

Dernières Nouvelles de l'Univers



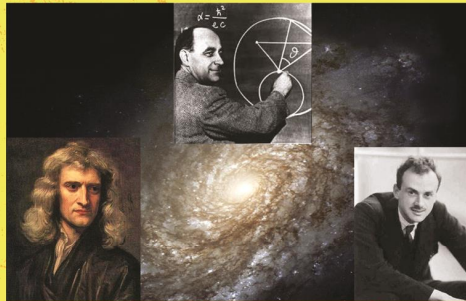
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DR CNRS, LERMA Observatoire de Paris
Ecole Internationale Daniel Chalonge

Open Session 26 MARS 2015

Observatoire de Paris



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'Eté 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 NOVEMBER 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. CNUIDDE, 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. PERISSA, and other colleagues



CONTENT OF THE UNIVERSE

ATOMS, the building blocks of stars and planets:
represent only the **4.6%**

DARK MATTER comprises **23.4 %** of the universe.
This matter, different from atoms, does not emit or absorb
light. It has only been detected indirectly by its gravity.

72% of the Universe, is composed of **DARK ENERGY**
that acts as a sort of an anti-gravity.
This energy, distinct from dark matter, is responsible for
the present-day acceleration of the universal expansion,
compatible with cosmological constant

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**

HIGHLIGHTS

(I) The Effective (Ginsburg-Landau) Theory of Inflation

PREDICTIONS vs Observations:

The Primordial Cosmic Banana: non-zero amount of primordial gravitons. And Forecasts for CMB exps.

NEW: BICEP2 !!!

(II) : TURNING POINT IN THE DARK MATTER

PROBLEM: DARK MATTER IN GALAXIES from

Theory and Observations: Warm (keV scale) dark matter

Physical Clarification and Simplification

GALAXY FORMATION AND EVOLUTION IN

AGREEMENT WITH OBSERVATIONS

naturally re-insert in COSMOLOGY (LWDM)

Analytical Results and Numerical

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.

-> Recent study : Destri, de Vega, Sanchez, (New Astronomy 22, 39, 2013) suggest that 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.

-> 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-

É Astronomical observations show that the **DM galaxy density profiles are cored**, that is, profiles which are flat at the center.

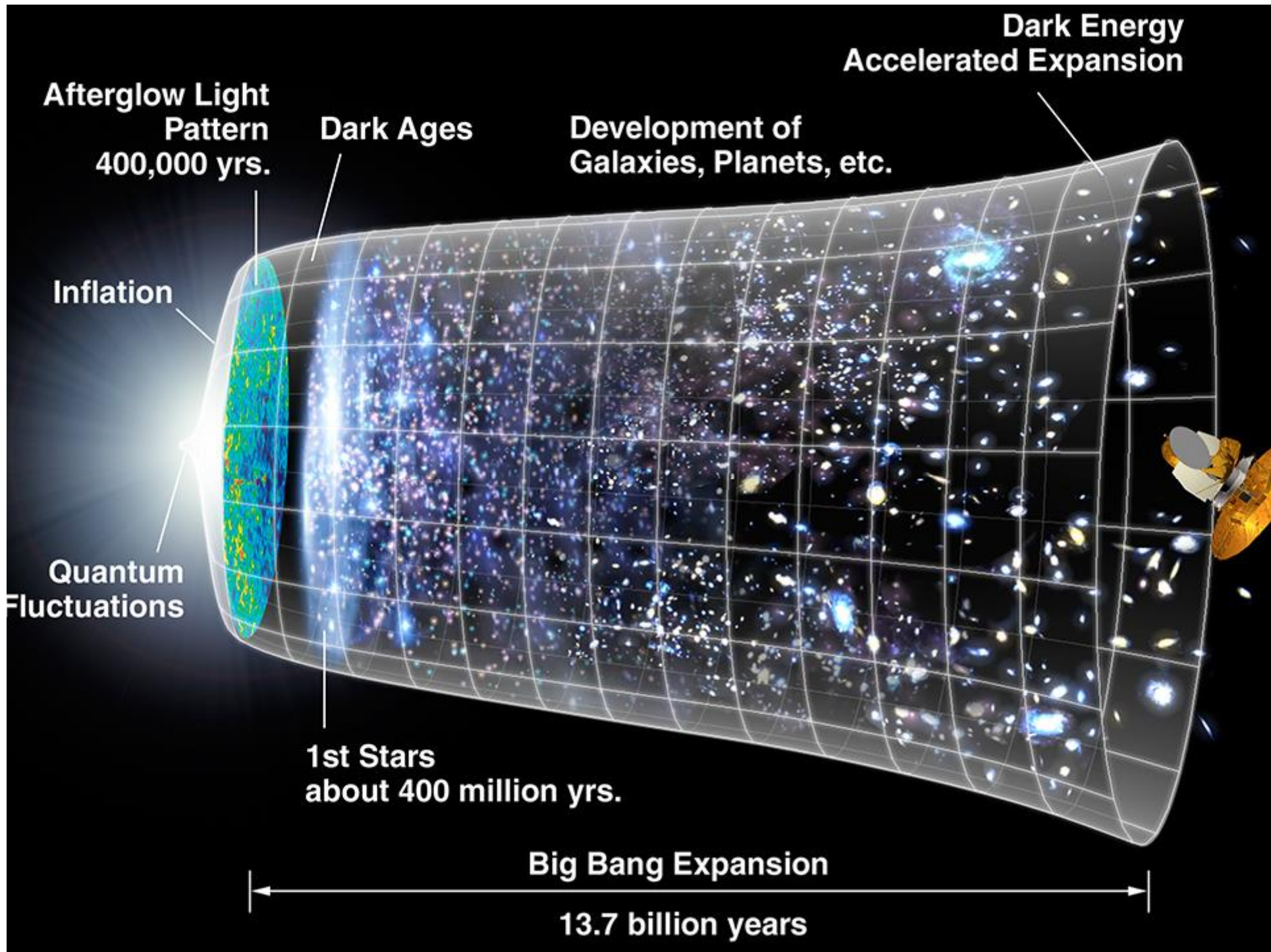
On the contrary, **N-body CDM simulations exhibit cusped density profiles**, with a typical $1/r$ cusped behaviour near the galaxy center $r = 0$.

Classical 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**.

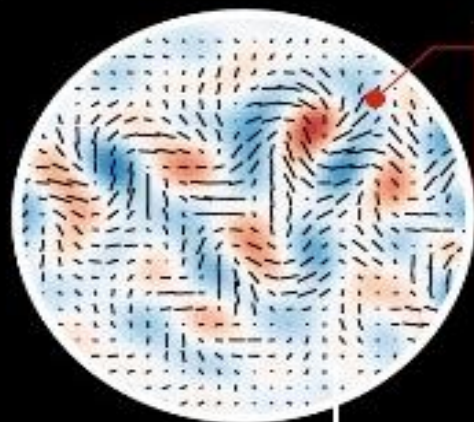
É **Fermions** always provide a non vanishing **pressure of quantum nature** due to the combined action of the Pauli exclusion principle and Heisenberg uncertainty principle.

É **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.**



An echo of the Big Bang

US scientists have detected gravitational waves, the first direct evidence of a super-rapid expansion of the universe known as cosmic inflation



The gravitational waves rippling through the universe after inflation gave a “twisting” pattern in the polarisation of the CMB*



Observed by the BICEP2 telescope stationed at the South Pole

- × Predicted by Albert Einstein’s theory in 1915
- × Cosmic inflation first proposed by US scientists Alan Guth in 1980

Cosmic inflation

A burst of exponential growth in less than the blink of an eye

BIG BANG

*Cosmic Microwave Background, or CMB, (light that spread across space)
380,000 years

EXPANSION OF THE UNIVERSE
13.77 billion years

First stars

Formation of galaxies, planets

Sources: Nasa, Bicep2

AFP

Quantum Fluctuations During Inflation and after

The Universe is homogeneous and isotropic after inflation thanks to the fast and **gigantic** expansion stretching lengths by a factor $e^{62} \simeq 10^{27}$. By the end of inflation: $T \sim 10^{14}$ GeV.

Quantum fluctuations around the classical inflaton and FRW geometry were of course **present**.

These inflationary quantum fluctuations are the **seeds** of the structure formation and of the CMB anisotropies today: galaxies, clusters, stars, planets, ...

