



*Warm Dark Matter Galaxy Theory
in Agreement with Observations*

New Results

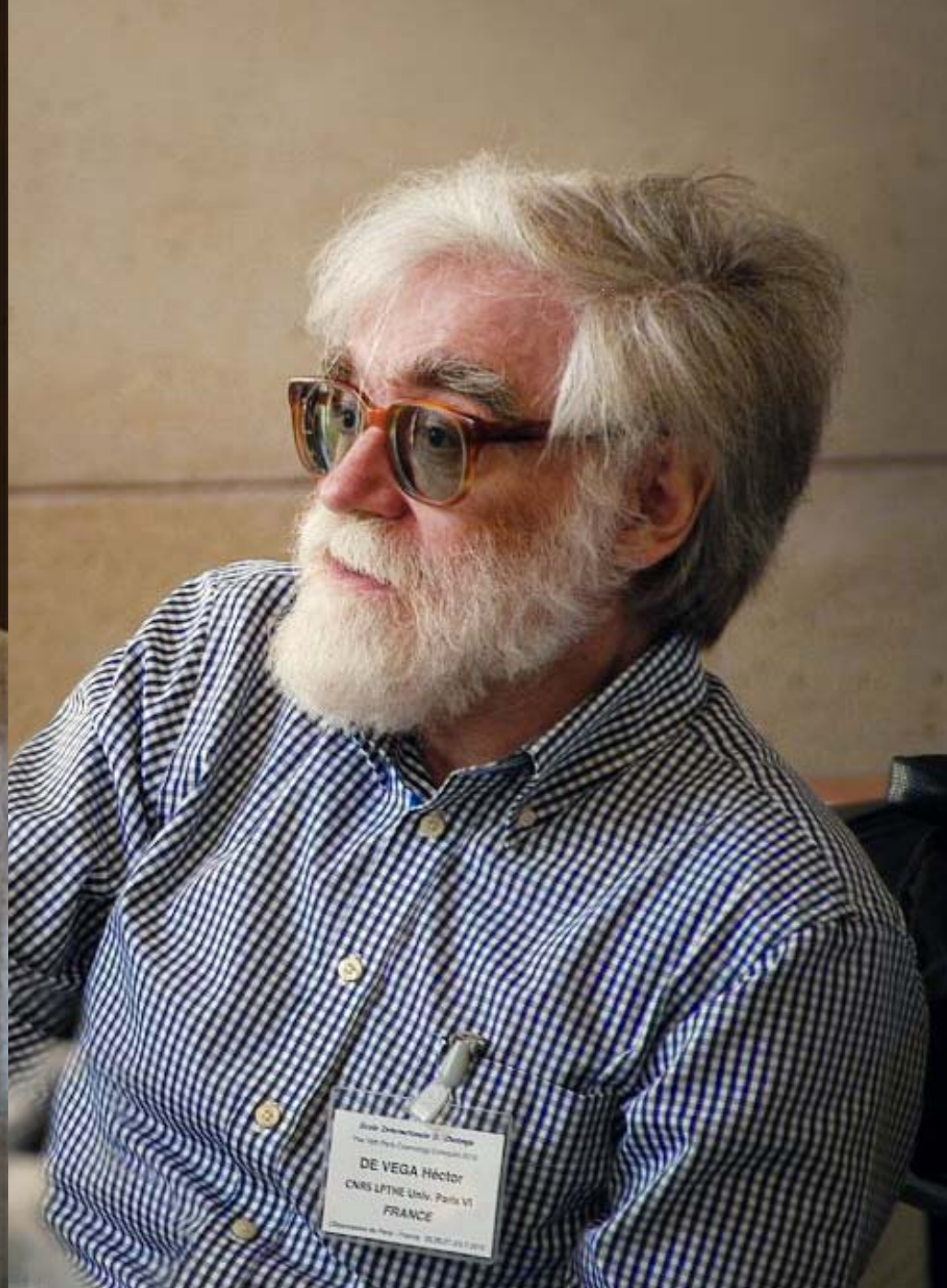
Norma G. SANCHEZ

DR CNRS LERMA Observatoire de Paris

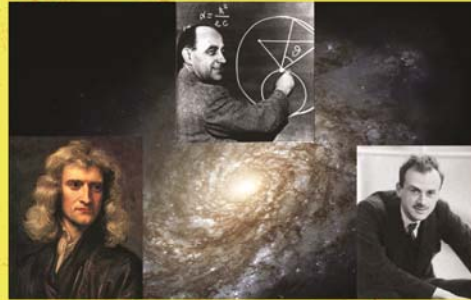
Chalonge Paris Colloquium 2015

22-24 JULY 2015





LA SCIENCE QUI DONNE ENVIE. UNE GRANDE AVENTURE SCIENTIFIQUE ET HUMAINE
SCIENCE WITH GREAT INTELLECTUAL ENDEAVOUR AND A HUMAN FACE



Newton, Fermi et Dirac réunis dans les galaxies par la matière noire tiède (keV)

PROGRAMME OF THE YEAR 2015

24 YEARS OF ACTIVITY. CALLING FOR UNDERSTANDING

26 MARCH 2015 : Opening Session 2015. Session ouverte de Culture Scientifique "Présentation du Programme 2015 et des Dernières Nouvelles de l'Univers". Observatoire de Paris, Bâtiment Perrault

21 MAY 2015 : Spring Open Session of Scientific Culture 2015. Session Ouverte de Printemps de Culture Scientifique Interdisciplinaire 2015 : "L'Homme et l'Univers". Observatoire de Paris, Bâtiment Perrault

9-12 JUNE 2015 : Chalonge Meudon Workshop 2015 "WDM Cosmology : from large to small scale structures in agreement with observations: galaxies, black holes, Neutrinos and Sterile Neutrinos". Observatoire de Paris, Château de Meudon-CIAS, Meudon

21-24 JULY 2015 : The 19th Paris Cosmology Colloquium Chalonge 2015: "Latest News from the Universe: WDM Cosmology, CMB, Dark Matter, Dark Energy, Neutrinos and Sterile Neutrinos". Observatoire de Paris, Bâtiment Perrault

24 JULY 2015 : Summer Open Session of Scientific Culture 2015. Session Ouverte d'Été de Culture Scientifique 2015 : A Surprise Session

AUTOMNE 2015 : Cycle Les grandes questions posées aujourd'hui à la Science: Où va la Science ? L'Exemple de la Matière Noire. Cité Internationale Univ. de Paris

16-17 OCTOBRE 2015 : Chalonge Turin Session 2015 "Latest News from the Universe, Dark Matter Galaxies and Particle Physics". Palazzo Lascaris & Accademia delle Scienze, Piemonte Région, Turin, Italy

26-27 NOVEMBRE 2015 : Concluding Session 2015 & Avant-Première 2016

Welcome to the Chalonge School A Laboratory of Ideas Research, Training, Scientific Culture

A beacon pioneering and developing research, projects and training. The programme offers unvaluable international current research view at the forefront of astrophysics and cosmology, international contacts at the highest level and a careful interdisciplinarity, with both Theory and Observations.

The programme is open to researchers, post-docs and advanced students of the different disciplines in the field, both theorists, experimentalists, observers. Advanced students, post-docs, young researchers are encouraged to participate. The programme includes scientific culture events with the latest results and exhibitions.

The Chalonge School Medal

The Chalonge Medal is coined exclusively for the Chalonge School by the Hôtel de la Monnaie de Paris (the French Mint). Only ten Chalonge medals have been awarded in the 24 years school history

Awarded Daniel Chalonge Medals

Subramanyan CHANDRASEKHAR (Nobel prize of physics)

Bruno PONTECORVO

George SMOOT (Nobel prize of physics)

Carlos FRENK

Anthony LASENBY

Bernard SADOULET (Fellow of the USA Academy of Arts And Sciences)

Peter BIERMANN

John MATHER (Nobel prize of physics)

Brian SCHMIDT (Nobel prize of Physics)

Gérard GILMORE (Fellow of the UK Royal Society)

And other Events
<http://chalonge.obspm.fr>

Engineering and Technical Support
D. ZIDANI, F. SEVRE, N. LETOURNEUR, J.-P. MICHEL,
S. CNUDDE, E. VERGNAUD, J. BERTHIER, and other colleagues

Science Organizers
N. G. SANCHEZ, H. J. DE VEGA, M. C. FALVELLA, A. ZANINI,
M. RAMON MEDRANO, A. PERRISA, and other colleagues



Basement- ground Zero

Dark matter is the dominant component of Galaxies and is an essential ingredient to understand Galaxy properties and Galaxy formation

Dark matter and Galaxy Formation must be treated in an cosmological context

The nature (the type) of Dark Matter and the cosmological model need to be explicitated when discussing galaxies and galaxy formation

All the building of galaxy formation depends on the nature of Dark Matter

CONTENTS

(I) The Standard Model of the Universe Includes Inflation

(II) THE NATURE OF DARK MATTER IN GALAXIES

from Theory and Observations: **Warm (keV scale) DM**

(III) NEW: THE ESSENTIAL ROLE OF QUANTUM PHYSICS IN WDM GALAXIES:

Semiclassical framework: Analytical Results and Numerical (including analytical) Results

Observed Galaxy cores and structures from Fermionic WDM and more results.

