Dark Matter Searches

Gianfranco Bertone

GRAPPA Institute, U. of Amsterdam

CosmoCruise, 6/9/2015

GRAPPA

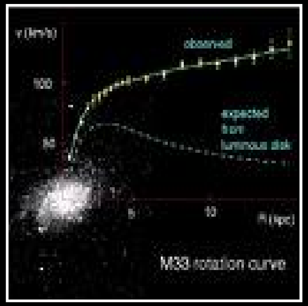
GRavitation AstroParticle Physics Amsterdam

erc

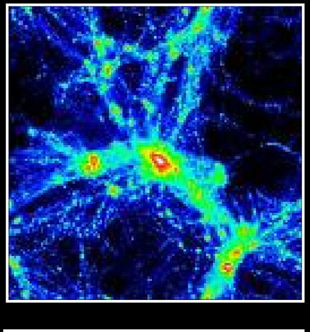
Evidence for Dark Matter

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

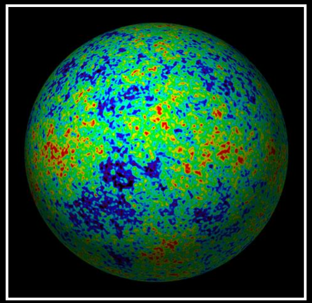
COSMOLOGICAL OBSERVATIONS



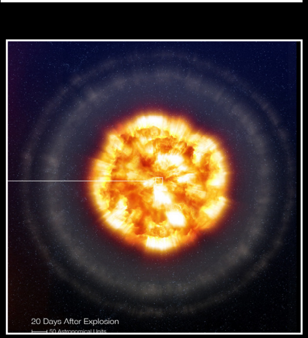
- **Rotation Curves**



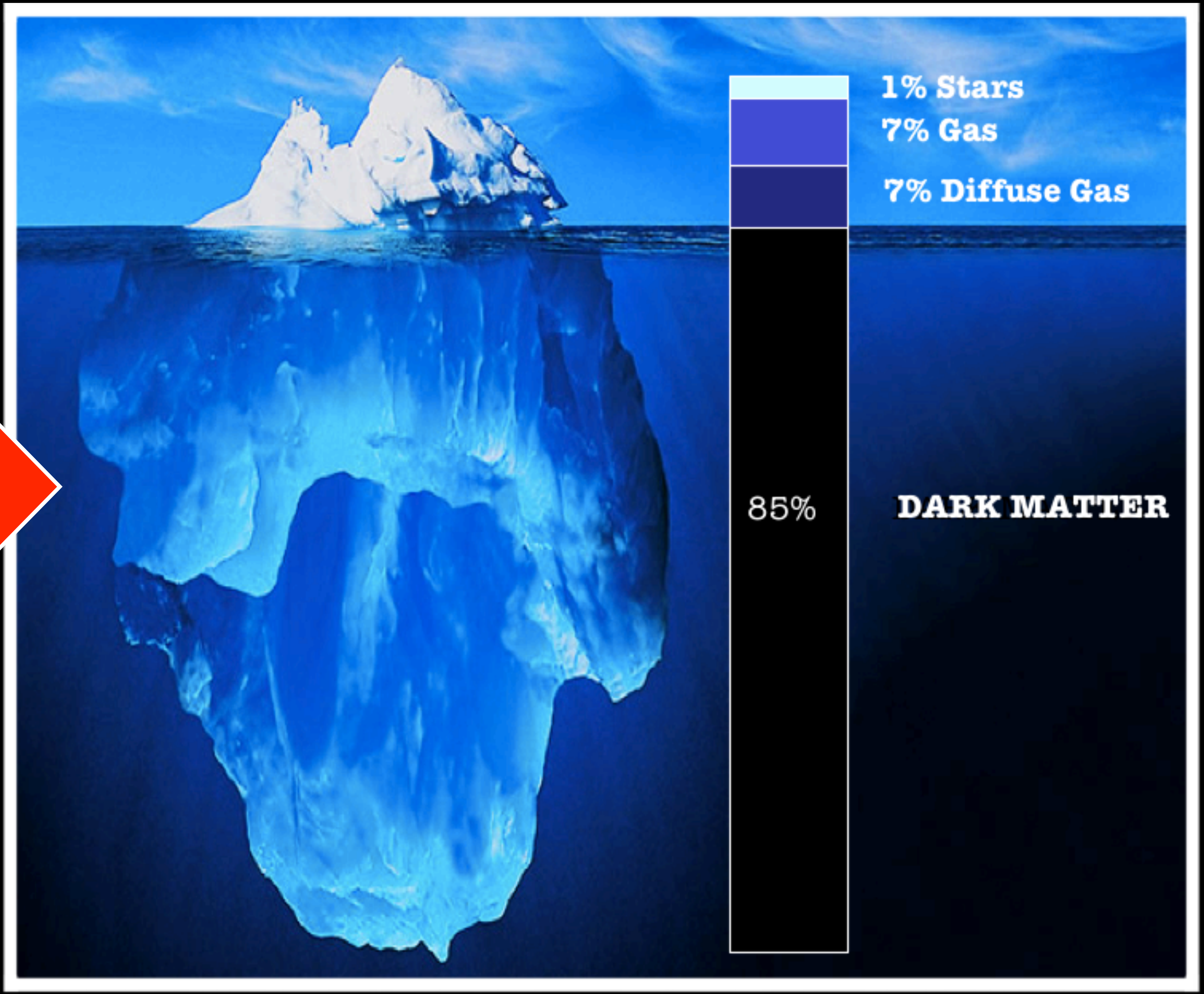
- **Clusters of galaxies**



- **CMB**



- **Type Ia Supernovae**



History of Dark Matter in 2 mins.

1. **Dark Matter exists**
   Kapteyn 1922, Oort 1927, Zwicky 1933, 1937; Schmidt 1936,; Hulst et al 1957; Freeman 1970; Shostak and Rogstad 1972; Roberts and Rots 1973, Rubin et al. 1978, Bosma 1978

2. **Dark Matter is ubiquitous**
   [Finzi 1959!], Ostriker, Peebles, Yahil 1974, Einasto et al. 1974, Faber & Gallagher 1979

3. **Dark Matter is a *new* particle**
   Peebles 1982 + Pagels, Primack, Bond, Szalay, White, ..

History & Future of Dark Matter

Public Symposium: join world-leading cosmologists who pioneered the discovery of dark matter to discuss its history and the prospects for detecting it.

22 june Koepelkerk **Amsterdam**
9.00-16.30

Gianfranco Bertone
Albert Bosma
Jim Peebles
Bernard Sadoulet
Joe Silk
Michael Turner
Simon White

Round tables chaired by
Jeroen van Dongen & Dan Hooper

Tickets are 15€ p.p. and can only be bought online via the website.
dmsymposium.science.uva.nl

ASTROPARTICLE PHYSICS 2014

A joint TeVPA/IDM conference
http://indico.cern.ch/e/TeVPAIDM

June 23 – 28, 2014
Amsterdam, NL

Videos of all lectures available online!

Have we found it yet?

Dec 19, 2009

Has dark matter finally been detected?

Hunt may well be over for a mysterious and invisible substance that accounts for three-quarters of the matter in the universe

Ian Sample, science correspondent
Follow @iansample Follow @guardian
The Guardian, Thursday 17 December 2009 23.00 GMT
Jump to comments (157)

A computer simulation shows how invisible dark matter coalesces in halos (shown in yellow). Photograph: Science Photo Library

CDMS data
10 GeV WIMP

May 26, 2013

Series: ... on science

New light cast on dark matter...

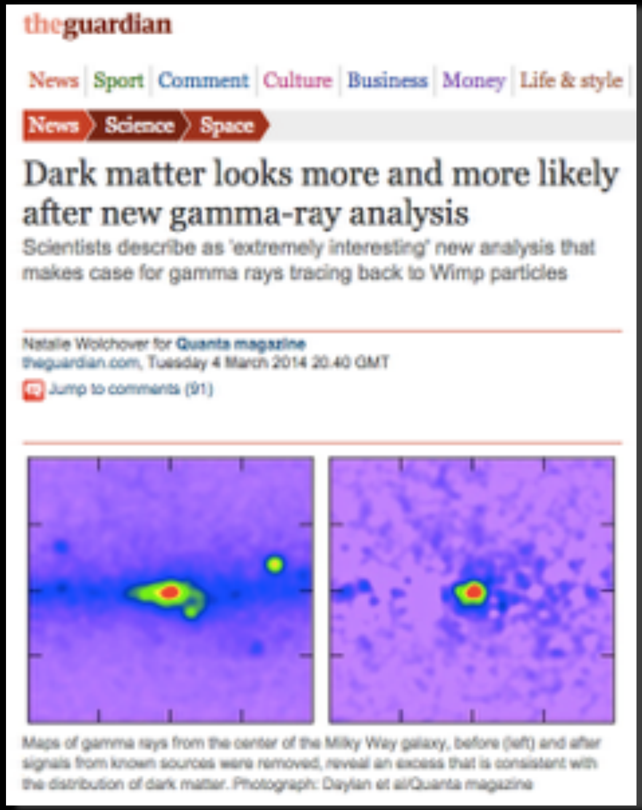
We may be a step closer to fathoming one of particle physics' deepest mysteries

Jeff Forshaw
The Observer, Sunday 26 May 2013
Jump to comments (72)

Mountain secrets: deep beneath the Gran Sasso massif in Italy, the Xenon experiments may soon reveal the truth about the existence of dark matter. Photograph: Interfoto/Alamy

AMS-02 data
1 TeV WIMP

Mar 4, 2014



Dark matter looks more and more likely after new gamma-ray analysis

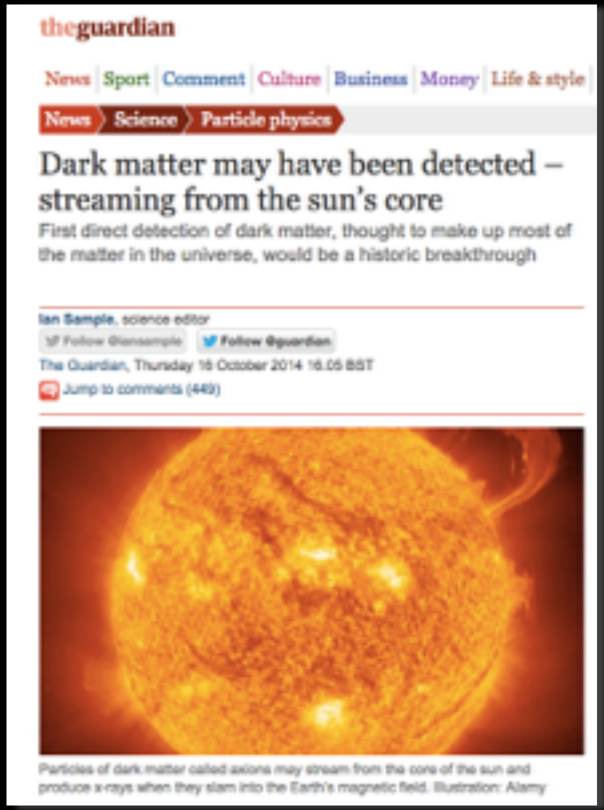
Scientists describe as 'extremely interesting' new analysis that makes case for gamma rays tracing back to Wimp particles

Natalie Wolchover for Quanta magazine
theguardian.com, Tuesday 4 March 2014 20.40 GMT
Jump to comments (91)

Maps of gamma rays from the center of the Milky Way galaxy, before (left) and after signals from known sources were removed, reveal an excess that is consistent with the distribution of dark matter. Photograph: Daylan et al/Quanta magazine

Fermi data
40 GeV WIMP
and (!)
Chandra/XMM
7 eV Sterile ν

Oct 16, 2014



Dark matter may have been detected – streaming from the sun's core

First direct detection of dark matter, thought to make up most of the matter in the universe, would be a historic breakthrough

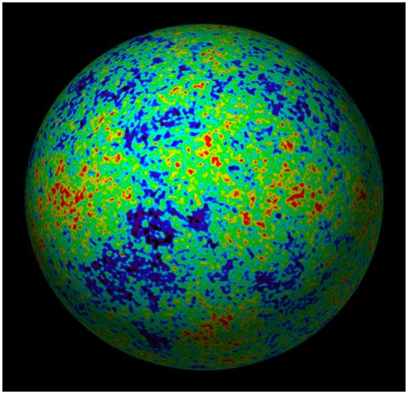
Ian Sample, science editor
The Guardian, Thursday 16 October 2014 16.05 BST
Jump to comments (449)

Particles of dark matter called axions may stream from the core of the sun and produce x-rays when they slam into the Earth's magnetic field. Illustration: Alamy

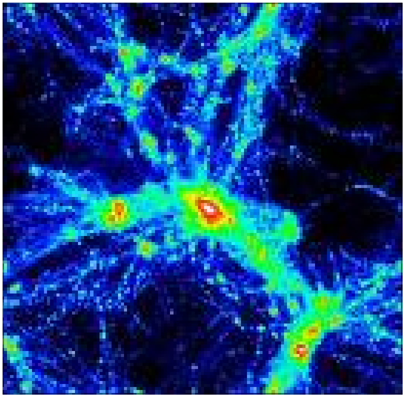
XMM data
μeV axion

What do we know?

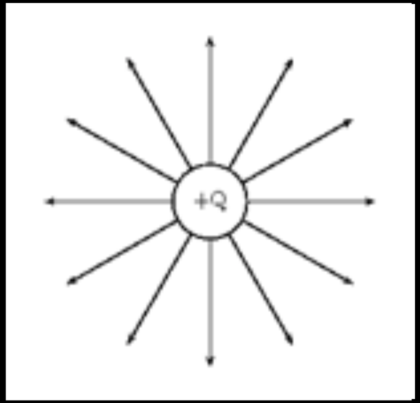
An extraordinarily rich zoo of non-baryonic Dark Matter candidates! In order to be considered a viable DM candidate, a new particle has to pass the following 10-point test



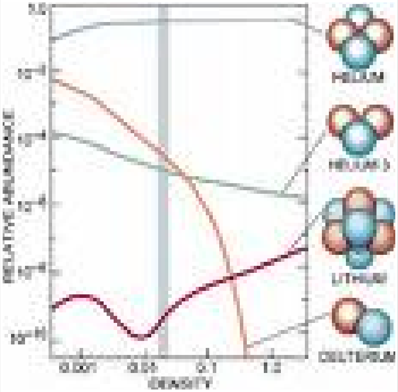
1) Ωh^2 OK?



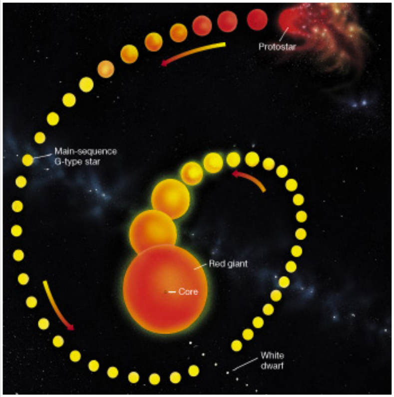
2) Is it cold?



3) Is it neutral?



4) Is BBN ok?



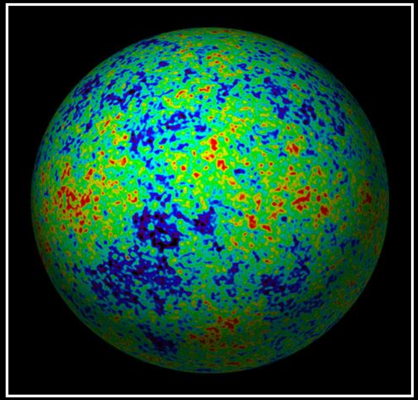
5) Stars OK?

TAOSO, GB & MASIERO 2007

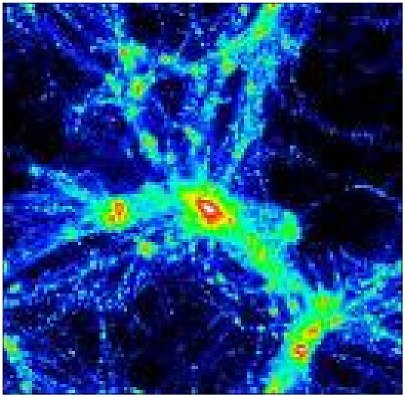
What do we know?

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

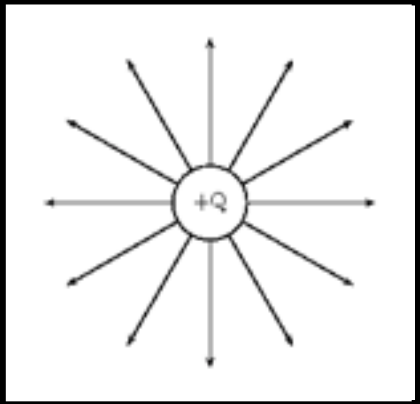
1) Ωh^2 OK?



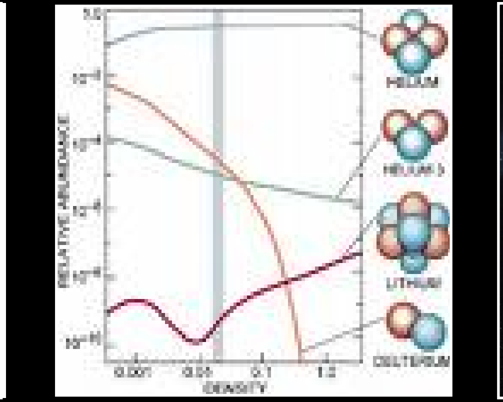
2) Is it cold?



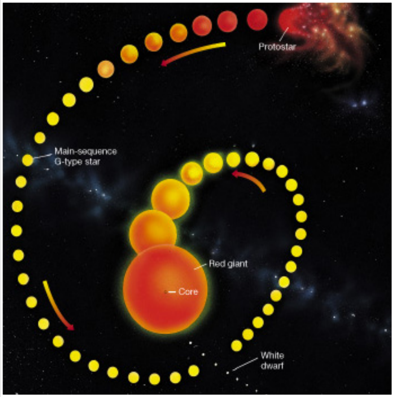
3) Is it neutral?



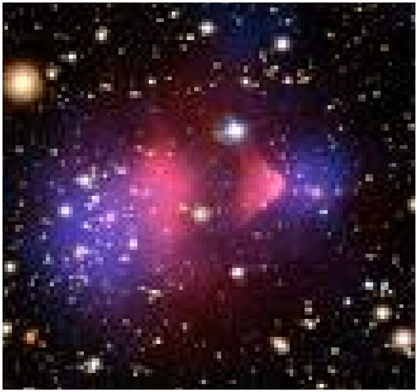
4) Is BBN ok?



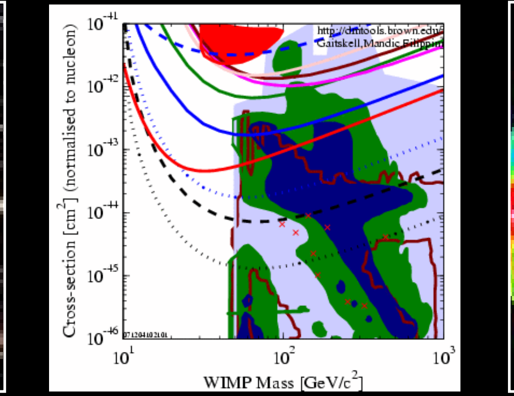
5) Stars OK?



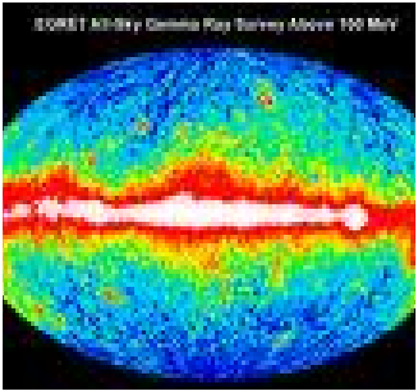
6) Collisionless?



7) Couplings OK?

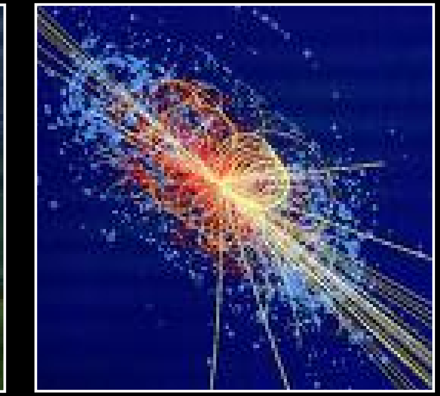


8) γ-rays OK?



9) Astro bounds?

10) Can probe it?



