Identifying Dark Matter

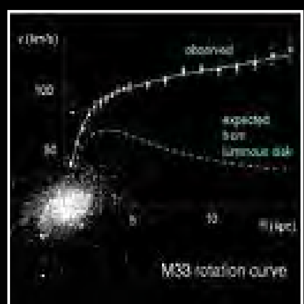
Gianfranco Bertone
GRAPPA Institute, U. of Amsterdam

CTA-Link Meeting
Buenos Aires, 20 Nov 2012

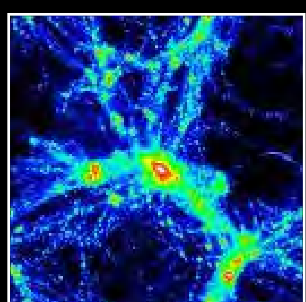
Evidence for Dark Matter

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

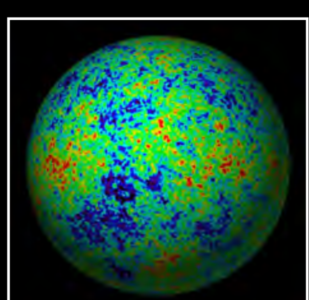
COSMOLOGICAL OBSERVATIONS



- Rotation Curves



- Clusters of galaxies



- CMB

- Type Ia Supernovae

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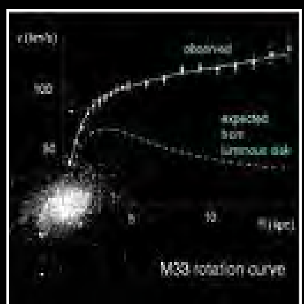

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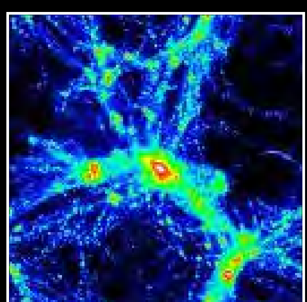

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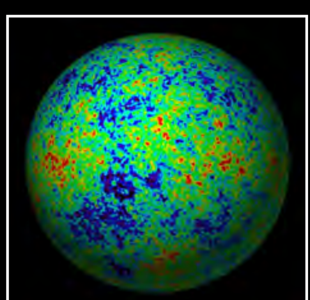
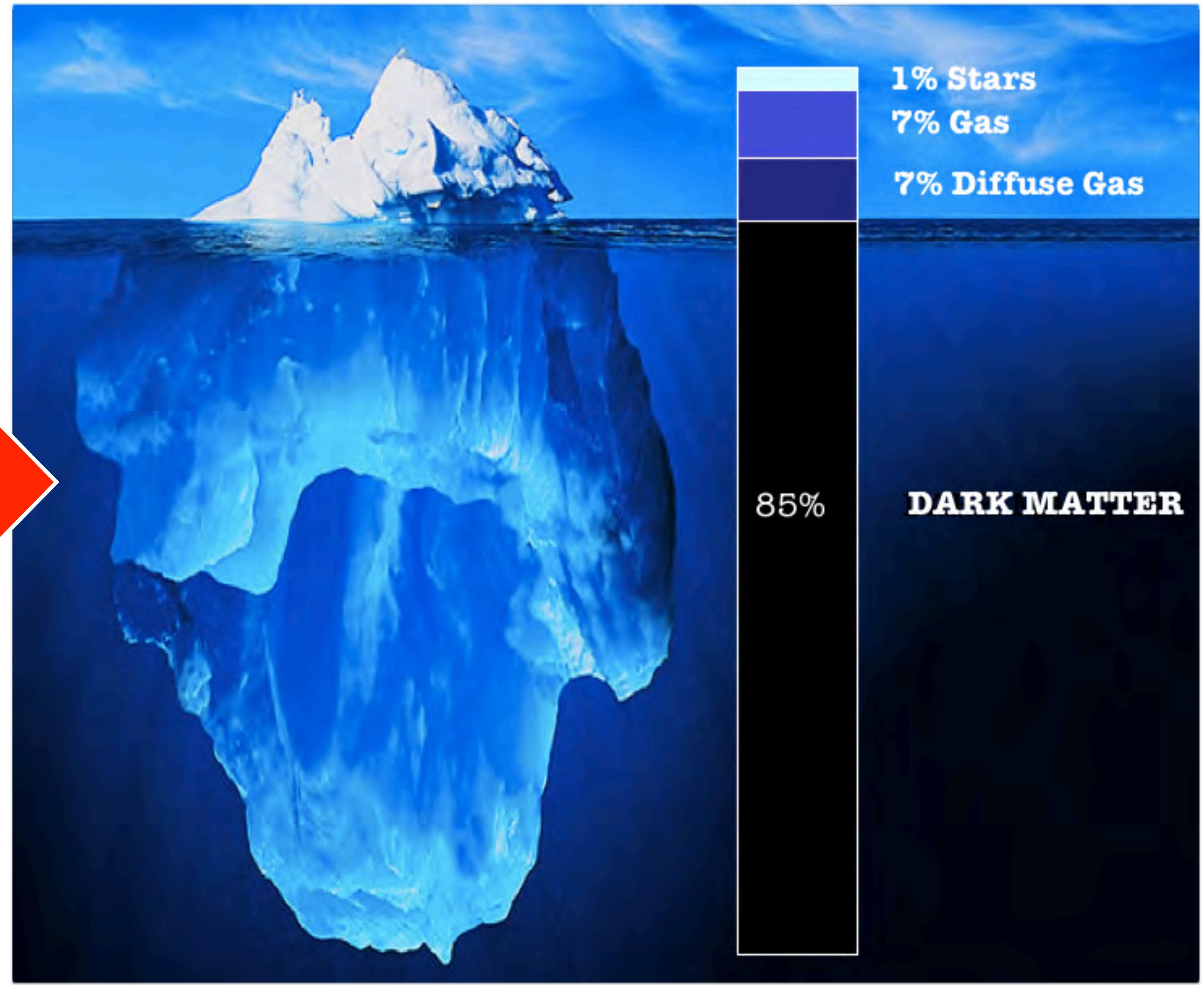


- CMB

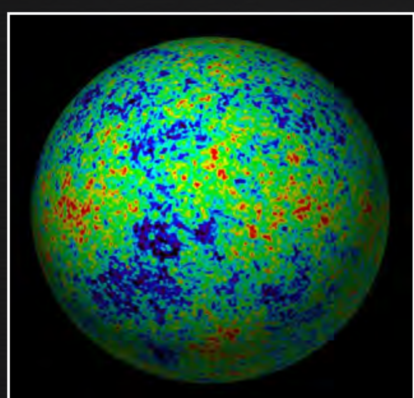
- Type Ia Supernovae



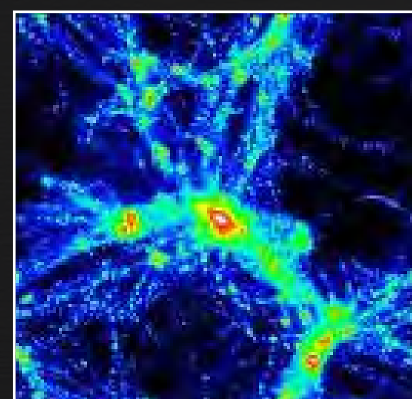
What do we know?

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

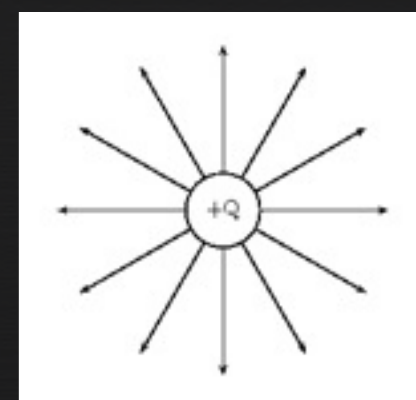
1) Ωh^2 OK?



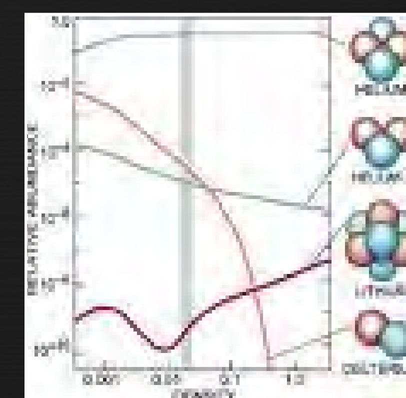
2) Is it cold?



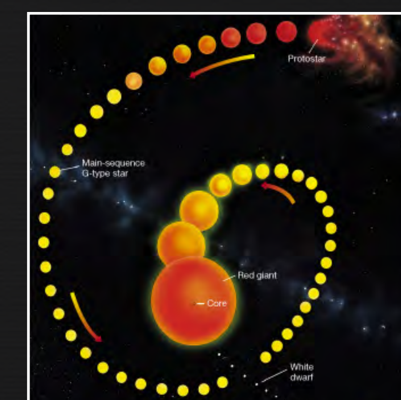
3) Is it neutral?



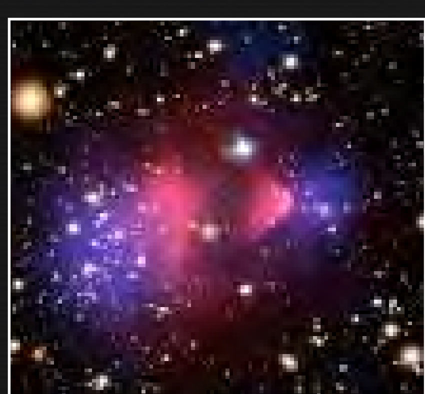
4) Is BBN ok?



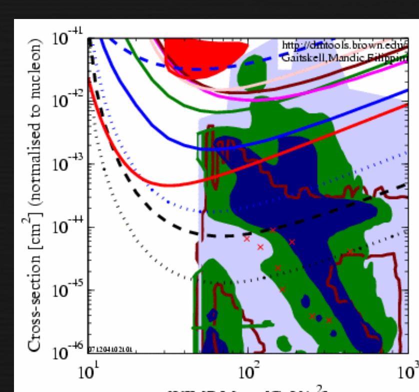
5) Stars OK?



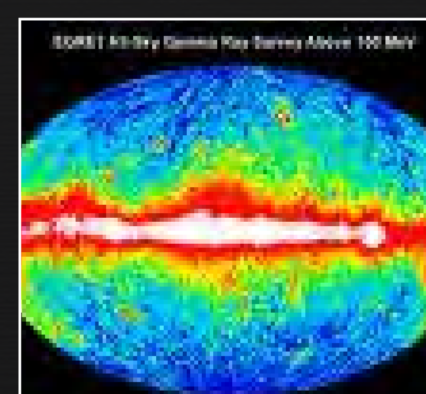
6) Collisionless?



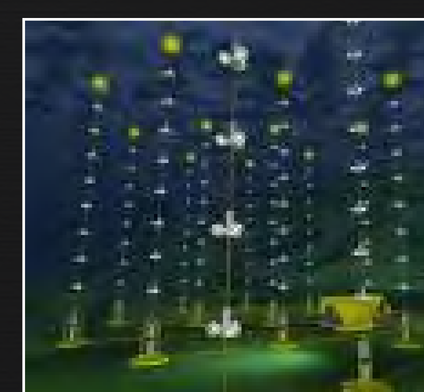
7) Couplings OK?



8) γ-rays OK?



9) Astro bounds?



10) Can probe it?

Taoso, GB & Masiero 2007

Dark Matter candidates

- Neutralino?

Dark Matter candidates

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

The DM candidates Zoo

WIMPs

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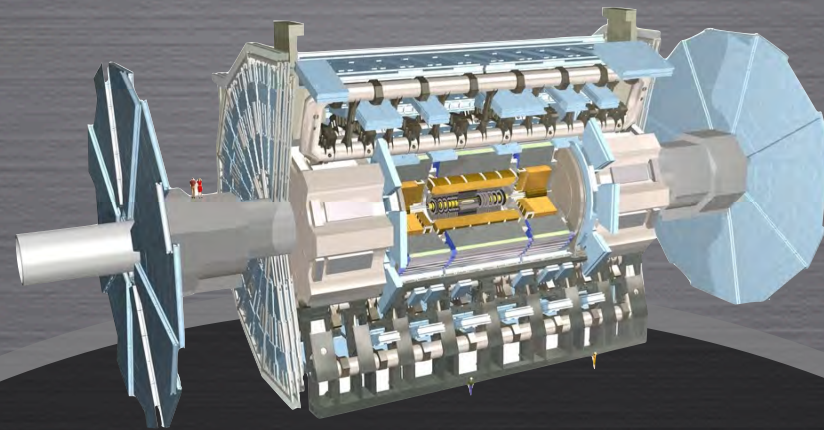
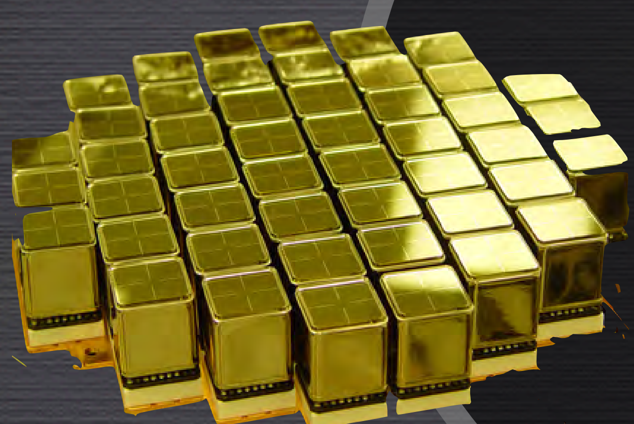
  Appropriate relic density achieved by a suitable combination of masses and couplings

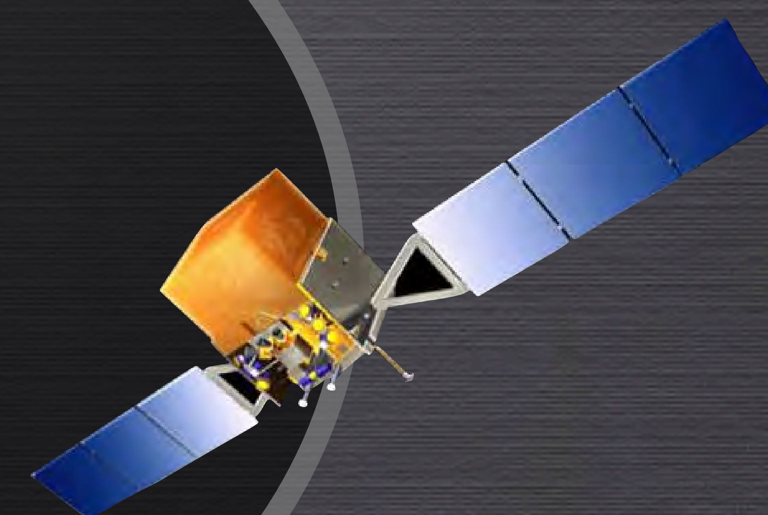
Dark Matter searches



Colliders

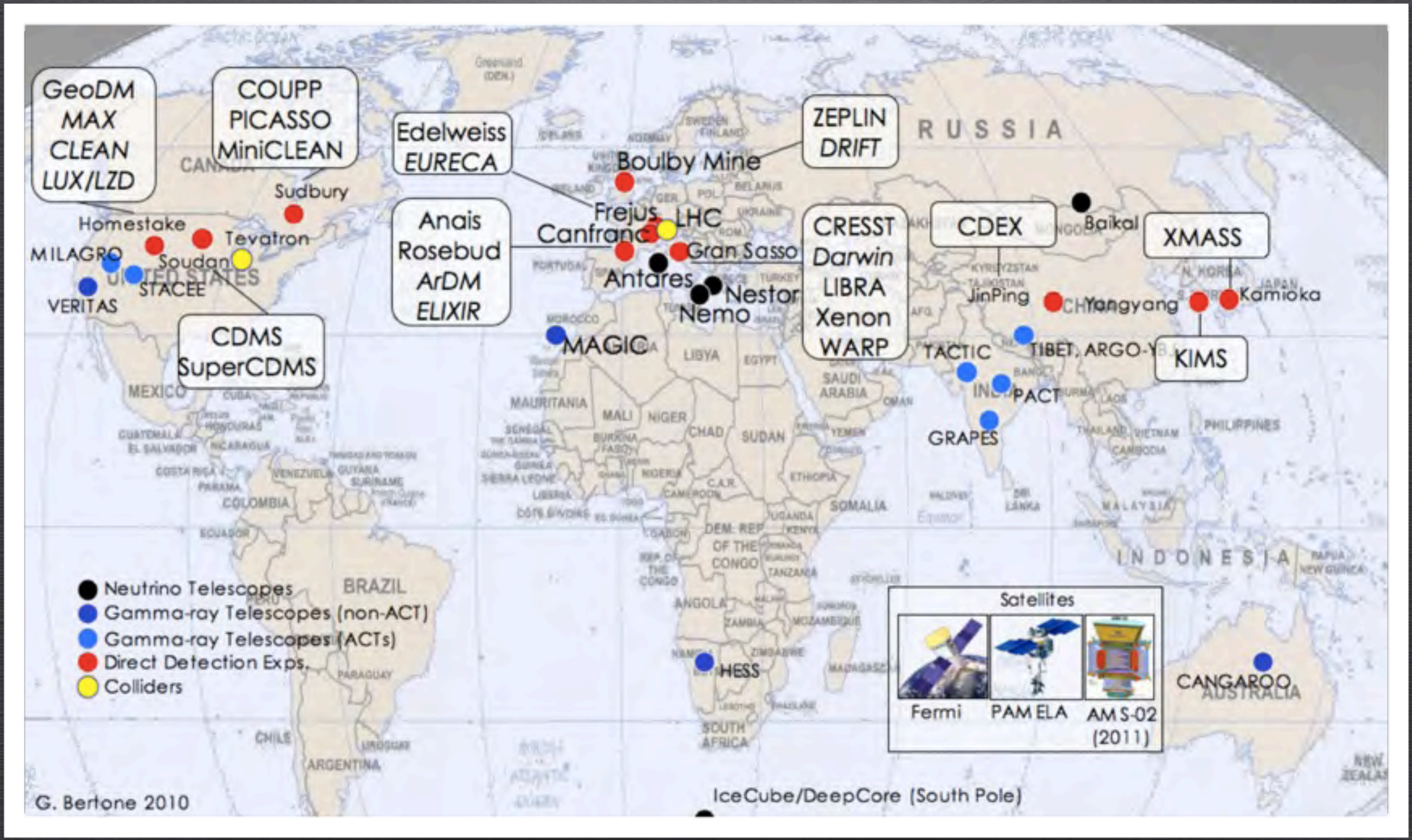


Direct Detection



Indirect Detection

Dark Matter-related Experiments circa 2012



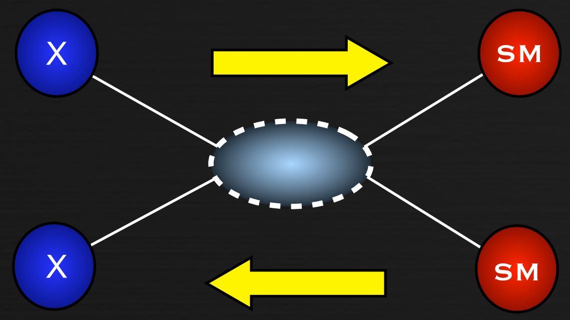
Download: http://www2.iap.fr/users/bertone/

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.

Indirect Detection

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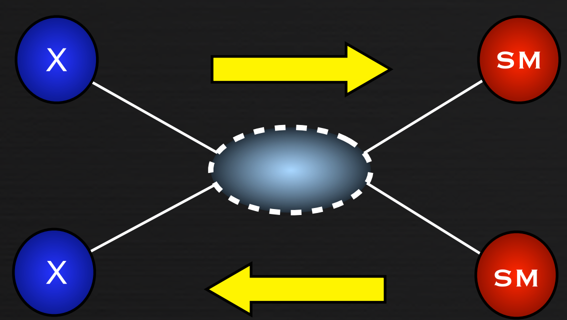

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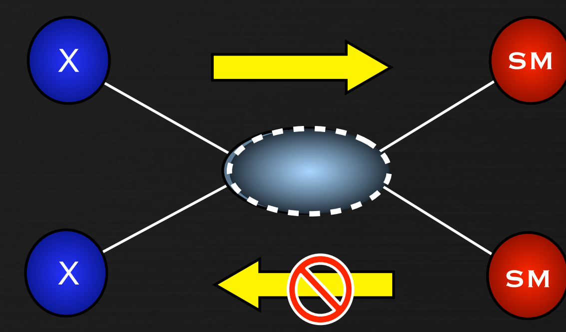
Today



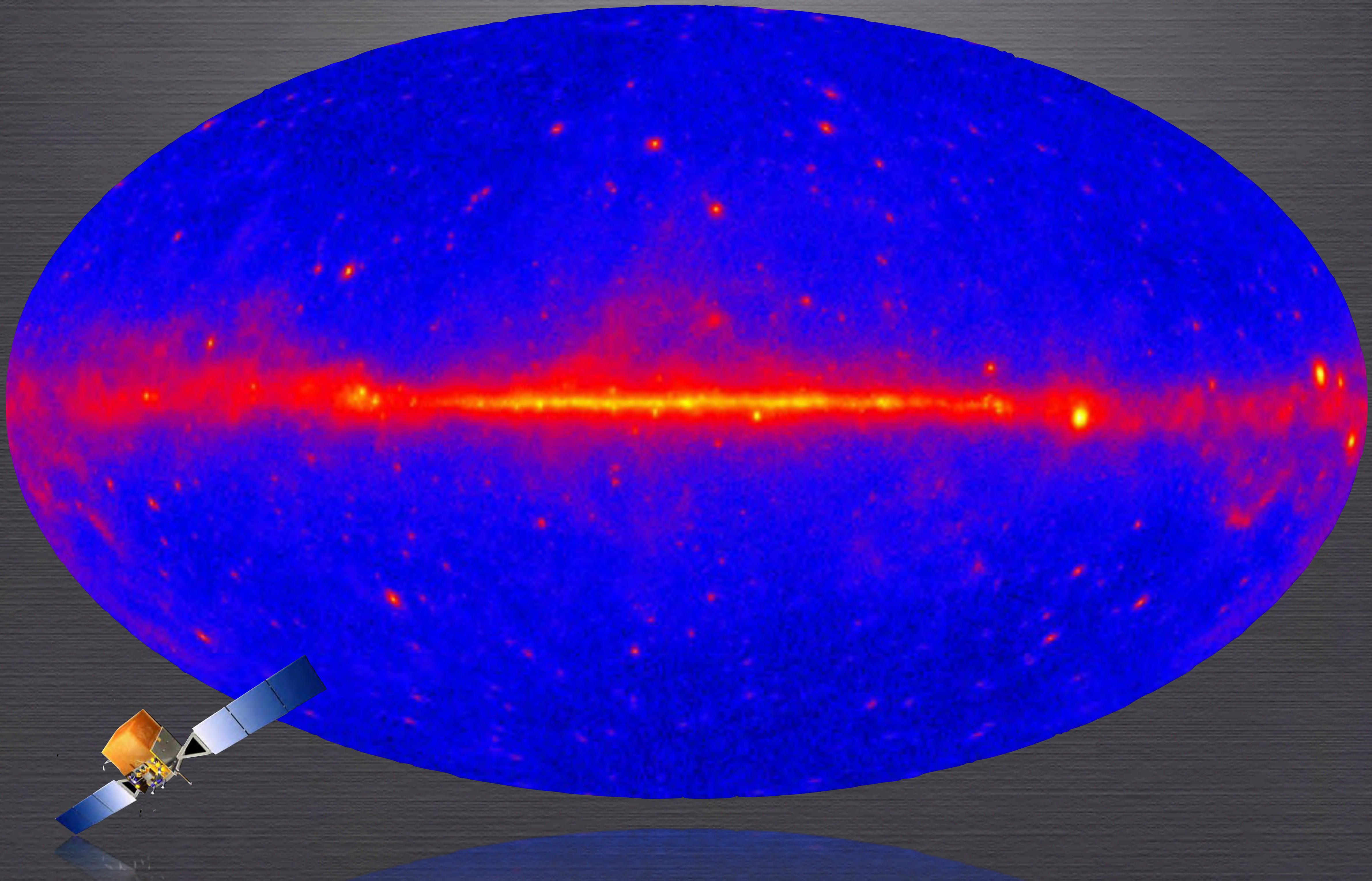
$$\frac{dn_\chi}{dt} = -(\sigma v)_o n_\chi^2$$

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.

