Dark Matter: the Big Picture

Gianfranco Bertone
GRAPPA Institute, U. of Amsterdam

"Prospects in low mass dark matter"
MPP, 30 Nov 2015

GRAPPA
GRavitation AstroParticle Physics Amsterdam

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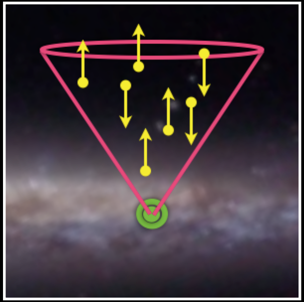
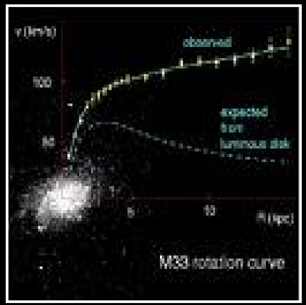
Evidence for Dark Matter

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

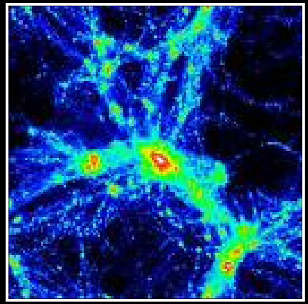
COSMOLOGICAL OBSERVATIONS



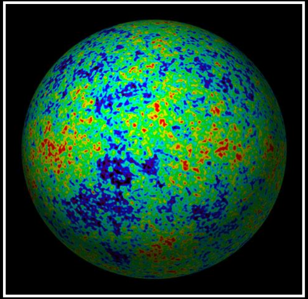
- **‘Local’ matter density**



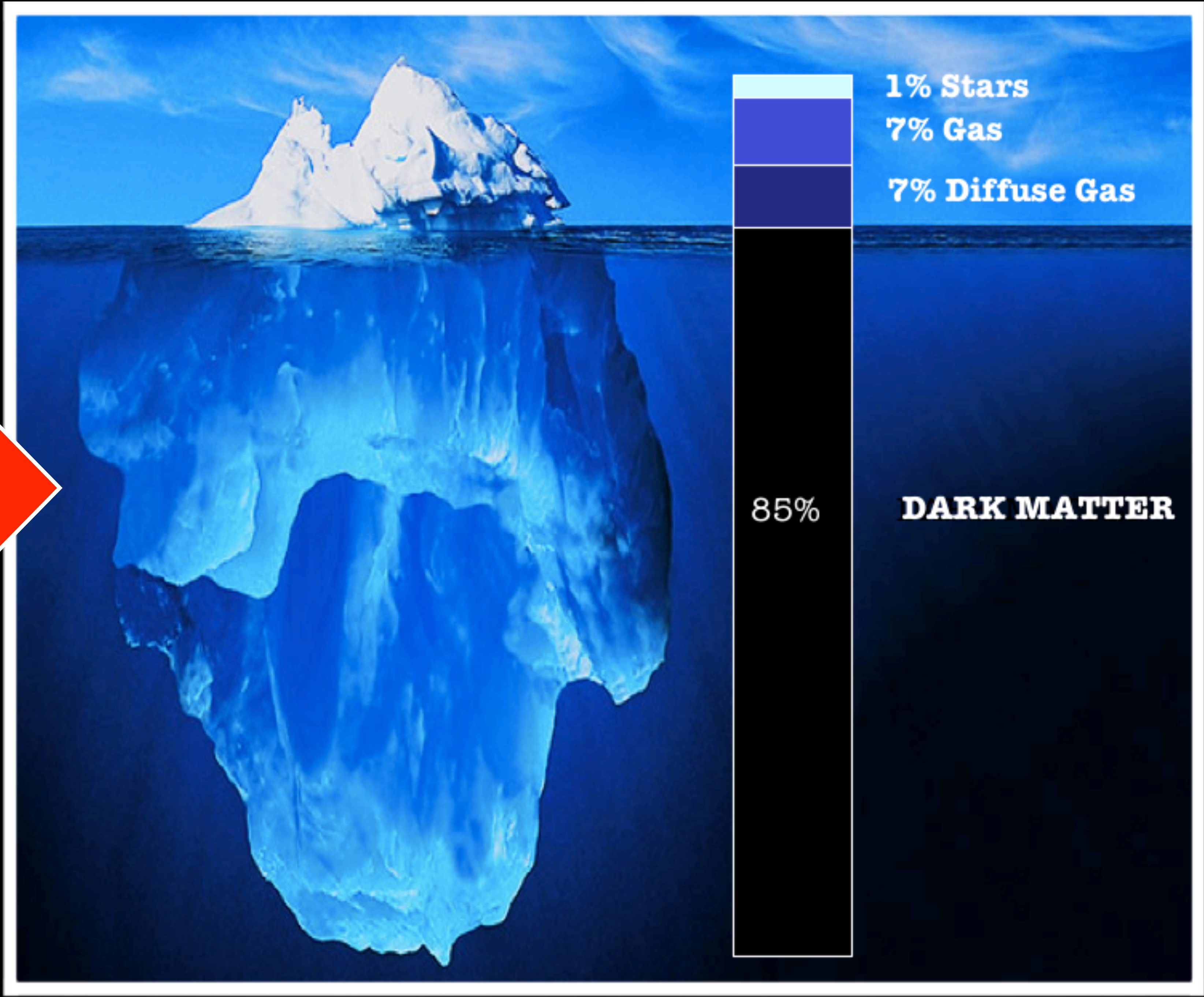
- **Rotation Curves**



- **Clusters of galaxies**



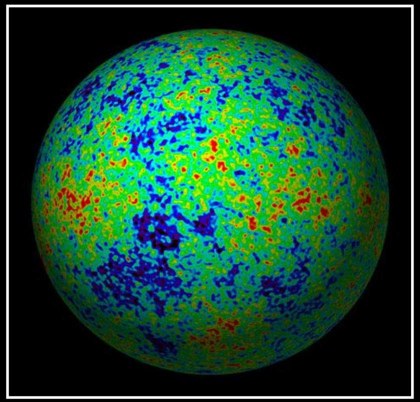
- **CMB**



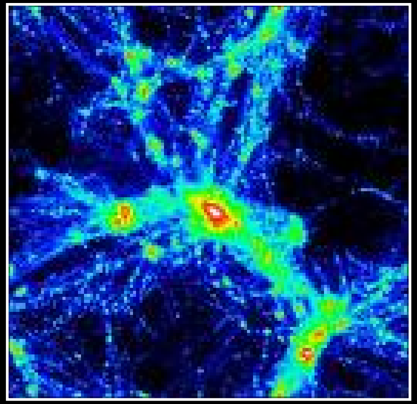
What do we know?

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

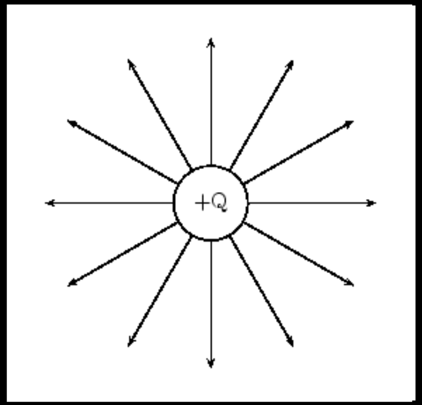
1) Ωh^2 OK?



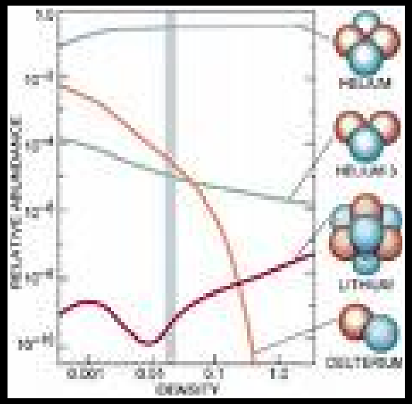
2) Is it cold?



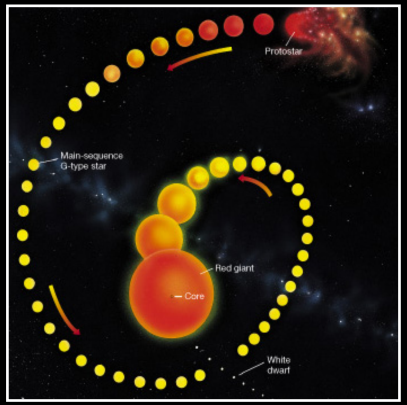
3) Is it neutral?



4) Is BBN ok?



5) Stars OK?



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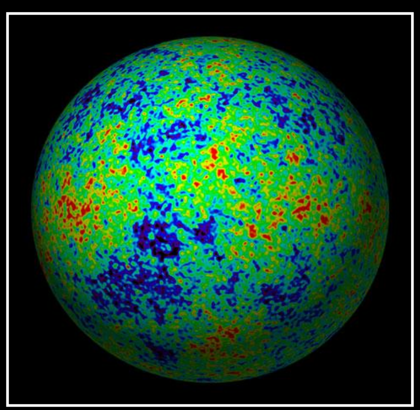

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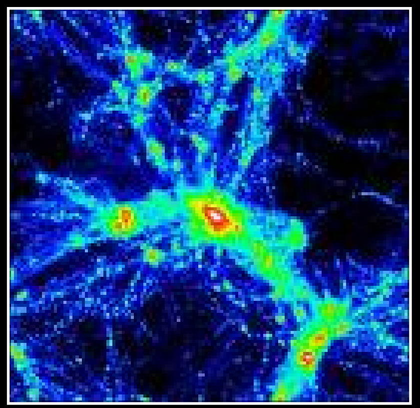

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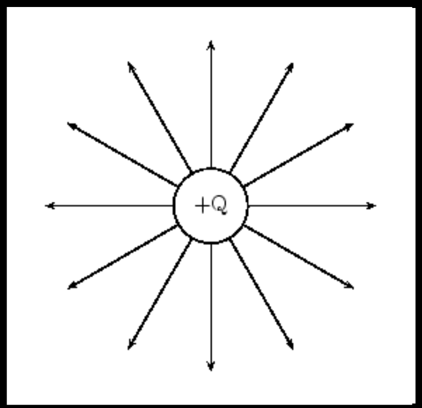

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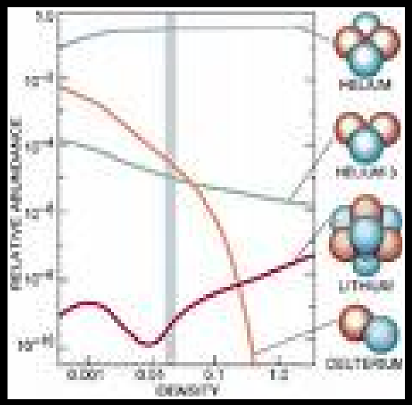

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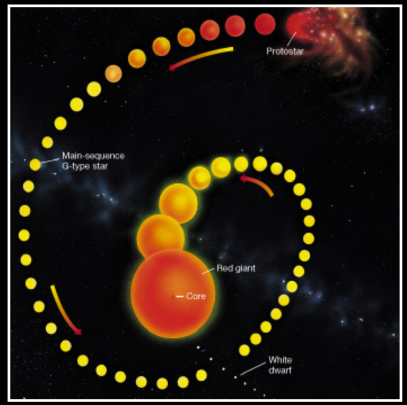
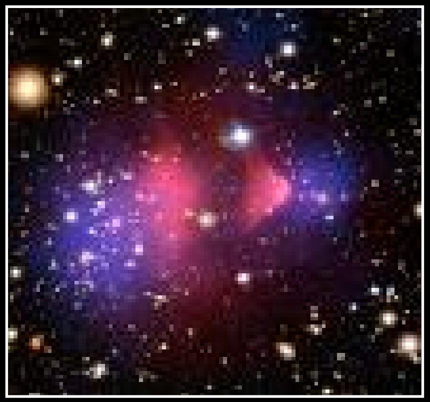
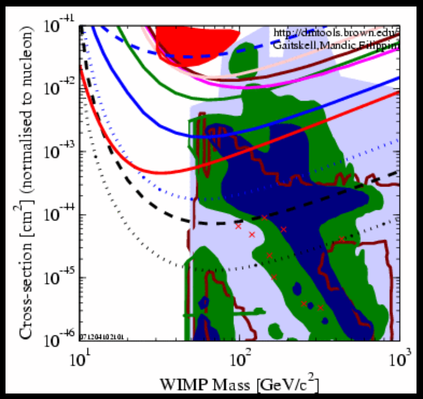


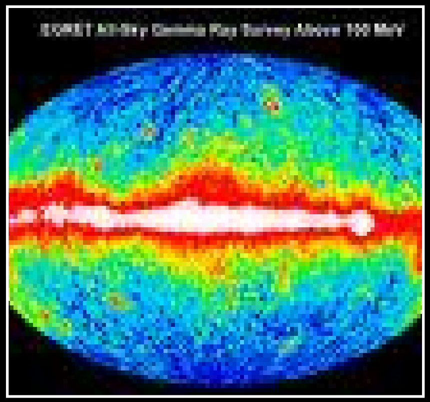
6) Collisionless?



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.

- **E.g. SUSY** Neutralino

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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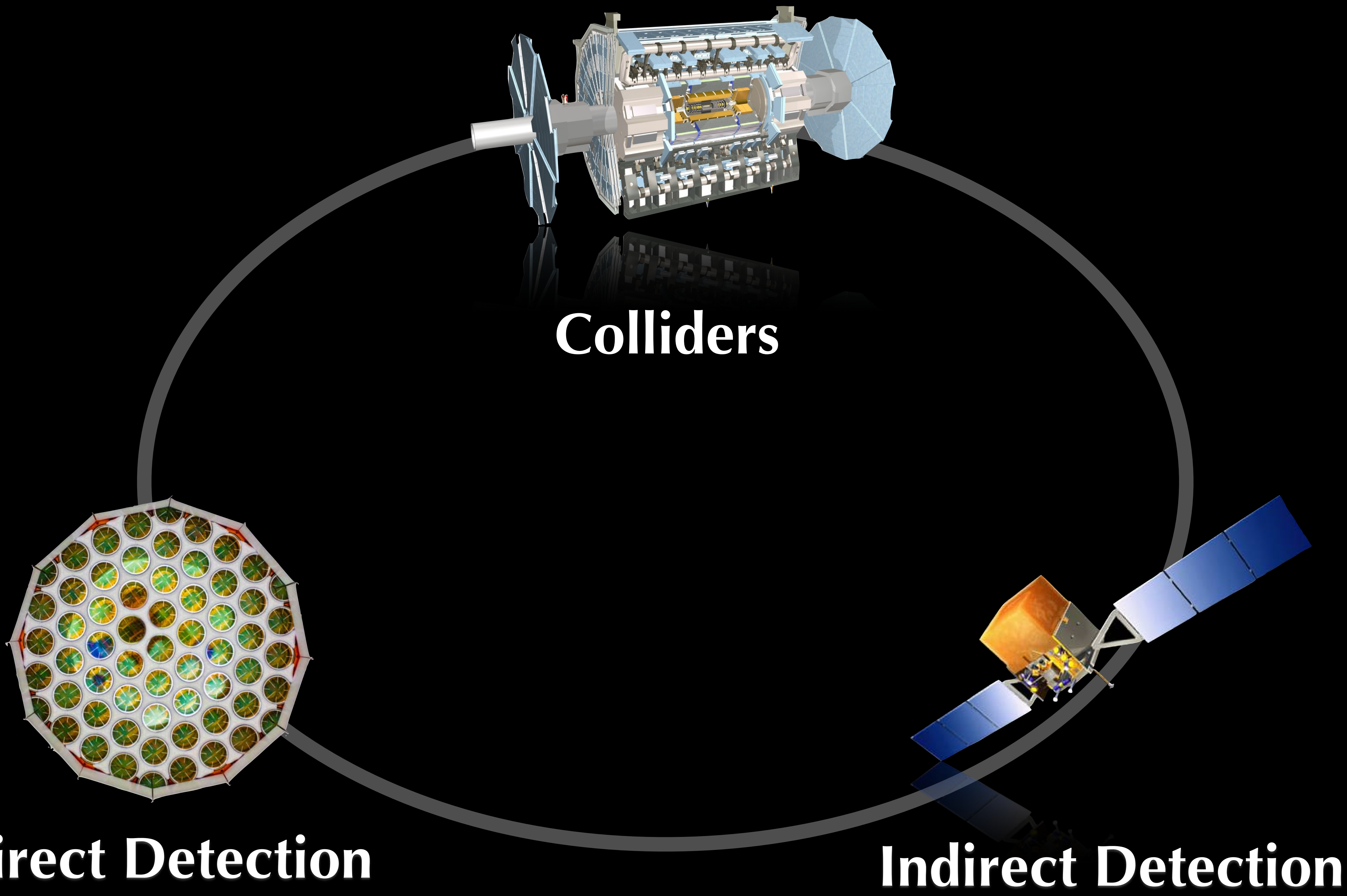
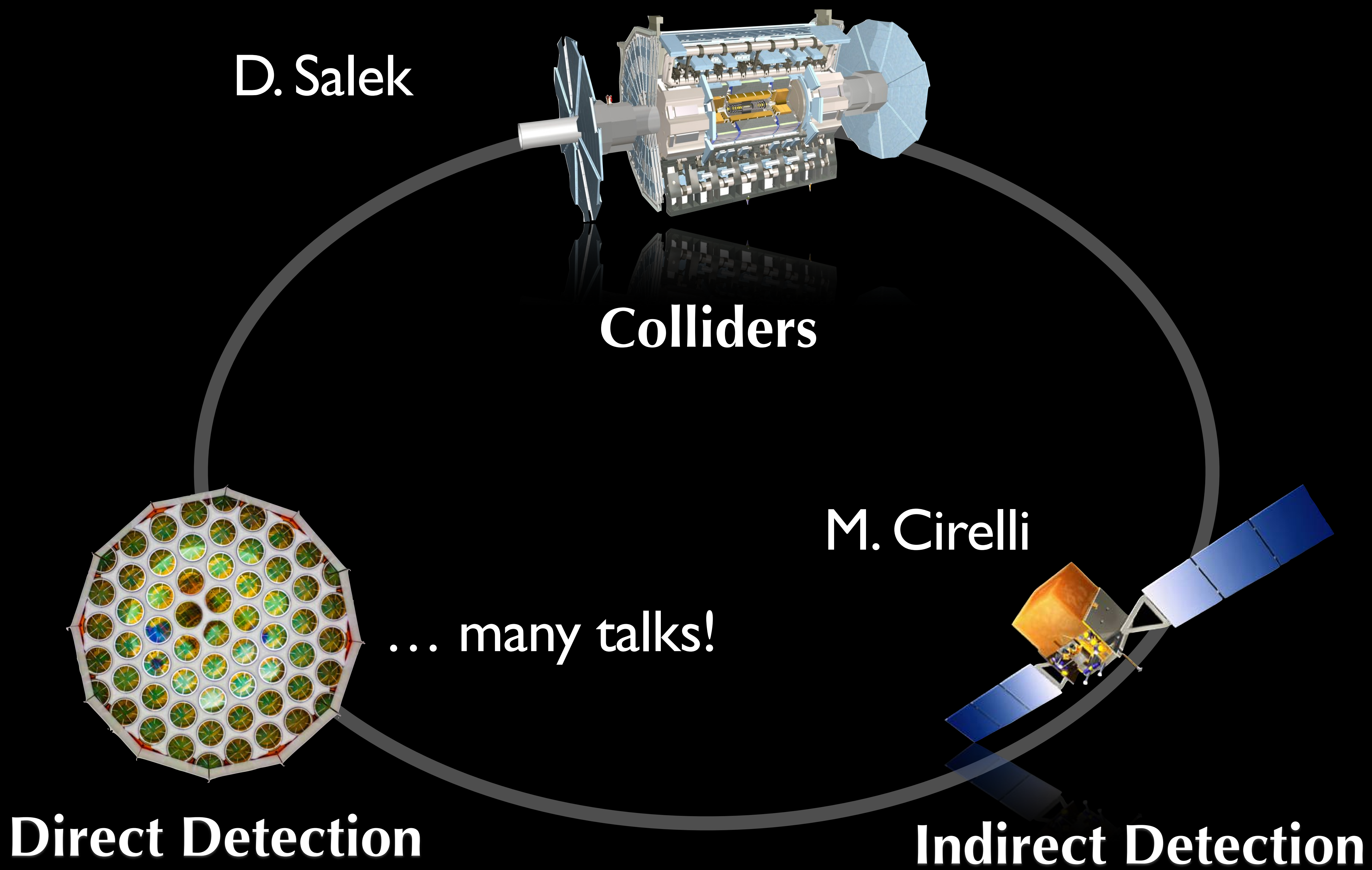
Talks by
A. Merle
T. Volansky
J. Redondo

The quest for Dark Matter



The quest for Dark Matter

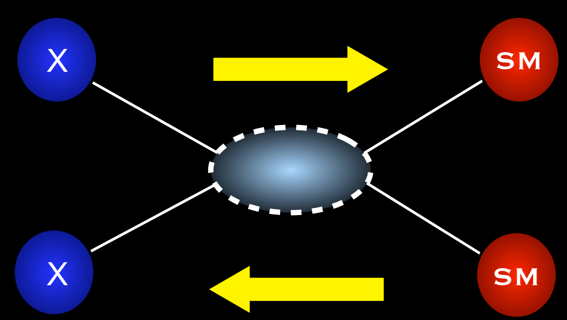


Indirect Detection

Why "annihilations"?