TAOSO, GB & MASIERO 2007

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

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

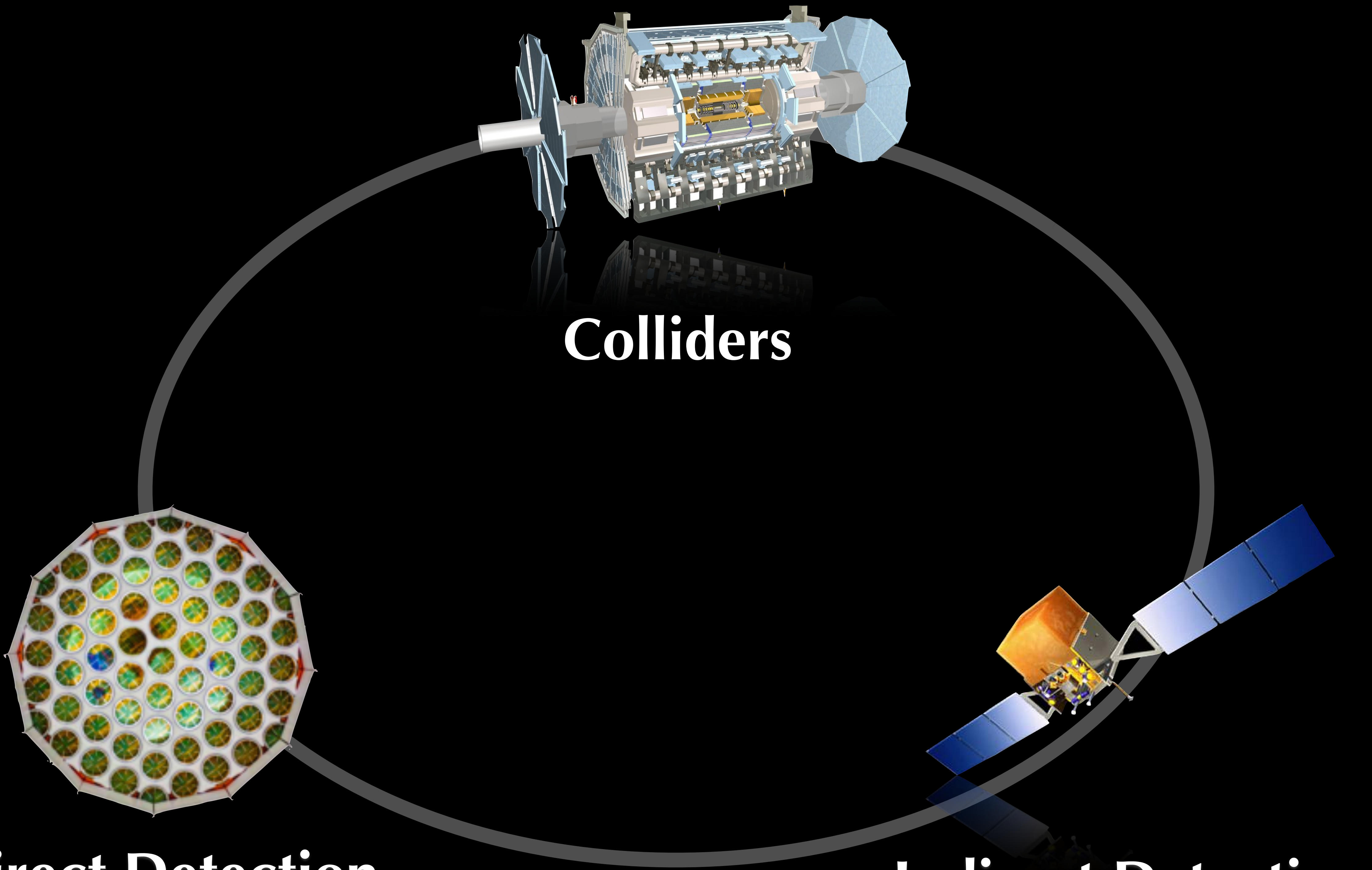
✦SuperWIMPs

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 quest for Dark Matter



Colliders

Direct Detection

Indirect Detection

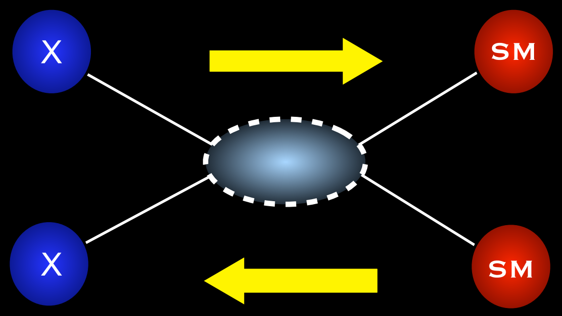
Indirect Detection

WHY "ANNIHILATIONS"?

X = DARK MATTER

SM = STANDARD MODEL PARTICLE

EARLY UNIVERSE



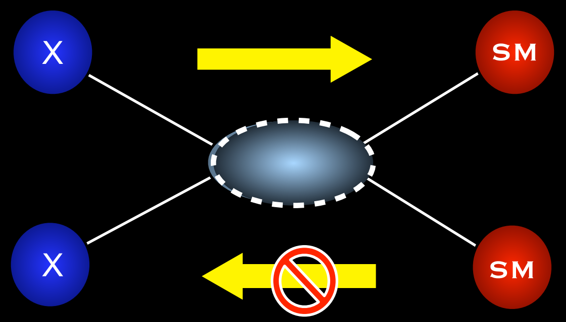
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

RELIC DENSITY (NR FREEZE-OUT)

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

Electroweak-scale cross sections can reproduce correct relic density.

TODAY



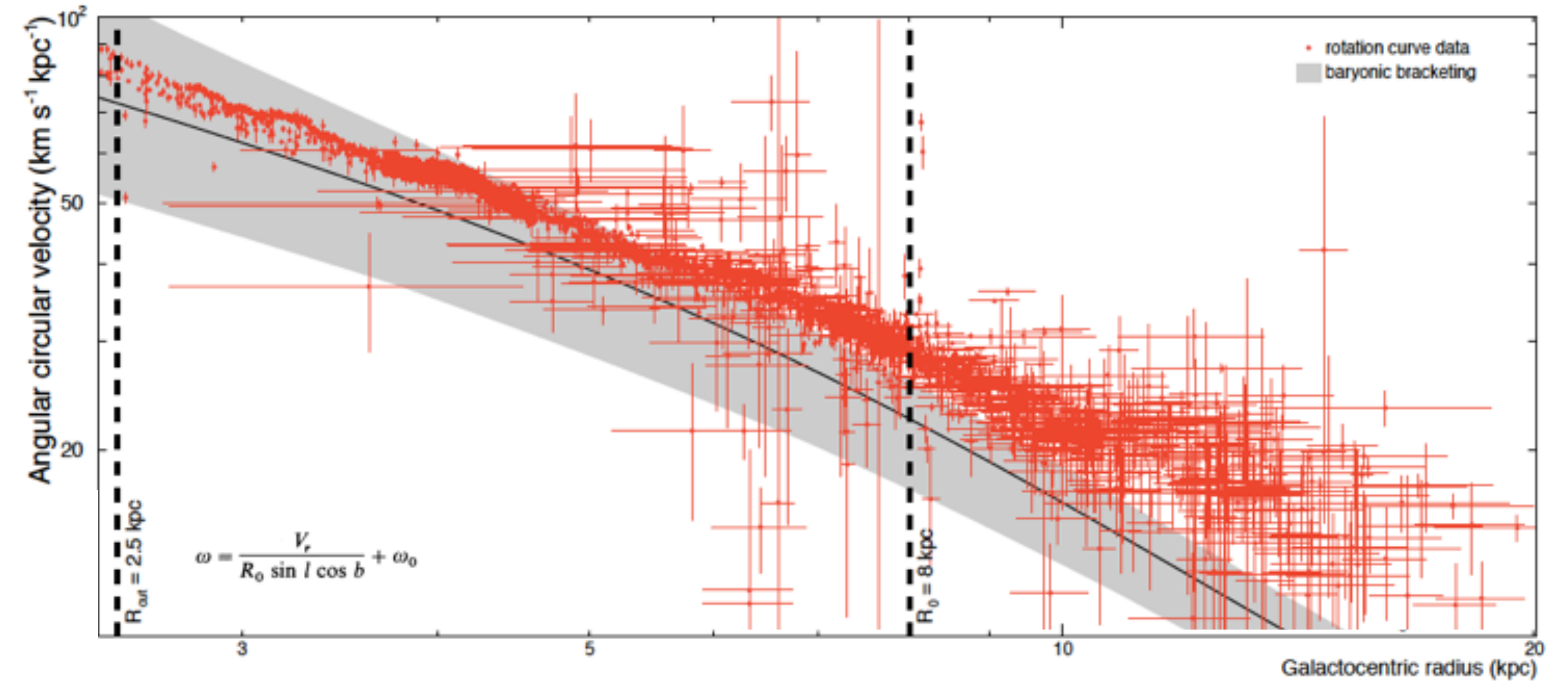
$$\frac{dn_\chi}{dt} = -(\sigma v)_o n_\chi^2$$

ANNIHILATION FLUX

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

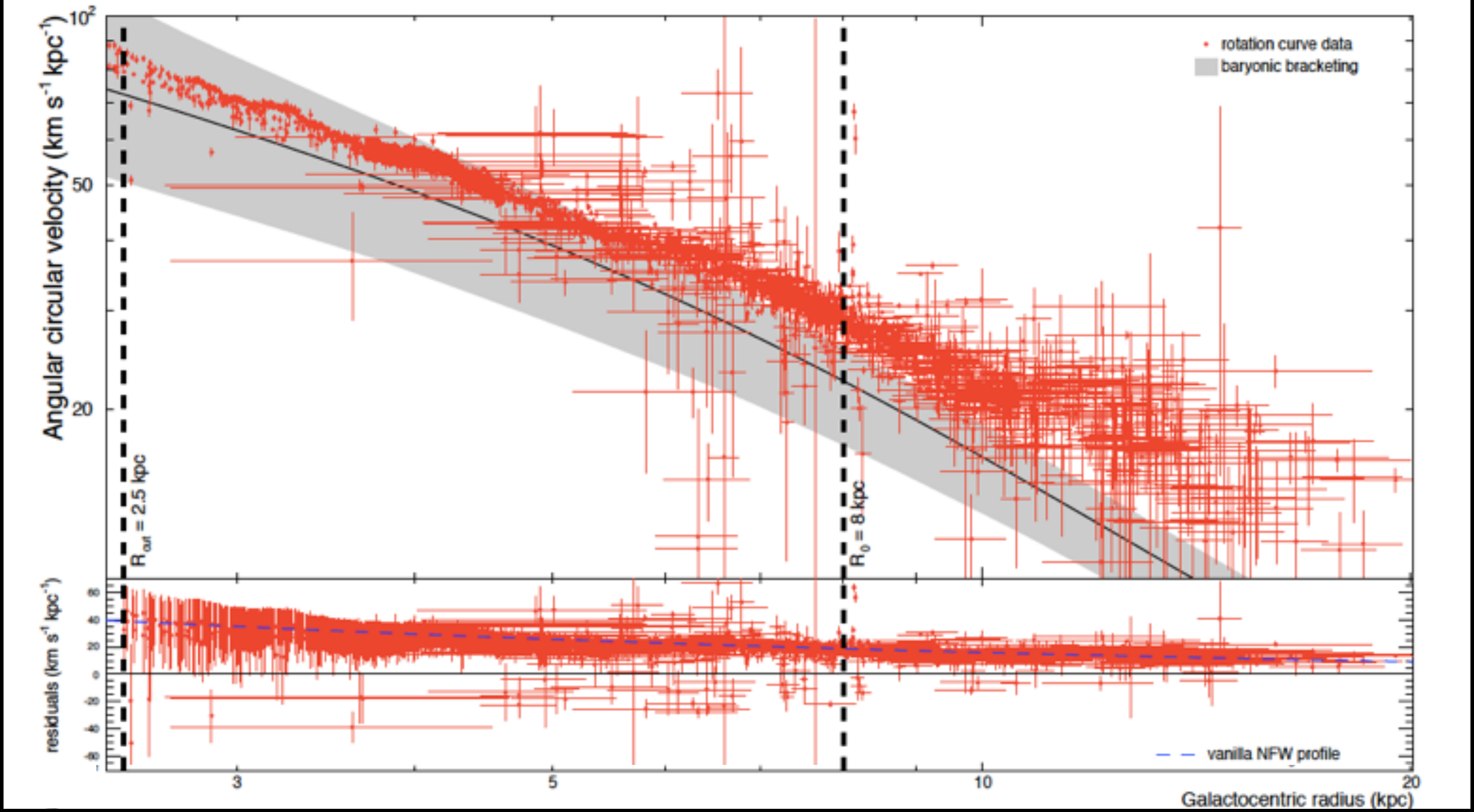
Particle physics input from extensions of the Standard Model. Need to specify distribution of DM along the line of sight.

Rotation curve of the Milky Way



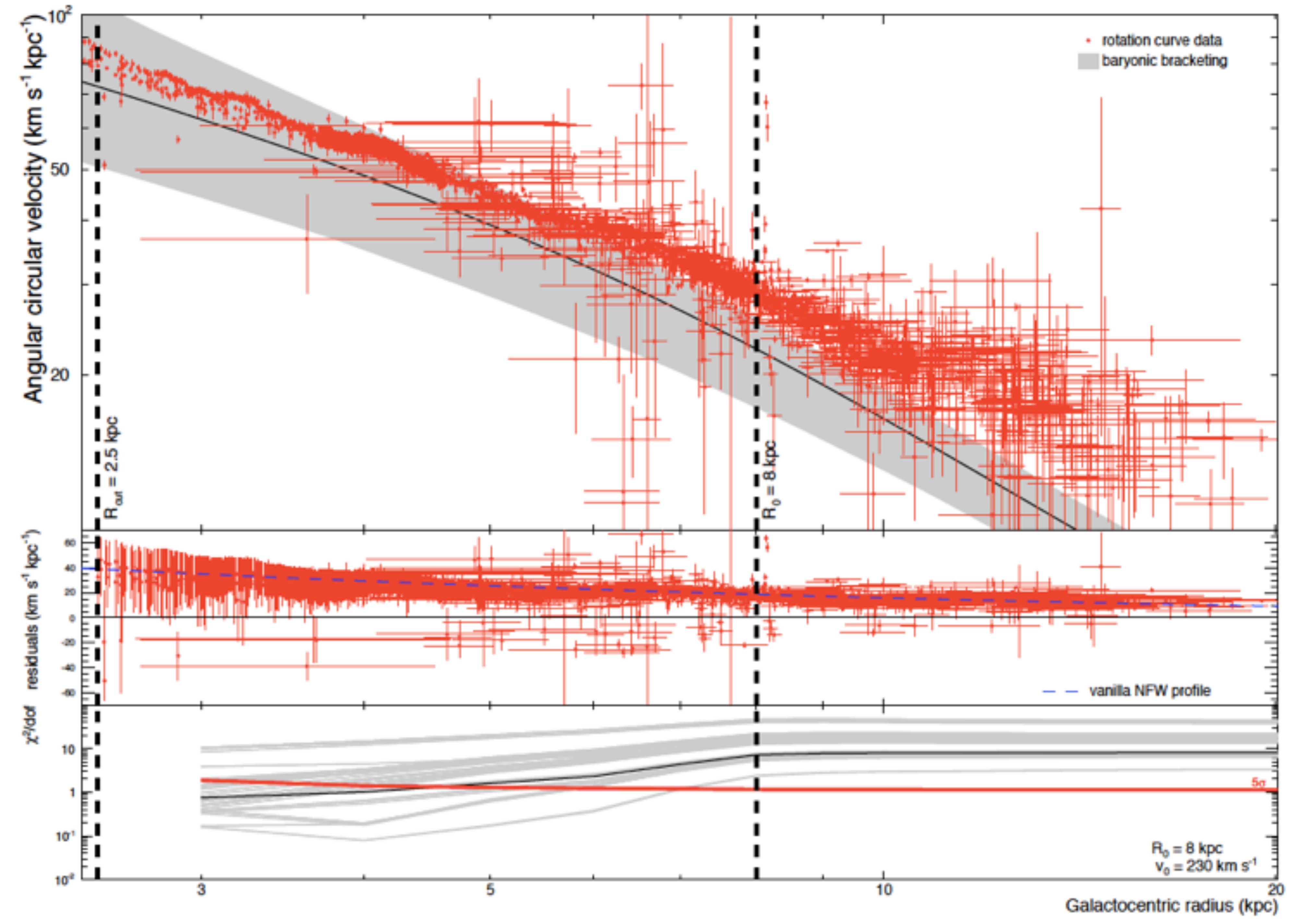
Iocco, Pato, GB, Nature Physics, arXiv:1502.03821

Rotation curve of the Milky Way



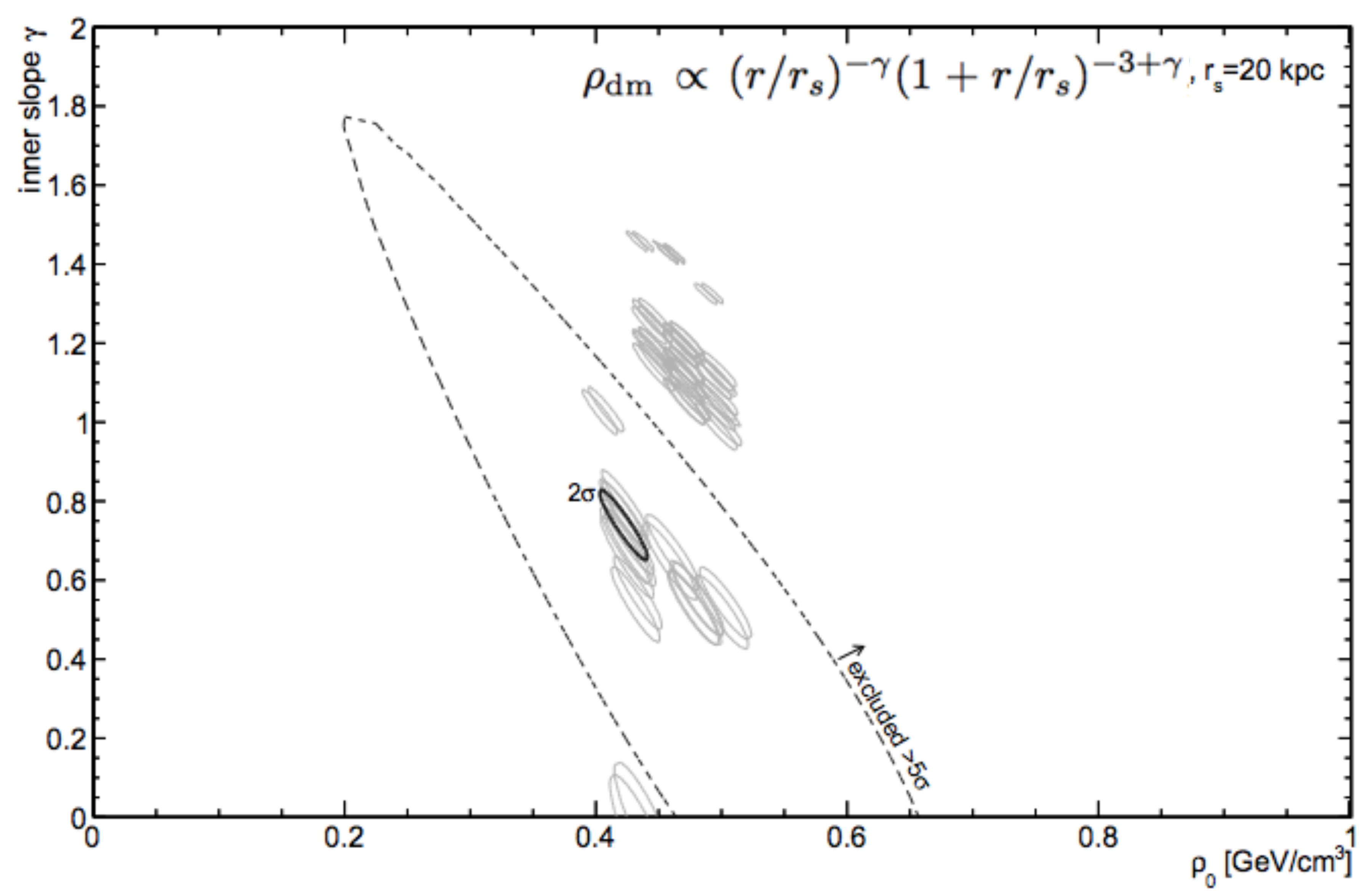
Iocco, Pato, GB, Nature Physics, arXiv:1502.03821

Rotation curve of the Milky Way



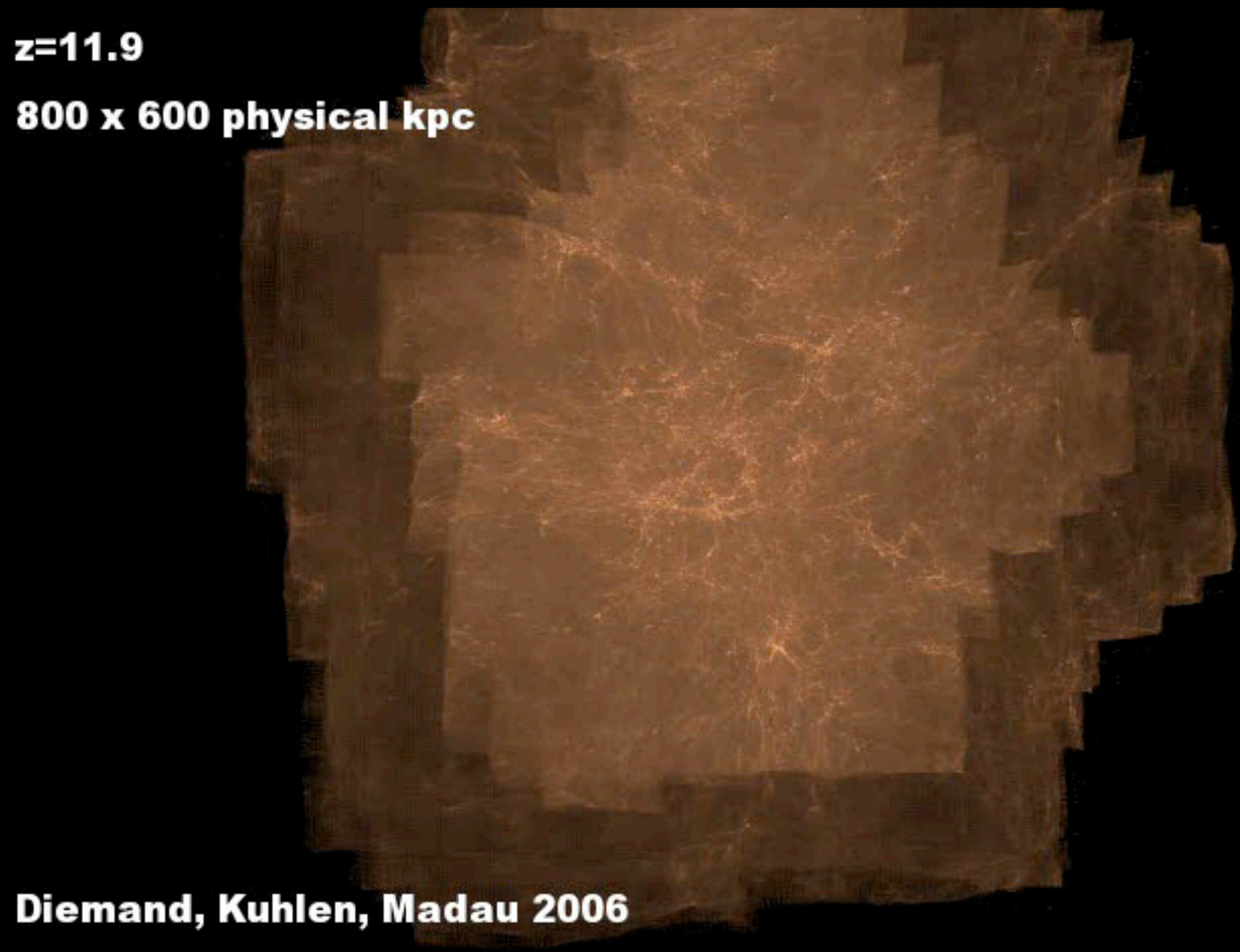
Iocco, Pato, GB, Nature Physics, arXiv:1502.03821