The FERMI sky



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

The 130 GeV Line

arXiv:1204.2797v2 [hep-ph] 8 Aug 2012

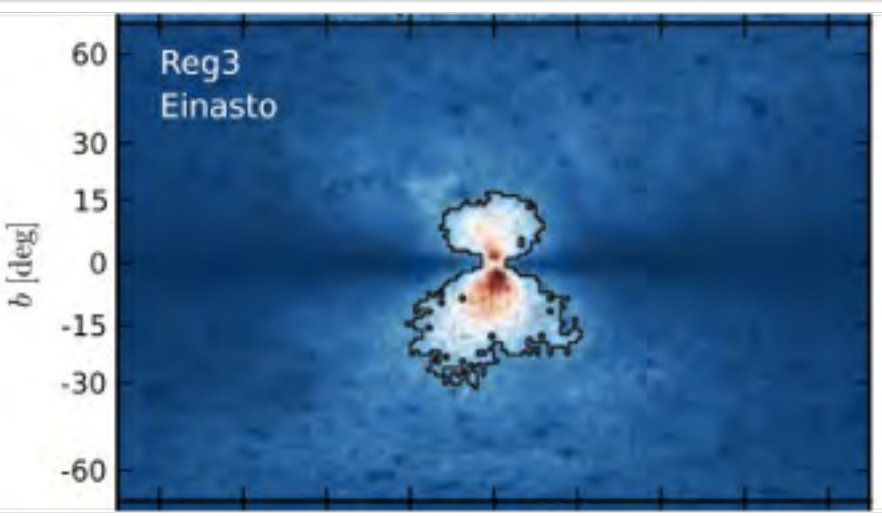
A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

Christoph Weniger

Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany

E-mail: weniger@mppmu.mpg.de

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 $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm^3\,s^{-1}}$ 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.



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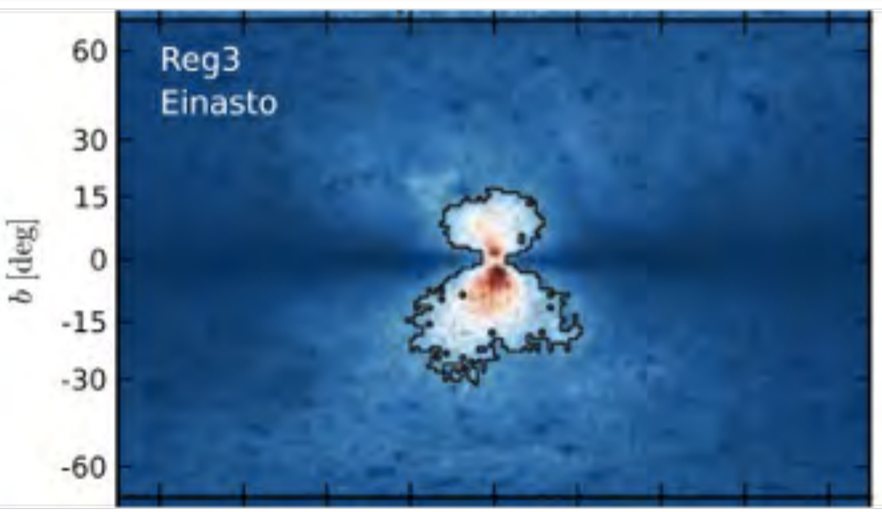

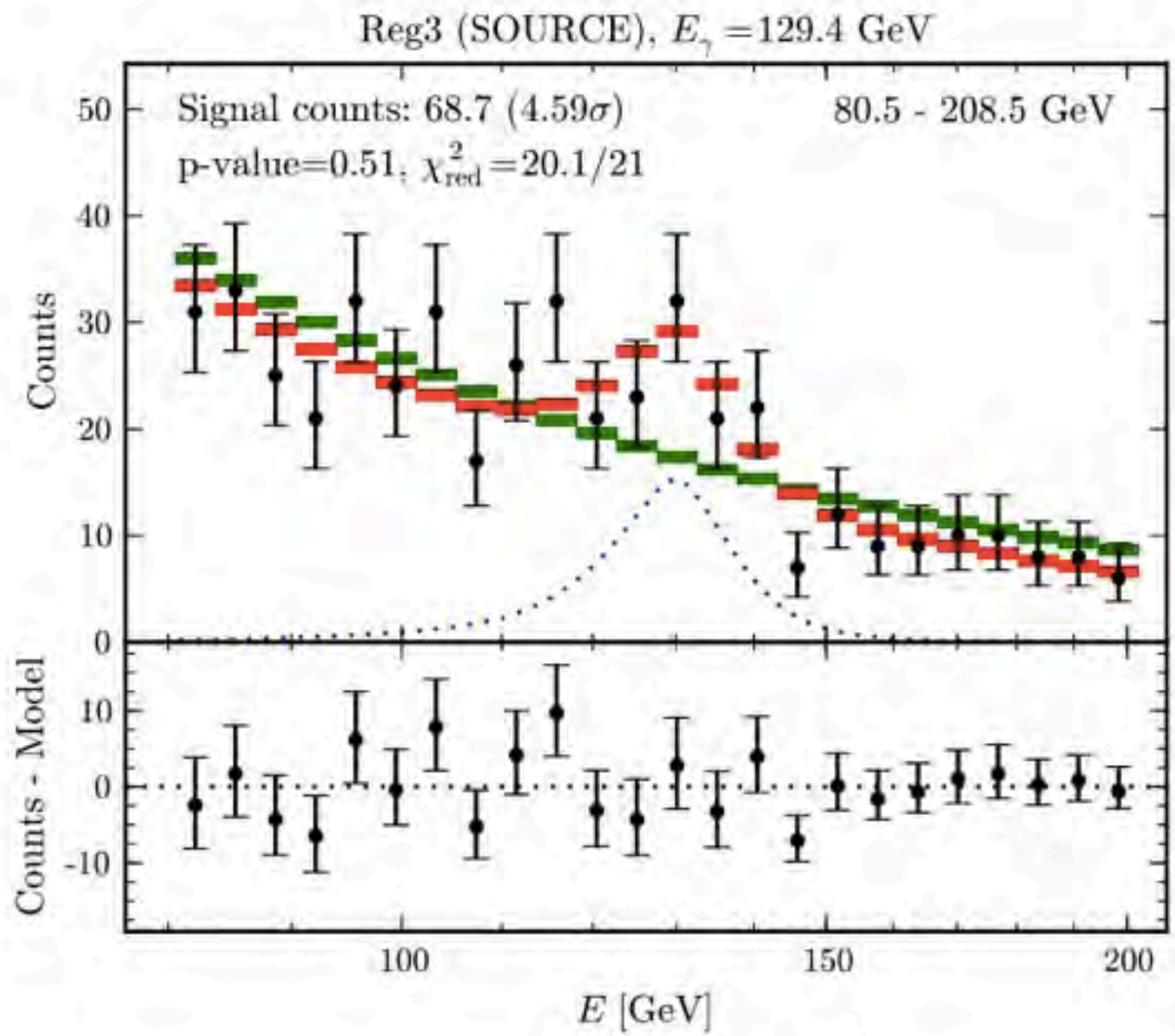

The 130 GeV Line

Not really what one would expect from Supersymmetry..

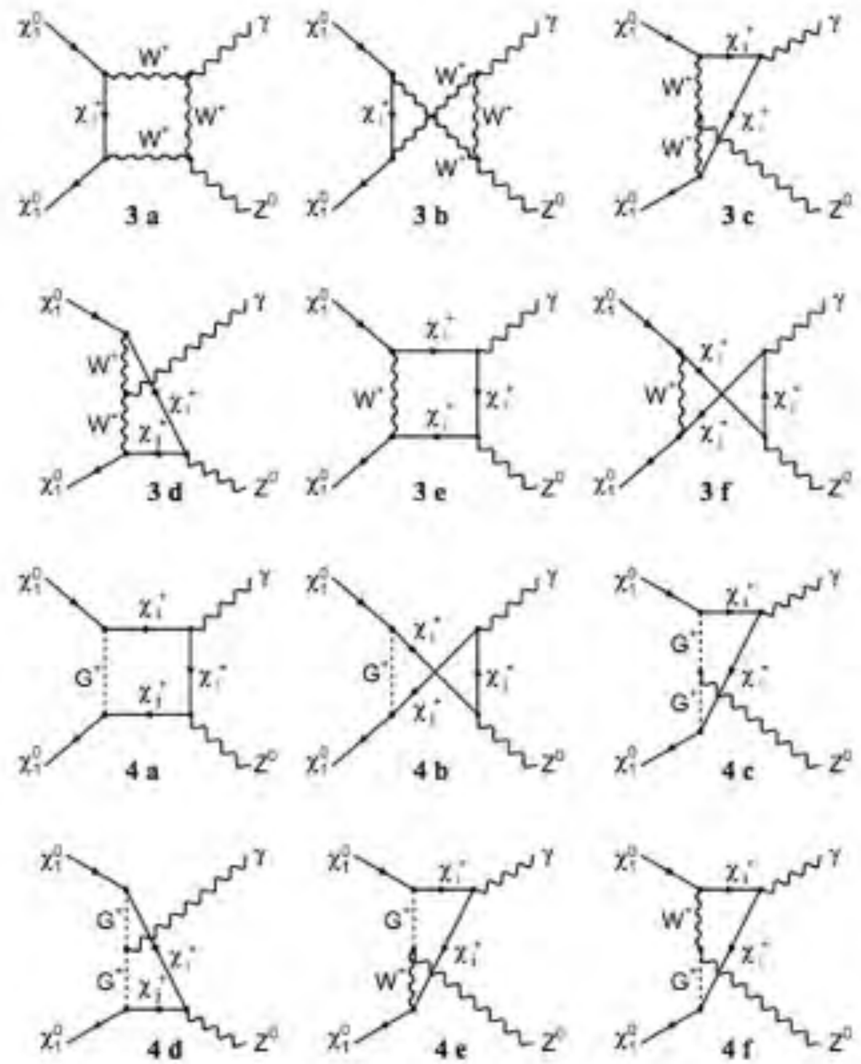

Figure 43: Diagrams contributing, at one loop level, to neutralino annihilation into a photon and a Z^0. From Ref. [480].

- Direct Annihilation to photons is loop-suppressed in SUSY
- hard to produce the line without overproducing low-energy photons

e.g. Cohen et al.
arXiv:1207.0800

The 130 GeV Line

assuming more general models:

Final states containing mono-chromatic photons:

$$\chi\chi \to P\gamma \qquad E_\gamma = m_\chi \left(1 - \frac{m_P^2}{4m_\chi^2}\right)$$

	$\gamma\gamma$	$H\gamma$	$Z\gamma$
$\gamma\gamma$	130	100	114
$H\gamma$	155	130	142
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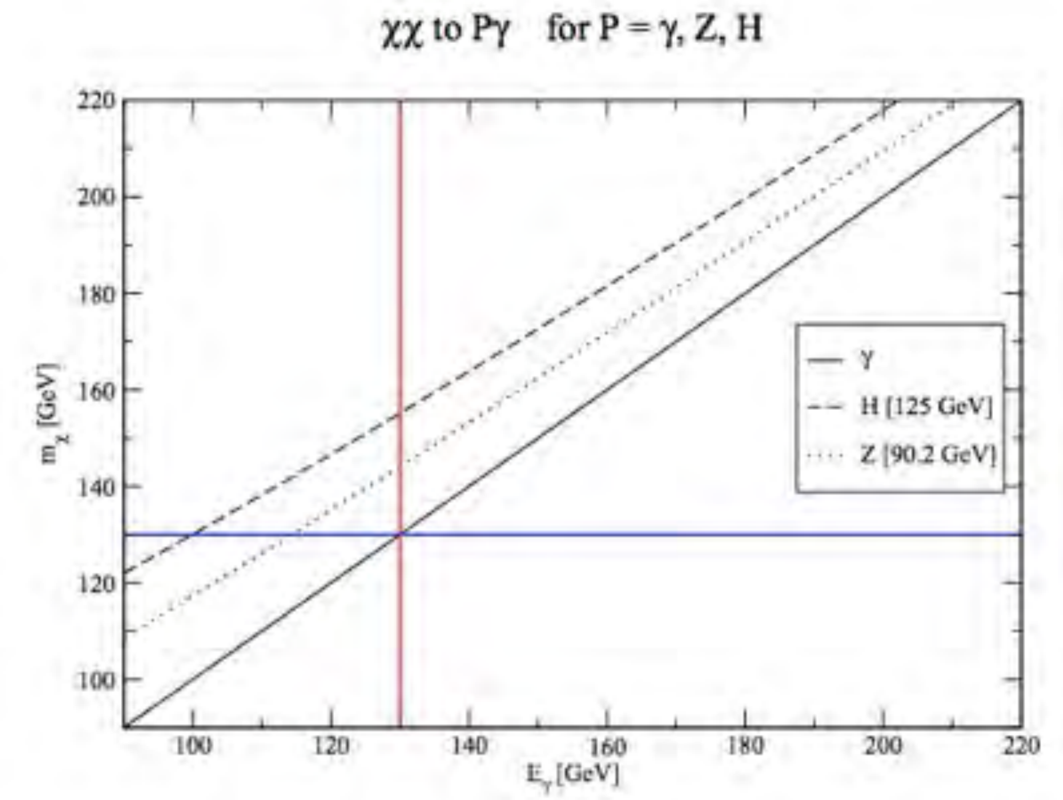

Bergstrom, GB et al. http://arxiv.org/pdf/1207.6773.pdf

The 130 GeV Line

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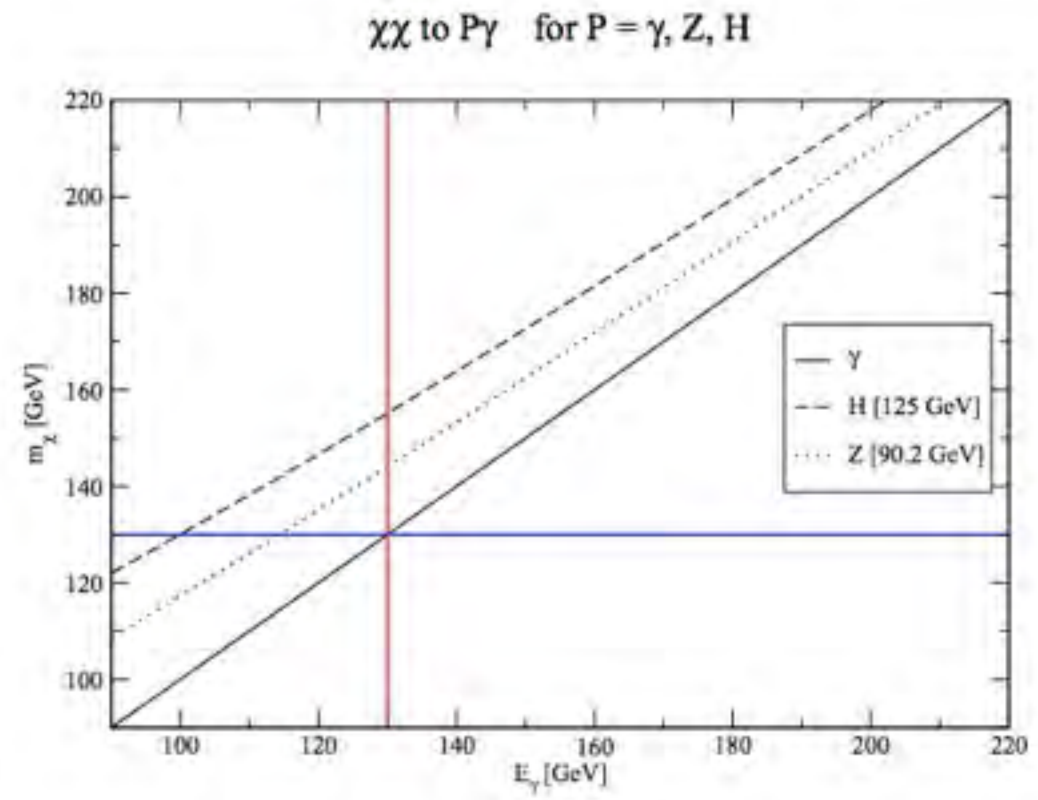
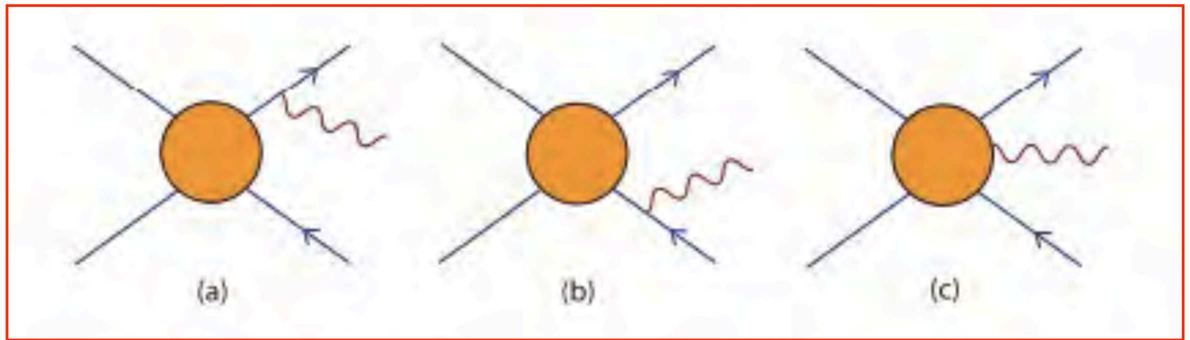
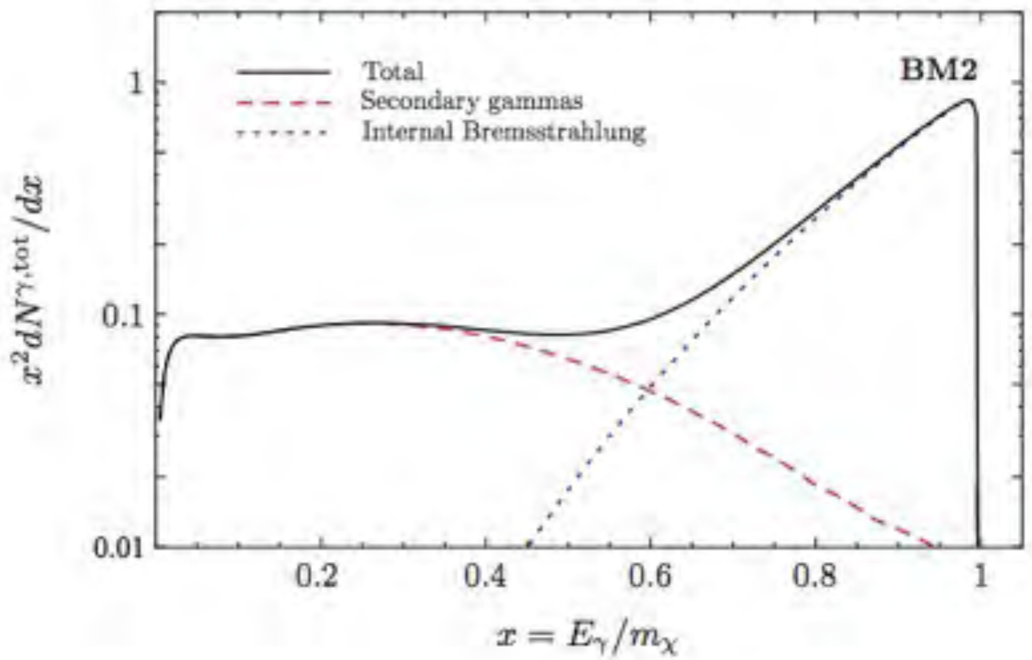


'Internal Bremsstrahlung'





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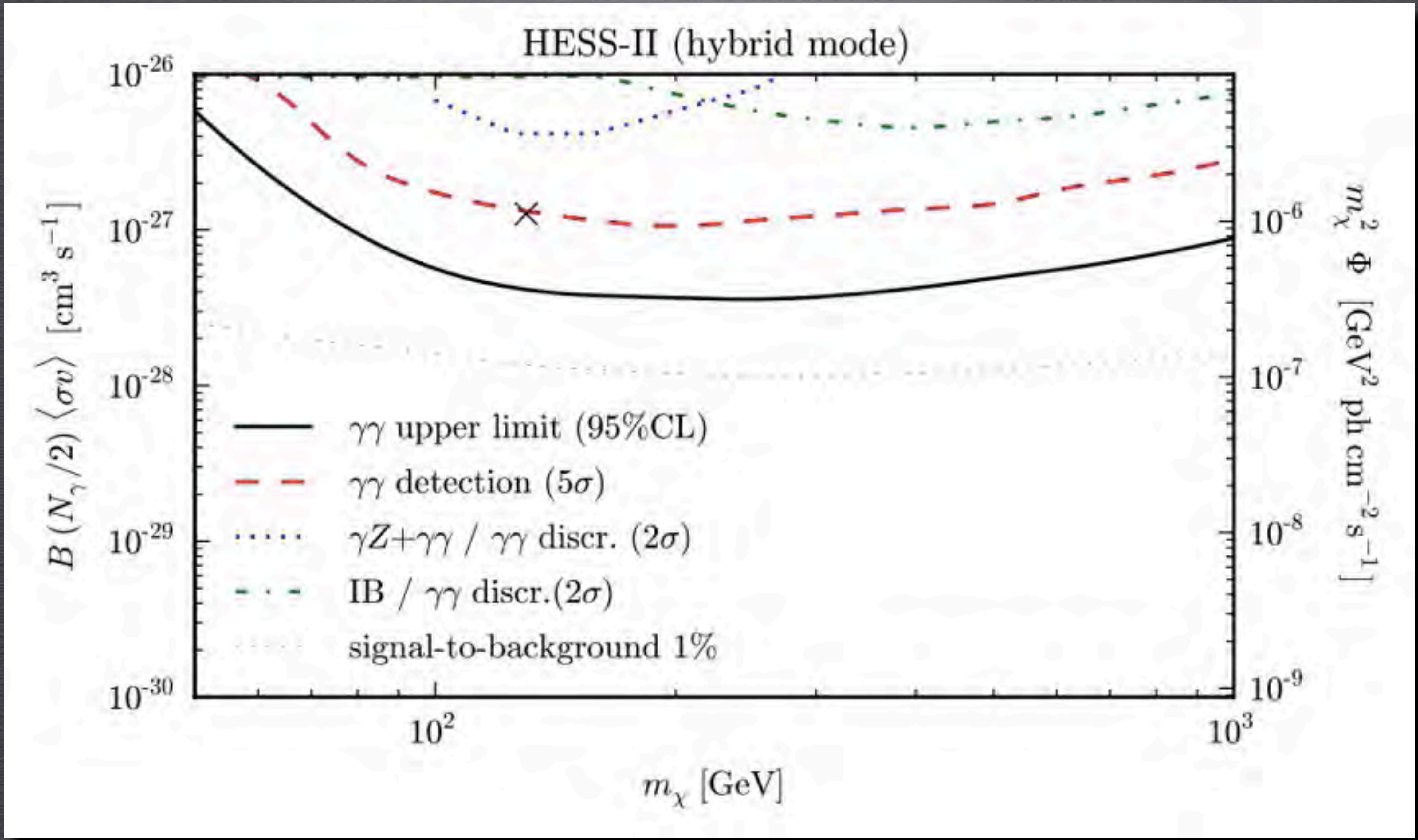