X = Dark Matter   SM = Standard Model Particle

Early Universe



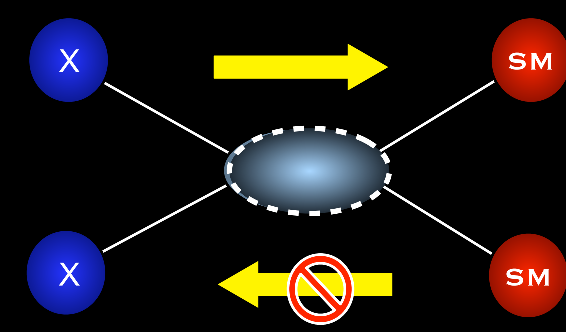
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle\left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

Relic density (NR freeze-out)

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

Electroweak-scale cross sections can reproduce correct relic density.

Today



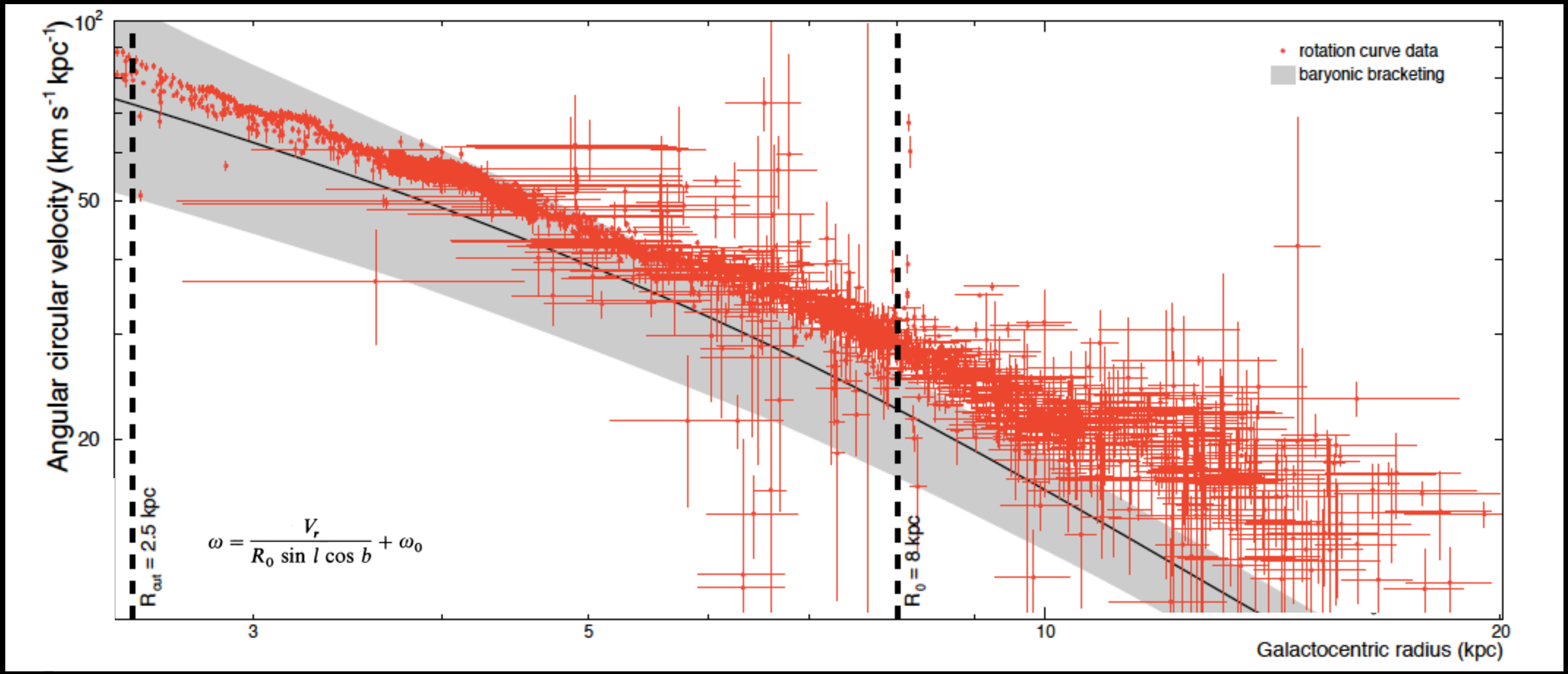
$$\frac{dn_\chi}{dt} = -(\sigma v)_o n_\chi^2$$

Annihilation Flux

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

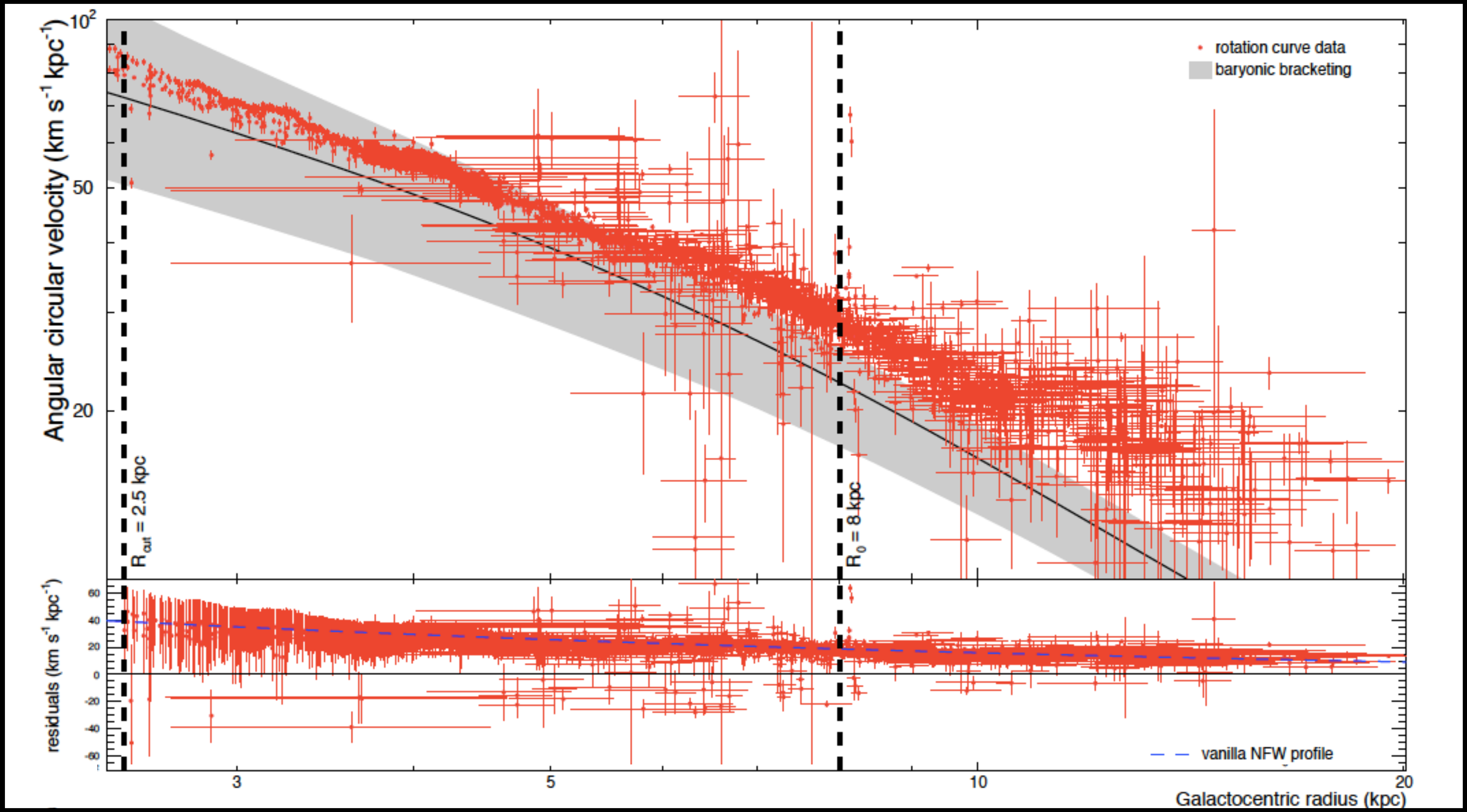
Particle physics input from extensions of the Standard Model. Need to specify distribution of DM along the line of sight.

Astro frontier: e.g. Rotation curve of the Milky Way



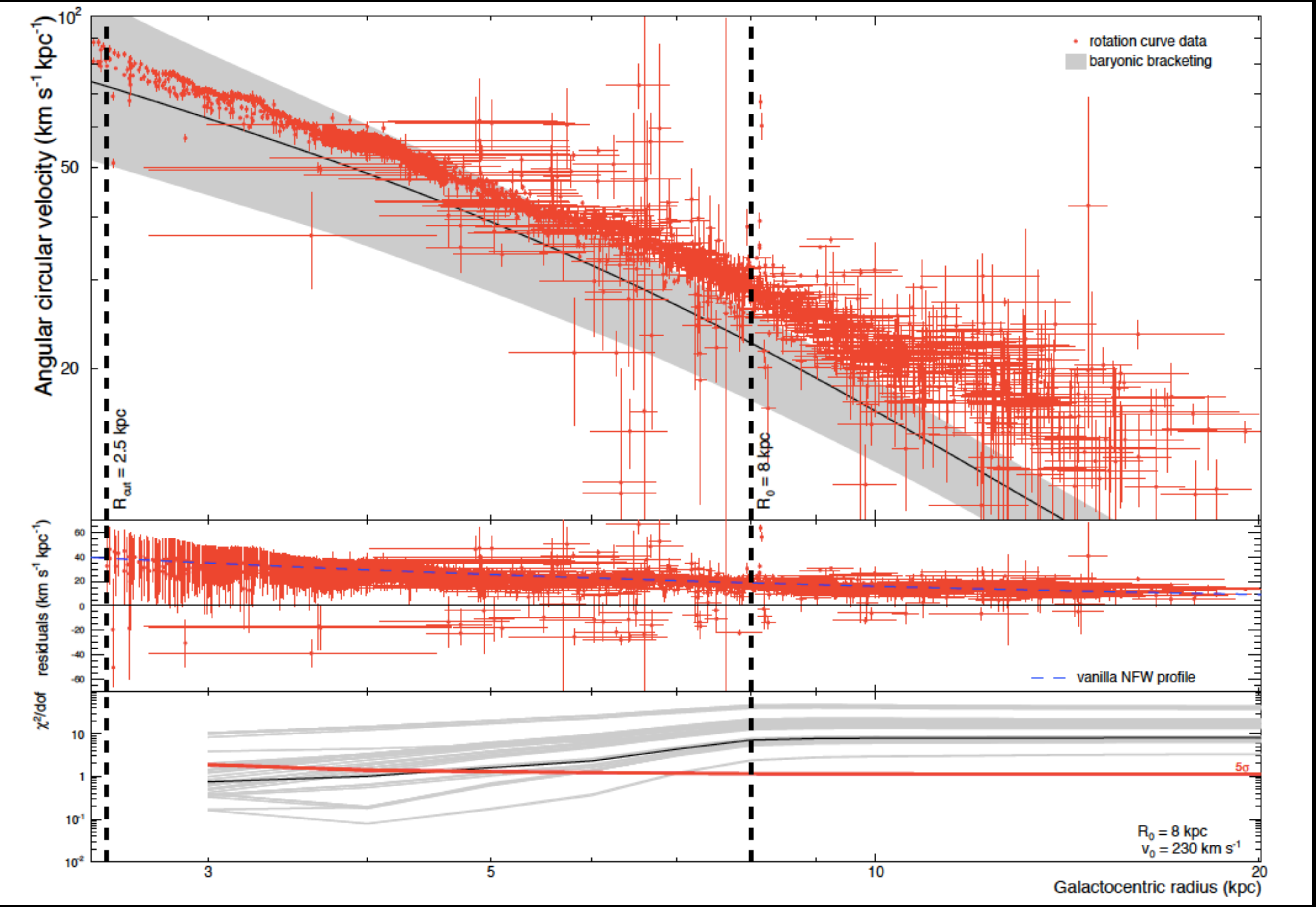
Iocco, Pato, GB, Nature Physics, arXiv:1502.03821

Rotation curve of the Milky Way



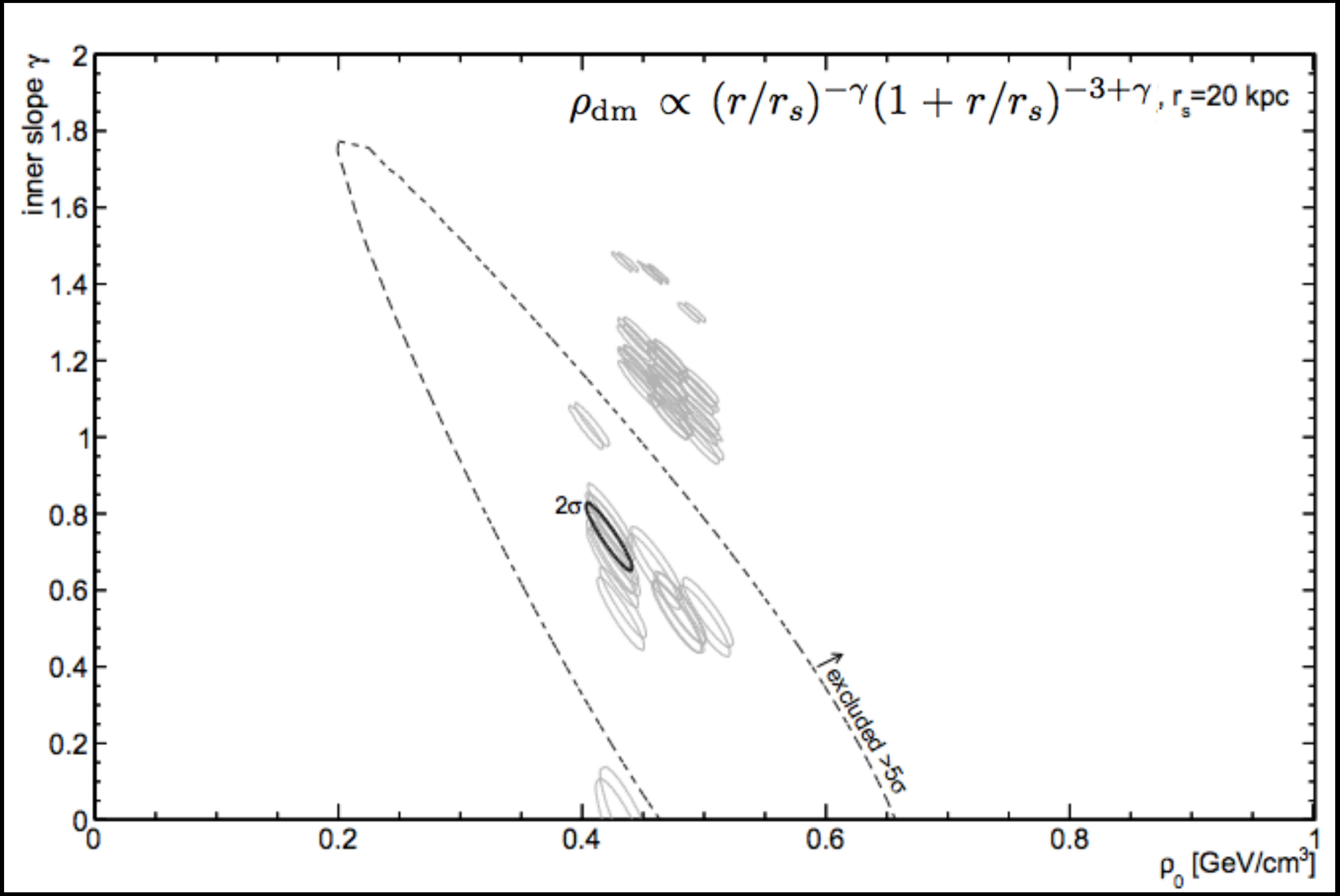
Iocco, Pato, GB, Nature Physics, arXiv:1502.03821