That is, our present universe **was built** out of inflationary quantum fluctuations. CMB anisotropies spectrum:

$$3 \times 10^{-32} \text{cm} < \lambda_{\text{begin inflation}} < 3 \times 10^{-28} \text{cm}$$

$$M_{\text{Planck}} \gtrsim 10^{18} \text{ GeV} > \lambda_{\text{begin inflation}}^{-1} > 10^{14} \text{ GeV.}$$

total redshift since inflation begins till today = 10^{56} :

$$0.1 \text{ Mpc} < \lambda_{\text{today}} < 1 \text{ Gpc}, \quad 1 \text{ pc} = 3 \times 10^{18} \text{ cm} = 200000 \text{ AU}$$

**THE ENERGY SCALE OF INFLATION IS THE
THE SCALE OF GRAVITY IN ITS SEMICLASSICAL
REGIME**

**(OR THE SEMICLASSICAL GRAVITY
TEMPERATURE)**

(EQUIVALENT TO THE HAWKING TEMPERATURE)

**The CMB allows to observe it
(while is not possible to observe for Black Holes)**

The Energy Scale of Inflation

Grand Unification Idea (GUT)

- Renormalization group running of electromagnetic, weak and strong couplings shows that they **all meet** at $E_{GUT} \simeq 2 \times 10^{16}$ GeV
- Neutrino masses are explained by the **see-saw** mechanism: $m_\nu \sim \frac{M_{\text{Fermi}}^2}{M_R}$ with $M_R \sim 10^{16}$ GeV.
- Inflation energy scale: $M \simeq 10^{16}$ GeV.

Conclusion: the GUT energy scale appears in at least **three** independent ways.

Moreover, moduli potentials: $V_{\text{moduli}} = M_{\text{SUSY}}^4 v \left(\frac{\phi}{M_{\text{Pl}}} \right)$
resemble inflation potentials provided $M_{\text{SUSY}} \sim 10^{16}$ GeV.
First observation of SUSY in nature??

From WMAP9 to Planck

Understanding the direction in which data are pointing:

É PREDICTIONS for Planck

É Standard Model of the Universe

É Standard Single field Inflation

É NO RUNNING of the Primordial Spectral Index

É NO Primordial NON GAUSSIANTY

É N_{eff} neutrinos : --> Besides meV active neutrinos:

É 1 or 2 sterile neutrinos

É Would opens the sterile neutrino Family:

É keV sterile neutrino óWDM-

ÉLarge Hadron Collider

É The first LHC results at 7-8 TeV, with the discovery of a candidate 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.**

É 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 signal) So far researchers who are racing to

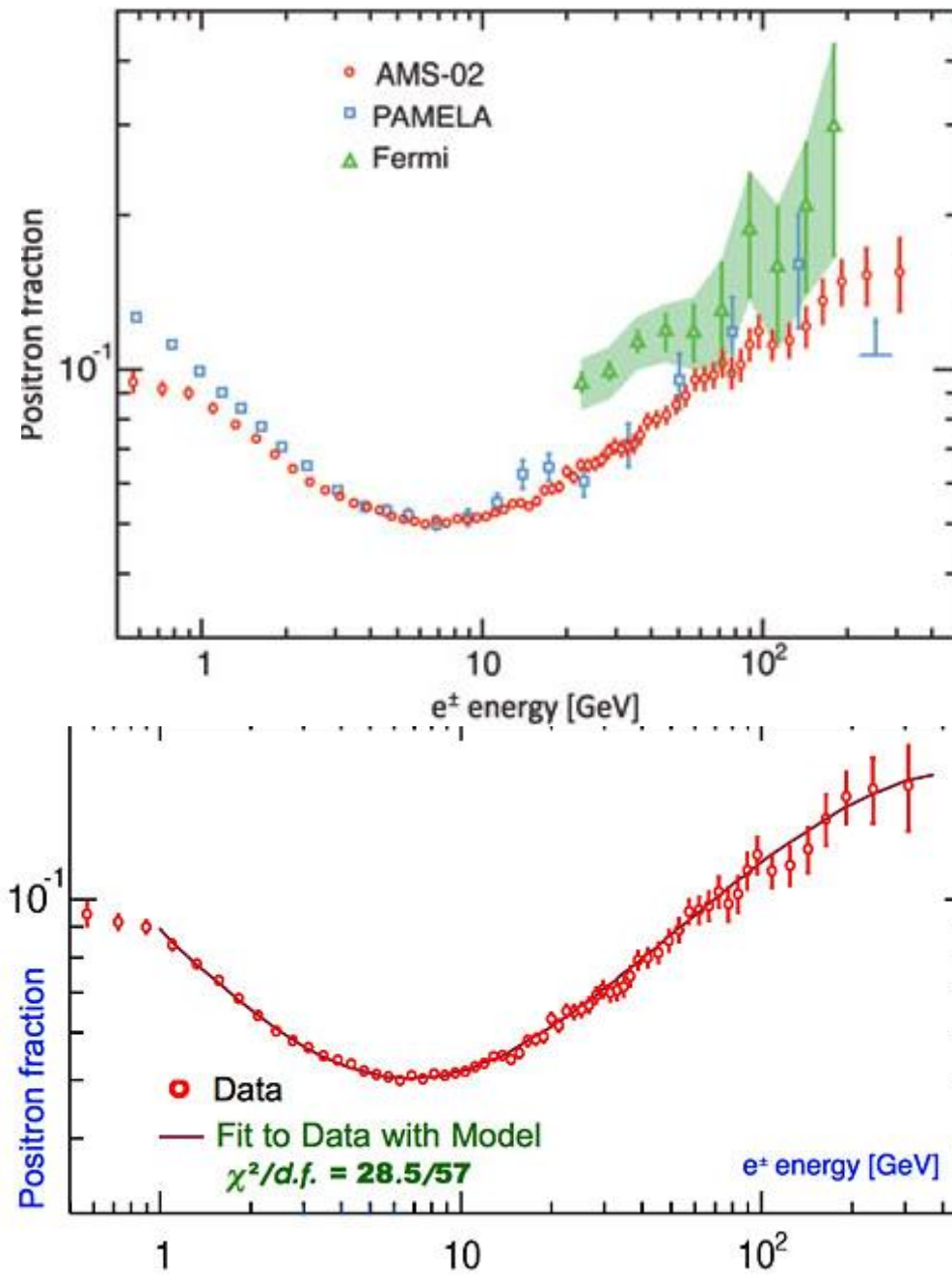
find evidence of so called "new physics", ie non-
standard models, have run into a series of dead ends.

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

LHC
AMS
PLANCK

Three beautiful and big experiments of performant instruments, technology, industry, achievements and successful operation which do not find the main scientific objective emphasized by them (for which they were designed)

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

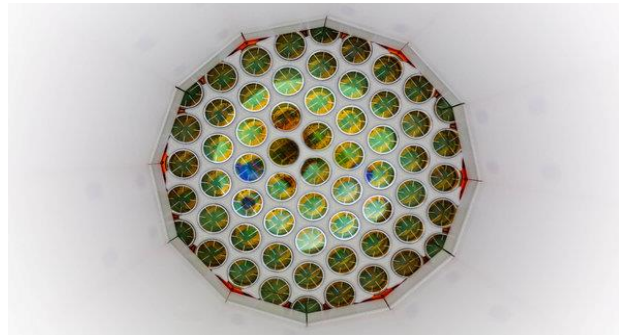
É Because:

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



É **They found no sign of WIMPS signals.**

beyond the expected background noise.

É The experiment did so at far better sensitivities

than any such experiment before it.

É First dark matter search results from Chinese underground lab hosting

É PandaX-I experiment

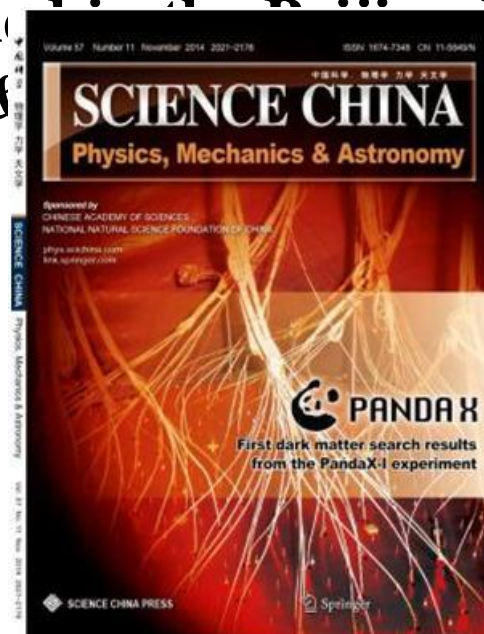
É 30 SEPTEMBER 2014

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*.