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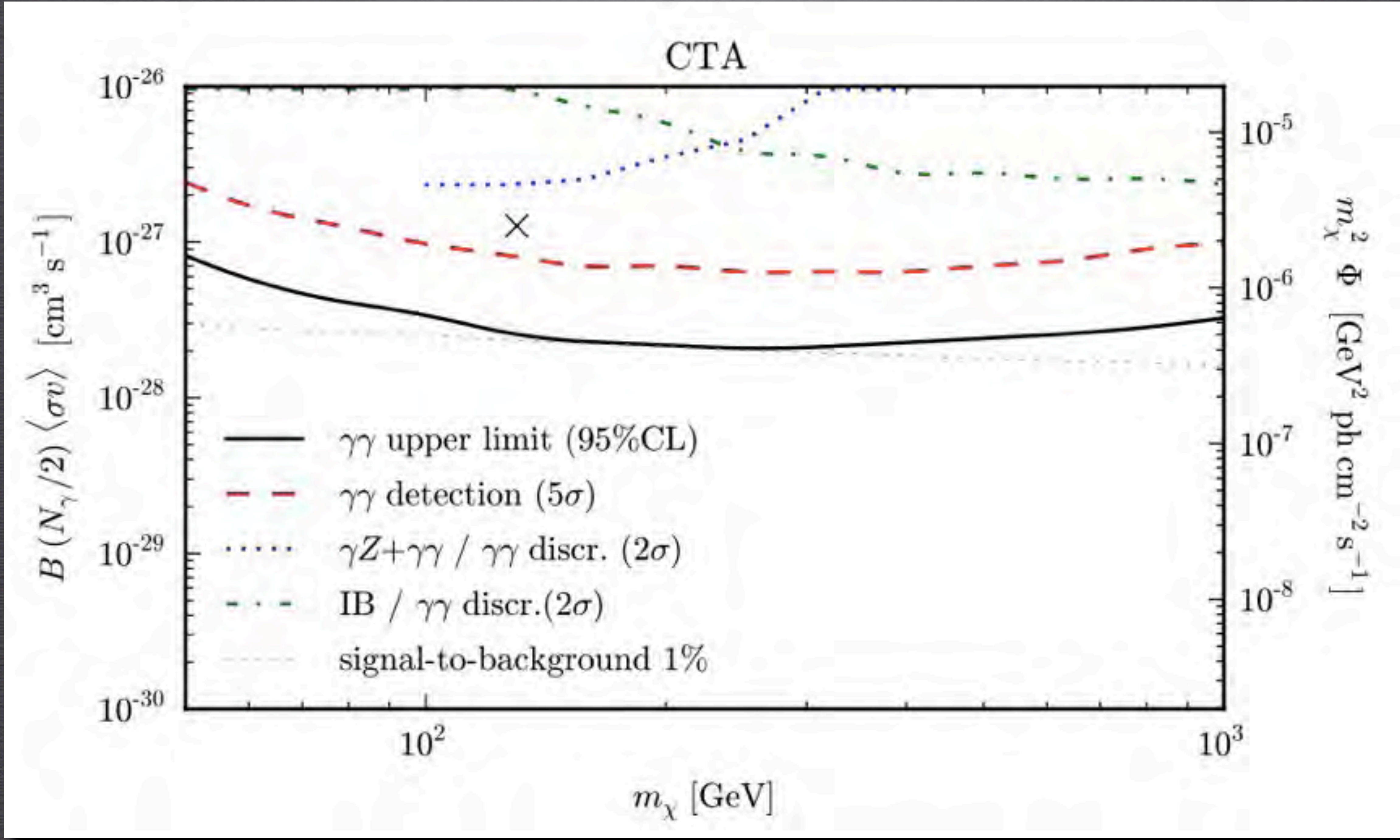

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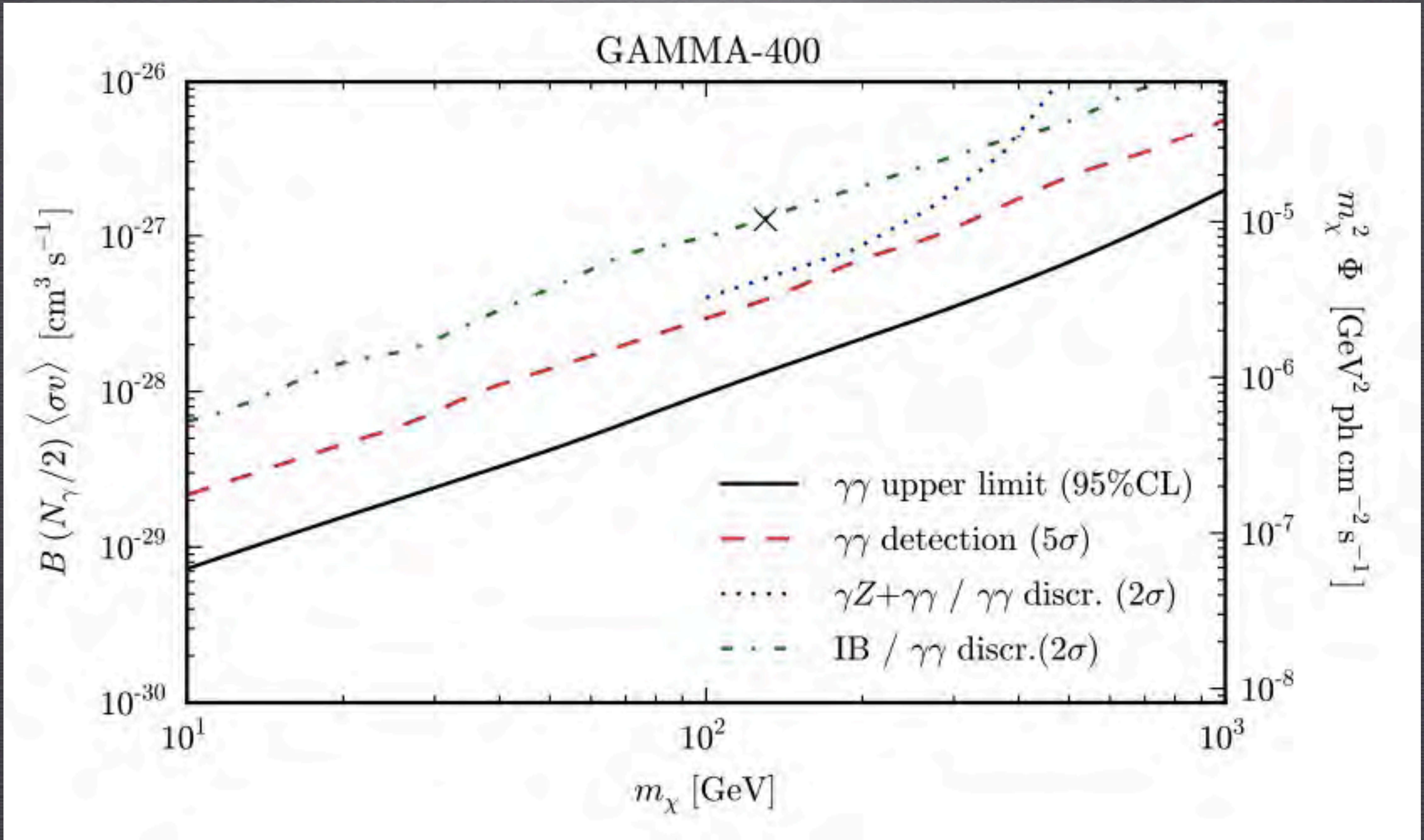

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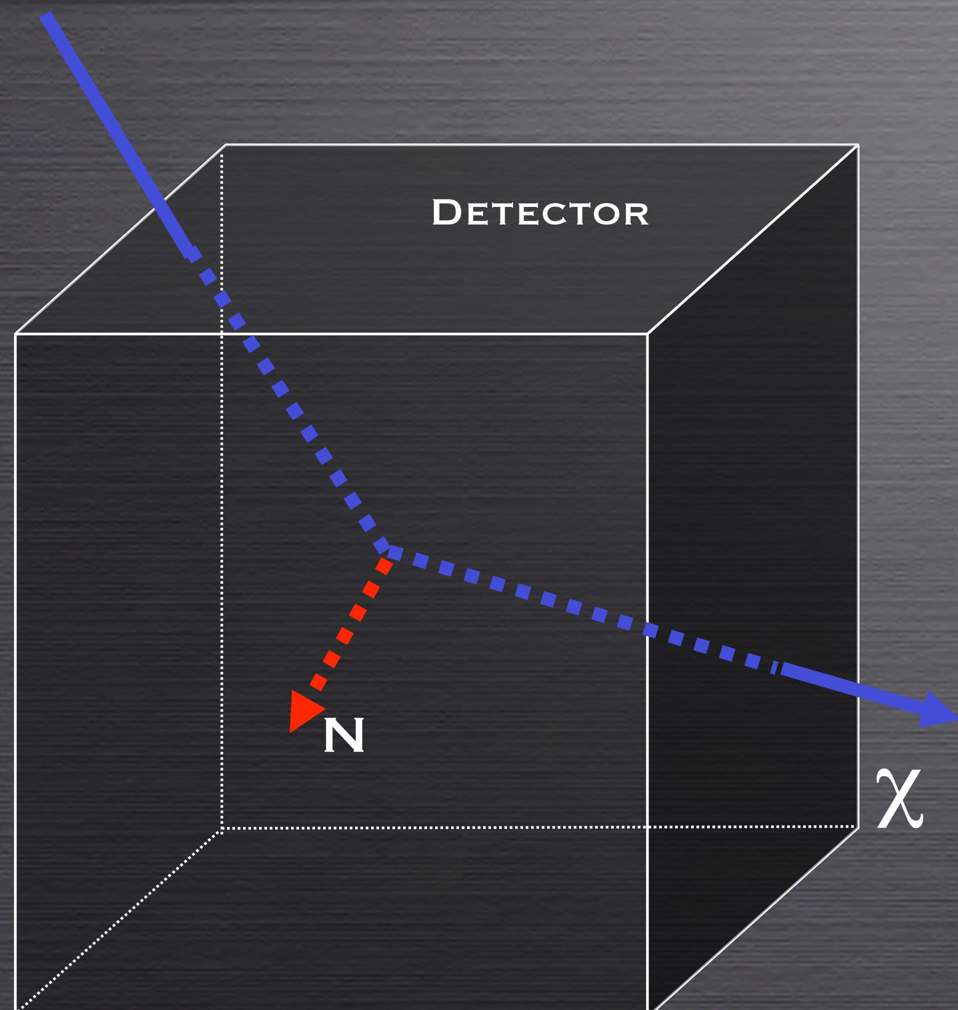
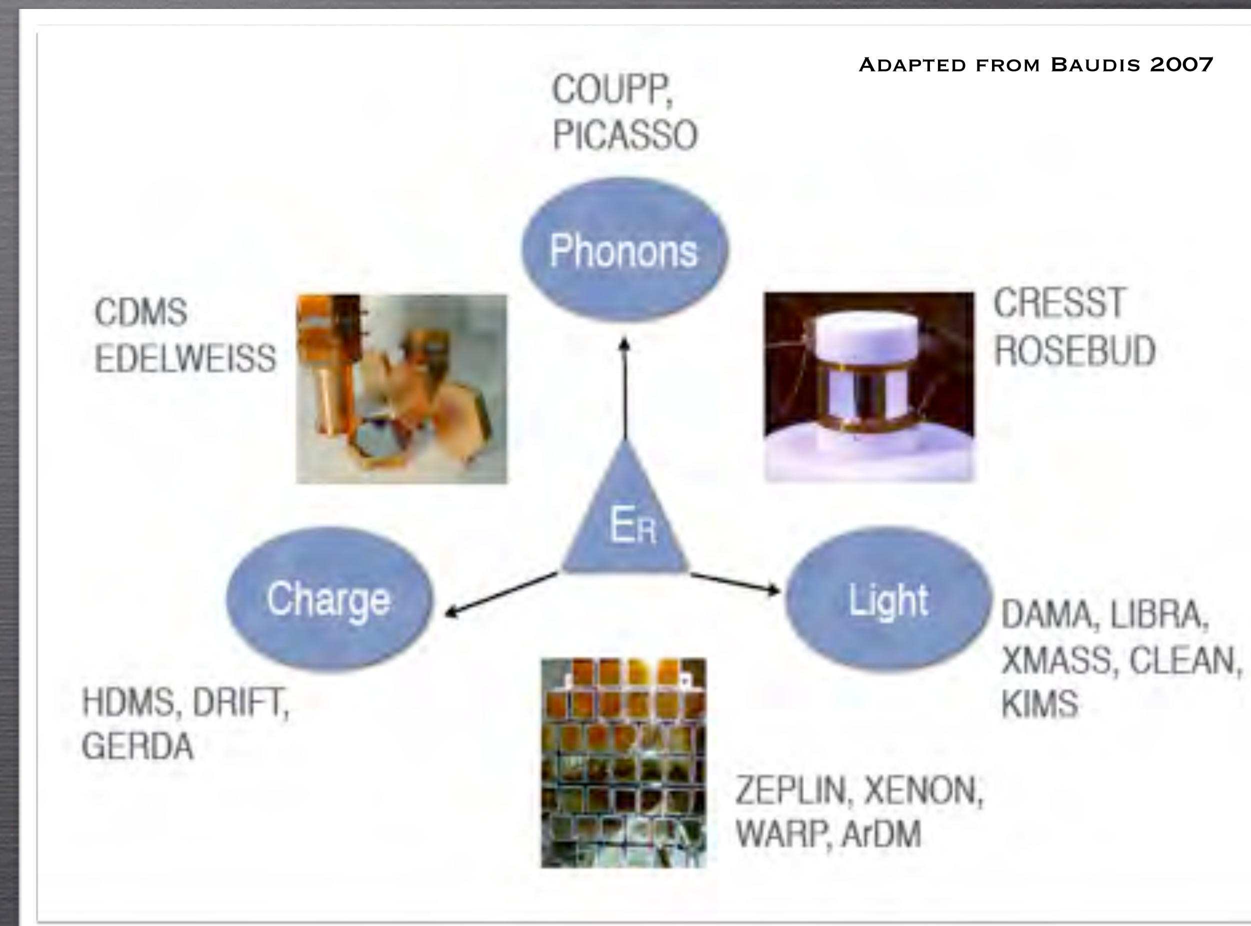
Direct Detection

Principle and Detection Techniques





DM Scatters off nuclei in the detector

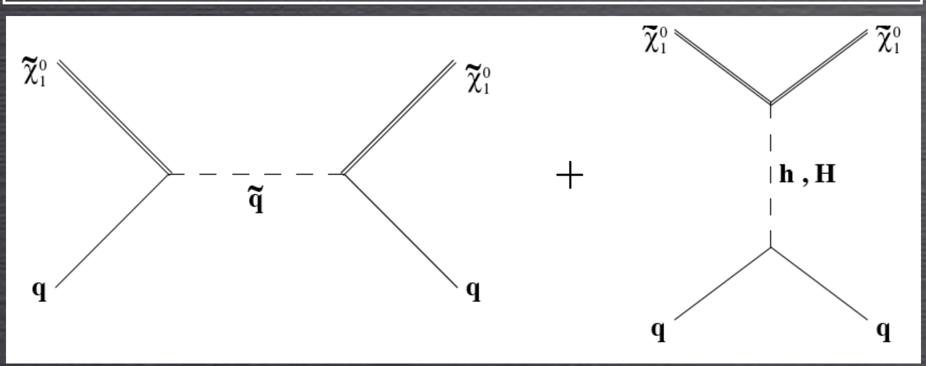
Detection of recoil energy via ionization (charges), scintillation (light) and heat (phonons)

Direct Detection

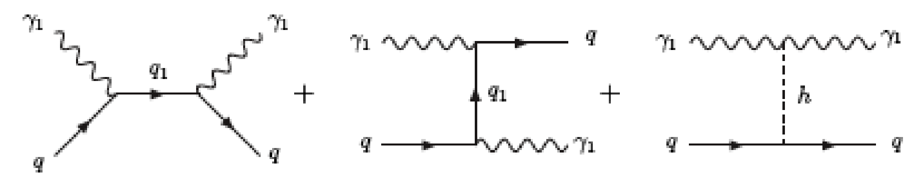
Differential Event Rate

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

SUSY: squarks and Higgs exchange



UED: 1st level quarks and Higgs exchange



Theoretical Uncertainties

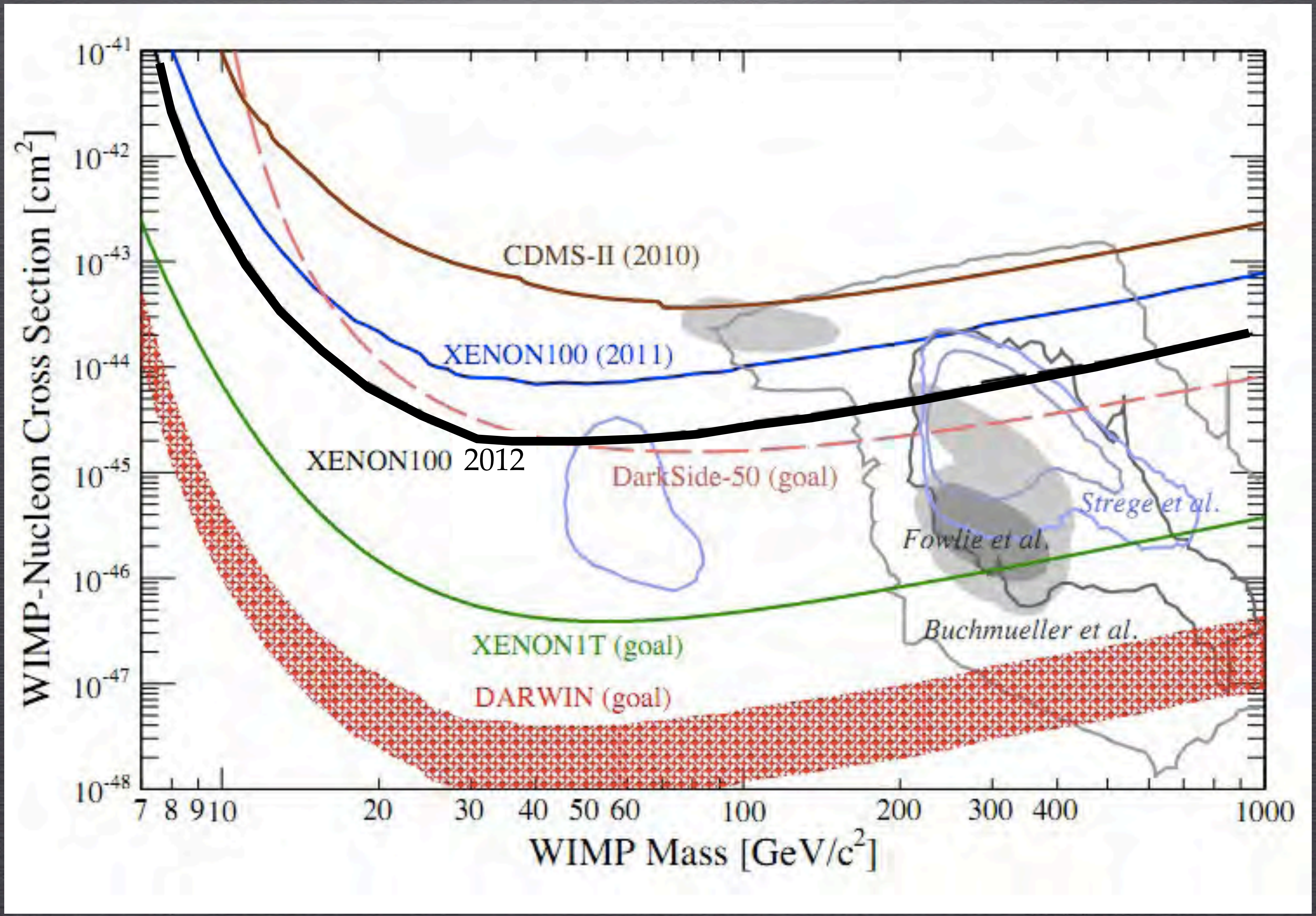
Ellis, Olive & Savage 2008; Bottino et al. 2000; etc.