Constraints on MW DM profile



Pato, Iocco, GB, arXiv: 1504.06324

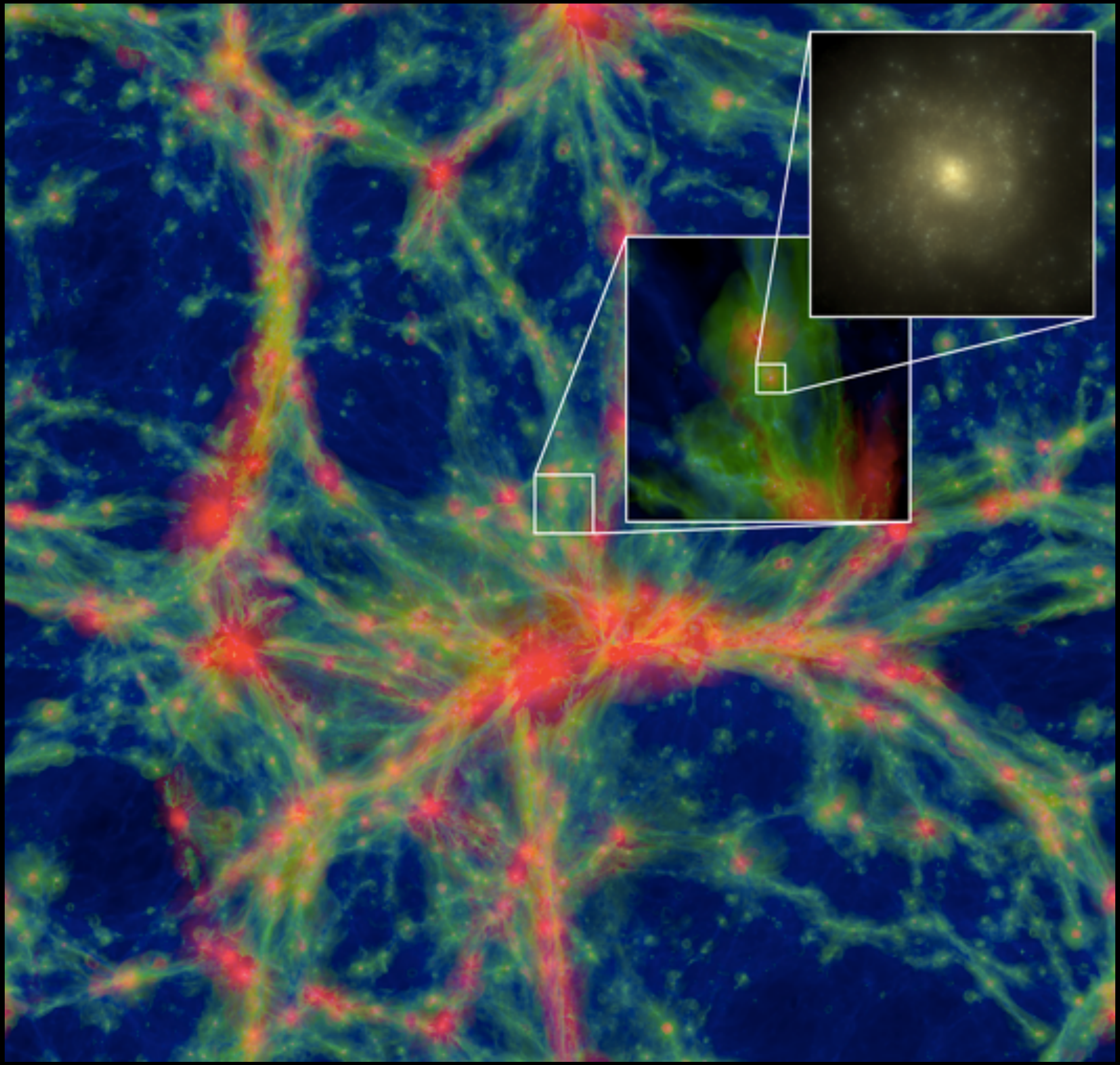
Mock Milky Ways



Diemand, Kuhlen, Madau 2006

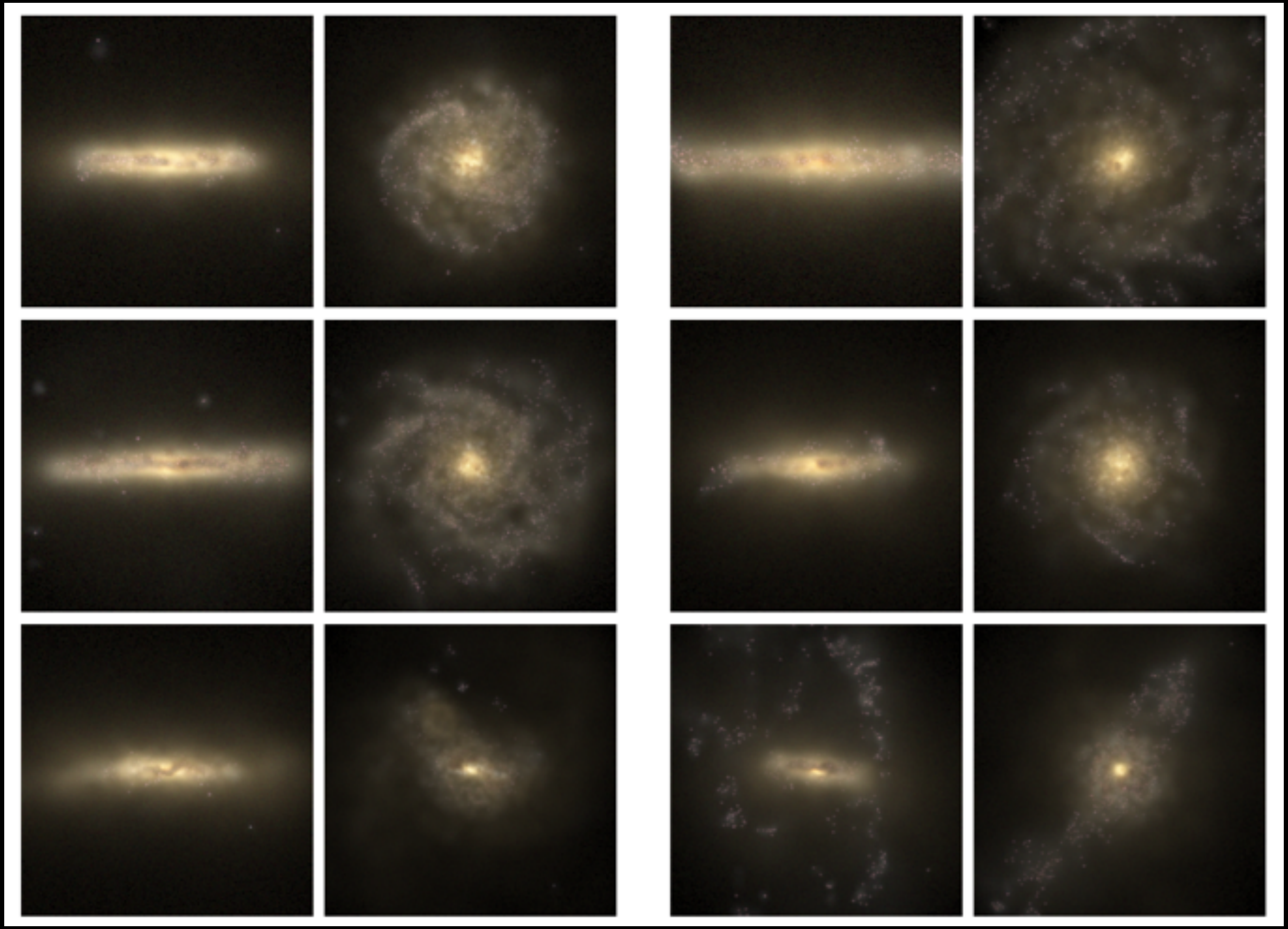
Simulating Galaxy Formation

The Eagle simulation



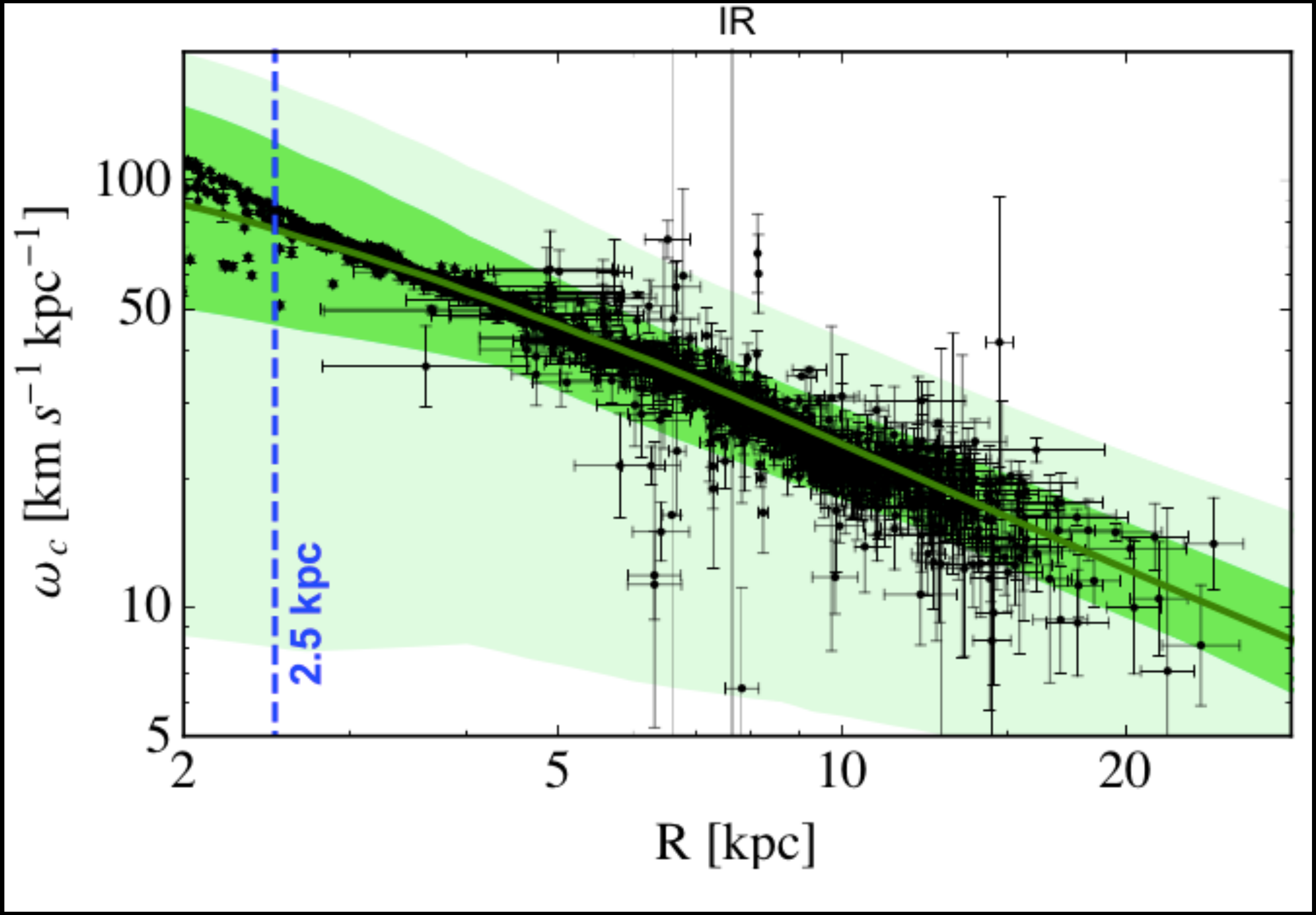
- One of the largest cosmological hydrodynamical simulations (7 billion particles)
- 1.5 months on 4000 cores DiRAC-2 supercomputer in Durham
- Runs a modified version of the GADGET-2 simulation code

