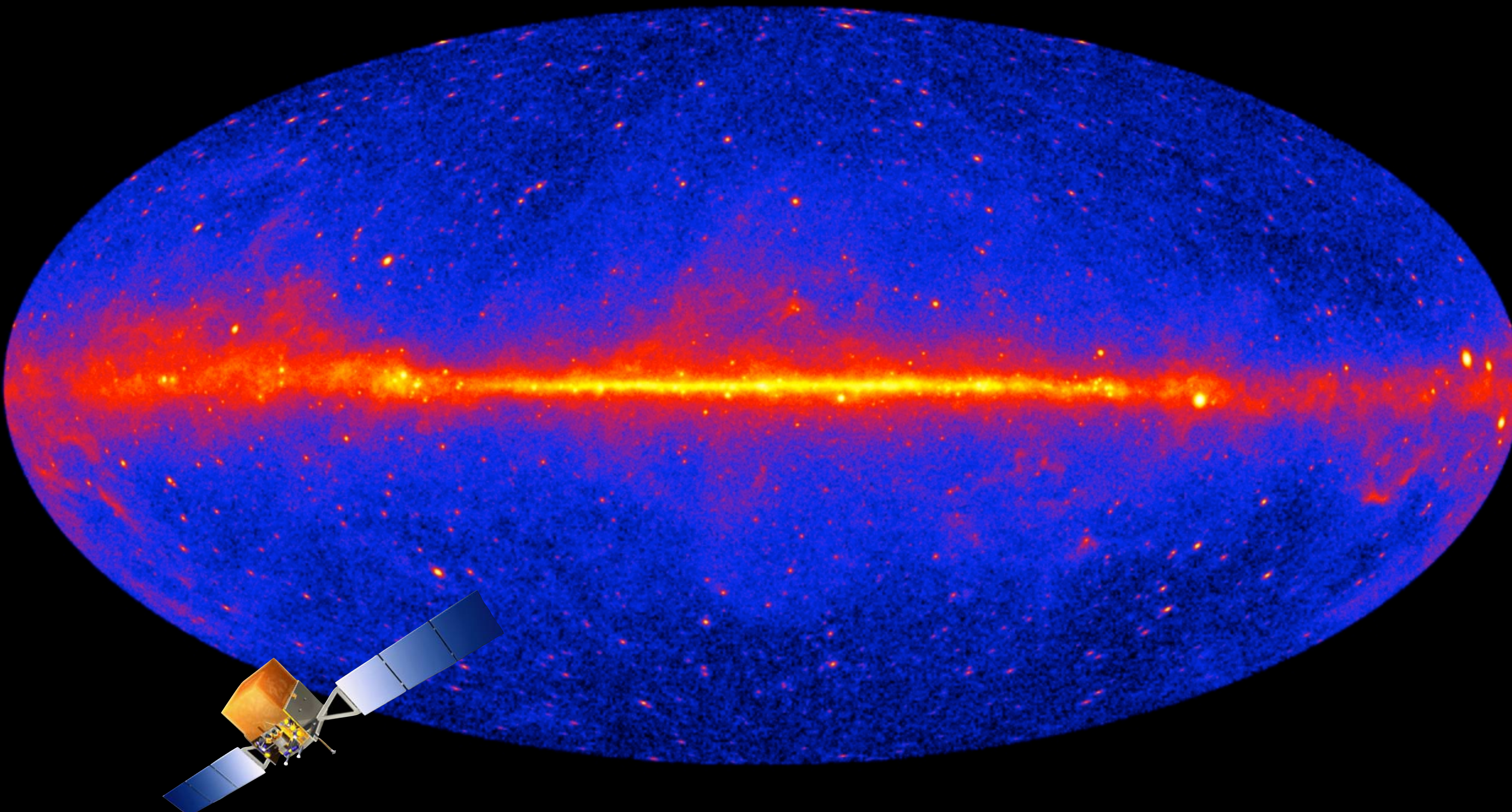
Pieri, GB, Branchini 2009



Full sky map of Number of photons above 3 GeV



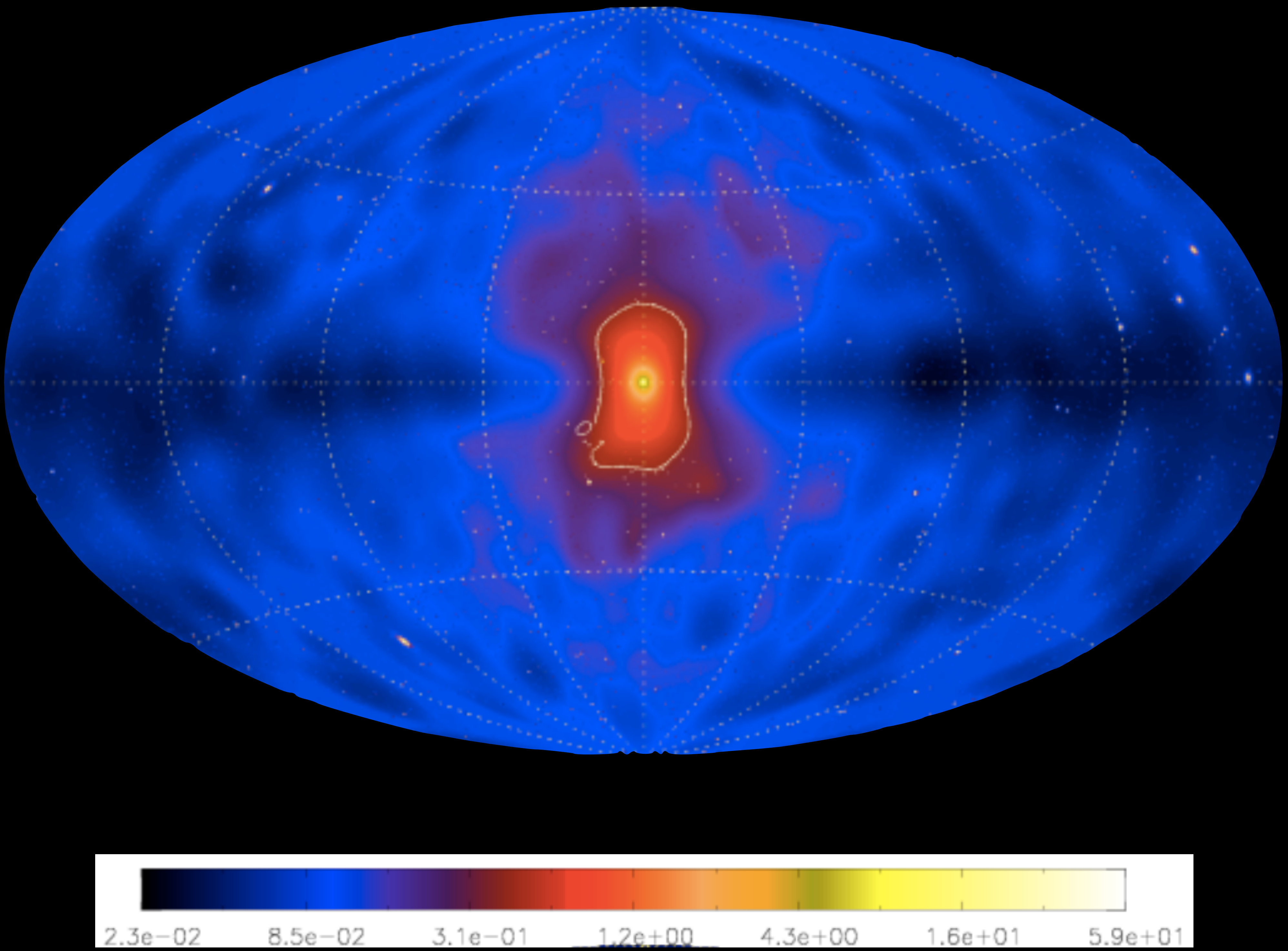
The FERMI sky



5-YEAR FULL-SKY MAP. HTTP://FERMI.GSFC.NASA.GOV

Optimal Sensitivity Map

Pieri, GB, Branchini 2009



Indirect Detection

RECENT FERMI CONSTRAINTS FROM DWARF GALAXIES ARXIV:1310.0828

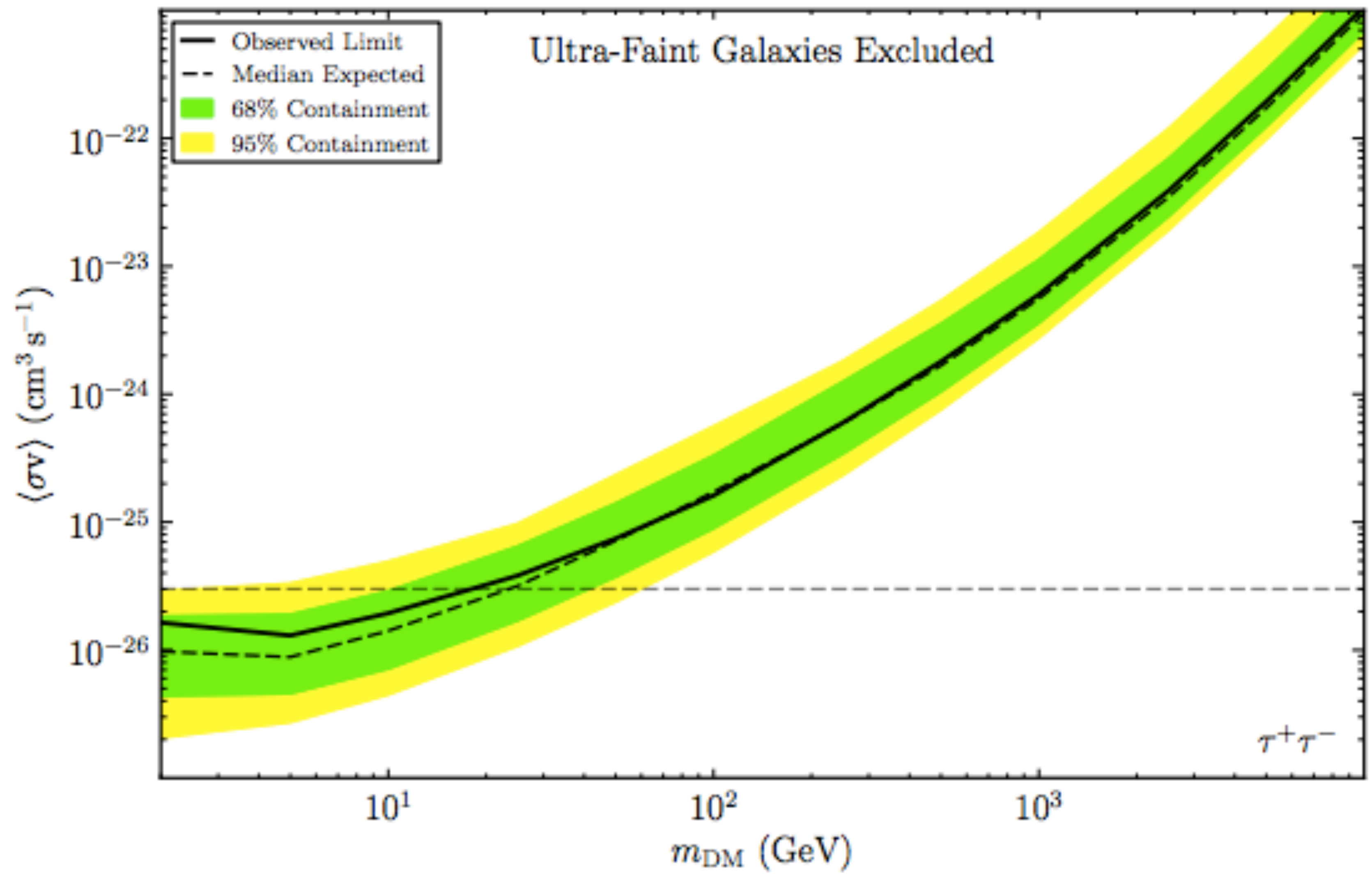


FIG. 6. Constraints on the dark matter annihilation cross section ($\tau^+\tau^-$ channel) at 95% CL derived from a combined analysis excluding three ultra-faint dwarf galaxies: Segue 1, Ursa Major II, and Willman 1 (solid line). The expected sensitivity is similarly calculated excluding these three ultra-faint dwarf galaxies and is represented in the same manner as in Figure 5.

The 130 GeV Line

Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation

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[c]Physik-Department T30d, Technische Universität München, James-Franck-Straße, 85748 Garching, Germany
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arXiv:1204.2797v2 [hep-ph] 8 Aug 2012

A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

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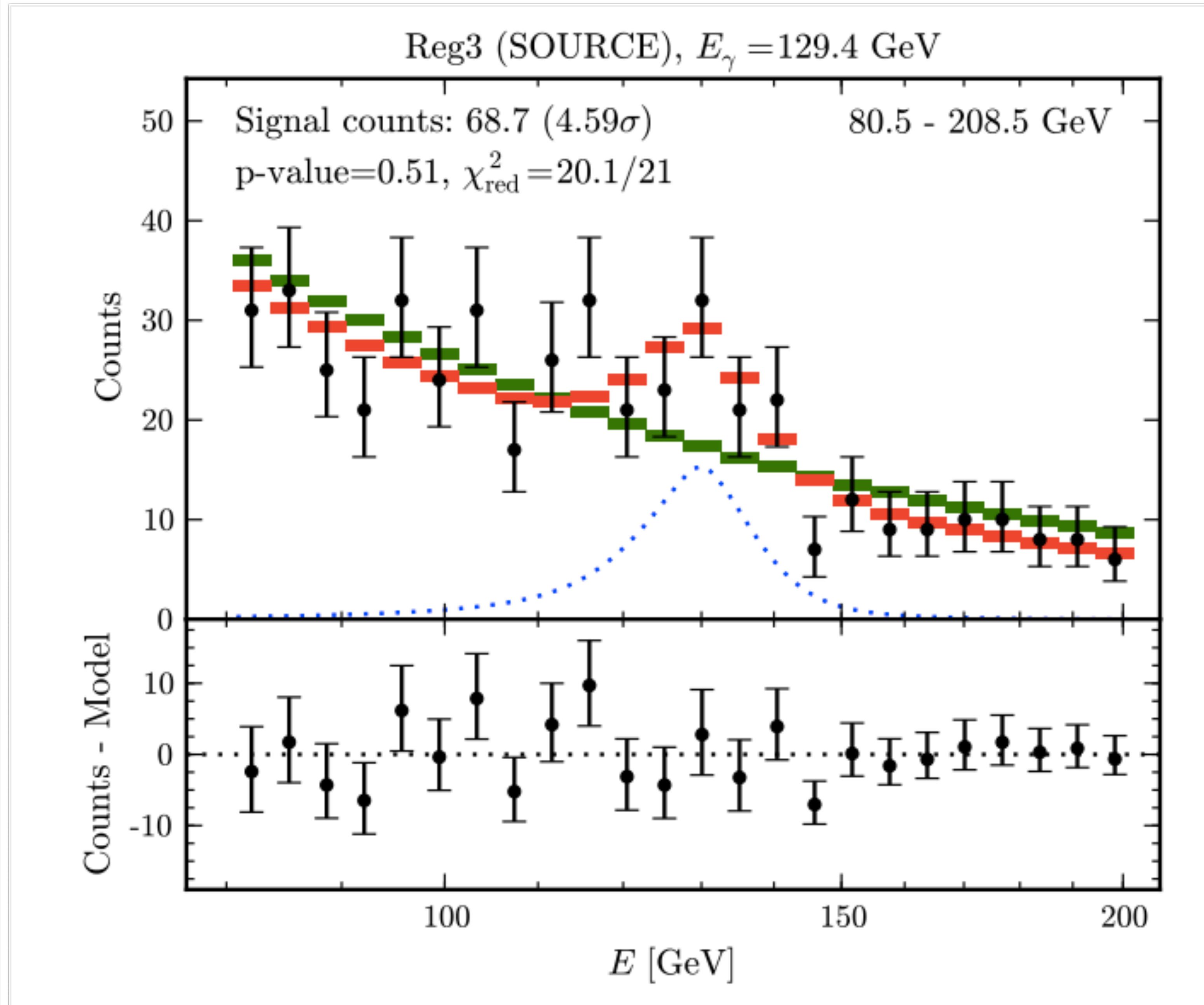
Abstract. The observation of a gamma-ray line in the cosmic-ray fluxes would be a smoking-gun signature for dark matter annihilation or decay in the Universe. We present an improved search for such signatures in the data of the Fermi Large Area Telescope (LAT), concentrating on energies between 20 and 300 GeV. Besides updating to 43 months of data, we use a new data-driven technique to select optimized target regions depending on the profile of the Galactic dark matter halo. In regions close to the Galactic center, we find a 4.6σ indication for a gamma-ray line at $E_\gamma \approx 130$ GeV. When taking into account the look-elsewhere effect the significance of the observed excess is 3.2σ. If interpreted in terms of dark matter particles annihilating into a photon pair, the observations imply a dark matter mass of $m_\chi = 129.8 \pm 2.4^{+7}_{-13}$ GeV and a partial annihilation cross-section of $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}$ cm^3 s^{-1} when using the Einasto dark matter profile. The evidence for the signal is based on about 50 photons; it will take a few years of additional data to clarify its existence.