(IV) NEW: The generic Galaxy types and properties from a same physical framework: From quantum (compact, dwarfs) to classical (dilute, large) galaxies. Equation of state

NEW RESULTS

FERMIONIC QUANTUM WDM and GRAVITATION DETERMINE THE OBSERVED PHYSICAL GALAXY PROPERTIES

- > Dark matter (DM) is the main component of galaxies. Quantum mechanics is a cornerstone of physics from microscopic to macroscopic systems as quantum liquids He^3 , white dwarf stars and neutron stars.
- > **NEW:** Quantum mechanics is also responsible of galaxy structures at the kpc scales and below: near the galaxy center, below 10 - 100 pc, the DM quantum effects are important for warm DM (WDM), that is for DM particles with masses in the keV scale. **dVS (New Astronomy 2013)**
dVS PRD 2013, dVSS MNRAS to appear, dVS 2014
- > **A new approach to galaxy structure with results in remarkable agreement with observations:**

(i) Dwarf galaxies turn to be quantum macroscopic objects for WDM supported against gravity by the WDM fermion pressure

(ii) Theoretical analytic framework based on Thomas-Fermi approach determine galaxy structure from the most compact dwarf galaxies to the largest dilute galaxies (spirals, ellipticals).

The obtained galaxy mass, halo radius, phase-space density, velocity dispersion, are fully consistent with observations.

(iii) Interestingly enough, a minimal galaxy mass and minimal velocity dispersion are found for DM dominated objects, which in turn imply an universal minimal mass $m_{\min} = 1.9 \text{ keV}$ for the WDM particle.

- OBSERVED GALAXY CORES vs CDM CUSPS and WDM CORES-

- Well established sets of astronomical observations show that the **DM galaxy density profiles are cored**, that is, profiles which are flat at the center.

On the contrary, **N-body CDM simulations exhibit cusped density profiles**, with a typical $1/r$ cusped behaviour near the galaxy center $r = 0$.

Classical Physics N-body WDM simulations exhibit cores but with sizes much smaller than the observed cores.

We have recently developed a new approach to this problem thanks to **Quantum Mechanics**.

- **Fermions** always provide a non vanishing **pressure of quantum nature** due to the combined action of the Pauli exclusion principle and Heisenberg uncertainty principle.
- **Quantum effects for WDM fermions rule out the presence of galaxy cusps for WDM and enlarge the classical core sizes because their repulsive and non-local nature extend well beyond the small pc scales.**
- **Smoothing the density profile at the central regions has an effect on the whole galaxy halo.**

THE MINIMAL GALAXY MASS

A minimal galaxy mass and minimal velocity dispersion are found.

This in turn implies a **minimal mass $m_{\min} = 1.91$ keV** for the WDM particle.

This **minimal WDM mass** is a **universal** value, independent of the WDM particle physics model because only relies on the **degenerate quantum fermion state**, which is universal whatever is the non-degenerate regime.

These results and the observed halo radius and mass of the compact galaxies also **provide further indication that the WDM particle mass m is approximately around 2 keV.**

More precise data will make this estimation more precise.

WDM THEORY OF GALAXIES

REPRODUCES THE OBSERVED GALAXY STRUCTURES

Gravity and Quantum Mechanics meet together in Galaxies

de Vega, Salucci, Sanchez MNRS 2014 reproduced the main observed properties of galaxies of all types, masses and sizes, as the rotation curves, density profiles, phase space density, and scaling relations between the galaxy masses, sizes and velocities, with a physical theory to galaxy structure which captures the essential ingredients of galaxies: **dark matter and gravity**.

Newton, Fermi and Dirac, meet together in Galaxies through Warm Dark Matter

This new framework **requires dark matter particles to be fermionic** with mass in the scale of thousands electron Volts (**keV "warm dark matter"**) and described by their quantum mechanical properties, as their quantum pressure resulting from the combination of the Pauli exclusion principle and the Heisenberg uncertainty principle. Compact dwarf galaxies are thus near the Fermi gas degenerate regime, while large dilute galaxies are in the classical gas Boltzmann regime.

This approach corresponds to the Schrödinger equation in the large number of particles regime **and is for galaxies the analogue of the Thomas-Fermi approach for atoms, with gravitation instead of the electric potential**.

Universal rotation curves and Universal density profiles:

The same for all galaxies

The theoretically obtained galaxy rotation curves and density profiles reproduce extremely well the observational curves from ten different and independent sets of data for galaxy masses from 5×10^9 solar masses until 5×10^{11} solar masses.

Remarkably enough, the normalized theoretical circular velocities and density profiles are universal (URC): they are the same for all galaxies of different types, sizes and masses, and they agree extremely well with the observational curves described by cored profiles (flat smooth profiles at the center) and their sizes.

Interestingly enough, small deviations from the exact scaling relations show up for compact dwarf galaxies as a manifestation of the quantum macroscopic effects present in these galaxies.

Robust Results

Results of this work are independent of any particular warm dark matter particle physics model, they only follow from the self-gravitation of the warm dark matter particles and their fermionic nature. These important results show the ability of this approach to describe the galaxy structures. **They also show that baryonic corrections are not very important to warm dark matter, consistent with the fact that dark matter is in average at least six times more abundant than baryons.** The fraction of dark matter over the total mass of galaxies goes from the 95% for large dilute galaxies till 99.99% for dwarf compact galaxies. The baryon fraction in large galaxies can only reach values up to 5 %.

Reference:

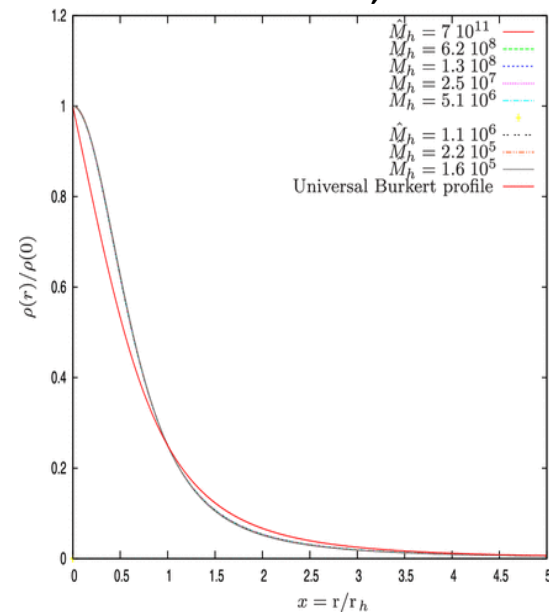
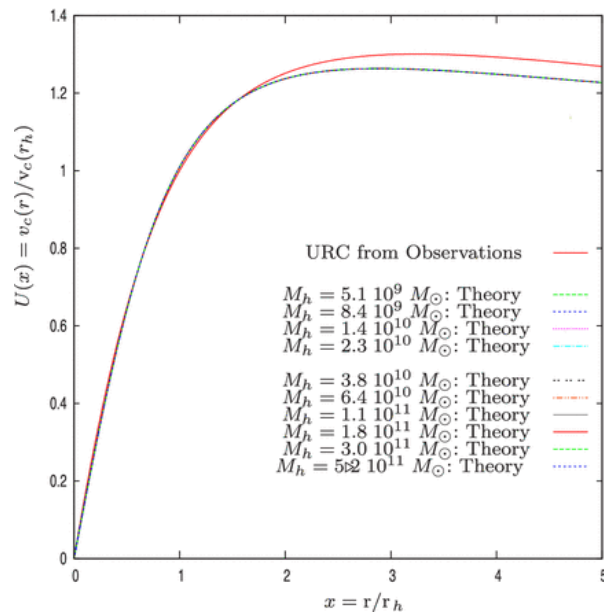
H. J. de Vega; P. Salucci; N. G.Sanchez MNRAS 442 (2): 2717-2727 (2014)

