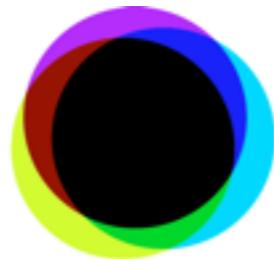


The quest for Dark Matter

Gianfranco Bertone
GRAPPA center of excellence
U. of Amsterdam

IFIC Colloquium, 29 June 2017

GRAPPA x
x
x



GRavitation AstroParticle Physics Amsterdam



Outline of the talk:

Part I - DM in Astrophysics & Cosmology

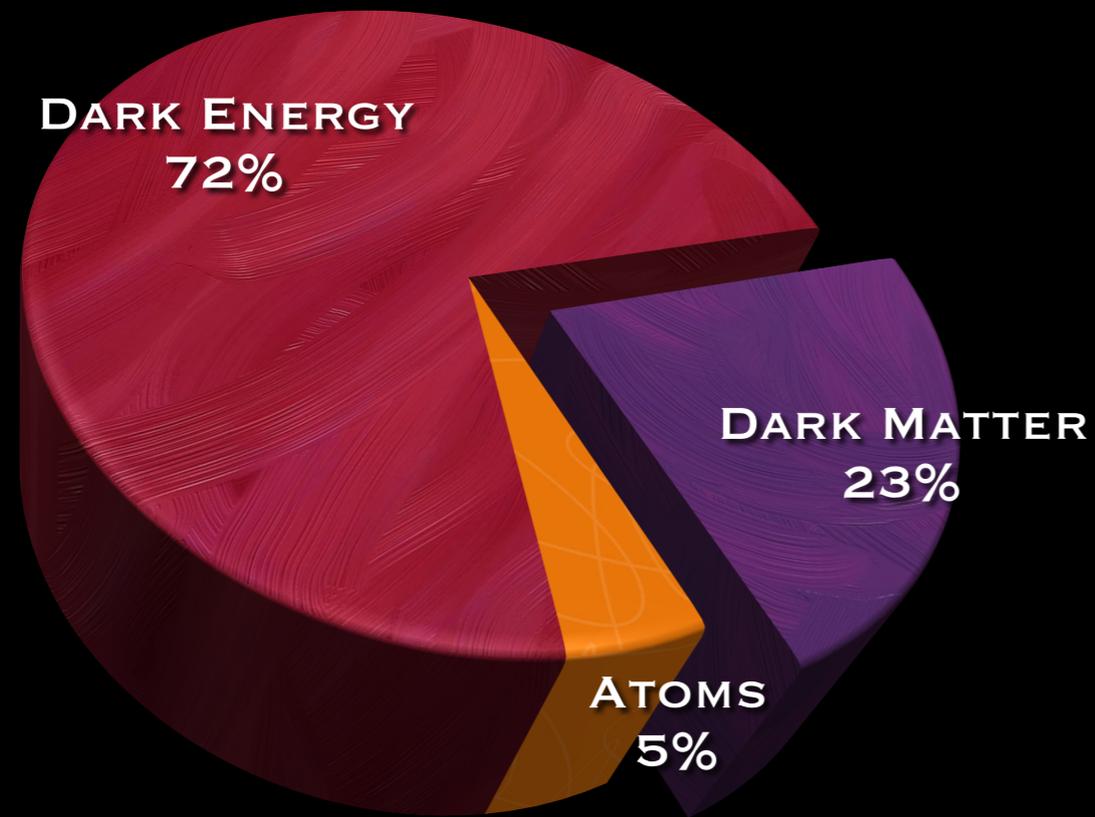
Part II - Dark Matter candidates

Part III - WIMPs

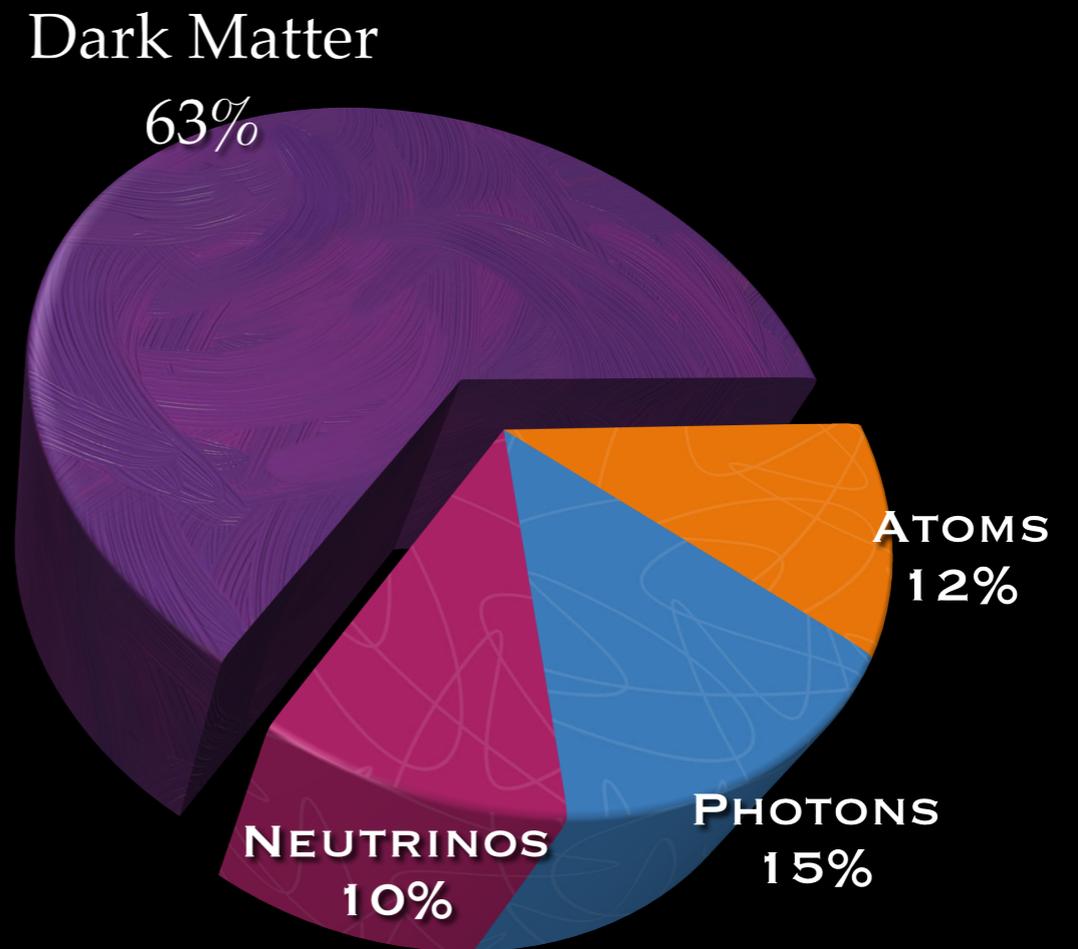
Part I

Dark Matter in Astrophysics and cosmology

What is the Universe made of?



TODAY

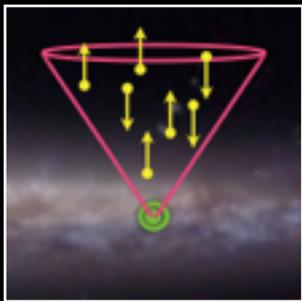


AT DECOUPLING

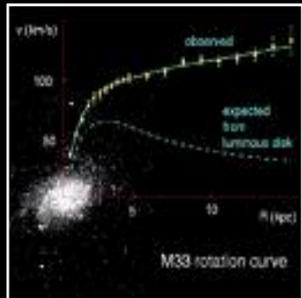
Evidence for Dark Matter

Assuming GR is correct, 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

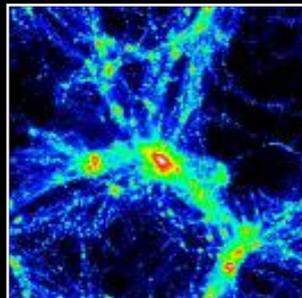
COSMOLOGICAL OBSERVATIONS



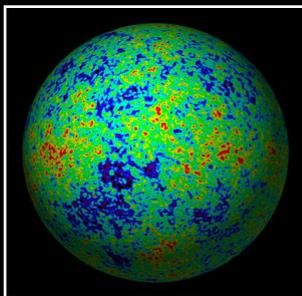
• 'Local' matter density



• Rotation Curves



• Clusters of galaxies

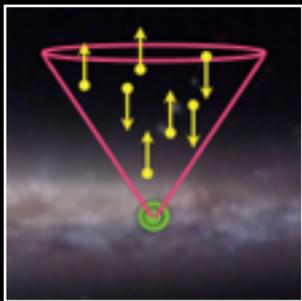


• CMB

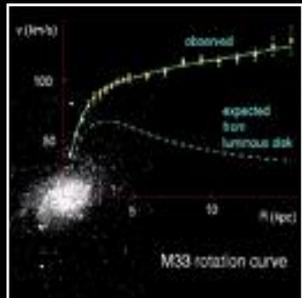
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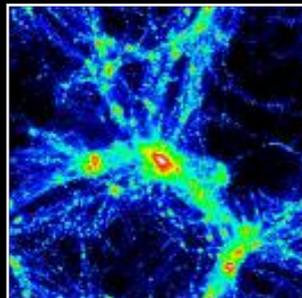
COSMOLOGICAL OBSERVATIONS



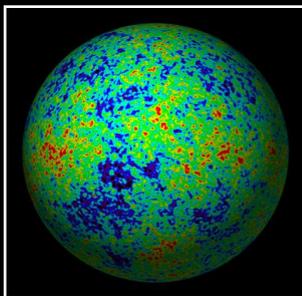
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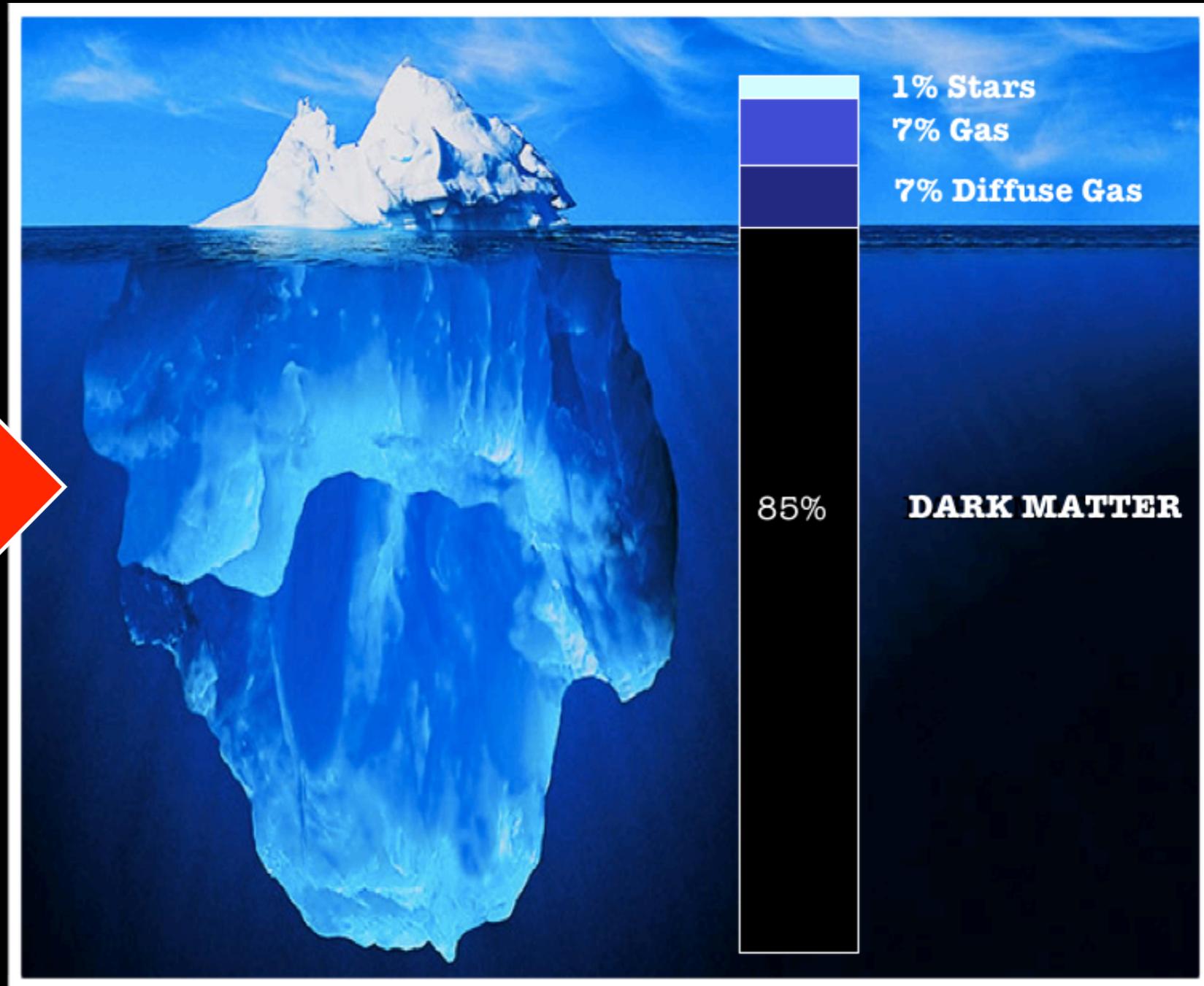
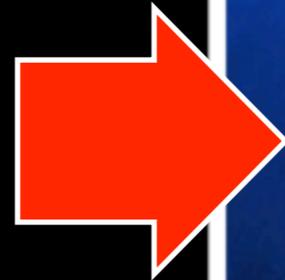
• Rotation Curves



• Clusters of galaxies



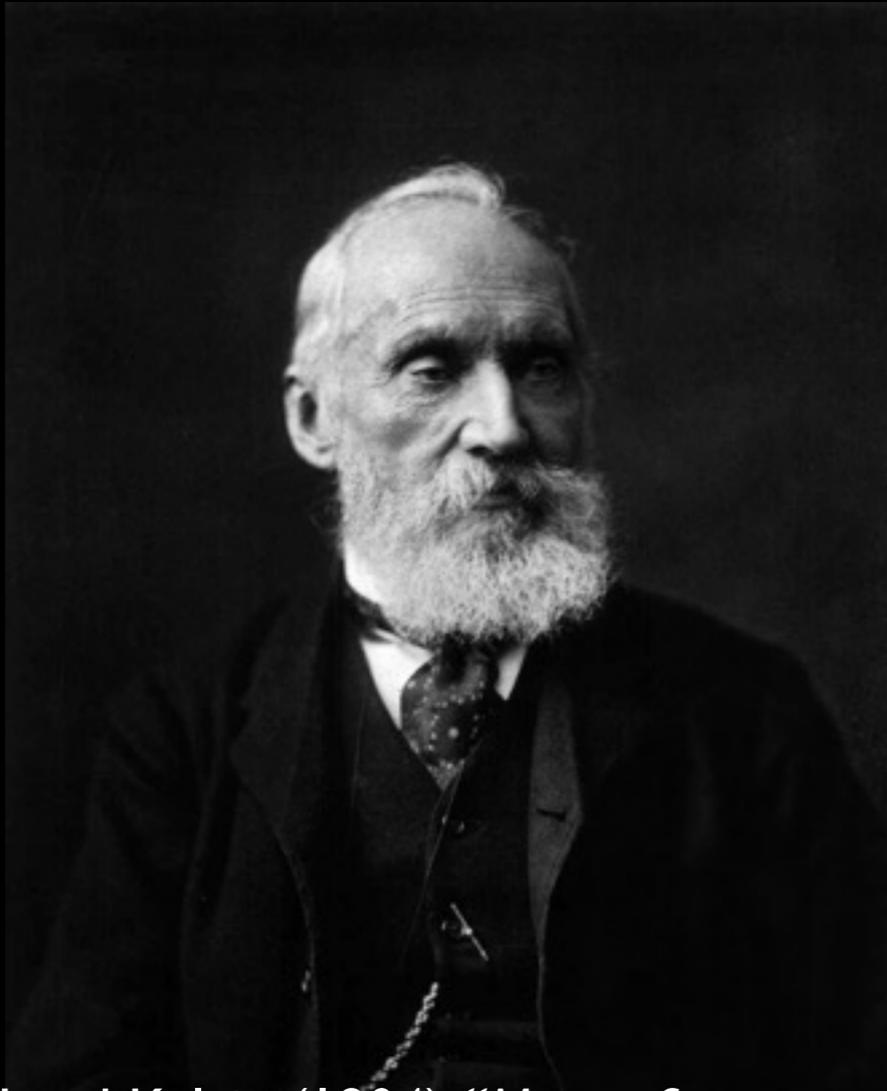
• CMB



A problem with a long history

“A history of Dark Matter” GB & Hooper 1605.04909

“How dark matter came to matter” de Swart, GB, van Dongen 1703.00013



Lord Kelvin (1904) *“Many of our stars, perhaps a great majority of them, may be dark bodies.”*

Henri Poincaré (1906) : *“Lord Kelvin’s method gives us the total number of stars including the dark ones; since his number is comparable to that which the telescope gives, then there is no dark matter, or at least not so much as there is of shining matter.”*

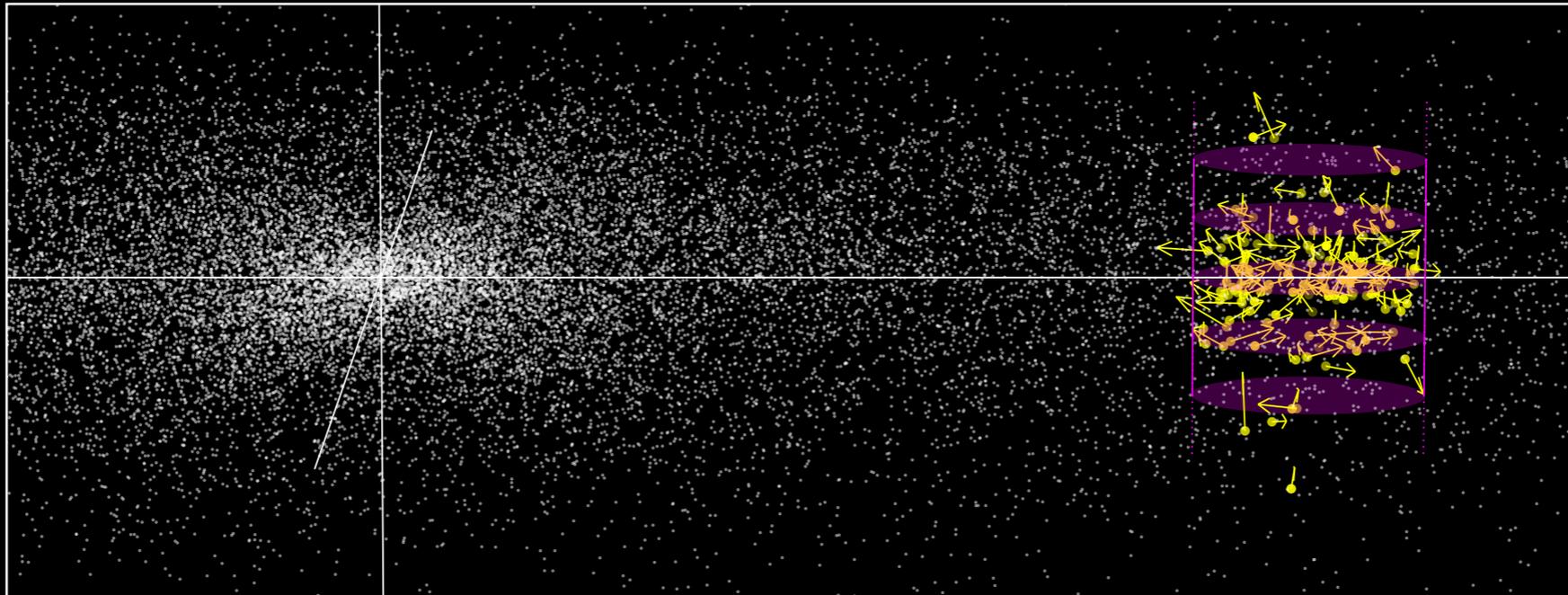


Dark Matter in the Milky Way



The dark matter distribution in the Galaxy is a crucial ingredient for dark matter searches

Local dark matter density

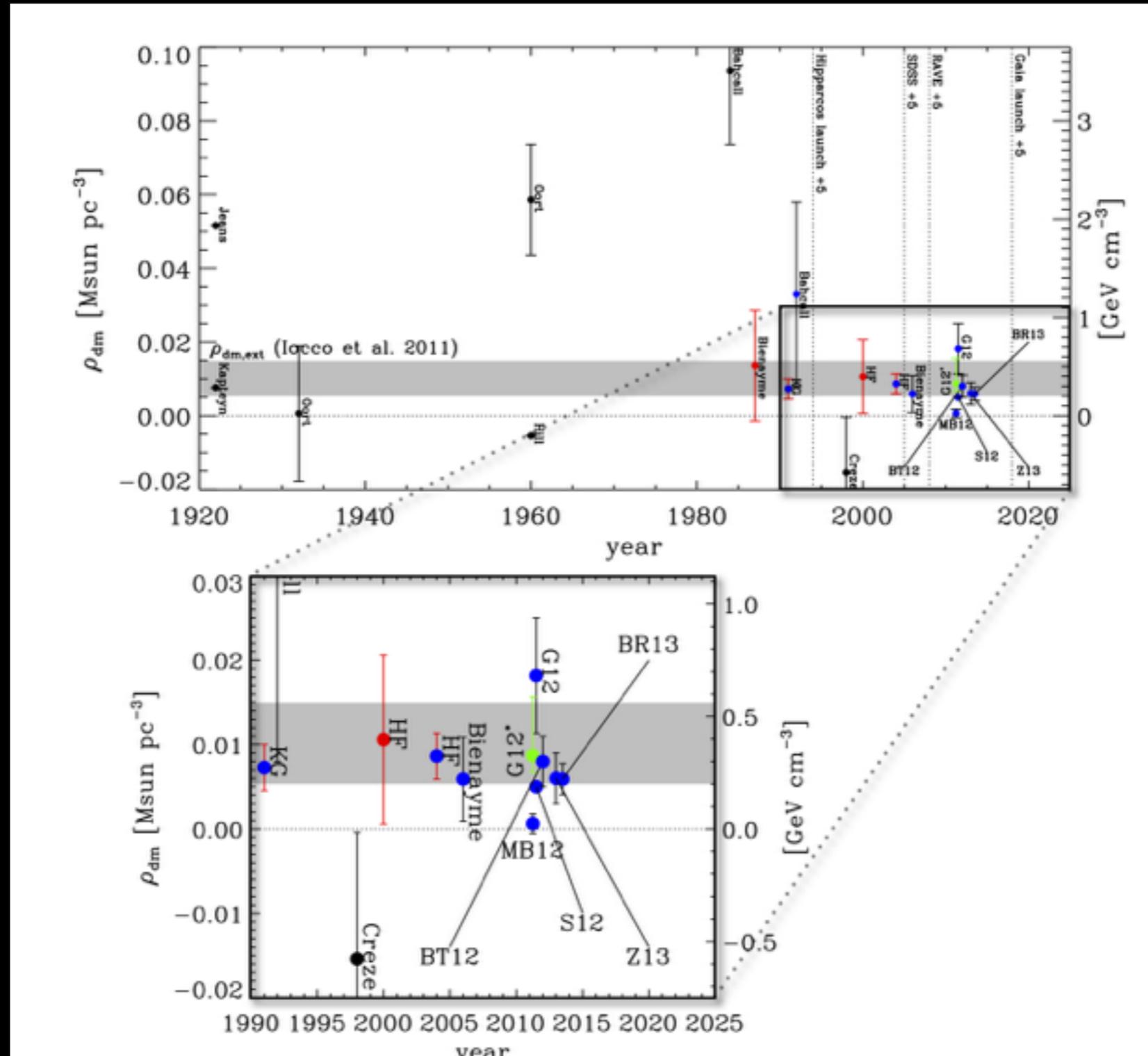


Under simplifying assumptions (e.g. *Silverwood, GB et al. 2016*), the gravitational potential can be reconstructed from the observed dynamics of tracer stars via the z-Jeans equation:

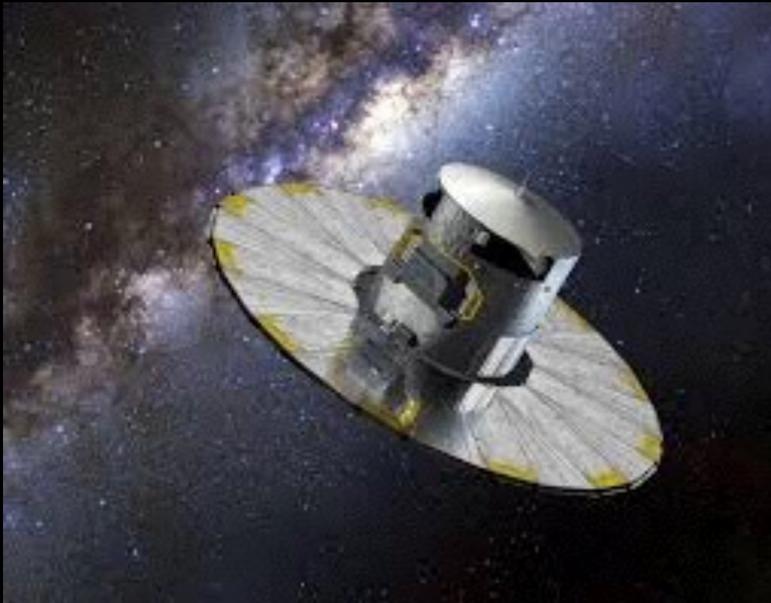
$$\underbrace{\frac{1}{R\nu} \frac{\partial}{\partial R} (R\nu\sigma_{Rz})}_{\text{'tilt' term: } \mathcal{T}} + \frac{1}{\nu} \frac{d}{dz} (\nu\sigma_z^2) = \underbrace{-\frac{d\Phi}{dz}}_{K_z}$$

where ν and σ_z^2 are the density and vertical velocity dispersion profile of a tracer population, σ_{Rz} is the Rz cross term in the velocity dispersion tensor

