

Matière Noire et Particules

Gianfranco Bertone
GRAPPA Institute, U. of Amsterdam

Seminaire @ Collège de France 4/2/2015

GRAPPA x
x
x



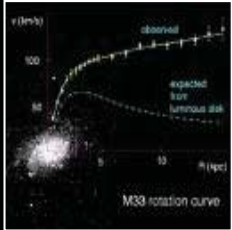
GRavitation AstroParticle Physics Amsterdam



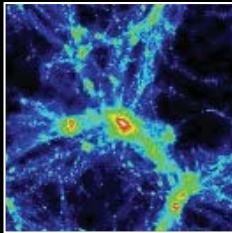
Preuves de l'existence de la MN

Plusieurs observations indépendantes à des échelles de longueur différentes

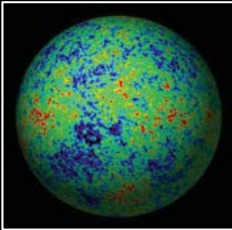
COSMOLOGICAL OBSERVATIONS



• COURBES DE ROTATION



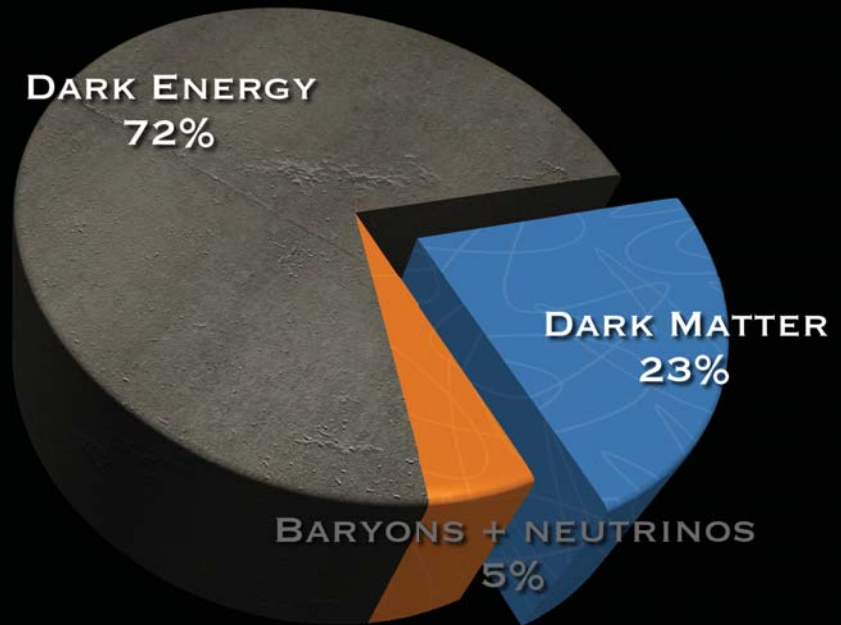
• AMAS DE GALAXIES



• FOND DIFFUS COSMOLOGIQUE



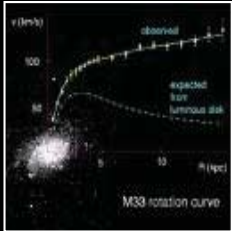
• SUPERNOVAE DE TYPE IA



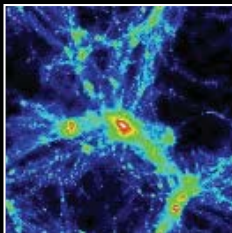
Preuves de l'existence de la MN

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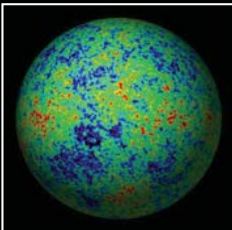
COSMOLOGICAL OBSERVATIONS



• COURBES DE ROTATION



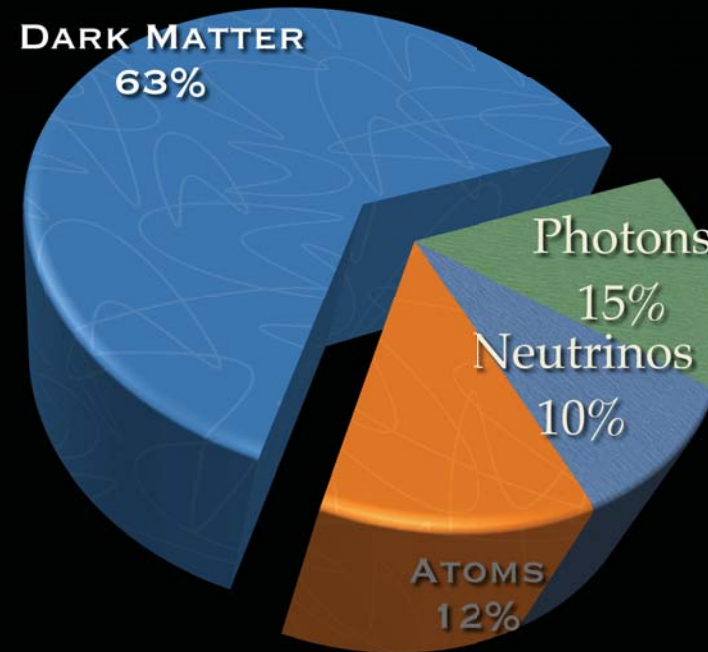
• AMAS DE GALAXIES



• FOND DIFFUS COSMOLOGIQUE



• SUPERNOVAE DE TYPE IA

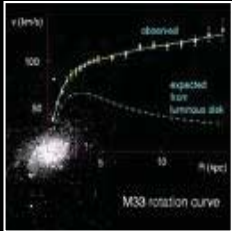


A $z=1100$, $t \sim 380'000$ ans, c.à.d. quand les grandes structures de l'univers ont commencé à se former.

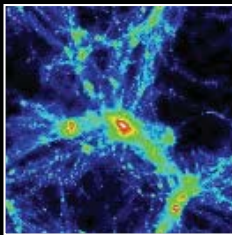
Preuves de l'existence de la MN

Plusieurs observations indépendantes à des échelles de longueur différentes

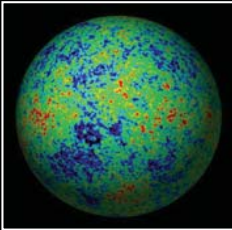
COSMOLOGICAL OBSERVATIONS



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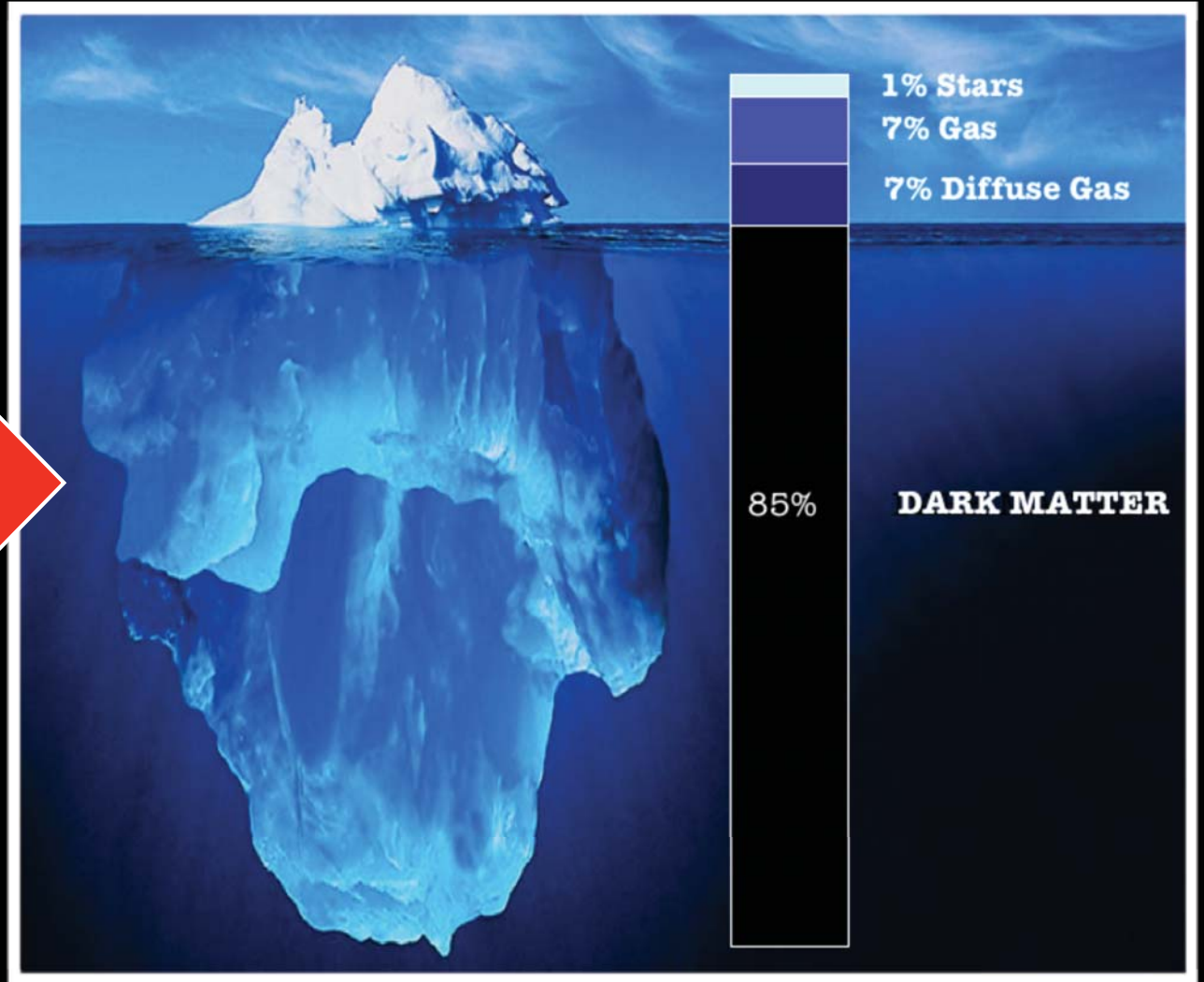
• AMAS DE GALAXIES



• FOND DIFFUS COSMOLOGIQUE



• SUPERNOVAE DE TYPE IA



Brève histoire d'une découverte

1. La matière noire existe

*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. La matière noire est partout

*[Finzi 1959!], Ostriker, Peebles, Yahil 1974, Einasto et
al. 1974, Faber & Gallagher 1979*



3. La matière noire est différente de la matière ordinaire

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>

Location: Amsterdam
Conference Venue: Tuschinski theater
Social Event: Scheepvaart Museum

June 23-28, 2014
Amsterdam, NL

Confirmed Speakers

<ul style="list-style-type: none"> David Hogg (University of Michigan) John Kollmeier (University of Michigan) Michael Kuhlen (University of Michigan) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan) 	<ul style="list-style-type: none"> David Hogg (University of Michigan) John Kollmeier (University of Michigan) Michael Kuhlen (University of Michigan) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan) 	<ul style="list-style-type: none"> David Hogg (University of Michigan) John Kollmeier (University of Michigan) Michael Kuhlen (University of Michigan) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan) 	<ul style="list-style-type: none"> David Hogg (University of Michigan) John Kollmeier (University of Michigan) Michael Kuhlen (University of Michigan) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan)
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Local Organizing Committee

<ul style="list-style-type: none"> Jeroen van Dongen (UvA) Dan Hooper (UvA) Michael Stenhouse (UvA) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan) 	<ul style="list-style-type: none"> Jeroen van Dongen (UvA) Dan Hooper (UvA) Michael Stenhouse (UvA) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan) David Spergel (Princeton University) Michael Turner (University of Michigan) Simon White (University of Michigan) Jim Peebles (University of Michigan) Bernard Sadoulet (University of Michigan) Joe Silk (University of Michigan) Gianfranco Bertone (University of Michigan) Albert Bosma (University of Michigan) Michael Stenhouse (University of Michigan)
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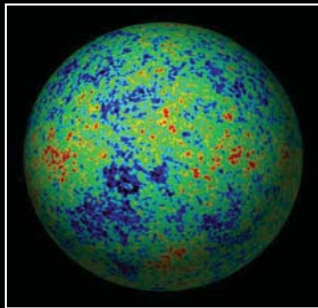


Videos of all lectures on YouTube

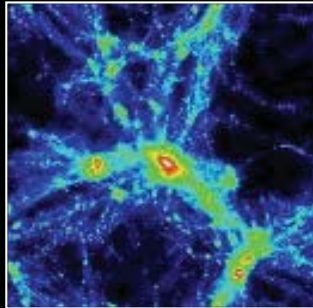
Qu'est ce qu'on sait?

Les 10 contraintes les plus importantes sur la nature de la particule de matière noire

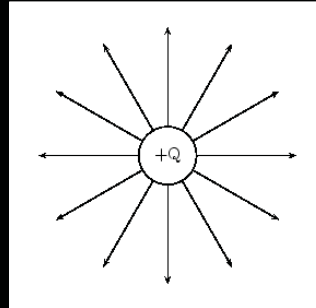
1) Ωh^2 OK?



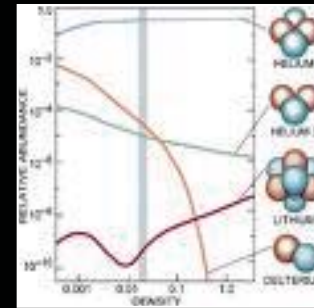
2) Is it cold?



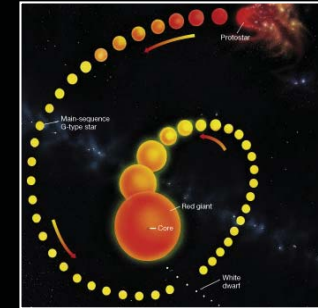
3) Is it neutral?



4) Is BBN ok?



5) Stars OK?

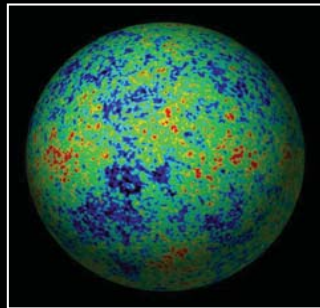


TAOSO, GB & MASIERO 2007

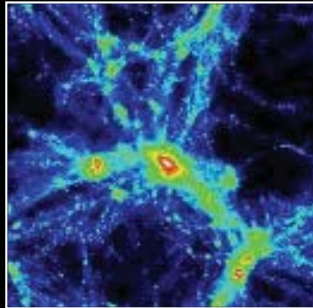
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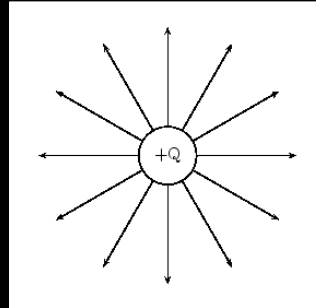
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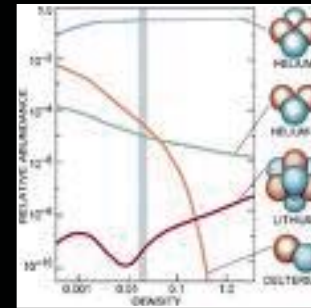
2) Is it cold?