Identifying MW-like galaxies



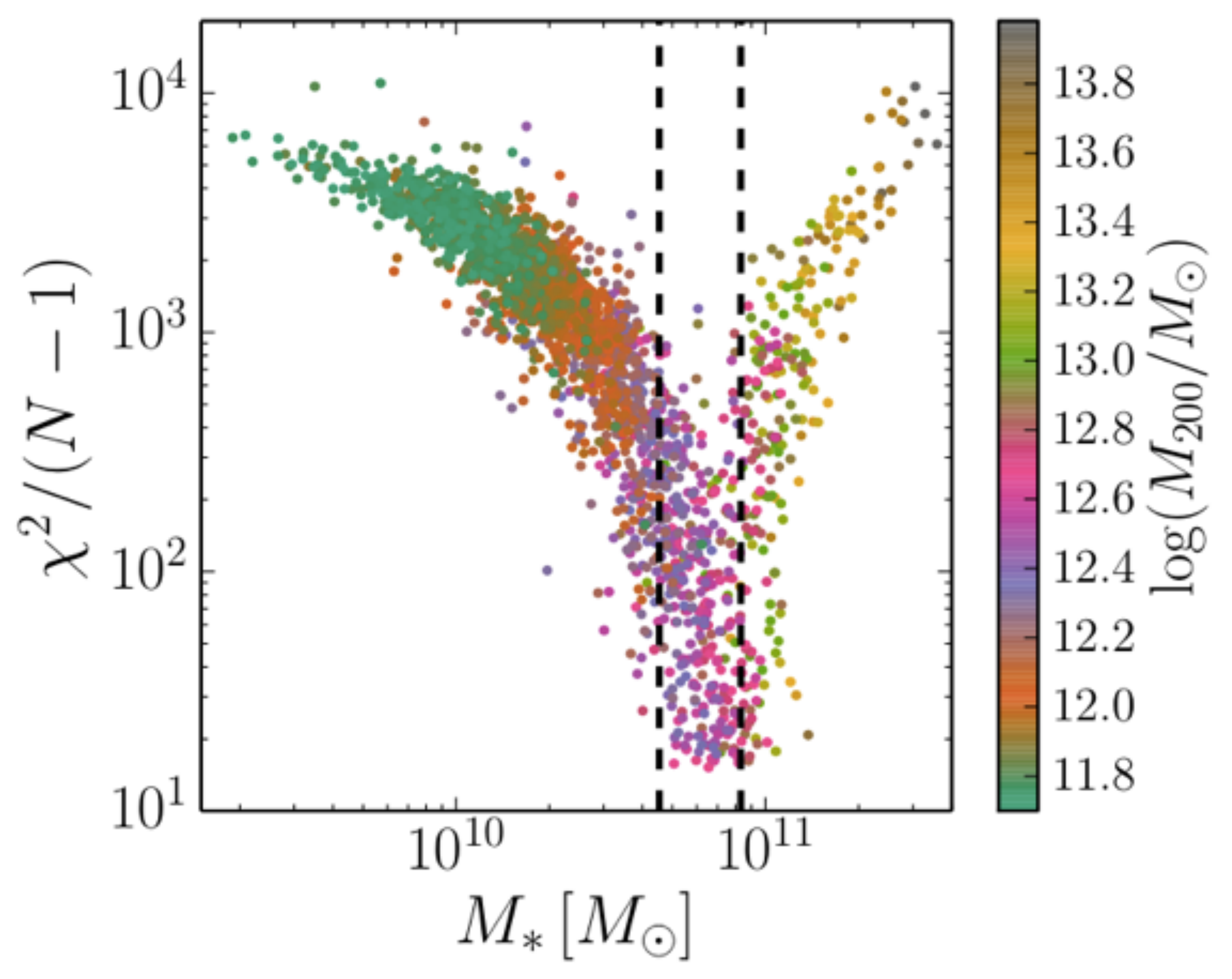
Calore, Bozorgnia, GB+ arXiv:1509.xxxxx

Identifying MW-like galaxies



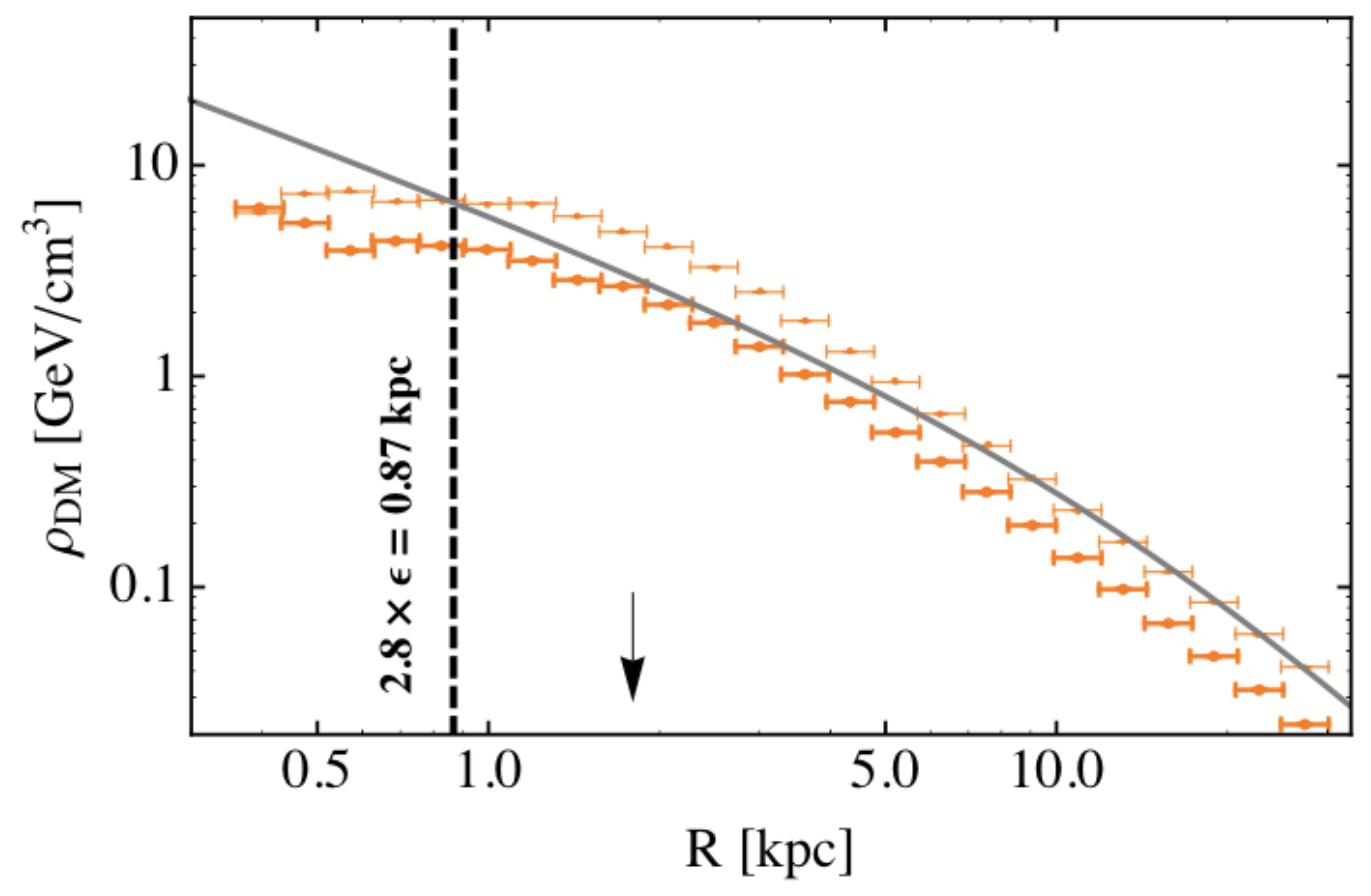
Calore, Bozorgnia, GB+ arXiv:1509.xxxxx

Identifying MW-analogues



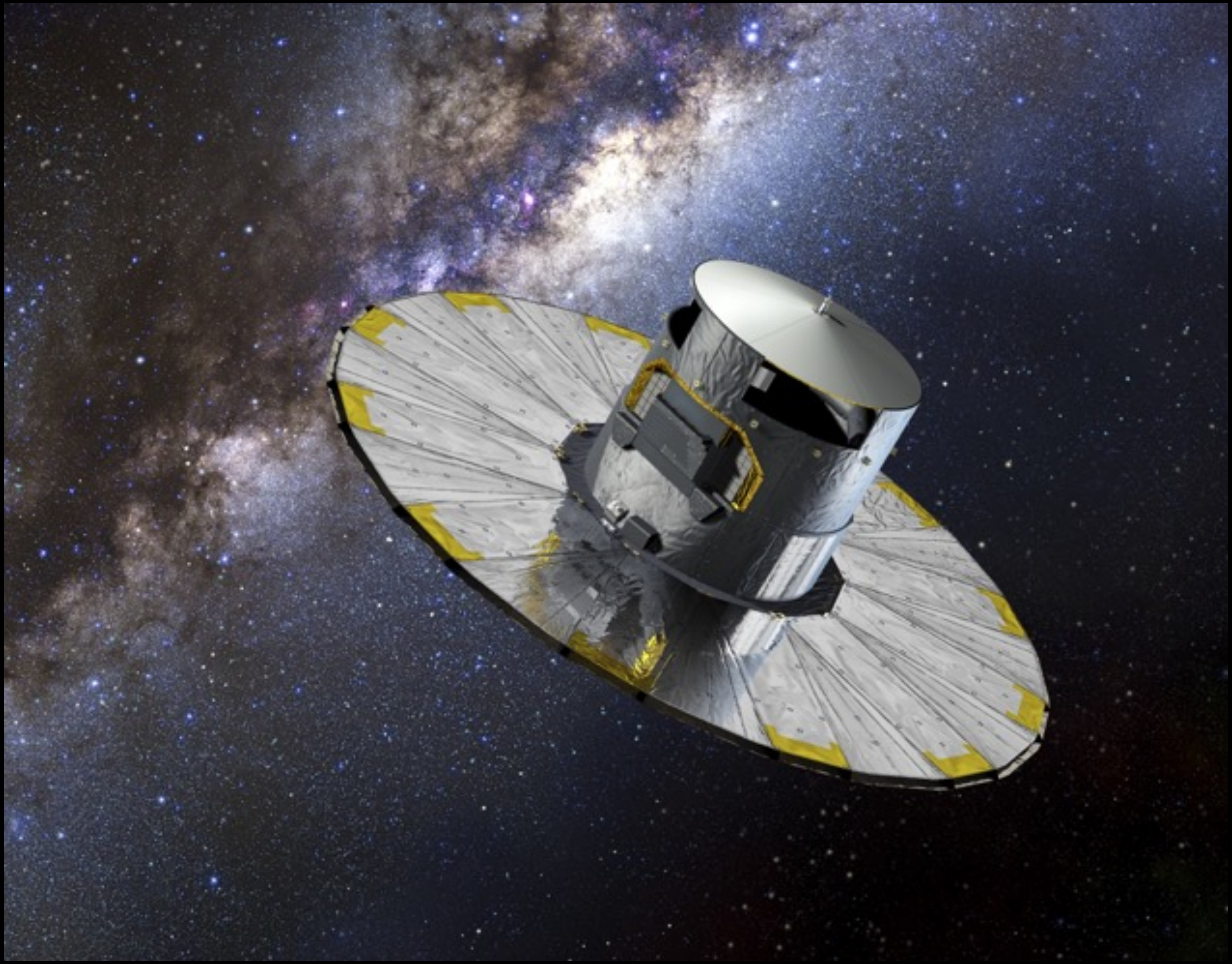
Calore, Bozorgnia, GB+ arXiv:1509.xxxxx

“Predicted” DM profile



Calore, Bozorgnia, GB+ arXiv:1509.xxxxx

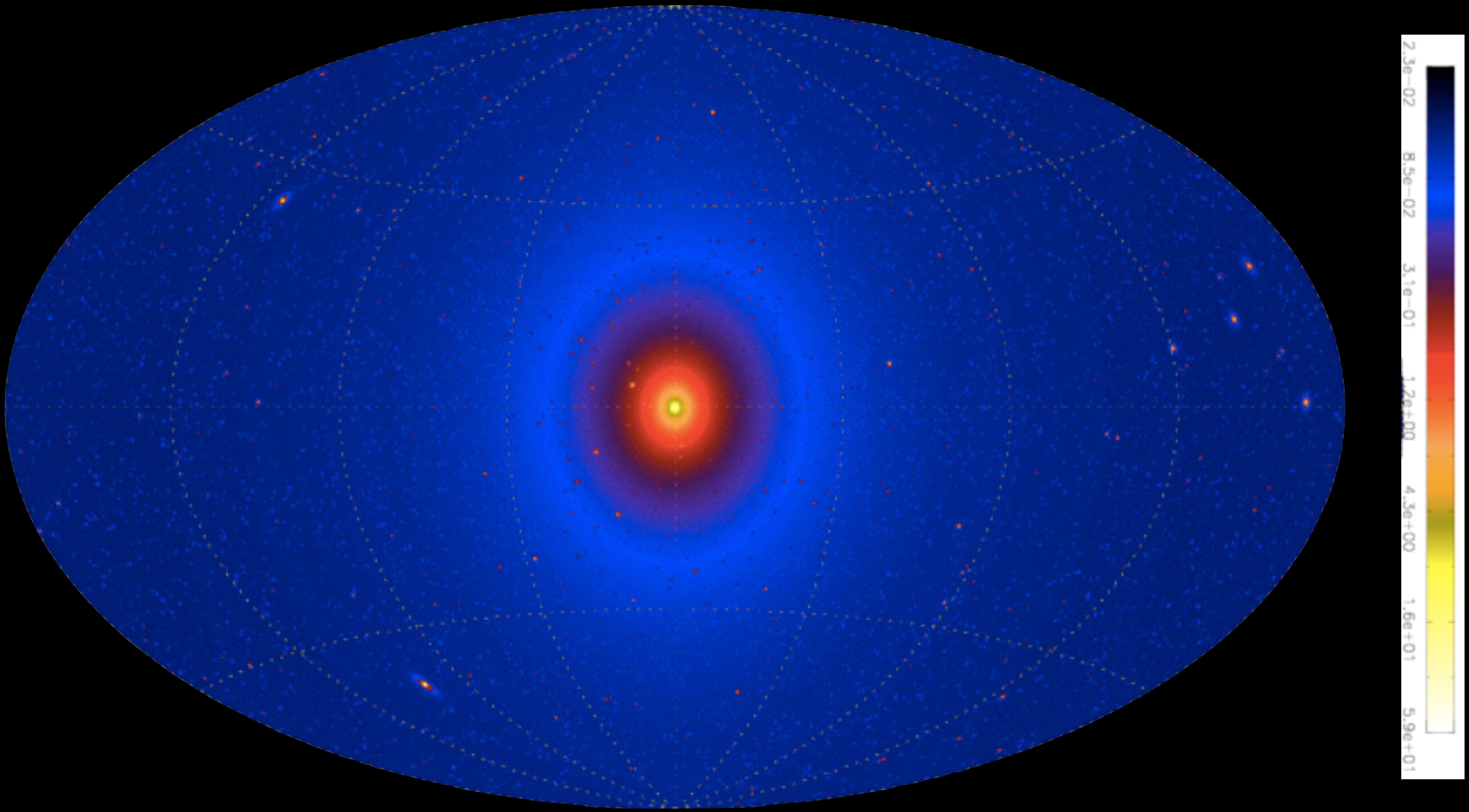
Better constraints on DM (and MoND) soon..



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

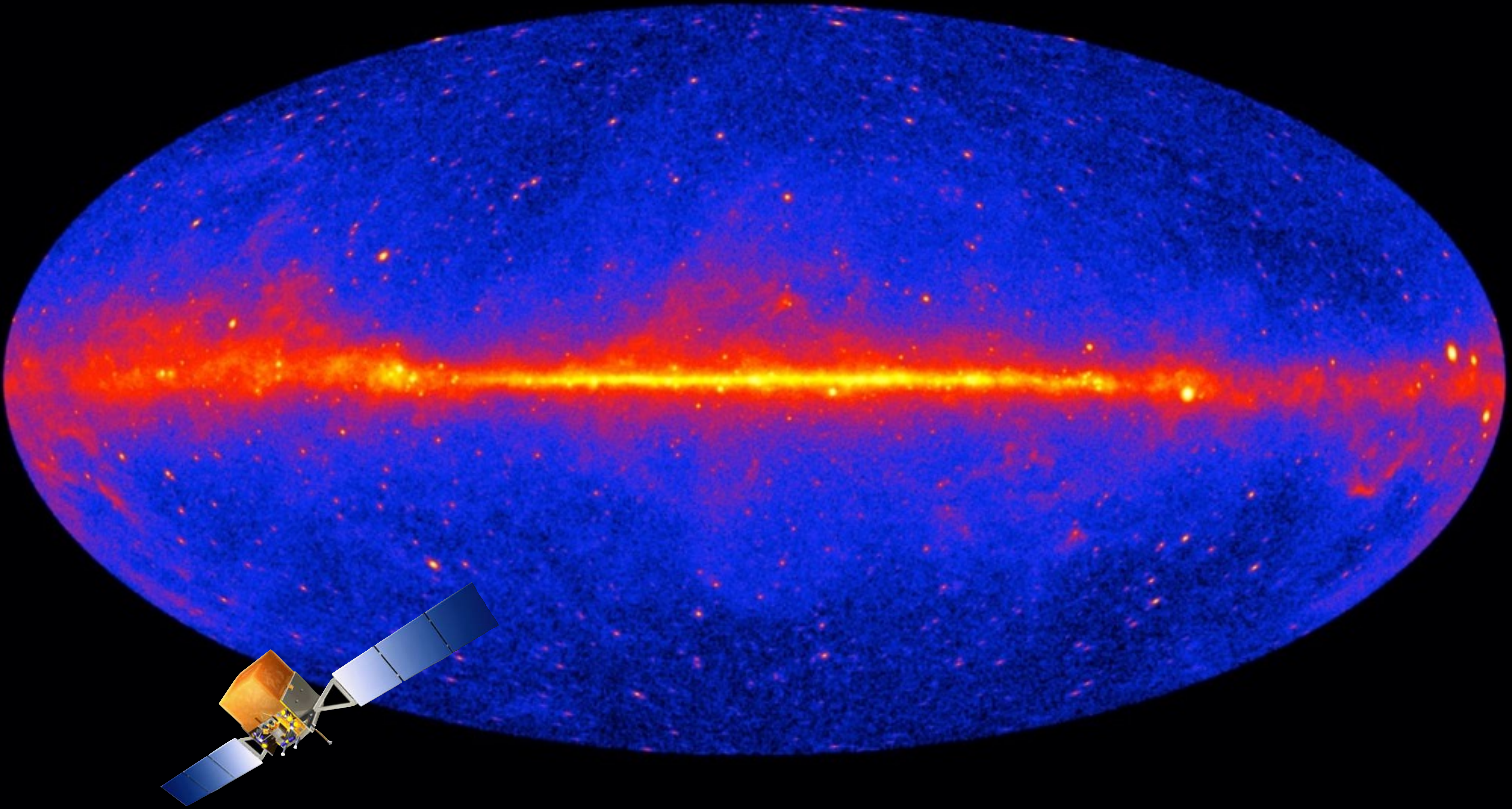
Predicted Annihilation Flux

Pieri, GB, Branchini 2009



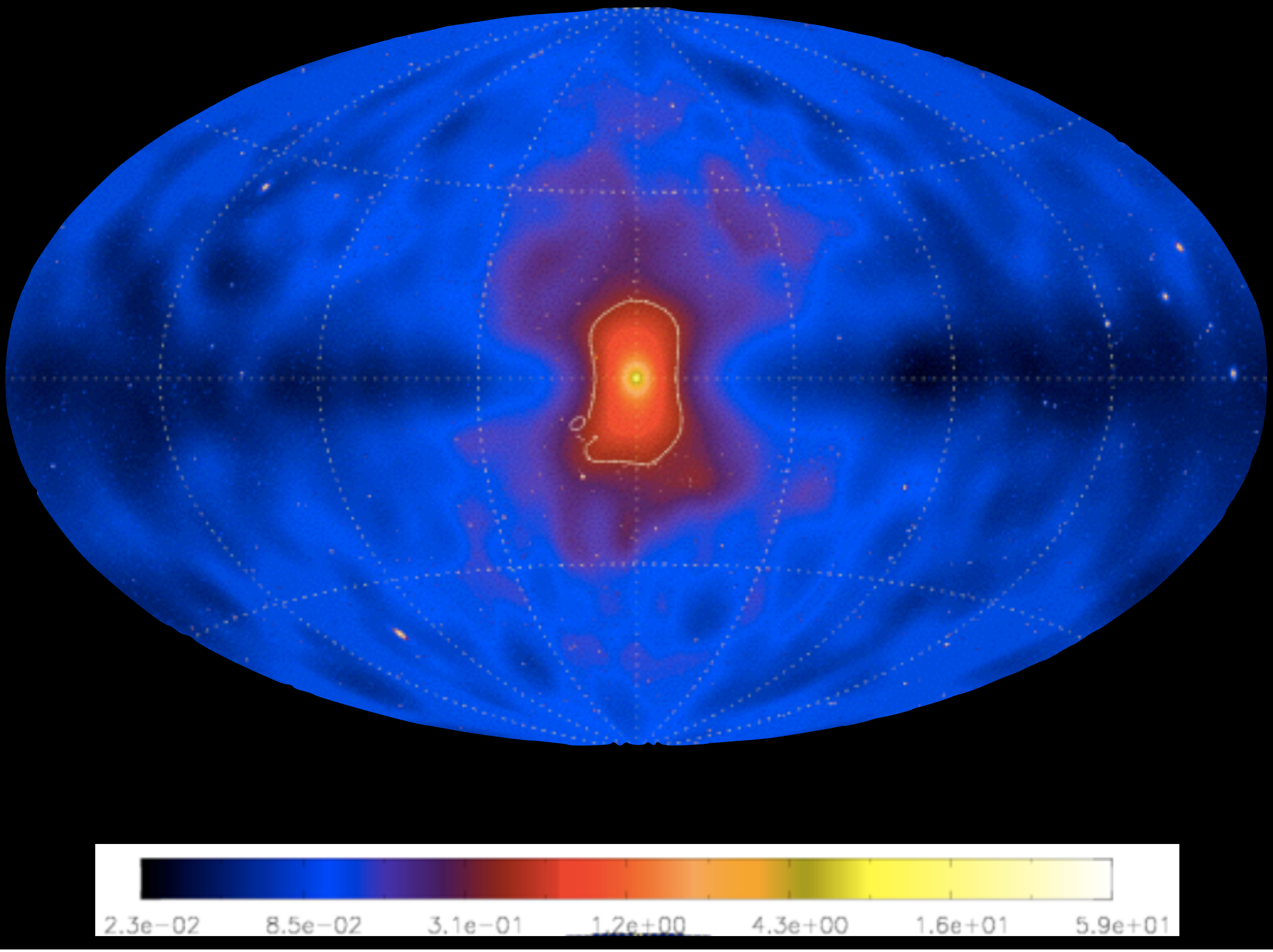
Full sky map of Number of photons above 3 GeV

The FERMI sky



“Sensitivity” Map

PIERI, GB, BRANCHINI 2009



The "GeV Excess"

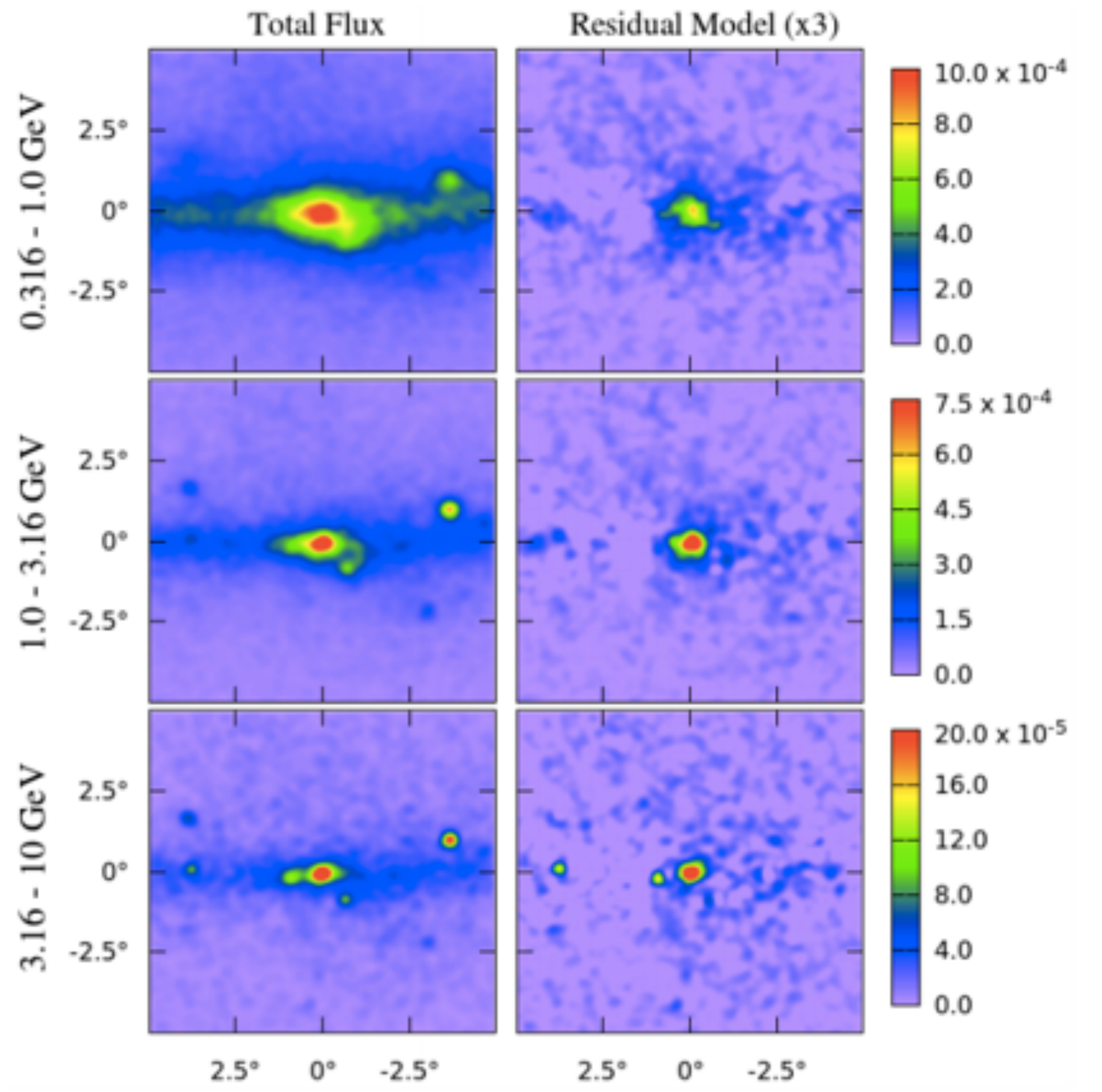
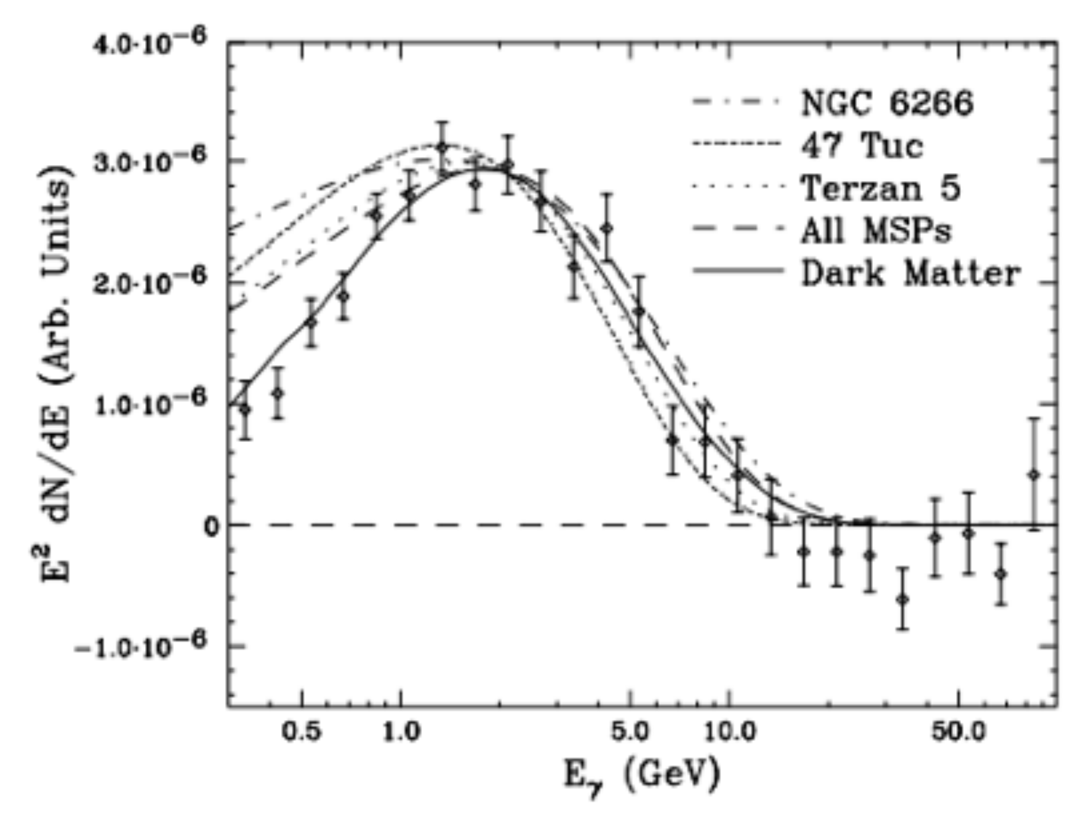


FIG. 9: The raw gamma-ray maps (left) and the residual maps after subtracting the best-fit Galactic diffuse model, 20 cm template, point sources, and isotropic template (right), in units of photons/cm^2/s/sr. The right frames clearly contain a significant central and spatially extended excess, peaking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

