Identifying Dark Matter

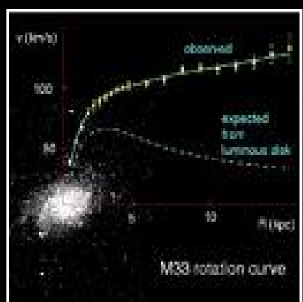
Gianfranco Bertone
GRAPPA Institute, U. of Amsterdam

XV International Workshop on Neutrino Telescopes

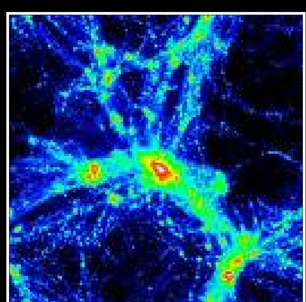
Evidence for Dark Matter

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

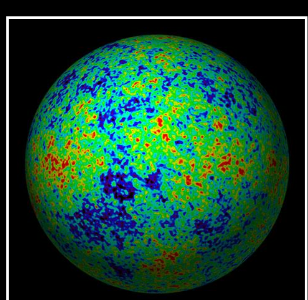
COSMOLOGICAL OBSERVATIONS



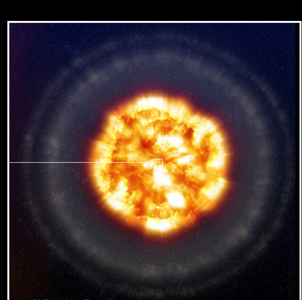
• Rotation Curves



• Clusters of galaxies



•CMB



•Type Ia Supernovae

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

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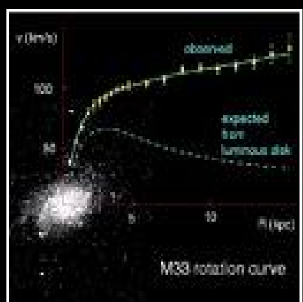

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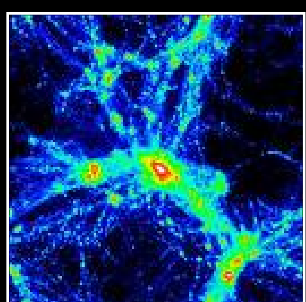

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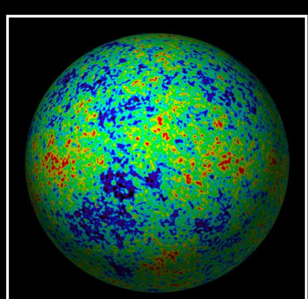
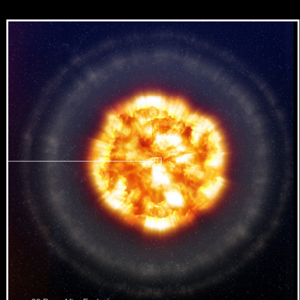
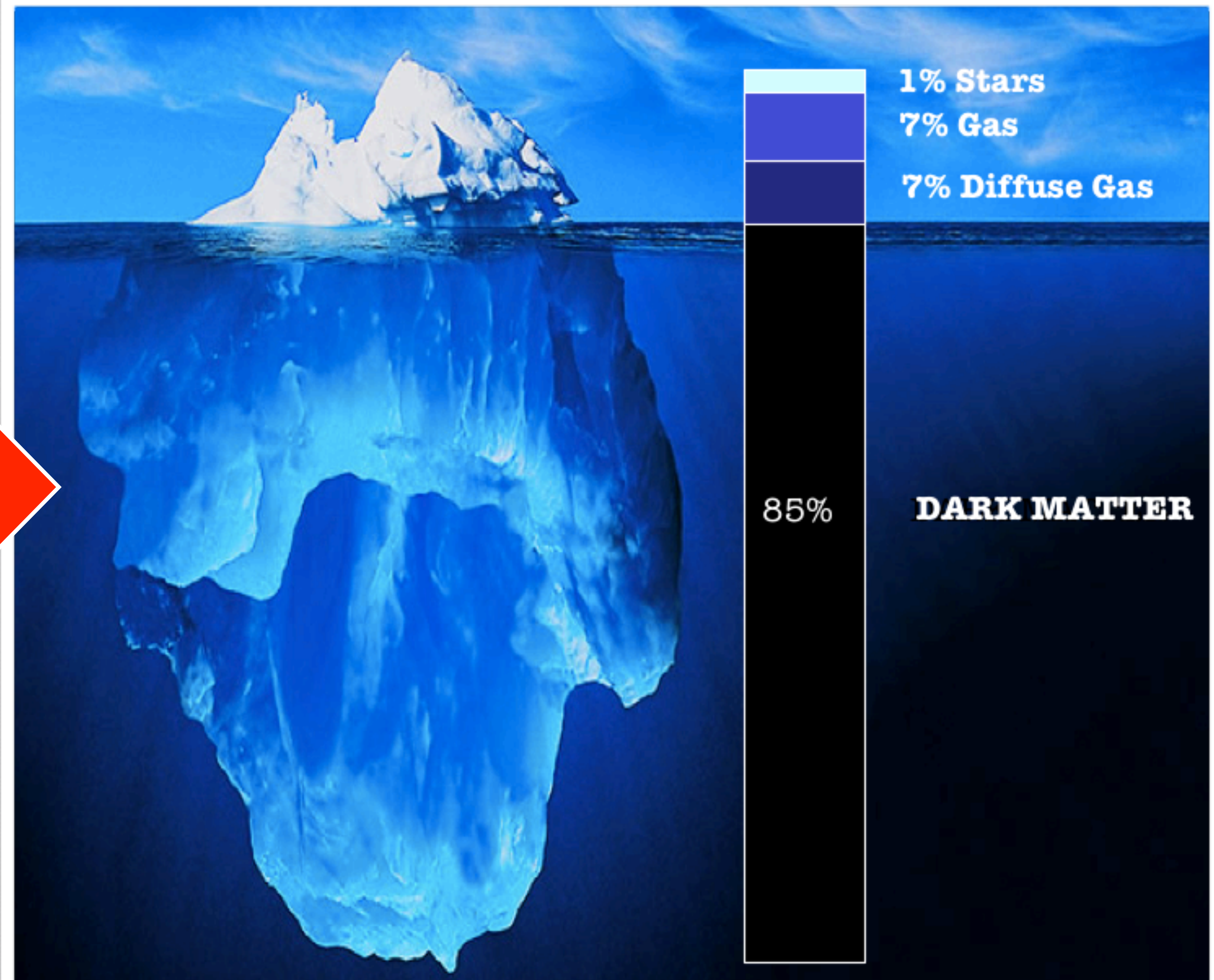


- CMB



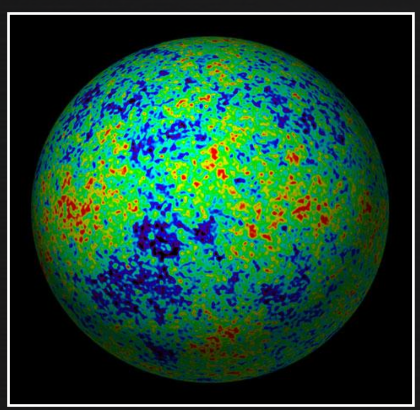
- Type Ia Supernovae



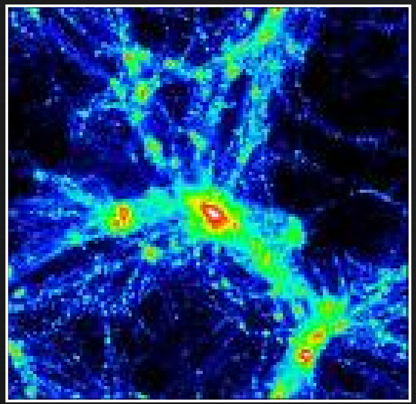
What do we know?

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

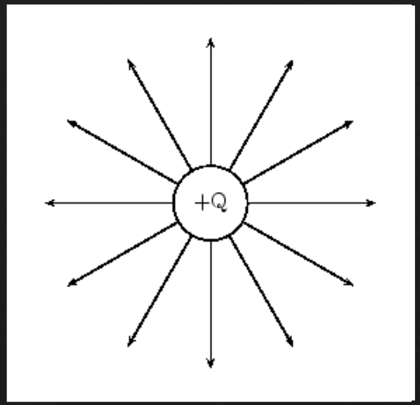
1) Ωh^2 OK?



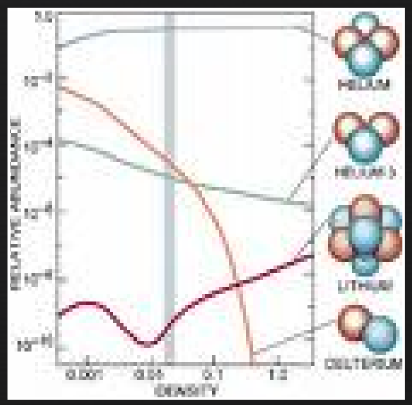
2) Is it cold?



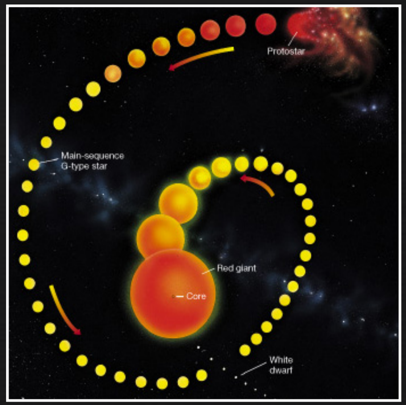
3) Is it neutral?



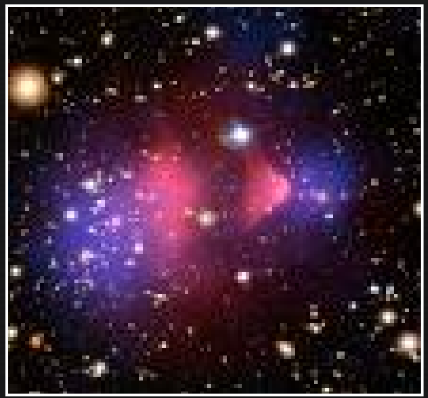
4) Is BBN ok?



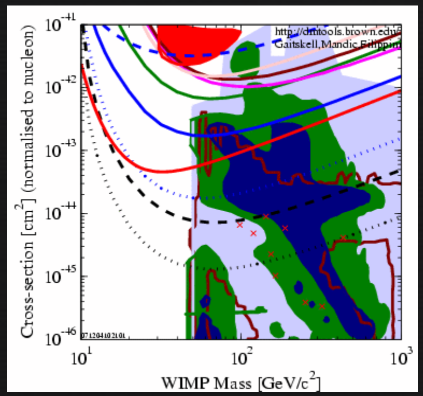
5) Stars OK?



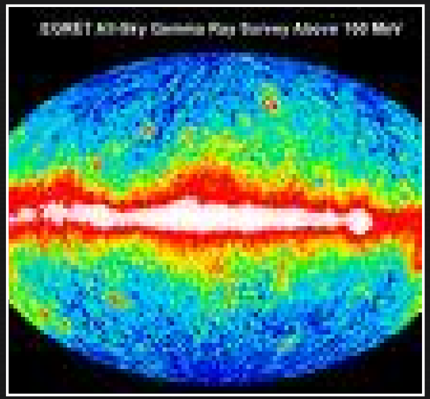
6) Collisionless?



7) Couplings OK?



8) γ-rays OK?



9) Astro bounds?

10) Can probe it?

Taoso, GB & Masiero 2007

Dark Matter candidates

- Neutralino?

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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- **SuperWIMPs**
  Inherit the appropriate relic density from the decay of the NTL particle of the new theory
- **WIMPless**
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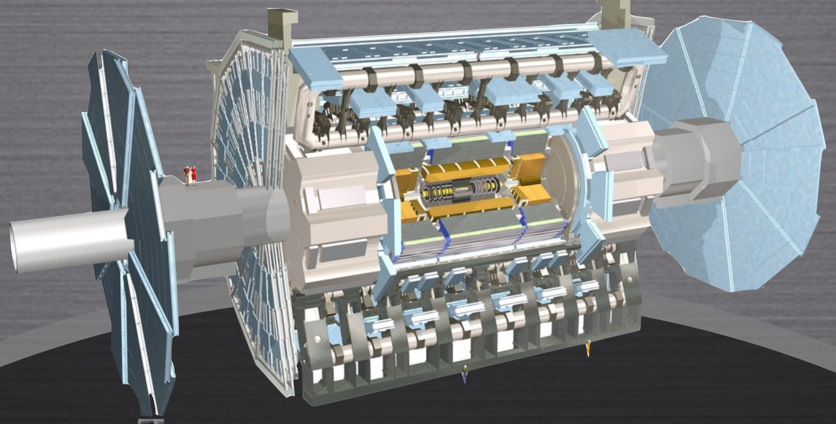
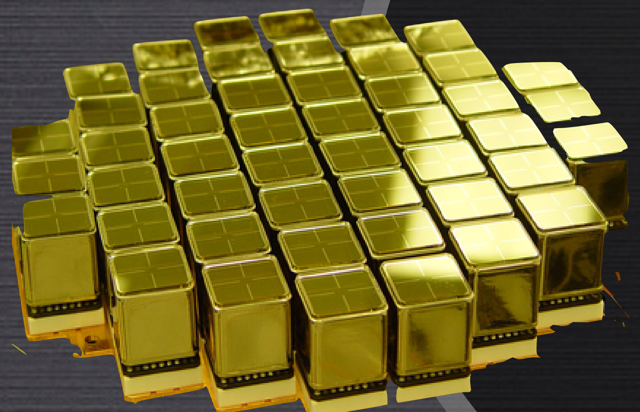
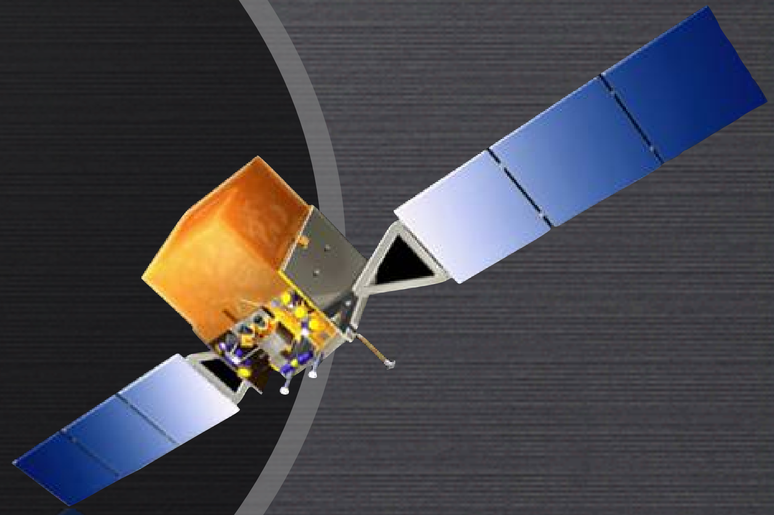
Dark Matter searches



Colliders



Direct Detection



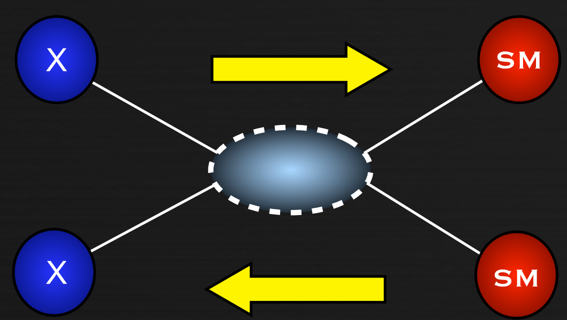
Indirect Detection

Indirect Detection

Why "annihilations"?