Local dark matter density



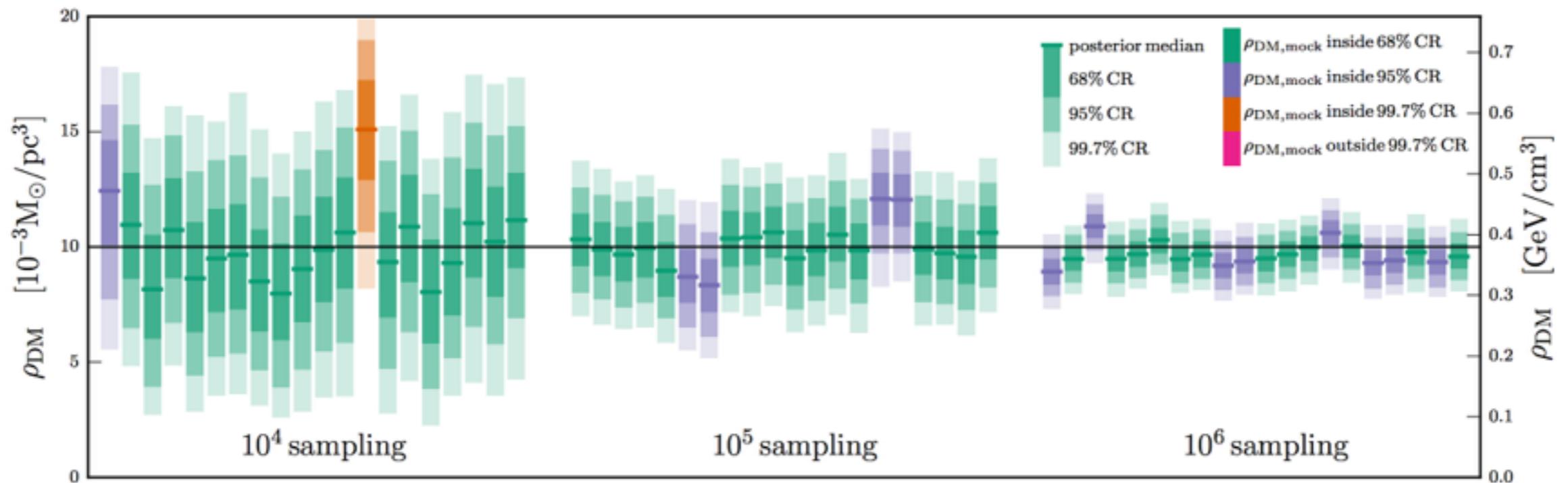
Local dark matter density



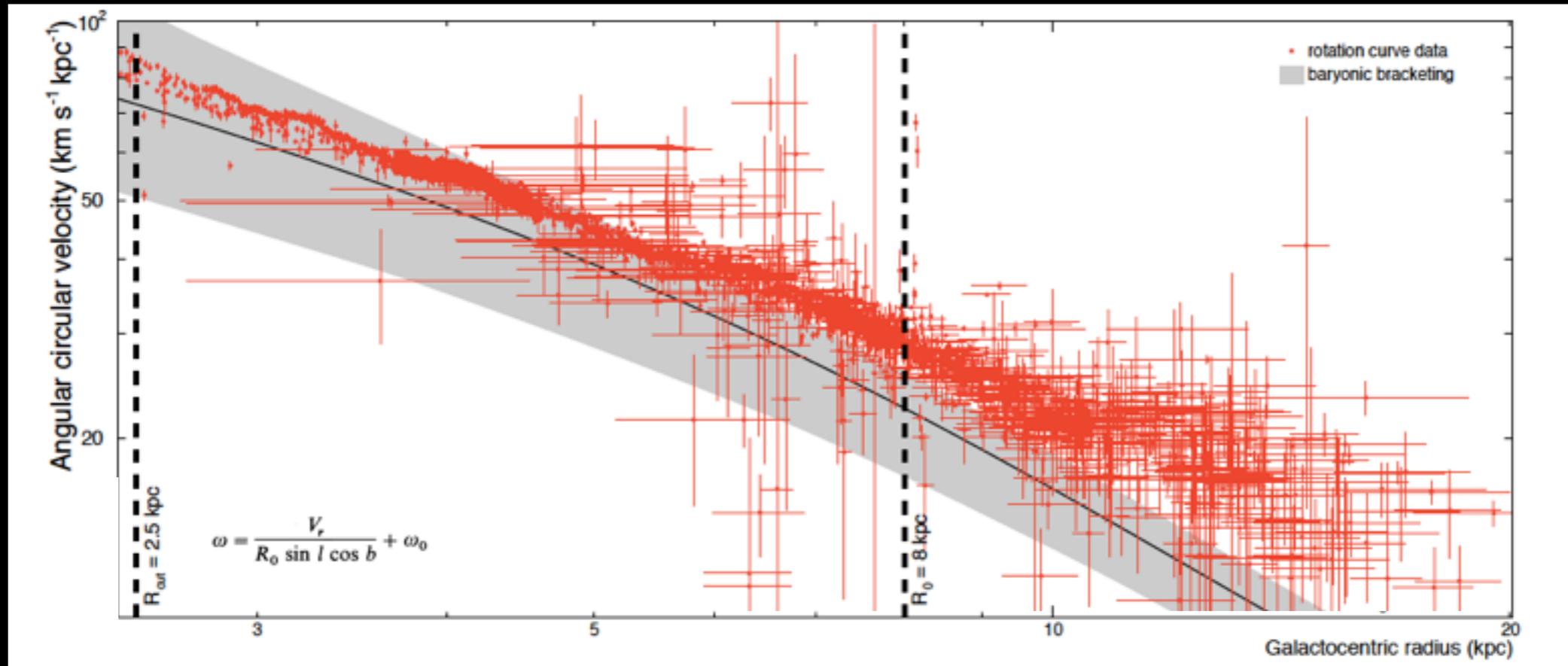
ESA Gaia satellite launched in 2013, will soon provide a precise 3d map of the Milky Way, including 3d velocities.

This will allow to substantially improve the statistical error on the determination of the local dark matter density.

Next challenge: systematic errors!

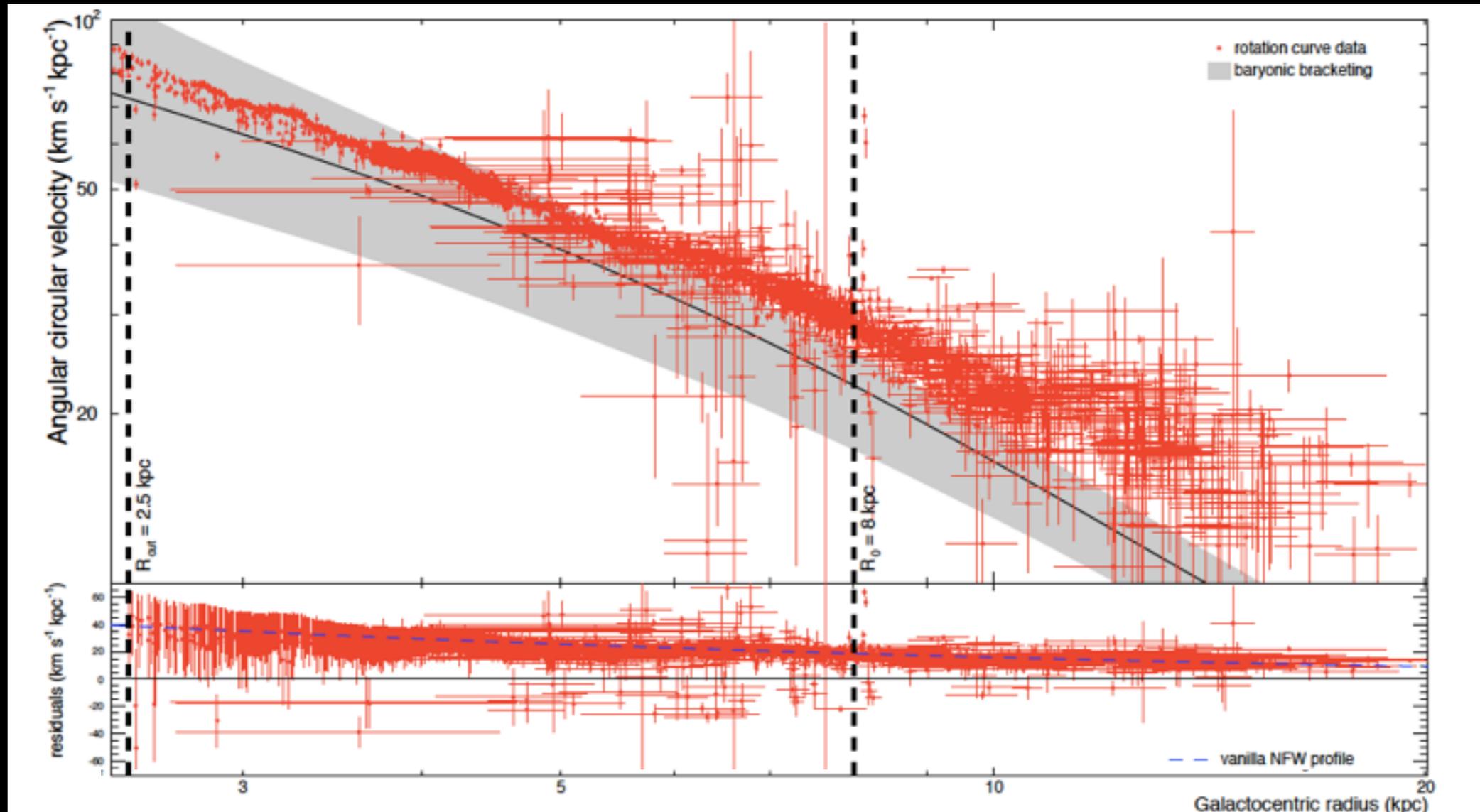


Global modelling: Rotation curve of the Milky Way



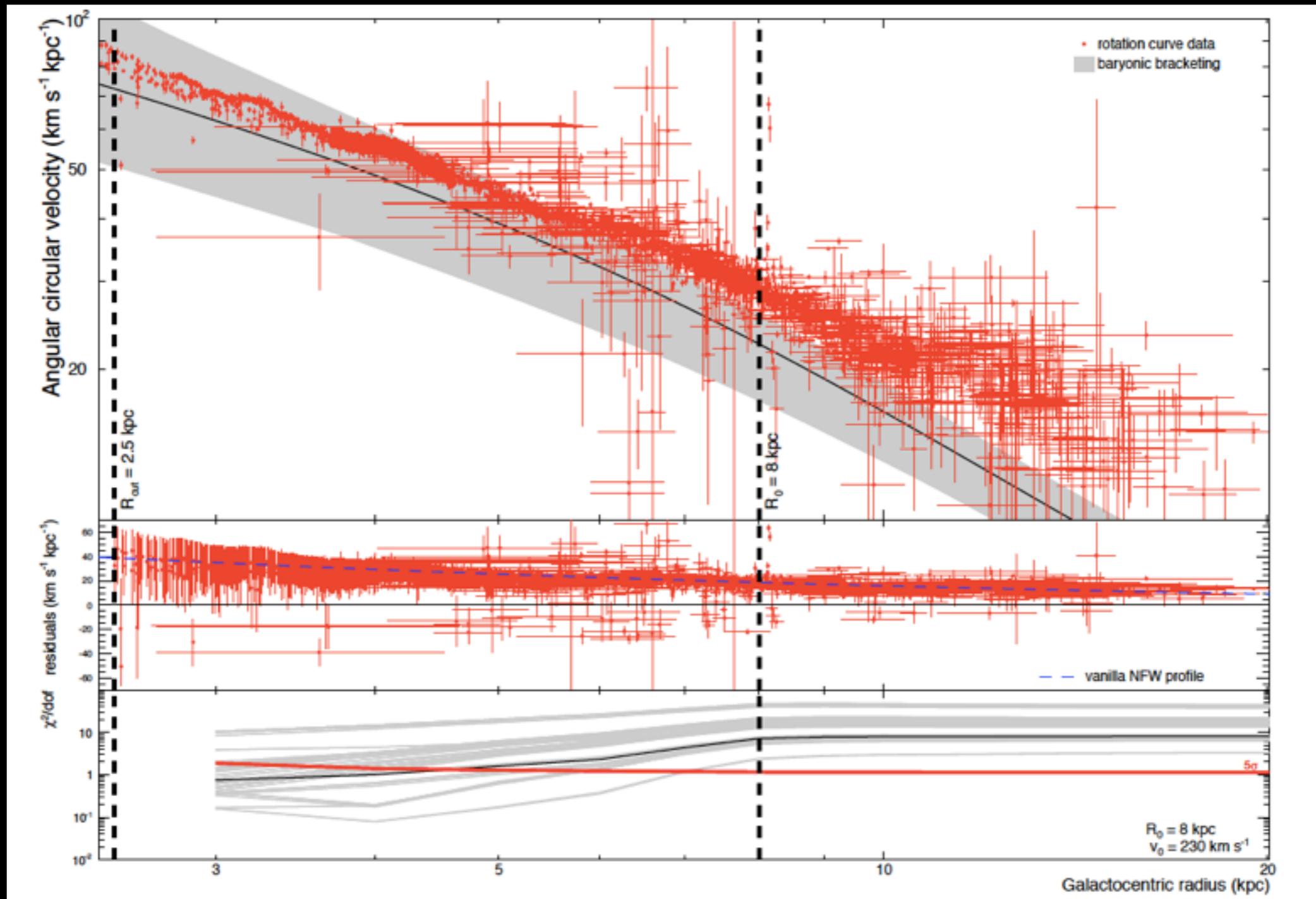
Iocco, Pato, GB, Nature Physics, arXiv:1502.03821

Rotation curve of the Milky Way



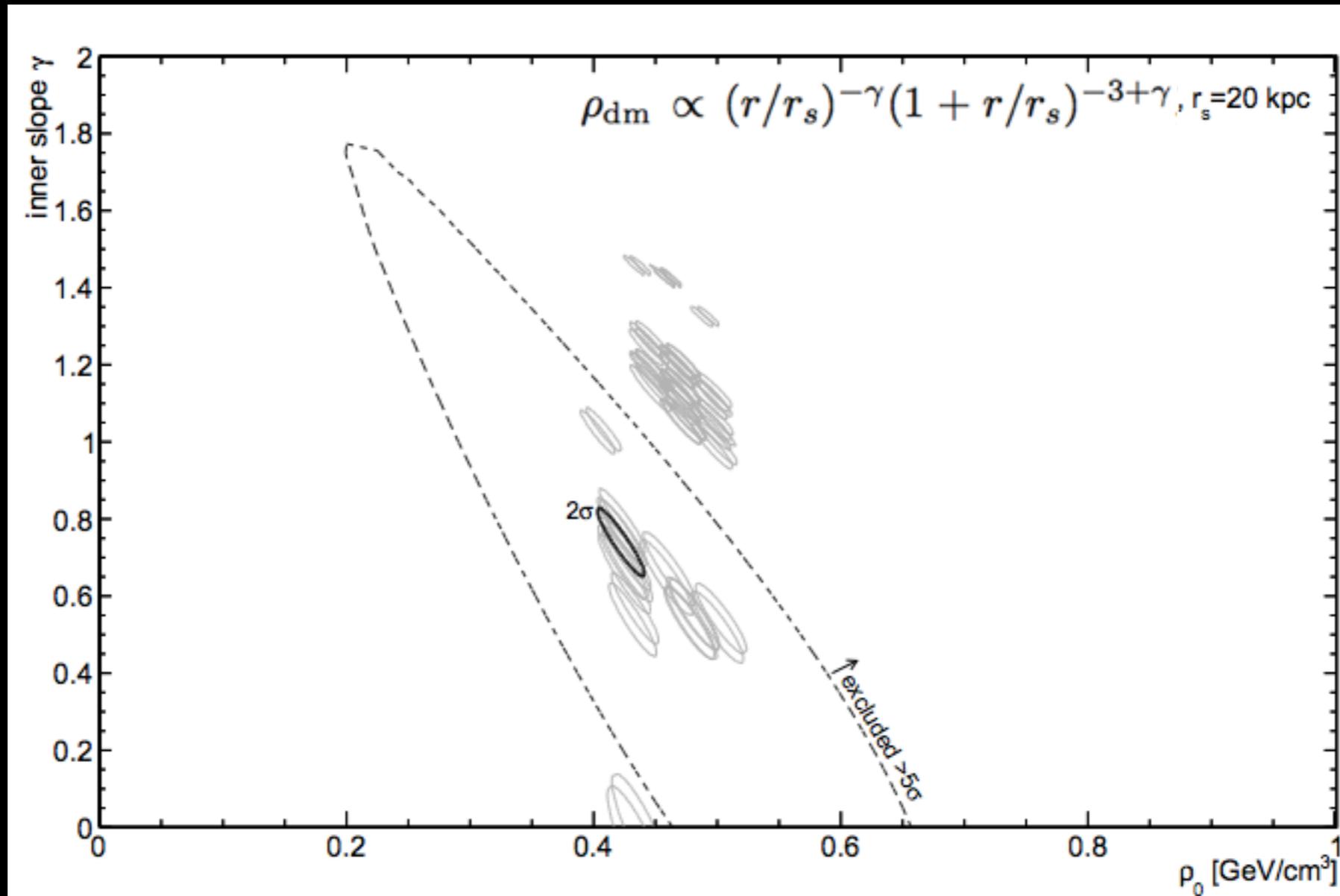
locco, Pato, GB, Nature Physics, arXiv:1502.03821

A tool to study DM distribution in the MW



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

Constraints on MW DM profile



Pato, Iocco, GB 1504.06324

Numerical simulations frontier

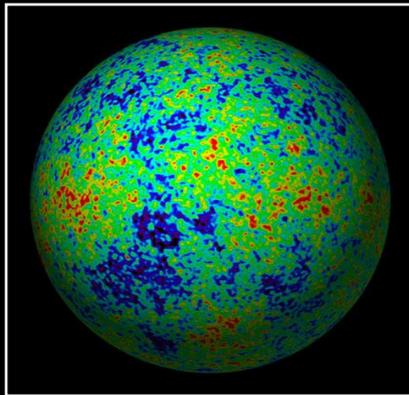
Part II

Dark Matter Candidates

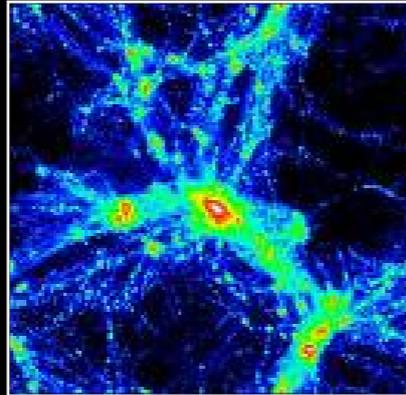
What do we know?

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

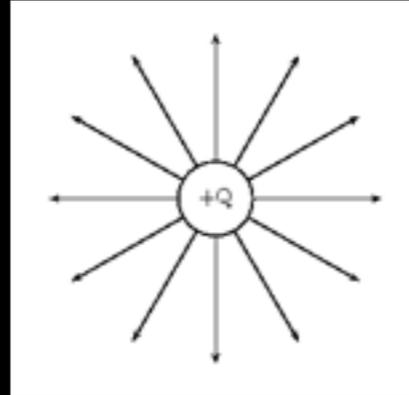
1) Ωh^2 OK?



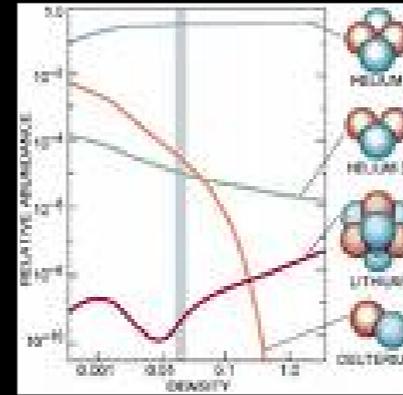
2) Is it cold?



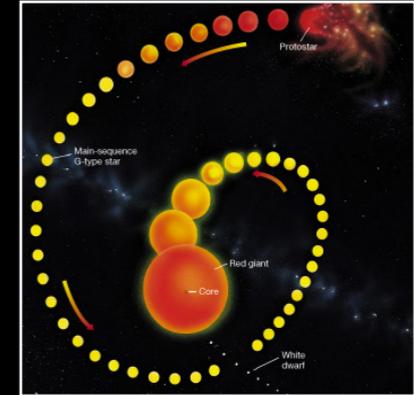
3) Is it neutral?



4) Is BBN ok?



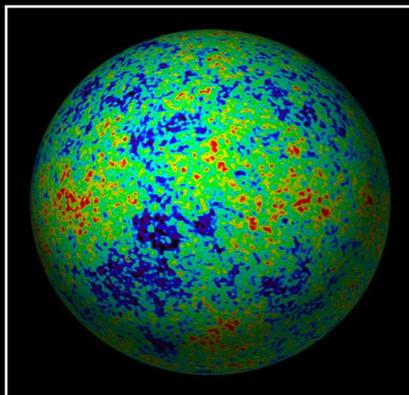
5) Stars OK?



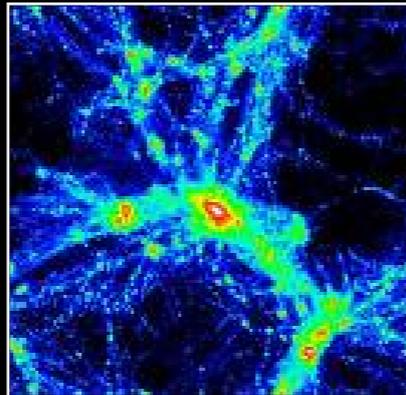
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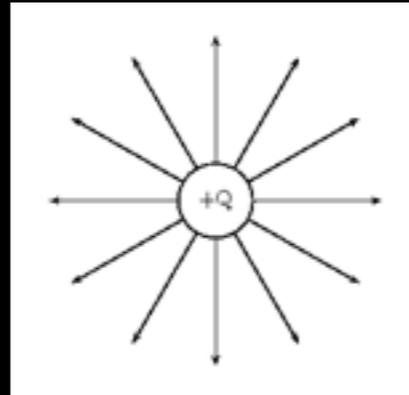
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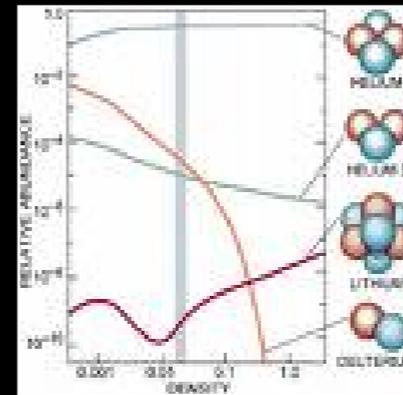
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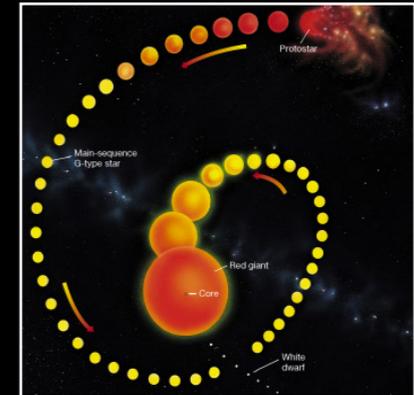
3) Is it neutral?



4) Is BBN ok?



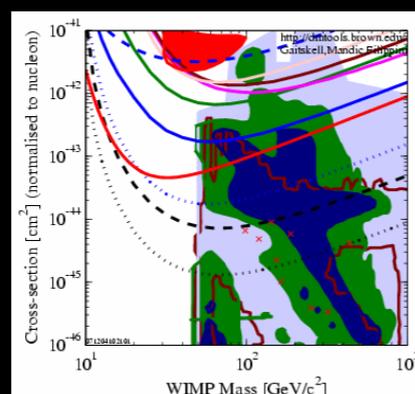
5) Stars OK?



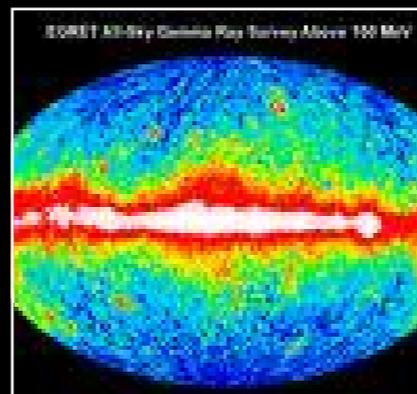
6) Collisionless?



7) Couplings OK?



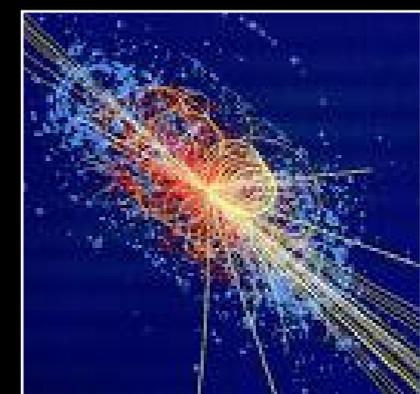
8) γ -rays OK?