Uncertainties on f(v)

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

Direct Detection

Status



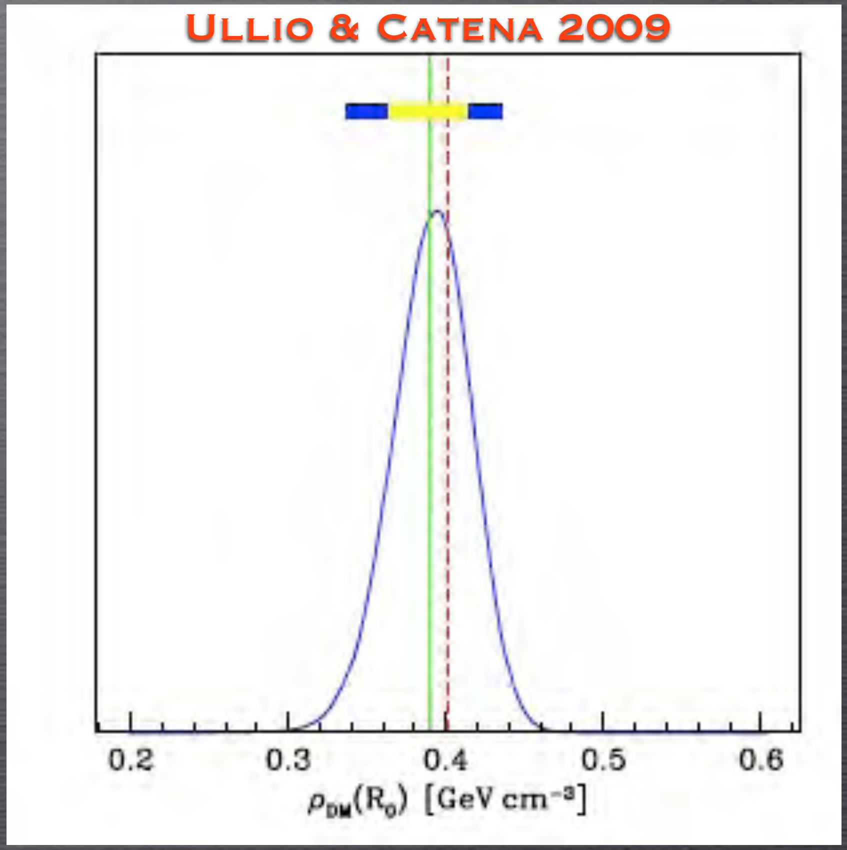
Adapted from Baudis (Darwin Collab.) [arXiv:1201.2402]

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



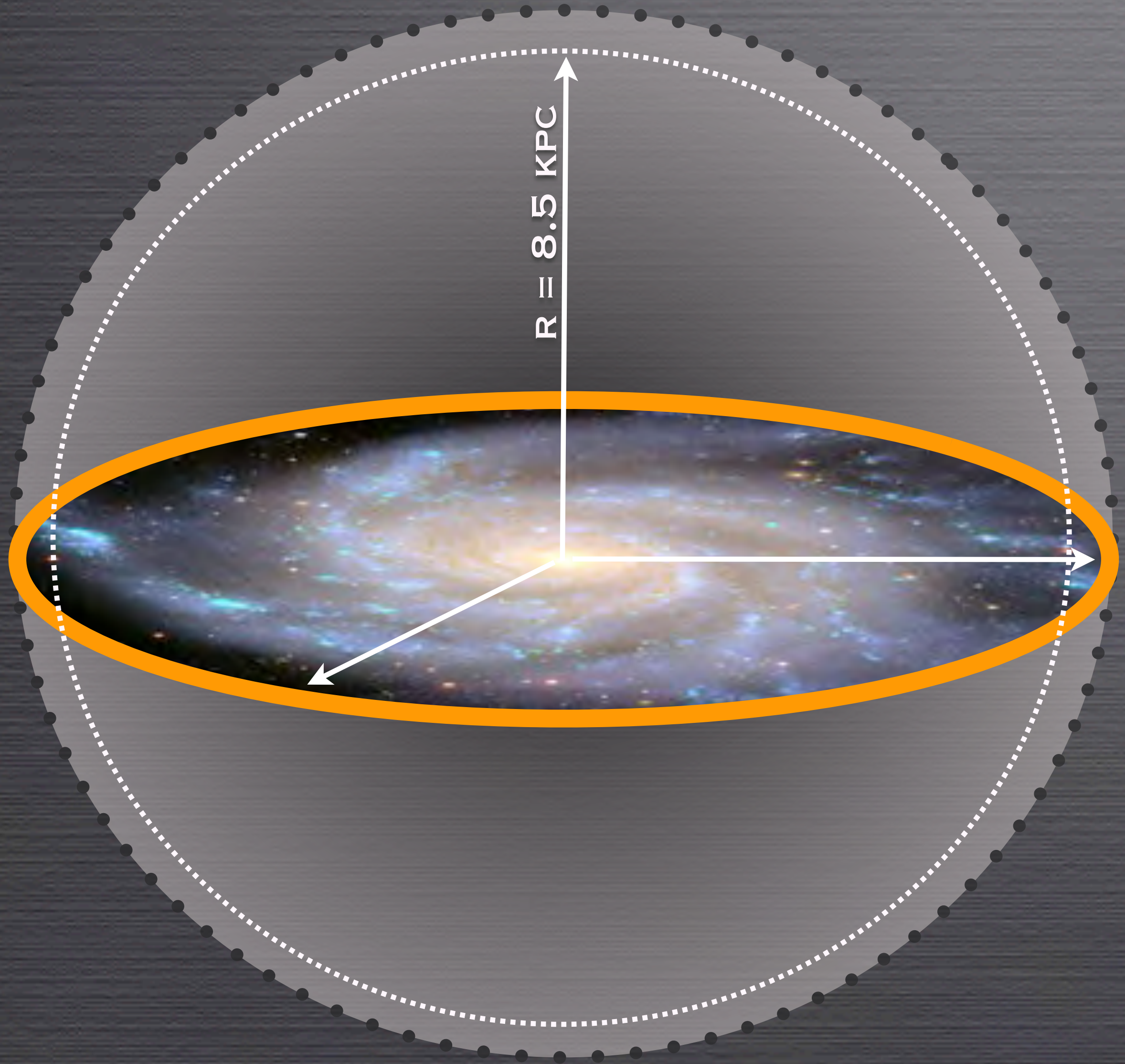
$$\rho_{DM}(R_0) = 0.389 \pm 0.025\,\mathrm{GeV\,cm^{-3}}$$

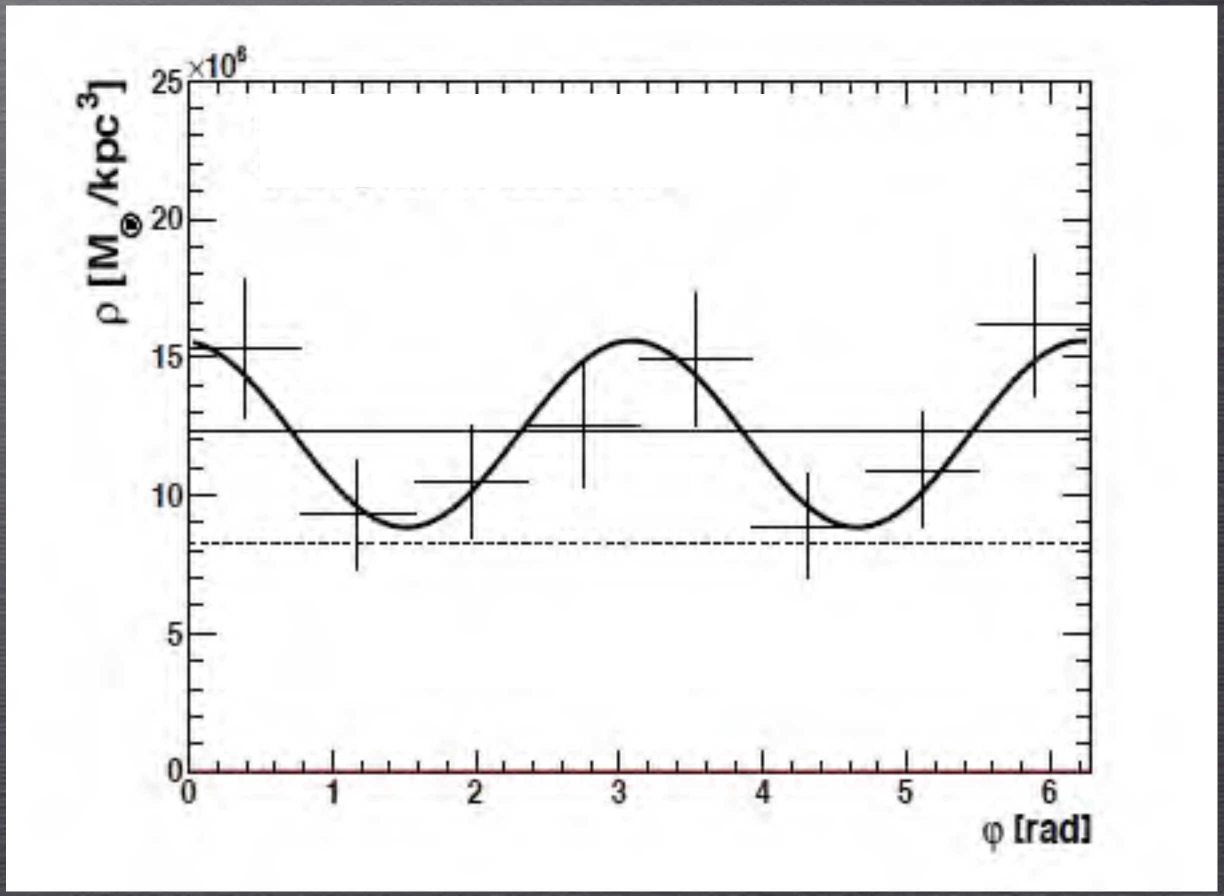
Constraints on M(<R) -> constraints on ρ_X

See also Strigari and Trotta 2009; Weber and De Boer 2009; Salucci et al. 2010; Garbari, Lake & Read 2010; Iocco, GB et al. 20111

Modulation of DM density

at fixed gc-distance (Pato, Agertz, GB, Moore, Teyssier, Moore 2010)





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

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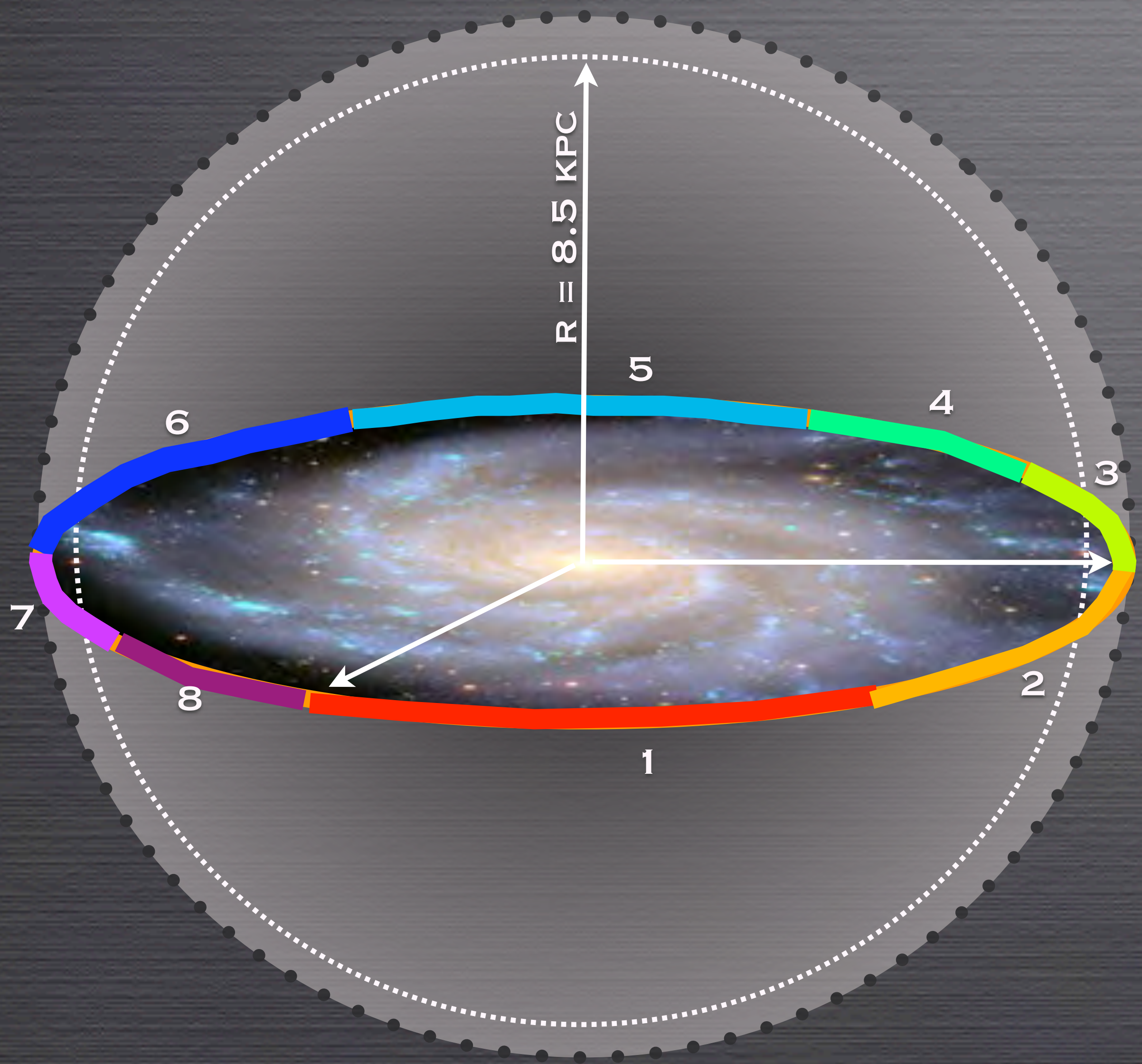

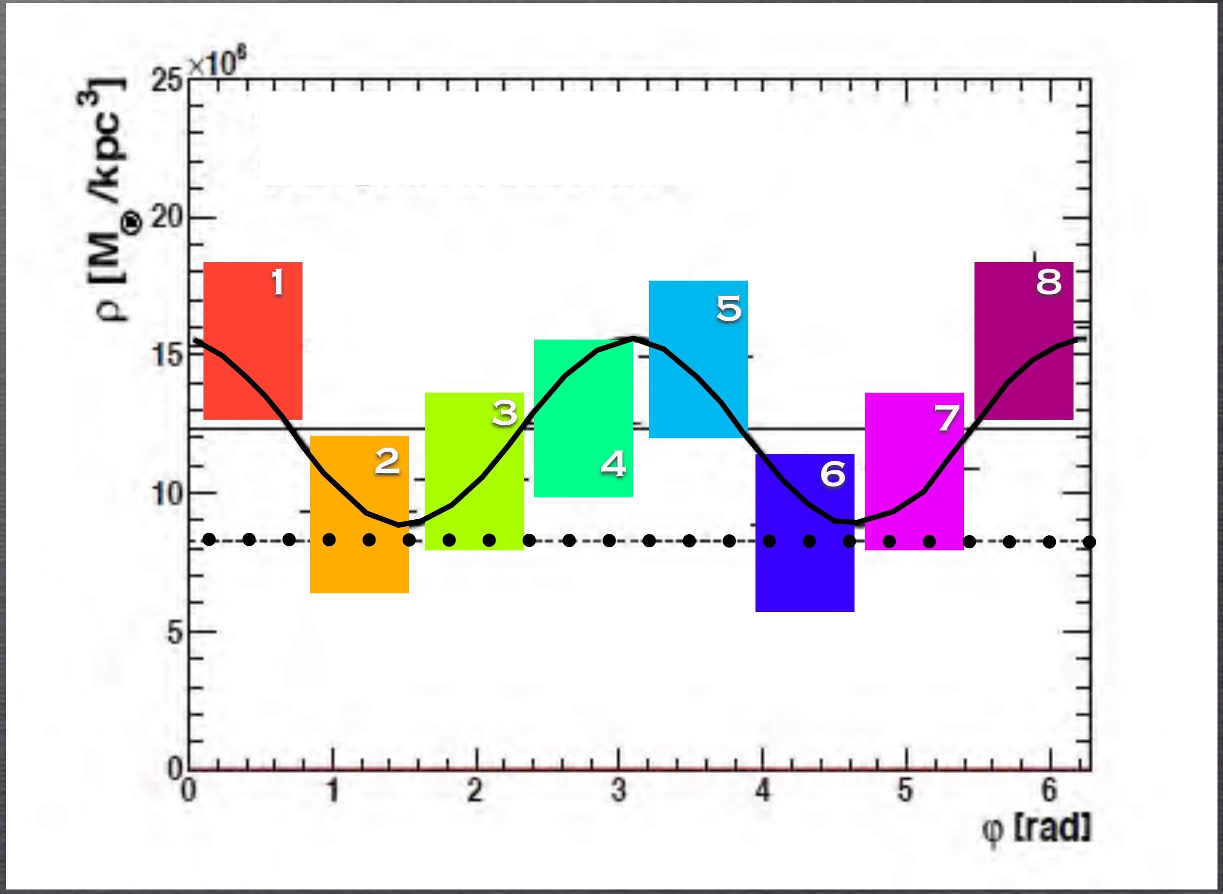

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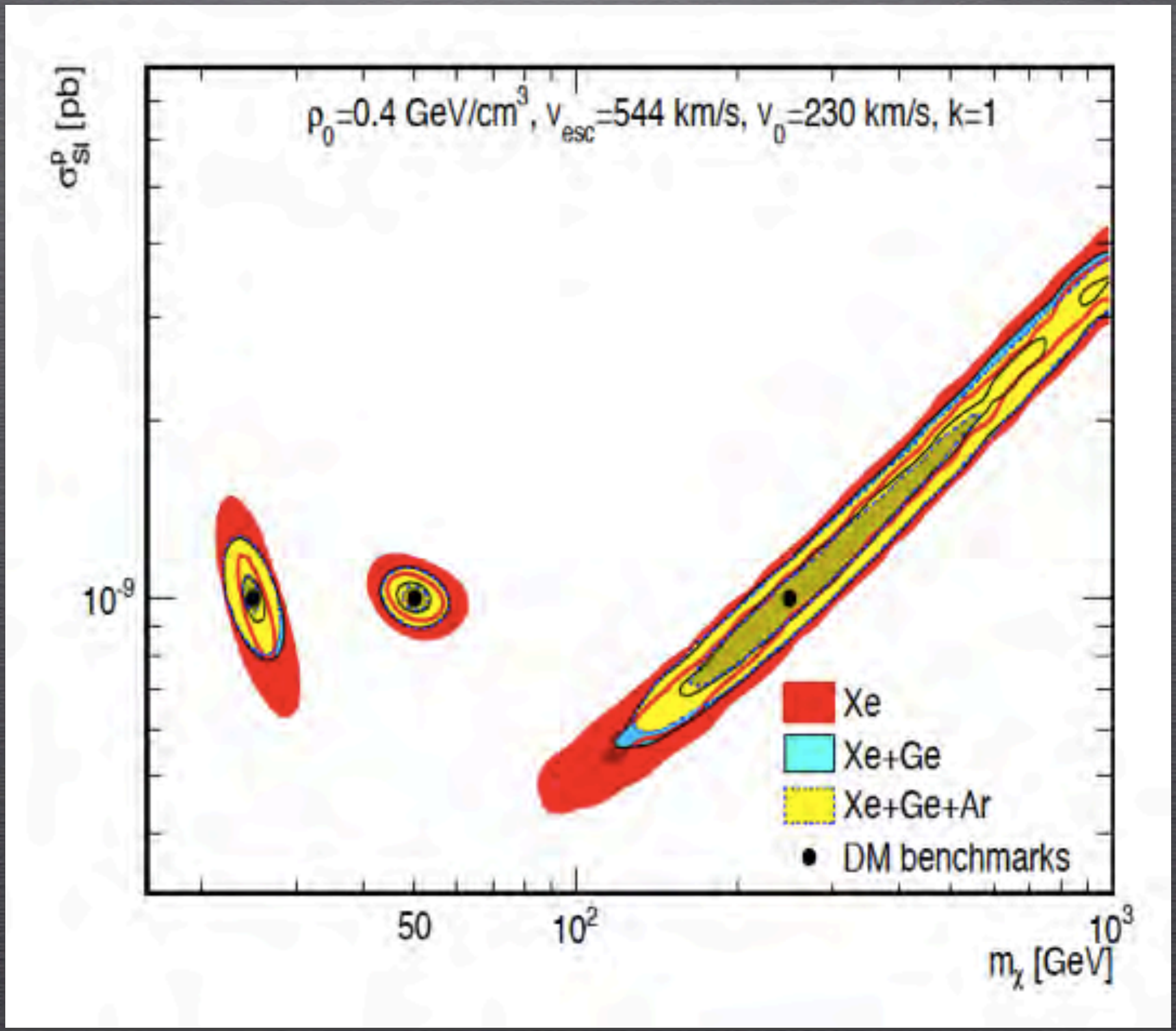
Complementarity of DD targets



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

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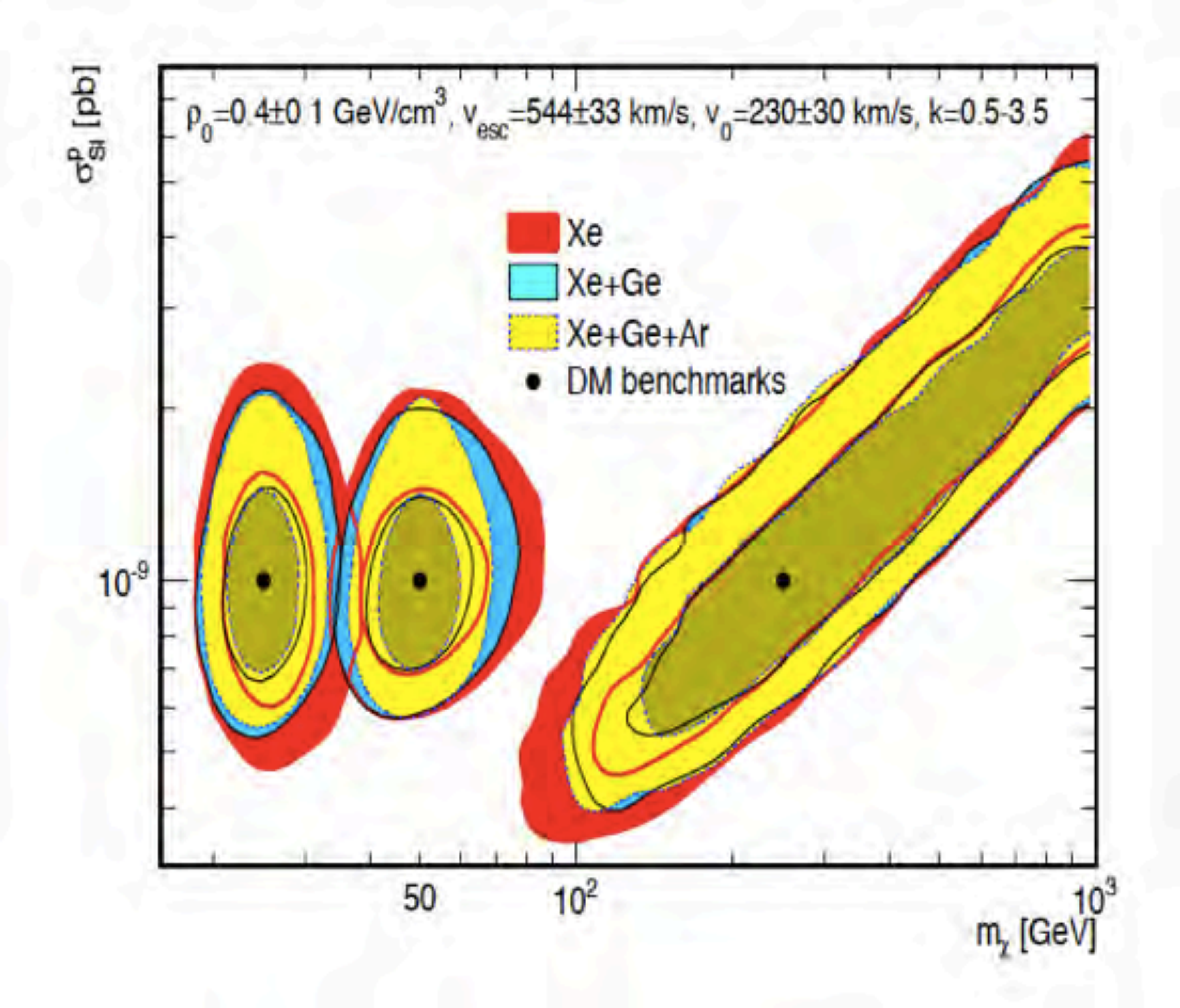

