

Le point sur la matière noire



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STAR Institute

http://www.theo.phys.ulg.ac.be/wiki/Dark_Matter

Plan

- Position du problème
- Les preuves d'existence
- Les causes possibles
- Une expérience de détection directe : DAMA
- Une expérience de détection indirecte : AMS02

Plan

- **Position du problème**
 - **la scène**
 - **les acteurs**
- Les preuves d'existence
- Les causes possibles
- Une expérience de détection directe : DAMA
- Une expérience de détection indirecte : AMS02

La scène

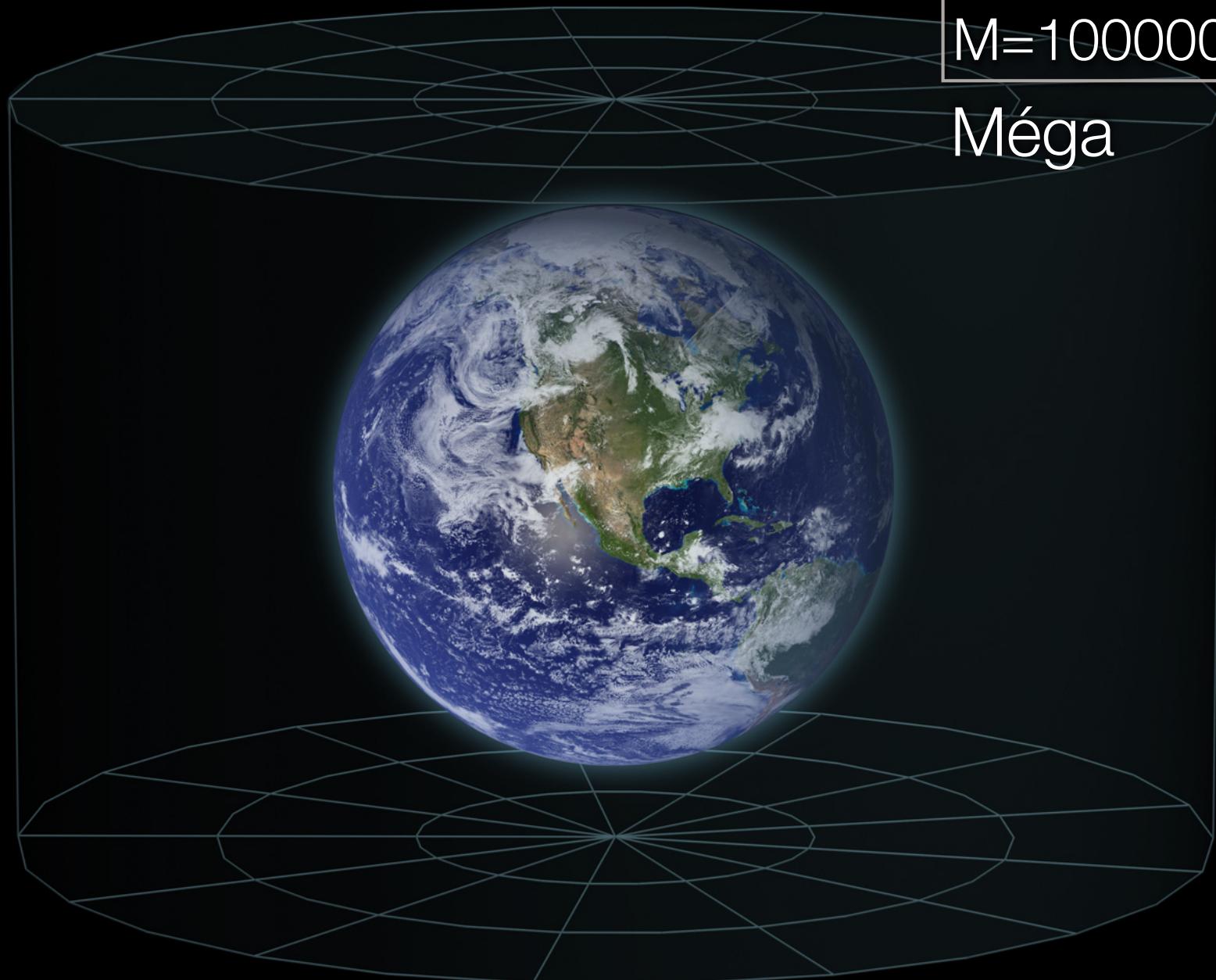


Terre

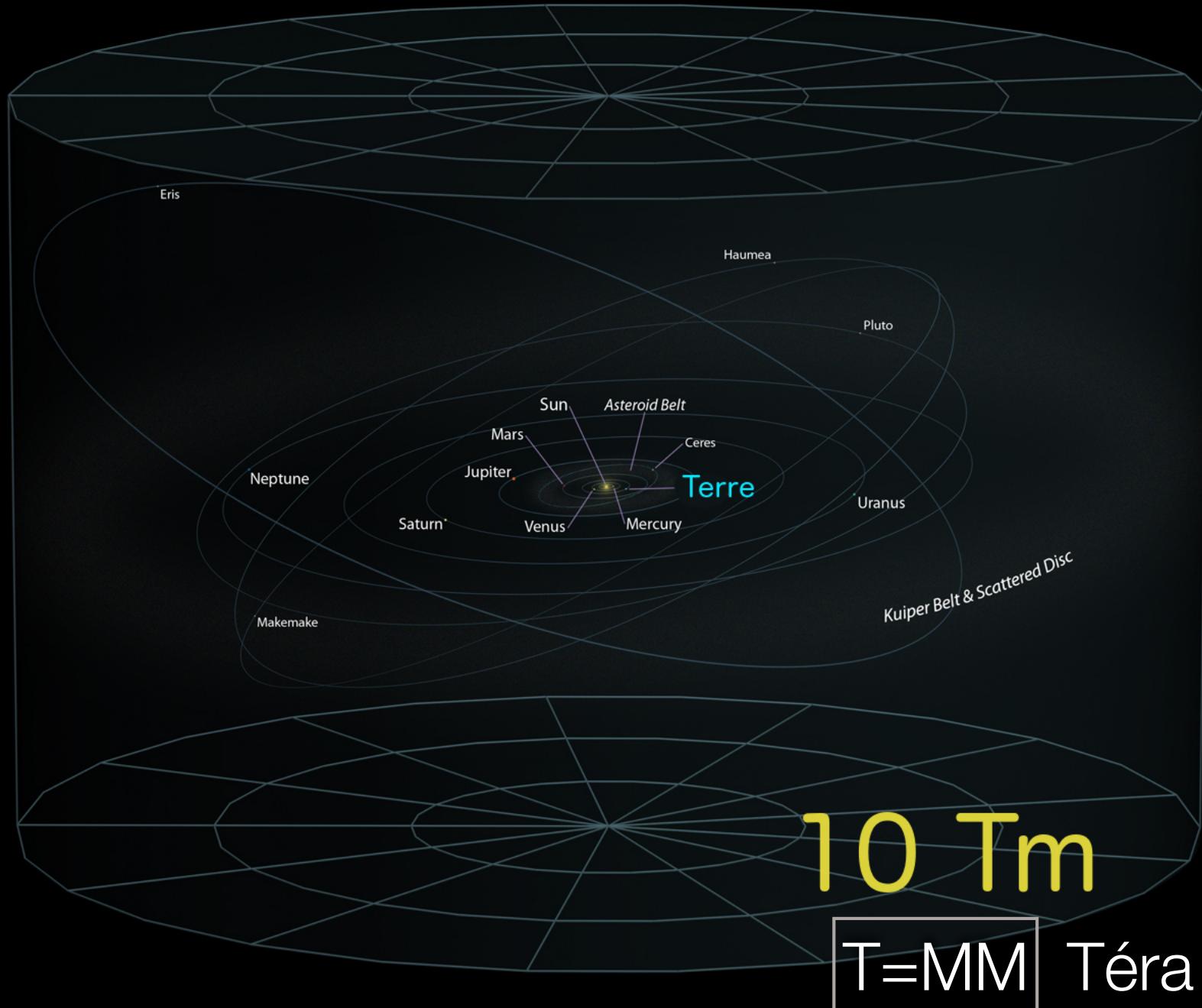
10 Mm

M=1000000

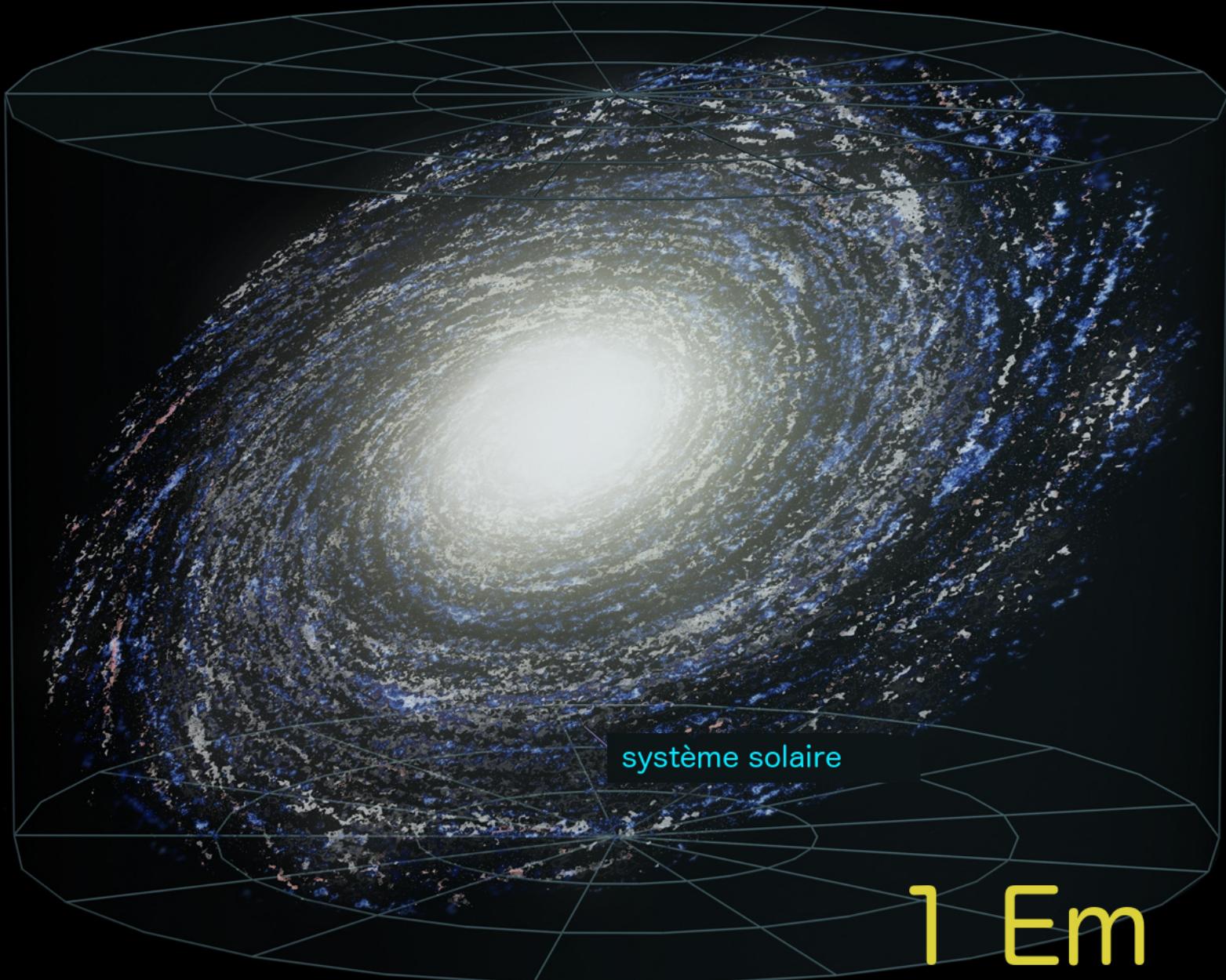
Méga



Système solaire

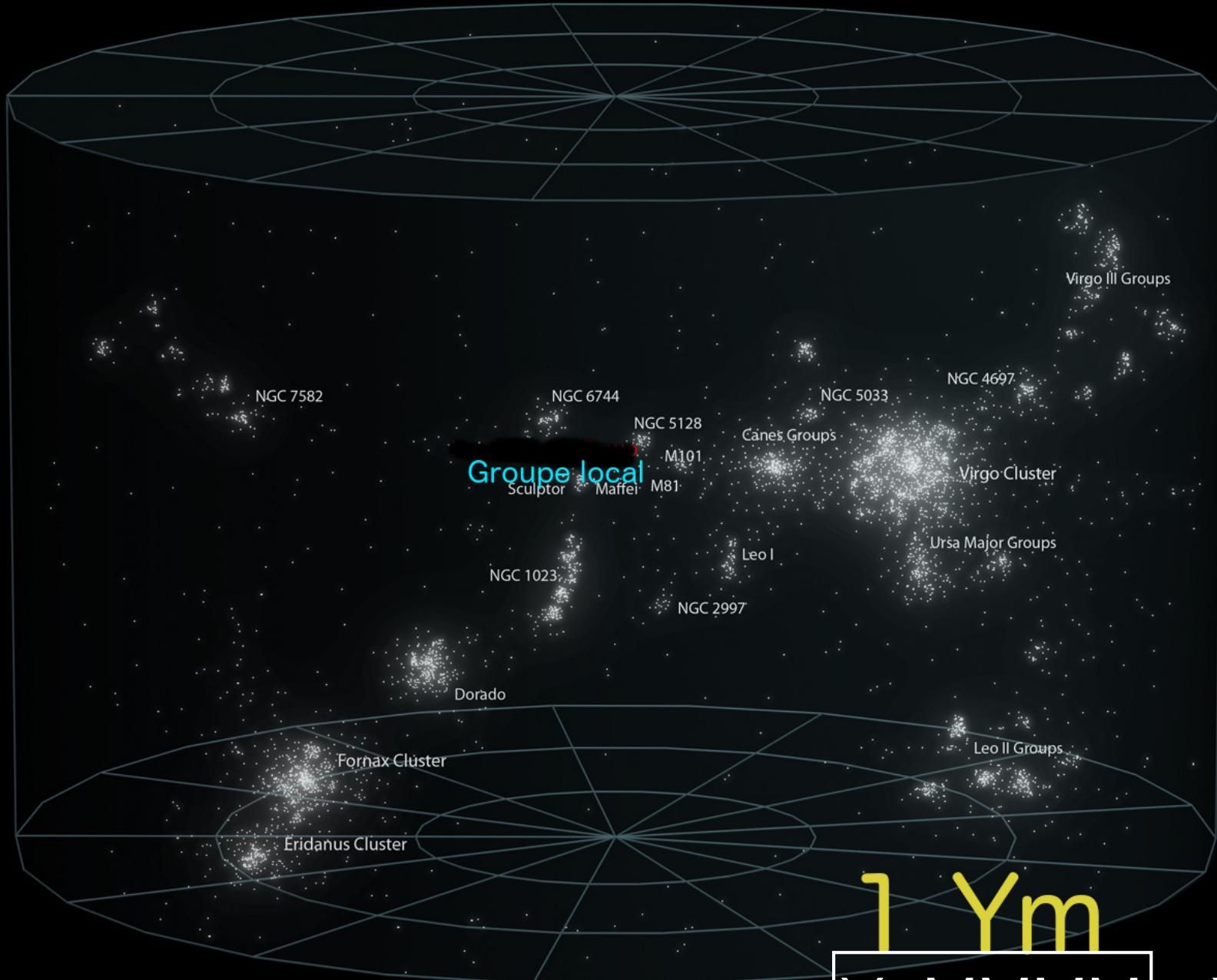


Voie Lactée



1 Em
E=MMM Exa

Superamas de la vierge



1 Ym
Y=MMMM

Yotta₈

Univers observable



Les acteurs

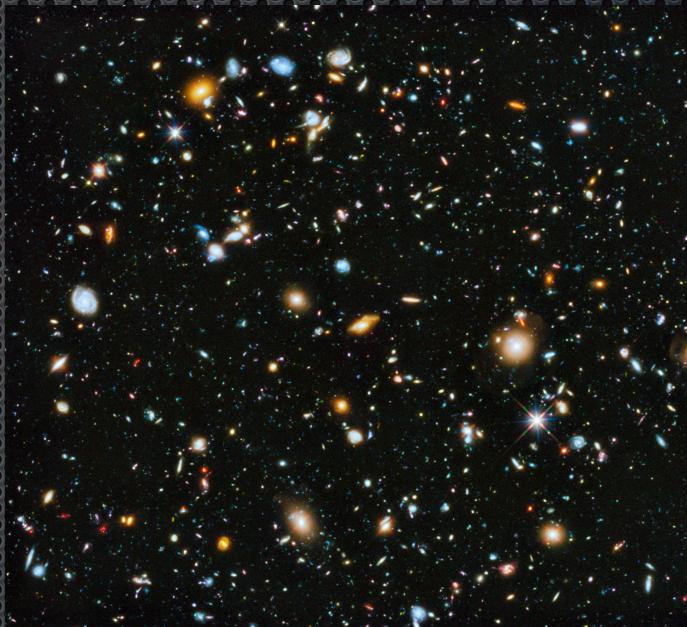


La matière

Echelles : masses



air (au sol) :
 $2,5 \times 10^{25}$
atomes/m³



Univers :
0.25 atomes
d'hydrogène/m³



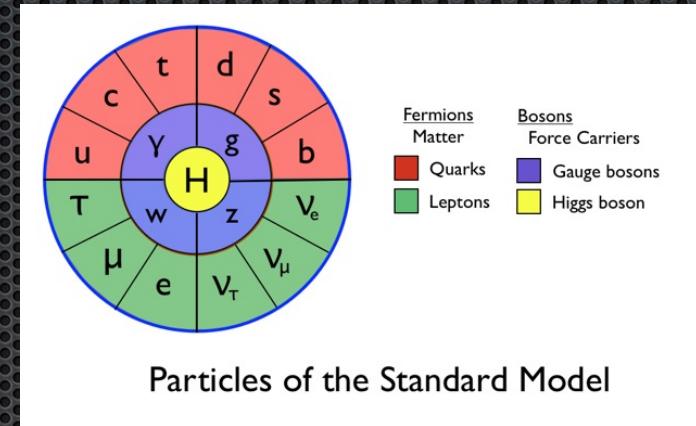
- Il manque 1 atome d'hydrogène/m³
- $(10^{27})^3 \text{ m}^3$
- Nombre d'atomes dans le soleil: 10^{57}
- Il manque 10^{24} soleils MMMM=Y

Matière

Les lois

Forces

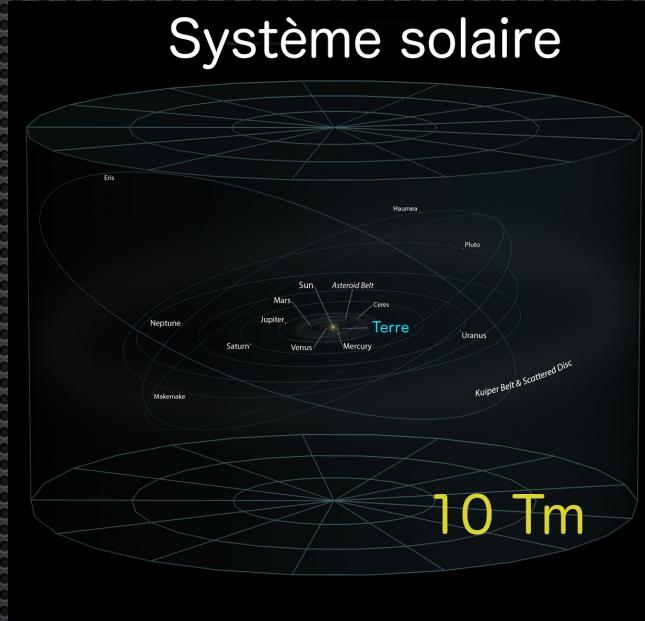
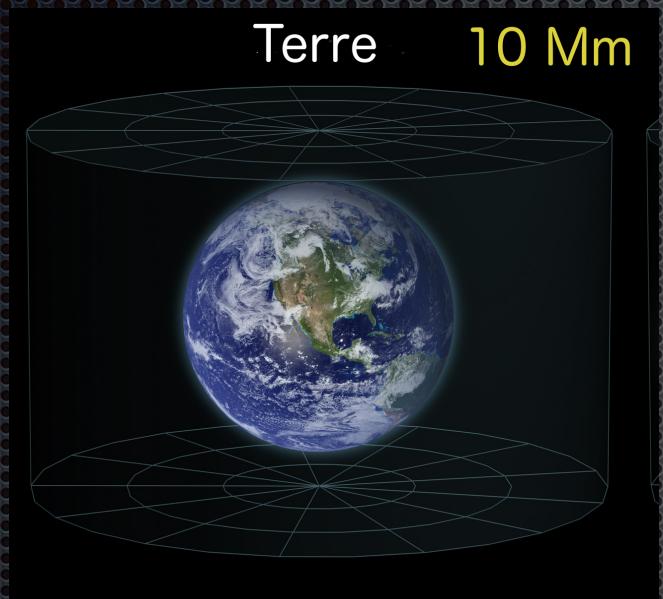
Espace-temps



$$SU(3) \otimes SU(2)_L \otimes U(1)_Y$$

$$G_{\mu\nu} = 8\pi G(T_{\mu\nu} + \rho_A g_{\mu\nu})$$

parfaites *localement*



Ne marchent pas aux grandes échelles



La gravité n'est pas suffisamment forte aux grandes échelles

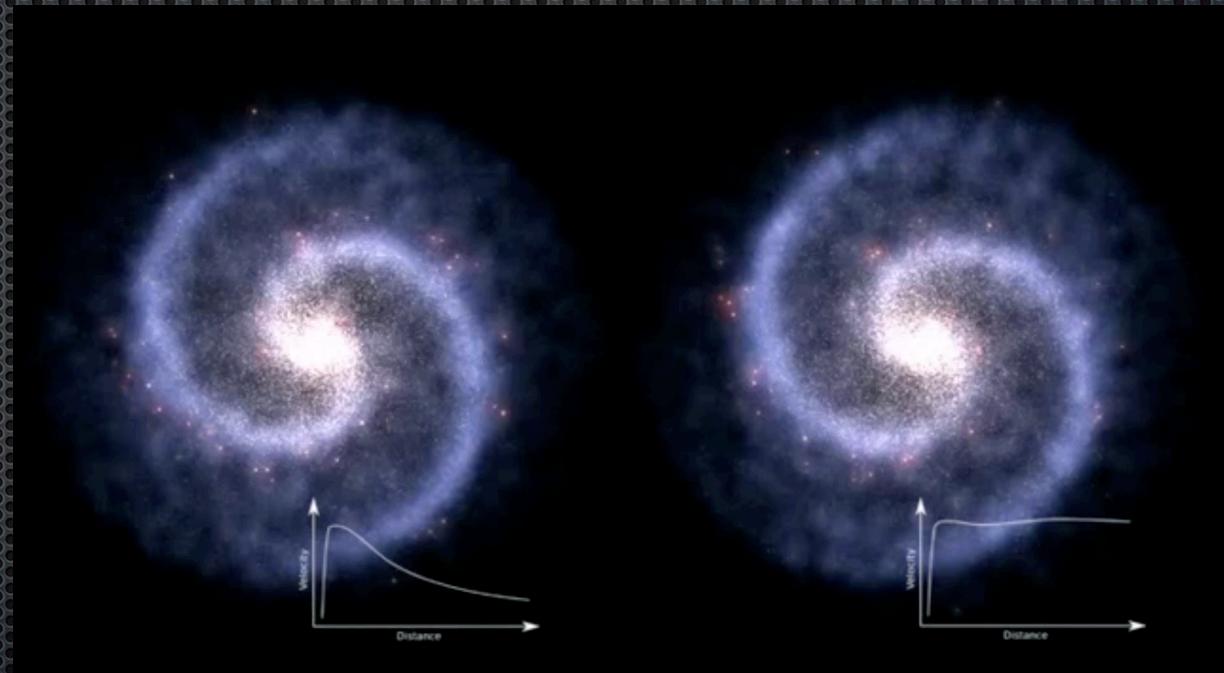
Plan

- Position du problème
- **Les preuves d'existence**
 - **Galaxies (Rubin)**
 - **Amas de galaxies (Zwicky)**
 - **Collisions d'amas de galaxies**
 - **Voie lactée (Oort)**
- Les causes possibles
- Des expériences de détection directe : DAMA et LUX
- Une expérience de détection indirecte : AMS