A tool to study DM distribution in the MW



Iocco, Pato, GB, Nature Physics, arXiv:1502.03821

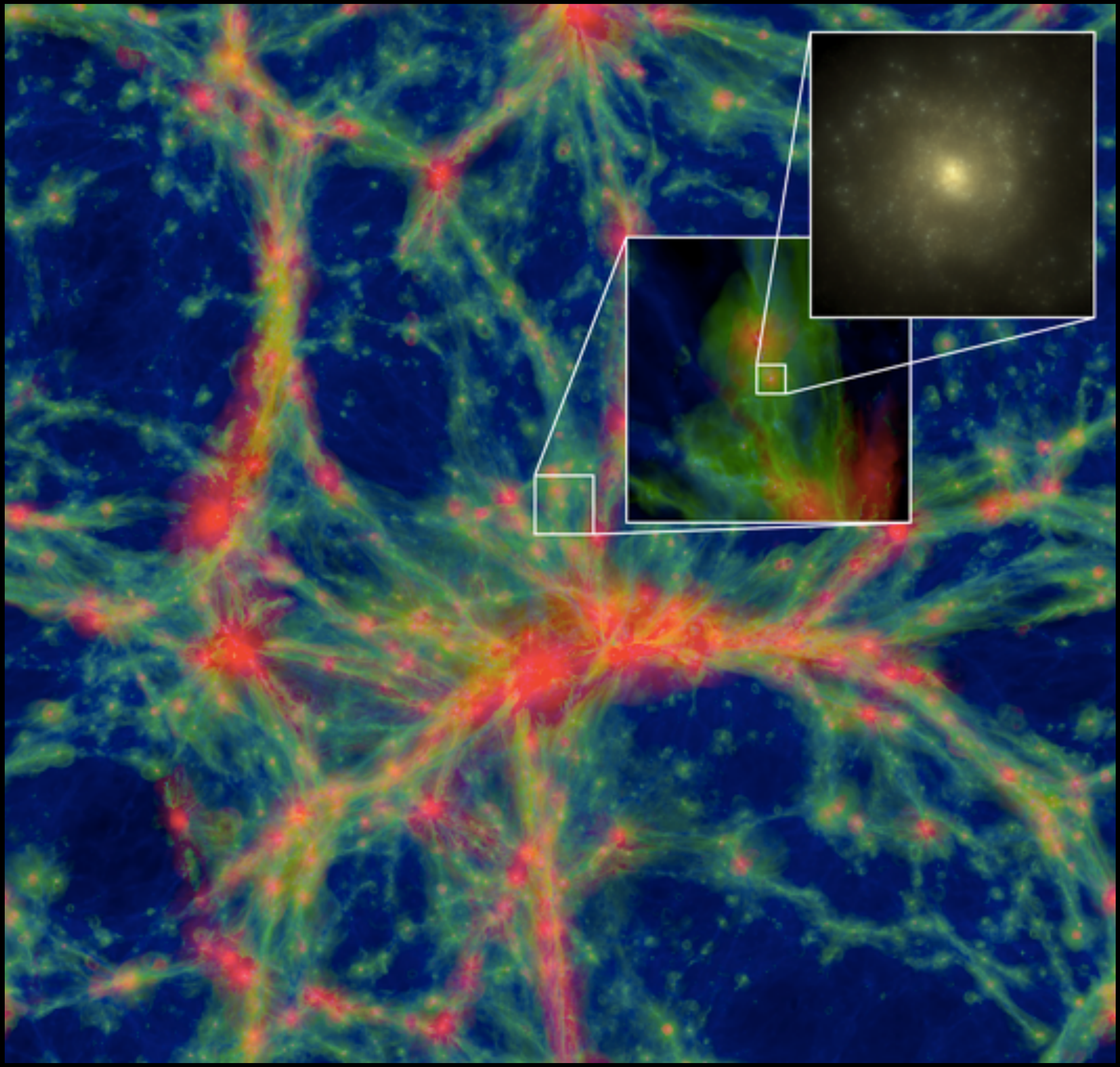
Constraints on MW DM profile



Pato, Iocco, GB, arXiv: 1504.06324

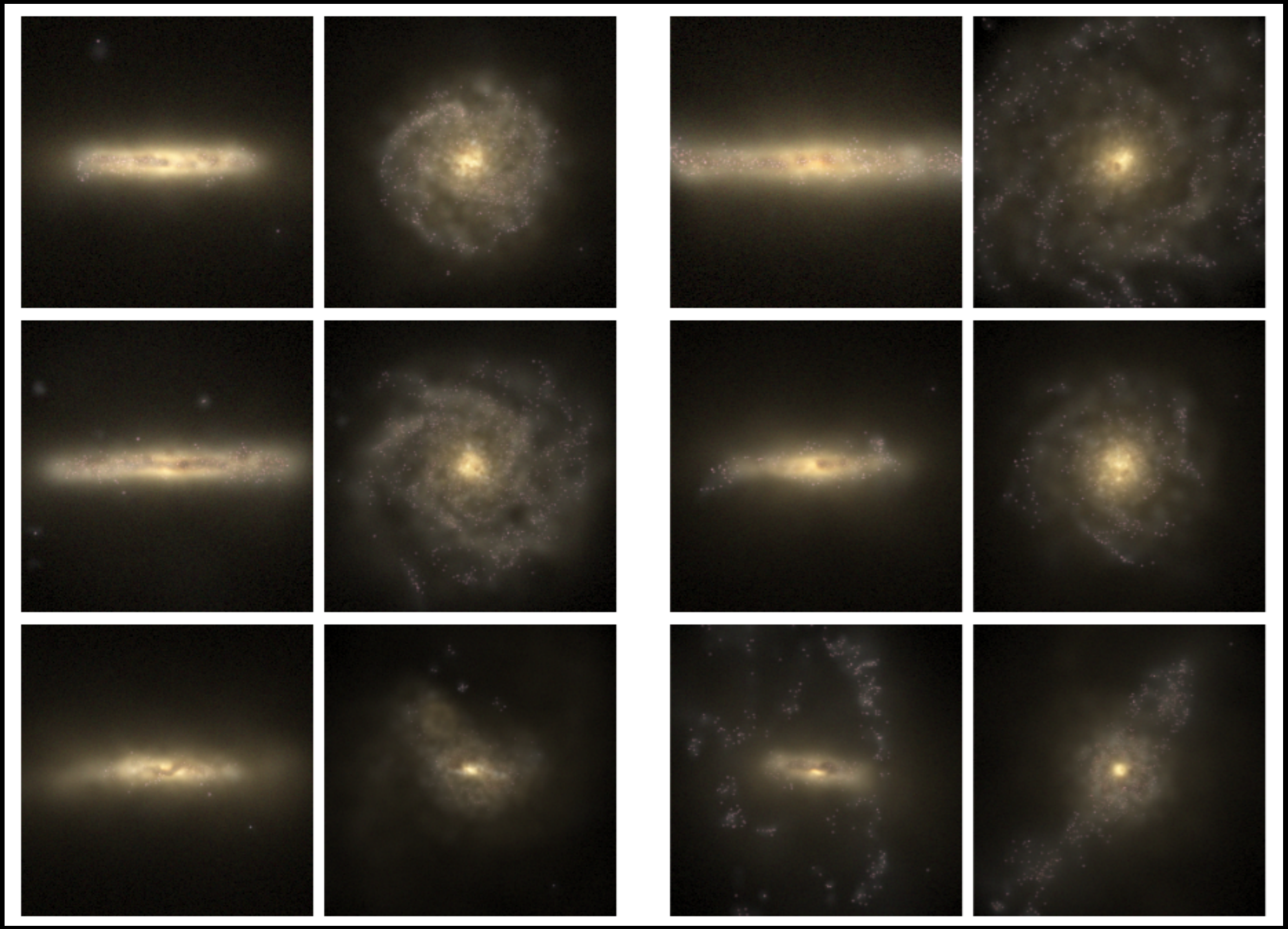
Numerical simulations frontier

The Eagle simulation



- One of the largest cosmological hydrodynamical simulations (7 billion particles)
- 1.5 months on 4000 cores DiRAC-2 supercomputer in Durham
- Runs a modified version of the GADGET-2 simulation code

Identifying MW-like galaxies



Calore, Bozorgnia, GB+ arXiv:1509.02164

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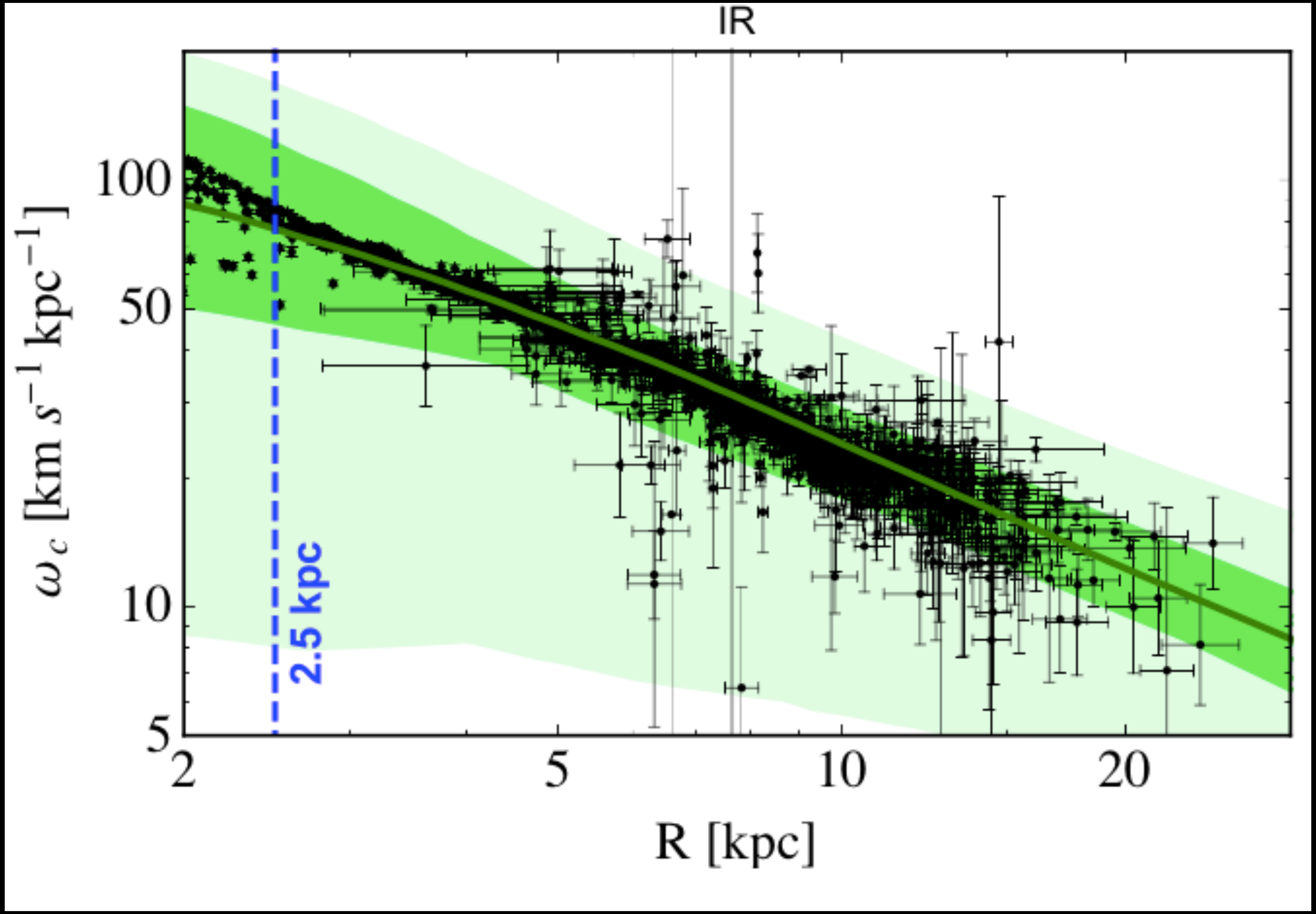
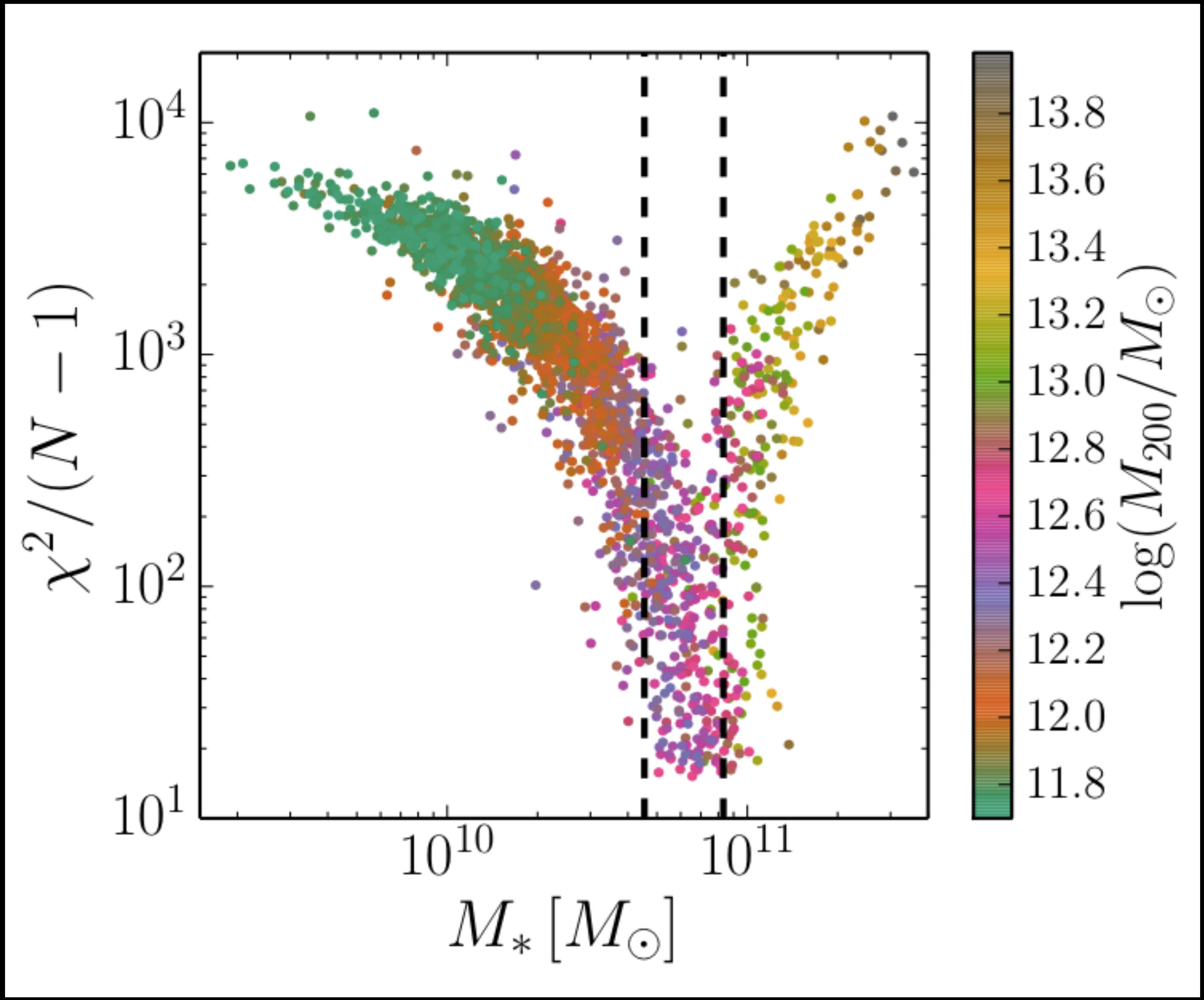