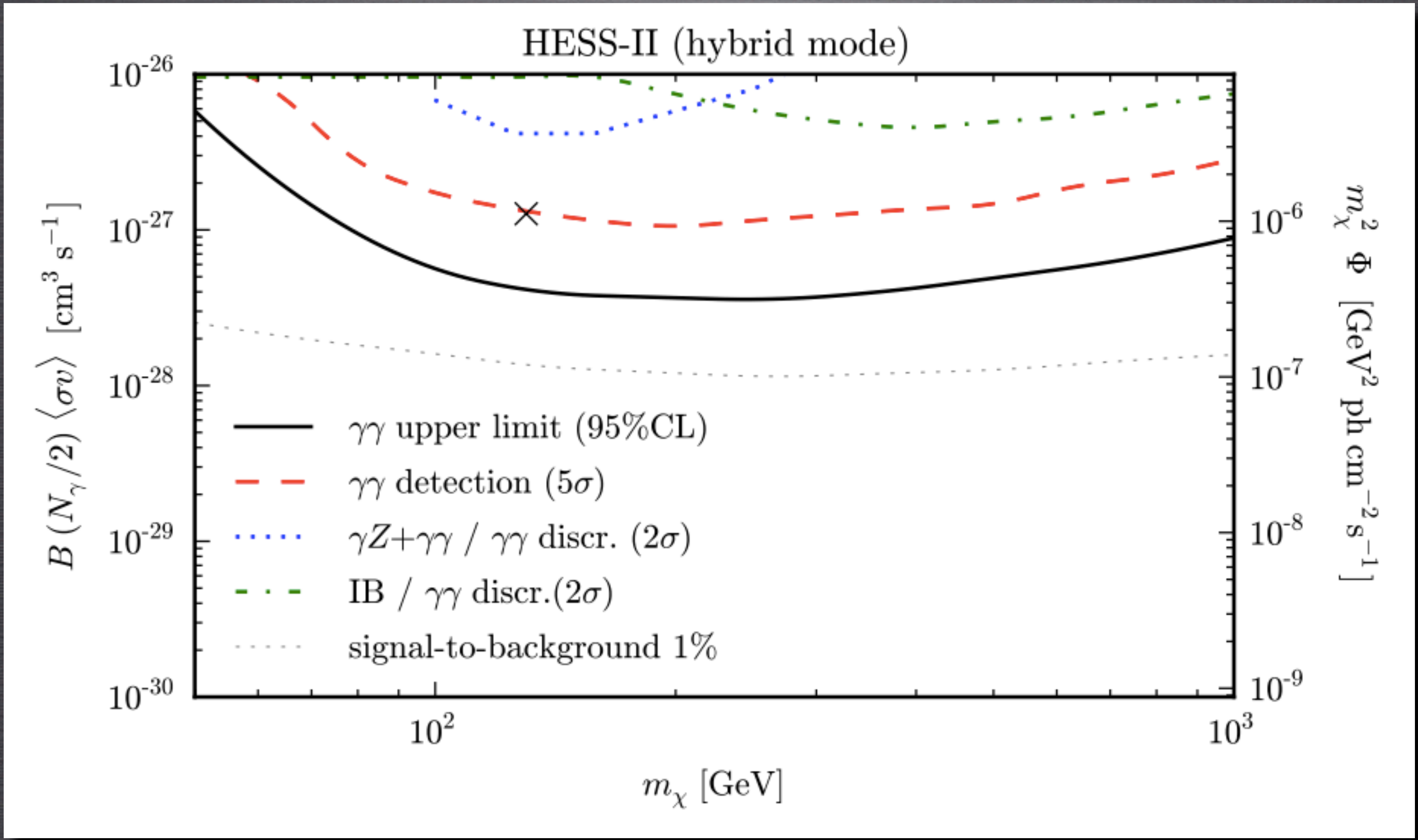


The 130 GeV Line

Recent development: arXiv:1310.2953
(M. Gustafsson for the Fermi collaboration)

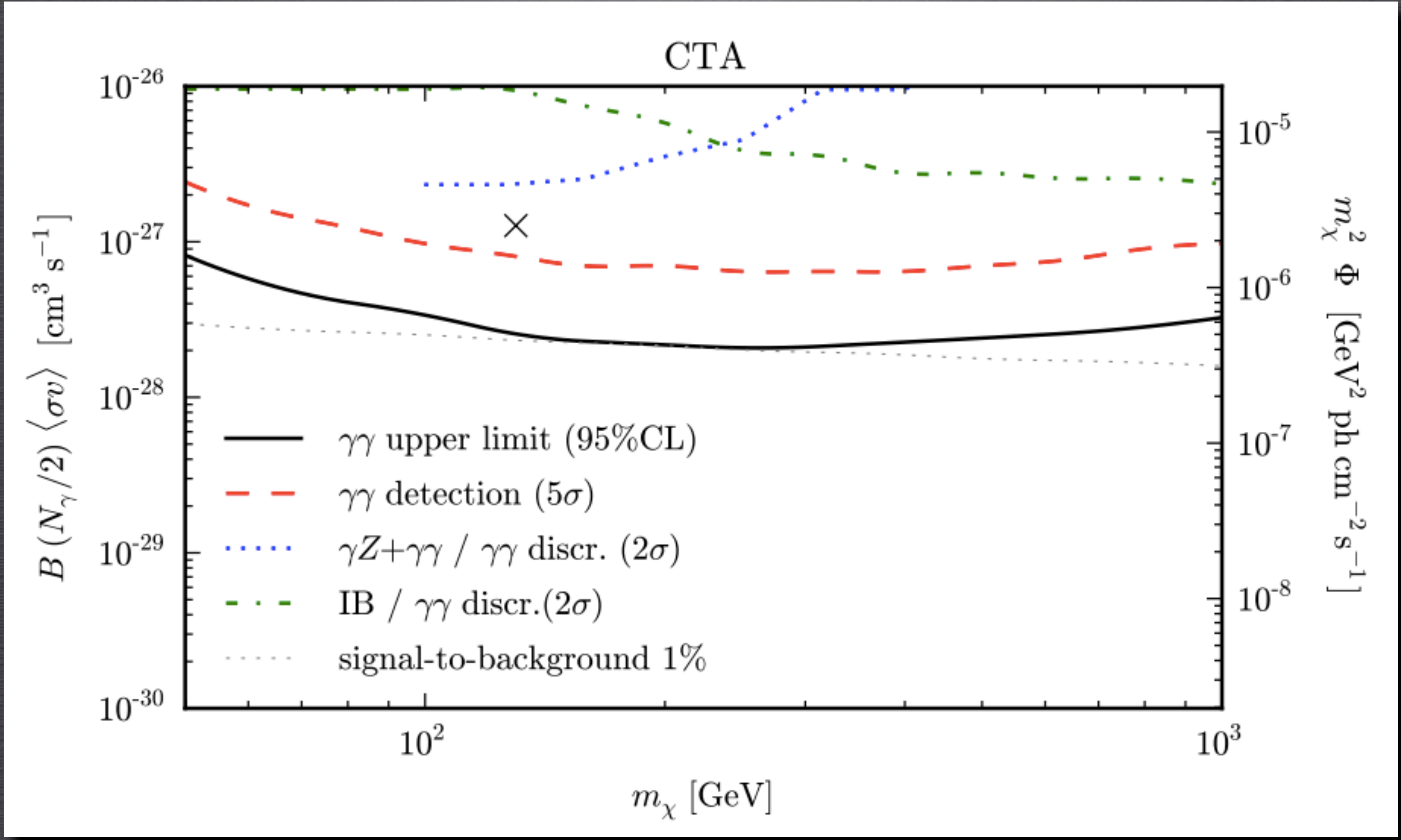
- New analysis with reprocessed P7REP CLEAN data: **global significance below 1σ**
- Next search with Fermi-LAT's upcoming Pass 8 data set
- The Fermi users' group new endorsed observing strategy: doubled exposure rate of the region around the GC

The 130 GeV Line



Bergstrom, GB et al. http://arxiv.org/pdf/1207.6773.pdf

The 130 GeV Line



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Indirect Detection

Recent results: Daylan et al. arXiv:1402.6703

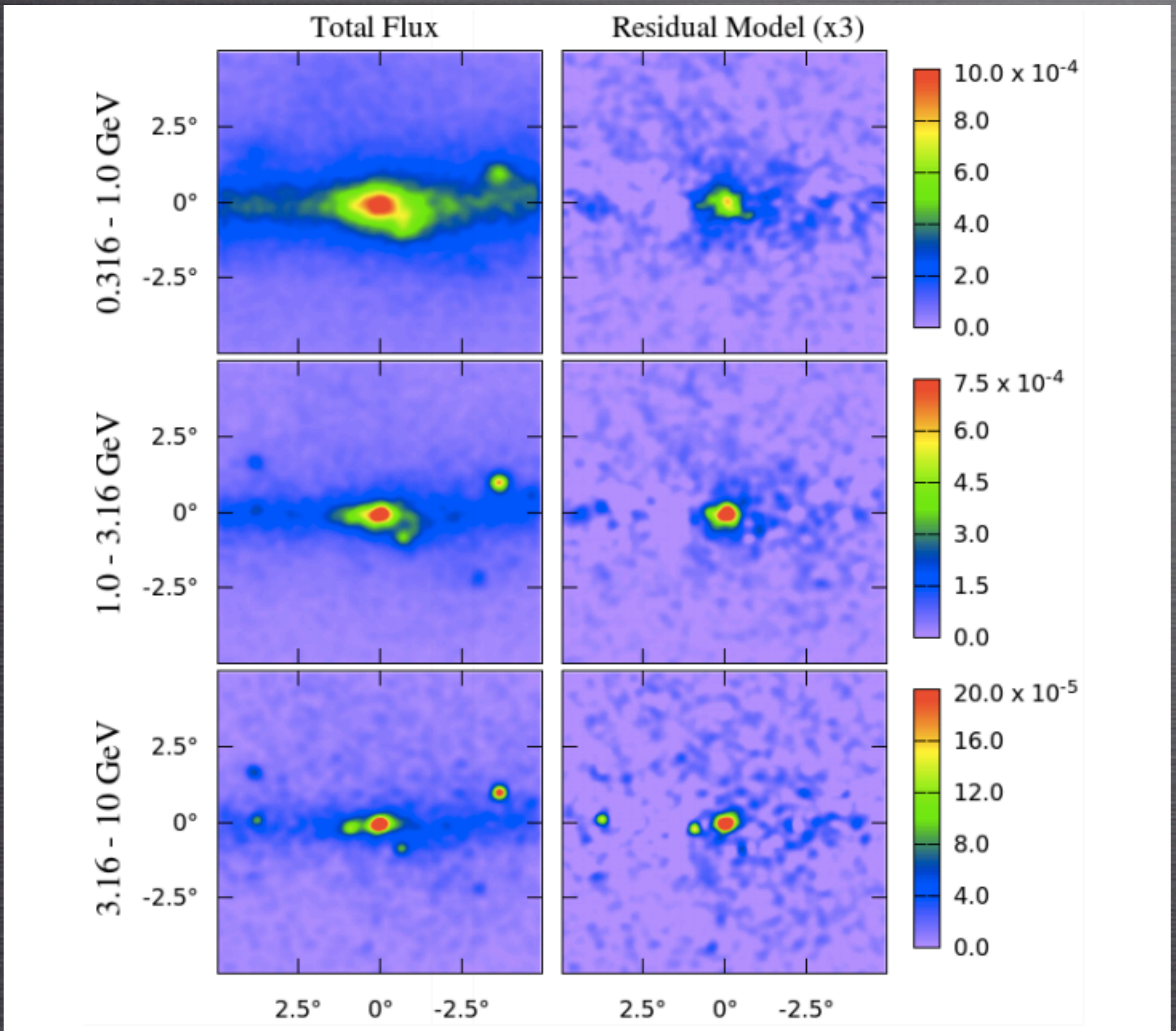
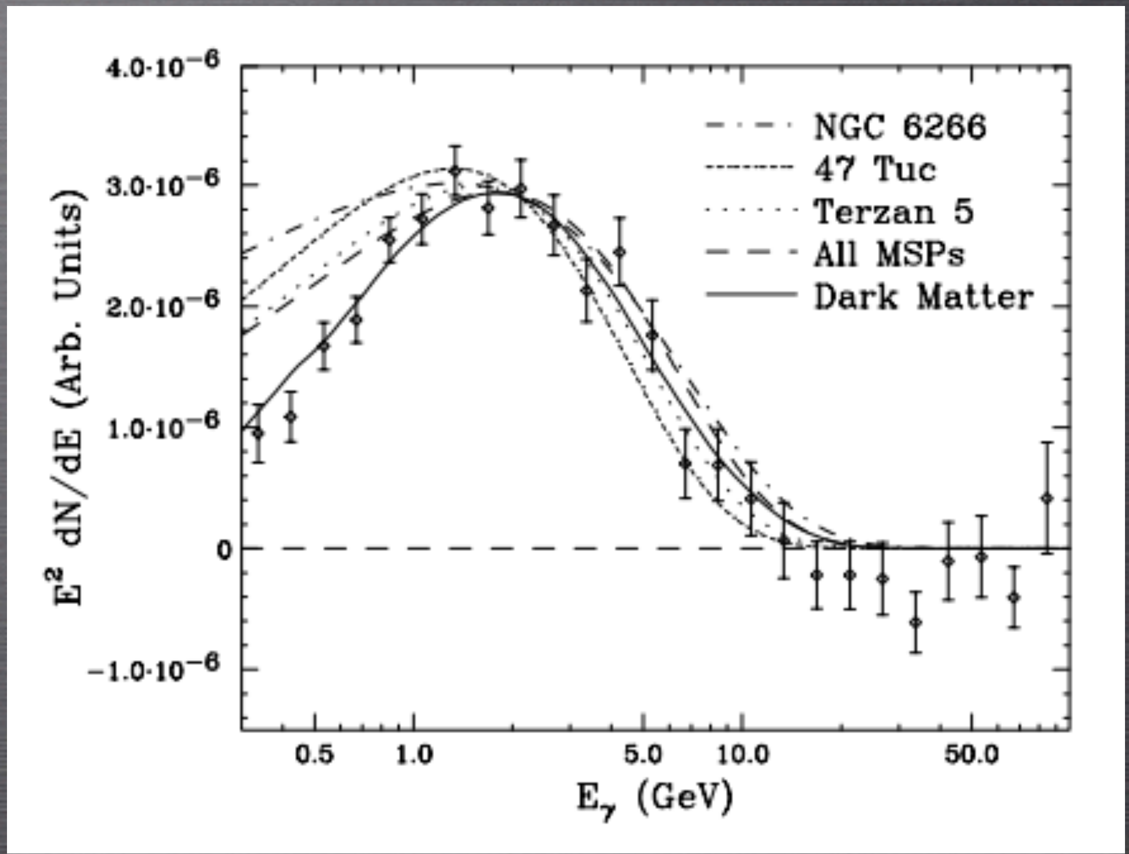