Galaxies

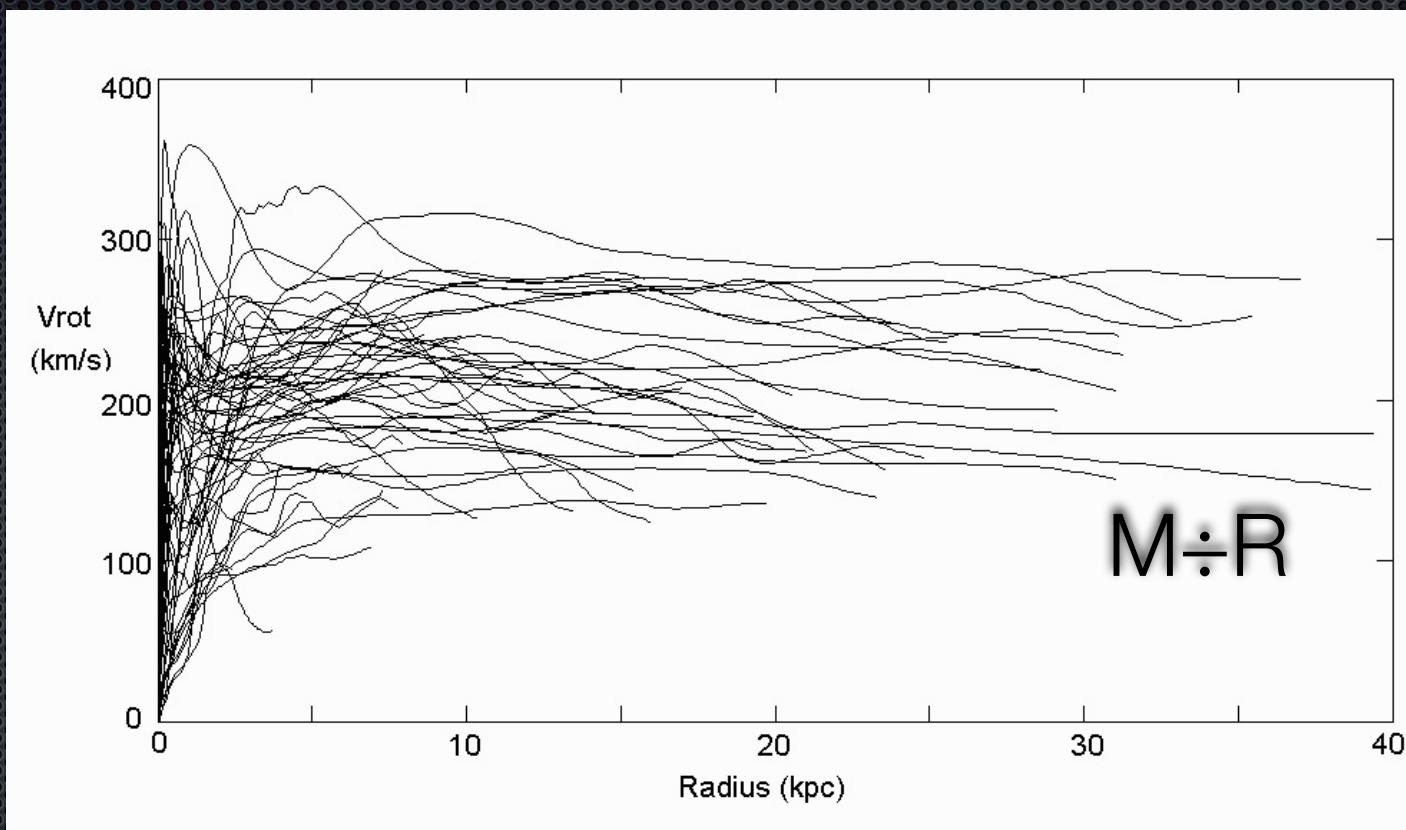


Rubin, V.C., Ford, W.K. & Thonnard, N. 1978, *Astrophys. J.* 225, L107
“Extended rotation curves of high-luminosity spiral galaxies”

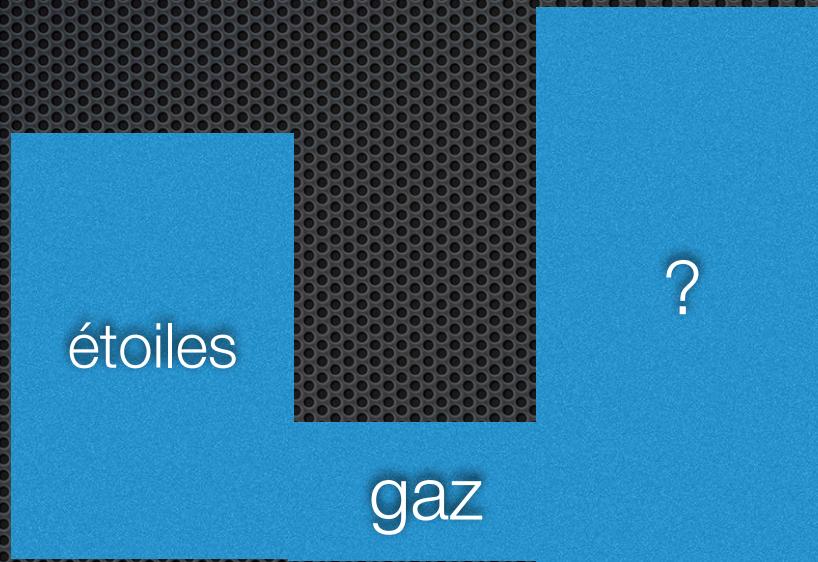


Données

"Rotation Curves of Spiral Galaxies," Y.Sofue & V.Rubin 2001, ARAA 39, 137-174



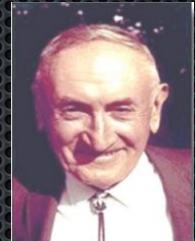
Composition galactique



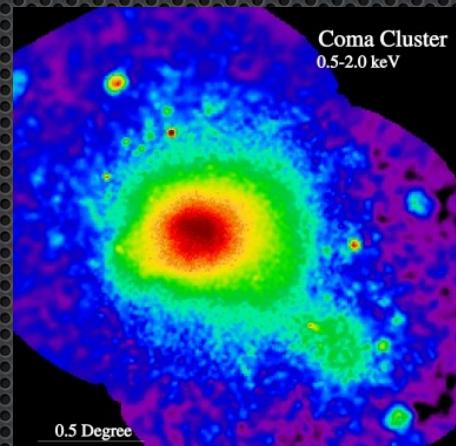
pour *la plupart* des galaxies

Amas:

- Zwicky, F. 1933, *Helv. Phys. Acta* 6, 110, “The redshift of extragalactic nebulae”: l’amas de la Chevelure de Bérénice



satellite HUBBLE



satellite ROSAT

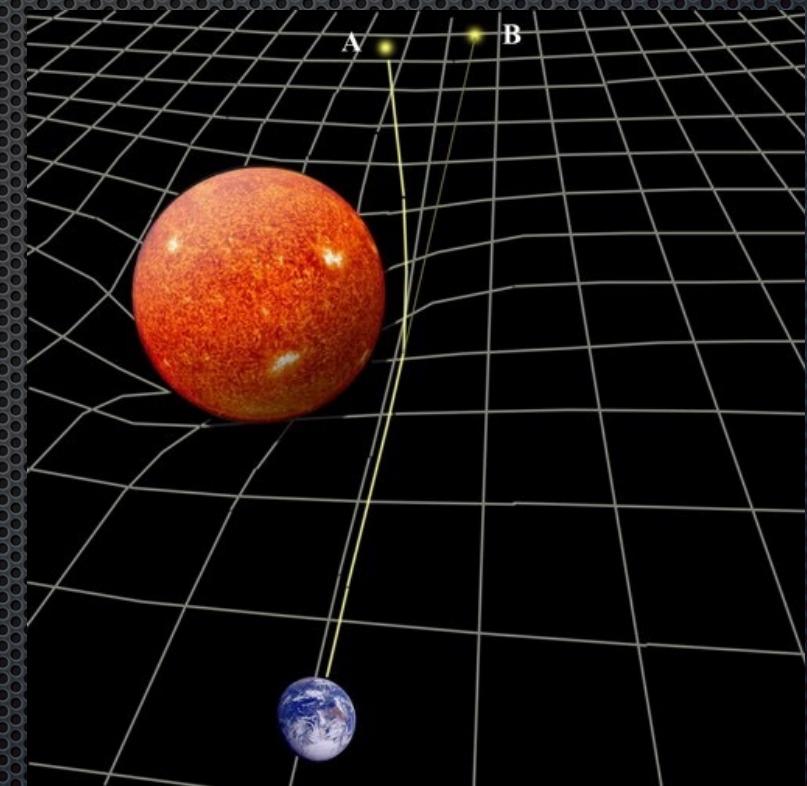
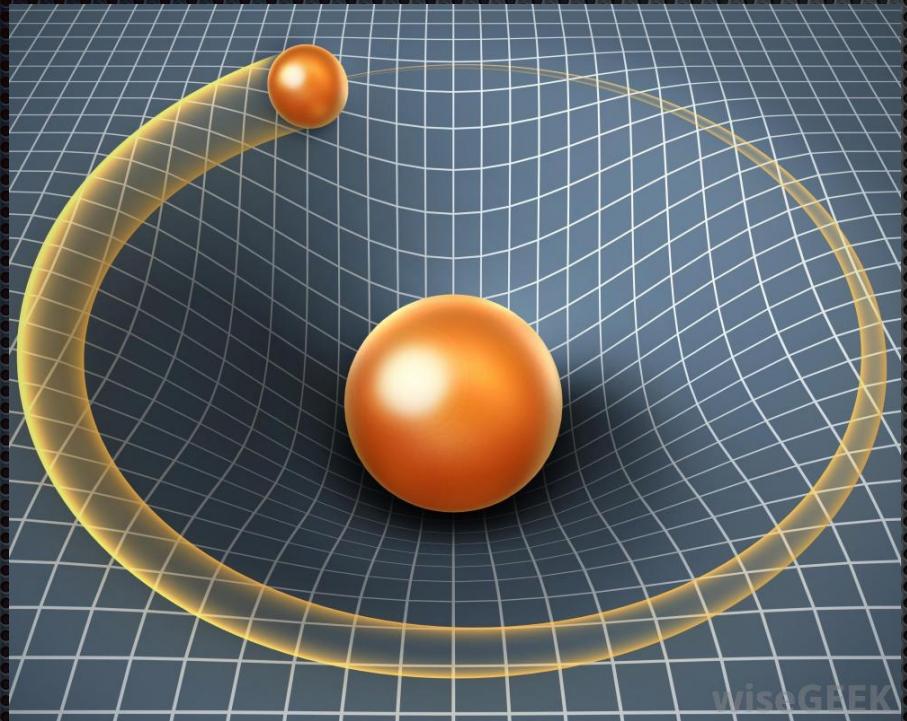
Relation entre l’énergie cinétique et le potentiel gravifique (théorème du viriel) –> estimation de la masse

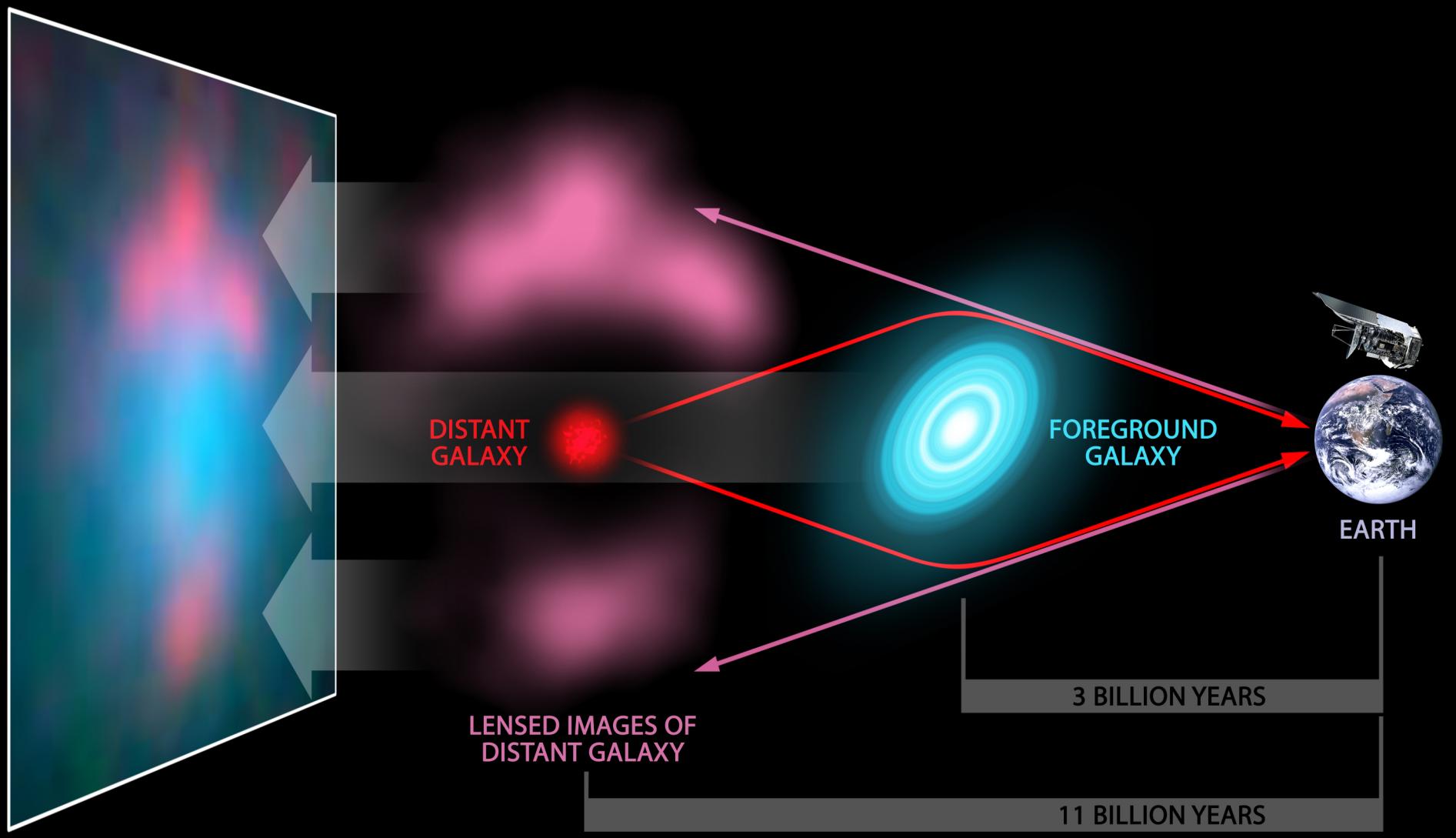
Estimation historique fausse : présence de gaz ionisé

Historiquement :
mouvement → gravité → masse

Aujourd’hui :
mesure directe à partir de
lentilles gravitationnelles
image → masse intermédiaire

Lentilles et microlentilles gravitationnelles





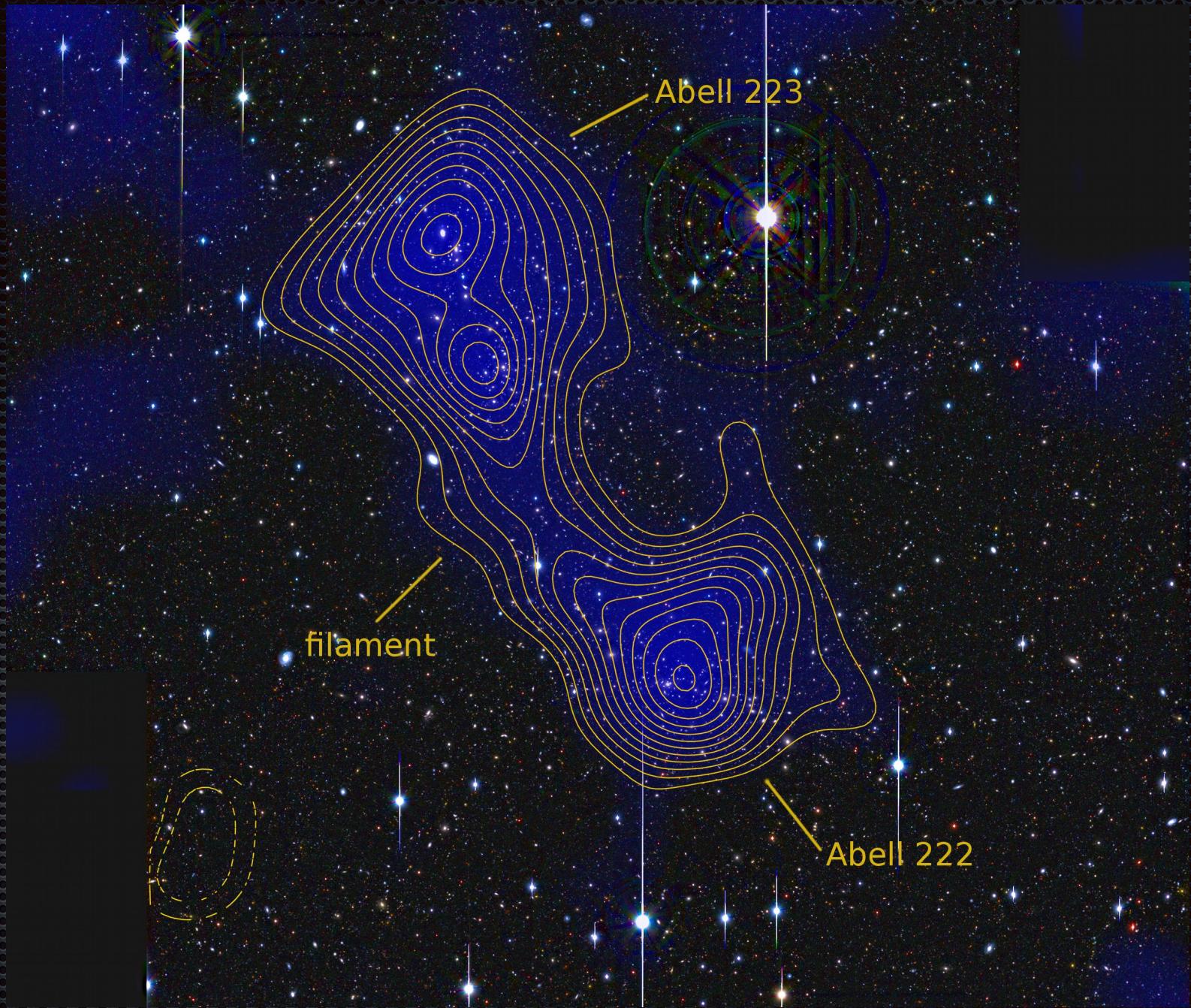


www.eso.org

Cartographie de la matière noire



Dark matter map in galaxy cluster Abell 1689
E. Jullo , P. Natarajan and J.-P. Kneib



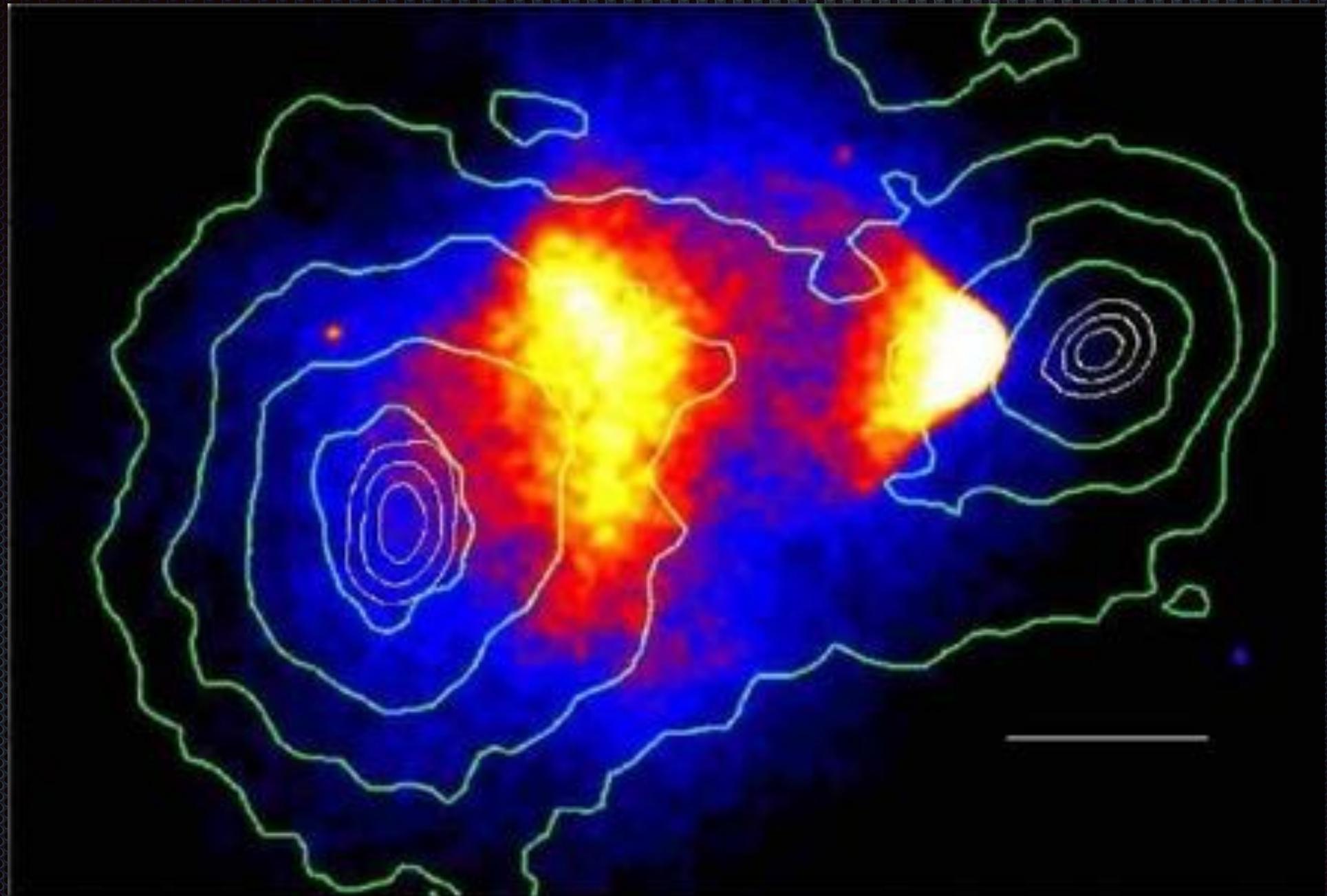
Gaz et collisions d'amas

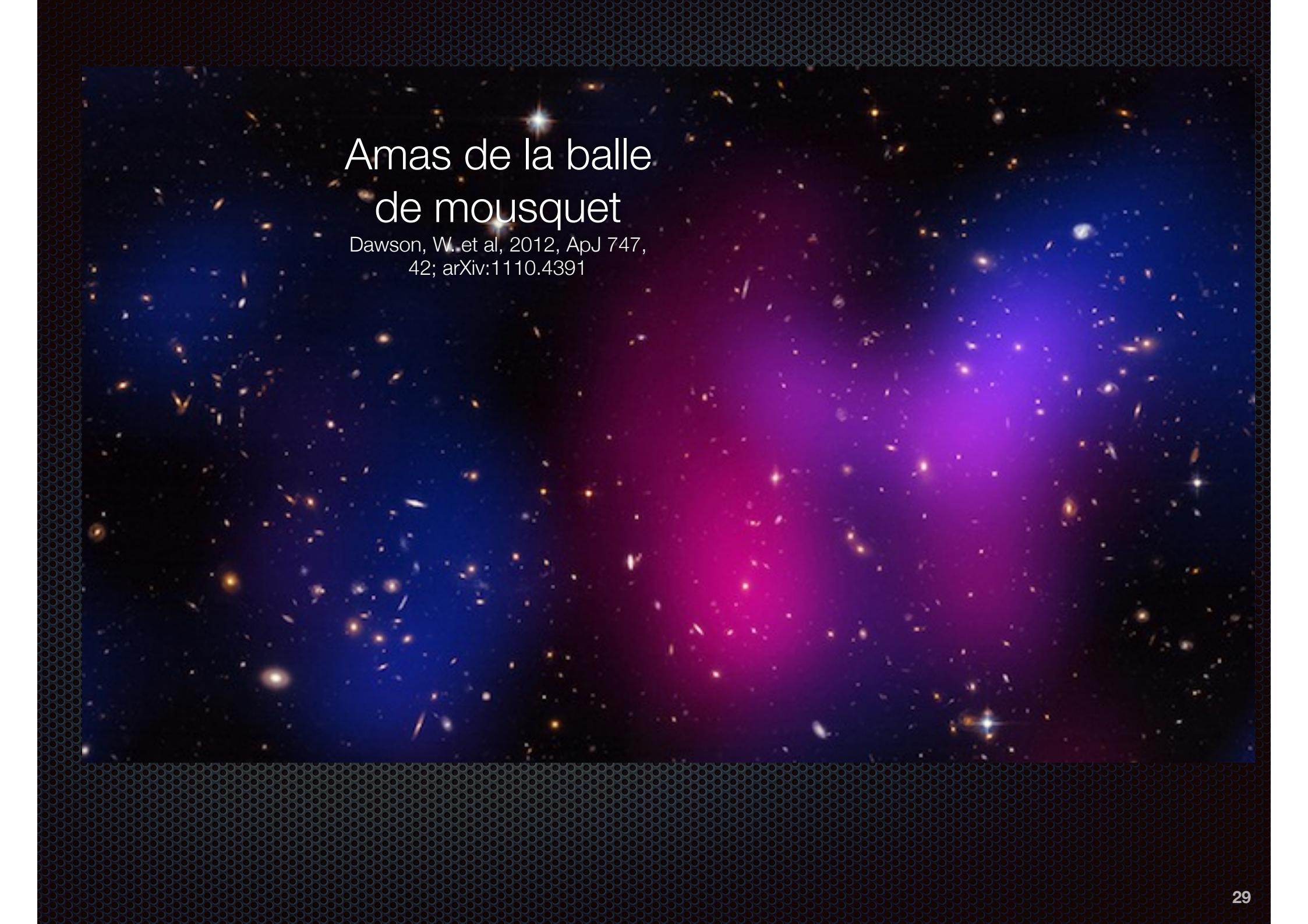


Amas du boulet



Chandra





Amas de la balle de mousquet

Dawson, W. et al, 2012, ApJ 747,
42; arXiv:1110.4391



The nongravitational interactions of
dark matter in colliding galaxy clusters
David Harvey, Richard Massey, Thomas Kitching,
Andy Taylor, Eric Tittley