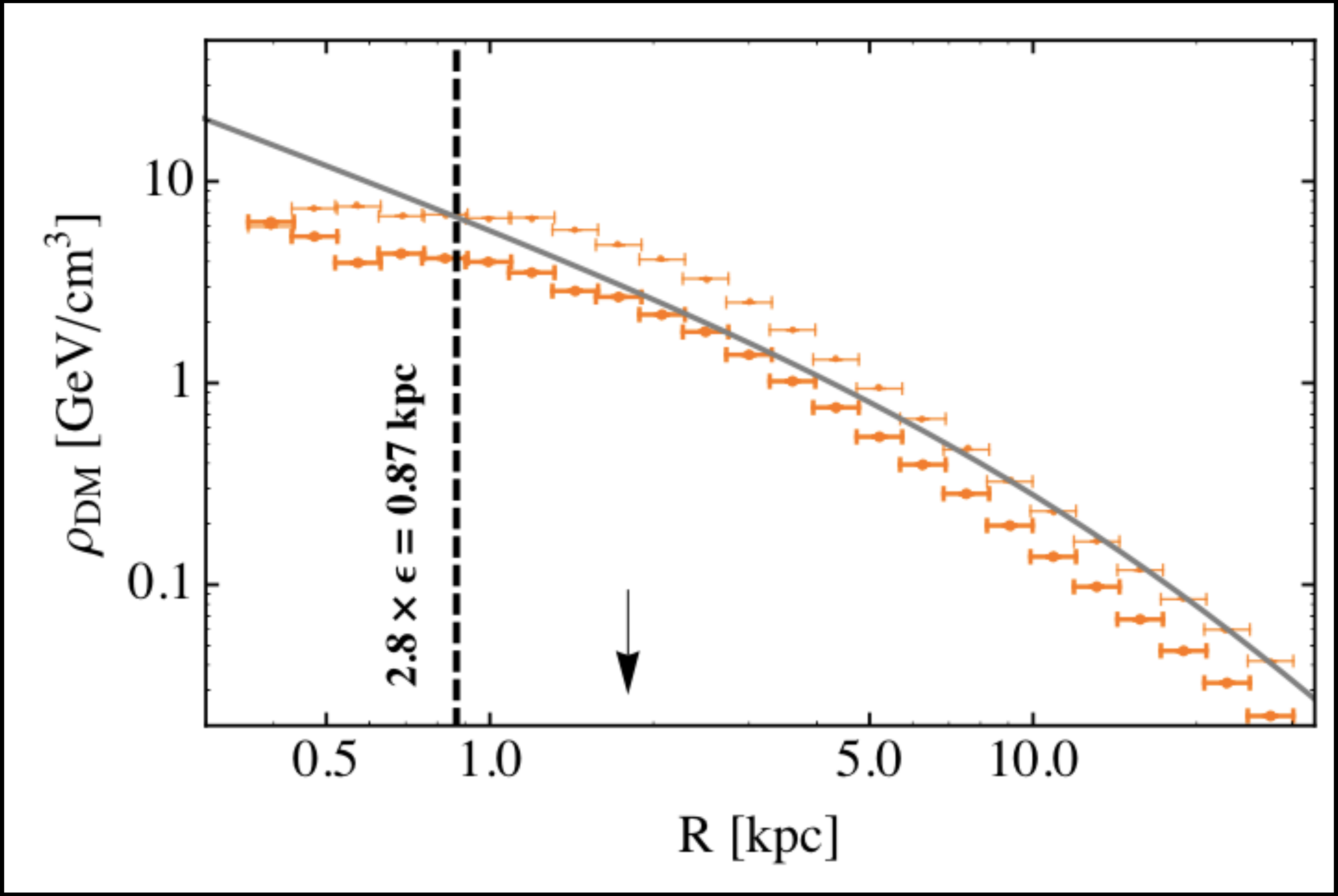
Calore, Bozorgnia, GB+ arXiv:1509.02164

Identifying MW-analogues



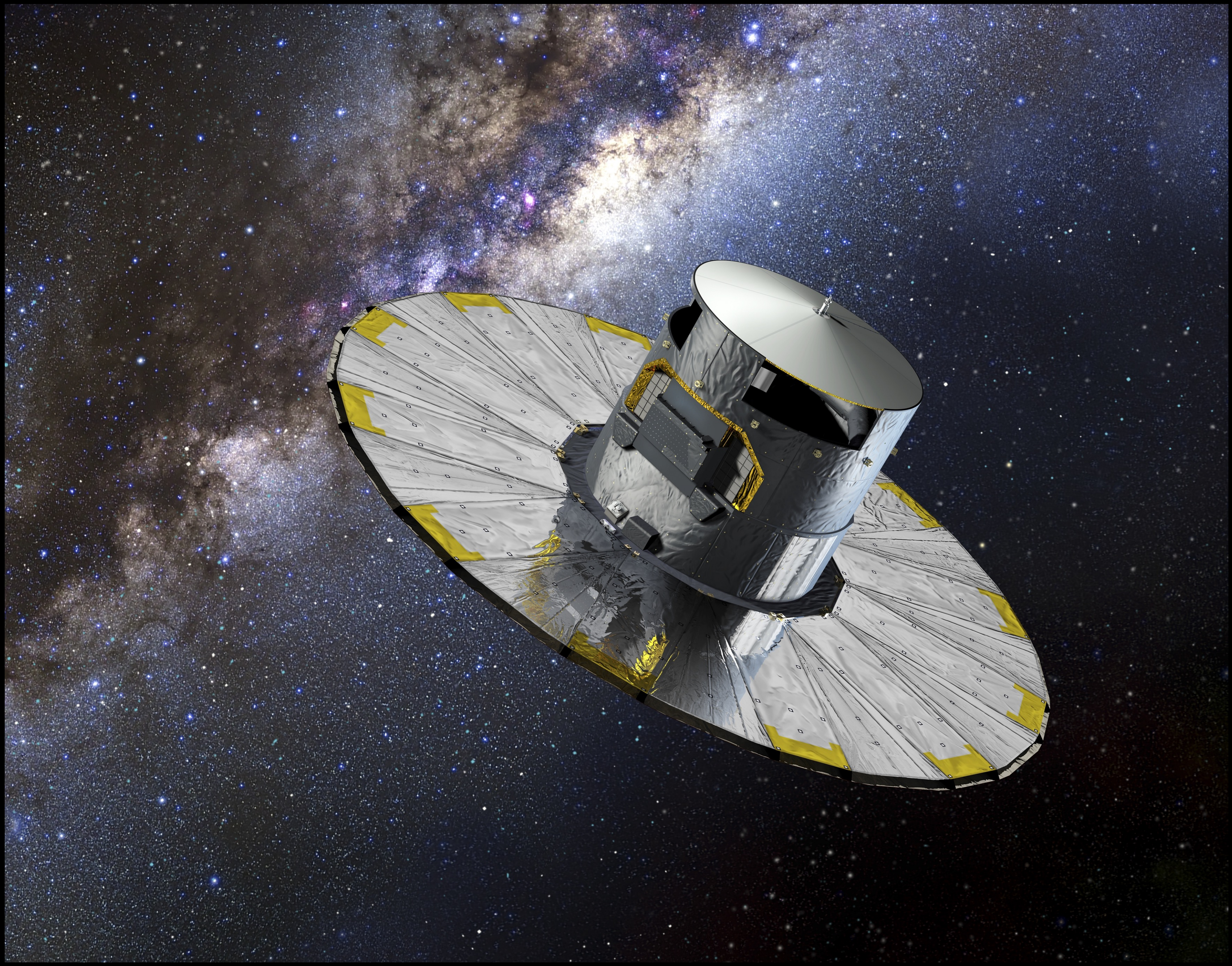
Calore, Bozorgnia, GB+ arXiv:1509.02164

“Predicted” DM profile



Calore, Bozorgnia, GB+ arXiv:1509.02164

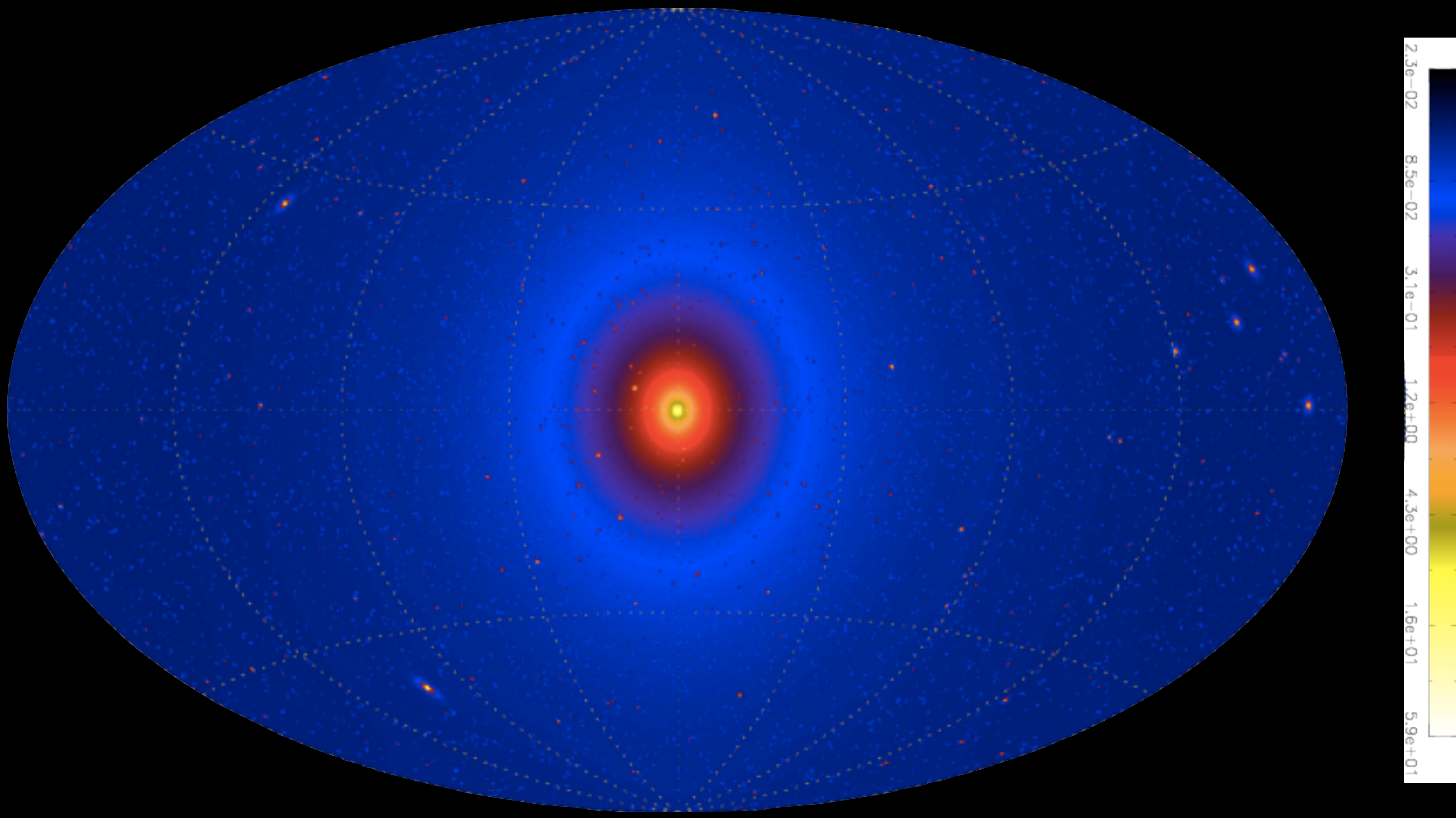
Better constraints on DM (and MoND) soon..



New astronomical surveys coming soon. ESA's Gaia satellite is currently charting a three-dimensional map of the Milky Way!

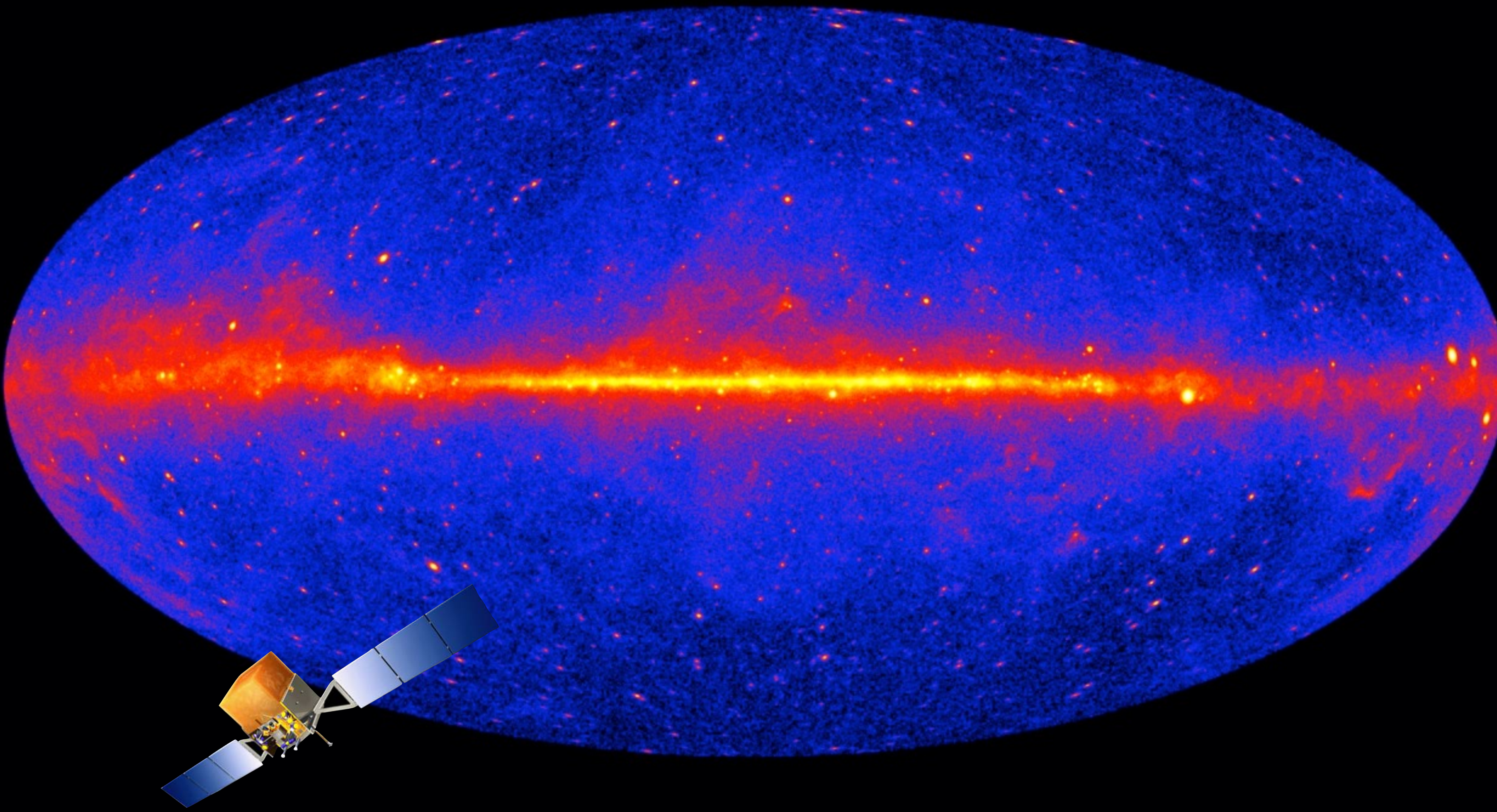
Predicted Annihilation Flux

Pieri, GB, Branchini 2009



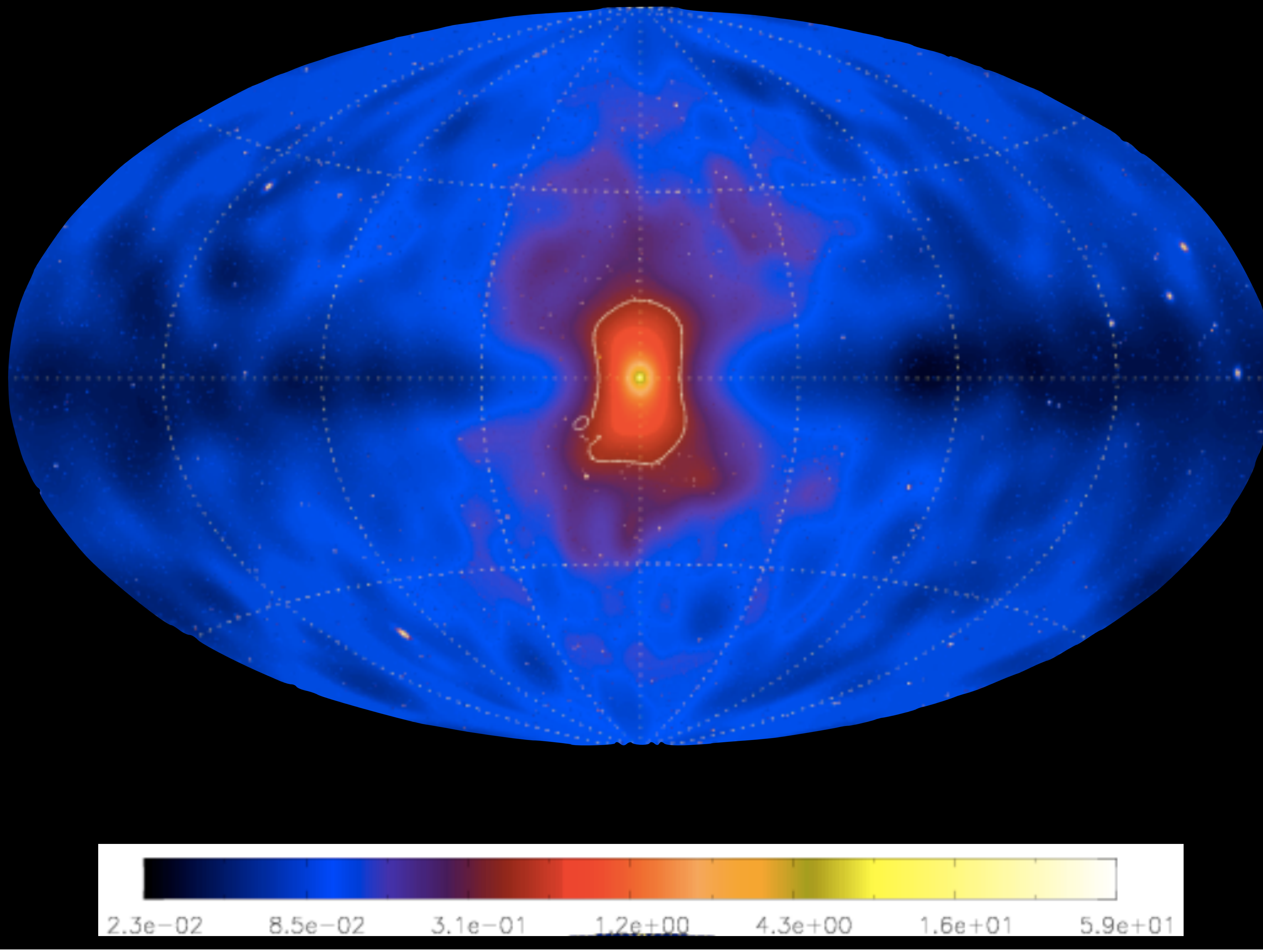
Full sky map of Number of photons above 3 GeV

The FERMI sky



"Sensitivity" Map

Pieri, GB, Branchini 2009



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The "GeV Excess"

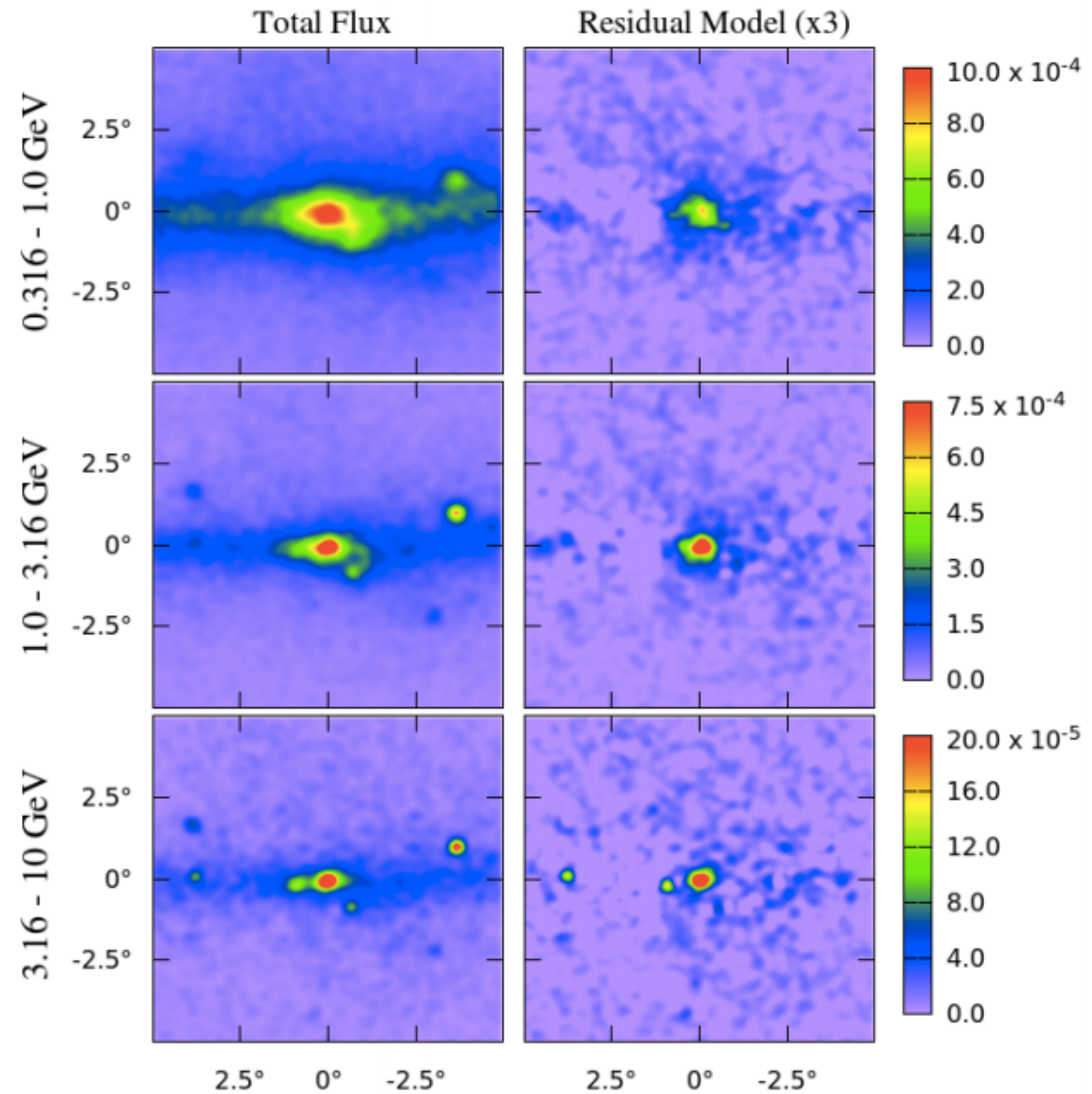
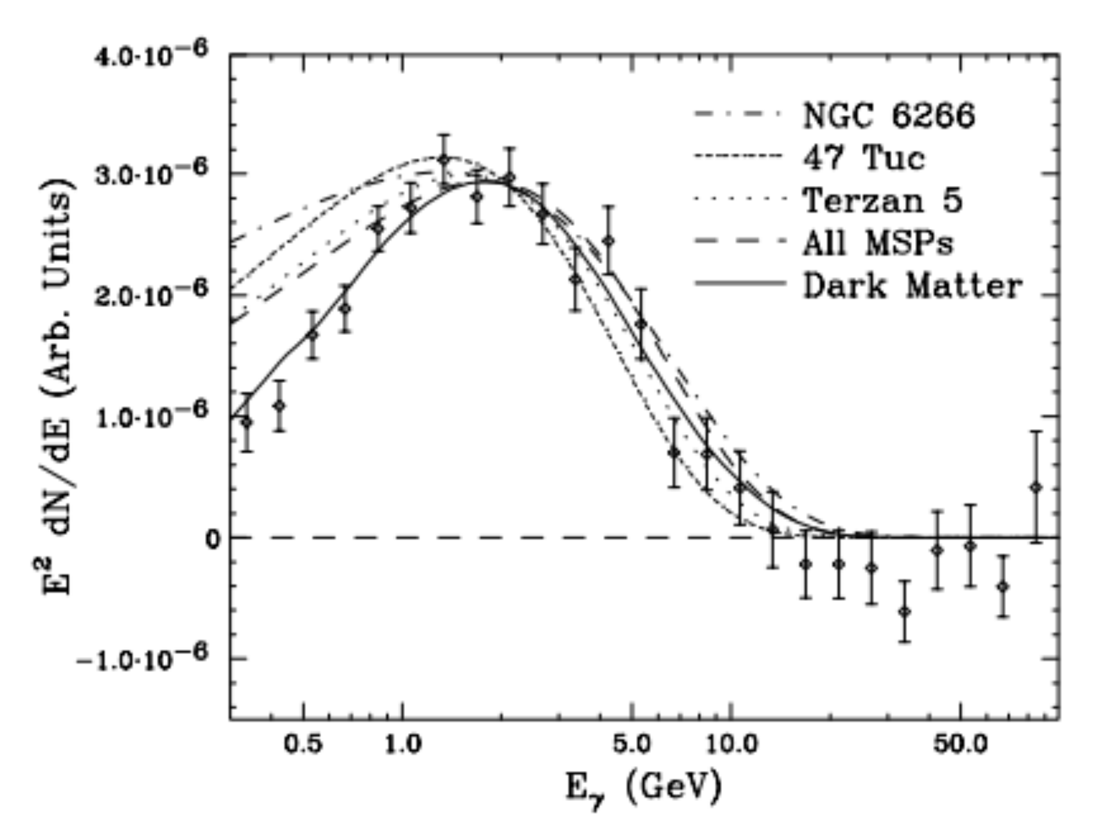