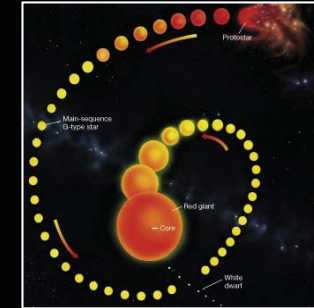
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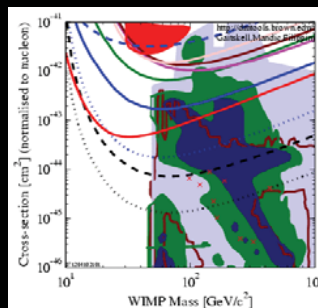
5) Stars OK?



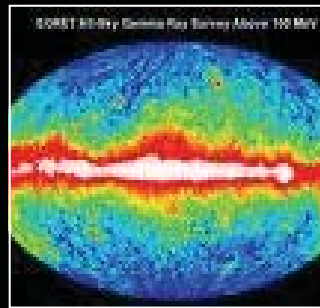
6) Collisionless?



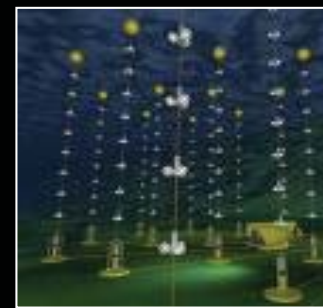
7) Couplings OK?



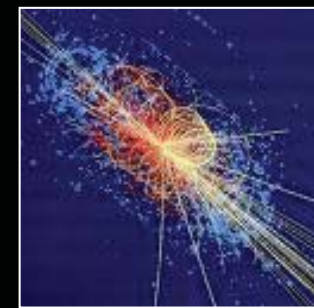
8) γ -rays OK?



9) Astro bounds?



10) Can probe it?



TAOSO, GB & MASIERO 2007

Avons-nous (enfin) détecté la matière noire?

Dec 19, 2009

the **guardian**


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News > Science > Astronomy

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

the **guardian** TheObserver

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News > Science > ... on science

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

the **guardian**

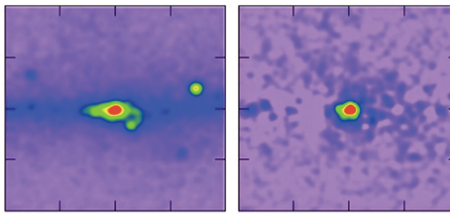
News | Sport | Comment | Culture | Business | Money | Life & style

News > Science > Space

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

the **guardian**

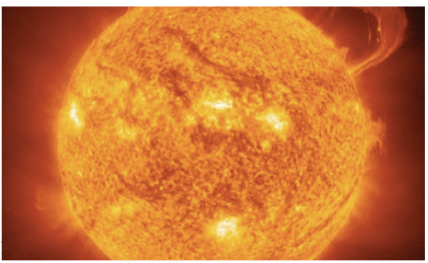
News | Sport | Comment | Culture | Business | Money | Life & style

News > Science > Particle physics

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
Follow @iansample Follow @guardian
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: Aiomy

XMM data
 μeV axion

Les Candidats

WIMPs

(particules massives interagissant faiblement)

CANDIDATS 'NATURELS'

prédits par des théories proposées pour expliquer des problèmes fondamentaux du modèle standard

- p.e. *neutralino* en Supersymétrie, photon KK en UED, etc.

CANDIDATES AD-HOC

Proposés pour expliquer la MN

- MN 'minimale'

Autres

✦ AXIONS

✦ NEUTRINOS STERILES

✦ SUPERWIMPS

✦ WIMPLESS

- Etc. (Axino, Q-balls.....)

Les Candidats

WIMPs

(particules massives interagissant faiblement)

CANDIDATS 'NATURELS'

prédits par des théories proposées pour expliquer des problèmes fondamentaux du modèle standard

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✦ AXIONS

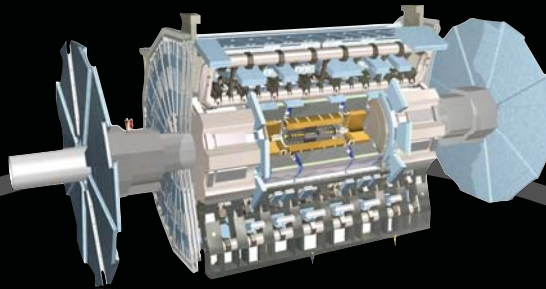
✦ NEUTRINOS STERILES

✦ SUPERWIMPS

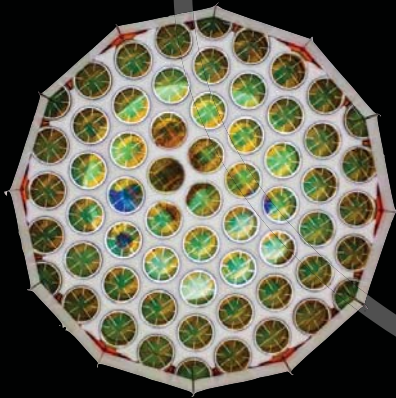
✦ WIMPLESS

- Etc. (Axino, Q-balls....)

À la recherche de la Matière Noire



Accélérateurs



Détection Directe



Détection Indirecte

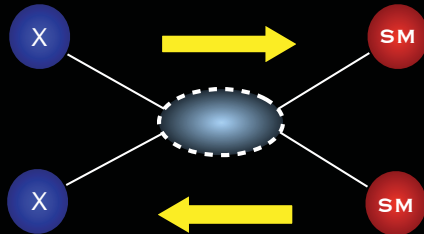
Détection Indirecte

POURQUOI ON PARLE D' "ANNIHILATION"?

X = MATIÈRE NOIRE

SM = PARTICULES DU MODÈLE STANDARD

UNIVERS PRIMORDIALE



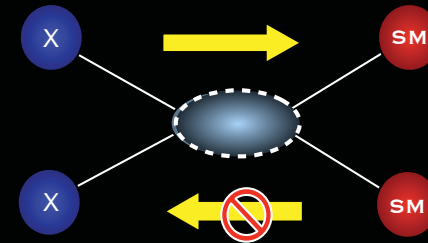
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle [n_\chi^2 - (n_\chi^{eq})^2]$$

DENSITÉ RELIQUE

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

Des sections efficaces à l'échelle électrofaible produisent la quantité observée de matière noire

AUJOURD'HUI



$$\frac{dn_\chi}{dt} = -(\sigma v)_0 n_\chi^2$$

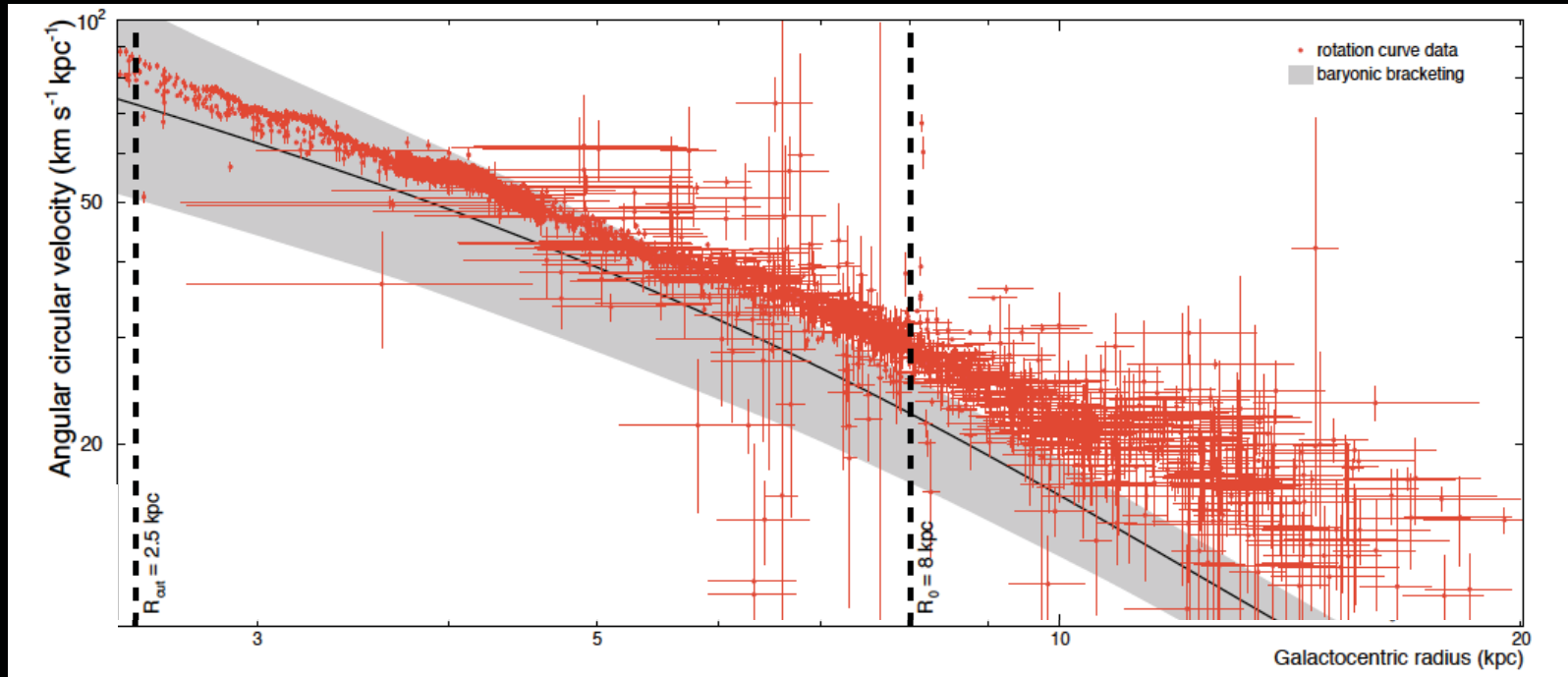
ANNIHILATION FLUX

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

Melange de quantités astrophysiques et de physique de particules - domaine des Astroparticules!