9) Astro bounds?



10) Can probe it?



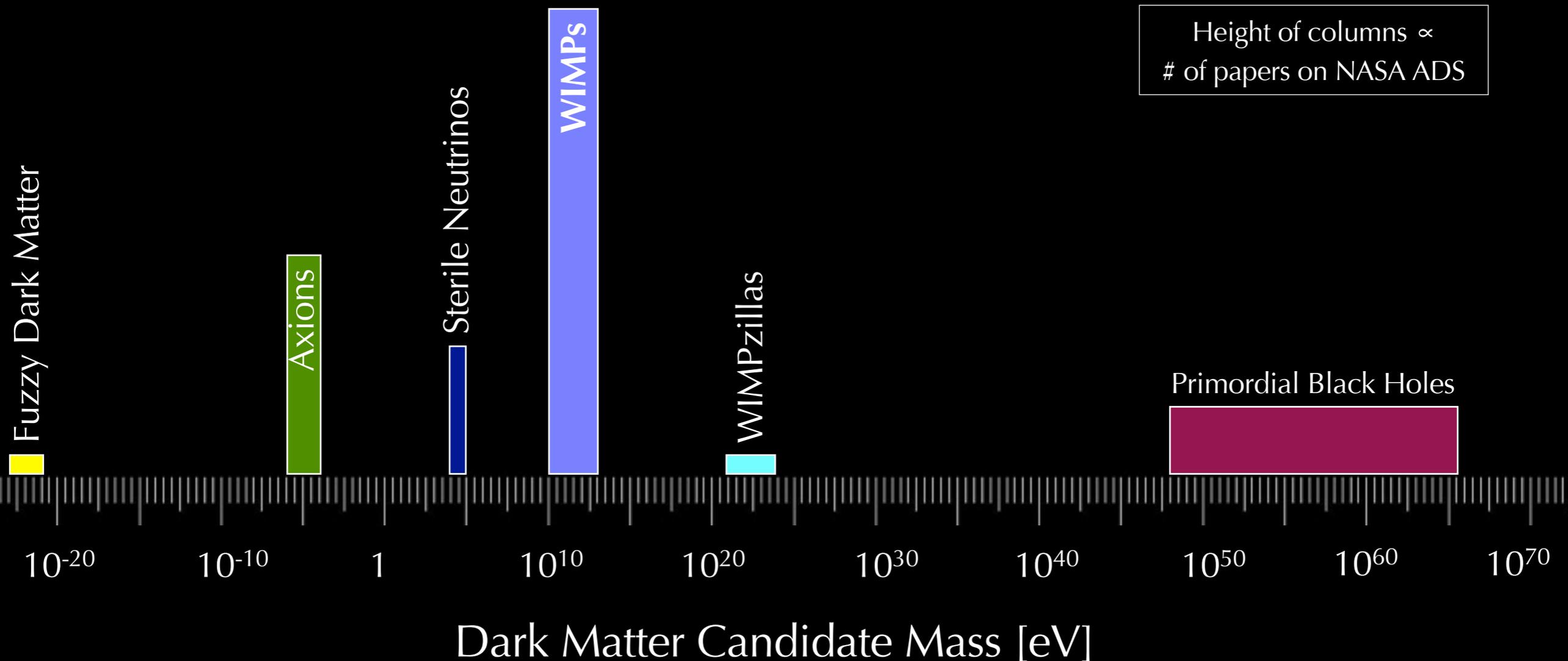
What is dark matter?

- GR with SM + 1 extra species of cold, neutral particles in the stress-energy tensor passes highly non-trivial tests (*CMB anisotropy spectrum, baryonic acoustic oscillations, weak & strong lensing, rotation curves of galaxies,..*)
- Cold dark matter **by far the simplest and most complete explanation of all these phenomena**
- Is Λ CDM perfect? No! Long-standing problems on small-scales: cusp/core, missing satellites, too-big-to-fail. Do we need better understanding of dark matter physics? of baryonic physics? Both?
- “*It is right to continue to challenge Λ CDM*” (e.g. modified gravity) “*but wrong to ignore the evidence from the abundance of tests*” (Peebles, 2017)



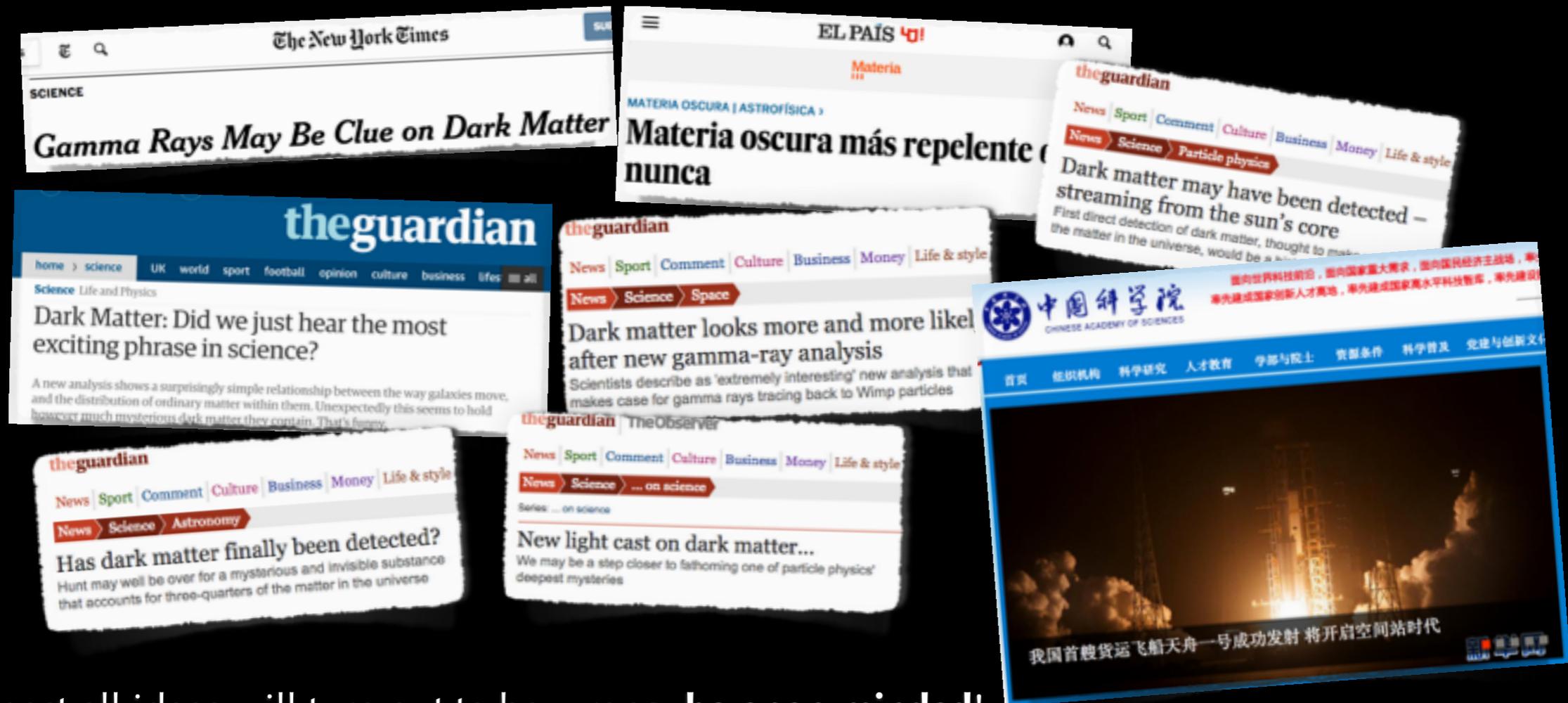
What is dark matter?

- No shortage of ideas..
- Tens of dark matter models, each with its own phenomenology
- Models span 90 orders of magnitude in DM candidate mass!



What is dark matter?

- Huge theoretical and experimental effort currently in progress
- Many hints / advances drawing strong attention from the media



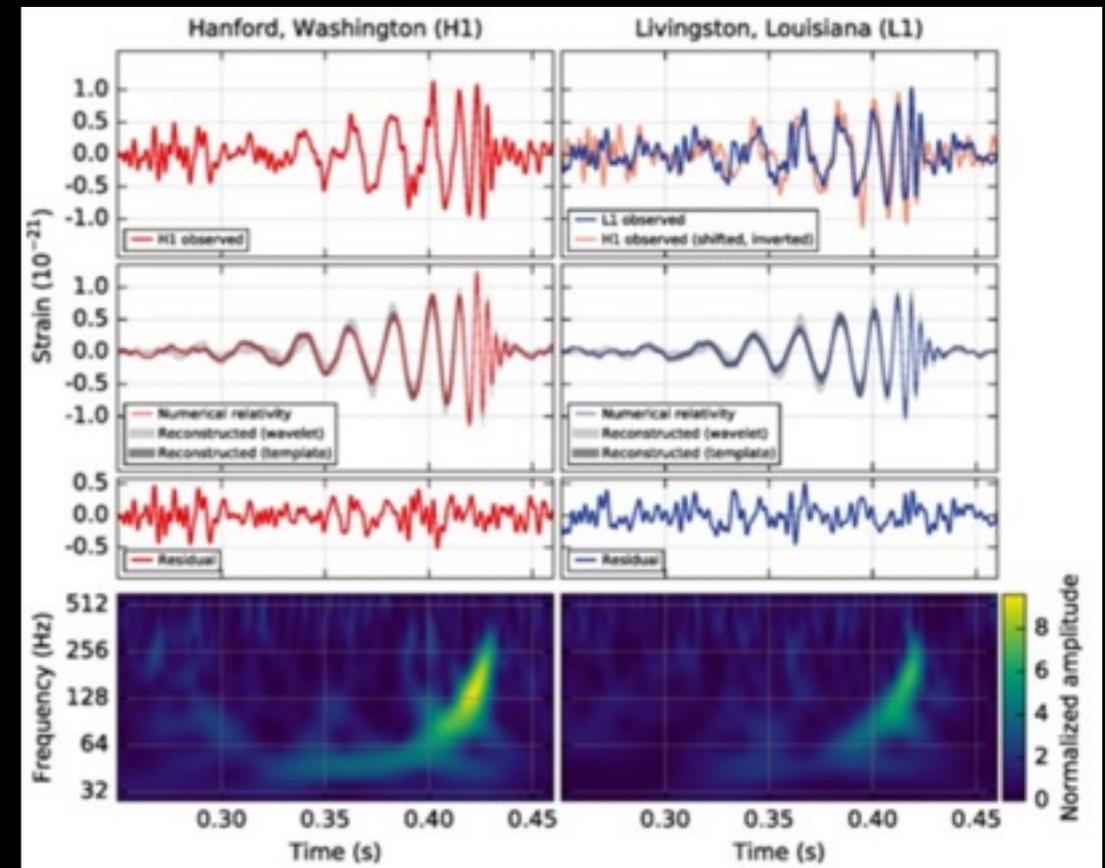
- Almost all ideas will turn out to be wrong: **be open-minded!**
- Can't possibly review all that's exciting in the field..

Dark Matter candidates, example I: Primordial Black Holes

LIGO collaboration, PRL 116, 061102



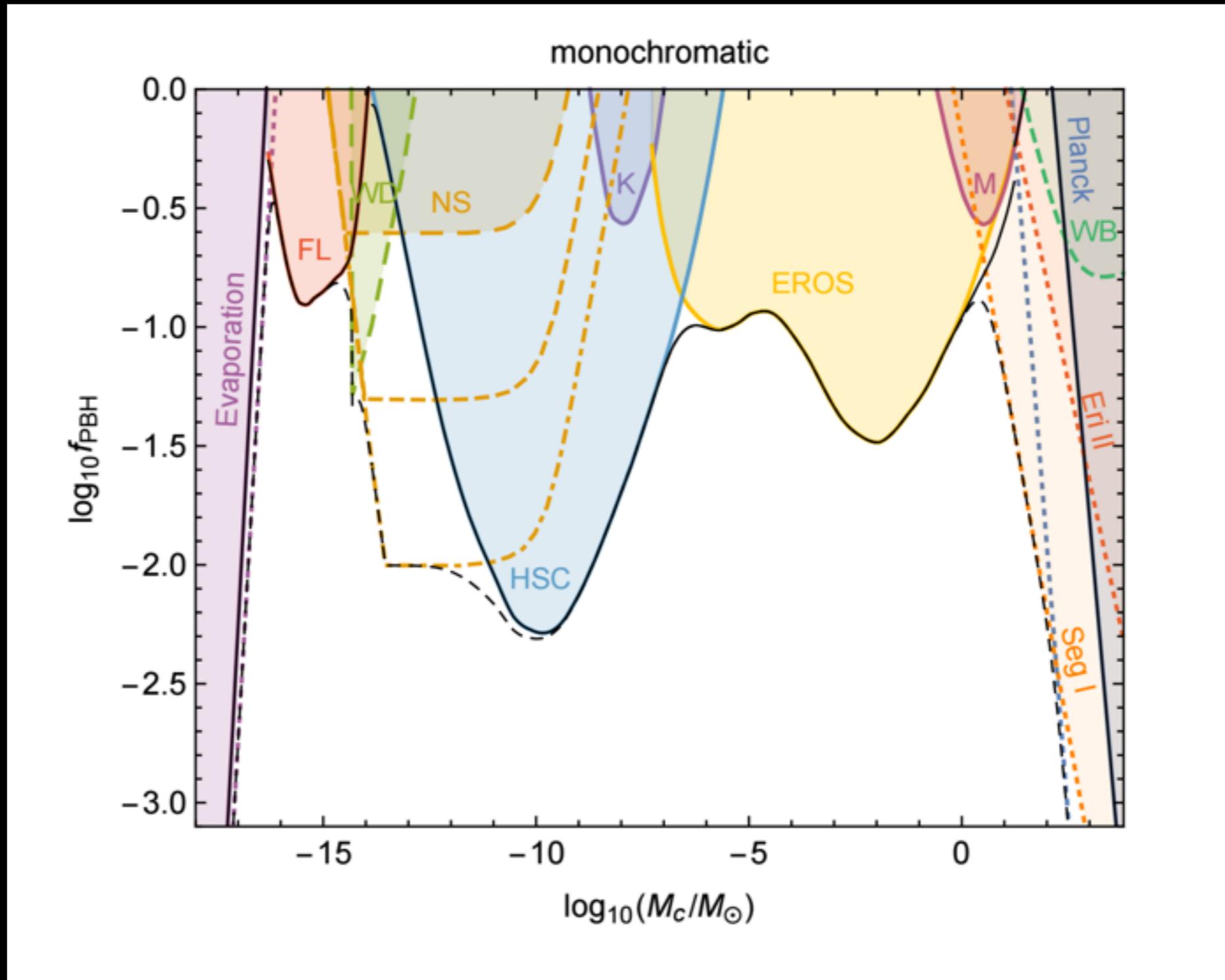
Primary black hole mass $36^{+5}_{-4} M_{\odot}$
Secondary black hole mass $29^{+4}_{-4} M_{\odot}$



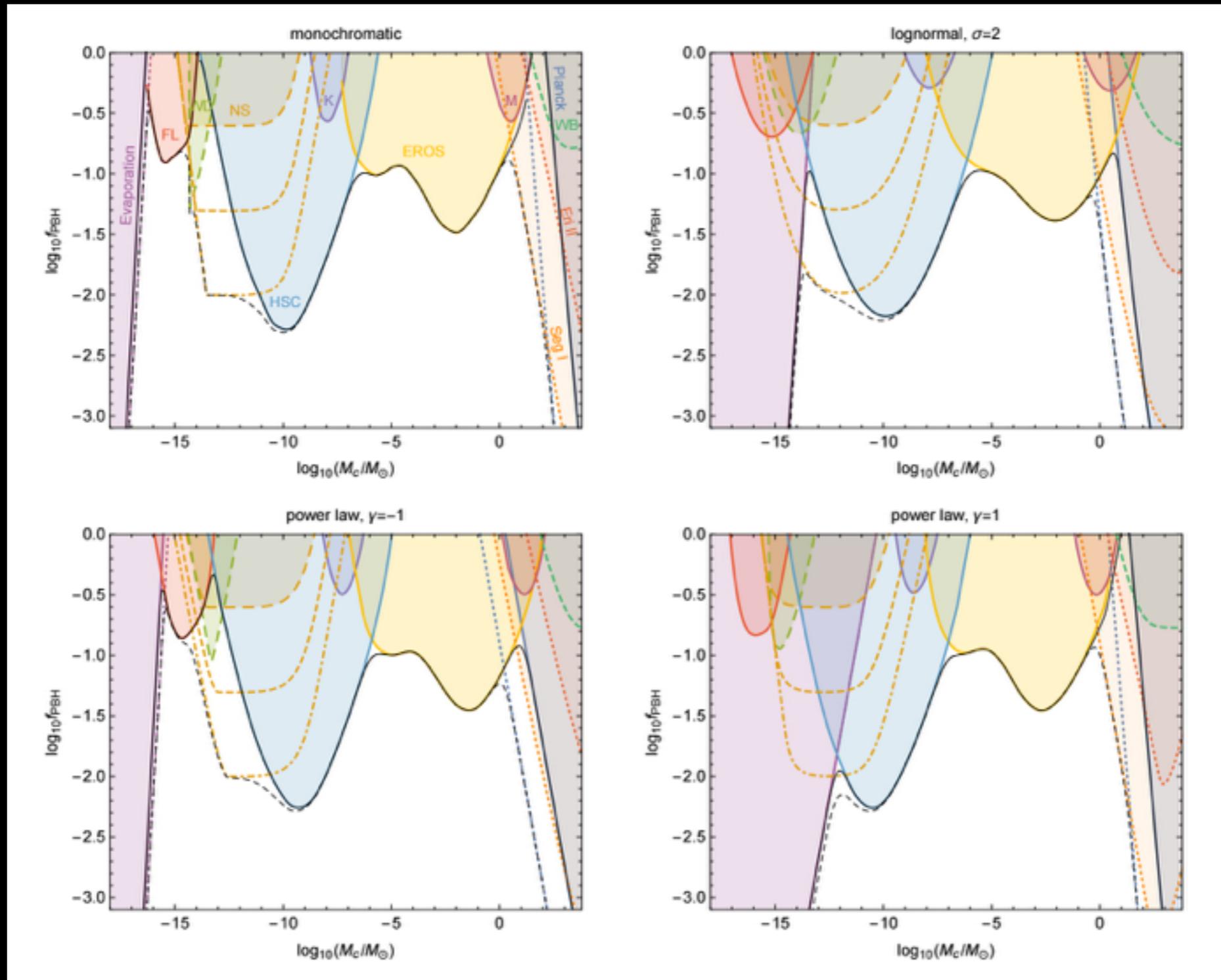
Could such BHs be 'the' DM?

(e.g. Bird et al. 1603.00464, Clesse & Garcia Bellido 1603.05234)

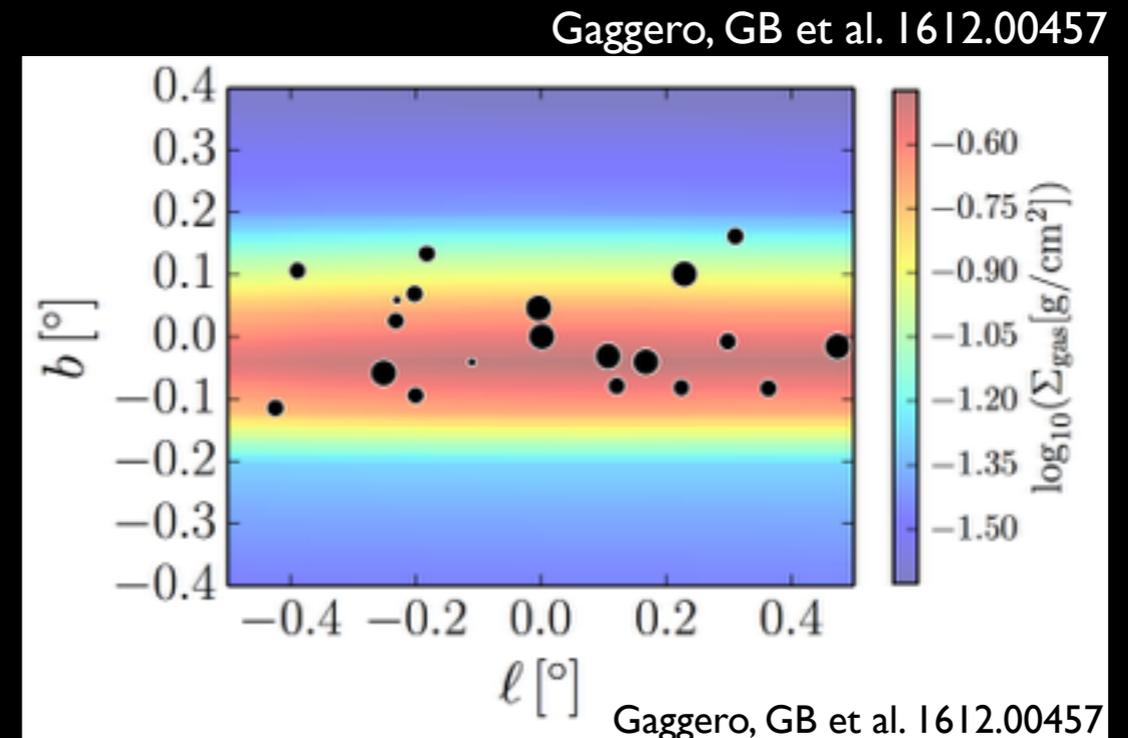
PBHs: overview of existing constraints



PBHs: overview of existing constraints



Dark Matter candidates, example I: Primordial Black Holes

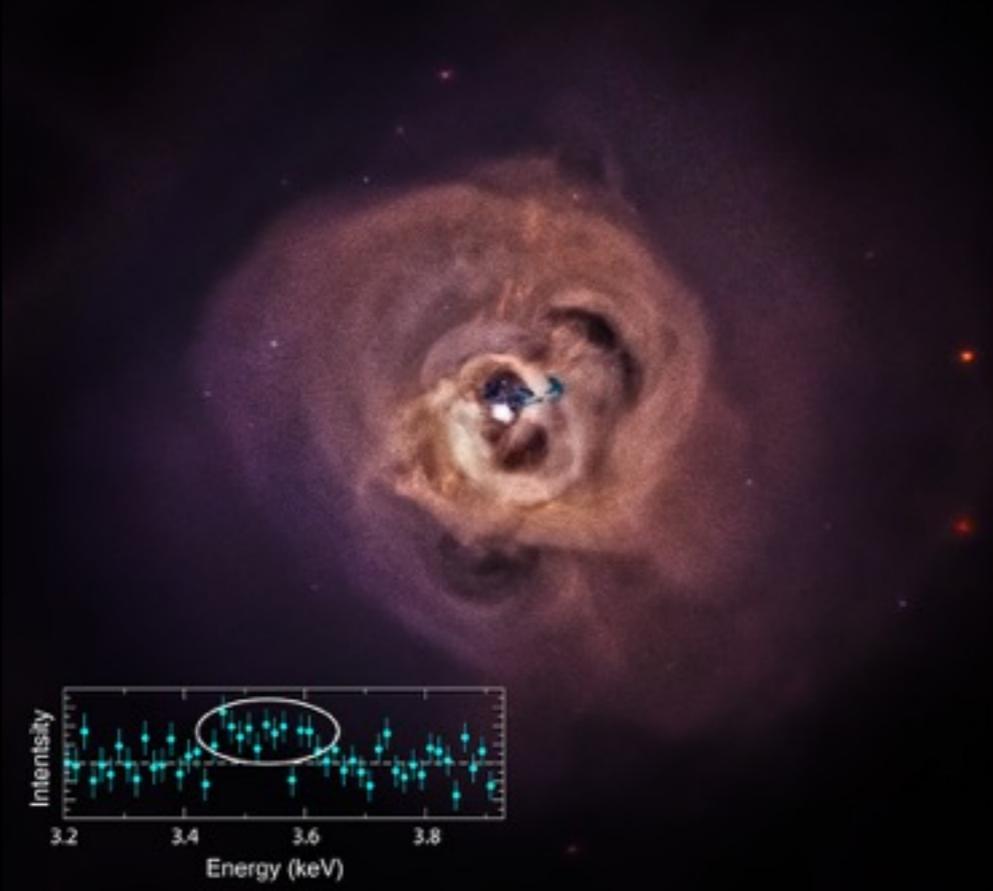


- If PBHs are out there (10^{10} objects in the Galactic bulge if PBHs = DM) they would accrete gas from the dense central molecular zone at the GC
- We should be able to directly observe them in radio and X-ray (Gaggero, GB et al. 1612.00457 - PRL Jun 12)
- Already strong constraints from VLA and Chandra. Interesting prospects for SKA.