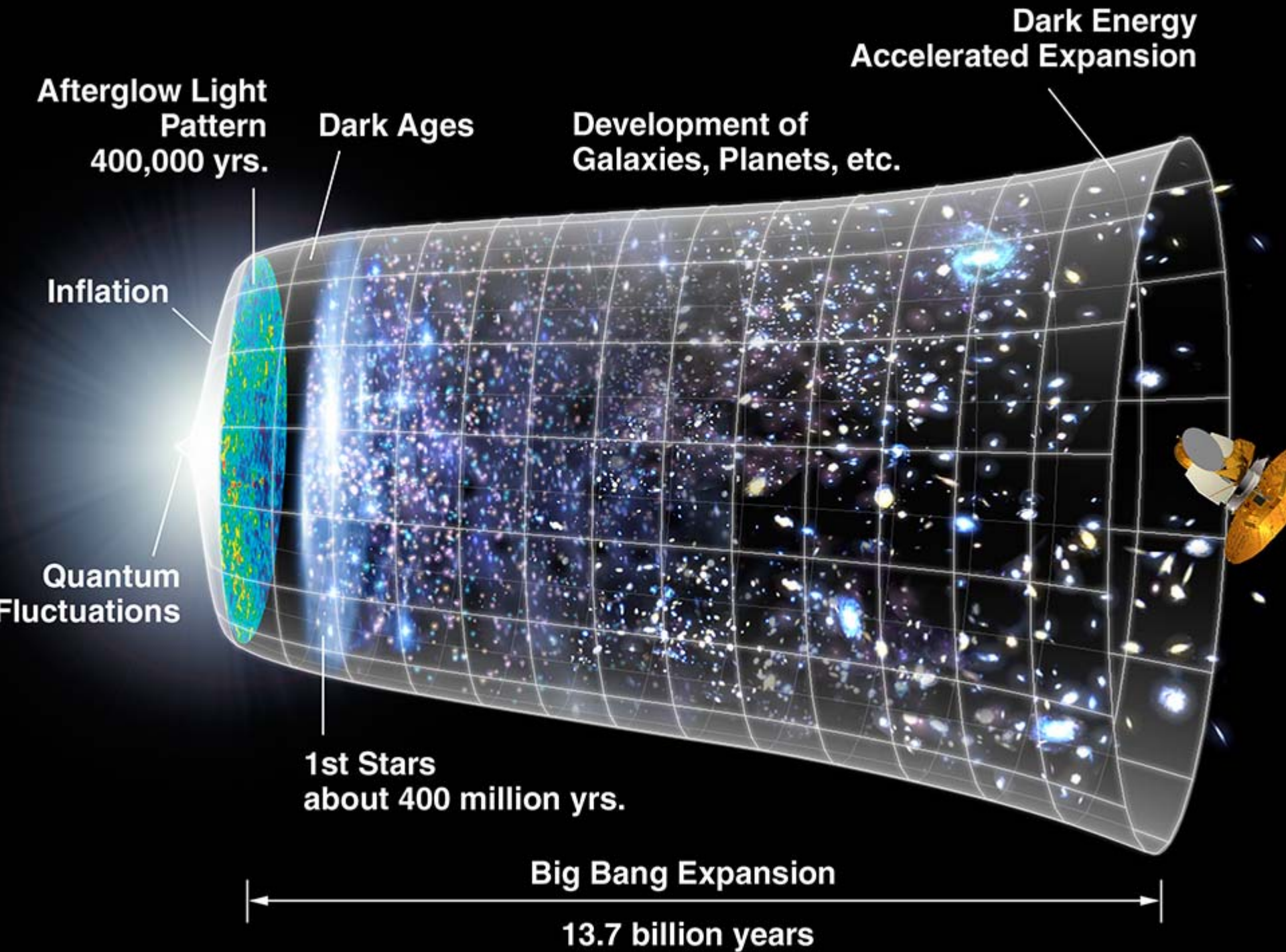
Newton, Fermi and Dirac, meet together in Galaxies through keV Warm Dark Matter



Rotation curves (left panel): The theoretical curves for 10 different galaxy masses all fall one into each other providing an **Universal Rotation Curve (URC)** which remarkably coincides with the **observed universal curve (displayed in red)**. Small deviations show up only at distances outside twice the halo radius.

The right panel shows the density profiles for the 10 galaxy masses: **All fall into the same and universal density profile which reproduces the observed universal density profile and its size (in red)**. Interestingly enough, small deviations show up for compact dwarf galaxies as a manifestation of **the quantum macroscopic effects predicted in these galaxies, and which can be further tested by next observations.** (Examples of other quantum macroscopic objects in nature are dwarf stars, neutron stars and the liquid Helium 3).







UPDATE and CLARIFICATIONS

LCDM agrees with CMB + LSS **BUT NOT** with **SSS (GALAXIES)**

LWDM agrees with CMB + LSS + **SSS (GALAXIES)**

The Standard Model of the Universe is LWDM

GR, Newtonian Gravity , FT, QFT

Sentences like « CMB confirms the LCDM model ... »

Must be completed by : « in large scales” » or updated:

CMB confirms the LWDM model in large scales

NEW: Gravity and Quantum Mechanics in Galaxies

Newton, Fermi and Dirac meet together in Galaxies because of keV WDM

2015 DARK MATTER UPDATE

- **THERE IS NO CUSP/CORE problem:**
 - **Observed Galaxy profiles are cored.**
 - **WDM Galaxy density profiles are cored**

- **THERE IS NO satellite problem**

- **WDM abundance of structures agrees with observations**

- **In addition, these are not fundamental problems.**

NO DM WIMPS,

NO DM annihilation,

NO DM axions.

NO DM bosons

Axions are ruled out as dark matter

Hot Dark Matter (eV particles or lighter) are ruled out because their free streaming length is **too large** \gtrsim Mpc and hence galaxies are not formed.

A Bose-Einstein condensate of light scalar particles **evades** this argument because of the quantum nature of the BE condensate. $\tau_{Jeans} \sim 5$ kpc implies $m_{axion} \sim 10^{-22}$ eV.

The phase-space density $Q = \rho/\sigma^3$ **decreases** during structure formation: $Q_{today} < Q_{primordial} \propto m^4$.

Computing $Q_{primordial}$ for a DM BE condensate we derived **lower bounds** on the DM particle mass m using the data for Q_{today} in dwarf galaxies:

$$\text{TE: } m \geq 0.155 \text{ MeV} \left(\frac{25}{g_d}\right)^{5/3}. \quad \text{Out of TE: } m \geq 14 \text{ eV} \left(\frac{25}{g_d}\right)^{5/3}$$

Axions with $m \sim 10^{-22}$ eV **are ruled out as DM candidates.**

D. Boyanovsky, H. J. de Vega, N. G. Sanchez, PRD 77, 043518 (08). H. de Vega, N. Sanchez, arXiv:1401.1214

From WMAP9 to Planck

Understanding the direction in which data are pointing:

- **PREDICTIONS for Planck**

- **Standard Model of the Universe**

- **Standard Single field Inflation**

- **NO RUNNING of the Primordial Spectral Index**

- **NO Primordial NON GAUSSIANTY**

Effective Theory of Inflation (ETI) confirmed by Planck

Quantity	ETI Prediction	Planck 2013
Spectral index $1 - n_s$	order $1/N = 0.02$	0.04
Running $dn_s/d\ln k$	order $1/N^2 = 0.0004$	< 0.01
Non-Gaussianity f_{NL}	order $1/N = 0.02$	< 6
	ETI + WMAP+LSS	
tensor/scalar ratio r	$r > 0.02$	< 0.11 see BICEP
inflaton potential curvature $V''(0)$	$V''(0) < 0$	$V''(0) < 0$

ETI + WMAP+LSS means the MCMC analysis combining the ETI with WMAP and LSS data. Such analysis calls for an inflaton potential with negative curvature at horizon exit. **The double well potential** is favoured (new inflation).