É **NEGATIVE RESULTS**

É **for Wimps**

É **China Science Press**

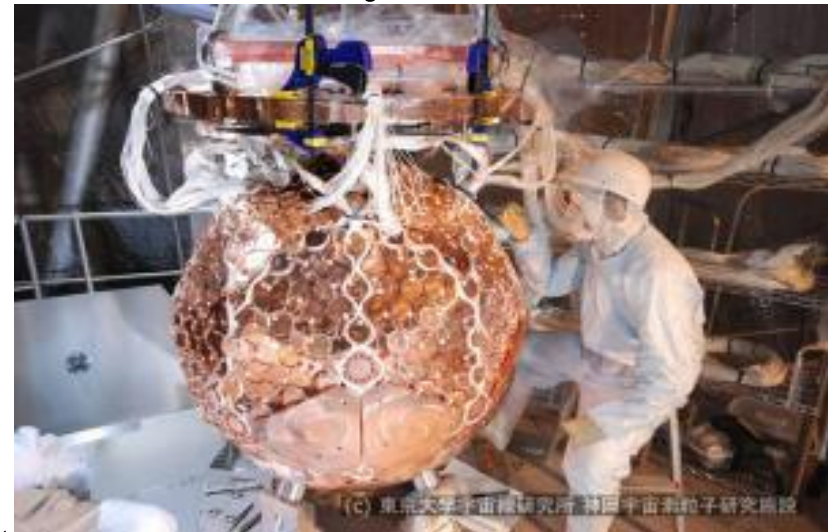


É **XMASS Recent News: October 6, 2014**

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 EditorsøSuggestion.**

NEGATIVE RESULTS for WIMPS



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

Planck et la matière noire, 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.

LHC
AMS
PLANCK

Three beautiful and big experiments of performant instruments, technology, industry, achievements and successful operation which do not find the main scientific objective emphasized by them (for which they were designed)

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. Haserkamp, JCAP,10,044H (2013) R. Battye & A. Moss, PRL 110, 051302 (2013) G. Covone et al. MNRAS 434, 1011 (2013)

Planck et les Paramètres cosmologiques

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 et les Neutrinos

É **At early times:** CMB sensitive to radiation The radiation density other than photons is described by the **parameter N_{eff} :** $\rho_{\text{rad}} = C(N_{\text{eff}})$ photons.

É **At late times:** CMB sensitive to neutrino masses

É **The Priors in the Planck analyse:**

É **Standard value for $N_{\text{eff}}= 3.046$, 3 active neutrinos**

□ **$\Sigma m_{\nu} = 0.06$ eV (1 massive, the other massless)**

É **This is the source of the conflict with the values of H_0 , lensing and clusters (σ_8)**

Planck et les Neutrinos. 2

É Une analyse plus fine que celle fait par Planck sur les données Planck 2013 a été faite par plusieurs groupes différents et donne N_{eff} compatible avec **4 neutrinos = les 3 actifs connus + 1 stérile et les paramètres cosmologiques sans tensions avec les autres observations .**

É

Donc, les données Planck 2014 pourront être a nouveau ré-analyses par d'autres teams et N_{eff} et les valeurs des paramètres cosmologiques corrigés.

Planck et les Neutrinos.3

- É → 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**).
- É → 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).
- É → **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.... —

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

$$r > 0.021$$

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

BICEP2 result 2014: r about 0.20-0.16

THE PRIMORDIAL GRAVITONS

LOWER BOUND on r (2008)

Our theory input (Effective Theory Inflation) in the MCMC data analysis of WMAP5+LSS+SN data).

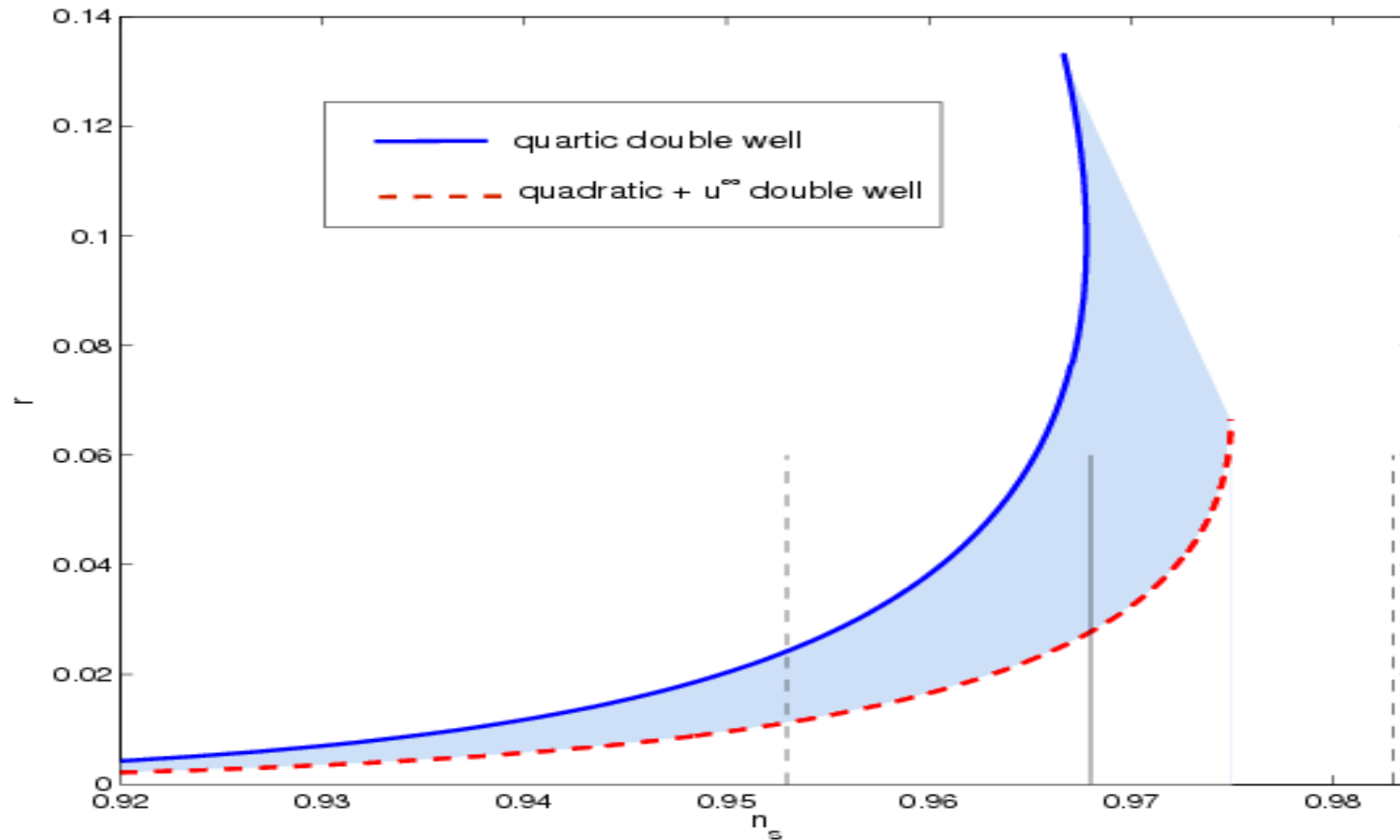
C. Destri, H J de Vega, N G Sanchez, Phys Rev D77, 043509 (2008) shows:

Besides the upper bound for r (tensor to scalar ratio) $r < 0.22$, we find a clear peak in the r distribution and we obtain a lower bound

$$\begin{aligned} r &> 0.023 \text{ at } 95\% \text{ CL and} \\ r &> 0.046 \text{ at } 68\% \text{ CL.} \end{aligned}$$

For the other cosmological parameters, both analysis agree.