Dark Matter candidates, example II: Decaying sterile neutrino

Spectral line discovered at 3.5 keV in X-ray observations

(Bulbul et al. 1402.2301, Boyarsky et al. 1402.4119)



- Line consistent with the decay of a 7.1 keV 'sterile neutrino'
- Ongoing debate to disentangle from contribution of 'mundane' astrophysical lines
- Leading to improved modelling of astrophysical backgrounds + detailed exploration of 'warm' dark matter cosmology

Dark Matter candidates, example II: Decaying sterile neutrino

arXiv.org > hep-ph > arXiv:1705.01837

Search or Article

(Help | Advanced search)

High Energy Physics – Phenomenology

Sterile neutrinos in cosmology

[Kevork N. Abazajian](#)

(Submitted on 4 May 2017 (v1), last revised 10 May 2017 (this version, v2))

Sterile neutrinos are natural extensions to the standard model of particle physics in neutrino mass generation mechanisms. If they are relatively light, less than approximately 10 keV, they can alter cosmology significantly, from the early Universe to the matter and radiation energy density today. Here, we review the cosmological role such light sterile neutrinos can play from the early Universe, including production of keV-scale sterile neutrinos as dark matter candidates, and dynamics of light eV-scale sterile neutrinos during the weakly-coupled active neutrino era. We review proposed signatures of light sterile neutrinos in cosmic microwave background and large scale structure data. We also discuss keV-scale sterile neutrino dark matter decay signatures in X-ray observations, including recent candidate ~ 3.5 keV X-ray line detections consistent with the decay of a ~ 7 keV sterile neutrino dark matter particle.

Comments: Invited review for Physics Reports. 33 pages, 6 figures, approximately 14,700 words; v2: typos corrected, references added and corrected

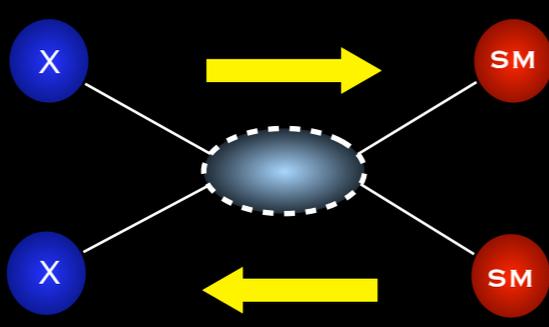
Part III

WIMPs

Focus on WIMPs

By far the most studied class of dark matter candidates.

The WIMP paradigm is based on a simple yet powerful idea:



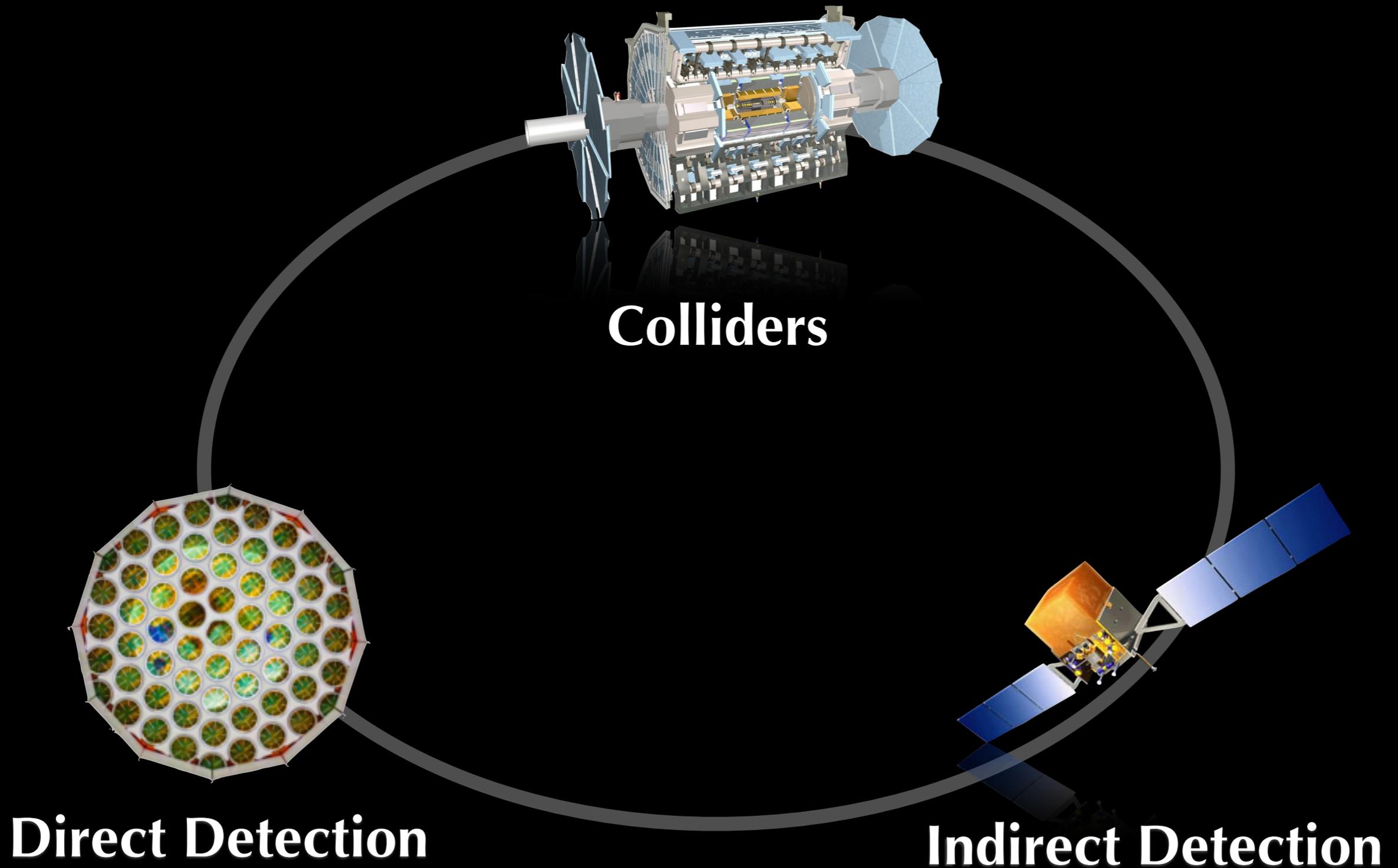
The diagram illustrates the WIMP paradigm. It shows a central interaction region represented by a dashed blue oval. Two blue circles labeled 'X' are on the left, and two red circles labeled 'SM' are on the right. A yellow arrow points from the left towards the central region, and another yellow arrow points from the right towards the central region, representing the annihilation of two WIMPs into two Standard Model particles. Conversely, a yellow arrow points from the central region towards the left, and another yellow arrow points from the central region towards the right, representing the production of two WIMPs from two Standard Model particles.

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

Electroweak-scale cross sections can reproduce correct relic density.

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

WIMPs searches



Indirect detection with gamma-rays

Given: a particle physics model (particle mass m_χ , annihilation cross section σv , # of photons per annihilation dN/dE) and the dark matter density profile $\rho(\mathbf{x})$, it is possible to calculate the expected rate of events in a detector.

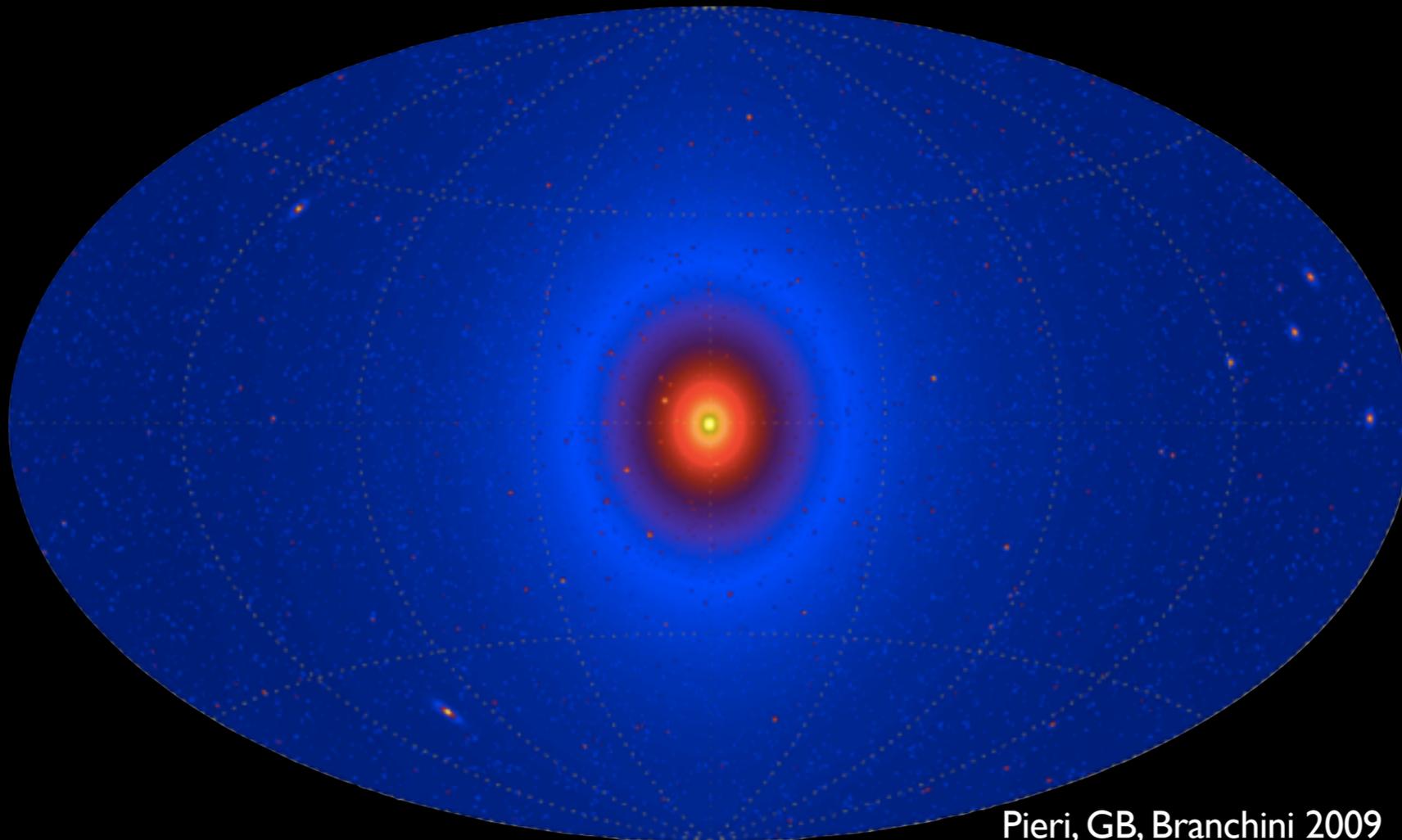
$$\Phi_i(\Omega, E_i) = \frac{dN}{dE_i} \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \int_{\text{los}} \rho_\chi^2(l, \Omega) dl$$

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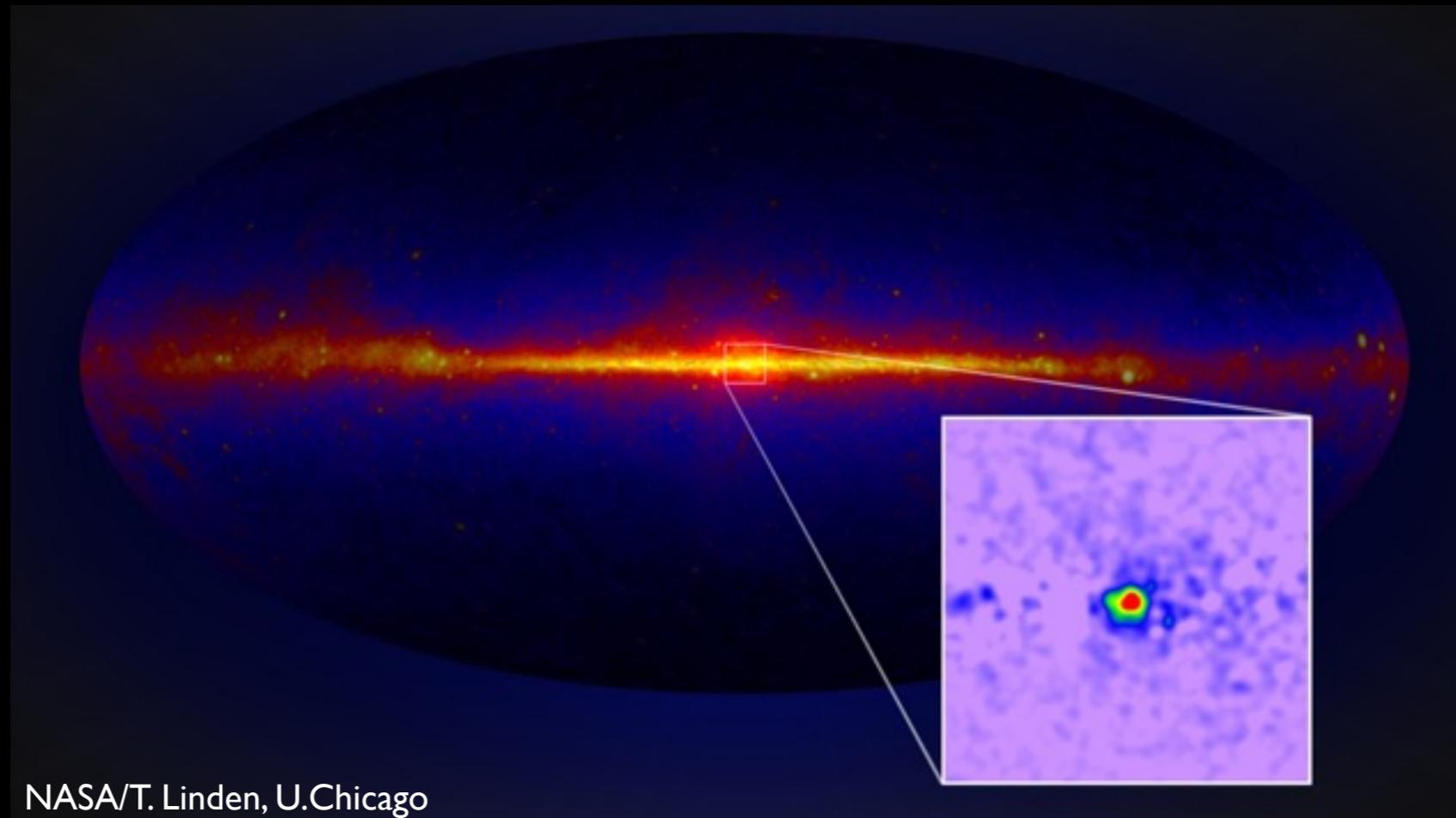
$$\Phi_i(\Omega, E_i) = \frac{dN}{dE_i} \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \int_{\text{los}} \rho_\chi^2(l, \Omega) dl$$

Full-sky map of predicted gamma-ray flux



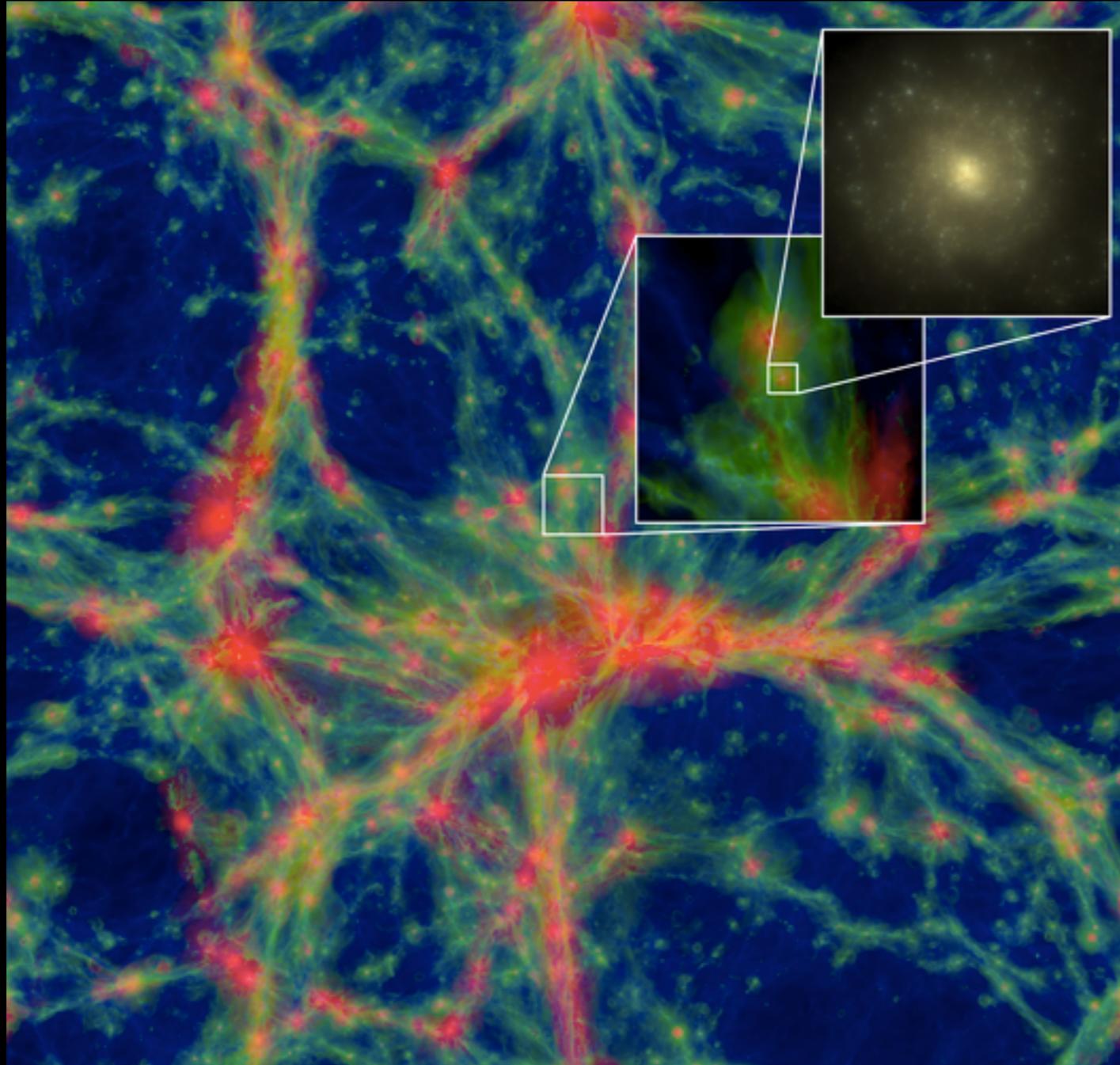
The GeV excess

Since 2009 (starting from Hooper & Goodenough 0910.2998) an excess of gamma-rays observed with the Fermi satellite in the direction of the Galactic center has been reported by several groups of authors.



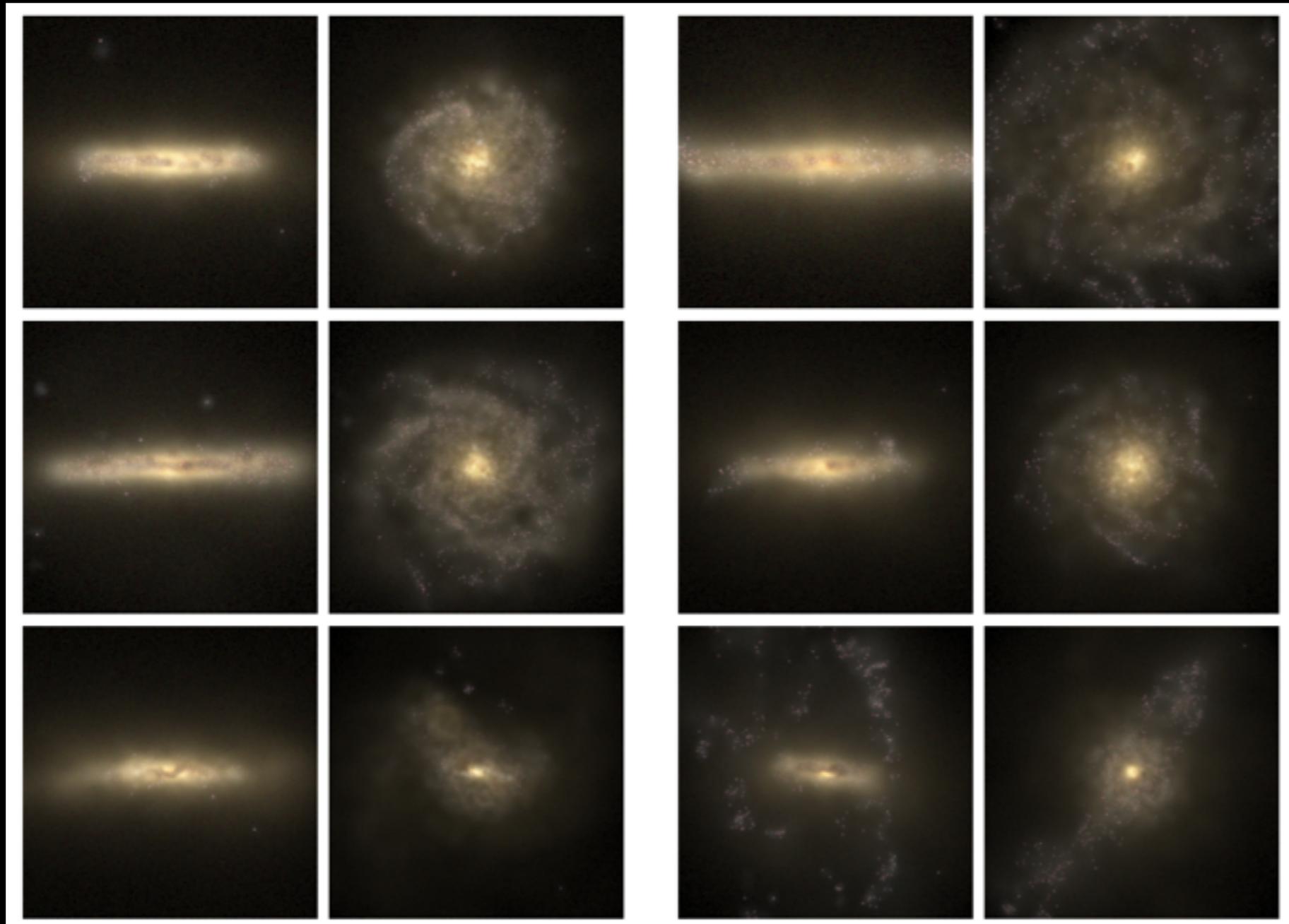
Intriguing aspect: roughly spherical around GC, compatible for morphology and energy spectrum with 'vanilla' WIMP annihilation...

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

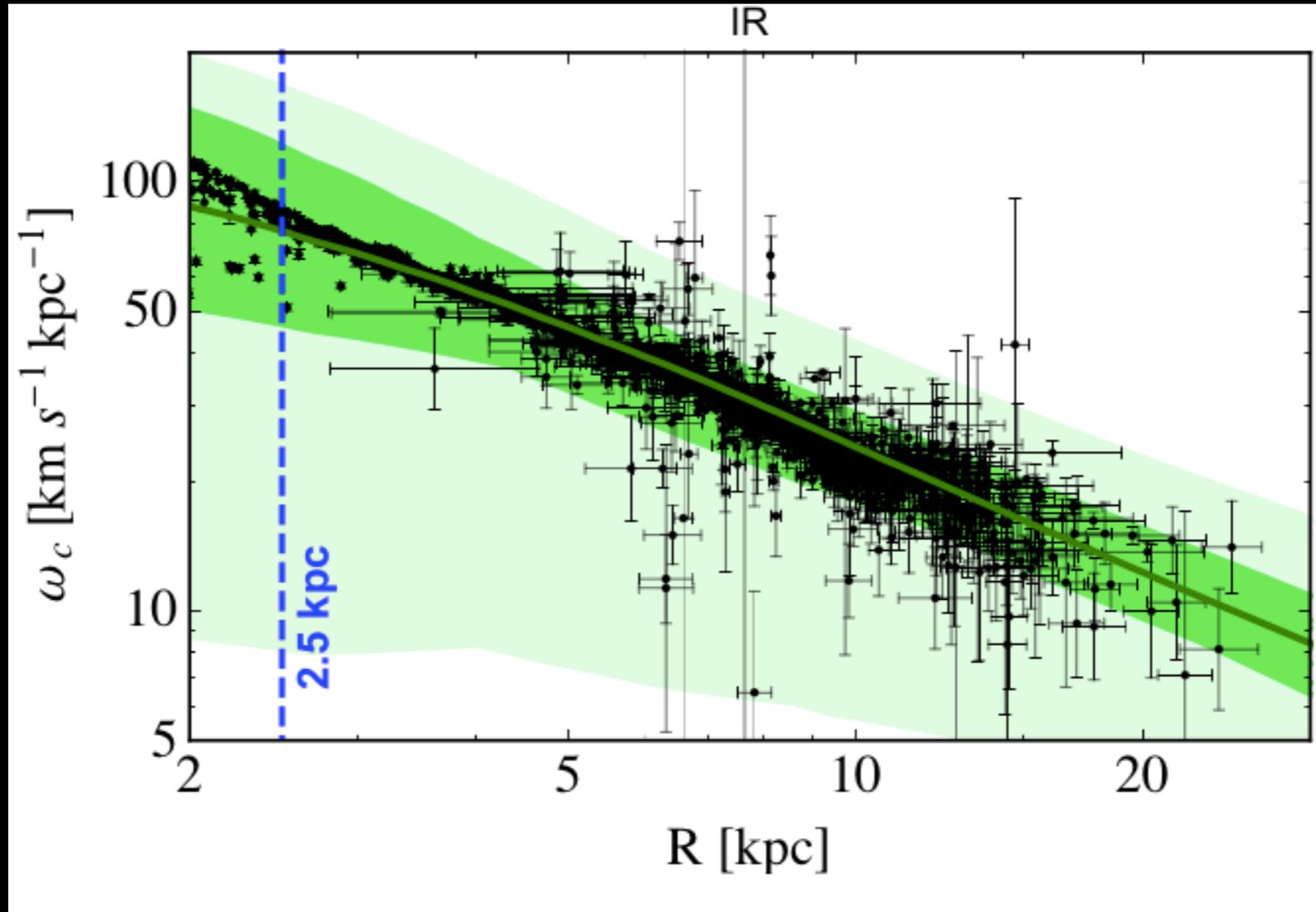
Identifying MW-like galaxies



Calore, Bozorgnia, GB+ arXiv:1509.02164

Visualisation of MW-like galaxies in the Eagle simulation.