Science 27 Mar 2015
Vol. 347, Issue 6229, pp. 1462-1465
DOI: 10.1126/science.1261381

Nouvelle carte 3-d

- Hyper Suprime-Cam (HSC), an ultra-wide-field camera installed at the prime focus of the Subaru telescope (8.2 m) in Hawaii: microlensing, 30 square degrees

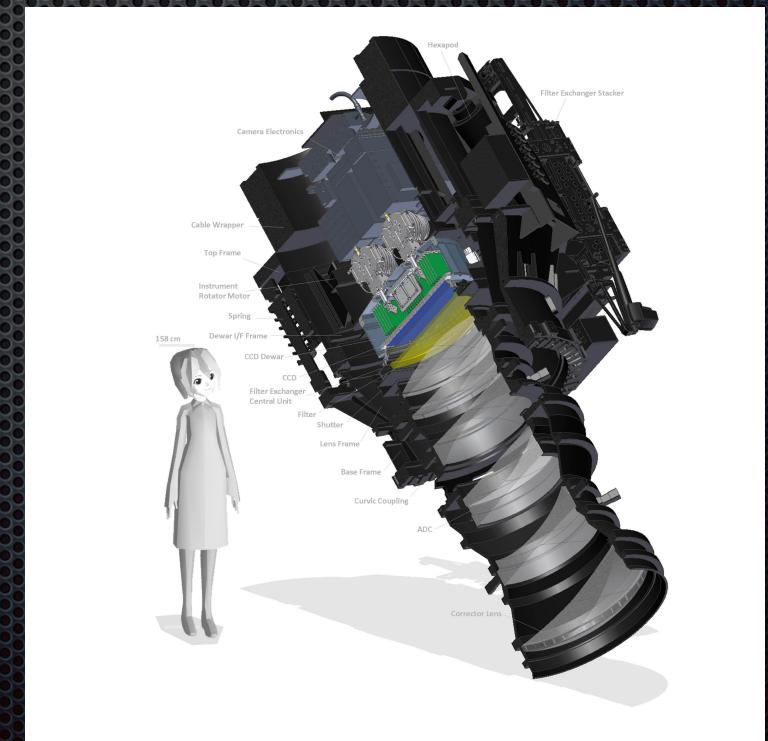
A large sample of shear-selected clusters from the Hyper Suprime-Cam Subaru Strategic Program S16A Wide field mass maps

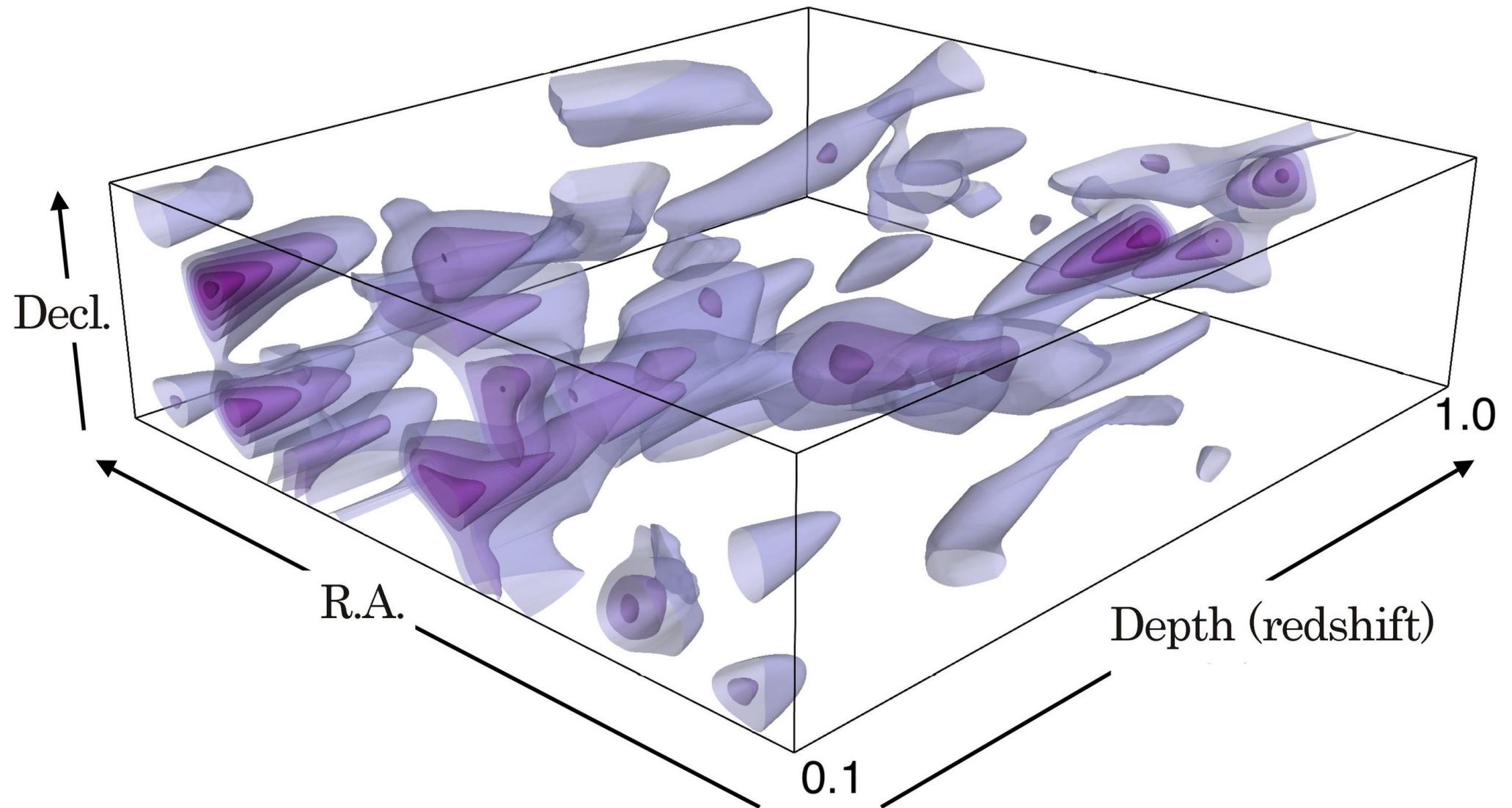
Satoshi Miyazaki , Masamune Oguri, Takashi Hamana, Masato Shirasaki, Michitaro Koike, Yutaka Komiyama, Keiichi Umetsu, Yousuke Utsumi, Nobuhiro Okabe, Surhud More ... Show more

Publications of the Astronomical Society of Japan, Volume 70, Issue SP1, 1 January 2018, S27,

<https://doi.org/10.1093/pasj/psx120>

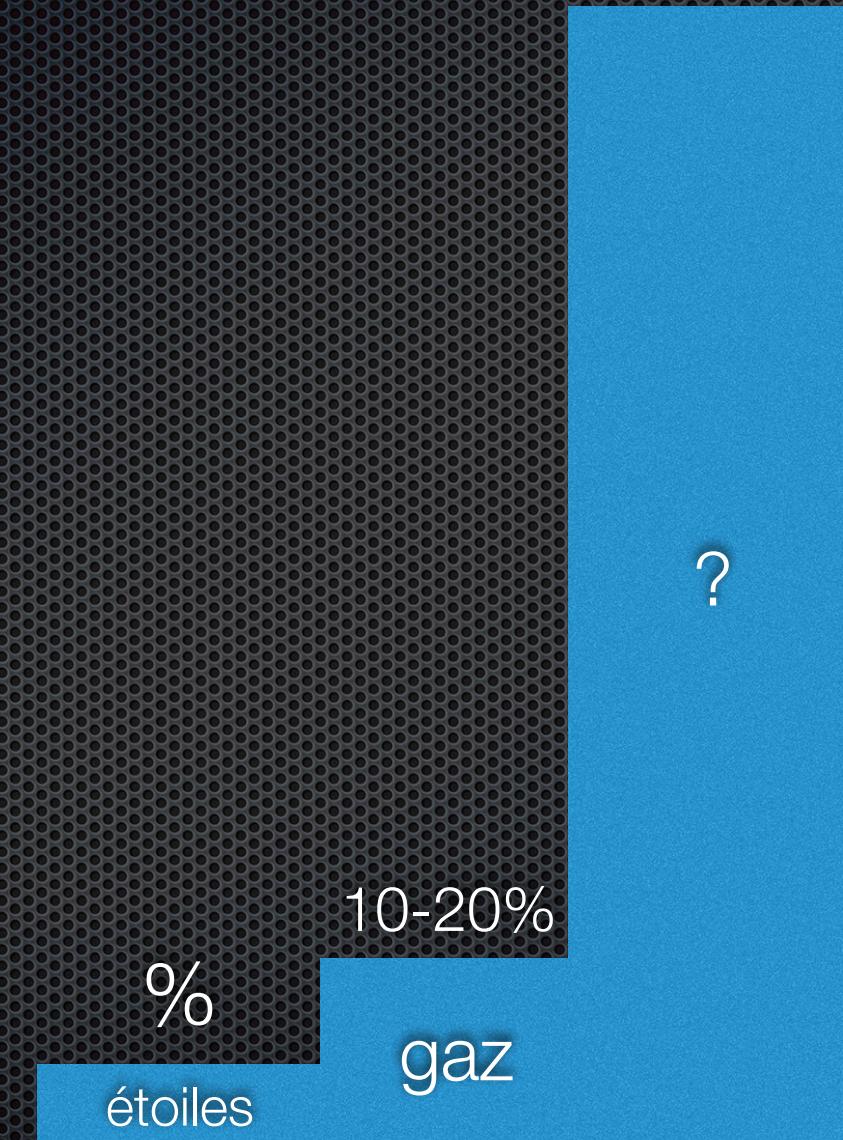
Published: 08 December 2017 Article history ▾

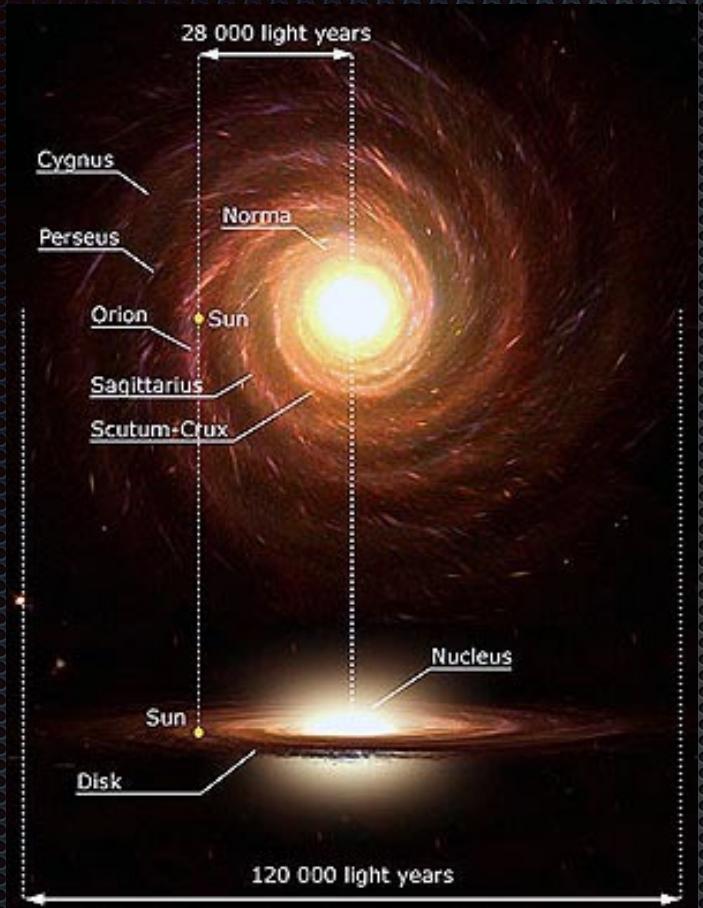




An example of 3D distribution of dark matter reconstructed via tomographic methods using the weak lensing technique combined with the redshift estimates of the background galaxies. Credit: University of Tokyo/NAOJ

Composition des amas de galaxies





Conclusion 1

Matière noire/matière standard=1 dans les galaxies;

=5 dans les amas

amas: $\rho_{\text{DM}} \approx 6 \cdot 10^{-28} \text{ g/cm}^3 = 400 \text{ atomes H m}^{-3}$

Localement: $\rho_{\text{DM}} \approx 6 \cdot 10^{-25} \text{ g/cm}^3 = 0.4 \cdot 10^6 \text{ atomes H m}^{-3}$

NB2: exceptions

Galaxie naine sphéroïdale
vieilles étoiles, beaucoup
de matière noire

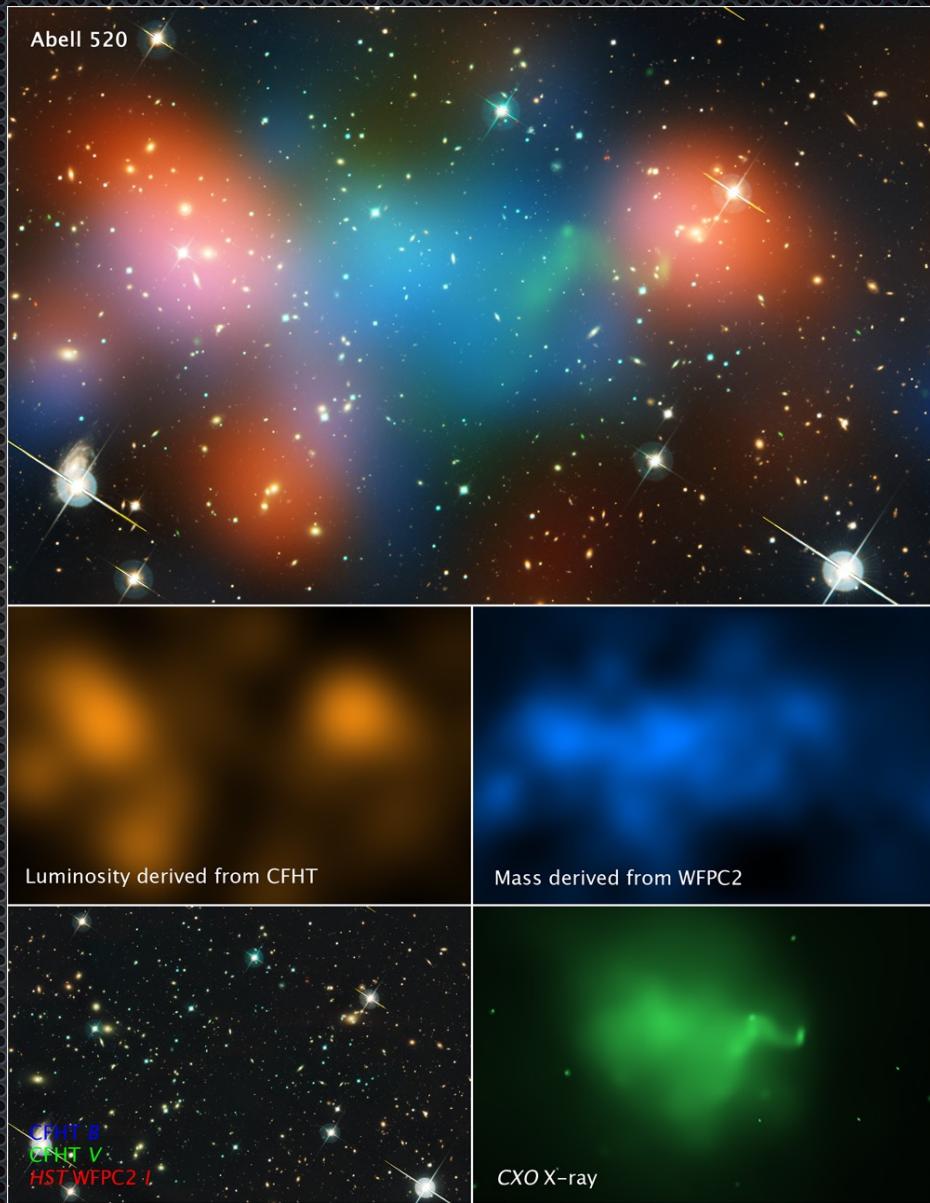


Amas globulaire
<6% matière noire



Abell 520

Douglas Clowe¹, Maxim Markevitch,
Maruša Bradač, Anthony H. Gonzalez,
Sun Mi Chung, Richard Massey, and
Dennis Zaritsky. The Astrophysical
Journal. doi:10.1088/0004-637x/
758/2/128



Mars 2018



NGC1052-DF2 is a large, but very diffuse galaxy located some 65 million light-years away. This image of the galaxy, which is thought to contain a negligible amount of dark matter, was captured by the Advanced Camera for Surveys on the Hubble Space Telescope.

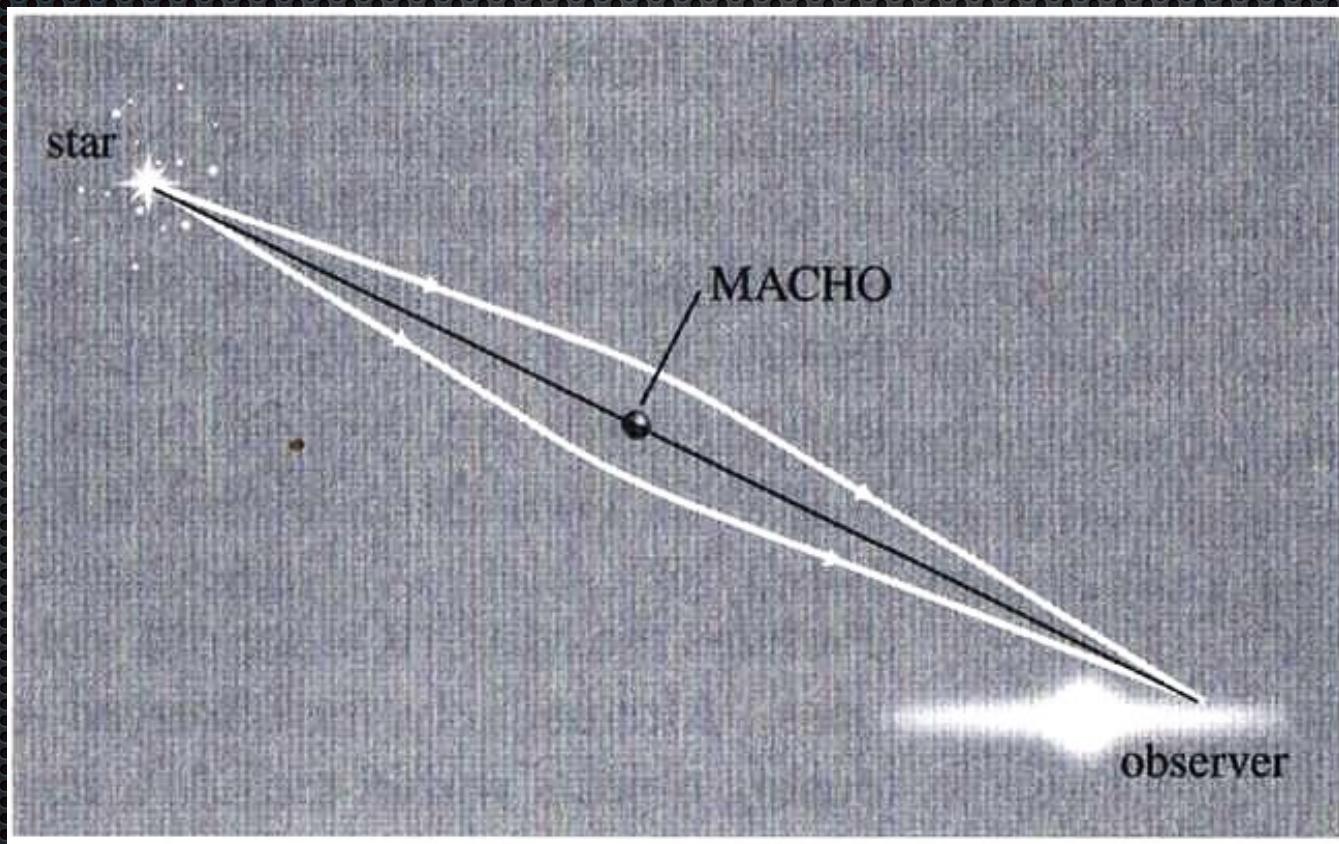
NASA/ESA/P. van Dokkum (Yale University)

Plan

- Position du problème
- Les preuves d'existence
- **Les causes possibles :**
 - **MACHOS**
 - **Gravité**
 - **WIMPS**
- Une expérience de détection directe : DAMA
- Une expérience de détection indirecte : AMS

Solution astrophysique

Massive Astrophysical Compact Halo Object (MACHO)



Etudes de microlentilles gravitationnelles

Moins de 20% de la matière noire est faite de MACHOS
pour

$2 \cdot 10^{22} \text{ kg}$ (0.3 masse lunaire) $< M <$ $2 \cdot 10^{32} \text{ (100 masses solaires)}$

- naines brunes, astéroïdes ;
- **trous noirs primordiaux** $10^{17} \text{ kg} < m < 10^{22} \text{ kg}$.