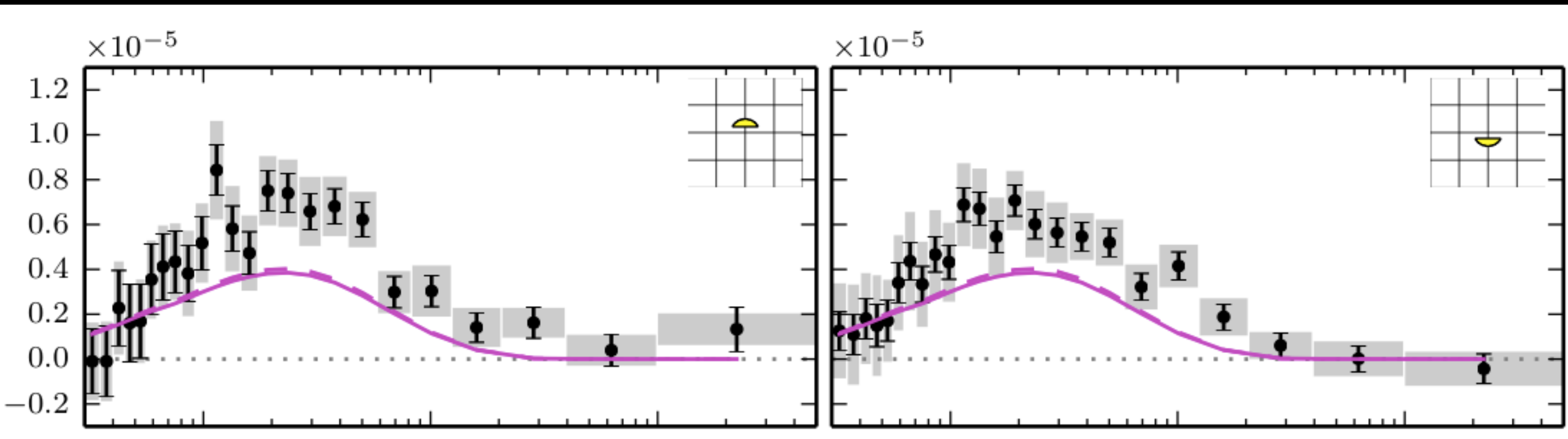
FIG. 9: The raw gamma-ray maps (left) and the residual maps after subtracting the best-fit Galactic diffuse model, 20 cm template, point sources, and isotropic template (right), in units of photons/cm^2/s/sr. The right frames clearly contain a significant central and spatially extended excess, peaking 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"

Daylan et al. arXiv:1402.6703

The GeV excess



Calore, Bozorgnia, GB+ arXiv:1509.02164

High resolution simulated haloes (Eagle sim.) that satisfy observational constraints exhibit, in the inner few kiloparsecs, dark matter profiles shallower than those required to explain the GeV excess via dark matter annihilation.

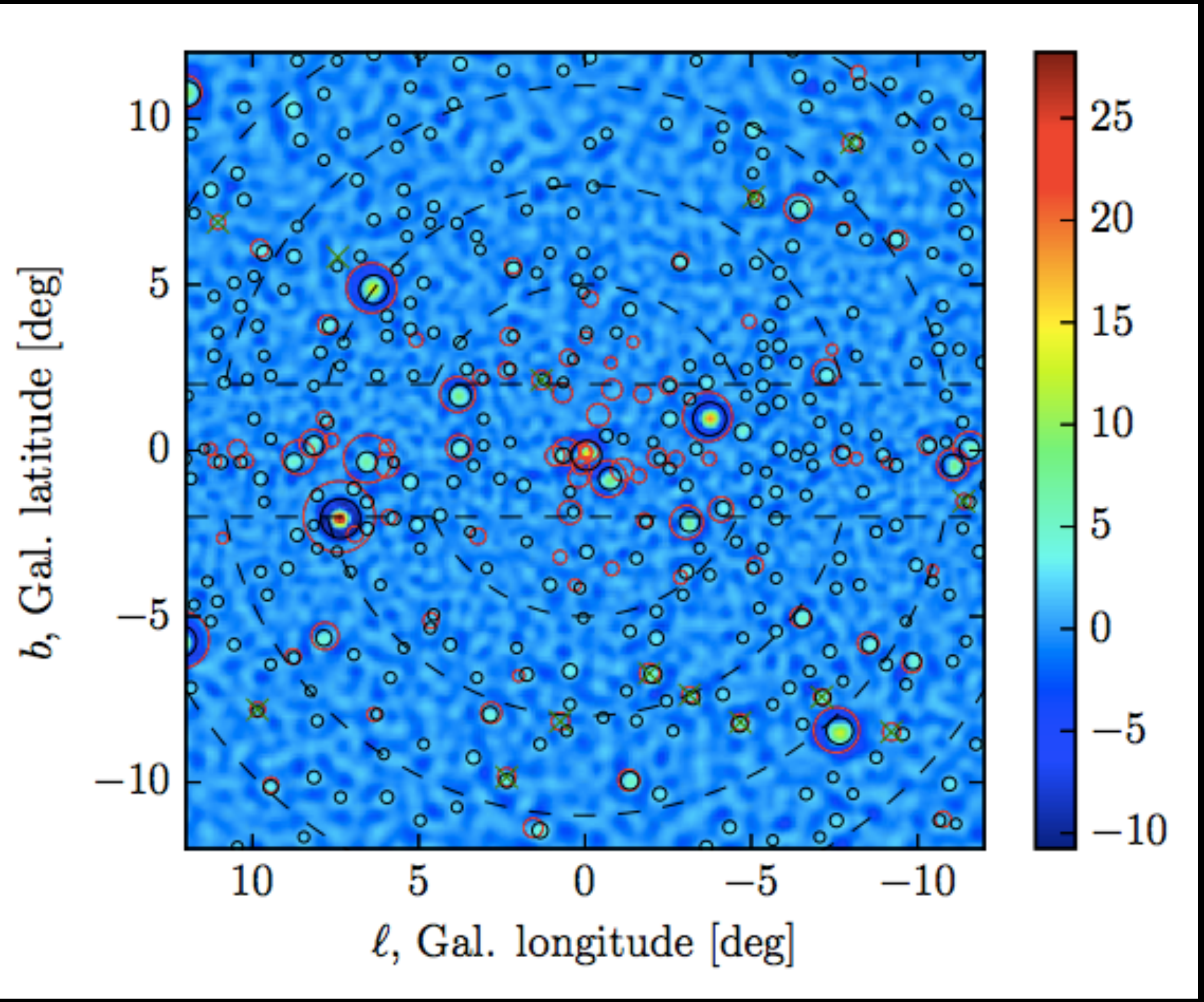
Usual problem with ID:

Difficult to rule out 'Standard' Astro interpretation

- 1506.05104 *Strong support for the millisecond pulsar origin of the Galactic center GeV excess*

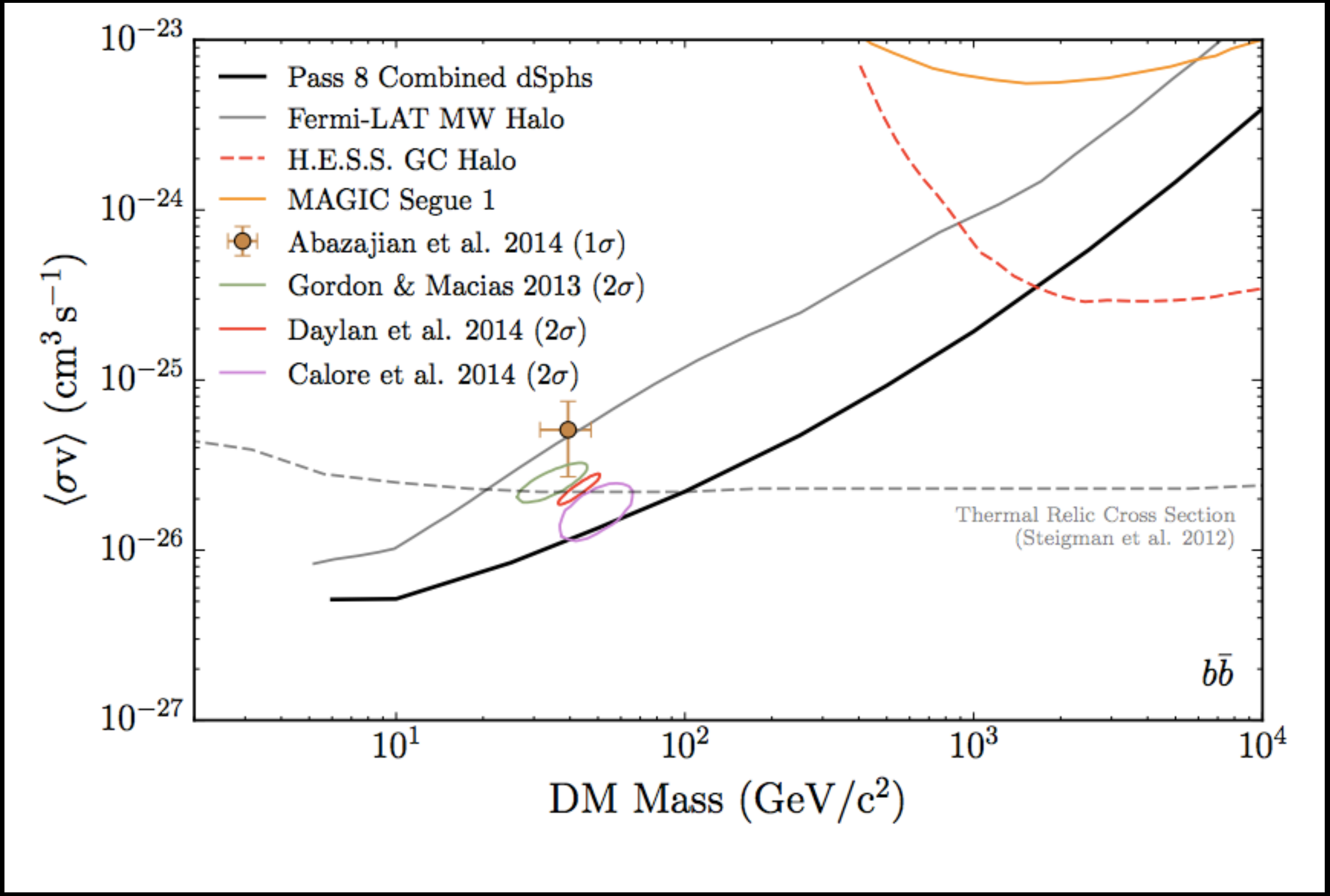
- 1506.05119 *The Galactic Center GeV Excess from a Series of Leptonic Cosmic-Ray Outbursts*

- 1506.05124 *Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy*



1506.05104

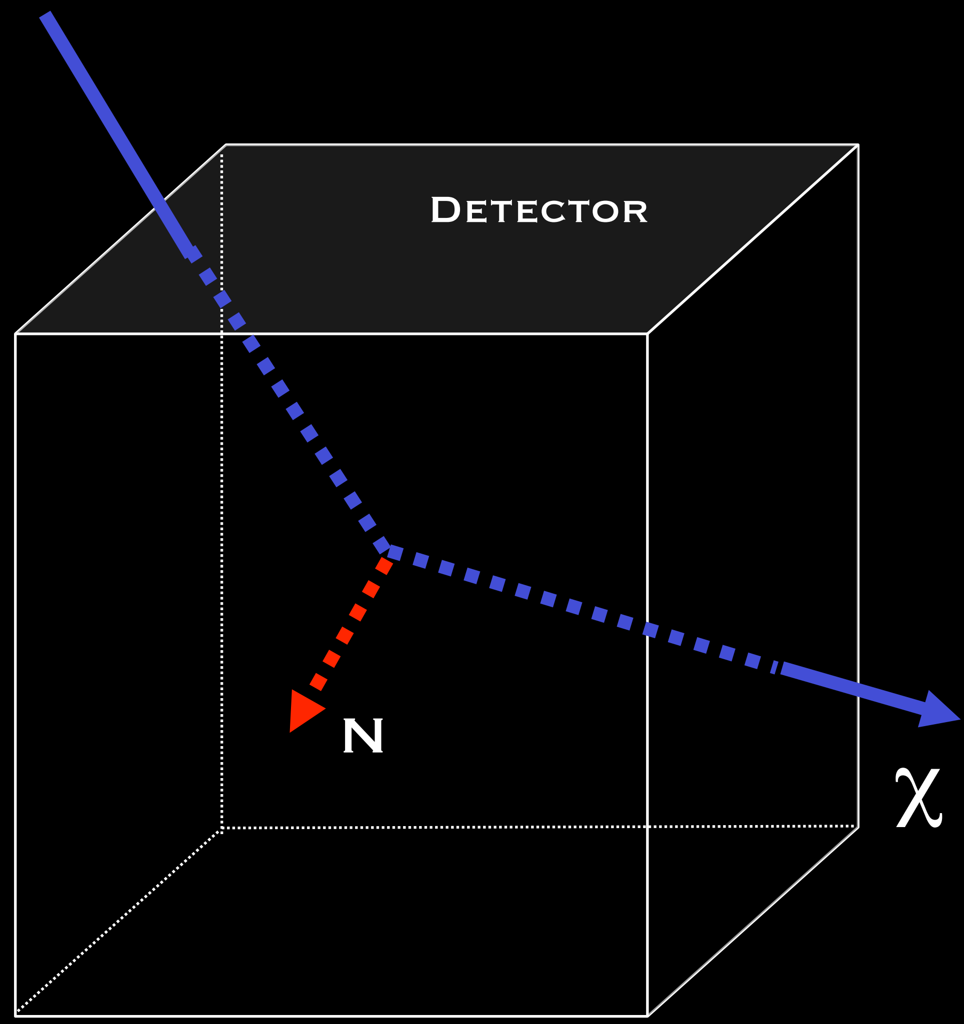
Stringent constraints from dwarf galaxies



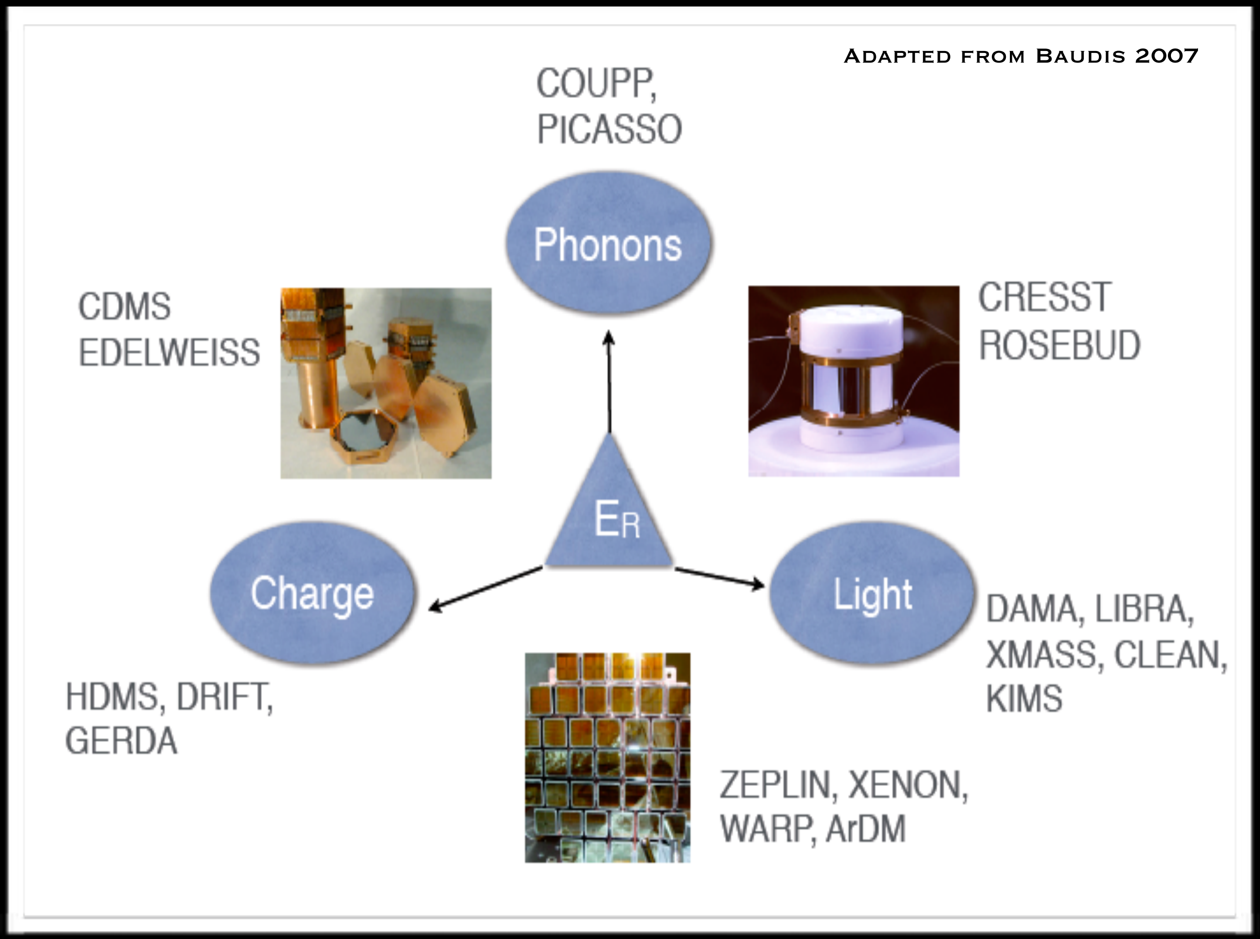
Fermi LAT coll. 1507.03530

Direct Detection

Principle and Detection Techniques



DM Scatters off nuclei in the detector



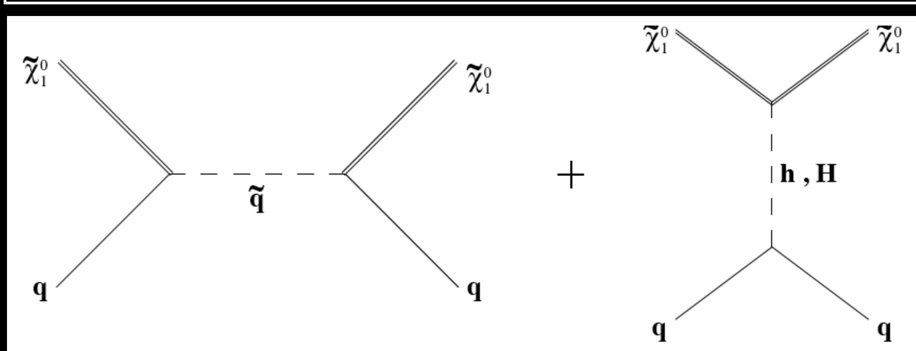
Detection of recoil energy via ionization (charges), scintillation (light) and heat (phonons)