D. Boyanovsky, C. Destri, H. J. de Vega, N. G. Sanchez, arXiv:0901.0549, IJMPA 24, 3669-3864 (2009).

Two key observable numbers :
associated to the primordial density and
primordial gravitons :

$$n_s = 0.9608 , \quad r$$

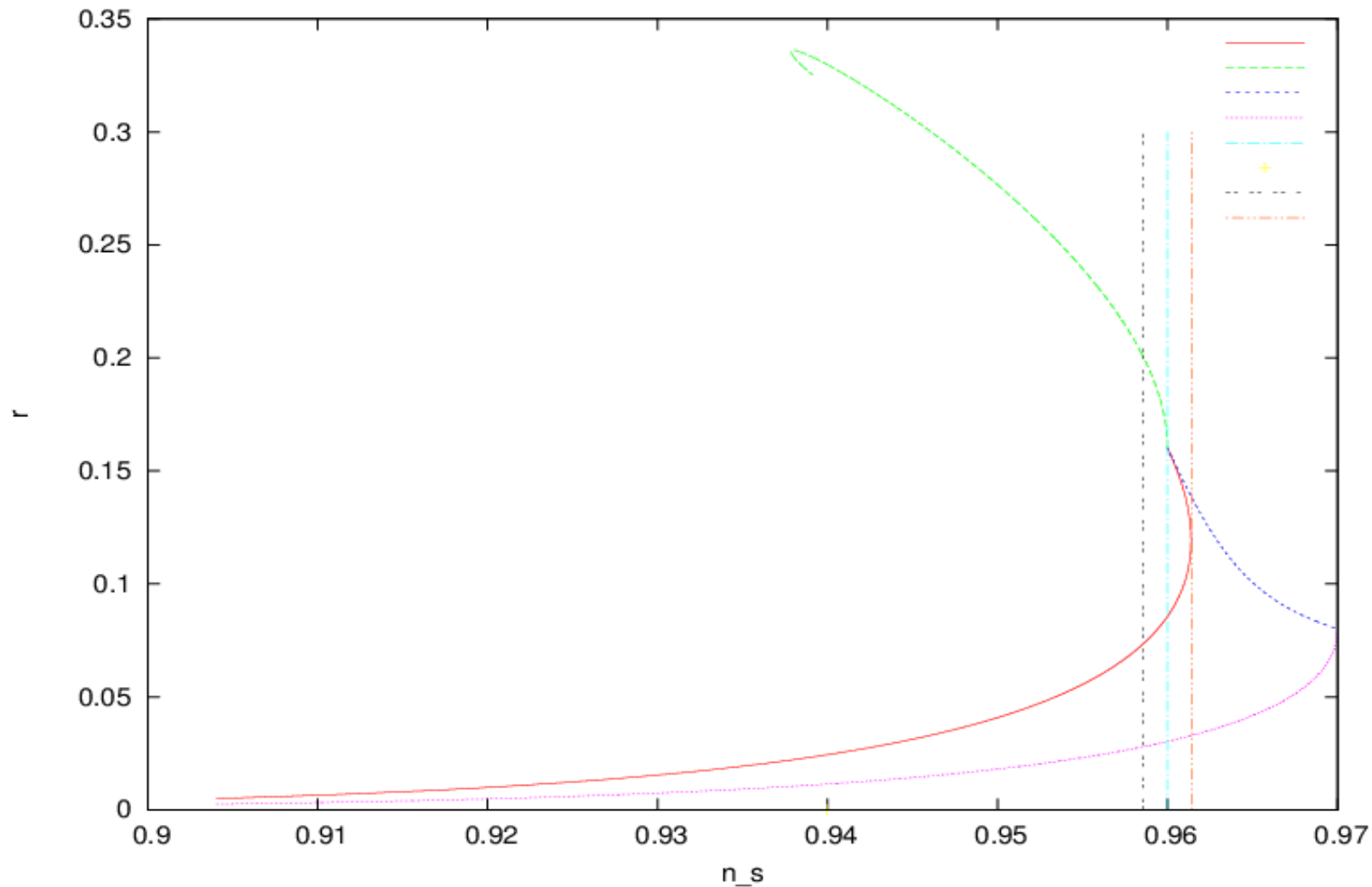
PREDICTIONS

$$r > 0.021 , \quad r = 0.05 - 0.04$$

DdS: Destri, de Vega, Sanchez & from WMAP data
(PRD 2008)

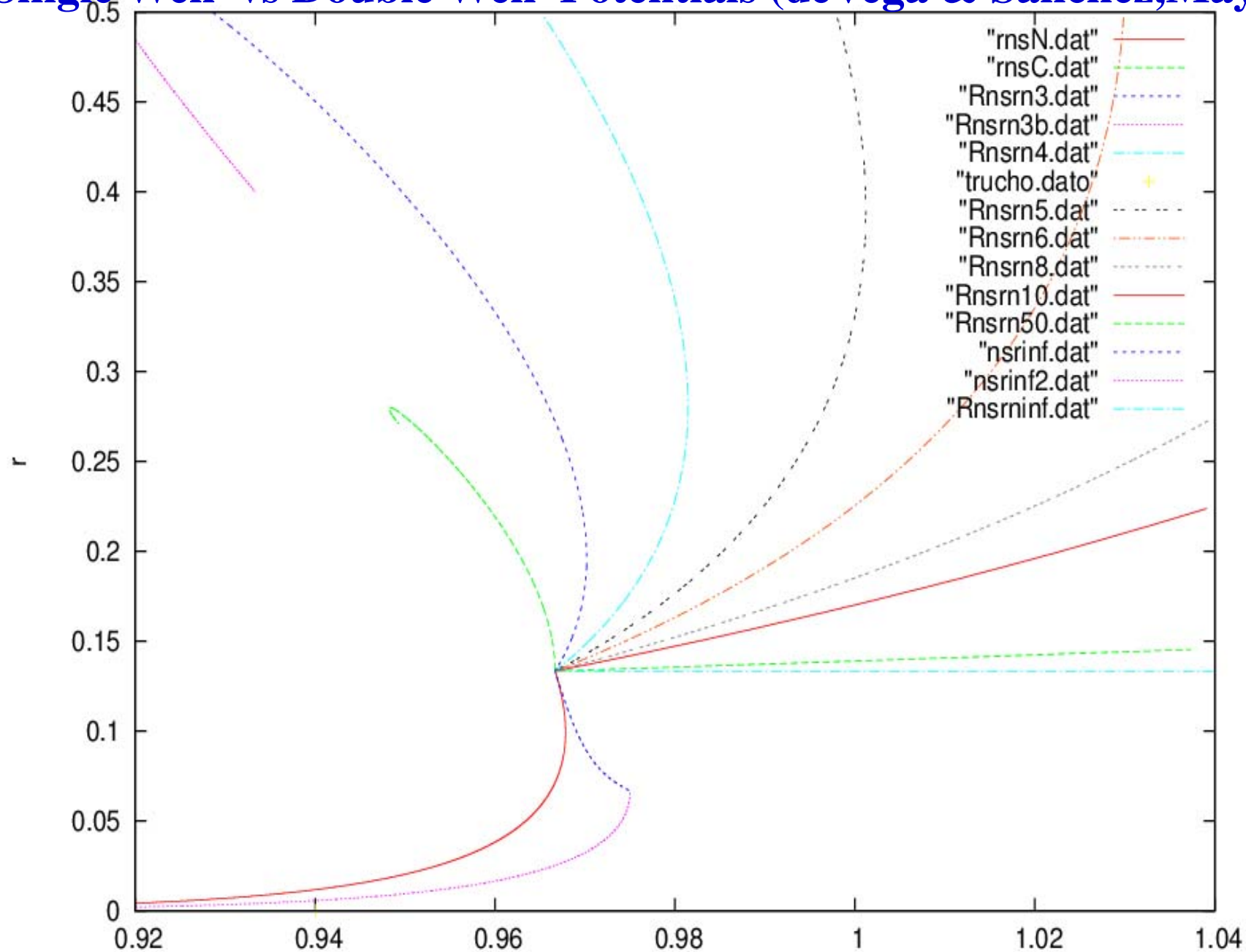
PlanckBICEP2Keck 2015: $r < 0.09$

Single and Double Well Inflaton Potentials



The **cosmic banana** for double well potentials ($N=50$) (de Vega, Sanchez, PRD 2006). Data 2014: $n_s = 0.96 \pm 0.014$.

Single Well vs Double Well Potentials (deVega & Sanchez, May 2014)



• Large Hadron Collider

- The first LHC results at 7-8 TeV, with the discovery of the Higgs boson and **the non observation of new particles or exotic phenomena**, have made a big step towards completing **the experimental confirmation of the Standard Model of particle physics.**
- It is thus a good moment **to recall our scientific predictions made several years ago on this matter because they are of full actuality.**

Large Hadron Collider - LHC-

The results are completely in line with
the Standard Model.

No evidence of SUSY at LHC

“Supersymmetry may not be dead but these latest results have certainly put it into hospital.”

(Prof Chris Parkes, spokesperson for the UK Participation in the LHCb experiment)

→ Does Not support wimps -CDM-

(In agreement with all dedicated wimp experiments at work from more than 20 years which have not found any

wimp's signal) “So far researchers who are racing to find evidence of so called "new physics", ie non-standard models, have run into a series of dead ends”.