Solution gravifique



- Modified Newtonian Dynamics (MOND), Milgrom 83 & Tensor–vector–scalar gravity (TeVeS), Bekenstein 2004

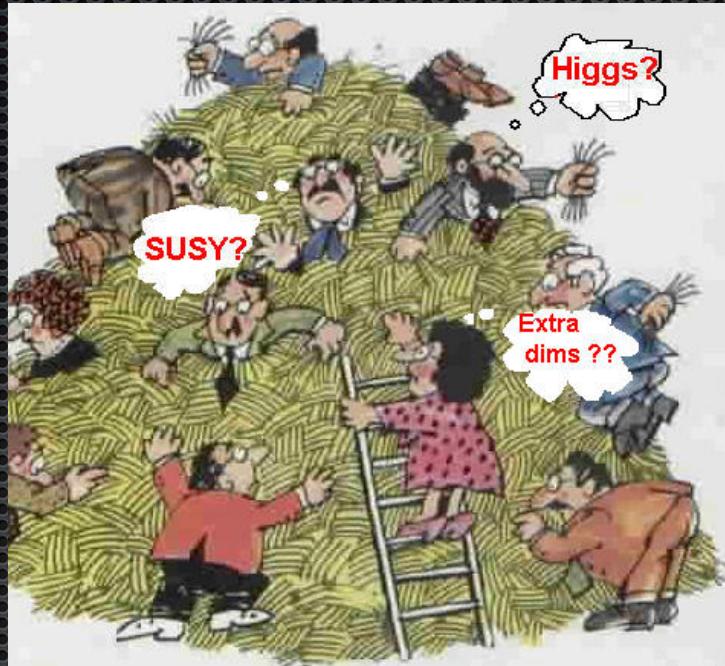
Changement de la loi de Newton à très faible accélération/grand R

$$\vec{F} = m\vec{a} \rightarrow \vec{F} = m f\left(\frac{a}{a_0}\right) \vec{a}$$

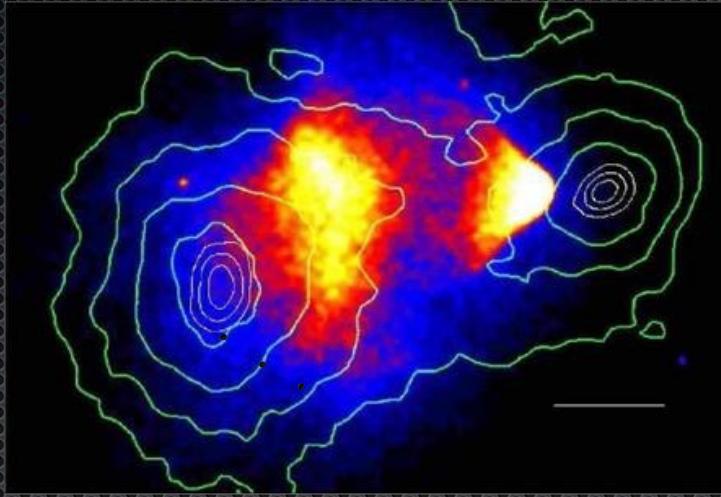
TeVeS (ou MOND)

- ▣ n'explique pas les amas de galaxies (un peu de matière noire est nécessaire)
- ▣ n'explique pas les galaxies pauvres en matière noire
- ▣ est largement exclu par les mesures d'ondes gravitationnelles (coalescence de naines blanches)

Solution particulière



- Le Modèle Standard n'est pas la théorie ultime
- Beaucoup de possibilités

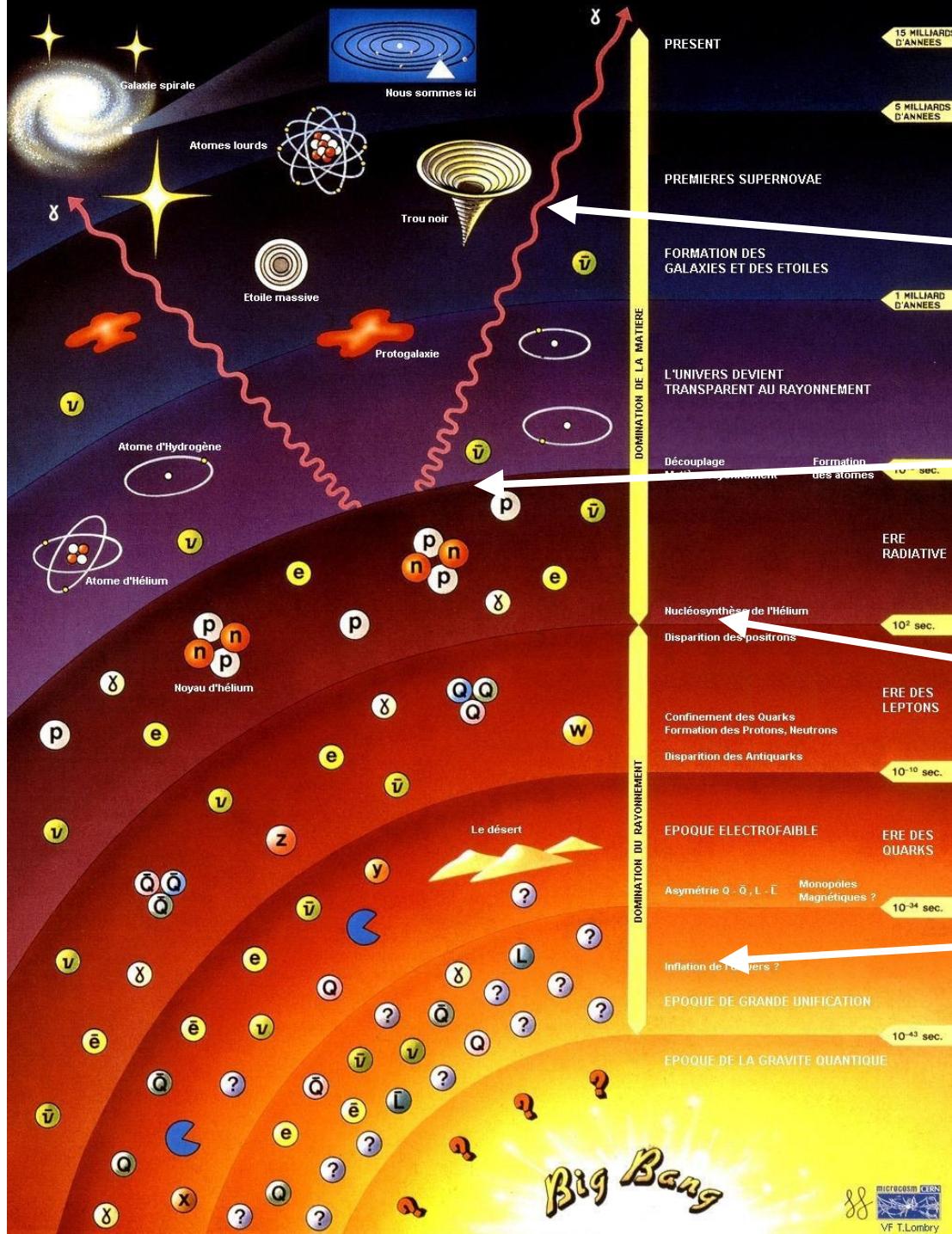


La matière noire a une faible probabilité d'interagir avec elle-même: entre atomes et noyaux
 $\sigma/m_{DM} < 1.8 \text{ kb/TeV}$
⇒ halo sphérique

WIMP=Weakly Interacting Massive Particle

L'Histoire de L'Univers

Cosmologie



- Formation de structures

Rayonnement fossile

Nucléosynthèse

Abondance de matière noire

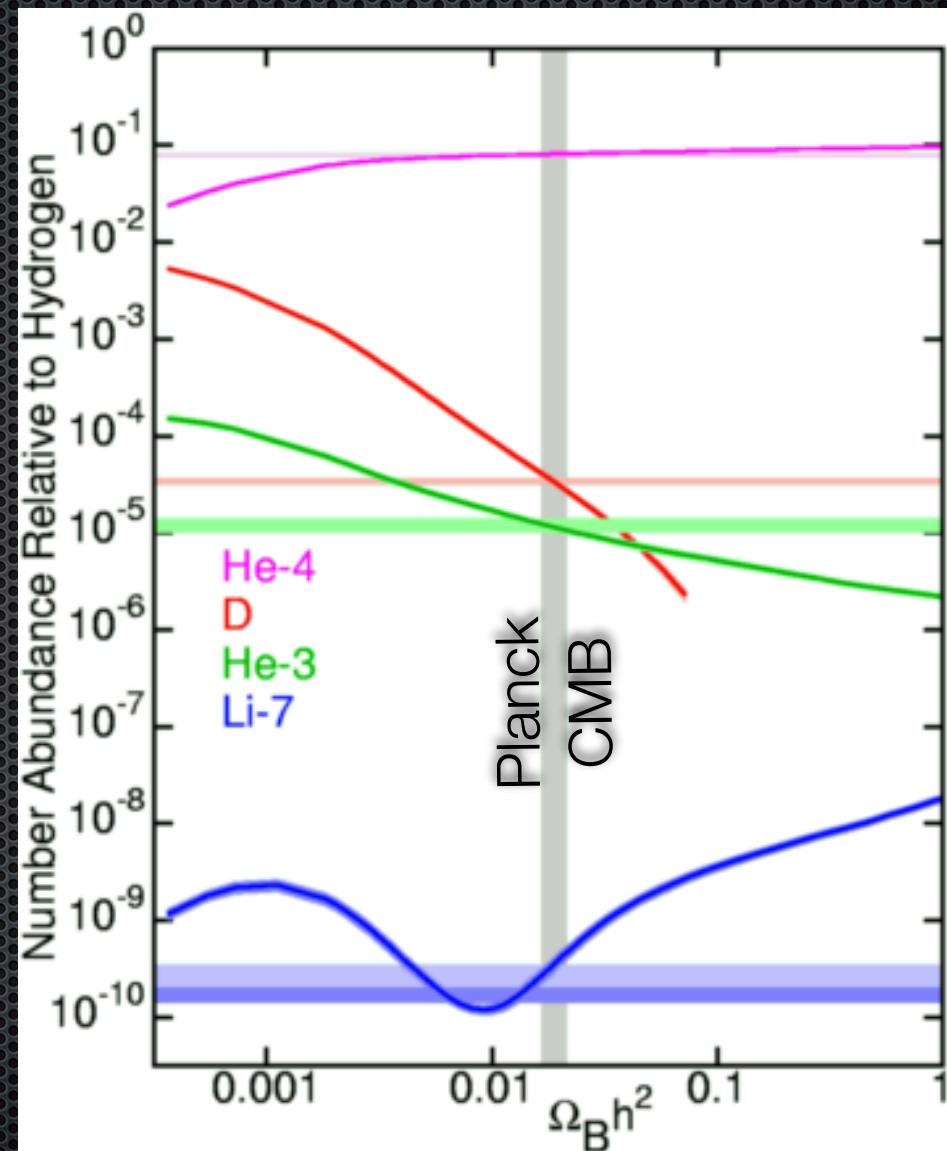
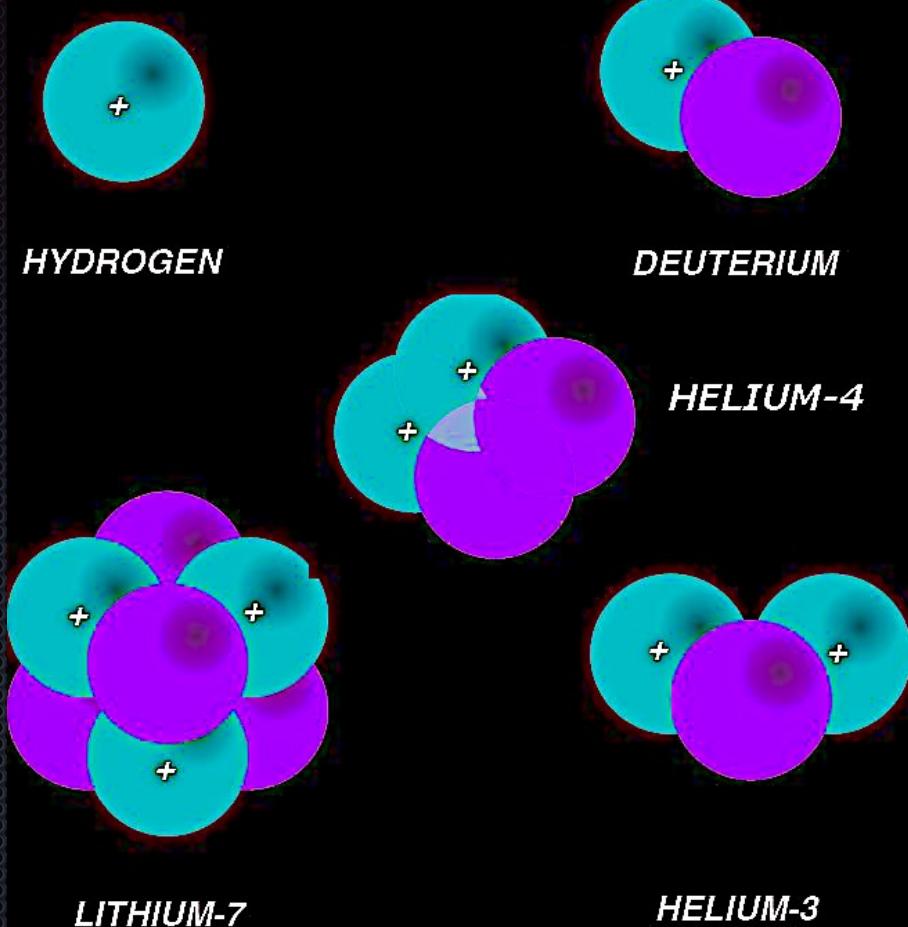
Abondance: “le miracle des WIMPs”

Interaction faible

$$M_{DM} \leq 100 \text{TeV}$$

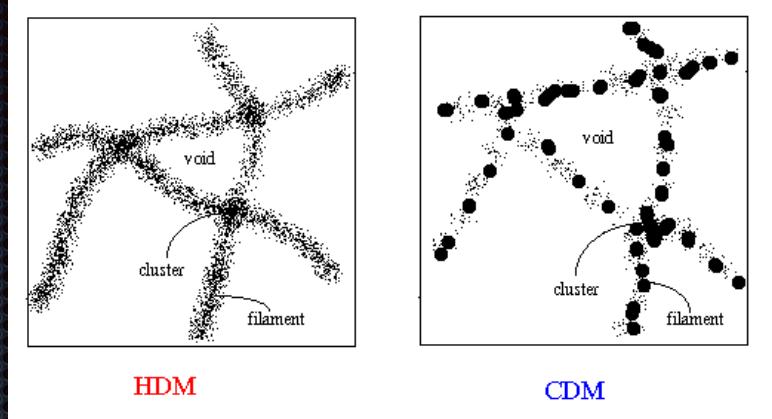
équivaut à 1 atome H/m³

Nucléosynthèse

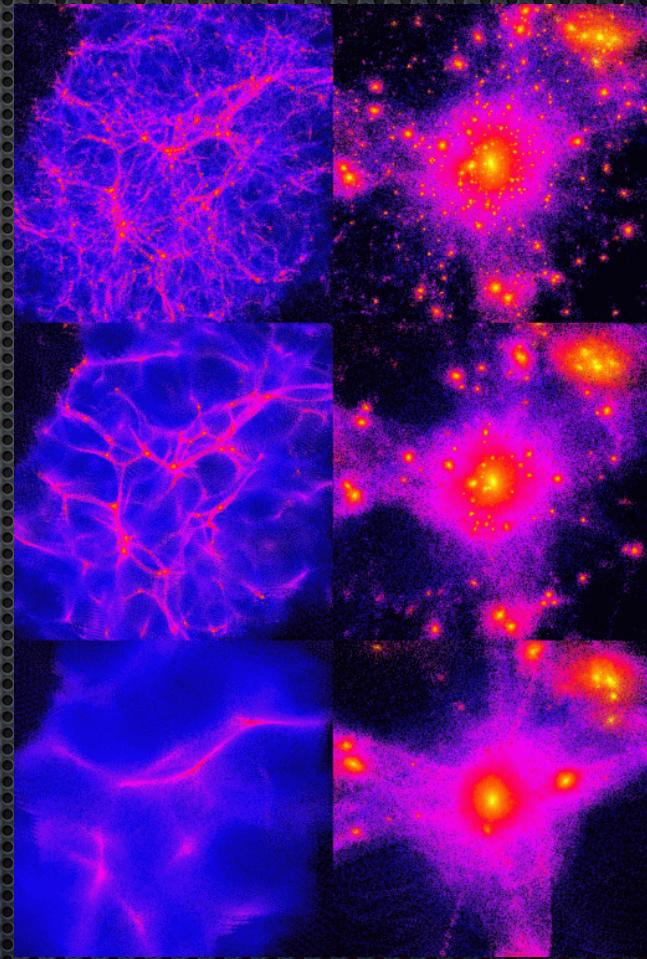


0.25 H/m³

Grandes structures



$v <<< c$
 $v \approx mm/s$



From top: Cold, Warm, and Hot dark matter simulations,
credit ITP, University of Zurich.

Densités dans l'Univers

- ☒ Matière noire : $1.3 \text{ GeV } c^{-2} \text{ m}^{-3}$ $M > 10 \text{ GeV}$
- ☒ protons&neutrons: $0.23 \text{ GeV } c^{-2} \text{ m}^{-3}$
- ☒ neutrinos: $0.026 \text{ GeV } c^{-2} \text{ m}^{-3}$
- ☒ photons: $0.00025 \text{ GeV } c^{-2} \text{ m}^{-3}$

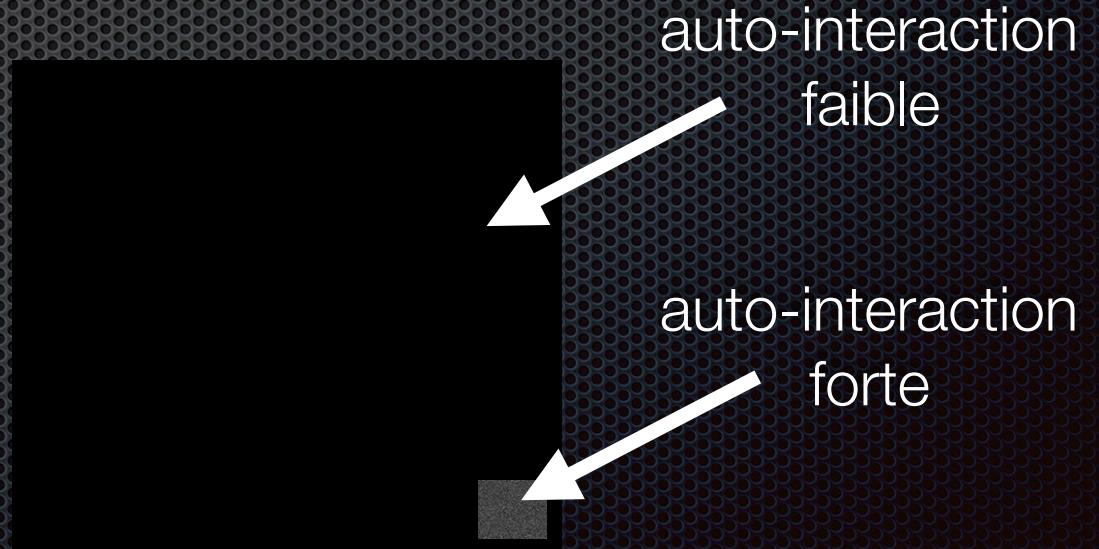
Conclusion 2: Carte d'identité de la matière noire

- Noire donc pas de charge électrique : composite ou neutre
- Stable ou temps de vie très long : nouveau nombre quantique/symétrie
- Associée à la matière standard (abondances similaires) : faiblement couplée à la matière standard
- Libre avant la nucléosynthèse : $10 \text{ MeV} < M$
- Non relativiste (lourde): $10 \text{ GeV} < M < 100 \text{ TeV}$
- “Petites” auto-interactions : (nucléaire OK: $100 \text{ b to } 10 \text{ kb}$)
- Abondance correcte : interactions similaires aux interactions faibles

Problèmes de structure :

- a) **Problème de concentration du halo:** trop de matière noire au centre des galaxies selon les simulations
- b) **Problème des satellites:** centaines de galaxies naines prédites contre dizaines d'observées.
- c) **Problème “trop gros pour échouer”:** certains sous-halos prédits doivent avoir des étoiles visibles non observées

Deux sortes de matière noire ?



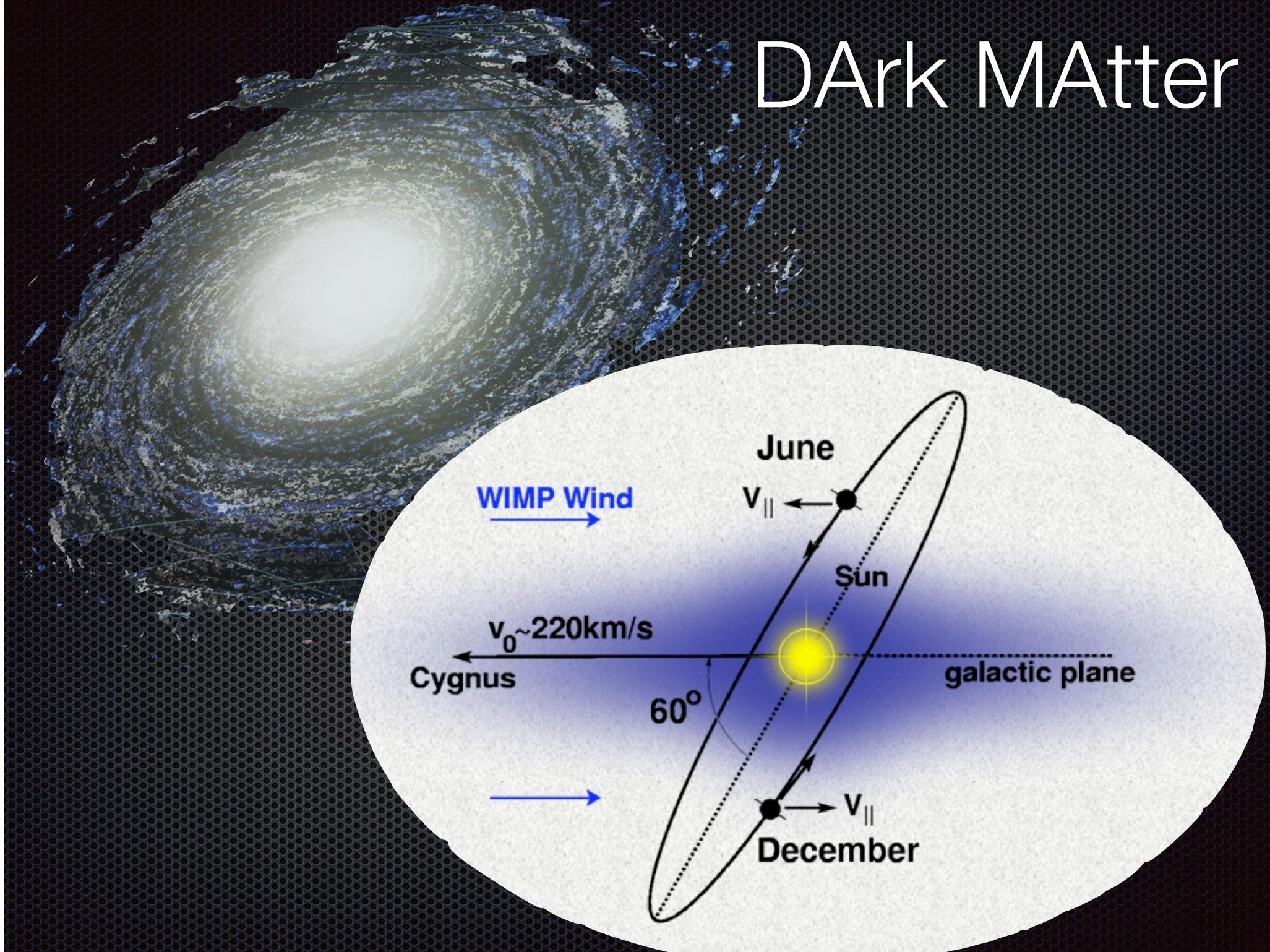
Observations?