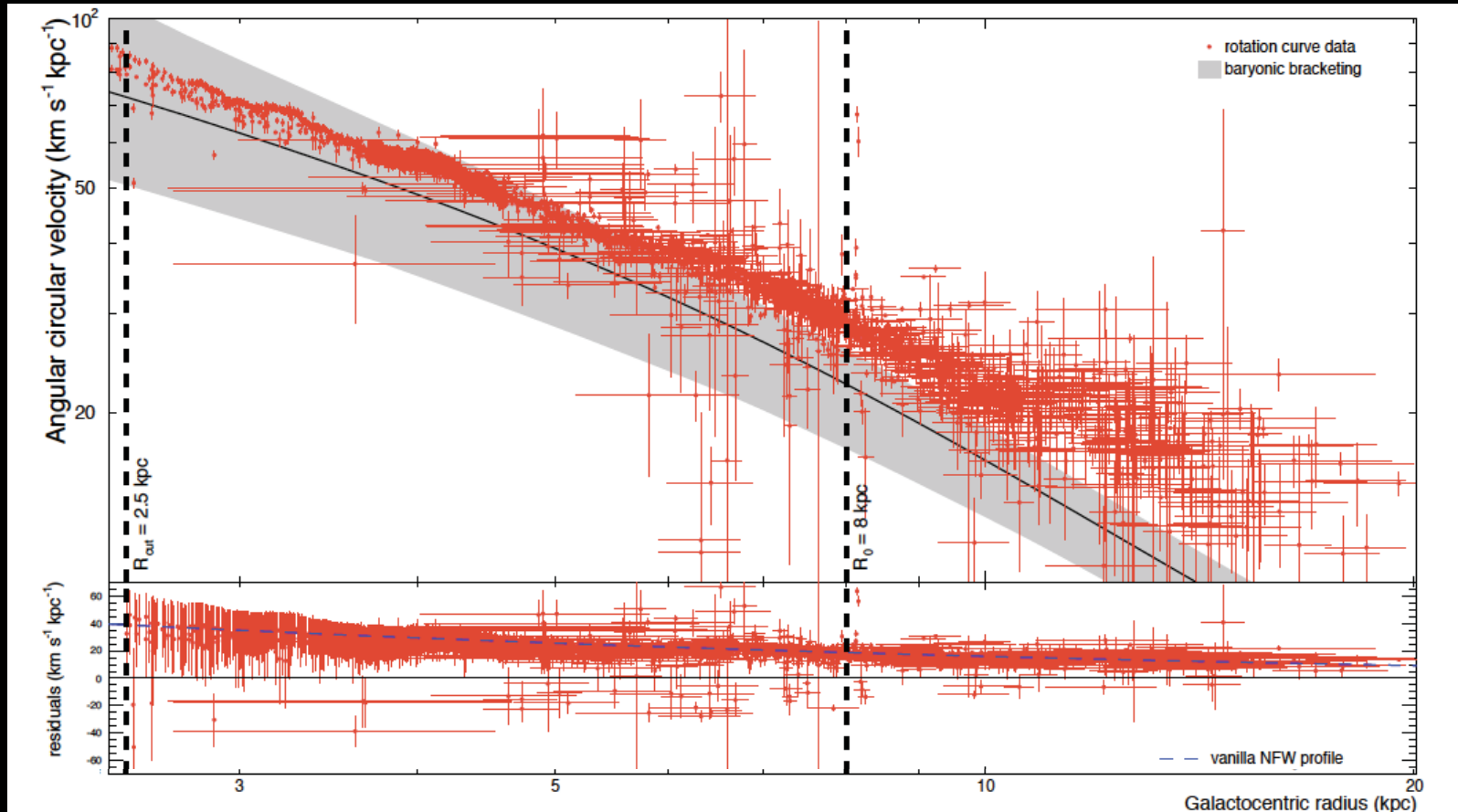
Simulation de la formation des Galaxies

Courbe de rotation de la Voie Lactée



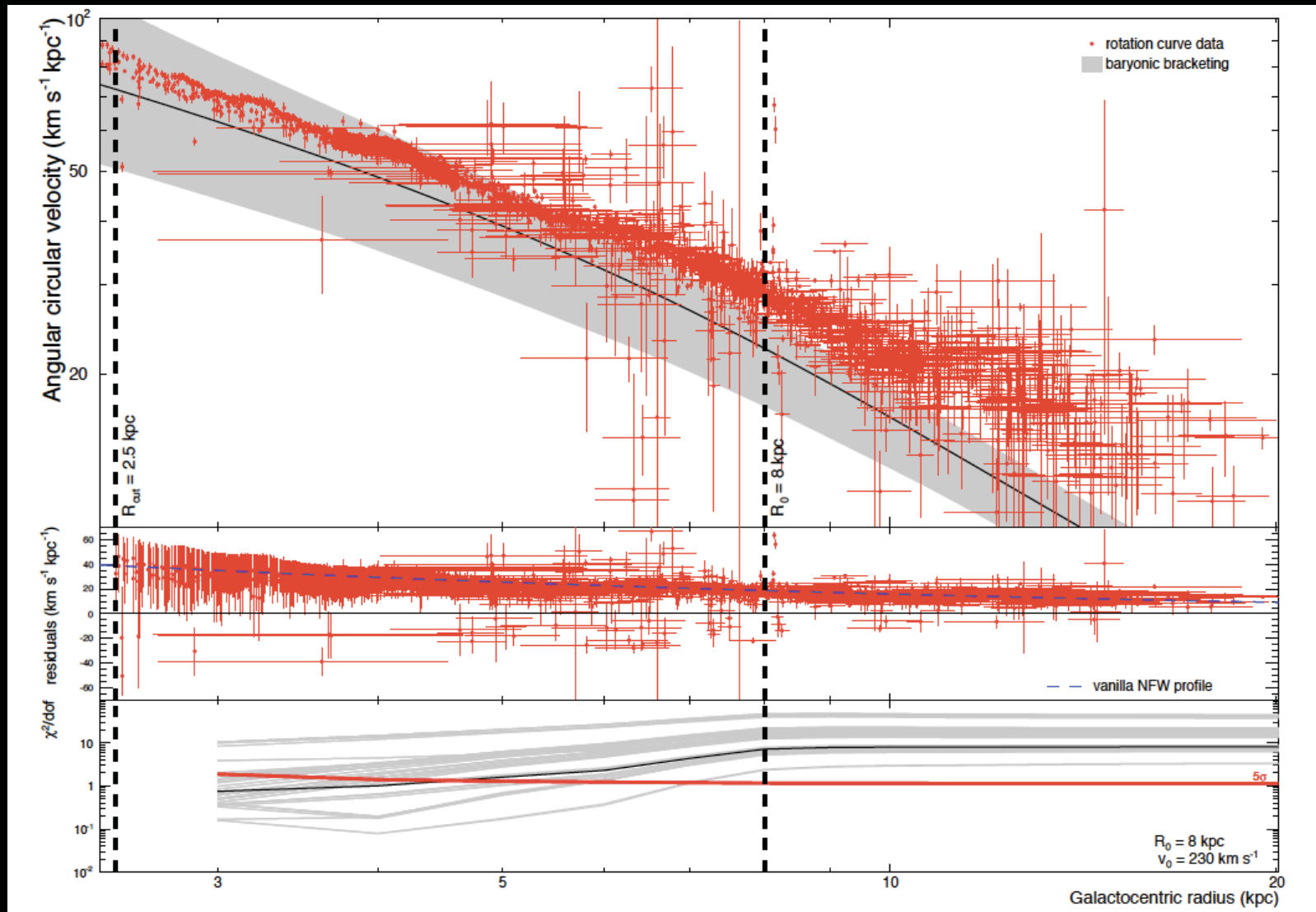
locco, Pato, GB, arXiv:1502.xxxx

Courbe de rotation de la Voie Lactée



locco, Pato, GB, arXiv:1502.xxxx

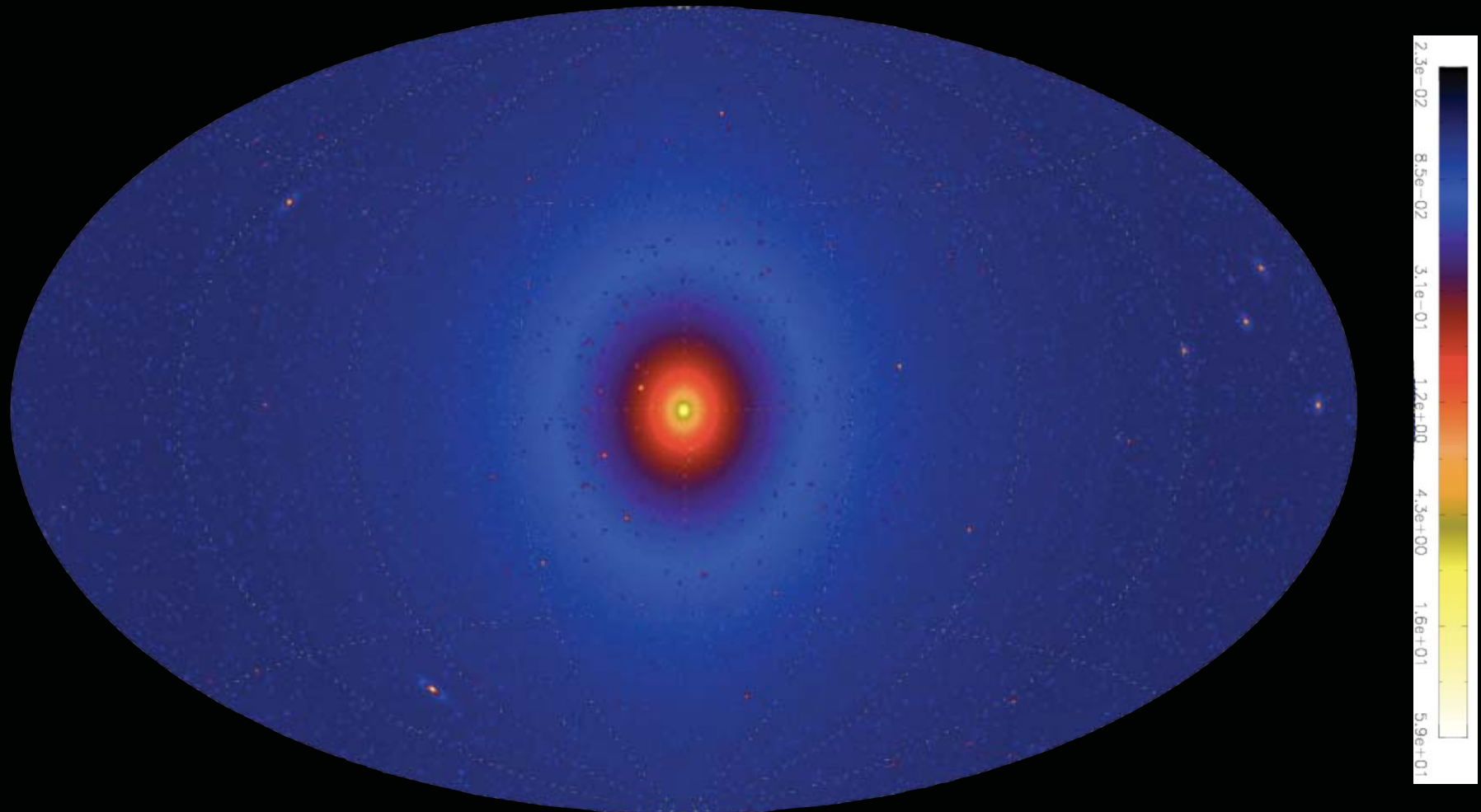
Courbe de rotation de la Voie Lactée



locco, Pato, GB, arXiv:1502.xxxx

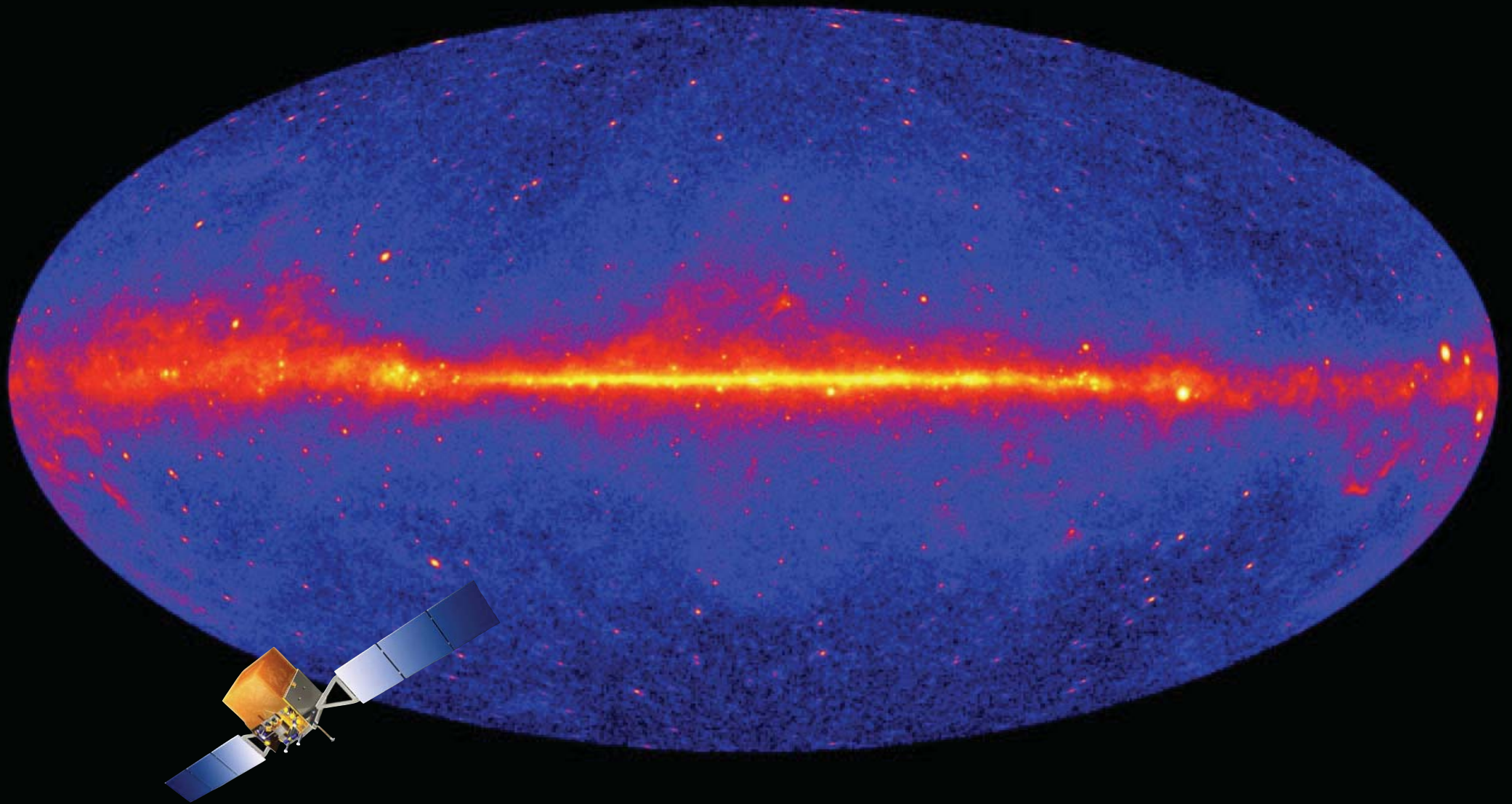
Flux d'annihilation prédit

PIERI, GB, BRANCHINI 2009



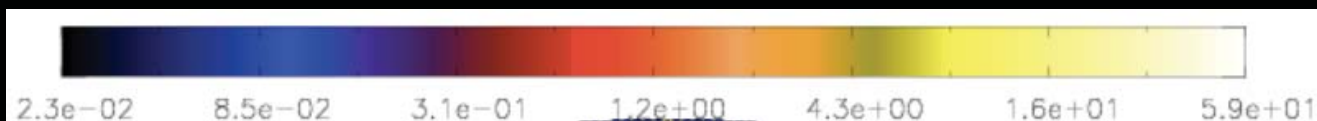
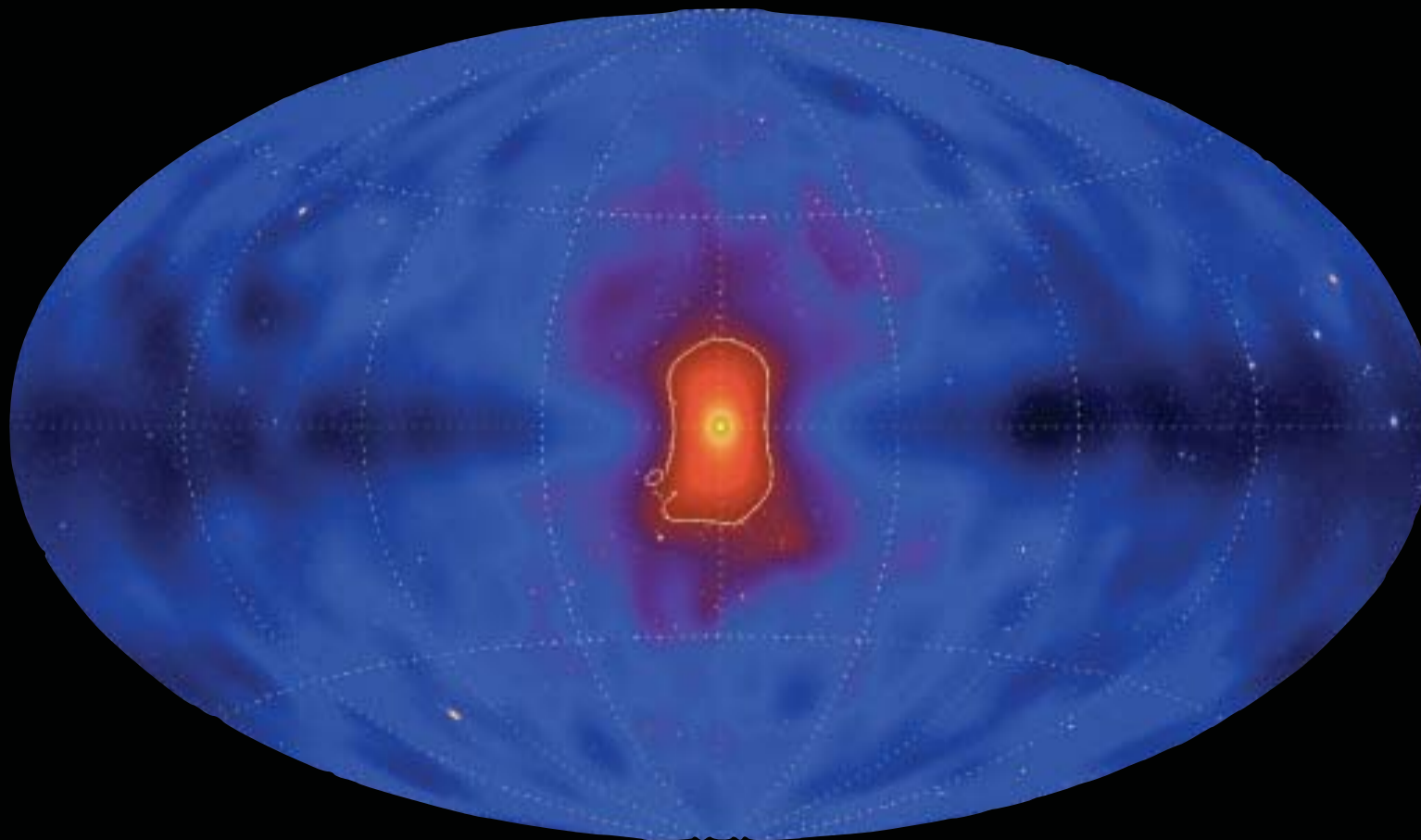
FULL SKY MAP OF NUMBER OF PHOTONS ABOVE 3 GEV