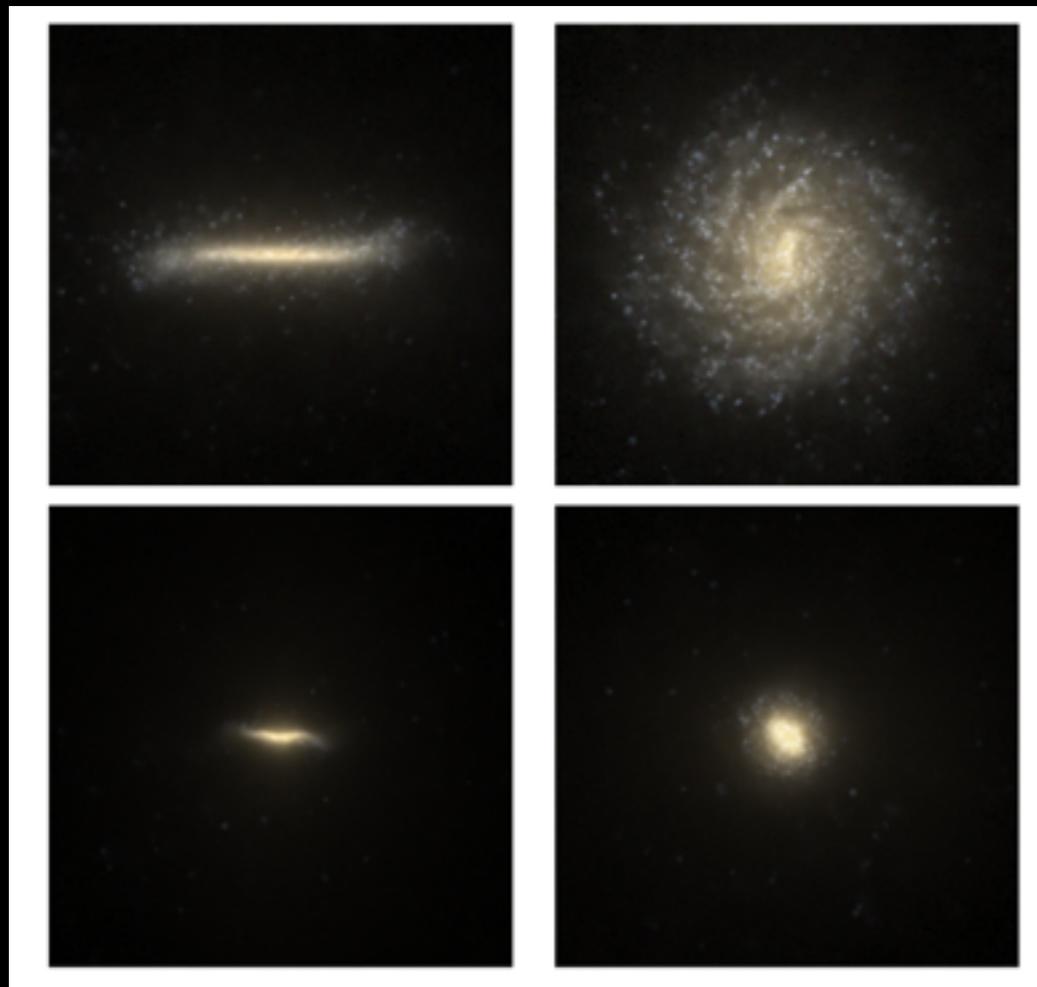
Identifying MW-like galaxies



Calore, Bozorgnia, GB+ arXiv:1509.02164

What does MW-like mean? Only a small fraction of the halos that satisfy halo mass constraints, have rotation curves compatible with observations.

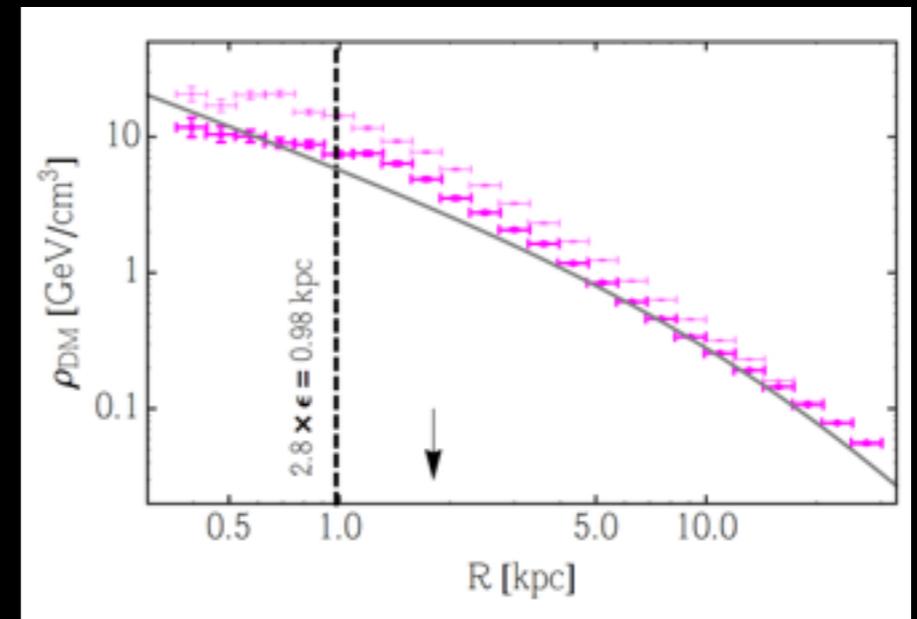
Understanding the impact of baryons on the dark matter distribution



Selection of halos that satisfy rotation curve constraints in the Eagle High-resolution hydrodynamic simulation

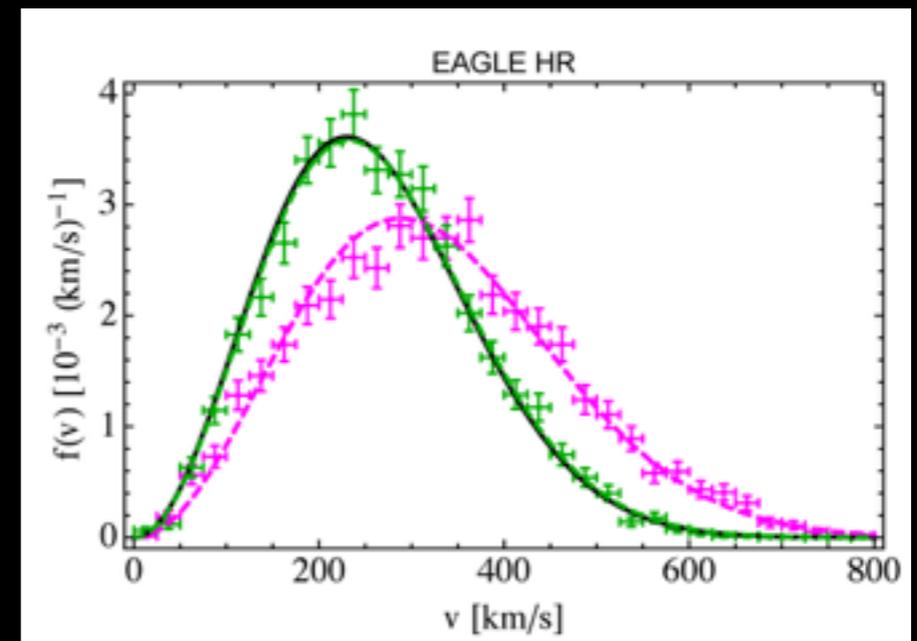
(GRAPPA + Eagle collab.: 1509.02164, 1601.04707)

Density profiles



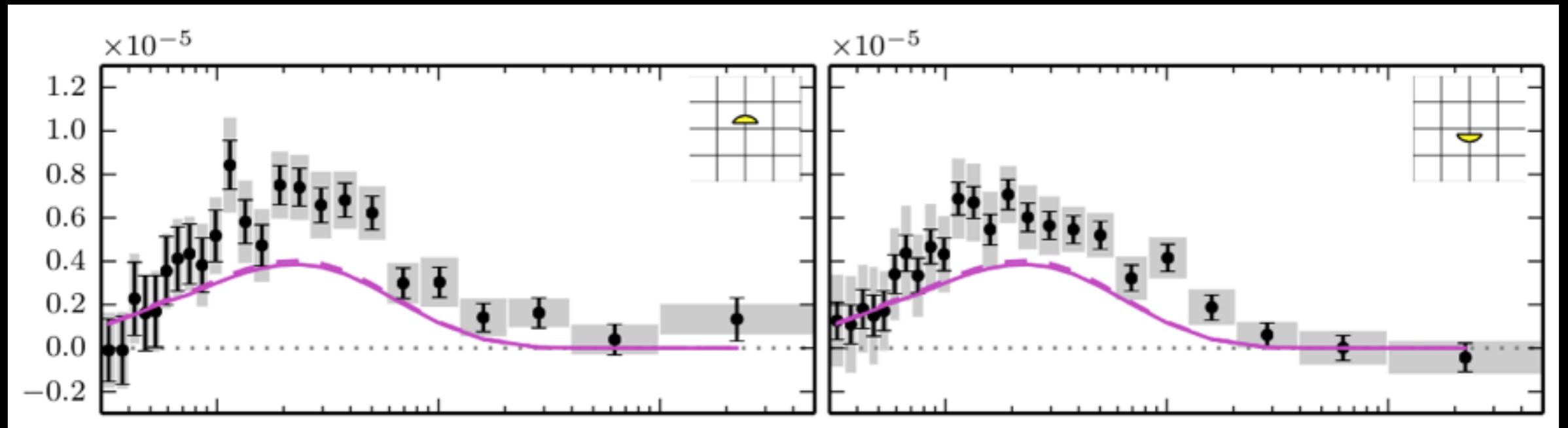
1509.02164

Velocity distribution



1601.04707

The GeV excess



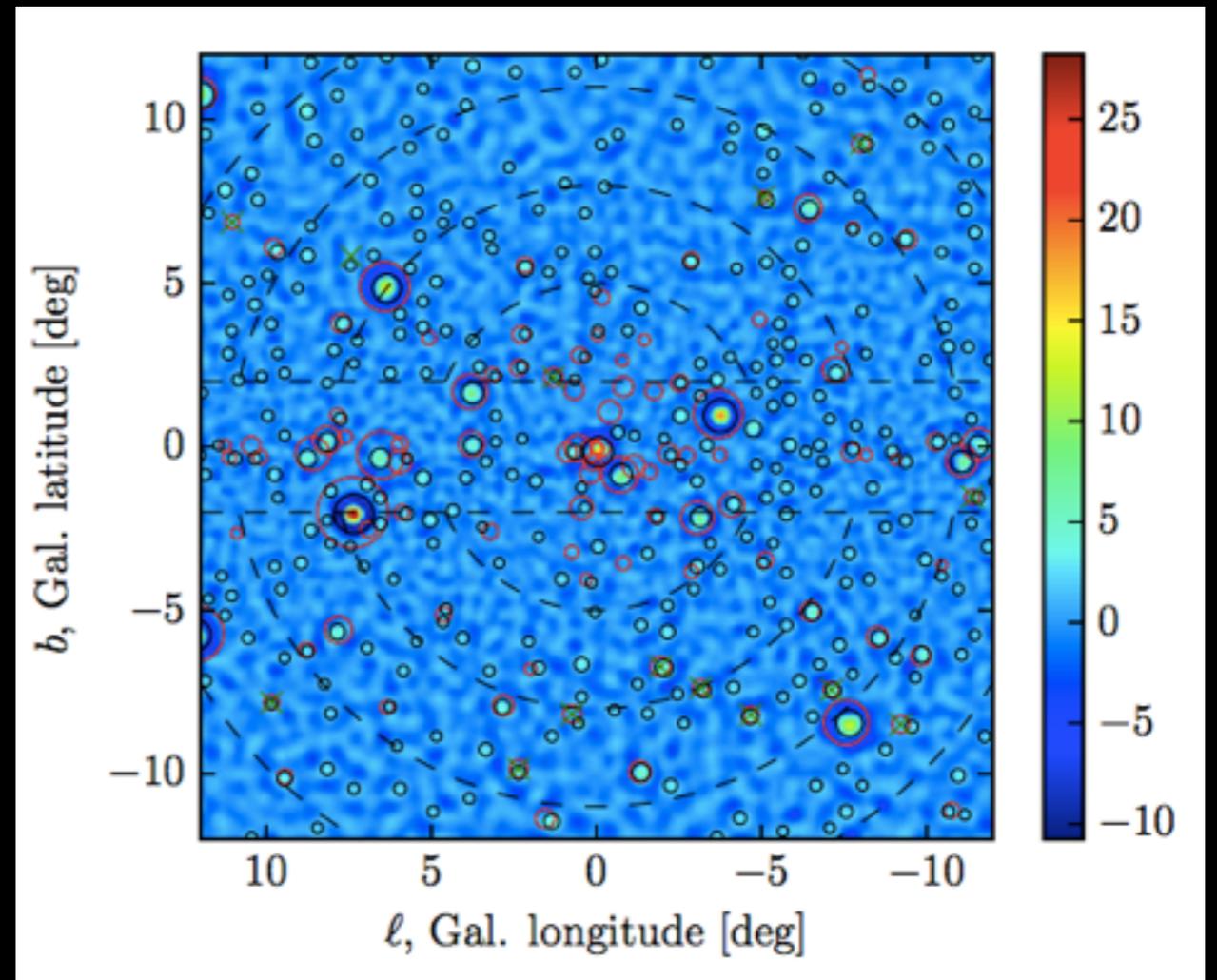
Calore, Bozorgnia, GB+ arXiv:1509.02164

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:

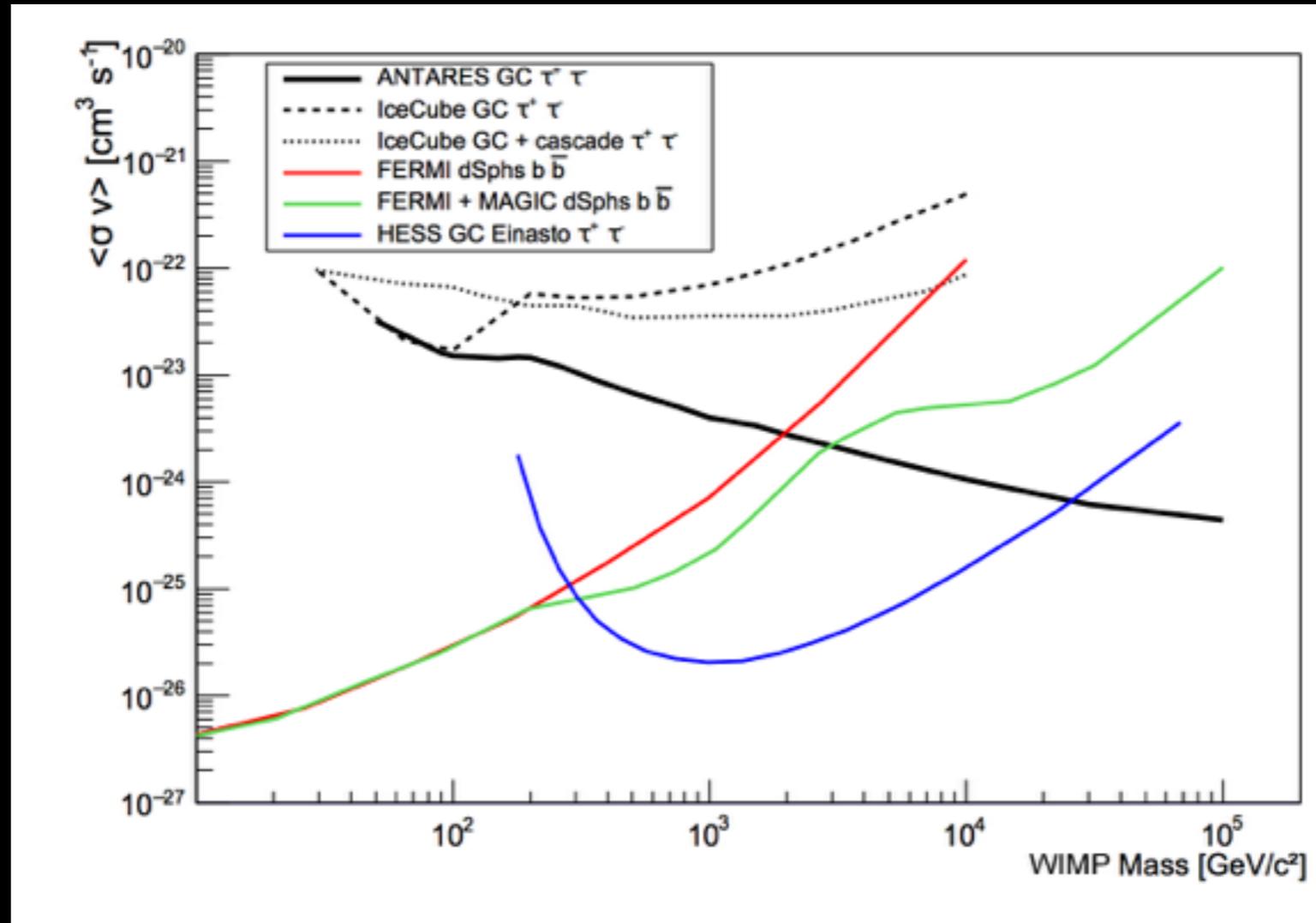
Difficult to rule out 'Standard' Astro interpretation

- 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*



Bartels et al., 1506.05104

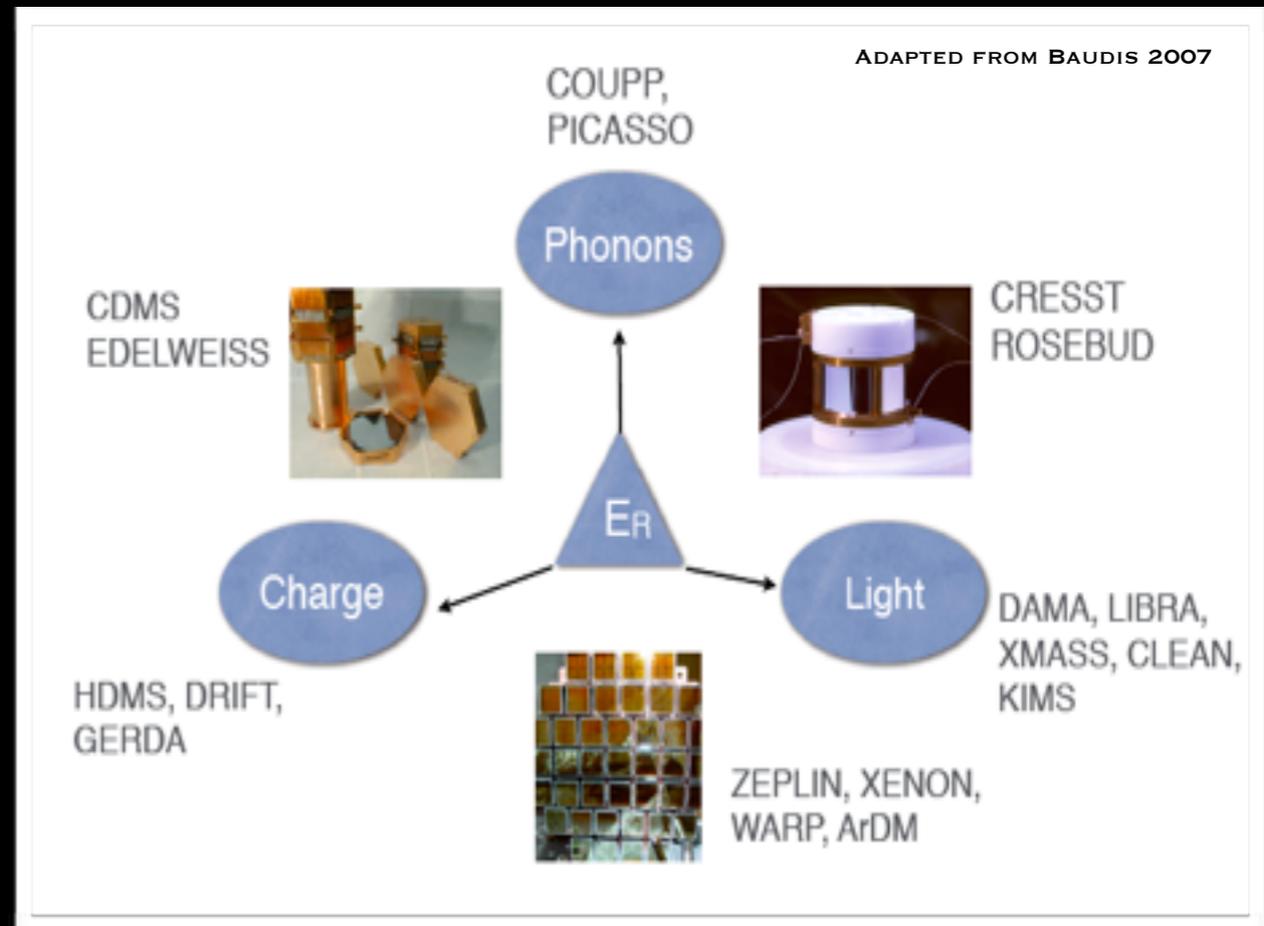
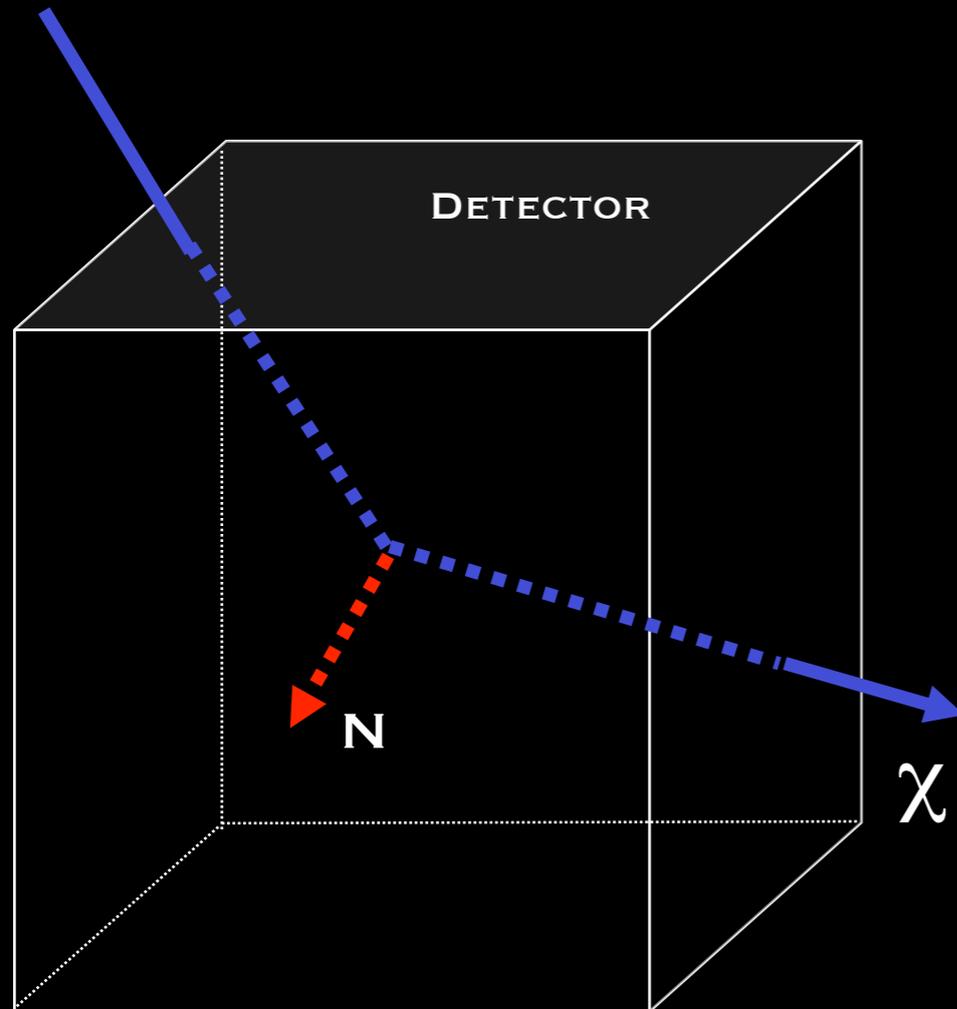
Complementary Indirect searches



Antares collaboration, 1612.04595

Direct Detection

Principle and Detection Techniques



Xenon detectors (e.g. LUX and Xenon1Ton)



Direct Detection

Differential Event Rate

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

Given:

- a particle physics model (particle mass m_χ and χN differential cross section $d\sigma_{\chi N}/dE_R$)
- the local dark matter density ρ_0 and the dark matter velocity distribution $f(\mathbf{v})$
- the experimental setup (v_{min})

it is possible to calculate the expected rate of events in a detector.