Plan

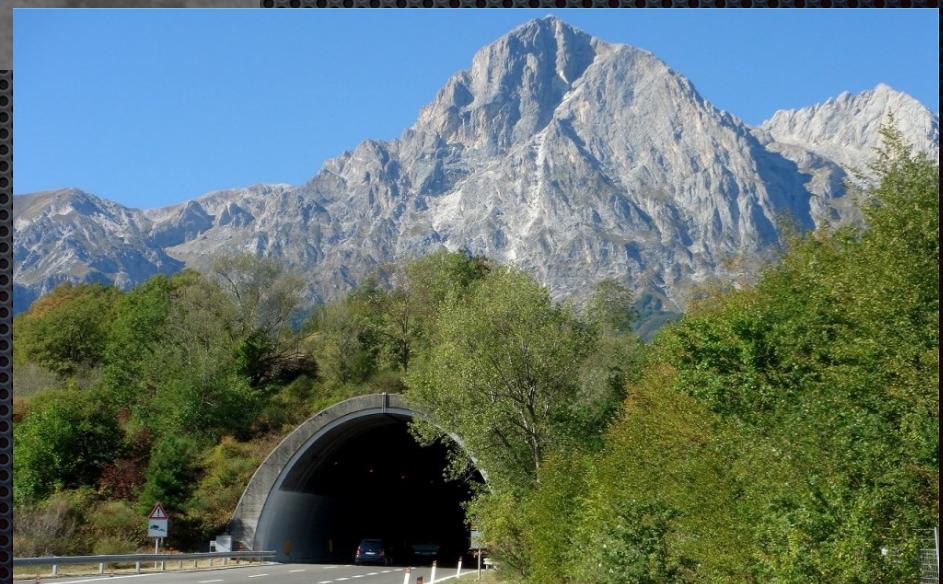
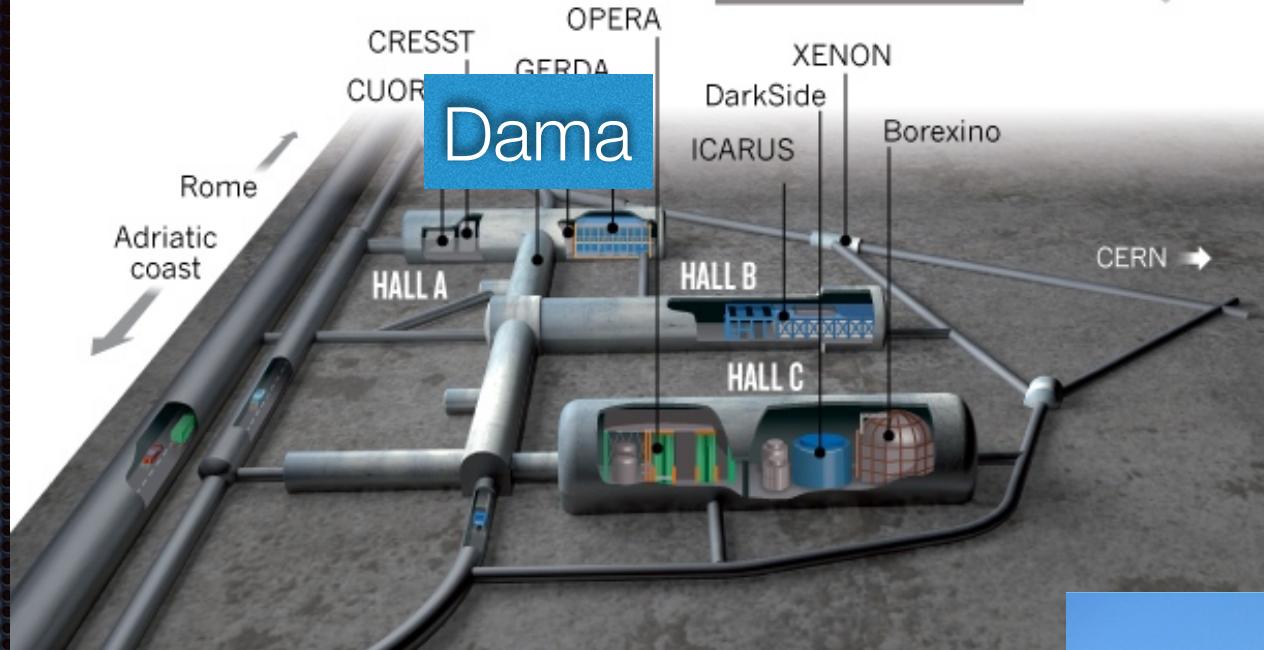
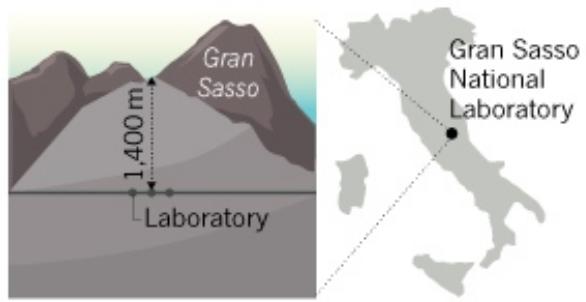
- Position du problème
- Les preuves d'existence
- Les causes possibles
- **Une expérience de détection directe : DAMA**
 - **Description**
 - **Résultats**
 - **Autres expériences**
- Une expérience de détection indirecte : AMS

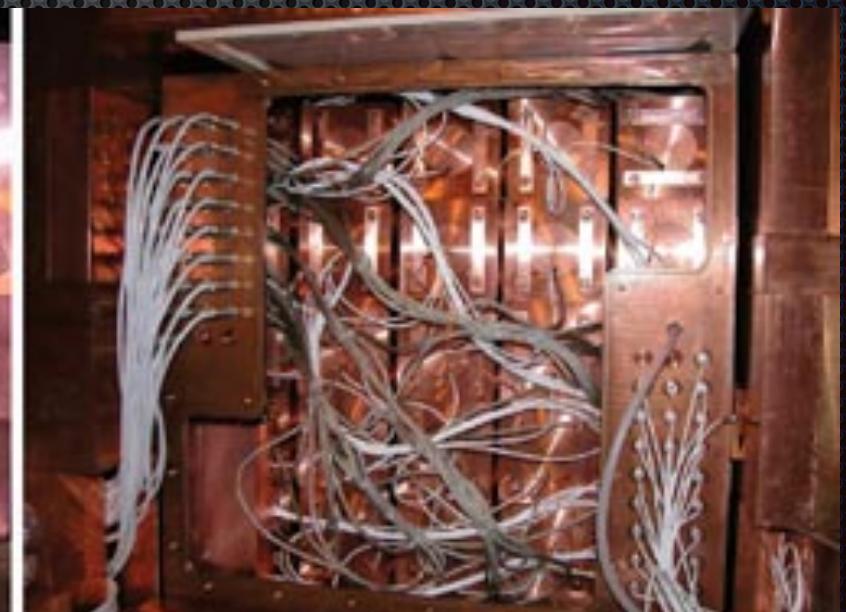
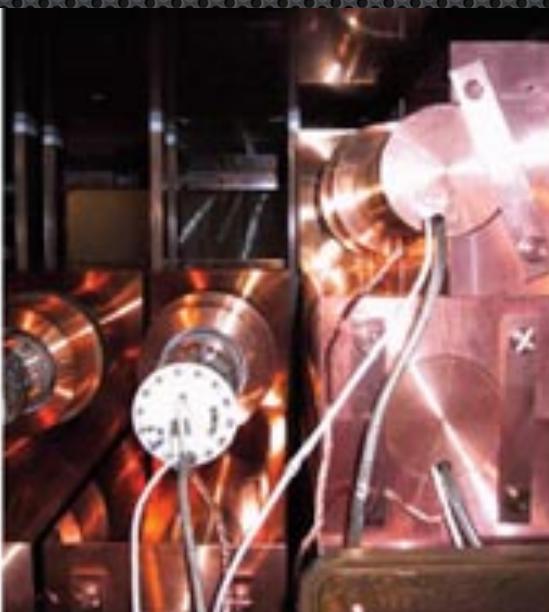
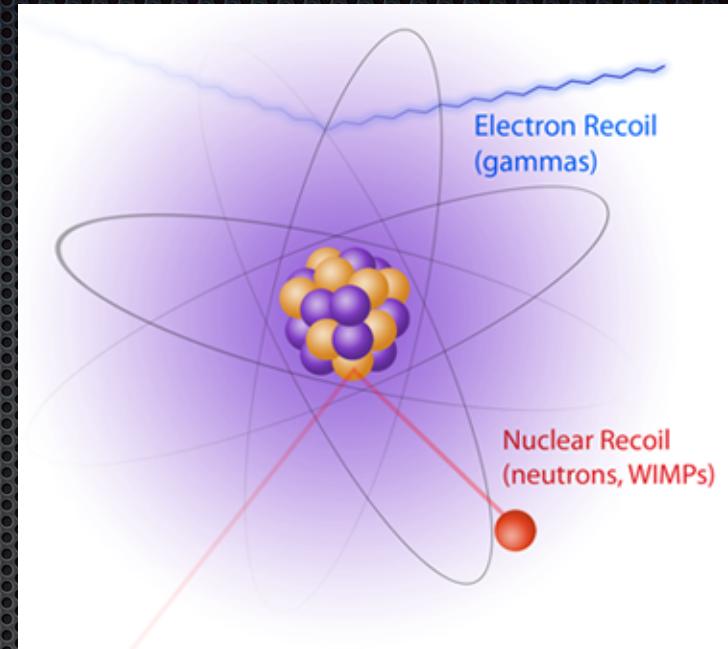
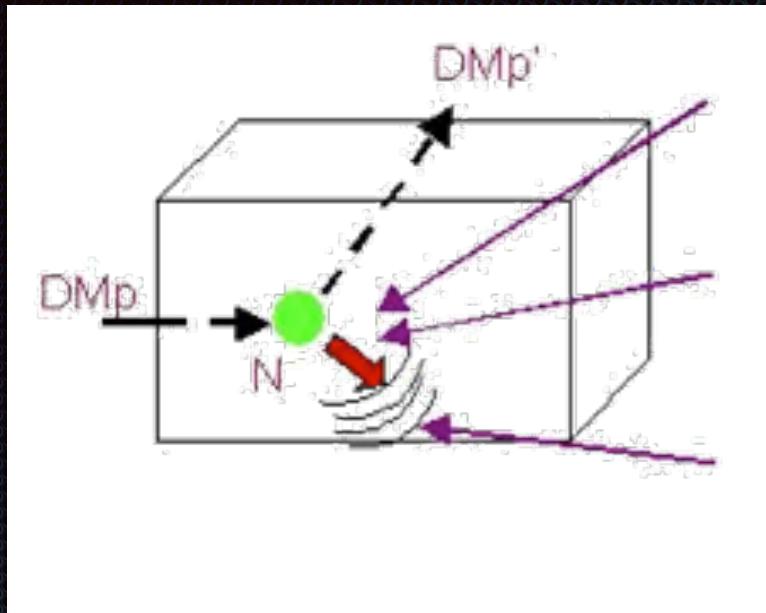
DArk MATter

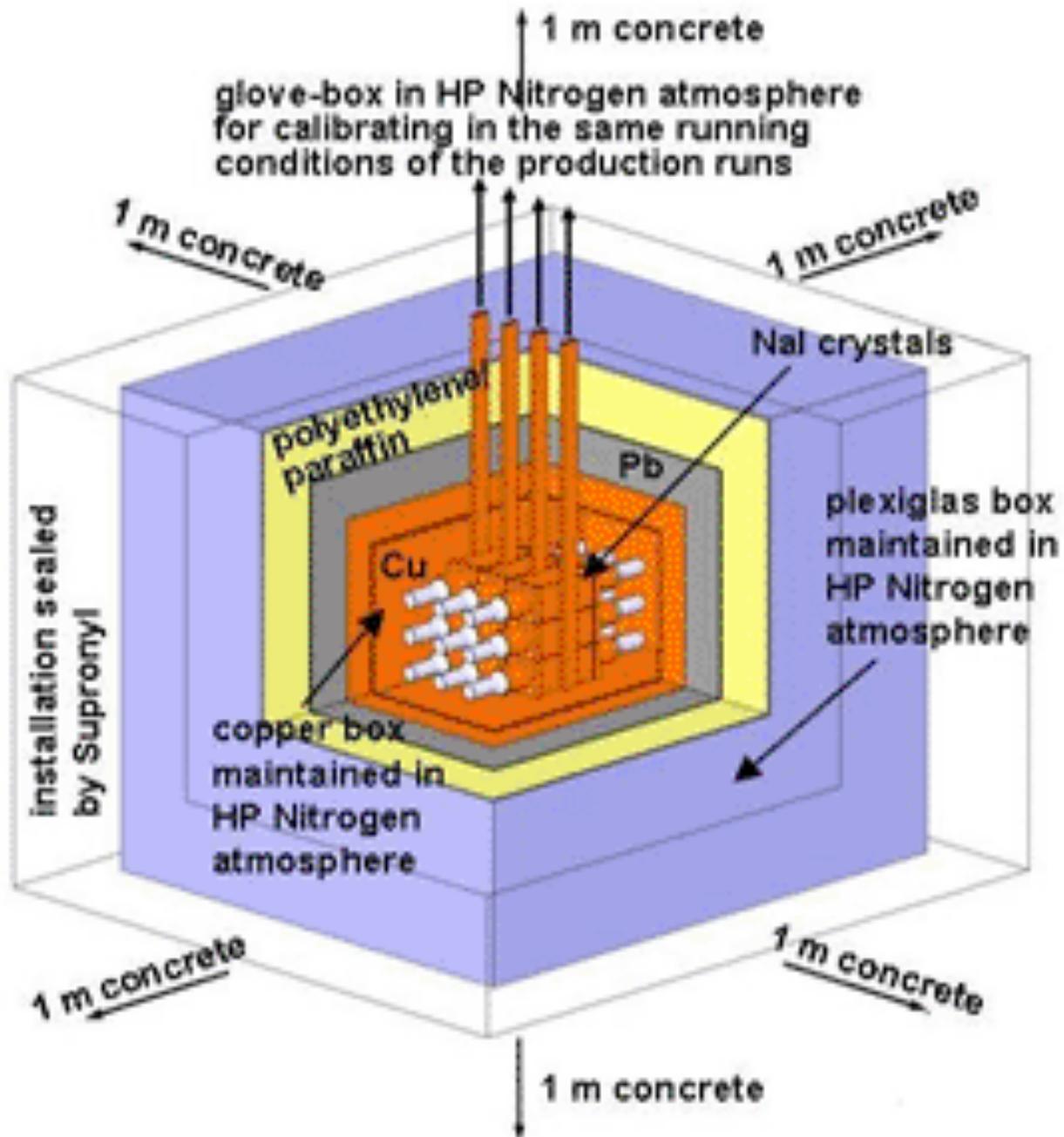


THE A, B AND C OF GRAN SASSO

Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.

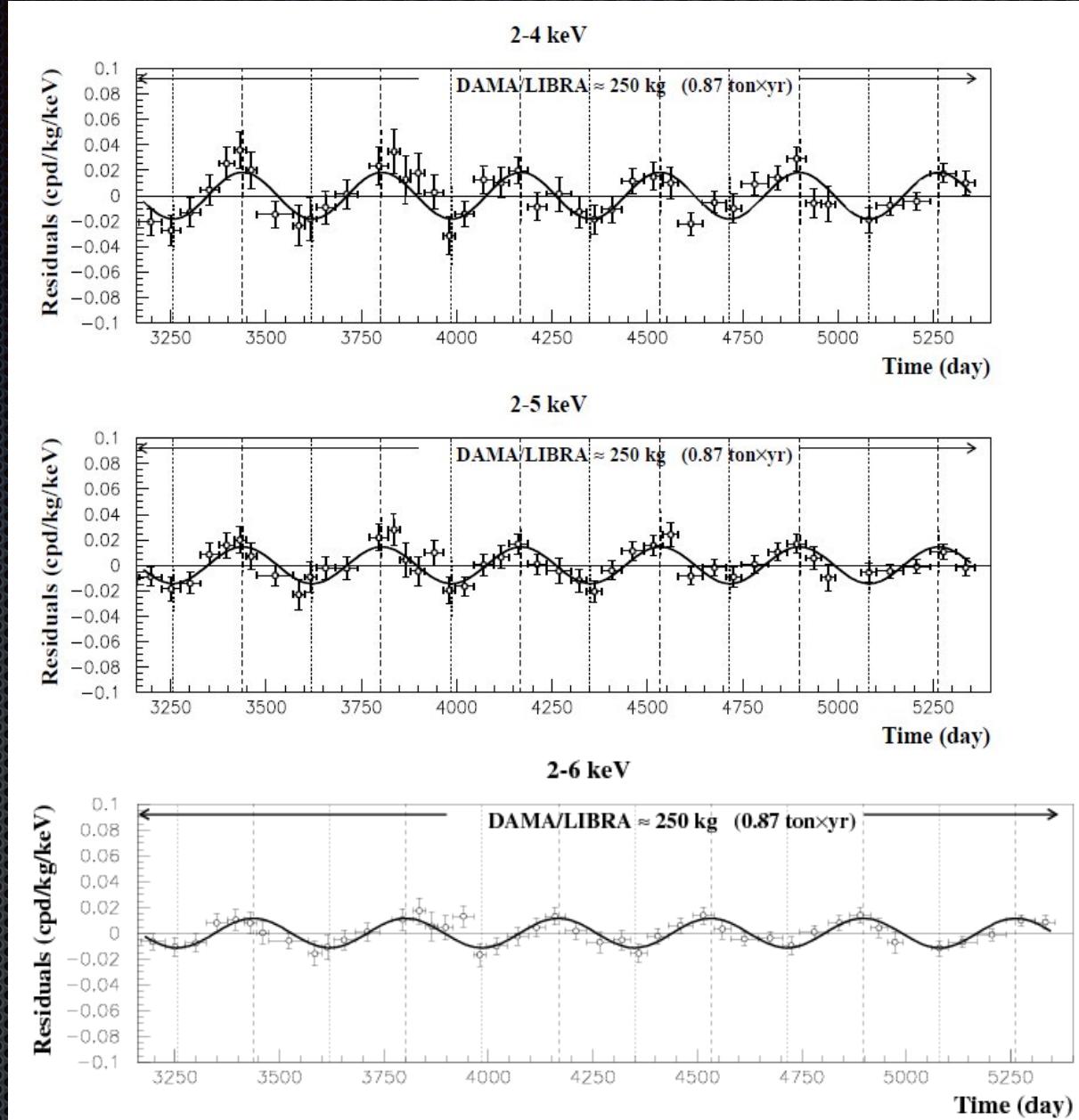






Simplified schema of ~ 100 kg $\text{NaI}(\text{Tl})$ set-up

Déetecte
les
photons



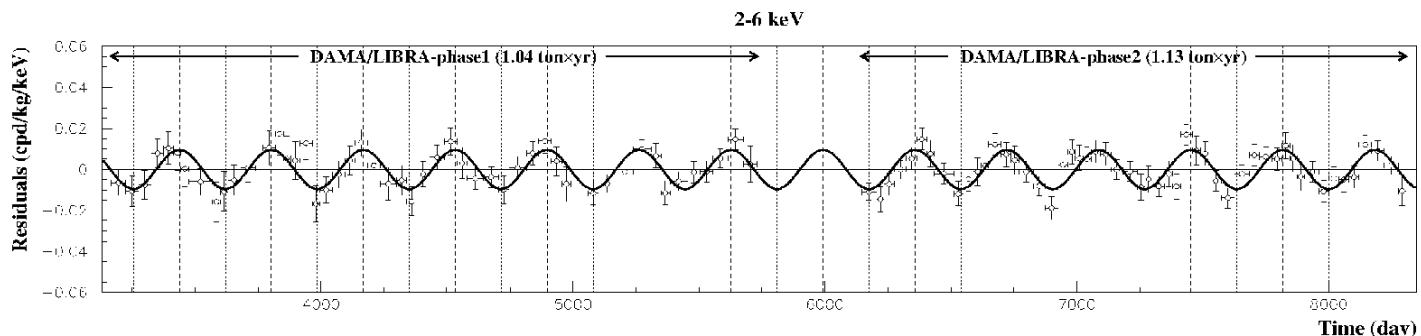
Niveau de confiance : 9σ ,
phase correcte, période correcte

Dernières nouvelles :

Model Independent DM Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.17 ton \times yr)



Absence of modulation? No

$$\bullet \text{2-6 keV: } \chi^2/\text{dof} = 199.3/102 \Rightarrow P(A=0) = 2.9 \times 10^{-8}$$