Les données de FERMI



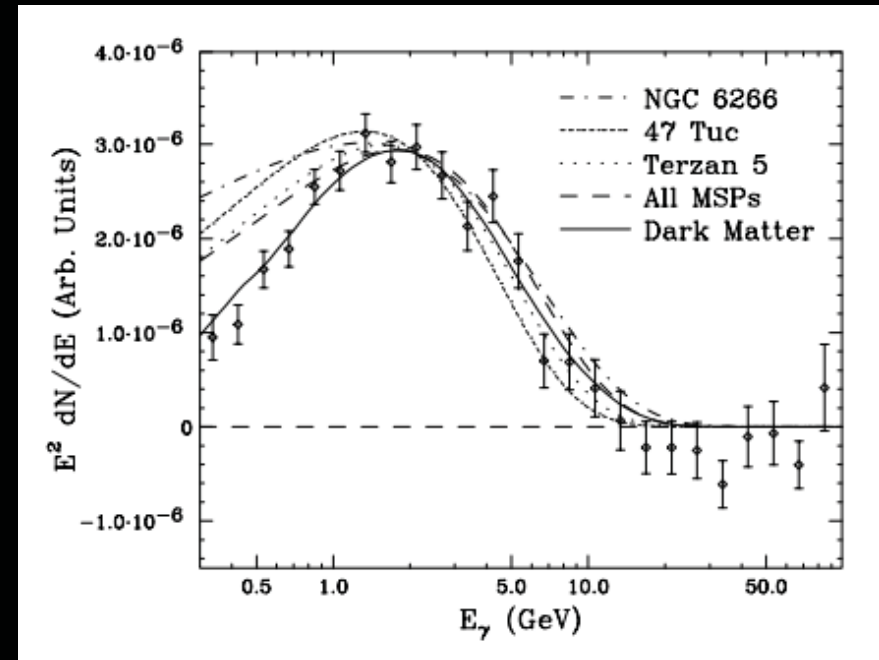
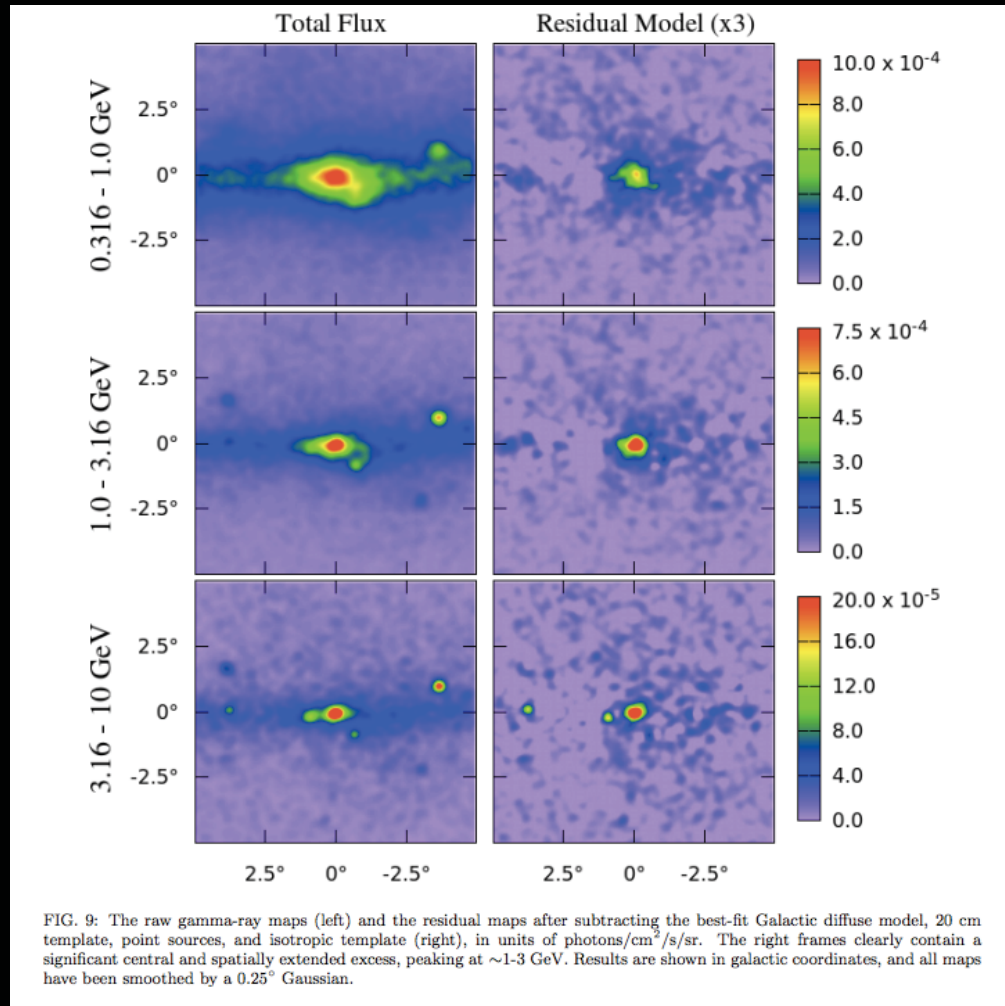
Carte de "Sensibilit e"

PIERI, GB, BRANCHINI 2009



Détection Indirecte

RÉSULTAT RÉCENT : DAYLAN ET AL. ARXIV:1402.6703

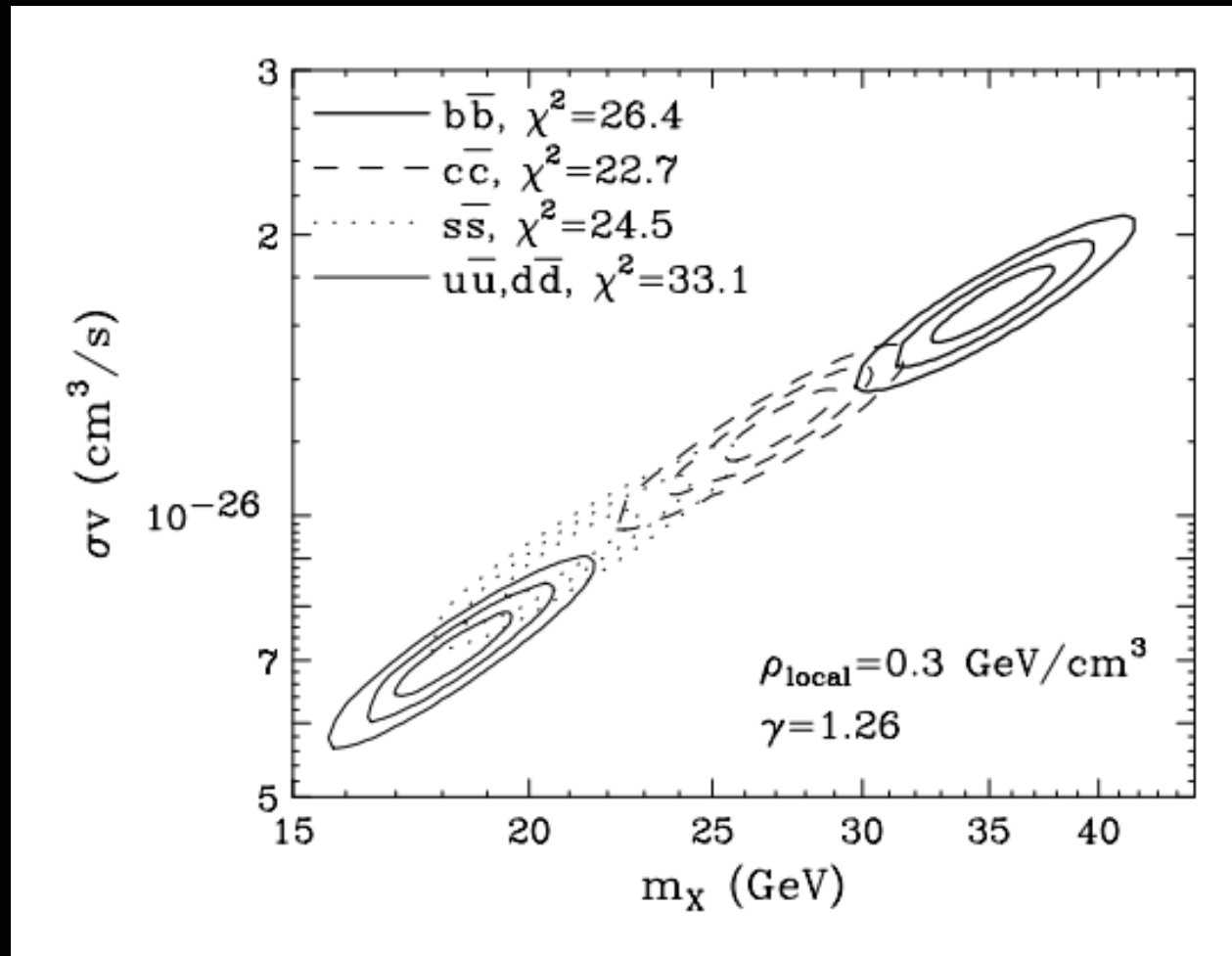


Un excès de rayons gamma du Centre Galactique, avec un spectre, distribution angulaire, et normalisation globale en accord avec ceux préditx par les modèles de matière noire les plus simples.

See also thorough analysis in Calore et al. arXiv:1409.0042

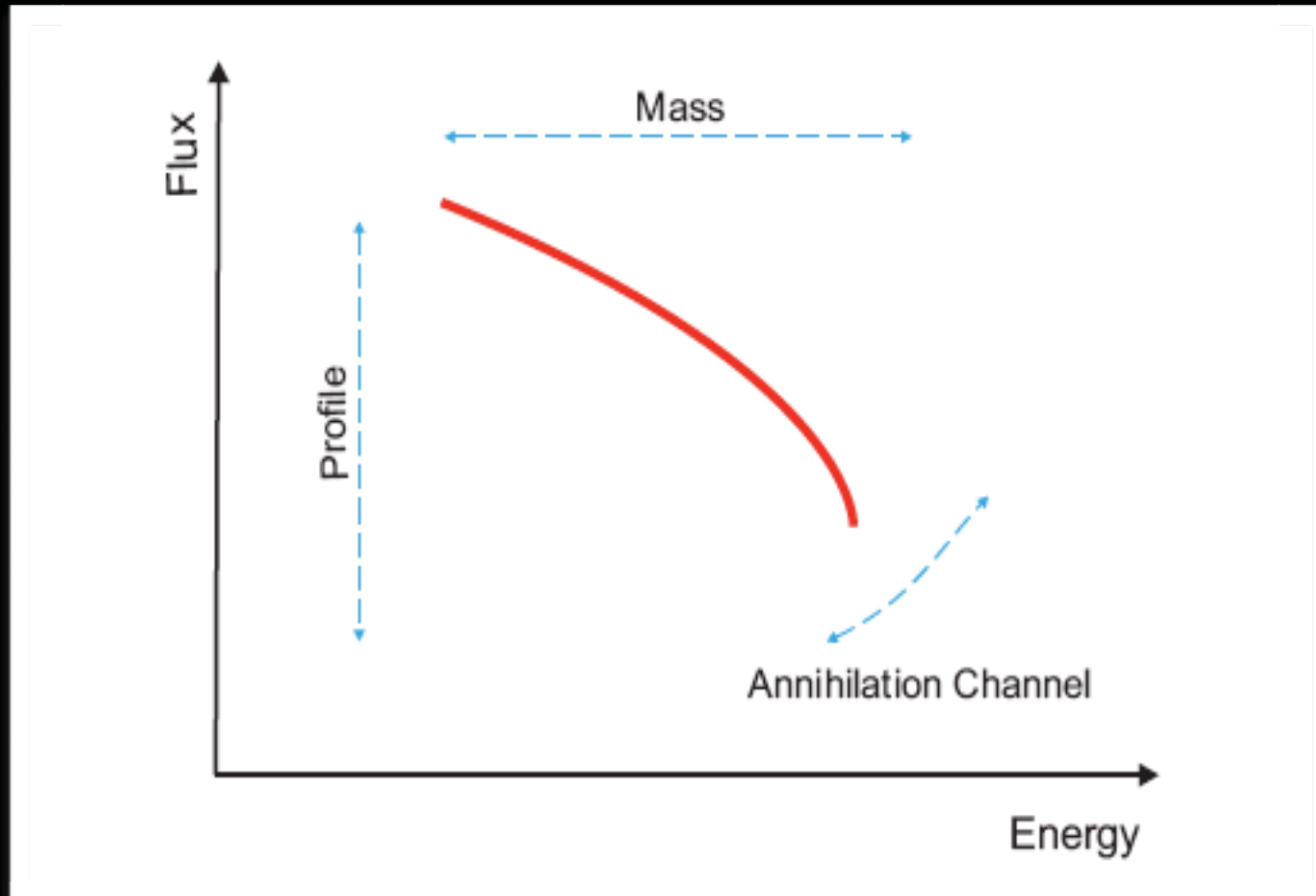
The GeV excess

<http://arxiv.org/abs/1402.6703>



...so what?!