X = Dark matter   SM = Standard model particle

Early Universe



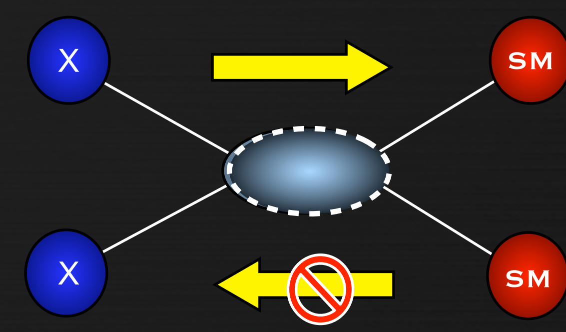
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

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



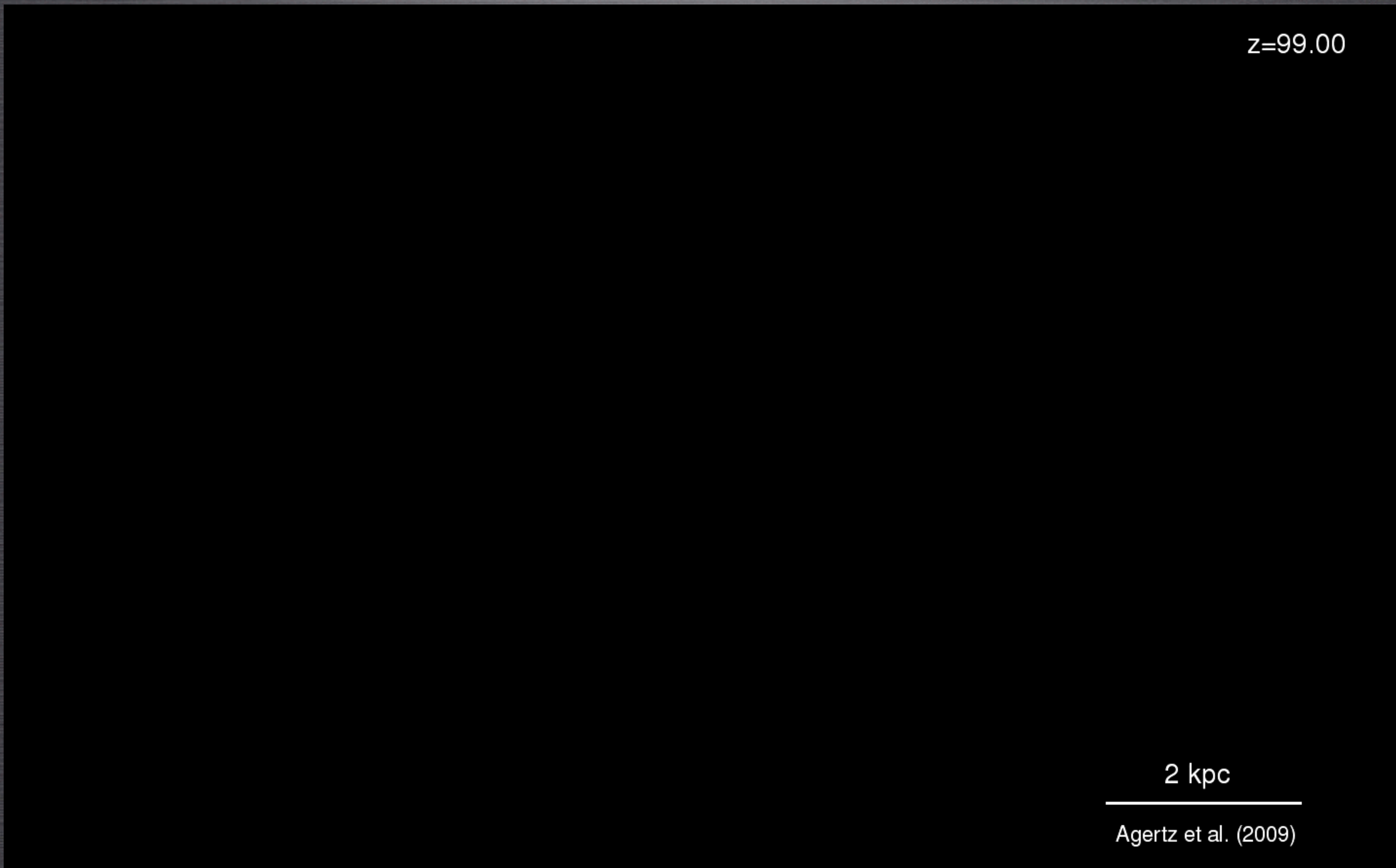
$$\frac{dn_\chi}{dt} = -(\sigma v)_o n_\chi^2$$

Annihilation Flux

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

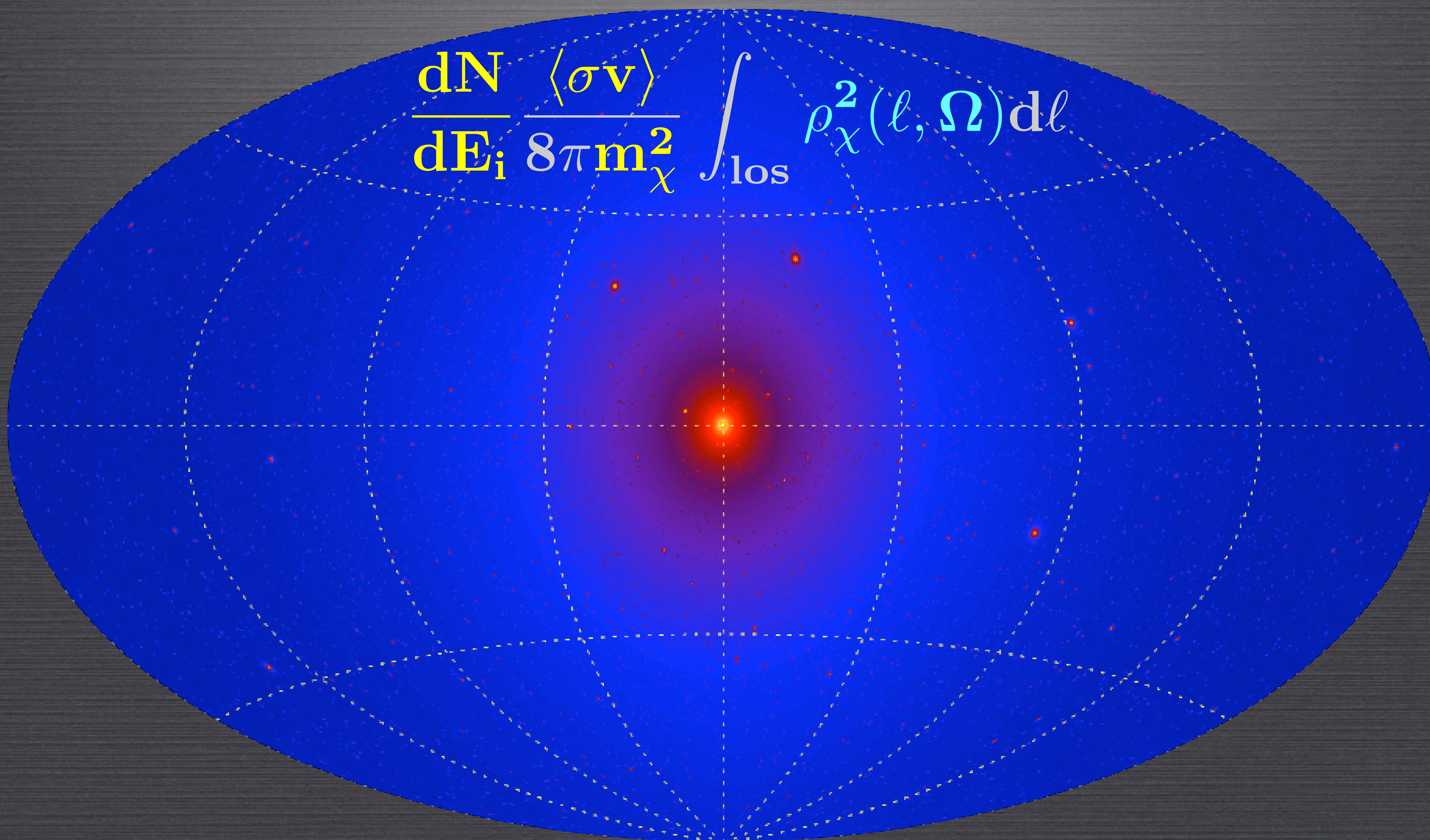
Particle physics input from extensions of the Standard Model. Need to specify distribution of DM along the line of sight.

Simulating Galaxy Formation



Evolution of the gas density (blue), temperature (red) and metallicity (green)

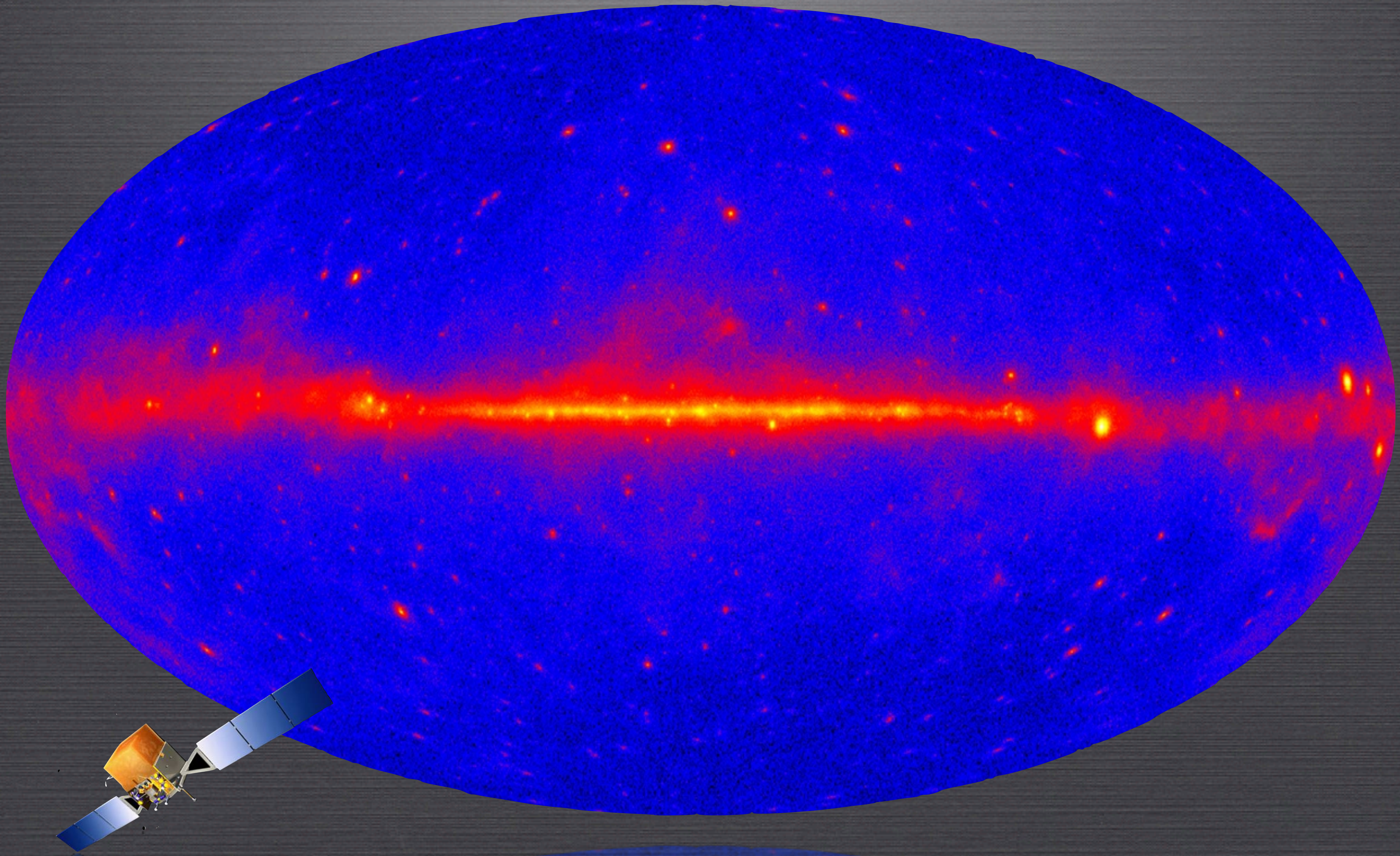
Add Wimp Model → Flux



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

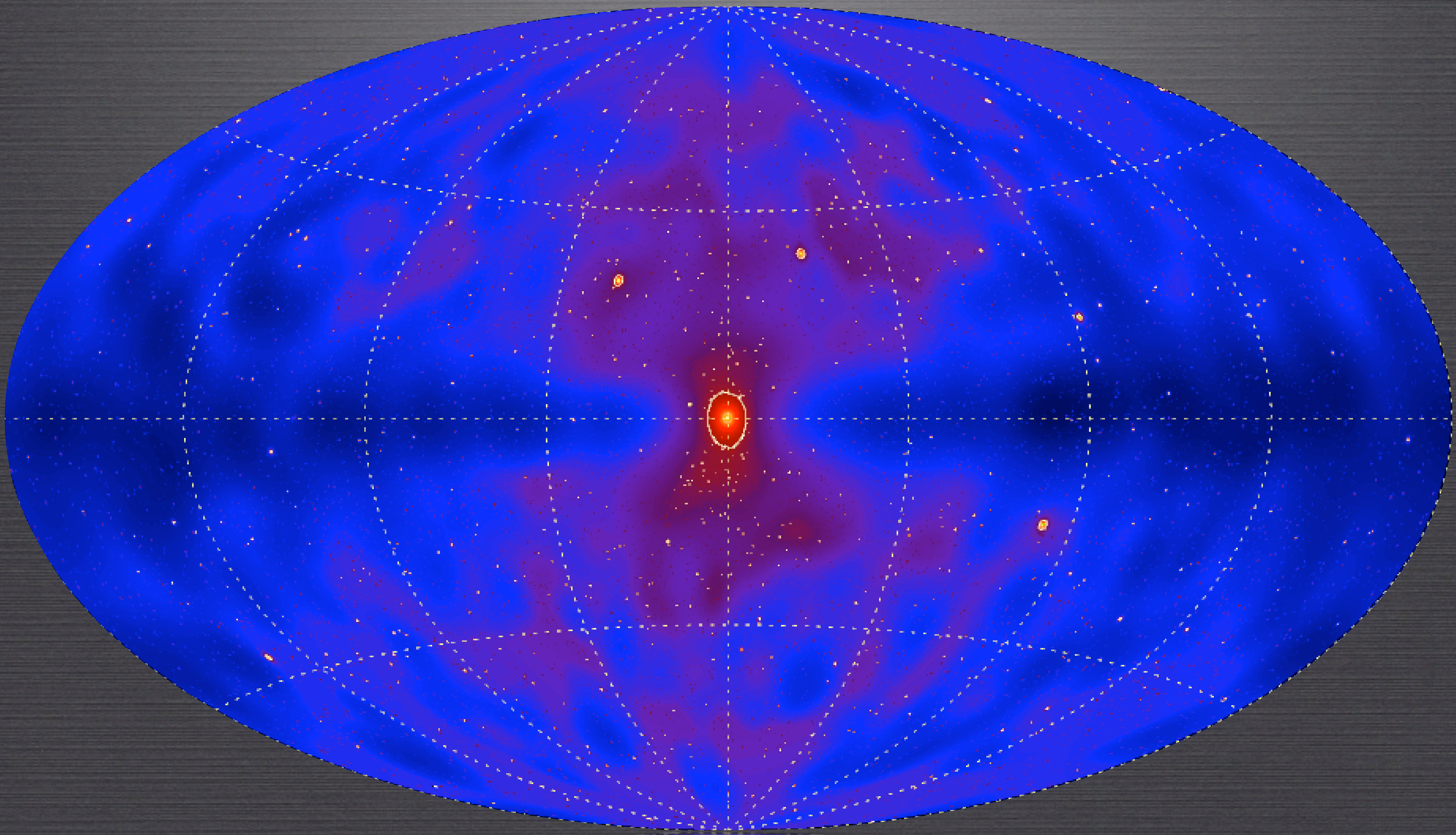
Pieri, GB, Branchini 2009

The FERMI sky



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

Sensitivity



Pieri, GB, Branchini 2009

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

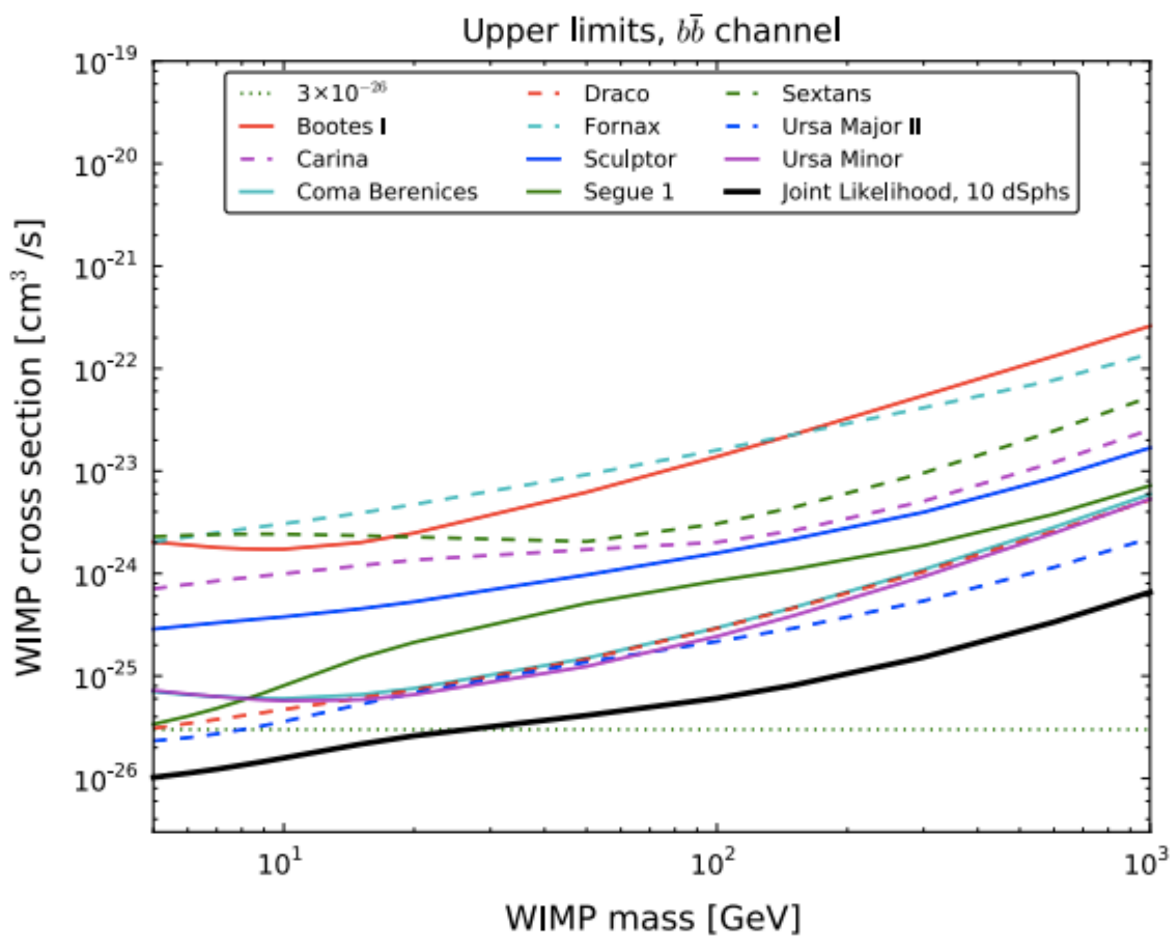
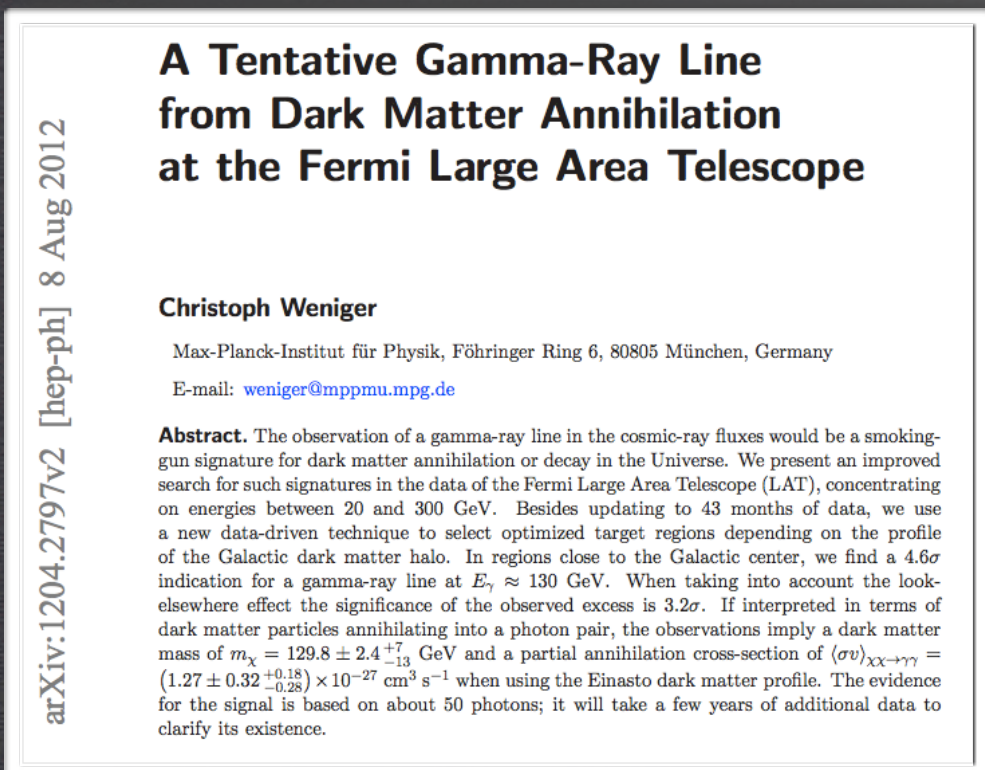


FIG. 1 (color online). Derived 95% C.L. upper limits on a WIMP annihilation cross section for all selected dSphs and for the joint likelihood analysis for annihilation into the $b\bar{b}$ final state. The most generic cross section ($\sim 3 \times 10^{-26}$ cm^3 s^{-1} for a purely *s*-wave cross section) is plotted as a reference. Uncertainties in the *J* factor are included.