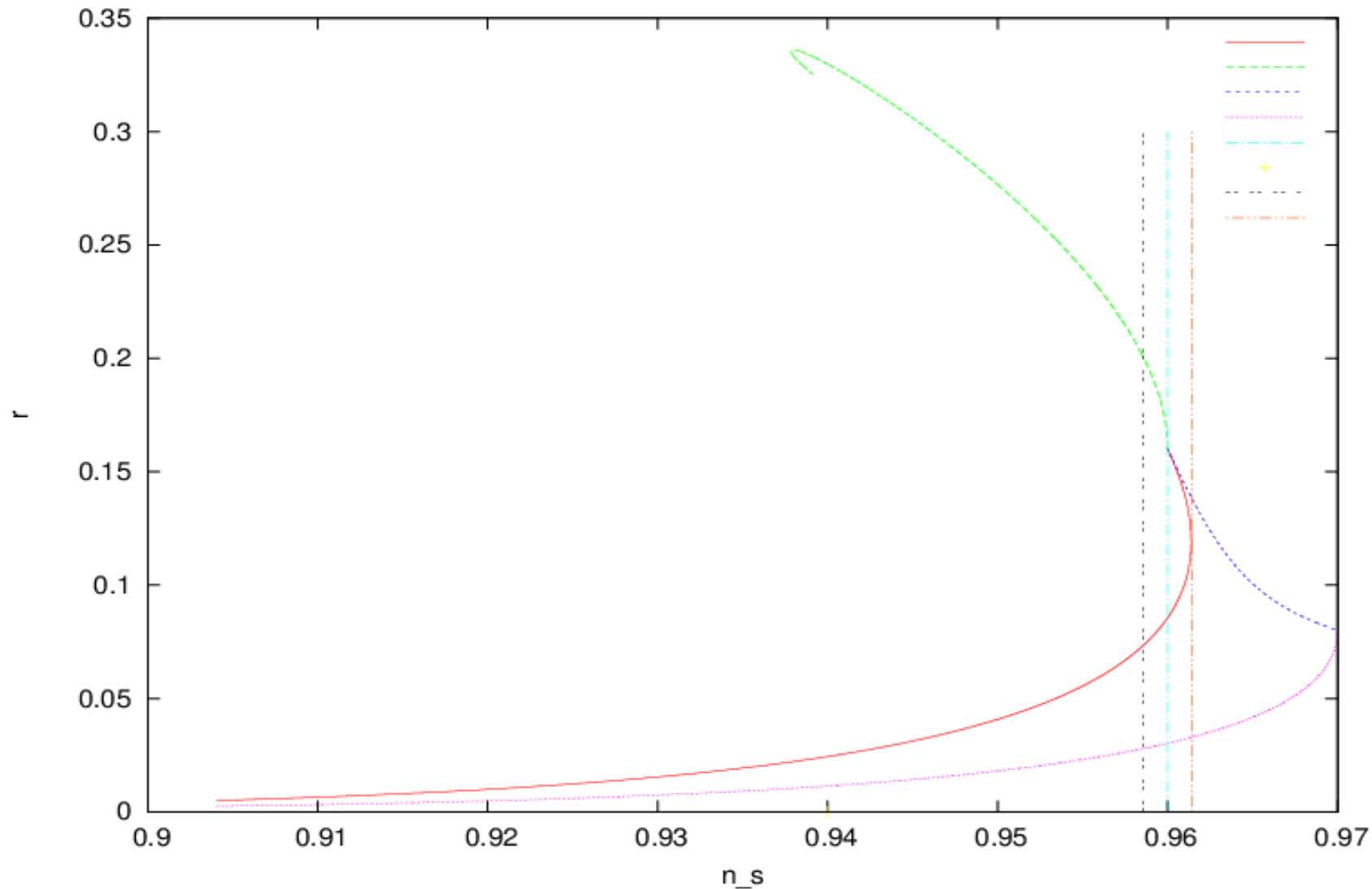




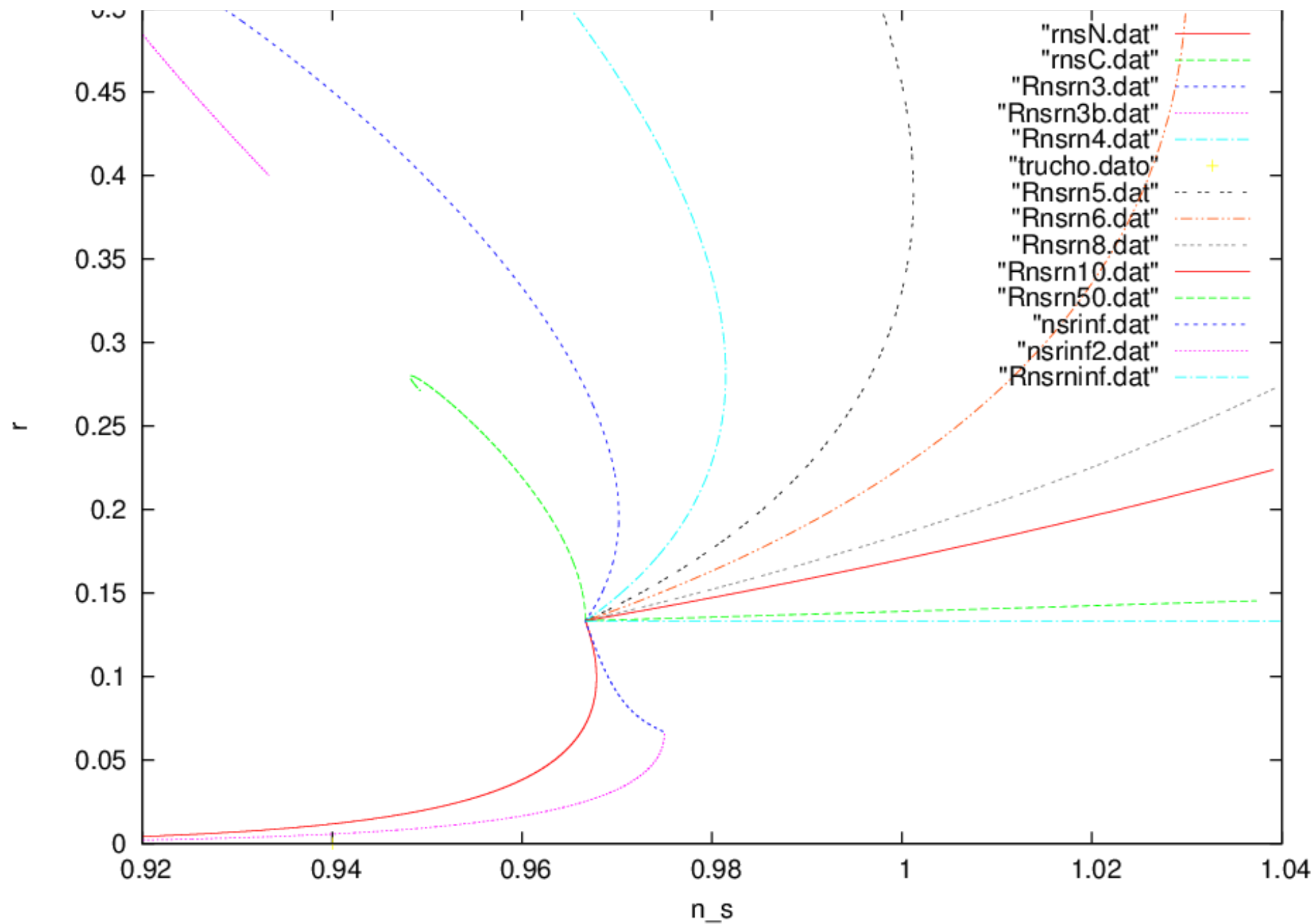
THE PRIMORDIAL COSMIC BANANA

The tensor to scalar ratio r (primordial gravitons) versus the scalar spectral index n_s . **The amount of r is always non zero**
H.J. de Vega, C. Destri, N.G. Sanchez, *Annals Phys* 326, 578(2011)

Single and Double Well Inflaton Potentials



The **cosmic banana** for double well potentials ($N=50$).
 $n_s = 0.96 \pm 0.014$ Planck + BAO + sterile (Melchiorri et al.)



Dark Matter Particles

DM particles decouple due to the universe expansion, their distribution function **freezes out** at decoupling.