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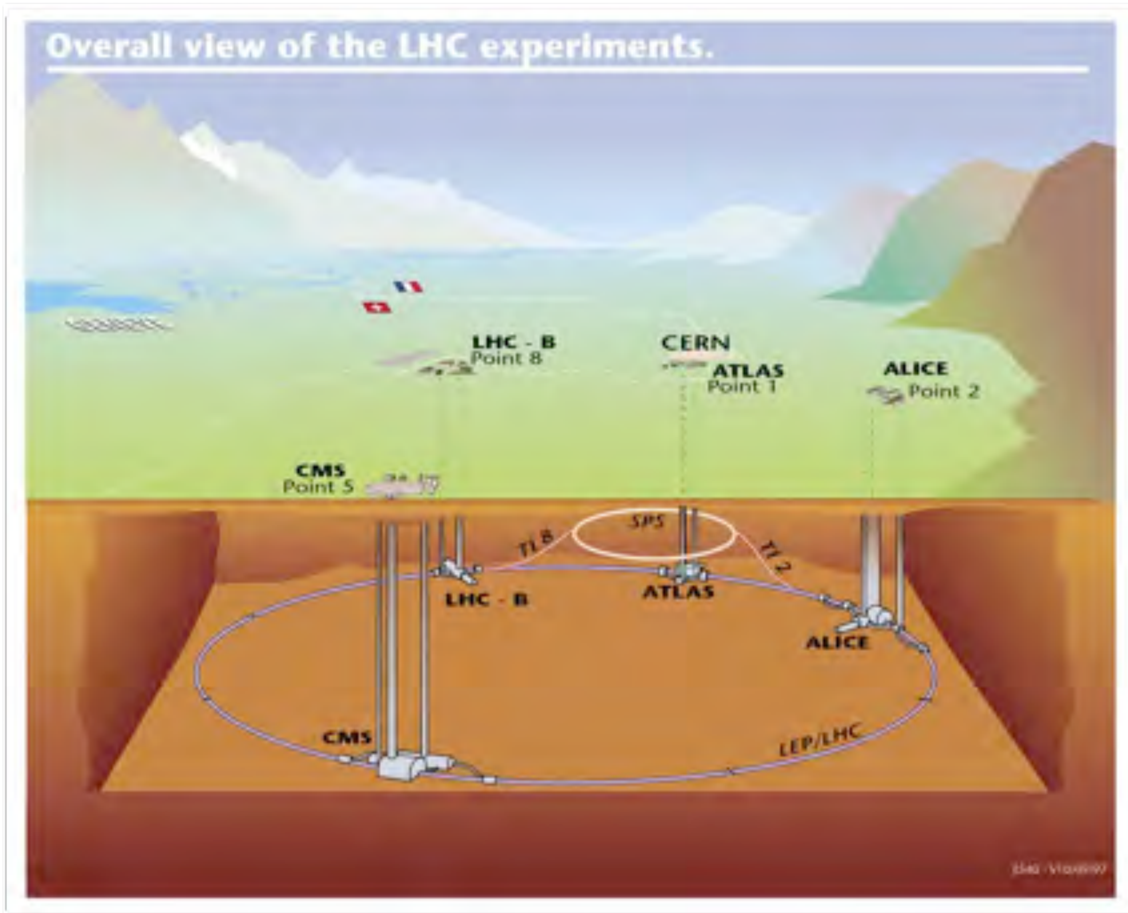
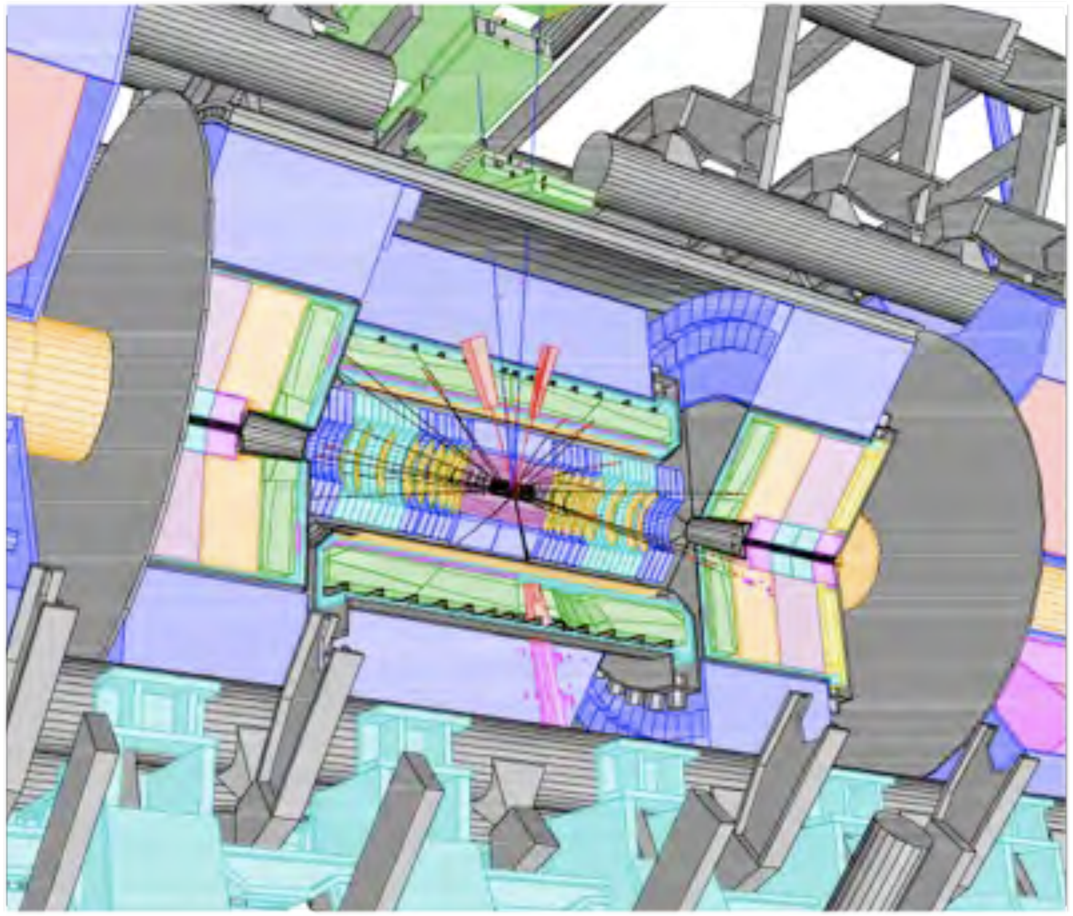
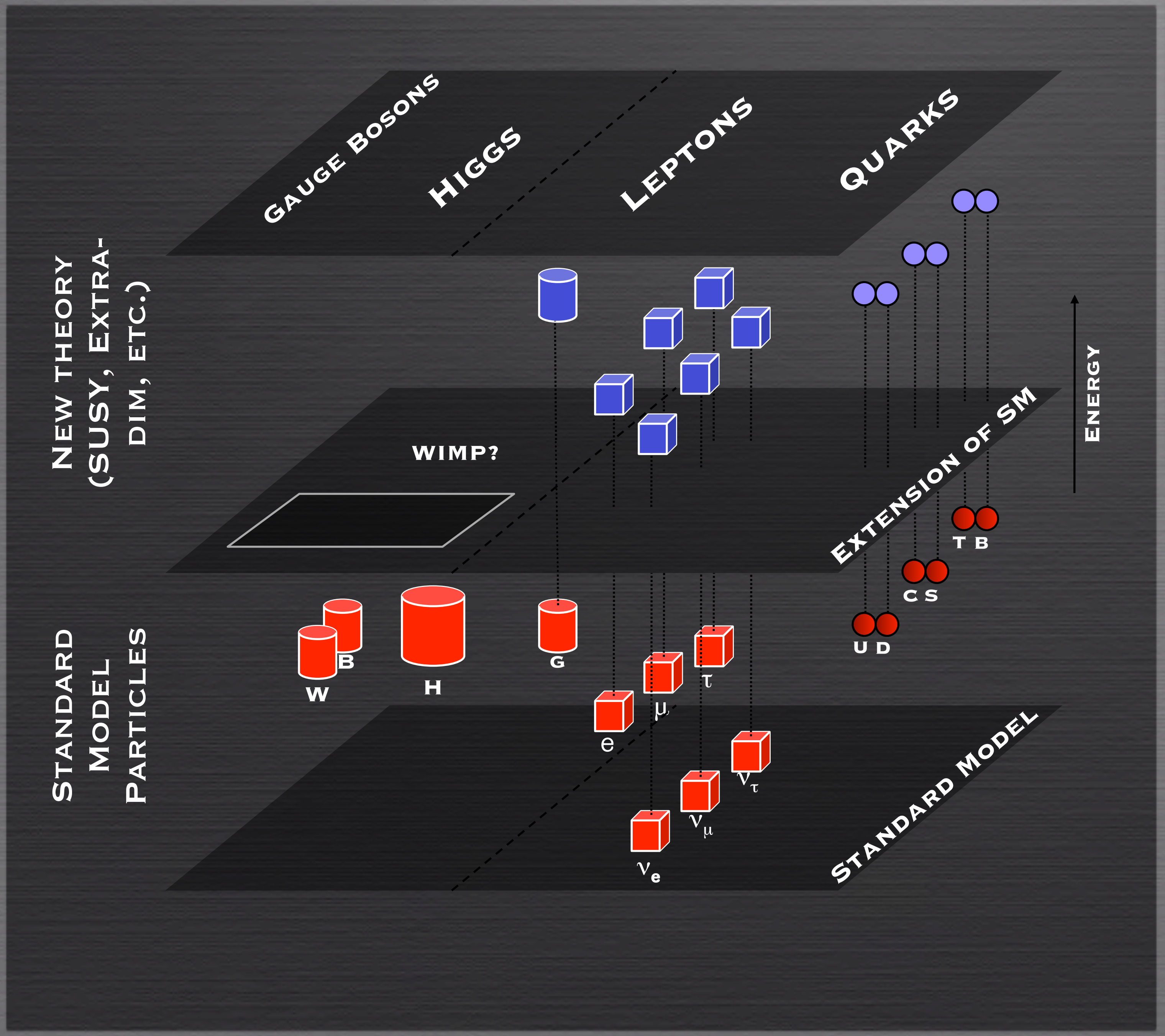
Dark Matter Searches at the LHC





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

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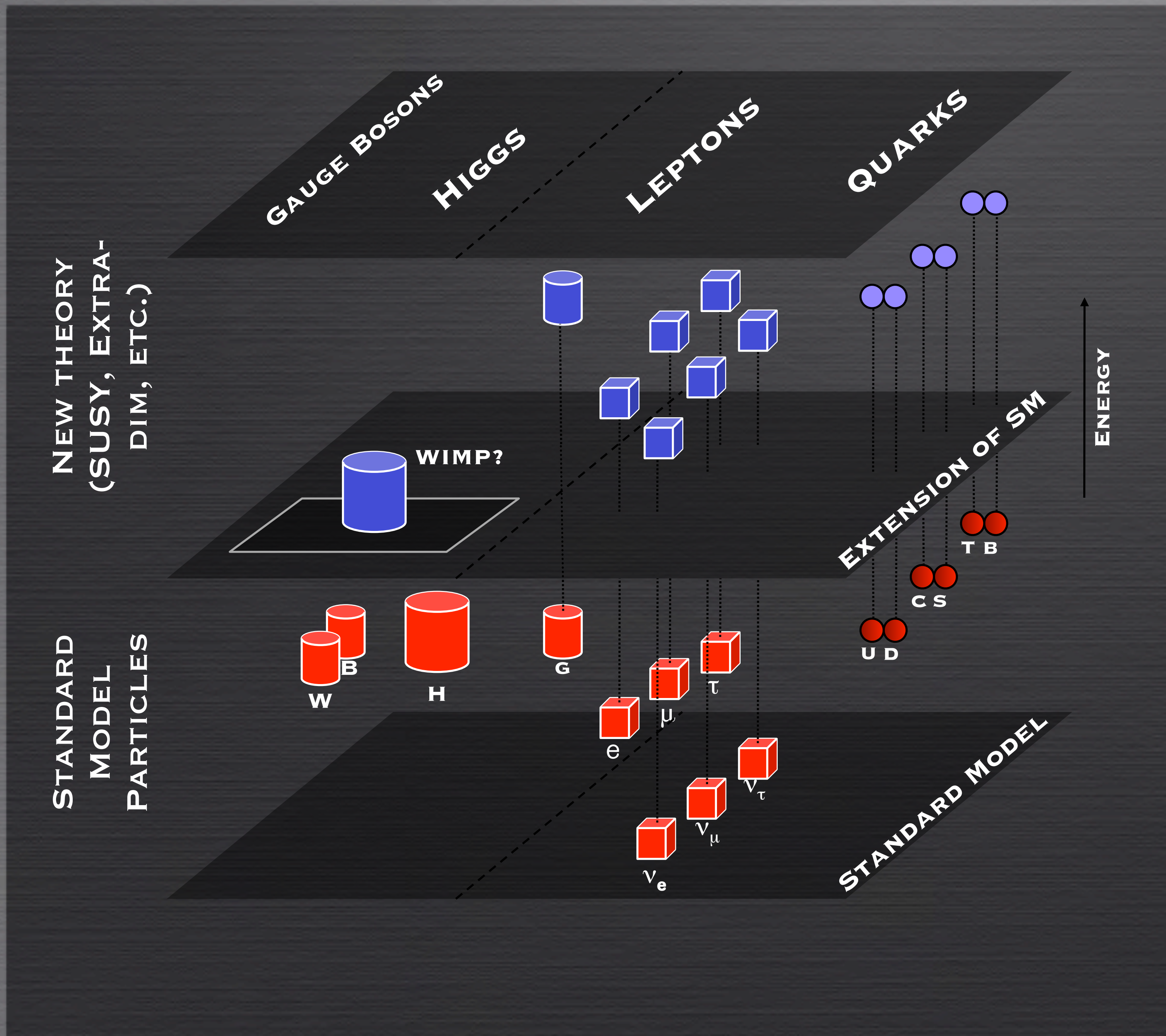

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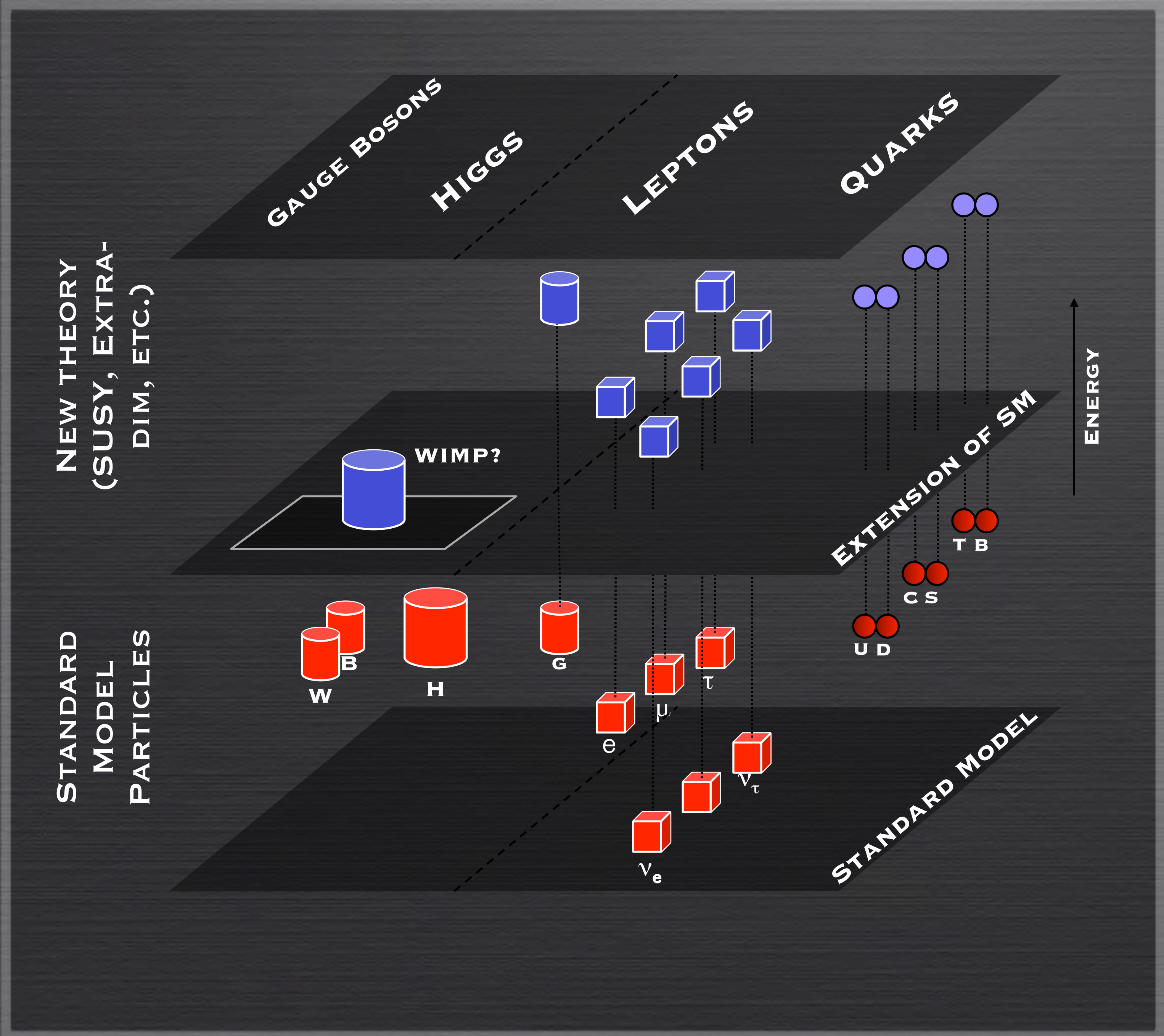
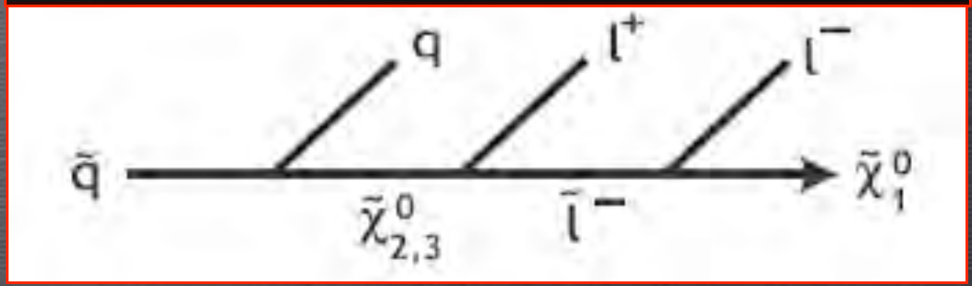


Search at LHC for processes like e.g.



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:

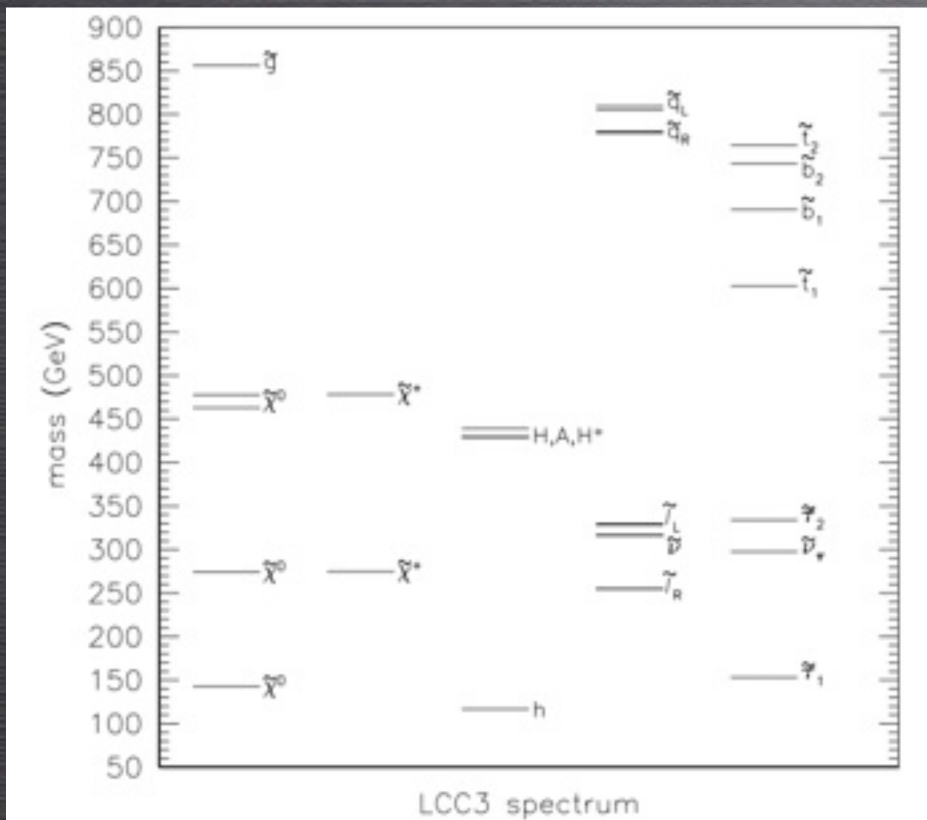
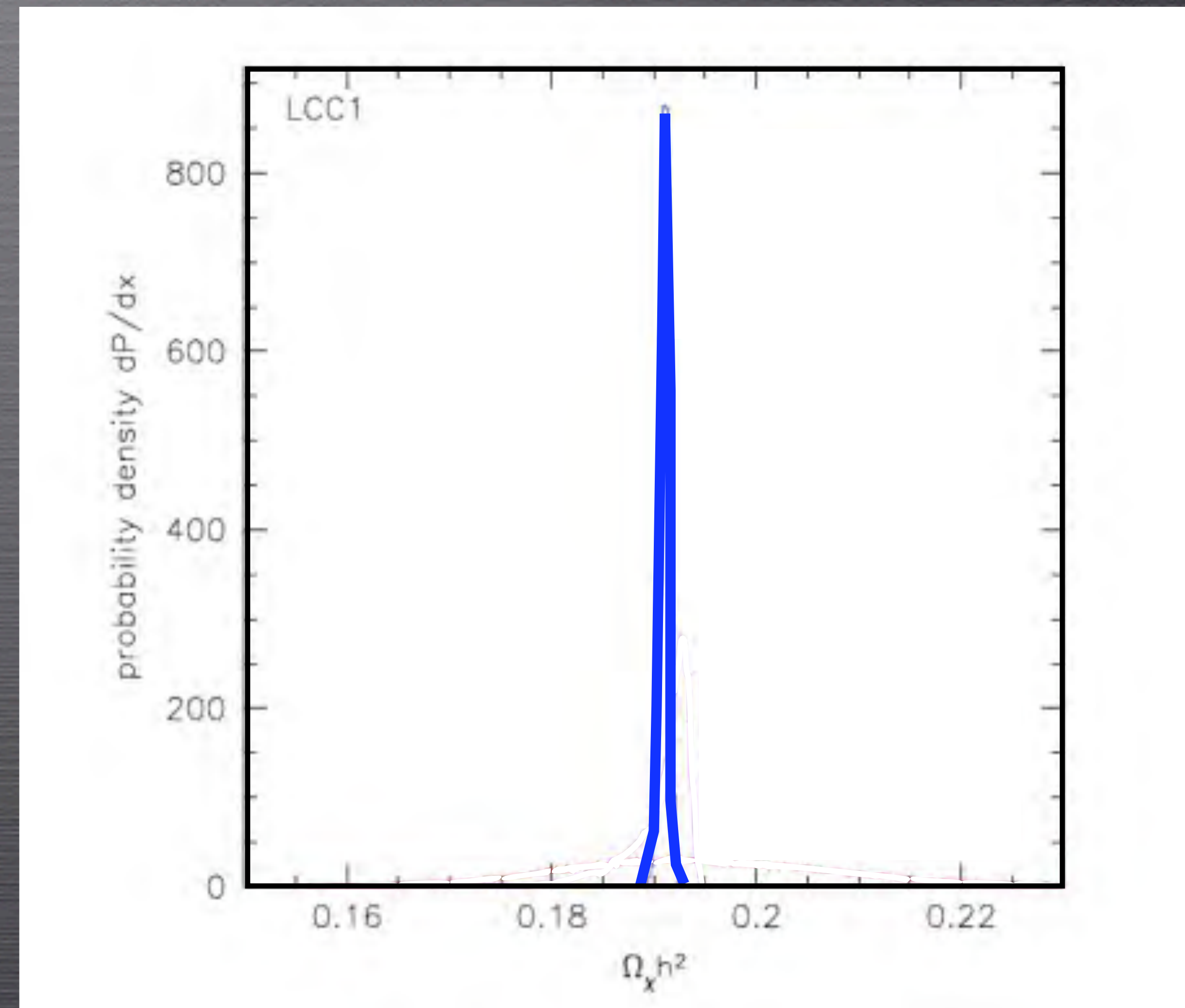
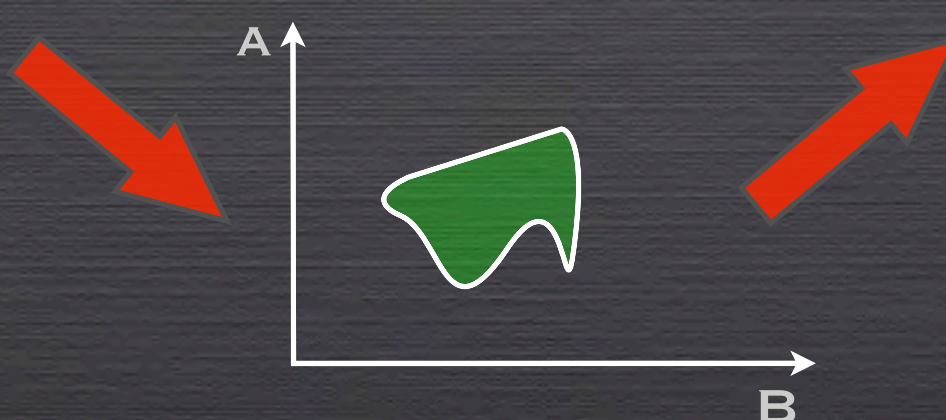


FIG. 34. Particle spectrum for point LCC3. The stau-neutralino mass splitting is 10.8 GeV. The lightest neutralino is predominantly *b*-ino, the second neutralino and light chargino are predominantly *W*-ino, and the heavy neutralinos and chargino are predominantly Higgsino.