Ackermann et al. (Fermi-LAT Collaboration)
PRL 107 (2011) 241302; arXiv:1108.3546

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

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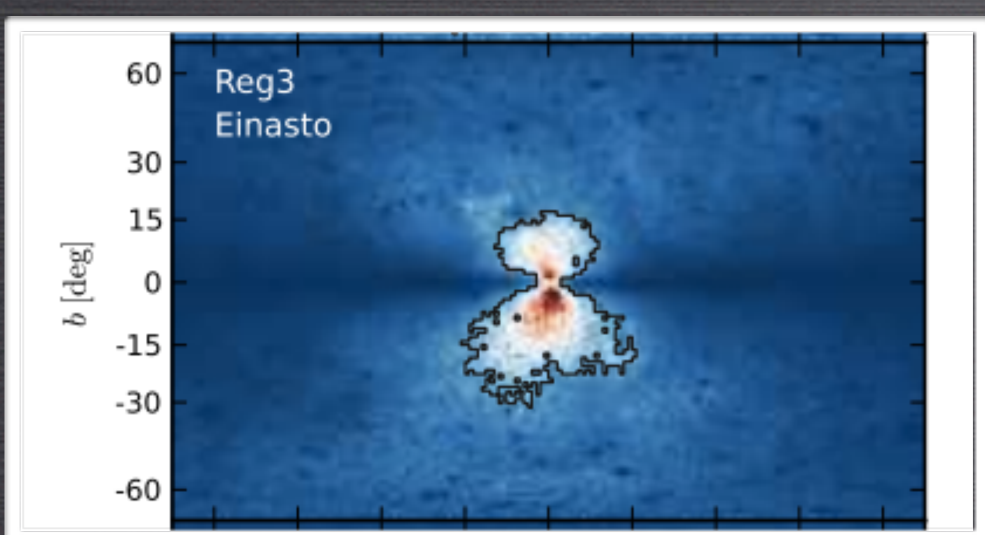
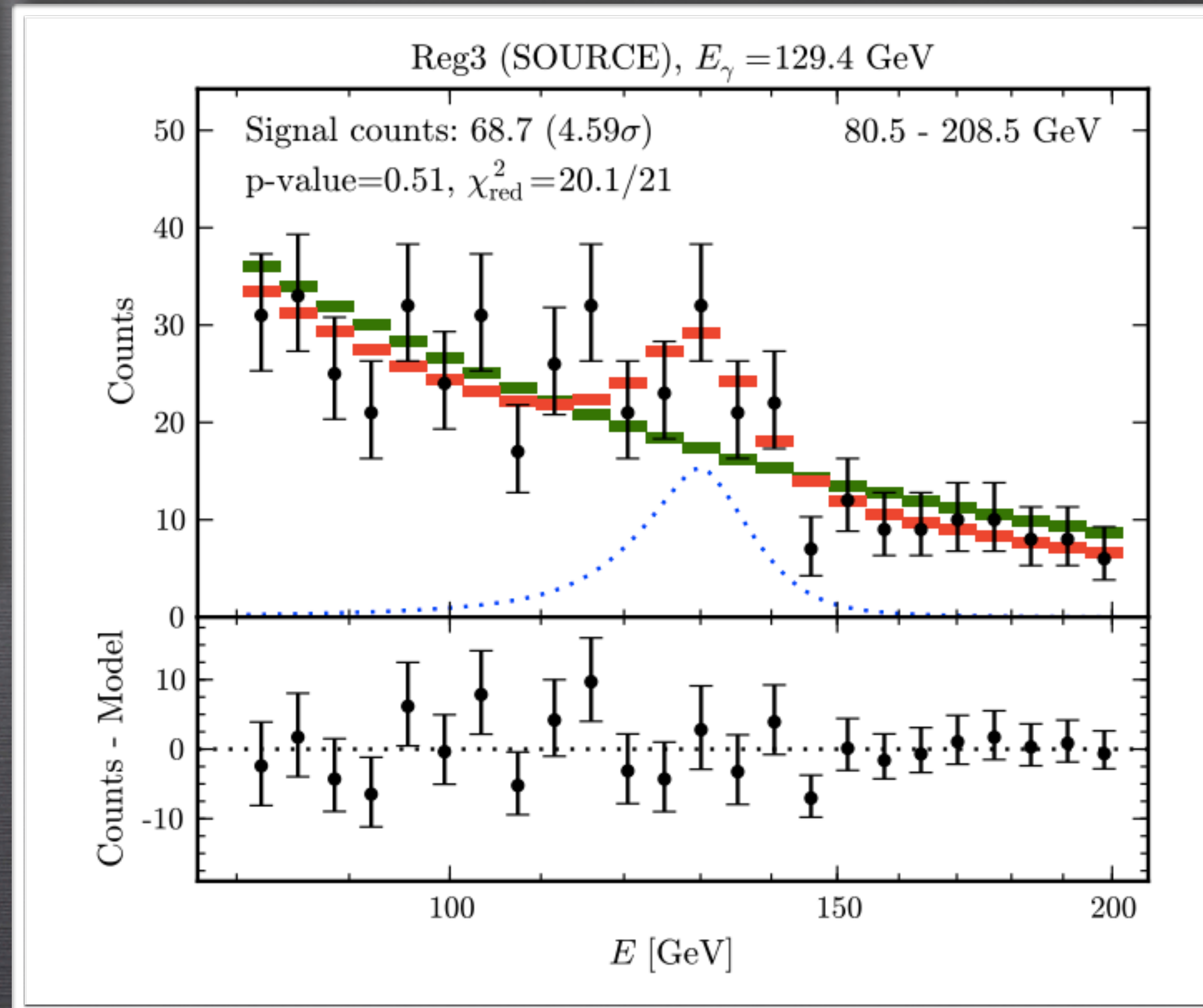
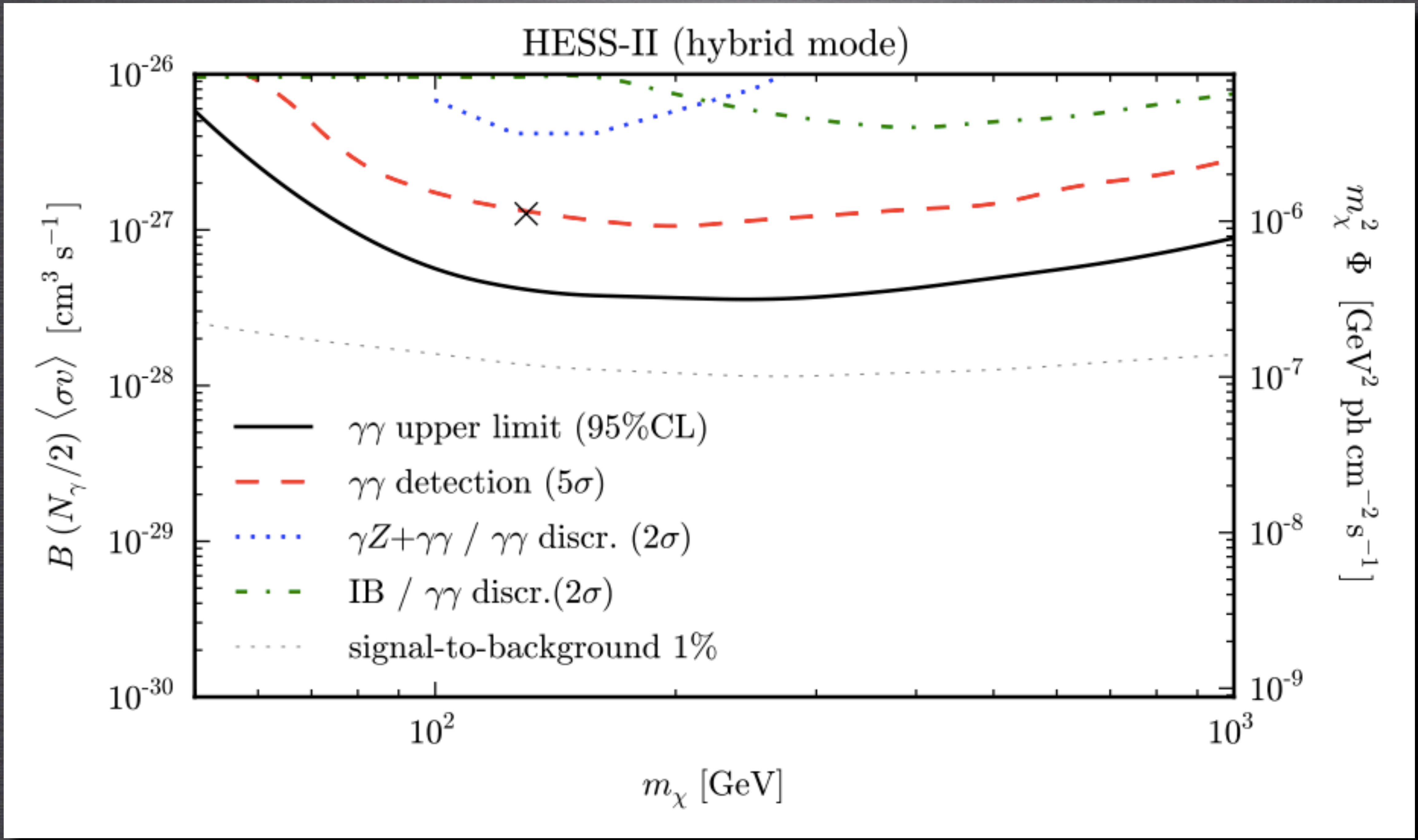
Abstract. The observation of a gamma-ray line in the cosmic-ray fluxes would be a smoking-gun signature for dark matter annihilation or decay in the Universe. We present an improved search for such signatures in the data of the Fermi Large Area Telescope (LAT), concentrating on energies between 20 and 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



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

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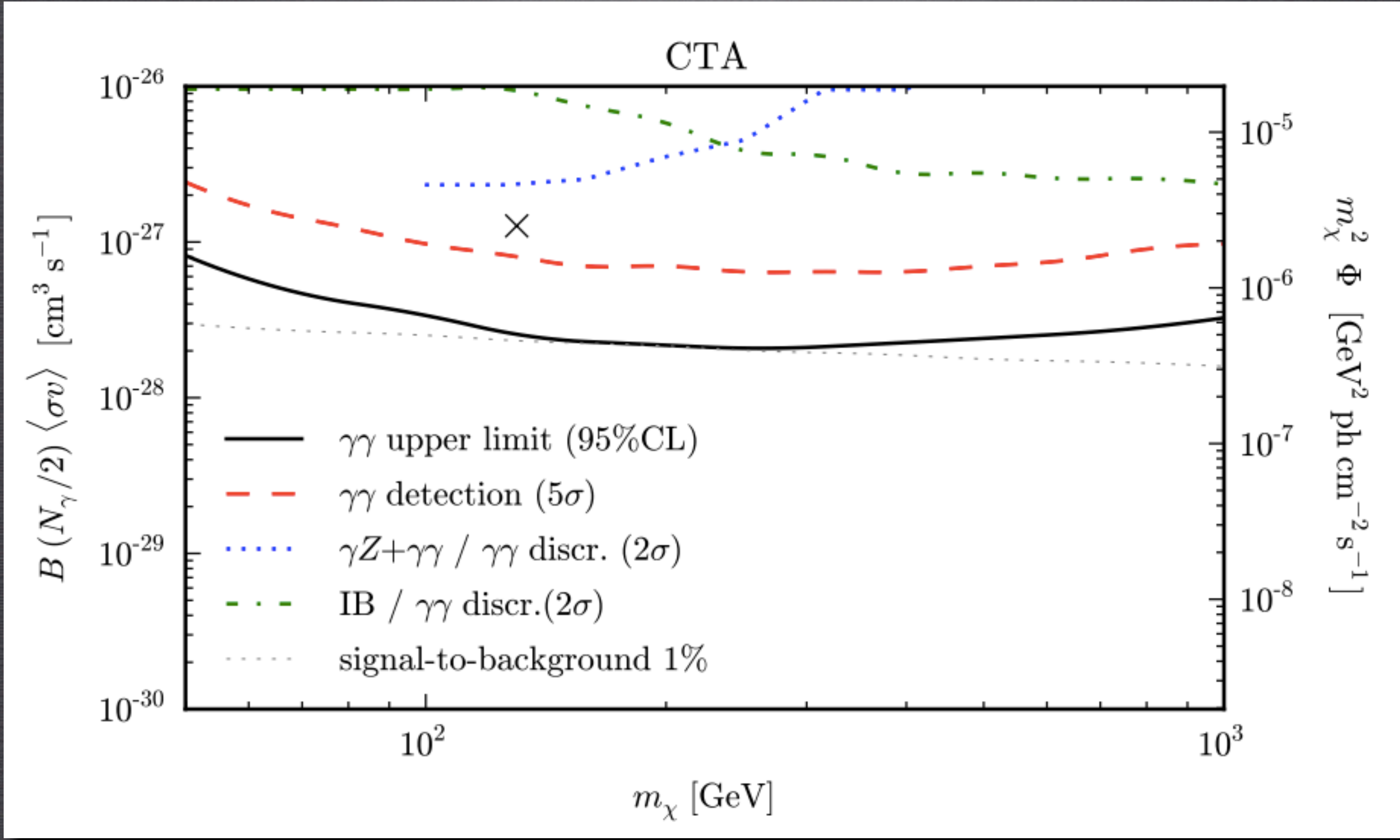