The characteristic length scale is the **free streaming scale** (or Jeans' scale). For DM particles decoupling UR:

$$r_{Jeans} = 57.2 \text{ kpc} \frac{\text{keV}}{m} \left(\frac{100}{g_d} \right)^{\frac{1}{3}}, \text{ solving the linear Boltz-V eqs.}$$

g_d = number of UR degrees of freedom at decoupling.

DM particles can **freely** propagate over distances of the order of the free streaming scale.

Therefore, structures at scales smaller or of the order of r_{Jeans} are **erased**.

The size of the DM galaxy cores is in the ~ 50 kpc scale $\Rightarrow m$ should be in the keV scale (WDM particles).

For neutrinos $m \sim \text{eV}$ HDM particles

$r_{Jeans} \sim 60 \text{ Mpc} \Rightarrow$ **NO GALAXIES FORMED.**

Dark Matter: from primordial fluctuations to Galaxies

❖ **Cold (CDM)**: small velocity dispersion: small structures form first, **bottom-up** hierarchical growth formation, *too heavy (GeV)*

❖ **Hot (HDM)** : large velocity dispersion: big structures form first, **top-down**, fragmentation, ruled out, *too light (eV)*

Warm (WDM): ``in between'' *right mass scale, (keV)*

ΛWDM Concordance Model:

CMB + LSS + SSS Observations

DM is WARM and COLLISIONLESS

CDM
Problems:

- { clumpy halo problem → large number of satellite galaxies
- { "satellite problem", overabundance of small structures
- ρ(r) ~ 1/r (cusp)
- And other problems ..

WARM DARK MATTER REPRODUCE

→ OBSERVED GALAXY DENSITIES
AND VELOCITY DISPERSIONS

→ OBSERVED GALAXY
CORED DENSITY PROFILES

-> OBSERVED SURFACE DENSITY VALUES OF
DARK MATTER DOMINATED GALAXIES

→ SOLVES the OVERABUNDANCE ($\tilde{\sigma}$ satellite)
PROBLEM and the CUSPS vs CORES Problem

É WDM OVERALL CONCLUSION

- É 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.**
- É 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.**

H. J. de Vega, N. G. Sanchez:
BLACK HOLES FORMED
by WDM and BARYONS

(GALACTIC SUPERMASSIVE, STELLAR)

Galaxy Structure from Classical Cosmological
Boltzmann-Vlasov equations:
Generalized Larson equations

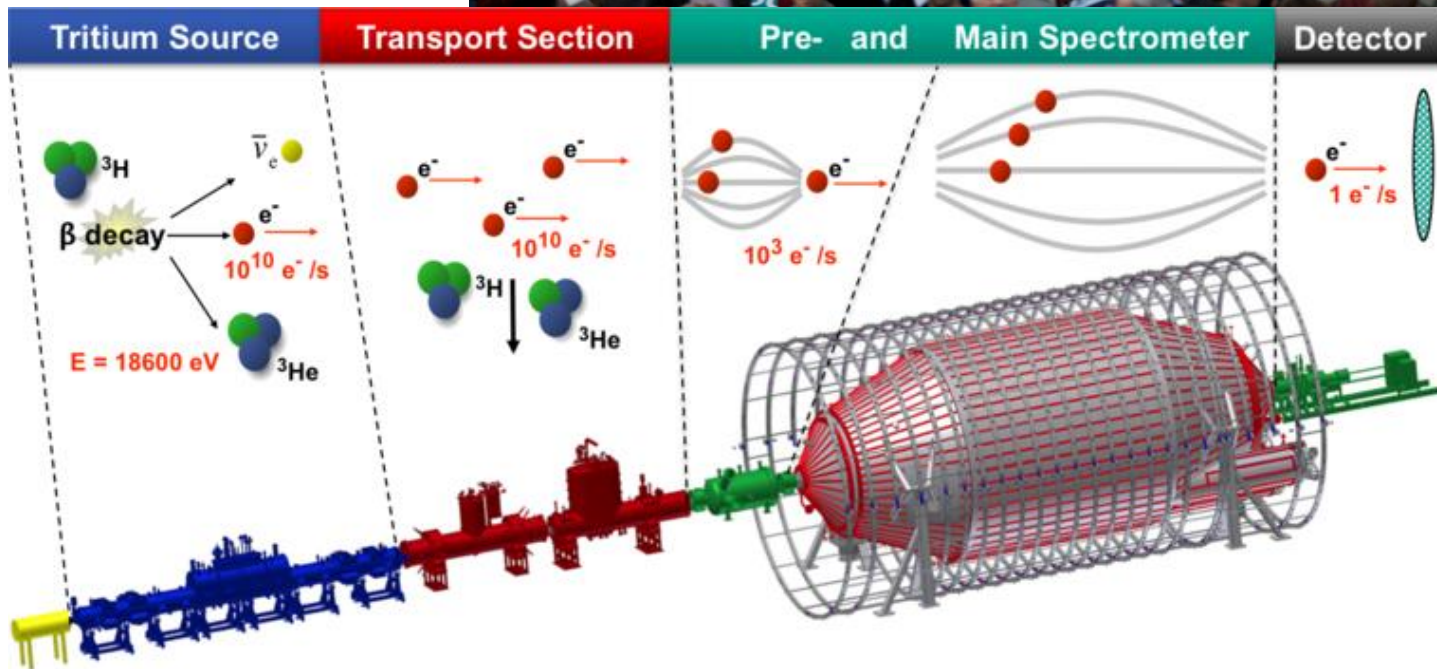
And other resultsÅ ..

keV Sterile Neutrino Warm Dark Matter

Sterile neutrinos can decay into an active-like neutrino and a monochromatic X-ray photon with an energy half the mass of the sterile neutrino. **Observing the X-ray photon provides a way to observe sterile neutrinos in DM halos.**

WDM keV sterile neutrinos can be copiously produced in the supernovae cores. SN stringently constrain the neutrino mixing angle squared to be 10^{-9} for $m > 100$ keV (in order to avoid excessive energy lost) but for smaller masses the SN bound is not so direct. **Within the models worked out till now, mixing angles are essentially unconstrained by SN in the keV mass range.**

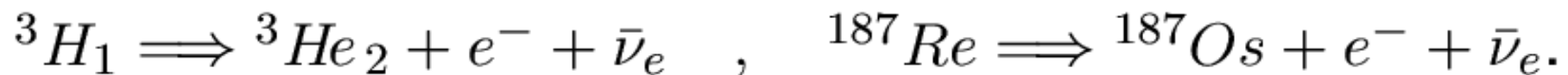
Sterile neutrinos are produced **out of thermal equilibrium** and their production can be non-resonant (in the absence of lepton asymmetries) **or resonantly enhanced** (if lepton asymmetries are present).



How to detect sterile neutrinos?

Sterile neutrinos **can be detected** in beta decay and in electron capture (EC) when a ν_s with mass in the keV scale is produced **instead** of an active ν_e .

Beta decay: the electron spectrum is slightly modified at energies around the mass (\sim keV) of the ν_s .



The electron energy spectrum is observed.



The nonradiative de-excitation of the Dy^* is observed and different for ν_s in the keV range than for active ν_e .

Experiments that may detect **sterile neutrinos**:

MARE (Milano), KATRIN (Karlsruhe), PTOLEMY (Princeton), ECHo (Heidelberg).

They search the mass of the ordinary neutrino.

L'équation d'état des galaxies

Nous avons dérivé **l'équation d'état** pour les galaxies, c'est à dire la relation entre la pression et la densité, et fourni son expression analytique:

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

É **Deux regimes des galaxies émergent :**

(i) Les grandes galaxies diluées pour $M_h > 2,3 \cdot 10^6 M_{\text{sun}}$ et températures effectives $T_0 > 0,017 \text{ K}$ décrites par le gaz de Boltzmann classique autogravitant avec une équation de gaz idéal dépendente de l'espace.

(ii) Les galaxies naines compactes pour $1,6 \cdot 10^6 M_{\text{sun}} > M_h > M_{\{h, \text{min}\}} = 30000 (2\text{keV} / m)^{\{16/5\}} M_{\text{sun}}$, $T_0 < 0,011 \text{ K}$ décrites par le régime de WDM fermionique quantique avec une équation d'état plus raide proche de l'état dégénéré. En particulier, la limite $T_0 = 0$ dégénérée ou limite quantique extrême donne la plus compacte et la plus petite galaxie.