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



Example of Inverse problem at LHC

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

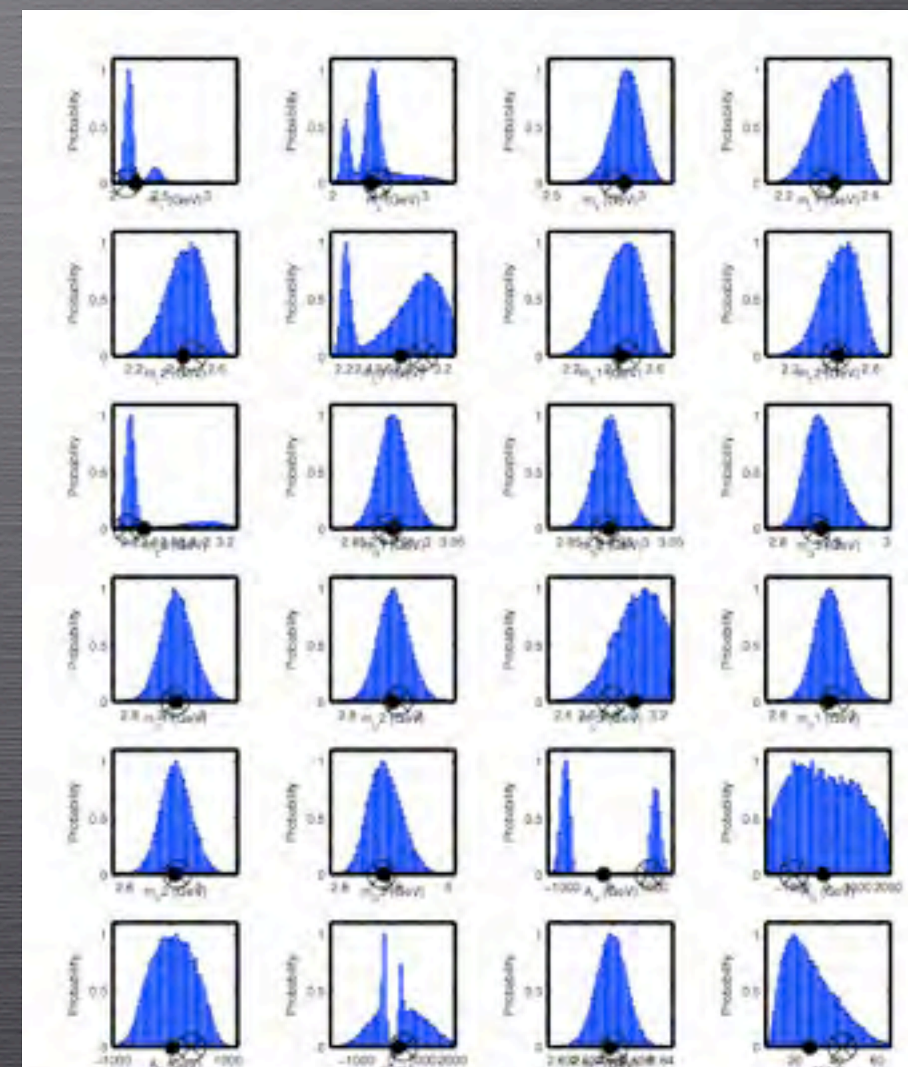
Mass	Benchmark value, μ	LHC error, σ
$m(\tilde{\chi}_1^0)$	139.3	14.0
$m(\tilde{\chi}_2^0)$	269.4	41.0
$m(\tilde{e}_R)$	257.3	50.0
$m(\tilde{\mu}_R)$	257.2	50.0
$m(h)$	118.50	0.25
$m(A)$	432.4	1.5
$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0)$	16.4	2.0
$m(\tilde{u}_R)$	859.4	78.0
$m(\tilde{d}_R)$	882.5	78.0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

- 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

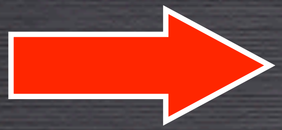
$$p(\mathbf{x}|\mathbf{d}) = \frac{p(\mathbf{d}|\mathbf{x})p(\mathbf{x})}{p(\mathbf{d})},$$

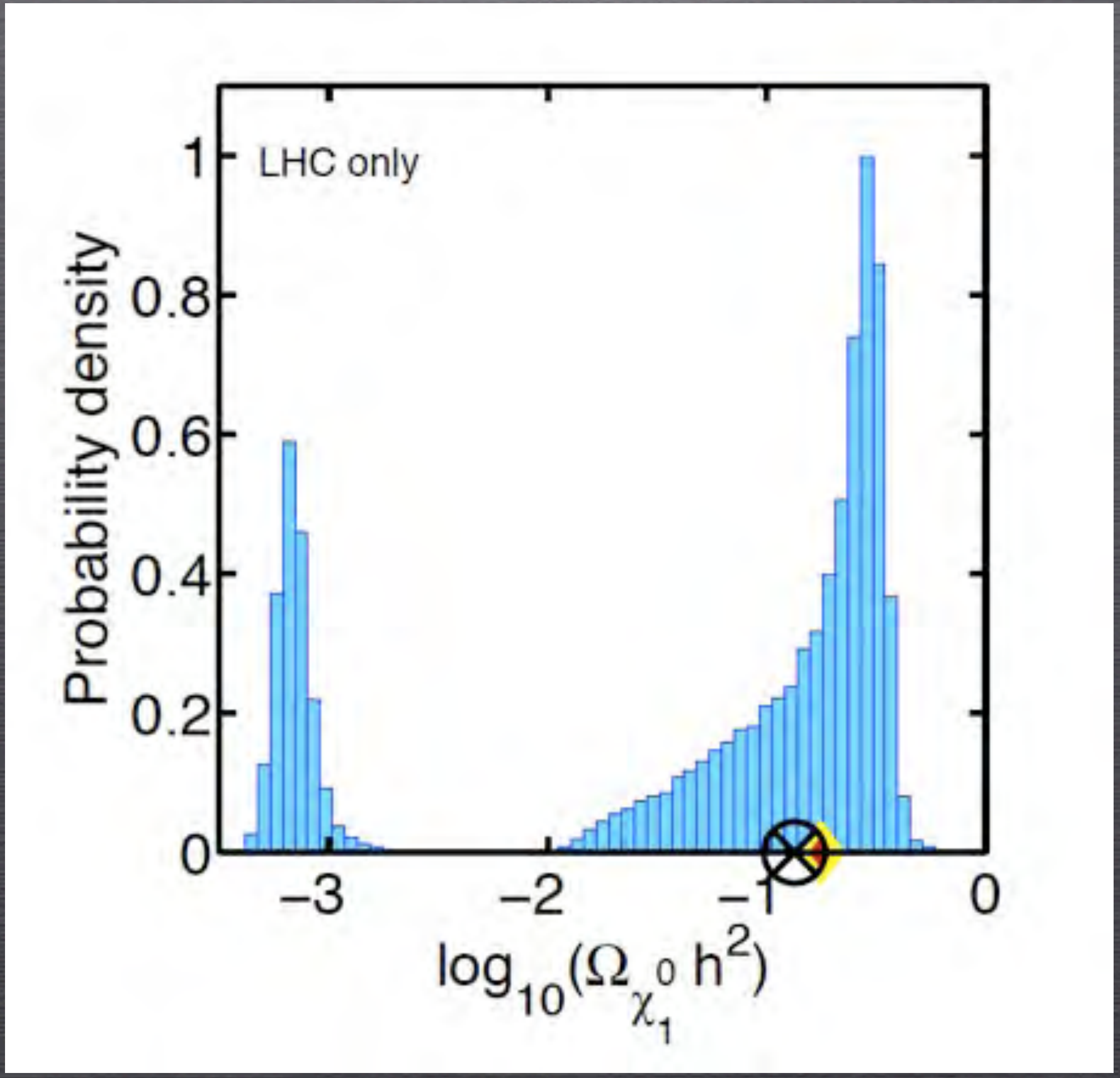
MCMC as implemented in the SuperBayes code



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

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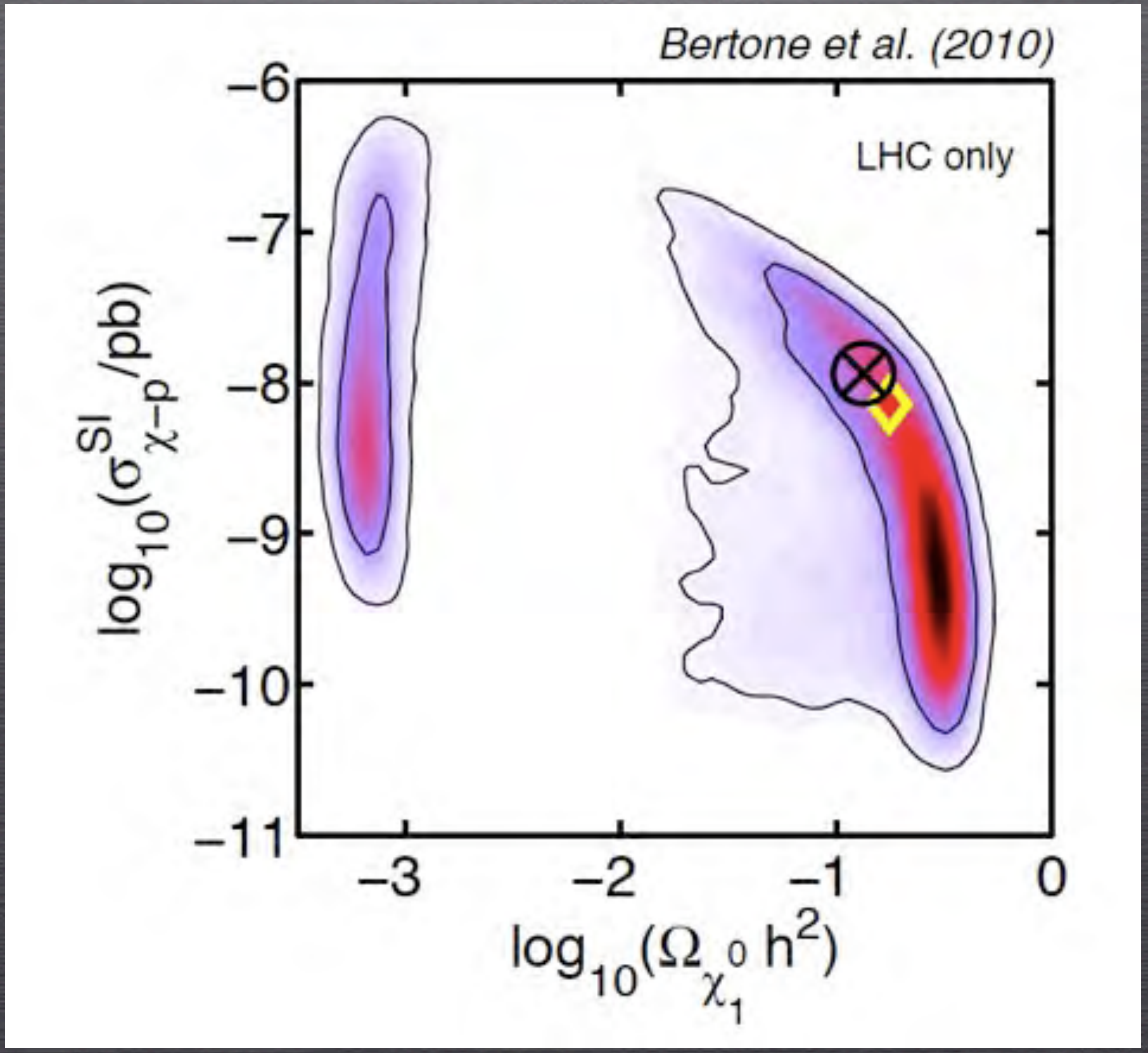
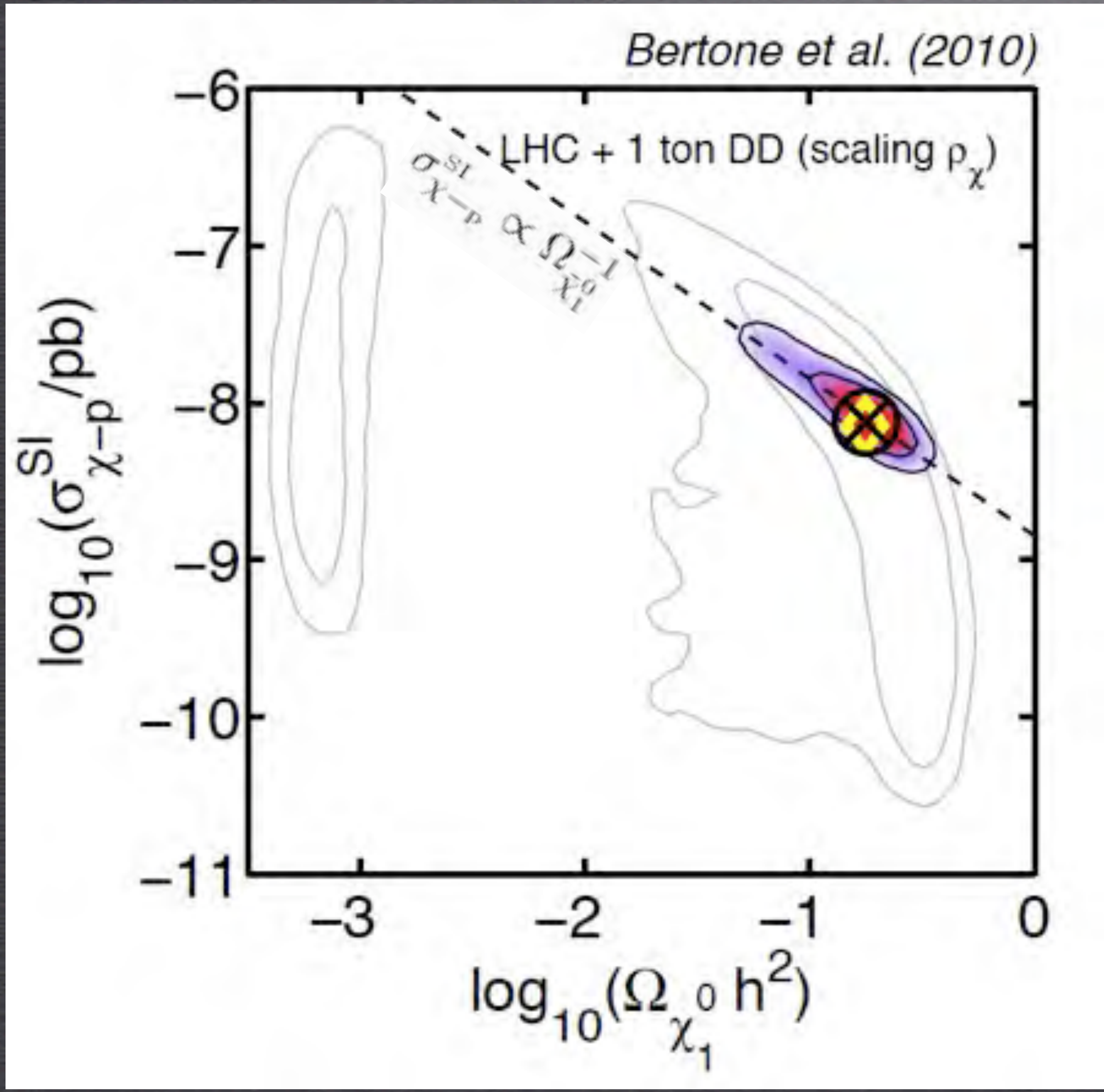


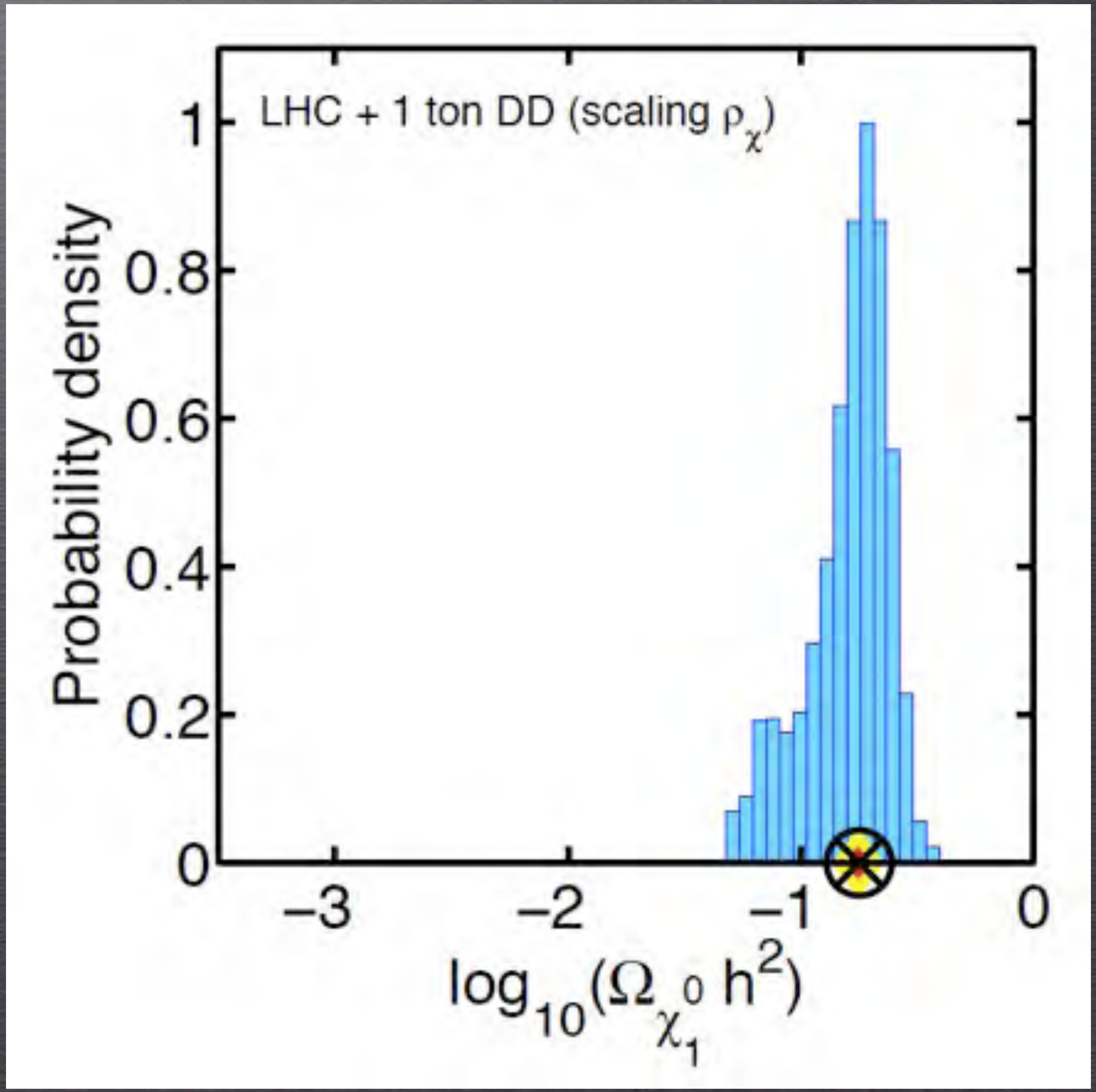
GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta, 2010

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?