Direct Detection

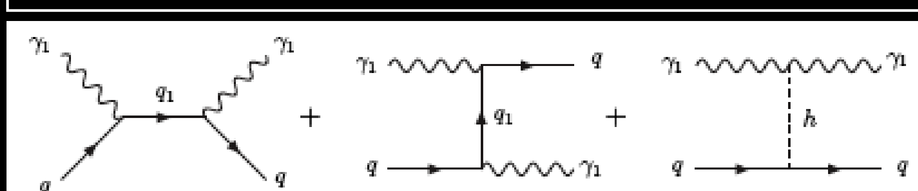
Differential Event Rate

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

SUSY: squarks and Higgs exchange



UED: 1st level quarks and Higgs exchange



Theoretical Uncertainties

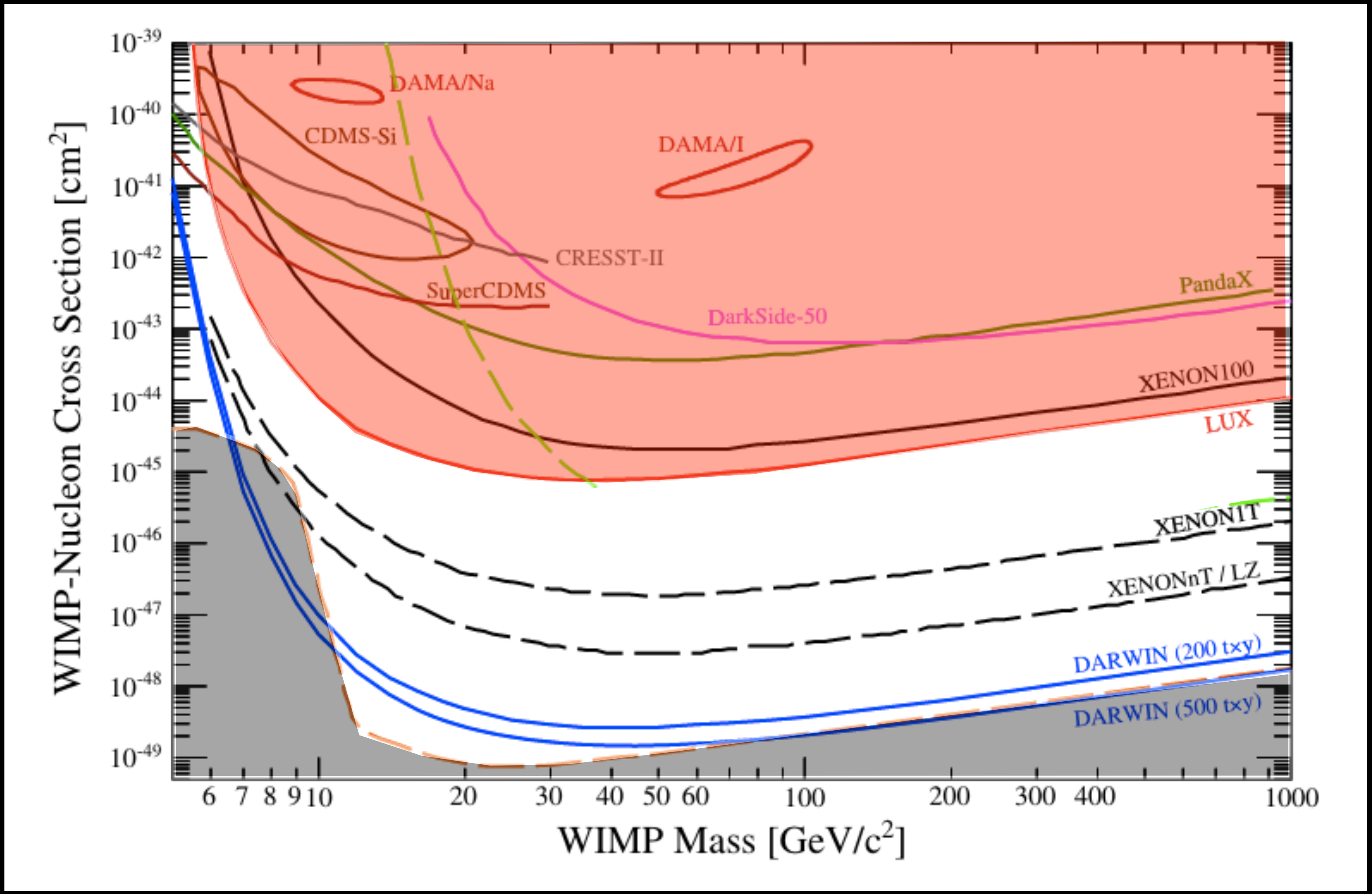
Ellis, Olive & Savage 2008; Bottino et al. 2000; etc.

Uncertainties on f(v)

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

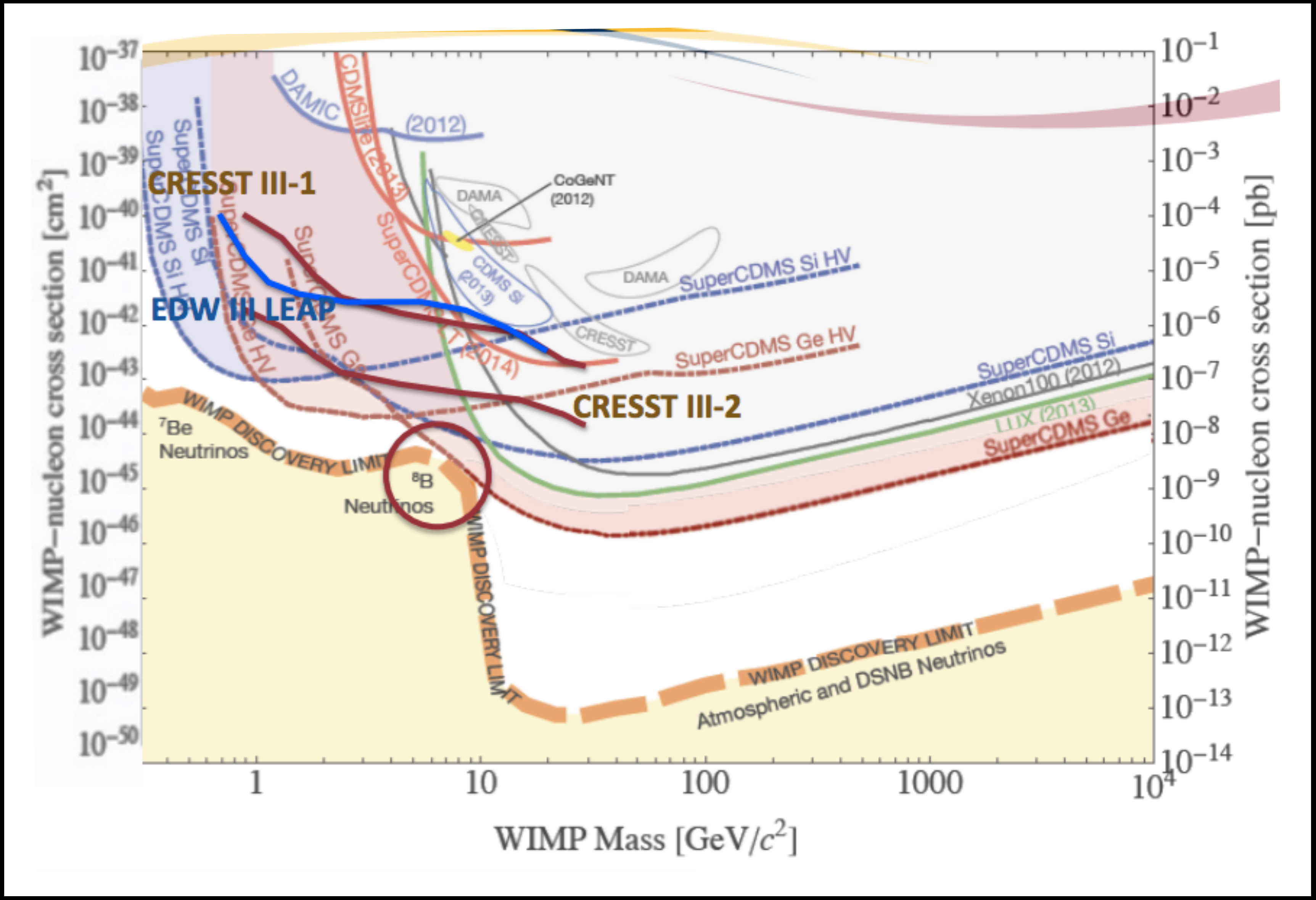
Status and prospects of DD

We can constrain $\rho_{loc} \times \sigma_{XN}$. If we assume the new particle makes all of the dark matter, and we fix all astro quantities, then:



Adapted from Baudis, *Ann. Phys.* (2015)

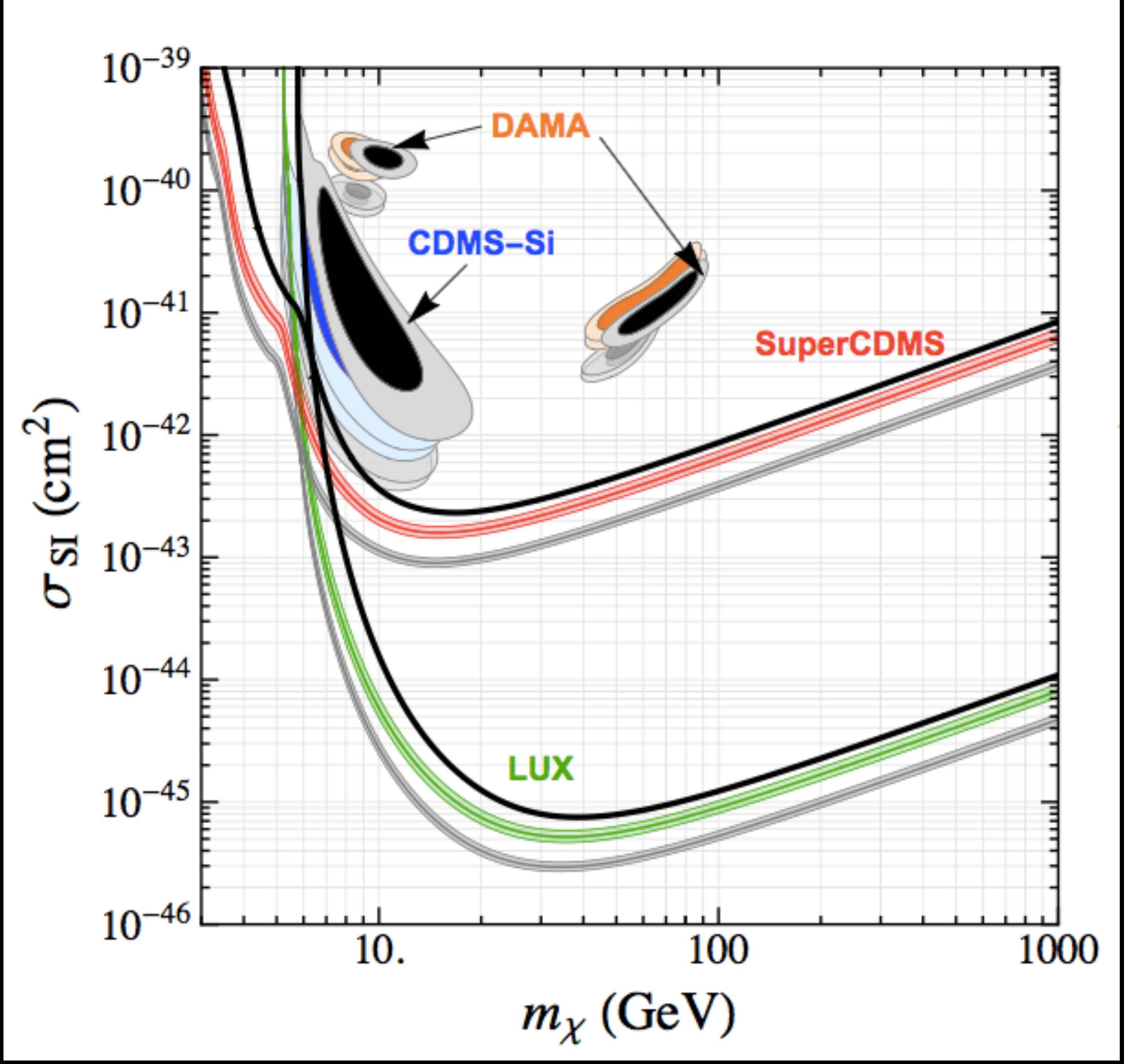
Prospects for ~GeV DM



Gerbier 2015

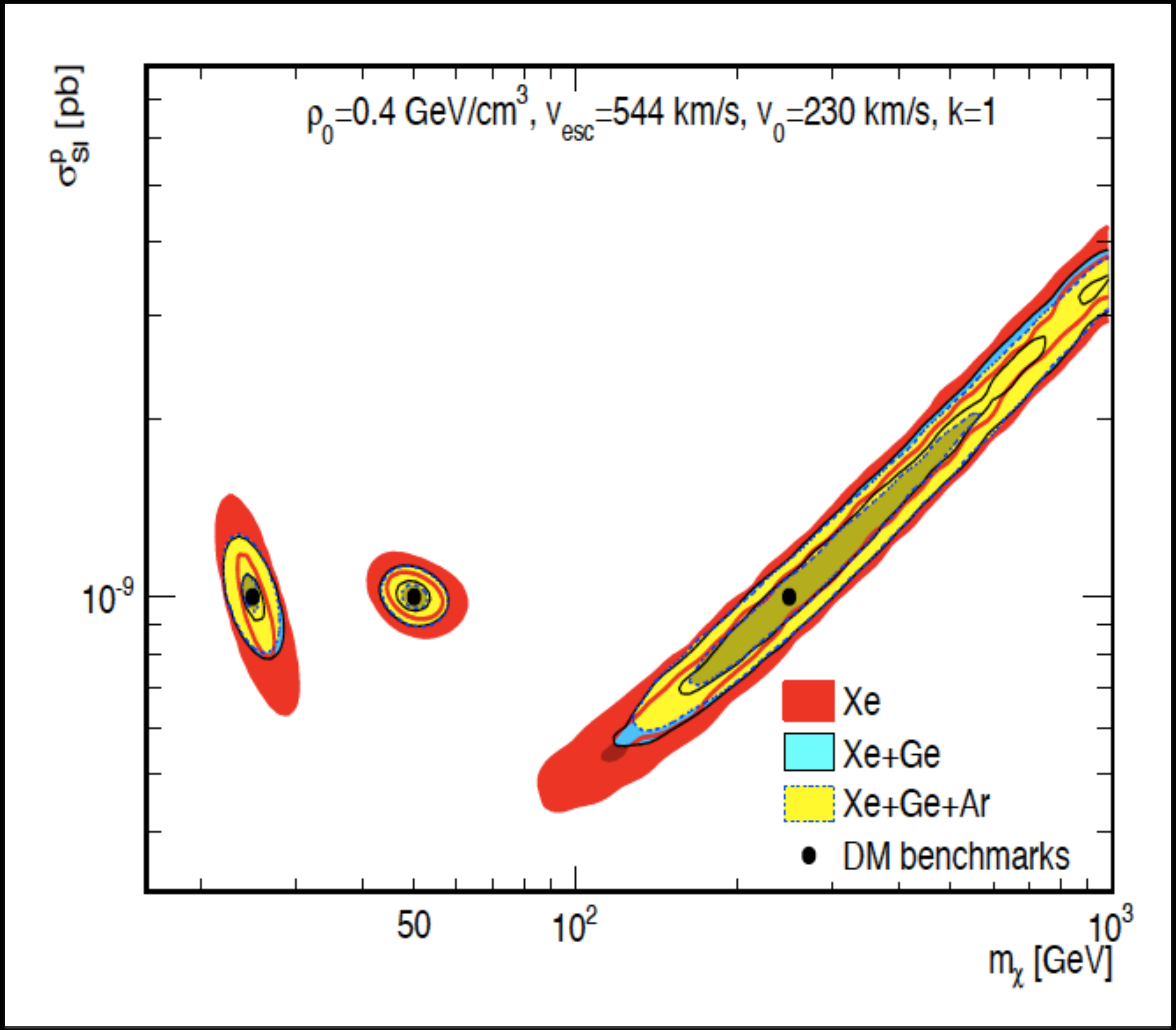
The role of Astrophysical uncertainties

Limits and hints for different Milky Way analogues



[Preliminary] Bozorgnia, Calore, GB & Eagle coll. 2015

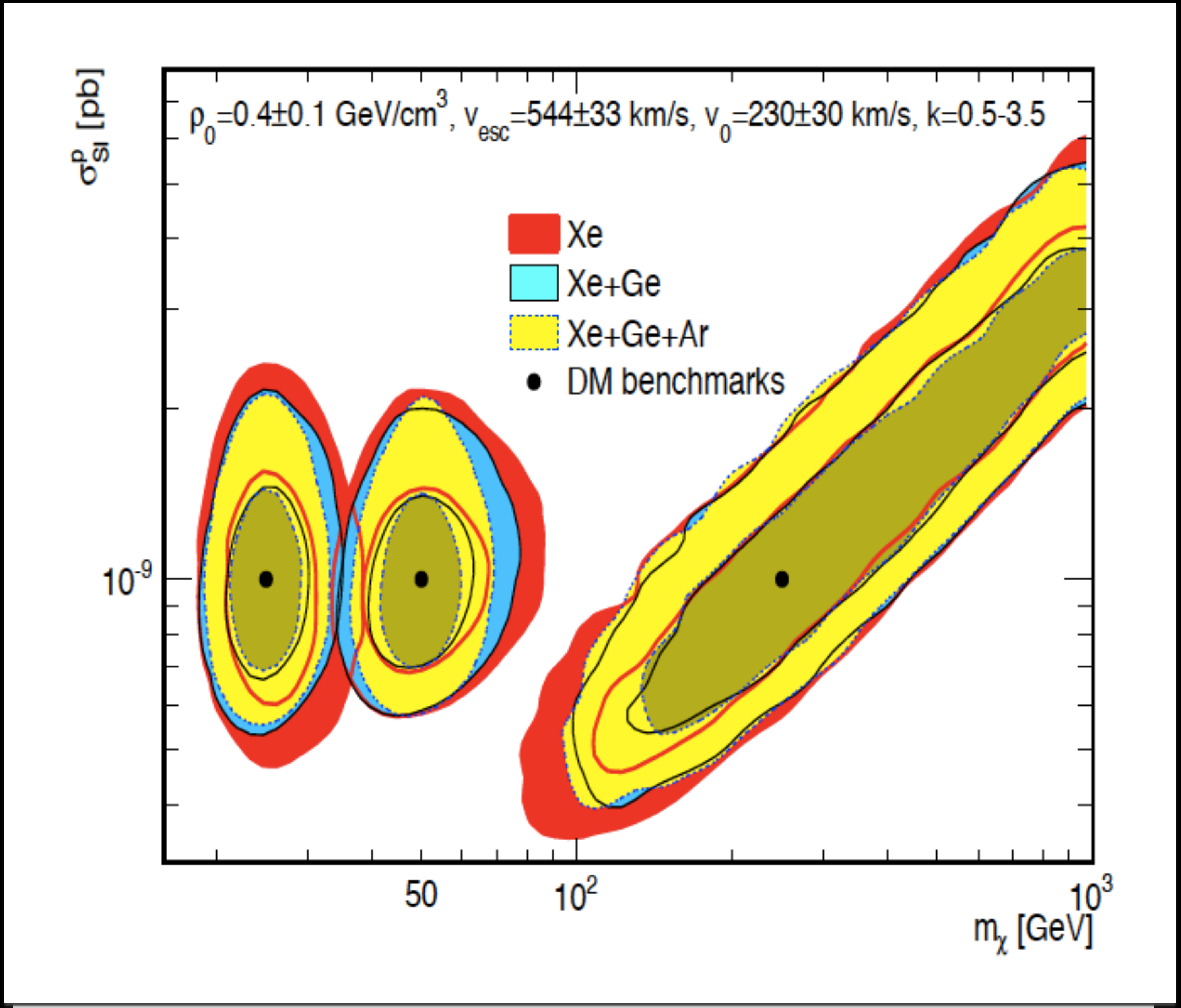
What do we learn in case of detection?