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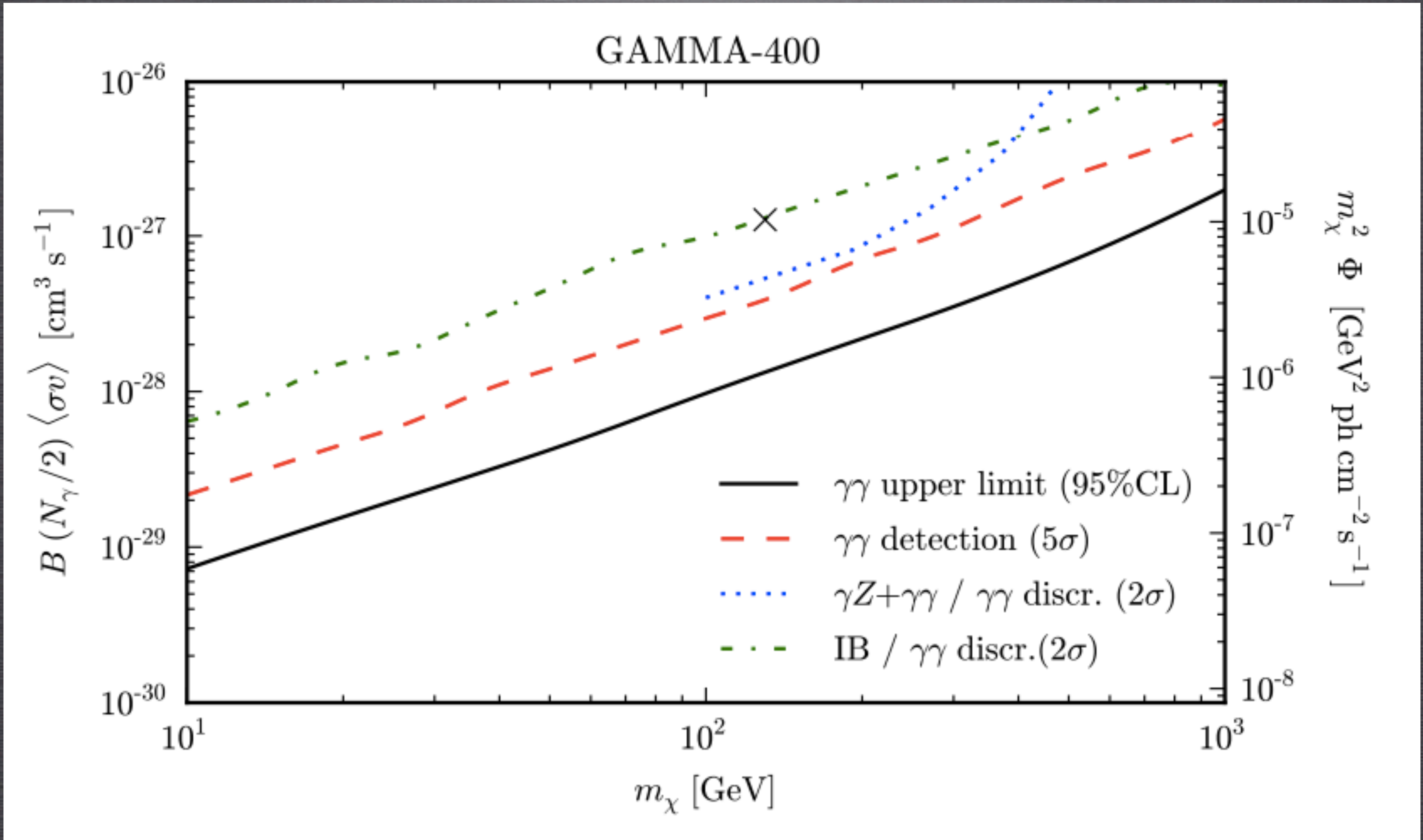
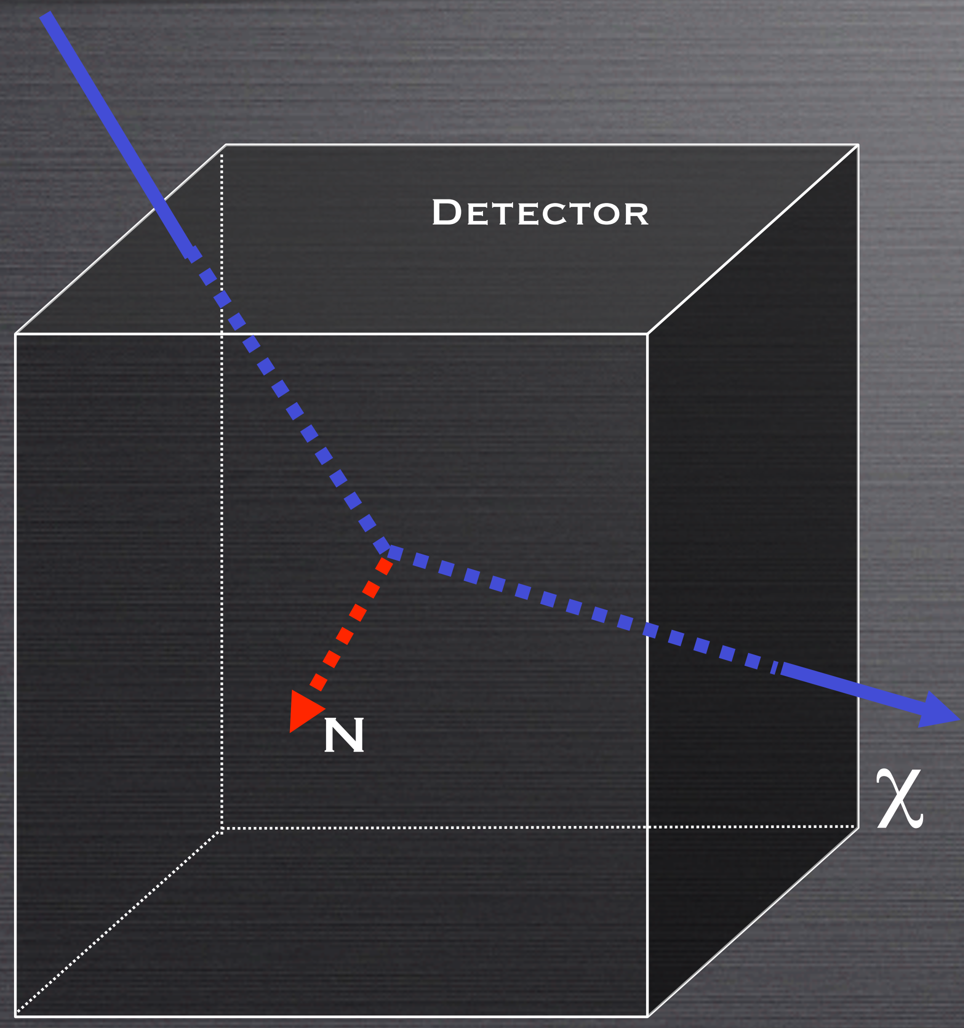
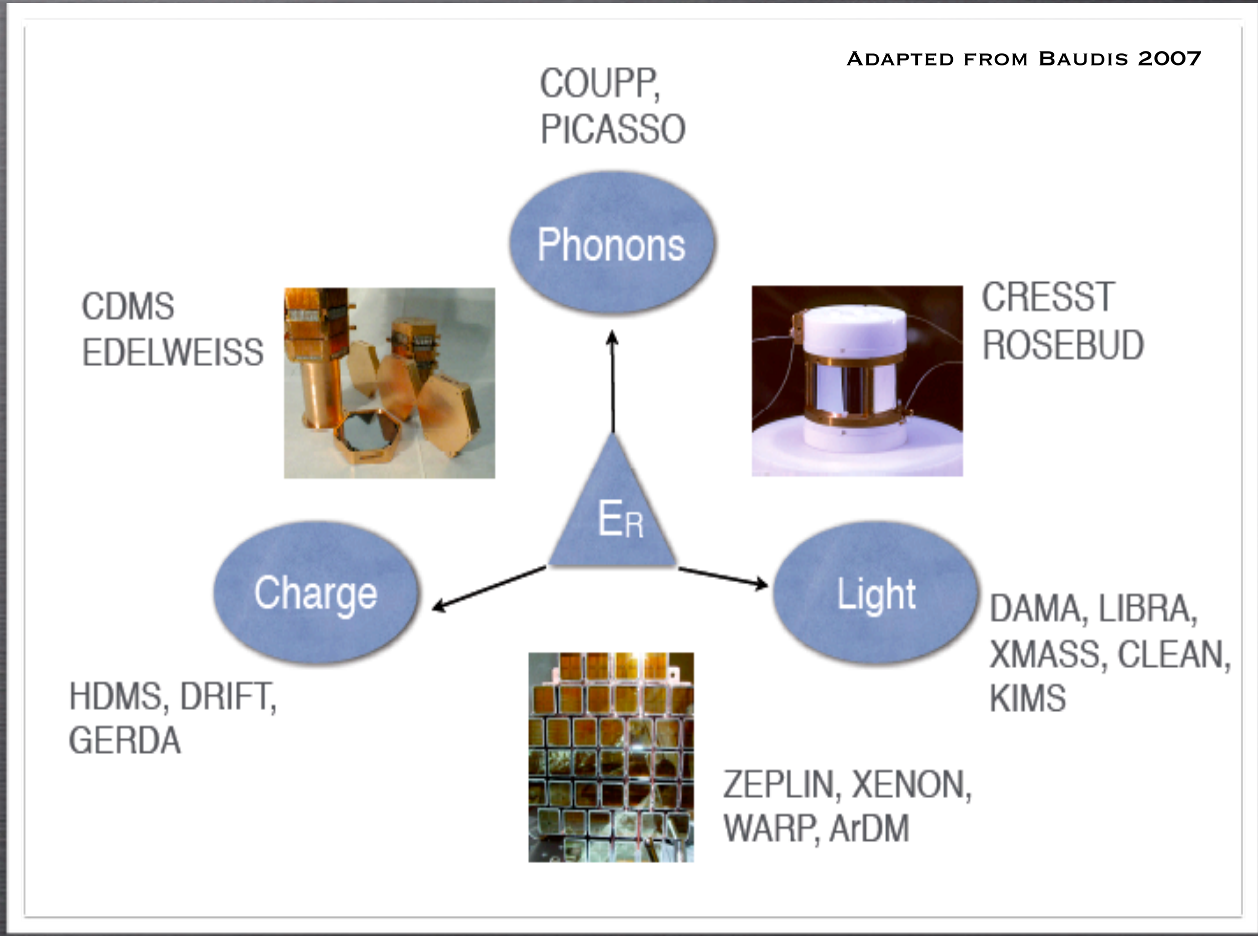


Bergstrom, GB et al. http://arxiv.org/pdf/1207.6773.pdf

Direct Detection

Principle and Detection Techniques





DM scatters off nuclei in the detector

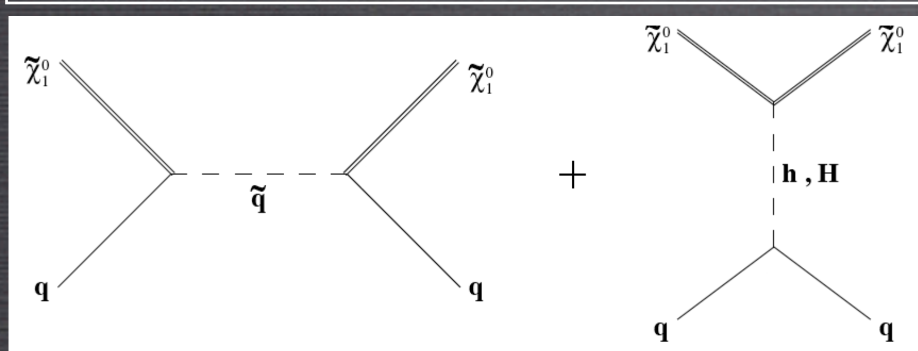
Detection of recoil energy via ionization (charges), scintillation (light) and heat (phonons)

Direct Detection

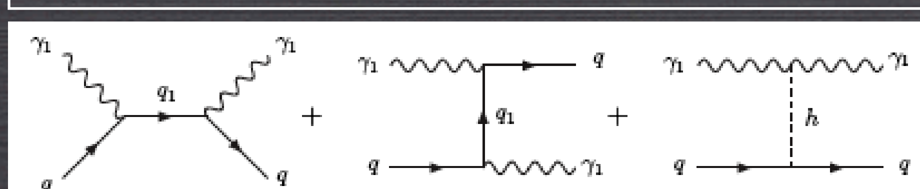
Differential Event Rate

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

SUSY: squarks and Higgs exchange



UED: 1st level quarks and Higgs exchange



Theoretical Uncertainties

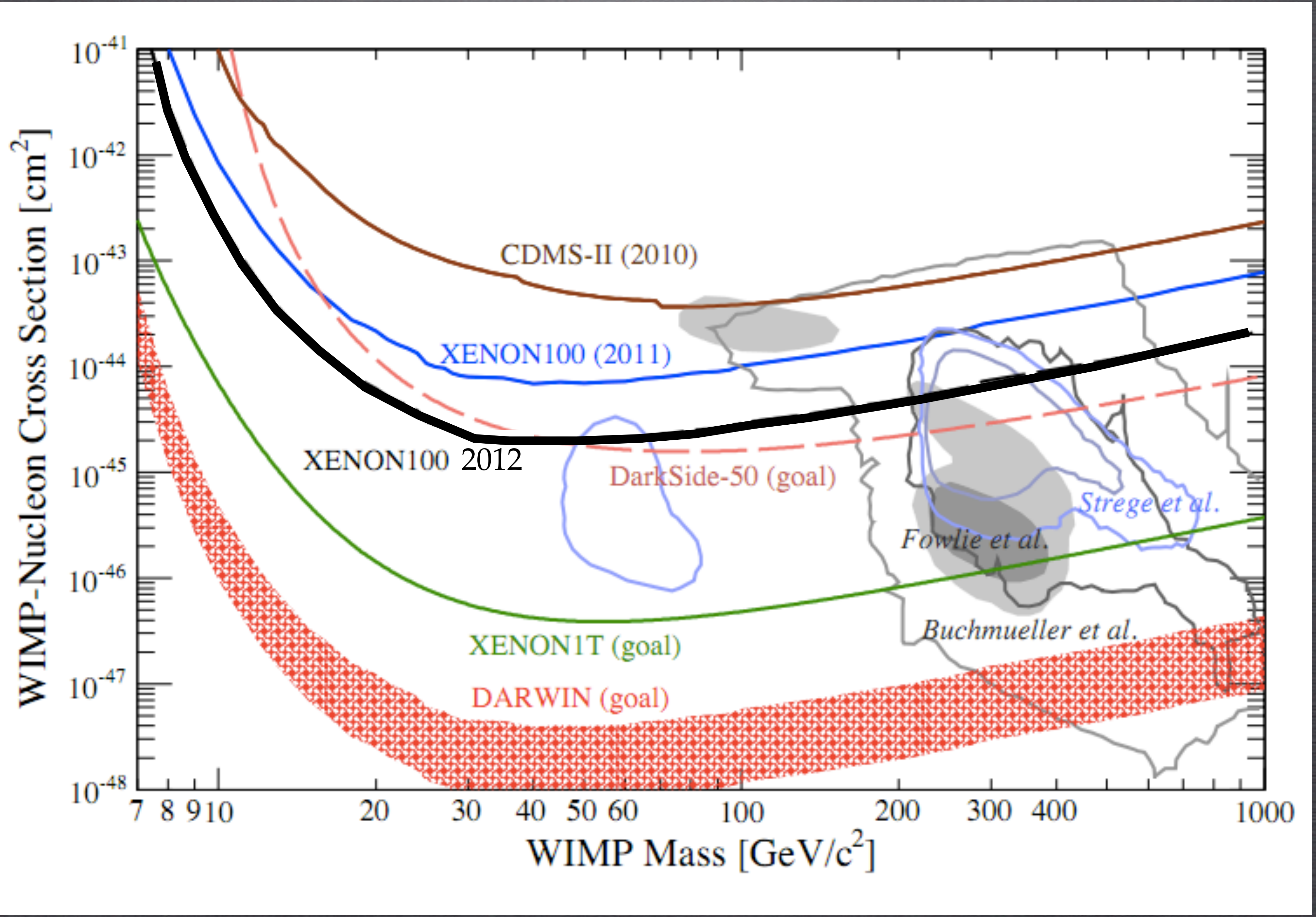
Ellis, Olive & Savage 2008; Bottino et al. 2000; etc.

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

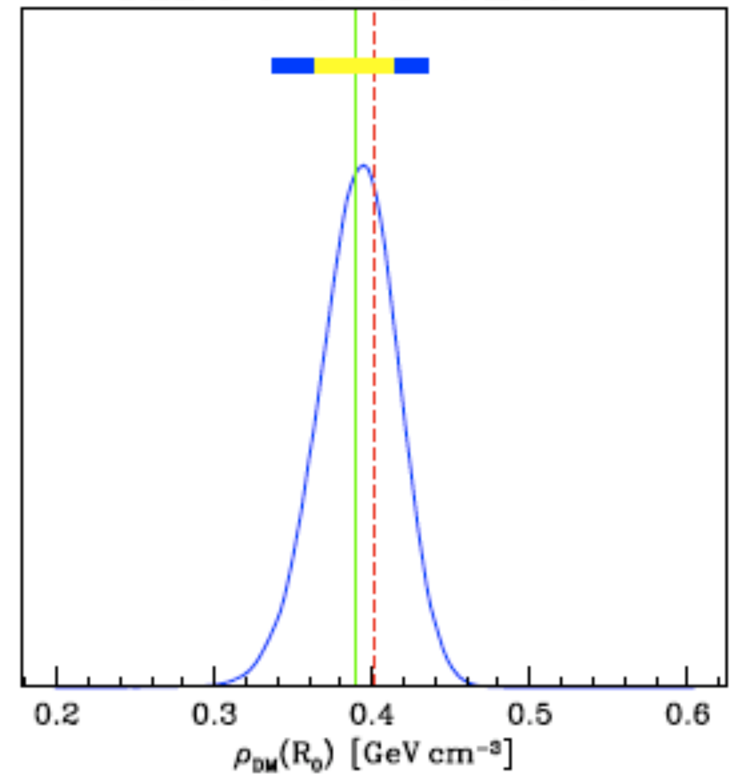
✦Blue Horizontal-Branch (BHB) halo stars from the SDSS