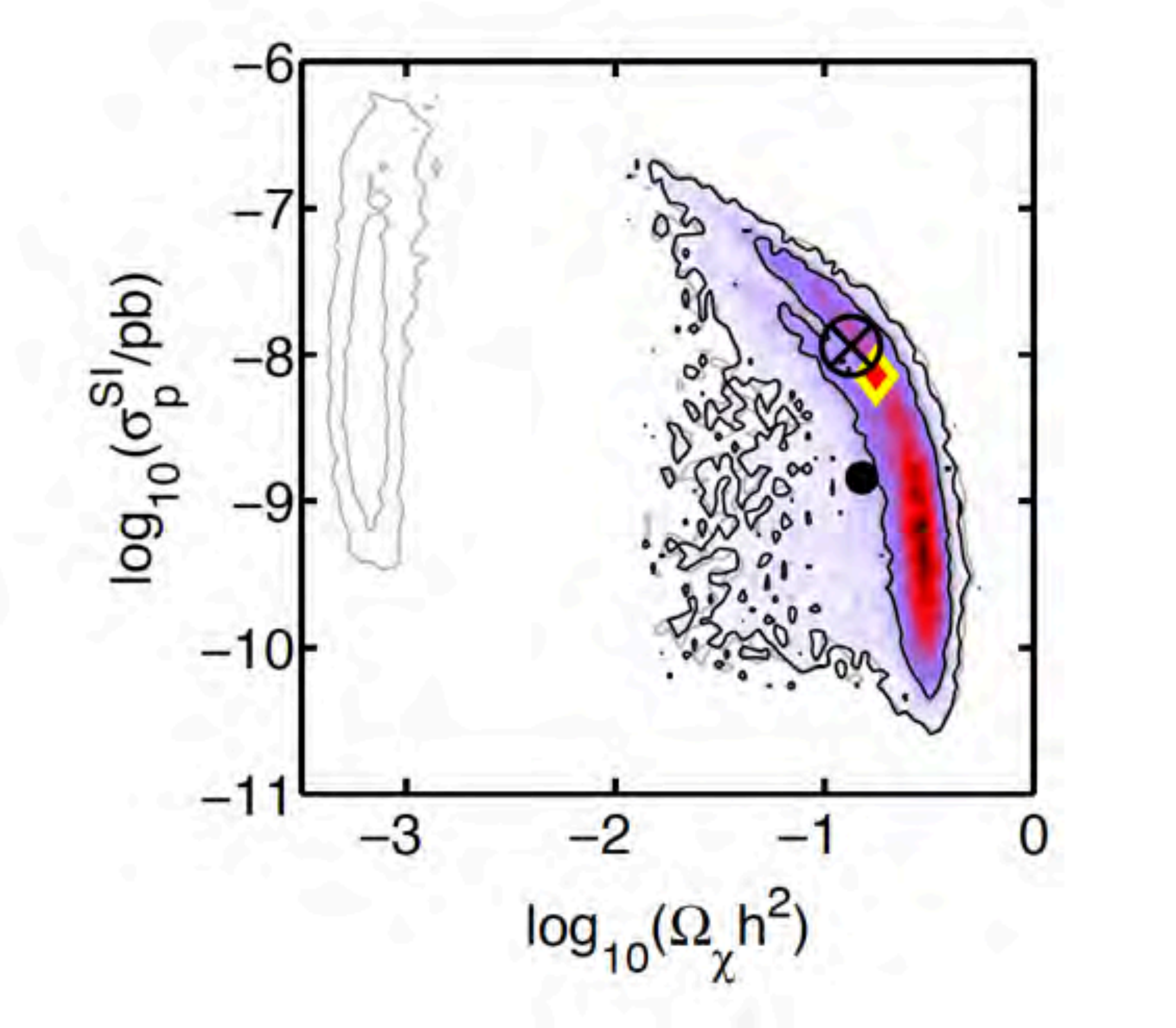
LHC + ID

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

Conclusions

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

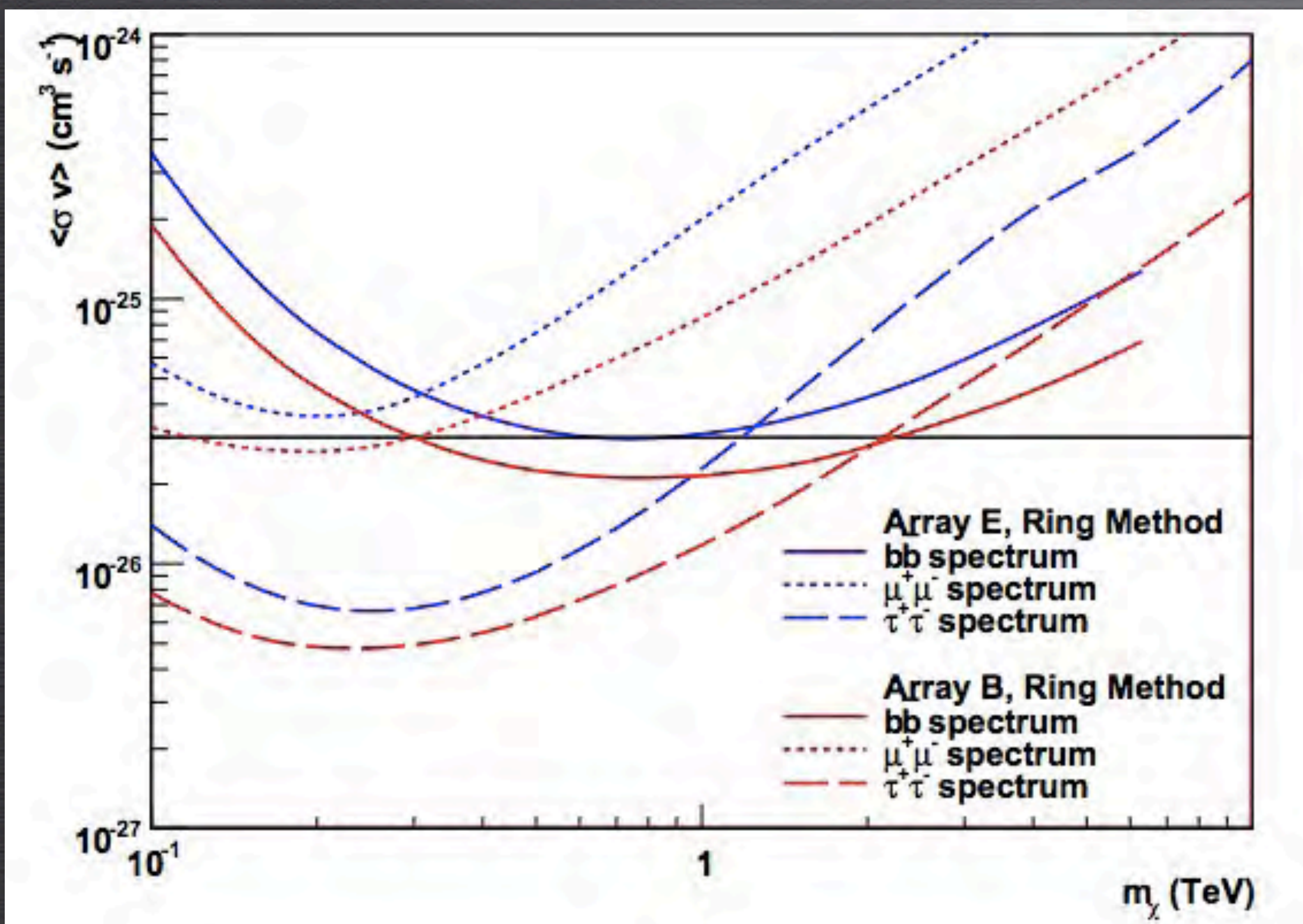
- DM *Indirect Detection* more and more constrained, but detection still possible

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

- LHC is running! Direct and indirect searches likely necessary to <u>identify</u> DM

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

Prospects for observing DM annihilation with CTA



	LST	MST	SST
A	3 (5°)	41 (8°)	-
B	5 (5°)	37 (8°)	-
C	-	29 (8°)	26 (10°)†
D	-	41 (7.4°)	16 (10°)†
E	4 (4.6°)	23 (8°)	32 (10°)
F	6 (4.8°)	29 (6.3°)	-
G	6 (5°)	9 (8°)	16 (10°)
H	-	25 (7°)	48 (10°)
I	3 (4.9°)	18 (8°)	56 (9°)
J	3 (4.9°)	30 (8°)	16 (9°)†
K	5 (5°)	-	72 (9.5°)
NA	4 (5°)	17 (6°)	-
NB	3 (5°)	17 (6°)	8 (8°)

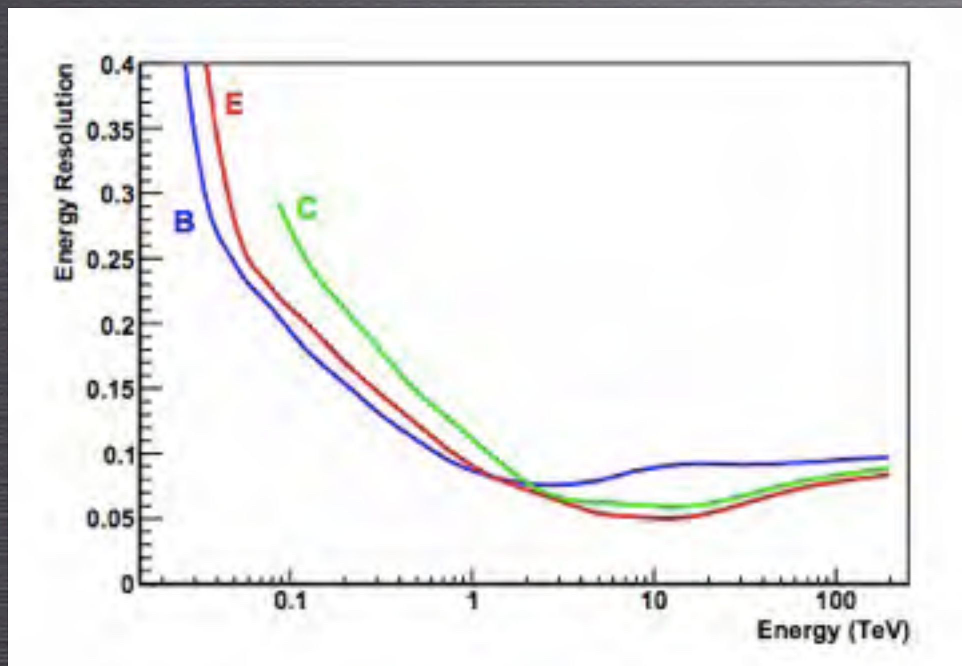
† With wide-field versions of MSTs instead of actual

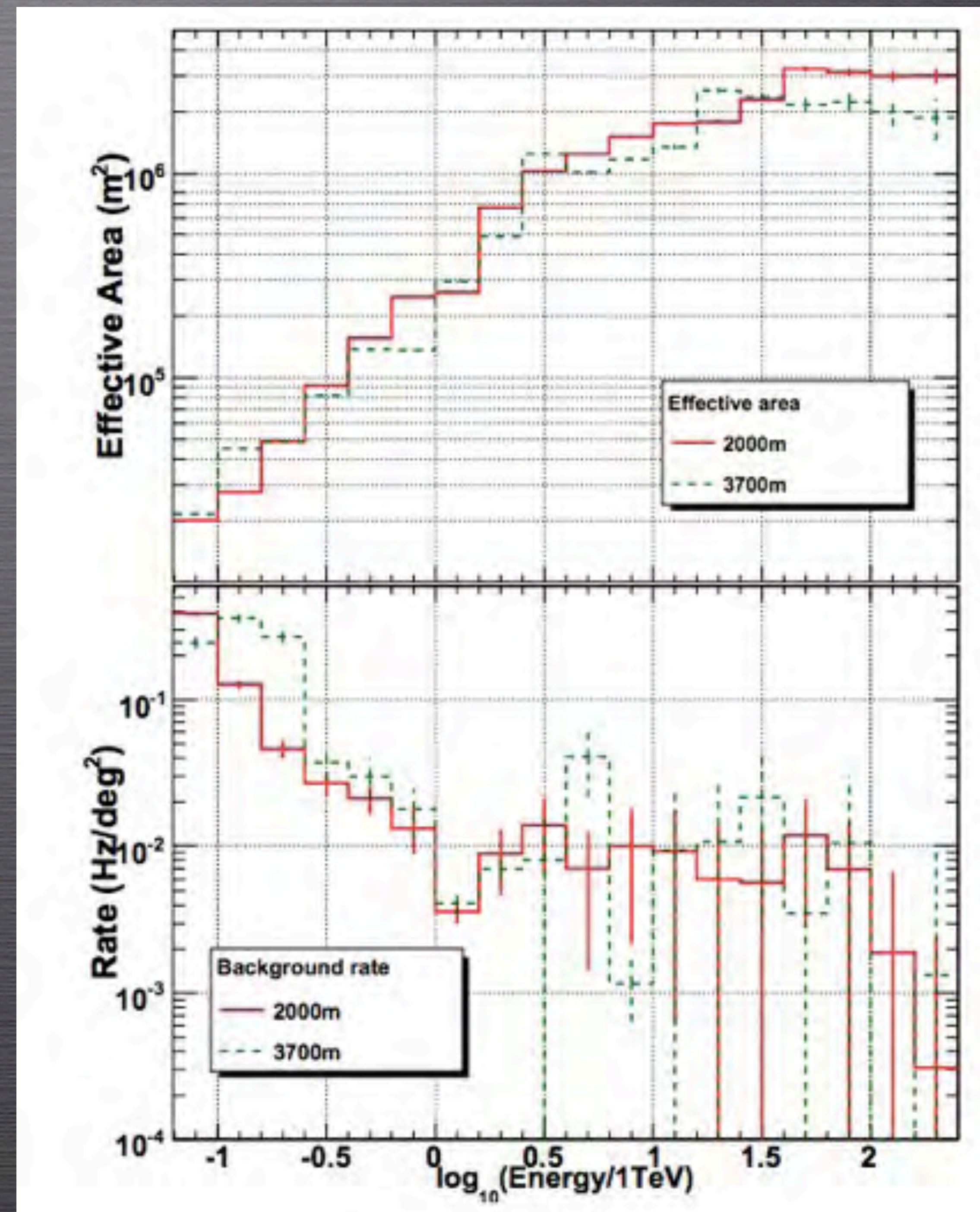
arxiv:1208.5356

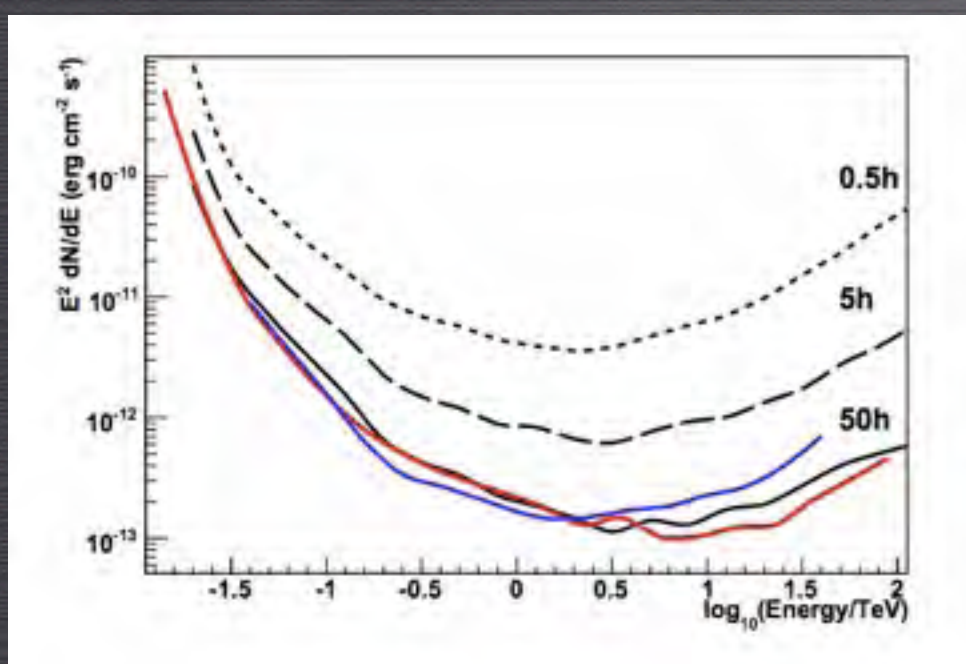
arxiv:1210.3503

The 130 GeV Line

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







http://arxiv.org/abs/1008.3703 http://arxiv.org/abs/1111.2183

The 130 GeV Line

Internal Bremsstrahlung

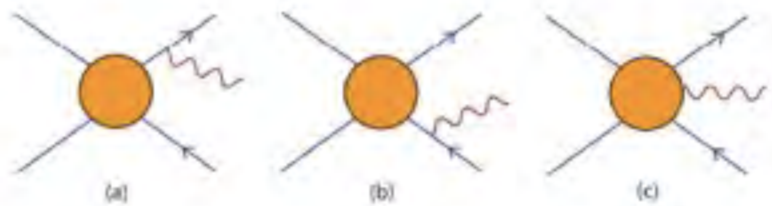
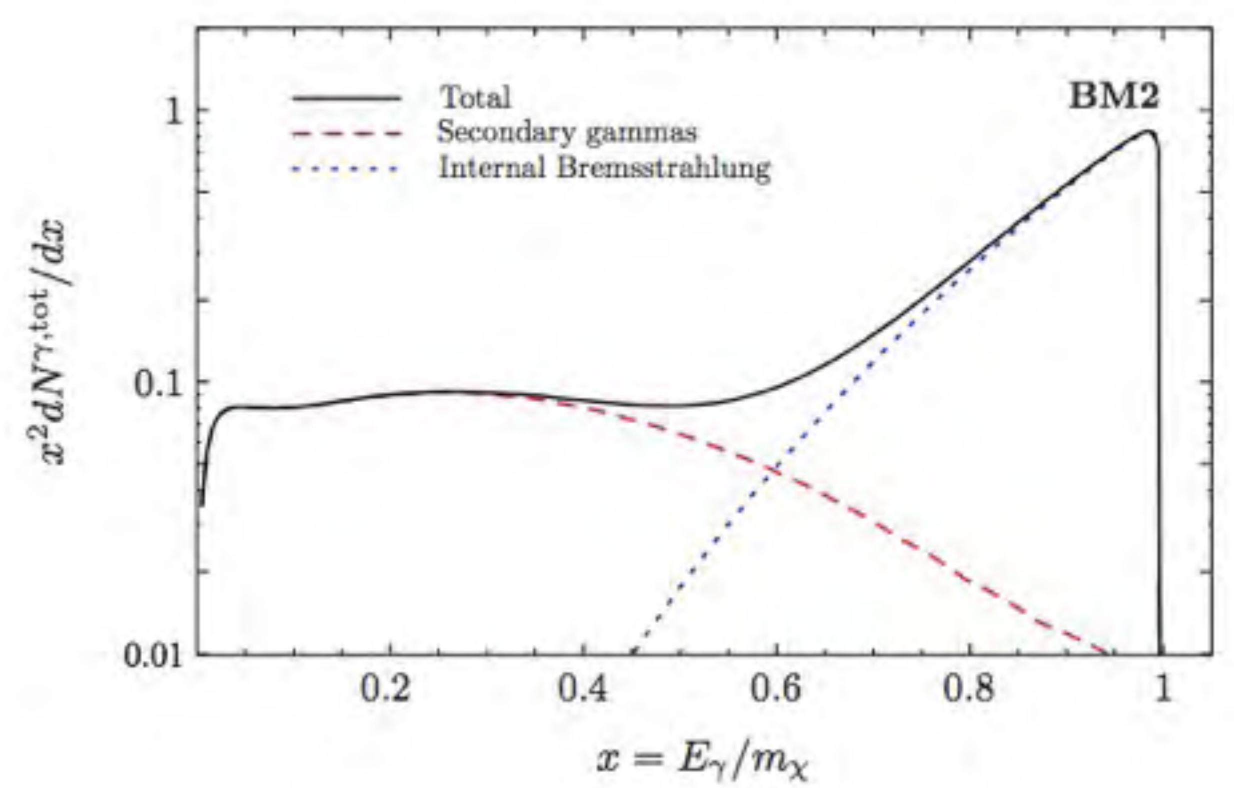


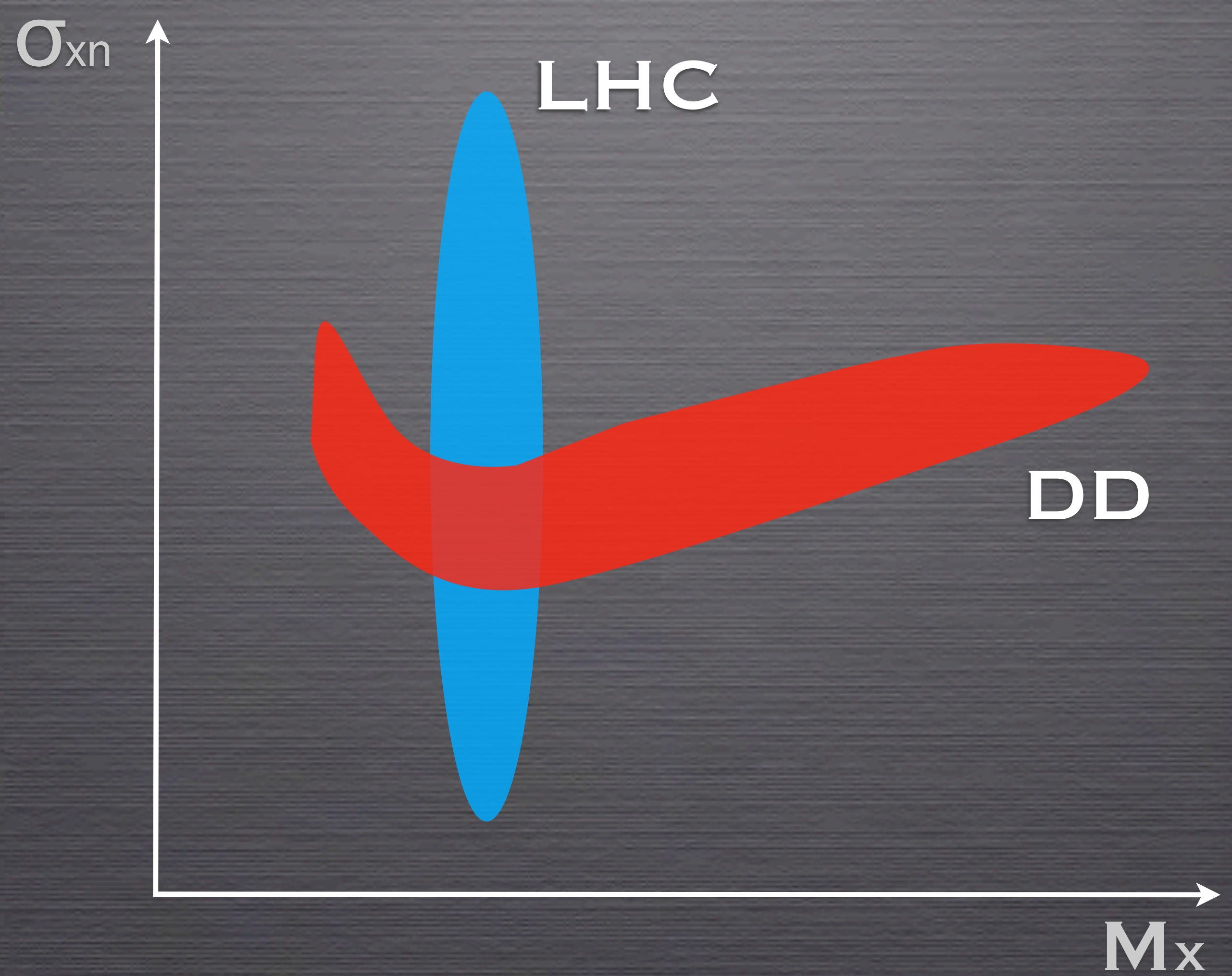
FIG. 1: *Types of diagrams that contribute to the first order QED corrections to WIMP annihilations into a pair of charged particle final states. The leading contributions to diagrams (a) and (b) are universal, referred to as* final state radiation *(FSR), with a spectral distribution which only depends slightly on the final state particle spin and has been calculated, e.g., in [16]. Internal bremsstrahlung from virtual particles (or* virtual internal bremsstrahlung, *VIB) as in diagram (c), on the other hand, is strongly dependent on details of the short-distance physics such as helicity properties of the initial state and masses of intermediate particles.*