Status of Direct Detection

arXiv.org > astro-ph > arXiv:1705.06655

Search or Article

(Help | Advanced search)

Astrophysics > Cosmology and Nongalactic Astrophysics

First Dark Matter Search Results from the XENON1T Experiment

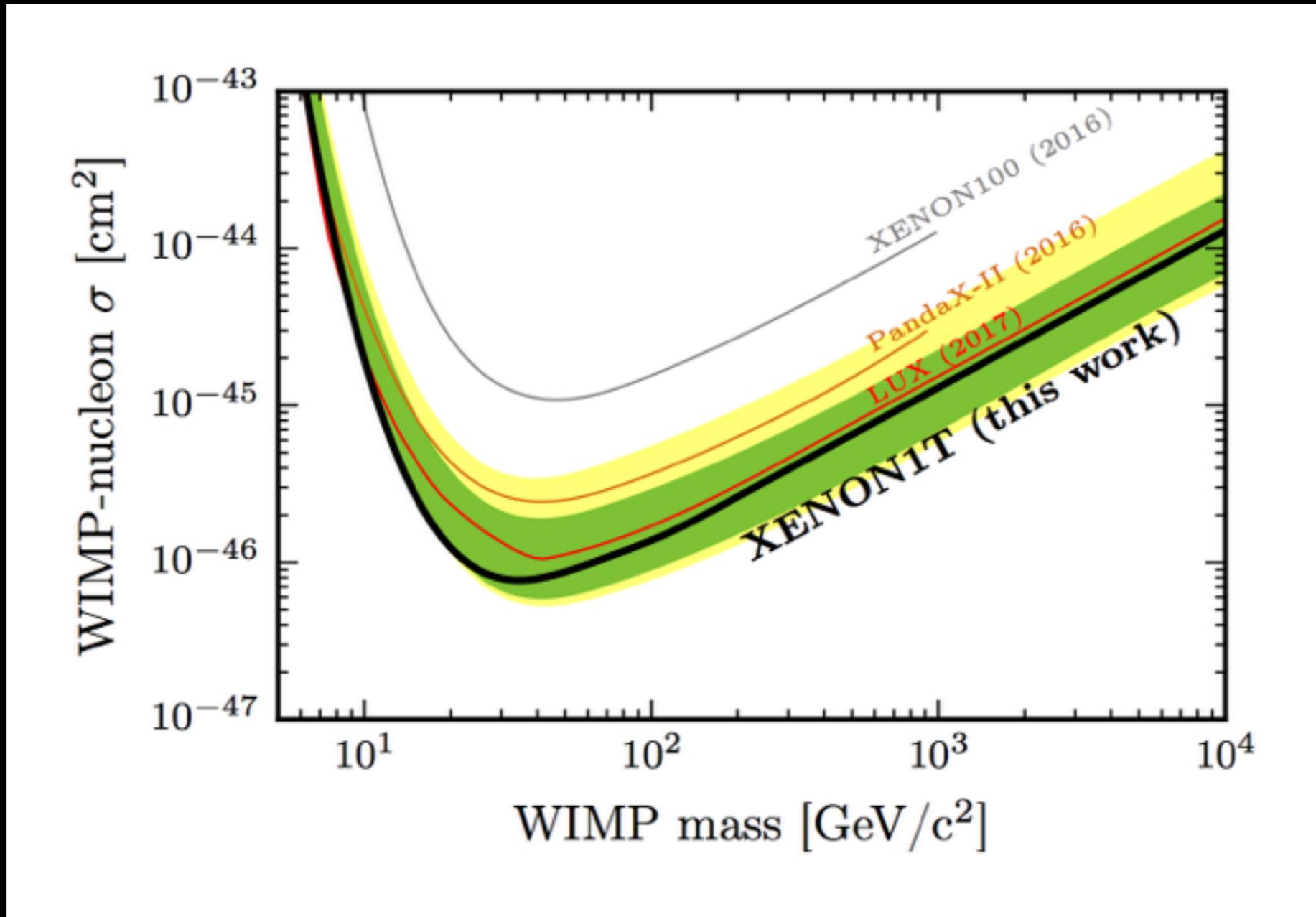
E. Aprile, J. Aalbers, F. Agostini, M. Alfonsi, F. D. Amaro, M. Anthony, F. Arneodo, P. Barrow, L. Baudis, B. Bauermeister, M. L. Benabderrahmane, T. Berger, P. A. Breur, A. Brown, A. Brown, E. Brown, S. Bruenner, G. Bruno, R. Budnik, L. Bütikofer, J. Calvén, J. M. R. Cardoso, M. Cervantes, D. Cichon, D. Coderre, A. P. Colijn, J. Conrad, J. P. Cussonneau, M. P. Decowski, P. de Perio, P. Di Gangi, A. Di Giovanni, S. Diglio, G. Eurin, J. Fei, A. D. Ferella, A. Fieguth, W. Fulgione, A. Gallo Rosso, M. Galloway, F. Gao, M. Garbini, R. Gardner, C. Geis, L. W. Goetzke, L. Grandi, Z. Greene, C. Grignon, C. Hasterok, E. Hogenbirk, J. Howlett, R. Itay, B. Kaminsky, S. Kazama, G. Kessler, A. Kish, H. Landsman, R. F. Lang, D. Lellouch, L. Levinson, Q. Lin, S. Lindemann, M. Lindner, F. Lombardi, et al. (62 additional authors not shown)

(Submitted on 18 May 2017)

We report the first dark matter search results from XENON1T, a ~ 2000 -kg-target-mass dual-phase (liquid-gas) xenon time projection chamber in operation at the Laboratori Nazionali del Gran Sasso in Italy and the first ton-scale detector of this kind. The blinded search used 34.2 live days of data acquired between November 2016 and January 2017. Inside the (1042 ± 12) kg fiducial mass and in the $[5, 40]$ keV_{nr} energy range of interest for WIMP dark matter searches, the electronic recoil background was $(1.93 \pm 0.25) \times 10^{-4}$ events/(kg \times day \times keV_{ee}), the lowest ever achieved in a dark matter detector. A profile likelihood analysis shows that the data is consistent with the background-only hypothesis. We derive the most stringent exclusion limits on the spin-independent WIMP-nucleon interaction cross section for WIMP masses above 10 GeV/ c^2 , with a minimum of 7.7×10^{-47} cm² for 35-GeV/ c^2 WIMPs at 90% confidence level.

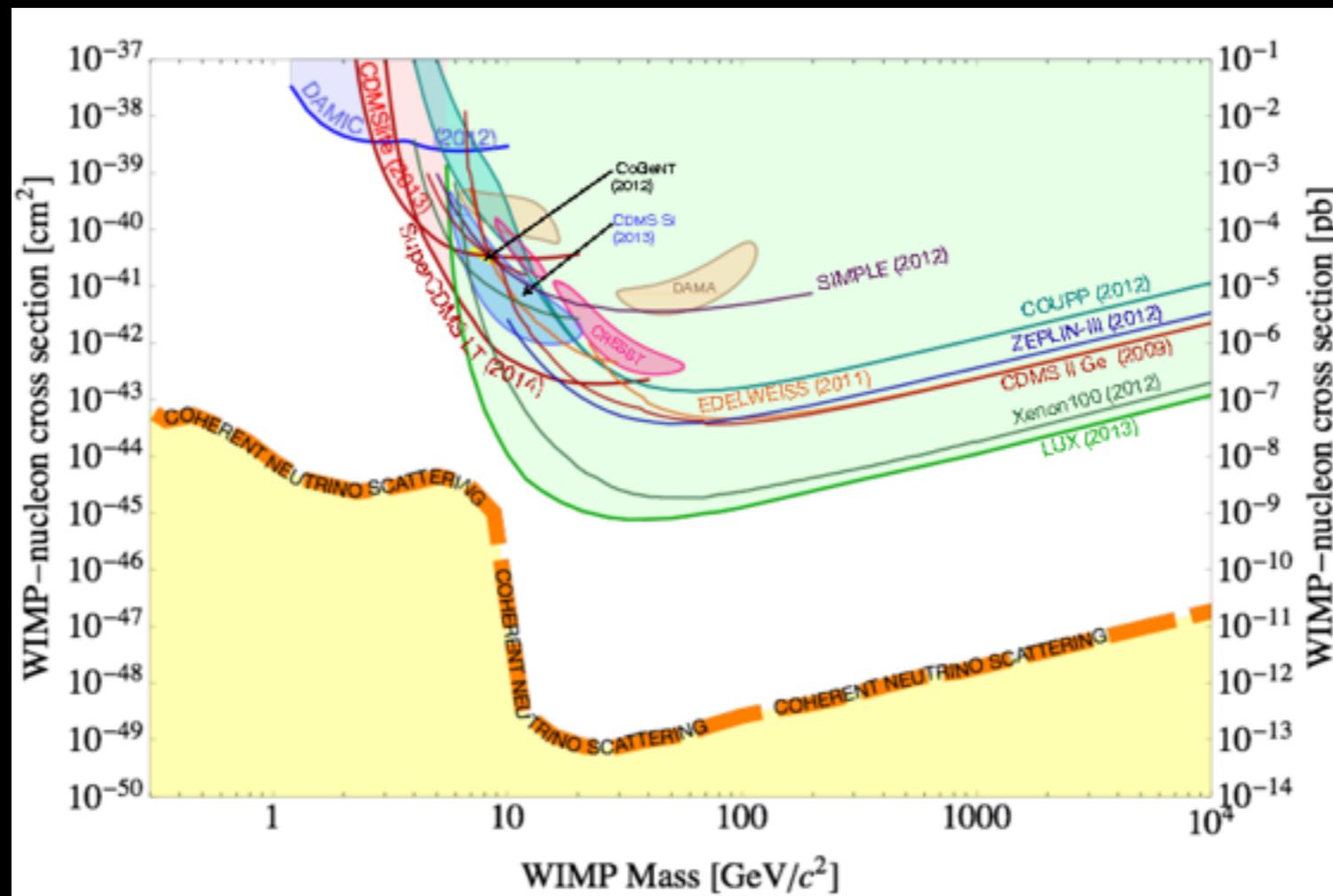
New results from the Xenon 1T collaboration announced in May

Status of Direct Detection



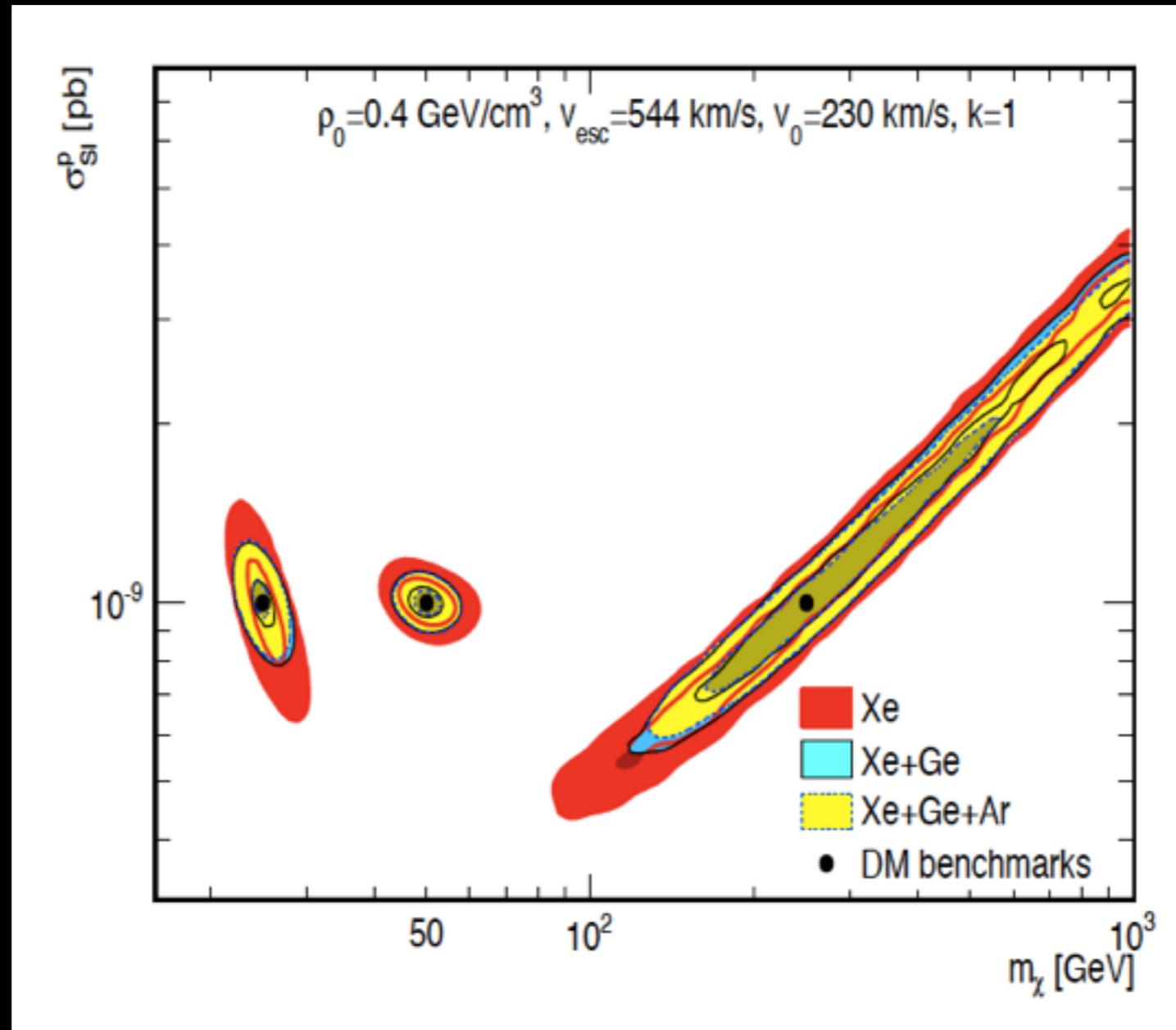
The “neutrino floor”

Fundamental limitation to direct detection



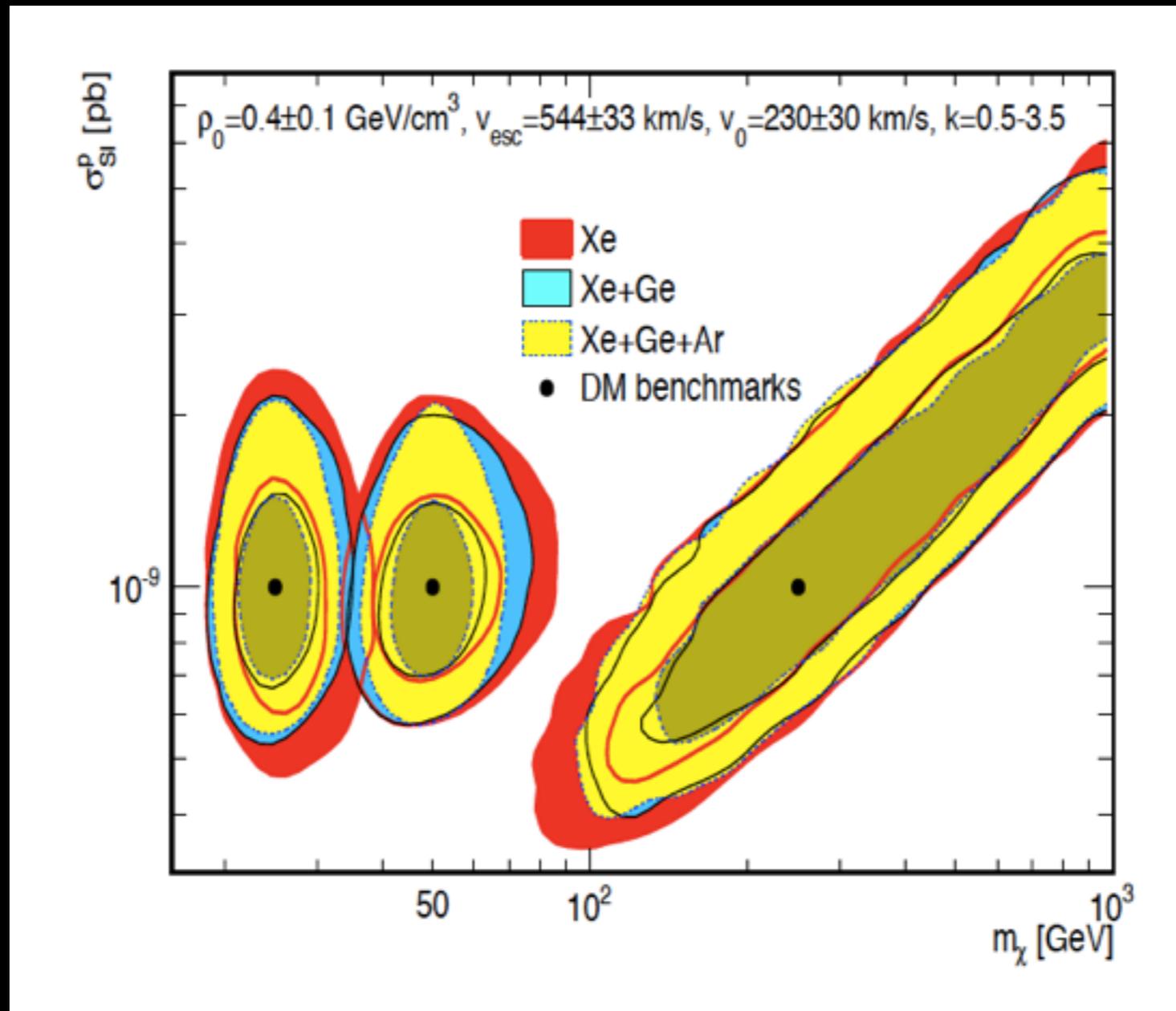
Billard et al., arXiv:1307.5458

What do we learn in case of detection?



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

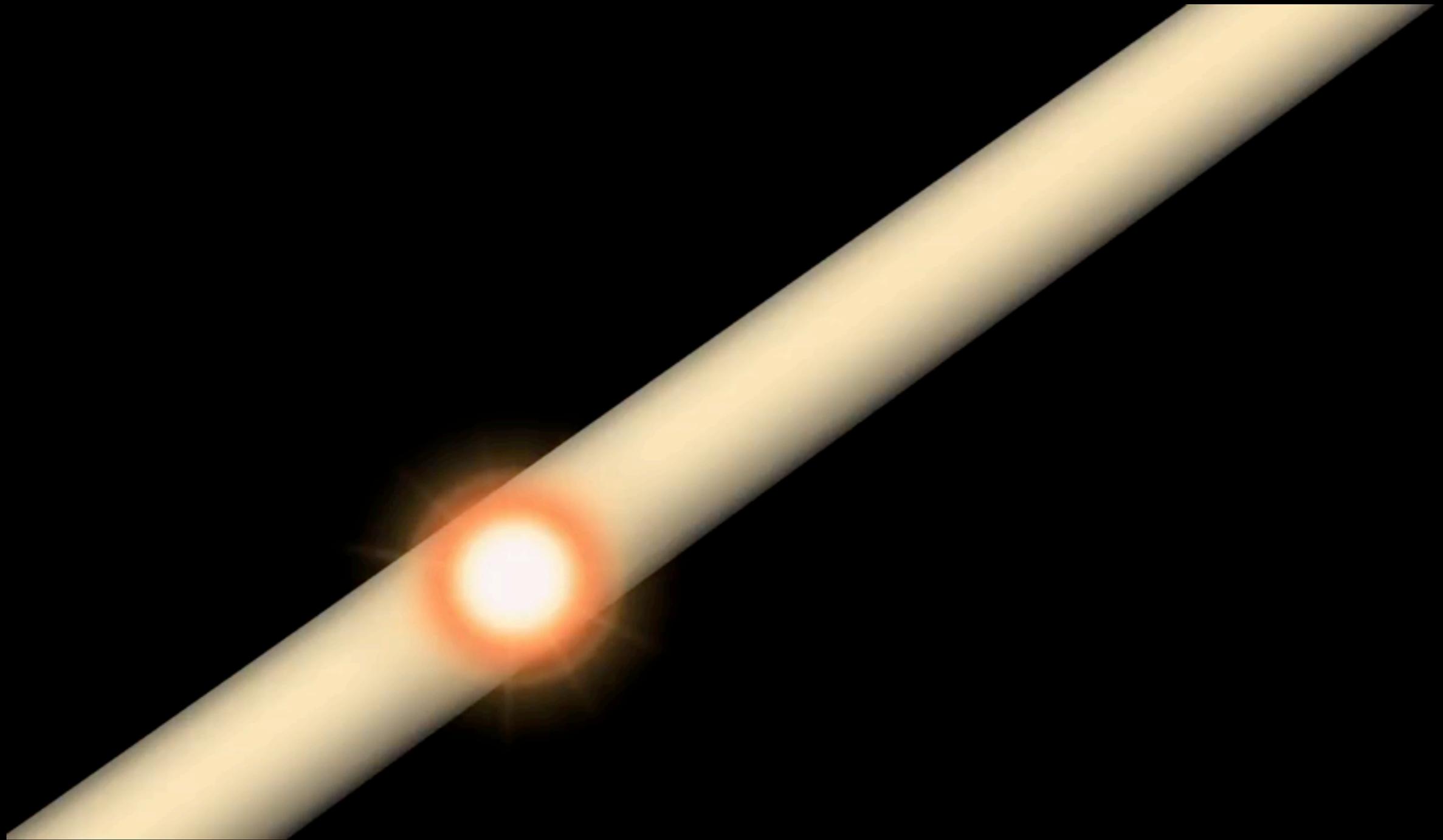
Astrophysical uncertainties



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

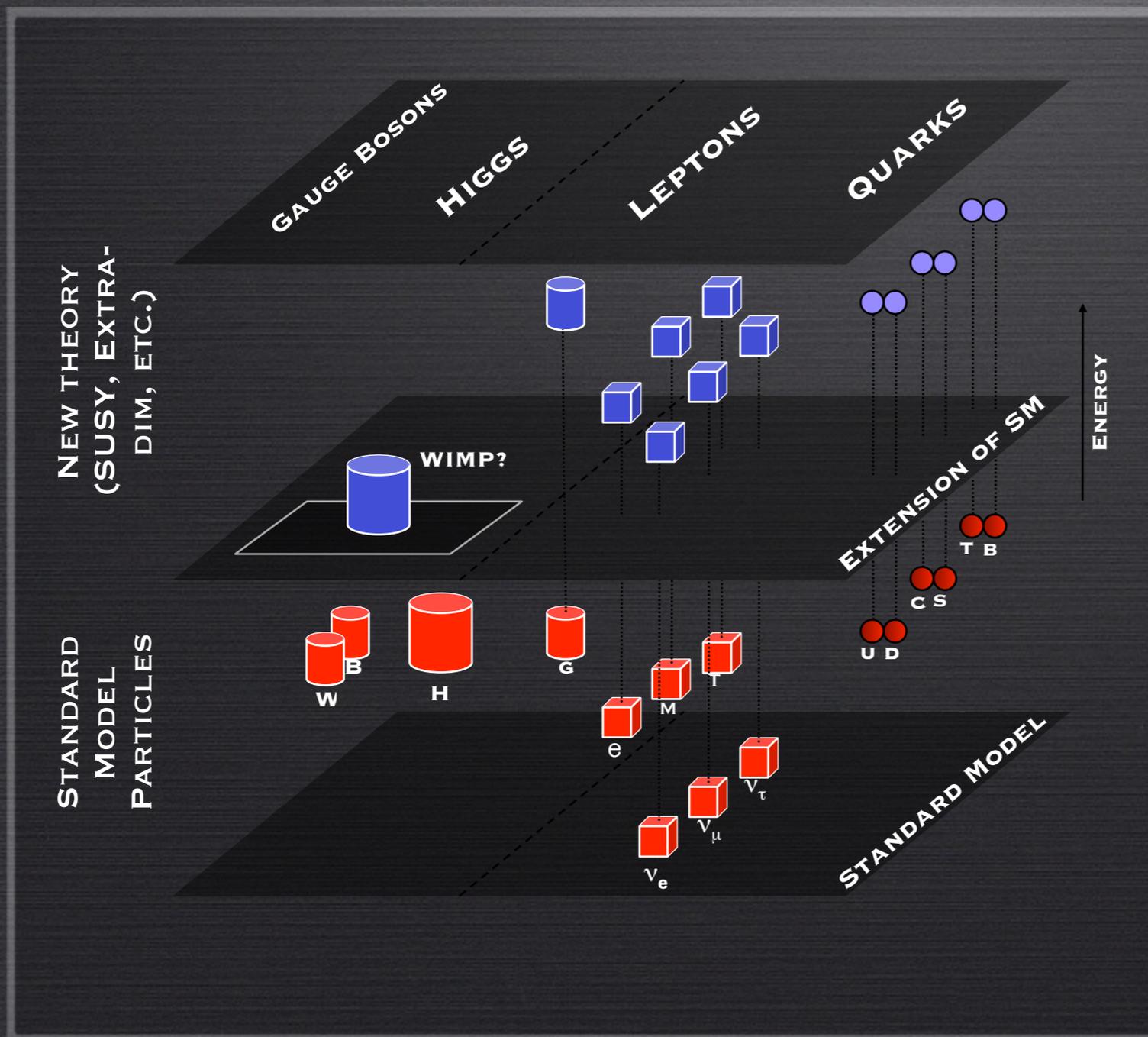
Here we ASSUMED that newly discovered particles are THE DM.
If we relax this assumption, we can only set a lower limit on the cross-section.