✦Estimates of Oort's constants

✦Motion of stars perpendicular to the Galactic plane

✦Velocity distribution of MW satellites

Ullio & Catena 2009



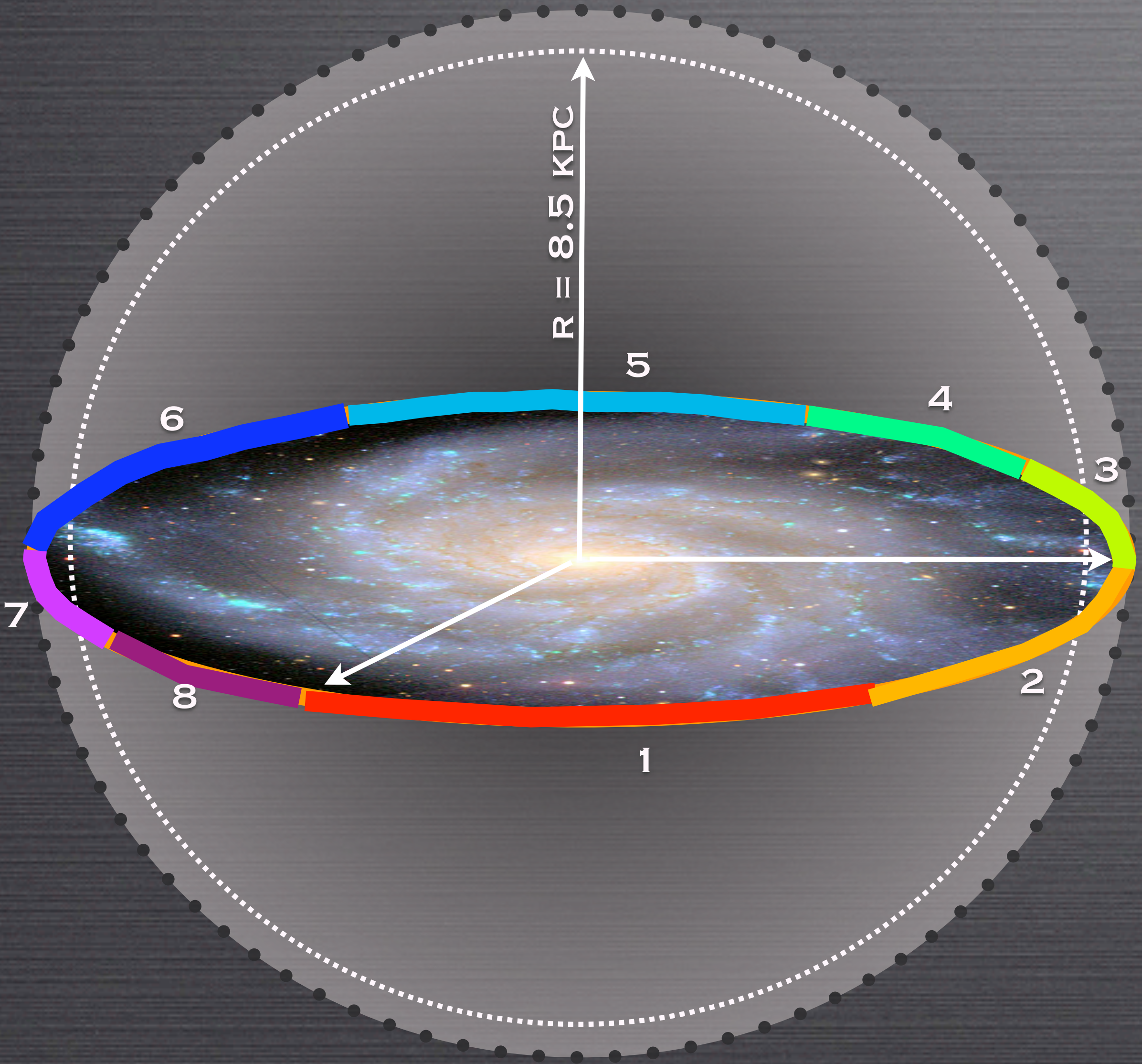
$$\rho_{DM}(R_0) = 0.389 \pm 0.025\,\mathrm{GeV\,cm^{-3}}$$

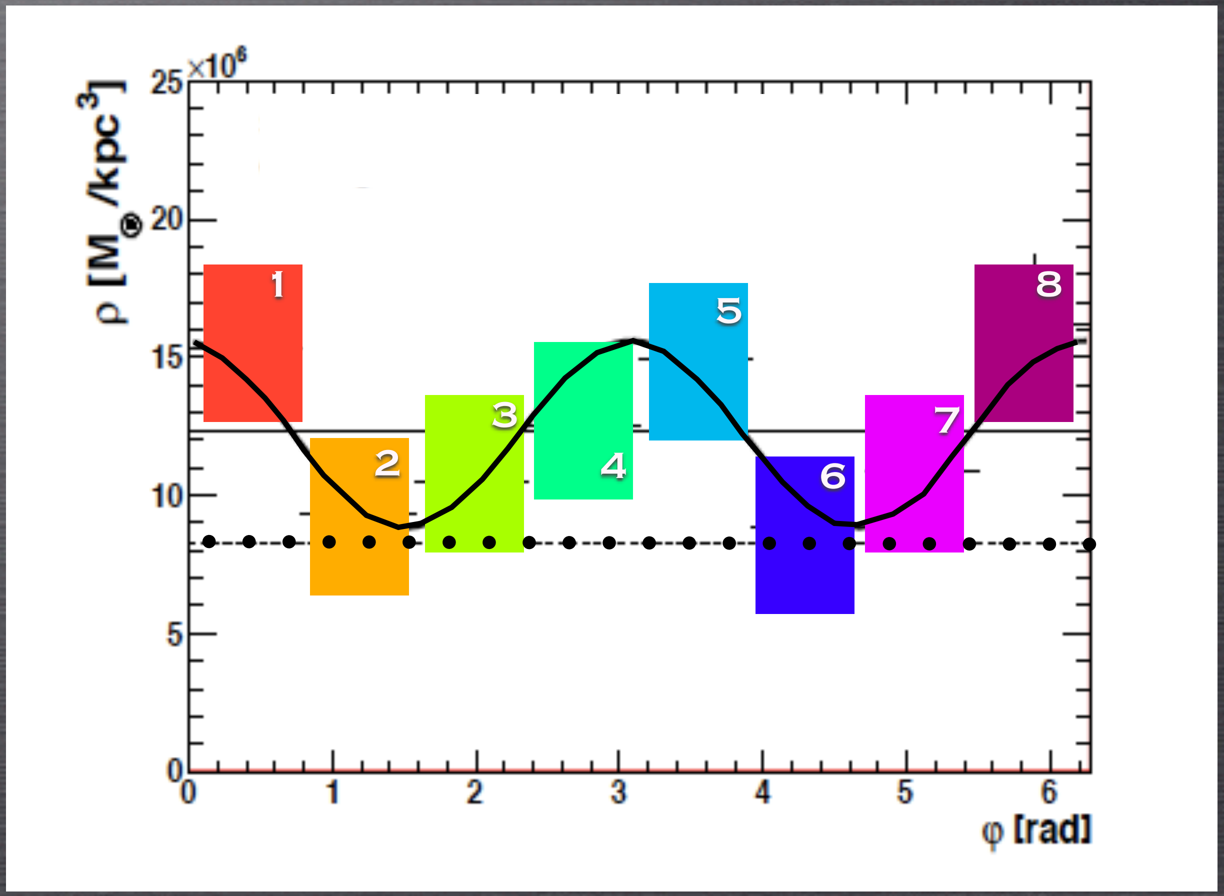
Constraints on M(<R) -> constraints on ρ_x

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

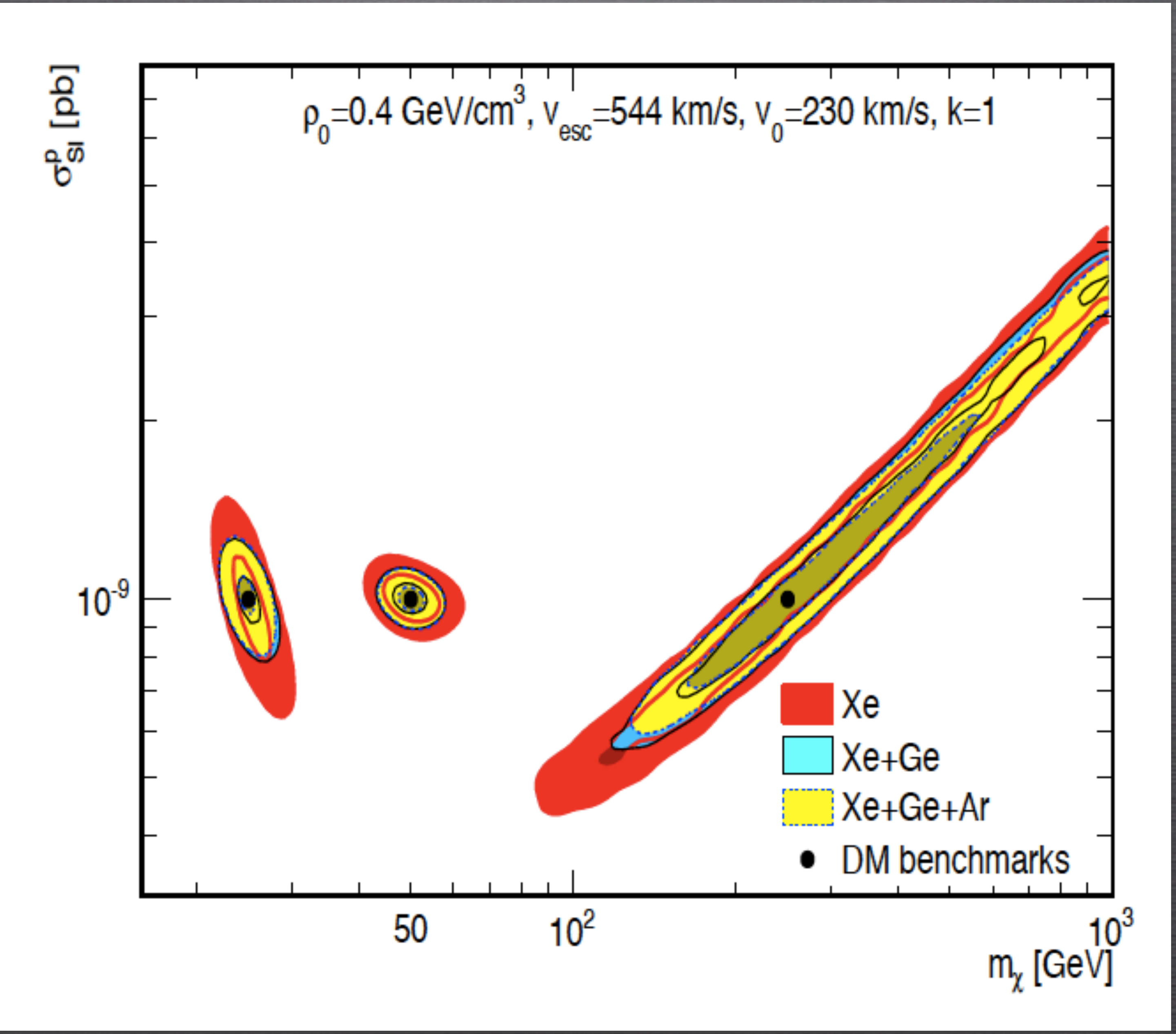
AT FIXED GC-DISTANCE (PATO, AGERTZ, GB, MOORE, TEYSSIER, MOORE 2010)





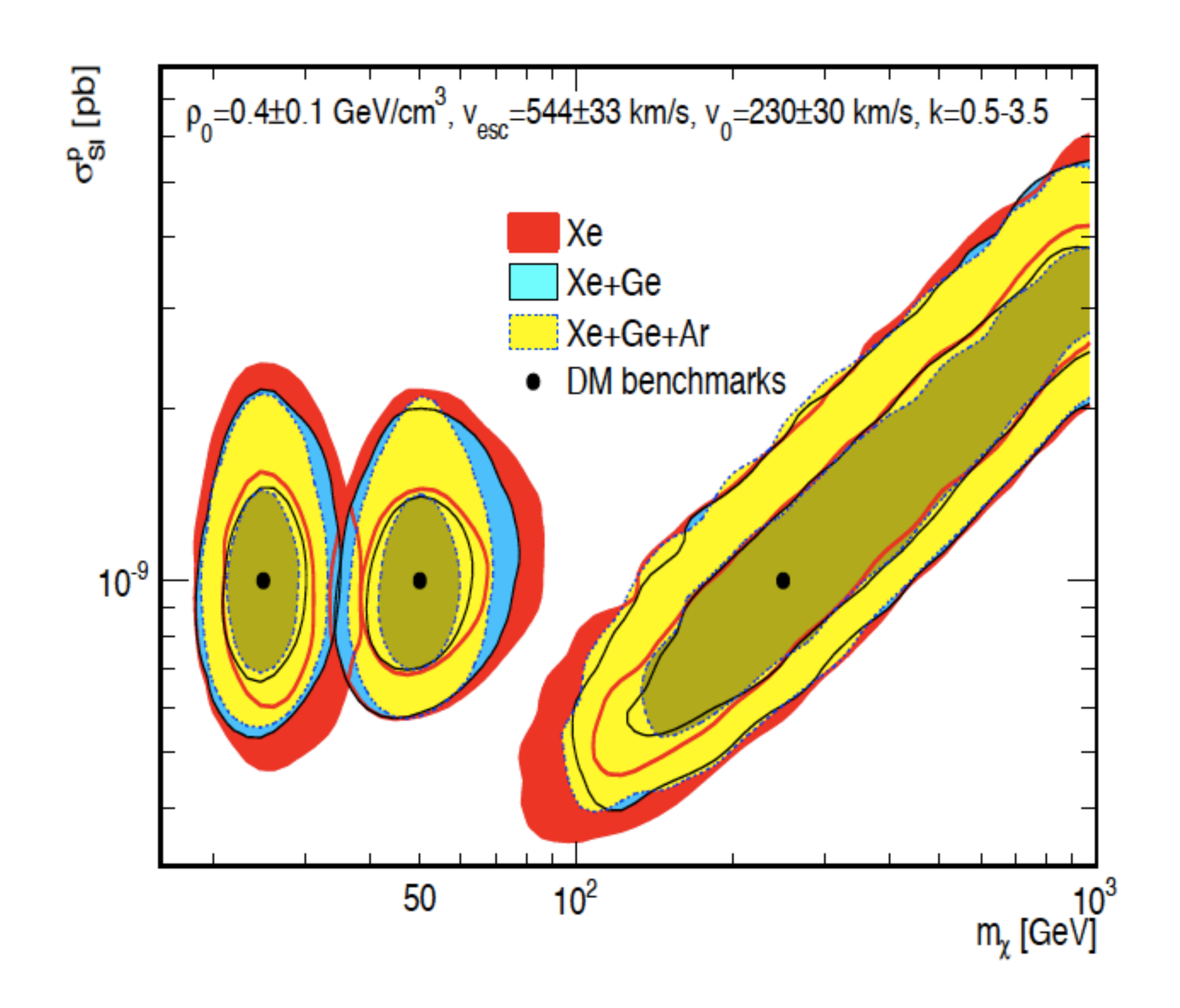
PATO, AGERTZ, GB, MOORE, TEYSSIER, MOORE 2010

Complementarity of DD targets



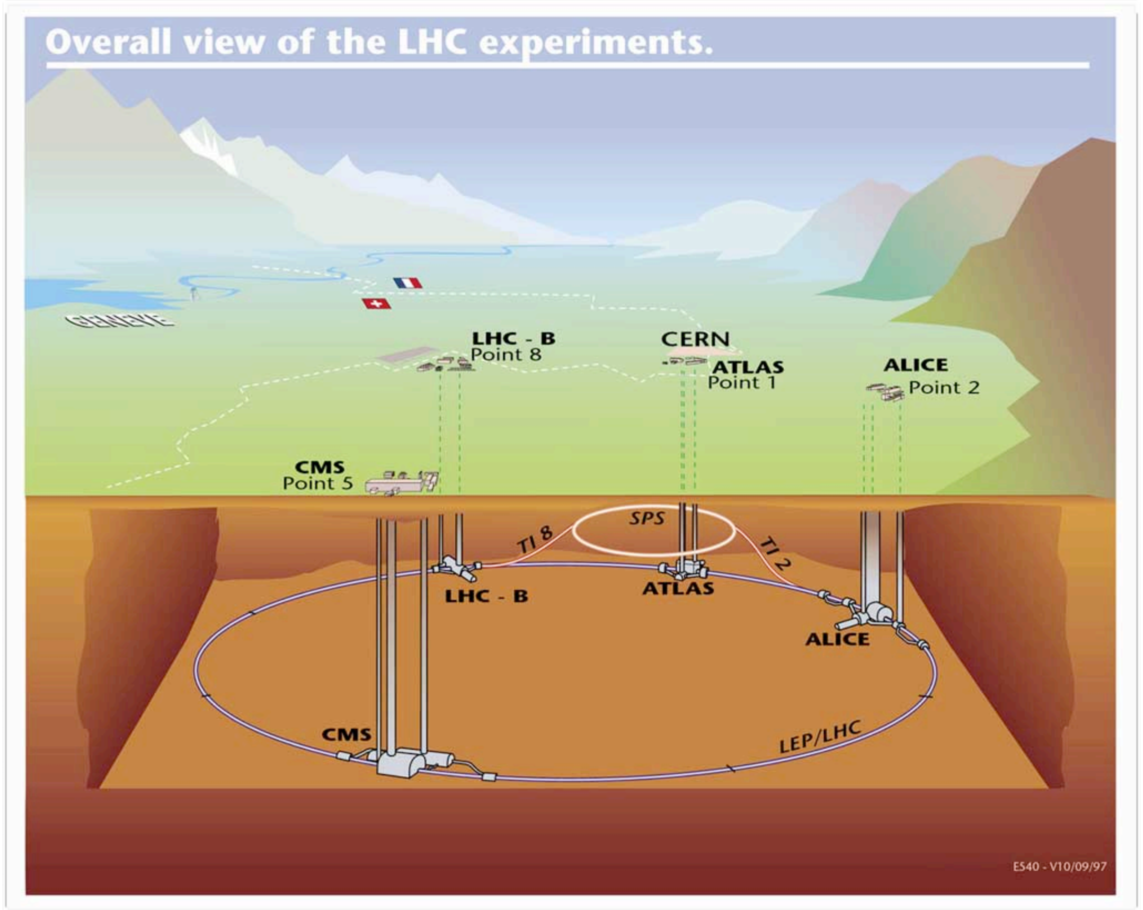
Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458