	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	

The Standard Model describes the basic building blocks that make up atoms and the forces of nature . Is very successful but It is not complete

Sterile Neutrinos

Standard Model (SM)

Quarks	2.4 MeV 2/3 Left u Right up	1.27 GeV 2/3 Left c Right charm	171.2 GeV 2/3 Left t Right top
	4.8 MeV -1/3 Left d Right down	104 MeV -1/3 Left s Right strange	4.2 GeV -1/3 Left b Right bottom
	< 1 eV 0 Left ν_e Right electron neutrino	< 1 eV 0 Left ν_μ Right muon neutrino	< 1 eV 0 Left ν_τ Right tau neutrino
	0.511 MeV -1 Left e Right electron	105.7 MeV -1 Left μ Right muon	1.777 GeV -1 Left τ Right tau

Neutrino Minimal SM (nuMSM)

Leptons	2.4 MeV 2/3 Left u Right up	1.27 GeV 2/3 Left c Right charm	171.2 GeV 2/3 Left t Right top
	4.8 MeV -1/3 Left d Right down	104 MeV -1/3 Left s Right strange	4.2 GeV -1/3 Left b Right bottom
	< 1 eV 0 Left ν_e Right electron neutrino	< 1 eV 0 Left ν_μ Right muon neutrino	< 1 eV 0 Left ν_τ Right tau neutrino
	0.511 MeV -1 Left e Right electron	105.7 MeV -1 Left μ Right muon	1.777 GeV -1 Left τ Right tau

< 1 eV 0 Left ν_e Right electron neutrino	N_1 sterile neutrino ~keV	< 1 eV 0 Left ν_μ Right muon neutrino	N_2 sterile neutrino ~GeV	< 1 eV 0 Left ν_τ Right tau neutrino	N_3 sterile neutrino ~GeV
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What next for the LHC?

APRIL 2015: The Large Hadron Collider (LHC) has been Et cela recommance....restarted after a two-year shutdown.

Searching Beyond the Standard Model of Particle Physics

PREDICTIONS :

NO Dark Matter at LHC

NO SUSY at LHC

NO Extra-dimensions at LHC

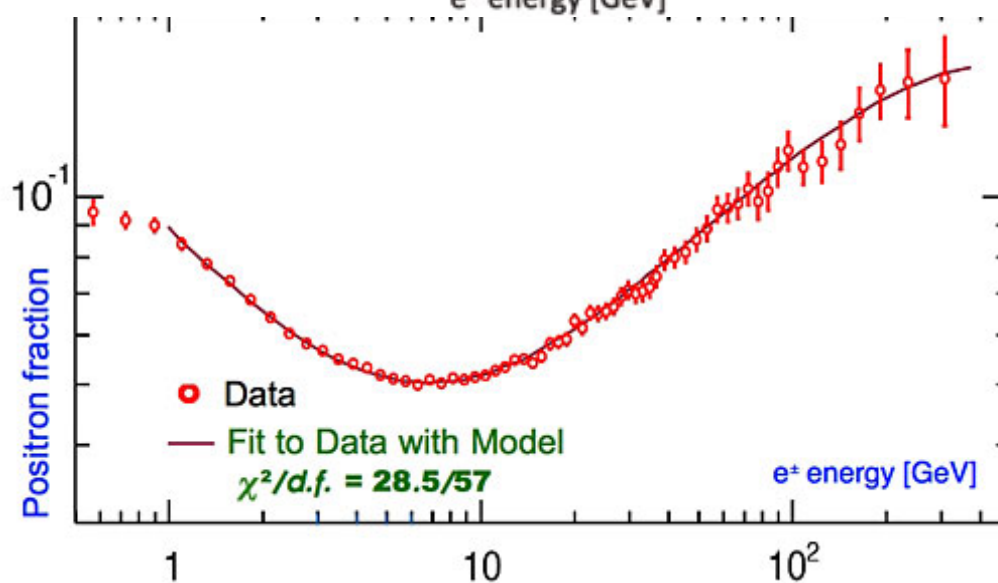
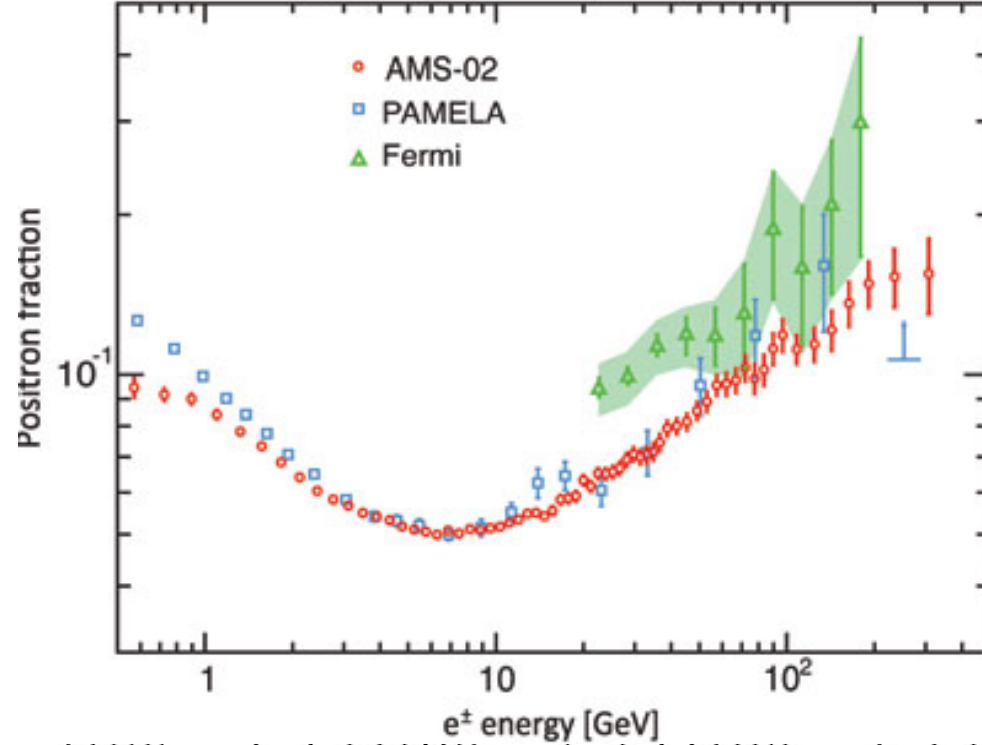
NO Black Holes at LHC

ANTIMATTER IN SPACE - AMS on board ISS Alpha Magnet Spectrometer



NASA

NASA



Positron excess in cosmic rays are not related to DM physics but to astrophysical sources and astrophysical mechanisms and can be explained by them

Planck and Dark Matter, Dec2014,2015

DM annihilation est absente: OK. Sur cet aspect, les données ne laissent pas d'ambigüité possible: **Souvenez-vous:**

Depuis plusieurs années nous avons toujours prédit, dit, et redit qu'il n'y a pas de DM annihilation importante et **que le positron excès (Pamela, FERMI, AMS-02, etc.) n'est pas du a DM annihilation mais**