The Large Hadron Collider



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

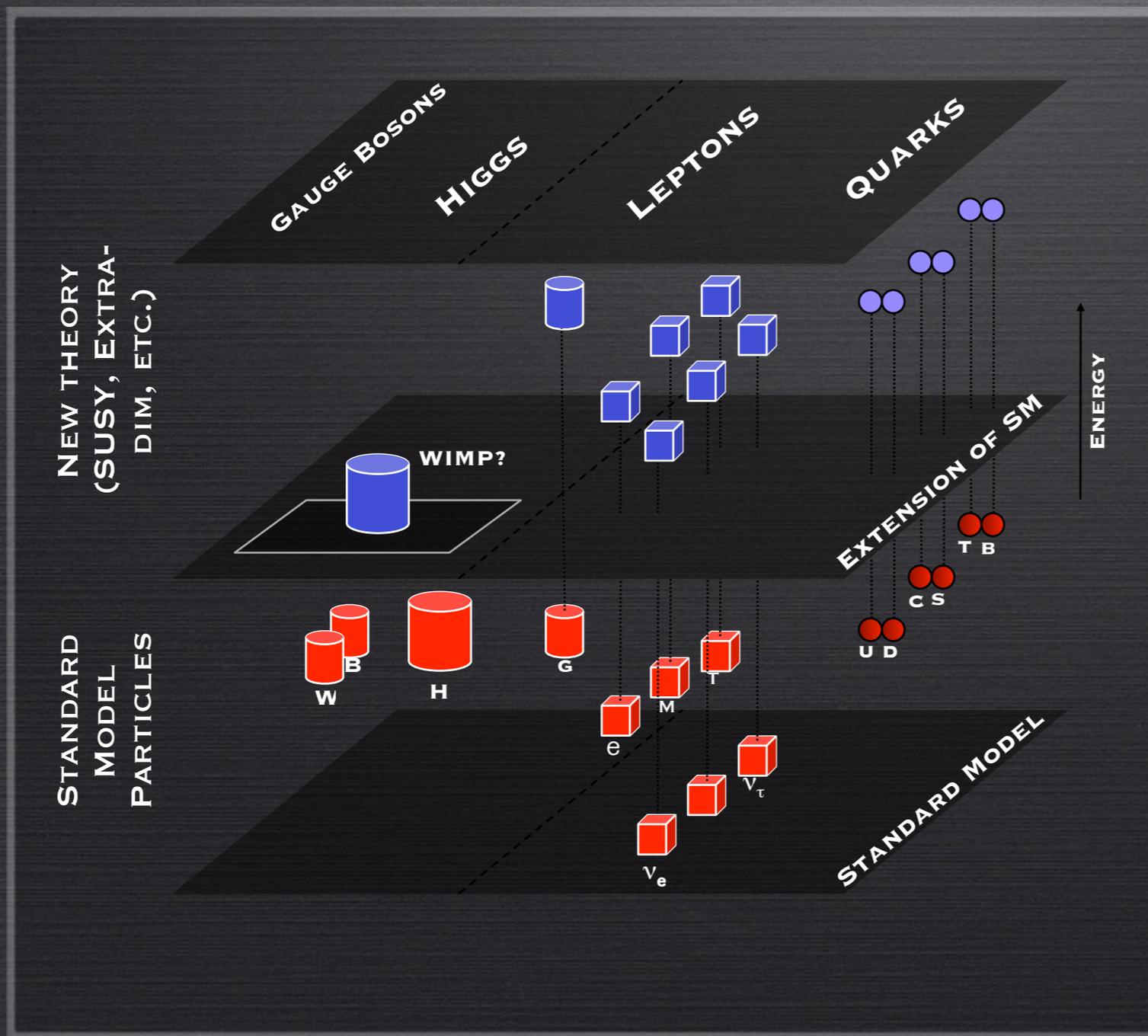


To explain the origin of the weak scale, extensions of the standard model often postulate the existence of new physics at ~ 100 GeV

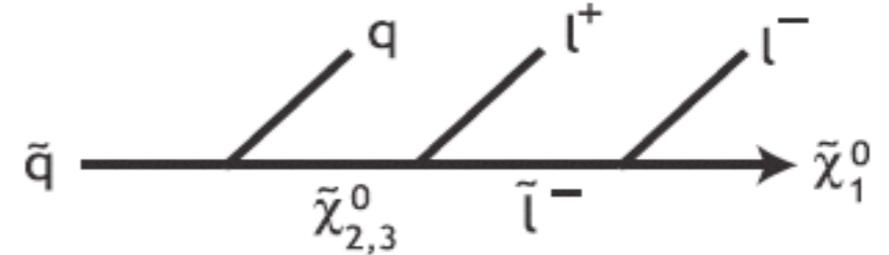
On the left, schematic view of the structure of possible extensions of the standard model

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.



SUSY searches Aug 2016

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

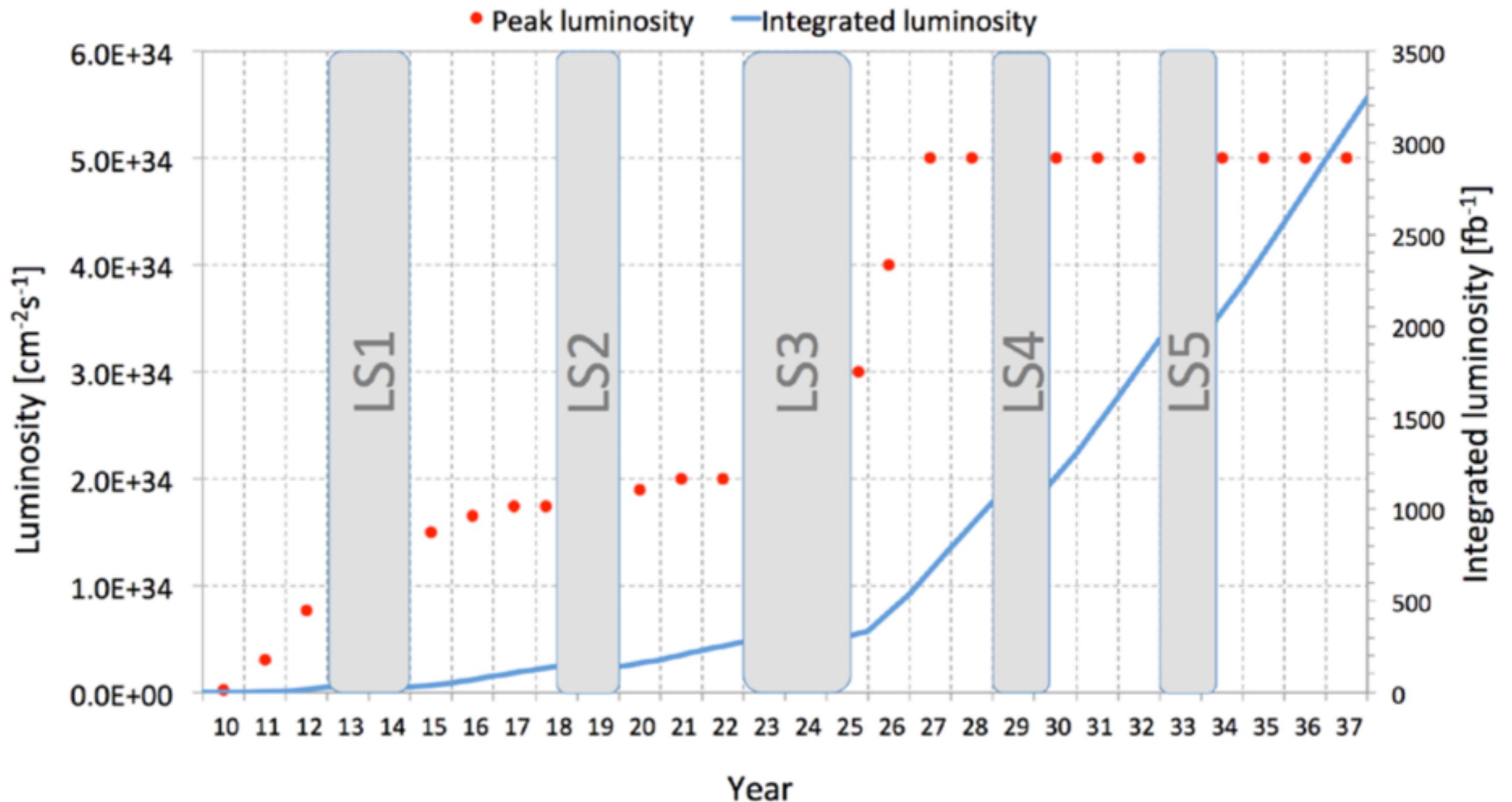
$\sqrt{s} = 7, 8, 13$ TeV

Model	e, μ, τ, γ	Jets	E_T^{miss} [$\mathcal{L} dt(\text{fb}^{-1})$]	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference	
Inclusive Searches	MSUGRA/CMSSM	0-3 $e, \mu/1-2 \tau$	2-10 jets/3 b	Yes	20.3	\tilde{g}, \tilde{u} 1.85 TeV	$m(\tilde{g})=m(\tilde{u})$	1507.05525
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	0	2-6 jets	Yes	13.3	\tilde{g} 1.35 TeV	$m(\tilde{g}) < 200$ GeV, $m(\tilde{1}^{\text{st}} \text{ gen. } \tilde{q}) = m(\tilde{2}^{\text{nd}} \text{ gen. } \tilde{q})$	ATLAS-CONF-2016-078
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$ (compressed)	mono-jet	1-3 jets	Yes	3.2	\tilde{g} 608 GeV	$m(\tilde{g}) = m(\tilde{1}^{\text{st}})$ < 5 GeV	1604.07773
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	0	2-6 jets	Yes	13.3	\tilde{g} 1.85 TeV	$m(\tilde{g}) = 0$ GeV	ATLAS-CONF-2016-078
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	0	2-6 jets	Yes	13.3	\tilde{g} 1.83 TeV	$m(\tilde{g}) < 400$ GeV, $m(\tilde{1}^{\text{st}}) = 0.5(m(\tilde{1}^{\text{st}}) + m(\tilde{2}^{\text{nd}}))$	ATLAS-CONF-2016-078
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	3 e, μ	4 jets	-	13.2	\tilde{g} 1.7 TeV	$m(\tilde{g}) < 400$ GeV	ATLAS-CONF-2016-037
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	2 e, μ (SS)	0-3 jets	Yes	13.2	\tilde{g} 1.8 TeV	$m(\tilde{g}) < 500$ GeV	ATLAS-CONF-2016-037
	GMSB (\tilde{g} NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	\tilde{g} 2.0 TeV	$m(\tilde{g}) < 500$ GeV	1507.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	\tilde{g} 1.85 TeV	$c\tau(\text{NLSP}) < 0.1$ mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	\tilde{g} 1.37 TeV	$m(\tilde{g}) < 950$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu = 0$	1507.05493
3 rd gen. \tilde{g} med.	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	0	3 b	Yes	14.8	\tilde{g} 1.89 TeV	$m(\tilde{g}) = 0$ GeV	ATLAS-CONF-2016-052
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	0-1 e, μ	3 b	Yes	14.8	\tilde{g} 1.89 TeV	$m(\tilde{g}) = 0$ GeV	ATLAS-CONF-2016-052
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	0-1 e, μ	3 b	Yes	20.1	\tilde{g} 1.37 TeV	$m(\tilde{g}) < 300$ GeV	1407.0609
3 rd gen. squarks direct production	$\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}^*$	0	2 b	Yes	3.2	\tilde{t}_1 840 GeV	$m(\tilde{t}_1) < 100$ GeV	1606.08772
	$\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}^*$	2 e, μ (SS)	1 b	Yes	13.2	\tilde{t}_1 325-685 GeV	$m(\tilde{t}_1) < 150$ GeV, $m(\tilde{1}^{\text{st}}) = m(\tilde{1}^{\text{st}}) + 100$ GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}^*$	0-2 e, μ	1-2 b	Yes	4.7/13.3	\tilde{t}_1 170 GeV	$m(\tilde{1}^{\text{st}}) = 2m(\tilde{1}^{\text{st}})$, $m(\tilde{1}^{\text{st}}) = 55$ GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{b}^*$ or \tilde{t}_1^*	0-2 e, μ	0-2 jets/1-2 b	Yes	4.7/13.3	\tilde{t}_1 90-198 GeV	$m(\tilde{1}^{\text{st}}) = 1$ GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{t}^*$	0	mono-jet	Yes	3.2	\tilde{t}_1 90-323 GeV	$m(\tilde{t}_1) = m(\tilde{1}^{\text{st}}) = 5$ GeV	1604.07773
	\tilde{t}_1, \tilde{t}_1 (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1 150-600 GeV	$m(\tilde{t}_1) > 150$ GeV	1403.5222
	$\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	13.3	\tilde{t}_1 290-700 GeV	$m(\tilde{t}_1) < 300$ GeV	ATLAS-CONF-2016-038
	$\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 + h$	1 e, μ	6 jets + 2 b	Yes	20.3	\tilde{t}_1 320-620 GeV	$m(\tilde{t}_1) = 0$ GeV	1506.08616
EW direct	$\tilde{t}_1, \tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{t}^*$	2 e, μ	0	Yes	20.3	\tilde{t}_1 90-335 GeV	$m(\tilde{t}_1) = 0$ GeV	1403.5294
	$\tilde{t}_1, \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 + \nu(\tilde{\nu})$	2 e, μ	0	Yes	20.3	\tilde{t}_1 140-475 GeV	$m(\tilde{t}_1) = 0$ GeV, $m(\tilde{1}^{\text{st}}) = 0.5(m(\tilde{1}^{\text{st}}) + m(\tilde{1}^{\text{st}}))$	1403.5294
	$\tilde{t}_1, \tilde{t}_1, \tilde{t}_1 \rightarrow \nu(\tilde{\nu})$	2 τ	-	Yes	20.3	\tilde{t}_1 355 GeV	$m(\tilde{1}^{\text{st}}) = 0$ GeV, $m(\tilde{1}^{\text{st}}) = 0.5(m(\tilde{1}^{\text{st}}) + m(\tilde{1}^{\text{st}}))$	1407.0350
	$\tilde{t}_1, \tilde{t}_1, \tilde{t}_1 \rightarrow \nu(\tilde{\nu}), \nu(\tilde{\nu}), \nu(\tilde{\nu})$	3 e, μ	0	Yes	20.3	\tilde{t}_1 715 GeV	$m(\tilde{1}^{\text{st}}) = m(\tilde{1}^{\text{st}})$, $m(\tilde{1}^{\text{st}}) = 0$, $m(\tilde{1}^{\text{st}}) = 0.5(m(\tilde{1}^{\text{st}}) + m(\tilde{1}^{\text{st}}))$	1402.7029
	$\tilde{t}_1, \tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{b}^*, Z\tilde{b}^*$	2-3 e, μ	0-2 jets	Yes	20.3	\tilde{t}_1 425 GeV	$m(\tilde{1}^{\text{st}}) = m(\tilde{1}^{\text{st}})$, $m(\tilde{1}^{\text{st}}) = 0$, \tilde{t} decoupled	1403.5294, 1402.7029
	$\tilde{t}_1, \tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{b}^*, h\tilde{b}^*, h\tilde{b}^*/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	\tilde{t}_1 270 GeV	$m(\tilde{1}^{\text{st}}) = m(\tilde{1}^{\text{st}})$, $m(\tilde{1}^{\text{st}}) = 0$, \tilde{t} decoupled	1501.07110
	$\tilde{t}_1, \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 + \nu$	4 e, μ	0	Yes	20.3	\tilde{t}_1 635 GeV	$m(\tilde{1}^{\text{st}}) = m(\tilde{1}^{\text{st}})$, $m(\tilde{1}^{\text{st}}) = 0$, $m(\tilde{1}^{\text{st}}) = 0.5(m(\tilde{1}^{\text{st}}) + m(\tilde{1}^{\text{st}}))$	1405.5086
	GGM (wino NLSP) weak prod.	1 $e, \mu + \gamma$	-	Yes	20.3	\tilde{W} 115-370 GeV	$c\tau < 1$ mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	\tilde{W} 500 GeV	$c\tau < 1$ mm	1507.05493
	Long-lived particles	Direct \tilde{t}_1, \tilde{t}_1 prod., long-lived \tilde{t}_1	Disapp. trk	1 jet	Yes	20.3	\tilde{t}_1 270 GeV	$m(\tilde{t}_1) = m(\tilde{1}^{\text{st}}) = 160$ MeV, $\tau(\tilde{t}_1) = 0.2$ ns
Direct \tilde{t}_1, \tilde{t}_1 prod., long-lived \tilde{t}_1		dE/dx trk	-	Yes	18.4	\tilde{t}_1 495 GeV	$m(\tilde{t}_1) = m(\tilde{1}^{\text{st}}) = 160$ MeV, $\tau(\tilde{t}_1) < 15$ ns	1506.05332
Stable, stopped \tilde{g} R-hadron		0	1-5 jets	Yes	27.9	\tilde{g} 850 GeV	$m(\tilde{g}) = 100$ GeV, $10 \mu\text{s} < c\tau(\tilde{g}) < 1000$ s	1310.6584
Stable \tilde{g} R-hadron		trk	-	-	3.2	\tilde{g} 1.58 TeV	-	1606.05129
Metastable \tilde{g} R-hadron		dE/dx trk	-	-	3.2	\tilde{g} 1.67 TeV	$m(\tilde{g}) = 100$ GeV, $\tau > 10$ ns	1604.04520
GMSB, stable $\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 + \nu(\tilde{\nu}) + \nu(\tilde{\nu})$		1-2 μ	-	-	19.1	\tilde{t}_1 537 GeV	$10 < \text{damp} < 50$	1411.6795
GMSB, $\tilde{t}_1 \rightarrow \gamma\tilde{G}$, long-lived \tilde{t}_1		2 γ	-	Yes	20.3	\tilde{t}_1 440 GeV	$1 < c\tau(\tilde{t}_1) < 3$ ns, SPS8 model	1409.5542
$\tilde{g}, \tilde{t}_1 \rightarrow \nu\tilde{q}/\nu\tilde{q}^*$		displ. $e\ell/\mu\tau/\mu\mu$	-	-	20.3	\tilde{t}_1 1.0 TeV	$7 < c\tau(\tilde{t}_1) < 740$ mm, $m(\tilde{g}) = 1.3$ TeV	1504.05162
GGM $\tilde{g}, \tilde{t}_1 \rightarrow Z\tilde{G}$		displ. vtx + jets	-	-	20.3	\tilde{t}_1 1.0 TeV	$6 < c\tau(\tilde{t}_1) < 480$ mm, $m(\tilde{g}) = 1.1$ TeV	1504.05162
RPV		LFV $g\tilde{g} \rightarrow \nu + X, \tilde{\nu} \rightarrow e\mu/\tau/\mu\tau$	$e\mu, \tau\tau, \mu\tau$	-	-	3.2	\tilde{g} 1.9 TeV	$\lambda_{121} = 0.11, \lambda_{131} = 0.07$
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g}, \tilde{t} 1.45 TeV	$m(\tilde{g}) = m(\tilde{t})$, $c\tau_{\tilde{g}, \tilde{t}} < 1$ mm	1404.2500
	$\tilde{t}_1, \tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{b}^*, \tilde{t}_1 \rightarrow \nu\tilde{q}, \nu\tilde{q}^*$	4 e, μ	-	Yes	13.3	\tilde{t}_1 1.14 TeV	$m(\tilde{t}_1) > 400$ GeV, $\lambda_{123} \neq 0$ ($k = 1, 2$)	ATLAS-CONF-2016-075
	$\tilde{t}_1, \tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{b}^*, \tilde{t}_1 \rightarrow \nu\tilde{q}, \nu\tilde{q}^*$	3 $e, \mu + \tau$	-	Yes	20.3	\tilde{t}_1 450 GeV	$m(\tilde{t}_1) = 0.2 \times m(\tilde{1}^{\text{st}})$, $\lambda_{123} \neq 0$	1405.5086
	$\tilde{g}, \tilde{g} \rightarrow \nu\tilde{q}$	0	4-5 large- R jets	-	14.8	\tilde{g} 1.08 TeV	$\text{BR}(\tilde{g} \rightarrow \nu\tilde{q}) = \text{BR}(\tilde{g} \rightarrow \nu\tilde{q}^*) = 0\%$	ATLAS-CONF-2016-057
	$\tilde{g}, \tilde{g} \rightarrow \nu\tilde{q}, \tilde{t}_1 \rightarrow \nu\tilde{q}$	0	4-5 large- R jets	-	14.8	\tilde{g} 1.55 TeV	$m(\tilde{t}_1) = 400$ GeV	ATLAS-CONF-2016-057
	$\tilde{g}, \tilde{g} \rightarrow \nu\tilde{q}, \tilde{t}_1 \rightarrow \nu\tilde{q}$	2 e, μ (SS)	0-3 b	Yes	13.2	\tilde{g} 1.3 TeV	$m(\tilde{t}_1) < 750$ GeV	ATLAS-CONF-2016-037
Other	$\tilde{t}_1, \tilde{t}_1 \rightarrow h\tilde{t}$	0	2 jets + 2 b	-	15.4	\tilde{t}_1 410 GeV	$\text{BR}(\tilde{t}_1 \rightarrow h\tilde{t}) > 20\%$	ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1, \tilde{t}_1 \rightarrow h\tilde{t}$	2 e, μ	2 b	-	20.3	\tilde{t}_1 0.4-1.0 TeV	-	ATLAS-CONF-2015-015
	Scalar charm, $\tilde{c} \rightarrow c\tilde{c}^*$	0	2 c	Yes	20.3	\tilde{c} 510 GeV	$m(\tilde{c}) < 200$ GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown.

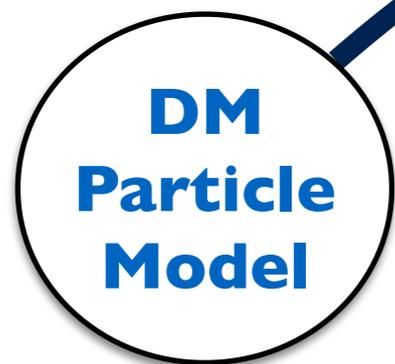
10⁻¹ 1 Mass scale [TeV]

LHC timeline

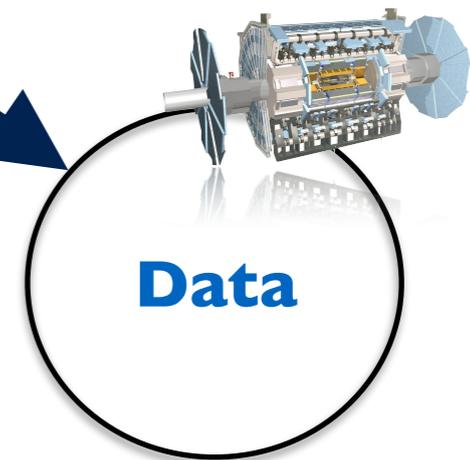


- We have just started exploring physics at the TeV scale with the LHC
- Current searches based only on $\sim 1\%$ of the final integrated luminosity
- Too early to despair!