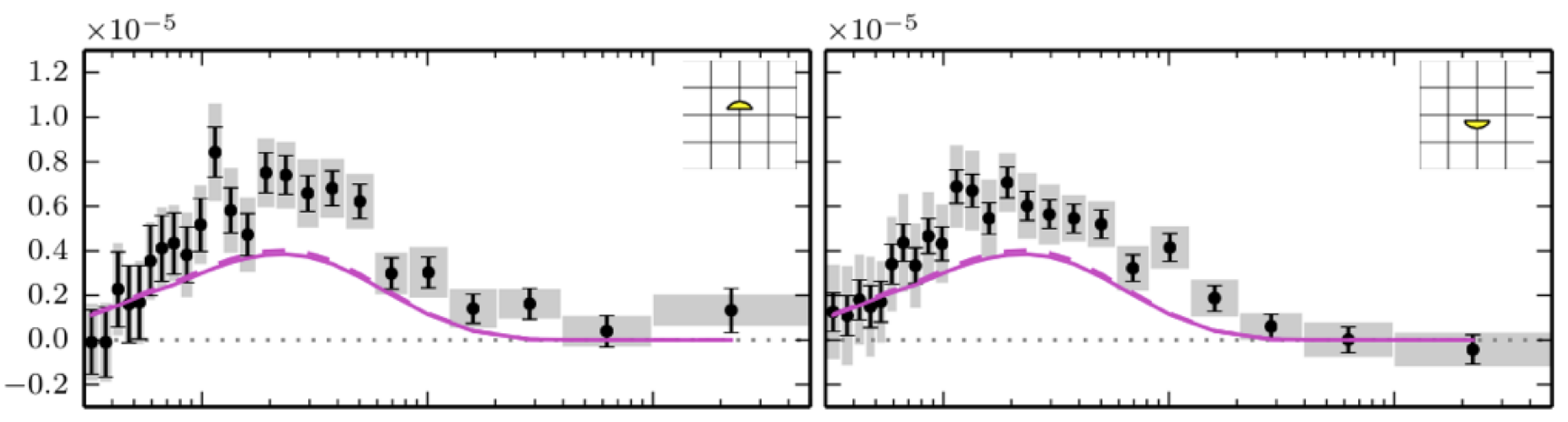
DAYLAN ET AL. ARXIV:1402.6703



"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"

More in Jenny's talk this afternoon

The GeV excess



Calore, Bozorgnia, GB+ arXiv:1509.xxxxx

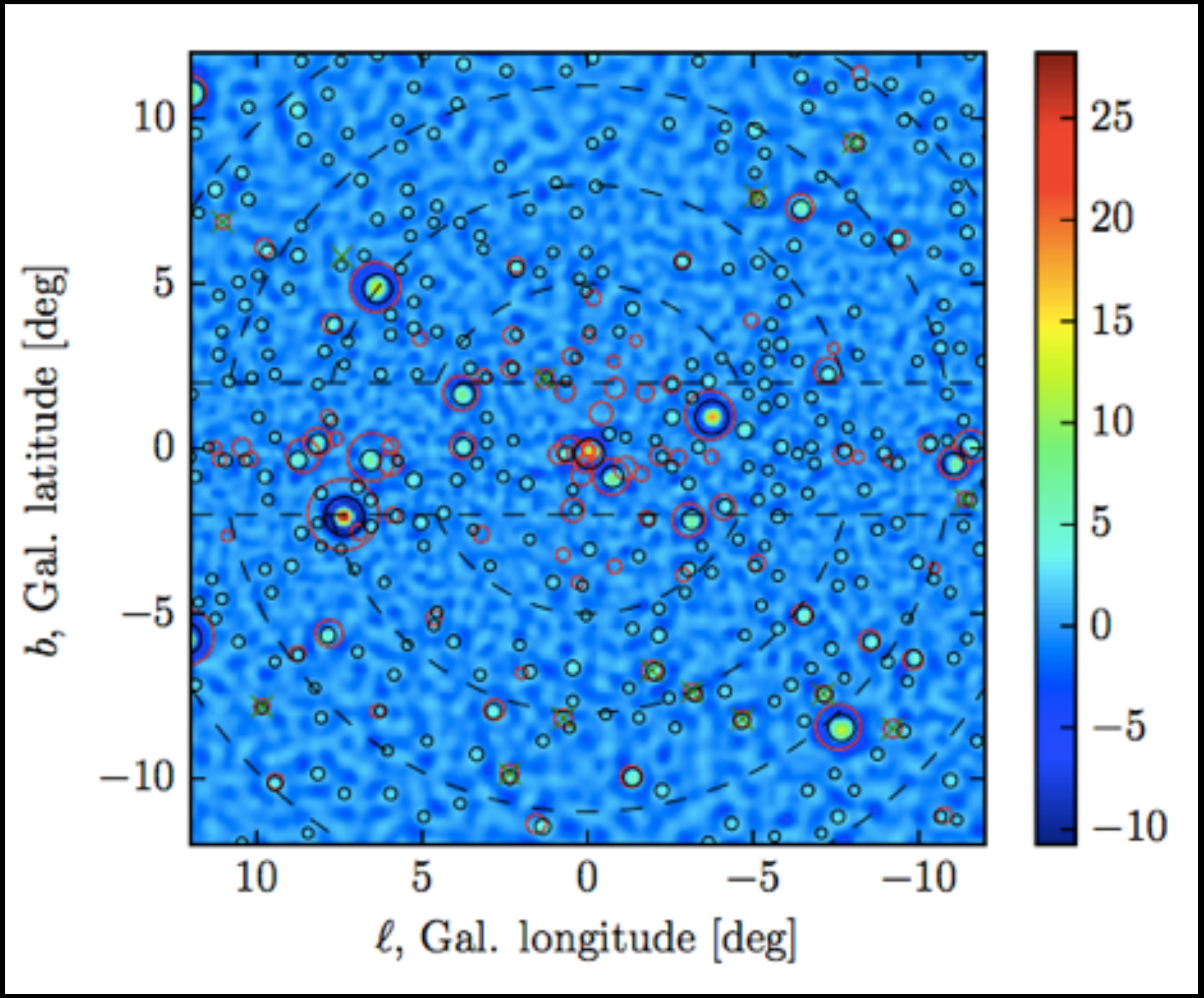
High resolution simulated haloes that satisfy observational constraints exhibit, in the inner few kiloparsecs, dark matter profiles shallower than those required to explain the GeV excess via dark matter annihilation.

Recently on the arXiv: ‘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*

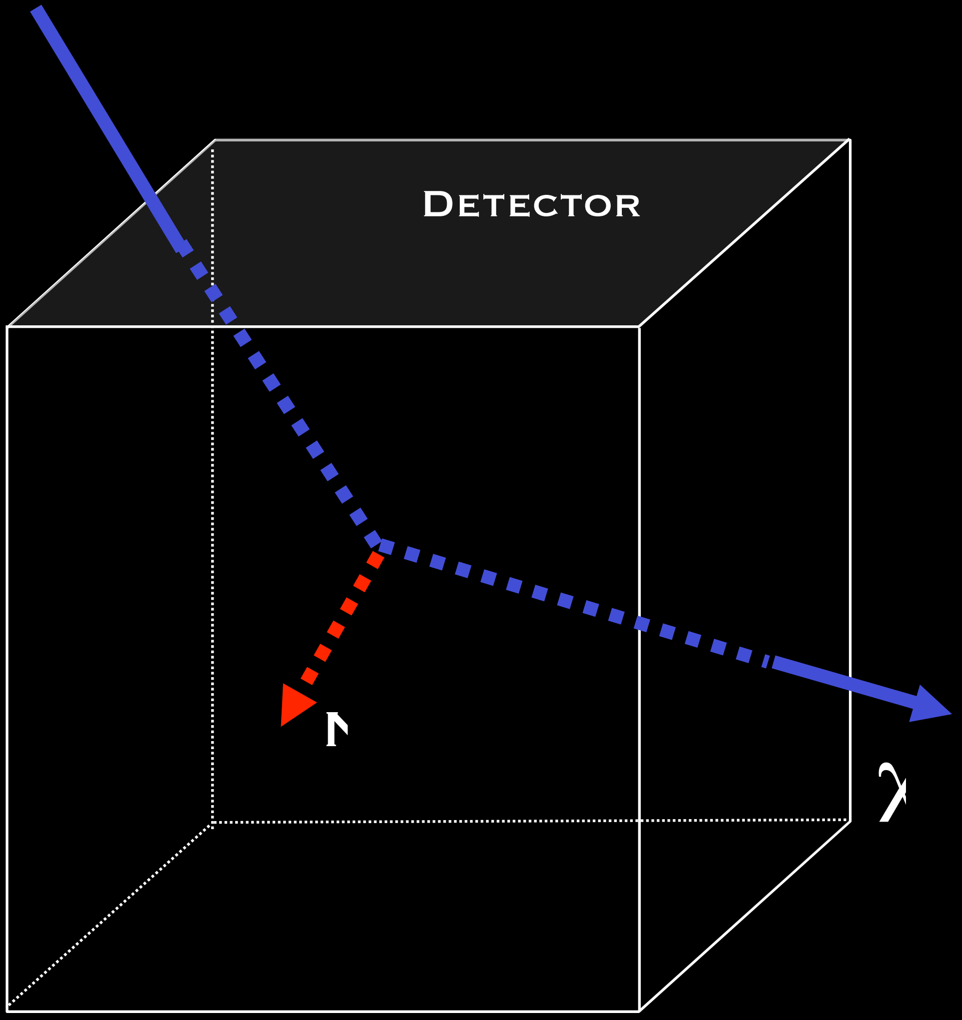
- 1506.05124 *Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy*

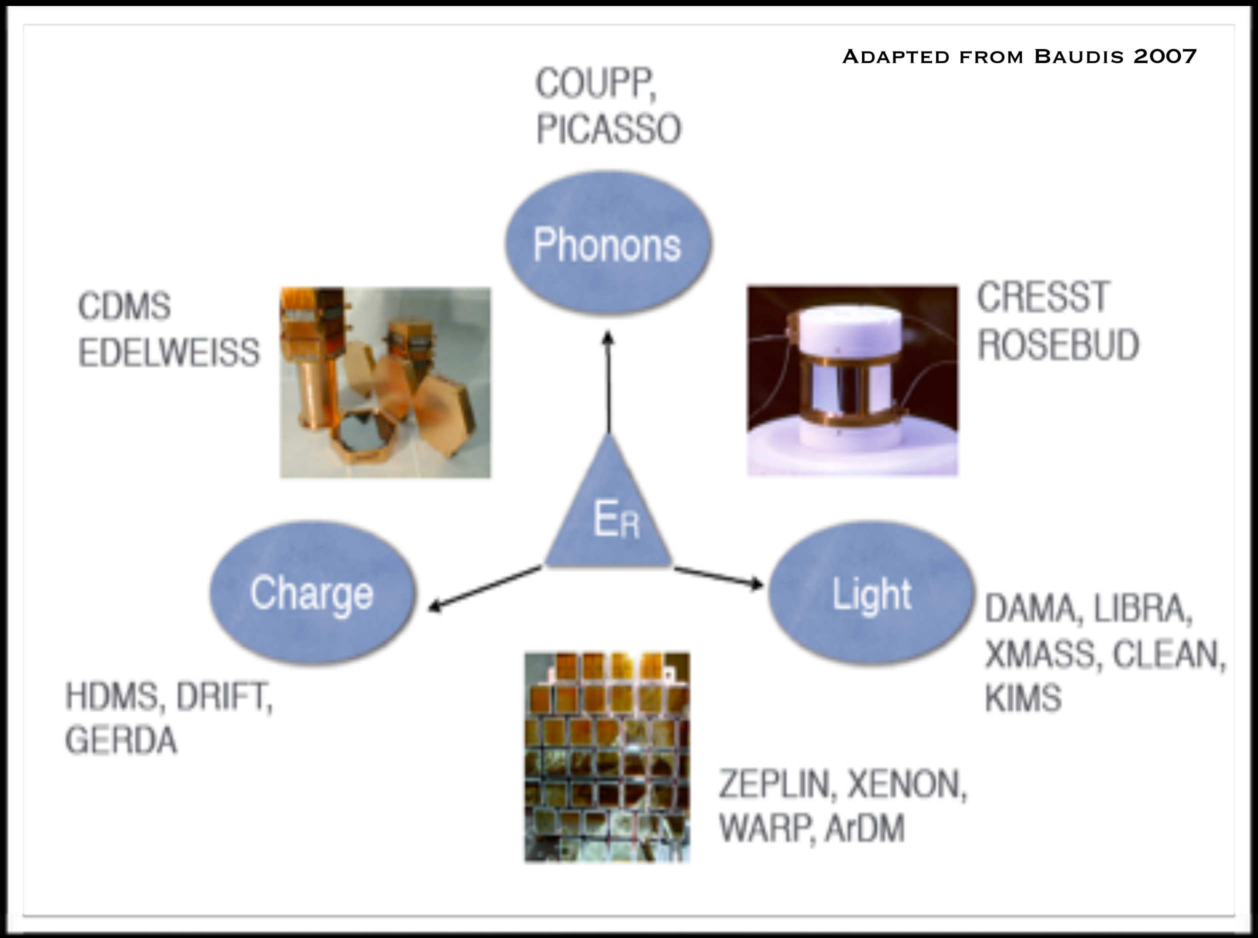


1506.05104

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)

Xenon detectors

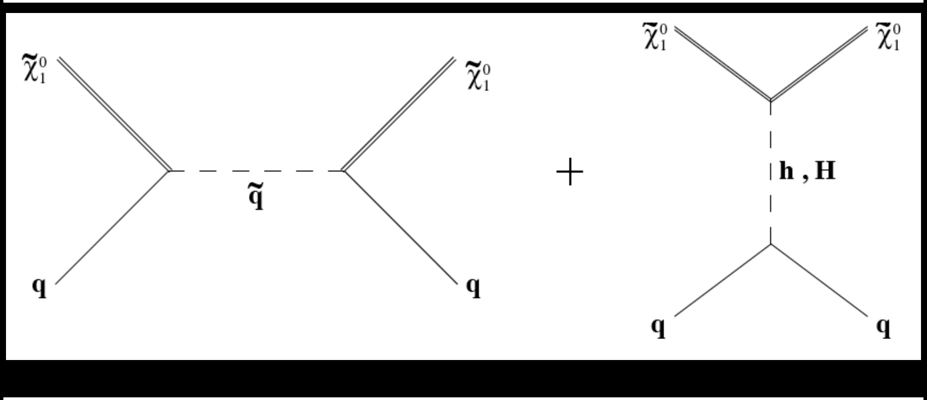
(e.g. LUX and Xenon100)

Direct Detection

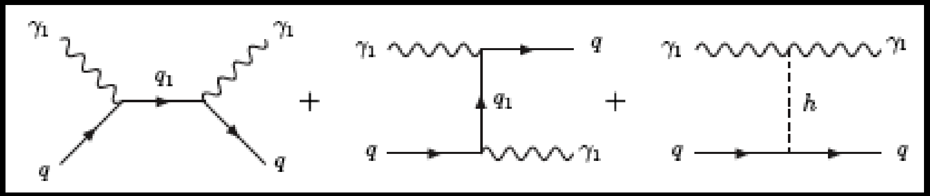
Differential Event Rate

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

SUSY: squarks and Higgs exchange



UED: 1st level quarks and Higgs exchange



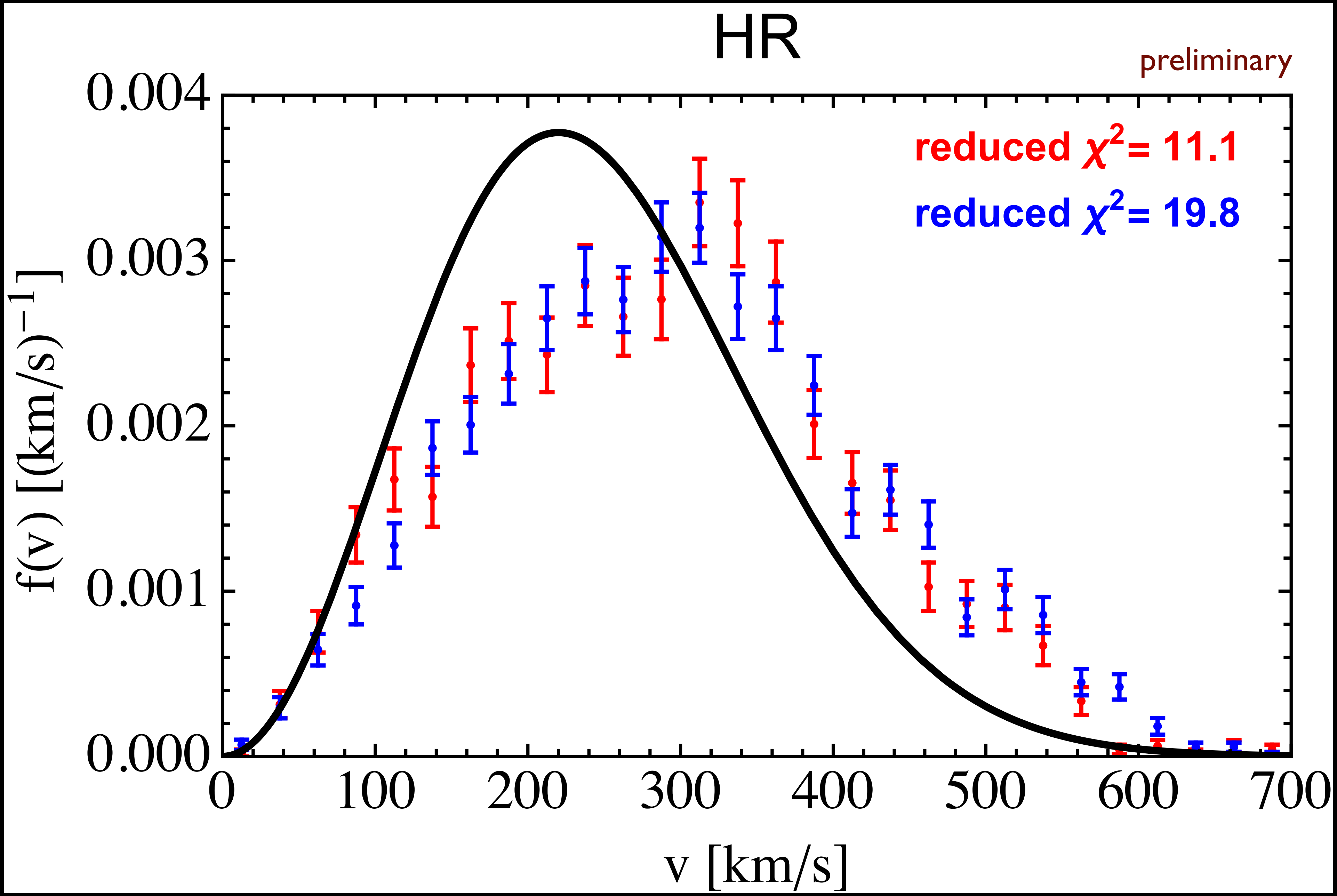
Theoretical Uncertainties

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

Uncertainties on f(v)

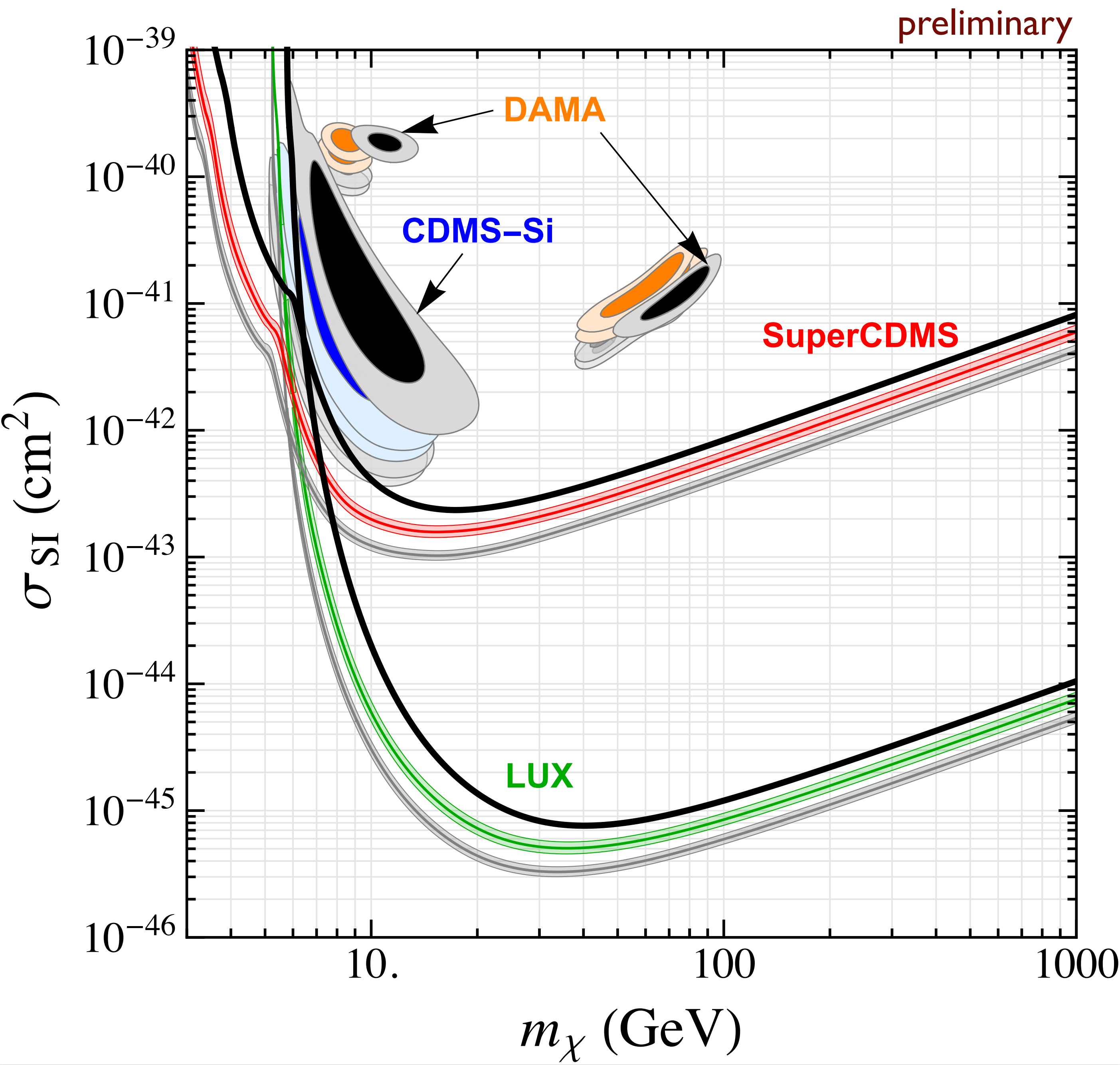
Ling et al. 2009; Widrow et al. 2000; Helmi et al 2002