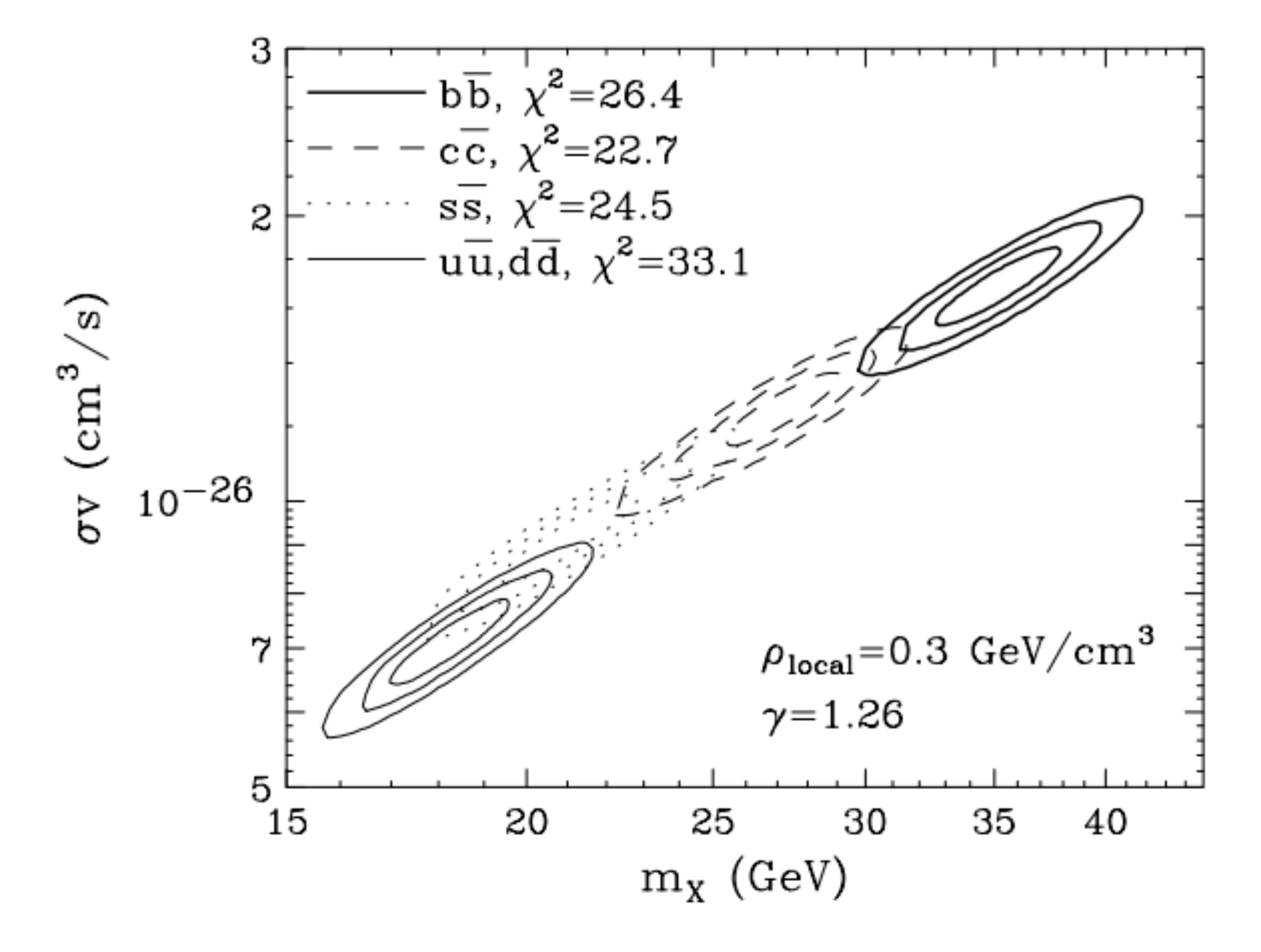
FIG. 9: The raw gamma-ray maps (left) and the residual maps after subtracting the best-fit Galactic diffuse model, 20 cm template, point sources, and isotropic template (right), in units of photons/cm^2/s/sr. The right frames clearly contain a significant central and spatially extended excess, peaking at ~1-3 GeV. Results are shown in galactic coordinates, and all maps have been smoothed by a 0.25° Gaussian.



"Within these maps, we find the GeV excess to be robust and highly statistically significant, with a spectrum, angular distribution, and overall normalization that is in good agreement with that predicted by simple annihilating dark matter models"

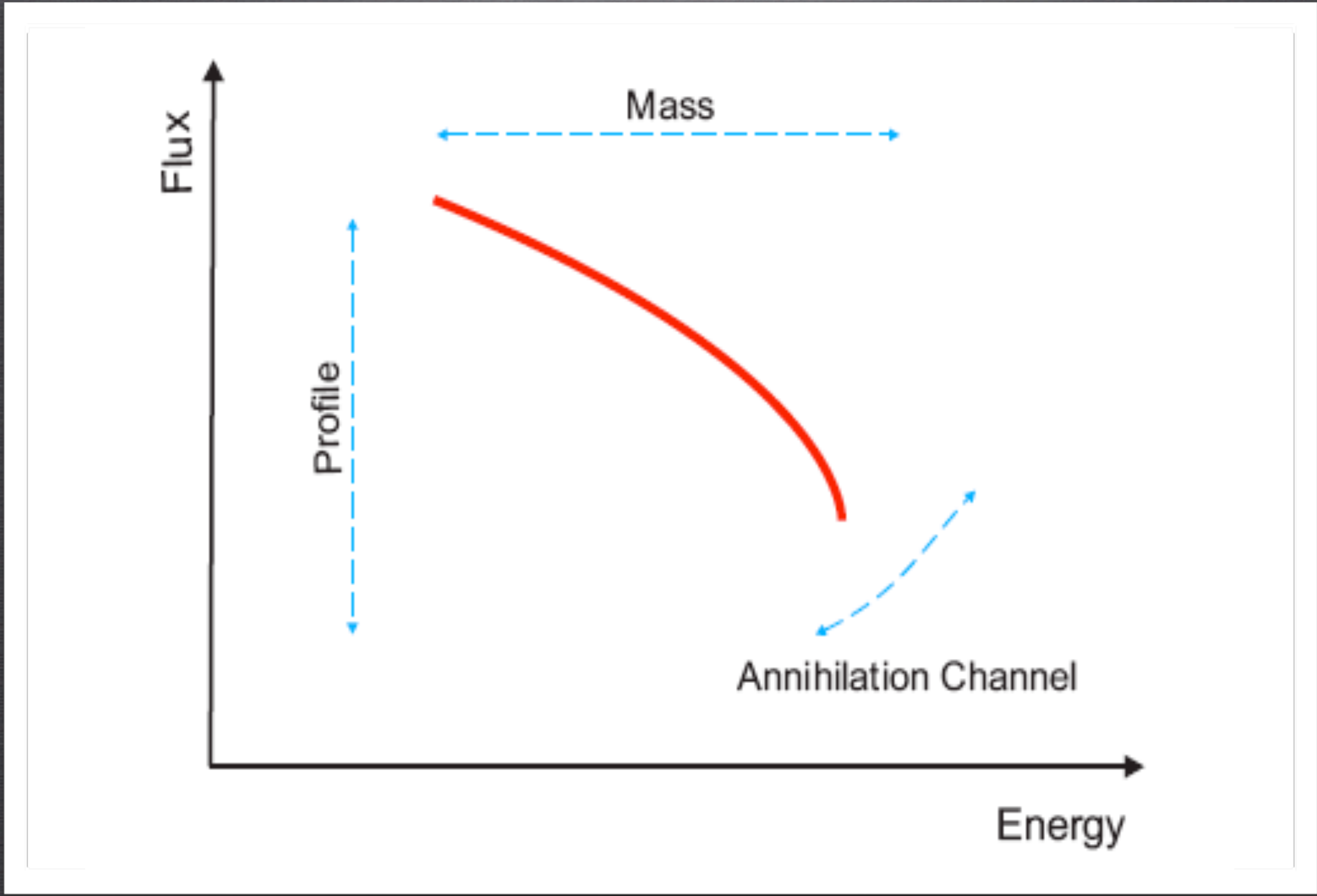
Indirect Detection

RECENT RESULTS: DAYLAN ET AL. ARXIV:1402.6703



'VANILLA' DM PROVIDES A NATURAL EXPLANATION..

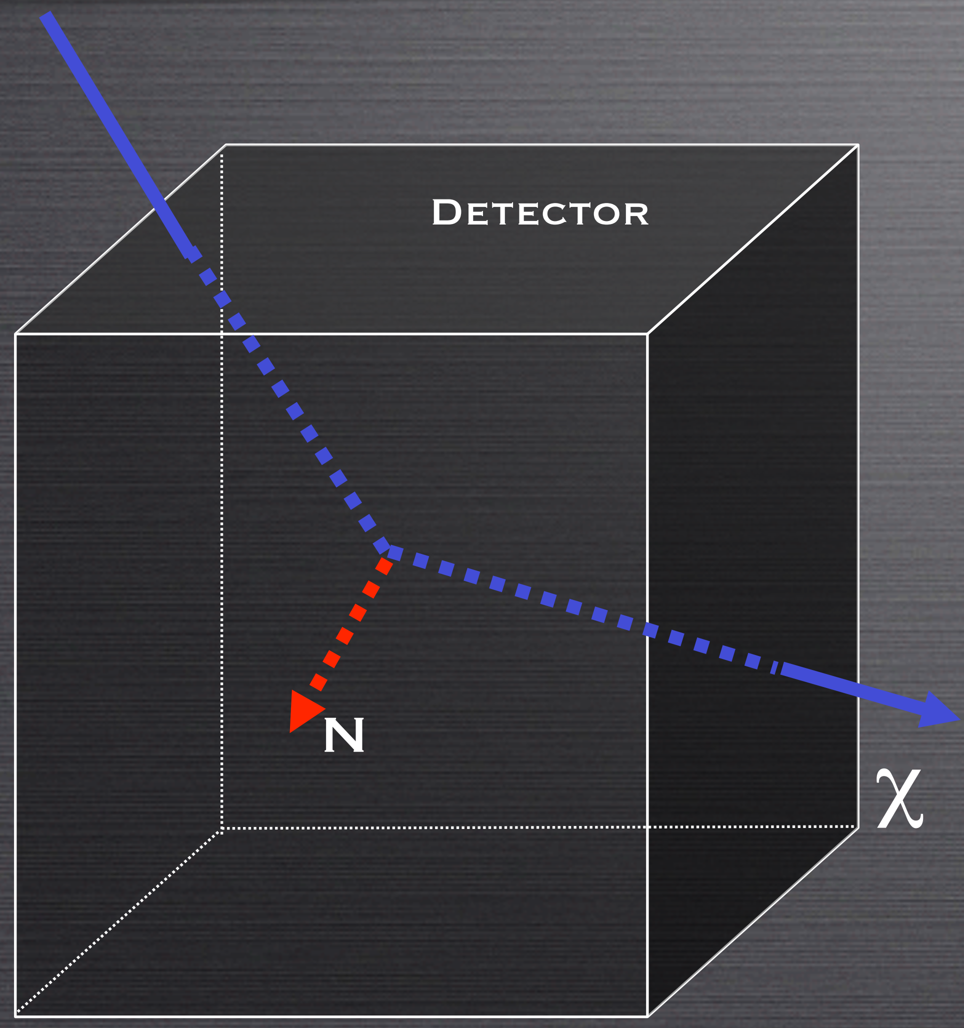
The trouble with indirect searches

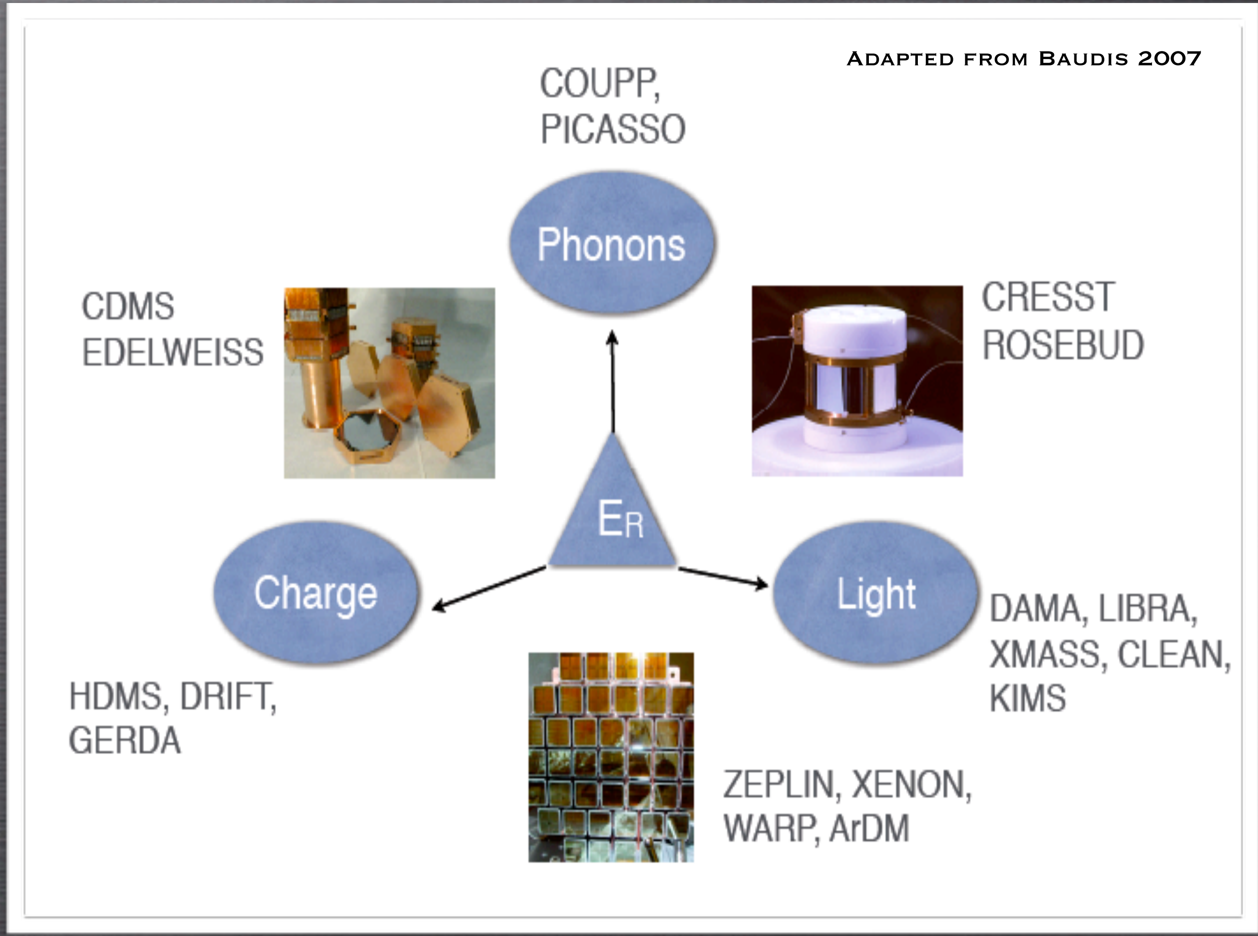


...which means that the "inverse problem" always admits a solution, even when the data have nothing to do with DM!