Fit on DAMA/LIBRA-phase1+
DAMA/LIBRA-phase2

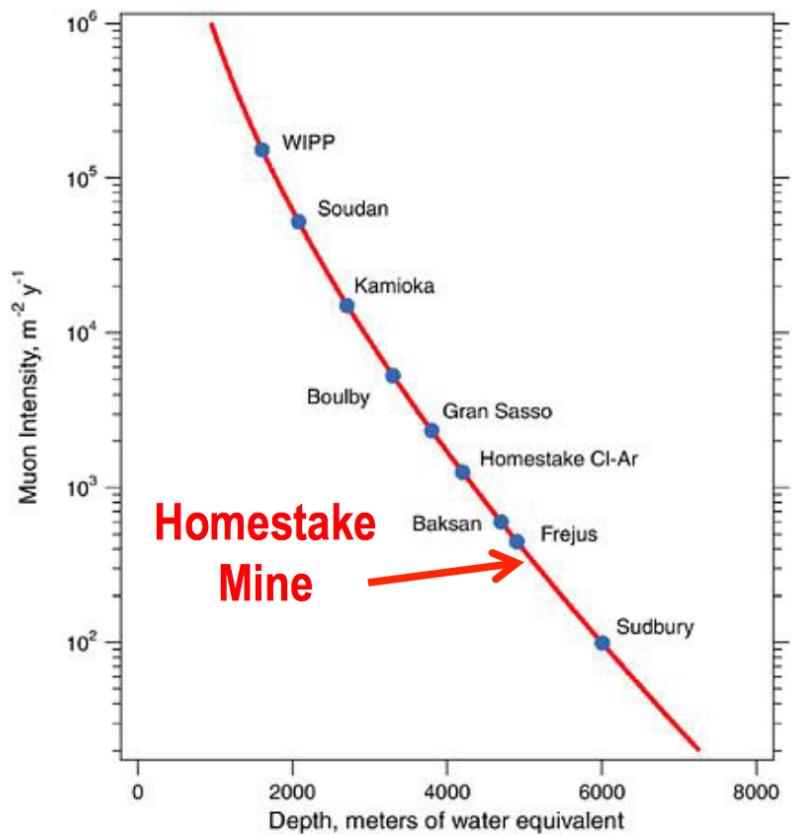
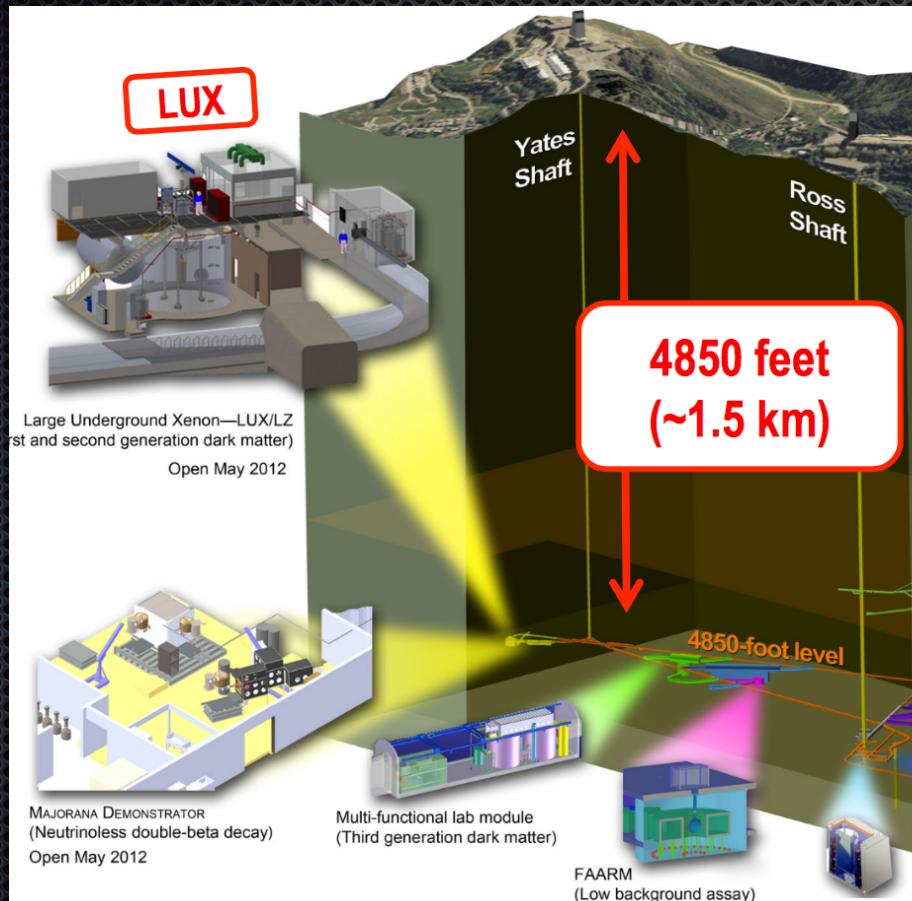
$$\text{Acos}[\omega(t-t_0)] ; \\ \text{continuous lines: } t_0 = 152.5 \text{ d, } T = 1.00 \text{ y}$$

2-6 keV

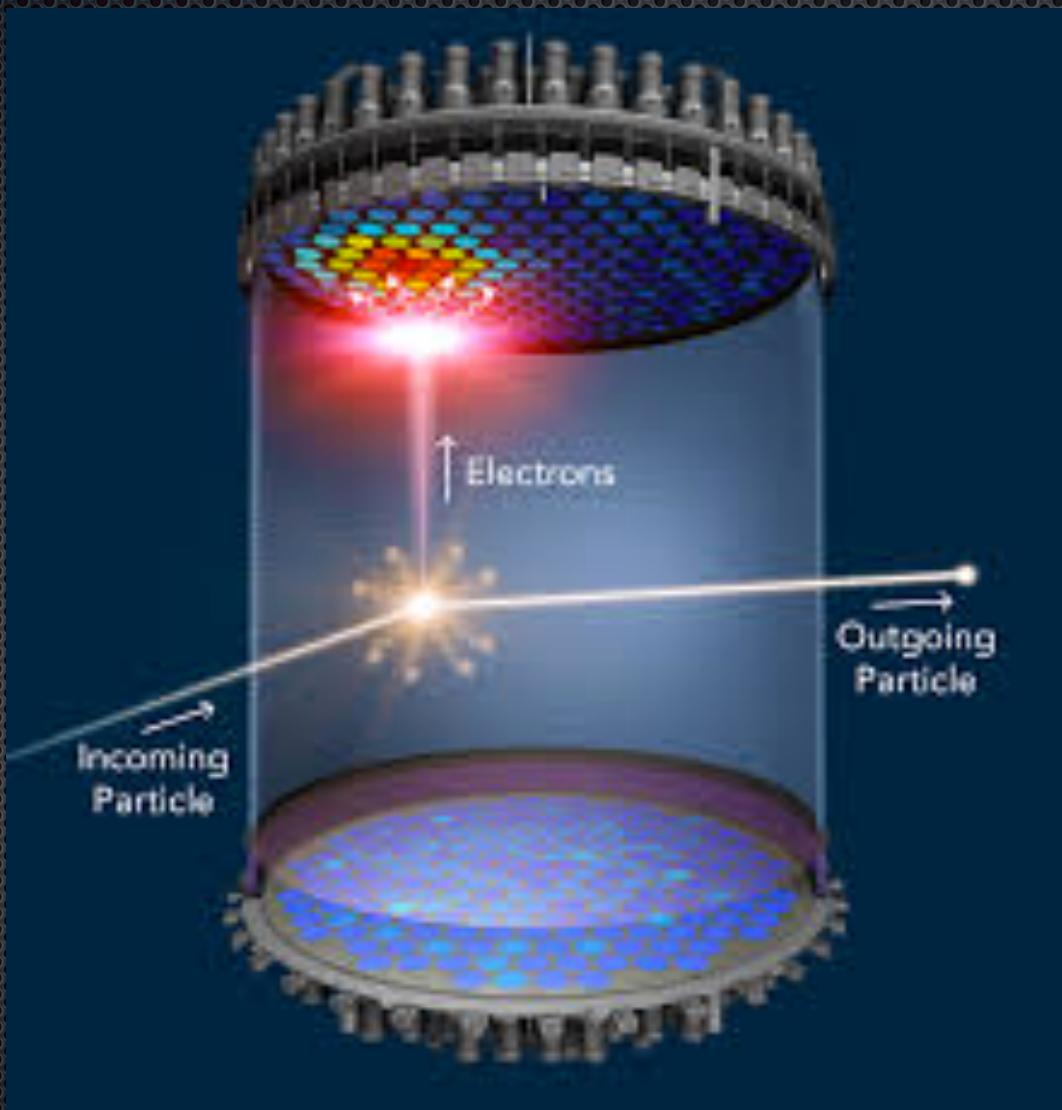
$$A = (0.0095 \pm 0.0008) \text{ cpd/kg/keV} \\ \chi^2/\text{dof} = 71.8/101 \quad 11.9\sigma \text{ C.L.}$$

The data of DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.9σ C.L.

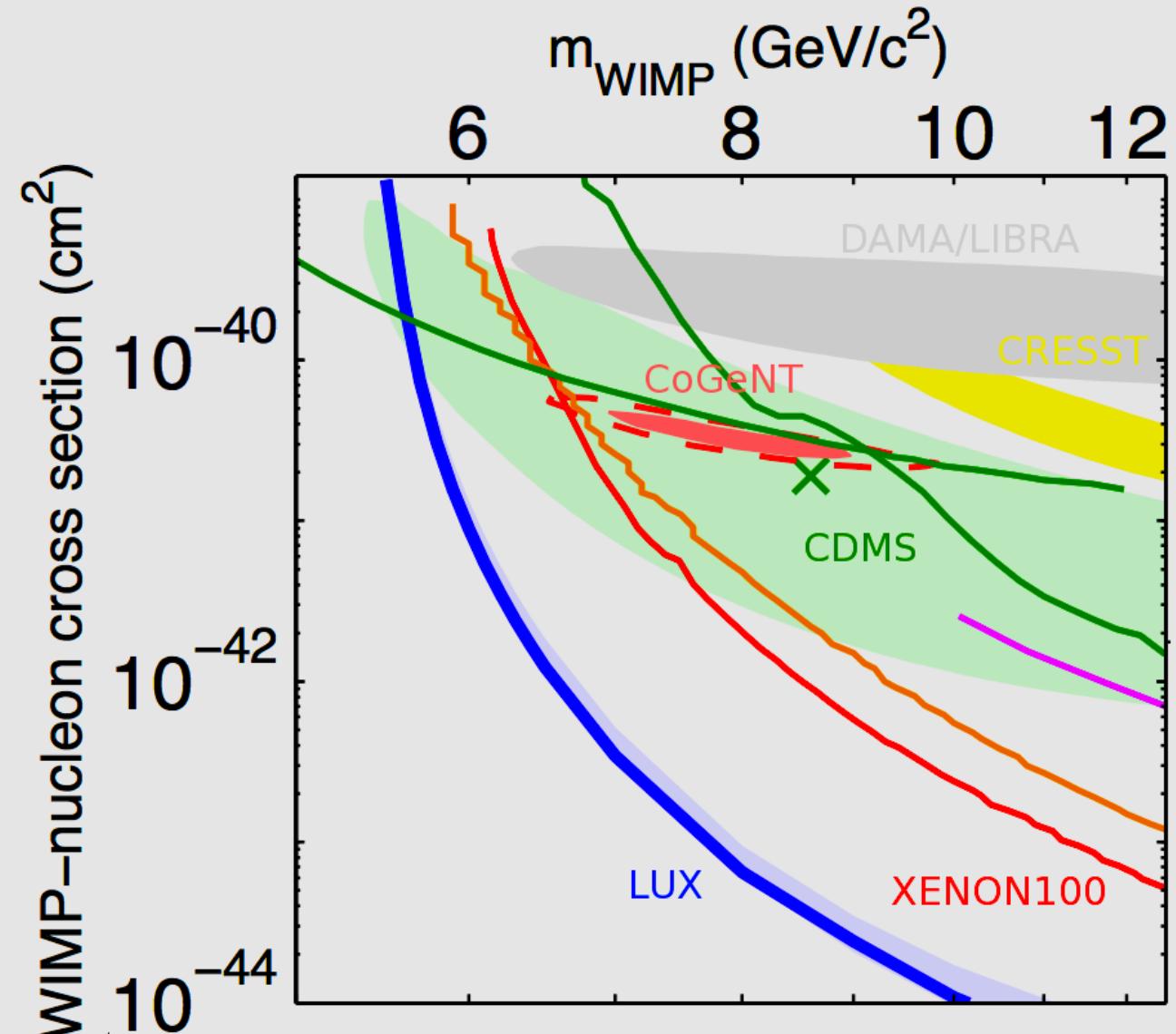
Mais...



LUX



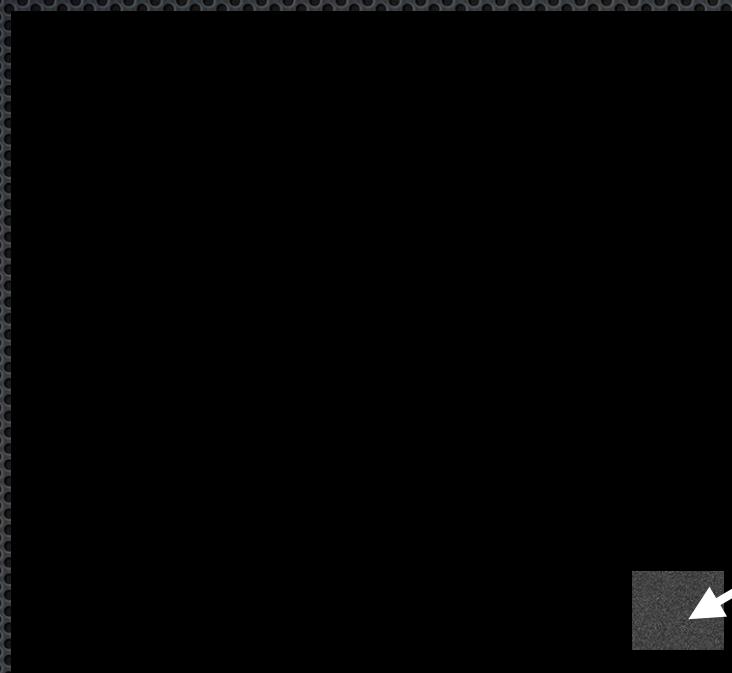
LUX ne voit pas de
recul nucléaire



- Deux modèles de matière noire peuvent reproduire toutes les expériences
 - ▶ interaction aussi forte que celle des neutrons
—>thermalisation
 - ▶ 5% de la matière noire
 - ▶ liaison avec éléments lourds (Thallium)

Q. Wallemacq et J.R.C., “Dark antiatoms can explain DAMA,” JCAP 1502 (2015) no.02, 011 [arXiv:1411.3178 [hep-ph]].

Conclusion 3:

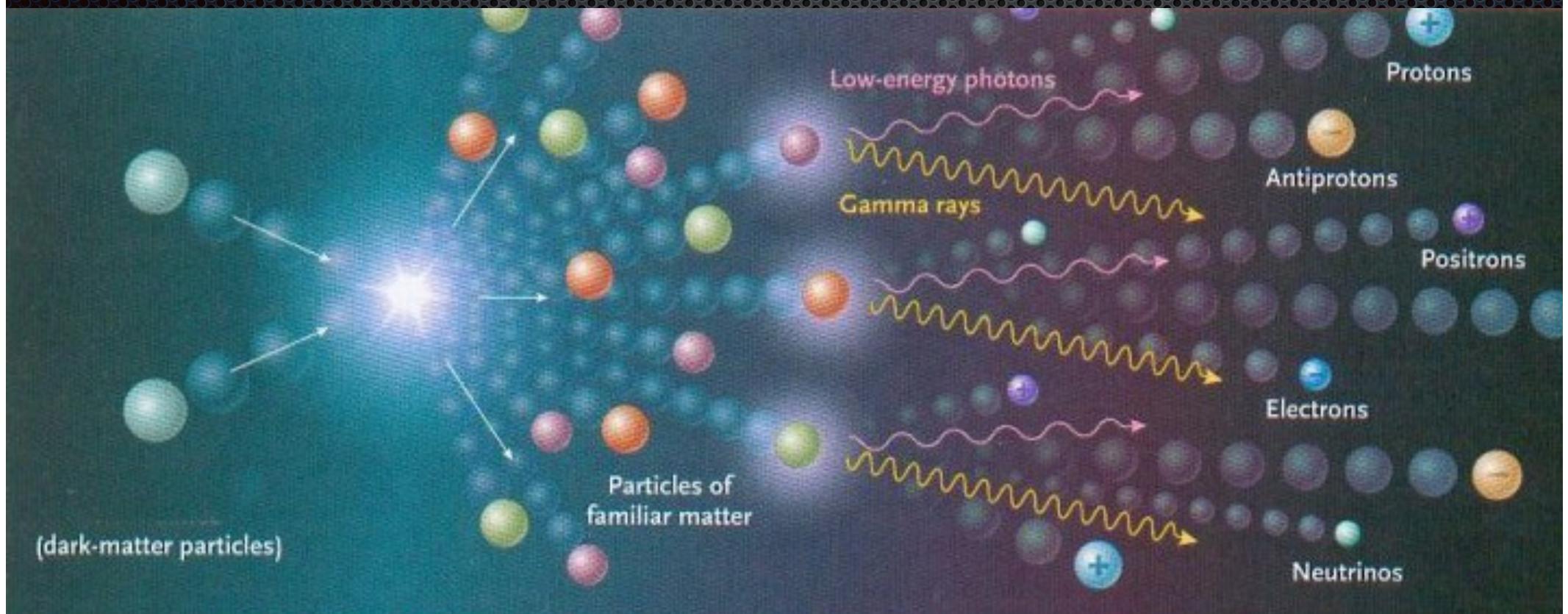


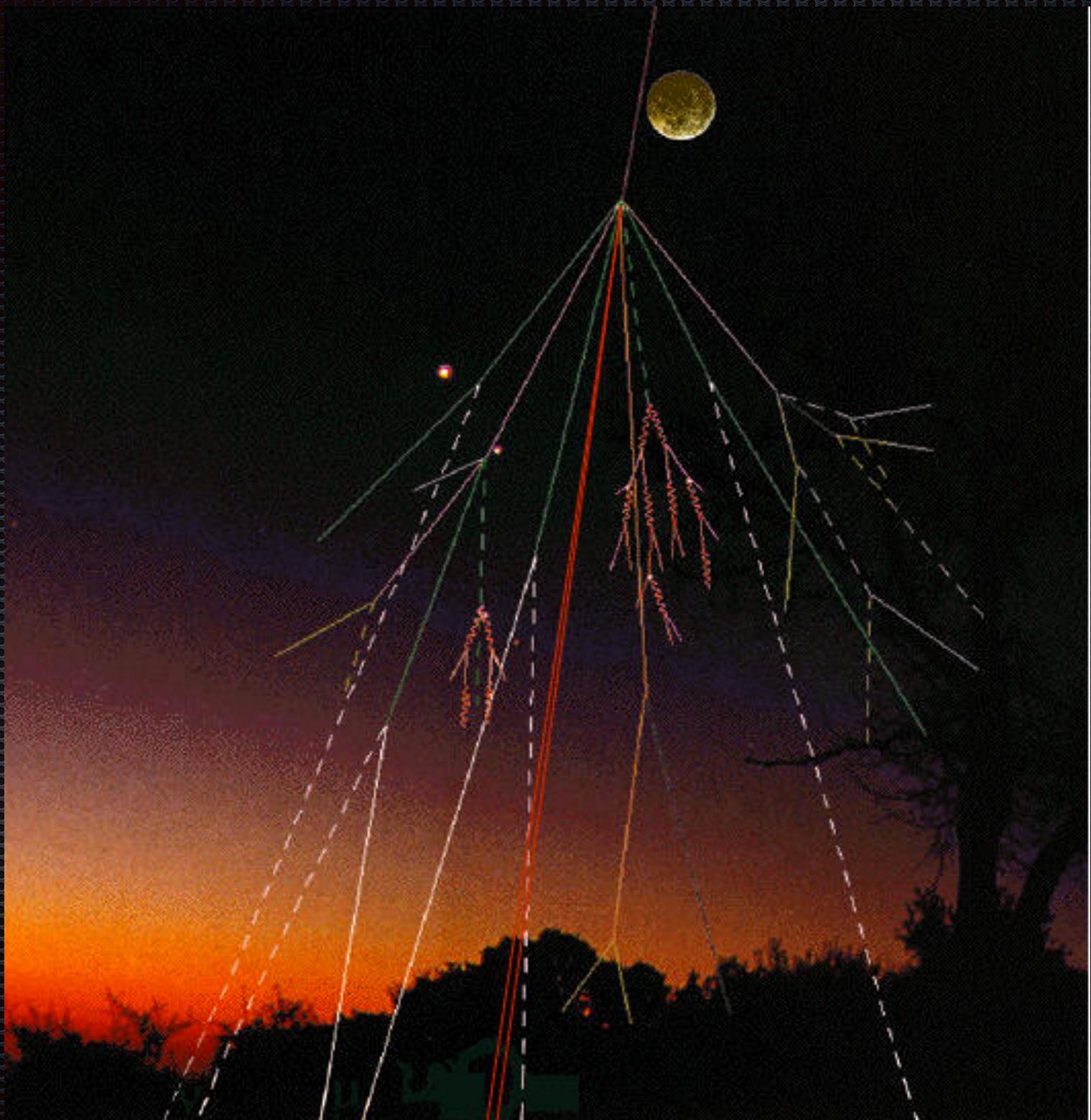
DAMA

Plan

- Position du problème
- Les preuves d'existence
- Les causes possibles
- Une expérience de détection directe : DAMA
- Une expérience de détection indirecte : AMS
 - L'idée de base
 - Le détecteur
 - Les résultats de 2016