f(v) from Hydro Simulations



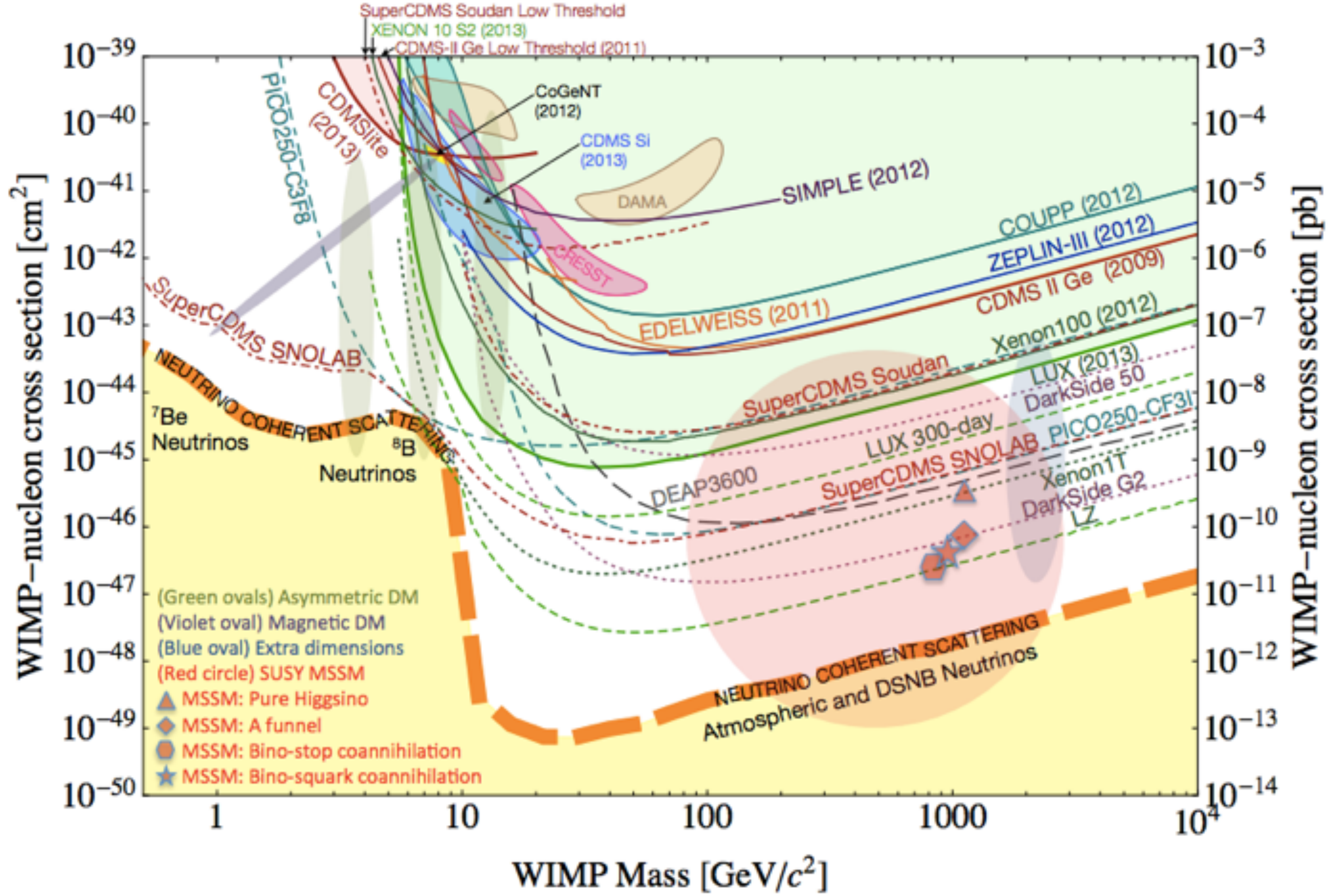
Bozorgnia, Calore, GB+ arXiv:1509.xxxxx

Status of Direct Detection



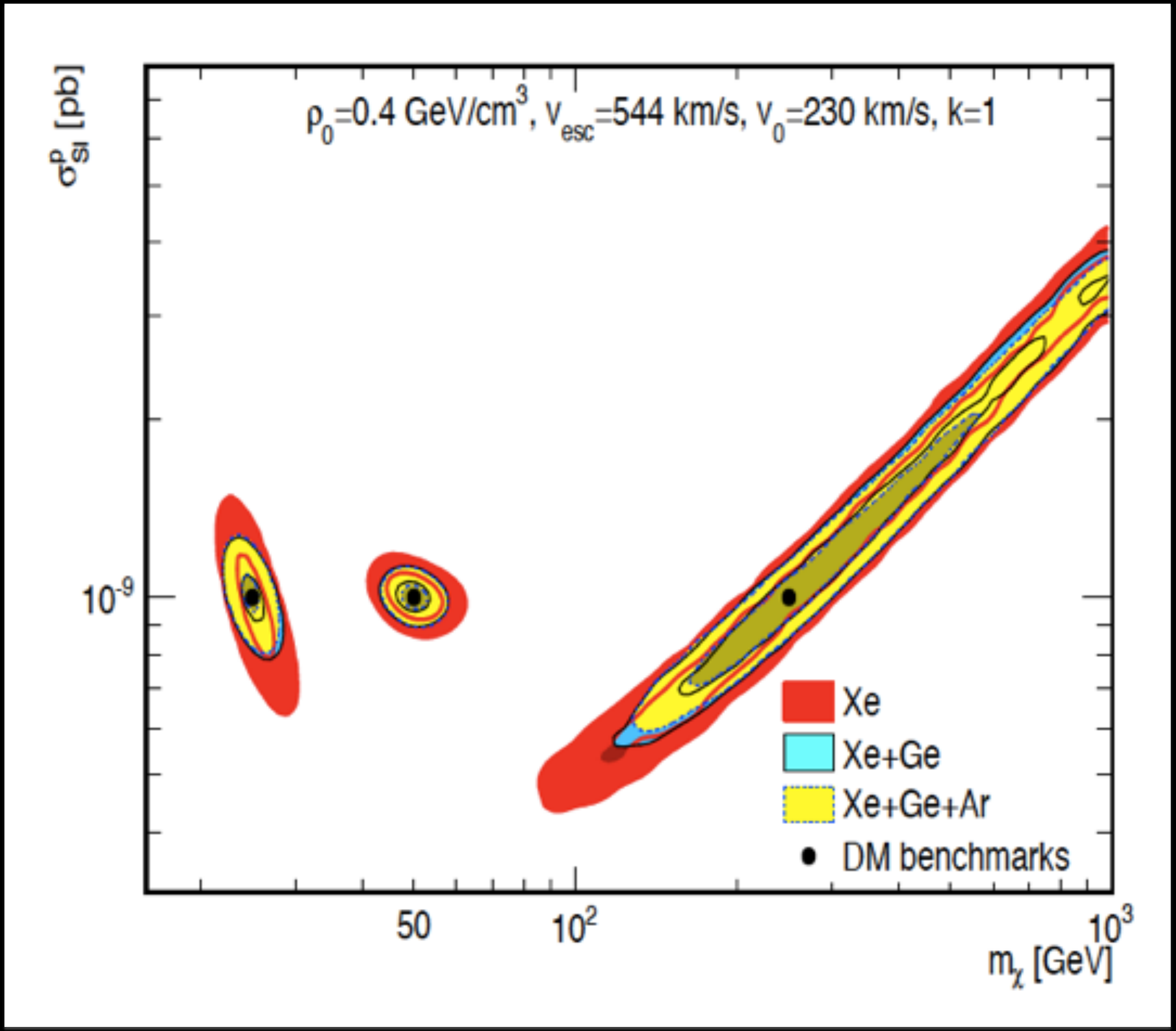
Bozorgnia, Calore, GB+ arXiv:1509.xxxxx

Status and prospects of DD



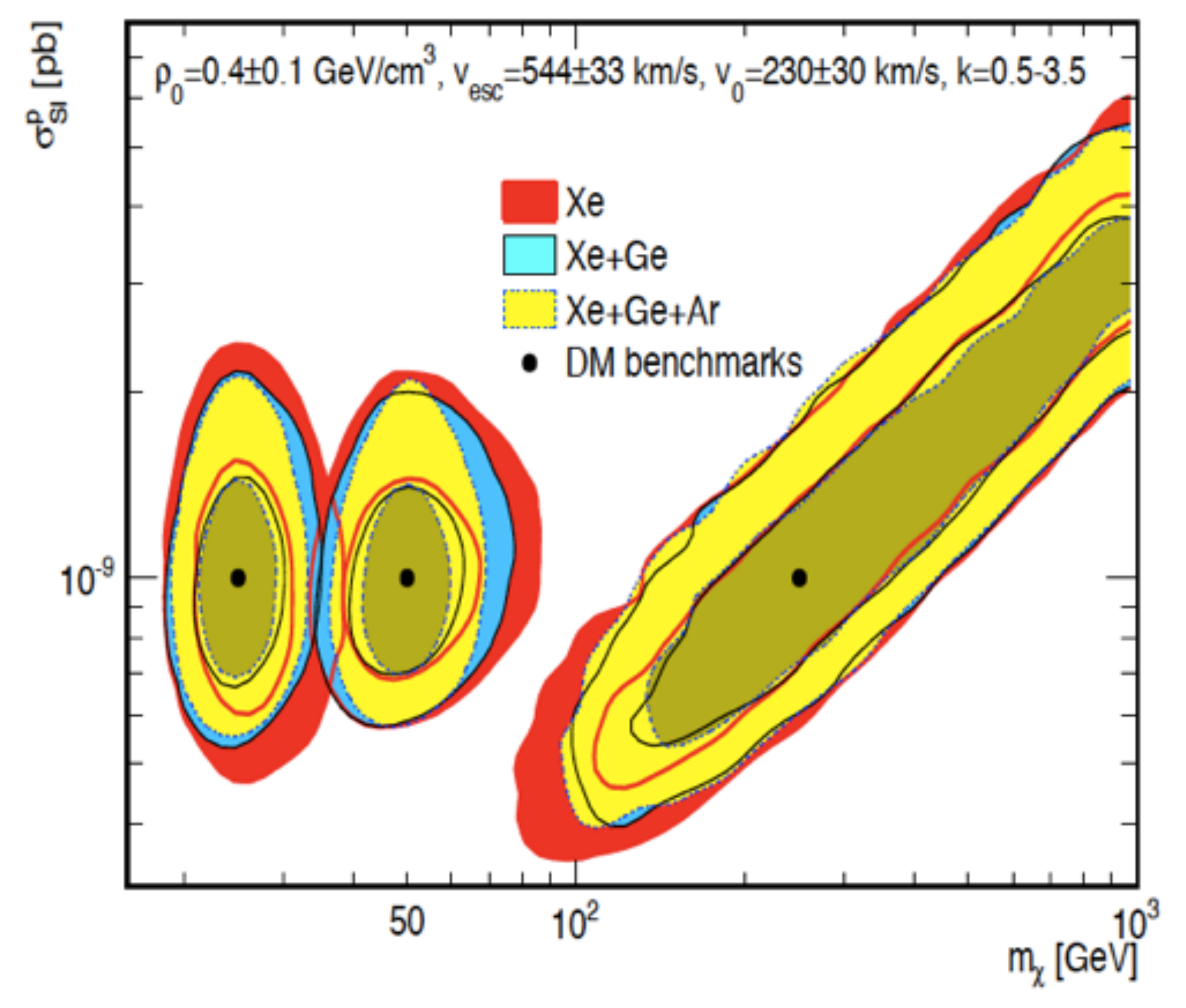
arXiv:1310.8214

Complementarity of DD targets



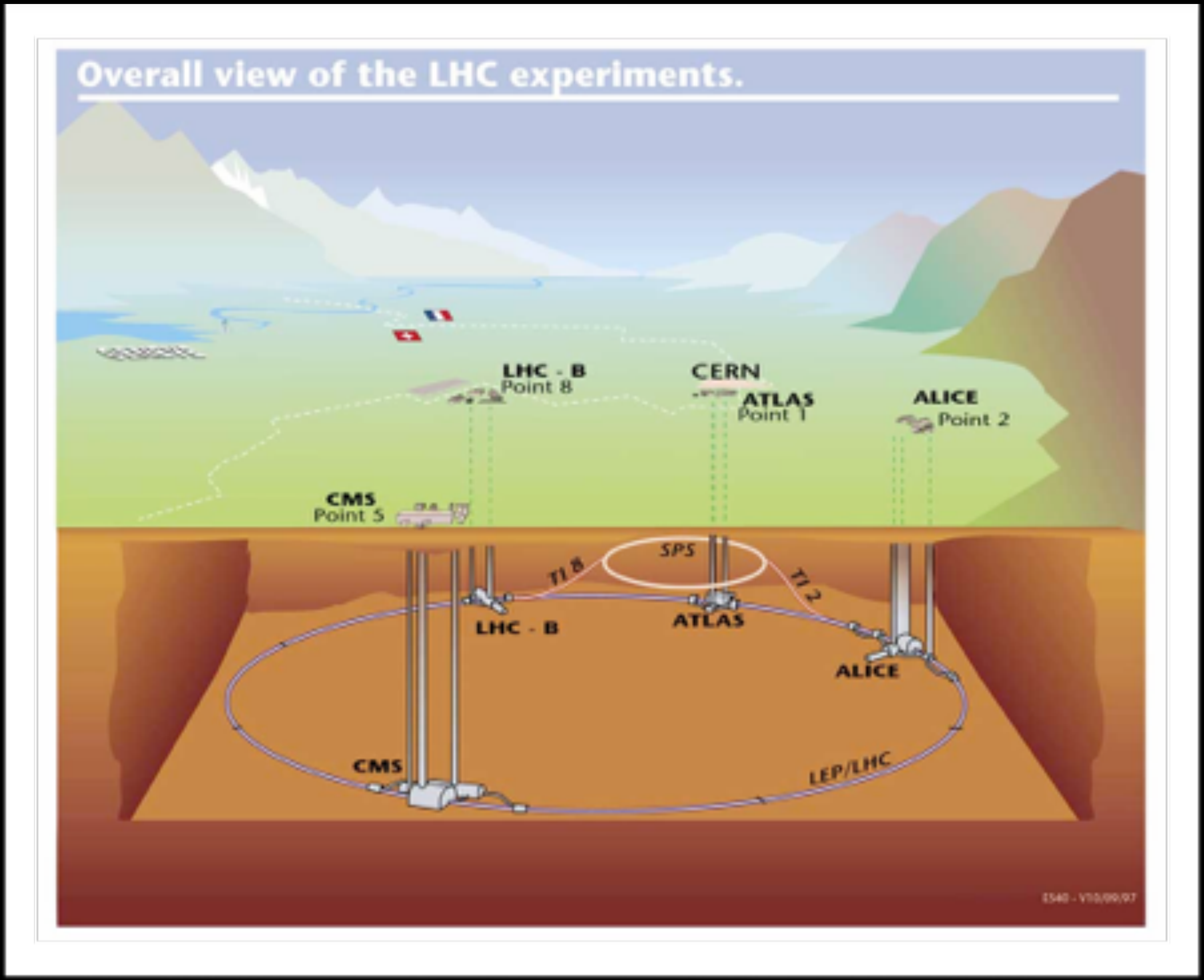
Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458

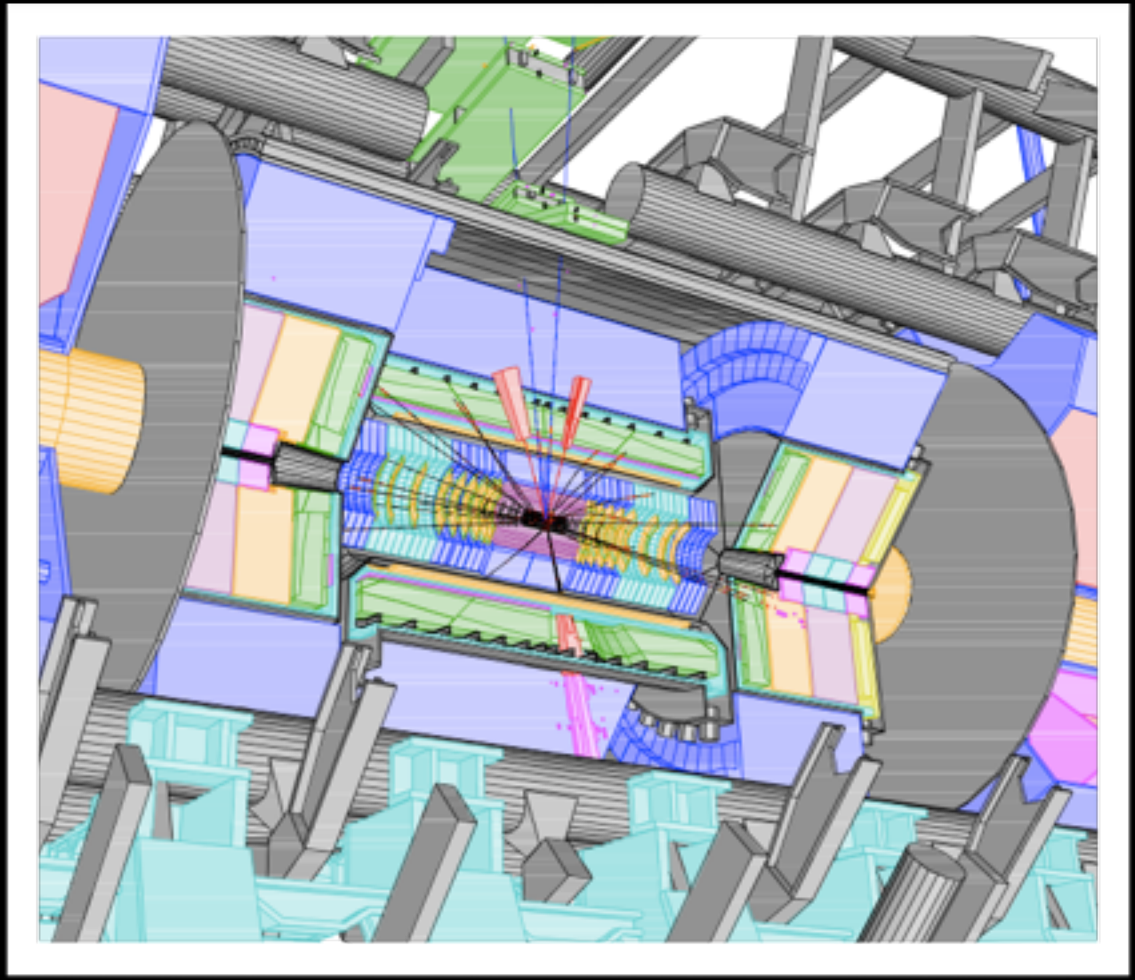
Complementarity of DD targets



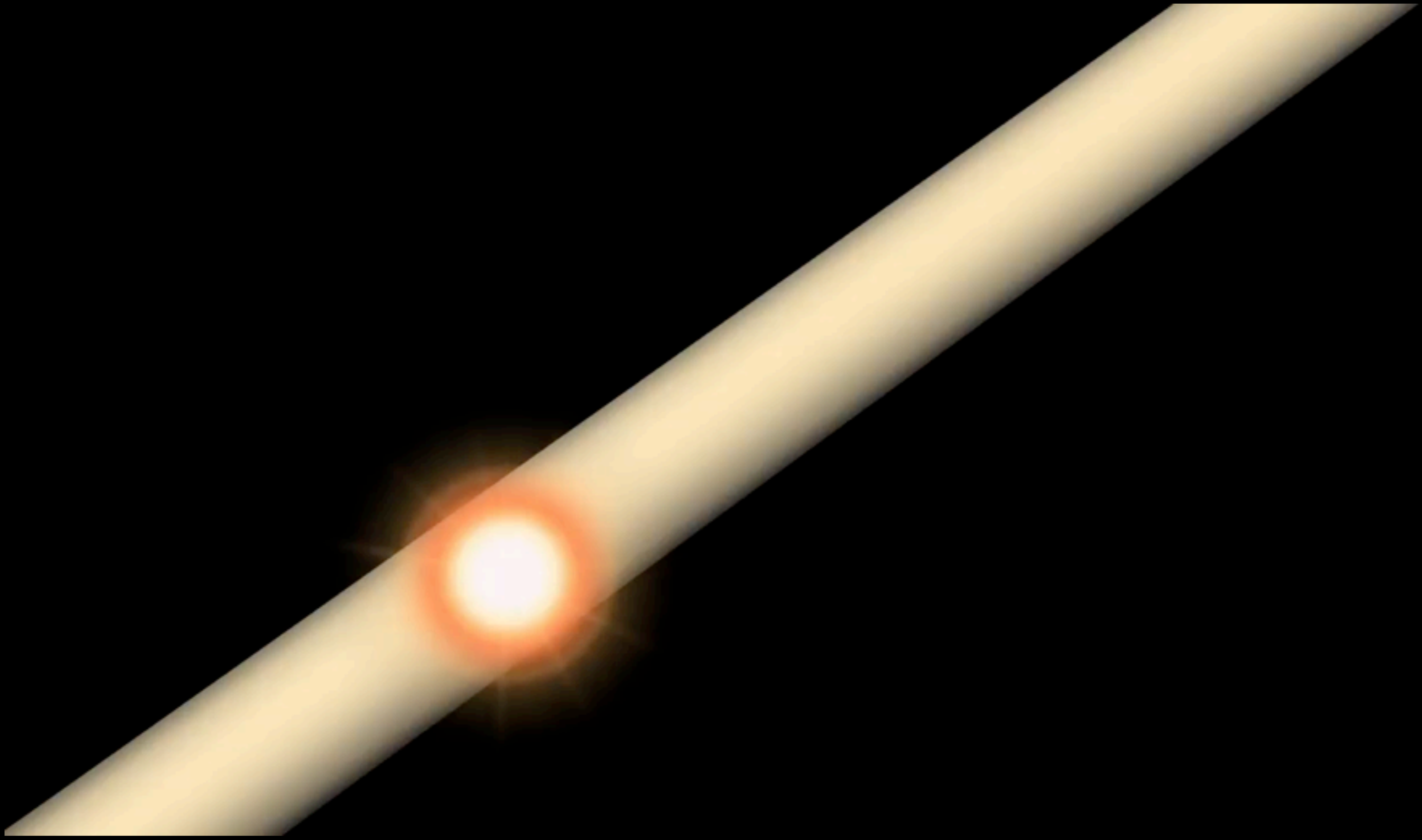
Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458