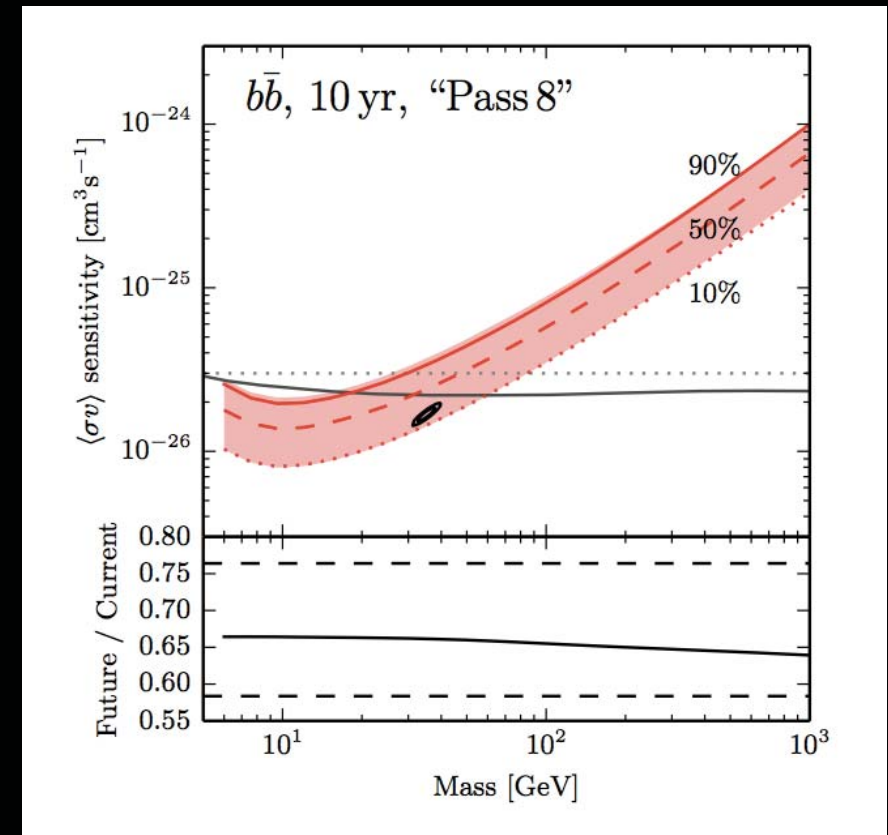
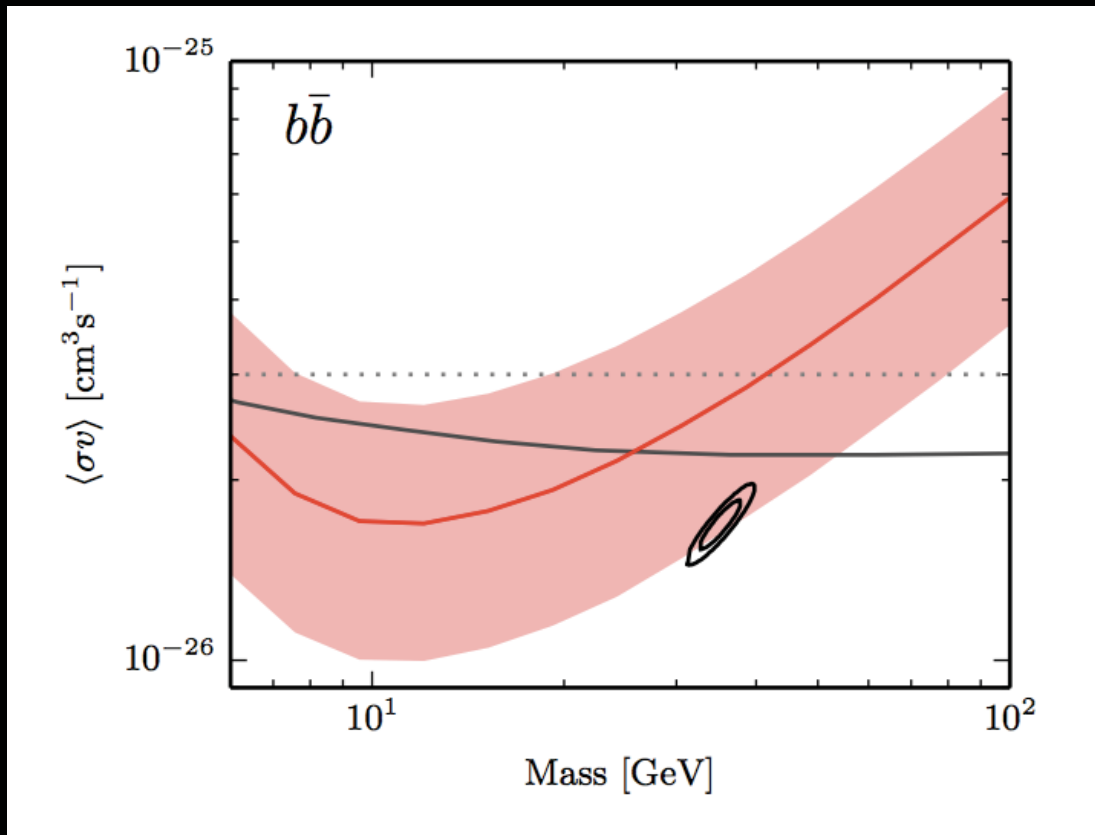
Le problème des recherches indirectes



on trouve toujours une solution au 'problème inverse',
meme quand les signal n'a rien a voir avec la MN!

Comment prouver l'interprétation MN de l'excès au CG?

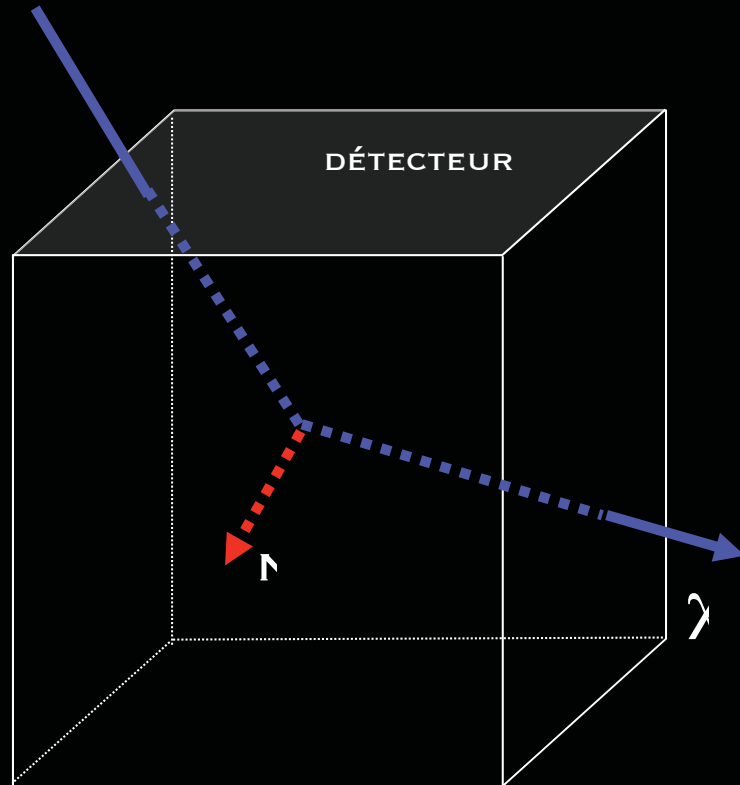
AVEC LES GALAXIES NAINES?



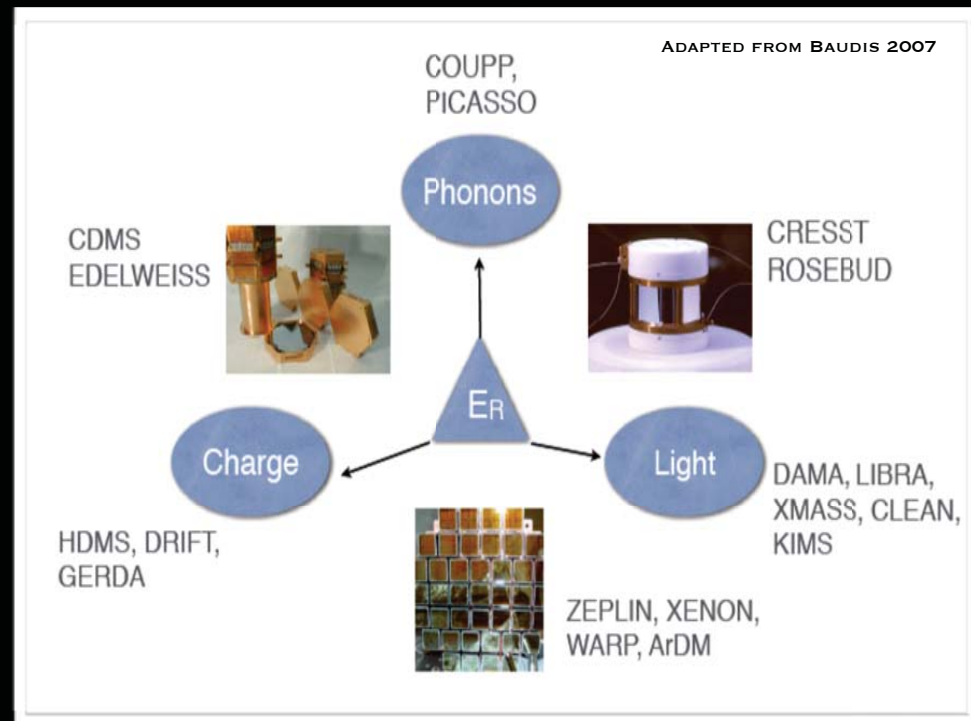
Geringer-Sameth et al., arXiv:1410.2242

Détection Directe

PRINCIPE AND TECHNIQUE DE DÉTECTION



LA MN INTERAGIT AVEC UN NOYAU DU DÉTECTEUR



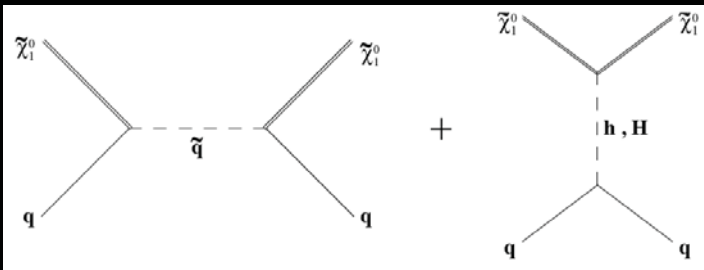
DÉTECTION DE L'ÉNERGIE DE RECOL VIA IONISATION (CHARGE), SCINTILLATION (LUMIÈRE) AND CHALEUR (PHONONS)

Détection Directe

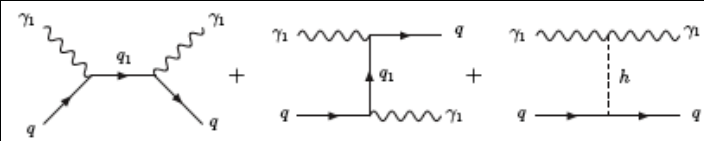
TAUX D'ÉVÉNEMENTS

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

SUSY: SQUARKS AND HIGGS EXCHANGE



UED: 1ST LEVEL QUARKS AND HIGGS EXCHANGE



INCERTITUDES THÉORIQUES

ELLIS, OLIVE & SAVAGE 2008; BOTTINO ET AL. 2000; ETC.

INCERTITUDE SUR LA F(V)

LING ET AL. 2009; WIDROW ET AL. 2000; HELMI ET AL 2002

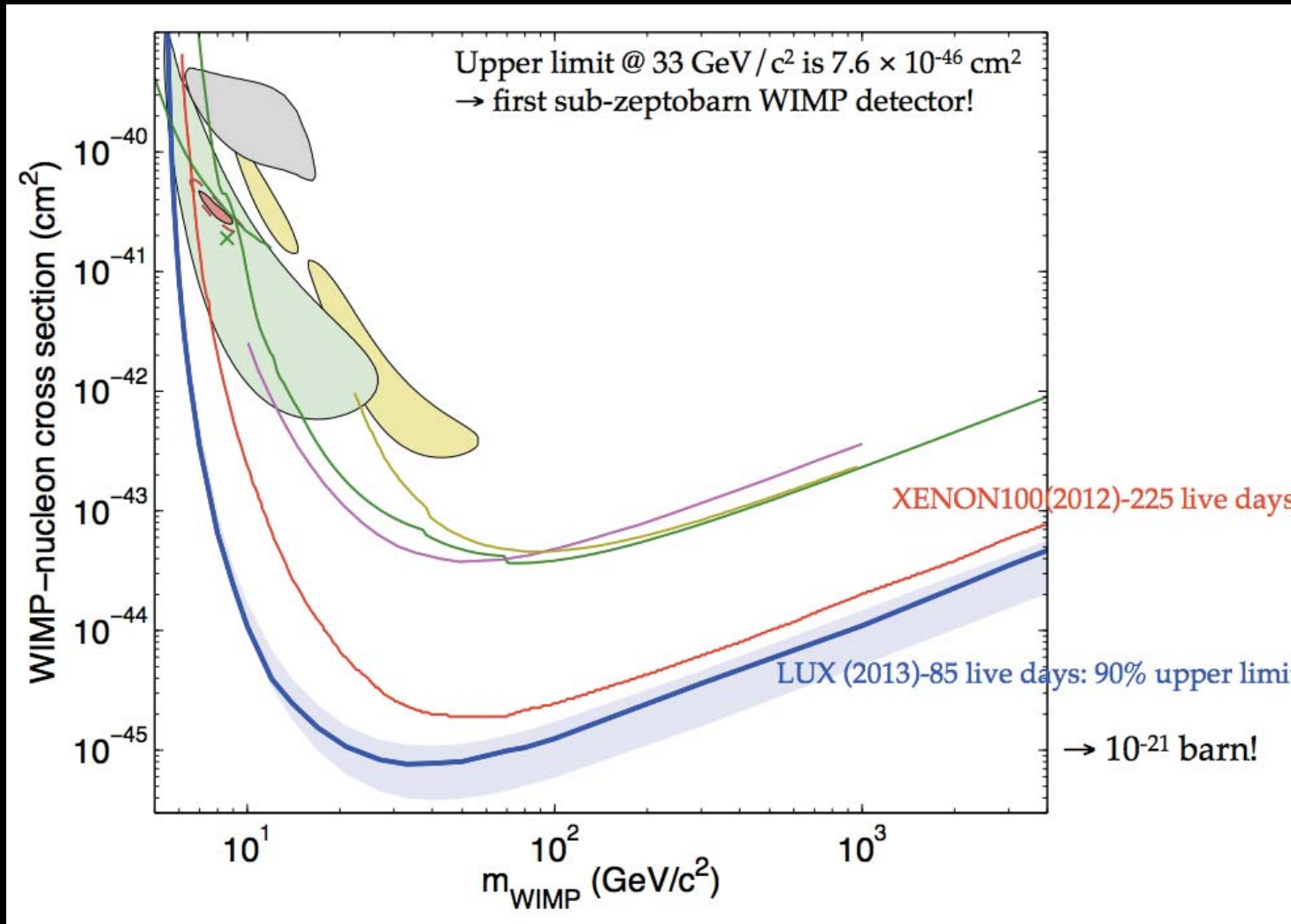
Comment on détecter 'directement' la MN? (e.g. LUX and Xenon1ton)