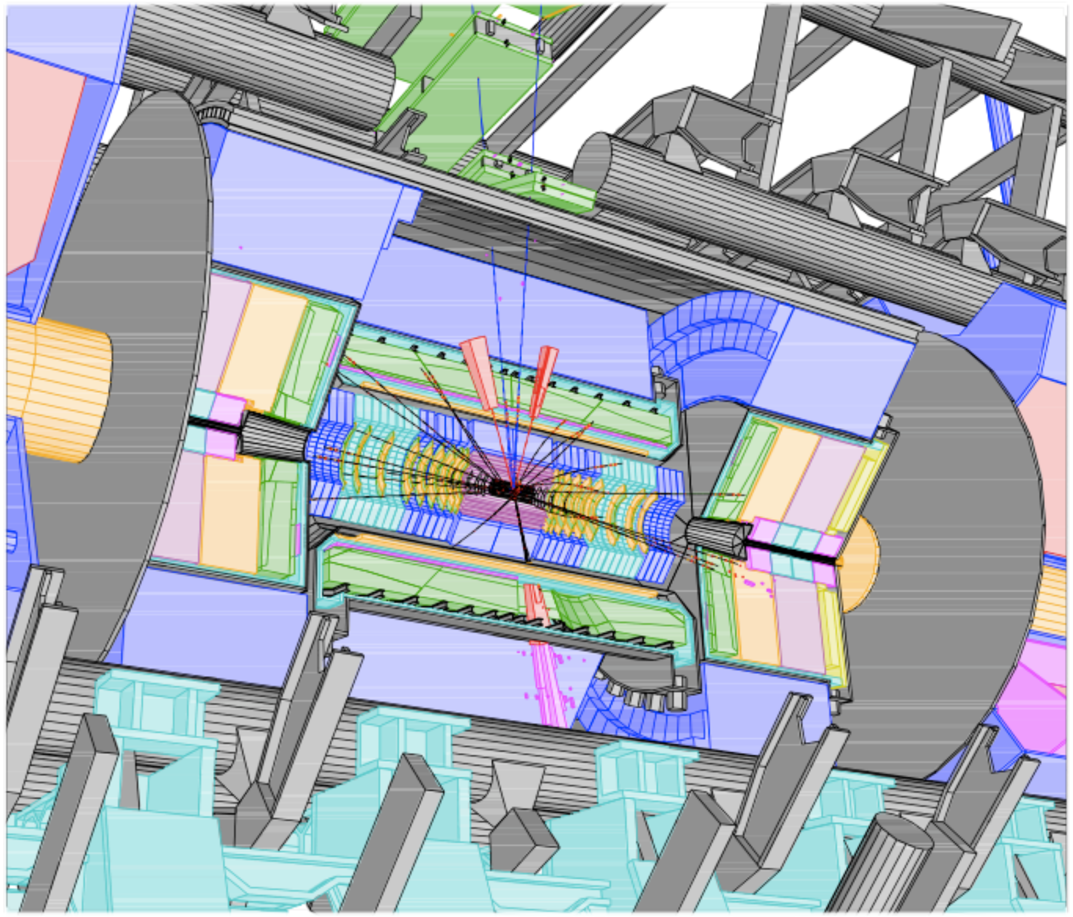
Complementarity of DD targets



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

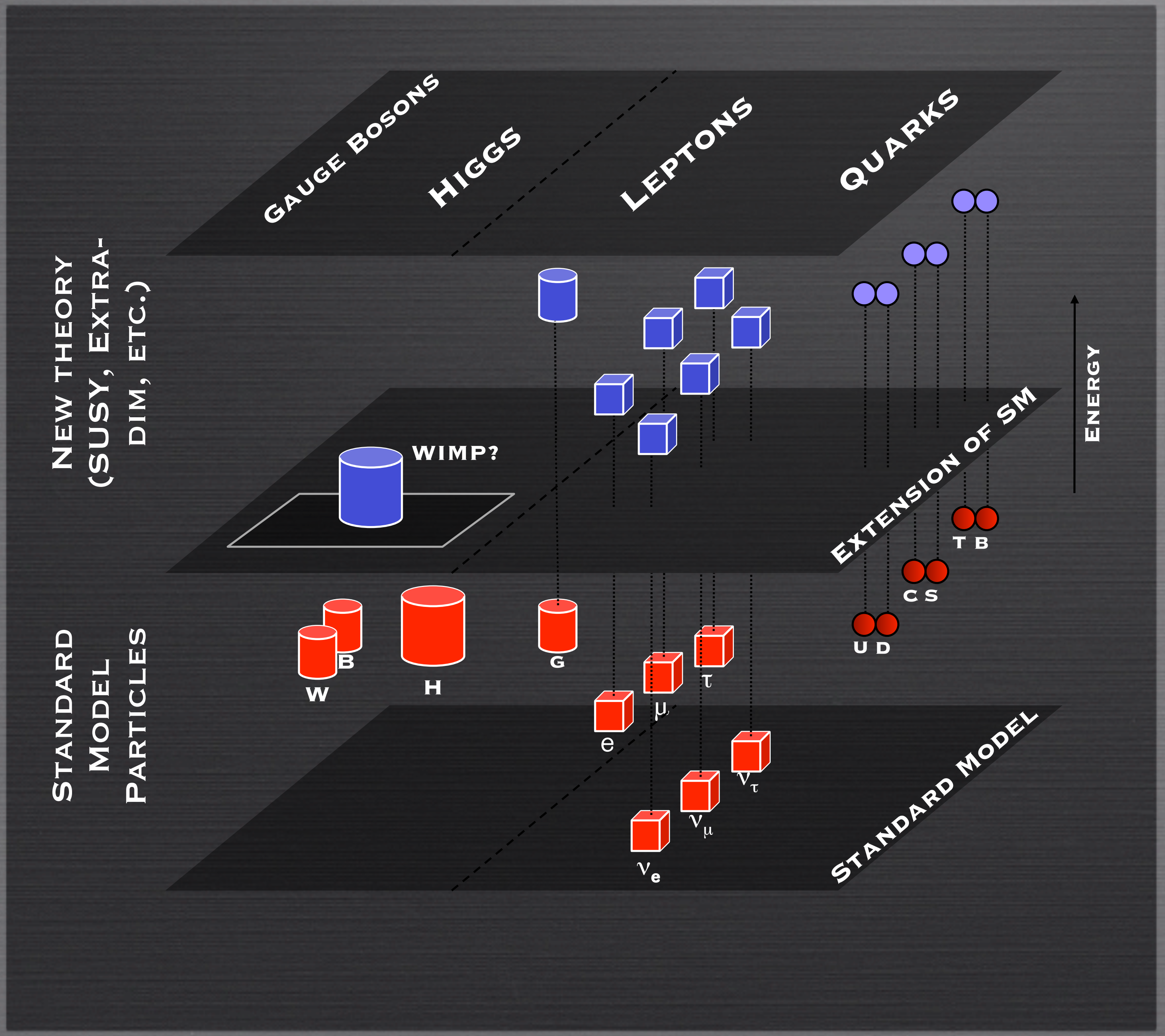
Dark Matter Searches at the LHC





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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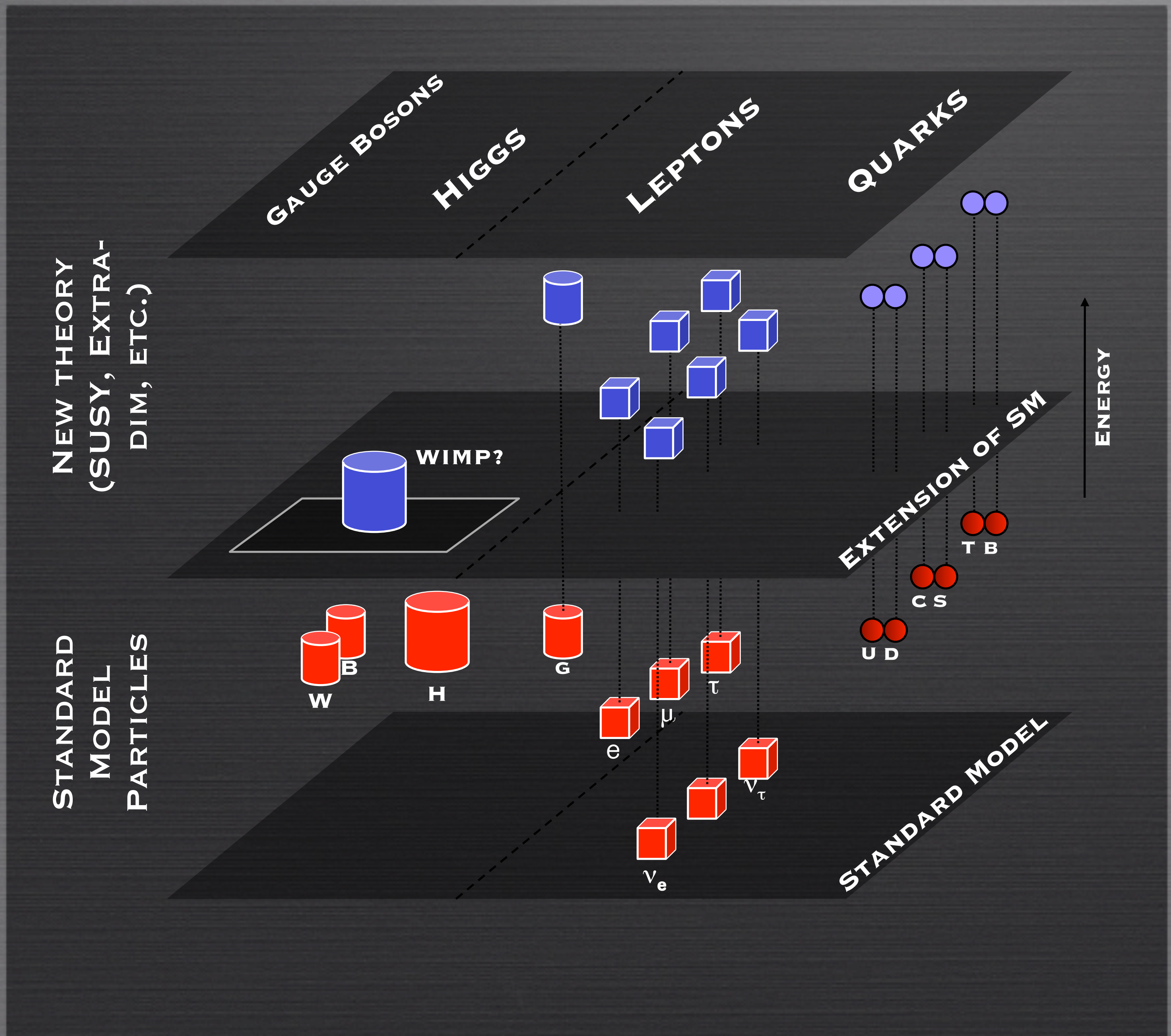
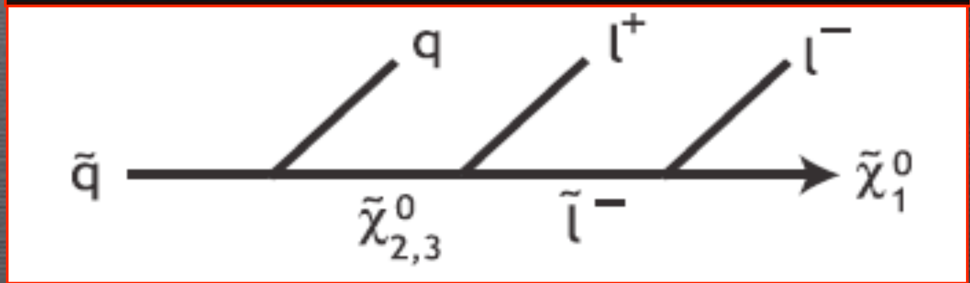


Search at LHC for processes like e.g.



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:

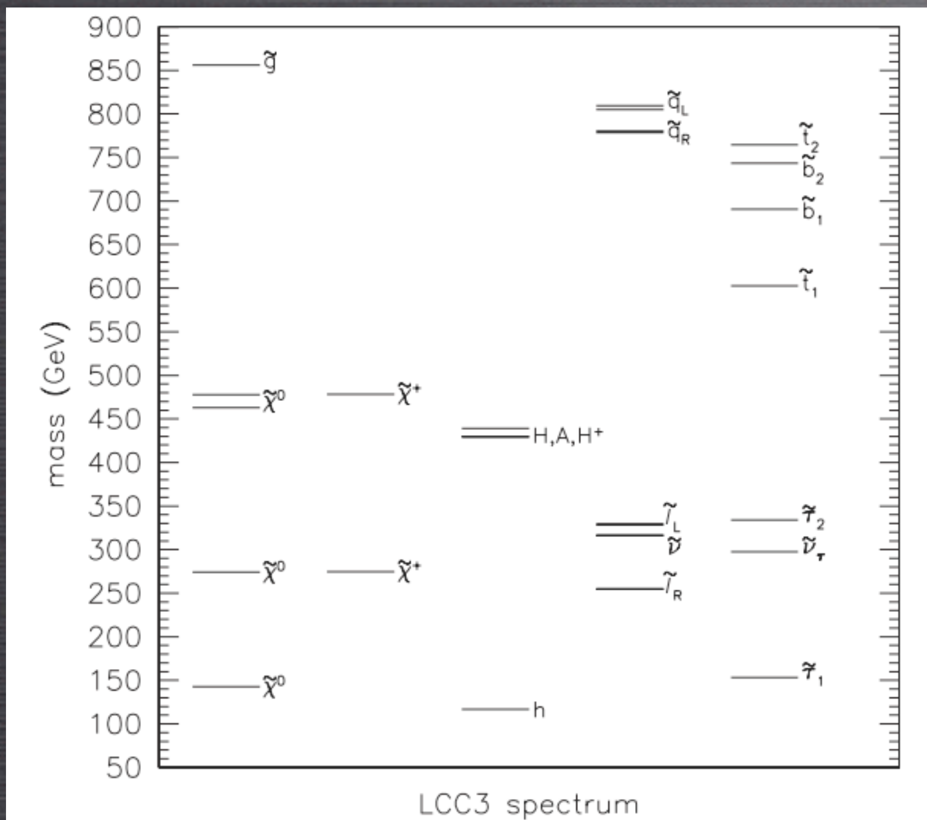
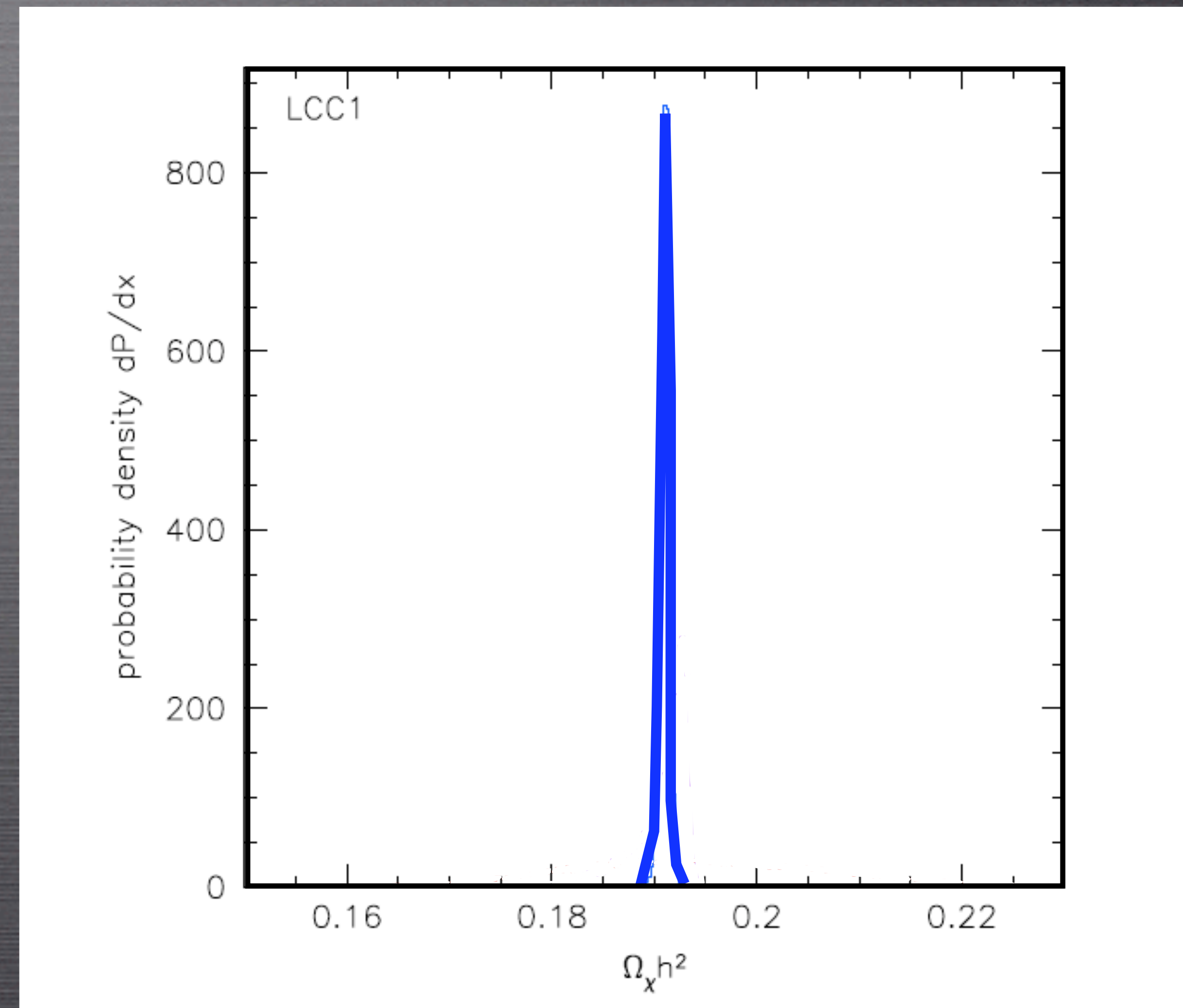
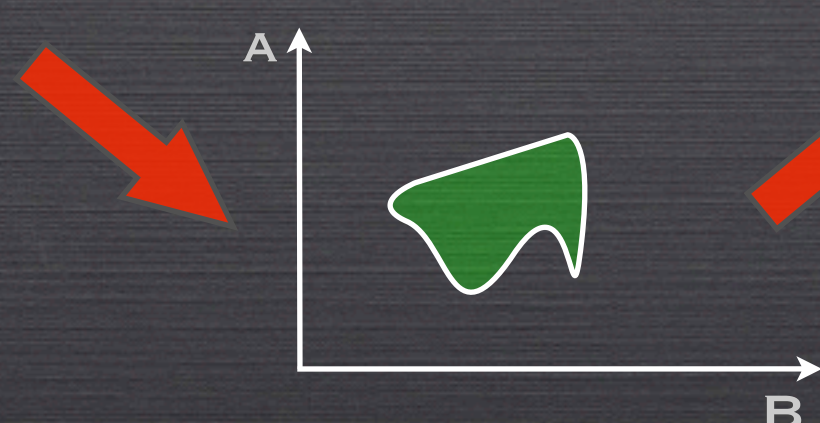


FIG. 34. Particle spectrum for point LCC3. The stau-neutralino mass splitting is 10.8 GeV. The lightest neutralino is predominantly *b*-ino, the second neutralino and light chargino are predominantly *W*-ino, and the heavy neutralinos and chargino are predominantly Higgsino.