La détection indirecte

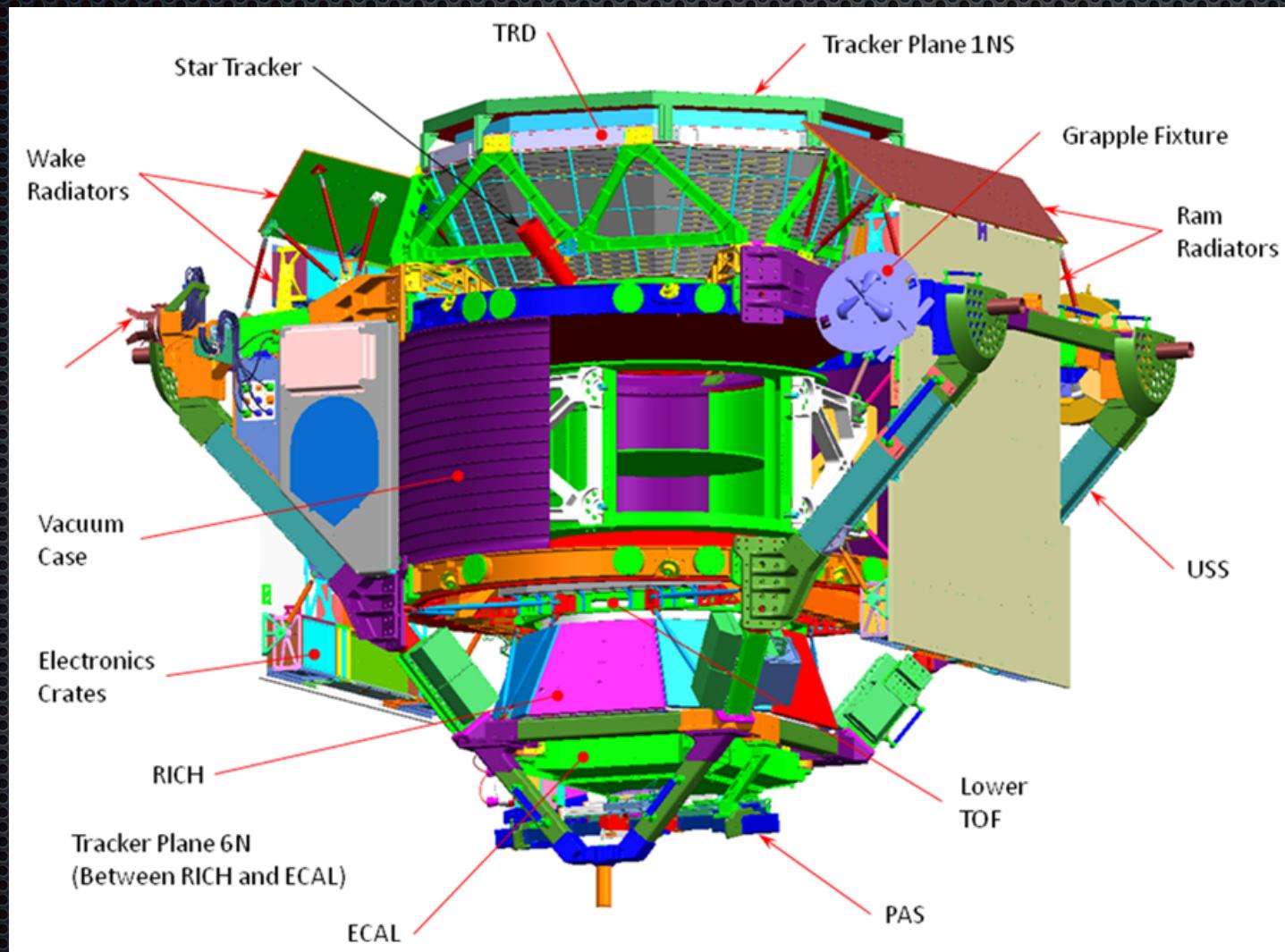


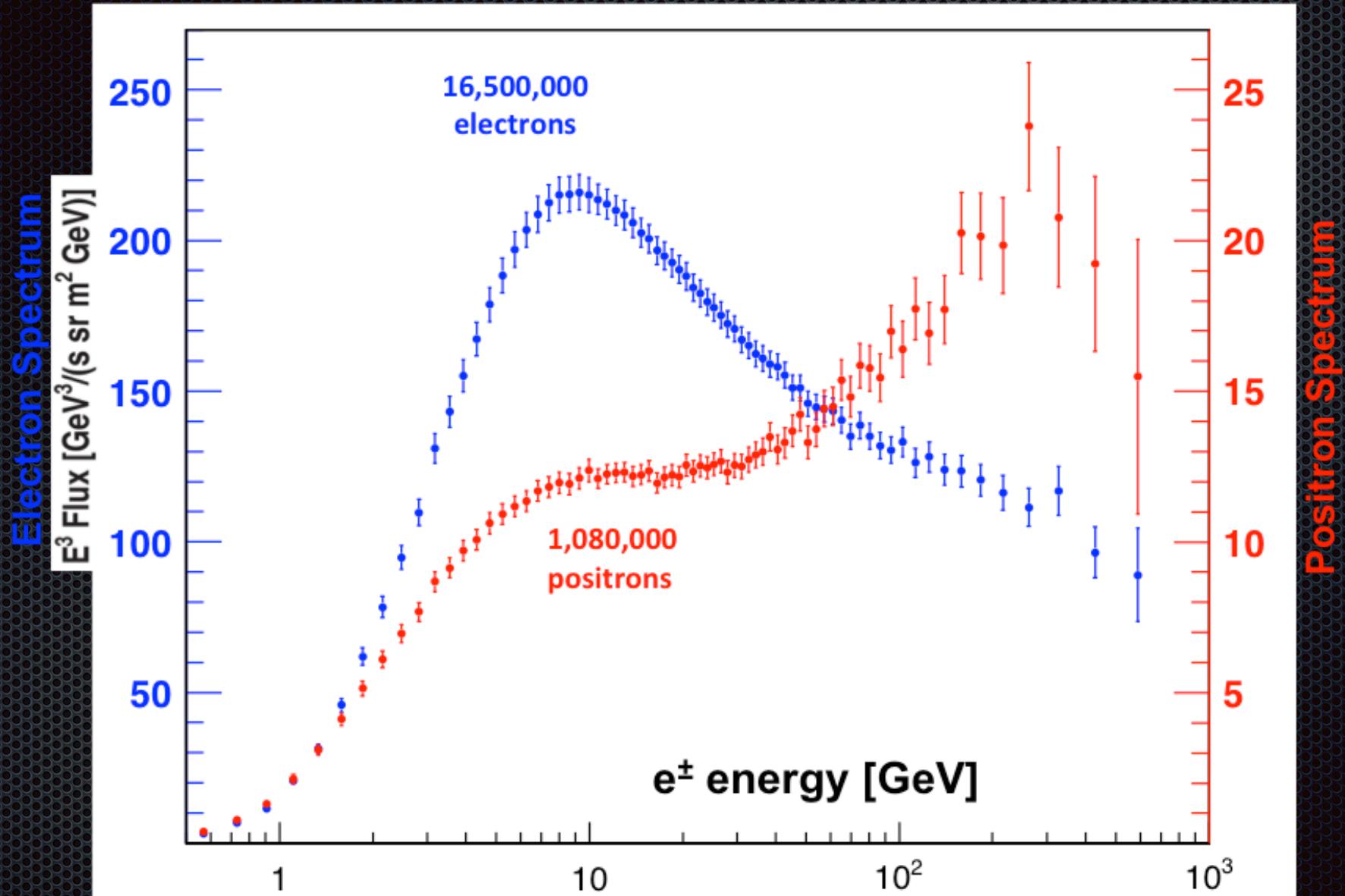


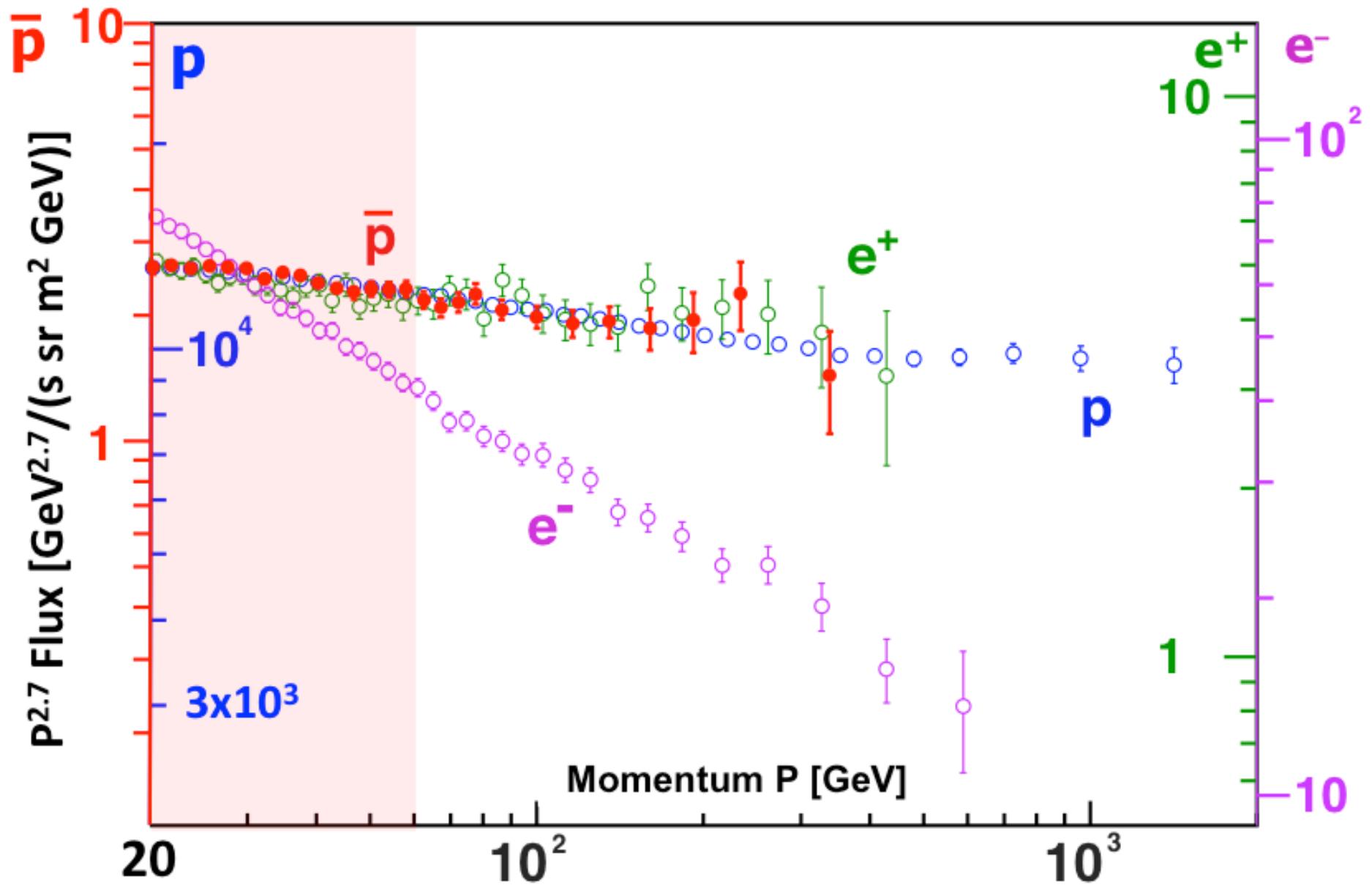


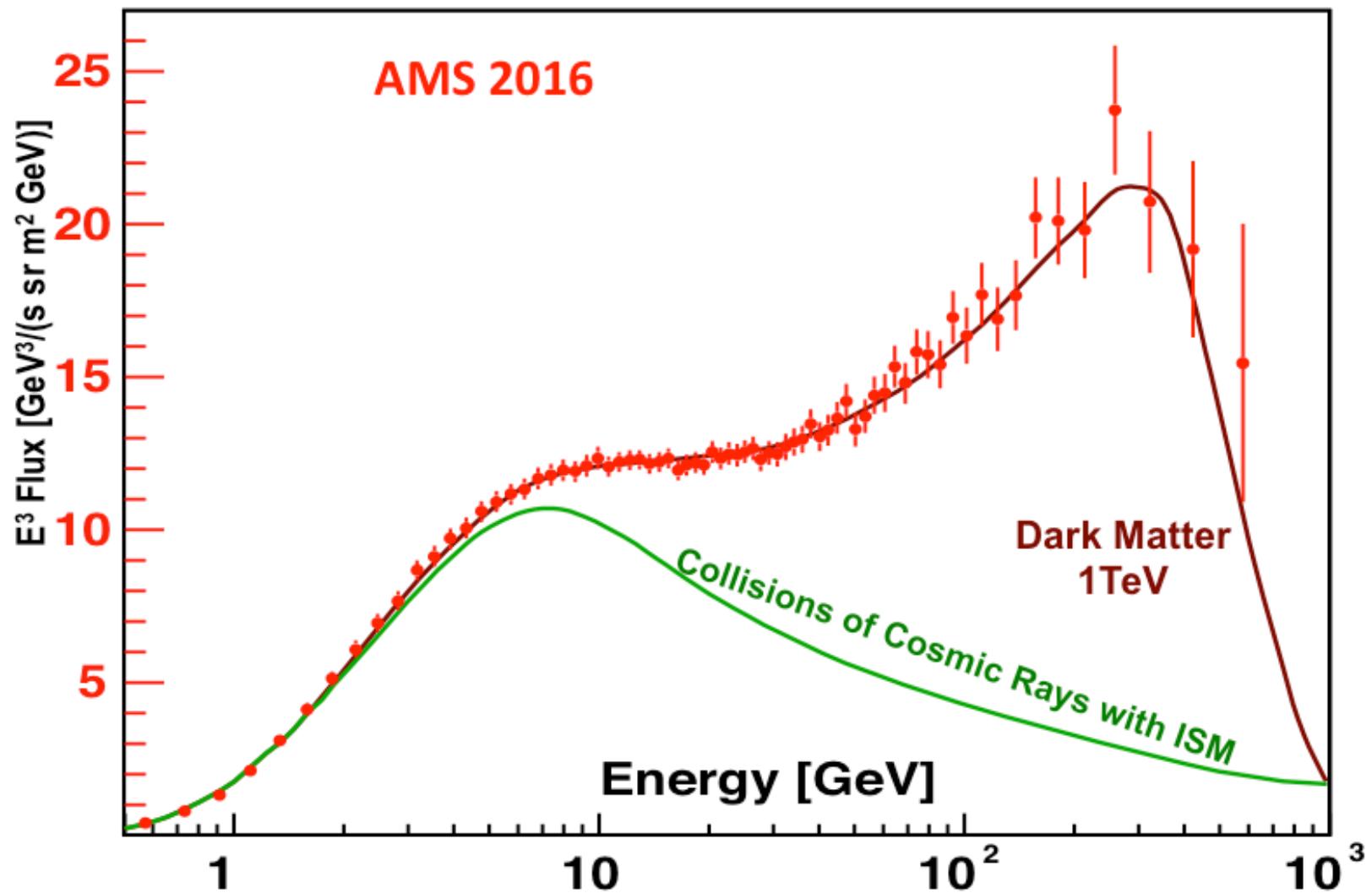
8,5 tonnes, 64 m³

1,5 milliard d'€

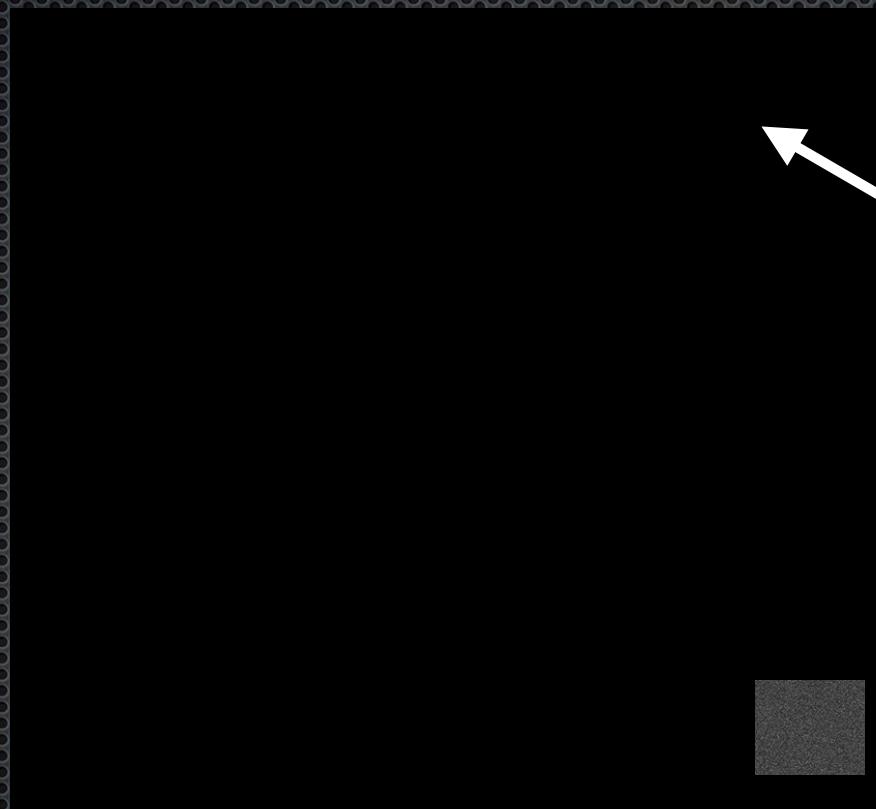








Conclusion 4



AMS02

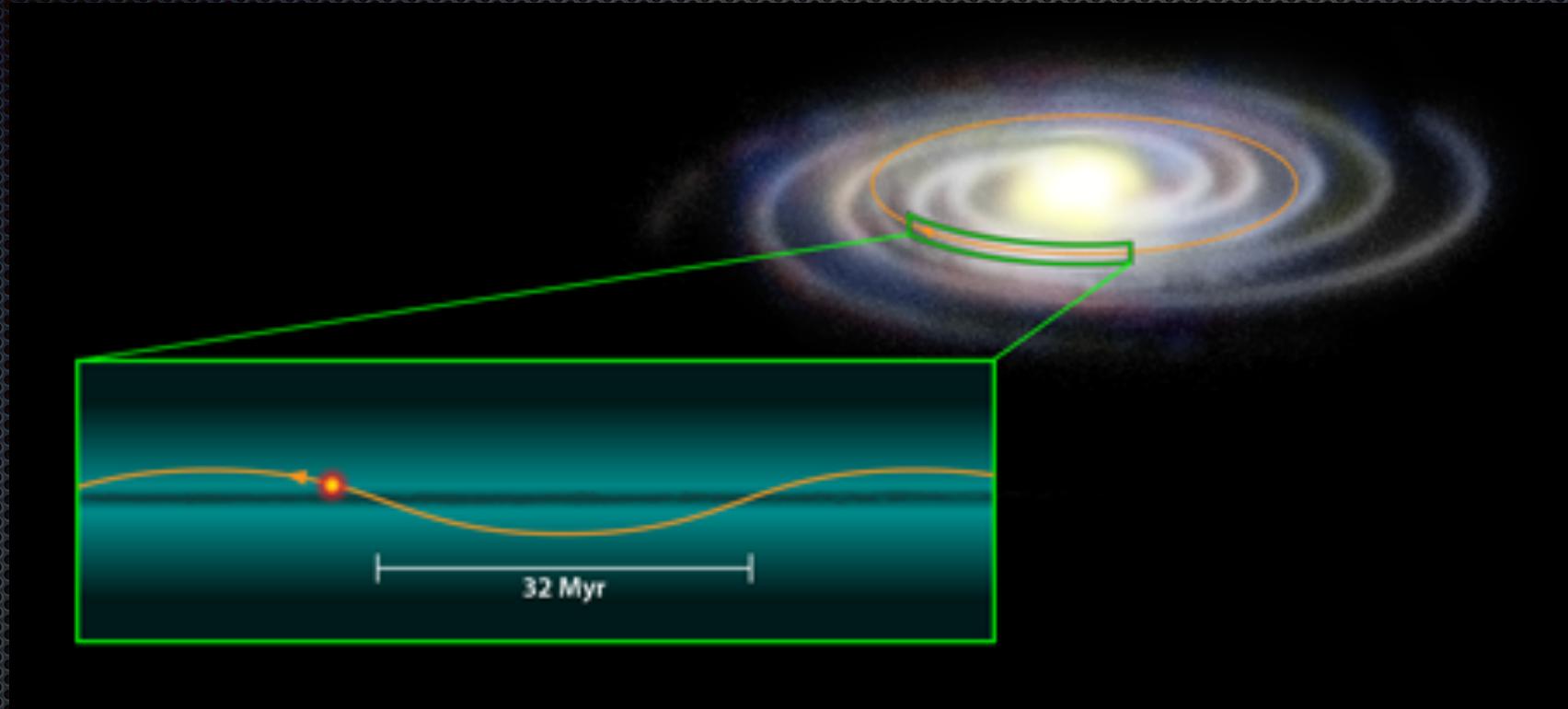
Conclusion

- Gravité différent à des échelles différentes
 exceptions
- MACHOs Nucleosynthèse primordiale ->
 pas p ou n
 trous noirs??
- Particules

Particules

- masses $1000 m_p$
- deux sortes:
 - 5% atomes noirs interagissant fort entre eux et peu avec nous
 - 95% particules neutres interagissant peu entre elles et avec nous

Nouvelles conséquences ?



Disque double et extinctions ?

Lisa Randall and Matthew Reece, “Dark Matter as a Trigger for Periodic Comet Impacts,” **Phys. Rev. Lett. 112, 161301 (2014)**

Futur



AMS02: jusqu'en 2024

Vérification de DAMA

ANALIS Experiment

250 kg NaI(Tl) scintillators to look for Dark Matter (DM) annual modulation at Canfranc Underground Laboratory (LSC)

$\alpha = 60^\circ$, $v_{\text{orbital}} = 30 \text{ km/s}$, $v_{\text{sun}} = 225 \text{ km/s}$

LSC, Spain 2450mwe

ANALIS Hall A

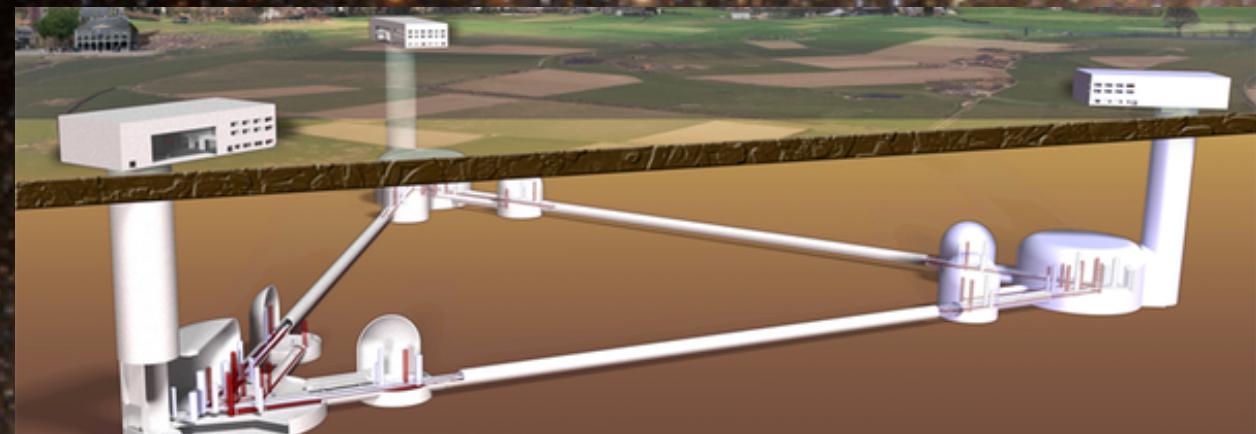
Goal:
Confirmation of DAMA/LIBRA positive signal with same target and technique

Experimental requirements:

- Energy threshold < 2 keVee
- Background < 2 c/(keV kg day)



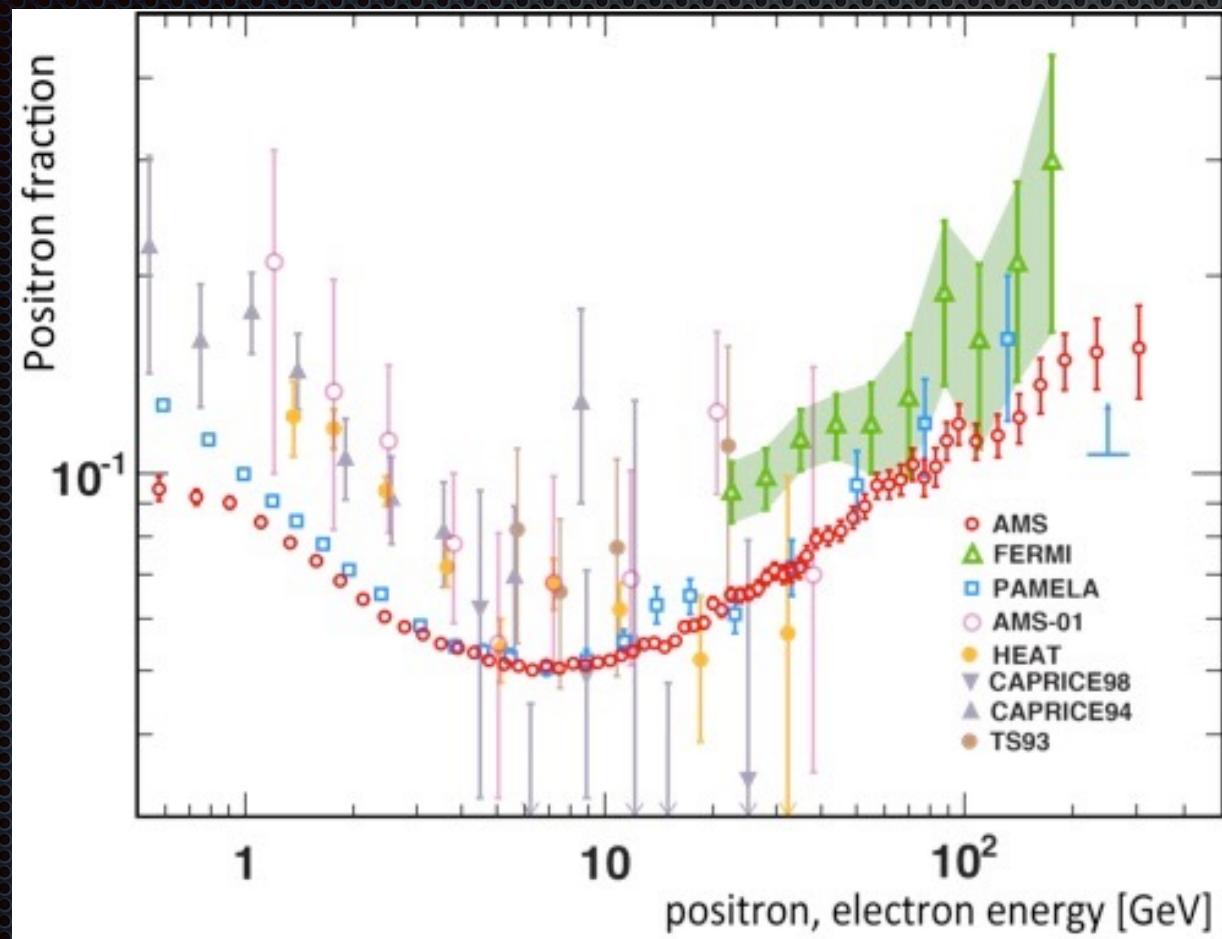
LIGO/VIRGO/Einstein telescope: trous noirs