Derniers résultats

LUX experiment, arXiv:1310.8214

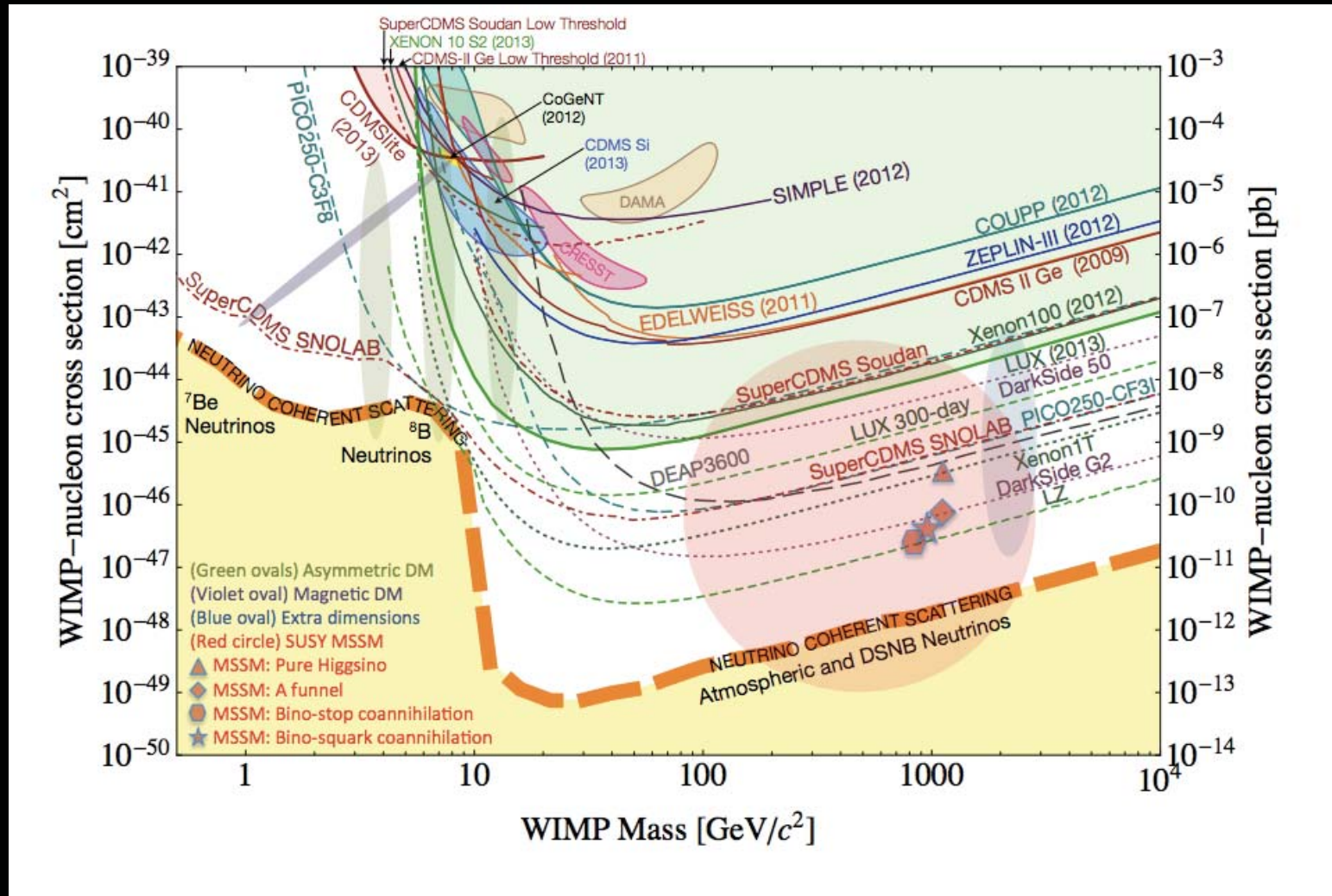
(Sanford Underground Research Facility - SURF)



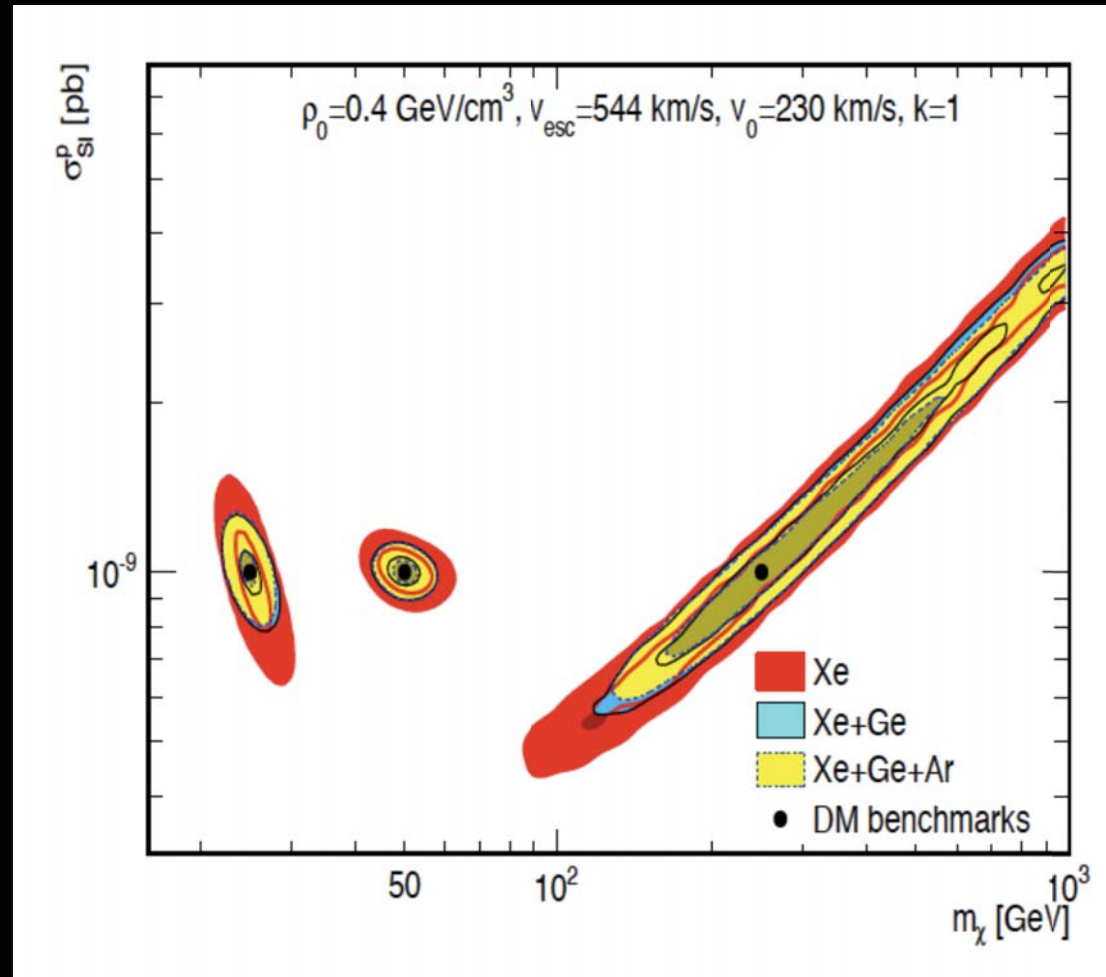
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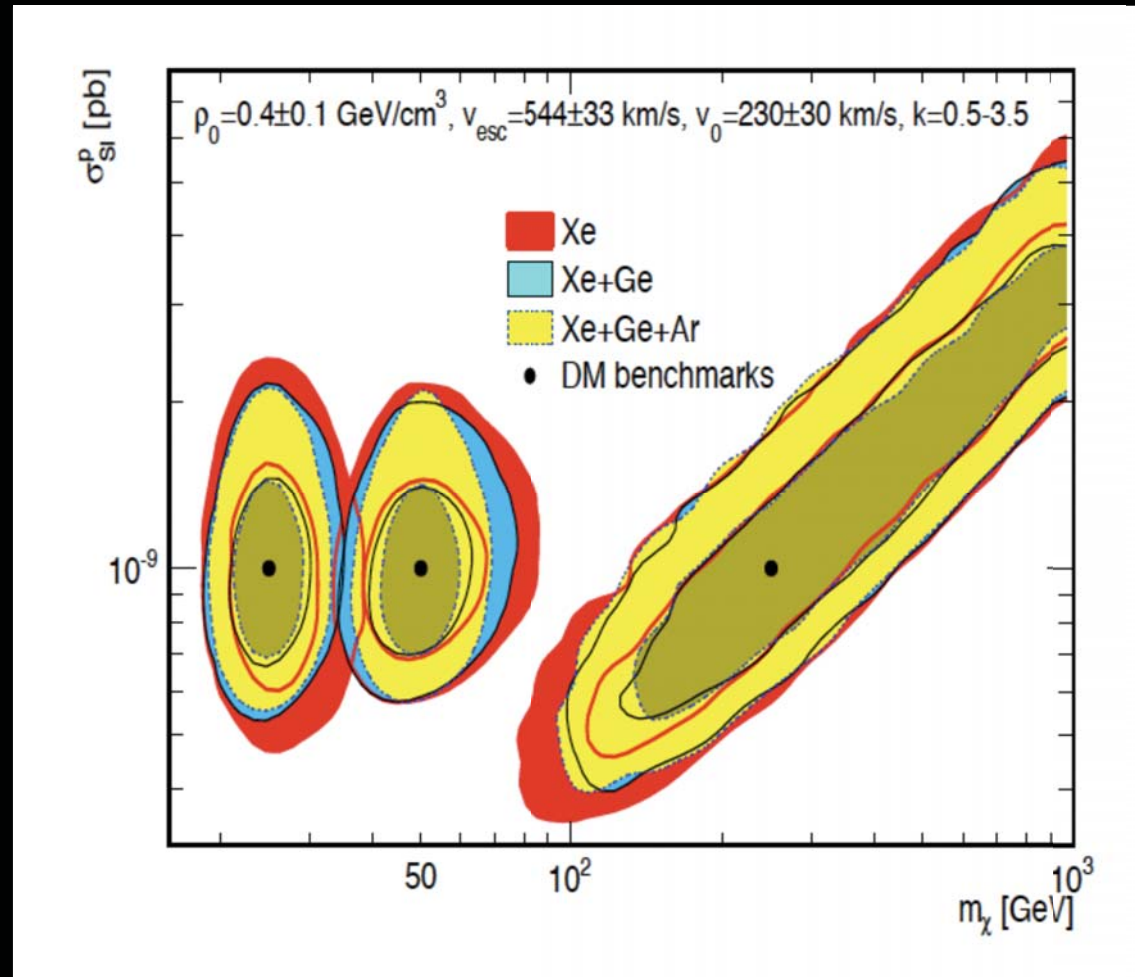


Complémentarité des expériences



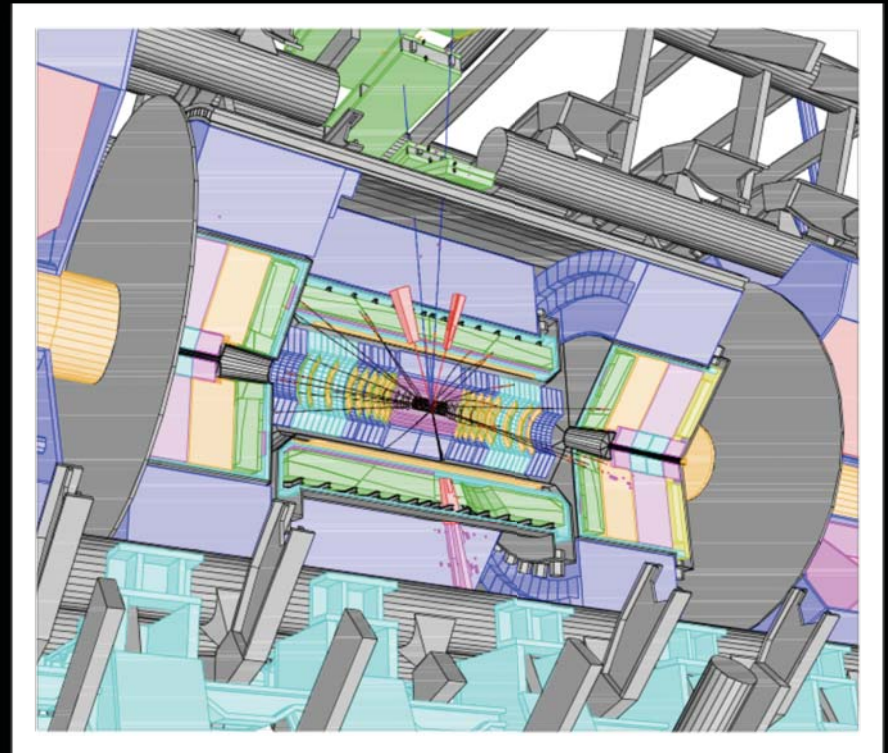
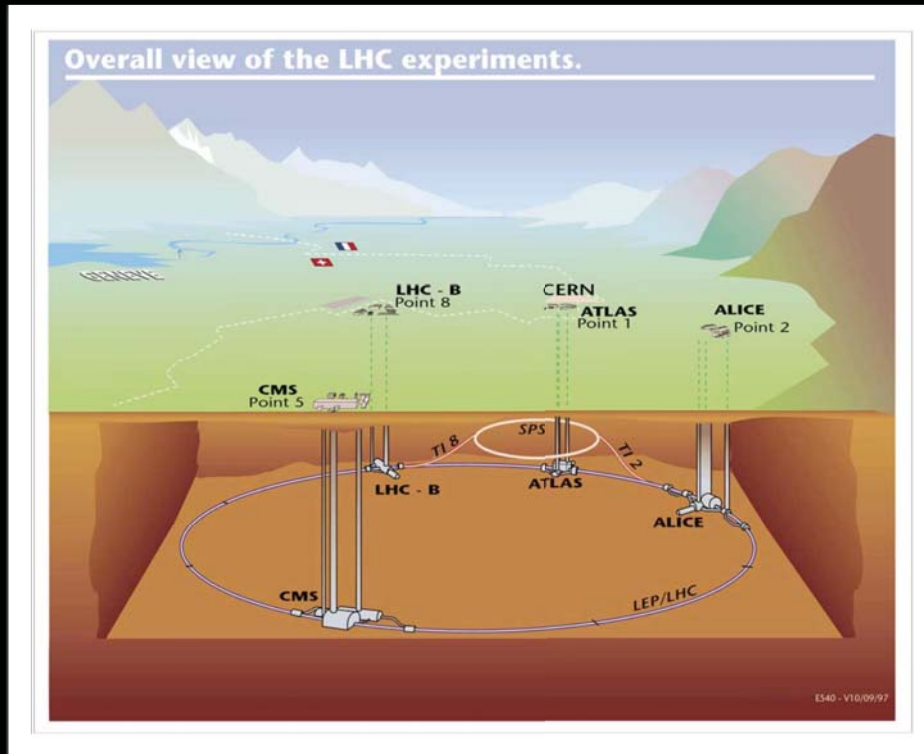
Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458