Bringmann, Bergstom and Edsjo
http://arxiv.org/pdf/0710.3169v3.pdf

LHC+DD

Combining accelerator and direct searches



LHC+DD

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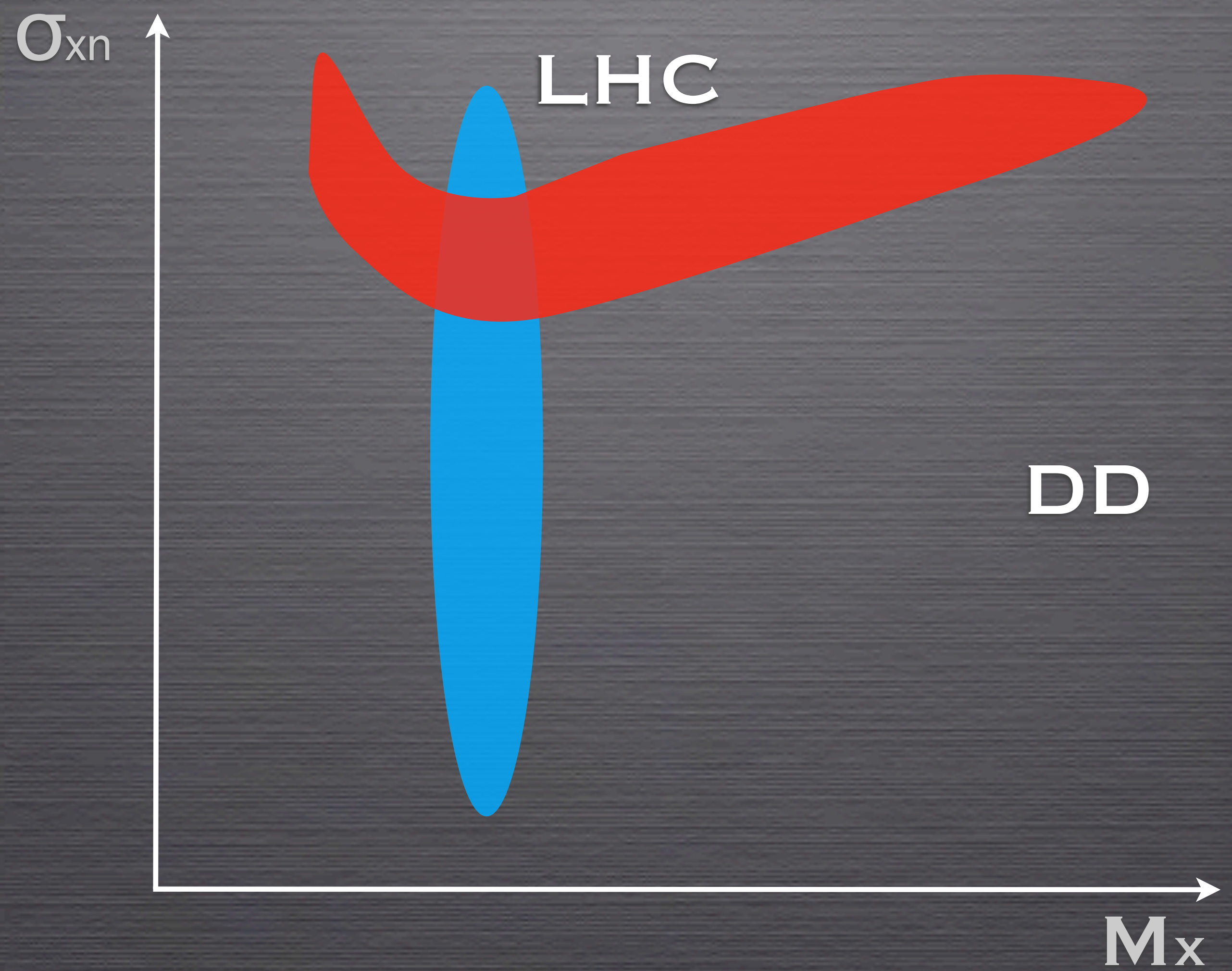

$$\rho_\chi < \rho_{dm}$$

LHC+DD

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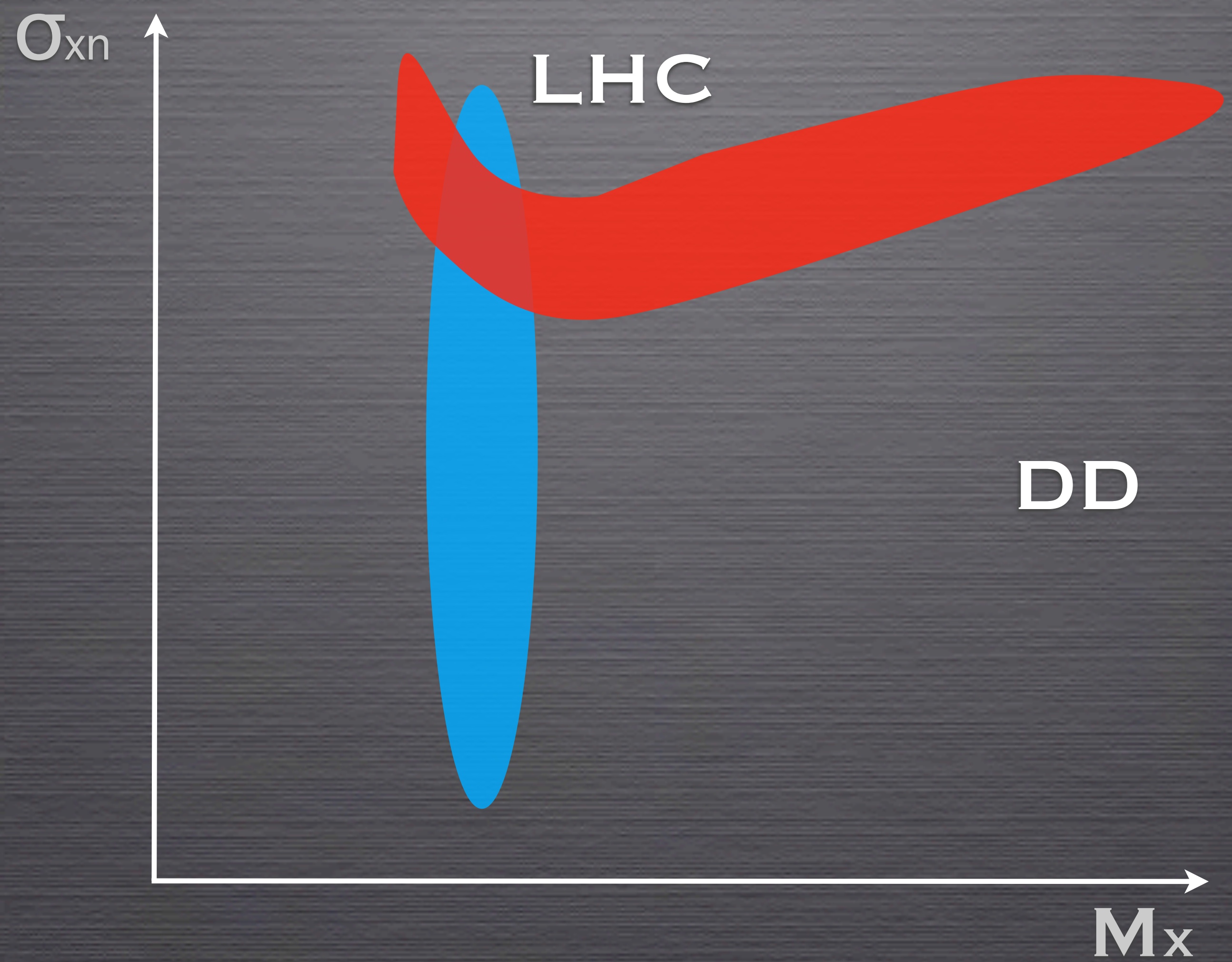

$$\rho_{\chi} < \rho_{dm}$$

$$f(v)$$

LHC+DD

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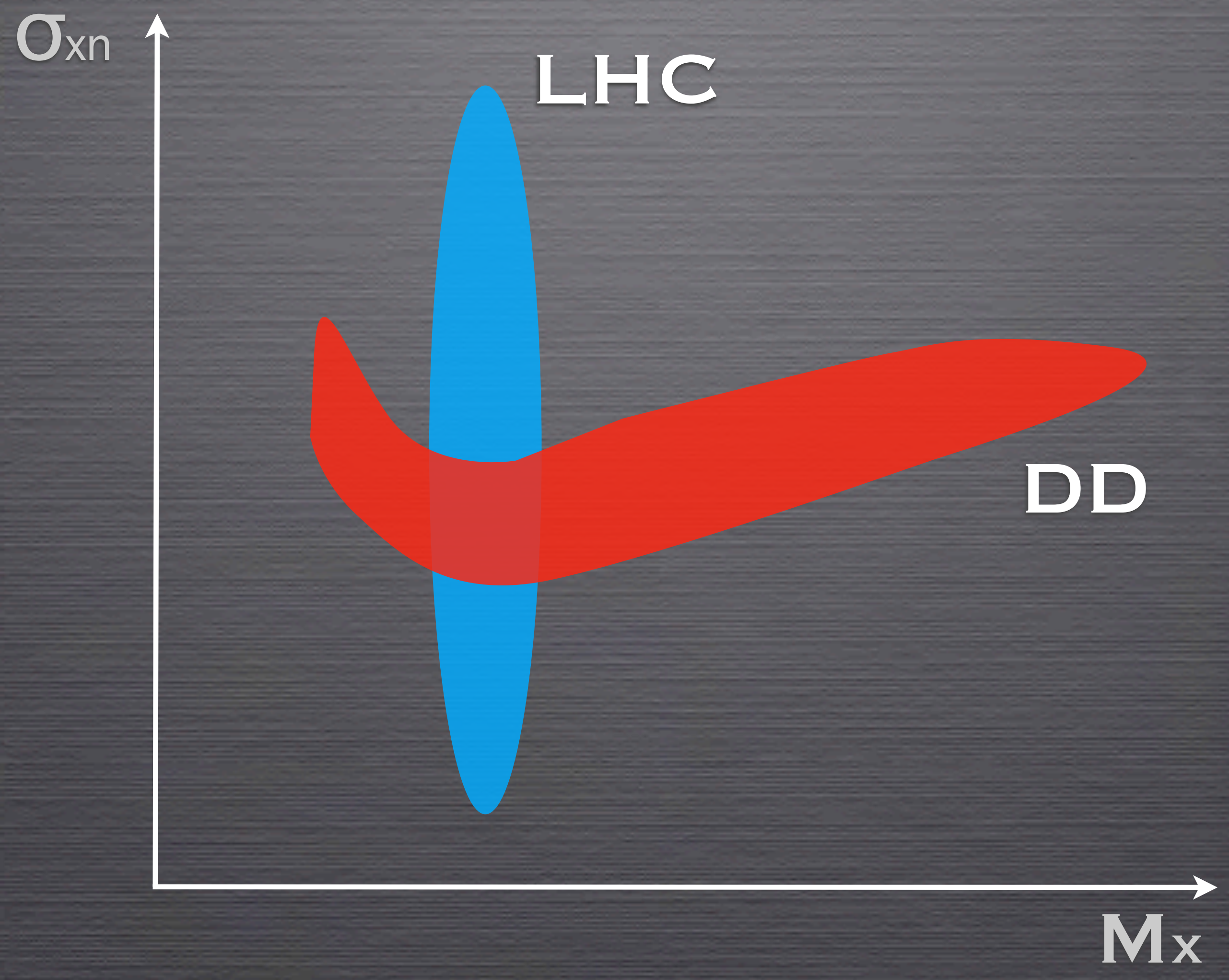


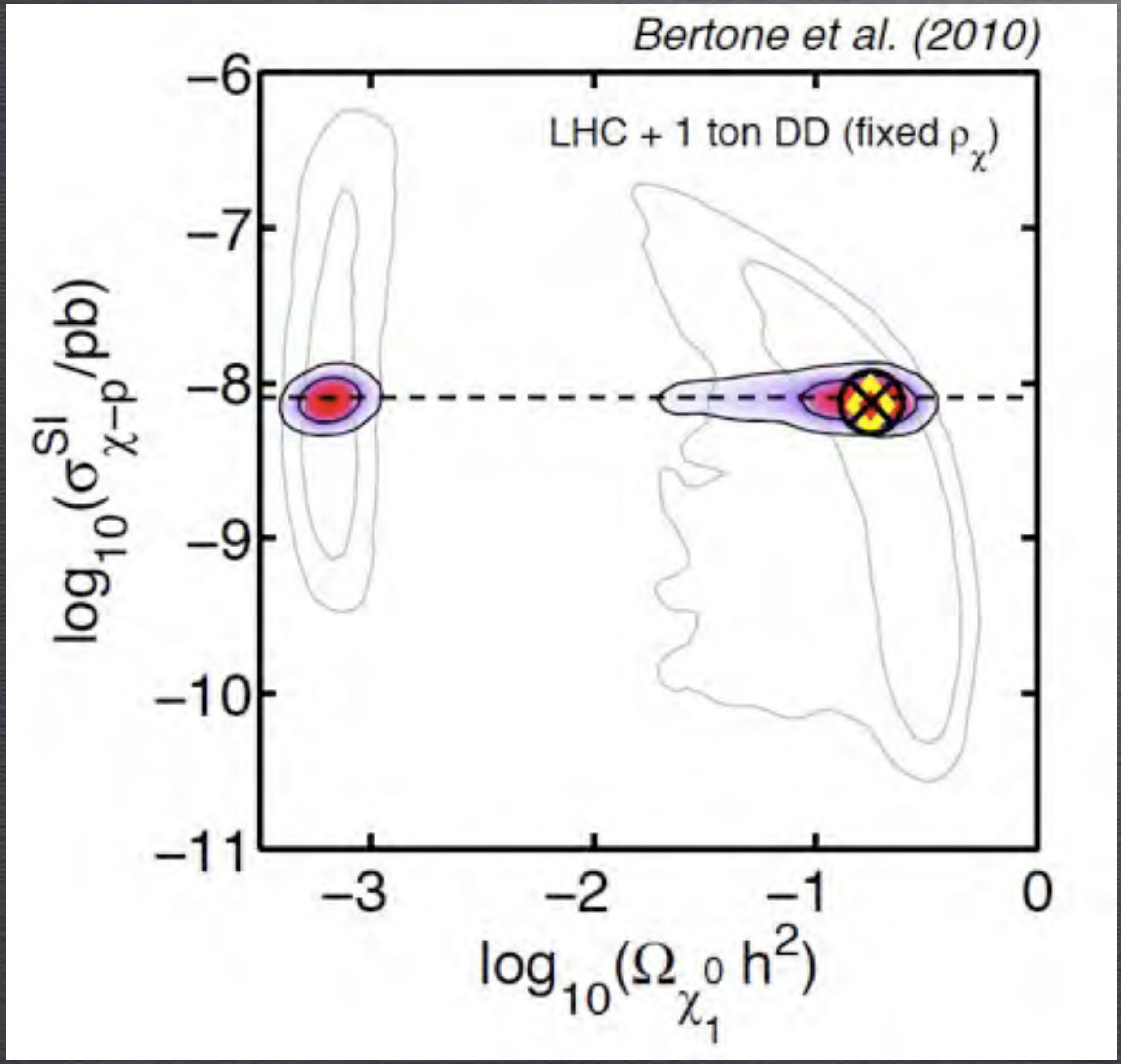
$\rho_\chi < \rho_{dm}$

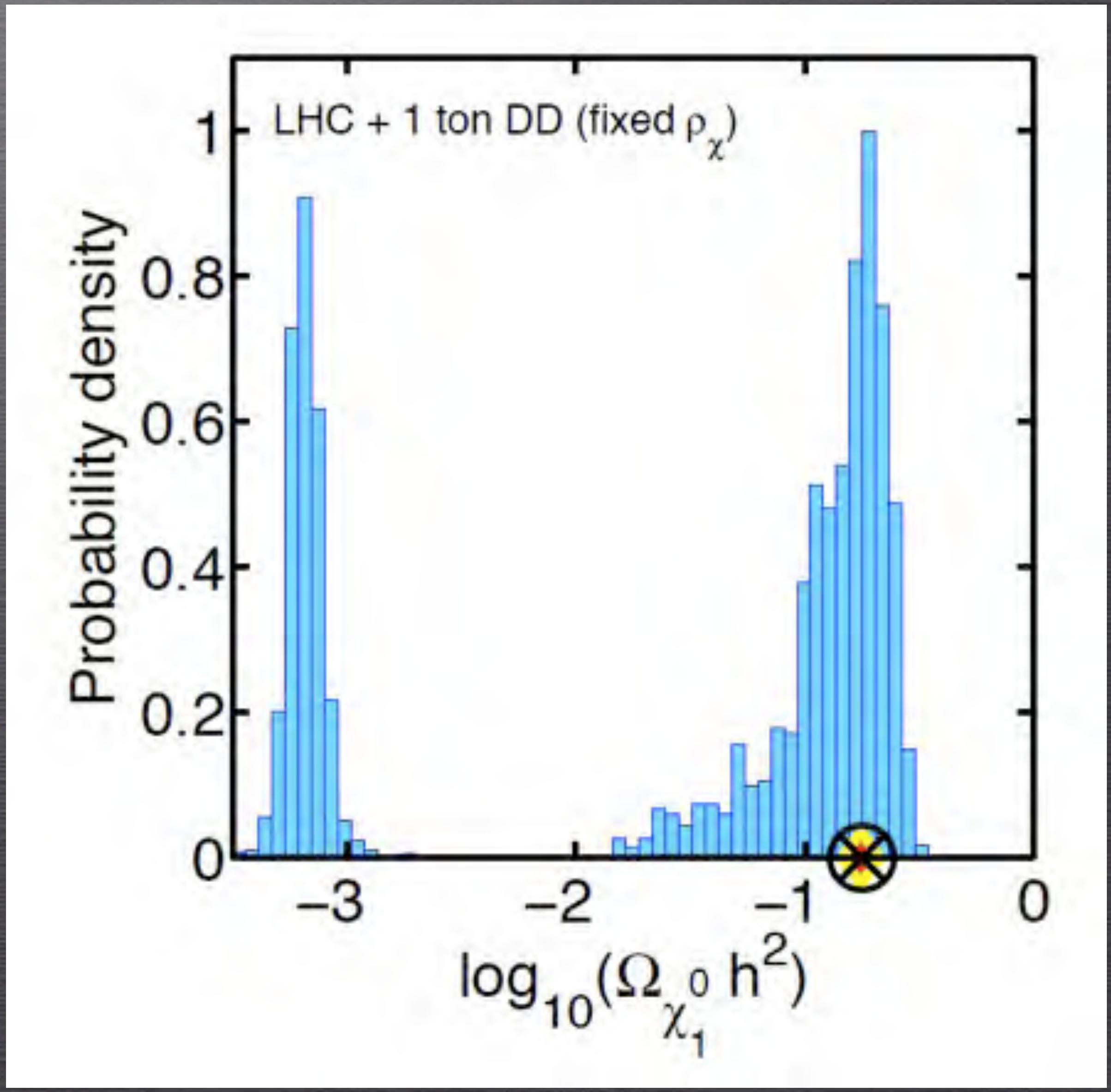
$f(v)$

1st possibility:

"Consistency check"

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





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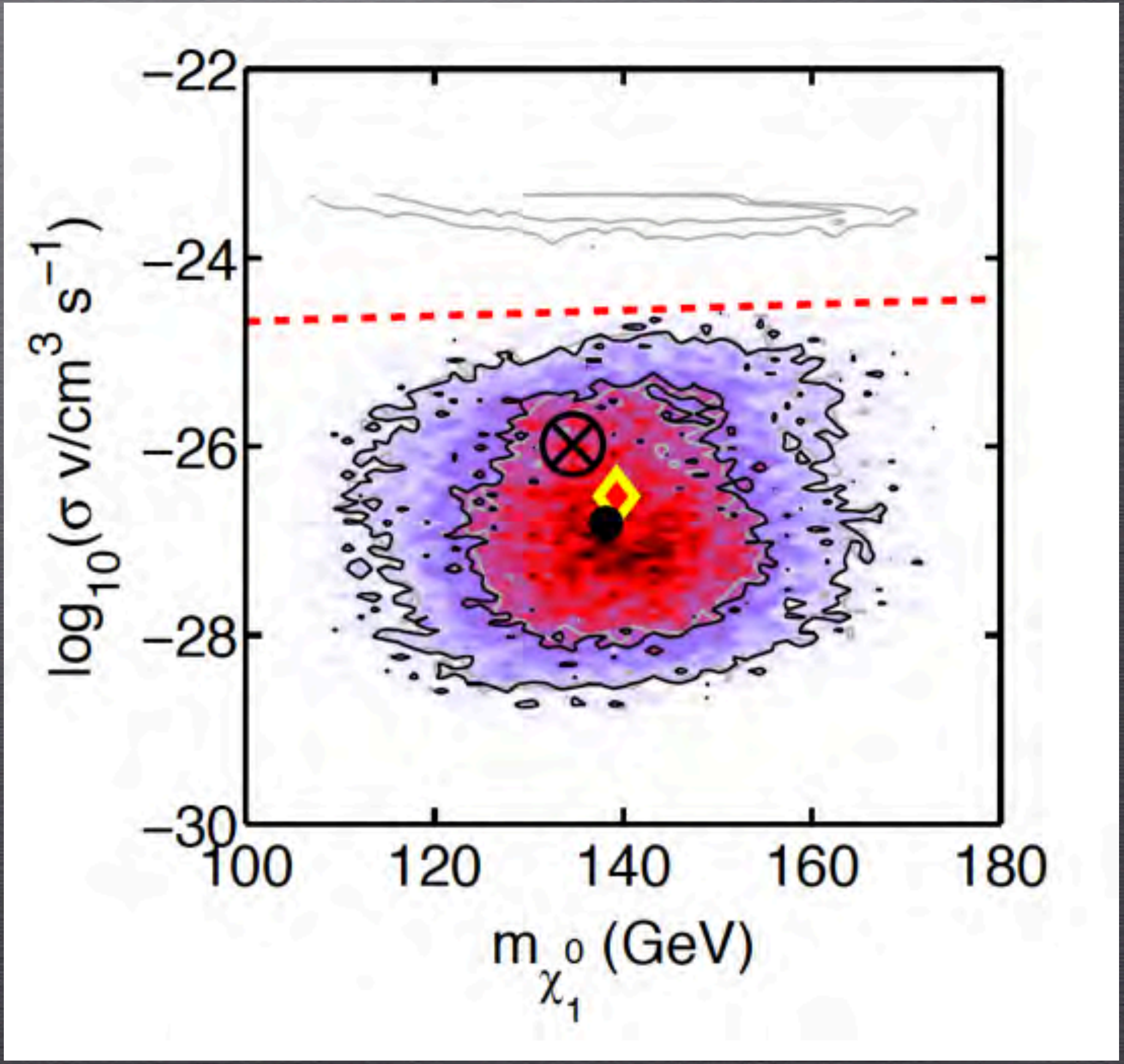
LHC + ID

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



GB, Fornasa, Pieri, Ruiz, Trotta 2011