De plus, les grandeurs dans le régime dilué : rayon du halo r_h vitesse au carré et température T_0 présentent des lois d'échelle en termes de la

(proche mais pas exactement à l'état dégénéré)
→ Les profils de densité et des vitesses sont des fonctions universelles de r / r_h quand normalisées à leurs valeurs à l'origine. Ainsi, les lois d'échelle et l'universalité dans les galaxies dans le régime dilué ont été reliées au comportement de gaz parfait WDM dans ce régime.

→ Ces résultats et les courbes de rotation théoriques reproduisent remarquablement pour $r < r_h$ les observations de galaxies.

→ Dans le régime compact des petites galaxies, l'équation d'état dépend de la masse de chaque galaxie, les profils de vitesse et de densité ne sont plus universels. La non-universalité reflète ici la physique quantique des fermions de la WDM dans le régime compact (proche mais pas exactement à l'état dégénéré).

La fonction distribution de la matière noire

Nous avons développée des méthodes inverses permettant de déterminer la fonction de distribution $f(E)$ à partir des données observationnelles ou des simulations numériques: Nous avons trouvé la fonction de distribution $f(E)$ de la matière noire (DM) des halos des galaxies et l'équation de l'état correspondante à partir des profils de densité DM observés.

C'est-à-dire, nous avons résolu pour la DM dans les galaxies l'analogue de l'équation intégrale d'Eddington utilisée au départ pour le gaz des étoiles dans les amas globulaires. Les profils de densité observés sont une base de départ très réaliste, ainsi les fonctions de distribution $f(E)$ qui en découlent sont des fonctions réalistes.

Matière noire. Théorie confrontée aux observations

La matière noire tiède (WDM) est composée des particules avec masse m dans l'échelle du keV ($1 < m < 10$ keV). Pour les grandes échelles, structures (au-delà de ~ 100 kpc) WDM donne des résultats identiques à la DM froide qui sont en accord avec les observations.

Pour les échelles intermédiaires, WDM donne l'abondance correcte des sous-structures. Dans les centres des halos de galaxies, (échelles plus petites que ~ 100 pc), les simulations à N-corps de la physique classique sont incorrectes pour la WDM parce que à ces échelles, les effets quantiques de la WDM sont importants.

Les calculs quantiques semi classiques (approche de Thomas-Fermi) fournissent des centres de galaxies, des dispersions de vitesse et des profils de densité en accord avec les observations. L'approche détermine de façon auto-consistante et non-linéaire le potentiel gravitationnel WDM compte tenu de sa fonction de distribution $f(E)$.

Les principales grandeurs : rayon du halo r_h , masse, M_h , dispersion de vitesse et densité de l'espace des phases ont été exprimées en fonction de la densité de surface, ceci permet de confronter les résultats théoriques à une très grande variété des observations étant donnée le caractère universel (ou quasi universel) de la densité de surface des galaxies.

NOUVEAUX RESULTATS

- (i) **Les profils de densité avec des coeurs** au centre du halo produisent des fonctions de distribution **finies et positives au centre**, tandis que les profils de densité avec des "cusps" **croissant comme $1/r$ ou plus**, produisent toujours des fonctions de distribution **divergentes au centre**.
- (ii) **Les cò urs observés** produisent des fonctions de distribution **proches des distributions de Boltzmann thermiques** pour $r < 3 r_h$, où r_h est le rayon du halo.
- (iii) Les expressions analytiques pour la vitesse de dispersion et la pression sont dérivés vérifiant **l'équation d'état de gaz idéal pour la DM avec une température locale $T(r) = mv^2(r) / 3$** . $T(r)$ est **lentement variable et s'avère constante dans la même région où la fonction de distribution est thermique**.
- (iv) Le halo de DM peut être considéré de façon consistante comme étant à **l'équilibre thermique local** avec une température constante $T(r) = T_0$ pour $r < 3 r_h$, et une température $T(r) = mv^2(r) / 3$ dépendante de l'espace pour $3 r_h < r < R_{\text{viriel}}$, qui diminue lentement avec r . C'est à dire, pour $r < R_{\text{viriel}}$, le halo de DM est **un gaz thermique auto-gravitant sans collisions**
- (v) $T(r)$ à l'extérieur du rayon du halo suit

La matière noire des halos des galaxies est thermalisée

“ Tous ces résultats montrent de façon robuste que le gaz de DM auto-gravitant peut **thermaliser** en dépit d'être sans collisions: Ceci est due à la interaction gravitationnelle entre les particules de DM et au fait que c'est un **système ergodique**:

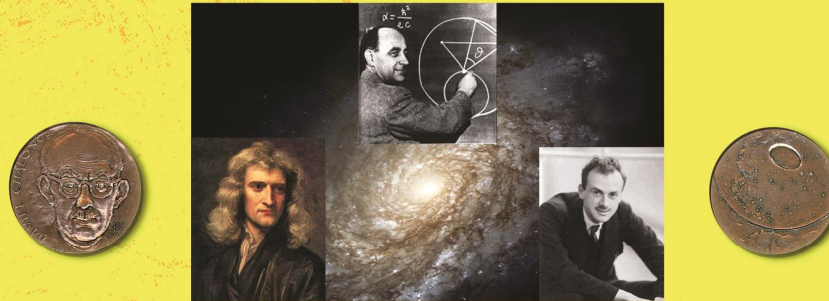
Le gaz auto-gravitant DM sans collisions est un système isolé qui n'est pas intégrable: les trajectoires des particules explorent ergodiquement la variété d'énergie constante dans l'espace des phases, couvrant uniformément et précisément la **mesure microcanonique** donnant comme résultat une **situation thermique**.

“ **Physiquement:** dans la région intérieure du halo le gaz thermalise car la densité est plus supérieure qu'à l'extérieur où les particules sont trop diluées pour thermaliser, même si elles sont virialisées.

La matière noire des halos des galaxies est thermalisée , II

- “ La virialisation commence toujours avant de thermalisation, et dans le processus de thermalisation il y a **flux de transfert d'énergie potentielle en énergie cinétique**.
- “ Dans la région extérieur de r_h l'énergie cinétique est plus faible que dans l'intérieur où la thermalisation est déjà atteinte. **Tout ceci est consistante avec le résultat trouvé:**
- “ . La température locale $T(r)$ à l'extérieur de r_h est bien inférieure à celle de la région interne où la thermalisation est déjà réalisée

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'Eté de Culture Scientifique 2015 : A Surprise Session

AUTOMME 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 NOVEMBER 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.

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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. CNUIDDE, E. VERGNAUD, J. BERTHIER, and other colleagues