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



Example of Inverse problem at LHC

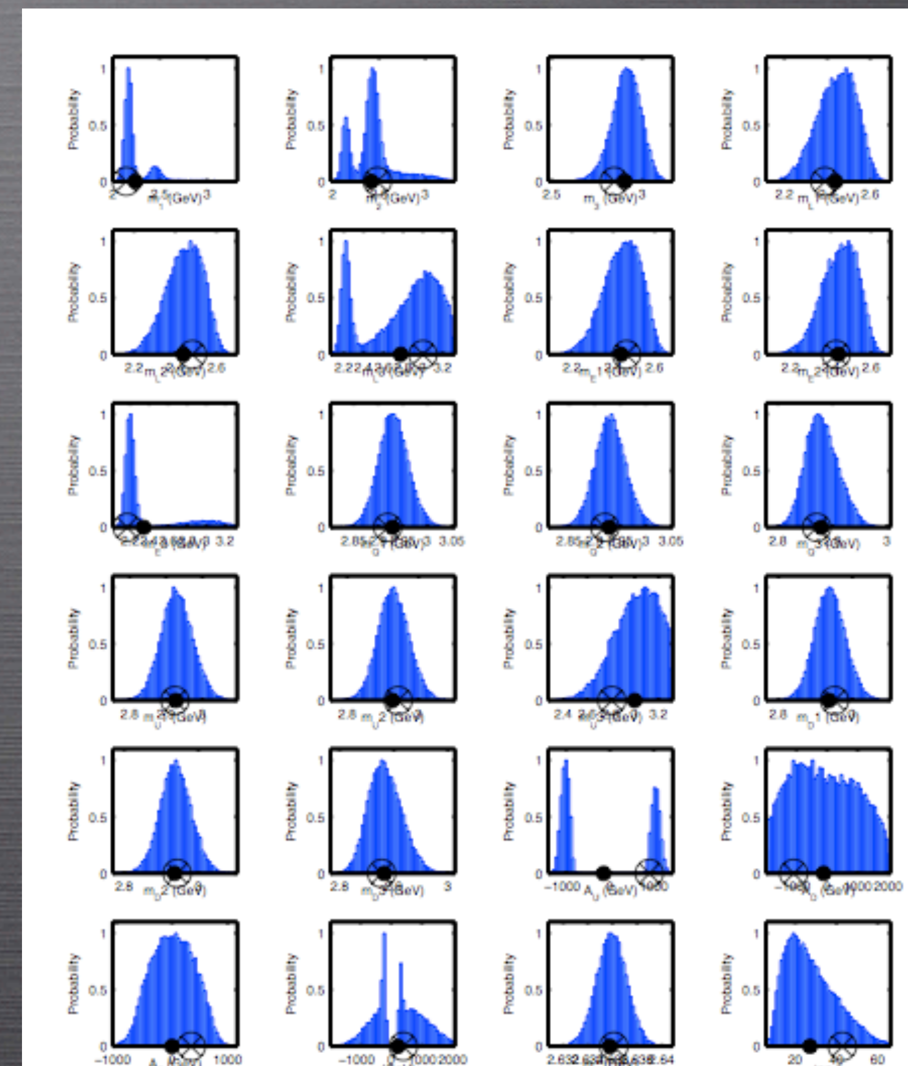
(example in the stau coannihilation region, 24 parms pMSSM)

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).

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

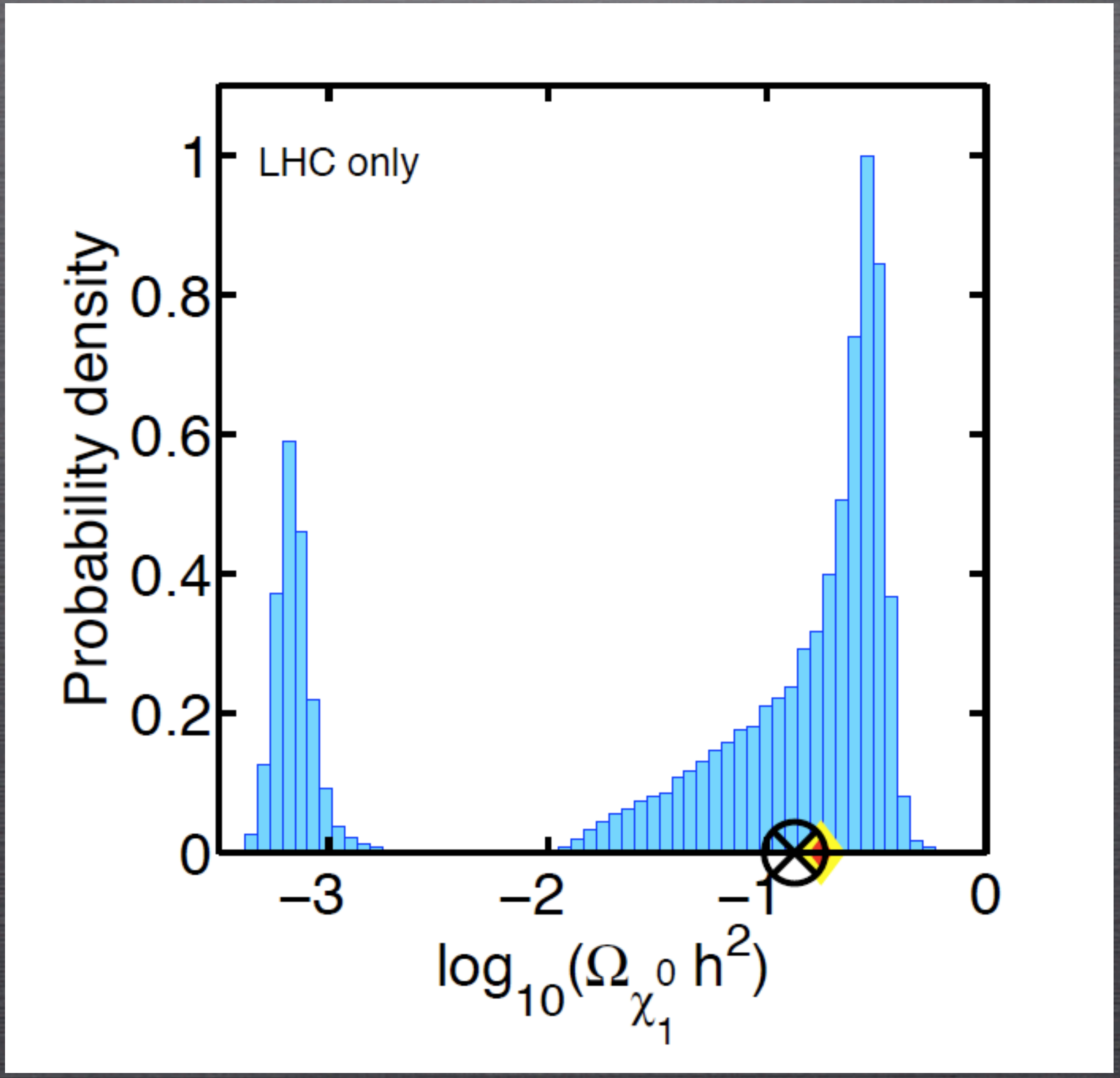
MCMC as implemented in the SuperBayes code



- 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

Example of Inverse problem at LHC

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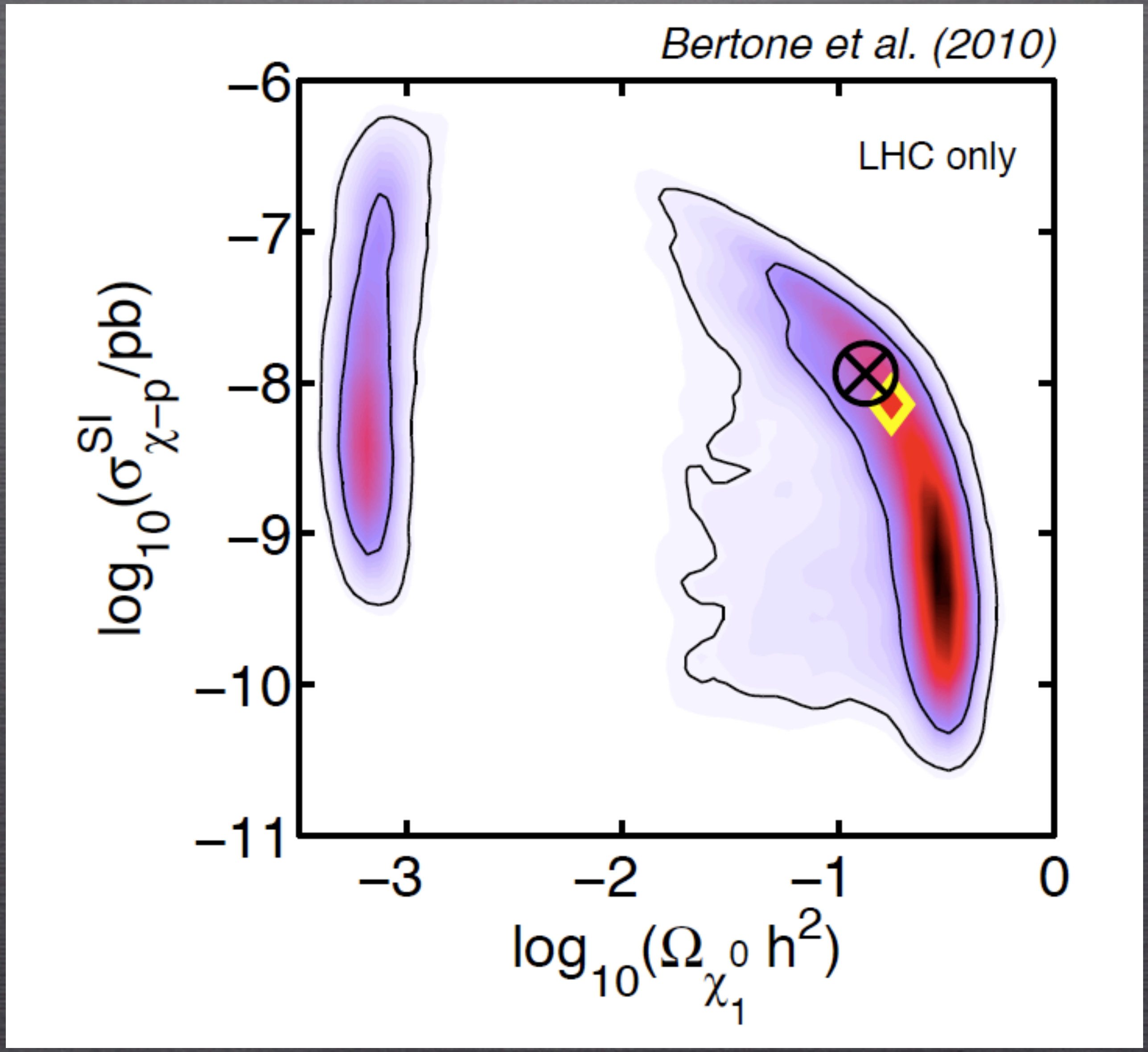
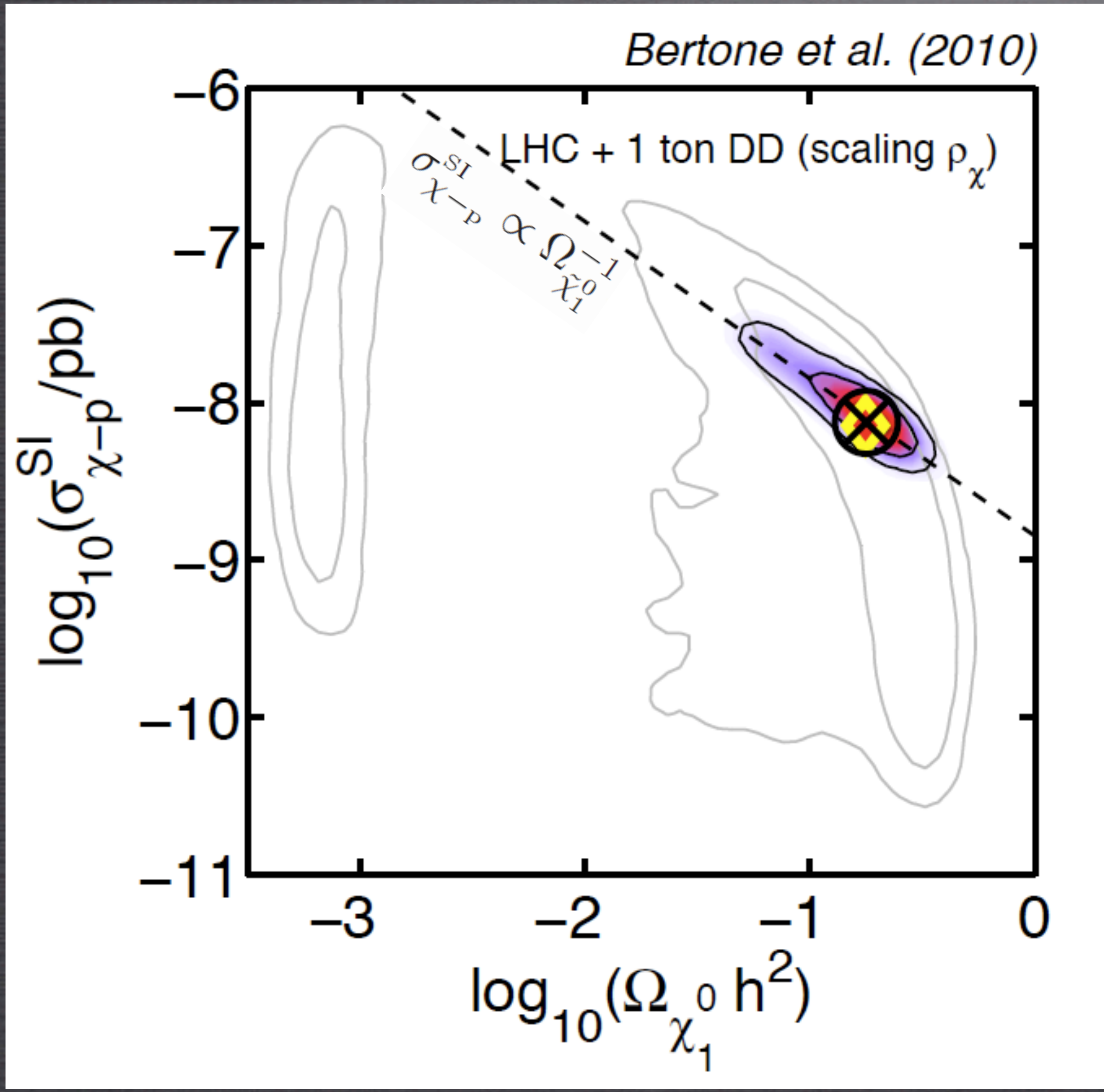


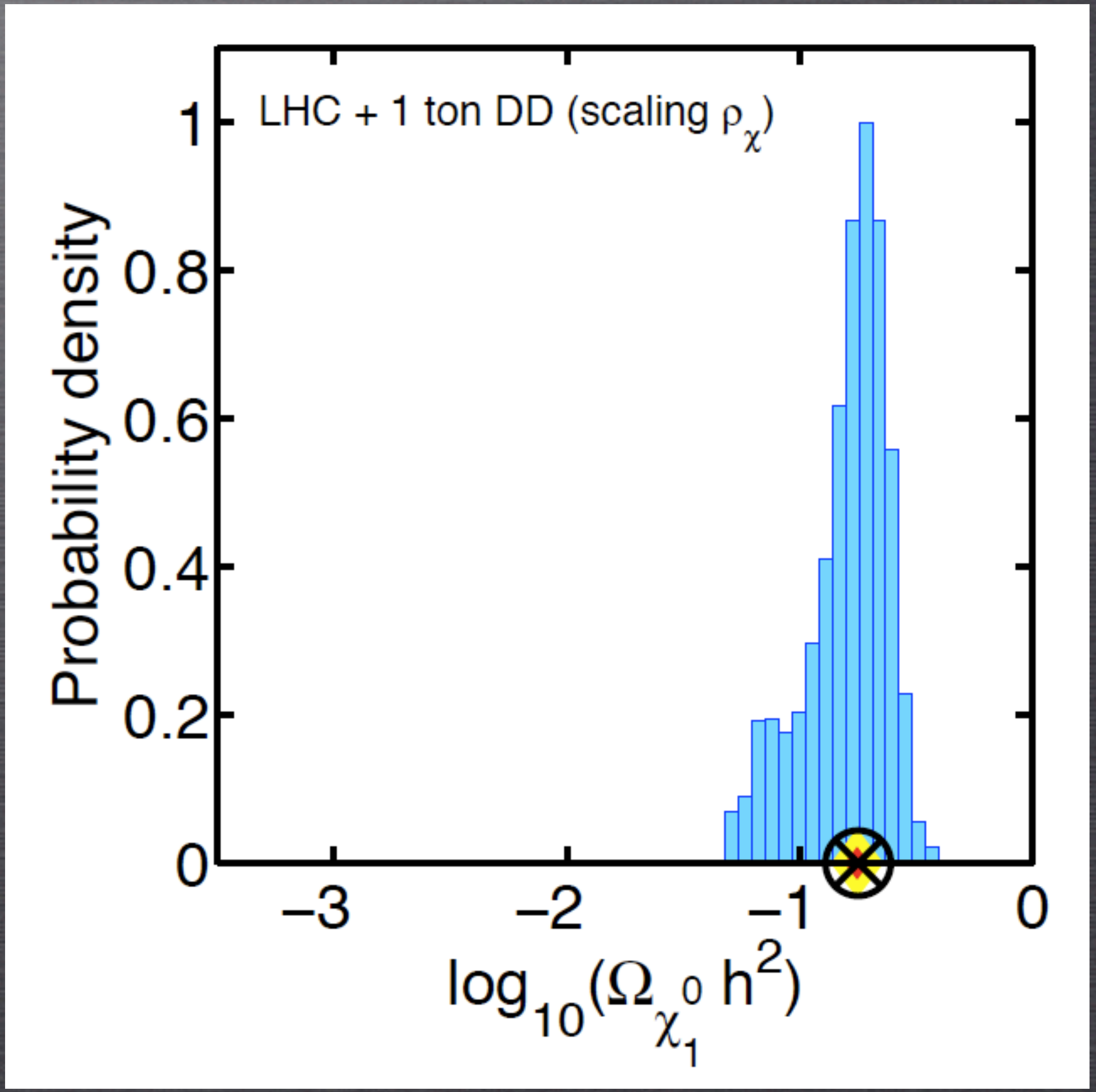
GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta, 2010