Dark Matter Searches at the LHC



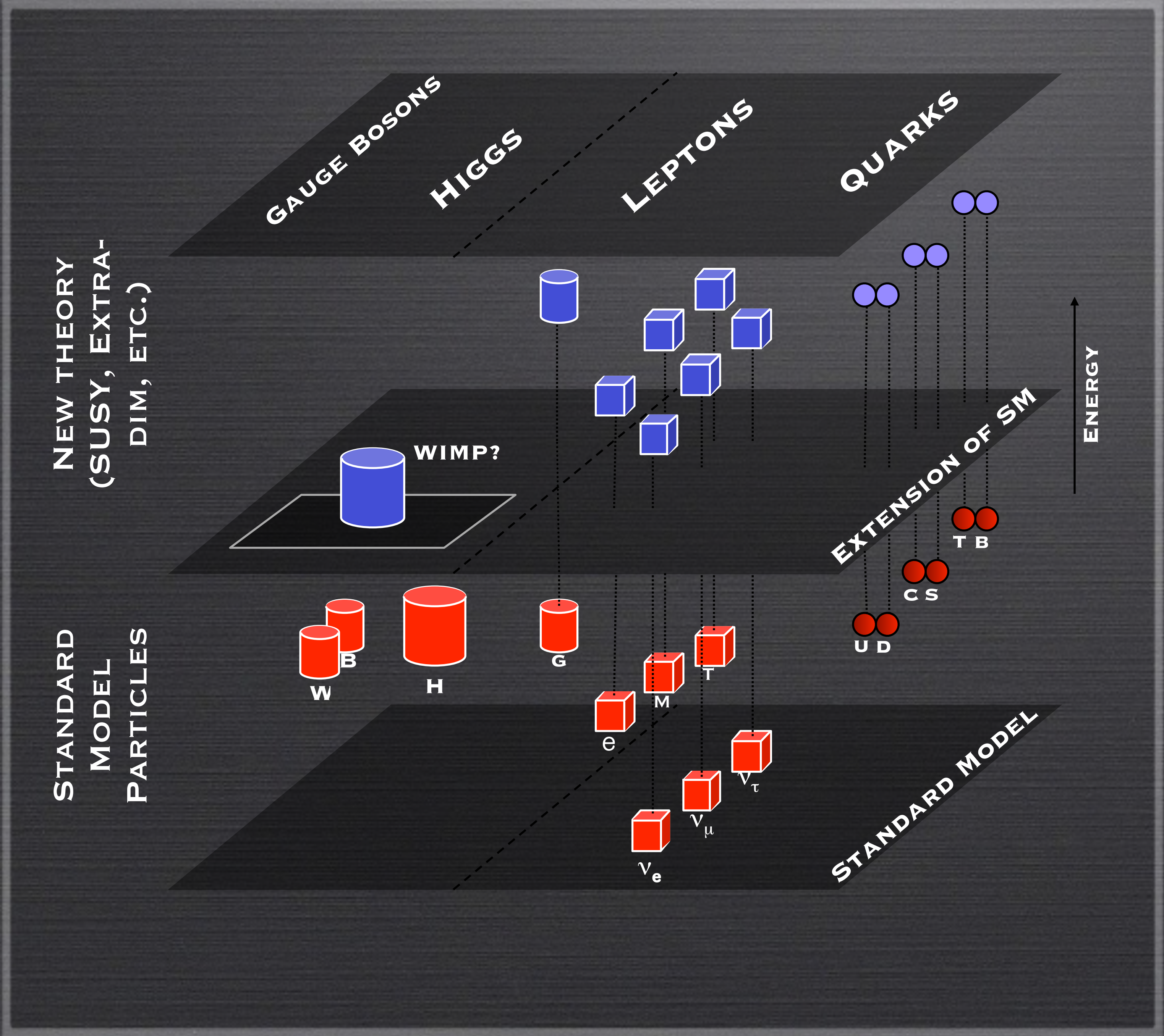


Colliding protons at the LHC



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

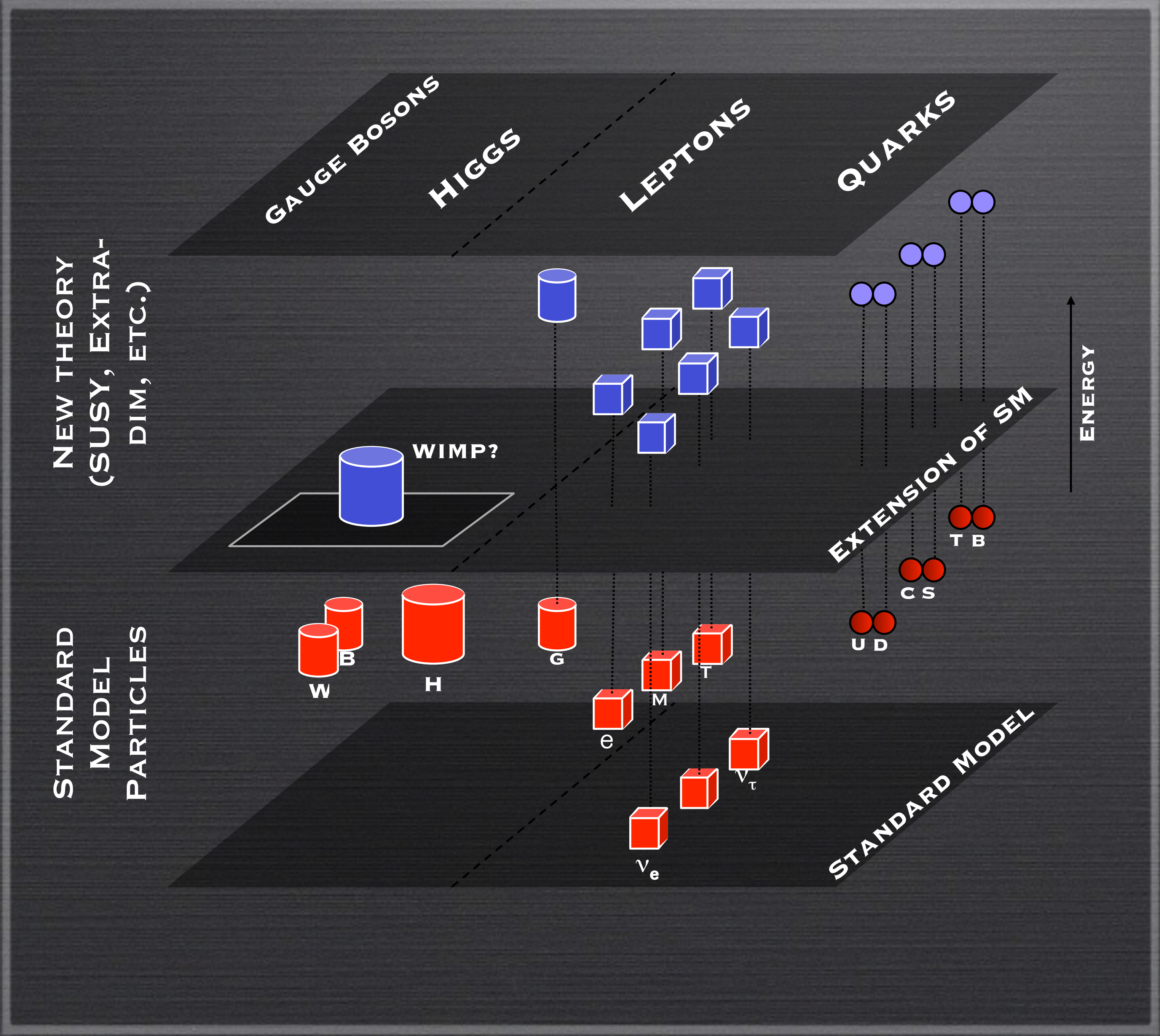


To explain the origin of the weak scale, extensions of the standard model often postulate the existence of new physics at ~100 GeV

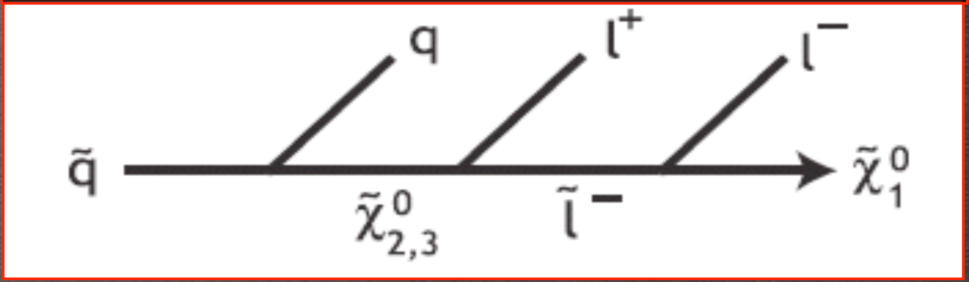
On the left, schematic view of the structure of possible extensions of the standard model

Beyond the Standard Model

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



SEARCH AT LHC FOR PROCESSES LIKE E.G.



Example of Inverse problem at LHC

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

The dream scenario:

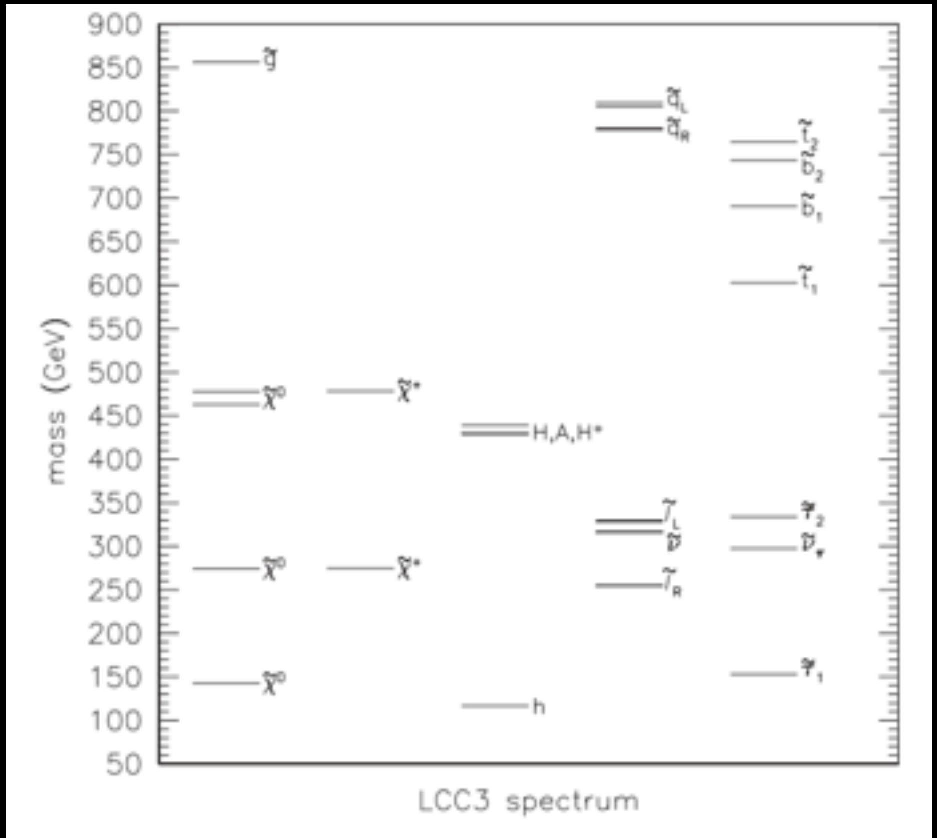
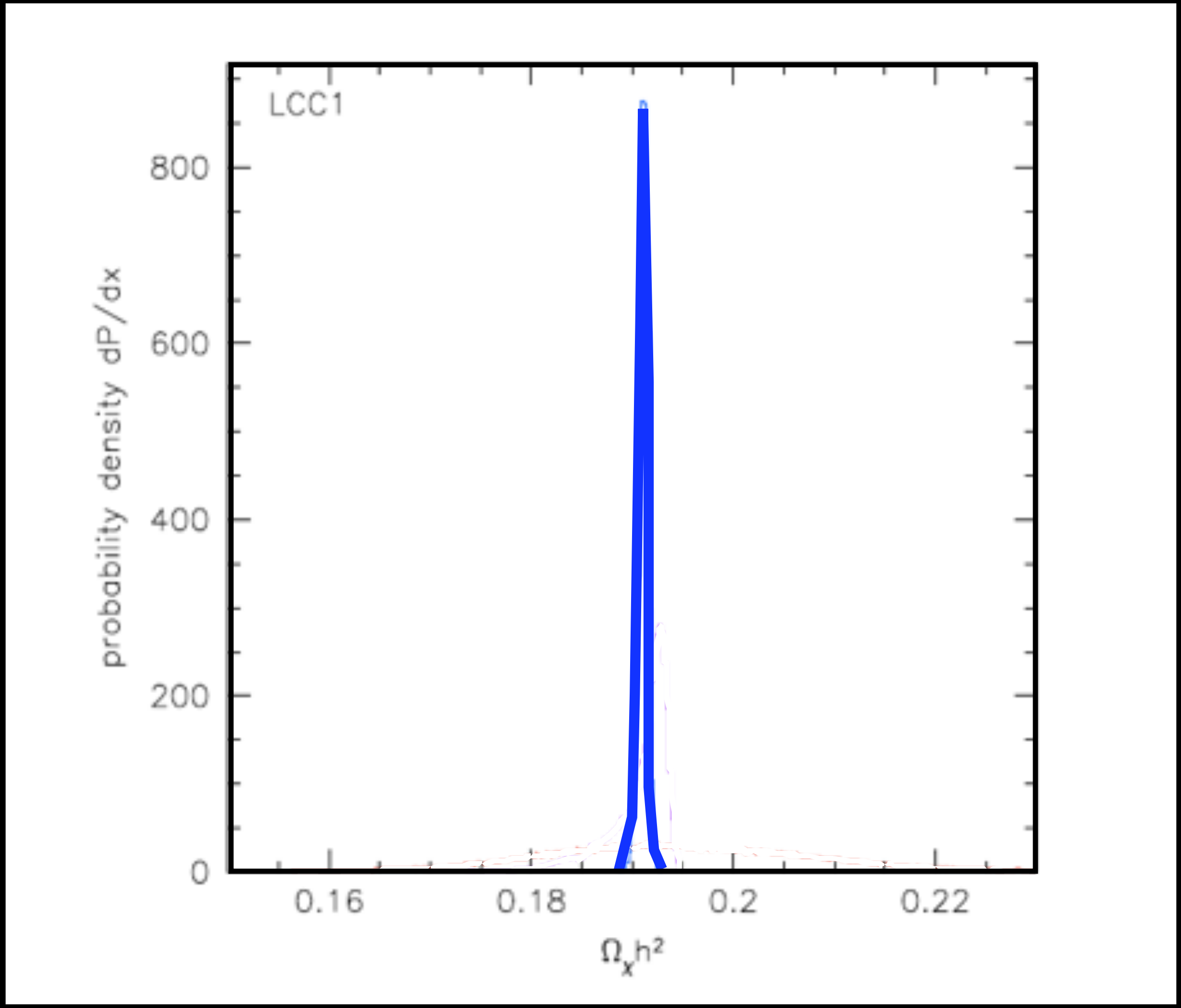
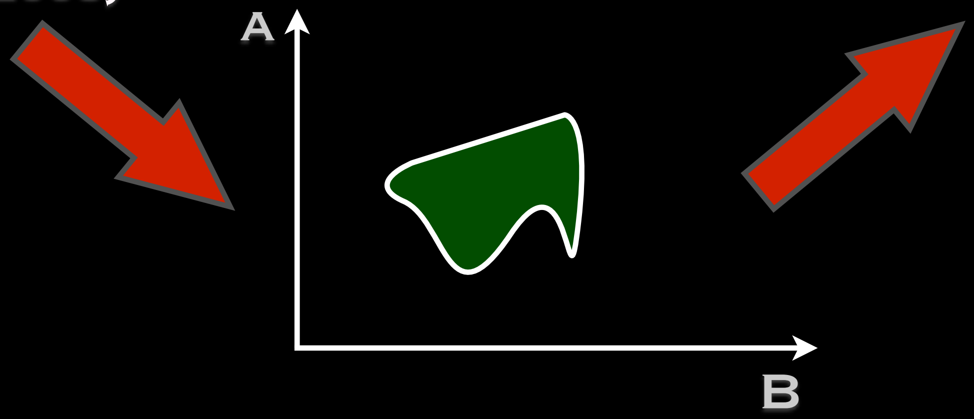


FIG. 34. Particle spectrum for point LCC3. The stau-neutralino mass splitting is 10.8 GeV. The lightest neutralino is predominantly *b*-ino, the second neutralino and light chargino are predominantly *W*-ino, and the heavy neutralinos and chargino are predominantly Higgsino.

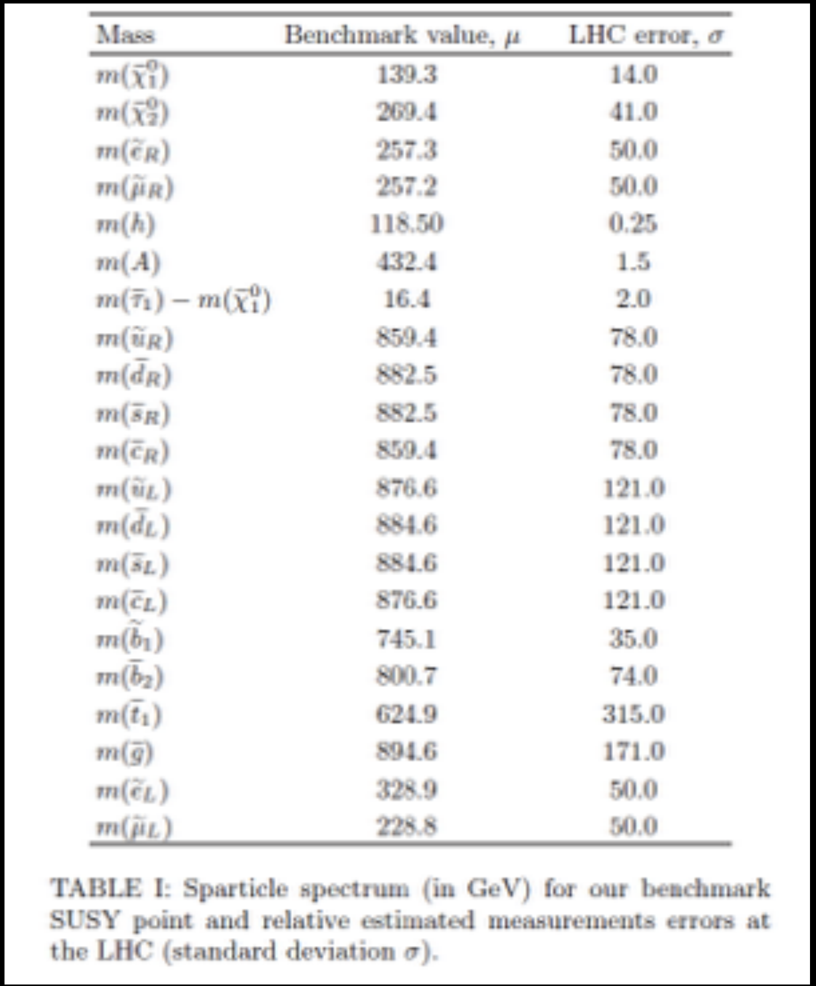


AD. FROM BALTZ ET AL (2005)