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

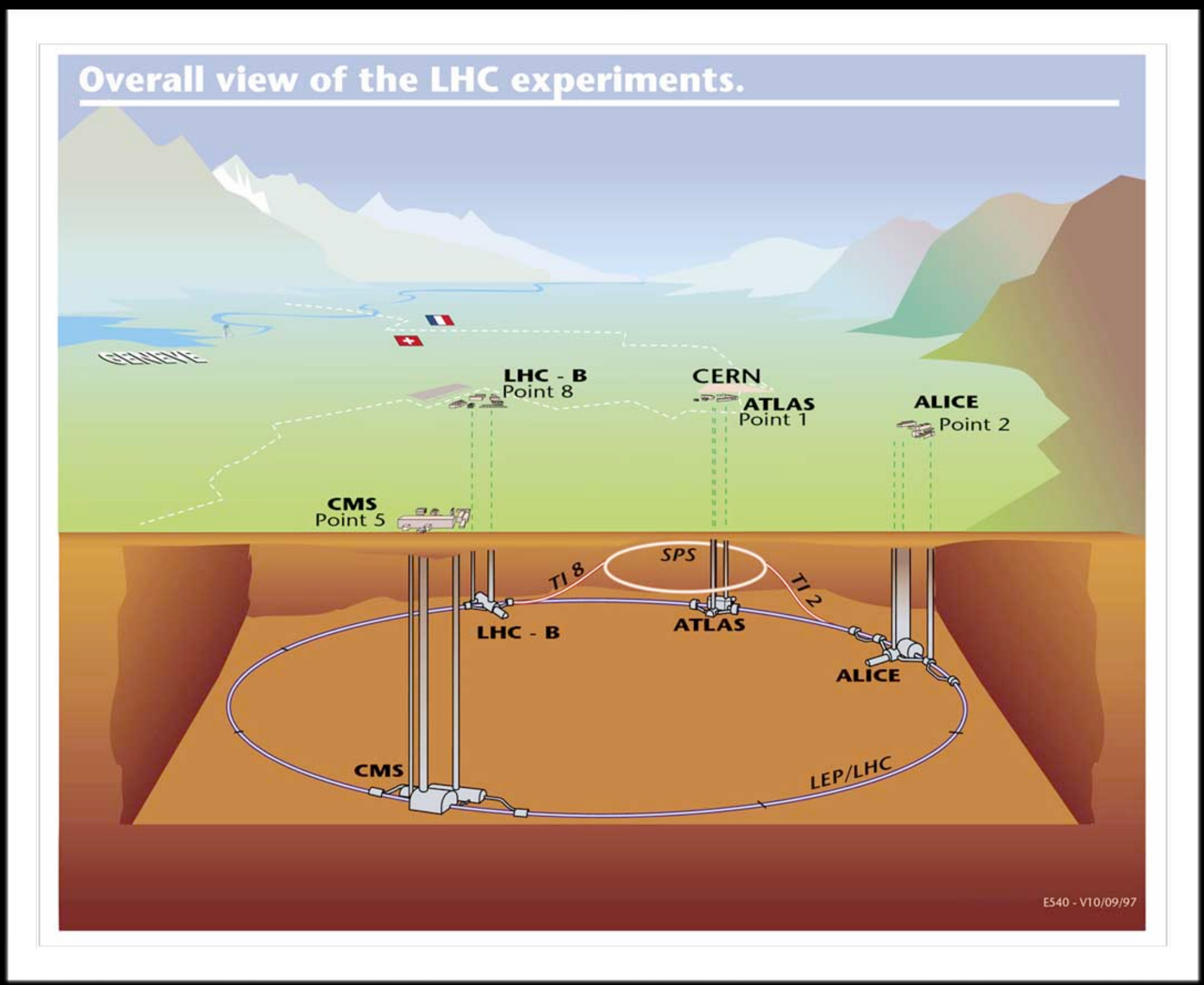
Astrophysical uncertainties

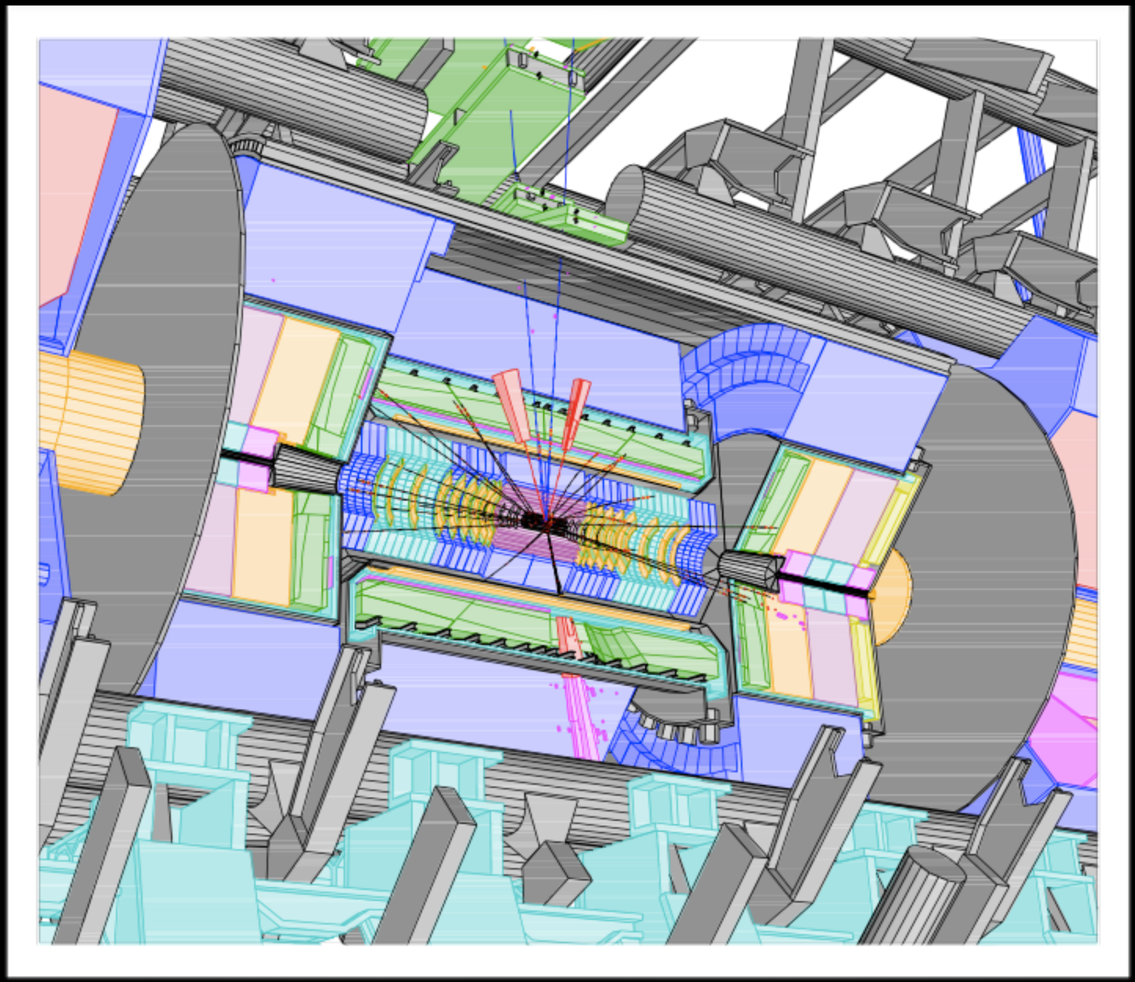
ASSUMING newly discovered particles are THE DM



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

Dark Matter Searches at the LHC





Suppose a new particle is found, we may measure its mass, couplings, LL on lifetime. But is this THE dark matter particle?

Example of Inverse DM problem at LHC

Inferring the relic density (thus the DM nature) of new particles from LHC data

The dream scenario:

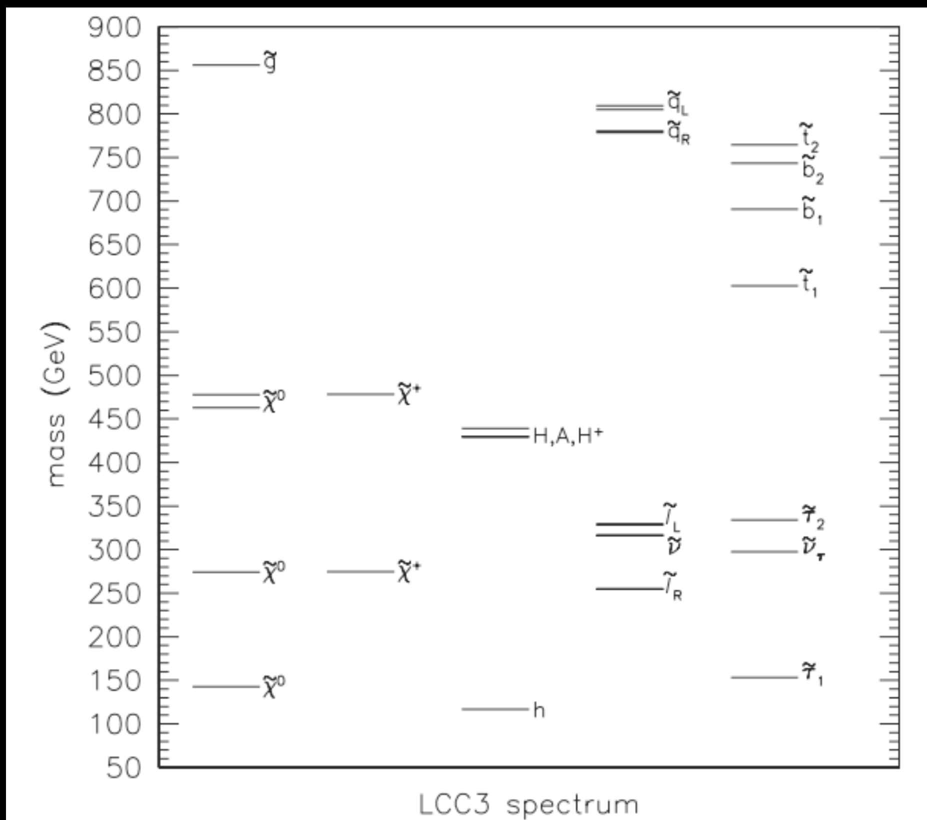
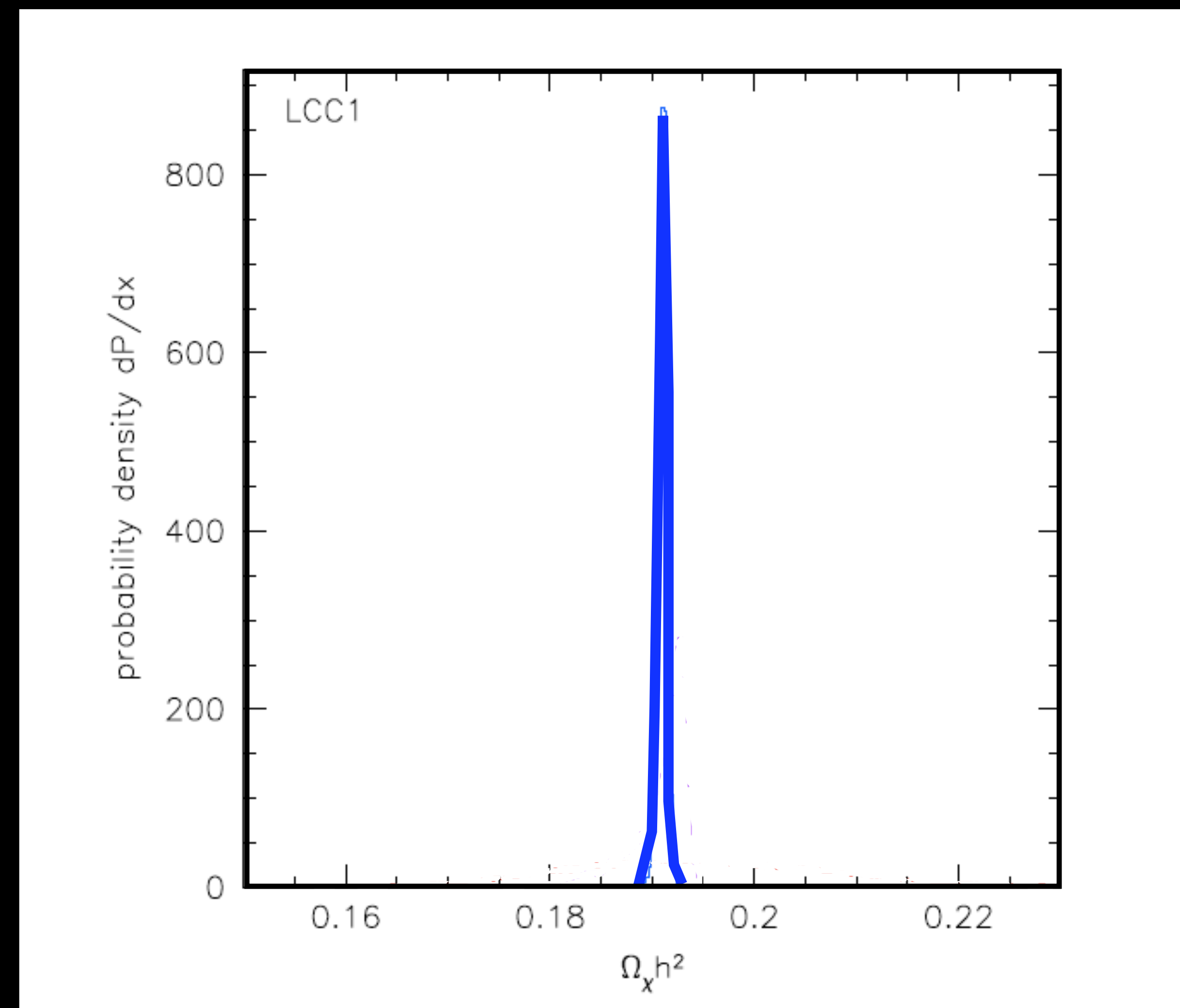
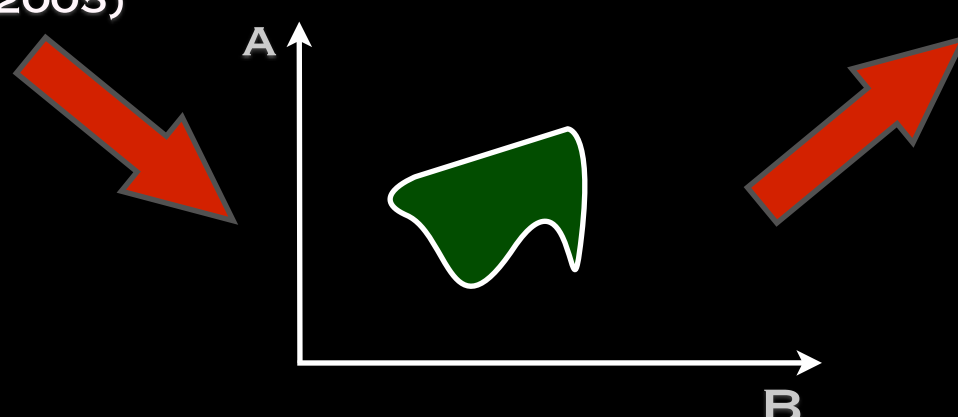


FIG. 34. Particle spectrum for point LCC3. The stau-neutralino mass splitting is 10.8 GeV. The lightest neutralino is predominantly *b*-ino, the second neutralino and light chargino are predominantly *W*-ino, and the heavy neutralinos and chargino are predominantly Higgsino.