Complémentarité des expériences

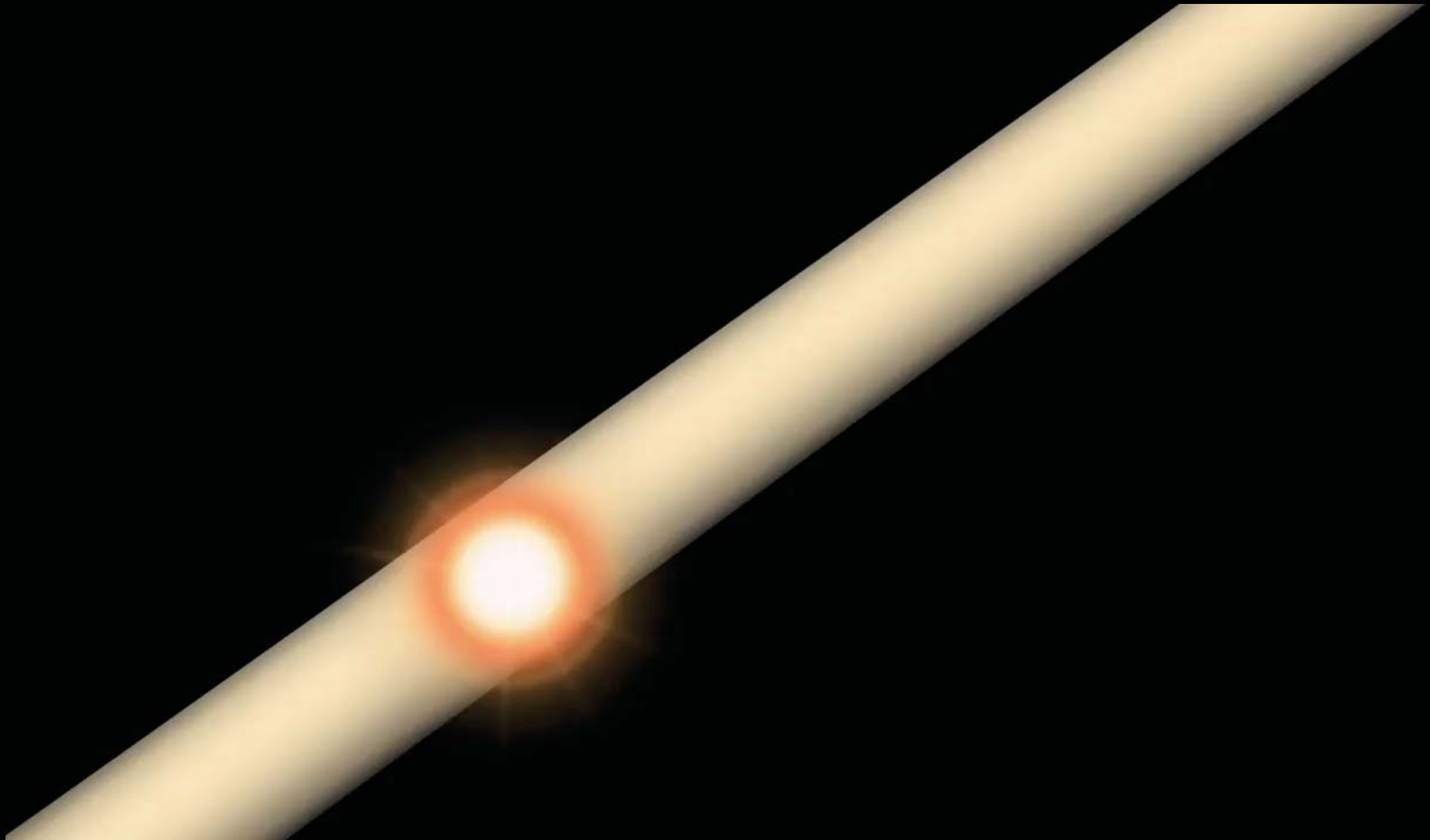


Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458

Recherche de MN au LHC

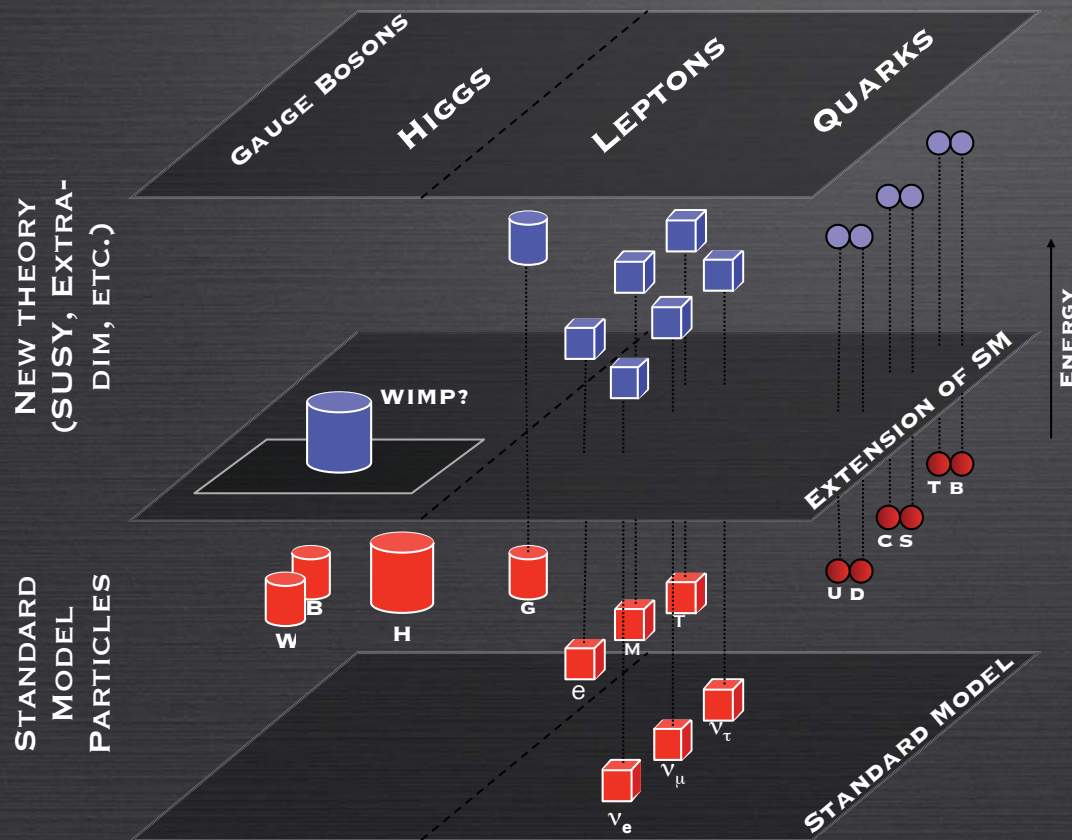


Colliding protons at the LHC



Physique au delà du Modèle Standard

Le Modèle Standard fournit une description des particules élémentaires et de leurs interactions, mais la plupart des théoriciens croient qu'une théorie plus fondamentale existe

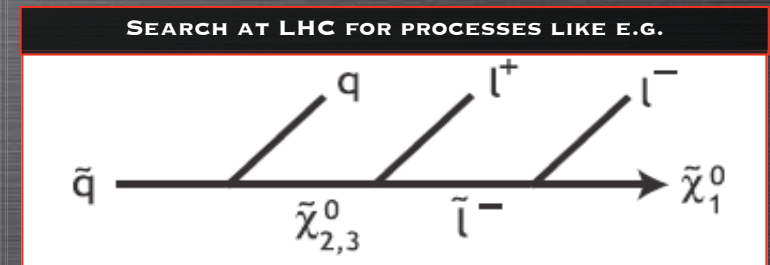
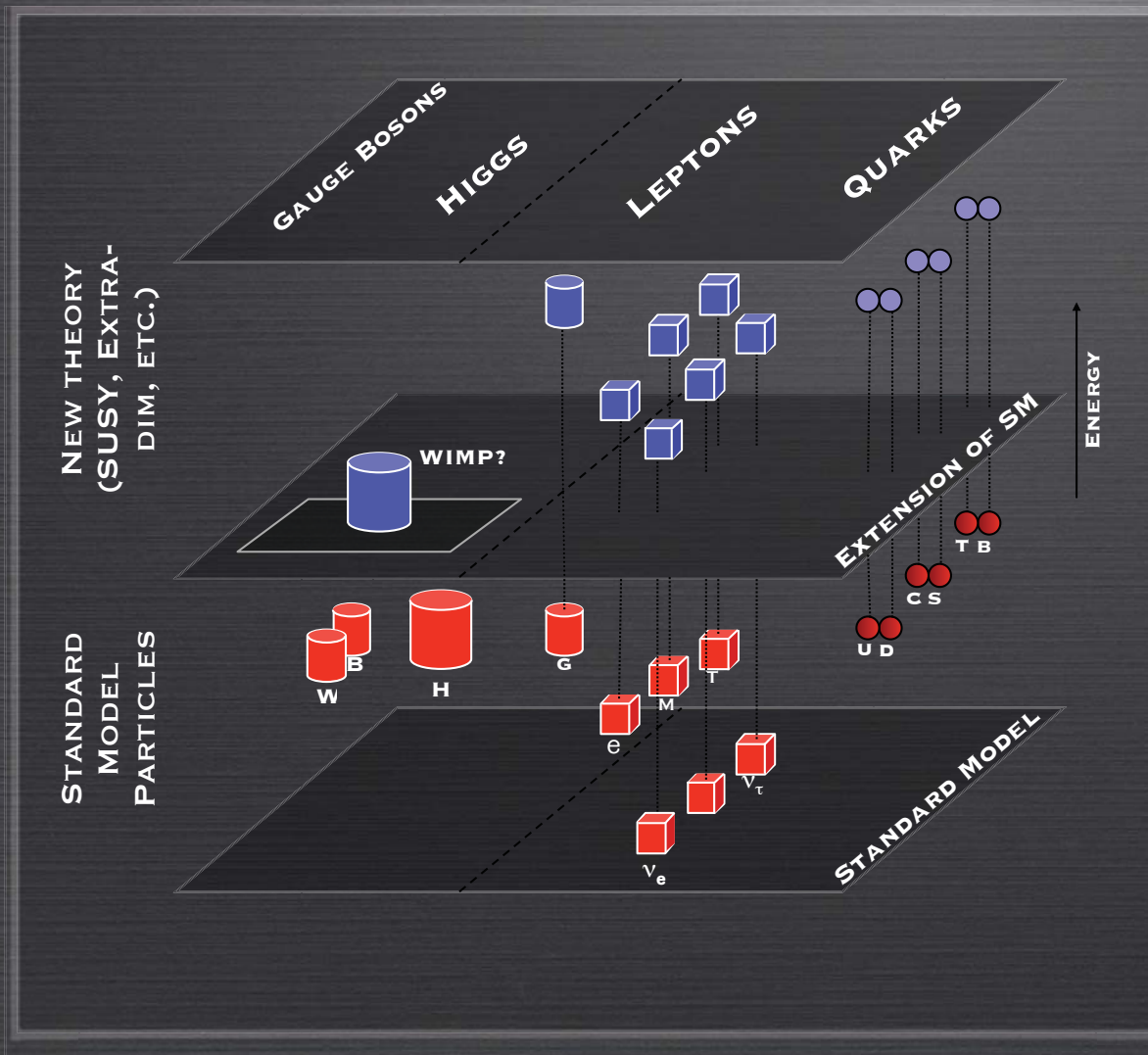


To explain the origin of the weak scale, extensions of the standard model often postulate the existence of new physics at ~ 100 GeV

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

Physique au delà du Modèle Standard

Le Modèle Standard fournit une description des particules élémentaires et de leurs interactions, mais la plupart des théoriciens croient qu'une théorie plus fondamentale existe



Exemple de “problème inverse” au LHC

Déduire la densité relicue nous permettrait d'identifier les nouvelles particules avec la matière noire. Ce que nous aimerions pouvoir faire:

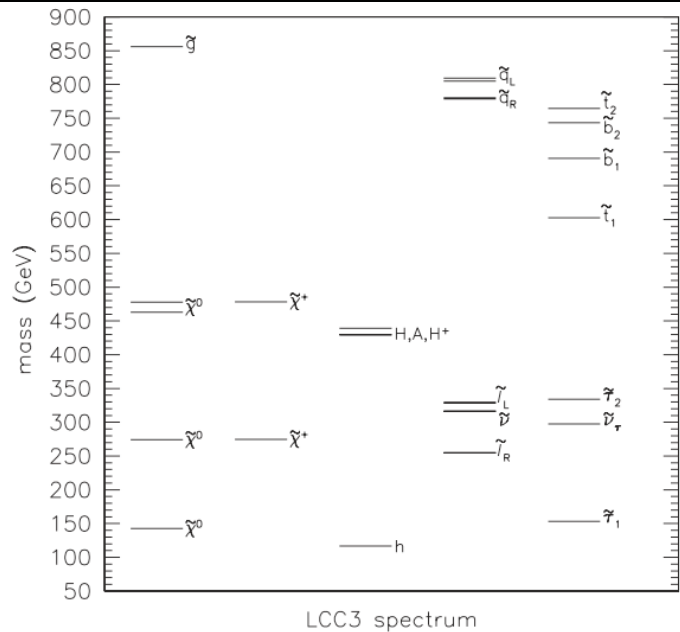
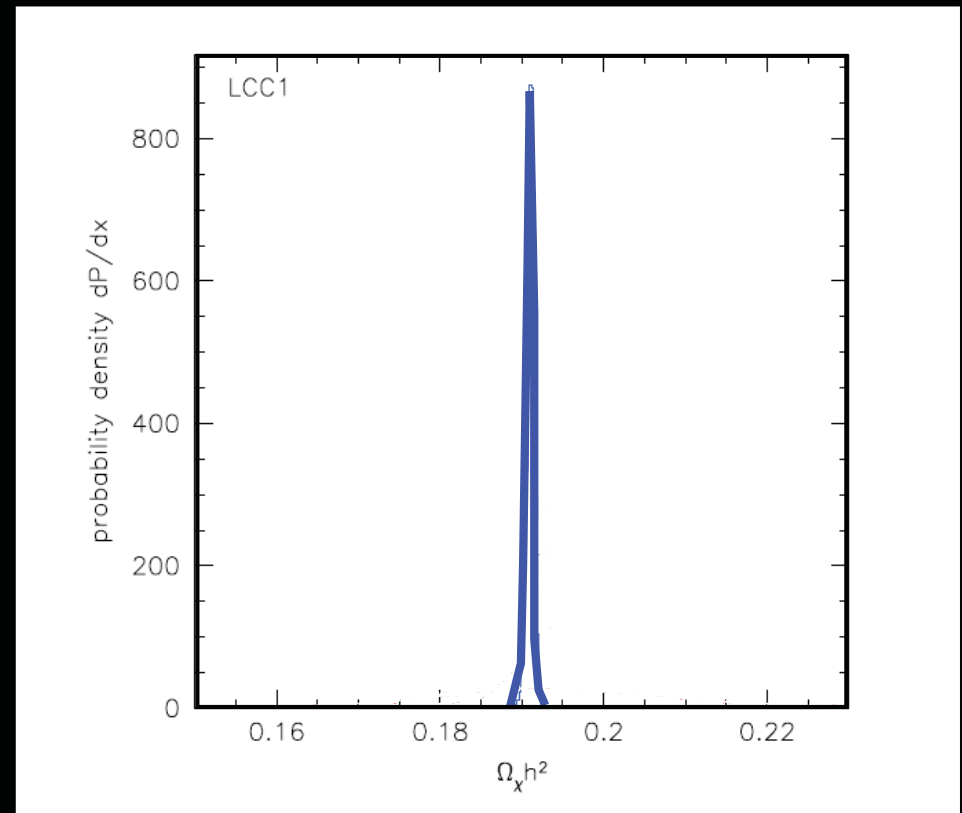
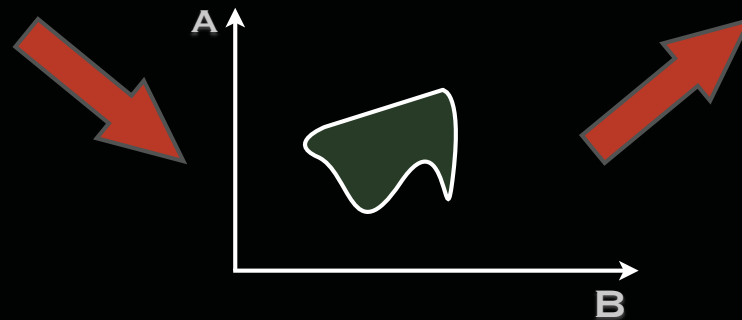


FIG. 34. Particle spectrum for point LCC3. The stau-neutralino mass splitting is 10.8 GeV. The lightest neutralino is predominantly *b*-ino, the second neutralino and light chargino are predominantly *W*-ino, and the heavy neutralinos and chargino are predominantly Higgsino.