Direct Detection

Principle and Detection Techniques





DM scatters off nuclei in the detector

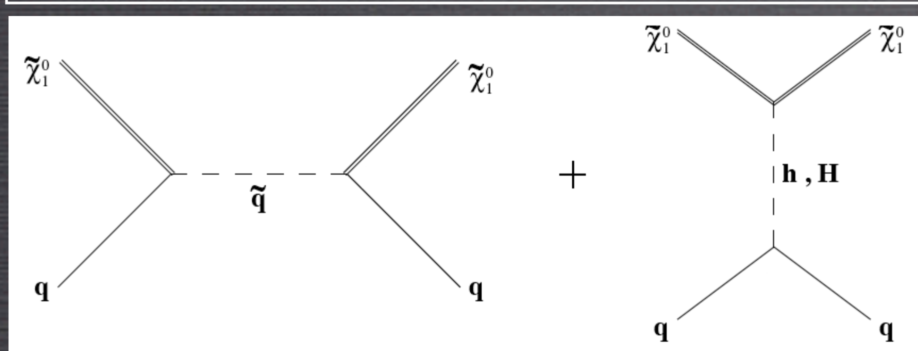
Detection of recoil energy via ionization (charges), scintillation (light) and heat (phonons)

Direct Detection

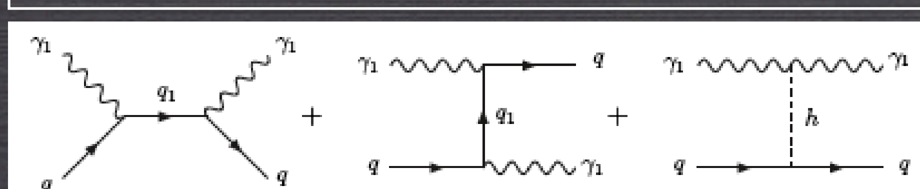
Differential Event Rate

$$\frac{dR}{dE_R}(E_R) = \frac{\rho_0}{m_\chi m_N}\int_{v>v_{min}} v f(\vec{v}+\vec{v_e})\frac{d\sigma_{\chi N}}{dE_R}(v, E_R)d^3\vec{v}$$

SUSY: squarks and Higgs exchange



UED: 1st level quarks and Higgs exchange



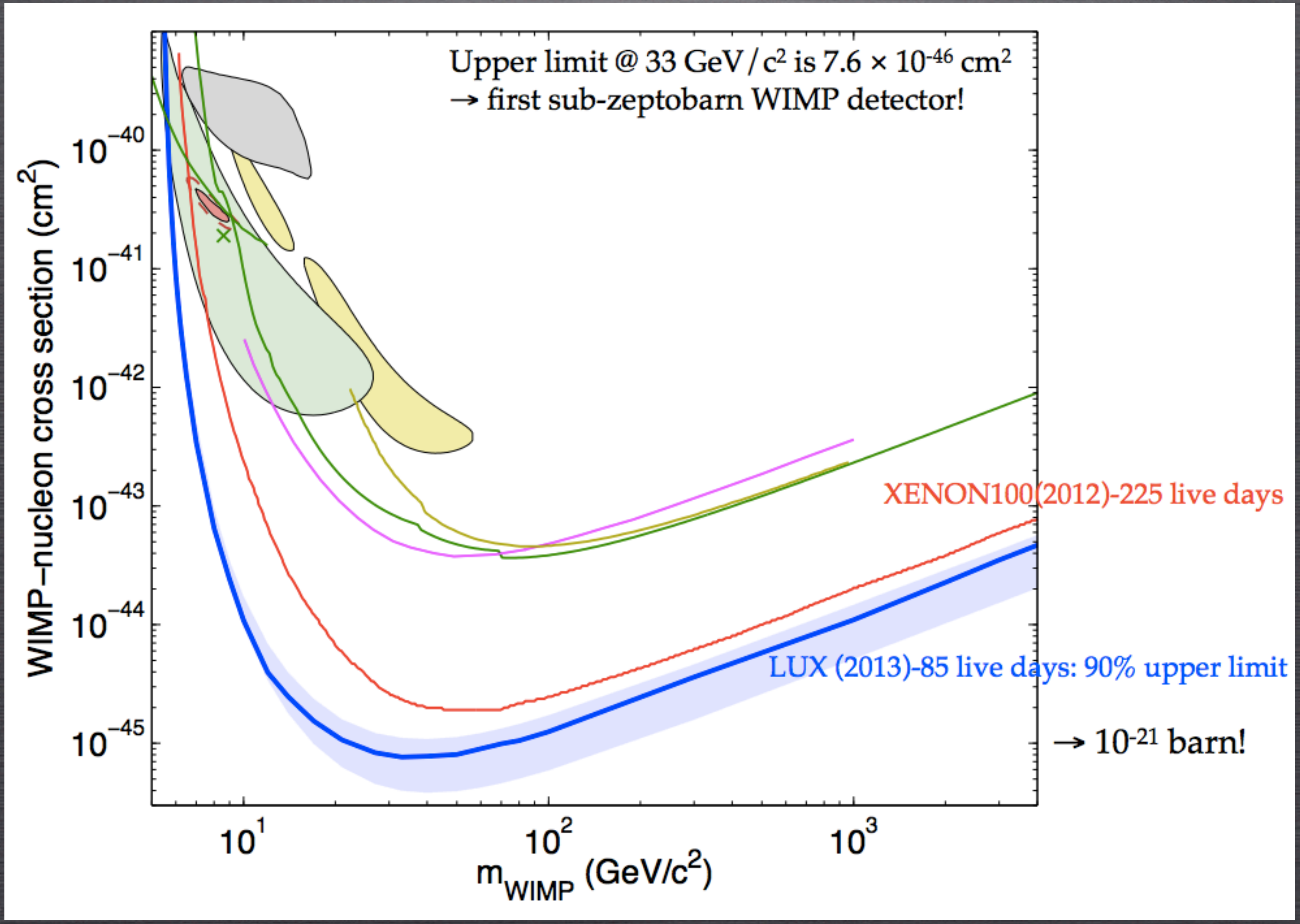
Theoretical Uncertainties

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

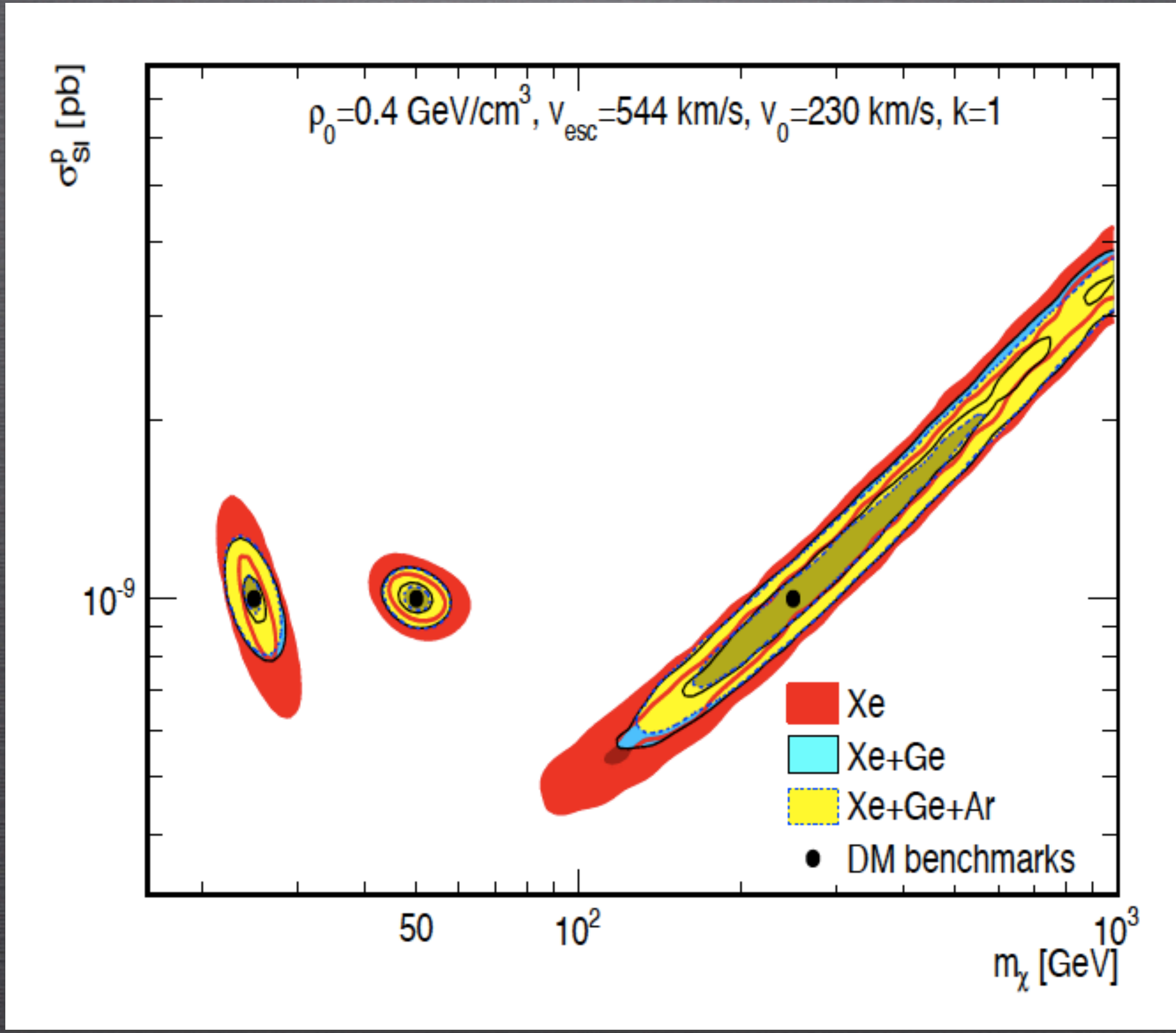
Uncertainties on f(v)

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

Latest results:
LUX experiment, arXiv:1310.8214
(Sanford Underground Research Facility - SURF)