DD+LHC

"Scaling" Ansatz

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



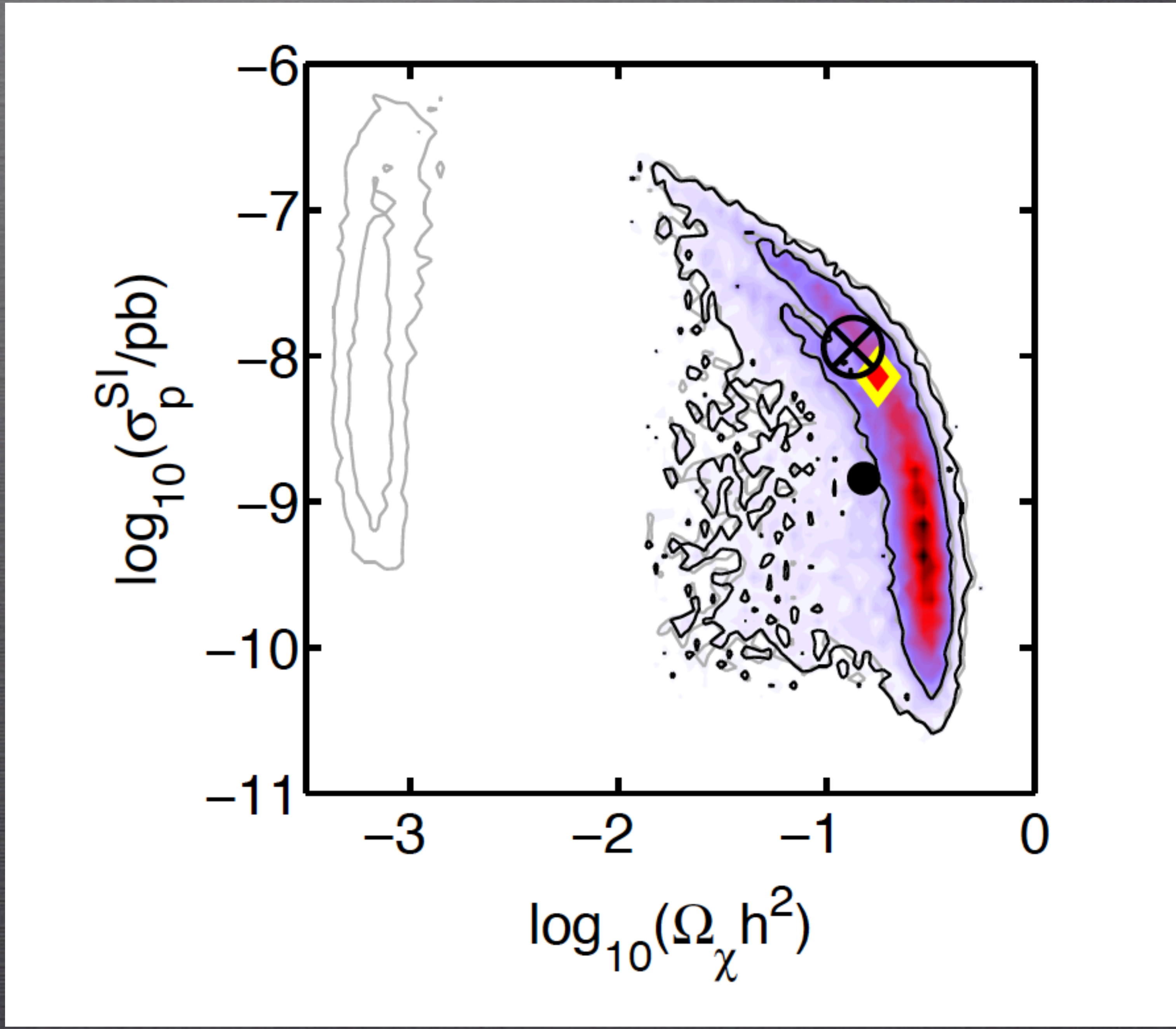


What happens if we add Fermi upper limits from dwarfs to the LHC posterior?

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

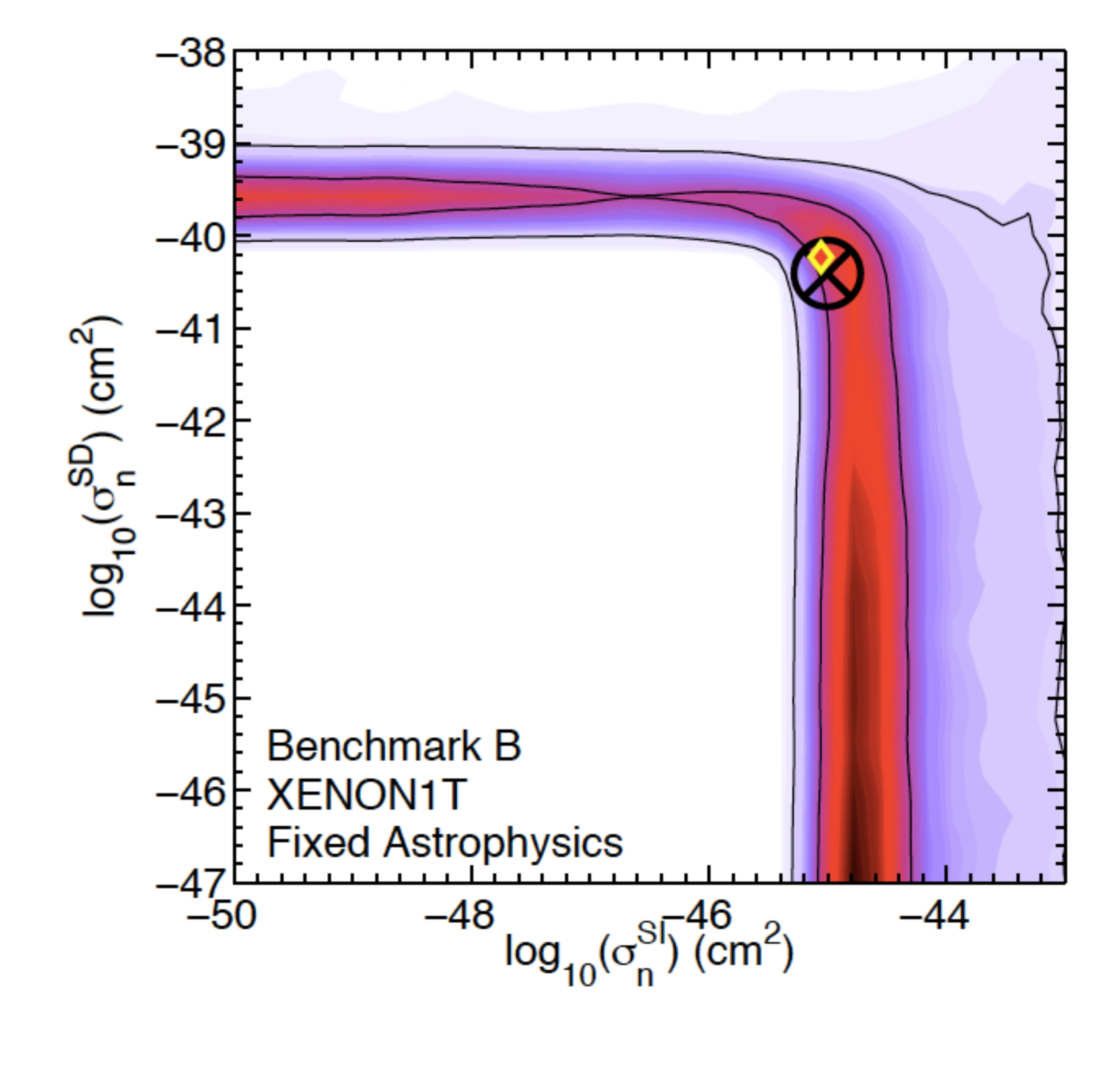


GB, Fornasa, Pieri, Ruiz, Trotta 2011

DD + ID

XENON1T

$$\frac{d\sigma}{dE} = \frac{d\sigma}{dE}\Big|_{SI} + \frac{d\sigma}{dE}\Big|_{SD}.$$



Arina, GB, Silverwood, in preparation

DD + ID

Xenon1T + Icecube 86

XENON1T

$$\frac{d\sigma}{dE} = \frac{d\sigma}{dE}\Big|_{SI} + \frac{d\sigma}{dE}\Big|_{SD}.$$

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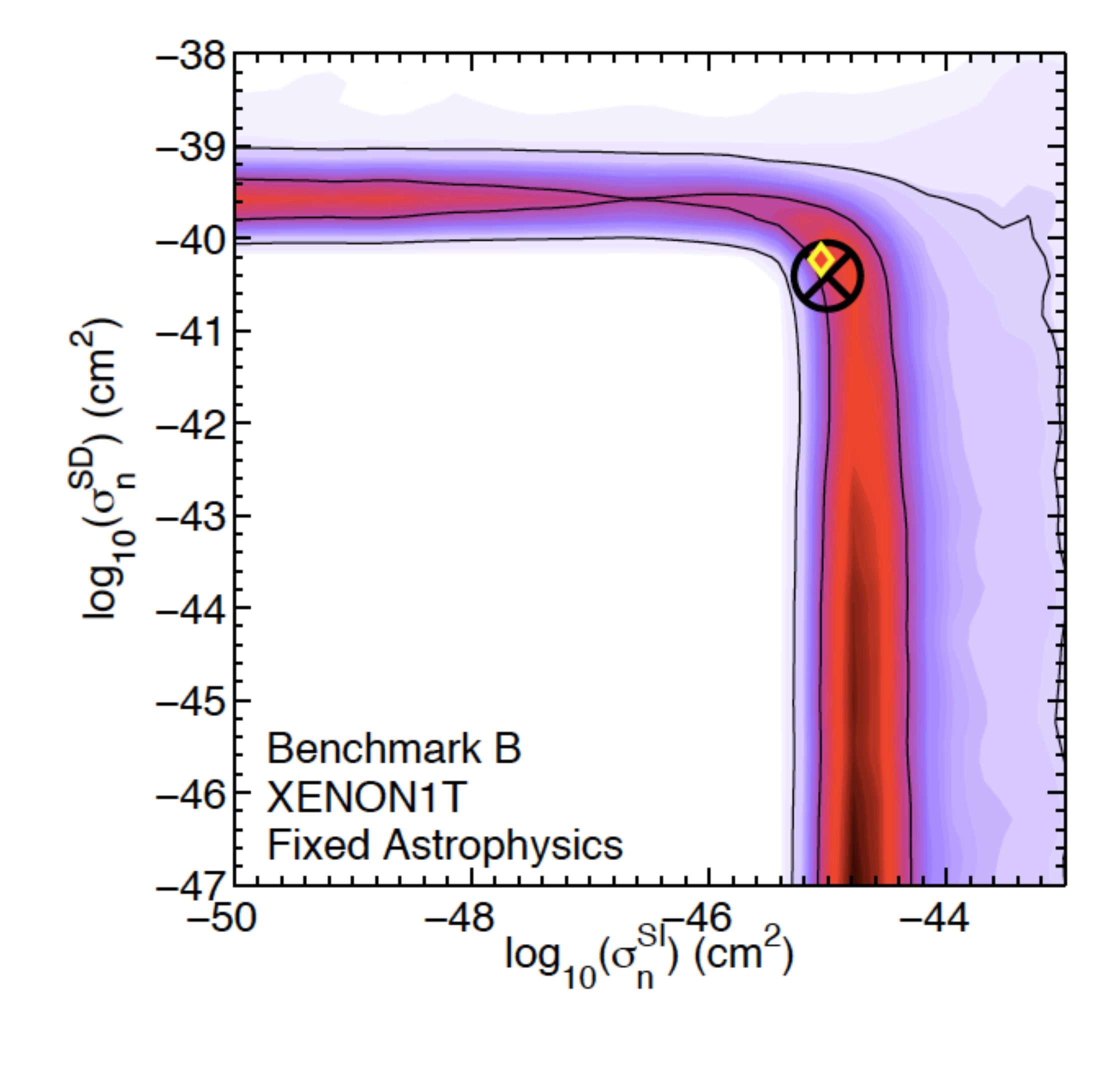
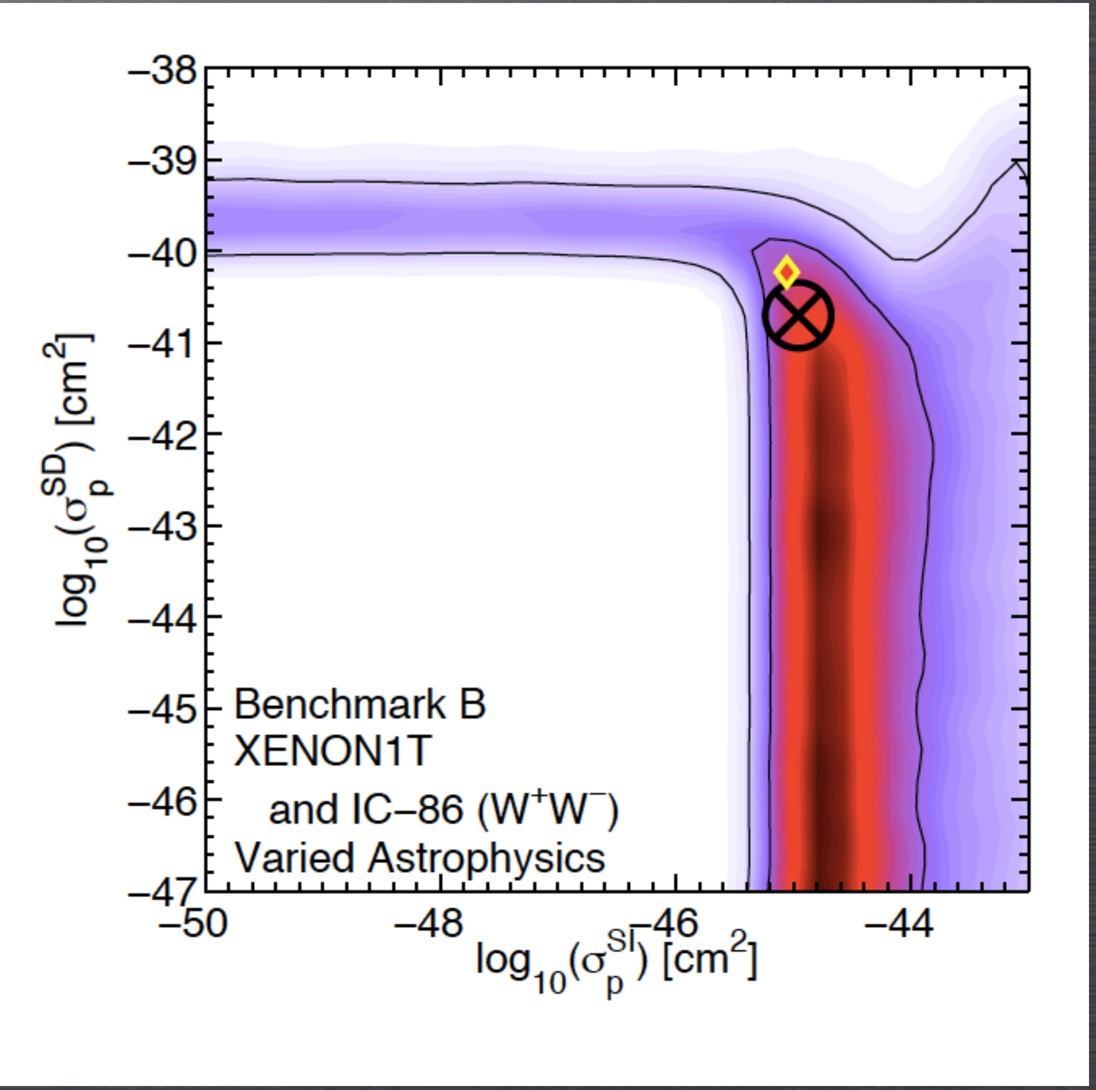
$$\sigma_i = \begin{cases} \sigma^{SI} + \sigma^{SD}, & \text{for } i = 1 \\ \beta^2 \sigma^{SI} A_i^2 & \text{for } i \geq 2. \end{cases}$$





ARINA, GB, SILVERWOOD, IN PREPARATION

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 soon running at full energy! 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!