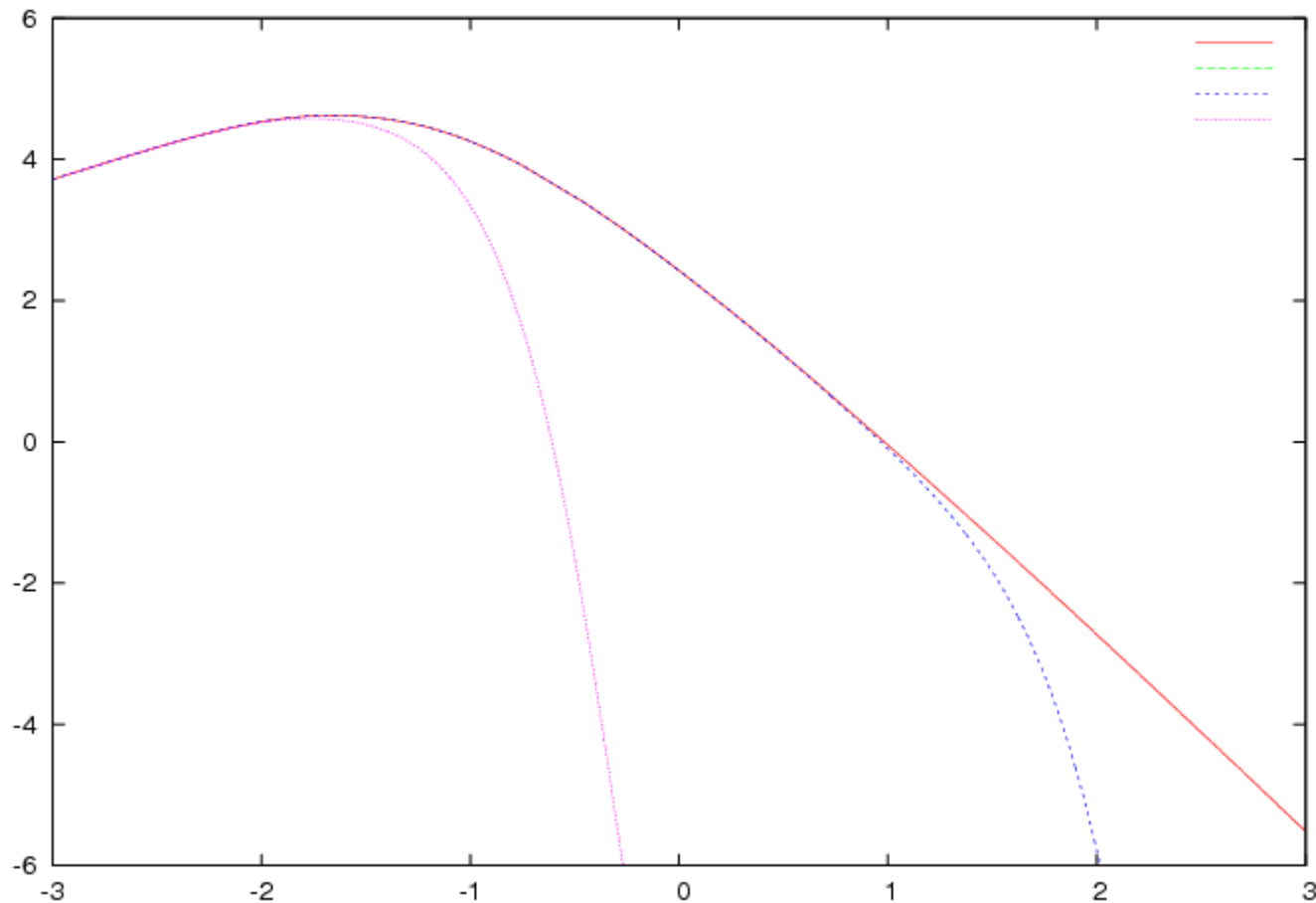
Science Organizers
N. G. SANCHEZ, H. J. DE VEGA, M. C. FALVELLA, A. ZANINI,
M. RAMON MEDRANO, A. PERISSA, and other colleagues



END

THANK YOU FOR YOUR ATTENTION

Linear primordial power today $P(k)$ vs. k Mpc h

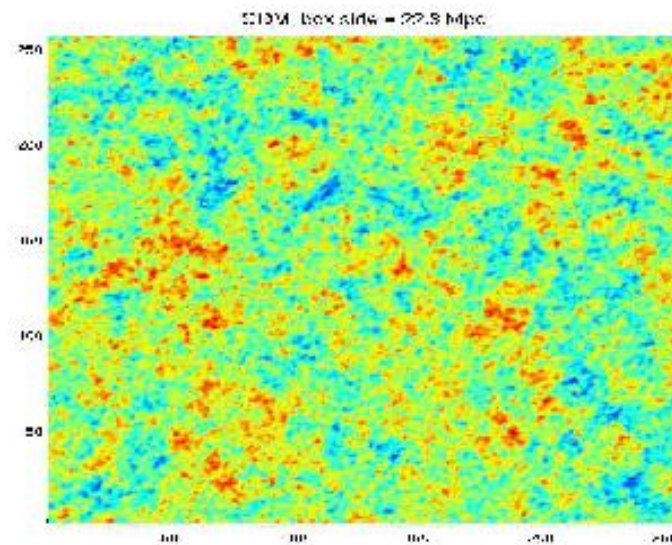


$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for **WIMPS**, **1 keV** DM particles and **10 eV** DM particles. $P(k) = P_0 k^{n_s} T^2(k)$.

$P(k)$ cutted for **1 keV** DM particles on scales $\lesssim 100$ kpc.

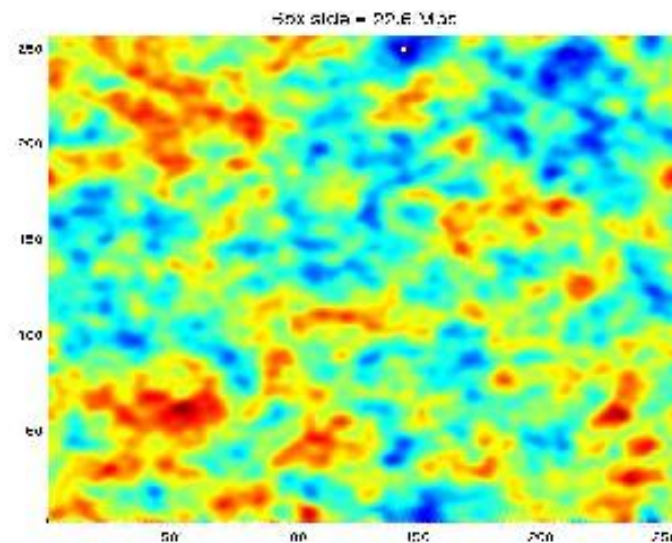
Transfer function in the MD era from Gilbert integral eq

WDM vs. CDM linear fluctuations today



Box side = 22.6 Mpc. [C. Destri, private communication].

WDM



Dwarf galaxies as quantum objects

— de Broglie wavelength of DM particles $\lambda_{dB} = \frac{\hbar}{m \sigma}$ —

d = mean distance between particles,

σ = DM mean velocity

$$d = \left(\frac{m}{\rho} \right)^{\frac{1}{3}}, \quad Q = \rho / \sigma^3, \quad Q = \text{phase space density.}$$

ratio: $\mathcal{R} = \frac{\lambda_{dB}}{d} = \hbar \left(\frac{Q}{m^4} \right)^{\frac{1}{3}}$

Observed values: $2 \times 10^{-3} < \mathcal{R} \left(\frac{m}{\text{keV}} \right)^{\frac{1}{3}} < 1.4$

The **larger** \mathcal{R} is for ultracompact dwarfs.

The **smaller** \mathcal{R} is for big spirals.

\mathcal{R} near unity (or above) means a **QUANTUM OBJECT**.

Observations alone show that compact dwarf galaxies are **quantum objects** (for WDM).

—

The quantum radius r_q for different kinds of DM

DM type	DM particle mass	r_q	
CDM	1 – 100 GeV	$1 - 10^4$ meters	in practice zero
WDM	1 – 10 keV	0.1 – 1 pc	compatible with observed cores
HDM	1 – 10 eV	kpc - Mpc	too big !

RESULTS

All the obtained density profiles are cored.

The Core Sizes are in agreement with the observations

from the compact galaxies where $r_h \sim 20$ pc till the spiral and elliptical galaxies where $r_h \sim 0.2 - 60$ kpc.

The larger and positive is the chemical potential $\nu(0)$, the smaller is the core.