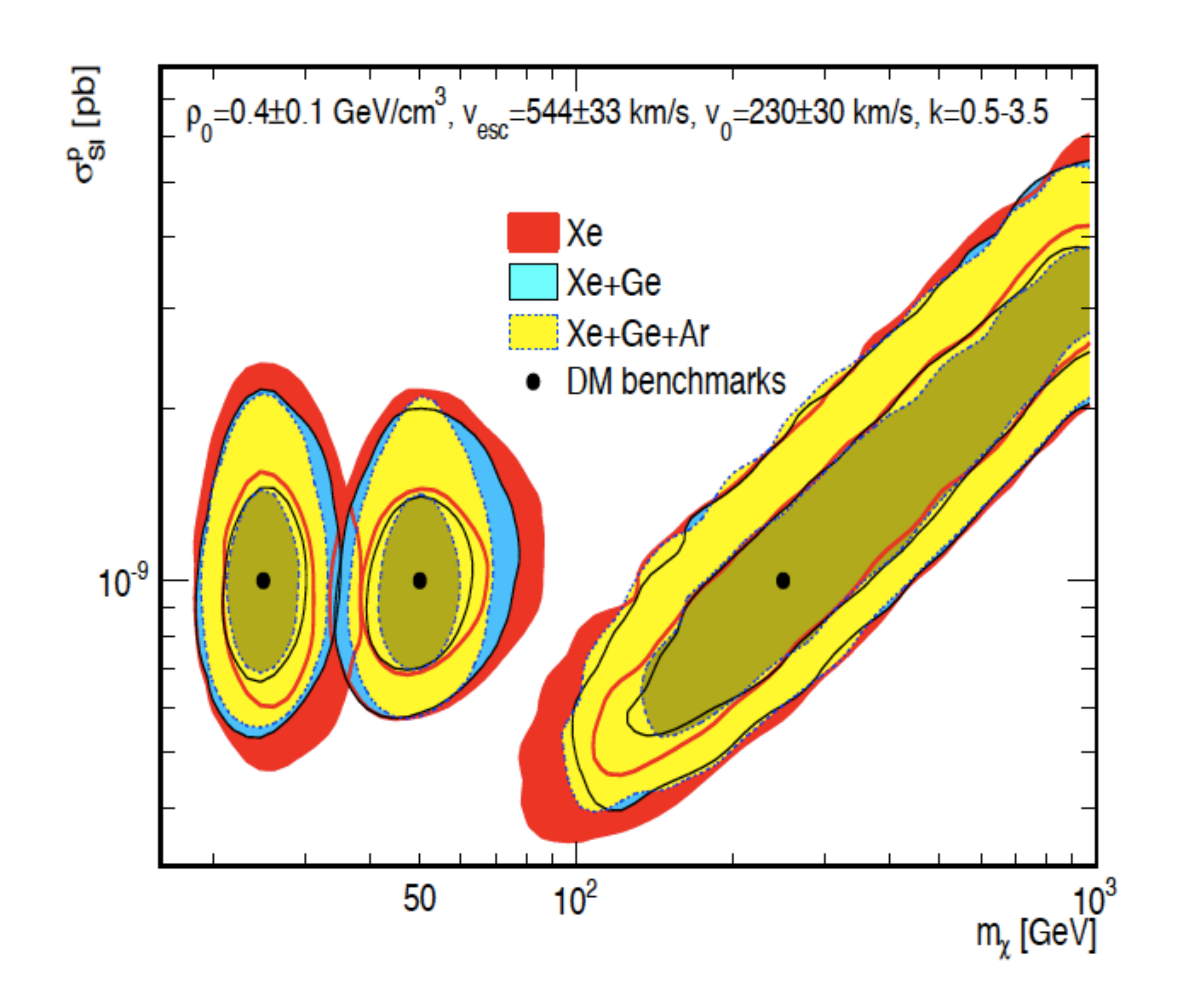


Complementarity of DD targets



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

Complementarity of DD targets



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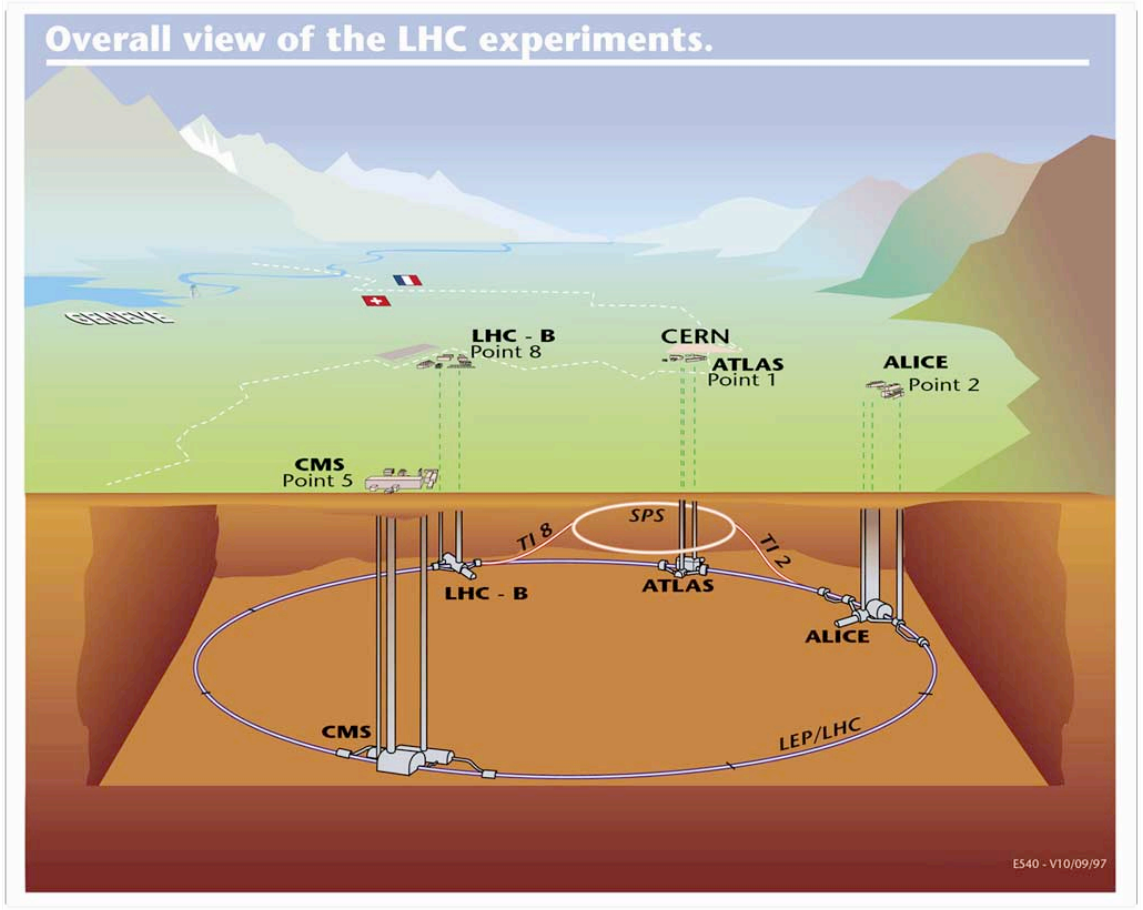
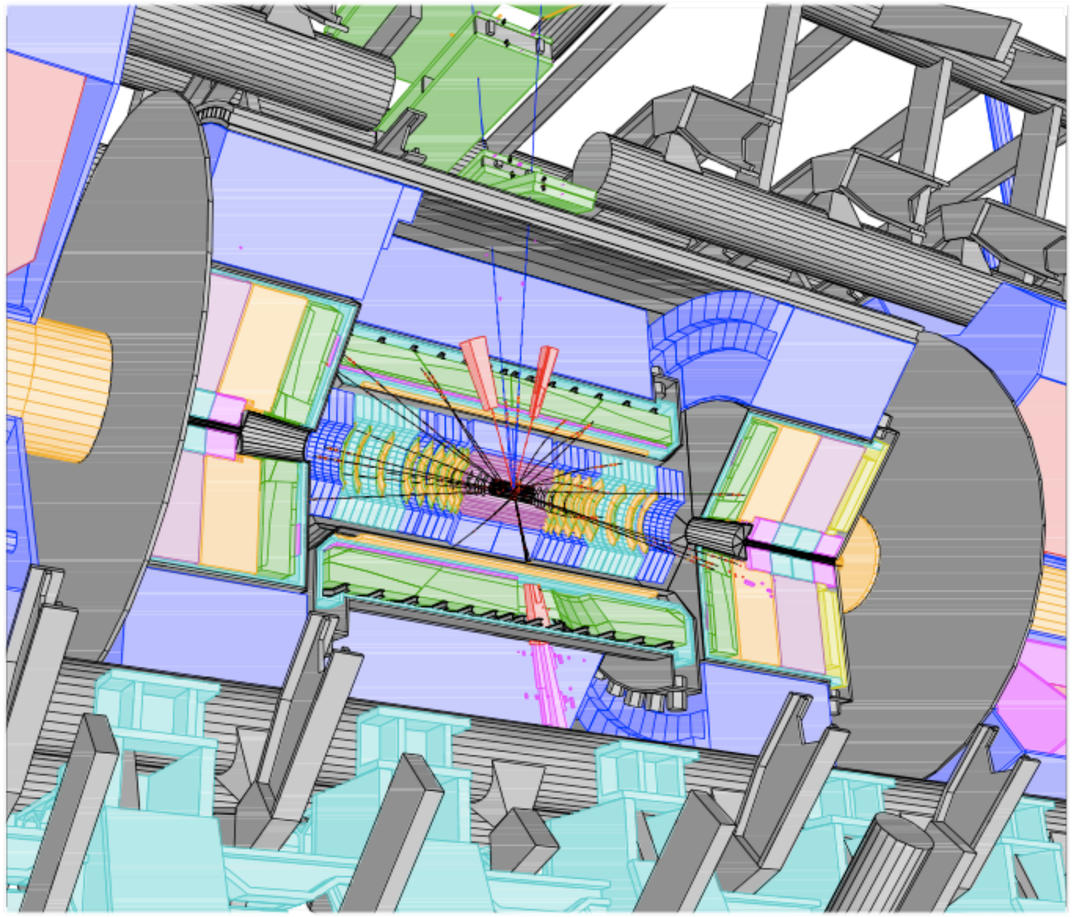
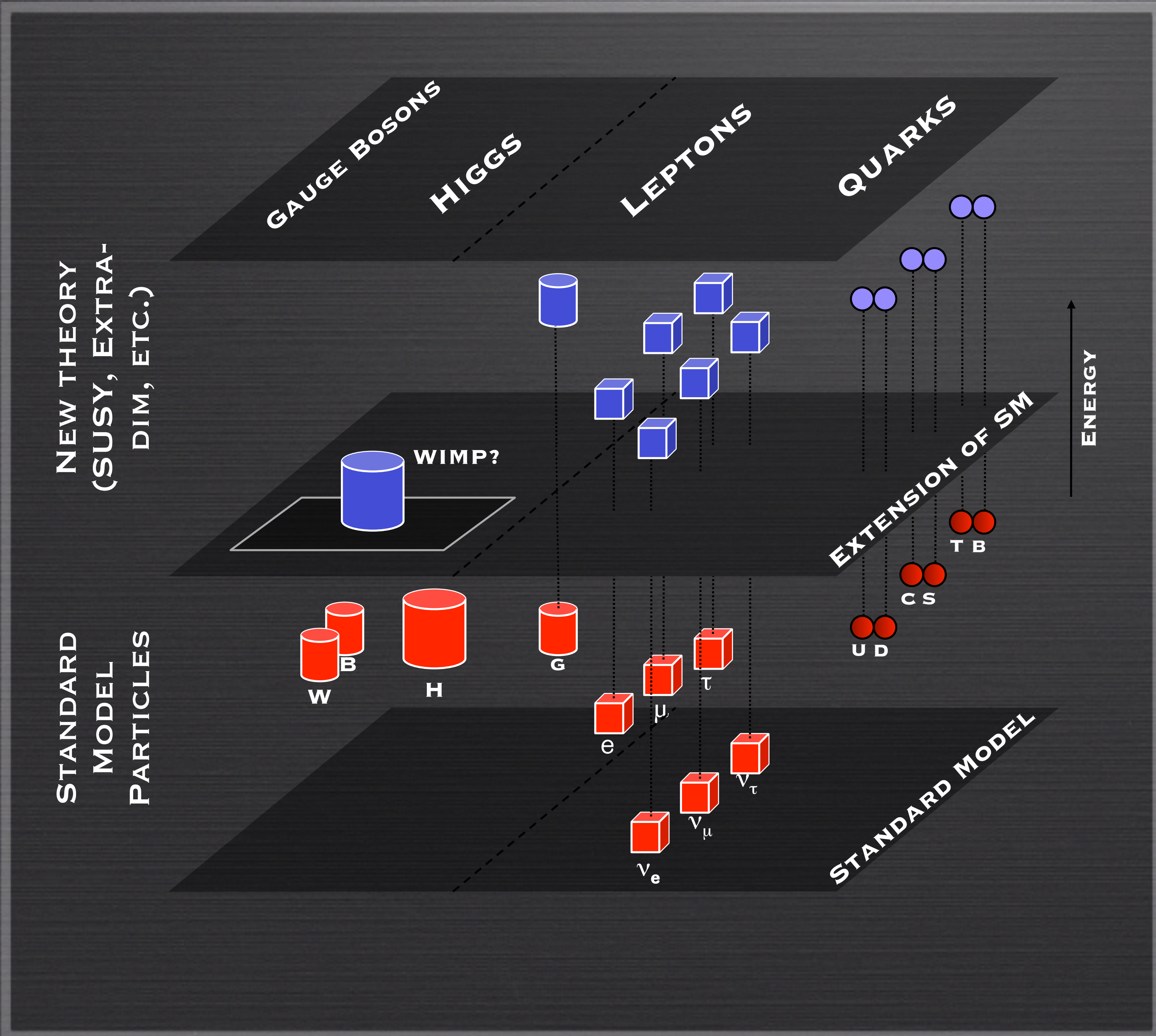
Dark Matter Searches at the LHC





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

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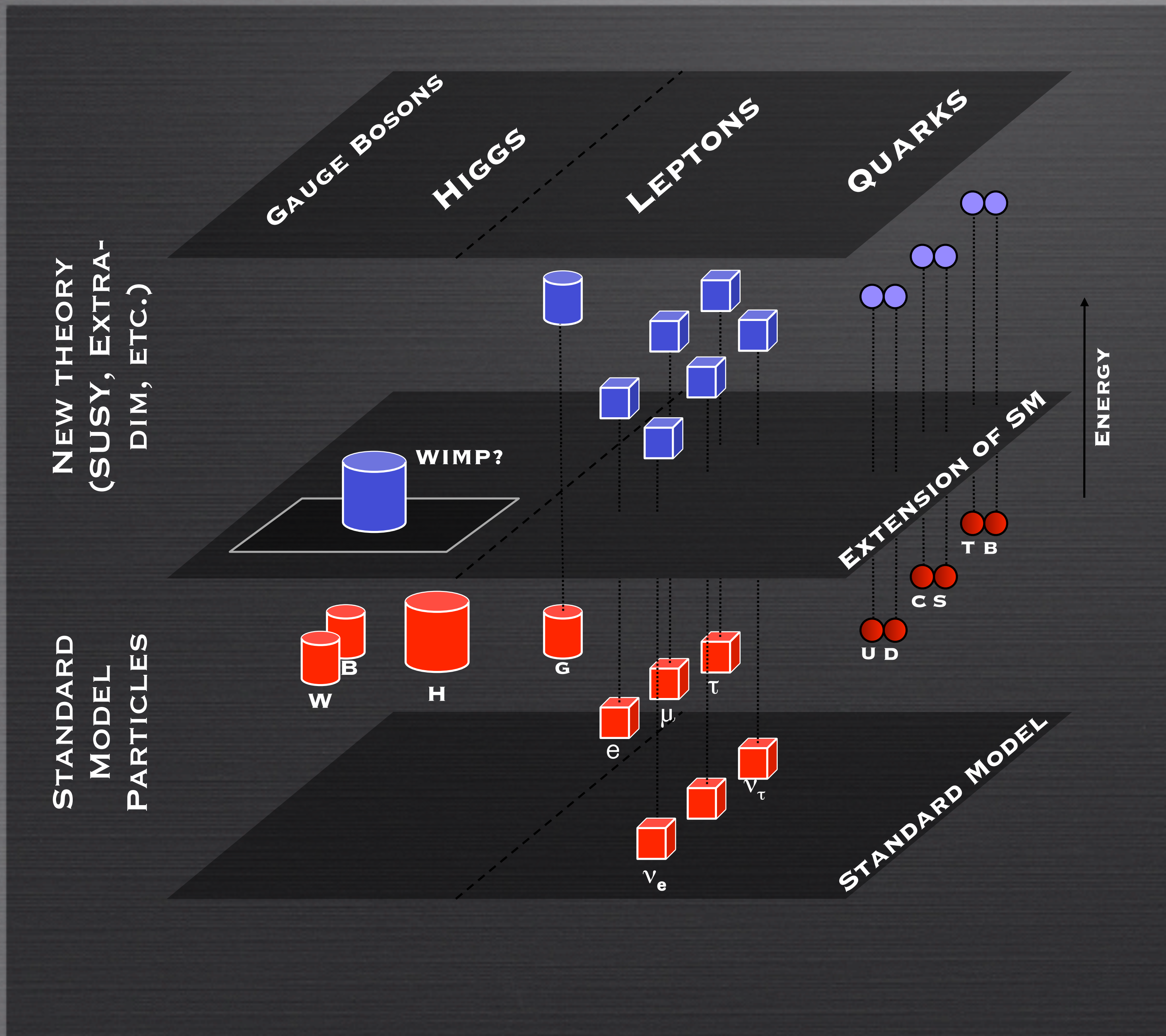
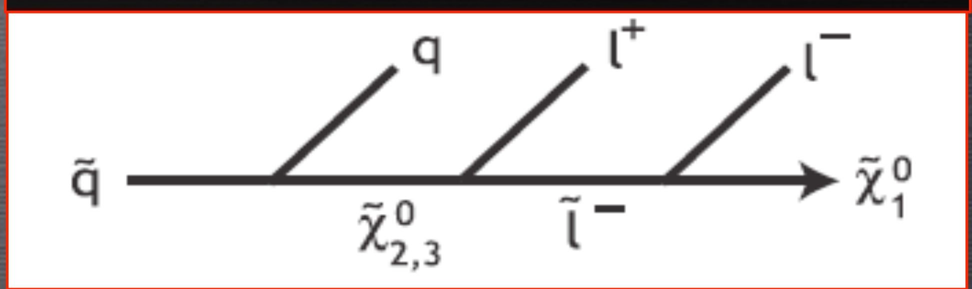


Search at LHC for processes like e.g.



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:

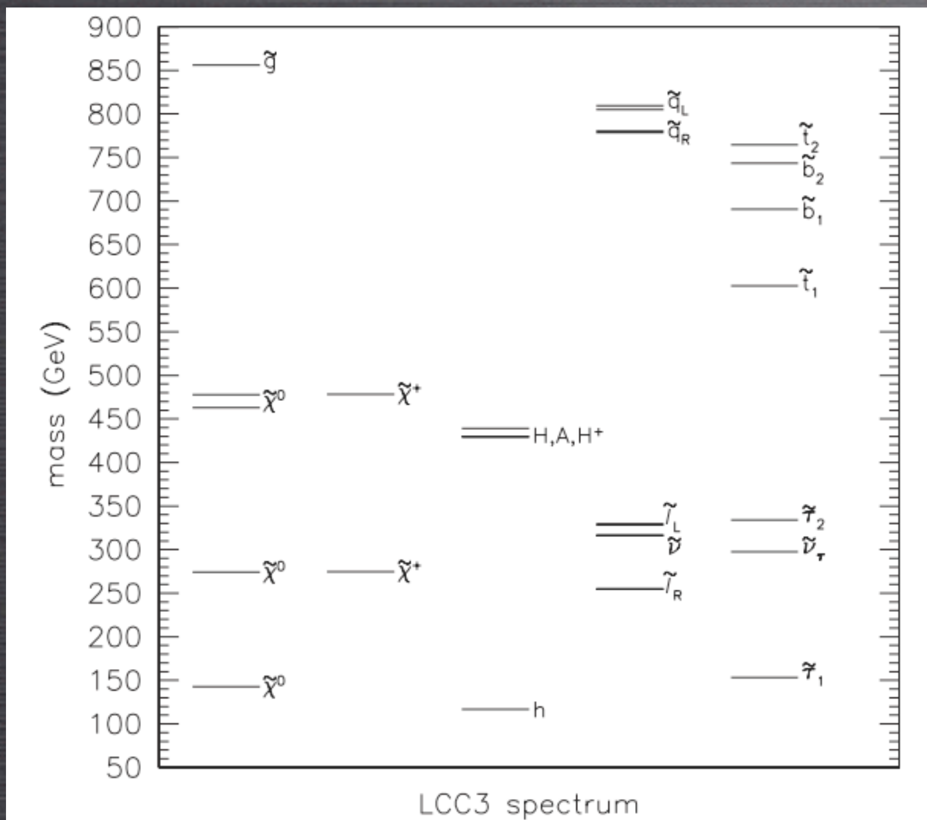
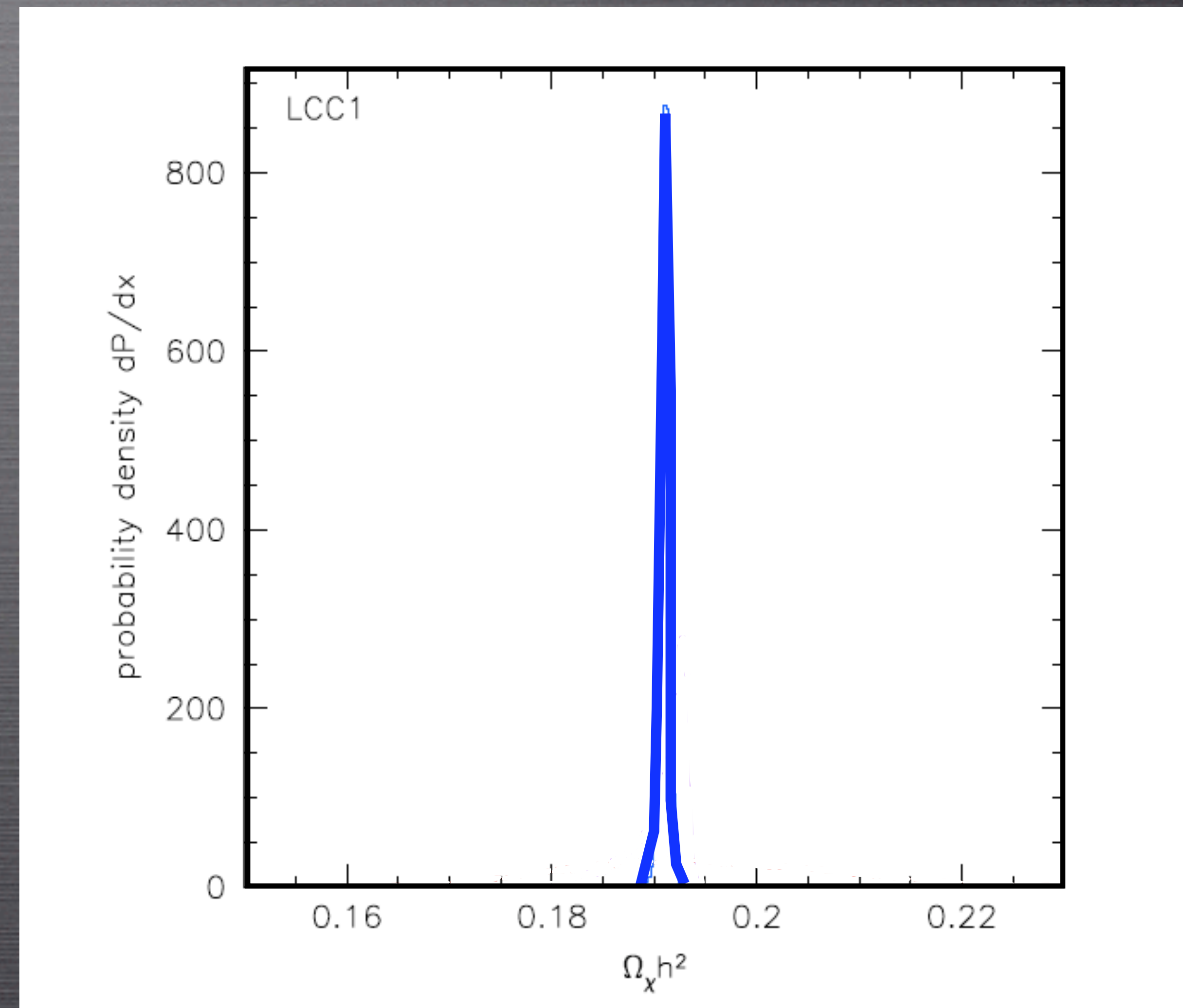
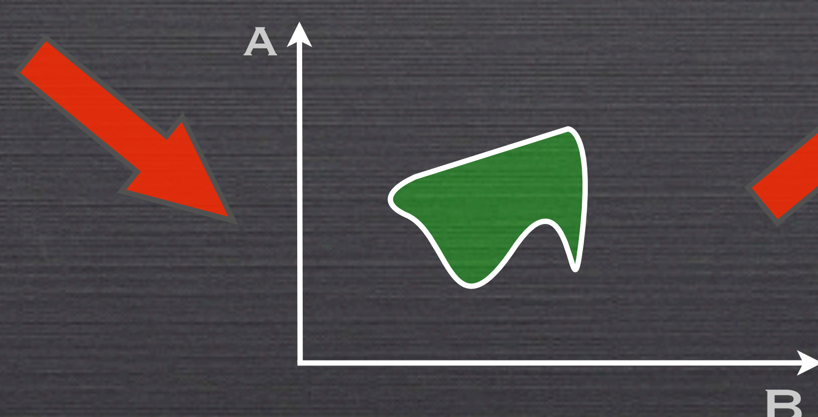


FIG. 34. Particle spectrum for point LCC3. The stau-neutralino mass splitting is 10.8 GeV. The lightest neutralino is predominantly *b*-ino, the second neutralino and light chargino are predominantly *W*-ino, and the heavy neutralinos and chargino are predominantly Higgsino.



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



Example of Inverse problem at LHC

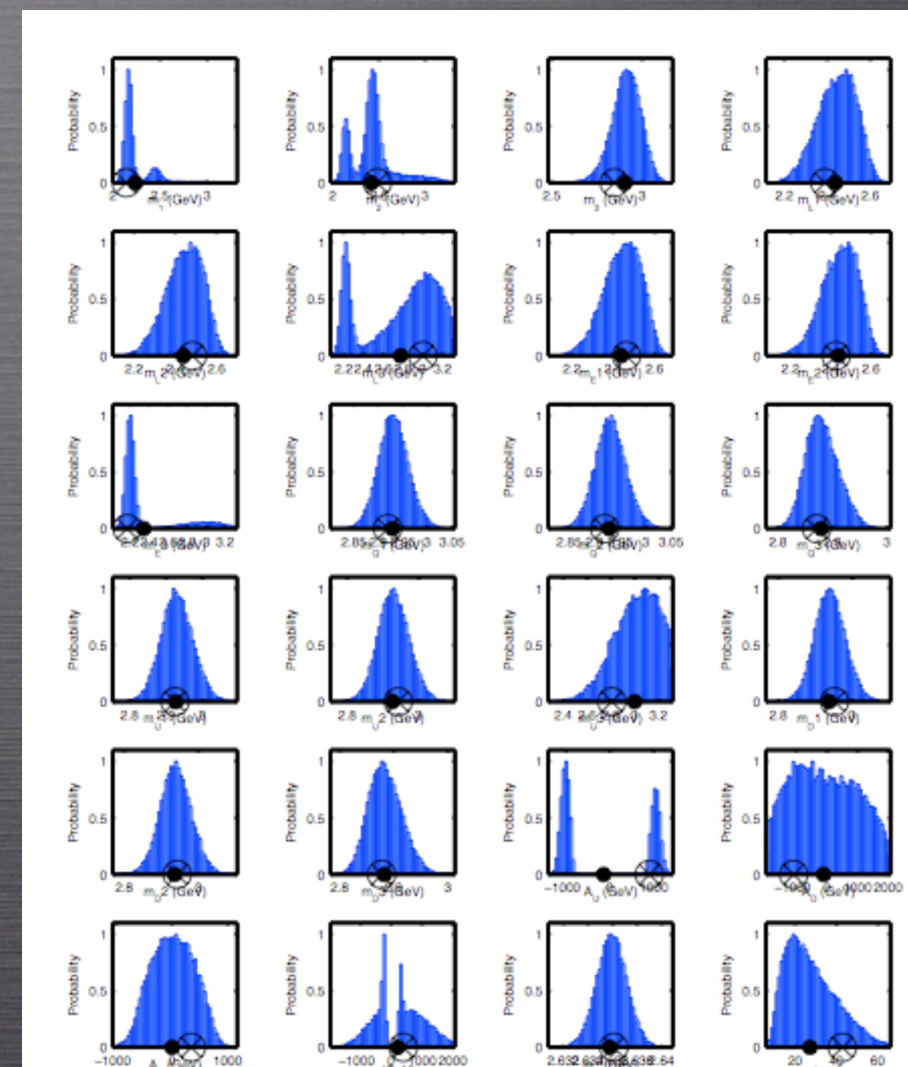
(example in the stau coannihilation region, 24 parms pMSSM)

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).

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

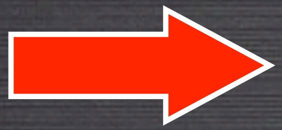
MCMC as implemented in the SuperBayes code

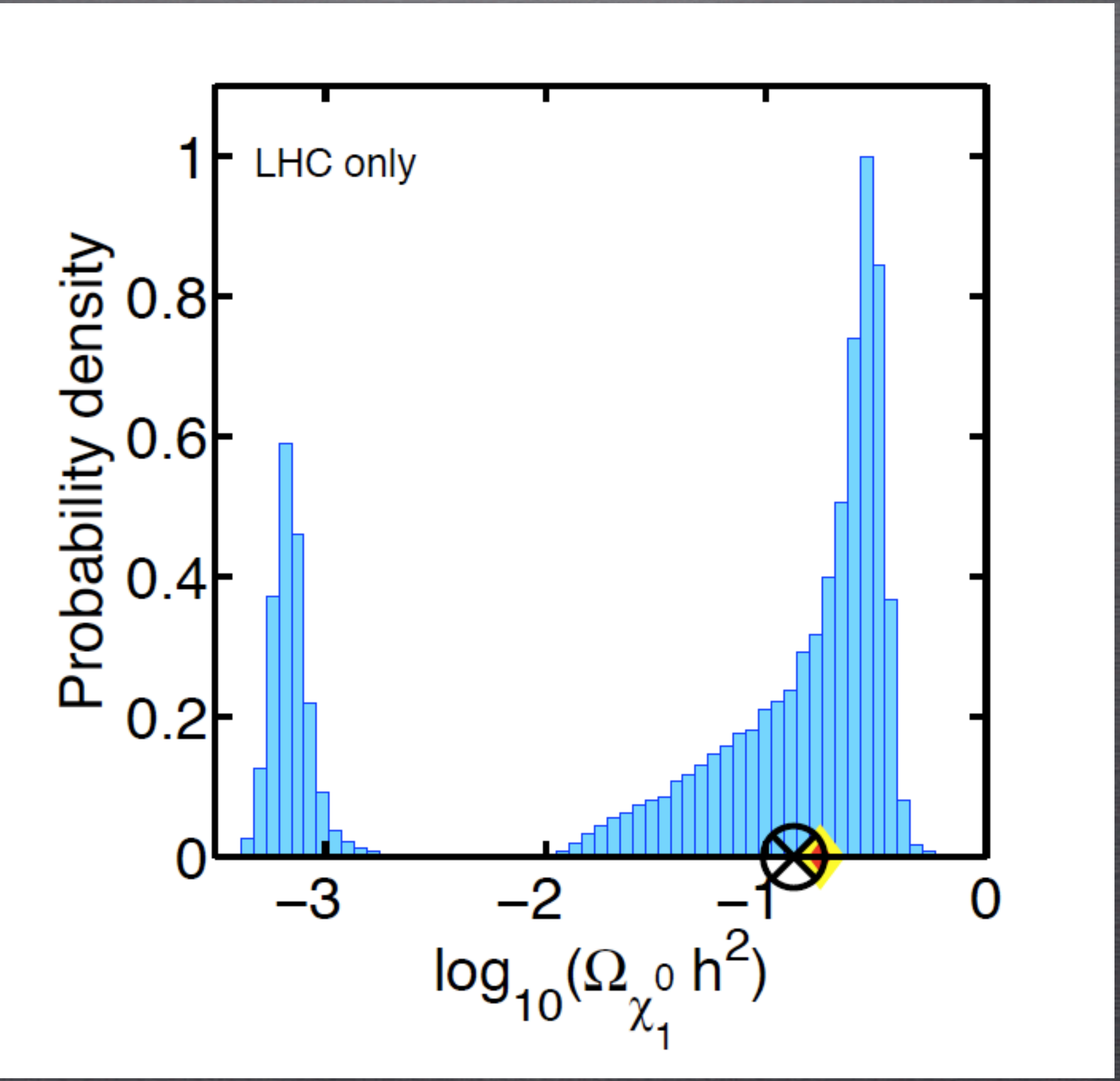


- Benchmark in the co-annihilation region (similar to LCC3 in Baltz et al.).
- Errors correspond to 300 fb-1.
- Error on mass difference with the stau ~10% for this model can be achieved with 10 fb-1

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

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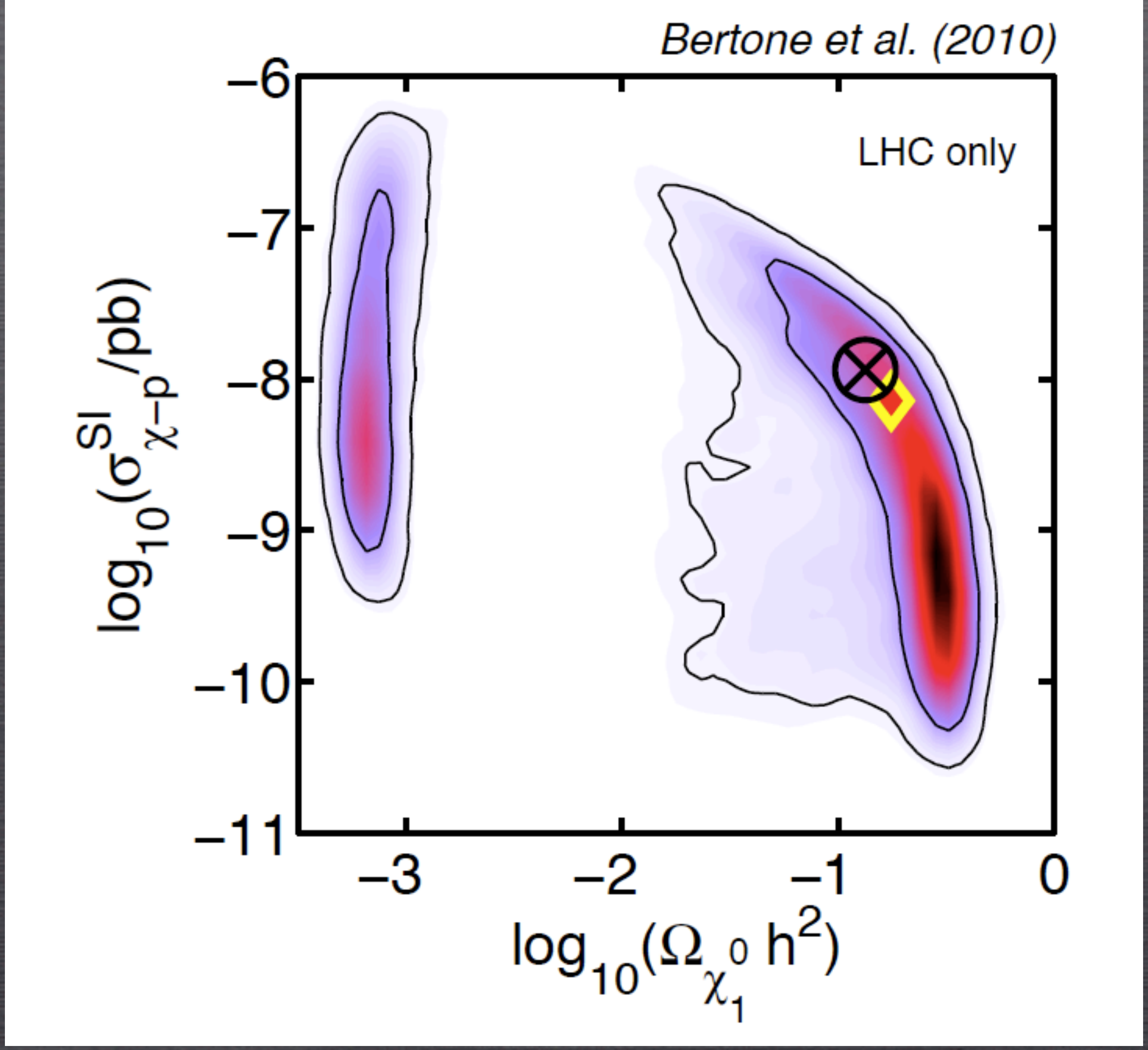
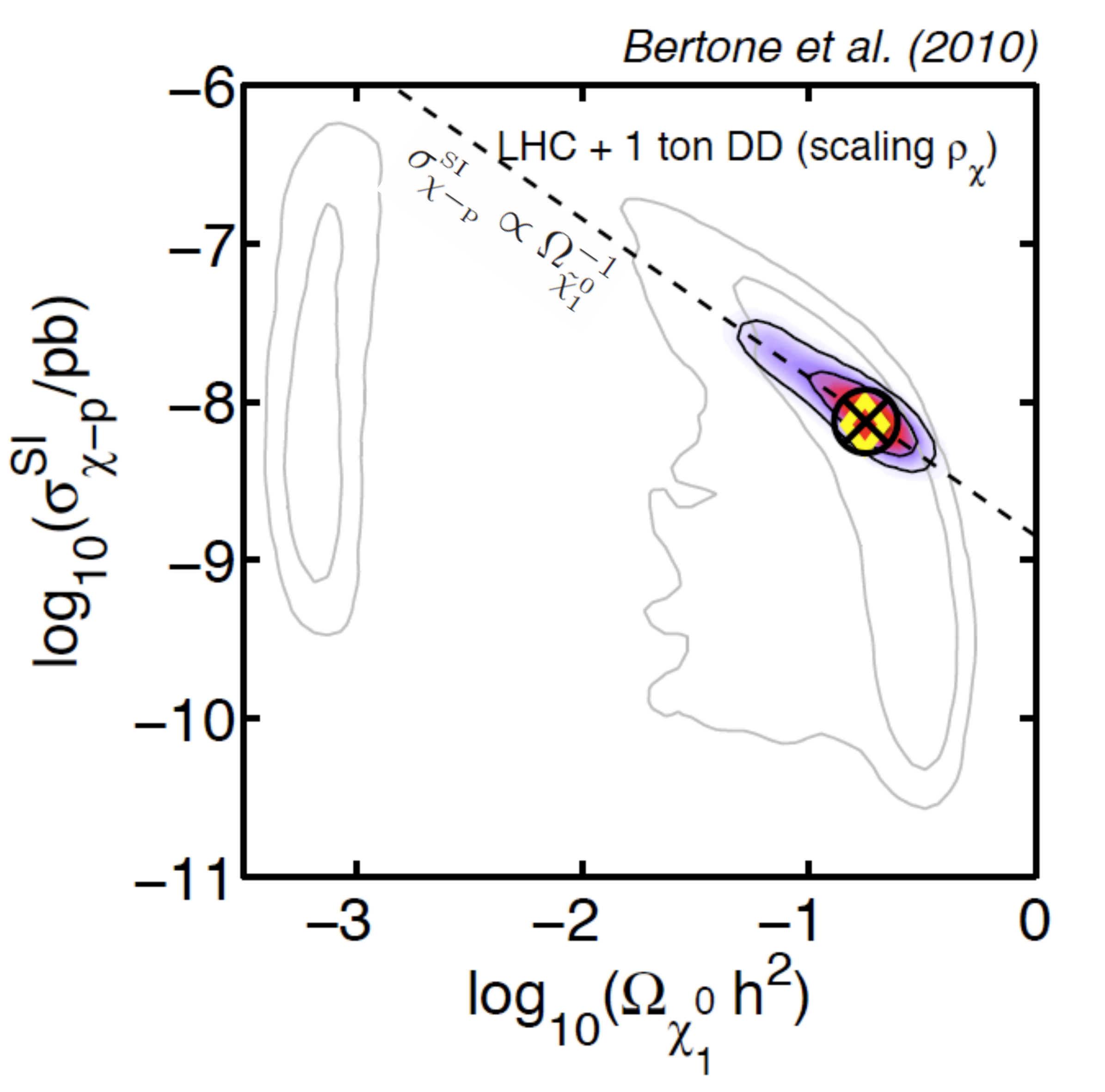