Merci

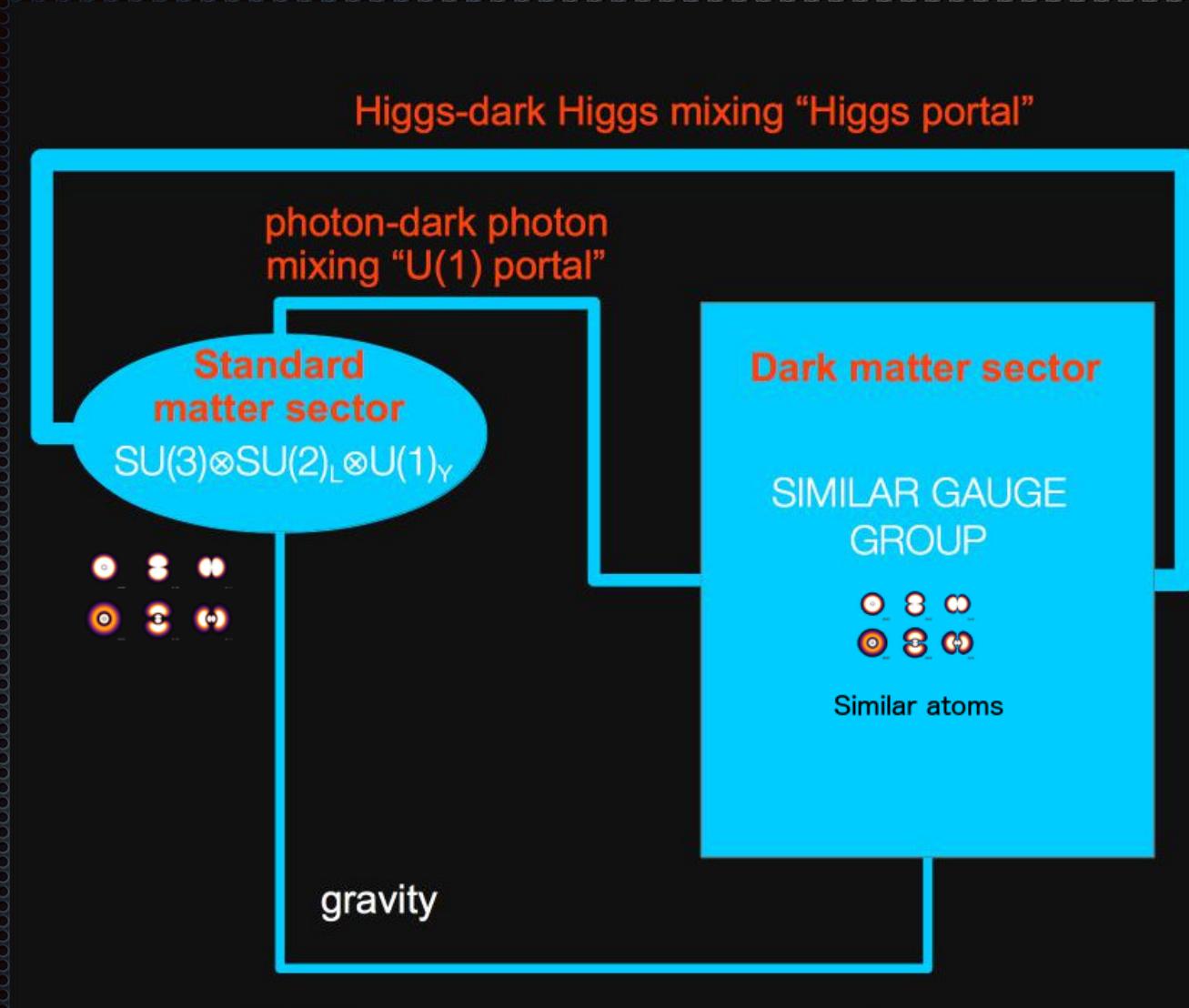
AMS-02

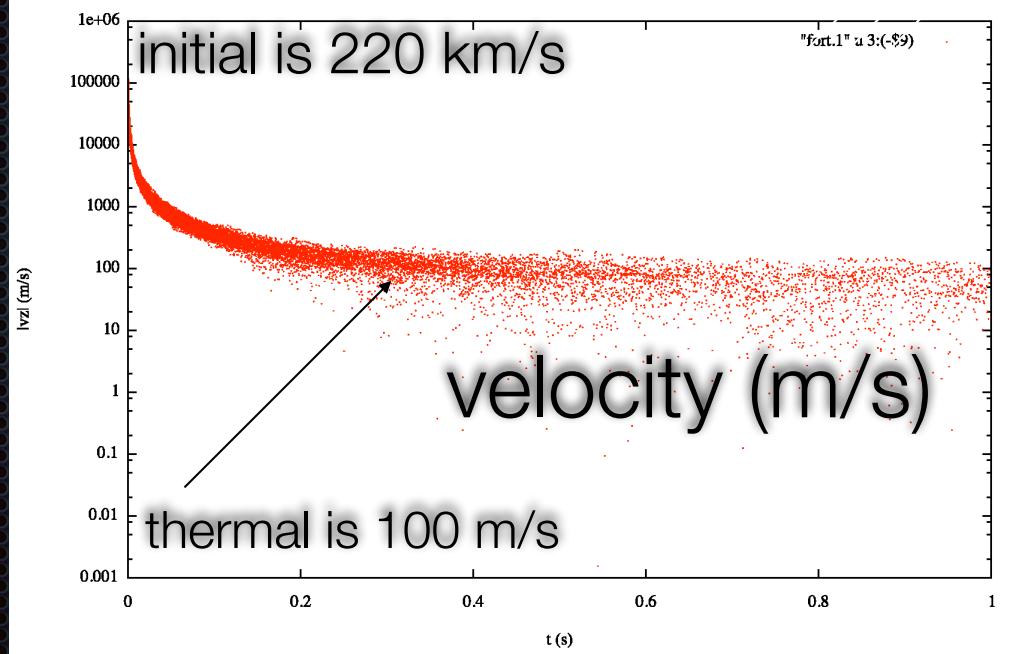
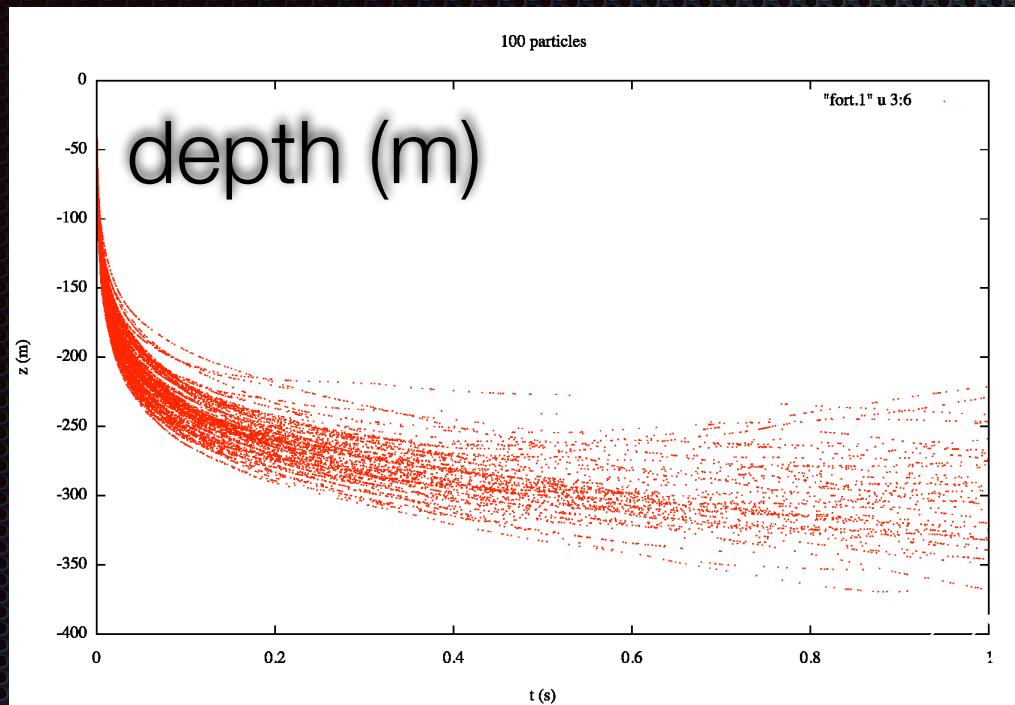
Alpha Magnetic Spectrometer



Signal confirmed

What are Dark Atoms?





$$\lambda = 1 \text{ m}$$

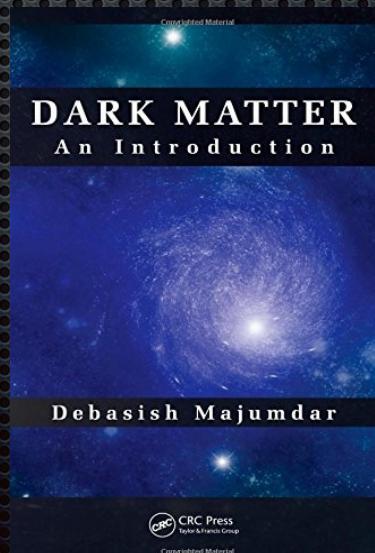
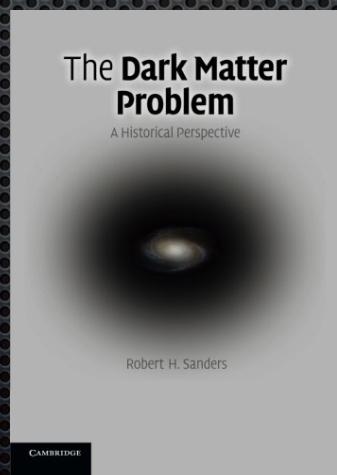
Thermal cloud then
slowly drifts down

$$v_d = 8.6/\text{s} \quad \lambda$$

Références

- Histoire de la matière noire : J. Einasto, "Dark Matter," *Braz. J. Phys.* 43 (2013) 369 [arXiv: 1308.2534 [astro-ph.CO]].
- La matière noire en astrophysique : J. Silk, "Dark matter: The astrophysical case," *Comptes Rendus Physique* 13 (2012) 724.
- Cosmologie et matière noire : S. Profumo, "TASI 2012 Lectures on Astrophysical Probes of Dark Matter," arXiv:1301.0952 [hep-ph]
- Expériences de détection directe: M. Schumann, "Dark Matter 2014," arXiv:1501.01200 [astro-ph.CO].
- AMS

http://www.theo.phys.ulg.ac.be/wiki/index.php/Dark_Matter

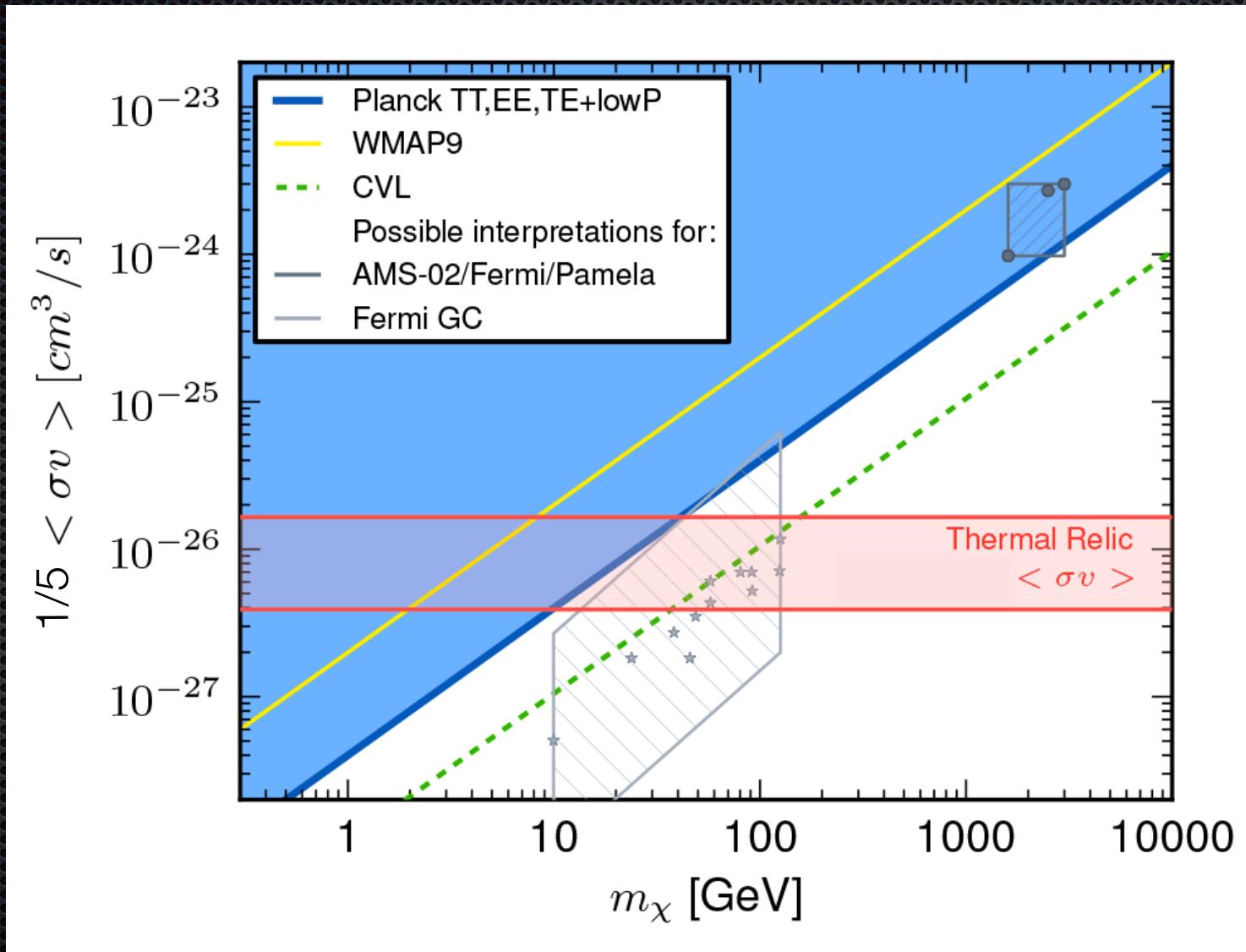


NB1: système solaire

mouvement des planètes =>
densité $< 1.4 \cdot 10^{-20} \text{ g/cm}^3$

(N. P. Pitjev E. V. Pitjeva, <http://arxiv.org/abs/1306.5534>)

Rayonnement fossile

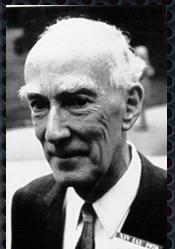


Caveat

- collaboration MACHO: moins de 20% de la matière vient d'objets compacts
- OGLE, EROS: limite plus basse
- A&A 575, A107 (2015): “A new look at microlensing limits on dark matter in the Galactic halo,” M. R. S. Hawkins. *“an all-MACHO halo can no longer be ruled out with any confidence”*

Voie lactée

J.H. Oort, 1932, Bull. Astr. Inst. Netherlands, 6, 249 “The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems”



LETTERS

NATURE PHYSICS DOI: 10.1038/NPHYS3237

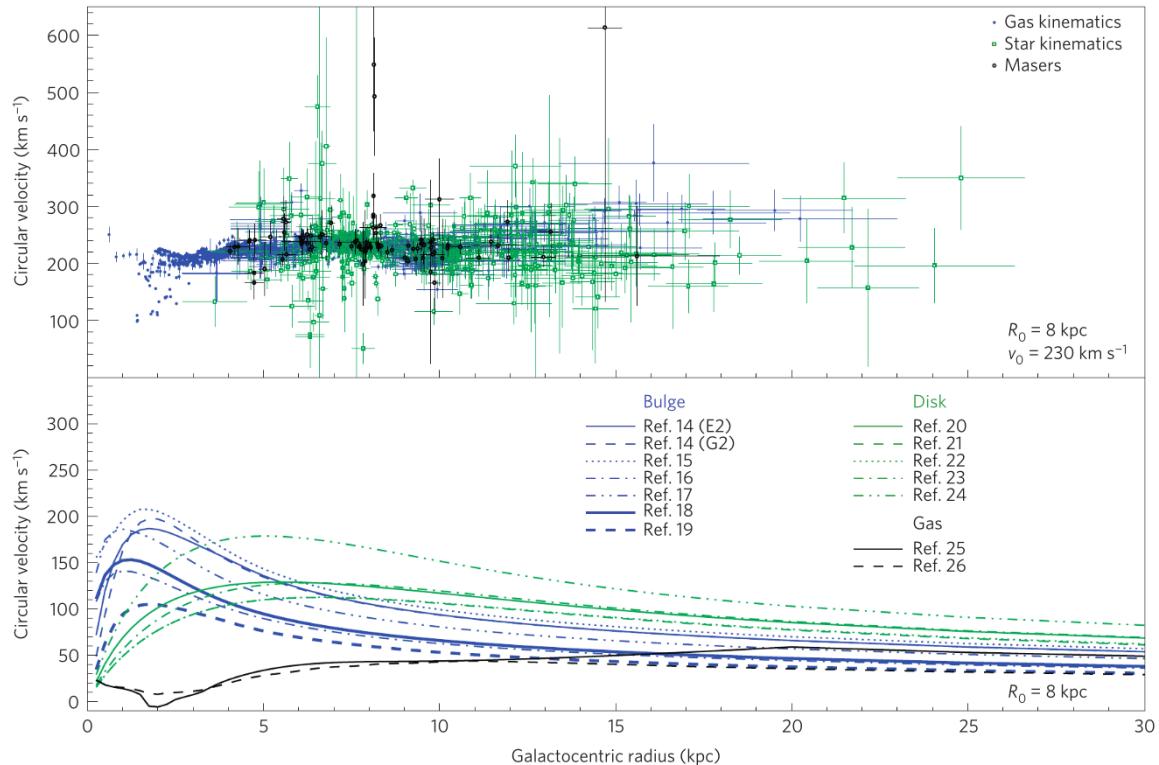


Figure 1 | The rotation curve of the Milky Way. In the top panel we show our compilation of rotation curve measurements as a function of Galactocentric radius, including data from gas kinematics (blue dots; HI terminal velocities, CO terminal velocities, HI thickness, HII regions, giant molecular clouds), star kinematics (open green squares; open clusters, planetary nebulae, classical cepheids, carbon stars) and masers (open black circles). Error bars correspond to 1σ uncertainties. The bottom panel shows the contribution to the rotation curve as predicted from different models for the stellar bulge (blue), stellar disk (green) and gas (black). We assume a distance to the Galactic Centre $R_0 = 8 \text{ kpc}$ in both panels, and a local circular velocity $v_0 = 230 \text{ km s}^{-1}$ in the top panel.

Fabio Iocco, Miguel Pato & Gianfranco Bertone
(15 Feb. 2015)

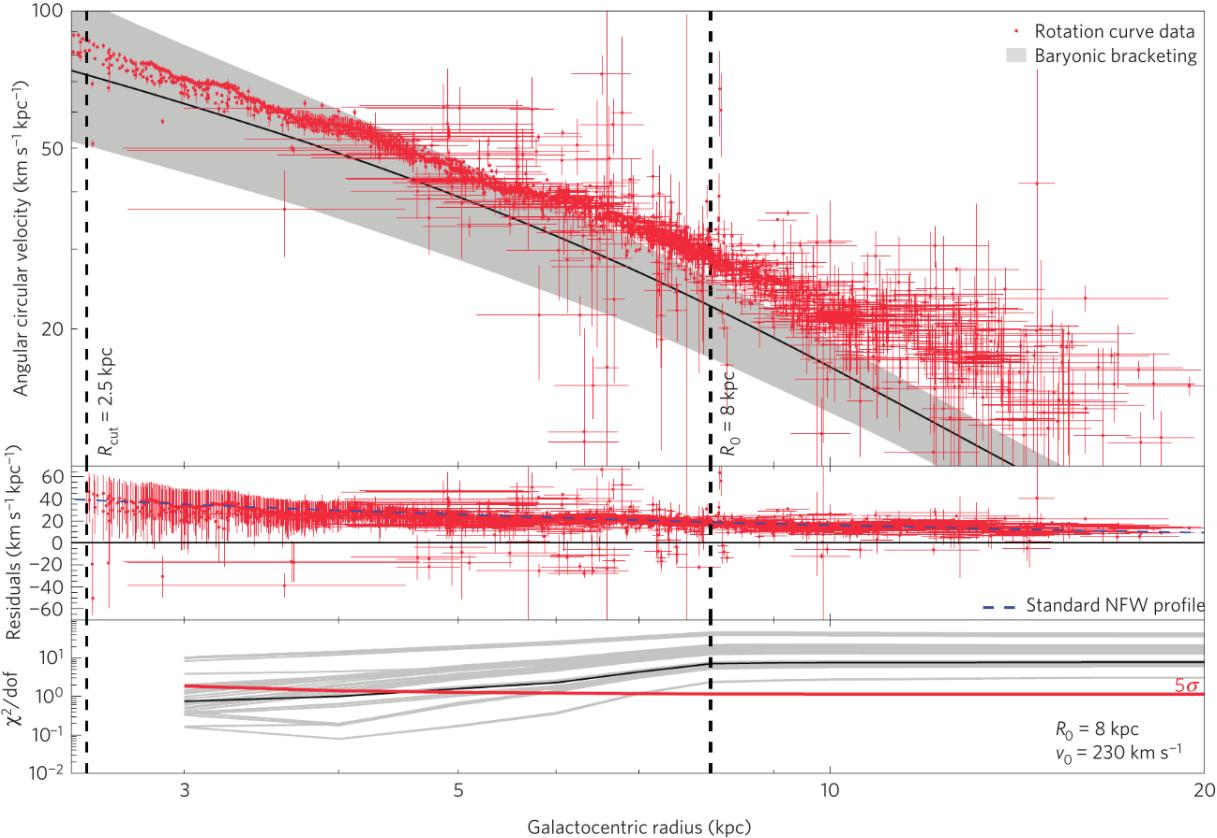


Figure 2 | Evidence for dark matter. In the top panel we show the angular velocity measurements from the compilation shown in Fig. 1 (red dots) together with the bracketing of the contribution of all baryonic models (grey band) as a function of Galactocentric radius. Error bars correspond to 1σ uncertainties, and the grey band shows the envelope of all baryonic models including 1σ uncertainties. The contribution of a fiducial baryonic model is marked with the black line. The residuals $(\omega_c^2 - \omega_b^2)^{1/2}$ between observed and predicted angular velocities for this baryonic model are shown in the central panel. The blue dashed line shows the contribution of a Navarro–Frenk–White profile with scale radius of 20 kpc normalized to a local dark matter density of 0.4 GeV cm^{-3} . The bottom panel shows the cumulative reduced χ^2 for each baryonic model as a function of Galactocentric radius. The black line shows the case of the fiducial model plotted in black in the top panel, and the thick red line represents the reduced χ^2 corresponding to 5σ significance. In this figure we assume a distance to the Galactic Centre $R_0 = 8 \text{ kpc}$ and a local circular velocity $v_0 = 230 \text{ km s}^{-1}$, and we ignore all measurements below $R_{\text{cut}} = 2.5 \text{ kpc}$.

$$\rho_{\text{DM},\text{Sun}} \approx 0.4 \text{ GeV/cm}^3$$

$$v_{\text{Sun}} \approx 230 \text{ km/s}$$



The galaxy cluster A~520 (the cosmic train wreck), in which the galaxies are seen displaced from the dark matter (lower left panel) and the X-ray gas (lower right panel). In the top panel, the lensing signal (blue) and its contour lines are superposed on the X-ray image (red) and the cluster galaxies (orange).

Gravitational Lensing - Bartelmann, Matthias
Class.Quant.Grav. 27 (2010) 233001
arXiv:1010.3829 [astro-ph.CO]