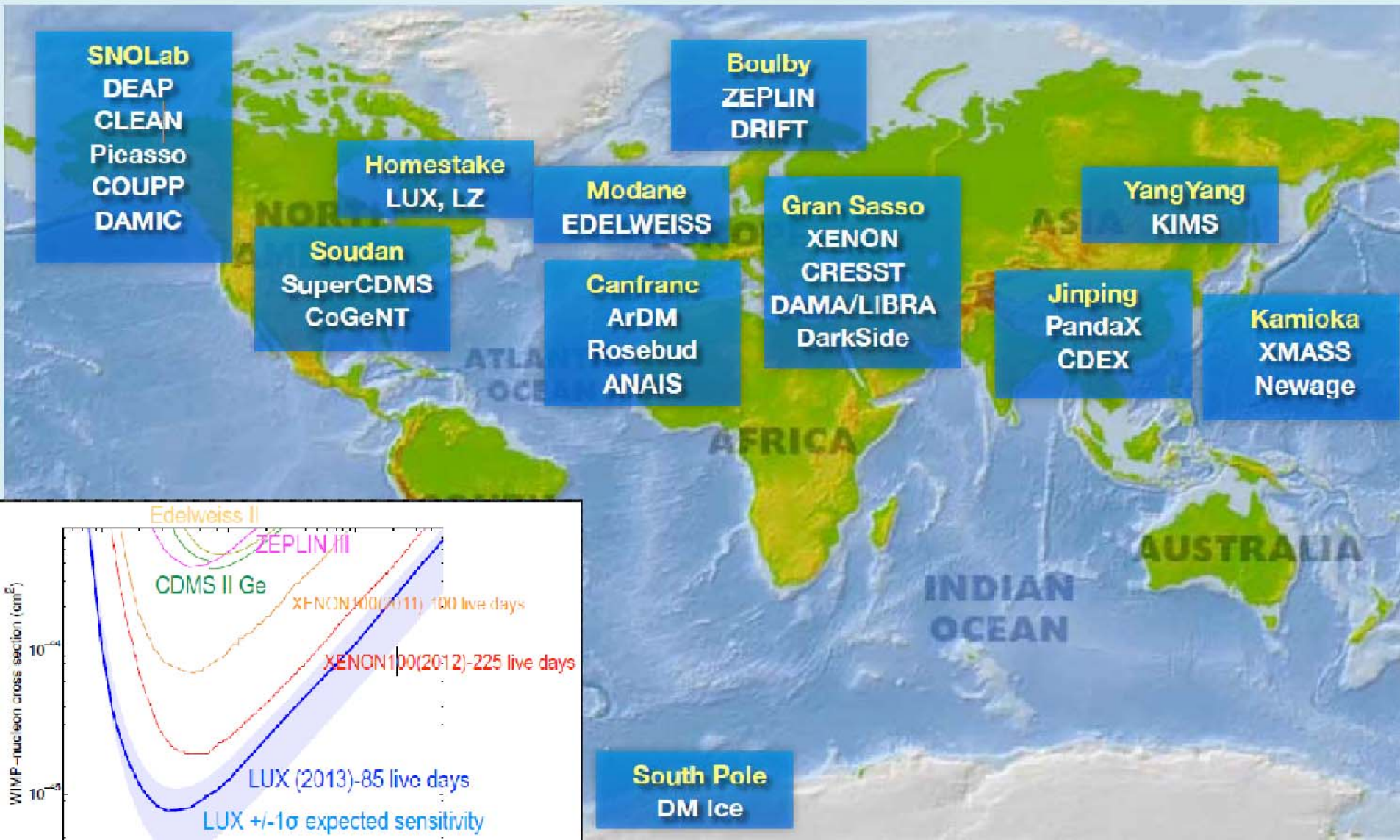
aux sources/ phénomènes astrophysiques: c'est dans nos slides., voir Programme 2014 chalonge par exemple

<http://chalonge.obspm.fr/Programme2014.html> Et ceci est de

plus, un autre résultat négatif

pour les modèles DM des Wimps, comme nous l'avons toujours dit.

Dans le monde entier



- **Why No Experimental Detection of the DM particle has been reached so far ?**

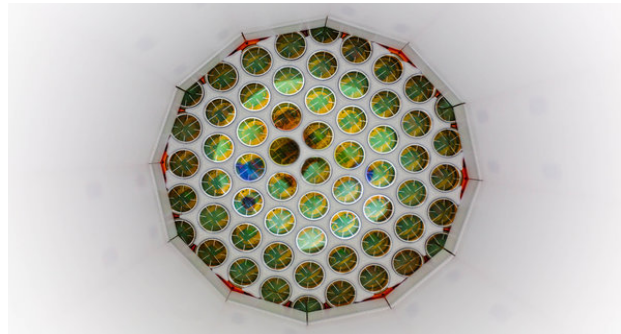
Because:

- All experimental searches for DM particles are dedicated to CDM: wimps of $m > 1$ GeV,
- While the DM particle mass is in the keV scale .
- Moreover, past, present and future reports of signals of such CDM experiments cannot be due to DM because of the same reason.
- The inconclusive signals in such experiments should be originated by phenomena of other kinds.
- In addition, such signals contradict each other supporting the idea that they are unrelated to any DM detection

LUX Large Underground Xenon Detector

30 October 2013

**Dark Matter Experiment Has Detected Nothing,
Researchers Say Proudly**



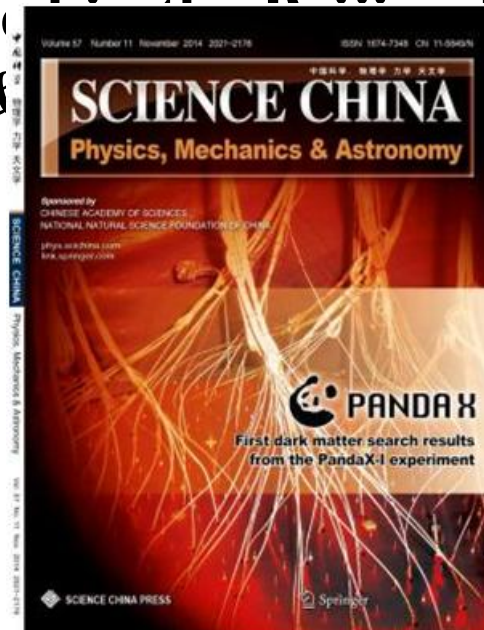
- **They found no sign of WIMPS signals.**
beyond the expected background noise.
- The experiment did so at far better sensitivities than any such experiment before it.

- **First dark matter search results from Chinese underground lab hosting**

- **PandaX-I experiment**

- **30 SEPTEMBER 2014**

Scientists across China and the United States collaborating on the PandaX search for dark matter from an underground lab in southwestern China report results from the first stage of the experiment in a new study published in the peer-reviewed journal *Science China Physics, Mechanics & Astronomy*.



- **NEGATIVE RESULTS**

- **for Wimps**

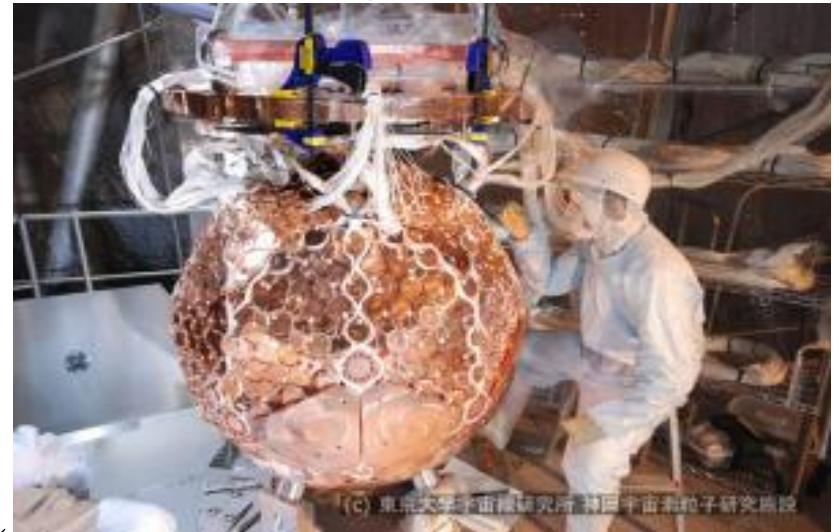
- **China Science Press**

• XMASS Recent News: October 6, 2014

A Warm Dark Matter Search Using

XMASS (Originally published by the University of Tokyo) The XMASS collaboration, led by Yoichiro Suzuki at the **Kavli IPMU**, has reported its latest results on the search for warm dark matter. Their results rule out the possibility that super-weakly interacting massive bosonic particles (bosonic super-WIMPs) This result was published in the September 19th issue of the Physical Review Letters as an Editors' Suggestion.

NEGATIVE RESULTS for WIMPS



- *Construction of XMASS I detector (2010/Feb./25) (C) Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), University of T.*

What next for the LHC?

APRIL 2015: The Large Hadron Collider (LHC) has been restarted after a two-year shutdown. Et cela recommence....Searching

Beyond the Standard Model of Particle Physics

PREDICTIONS:

NO Dark Matter at LHC

NO SUSY at LHC

NO Extra-dimensions at LHC

NO Black Holes at LHC

Recent News on Cosmological Observables

Before 2013: Hubble constant $H_0 = 73.8 \pm 2.4 \frac{\text{km}}{\text{s}} \frac{1}{\text{Mpc}}$ from direct observations of Cepheids by HST, $\Omega_m = 0.27 \pm 0.03$. A G Riess et al. ApJ 730, 119 (2011).

Planck 2013: $H_0 = 67.3 \pm 1.2 \frac{\text{km}}{\text{s}} \frac{1}{\text{Mpc}}$. $\Omega_m = 0.32 \pm 0.02$.

Planck **assumed** here only three massless neutrinos and **no sterile neutrinos** ν_s .