Ad. from Baltz et al (2005)





Example of Inverse DM problem at LHC

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

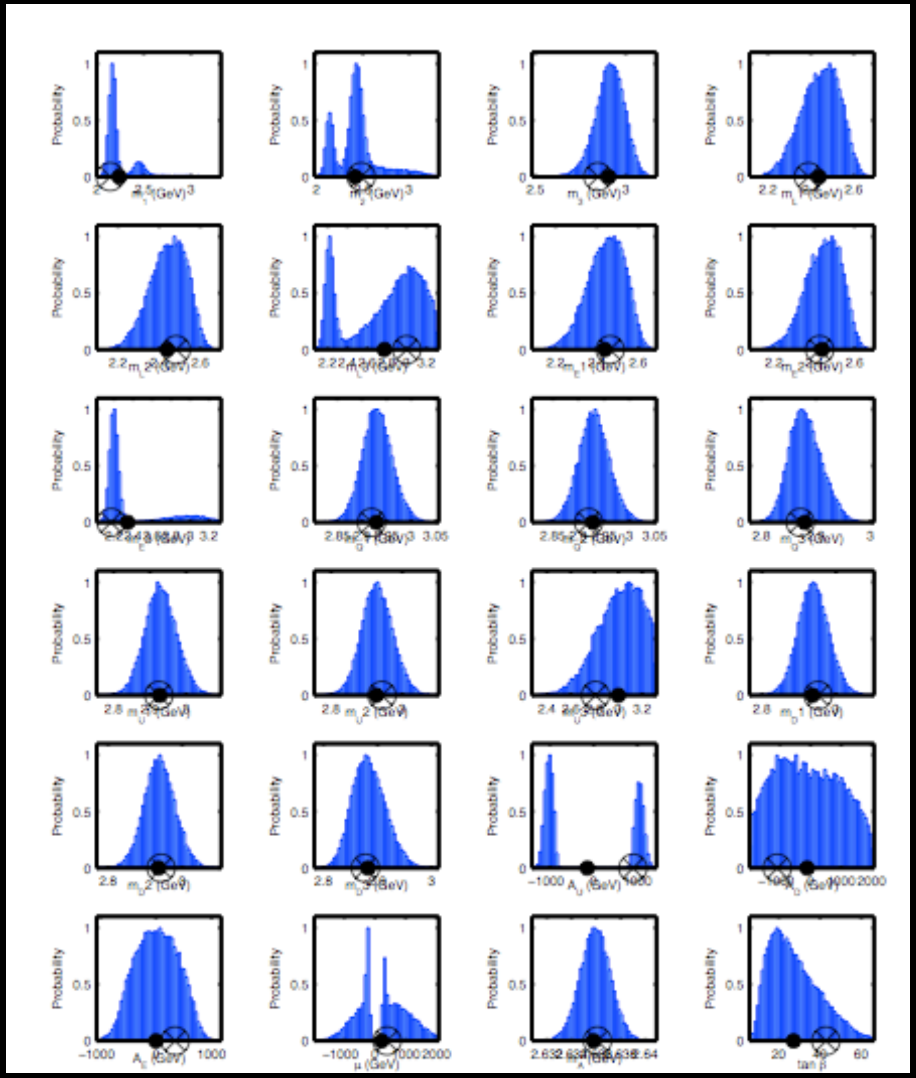
Mass	Benchmark value, μ	LHC error, σ
$m(\tilde{\chi}_1^0)$	139.3	14.0
$m(\tilde{\chi}_2^0)$	269.4	41.0
$m(\tilde{e}_R)$	257.3	50.0
$m(\tilde{\mu}_R)$	257.2	50.0
$m(h)$	118.50	0.25
$m(A)$	432.4	1.5
$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0)$	16.4	2.0
$m(\tilde{u}_R)$	859.4	78.0
$m(\tilde{d}_R)$	882.5	78.0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

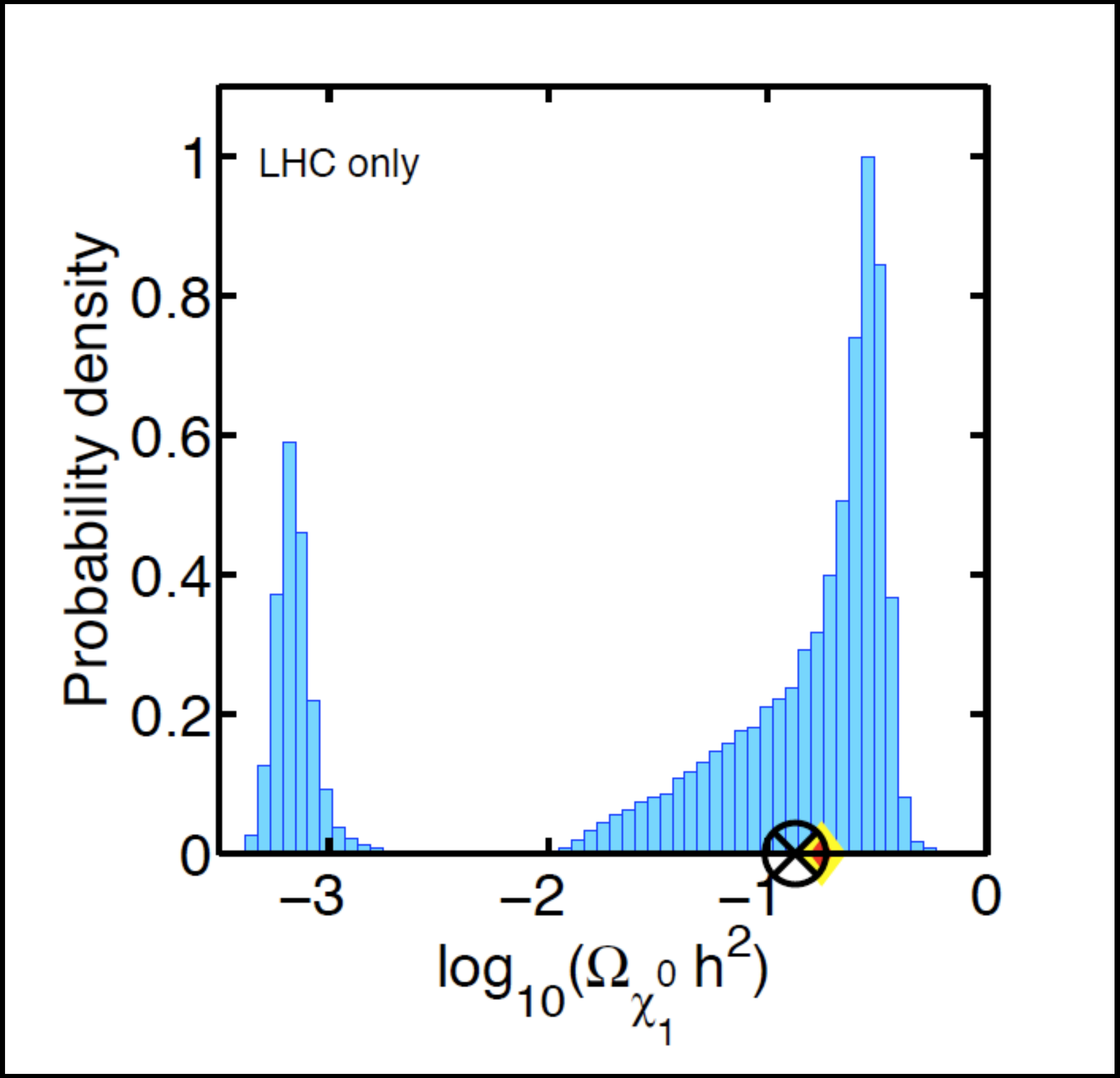
$$p(\mathbf{x}|\mathbf{d}) = \frac{p(\mathbf{d}|\mathbf{x})p(\mathbf{x})}{p(\mathbf{d})},$$

MCMC as implemented in the SuperBayes code



Example of Inverse DM 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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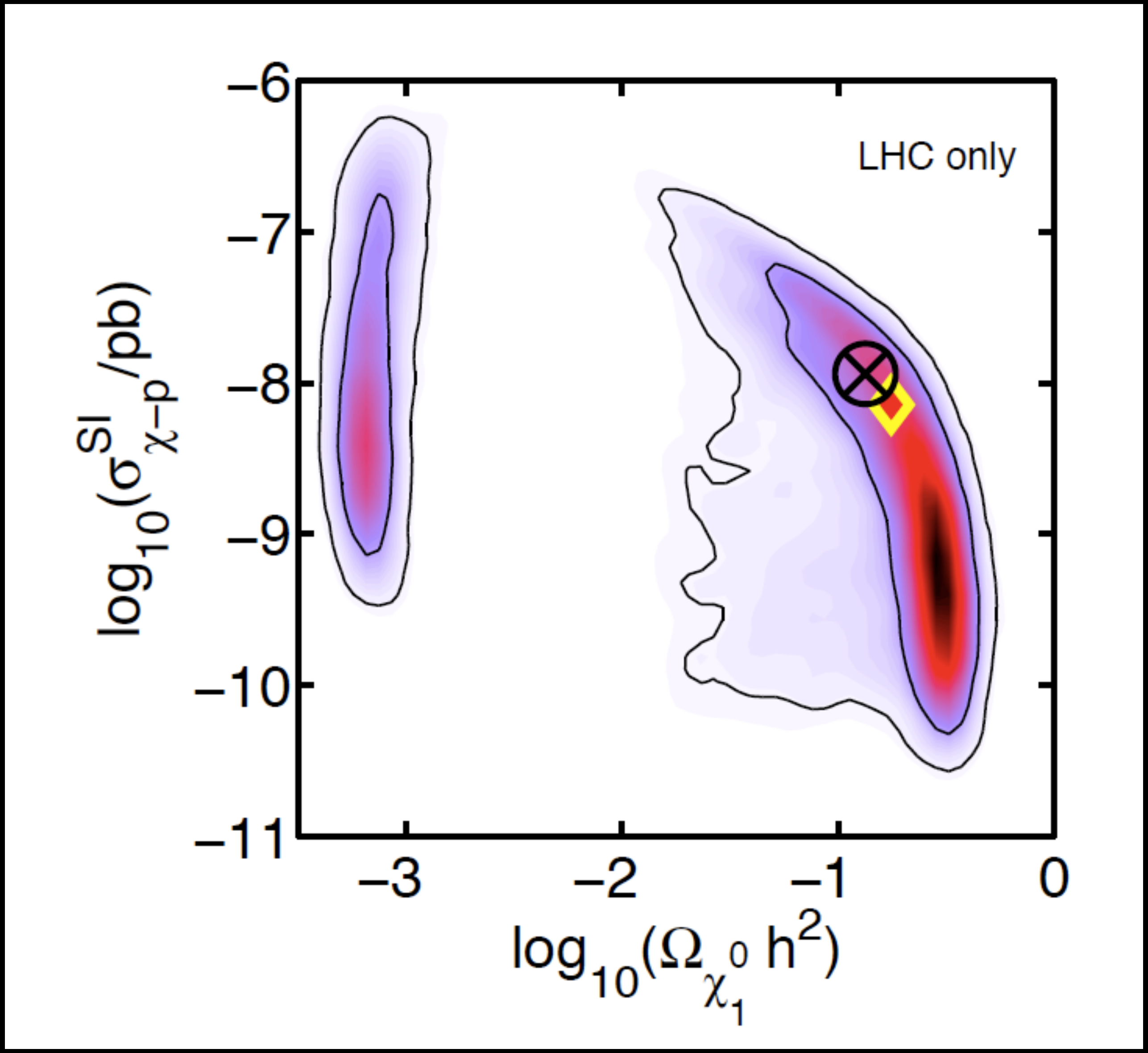


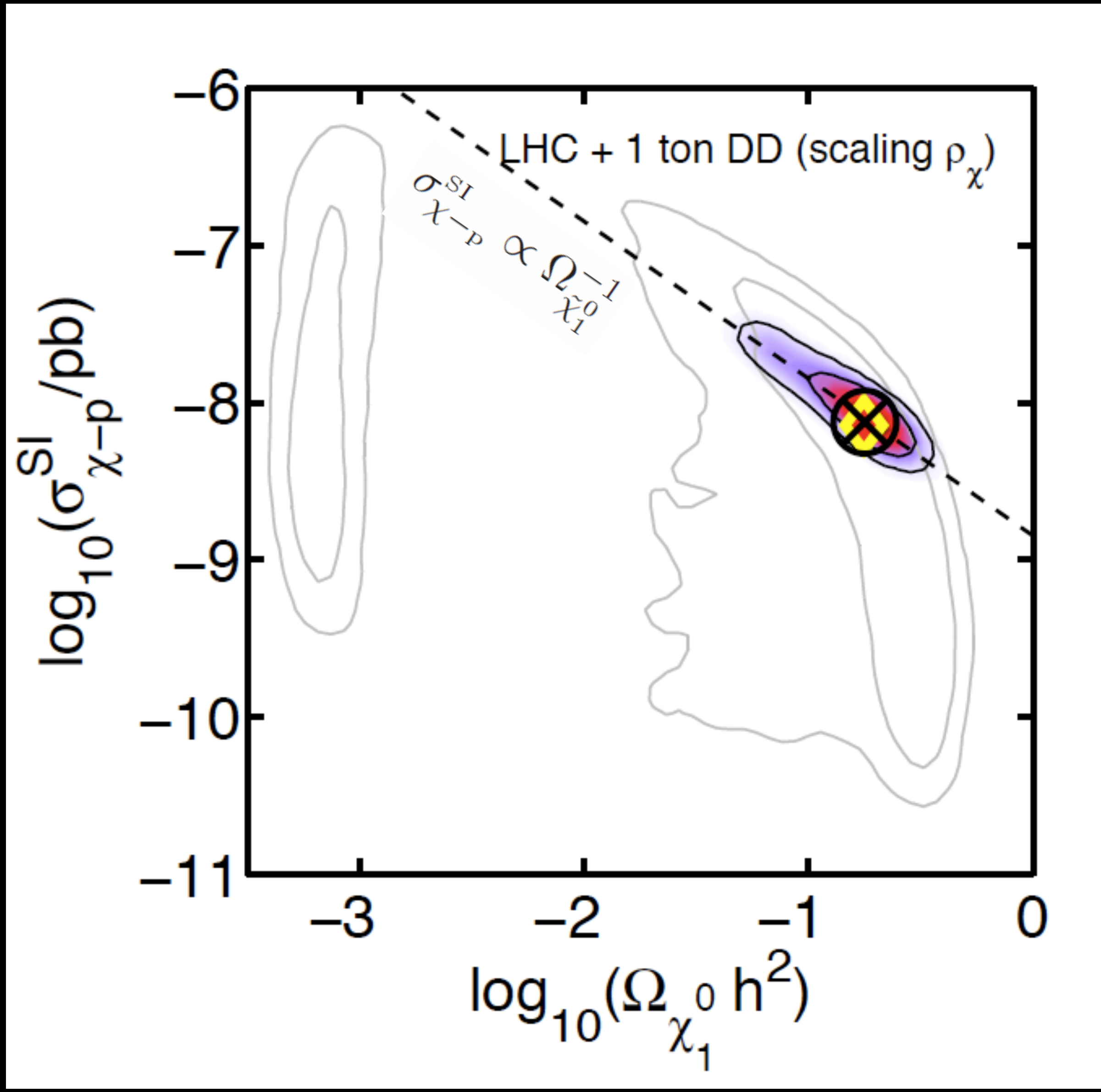
GB, Cerdeno, Fornasa, Ruiz de Austri & Trotta, 2010

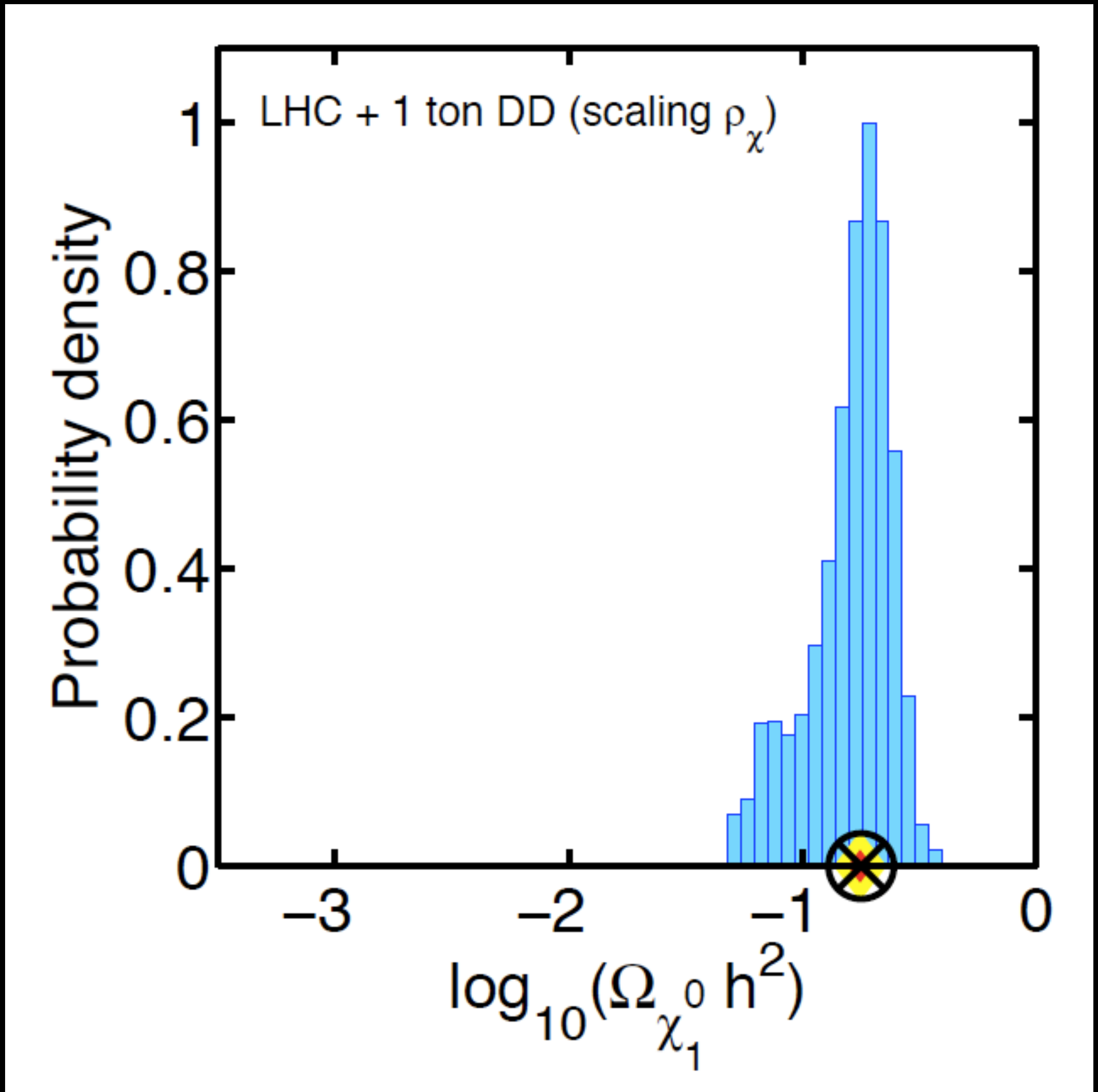
DD+LHC: "Scaling" Ansatz

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

"If the neutralino contributes x% of the local dark matter density ρ_{dm}, then it also contributes x% of the total dark matter abundance Ω_{dm}"

DD+LHC





If this discovery program works, we would validate our particle physics and cosmological model. If it doesn't, it could point towards additional forms of dark matter, or modified cosmology.

Conclusions

- *Huge* Theoretical and experimental effort towards the identification of DM. It is OK to be skeptical about current claims of detection..

- *Indirect Detection* more and more constrained, though there are some tantalizing hints

- DM *Direct Detection* looks promising. Info from other experiments is needed to determine DM particle properties

- Run II of the LHC will soon provide crucial information! Even in case of detection, complementary information from (in)direct searches (or new accelerators!) likely necessary to *identify* DM

- WIMP paradigm well motivated, but not a dogma. Important to diversify DM searches (light DM, axions, sterile neutrinos etc.), as WIMPs will soon be discovered or slowly abandoned..