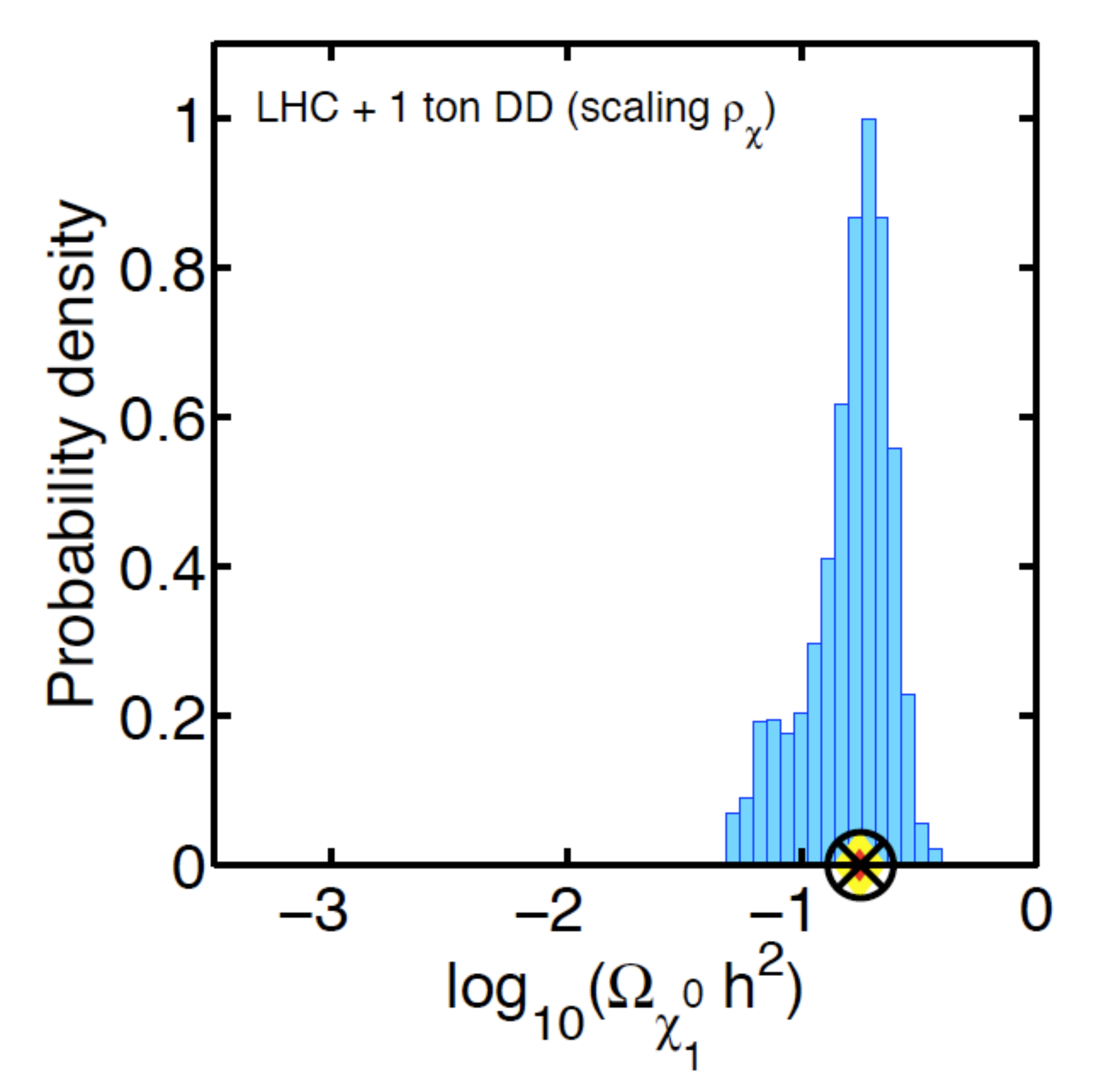
GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta, 2010

DD+LHC

"Scaling" Ansatz

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



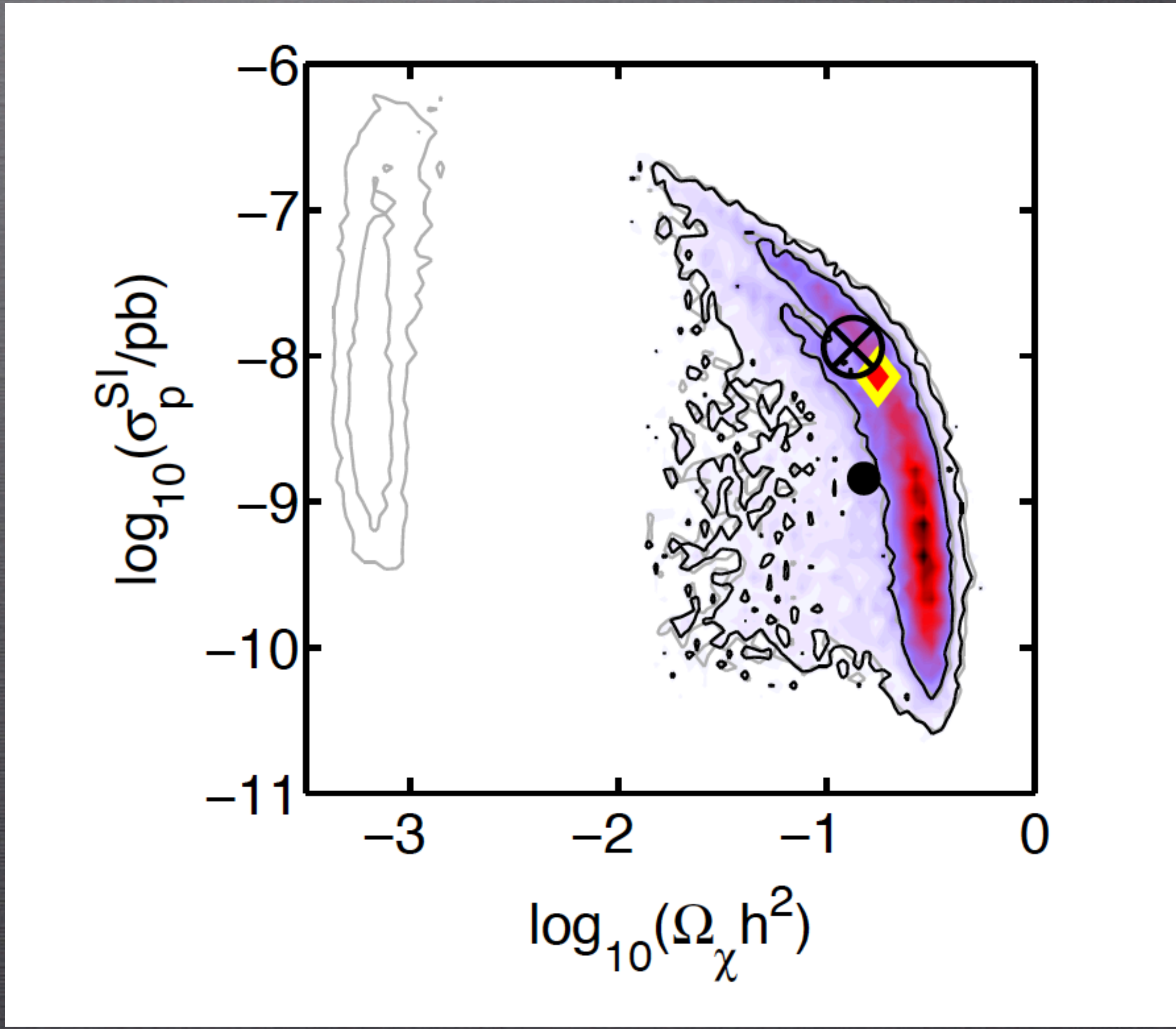


What happens if we add these constraints to the LHC posterior?

LHC + ID

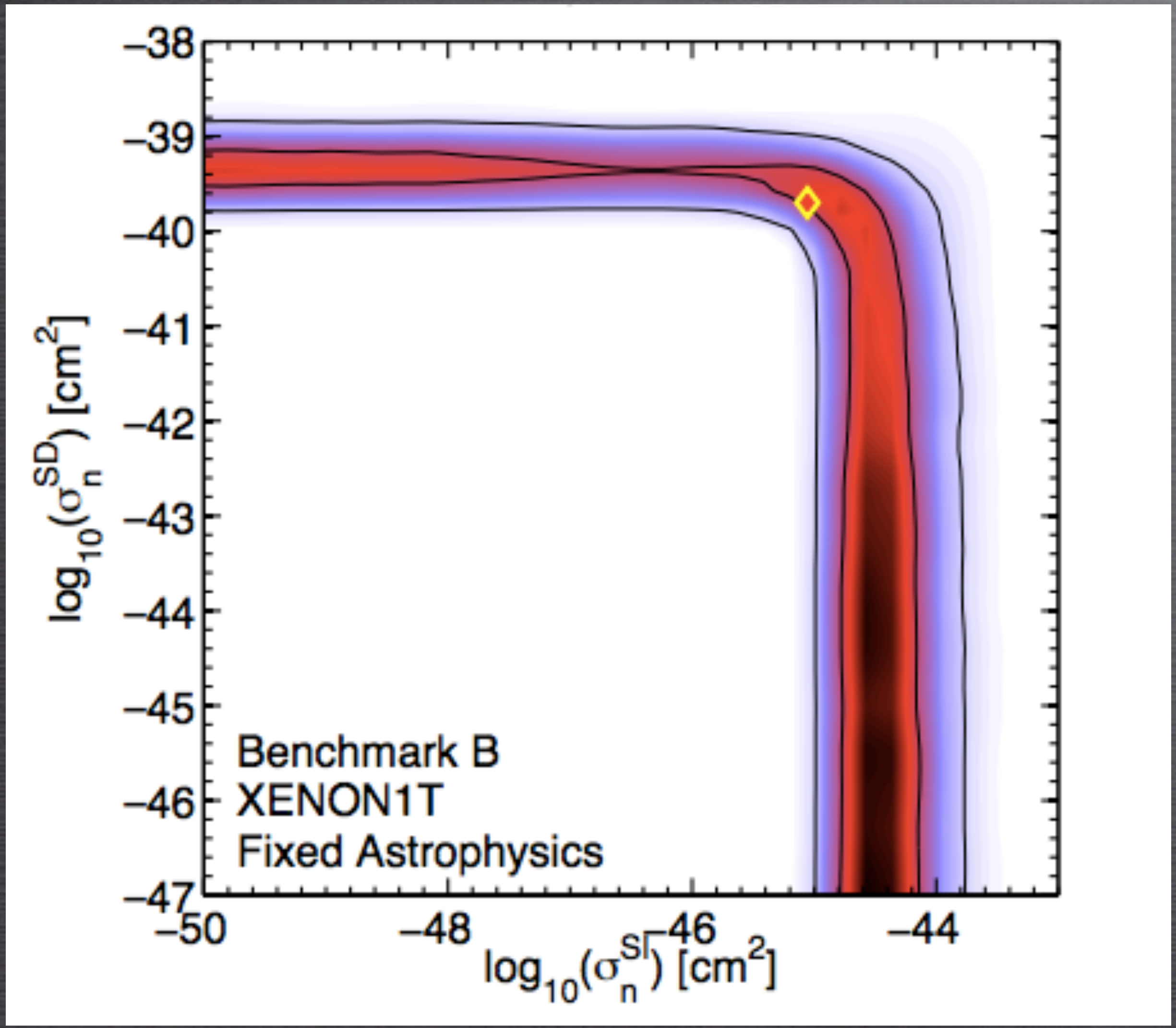
IF we identify
neutralino ≡ Dark Matter
(in Draco for Fermi, or in the Universe in the case of CMB)