There is today **strong evidence** for ν_s with $m_s \sim \text{eV}$ from short baseline experiments (reactors, MiniBoone, LSND).

Adding **one** ν_s yields:

$H_0 = 70 \pm 1.2 \frac{\text{km}}{\text{s}} \frac{1}{\text{Mpc}}$. $\Omega_m = 0.30 \pm 0.01$ for $m_s = 0.4 \text{ eV}$.

These values for H_0 and Ω_m **are compatible** with the direct astronomical measurements.

M. Wyman et al. PRL. 112, 051302 (2014), J. Hamann & J. Hasekamp, JCAP,10,044H (2013) R. Battye & A. Moss, PRL. 110, 051302 (2013), G. Caronni et al. IJGFP 1011

Planck and the cosmological parameters

La valeur **Neff est très importante** et corrélée aux autres paramètres cosmologiques.

Planck a refait l'analyse des données 2014/2015 avec les mêmes priors (a priori) que en 2013 : ils ont donc très peu des corrections aux paramètres cosmologiques par rapport a Planck 2013 et donc ils ont un **Neff compatible avec 3 neutrinos** et les mêmes problèmes 2013 pour H_0 , pour la proportion de dark énergie et pour the dark matter proportion, pour σ_8 , etc. , car ils sont tous corrèles

Trop haute oméga DM (of about 26-27 %) , une **trop basse oméga lambda** (68%) et une **trop basse H_0** pour n'arriver qu'a Neff compatible avec 3 neutrinos.... et donc ils ont les mêmes qu'avant.

Planck and Neutrinos

- **At early times:** CMB sensitive to radiation The radiation density other than photons is described by the **parameter N_{eff}** : $\rho_{\text{rad}} = C(N_{\text{eff}}) \rho_{\text{photons}}$.
- **At late times:** CMB sensitive to neutrino masses
- **The Priors in the Planck analyse:**
- **Standard value for $N_{\text{eff}} = 3.046$, 3 active neutrinos**
- **$\Sigma m_{\nu} = 0.06 \text{ eV}$ (1 massive, the other massless)**
- **Tension with the values of H_0 , lensing and clusters (σ_8)**

Planck and Neutrinos

- → En fait le **CMB** est sensible à la valeur de σ_8 très tôt dans l'Univers, à **redshift = 1100** (moment où l'Univers devient transparent **380 000** après le **Big Bang**), alors que les amas qui se forment tard, mesurent la valeur de σ_8 à $z \sim 1$ (il y a **8 milliards d'années**).
- → La relation entre ces deux valeurs dépend de la croissance des structures. **Or celle-ci est ralentie par les neutrinos**, d'autant plus qu'ils sont massifs. **Dans le modèle standard de la cosmologie, la somme des masses des neutrinos est aujourd'hui fixée à une valeur minimale de 0.06 eV** (correspondant à la mesure de la somme des masses d'oscillation déterminée par les expériences de neutrinos et en considérant que la masse du neutrino le plus léger est nul).
- → **Le désaccord sur σ_8 entre le CMB et amas peut être résolu** si on permet que la somme des masses des neutrinos soit comprise entre **0.2 et 0.3 eV**. Cependant, cette valeur haute doit être confrontée aux contraintes posées par les BAO et l'analyse des forêts Lyman

Sterile Neutrinos ν

Rhenium and Tritium **beta decay** (MARE, KATRIN).

Theoretical analysis: H J de V, O. Moreno, E. Moya de Guerra, M. Ramón Medrano, N. Sánchez, Nucl. Phys. B866, 177 (2013).

[Other possibility to detect a sterile ν_s : a precise measure of nucleus recoil in tritium beta decay.]

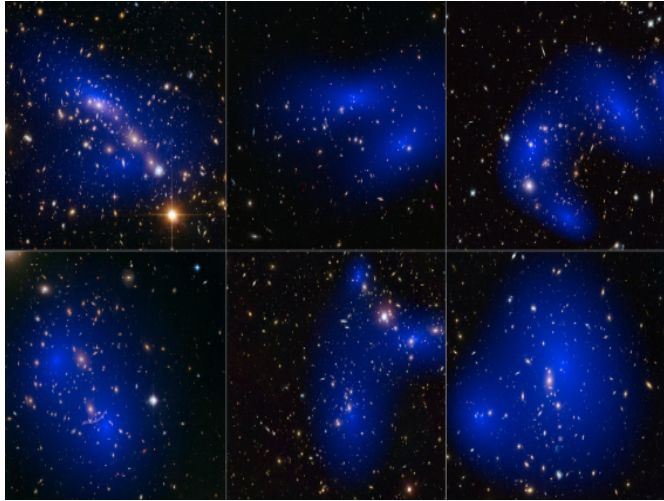
Conclusion: the empty slot of right-handed neutrinos in the Standard Model of particle physics can be filled by **keV-scale sterile neutrinos** describing the DM.

An appealing **mass** neutrino hierarchy appears:

- Active neutrino: \sim mili eV
- Light sterile neutrino: \sim eV
- Dark Matter: \sim keV
- Unstable sterile neutrino: \sim MeV....



Dark matter even darker than once thought



Hubble & Chandra show that dark matter interacts with itself even less than previously thought, and narrow down the options for what **dark matter** might be.

Self-interacting dark matter becomes disfavored

Good News for WDM
(Less options a CDM:
WDM and self-interacting DM)

The non-gravitational interactions of dark matter in colliding galaxy clusters

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Collisions between galaxy clusters provide a test of the non-gravitational forces acting on dark matter.

Previously: Dark matter's lack of deceleration in the 'bullet cluster collision' constrained its **Self-interaction cross-section $DM/m < 1.25 \text{ cm}^2/\text{g}$ (68% CL)**

Using the Chandra and Hubble Space Telescopes 72 collisions have now been observed. Combining these measurements statistically, imply :

- 1. The existence of dark mass at 7.6 sigma significance.**
- 2. Self-interaction cross-section $DM/m < 0.47 \text{ cm}^2/\text{g}$ (95% CL) → disfavoring the proposed extensions to the standard model: self-interacting DM**

**30 systems, mostly between redshift $0.2 < z < 0.6$
plus two at $z > 0.8$,
containing 72 pieces of structure in total**