Example of Inverse problem at LHC

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



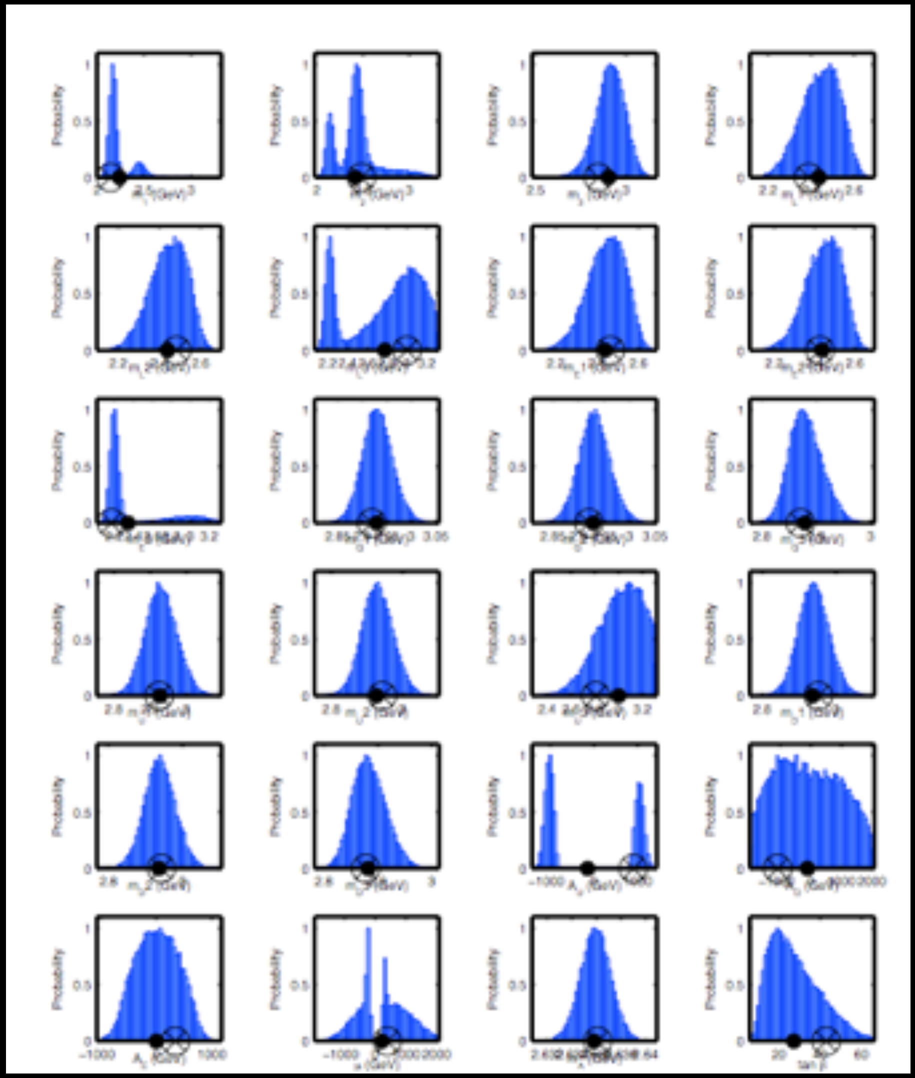
Mass	Benchmark value, μ	LHC error, σ
$m(\tilde{\chi}_1^0)$	139.3	14.0
$m(\tilde{\chi}_2^0)$	269.4	41.0
$m(\tilde{e}_R)$	257.3	50.0
$m(\tilde{\mu}_R)$	257.2	50.0
$m(h)$	118.50	0.25
$m(A)$	432.4	1.5
$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0)$	16.4	2.0
$m(\tilde{u}_R)$	859.4	78.0
$m(\tilde{d}_R)$	882.5	78.0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

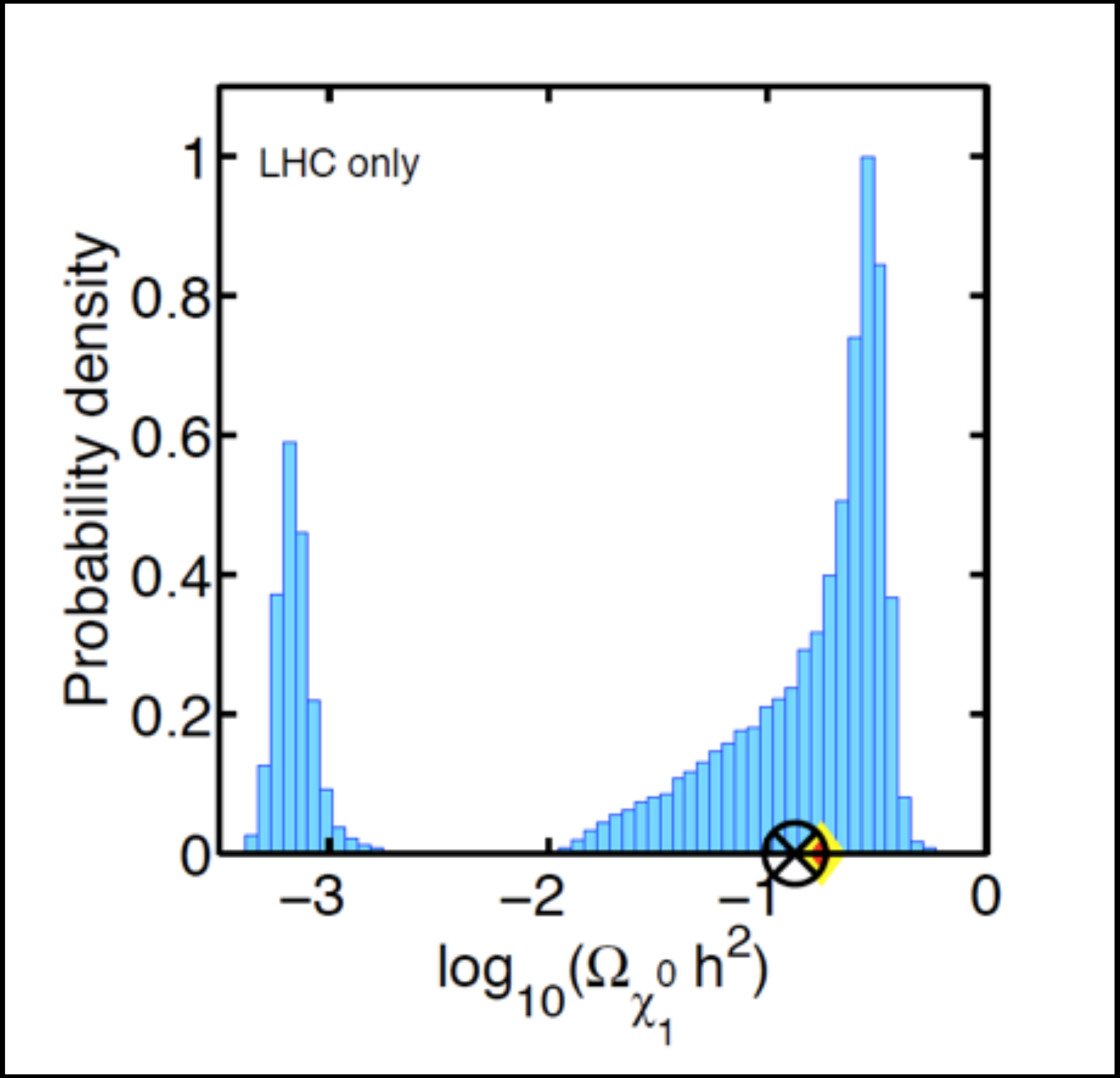
$$p(\mathbf{x}|\mathbf{d}) = \frac{p(\mathbf{d}|\mathbf{x})p(\mathbf{x})}{p(\mathbf{d})},$$

MCMC AS IMPLEMENTED IN THE SUPERBAYES CODE



Example of Inverse problem at LHC

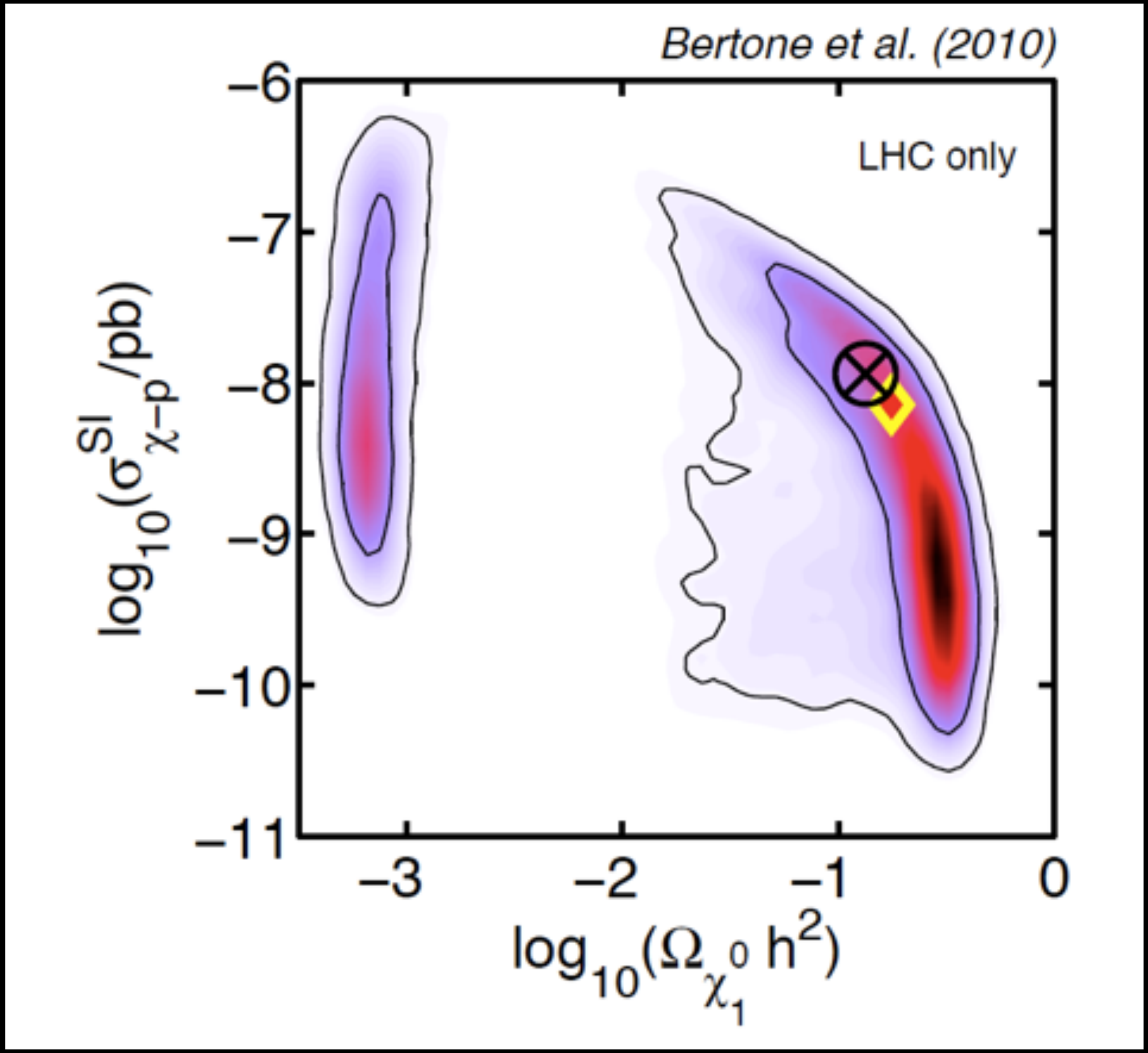
what we will most probably get
(example in the stau coannihilation region, 24 parms MSSM)



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

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

DD+LHC

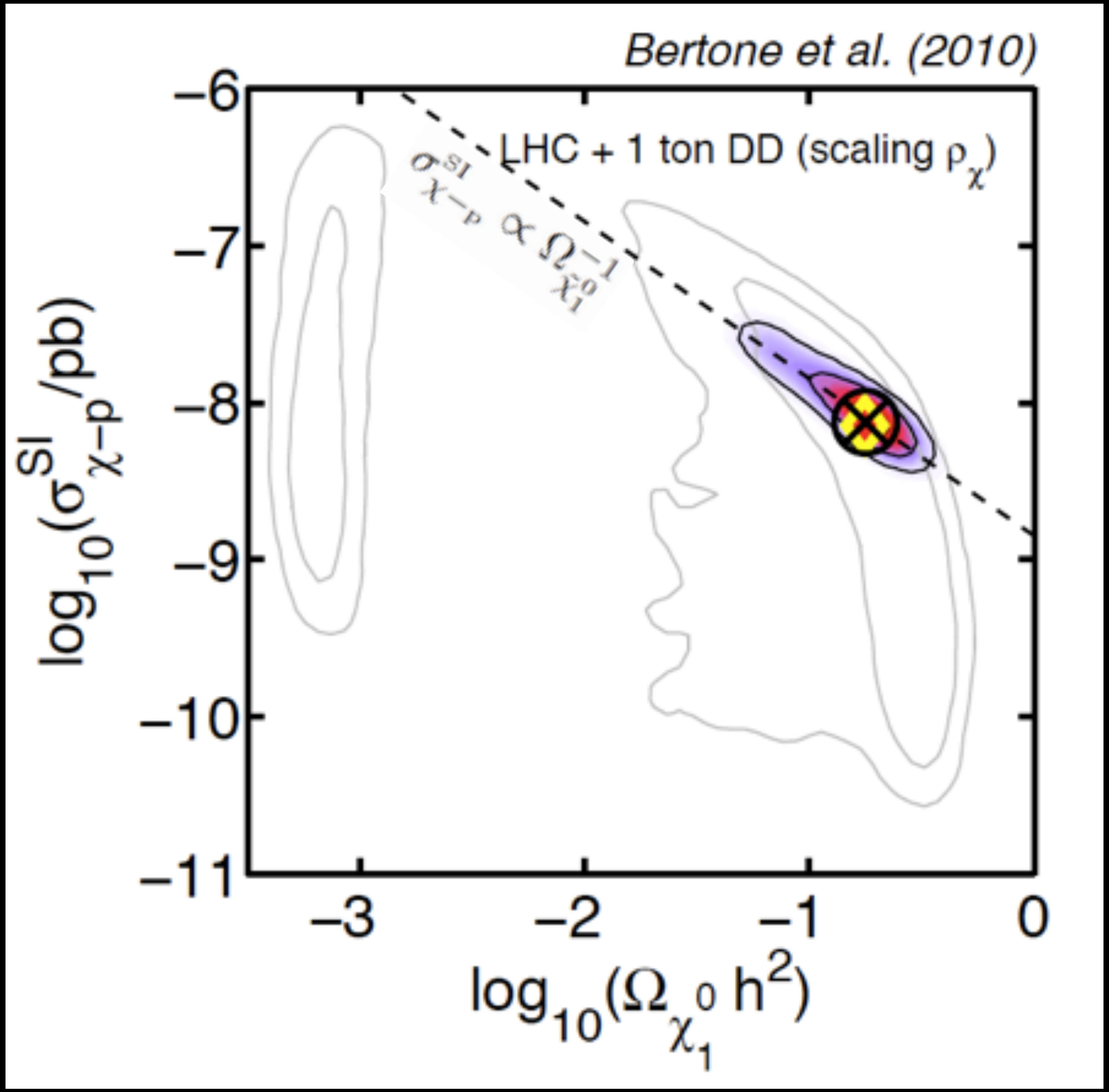
“Scaling” Ansatz

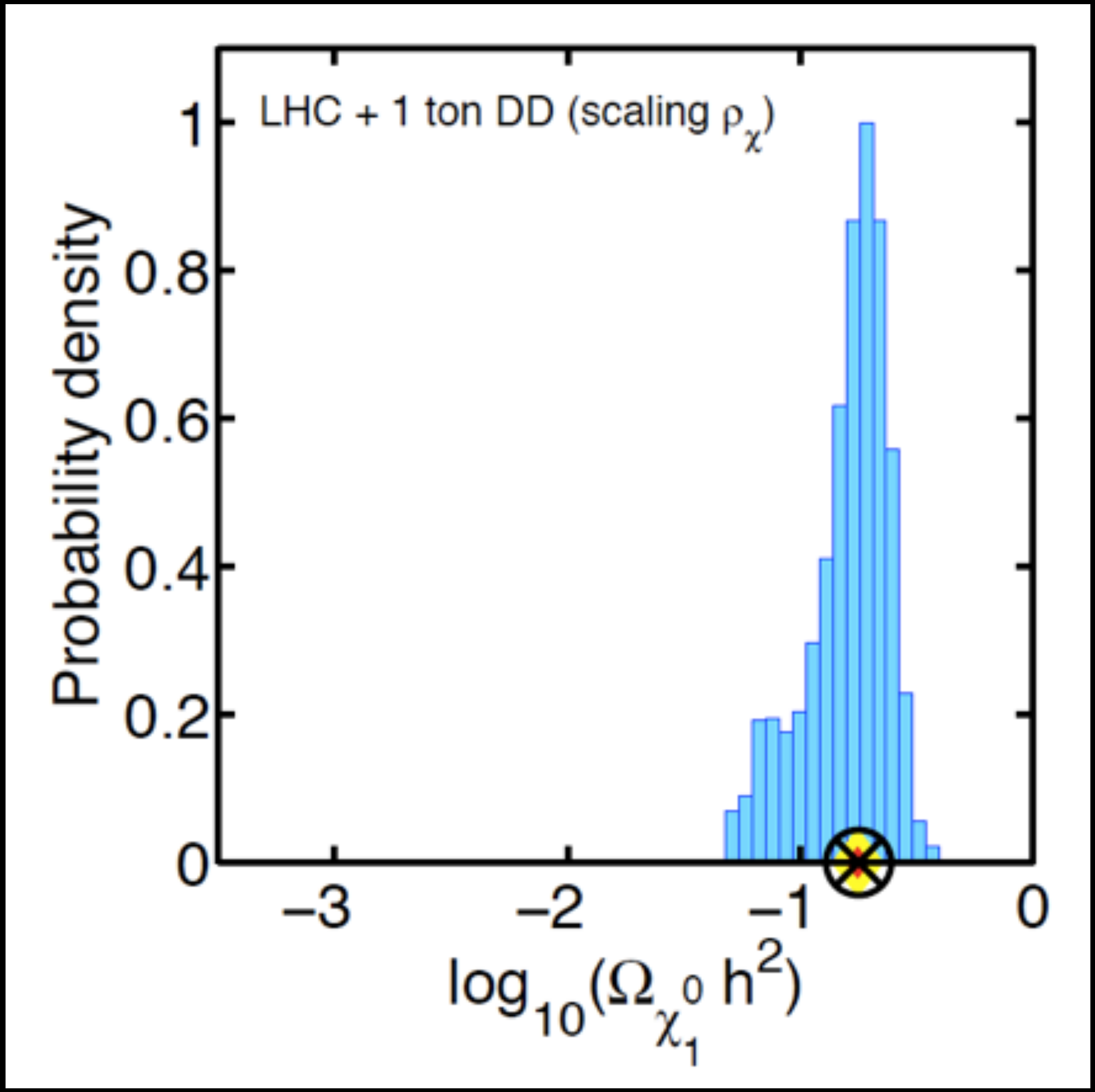
$$\frac{\rho_\chi}{\rho_{dm}} = \frac{\Omega_\chi}{\Omega_{dm}}$$

DD+LHC

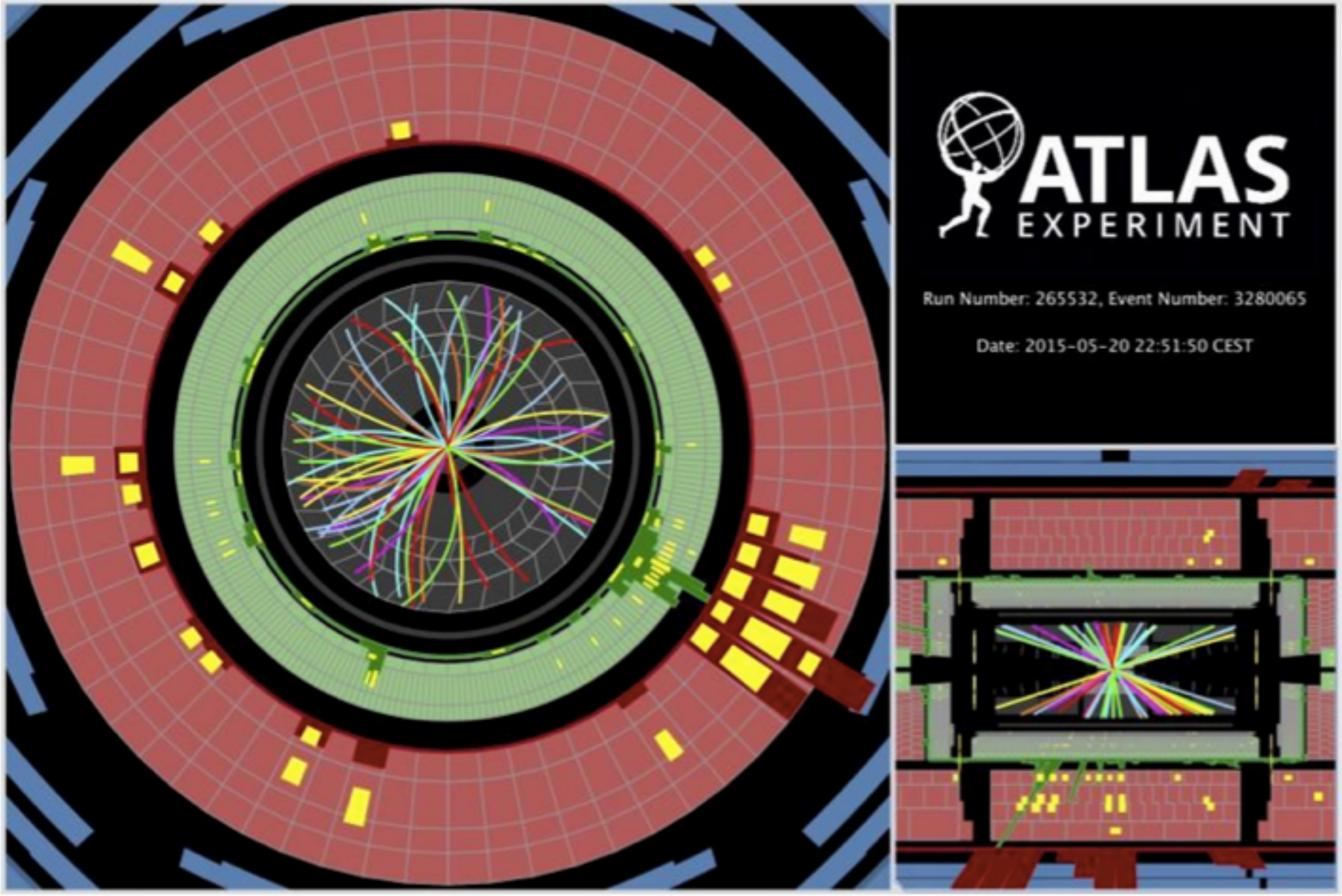
"Scaling" Ansatz

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





May 2015: First images of 13 TeV collisions!!



Protons collide at 13 TeV sending showers of particles through the ATLAS detector (Image: ATLAS)

http://home.web.cern.ch/about/updates/2015/05/first-images-collisions-13-tev

Conclusions

- *Huge* Theoretical and experimental effort towards the identification of DM. It is OK to be skeptical about 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, (in)direct searches likely necessary to identify DM

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