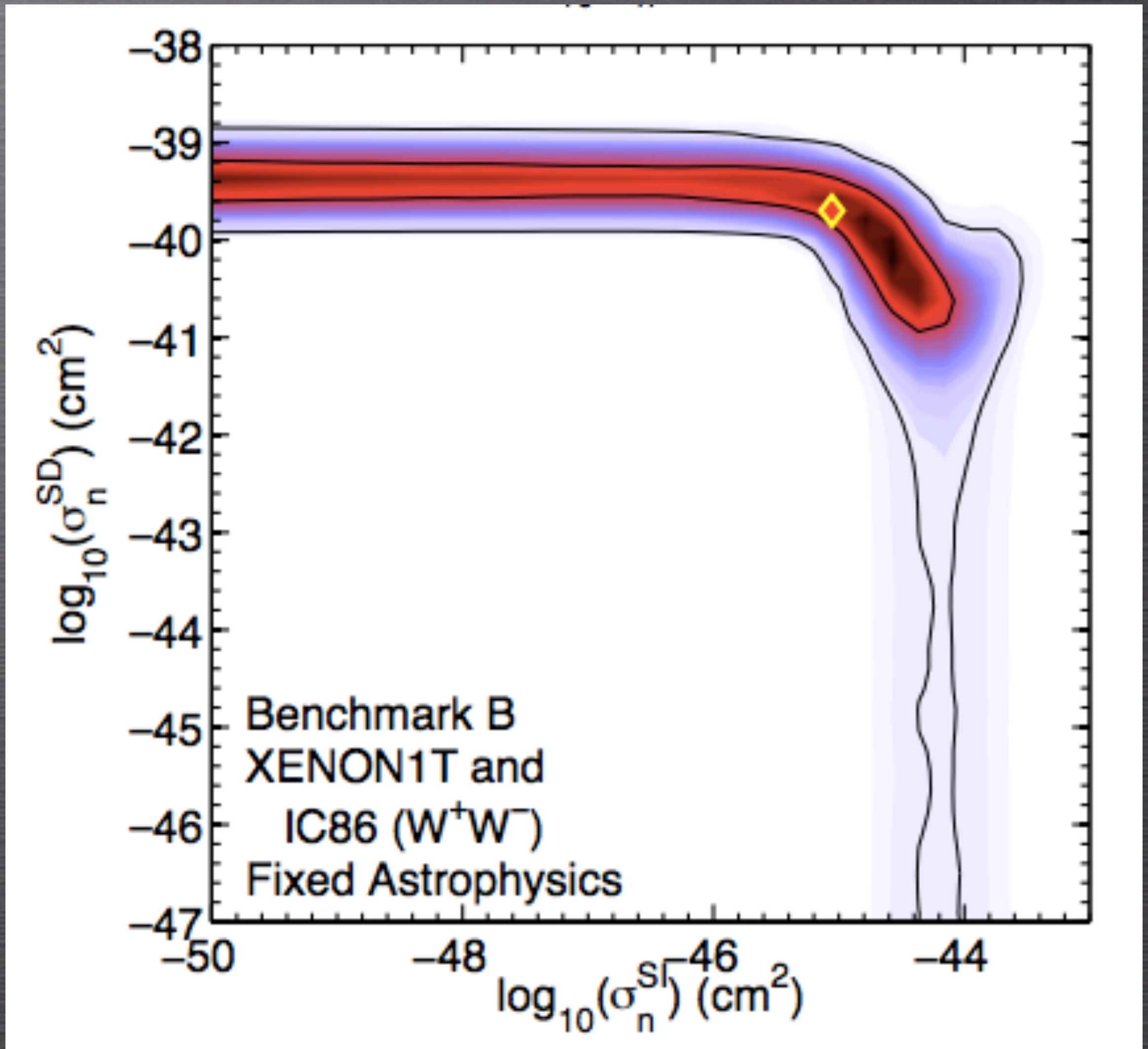
THEN
we can exclude the spurious solution at low relic density



GB, Fornasa, Pieri, Ruiz, Trotta 2011

Xenon + IceCube





Arina, Bertone, Silverwood, 2013

Conclusions

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

- DM *Indirect Detection* more and more constrained, but there are tantalizing hints..

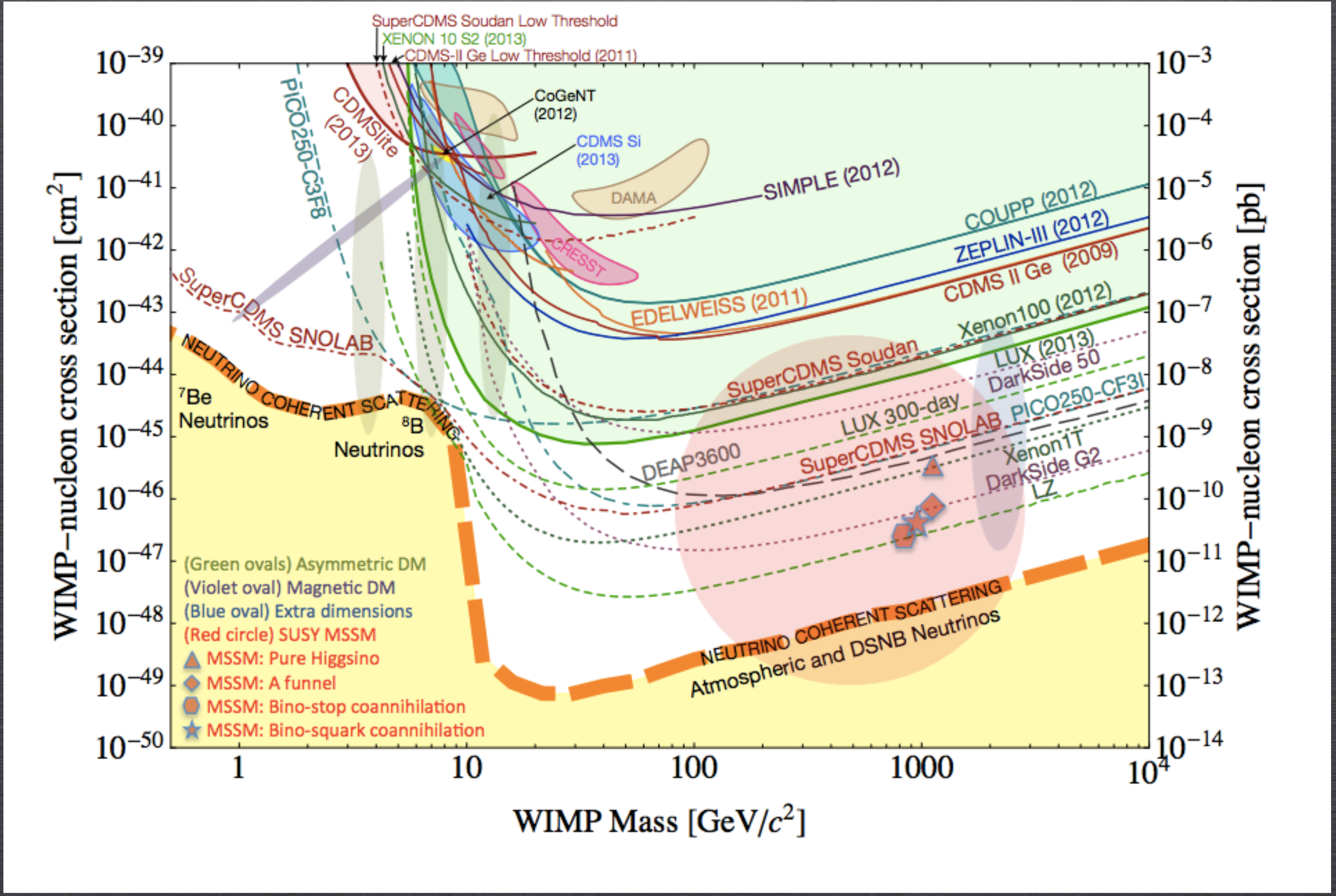
- DM *Direct Detection* looks promising. Info from other exps. is needed to determine DM parameters

- Run II of the LHC (2015) is expected to provide crucial information! Even in case of direct and indirect searches likely necessary to identify DM

- Next 5-10 years are crucial: this is the *moment of truth* for WIMP Dark Matter!

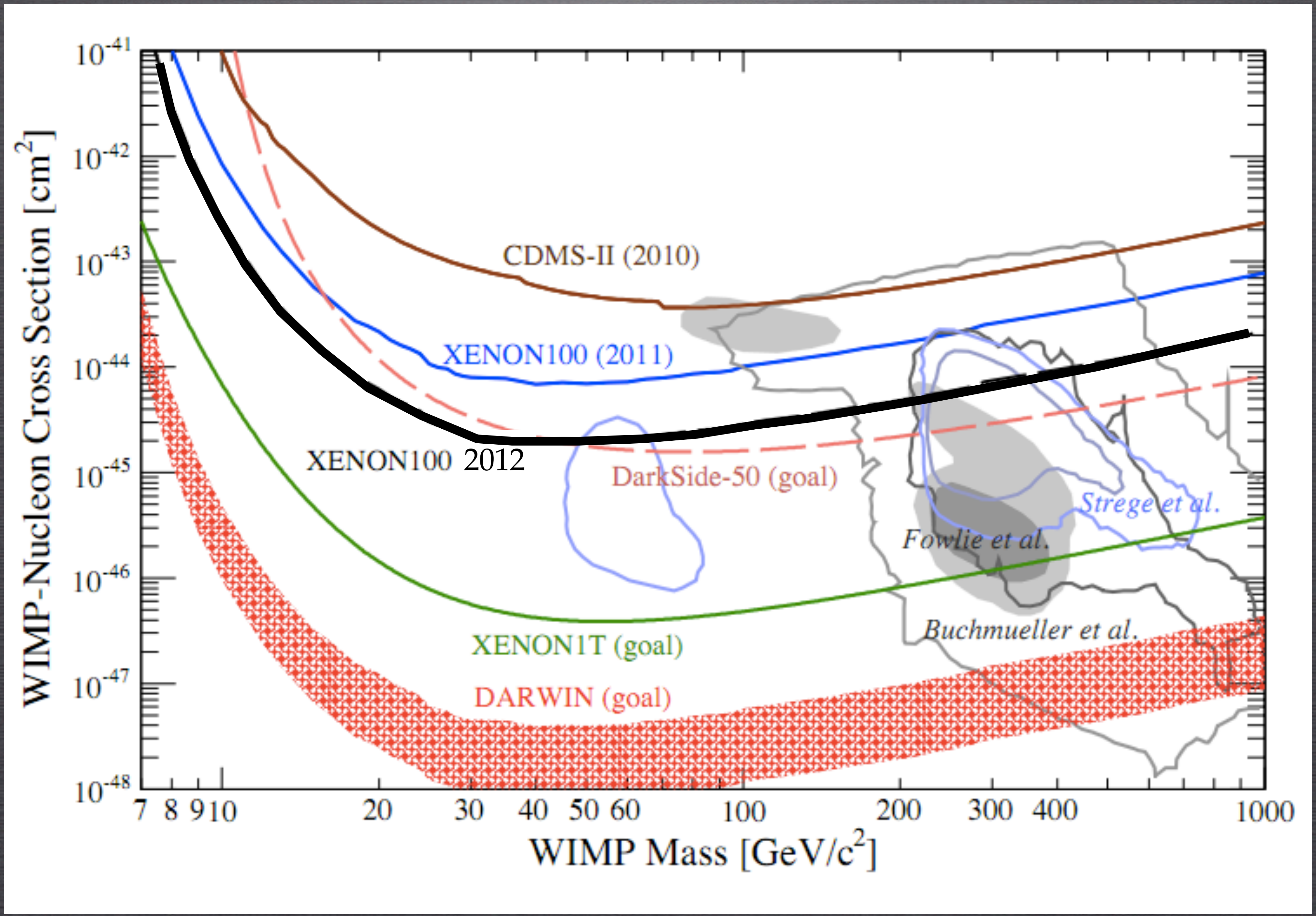

ASTROPARTICLE
PHYSICS 2014
A joint TeVPA/IDM conference
http://indico.cern.ch/e/TeVPAIDM
Location:
Amsterdam
Conference Venue:
Tuschinski theater
Social Event:
Scheepvaart Museum
June 23 – 28, 2014
Amsterdam, NL
Confirmed Speakers
Local Organising Committee

Latest results:
LUX experiment, arXiv:1310.8214
(Sanford Underground Research Facility - SURF)



Direct Detection

Status



Adapted from Baudis (Darwin Collab.) [arXiv:1201.2402]

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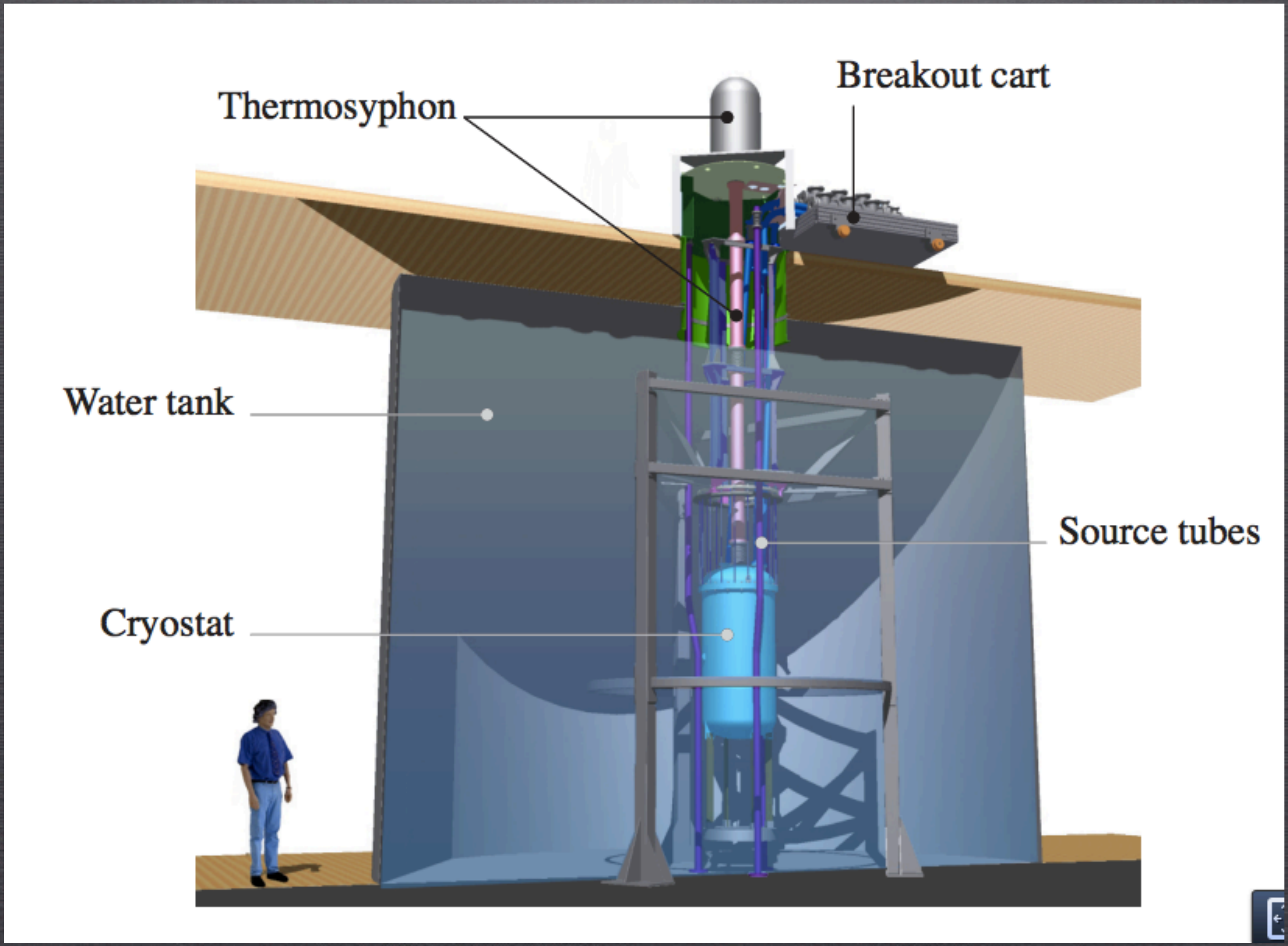

Xenon detectors
(e.g. LUX and Xenon100)