**EXISTENCE of DARK MATTER is
Reaffirmed:**

**Observations that do not presuppose
the existence of dark matter show that**

clusters of galaxies with 10^{14} Msun

**contain only 3.2% of their mass
in the form of stars.**

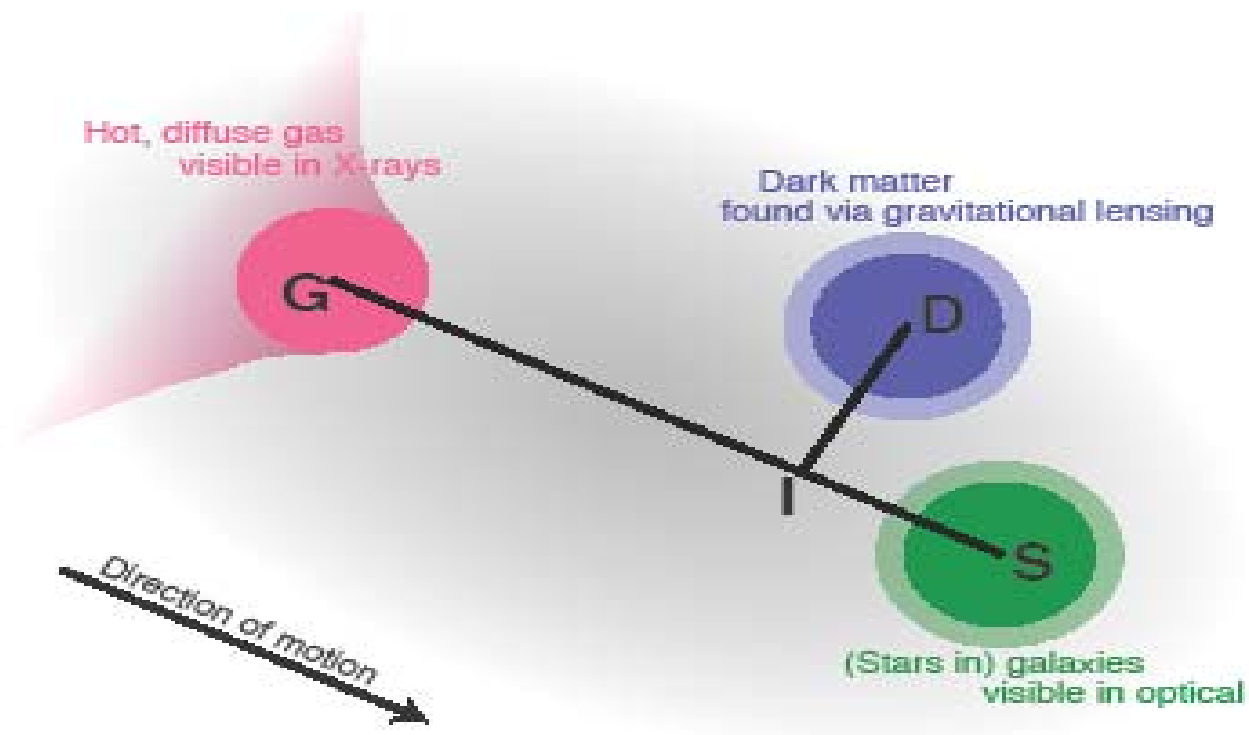


Figure 1: Cartoon showing the three components in each piece of substructure, and their relative offsets, illustrated by black lines. The three components remain within a common gravitational potential, but their centroids become offset due to the different forces acting on them, plus measurement noise. We assume the direction of motion to be defined by the vector from the diffuse, mainly hydrogen gas (which is stripped by ram pressure) to the galaxies (for which interaction is a rare event). We then measure the lag from the galaxies to the gas δ_{SG} , and to the dark matter in a parallel δ_{SI} and perpendicular δ_{DI} direction.



Le suivi d'une collision galactique au moyen du Très Grand Télescope de l'ESO et du Télescope Spatial Hubble du consortium NASA/ESA a permis de collecter des informations sur **la matière noire**.



En combinant les données du VLT de l'ESO au Chili aux images acquises par le télescope spatial Hubble, la collision simultanée de quatre galaxies au sein de l'amas Abell 3827 a été étudiée.

Elle a notamment été en mesure de localiser la matière contenue au sein de ce système et de comparer la **distribution de matière noire** aux positions occupées par les galaxies lumineuses.

A
SUIVRE....

The equation of state of galaxies

We have derived **the equation of state** of galaxies, that is the relation between pressure and density, and provided its analytic expression :

$$P(r) = V^2(r) \rho(r)$$

Two regimes for galaxies emerge :

(i) Large dilute galaxies for $M_h > 2,3 \cdot 10^6 M_{\text{sun}}$ and effective temperatures $T_0 > 0,017 \text{ K}$ described by the classical Boltzmann gaz selfgravitational with local ideal gaz equation of state at each point (r-dependent).

(ii) Compact dwarf galaxies for $1,6 \cdot 10^6 M_{\text{sun}} > M_h > M_{\{h, \text{min}\}} = 30000 (2\text{keV} / m)^{\{16/5\}} M_{\text{sun}}$, $T_0 < 0,011 \text{ K}$ described by the fermion WDM quantum regime with an equation of state more steep near (but not at) the degenerate state. In particular, the denerated limit $T_0 =$ or extreme quantum limit yields **the more compact and smallest galaxy**. Moreover, in the dilute regime: the halo radius r_h the v_2 and the temperature T_0 show scaling laws in terms of M_h . The amplitudes of these analytic scaling laws have been

proch, mais pas exactement à l'état dégénéré).

→ The normalized density and velocity profiles are universal functions of r / r_h . Thus, the scaling laws and the universality appearing in the dilute classical regime of large galaxies are linked to the ideal gaz behaviour of WDM in this regime.

→ These results and the theoretical rotation curves remarkably reproduce for $r < r_h$ the galaxy observations.

→ In the compact regime of small galaxies the equation of state depends on the mass of each galaxy, the density and velocity profiles are not anymore universal, this reflects the quantum physics of the WDM fermions in the compact regime (which generically are near but not at exactly the degenerate limit-state)

The Distribution Function of Dark Matter

- We developed inverse methods allowing to determine **the distribution function $f(E)$** from the real density profiles obtained from observations or from numerical simulations:
- Thus, we have found **the distribution function $f(E)$ of galaxy DM halos and the corresponding equation of state from the DM observed density profiles**.
- That is to say, we have solved for galaxies the analogue of the integral Eddington equation of the gaz of stars in globular clusters. **The observed density profiles are a realistic starting point**, thus the $f(E)$ obtained from them are **realistic fonctions**.

NEW RESULTS

(i) CORED density profiles produce distribution functions which are finite and positives at the center , while cusped density profiles with "cusps" growing as $1/r$ or more, always produce distribution functions which are divergent at the center.

(ii) The observed CORED density profiles produce distribution functions which are very near the THERMAL Boltzmann distributions for $r < 3 r_h$. (r_h being the halo radius).

(iii) The analytic expresions for the dispersion velocity and the pressure are derived, they verify the ideal gaz equation of state for the DM with a local temperature
$$T(r) = mv^2 (r) / 3.$$

T (r) is slowly variable and turns out to be constant in the same region where the distribution function is thermal.

(iv) The DM halos can be consistently considered as being in Local Thermal Equilibrium with a temperature

$$T(r) = T_0 \text{ constant for } r < 3 r_h,$$

$$\text{and } T(r) = mv^2(r) / 3$$

$$\text{for } 3 r_h < r < R_{\text{viriel}},$$

which slowly decreases with r .

That is to say, for $r < R_{\text{viriel}}$,

the DM halo is a Self-Gravitant

Thermal Gaz without collisions.

(v) In the external halo region $T(r)$ follows nicely the decreasing of the squared circular velocity

The DM in the halos of galaxies is thermalized

- All these results show robustly that the DM self-gravitating gas can thermalize in despite of being collisionless:
- This is due to the gravitational interaction between the DM particles and to the fact that this is an ergodic system.
- The collisionless self-gravitating gas is an isolated system which is not integrable.
- Namely, the particle trajectories explore ergodically the constant energy manifold in phase-space, covering it uniformly according to precisely the microcanonical measure and yielding to a thermal situation

- **Physically, these phenomena can be clearly understood :**

- **In the inner halo region the density is higher than beyond the halo radius.**

The gravitational interaction in the inner region is strong enough and thermalizes the self-gravitating gas of DM particles

while beyond the halo radius the particles are too dilute to thermalize, namely, although they are virialized, they had not enough time to accomplish thermalization.

The DM in the galaxy halos is thermalized II

- **Virialization always starts before than thermalization.**
- **In the process of thermalization there is an energy transfer flow of potential energy into kinetic energy.**
- **Clearly, in the outside halo region we find that the kinetic energy is lower than in the inside the region thermalization is already achieved.**
- **And All these results are consistent with the result found : The local temperature $T(r)$ in the outside halo region is lower than the temperature inside the halo region where thermalization is achieved.**

WARM DARK MATTER REPRODUCE

→ OBSERVED GALAXY DENSITIES
AND VELOCITY DISPERSIONS

→ SOLVES the OVERABUNDANCE (“satellite”) PROBLEM

-> OBSERVED SURFACE DENSITY VALUES OF DARK MATTER DOMINATED GALAXIES

→ OBSERVED GALAXY
CORED DENSITY PROFILES : QUANTUM
MECHANICS

• **WDM OVERALL CONCLUSION**

- **To conclude, we find it is highly remarkable that in the context of warm dark matter, the quantum description provided by this semiclassical framework, (quantum WDM and classical gravitation), is able to reproduce such broad variety of galaxies.**
- **The resulting galaxy, halo radius, galaxy masses and velocity dispersion are fully consistent with observations for all different types of galaxies. Fermionic WDM treated quantum mechanically, as it must be, is able to reproduce the observed galactic cores and their sizes. In addition, WDM simulations produce the right DM structures in agreement with observations for scales $>$ kpc.**

WDM + BARYONS

Baryons have not been included in this study. This is fully justified because on one hand **dwarf compact galaxies are composed today 99.99 % of DM, and** on the other hand **the baryon fraction in large galaxies can reach values up to 1 - 3 %.**

Since Fermionic WDM by itself produces galaxy main properties and structures in agreement with observations for all types of galaxies, masses and sizes, the effect of including baryons is expected to be a small correction to these pure WDM galaxy structural results, consistent with the fact that dark matter is in average six times more abundant than baryons.

- *Science is built up with facts,*
 - *as a house is with stones.*
- *But a collection of facts is no more a science*
 - *than a heap of stones is a house.*

-- **Henri Poincaré**

- *La science est construit avec des faits,*
- *ainsi comme une maison est construite*
 - *avec des pierres.*
- *Mais une collection de faits n'est pas une science, ainsi comme un tas de pierres n'est pas une maison.*

END

THANK YOU FOR YOUR ATTENTION