Statistical inference at the LHC: predicting LHC phenomenology



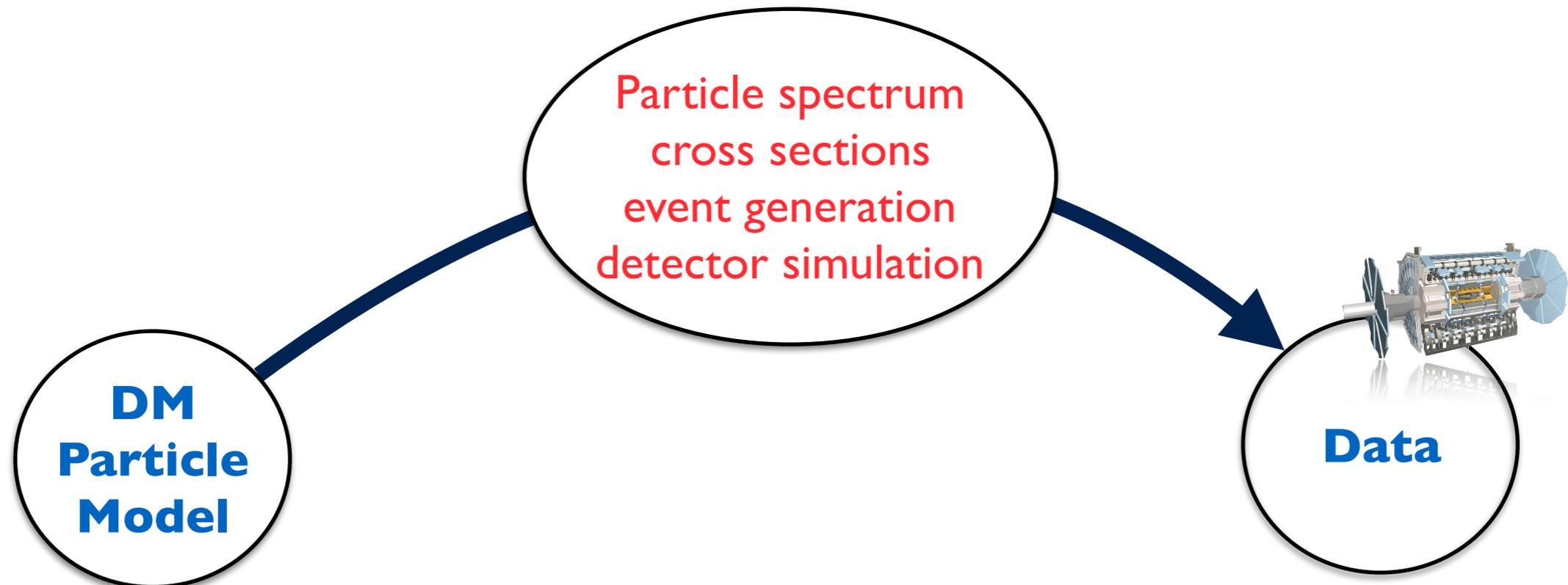
Parameters of the Lagrangian



LHC observables: e.g. n. of events in pre-defined signal regions

Given a particle theory model we know how to make predictions

Statistical inference at the LHC: predicting LHC phenomenology

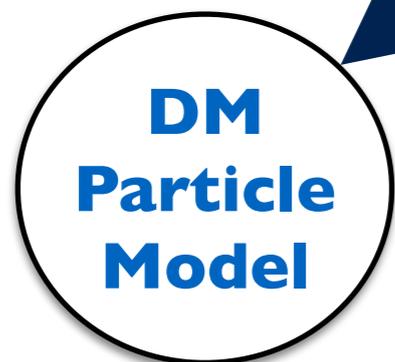


Parameters of the Lagrangian

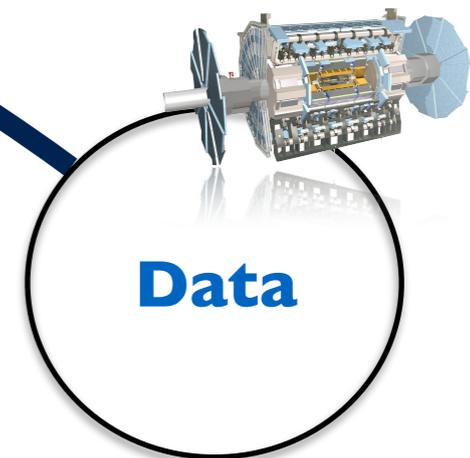
LHC observables: e.g. n. of events in pre-defined signal regions

Given a particle theory model we know how to make predictions

Statistical inference at the LHC: inverse problem - from data to DM



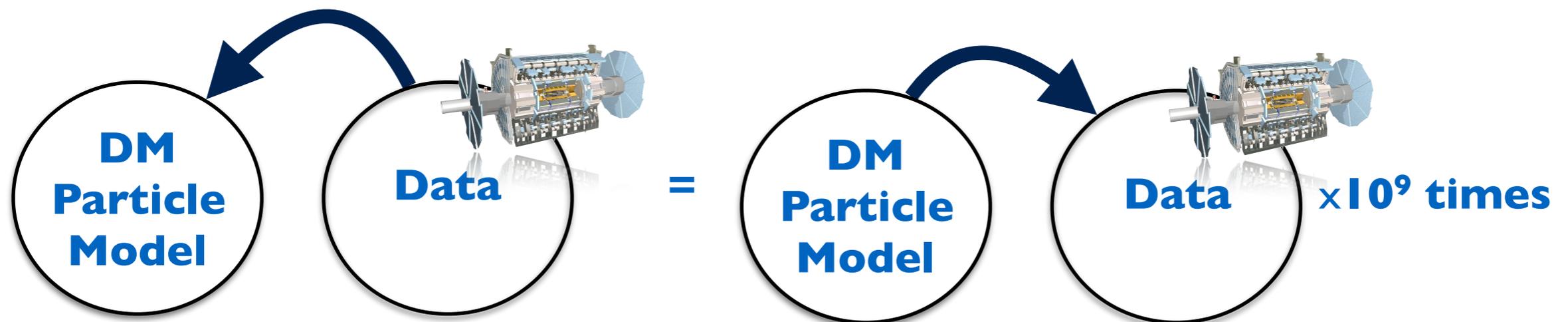
Parameters of the Lagrangian



LHC observables: e.g. n. of events in pre-defined signal regions

In order to identify the regions of the parameter space compatible with data, we need to ‘walk’ in the parameter space, estimate the predicted signal, and compare (via a likelihood) with data.

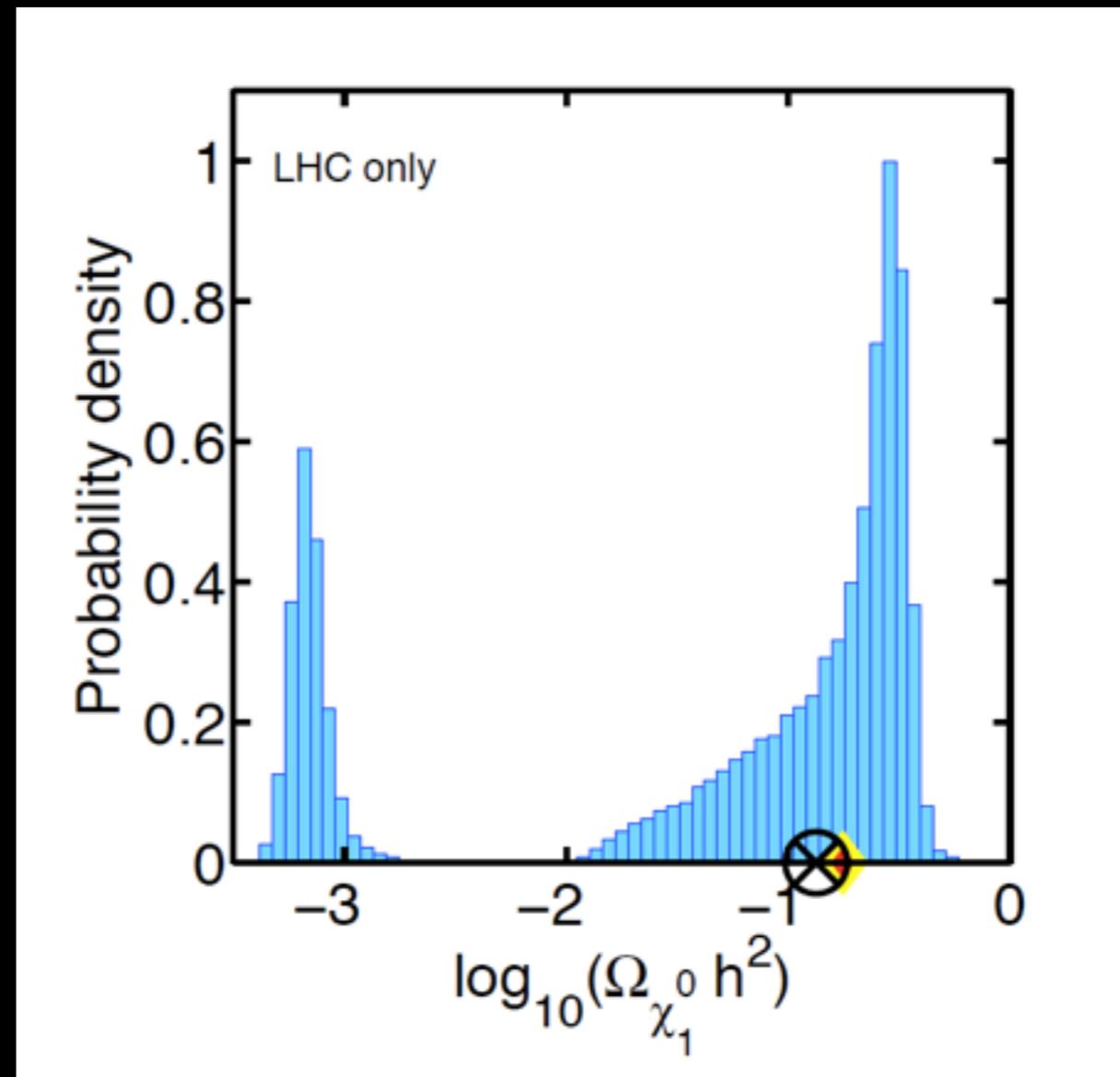
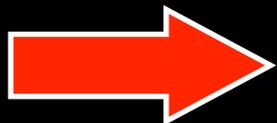
Statistical inference at the LHC: inverse problem - from data to DM



Grid scans of the parameter space are painfully inefficient. Even 'smart' likelihood-driven bayesian scans require enormous resources e.g. for 19-d SUSY models need $\sim 10^9$ likelihood evaluations -> centuries of CPU time

Example of Inverse DM problem at LHC

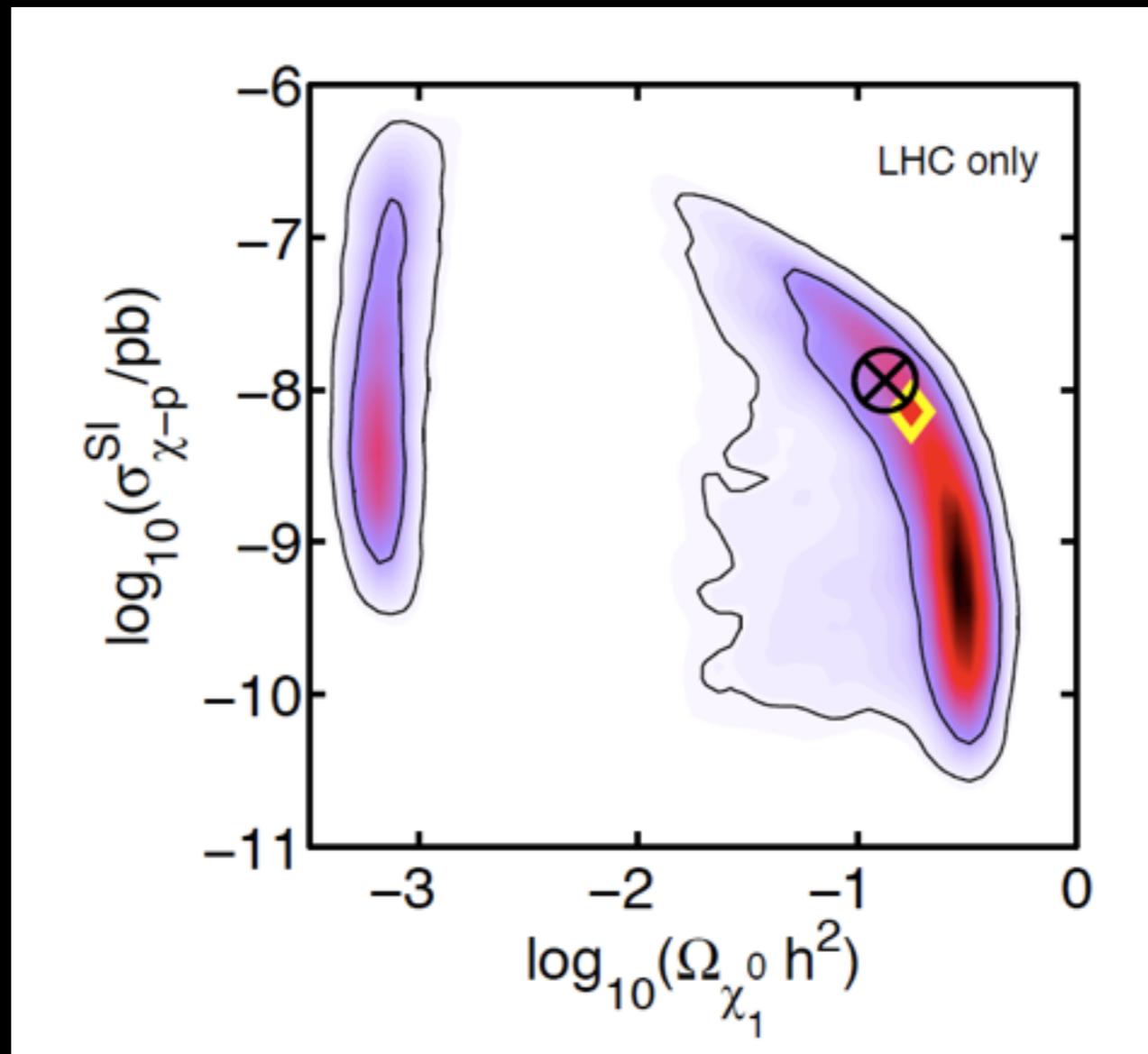
what we can realistically achieve
(example in the stau coannihilation region, 24 parms MSSM)



GB, CERDENO, FORNESA, RUIZ DE AUSTRI & TROTTA, 2010

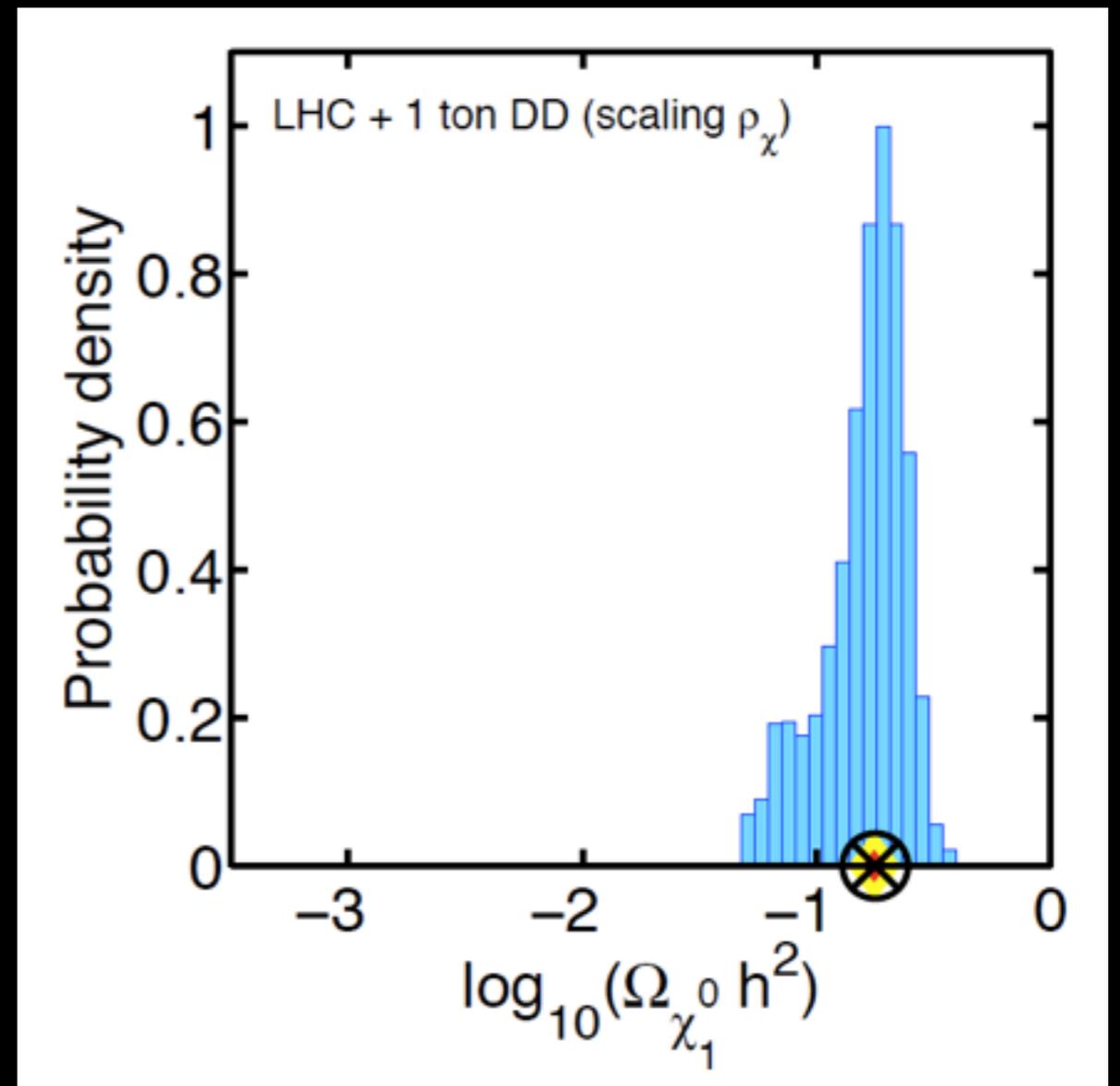
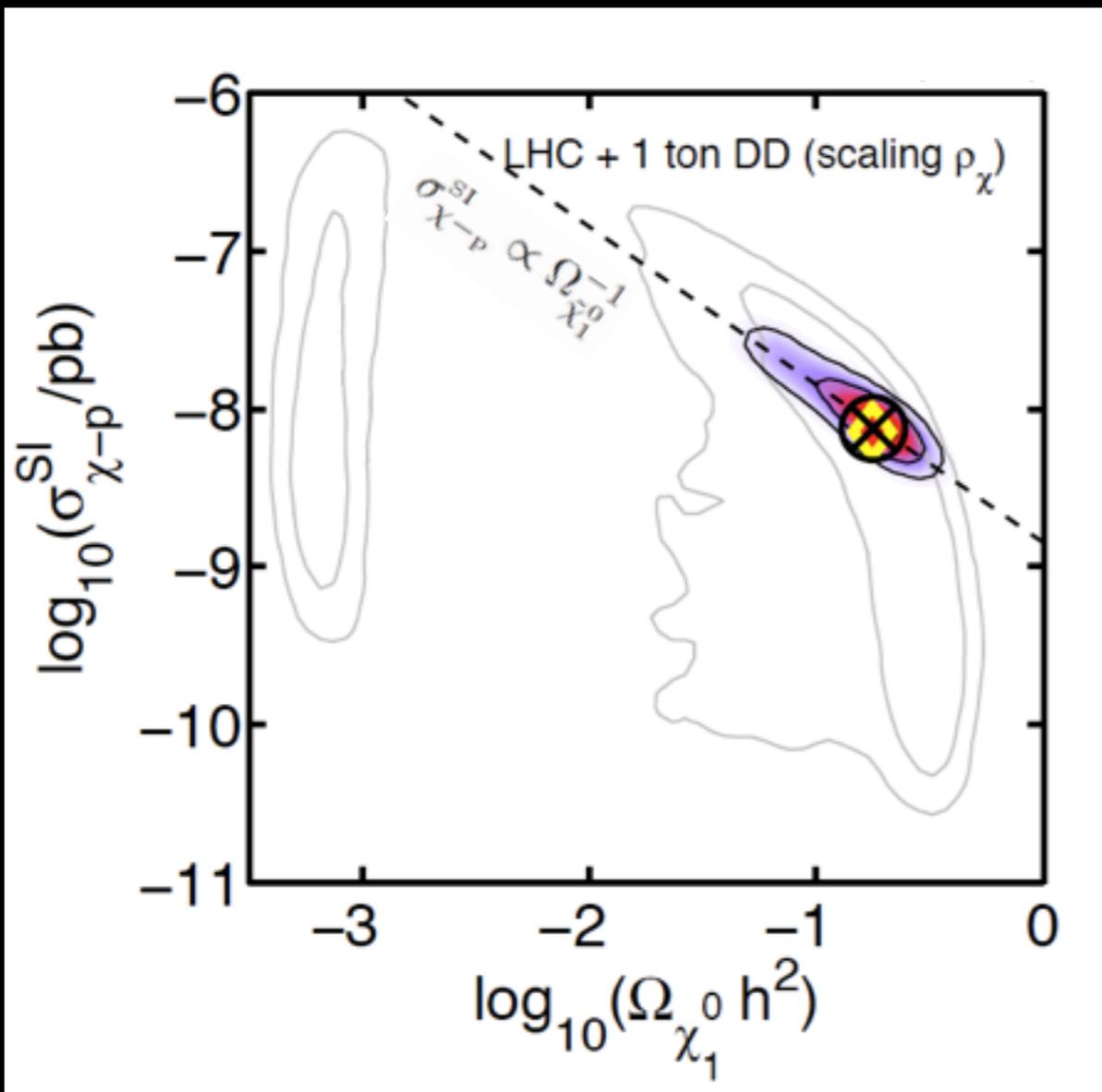
Example of Inverse problem at LHC

what we can realistically achieve
(example in the stau coannihilation region, 24 parms MSSM)



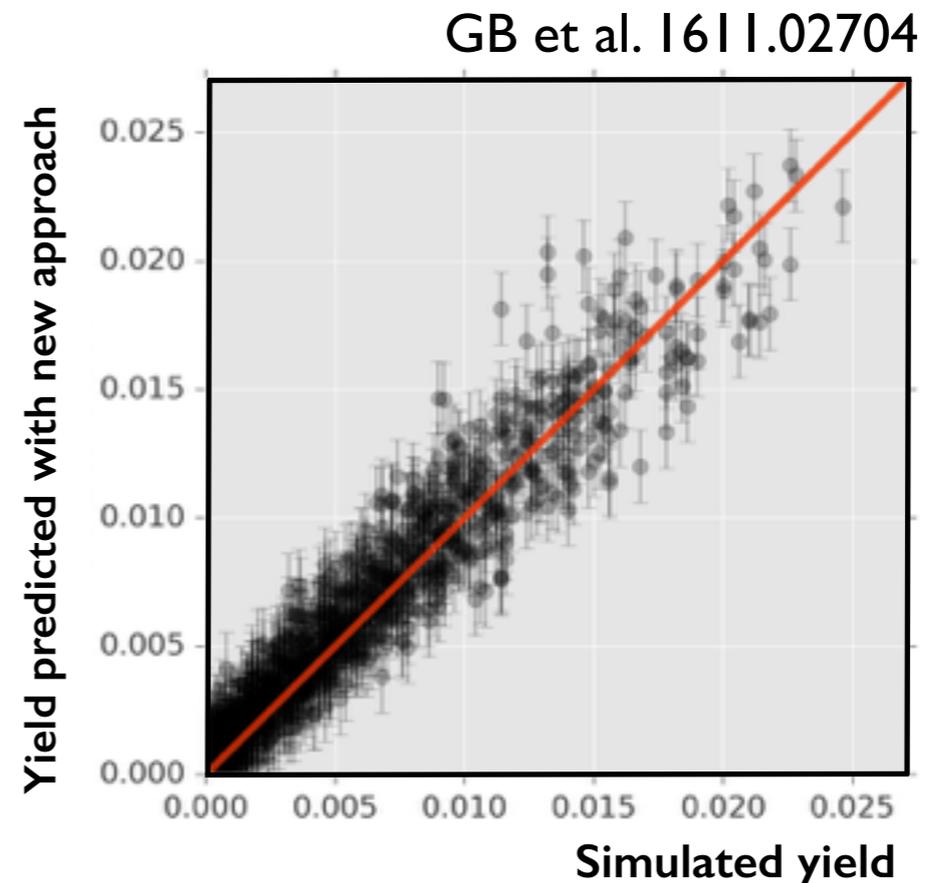
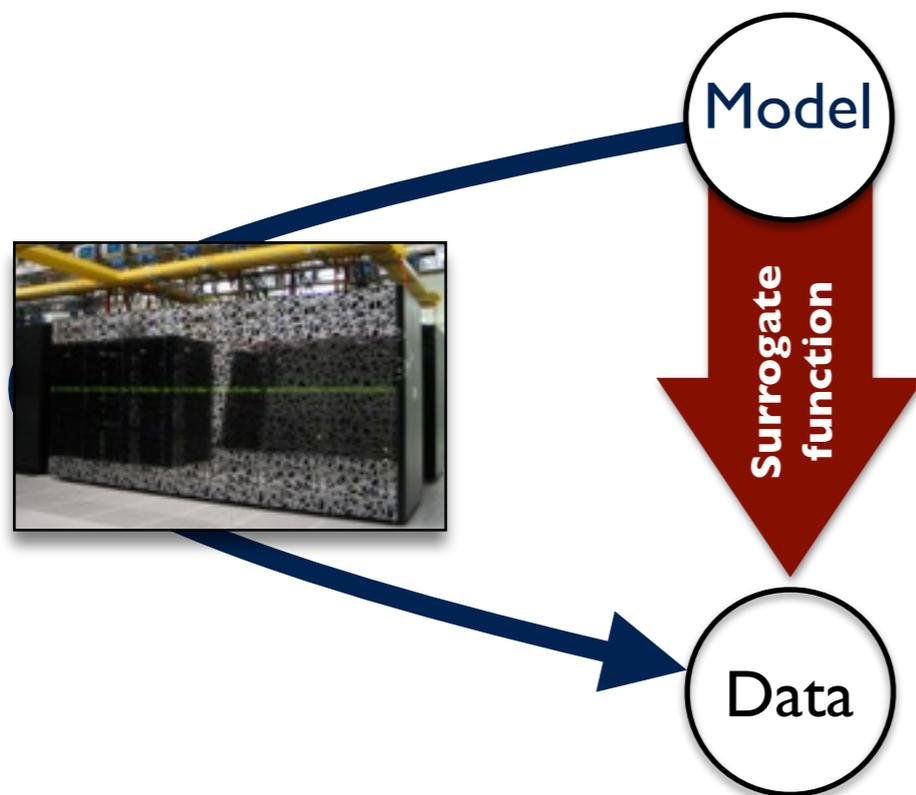
GB, CERDENO, FORNESA, RUIZ DE AUSTRI & TROTTA, 2010

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.

Speeding up statistical inference with machine learning tools (with IFIC member R. Ruiz de Austri)



The exploration of the parameter spaces of full theoretical models is very expensive. New machine learning methods (*distributed gaussian processes, deep neural networks*) bring the computation time from \sim CPU centuries to \sim CPU weeks! Can be run by a PhD student in 1 day on a desktop computer!

Conclusions

- Extraordinarily rich theoretical and experimental programme to identify DM. Many interesting ideas: tens of dark matter candidates, each with its own predictions.
- *No guaranteed discovery.* The field is completely open, only data can tell us what is the way forward. Fortunately many new experiments running or planned - we will get answers soon!
- This approach is pushing the frontiers of astrophysics, particle physics & cosmology
- Important to think strategically about *identifying* DM - not “just” discovering DM candidates - in order to check for possible ‘multi-component’ scenarios, and to allow precision tests of cosmology