**The minimal one arises in the degenerate case $\nu(0) \rightarrow +\infty$
(compact dwarf galaxies).**

And

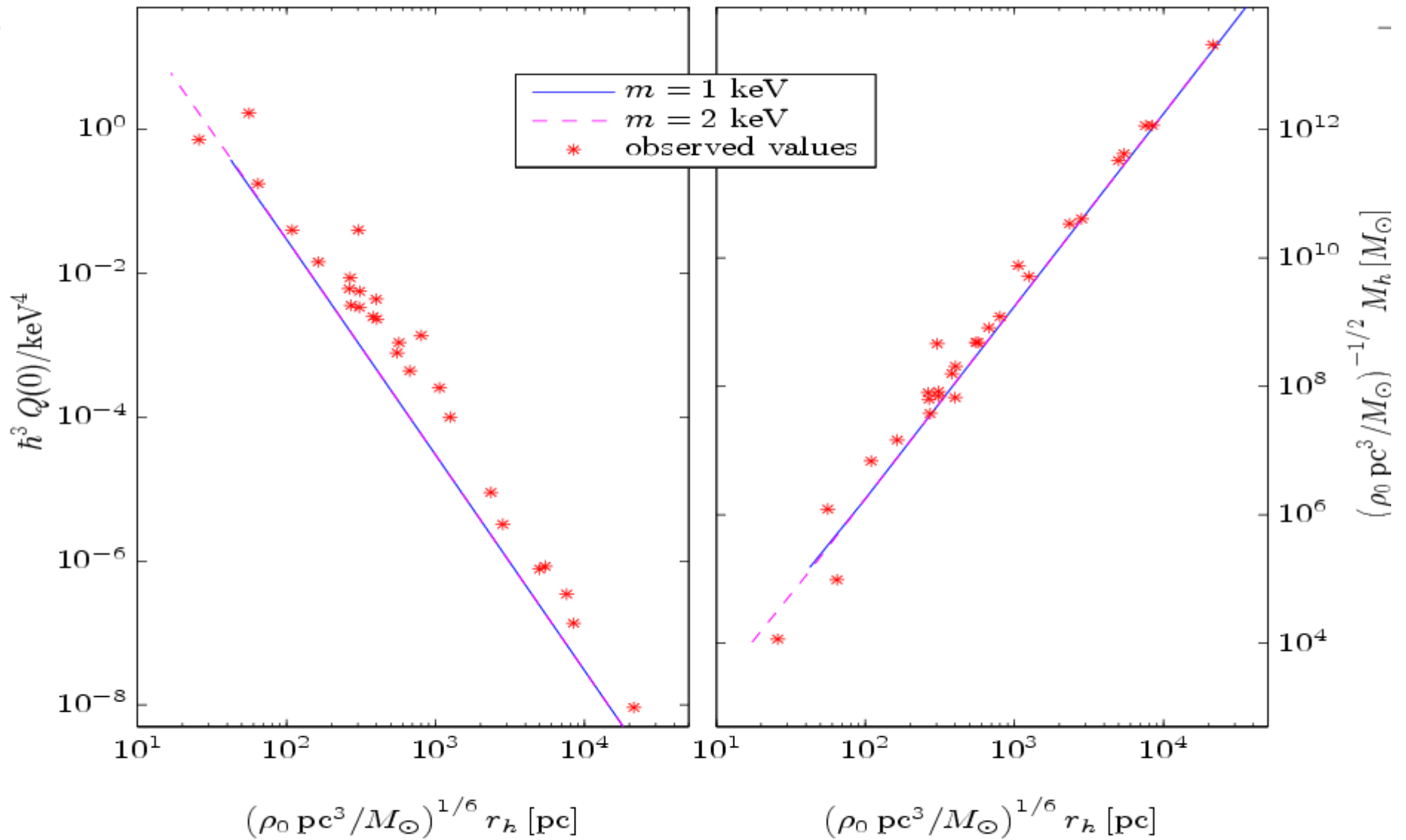
The Phase-space Density

The Galaxy halo Masses.

**Agreement is found in all the range of galaxies
for a DM particle mass m around 2 keV.**

Error bars of the observational data are not shown but they are at least about 10-20 %.

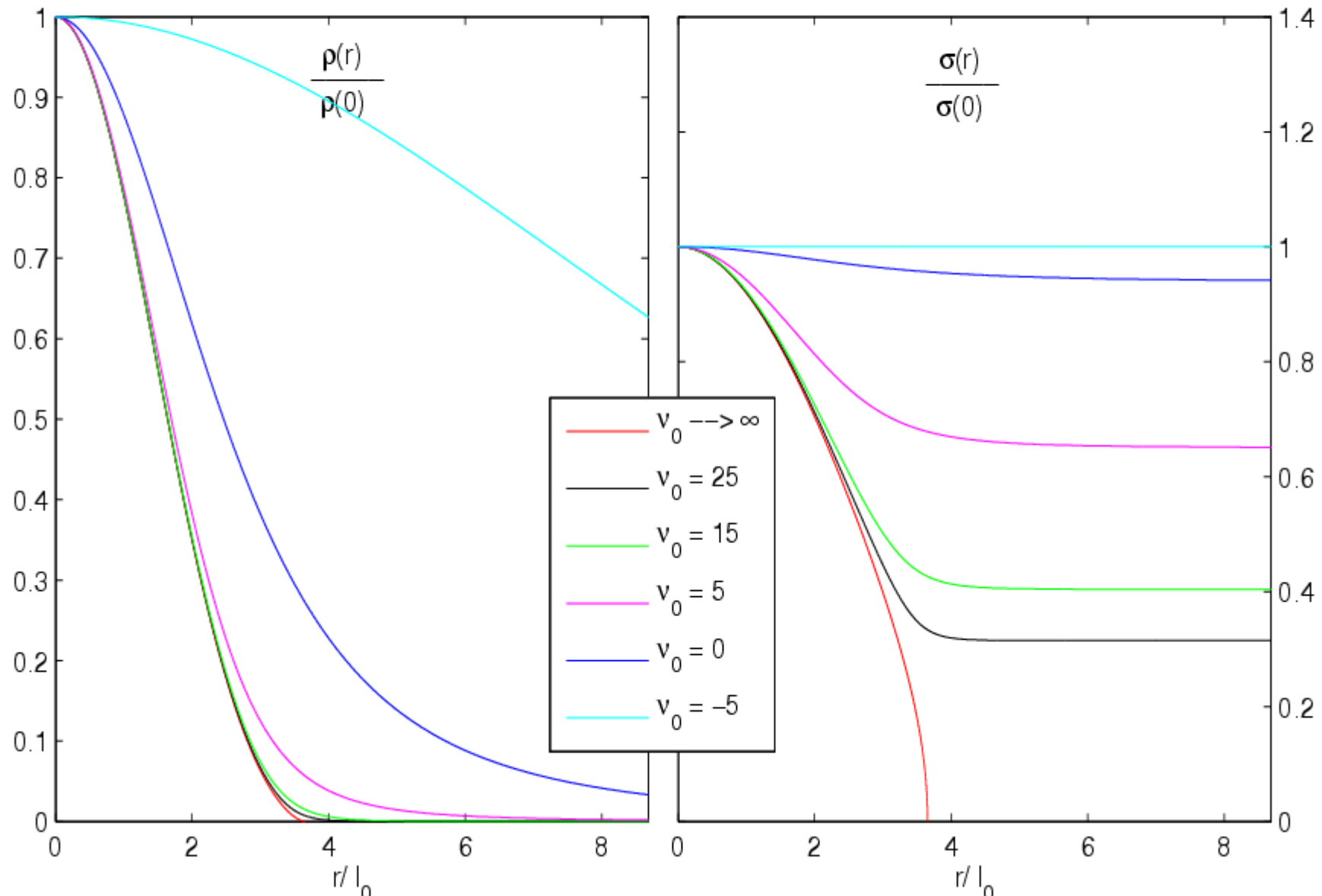
Q vs. halo radius. Galaxy observations vs. Thomas-Fermi



observed $Q = \rho/\sigma^3$ from stars are **upper bounds** for DM Q

Density and velocity profiles from Thomas-Fermi

Cored density profile and velocity profile obtained from Thomas-Fermi.



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.

Minimal galaxy mass from degenerate WDM

—The halo radius, the velocity dispersion and the galaxy mass take their **minimum** values for degenerate WDM: —

$$r_{h \min} = 24.51 \dots \text{ pc} \left(\frac{m}{\text{keV}} \right)^{\frac{4}{3}} \left[\rho(0) \frac{\text{pc}^3}{M_{\odot}} \right]^{\frac{1}{6}}$$

$$M_{\min} = 2.939 \dots 10^5 M_{\odot} \left(\frac{\text{keV}}{m} \right)^4 \sqrt{\rho(0) \frac{\text{pc}^3}{M_{\odot}}}$$

$$\sigma_{\min}(0) = 2.751 \dots \frac{\text{km}}{\text{s}} \left(\frac{\text{keV}}{m} \right)^{\frac{4}{3}} \left[\rho(0) \frac{\text{pc}^3}{M_{\odot}} \right]^{\frac{1}{3}} .$$

These **minimum** values **correspond** to the observations of compact dwarf galaxies.

Lightest known compact dwarf galaxy is Willman I:

$$M_{\text{Willman I}} = 2.9 \cdot 10^4 M_{\odot}$$

Imposing $M_{\text{Willman I}} > M_{\min}$ yields the **lower bound** for the WDM particle mass: $m > 1.91 \text{ keV}$.