AD. FROM BALTZ, BATTAGLIA, PESKIN, WIZANSKY (2005)



Exemple de “problème inverse” au LHC

(exemple dans la ‘stau coannihilation region’, 24 parms MSSM)

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.).

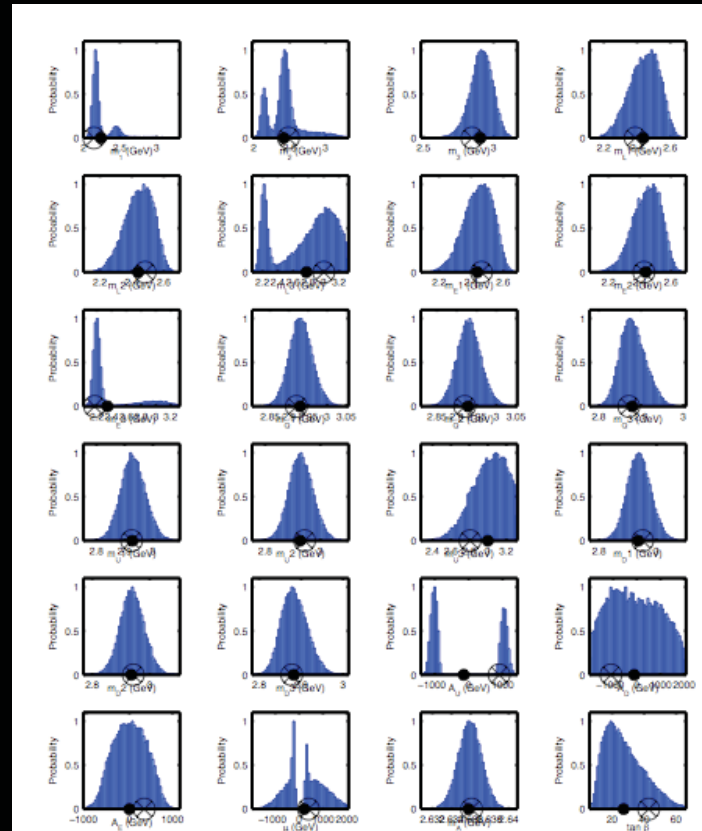
✦ ERRORS CORRESPOND TO 300 FB-1.

✦ ERROR ON MASS DIFFERENCE WITH THE STAU $\sim 10\%$ FOR THIS MODEL CAN BE ACHIEVED WITH 10 FB-1

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

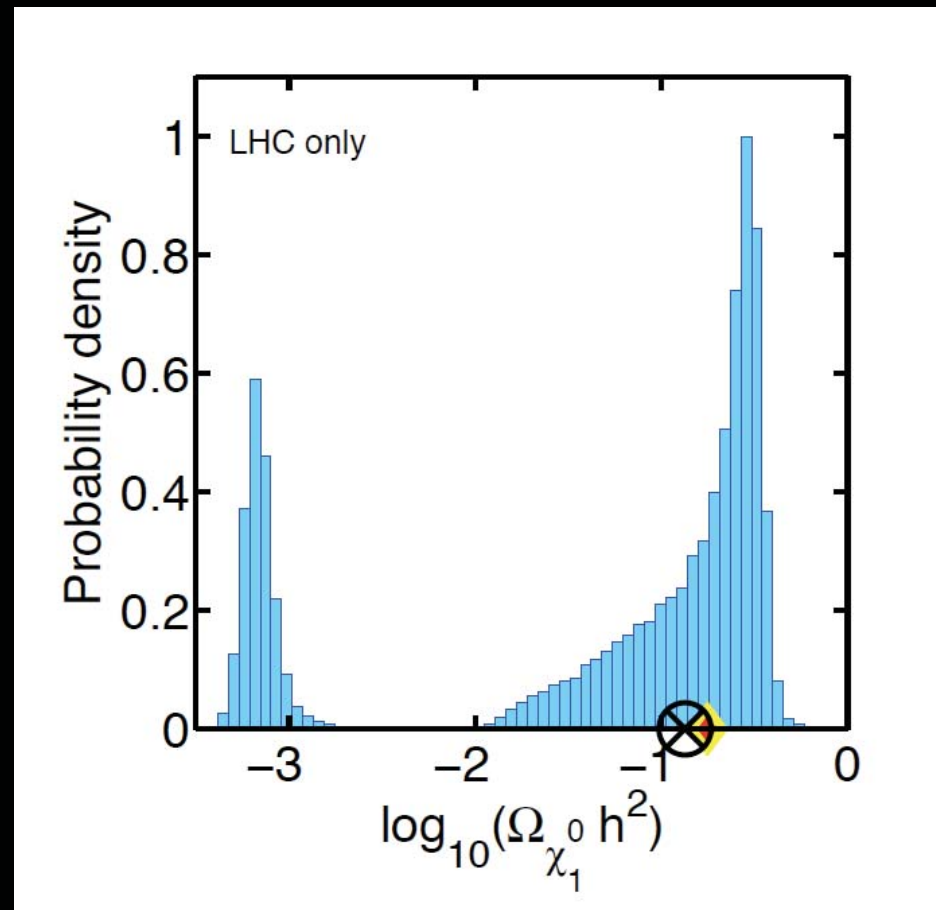


MCMC AS
IMPLEMENTED IN THE
SUPERBAYES CODE



Exemple de “problème inverse” au LHC

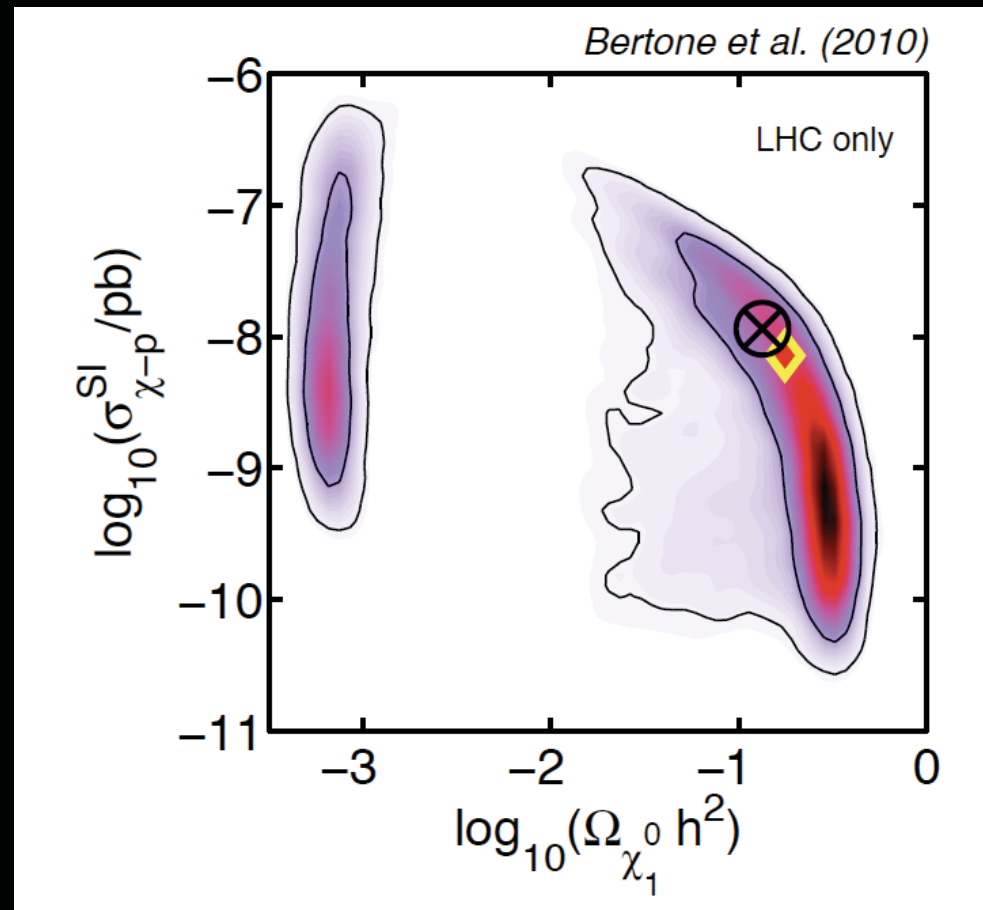
ce que nous allons probablement obtenir
(exemple dans la 'stau coannihilation region', 24 parms MSSM)



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

Exemple de “problème inverse” au LHC

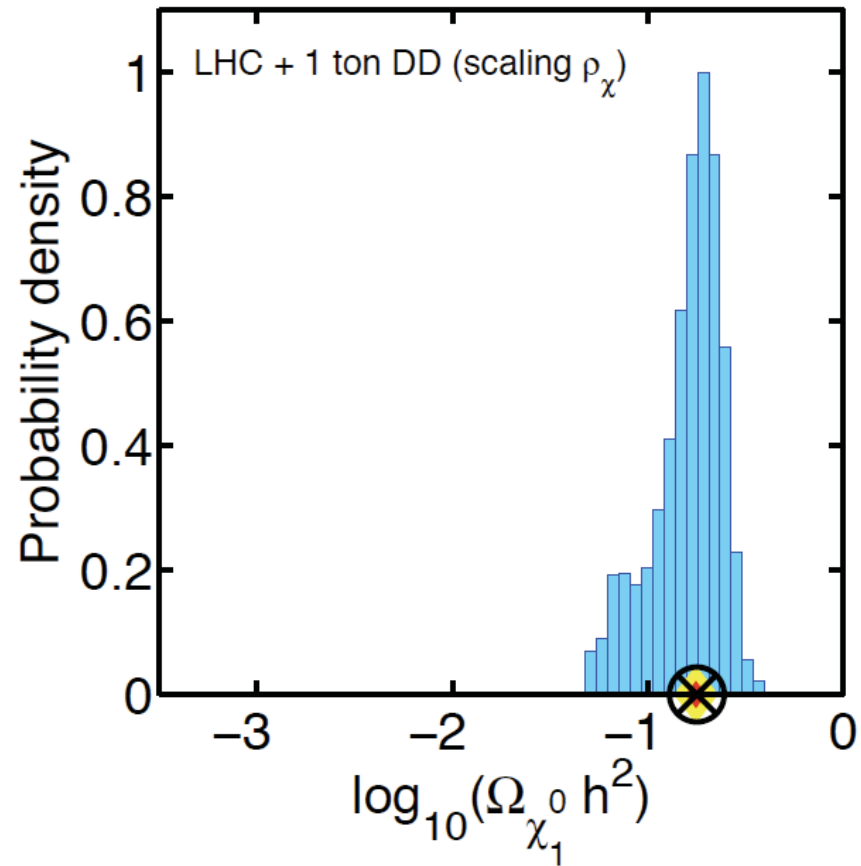
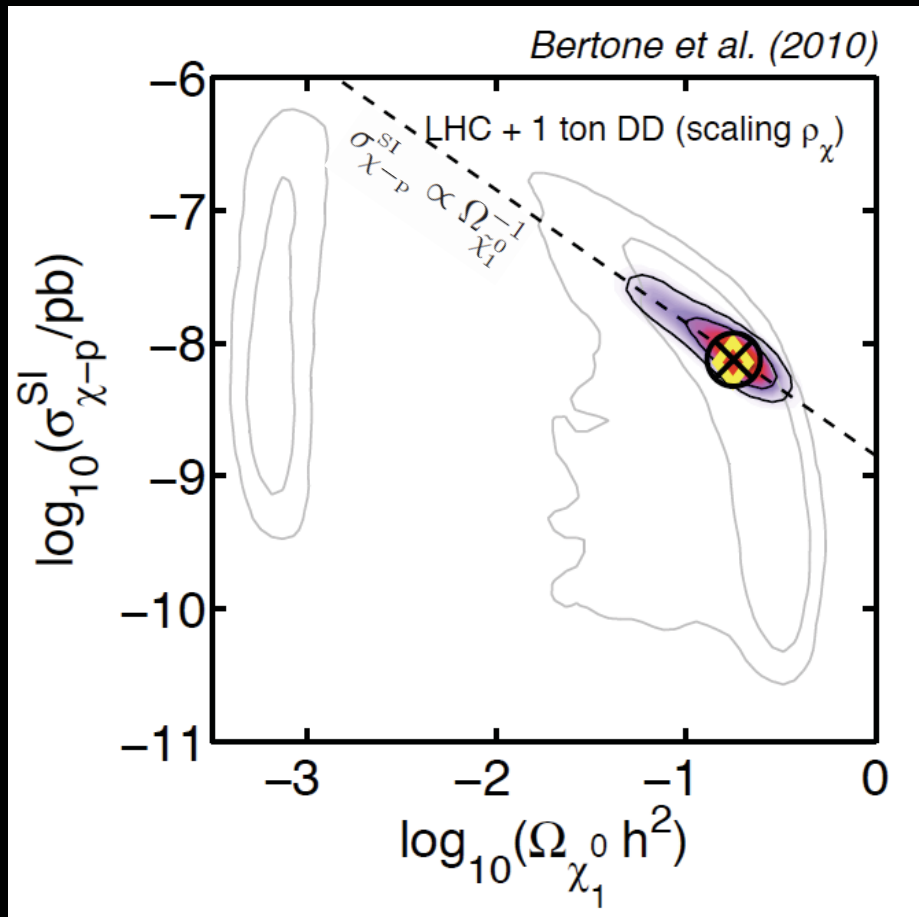
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GB, CERDENO, FORNESA, RUIZ DE AUSTRI & TROTTA, 2010

“Scaling” Ansatz

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



Conclusions

- Beaucoup d'efforts pour identifier les particules de matière noire, et des résultats intéressants. Mais on est en droit d'être sceptique et d'exiger des preuves irréfutables
- *Détection indirecte: un excès de photons vers le centre Galactique. Peut être due à la matière noire, peut être pas.*
- *Détection directe: des expériences de nouvelle génération vont fournir des données précieuses. Infos provenant d'autres techniques de détection nécessaires pour l'identification de la MN*
- Run II du LHC va bientôt commencer. Même si des nouvelles particules sont découvertes, analyse conjointe sera indispensable
- Les 5-10 prochaines années seront décisives: c'est le moment de la vérité pour les WIMPs